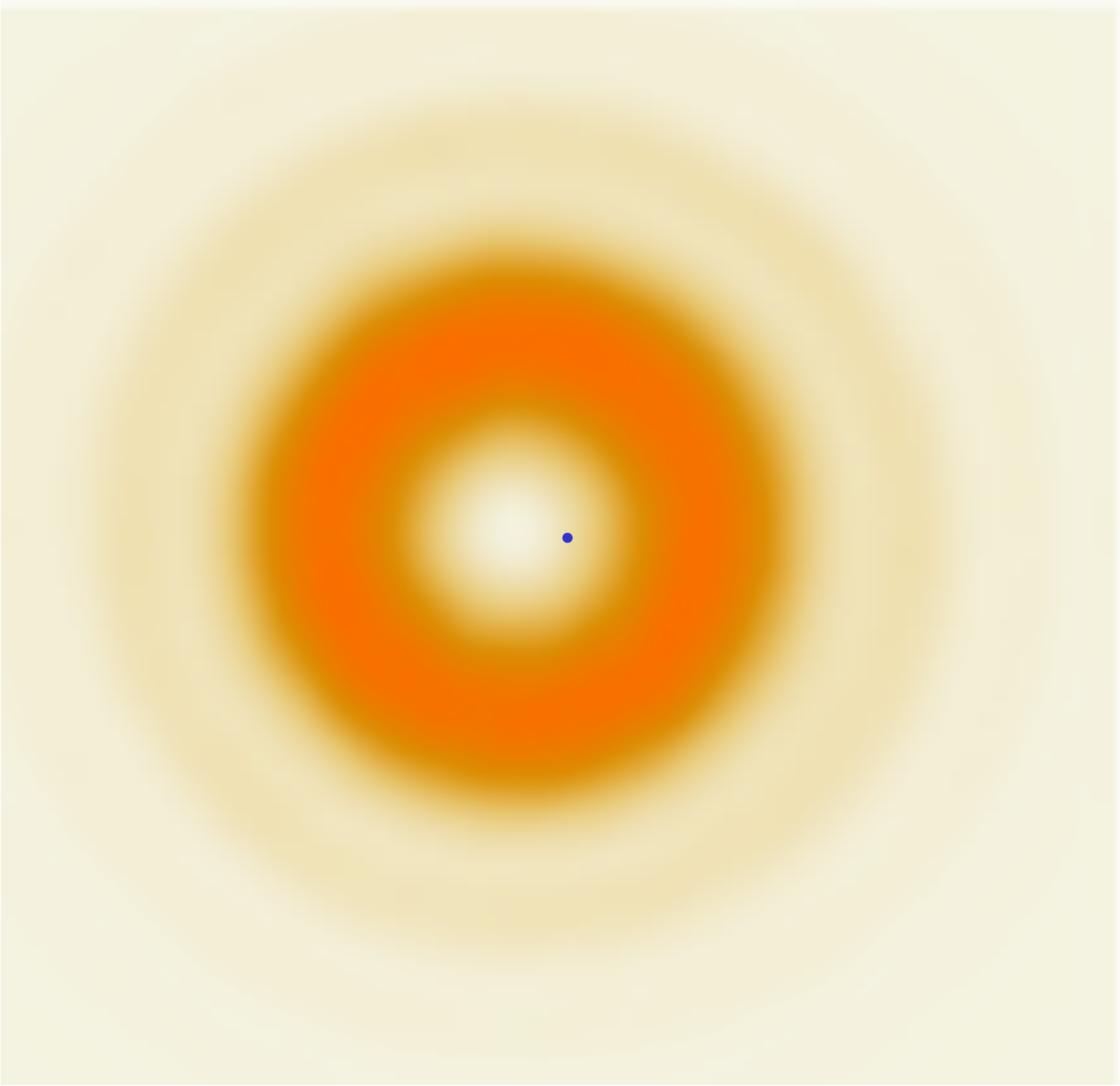
How to twist, turn, and kick ions using structured light



Slides ↓↓

Christian Schmiegelow
Universidad de Buenos Aires & CONICET
Ciudad de Buenos Aires - Argentina

Paraty 2025 - RJ - Brasil

Mini Bio

Christian T. Schmiegelow

Slides ⇈

2001 - Undergraduate
-- Universidad Nacional de la Plata

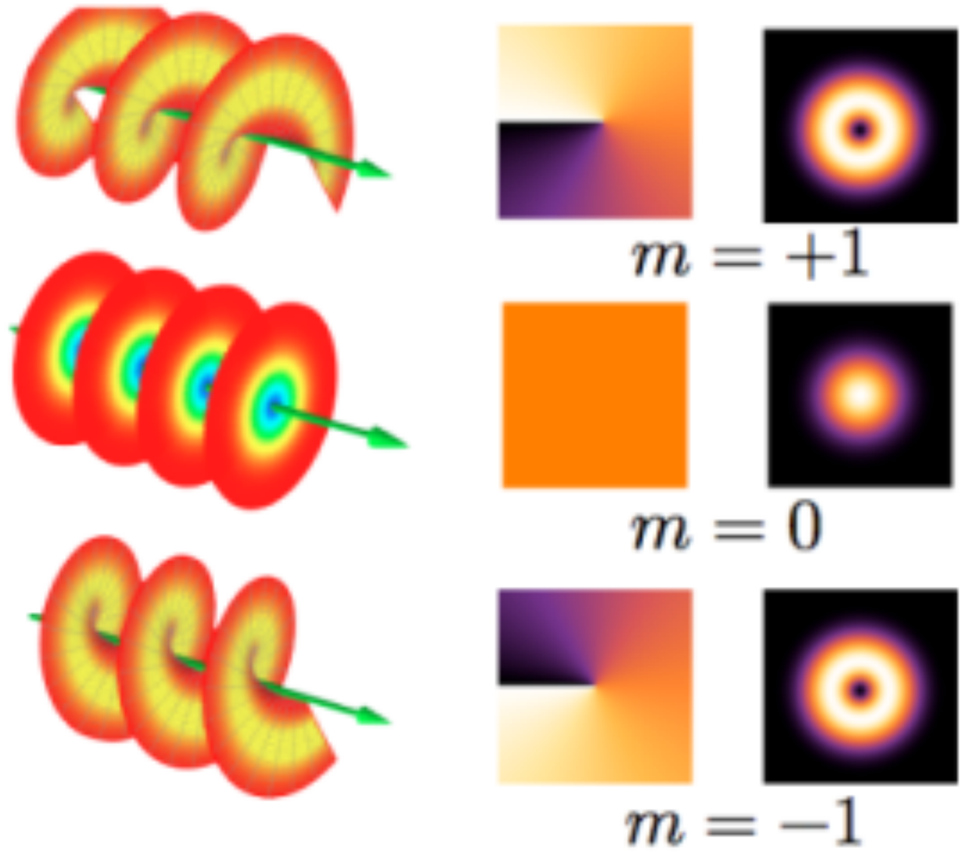
2007- PhD on Q. Info. with Photons
-- Universidad de Buenos Aires
-- dir. Juan Pablo Paz and Miguel Larotona

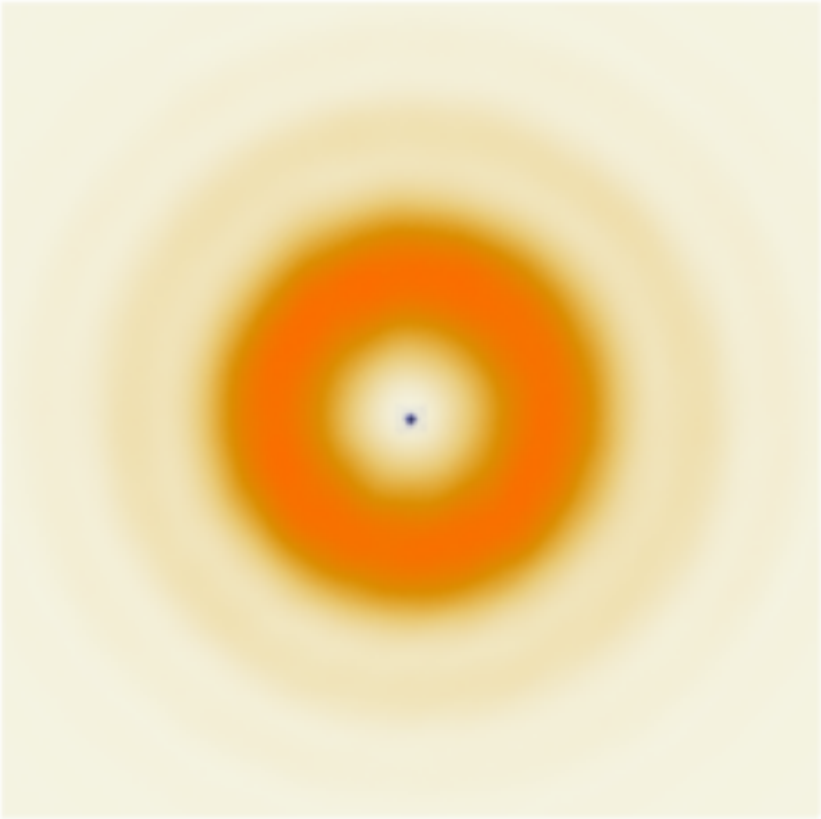
2013- Postdoc on Trapped Ions
-- Universität Mainz
-- at Ferdinand Schmidt-Kaler's group

2016- Cold Ions and Atoms Lab
-- University of Buenos Aires & CONICET

Cold Ions and Atoms Lab main lab interests

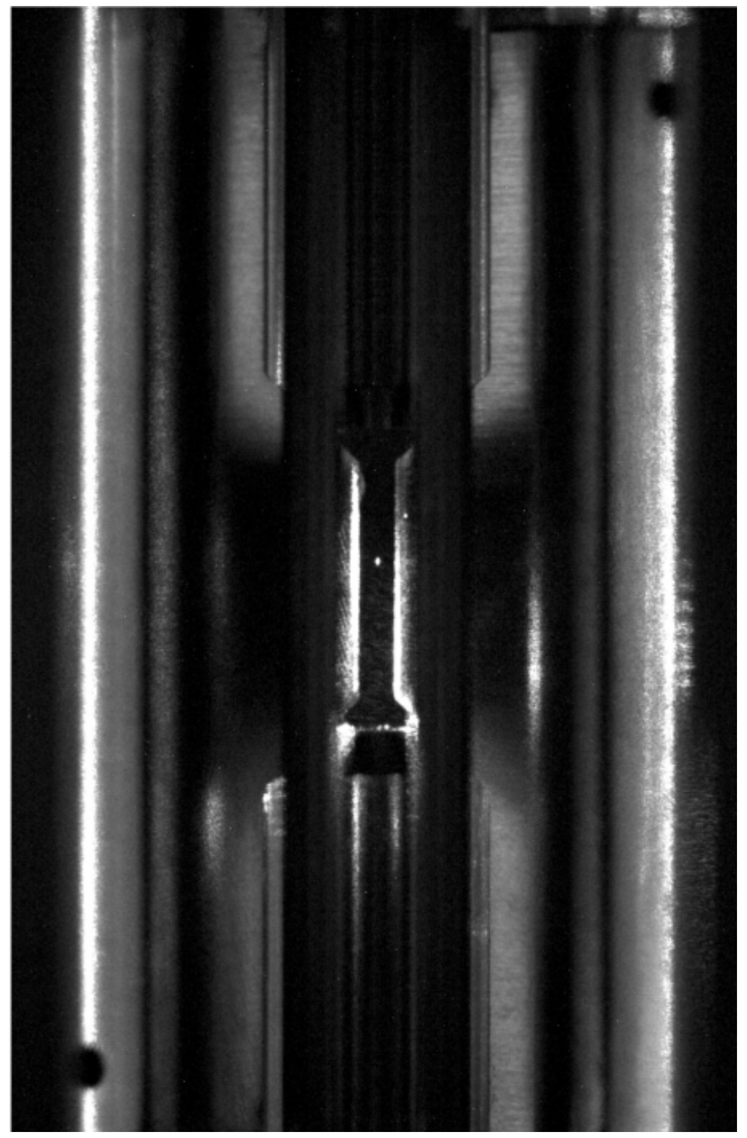
Quantum Optics with Structured Beams

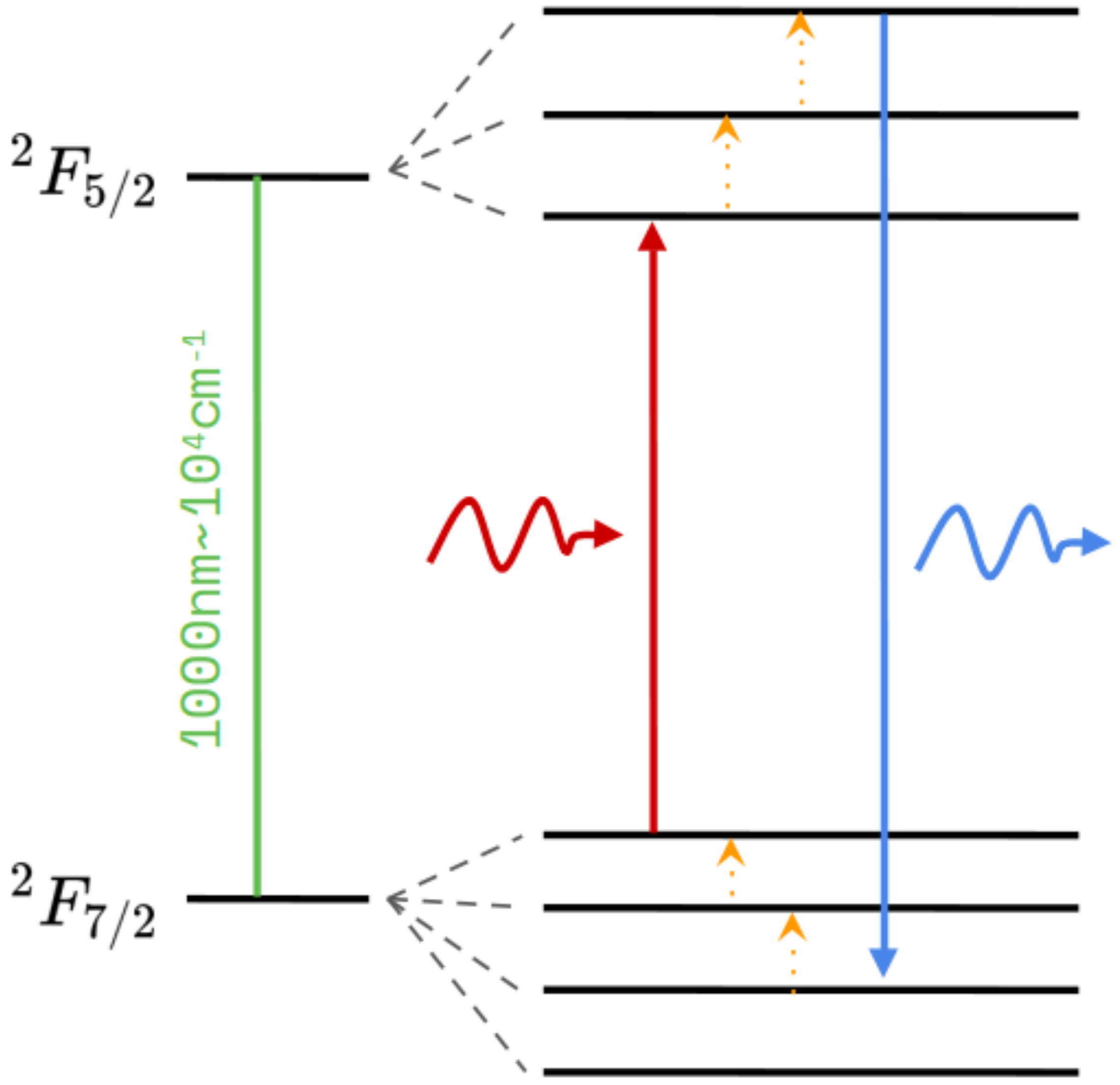




- fundamental quantum physics
- metrology
- quantum logic
- thermodynamics

Optical Cooling of Solids





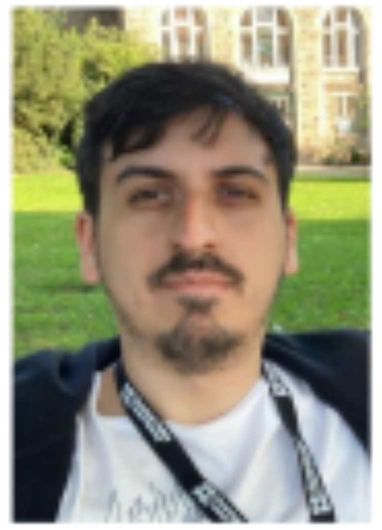
- nanoparticle trapping
- laser refrigeration via color centers
- thermodynamics of mesoscopic systems

Team @ Universidad de Buenos Aires

Equipo LIAF

Christian
Schmiegelow
Project Leader

Marcelo
Luda
Associate researcher



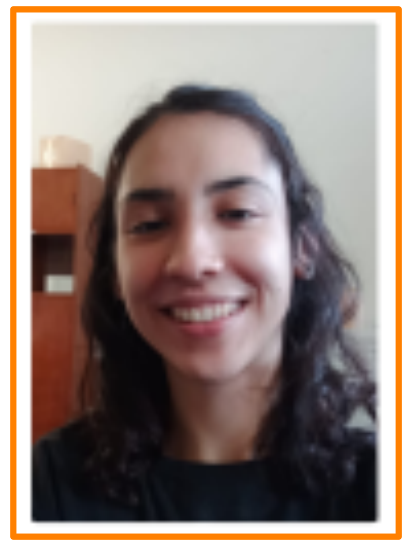
Nicolás
Nuñez Barreto
Postdoc

Iones atrapados

Lautaro
Filgueira
PhD Student

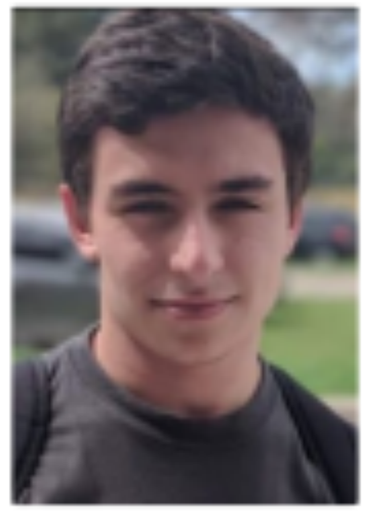
Muriel
Bonetto
PhD Student

Corina
Révora
PhD Student

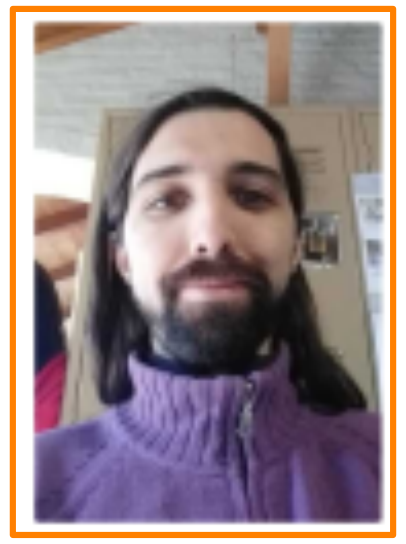


Carolina
Vlatko
PhD Student

Nanopartículas



Lucas
Mendicino
PhD Student



Santiago
Gliosca
PhD Student

Equipo teoría

Universidad de la República (Uruguay)

Cecilia
Cormick
Researcher

Universidad de Buenos Aires

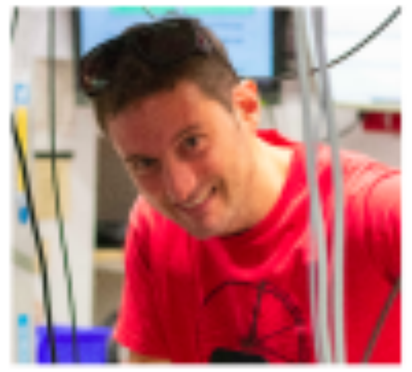
Juan Pablo
Paz
Researcher

Augusto
Roncaglia
Researcher

Franco
Mayo
PhD Student

Collab @ Uni-Mainz

Ferdinand Schmidt-Kaler



Maurizio Verde

Ulrich Poshinger

Felix Stopp

Johnas Schultz

Structure of this course

1) Structured light basics

2) Structured light and atoms

3) Structured light and optical forces

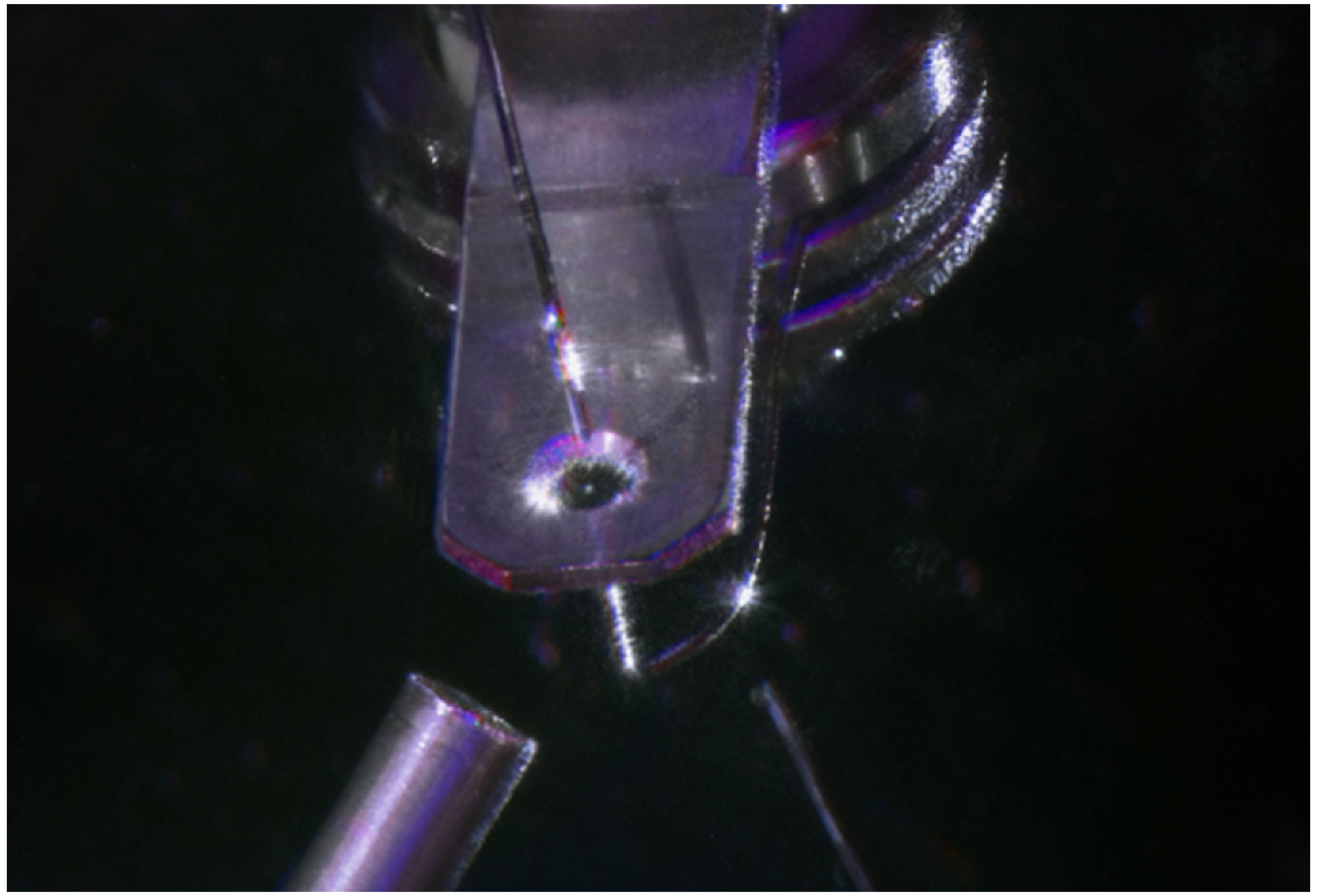
Structure of this course

1) Structured light basics

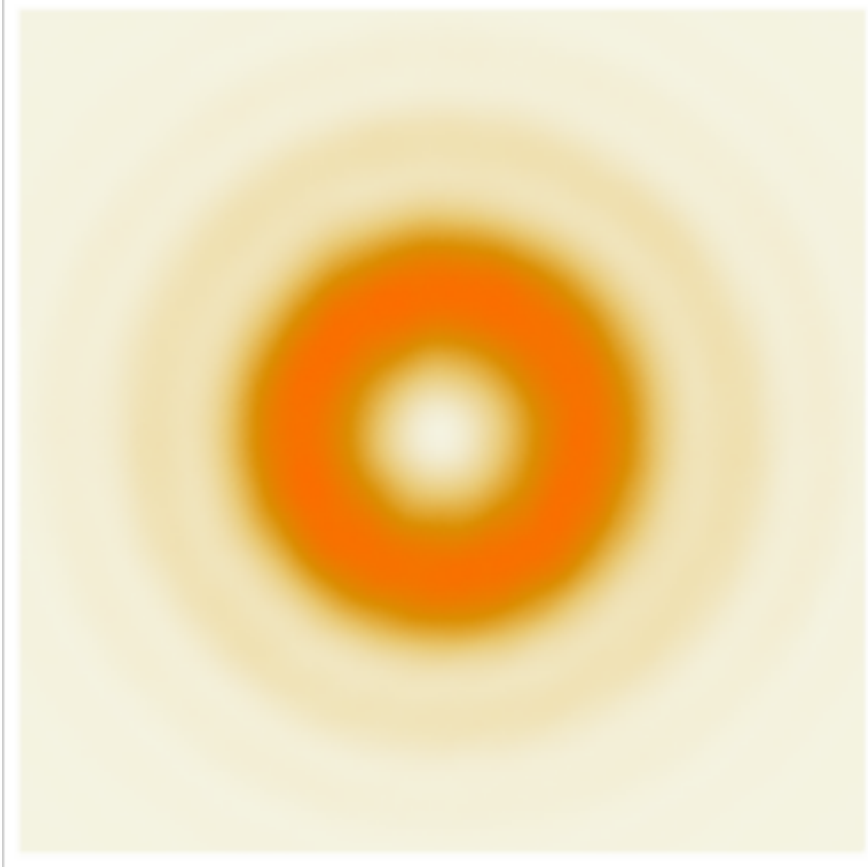
- P0) Motivation
- P1) Brief history of Light Matter Interaction
- P2) Gaussian and Structured Beams
- P3) Orbital angular momentum of light
- P4) Beyon the paraxial approximation
- P5) Generation of Structured Beams

