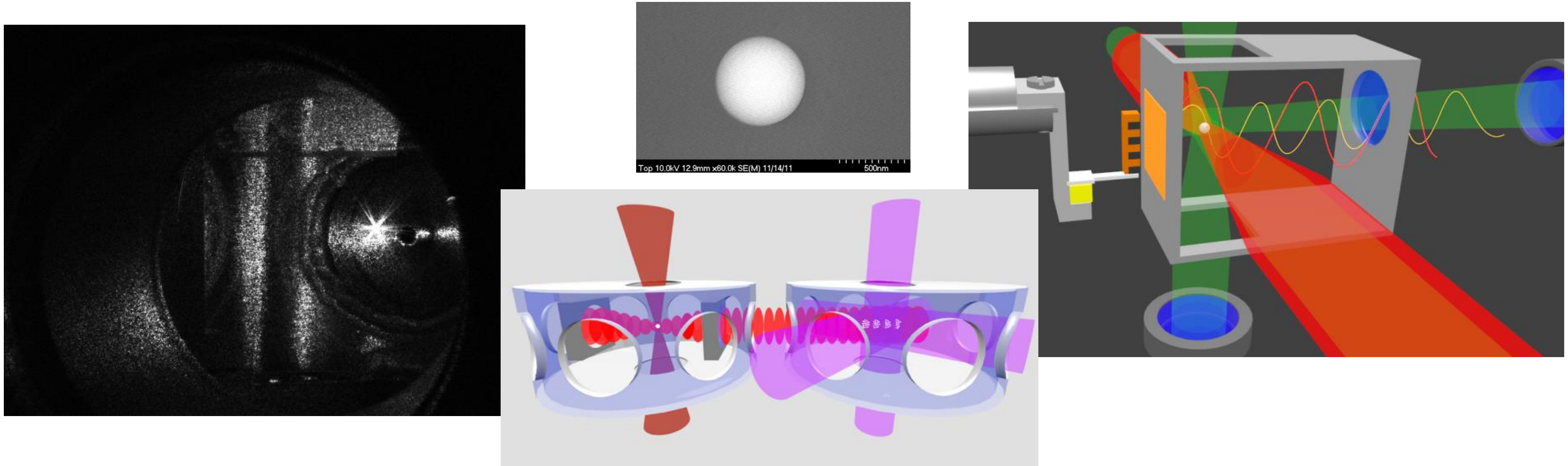
Ultrasensitive force detection and fundamental physics with optically trapped nanospheres



A. Geraci, Northwestern University

Intersections between Nuclear Physics
and Quantum Information, Mar. 29, 2018

Our lab has moved!

University of Nevada, Reno

Northwestern University

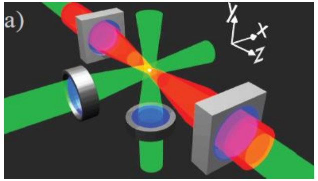
Center for Fundamental Physics (CFP)

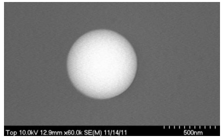
Openings for Postdocs and students!

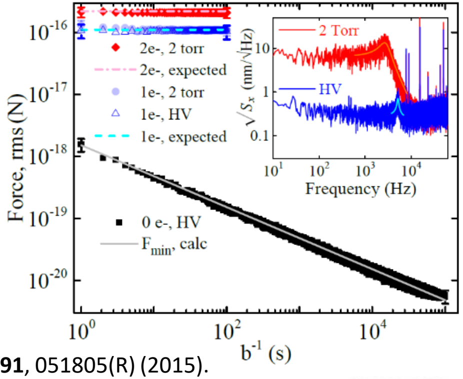
Our lab: fundamental physics with resonant sensors

Techniques

Mechanical Resonance:
Optically levitated nanospheres

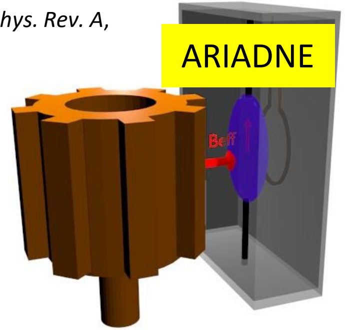






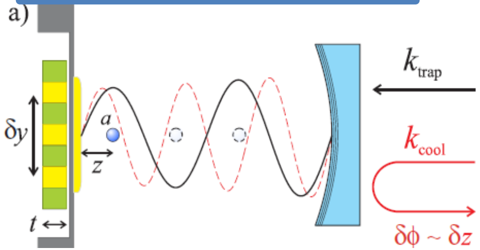
G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).
G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).

Spin Resonance:
NMR –Laser polarized gases or liquids



New Physics

Gravity at micron scales



AG., S. Papp, and J. Kitching, *Phys. Rev. Lett.* **105**, 101101 (2010).

Gravitational Waves

A. Arvanitaki and AG., *Phys. Rev. Lett.* **110**, 071105 (2013).

Spin-dependent forces
- QCD Axion

A. Arvanitaki and AG., *Phys. Rev. Lett.* **113**, 161801 (2014).

The Standard Model

Provides an adequate description of the electromagnetic, weak, and strong interactions.

The Interactions:

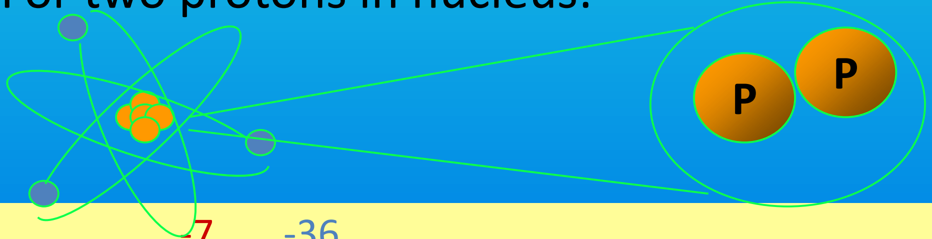
Strong: Holds nucleons together

Electromagnetic: Acts between charged particles

Weak: Causes certain decays

Gravity: Attraction between masses

For two protons in nucleus:



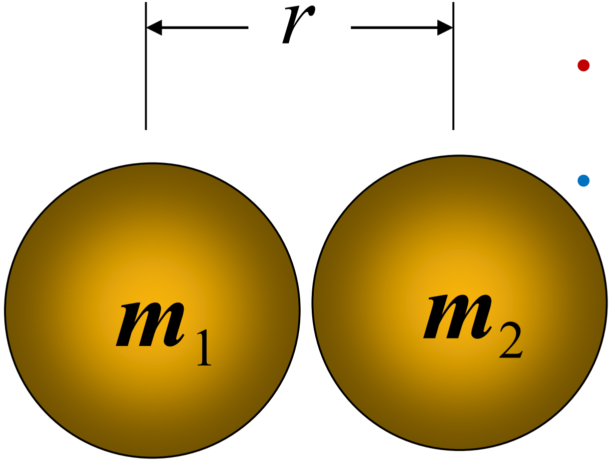
Strong : Electromagnetic : Weak : Gravity= 20 : 1 : 10^{-7} : 10^{-36}

The Hierarchy Problem: Why is Gravity so small?

