The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1932-6

Winter College on Micro and Nano Photonics for Life Sciences

11 - 22 February 2008

Optical Trapping and structured light.
(3 lectures)

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Optical Trapping and structured light (3 lectures)

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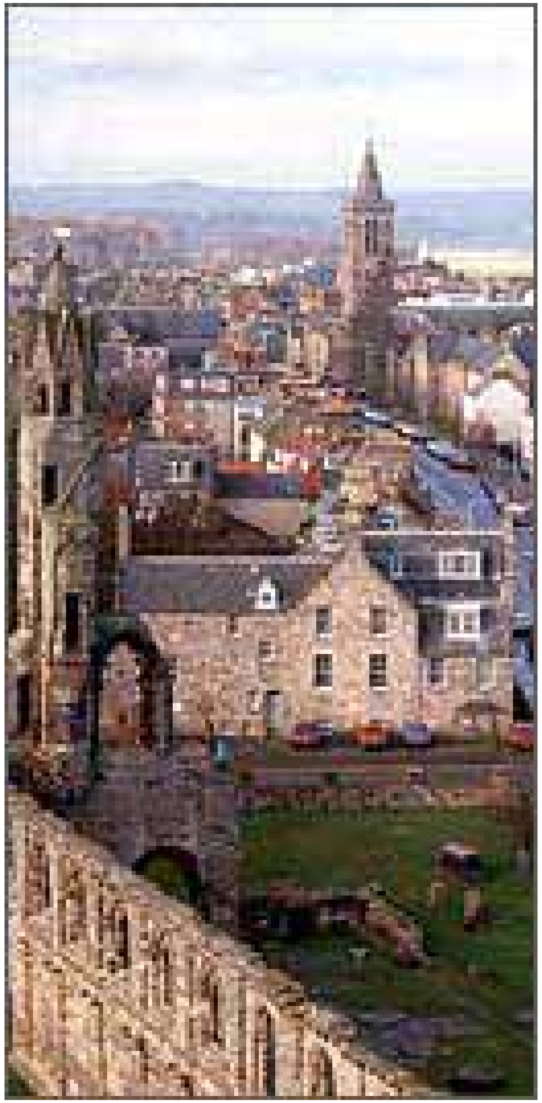
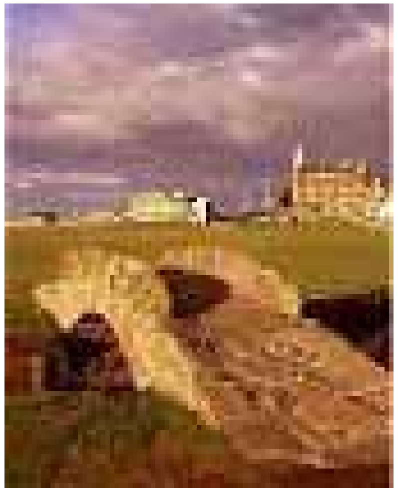
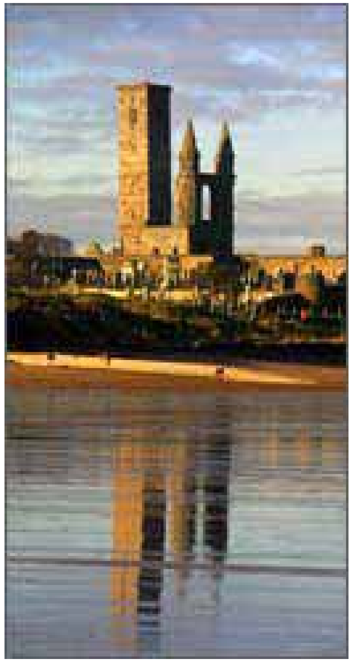
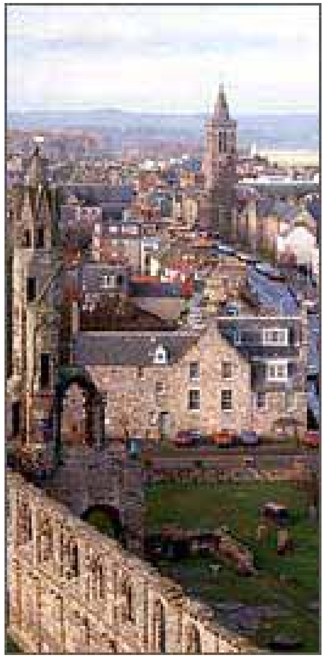
ICTP Winter School
February 2008

St Andrews: www.st-and.ac.uk



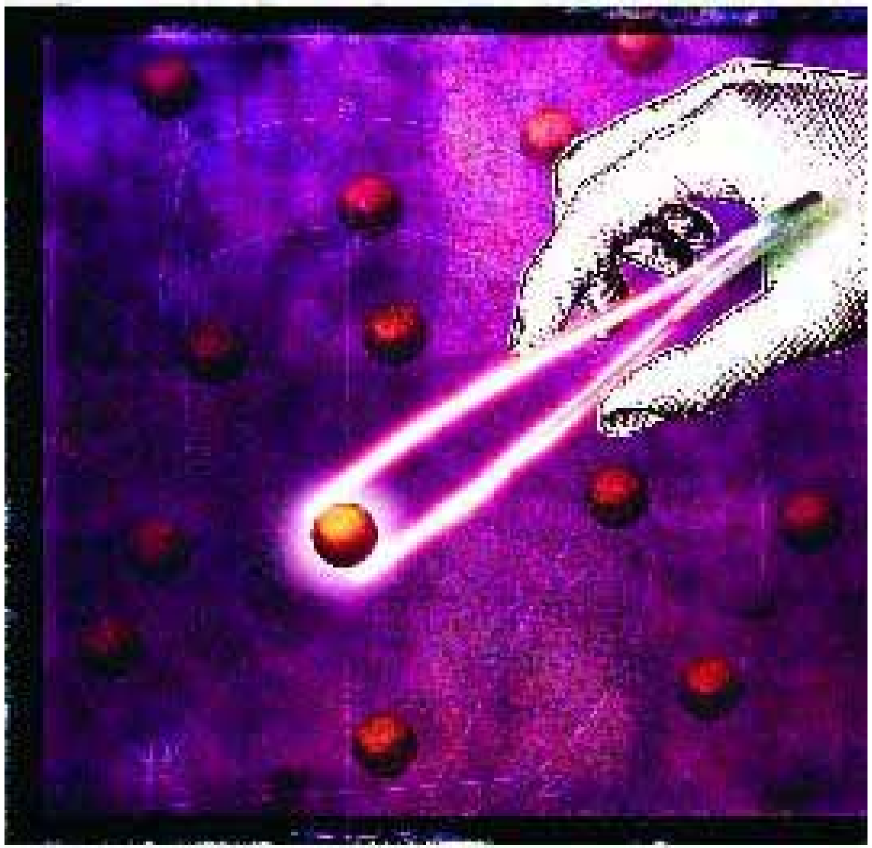
Life at St Andrews



These lectures

- **Lecture 1: why Multiple traps, how to make multiple traps**
- **Lecture 2: More exotic light fields: the LG beam and the Bessel beam**
- **Lecture 3: Optical separation and microfluidics. Integration with other modalities**

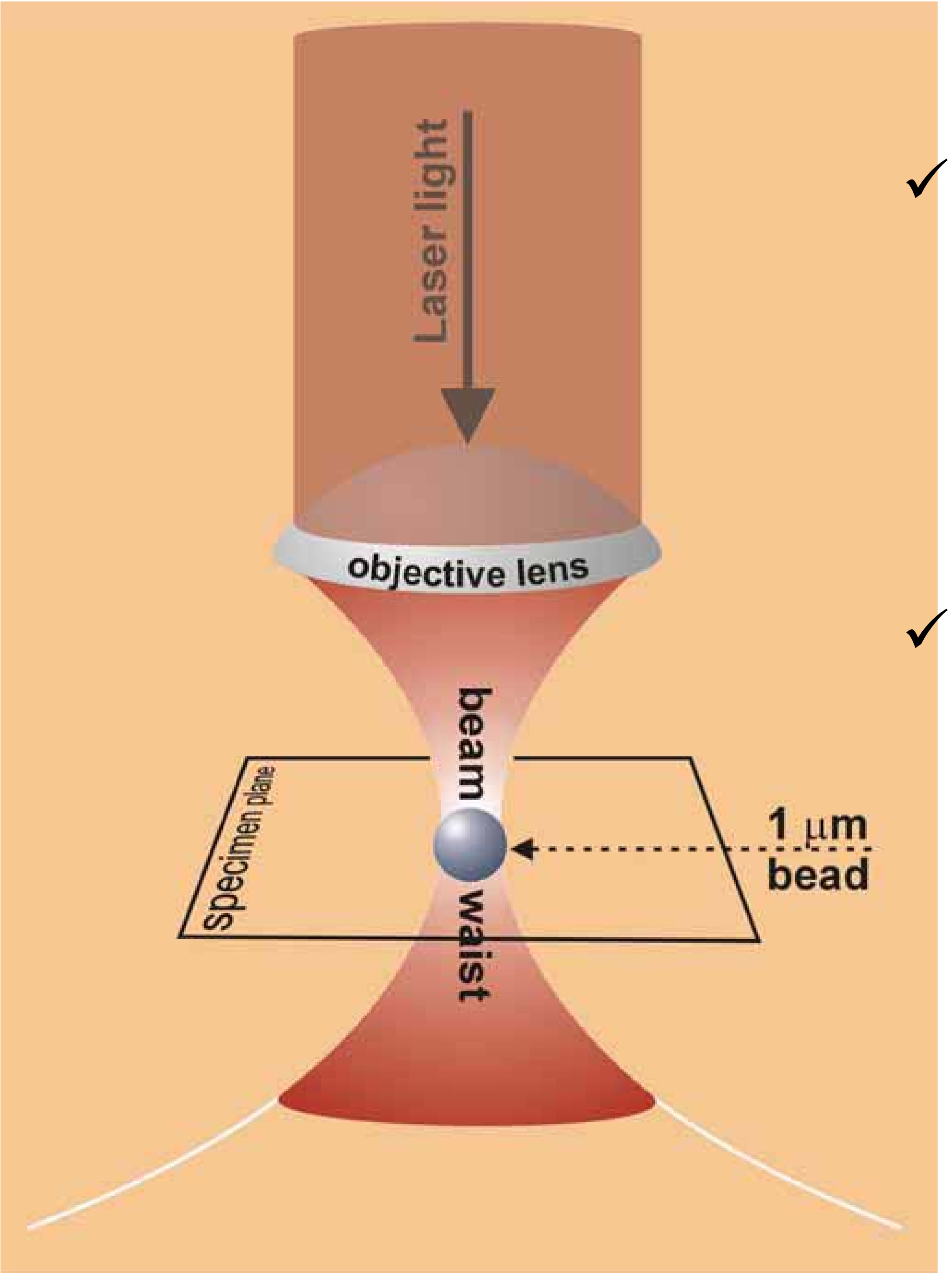


Reviews:
Dholakia K and Reece P 2006 Optical micromanipulation takes hold *Nano Today* 1 18-27
Dholakia. K, Reece. P, Gu. M, 2008 Optical micromanipulation *Chem. Soc. Rev* 37 42 – 55
Neuman K C and Block S M 2004 Optical trapping *Review of Scientific Instruments* 75 2787-809

www.st-and.ac.uk/~atomtrap

Slide acknowledgements: G Spalding and the Optical Trapping Group

At the heart of a basic trap:



✓ Laser

- Pick frequency to minimize absorption (no “optocution”).
- Power depends entirely upon application
- Beam Quality: $M^2 < 1.1$, TEM_{00} typical
- Pointing stability: critical for high-res. work

✓ Objective Lens

- Magnification doesn’t matter, *aberrations* do
- A numerical aperture (N.A.) > 1 is essential *if* 3D traps are required

PROTOCOL

Construction and calibration of an optical trap on a fluorescence optical microscope

Woei Ming Lee, Peter J Reece, Robert F Marchington, Nikolaus K Metzger & Kishan Dholakia

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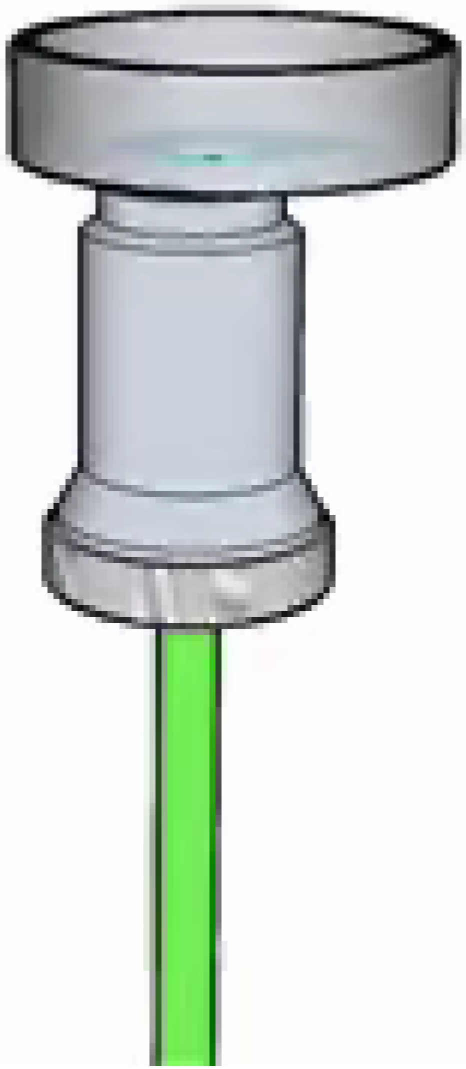
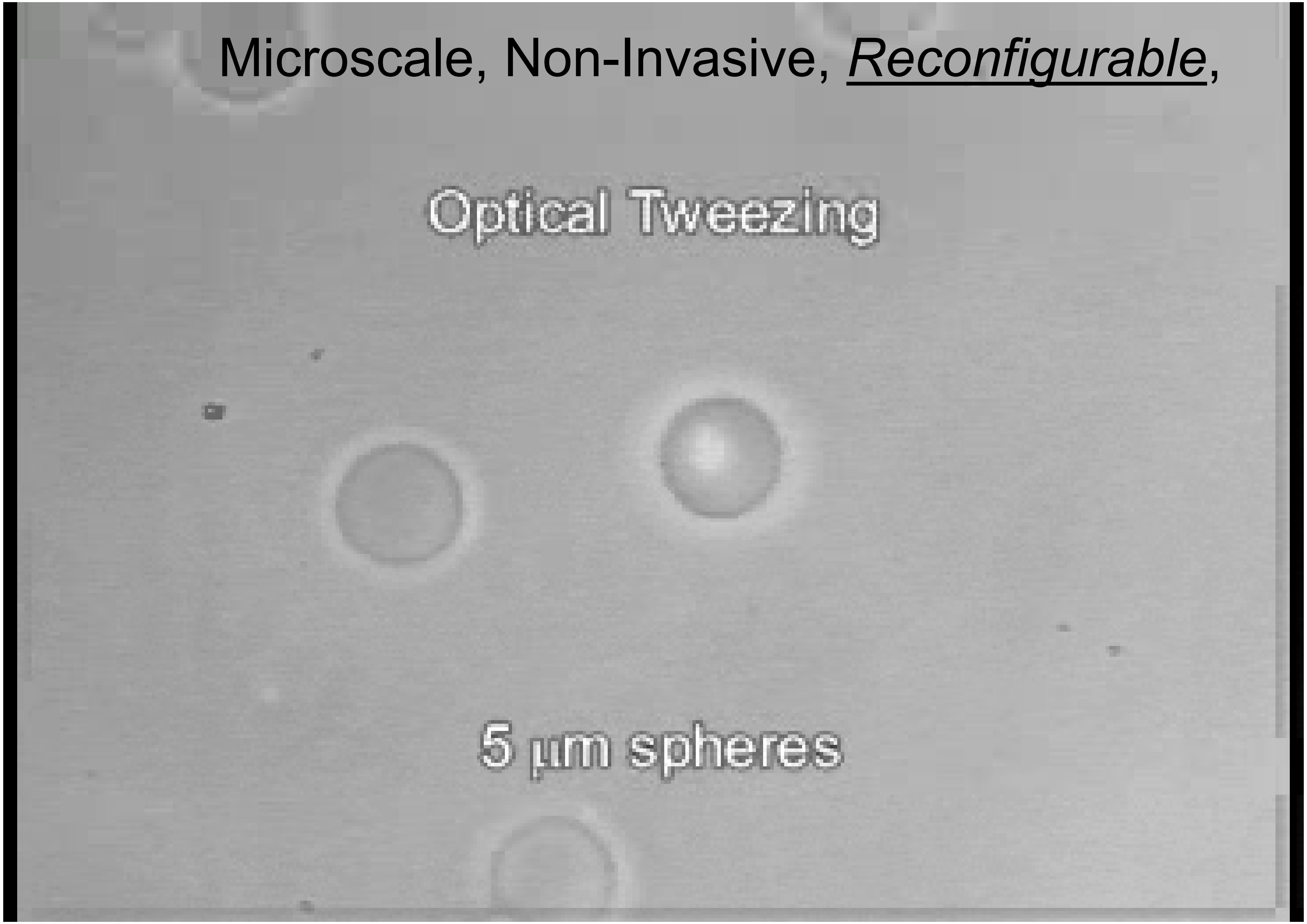
Published online 13 December 2007; doi:10.1038/nprot.2007.446

The application of optical traps has come to the fore in the last three decades. They provide a powerful, sterile and noninvasive tool for the manipulation of cells, single biological macromolecules, colloidal microparticles and nanoparticles. An optically trapped microsphere may act as a force transducer that is used to measure forces in the piconewton regime. By setting up a well-calibrated single-beam optical trap within a fluorescence microscope system, one can measure forces and collect fluorescence signals upon biological systems simultaneously. In this protocol, we aim to provide a clear exposition of the methodology of assembling and operating a single-beam gradient force trap (optical tweezers) on an inverted fluorescence microscope. A step-by-step guide is given for alignment and operation, with discussion of common pitfalls.

Nature Protocols, **2**, 3226 (2007) and references therein



Microscale, Non-Invasive, *<u>Reconfigurable</u>*,



Trapping metal nanospheres

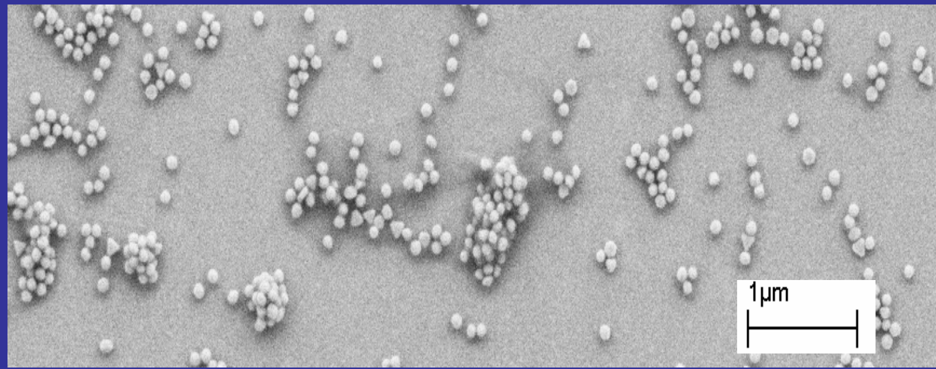
absorption force

$$F_{abs} = n_m < S > \frac{C_{abs}}{c}$$

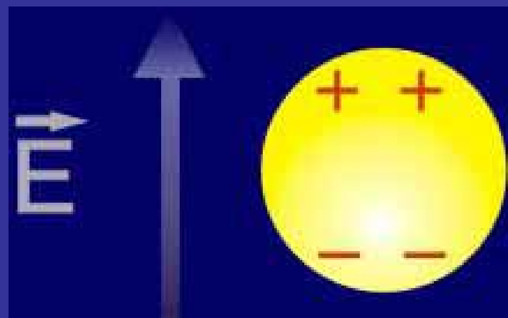
$$C_{abs} = \frac{2\pi n_m}{\lambda} \mathrm{Im}[\alpha]$$

$$\frac{F_{grad}}{F_{scat}} \propto \frac{F_{abs}}{F_{scat}} \propto \frac{1}{a^3}$$

Svoboda, Optics Letters 19, p930, 1994



polarisability



particle plasmon

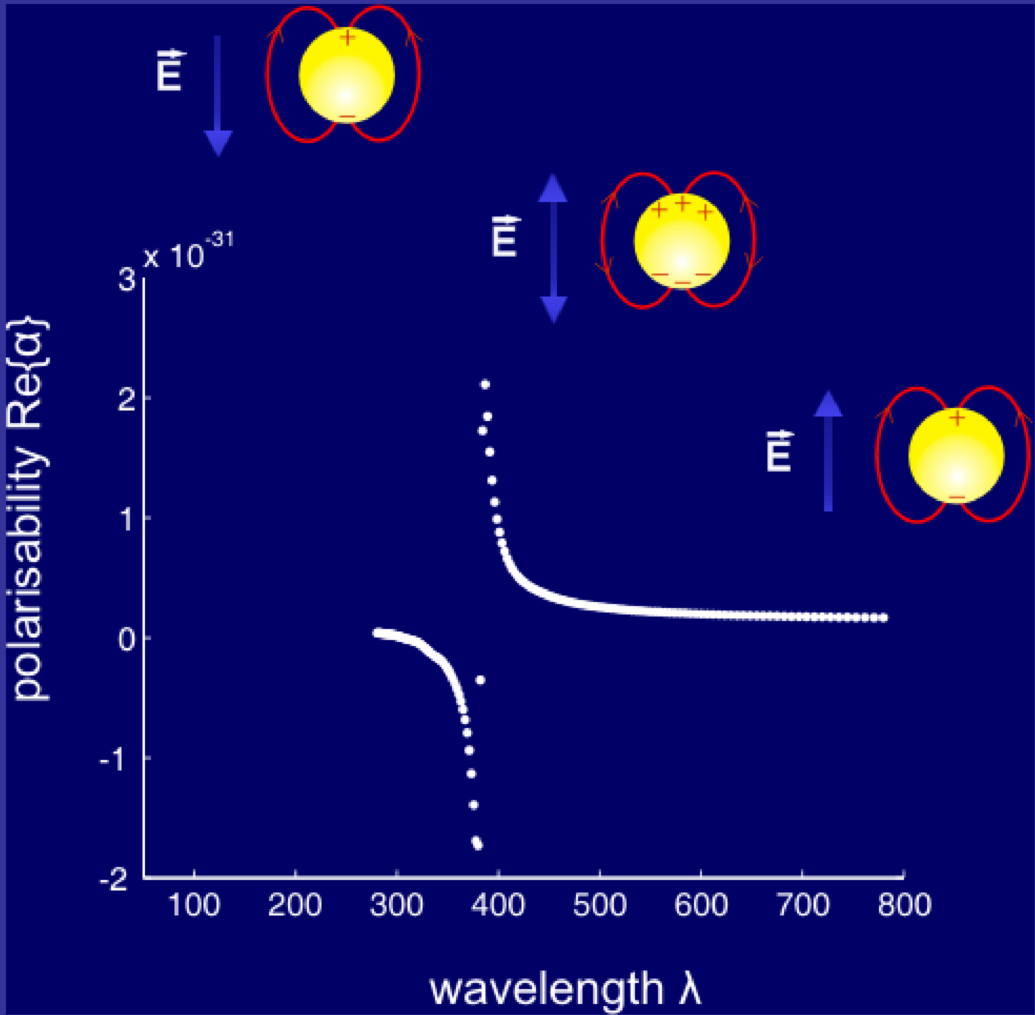
Trapping metal nanospheres

red-detuning

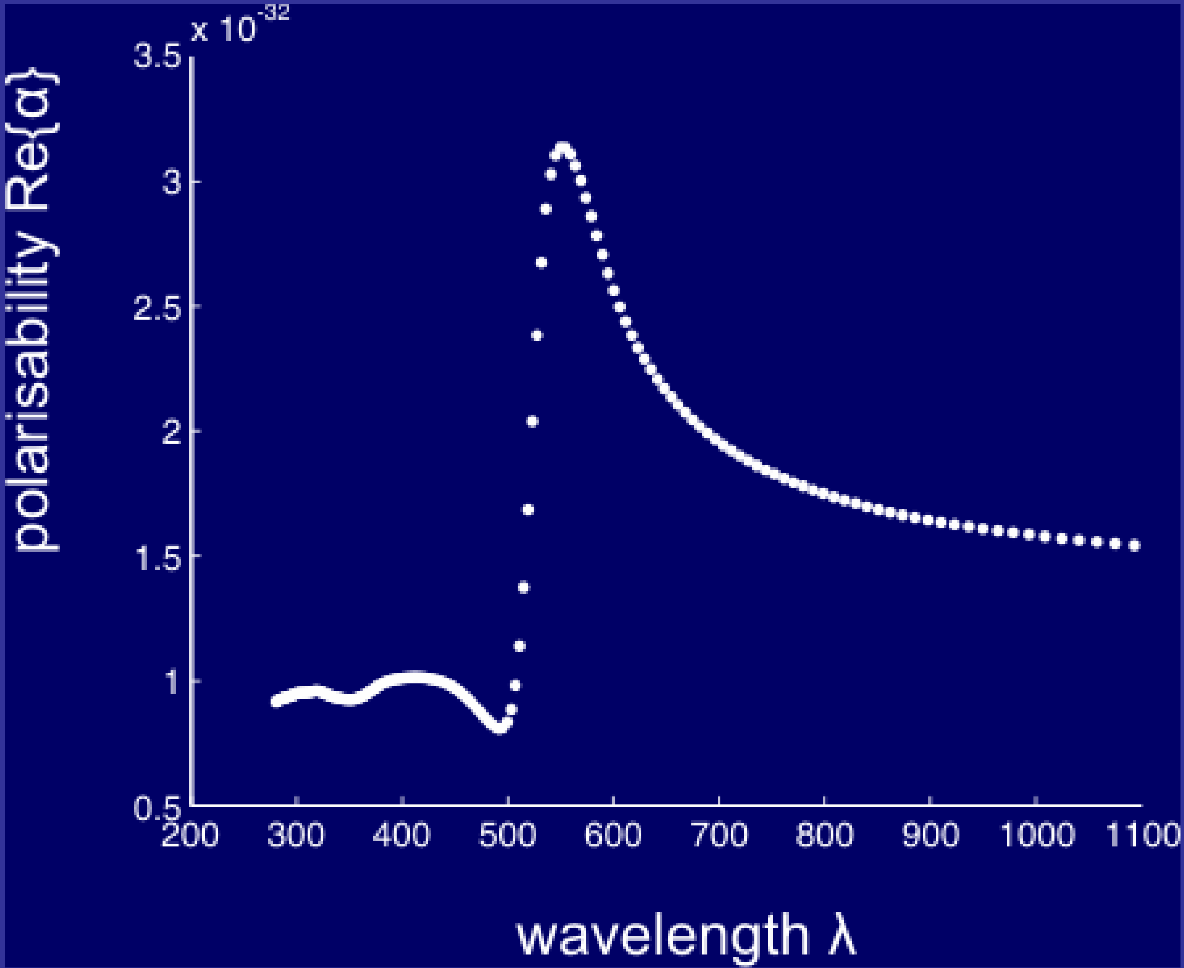
blue-detuning

$$F_{grad} = \frac{\alpha}{2} \nabla < E^2 >$$

$$\alpha = 3V \frac{\varepsilon p - \varepsilon}{\varepsilon p + 2\varepsilon}$$



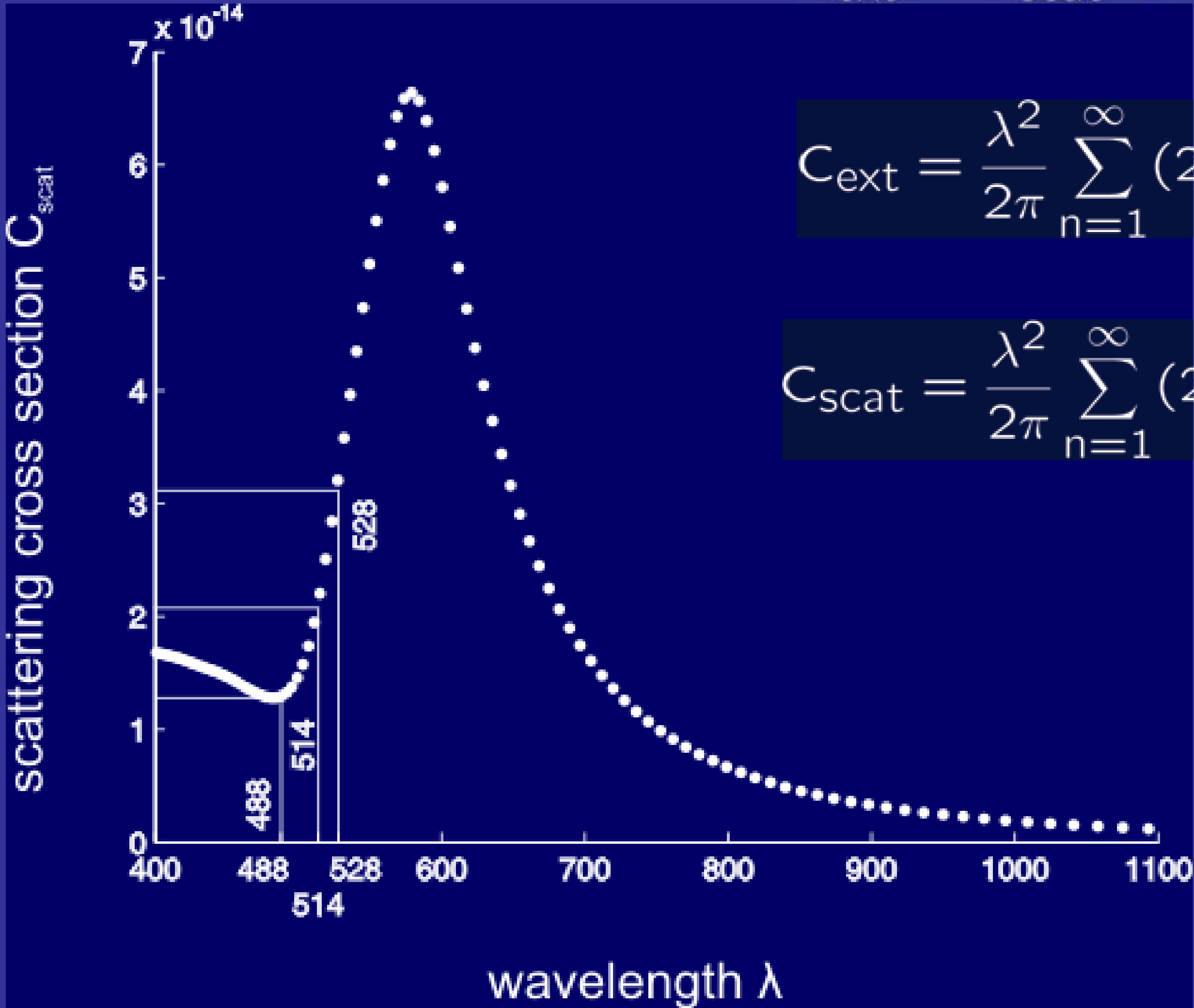
Trapping gold nanospheres



$$\alpha = 3V \frac{\varepsilon_p - \varepsilon}{\varepsilon_p + 2\varepsilon}$$

Mie theory

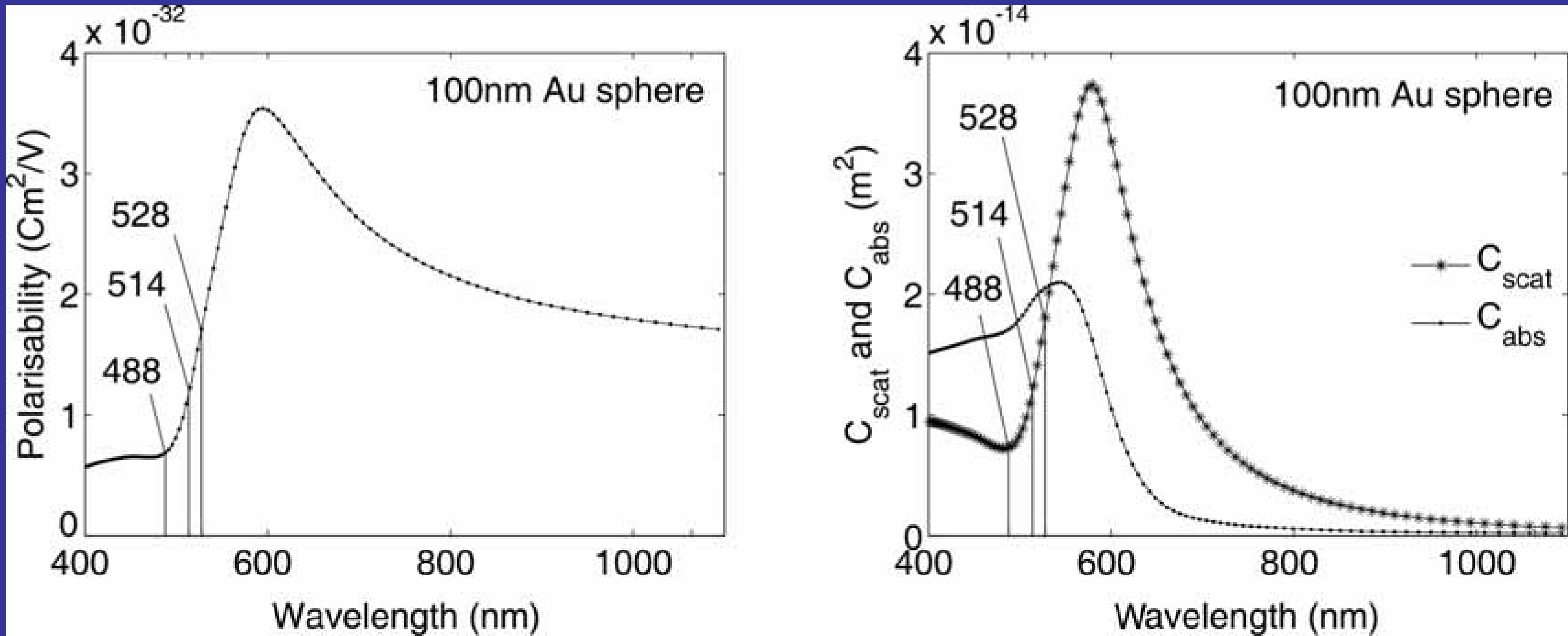
$$C_{ext} = C_{scat} + C_{abs}$$



$$C_{ext} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1)\mathrm{Re}[a_n + b_n]$$

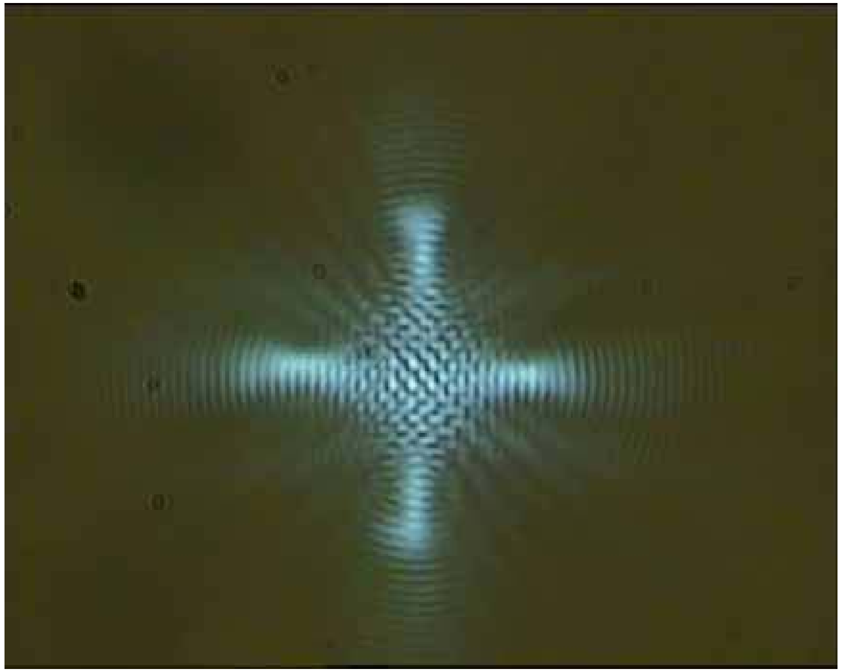
$$C_{scat} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1)(|a_n|^2 + |b_n|^2)$$

Behaviour near resonance



The real part of the polarisability α of a 100nm gold sphere calculated with the scattering *Cscat* and absorption cross section *Cabs* from Mie theory (see equation 4) and permittivity values from Johnson et al. [17]. The polarisability and thus the gradient force *Fgrad* is decreased by 30% and 70% for 488nm, 514nm and about the same at 528nm as compared to 1064nm. (right) The scattering cross section *Cscat* and the absorption cross section *Cabs* of a 100nm gold sphere calculated with Mie theory plotted against the wavelength of excitation.