Dancing in the dark - the Sao Paulo anecdote, ca. 2008

an ion trap



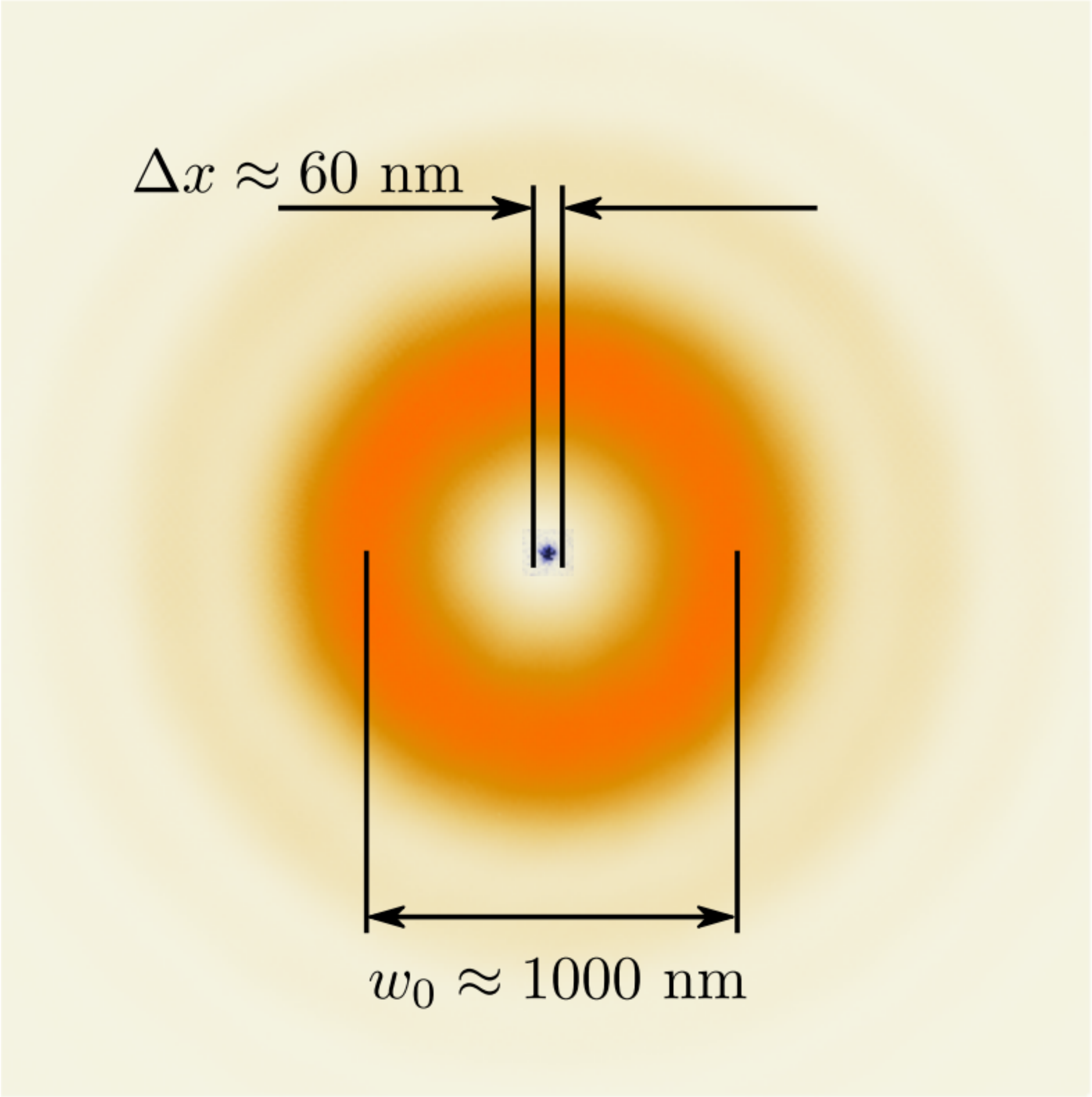
a hollow beam



Zelaquett Khoury

Ferdi Schmidt-Kaler

ion in a beam



Part 1

A brief history of light-matter interactions

Polarization Rotation - the begining

1811

Argo: rotation of polarization by Quartz crystals

1815

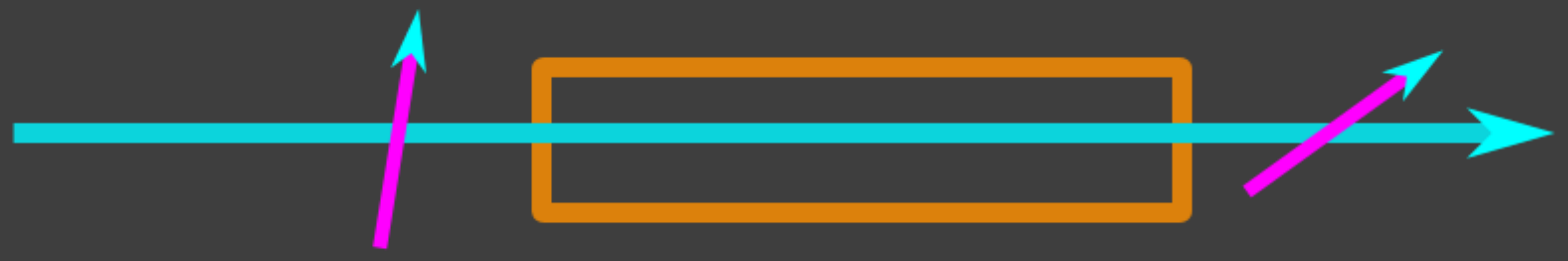
Biot: rotarion of polarization by Organic Chemicals

1820

Herschel: quartz and "anti-quartz"

1849 and 1974

Pasterur, van't Hoff and Lebel:
dextro and levo molecules explanation



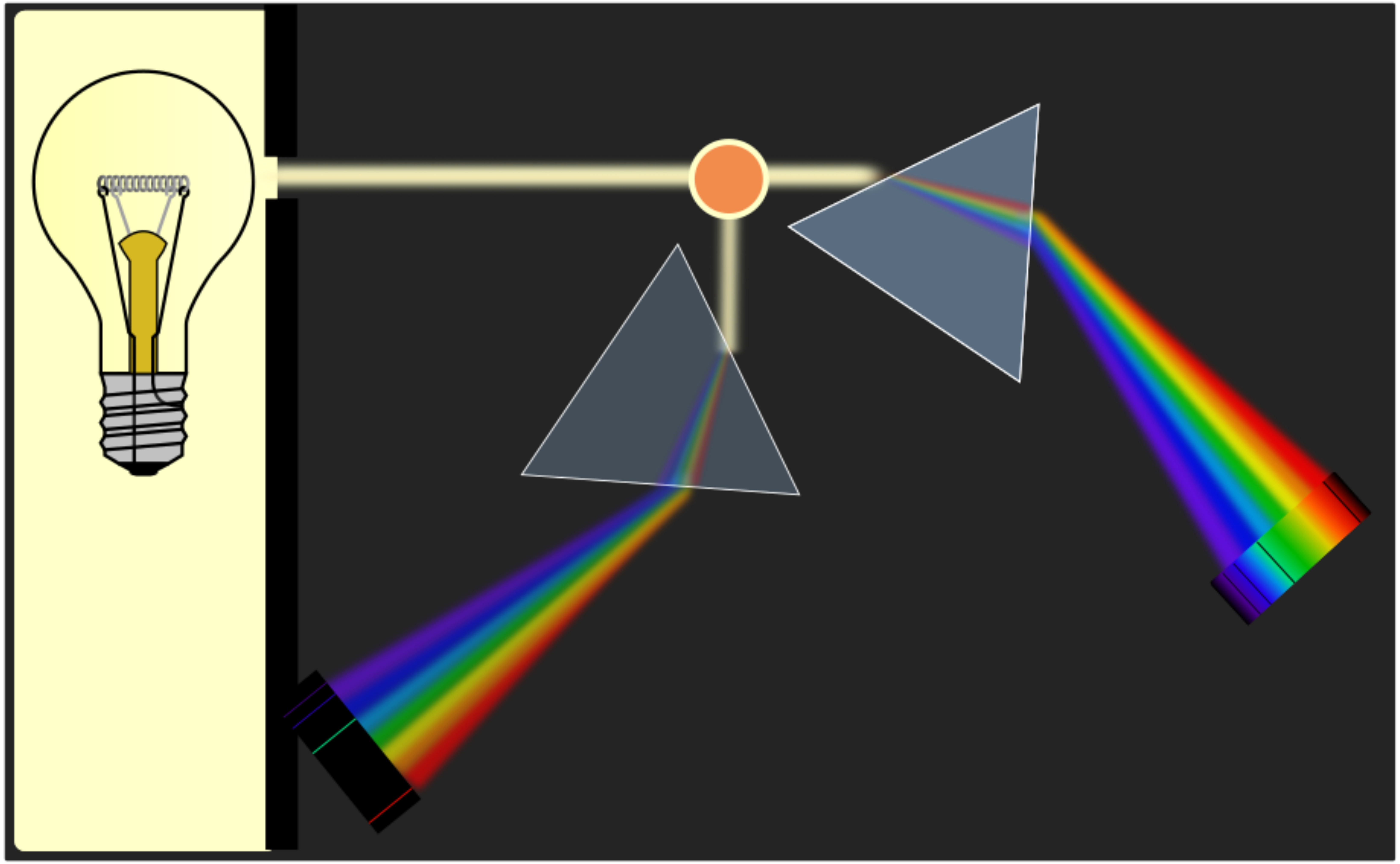
Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum			
Spin Angular Momentum			✓ Optical Activity
Orbital Angular Momentum			

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum			✓ Refraction
Spin Angular Momentum			✓ Optical Activity
Orbital Angular Momentum			

Atomic Spectroscopy - Zeeman splitting



Zeeman (1896) and Raman and Bhagavantam (1931)

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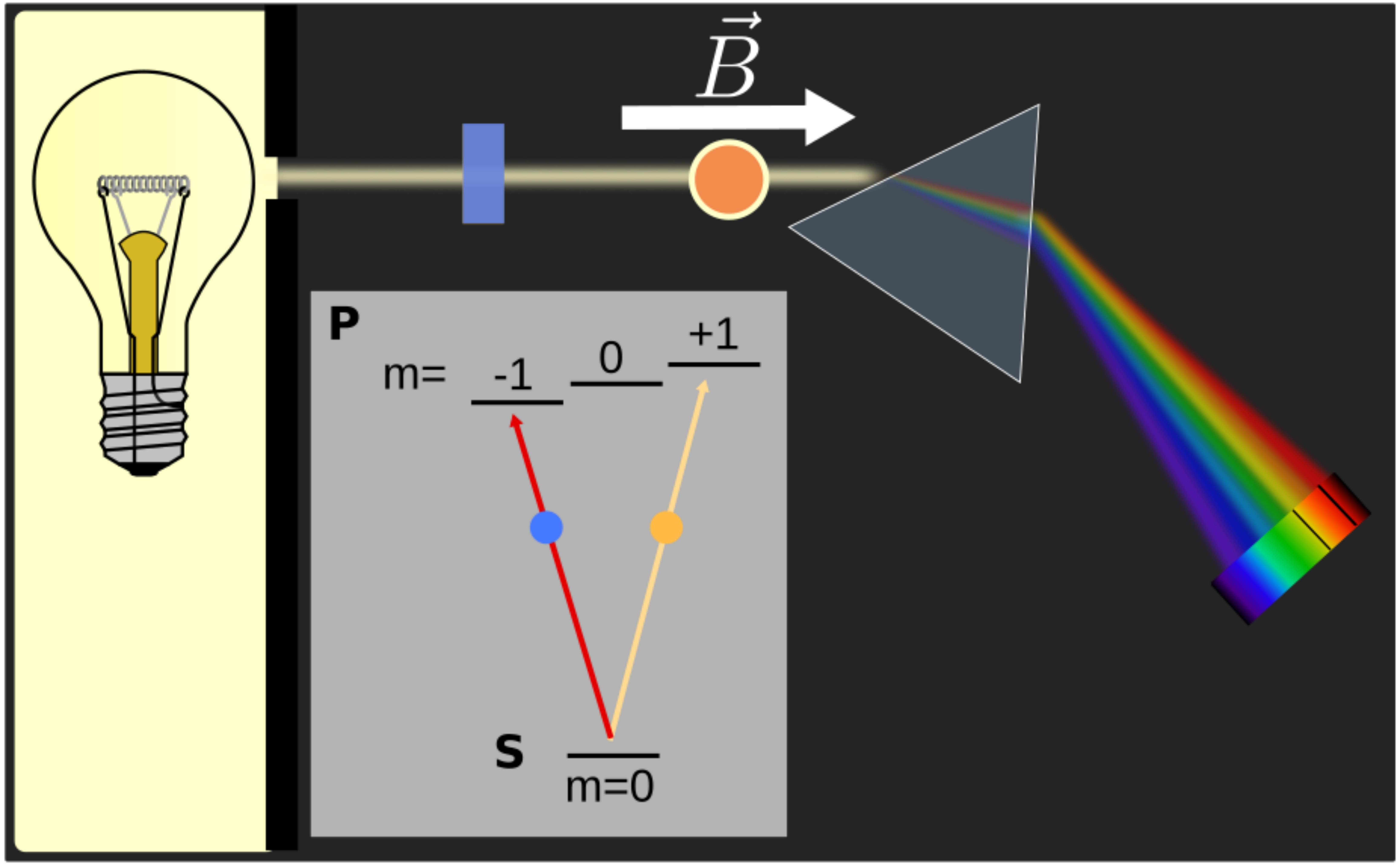
Atomic Spectroscopy - the begining



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Atomic Spectroscopy - the begining

Über eine Anomalie bei der Polarisation der Ramanstrahlung
- W. Hanle, Naturwissenschaften May 1931, Volume 19, Issue 18, pp 375–375
- R. Bär, Naturwissenschaften May 1931, Volume 19, Issue 22, pp 463–463

Evidence for the Spin of the Photon from Light-Scattering.
- C. V. Raman & S. Bhagavantam, Nature 128, 114-115 (18 July 1931)

Also...
- A. Kastler, Compt. Rend., 193 (1931) 1075.
- J. Cabannes, J. Phys., 2 (1931) 381.

Non existence d'un spin des photons
A. Kastler - J. Phys. Radium 2, 159-164 (1931)
....
....
....
The Nobel Prize in Physics 1966 was awarded to Alfred Kastler "for the discovery and development of optical methods for studying Hertzian resonances in atoms".

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum	✓ Fraunhofer		✓ Refraction
Spin Angular Momentum	✓ Hanle & Bär		✓ Optical Activity
Orbital Angular Momentum			

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Light-Matter Interaction

Light field description

Oscilating Field

$$A = A_{lp}(\rho, \phi, z)\ \vec{\epsilon}\ e^{-i\omega t}$$

Light field description

Oscilating Field

$$A = A_{lp}(\rho, \phi, z)\ \vec{\epsilon}\ e^{-i\omega t}$$

Light-Matter Interaction - mechanical effects, angular momentum

JULY 15, 1936 PHYSICAL REVIEW VOLUME 50

Mechanical Detection and Measurement of the Angular Momentum of Light

RICHARD A. BETH,* *Worcester Polytechnic Institute, Worcester, Mass. and Palmer Physical Laboratory, Princeton University*

(Received May 8, 1936)

The electromagnetic theory of the torque exerted by a beam of polarized light on a doubly refracting plate which alters its state of polarization is summarized. The same quantitative result is obtained by assigning an angular momentum of $\hbar$ $(-\hbar)$ to each quantum of left (right) circularly polarized light in a vacuum, and assuming the conservation of angular momentum holds at the face of the plate. The apparatus used to detect and measure this effect was designed to enhance the moment of force to be measured by an appropriate arrangement of quartz wave plates, and to reduce interferences. The results of about 120 determinations by two observers working independently show the magnitude and sign of the effect to be correct, and show that it varies as predicted by the theory with each of three experimental variables which could be independently adjusted.

Beth (1936)

Light-Matter Interaction - mechanical effects, angular momentum

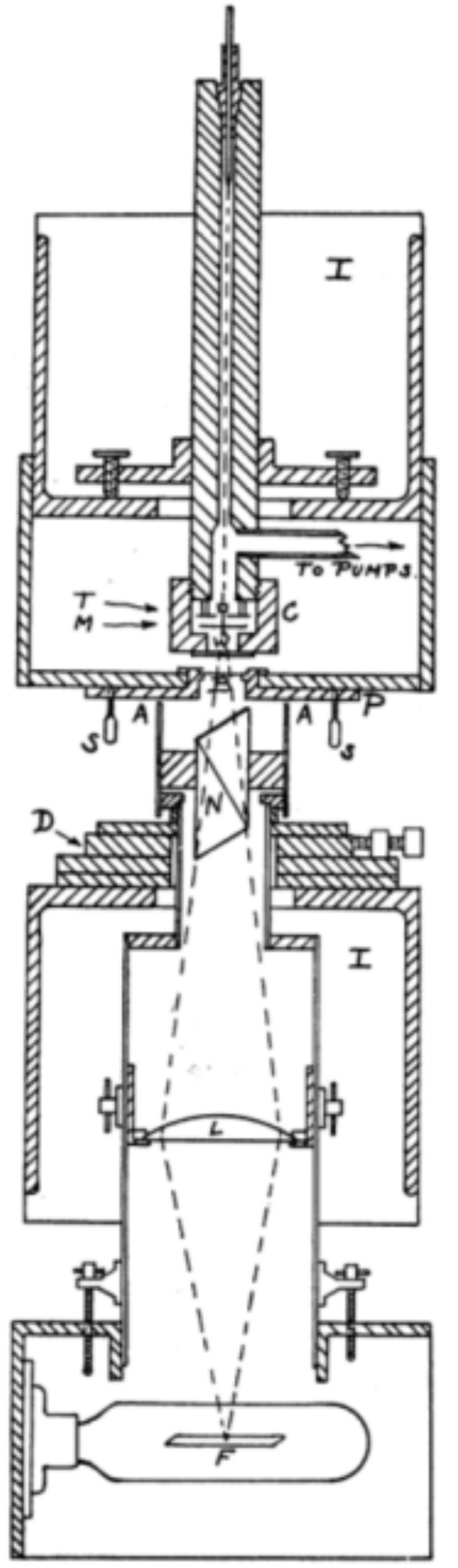


FIG. 1. Diagram of apparatus.

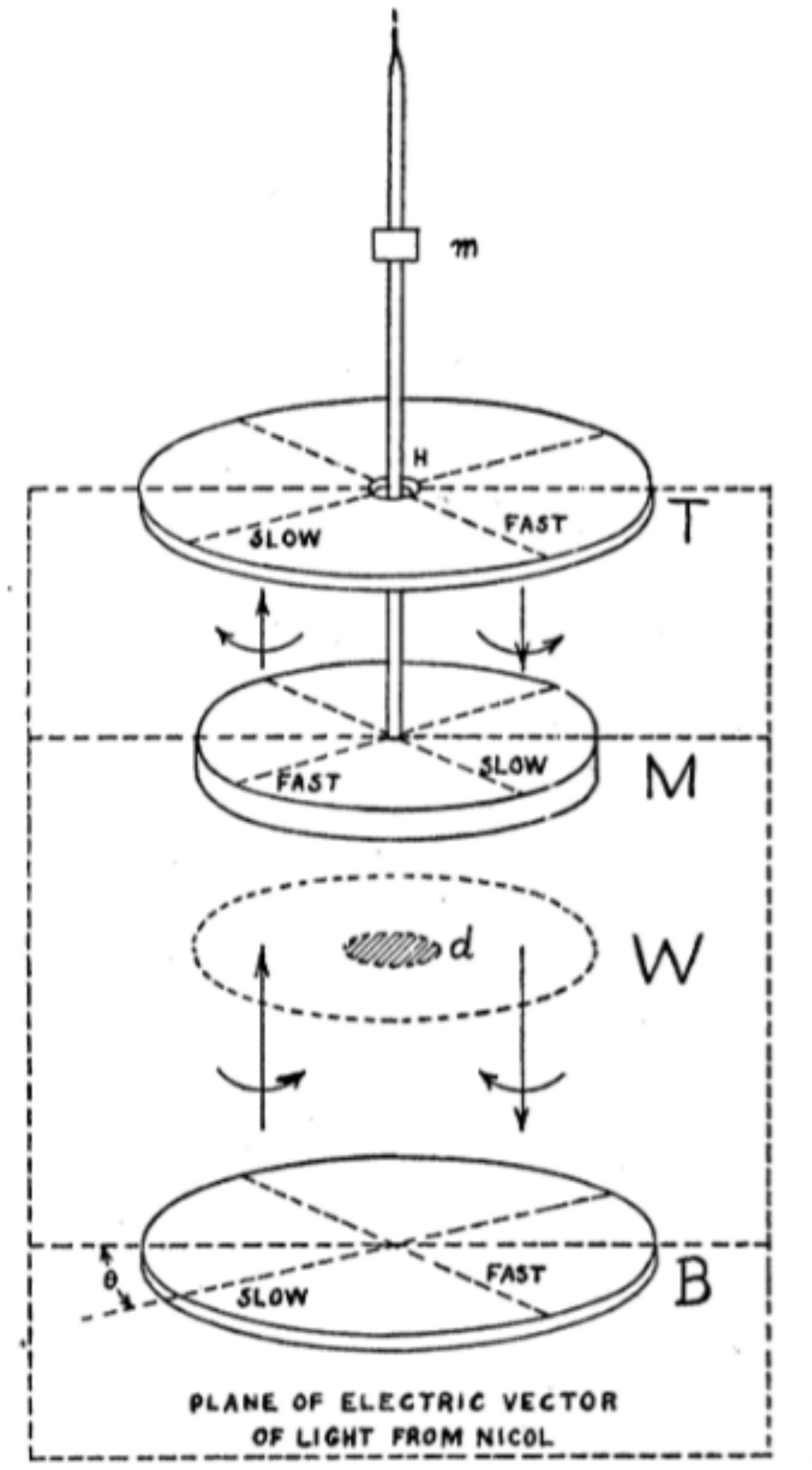
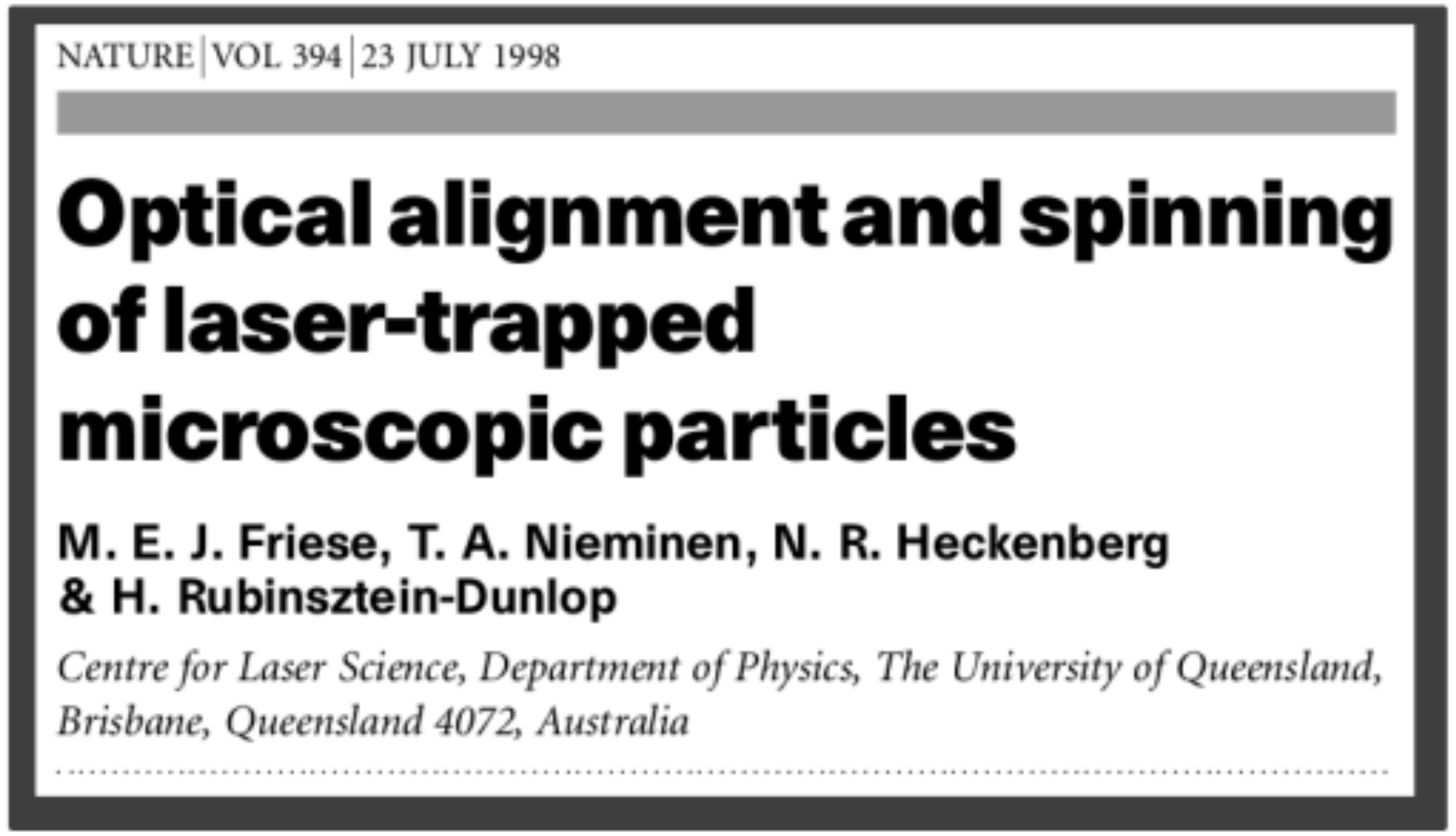


FIG. 3. Wave plate arrangement.

Beth (1936)

