Levitated optomechanics

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Nottingham, Nov 12, 2018

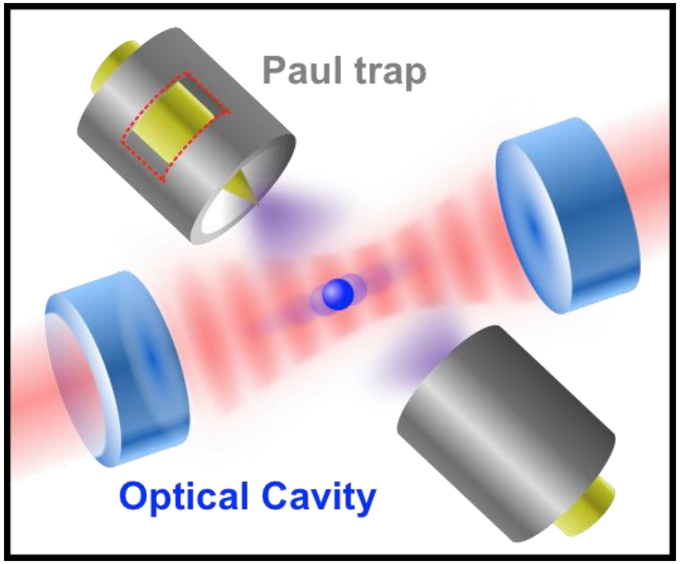
Outline

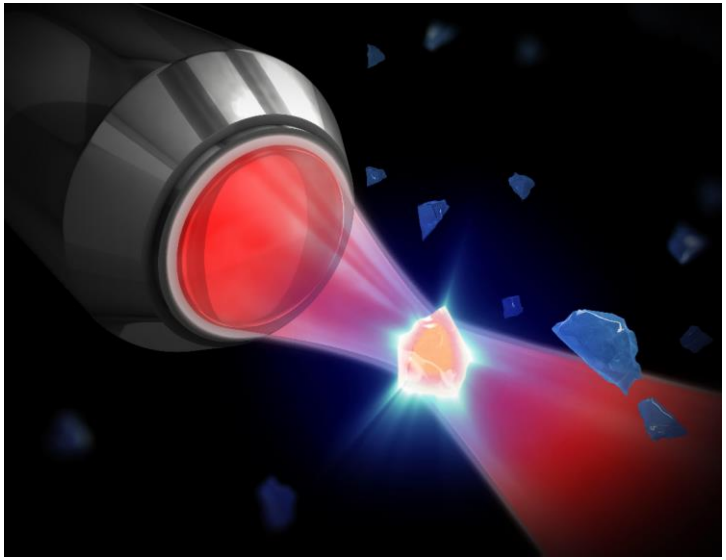
Part 1

- Introduction – why we do it
  - General introduction to optomechanics
  - Levitated optomechanics
- Trapping
  - Optical
  - Electric
  - Magnetic
  - Hybrid approaches
  - Decoherence
- Cooling
  - Cavity cooling
  - Requirements for ground state cooling

Part 2

- Cooling (again)
  - Cavity cooling again (Discussion)
  - Cooling
  - Feedback cooling
  - Cold atoms (Discussion – working groups)
  - Cooling phonons
- Observing non-classical motion
  - Interferometry
  - The creation of in trap non-classical motion
- Testing collapse models
  - What are collapse models
  - Why collapse models
  - Testing
- Interferometry
  - Conventional
  - In-trap





Cavity optomechanics

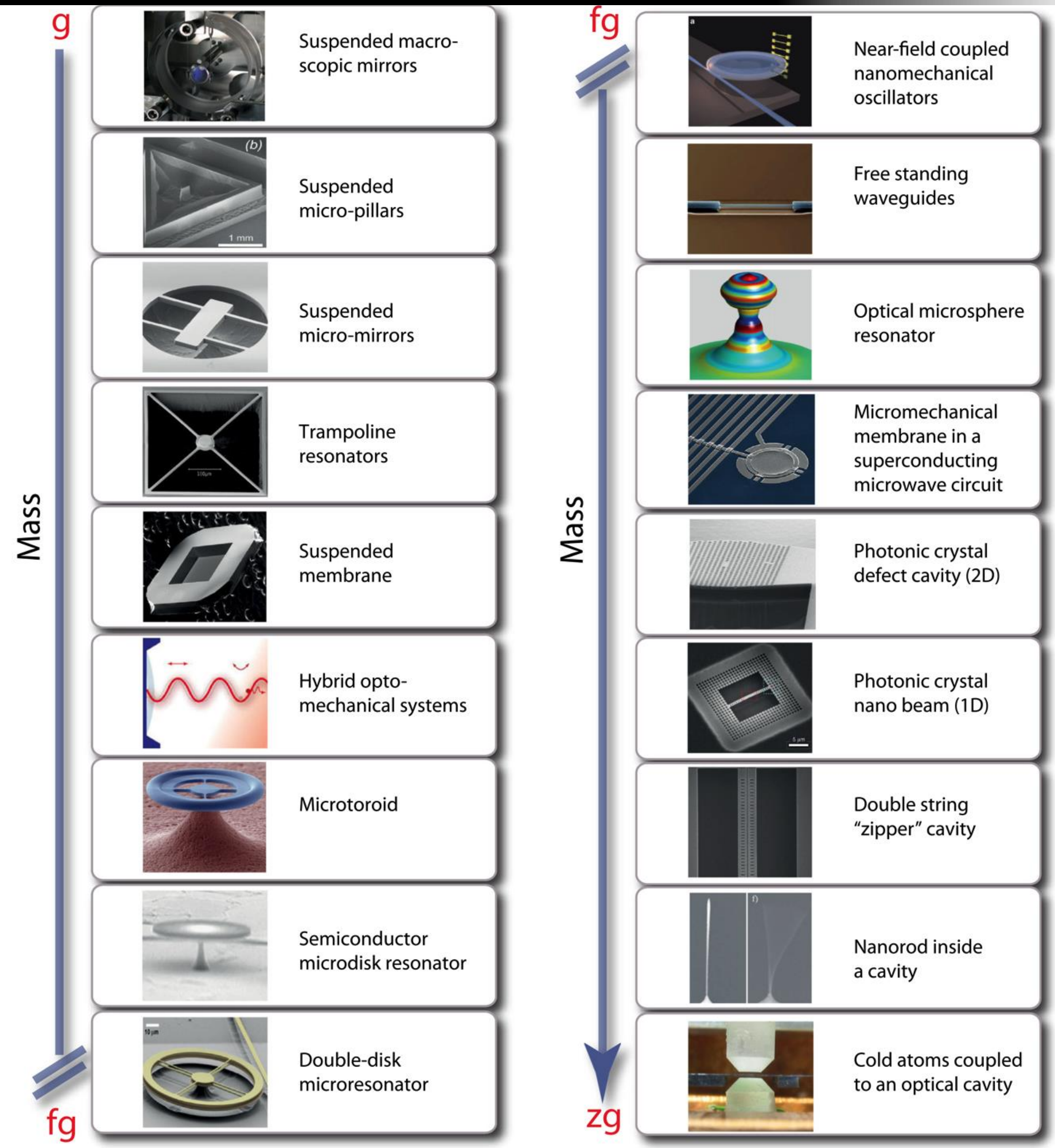
Control and cooling of oscillators with light

Enhanced by optical cavity

Engineered systems

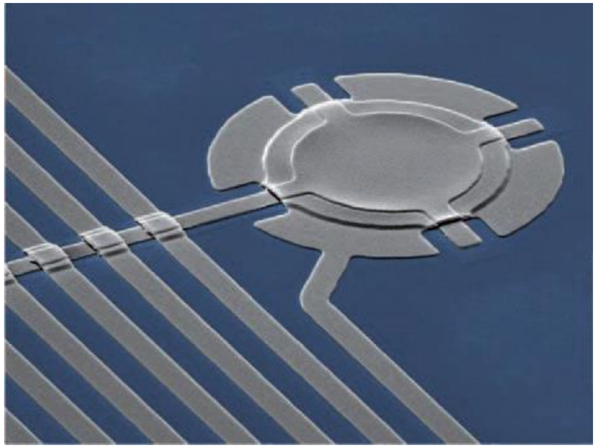
Can be cooled to ground state

Quantum limited sensing

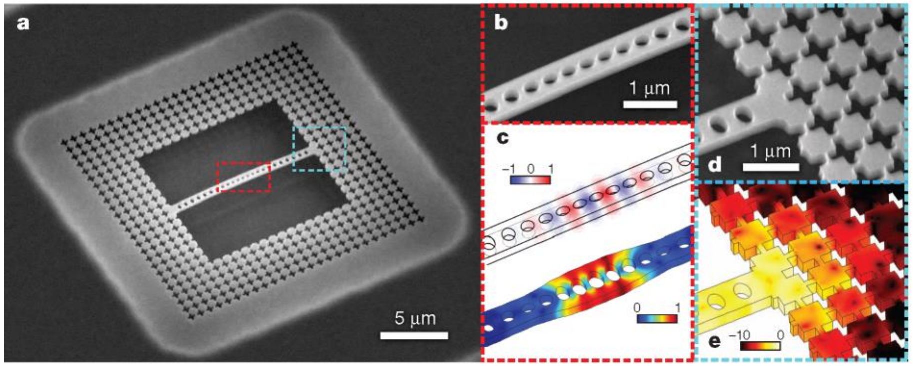


T. J. Kippenberg, K. J. Vahala, *Science* 321, 1172 (2008)

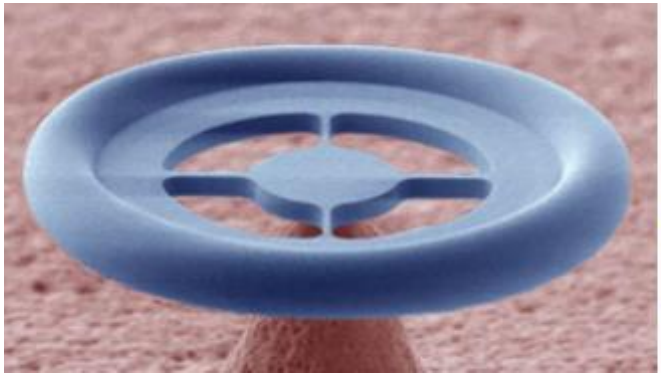
Nano and micro-mechanical oscillators



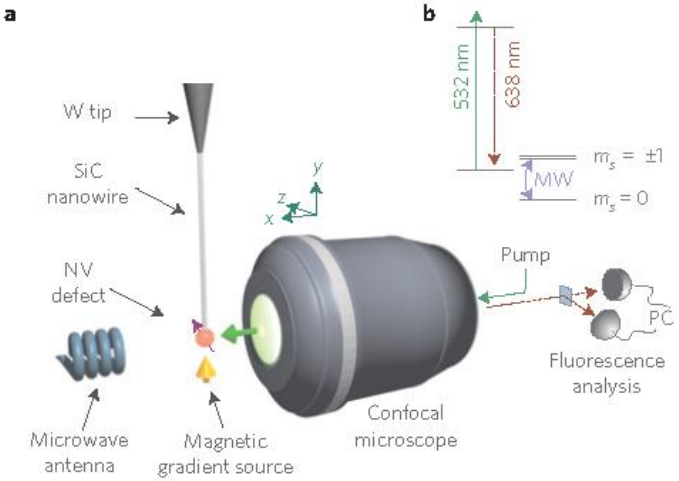
Teufel *et al.* Nature **475** 379 (2011)



Chan *et al.* Nature **478** 89 (2011)



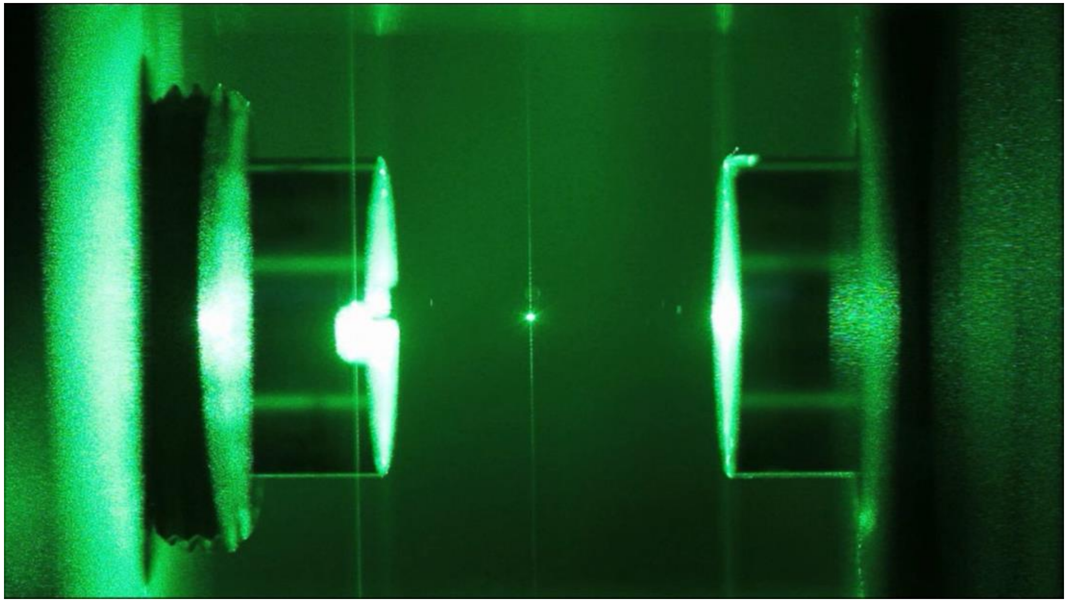
Riviere *et al.* *PRA* **83** 063835 (2011)



Arcizet *et al.* Nature Physics **7** 879 (2011)

Levitated optomechanics

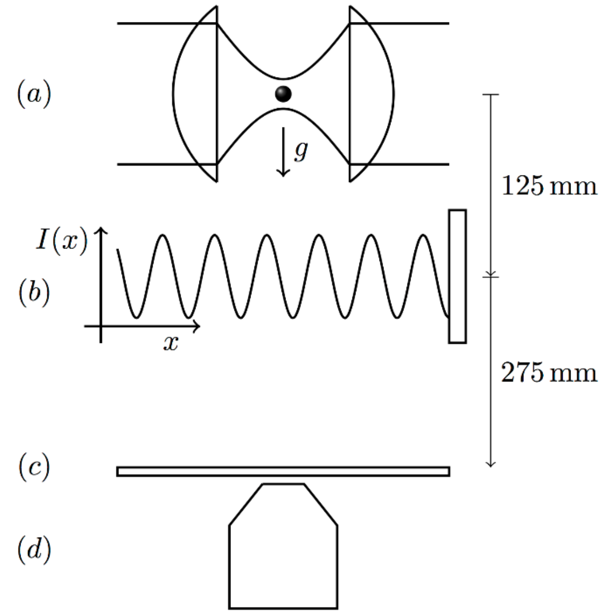
- Uses tools developed for atomic physics and and optical trapping community
- Field insulates the particle from environment
- Tunable spring constant/ trapping freq.
- Can be released

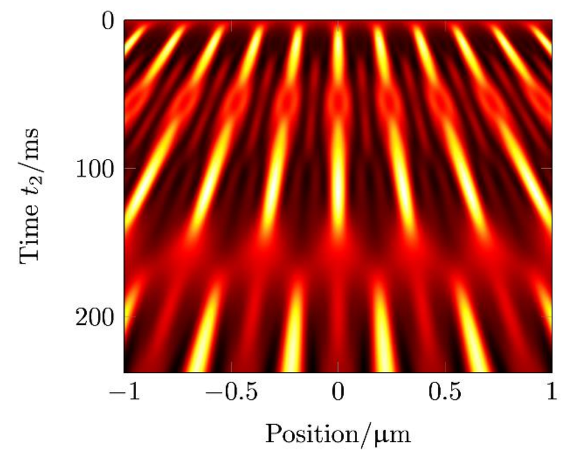


- QM of macroscopic systems
  - Non-classicality
  - Superposition
  - Collapse
- Force sensing
  - Grav. waves
  - Grav. at small scales

Testing superposition for massive particles

- Trap and cool
- Switch off the levitating field
- Record position





ARTICLE

Received 18 Mar 2014 | Accepted 24 Jul 2014 | Published 2 Sep 2014 DOI: 10.1038/ncomms5788

Near-field interferometry of a free-falling nanoparticle from a point-like source

James Bateman[1], Stefan Nimmrichter[2], Klaus Hornberger[2] & Hendrik Ulbricht[1]

Matter-wave interferometry

PRL **111**, 180403 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

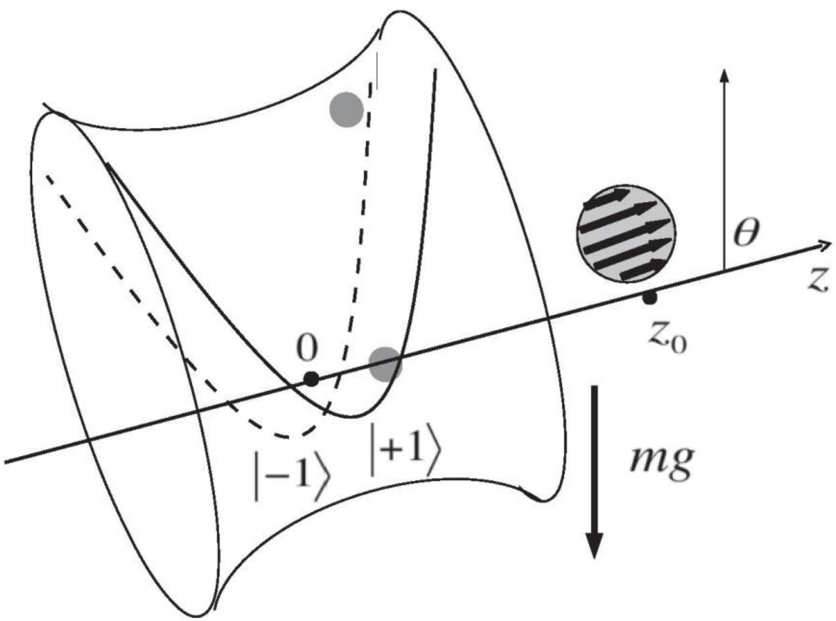
Matter-Wave Interferometry of a Levitated Thermal Nano-Oscillator Induced and Probed by a Spin

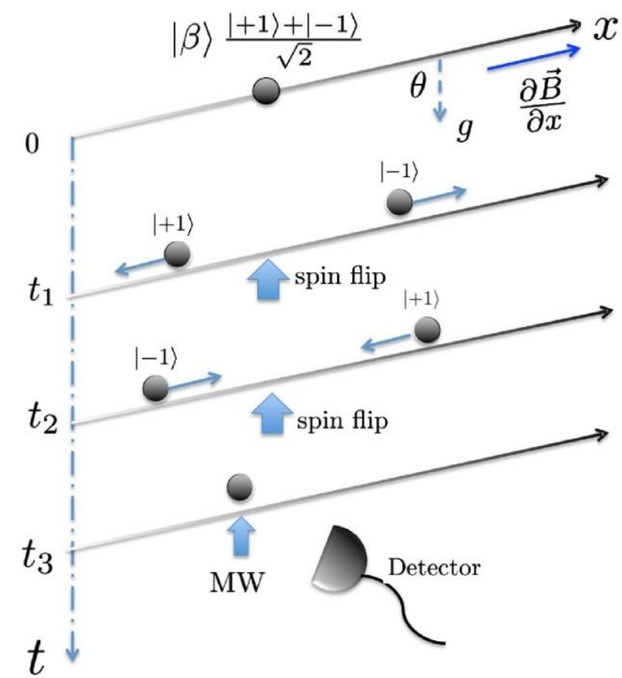
M. Scala,[1] M. S. Kim,[2] G. W. Morley,[3] P. F. Barker,[1] and S. Bose[1]

PRL **117**, 143003 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions

C. Wan,[1] M. Scala,[1] G. W. Morley,[2] ATM. A. Rahman,[2,3] H. Ulbricht,[4] J. Bateman,[5] P. F. Barker,[3] S. Bose,[3,*] and M. S. Kim[1]





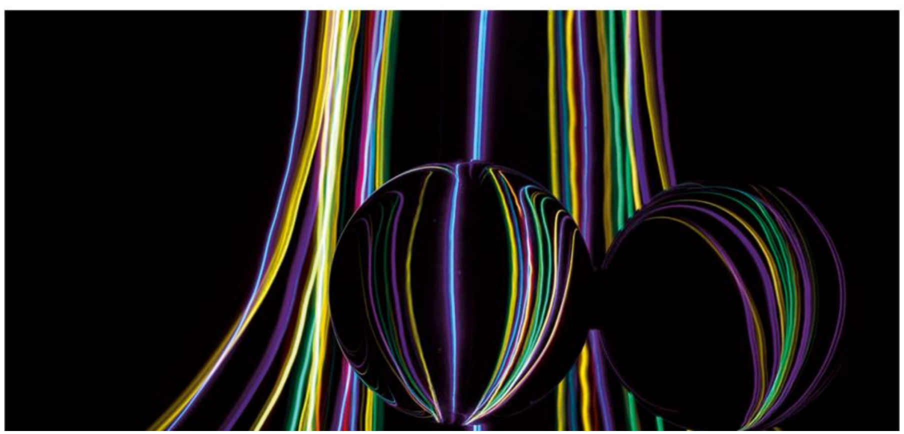
Is gravity quantum?