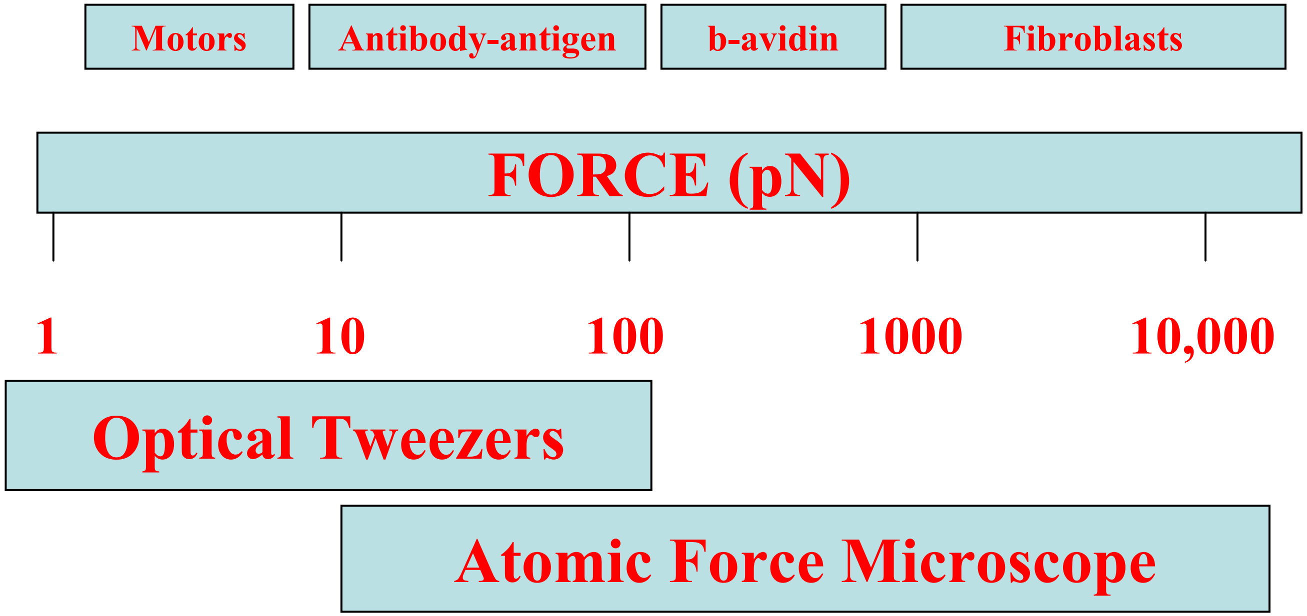
Single 100nm particle



Array of 100nm particle

PicoNewton forces

- 1 picoNewton (pN, 10^{-12} N) is roughly equal to…
  - … the gravitational attraction between you and a book at arm's length
  - … the radiation pressure on a penny from a flashlight 1 yard away
  - … 1 millionth the weight of a grain of salt

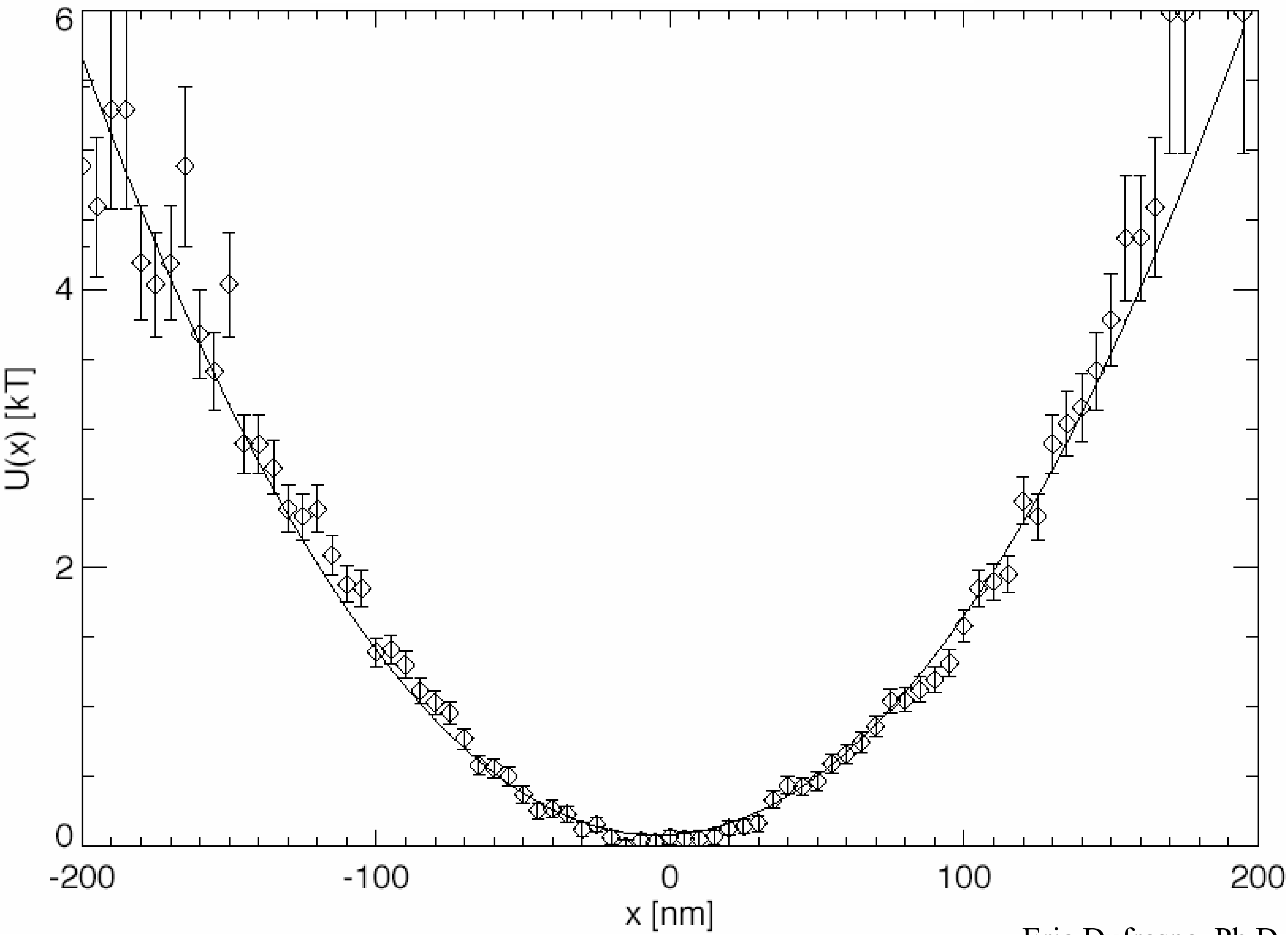


http://yakko.bme.virginia.edu/lab/laserpresent.htm

For a given laser power and particle size, trapped matter experiences

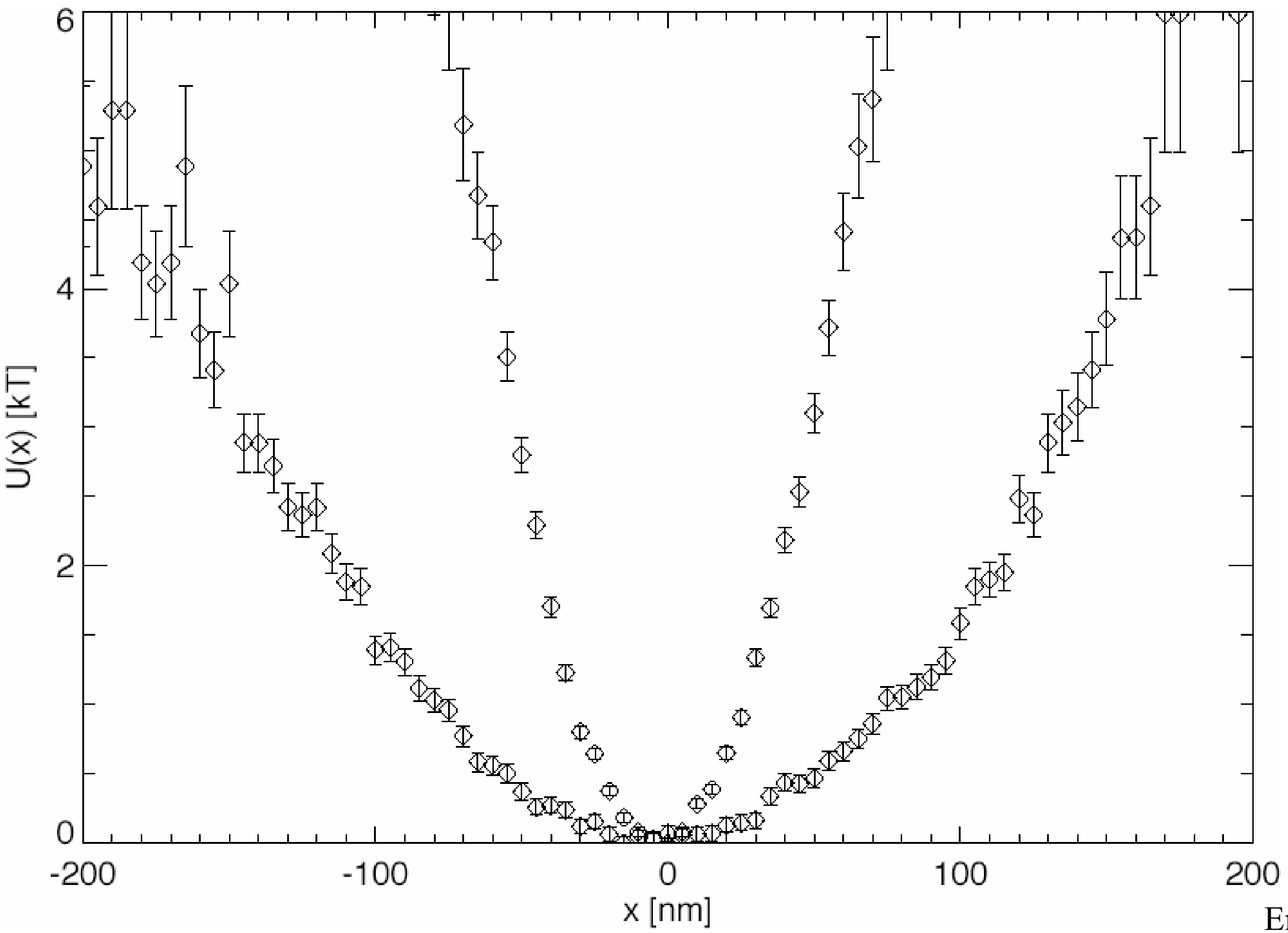
A *Parabolic* Potential Energy “Well”

(for small displacements)



Eric Dufresne, Ph.D. thesis, 2000

Trap "Extent", Part II



Potential Well as a function of laser power

Eric Dufresne, Ph.D. thesis, 2000

Due to Brownian motion the <u>RMS displacement</u> in the trap may of the order of 10nm which is much more than an order of magnitude less than the <u>trap capture range</u>. Though x_{rms} can be quite small, this can remain an issue for single molecule studies.

A Classical Oscillator

A *parabolic* “well” implies a *linear* relationship between force and displacement, as with a mass on a spring.

$$m \frac{\partial^2 x}{\partial t^2} + \beta \frac{\partial x}{\partial t} + \kappa x = 0$$

-- where κ is the elastic constant or stiffness of the optical trap and β is the damping parameter.

With no damping (*e.g.*, in vacuum) the result would be a resonant frequency as follows:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{\kappa}{m}}$$

Mass of object: 5×10^{-16} kg

Typical trap stiffness: $0.05 pN \ \ nm^{-1}$

$\Rightarrow$ $\boxed{f_{res} \approx 50 kHz}$

For review: Molloy and Padgett, *Contemp. Phys* (2002)

In typical biological applications, the stiffness of the optical tweezers is around 0.05 pN/Nm and the trapped objects are around diameter 1 micron, corresponding to a mass of 10^{-16}kg.. Hence, the resonant frequency would be around 50kHz.

However, because biological experiments must be performed in an aqueous medium, significant damping force arises. For a particle of radius r , moving in a fluid of viscosity, the Stoke's drag constant

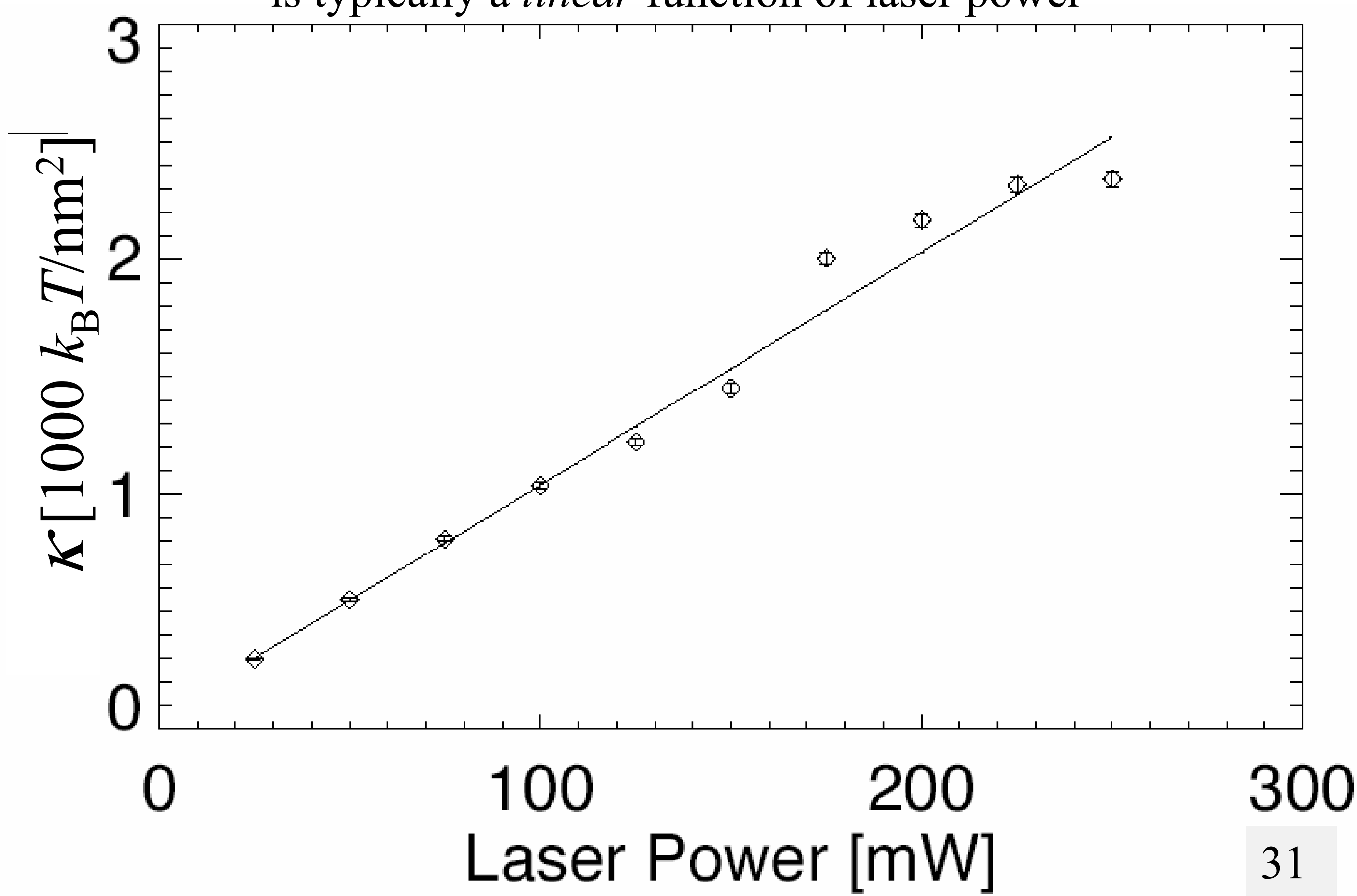
$$\beta = 6\pi r\eta$$

For typical biological application we find that the roll-off frequency well below 1 kHz. Since this is much lower than the resonant frequency, the motion is very over-damped.

In fact, it means that inertial and gravitational forces can be ignored altogether

Trap "Stiffness"

is typically a *linear* function of laser power



Eric Dufresne, Ph.D. thesis, 2000

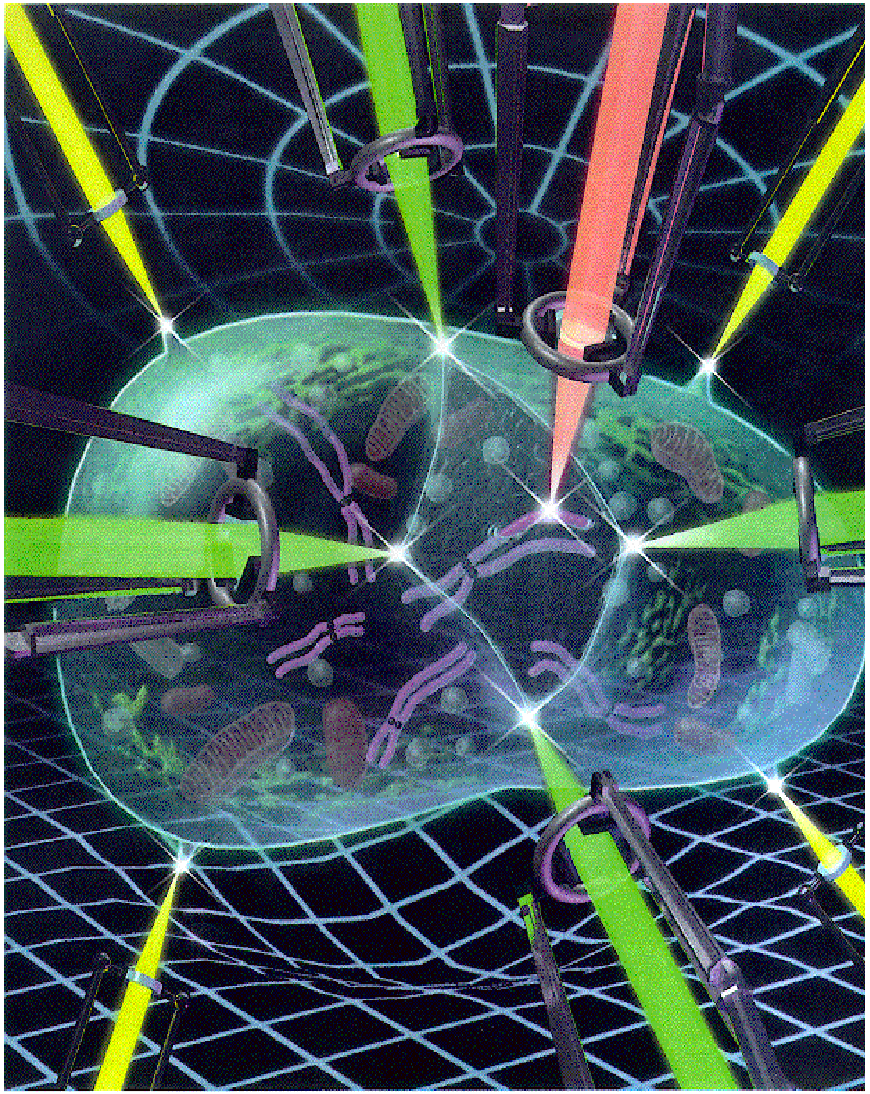
- All living cells contain a wide variety of *molecular motors* that take chemical energy and convert this to work.

- Functions that are essential to life; eg DNA replication, RNA transcription and protein synthesis to cell division, vesicle trafficking, cell locomotion, endocytosis.

There are two types of molecular motor:

1. “Rotary motors” are embedded in membranes. Powered by the flow of ions across transmembrane electrochemical gradients; eg the bacterial flagellar motor.

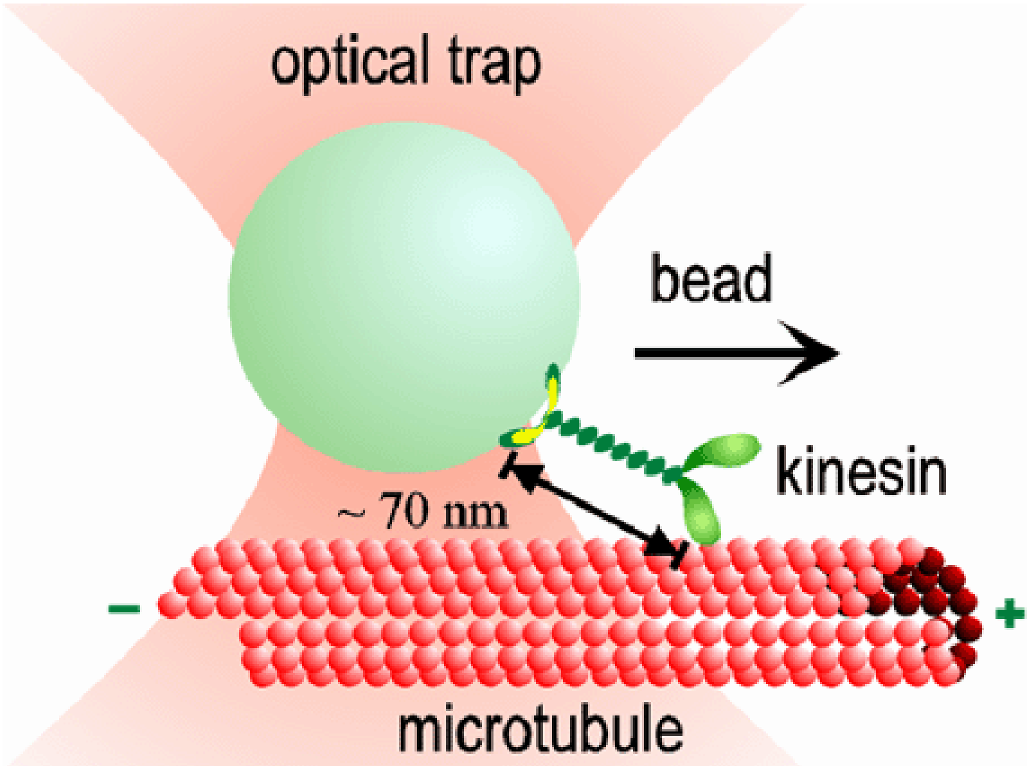
2. “Linear motors” work in an isotropic chemical environment: energy from chemical reactions, usually the hydrolysis of the chemical, adenosine triphosphate (ATP) to adenosine diphosphate (ADP) and phosphate.



From industrial physicist 1999

Single-Molecule Biology: study of molecular motors (“rowers and porters”) requires:

Tethering or Clamping of Single Molecules



From S. Block lab:
www.stanford.edu/group/blocklab/ResearchMain.htm

Why create multiple traps?

-Gaussian beam limiting

-Novel beam shapes useful: eg trapping low index particles

-Rotation: studies of angular momentum and microrheology

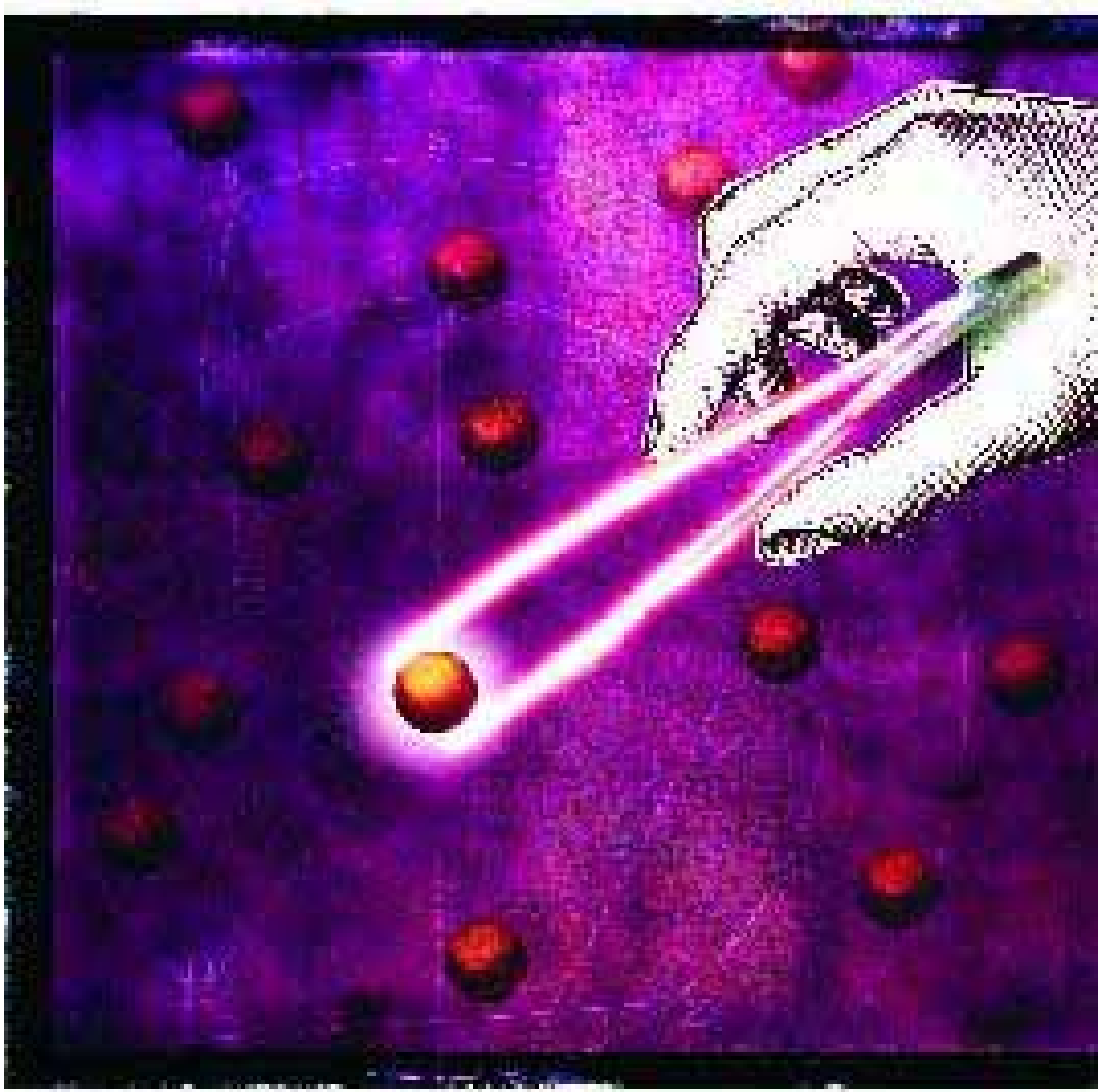
-Multiplexed studies in biology

-Cell organisation in 2D/3D

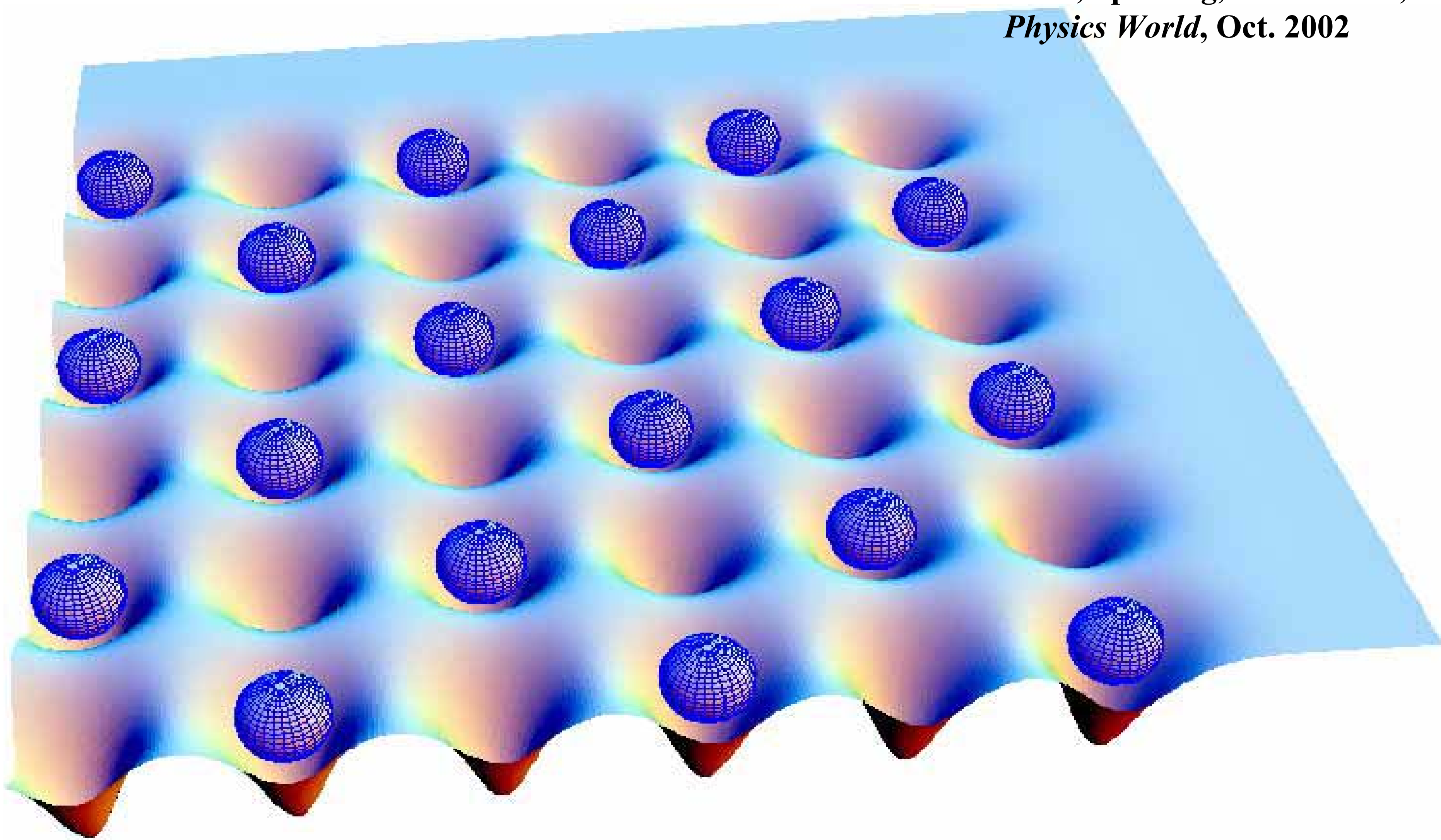
-Studies of colloid in 2D/3D

-Multi-particle interactions

-Creation of optical potential energy landscapes

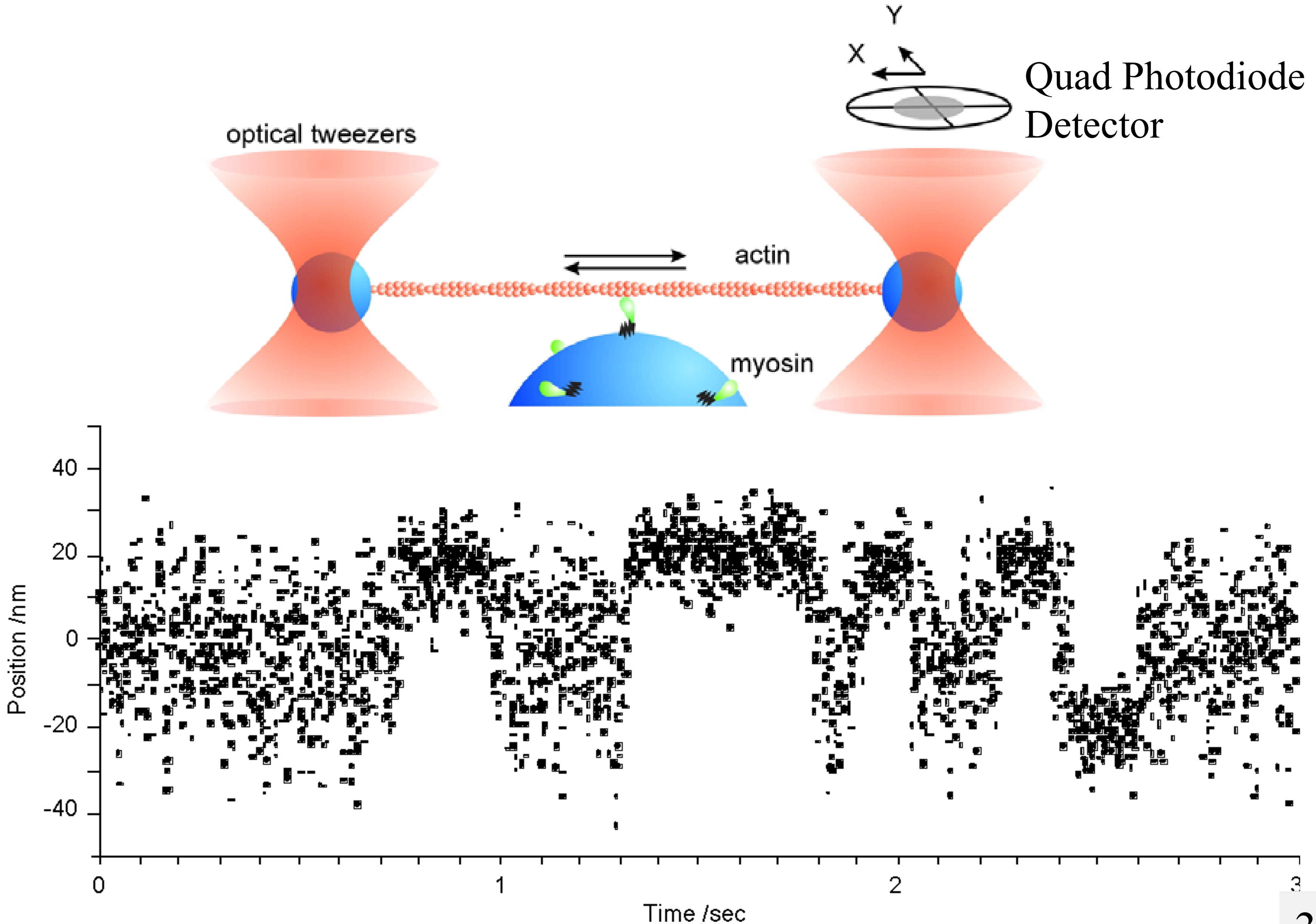


Dholakia, Spalding, MacDonald,
Physics World, Oct. 2002



Holographic /interferometric/time sharing can create 2D/3D arrays of trap sites: useful for optical sorting/guiding and other studies

Two or more tweezers often needed..



