Administrative issues

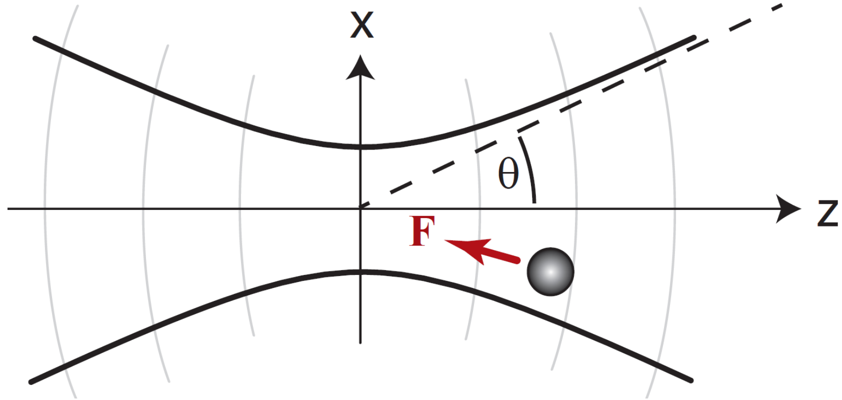
- Three presentations today

On the menu today

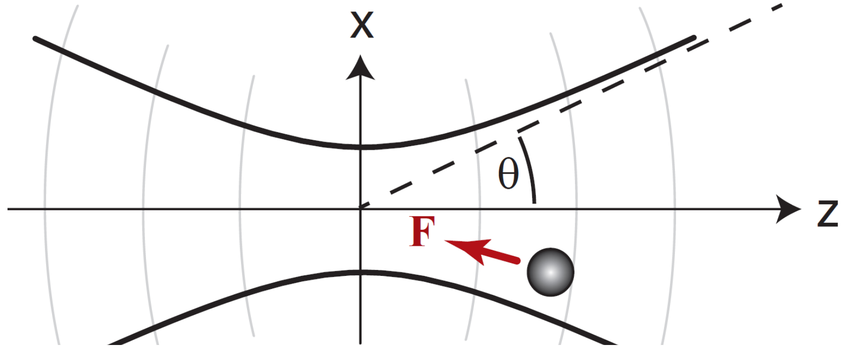
Optical forces

- Force on a dipolar scatterer
- Optical traps and optical tweezers
- Levitated optomechanics

Dipolar scatterer in focused field



Dipolar scatterer in focused field



$$\mathbf{F}(\mathbf{r}) = \underbrace{\frac{\alpha'}{2}\sum_i \mathrm{Re}\left\{E_i^*(\mathbf{r})\,\nabla E_i(\mathbf{r})\right\}}_{} + \underbrace{\frac{\alpha''}{2}\sum_i \mathrm{Im}\left\{E_i^*(\mathbf{r})\,\nabla E_i(\mathbf{r})\right\}}_{}$$

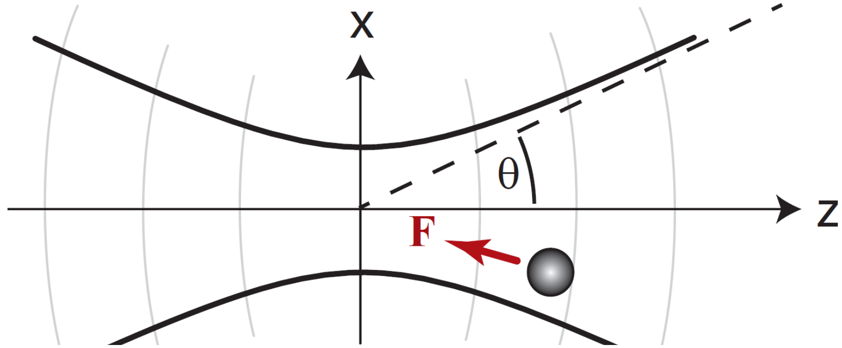
Gradient force: $\mathbf{F}_{\mathrm{grad}} = (\alpha'/4)\nabla(\mathbf{E}^*\cdot\mathbf{E})$

Scattering force

- Gradient force pulls scatterer to region of largest field intensity
- Scattering force pushes scatterer along propagation direction

Dipolar scatterer in focused field

$$\alpha = \alpha' + \mathrm{i}\alpha''$$



For small particles:

$$\alpha'' = \frac{k^3}{6\pi\varepsilon_0}\alpha'^2$$

$$\mathbf{F}(\mathbf{r}) = \underbrace{\frac{\alpha'}{2}\sum_i \mathrm{Re}\left\{E_i^*(\mathbf{r})\,\nabla E_i(\mathbf{r})\right\}} + \underbrace{\frac{\alpha''}{2}\sum_i \mathrm{Im}\left\{E_i^*(\mathbf{r})\,\nabla E_i(\mathbf{r})\right\}}$$

Gradient force: $\mathbf{F}_{\mathrm{grad}} = (\alpha'/4)\nabla(\mathbf{E}^{*}\cdot\,\mathbf{E})$