Testing gravity at short range

$$V_N = -G\frac{m_1 m_2}{r}\left(1+\underset{\nearrow}{\alpha}\, e^{-r/\lambda}\right)$$

Exotic particles (new physics)

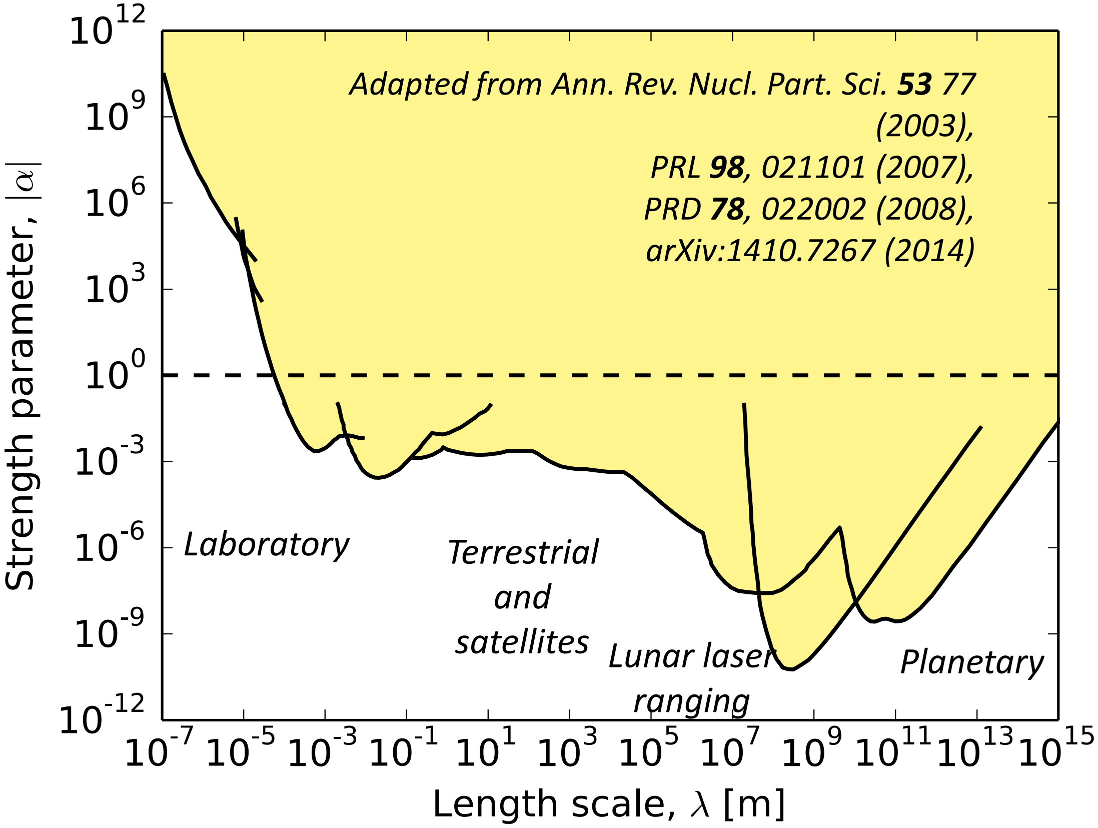


λ < 1 mm

- Supersymmetry/string theory
  (moduli, radion, dilaton)
- Particles in large extra dimensions
  (Gravitons, scalars, vectors?)

Landscape for non-Newtonian corrections

$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$



E.G. Adelberger, B.R. Heckel, A.E. Nelson, Ann. Rev. Nucl. Part. Sci. **53** 77, (2003)

Experimental challenge: scaling of gravitational force

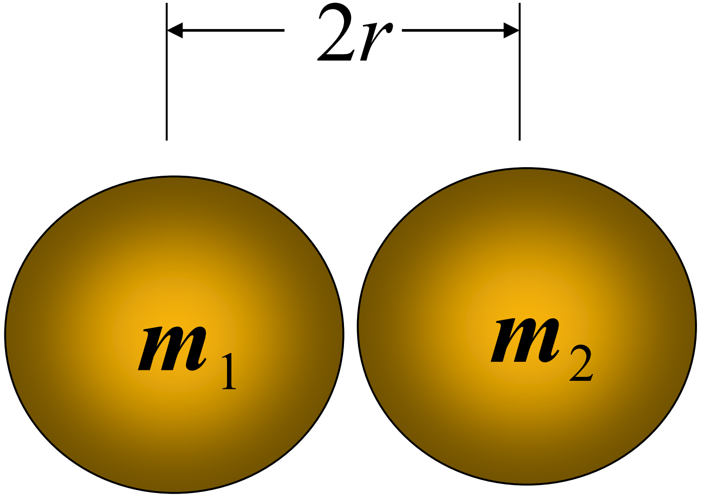
$$V_N = -G\frac{m_1 m_2}{r}$$

$$F_N = G_N \frac{\rho^2 (4\pi r^3/3)^2}{4r^2} \sim G_N \rho^2 r^4$$

$$F_N \cong 0.1 r^4 \quad \text{for} \quad \rho \sim 20 gr/cm^3$$

In the range of experimental interest:

$\boldsymbol{r \sim 10\ \mu m}$; $F_N \sim 10^{-21} N$



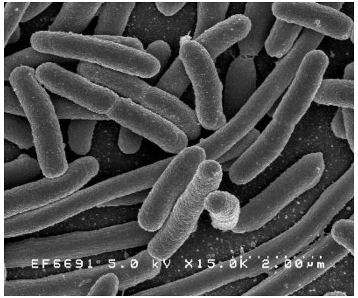
Small forces

- Bathroom scales measure 10^{-1} *N*

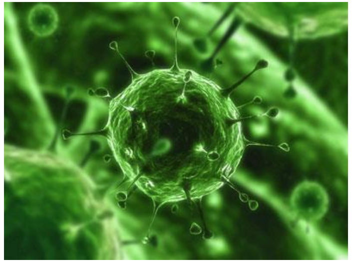
70 kg ~ 700 N

Dust mite 10^{-7} N

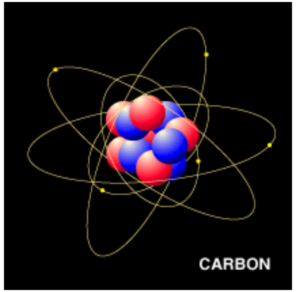
E. coli 10^{-15} N



Virus 10^{-19} N



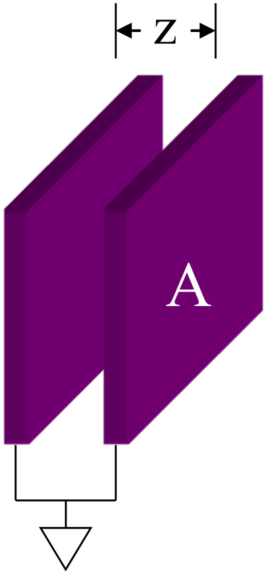
Carbon atom 10^{-25} N

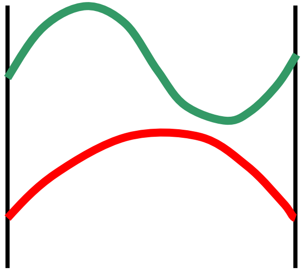


- AFM measures 10^{-11} *N*

Experimental challenge: electromagnetic background forces

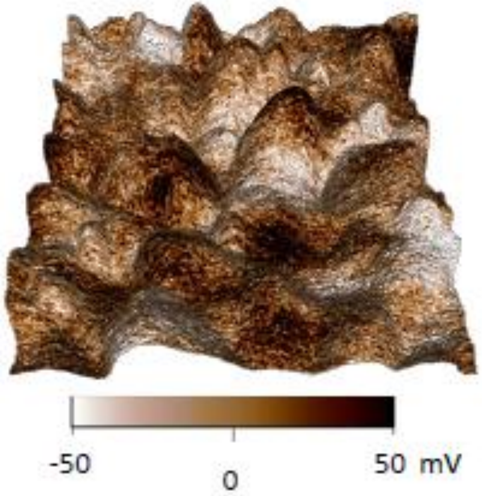
Casimir effect (1948):





