Optical manipulation of small objects:

from atoms and molecules to subwavelength particles

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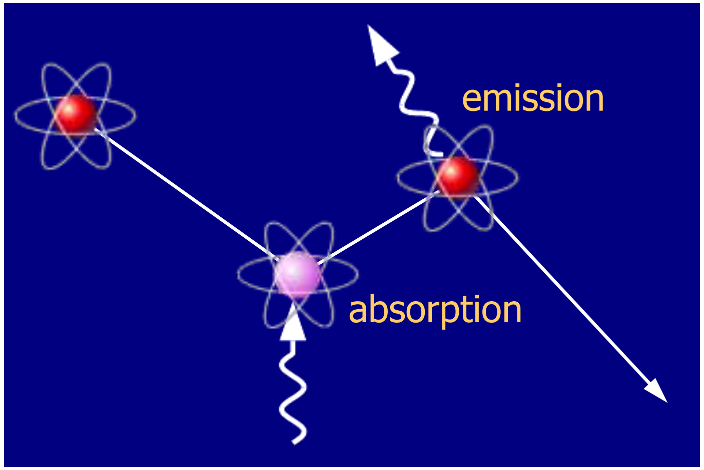
Outline

1. Introduction
    - light momentum and history of light pressure
    - general description of light forces on small objects
2. Laser cooling and trapping of atoms
    - spontaneous light force
    - Doppler cooling for a two-level atom
    - sub-Doppler cooling
    - stimulated light force
    - magneto-optical trap (MOT)
    - pulsed traps
3. Optical tweezers
    - history of optical trapping
    - optical tweezers physics
    - optical tweezers applications
4. Optical trapping of metall nanoparticles

Mechanical effect of the photon



Electromagnetic waves carry momentum

$$P = D \times B$$

B is the magnetic flux density
D is the electric displacement field

Photons carry momentum

$$p = \hbar k$$

visible photon $p \approx 10^{-27} kg \cdot m / s$

For Rb the recoil velocity p/M_{Rb} is about 6 *mm/s*

Light momentum may be changed as a result of absorption, reflection, scattering or refraction.
This induces a momentum transfer from light to the object in its pathway. According to Newton’s second law, the change of momentum *p* of light results in a force being applied $F = \partial p/\partial t$. This force is in the femto-picoNewton regime and thus not apparent in everyday life.

Light pressure in space

Kepler: *Comet tails point away from the sun due to radiation pressure* (1619)

Physics:

gravity force $$F_{grav} \propto m \propto a^3$$

light pressure $$F_{light} \propto S \propto a^2$$

for small *a* $$F_{light} > F_{grav}$$

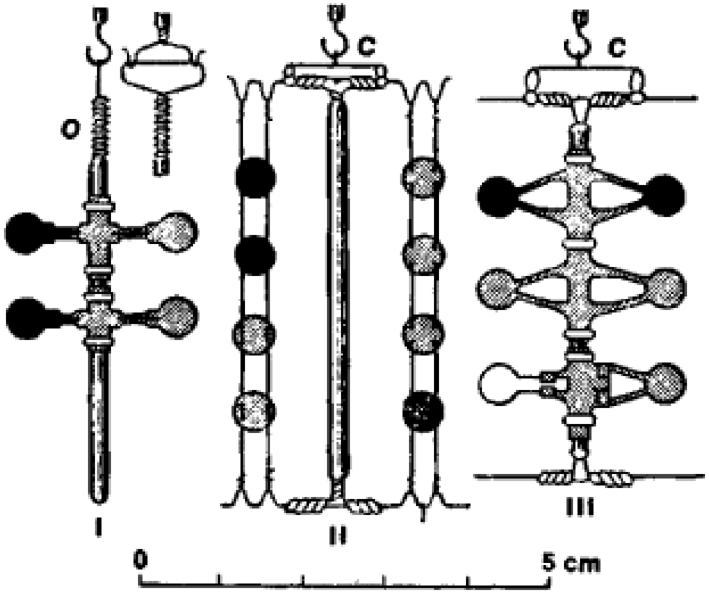
Comet Hale–Bopp (1997), the most widely observed comet of the 20th century.

Light pressure on the Earth

Thus, if in strong sunlight the energy of the light which falls on one square foot is 83.4 foot pounds per second, the mean energy in one cubic foot of sunlight is about 0.0000000882 of a foot pound, and ***the mean pressure on a square foot is 0.0000000882 of a pound weight*** **(4.3 x 10^{-6} N/m^2)*.*** *A flat body exposed to sunlight would experience this pressure on its illuminated side only, and would therefore be repelled from the side on which the light falls.*

J. C. Maxwell, *A treatise on electricity and magnetism* (1891)

Lebedev’s experiments (1899)



Various systems of vanes in Lebedev’s experiments

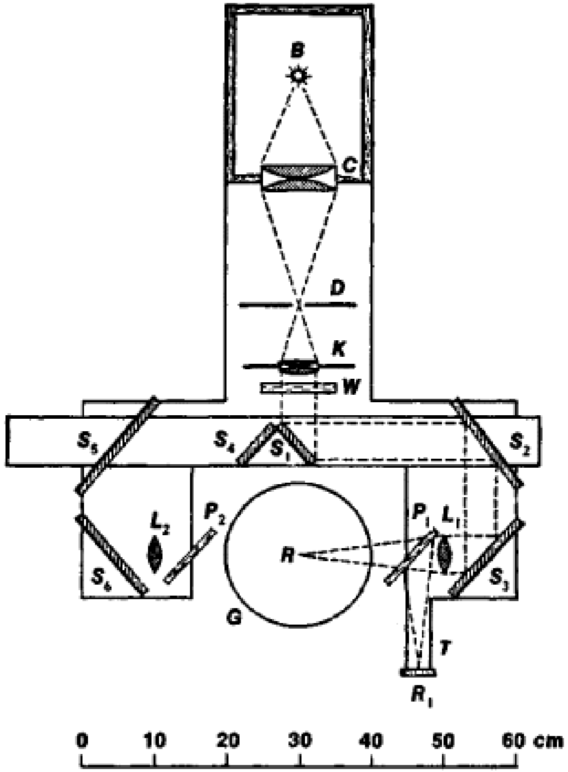
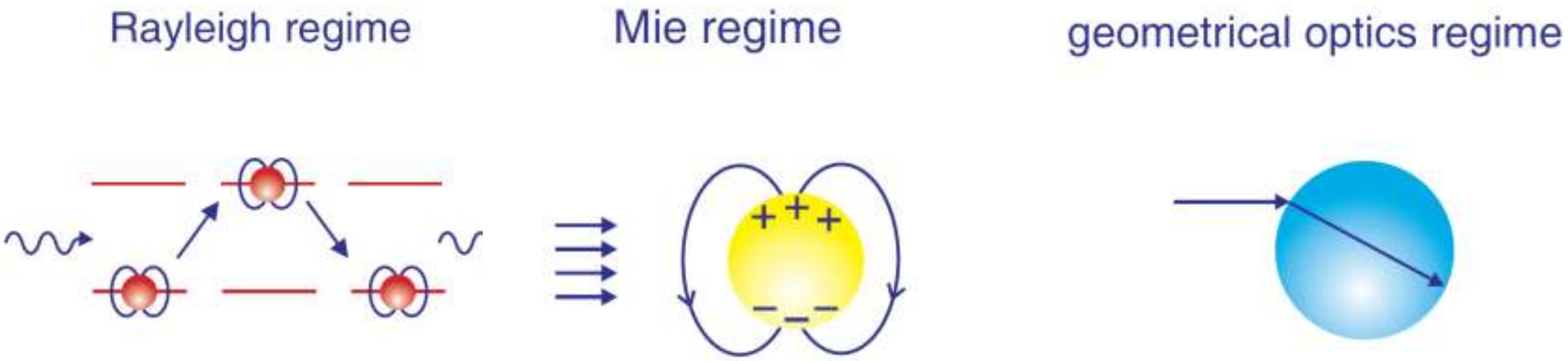


Diagram of Lebedev’s experiment

Particle size regimes



point dipole:
atoms, molecules,
nanoparticles a<< λ

nanoparticles a ≈ λ

refractive objects, a >>λ

$$T_{ij} = \epsilon_h \epsilon_0 E_i E_j^* + \mu_h \mu_0 H_i H_j^* - \frac{1}{2}\delta_{ij}(\epsilon_h \epsilon_0 E_k E_k^* + \mu_h \mu_0 H_k H_k^*)$$

Maxwell's stress tensor

$$\begin{aligned} < F_i > &= \frac{1}{2}\Re\left(\int_S T_{ij} n_j ds\right) \\ &= \int_V < f_i > dv = \int_V \frac{1}{2}\Re\left(\partial_j T_{ij}\right) dv \end{aligned}$$

total
optical
force

The exact expression for the momentum of the electromagnetic field in a material medium has been a subject of debate for a long time, which is known as the Abraham-Minkowski controversy

Force in Rayleigh regime

For **small particles (typically a< λ/20)** the field to be constant across the particle. For these point-like dipole particles it is possible to estimate **their total microscopic polarization as proportional to the incident electric field**

$$p = \varepsilon_0 \varepsilon_h \alpha E$$

where α is the polarizability.

The induced polarization varies together with the incident electric field implying an oscillating dipole that is associated with a current **j = ∂_tp.** This current, in conjunction with the optical Lorentz force gives the total optical force acting on the nanoparticle

$$< F >= \frac{\varepsilon_0 \varepsilon_h}{2} \Re[\alpha (E \cdot \nabla) E^* + \alpha \partial_t E \times \mu H^*]$$

Gradient and scattering forces

Force in Rayleigh regime is the sum of the gradient force and the extinction (scattering) force

$$<F>=F_{grad}+F_{ext}$$

$$<F_{grad}>=\frac{\varepsilon_0\varepsilon_h}{4}\Re(\alpha)\nabla(E\cdot E^*)$$

- the gradient force

$$F_{ext}=F_{scat}+F_{abs}=\frac{n_h}{c}C_{scat}<S>+\frac{n_h}{c}C_{abs}<S>$$

- the extinction force

$$<S>=\frac{1}{2}\Re(E\times H^*)$$

-the optical cycle averaged Poynting vector

$$C_{scat}=\frac{n_h^4k_0^4}{6\pi}|\alpha|^2,\quad C_{abs}=-\frac{n_hk_0}{\varepsilon_0}\Im(\alpha_0)$$

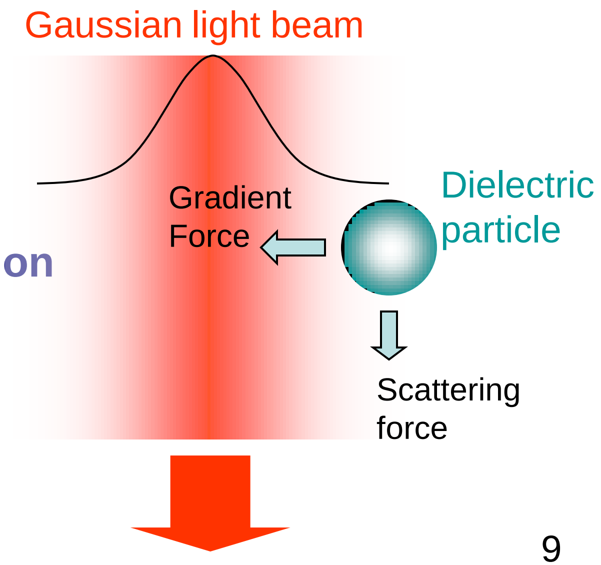
-the scattering and absorption cross sections within the Rayleigh approximation

$$\alpha_0=4\pi a^3\frac{\varepsilon_n-\varepsilon_h}{\varepsilon_n+2\varepsilon_h}$$

