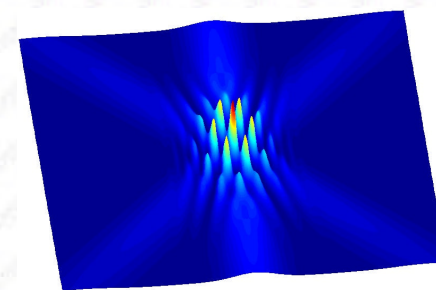
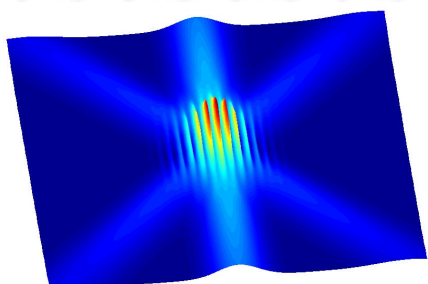


Prostorově tvarované světelné svazky a jejich využití k usměrnění pohybu mikroobjektů



Pavel Zemánek

Tomáš Čížmár

Martin Šiler

Vítězslav Karásek

Petr Jákl

Jan Ježek

Mojmír Šerý



ISI
ASCR

Ústav přístrojové techniky
Akademie věd České republiky
Brno

Skupina

Optických Mikromanipulačních TECHnik

<http://www.isibrno.cz/omitec>



ISI
ASCR

Co Vás čeká ?

- **Mechanické účinky světla a optická past**
- **Prostorové tvarování svazků**
- **Optický dopravník**
- **Optické třídění**
- **Prostorové samouspořádávání objektů**

Mechanické účinky světla



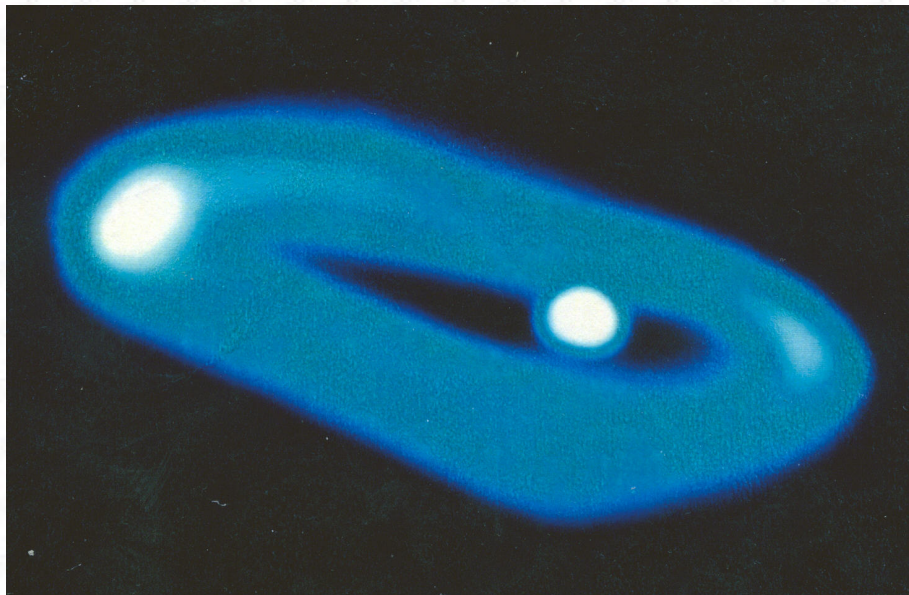
Johannes Kepler

(27.12 1571 - 15.1 1630)

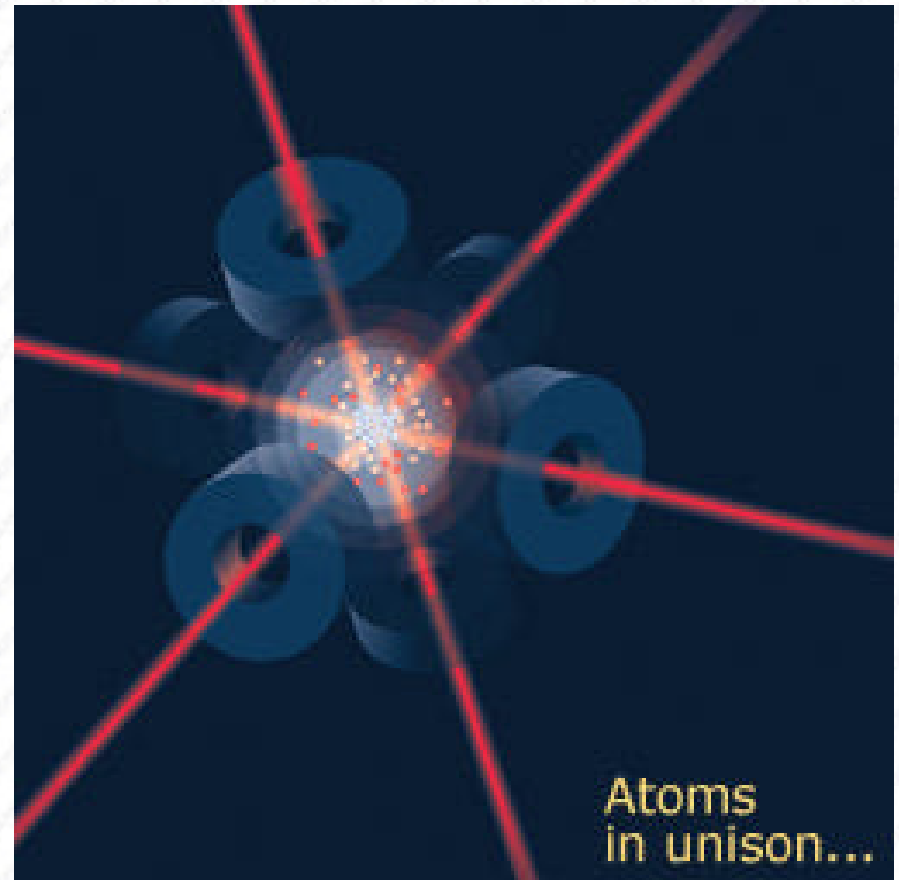
Kdo se dnes zajímá o mechanické účinky světla ?

světlo

- zpomaluje a zachytává atomy



Oblak zchlazených atomů Cs zachycených do šestice mírně vyosených laserových svazků (C. J. Foot, 1993, University of Oxford)



Kdo se dnes zajímá o mechanické účinky světla ?

světlo

- zpomaluje a zachytává atomy

Nobelova cena za fyziku 1997:

S. Chu,

C. Cohen-Tannoudji,

W. D. Phillips

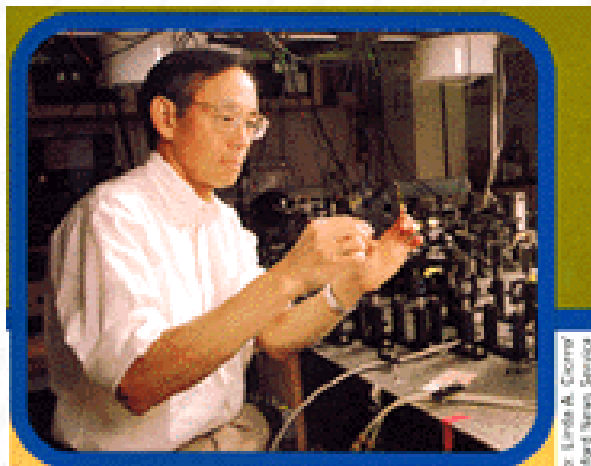


Photo: Linda A. Cooney
Stanford News Service

Steven Chu

Stanford University, Stanford,
California, USA



Photo: Francis Roggan

Claude Cohen-Tannoudji

Collège de France and École Normale
Supérieure, Paris, France

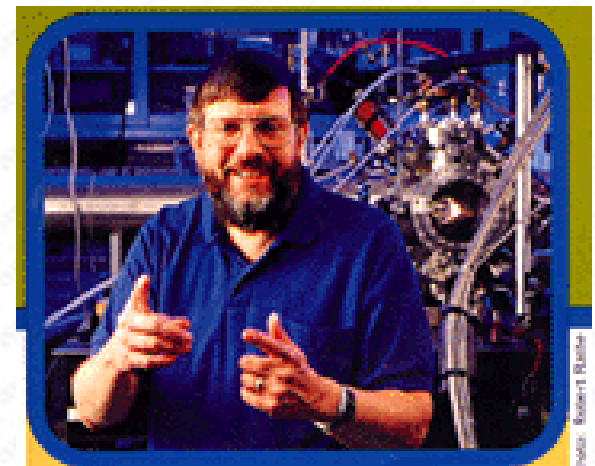


Photo: Robert Blaise

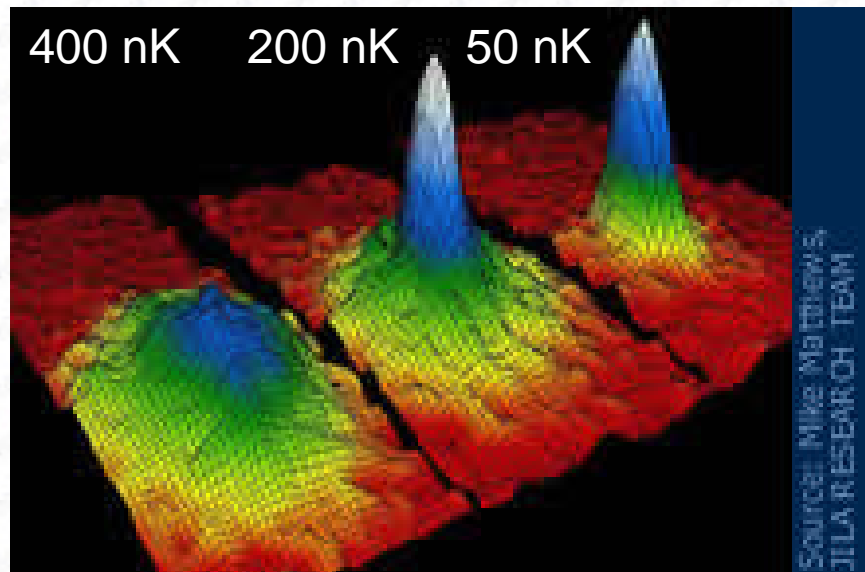
William D. Phillips

National Institute of Standards and
Technology, Gaithersburg, Maryland, USA

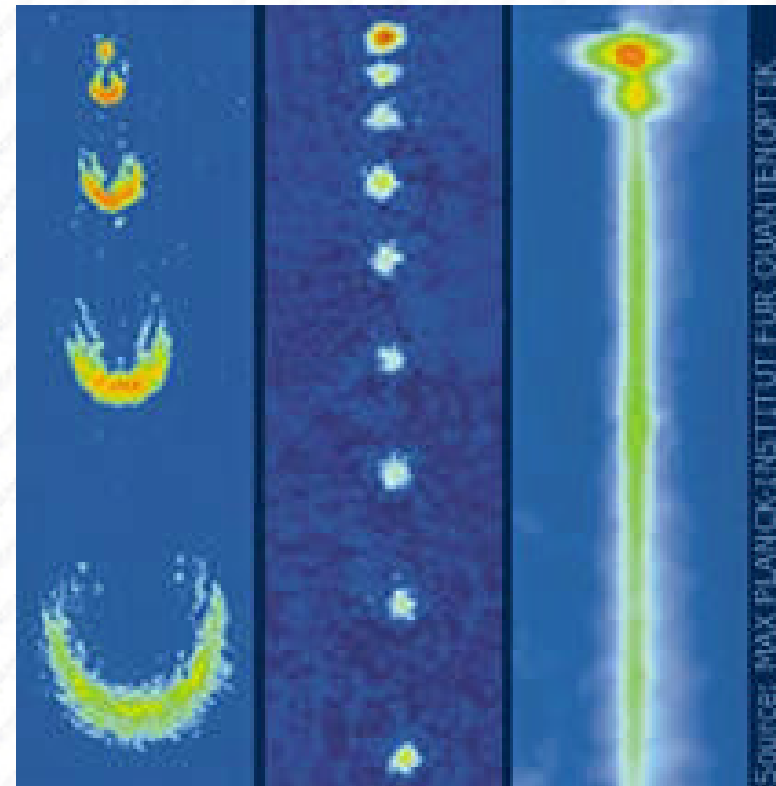
Kdo se dnes zajímá o mechanické účinky světla ?

světlo

- zpomaluje a zachytává atomy.
- spoluvytváří z atomů Boseův-Einsteinův kondenzát



BEC - hustota oblaku Rb atomů, teplota klesá zleva doprava (Cornell, Wieman, JILA)



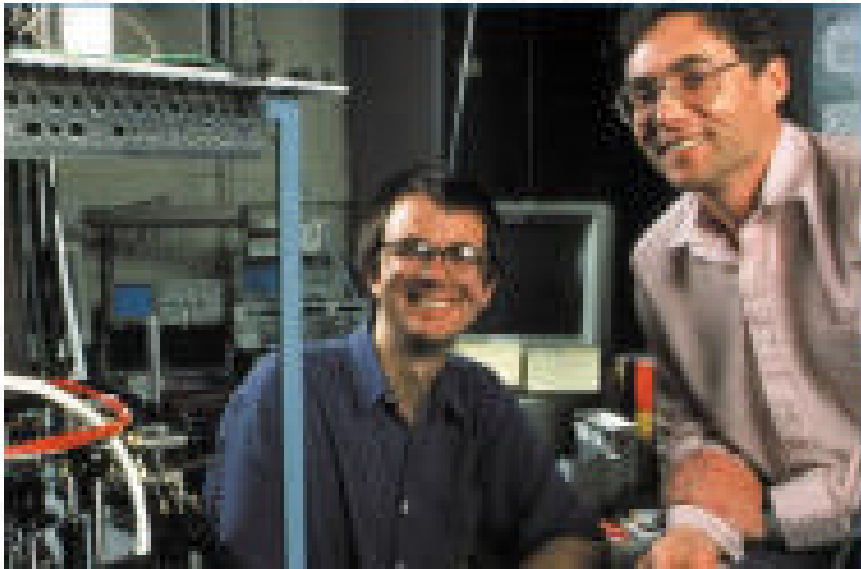
Atomový laser - zařízení vysílající koherentní atomy (W. Ketterle, MIT)

Kdo se dnes zajímá o mechanické účinky světla ?

světlo

- spoluvytváří z atomů Boseův-Einsteinův kondenzát

Nobelova cena za fyziku 2001:



**Eric A. Cornell
(1961)**
JILA and National
Institute of
Standards and
Technology (NIST),
Boulder, Colorado,
USA.

**Carl E. Wieman
(1951)**
JILA and University
of Colorado, Boulder,
Colorado, USA.

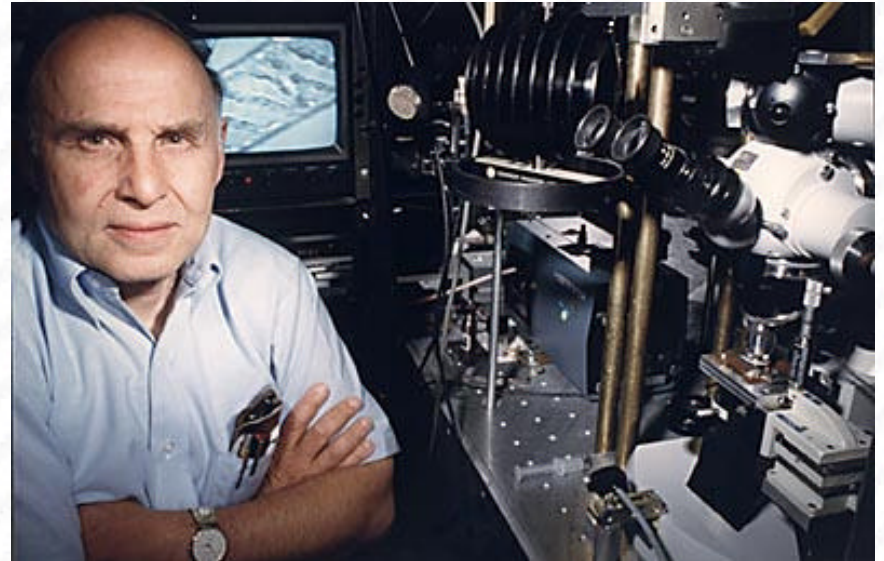


Wolfgang Ketterle (1957)
Massachusetts Institute of
Technology (MIT),
Cambridge, Massachusetts,
USA.

Kdo se dnes zajímá o mechanické účinky světla ?

světlo

- zpomaluje a zachytává atomy
- spoluvytváří z atomů Boseův-Einsteinův kondenzát
- urychluje, zpomaluje, deformuje a zachytává mikročástice (A. Ashkin 1970, 1986)
- manipuluje s DNA, viry, bakteriemi, uvnitř živých buněk, měří pN síly působící na zachycené částice nebo mezi makromolekulami, přepaluje chromozómy, fúzuje živé buňky...(1986-2004)



Arthur Ashkin - první novodobý badatel, který se systematicky věnoval studiu silových účinků světla na atomy a mikroobjekty. (Bell Laboratories, Lucent Technologies, Holmdel, New Jersey, USA)

Lze tyto jevy snadno a rychle pochopit ?

ANO!

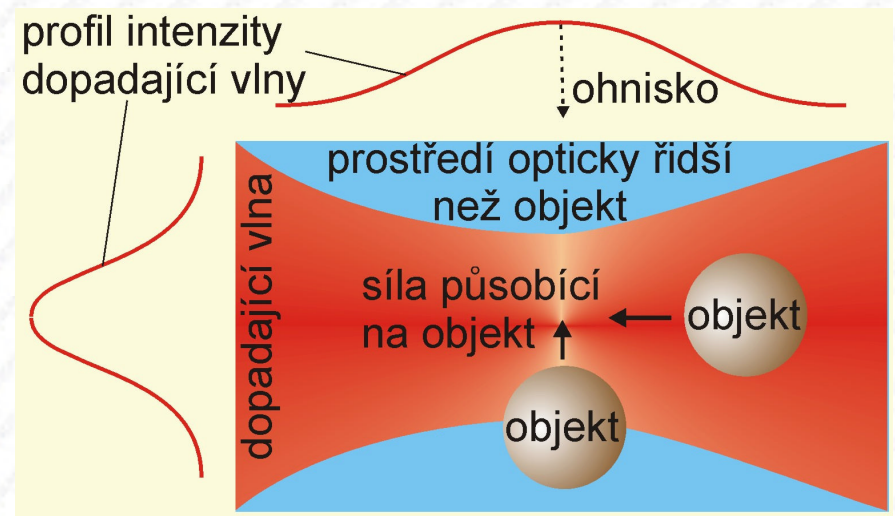
Chování malé polystyrénové kuličky ve fokusem laserového svazku

Předpokládejme, že objekt (mikrokulička) je mnohem větší, než je vlnová délka záření, které na něj dopadá.

Změna hybnosti fotonu

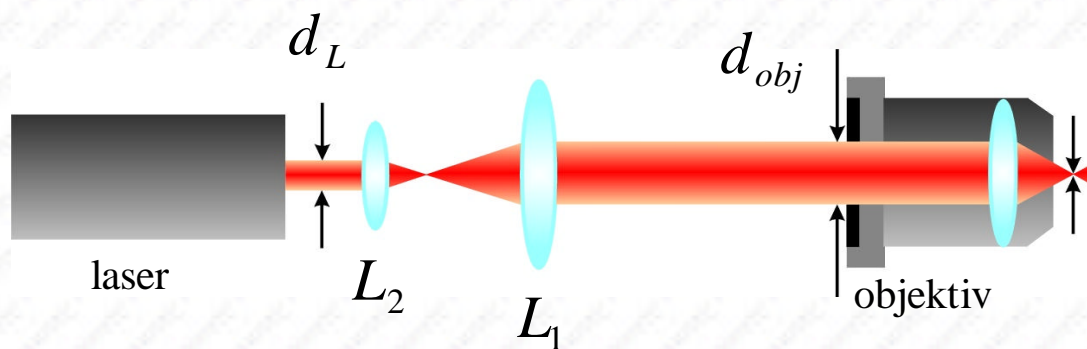
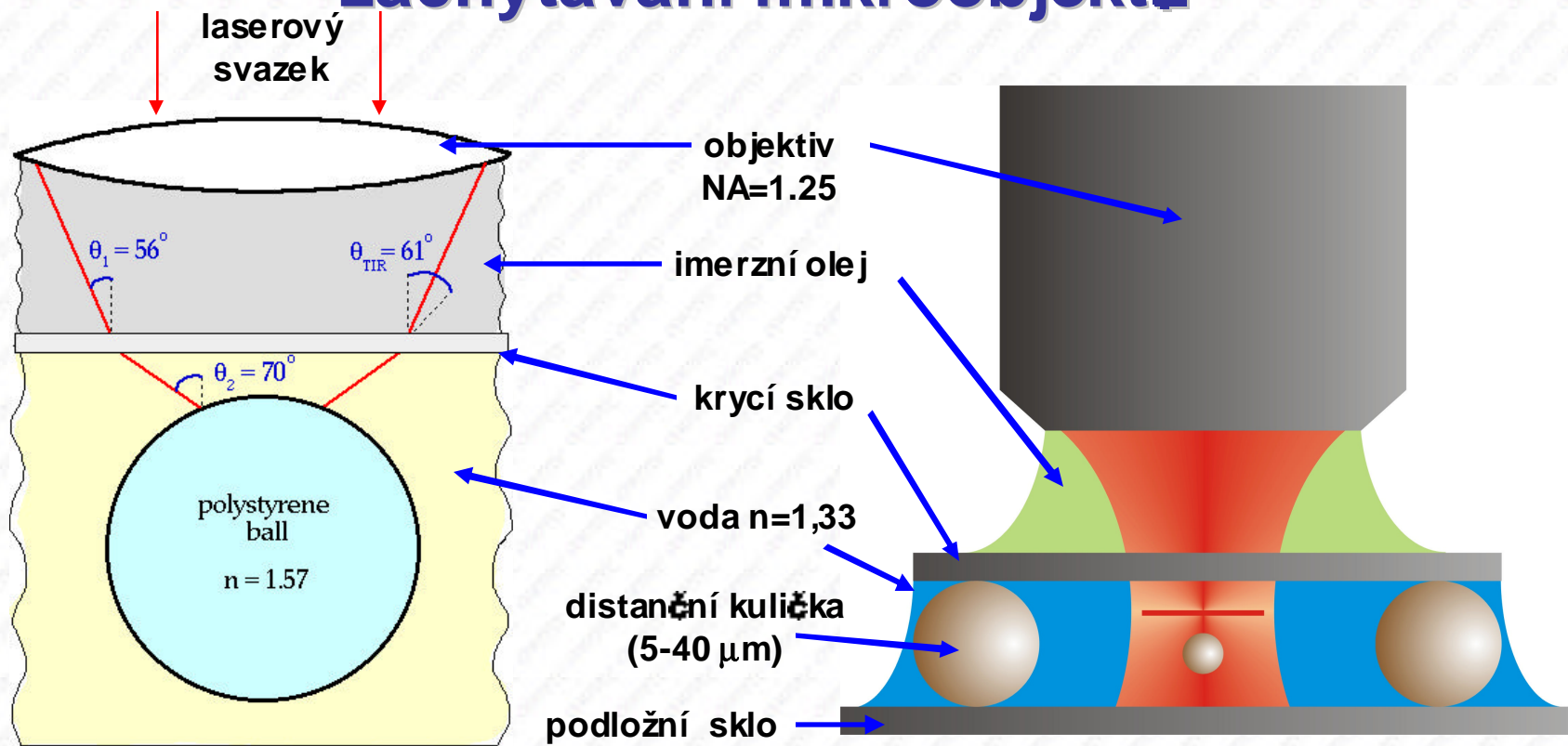