$$F_C(z) = \frac{\pi^2}{240}\frac{\hbar c}{z^4}A$$

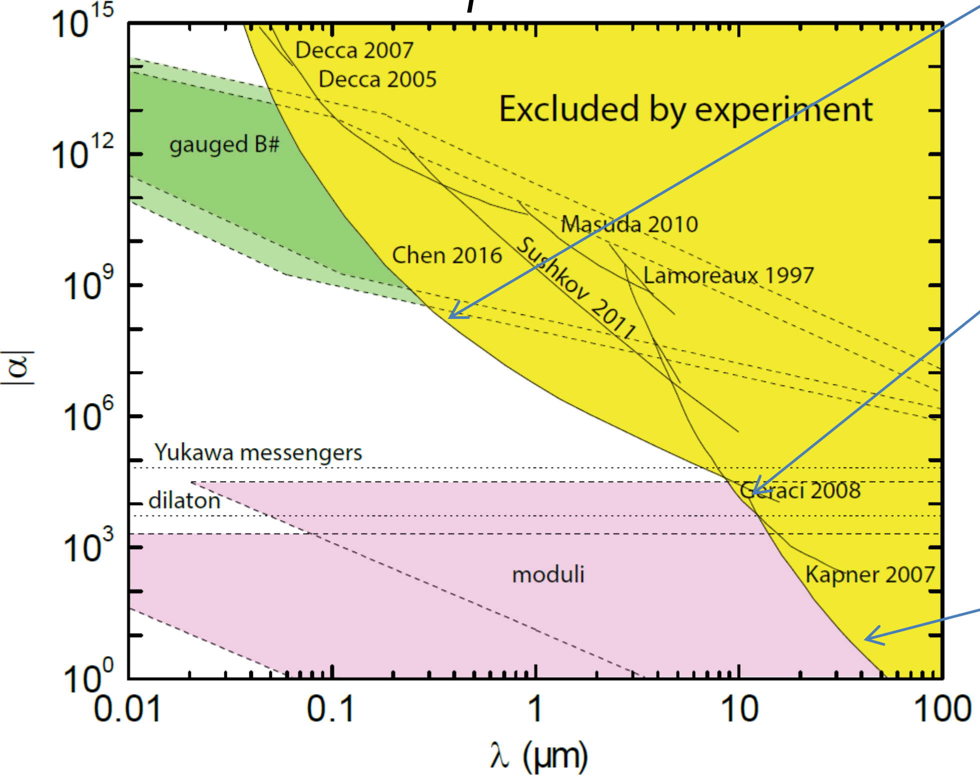
Electrostatic Patch Potentials:



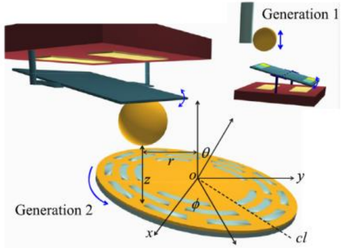
J. L. Garrett, D. Somers, J. N. Munday
J. Phys.: Condens. Matter 27 (2015) 214012

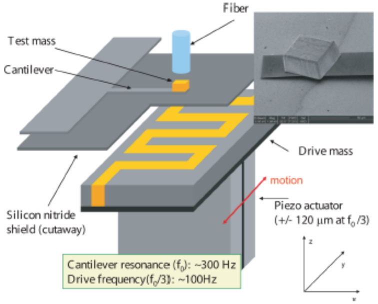
Force-distance parameter space

$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$



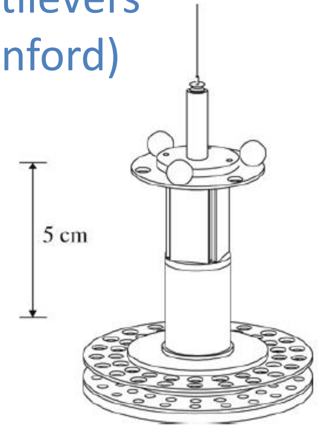
Casimir measurements (Indiana)





Cantilevers (Stanford)

Torsion balance experiments (U Washington)

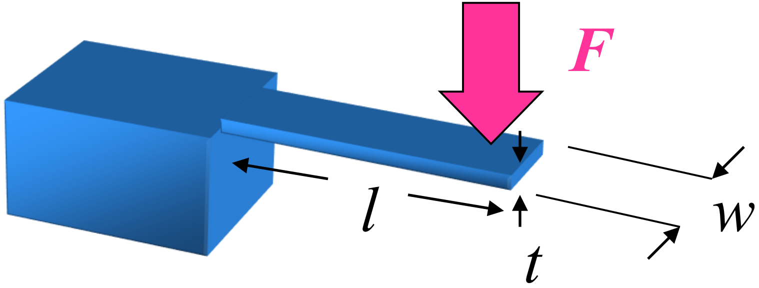


Resonant force detection

- Cantilever is like a spring:

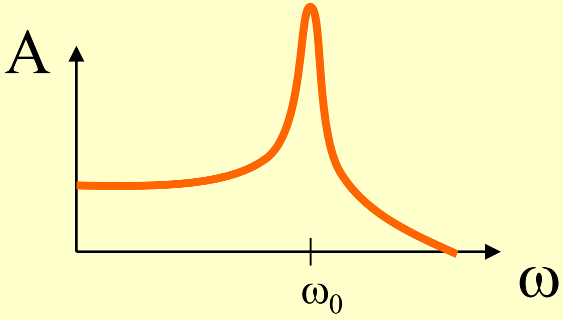
$$F = -Kx$$

$$\omega_0 = \sqrt{\frac{K}{m}}$$



Sinusoidal driving force

Amplitude:



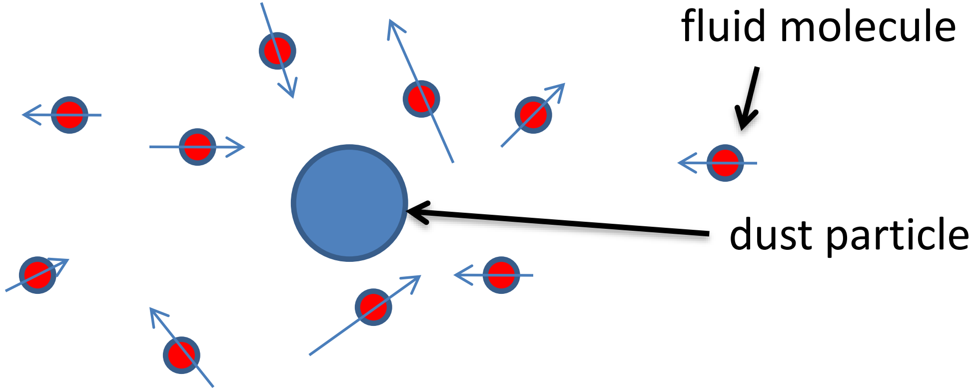
$$A_{(\omega=0)} = \frac{F}{k}$$ Constant force

$$A_{(\omega=\omega_0)} = \frac{F}{k}Q$$ Driving force on resonance of cantilever ω_0

Q can be very large >100,000

Fundamental limitation: thermal noise

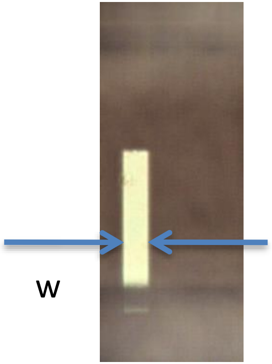
Brownian motion – random "kicks" given to particle due to thermal bath



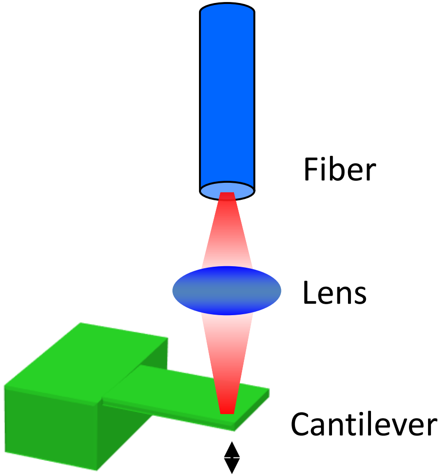
- Random "kicks" are given to cantilever due to finite T of oscillator

$$\frac{1}{2}k\left\langle x^2\right\rangle = \frac{1}{2}k_B T \Longrightarrow \boxed{F_{\min} = \left(\frac{4kk_B Tb}{Q\omega_0}\right)^{1/2}}$$