Scattering force

- Gradient force pulls scatterer to region of largest field intensity
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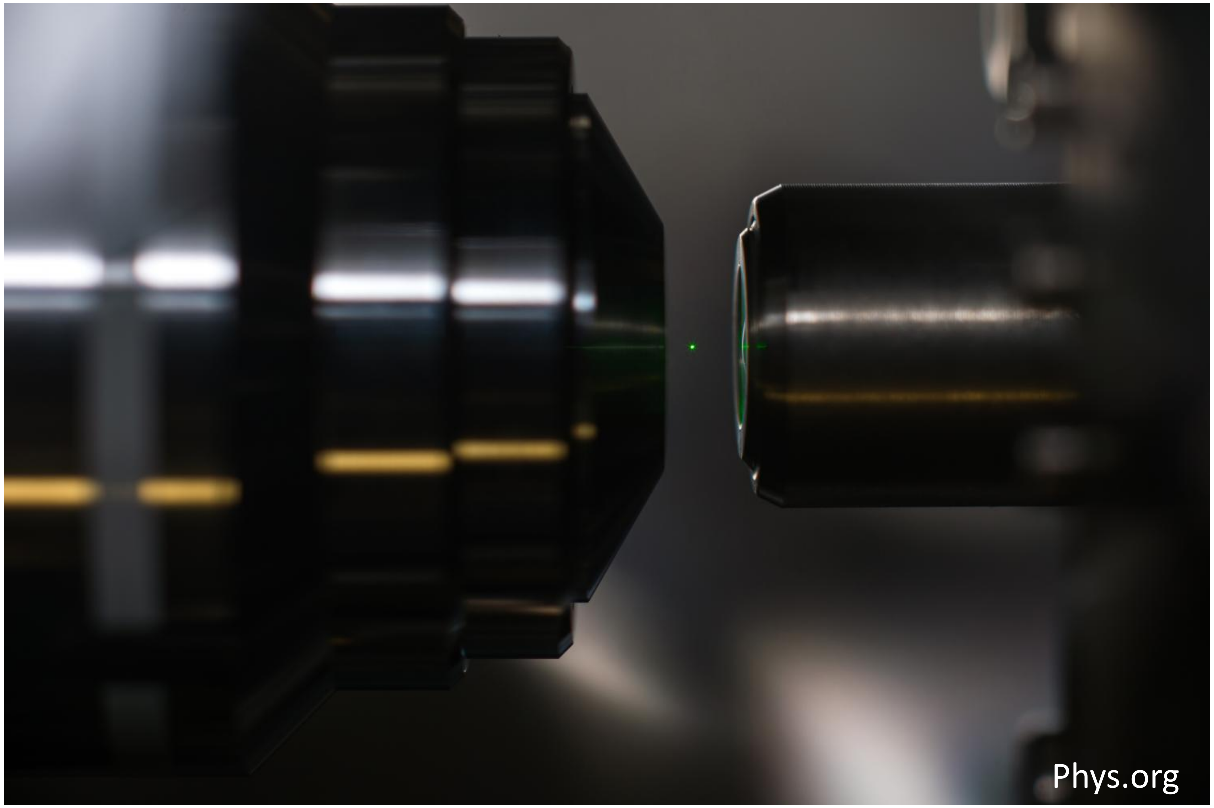
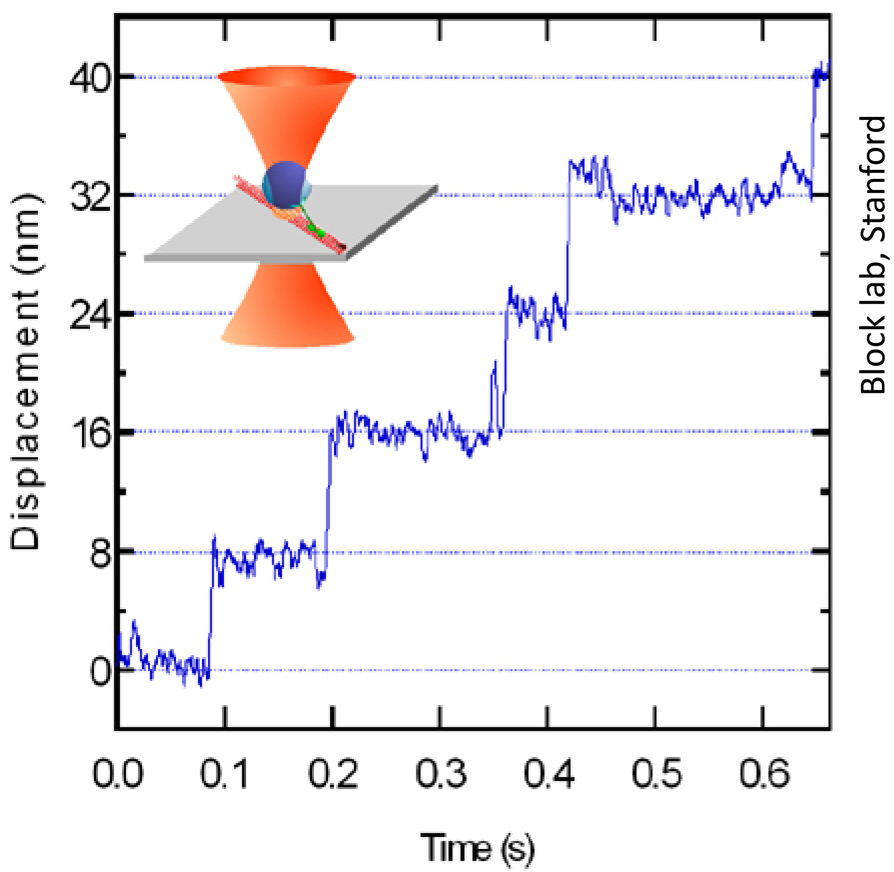
Example: Optical trapping