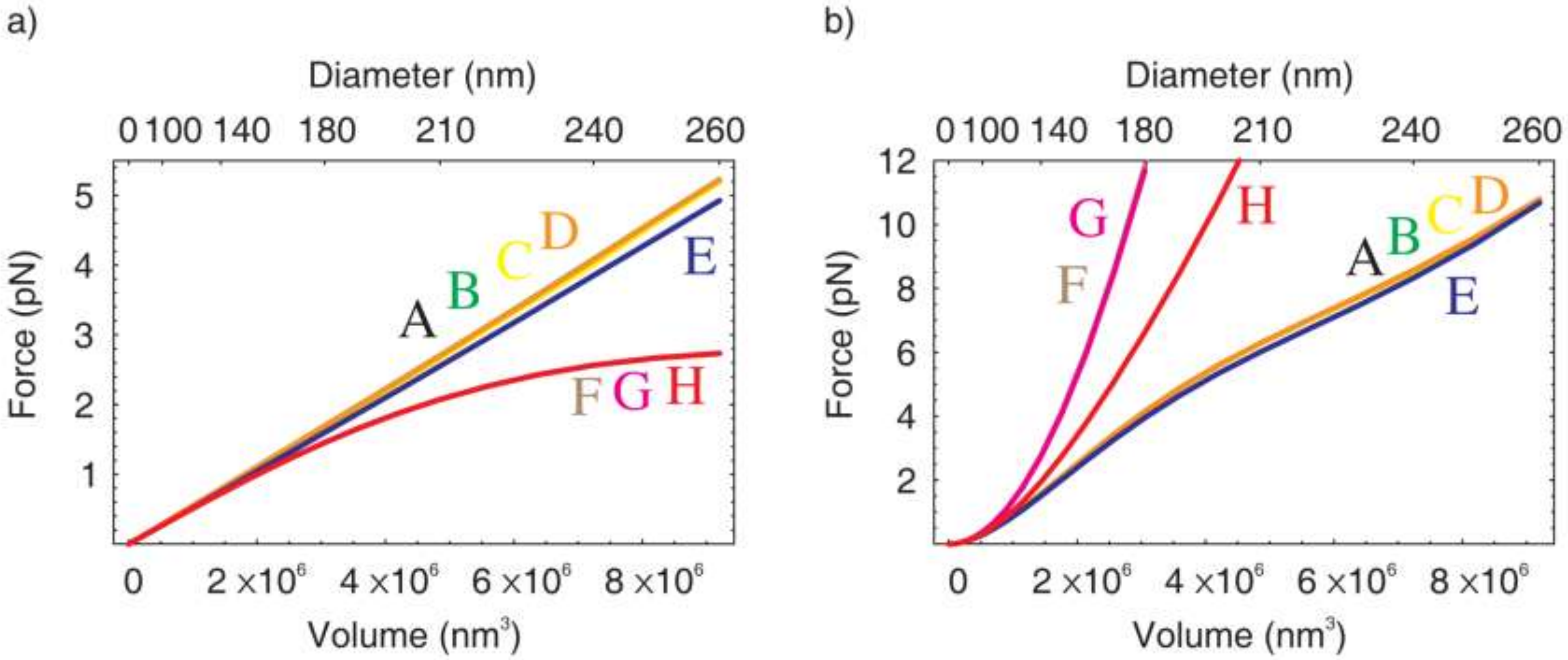
- standard polarizability

$$\alpha=\frac{\alpha_0}{1+i\dfrac{n_h^3k_0^3}{6\pi}\alpha_0}$$

- polarizability corrected by radiative reaction



Optical forces acting on a dielectric nanoparticle



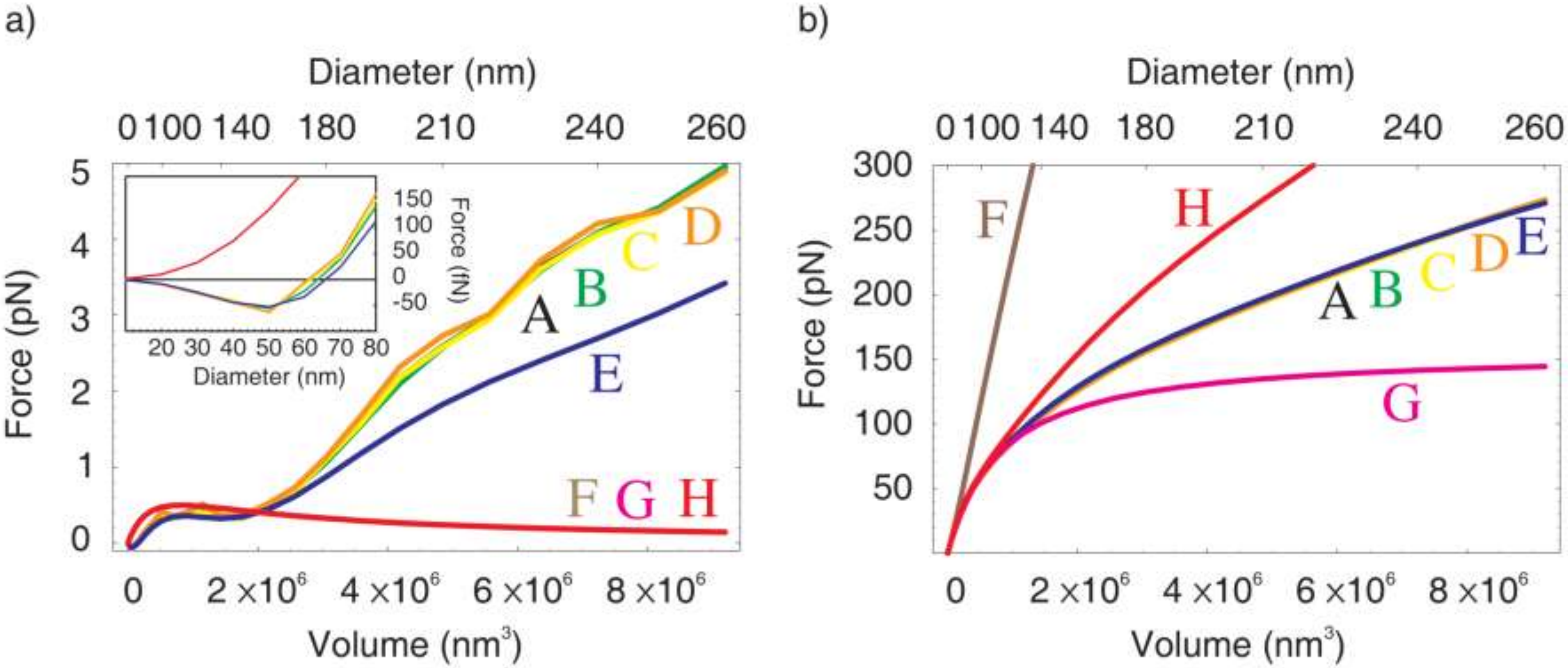
Optical forces acting on a dielectric nanoparticle (n = 1.59) in water.

The nanoparticle is in the focal plane of a linearly polarized Gaussian beam (waist 1µm, wavelength λ = 500 nm) laterally offset by 300 nm.

The transversal (a) and longitudinal (b) optical forces acting are calculated for the different models: A Maxwell’s stress tensor ; B Surface gradient forces ; C,D Lorentz force; E Lorenz-Mie forces; F Gradient and scattering forces; G Dipole approximation ; H Gradient and scattering forces using Lorenz-Mie scattering and absorption coefficients.

M. Dienerowitz, M. Mazilu, and K. Dholakia, Journal of Nanophotonics, Vol. 2, 021875 (2008)

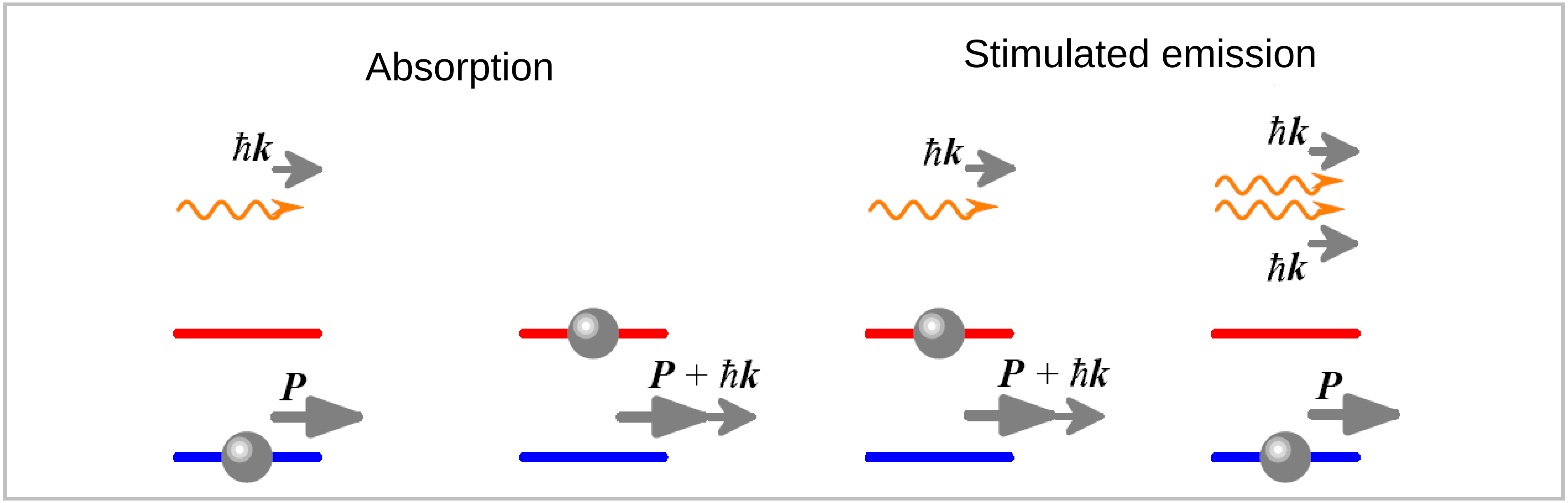
Optical forces acting on a metall nanoparticle



Optical forces acting on a gold nanoparticle ($n = 0.86 - 1.85i$) in water.

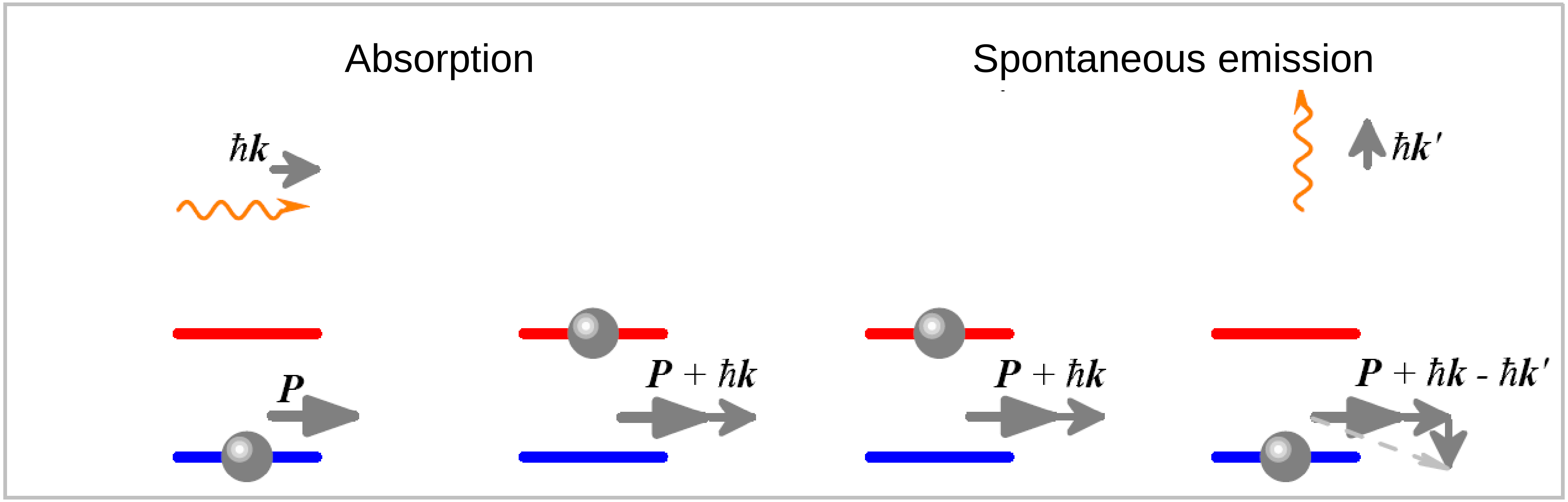
M. Dienerowitz, M. Mazilu, and K. Dholakia, Journal of Nanophotonics, Vol. 2, 021875 (2008)

Elementary processes of interaction of light with atoms. Absorption vs stimulated emission



$$F = 0$$

Elementary processes…
Absorption vs spontaneous emission



$$\boxed{\vec{F} = \frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + [2(\delta - \vec{k} \cdot \vec{v})/\gamma]^2}}$$

- scattering (spontaneous, radiative) force

s_0 is the dimensionless intensity. For large s_0

$$\vec{F} = \frac{\hbar \vec{k} \gamma}{2}$$

FORCE IN WEAK STANDING WAVE

For one beam $$\vec{F} = \frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + [2(\delta - \vec{k} \cdot \vec{v})/\gamma]^2}$$

For other beam $$\vec{F} = -\frac{\hbar \vec{k} \gamma}{2} \frac{s_0}{1 + s_0 + [2(\delta + \vec{k} \cdot \vec{v})/\gamma]^2}$$

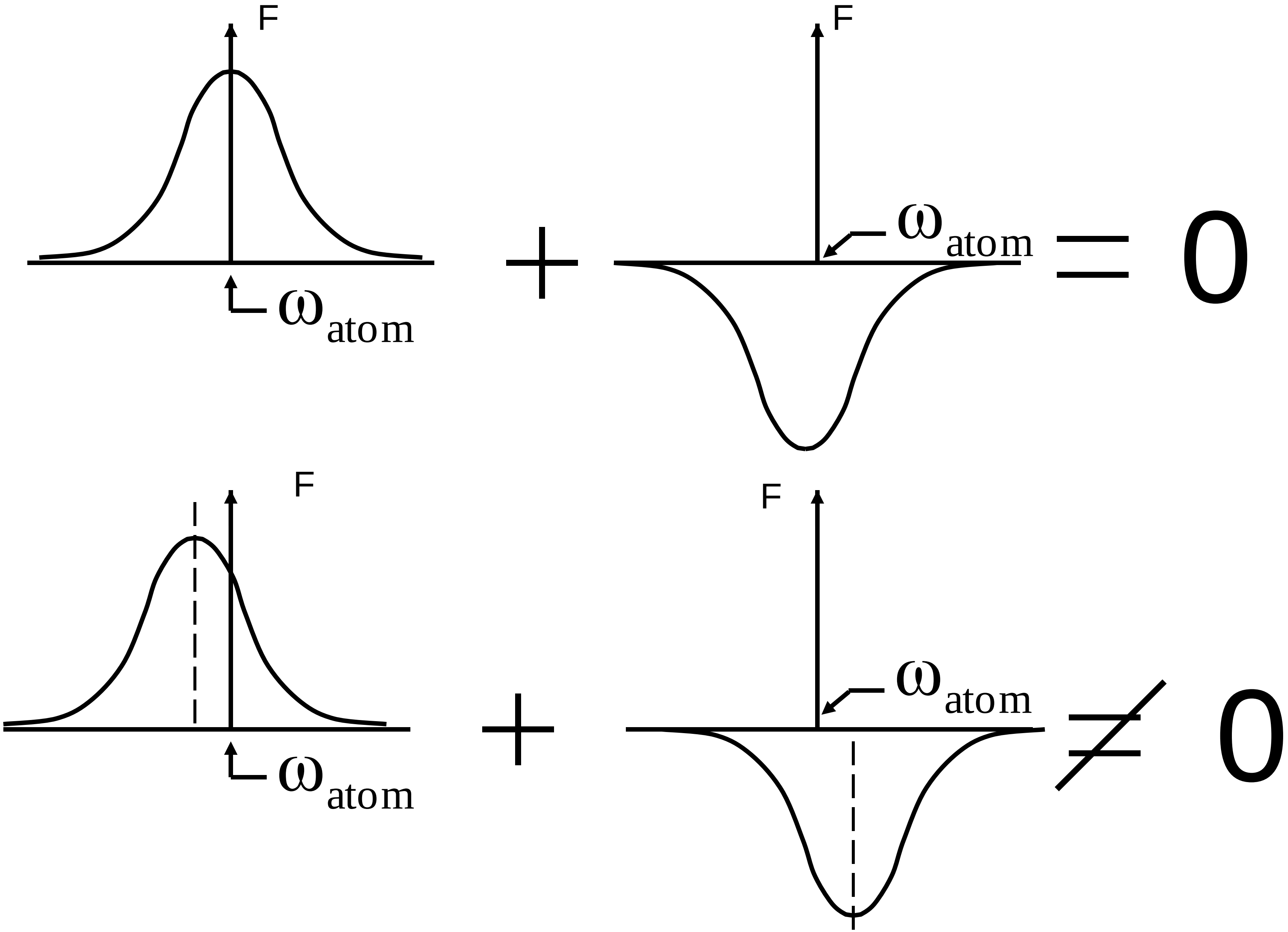
Add them together, make approximation that $(\vec{\mathbf{k}} \cdot \vec{\mathbf{v}}/\gamma)^4 \ll 1$, and find

$$\vec{F}_{\text{tot}} = \frac{8\hbar k^2 \delta s_0 \vec{v}}{\gamma[1 + s_0 + (2\delta/\gamma)^2]}$$

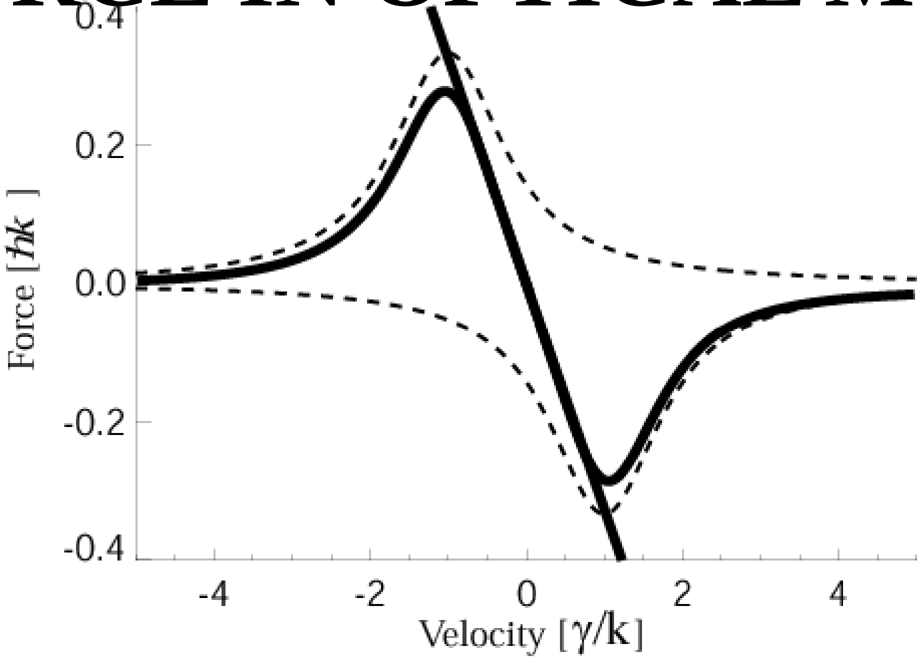
$\vec{\mathbf{F}}$ is opposite to $\vec{\mathbf{v}}$ for $\delta < 0$. Also, $\vec{\mathbf{F}} \propto \vec{\mathbf{v}}$ (small $|\vec{\mathbf{v}}|$)

