Optical Manipulation for Biomedicine

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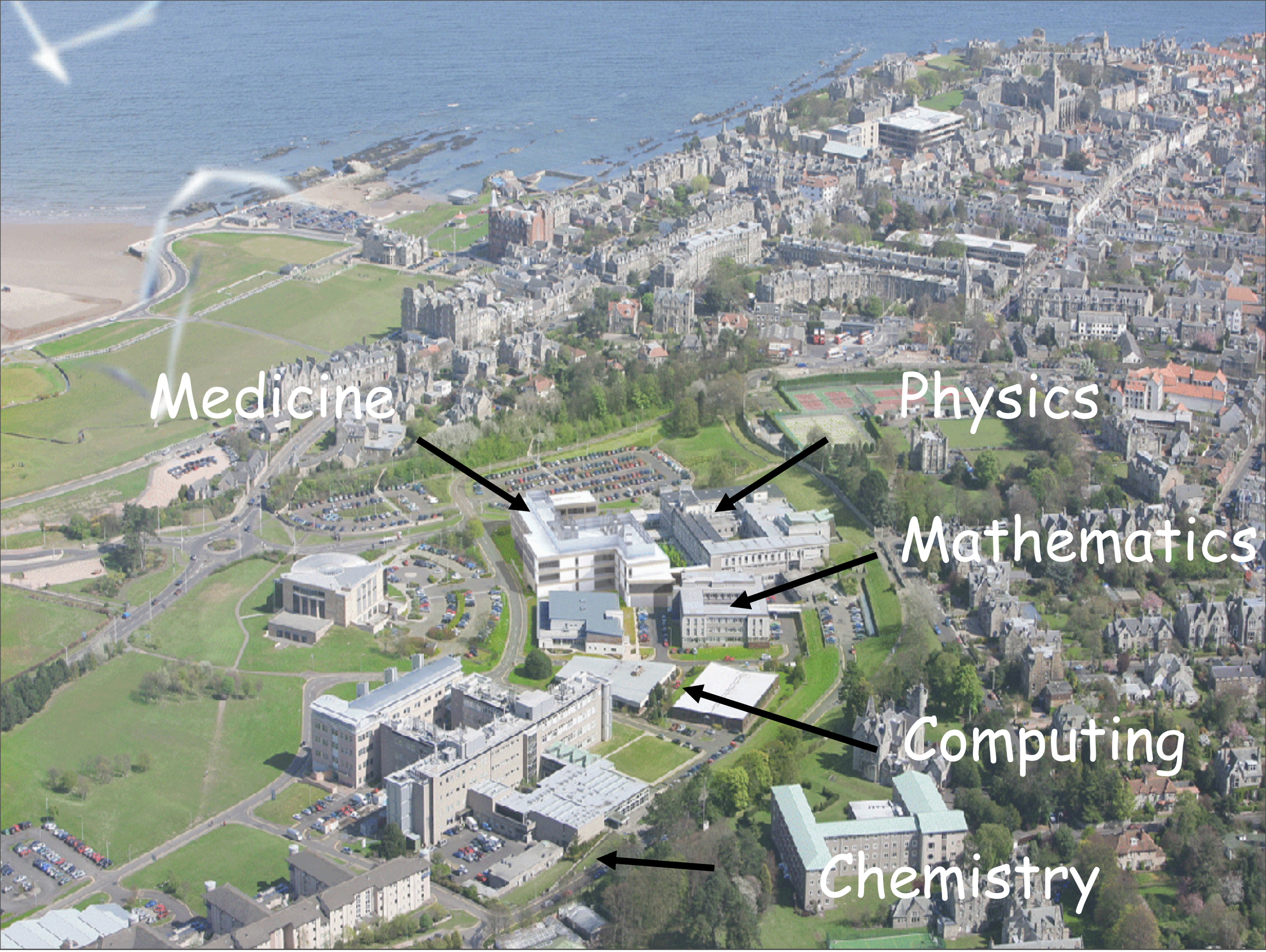
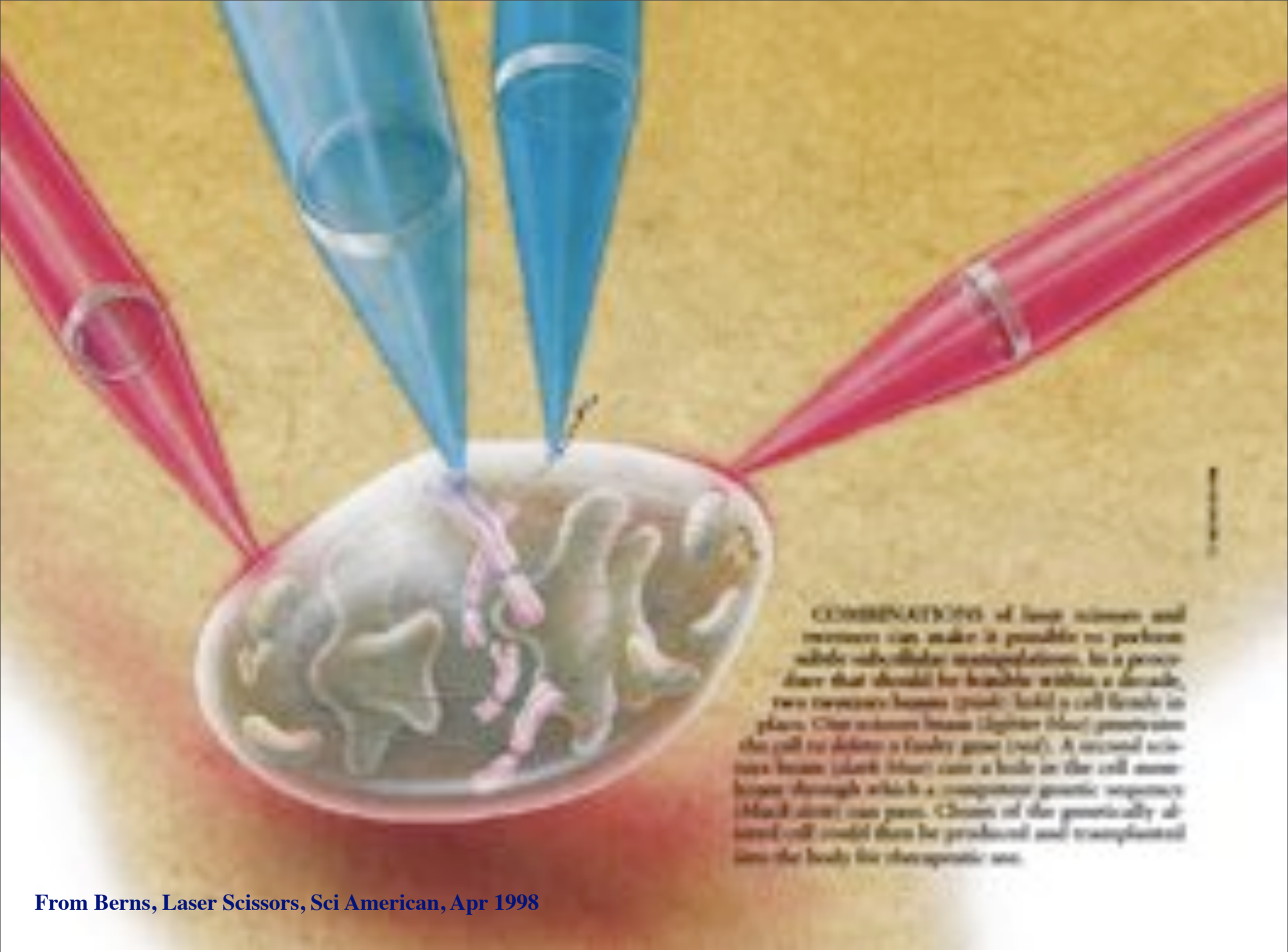
XIX International Summer School
"Nicolás Cabrera"
Fluorescent Nanoparticles in Biomedicine
Madrid, Spain. 16th-20th July 2012


Medicine
Physics
Mathematics
Computing
Chemistry

optical manipulation



From Berns, Laser Scissors, Sci American, Apr 1998

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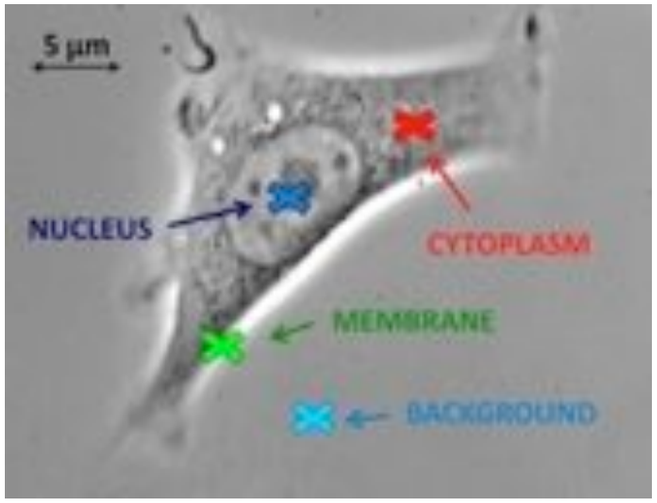
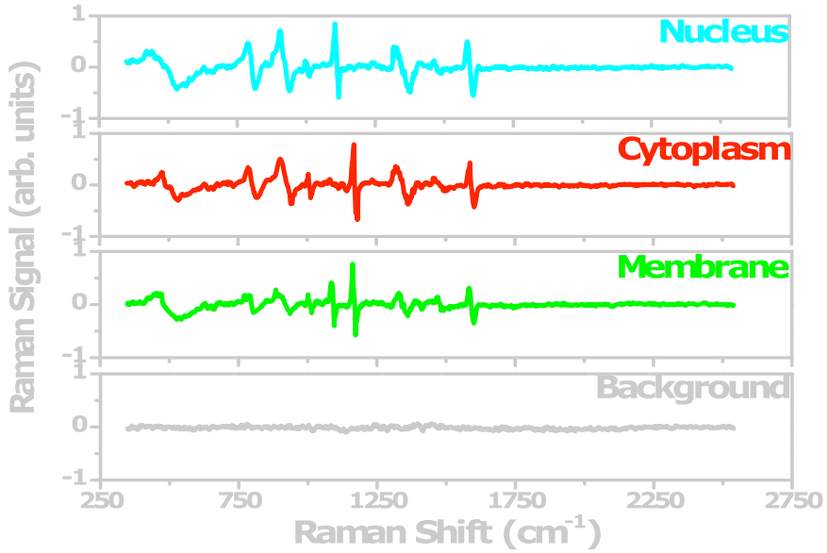
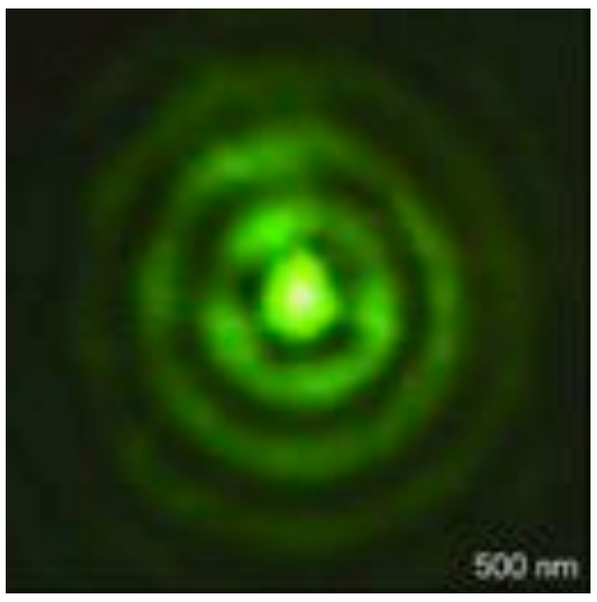
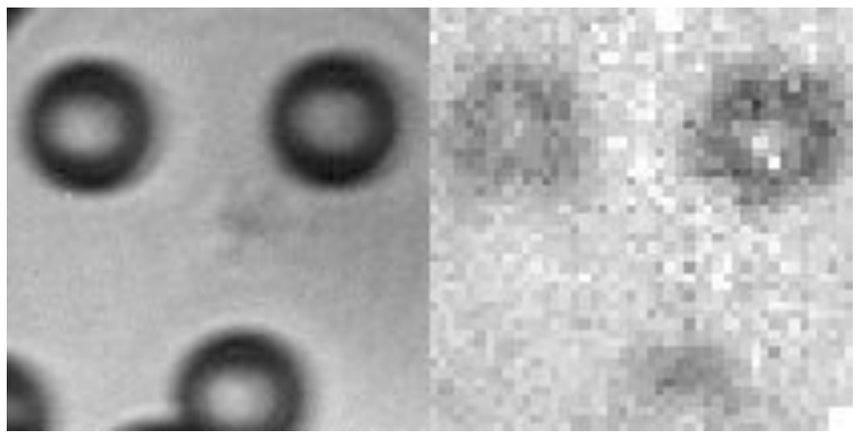




Raman

Photoporation





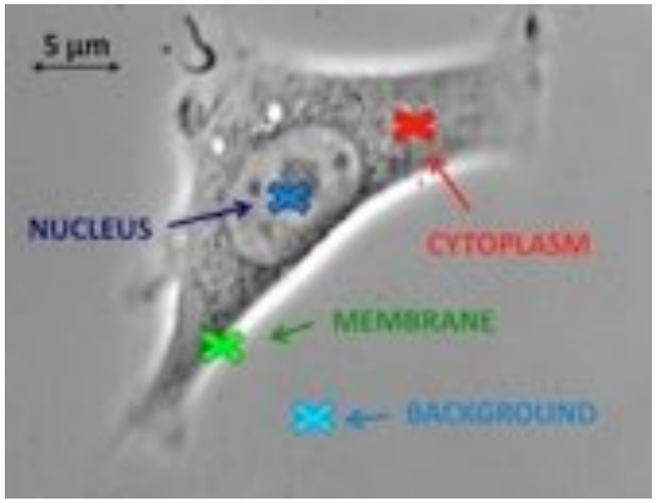
particle/cell manipulation

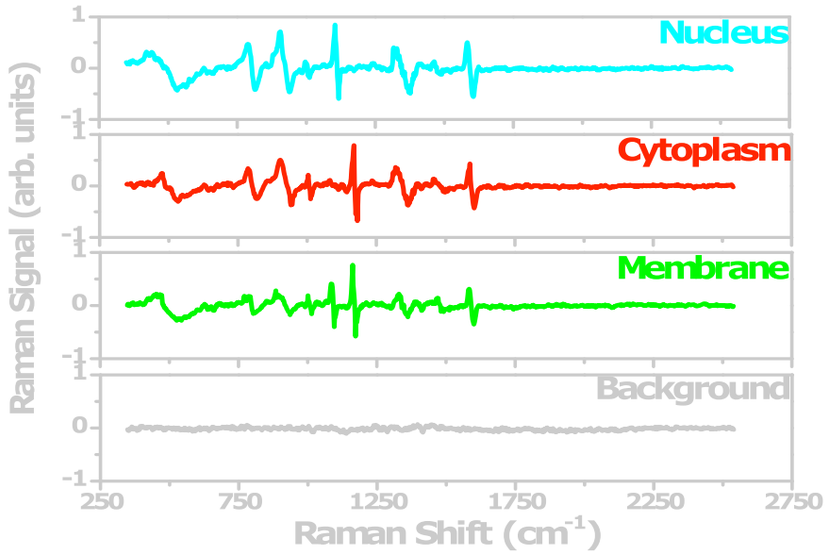
Shaping light

Light through ‘disorder’

Optical Manipulation Group

optical manipulation





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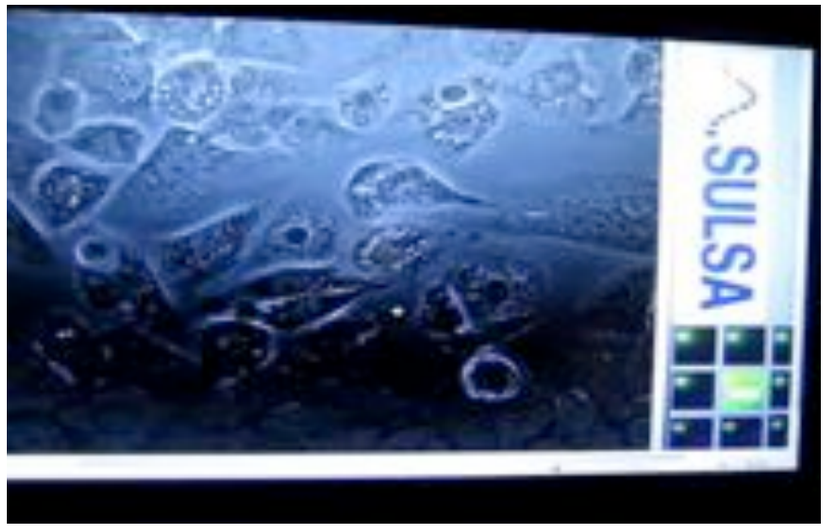

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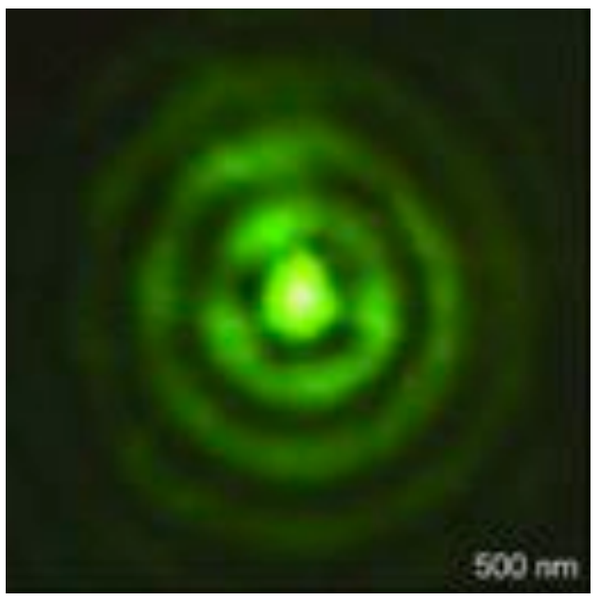

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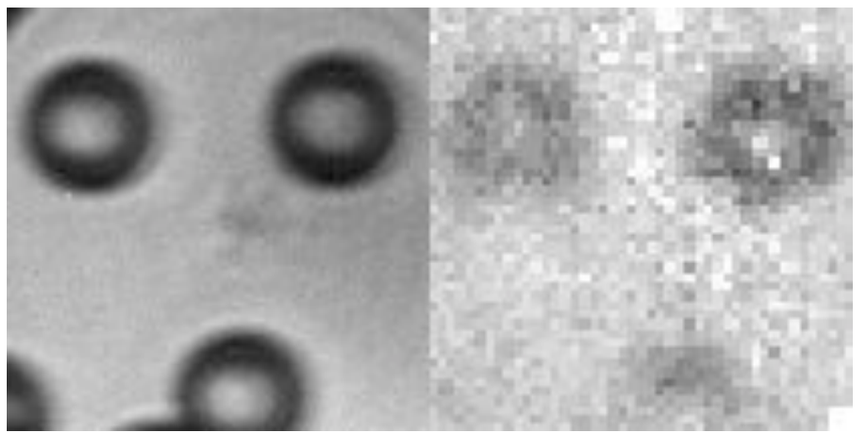
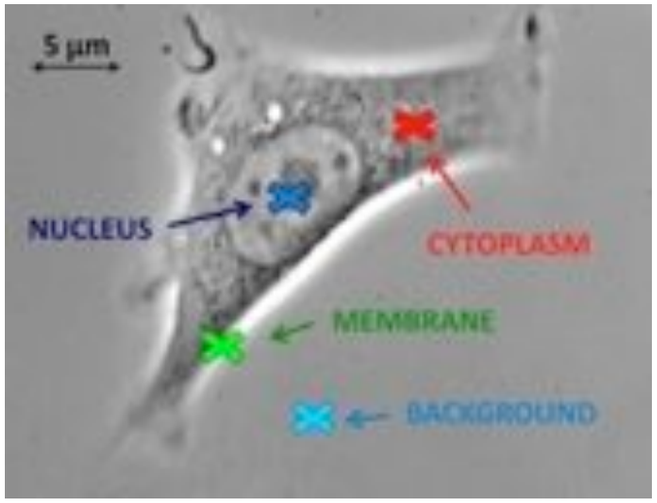
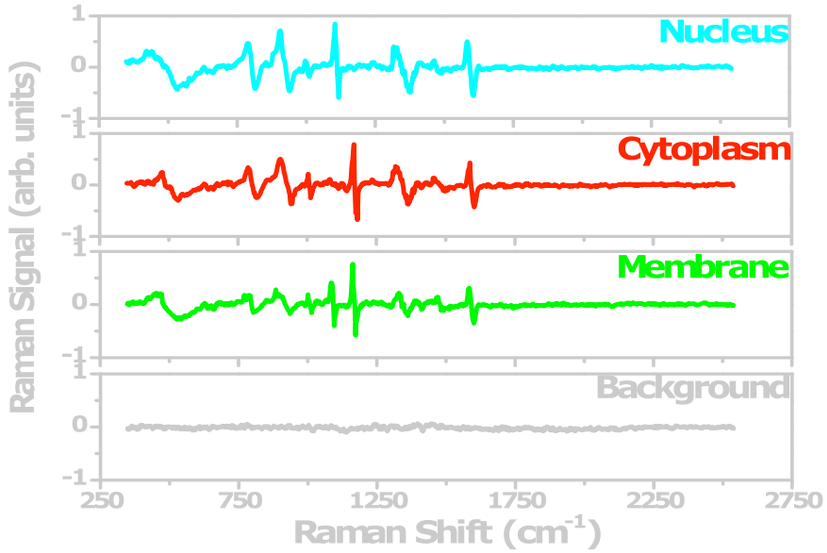


Light through ‘disorder’

Optical Manipulation Group





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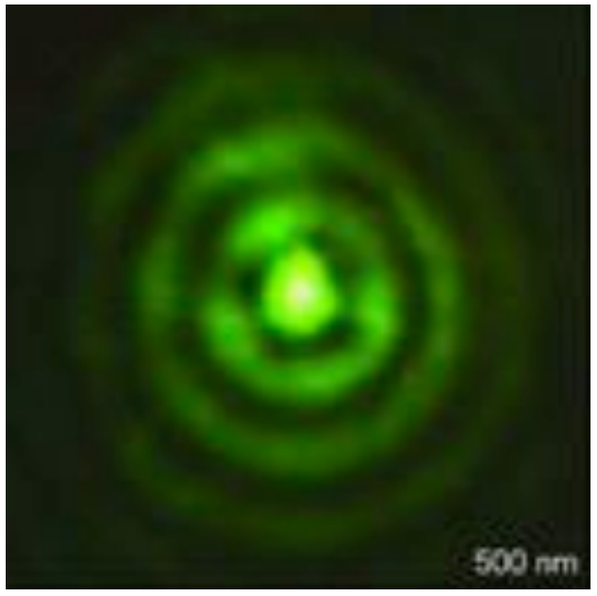

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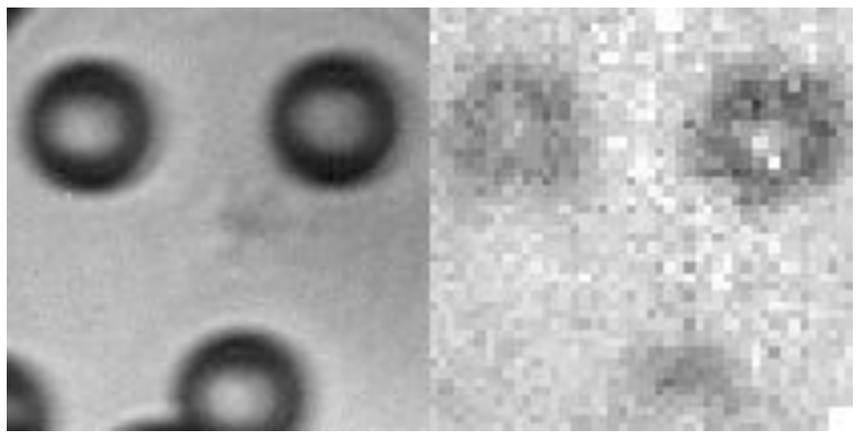

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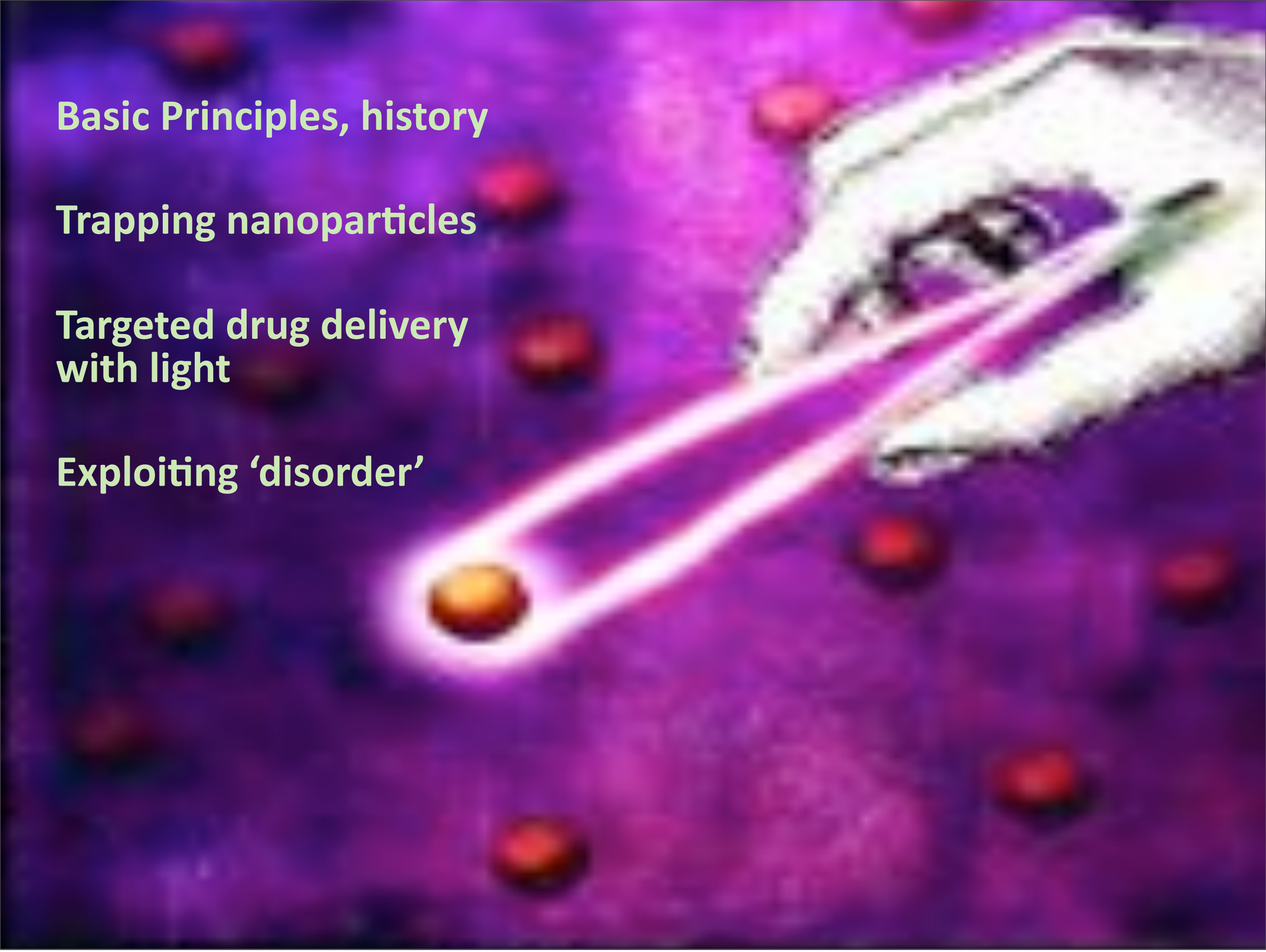
Basic Principles, history
Trapping nanoparticles
Targeted drug delivery with light
Exploiting ‘disorder’

Johannes Kepler & Comet Tails

http://antwrp.gsfc.nasa.gov/apod/ap980717.html

http://sohowww.nascom.nasa.gov/hotshots/

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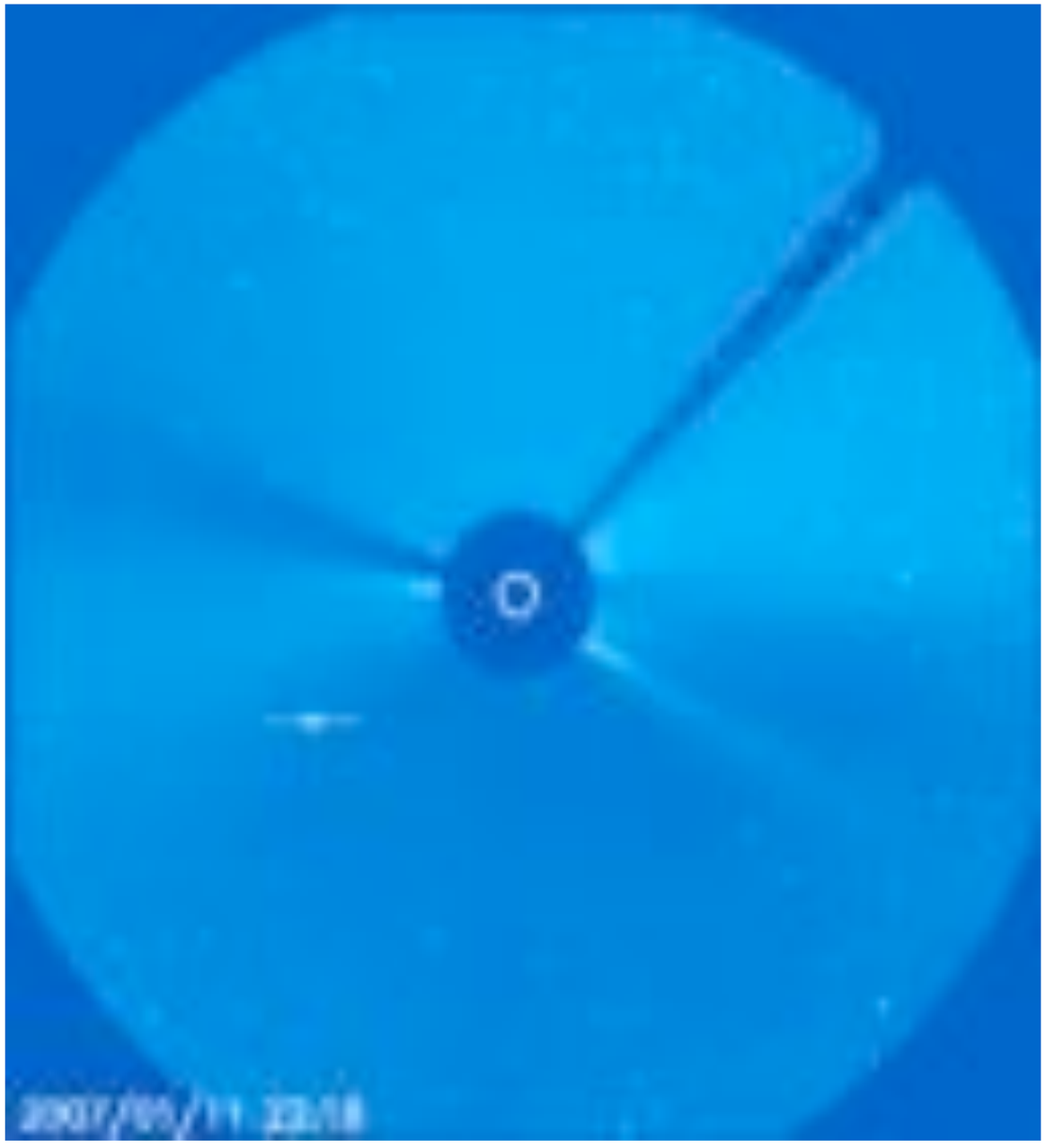

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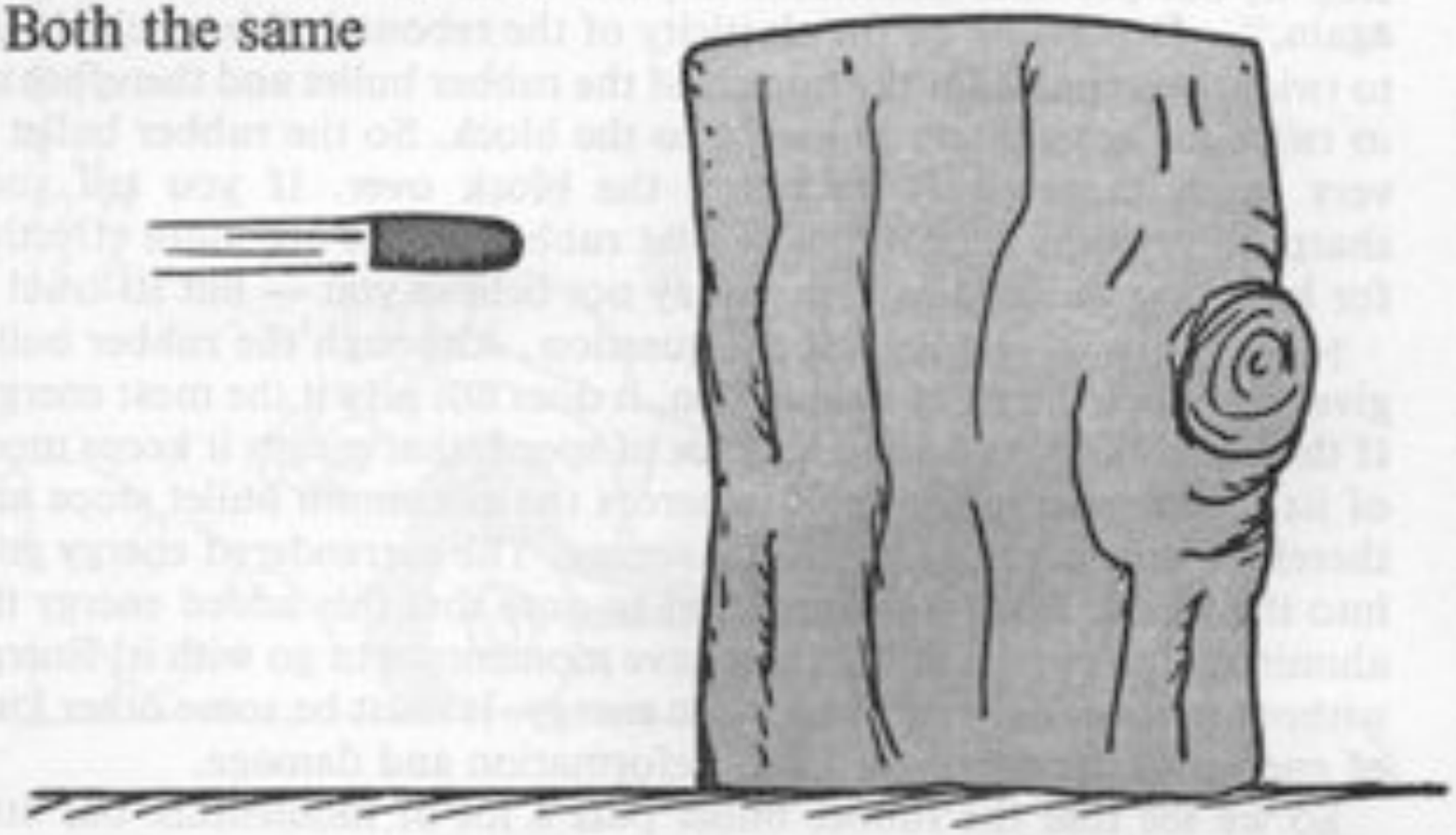
RUBBER BULLET

A rubber bullet and an aluminum bullet both have the same size, speed, and mass. They are fired at a block of wood. Which is most likely to knock the block over?

a) The rubber bullet
b) The aluminum bullet
c) Both the same



Which is most likely to damage the block?

a) The rubber bullet
b) The aluminum bullet
c) Both the same

optical manipulation

From: **Thinking like a physicist, N Thompson**

optical manipulation

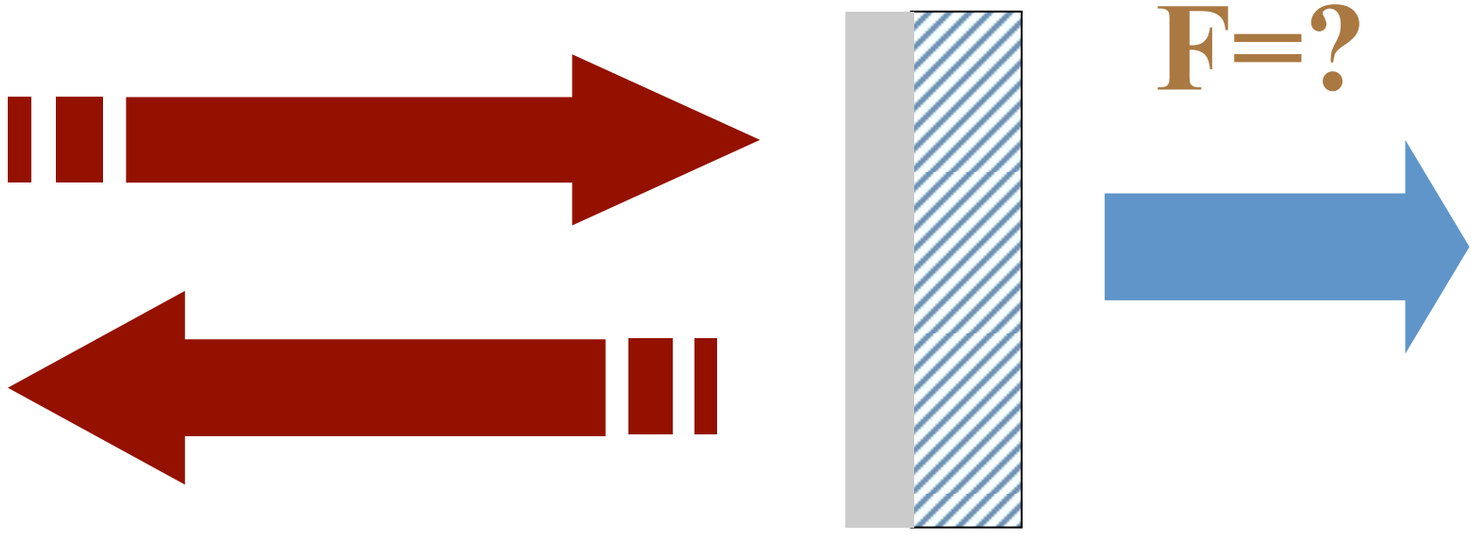
- Knock the block over?
- The rubber bullet: maximum momentum transfer

optical manipulation

- Knock the block over?
- The rubber bullet: maximum momentum transfer

- Damage the block?
- The aluminium bullet: maximum energy transfer

Optical force on a mirror



Very small!! But for a microscopic sphere use Newton's laws…..

$$Power = \frac{\dot{n}hc}{\lambda} = P \qquad momentum = \frac{h}{\lambda}$$

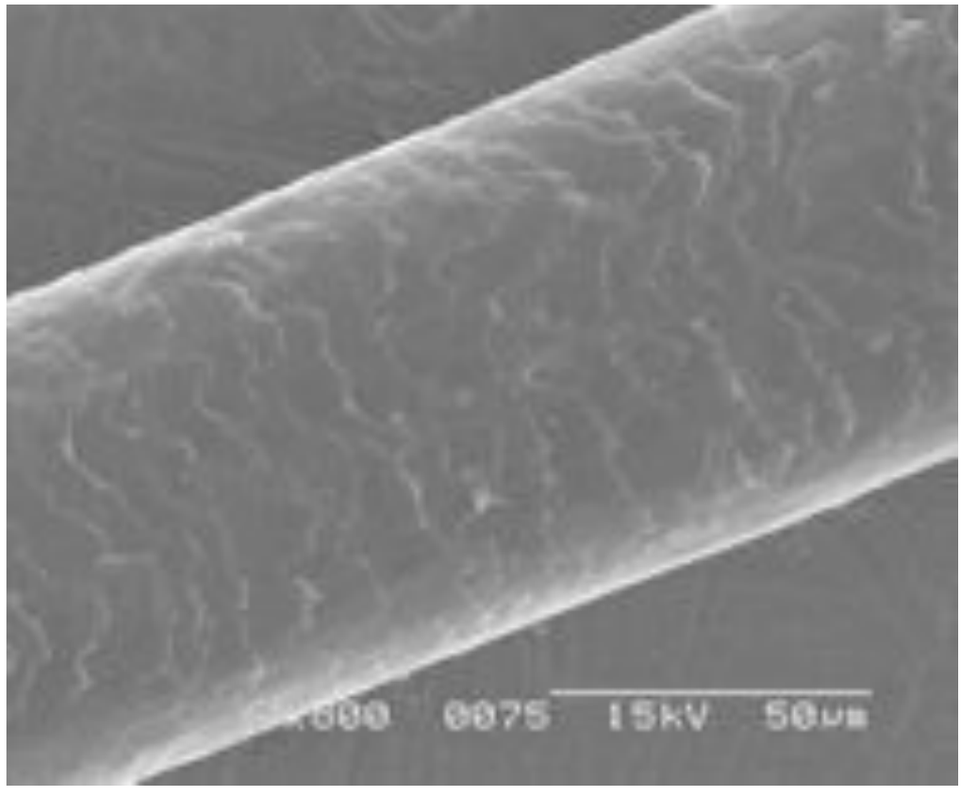
$$F = rate\ of\ change\ of\ momentum = \frac{2P}{c}$$

$$F \approx pN\ for\ mW\ of\ laser\ power$$

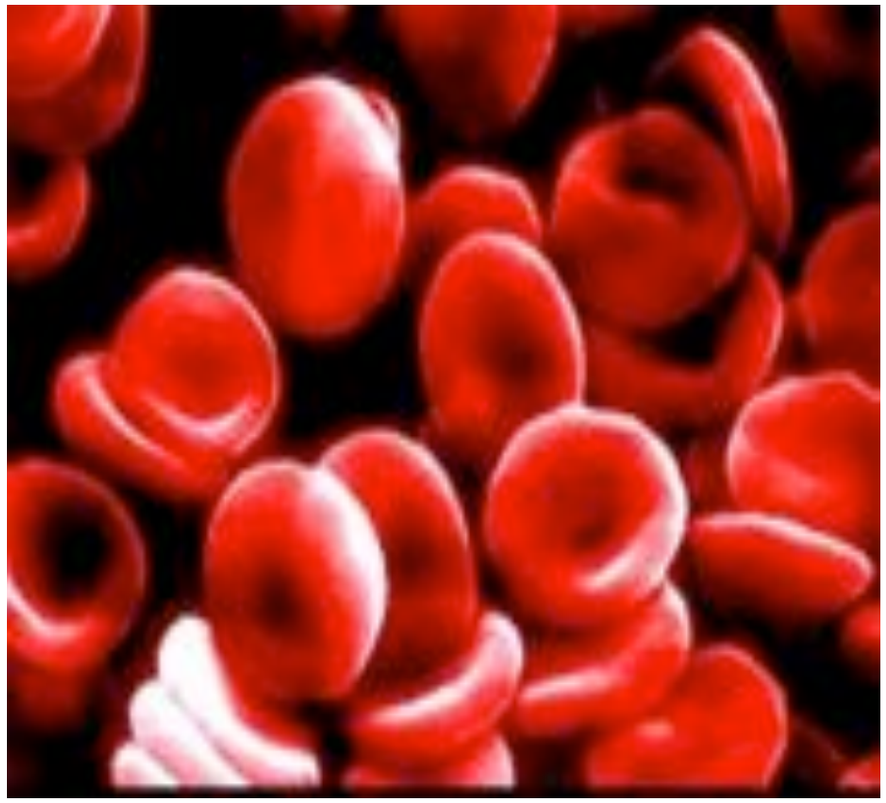
$$\frac{F}{M} = a = 10^5\, g!$$

Independent of wavelength

Size Scale



Human Hair:
~60μm (0.06mm)



Red Blood Cell:
~10 microns (0.01mm)

Light may interrogate, trap and separate objects at this scale

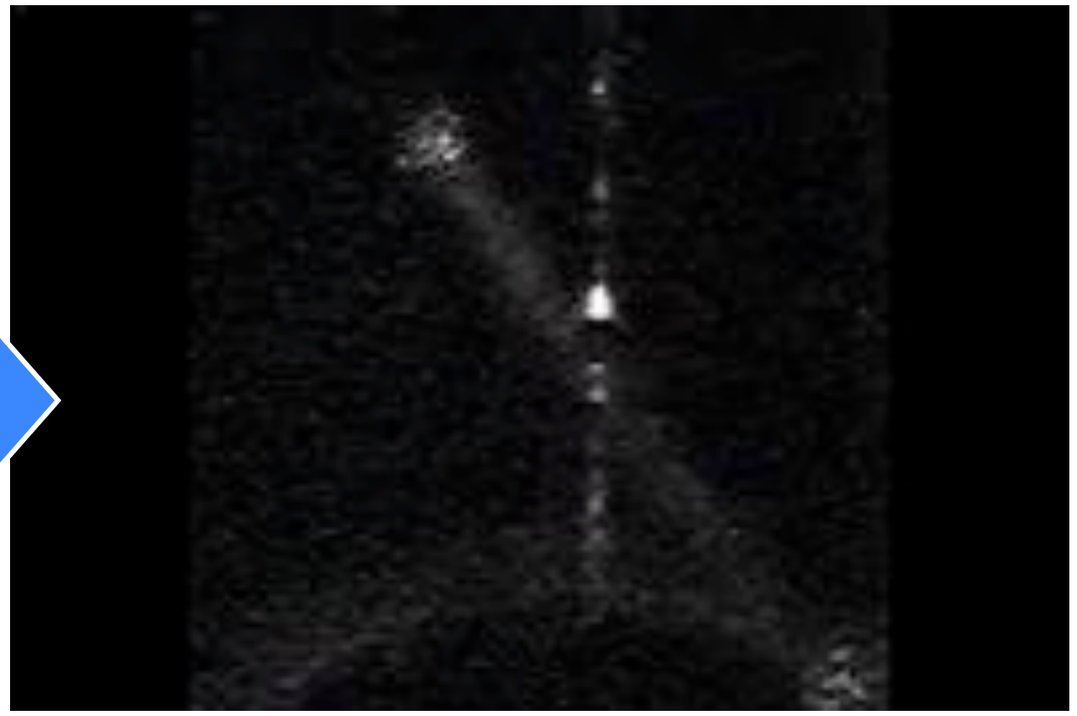
1 micron= 1 millionth of a metre! right down to a single atom

A Basic “Levitation Trap”

At Illinois Wesleyan (USA)|, a fire hose is used to demonstrate the stability of objects in a pressure stream. *Because* light carries momentum, similar “levitation traps” can be made using streams of light.