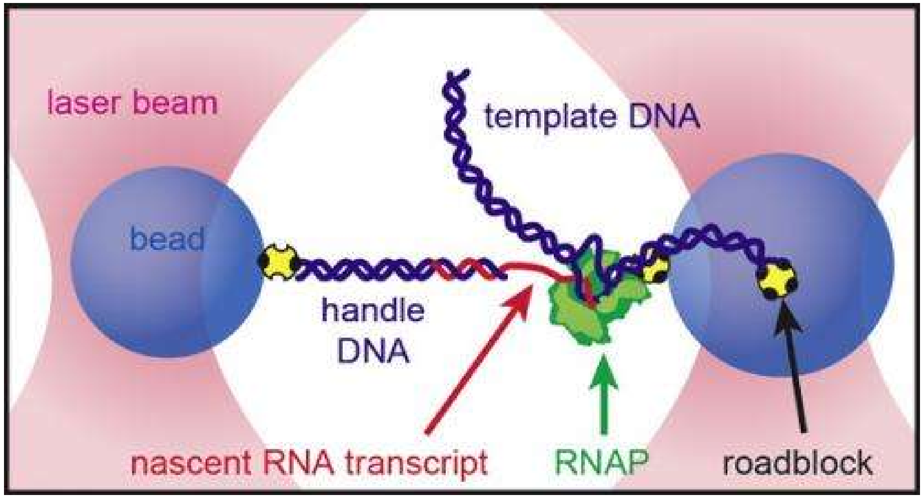


- Optical forces allow trapping and levitation of nano- and micro-particles in vacuum, gas and liquid

Applications of optical trapping in biology



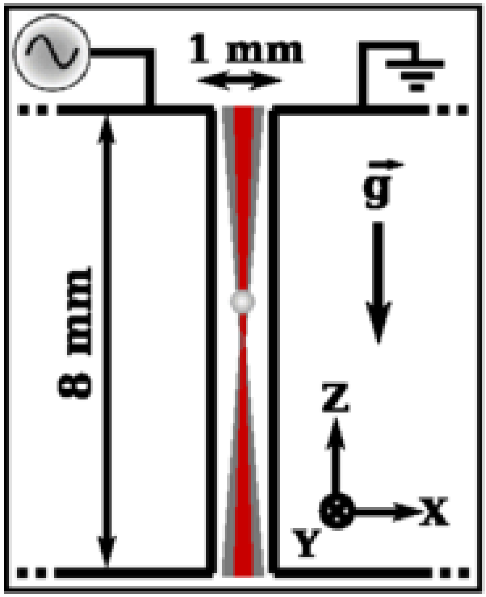
- Molecular motor taking steps against a pN force
- Absolute measurement of motor force and step size



"By keeping the tension between the two beads constant and measuring the distance between them as they moved apart, Block was able to gauge the changing length of the new RNA strand.
"What we got was a blow-by-blow readout of how RNA folds as it is processed by RNA polymerase," said Block."
(from phys.org)

Read more at: https://phys.org/news/2012-10-optical-tweezers-sub-nanoscale-precision-processand.html#jCp

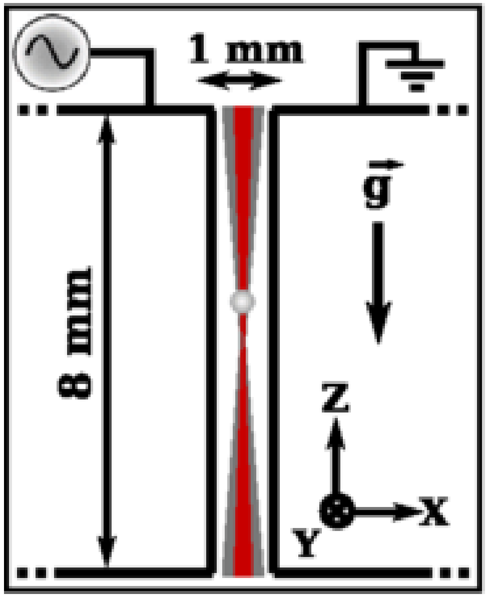
Applications of optical trapping in physics



Moore et al., PRL 113, 251801

- Search for millicharged particles
- Charged optically levitated nanoparticle is an ultrasensitive force sensor
- Here: Coulomb force
- Are there charges with q<<e?

