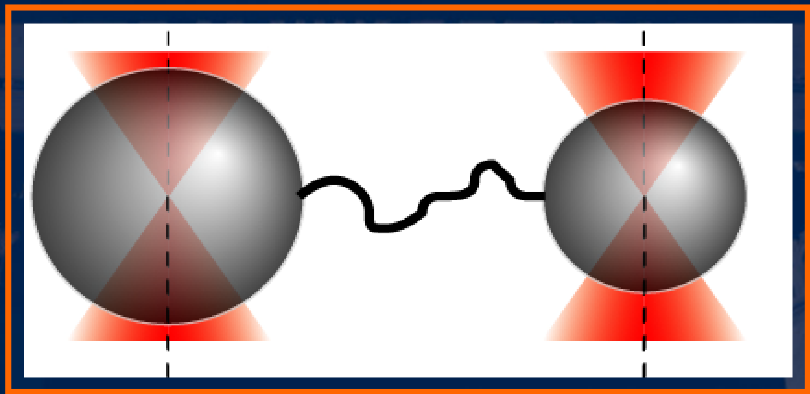

p = h/λ

UNIVERSITY OF ILLINOIS

AT URBANA-CHAMPAIGN

Yann Chemla

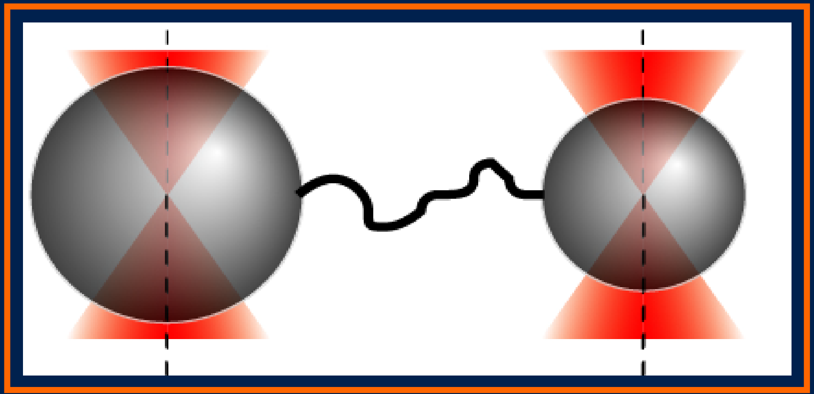


Phys 498 – Optical traps

1867

www.uiuc.edu

A Bit of History



Ashkin builds first optical trap

VOLUME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

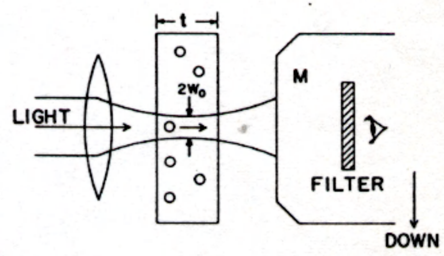
1970!

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

A. Ashkin
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 3 December 1969)

Micron-sized particles have been accelerated and trapped in stable optical potential wells using only the force of radiation pressure from a continuous laser. It is hypothesized that similar accelerations and trapping are possible with atoms and molecules using laser light tuned to specific optical transitions. The implications for isotope separation and other applications of physical interest are discussed.

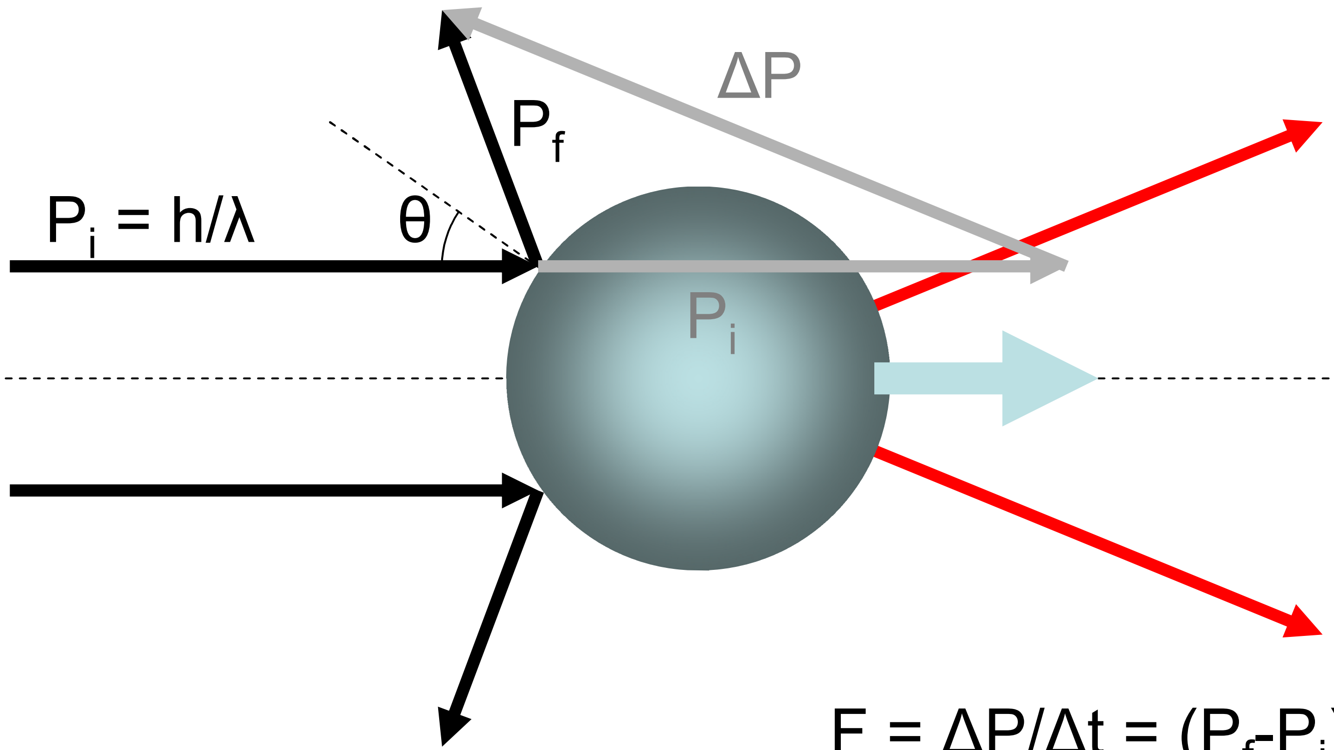
Nobel prize Physics, 1997



(a)

FIG. 1. (a) Geometry of glass cell, $t = 120\ \mu m$, for observing micron particle motions in a focused laser beam with a microscope *M*. (b) The trapping of a high-index particle in a stable optical well. Note position of the TEM_{00}-mode beam waists.