A Basic “Levitation Trap”

optical manipulation



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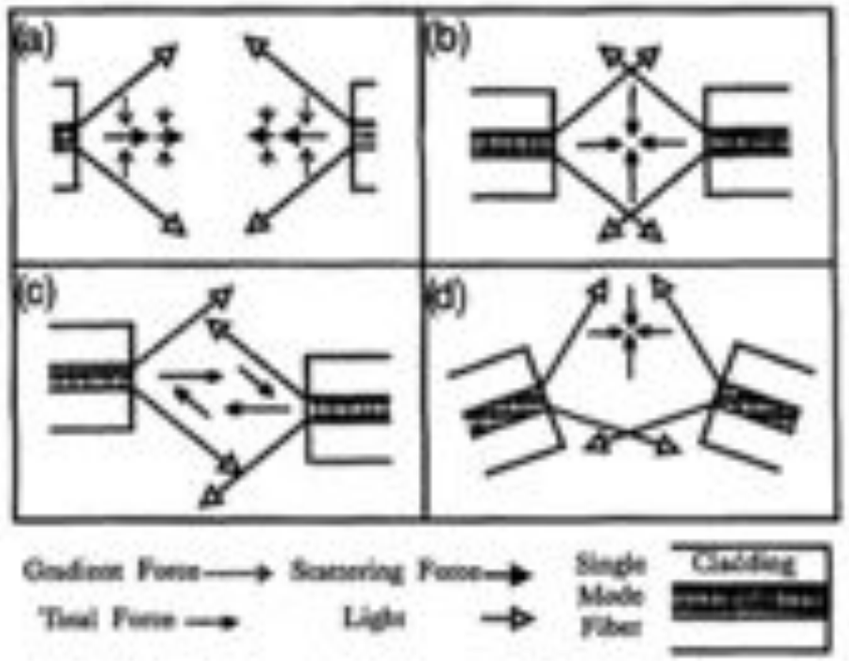
Dual Beam counter-propagating trap

Ashkin, *Phys Rev. Lett.* **24**, 156 (1970)

Can see this as an interplay between “gradient” and “Scattering” forces - as in ALL traps

Constable et al Opt Lett 1994

Video: M Ristch-Marte group, Innsbruck



Large capture Range

Holds large cells

minimised cell damage

Microfluidics, combine with other modalities

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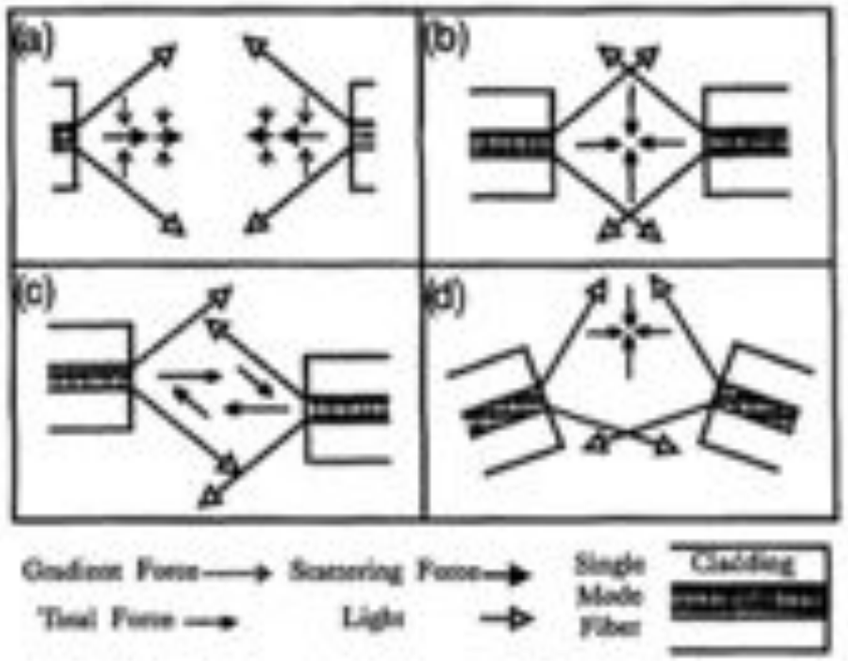
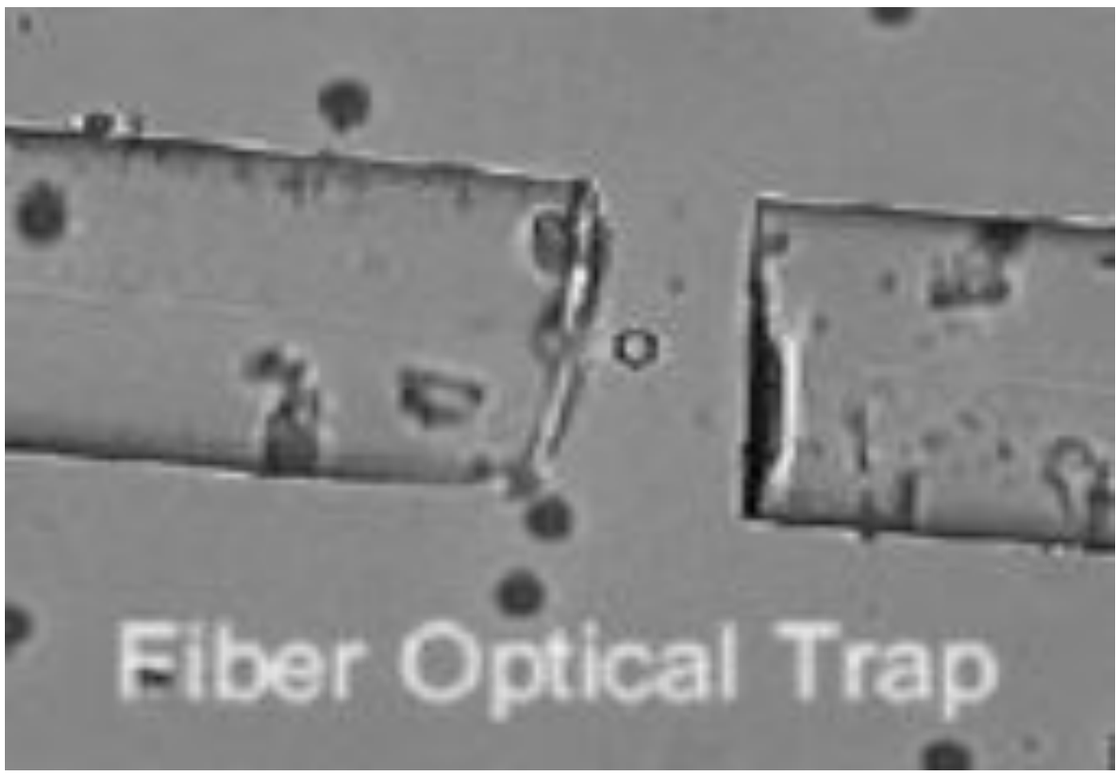
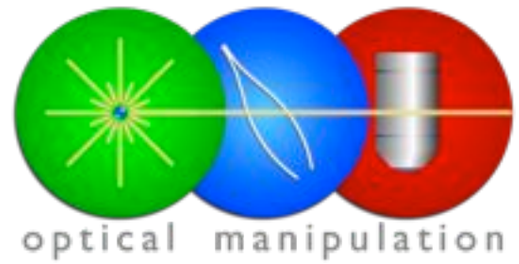




Optical Surface Forces

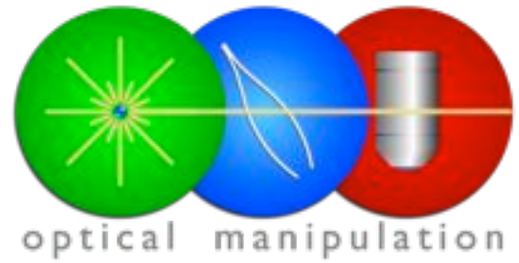


Momentum of a light ray

$$p = \frac{n_i E}{c}$$

J. Guck, *et al*. *Phys*. *Rev*. *Lett*. **84**:5451, 2000

Optical Surface Forces



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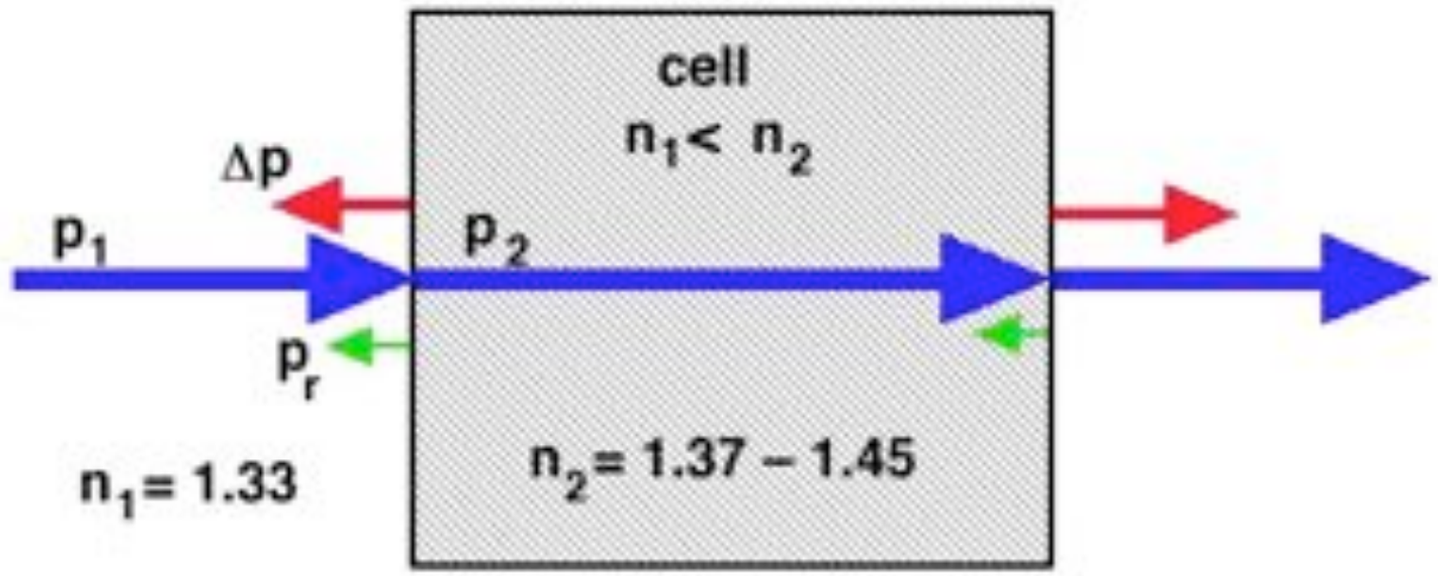
$$p = \frac{n_i E}{c}$$

Conservation of momentum at surface

$$\Delta p = \frac{E}{c}\left(n_1 + Rn_1 - (1-R)n_2\right)$$

$$= \frac{2n_1 E}{c}\left(\frac{1-n}{1+n}\right) < 0$$

$$n = \frac{n_2}{n_1} > 1$$



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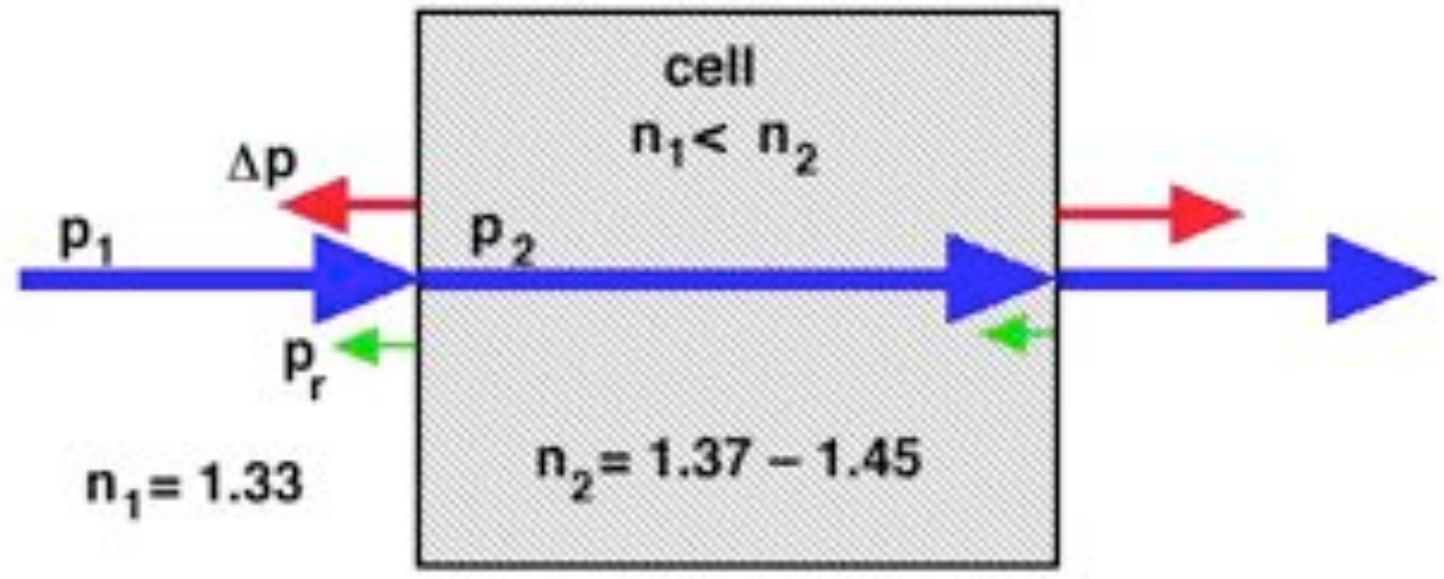
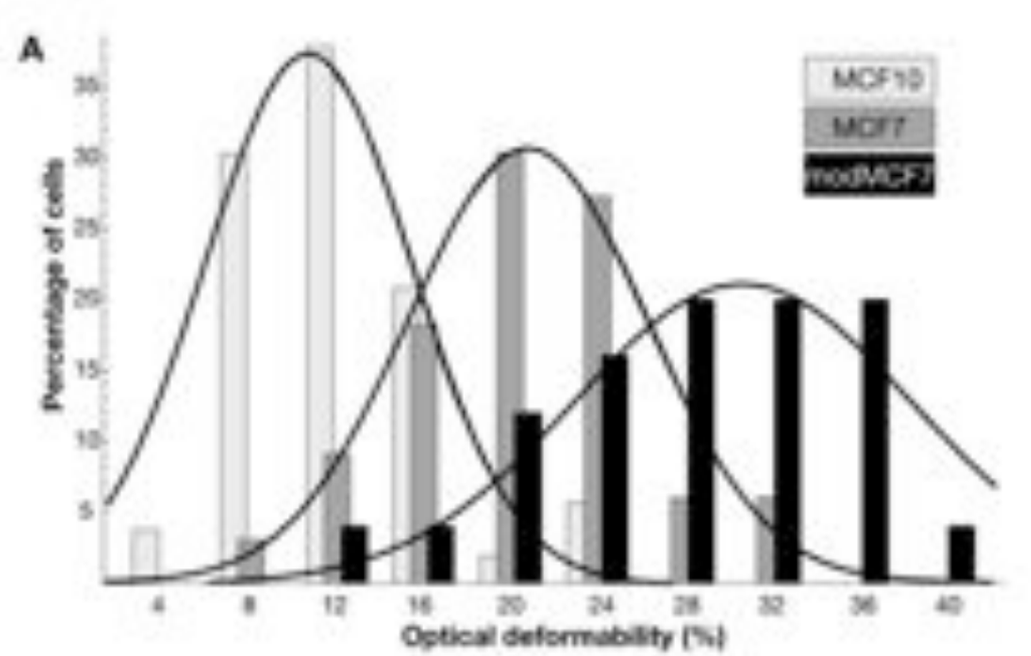


Whenever light enters or exits a dielectric medium it exerts a force AWAY from the denser medium and NORMAL to the surface – COUNTERINTUITIVE!

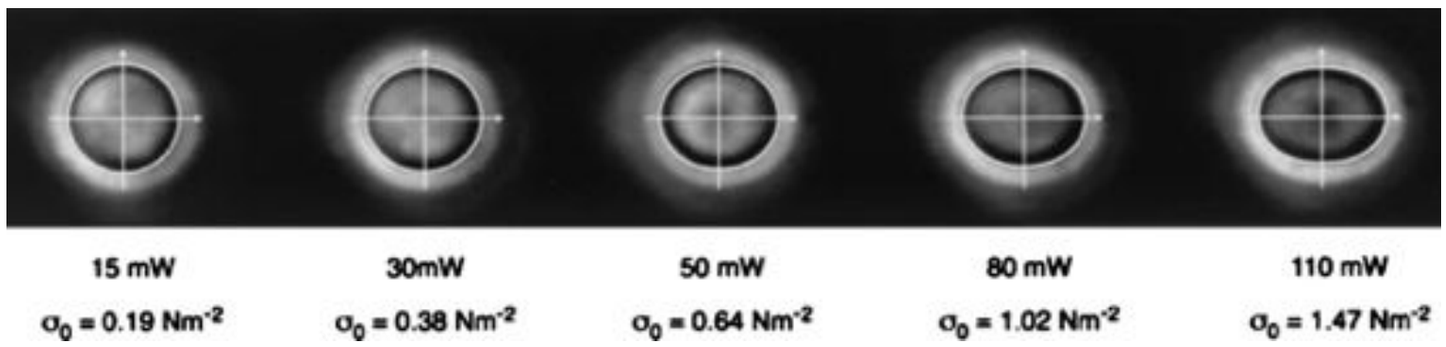
J. Guck, *et al*. *Phys*. *Rev*. *Lett*. **84**:5451, 2000

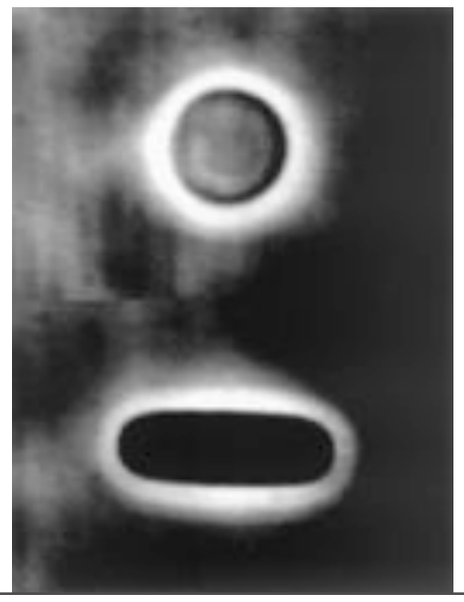
Light forces may probe cancer

optical manipulation



Even metastatic cancer cells (modMCF7) can be distinguished from less aggressive cancer cells (MCF7) and from normal cells (MCF10)





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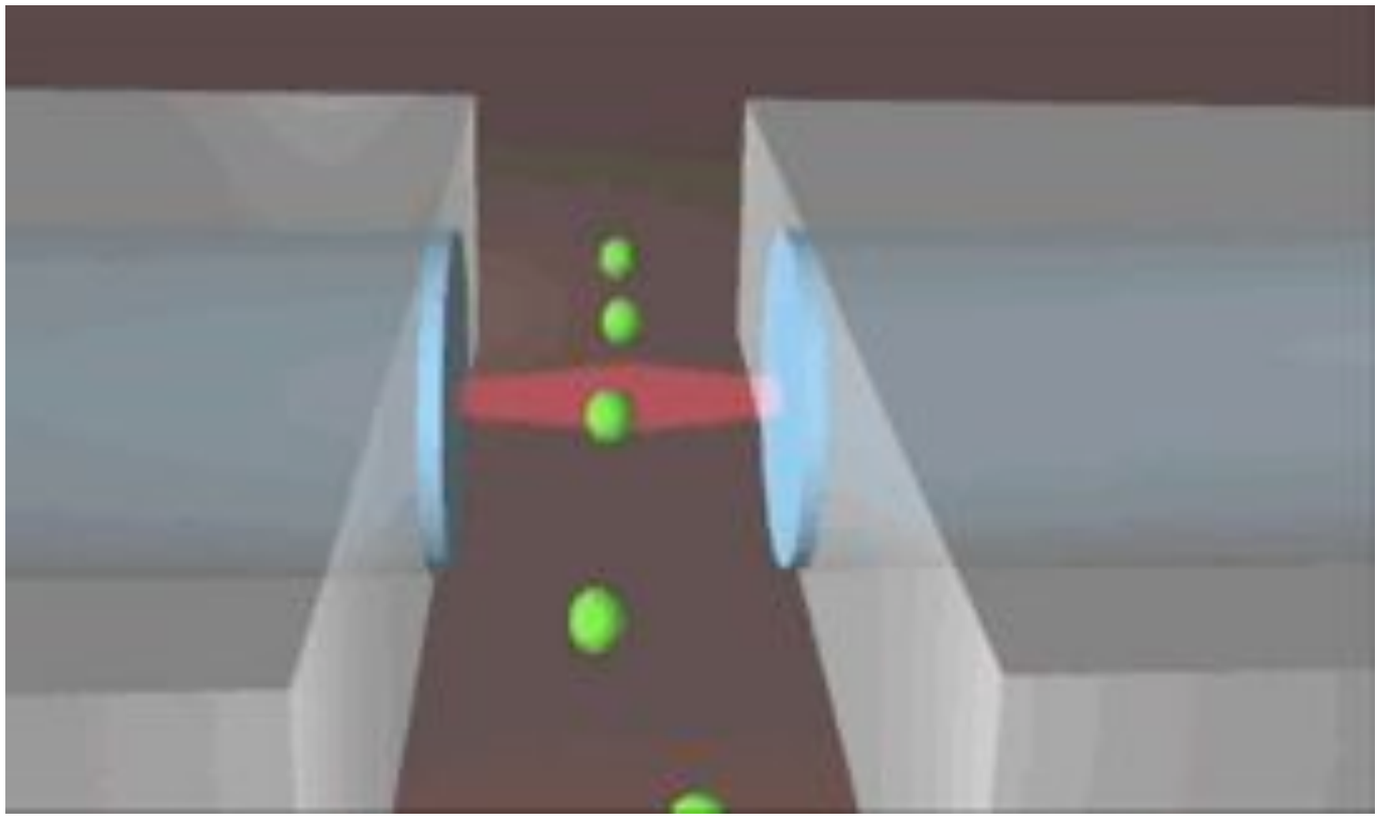

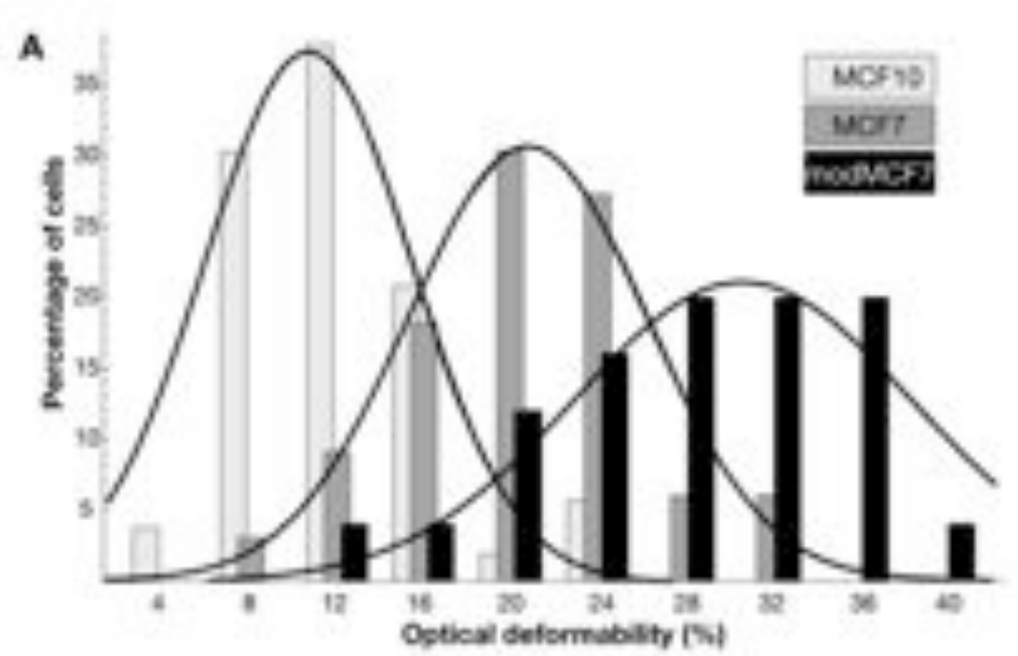

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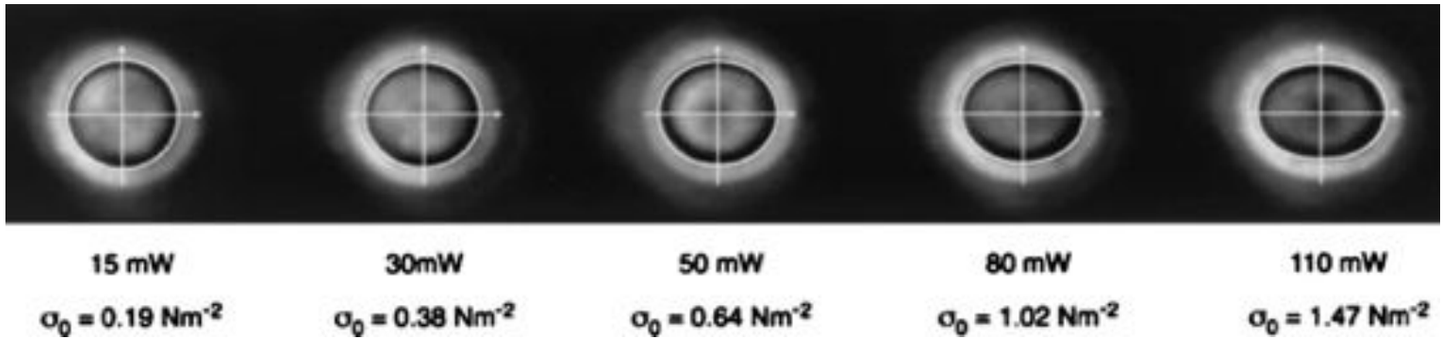

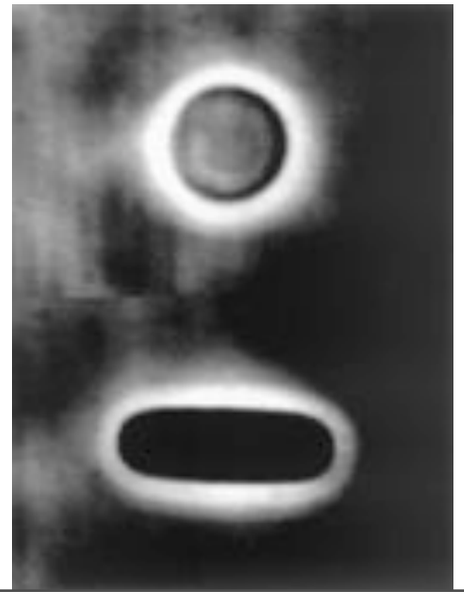

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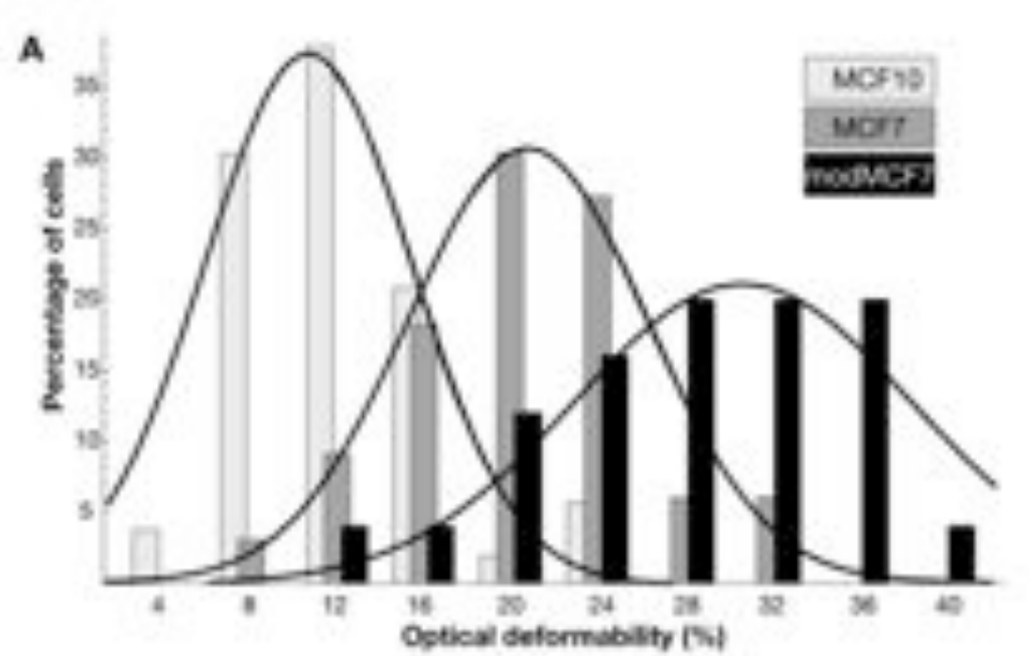

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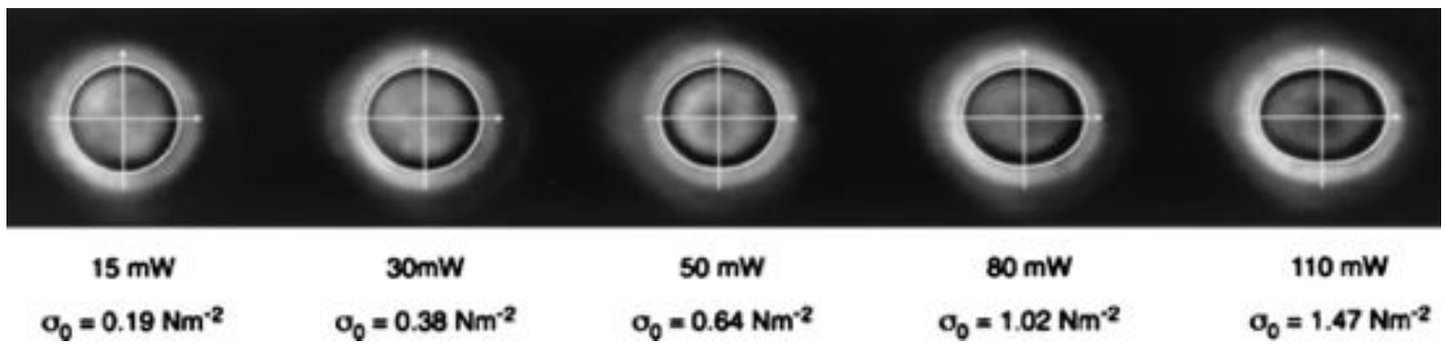

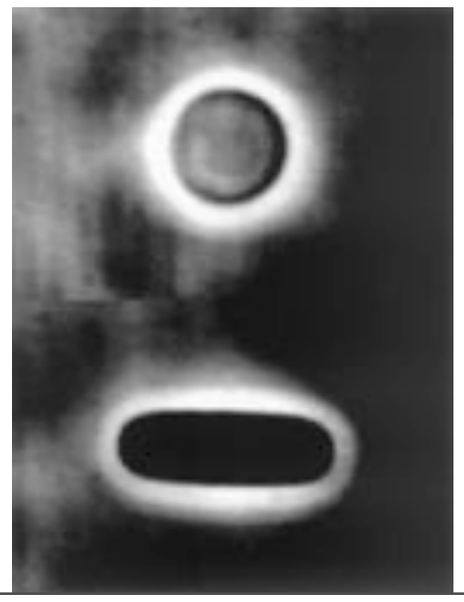

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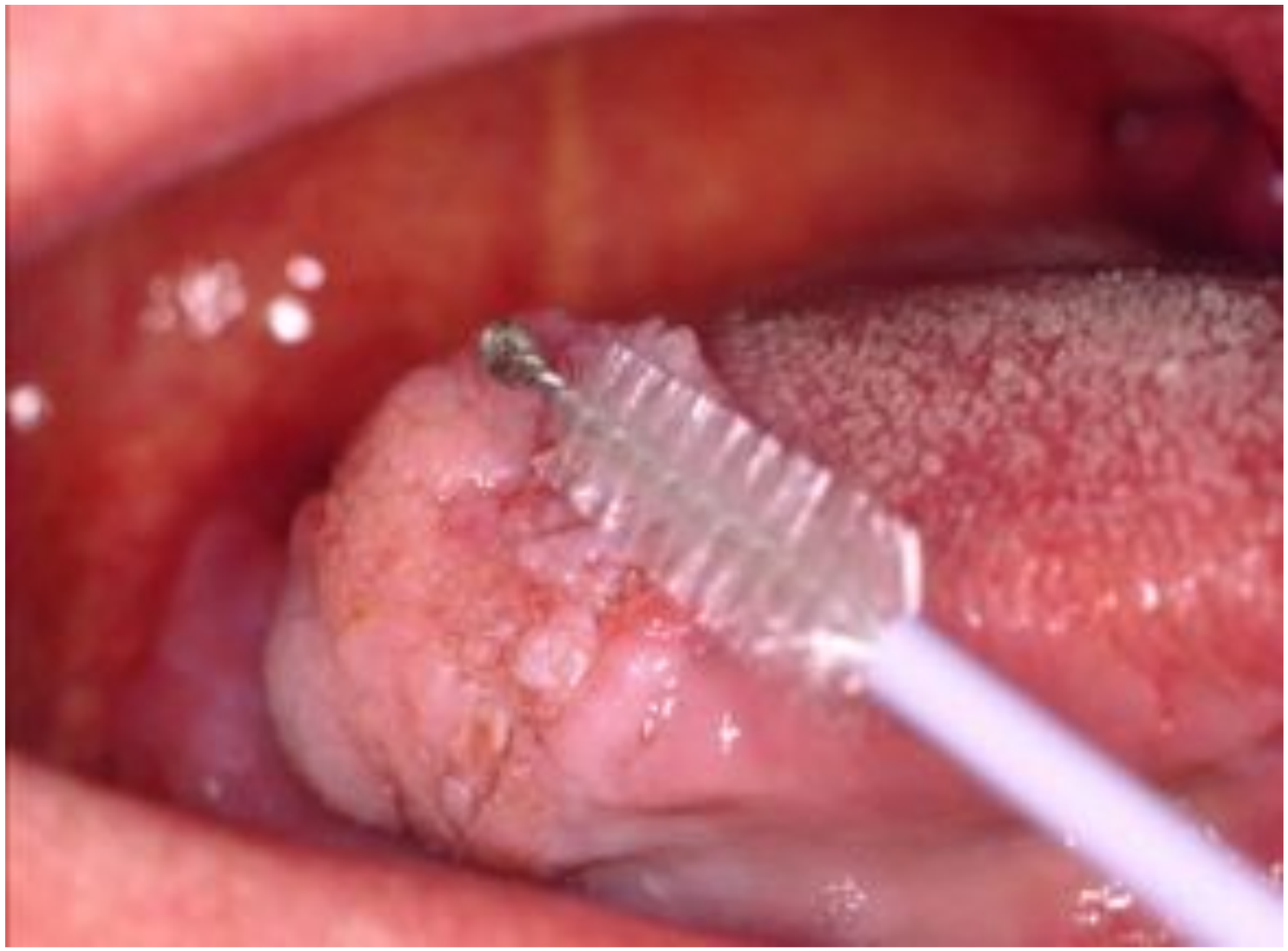
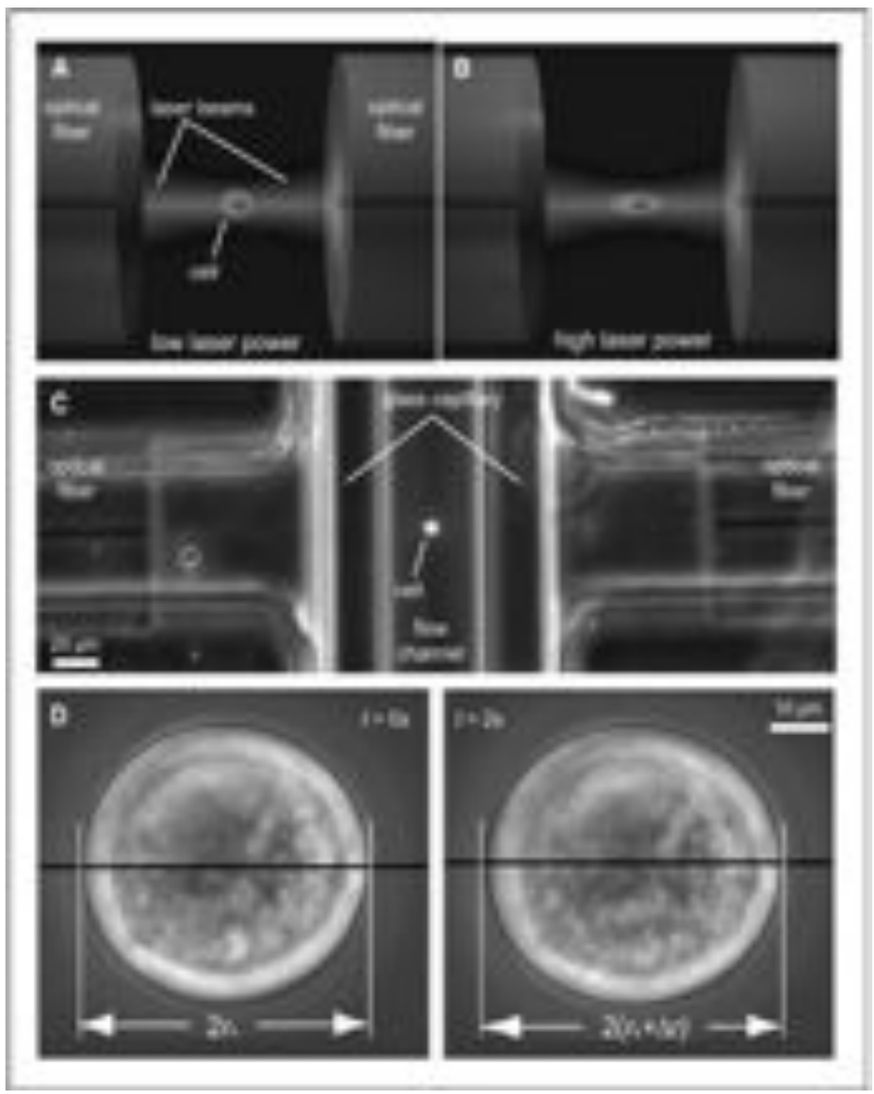
Screening for Oral Carcinomas

optical manipulation



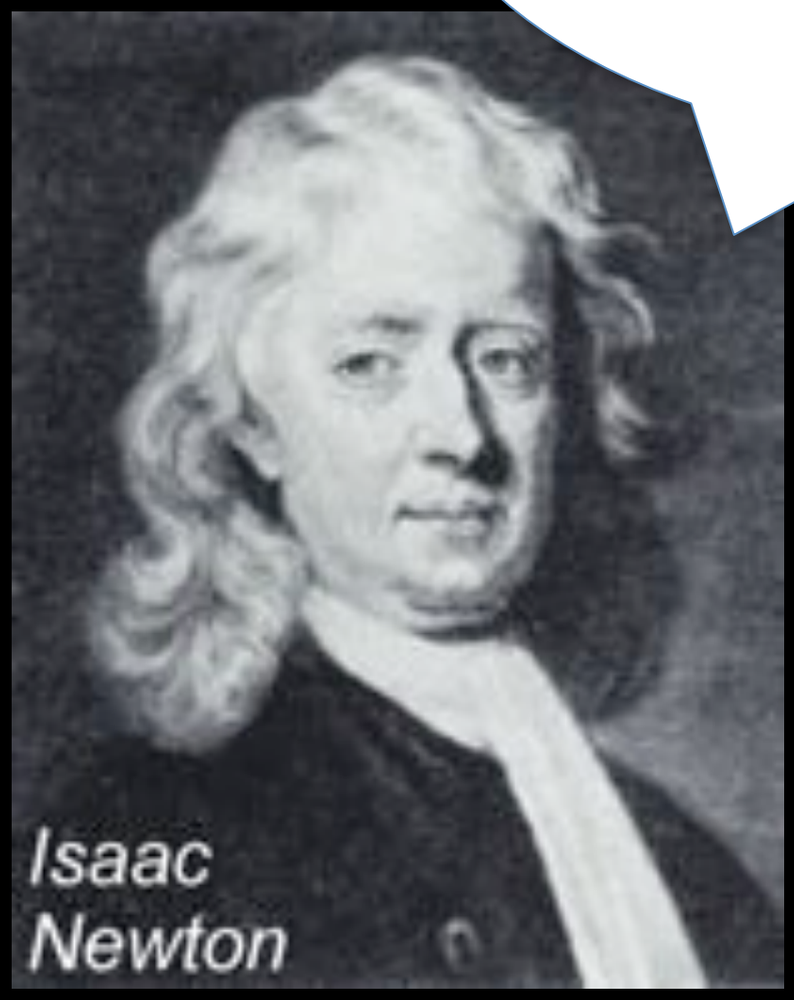


- Use of this principle for a clinical application is possible
- successful clinical trials recently undertaken