Applications of optical trapping in physics



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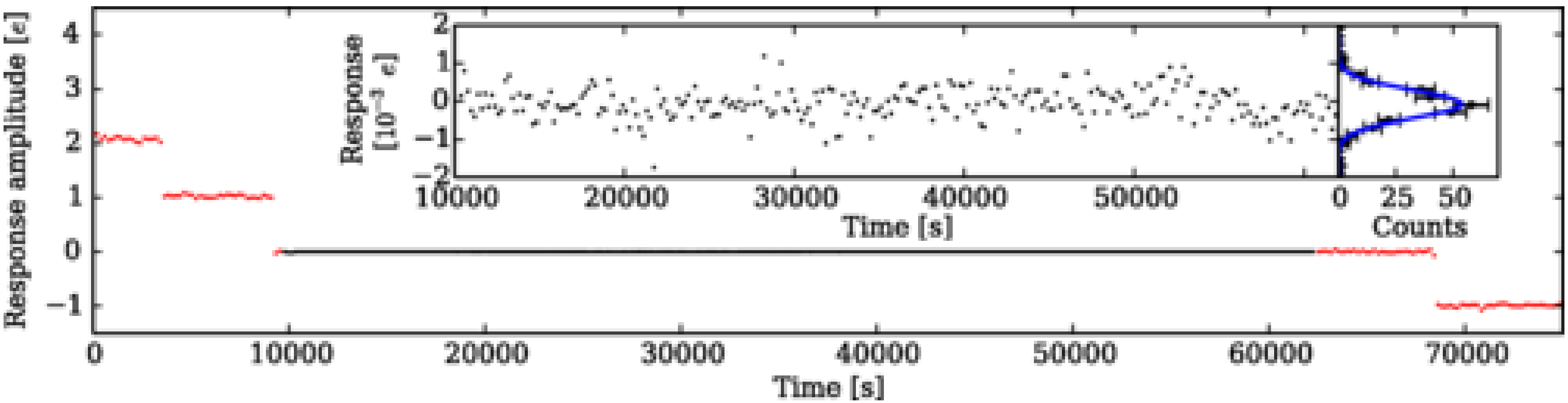
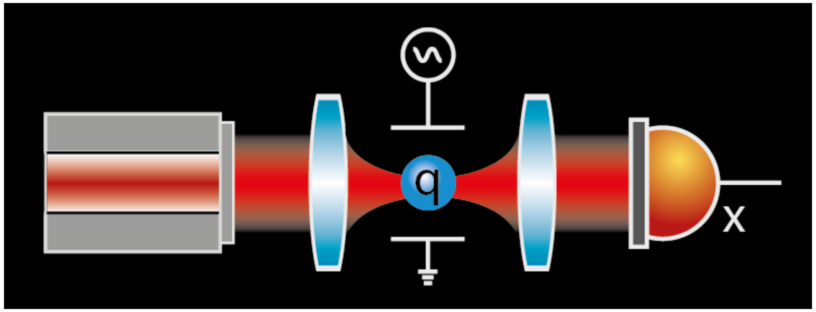
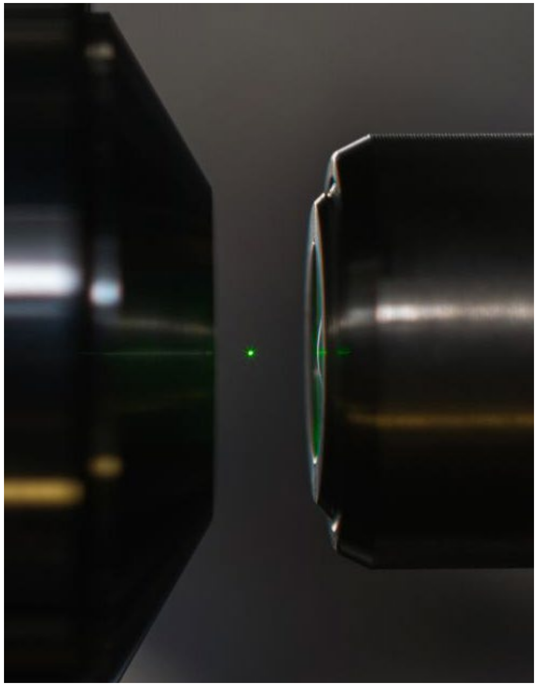


Levitated optomechanics in vacuum

$$m\ddot{x} + m\gamma_{\text{gas}}\dot{x} + m\Omega_0^2 x = F_{\text{fluct}}$$

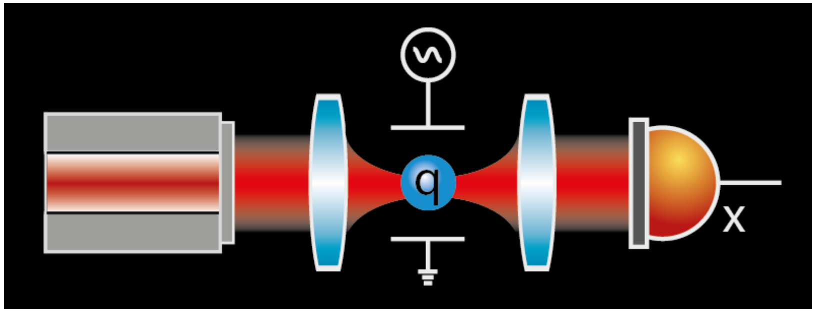


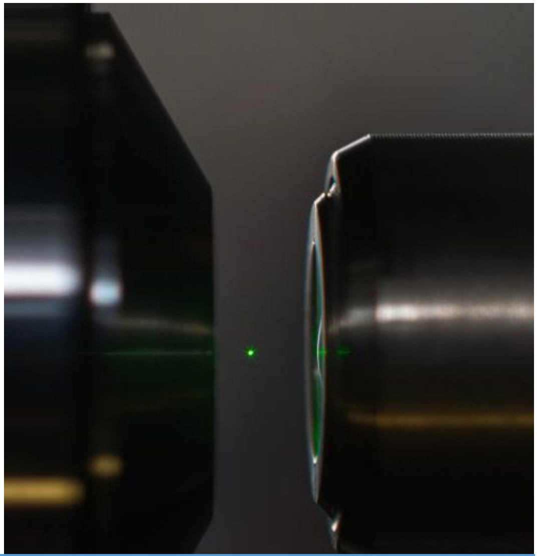


- Levitated glass particle (100 nm diameter)
- Measure position by (a form of) imaging
- Observe (Brownian) motion of particle