From review in optical tweezers, Padgett and Molloy, *Contemp. Phys.* **43**, 241 (2002)

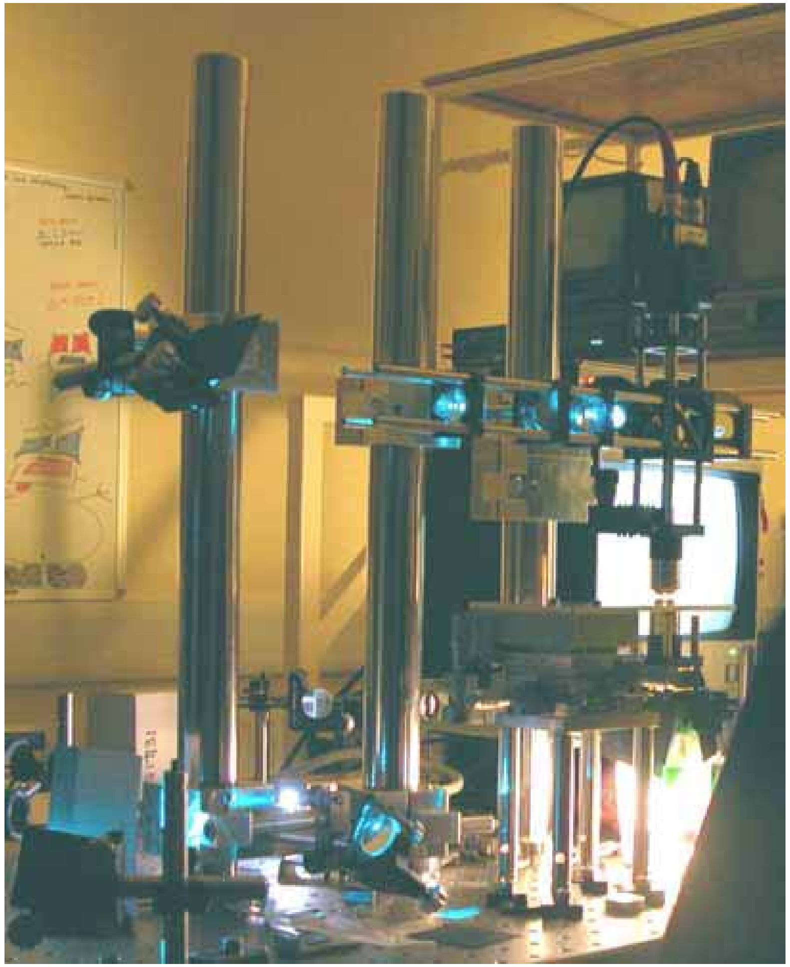
Biological studies need two more more traps…Tying a knot in DNA…

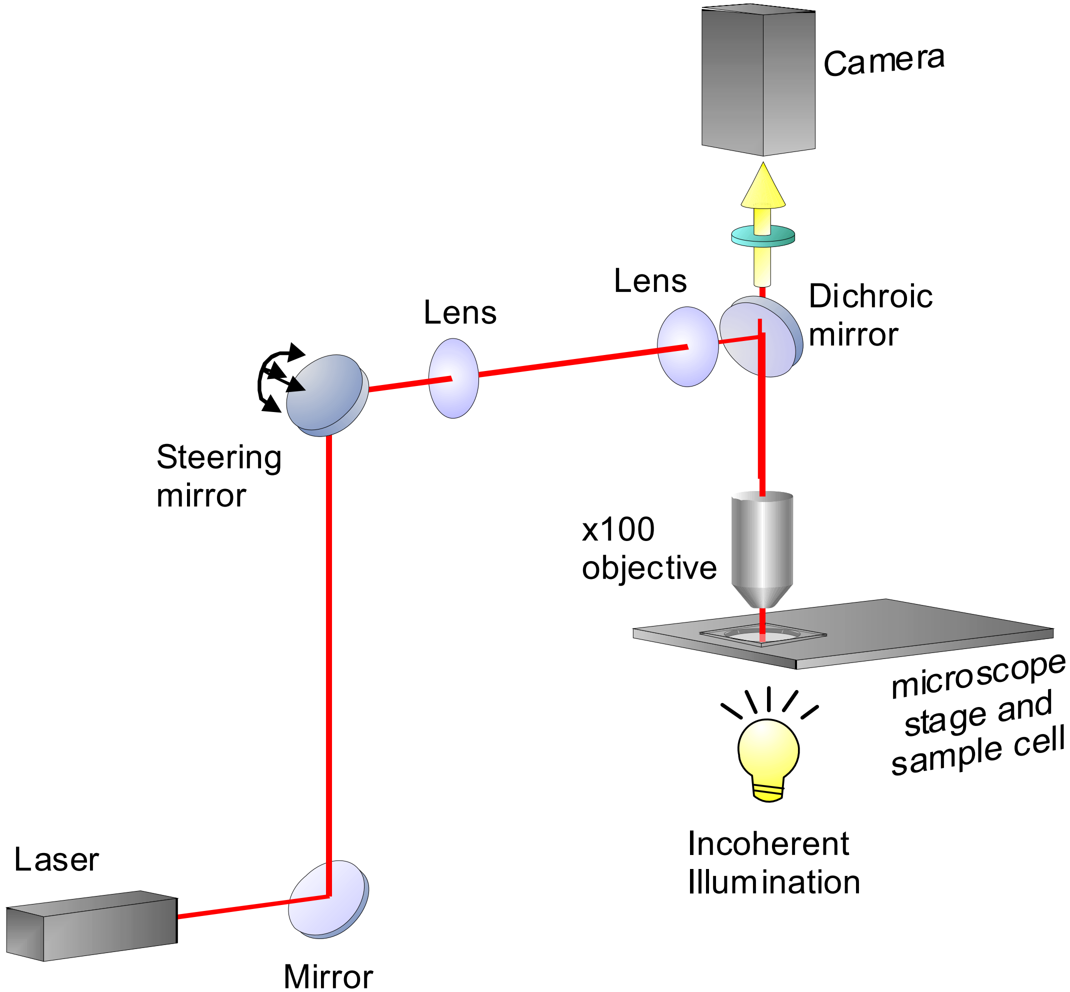
The enzymology of topoisomerases at the single molecule level.
Such polymeric topological constraints arise naturally in cells during DNA Replication. Knotting, is important in elucidating the mechanisms of DNA recombination
Xiaoyan R. Bao, Heun Jin Lee, and Stephen R. Quake, Phys Rev Lett 91, 265506 (Dec 2003)

Question:

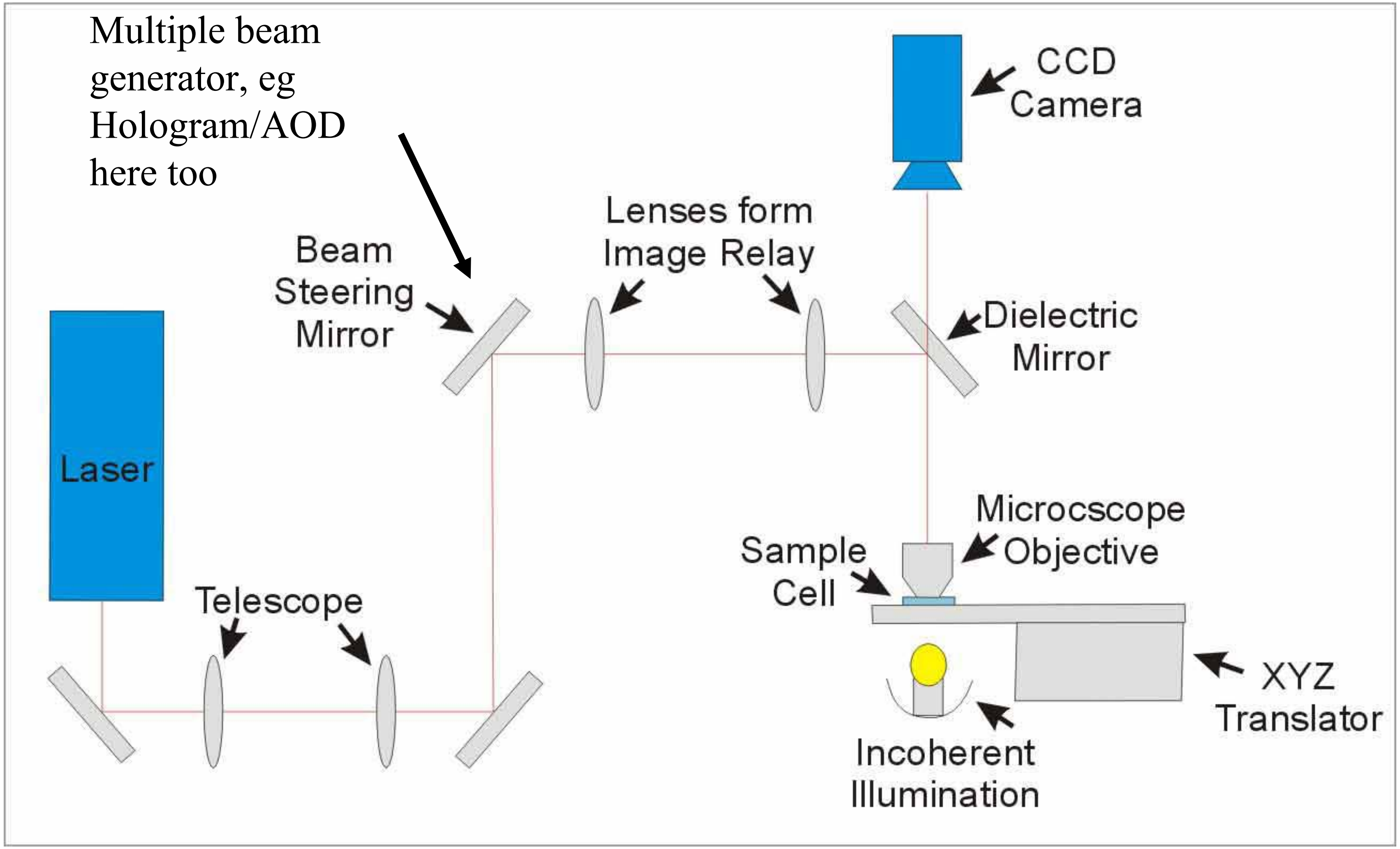
“How do I make more than one trap?”

Basic Steerable Tweezers Setup





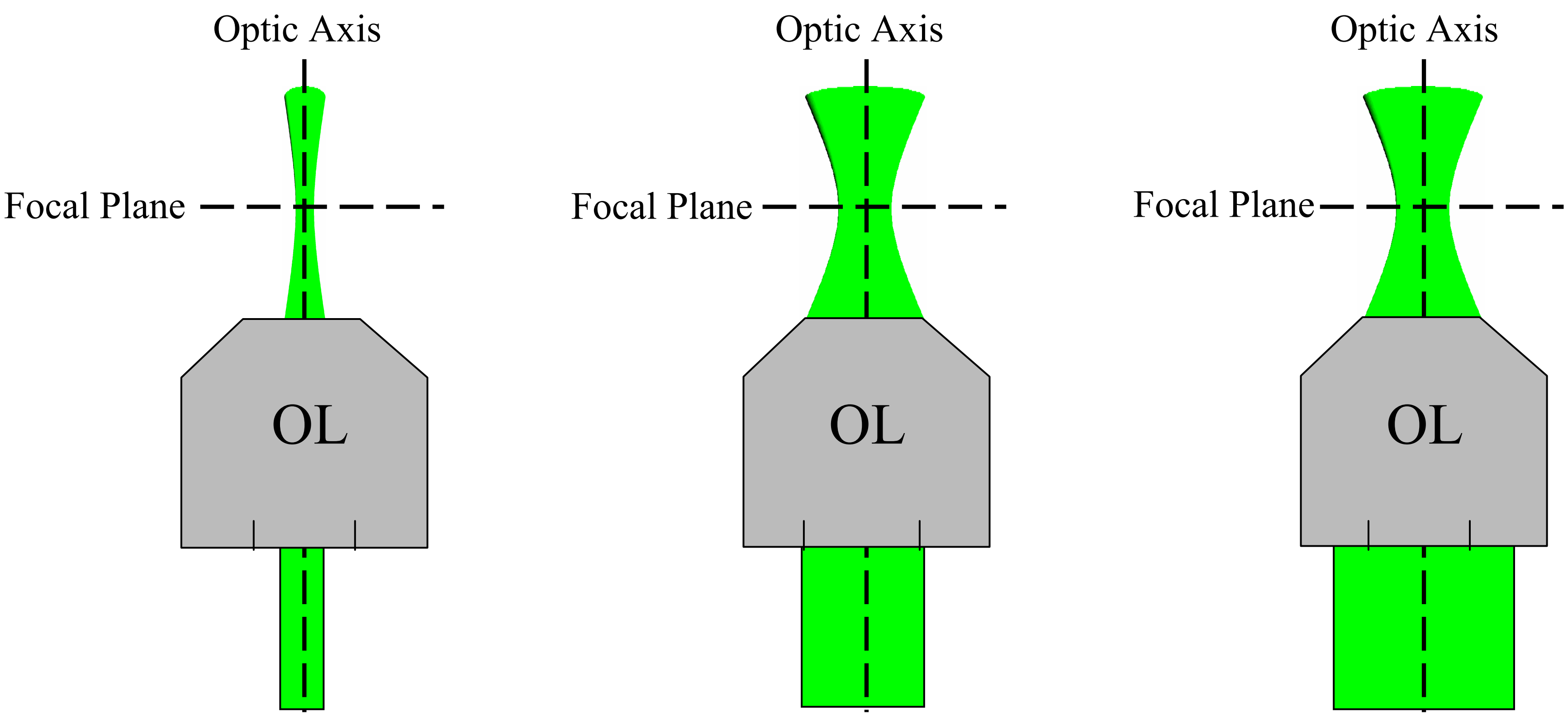
The steering mirror must be made “conjugate” to the entrance pupil (back aperture) of the objective lens.


Multiple beam generator, eg Hologram/AOD here too
Beam Steering Mirror
Lenses form Image Relay
CCD Camera
Dielectric Mirror
Laser
Telescope
Microcscope Objective
Sample Cell
XYZ Translator
Incoherent Illumination

High N.A. lens required

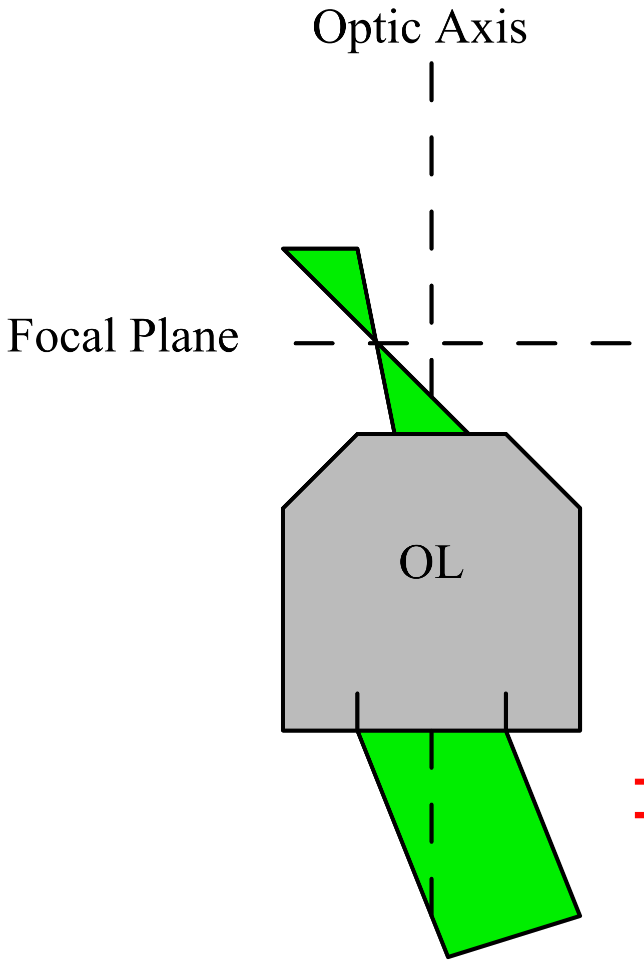
to produce strong axial gradients needed for 3D trapping with a single beam

⇒ Moreover, the laser should *fill* the back aperture of the objective:



"Underfilled" "Filled" "Overfilled"

Trap Positioning in 2D

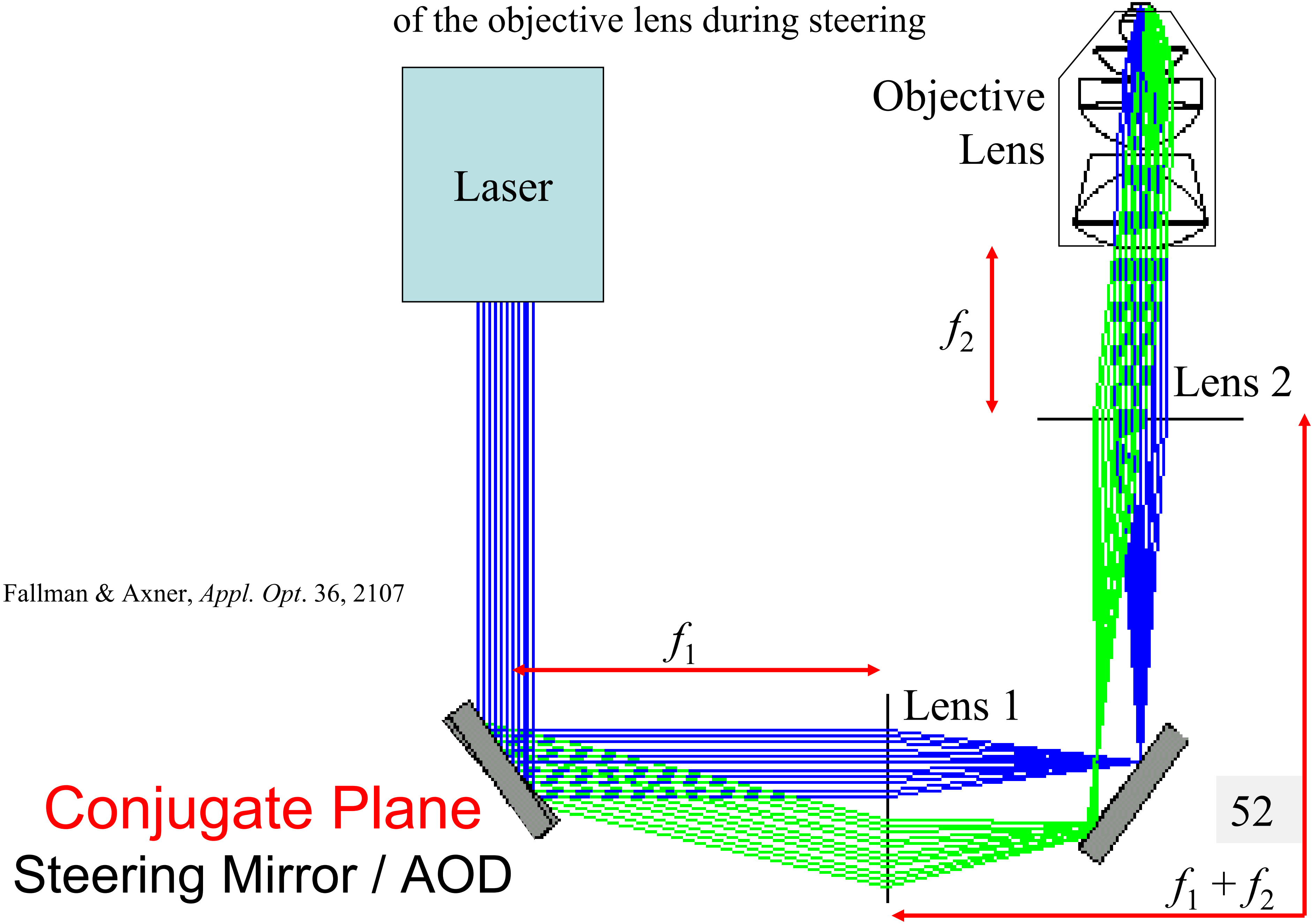


• Changing the entrance angle of the laser allows trap "steering"

• Multiple entrance beams yield multiple traps

⇒ Requires additional design elements

This lens arrangement prevents the beam from "walking off" of the back aperture of the objective lens during steering

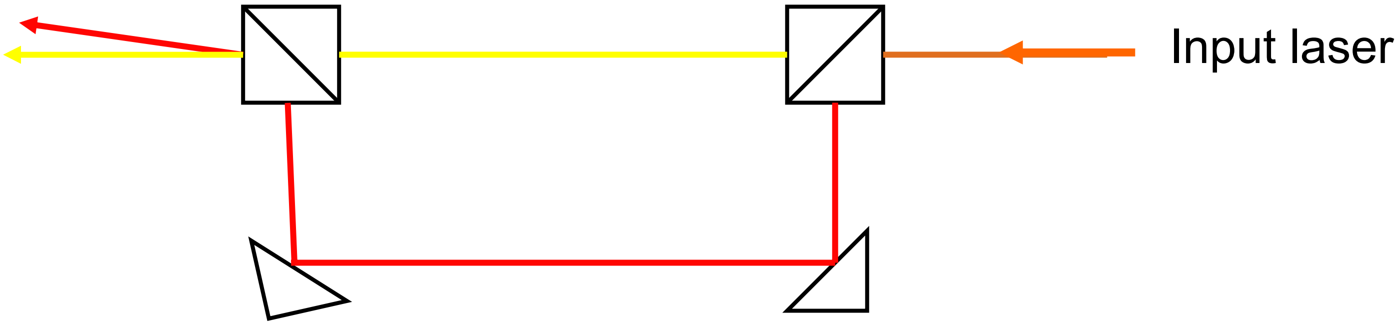


Fallman & Axner, *Appl. Opt*. 36, 2107

Simplest two beam trap

Fallman E and Axner O 1997 Design for fully steerable dual-trap optical tweezers *Applied Optics* 36 2107-13

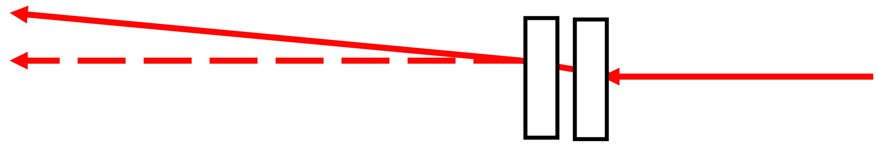
<u>Polarizing Beamsplitters</u> work for two-beam traps



Versatile, no complex optics, easily steerable

Multiple Traps 1:

<u>*Time-share*</u> the laser beam:



Acousto-Optic Deflectors (AODs) can be scanned at *hundreds* of kHz: place at position of conjugate mirror

<u>Time-share</u>: Repositioning the laser on such a short time-scale that the trapped particles experience only a time-averaged potential.

Time sharing the light field can create multiple traps positions. Video in collaboration with I Poberaj group, Slovenia

[New Folder\tetris_divx5.02.avi]

A 1 micron diameter object has a diffusion coefficient, given by Einstein's relation:

$$D = \frac{k_b T}{\beta}$$

and a diffusion distance, , over time, , given by:

$$d = \sqrt{2Dt}$$

For example, for this object suspended in water, the diffusion coefficient is. $D = 4 \times 10^{-13} m^2 \ s^{-1}$

If the optical tweezers are absent for 25 microsecs, the diffusion distance is about 5nm.

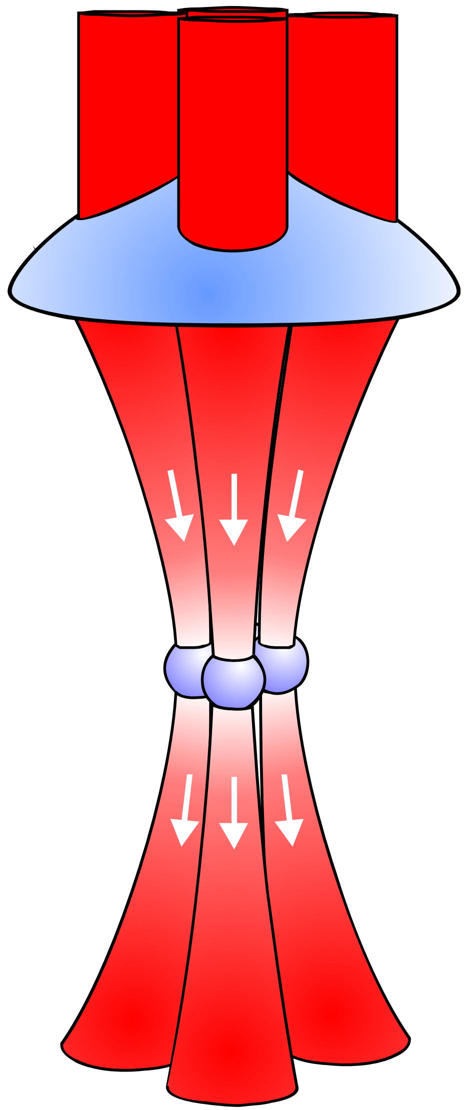
This represents a maximum limit to the accuracy to which the spheres can be positioned or their position measured.

Tweezing Large Numbers of Particles

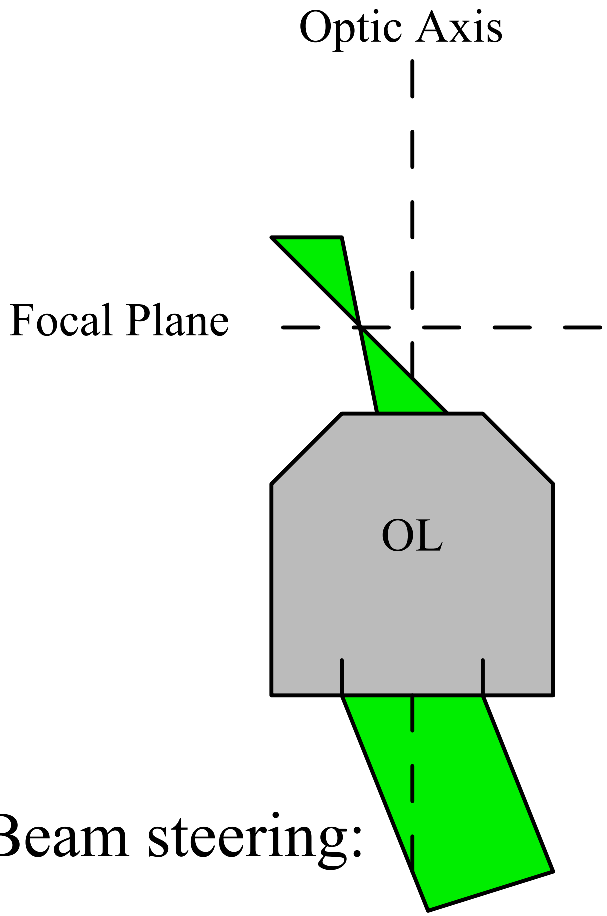
Conventionally tweezing is of a *single* particle in a *single* beam, though dual-beam traps are commonly used for interaction measurements.

Would be useful to be able to tweeze more particles at once.

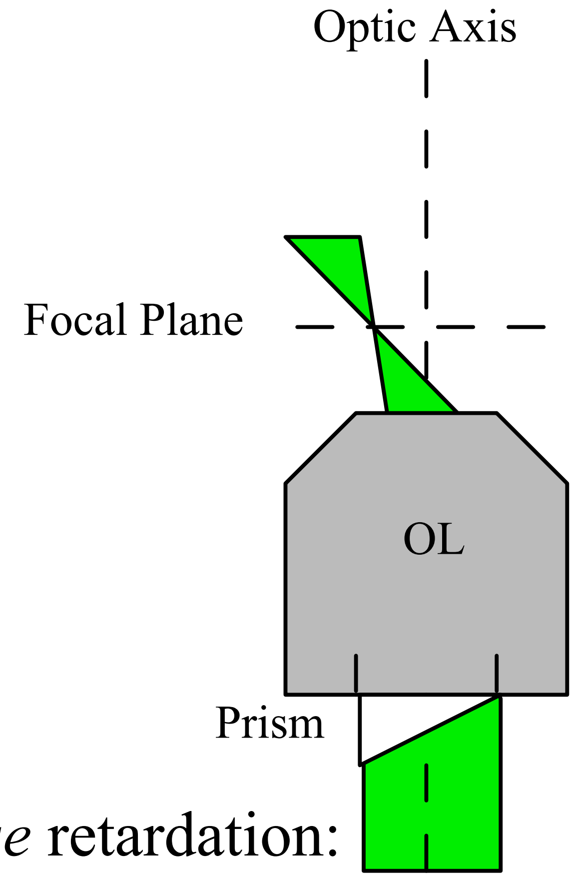
Can do this with ONE beam by mimicking the *relative phase shifts* associated with multiple inputs.



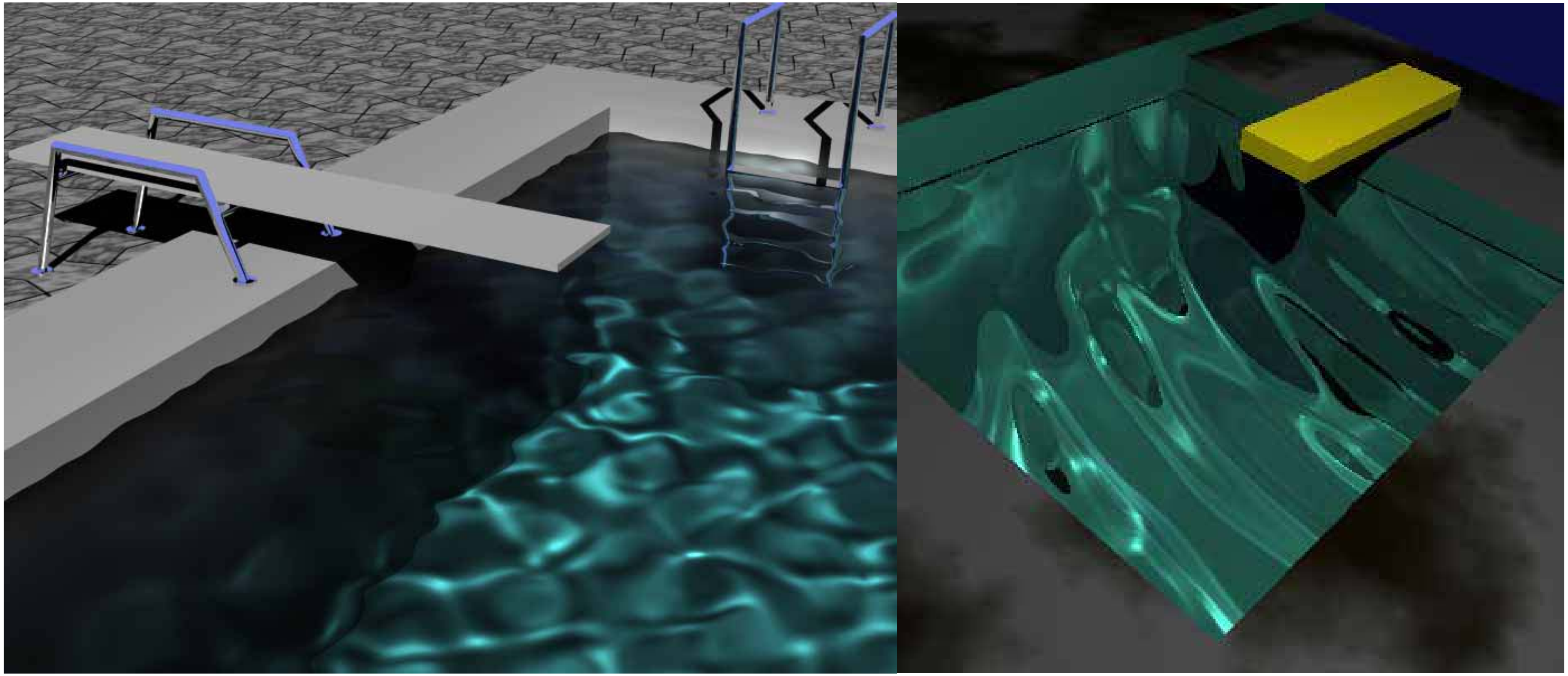
“Steering” with a Phase-Only Optic



Beam steering: is equivalent to … a *phase* retardation:

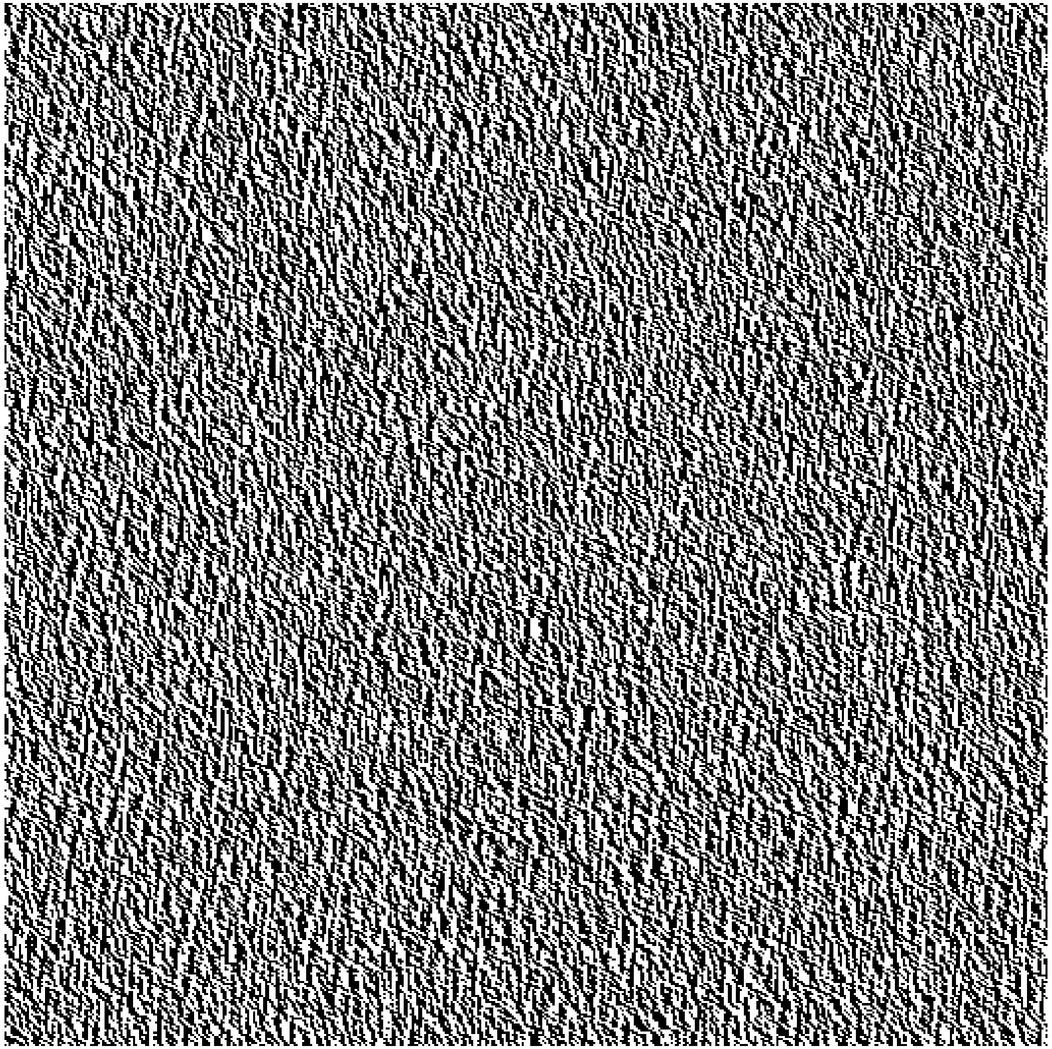


In fact, phase-only modulation allows for complex designer optical “landscapes”



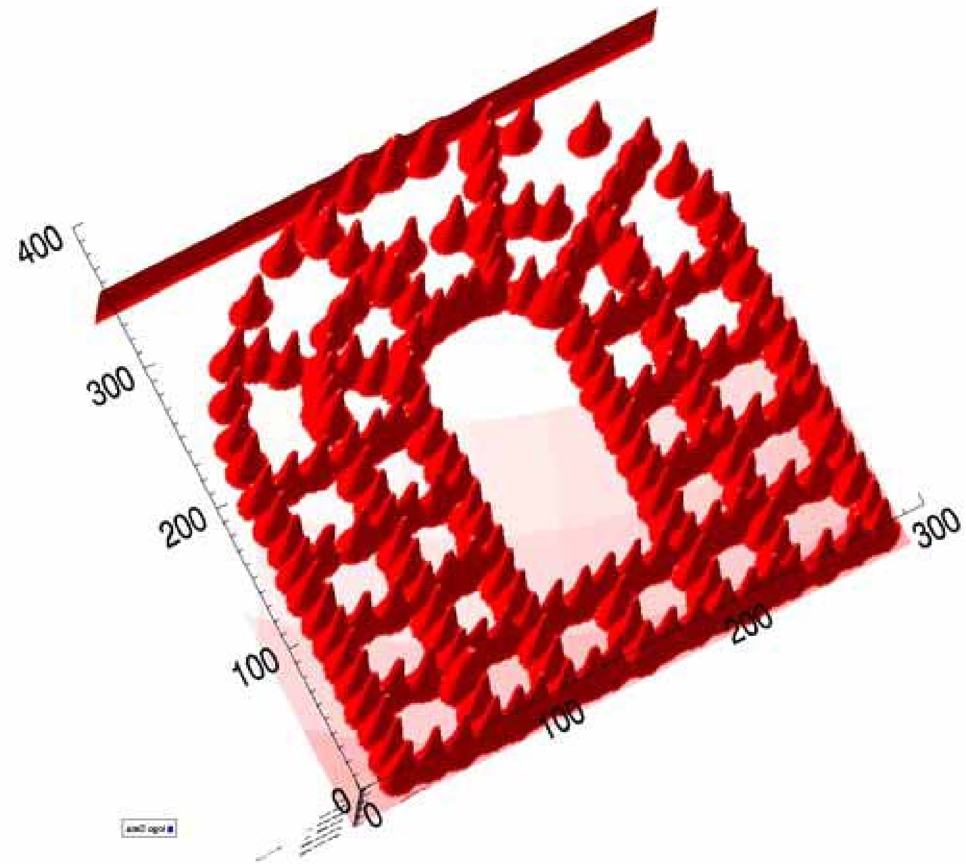
Optical “Caustics”