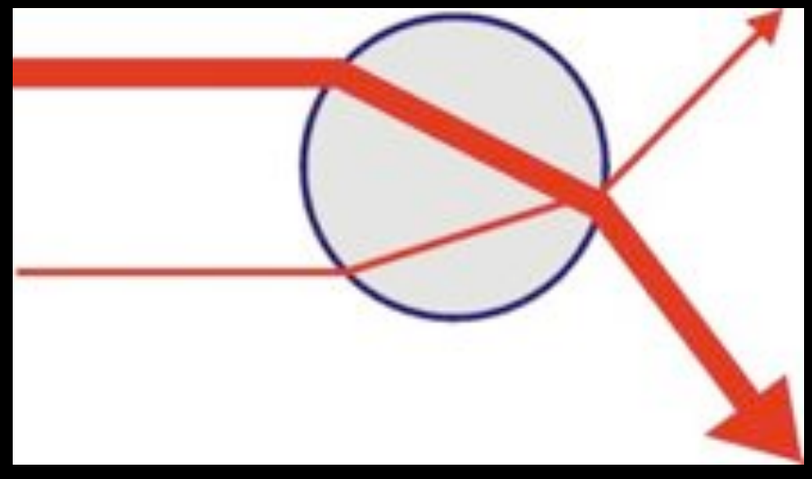
T. W. Remmerbach, F. Wottawah, J. Dietrich, B. Lincoln, Ch. Wittekind, and J. Guck,
Oral cancer diagnosis by mechanical phenotyping
Cancer Res. **65**(5):1728-32 (2009)

optical manipulation

For every action force there is a corresponding reaction force which is equal in magnitude and opposite in direction

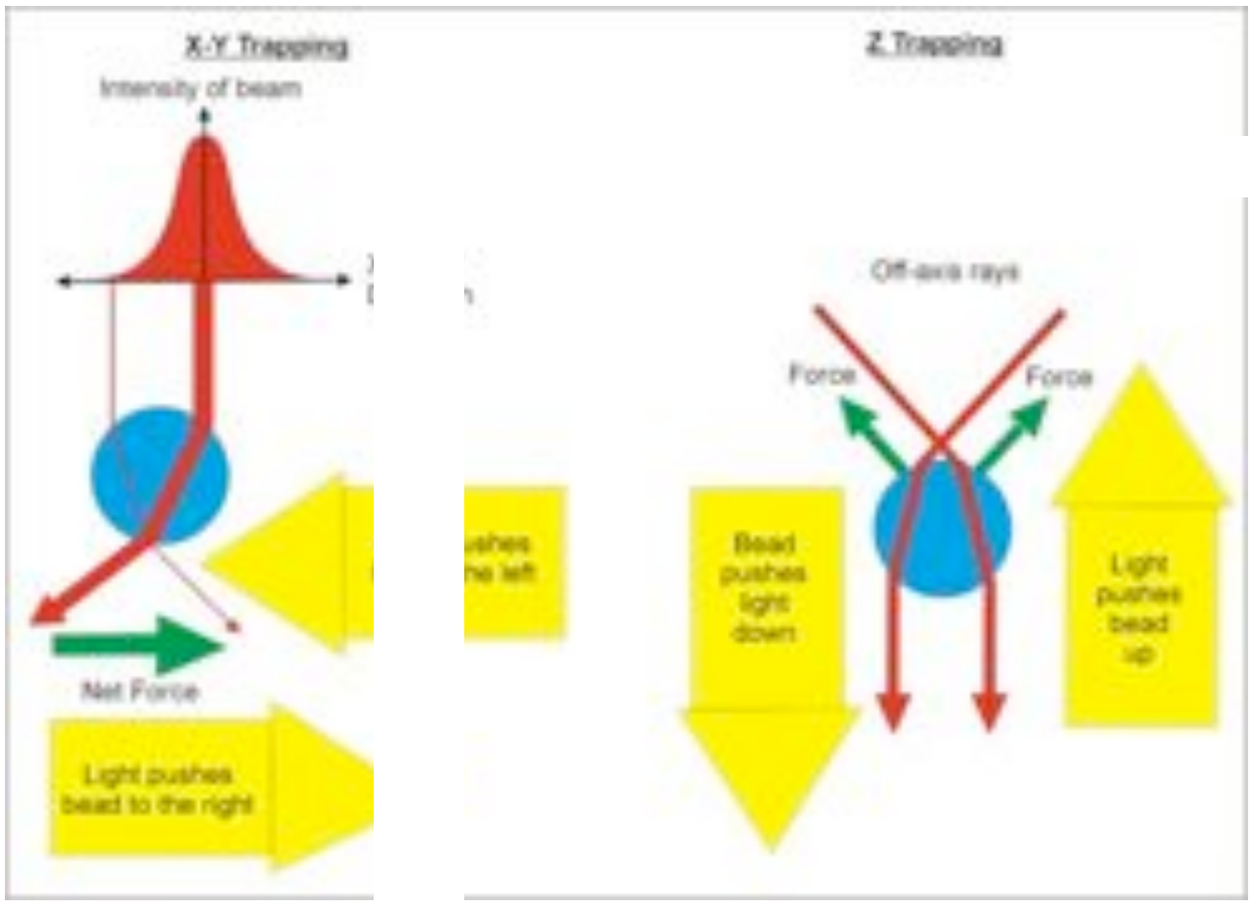


As light is bent by a particle it exerts a force allowing us to use light to trap microscopic particles - REFRACTION



A tightly focused beam may result in a *3D* trap

optical manipulation



Refraction makes light change momentum
In return, the particle experiences an equa
but opposite change in momentum

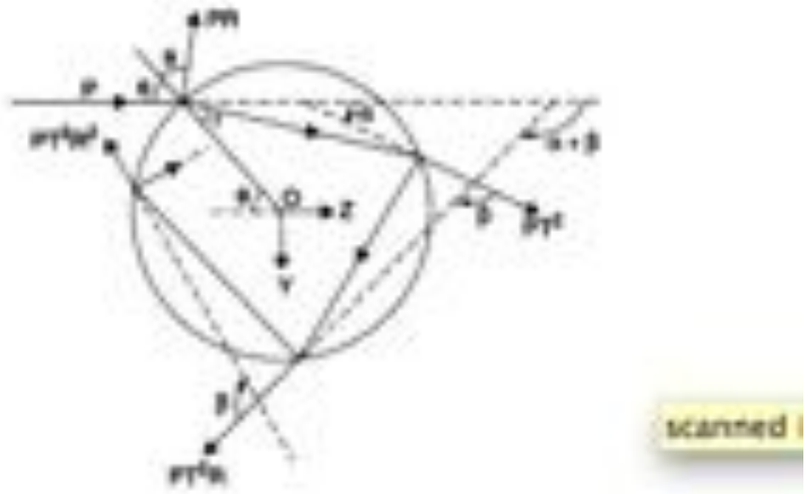


FIGURE 3 Geometry for calculating the force due to the scattering of a single incident ray of power P by a dielectric sphere, showing the reflected ray PR and infinite set of refracted rays PT^nR^n.

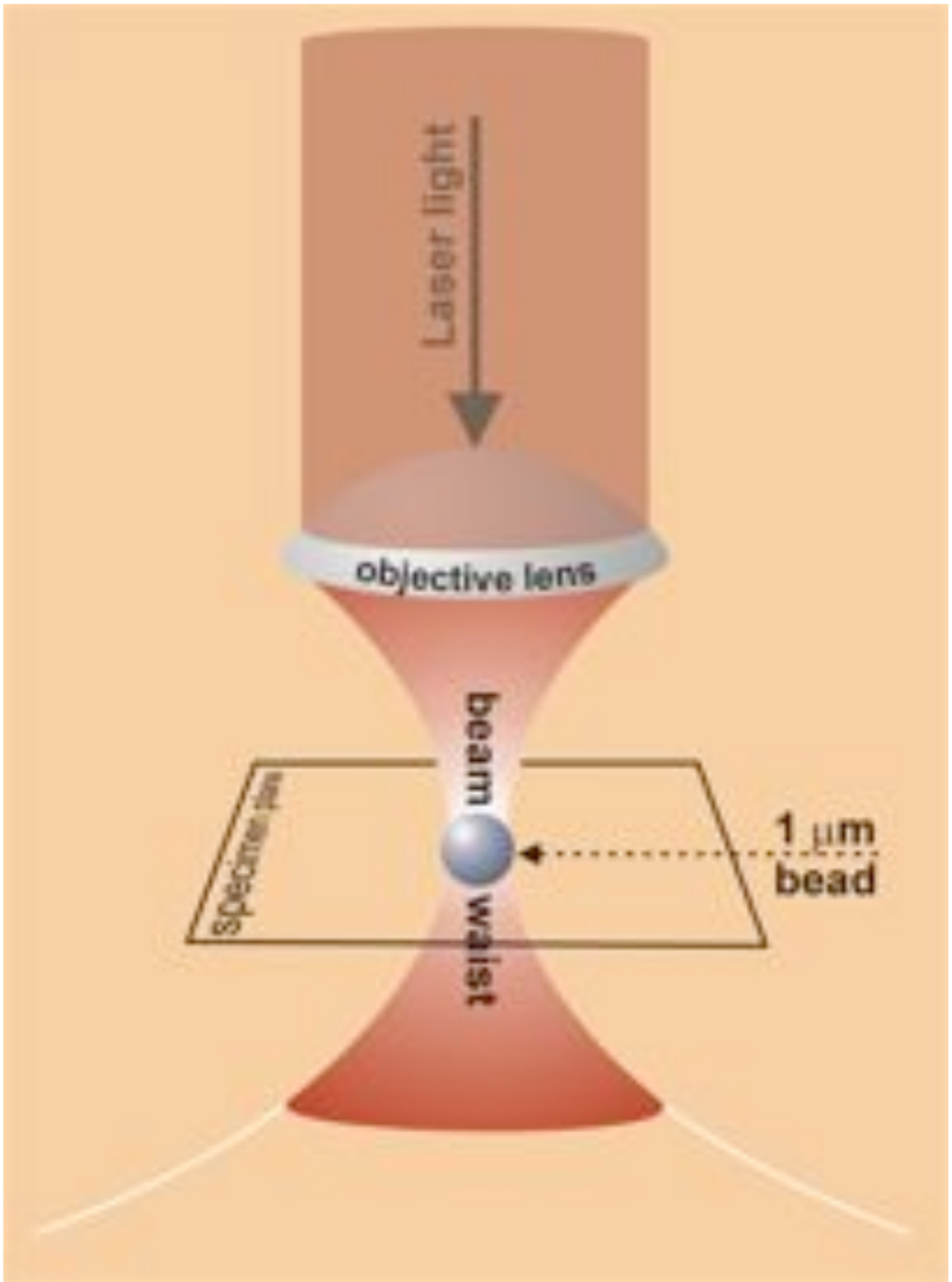
Forces calculated using Fresnel equations/ray optics (particle>>wavelength)

Figure from Ashkin et al.,Biophys J. 1992 February; 61(2): 569–582.

$$F_{\text{grad}} \propto \alpha . \nabla I(r) \qquad F_{\text{scat}} \propto I(r) \qquad \boldsymbol{F}_{\text{trap}} = -\kappa \boldsymbol{x}$$

At the heart of a basic trap:

optical manipulation



- ✓ **Laser**
  - **Wavelength minimize absorption (no "optocution")**
  - **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.) > 1.2 is essential *if* 3D traps are required**

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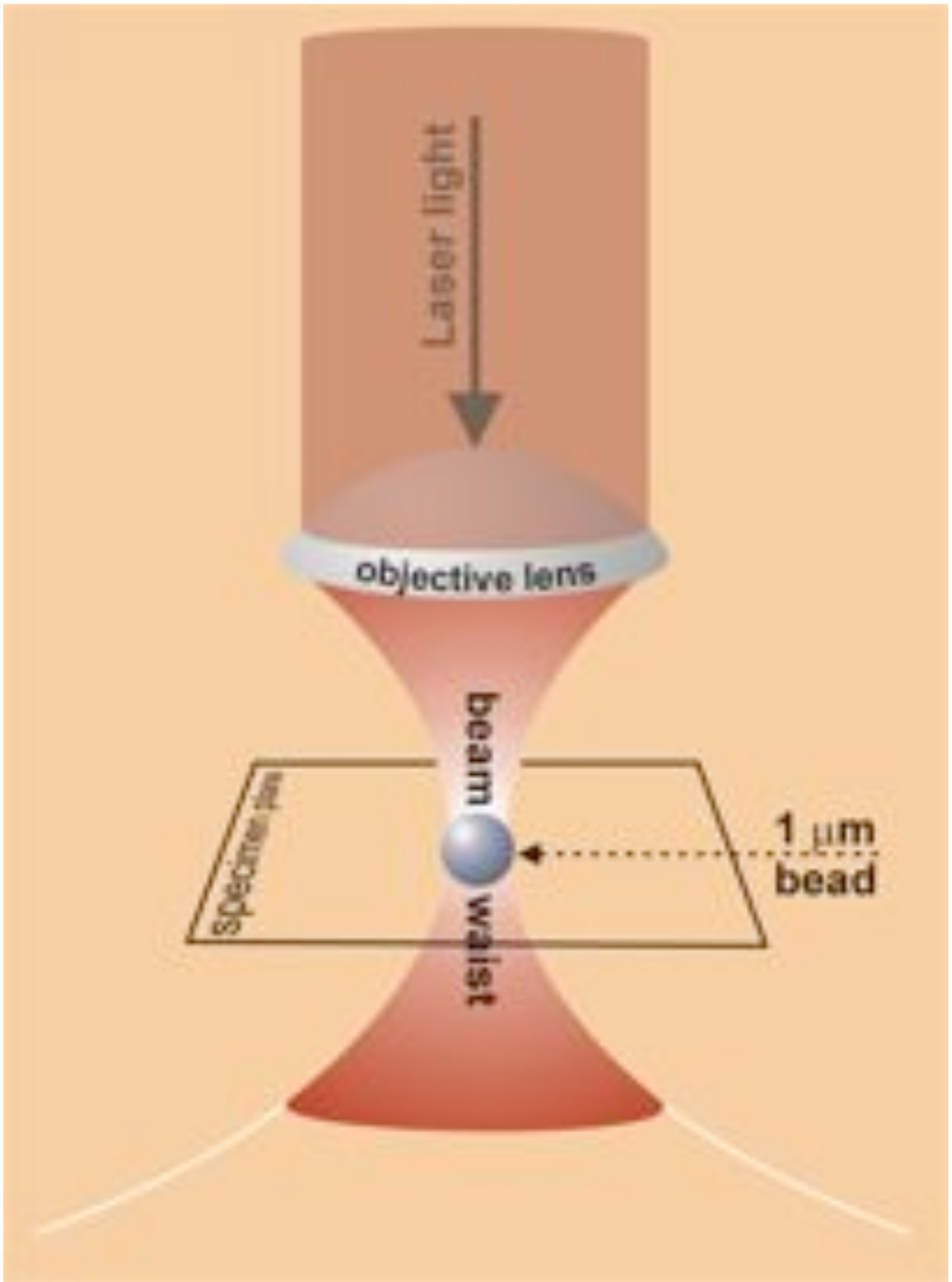

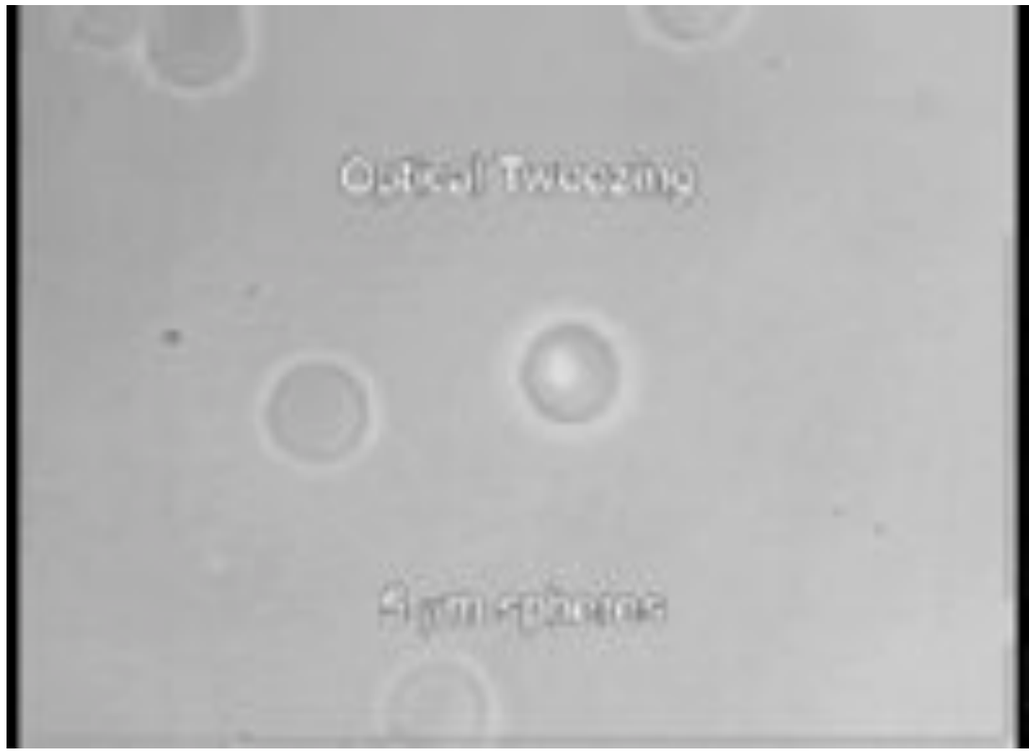

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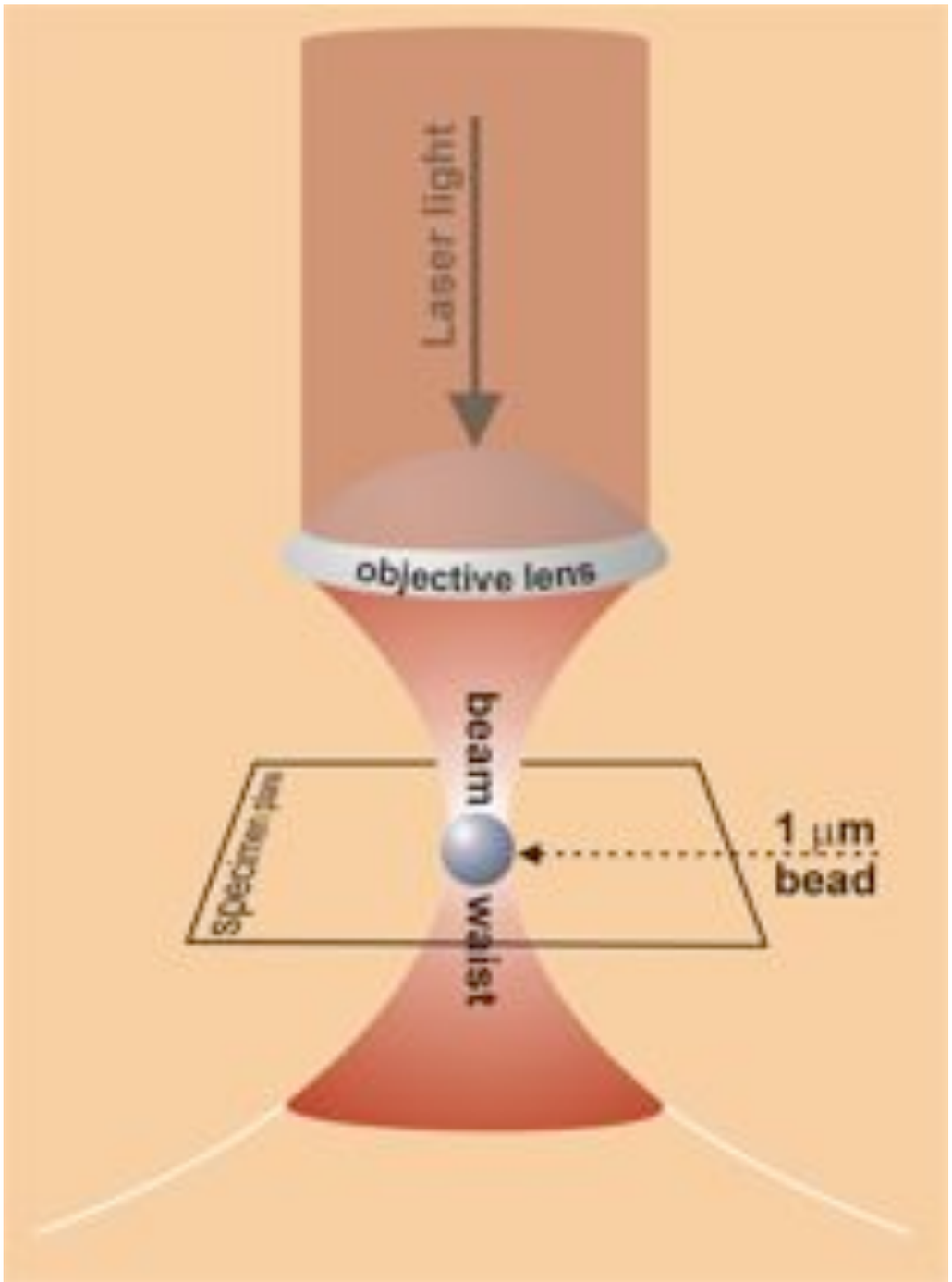

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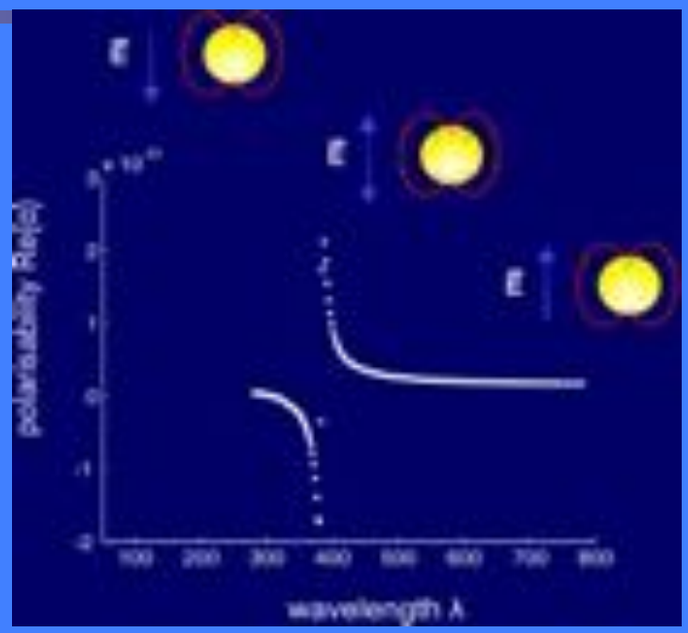
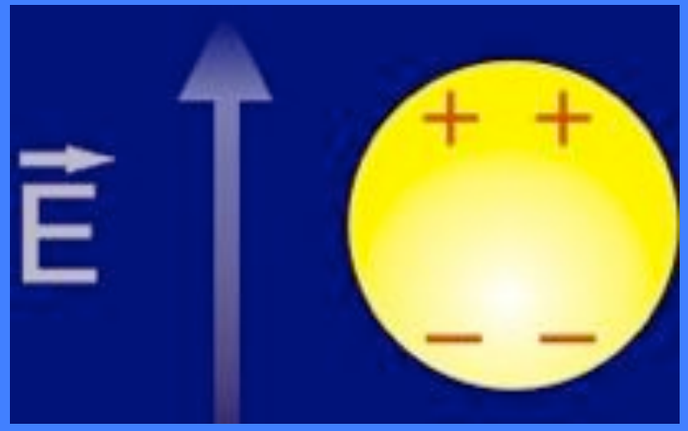
polarisability key in optical trapping

$$F_{abs} = n_m \langle S \rangle \frac{C_{abs}}{c}$$





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

particle plasmon

Svoboda, Optics Letters 19, p930, 1994

Trapping metal nanospheres

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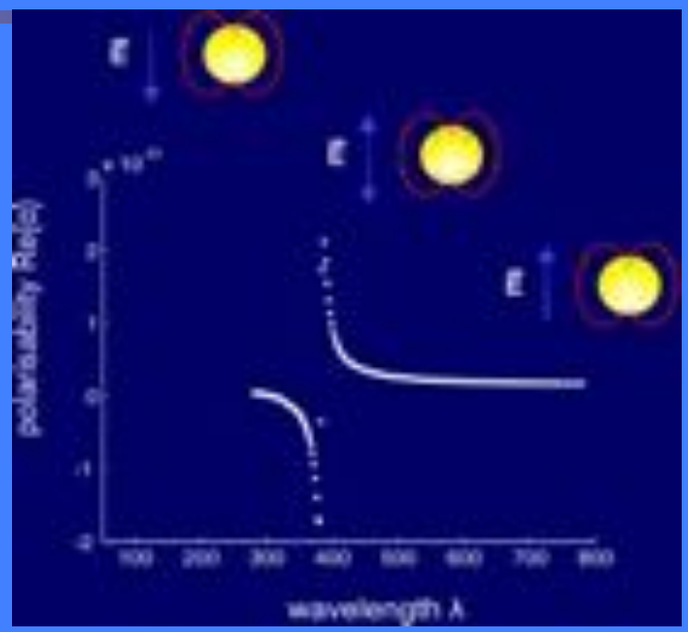

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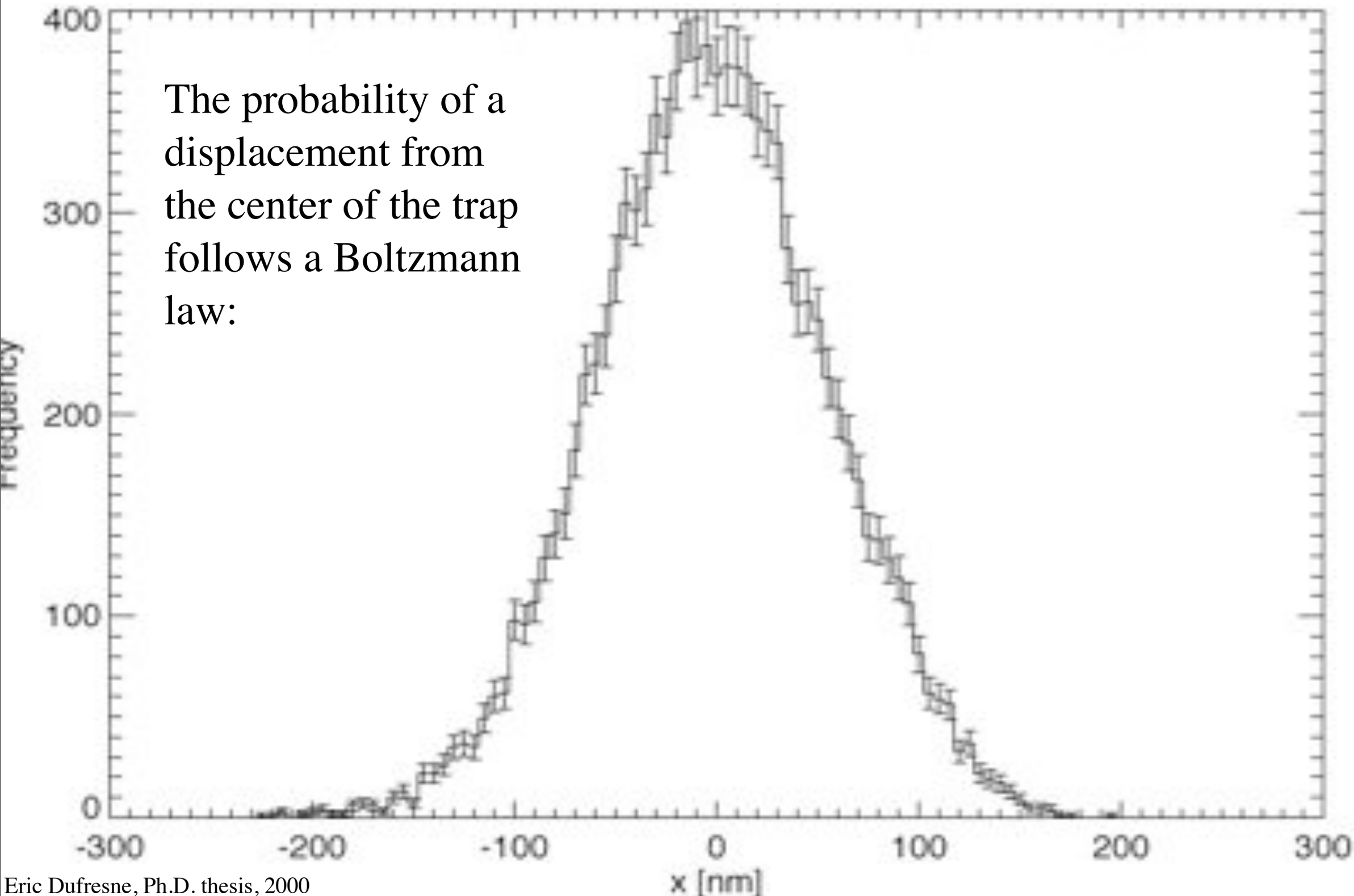
Histogram of Particle Position

optical manipulation

The probability of a displacement from the center of the trap follows a Boltzmann law:



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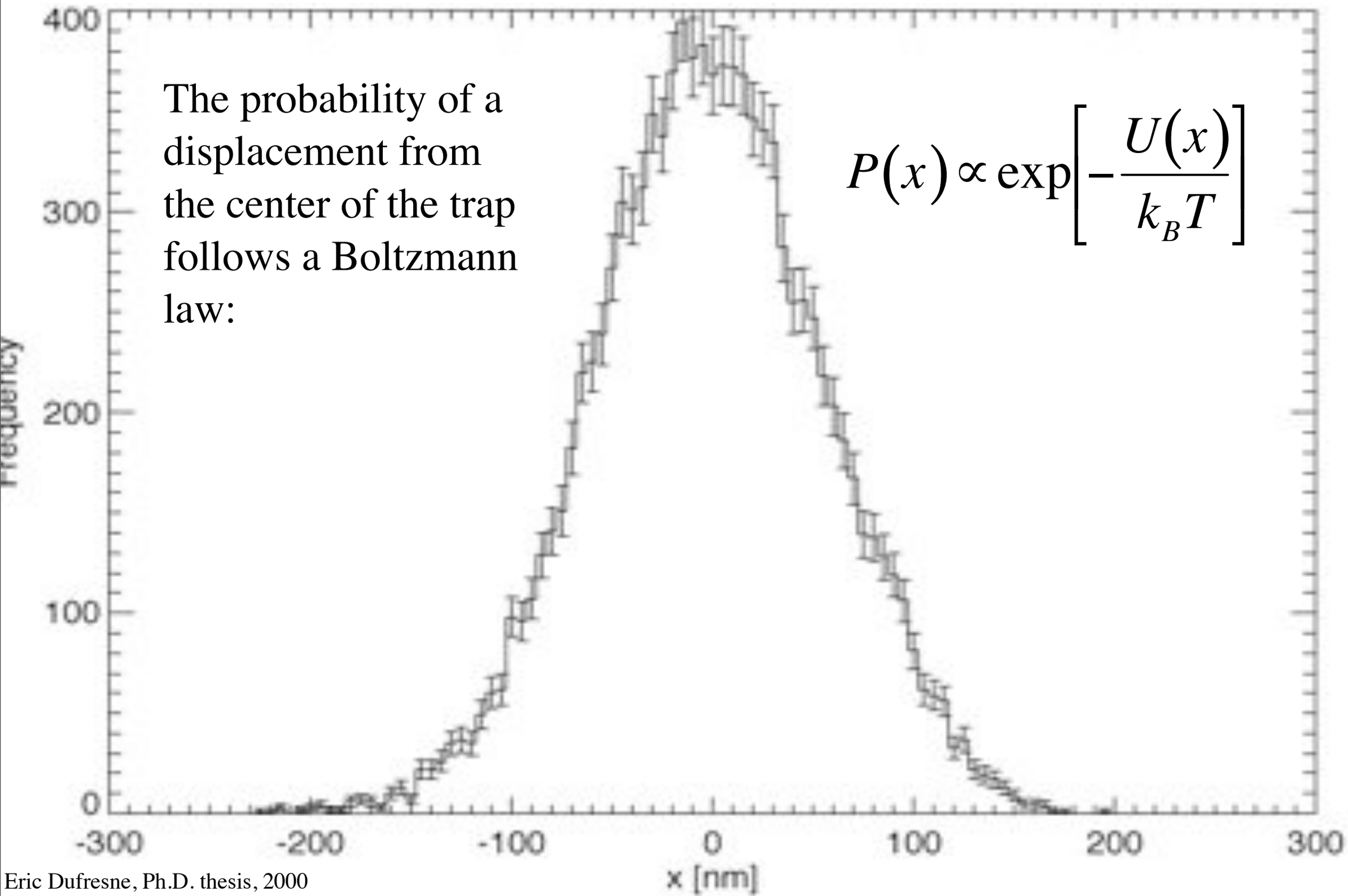

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$$P(x) \propto \exp\left[-\frac{U(x)}{k_B T}\right]$$

Eric Dufresne, Ph.D. thesis, 2000

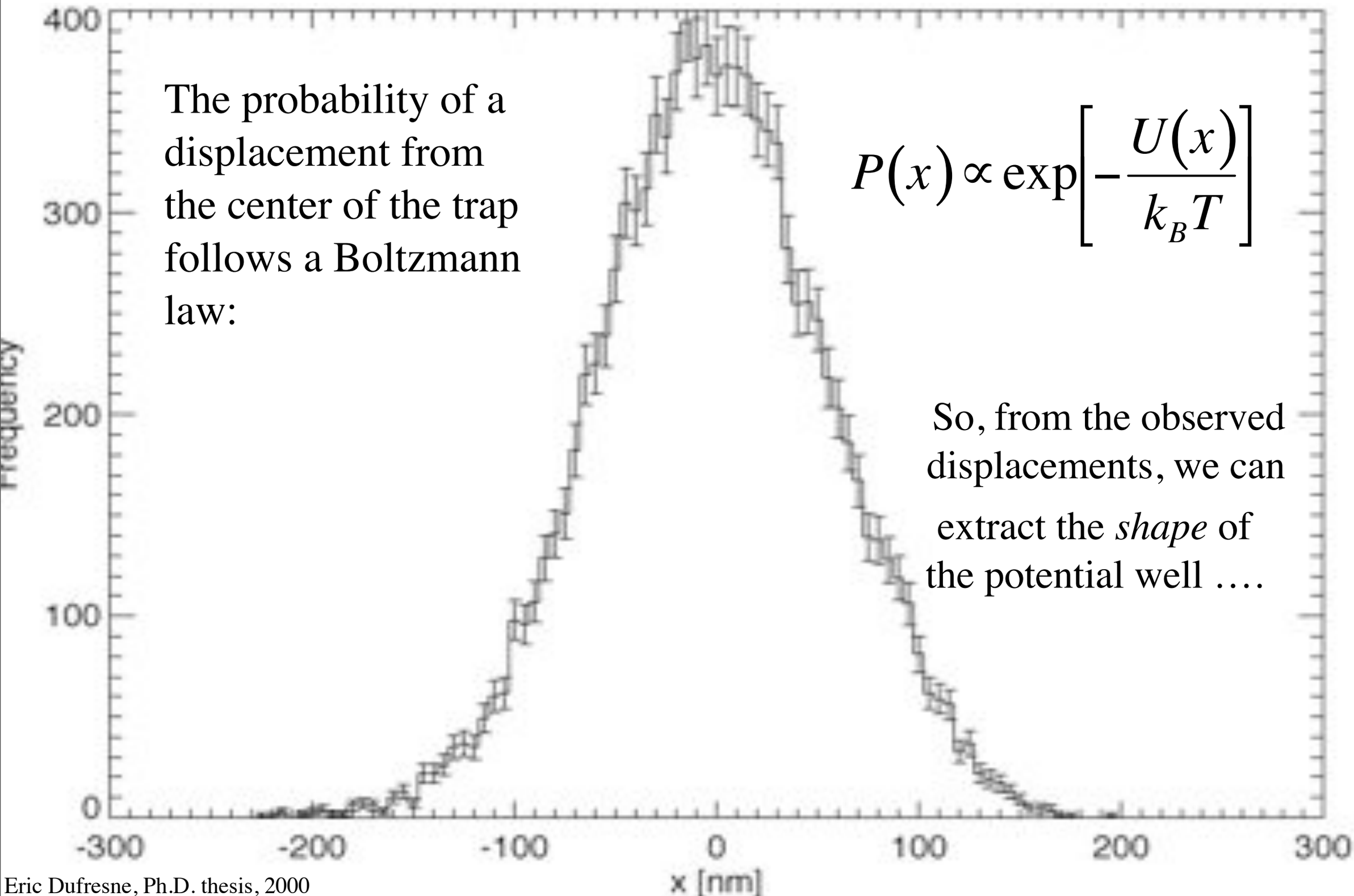
Histogram of Particle Position

optical manipulation

The probability of a displacement from the center of the trap follows a Boltzmann law:

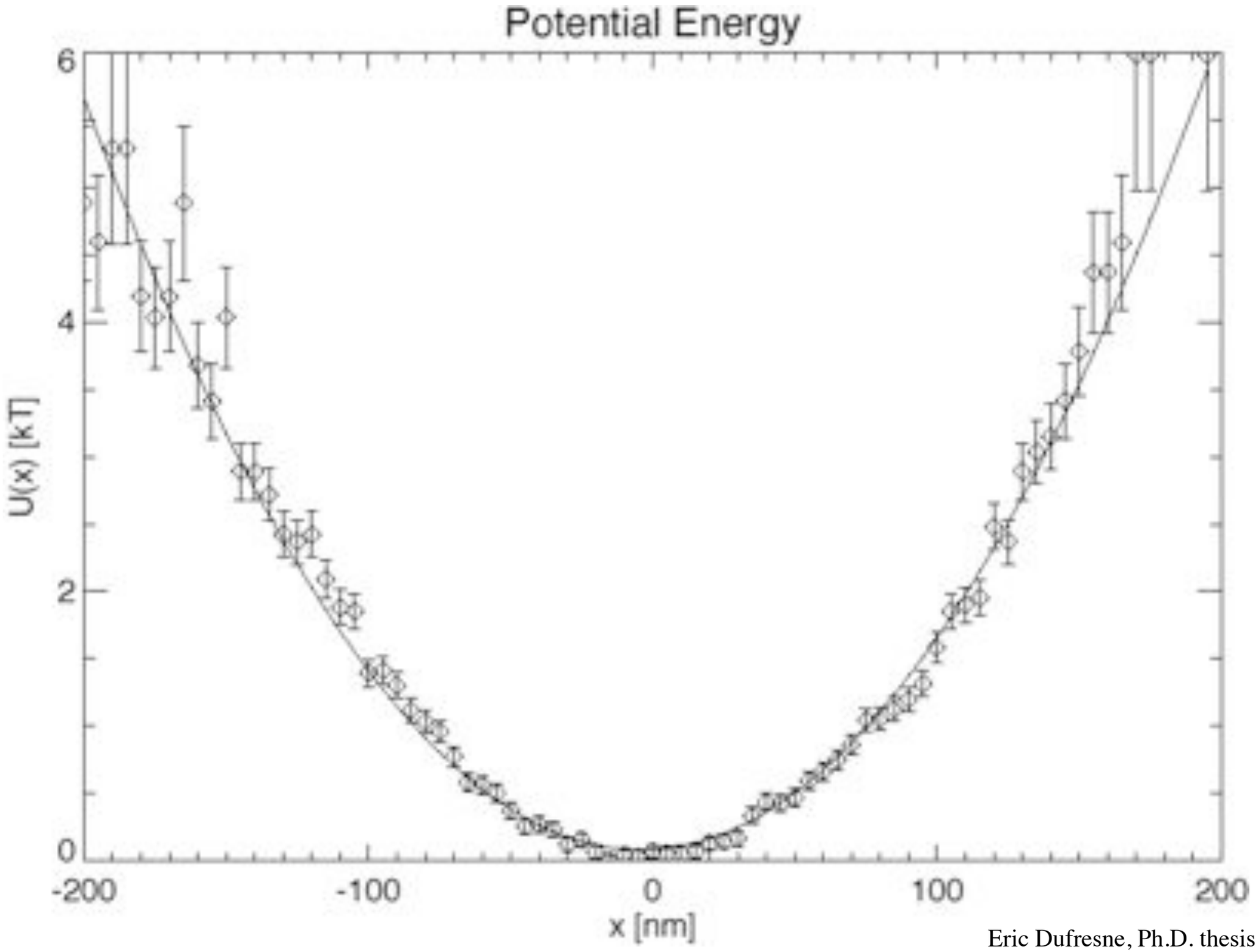
$$P(x) \propto \exp\left[-\frac{U(x)}{k_B T}\right]$$

So, from the observed displacements, we can extract the *shape* of the potential well ….