Levitated optomechanics

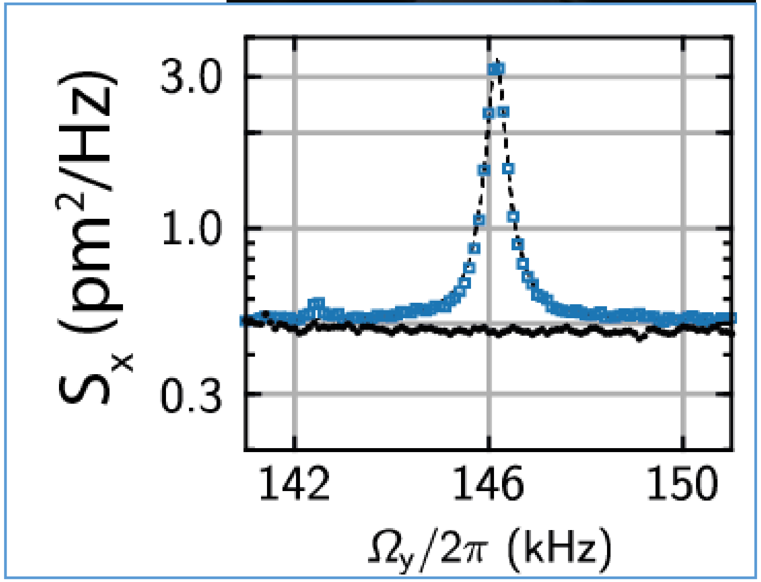
$$m\ddot{x} + m\gamma_{\mathrm{gas}}\dot{x} + m\Omega_0^2 x = F_{\mathrm{fluct}}$$





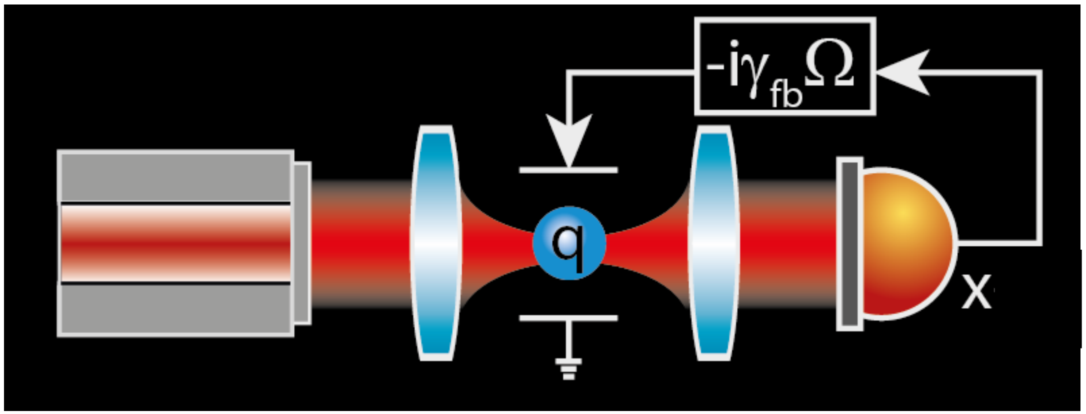
- Levitated glass particle (100 nm diameter)
- Measure position by (a form of) imaging

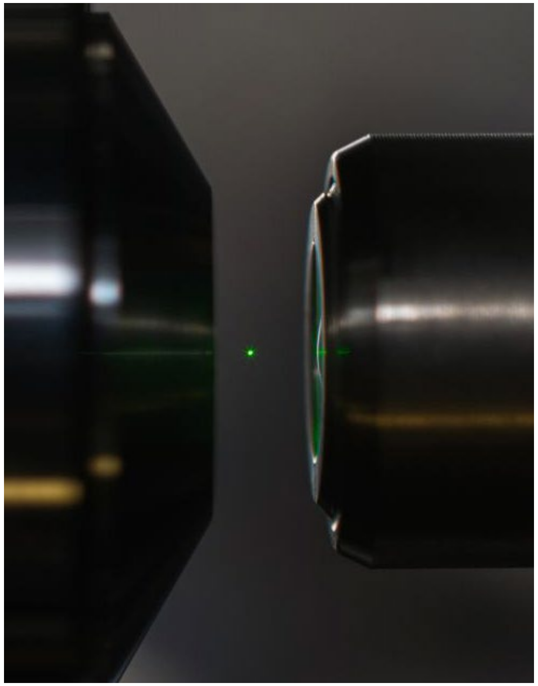
This is localization microscopy!



Levitated optomechanics – cold damping

$$m\ddot{x} + m\gamma_{\text{gas}}\dot{x} + m\Omega_0^2 x = F_{\text{fluct}} + F_{\text{fb}}$$





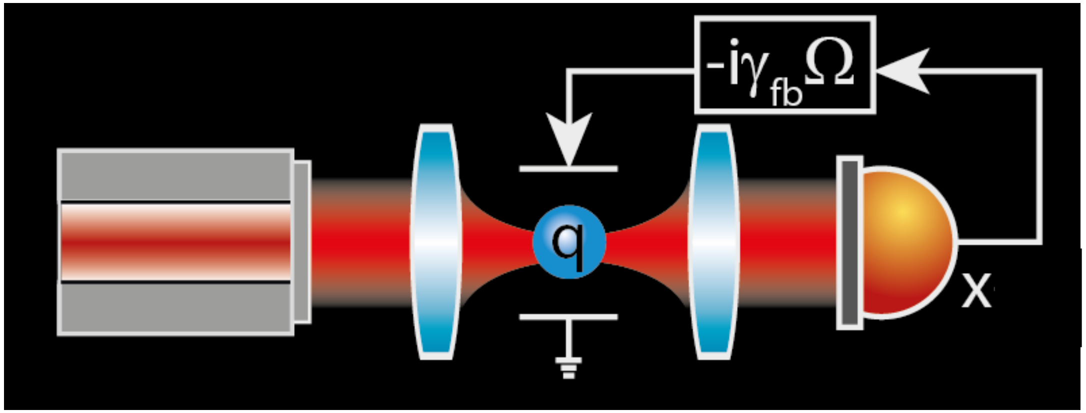
$$F_{\text{fb}} = -m\gamma_{\text{fb}}\dot{x}$$

