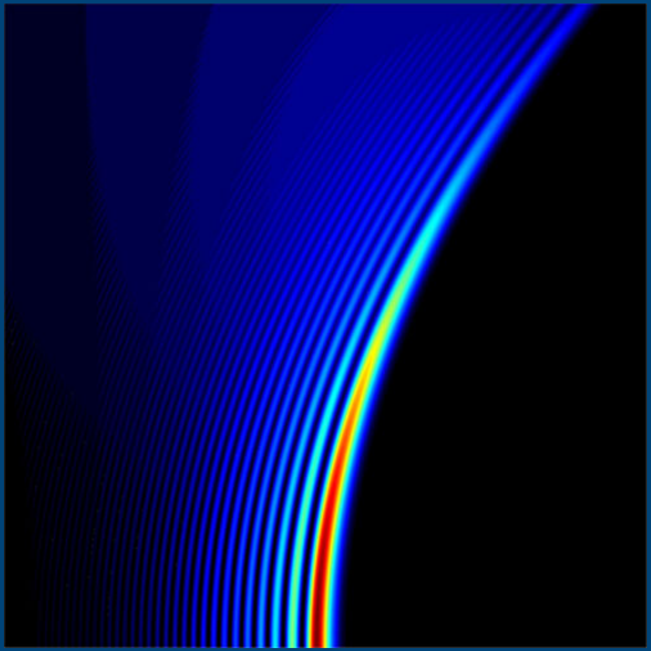
Optical Airy beams and bullets



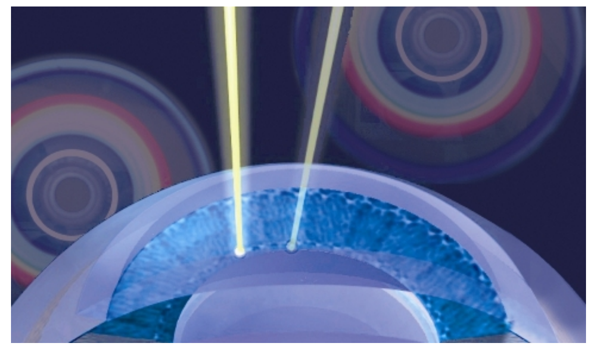
Demetri Christodoulides

UNIVERSITY OF CENTRAL FLORIDA

CREOL & FPCE

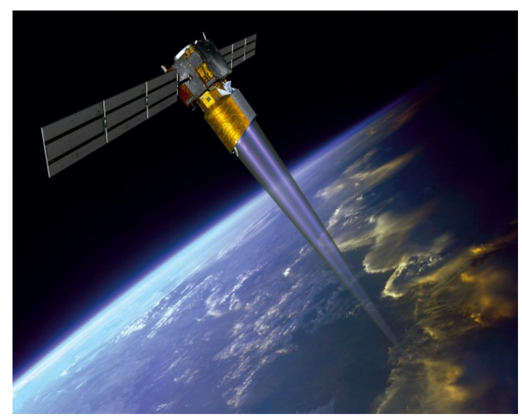
THE COLLEGE OF OPTICS AND PHOTONICS

CREOL-College of Optics and Photonics



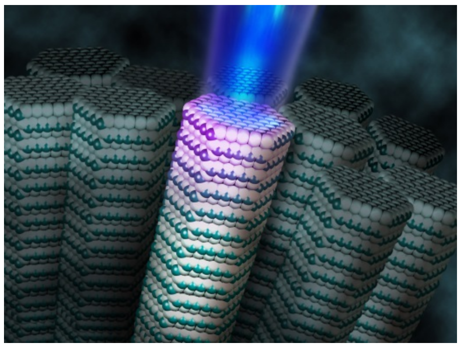
Medical applications

Lasers

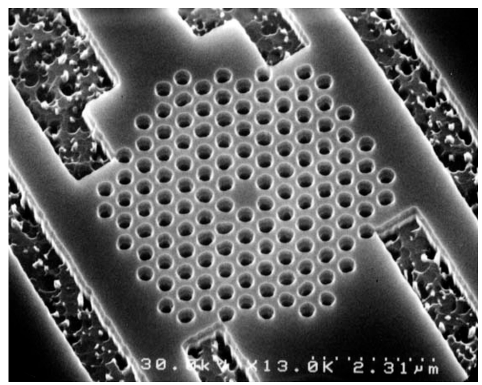


Military

CREOL-College of Optics and Photonics



Nanolasers



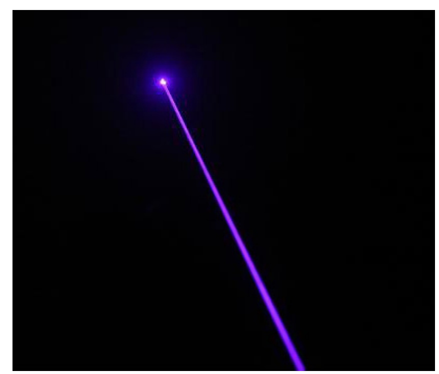
Integrated optics

Optical fibers

Light travels in straight lines

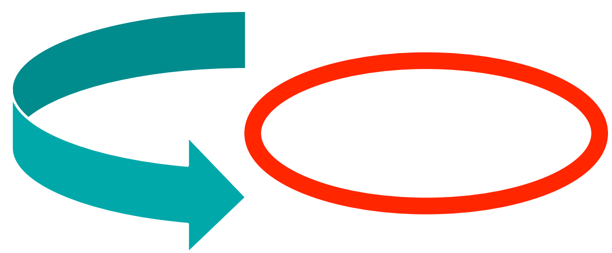
Euclid of Alexandria
325-265 BC

Optica



Yet, can light bend ?

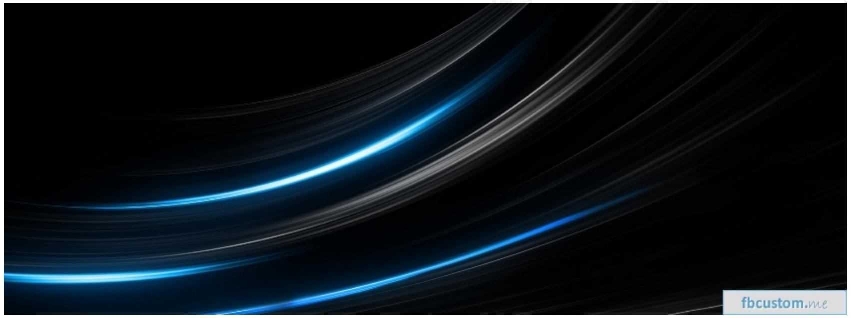
Can light bend?



Are curved light trajectories possible?

science fiction

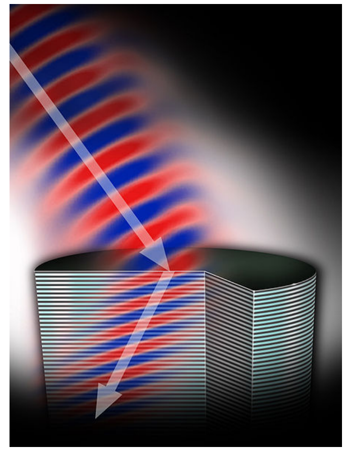
arts



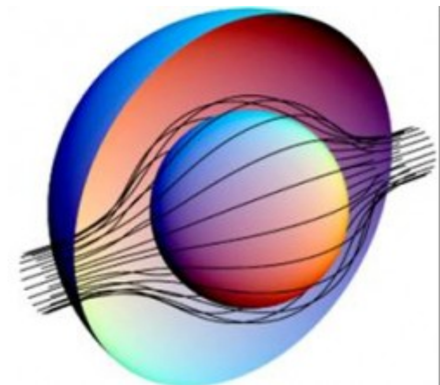
Bending light

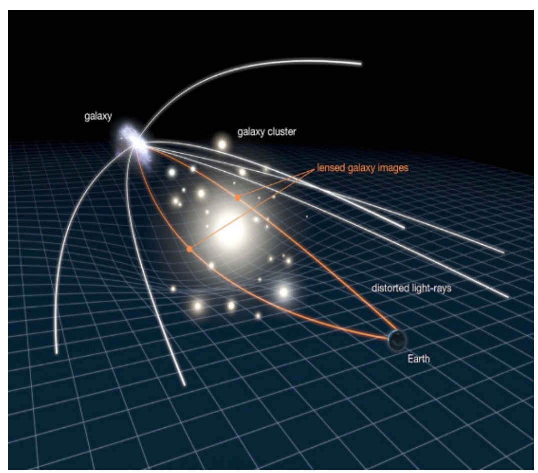
Refraction

Negative refraction



Cloaking





Gravitational lensing

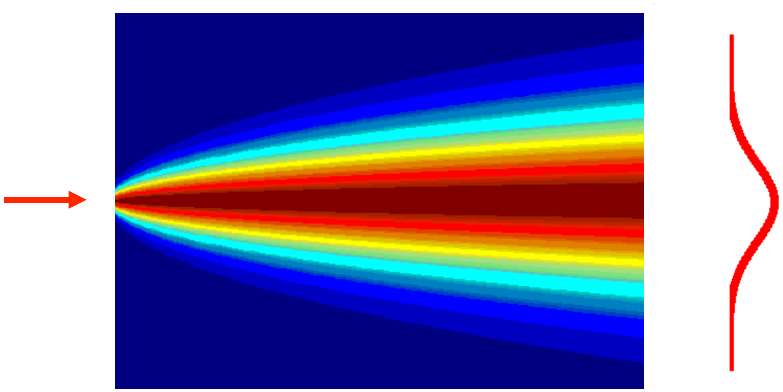
Optical diffraction

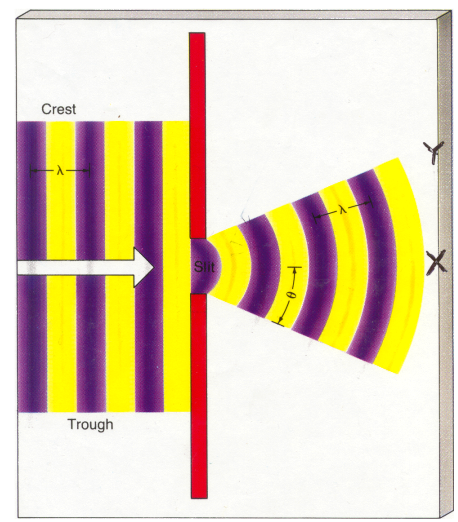
Diffraction

Francesco Grimaldi
1613-1663

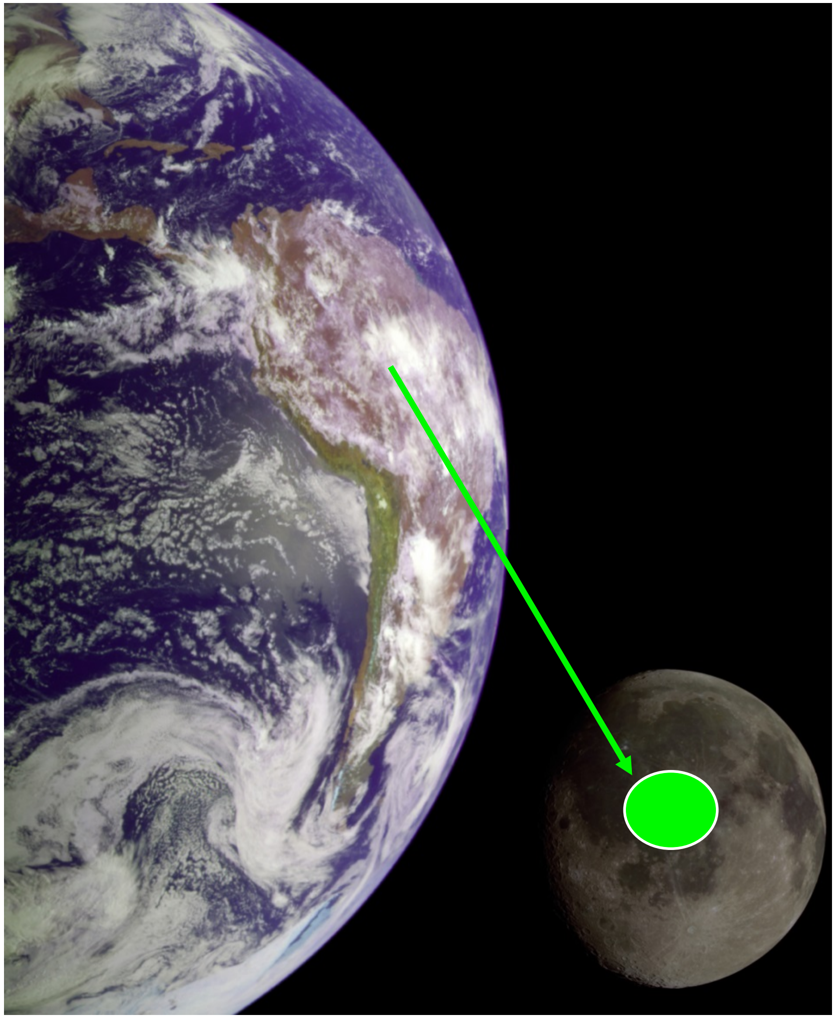
Diffraction is defined as "any deviation of light rays from rectilinear paths that can not be interpreted as reflection or refraction".

Diffraction of a Gaussian beam





Diffraction

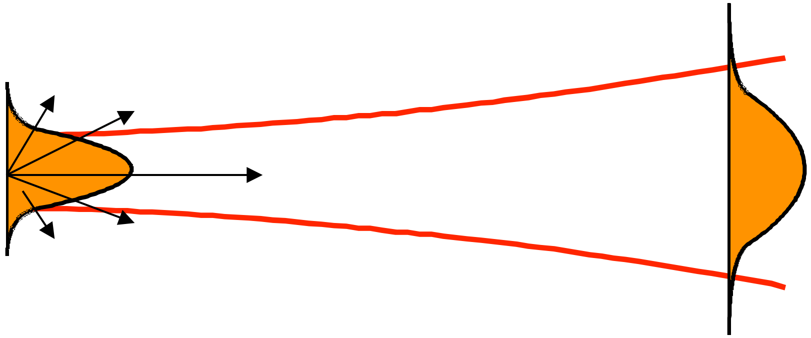


A beam from a green laser pointer, 1 mm in diameter, will have a diameter of 1500 km when it reaches the moon.

That will be the size of Texas !

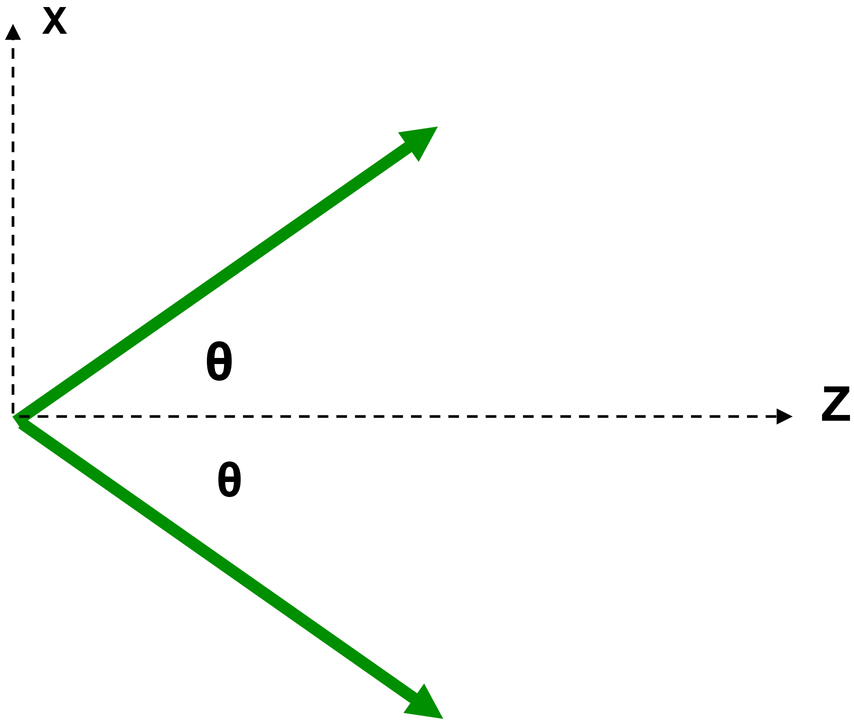
Why optical beams diffract?

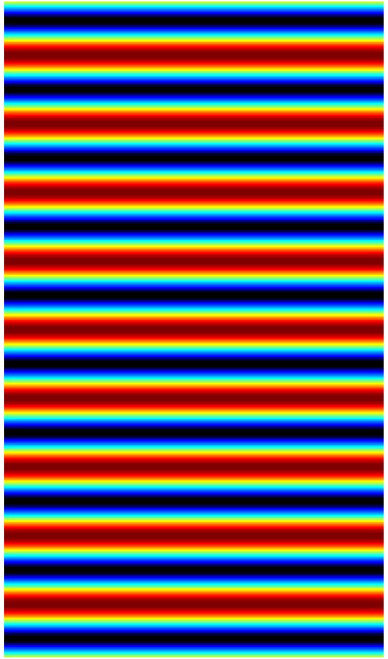
Intuitively one may say that all plane waves components comprising the beam tend to walk-off from each other and a as a result the beam diffracts.



Non-diffracting beams & waves

Diffraction-free patterns?



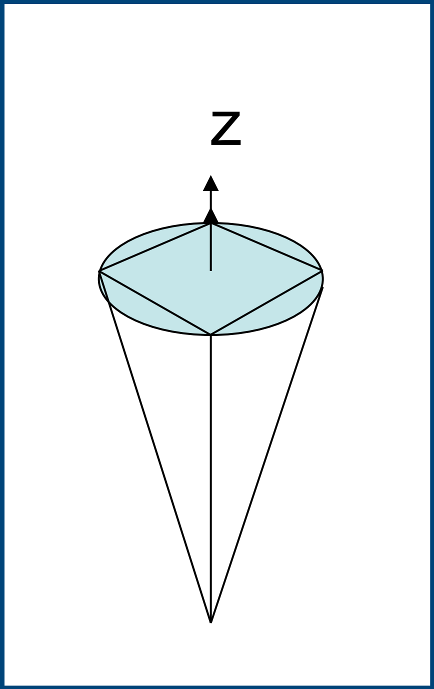


$$E = E_0 \exp\left[i\left(k_x x + k_z z\right)\right] + E_0 \exp\left[i\left(-k_x x + k_z z\right)\right]$$

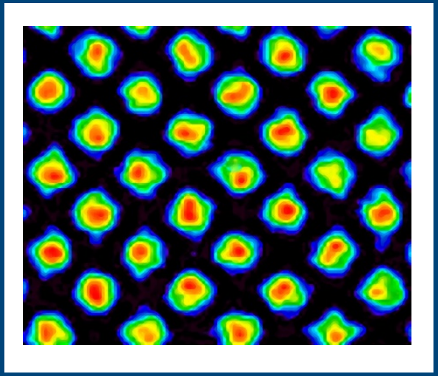
$$E = 2E_0 \cos(k_x x) \exp\left[ik_z z\right]$$

$$I = \left|E\right|^2 = 4E_0^2 \cos^2(k_x x)$$

Non-diffracting beams
- conical plane wave superposition



4-waves

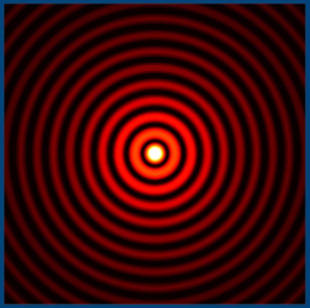


21 waves

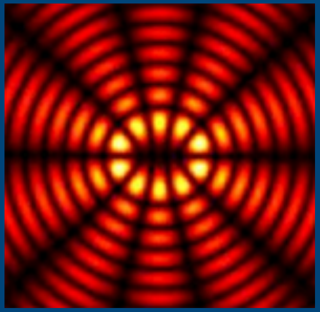
Non-Diffracting Beams

A non-diffracting beam remains intensity invariant during propagation.