UCL

New Scientist

NEWS & TECHNOLOGY 22 November 2017

Free-fall experiment could test if gravity is a quantum force



A Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew Geraci,[6] Peter Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

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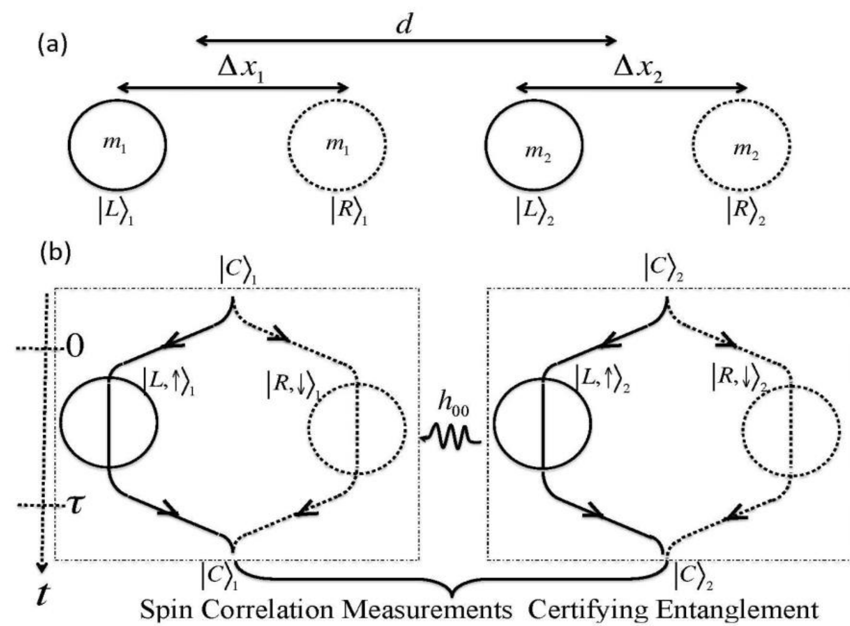
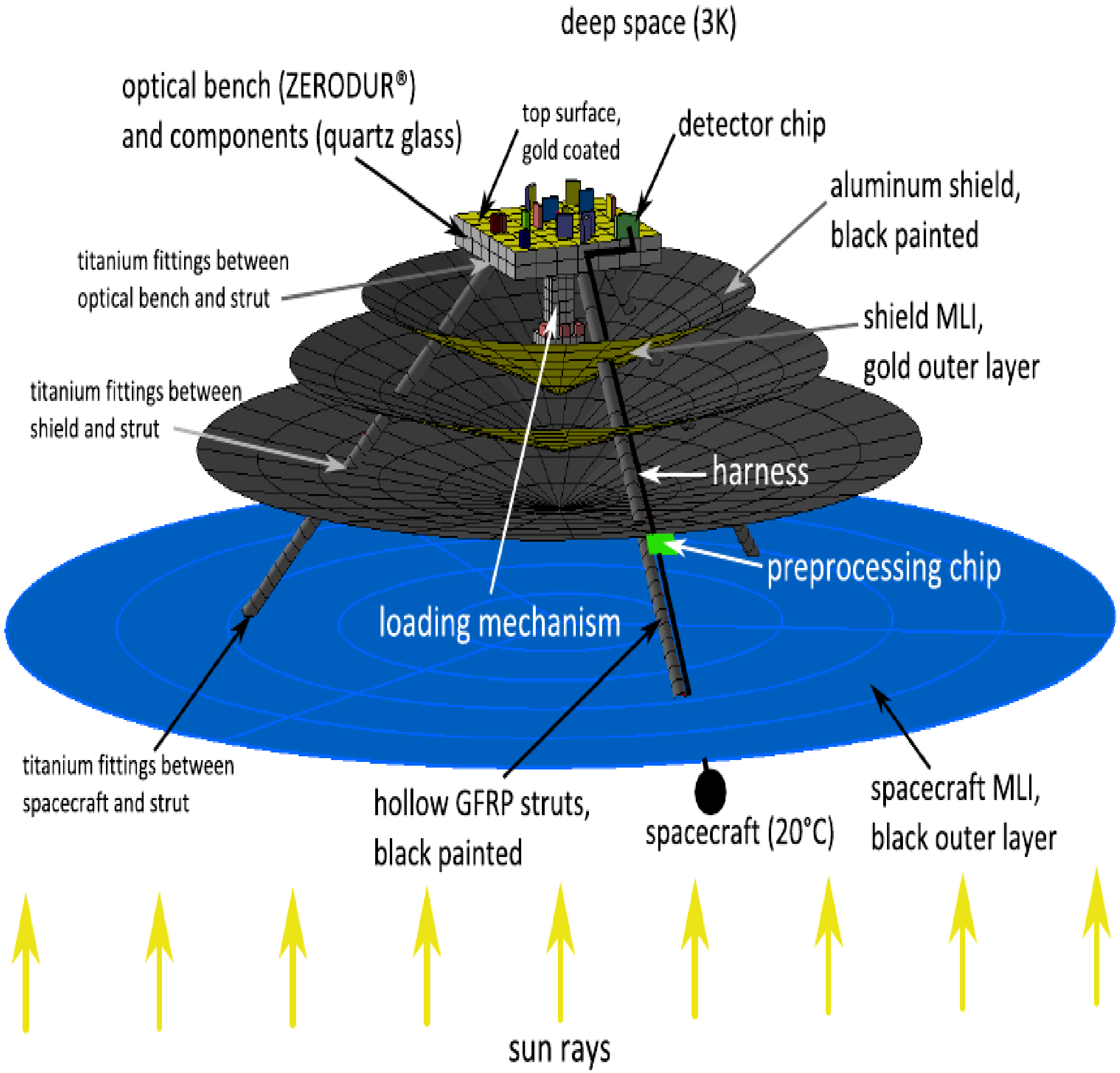


MAQRO – Macroscopic quantum resonators



Force sensing

PRL 105, 101101 (2010) PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 20

Short-Range Force Detection Using Optically Cooled Levitated Microspheres

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Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 2 June 2010; published 30 August 2010)

PRL 110, 071105 (2013) PHYSICAL REVIEW LETTERS week en 15 FEBRUA

Detecting High-Frequency Gravitational Waves with Optically Levitated Sensors

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(Received 18 July 2012; published 14 February 2013)

We propose a tunable resonant sensor to detect gravitational waves in the frequency range of 50–300 kHz using optically trapped and cooled dielectric microspheres or microdisks. The technique we describe can exceed the sensitivity of laser-based gravitational wave observatories in this frequency range, using an instrument of only a few percent of their size. Such a device extends the search volume for gravitational wave sources above 100 kHz by 1 to 3 orders of magnitude, and could detect monochromatic gravitational radiation from the annihilation of QCD axions in the cloud they form around stellar mass black holes within our galaxy due to the superradiance effect.

Levitated optomechanics with a fiber Fabry-Perot interferometer

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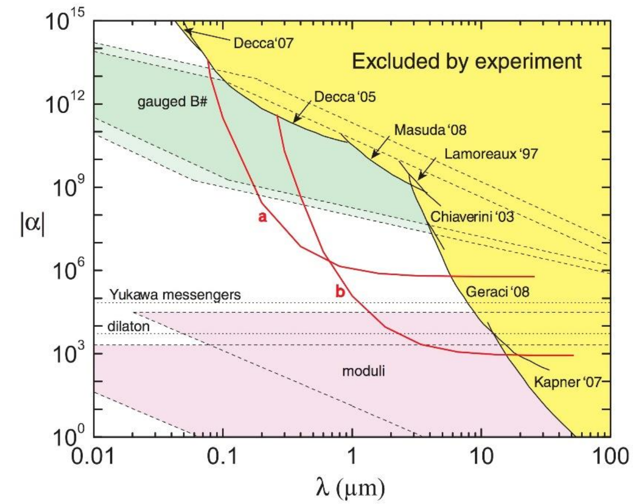
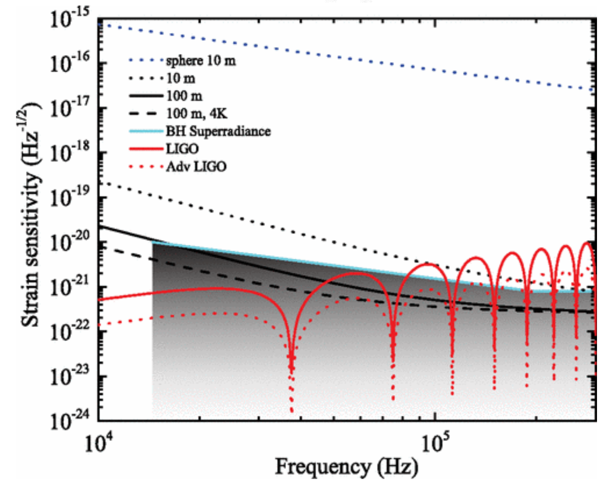
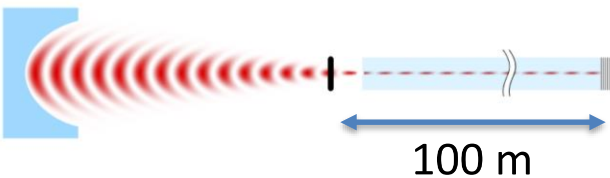
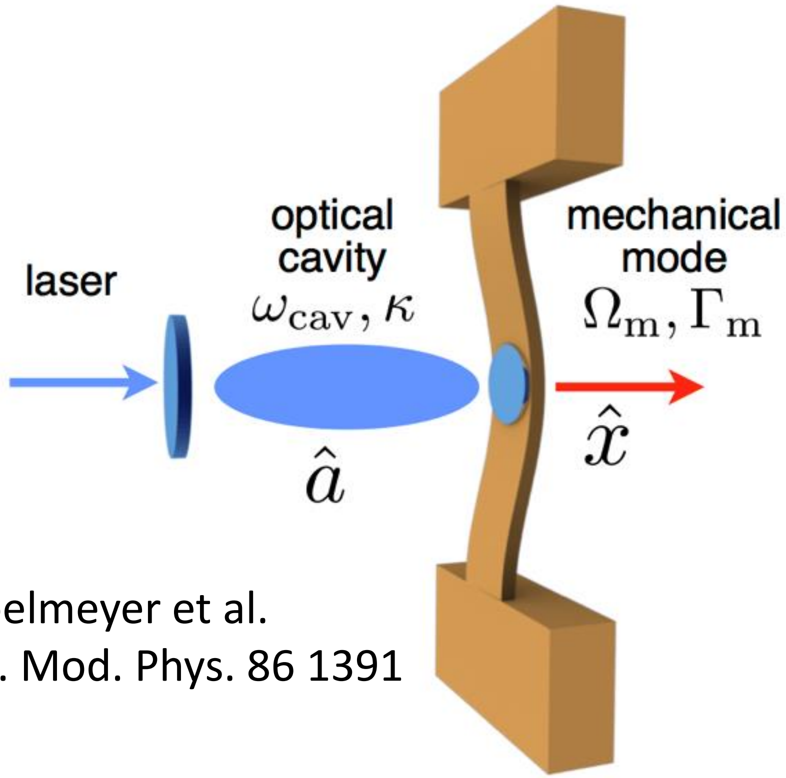


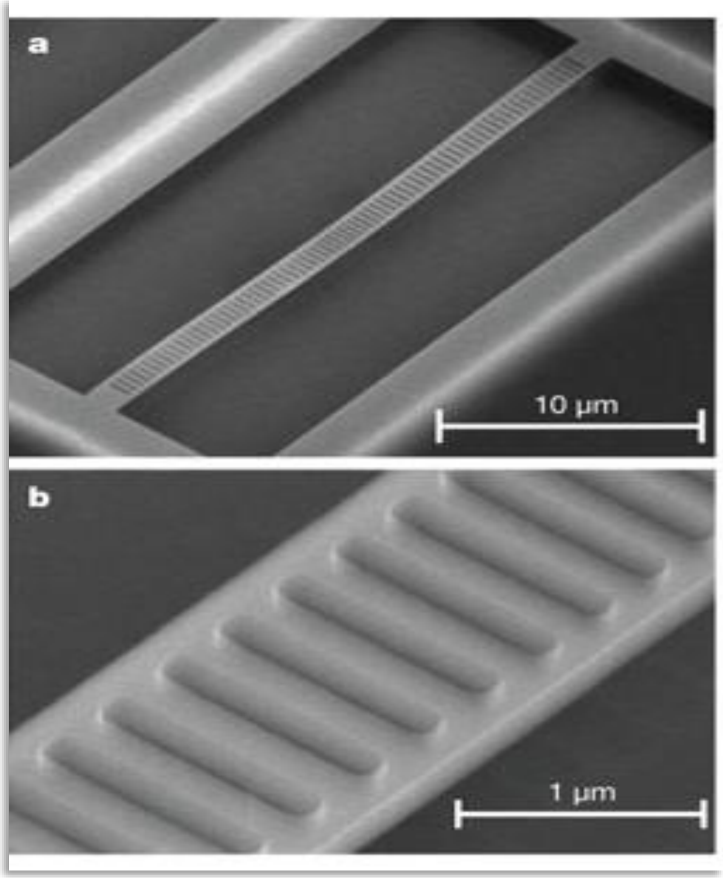




Coupling phonons and photons



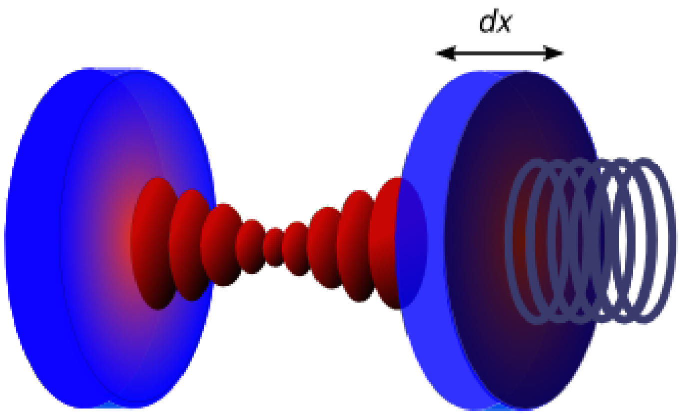
Aspelmeyer et al.
Rev. Mod. Phys. 86 1391



Eichenfield *et al.* Nature (2009)

Devices with masses that span 18 orders of magnitude

Driven optical cavity



$$\dot{\hat{a}} = \frac{\kappa}{2}\hat{a} + i\Delta\hat{a} + \sqrt{\kappa_{ex}}\hat{a}_{in} + \sqrt{\kappa_0}\hat{f}_{in}$$

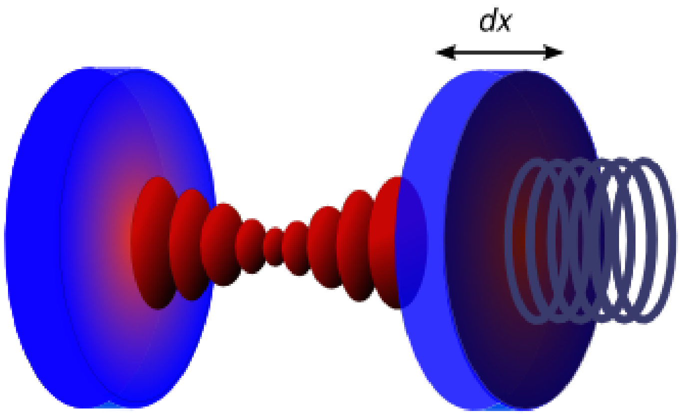
$$P = \hbar\omega_c\langle\hat{a}^\dagger_{in}\hat{a}_{in}\rangle$$

$$\bar{n}_c = |\langle\hat{a}\rangle|^2 = \frac{\kappa_{ex}}{\Delta^2 + (\kappa/2)^2}$$

$$Q_{opt} = \omega_c/\kappa$$

$$\langle\hat{F}\rangle = 2\hbar k\frac{\bar{n}_c}{\tau_c} = \hbar\frac{\omega}{L}\langle\hat{a}^\dagger\hat{a}\rangle, \tau_c = 2L/c$$

Mechanical resonators



Equation of motion for mass m, damping rate Γ_m

$$m\ddot{x}(t) + m\Gamma_m\dot{x}(t) + m\Omega_m^2 x(t) = F_{ext}(t)$$

Useful to express as a function of frequency

$$x(\omega) = \int_{-\infty}^{+\infty} x(t) e^{i\omega t} dt$$

Linear response theory gives

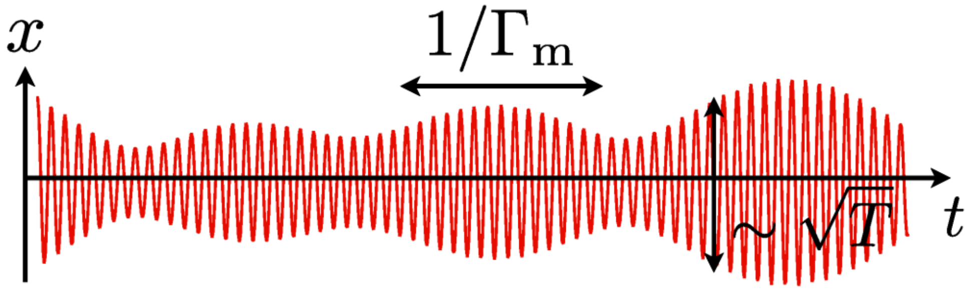
$$\delta x(\omega) = \chi_{xx}(\omega) F_{ext}(\omega)$$

where the susceptibility is

$$\chi_{xx}(\omega) = (m(\Omega_m^2 - \omega^2) - im\Gamma_m\omega)^{-1}$$

Mechanical resonators

Position as a function of time



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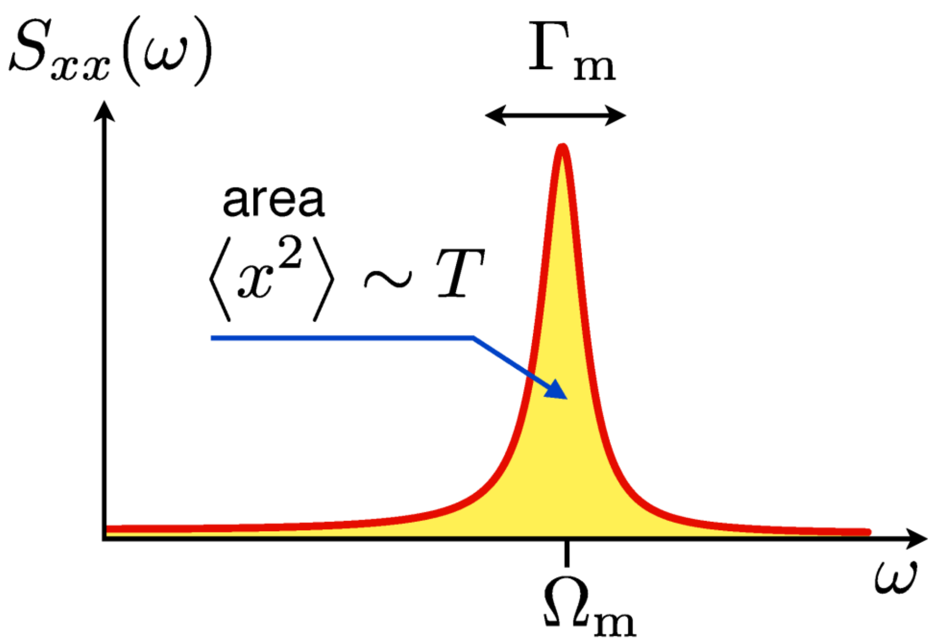
Position power spectral density (PSD)

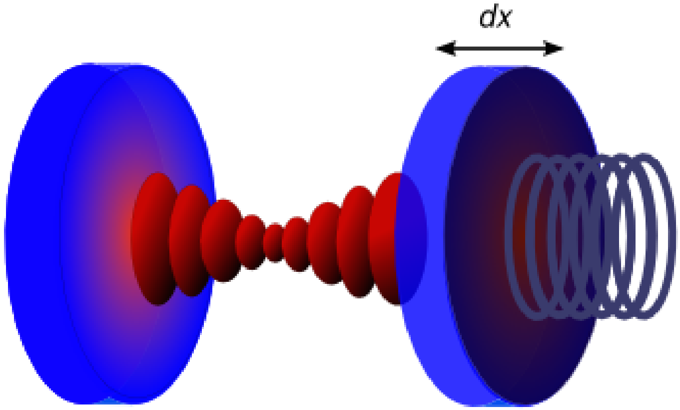
$$S_{xx}(\omega) = \int_{-\infty}^{\infty} \langle x(t)x(0)\rangle e^{i\omega t} dt$$



Weiner-Kinchine theorem

$$\int_{-\infty}^{+\infty} S_{xx} \frac{d\omega}{2\pi} = \langle x^2 \rangle = \frac{k_B T}{m\Omega_m^2}$$

A quantum phonon picture



Assuming harmonic motion, the Hamiltonian for the oscillator is

$$\hat{H} = \hbar\Omega_m \hat{b}^\dagger \hat{b} + \frac{1}{2}\hbar\Omega_m$$ where Phonon number is: $\bar{n} = \langle \hat{b}^\dagger \hat{b} \rangle$

and where $\hat{x} = x_{zpf}(\hat{b} + \hat{b}^\dagger), \hat{p} = im\Omega_m x_{zpf}(\hat{b} - \hat{b}^\dagger)$

The extent of the ground state (zero phonon fluctuation) is

$$x_{zpf} = \sqrt{\frac{\hbar}{2m\Omega_m}}$$

$$x_{zpf}^2 = \langle 0|\hat{x}^2|0\rangle$$

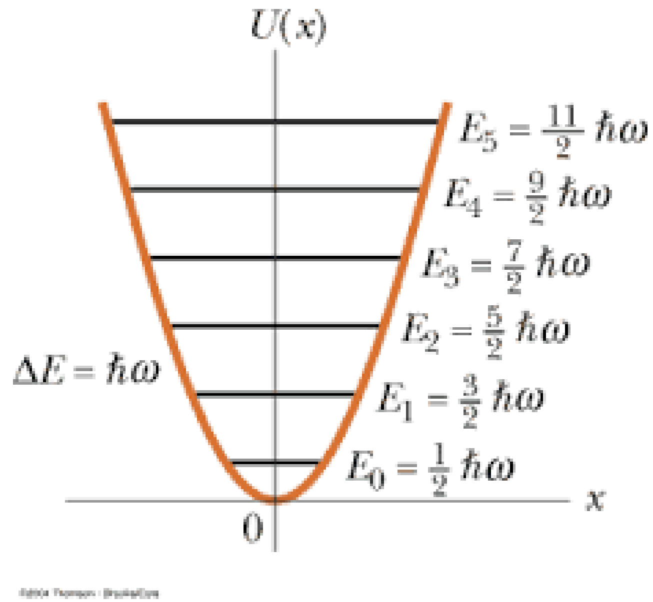
Heating due to a thermal bath

If the oscillator is coupled to a thermal bath, the heating rate is

$$\dot{\hat{n}} = -\Gamma_m(\langle n \rangle - \bar{n}_{th})$$

For low initial occupancy

$$\dot{\hat{n}}(t=0) = \bar{n}_{th}\Gamma_m \approx \frac{k_B T_{bath}}{\hbar Q_m}$$



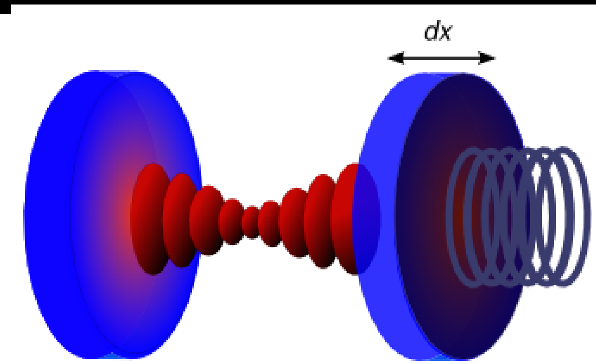
The average thermal occupancy is

$$\bar{n}_{th} \approx \frac{k_B T_{bath}}{\hbar \Omega_m}$$

“Q f” product

$$\frac{\Omega_m}{\bar{n}_{th}\Gamma_m} = Q_m f_m \frac{\hbar}{k_B T}$$

Cavity + Oscillator



Unperturbed Hamiltonian (cav + osc)

$$\hat{H}_0 = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\Omega_m \hat{b}^\dagger \hat{b}$$

Cavity resonance perturbed by radiation pressures

$$\omega_c(x) \approx \omega_c + x\partial\omega_c/\partial x + ...$$

Modifies the cavity Hamiltonian

$$\hbar\omega_c(x)\hat{a}^\dagger \hat{a} \approx \hbar(\omega_c - G\hat{x})\hat{a}^\dagger \hat{a}$$