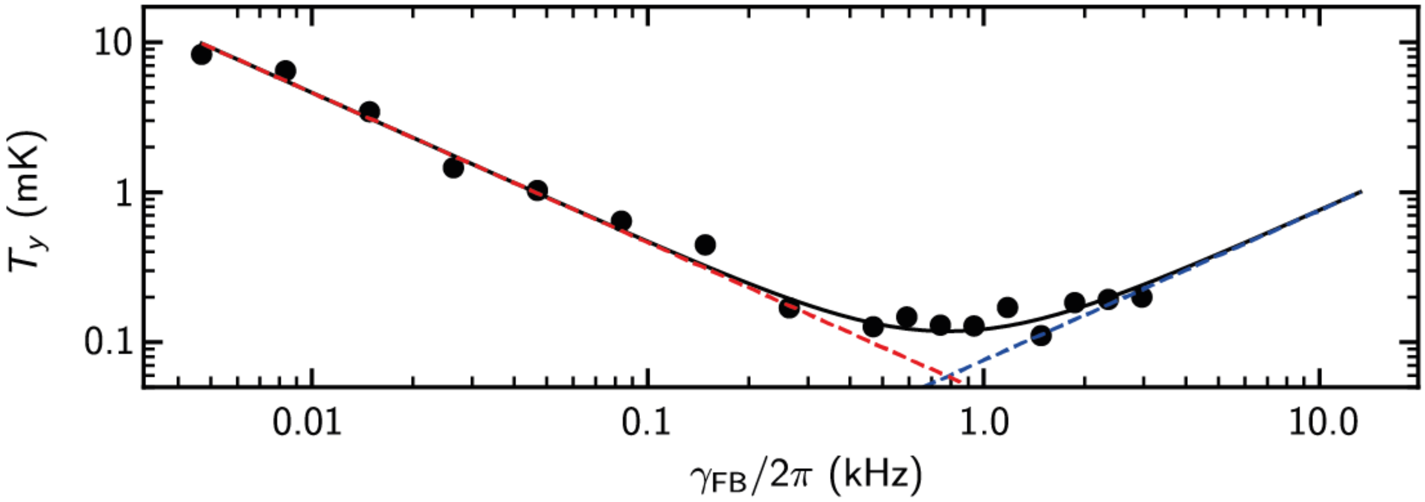
- Levitated particles carry net electric charge
- Charge can be controlled
- Charge allows us to apply a Coulomb force

Levitated optomechanics – cold damping

$$m\ddot{x} + m\gamma_{\text{gas}}\dot{x} + m\Omega_0^2 x = F_{\text{fluct}} + F_{\text{fb}}$$

$$T_{\text{eff}} = \frac{\gamma_{\text{gas}} T_{\text{gas}}}{\gamma_{\text{gas}} + \gamma_{\text{fb}}}$$



