Control of Laser-Beam Self-Focusing, Filamentation, and Rogue-Wave Formation Using Structured Light Beams

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The visuals of this talk will be posted at boydnlo.ca/presentations

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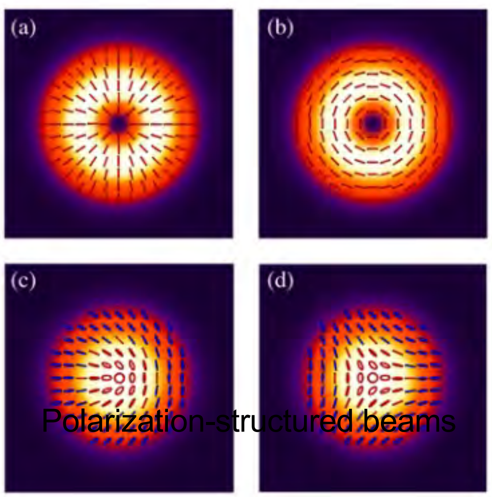
Research Vision

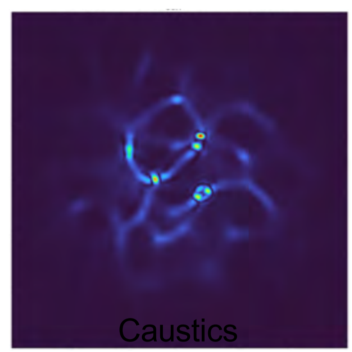
Controlling Laser Filamentation Using Polarization-Structured Light Beams

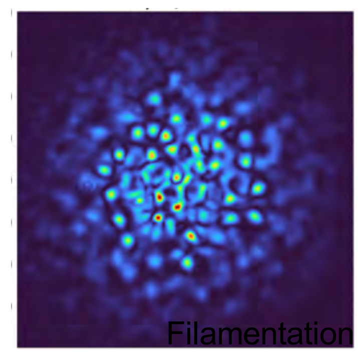
- Suppress filamentation using polarization structured beams.



Polarization-structured beams

- Understand the relation among nonlinear caustic formation, rogue wave formation, and small scale filamentation and how nonlinear propagation affects the spatial coherence of light.


Caustics


Filamentation

[1] Frédéric Bouchard, Hugo Larocque, Alison M. Yao, Christopher Travis, Israel De Leon, Andrea Rubano, Ebrahim Karimi, Gian-Luca Oppo, and Robert W. Boyd, Polarization Shaping for Control of Nonlinear Propagation,, Phys. Rev. Lett. 117, 233903, 2016

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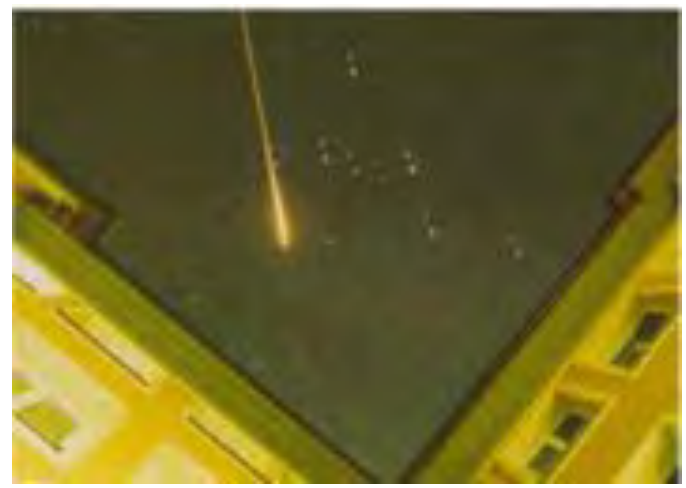
1. Background on self-action effects
2. Control using spatially structured light beams
3. Caustics and rogue waves
4. Control through the spatial spectrum of phase noise
5. Polarization knots

Why Care About Self-Focusing and Filamentation

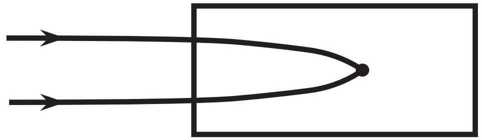
- Applications of NLO
  - Optical switching
  - Laser modelocking
  - Directed energy
- We want to
  - prevent filamentation
  - control self focusing



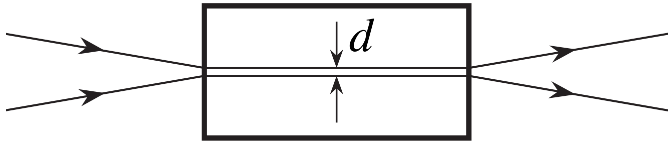
Self-Action Effects in Nonlinear Optics

Self-action effects: light beam modifies its own propagation

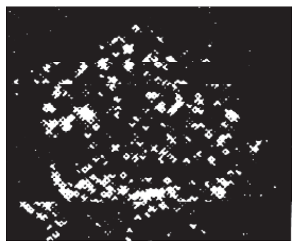
self-focusing



self-trapping



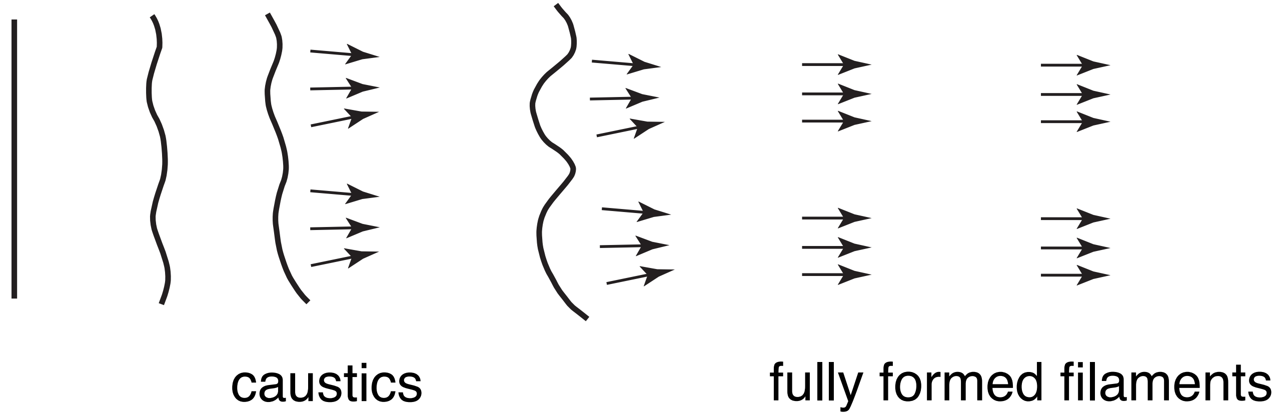
filamentation
or small-scale filamentation
or nonlinear beam breakup

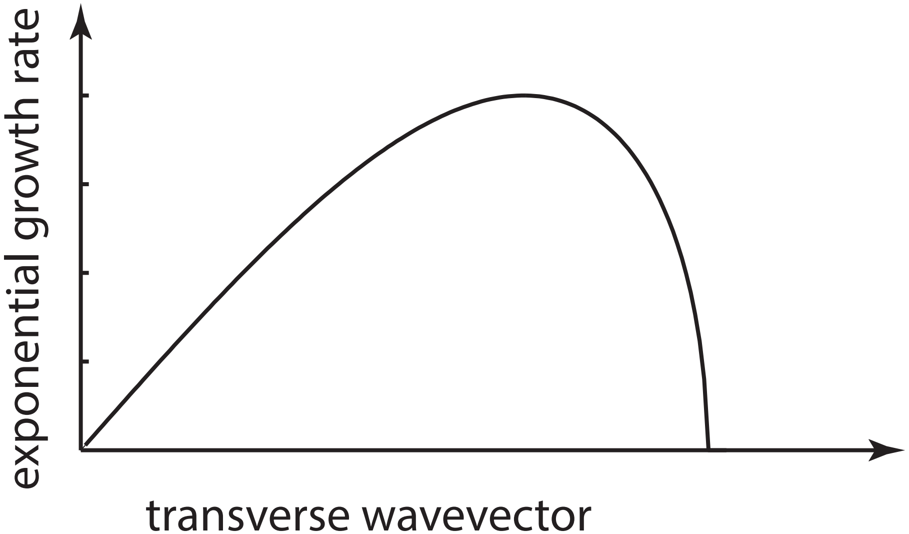


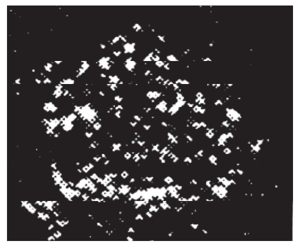
Beam Breakup by Small-Scale Filamentation

Predicted by Bespalov and Talanov (1966)

Exponential growth of wavefront imperfections by four-wave mixing processes







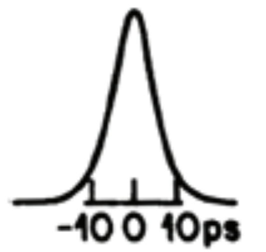
What is the transverse correlation length of noise present on the laser beam?

Optical Solitons

Field distributions that propagate without change of form

Temporal solitons (nonlinearity balances gvd)

$$\frac{\partial \tilde{A}_s}{\partial z} + \frac{1}{2} i k_2 \frac{\partial^2 \tilde{A}_s}{\partial \tau^2} = i\gamma |\tilde{A}_s|^2 \tilde{A}_s.$$

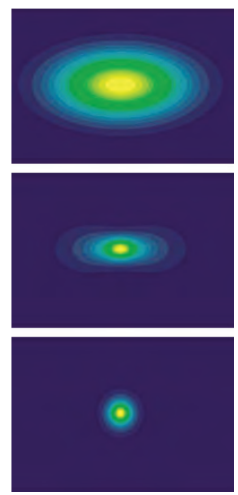


1973: Hasegawa & Tappert

1980: Mollenauer, Stolen, Gordon

Spatial solitons (nonlinearity balances diffraction)

$$2ik_0 \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial x^2} = -3\chi^{(3)} \frac{\omega^2}{c^2} |A|^2 A$$



1964: Garmire, Chiao, Townes

1974: Ashkin and Bjorkholm (Na)

1985: Barthelemy, Froehly (CS2)

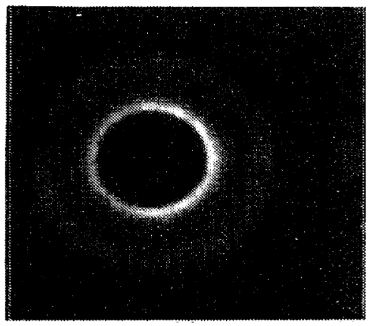
1991: Aitchison et al. (planar glass waveguide

1992: Segev, (photorefractive)

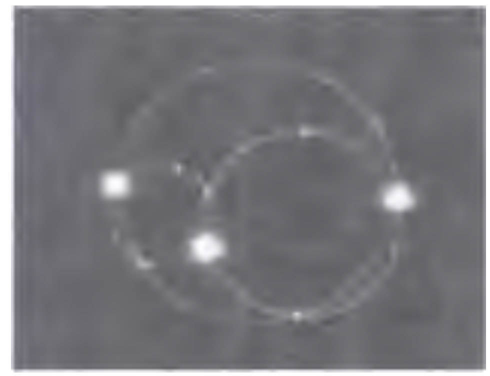
Self-Focusing Can Produce Unusual Beam Patterns

Pattern depends sensitively upon initial conditions

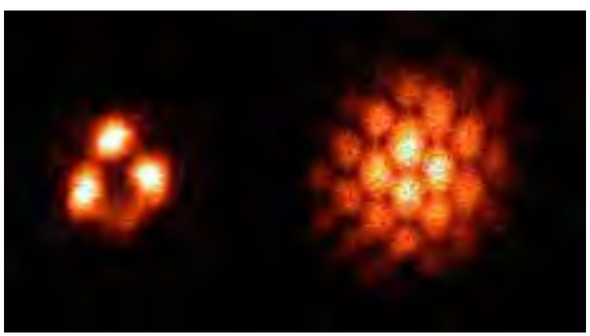
- Conical emission
  Harter et al., PRL 46, 1192 (1981)



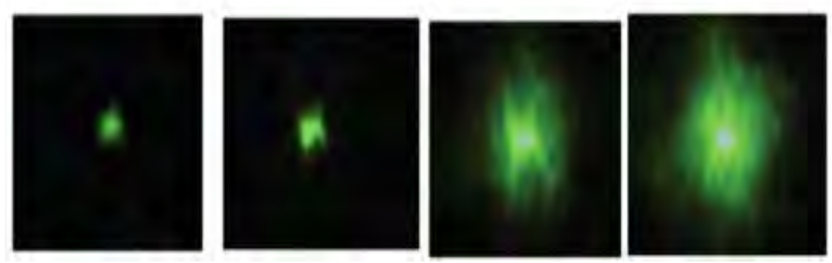
- Multiple ring patterns
  Kauranen et al, Opt. Lett. 16, 943, 1991;



- Honeycomb pattern formation
  Bennink et al., PRL 88, 113901 2002.