Textured Glass = Transmission Hologram
sculpting light

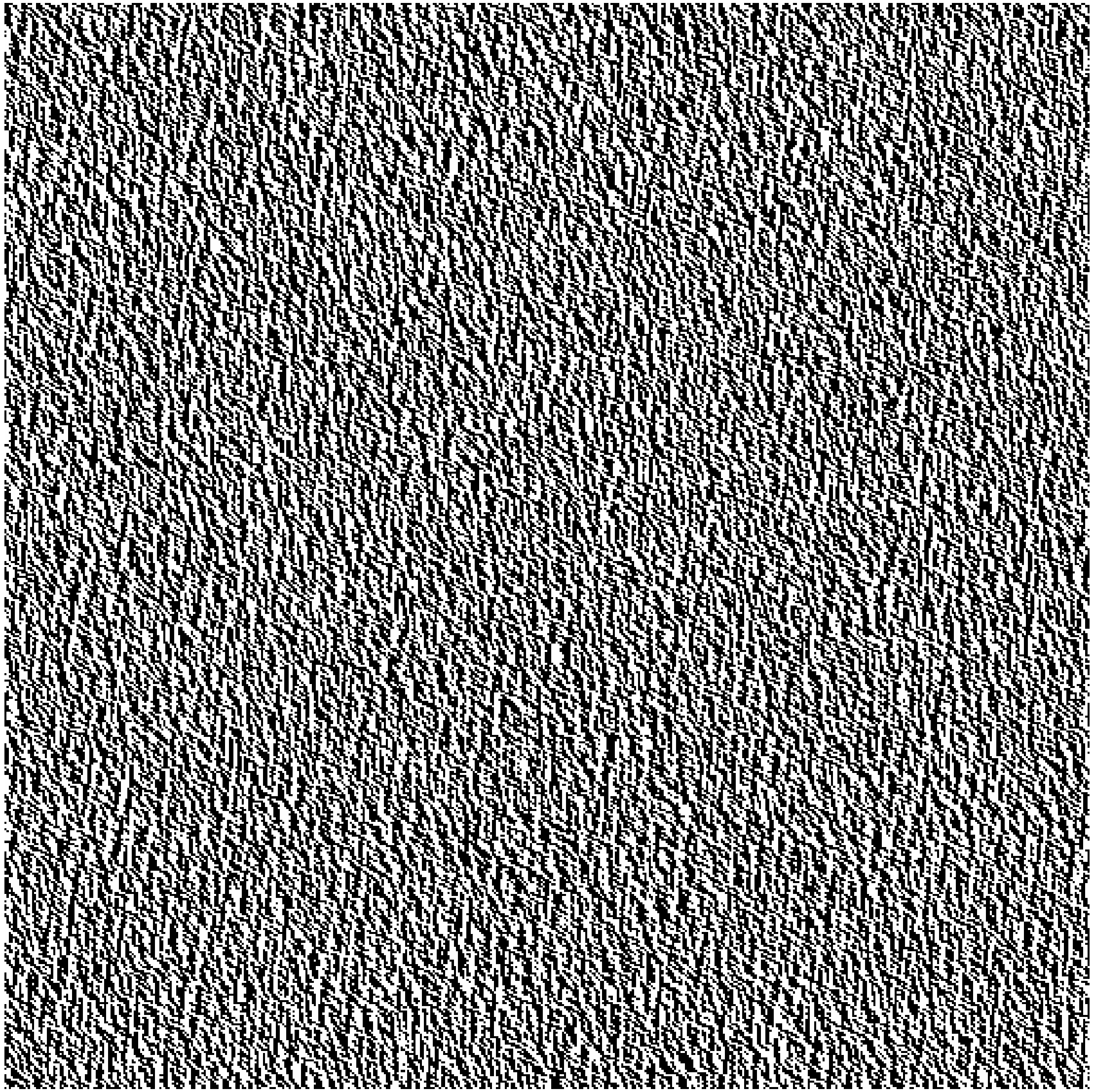


The result of passing light through this phase modulator is…

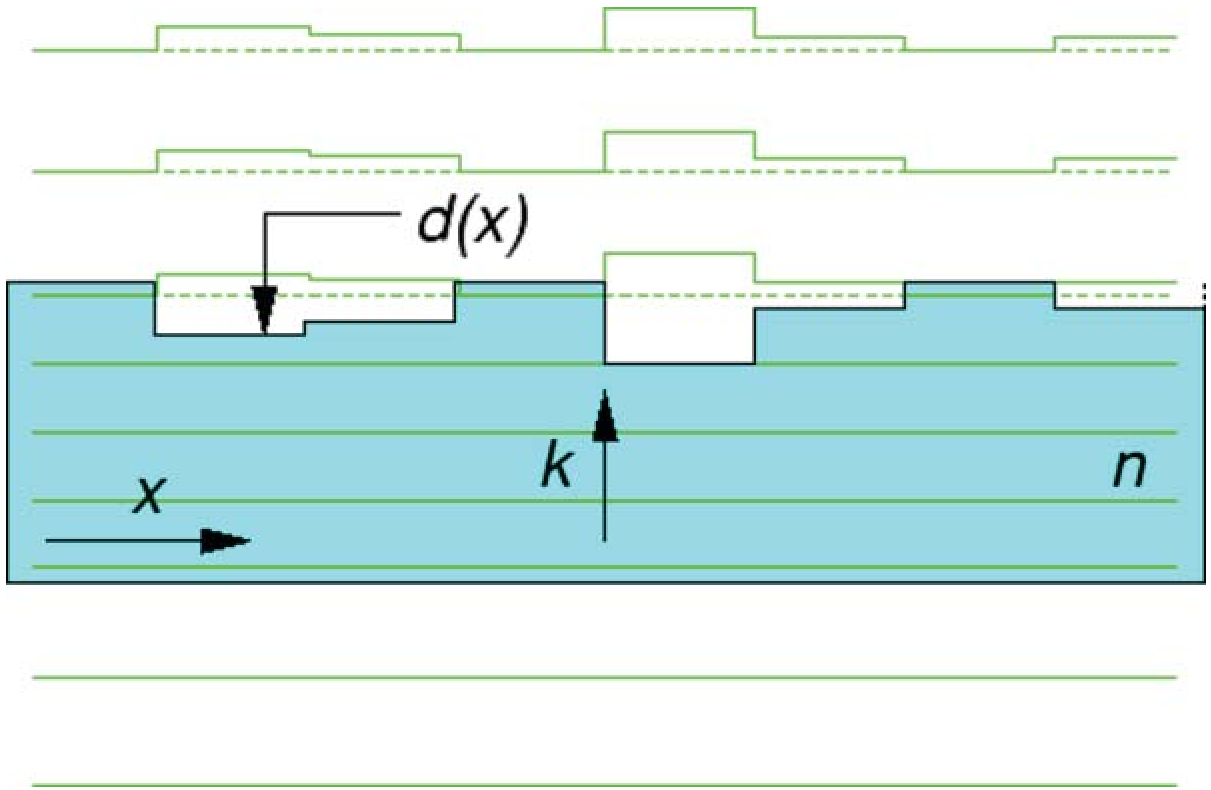
The "Wesleyan Window"
(symbol of Illinois Wesleyan Univ.)



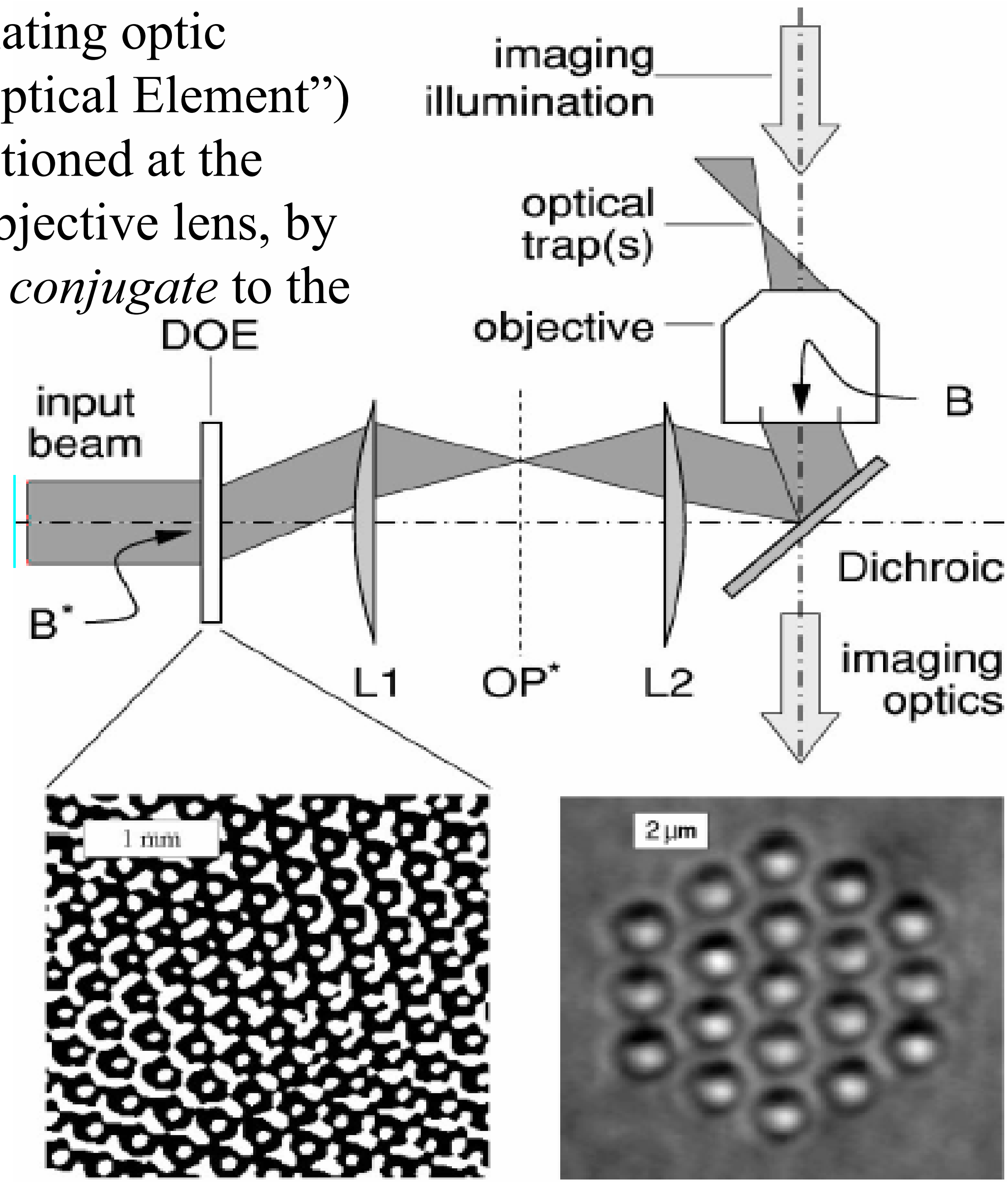
Hologram of “IWU Window”



Sculpting Optical "Landscapes"

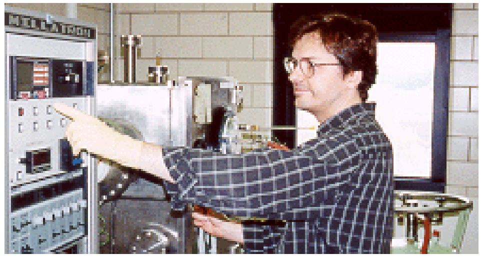


The phase modulating optic (a “Diffracting Optical Element”) is *effectively* positioned at the entrance of the objective lens, by making the DOE *conjugate* to the back aperture

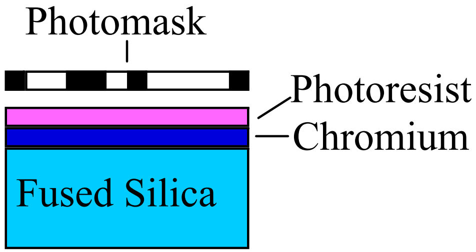


Rev. Sci. Instr. **72**, 1810

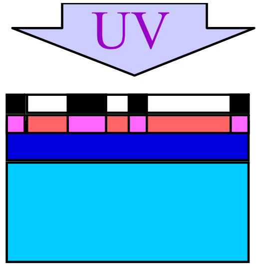
After a few minor steps, ...



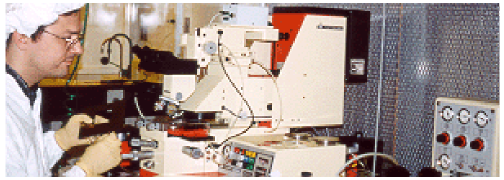
(a)



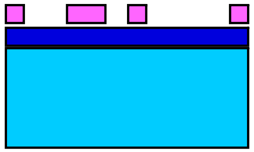
(b)



Expose Photoresist

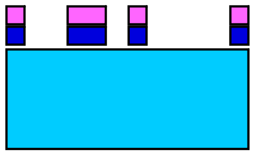


(c)



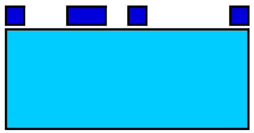
Develop Photoresist

(d)



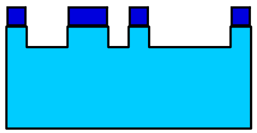
Etch Chromium

(e)



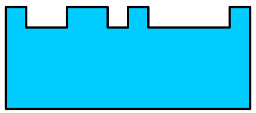
Remove Photoresist

(f)

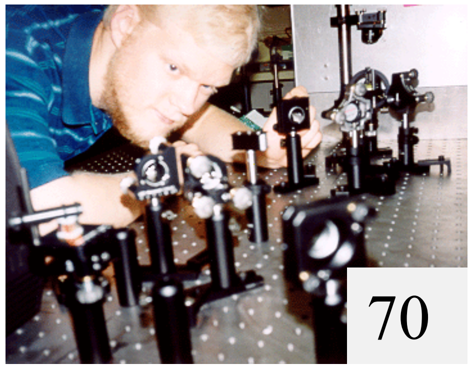


Etch Fused Silica

(g)

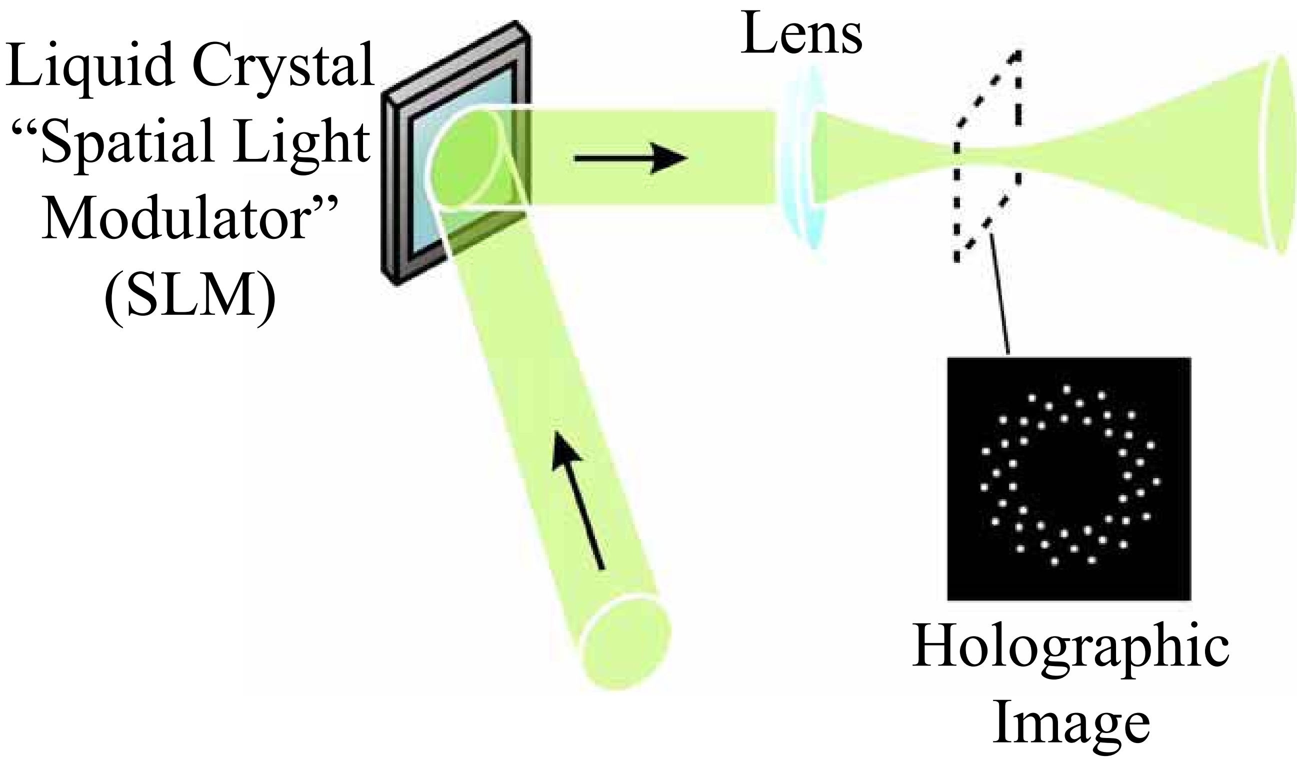


Remove Chromium



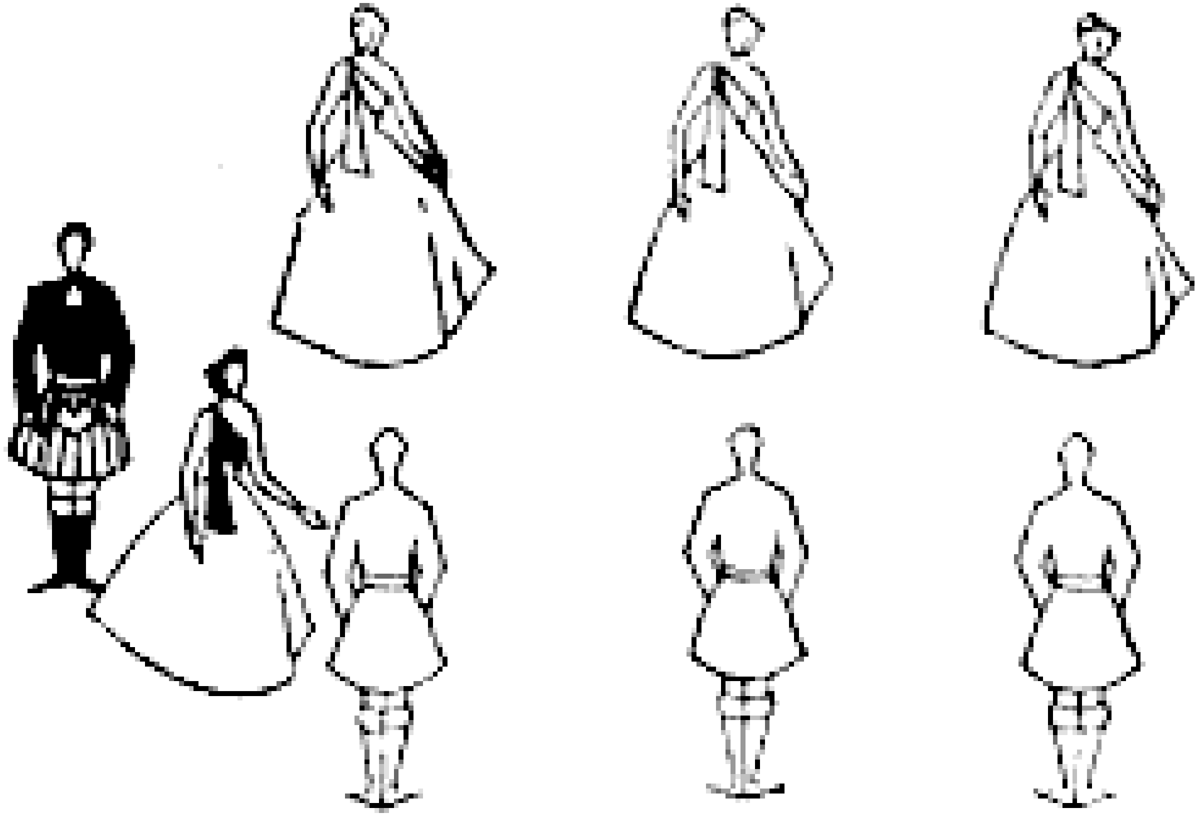
Dynamic control is possible through

Liquid Crystal Display Technology



SLM technology also allows for easy creation of beams with *novel* characteristics:

Scottish Country Dancing



http://www.geocities.com/Colosseum/Midfield/3705/StriptheWillow.htm

Multiple Traps 2:

What happens when students with too much time on their hands…

Physically Split **the laser beam:**

"Strip the Willow" (a traditional Scottish dance)

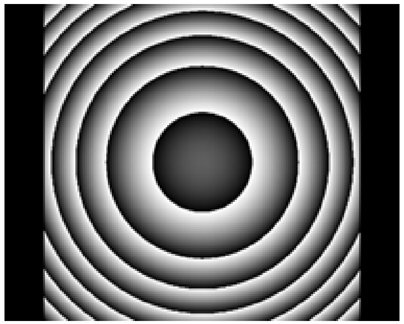
StripTheWillow.mp4

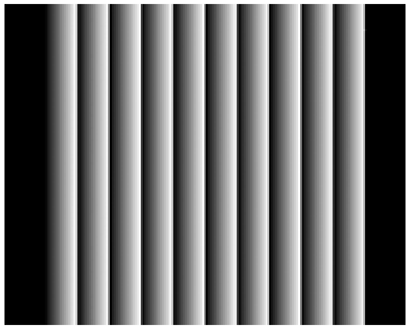
Attach\Strip_The_Willow_USTAN1.avi

Phase-only holograms have been used to simultaneously create hundreds of traps, (though sophisticated control has only been shown with smaller ensembles).

Simple Phase Profiles (as at left) can be added (modulo 2π) to steer traps in *three* dimensions

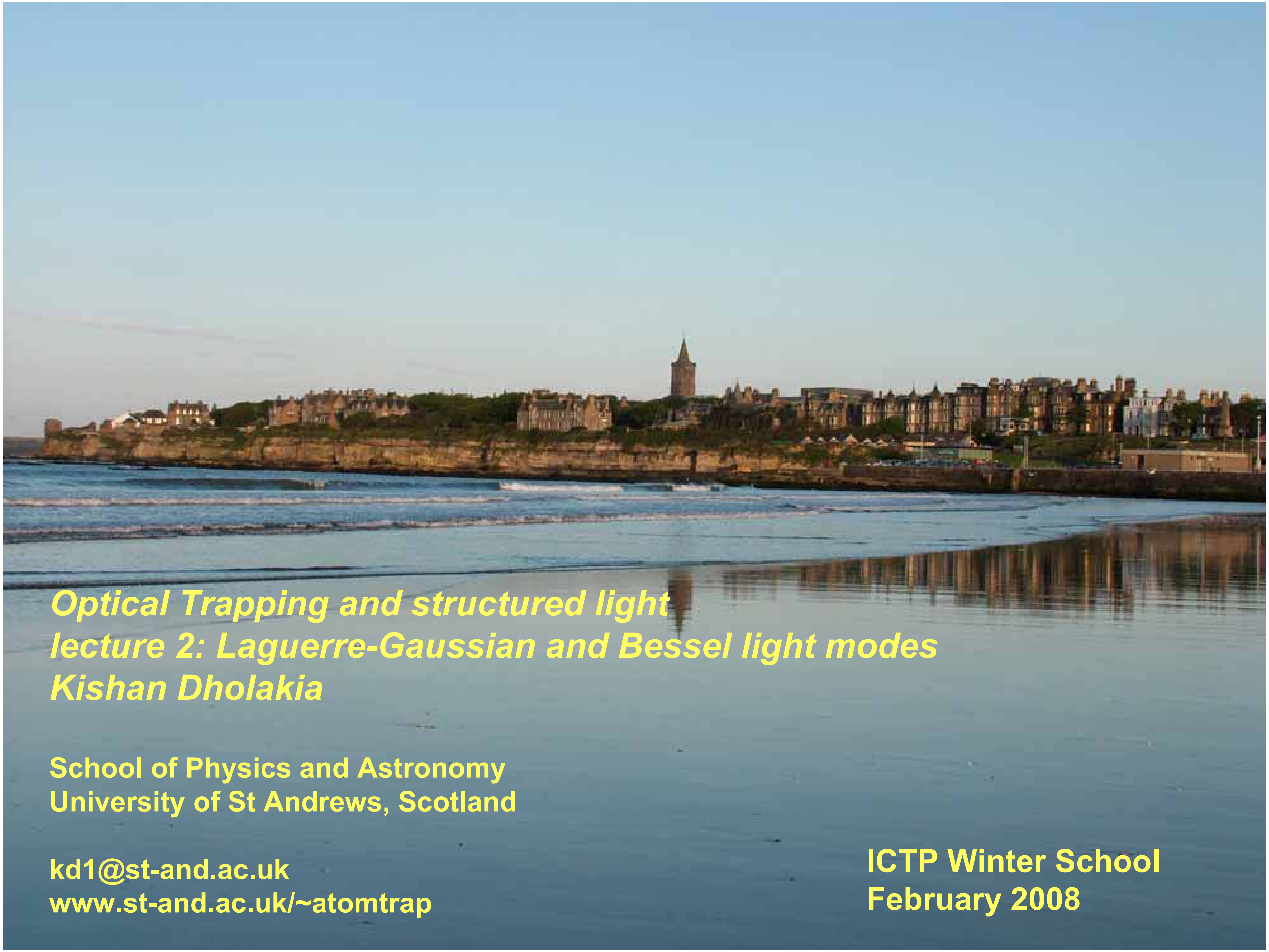
Fresnel Lens





Blazed Grating

Video from j Courtial and Miles Padgett group, Univ. of Glasgow



Optical Trapping and structured light
lecture 2: Laguerre-Gaussian and Bessel light modes
Kishan Dholakia

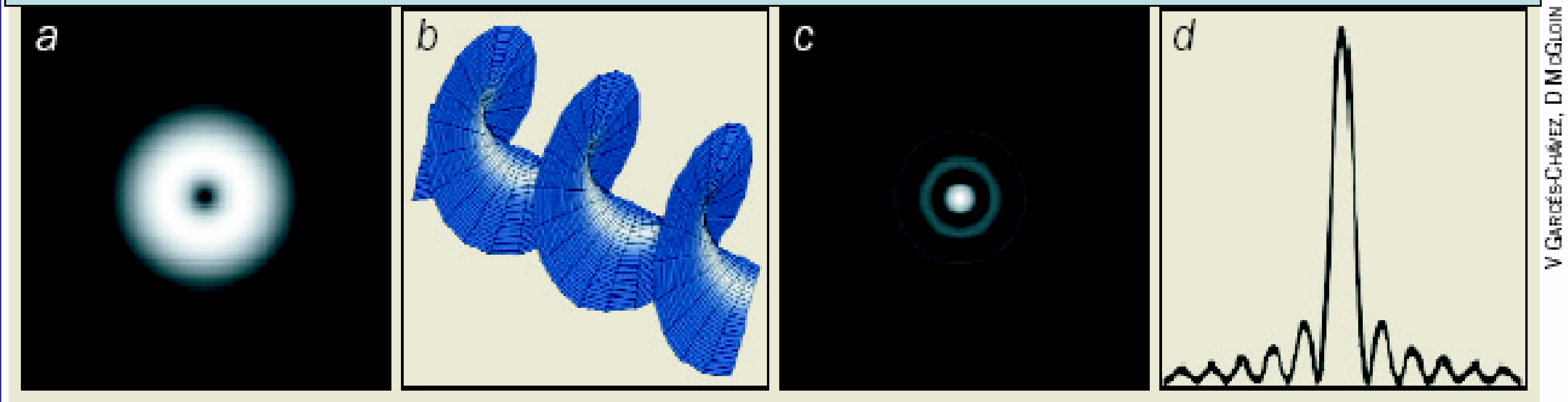
School of Physics and Astronomy
University of St Andrews, Scotland

kd1@st-and.ac.uk
www.st-and.ac.uk/~atomtrap

ICTP Winter School
February 2008

Introductory Reference: Dholakia, Spalding, MacDonald, *Physics World*, Oct. 2002

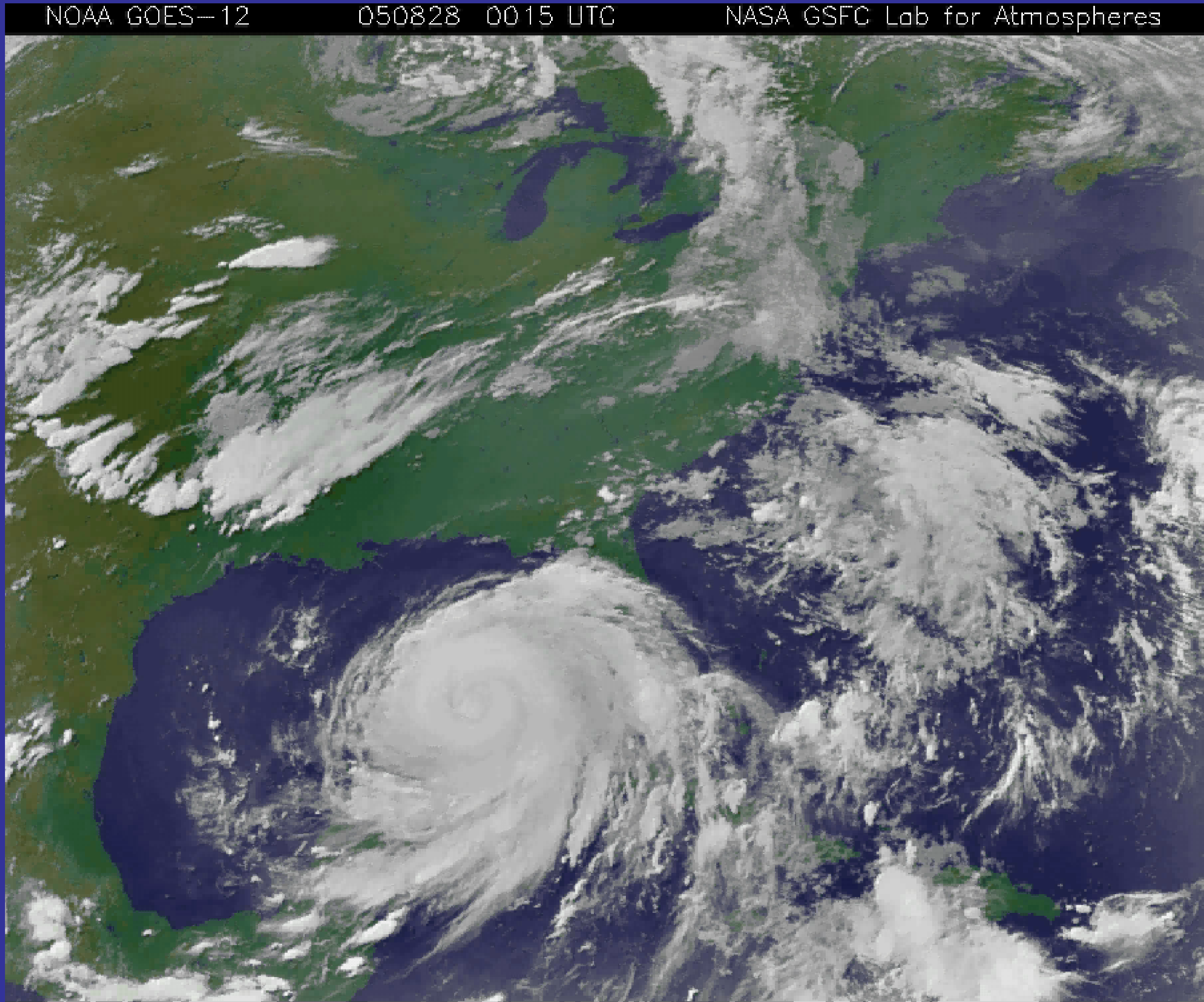
Novel Beams Extend the Optical "Toolkit"



Beams used in optical traps need not be Gaussian.

(*a*) Laguerre-Gaussian (LG) optical modes have helical wavefronts (*b*), which - in addition to polarization - control the *angular momentum* transmitted to a trapped particle. Trap low index particles.

(*c*, *d*) Bessel beams have a *number* of special properties useful in particle manipulation.