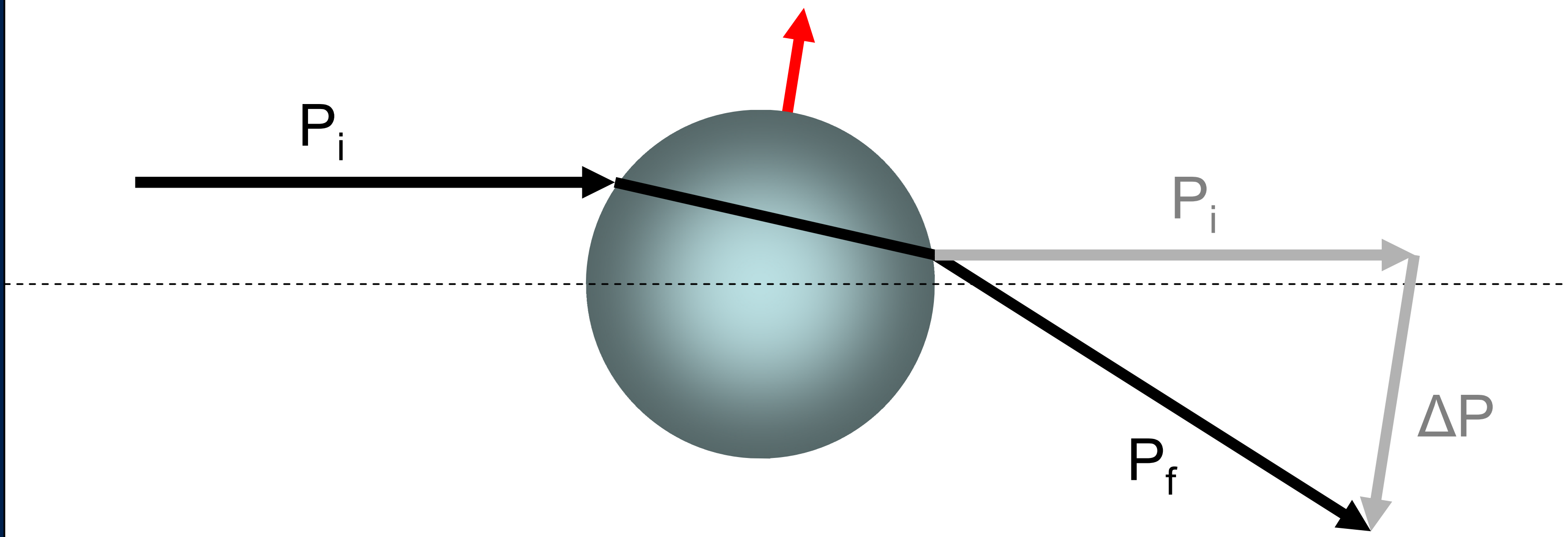
Optical scattering forces – reflection



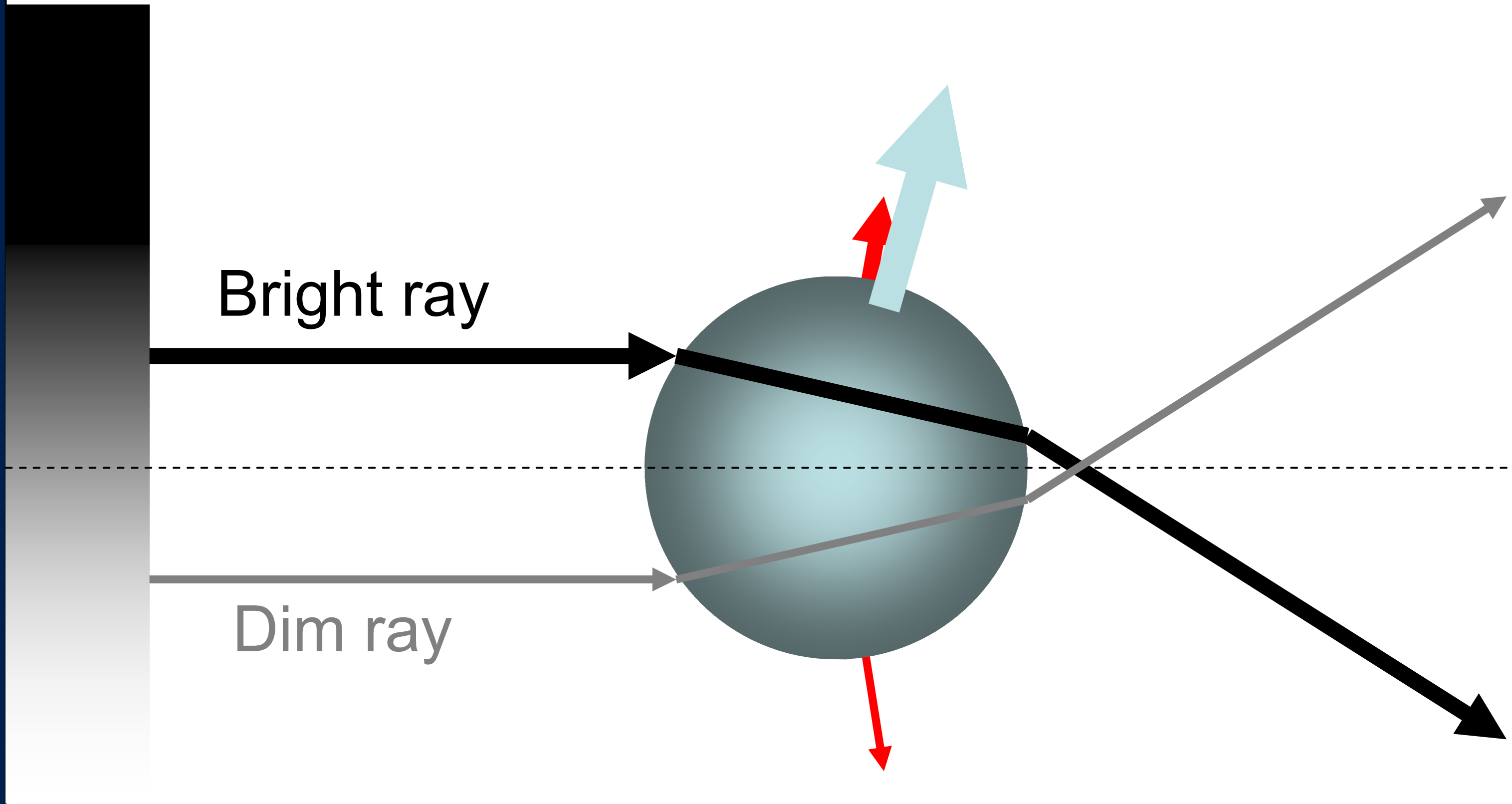
$$F = \Delta P/\Delta t = (P_f - P_i)/\Delta t$$

Newton's third law – for every action there is an equal and opposite reaction

Optical forces – Refraction

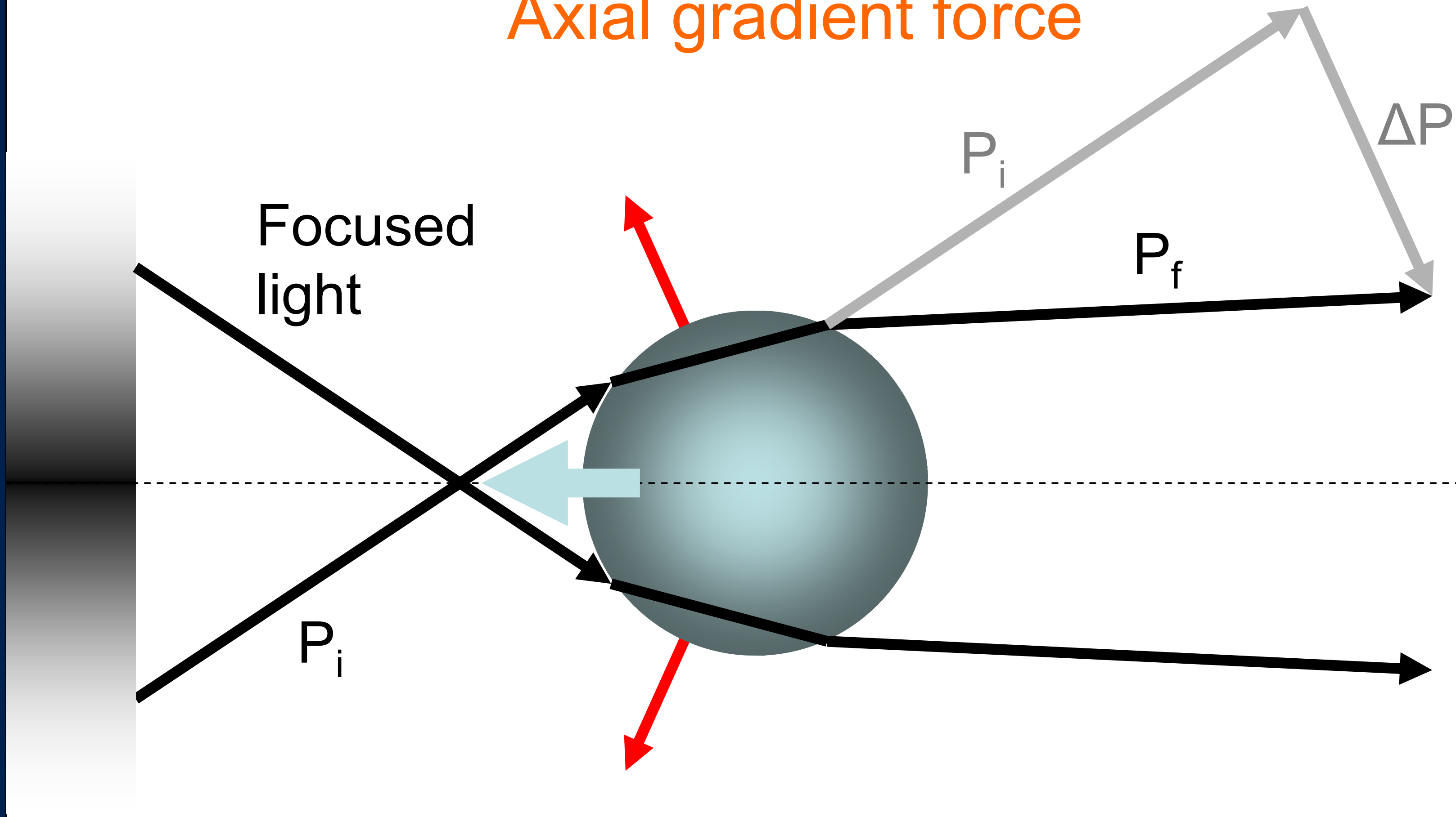


Lateral gradient force



Object feels a force toward brighter light

Axial gradient force



Object feels a force toward focus

Force ~ gradient intensity

Ashkin builds first optical trap

VOLUME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

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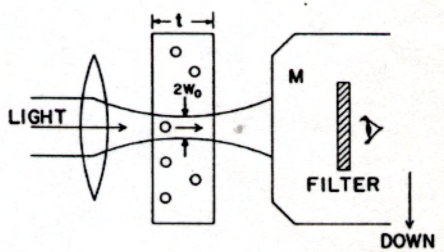

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FIG. 1. (a) Geometry of glass cell, $t = 120\ \mu m$, for observing micron particle motions in a focused laser beam with a microscope M. (b) The trapping of a high-index particle in a stable optical well. Note position of the TEM_{00}-mode beam waists.

Counter-propagating beams cancel scattering force

First single-beam gradient optical trap

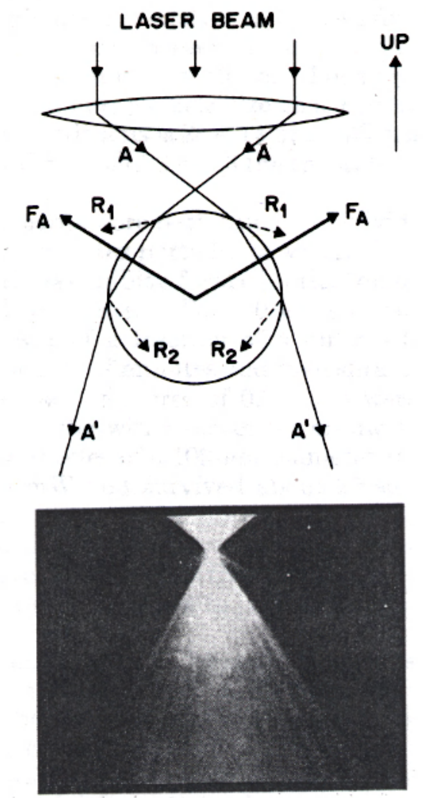
288 OPTICS LETTERS / Vol. 11, No. 5 / May 1986

Observation of a single-beam gradient force optical trap for dielectric particles

A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and Steven Chu

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Stable single-beam trap requires $F_{grad} > F_{scat}$ i.e., large gradient



b)

Fig. 1. a) Diagram showing the ray optics of a spherical Mie particle trapped in water by the highly convergent light of a single-beam gradient force trap. b) Photograph, taken in fluorescence, of a 10-μm sphere trapped in water, showing the paths of the incident and scattered light rays.

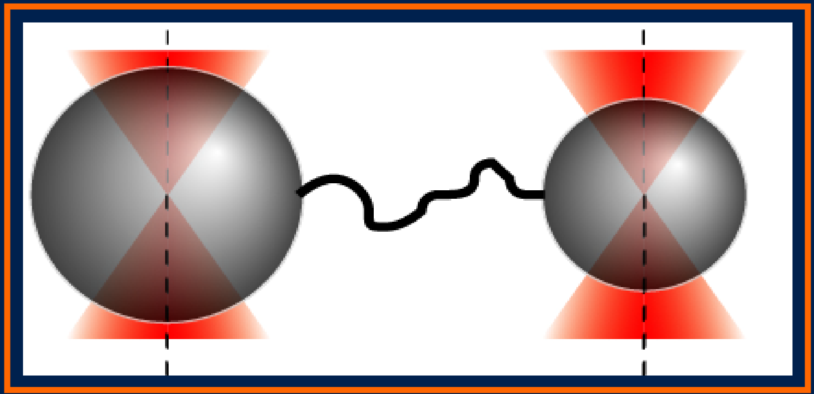
Key points

Light generates 2 types of optical forces:
scattering, *gradient*

Trap strength depends on light intensity, gradient

Trap is harmonic: k ~ 0.1pN/nm

Optical traps & biology



Infrared trap supports life

Optical trapping and manipulation of single cells using infrared laser beams

A. Ashkin*, J. M. Dziedzic* & T. Yamane†

* AT&T Bell Laboratories, Holmdel, New Jersey 07733, USA
† AT&T Bell Laboratories, Murray Hill, New Jersey 07974, USA

Use of optical traps for the manipulation of biological particles was recently proposed, and initial observations of laser trapping of bacteria and viruses with visible argon-laser light were reported[1]. We report here the use of infrared (IR) light to make much improved laser traps with significantly less optical damage to a variety of living cells. Using IR light we have observed the reproduction of *Escherichia coli* within optical traps at power levels sufficient to give manipulation at velocities up to ~500 $\mu m\ s^{-1}$. Reproduction of yeast cells by budding was also achieved in IR traps capable of manipulating individual cells and clumps of cells at velocities of ~100 $\mu m\ s^{-1}$. Damage-free trapping and manipulation of suspensions of red blood cells of humans and of organelles located within individual living cells of spirogyra was also achieved, largely as a result of the reduced absorption of haemoglobin and chlorophyll in the IR. Trapping of many types of small protozoa and manipulation of organelles within protozoa is also possible. The manipulative capabilities of optical techniques were exploited in experiments showing separation of individual bacteria from one sample and their introduction into another sample. Optical orientation of individual bacterial cells in space was also achieved using a pair of laser-beam traps. These new manipulative techniques using IR light are capable of producing large forces under damage-free conditions and improve the prospects for wider use of optical manipulation techniques in microbiology.