- Loss of spatial coherence
  Schweinsberg et al., Phys. Rev. A 84, 053837 (2011).



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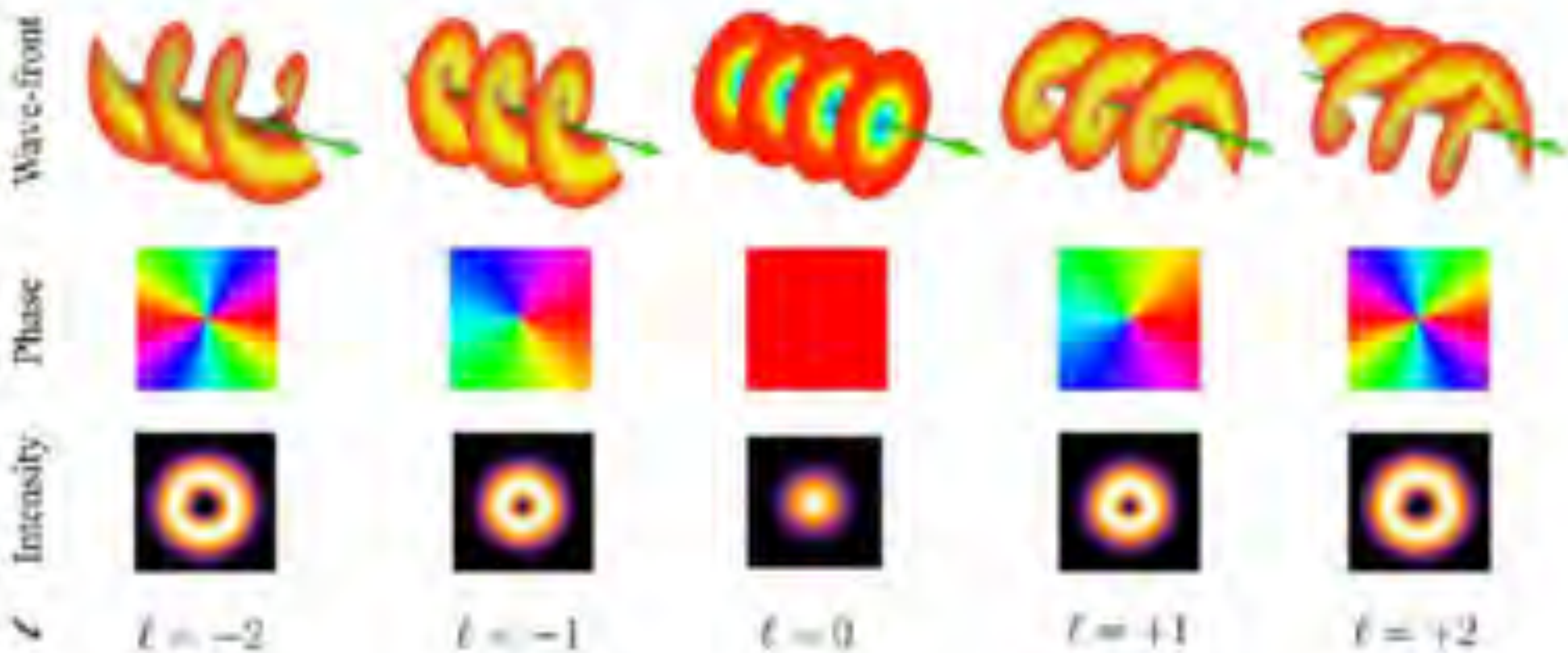
Self-Focusing of Structured Light: OAM States of Light

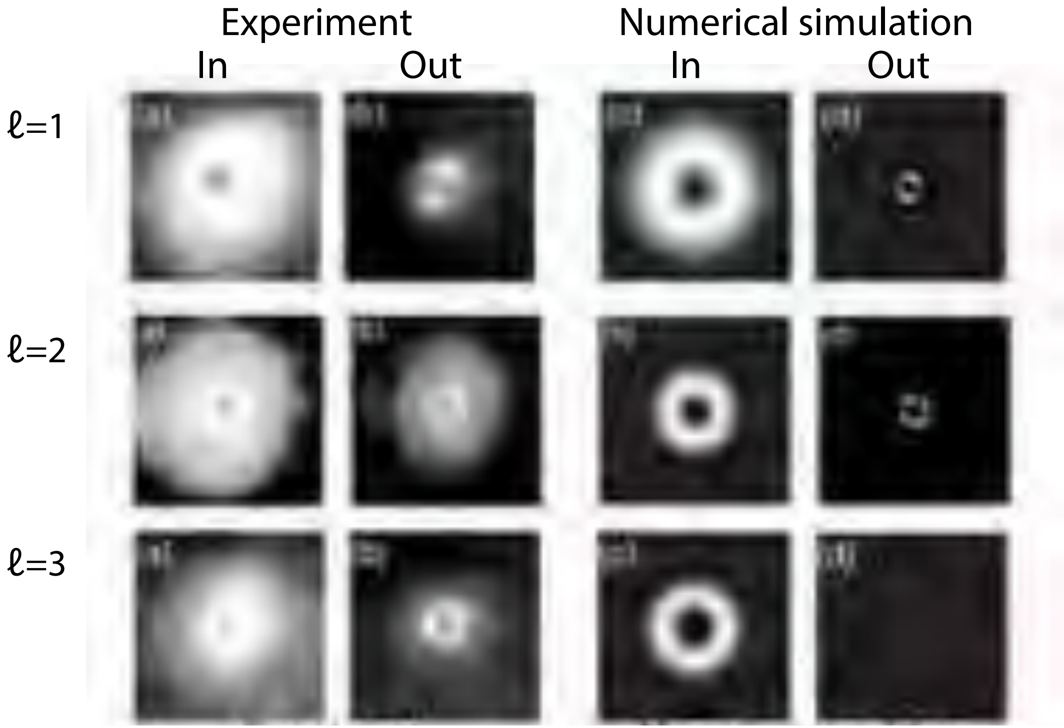
- Light can carry spin angular momentum by means of its circular polarization.
- Light can also carry orbital angular momentum by mean of a phase winding of the optical wavefront
- A well-known example are the Laguerre-Gauss modes. These modes contain a phase factor of $\exp(i\ell\phi)$ and carry angular momentum of $\ell\hbar$ per photon



- How is self-focusing modified by the structuring of a light beam?

Breakup of Ring Beams Carrying Orbital Angular Momentum (OAM) in Sodium Vapor

- Firth and Skryabin predicted that ring shaped beams in a saturable Kerr medium are unstable to azimuthal instabilities. (1997)
- Beams with OAM of $\ell\hbar$ tend to break into 2ℓ filaments.
  (But aberrated OAM beams tend to break into $2\ell+1$ filaments.)

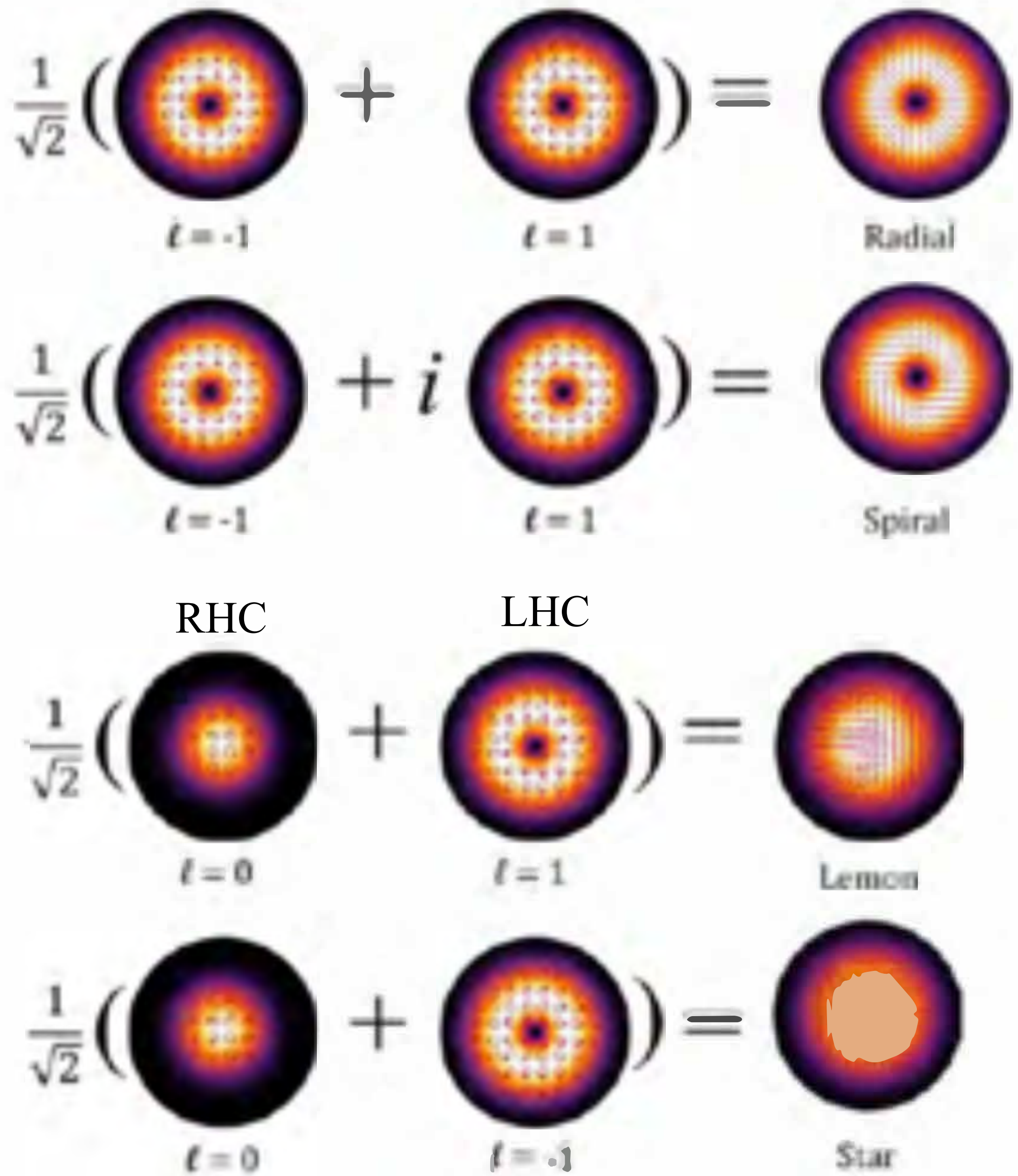


M.S. Bigelow, P. Zerom, and R.W. Boyd, Phys. Rev. Lett 92, 083902 (2004)