Light-Matter Interaction - mechanical effects, angular momentum

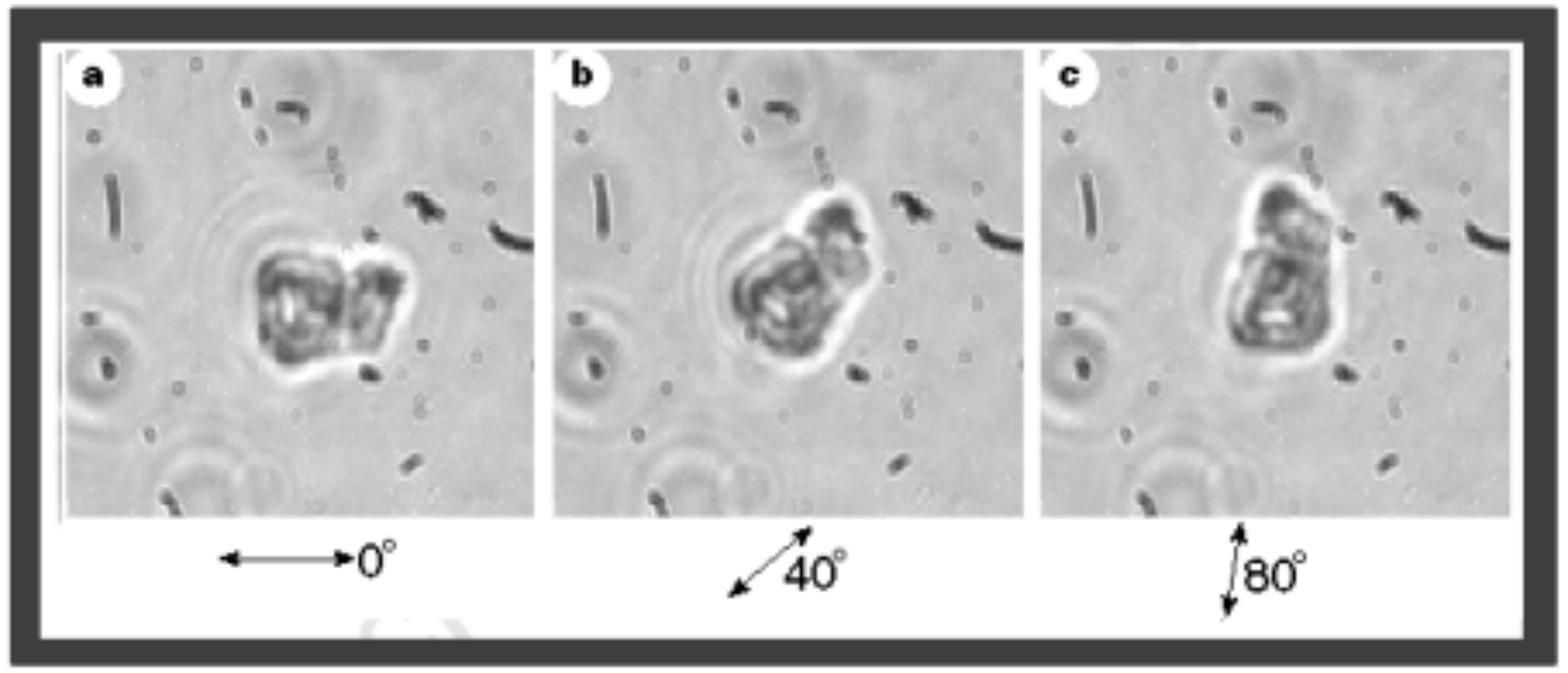


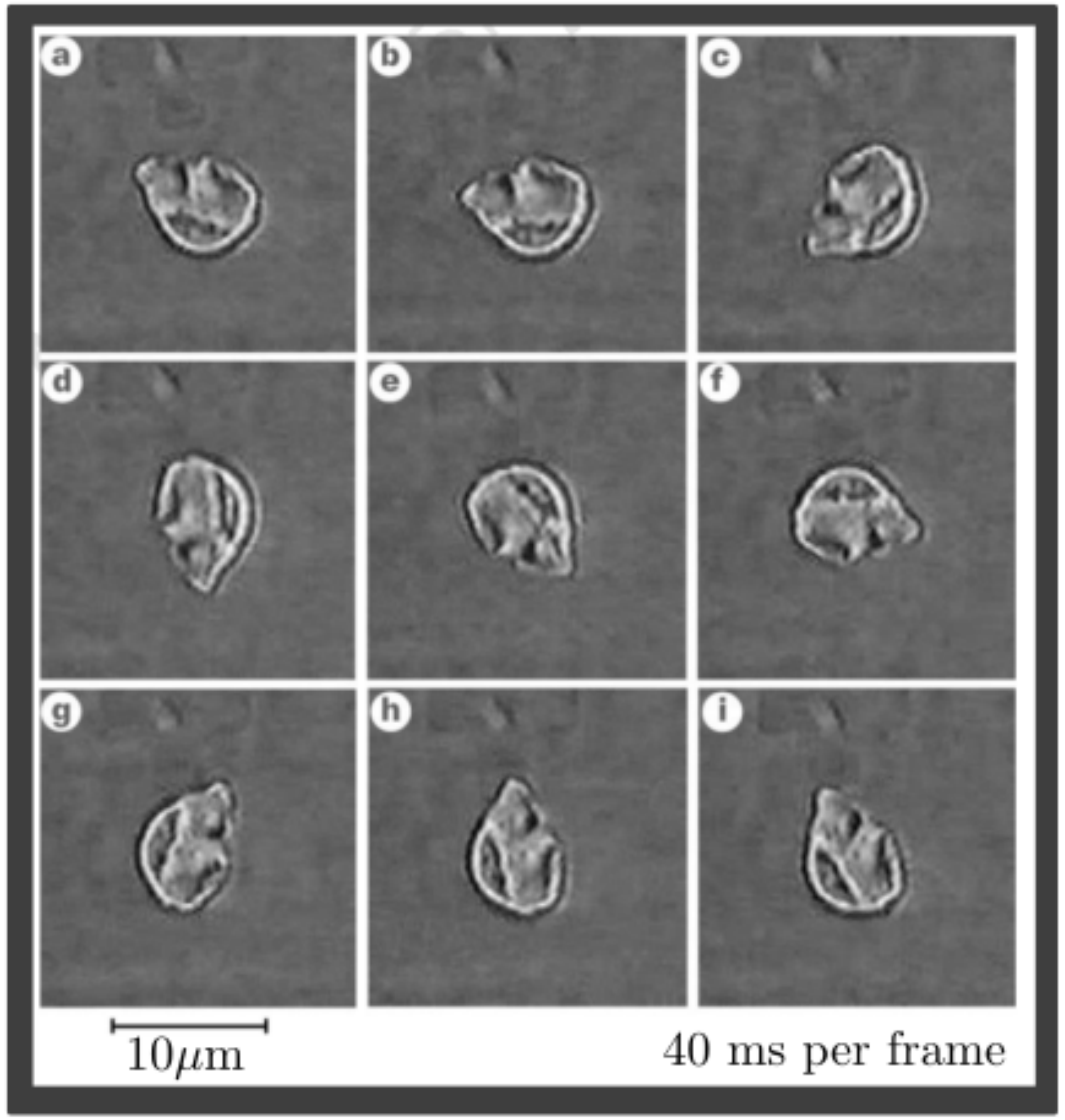
NATURE | VOL 394 | 23 JULY 1998

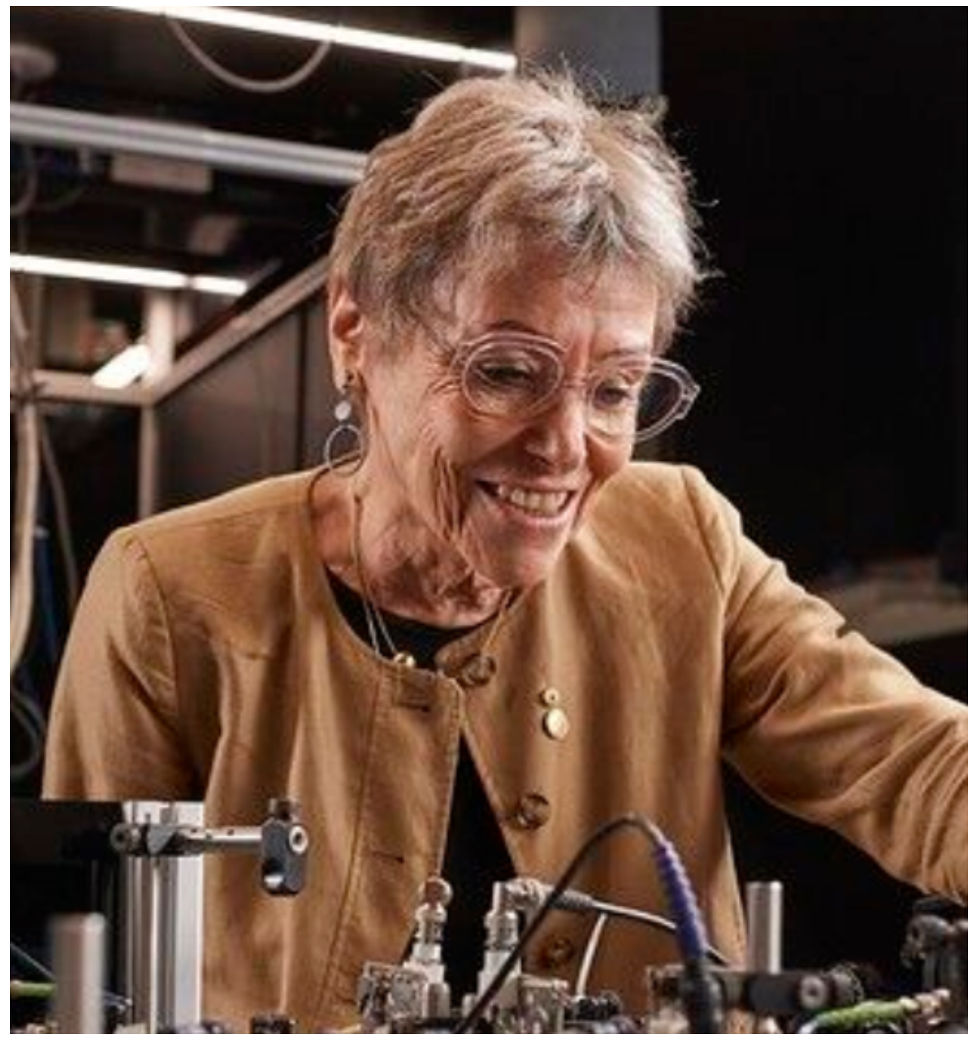
Optical alignment and spinning of laser-trapped microscopic particles

M. E. J. Friese, T. A. Nieminen, N. R. Heckenberg & H. Rubinsztein-Dunlop

Centre for Laser Science, Department of Physics, The University of Queensland, Brisbane, Queensland 4072, Australia







Rubinsztein-Dunlop

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
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Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum			

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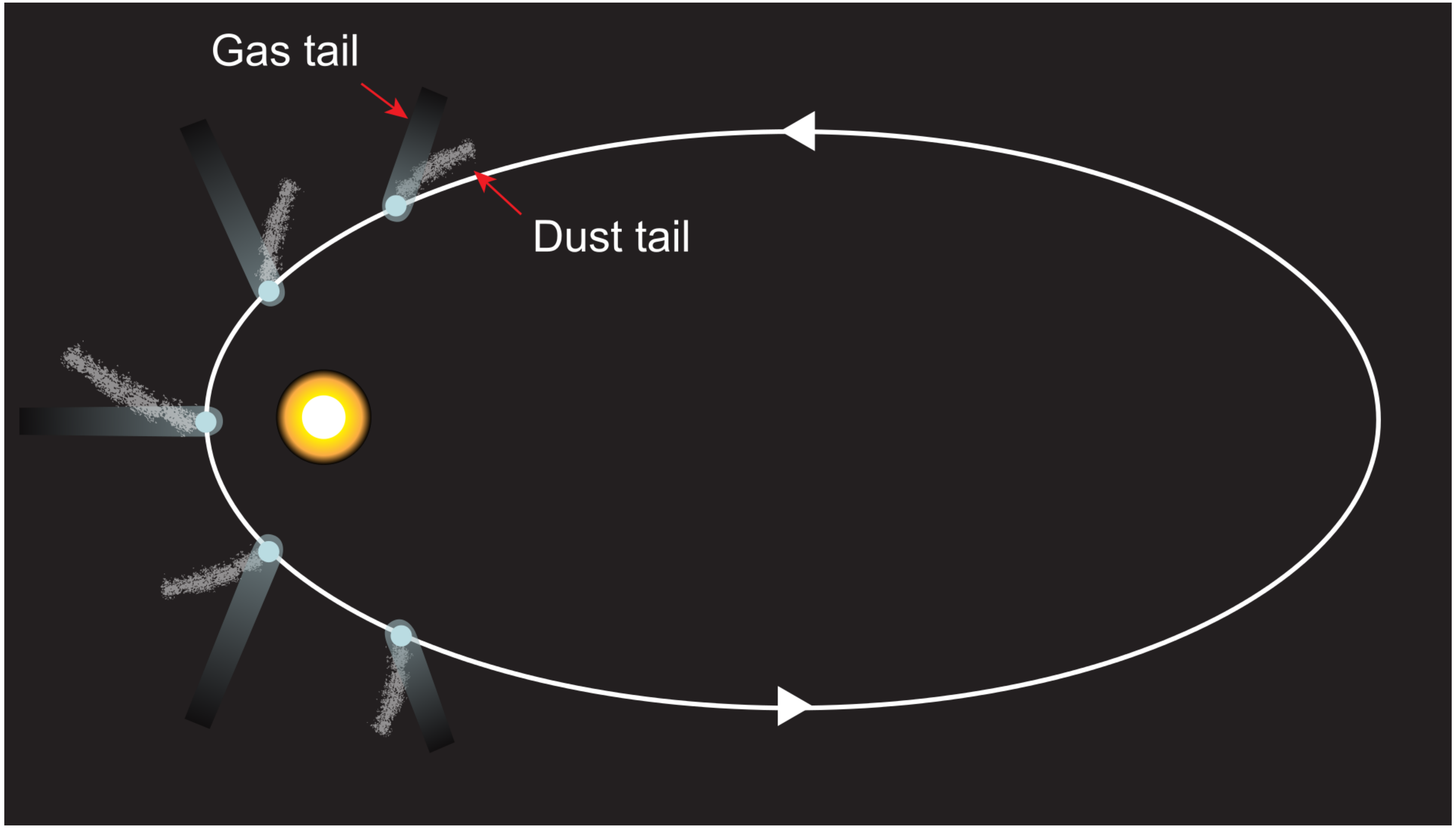
Light-Matter Interaction - mechanical effects, linear momentum

1619
Kepler: Comet Tails
1901
Nicols radiometer
19xx
Photon recoil
19xx
Satellites and spacecrafts

NOT - Crooks Radiometer.

Light-Matter Interaction - mechanical effects, linear momentum

Radiation pressure - comets and Kepler

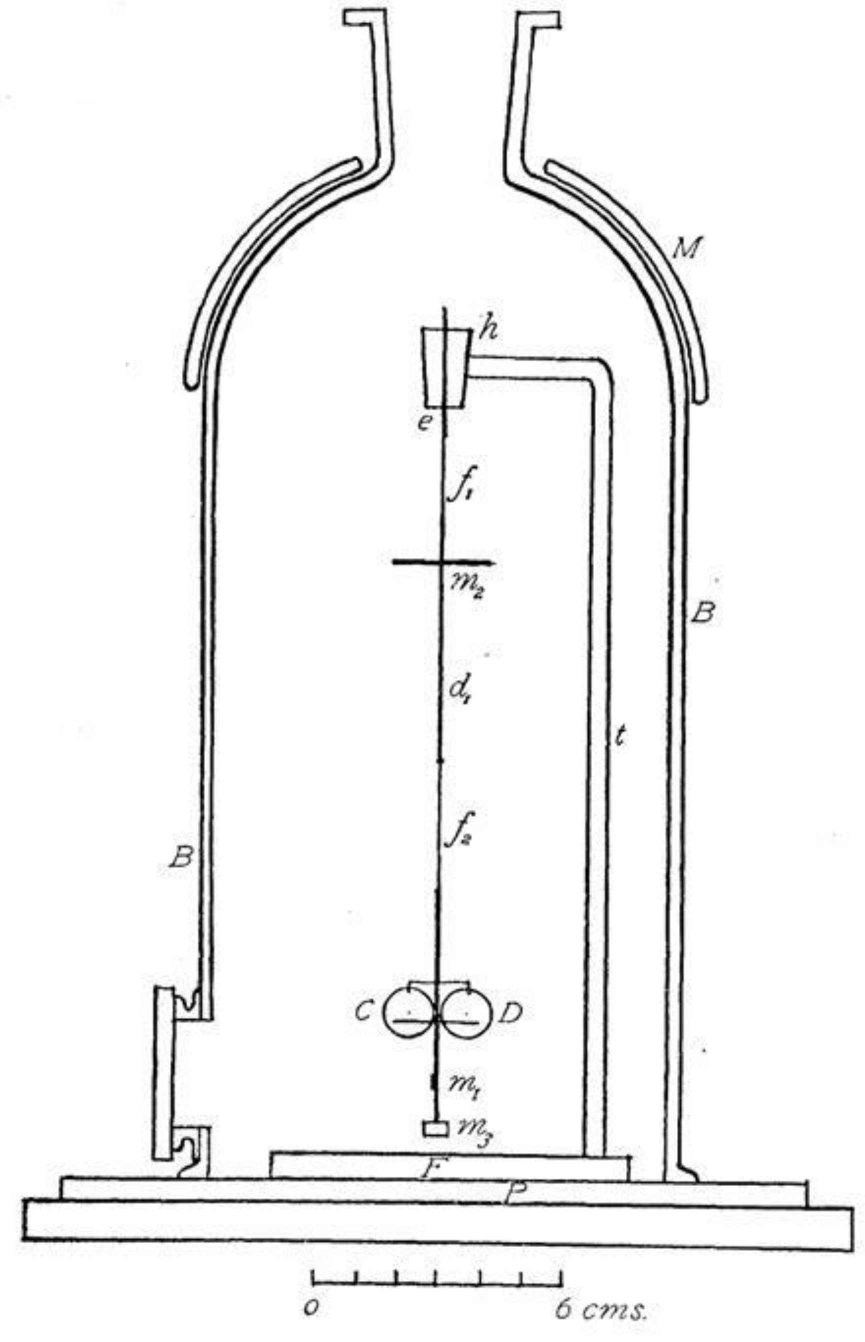


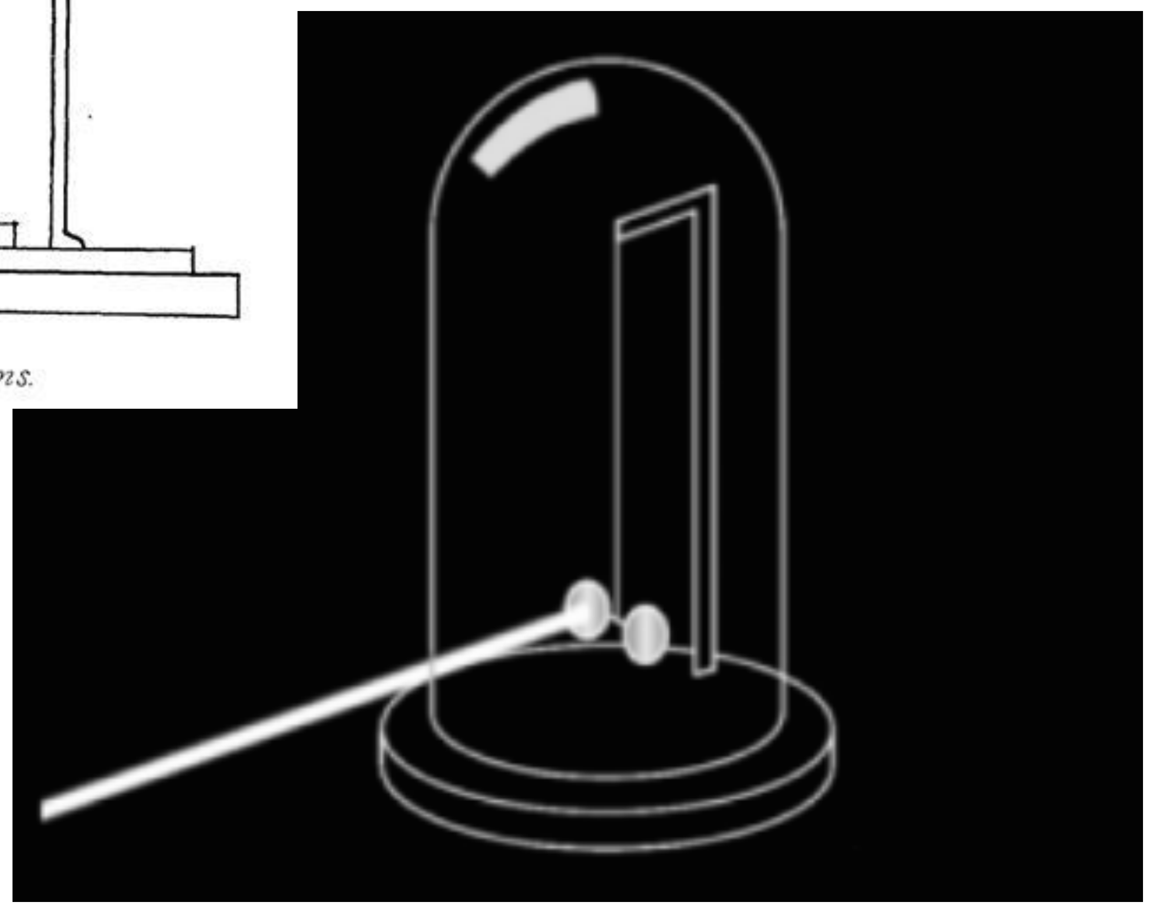
Pressure is always in the propagation direction - longitudinal -

Light-Matter Interaction - mechanical effects, linear momentum

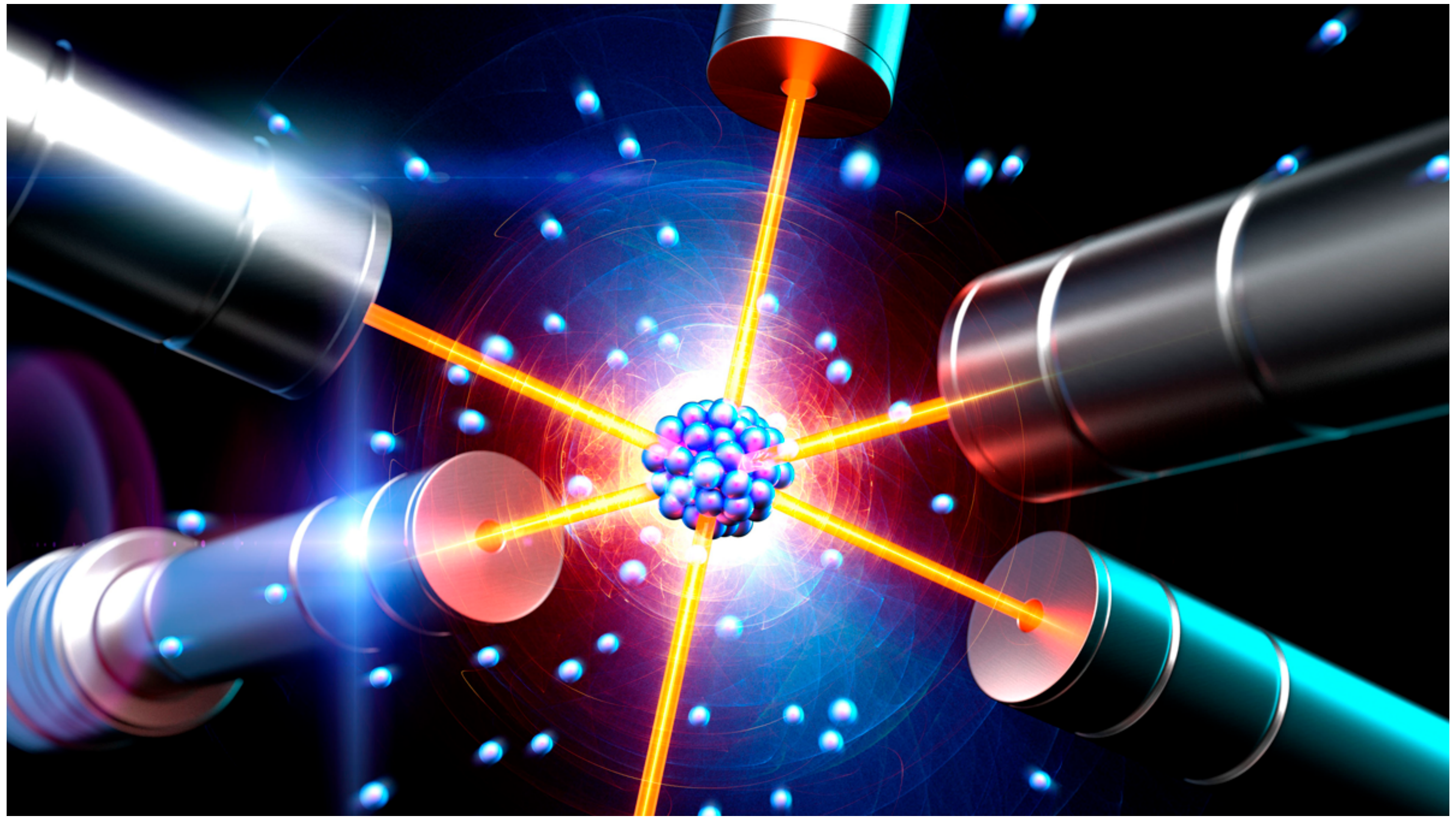
Radiation pressure - comets and Kepler

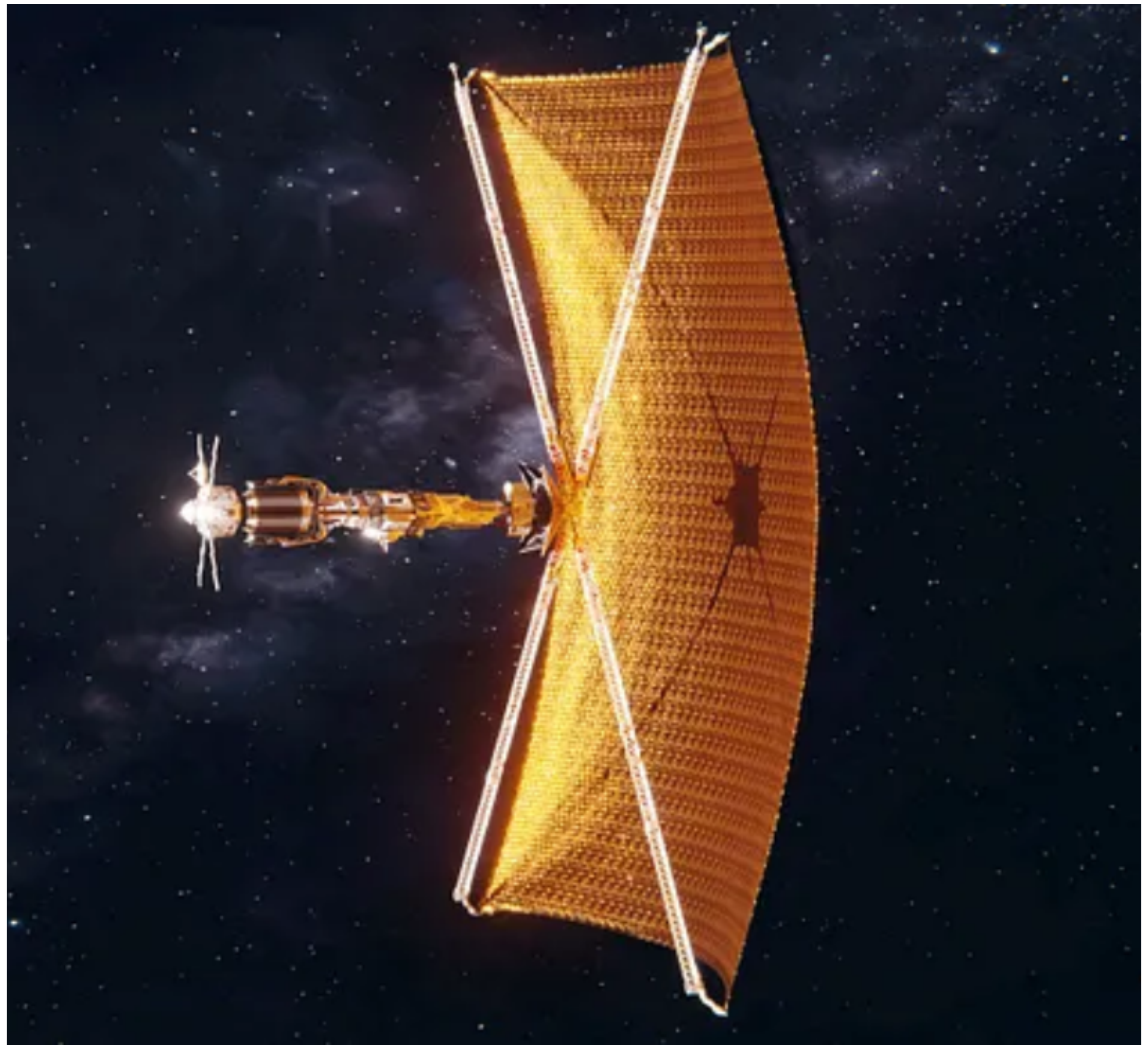
Nichols and Crookes radiometers



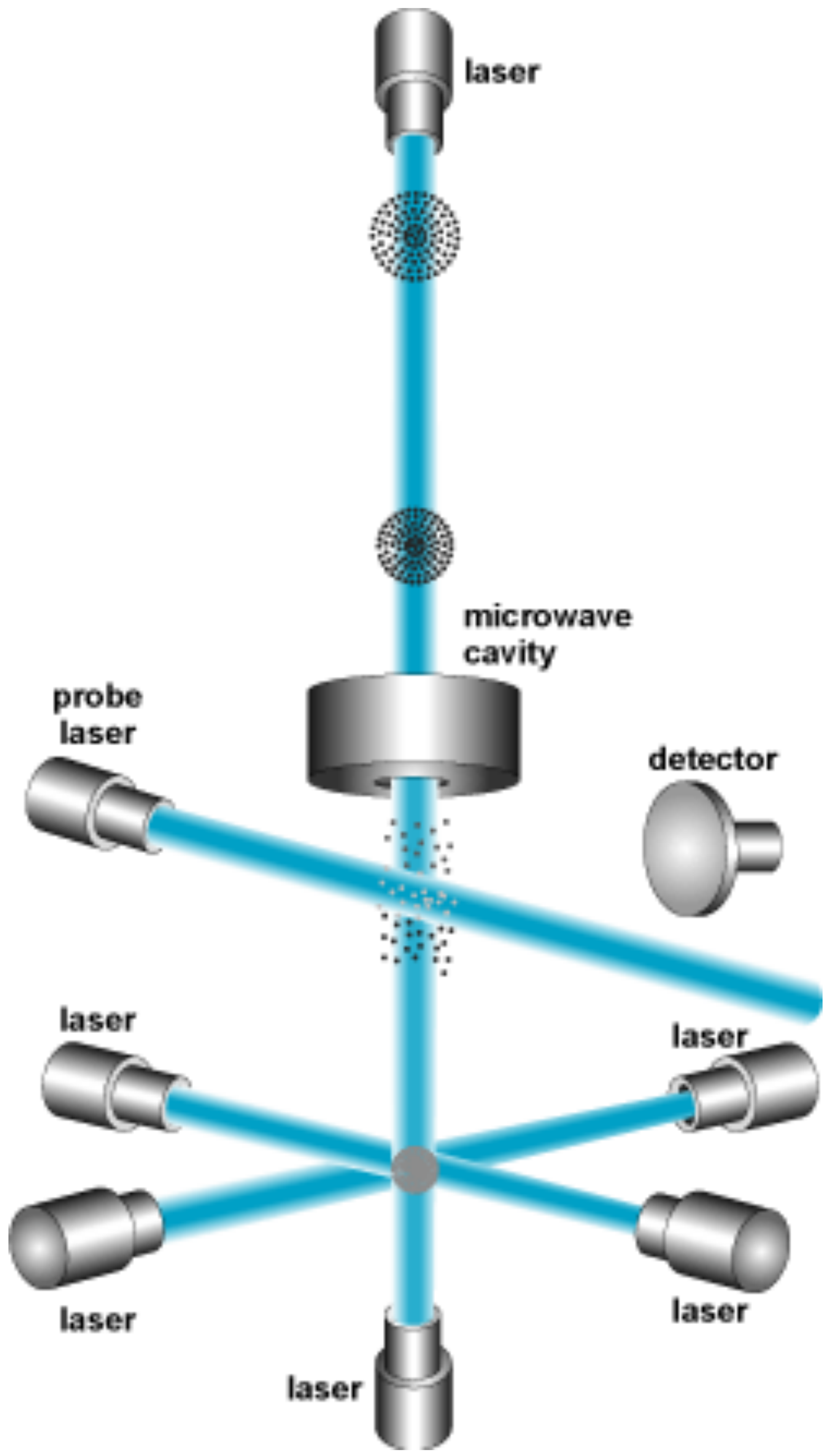


Atomic Cooling, Fountains and Solar Sails





Atomic Cooling, Fountains and Solar Sails



Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum	✓ Fraunhofer	✓ Radiation Pressure	✓ Refraction
Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum			

Christian Schmiegelow - Universidad de Buenos Aires

Light field description

Plane Wave

$$A = A_{lp}(\rho, \phi, z)\vec{\epsilon}e^{ikz}e^{-i\omega t}$$

- Part 2 -

Gaussian and Structured Beams

Gaussian Beams - from Saleh & Teich

The wave equation, and the Helmotz equation.