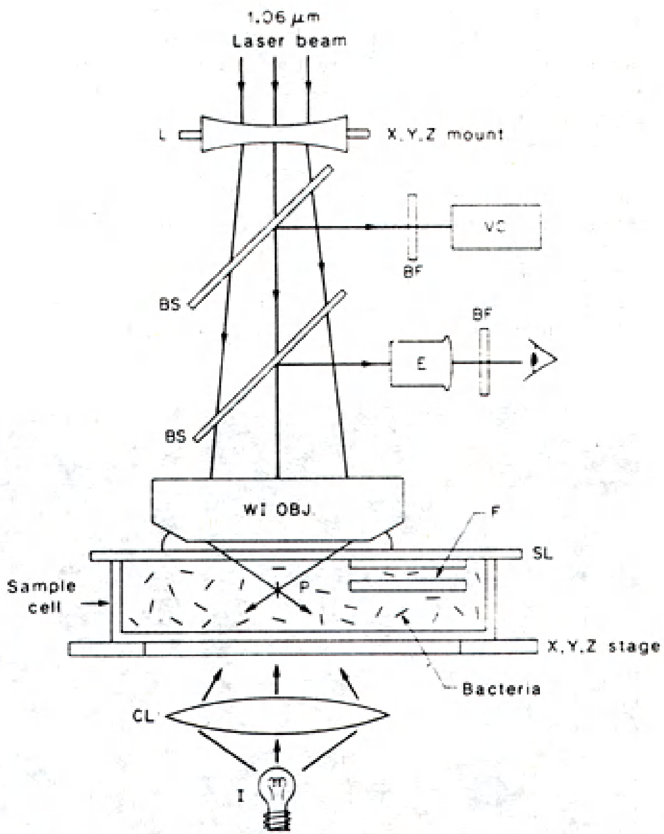
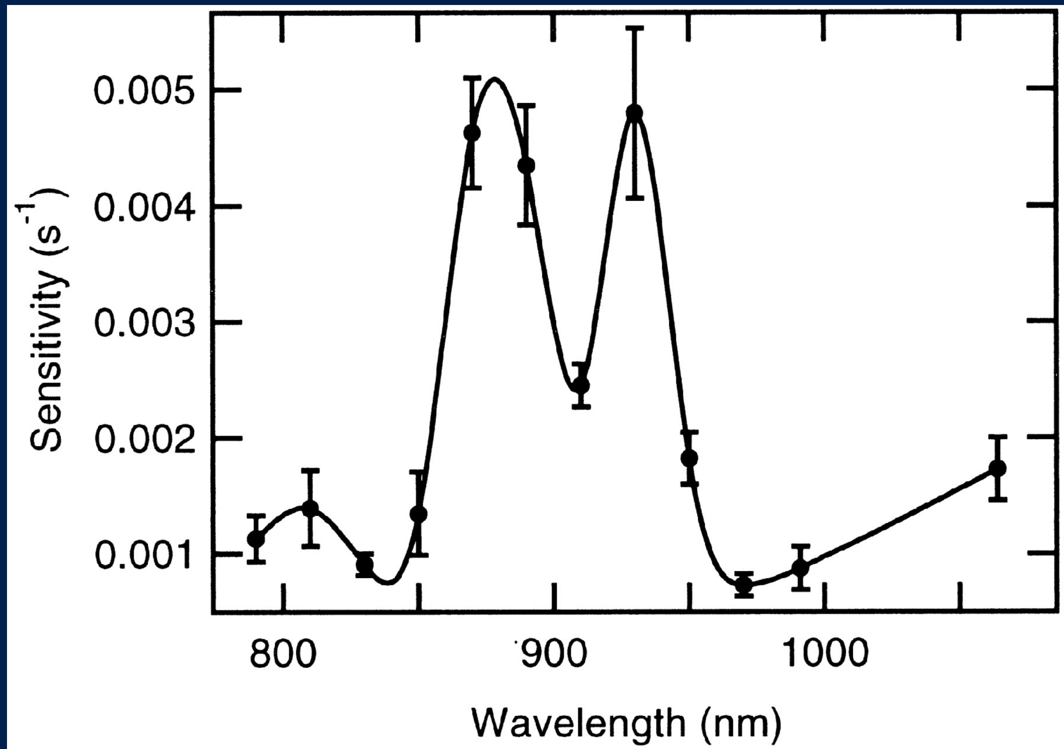


Fig. 1 Combined high-resolution optical microscope and 1.06 μm infra-red laser trap for observing, manipulating and separating bacteria and other organisms.

Nature, 1987

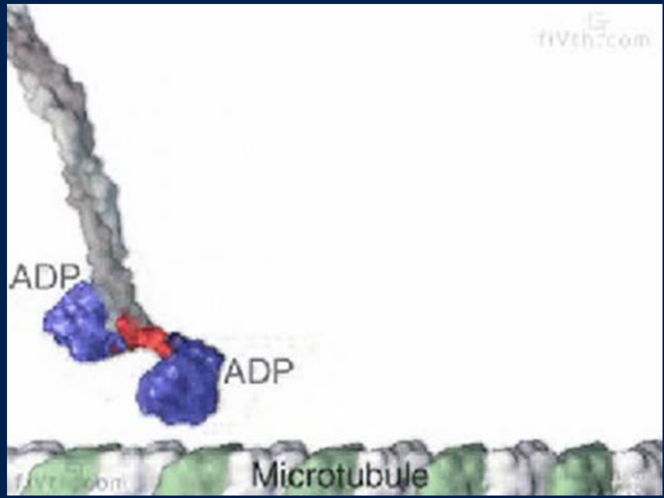
IR traps and photodamage



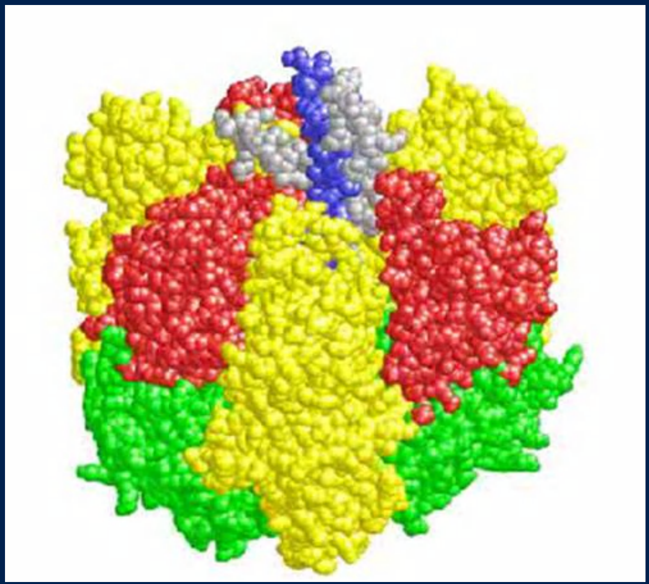
Neuman et al. Biophys J. 1999

Biological scales

Force: 1-100 picoNewton (pN)
Distance: <1–10 nanometer (nm)