Where G is the coupling

$$\hat{H}_{int} = -\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

$$g_0 = G x_{zpf}$$

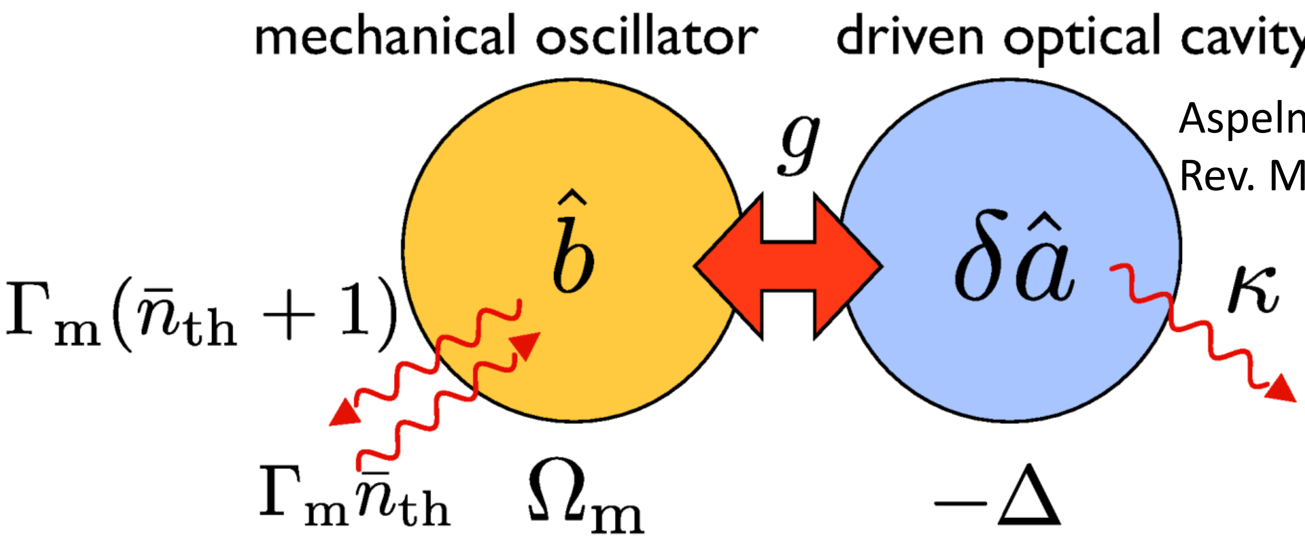
Cavity + Oscillator

In the rotating wave approximation (RWA) and assuming the field undergoes small fluctuations about mean

$$\hat{a} = \bar{\alpha} + \delta\hat{a} \qquad \langle \hat{a} \rangle = \bar{\alpha}$$

The approximate Hamiltonian is

$$\hat{H} \approx -\hbar\Delta\delta\hat{a}^\dagger\delta\hat{a} + \hbar\Omega_m\hat{b}^\dagger\hat{b} - \hbar g_0\sqrt{\bar{n}_c}(\delta\hat{a}^\dagger + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$



Aspelmeyer et al.
Rev. Mod. Phys. 86 1391

Equations of motion

The following equations of motion can be derived

$$\delta\dot{\hat{a}} = (i\Delta - \kappa/2)\delta\hat{a} + ig(\hat{b} + \hat{b}^{\dagger}) + \sqrt{\kappa_{ex}}\delta a_{in}(t) + \sqrt{\kappa_0}\hat{f}_{in}(t)$$

$$\dot{\hat{b}} = (-i\Omega_m - \Gamma_m/2)\delta\hat{a} + ig(\delta\hat{a} + \delta\hat{a}^{\dagger}) + \sqrt{\Omega_m}\hat{b}_{in}(t)$$

Which we can derive the classical equations

$$\hat{a} = \bar{\alpha} + \delta\hat{a} \qquad \langle\hat{a}\rangle = \bar{\alpha}$$

$$\delta\dot{\alpha} = (i\Delta - \kappa/2)\delta\alpha + iG\bar{\alpha}x$$

$$m\ddot{x} = -m\Omega_m^2 - m\Gamma_m\dot{x} + \hbar G(\bar{\alpha}^*\delta\alpha + \bar{\alpha}\delta\alpha^*)$$

Equations of motion (frequency)

We can take the Fourier transform to get

$$-i\omega\delta\alpha(\omega) = (i\Delta - \kappa/2)\delta\alpha(\omega) + iG\bar{\alpha}x(\omega)$$

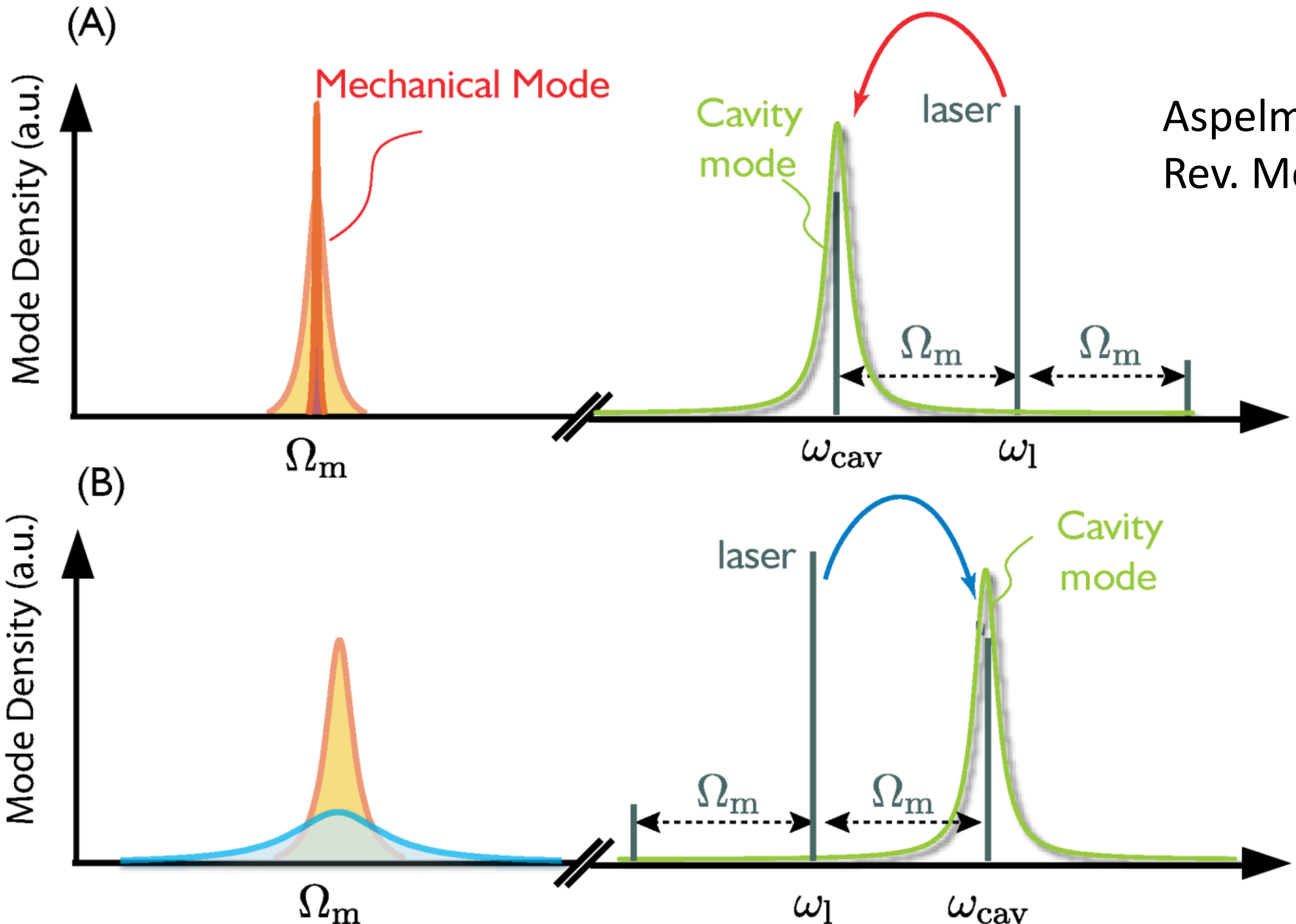
$$-m\omega^2 x(\omega) = -m\Omega_m^2 x(\omega) + i\omega m\Gamma_m x(\omega) + \hbar G(\bar{\alpha}^*\delta\alpha(\omega) + \bar{\alpha}\delta\alpha^*(\omega))$$

Which allows us to find the optomechanical susceptibility

$$\chi_{xx}(\omega) = [m(\Omega_m^2 - 2\omega\delta\Omega_m) - \omega^2 - i\omega(\Gamma_m + \Gamma_{opt})]^{-1}$$

Optical damping/heating

$$\Gamma_{opt}(\omega) = g^2 \frac{\Omega_m}{\omega} [\frac{\kappa}{(\Delta+\omega)^2+\kappa^2/4} - \frac{\kappa}{(\Delta-\omega)^2+\kappa^2/4}]$$



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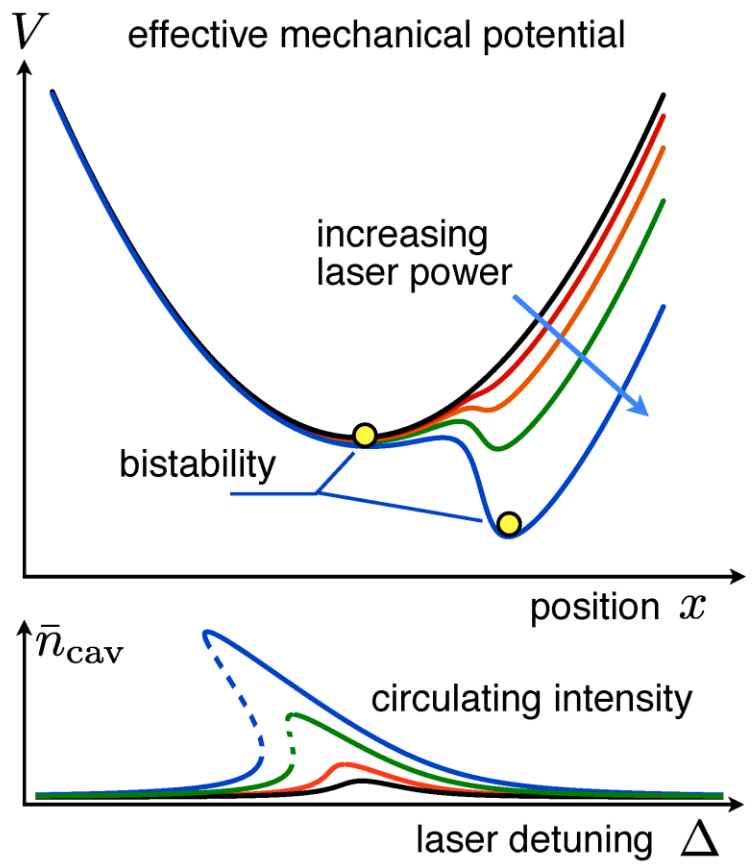
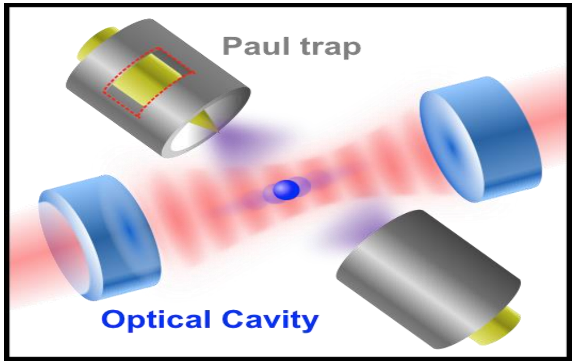
Frequency shift

$$\delta\Omega(\omega) = g^2 \frac{\Omega_m}{\omega}\left[\frac{\Delta+\omega}{(\Delta+\omega)^2+\kappa^2/4} + \frac{\Delta-\omega}{(\Delta-\omega)^2+\kappa^2/4}\right]$$



A levitated particle in a cavity

A particle placed in cavity field shifts the resonant frequency



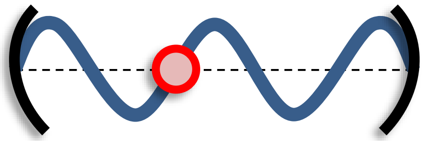
$$\frac{\delta(\omega)}{\omega} = -\frac{1}{2}\frac{\int d^3\mathbf{r}\delta\mathbf{P}.\mathbf{E}(\mathbf{r})}{\int d^3\mathbf{r}\epsilon_0\mathbf{E^2}(\mathbf{r})}$$

For a point like nanoparticle

$$\mathbf{P}(\mathbf{r}^{'}) = \alpha_p E(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}^{'})$$

This leads to a non-linear frequency shift

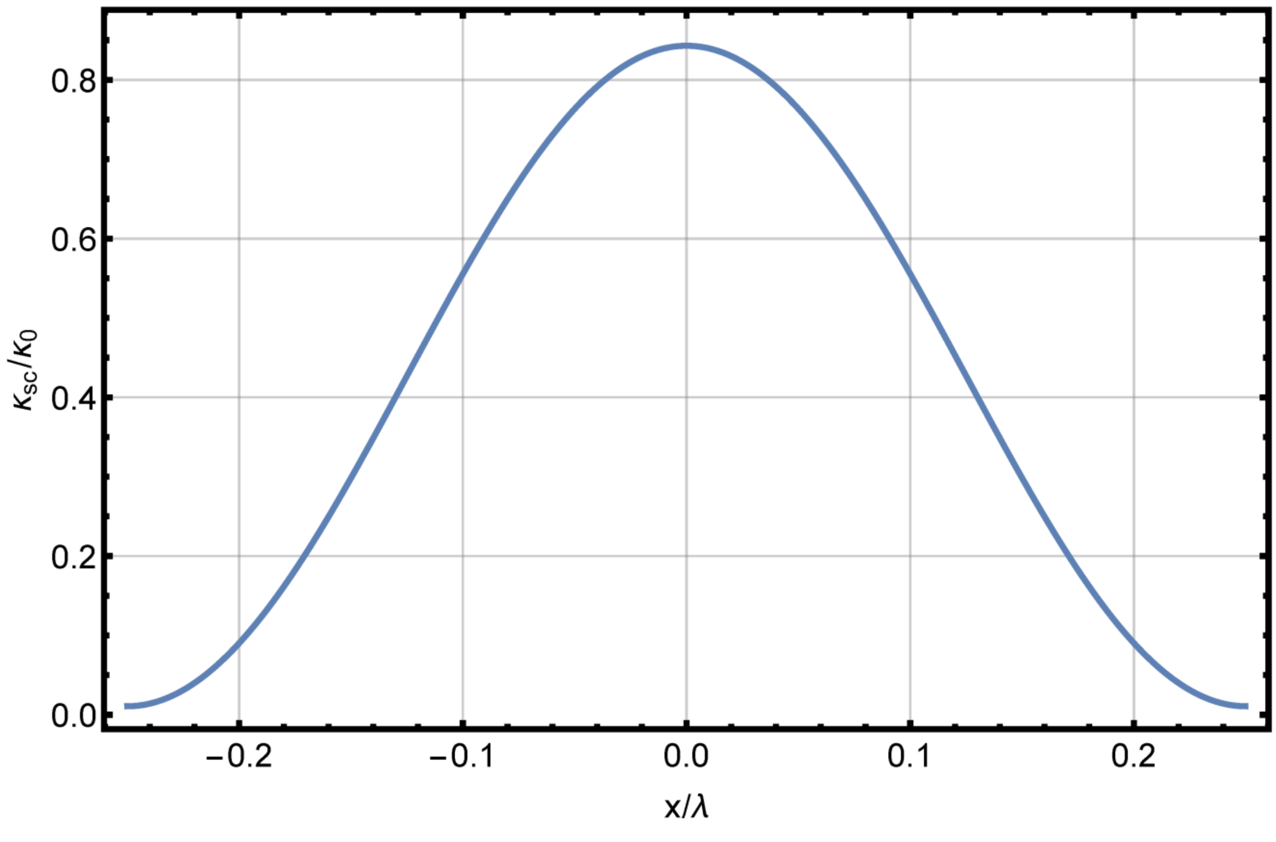
$$\delta\omega = -\frac{3}{2}\frac{V_s}{V_m}\frac{n^2-1}{n^2+2}cos^2(kx)\omega_L$$



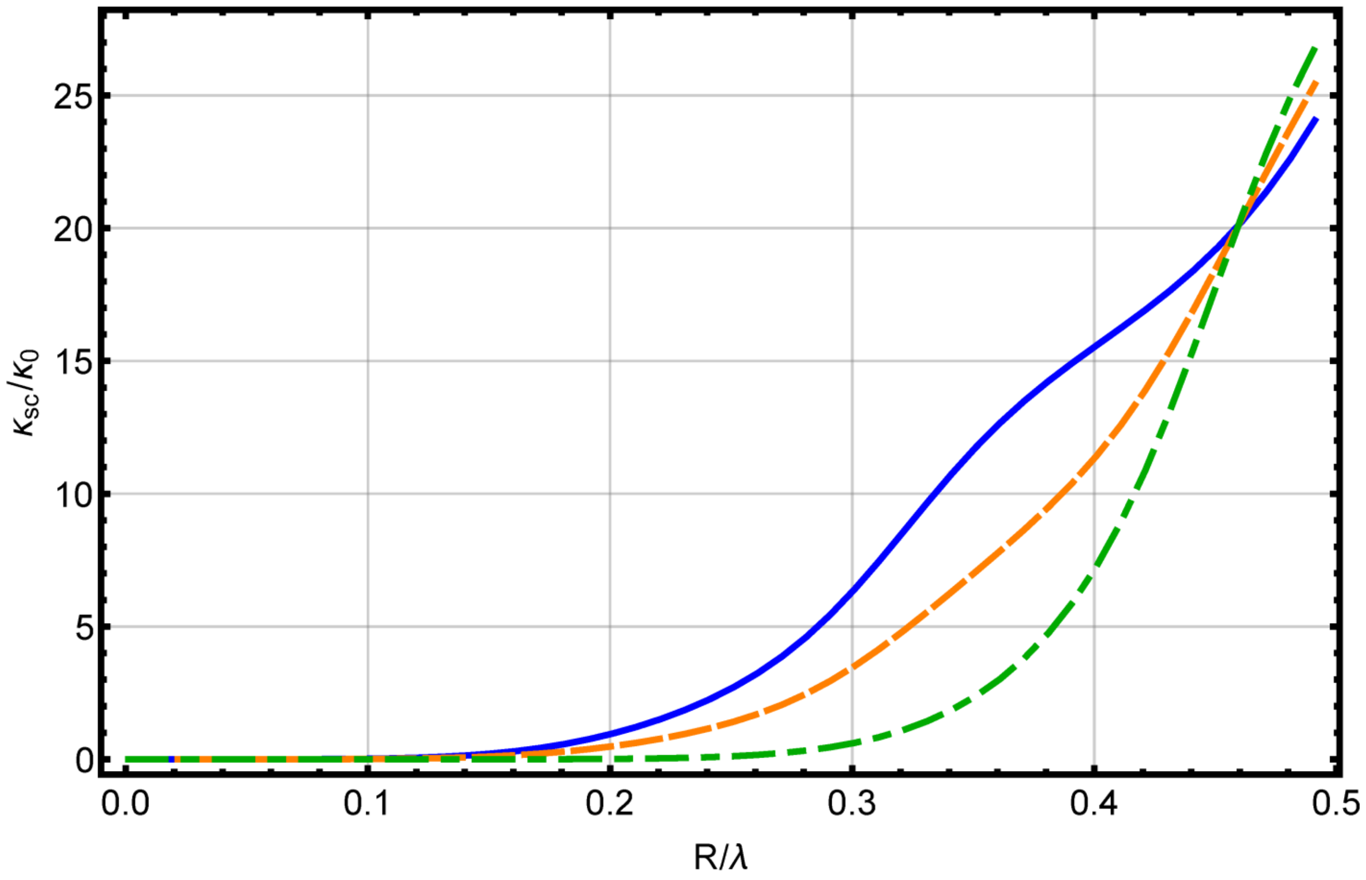
But the coupling can be made linear

$$g_0 = \partial\omega(x)/\partial x|_{x=\lambda/8} = \frac{3V_s}{2V_m}\frac{n^2-1}{n^2+2}\omega_L$$

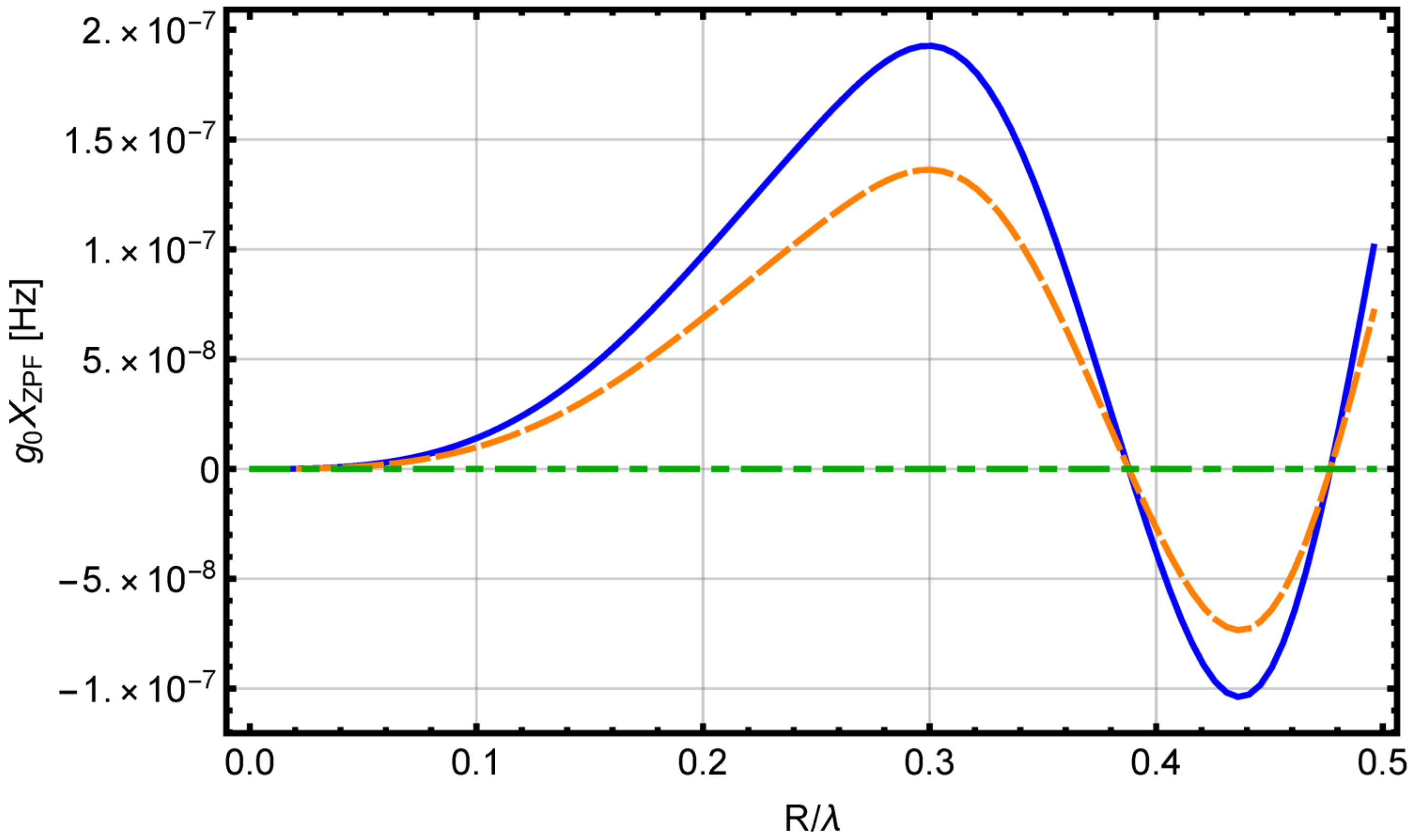
Scattering out of cavity



Scattering with size



Coupling with size



Equations of motion for levitation

Fluctuation in laser phase

Cavity and scattering losses

$$\dot{\hat{a}} = -(\kappa + i(\Delta - g_0 \, cos^2(kx_s))\hat{a} + i\dot{\phi}\alpha_s - ikg_0 sin(2kx_s)\hat{x}\alpha_s + \sqrt{2(\kappa_c + \kappa_{sc})}\hat{a}_c^{in} + \sqrt{2\kappa_i}(\hat{a}_i^{in} + \epsilon) + \sqrt{2\kappa_o}\hat{a}_o^{in}$$