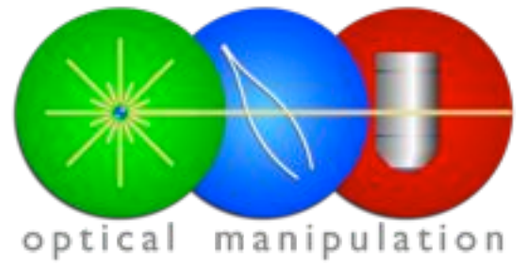
Eric Dufresne, Ph.D. thesis, 2000

For a given laser power and particle size, trapped matter experiences A *Parabolic* Potential Energy "Well"



Eric Dufresne, Ph.D. thesis, 2000

A Classical Oscillator

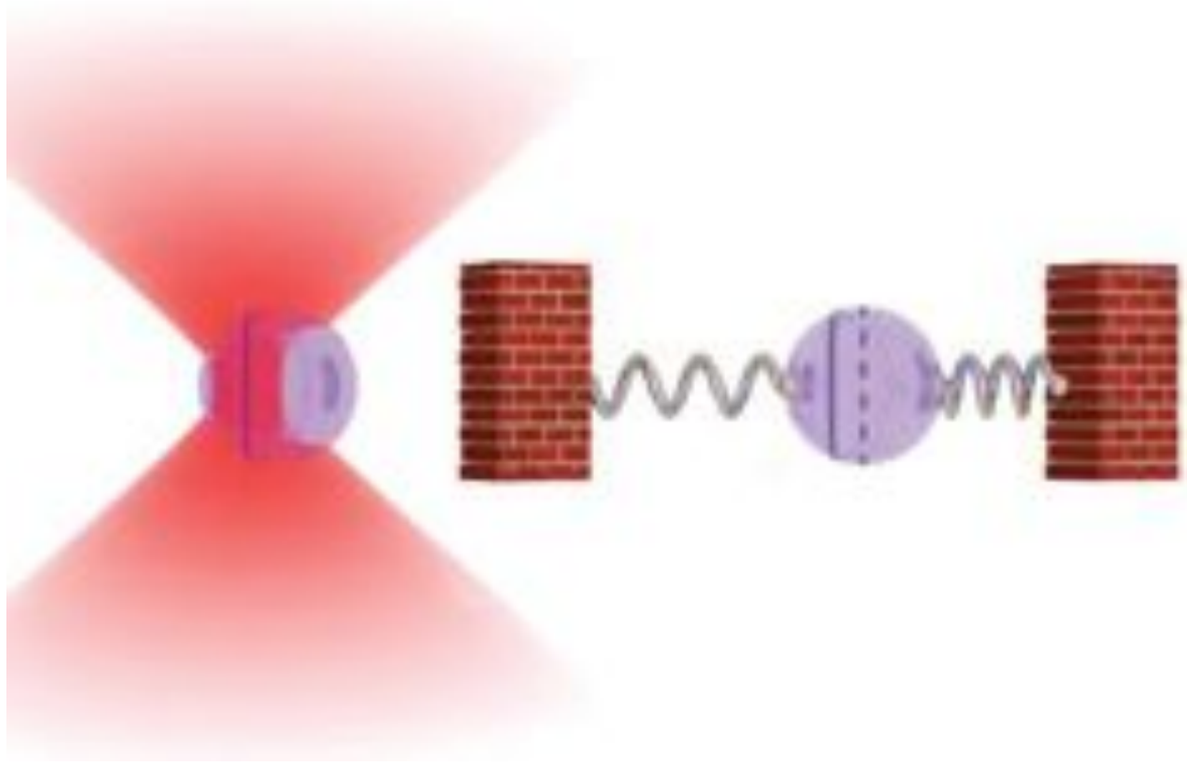


A *parabolic* “well” implies a *linear* relationship between force and displacement, as with a mass on a spring.

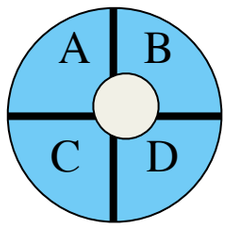
$$m\frac{\partial^2 x}{\partial t^2} + \beta\frac{\partial x}{\partial t} + \kappa x = 0$$

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

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



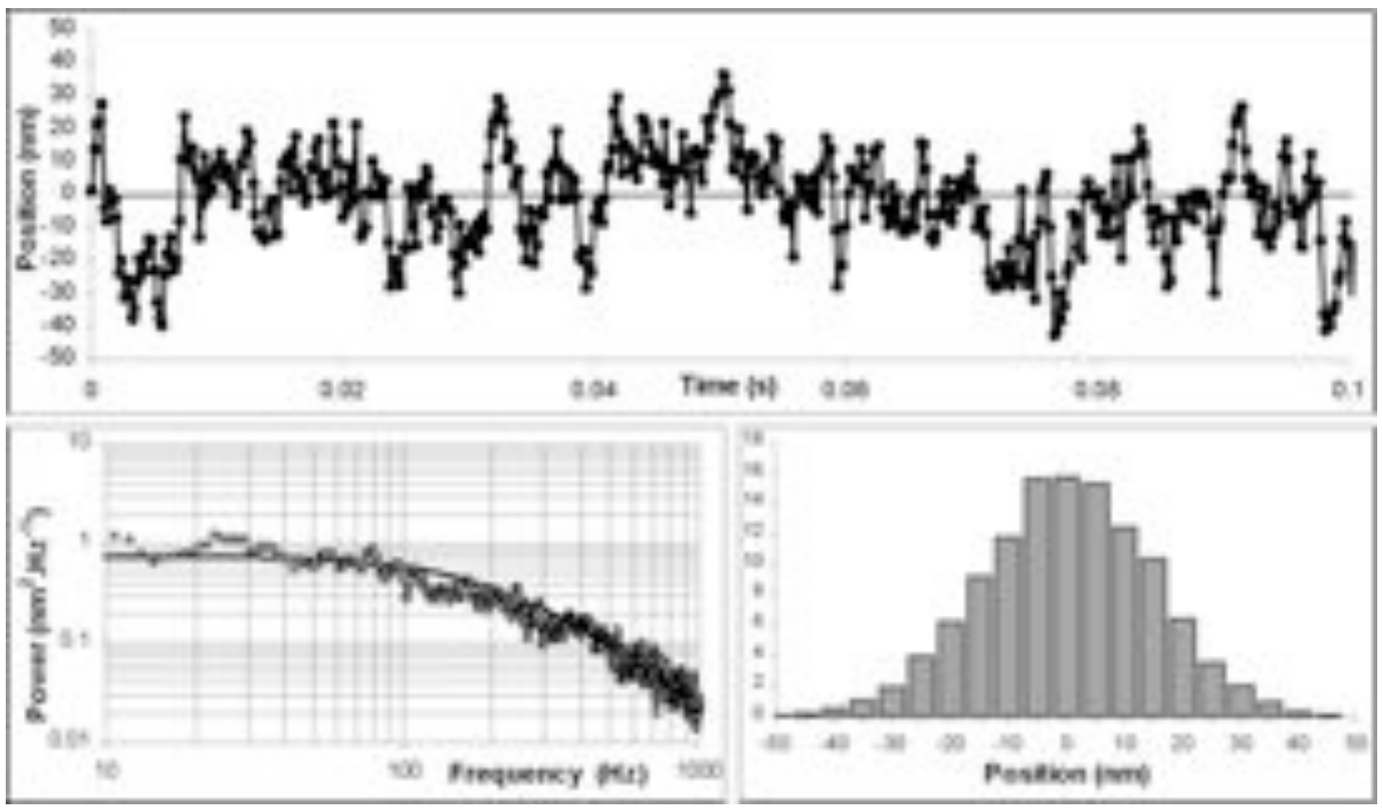
Project a magnified image of the trapped sphere onto a quadrant photodiode.



The position of the sphere is defined by differential signals from the quadrants.

$$\begin{cases} x = (A + C) - (B + D) \\ y = (A + B) - (C + D) \end{cases}$$

Use of a quadrant photodiode provides higher capture rate than CCDs while retaining nanometer-scale position detection (“centre of gravity”)



Power Spectrum method

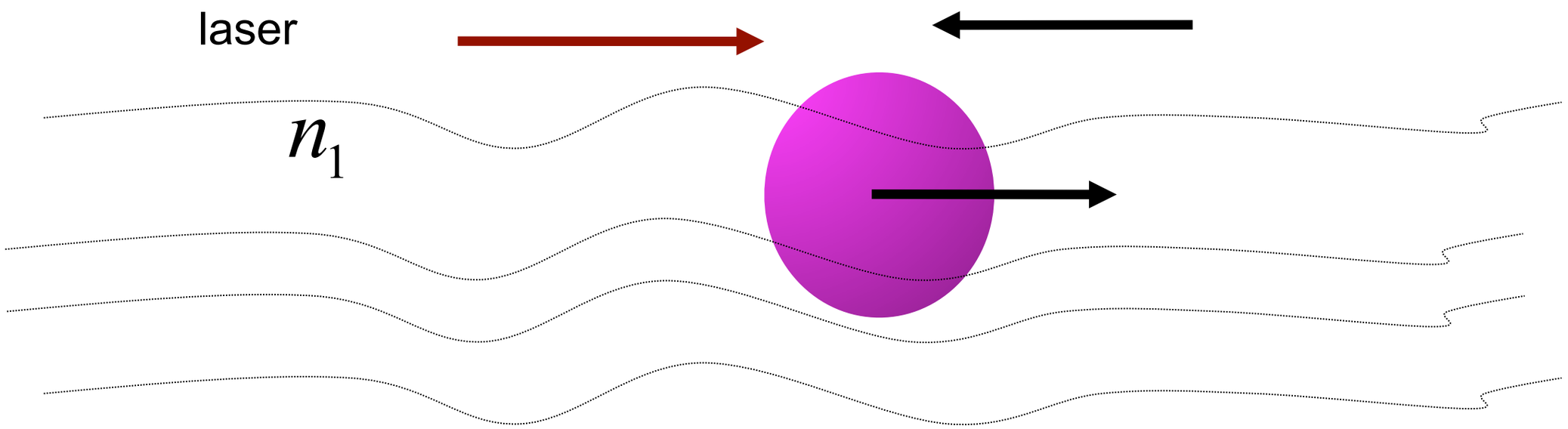
Picture from Molloy and Padgett, *Contemp. Phys* **43**, 241 (2002): see also Berg-Sorenson and Flyvbjerg Rev Sci Instrum (2004)

Measuring forces: hydrodynamic drag method

Momentum transfer to the trapped particle.

$$F = Q\frac{n_1 P}{c}$$

$$\boldsymbol{F}_{drag} = 6\pi\eta \boldsymbol{r} \boldsymbol{V}_{fluid\,(sphere)}$$



the hydrodynamic determination of trap stiffness requires (i) accurate position calibration and (ii) accurate knowledge of β, including Faxen's law correction.

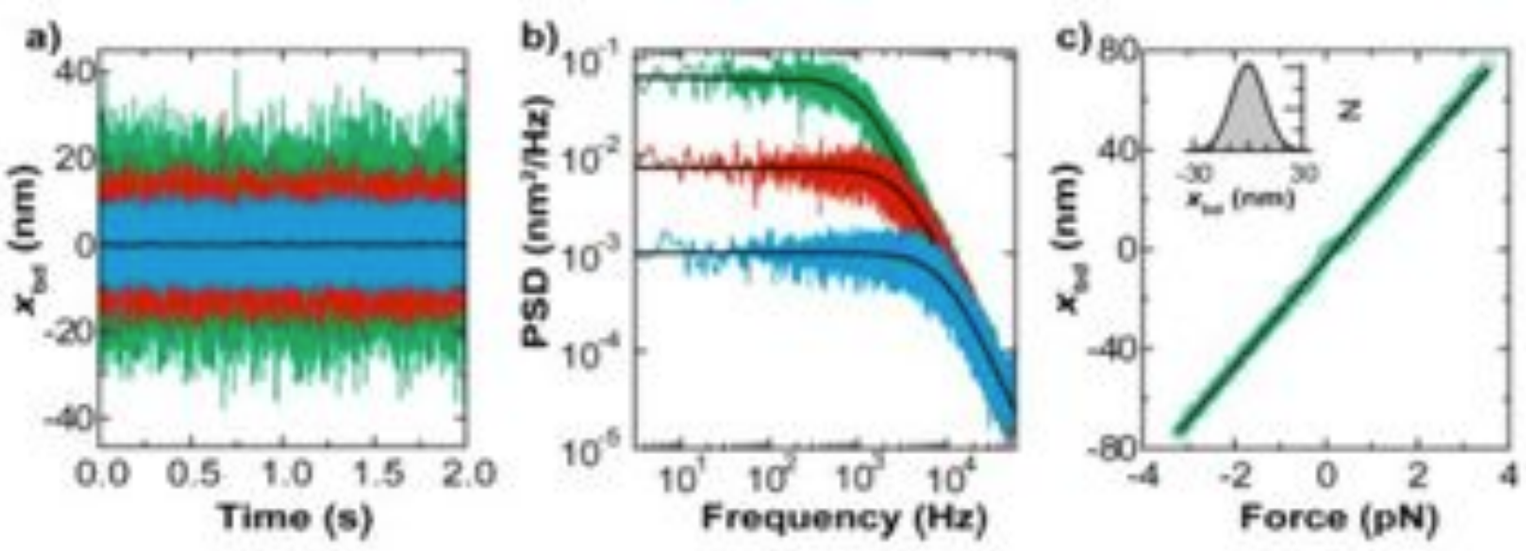
$$k_{\text{trap}} = \frac{F_{\text{drag}}}{x_{\text{bd}}} = \frac{\beta v_{\text{fluid}}}{x_{\text{bd}}}$$

Equipartition Theorem

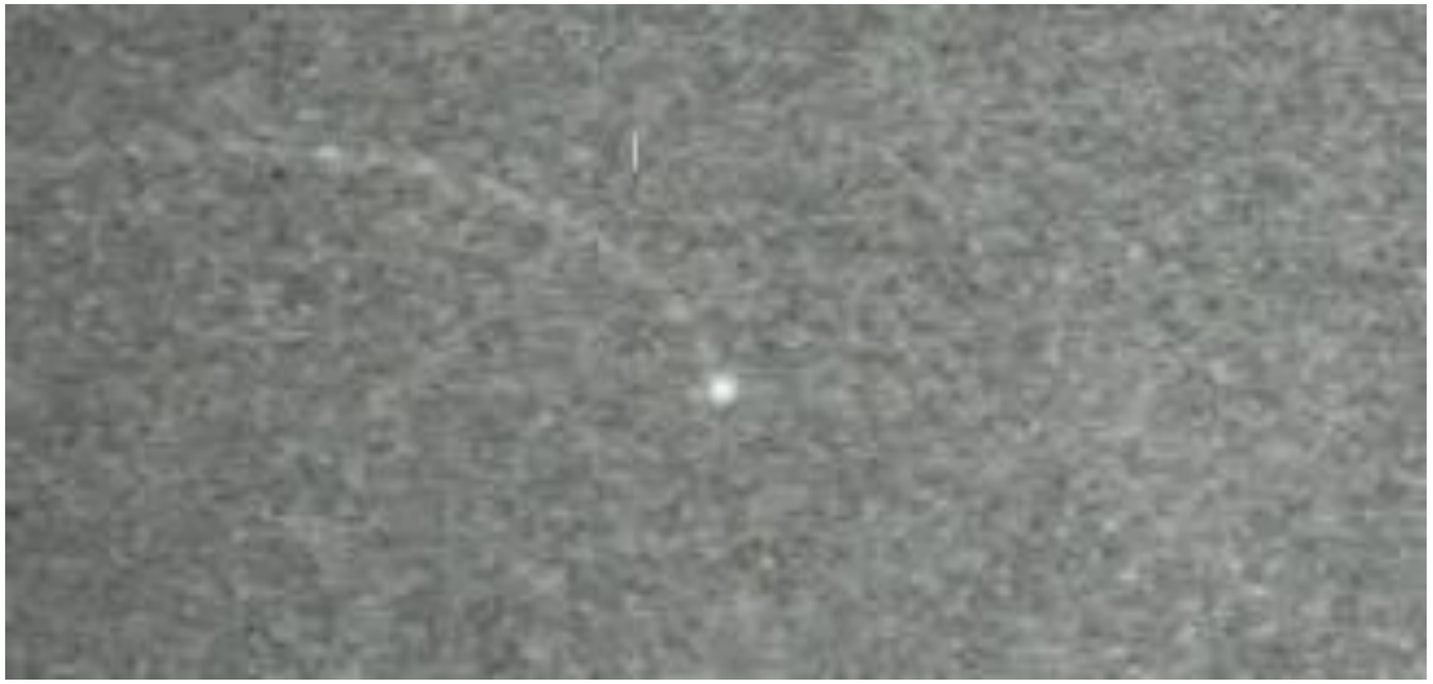
$$\frac{1}{2}k_{\mathrm{B}}T = \frac{1}{2}k_{\mathrm{trap}}\left\langle x_{\mathrm{bd}}^2 \right\rangle$$

The equipartition method requires
(i) a harmonic trap,
(ii) adequate electronic bandwidth,
(iii) accurate position calibration, and (iv) low instrumental drift.
A harmonic trap is an assumption of the equipartition theorem.

How does data look from each method?

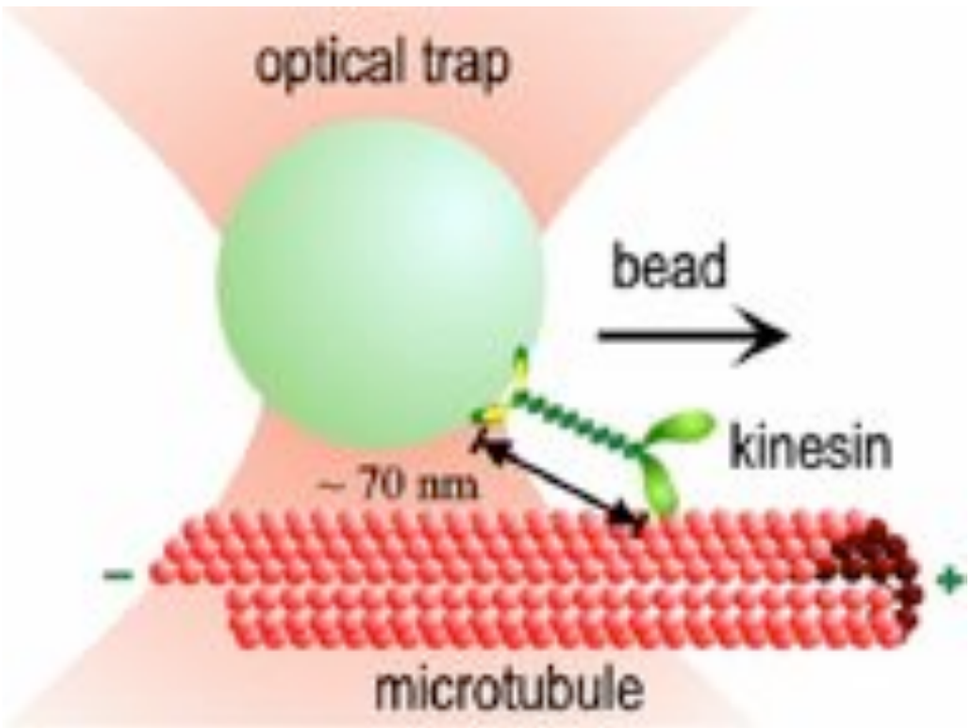


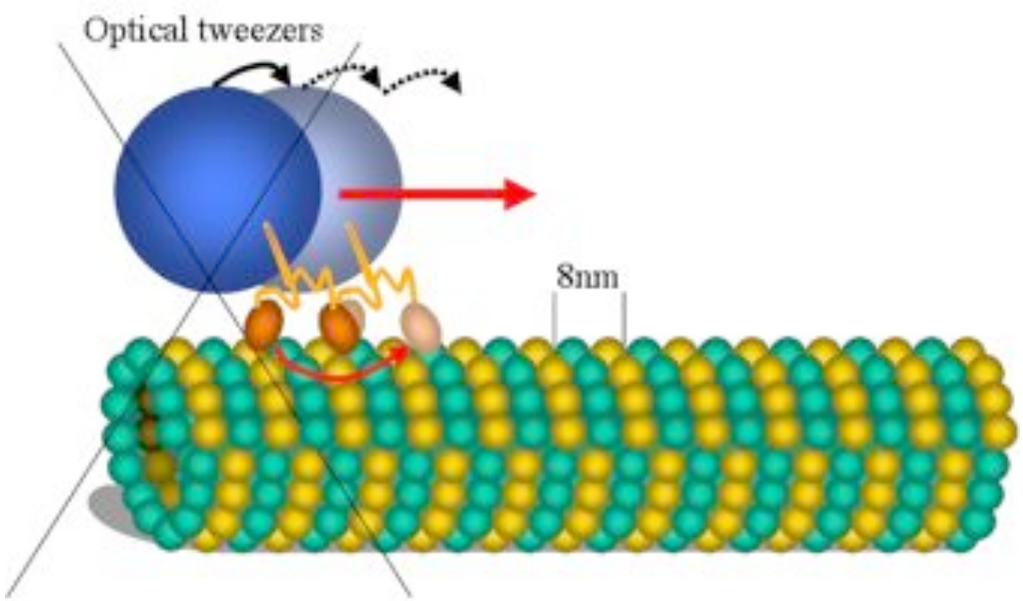
Tying a knot in DNA and other studies…



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)

Other systems
kinesin, actin-myosin, DNA





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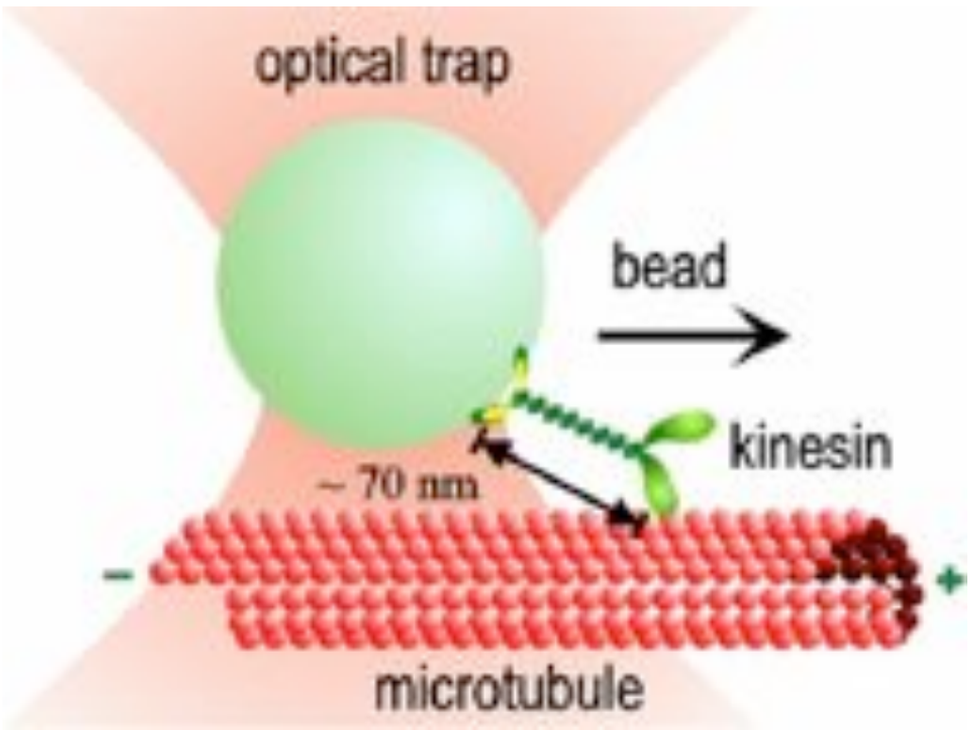

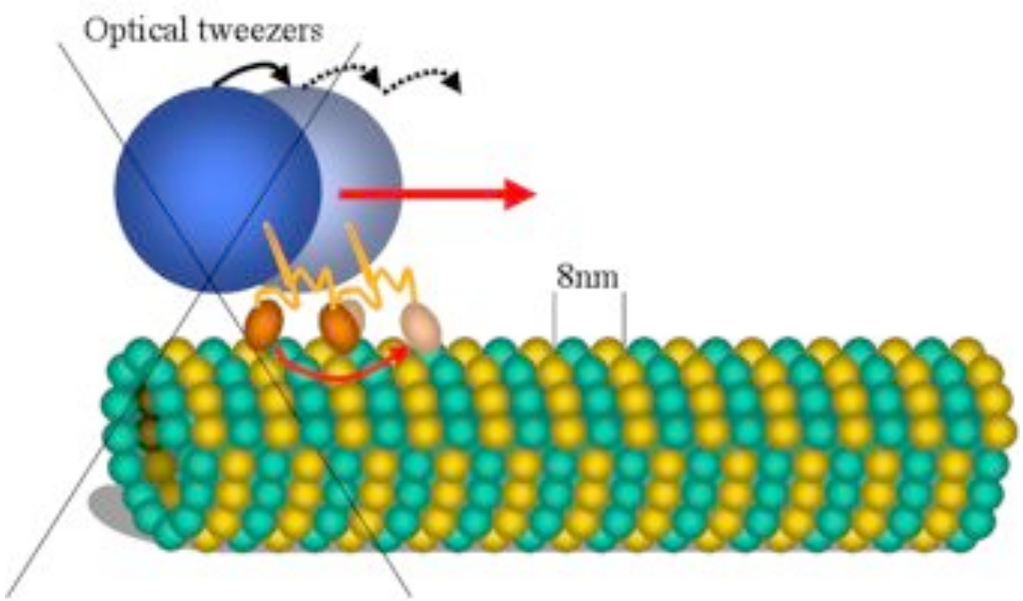

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Vol. 5, No. 10
1937−1942

optical manipulation

Expanding the Optical Trapping Range of Gold Nanoparticles

Poul Martin Hansen,† Vikram Kjoller Bhatia,‡ Niels Harrit,‡ and Lene Oddershede*,†

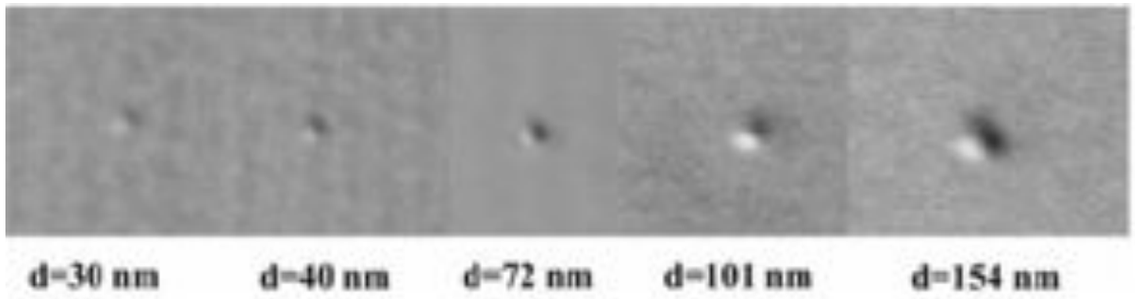


Figure 1. DIC images of gold beads stuck to a surface. The diameters of the beads are between 30 and 154 nm. Particles larger than this were directly observable in a bright field microscope.

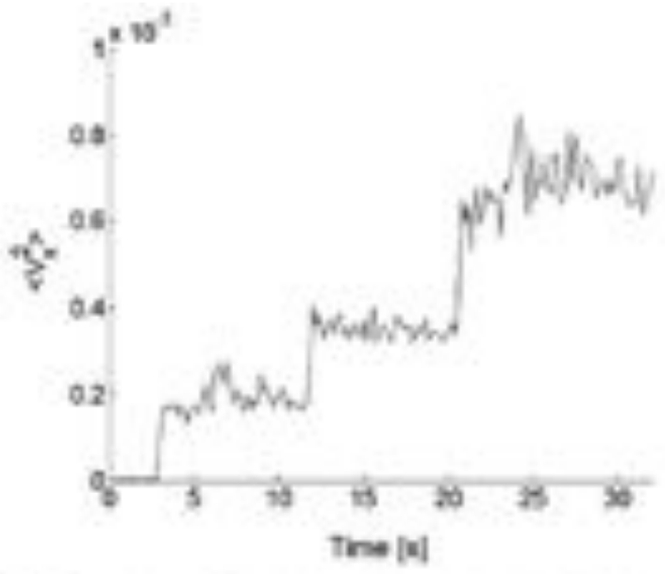


Figure 3. The variance of the signal from the photodiode recorded while successive gold particles, $d = 40 \pm 6$ nm, diffuse into the trap.

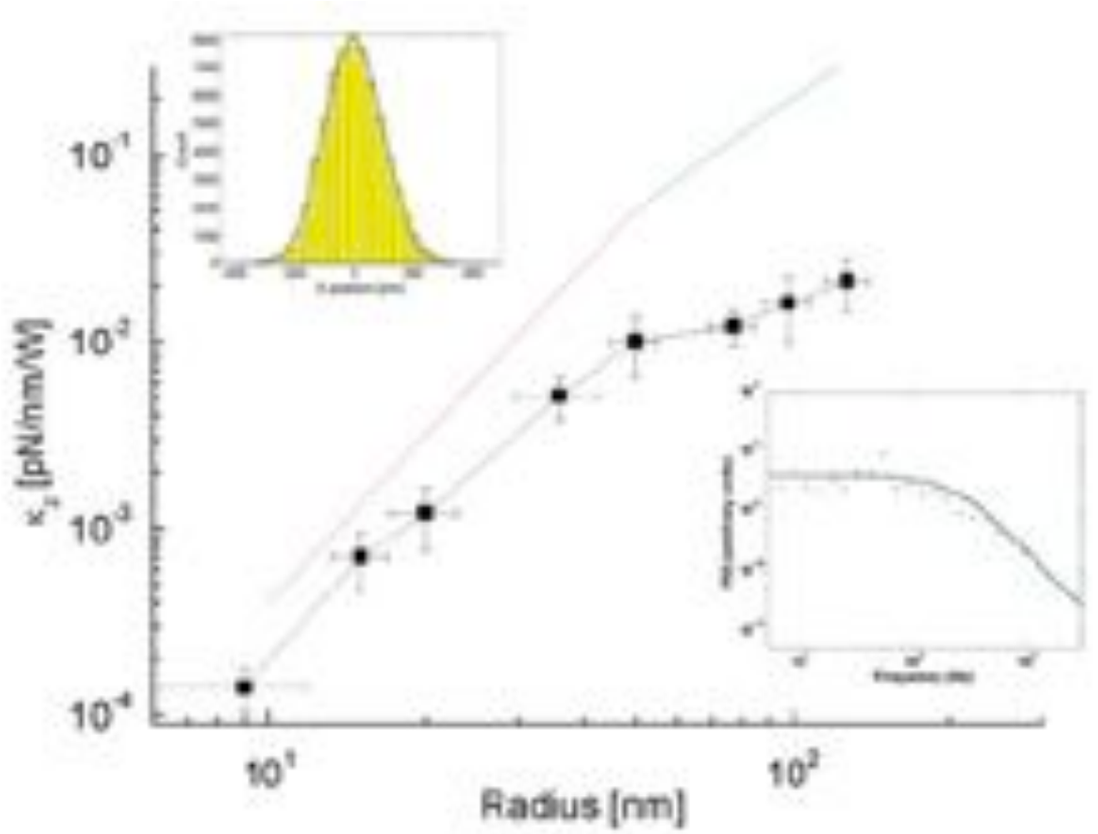


Figure 5. Normalized trapping strength in the direction parallel to the propagation of the laser light as a function of bead size. Upper inset shows the position histogram and the lower inset shows a typical power spectrum for a $d = 70$ nm gold bead. The red and blue lines with slopes of 3 and 2, respectively, are drawn for comparison.

Gold nanoparticles: enhanced optical trapping and sensitivity coupled with significant heating

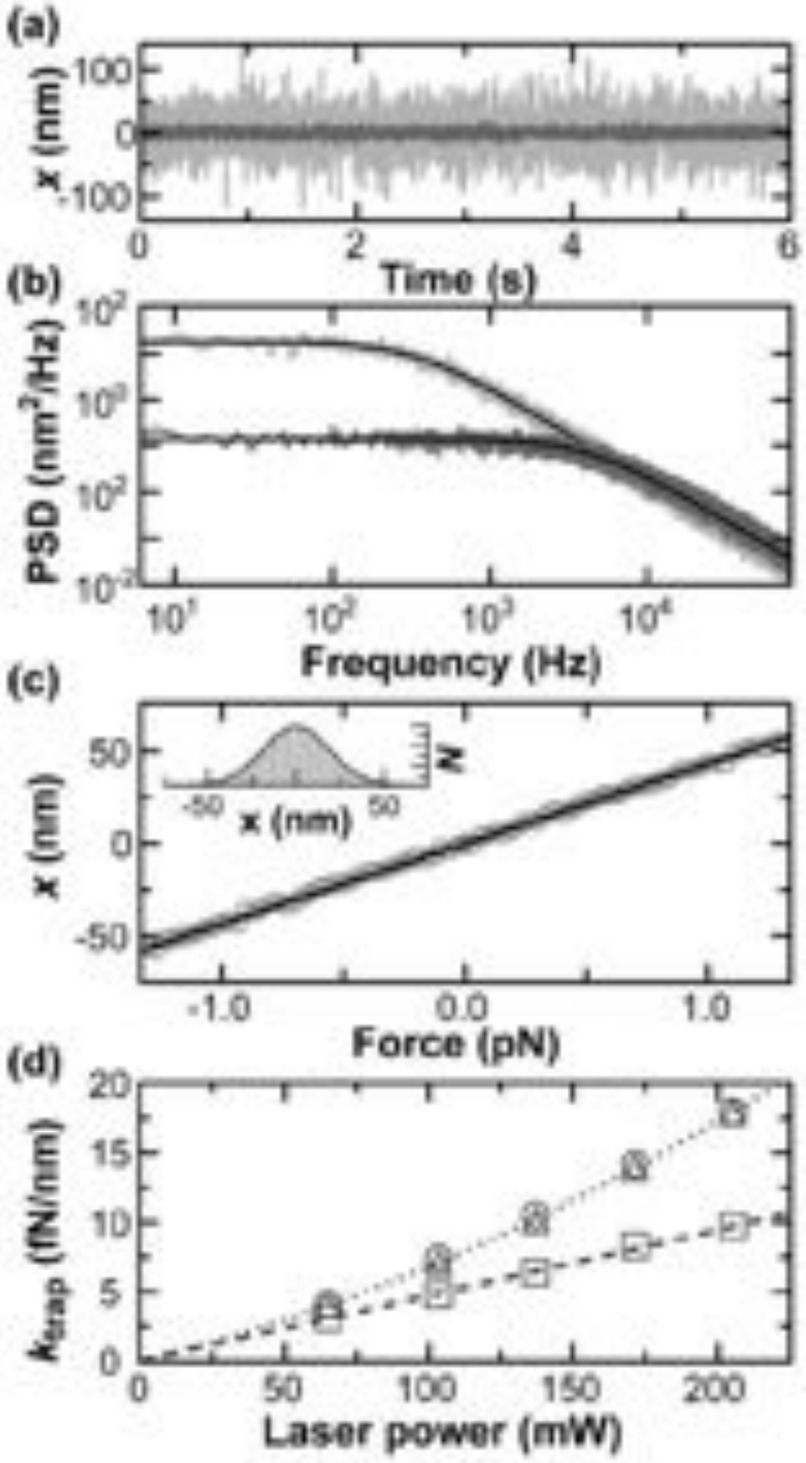


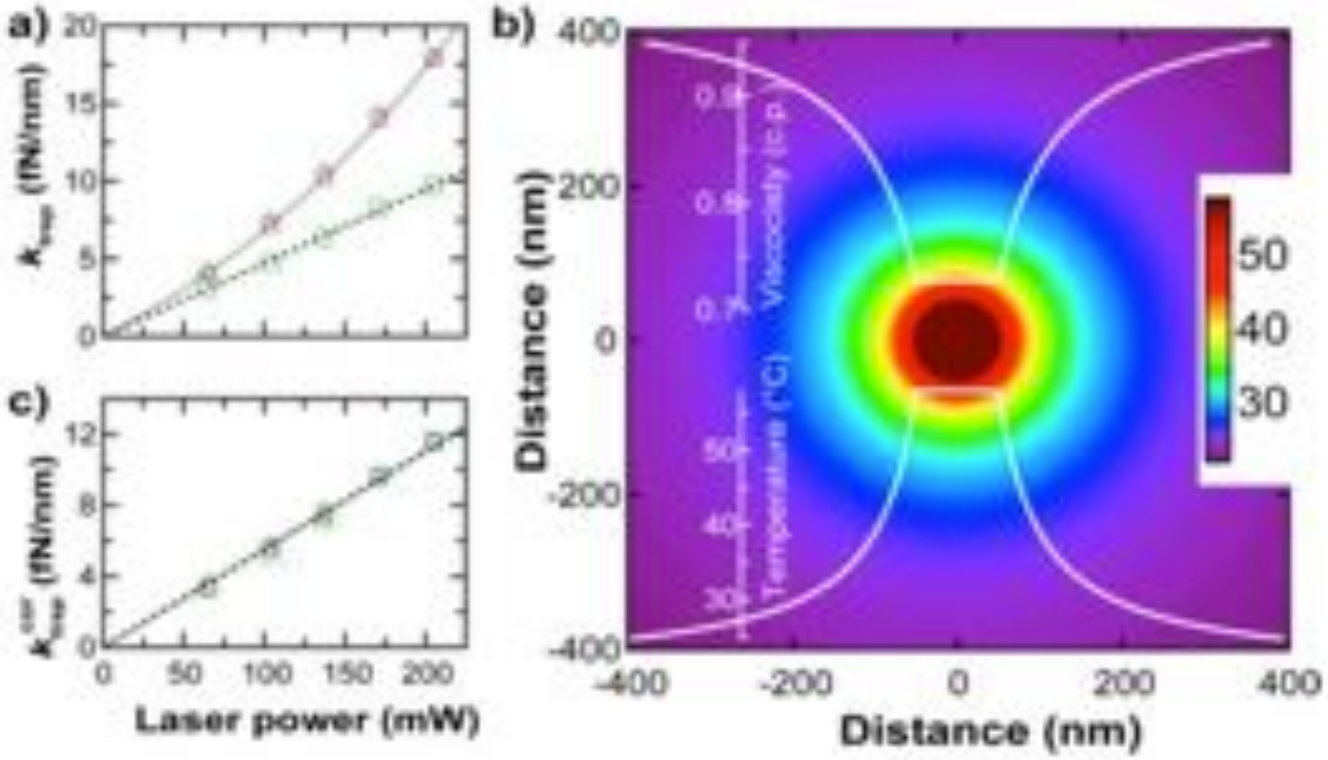
Fig. 1. (a) Position record, x, of a gold (dark gray) and a polystyrene, PS (light gray), bead smoothed to 200 Hz. (b) Averaged power spectra fit for the same gold (dark gray) and PS bead (light gray). Modified Lorentzian (Ref. 6) fits (solid curve) yielded roll-off frequencies, f_0 of 4283.1±9.8 Hz and 330.1±0.7 Hz, respectively. Measurements were done using a gold (R_b=50 nm) and a PS (R_b=55 nm) particle at a 200 kHz data acquisition rate and P=205 mW. (c) Hydrodynamic drag calibration of a gold particle (circle) demonstrating trap linearity, where k_d=23 fN/nm was deduced by a linear fit (line). Inset: histogram of x fitted to a Gaussian confirms trap linearity. (d) Comparison of the three different estimations of trap stiffness as a function of laser power, k_d (circle), k_{eq} (rectangle), and k_{ps} (triangle).

Three methods for estimating k_{trap}: equipartition theorem k_{eq}, power spectrum k_{ps}, and hydrodynamic drag k_d.

Each method depends on different physical parameters and assumptions.

Trapping gold nanoparticles: an illustration

optical manipulation



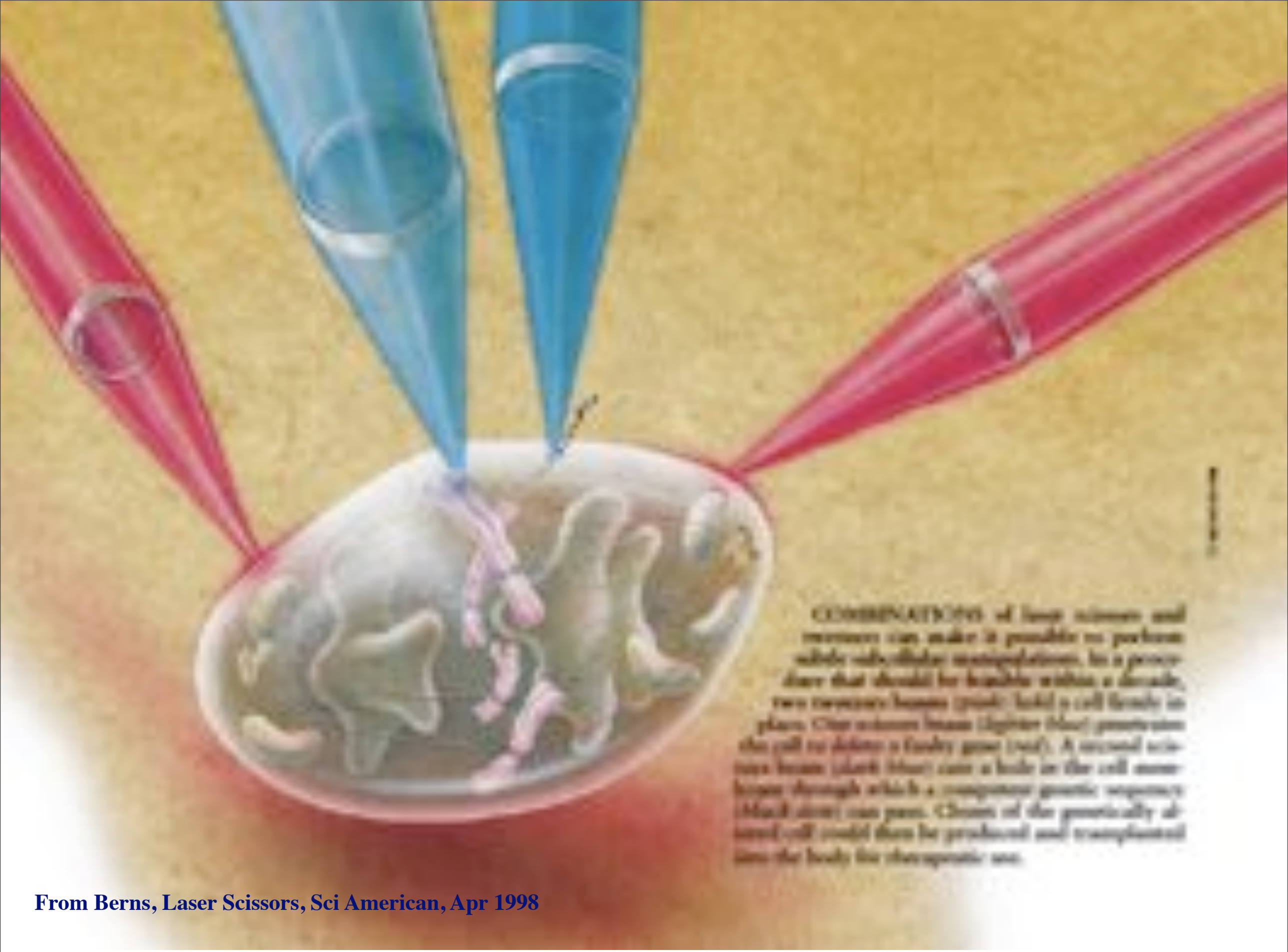
T Perkins
Laser & Photon. Rev. 3, No. 1–2, 203–220 (2009);
Seol et al. Opt. Lett. 31, 2429–2431 (2006).