General wave equation for (complex) field U

$$\nabla^2 U - \frac{1}{c^2}\frac{\partial^2 U}{\partial t^2} = 0$$

General (complex) oscillating solution

$$U(\mathbf{r}, t) = U(\mathbf{r}) \exp(j\, 2\pi\nu t)$$

The real fields...

$$u = \Re(U)$$

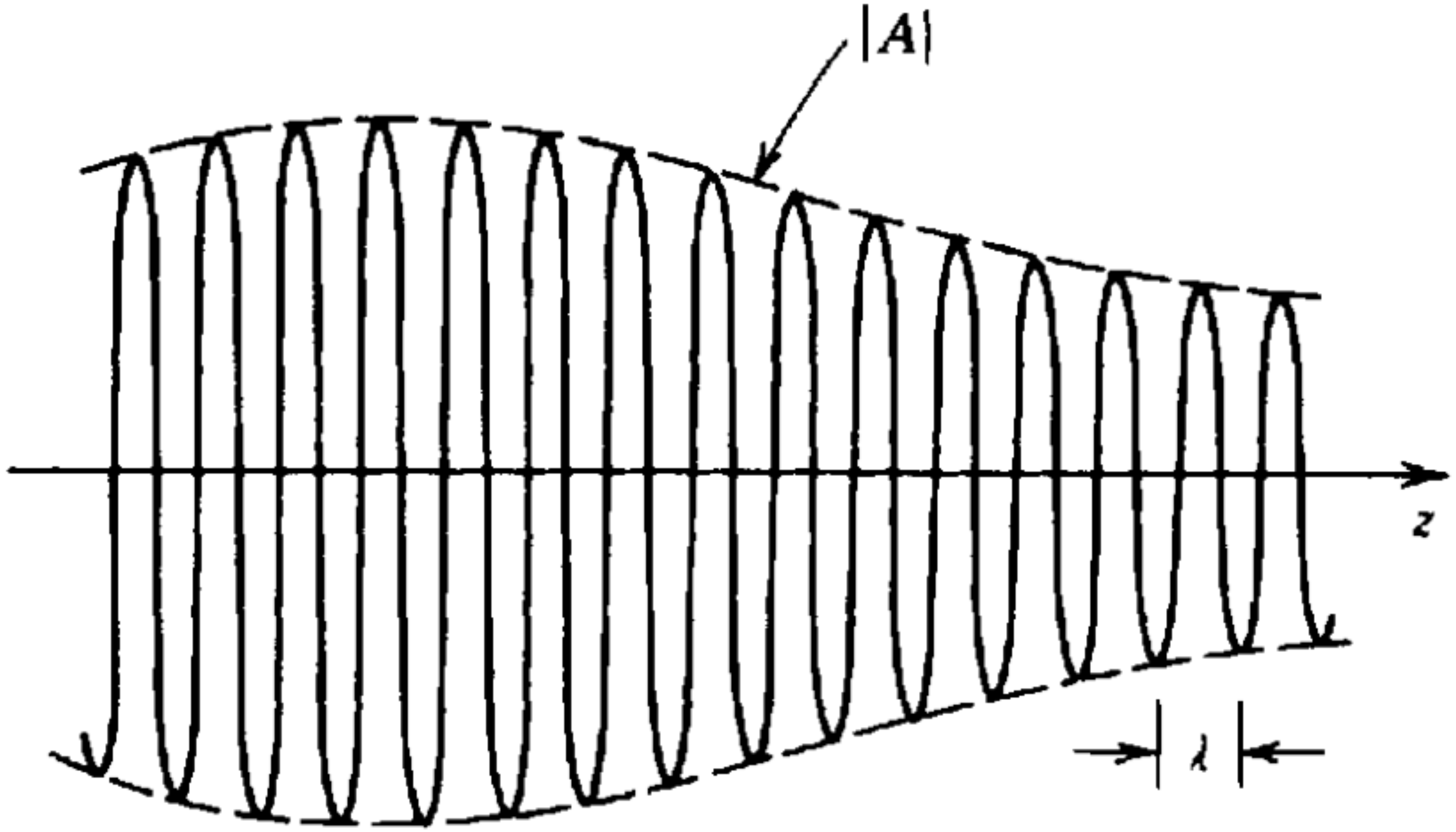
Leads to the Helmholz equation

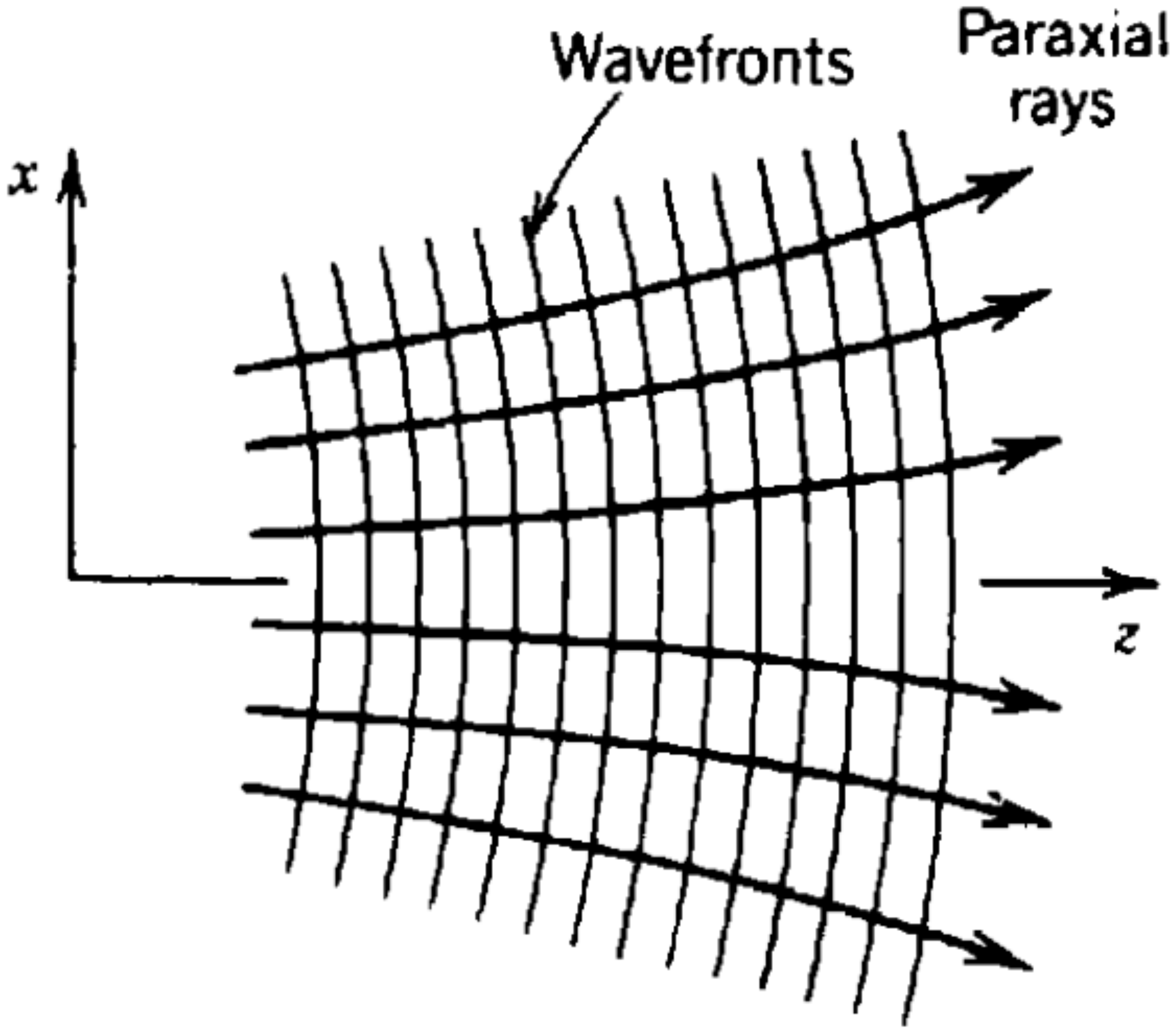
$$(\nabla^2 - k^2) U(\mathbf{r}) = 0$$

$$k = \frac{2\pi\nu}{c} = \frac{\omega}{c}$$

Gaussian Beams - from Saleh & Teich

The paraxial approximation





Slow varying envelope (and phase) A(r)

$$U(\mathbf{r}) = A(\mathbf{r}) \exp(j\, kz)$$

$$u(\mathbf{r}, t) = |A(\mathbf{r})| \cos(2\pi\nu t - kz + \arg\{A(\mathbf{r})\})$$

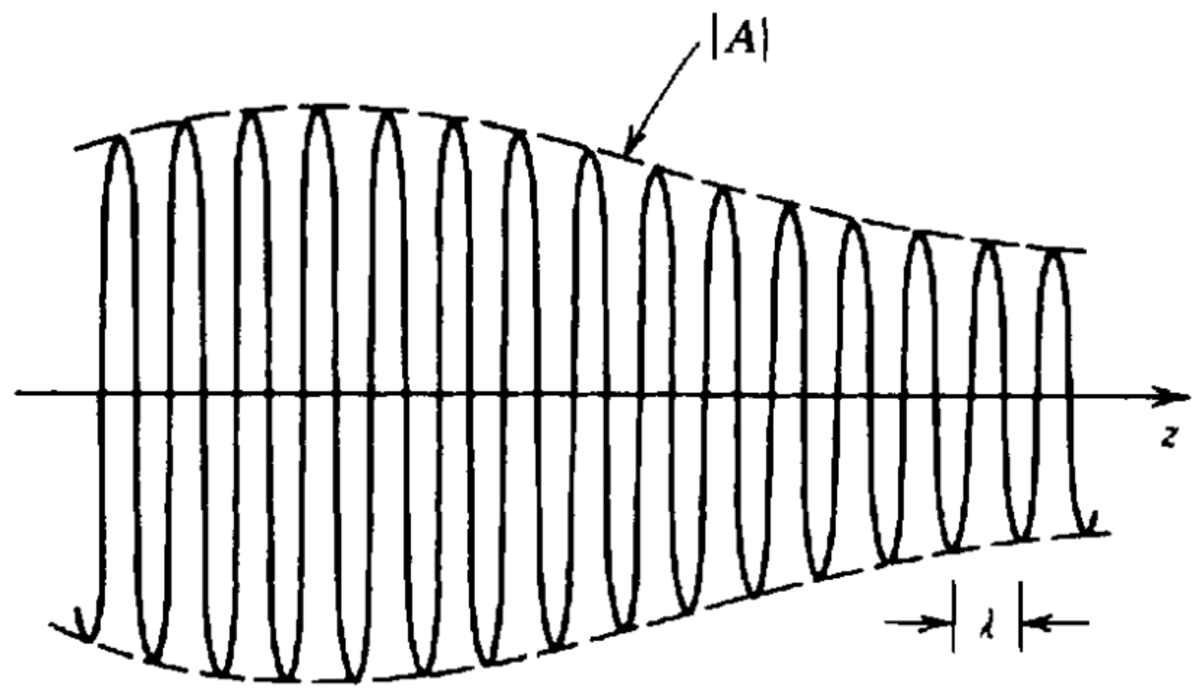
Gaussian Beams - from Saleh & Teich

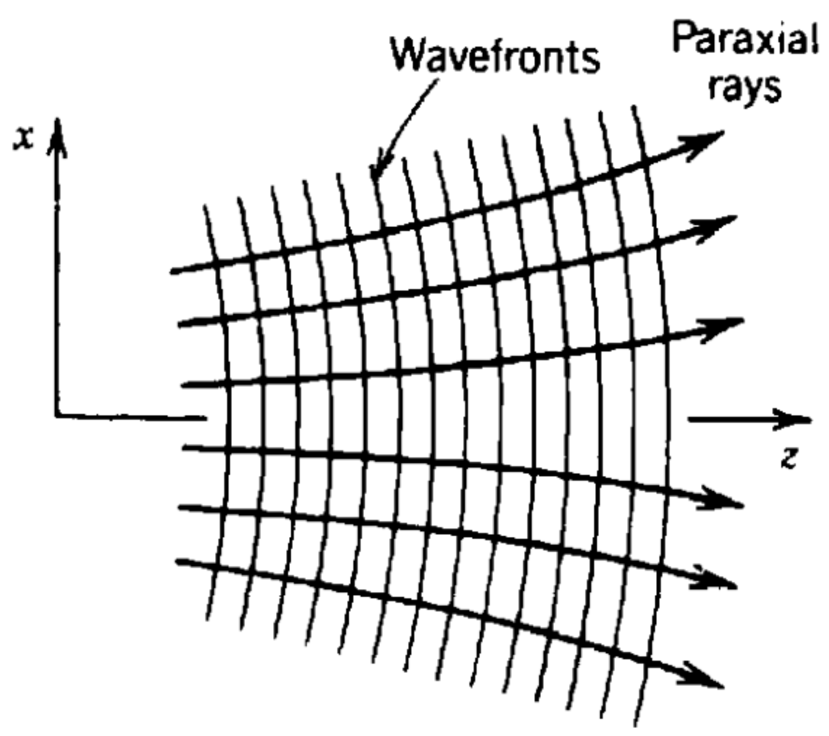
The paraxial approximation

Slow varying envelope (and phase) A(r)

$$U(\mathbf{r}) = A(\mathbf{r})\exp(j\,kz)$$

$$u(\mathbf{r},t) = |A(\mathbf{r})|\cos(2\pi\nu t - kz + \arg\{A(\mathbf{r})\})$$





The paraxial assumtions

$$\frac{\partial A}{\partial z} \ll kA \qquad \frac{\partial^2 A}{\partial z^2} \ll k^2 A$$

Transform the Helmholtz eqation

$$(\nabla^2 - k^2)U(\mathbf{r}) = 0$$

onto the Paraxial Equation

$$\nabla_T^2 A - j2k\frac{\partial A}{\partial z} = 0$$

with the transversal Lapacian

$$\nabla_T^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$$

Gaussian Beams - from Saleh & Teich

Gaussian Beams

To solve the Helmholz equation

$$\nabla_T^2 A - j2k\frac{\partial A}{\partial z} = 0$$

We take inspiration from the paraboloidal (spherical) wave:

$$A(r) = \frac{A_1}{z}\exp\left[-jk\frac{\rho^2}{2z}\right],\ \rho^2 = x^2 + y^2$$

... and seach for a more general solution with the anzatz:

$$A(r) = \frac{A_1}{q(z)}\exp\left[-jk\frac{\rho^2}{2q(z)}\right],\ q(z) = z + jz_0$$

To find the Gaussian wave function:

$$U(\mathbf{r}) = A_0\frac{W_0}{W(z)}\exp\left[-\frac{\rho^2}{W^2(z)}\right]\exp\left[-jkz - jk\frac{\rho^2}{2R(z)} + j\zeta(z)\right]$$

normalization

Gaussian envelope

plane wave

curvature

Gouy phase

where

$$W(z) = W_0\left[1 + \left(\frac{z}{z_0}\right)^2\right]^{1/2}$$

$$R(z) = z\left[1 + \left(\frac{z_0}{z}\right)^2\right]$$

$$\zeta(z) = \tan^{-1}\frac{z}{z_0}$$

$$W_0 = \left(\frac{\lambda z_0}{\pi}\right)^{1/2}$$

Gaussian Beams - from Saleh & Teich

Envelope, divergence, and focus limit.

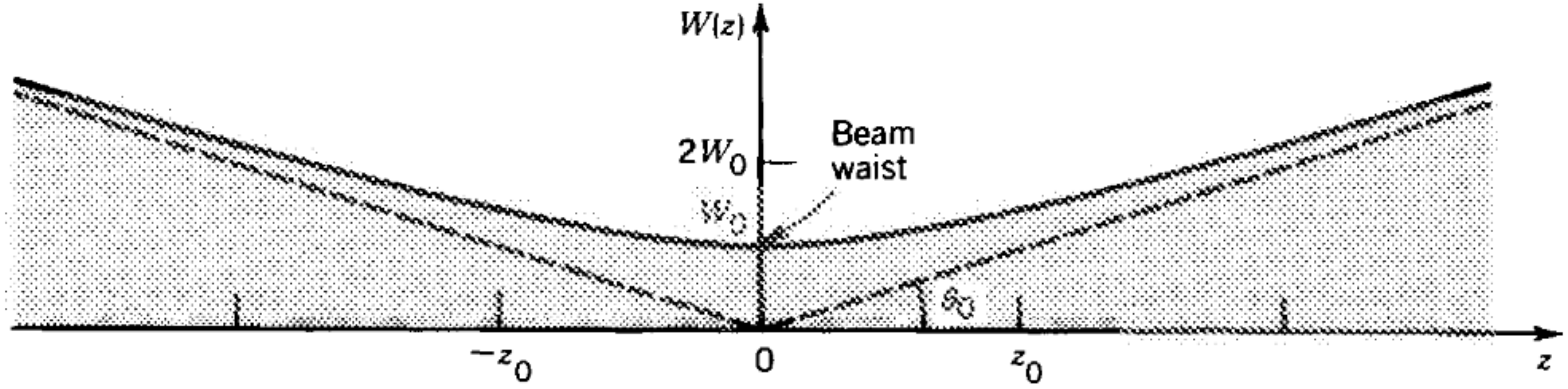
In the Gaussian beam

$$U(\mathbf{r}) = A_0 \frac{W_0}{W(z)} \exp\left[-\frac{\rho^2}{W^2(z)}\right] \exp\left[-jkz - jk\frac{\rho^2}{2R(z)} + j\zeta(z)\right]$$

The waist / envelope is:

$$W(z) = W_0\left[1 + \left(\frac{z}{z_0}\right)^2\right]^{1/2}$$

$$W_0 = \left(\frac{\lambda z_0}{\pi}\right)^{1/2}$$



Ehich leads to a divergence:

$$\theta_0 = \frac{\lambda}{\pi W_0}.$$

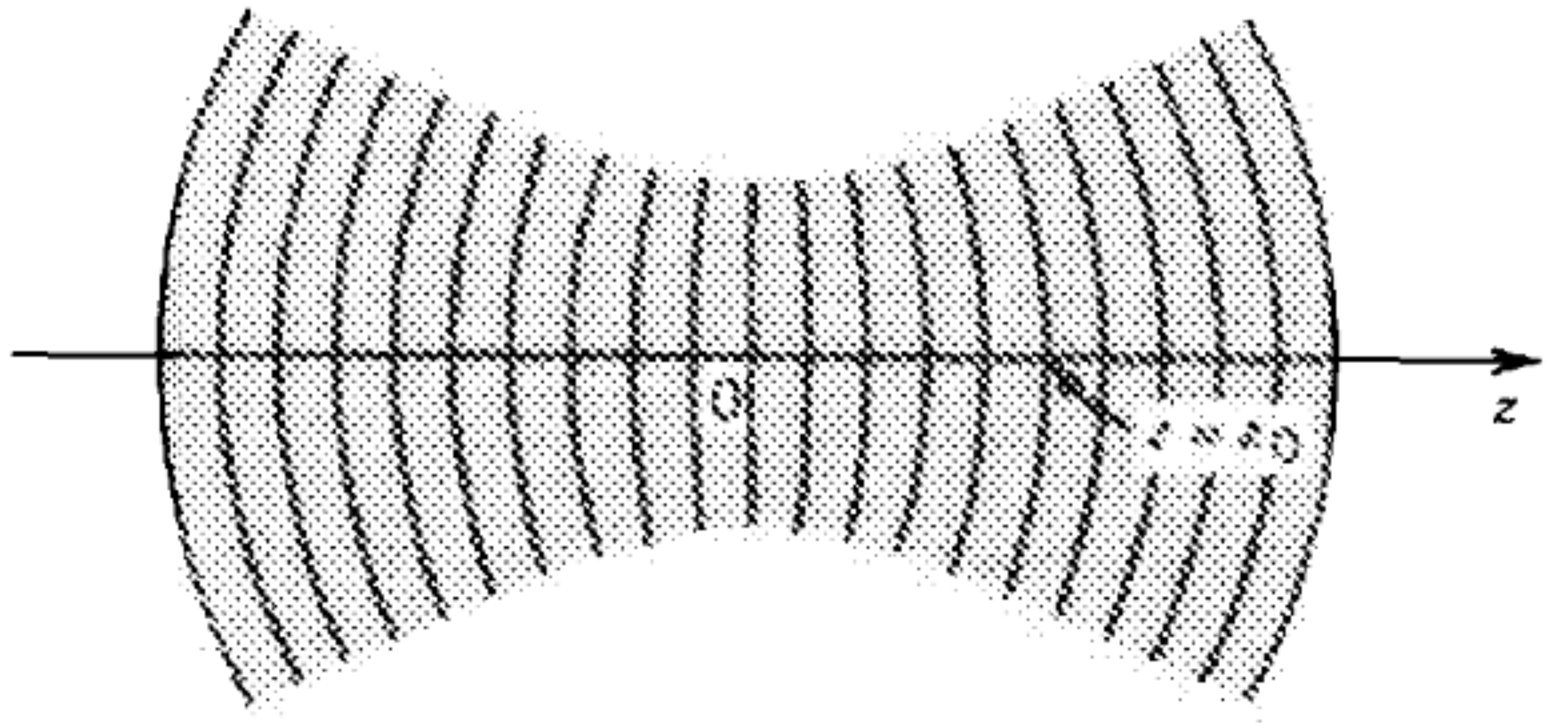
Extra: focus limit. Abbe/Helmoltz $d = \frac{\lambda}{2\sin(\theta)} \approx \frac{\lambda}{2\theta}$

Gaussian $d = 2W_0 = \frac{2\lambda}{\pi\theta}$

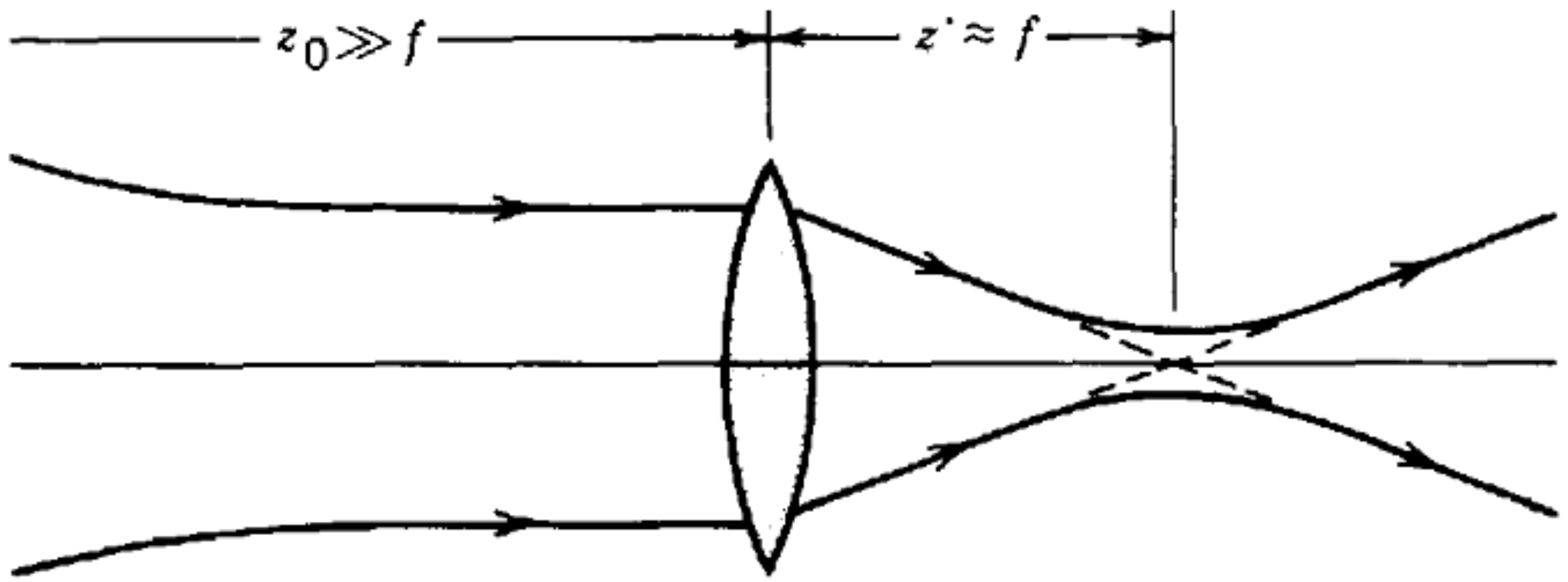
Gaussian Beams - from Saleh & Teich

Shapes and wave forms.