Cavity input and output losses

Detuning as a function of particle position

$$\dot{\hat{p}} = -\hbar k g_0 \hat{a}^\dagger \hat{a} \, sin(2k\hat{x}) - \gamma_m \hat{p} + \zeta$$

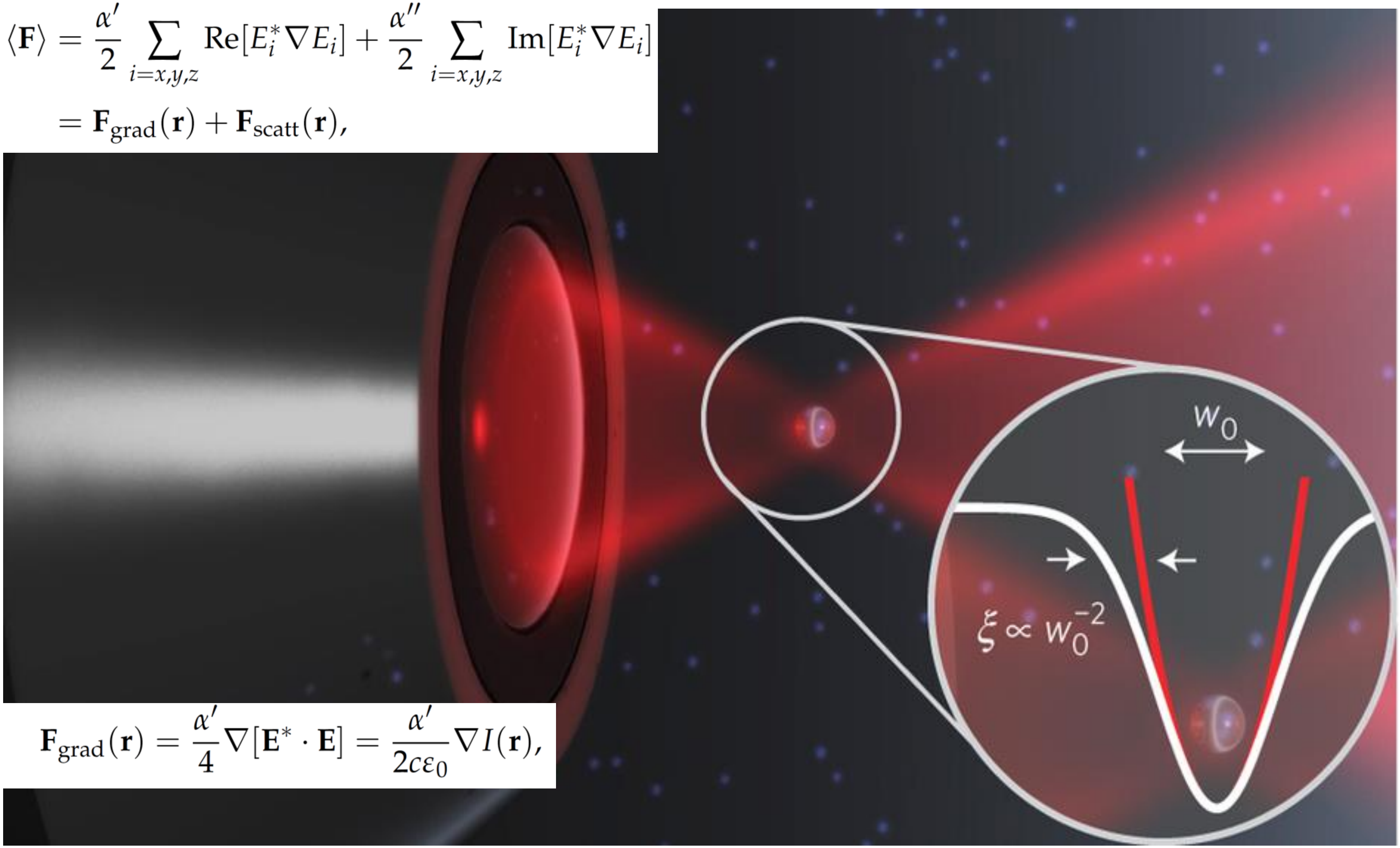
$$\dot{\hat{x}} = \frac{\hat{p}}{m}$$

Mechanical damping (gas +photon)

Optical trapping

Gieseler *et al.* *Nature Phys.* **9** 806 (2012)

$$\langle \mathbf{F} \rangle = \frac{\alpha'}{2} \sum_{i=x,y,z} \mathrm{Re}[E_i^* \nabla E_i] + \frac{\alpha''}{2} \sum_{i=x,y,z} \mathrm{Im}[E_i^* \nabla E_i]$$
$$= \mathbf{F}_{\mathrm{grad}}(\mathbf{r}) + \mathbf{F}_{\mathrm{scatt}}(\mathbf{r}),$$



$$\mathbf{F}_{\mathrm{grad}}(\mathbf{r}) = \frac{\alpha'}{4} \nabla [\mathbf{E}^* \cdot \mathbf{E}] = \frac{\alpha'}{2c\varepsilon_0} \nabla I(\mathbf{r}),$$

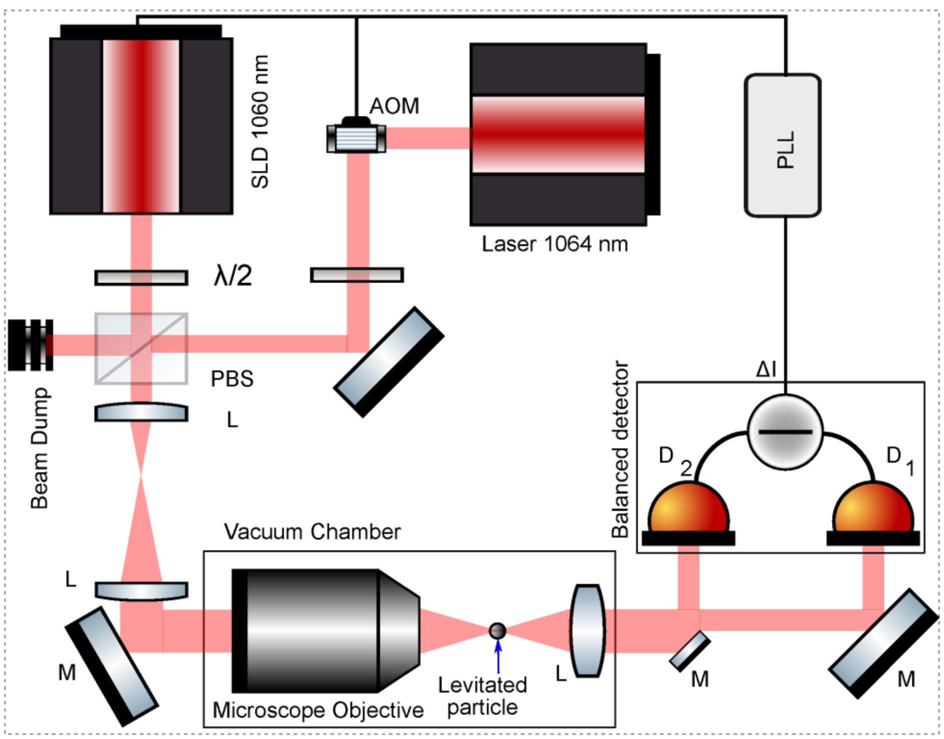
Optical trapping

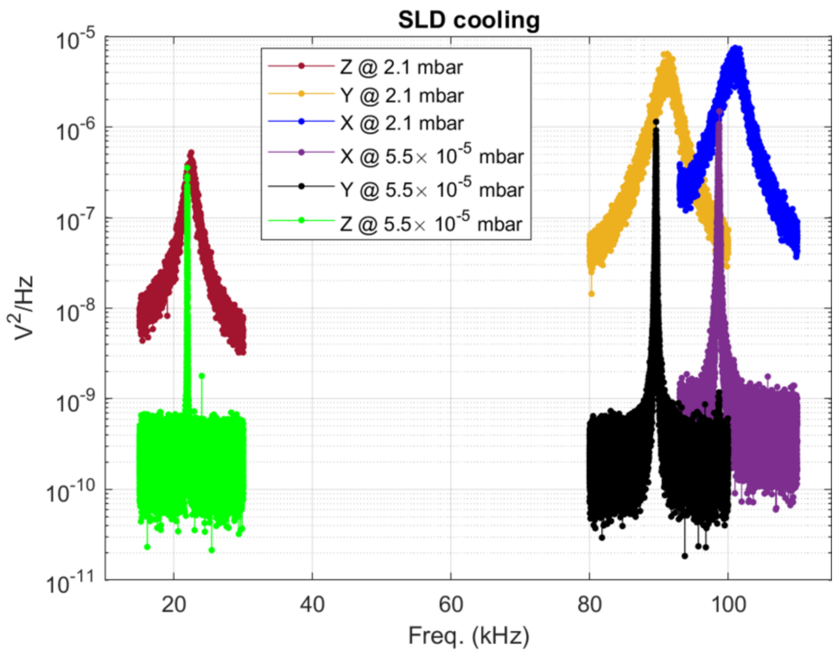
$$I^{FF}(\mathbf{r}',\mathbf{r}_\mathrm{p}) = \frac{c\varepsilon_0}{2}\left|\mathbf{E}_\mathrm{dp}(\mathbf{r}',\mathbf{r}_\mathrm{p}) + \mathbf{E}_\mathrm{ref}(\mathbf{r}')\right|^2$$

$$\approx \frac{c\varepsilon_0}{2}\left|\mathbf{E}_\mathrm{ref}\right|^2 + c\varepsilon_0\,\mathrm{Re}\left[\mathbf{E}_\mathrm{ref}\mathbf{E}^*_\mathrm{dp}\right]$$

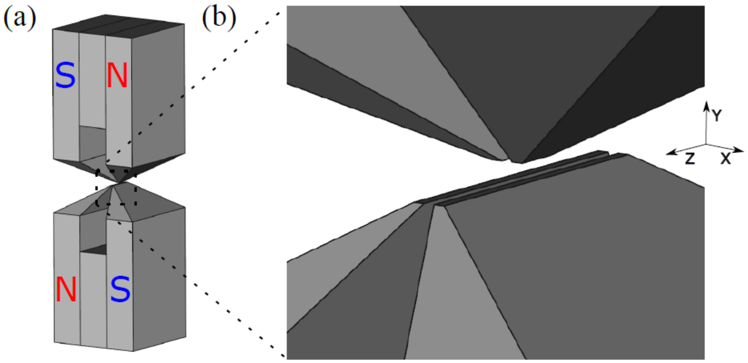
$$\approx \frac{c\varepsilon_0}{2}\left|\mathbf{E}_\mathrm{ref}\right|^2 + \frac{\alpha E_0^2 z_0 \omega^2}{4\pi c f_\mathrm{cl}^2} e^{-ik\left[\frac{xx_p}{f_\mathrm{cl}}+\frac{yy_\mathrm{p}}{f_\mathrm{cl}}-z_\mathrm{p}\left(1-\frac{\rho^2}{2f_\mathrm{cl}^2}\right)+\frac{\pi}{2k}\right]}$$

Detection of motion



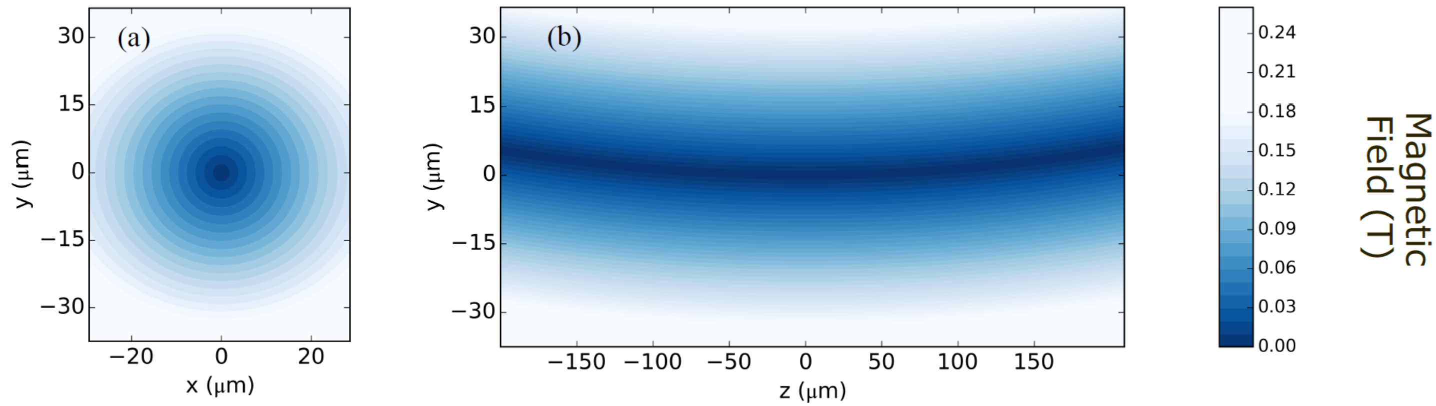


Magnetic trapping

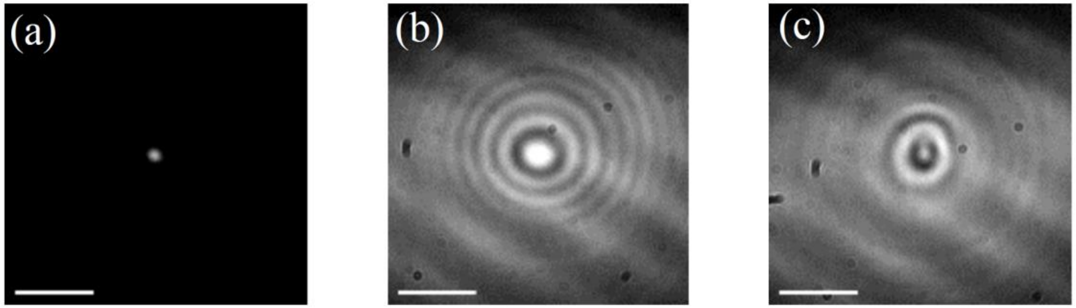


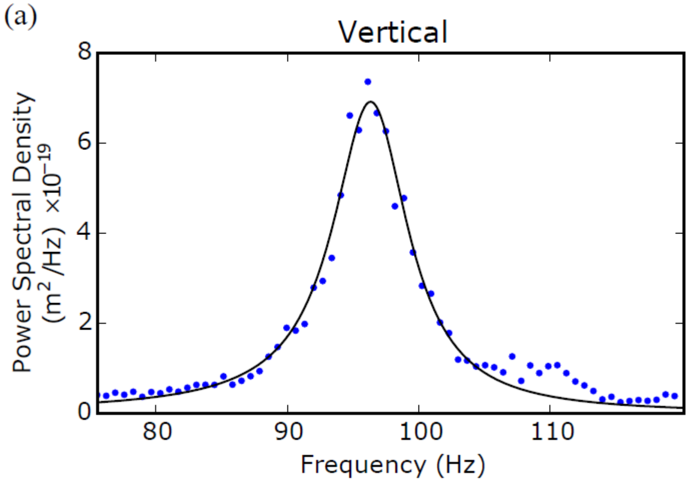
$$U = -\frac{\chi B^2 V}{2\mu_0} + mgy$$

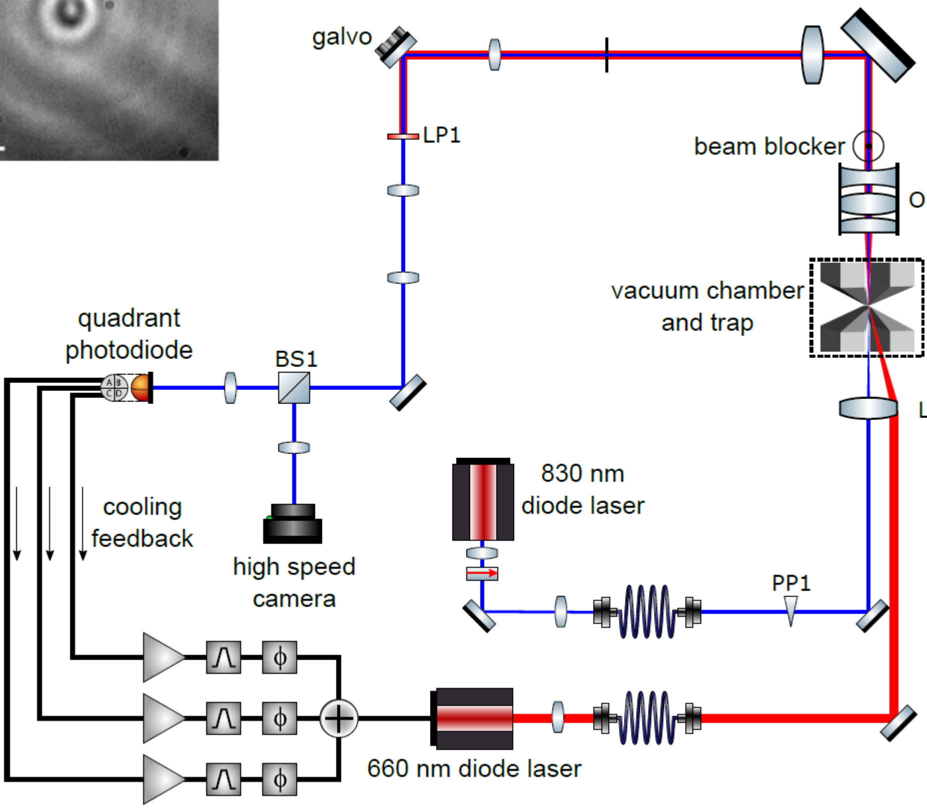
Bradley R Slezak et al 2018 New J. Phys.20 063028



Magnetic trapping





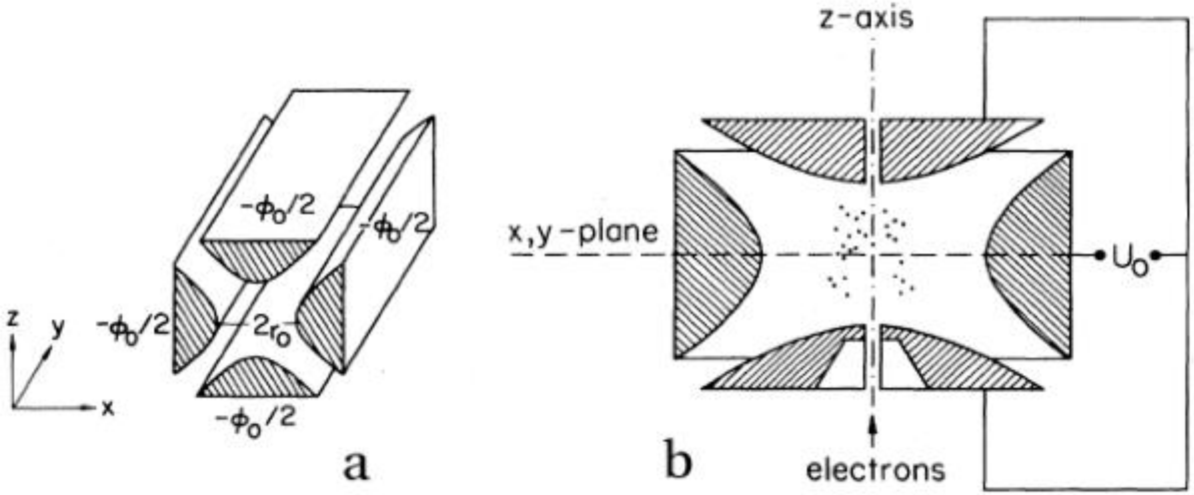


Electrical trapping – Paul trap

3-D potential for charged particle

$$\Phi = \frac{\Phi_0}{2r_0^2}(\alpha x^2 + \beta y^2 + \gamma z^2)$$

$$\nabla^2\Phi = 0 \rightarrow \alpha + \beta + \gamma = 0$$



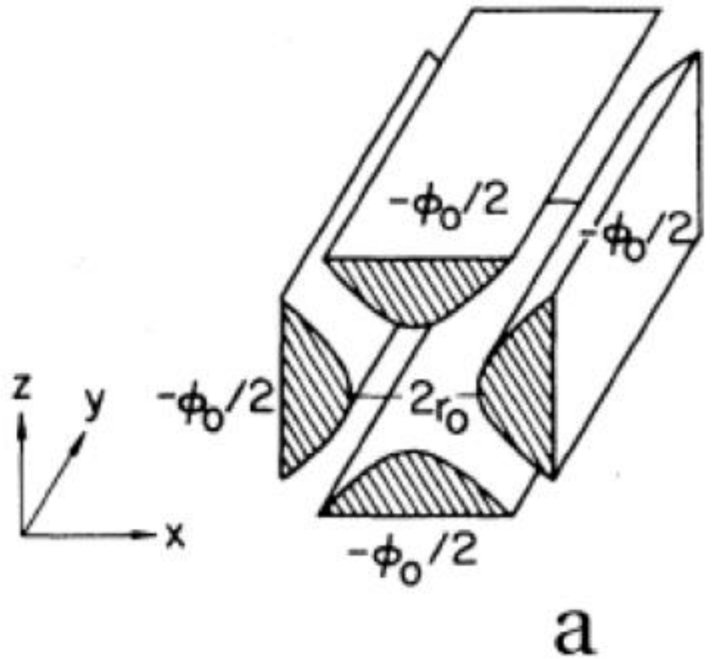
Linear Paul trap

$$\alpha = 1, \beta = 0, \gamma = -1$$
$$\Phi = \frac{\Phi_0}{2r_0^2}(x^2 - z^2)$$

https://youtu.be/XTJznUkAmIY

$$\Phi_0 = U + V\cos\omega t$$

$$\ddot{x} + \frac{e}{mr_0^2}(U + V\cos\omega t)x = 0$$
$$\ddot{z} - \frac{e}{mr_0^2}(U + V\cos\omega t)z = 0$$