Space-Varying Polarized Light Beams

- Vector Vortex Beams

- Poincare Beams

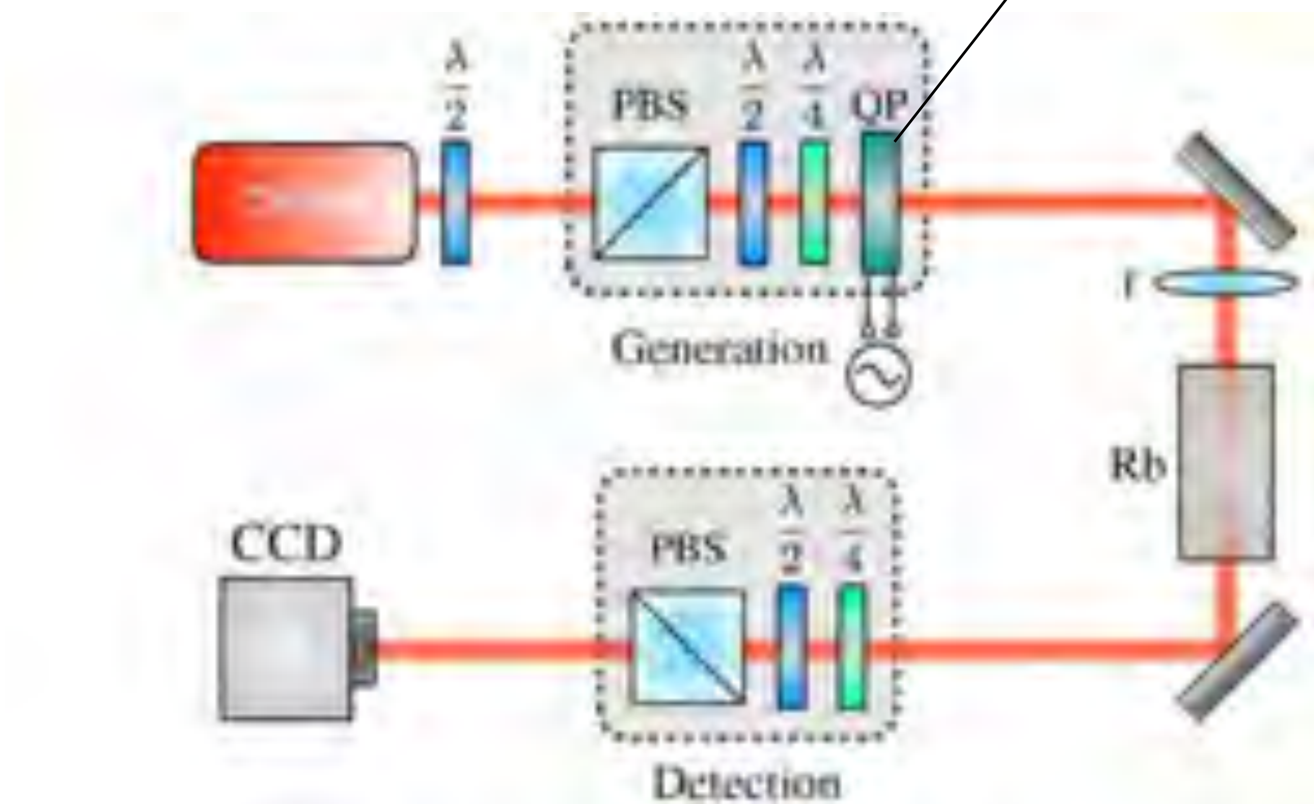


- How do these beams behave under conditions of self-focusing and filamentation?

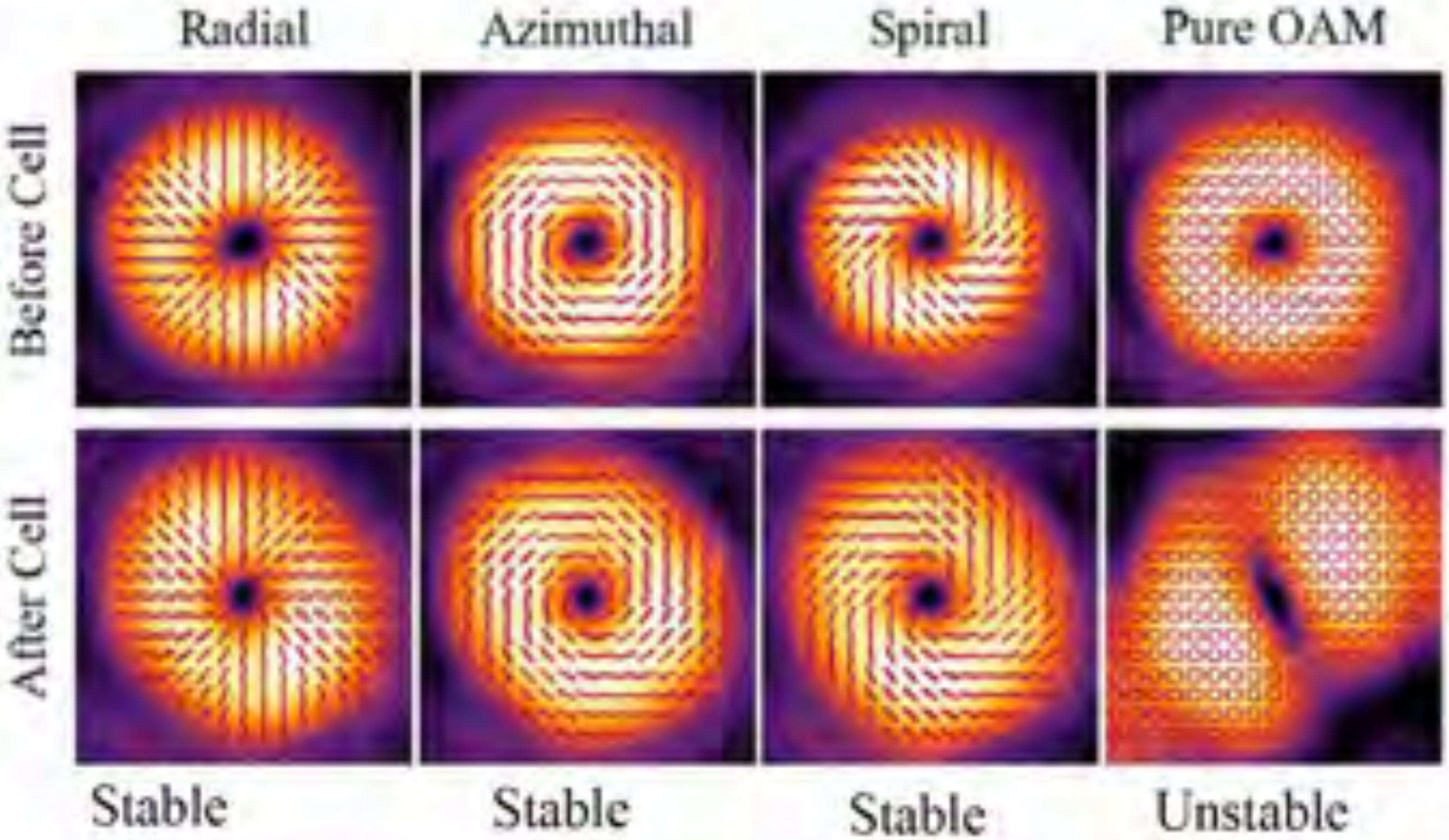
Bouchard et al, PRL 117, 233903 (2016).

Experimental Setup

Q-plate: SAM to OAM converter



Results – Vector Beams (Experimental Results)



Intensity and polarization distributions of vector and LG beams before and after propagating through the Rb atomic vapour.

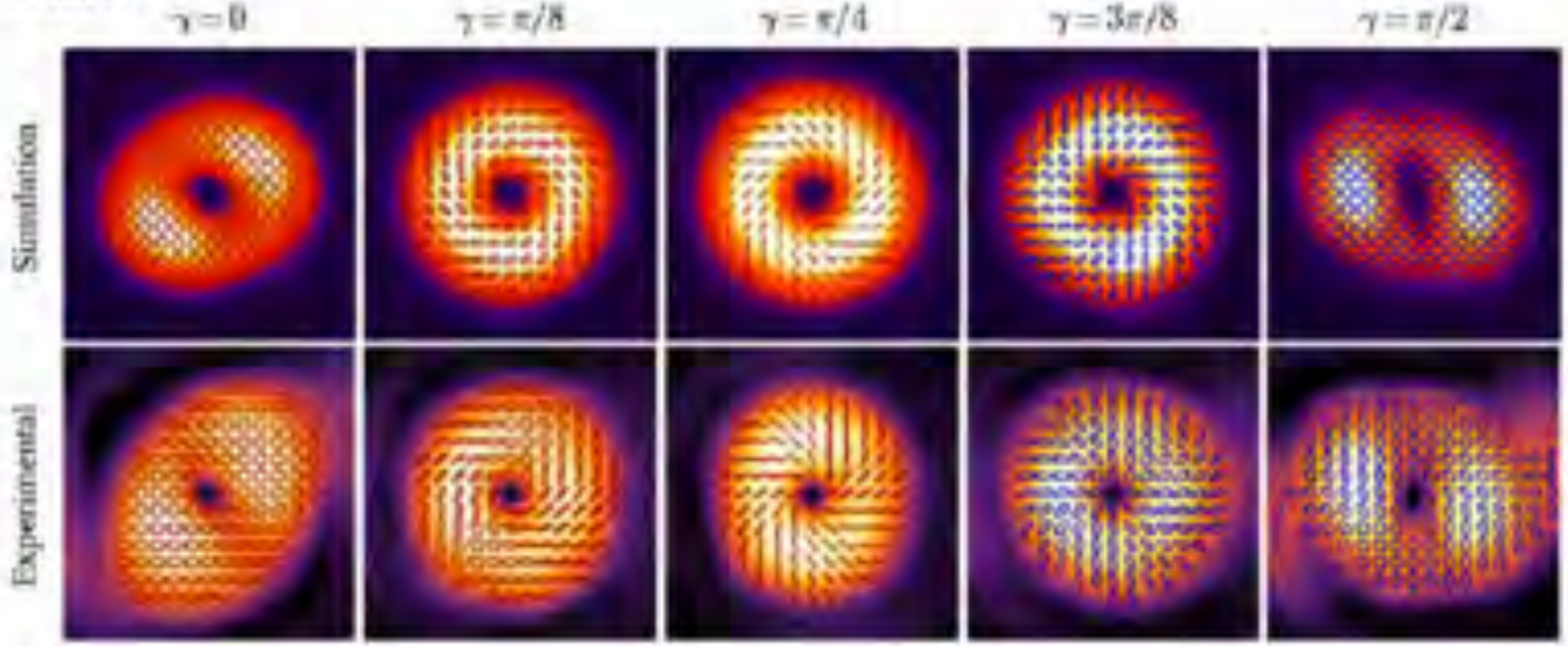
Numerical Modeling of the Experimental Results

- Coupled nonlinear propagation equations

$$\frac{\partial E_L}{\partial \zeta} - \frac{i}{2}\nabla_\perp^2 E_L = i\gamma \frac{|E_L|^2 + \nu |E_R|^2}{1 + \sigma\left(|E_L|^2 + \nu |E_R|^2\right)} E_L$$

$$\frac{\partial E_R}{\partial \zeta} - \frac{i}{2}\nabla_\perp^2 E_R = i\gamma \frac{|E_R|^2 + \nu |E_L|^2}{1 + \sigma\left(|E_R|^2 + \nu |E_L|^2\right)} E_R$$

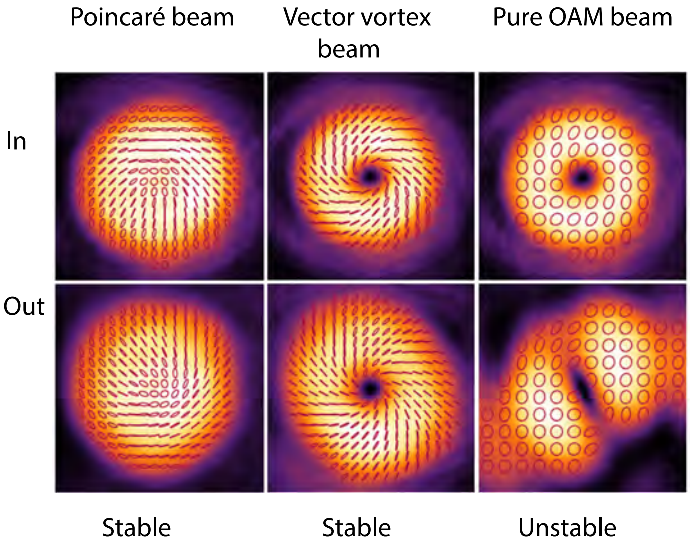
- Comparison



Conclusions: stability of vector OAM beams

- Pure OAM beam:
  beam breakup
- Vector vortex beams:
  stable propagation
- Poincaré beams:
  stable propagation

Bouchard et al, PRL 117, 233903 (2016).