Credit G Swartzlander, Tucson, Arizona

Credit: NASA Langley Research Center (NASA-LaRC). Wake vortex study at Wallops Island

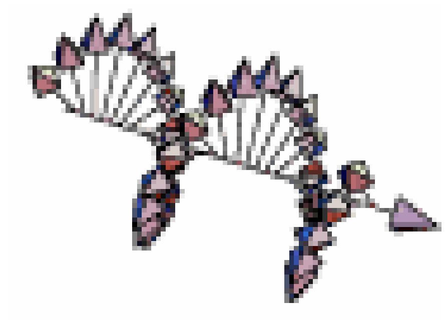
The angular momentum of light

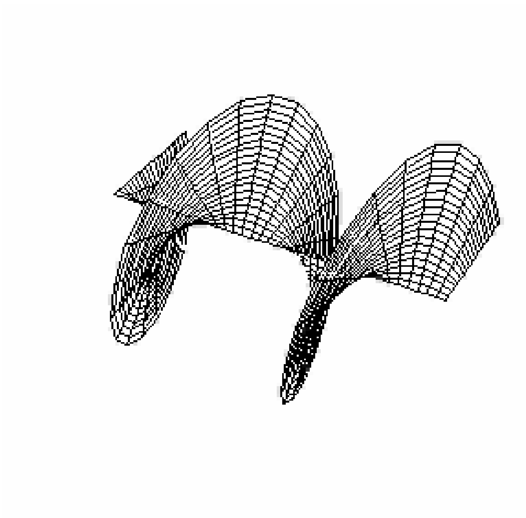
$$j = \varepsilon_o \left[r \times \langle E \times B \rangle \right]$$

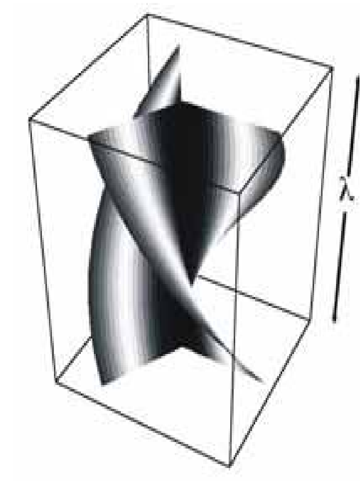
L. Allen et al PRA, **45**, 8185 (1992)

Spin: due to polarisation state (rotating E-field)

Orbital: due to inclined wavefronts

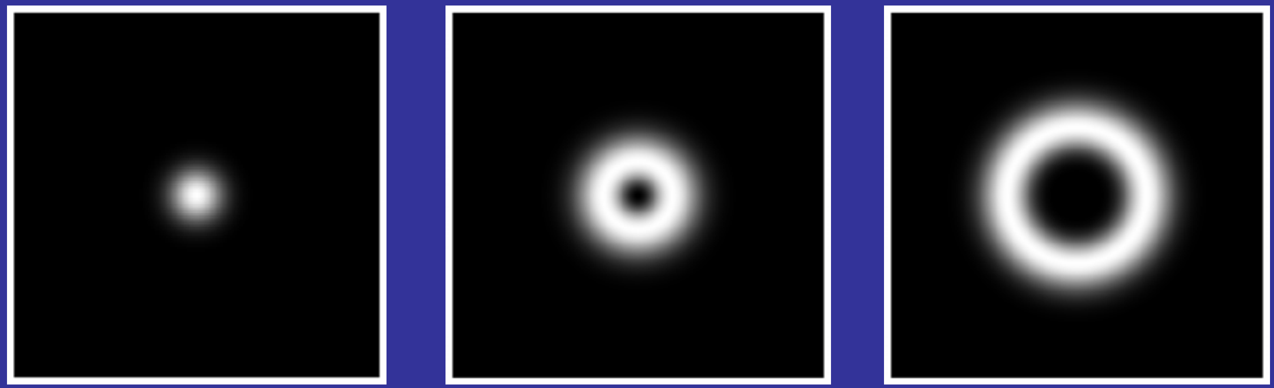




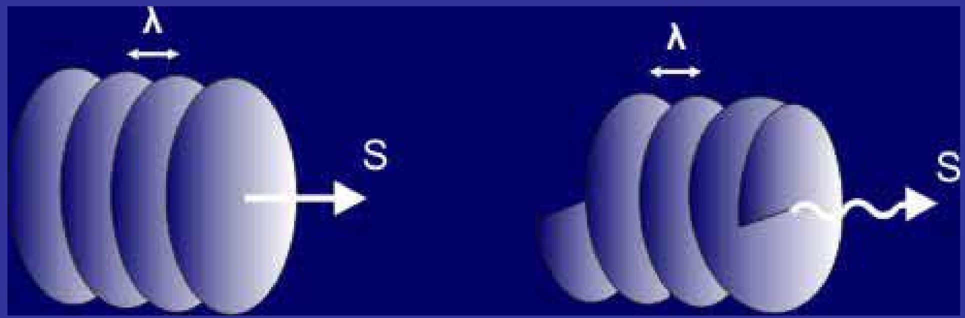


Laguerre-Gaussian modes: an optical vortex

- **circularly symmetric modes, characterised by**
  - **radial mode index *p***
  - **azimuthal mode index *l*   (determines helicity): *<u>this leads to helical wavefronts and orbital angular momentum</u>***

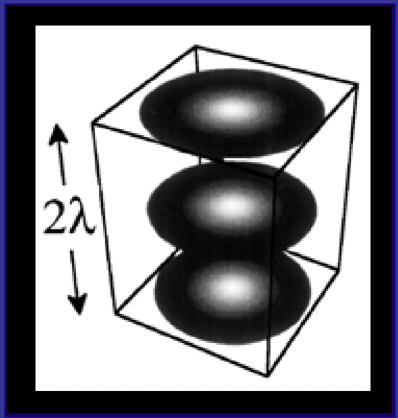


$p = 0, l = 0$ $p = 0, l = 1$ $p = 0, l = 4$

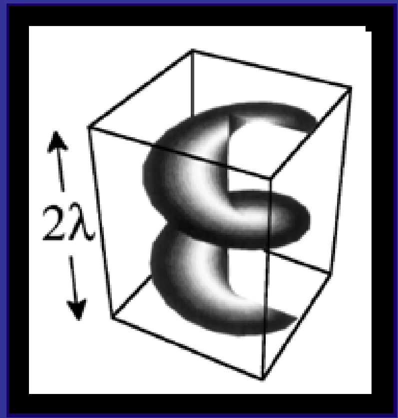


*L. Allen et al., PRA **45**, 8185 (1992)*

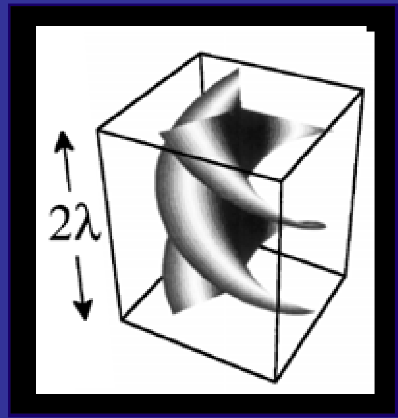
Laguerre-Gaussian modes



l = 0



l = 1

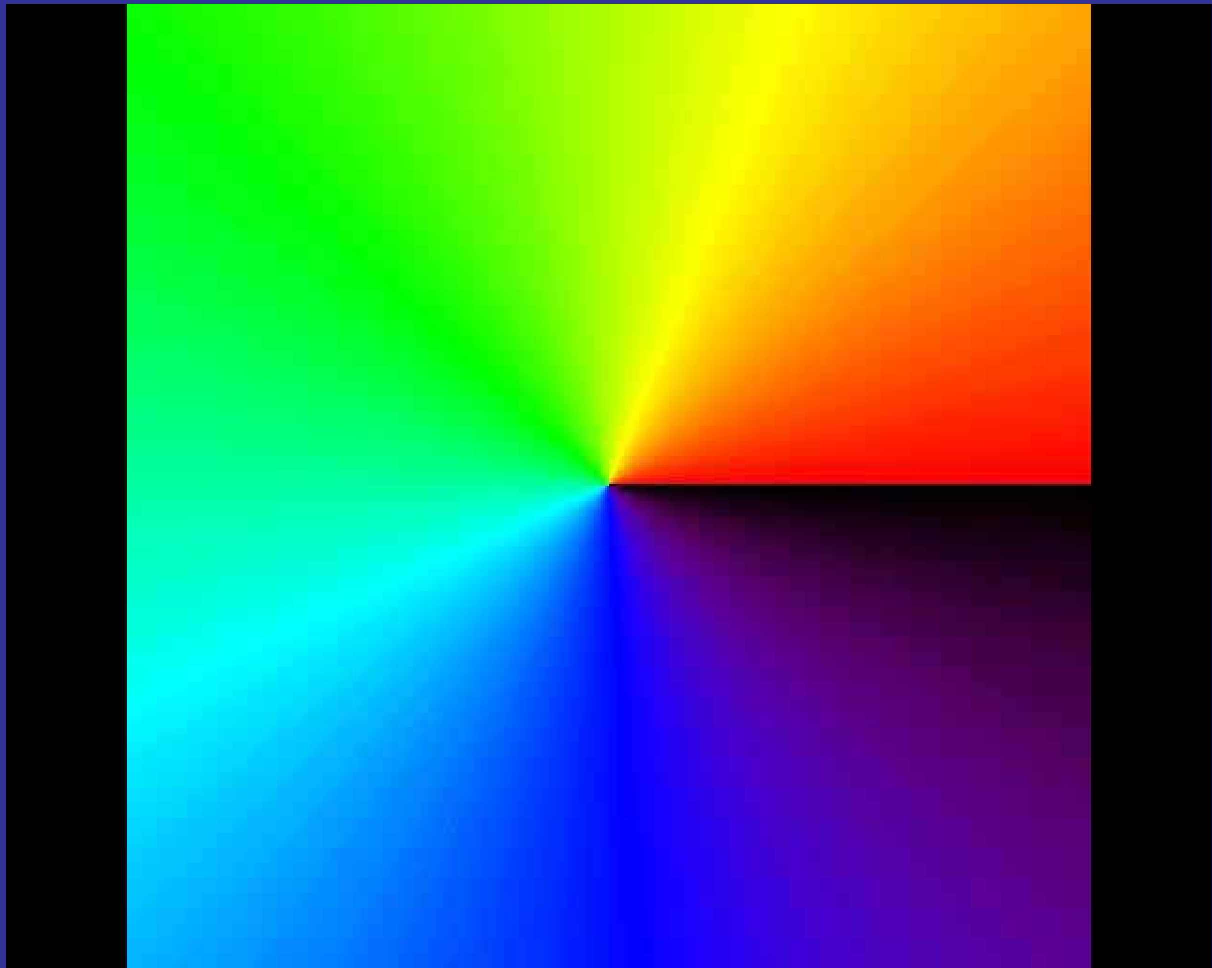


l = 3

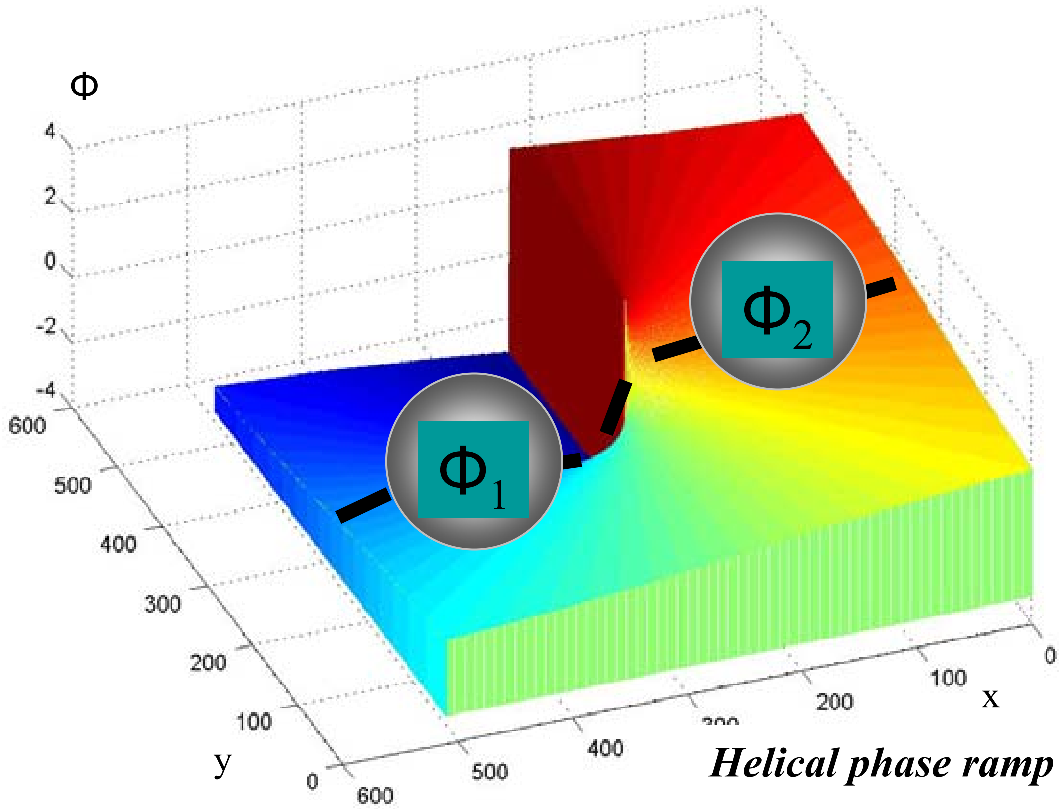
$$E_p^l \propto \underbrace{e^{-il\phi}\, L_p^l\left[\frac{2r^2}{\omega^2}\right]\left(\frac{r\sqrt{2}}{\omega}\right)^l e^{-i\Psi(1+2p+l)}}_{Laguerre-Gaussian} \quad \underbrace{e^{-\frac{r^2}{\omega^2}}\, e^{-\frac{ikr^2}{2R}}}_{Gaussian}$$

J. Courtial et al., PhysRevLett 80, 3217, 1998

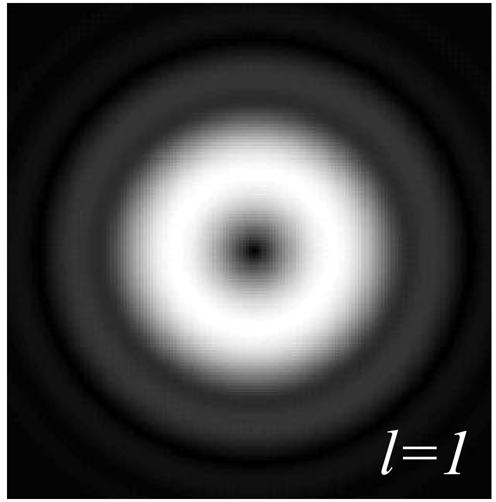
“Optical Vortex” Holograms



Here color represents *phase*, which is a periodic variable (0 - 2π)
so the horizontal line is *not* a discontinuity.



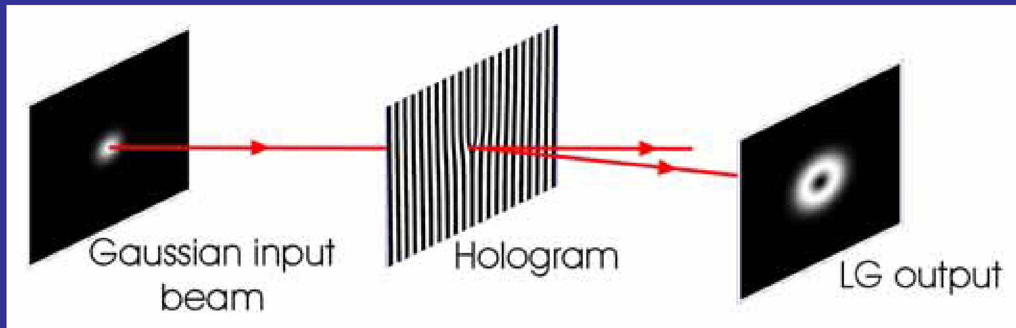
Helical phase ramp



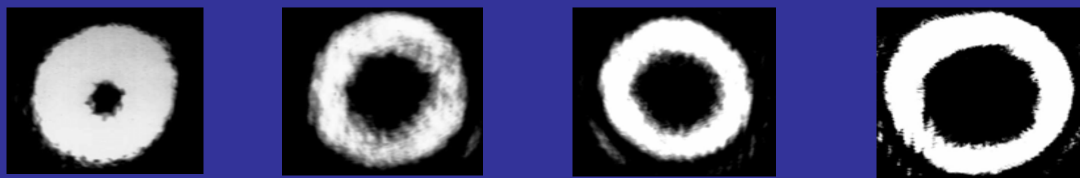
The phase difference at opposite ends of the LG is Φ_1- Φ_2= π (for a single helical phase ramp).

Generating LG beams

- They can be produced using computer generated holograms



- $$E_p^l \propto \underbrace{e^{-il\phi} L_p^l\left[\frac{2r^2}{\omega^2}\right]\left(\frac{r\sqrt{2}}{\omega}\right)^l e^{-i\Psi(1+2p+l)}}_{Laguerre-Gaussian}\ \underbrace{e^{-\frac{r^2}{\omega^2}}\, e^{-\frac{ikr^2}{2R}}}_{Gaussian}$$

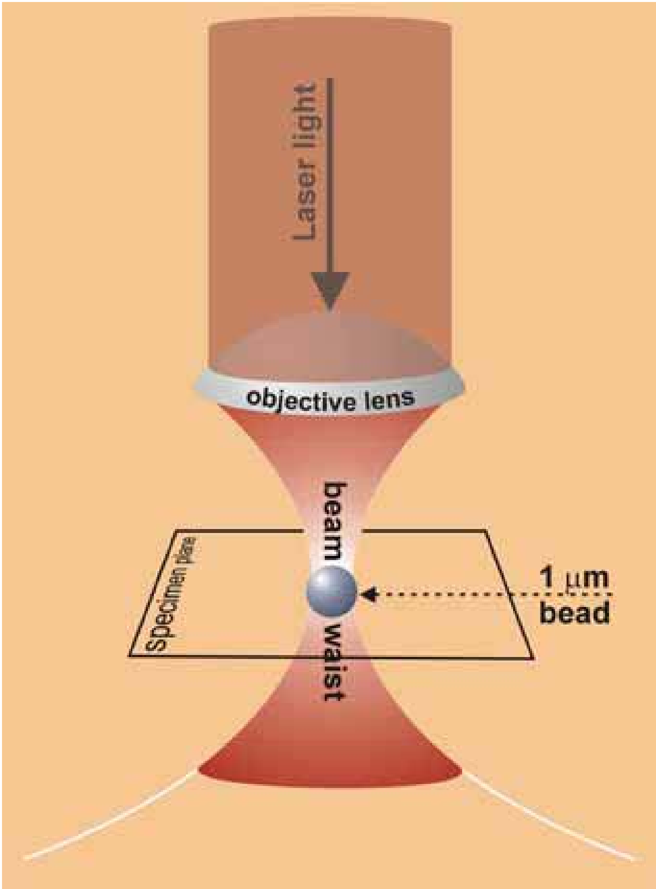


l=1 l=2 l=3 l=6

Enhancing the optical toolkit: rotation and optical angular momentum

1. Transfer spin or orbital angular momentum
2. Asymmetric or rotating light patterns (better?)

Studies of light



Micromachines

Orienting bio-matter

microfluidics

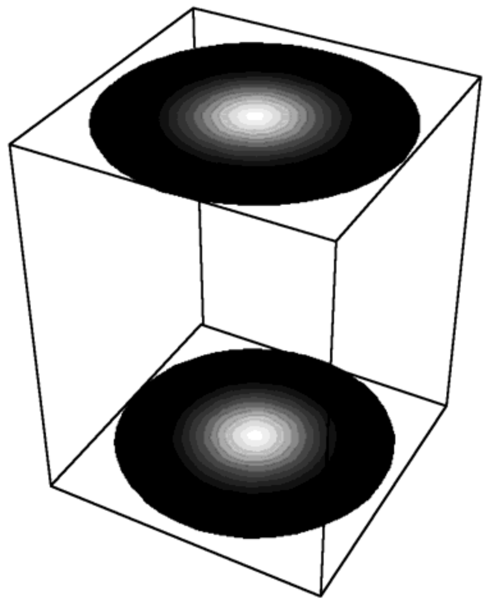
novel hydrodynamics and microrheology

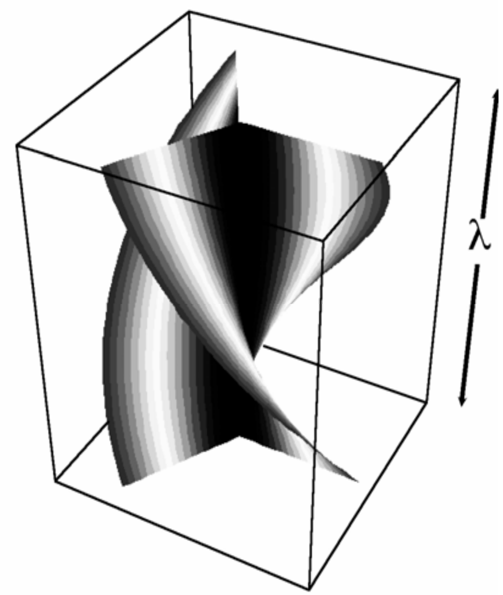
Laguerre-Gaussian Light beams

- Helical phase front (compare a plane wave)

- Poynting vector **S** follows a helical path

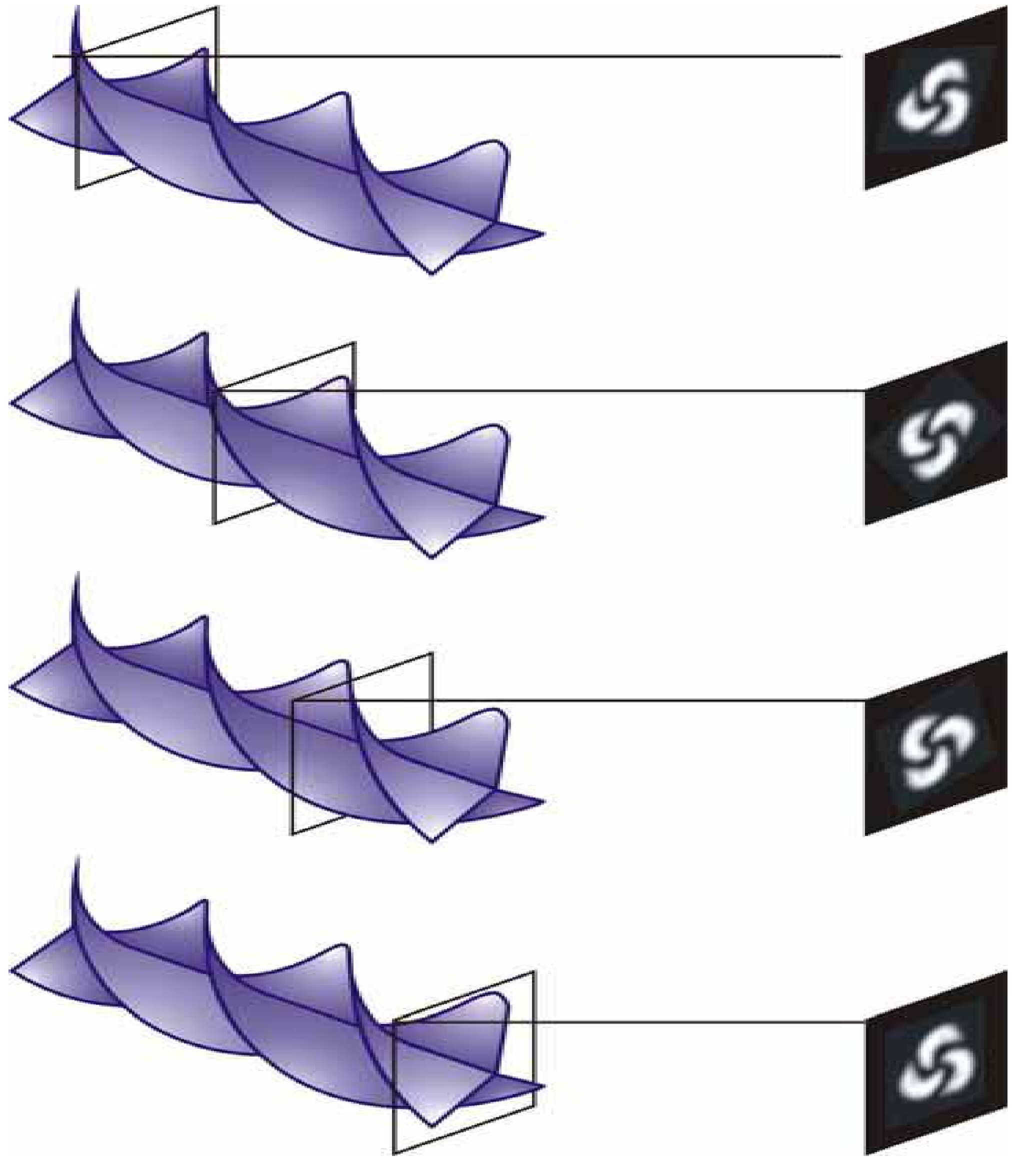
→ **Orbital angular momentum**



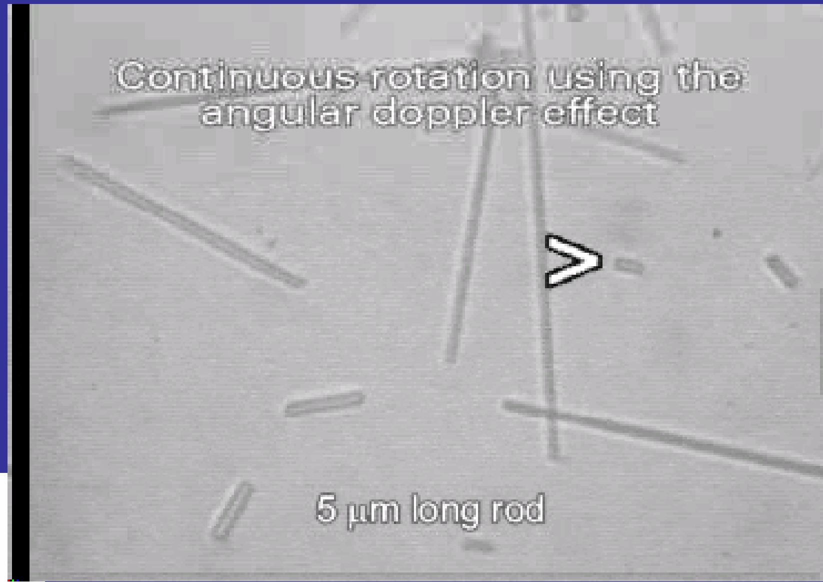


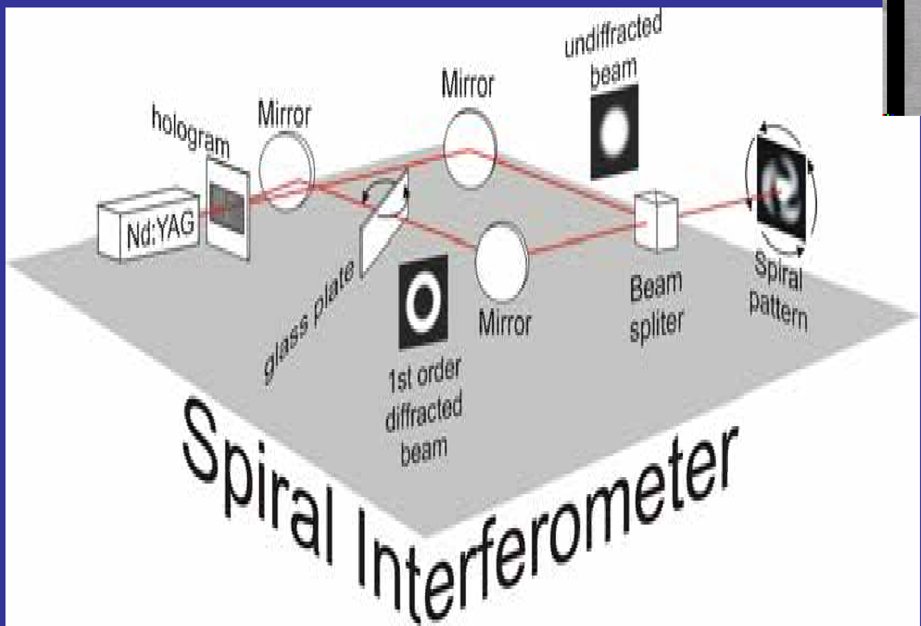
Rotation using OAM: He et al, PRL 1995 (absorption); Rotation with spin AM: Friese et al. Nature 1998 (birefringent)

Interference creates a rotating spiral pattern



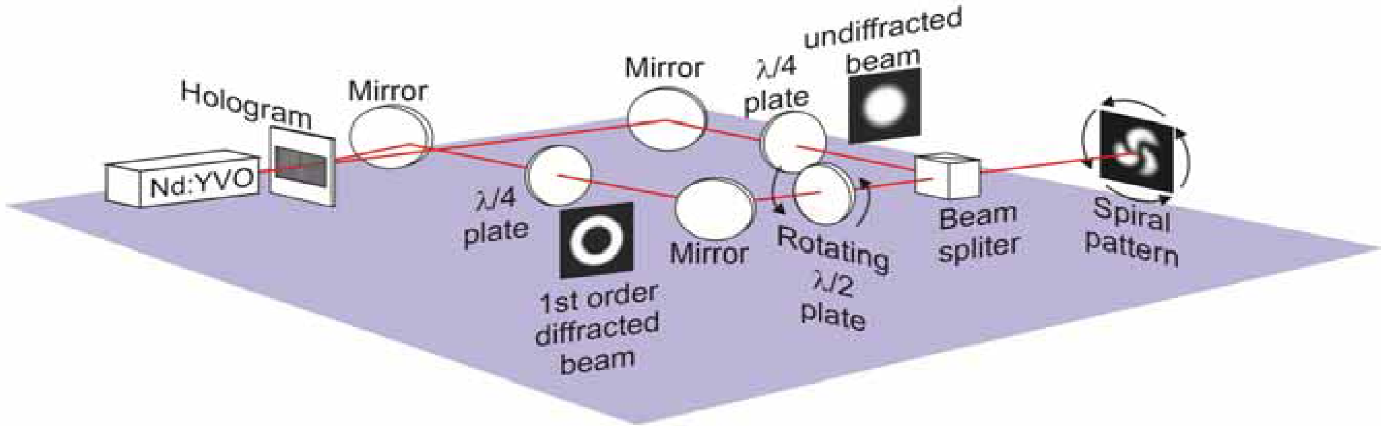
Visualising and using the helical wavefront



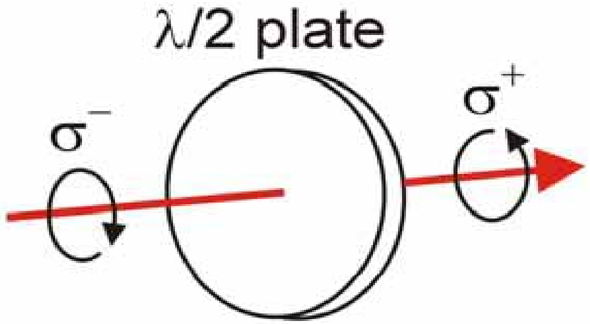


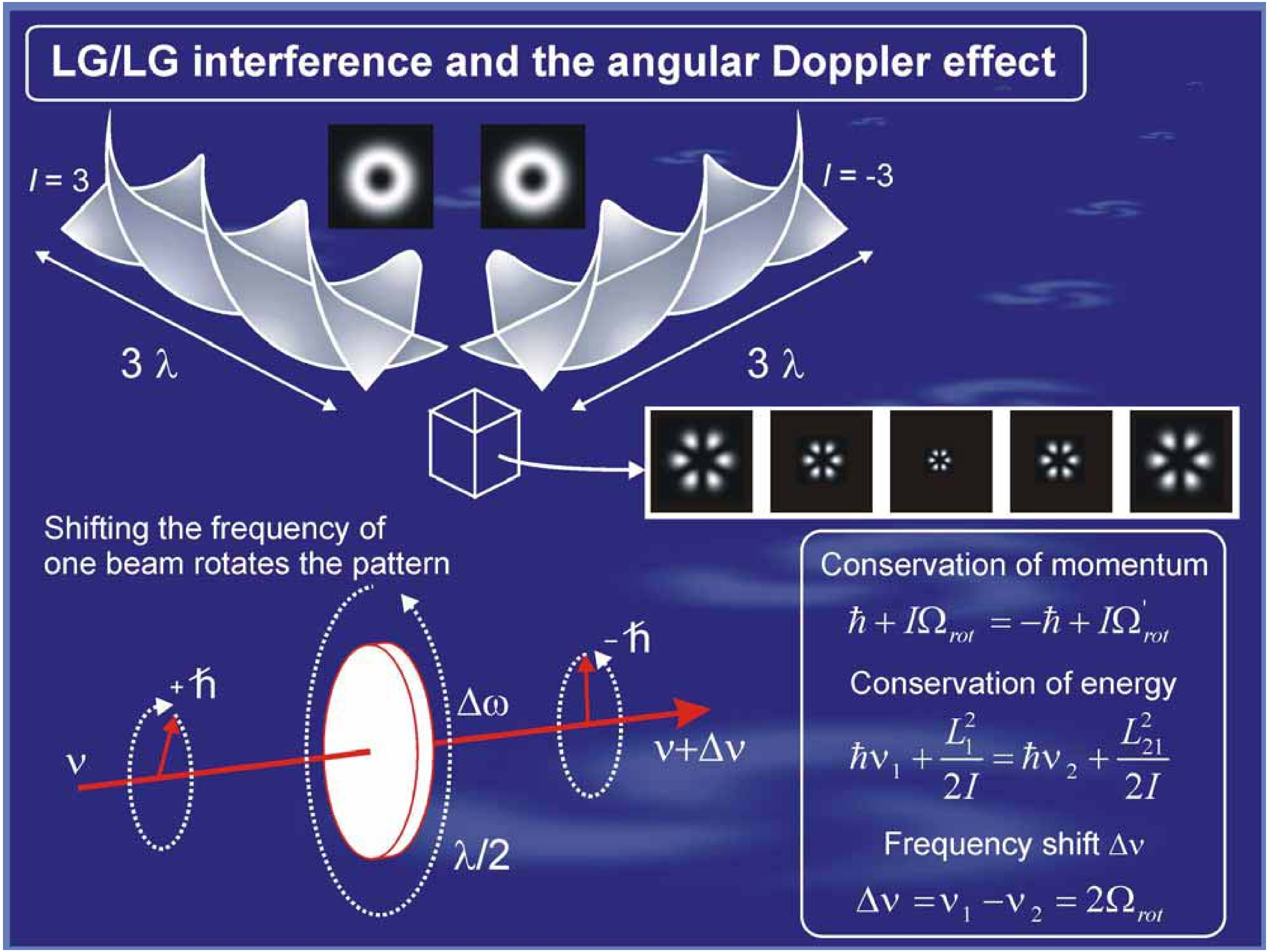
- May be used for rotation: Science **292**, 912 (2001) and 3D structures: Science **296**, 1101 (2002). Naturally such rotation may be achieved with other rotating light patterns.

The Angular Doppler Effect; continuous rotation of particles



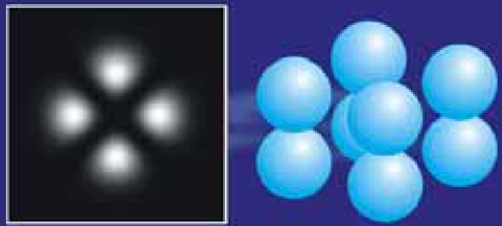
Frequency of light shifts going through a rotating half-wave plate. The frequency difference between the two arms results in pattern rotation.



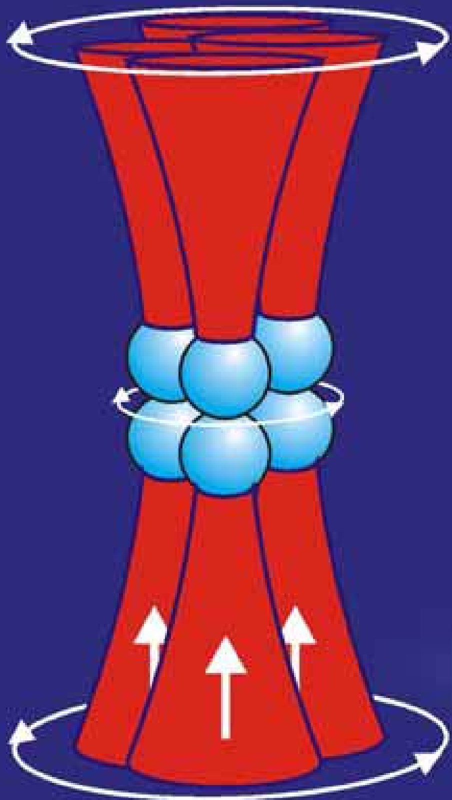

LG/LG interference and the angular Doppler effect
l = 3
l = -3
3 λ
3 λ
Shifting the frequency of
one beam rotates the pattern
+ħ
ν
Δω
λ/2
- ħ
ν+Δν
Conservation of momentum
$\hbar + I\Omega_{rot} = -\hbar + I\Omega'_{rot}$
Conservation of energy
$\hbar\nu_1 + \frac{L_1^2}{2I} = \hbar\nu_2 + \frac{L_{21}^2}{2I}$
Frequency shift Δν
$\Delta\nu = \nu_1 - \nu_2 = 2\Omega_{rot}$

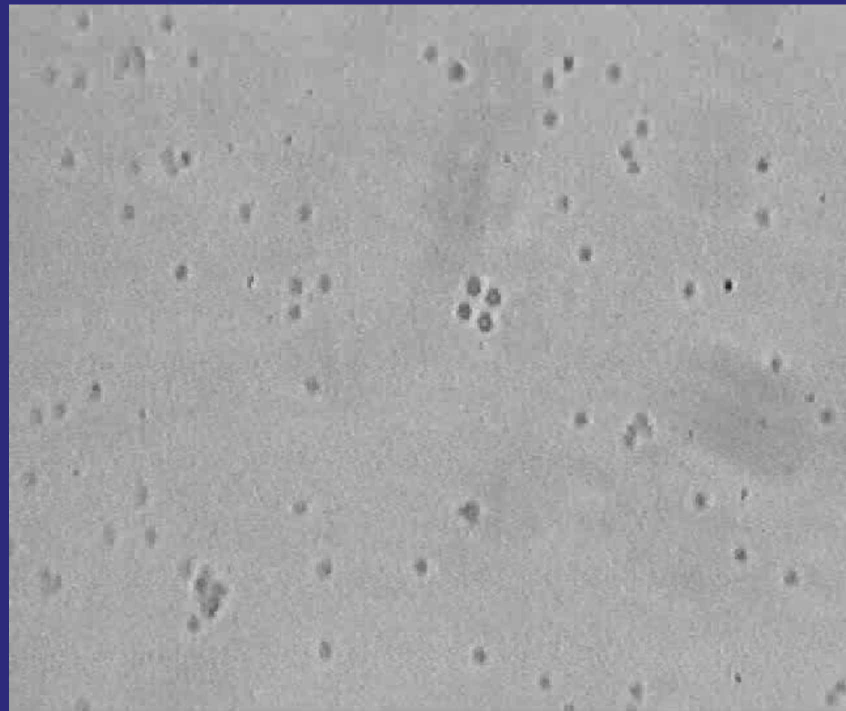
Creation of 3D structures

LG $l = 2 + l = -2$

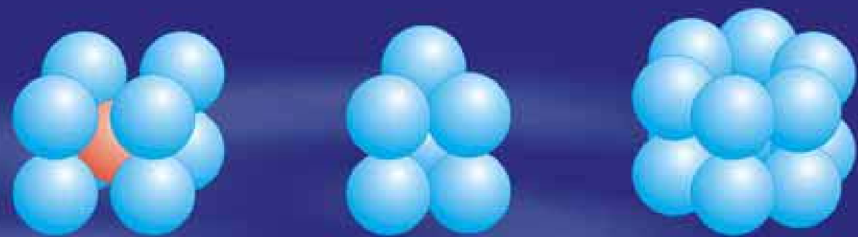


simple cubic structure





other unit cells



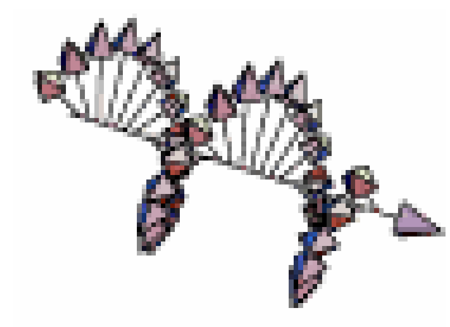
Science, vol296, 1101 (2002)

The angular momentum of light

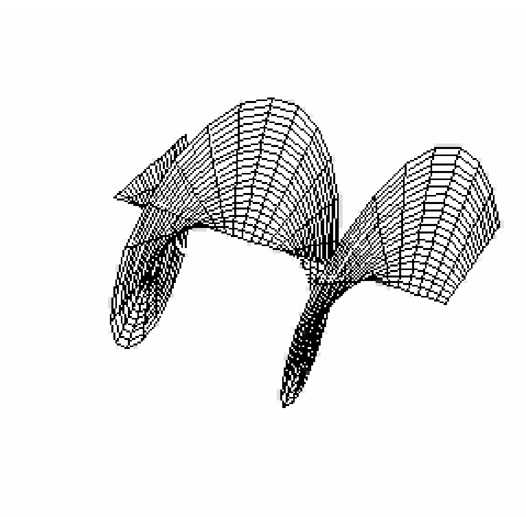
$$j = \varepsilon_o \left[r \times \langle E \times B \rangle \right]$$

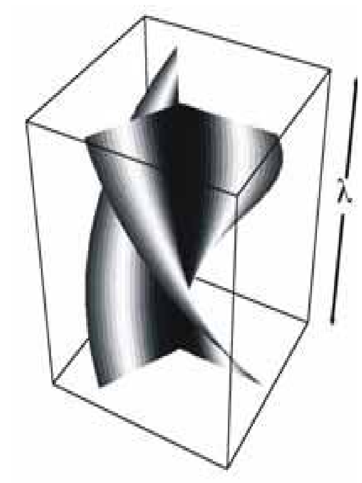
L. Allen et al PRA, **45**, 8185 (1992)

Spin: due to polarisation state (rotating E-field)



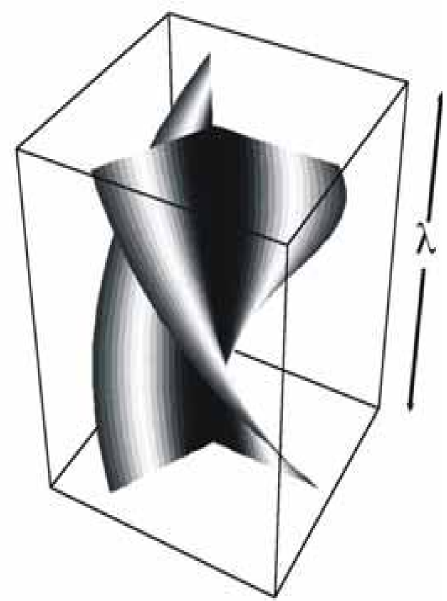
Orbital: due to inclined wavefronts





How can we transfer optical angular momentum?