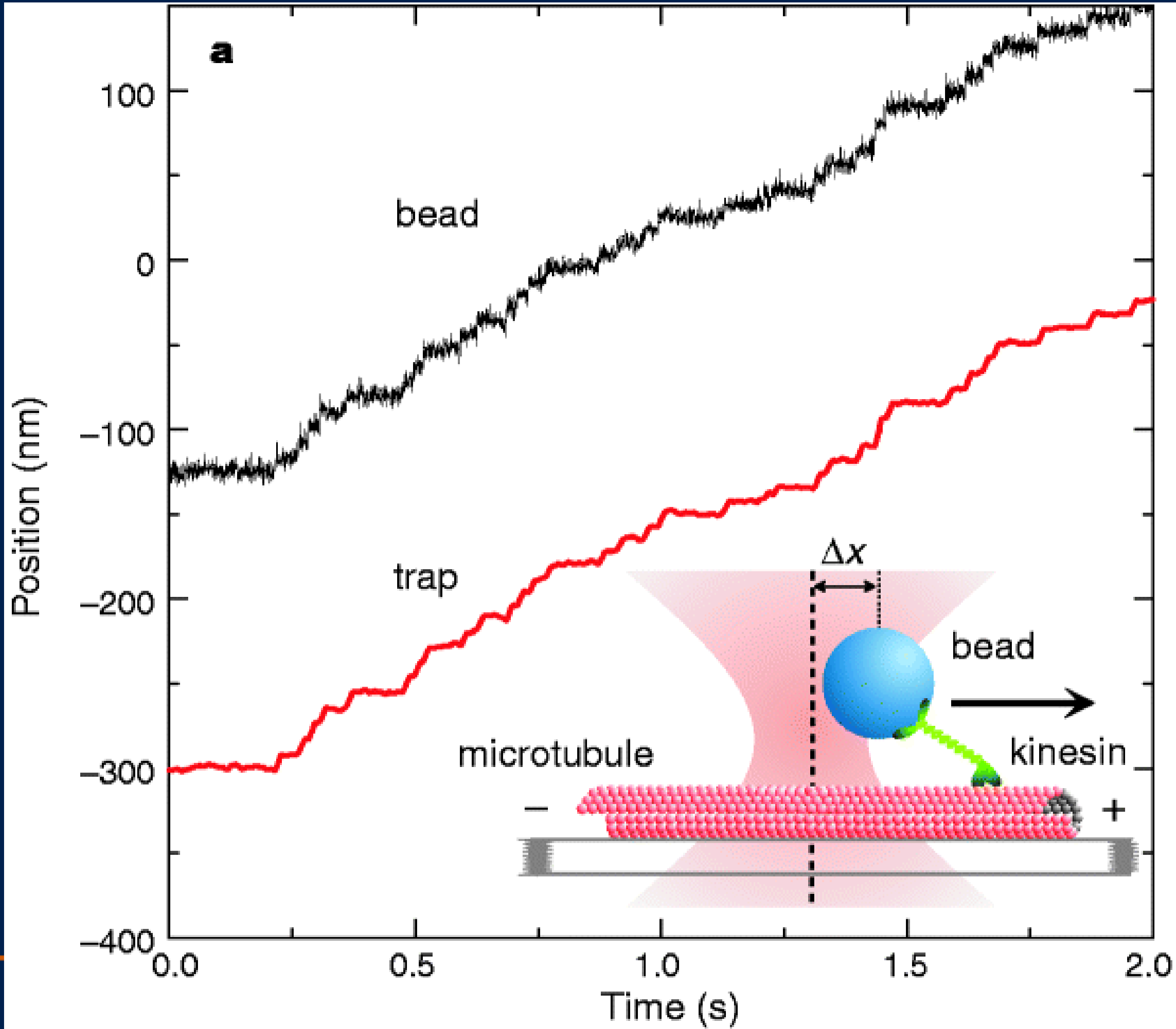


www.scripps.edu/cb/milligan/projects.html

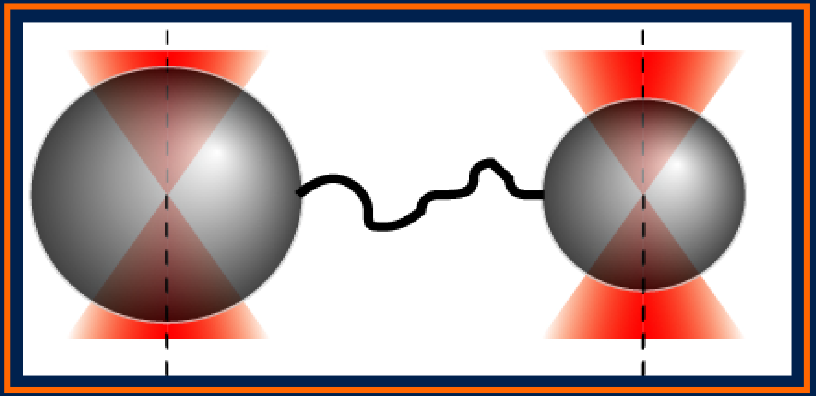


www.cnr.berkeley.edu/~hongwang/Project

www.alice.berkeley.edu


a
100
0
−100
−200
−300
−400
Position (nm)
0.0
0.5
1.0
1.5
2.0
Time (s)
bead
trap
Δx
bead
kinesin
microtubule
−
+

Practical optical traps

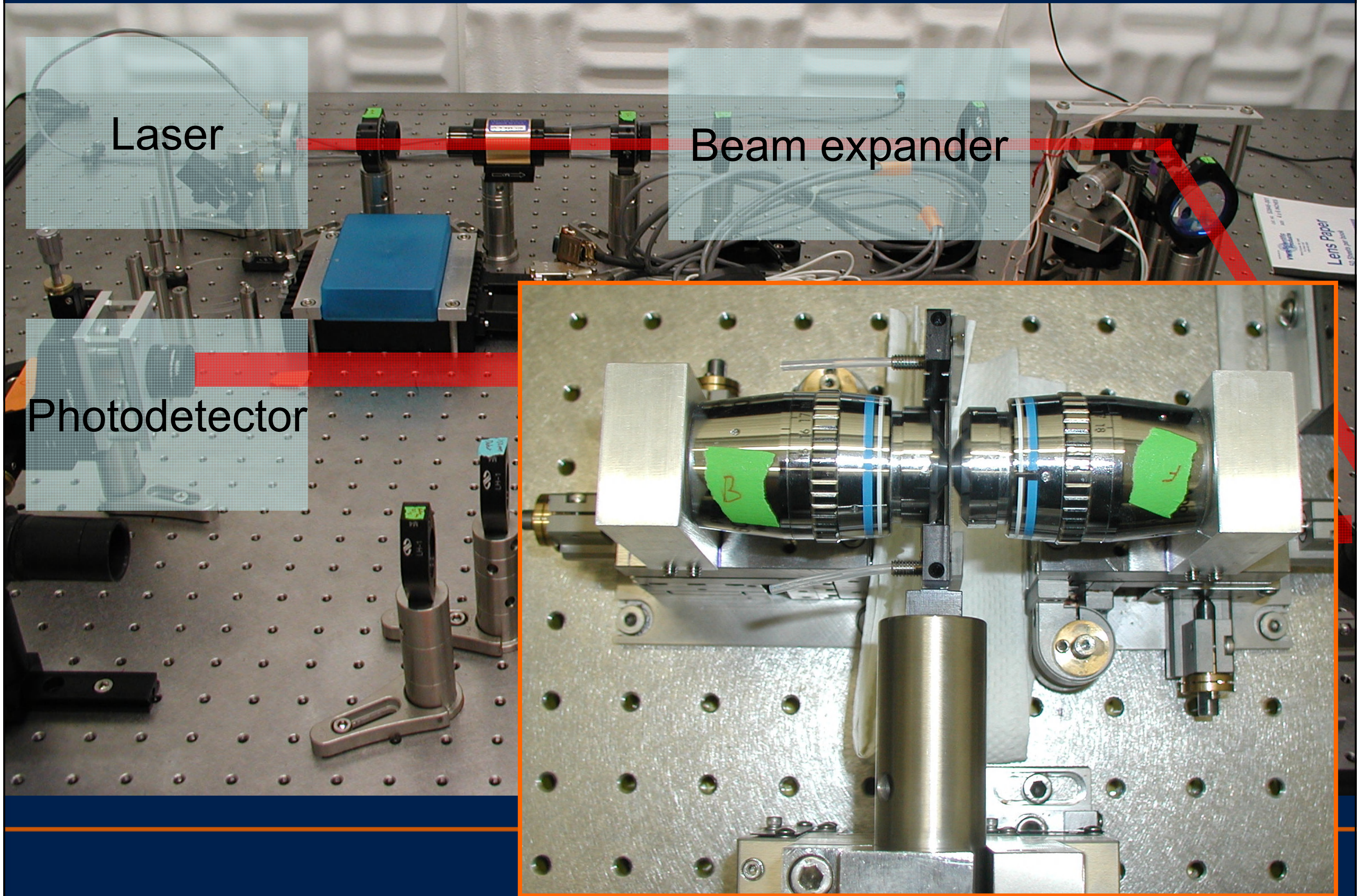


Requirements for a *quantitative* optical trap:

1) Manipulation – intense light (laser), large gradient (high NA objective), moveable stage (piezo stage) or trap (piezo mirror, AOD, …)

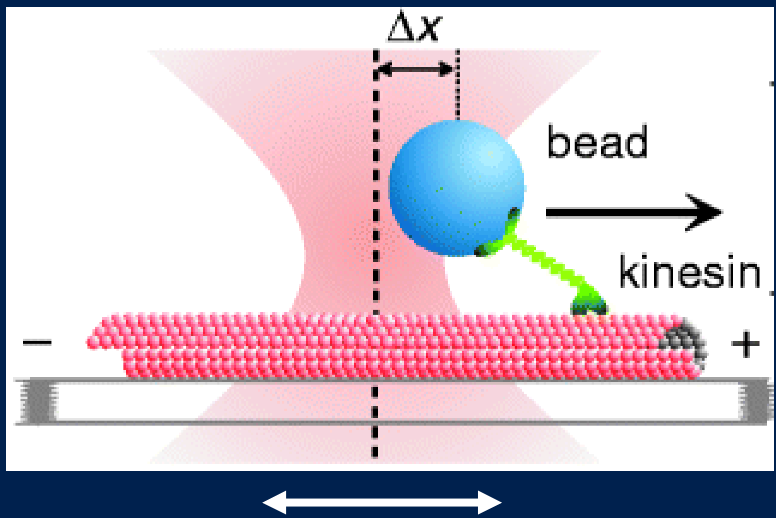
2) Measurement – collection and detection optics (BFP interferometry)

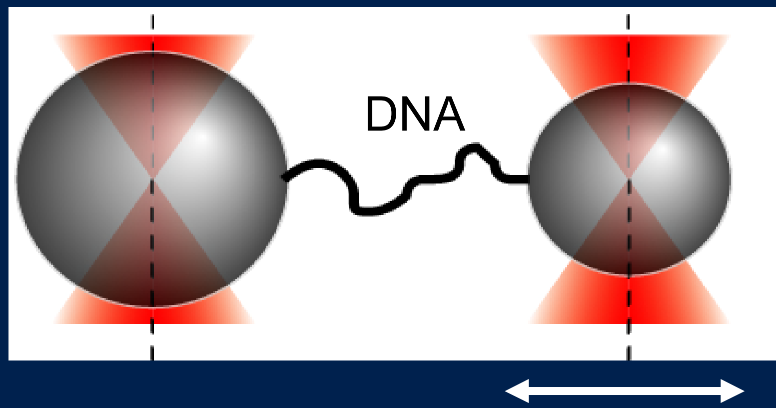
3) Calibration – convert raw data into forces (pN), displacements (nm)


Laser
Beam expander
Photodetector

1) Manipulation

Want to apply forces – need ability to move stage or trap (piezo stage, steerable mirror, AOD…)