Institut für den Wissenschaftlichen Film,
Göttingen



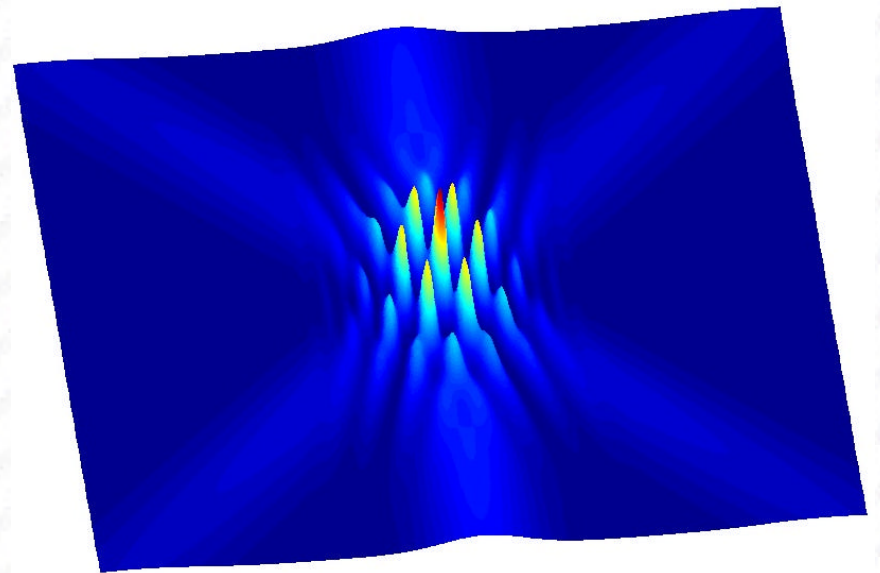
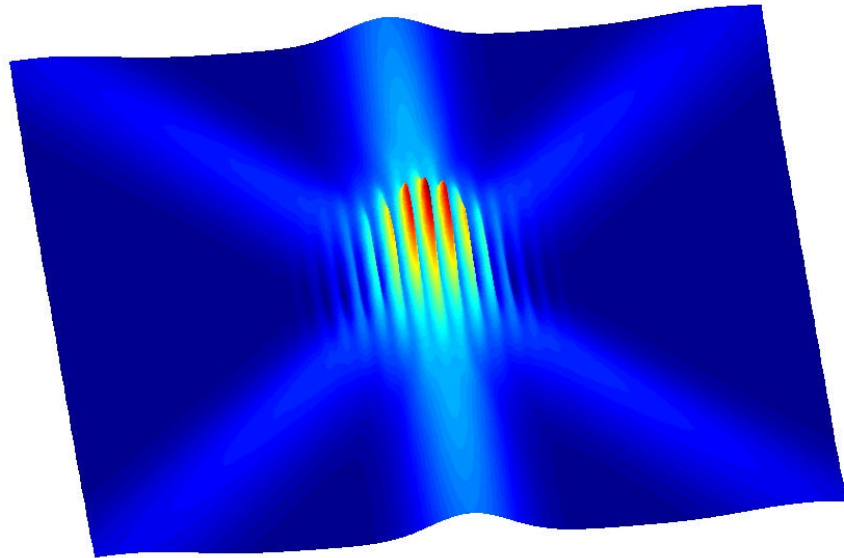
Gradientní síla - táhne kuličku o indexu lomu větším než okolní médium do místa s největší optickou intenzitou

Experimentální uspořádání pro prostorové zachytávání mikroobjektů



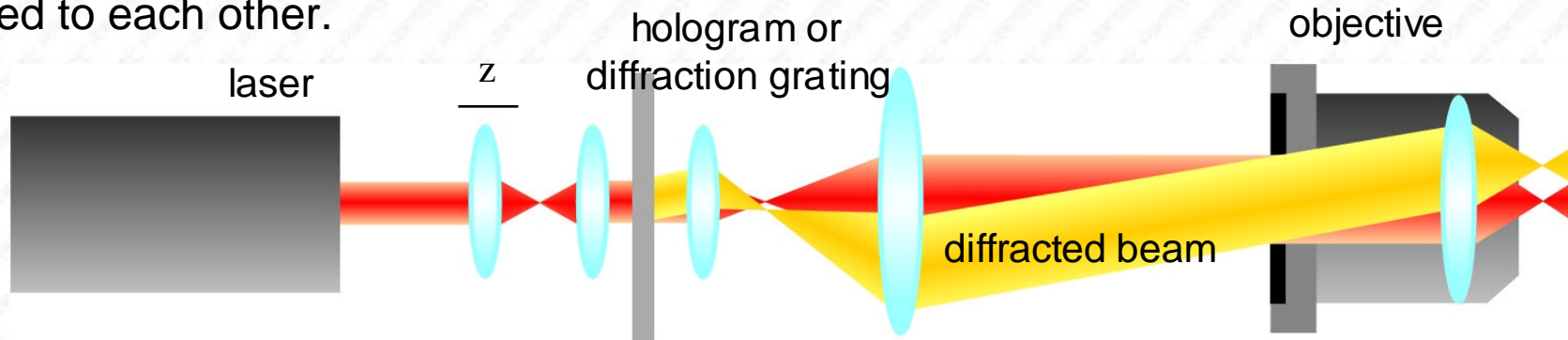
$$d_{obj} = d_L \frac{f_{L1}}{f_{L2}}$$

Prostorové tvarování svazků

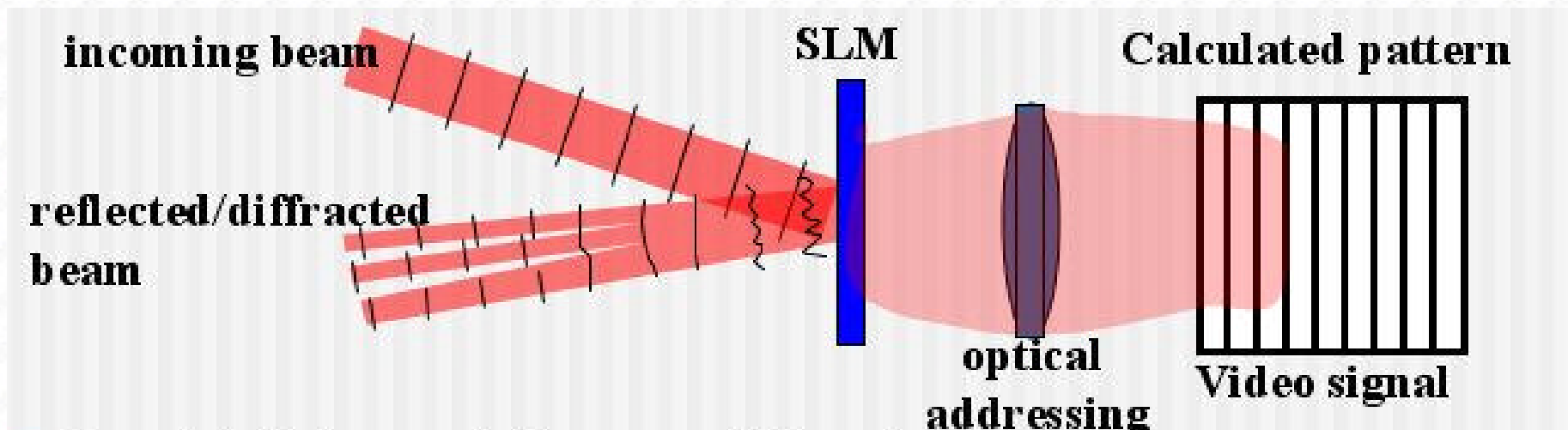


How to create complicated light pattern ?

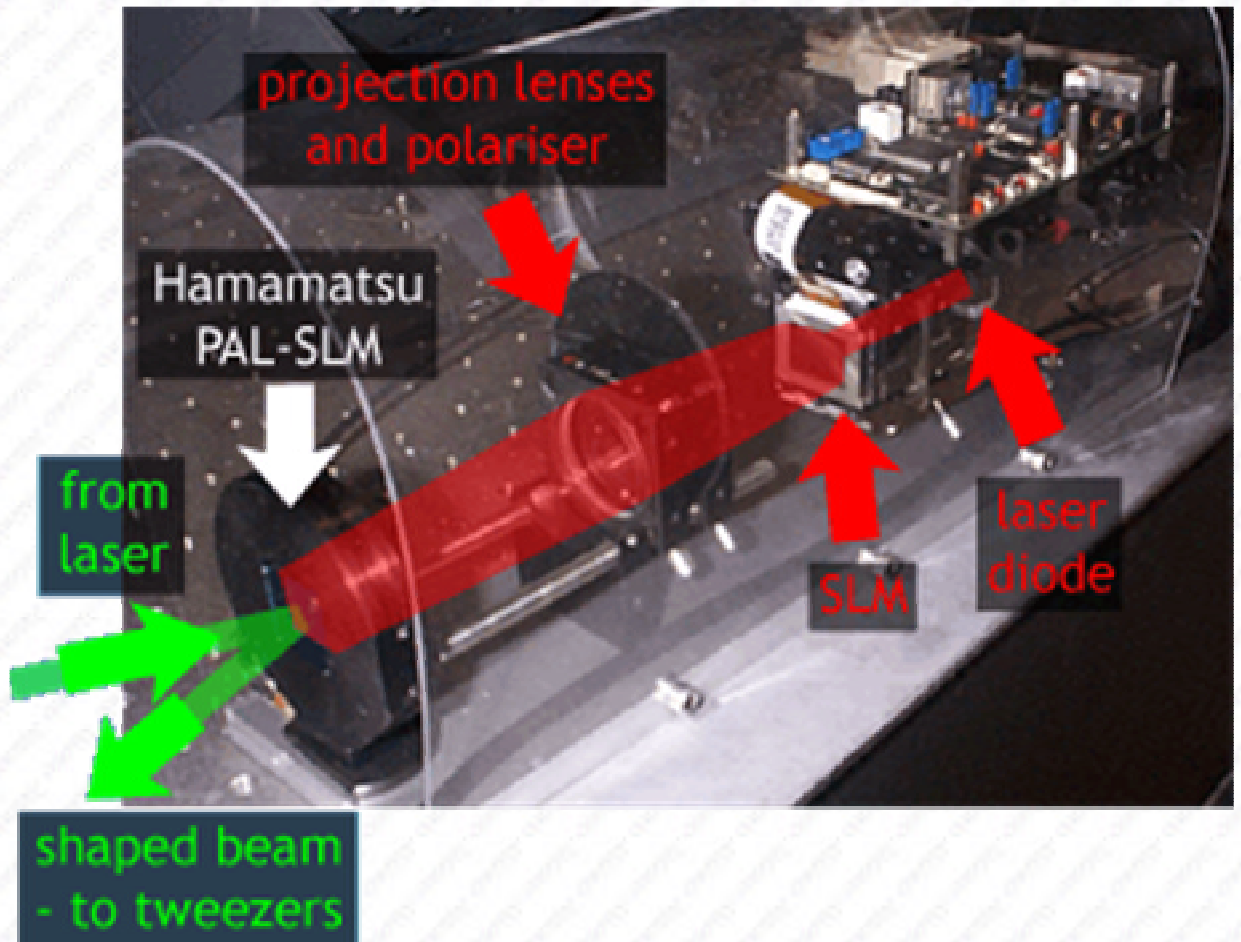
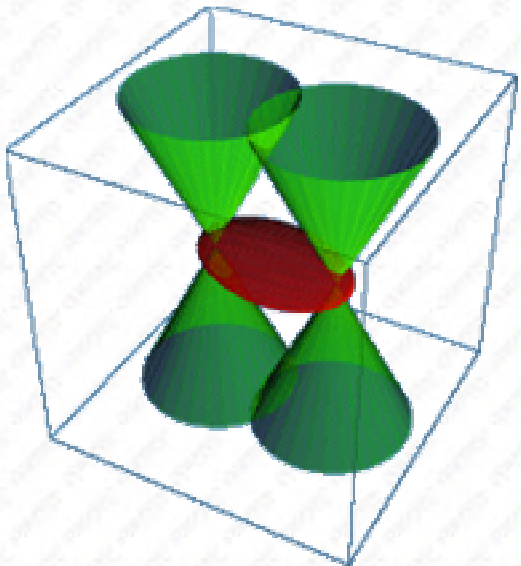
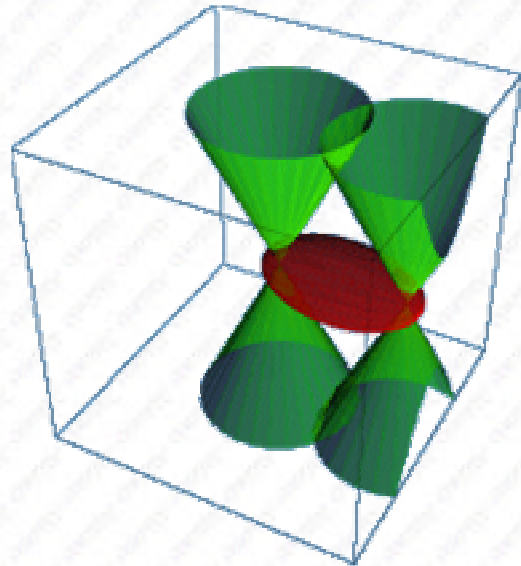
Static hologram or diffraction grating can create more than 2 traps but they are fixed to each other.



Dynamic hologram can be generated by a device called Spatial Light Modulator. It is a matrix of independently addressed cells (electrically or optically), each of them can change amplitude or phase of the transmitted or reflected light.

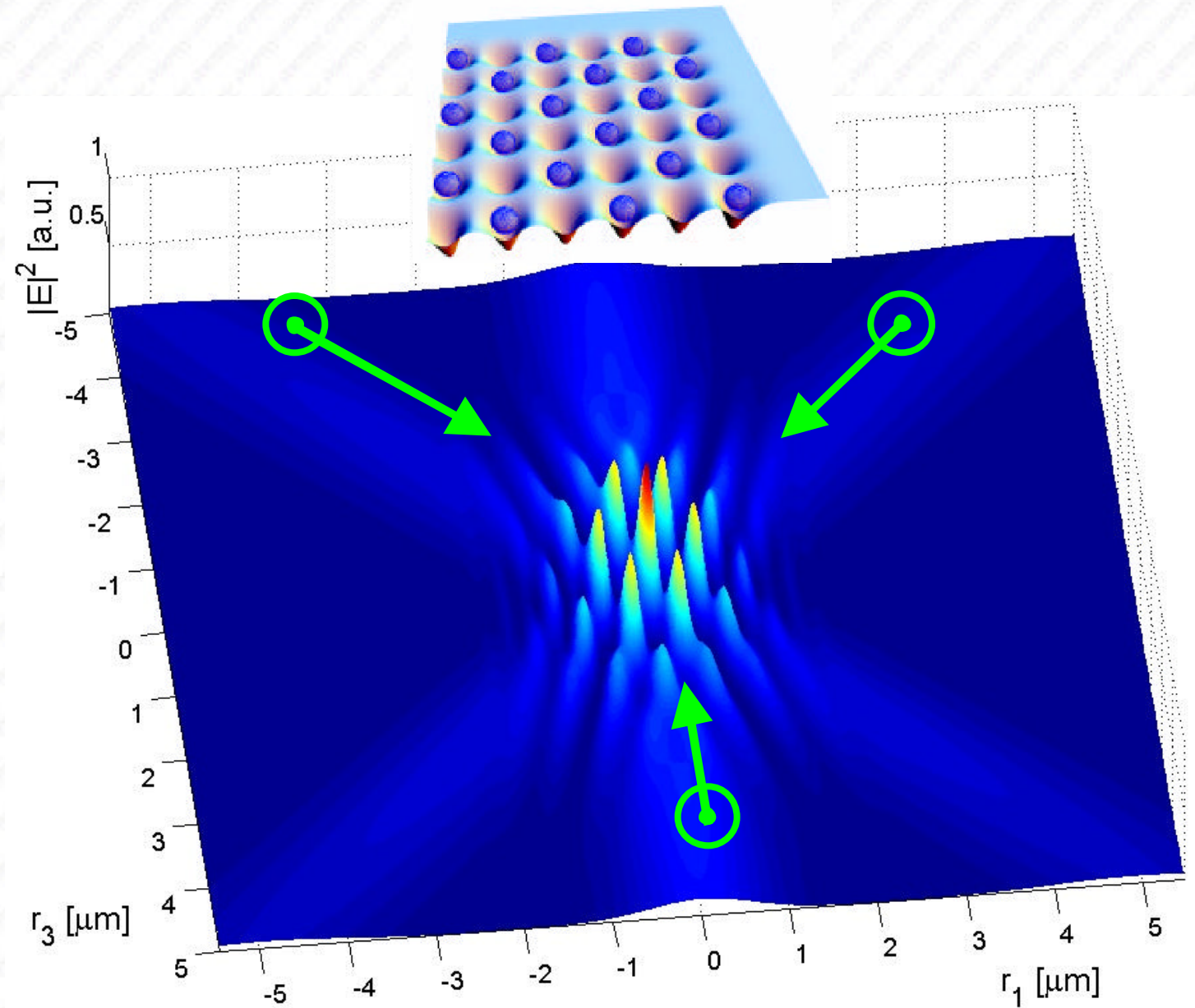


Dynamic holograms



M. Padgett, University of Glasgow

„Optical landscapes“, Optical lattice

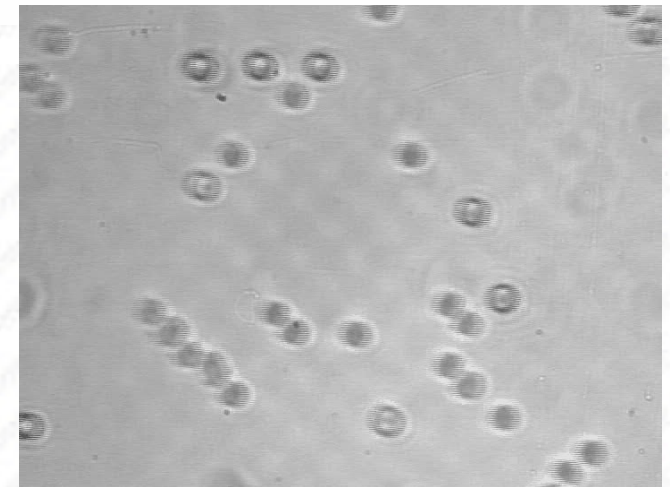
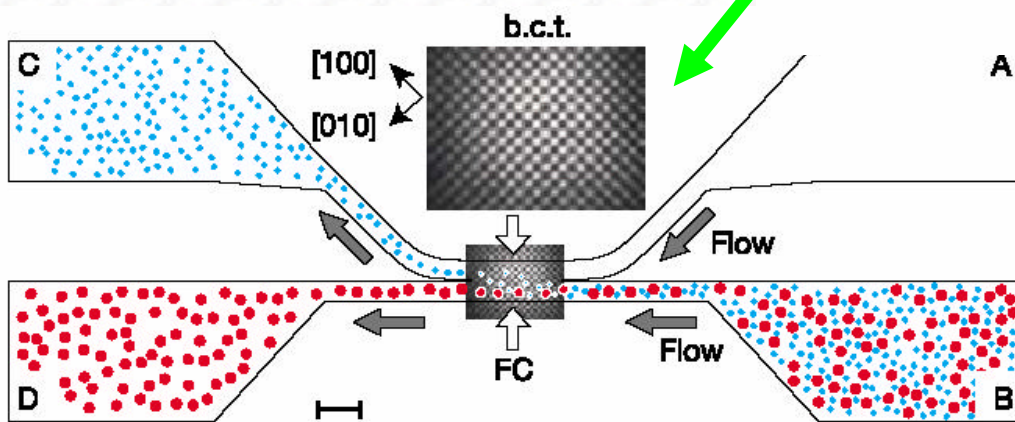
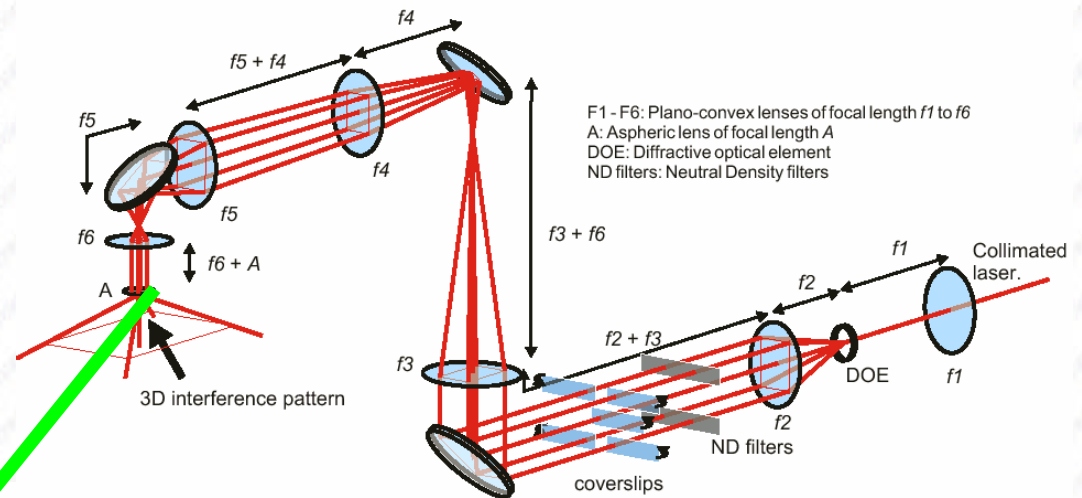


Optical sorting in optical lattice

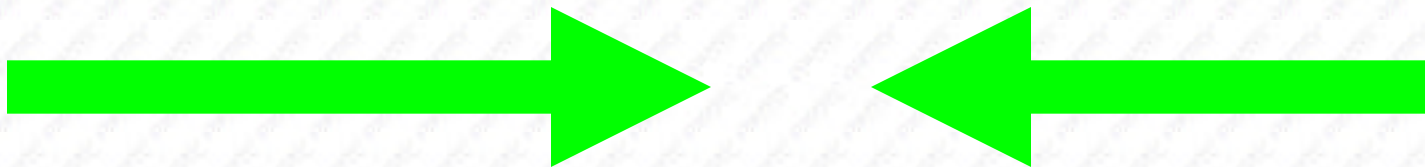
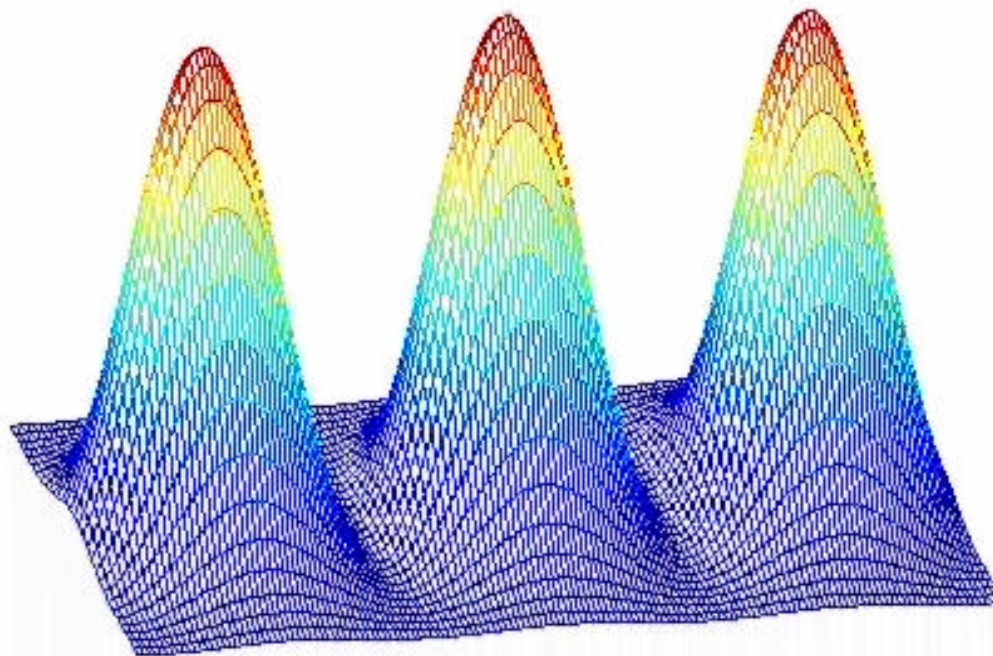
- Recently particle behavior in complicated optical fields started to be studied and showed new possibilities like particle sorting according to their size or optical properties, employment of stochastic mechanisms for directed particle motion in tilted potentials etc.