Bessel



Mathieu



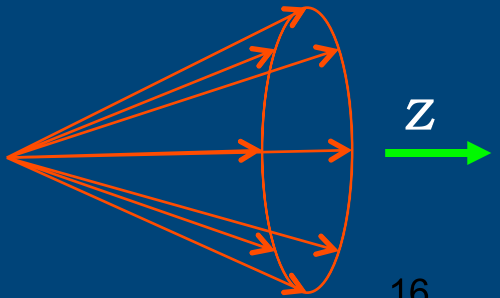
Non-diffracting beams share two common characteristics:

Non-diffracting beams (like plane waves) are known to convey **infinite power or energy.**

All the known non-diffracting beams can be generated through conical superposition of plane waves.

On the other hand, finite energy beams/ pulses are known to eventually diffract or disperse.

$$k_{x,i}^2 + k_{y,i}^2 = const.$$



J. Durnin, J. J. Miceli, and J. H. Eberly, PRL **58**, 1499 (1987).
J. C. Gutiérrez-Vega, M. D. Iturbe-Castillo, and S. Chávez-Cerda, Opt. Lett. 25, 1493-1495 (2000)

One-dimensional non-diffracting accelerating beams:

Airy-beams

Non-spreading Airy wavepackets

$$i\hbar\frac{\partial\psi}{\partial t}+\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}=0$$

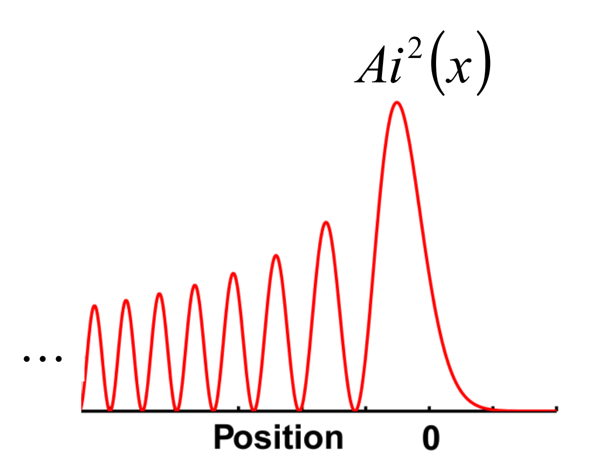
Free particle
1D Schrödinger equation

The *Airy wavepacket* is a unique, non-spreading and accelerating solution!

$$\psi(x,t)=Ai\left[\frac{B}{\hbar^{2/3}}\left(x-\frac{B^3t^2}{4m^2}\right)\right]\exp\left\{\left(iB^3t/2m\hbar\right)\left[x-\left(B^3t^2/6m^2\right)\right]\right\}$$

acceleration term

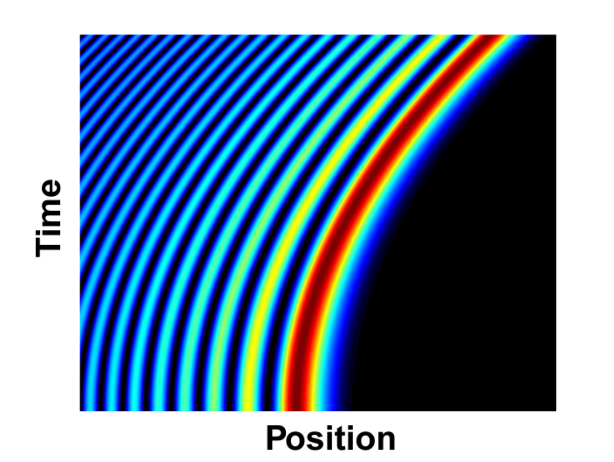
Airy function



Michael Berry and Nandor Balazs, Am. J. Phys. **47**, 264 (1979)

Airy wavefunction is not square integrable

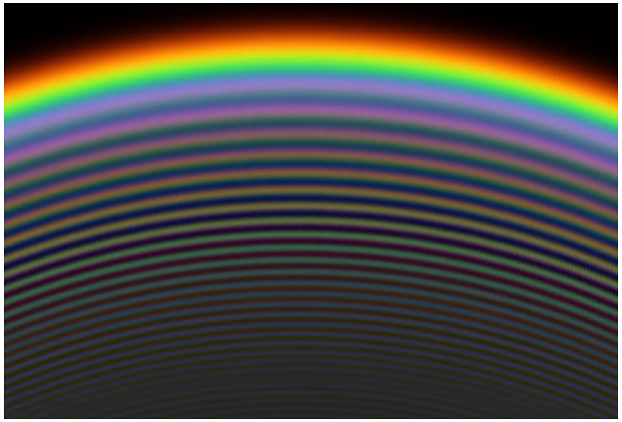
Acceleration of a nonspreading Airy wave

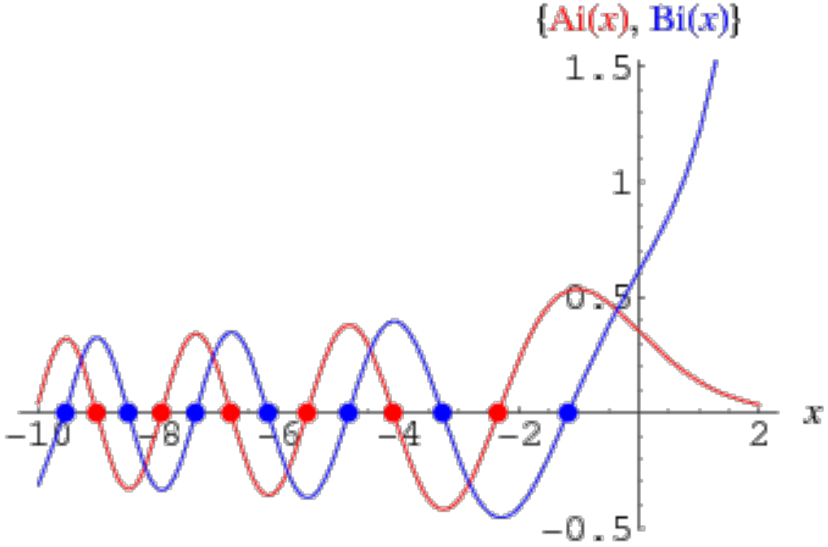


The Airy function

George Biddell Airy
1801-1892

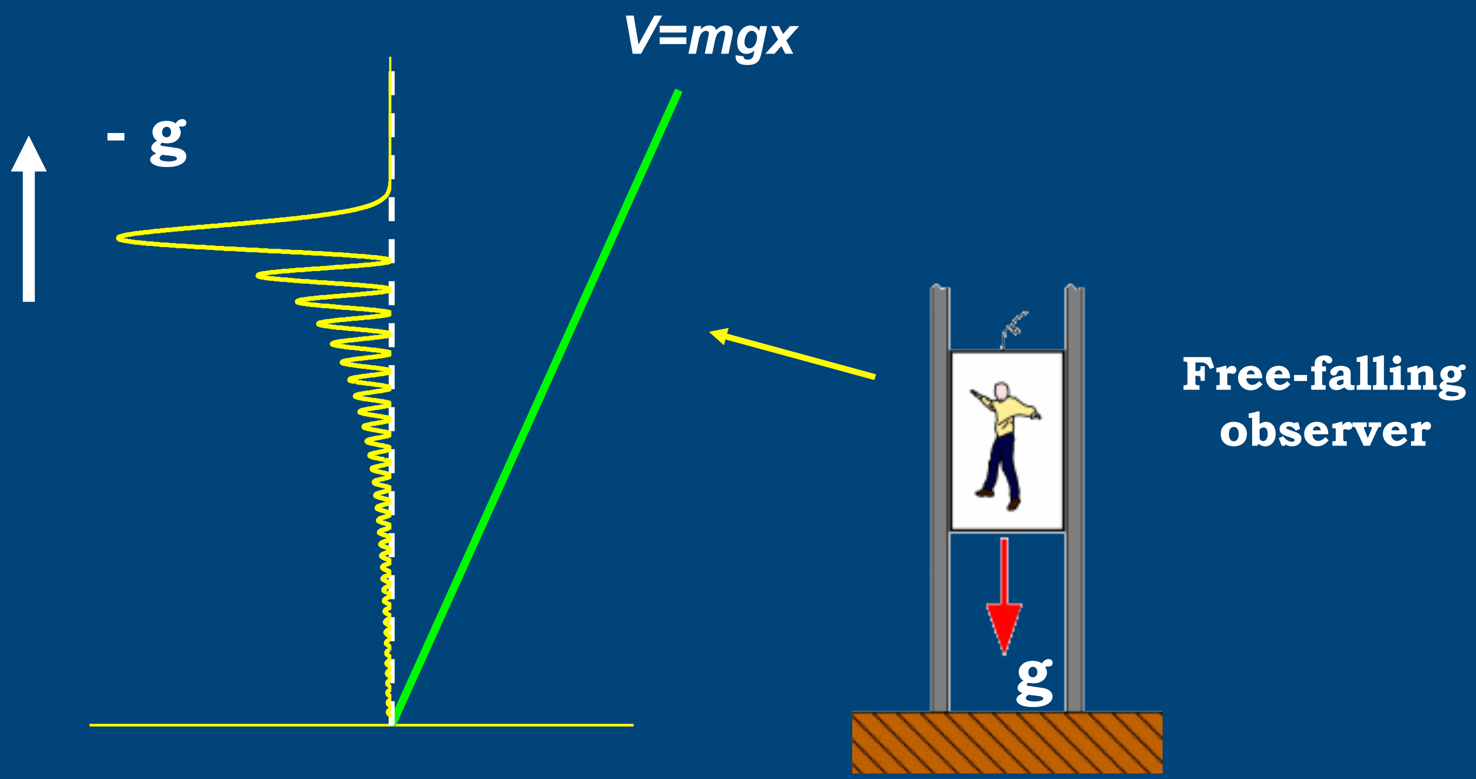
$$\frac{d^2 y}{dx^2} = xy$$





Rainbow

Why do Airy packets freely accelerate?



Equivalence principle & quantum mechanics

D. M. Greenberger, Am. J. Phys. **48**, 256 (1980)

Uniqueness

It can be formally shown that the Airy state is the only non-dispersing wavepacket in 1D.

K. Unnikrishnan and A. R. P. Rau, Am. J. Phys. 64, 1034 (1996)

Finite Energy Optical Airy Beams

Schrödinger Equation

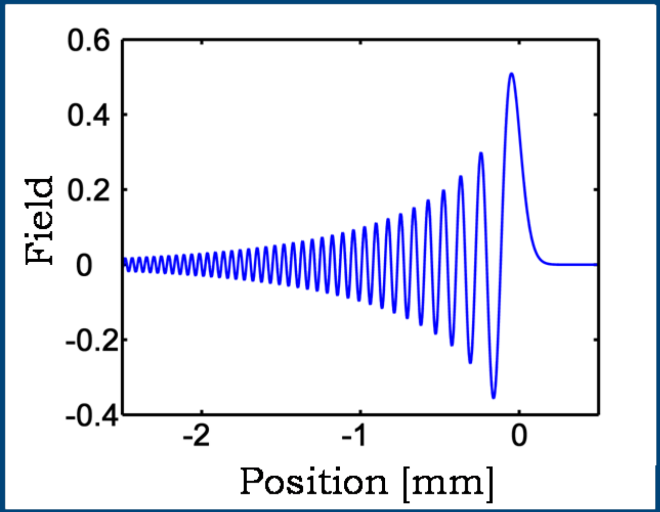
$$i\frac{\partial \psi}{\partial t}+\frac{\hbar}{2m}\frac{\partial^2 \psi}{\partial x^2}=0$$

Paraxial Diffraction Equation

$$i\frac{\partial \varphi}{\partial z}+\frac{1}{2k}\frac{\partial^2 \varphi}{\partial x^2}=0$$

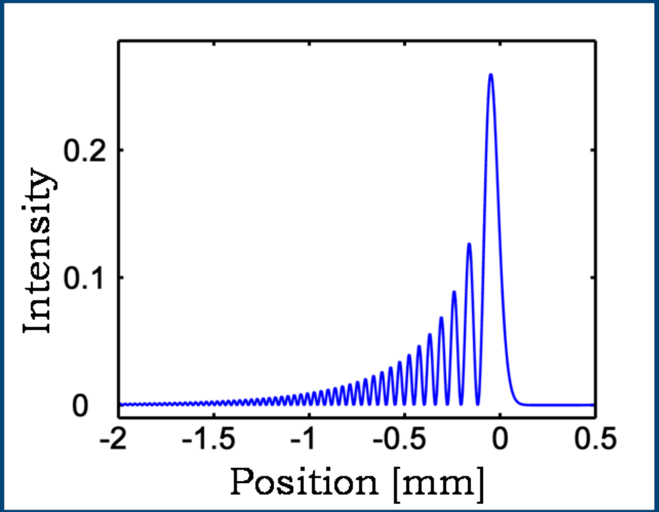
Finite power optical Airy beams have recently been suggested*:

$$\varphi(x, z=0)=Ai(x/x_0)\exp[x/w]$$



x_0 : transverse scale

w : aperture width

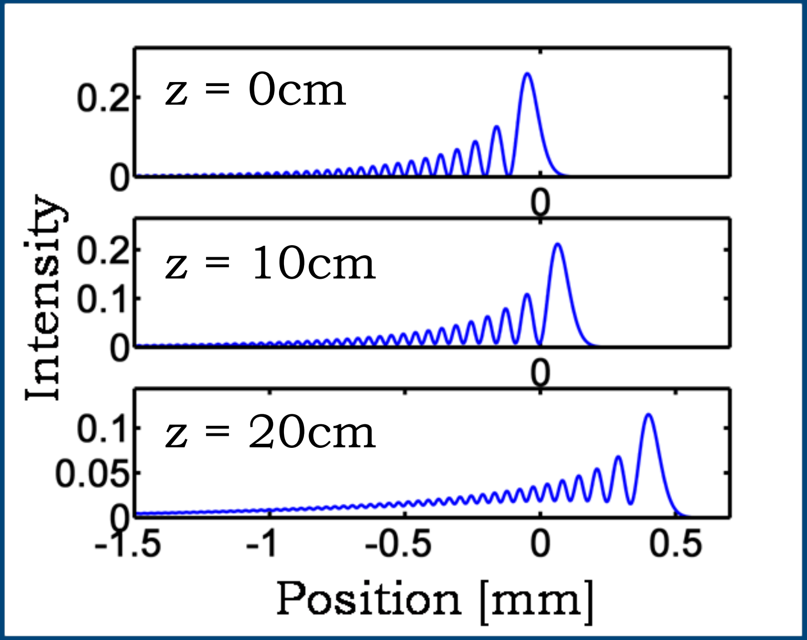


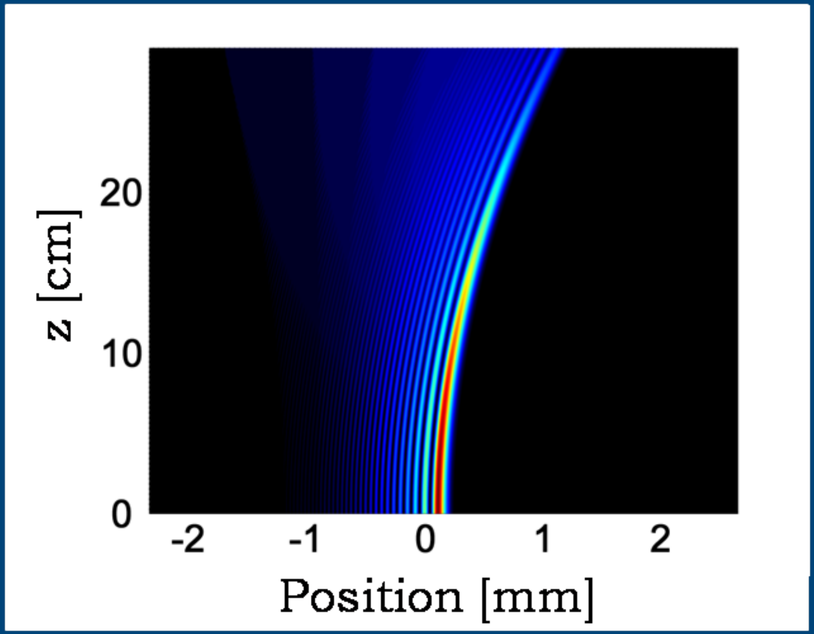
* G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007)

Acceleration dynamics of Airy Beams

Finite energy Airy stripe beams propagate according to* :

$$I = \left|\varphi(x,z)\right|^2 = \left| Ai\left[x/x_0 - \frac{1}{4k^2 x_0^4} z^2 + i\frac{1}{kwx_0} z \right] \right|^2 \exp\left(2x/w\right) \exp\left(-\frac{1}{k^2 w x_0^3} z^2 \right)$$

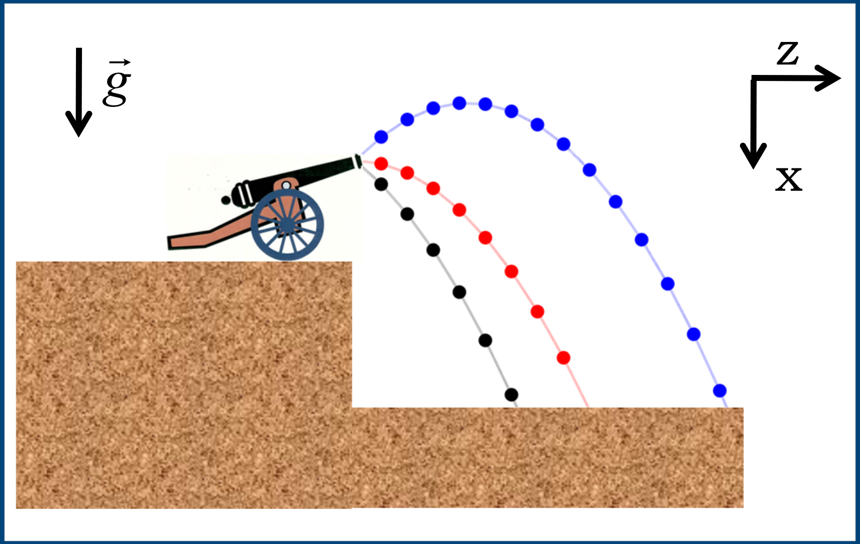


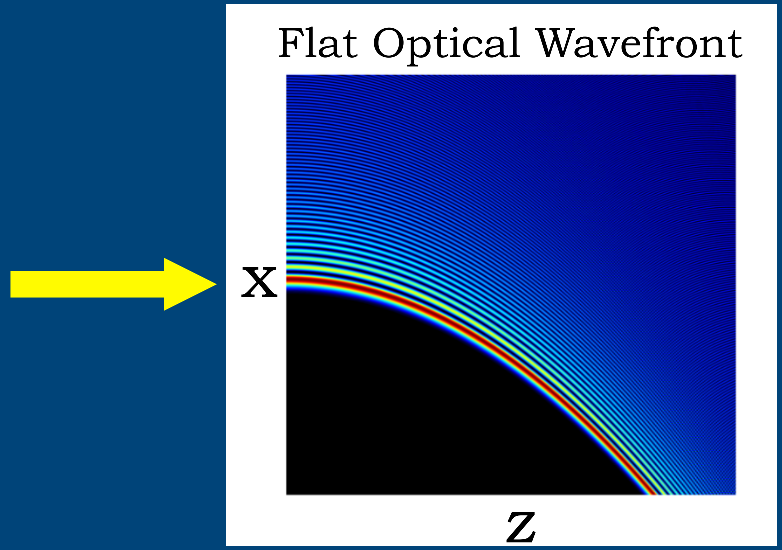


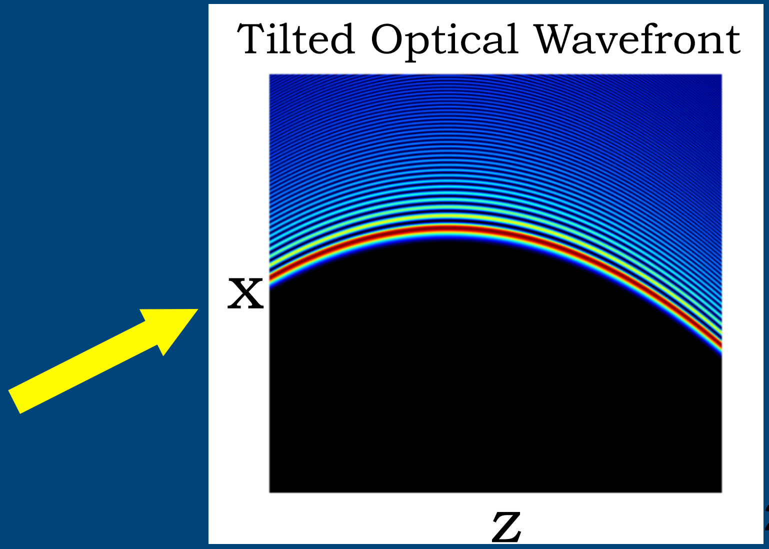
* G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007)

Optical analog of projectile ballistics

The Airy beam moves on a parabolic trajectory very much like a body under the action of gravity!