Comment

- Almost 60 years after their inceptions, self-focusing and filamentation remain fascinating topics for investigation.

- If you want to learn more:

Control of Laser-Beam Self-Focusing, Filamentation, and Rogue-Wave Formation Using Structured Light Beams

1. Background on self-action effects
2. Control using spatially structured polarization
3. Caustics and rogue waves (they are intimately related)
4. Control through the spatial spectrum of phase noise
5. Polarization knots

Influence of Nonlinearity on the Creation of Rogue Waves

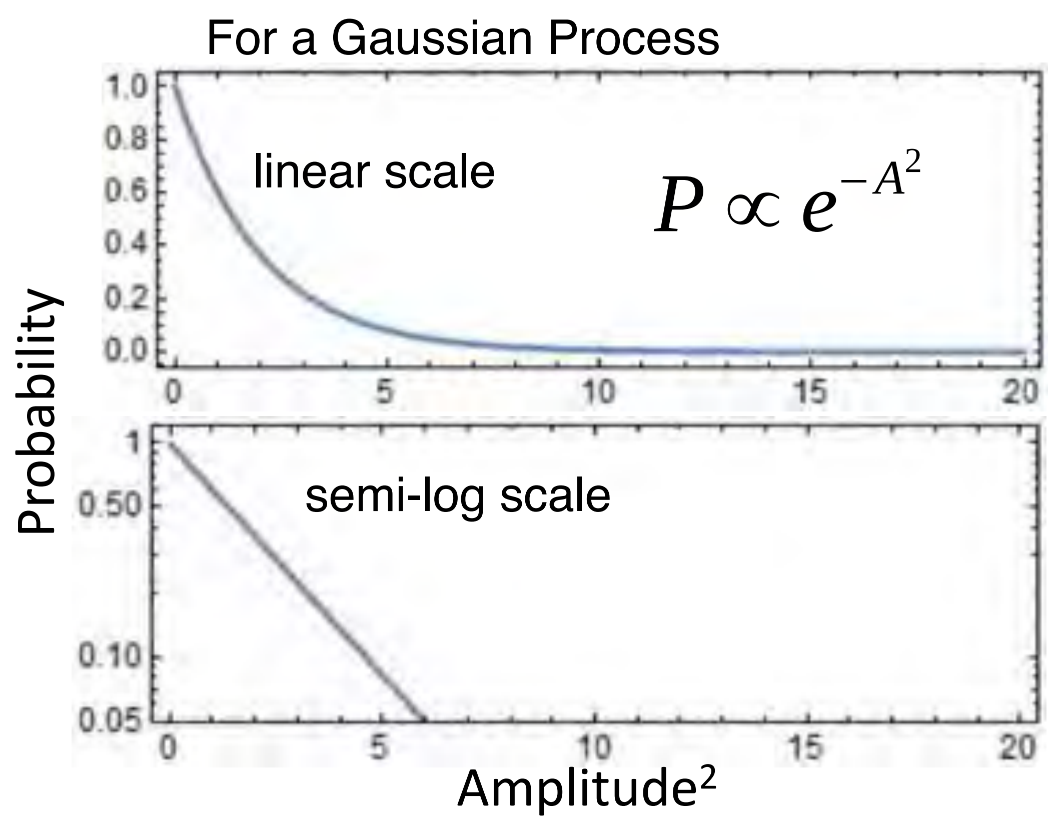
- Study rogue-wave behavior in a well-characterized optical system
- Is nonlinearity important? Required? Or does it actually inhibit rogue-wave formation?

A. Safari, R. Fickler, M. J. Padgett and R. W. Boyd, Generation of Caustics and Rogue Waves from Nonlinear Instability, Phys. Rev. Lett. 119, 203901 (2017).

Oceanic rogue waves

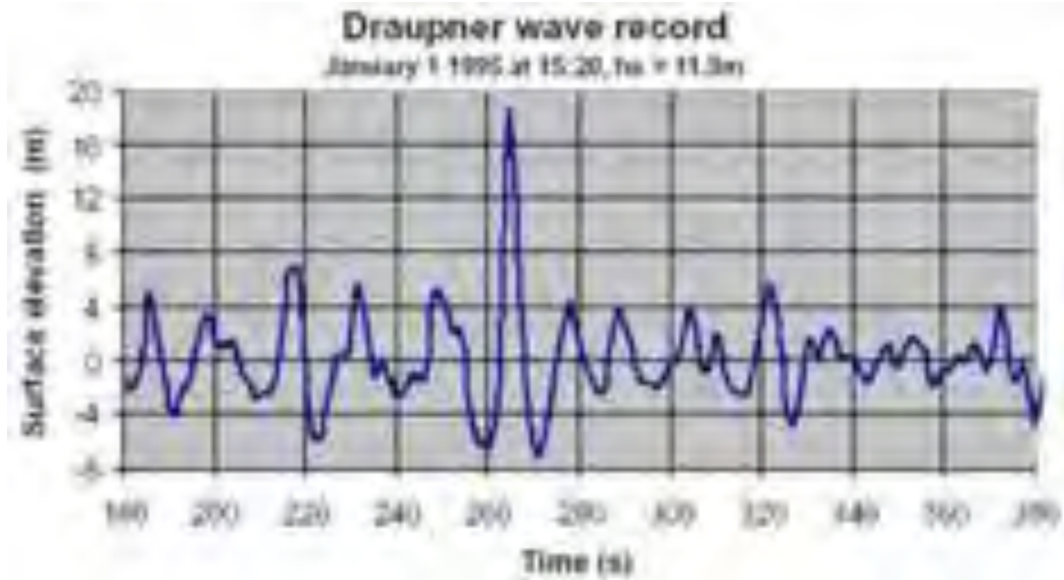
Before 1995

Sailors: we see gigantic waves.
Scientists: it is a fairy tale!
Ocean waves follow
Gaussian distribution.



Oceanic rogue waves

First scientific observation of rogue waves in Draupner oil platform (1995):



Characteristics of rogue waves

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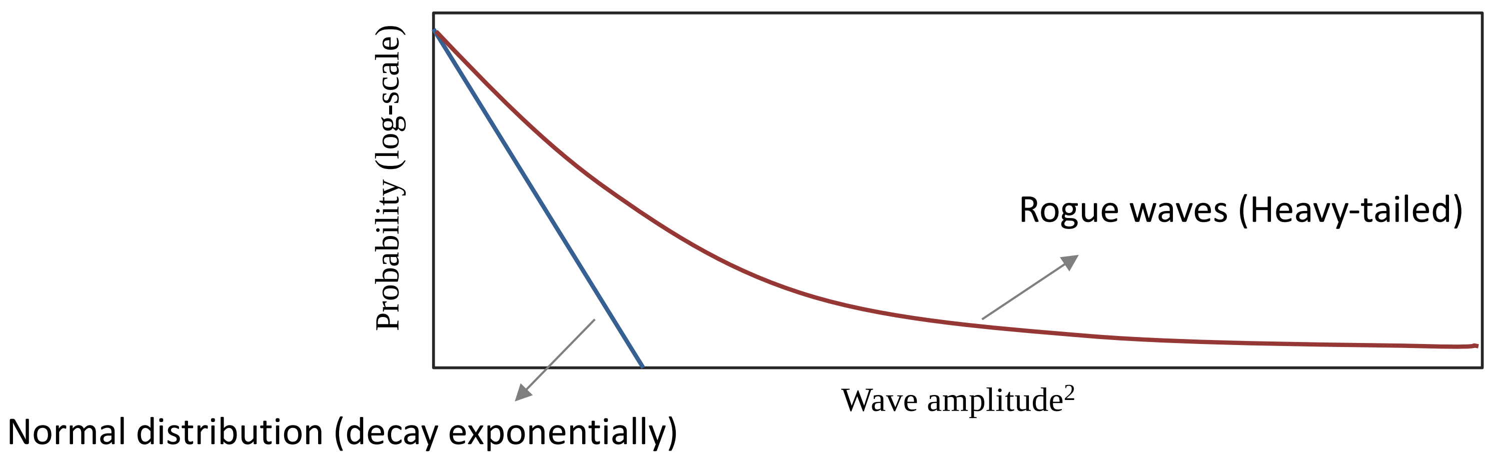
- Rogue waves appear from nowhere and disappear without a trace.
- Rogue waves ≠ accidental constructive interference
- They occur much more frequently than expected in ordinary wave statistics.

Probability distribution in rogue systems:



- Not limited to ocean: Observed in many other wave systems including **optics**.

A. Safari, R. Fickler, M. J. Padgett and R. W. Boyd, Generation of Caustics and Rogue Waves from Nonlinear Instability, Phys. Rev. Lett. 119, 203901 (2017).

Rogue waves in 1D vs 2D systems

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"Nonlinear Schrödinger equation" explains the wave dynamics in the ocean as well as in optics.

Rogue events studied extensively in 1D systems, such as optical fibers.

$$\frac{\partial A}{\partial x} + \frac{1}{2} i k_2 \frac{\partial^2 A}{\partial t^2} = i\gamma \left|A\right|^2 A$$

D. R. Solli, C. Ropers, P. Koonath & B. Jalali, Nature 450, 1054 (2007).
J.M. Dudley et al, Nat. Photon, 8, 755 (2014)

Water waves are not 1D.

$$2ik \frac{\partial A}{\partial x} + \nabla_\perp^2 A = i\gamma \left|A\right|^2 A$$

Two focusing effects in 2D systems:

- **Linear**: Spatial (geometrical) focusing
- **Nonlinear**: Self focusing

Optical caustics

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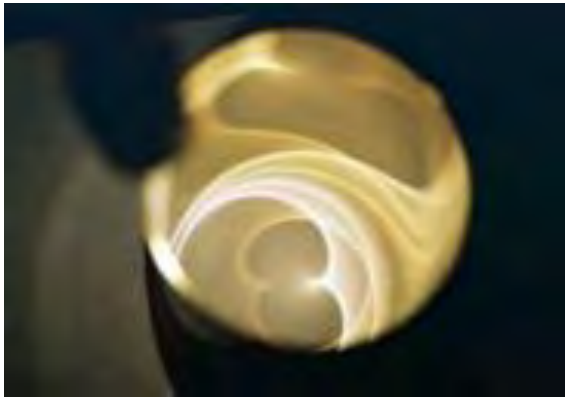
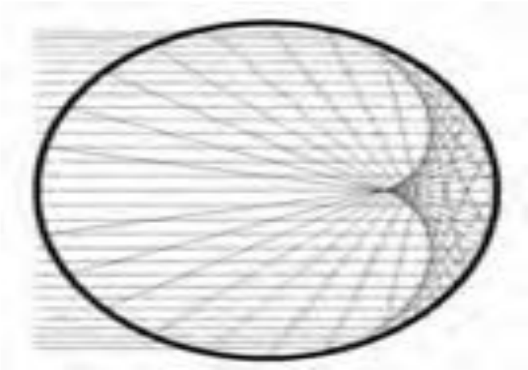
Swimming pool



Coffee cup



Ray picture

- Caustics are defined as the envelope of a family of rays
- Singularities in ray optics
- Catastrophe theory is required to remove singularity

Books:
J.F. Nye, *Natural Focusing and Fine Structure of Light.*
Y.A. Kravtsov, *Caustics, Catastrophes and Wave Fields.*
O.N. Stavroudis, *The Optics of Rays, Wavefronts, and Caustics*.