Example: Silicon microcantilevers



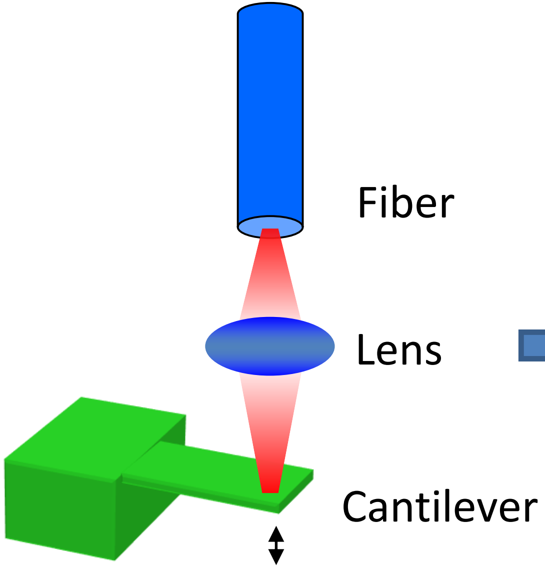
w= 50 µm
l= 250 µm
t=0.3 µm



$$F_{\min} = \sqrt{\frac{4k\, k_B T b}{\omega_0 Q}}$$

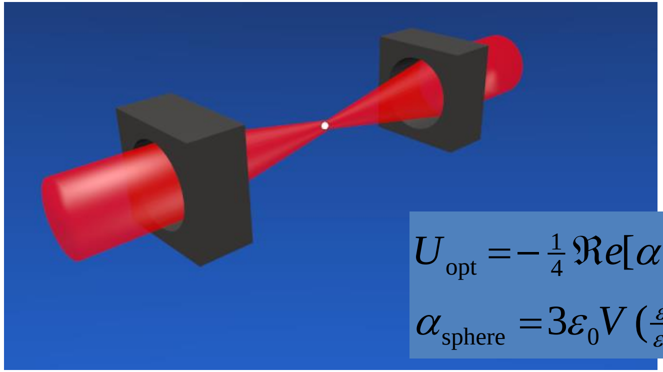
Silicon Cantilevers:
$F_{min} \sim 10 \times 10^{-18}$ N/√Hz at 4 K at $Q=10^5$

Improving sensitivity



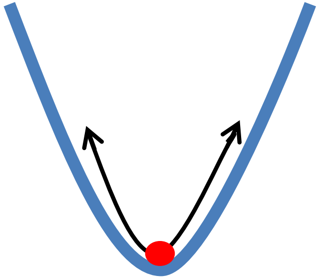
Limitations on Q: Clamping, surface imperfections, internal materials losses

Levitate the force sensor!



$$U_{\mathrm{opt}} = -\tfrac{1}{4}\Re e[\alpha]|E|^2$$

$$\alpha_{\mathrm{sphere}} = 3\varepsilon_0 V\left(\tfrac{\varepsilon-1}{\varepsilon+2}\right)$$

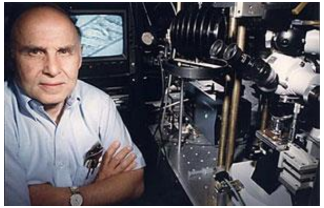


CM motion decoupled from environment – no clamping, materials losses

Levitated optomechanics

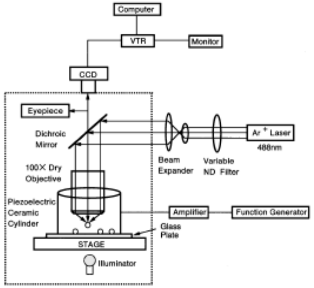
- Ashkin, Bell Labs, 1970s
- Ashkin (76) Levitation in high vacuum

Optical tweezers → biology, biophysics

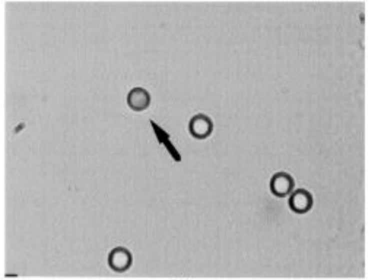


- Omori (97)

r=1.5,2,2.5 μm



Optical Microscope



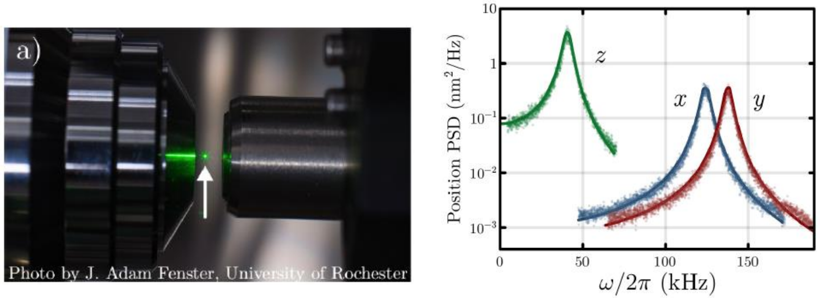
(a)

- Recently → proposals/experiments for ground state cooling

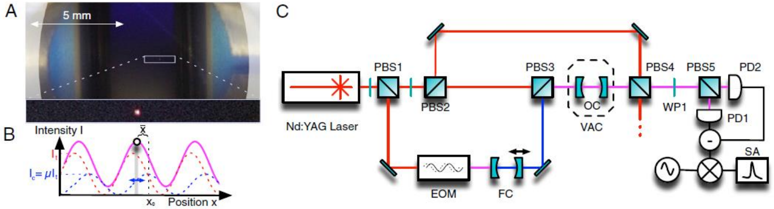
D.E. Chang *et. al.*, PNAS (2009)

O. Romero-Isart et.al. New J. Phys. (2010)

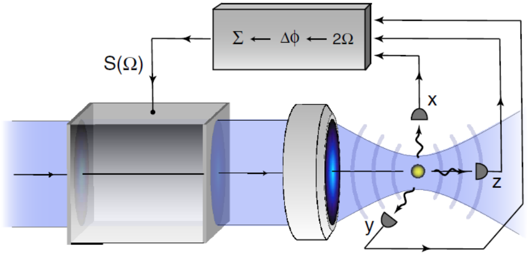
Levitated bead experiments



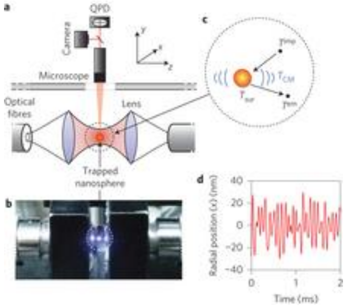
B. Rodenburg et. al, Optica 3, 318-323 (2016)



N. Kiesel, F. Blaser, U. Delic, D. Grass, R. Kaltenbaek, M. Aspelmeyer, doi: 10.1073/pnas.1309167110



J. Gieseler, B. Deutsch, R. Quidant *et. al.*, PRL **109**, 103603 (2012).

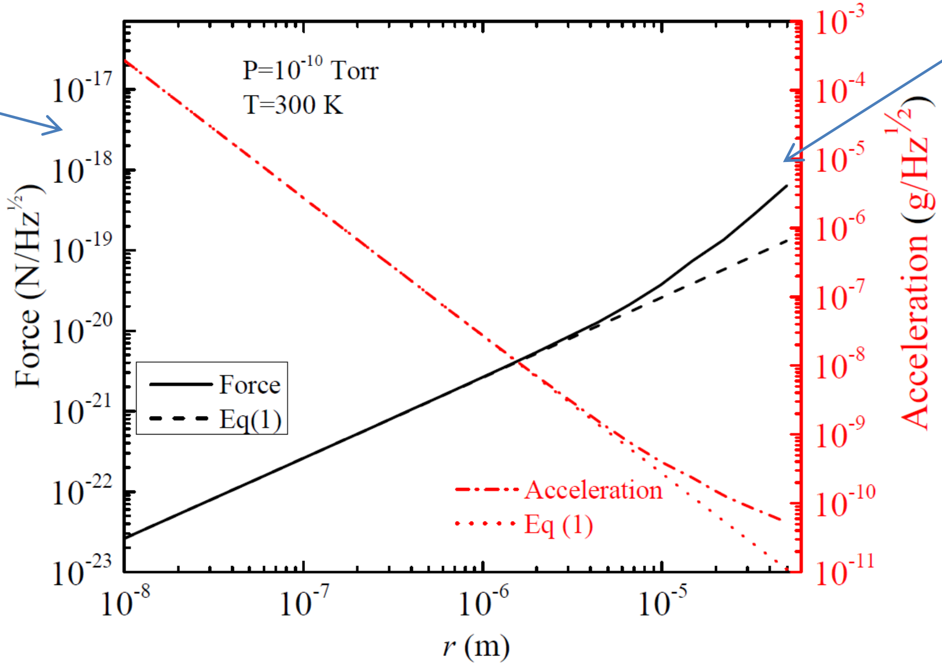


J. Millen, T. Deesuwan, P. Barker, J. Anders. *Nature Nanotechnology*, 2014; DOI: 10.1038/nnano.2014.82

Projected force sensitivity

$$F_{\min} = \left(4 k_B T \gamma m\right)^{1/2} \quad (1)$$

Cantilevers



Photon recoil heating

Seen recently by
Novotny group
V. Jain et. al.,
PRL 116, 243601
(2016)