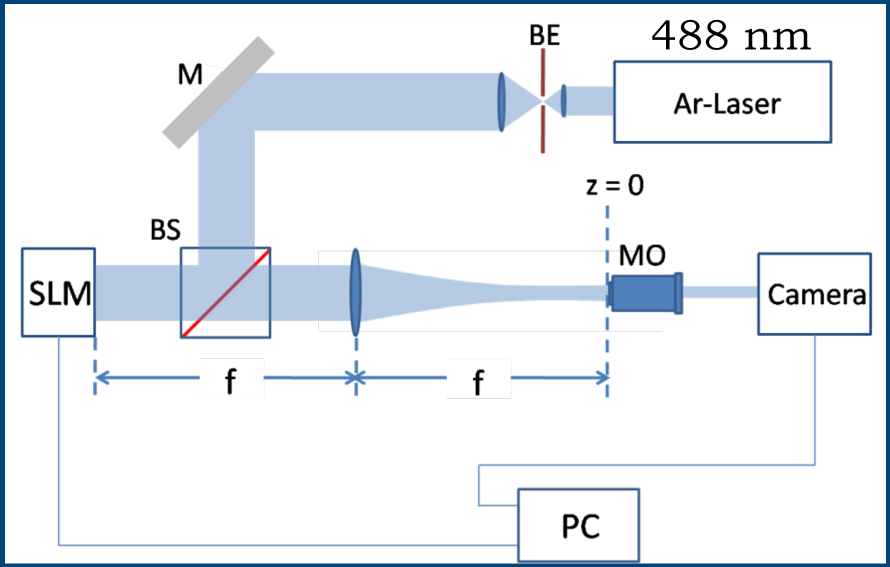




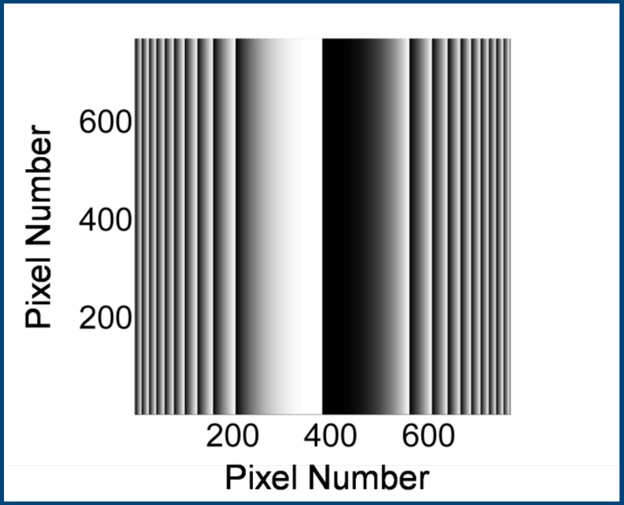
Experimental Set-up

Angular Spectrum $$\Phi_0(k) = \exp\left(-ak^2\right)\exp\left(\frac{i}{3}k^3\right)$$

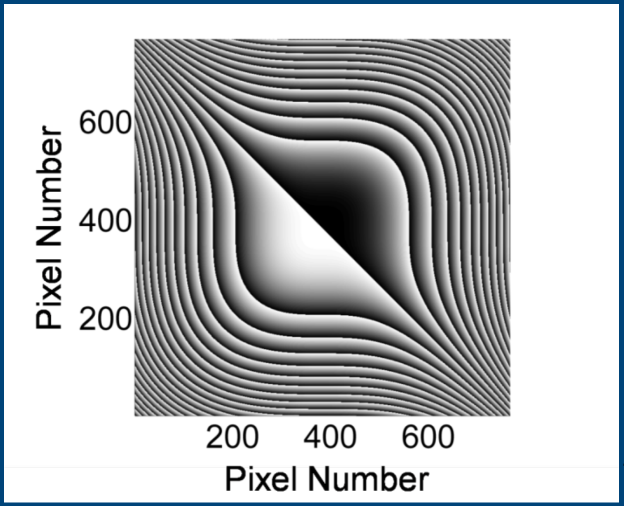
We can synthesize a truncated Airy wave by imposing a cubic phase on a Gaussian beam and then taking its Fourier transform using a lens



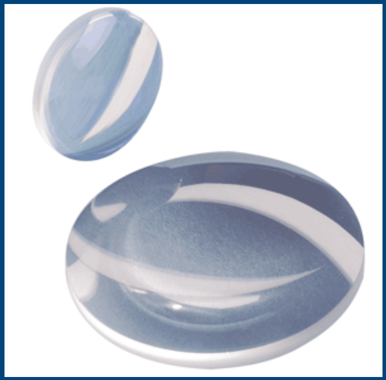
Phase Mask for 1D



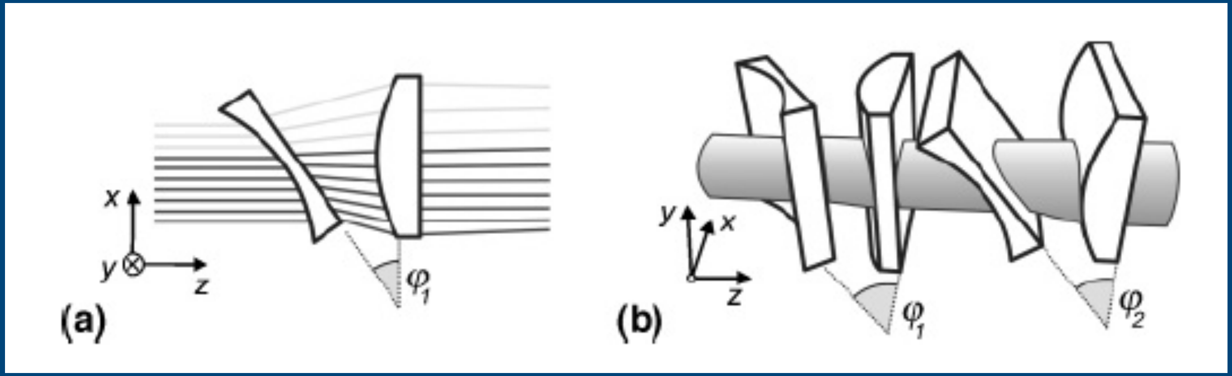
Phase Mask for 2D

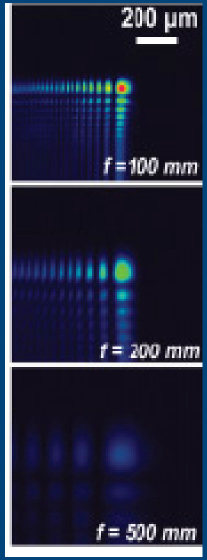


Other possibilities-2D cubic phase masks



U. of Arizona

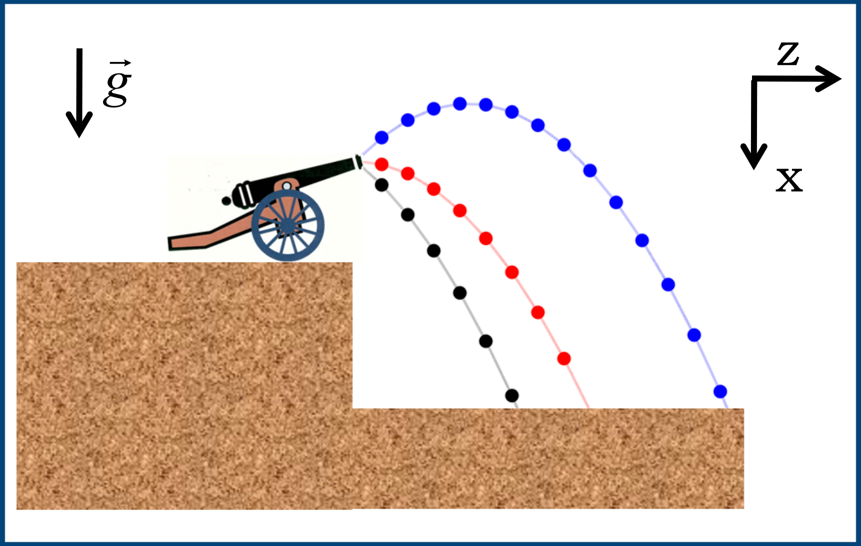


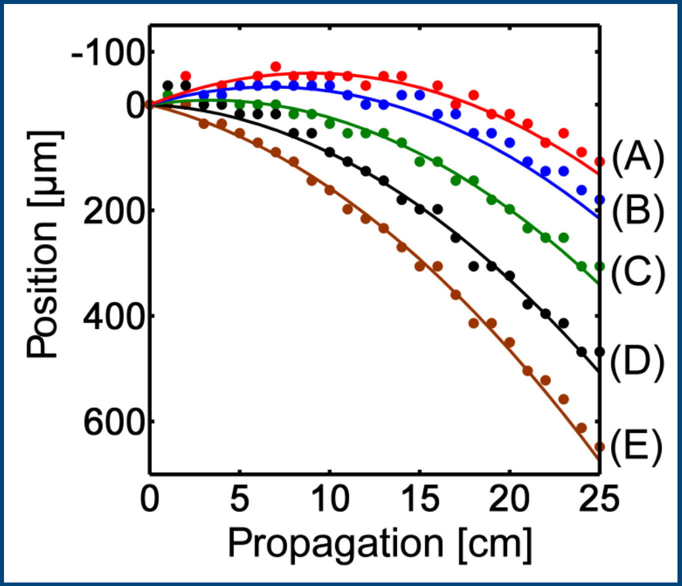


Papazoglou et al, PRA A 81, 061807(R) (2010)

Ballistic dynamics of Airy beams

An Airy beam can move on parabolic trajectories very much like a cannonball under the action of gravity!





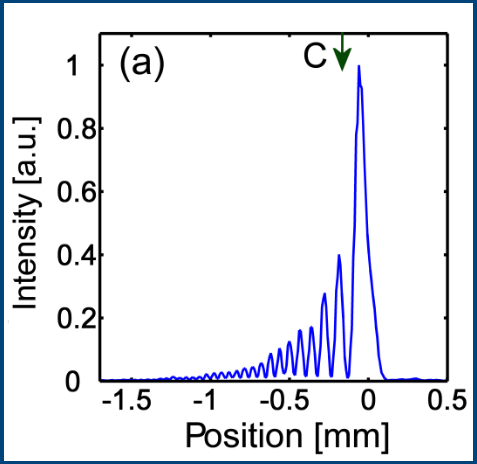
Parabolic deflection of the beam:

$$x_d = \theta z + z^2/(4k^2 x_0^3)$$

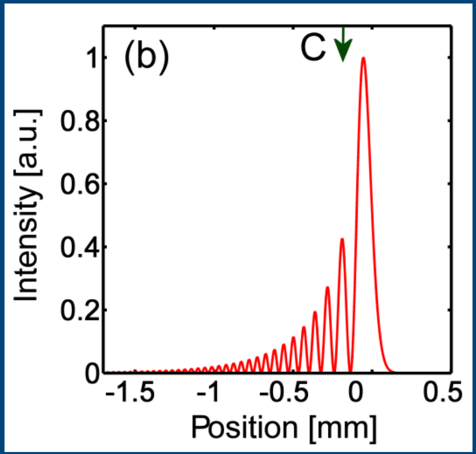
* G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, Optics Letters **33,** 207 (2008)

Ballistic dynamics of Airy beams

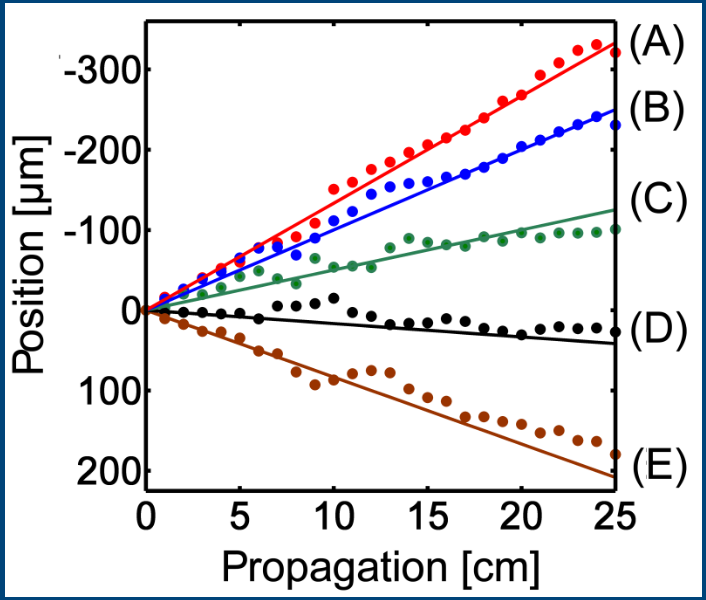
Experiment



Theory



Beam's center of gravity moves on straight lines



$$\bar{x} = \int_{-\infty}^{\infty} dx\, x \left| E \right|^2$$

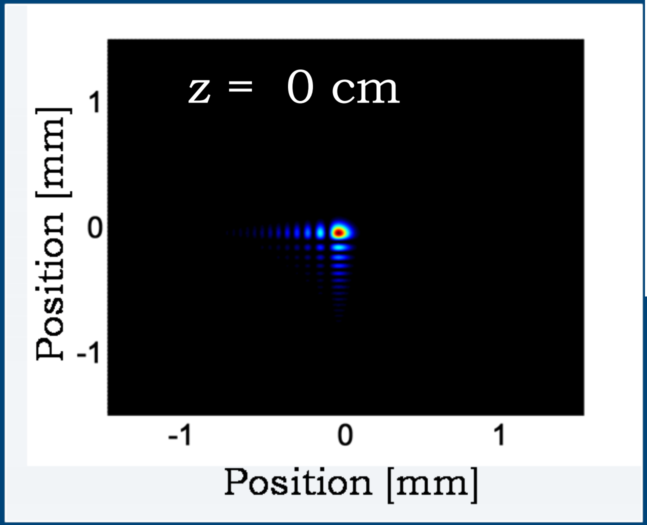
In agreement with Ehrenfest's theorem

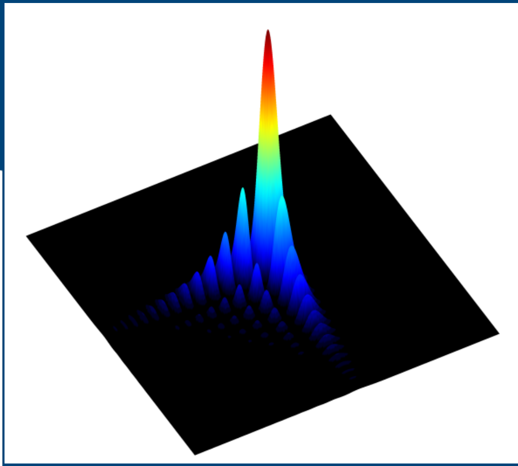
Transverse electromagnetic momentum is conserved !

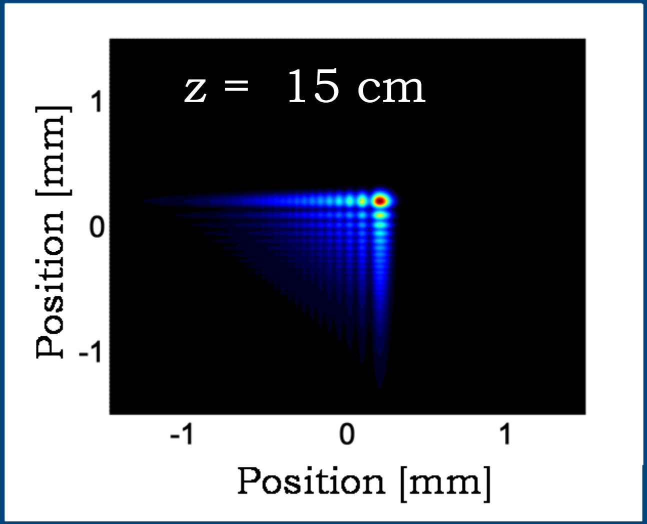
2-D Airy Beams

Similarly, we can introduce 2D finite energy Airy beams:

$$\phi(x, y, z=0) = Ai(x/x_0)\, Ai(y/y_0) \exp[(x/w_1) + (y/w_2)]$$







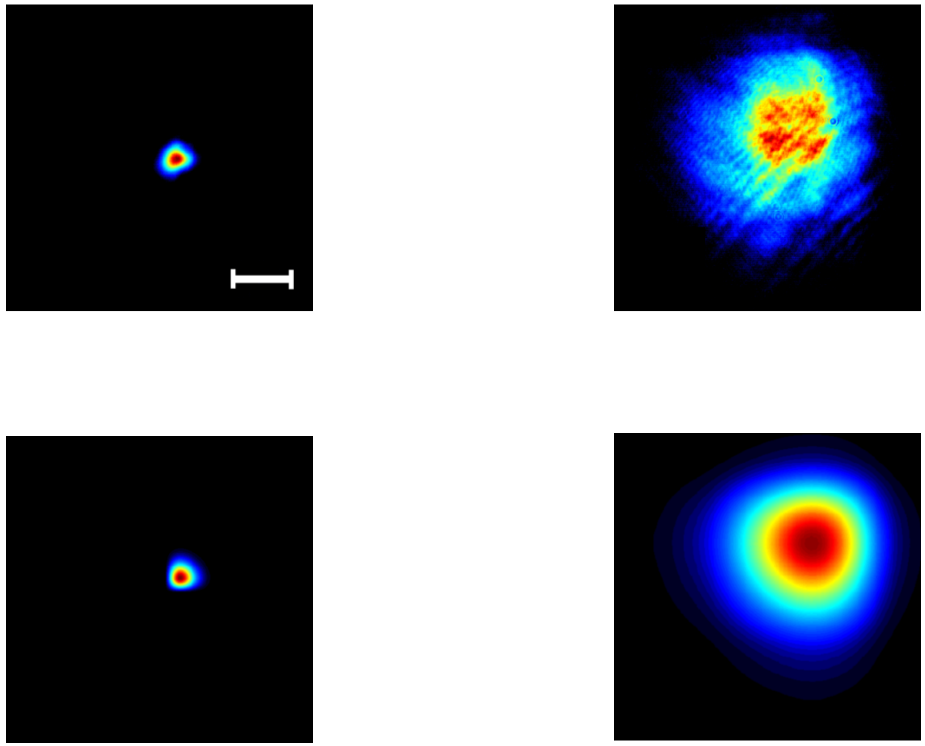
<u>Example:</u> $x_0 = y_0 = 50\mu m \quad w_1 = w_2 = 0.5mm$

Diffraction of the main lobe

Input $z = 30cm$

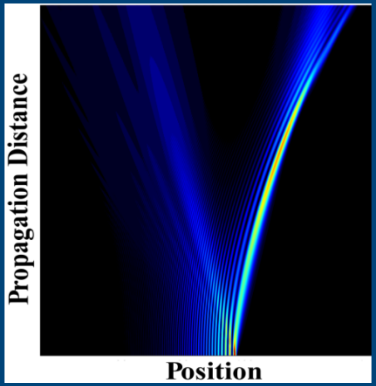
Experiment

Theory

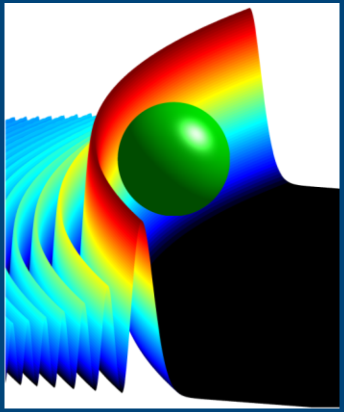


The main lobe launched in isolation has experienced a 5-fold increase in the beam width, while the peak intensity has dropped to 5% of its initial value.