Called “optical molasses”

GRAPHICAL CALCULATION OF FORCE



THE FORCE IN OPTICAL MOLASSES

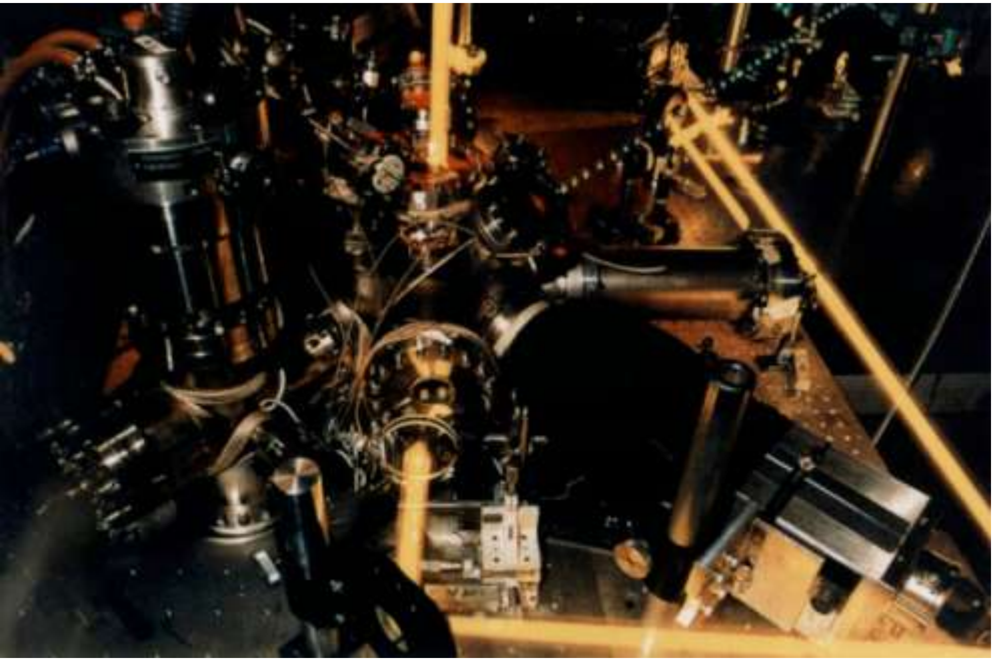


$$\boxed{\vec{F}_{tot} = \frac{8\hbar k^2 \delta s_0 \vec{v}}{\gamma[1 + s_0 + (2\delta/\gamma)^2]}}$$

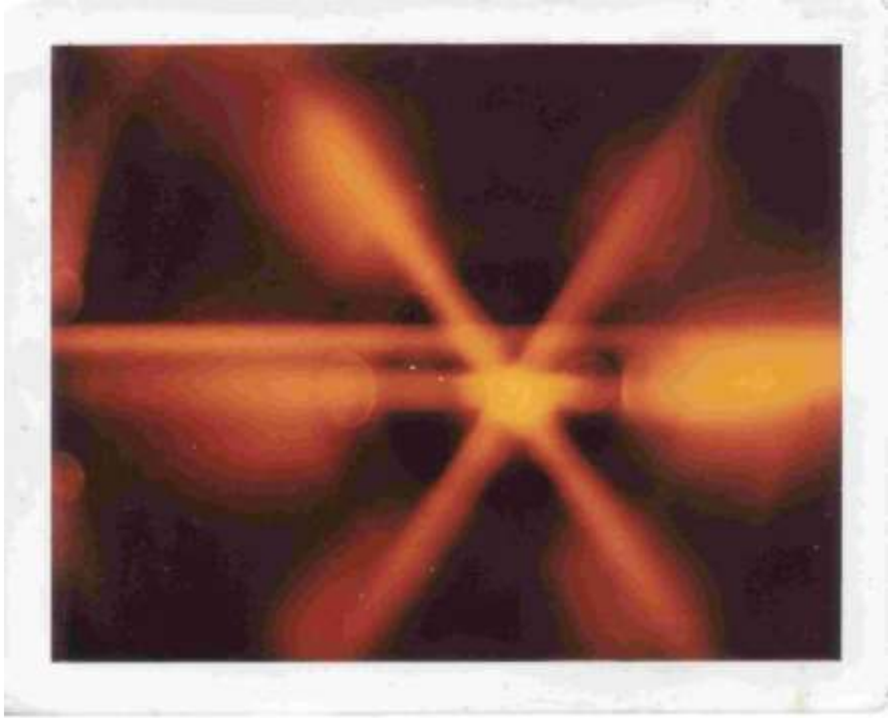
Pure damping force!!

It vanishes only when all atoms have v=0 !

MOLASSES EXPERIMENTS (I)



Steven Chu experimental setup



Taken with an ordinary camera - 1986

COOLING LIMIT(I)

Of course we can never cool to $T = 0$, and the limit is set because the damping force isn't continuous. There is a little spontaneous emission "bump" of finite size $\hbar k$ accompanying each absorption, and these constitute a heating effect because they're random.

The cooling and heating compete with each other, and steady state (NOT EQUILIBRIUM !) is reached when the rates become equal.

The cooling rate is the damping force times the velocity.

$$\left.\frac{dE}{dt}\right|_{\text{cool}} = \vec{F}\vec{v} = \frac{8\hbar k^2 \delta s_0 |\vec{v}|^2}{\gamma[1 + s_0 + (2\delta/\gamma)^2]^2}$$

COOLING LIMIT (II)

The heating rate is straightforward. Each absorption must supply at least the kinetic energy $E_R = (\hbar k)^2/2M \equiv \hbar\omega_r$, so conservation of energy requires the light frequency to be $\omega_a + \omega_r$.

The atomic energy $\hbar\omega_a$ of each spontaneous emission must be shared with kinetic energy of recoil, so conservation of energy requires the fluorescence frequency to be $\omega_a - \omega_r$.

The light field loses energy $\hbar[(\omega_a + \omega_r) - (\omega_a - \omega_r)] = 2\hbar\omega_r$ so the atoms gain this as kinetic energy at the spontaneous emission rate γ_p.

$$\left.\frac{dE}{dt}\right|_{heat} = (2\hbar\omega_r)\frac{s_0\gamma/2}{1+s_0+[2\delta/\gamma]^2}$$

COOLING LIMIT (III)

So we set the cooling rate and heating rates equal:

$$\left.\frac{dE}{dt}\right|_{cool} = \left.\frac{dE}{dt}\right|_{heat}$$

and obtain

$$mv^2 = \frac{\hbar\gamma}{4}\left[\frac{2\delta}{\gamma} + \frac{\gamma}{2\delta}\right]$$

which is minimum at $|\delta| = \gamma/2$ so the kinetic energy is $\hbar\gamma/4$, or

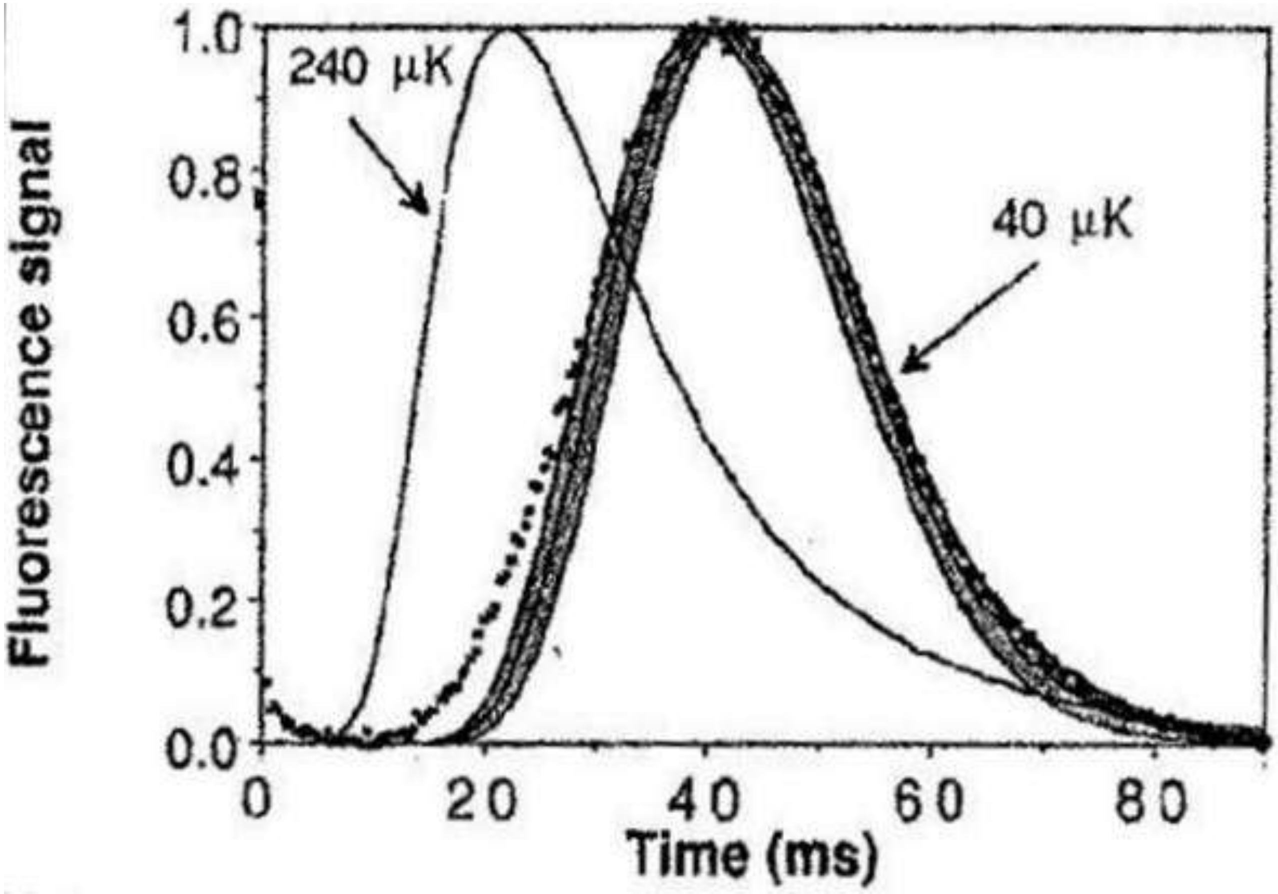
$$\boxed{T = \hbar\gamma/2k_B}$$

This is the “Doppler cooling limit” and is typically a few hundred μK

MOLASSES EXPERIMENTS (II)

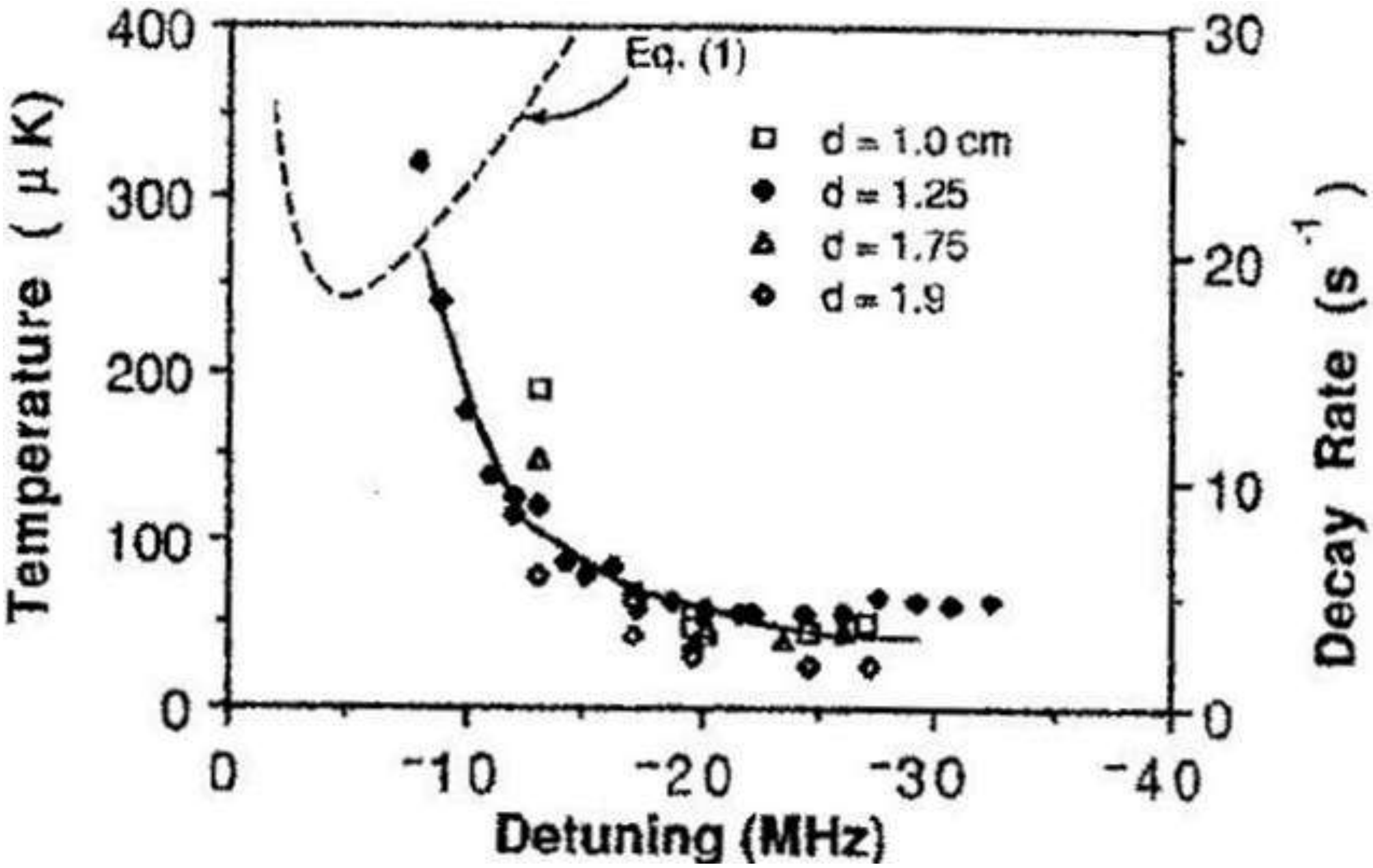
Experiments to measure $T = \hbar\gamma/2k_B$, and especially its dependence on δ, failed dramatically. T was too low!!