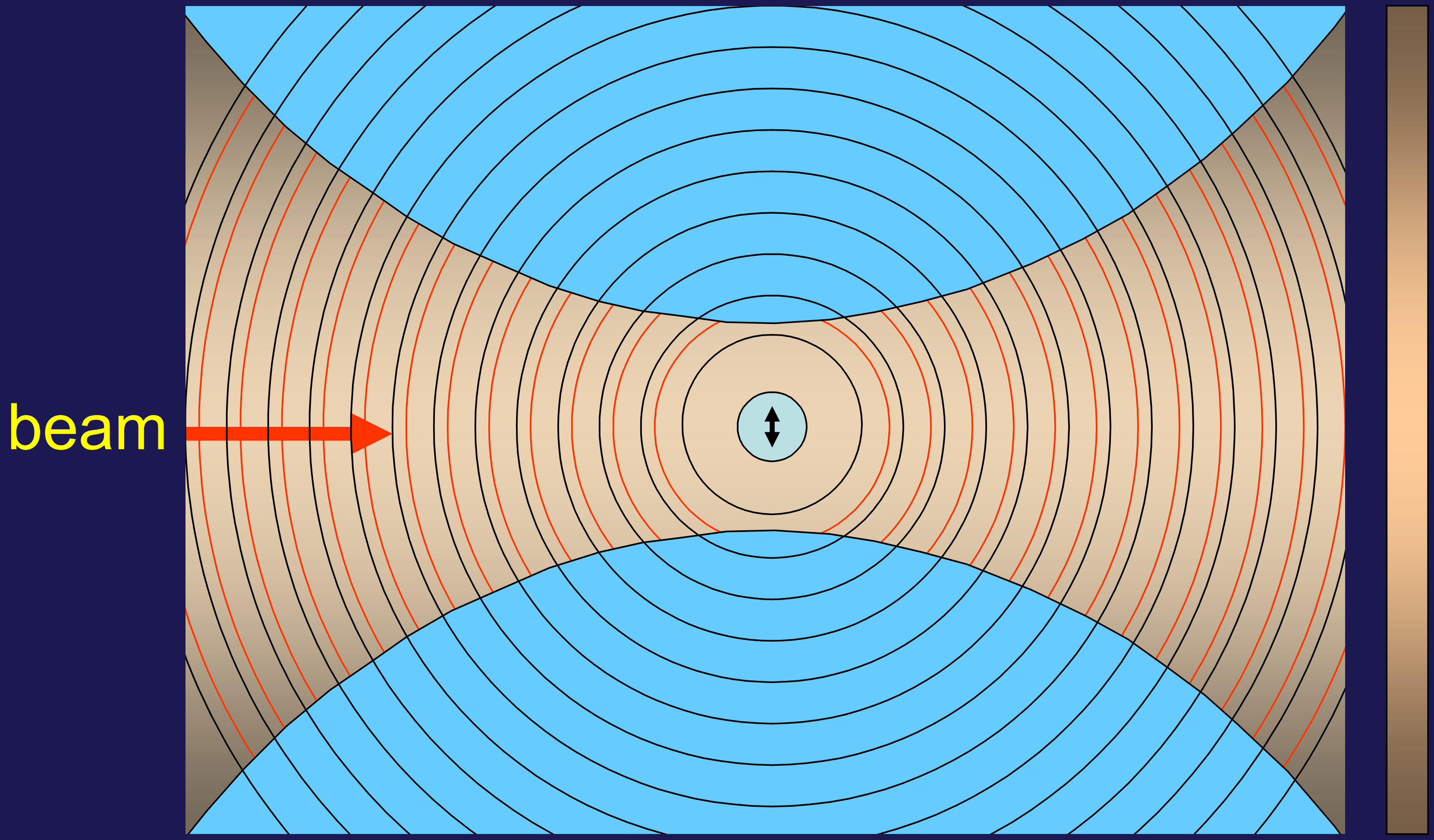


2) Measurement

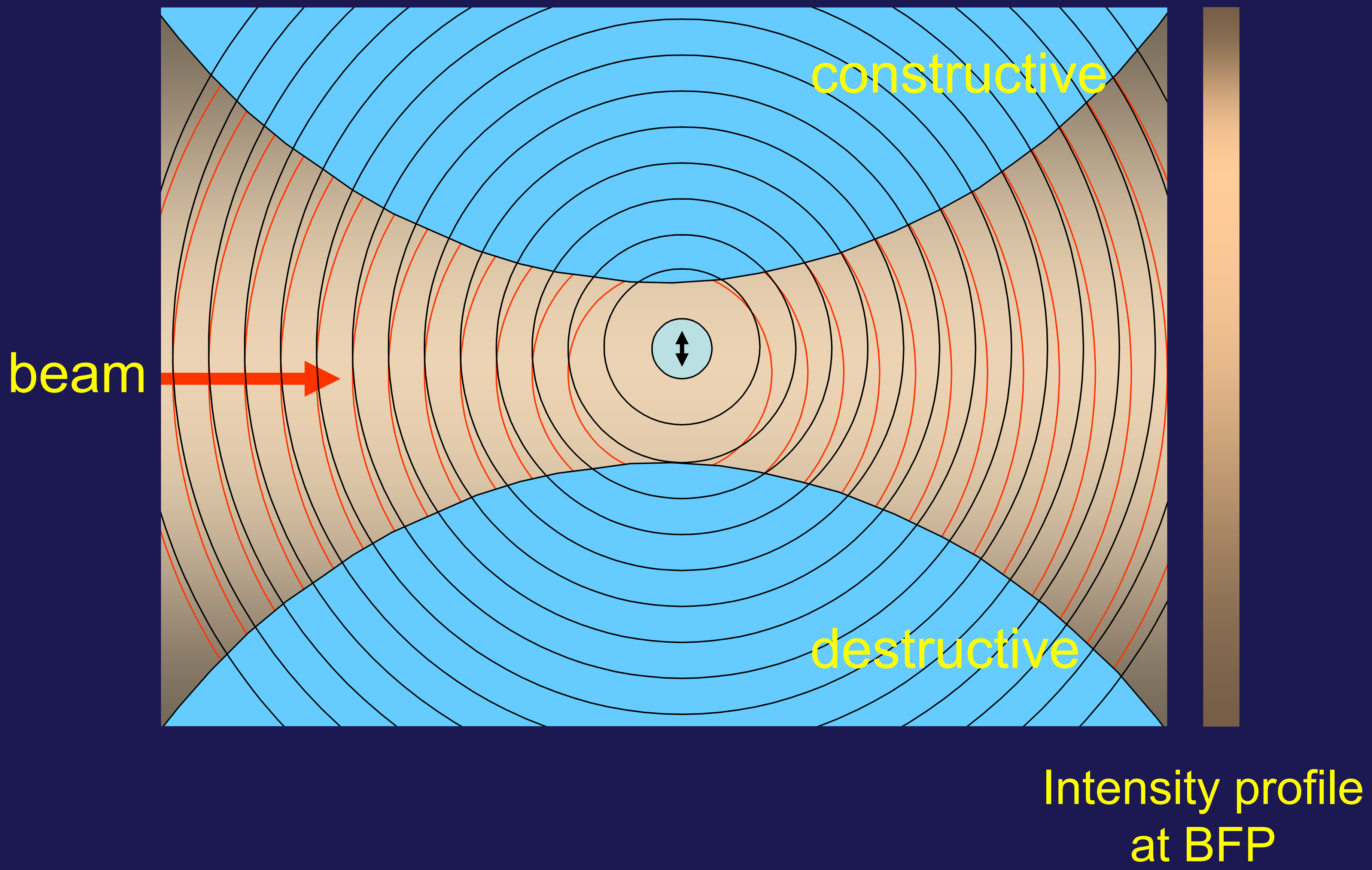
Want to measure forces, displacements – need to detect deflection of bead from trap center