Possibilities



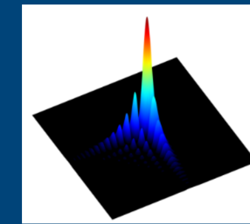
Airy beams can "**heal**" themselves during propagation.



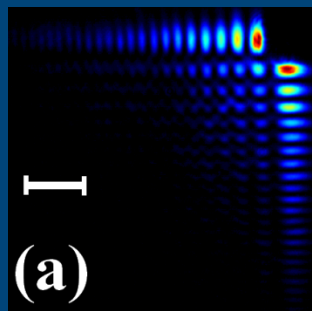
Airy beams can circumvent opaque obstacles.

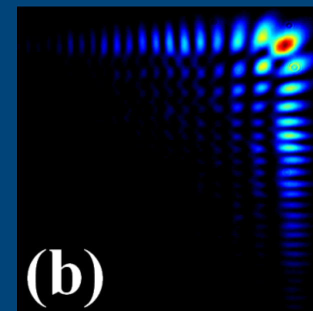
Spatio-temporal **optical bullets** resisting both diffraction and dispersion effects.

Self-healing of Airy Beams



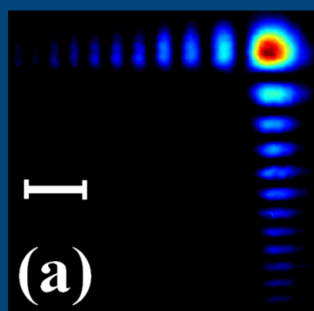
Input Beam

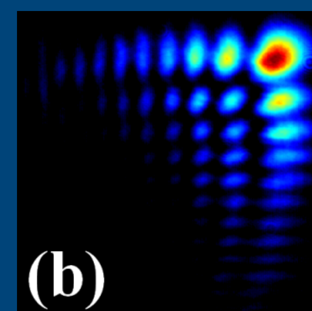




Self-healed Beam

Input Beam



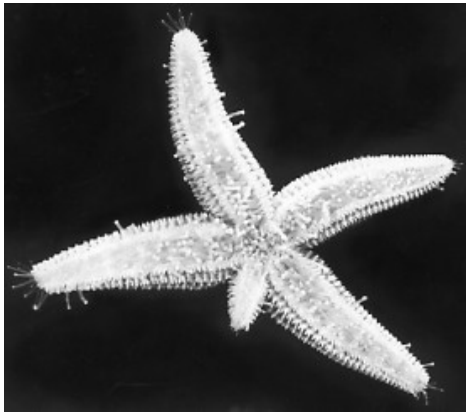


Self-healed Beam

Airy beams are robust and self-reconstruct even under severe perturbations

Broky, Siviloglou, Dogariu, and Christodoulides, "Self-healing properties of optical Airy beams," Opt. Express **16**, 12891 (2008)

Self-healing

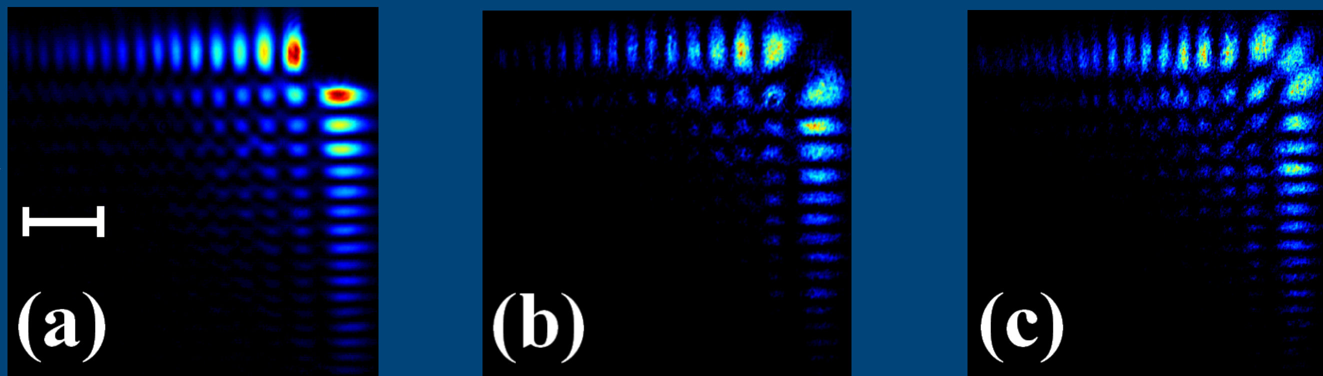


Regeneration

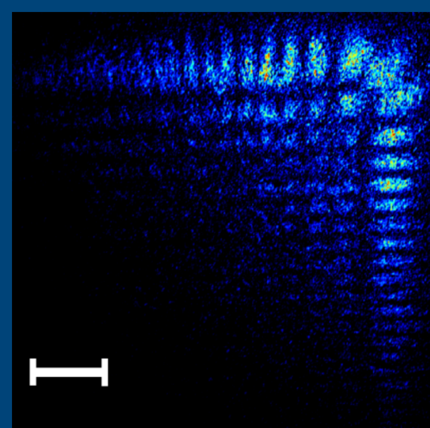
Airy Beams in adverse environments:
I. Scattering media

Z = 0 cm **Z = 5 cm** **Z = 10 cm**

Diameter = 0.5 µm
Moderate Scattering



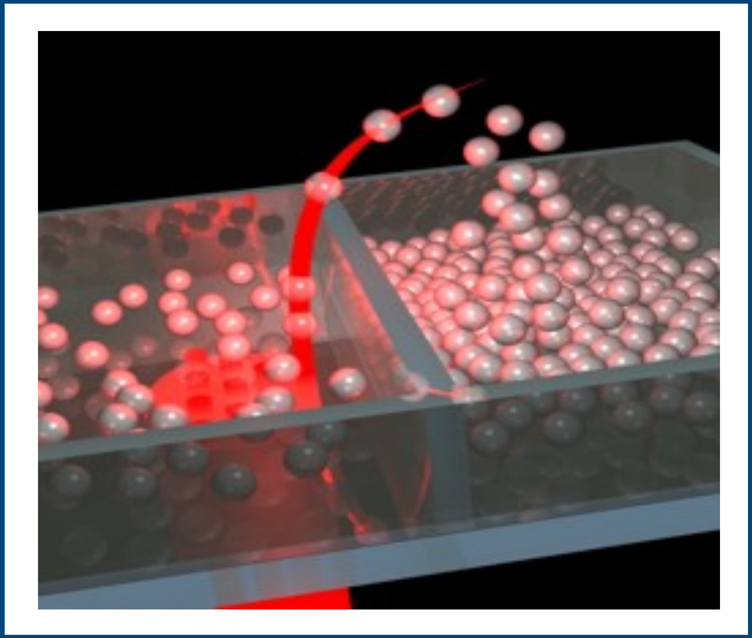
Diameter = 1.5 µm
Severe Scattering

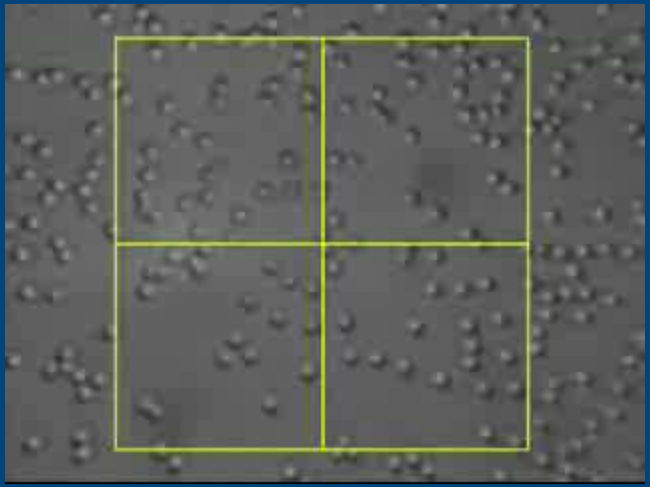


Silica microspheres (n=1.47) suspended in water (n=1.33)

Concentration: 0.2 % w/w

Optical nano-particle manipulation using curved Airy beams

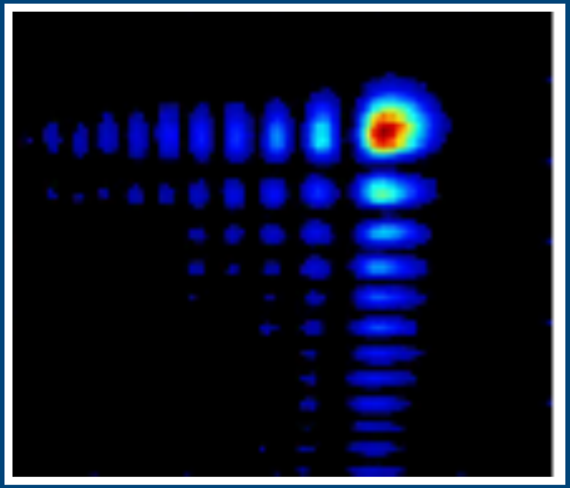




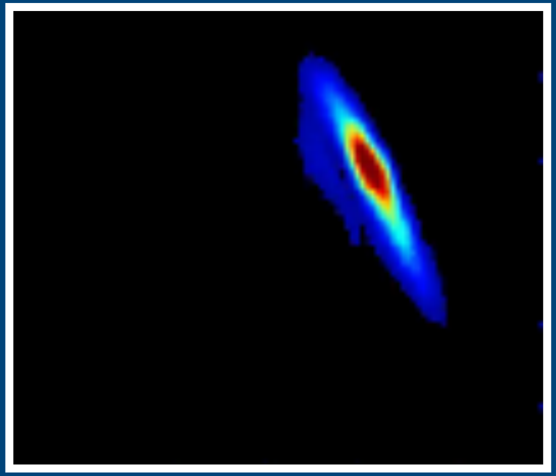
Baumgartl, Mazilu & Dholakia
***Nature Photonics* 2, 675 - 678 (2008)**

Airy Beams in adverse environments: Turbulent media

Airy beam



Gaussian beam



Airy beams are resilient under turbulence while a comparable Gaussian beam is badly deformed.

Scintillation dynamics of Airy beams under turbulence

Scintillation of Airy beam arrays in atmospheric turbulence

Yalong Gu* and Greg Gbur
Department of Physics and Optical Science, University of North Carolina at Charlotte, Charlotte, North Carolina 28223, USA
**Corresponding author: ygu4@uncc.edu*

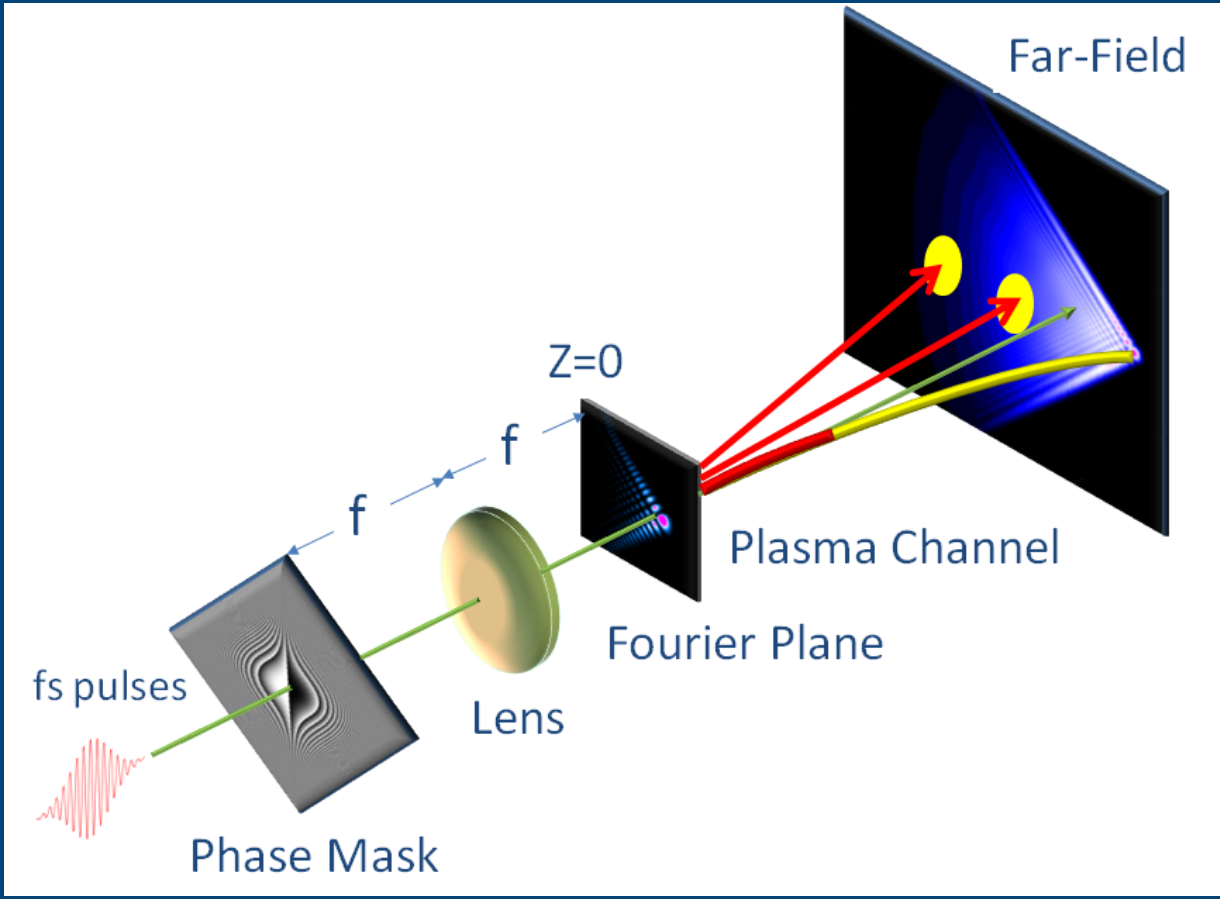
Received August 9, 2010; revised September 14, 2010; accepted September 17, 2010;
posted September 27, 2010 (Doc. ID 133186); published October 12, 2010

We investigate the scintillation properties of Airy beam arrays in atmospheric turbulence. By utilizing the "self-bending" propagation property of Airy beams, the constituent beamlets propagate through relatively independent regions of turbulence but still largely overlap at the on-axis detector. Through numeric simulations, it is shown that the scintillation of an Airy beam array is significantly reduced and close to the theoretical minimum. © 2010

Optics Letters vol. 35, pp. 3456, (2010)

Airy beams in optical filamentation studies

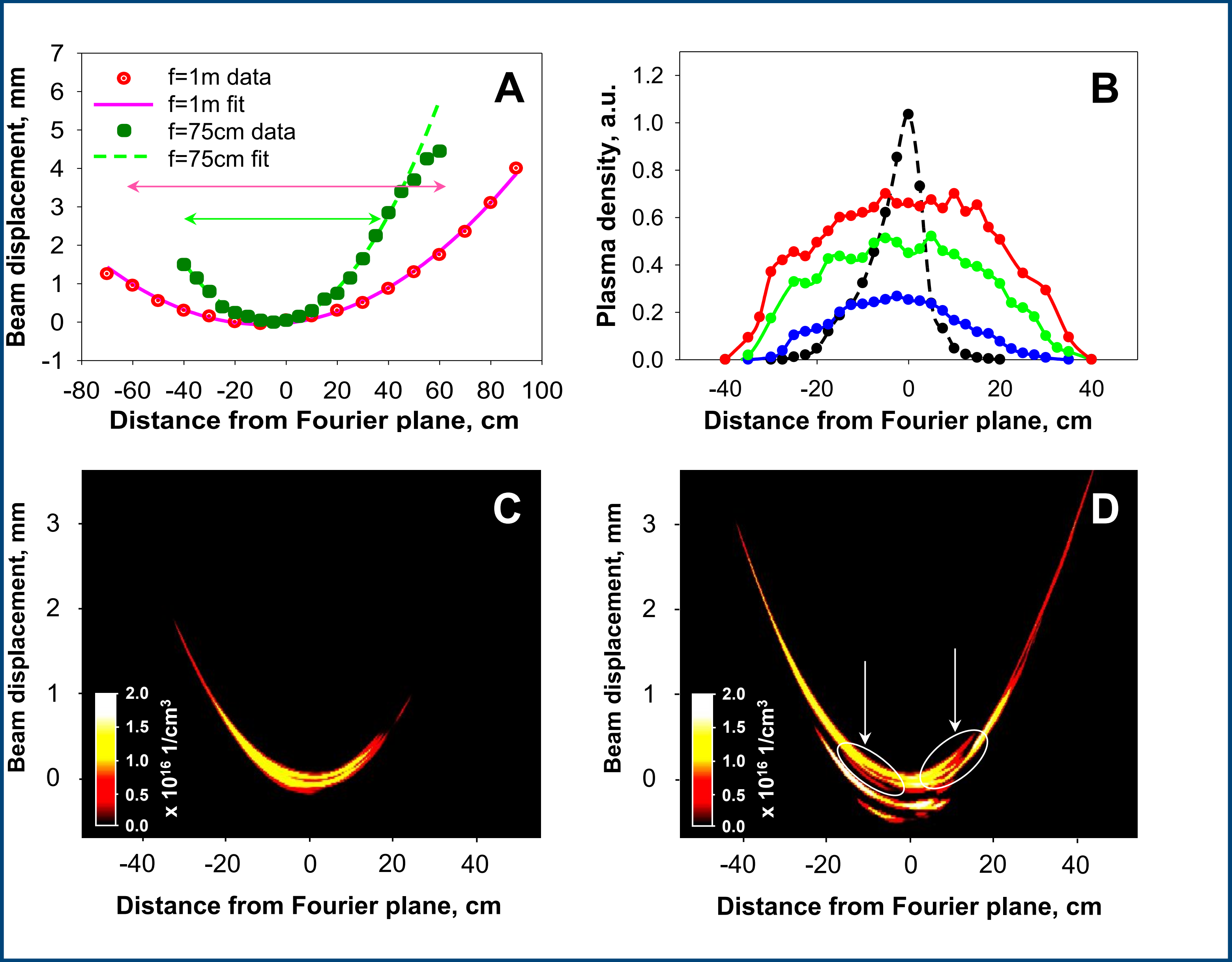
Curved plasma channel generation using ultra-intense Airy beams in air