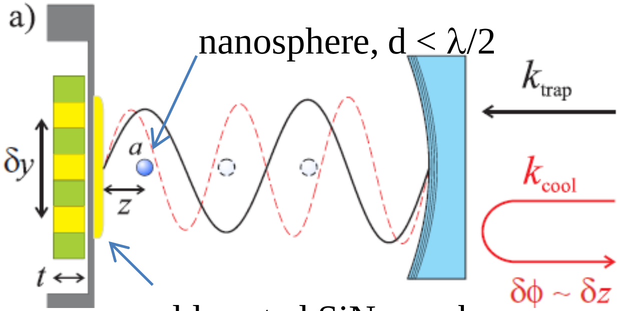
Ions

20 zN/Hz$^{1/2}$ Gieseler, Novotny, Quidant (Nature Phys. 2013)

Z. Yin, A. Geraci, T. Li, Int. J. Mod. Phys. B 27,1330018 (2013).

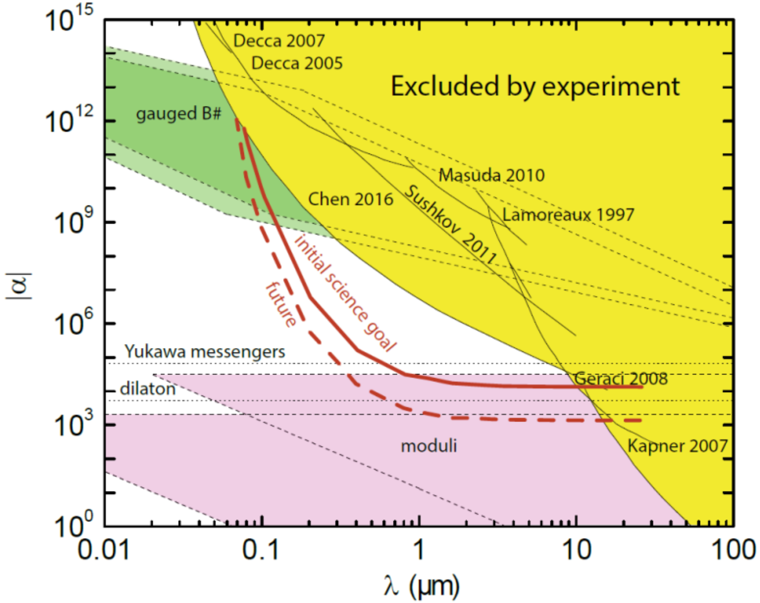
Projected sensitivity

Drive mass device (Au/Si)



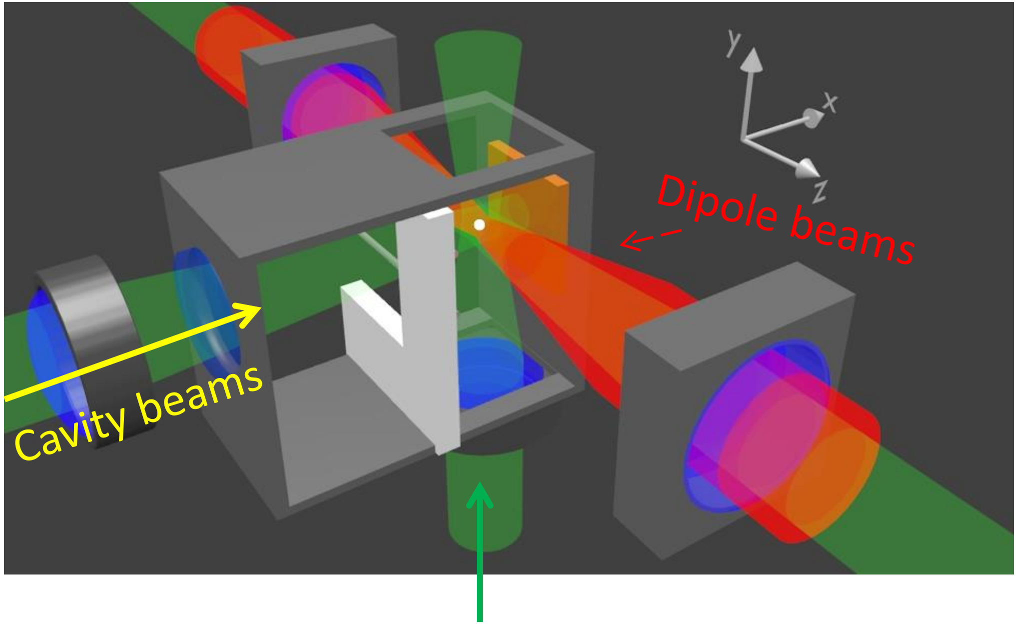
nanosphere, d < λ/2

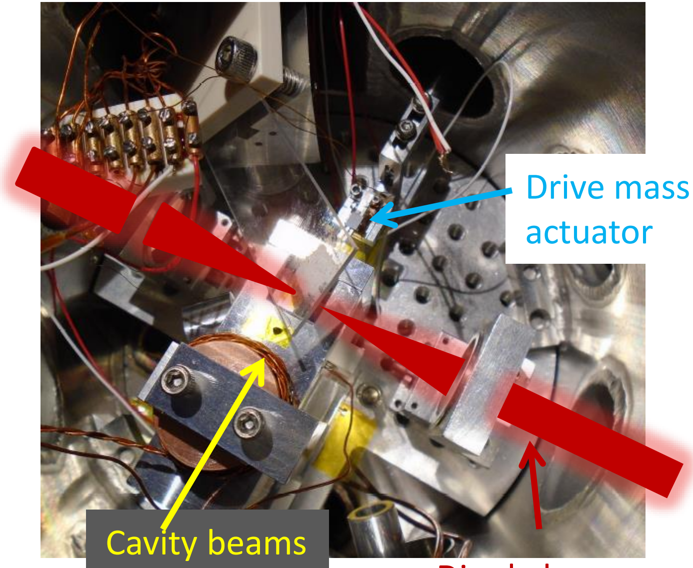
gold coated SiN membrane (stationary)

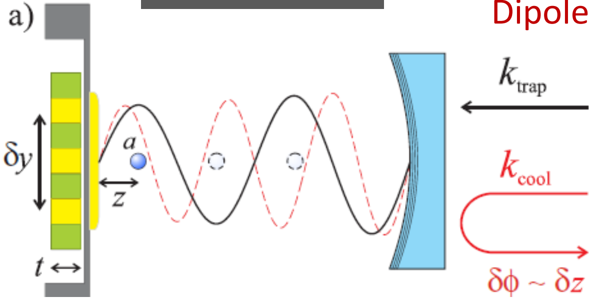


AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Experimental Setup

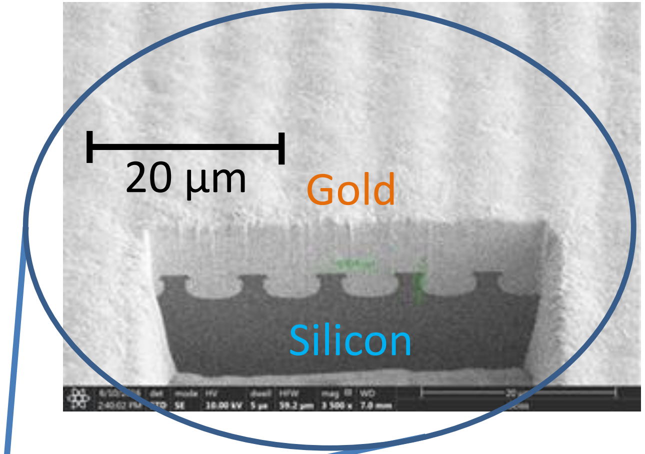


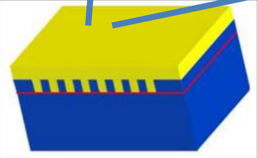




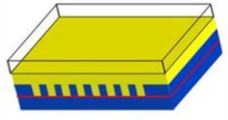
AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)
G. Ranjit et.al., PRA 91, 051805(R) (2015).
G. Ranjit et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Drive Mass fabrication