M. P. McDonald, G. C. Spalding,
and K. Dholakia

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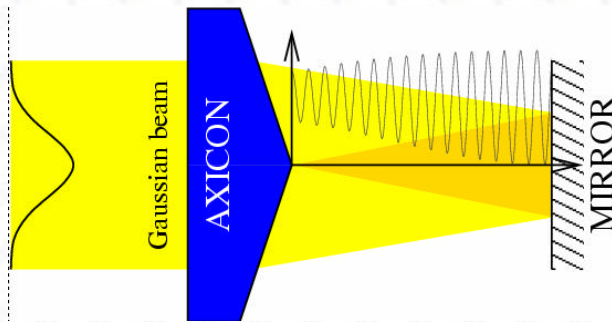


Optický dopravník

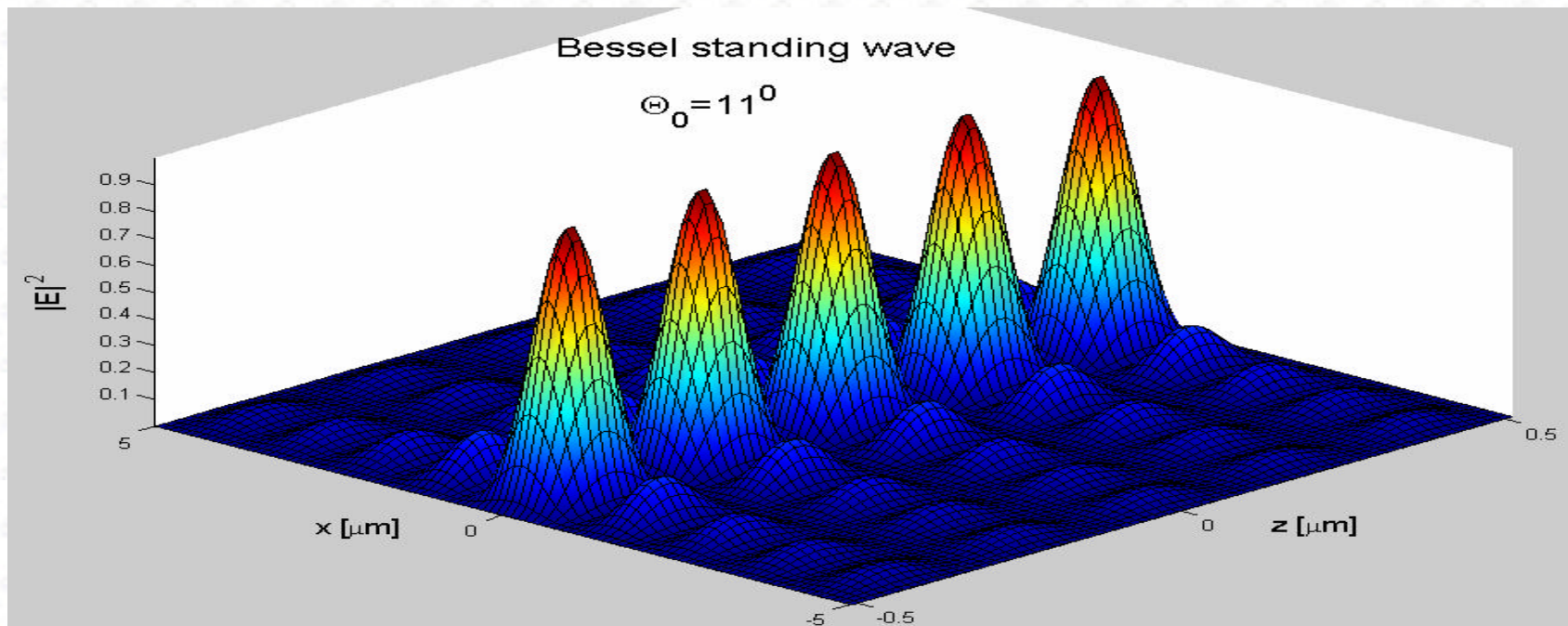
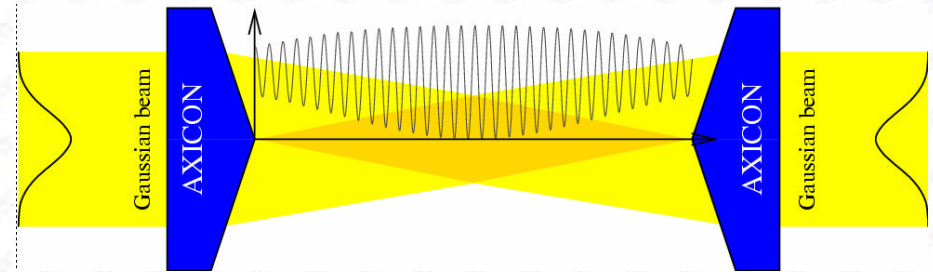


Generation of Bessel standing wave traps

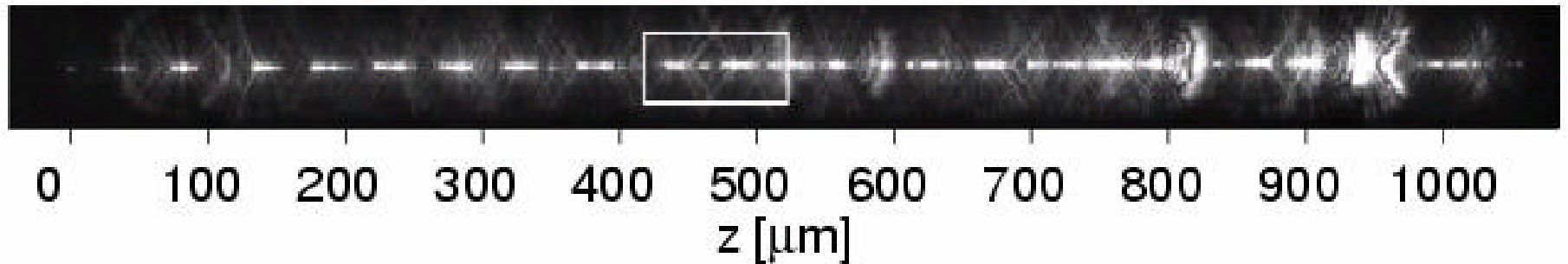
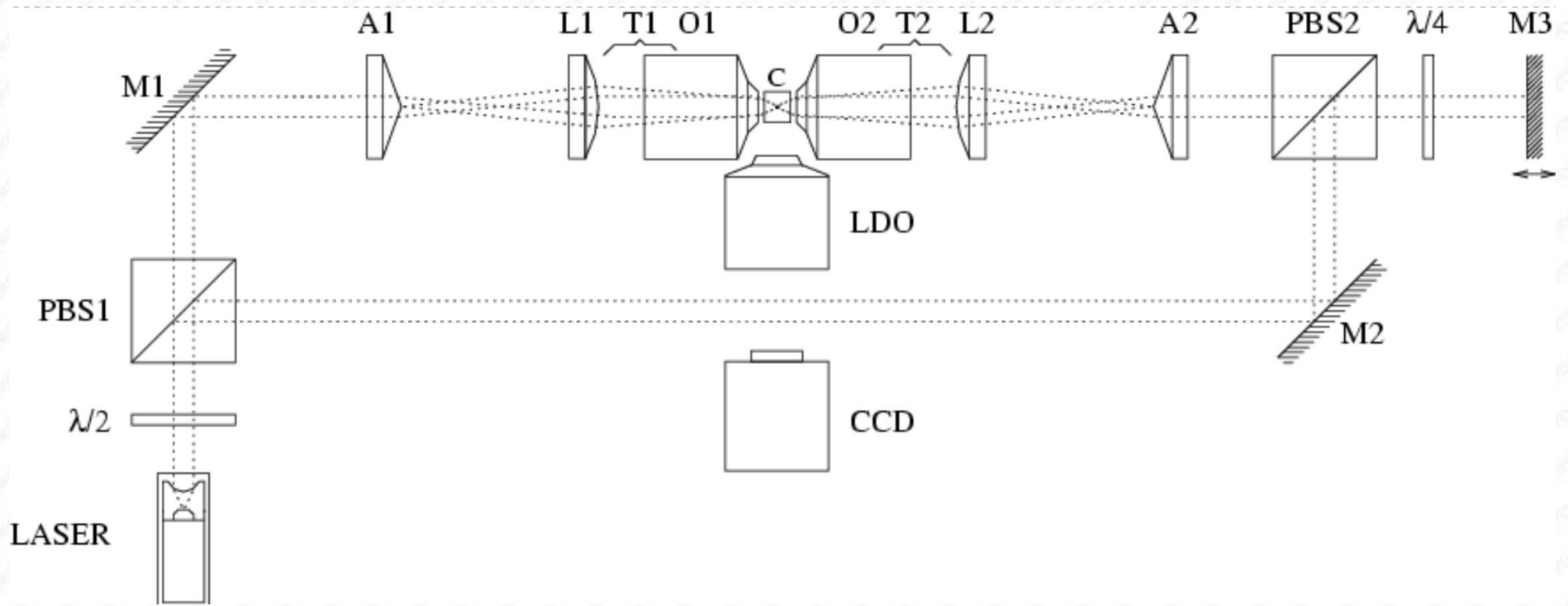
1. Using retro-reflected incident beam



2. Using two independent counter-propagating beams.

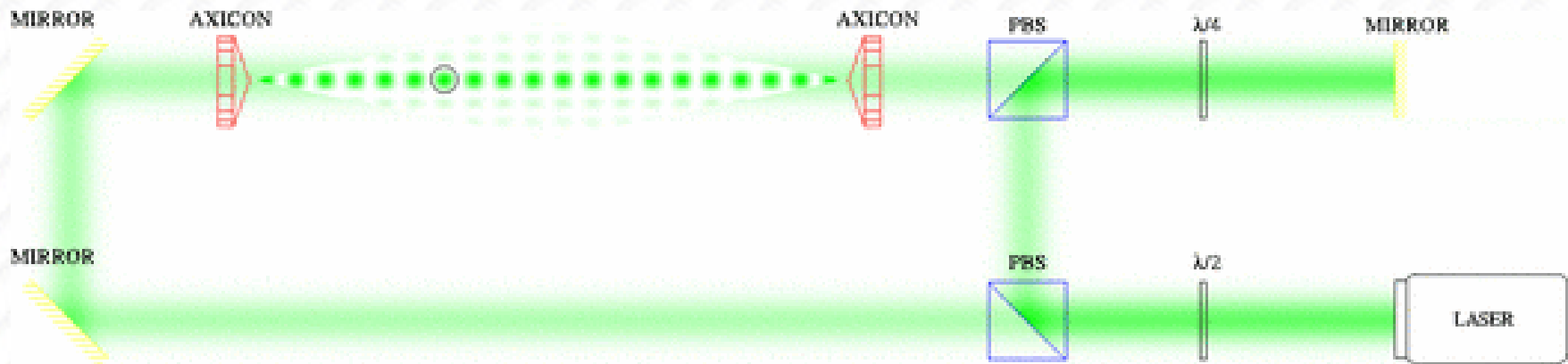
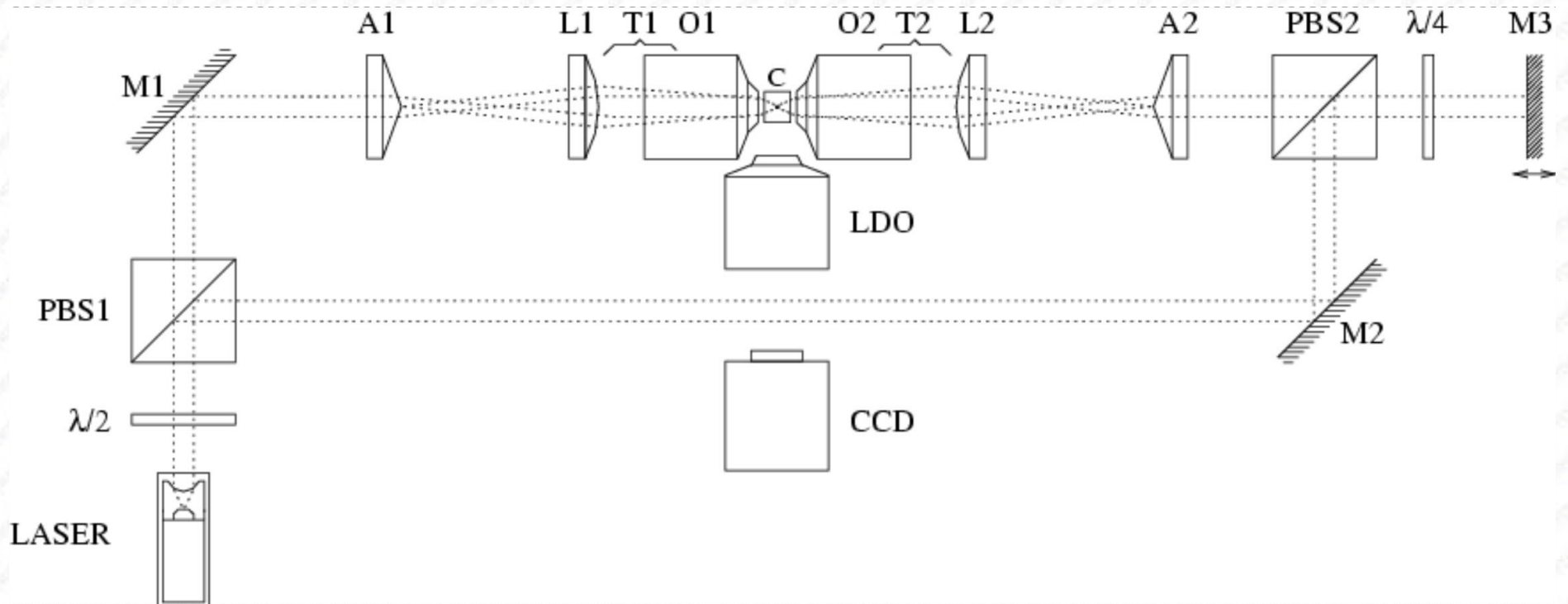


Generation of Bessel standing wave traps

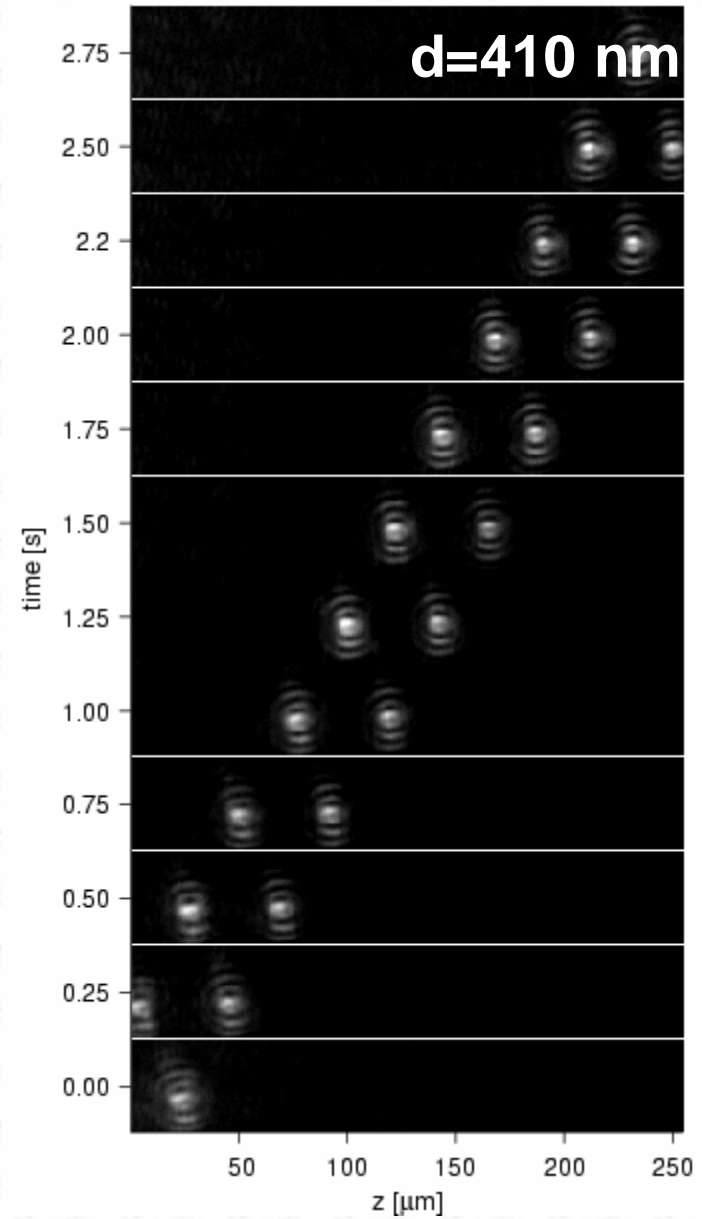
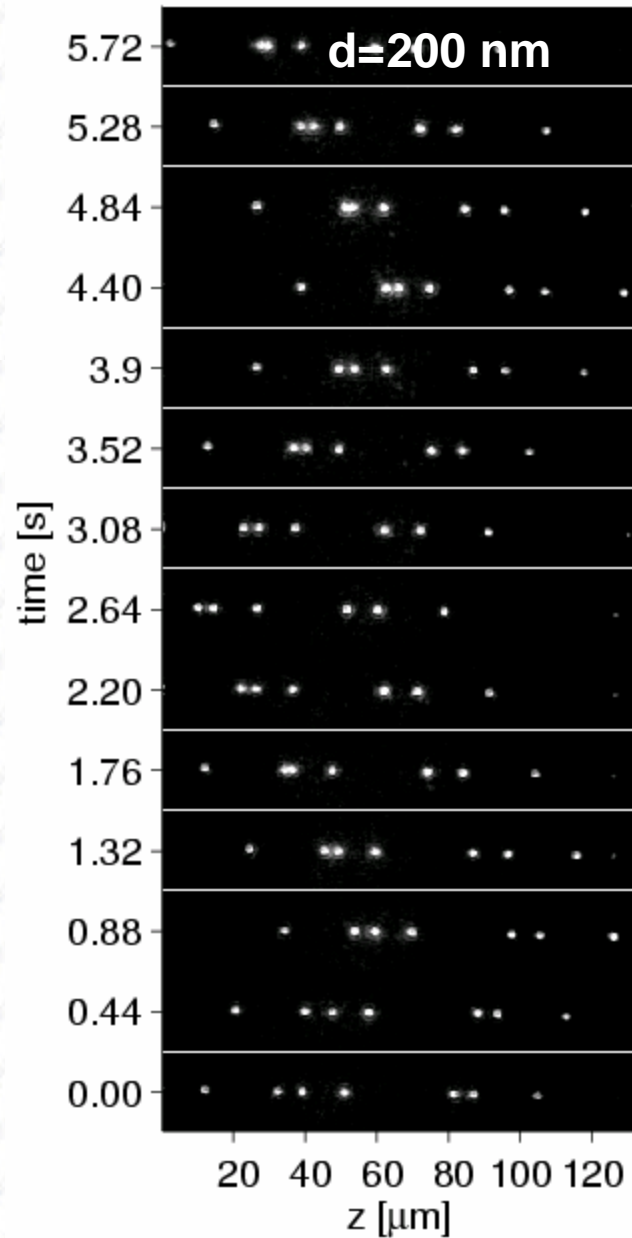


1mm long array of polystyrene beads of radius 175 nm.

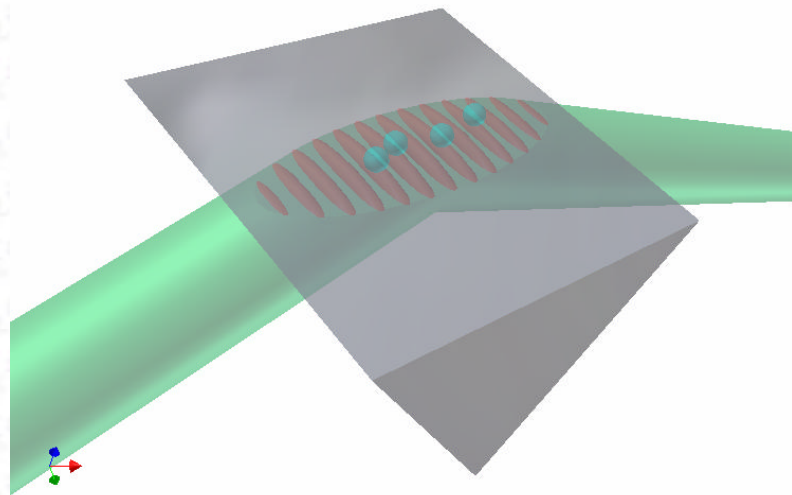
Optical conveyor belt using Bessel standing wave



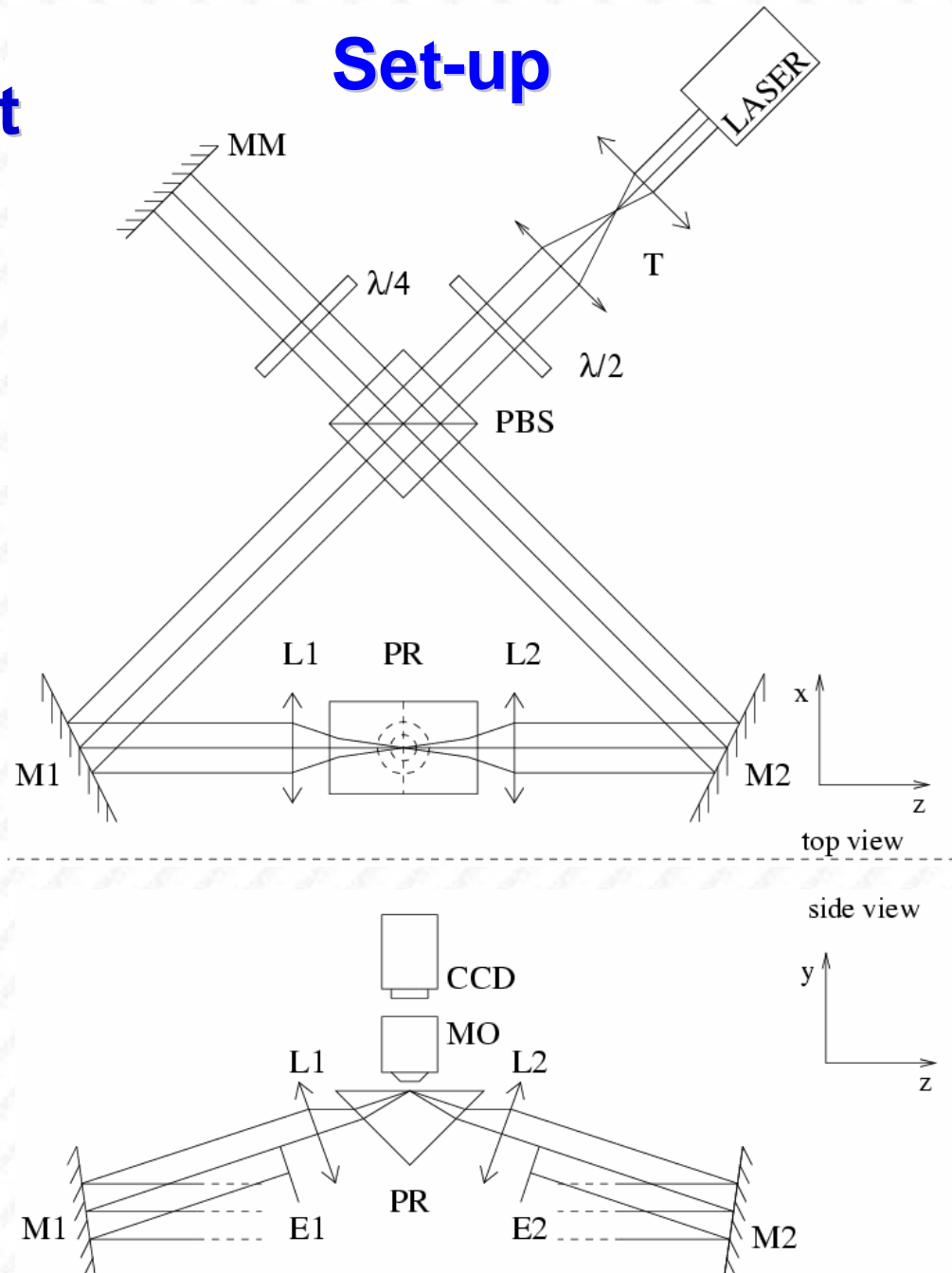
Optical conveyor belt using Bessel standing wave