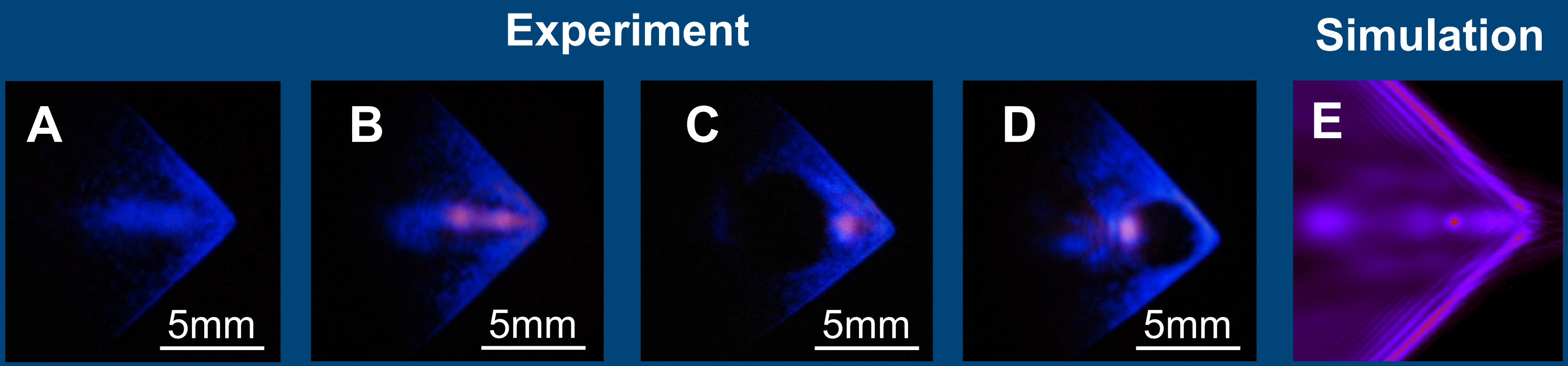
U. of Arizona /CREOL

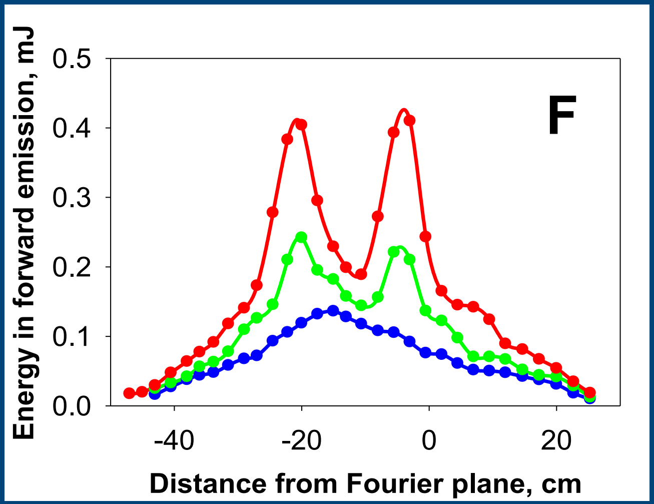
Science, 324, 5923 (2009)

Curved plasma channel generation using ultra-intense Airy beams in air



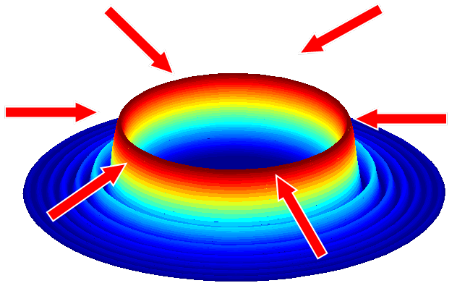
Curved plasma channel generation using ultra-intense Airy beams in air

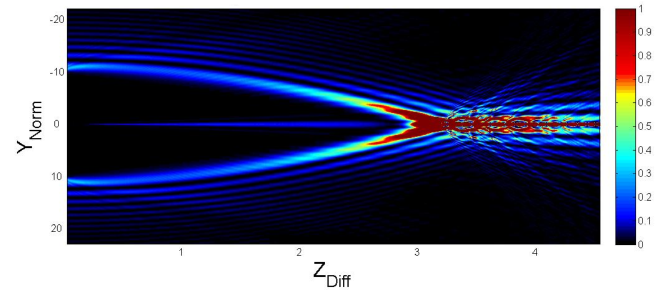


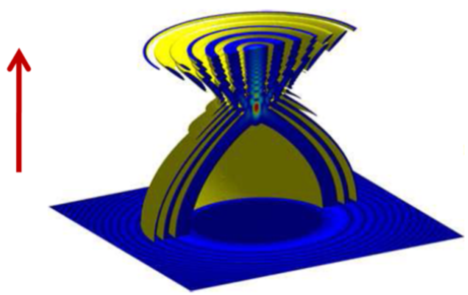


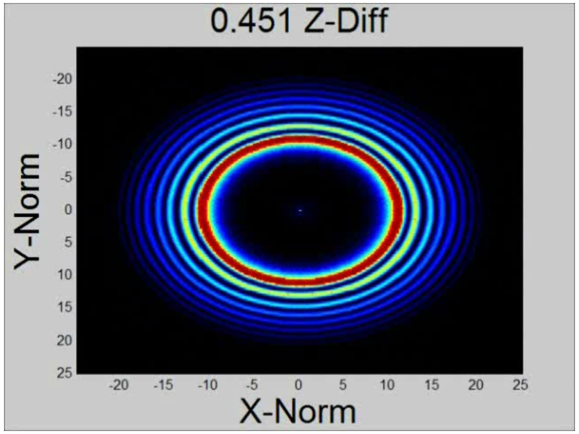
Intensity
distribution of the forward emission along the filament, for different values of pulse energy.
At energies above 5 mJ, the distribution develops two peaks consistent with the experimentally observed emission patterns

Abruptly auto-focusing waves



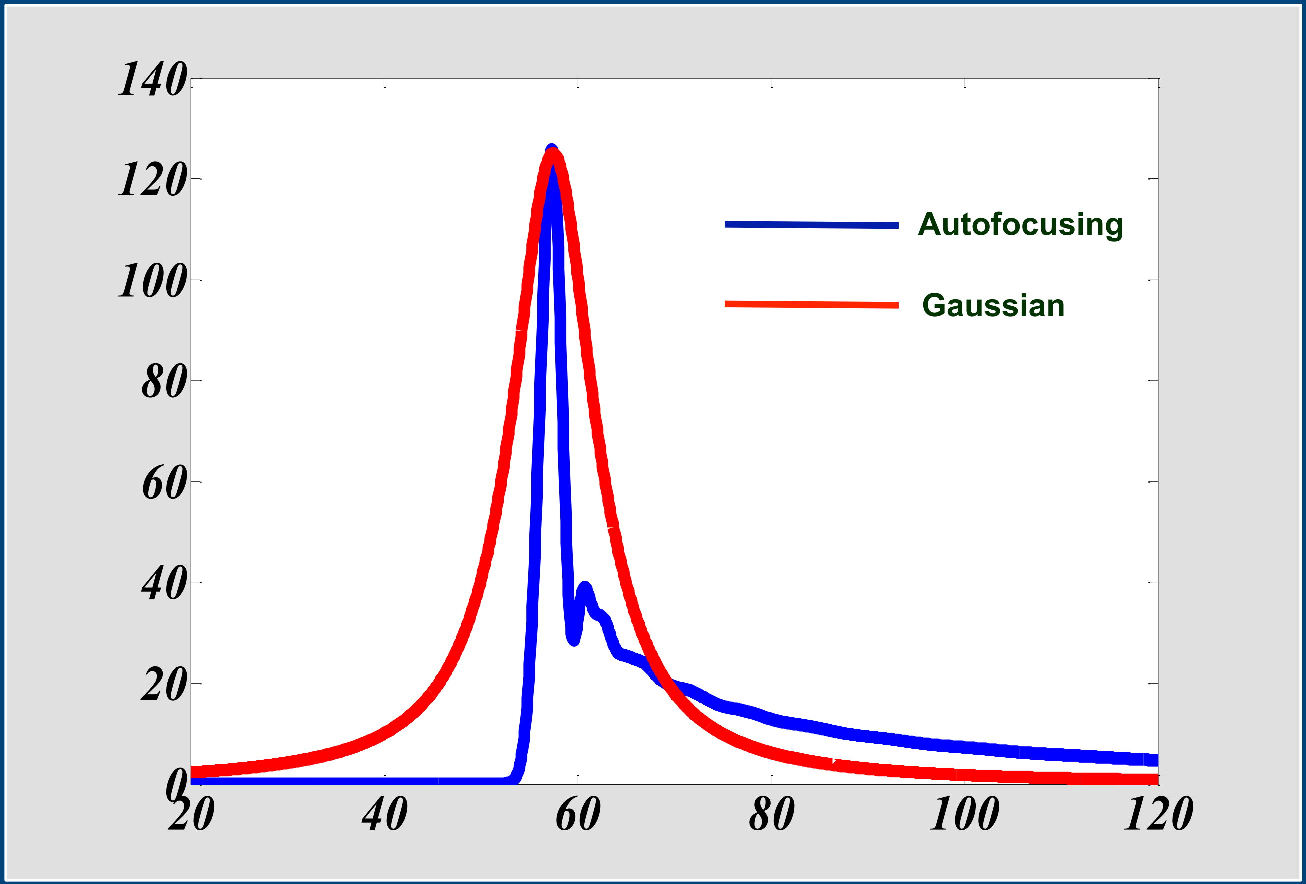




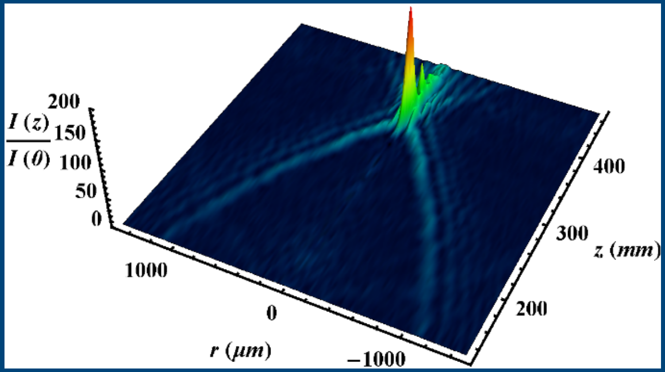


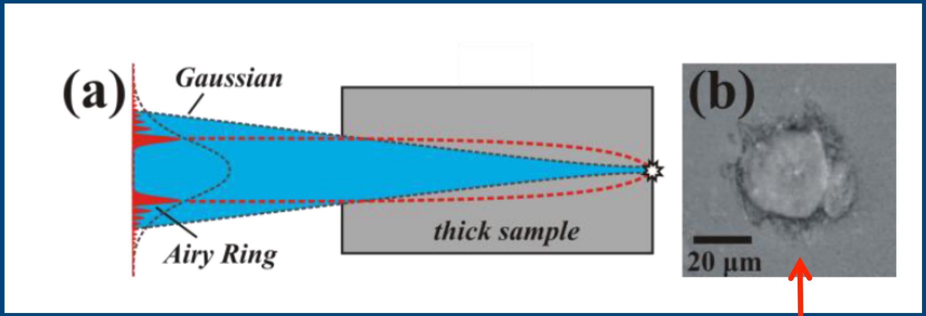
Efremidis, Christodoulides, Opt. Lett. 35, 4045-4047 (2010)

Autofocusing waves versus Gaussian beams

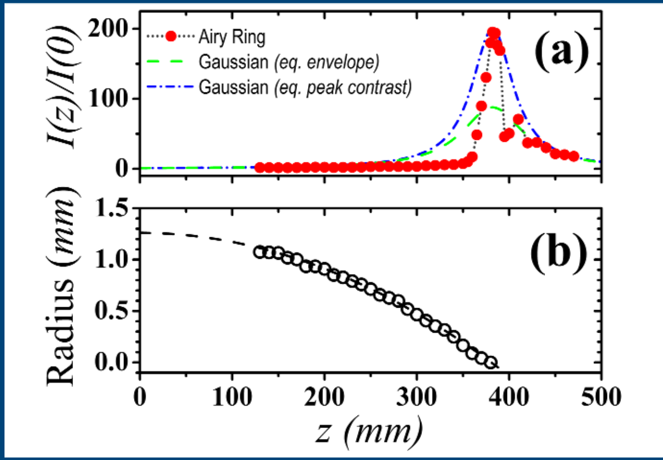


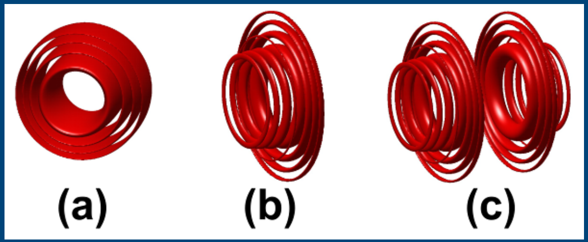
Experimental observation of auto-focusing waves



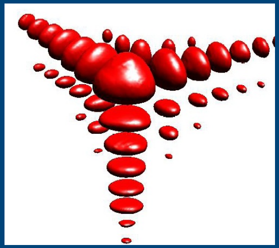


Fused silica ablation





Time-domain enhancement using Airy bullets



Airyx3
PRL 2010

Experimental results: Tzortzakis,FORTH Crete, OL vol. 36, p. 1842 (2011)

Optical Airy Bullets

Optical Bullets

An spatio-temporal optical wave propagating under the influence of diffraction and dispersion obeys:

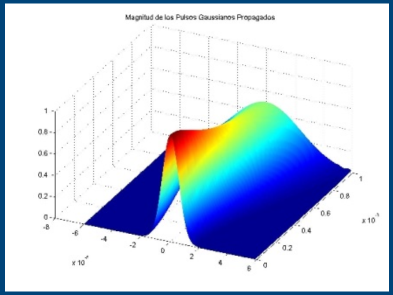
$$i\frac{\partial E}{\partial z}+\frac{1}{2k}\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)-\frac{k_0''}{2}\frac{\partial^2 E}{\partial \tau^2}=0$$

Diffraction **Dispersion**

$k_0'' > 0$: Normal dispersion

$k_0'' < 0$: Anomalous dispersion

Broadening in both space and time occurs



Nonlinear optical bullets

In the presence of nonlinearity one finds that:

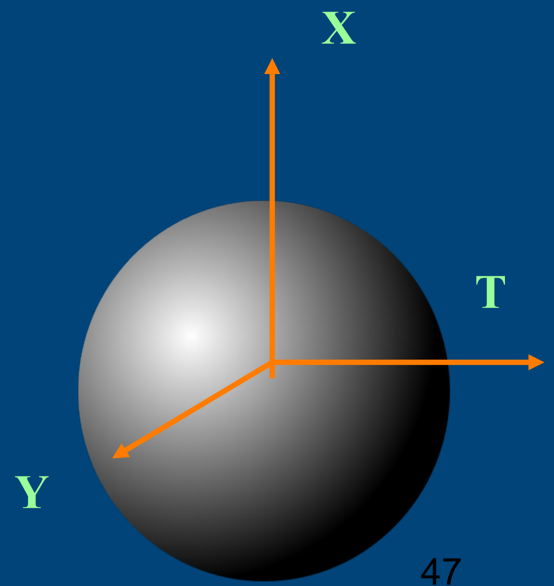
$$i\frac{\partial E}{\partial z}+\frac{1}{2k}\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)-\frac{k_0''}{2}\frac{\partial^2 E}{\partial \tau^2}+k_0 n_2|E|^2 E=0$$

If the dispersion and diffraction lengths are <u>equal</u> and if the dispersion is <u>anomalous</u>:

$$L_{dispersion}=L_{diffraction}=\frac{\tau_0^2}{|k_0''|}=\frac{w_0^2}{k}$$

$$i\frac{\partial \psi}{\partial Z}+\frac{1}{2}\left(\frac{\partial^2 \psi}{\partial X^2}+\frac{\partial^2 \psi}{\partial Y^2}\right)+\frac{1}{2}\frac{\partial^2 \psi}{\partial T^2}+|\psi|^2\psi=0$$

Spherical optical bullet

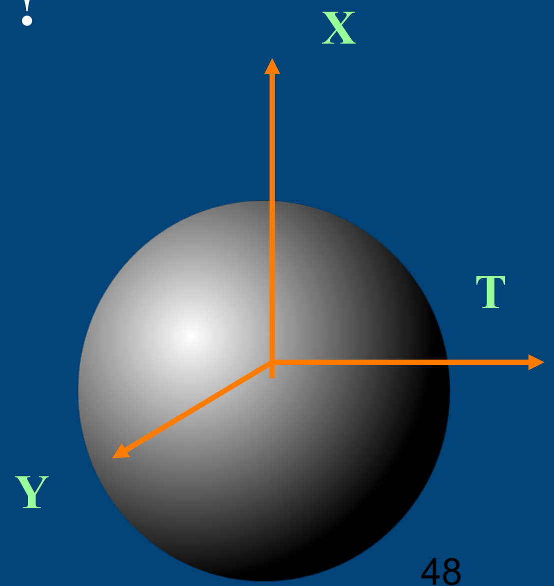


Y. Silberberg, Optics Letters 15, 1282 (1990)

Nonlinear optical bullets

- **They demand equalization of dispersion and diffraction lengths (they are spherical)**
- **They only exist under anomalous dispersive conditions**
- **They need high power levels**
- **Nonlinear optical bullets are highly unstable- they implode/explode during propagation !**

Never observed experimentally except in phase matched chi-2 crystals and only in 2+1 D (Frank Wise group-Cornell)



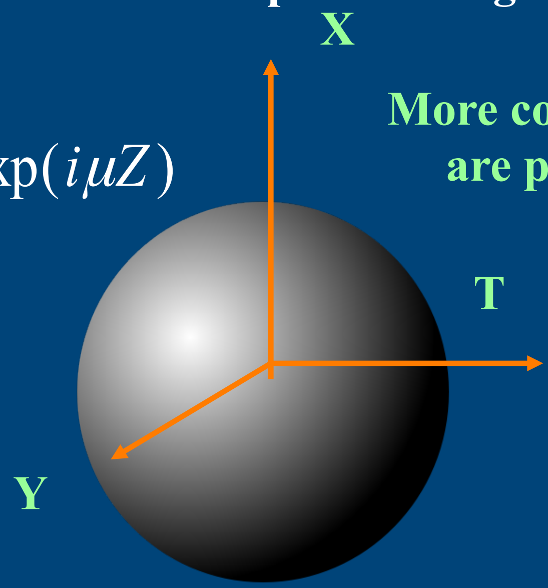
Are linear optical bullets possible?

$$i\frac{\partial \psi}{\partial Z}+\frac{1}{2}\left(\frac{\partial^2\psi}{\partial X^2}+\frac{\partial^2\psi}{\partial Y^2}\right)+\frac{1}{2}\frac{\partial^2\psi}{\partial T^2}=0$$

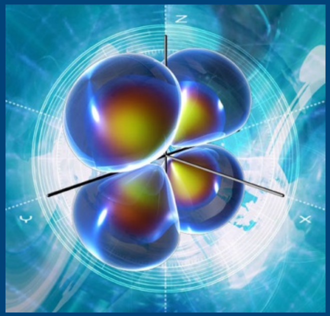
Anomalous dispersion

Yes, as long as the diffraction and dispersion lengths are again equal!

$$\psi=\frac{\sin\sqrt{X^2+Y^2+T^2}}{\sqrt{X^2+Y^2+T^2}}\exp(i\mu Z)$$



More complicated bullets are possible as well.



- **Very difficult to synthesize**
- **Complex spectra**
- **Need dispersion +diffraction equalization**
- **Possible under anomalous dispersion**

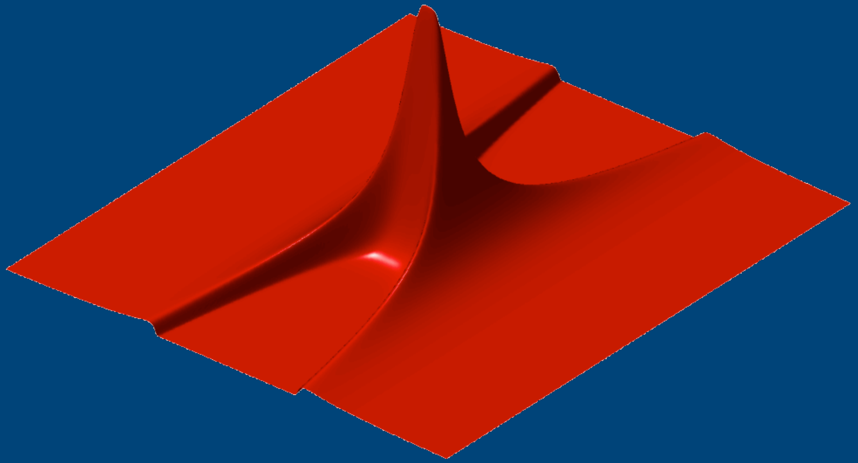
Are linear optical bullets possible?

$$i\frac{\partial \psi}{\partial Z}+\frac{1}{2}\left(\frac{\partial^2\psi}{\partial X^2}+\frac{\partial^2\psi}{\partial Y^2}\right)-\frac{1}{2}\frac{\partial^2\psi}{\partial T^2}=0$$

Normal dispersion

Again, as long as the diffraction and dispersion lengths are equal!

$$\psi=\frac{1}{\sqrt{X^2+Y^2+(iT+c)^2}}$$



X-waves

- **Very difficult to synthesize**
- **Complex spectra**
- **Need diffraction +dispersion equalization**
- **Possible under normal dispersion**

Lu and Greenleaf, Ultrasonics 39 (1992).
Di Trapani et al, PRL 1994.
Christodoulides, Efremidis, Optics Letters **29**, 1446 (2004).