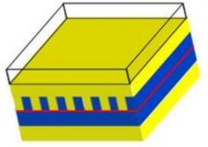




Microfabricated source mass



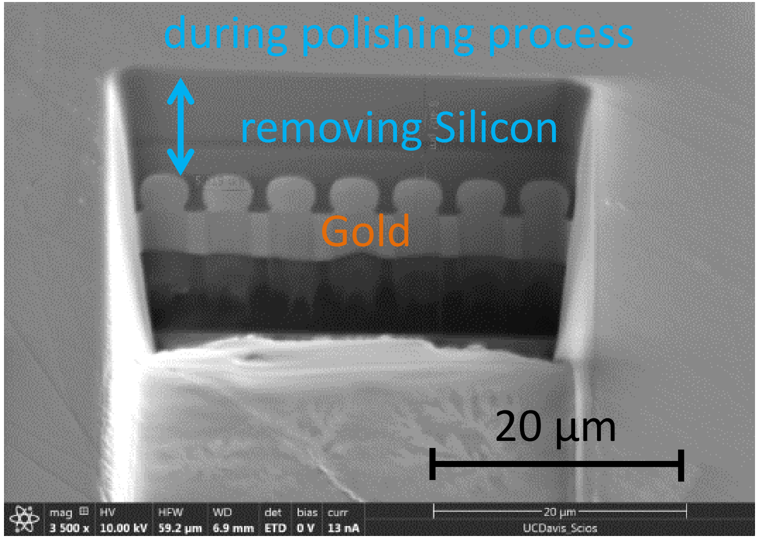
Polished source mass glued to a glass square



Finished mass after gold coating it and dicing it

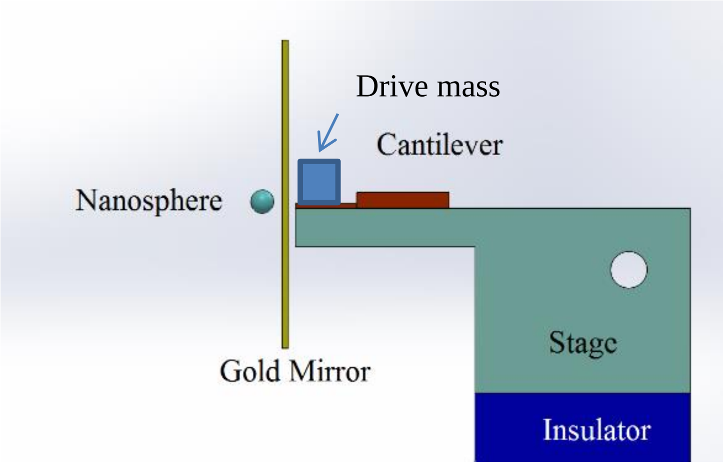
- 🟨 Gold
- 🟦 Silicon
- 🟥 Oxide

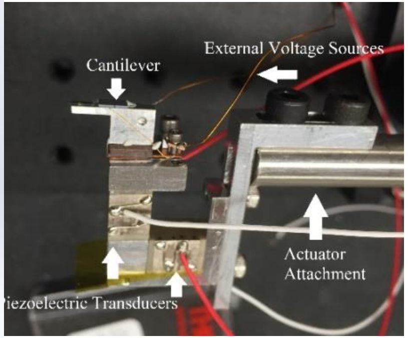
Buried drive mass technique – eliminates corrugation