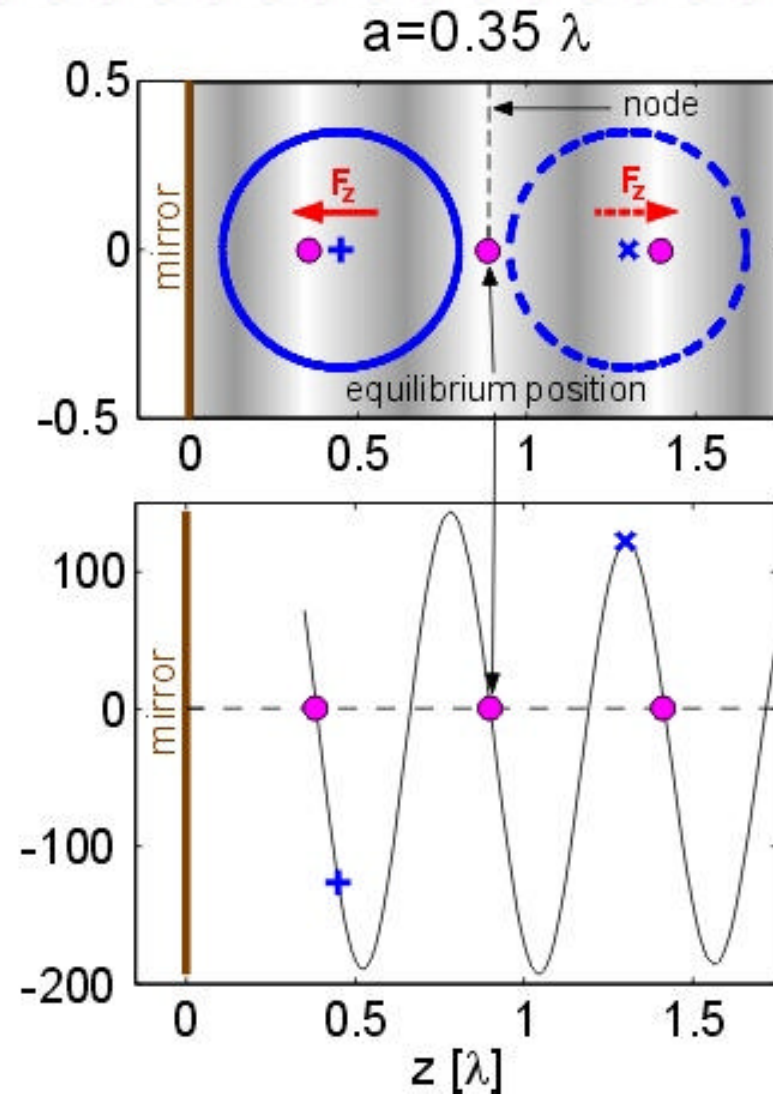
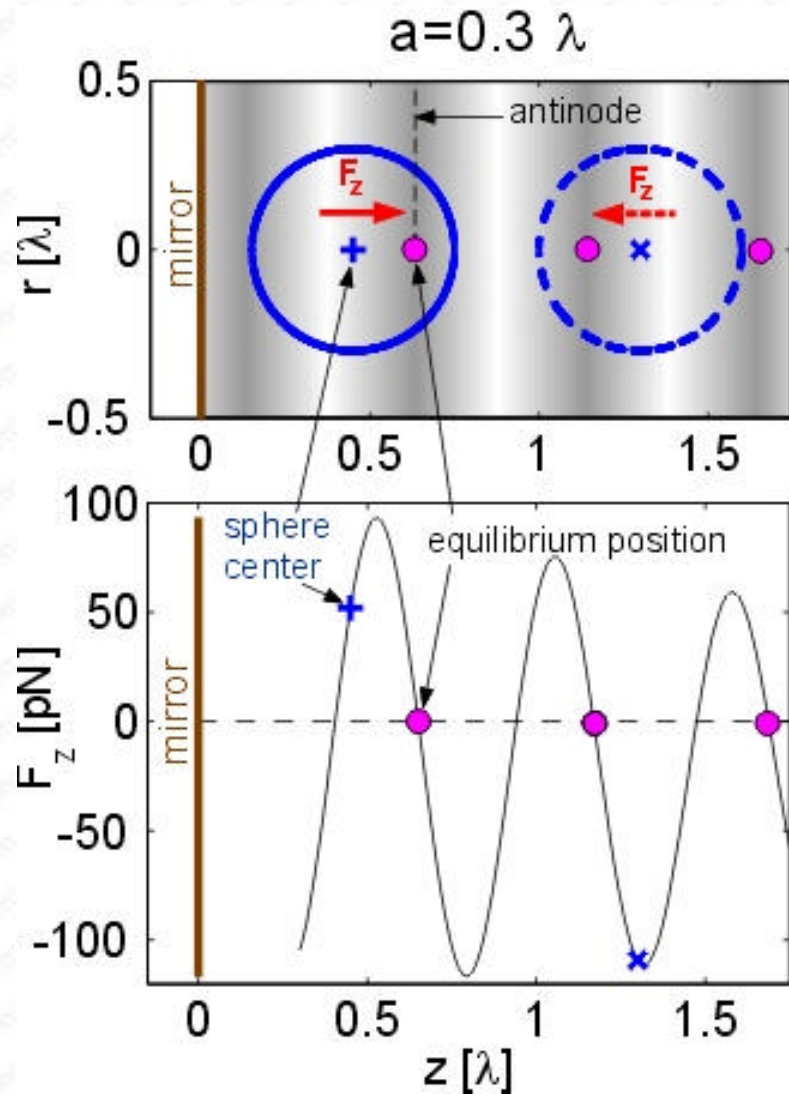
Optical conveyor belt using evanescent standing wave



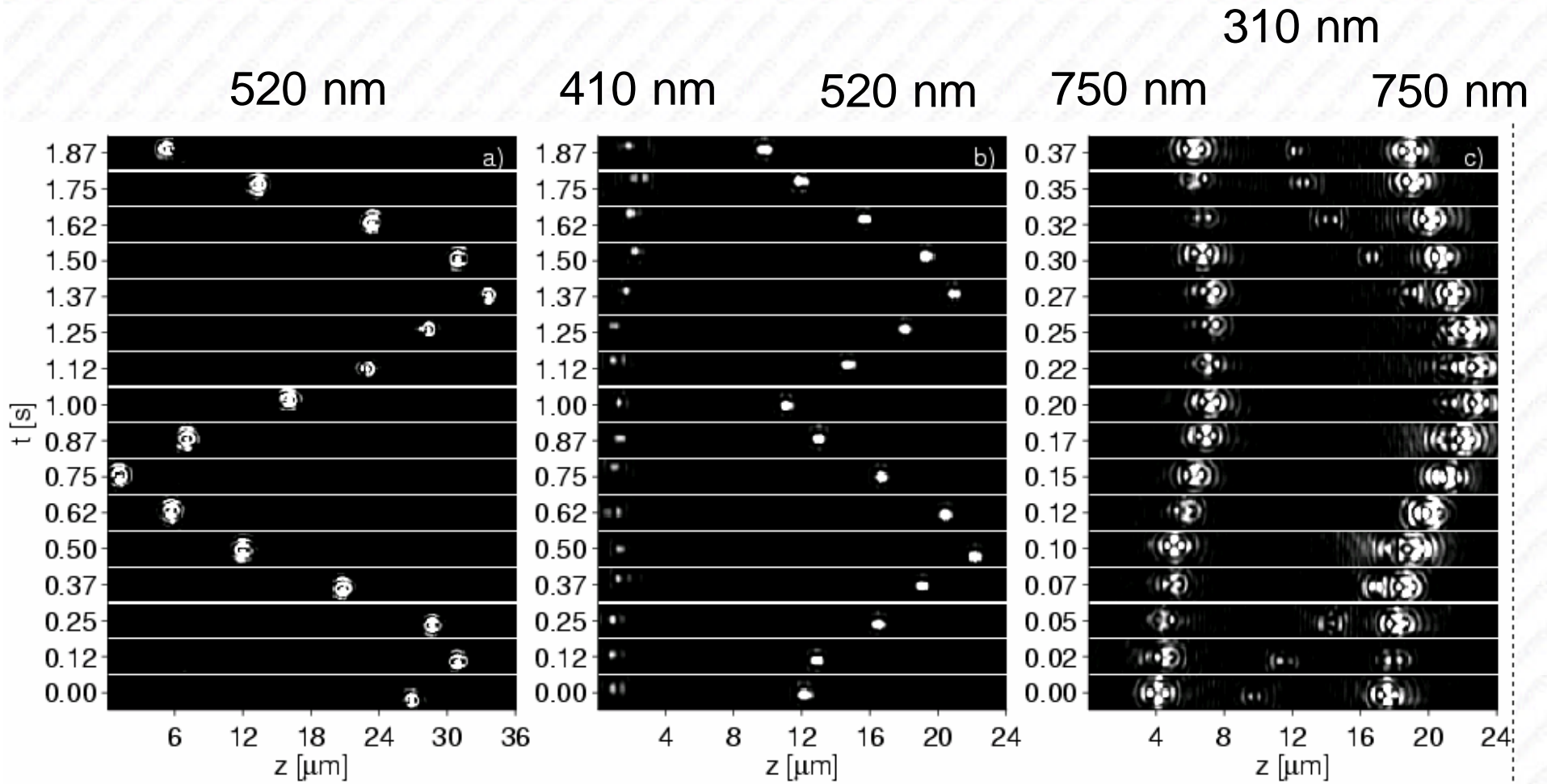
Set-up



Object behaviour in the standing wave

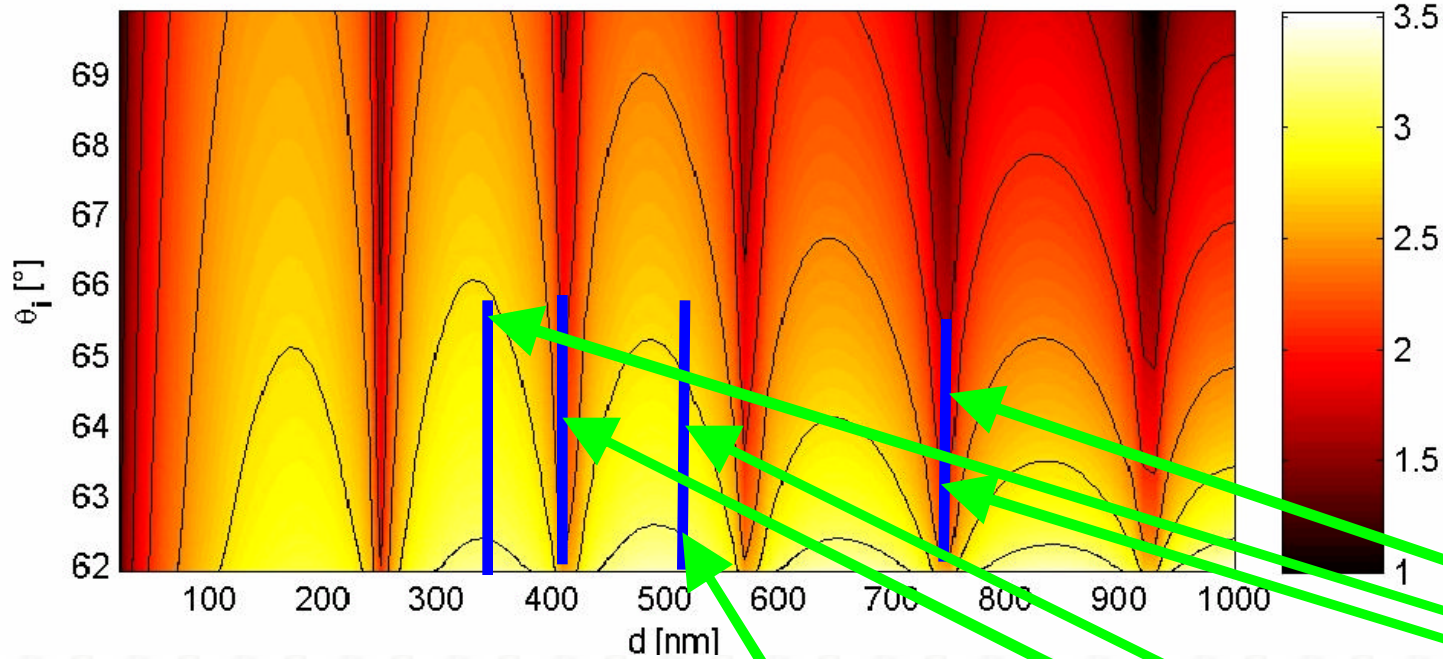


Near-surface conveyor belt



Why some does not move?

$\log \Delta U [k_B T]$



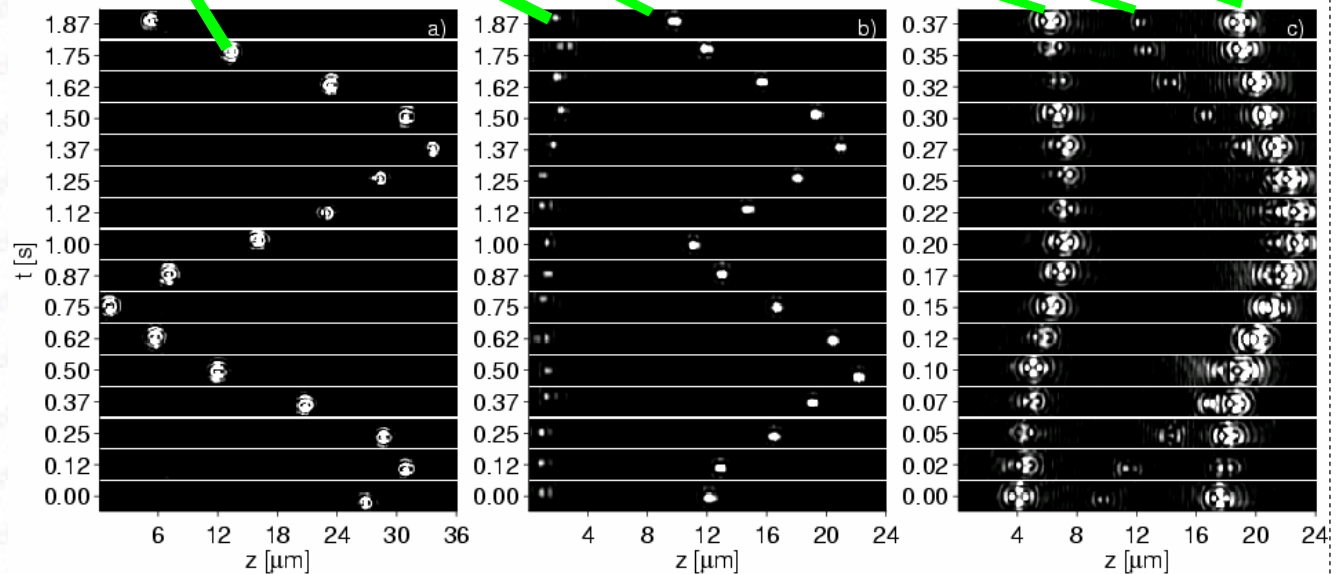
θ_i – incident angle of the plane wave

d – diameter of the bead

ΔU – depth of the optical trap

Contours - 33, 100, 333,

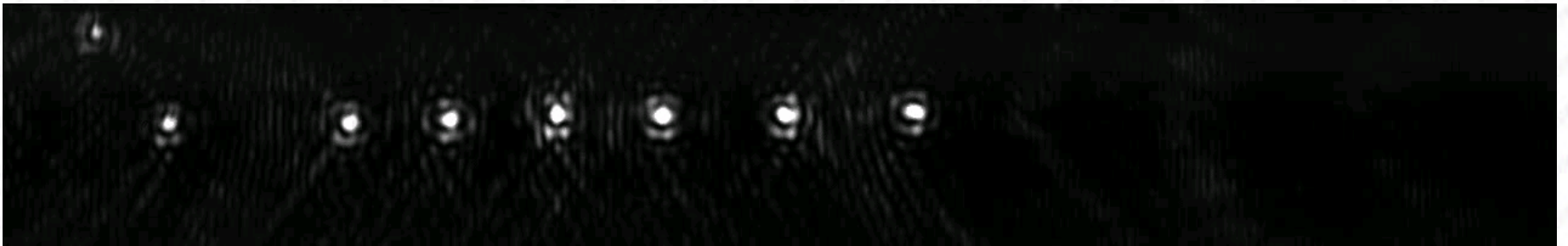
1000, 3333 $k_B T$.



Near-surface conveyor belt



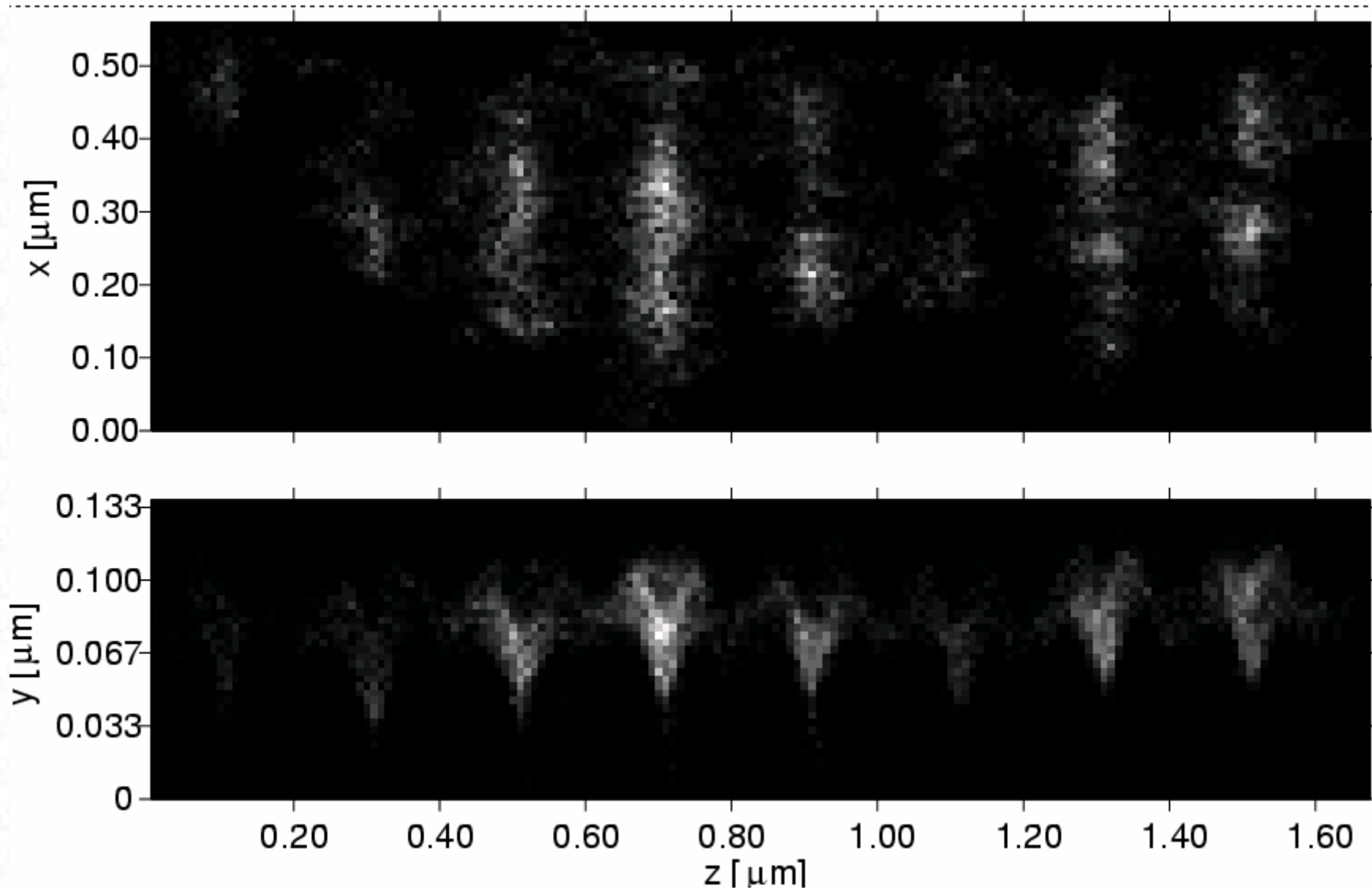
Polystyrene beads of diameter 520 nm – real time.



Polystyrene beads of diameter 520 nm – 40x slower.

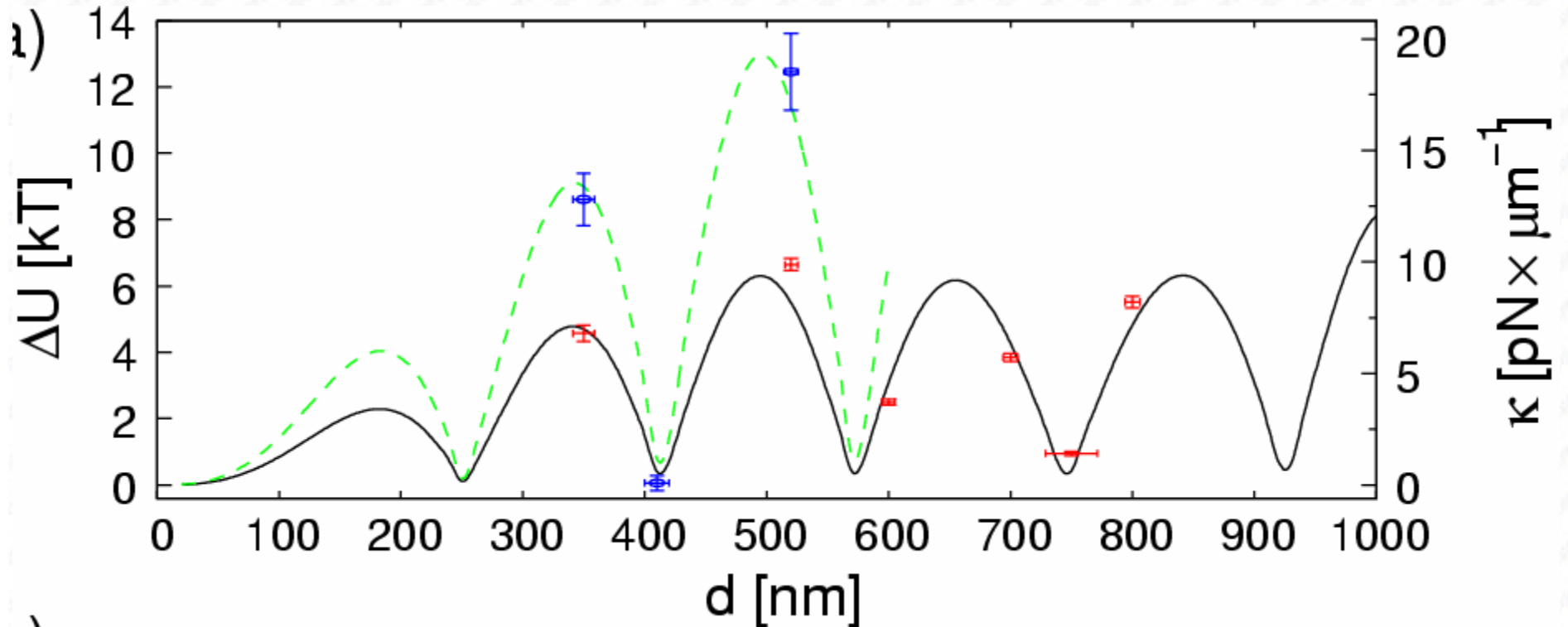
Analyzes of the system

1. histogram of particle positions



Analyzes of the system

2. depths of the optical traps



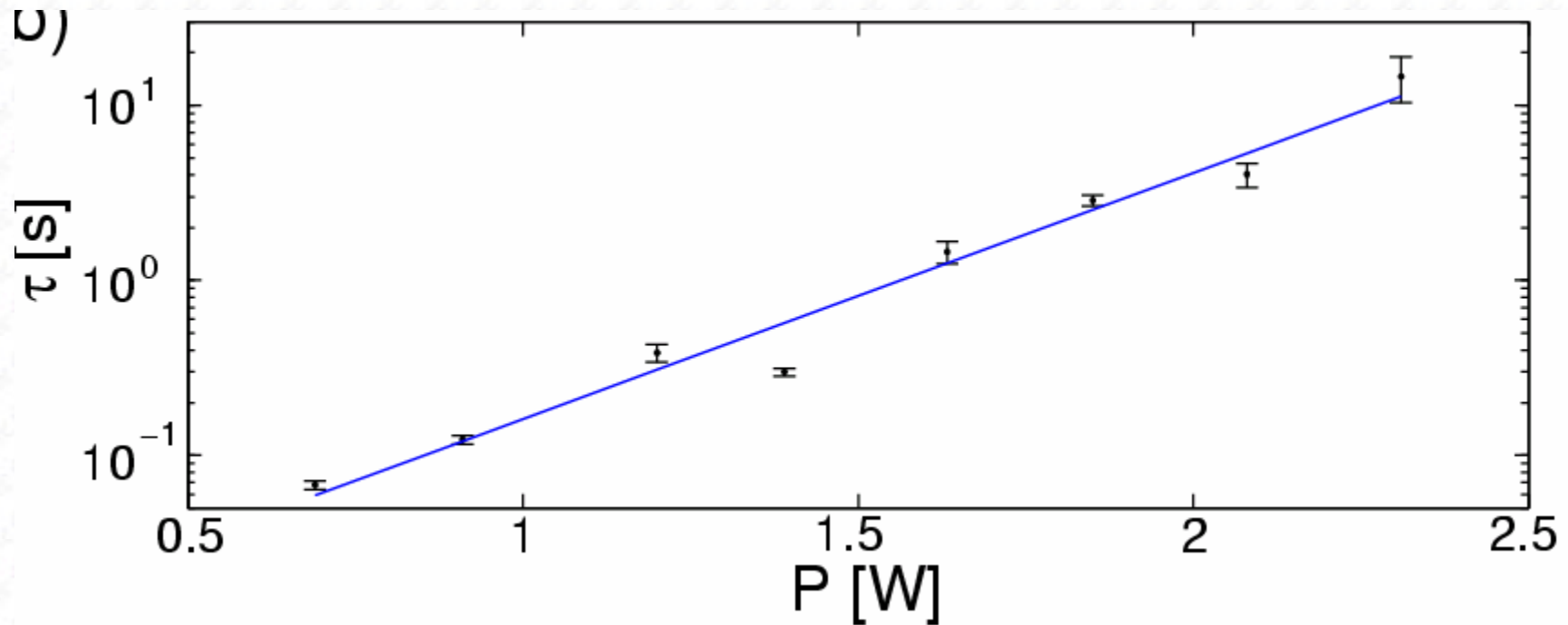
From the fit:

$\Theta_i=62.008$, $E=5.84 \times 10^{10}$ V/m – critical angle

$\Theta_i=61.92$, $E=7.28 \times 10^{10}$ V/m

Analyzes of the system

3. mean first passage time



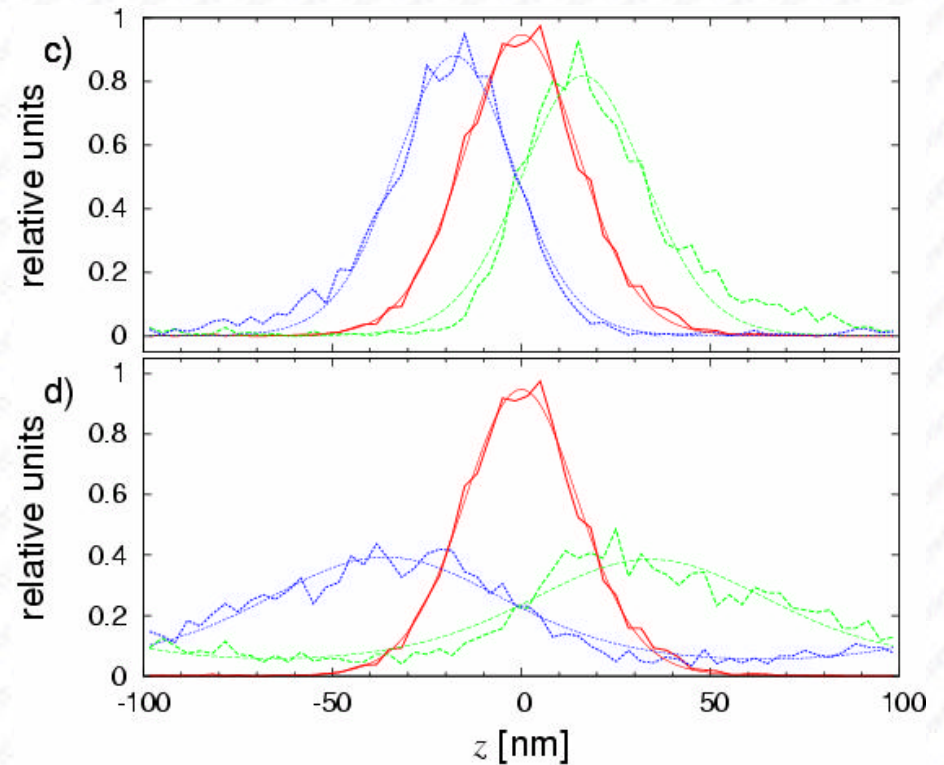
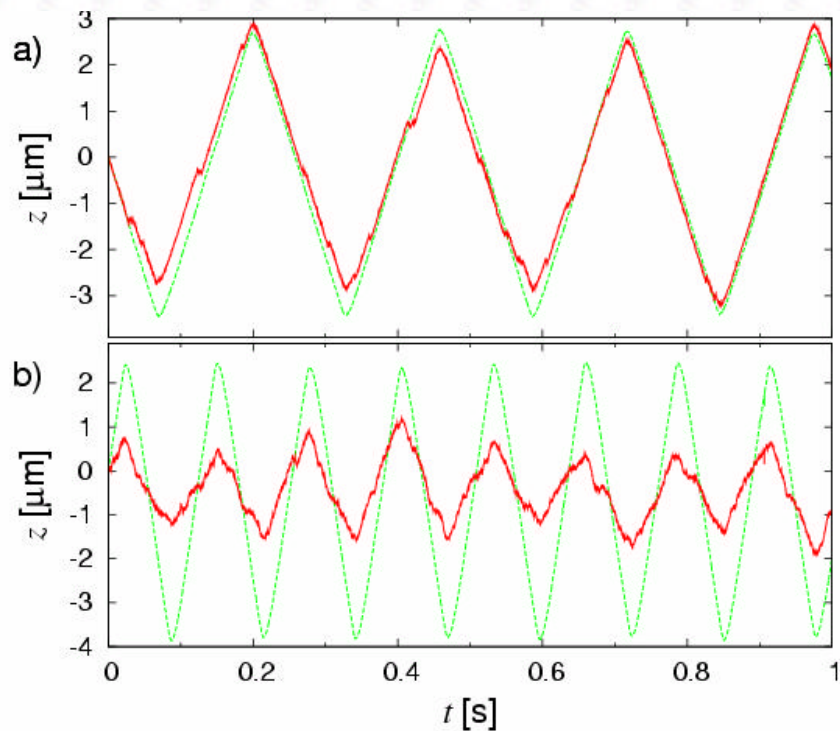
Object diameter: 520 nm.