Optical bullets

To overcome these problems one has to disengage space and time- e.g. use separation of variables!

Given that 3 can be written only as:

2+1=3
1+1+1=3

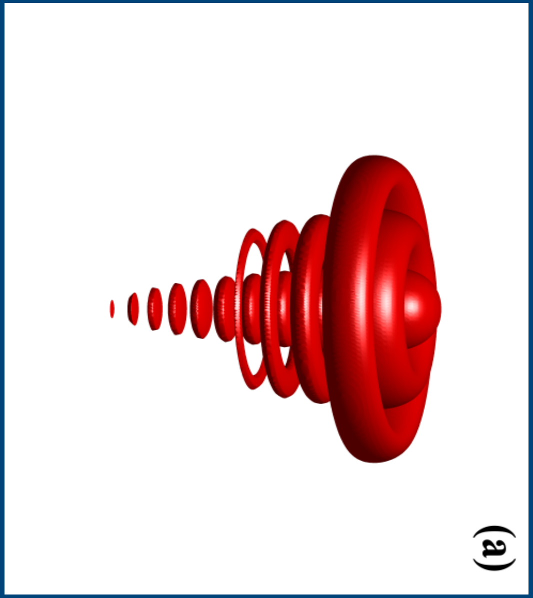
A 1D non-dispersing packet is absolutely necessary as a building block.

Spatio-Temporal Airy Bullets

$$i\frac{\partial\psi}{\partial Z}+\frac{1}{2}\left(\frac{\partial^2\psi}{\partial X^2}+\frac{\partial^2\psi}{\partial Y^2}\right)+\varepsilon\frac{1}{2}\frac{\partial^2\psi}{\partial T^2}=0$$

$$L_{dispersion}\neq L_{diffraction}$$

$$\psi = Ai(\alpha T)J_0(\beta r)$$

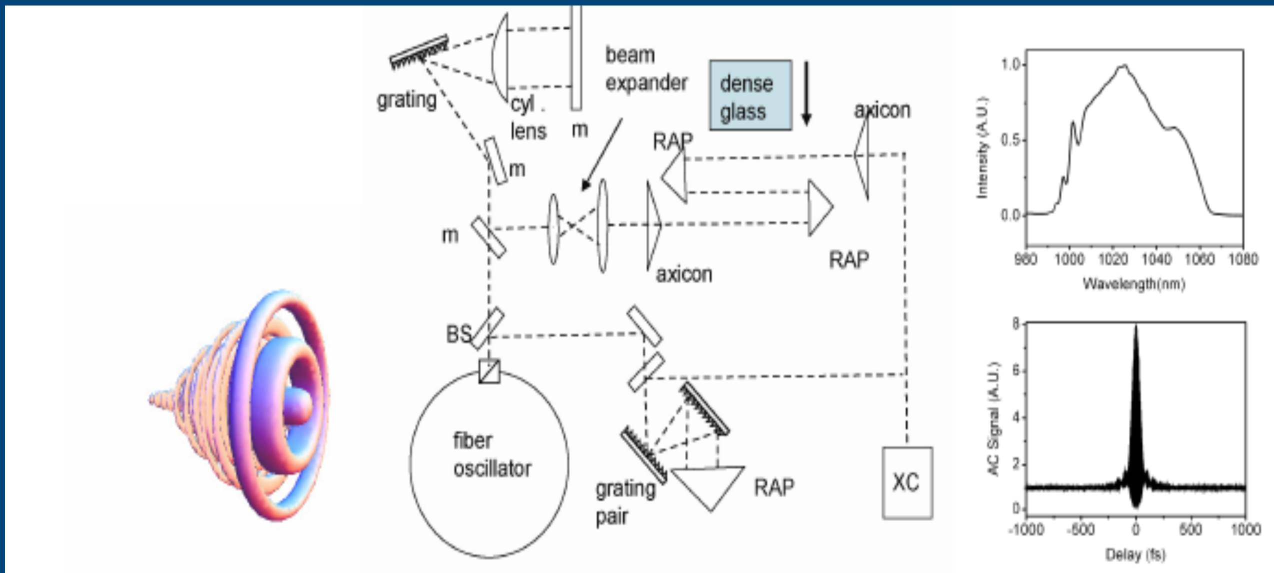


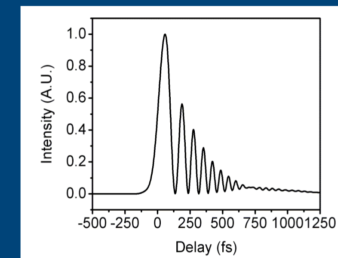
Airy-Bessel Bullet

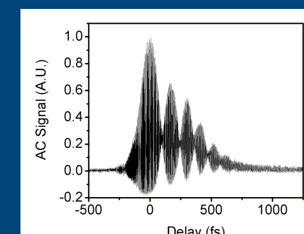
- **Easy to synthesize**
- **Does not need diffraction +dispersion equalization**
- **Possible under any dispersion conditions**

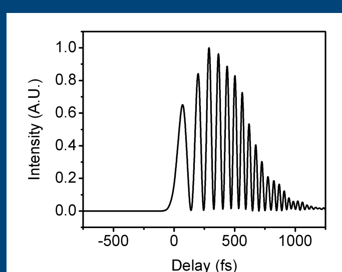
G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007)

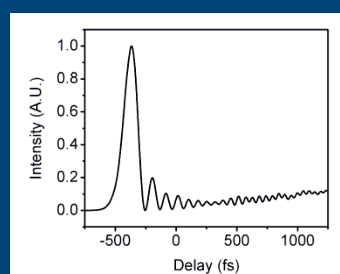
Airy-Bessel Optical bullets









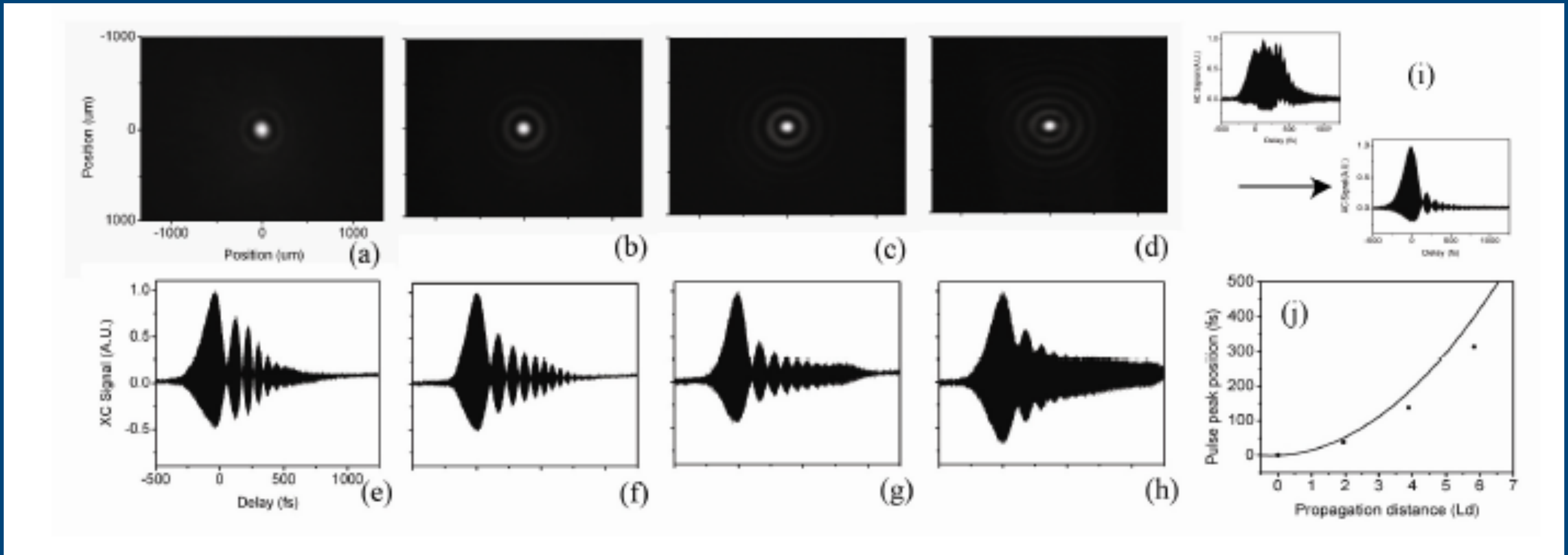


Cornell-CREOL

Frank Wise's group

Self-healing in time after 6 L_d

Airy+Bessel optical bullets



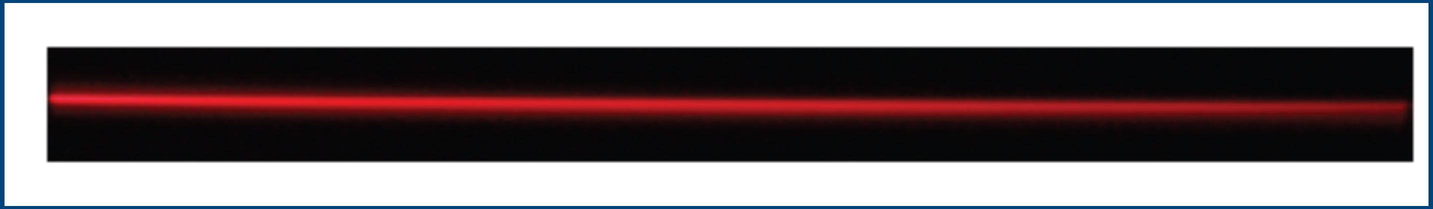
12 diffraction + 6 dispersion lengths
90 micros-90fs
1020 nm

Cornell / CREOL

Airy-Bessel optical bullets

Two-photon fluorescence

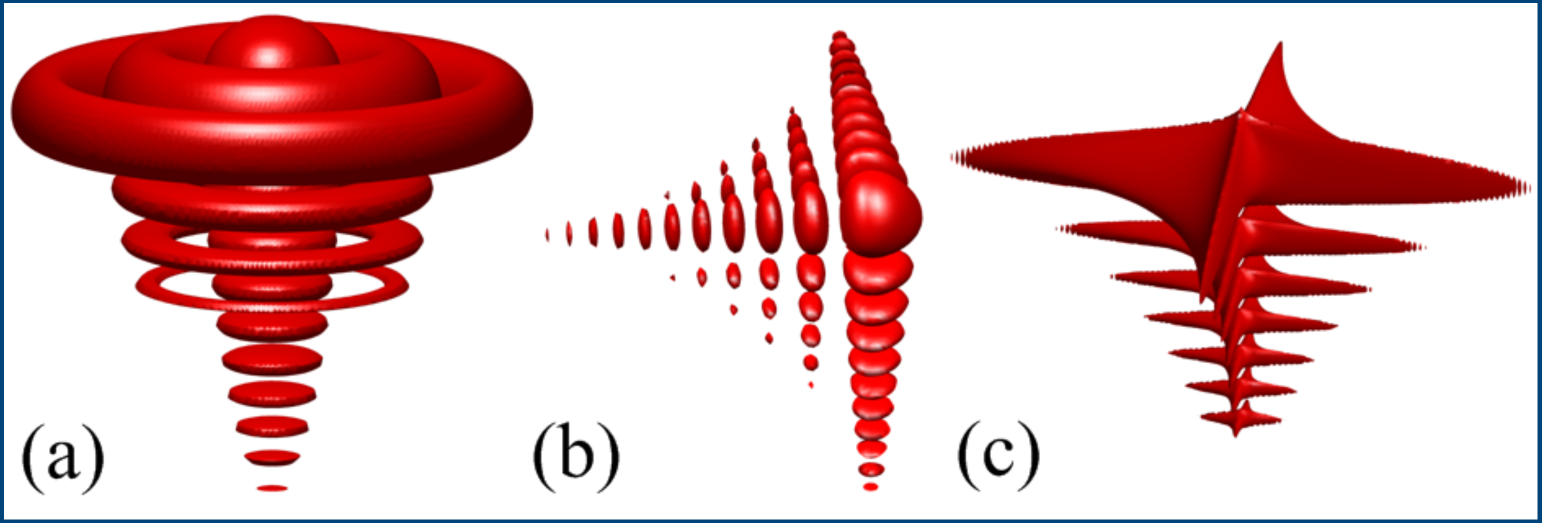
Bessel-Gauss (90 fs)



Bessel-Airy (90 fs main pulse lobe)

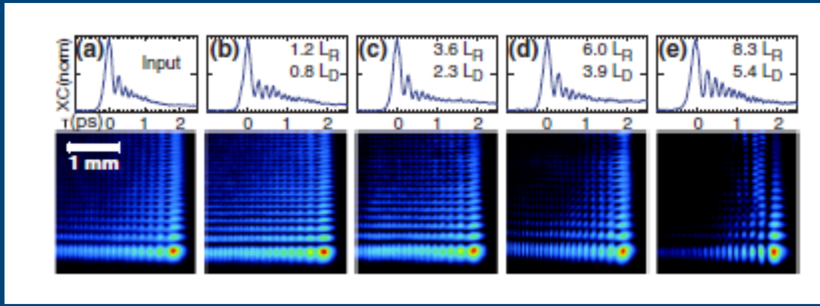
Spatio-Temporal Airy Bullets

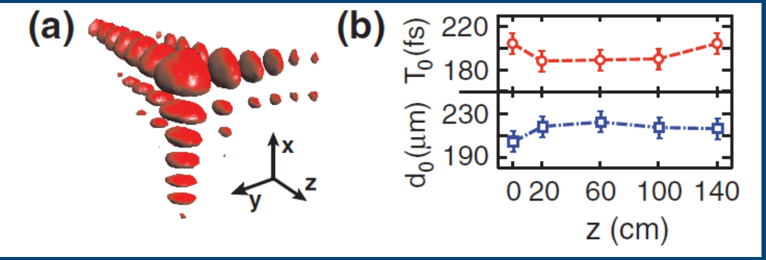
Airy is the only non-dispersing wavepacket in 1-D



(a) Airy-Bessel (b) 3D Airy and (c) Airy-X optical non-dispersing bullets.

Airy Bullets





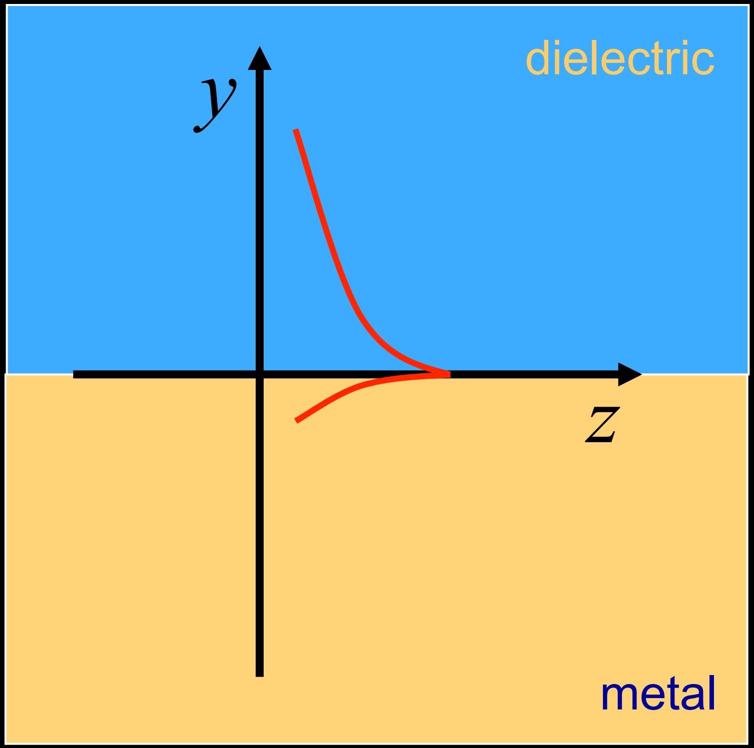
Papazoglou et al, PRL 105, 253901 (2010)

Airy plasmons

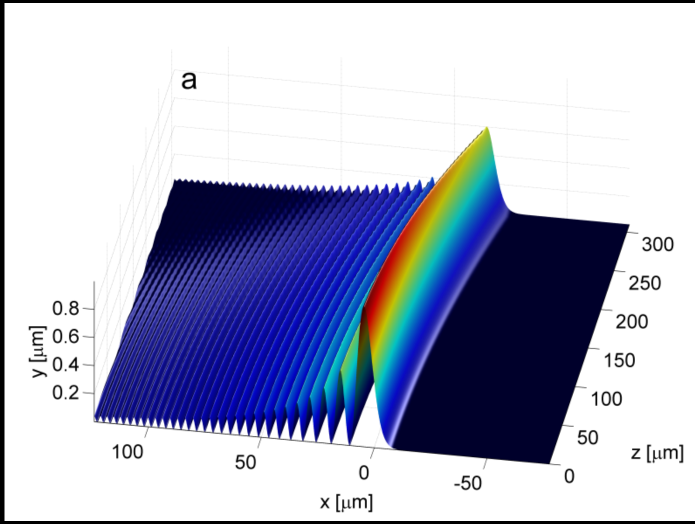
$$\nabla^2 E_y + k_0^2 \varepsilon E_y = 0$$

$$\begin{cases} E_y(x,y,z) = A(x,z)e^{ik_z z}e^{-\alpha y} \\ \alpha_d^2 = k_z^2 - k_0^2 \varepsilon_d \\ k_z = k_0 \sqrt{\varepsilon_d \varepsilon_m / (\varepsilon_d + \varepsilon_m)} \end{cases}$$

$$\frac{\partial^2 A}{\partial x^2} + 2ik_z \frac{\partial A}{\partial z} = 0$$



Airy plasmon propagation.