Stability

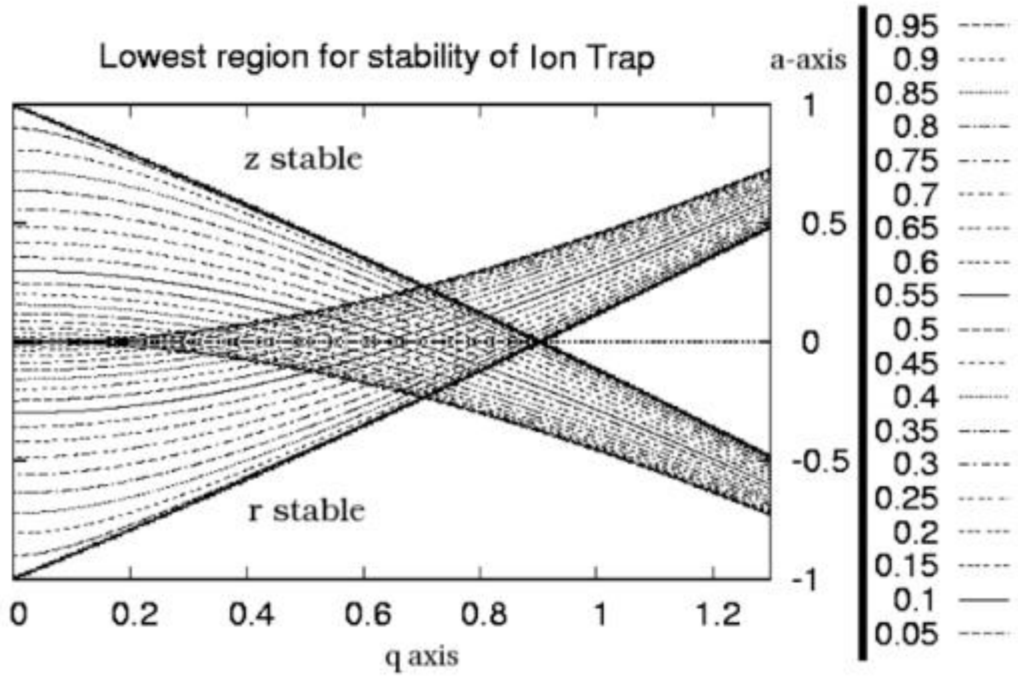
$$\ddot{\eta} + (a - 2q\cos 2\tau)\eta = 0$$

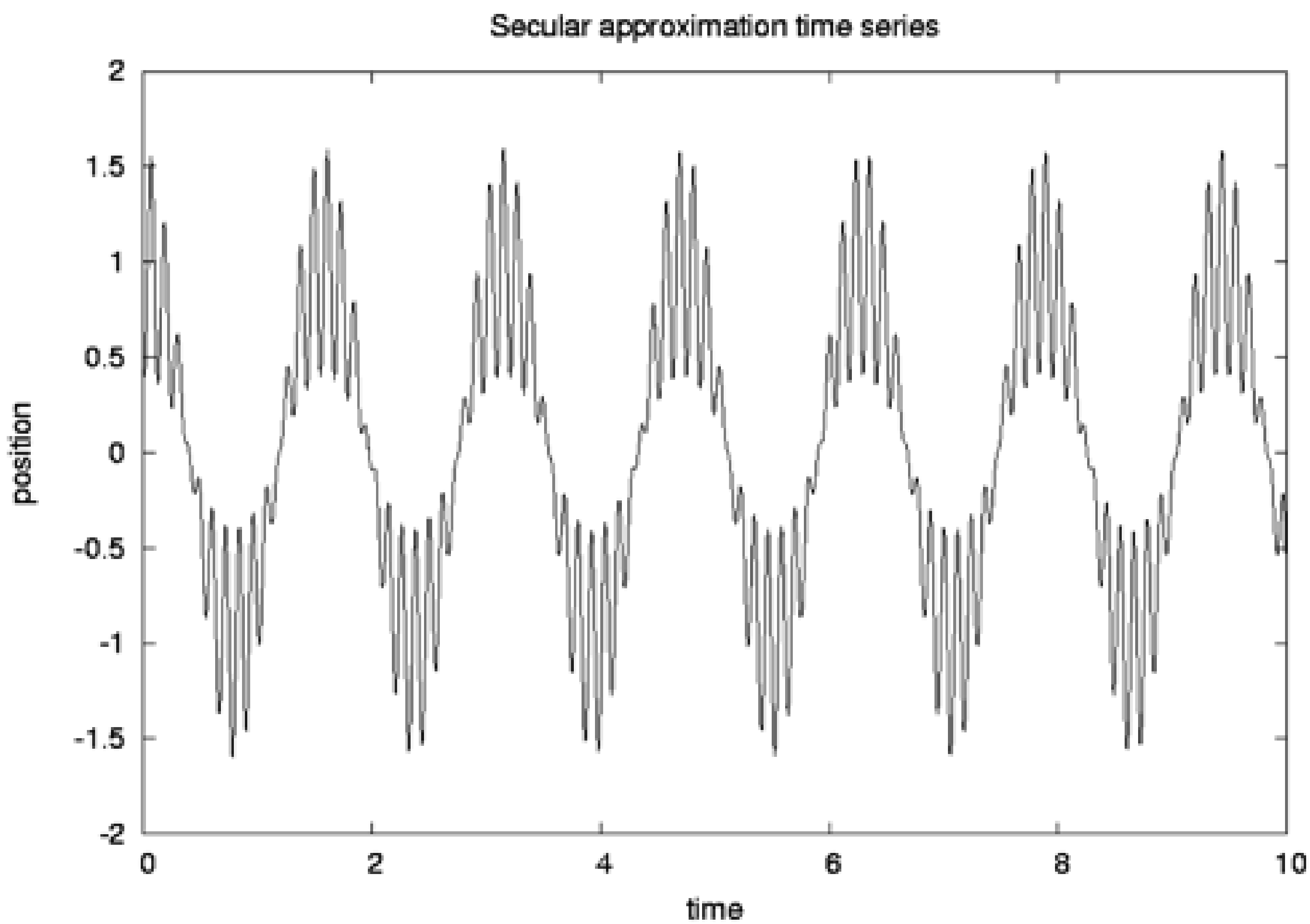
Mathieu Eqn

$$a = \frac{4eU}{mr_0^2\omega^2}$$

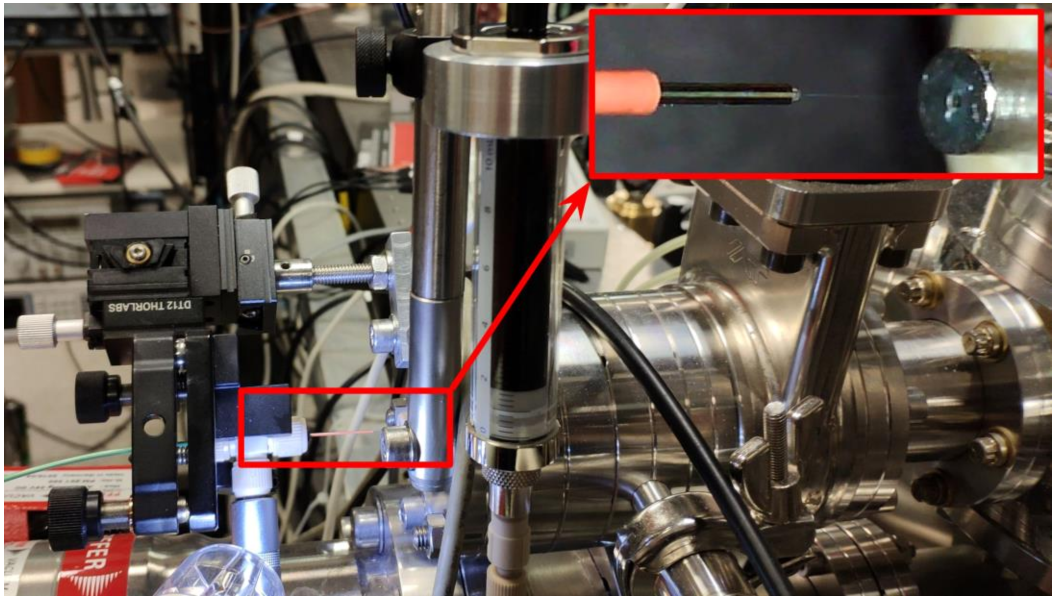
$$q = \frac{-2eV}{mr_0^2\omega^2}$$

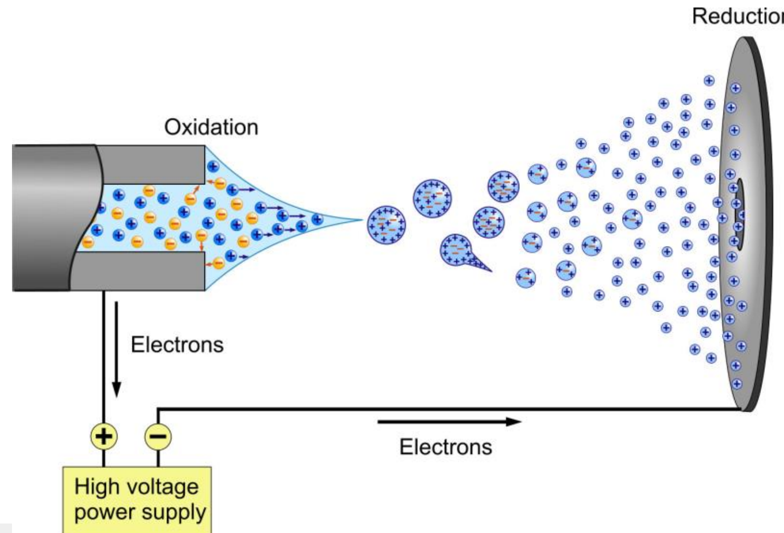
$$\tau = \frac{\omega t}{2}$$

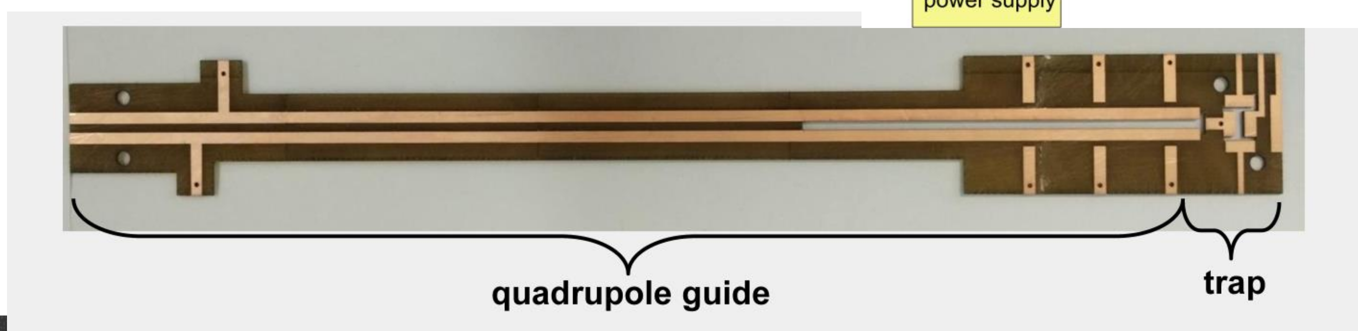


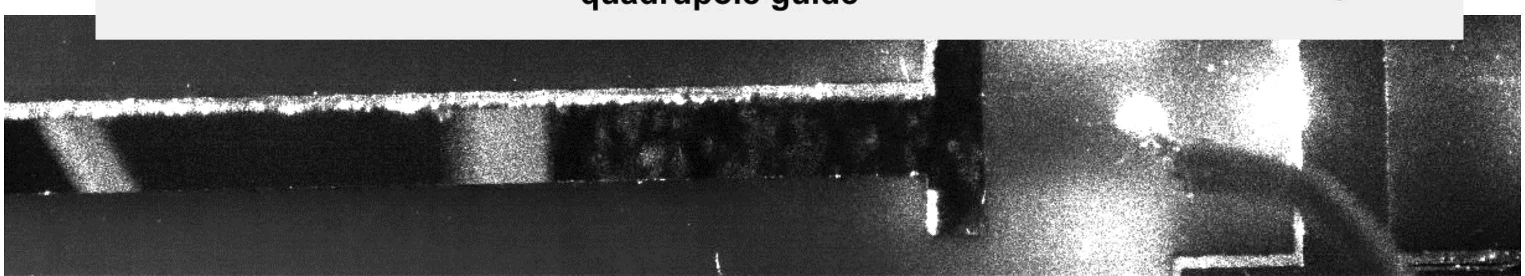

Secular approximation time series
position
time
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
8
10

Electrospray loading







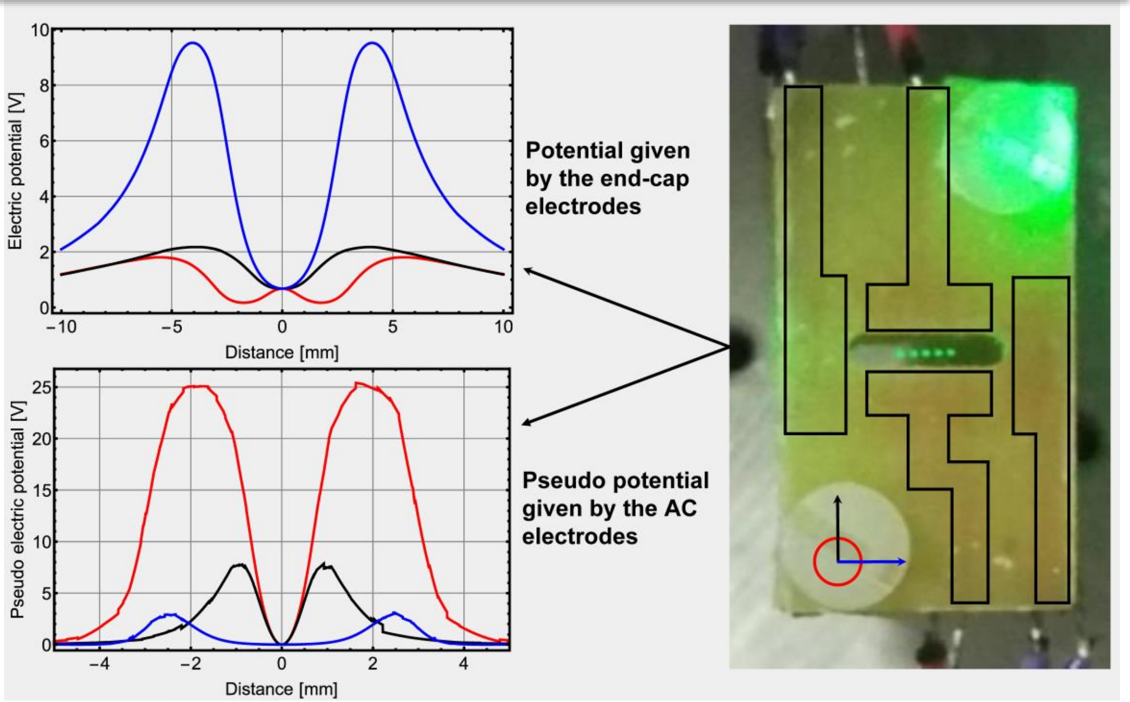


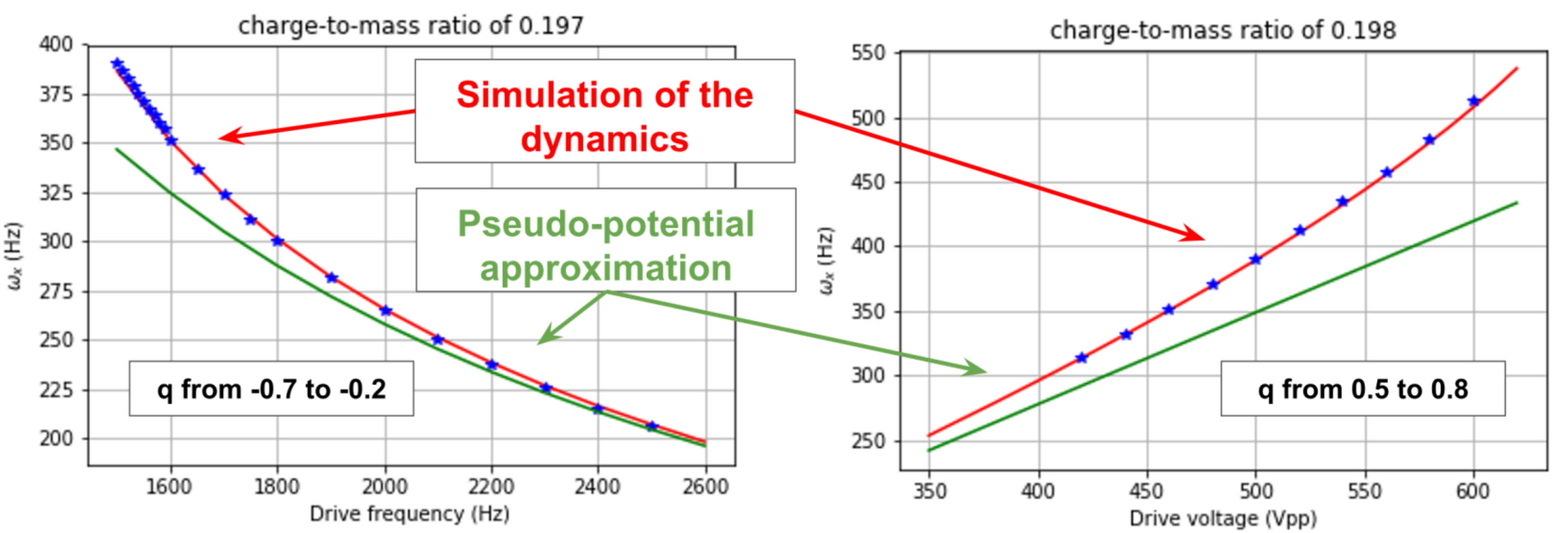
Linear Paul trap

$$\omega_x = \sqrt{\frac{q^2}{m^2}\frac{V_o^2\eta^2}{2l^4\omega_d^2} - \epsilon\frac{q}{m}\frac{2U_o\kappa}{d^2}},$$

$$\omega_y = \sqrt{\frac{q^2}{m^2}\frac{V_o^2\eta^2}{2l^4\omega_d^2} - (1-\epsilon)\frac{q}{m}\frac{2U_o\kappa}{d^2}},$$

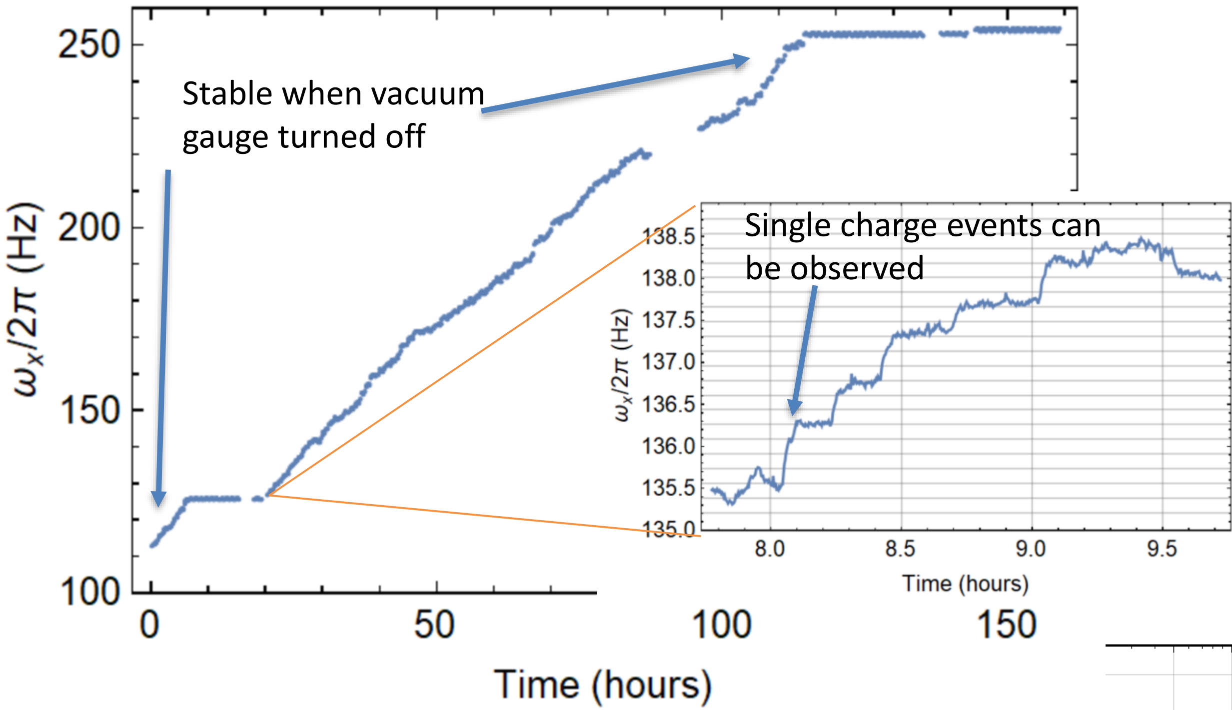
$$\omega_z = \sqrt{\frac{q^2}{m^2}\frac{V_o^2\eta^2\sigma^2}{2l^4\omega_d^2} + 2\frac{q}{m}\frac{2U_o\kappa}{d^2}},$$