- Absorption can work
- Scattering from an inclined wavefront (orbital) and possibly spin
- Spin: birefringence
- Orbital: astigmatism



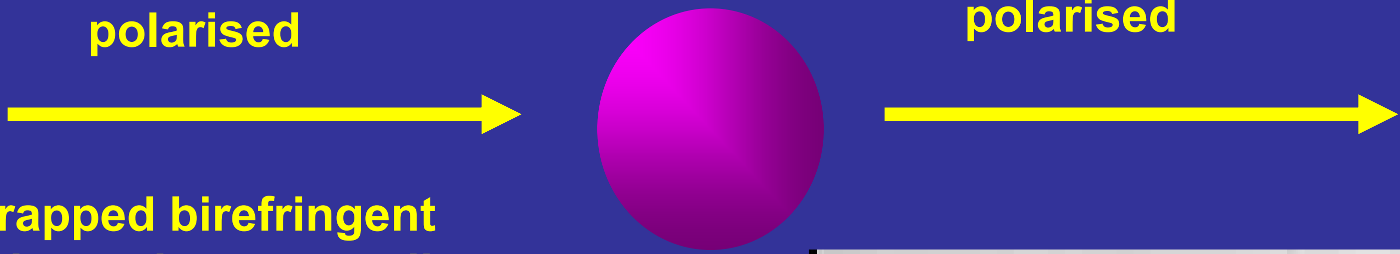
Two original papers:

He et al., Phys Rev Lett (1995) – OAM transfer by absorption

Friese et al. Nature (1998) – spin AM transfer by birefringence

Rotation using birefringence

RH circularly polarised

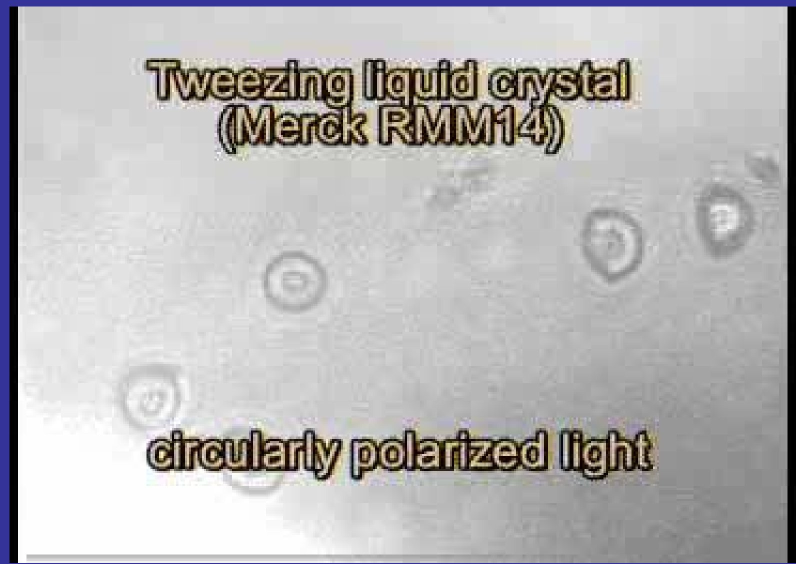


LH circularly polarised

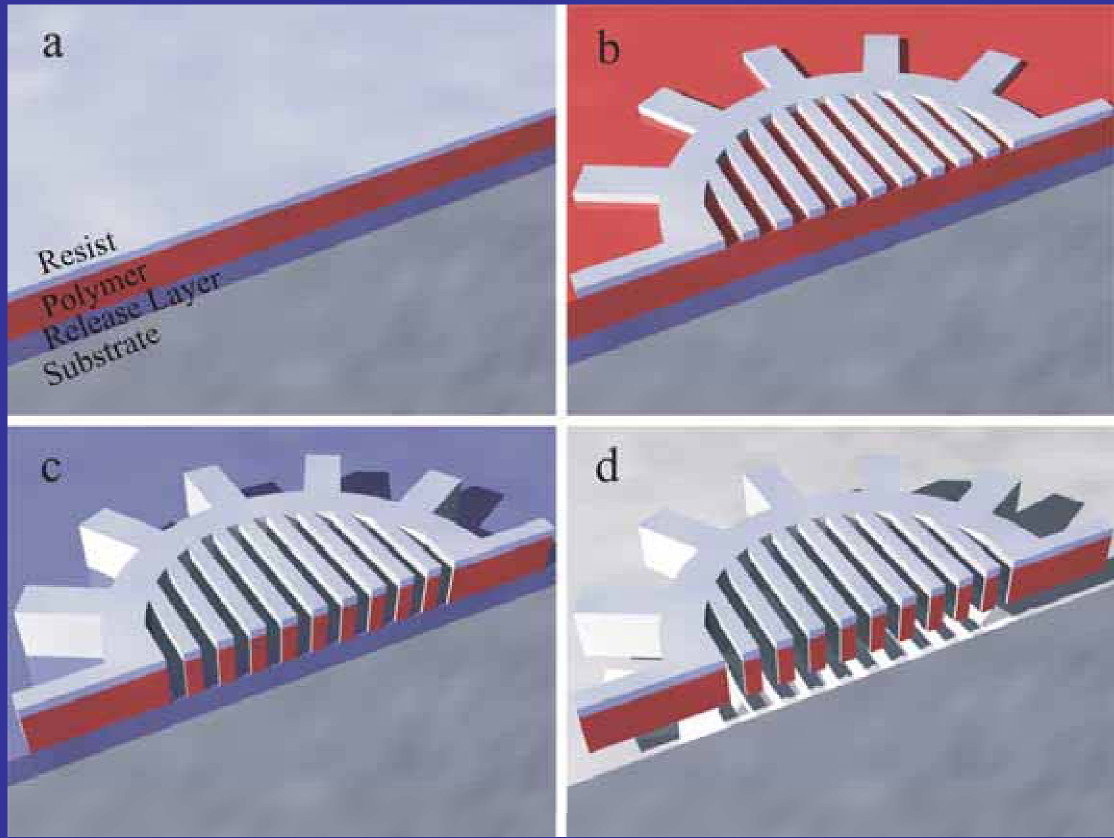
Trapped birefringent microsphere: acts like a waveplate

$2\hbar$ Per photon transferred

$$\phi = \frac{2\pi}{\lambda}(n_e - n_o)d$$

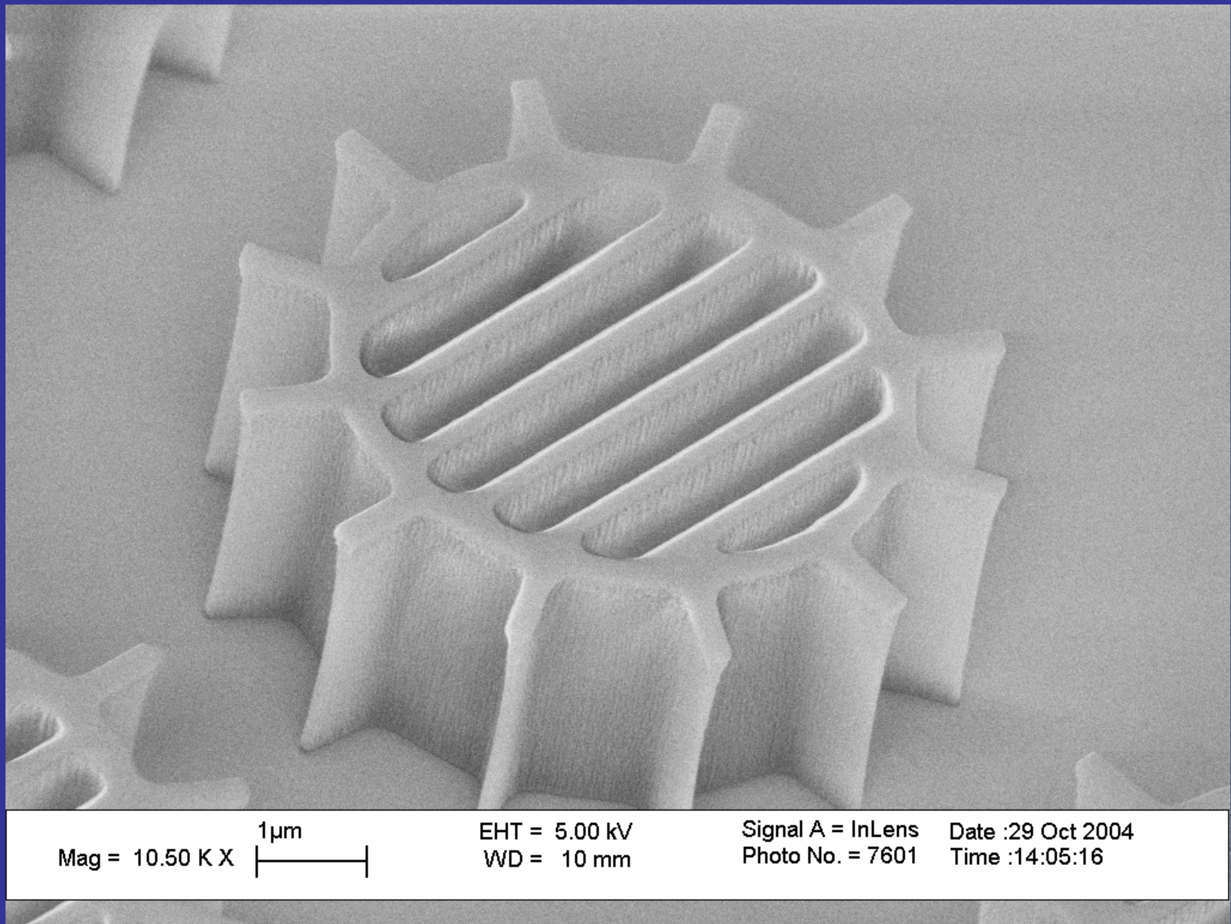


Plus points: no need for complex beam shapes, fast rotation rates: USEFUL FOR MICRORHEOLOGY: LOCAL VISCOSITY



Fabrication of a microgear. a, Substrate with release layer, polymer layer and resist layer spun on. **b**, The resist layer is patterned by e-beam lithography. **c**, The pattern is transferred into the polymer by reactive ion etching. **d**, The microgear is released by dissolving the release layer.

Use of form birefringence for cogs

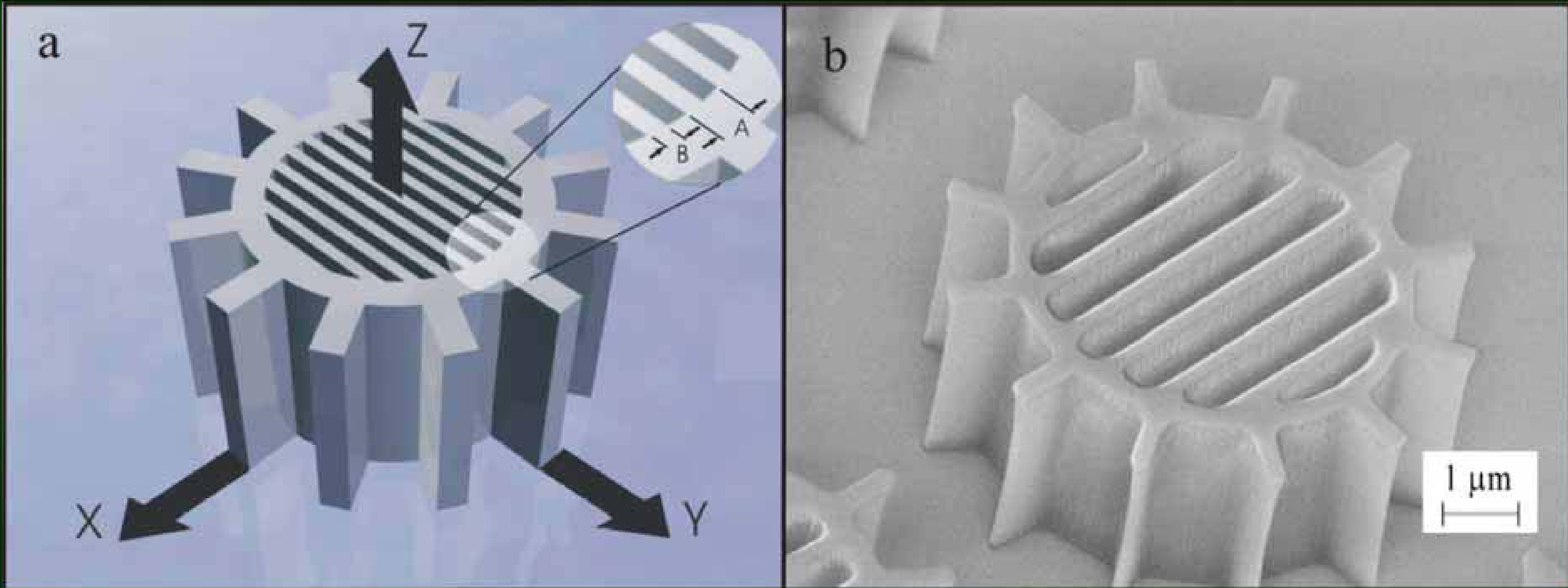


A birefringence induced by writing a special structure

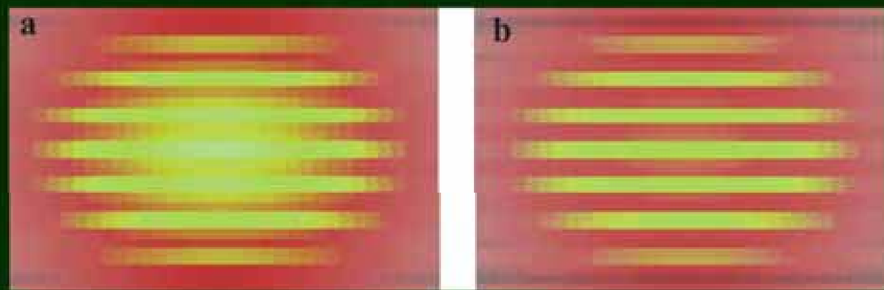
Form birefringence of rods: Bishop et al., PRA 68, 033802-1 (2003). Indirect cog rotation by Friese et al APL **78**, 547 (2001)

Microfluidic actuators - form birefringent cogs

Microfluidic systems require a range of actuators including pumps and mixers. Two examples we have been building are positive displacement pumps and diaphragm pumps.



By fabricating a 1D photonic crystal into a microgear we are able to manufacture a form birefringence. This birefringence can be used to transfer spin angular momentum from a circularly polarised laser beam to make a cog rotate

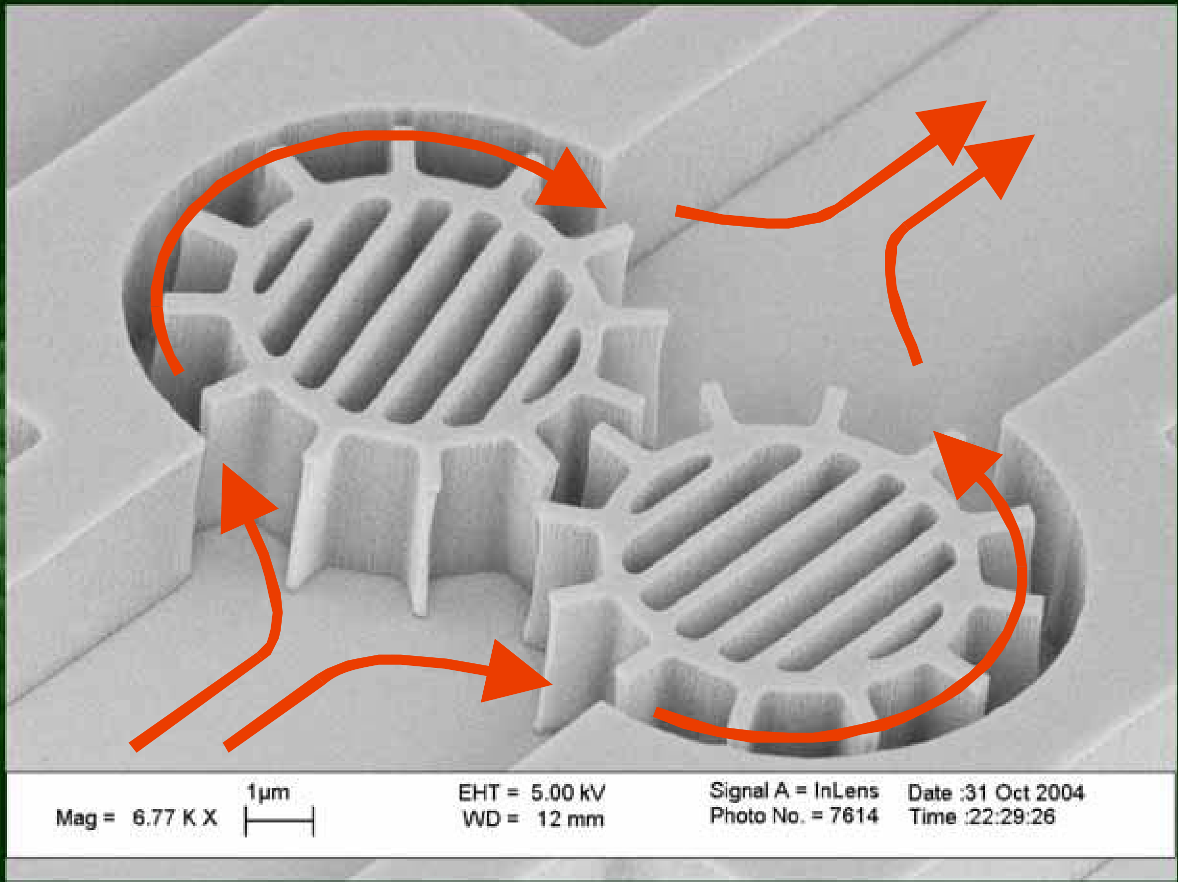


TE mode in cog TM mode in cog

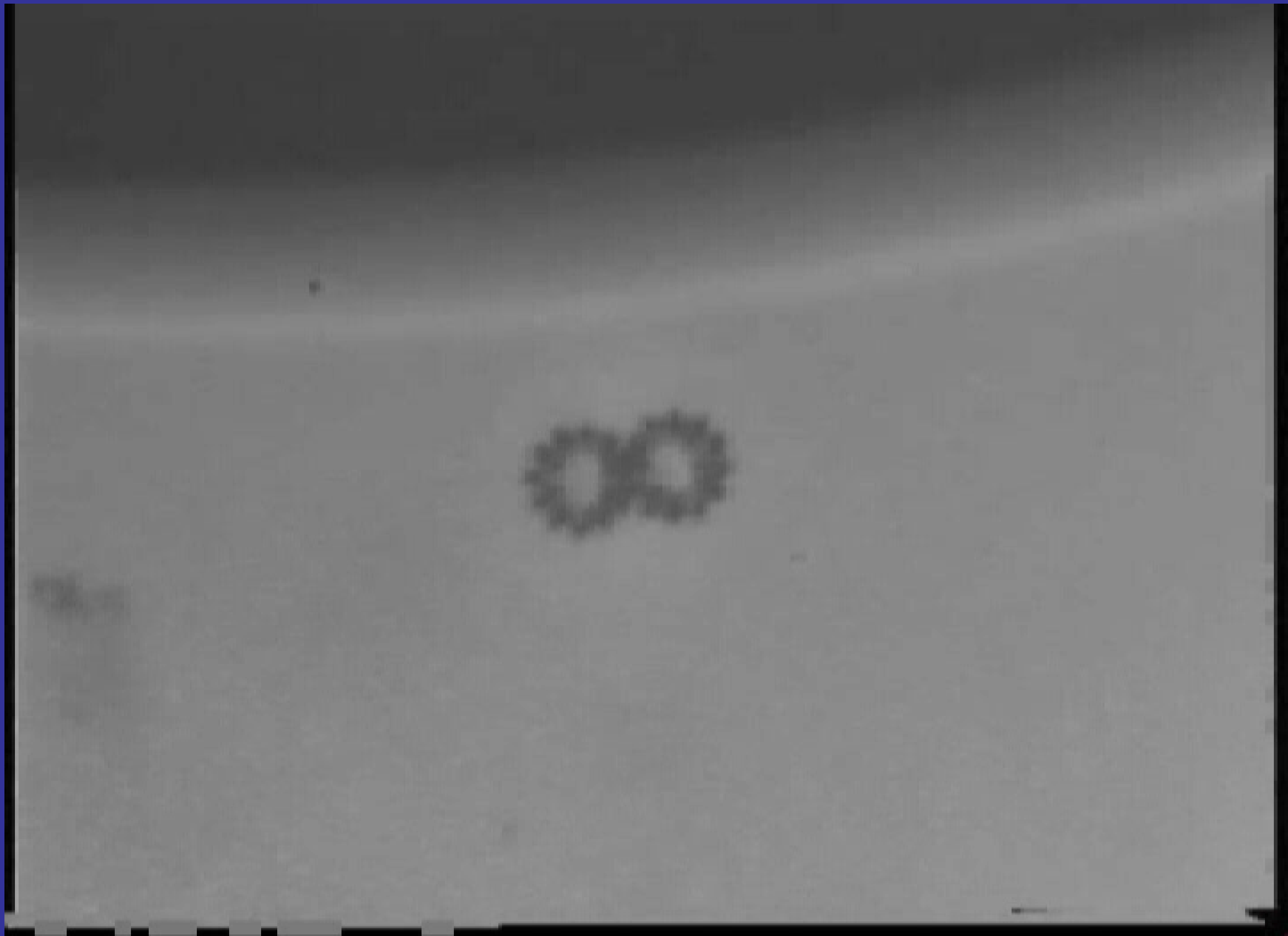
Form birefringent pumps

The requirement on the optics for rotating form birefringent cogs are very low such making it ideally suited to lab-on-a-chip integration.

By using AR coated silicon it might be possible to manufacture a bire-fringence an order of magnitude higher than that of calcite.



The speed of the cog can be controlled either by power or by using a controllably rotated linear polarisation where the cog continuously re-aligns to the direction of polarisation.



S. Neale et al., vol. 4, p530 Nature Materials (2005)New Folder\Marr1.mov

Light beams with angular momentum

Linear momentum density

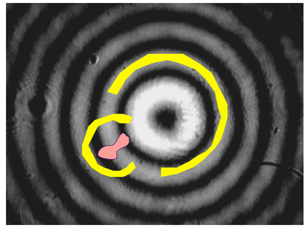
$$\mathbf{p} = \frac{\varepsilon_0}{2}\left(\mathbf{E}^* \times \mathbf{B} + \mathbf{E} \times \mathbf{B}^*\right) = i\omega\frac{\varepsilon_0}{2}\left(u^*\nabla u - u\nabla u^*\right) + \omega k\varepsilon_0 |u|^2 \mathbf{z} + \omega\sigma\frac{\varepsilon_0}{2}\frac{\partial |u|^2}{\partial r}\mathbf{\Phi}$$

$$u(r,\phi,z) = u(r,z)\exp(il\phi)$$

The cross product of this momentum density with a radius vector $\mathbf{r} \equiv (r,0,z)$ gives an angular momentum density. The angular momentum density in the z –direction depends upon the $\mathbf{\Phi}$ component of $\mathbf{p}$, such that

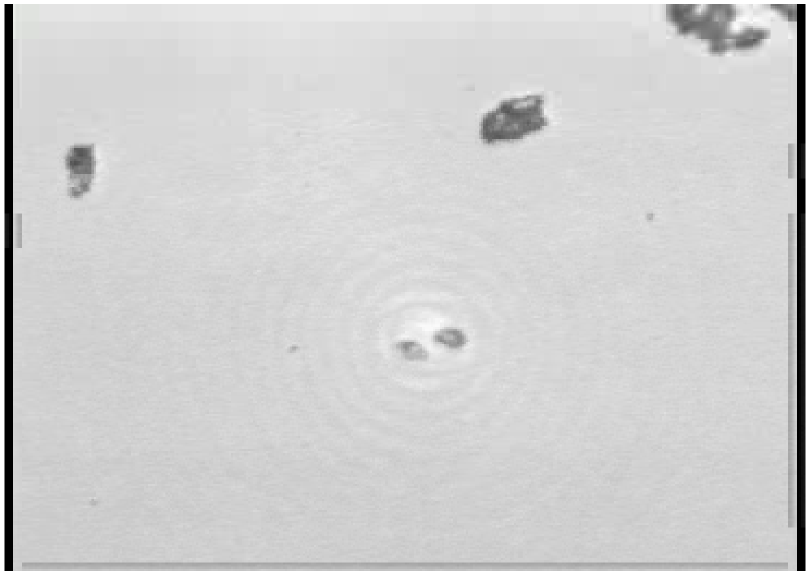
$j_z = rp_\phi$.

Simultaneous transfer of spin and orbital AM to an optically trapped birefringent particle.



Spin: rotation around particle axis (INTRINSIC)

Orbital: rotation around beam axis (EXTRINSIC or INTRINSIC)



Conclusive demonstration of intrinsic/extrinsic AM. Particle now a probe of local AM of the light field.

V. Garcés-Chávez et al., PRL **91**, 093602 (2003)

A.T. O'Neil et al., PRL **88**, 53601 (2002)

Trapping metal nanospheres

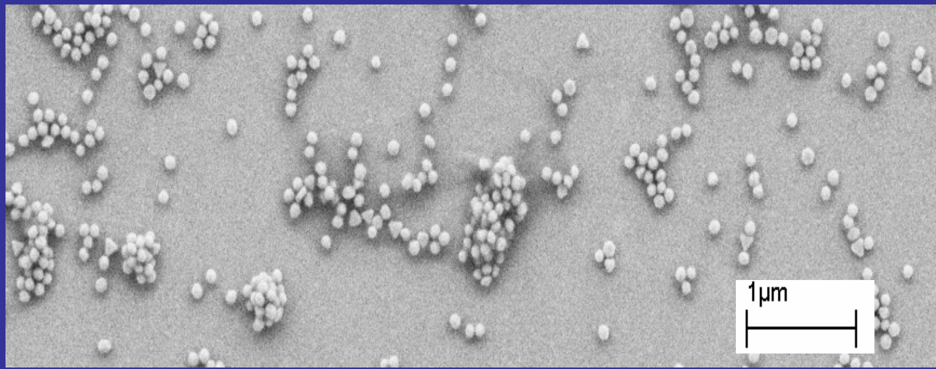
absorption force

$$F_{abs} = n_m < S > \frac{C_{abs}}{c}$$

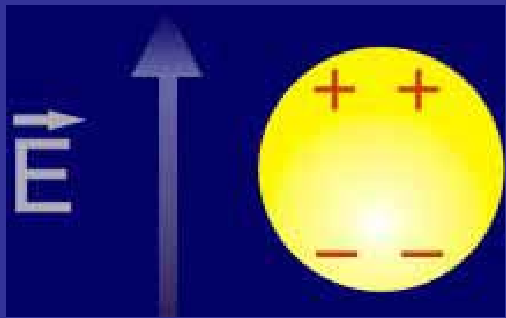
$$C_{abs} = \frac{2\pi n_m}{\lambda} \mathrm{Im}[\alpha]$$

$$\frac{F_{grad}}{F_{scat}} \propto \frac{F_{abs}}{F_{scat}} \propto \frac{1}{a^3}$$