Trapping of gold nanoparticles: (a) Comparison of the three different estimations of trap stiffness as a function of laser power for gold nanoparticles (radius 50nm) by equipartition theorem, hydrodynamic drag and power spectrum: *k*eq (*rectangles*), *k*d (*circles*), and *k*ps (*triangles*), respectively. (b) Temperature gradient surrounding a gold nanoparticle when trapped with 205mW at the laser focus as determined by a steady-state heat-flow calculation. (Inset) Radial temperature and water viscosity around the gold nanoparticle. (c) Estimations of trap stiffness corrected for the local temperature and viscosity show quantitative agreement and the theoretically expected linear dependence on laser power.

superlinear rise in both the hydrodynamic drag and power-spectrum methods as a function of laser power

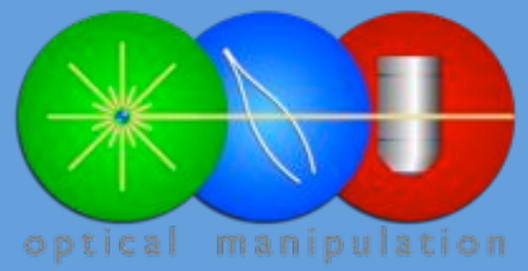
hydrodynamic-drag and power-spectrum methods depend on fluid viscosity η

heating of 266 ∘C/W !



From Berns, Laser Scissors, Sci American, Apr 1998

What is transfection?



Transfection: The transfer of exogenous DNA into a cell.

www.nature.com

What is transfection?

optical manipulation

Transfection: The transfer of exogenous DNA into a cell.

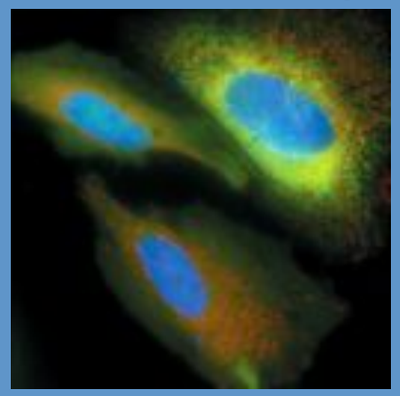
www.nature.com

How to transfect ?

dragon.zoo.utoronto.ca

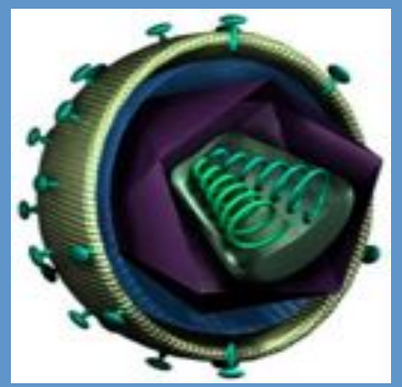
Electro/ Sonoporation:
Cells exposed to pulses of high electrical voltage or to acoustic waves

Invitrogen



Chemical transfection:
Lipofectamine or *calcium phosphate.* Cells take up DNA by phagocytosis or membrane fusion

waisman.wisc.edu

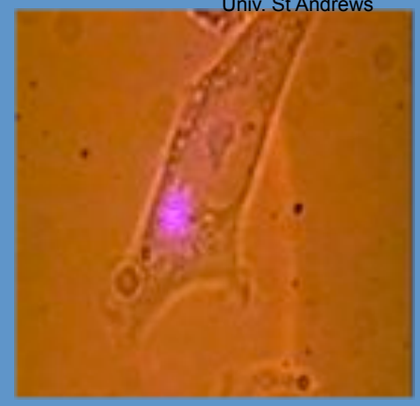


Viral vectors:
Use of viruses to transport genomes inside cells they infect.

ohsu.edu

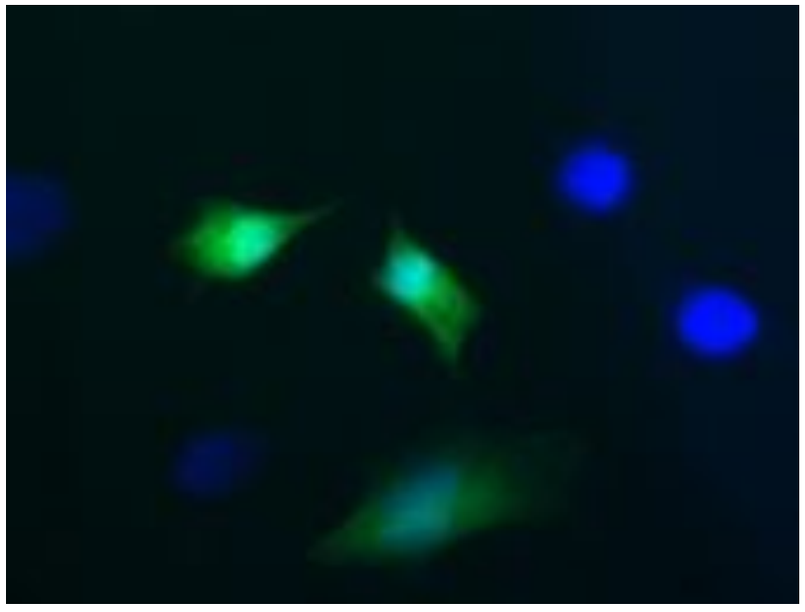
Microinjection:
Plasmid injected directly into the cell nucleus.

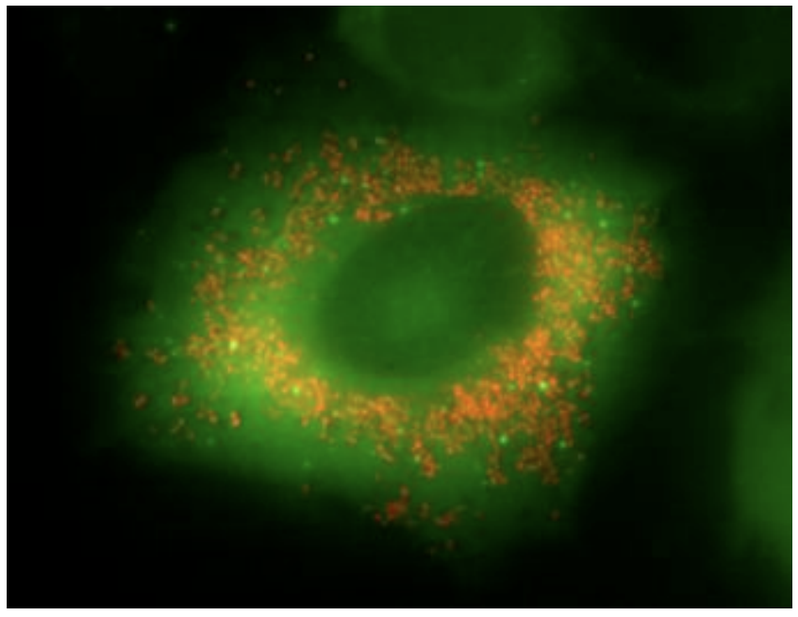
Univ. St Andrews



Optical:
Focussed laser opens transient pores in cell membrane

optical manipulation

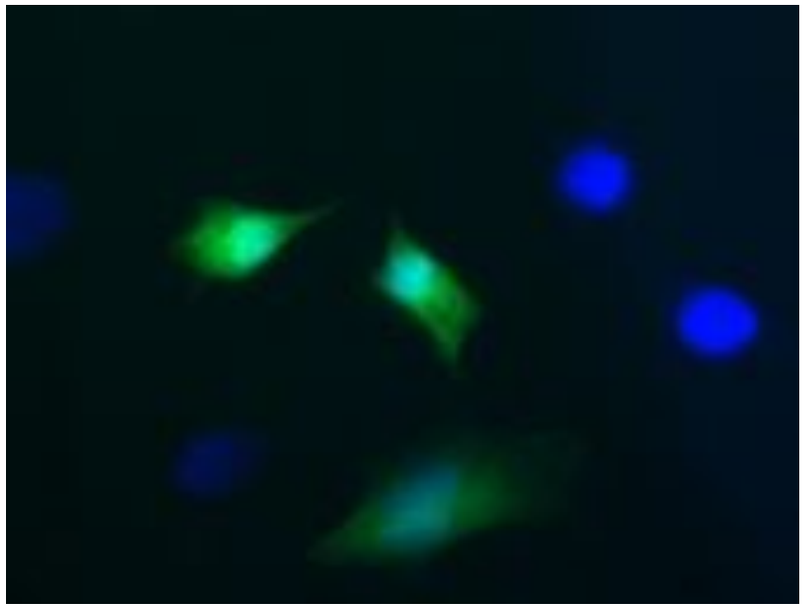


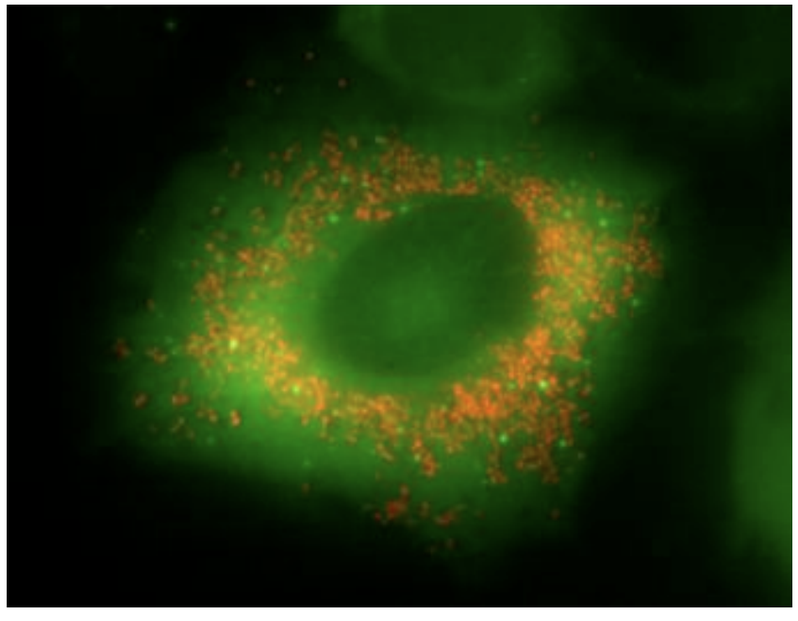


Tirlapur and Konig Nature 2002; Stevenson et al Opt Express (2006)

Mechanisms: low e- plasma using fs light
Vogel et al. Appl Phys B (20025)

optical manipulation





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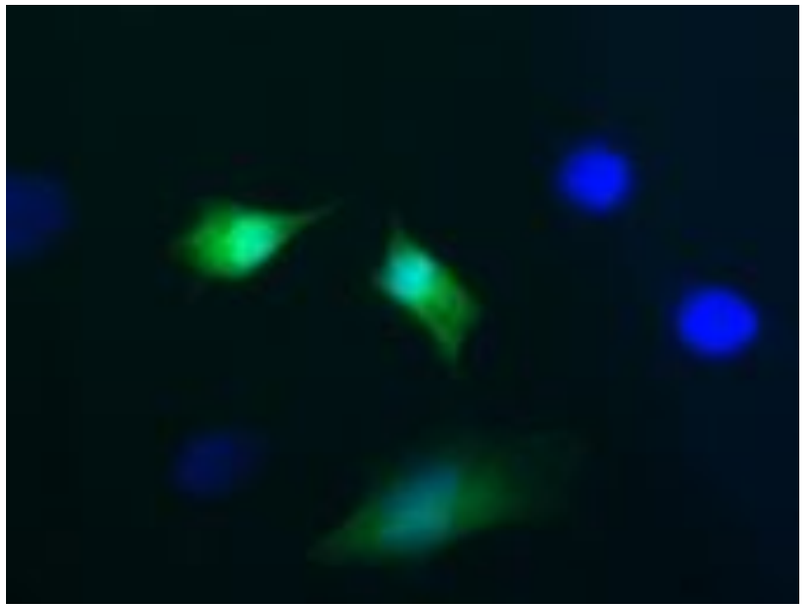

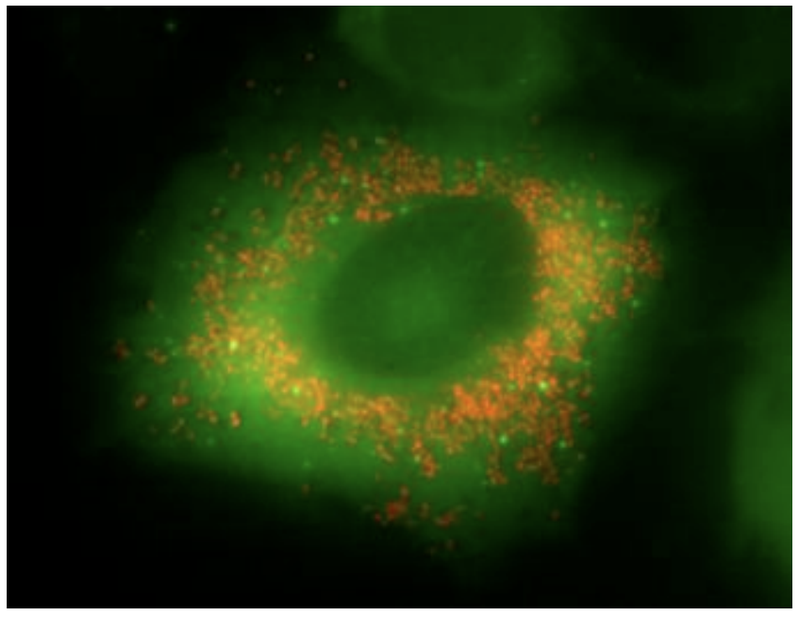

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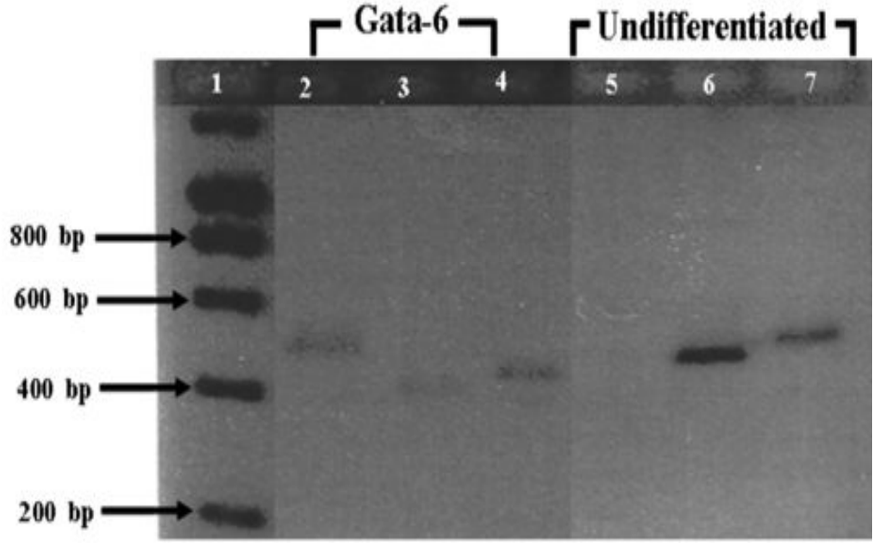
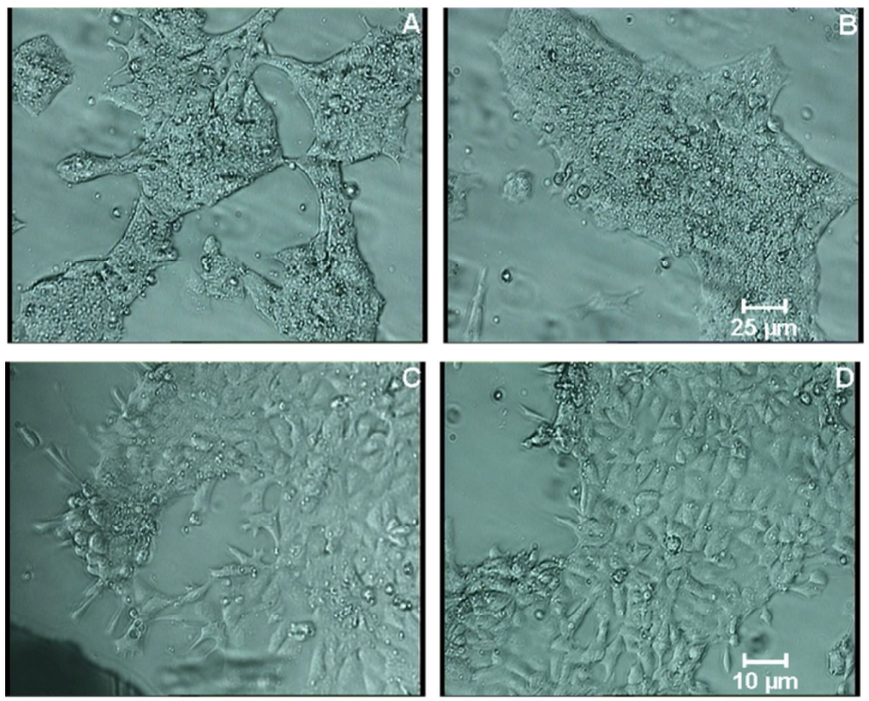
Mechanisms: low e- plasma using fs light
Vogel et al. Appl Phys B (20025)

Photoporation: stem cell differentiation with light

optical manipulation



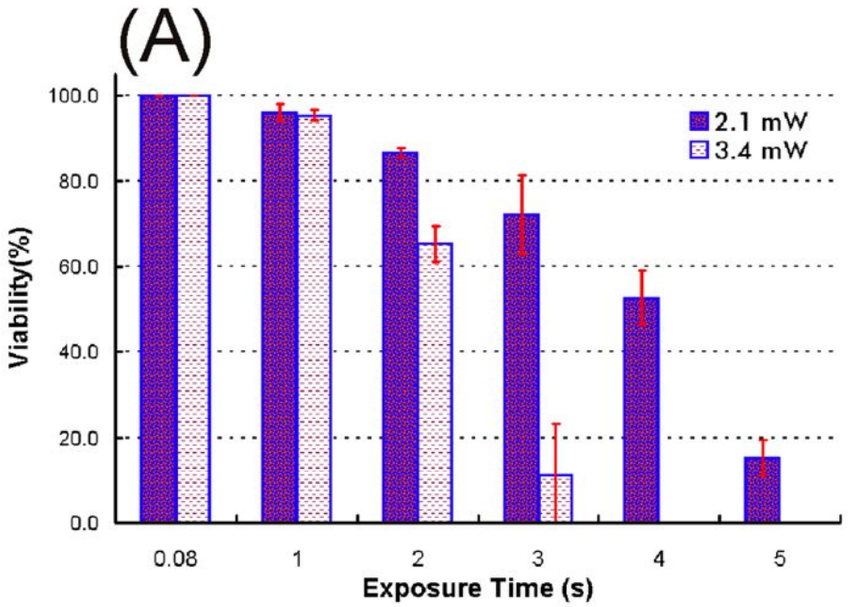


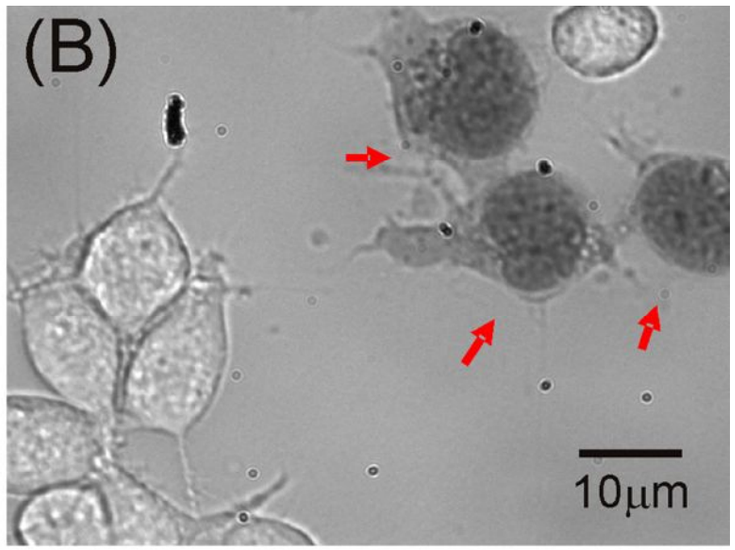
rt-PCR analysis of germ layer markers. Lane 1: Molecular weight marker: Hyperladder 1 molecular weight marker (*Bioline*), Lane 2: rtPCR product for Gata-4, Lane 3: rtPCR product for Oct-4, Lane 4: rtPCR product for Nanog gene transcripts in differentiated cells (Gata-6). Lane 5: rtPCR product for Gata-4, Lane 6: rtPCR product for Oct-4, Lane 7: rtPCR product for Nanog gene transcripts in undifferentiated cells.

Photographs A & B (negative controls) are brightfield images of the E14g2a cell colonies 48 hrs post routine sub-culturing, growing in the presence of LIF

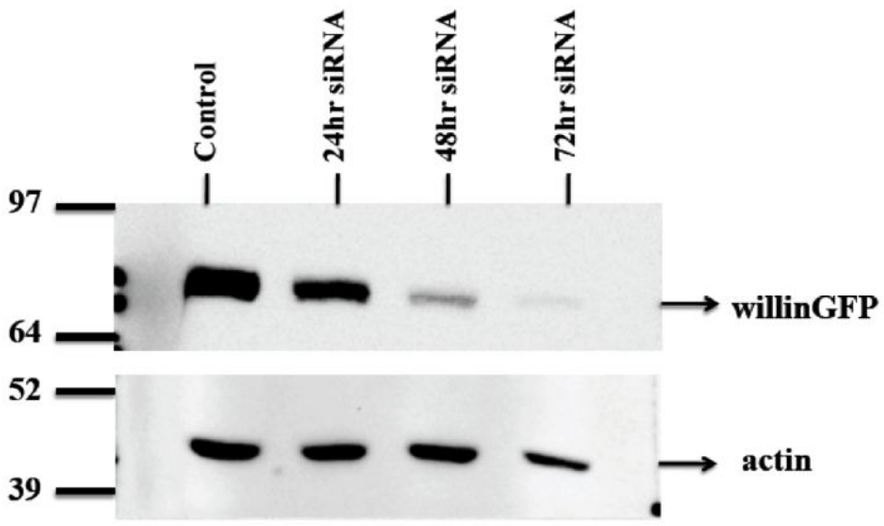
P Mthunzi et al., J Biomed. Optics 15, 041507 (2010); A. Uchugonova et al Opt. Express 16, 9357–9364 2008

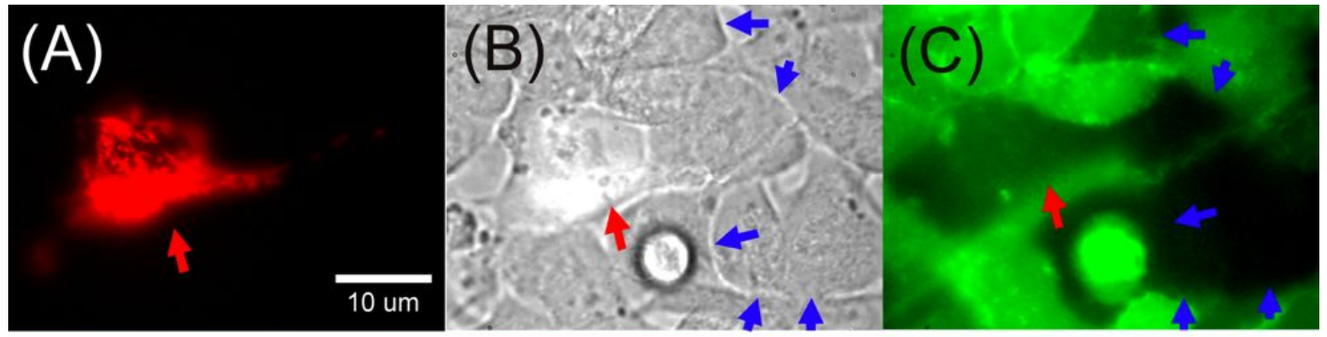
Gene silencing with phototransfection





Gene silencing: willin



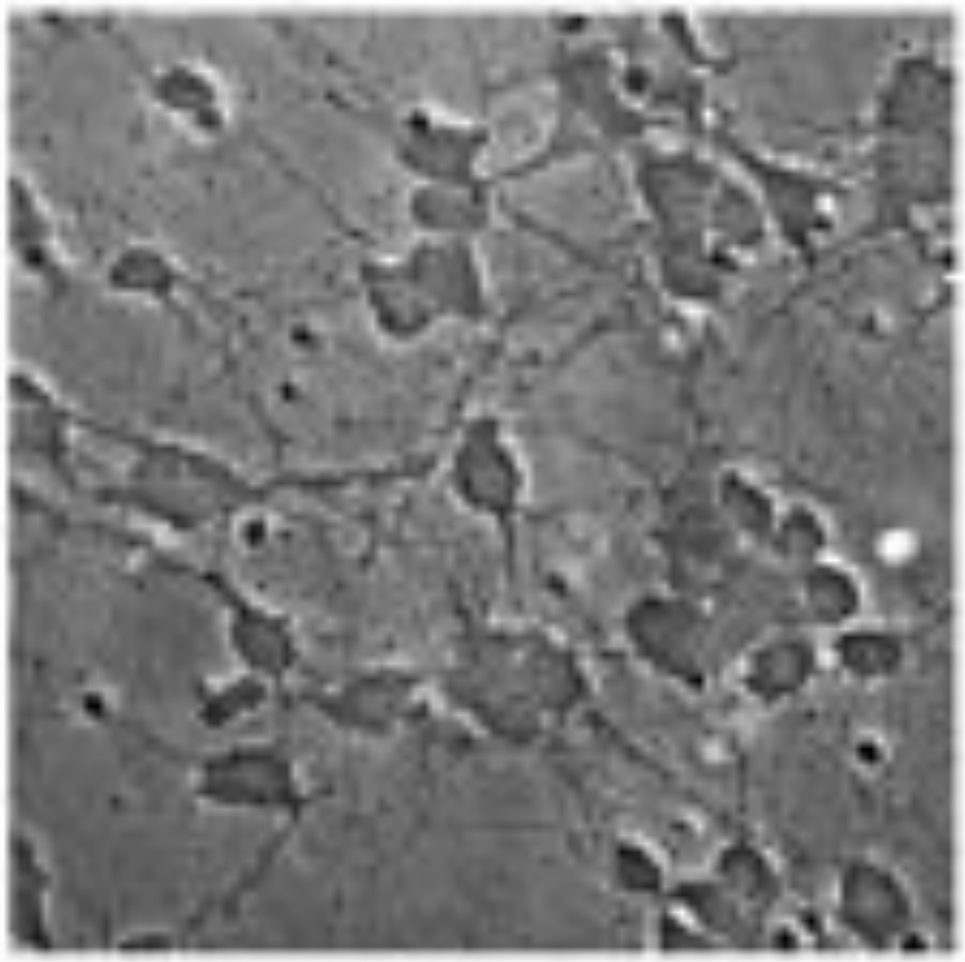


Western blot analysis showing reduction of willin-GFP expression after 48 h of 5 nM siRNA chemical transfection. TRex willin-GFP cells were induced with 1 g/ml tetracycline to express willin-GFP 24 h prior to siRNA treatment. Western blots were probed with anti-GFP and anti-actin, with the latter used as a loading control.

ML Torres et al., J. Biomed. Opt **15(2), 041506 (2010) - violet diode study (mechanism is different)**

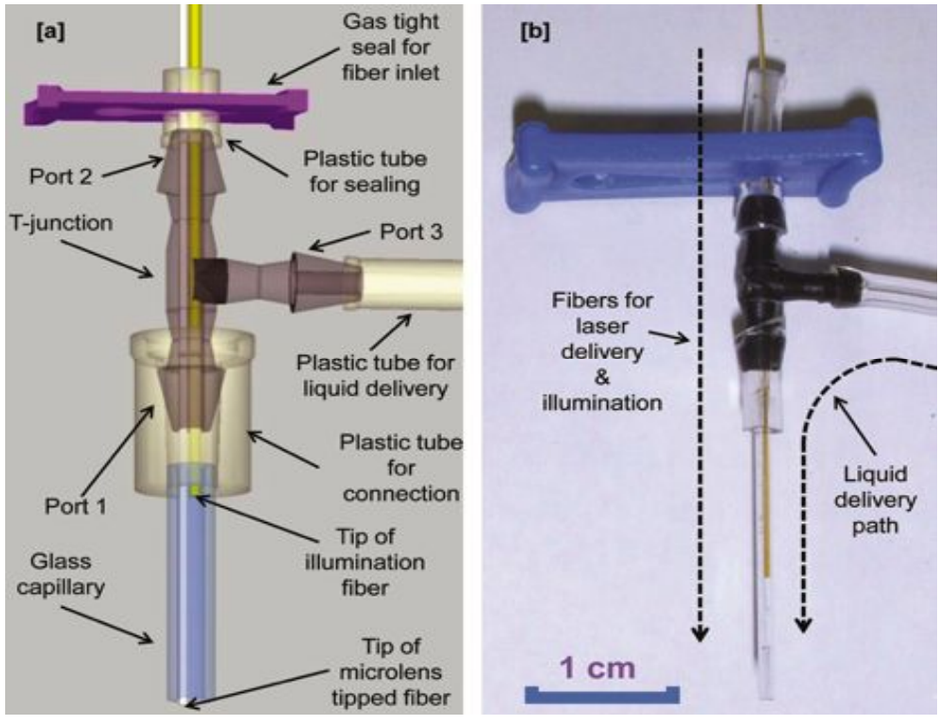
Optical transfection of primary rat cortical neurons

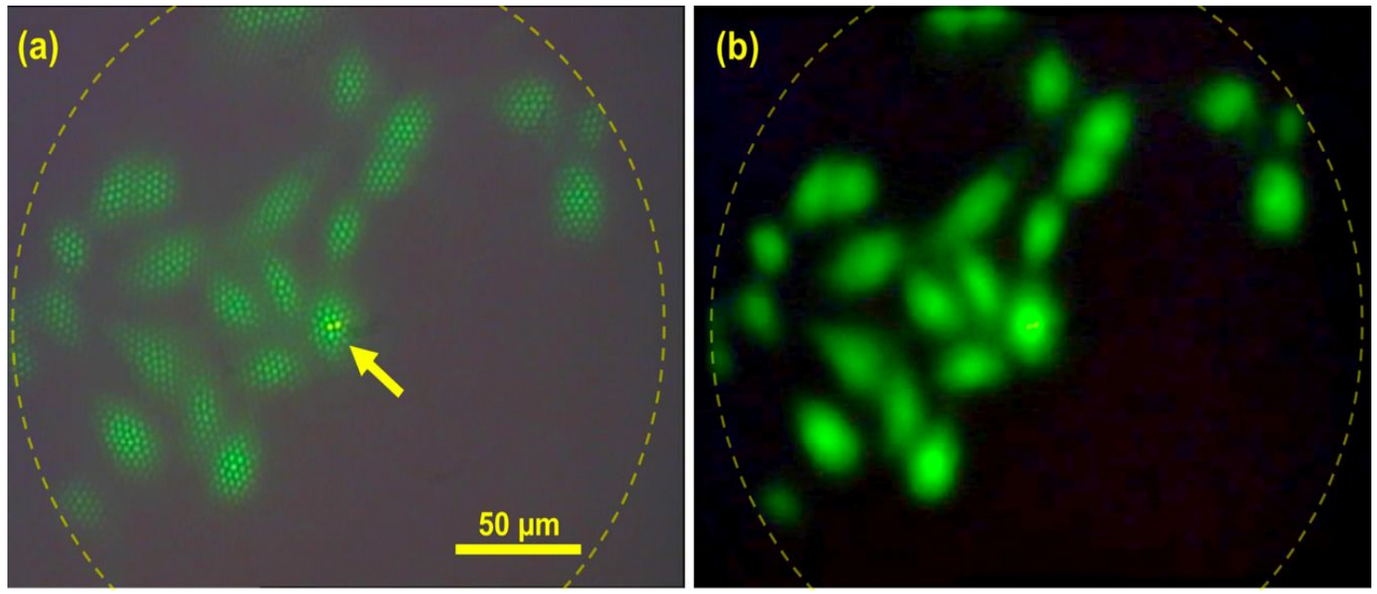
- Selective delivery of genes into single neurons
- Paves the way towards optically programmed neural circuits



M. Antkowiak et al. – in preparation

Towards fibre (light) and drug delivery in vivo..

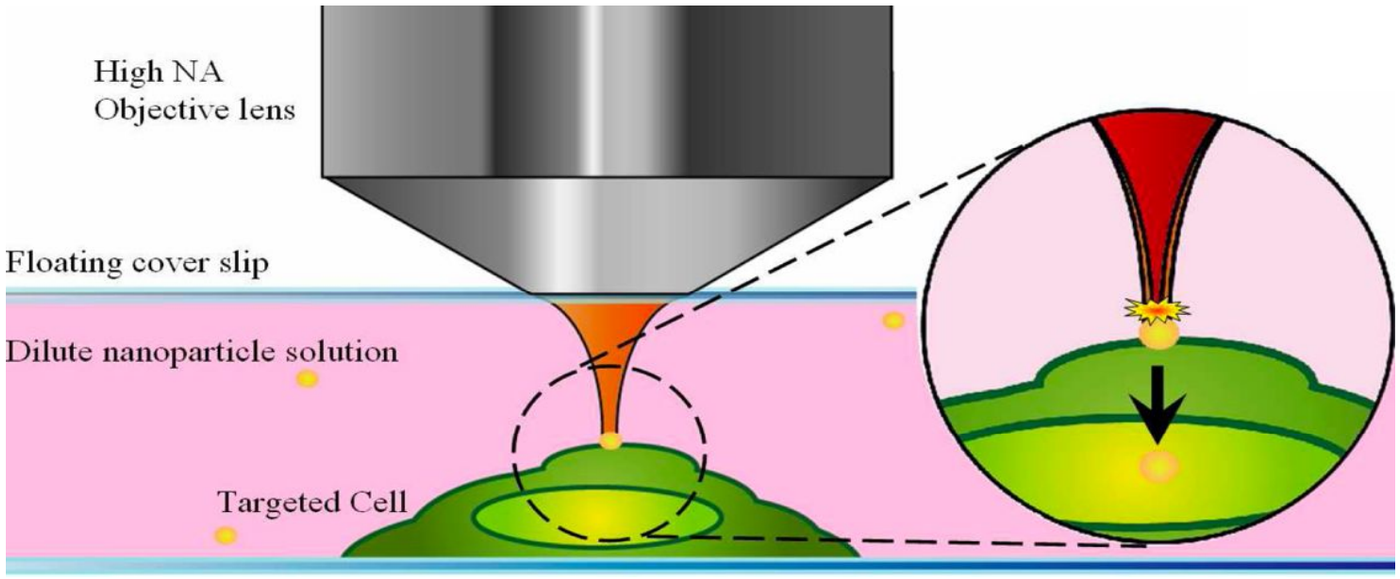


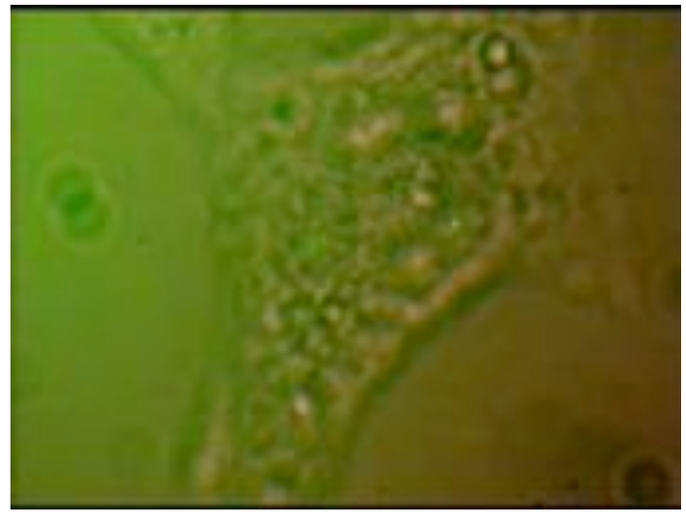


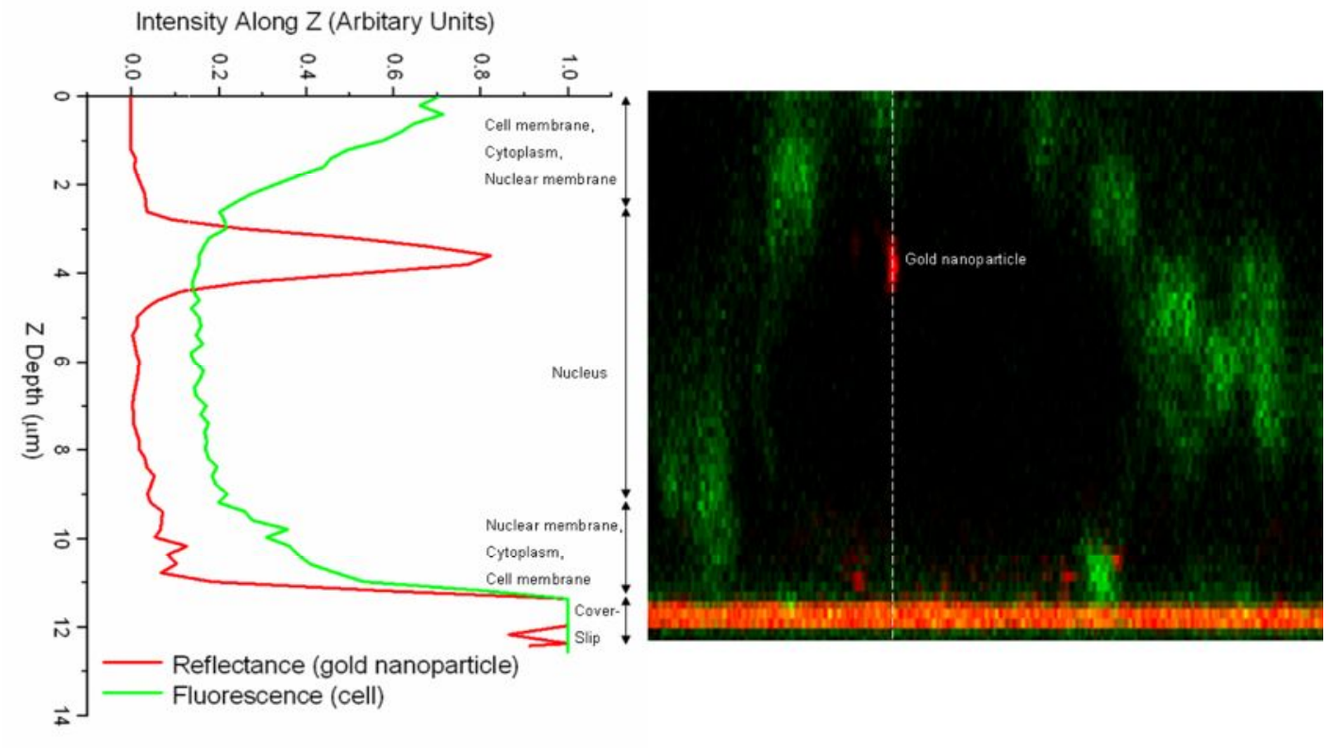
a) Fluorescent imaging of cells through the imaging fiber captured by the CCD camera. Individual pixels can be clearly resolved. The arrow indicates a cell that's being irradiated by a laser beam. Two relative brighter pixels in the centre of the cell are the back reflection from the cell. (b) By adding a FFT band pass filter, increasing the image intensity then adding a background noise filter to (a), a more convenient view can be obtained. The dashed circle indicates the field of the view (image circle).

Optical transfection using an endoscope-like system
N. Ma, F. Gunn-Moore, and K. Dholakia, J. Biomed. Opt. **16**, 028002 (2011).

Insertion of a gold nanoparticle



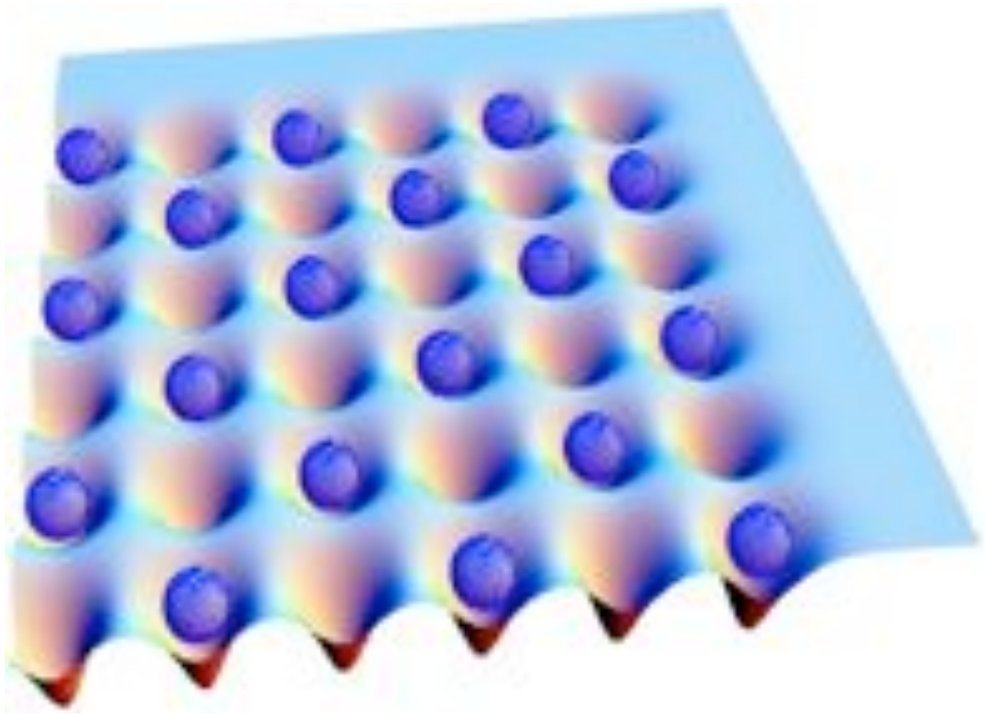




The 100 nm (red) gold nanoparticle was imaged by CLSRM and the green FM 4-64FX stained cell was imaged by CLSM. The green signal observed in figure 4 is a combination of the plasma membrane, cytosolic membranes, and the nuclear membrane

Targeted optical injection of gold nanoparticles into single mammalian cells, C. McDougall, D. J. Stevenson, C. T. A. Brown, F. Gunn-Moore, and K. Dholakia, *Journal Of Biophotonics* **2**, 736--743 (2009)

Why shape your light field ?