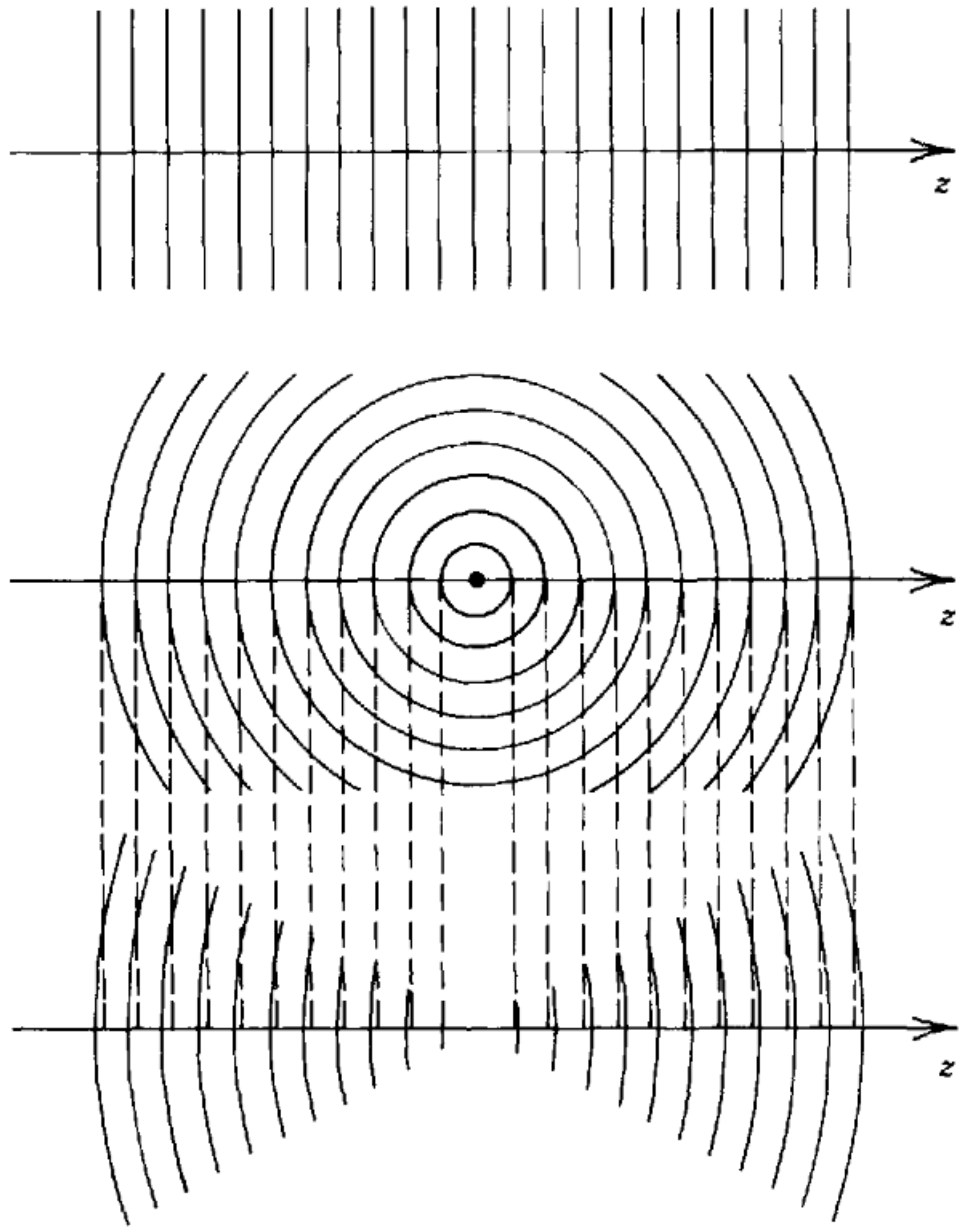
Focus and curvature



Collimating and Focusing



Plane/Sperical/Gaussian



Hermite-Gaussian Beams - square structure

Searching for a more general solution to
the paraxial equation. (y cartesian coordinates)

$$A(x, y, z) = \mathscr{X}\left[\sqrt{2}\,\frac{x}{W(z)}\right]\mathscr{Y}\left[\sqrt{2}\,\frac{y}{W(z)}\right]\exp[j\mathscr{Z}(z)]A_G(x, y, z),$$

In the paraxial equation, leads to the separation of variables:

$$\frac{1}{\mathscr{X}}\left(\frac{\partial^2\mathscr{X}}{\partial u^2} - 2u\frac{\partial\mathscr{X}}{\partial u}\right) + \frac{1}{\mathscr{Y}}\left(\frac{\partial^2\mathscr{Y}}{\partial v^2} - 2v\frac{\partial\mathscr{Y}}{\partial v}\right) + kW^2(z)\frac{\partial\mathscr{Z}}{\partial z} = 0.$$

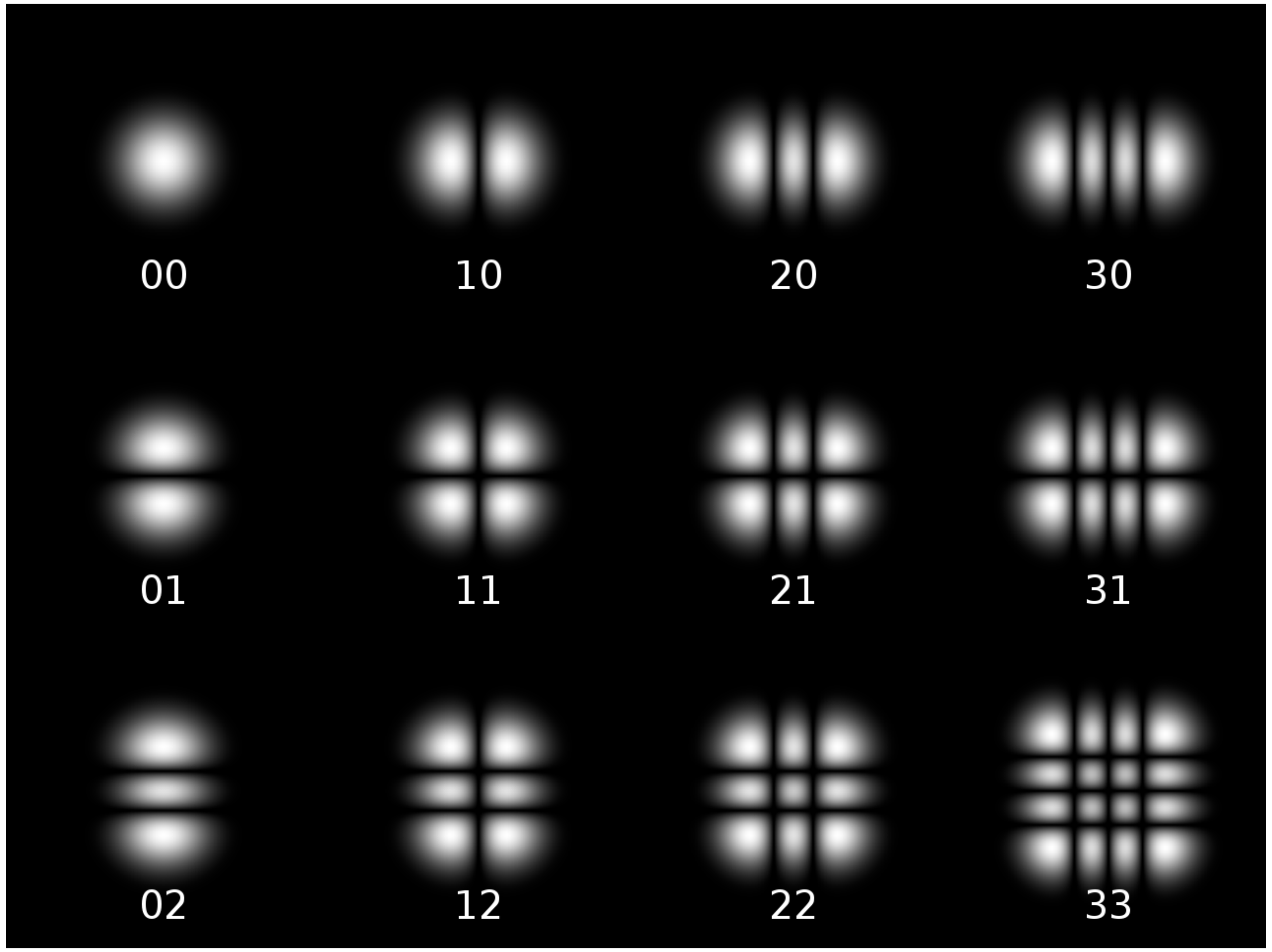
With recurrent polinomials as the solution.
Hermite, polinomials.

$$H_{l+1}(u) = 2uH_l(u) - 2lH_{l-1}(u)$$

$$H_0(u) = 1, \qquad H_1(u) = 2u.$$

$$H_2(u) = 4u^2 - 2, \qquad H_3(u) = 8u^3 - 12u, \qquad \ldots.$$

$\mathrm{HG}_{nm}(x, y)$ Hermite-Gaussian beam profiles.



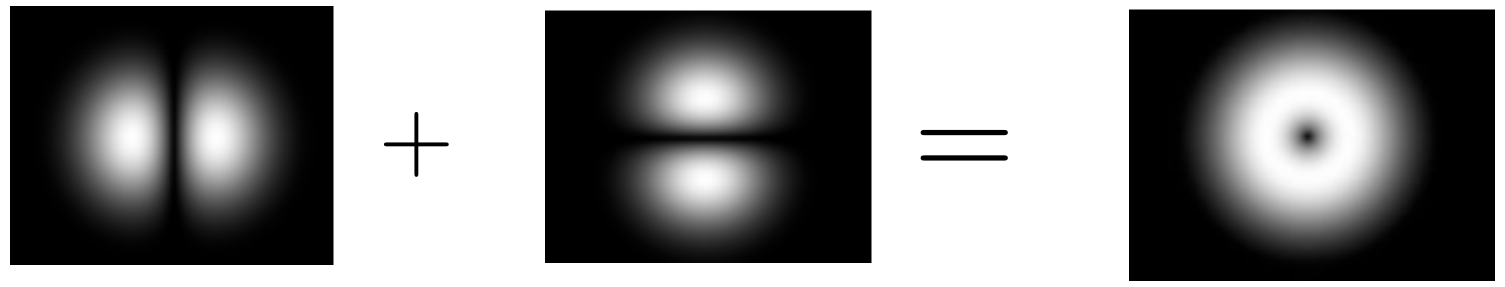
the profile shape is unchaged upon propagation.

Laguerre-Gaussian Beams - cylindrical structure

Searching for cylindrical-symmetric solutions. LG_{lp}

Two paths.

1) Linear cominations of Hermite Gaussian Beams



$$\mathrm{HG}_{01} \pm j\mathrm{HG}_{10} = \mathrm{LG}_{\pm 1,0}$$

2) Solve the paraxial equation in cylindrical coordinates

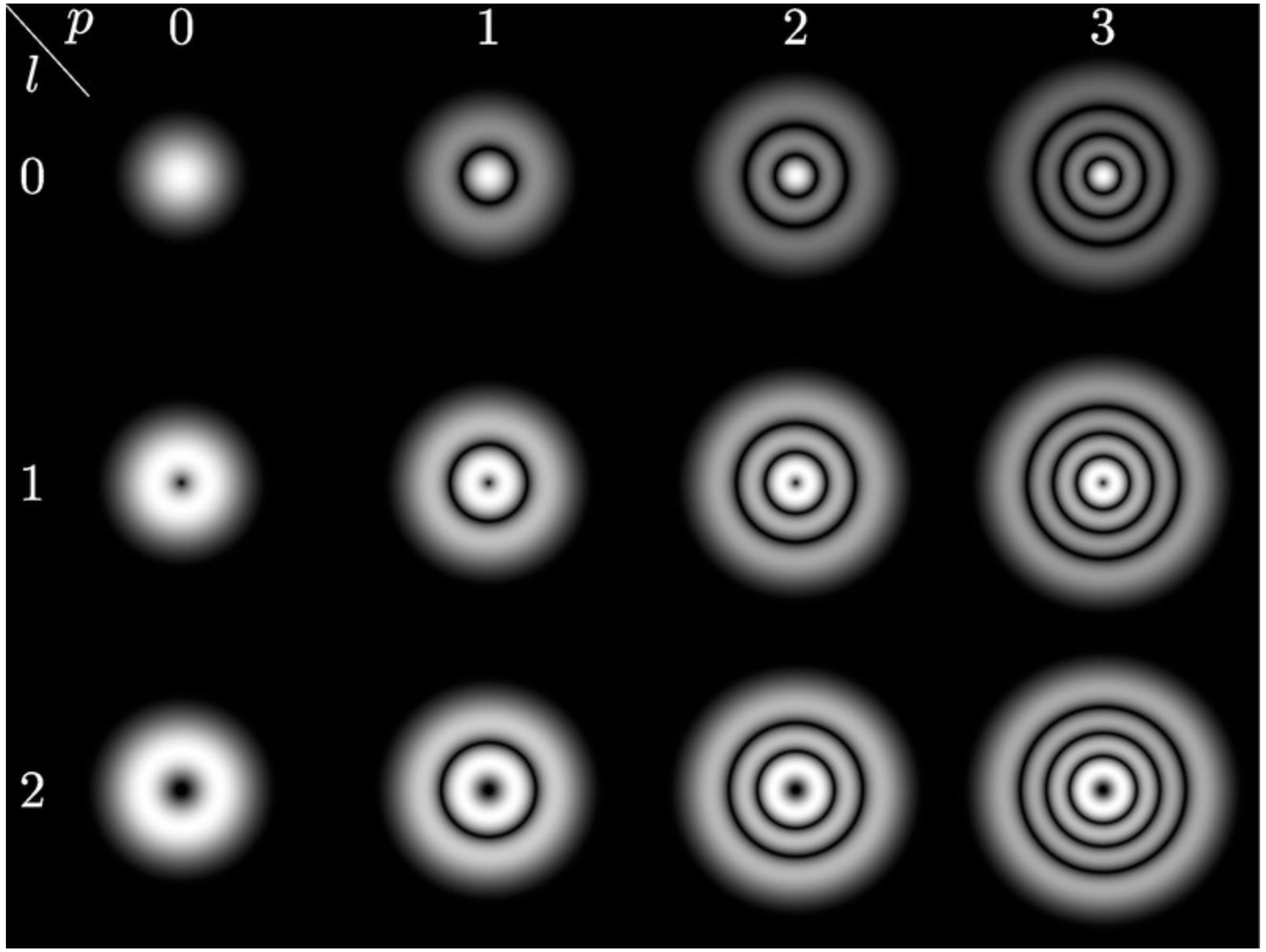
$$A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$$

$$\mathbf{A}_{lp} = \mathbf{A_0} \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z)\right) \sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)}\right)^{|l|} \mathcal{L}_p^{|l|}\left(\frac{2\rho^2}{w^2(z)}\right) \exp(il\phi)$$

Laguerre Polynomials

azimuthal phase

$\mathrm{LG}_{lp}(\rho, \theta)$ Laguerre-Gaussian beam profiles.



the profile shape is unchaged upon propagation.

!! Wikipedia might be wrong. Collaborate !!

Twisted Light

$$A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$$

$$\mathbf{A}_{lp} = \mathbf{A_0} \; \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z) \right)$$

$$\sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)} \right)^{|l|} \mathcal{L}_p^{|l|} \left(\frac{2\rho^2}{w^2(z)} \right) \exp(il\phi)$$

$l = 0$ $\quad$ $l = 1$ $\quad$ $l = 2$

- Part 3 -

Orbital Angular momentum of Light

Laguerre-Gaussian Beams - angular momentum

PHYSICAL REVIEW A VOLUME 45, NUMBER 11 1 JUNE 1992

Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman
Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
(Received 6 January 1992)

Laser light with a Laguerre-Gaussian amplitude distribution is found to have a well-defined orbital angular momentum. An astigmatic optical system may be used to transform a high-order Laguerre-Gaussian mode into a high-order Hermite-Gaussian mode reversibly. An experiment is proposed to measure the mechanical torque induced by the transfer of orbital angular momentum associated with such a transformation.

PACS number(s): 42.50.Vk

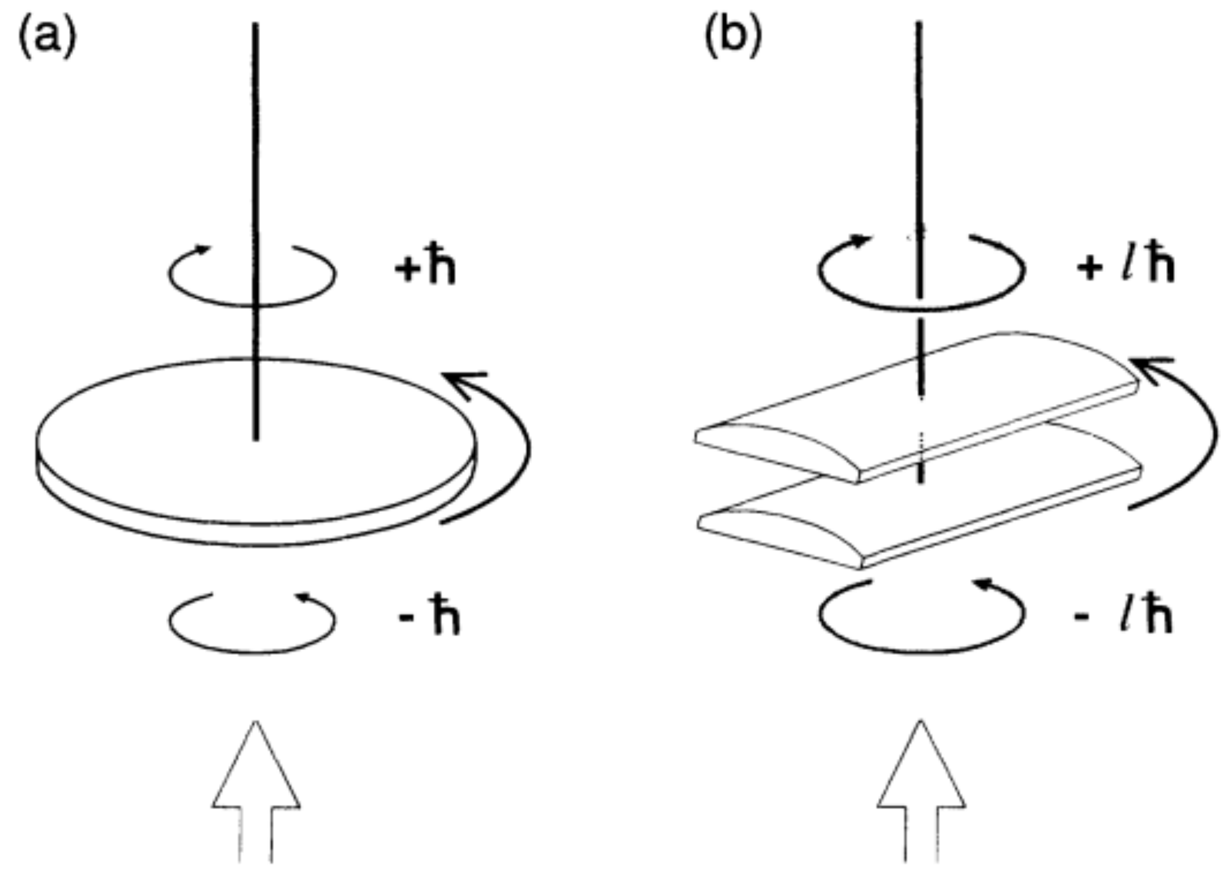


FIG. 1. (a) A suspended $\lambda/2$ birefringent plate undergoes torque in transforming right-handed into left-handed circularly polarized light. (b) Suspended cylindrical lenses undergo torque in transforming a Laguerre-Gaussian mode of orbital angular momentum $-l\hbar$ per photon, into one with $+l\hbar$ per photon.

Laguerre-Gaussian Beams - angular momentum

Angular momentum of an EM beam

$$\mathbf{M}=\epsilon_0 \mathbf{r}\times(\mathbf{E}\times\mathbf{B})$$

while the total angular momentum of the field is

$$\mathbf{J}=\epsilon_0 \int \mathbf{r}\times(\mathbf{E}\times\mathbf{B})d\mathbf{r} \ .$$

Take a Laguerre-Gaussian beam:

$$\mathbf{A}=\mathbf{x}u(x,y,z)e^{-ikz}$$

$$u_{pl}(r,\phi,z)=\frac{C}{(1+z^2/z_R^2)^{1/2}}\left[\frac{r\sqrt{2}}{w(z)}\right]^l L_p^l\left[\frac{2r^2}{w^2(z)}\right]$$
$$\times\exp\left[\frac{-r^2}{w^2(z)}\right]\exp\frac{-ikr^2z}{2(z^2+z_R^2)}\exp(-il\phi)$$
$$\times\exp\left[i(2p+l+1)\tan^{-1}\frac{z}{z_R}\right],$$

And you get, for linear polarization:

$$\mathbf{M}=-\frac{l}{\omega}\frac{z}{r}|u|^2\mathbf{r}+\frac{r}{c}\left[\frac{z^2}{(z^2+z_R^2)}-1\right]|u|^2\boldsymbol{\phi}+\frac{l}{\omega}|u|^2\mathbf{z} \ .$$

And for circular polarization:

$$M_z=\frac{l}{\omega}|u|^2+\frac{\sigma_z r}{2\omega}\frac{\partial|u|^2}{\partial r} \ .$$

spin / intrinsic / polarization AM

orbital / structure / vortex AM

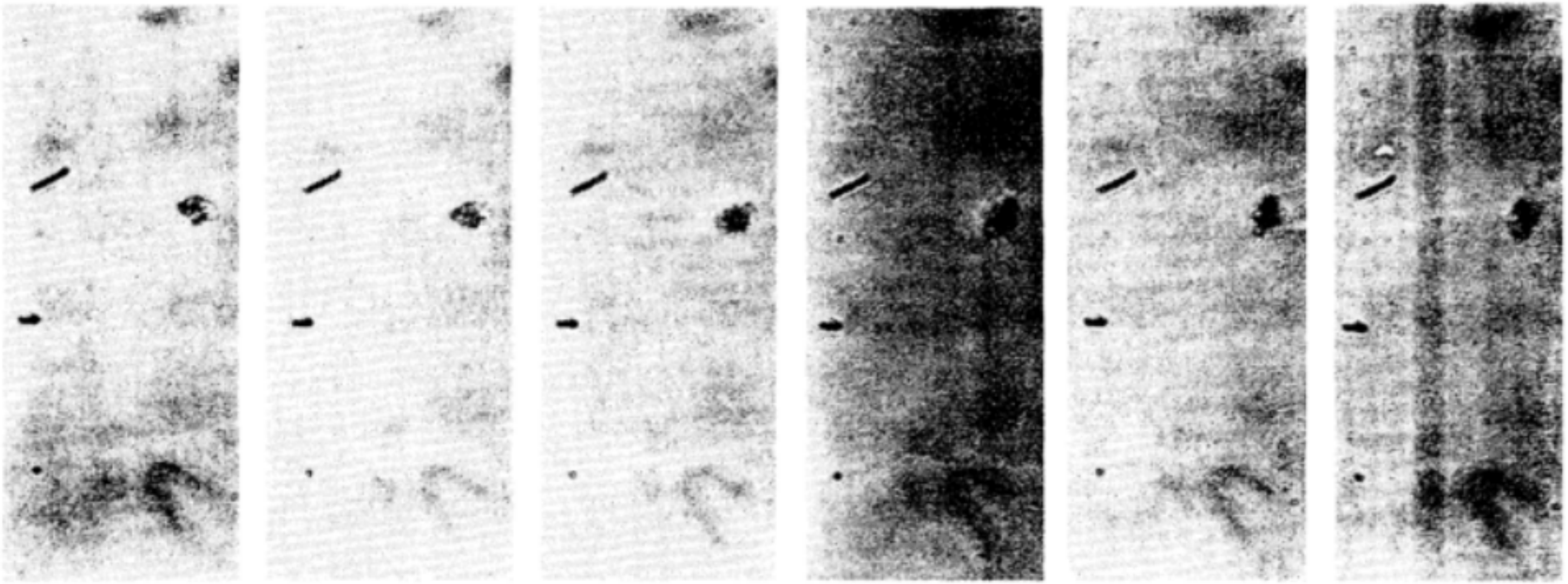
Orbital Angular Momentu - first experiment

VOLUME 75, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1995

pg. 826

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop
Department of Physics, The University of Queensland, Brisbane, Queensland, Australia Q4072



Orbital Angular Momentum

Video intermission coutersy of the
University of Southampton – Optoelectronics Research Centre

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum	✓ Fraunhofer	✓ Radiation Pressure	✓ Refraction
Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum		✓ Rubenstein Dunlop	

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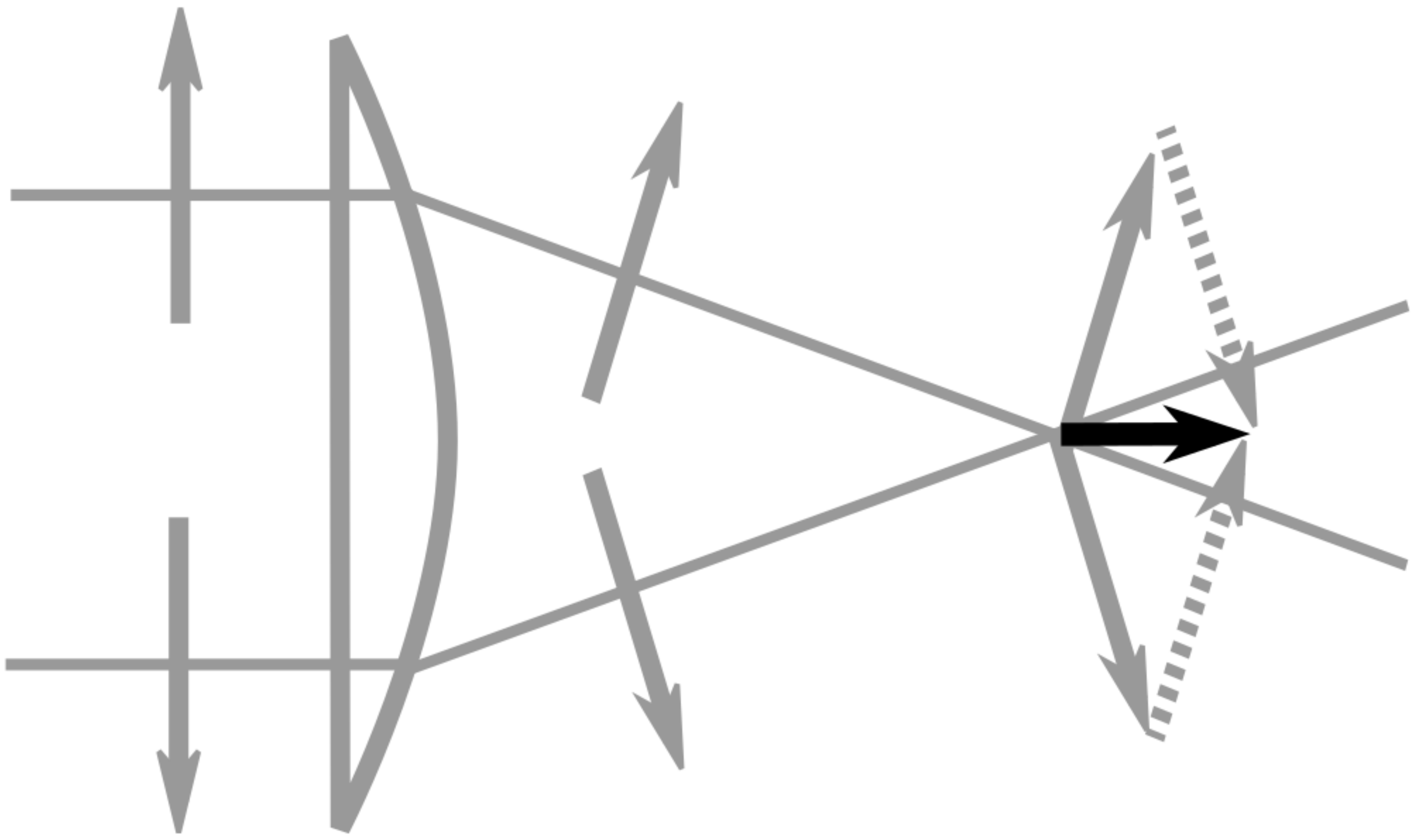
- Part 4 -

Beyond paraxial beams: strong focusing

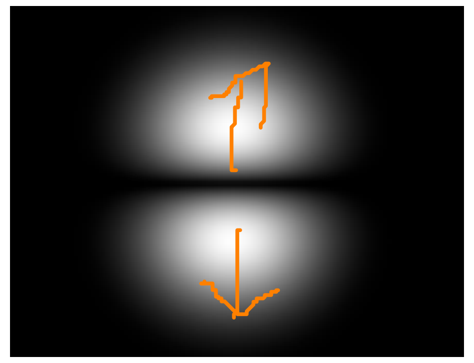
Stong Focusing of Beams - beyond the paraxial approximation

Appearence of longitudinal components due to focusing



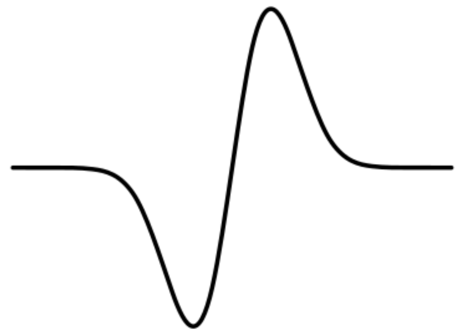
Example, HG beam with
linear polarization

$\mathrm{HG}_{01}(x,y)$



The polarization, field vector is opposite
on each lobe, due to the HG function.