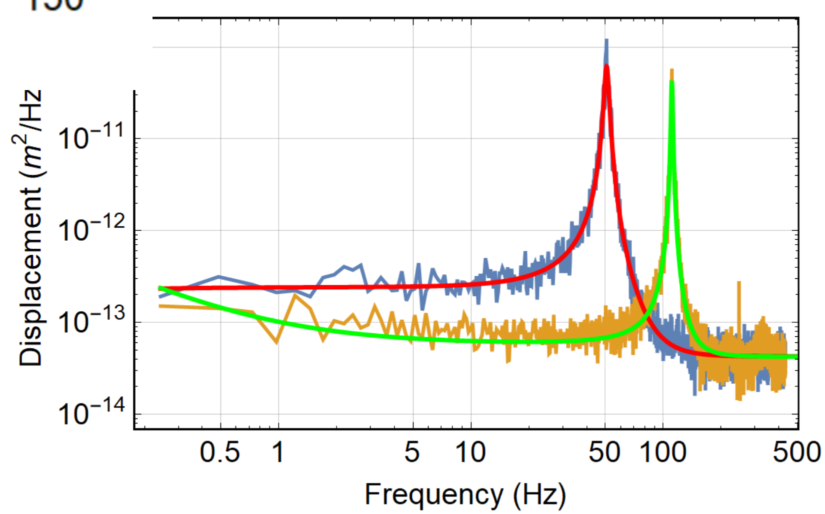




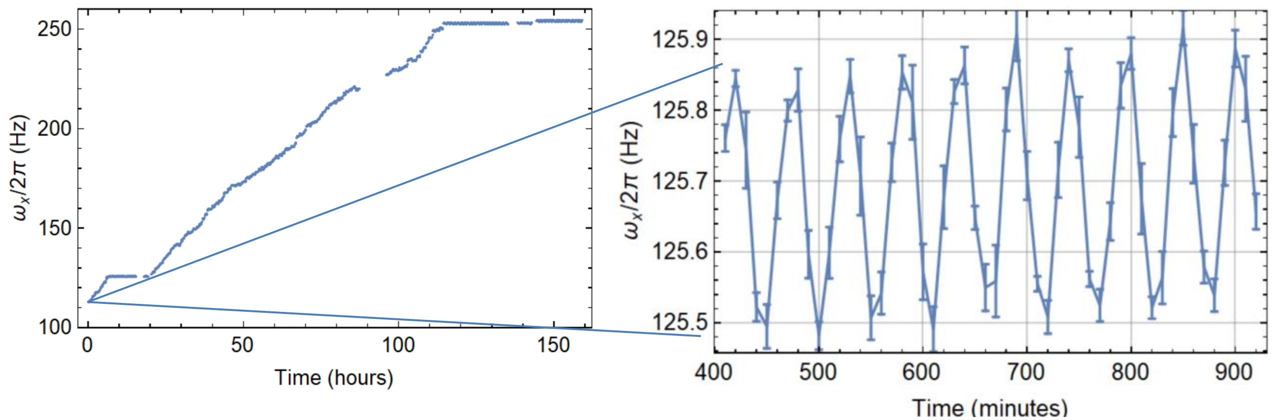
A levitated particle in a cavity

Frequency changes measured for > 6 days



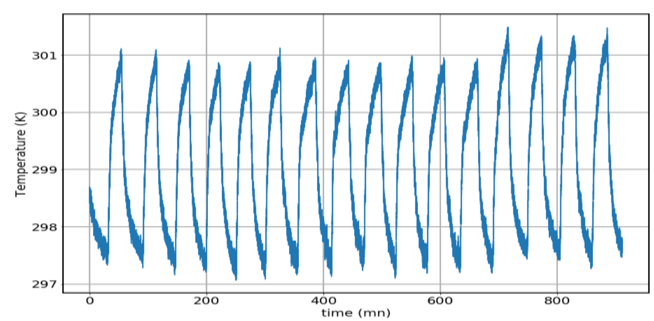


A levitated particle in a cavity



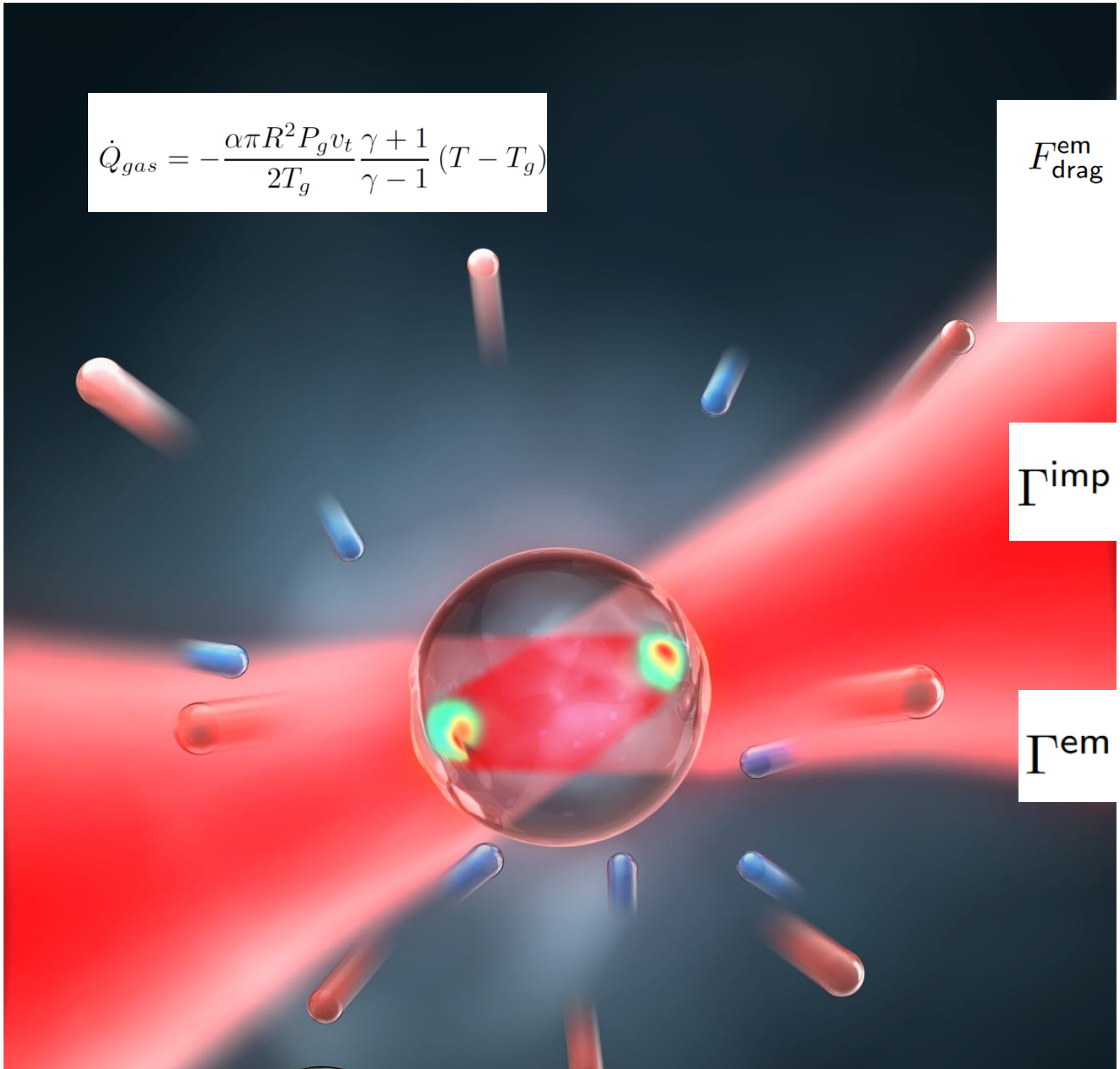
Frequency stability limited by 3 degree C room temperature fluctuation

- 200 nm displacement of electrodes in holders
- thermal fluctuations in drive electronics



Decoherence – gas collisions

UCL



$$\dot{Q}_{gas} = -\frac{\alpha\pi R^2 P_g v_t}{2T_g}\frac{\gamma+1}{\gamma-1}(T-T_g)$$

$$F^{\mathrm{em}}_{\mathrm{drag}} = -\int_0^{\pi}\int_0^{2\pi} p^{S,\mathrm{em}}\cos\theta\,\mathrm{d}S = \frac{mNR^2\pi^{3/2}}{3\sqrt{h'}}V \overset{!}{=} M\,\Gamma^{\mathrm{em}}\,V.$$

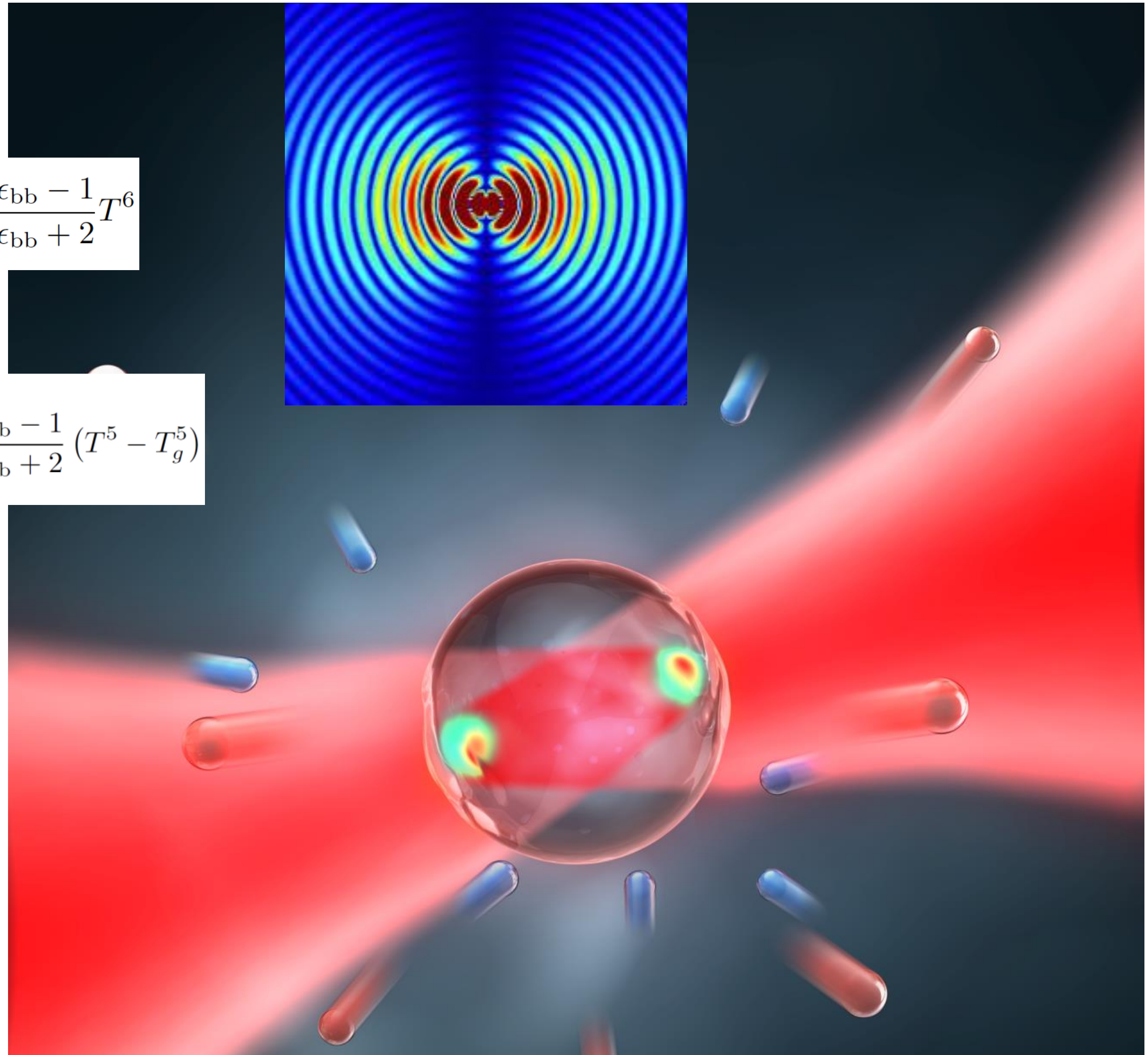
$$\Gamma^{\mathrm{imp}} = \frac{4\pi}{3}\frac{mNR^2\bar{v}_{T_{\mathrm{imp}}}}{M}$$

$$\Gamma^{\mathrm{em}} = \frac{\pi}{8}\sqrt{\frac{T^{\mathrm{em}}}{T^{\mathrm{imp}}}}\,\Gamma^{\mathrm{imp}}$$

Decoherence – black body

$$S_{ff,\mathrm{bb}} = \frac{160}{\pi}\frac{R^3 k_B^6}{c^5 \hbar^4}\mathrm{Im}\frac{\epsilon_{\mathrm{bb}}-1}{\epsilon_{\mathrm{bb}}+2}T^6$$

$$\dot{Q}_{bb} = -\frac{72\zeta(5)}{\pi^2}\frac{V k_B^5}{c^3 \hbar^4}\mathrm{Im}\frac{\epsilon_{\mathrm{bb}}-1}{\epsilon_{\mathrm{bb}}+2}\left(T^5 - T_g^5\right)$$



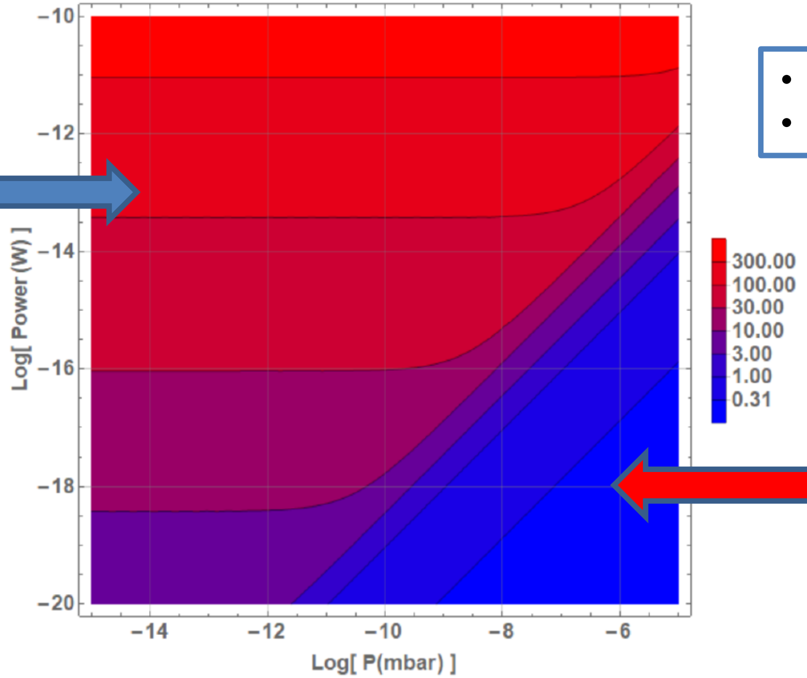
Decoherence – black body

Internal temperature: determines gas collision effective temperature

Low pressure
High power

Cooling dominated by blackbody emission

NEED TO WORK IN THIS REGIME!

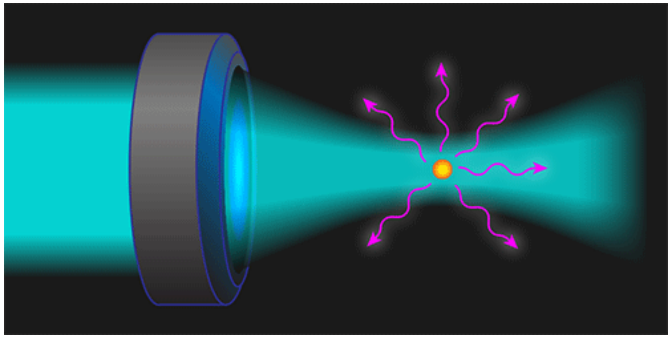


- **Optical trapping is often not option**
- **Other noises needs to be very low**

High pressure
Low power

Cooling dominated by Gas collisions

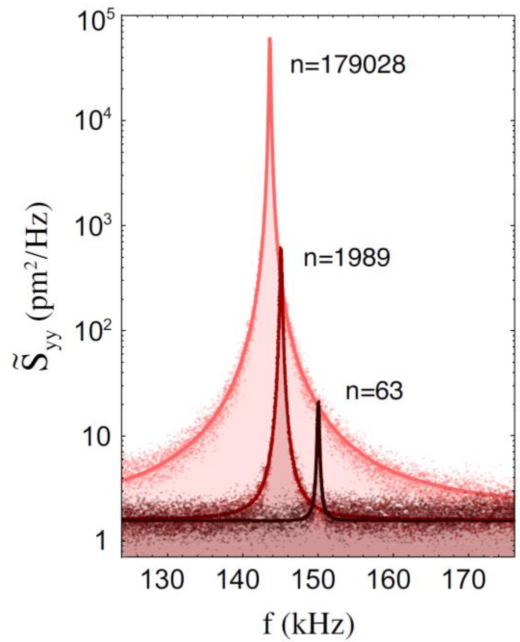
Decoherence – photon recoil

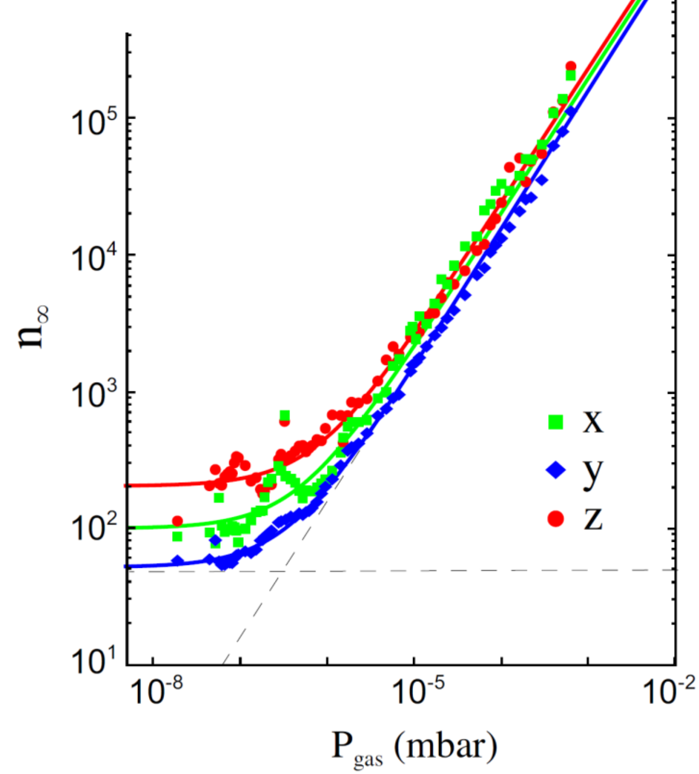


$$S_{yy}(\Omega) = |\chi(\Omega)|^2 \; S^F_{uu}$$

$$\Gamma_{\mathrm{recoil}} = \frac{1}{5}\,\frac{P_{\mathrm{scatt}}}{mc^2}\,\frac{\omega_0}{\Omega_0}$$

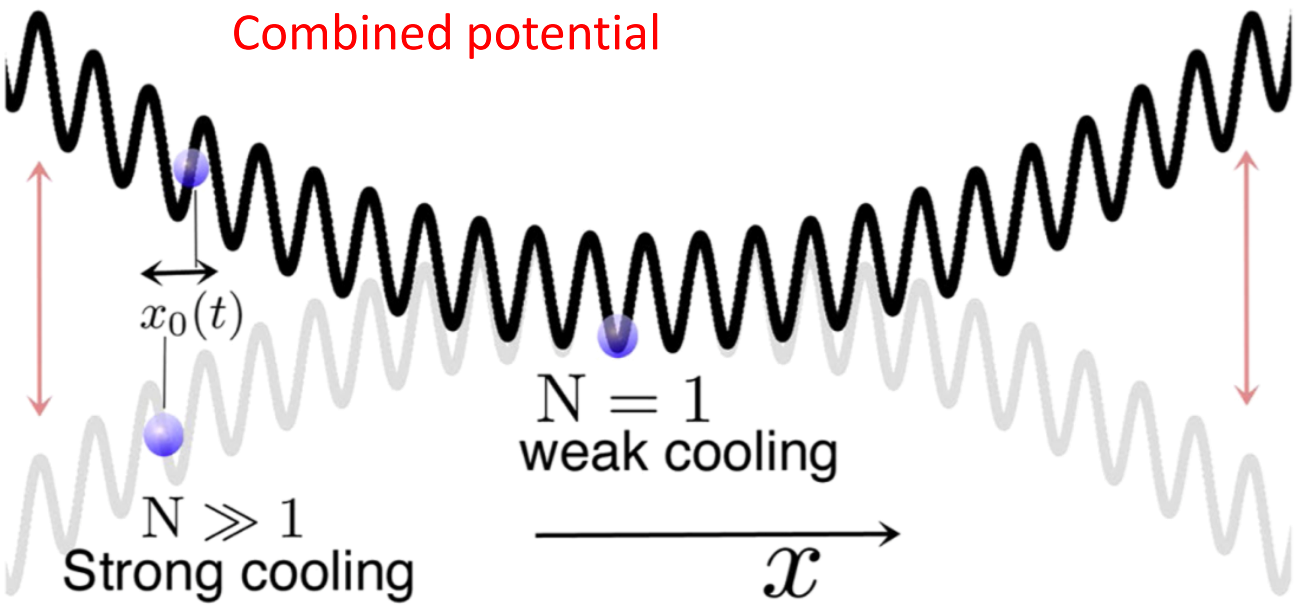
$$S^F_{yy} = \frac{2}{5}\,\frac{\hbar\omega_0}{2\pi c^2}\,P_{\mathrm{scatt}}$$





Cooling in a electro-optical trap

Combined potential



Coupling

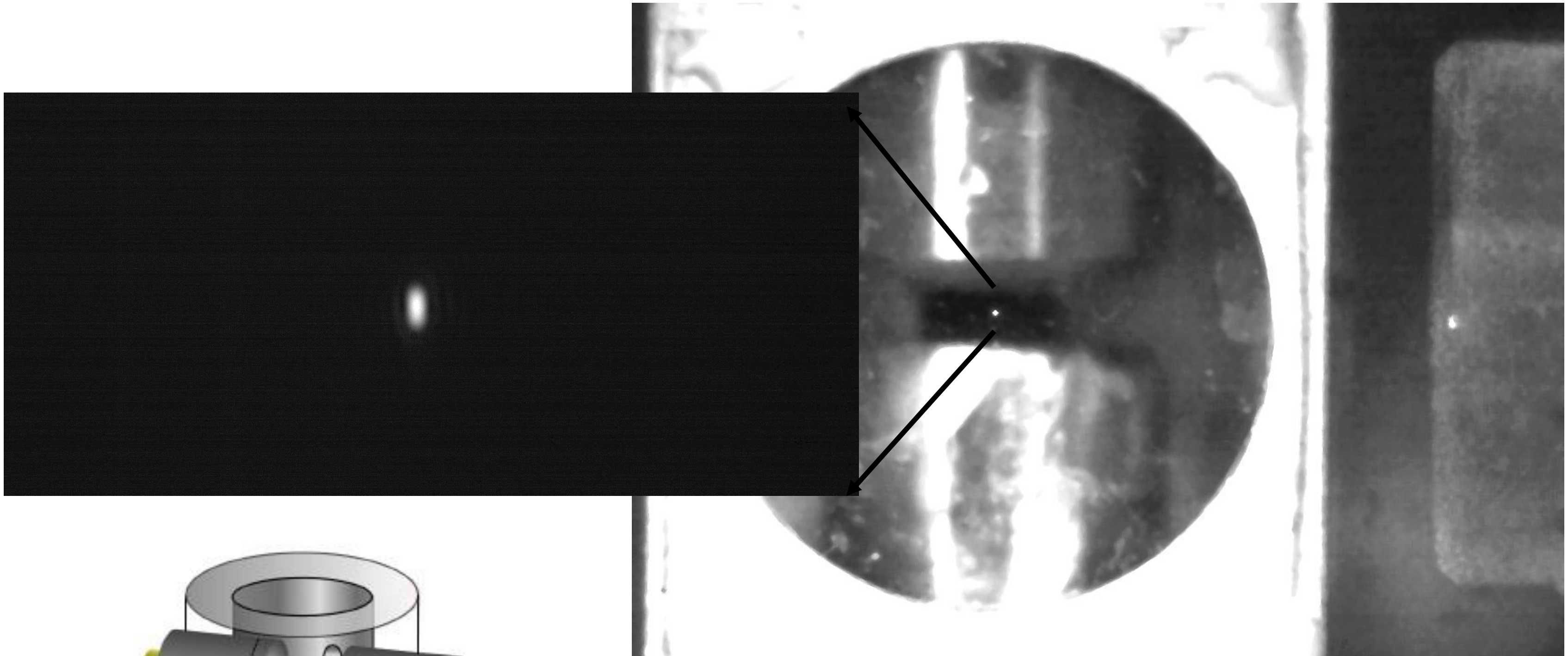
$$A = \frac{\omega_l}{2V_c\epsilon_0}\alpha$$