Svoboda, Optics Letters 19, p930, 1994



polarisability



particle plasmon

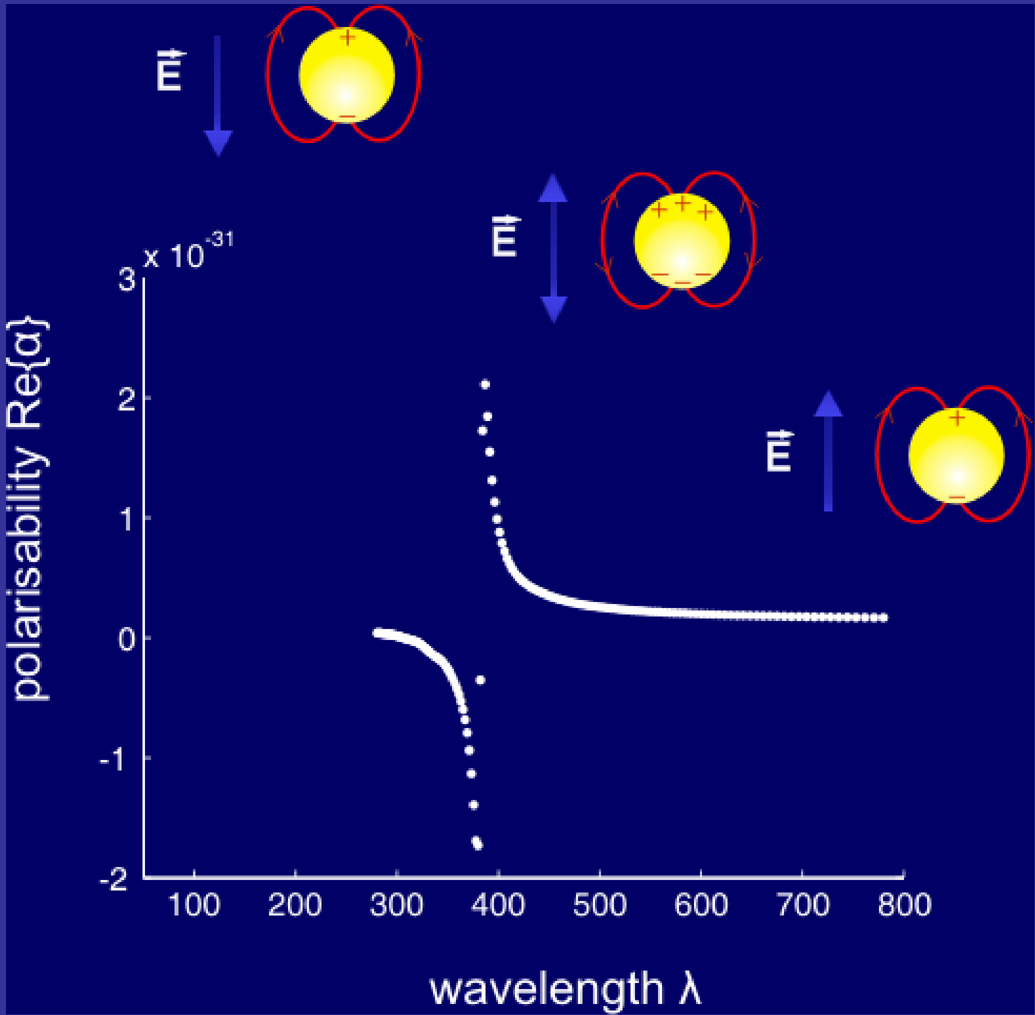
Trapping metal nanospheres

red-detuning

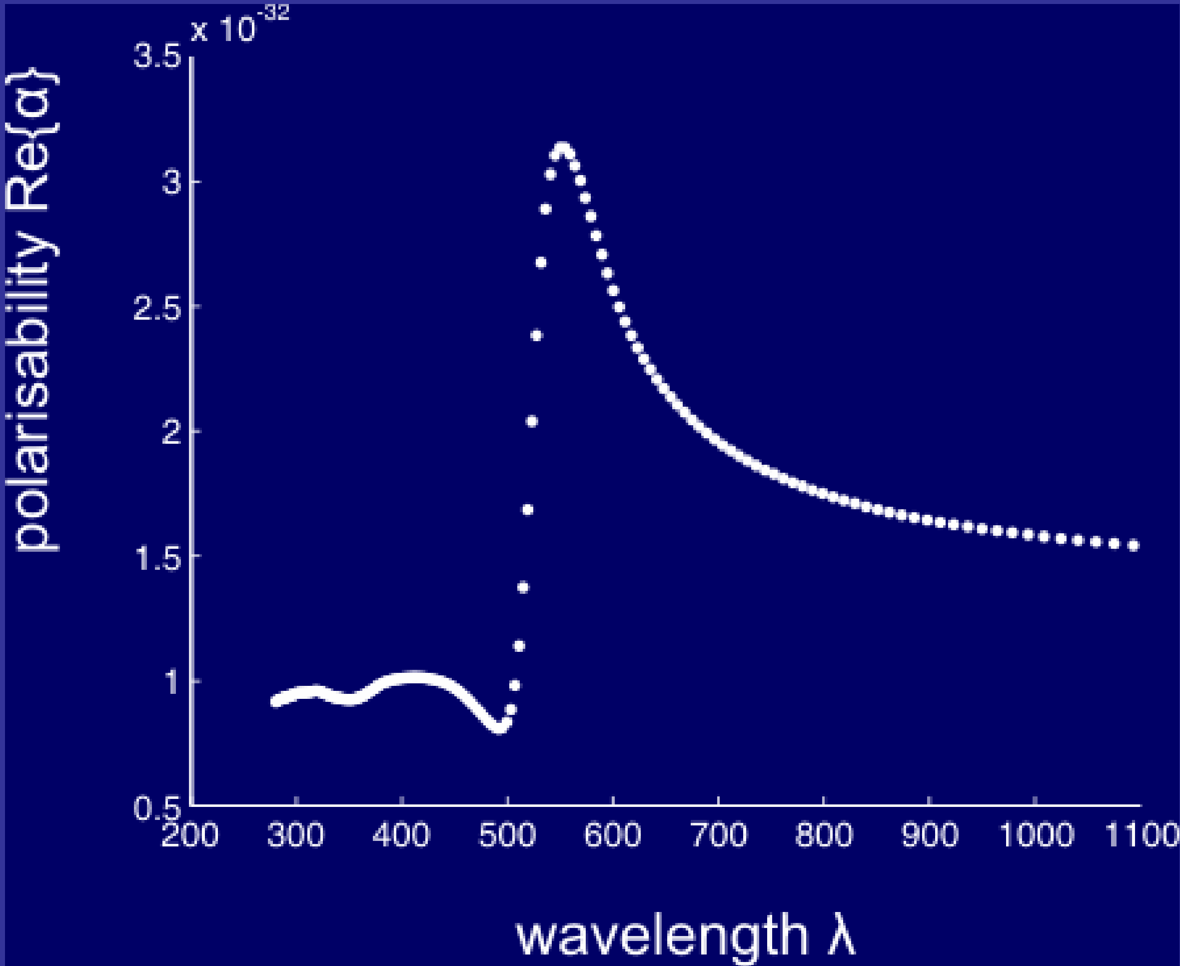
blue-detuning

$$F_{grad} = \frac{\alpha}{2} \nabla < E^2 >$$

$$\alpha = 3V \frac{\varepsilon_p - \varepsilon}{\varepsilon_p + 2\varepsilon}$$



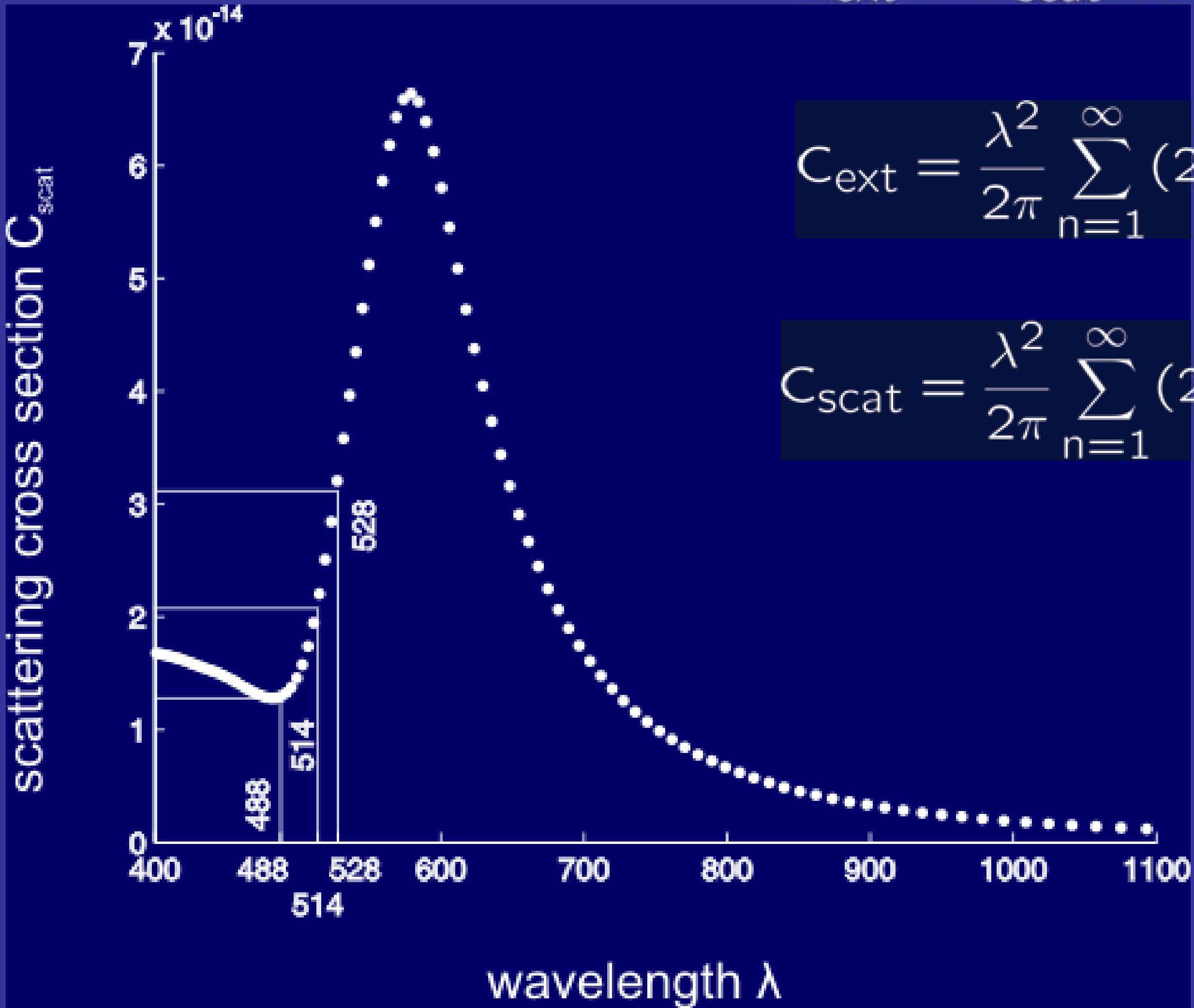
Trapping gold nanospheres



$$\alpha = 3V \frac{\varepsilon_p - \varepsilon}{\varepsilon_p + 2\varepsilon}$$

Mie theory

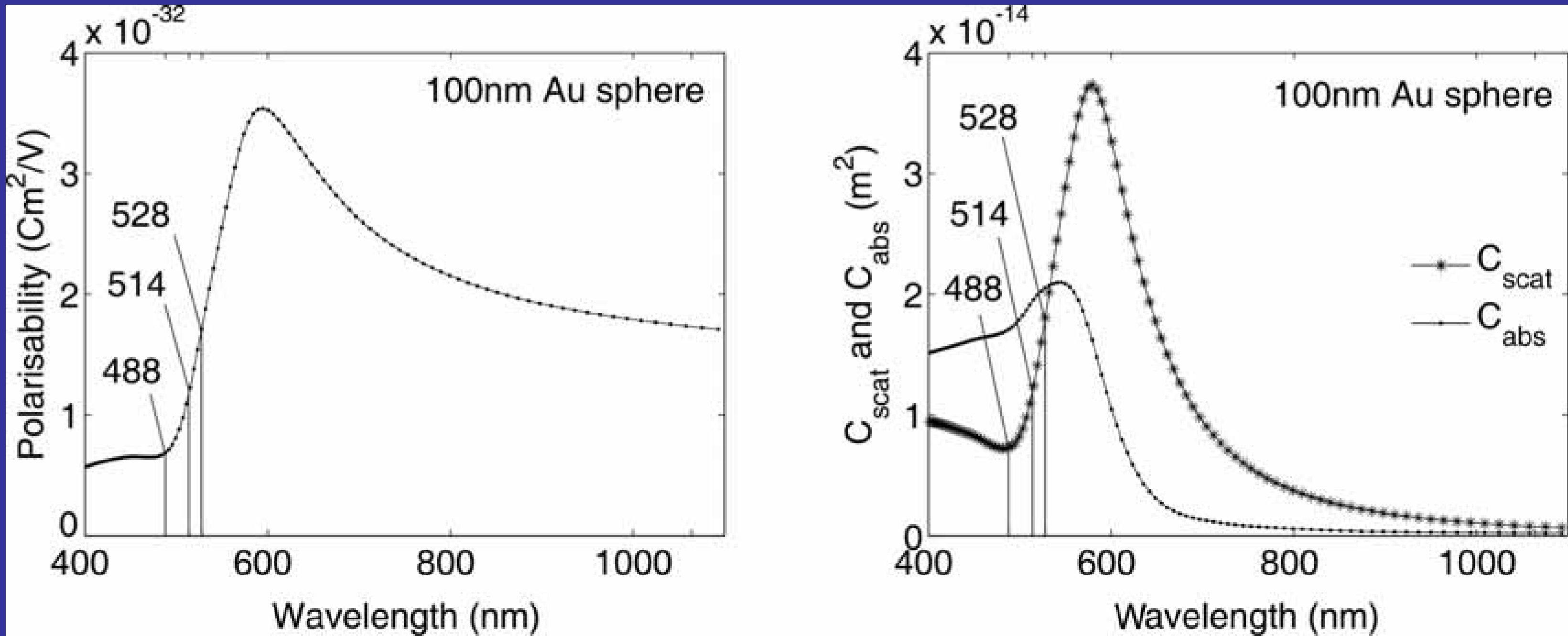
$$C_{ext} = C_{scat} + C_{abs}$$



$$C_{ext} = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}[a_n + b_n]$$

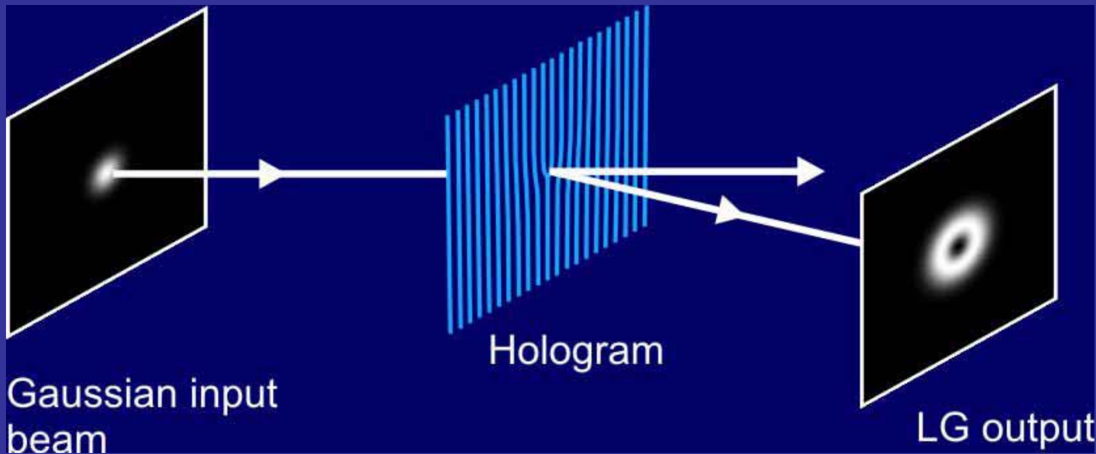
$$C_{scat} = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2)$$

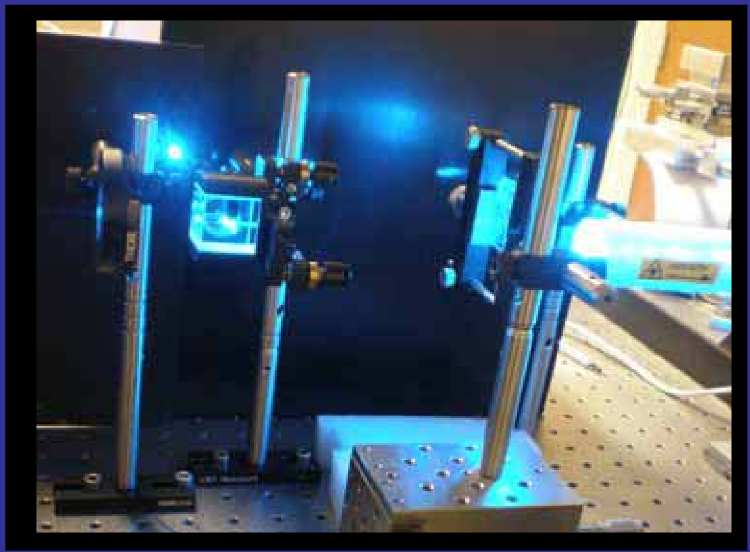
Behaviour near resonance

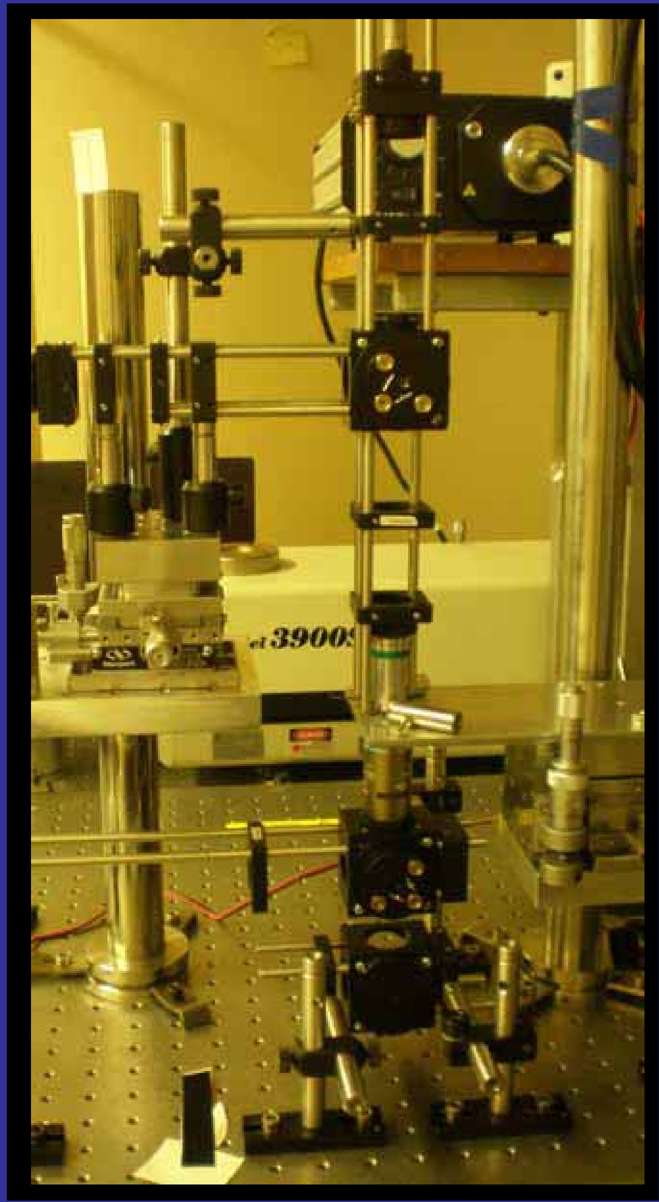


The real part of the polarisability α of a 100nm gold sphere calculated with the scattering *Cscat* and absorption cross section *Cabs* from Mie theory (see equation 4) and permittivity values from Johnson et al. [17]. The polarisability and thus the gradient force *Fgrad* is decreased by 30% and 70% for 488nm, 514nm and about the same at 528nm as compared to 1064nm. (right) The scattering cross section *Cscat* and the absorption cross section *Cabs* of a 100nm gold sphere calculated with Mie theory plotted against the wavelength of excitation.

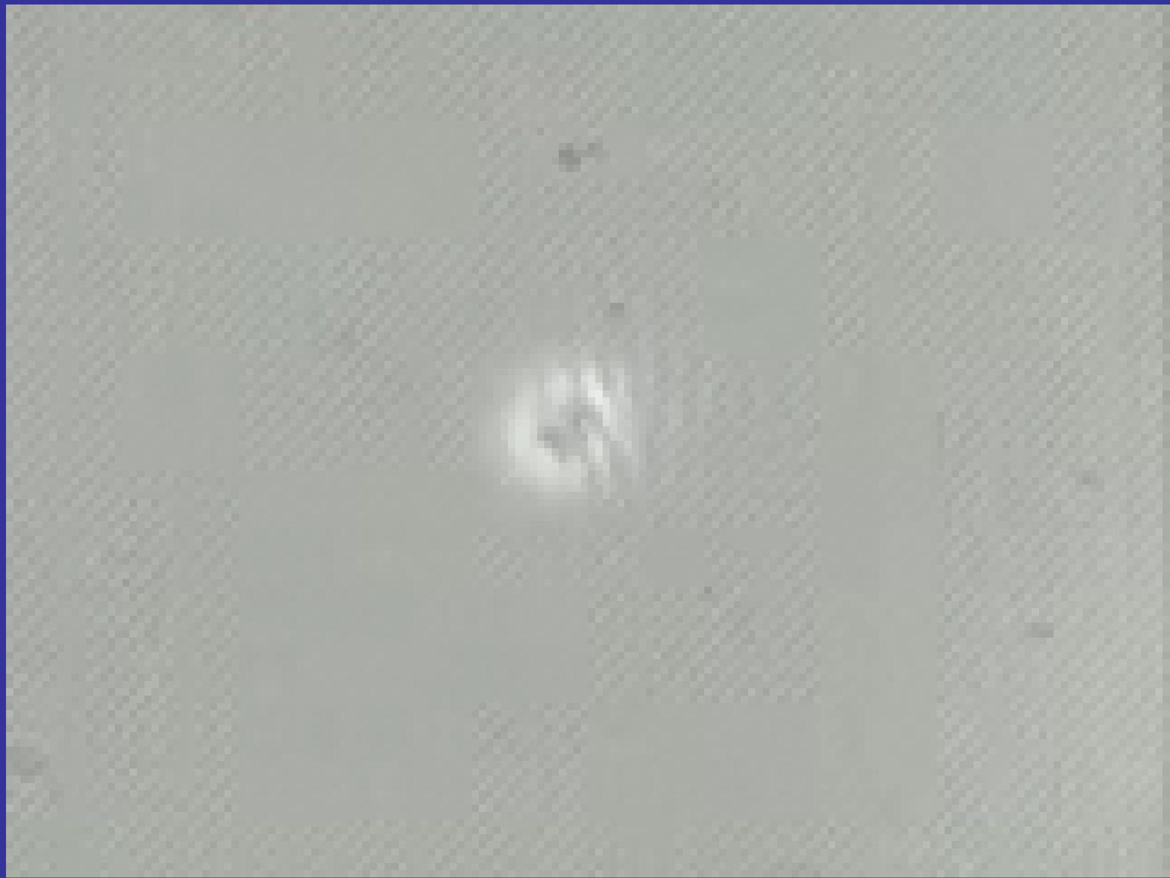
Experiment - setup







orbital angular momentum transfer + optical “binding“



[..\Desktop\ShortMovies\blue-detuned trap\250nml1514nm30mW.mov]

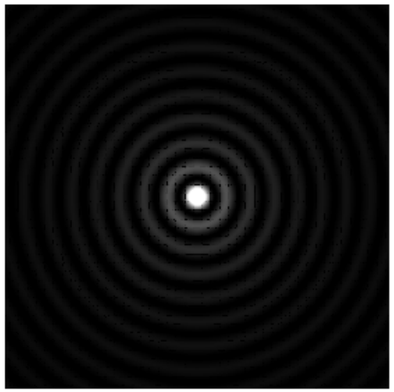
Bessel light beams

Bessel beams have an intensity cross-section that does not change as they propagate: termed "propagation-invariant". **THE CENTRE DOES NOT SPREAD.**

$$E(r,\phi,z) = AJ_n(k_r r)\exp(ik_z z)\exp(in\phi)$$

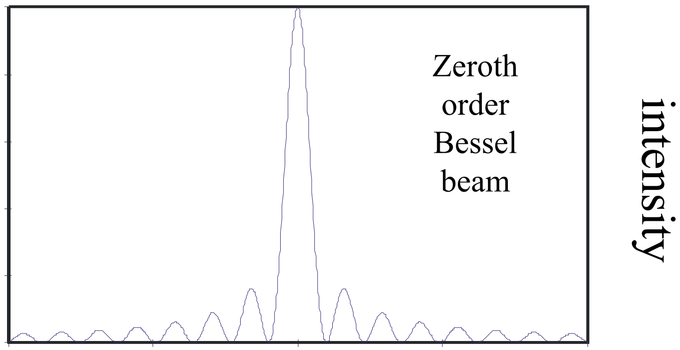
Durnin et al, JOSA A and PRL 1986/1987

With k_r and k_z being the radial and longitudinal components of the wavevector $|k| = 2\pi/\lambda = \sqrt{k_r^2 + k_z^2}$

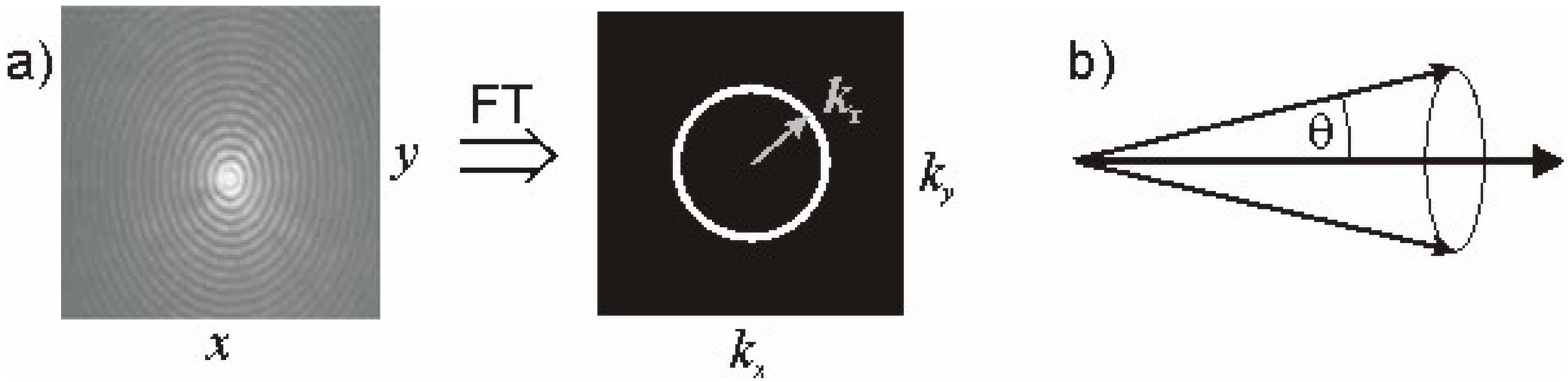


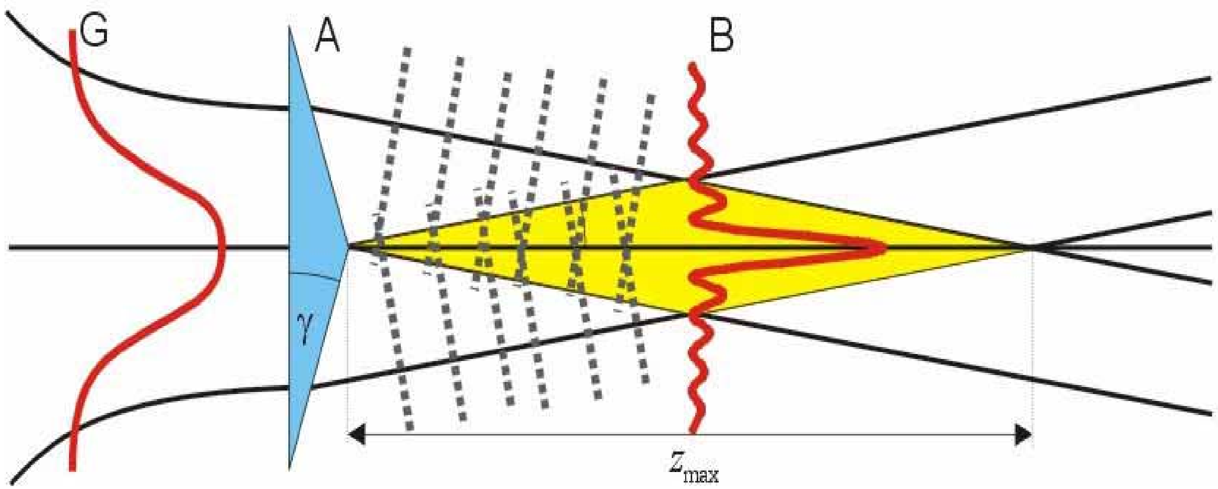
The Bessel beam showing the narrow central maximum

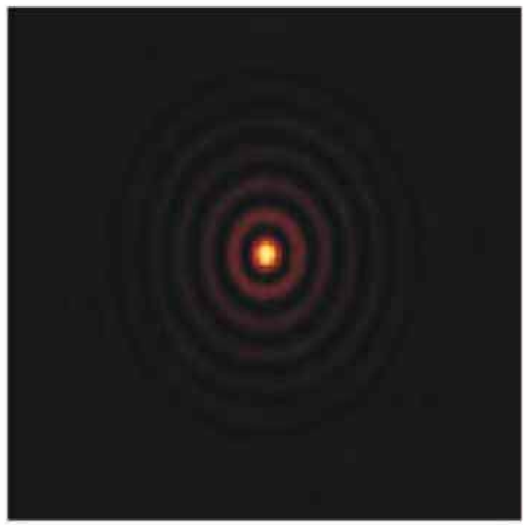
Radial intensity profile



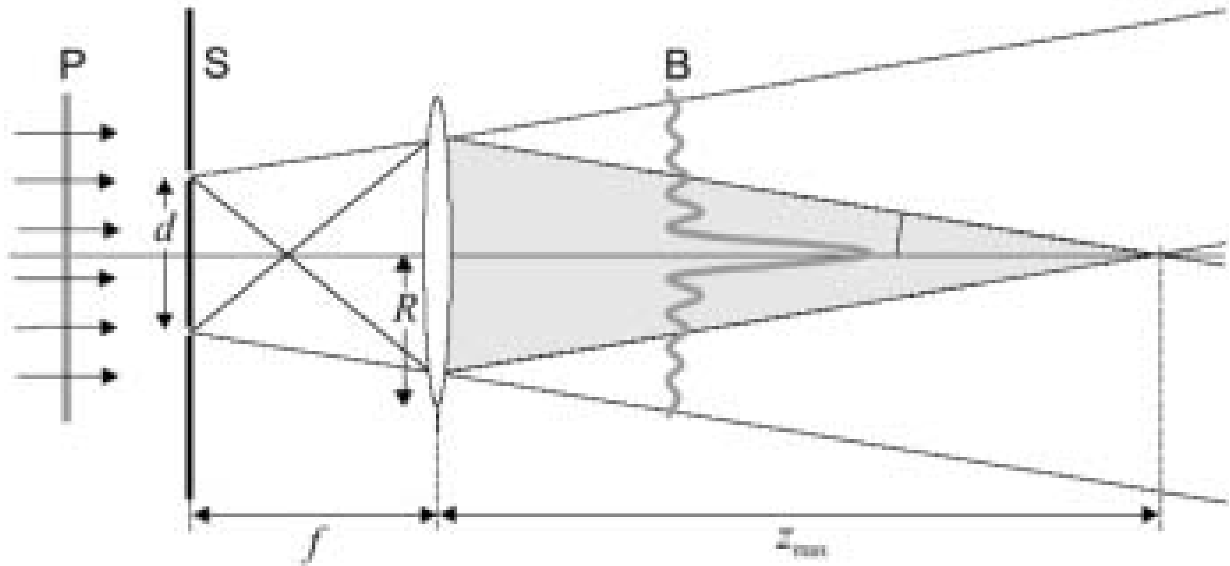
Visualising the form of the Bessel beam







Experimental Bessel beam



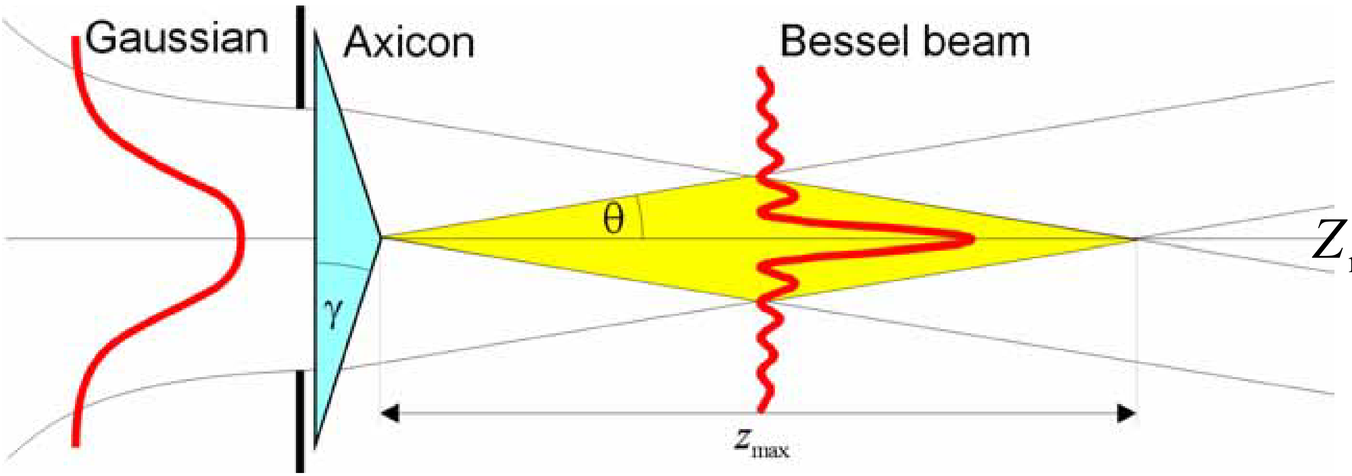
Not efficient, but shows the physics nicely

Review: Contemp Phys **46**, 15 (2005)

Make a Bessel beam at home: Am. J. Phys **67**, 912-915 (1999)

Experimental Bessel beam

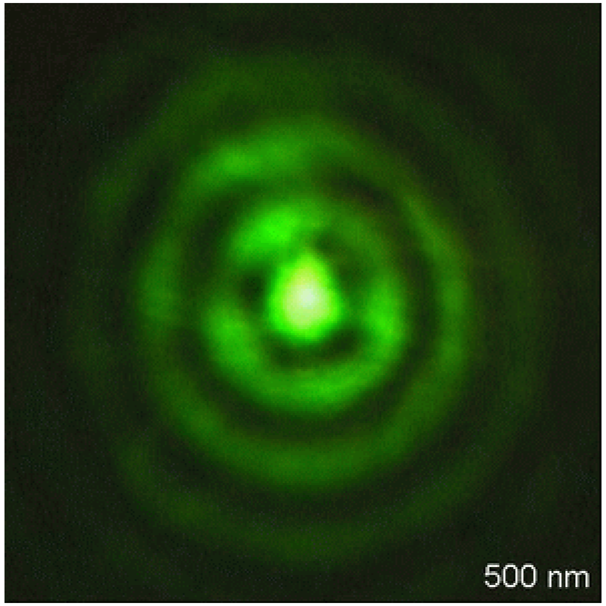
- Finite experimental aperture limits propagation distance of “non-diffracting” central maximum to z_{max}
- The on-axis intensity is no longer constant
- The **axicon** offers the most efficient method for generating a Bessel beam in the laboratory:

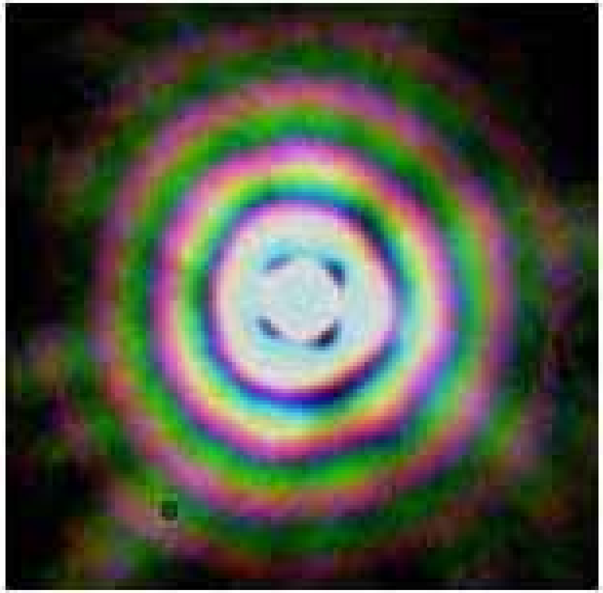


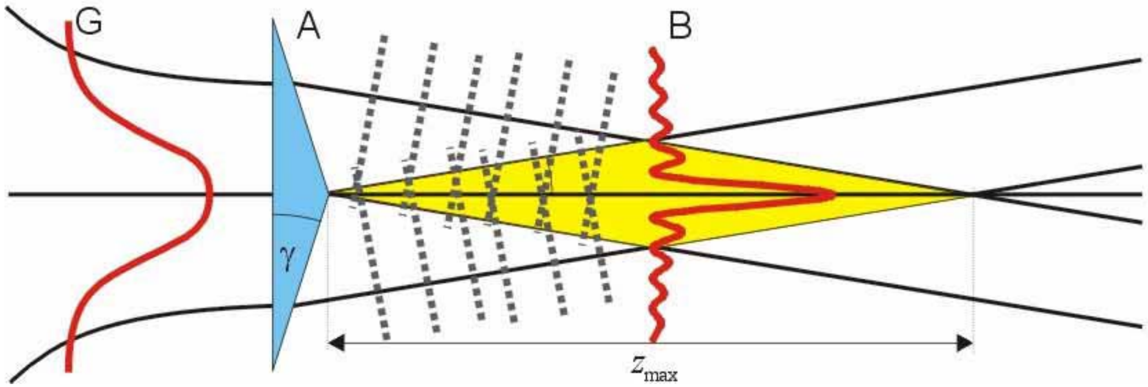
$$Z_{max} \approx \frac{k}{k_r}\omega_0 \approx \frac{\omega_0}{\theta}$$

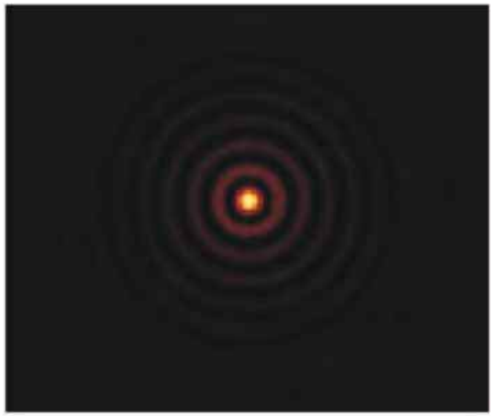
White light Bessel beams

Fischer et al., Opt. Express Aug 22, 2005

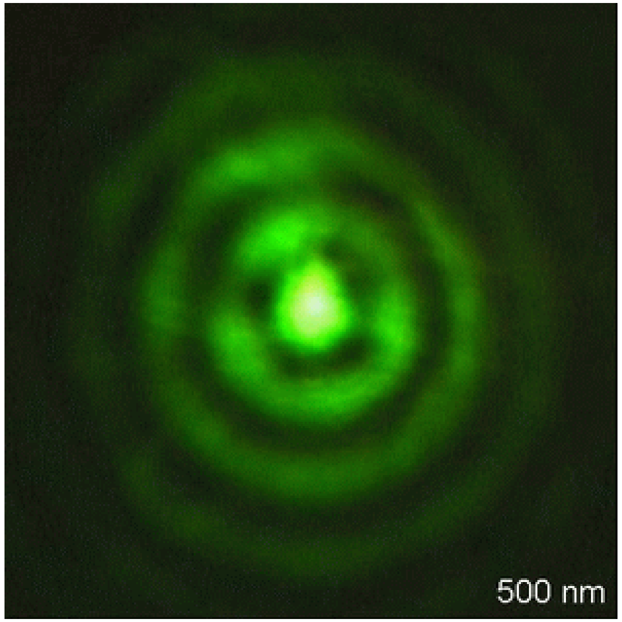


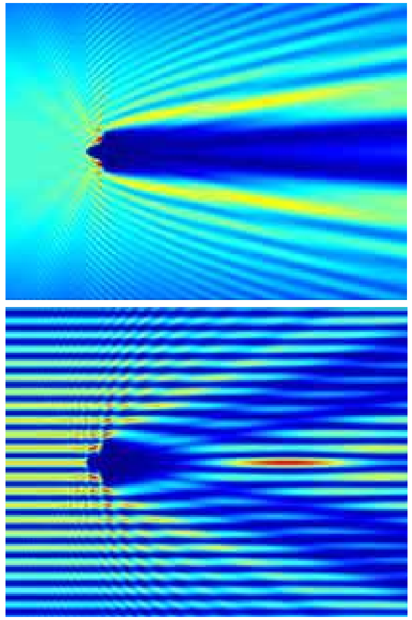


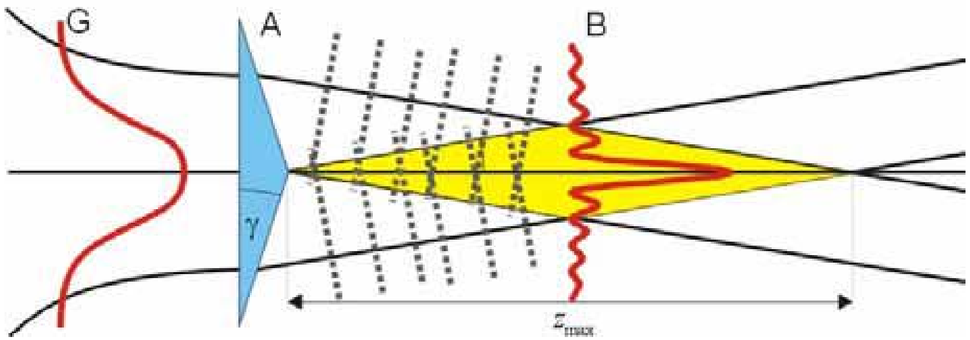




Bessel beams: an optical rod of light







OPTICAL BEAMS

Highlight of Optics 2006

White Light Takes Shape

Pascal Fischer, Ewan M. Wright, Tom Brown, Wilson Sibbett, Jill E. Morris, Carlos López-Mariscal, Antonia E. Carruthers and Kishan Dholakia

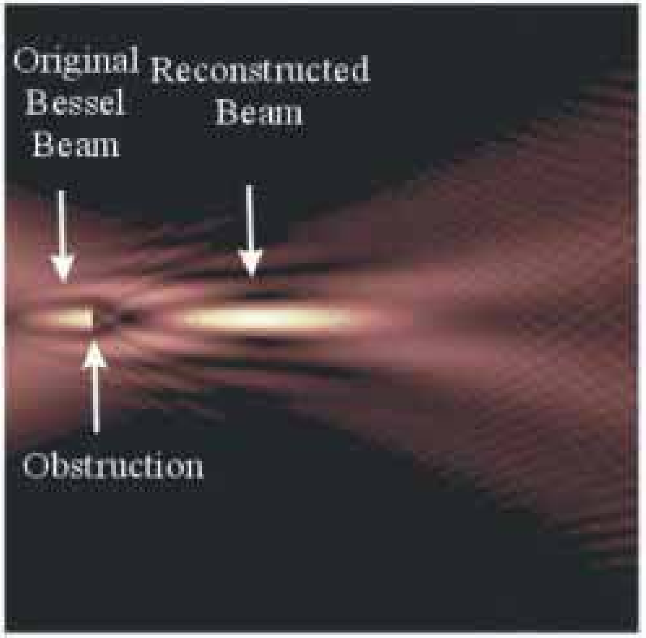
Coherence in both the temporal and spatial domains is central to understanding the rich and diverse range of phenomena involving light and matter interactions. Indeed, the ability to predict the relative phases between light beams, for instance, may lead to well-defined interference. With broadband light that has relatively poor phase coherence, interference is observed in the temporal domain only when the optical path lengths are matched, as exploited for optical sectioning using coherence tomography.