$\mathrm{HG}_{01}(y)$



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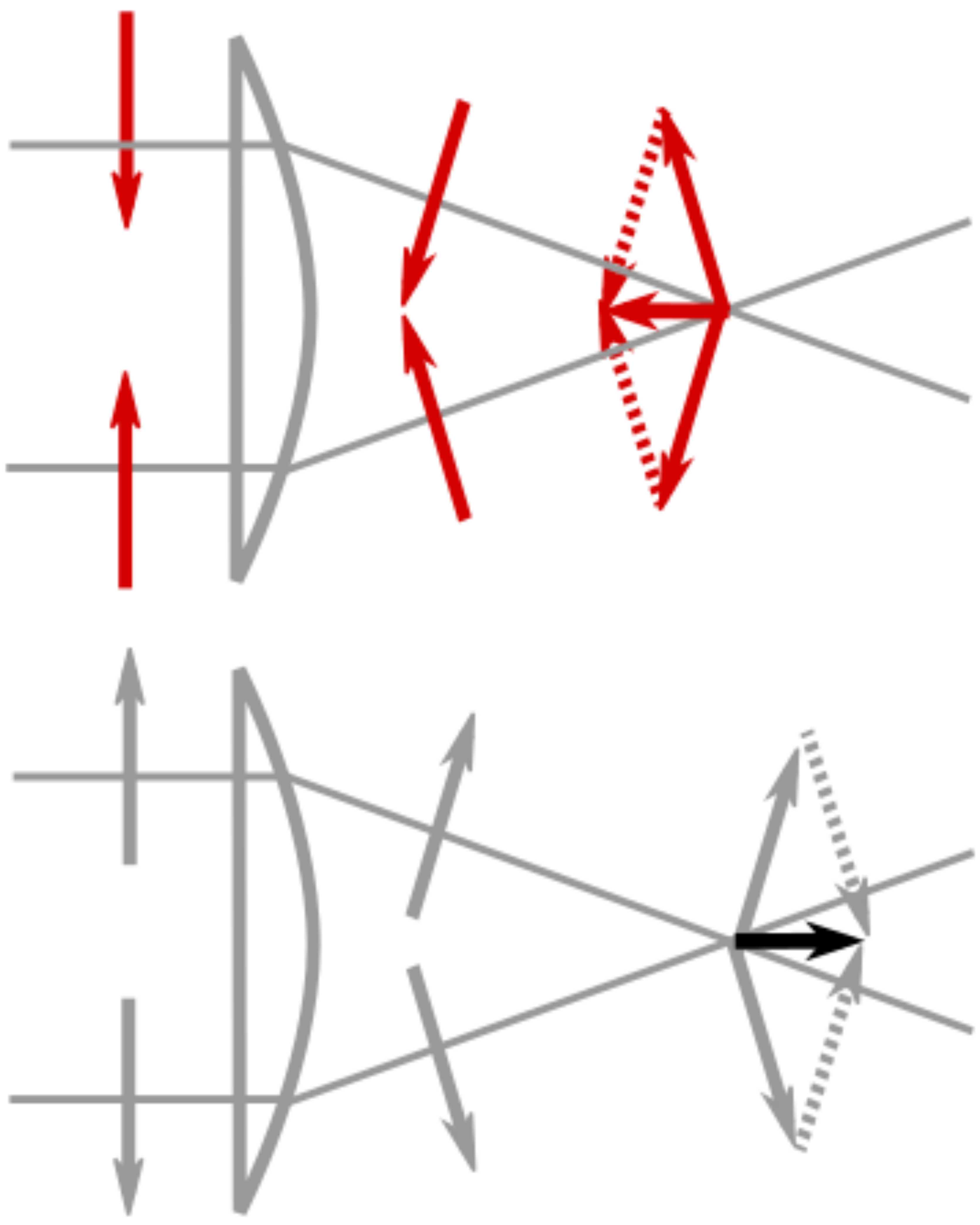
Stong Focusing of Beams - beyond the paraxial approximation



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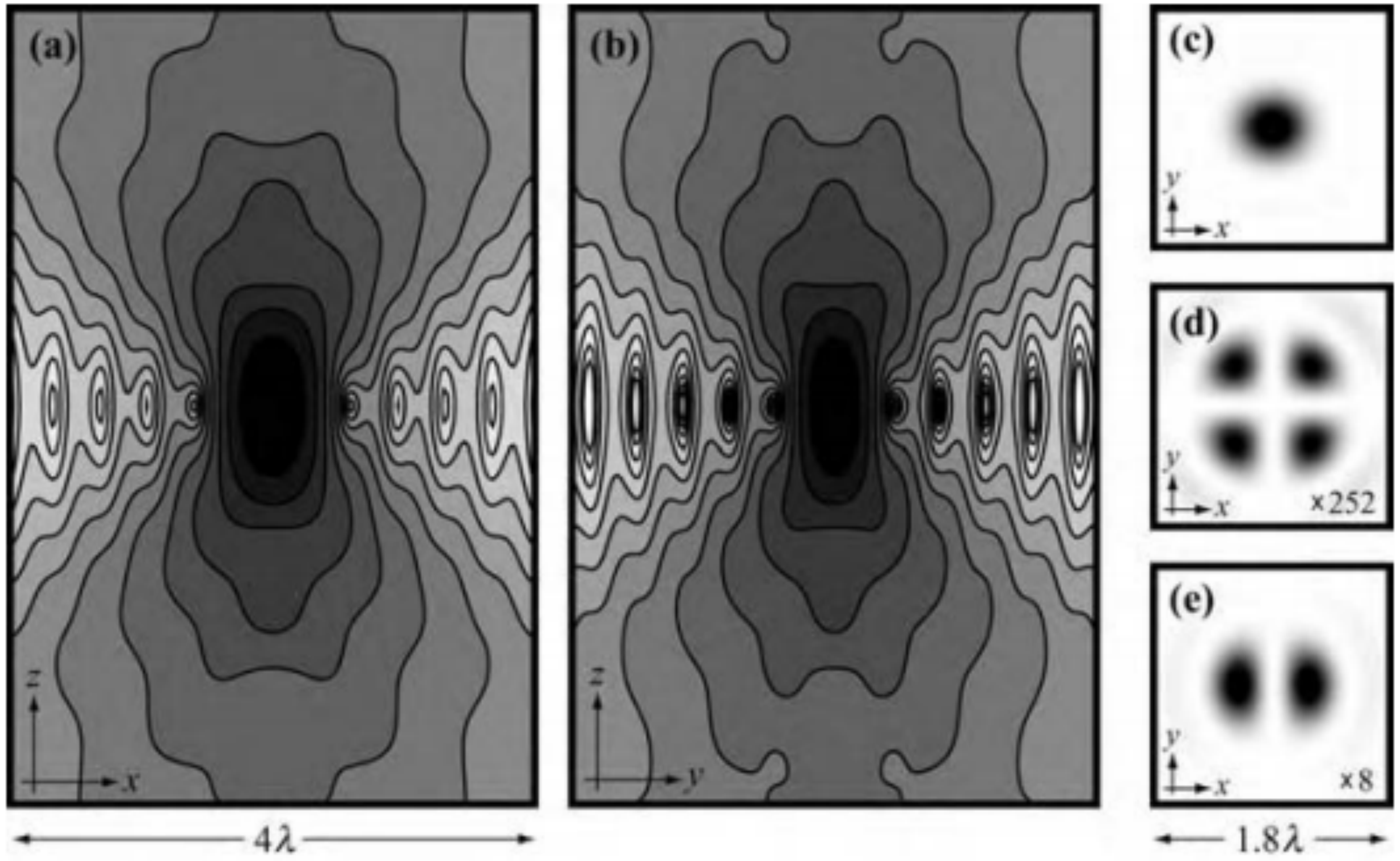
Stong Focusing of Beams - beyond the paraxial approximation

Focusing of a Gaussian, linearly-polarized beam.

Ref: Novotni, principles of nano optics.



x polarization component (original)

y polarization component (opposite)

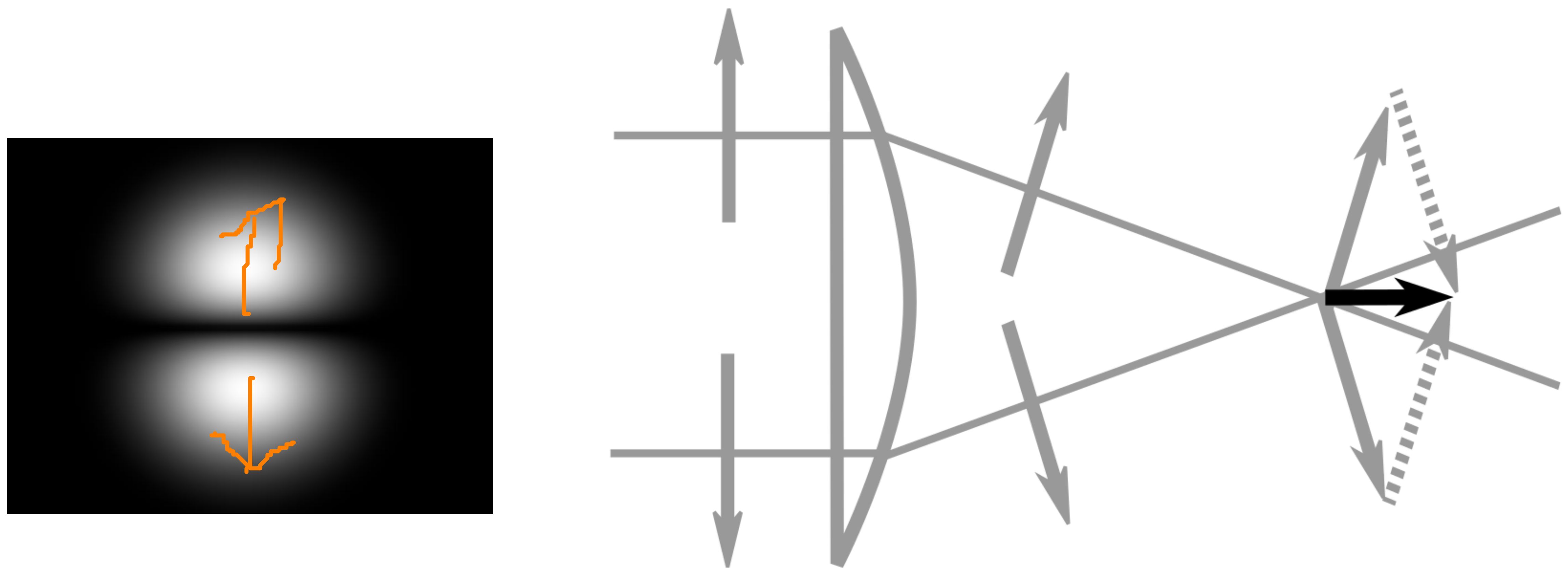
z polarization component (longitudinal)

Figure 3.10 (a, b) Contour plots of constant $|\mathbf{E}|^2$ in the focal region of a focused Gaussian beam (NA = 1.4, $n = 1.518$, $f_0 = 1$); (a) plane of incident polarization (x, z), (b) plane perpendicular to plane of incident polarization (y, z). A logarithmic scaling is used with a factor of 2 between adjacent contour lines. (c, d, e) show the magnitude of the individual field components $|\mathbf{E}_x|^2$, $|\mathbf{E}_y|^2$, and $|\mathbf{E}_z|^2$ in the focal plane $(z = 0)$, respectively. A linear scale is used.

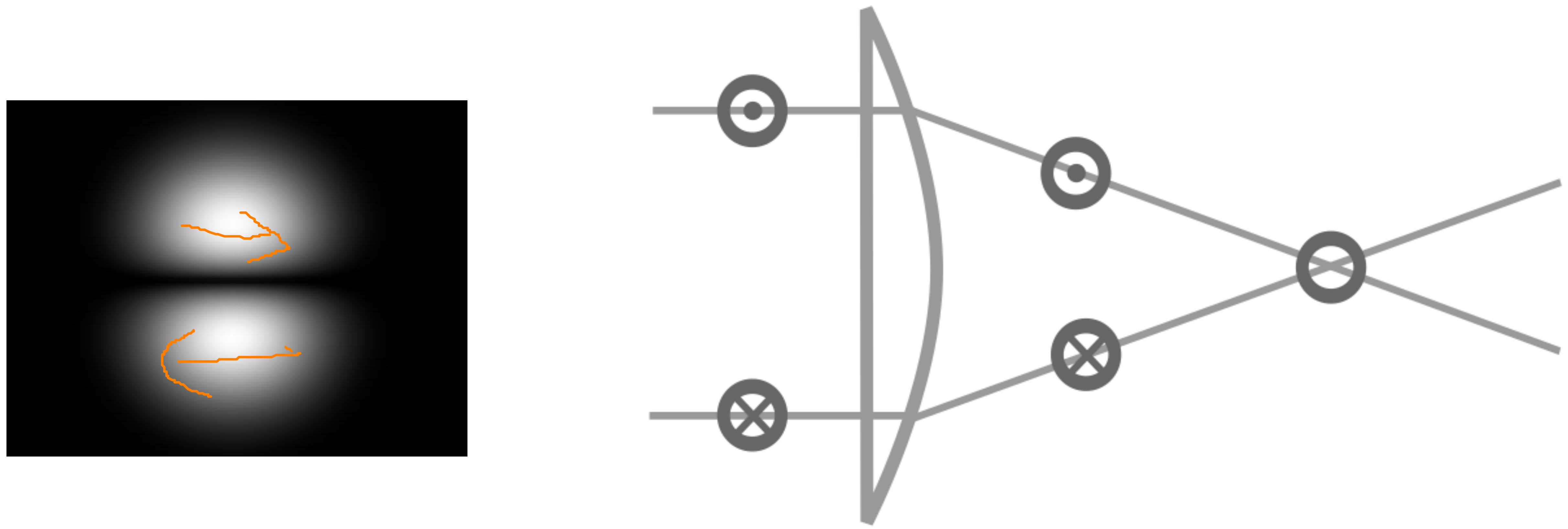
Stong Focusing of Beams - beyond the paraxial approximation

Appearence of longitudinal components due to focusing in HG beams

$\mathrm{HG}_{01}(x,y)\hat{y}$



$\mathrm{HG}_{01}(x,y)\hat{x}$



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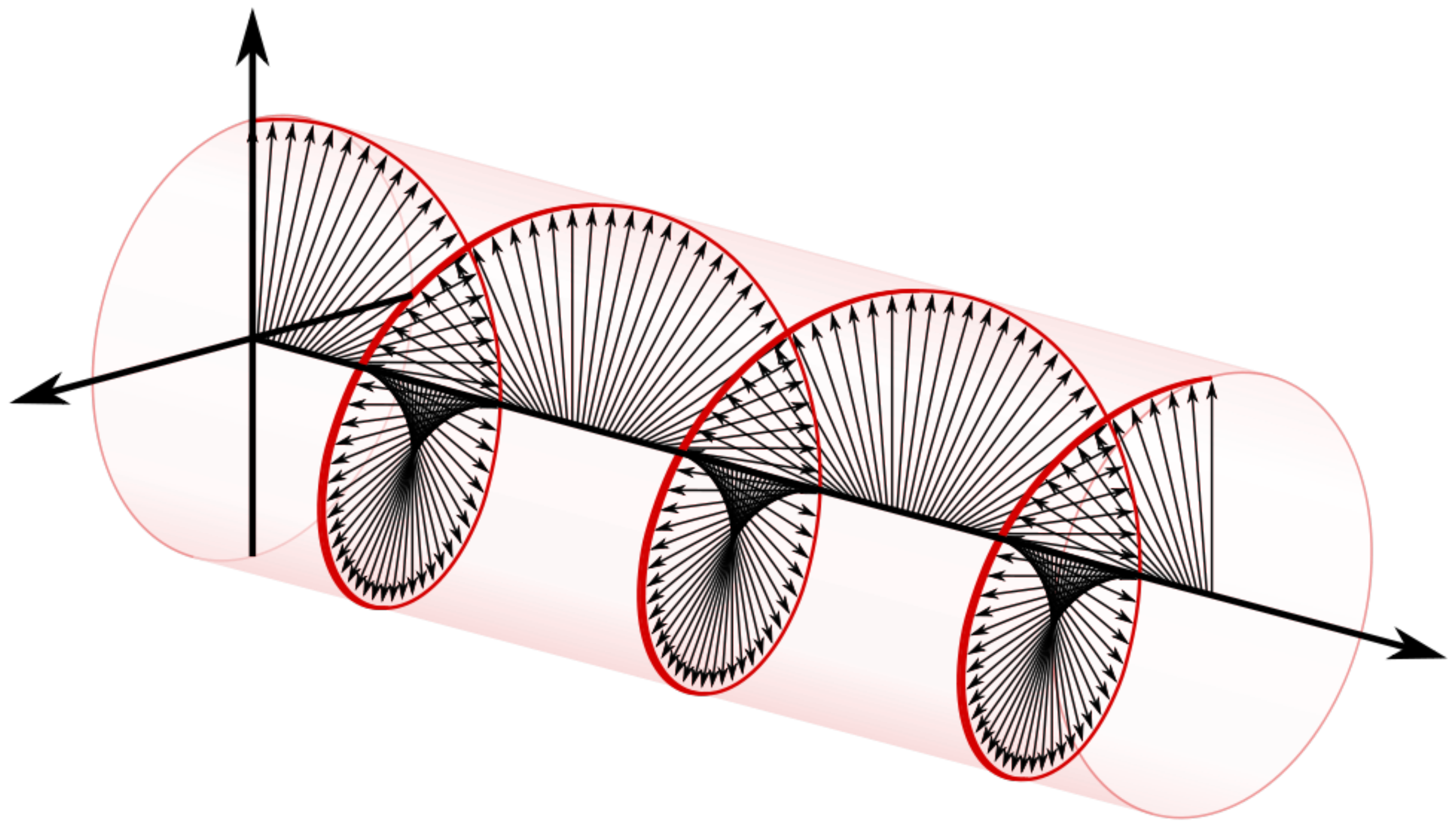
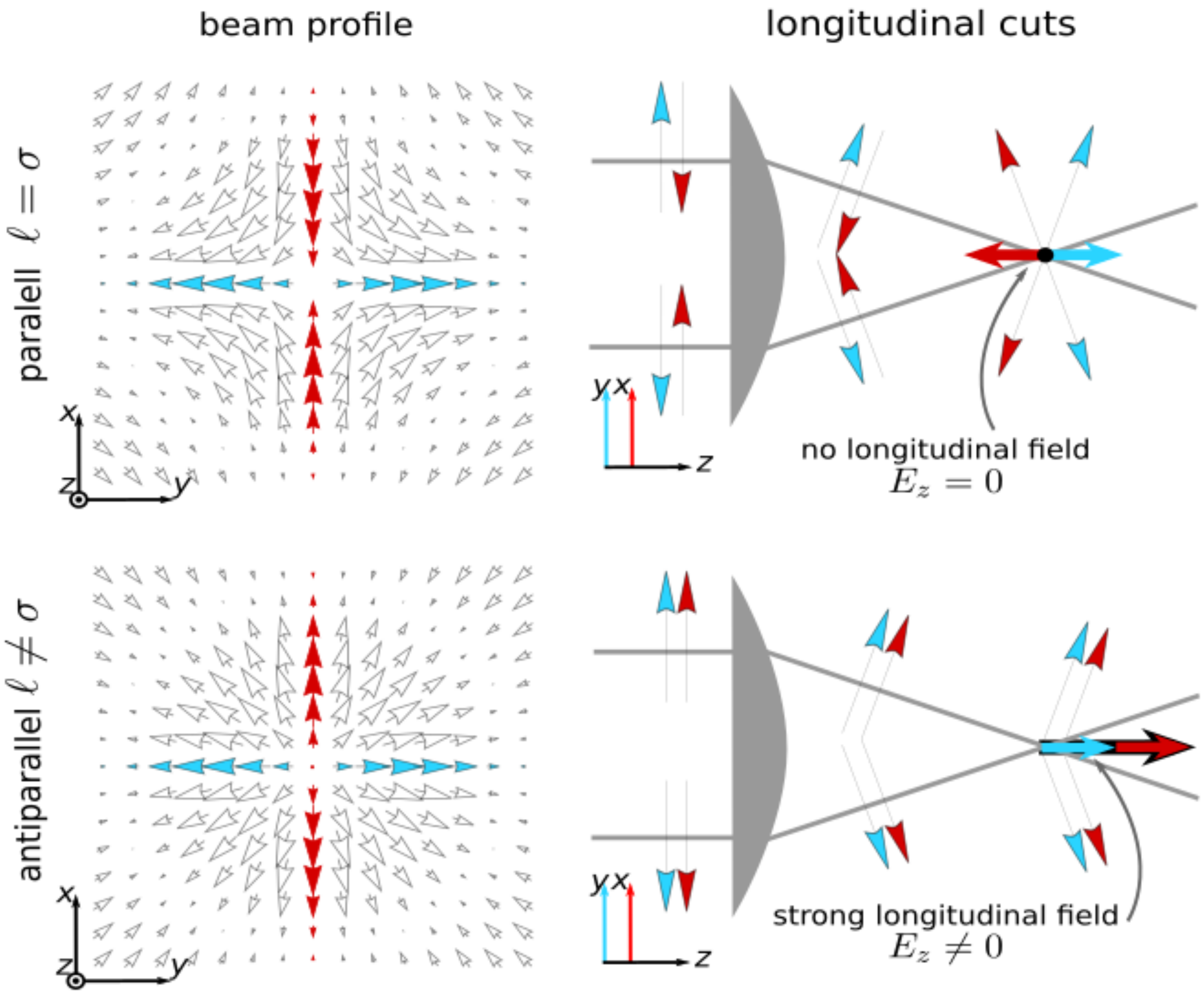
Stong Focusing of Beams - beyond the paraxial approximation

Focusing of LG beams with circular polarization





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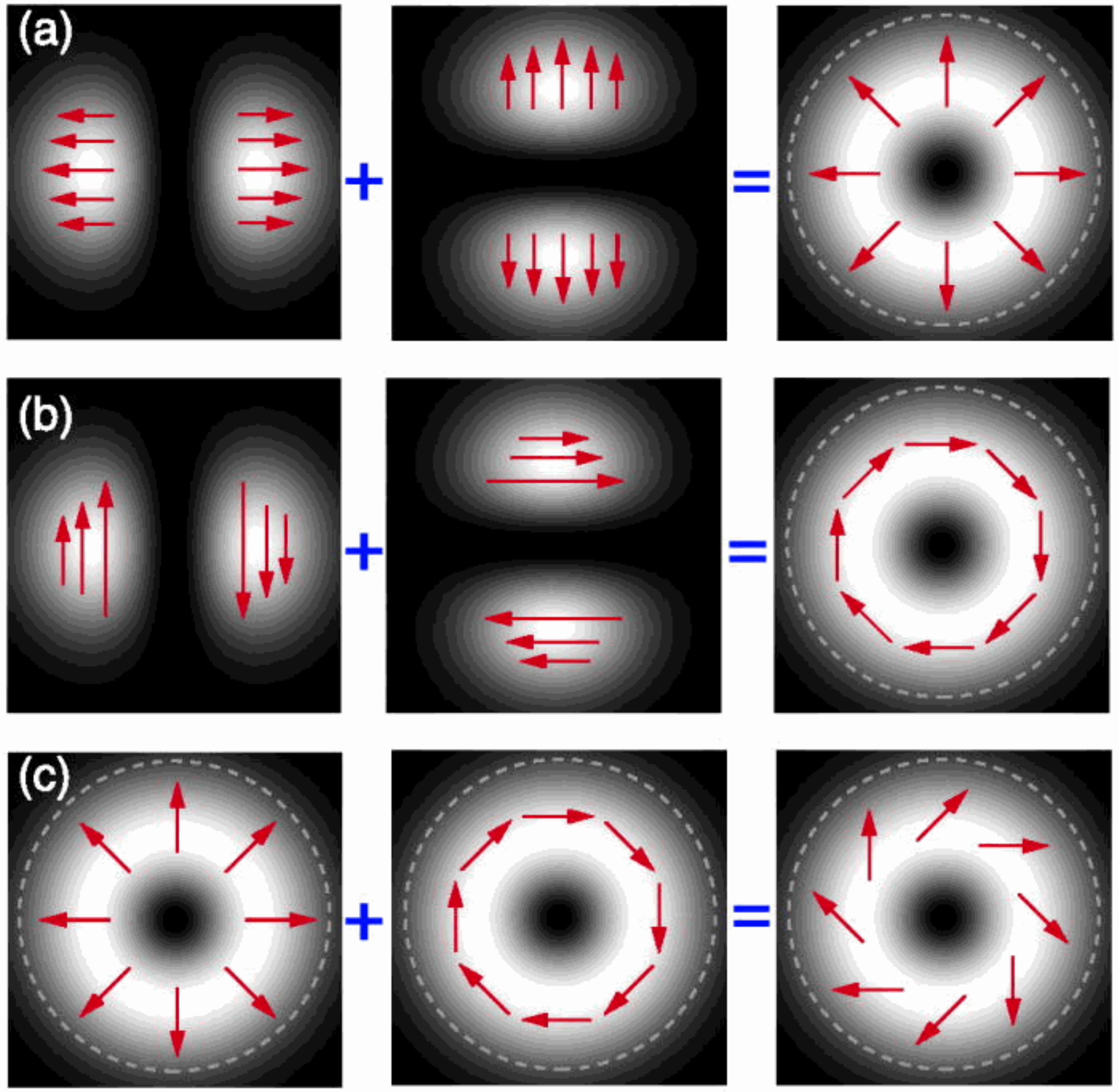
Stong Focusing of Beams - vector beams

More intricate, vector beams.

cred. Moreno & Davis

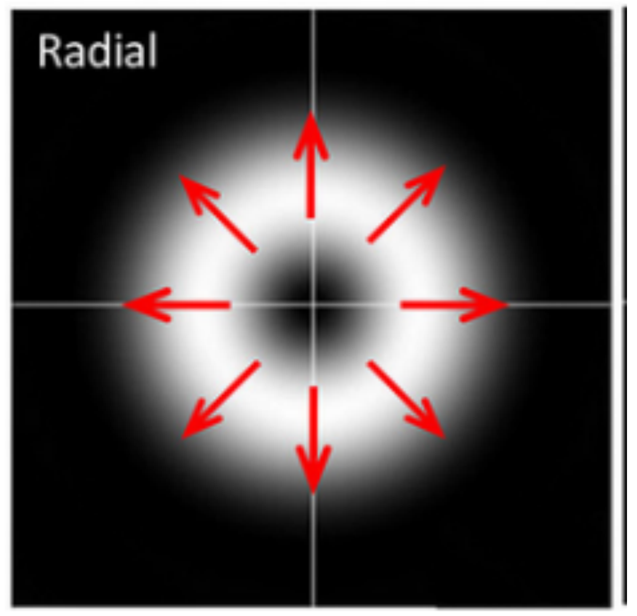
Generation of vector beams from HG beams

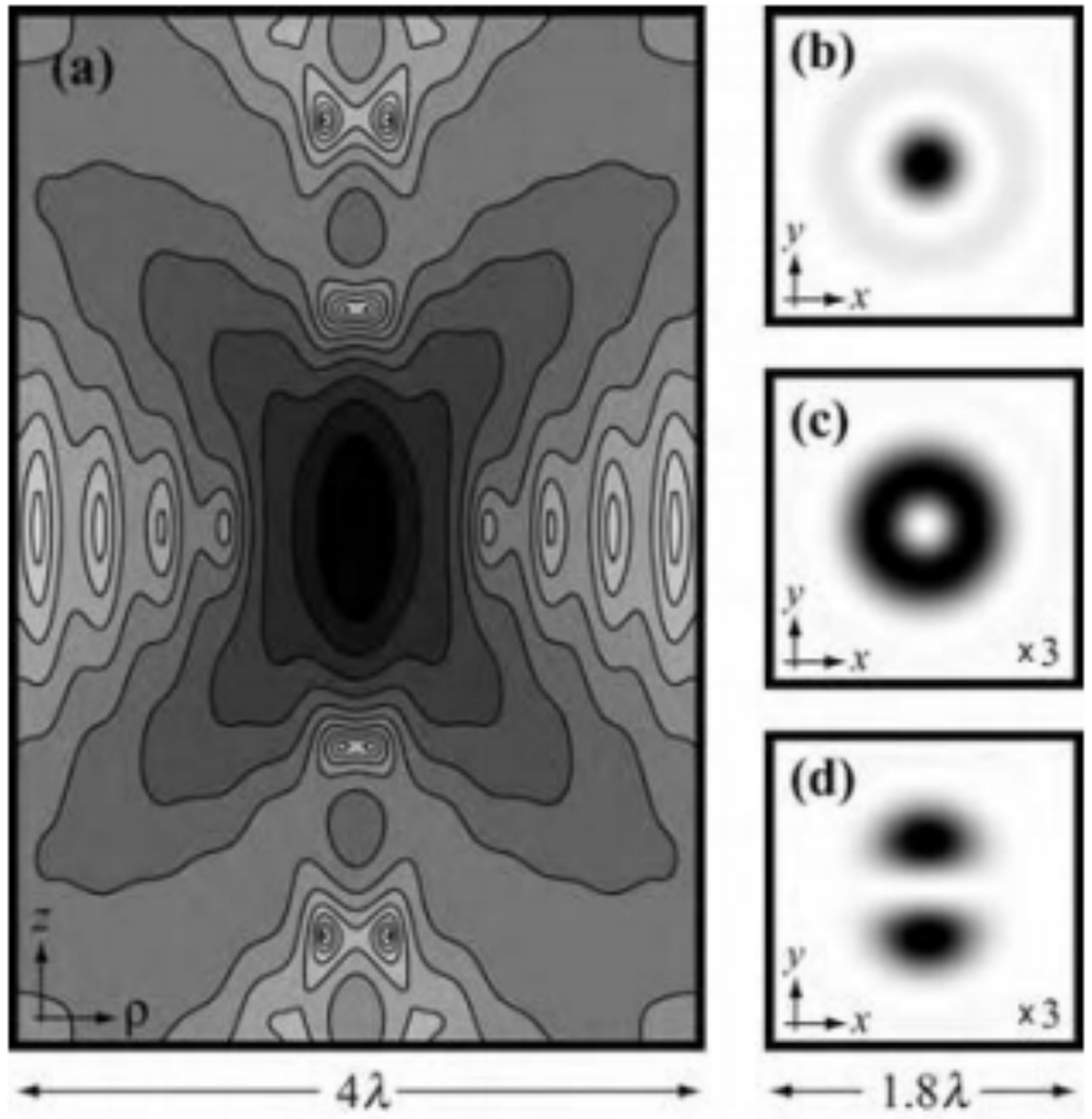


cred. Umerton et.al.