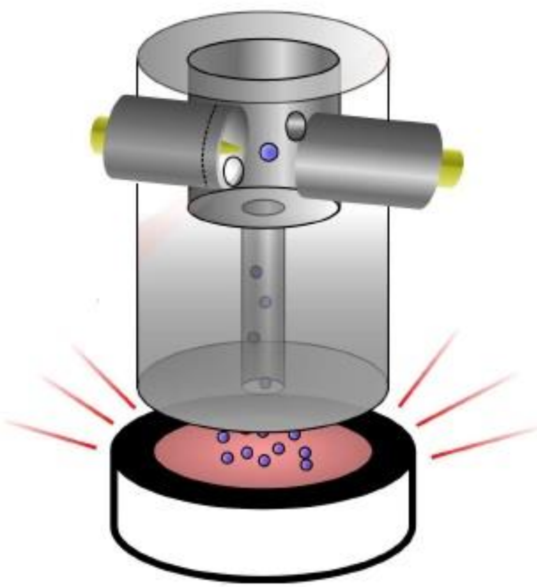
Equations of motion

$$\dot{p_x}(t) = -\hbar k A|a(t)|^2 \sin 2(kx) \exp[-(z^2+y^2)/w_0^2] - \Gamma_M p_x - \omega_T^2 x \cos\omega t$$

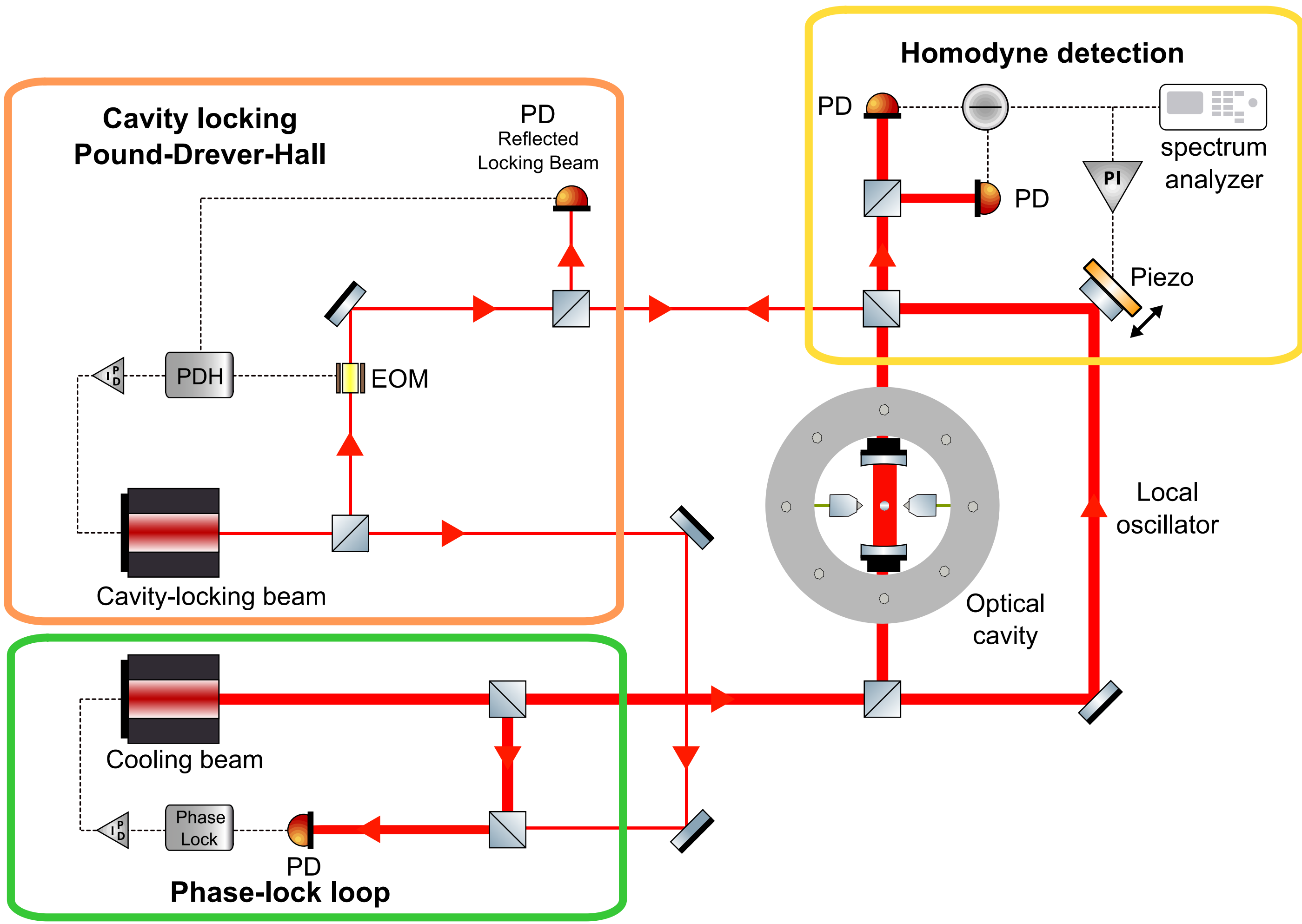
$$\dot{a}(t) = i\Delta a - iE + iAa\cos^2(kx)\exp[-(z^2+y^2)/w_0^2] - \frac{\kappa}{2}a$$

Hybrid trap





Cavity cooling

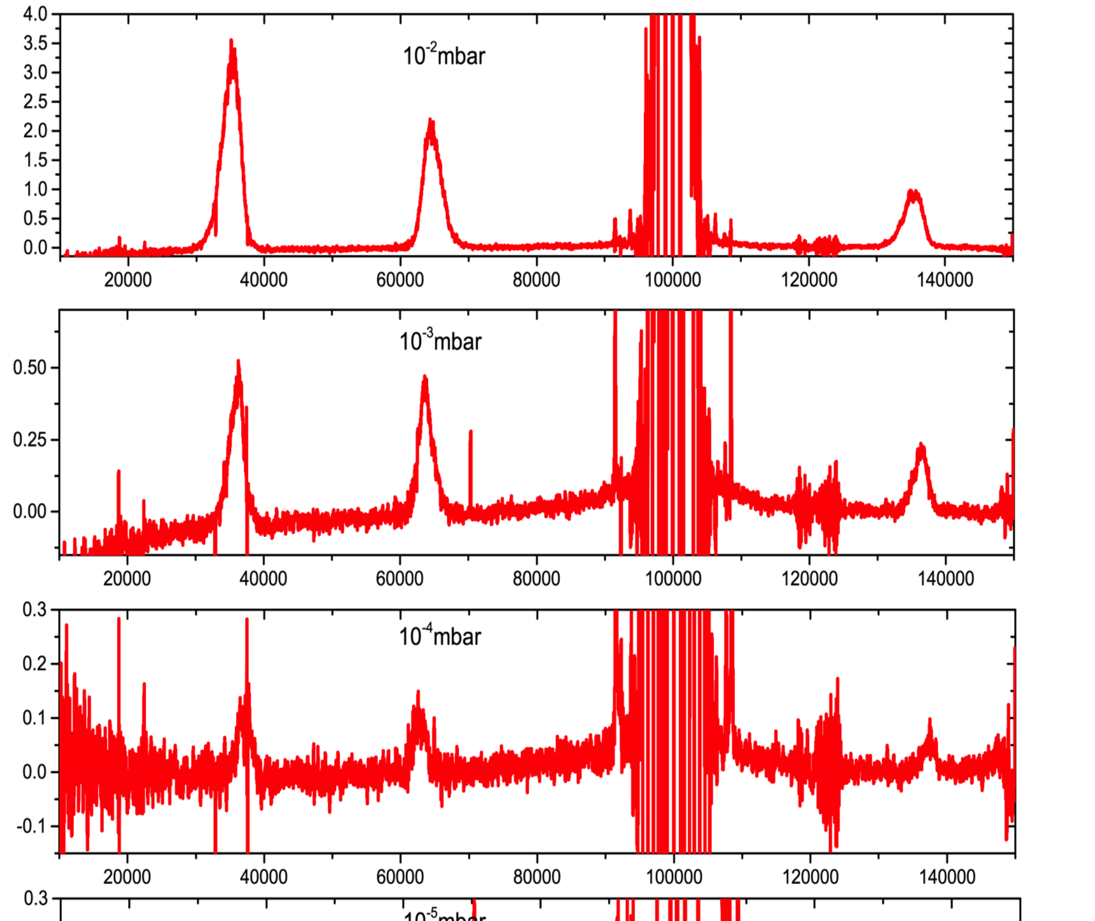


Cooling optomechanical motion

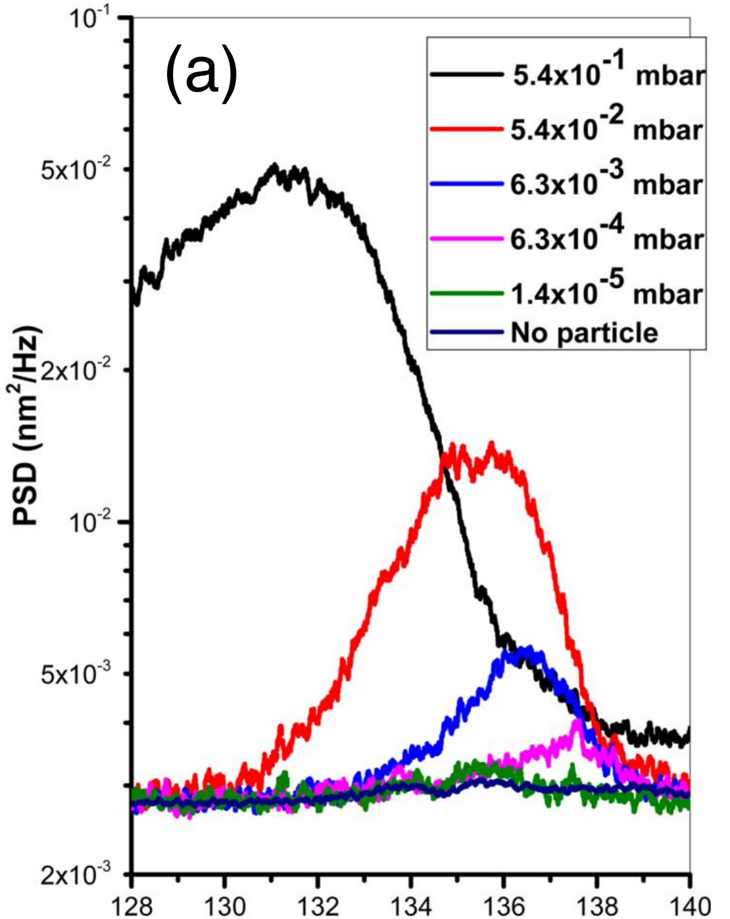
F= 40 000, Linewidth 300 kHz, Cooling rate 1 kHz, Heating rate 5mHz

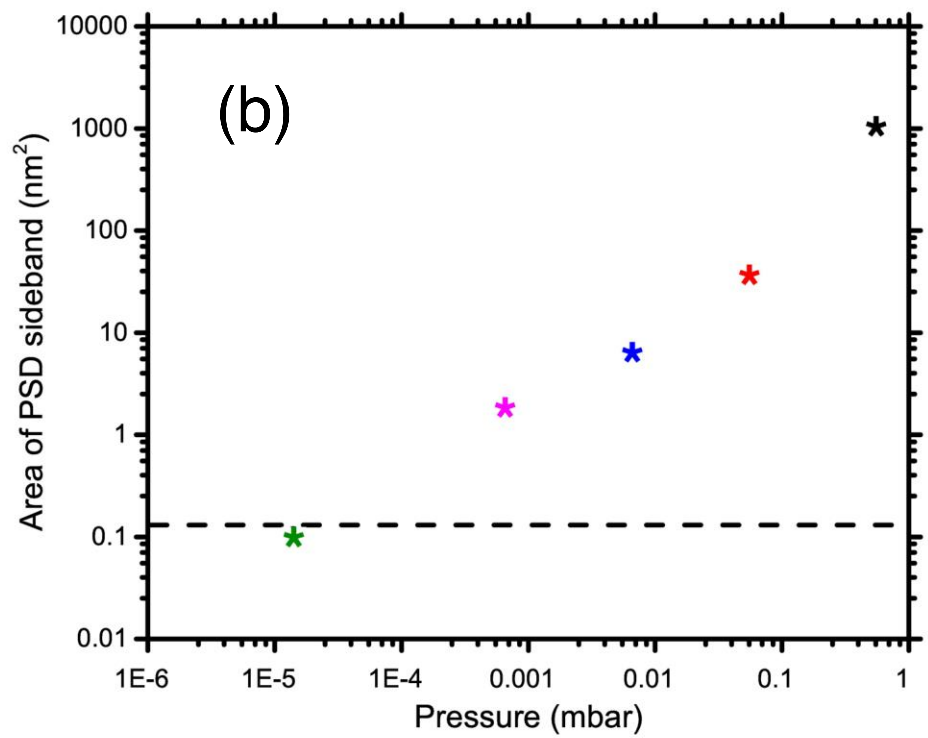
Temp reduced by 10^5 and reaches mK at 10^{-6} mbar

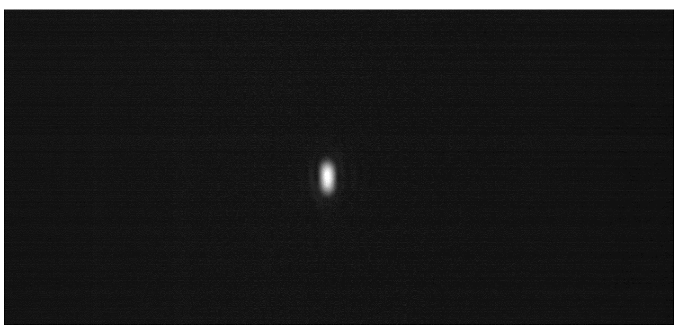
Particle remains trapped but cannot measure mechanical frequency at 10^{-6} mbar



Millikelvin temperatures





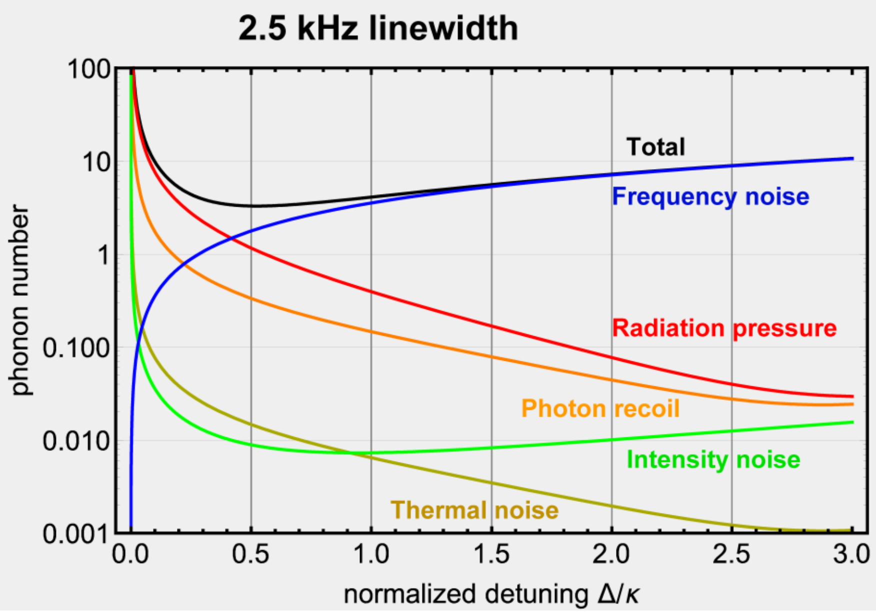


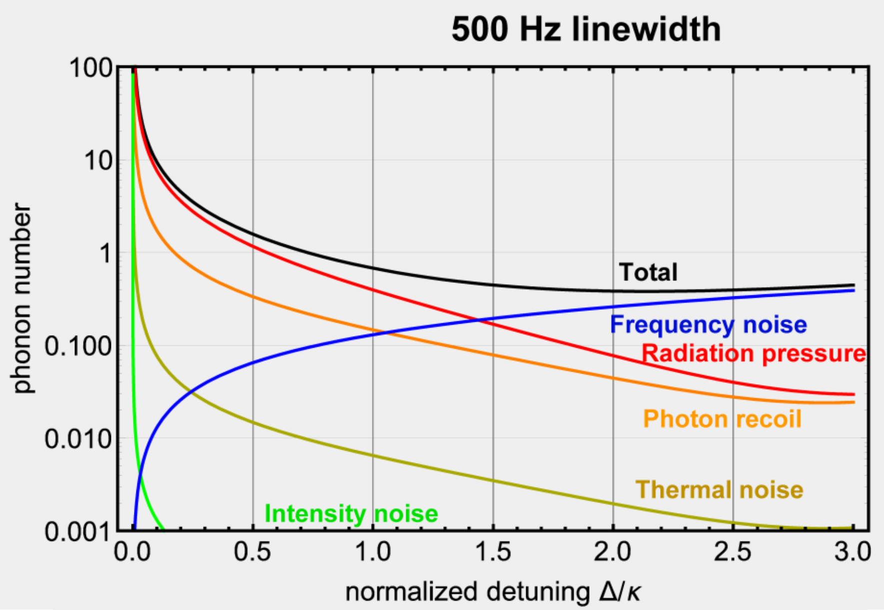
$\mathcal{F}$=20 000-200 000
g_{eff}=8kHz
N∼350
Q ∼3
Γ=2000s^{-1}

L_{cav}= 13mm
λ=1064nm
radius=209nm
m=1x10^{-16}kg
ω_m= 40-100kHz

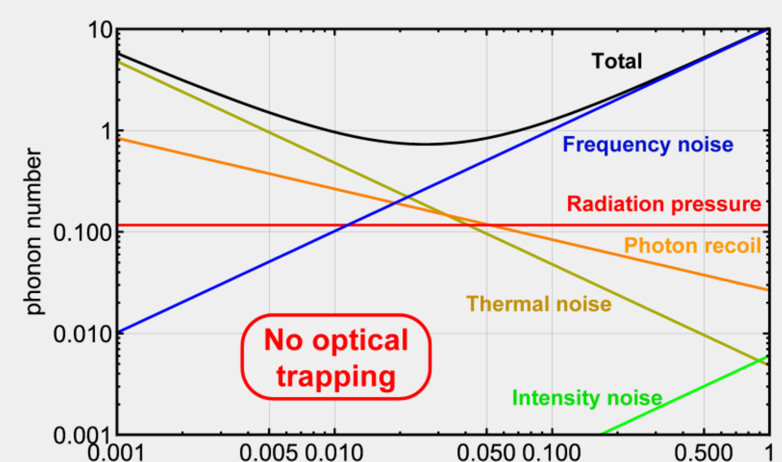
Noise control

Cooling of a mechanical frequency of 100 kHz, 10e-8 mbar for different linewidths of the filtering cavity (Science cavity 26 kHz, 200 nm,)

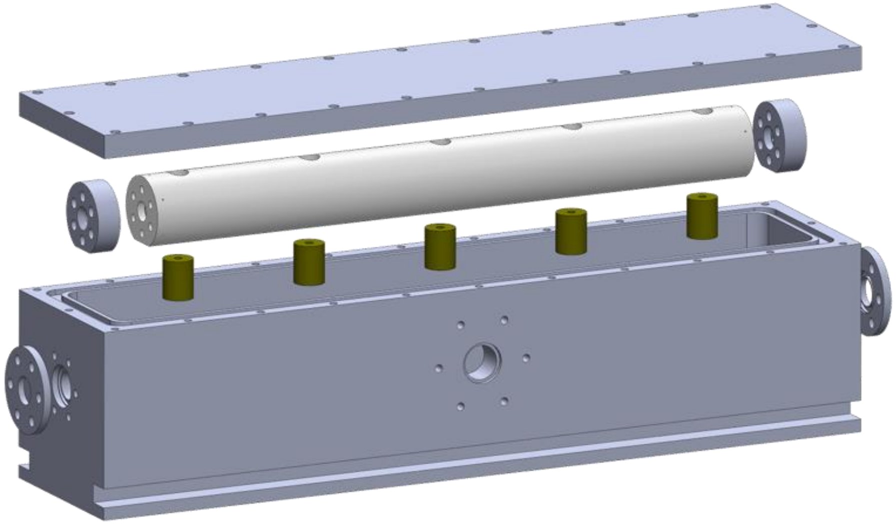




Cooling of a secular frequency of 50 kHz and a filtering cavity of 2.5 kHz linewidth