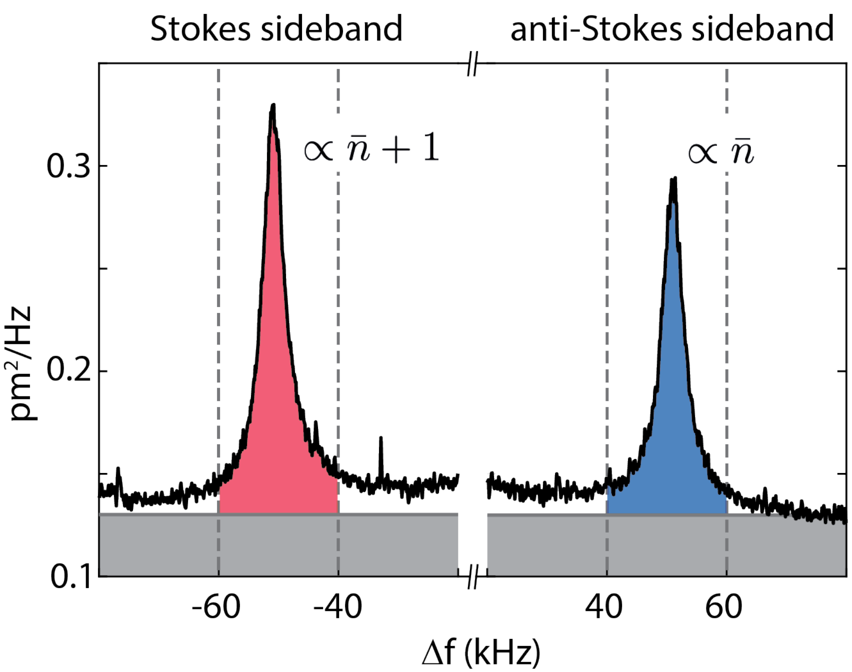


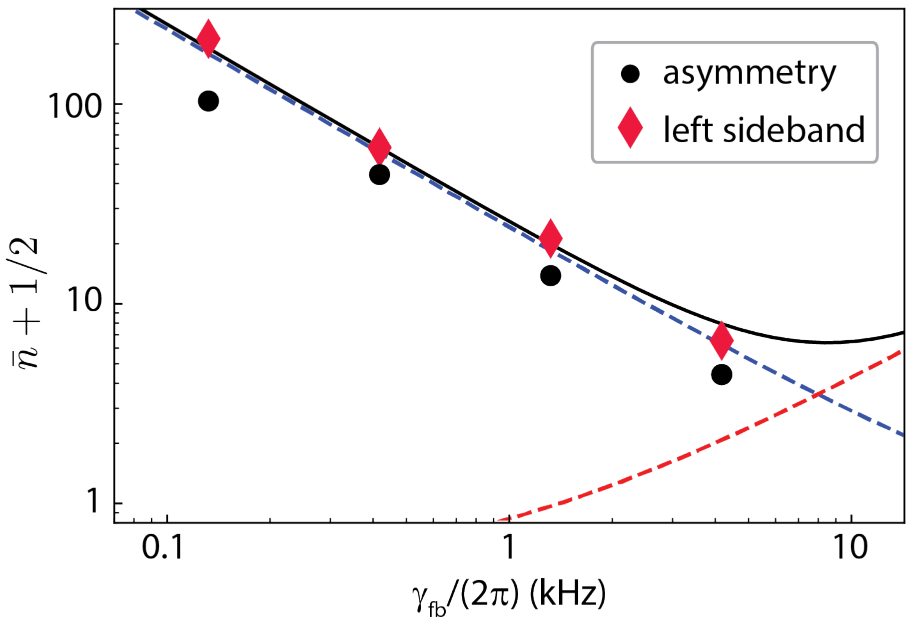
Sideband thermometry

Sideband thermometry

$$m\ddot{x} + m\gamma_{\mathrm{gas}}\dot{x} + m\Omega_0^2 x = F_{\mathrm{fluct}} + F_{\mathrm{fb}}$$

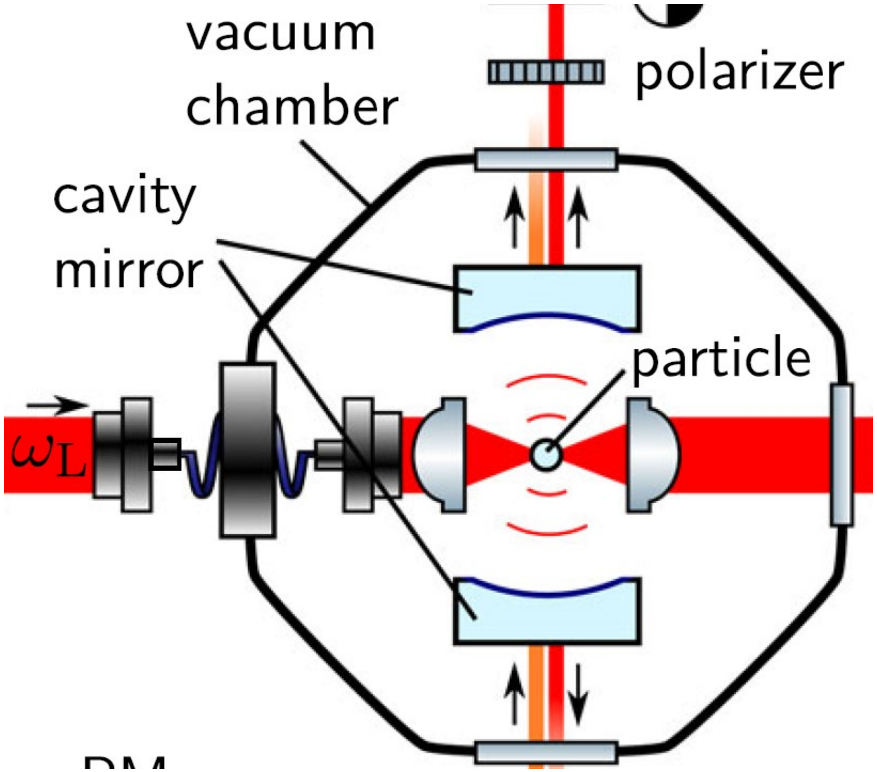
$$T_{\mathrm{eff}} = \frac{\gamma_{\mathrm{gas}} T_{\mathrm{gas}}}{\gamma_{\mathrm{gas}} + \gamma_{\mathrm{fb}}}$$





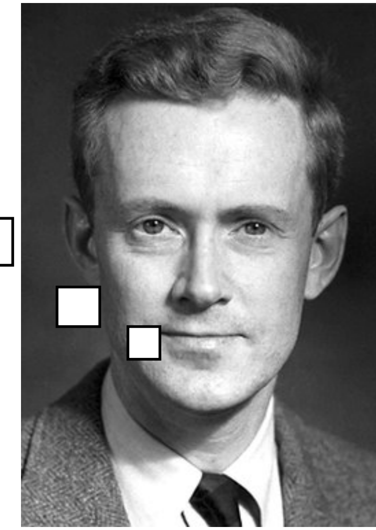
Tebbenjohanns et al., PRL 124, 013603 (2020)

Cavity-control of a levitated nanoparticle



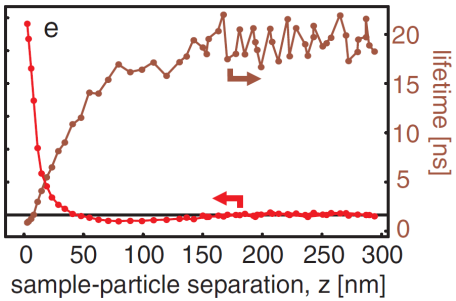
Use a cavity to tailor light-matter interaction strength!