Time of flight calculations and measurements



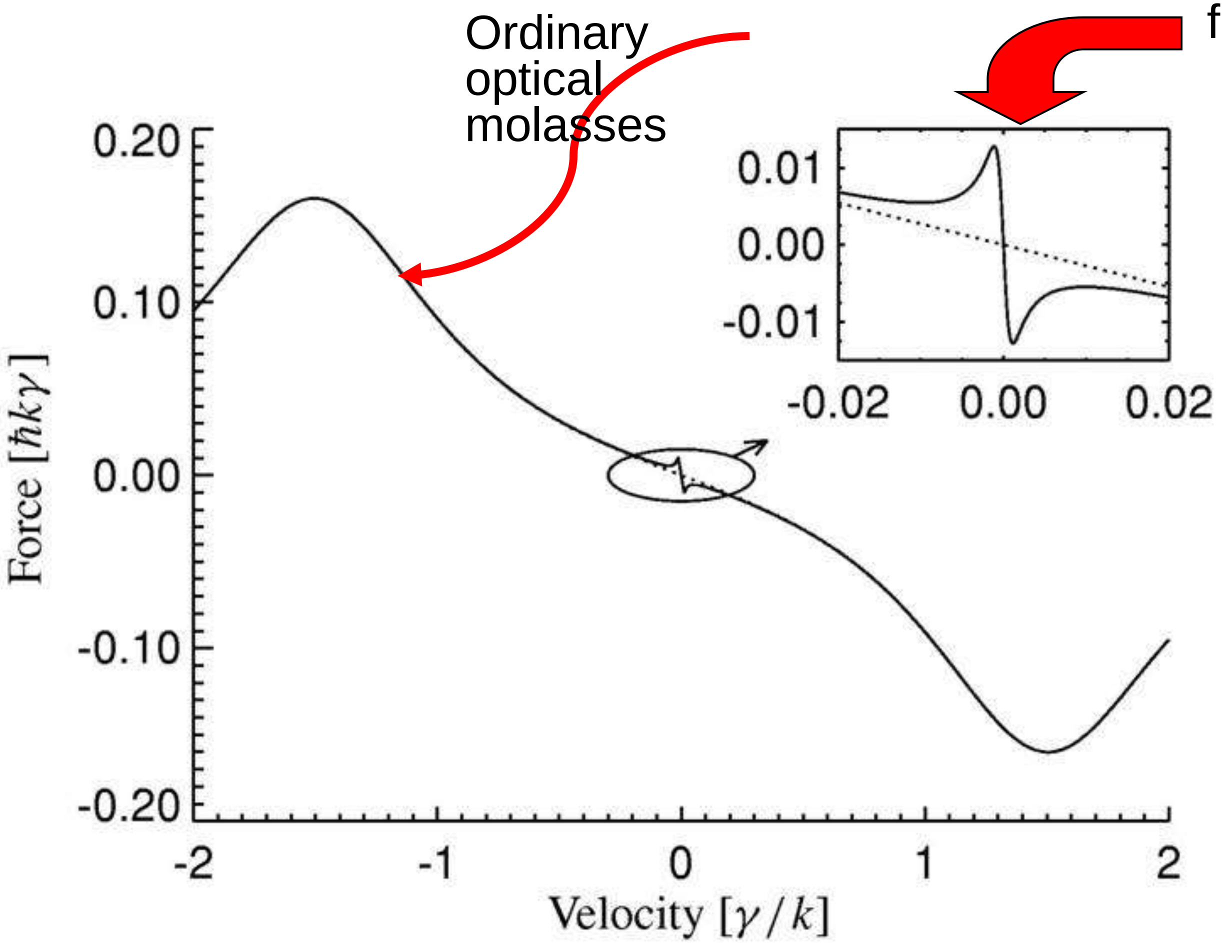
MOLASSES EXPERIMENTS (III)

Temperatures extracted from TOF measurements



Clearly something was wrong!

AVERAGE FORCE vs. VELOCITY (multilevel atom)



Ordinary optical molasses

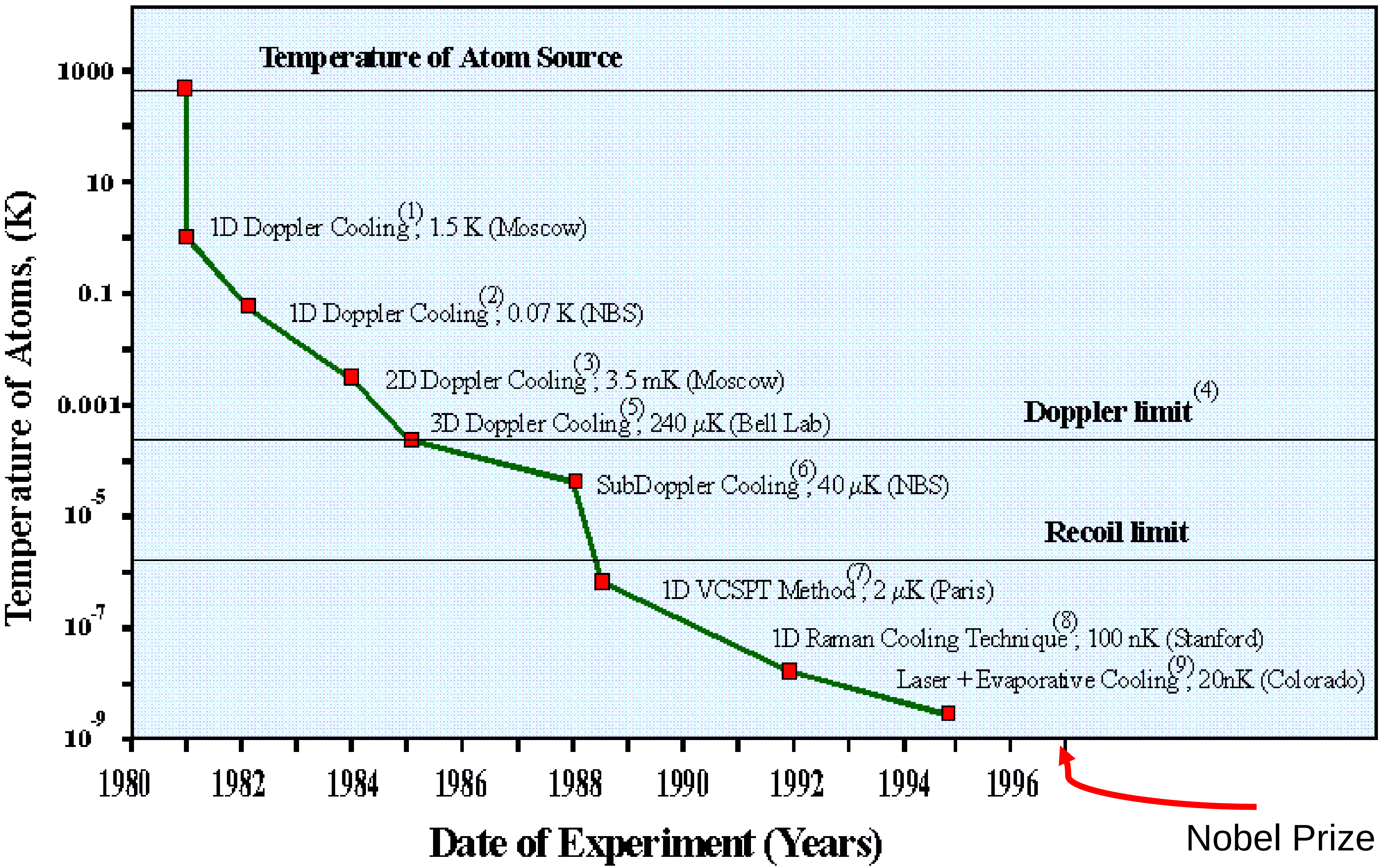
polgrad force

The experimental limit was a “few” recoils $v \sim v_R \sim 4$ mm/s.

This is a Fourier transform limit in space:

$$\Delta p \, \Delta z \geq \hbar$$

Progress in Laser Cooling of Neutral Atoms
(Milestone's Experiments)

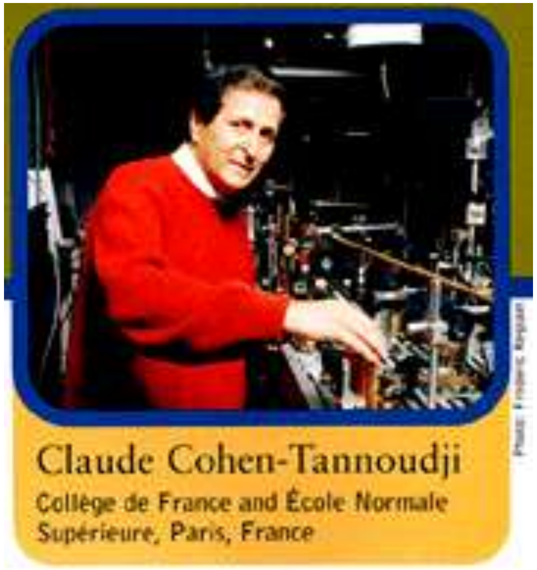


Nobel Prize (!)

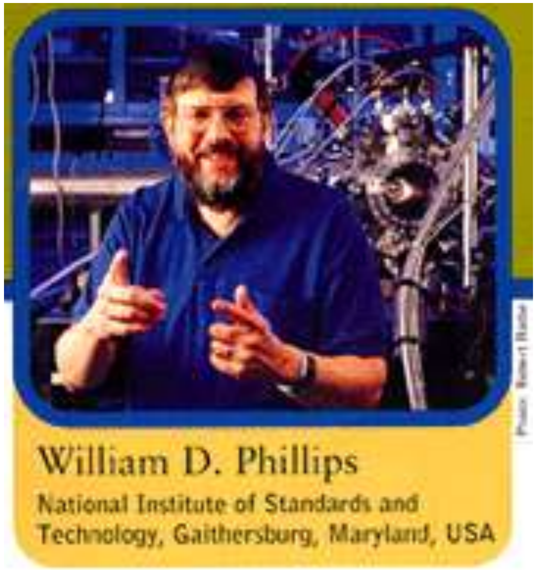
The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to
Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**
for their developments of methods to cool and trap atoms with laser light.

Steven Chu
Stanford University, Stanford, California, USA



Claude Cohen-Tannoudji
Collège de France and École Normale Supérieure, Paris, France



William D. Phillips
National Institute of Standards and Technology, Gaithersburg, Maryland, USA

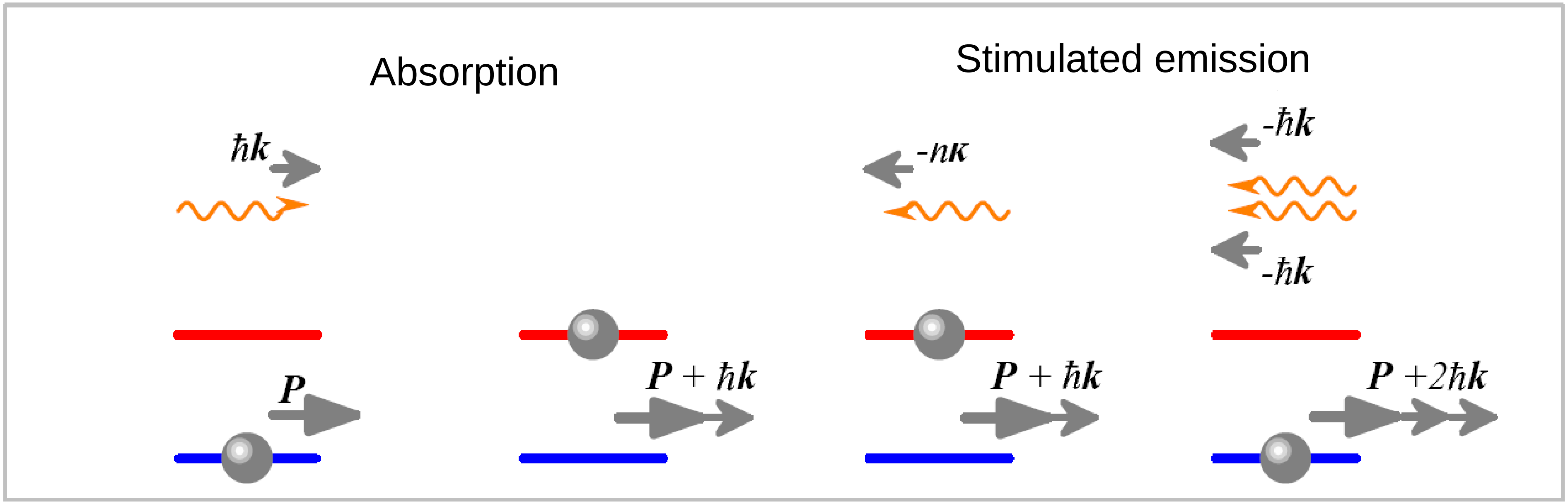
Hal Metcalf and Vladilen Letokhov– the forth and fifth(?) Nobel prize winners

Stony Brook,
SUNY (2000)

Lenin State Prize (1978)
jointly V.P. Chebotayev

Elementary processes of interaction of light with atoms.

Absorption vs stimulated emission in counterpropagating wave



Absorption

Stimulated emission

$$F = \frac{2\hbar k}{T}$$

Stimulated force

increases with the rate of of transitions

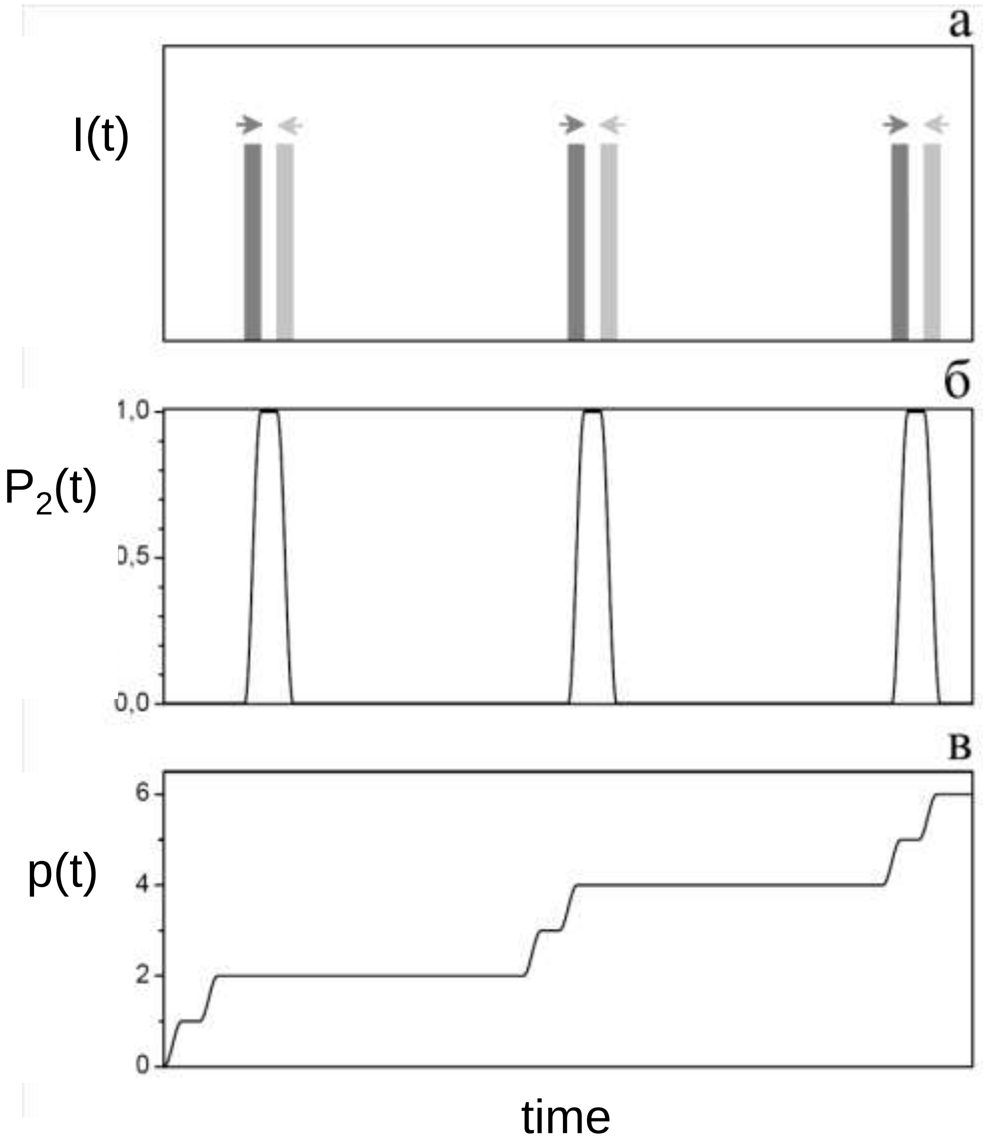
How we can organize this?