Frequency noise



Filtering cavity to reduce laser frequency noise

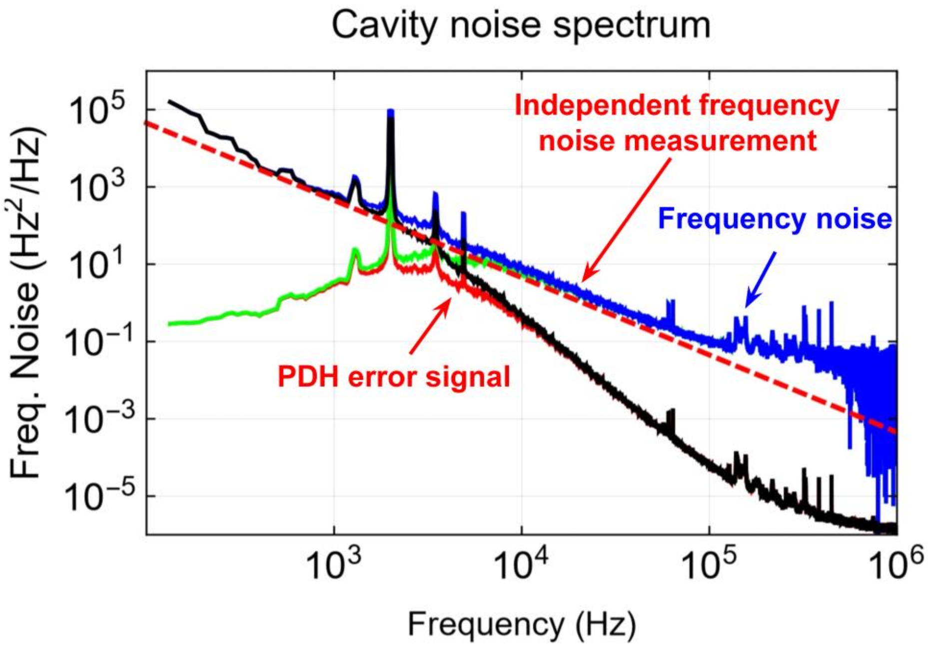
•Cavity length: 400 mm

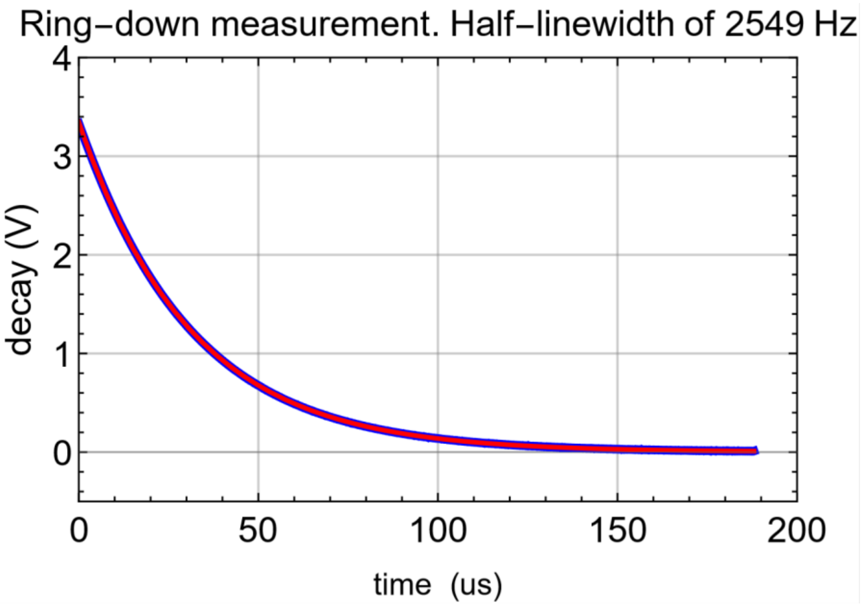
•Cavity half-linewidth: 3.0 kHz

•Mirror holders made of INVAR

•Torlon feet for thermal isolation

Pressure of 10^{-2} mbar



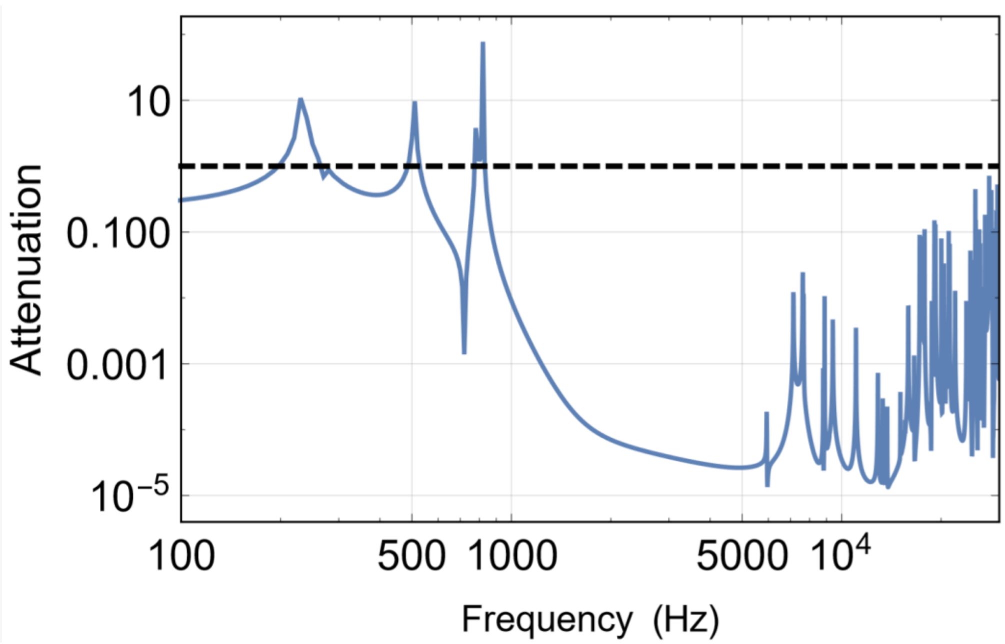


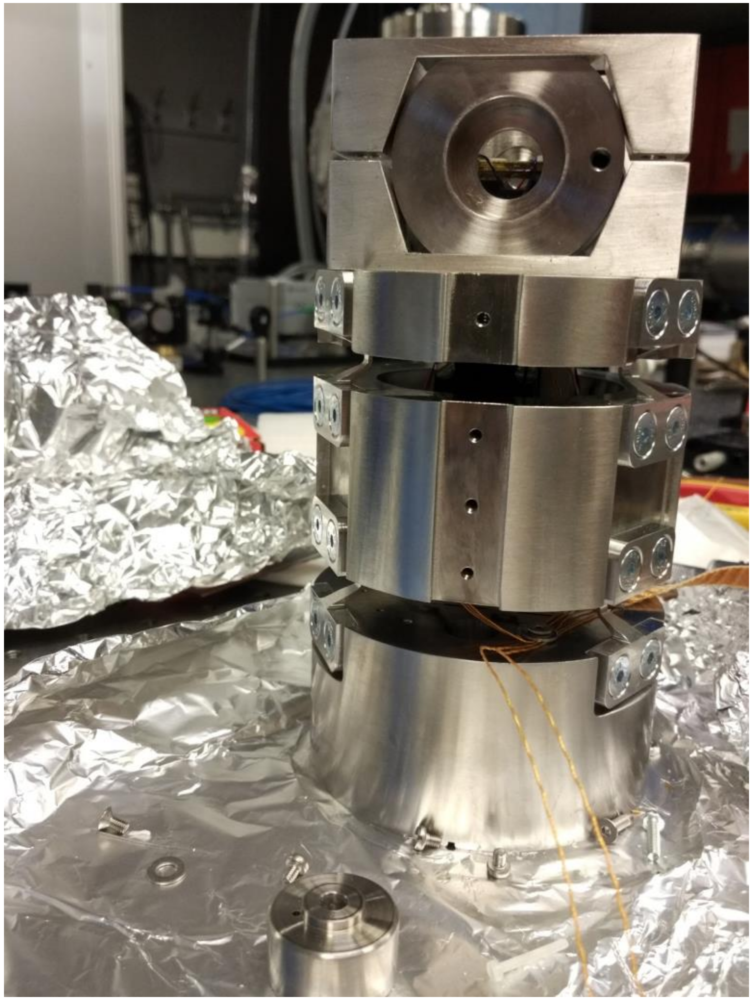
Environmental noise

Mechanical isolation of the cavity holder to reduce displacement noise

Design of high-Q mechanical springs inspired from the AURIGA detector

- Resonance frequency at 500 Hz
- Two-level isolation to further reduce noise

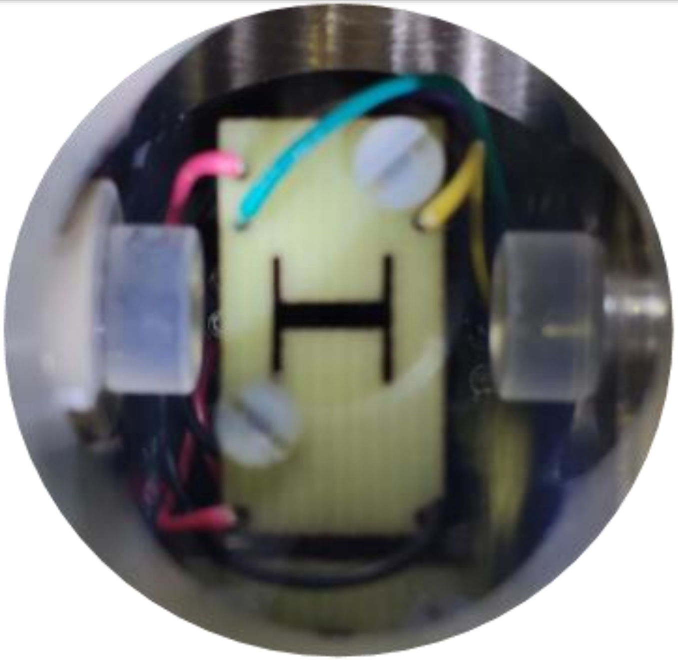


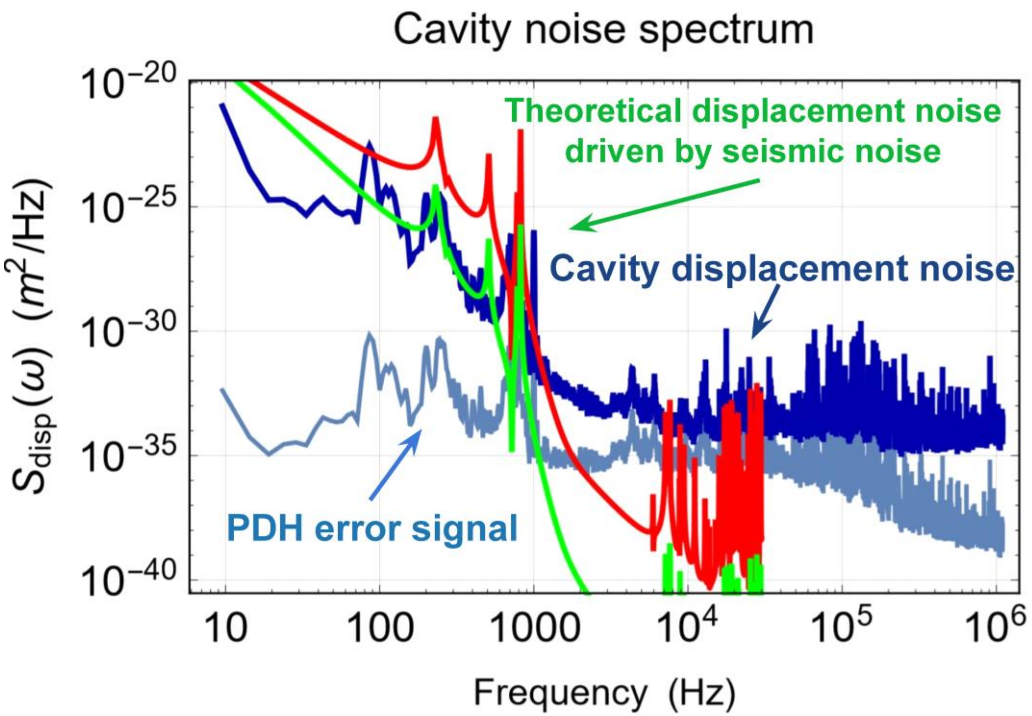


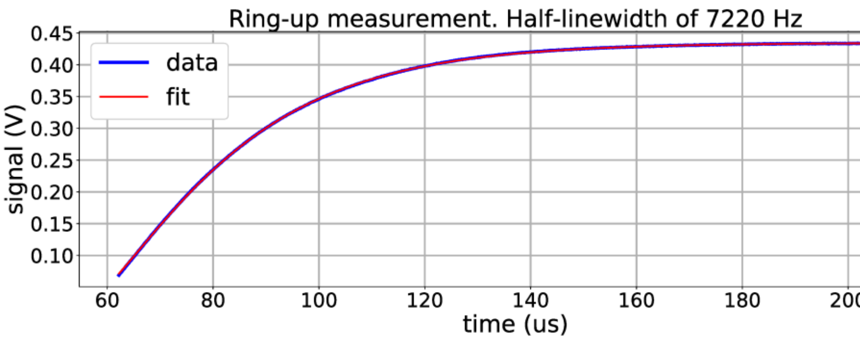
Cooling cavity

High finesse cavity (F≈700000)

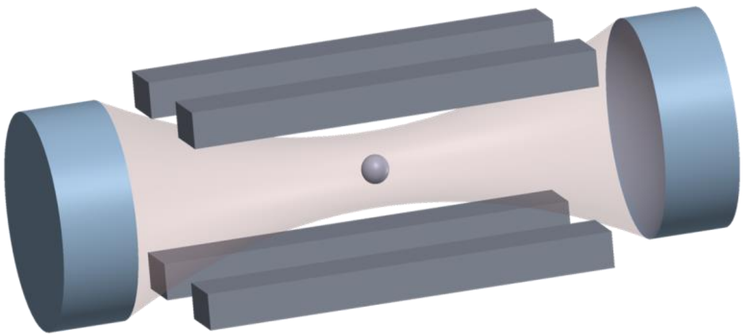
- Optical trapping and cavity cooling
- Sensing the particle motion
- Mirror transmission coefficients of 2.8 ±0.5 ppm
- Cavity length: 14.6 mm ±1%

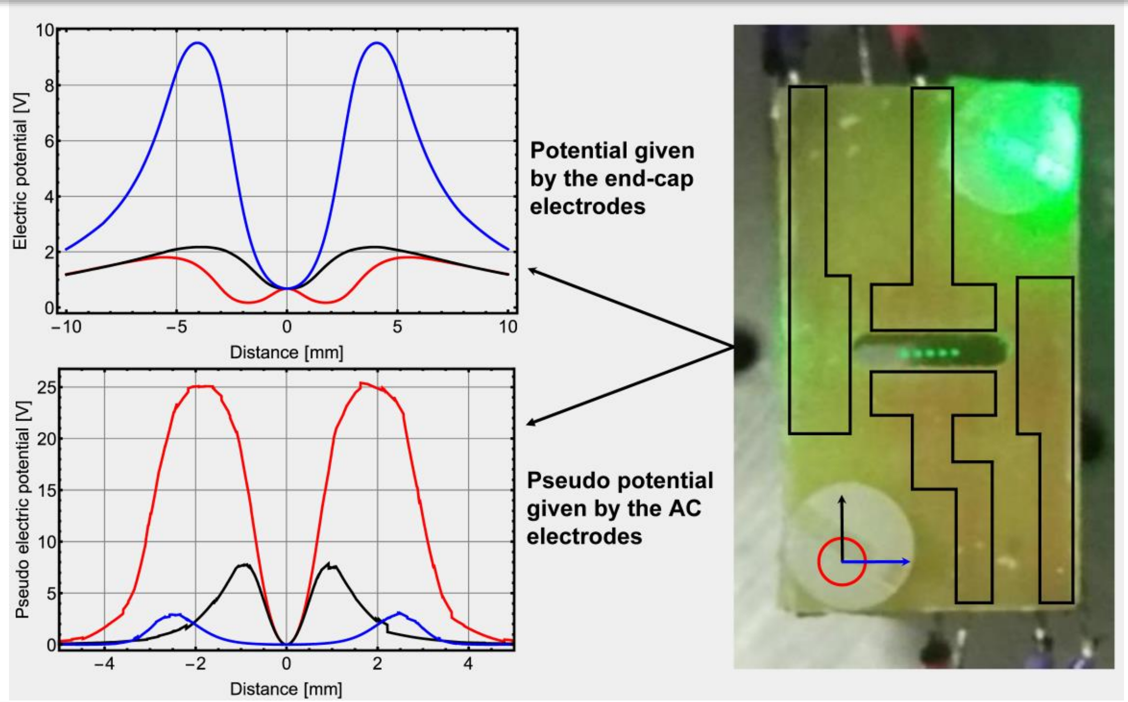


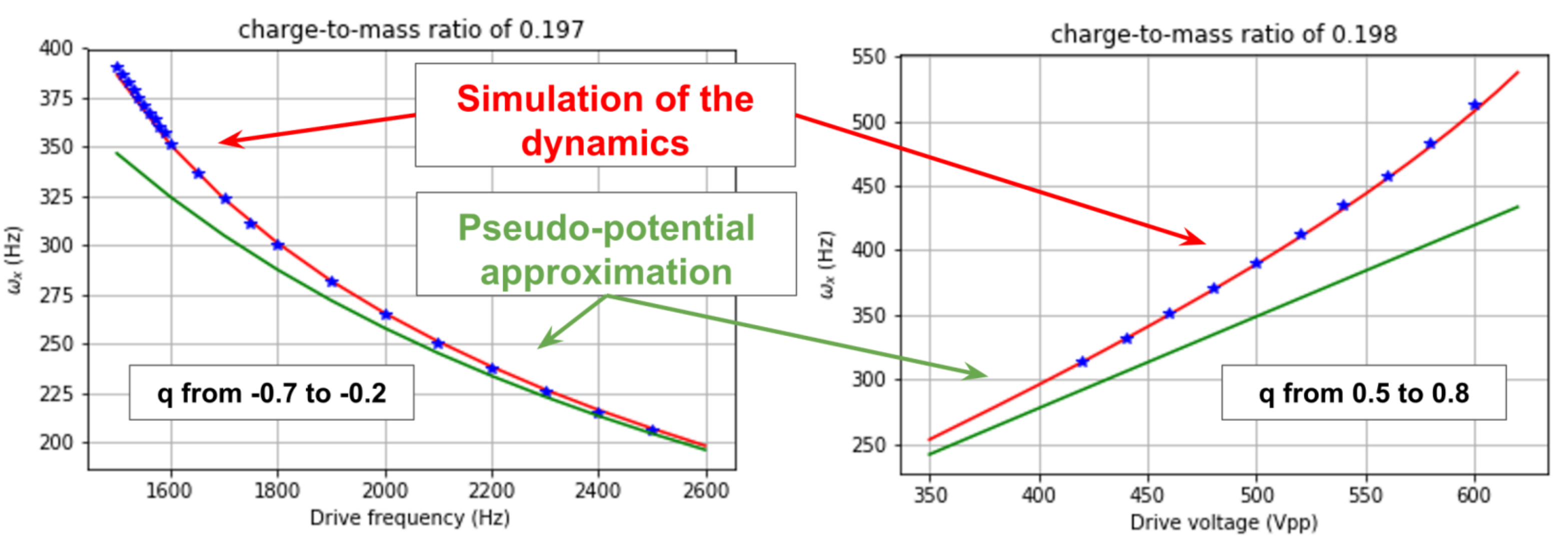




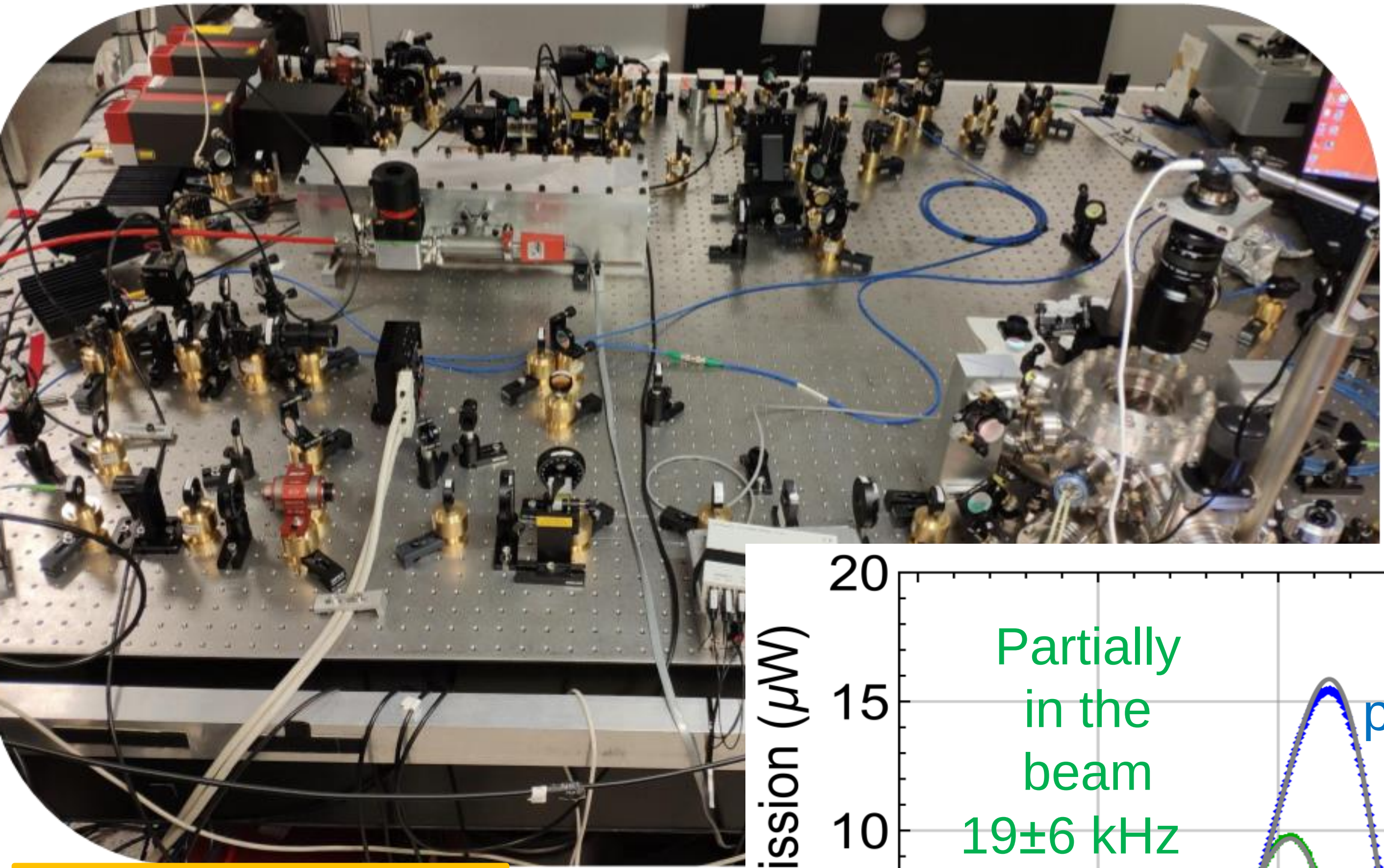
Linear Paul trap

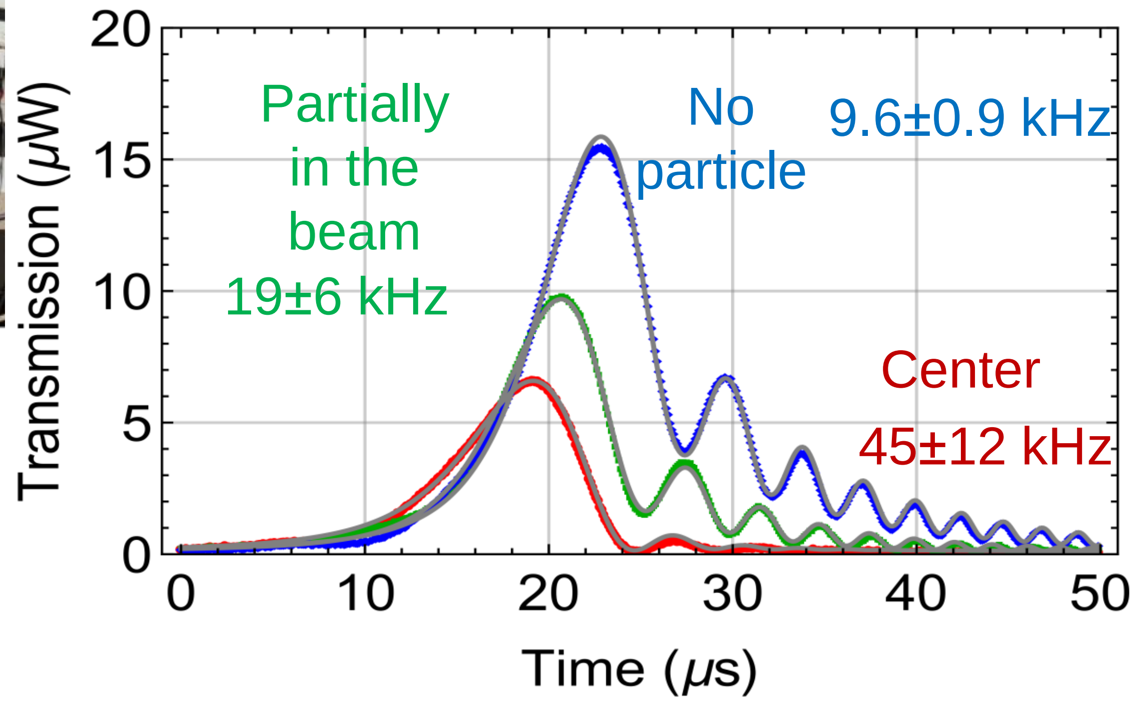






New system





Cavity parameters

λ = 1064 nm
L = 14.6 mm (± 1%)
$\kappa/2\pi$ = 7.5 kHz
$\mathcal{F}$ ≈ 700000
w_o= 62 μm

End of part 1

Part 2

- Cooling (again)
  - Cavity cooling again (Discussion)
  - Cooling
  - Feedback cooling
  - Cold atoms (Discussion – working groups)
  - Cooling phonons
- Observing non-classical motion
  - Interferometry
  - The creation of in trap non-classical motion
- Testing collapse models
  - What are collapse models
  - Why collapse models
  - Testing
- Interferometry
  - Conventional
  - In-trap