How does one quantify caustic properties?

–There are two common metrics

–Scintillation index → $$\beta^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

Defines "sharpness" of beam.
= 1 for speckle pattern.

–Statistical distribution of pixel intensities

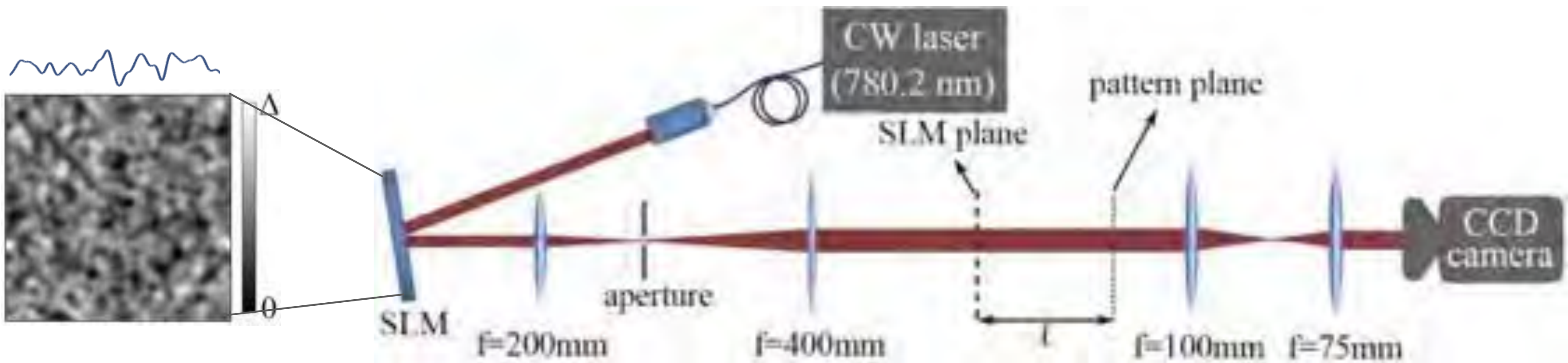
$$p(I) = A \exp(-B I^{C})$$

= 1 for speckle pattern

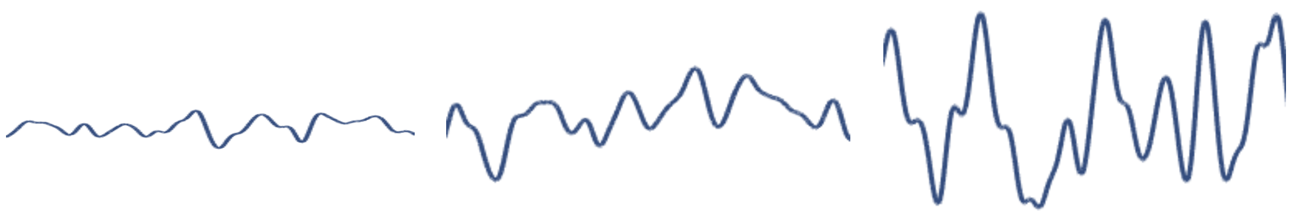
< 1 for caustics (long-tailed distribution)

Distribution [X] (see cover slide)

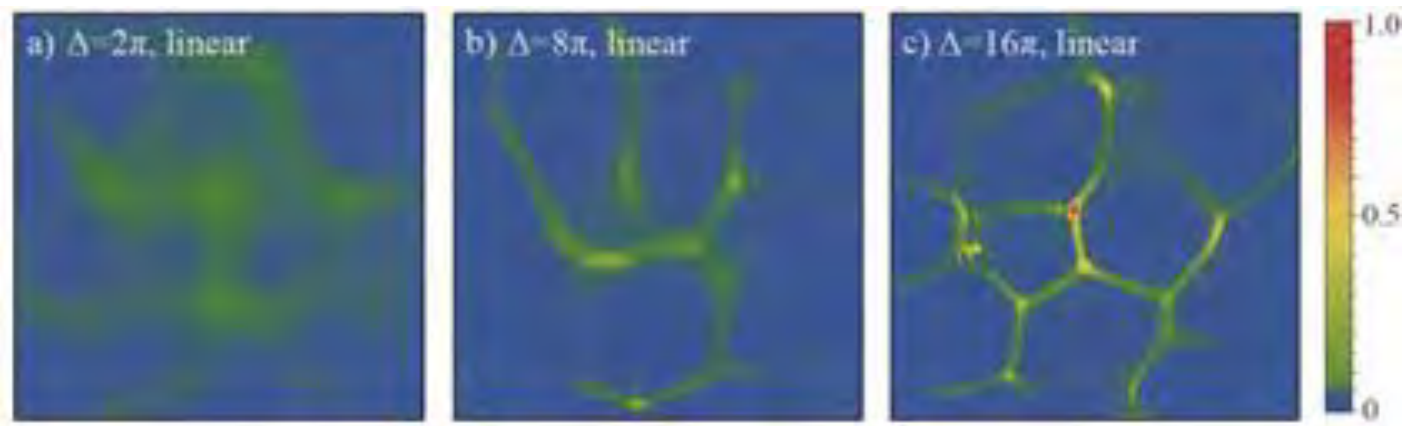
Generation of optical caustics



Phase variations:



Corresponding intensity variations:



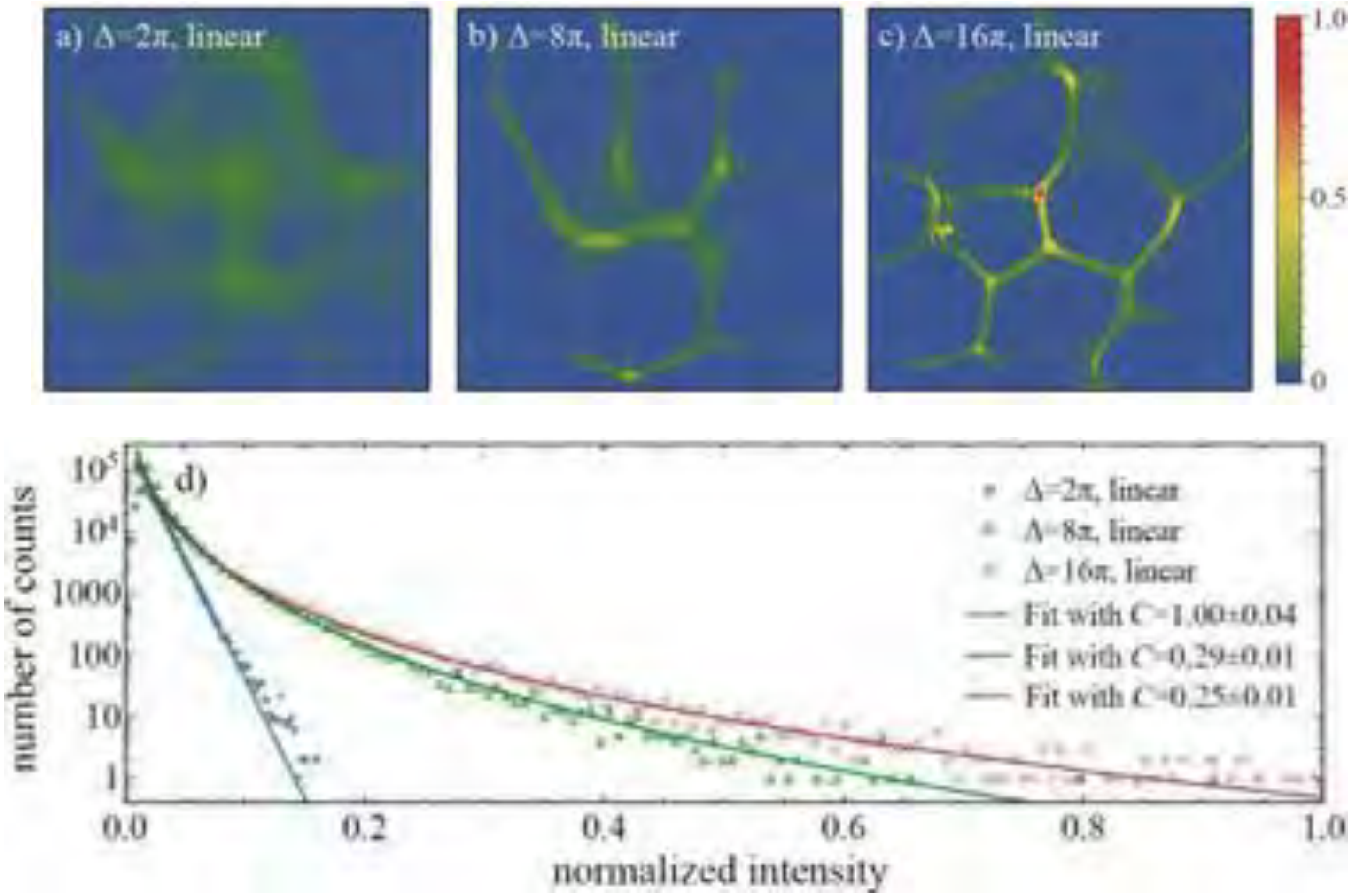
A sharp caustic is formed only if the phase variations are large

Statistics of caustics

Caustics exhibit long-tailed probability distribution

1000 different patterns for each Δ

Intensity distributions with fit to $A\exp\left(-BI^{C}\right)$



A. Mathis, L. Froehly, S. Toenger, F. Dias, G. Genty & J. Dudley. *Scientific Reports* **5**, 1 (2015).

Effect of Nonlinearity on Caustic Formation

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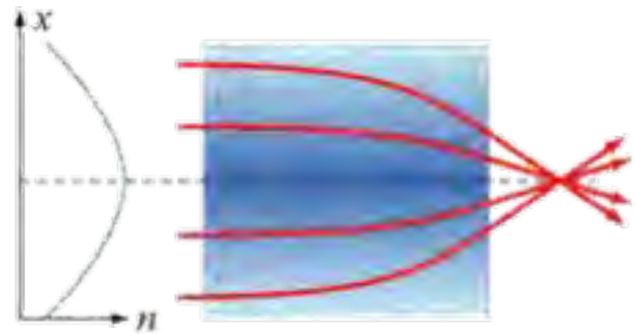
Self focusing:

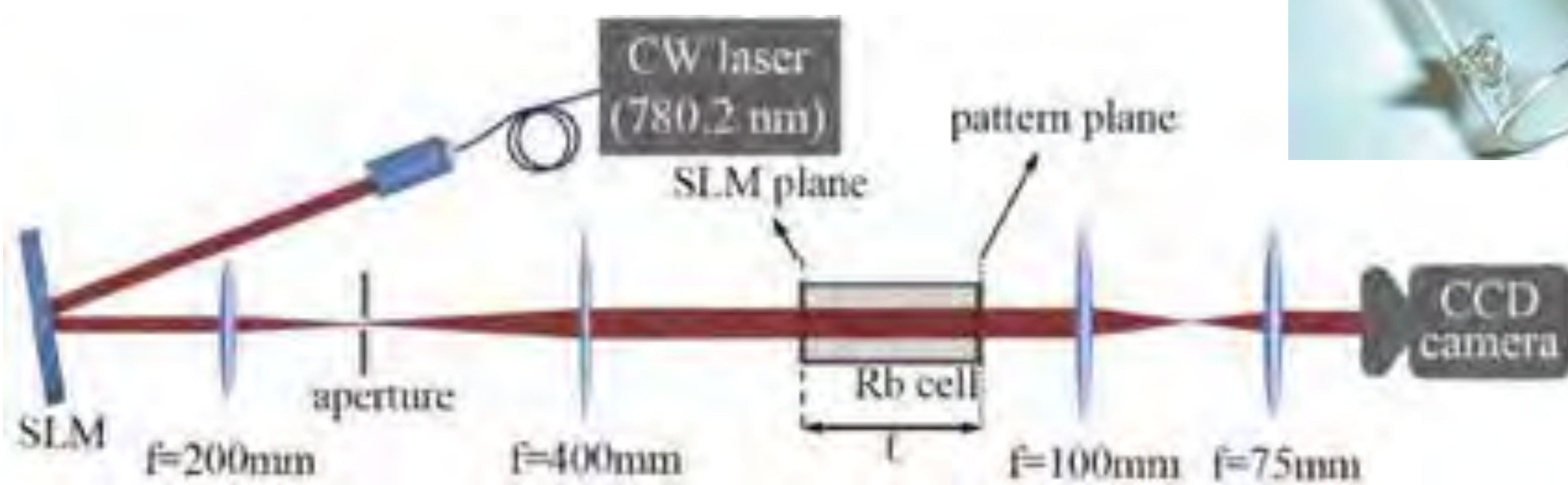
Refractive index depends on intensity:

$$n = n_0 + n_2 I$$



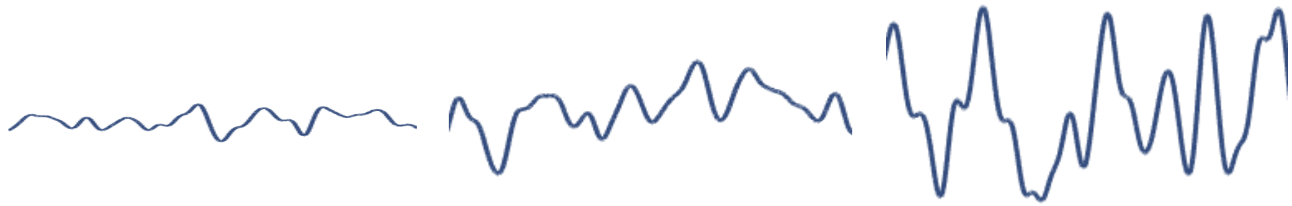
Rubidium cell

Rubidium vapors show large nonlinear effects



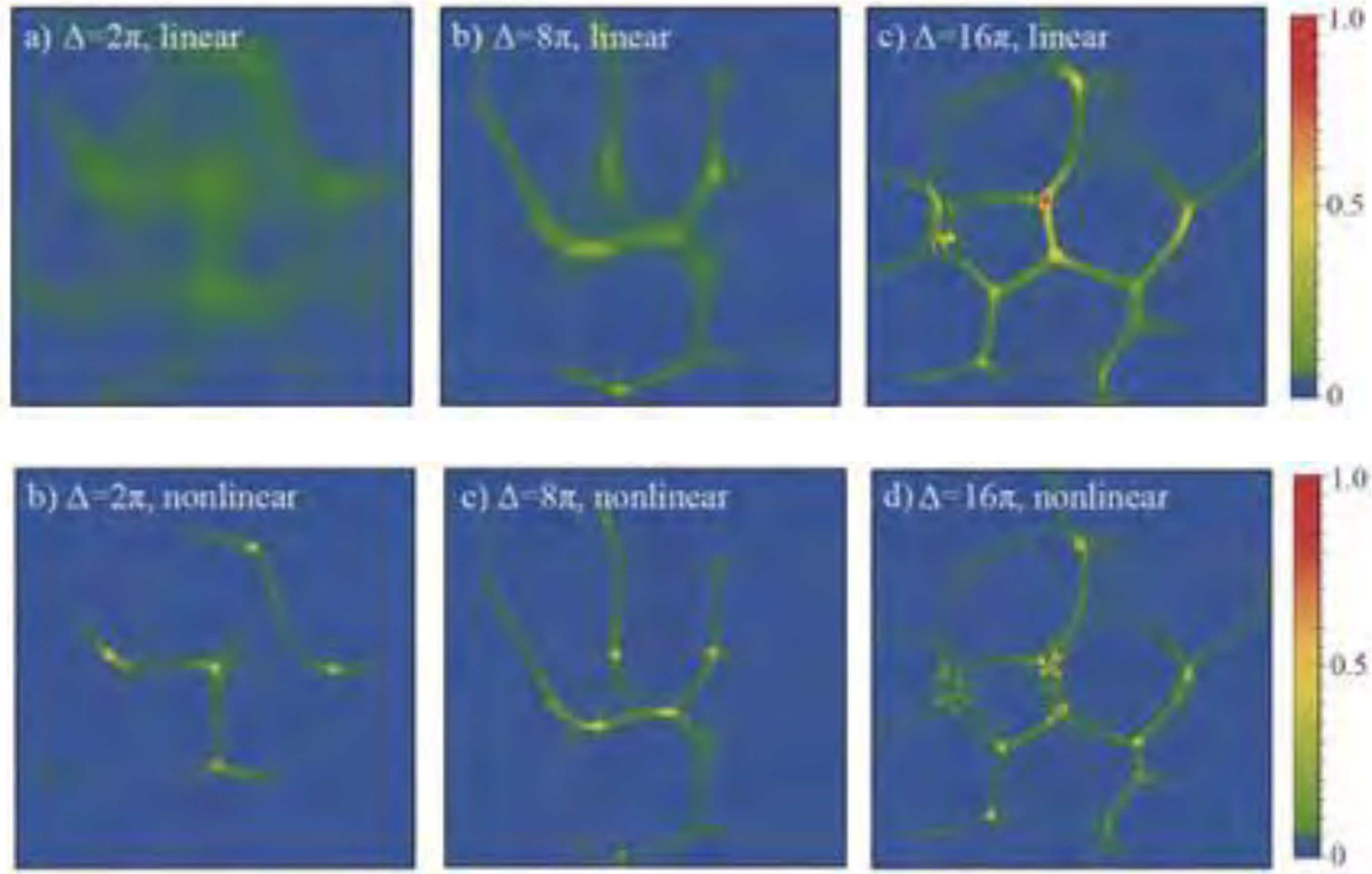
Effect of nonlinearity on caustics

Phase variations:



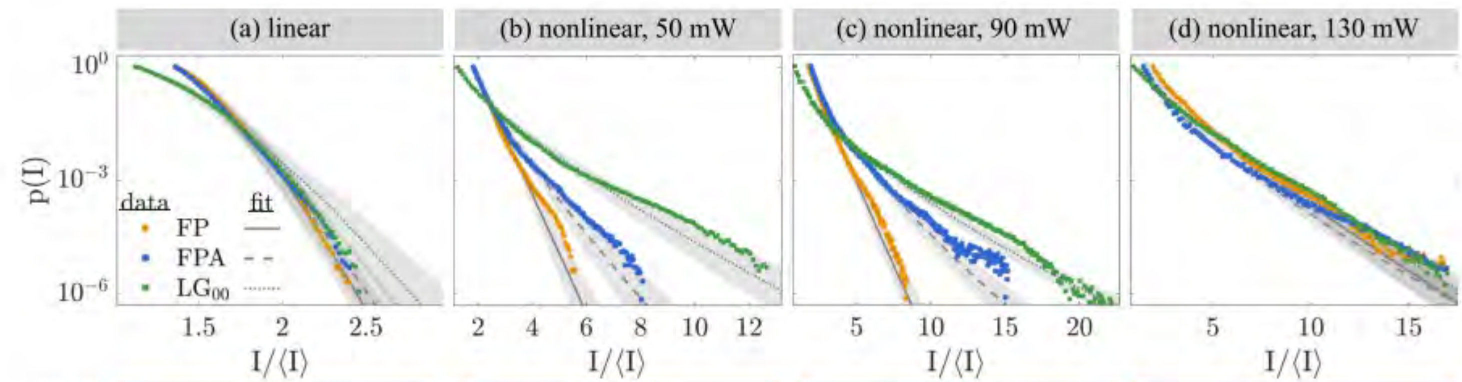
After linear propagation:

After nonlinear propagation:

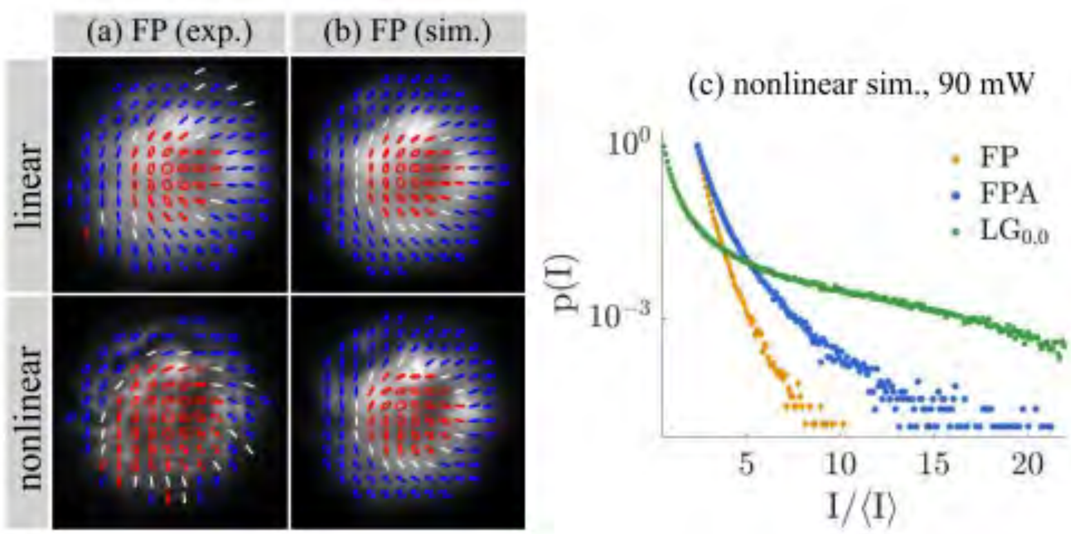


CONTROLLING LASER BEAM FILAMENTATION USING POLARIZATION-STRUCTURED LIGHT

Suppression of Nonlinear Optical Rogue Wave Formation Using Polarization-Structured Beams



	(a) linear	(b) nonlinear, 50 mW	(c) nonlinear, 90 mW	(d) nonlinear, 130 mW
γ(FP)	1.38(9)	1.02(6)	0.96(3)	0.82(2)
γ(FPA)	1.24(8)	0.84(4)	0.72(2)	0.76(2)
$\gamma(LG_{00})$	1.4(1)	0.79(3)	0.66(1)	0.87(2)