Pi-pulses !

half-cycle of Rabi oscillation provides complete population transfer between two states

$$F_\pi = \frac{2\hbar k}{T}$$

Kazantsev, Sov Phys JETP **39** 784 (1974)



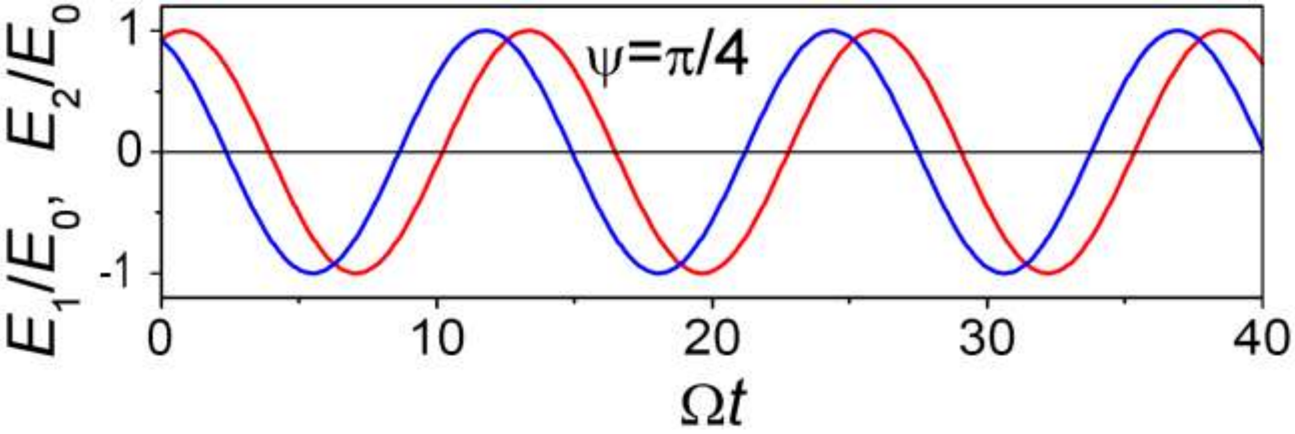
Bichromatic force

Counter-propagating amplitude modulated waves

$$\mathrm{E}(t) = E_1(t) + E_2(t)$$

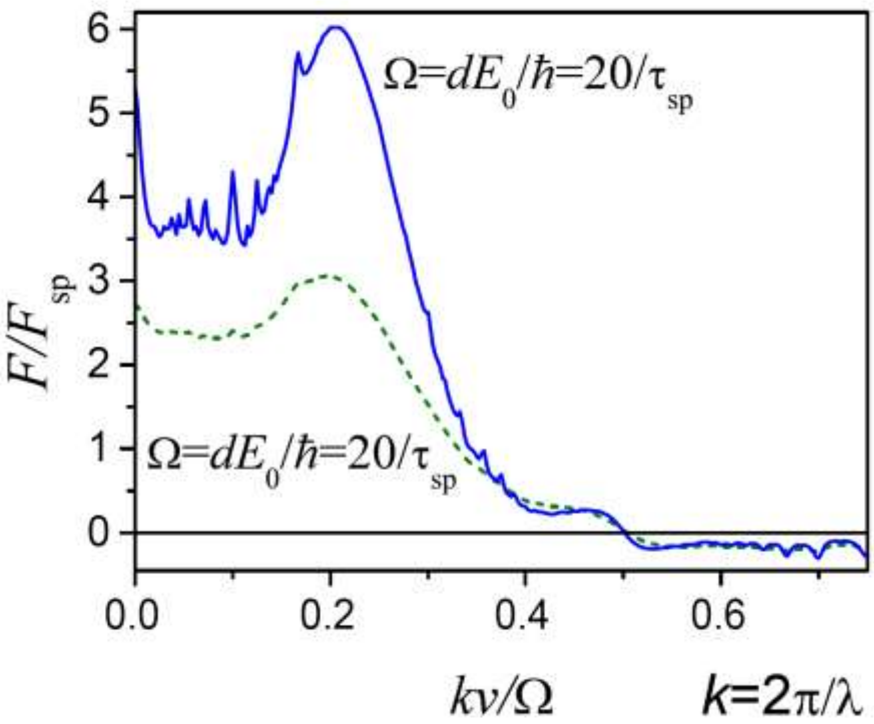
$$E_1(t) = E_0 \cos(\omega t - kz)\cos\left(\tfrac{1}{2}\Omega t - \tfrac{1}{2}\psi\right)$$

$$E_2(t) = E_0 \cos(\omega t + kz)\cos\left(\tfrac{1}{2}\Omega t + \tfrac{1}{2}\psi\right)$$



V. S. Voitsekhovich et al., Sov. Phys. Tech. Phys. 33, 690 (1988);

Bichromatic force- velocity dependence



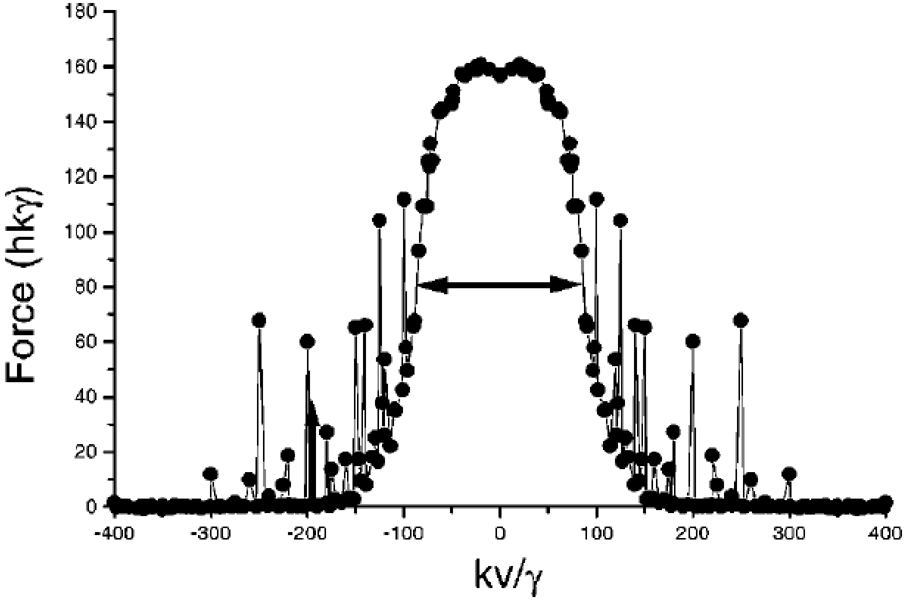
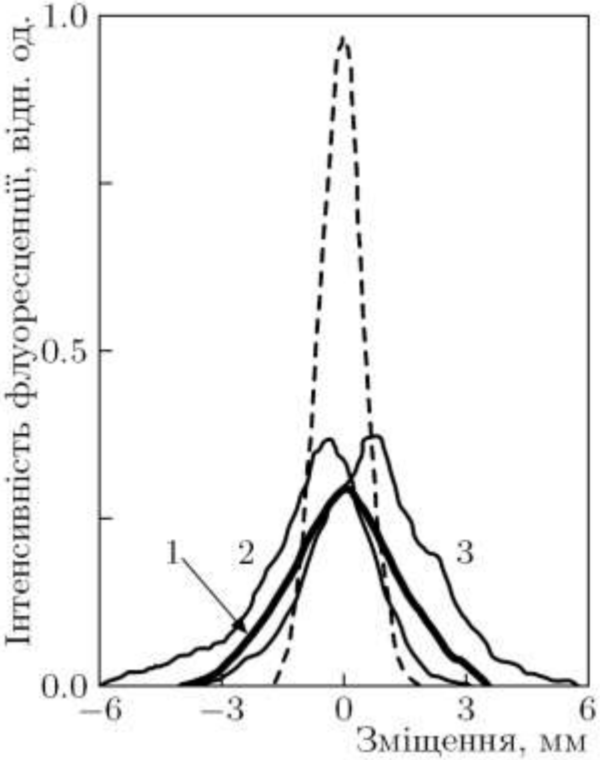


FIG. 9. The force as function of the velocity for $\delta = 500\gamma$ in optimal case of $\Omega_0 = 500\sqrt{6}\gamma$ and $\chi_0 = \pi/4$.

Yatsenko L., Metcalf H. Dressed-atom description of the bichromatic force. Physical Review A, V. 70, N 6, 063402 (2004)

First observation of stimulated force

V. Voitsekhovich et al., JETP Lett. 49, 161 (1989)



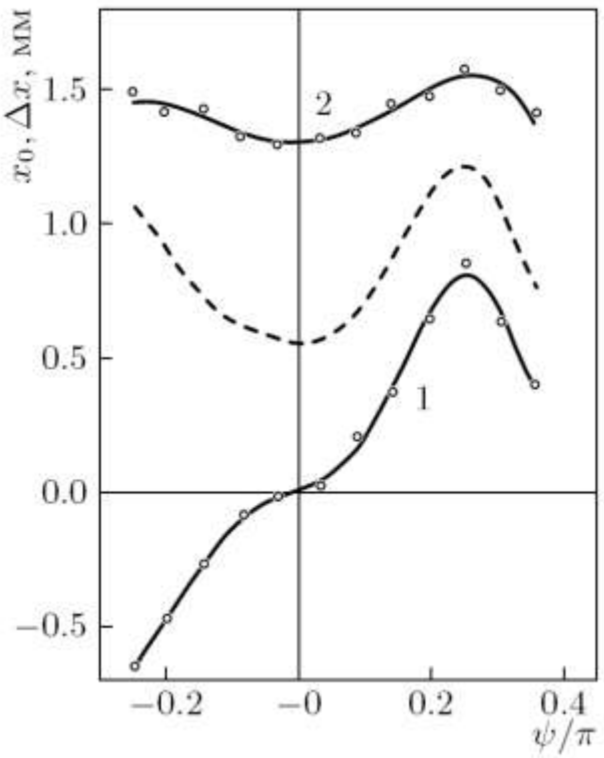


Рис. 30. Функція поперечного просторового розподілу пучка атомів Na в площині спостереження: 1 — $\psi = 0$, 2 — $\psi = -\pi/4$, 3 — $\psi = \pi/4$. Штриховою лінією показано поперечний розподіл без лазерного випромінювання

Рис. 31. Залежність зсуву центра мас x_0 (крива 1) і розмивання Δx (крива 2) пучка від різниці фаз ψ амплітудної модуляції зустрічних хвиль. Штриховою лінією показано розмивання пучка без урахування імпульсної дифузії

Recent results

PHYSICAL REVIEW A **70**, 063402 (2004)

Dressed-atom description of the bichromatic force

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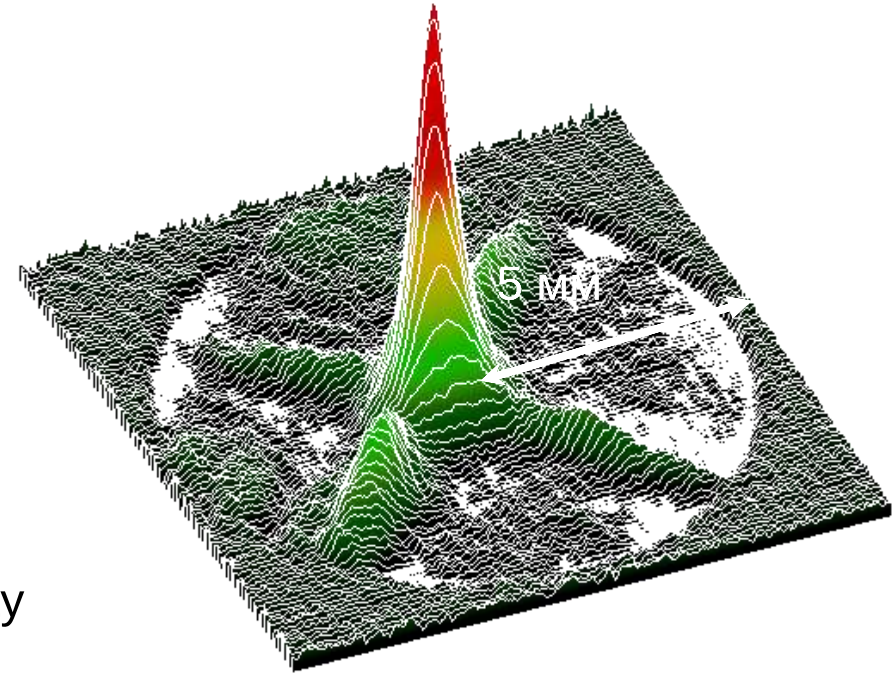
Harold Metcalf
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11790-3800, USA
(Received 21 July 2004; published 2 December 2004)

He beam collimation



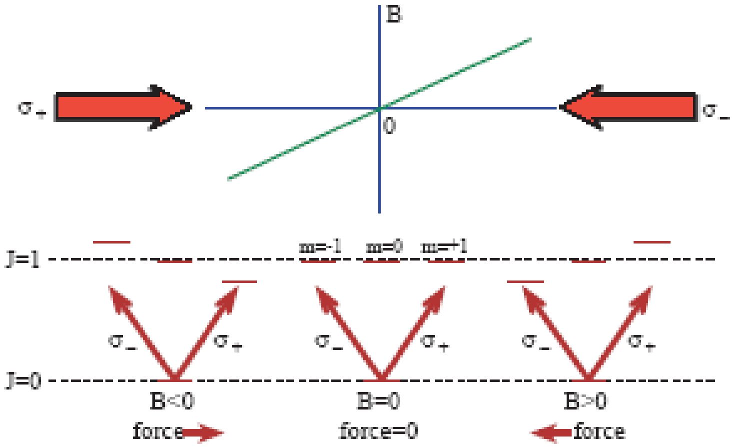
Bichromatic Slowing of Metastable Helium
M. A. Chieda and E. E. Eyler

arXiv:1207.4989v1 [physics.atom-ph]
Physics Department, University of Connecticut, Storrs, CT 06269
(Dated: **July 23, 2012**)