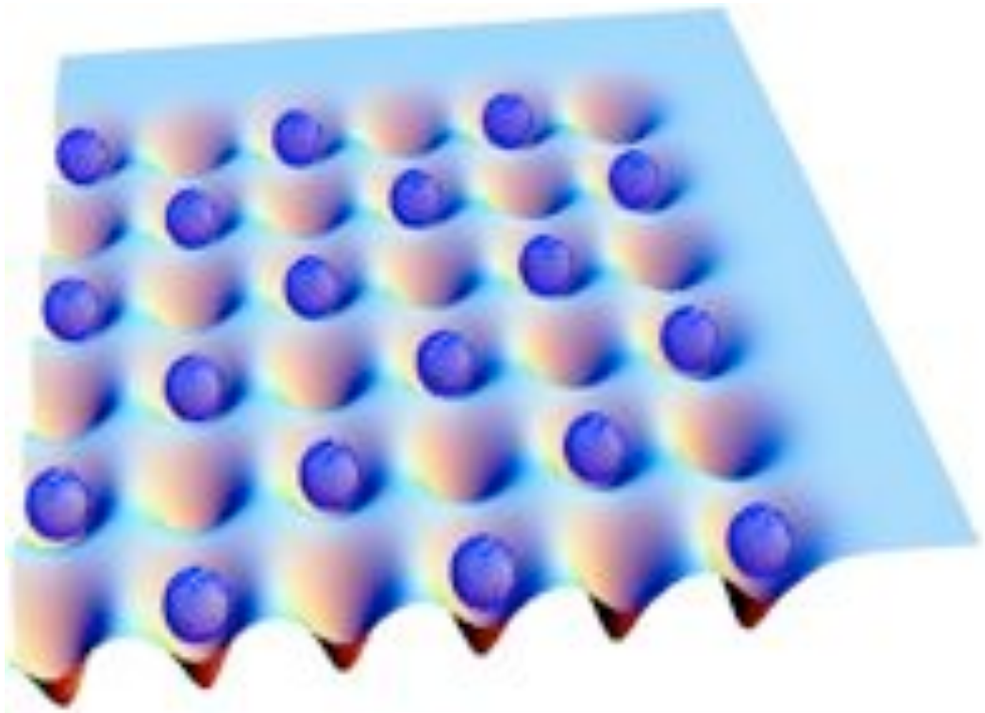
(video in collaboration with I Poberaj group).

Microscopy
Optical tweezers
Nanosurgery at depth
Imaging at depth
...

A microfluidic pump made from glass beads the size of a heart valve. (DM Marr et al. Science 2002)

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

Why shape your light field ?



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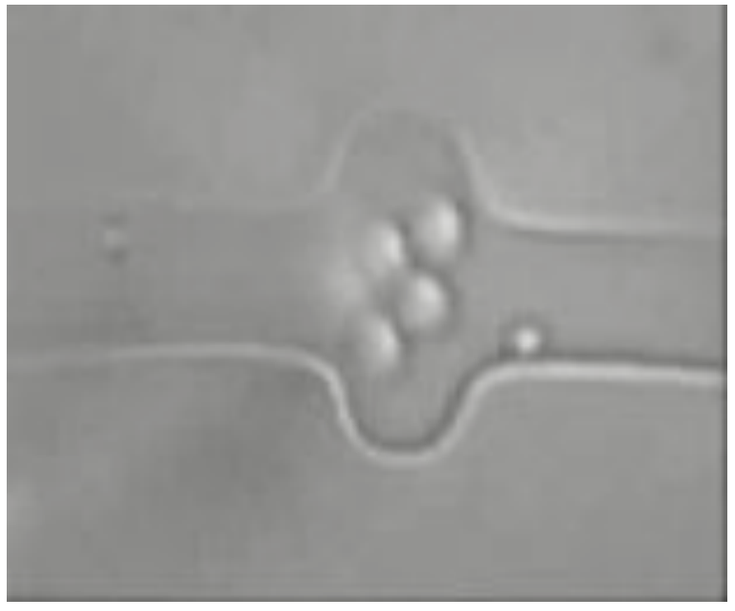

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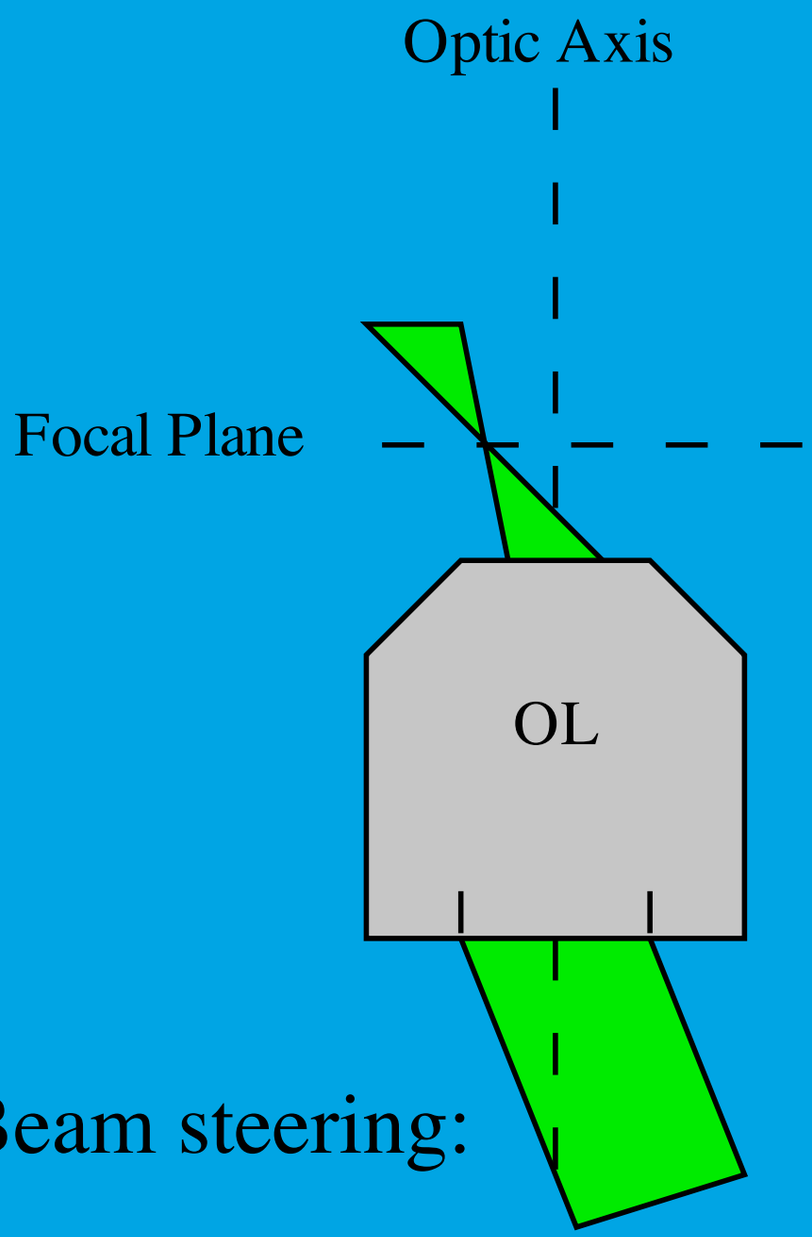
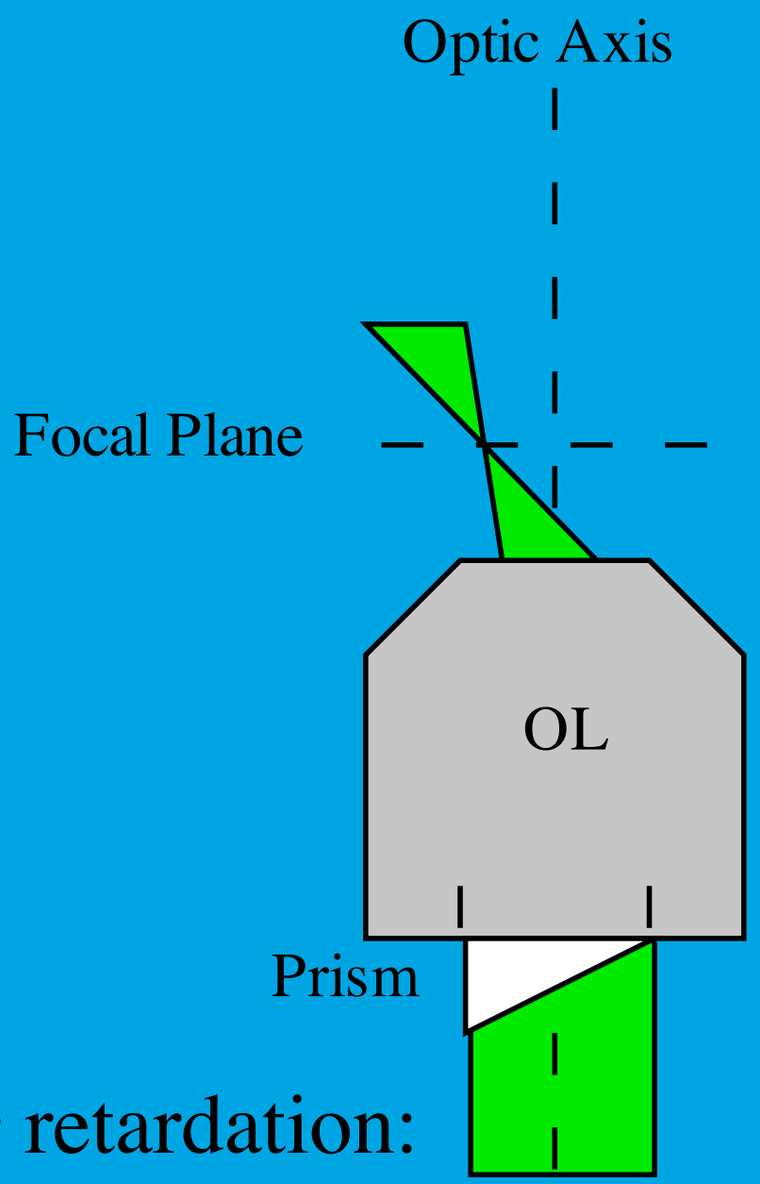
“Steering” with a Phase-Only Optic



Beam steering:

is equivalent to …a *phase* retardation:

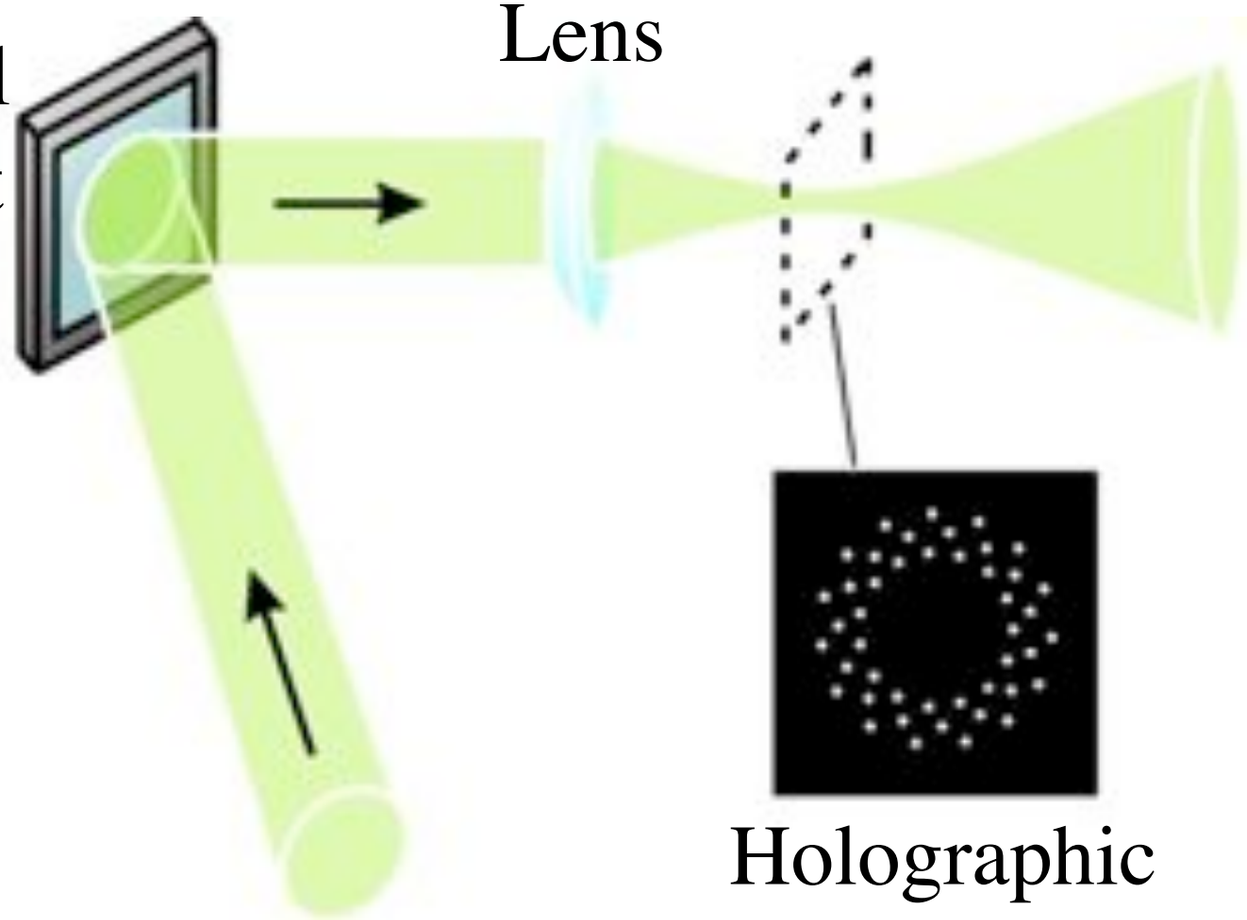


Dynamic control is possible through

optical manipulation

Liquid Crystal Display Technology

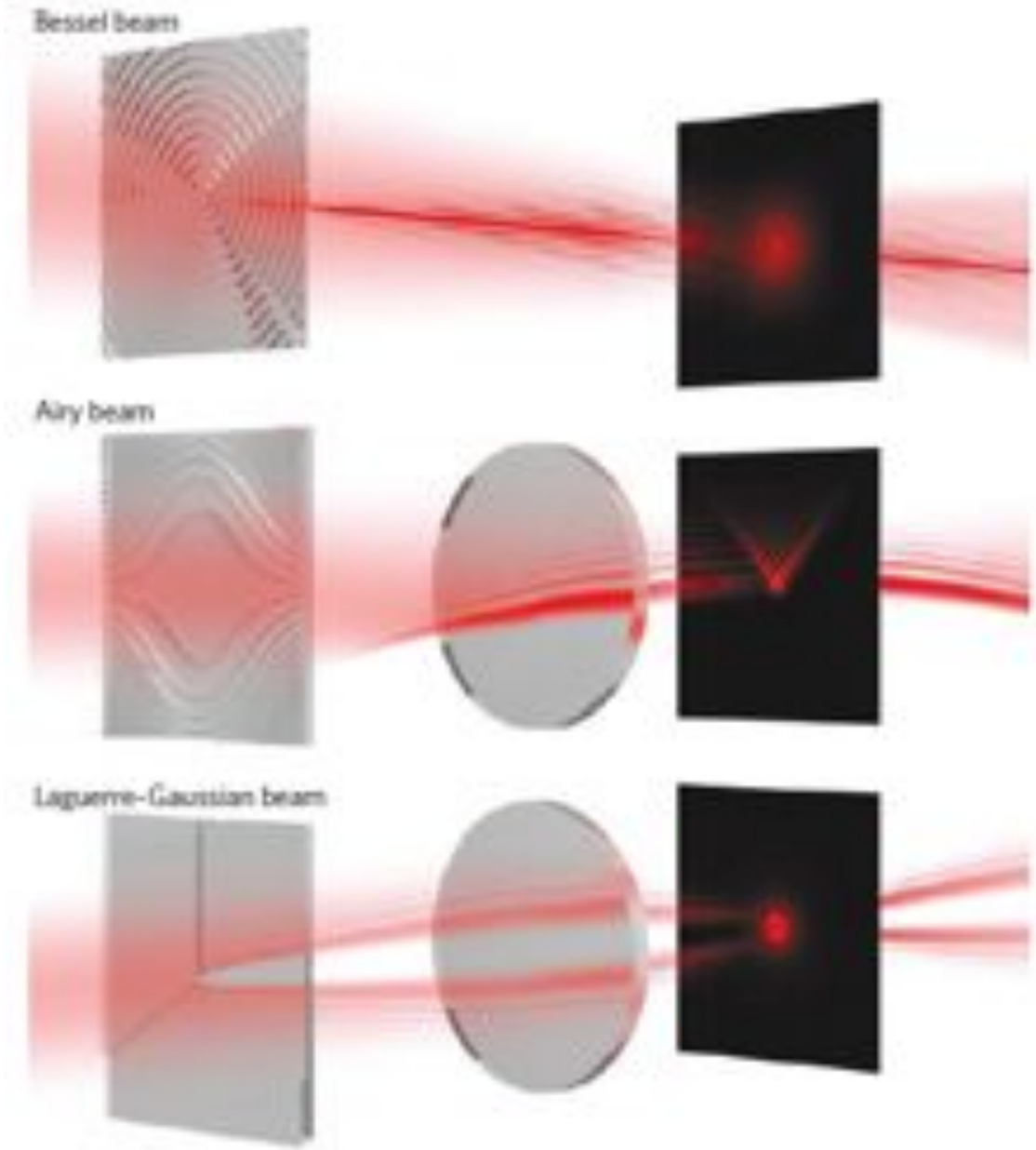
Liquid Crystal "Spatial Light Modulator" (SLM)



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

Shaping Light for Manipulation

optical manipulation



Spatial light modulator (SLM)

Millions of pixels
Group into 1000's of segments

LCD and MEMS versions

Intensity and/or phase modulation

nature photonics

FOCUS | REVIEW ARTICLES

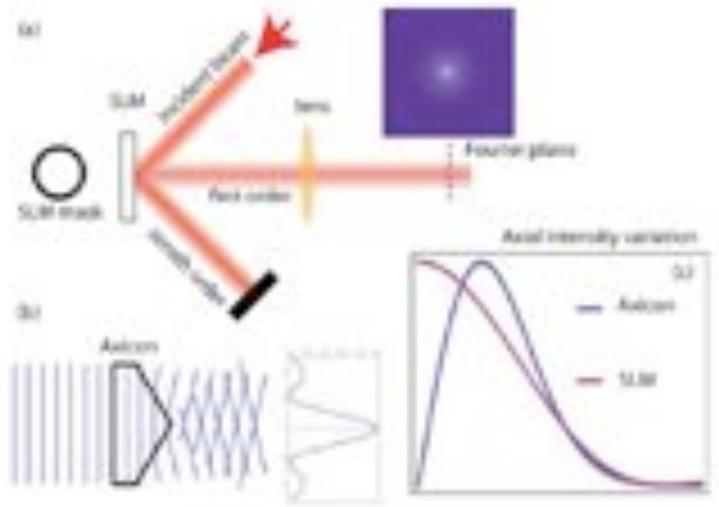
PUBLISHED ONLINE: 31 MAY 2011 | DOI: 10.1038/NPHOTON.2011.80

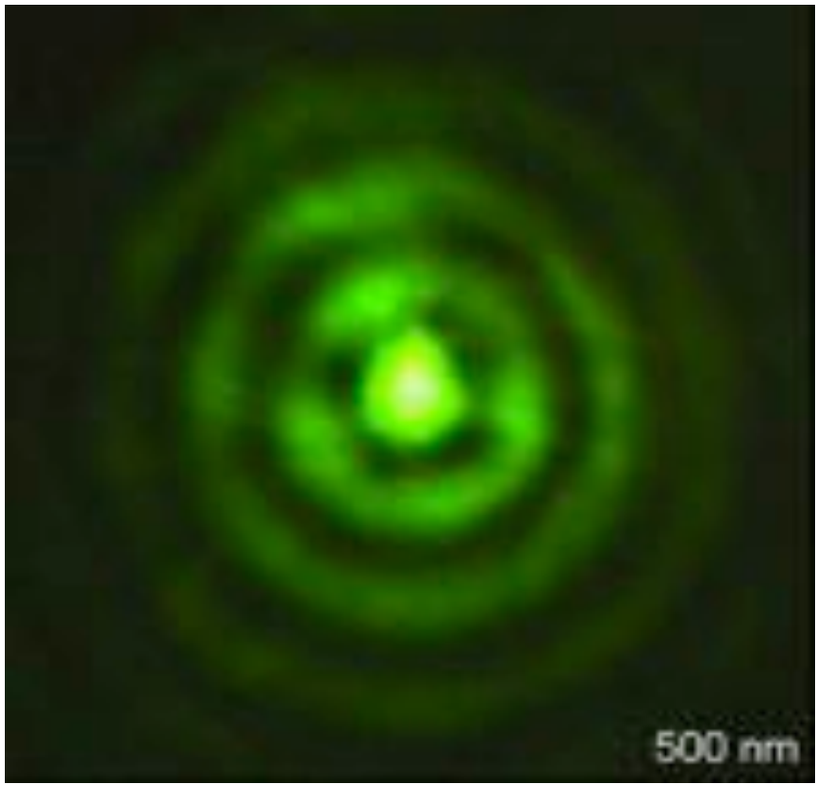
Shaping the future of manipulation

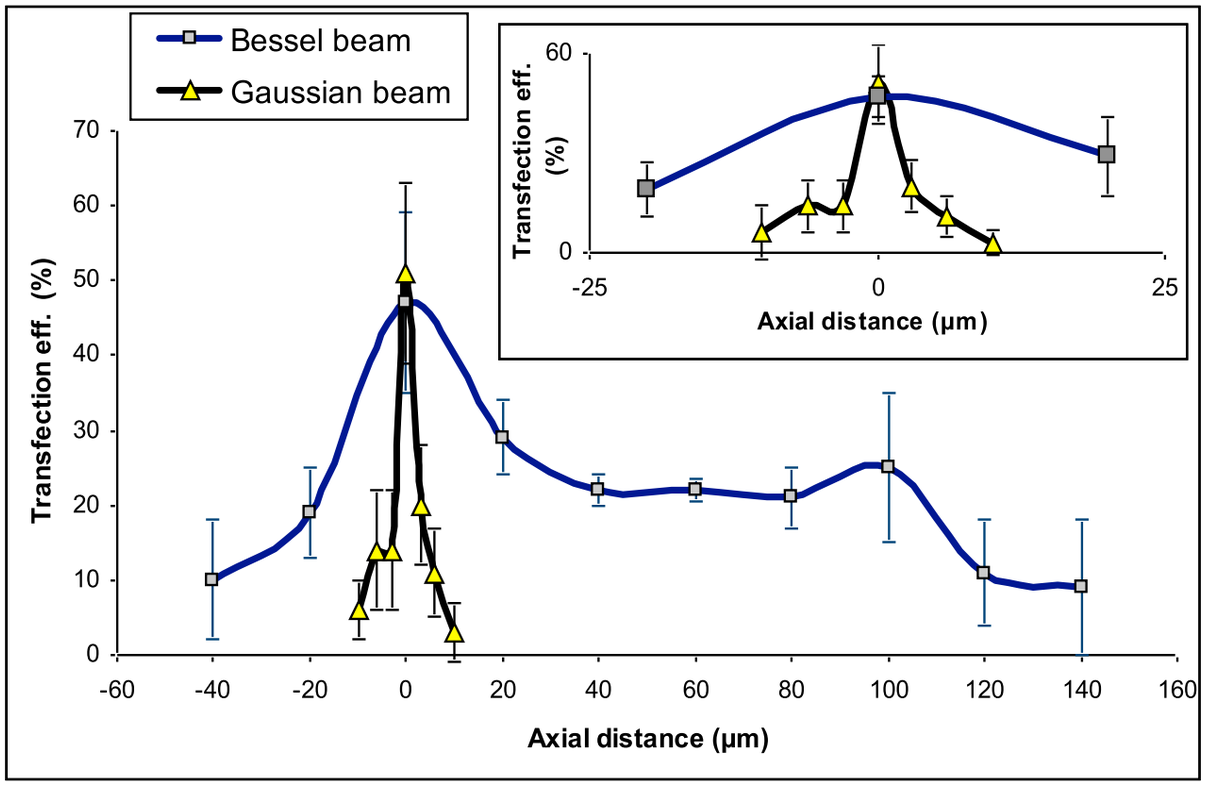
K. Dholakia[1]* and T. Čižmár[2]

Finding the cell membrane

optical manipulation





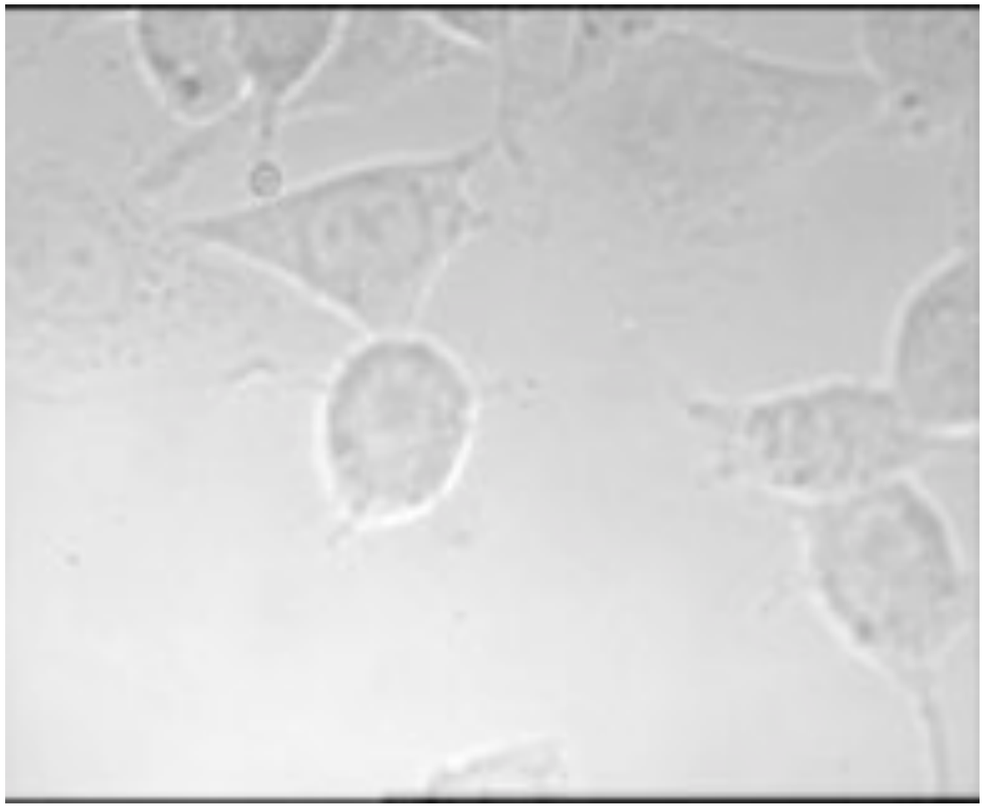


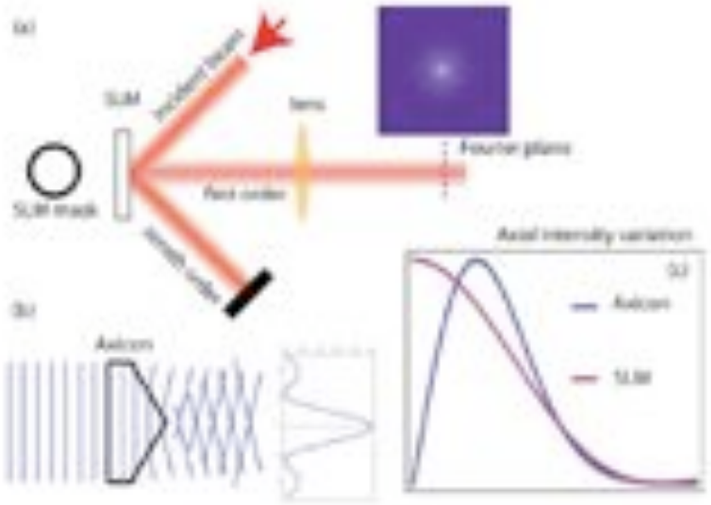
X. Tsampoula et al. Appl. Phys Lett **91**, 053902 (2007)

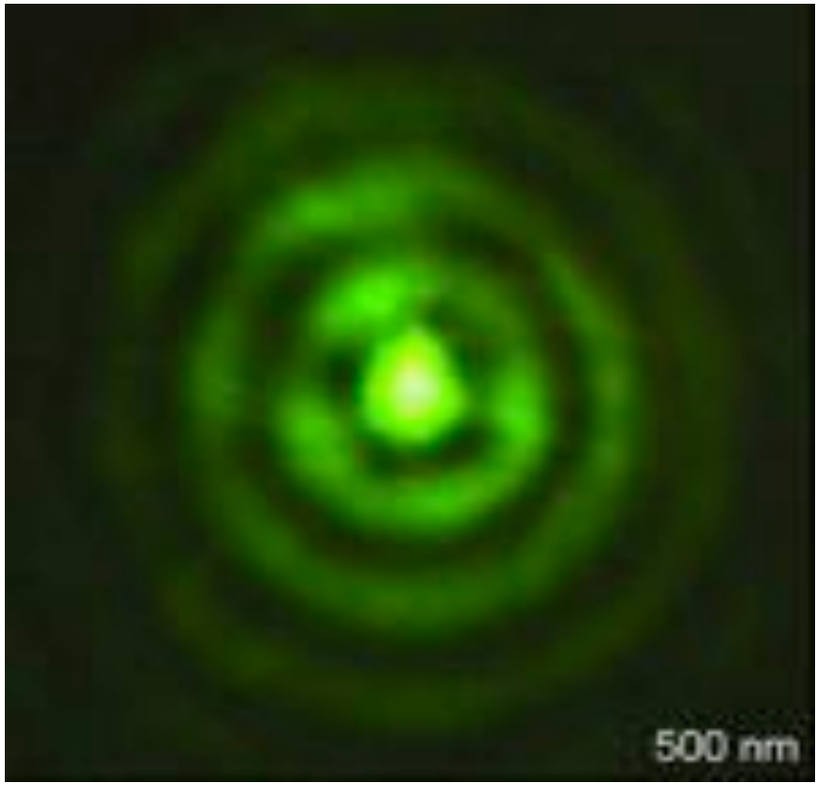
T Cizmar et al.Opt Express **16**, 14024(2008)

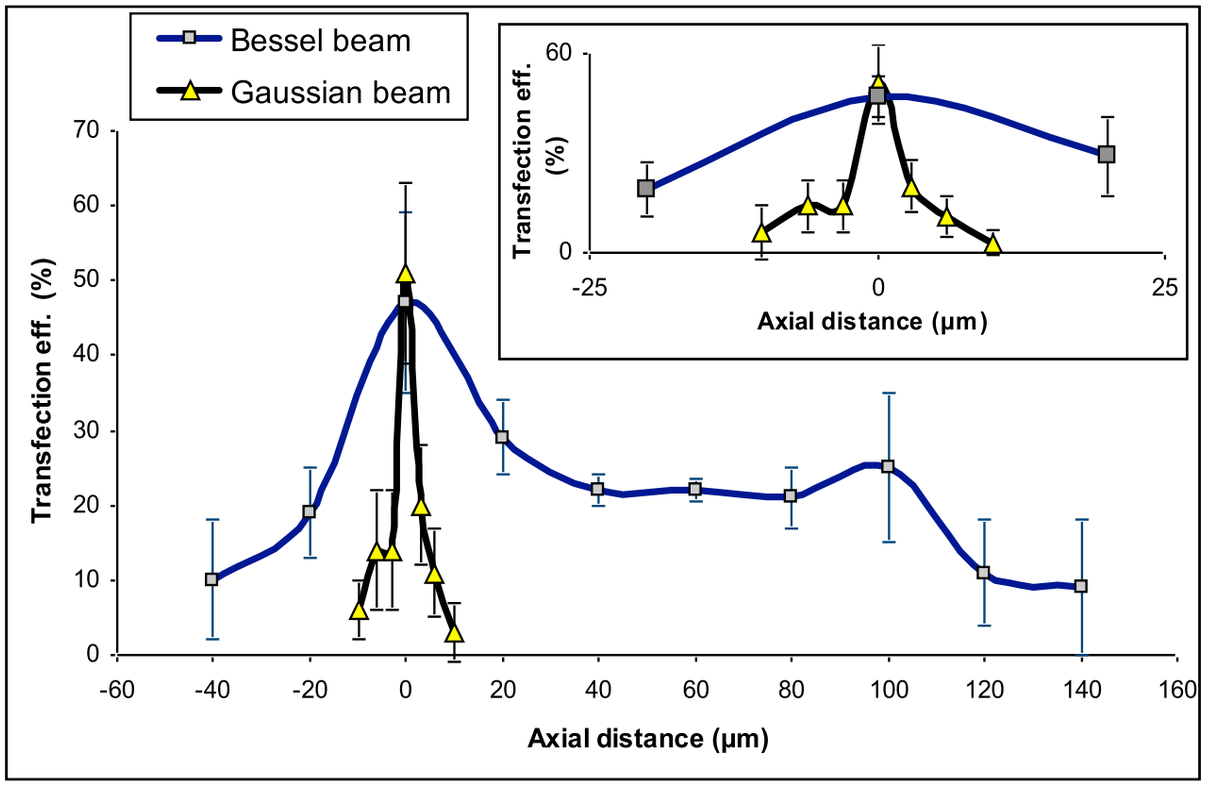
Finding the cell membrane

optical manipulation









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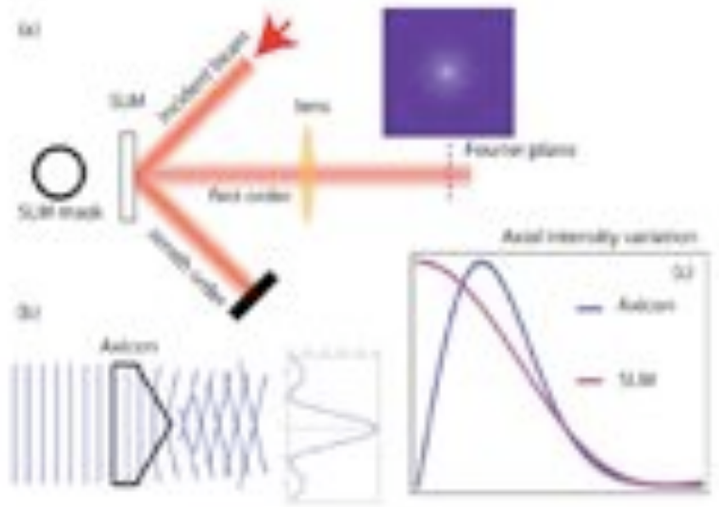

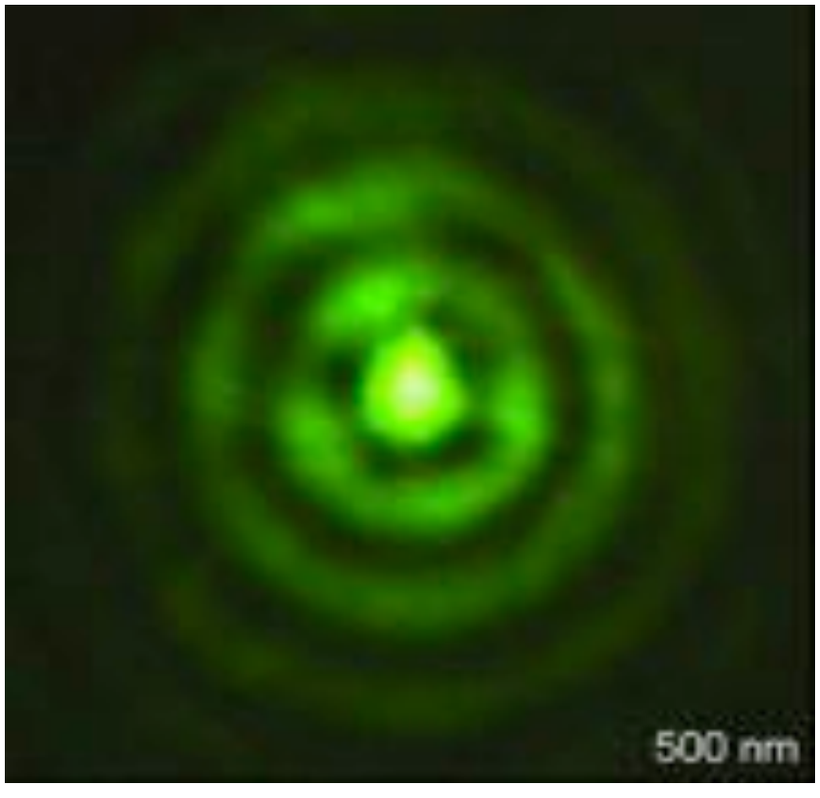

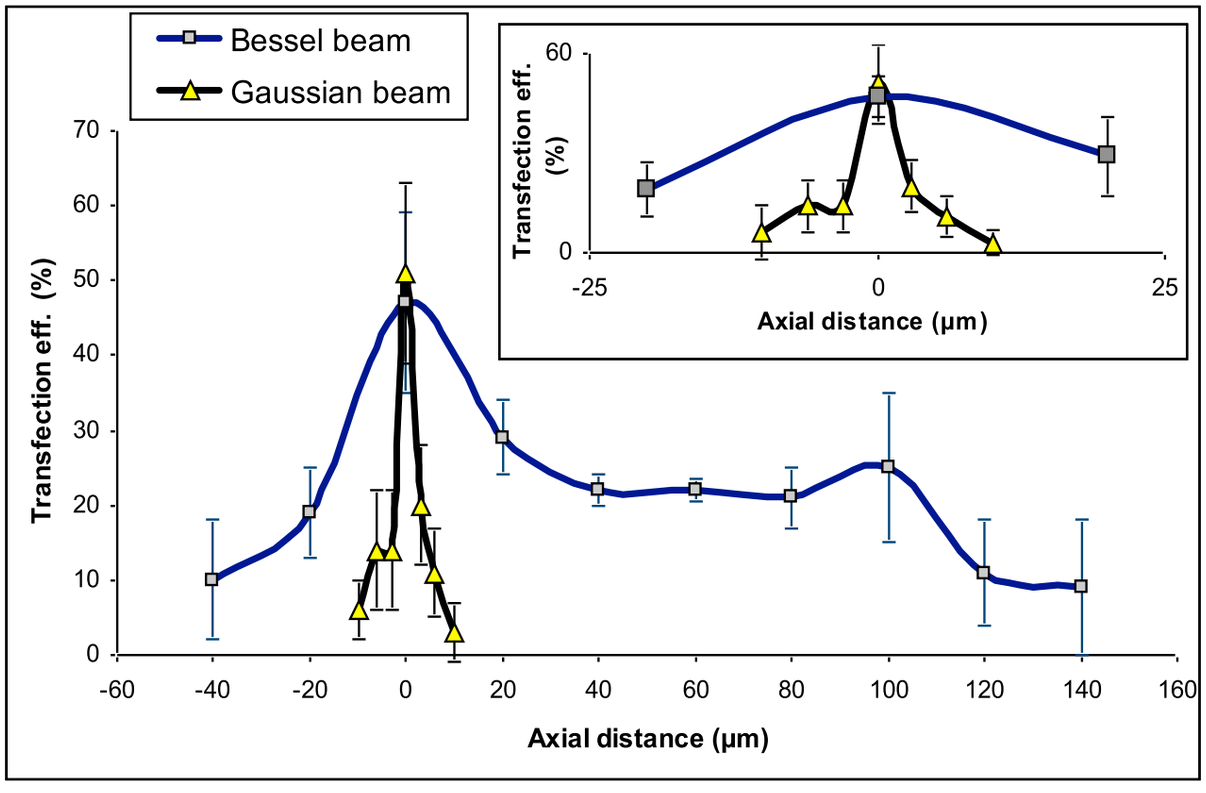

X. Tsampoula et al. Appl. Phys Lett **91**, 053902 (2007)

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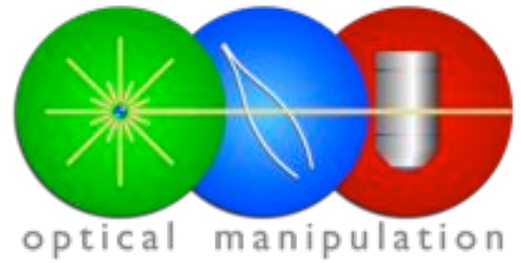
Put this all together...