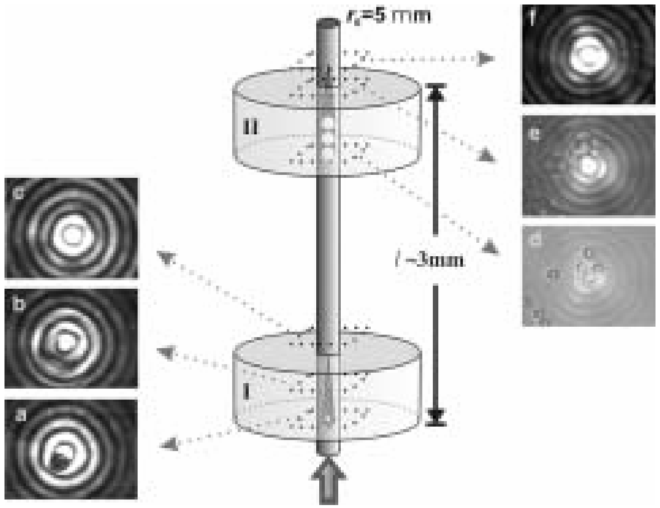
By contrast, lasers more typically exhibit outstanding spatial and temporal coherence properties. These sources normally operate with a Gaussian output beam profile but recently more specialized light patterns have enabled dramatic impacts to be made in many areas of physics. The Bessel beam is a primary example in this respect and represents an intriguing propagation invariant or pseudo "non-diffracting" light source. Durnin elucidated the zeroth-order Bessel beam solutions for the free-space scalar wave equation: The beam comprises a narrow central region surrounded by a series of concentric rings.[1]

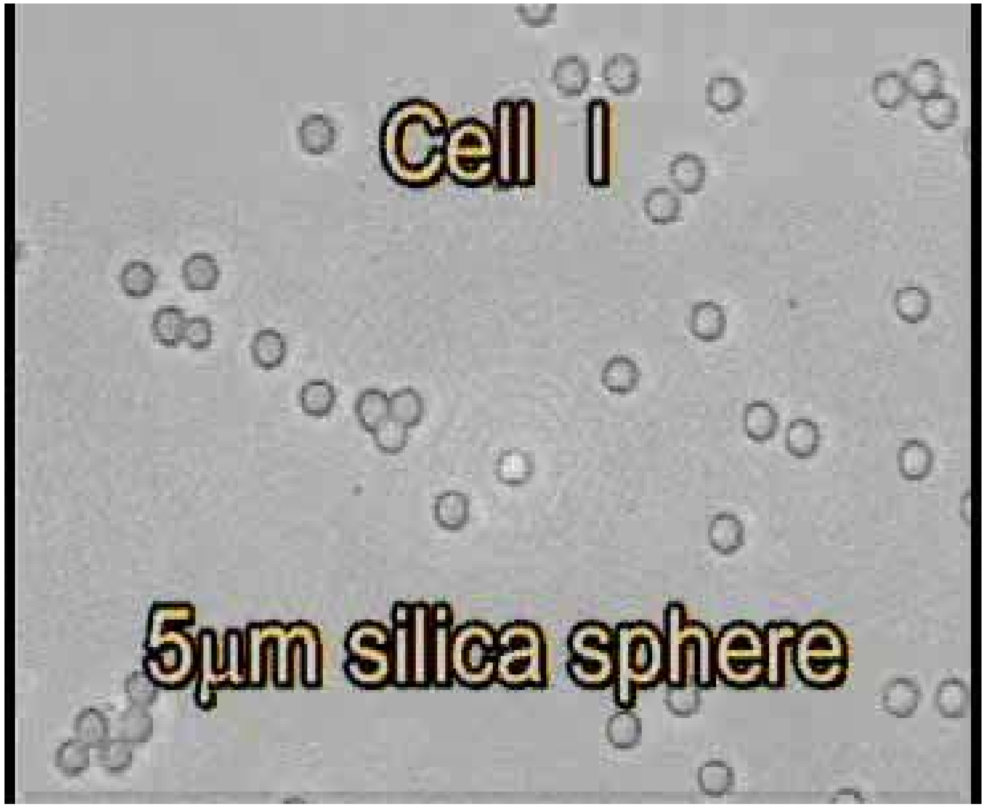
So how may we interpret this Bessel beam? Any light beam can be thought of as a superposition of plane waves. As the waves propagate, they experience relative phase shifts. In most cases, each plane wave component suffers a distinctive phase shift such that the resultant beam—the interference pattern of the plane waves changes shape. There exist, a non-diffracting beam be made without having a temporally coherent source? In other words, would it be possible to sculpt or shape white light to form such a beam?

In recent work, we have explored the generation of such "non-diffracting" light fields using broadband and incoherent light sources.[2] We have made "white" Bessel light modes from laser diodes operating below threshold, supercontinuum light sources and even halogen bulbs. The main criterion we found was the need to ensure good spatial coherence in the light field. Remarkably, the superposition of the conical wave-vectors arising from passage through the axicon and the inherent absence of chromatic aberration results in a pure focal line of white light.

The Bessel beam may self heal around obstacles

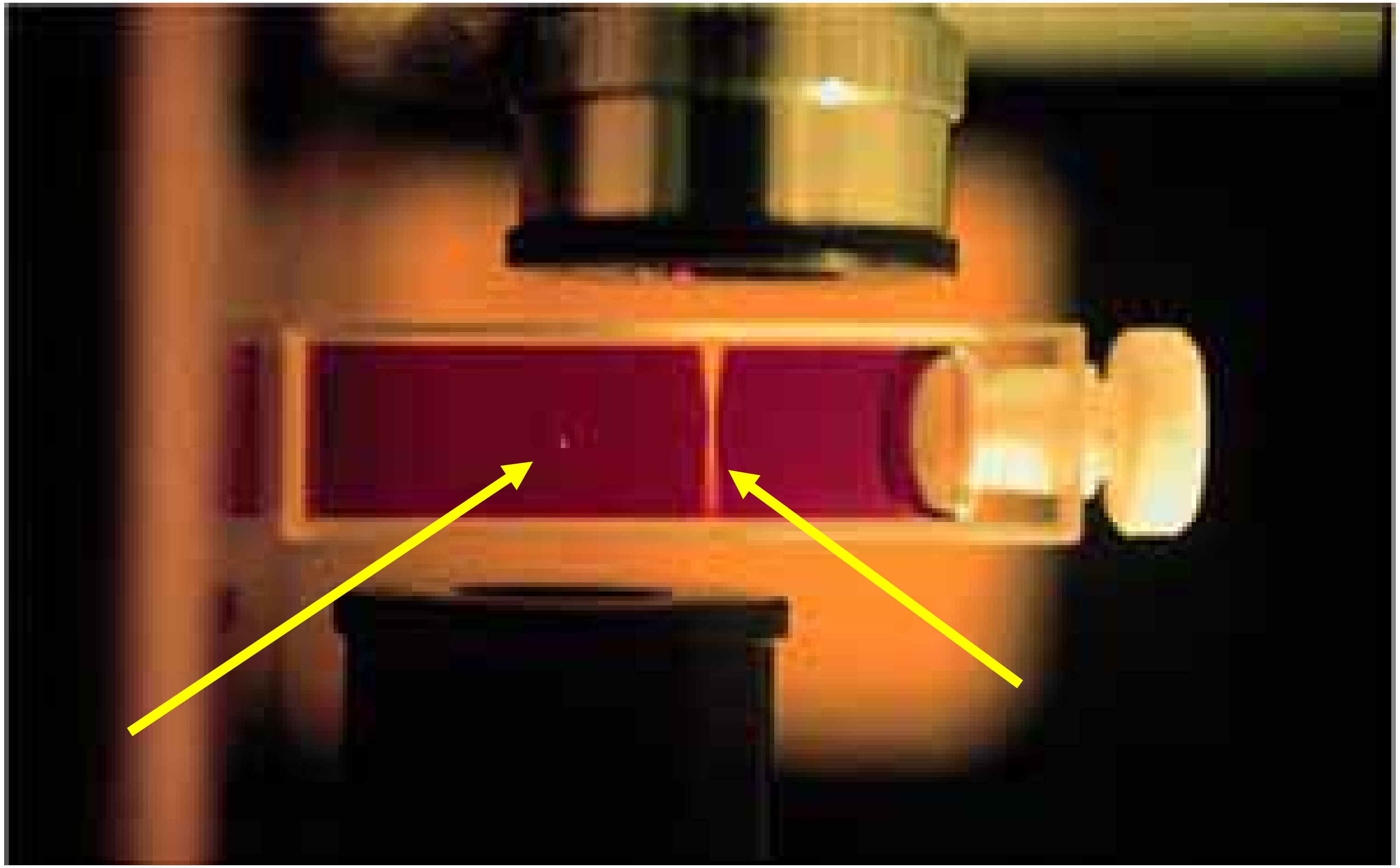






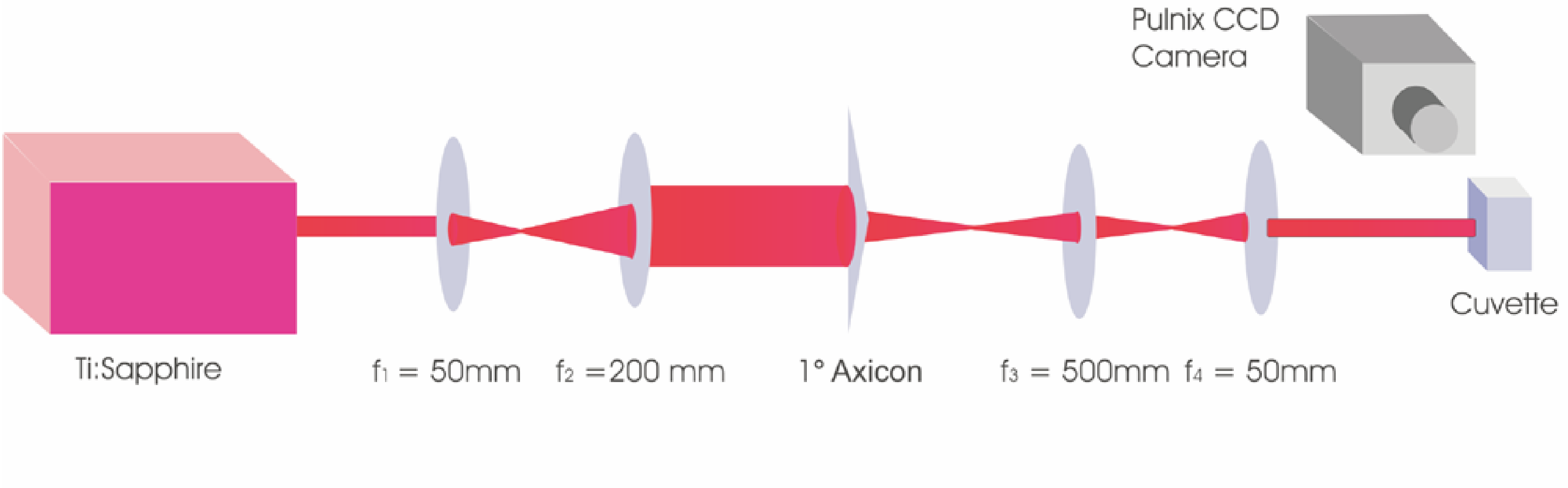
Vertical Bessel beam self-heals around obstacles:

See V Garces-Chavez et al., Nature **419**, 145 (2002)



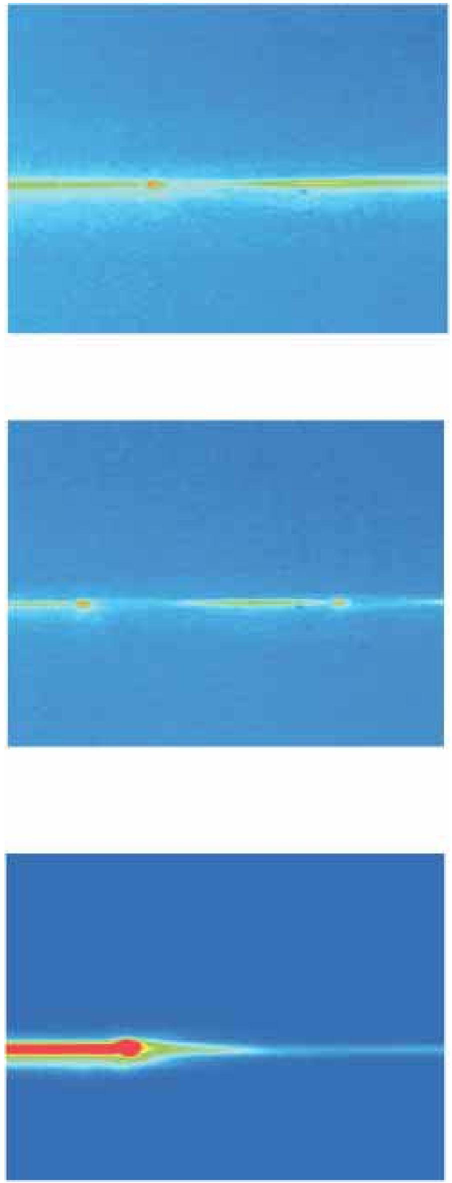
A cuvette of fluorescent dye excited by single photon excitation (right line) and multiphoton excitation (localized spot of fluorescence at left) illustrating that two photon excitation is confined to the focus of the excitation beam (courtesy of Brad Amos MRC, Cambridge).

Optical guiding in Gaussian and Bessel femtosecond beams

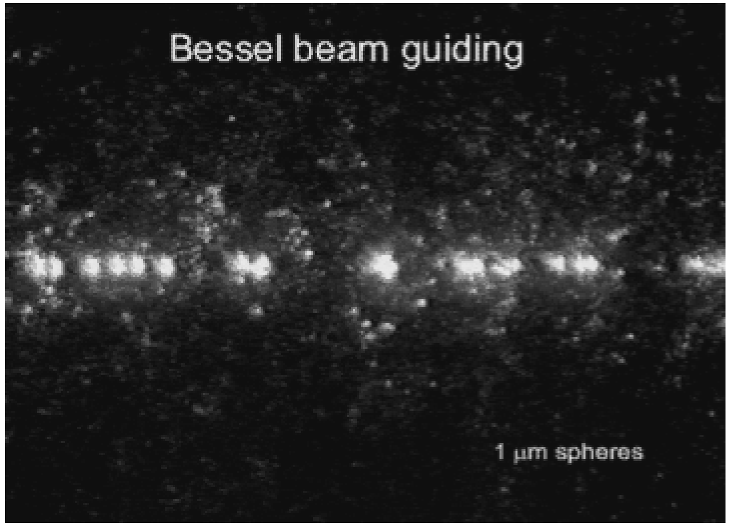


H. Little et al., Opt Express 12, 2560 (2004);

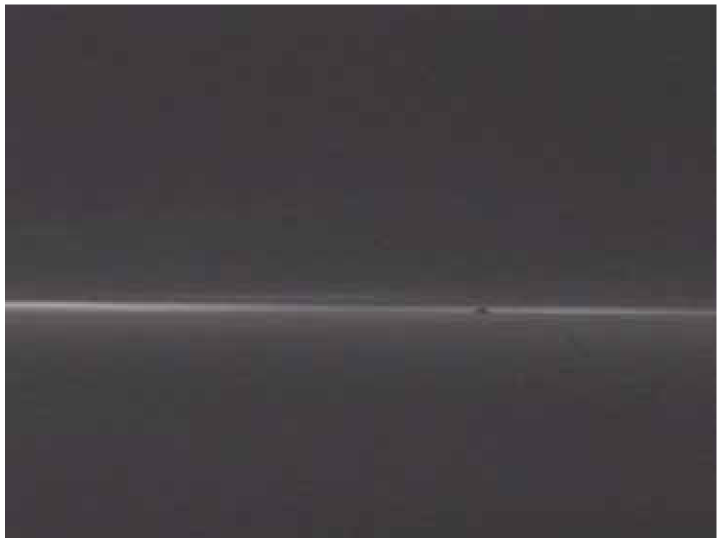
K. Dholakia et al. New J. Phys. 6, 136 (2004)



CW guiding

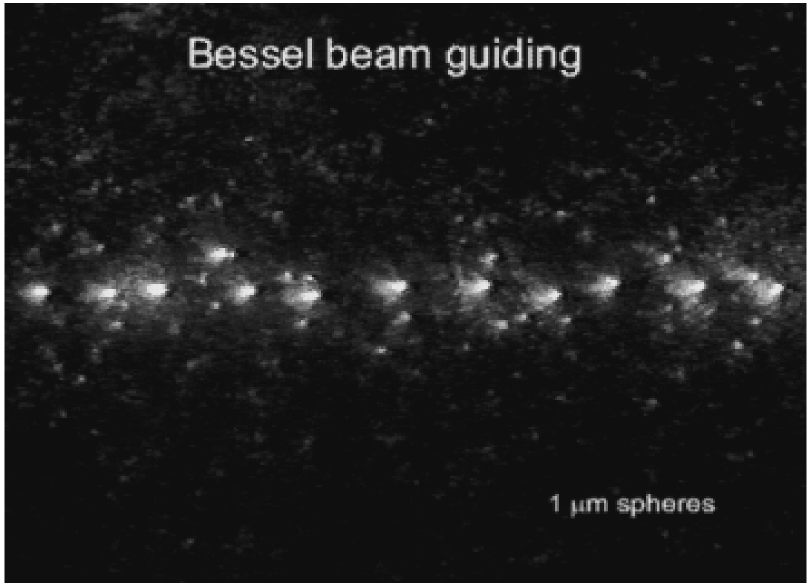


femtosecond guiding: visualise the beam using fluorescent dye



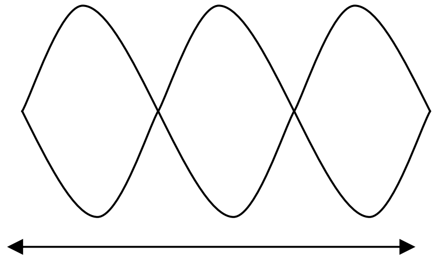
H. Little et al., Opt Express 12, 2560 (2004); K. Dholakia et al. New J. Phys. 6, 136 (2004)

THE OPTICAL CONVEYOR BELT: motion and localisation of nano-particles and cells.



Bessel beam : J, Arlt et al. Opt. Comm. 197, 239 (2001)

Standing wave traps: see Zemanek group work eg Opt. Lett 1997



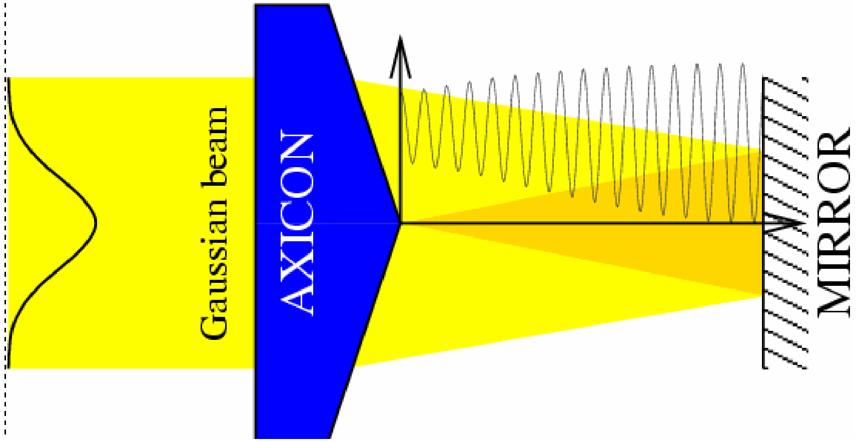
Can we make localised 3D traps for nano-objects?

Coherent beams may interfere.

Angular Doppler effect for motion

Generation of Bessel standing wave traps

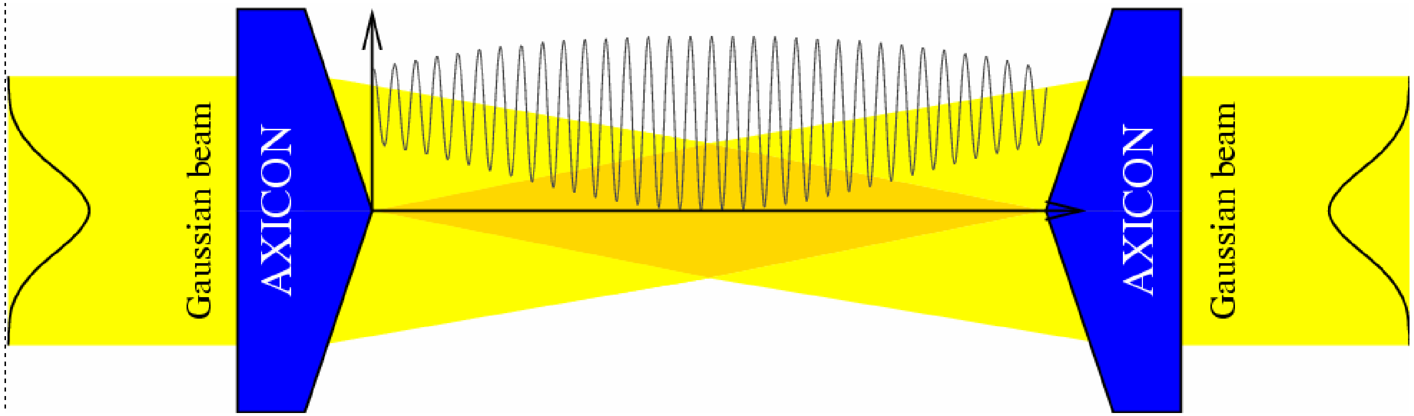
1. Using retro-reflected incident beam



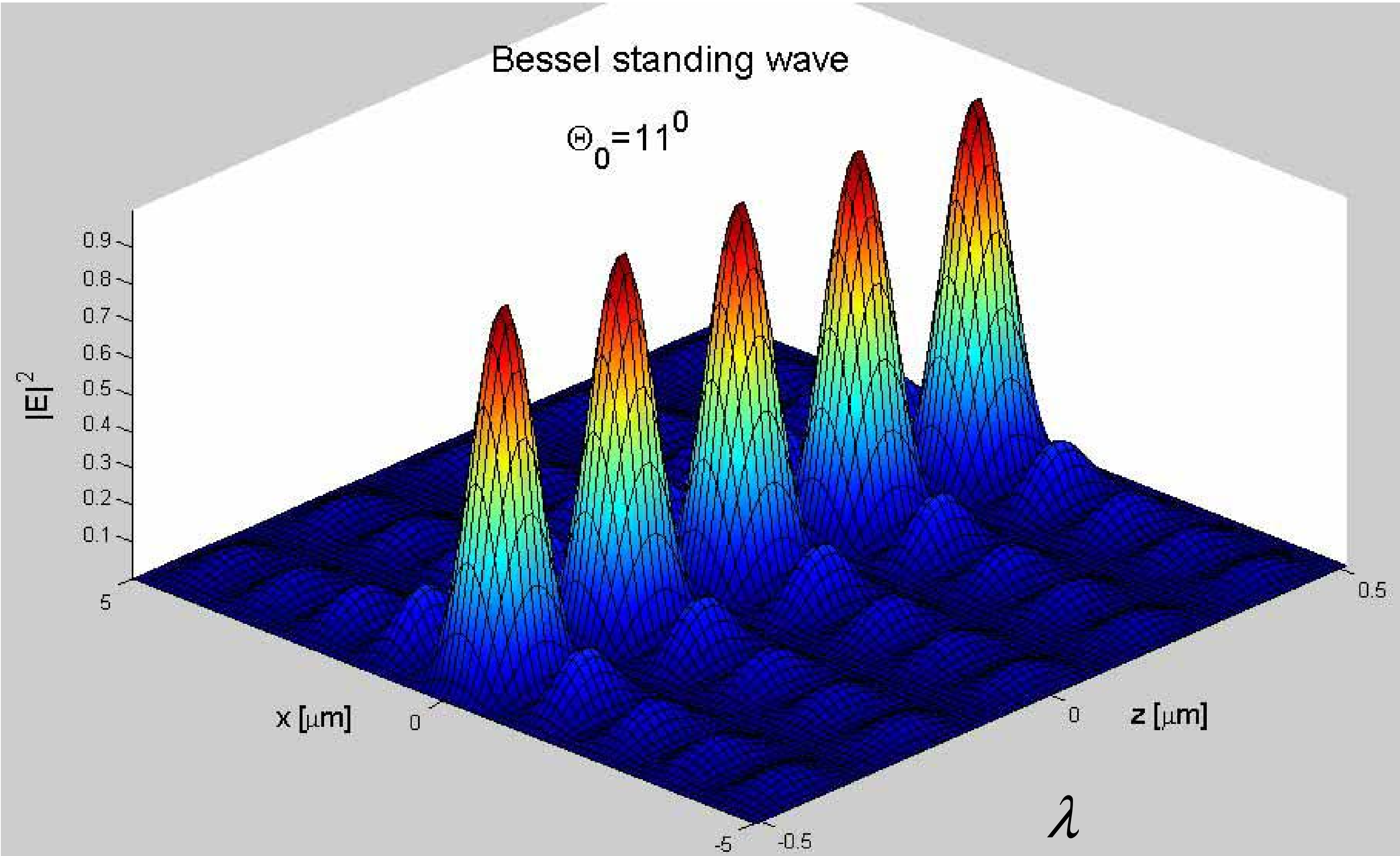
+ Easier alignment, better focusing, smaller convection, confinement of smaller object

- View along propagation axis, smaller trapping volume, unutilized potential of non-diffracting beam

2. Using two independent counter-propagating beams.

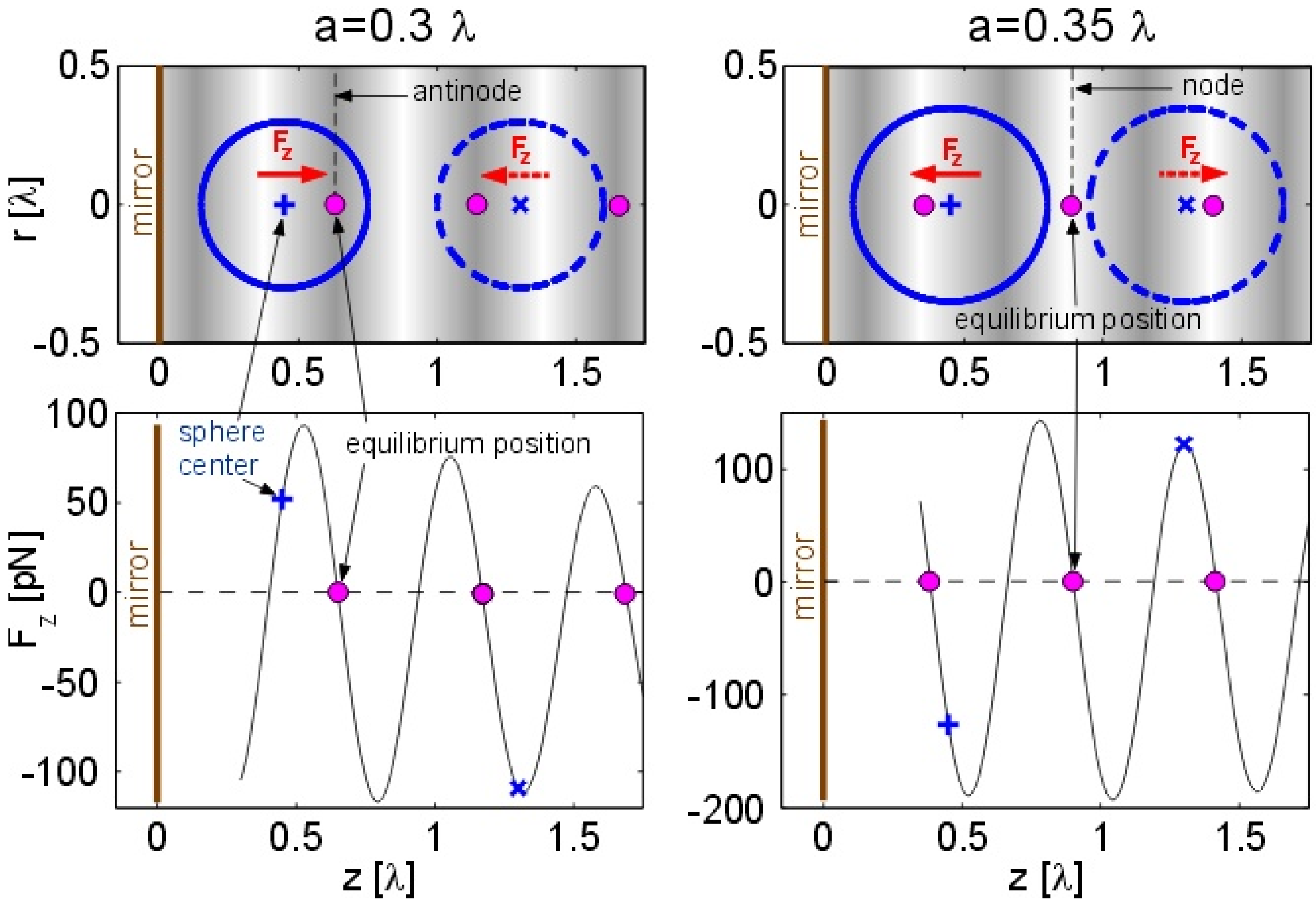


Calculation of optical forces acting on microparticles in Bessel standing wave



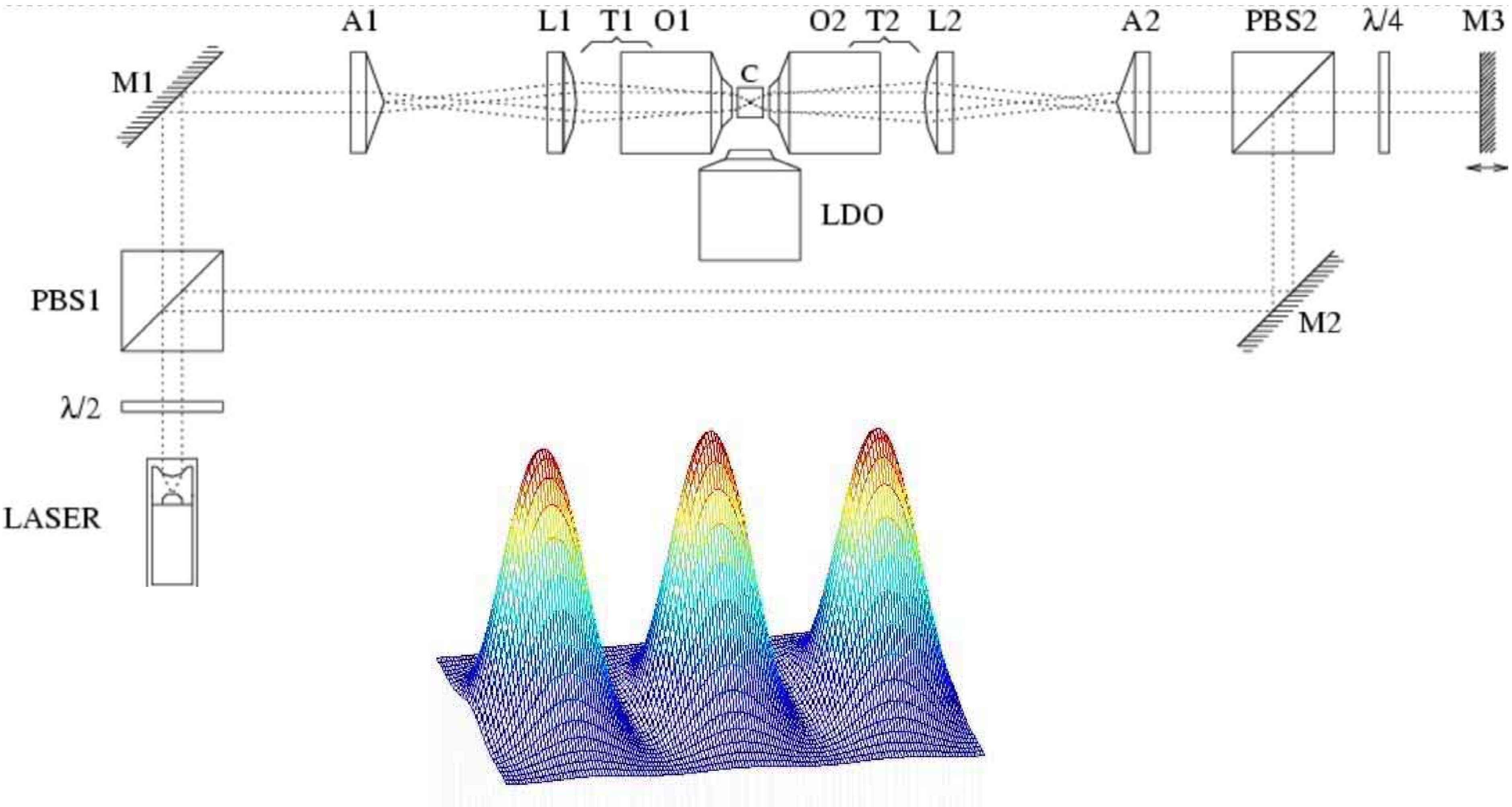
$$\frac{\lambda}{2\cos(\Theta_0)}$$

Calculation of optical forces acting on microparticles in Bessel standing wave



Interference pattern generation : Generation of Bessel standing wave traps

2. Using two independent counter-propagating beams.



Interference pattern generation Optical conveyor belt for trapped objects and biological cells.

T Cizmar et al, Appl. Phys Lett 86, 174101 (2005)