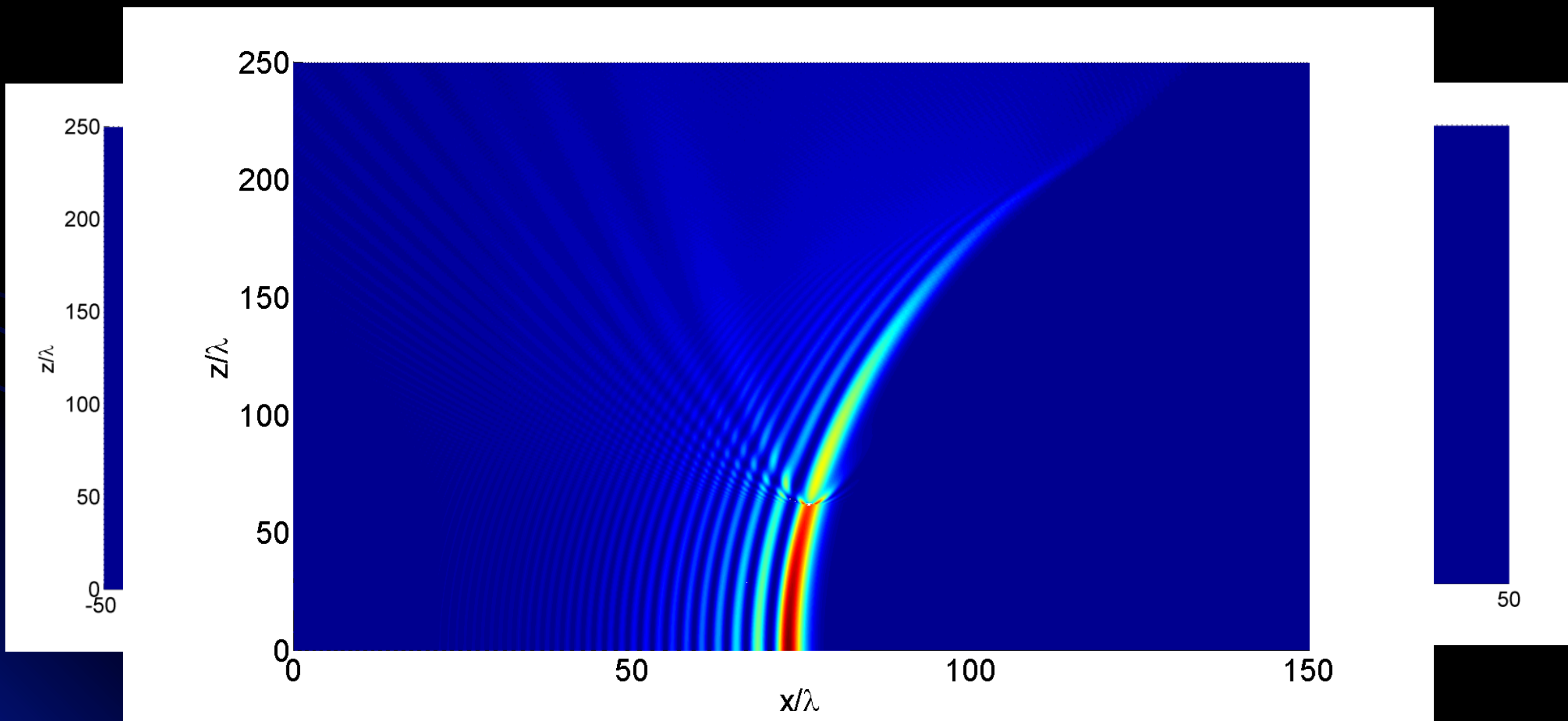


$$A(x,z)=\mathrm{Ai}\left[\frac{x}{x_0}-\left(\frac{z}{2k_z x_0^2}\right)^2+i\frac{az}{k_z x_0^2}\right]\exp\left[i\left(\frac{x+a^2x_0}{2x_0}\frac{z}{k_z x_0^2}-\frac{1}{12}\left(\frac{z}{k_z x_0^2}\right)^3\right)\right]\exp\left[a\frac{x}{x_0}-\frac{a}{2}\left(\frac{z}{k_z x_0^2}\right)^2\right]$$

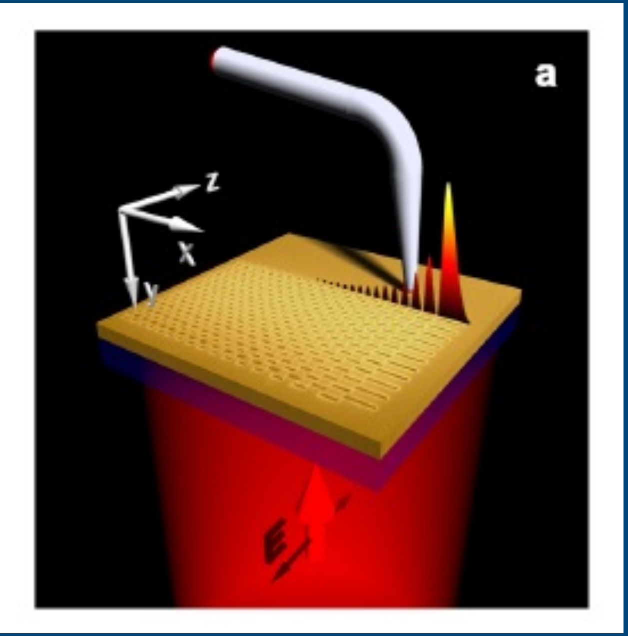
A. Salandrino and D. Christodoulides, Opt. Lett. 35, 2082-2084 (2010)

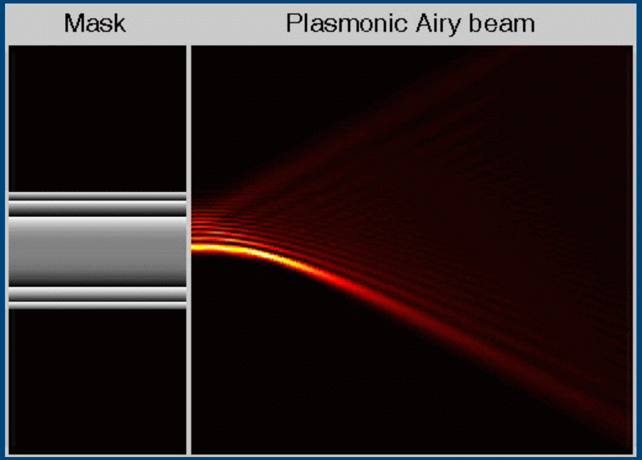
Airy plasmons

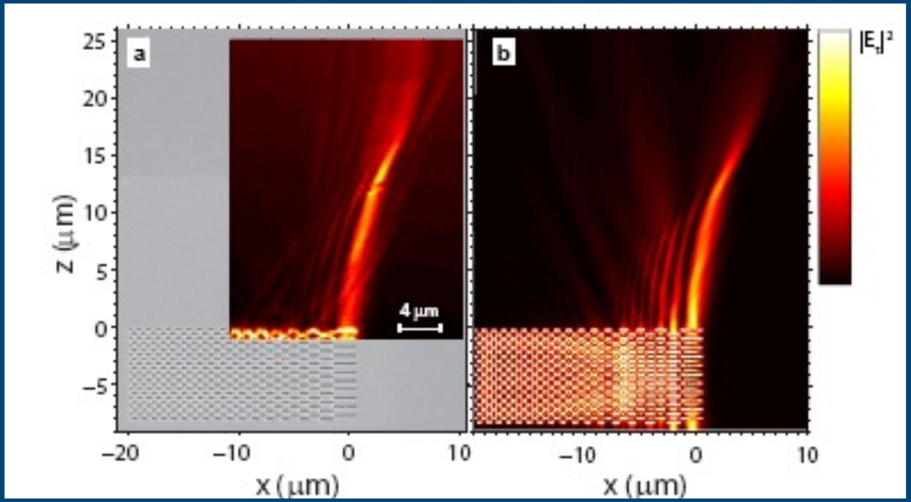
- 1D diffraction-free propagation
- Self-healing behavior



Experimental observation of Airy plasmons

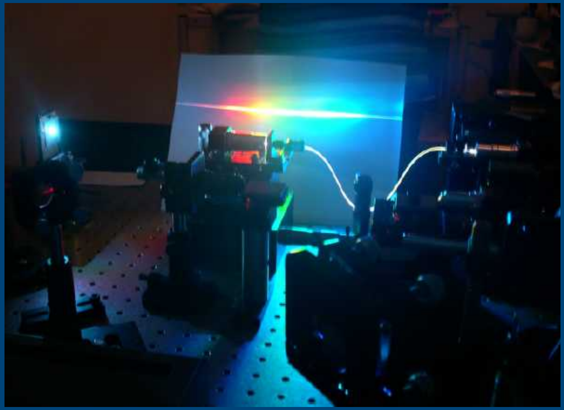


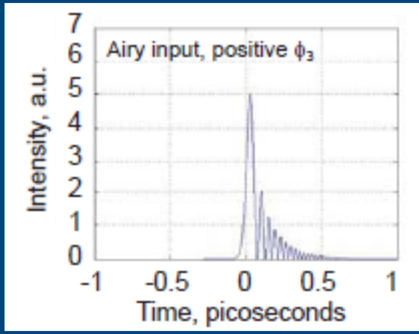


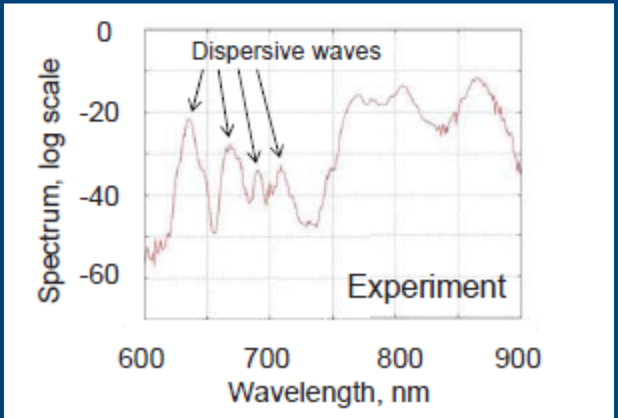


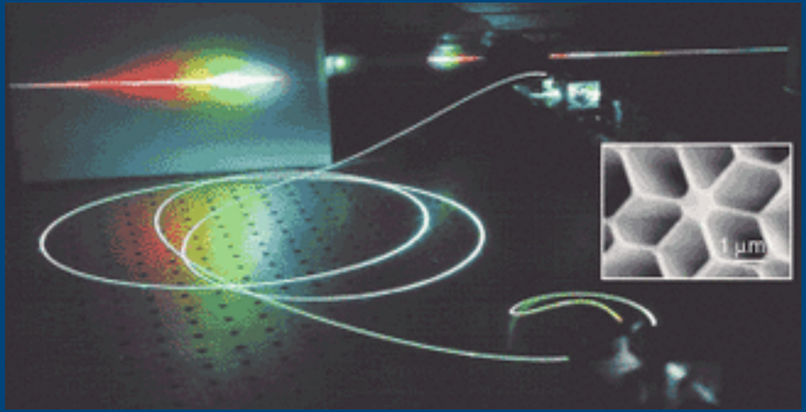
Kivshar's group-Australia: PRL 107, 116802 (2011).
Zhang's group, Opt. Lett. 36, 3191 (2011).
Zhu's group-Nanjing University PRL (2011).

Super-continuum generation using Airy pulses



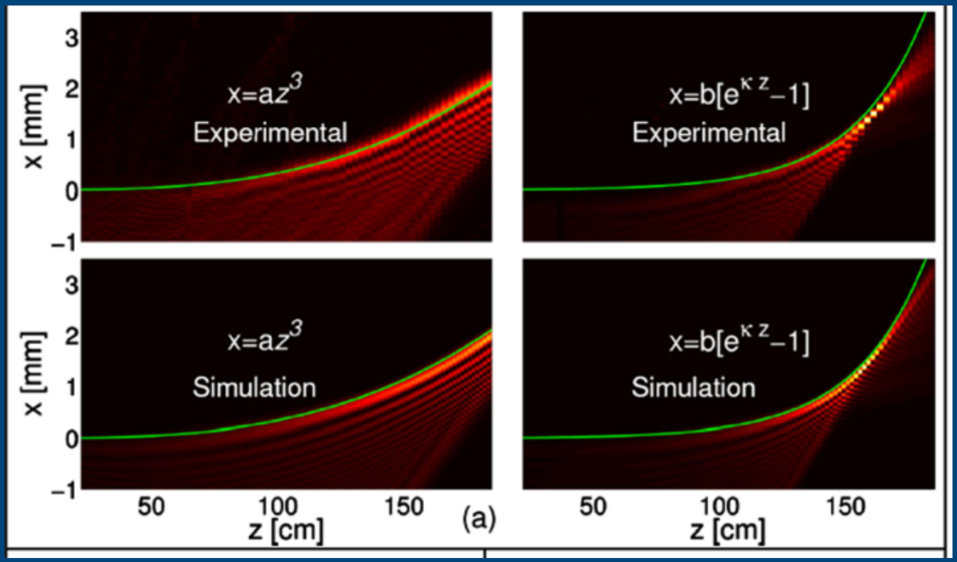






Polynkin et al. U. of Arizona, Phys. Rev. Lett. 107, 243901 (2011)

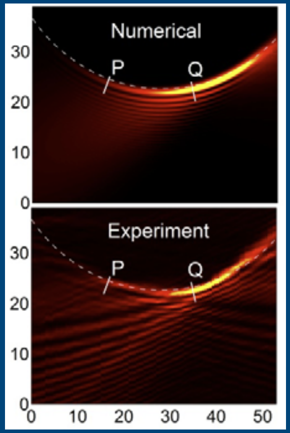
New directions



PRL 108, 163901 (2012)

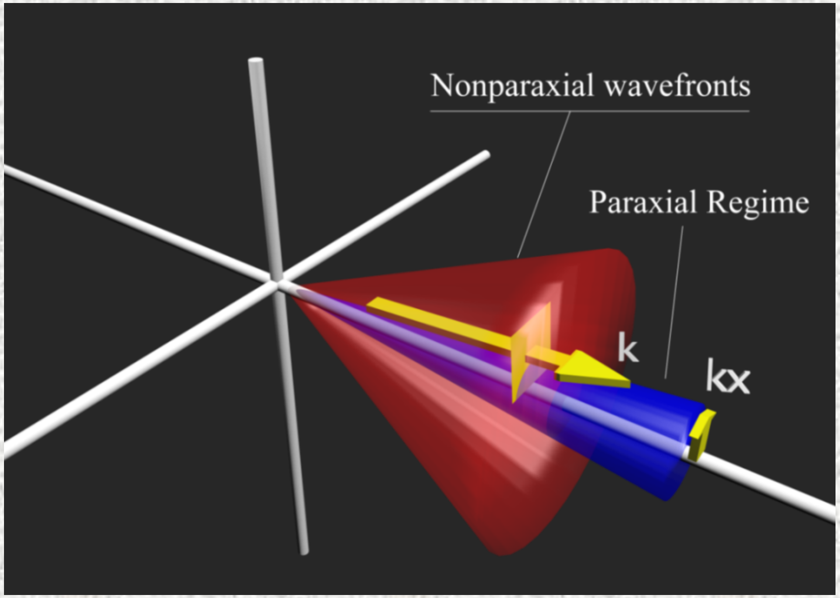
Technion
Segev's group

Sending femtosecond pulses along curved trajectories



John Dudley's group

Can we identify similar accelerating beams which are non-paraxial?



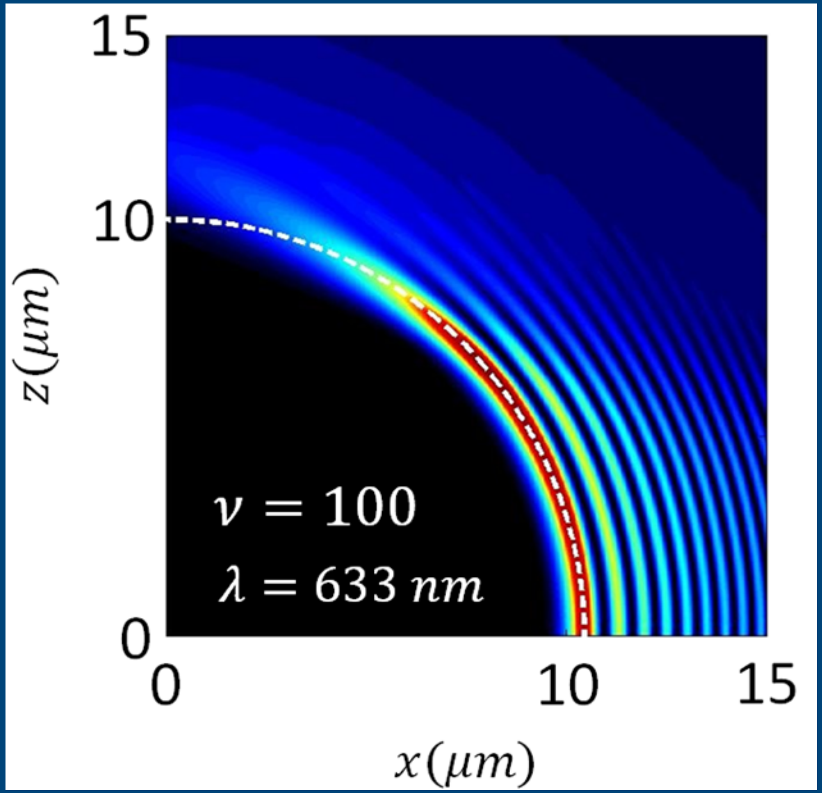
To do so we must use a non-paraxial formulation based on Helmholtz equation

$$(\nabla^2 + k^2)\{\vec{E}, \vec{H}\} = 0$$

New directions

Non-paraxial accelerating Bessel wave-packets, solutions to Maxwell's equations

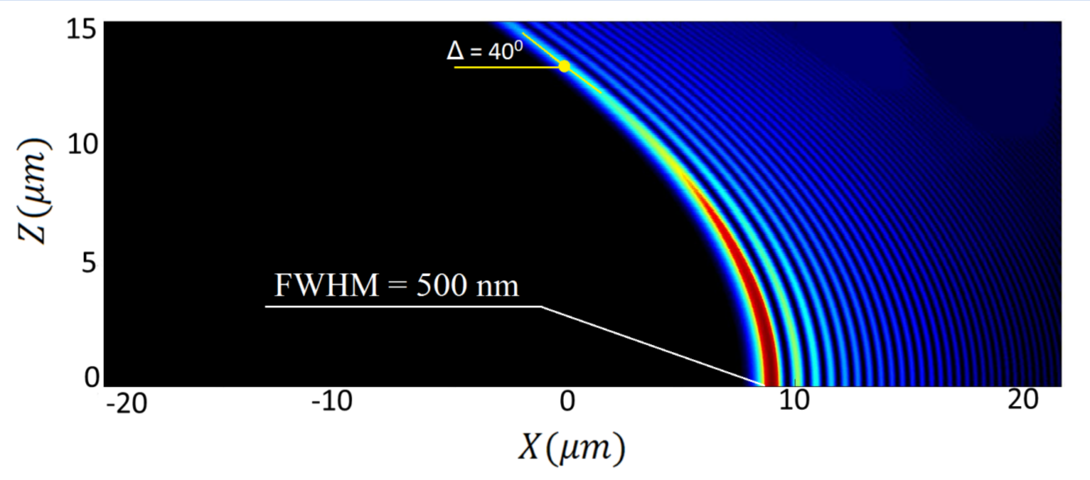
$$\vec{E} = \hat{y} J_\nu(kr)\exp(i\nu\theta)\exp(-i\omega t)$$



$$\vec{E}(x,0) = \hat{y} J_\nu(kx)$$

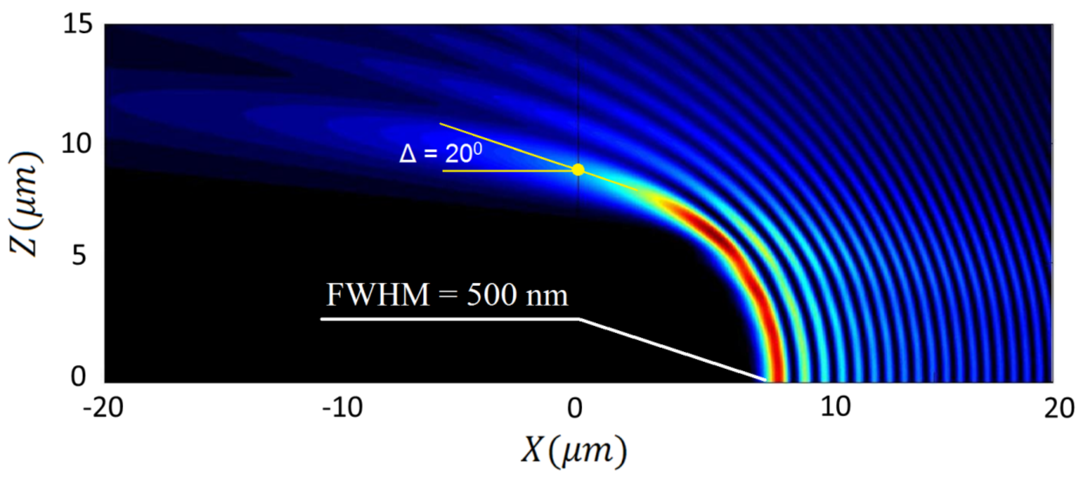
Kaminer, Bekenstein, Nemirovsky, and Segev, PRL 108, 163901 (2012).