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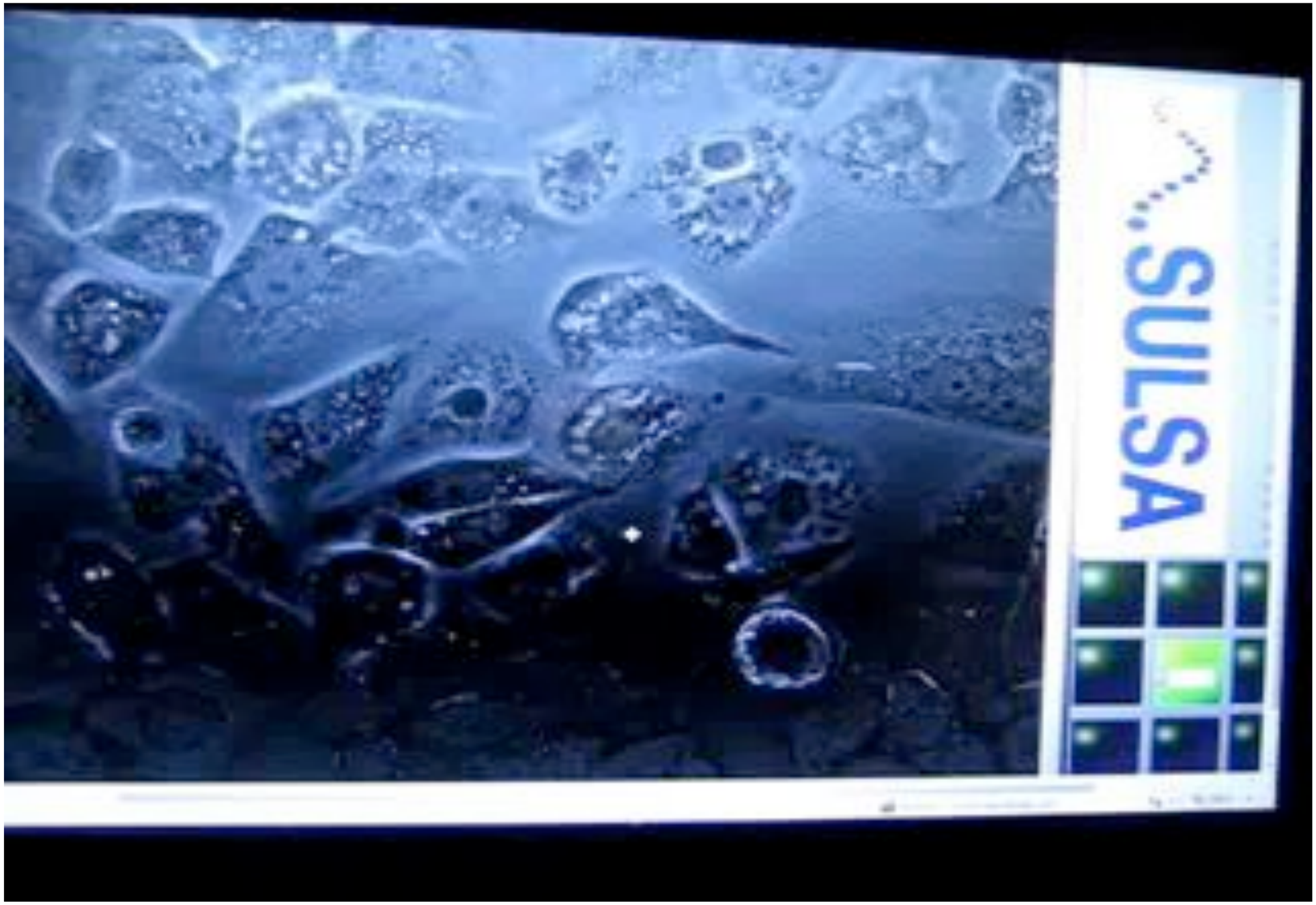

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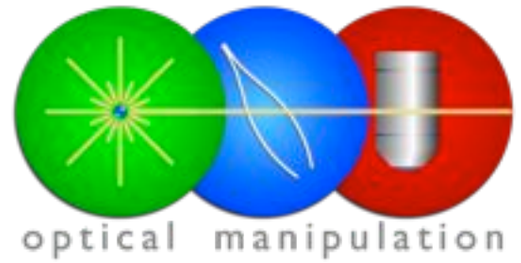
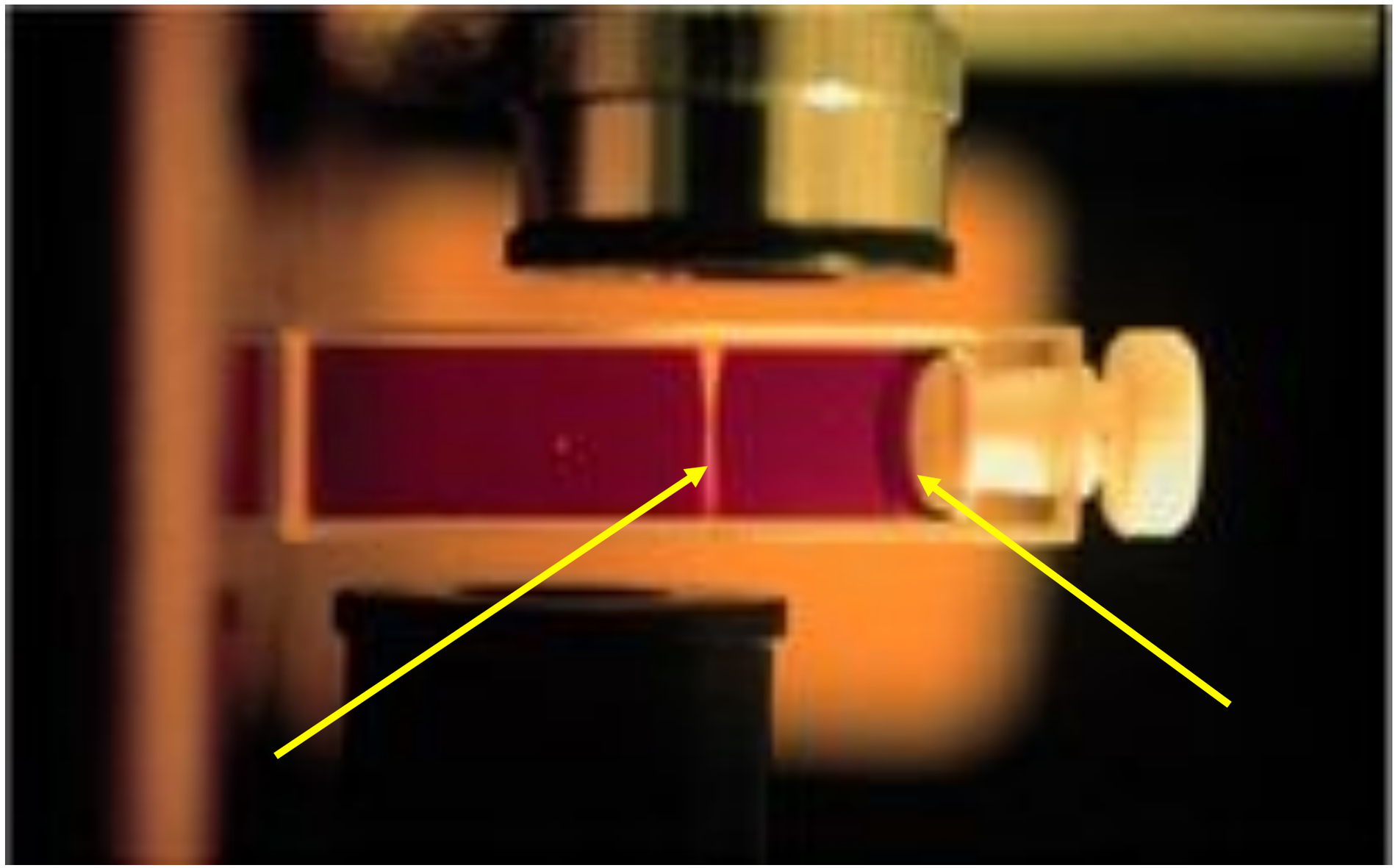
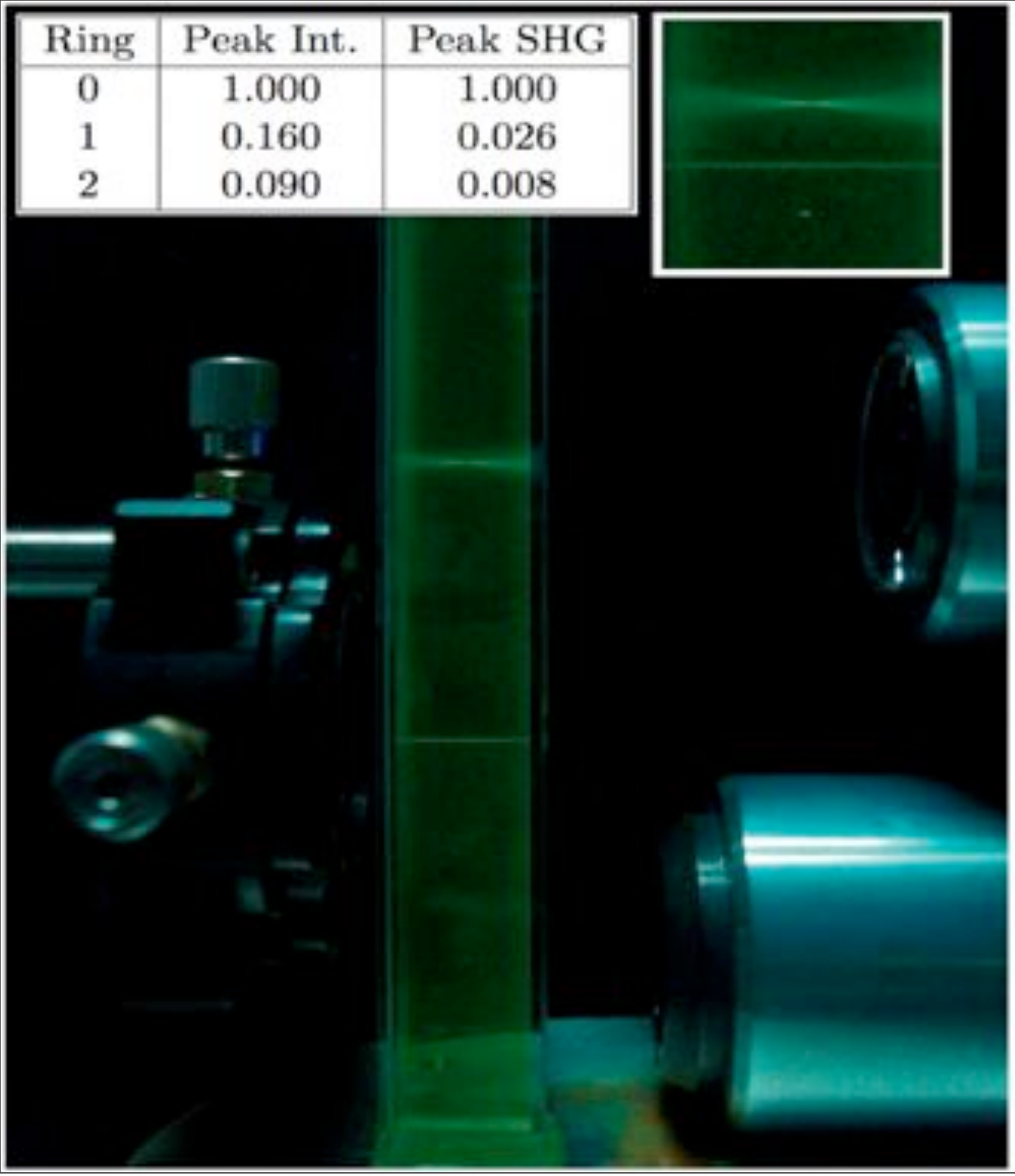


optical manipulation



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).

Ring	Peak Int.	Peak SHG
0	1.000	1.000
1	0.160	0.026
2	0.090	0.008

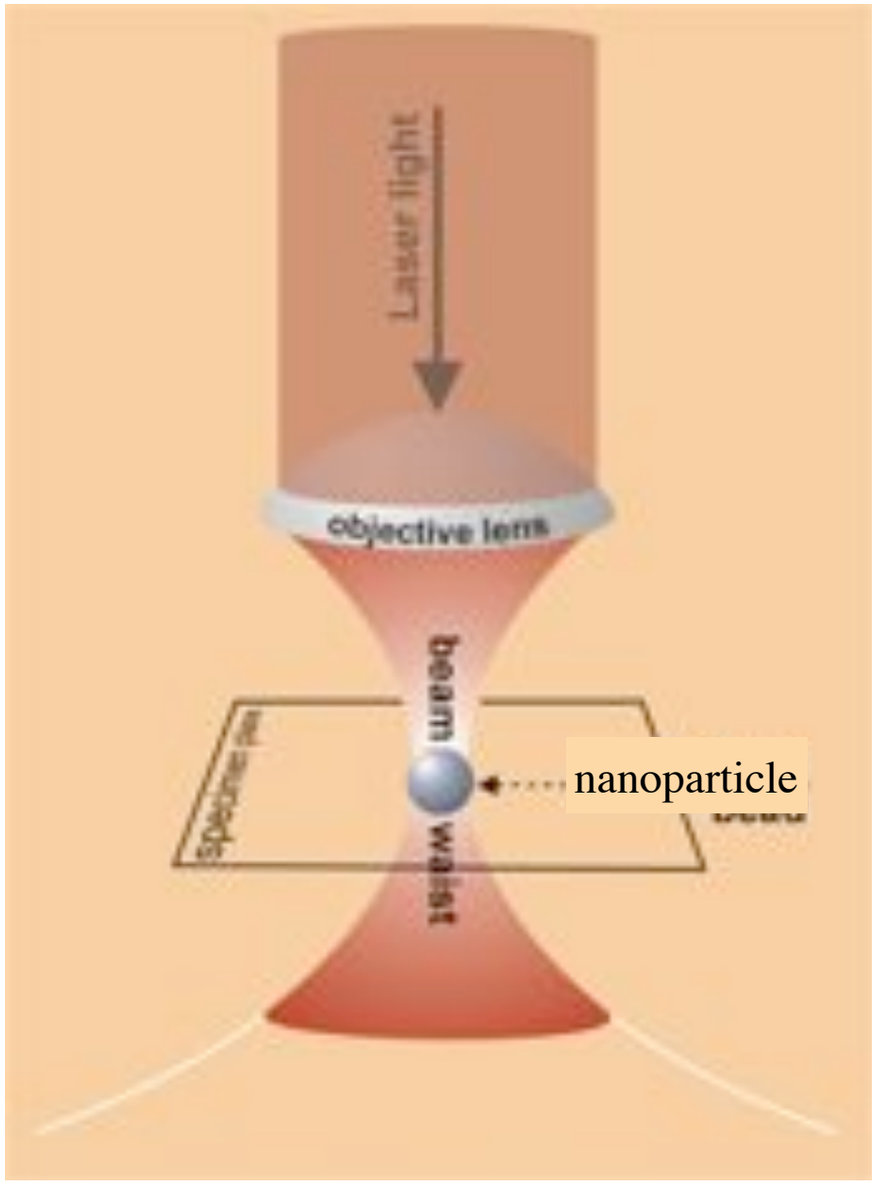


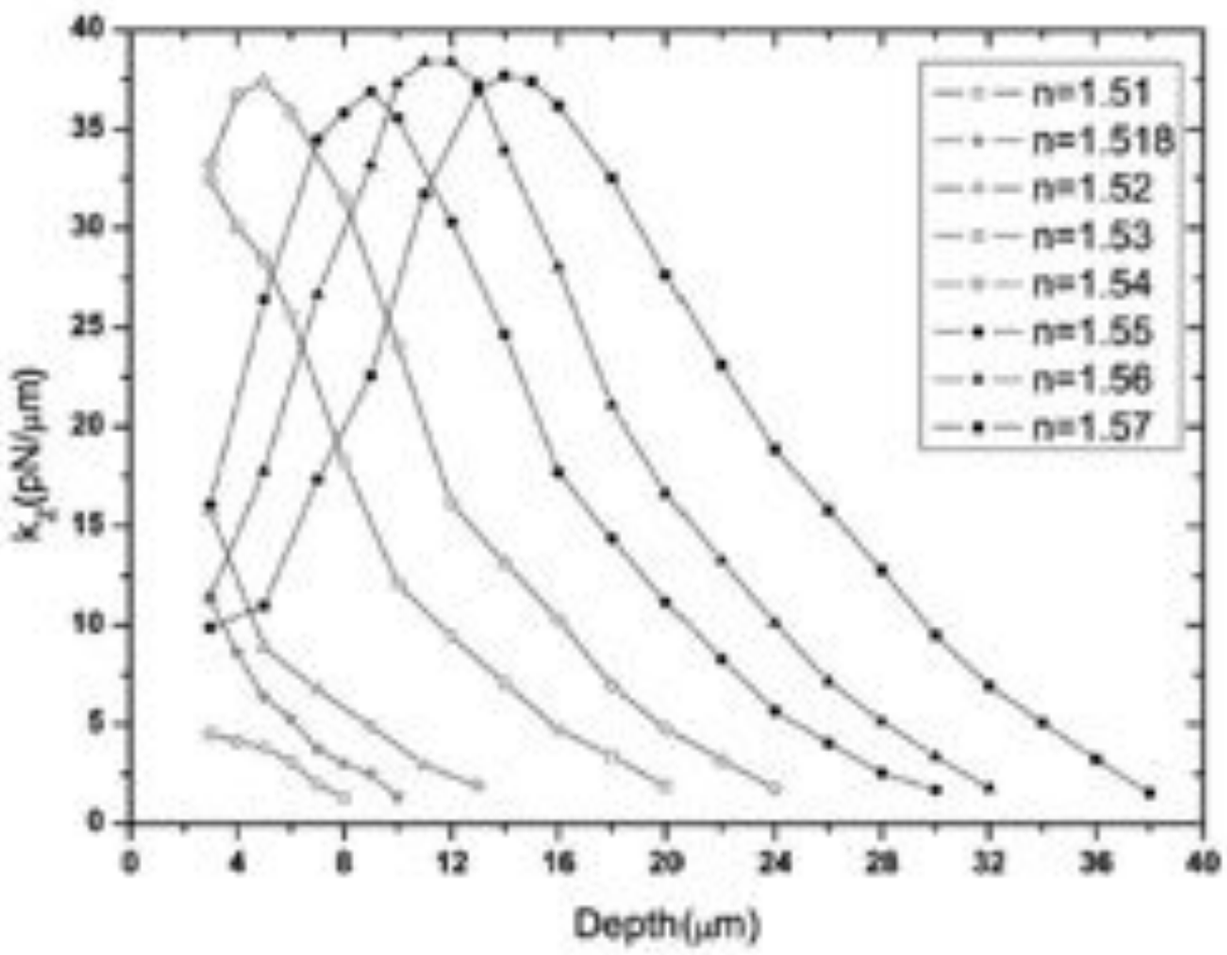
optical manipulation

Single and two photon excitation revisited

Picture by C McDougall and CTA Brown

Importance of aberrations





Changing the refractive index n of the immersion oil for the trapping objective increases the trap stiffness $\varkappa$. The trapping potential in single beam tweezers is harmonic and can be described as $F = -\varkappa(x - x_0)$ with the trap stiffness $\varkappa$, the equilibrium position of the particle x_0 and the position of the particle x. Increasing the trap stiffness $\varkappa$ allows to use less laser power and still exert the same force on the particle. The correct choice of the position (depth) of the beam focus and thus the trapping position in the sample chamber is also important

Optimizing immersion media refractive index improves optical trapping by compensating spherical aberrations S.N.S. Reihani and L. Oddershede, Optics Letters, vol.32, p.1998-2000 (2007)

In clear media we control light using **precision**

In opaque scattering media we control light using **Information**

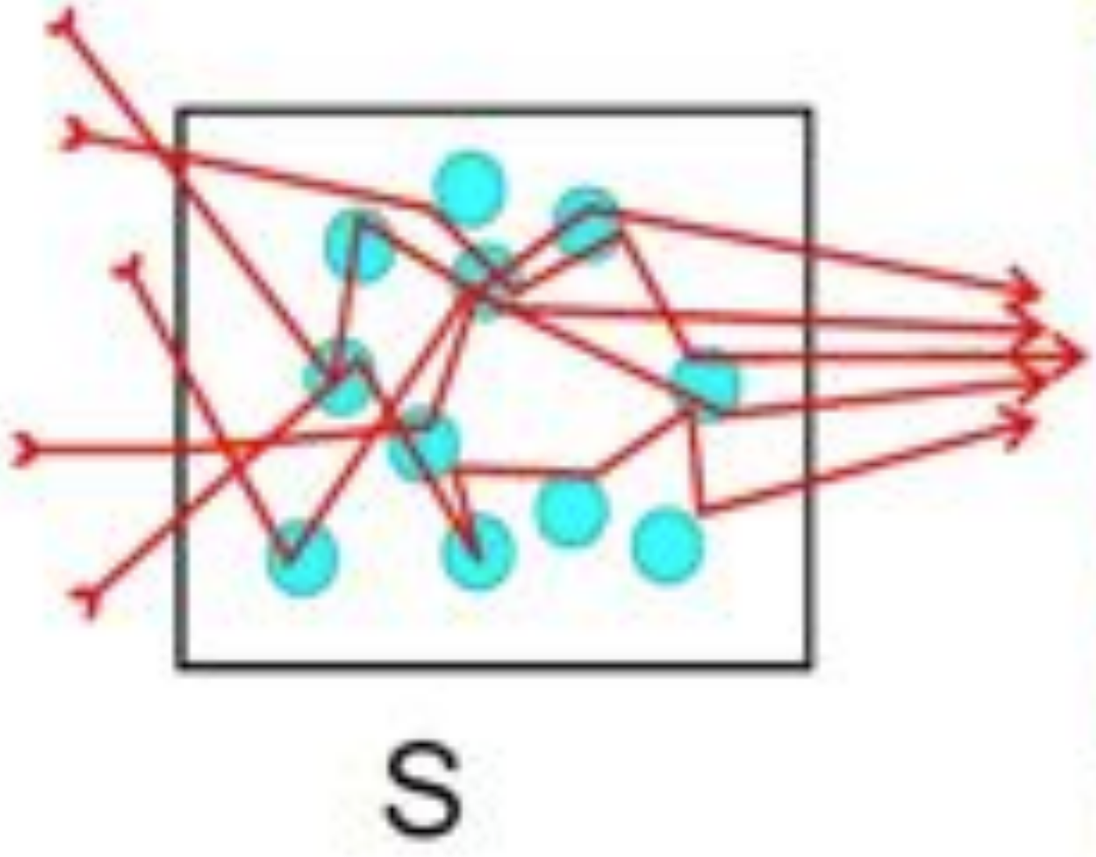
T. Cizmar et al. Nat Photonics 4, 388 (2010); Nature Comms (to appear 2012)

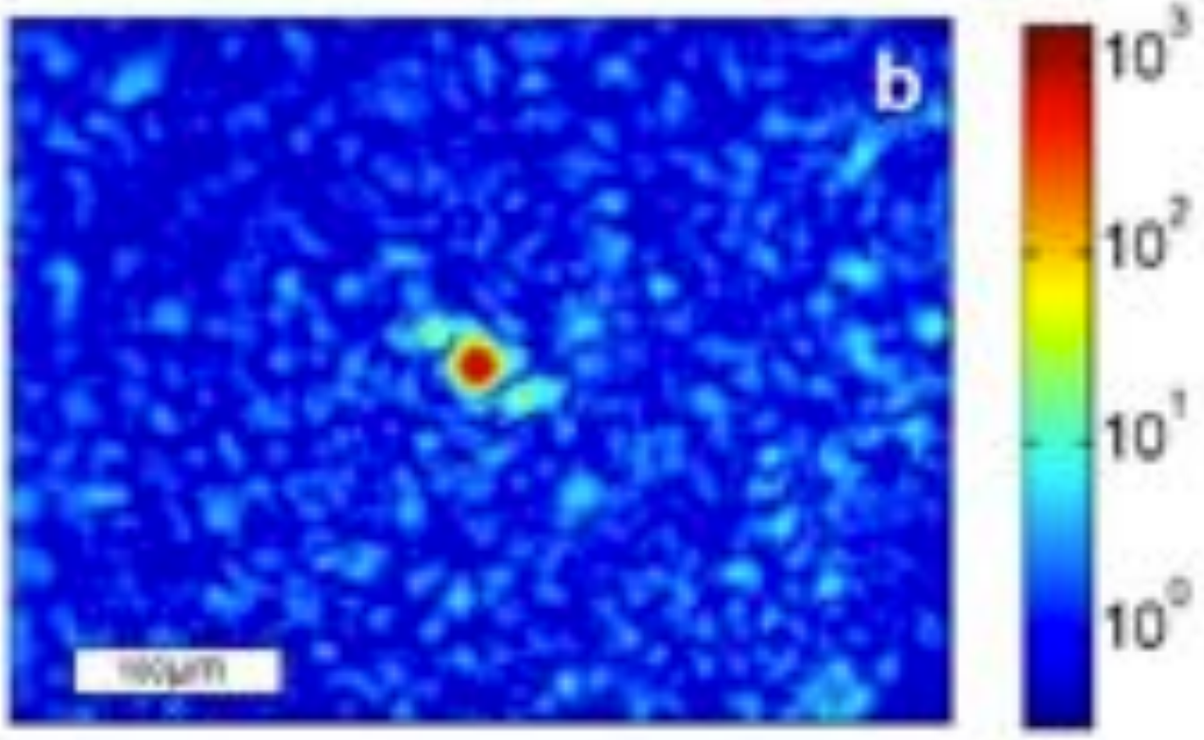
van Putten& APM, Physics **3**, 22 (2010)
Popoff et al., PRL **104** (2010)
First theoretical proposal: I. Freund (1990)

Using disorder for Nano-optics

optical manipulation

A complicated incident field pattern transformed into a focus





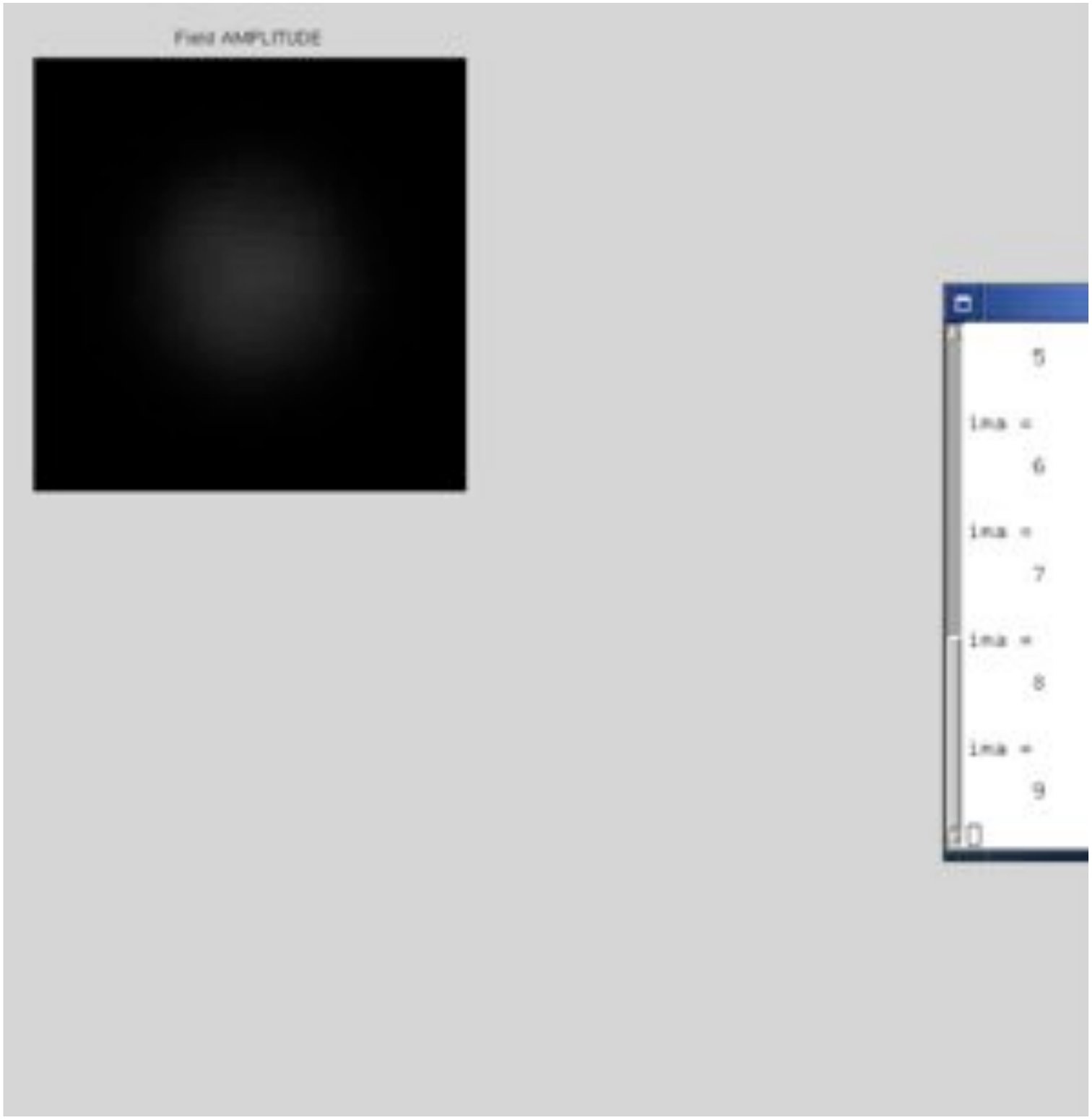
measured transmission normalized by average diffuse intensity

optical manipulation

Principle of *in situ* aberration correction method

The individual modes can be independently turned on and off
The phase of each mode can be individually manipulated.

Principle of *in situ* aberration correction method



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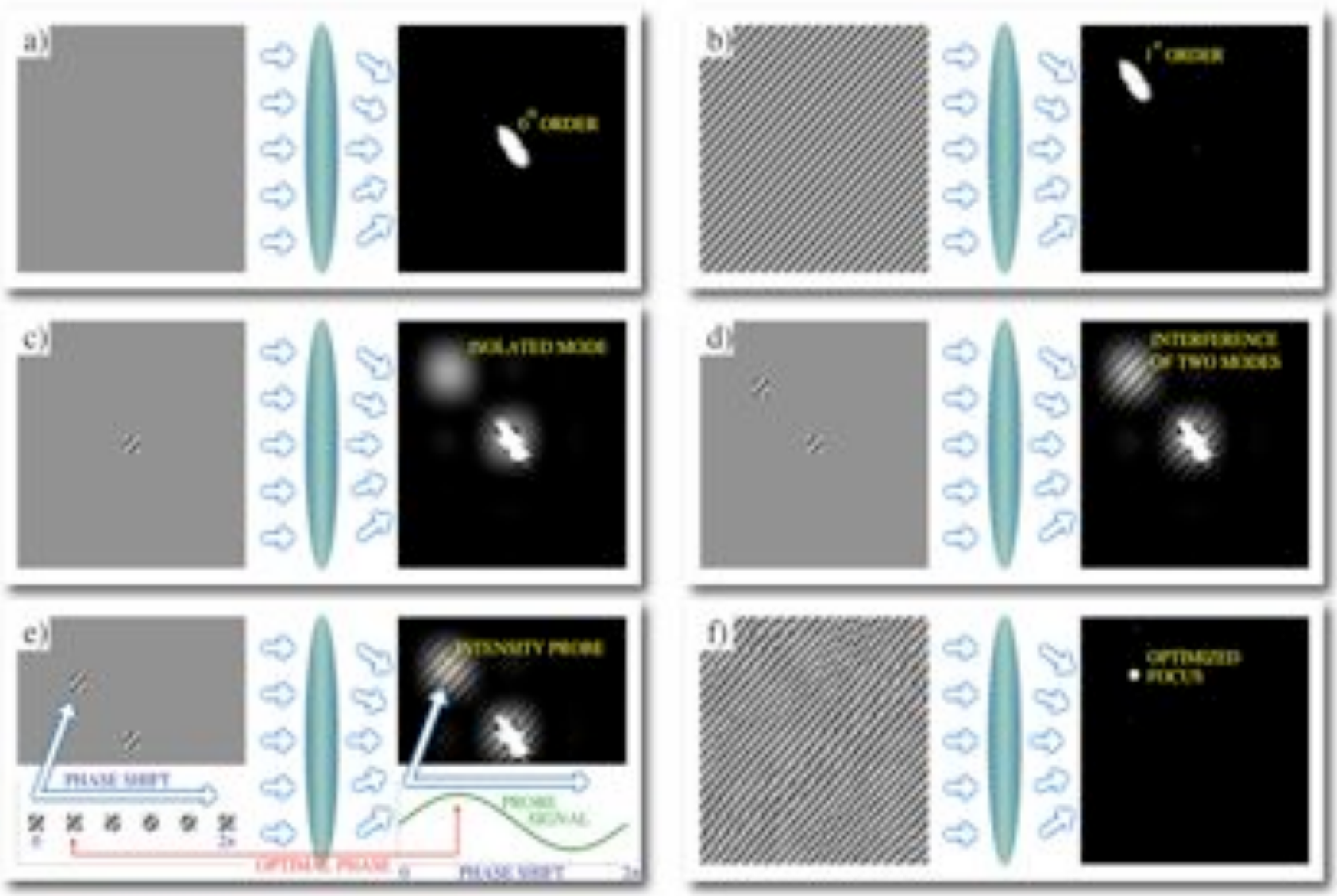

$$I_p(t) \propto |E_t|^2 + |E_r|^2 + 2|E_t||E_r| \cos(\psi_t - \psi_r + vt).$$

The individual “modes” can be independently turned on and off. The phase of each mode can be individually manipulated.

Evaluation of optical trapping

- λ = 532 nm
- Objective - Olumpus UPlanSapo 60x 1.2 W
- Optical power < 200 mW per particle in the sample plane

- λ = 532 nm
- Objective - Condensed NIKON D-CUO (Oil) 1.4
- Optical power ≈ 15 mW per particle in the sample plane

T Cizmar et al. Nature Photonics, 4, 388 (2010)

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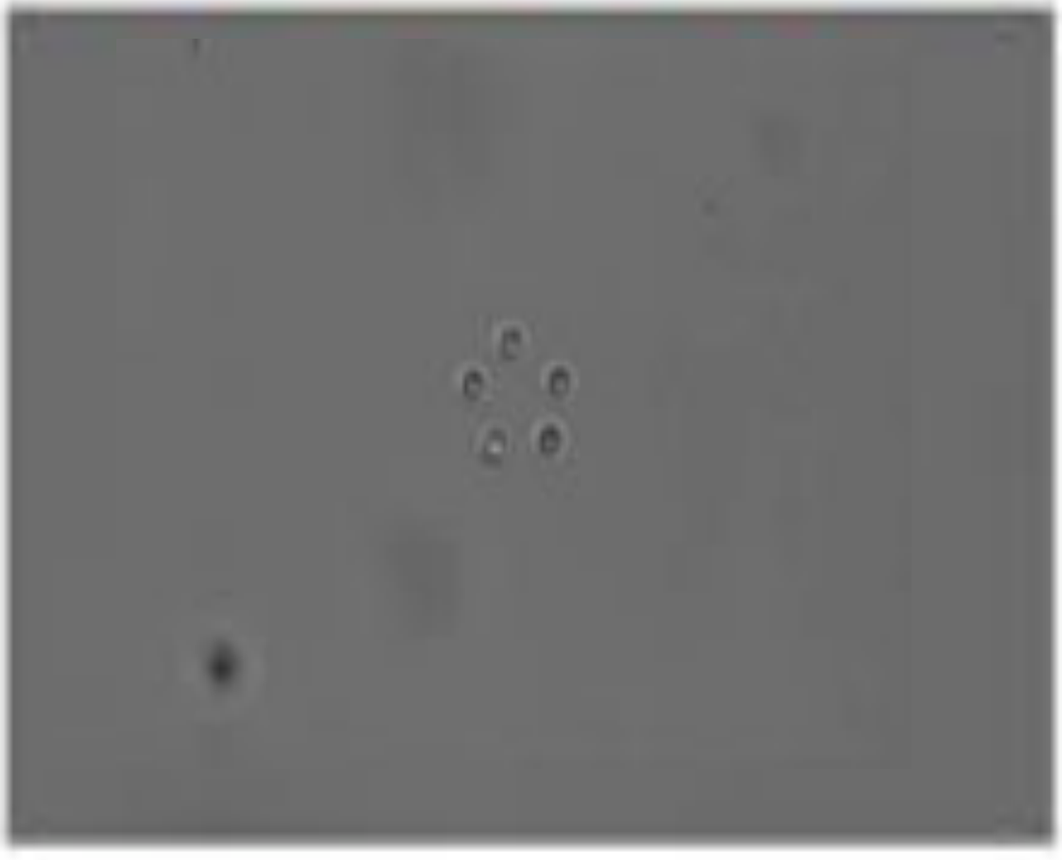

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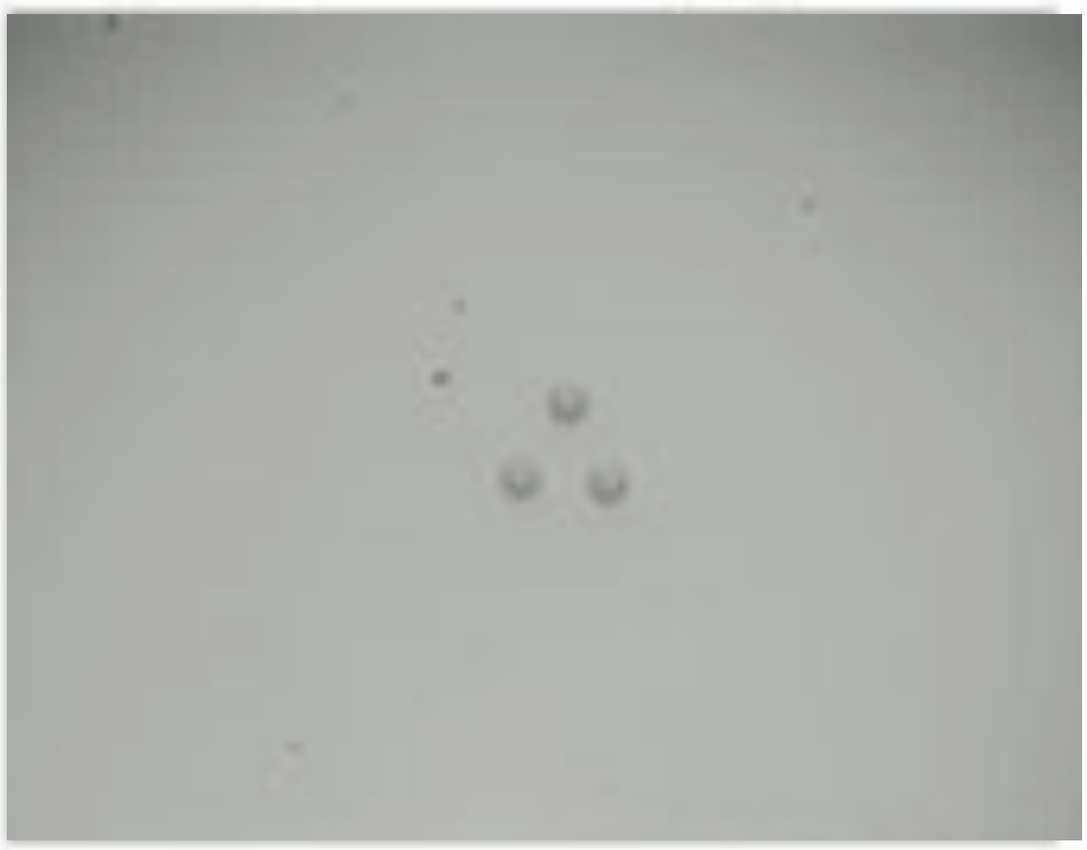


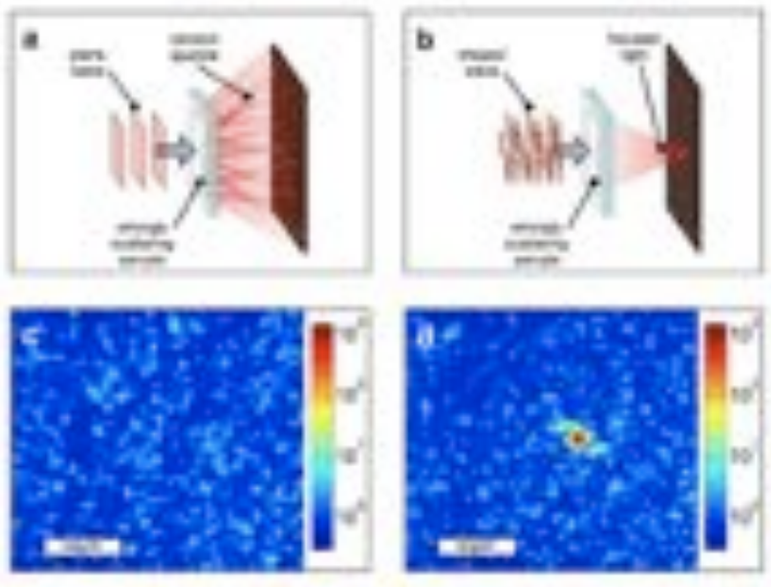
T Cizmar et al. Nature Photonics, 4, 388 (2010)

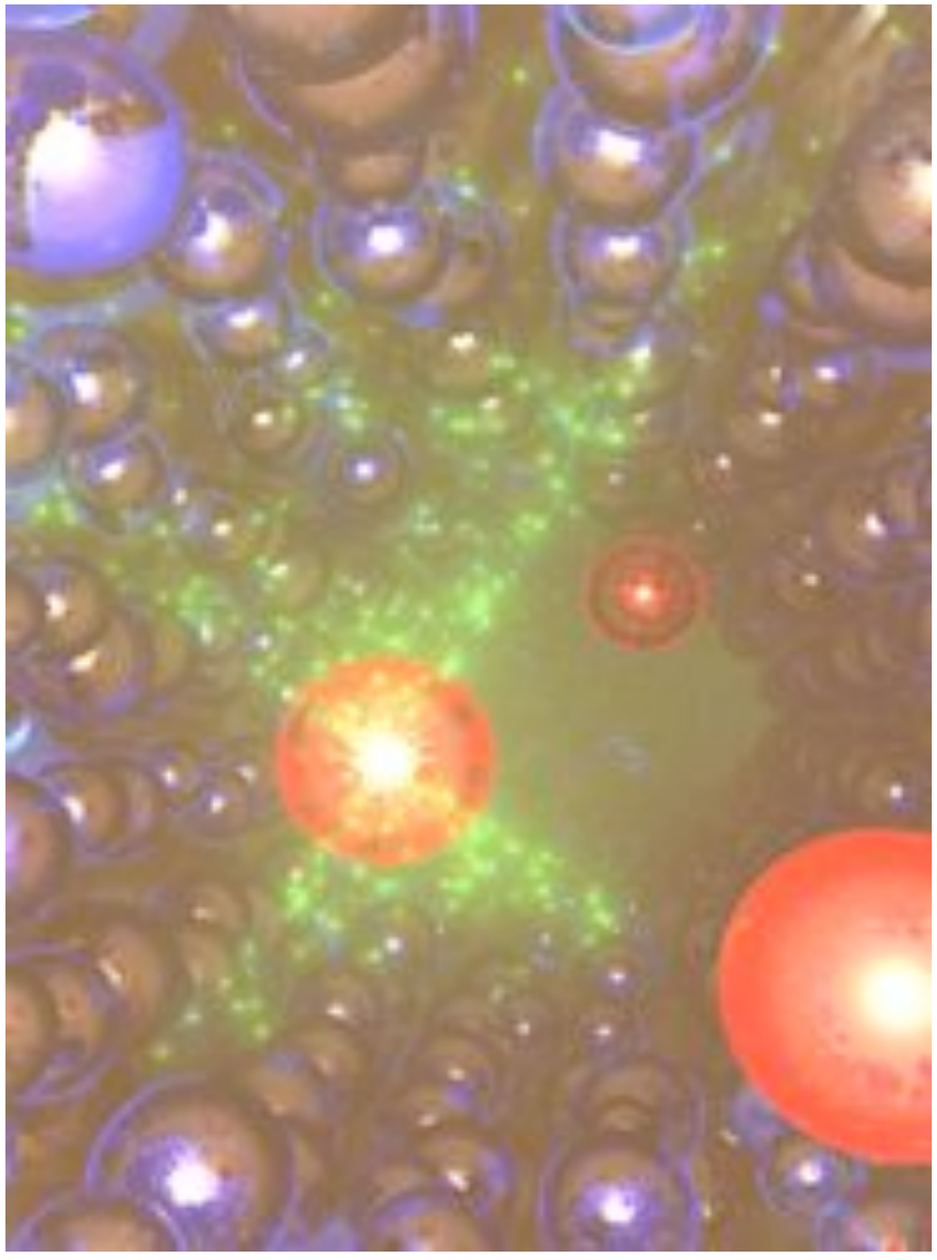
Trapping and focusing through turbulence?