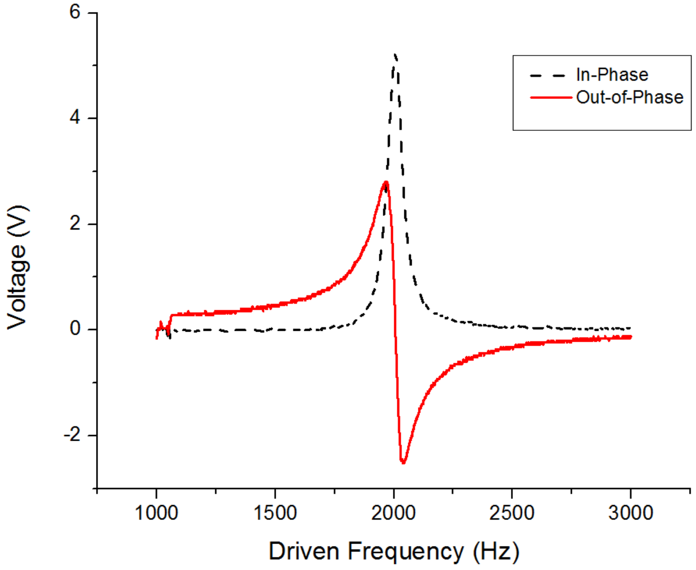
MEMS actuator

- Device for positioning drive mass

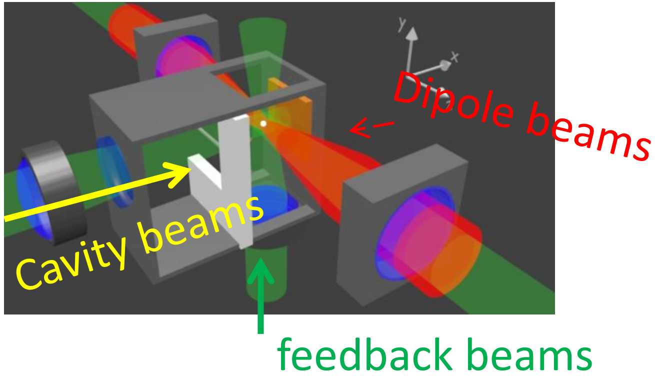


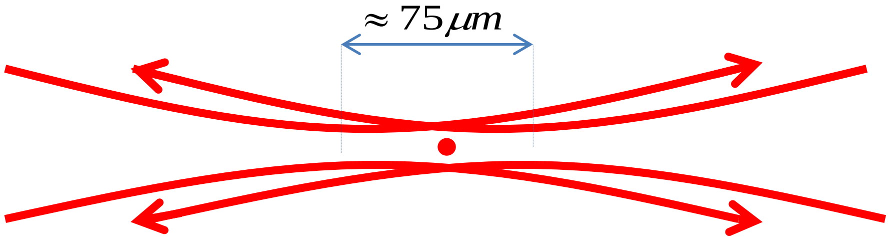


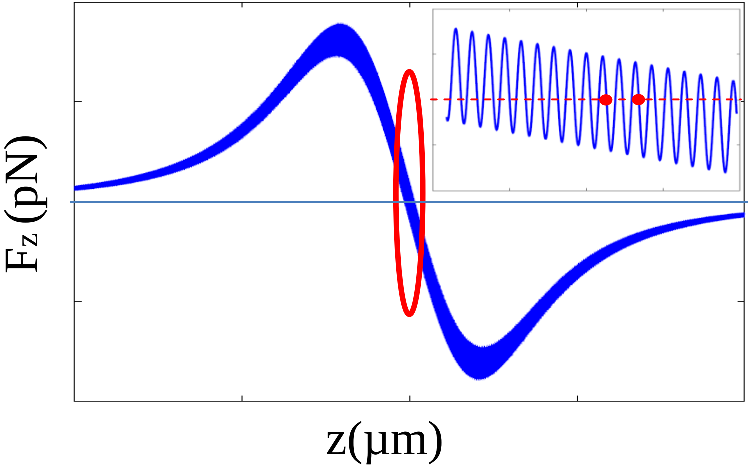
100V DC, 10V AC
~5 um displacement

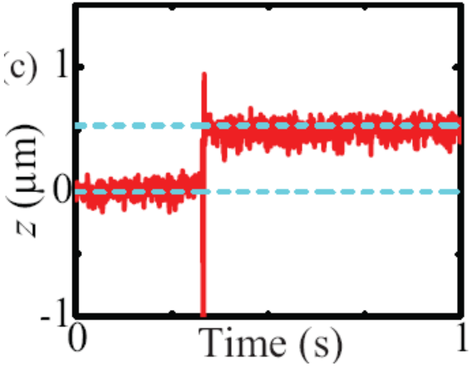


Standing wave optical trap

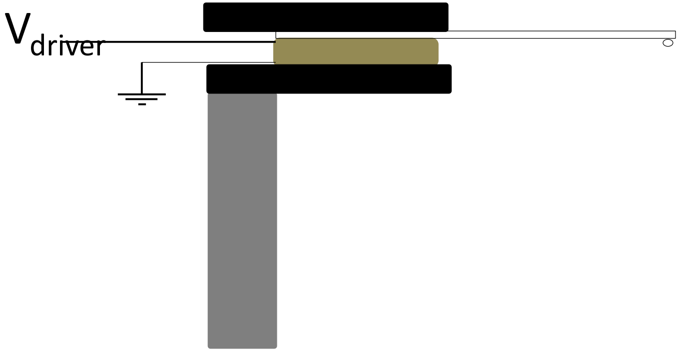


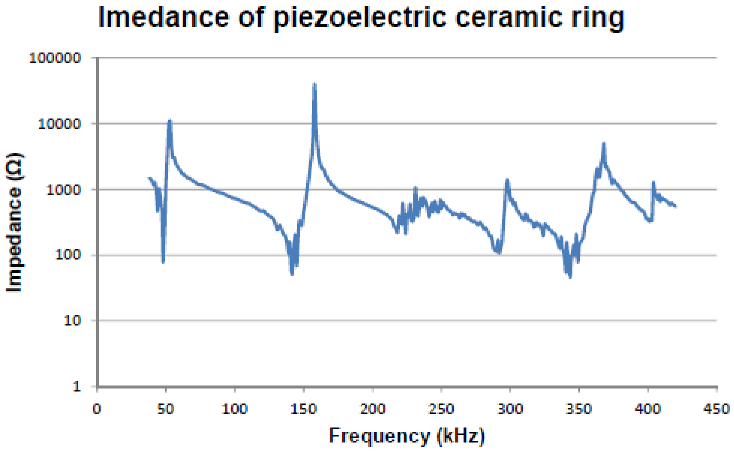






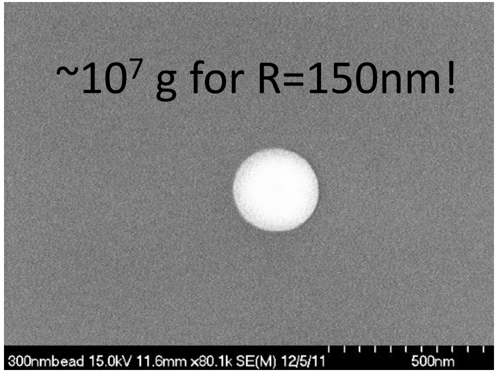
Trap loading



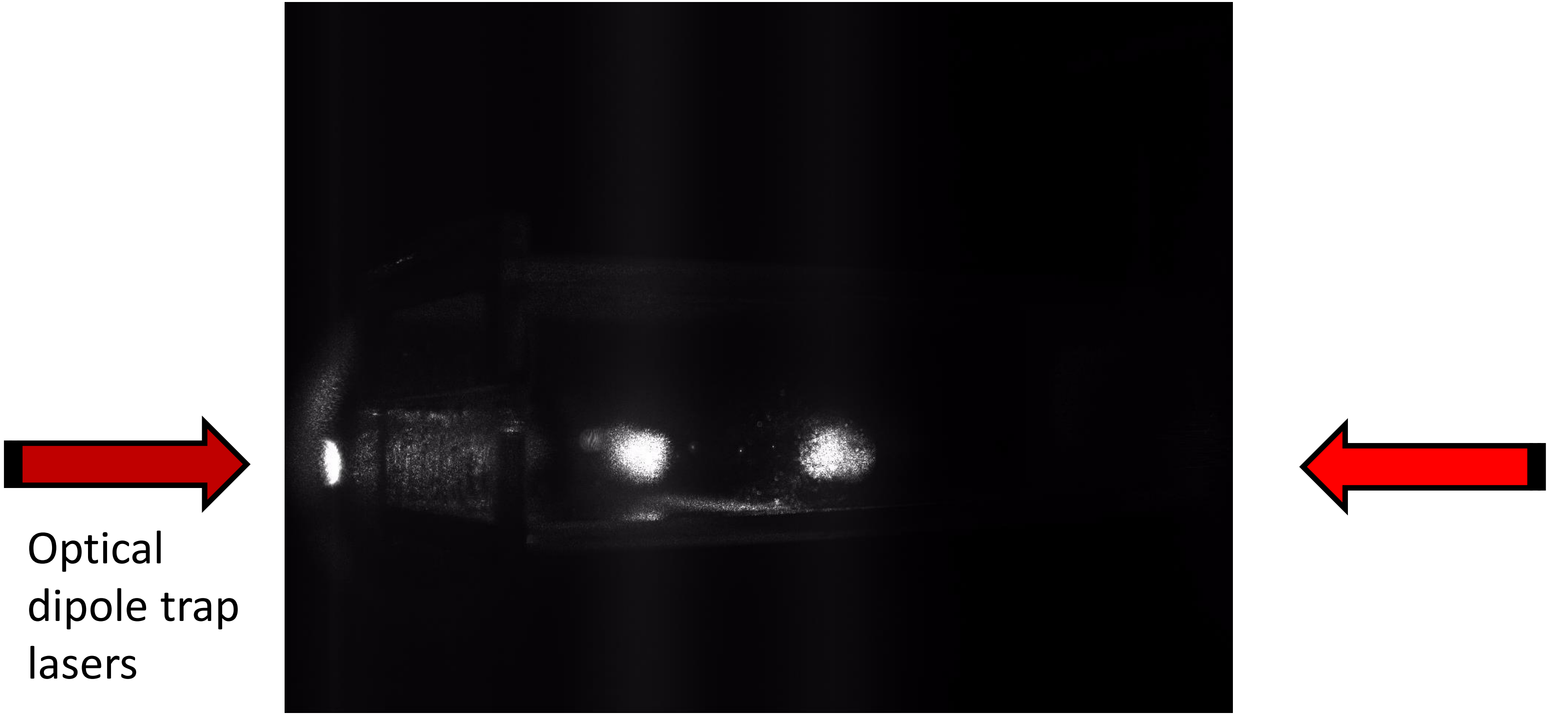

Imedance of piezoelectric ceramic ring

- Acceleration required to release a nanometer-sized sphere from a substrate

$$a \propto \frac{1}{R^2}$$

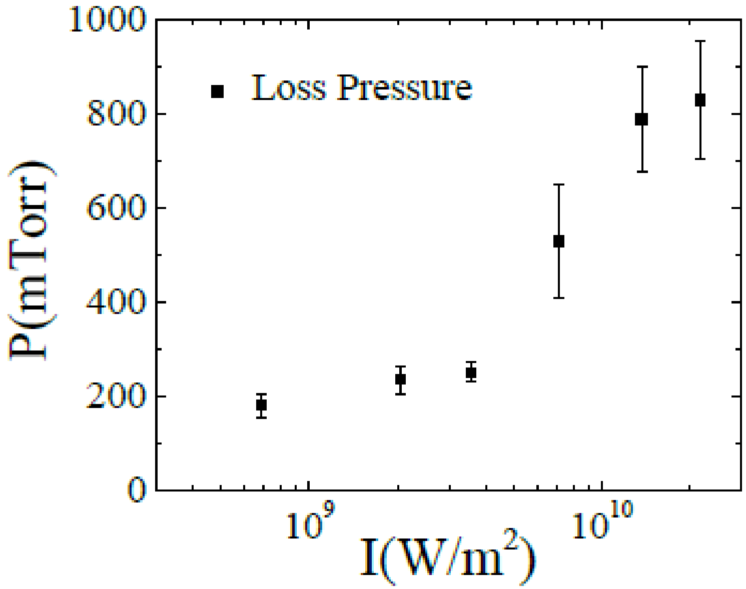

~10^7 g for R=150nm!