Stong Focusing of Beams - vector beams

Focusing of a radially polarized beam





z polarization component (longitudinal)

radial polarization component (original)

y polarization component (original)

Figure 3.13 (a) Contour plots of constant $|\mathbf{E}|^2$ in the focal region of a focused radially polarized doughnut mode (NA = 1.4, n = 1.518, f_0 = 1) in the (ρ, z) plane. The intensity is rotationally symmetric with respect to the z-axis. A logarithmic scaling is used with a factor of 2 between adjacent contour lines. (b, c, d) show the magnitude of the individual field components $|\mathbf{E}_z|^2$, $|\mathbf{E}_\rho|^2$, and $|\mathbf{E}_y|^2$ in the focal plane (z = 0), respectively. A linear scale is used.

Stong Focusing of Beams - vector beams

VOLUME 91, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2003

Sharper Focus for a Radially Polarized Light Beam

R. Dorn, S. Quabis,* and G. Leuchs

Max-Planck-Research-Group for Optics, Information and Photonics, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

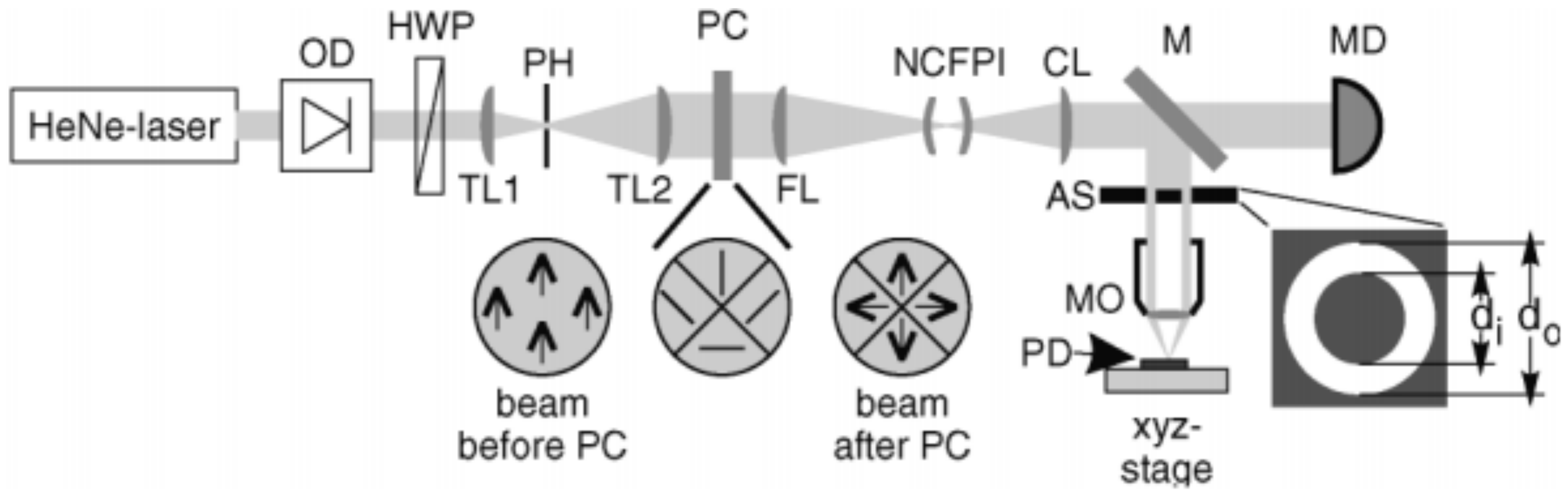
(Received 19 May 2003; published 2 December 2003)

We experimentally demonstrate for the first time that a radially polarized field can be focused to a spot size significantly smaller [$0.16(1)\lambda^2$] than for linear polarization ($0.26\lambda^2$). The effect of the vector properties of light is shown by a comparison of the focal intensity distribution for radially and azimuthally polarized input fields. For strong focusing, a radially polarized field leads to a longitudinal electric field component at the focus which is sharp and centered at the optical axis. The relative contribution of this component is enhanced by using an annular aperture.

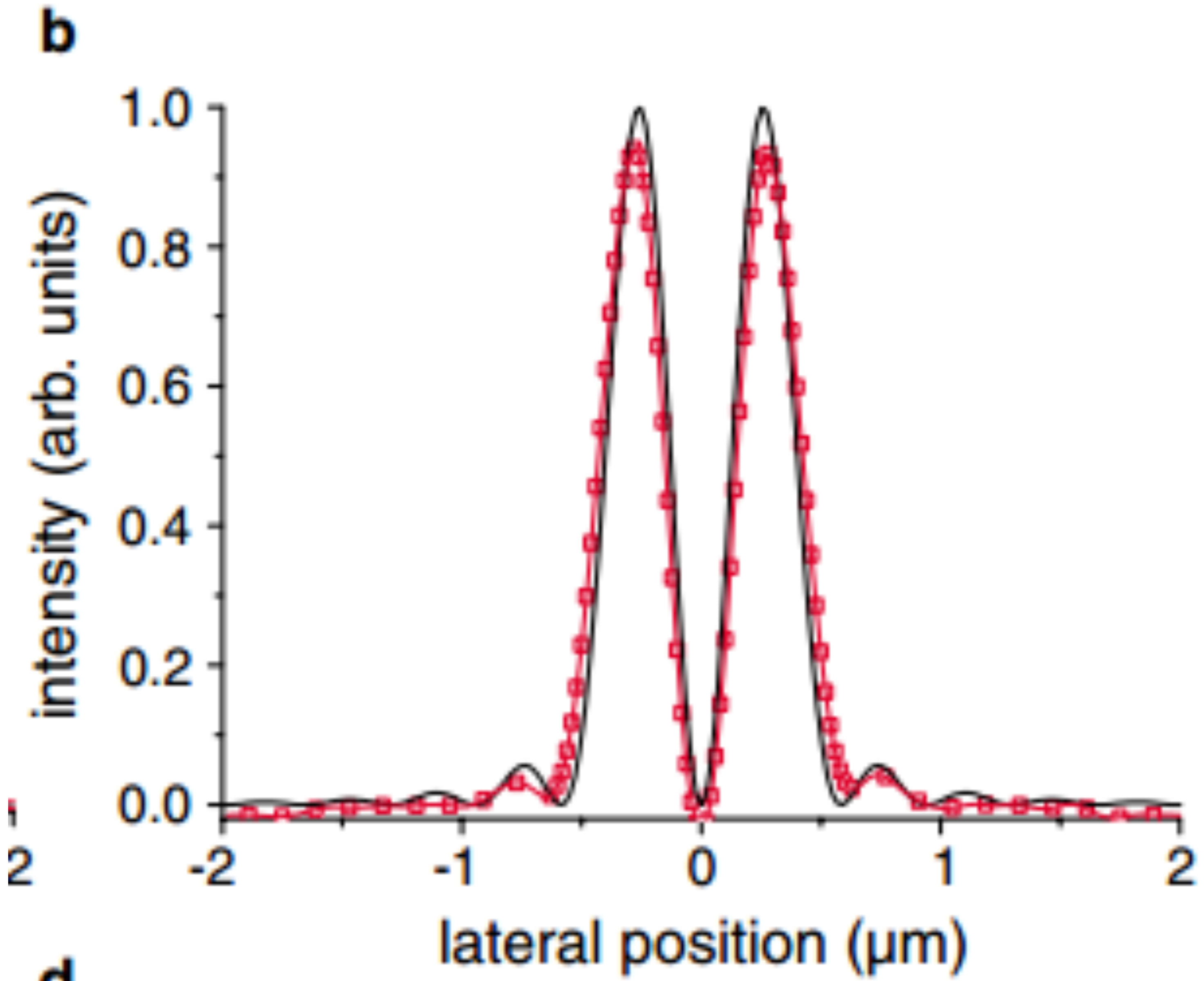
Stong Focusing of Beams - vector beams

Sharper Focus for a Radially Polarized Light Beam

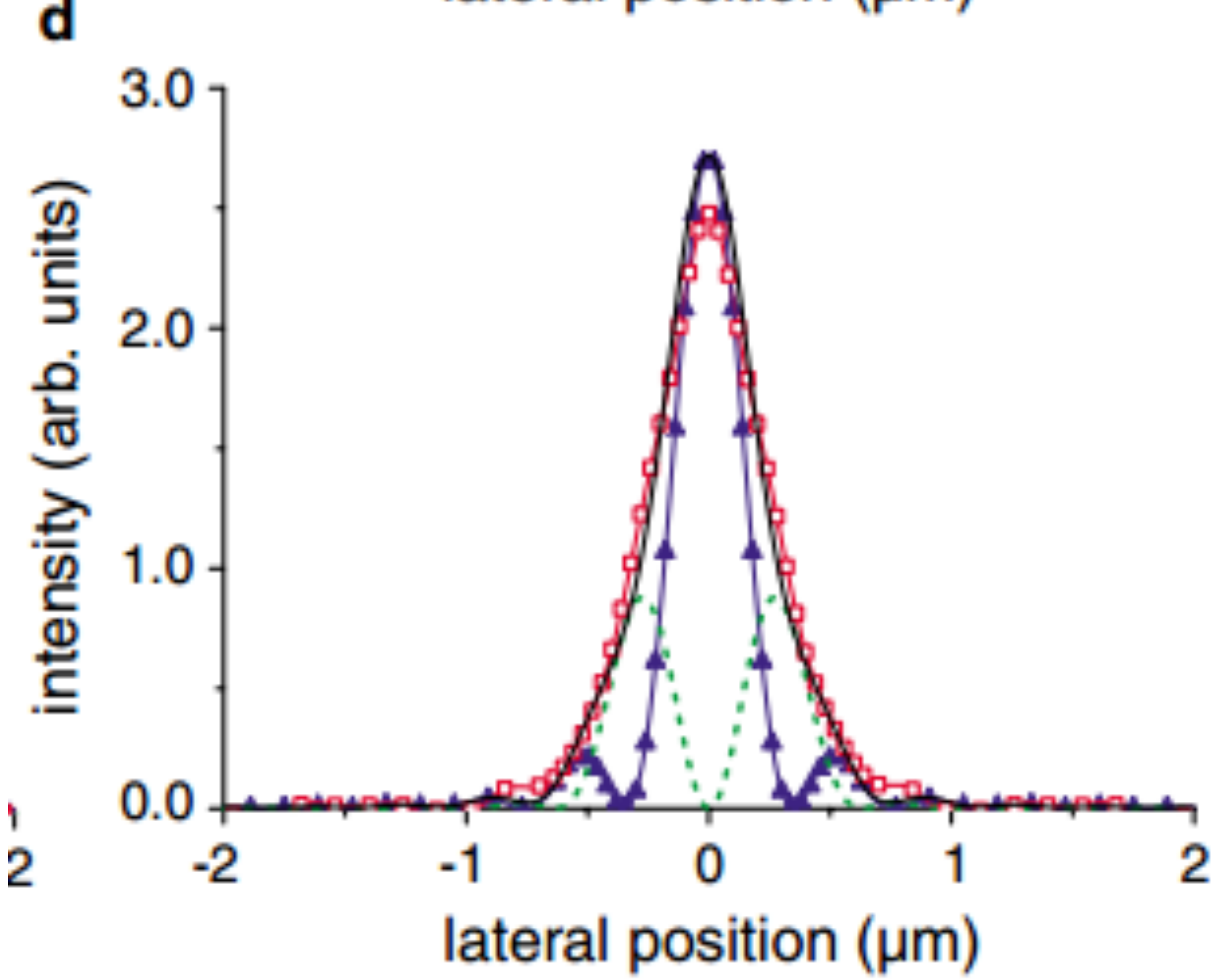
R. Dorn, S. Quabis,* and G. Leuchs



Azimuthal



Radial

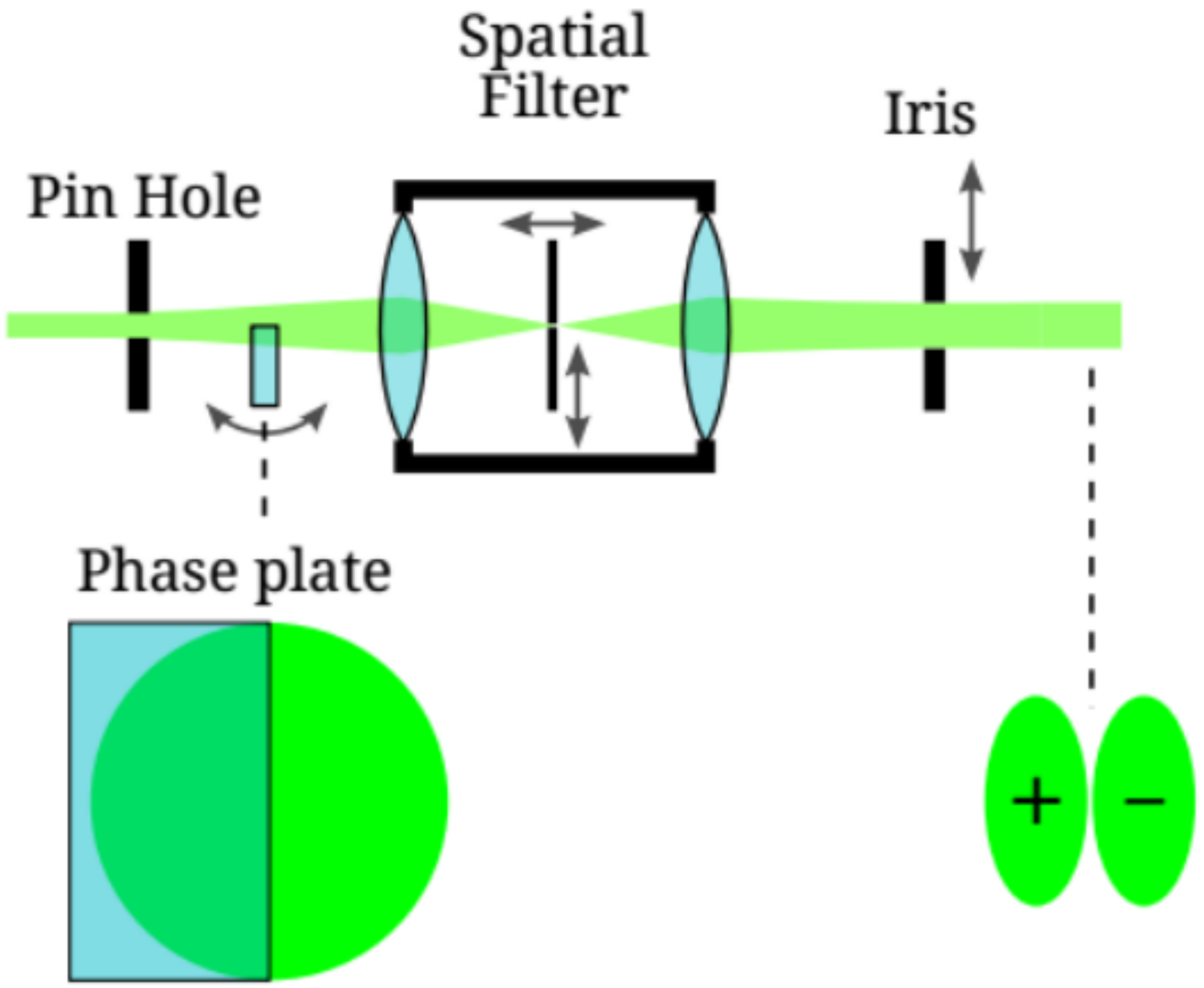


- Part 5 -

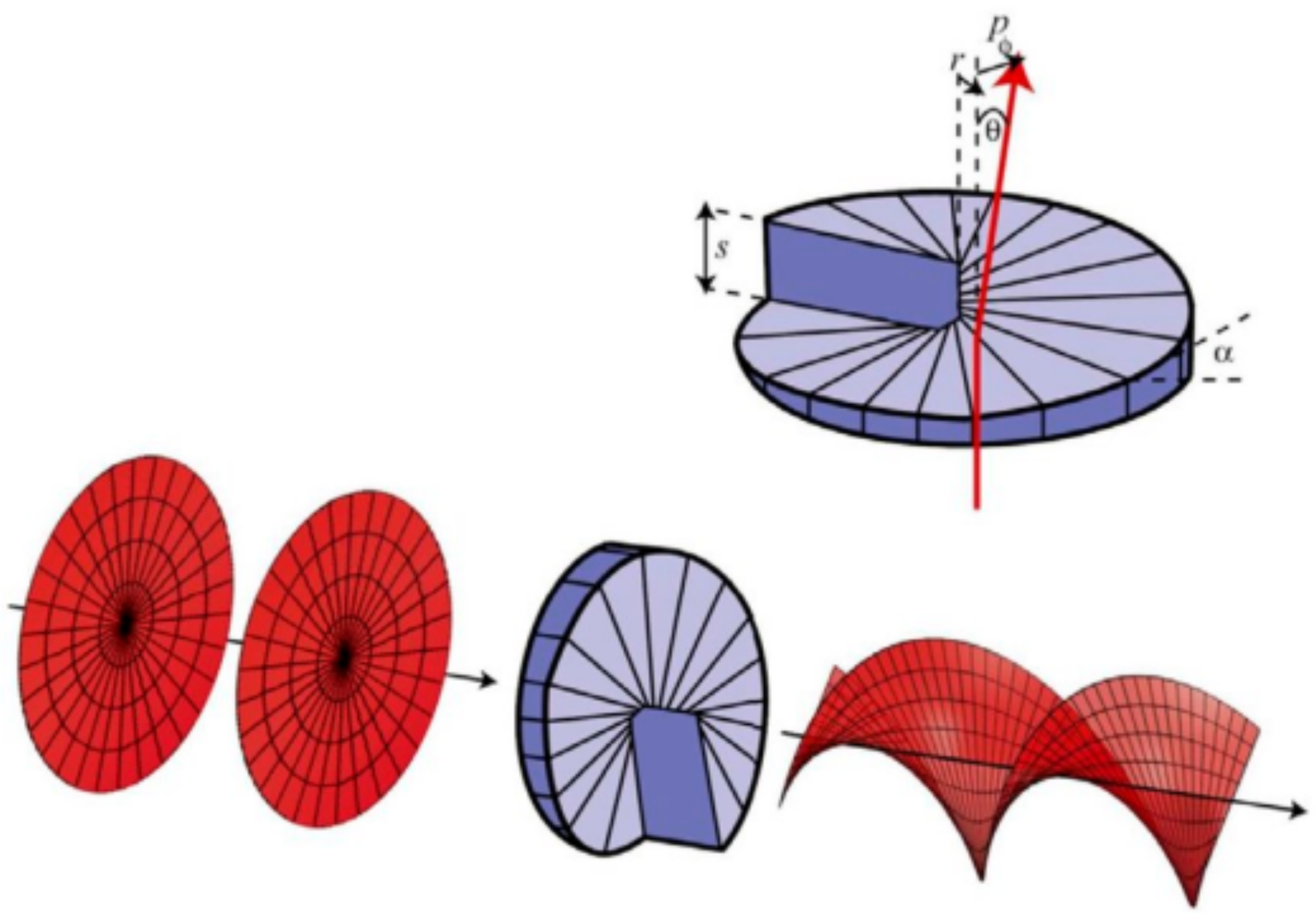
Generation of structured beams

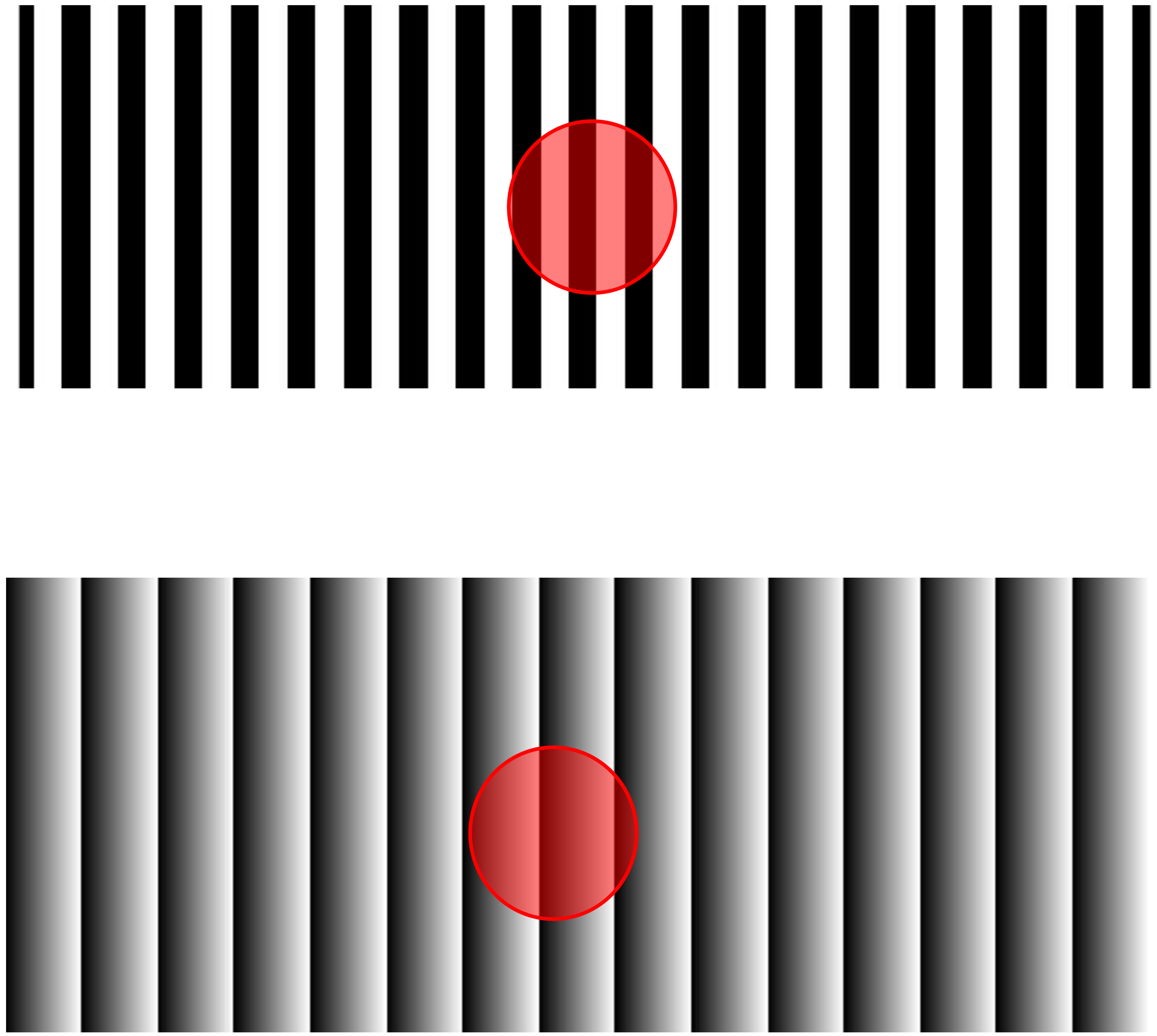
Phase and amplitude modulation
Holography
Waveform matching holography, Carpenter