Non-paraxial Airy and Bessel beams



-----------Airy-------------

For a FWHM of 500 nm, the main lobe can bent 50^0 after 10 μm

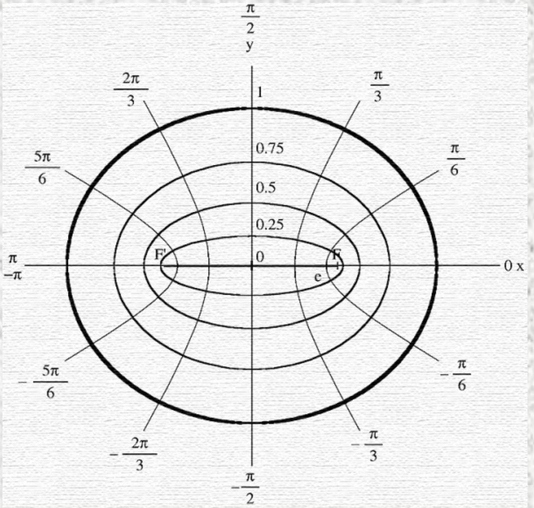


----------Bessel------------

- For a FWHM of 500 nm, the main lobe can bent 70^0 after 10 μm

Are there any other accelerating vectorial solutions of Maxwell's equations ?

Elliptic Helmholtz equation



$$\left[\frac{2}{f^2(cosh\,2u - cos\,2v)}\left(\frac{\partial^2}{\partial u^2} + \frac{\partial^2}{\partial v^2}\right) + k^2\right]\psi_z = 0$$

$$x = f\cosh u \cos v\,; \quad y = f \sinh u \sin v$$

$$0 \le u < \infty\,; \quad 0 \le v \le 2\pi$$

For $E_z = R(u)S(v)$

$$\begin{cases} \left[\dfrac{d^2}{dv^2} + (a - 2q cos2v)\right] S(v) = 0 \\ \left[\dfrac{d^2}{du^2} - (a - 2q cosh2u)\right] R(u) = 0 \end{cases}$$

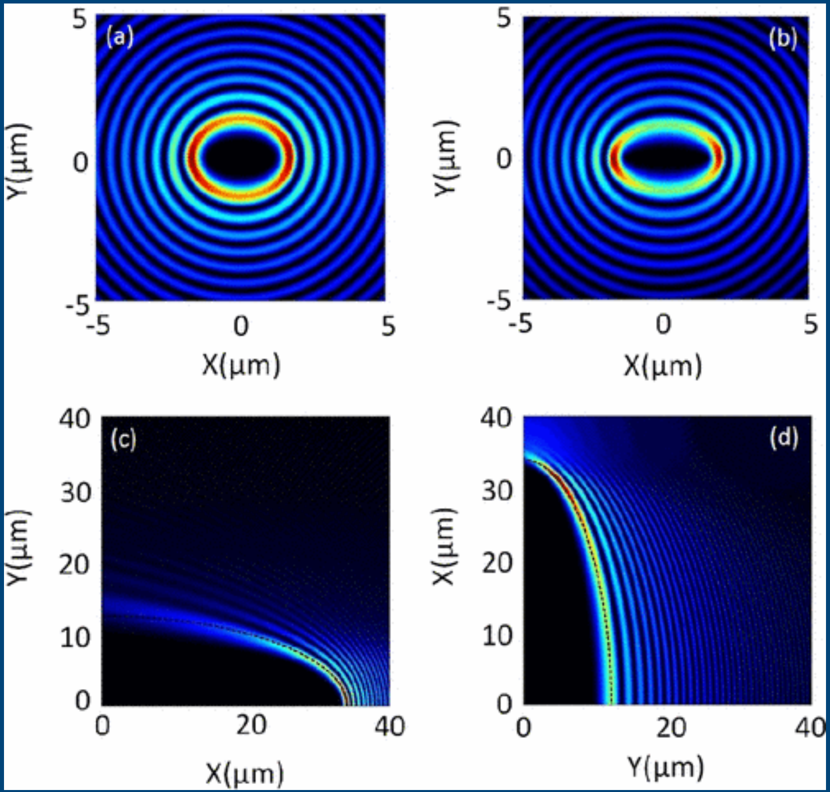
$q = f^2k^2/4$ and parameter a can be obtained from sequence of eigenvalues $a_m (m = 1,2,..)$ from differential equation on $S(v)$.

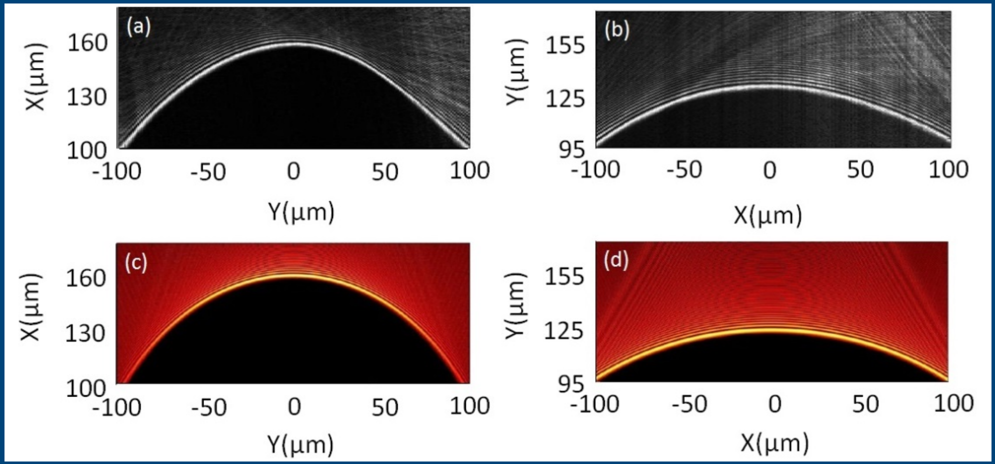
$$\psi_z^m(u, v; q) = \underbrace{Ac_{e,m}(v; q) Mc_m^{(1)}(u; q)}_{\text{Even Radial/Angular Mathieu Functions}} + \underbrace{iBs_{e,m}(v; q) Ms_m^{(1)}(u; q)}_{\text{Odd Radial/Angular Mathieu Functions}}$$

* P. Aleahmad, M. A. Miri, M. S. Mills, I. Kaminer, M. Segev and D. N. Christodoulides, *Phys. Rev. Lett.* **109**, 203902 (2012)

* P. Zhang, Y. Hu, T. Li, D. Cannan, X. Yin, R. Morandotti, Z. Chen, and X. Zhang, *Phys. Rev. Lett.* **109**, 193901 (2012)

Future directions



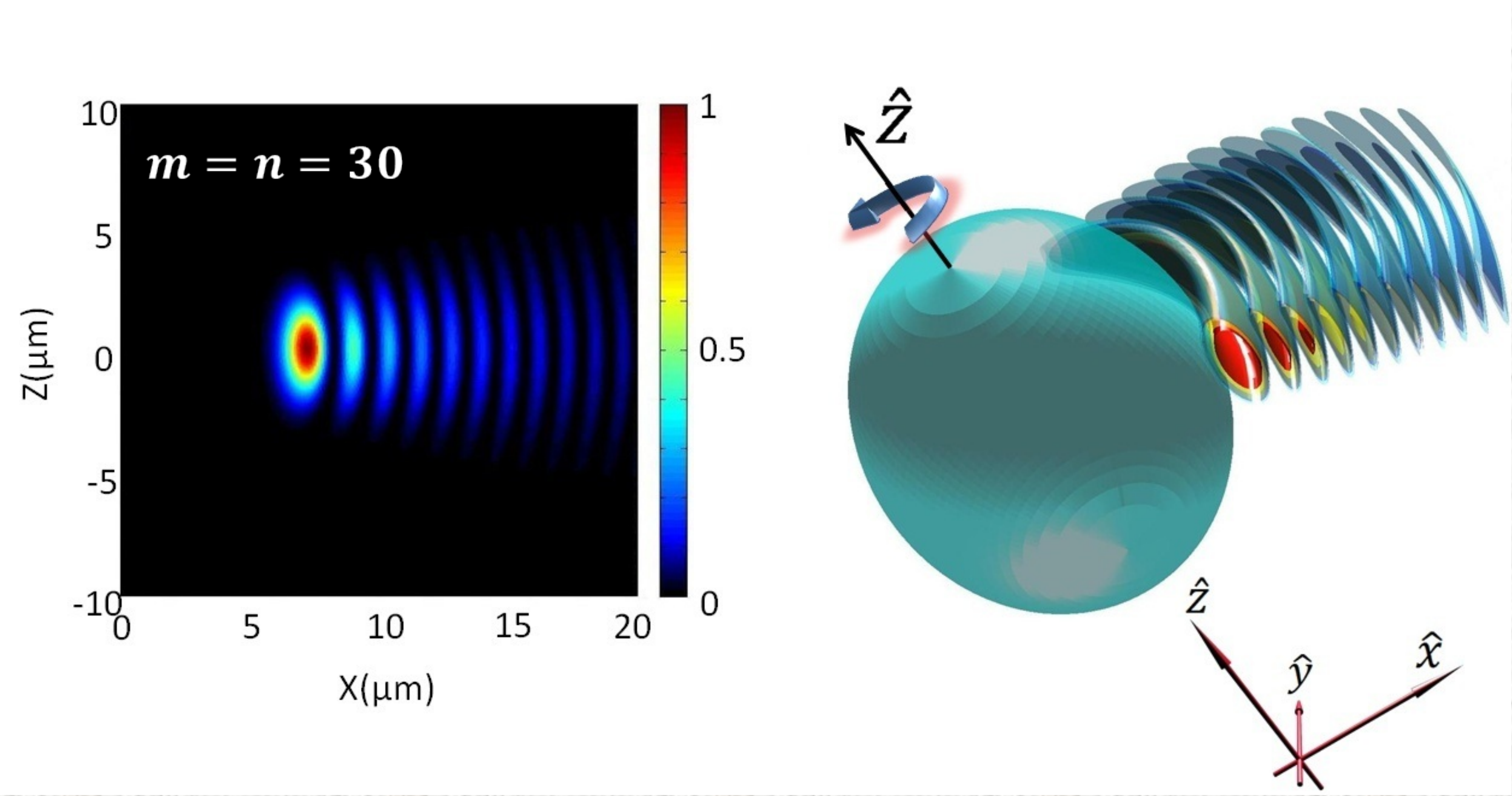


experimental results

Aleahmad, Miri, Mills, Kaminer, Segev, and Christodoulides PRL 109, pp. 203902 (2012)

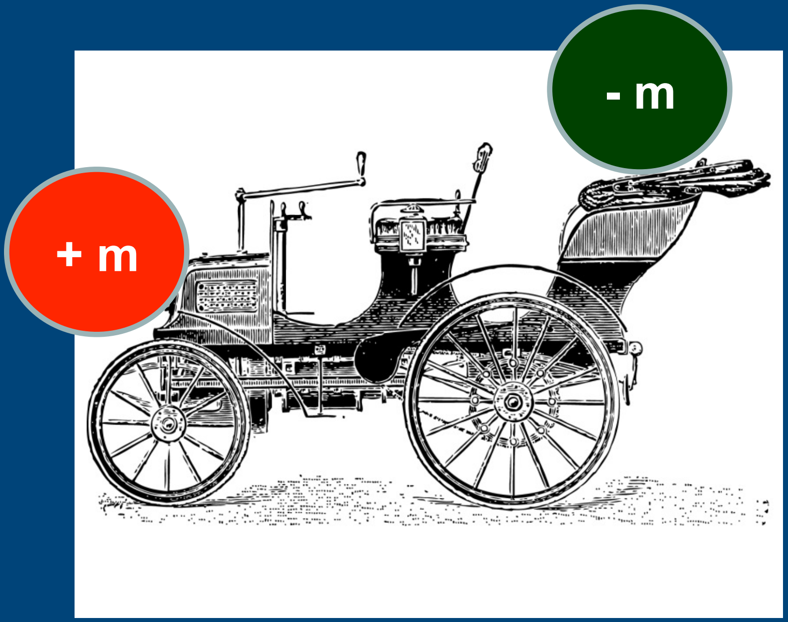
Prolate Spheroidal Coordinates

$$\psi = \underbrace{R_{mn}(c;\xi)}_{\text{Radial Prolate-Spheroid function}} \cdot \underbrace{S_{mn}(c;\eta)}_{\text{Angular Prolate-Spheroid function}} \cdot e^{im\phi}$$



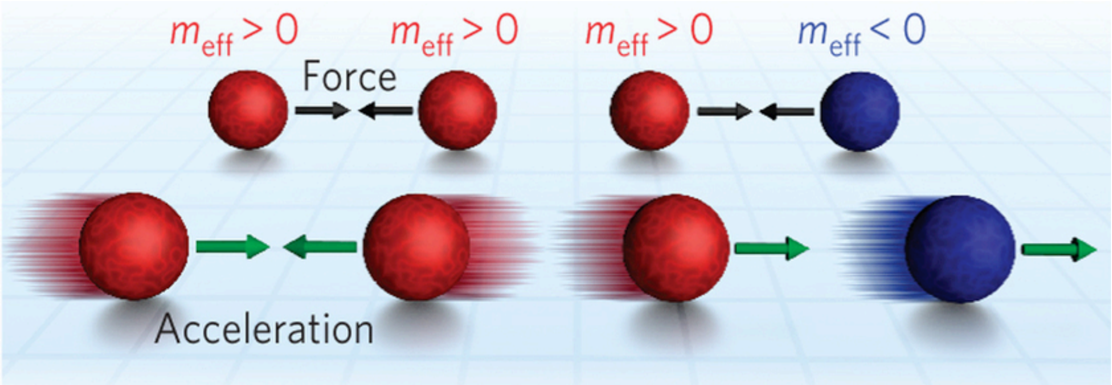
Diametric drive acceleration

warp drive ??

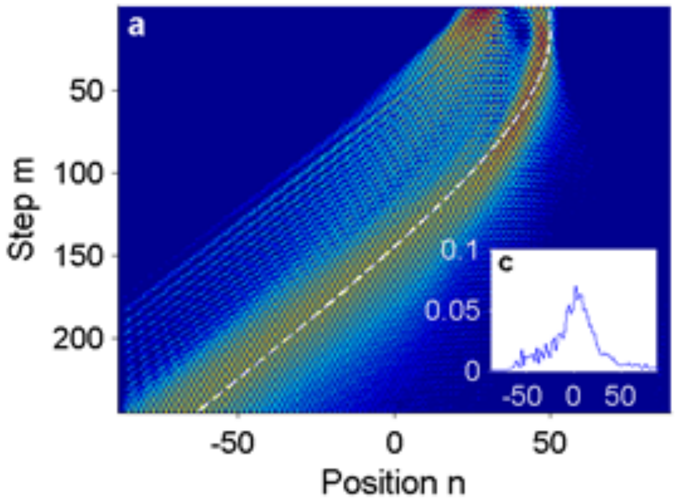


diametric drive

Diametric drive acceleration: Newton's third law



Experimental observation of diametric drive acceleration



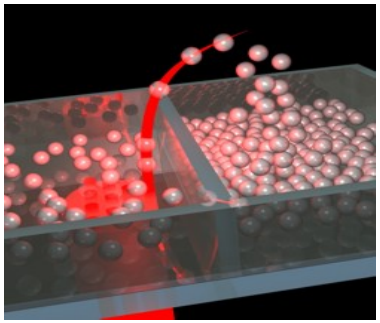
Max Planck Erlangen-CREOL,
Nature Physics, pp. 780-784, 2013

In principle Airy beams can be used in:

- **Optics**
- **Microwaves**
- **Acoustics-Ultrasonics**

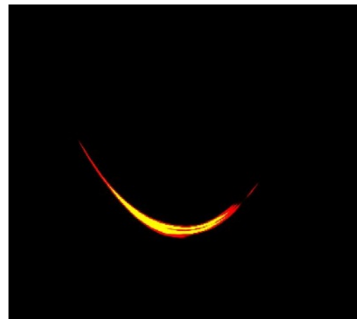
Airy beams and pulses: applications

Biophotonics



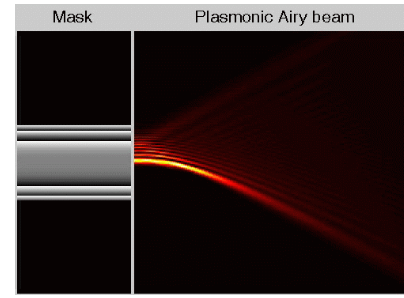
St. Andrews

Filamentation



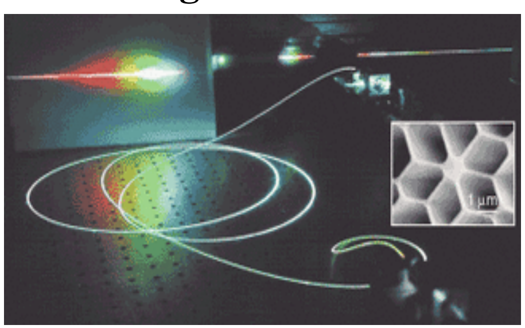
Arizona/UCF

Plasmonics



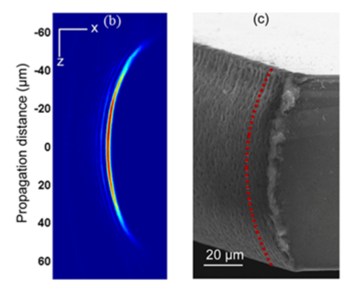
Berkeley/ANU/Nanjing

Super-continuum generation



U. Of Arizona

Micromachining



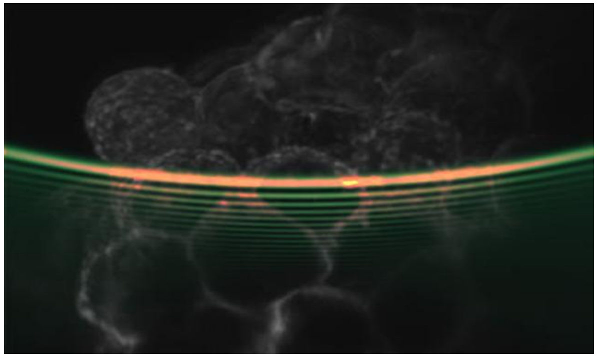
J. Europ. Opt. Soc. Rap. Public. 8, 13019 (2013)

Franche-Comté

Airy beams and pulses:applications

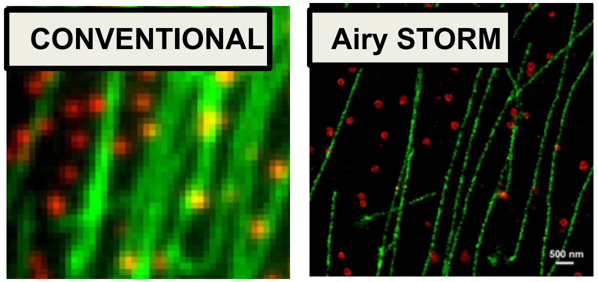
Light-sheet microscopy using Airy beams

Higher contrast and resolution 10X FOV



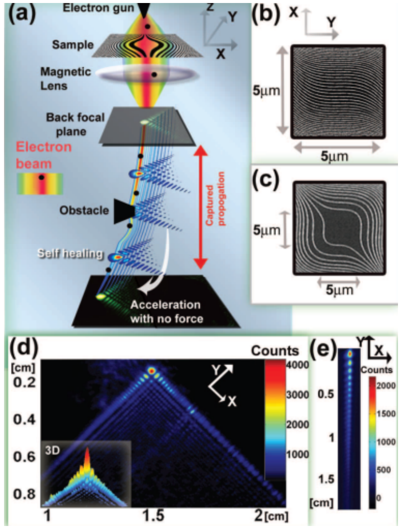
St. Andrews
Nat. Methods, April 2014

Stochastic optical reconstruction microscopy (STORM) using Airy point spread function



Harvard
Nature Photonics, April 2014

Electron Airy beams



Tel-Aviv

Nature, 331 (2013)

Caustics are everywhere