FUTURE ??

- the particle does not follow the motion of the standing wave structure exactly, it jumps between neighboring positions depending on the velocity of the movement.

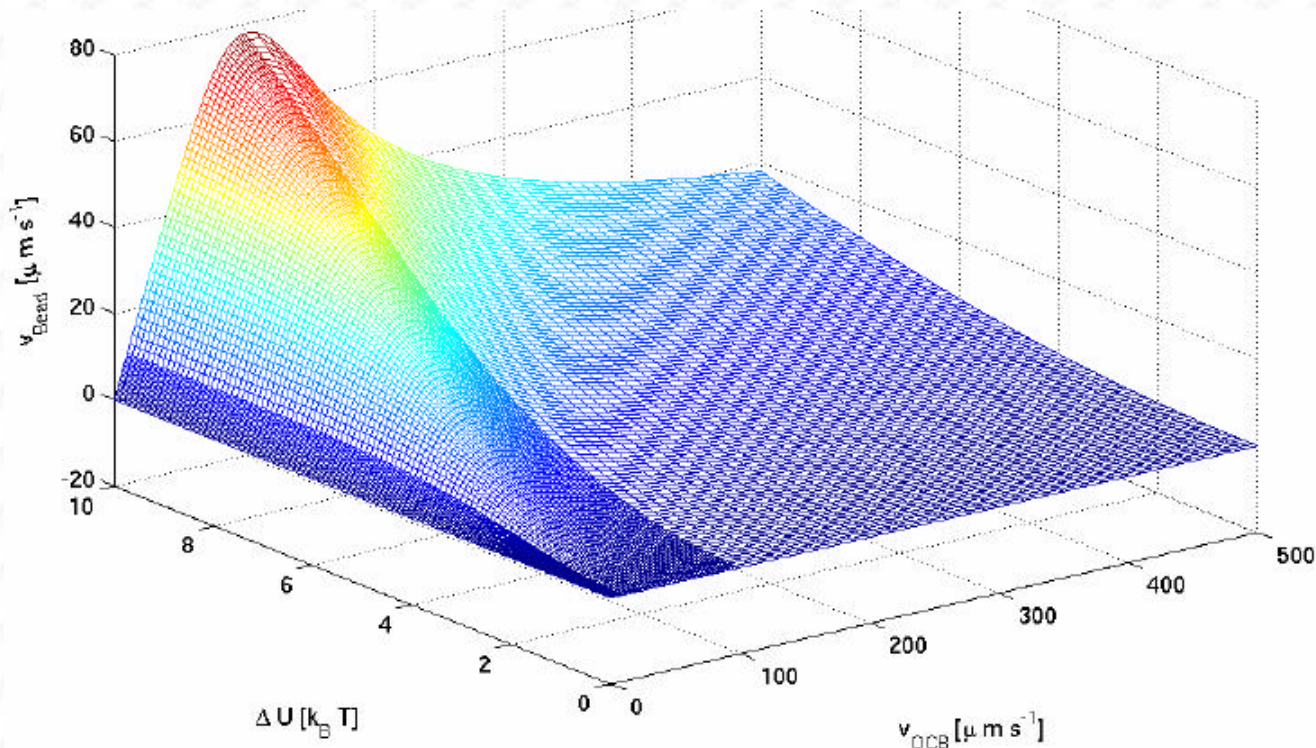
Brownian surfer X

Brownian swimmer



FUTURE ??

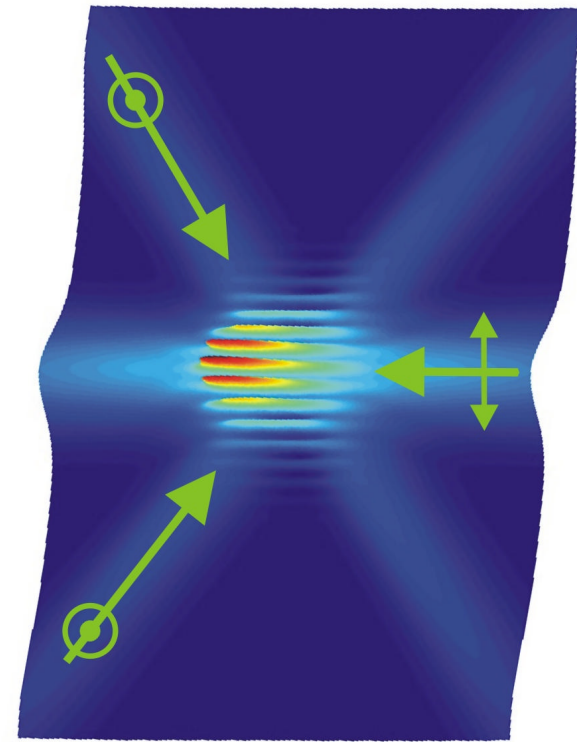
Brownian surfer X Brownian swimmer



**Motion of microobjects can be rectified even without optical trapping
– just by motional periodic potential.**

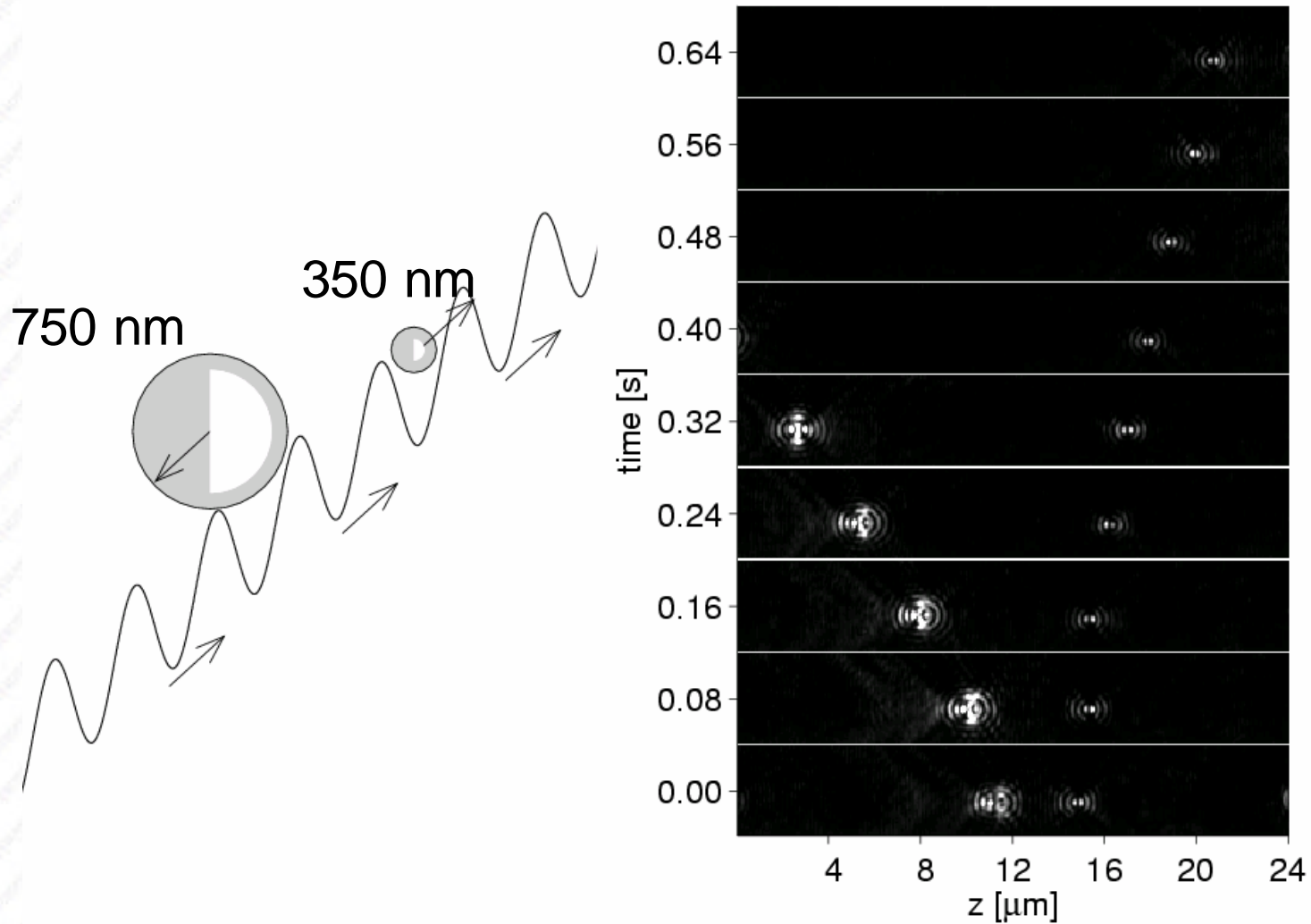
EXPERIMENTAL & THEORETICAL STUDY IN 1D AND 2D

Optické třídění objektů



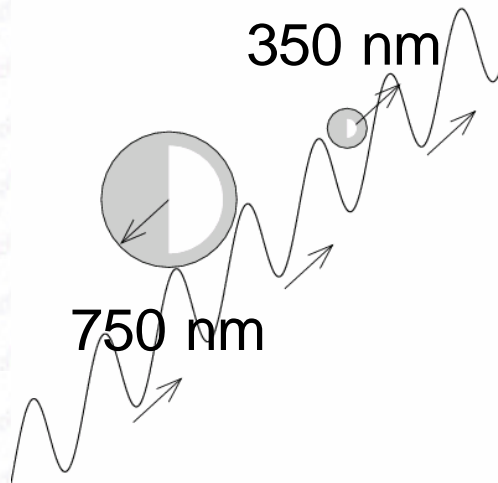
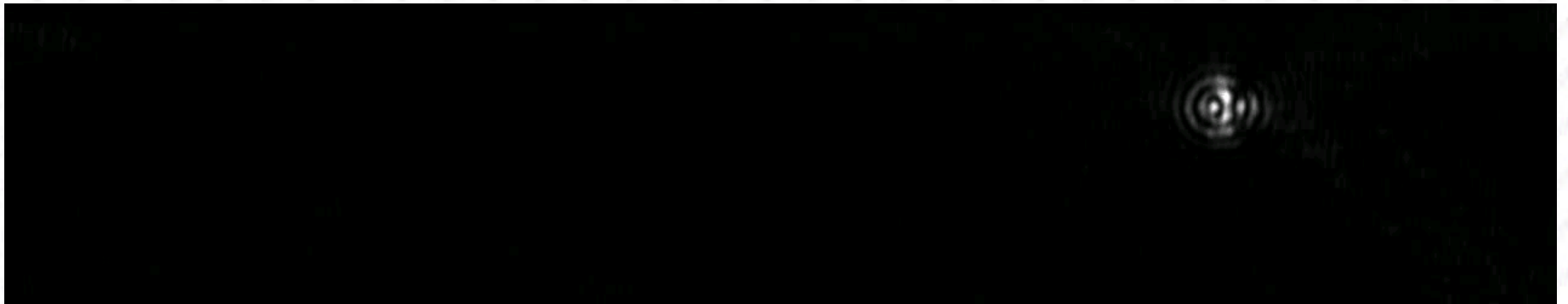
Near-surface sorter of sub-micron objects

The first optical sorting of sub-micron objects according to their size

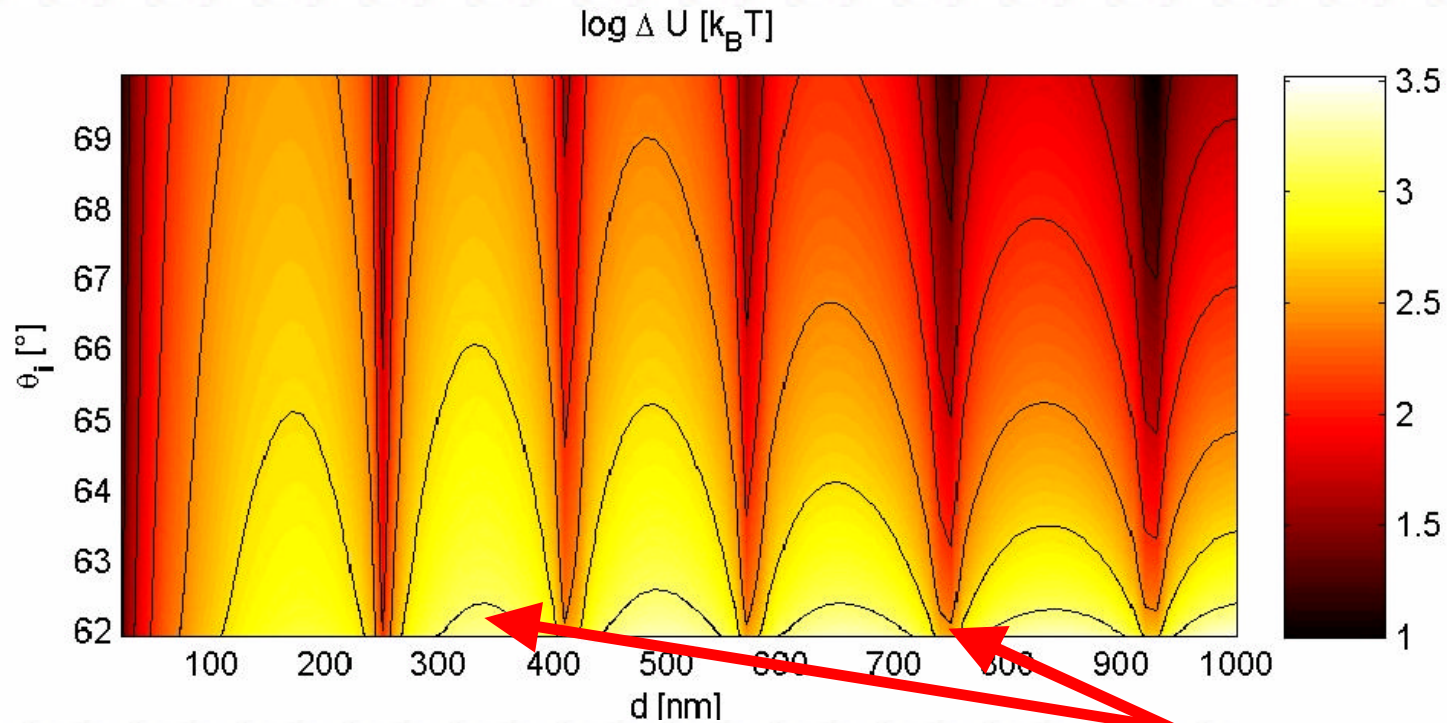


Near-surface sorter of sub-micron objects

The first optical sorting of sub-micron objects according to their size



Why it sorts?

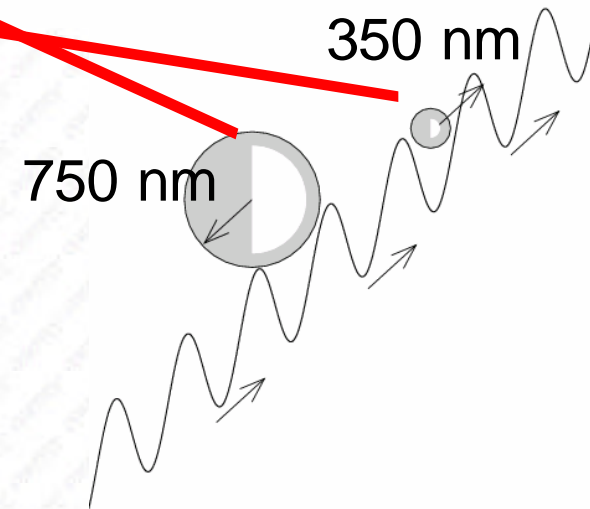


Θ_i – incident angle of the plane wave

d – diameter of the bead

ΔU – depth of the optical trap

Contours - 33, 100, 333, 1000, 3333 kT.



FUTURE ??

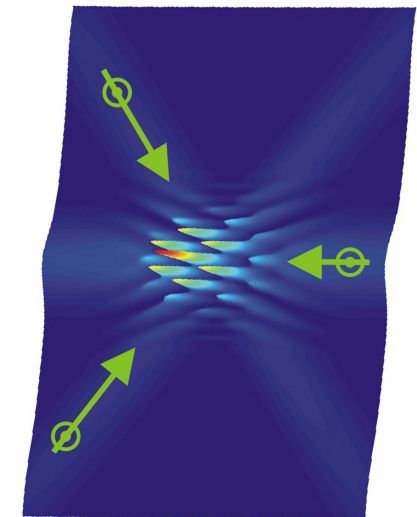
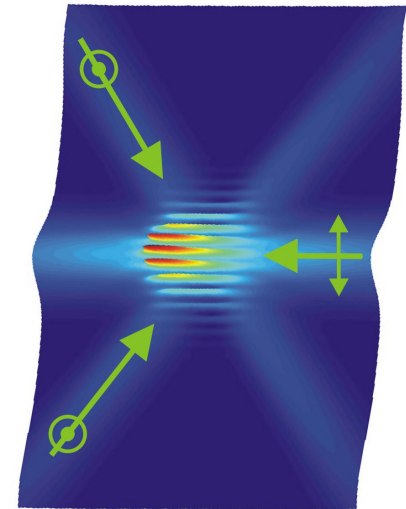
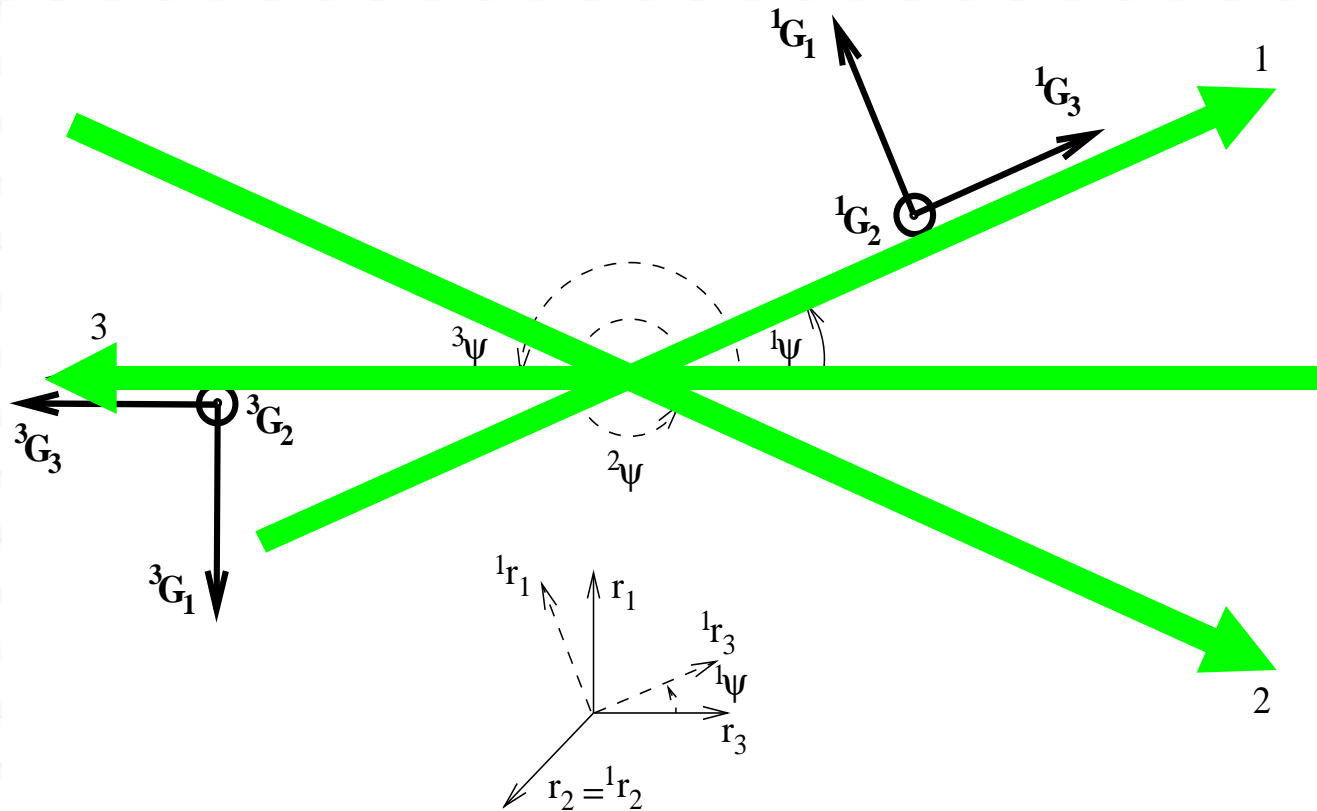
Optical sorting of bio-species using motional standing wave