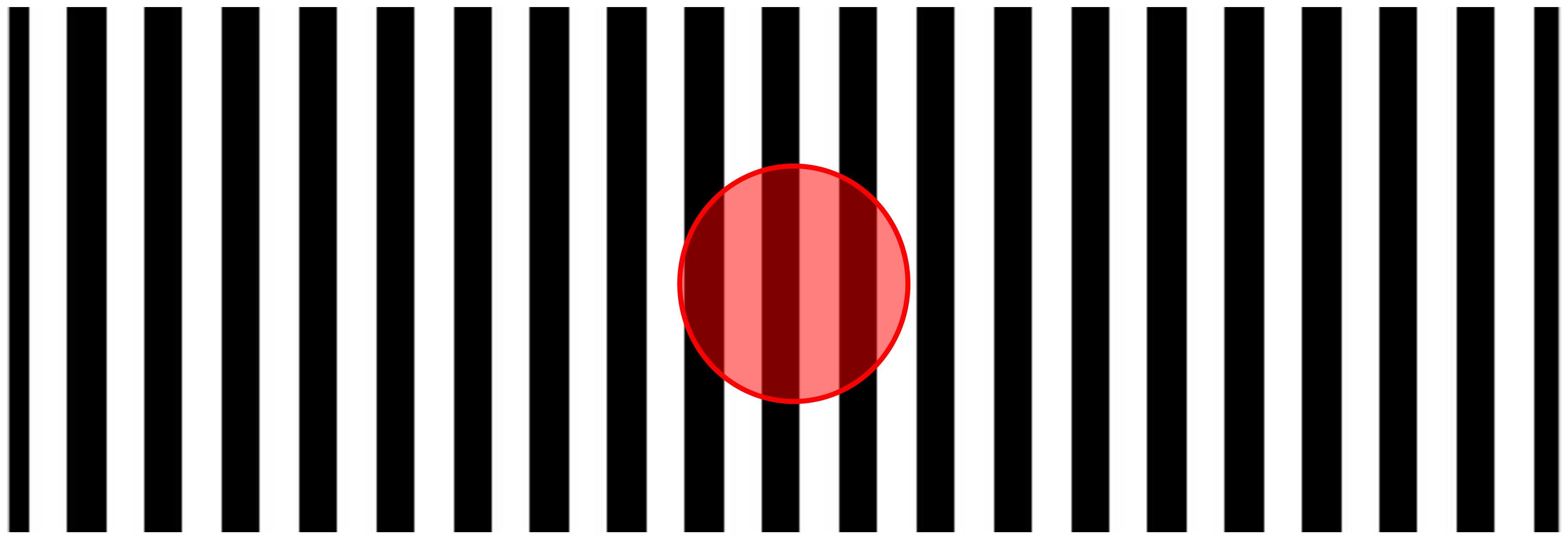
Cartesian phase plates

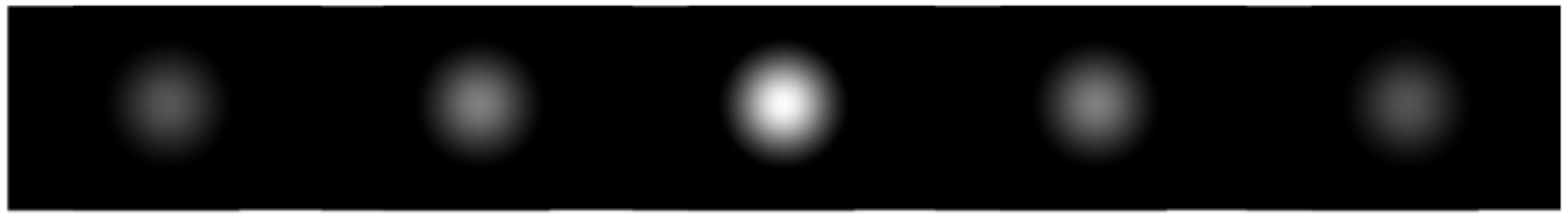


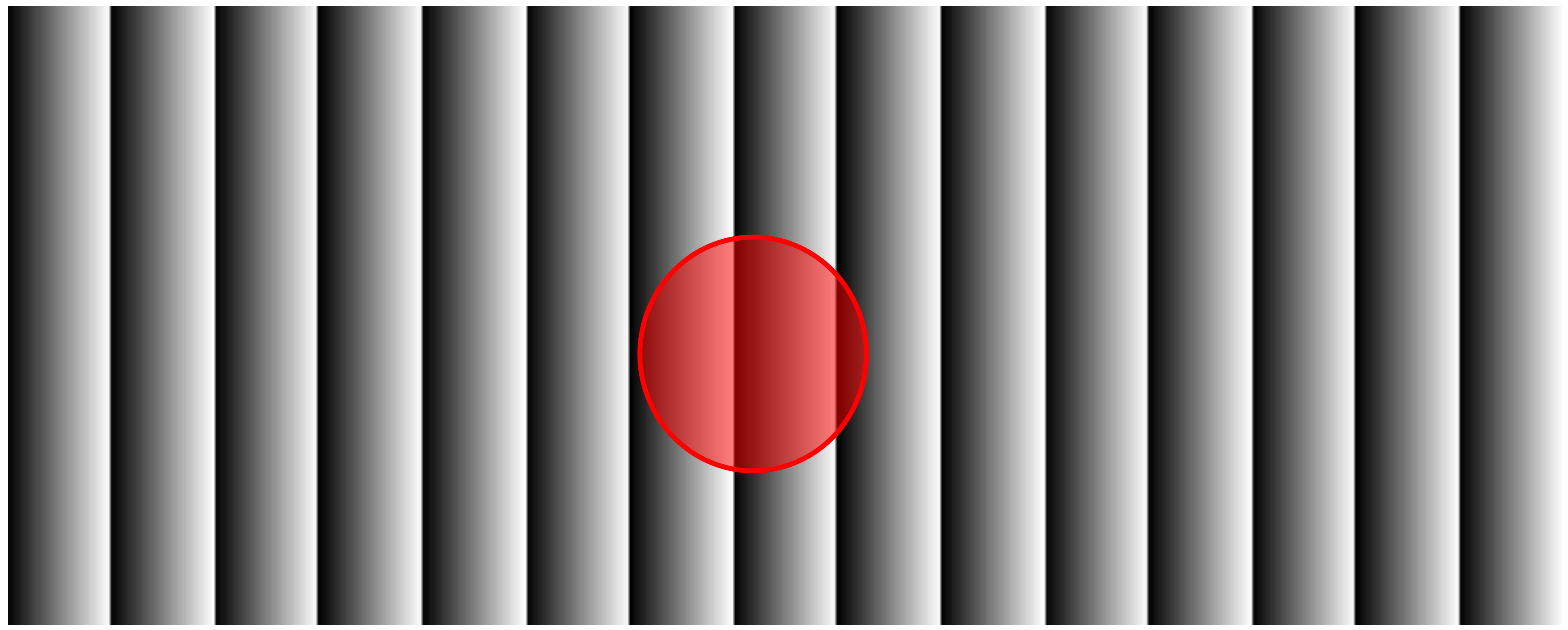
Spiral phase plates

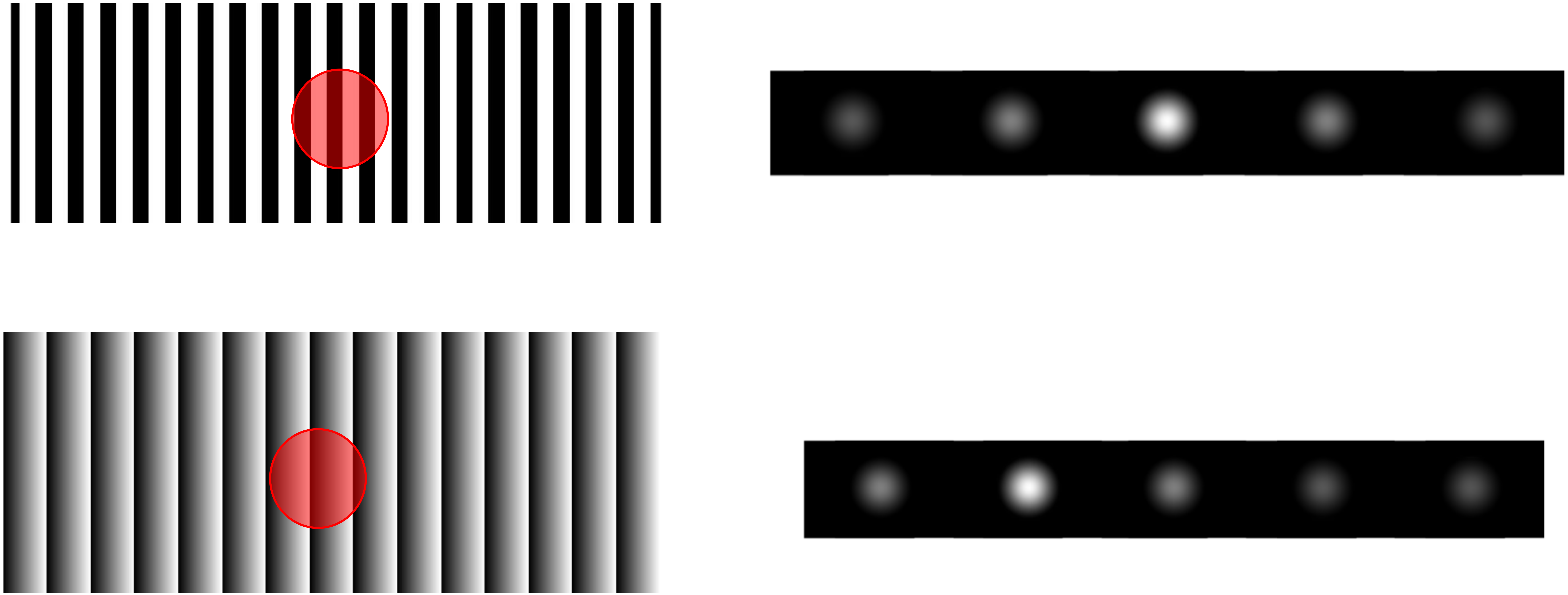


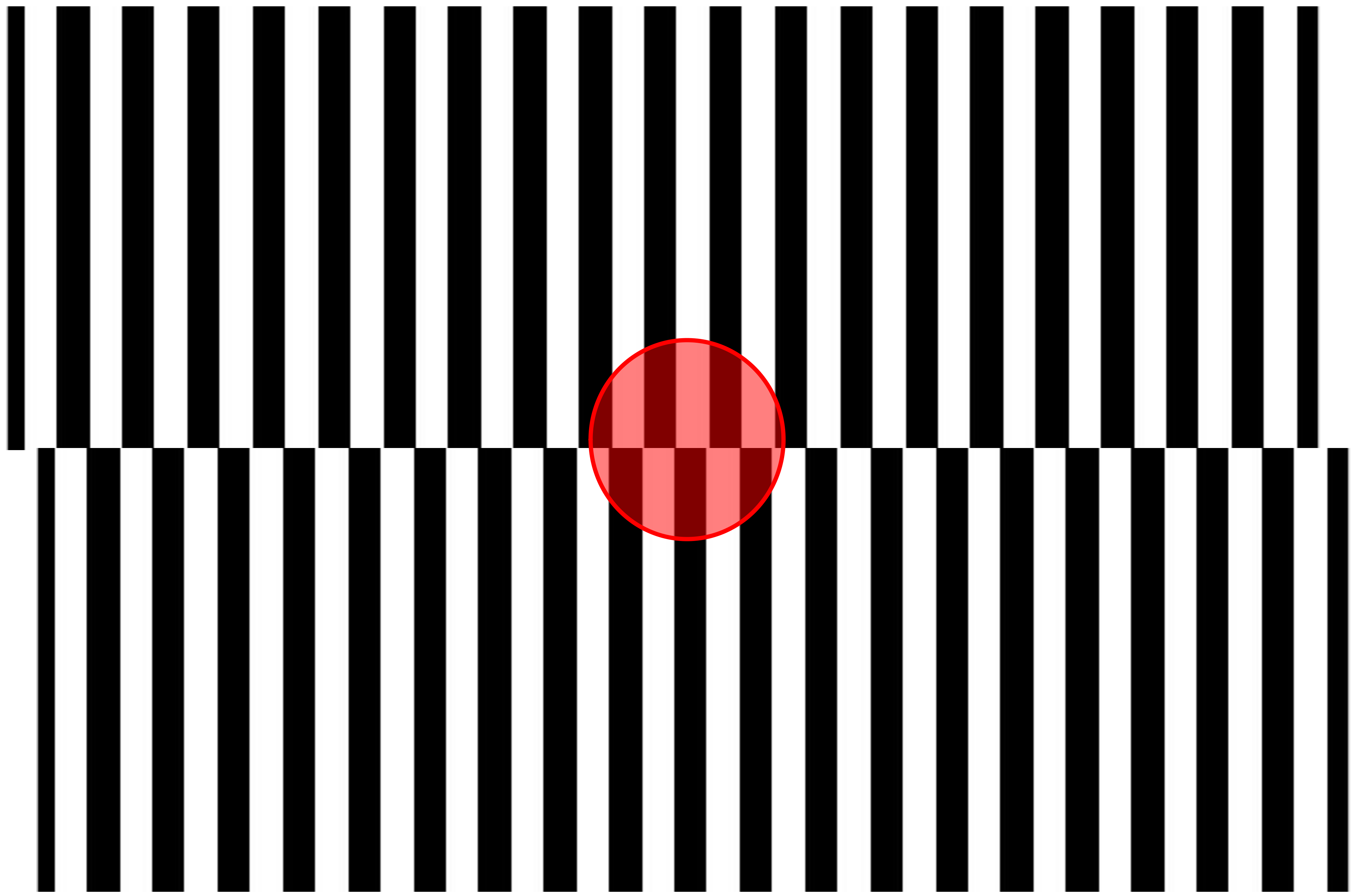


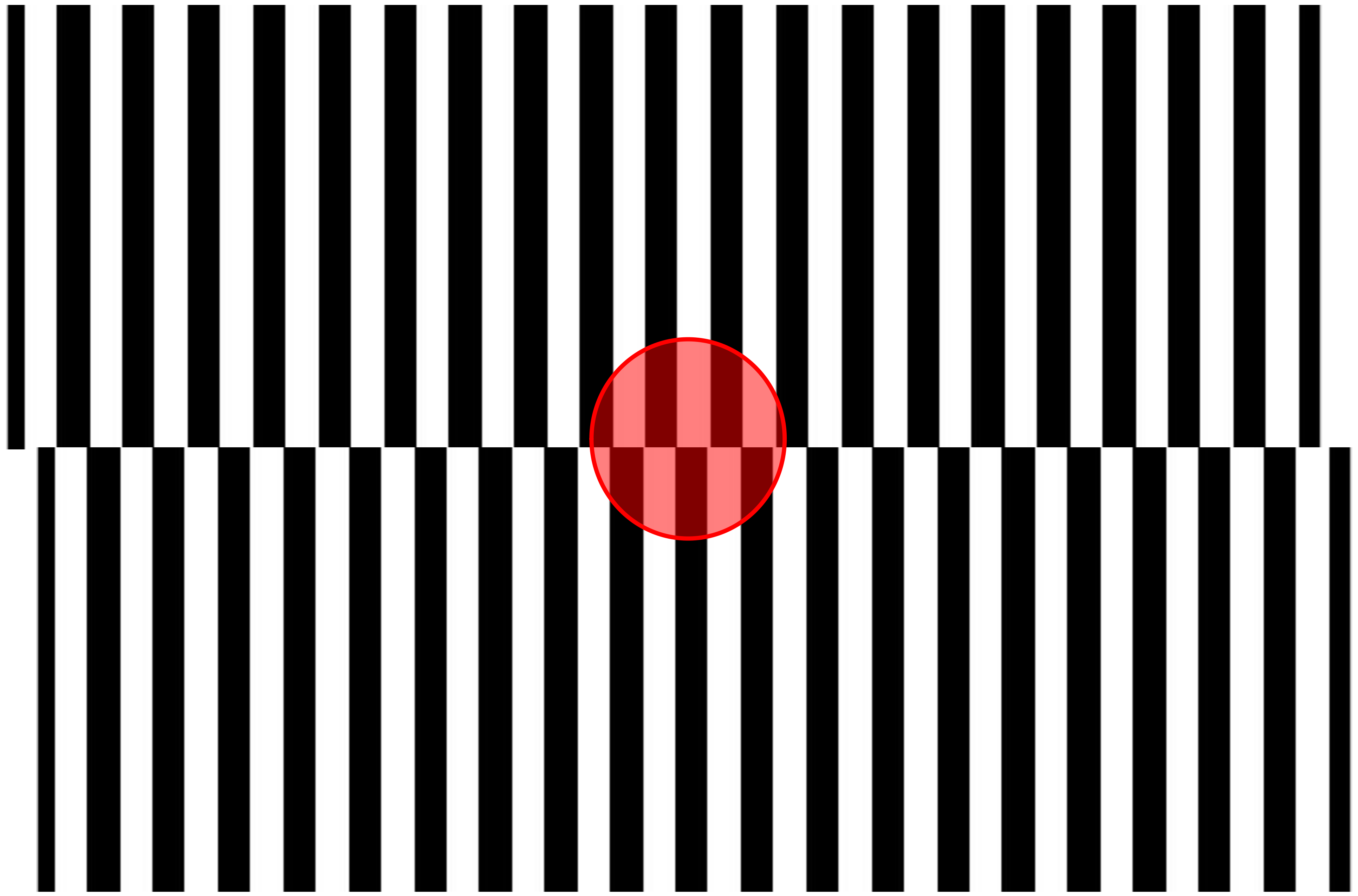


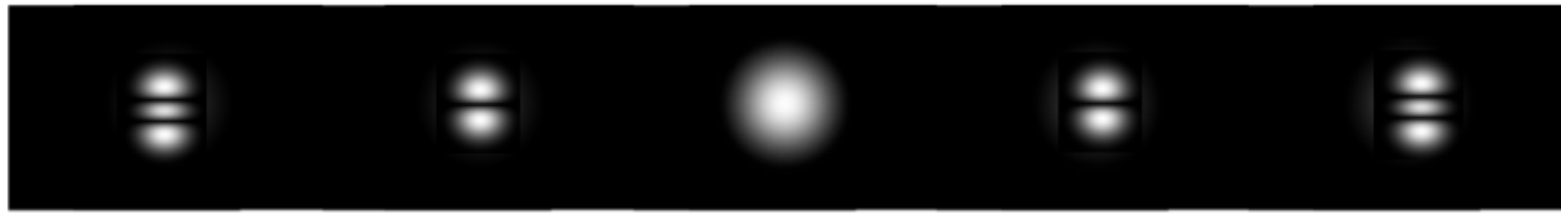


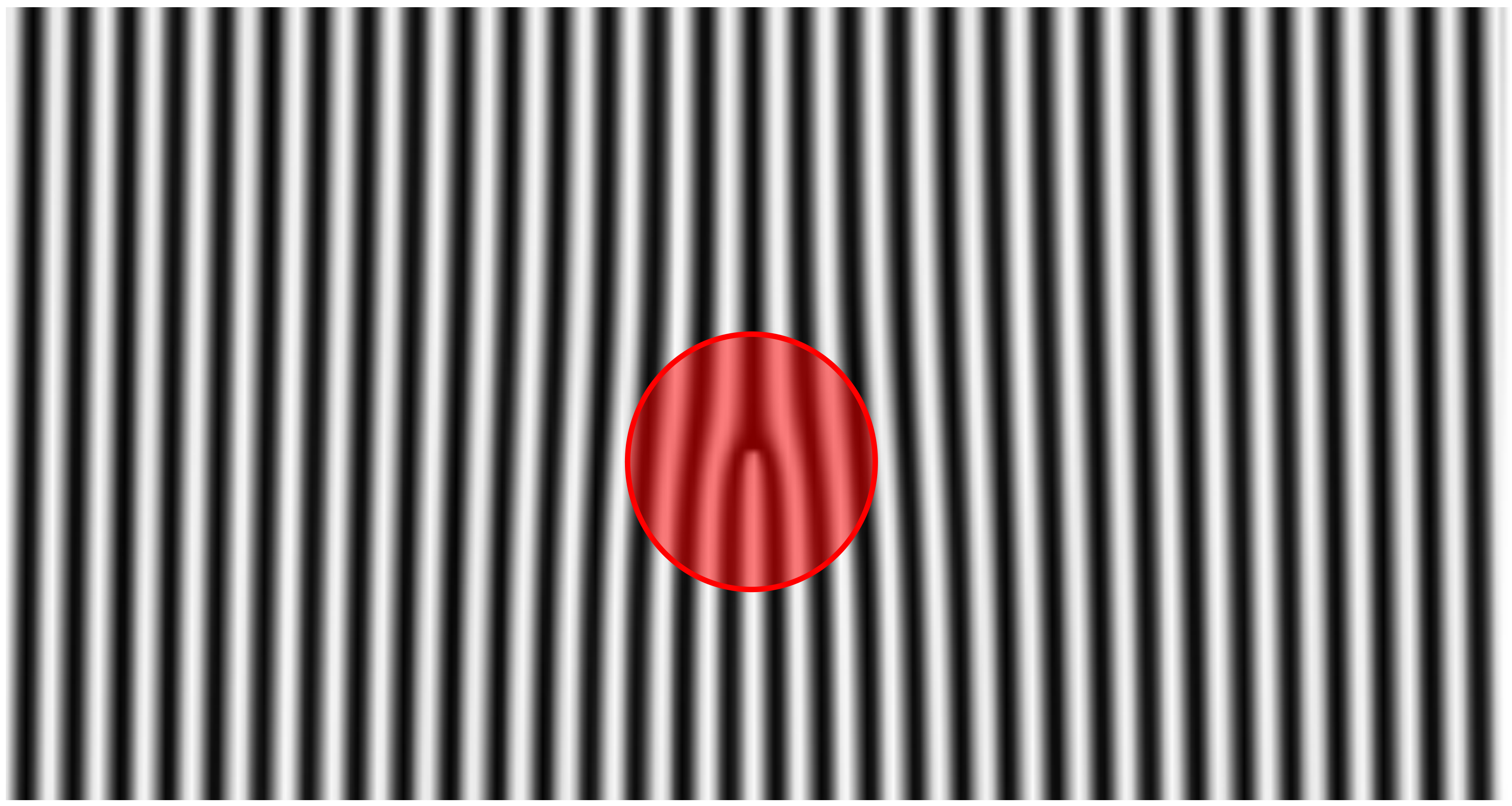


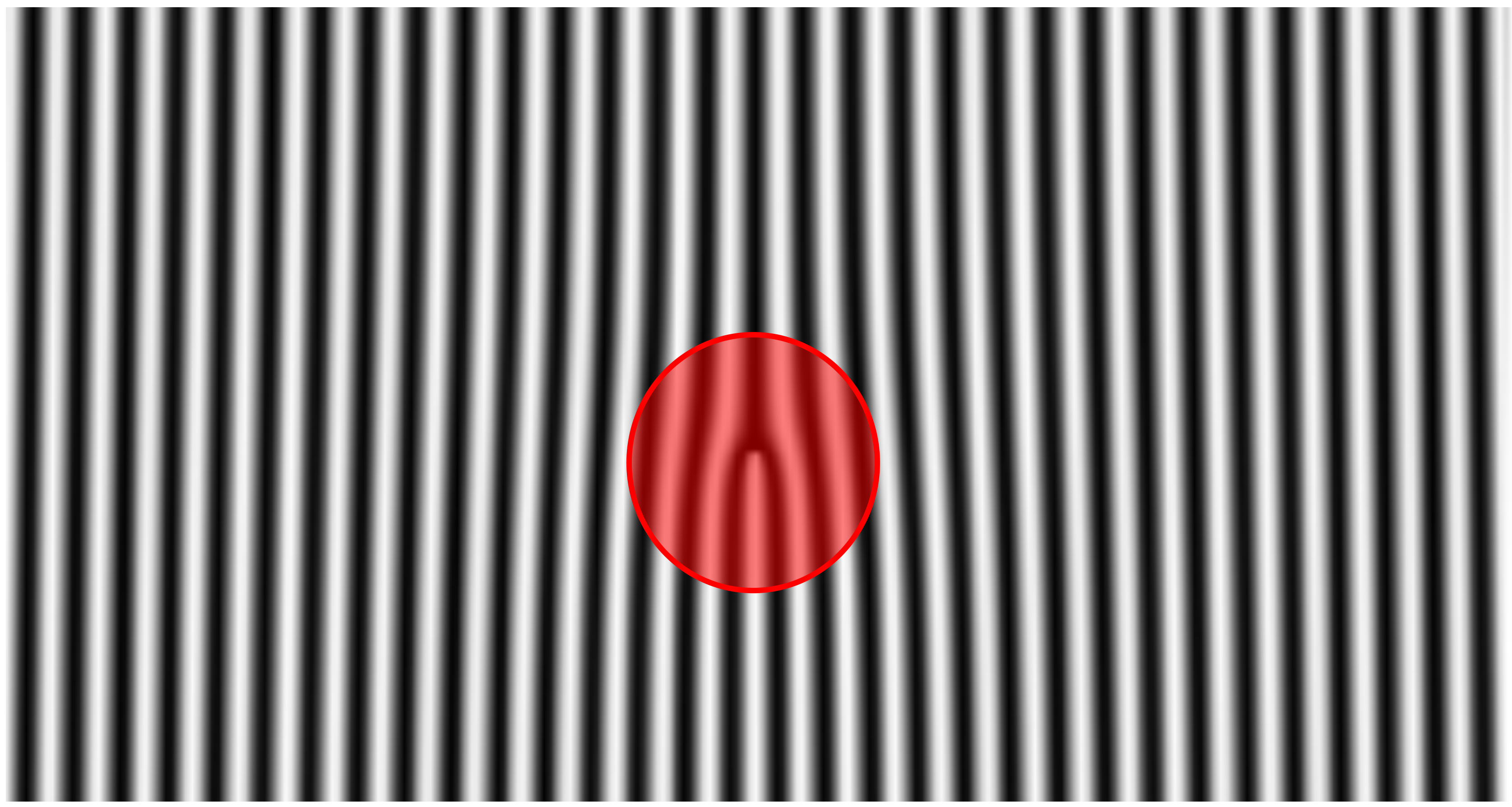


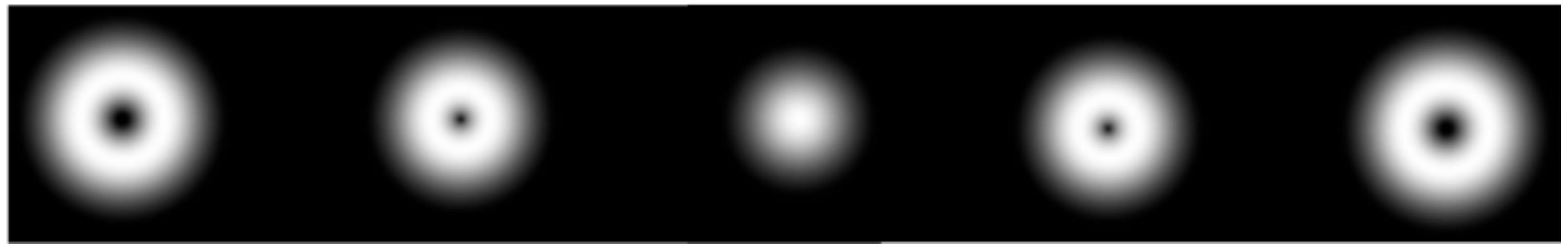






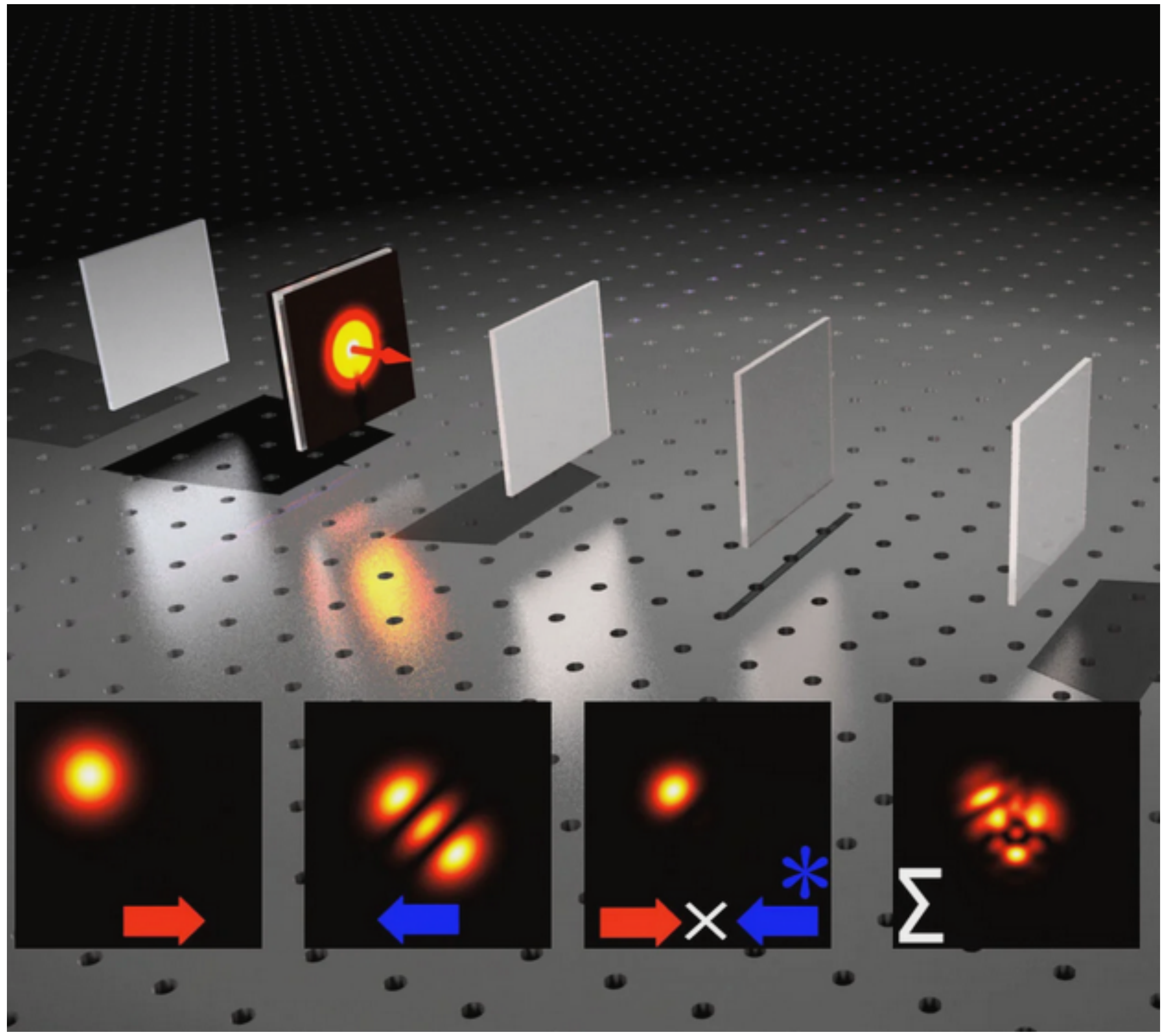




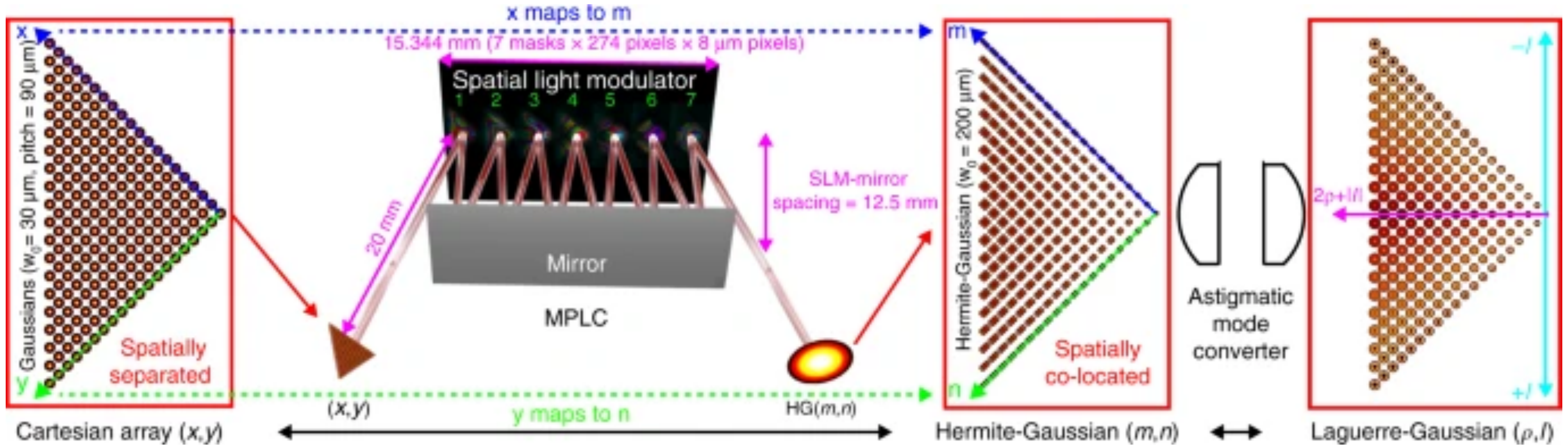


A small discussion on phase/ amplitude plates and beam conversions.

The Holography Principle and Waveform Matching



check Joel Carpenter's work.



- Part X - Exercises

- Calculate the Gaussian solution to the paraxial Helmolz equation from the sperical wave ansatz.
    - Show that the Hermite- and Laguerre-Gaussian solutions are also solutions of the same equation.

- Derive the formula for the total angular momentum of a Laguerre Gaussian Beam.

- Calculate de hologram needed to generate a Laguerre-Gaussian beam using purely a phase plate.

Thank you for you attention.