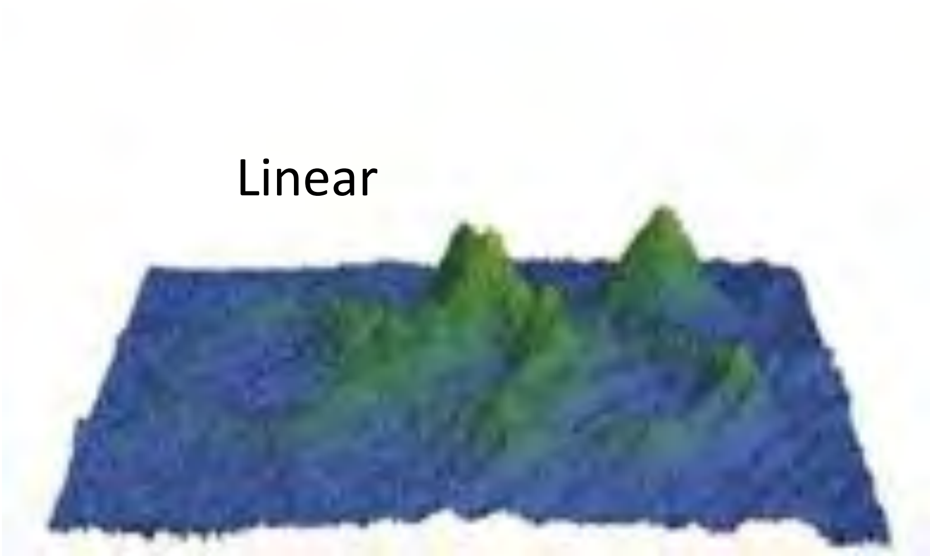


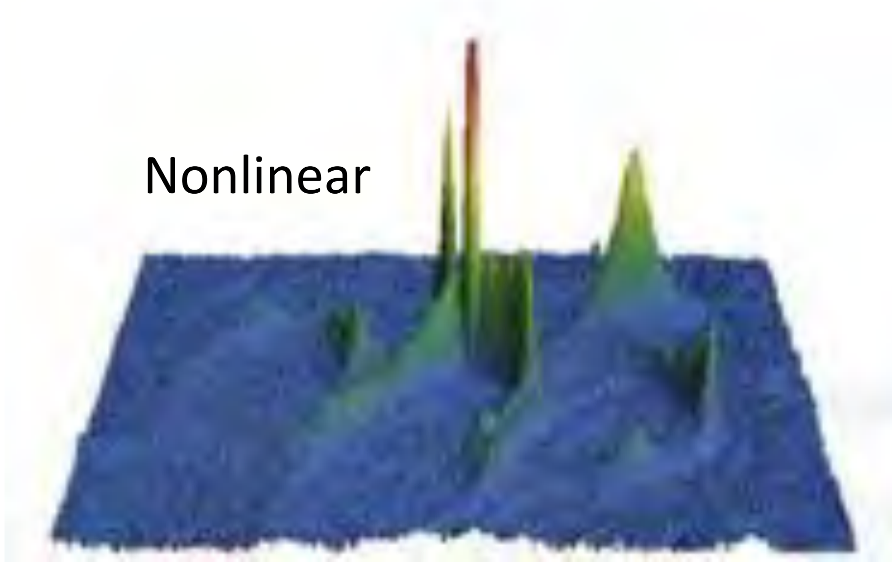
- ✓ Full-Poincare beams are much less susceptible to rogue wave formation compared to a Gaussian beam, or a Full-Poincare amplitude beam.

A. Nicholas Black, Saumya Choudhary, E. Samuel Arroyo-Rivera, Hayden Woodworth, and Robert W. Boyd, Physical Review Letters 129, 133902 (2022)

Conclusions

- Caustics are rogue waves
- Generation of caustics by linear propagation requires large phase fluctuations
- Nonlinear effects can enhance the generation of caustics.





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A. Nicholas Black, Saumya Choudhary, E. Samuel Arroyo-Rivera, Hayden Woodworth, and Robert W. Boyd, Physical Review Letters 129, 133902 (2022)

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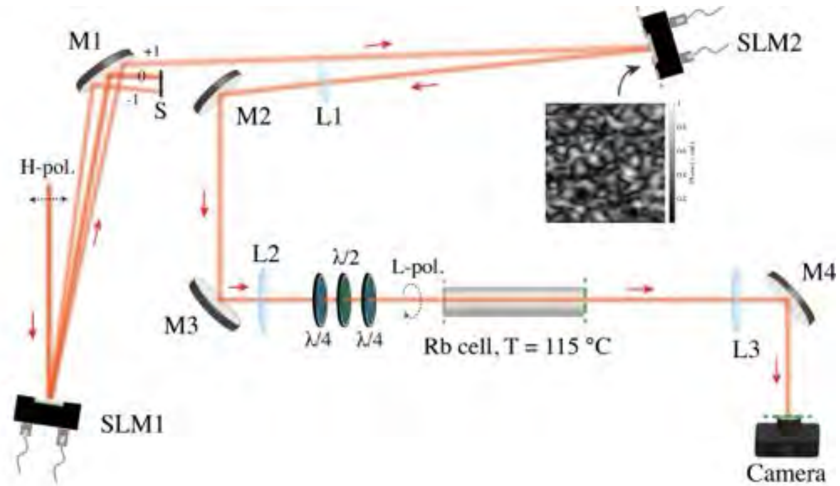
5. Polarization knots

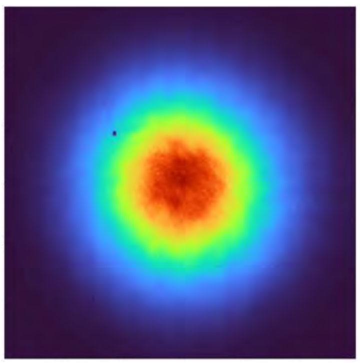
Experimental setup

- SLM1 has a phase-only grating for generating a clean Gaussian beam in its 1st diffractive order.
- SLM2 adds a random phase mask on the waist of the beam with a maximum amplitude of π radians, and a Gaussian angular spectrum of width $\propto 1/L_{\mathrm{corr}}$. The smaller the value of L_{corr}, the more granular is the phase noise added to the beam.
- SLM2 is then imaged on the entrance of a heated rubidium cell.
- The output facet of the cell is imaged on a camera, which records images of the beam after propagation through the cell.
- We vary the beam power and L_{corr} of the phase mask.
- Intensity histograms are obtained from the beam images recorded for 500 different phase masks for each dataset.



S. Choudhary, A.N. Black, A. Antikainen, and R.W. Boyd, to be published.

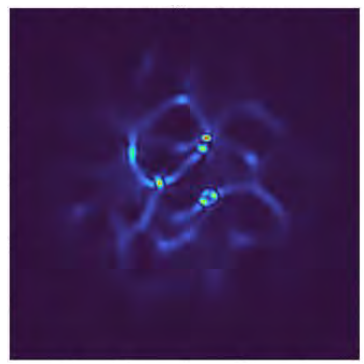
Intensity statistics



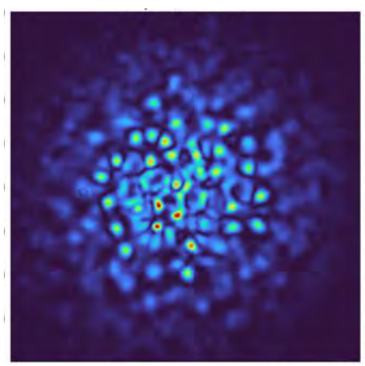
Input beam

(false color)

Rubidium cell

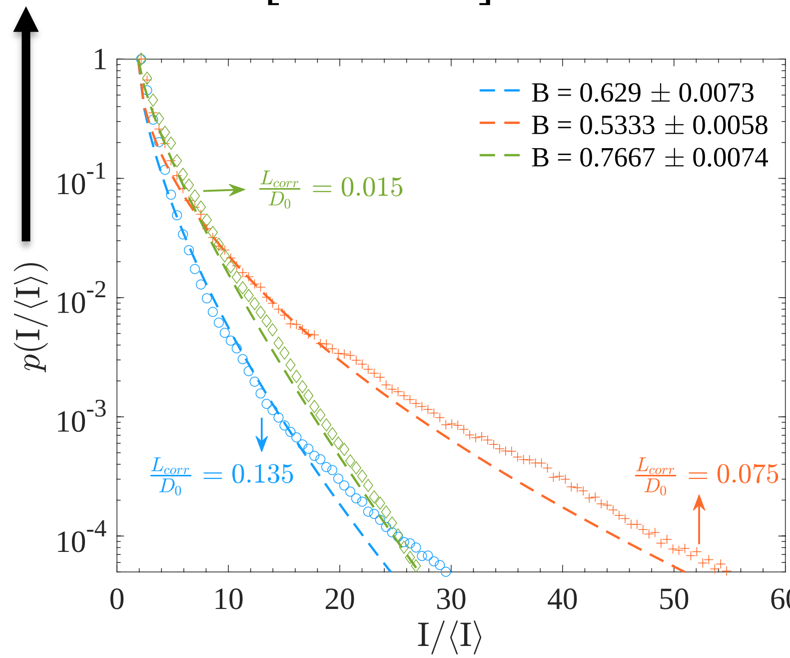


$P_{in} = 90\ mW, L_{corr} = 250\ \mu m$



$P_{in} = 90\ mW, L_{corr} = 50\ \mu m$

$$p\left(\frac{I}{\langle I\rangle}\right) = \frac{1}{N} exp\left[- A \left(\frac{I}{\langle I\rangle}\right)^{B}\right]$$



Measured intensity histograms (markers) for beam powers of 90 mW, and variousL_{corr} normalized to the beam diameter $\boldsymbol{D_0}$. The dashed lines are the maximum likelihood estimation (MLE) fits of the stretched exponential function to the respective intensity statistics (shown by same color markers). The intensity exponent 'B' obtained from the fit is stated in the legend.

S. Choudhary, A.N. Black, A. Antikainen, and R.W. Boyd, to be published.

Control of Laser-Beam Self-Focusing, Filamentation, and Rogue-Wave Formation Using Structured Light Beams

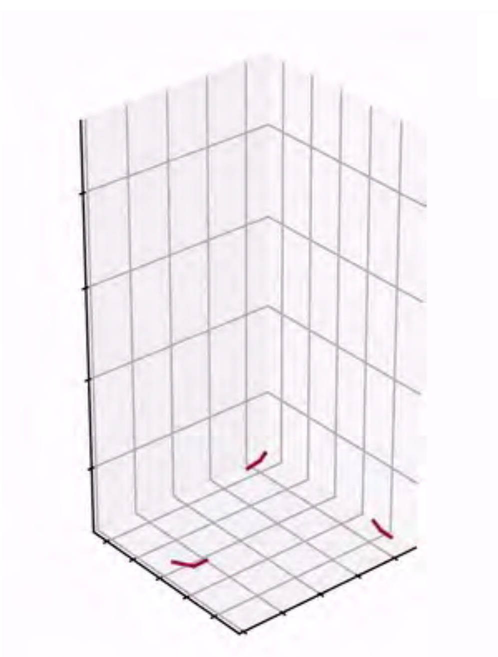
1. Background on self-action effects
2. Control using spatially structured polarization
3. Caustics and rogue waves
4. Control through the spatial spectrum of phase noise
5. Polarization knots

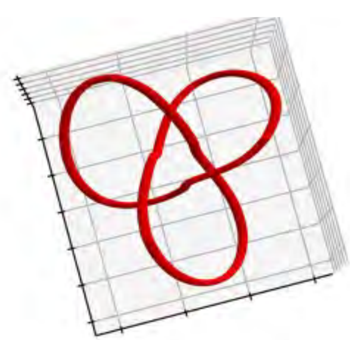
Polarization Knots

Polarization knots

- In polarization-knotted beams, trajectories of the points of purely circular polarization form a 3D knotted structure.
- How do polarization-knotted beams propagate in nonlinear media, or in turbulence?