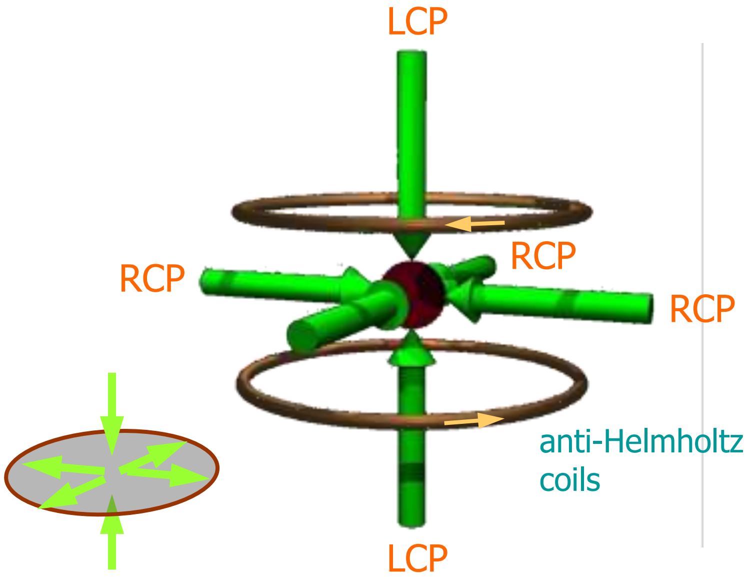
Helium atoms are slowed by 370 m/s using a BCF profile with a velocity width of <125 m/s

Magneto-optical trap (MOT)

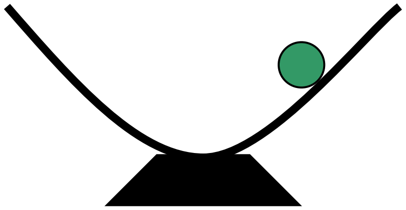
- Cooling, velocity-dependent force: Doppler effect
- Trapping, position-dependent force: Zeeman effect



1-D case



3-D case

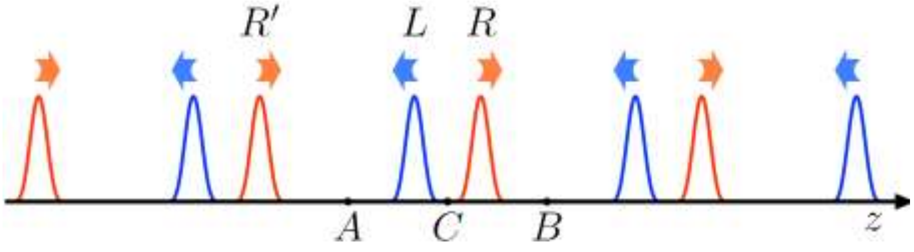


T. Peters, B. Wittrock, F. Blatt, T.Halfmann and L. P. Yatsenko.

Phys. Rev. A 85, 063416 (2012)

Thermometry of ultracold atoms by electromagnetically induced transparency

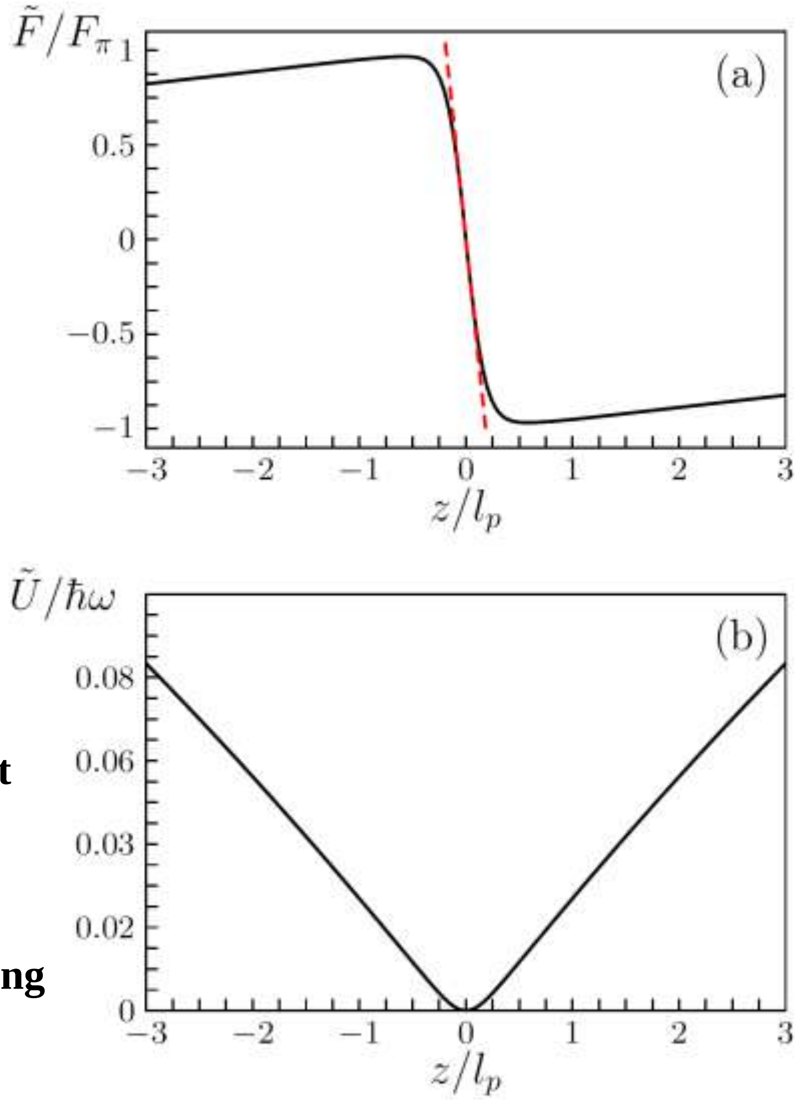
Trapping of atoms and nanoparticles by counterpropagating short pulse trains



Counterpropagating short pi-pulse trains
“collides” at C

T. G. M. Freegarde, J. Waltz, T W Hansch, **Confinement and manipulation of atoms using short laser pulses.** Opt. Commun. 117, 262-267 (1995)

V. I. Romanenko, L. P. Yatsenko, **Theory of one-dimensional trapping of atoms by counterpropagating short pulse trains,**
J. Phys. B: At. Mol. Opt. Phys. **44,** 115305 (2011)

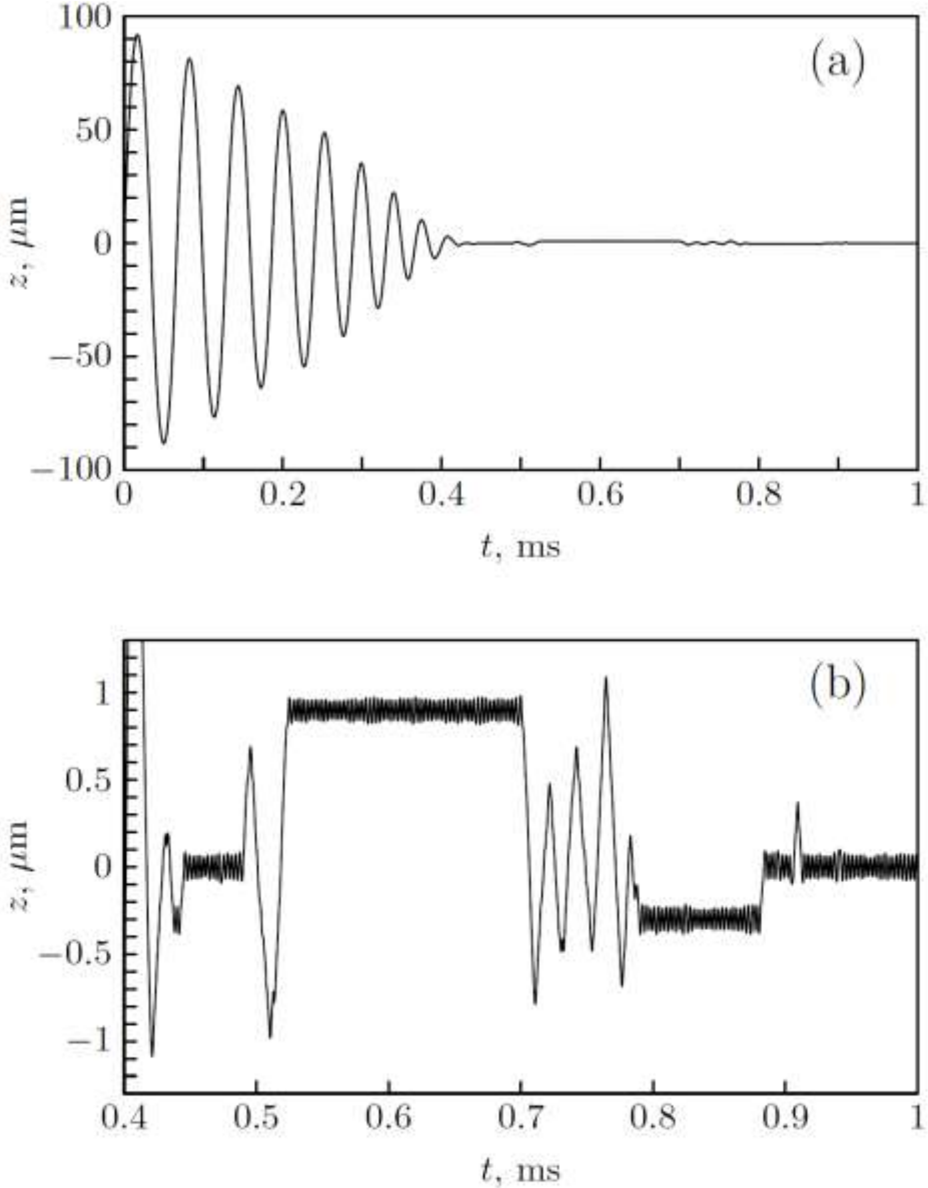


Motion of atoms and nanoparticles in pulse trap

Processes:

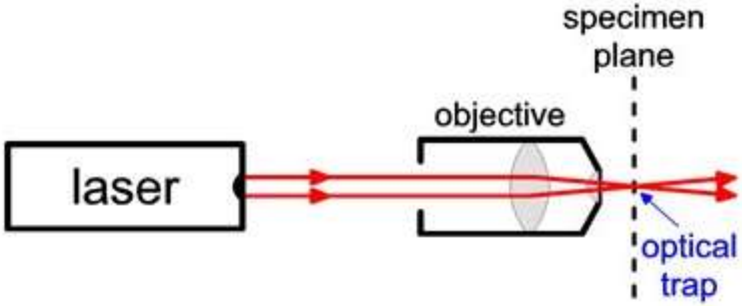
1. Momentum diffusion
2. Friction force (in the field of detuned pulses)

Parameters:
M=200 amu
Pi-pulses, τ= 1 ps, T = 10 ns,
λ=600 nm,
ω_0-ω = 10^{10} s^{-1}
$\gamma = 2\pi \cdot 10$ MHz
Initial conditions: z=0, v=10 m/s



V.I. Romanenko, A.V.Romanenko, Ye.G.Udoviska, L.P. Yatsenko, **Momentum diffusion of atoms and nanoparticles in the trap formed by counterpropagating trains of light pulses**, Submitted to UJP

Optical Tweezers



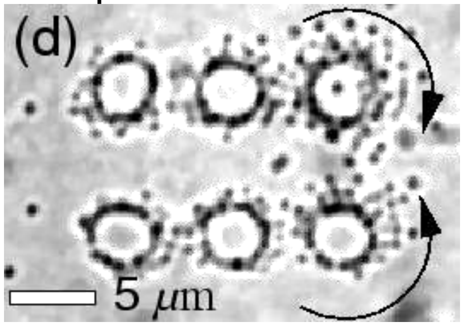
http://www.stanford.edu/group/blocklab/Optical%20Tweezers%20Introduction.htm

Mesoscopic scale –

- 10’s of nm – 100’s of μm,
- forces from femtonewtons - nanonewtons,
- time scales ranging from a microsecond and up.

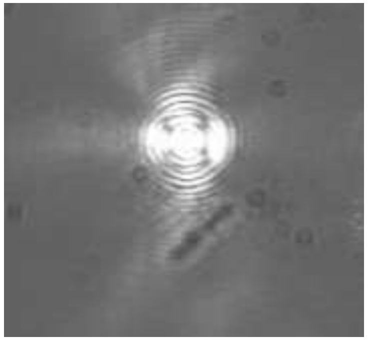
Trapped : dielectric spheres, viruses, bacteria, living cells, organelles, small metal particles, and even strands of DNA.

Trapped dielectric spheres in optical vortices



http://physics.nyu.edu/grierlab/pump2b/

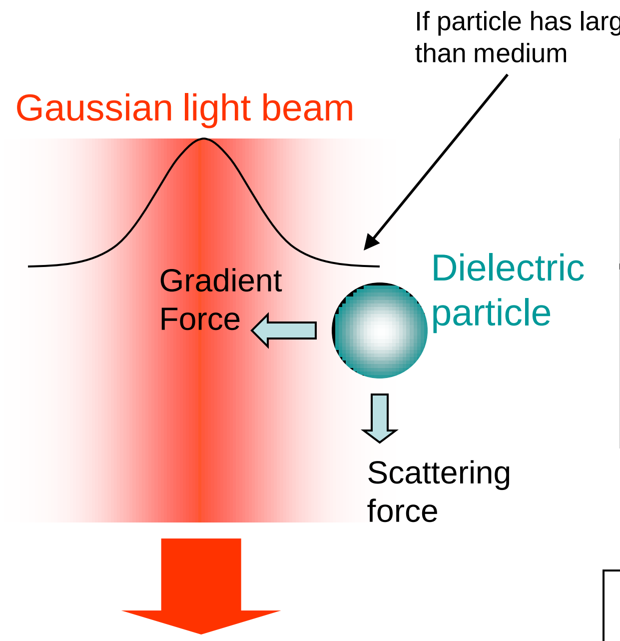
Bacteria



http://www.nbi.dk/~tweezer/dk/mobilitet.htm

Optical Tweezers Physics

- Scattering force (in direction of light propagation)
- Gradient force (in direction of light intensity gradient)
- Trapping stable when gradient force > scattering force. (Fallman 97)