**EXPERIMENTAL & THEORETICAL
STUDY WITH LYPOSOMES**

IN 1D AND POTENTIALLY 2D

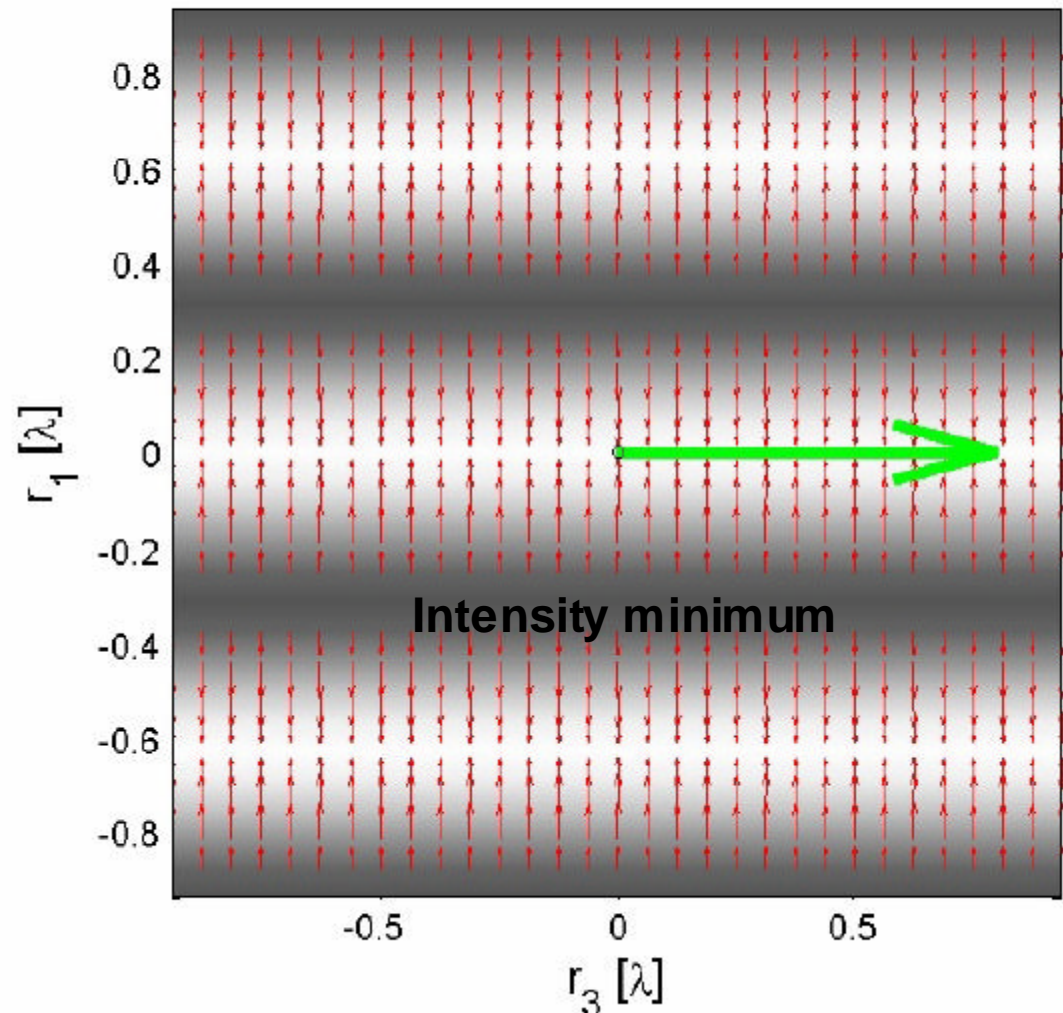
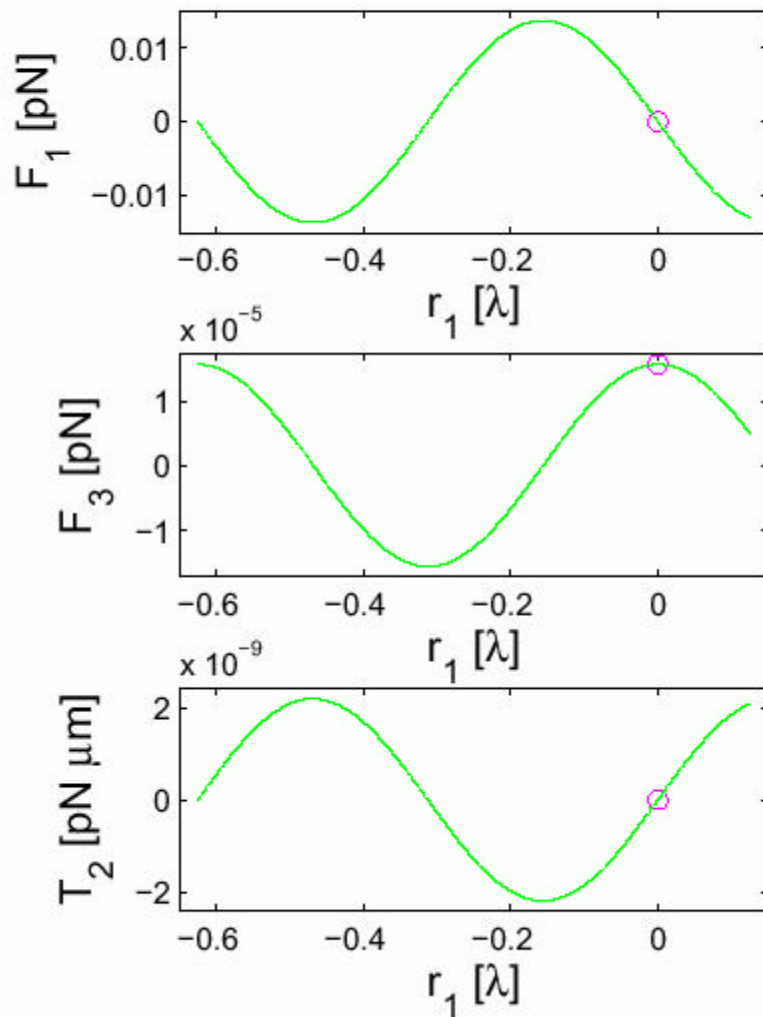
Three laser beams in a planar arrangement



We assume three laser beams with their axes in one plane. Two co-propagating beams interfere and the third counter-propagating either interferes or does not interfere.

How size of the sphere influences the forces

a) $a = 0.013\lambda$, $v_z = 6.3\mu\text{m}/\text{s}$, $P_{min} = 37.9\text{W}$

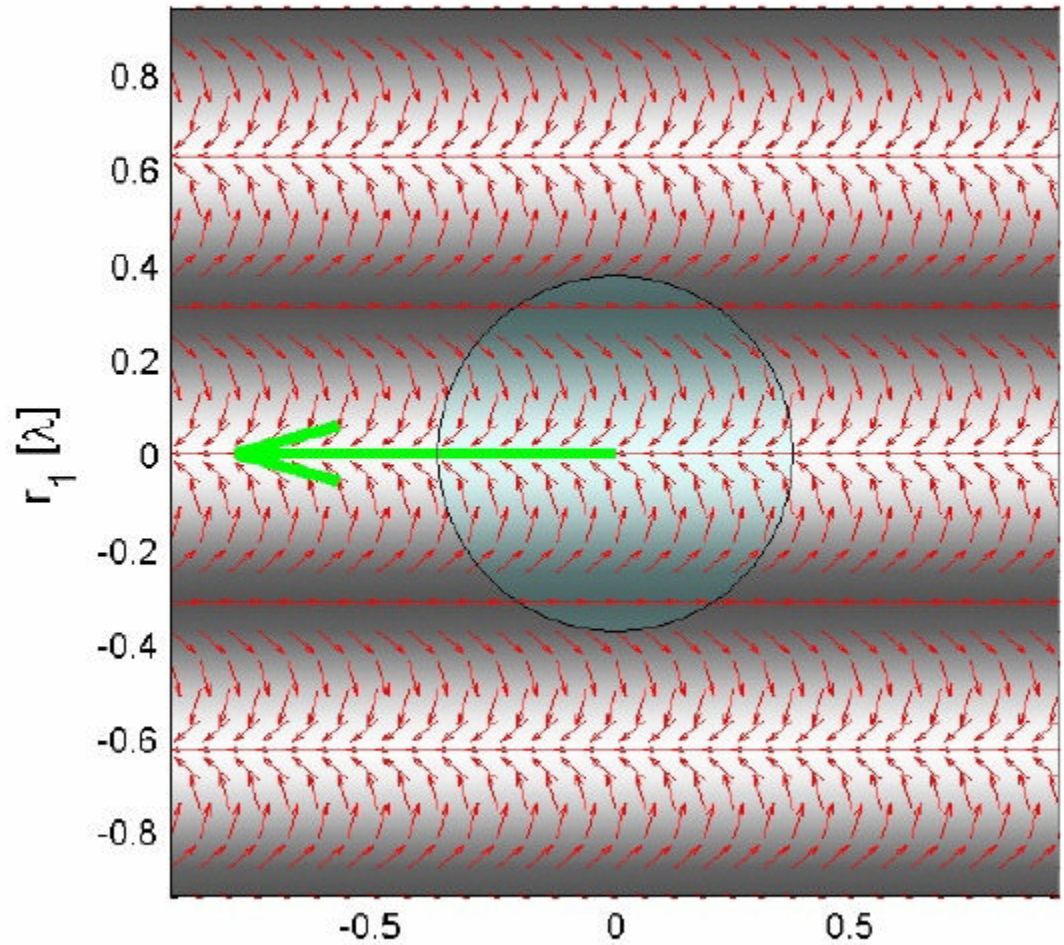
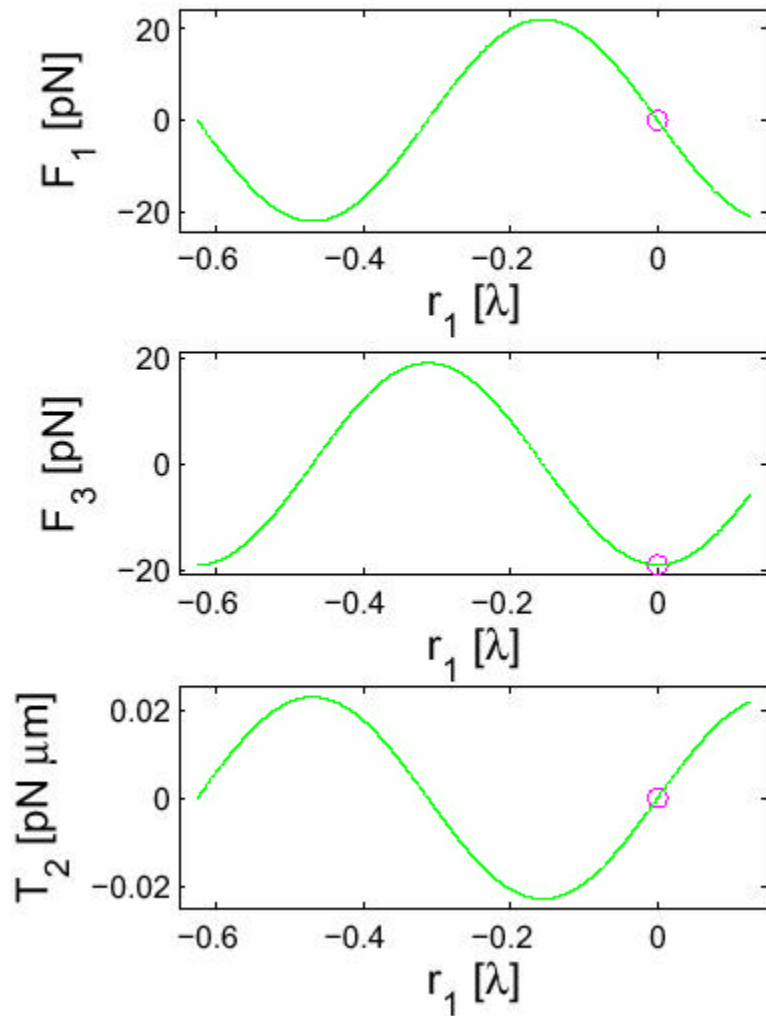


$n_p = 1.59 + 0.0004i$; $\psi = 53^\circ$ ($\Delta_x = 0.25\mu\text{m}$); $\lambda = 532\text{nm}$

$${}^3P = 2 {}^1P \cos \psi$$

How size of the sphere influences the forces

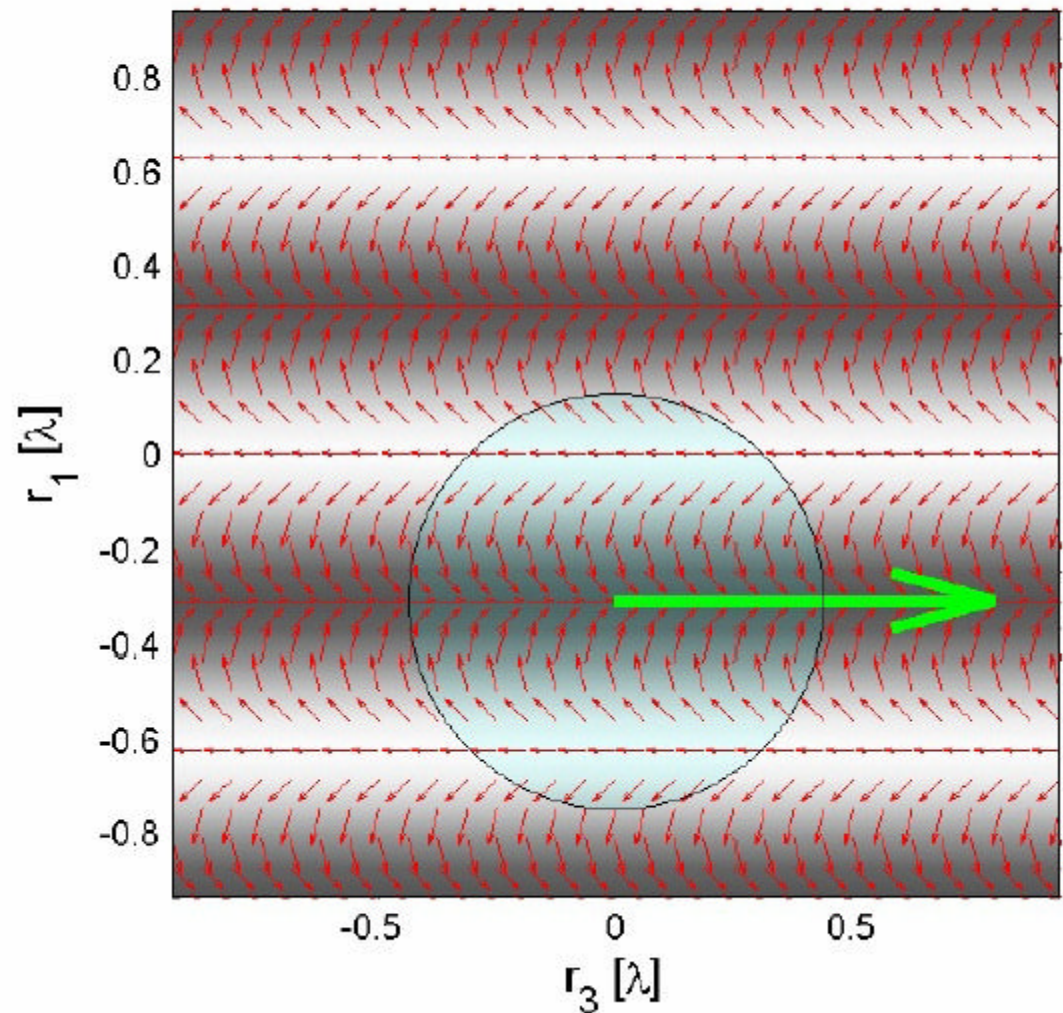
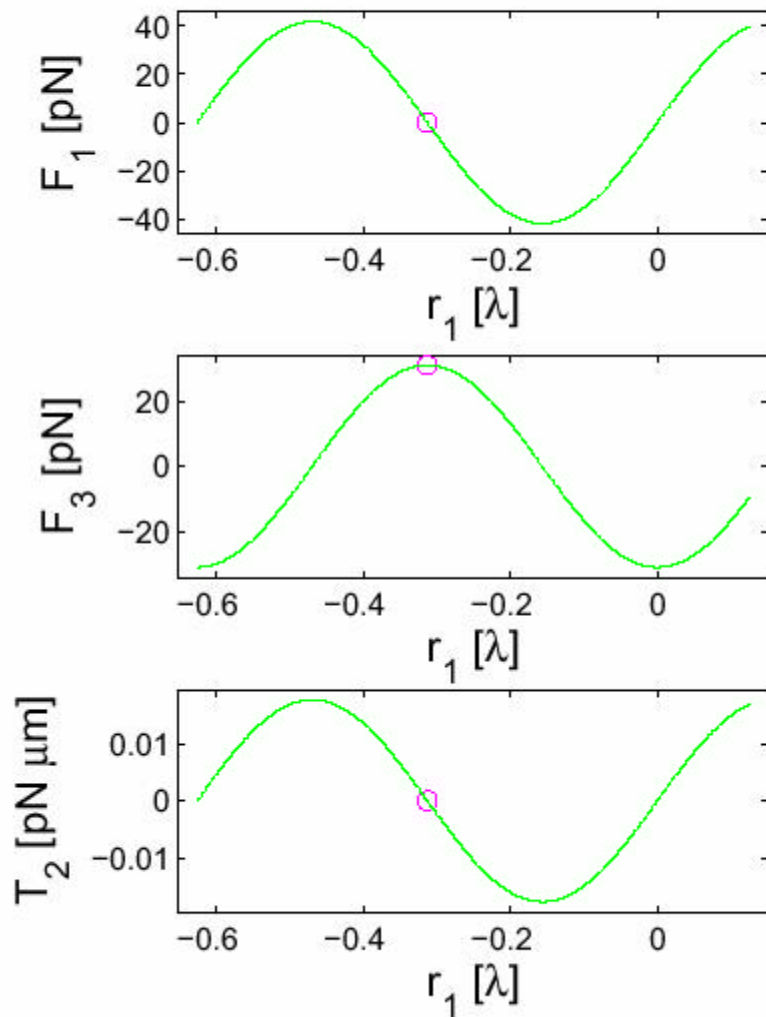
b) $a = 0.376\lambda$, $v_z = -158.0\mu\text{m}/\text{s}$, $P_{min} = 0.024\text{W}$



$${}^3P = 2 {}^1P \cos \psi$$

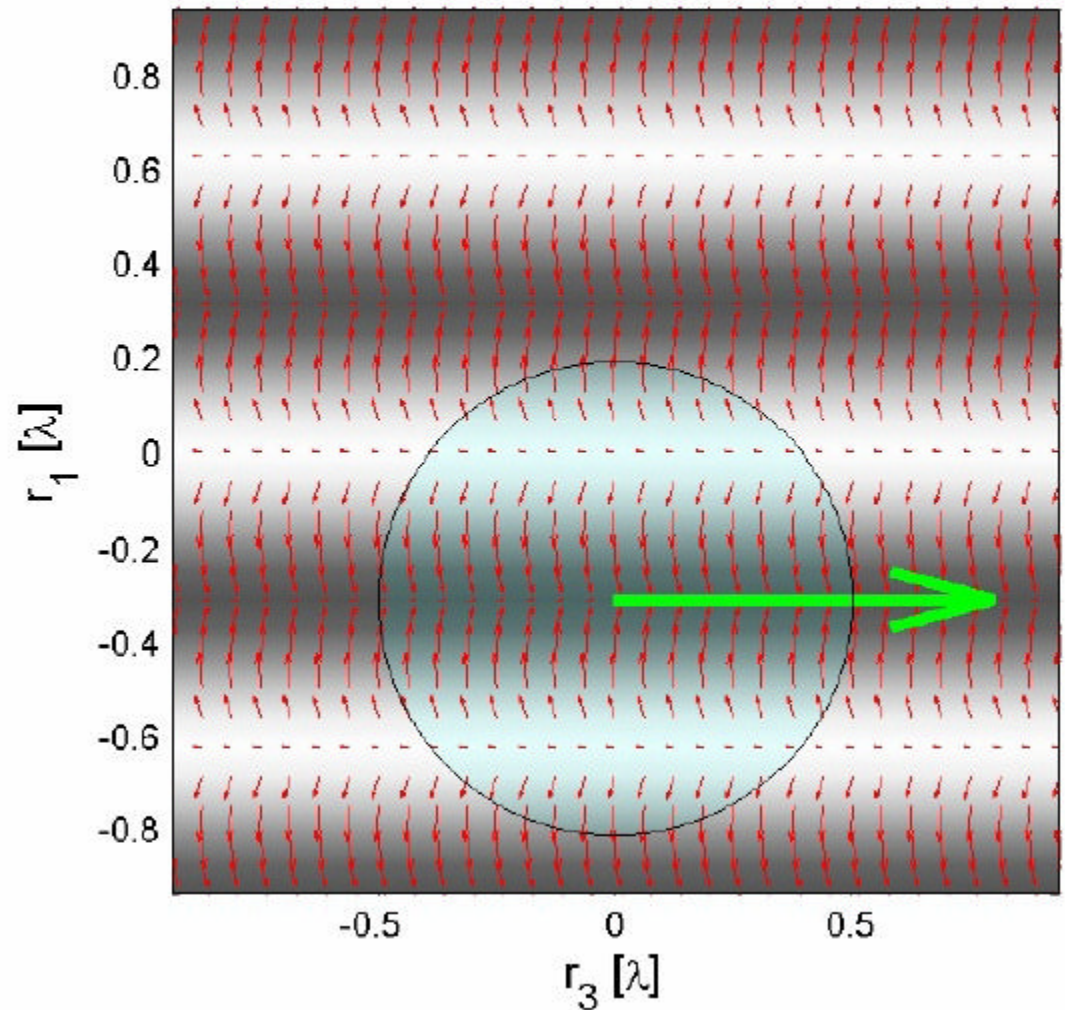
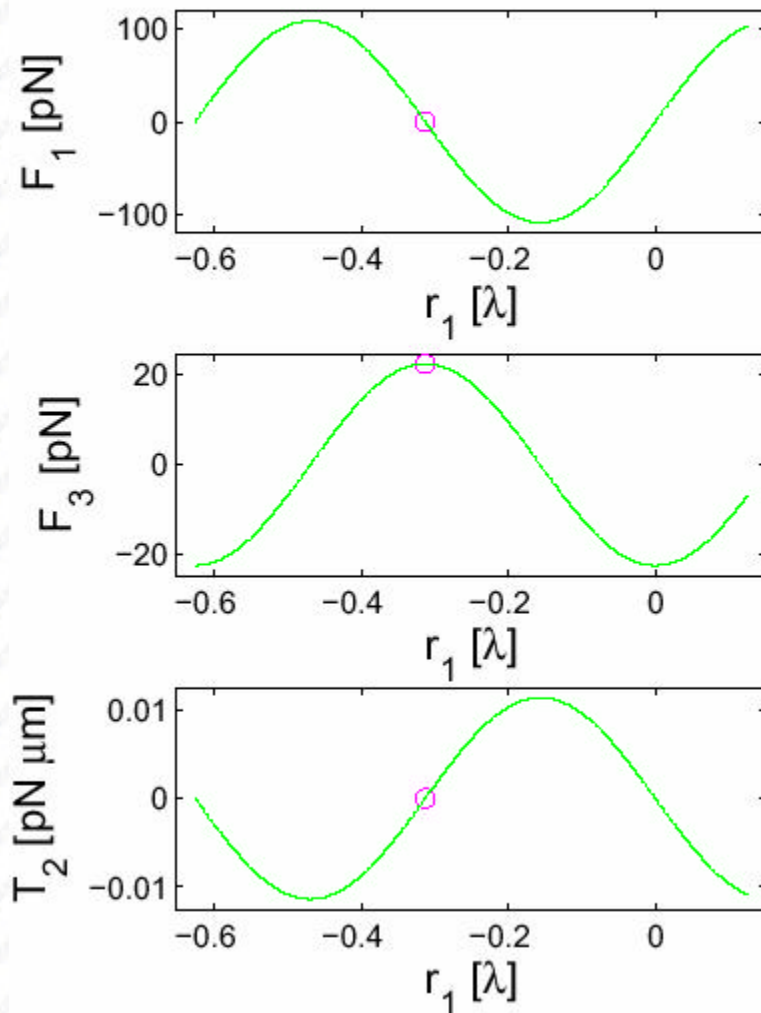
How size of the sphere influences the forces

c) $a = 0.438\lambda$, $v_z = 117.0\mu\text{m}/\text{s}$, $P_{\text{min}} = 0.012\text{W}$