1) Video microscopy
2) Laser-based method – Back-focal plane interferometry

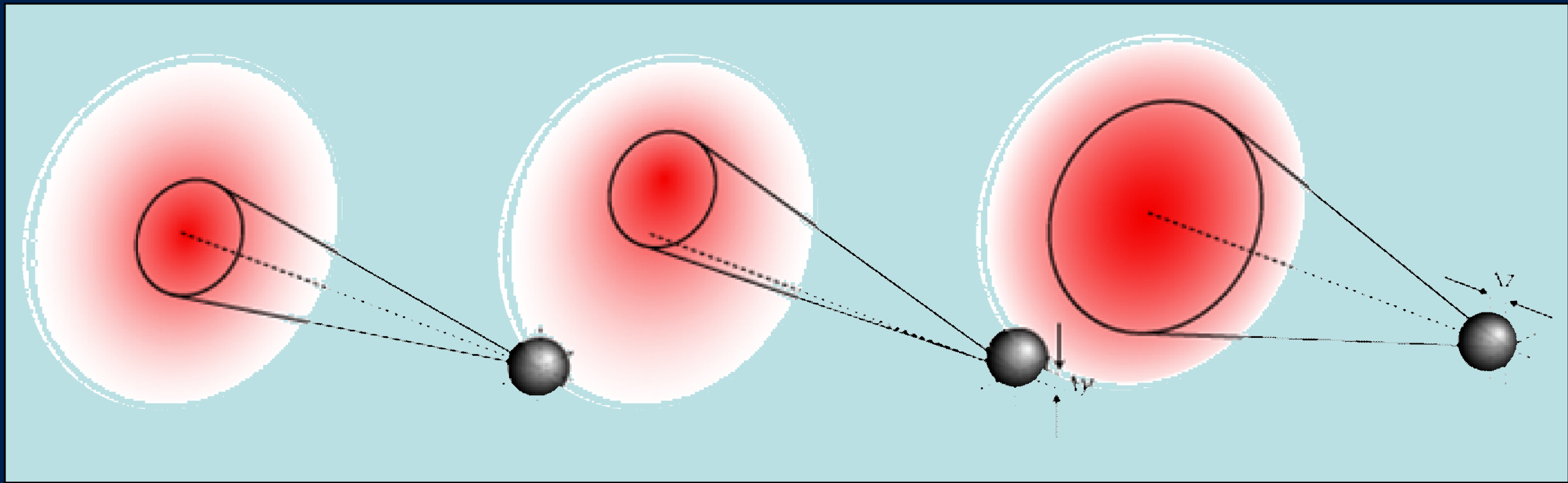
Back Focal Plane (BFP) interferometry



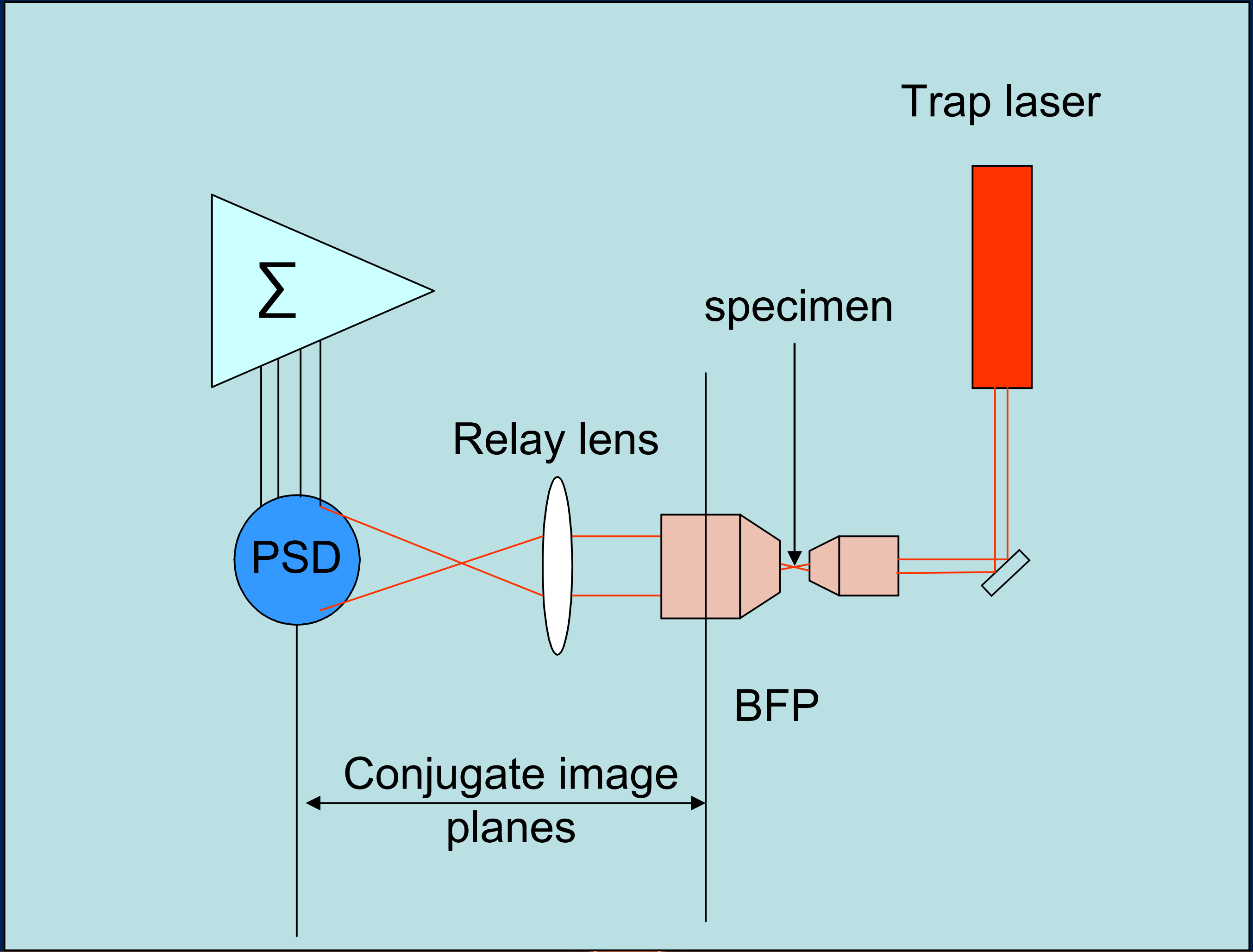
Back Focal Plane (BFP) interferometry



Back Focal Plane (BFP) interferometry

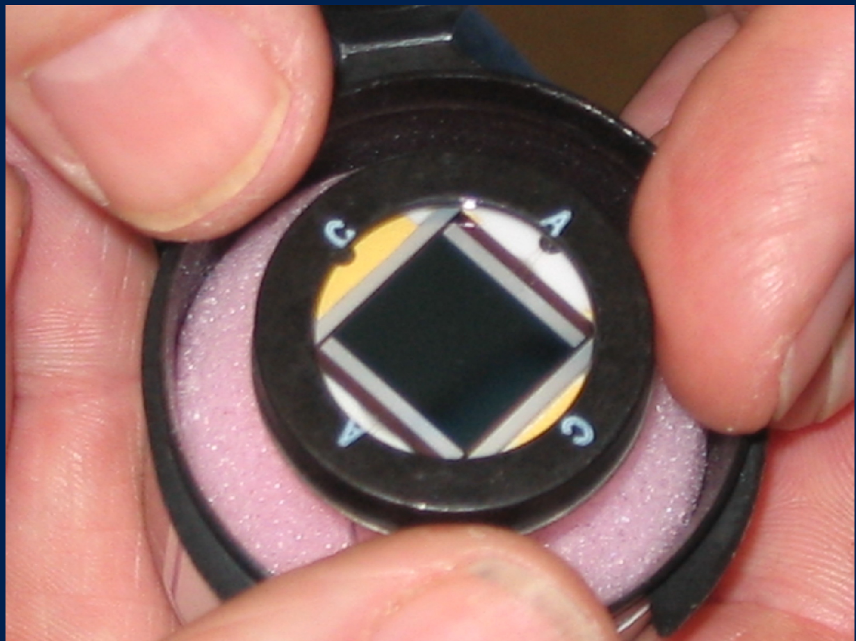


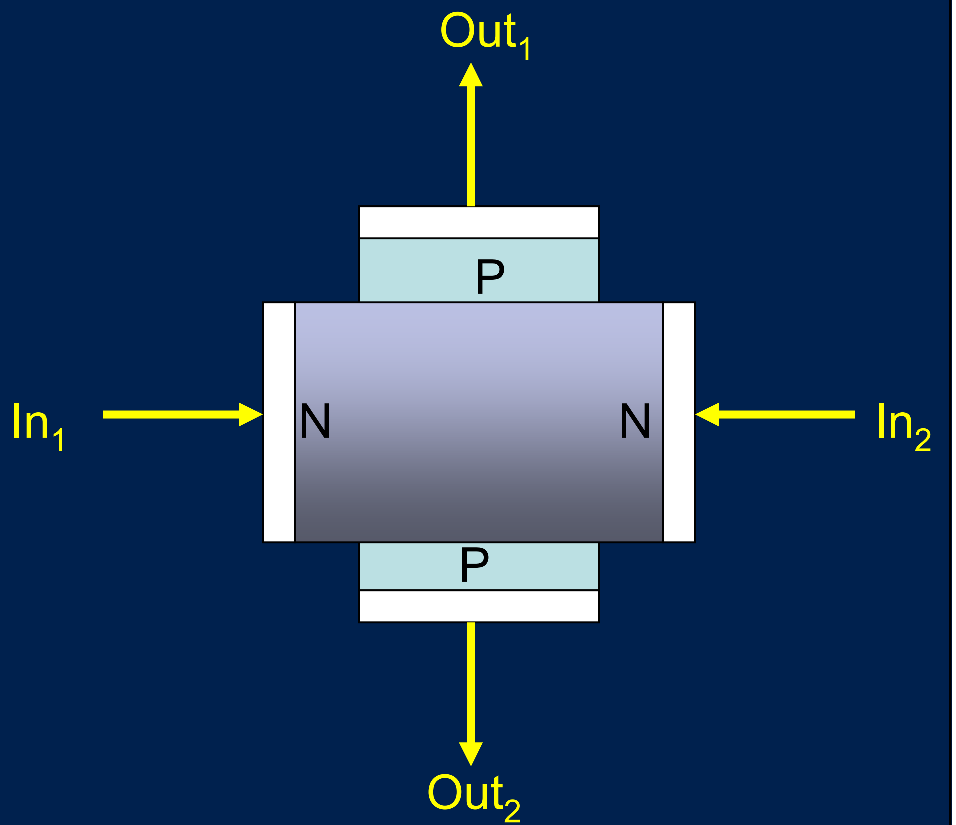
BFP imaged onto detector



Position sensitive detector (PSD)

Plate resistors separated by reverse-biased PIN photodiode

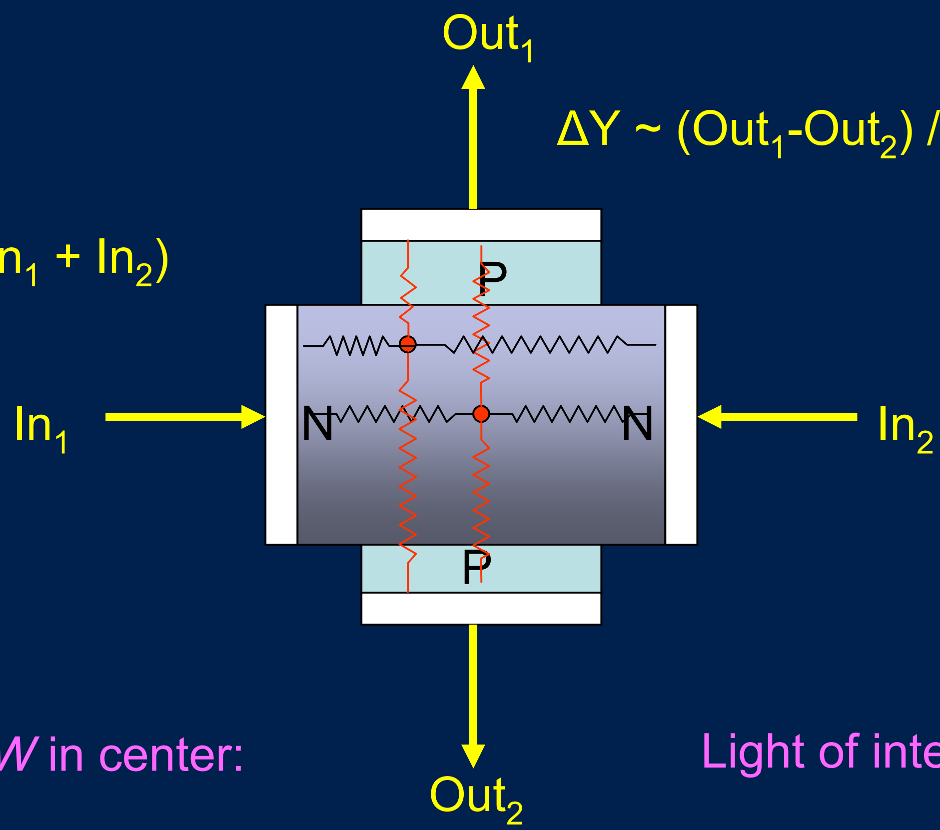




Opposite electrodes at same potential – no conduction with no light

$\Delta Y \sim (Out_1 - Out_2) / (Out_1 + Out_2)$

$\Delta X \sim (In_1 - In_2) / (In_1 + In_2)$



Light of intensity *W* in center:

$In_1 + In_2 = Out_1 + Out_2 = W$

by charge conservation

$Out_1 = Out_2 = \frac{1}{2} W$ *and* $In_1 = In_2 = \frac{1}{2} W$

by symmetry

Light of intensity *W* off center:

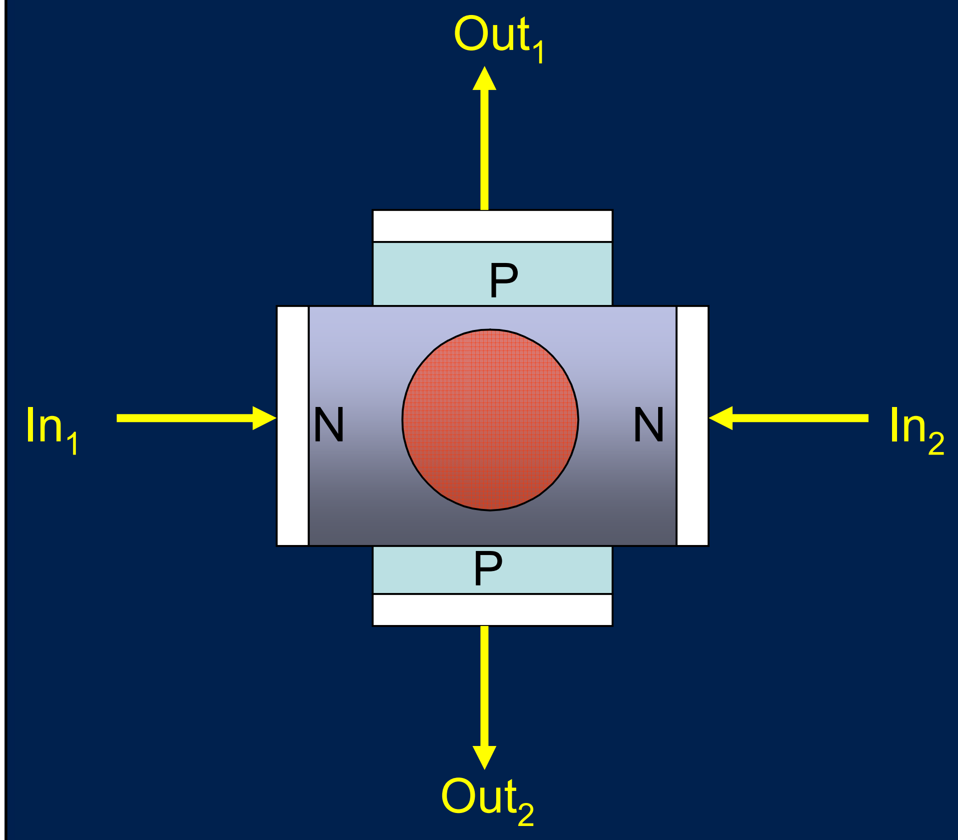
$Out_1 + Out_2 = W = In_1 + In_2$

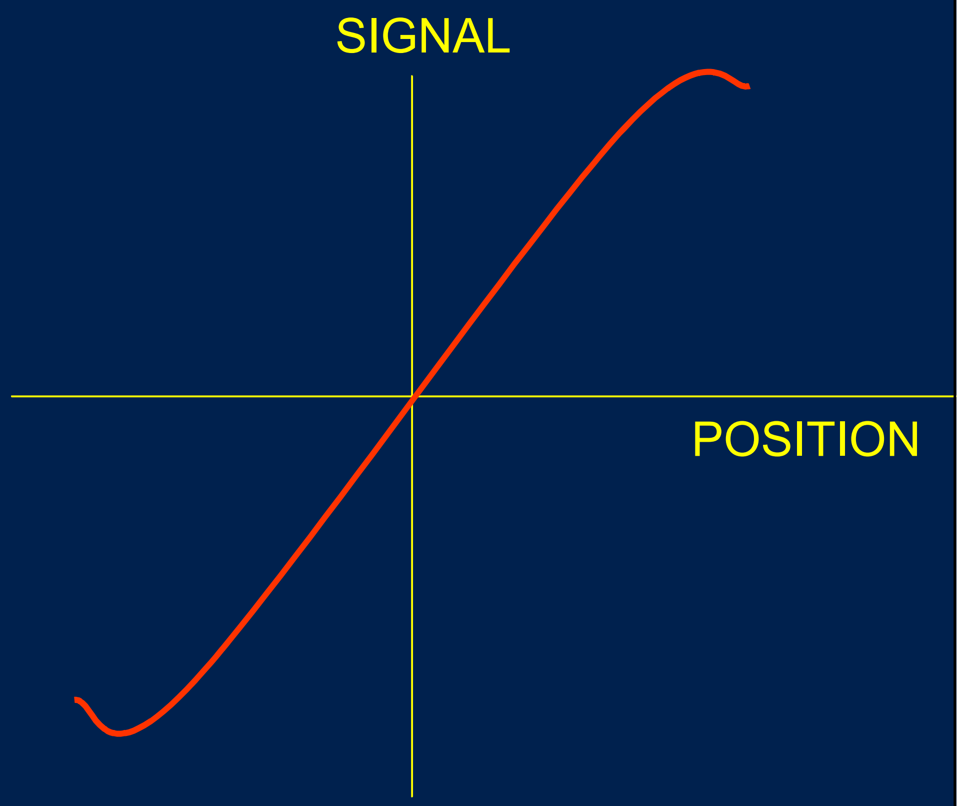
still holds

$In_1 > In_2$ *and* $Out_1 > Out_2$

due to resistance asymmetry

Multiple rays add their currents linearly to the electrodes, where each ray's power adds W_i current to the total sum.





$\Delta X \sim (In_1 - In_2) / (In_1 + In_2)$

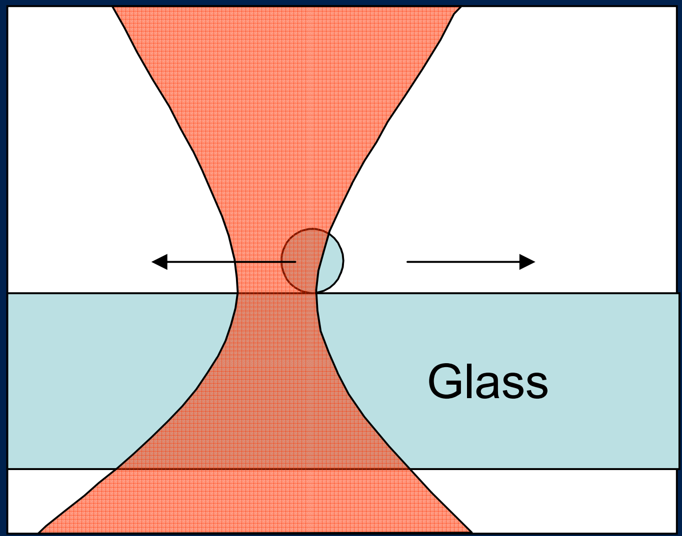
$\Delta Y \sim (Out_1 - Out_2) / (Out_1 + Out_2)$

3) Calibration

Want to measure forces, displaces – measure voltages from PSD – need calibration

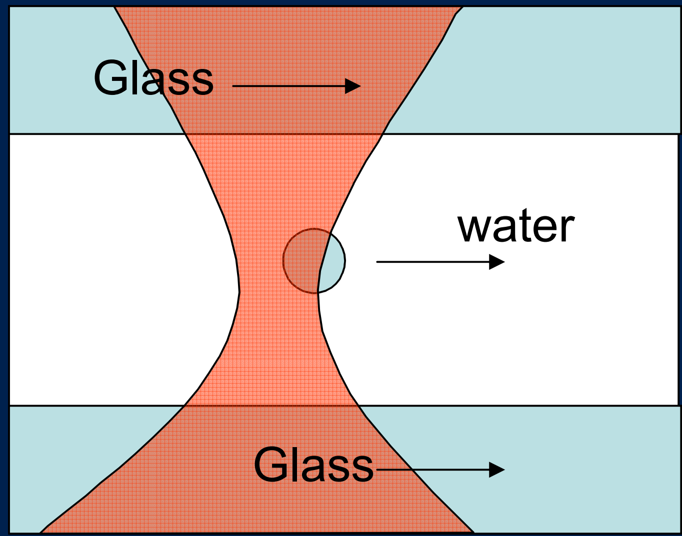
$$\Delta x = \alpha\, \Delta V$$
$$F = k\Delta x = \alpha\, k\Delta V$$

Calibrate with a known displacement



Move bead relative to trap

Calibrate with a known force



Stokes law: $F = \gamma v$

Brownian motion as test force

Langevin equation:

$$\gamma \dot{x} + kx = F(t)$$

Drag force
$\gamma = 3\pi\eta d$

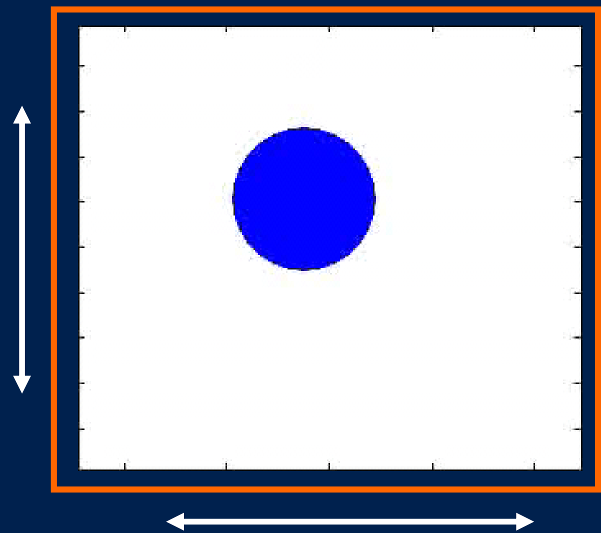
Trap force

Fluctuating Brownian force

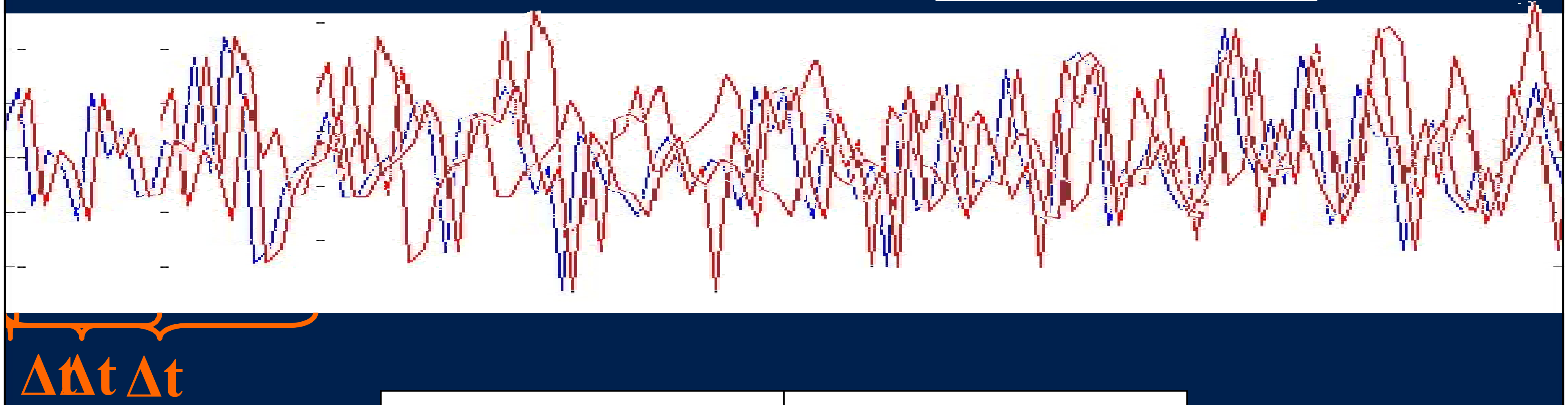
$$<F(t)> = 0$$

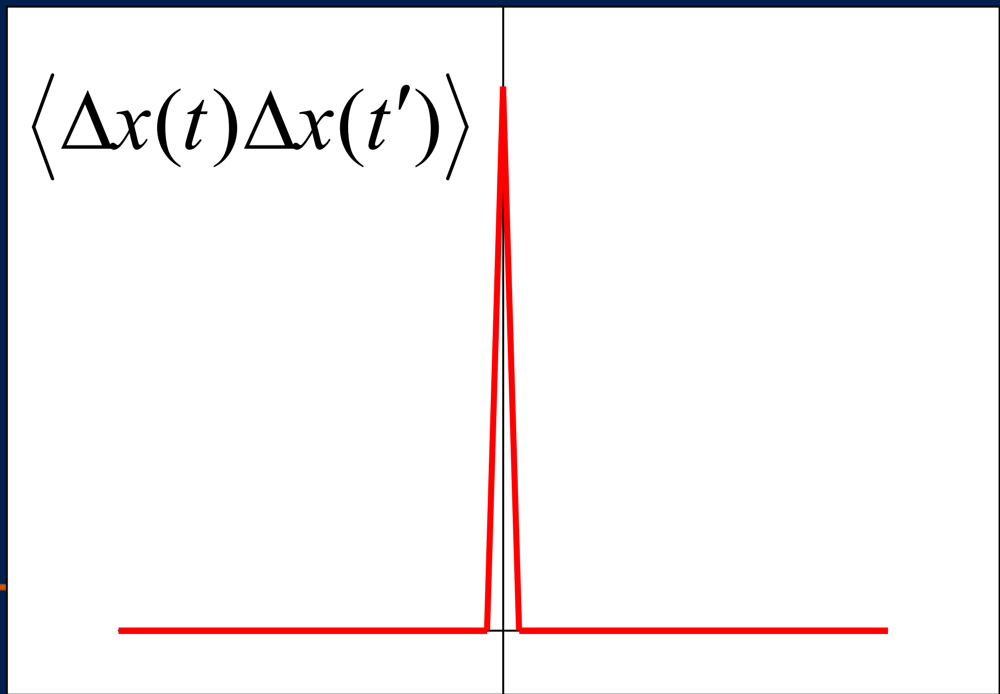
$$<F(t)F(t')> = 2k_B T \gamma \delta\,(t-t')$$

$k_B T$

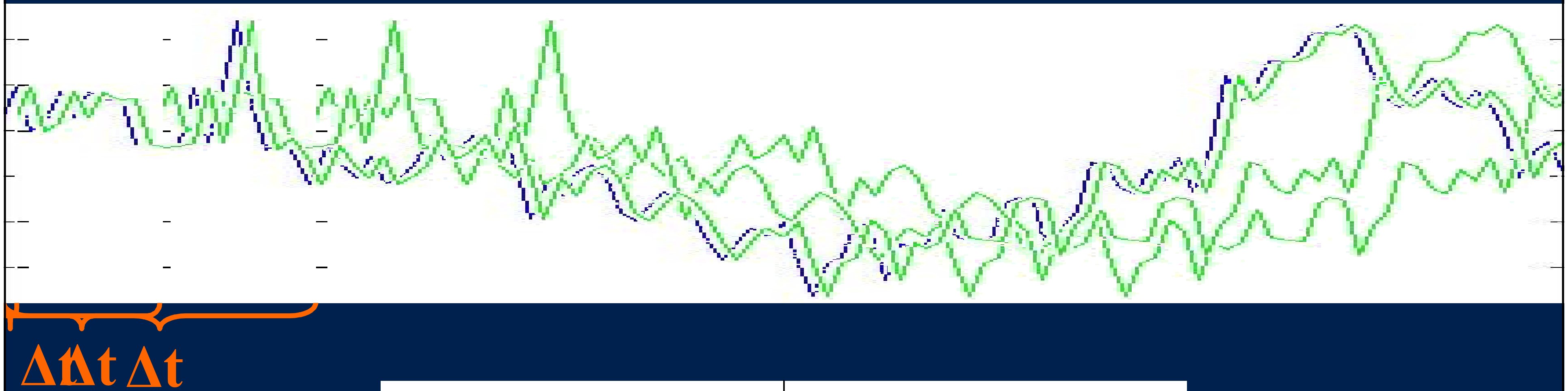


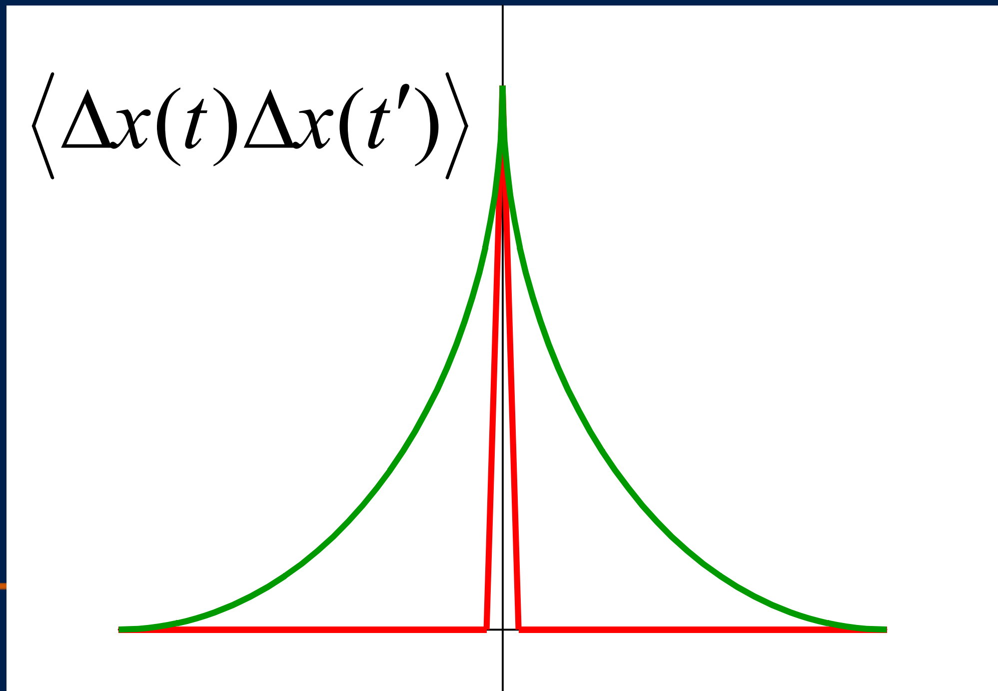
Autocorrelation function $\langle \Delta x(t) \Delta x(t') \rangle$





Autocorrelation function $\langle \Delta x(t)\Delta x(t') \rangle$





Brownian motion as test force

Langevin equation:

$$\gamma\dot{x} + kx = F(t)$$

Exponential autocorrelation f'n

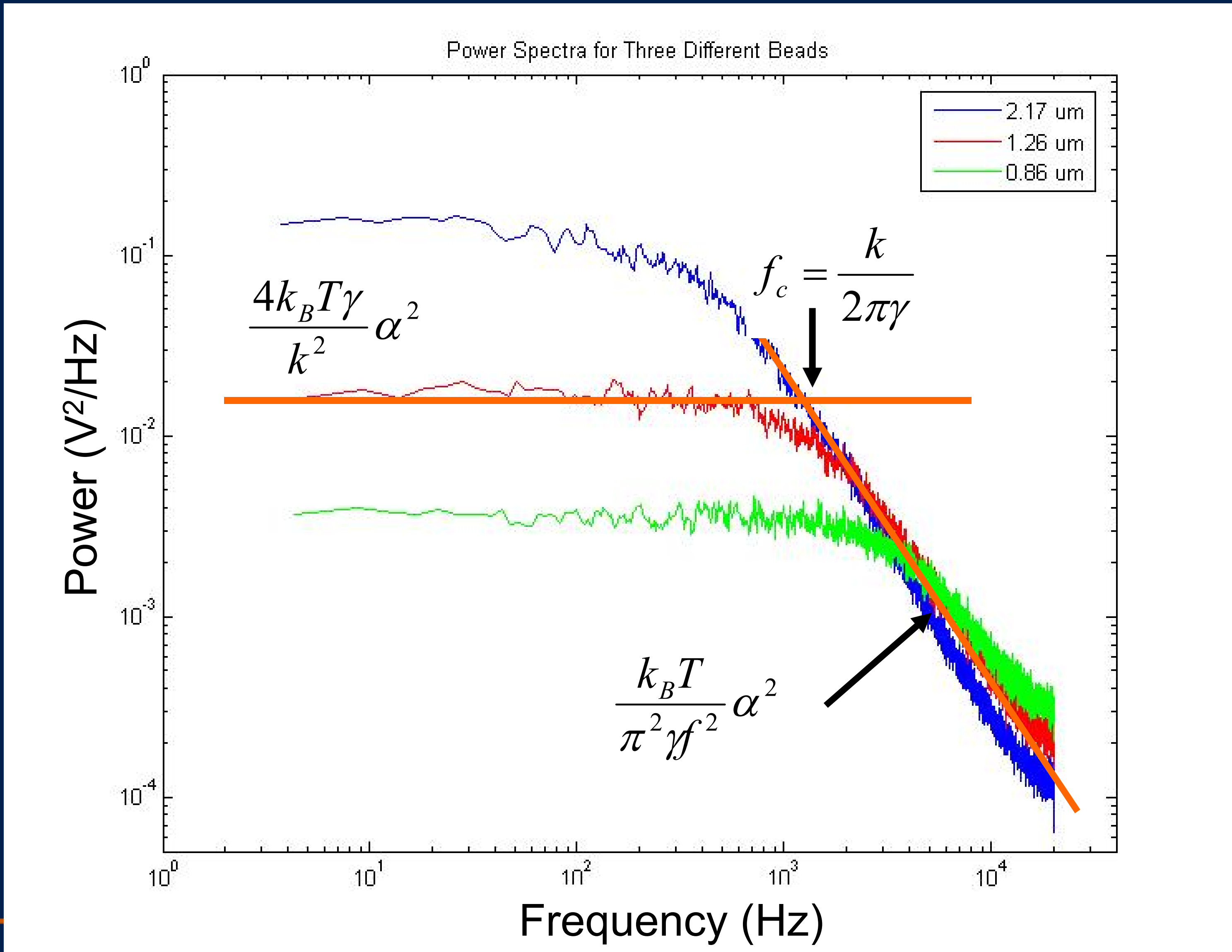
$$\left\langle \Delta x(t)\Delta x(t')\right\rangle = \frac{k_B T}{k} e^{-k|t-t'|/\gamma}$$

$$\left\langle \Delta x^2 \right\rangle = \frac{k_B T}{k}$$

FT → Lorentzian power spectrum

$$S_x(f) = \frac{4k_B T\gamma}{k^2} \frac{1}{1+(f/f_c)^2}$$

Corner frequency $f_c = k/2\pi\gamma$


Power Spectra for Three Different Beads
2.17 um
1.26 um
0.86 um
$\frac{4k_BT\gamma}{k^2}\alpha^2$
$f_c = \frac{k}{2\pi\gamma}$
$\frac{k_BT}{\pi^2\gamma f^2}\alpha^2$
Power (V²/Hz)
Frequency (Hz)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4