If particle has larger index than medium

Gaussian light beam

Gradient Force

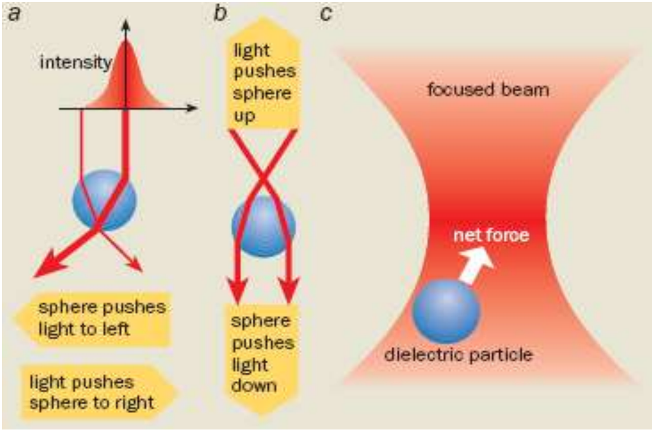
Dielectric particle

Scattering force

Maximize

$\frac{\text{Gradient force}}{\text{Scattering force}}$ ratio

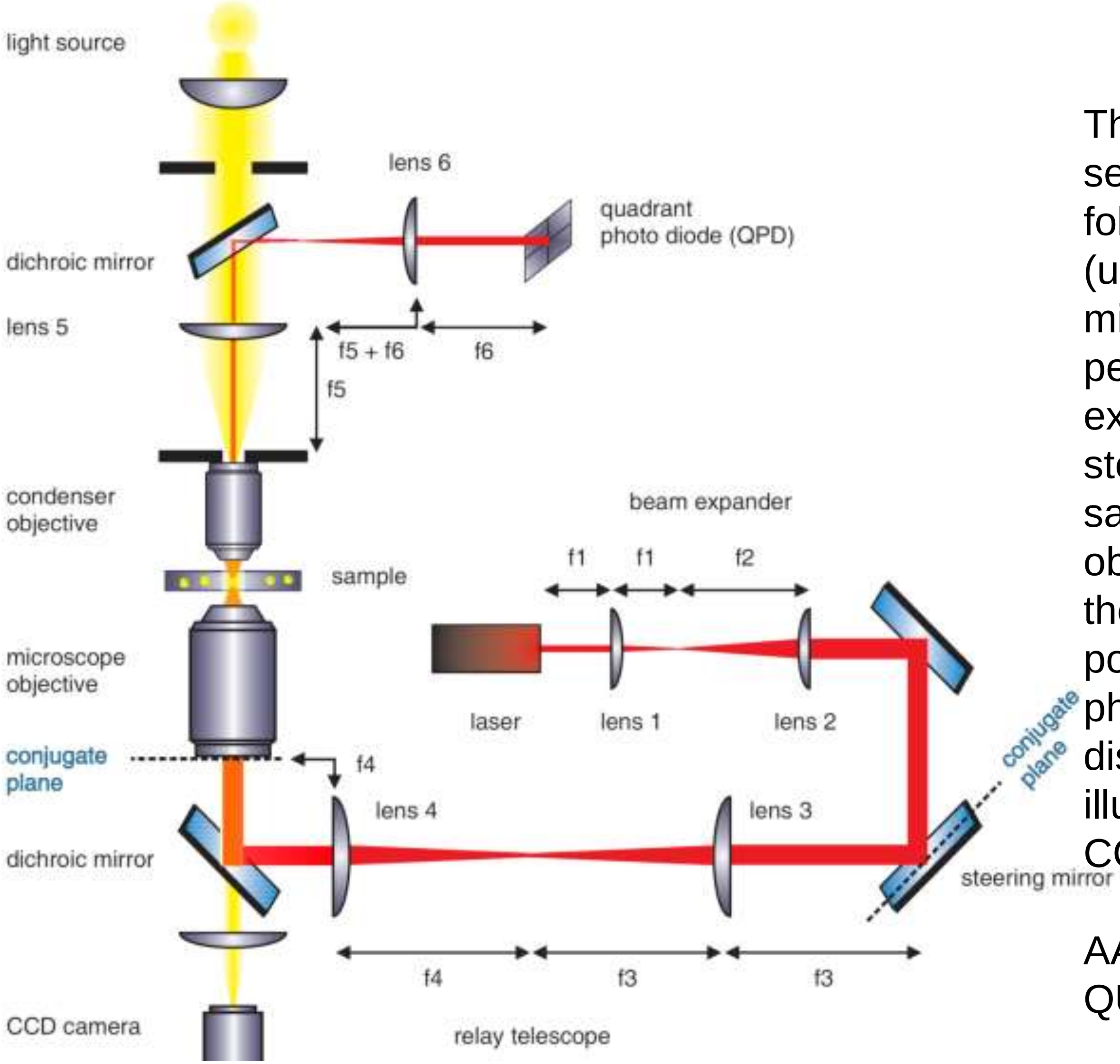
focus beam using a high NA objective lens.



After Dholakia (2002)

The single most important element of the OT is the objective lens used to focus the trapping laser.

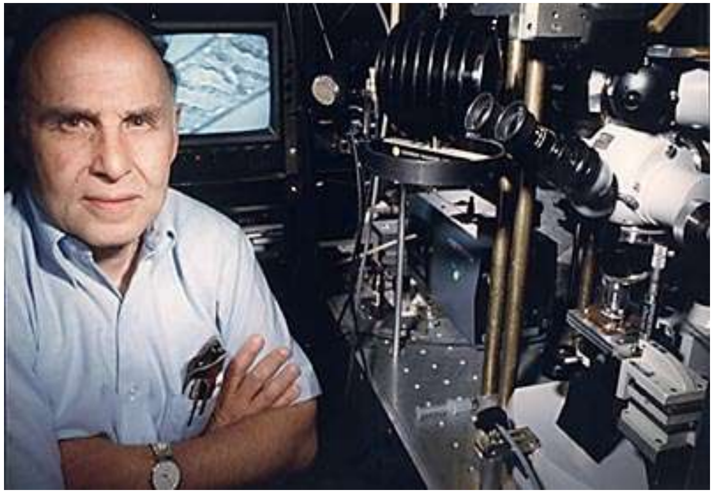
A generic optical tweezer diagram



The most basic optical tweezer setup will likely include the following components: a laser (usually Nd:YAG, estimated minimum optical power required per trap ~5 mW), a beam expander, some optics used to steer the beam location in the sample plane, a microscope objective and condenser to create the trap in the sample plane, a position detector (e.g. quadrant photodiode) to measure beam displacements and a microscope illumination source coupled to a CCD camera.

AA OPTO-ELECTRONIC
QUANTA TECH

History of optical trapping



http://www.bell-labs.com/user/feature/archives/ashkin/

Undated photo – Arthur Ashkin

Timeline

1958 Invention of Laser,

1970 Arthur Ashkin levitates micron sized particles, Bell Labs,

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

1986 Demo of Optical tweezers

1987 Ashkin manipulates live bacteria and viruses

1989 Block&Berg measure stiffness of bacterial flagella

1990 Steven Chu reports manipulation of DNA using OT

1991 Karl Greulich and colleagues use optical tweezers to isolate individual chromosomes

1993 J. J. Krol develops multiple trap system

1993…a whole bunch of biology stuff I don't know how to appreciate…2004

2004 Block builds first combination optical trap/fluorescence instrument

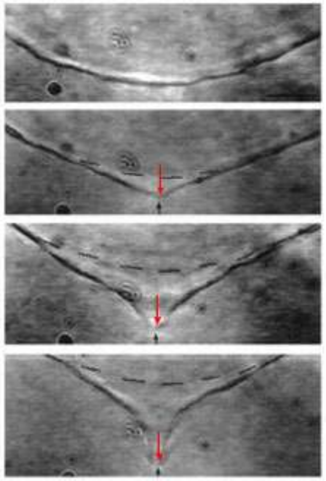
2004-2008 OT of plasmonic nanoparticles

Adapted from article by Don Monroe, "The Optical Trap", *The Scientist* 2005, **19**(16)**:**48

Optical trapping applications

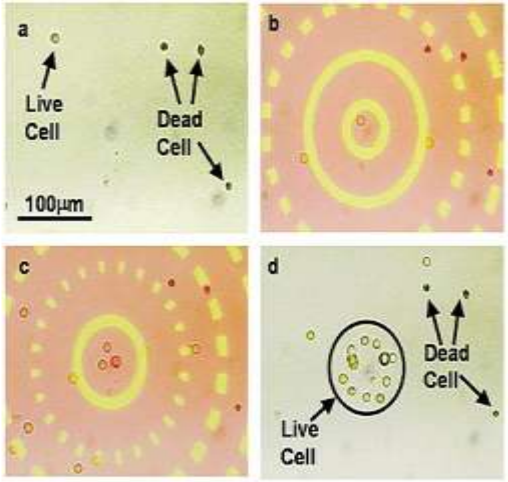
- ***Physics***
  - tool to study the physics of colloids, aerosols and mesoscopic systems
- ***Nanotechnology***
  - manipulation and assembly of carbon nanotubes and nanoparticles
- ***Biology***
  - the study of molecular motors
  - protein conformational changes (folding / unfolding pathways)
  - protein-protein binding / unbinding processes
  - DNA-protein interactions
  - DNA mechanical properties
  - single cell experiments including cell transport, positioning, sorting, assembling and patterning
  - cell nanosurgery
  - optical guiding and force measurements for the mechanical characterization of cells
  - study of intracellular processes in vivo
- ***Medicine and biomedical sciences***
  - in-vitro fertilization, cell-cell interaction, microbiology, immunology, stem-cell research, single-cell transfection, tissue engineering and regenerative medicine

Membrane deformation



http://mayoresearch.mayo.edu/mayo/research/hubmayr/strain_laser.cfm

Cell sorting

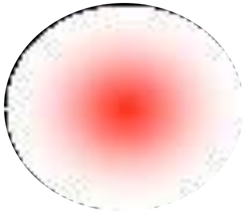


http://www.berkeley.edu/news/media/releases/2005/07/20_optotweezer.shtml

Adapted from article by Ione Verdeny et al., "Optical trapping: A review of essential concepts ", Opt. Pura Apl. 44 (3) 527-551 (2011)

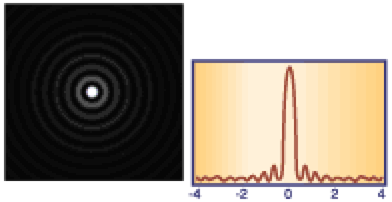
The technology of optical trapping:

Beam types and trapping shapes



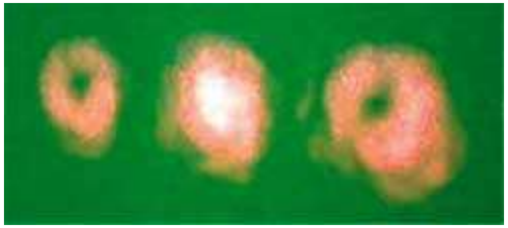
Gaussian Beams

Bessel Beams

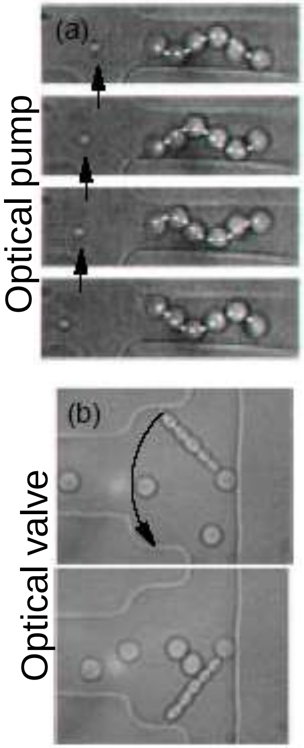


http://oemagazine.com/fromTheMagazine/jan03/tutorial.html

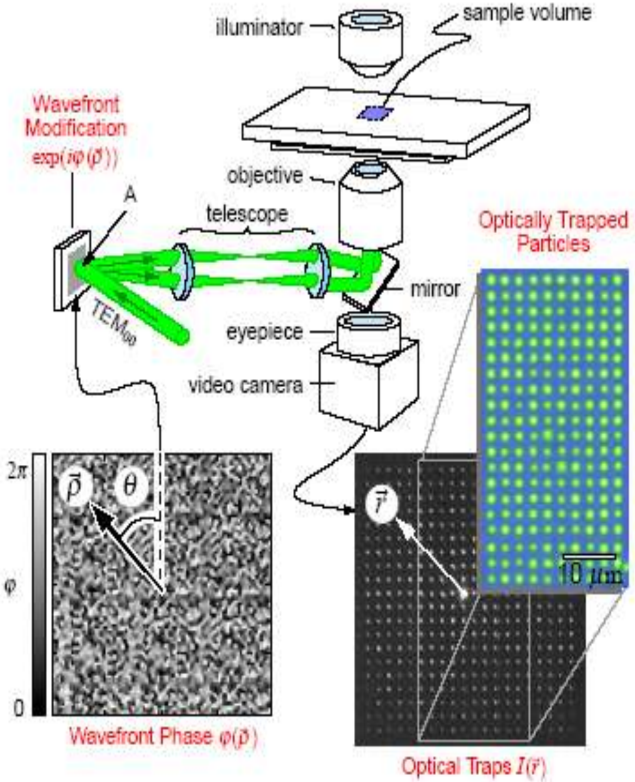
Holographically generated Laguerre-Gaussian beams



http://www.phys.ucl.ac.uk/department/AnnRev2005/amop.html



After Terray, et al. (2002)

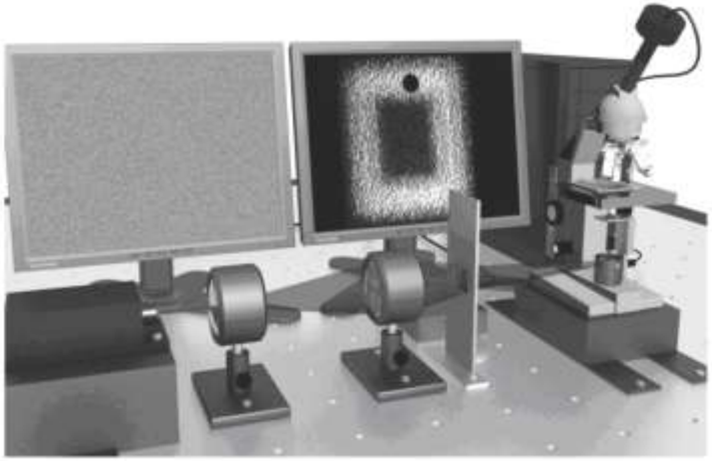


Holographic beam steering system

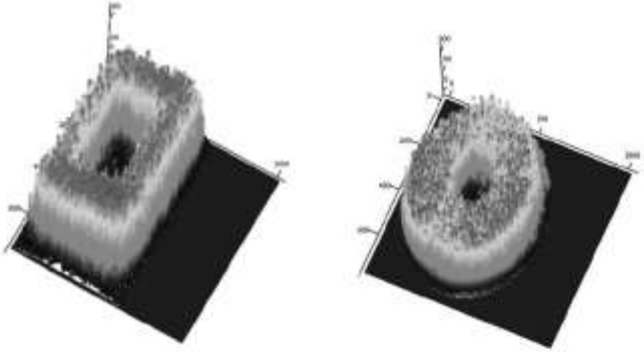
After Grier (2003)

Terray, A., Aokey, J & Marr, D. W. M. Fabrication of linear colloidal structures for microfluidic applications. Appl. Phys. Lett. 81, 1555-7 (2002); Terray, A., Aokey, J & Marr, D. W. M. Microfluidic control using colodial devices, Science 296, 1841-4 (2002)

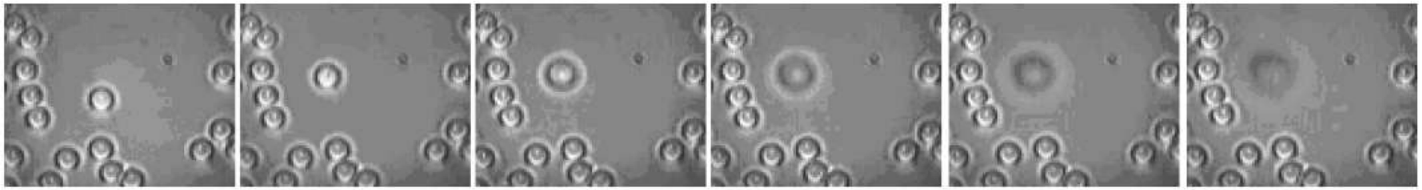
Holographic optical tweezer in IoP NANU



OT setup



Laser beams obtained using SLM



Trapping of dielectric particle

Commercial Optical trapping systems -- Cell Robotics --

http://www.cellrobotics.com

Cell Robotics Premier workstation

http://www.cellrobotics.com/workstation/pws.html

OT work stations

Add-on modules for existing microscopes.

Laser scissors ® system :

shorts bursts of UV light from a nitrogen laser to ablate specimen parts with sub-micron precision.