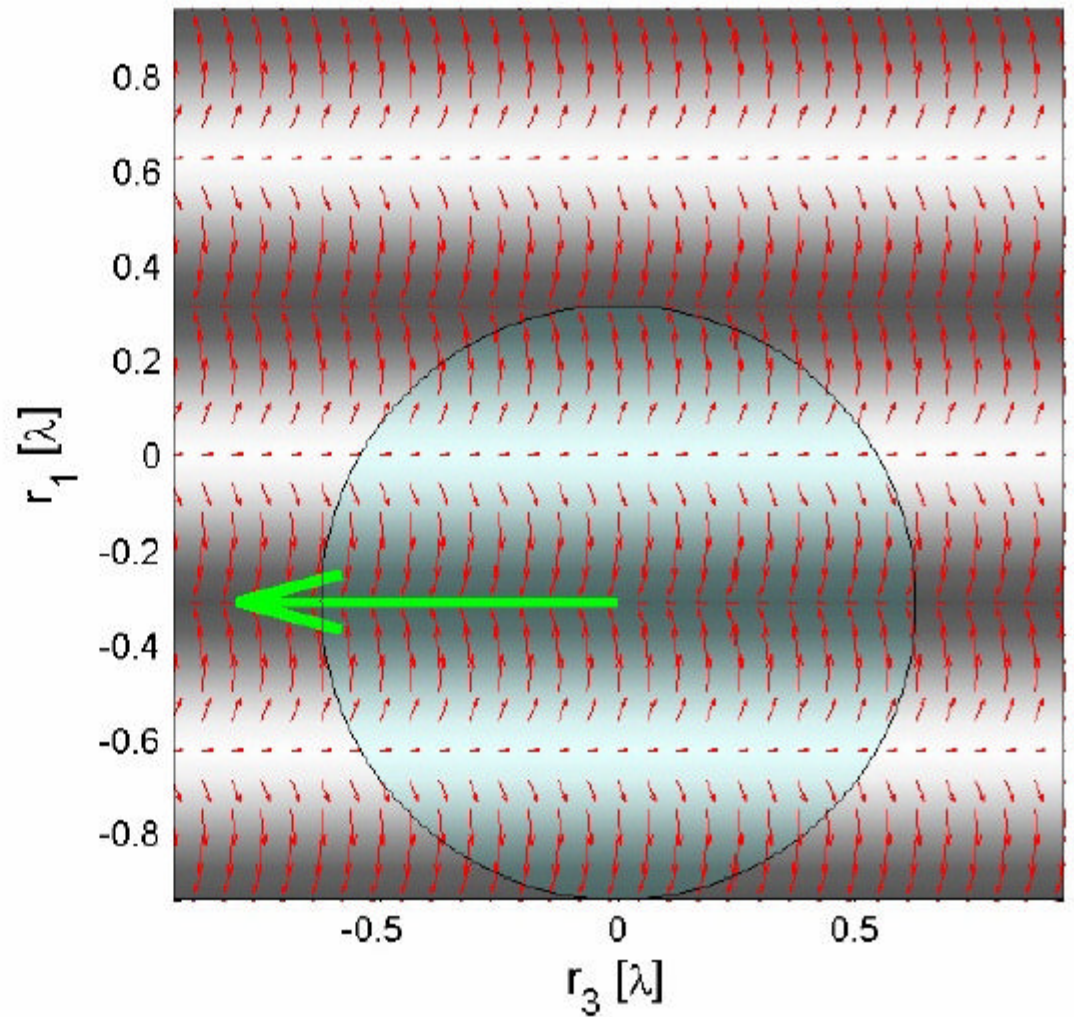
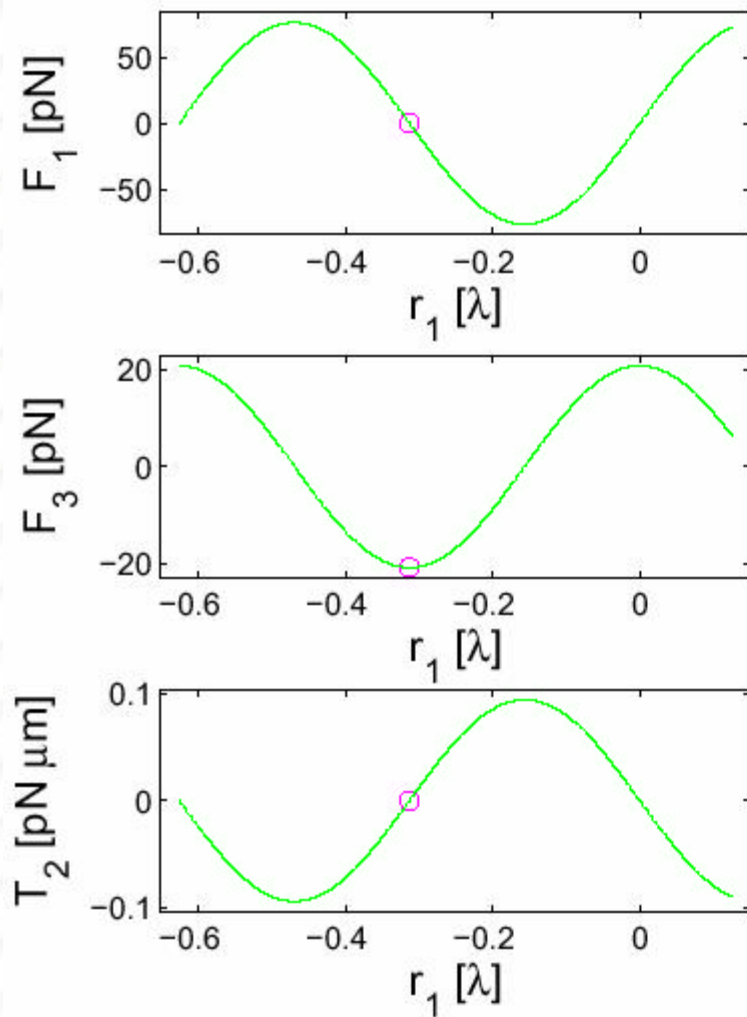
How size of the sphere influences the forces

d) $a = 0.501\lambda$, $v_z = 28.60\mu\text{m}/\text{s}$, $P_{min} = 0.005\text{W}$



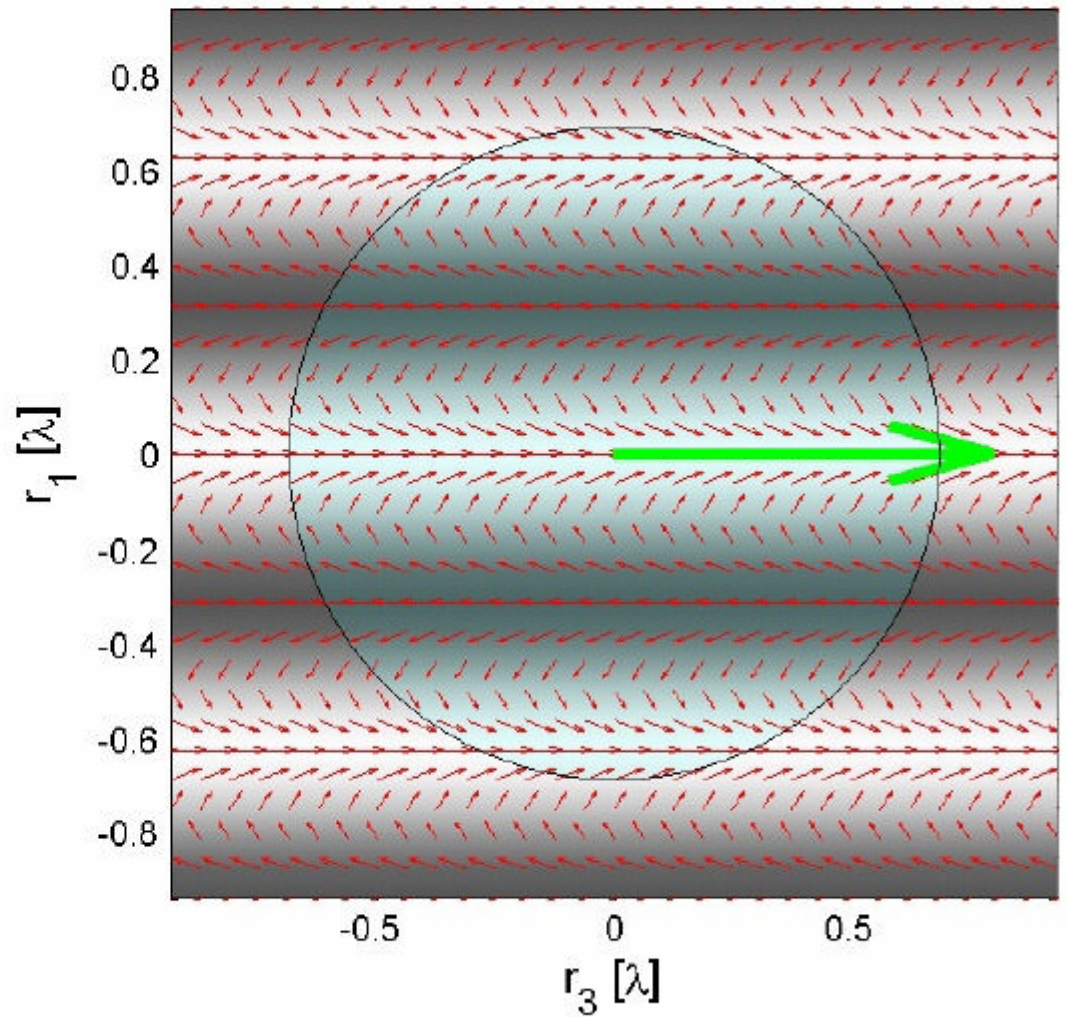
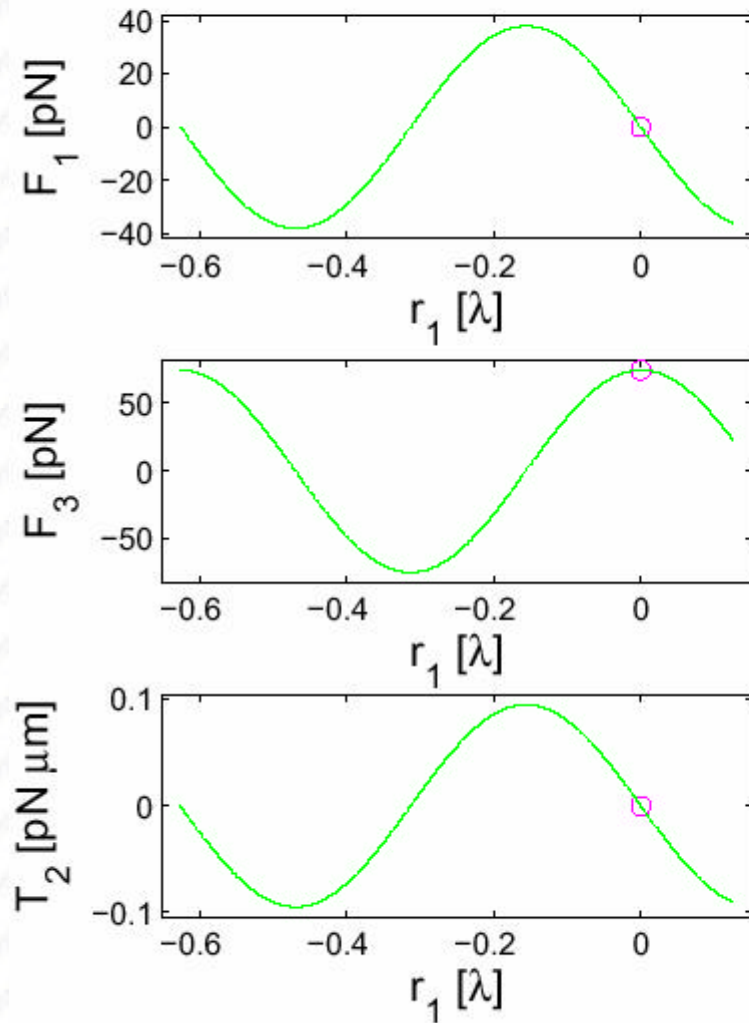
How size of the sphere influences the forces

d) $a = 0.626\lambda$, $v_z = -30.0\mu\text{m}/\text{s}$, $P_{\text{min}} = 0.007\text{W}$

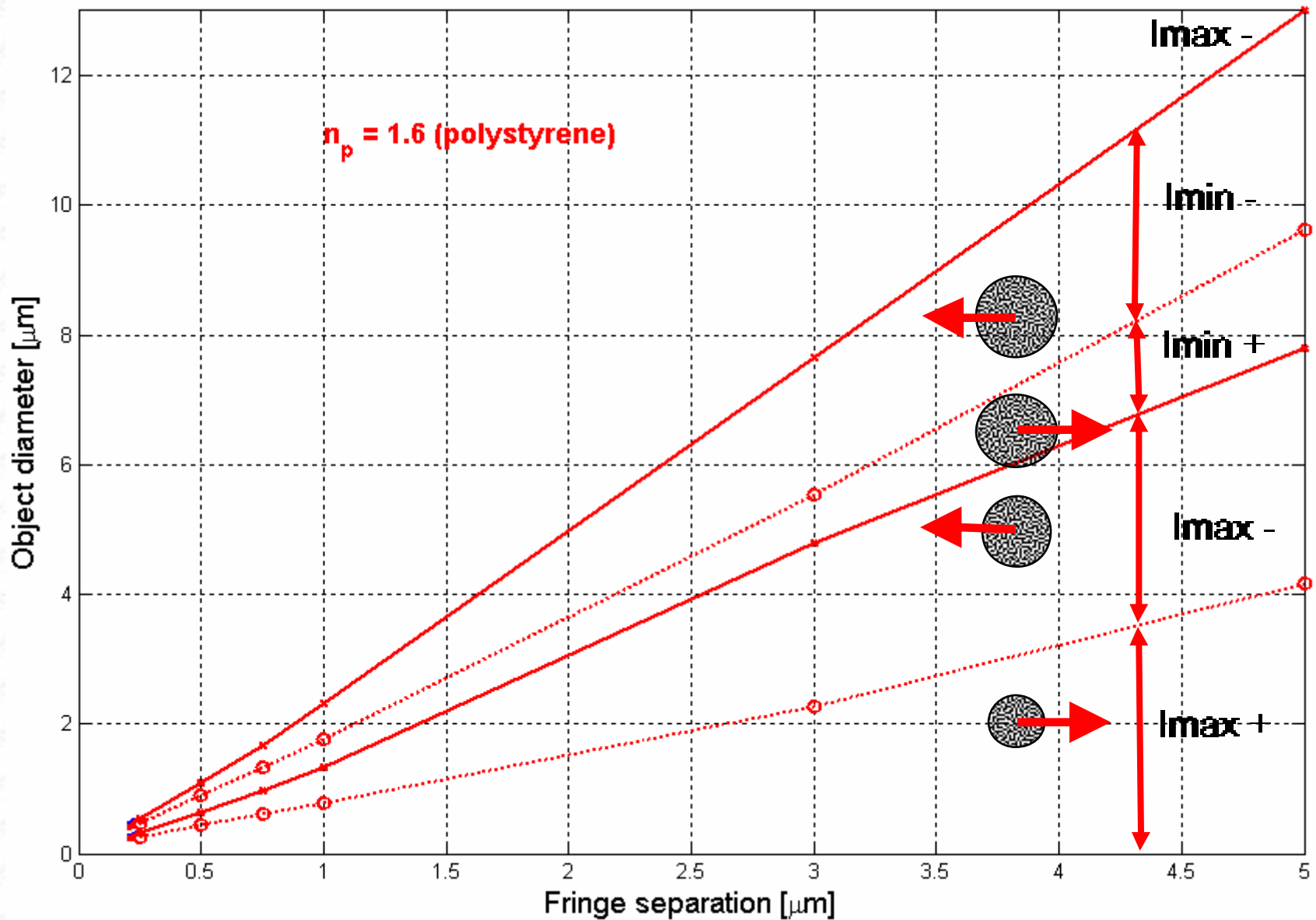


How size of the sphere influences the forces

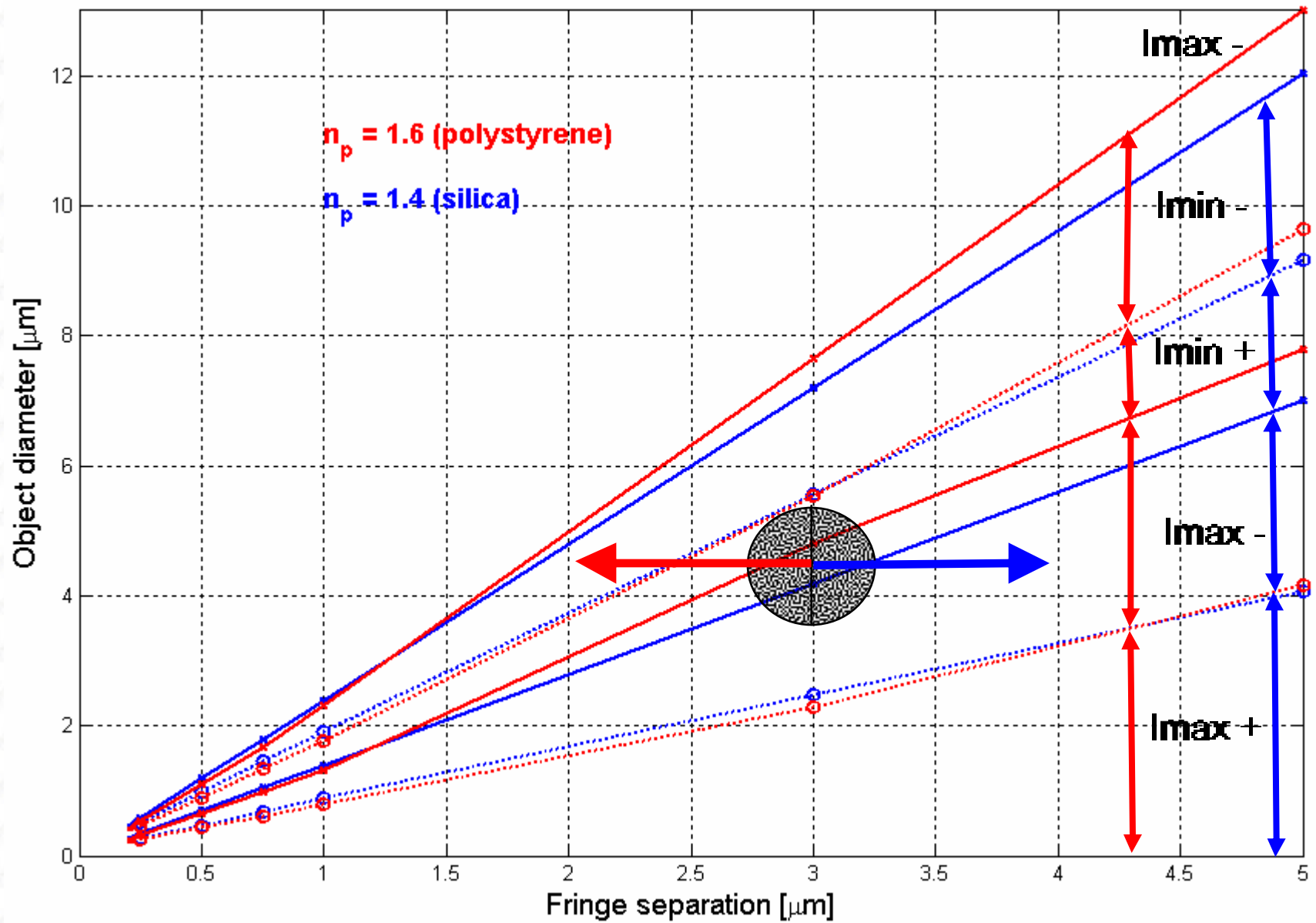
e) $a = 0.689\lambda$, $v_z = 196.3\mu\text{m}/\text{s}$, $P_{\text{min}} = 0.0137\text{W}$



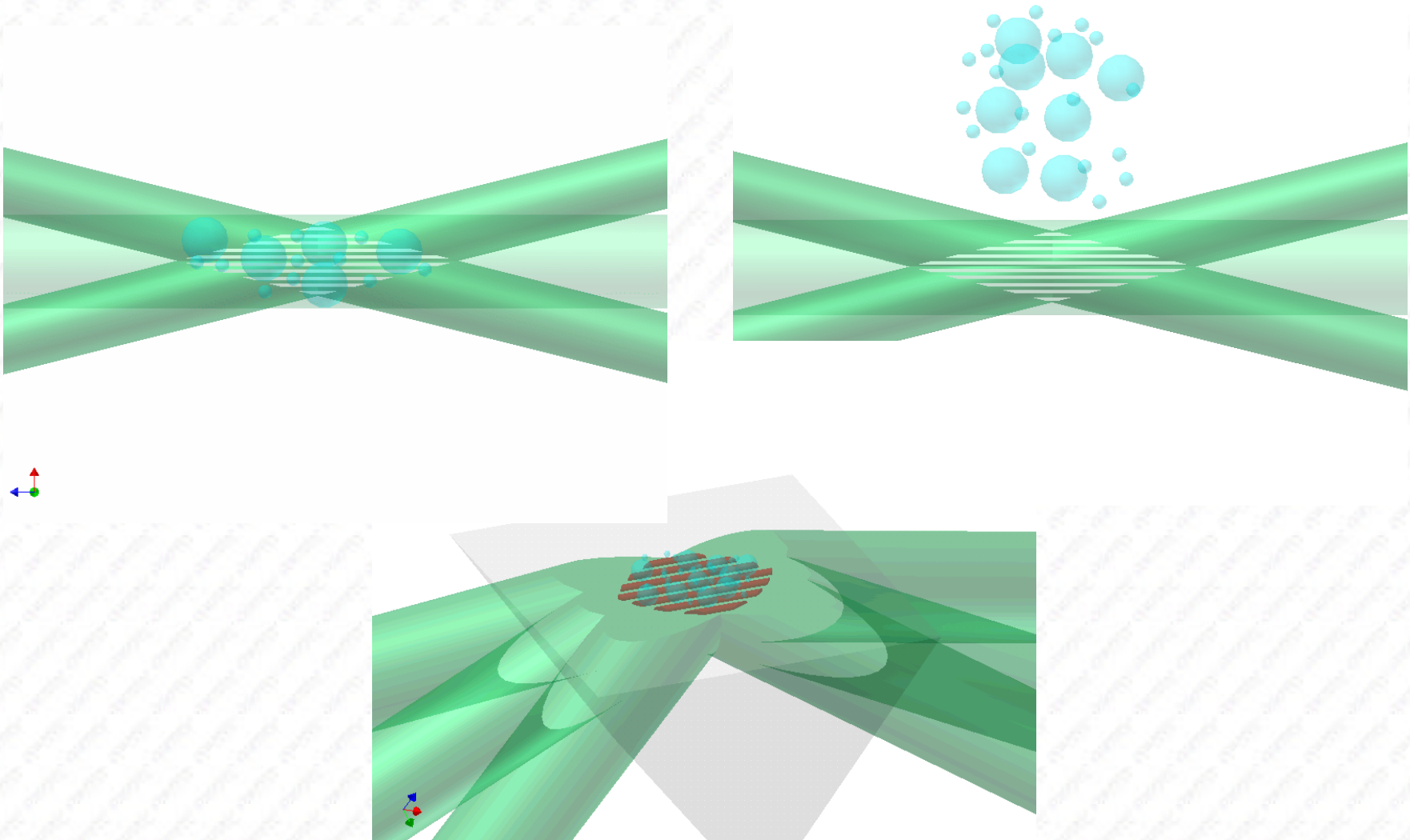
How to select configuration for sorting ???



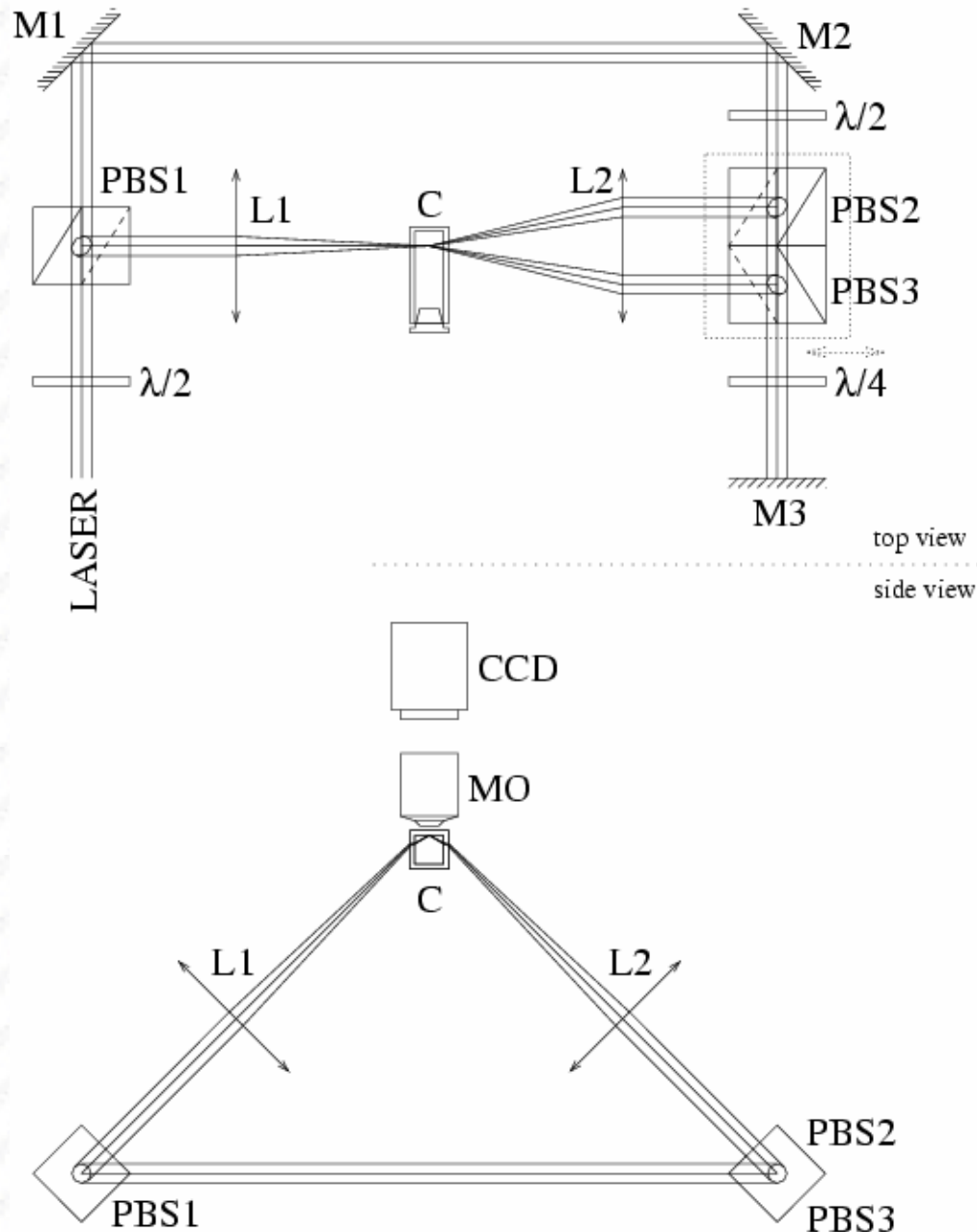
How to select configuration for sorting ???