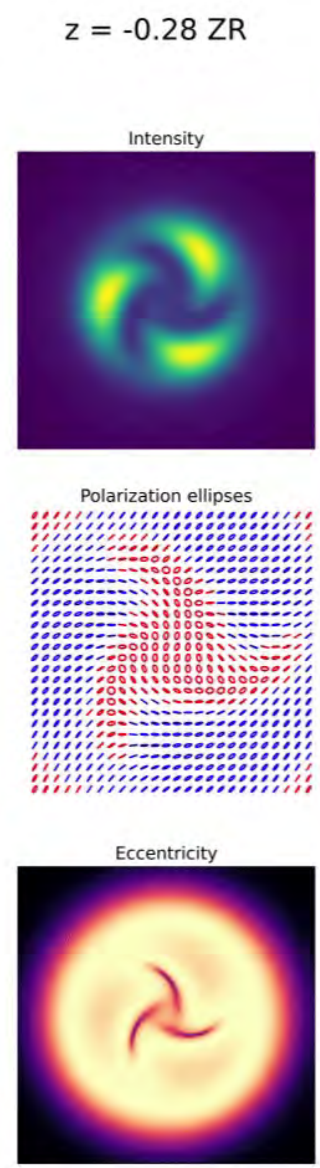
Numerical results for linear propagation





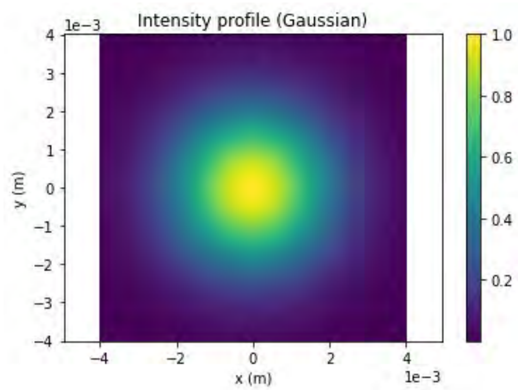
Top view

Trefoil knot

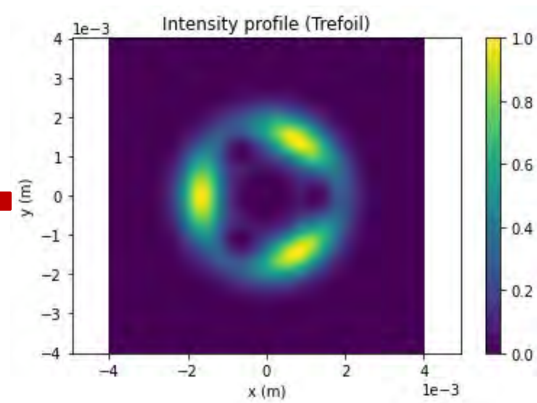


Polarization Knots

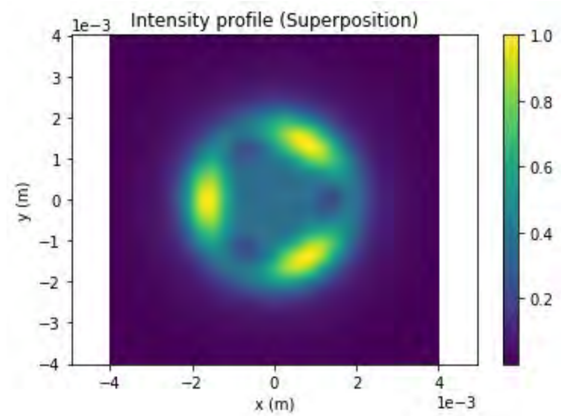
Polarization knots



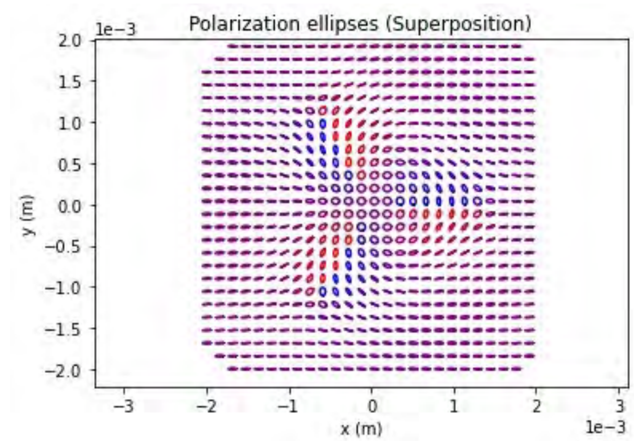
Gaussian, Left circular polarization

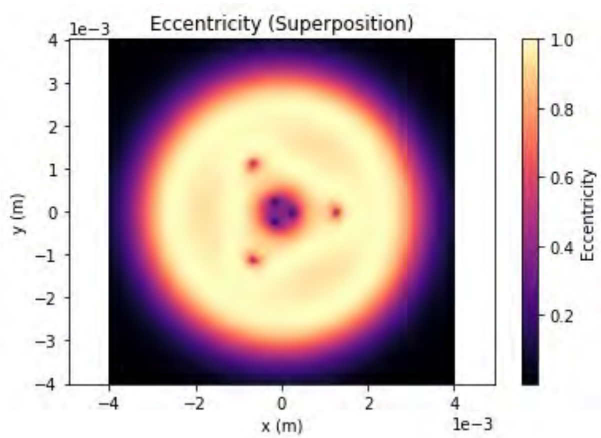


Trefoil phase knot, right circular polarization



Trefoil polarization knot





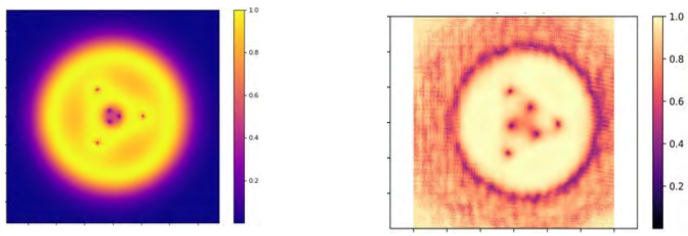
We want to find out if there are topological quantities that are preserved under nonlinear propagation and through turbulence.

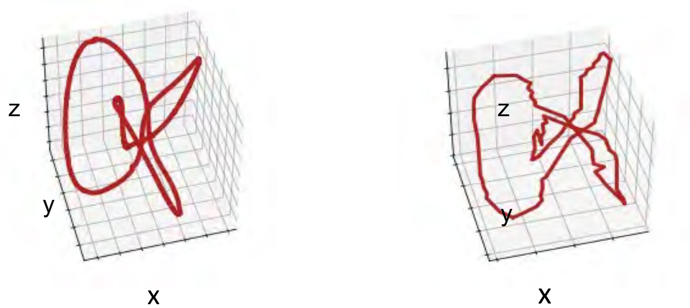
Polarization Knots

Linear Propagation

Simulation | **Experiment**

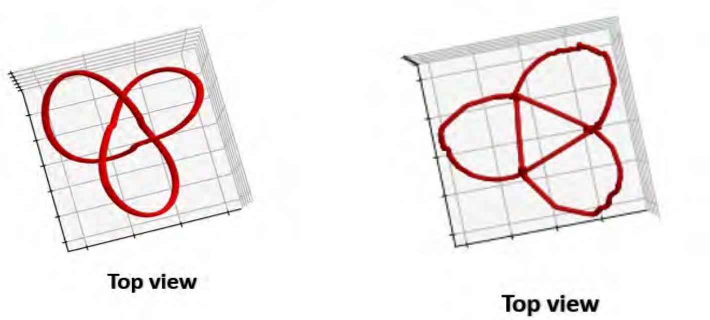
Polarization ellipse eccentricity





Trefoil knot formed along propagation

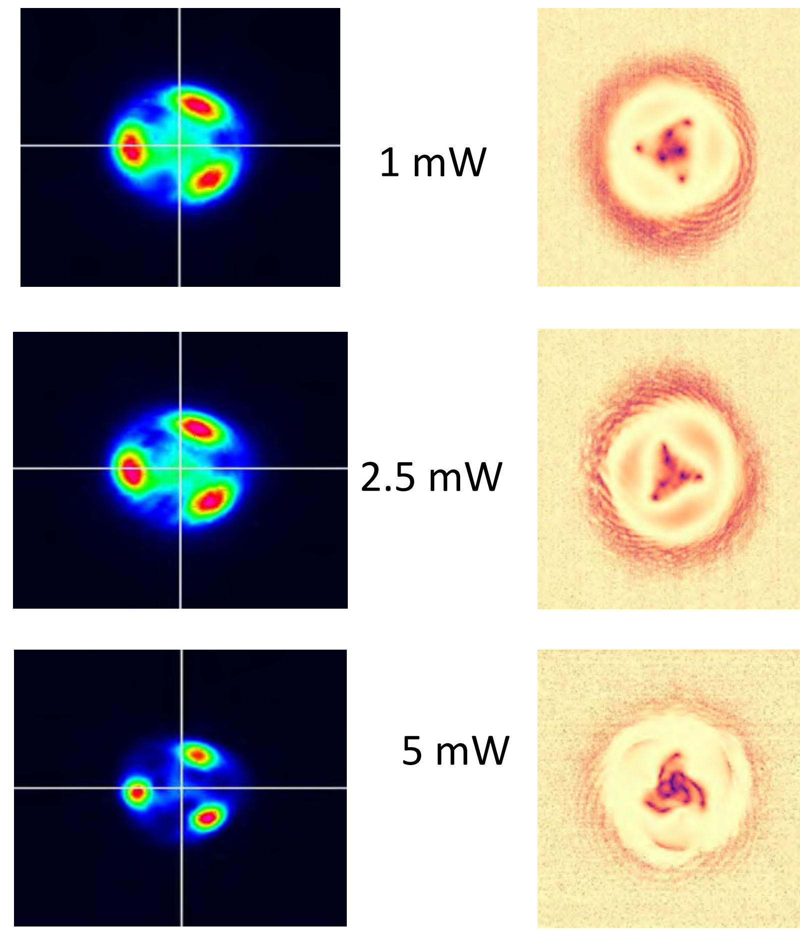
Trefoil knot formed along propagation



Trefoil knot

Nonlinear Propagation in Rubidium

Output Intensity | Polarization ellipse eccentricity

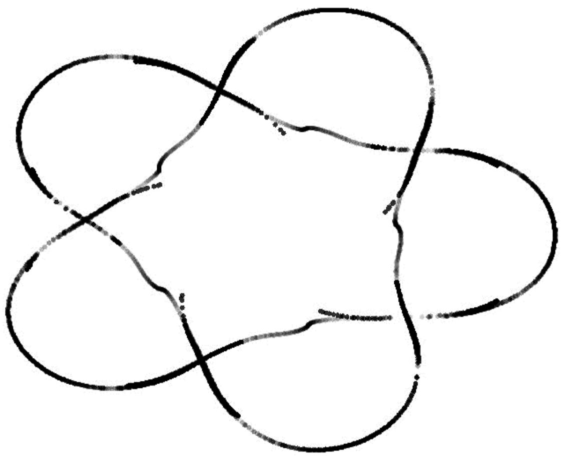


Symmetry is preserved under nonlinear propagation

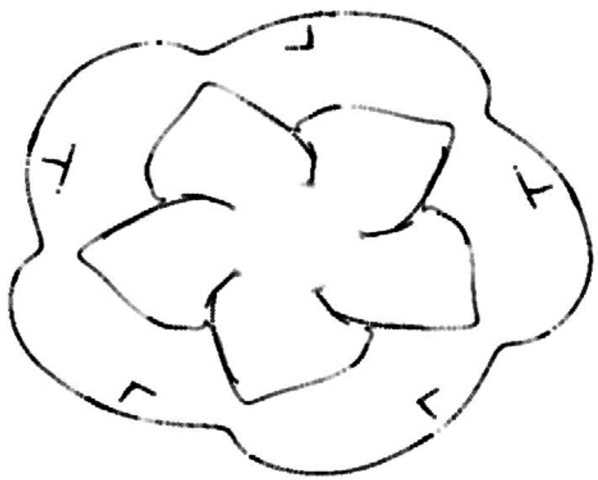
Polarization Knots

Polarization knots

Simulation
Cinquefoil knot



Linear propagation



Nonlinear propagation

- Under strong nonlinearity, the knot ceases to exist, but closed trajectories of eccentricity minima remain visible, parts of which are lighter gray, indicating elliptical polarization. The nonlinearity has ”untied” the knot entirely. Yet, the five-fold symmetry is preserved.

Special Thanks To My Students and Postdocs!

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