Commercial Optical trapping systems

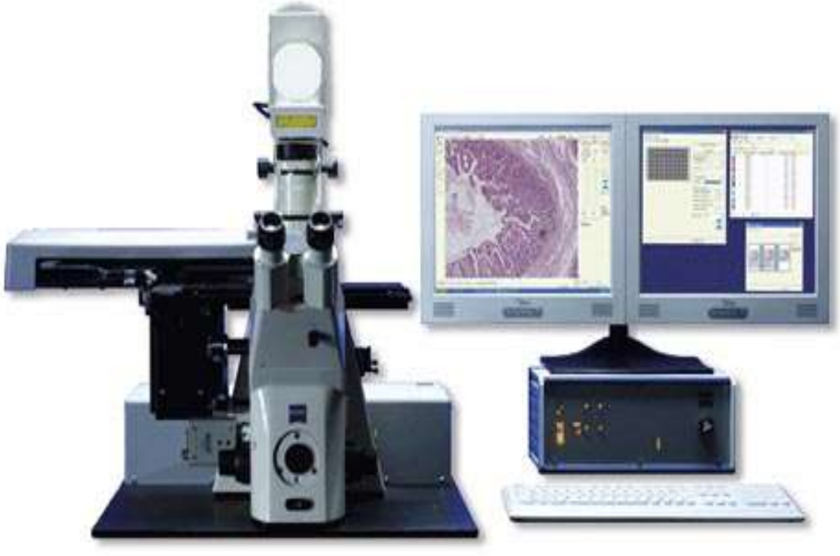
-- P.A.L.M. Microlaser Technologies –

http://www.palm-microlaser.com

Laser **M**icrodissection and **P**ressure **C**atapulting (LMPC) technology

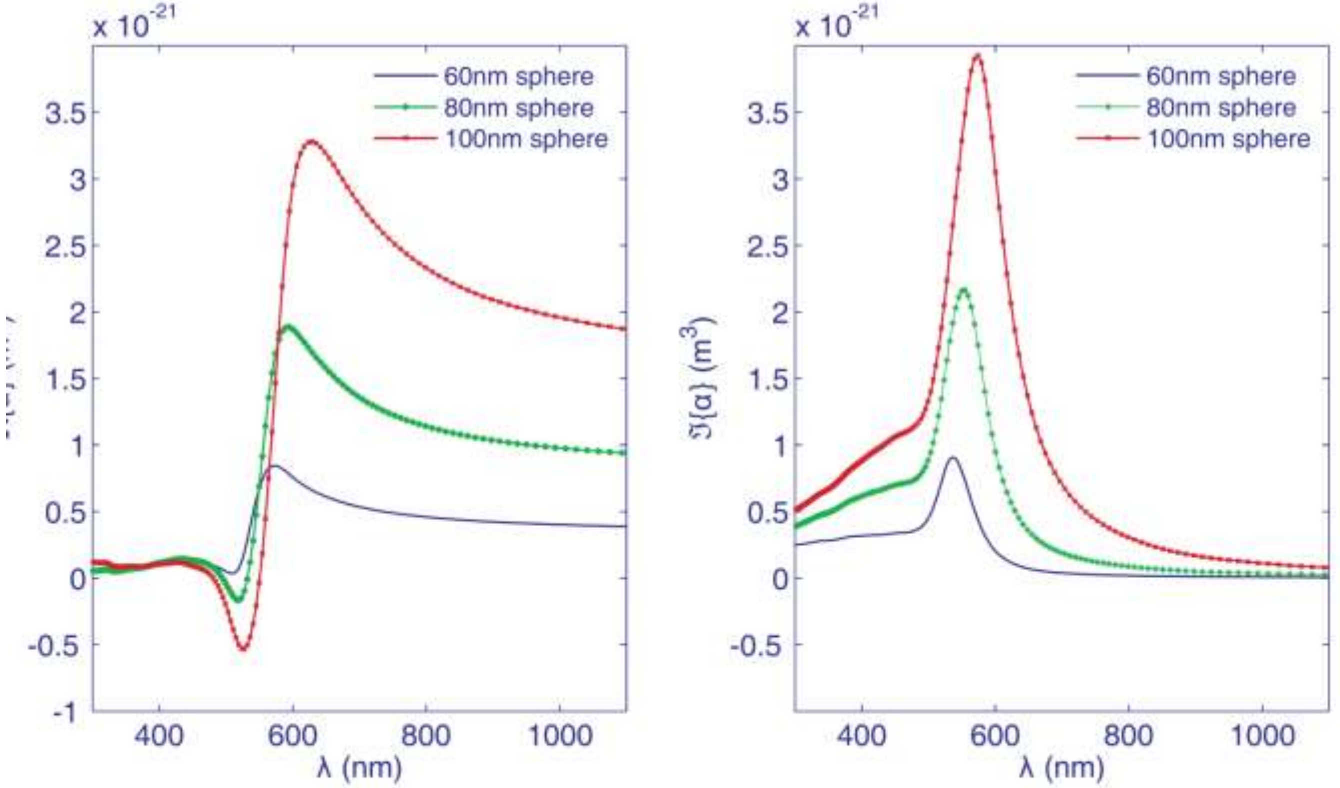
How does P.A.L.M.'s LMPC-technology function?
An UV beam is focused and used to cut out specimen.

The isolated specimens are ejected out of the object plane and catapulted directly into a sample holder with the help of a single defocused laser pulse and can be "beamed" several millimeters away, even against gravity.



http://www.palm-microlaser.com/dasat/

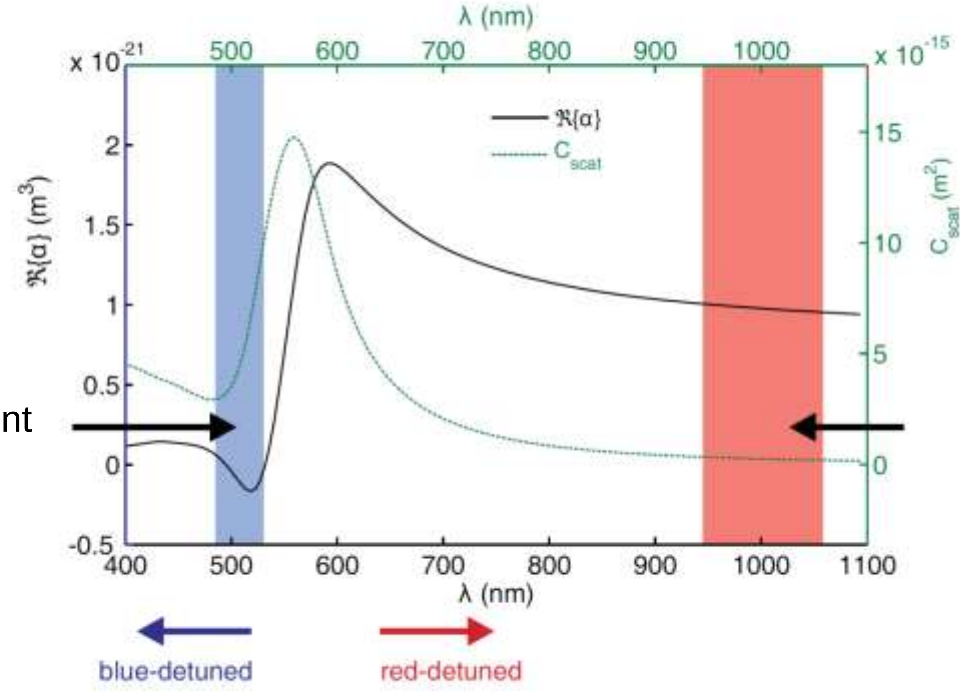
Optical trapping of metal nanoparticles (I)



The polarisability α_{ext} for gold nanospheres with various diameters.
The red-shifting and broadening of the resonance indicate that dynamic depolarisation and damping effects are included in the model. Another important change compared to the polarisability obtained with the static model is the negative real part below the resonance

M. Dienerowitz. PhD thesisat the University of St. Andrews (2010) http://hdl.handle.net/10023/1634

Optical trapping of metal nanoparticles (II)



optical confinement

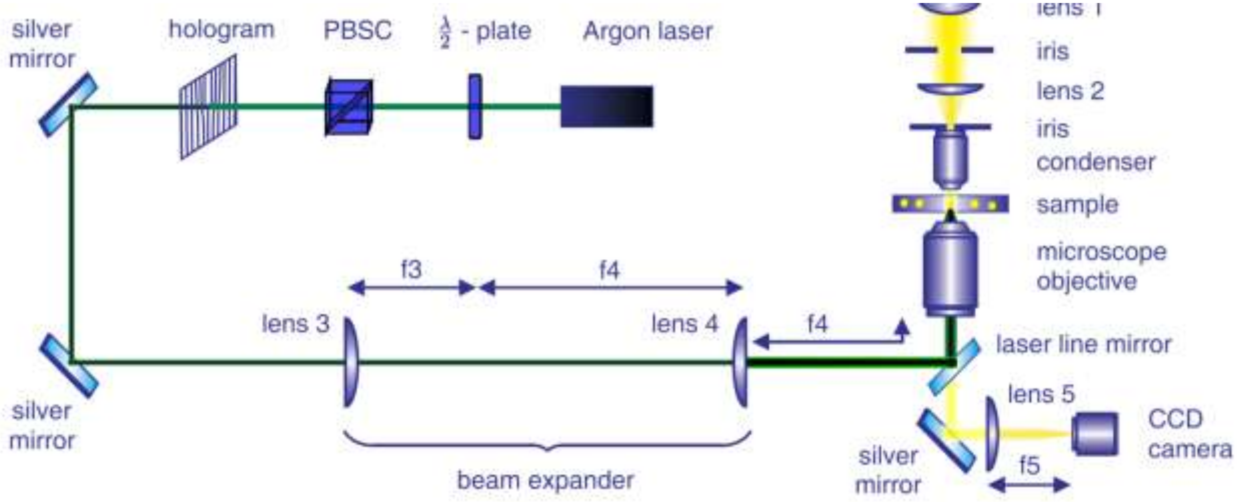
optical tweezing in 3D

The wavelenth dependence of the polarizability α (left axis) and scattering cross section C_{scat} (right axis) of a 80nm gold sphere.

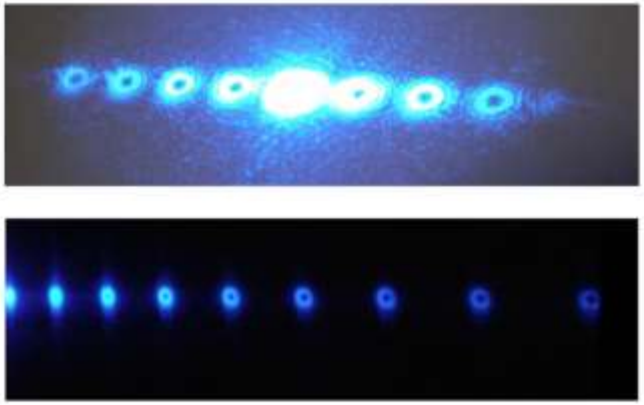
This wavelength dependence consequently appears in the trapping force, as it is the result of a fine balance between scattering and gradient force components. Marked are the wavelength regions investigated so far. The wavelength region above the resonance is commonly referred to as red-detuned, below as blue-detuned. Experiments characterising trapping of metal nanoparticles on the red-detuned side close to resonance are still lacking to date.

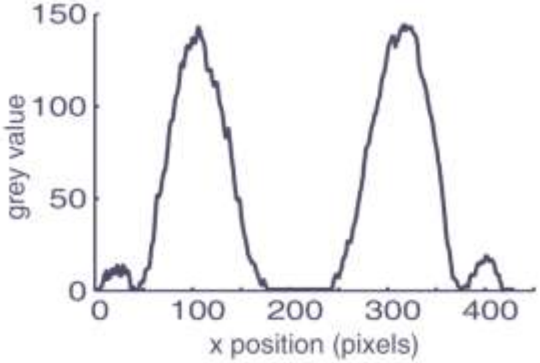
M. Dienerowitz. http://hdl.handle.net/10023/1634

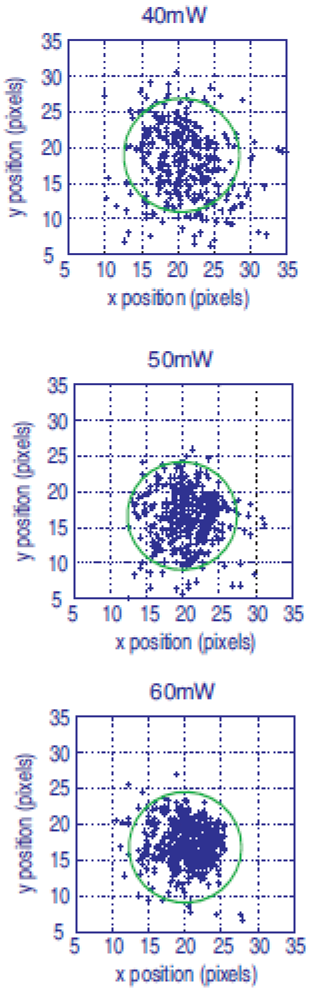
Optical trapping of metal nanoparticles (III)



Setup for the Laguerre-Gaussian (LG) trap



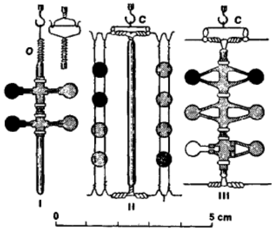


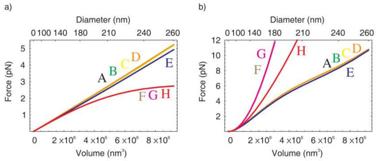


M. Dienerowitz. http://hdl.handle.net/10023/1634

1. Introduction

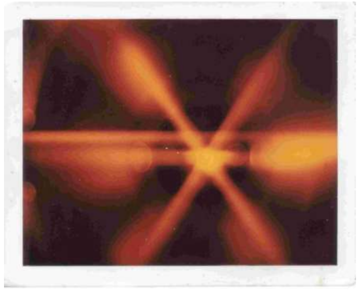
- light momentum and history of light pressure
- general description of light forces on small objects

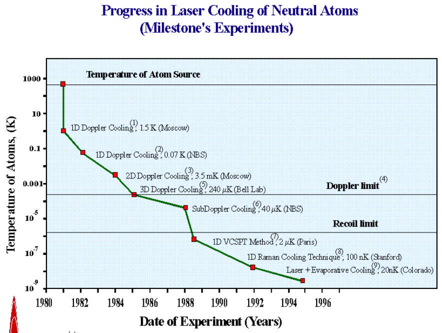


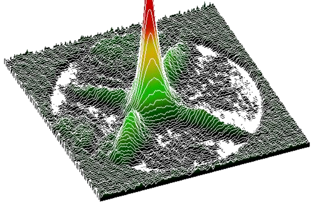


2. Laser cooling and trapping of atoms

- spontaneous light force
- Doppler cooling for a two-level atom
- sub-Doppler cooling
- stimulated light force
- magneto-optical trap (MOT)
- pulsed traps

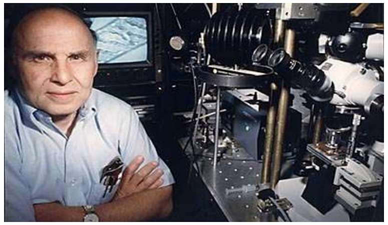


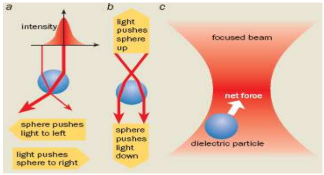




3. Optical tweezers

- history of optical trapping
- optical tweezers physics
- use of optical tweezers in bioapplications





4. Optical trapping of metall nanoparticles