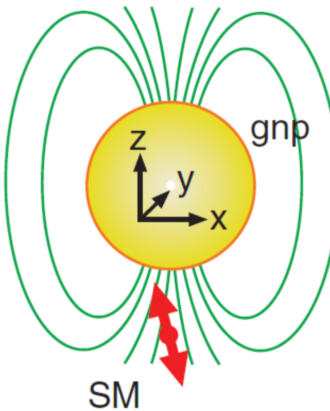
Remember him?



Photonic structures to control LDOS

Optical antennas

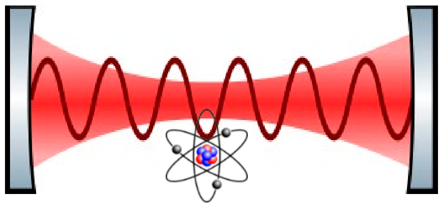


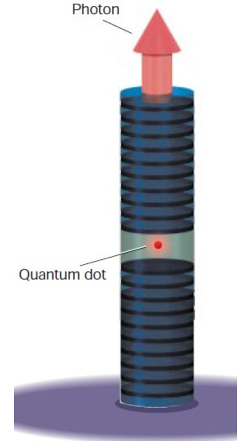


Kühn et al., PRL 97, 017402 (2006)

- Modulate LDOS on a sub-λ scale
- Rely on resonances of conduction electrons of metal nanoparticles
- Rely on evanescent fields

Cavities





Vahala, Nature 424, 839

- Modulate LDOS on a λ scale
- Rely on interference of propagating waves
- LDOS enhancement limited to Purcell factor

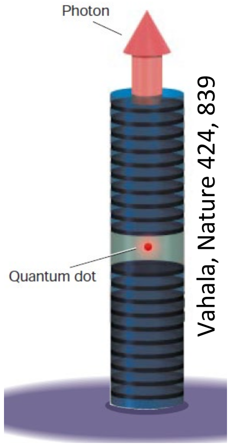
Fermi's Golden Rule

$$\gamma = \frac{\pi\omega}{3\hbar\epsilon_0} |\hat{\boldsymbol{p}}|^2 \; \rho_{\mathbf{n}}(\boldsymbol{r}_0, \omega)$$

Local Density of Optical States

$$\rho_{\mathbf{n}}(\boldsymbol{r}_0, \omega) = \frac{6\omega n^2}{\pi c^2} \left\{ \boldsymbol{n}_p^{\intercal} \, \mathrm{Im}\left[\overleftrightarrow{\boldsymbol{G}}(\boldsymbol{r}_0, \boldsymbol{r}_0; \omega) \right] \boldsymbol{n}_p \right\}$$

Summary – light matter interaction



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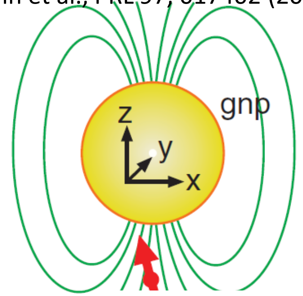
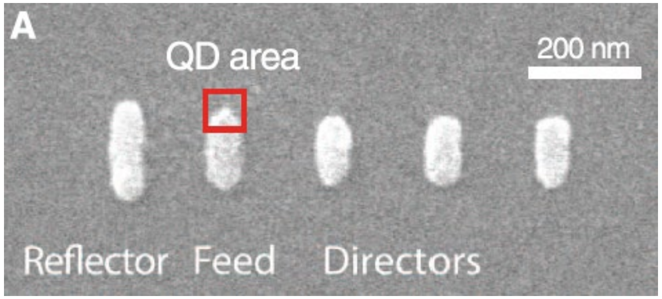
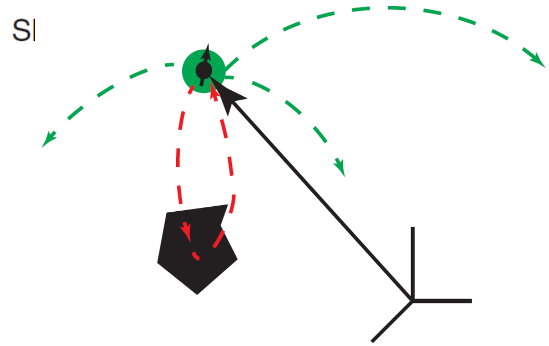


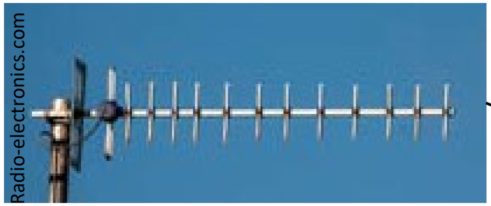
Curto et al., Science 329, 930 (2010)

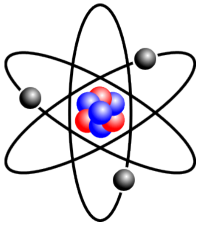


Quantum emitters are probes for their electromagnetic environment.



Quantum emission can be tailored via the emitter's electromagnetic environment.





kT

Ry

100 meV

1 eV

10 eV