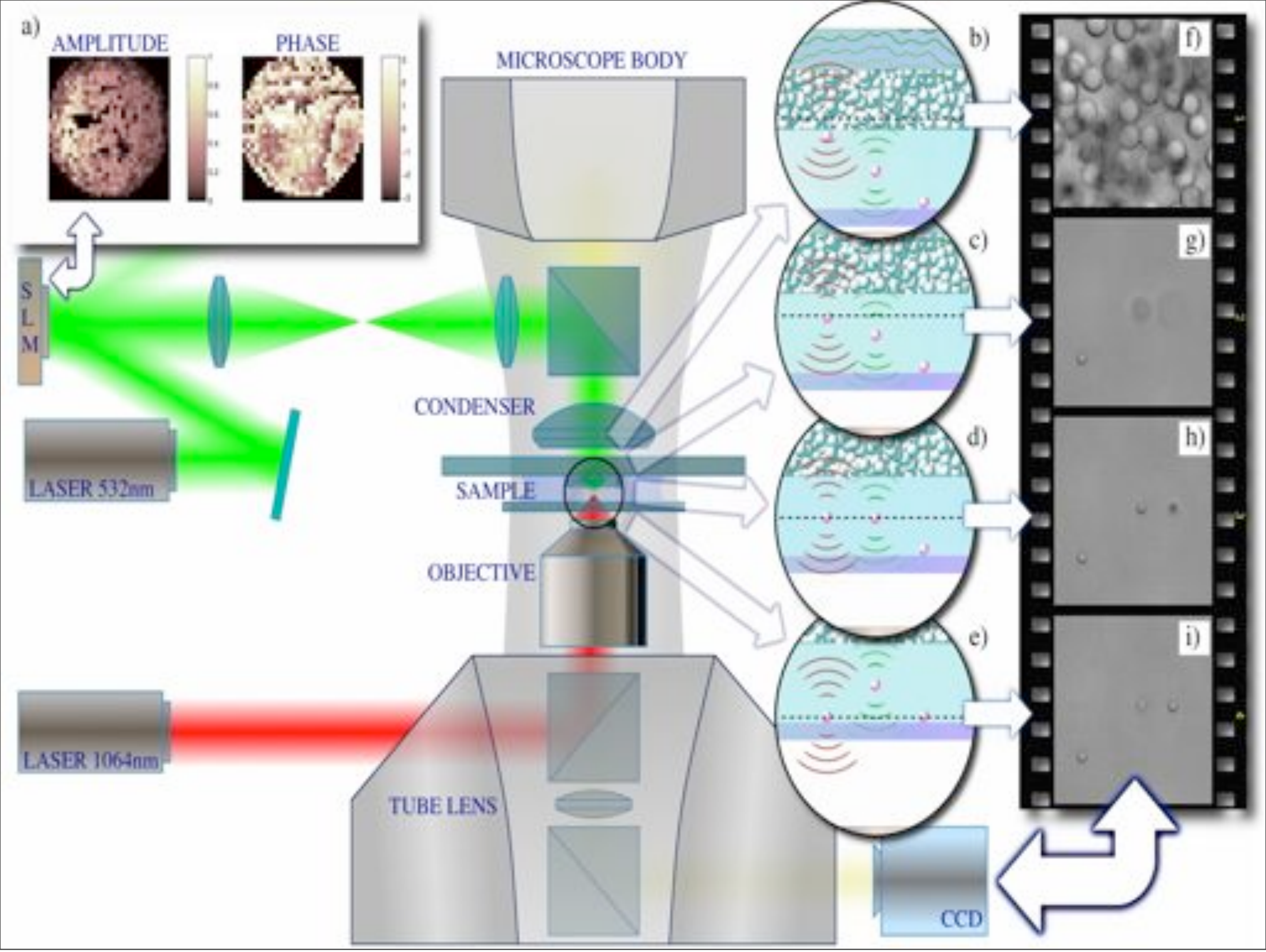
optical manipulation

I. M. Vellekoop and A. P. Mosk:

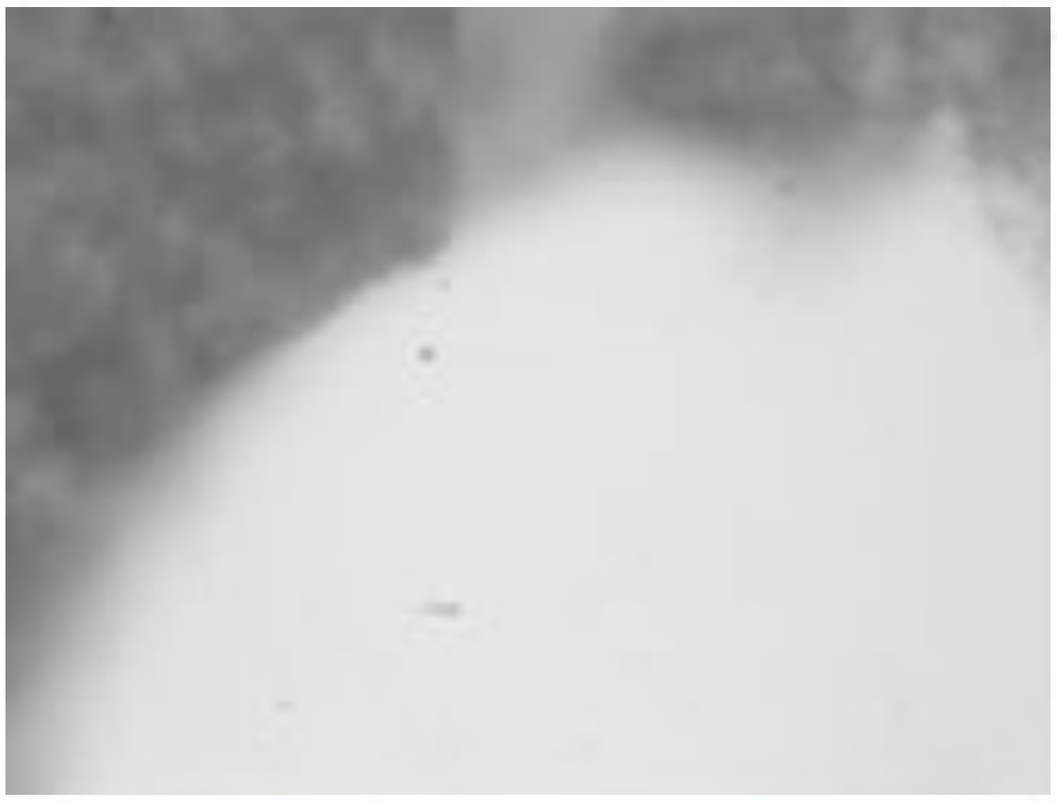
- *Focusing coherent light through opaque strongly scattering media*, Opt. Lett. 32, 2309-2311 (2007)
- *Phase control algorithms for focusing light through turbid media*, Opt. Comm. 281, 3071 - 3080 (2008)
- *Universal optimal transmission of light through disordered materials*, Phys. Rev. Lett. 101, 120601 (2008)





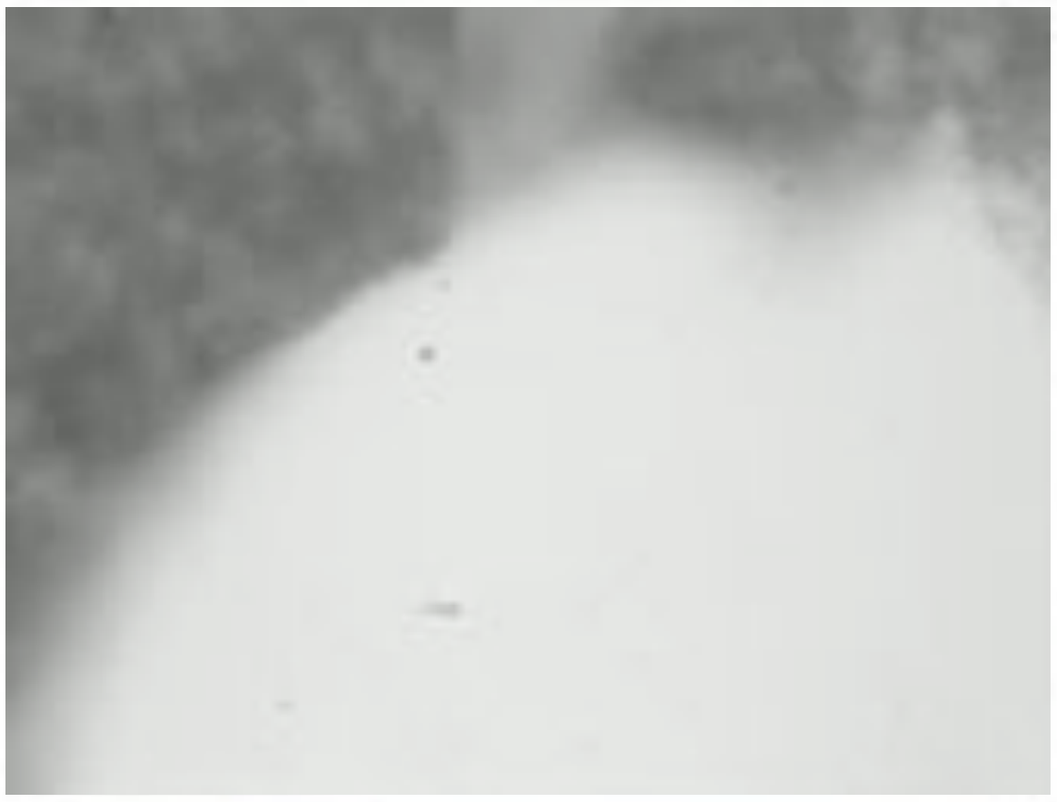

a)
AMPLITUDE
PHASE
MICROSCOPE BODY
b)
c)
d)
e)
f)
g)
h)
i)
SLM
LASER 532nm
CONDENSER
SAMPLE
OBJECTIVE
LASER 1064nm
TUBE LENS
CCD

Optical trapping through a turbid medium



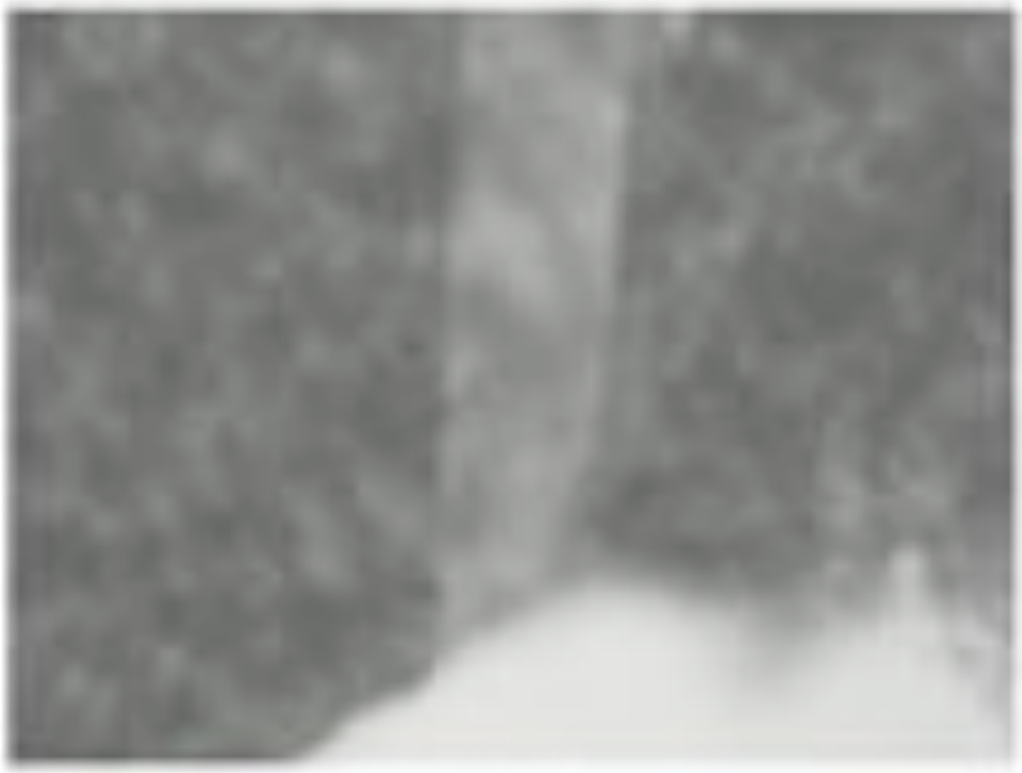
T Cizmar et al. Nature Photonics, 4, 388 (2010)

Optical trapping through a turbid medium



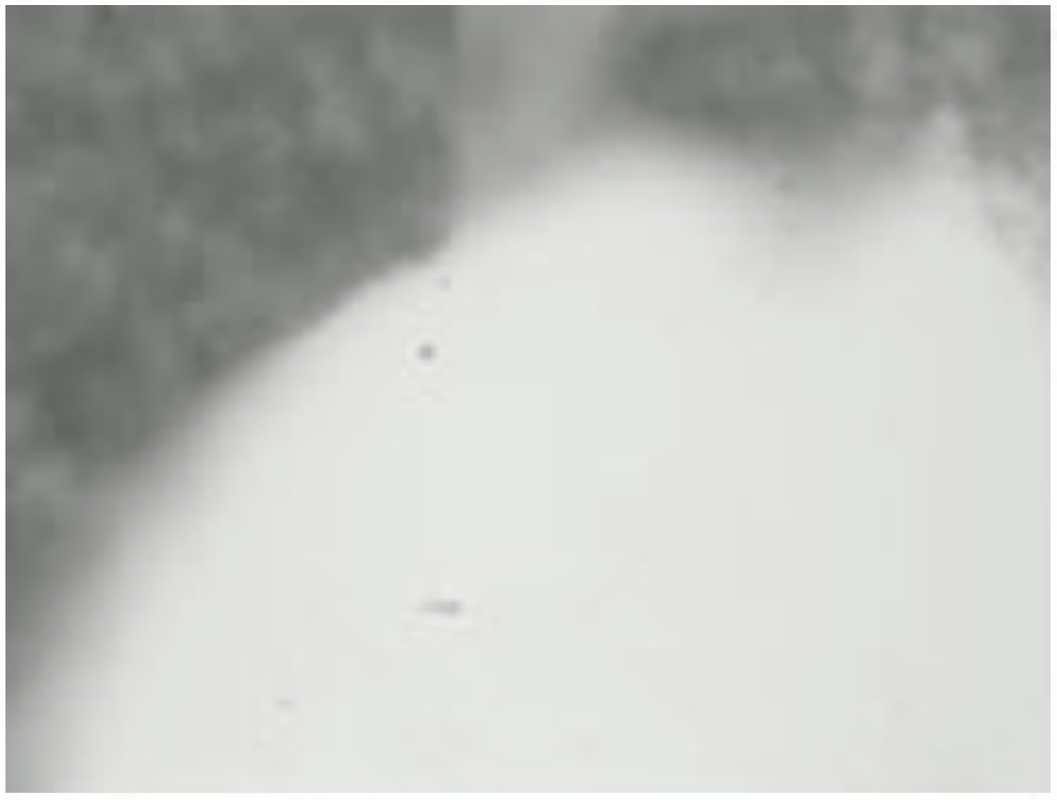
T Cizmar et al. Nature Photonics, 4, 388 (2010)

Optical trapping through a turbid medium



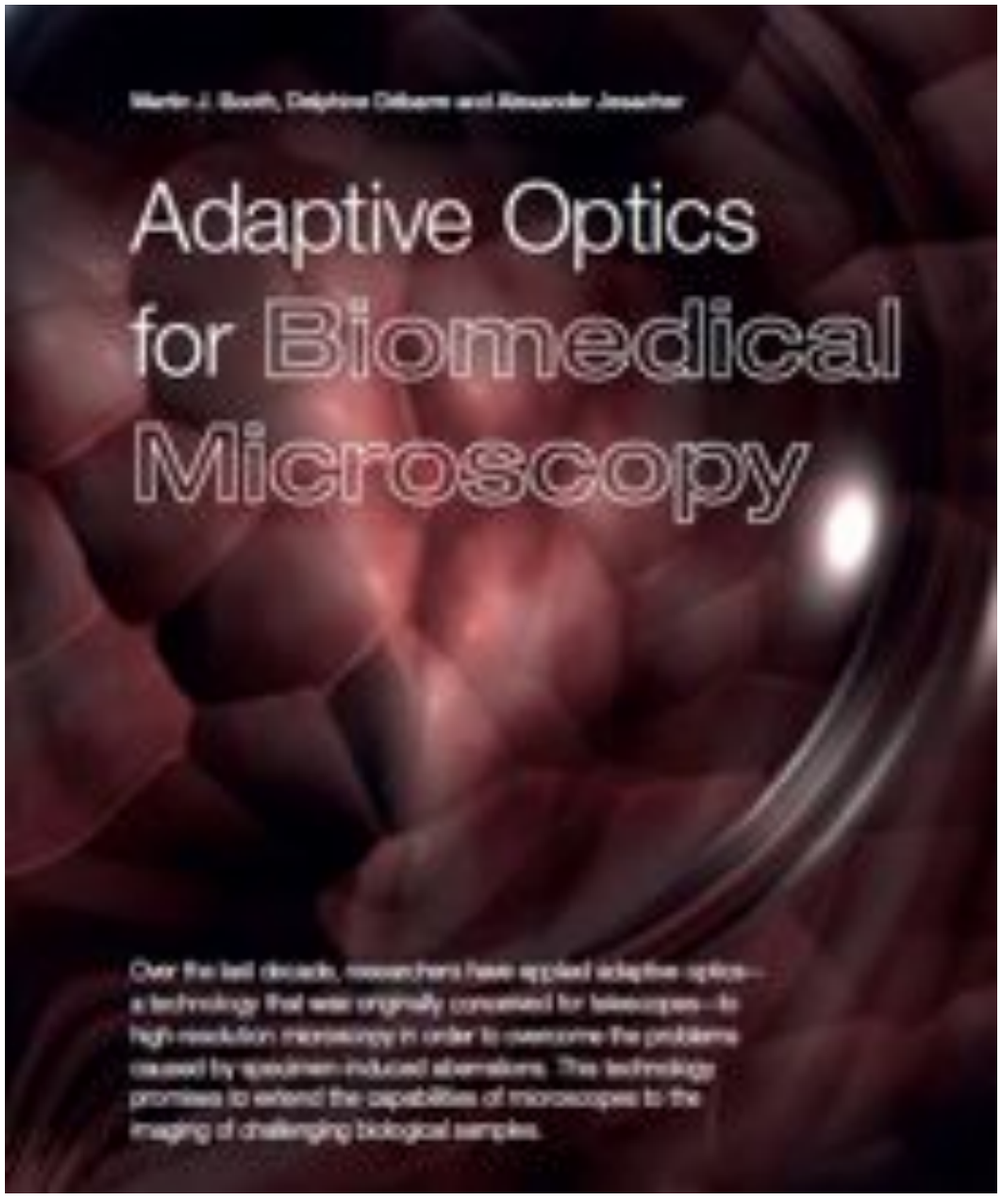
T Cizmar et al. Nature Photonics, 4, 388 (2010)

Optical trapping through a turbid medium



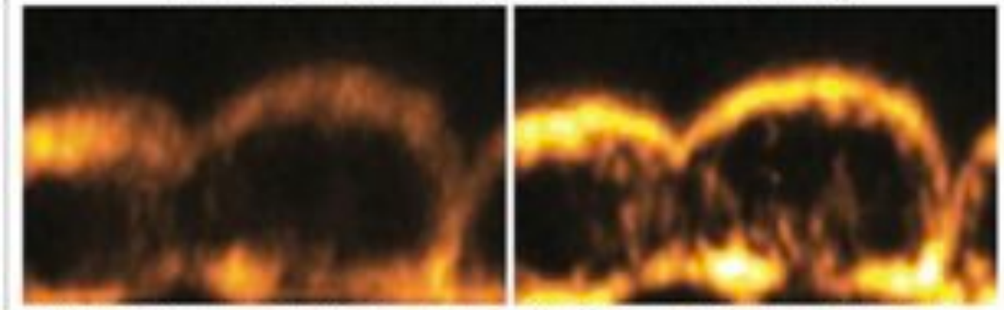
T Cizmar et al. Nature Photonics, 4, 388 (2010)

optical manipulation

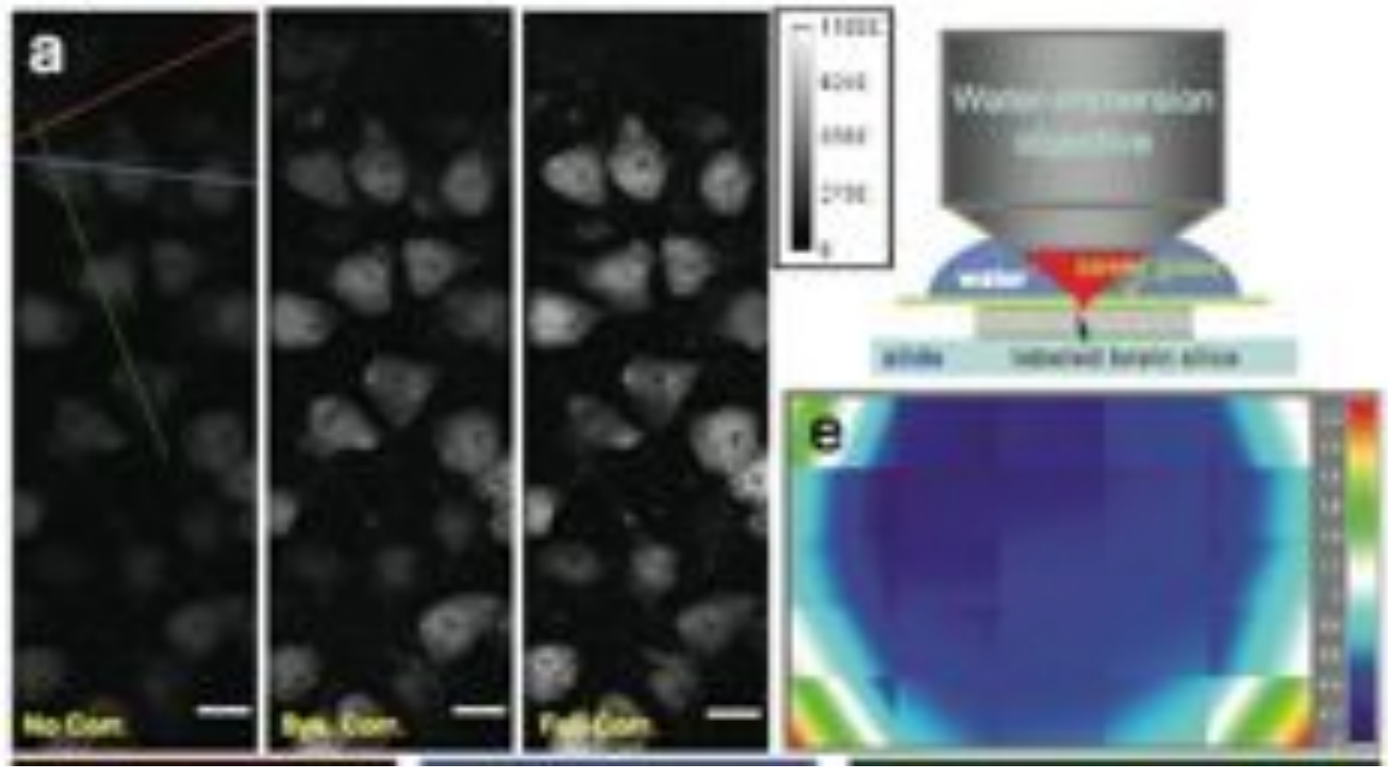


Aberration correction at the top surface of an antibody- labeled 300 μm thick fixed mouse brain slice. From Ji et al Nature Methods 2010

[Mouse embryo images from an adaptive third harmonic generation microscope]

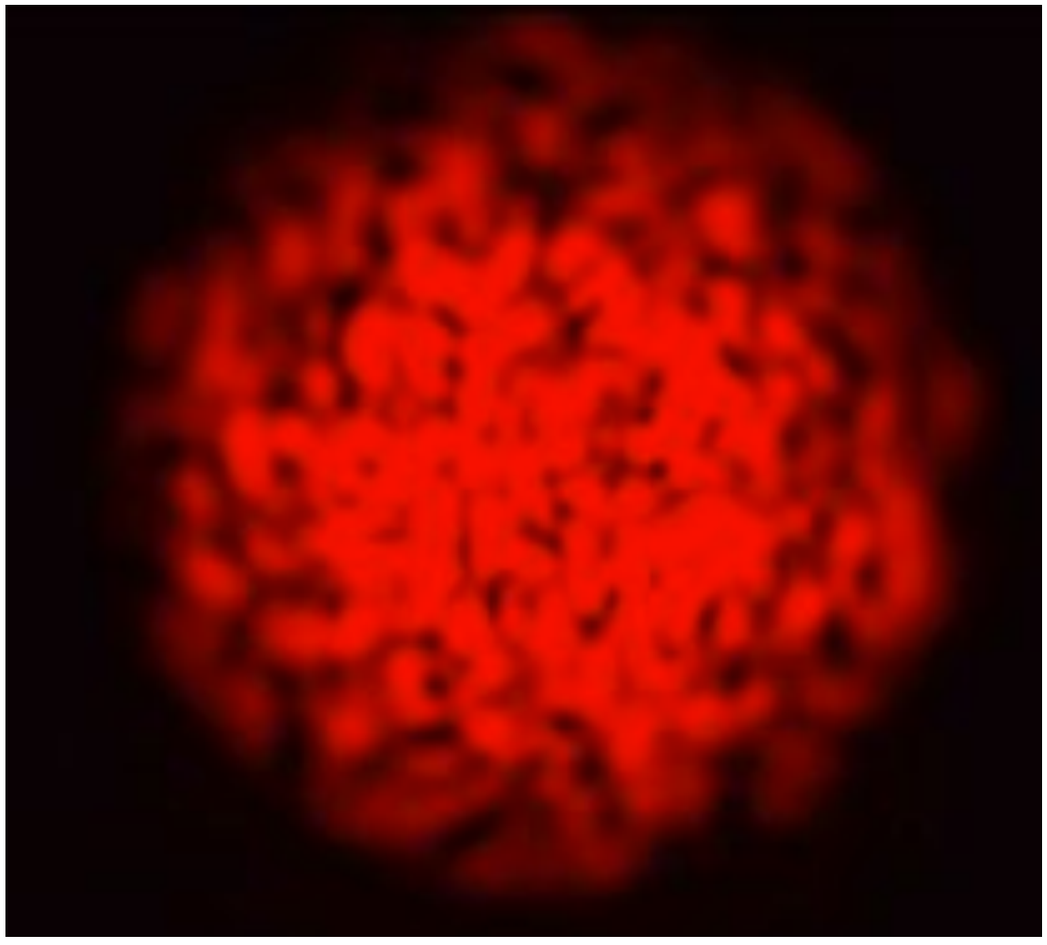


(Left) Without aberration correction. (Right) With aberration correction. Aberration correction leads to increased signal and improved resolution, particularly along the optic axis (vertical).



ptics and Photonics News, Vol. 23, Issue 1, pp. 22-29 (2012)

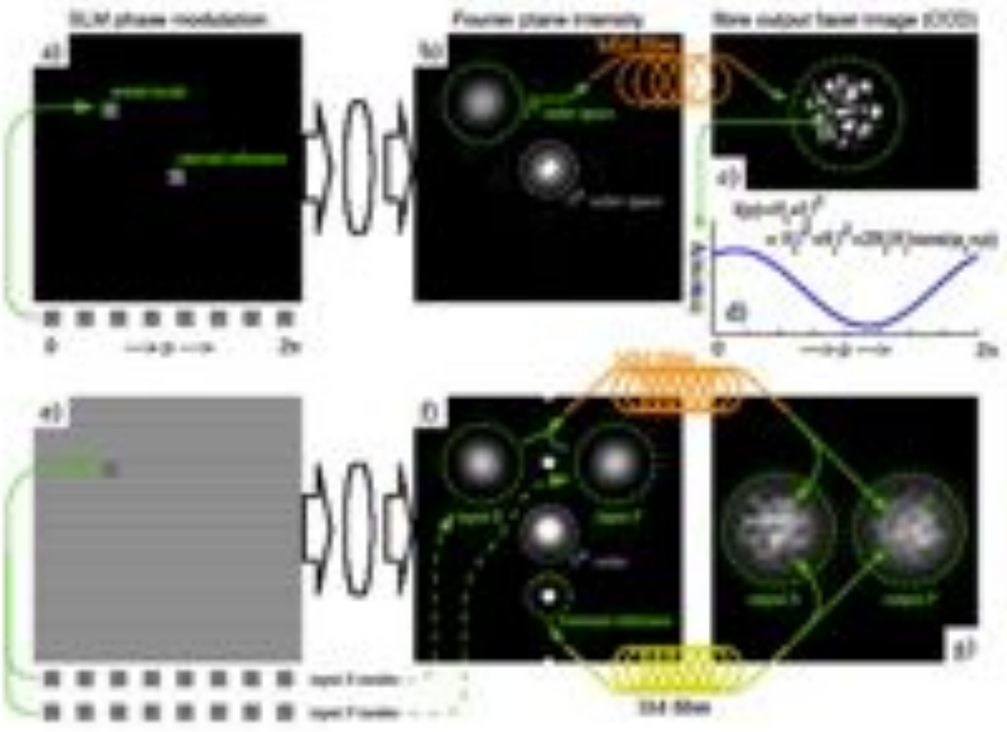
Multimode optical fibre

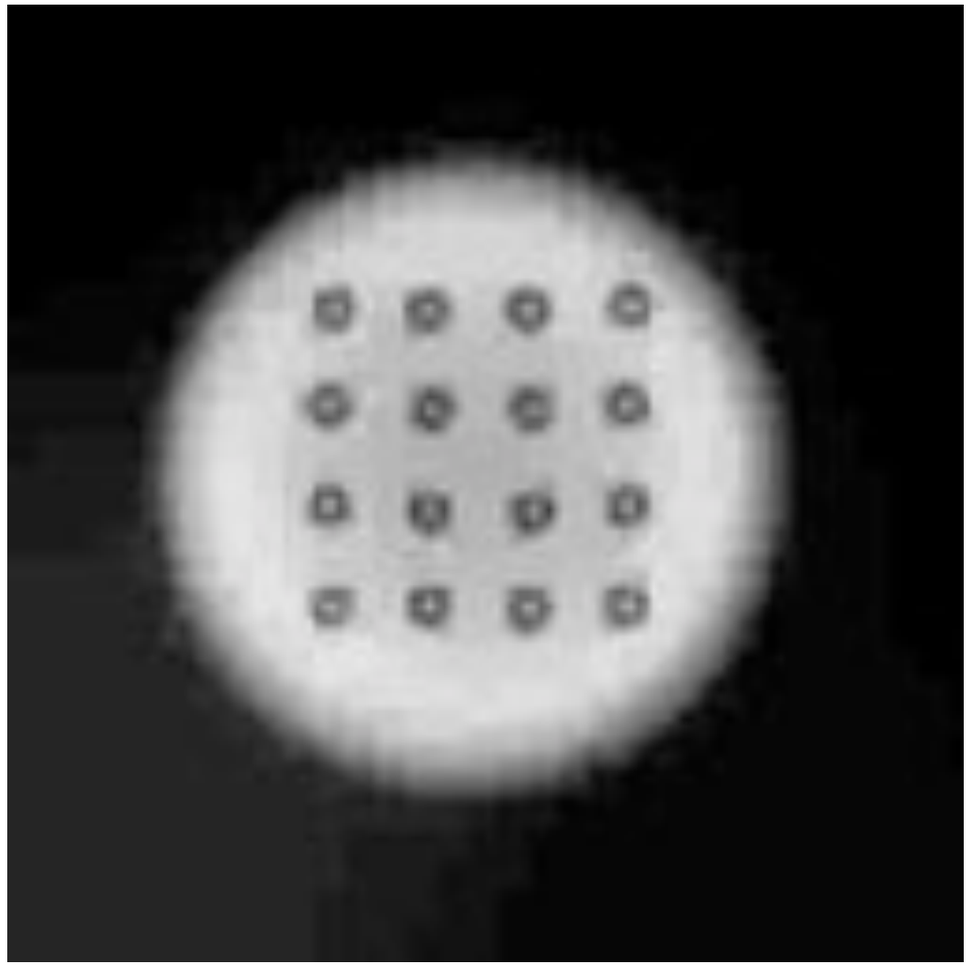


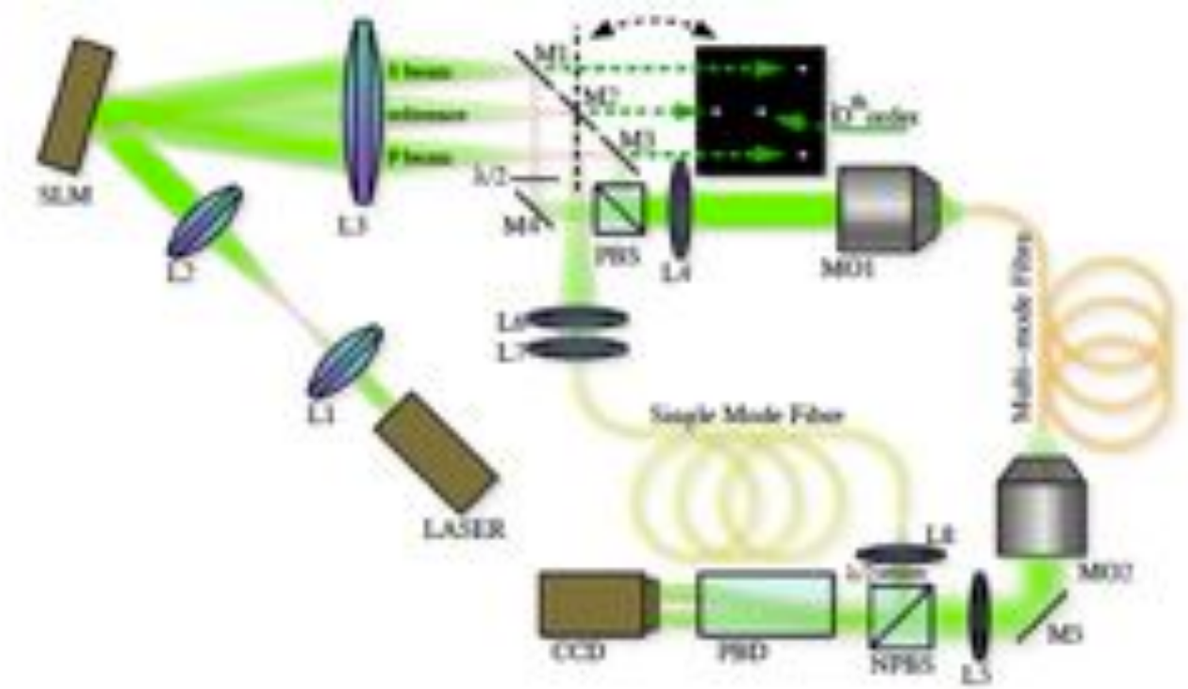
Granular pattern (‘speckle’) due to interference of lots of modes

Shaping light transmission through a multimode fibre

optical manipulation



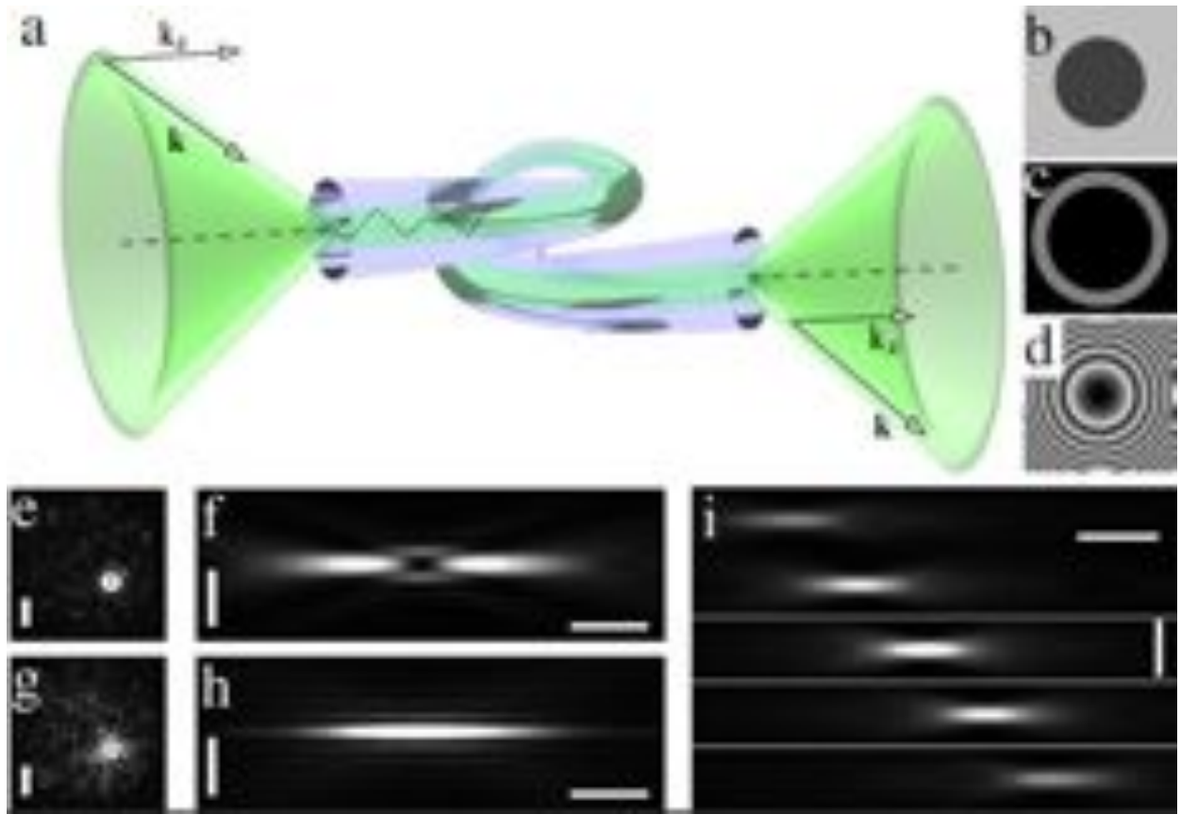


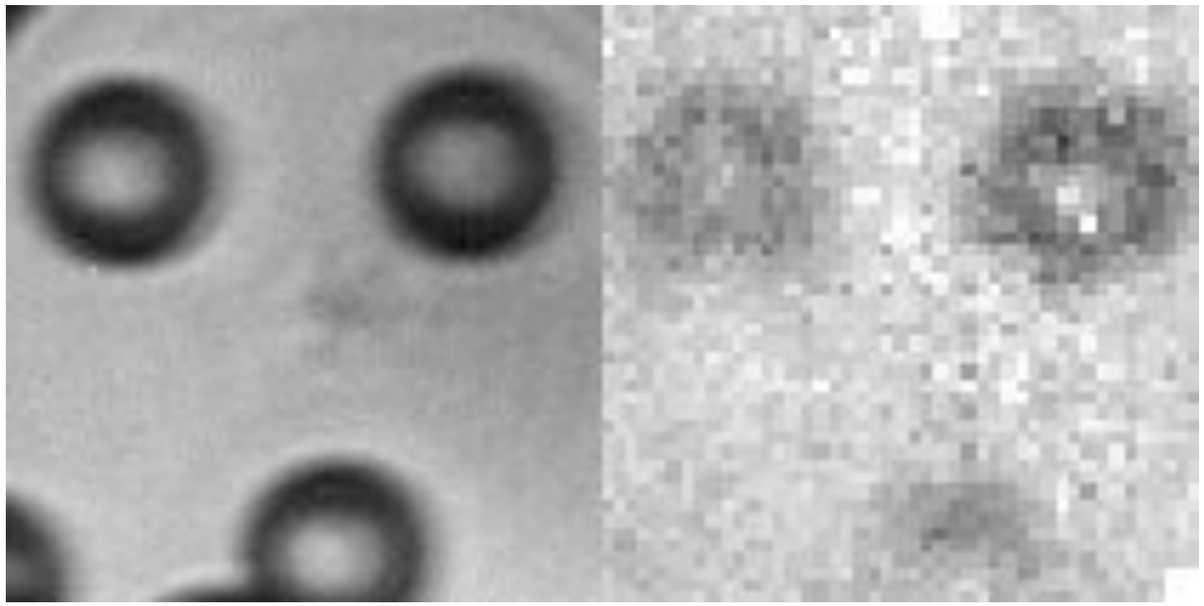


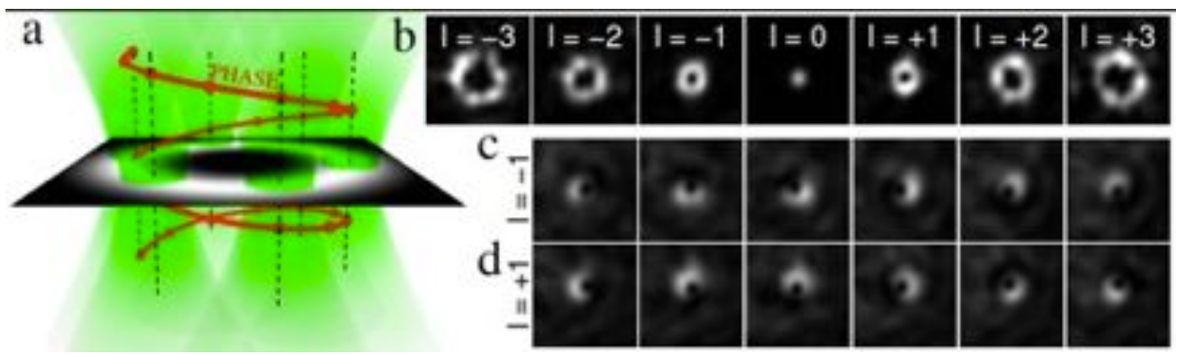
Tomáš Čižmár and Kishan Dholakia, "Shaping the light transmission through a multimode optical fibre: complex transformation analysis and applications in biophotonics," Opt. Express **19**, 18871-18884 (2011);
see also: Roberto di Leonardo group work: S. Bianchi, R. Di Leonardo, Lab Chip, **12**, 635-639, (2012)

Exploiting disorder: imaging and beam shaping

optical manipulation







bright field, dark field, fluorescence imaging and excitation in "fibres" ~1/10 of diameter of present endoscopes

T Cizmar and K Dholakia, Nature Communications (accepted, 2012)

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