Optical sorting using 3-beam configuration



Pilot experiments



Laser: Verdi V5

PBS: Polarizing beam splitters

L1, L2: lenses

M: mirrors

$\lambda/2$, $\lambda/4$: half plate, quarter plate

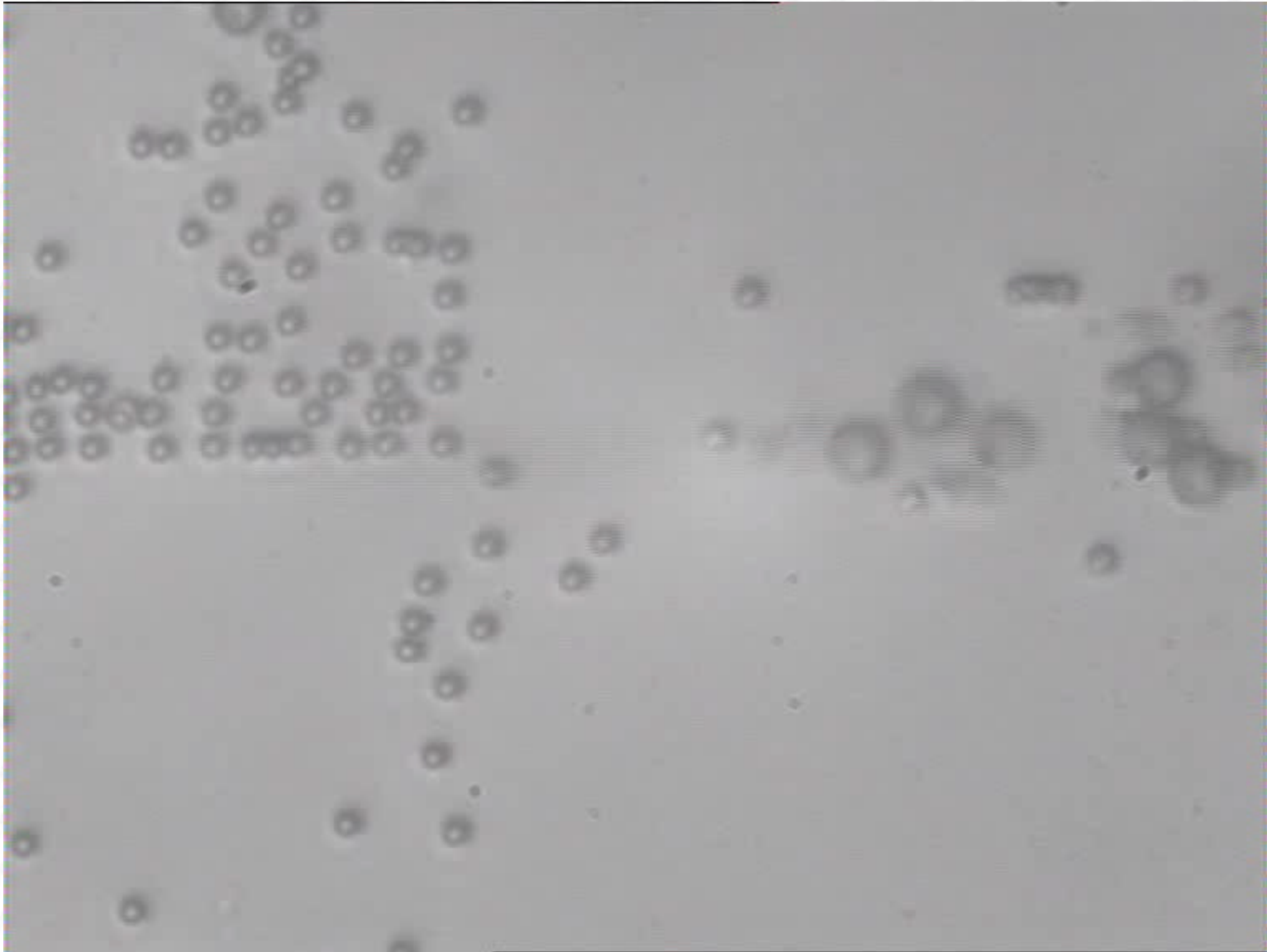
C: cuvette

MO: microscope objective

Sample: polydisperzed solution
of 2 μm and 5 μm polymer beads

Fringe separation: 2.7 μm

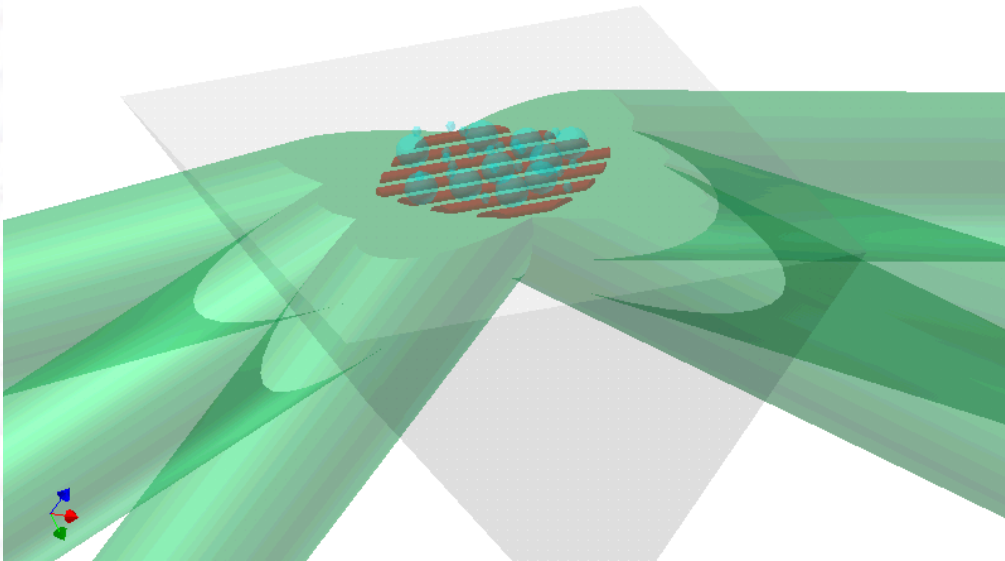
Static optical sorting – pilot experiments



Polystyrene particle diameter 2 and 5 μm , **NO LIQUID FLOW**

FUTURE ??

Optical sorting using 3-beam configuration

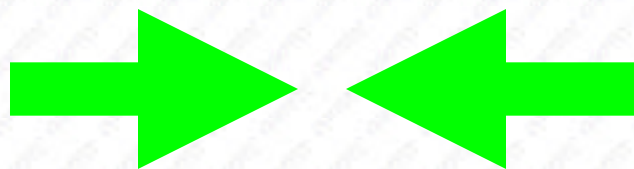


Sorting of bigger objects and living cells.

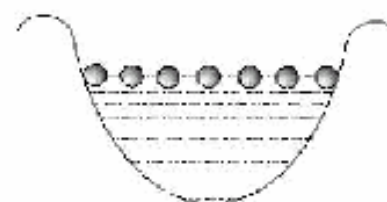
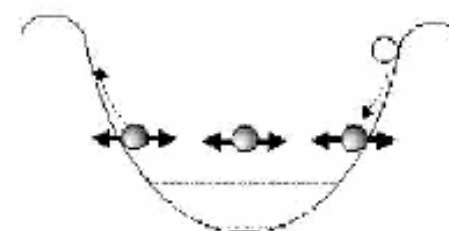
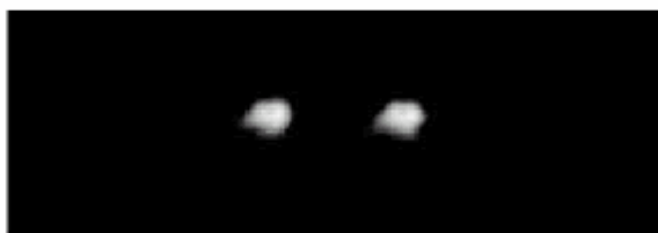
Prostorové samouspořádání mikroobjektů



Optical self-organizing - optical binding

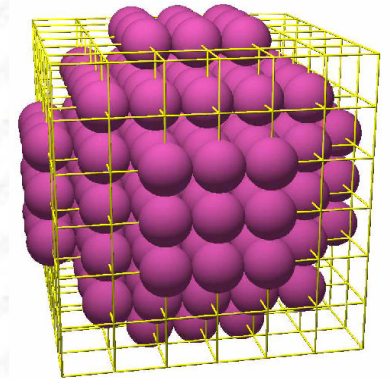


Counter-propagating
non-interfering
beams



Optical binding

Coupled dipoles model



Electric field \mathbf{E}_i at place \mathbf{r}_i of i -th dipole is connected to dipole momentum \mathbf{p}_i of this dipole by polarisability α :

$$\mathbf{p}_i = \alpha \mathbf{E}_i.$$

Electric field in place of i -th dipole is composed from two parts:

$$\frac{\mathbf{p}_i}{\alpha} = \mathbf{E}_{\text{inc},i} - \sum_{j \neq i} \mathbf{A}_{ij} \mathbf{p}_j.$$

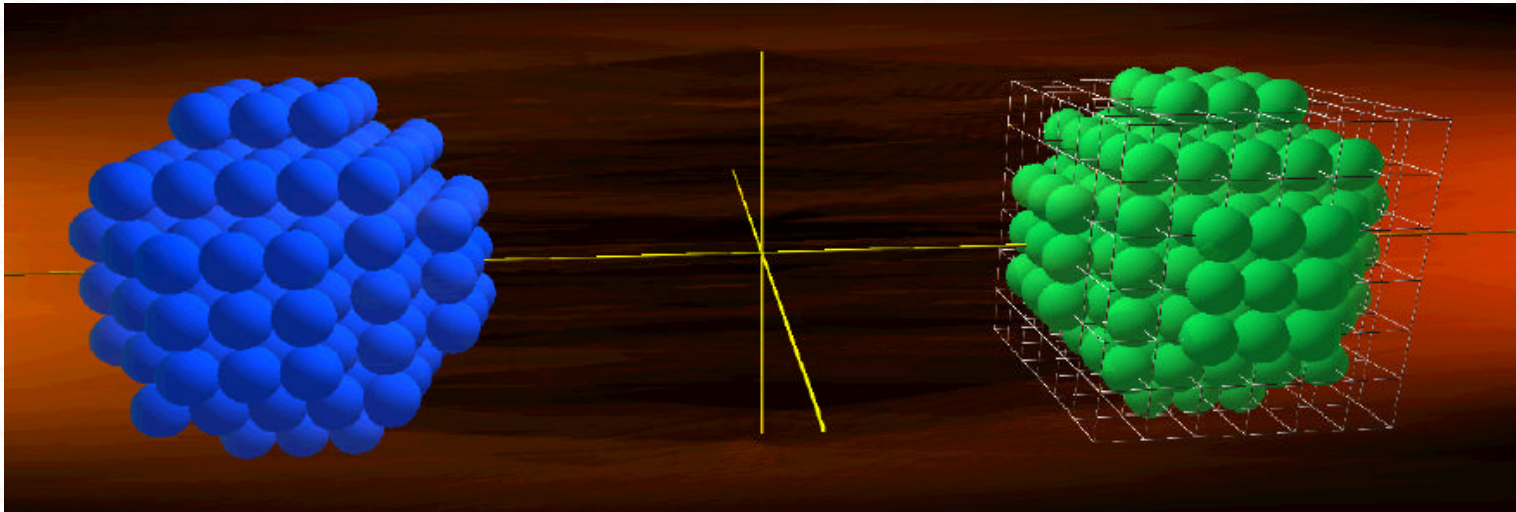
The incident field $\mathbf{E}_{\text{inc},i}$ and field from other dipoles \mathbf{p}_j by radiation matrix \mathbf{A}_{ij} .

$$\mathbf{A}_{ij} = \frac{\exp(ikr_{ij})}{4\pi\epsilon_0\epsilon_r r_{ij}} \times \left[k^2(\hat{\mathbf{n}}_{ij}\hat{\mathbf{n}}_{ij} - \mathbf{1}_3) + \frac{ikr_{ij} - 1}{r_{ij}^2}(3\hat{\mathbf{n}}_{ij}\hat{\mathbf{n}}_{ij} - \mathbf{1}_3) \right],$$

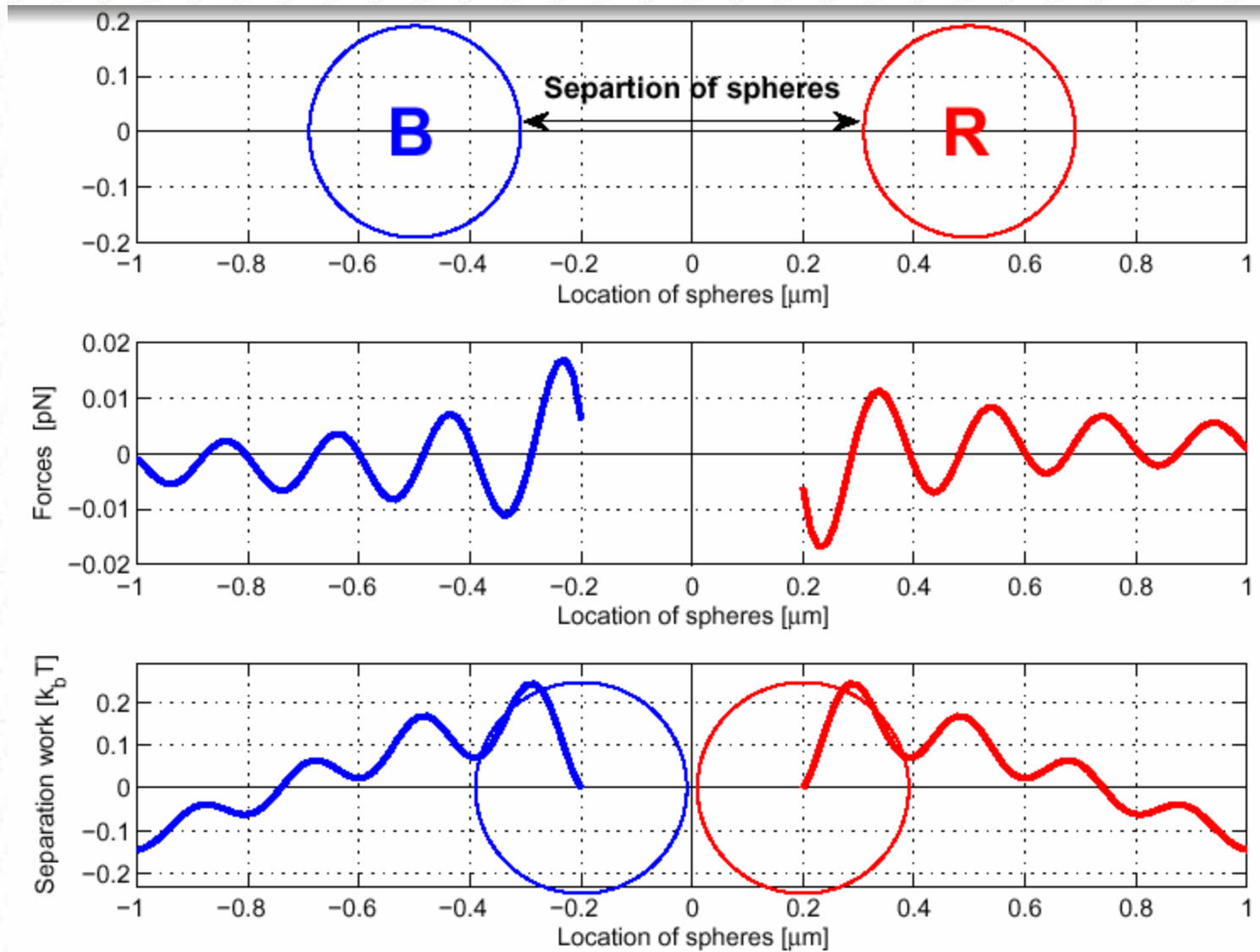
where $\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$, $r_{ij} = |\mathbf{r}_{ij}|$ and $\hat{\mathbf{n}}_{ij} = \mathbf{r}_{ij}/r_{ij}$.

Optical binding

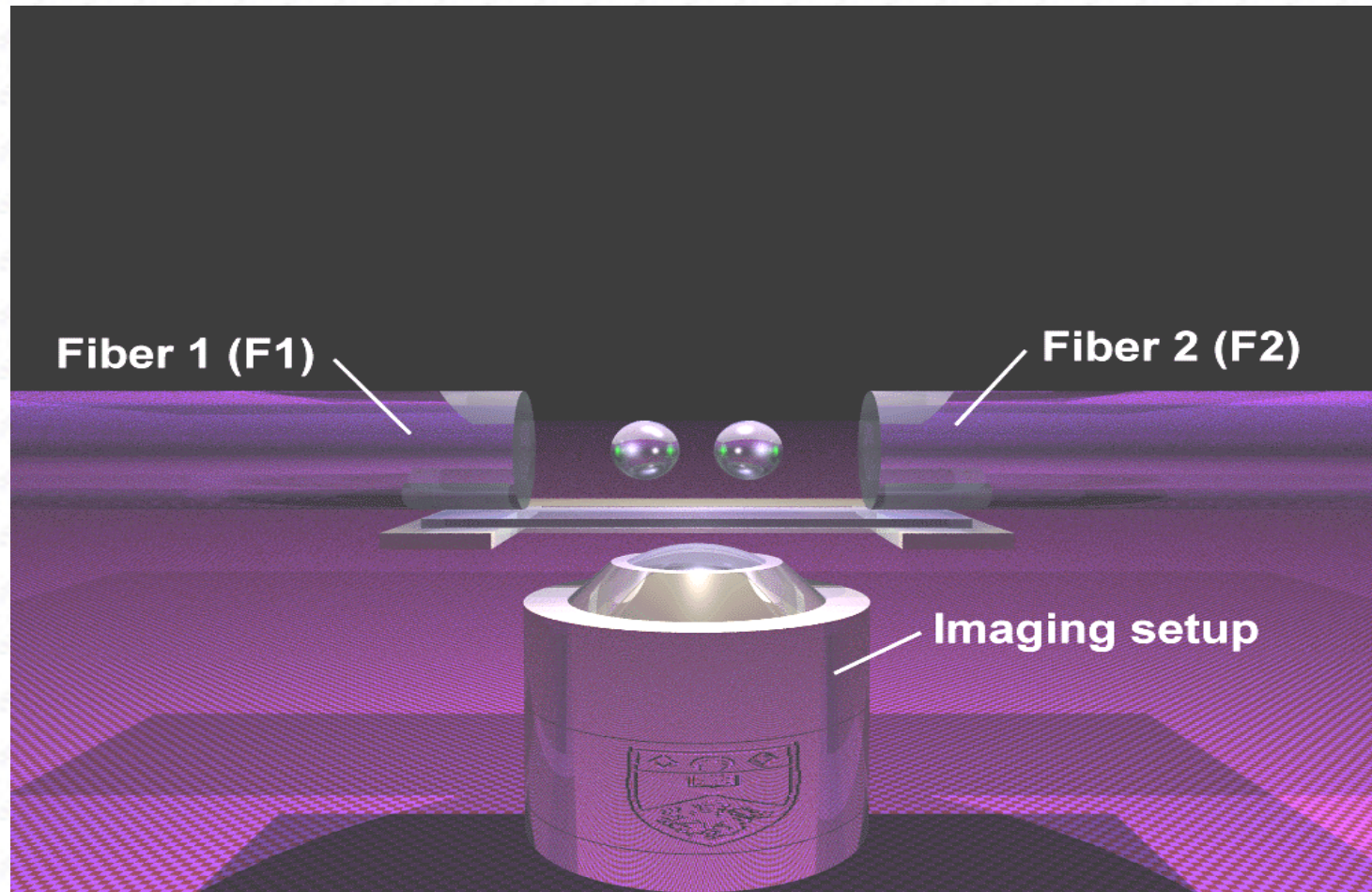
Configuration with 2 beads



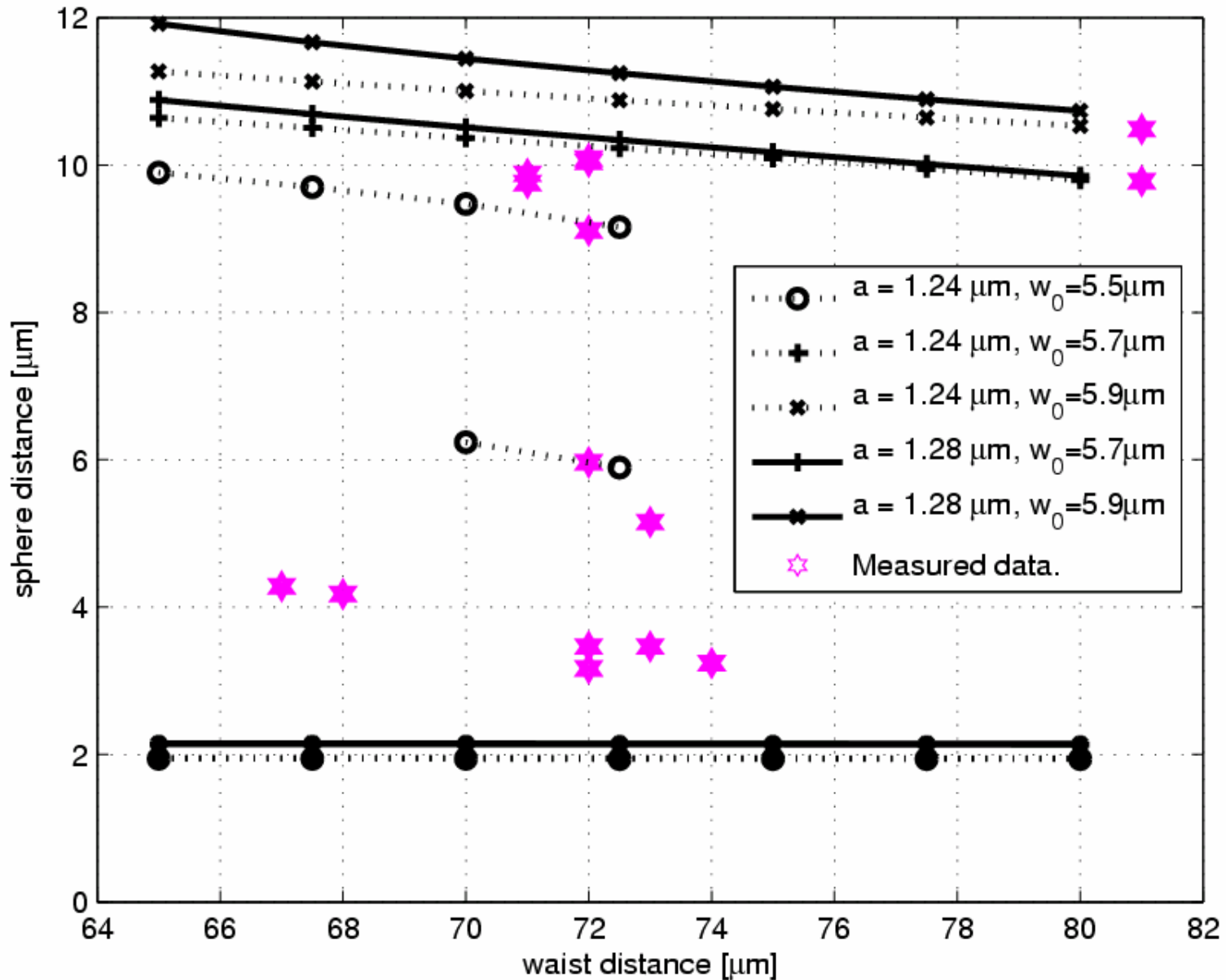
Optical binding – theoretical model



Optical binding - experiments



Optical binding – comparison theory & experiments



Optical binding

Theoretical simulations reveal that the distance between objects is very sensitive to refractive indices of the objects and surrounding materials and geometrical configuration. Therefore the exact comparison with experimental results are very difficult because the parameters are usually known with lower precision.

Future

Optical binding in non-diffracting beams and in the evanescent waves near the surface.