Loading optical trap



Optical dipole trap lasers

Trapping instabilities



$$U(r,z) = -\frac{1}{4}\alpha E^2(r,z)$$

$$E(r,z) = \sqrt{\frac{2I(r,z)}{c\epsilon_0}}$$

Trap depth > 10^6 K !

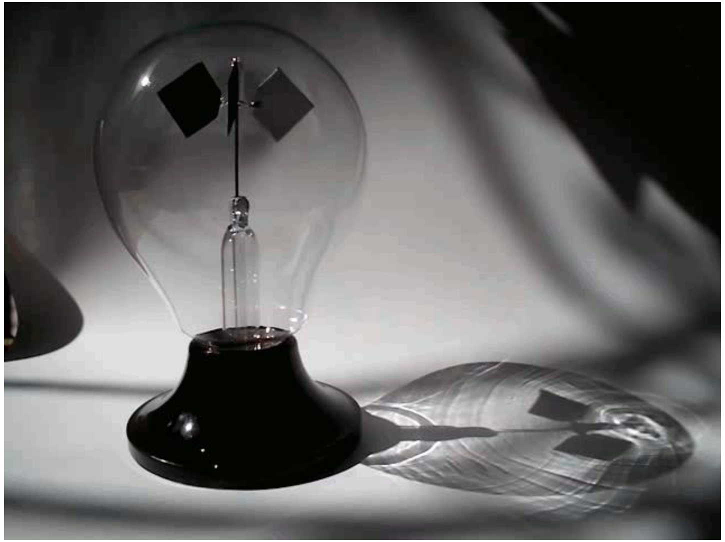
Without feedback cooling particle is lost < 1 Torr

Trapping instabilities

- **Radiometric forces**

Trap instabilities arise from uneven heating of the sphere surface

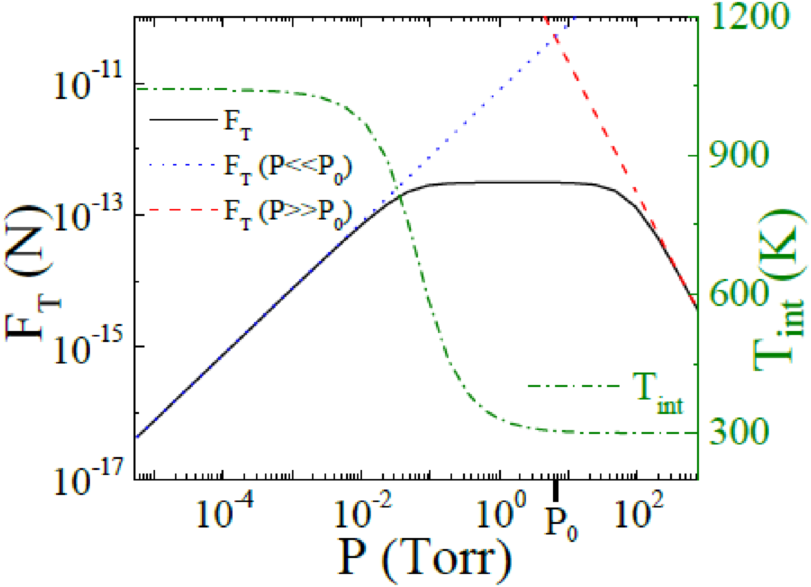
Important when mean free path ~ object size

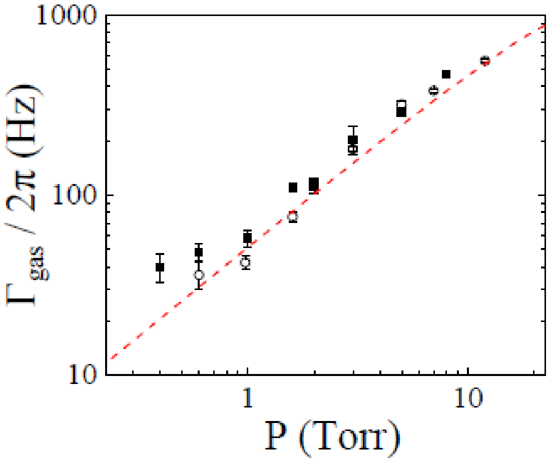


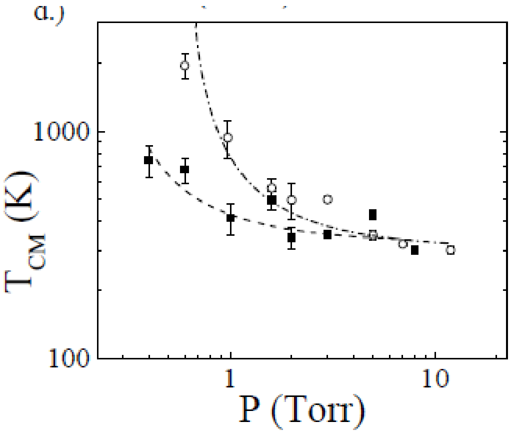
Crooke's Radiometer

Radiometric forces

$$F_T = -\frac{\pi r^2 \eta \sqrt{\frac{\alpha R_g}{MT}}\Gamma_i}{\frac{P}{P_0}+\frac{P_0}{P}}$$







1% temp gradient across surface

R=1.5 μm, I=2 x 10^9 W/m^2

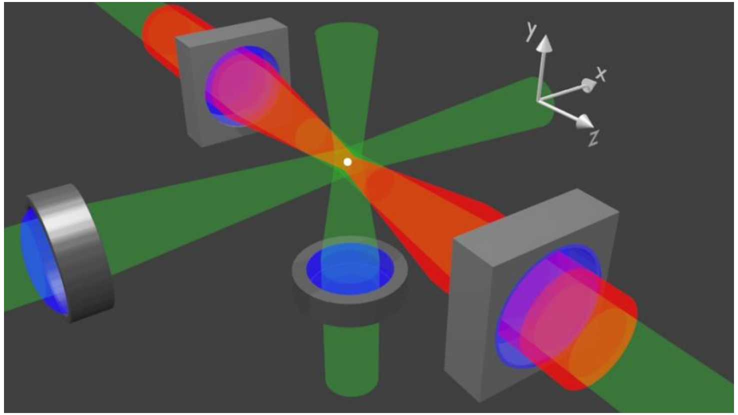
Ranjit et.al., PRA 91, 051805(R) (2015).

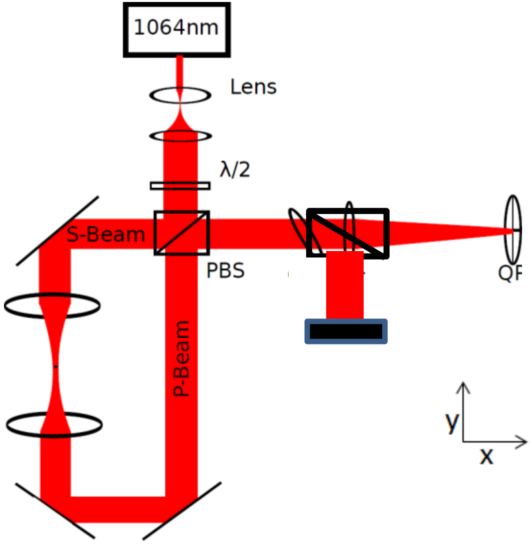
Heating rate > gas damping rate

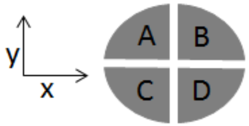
→ Particle loss → Need feedback!

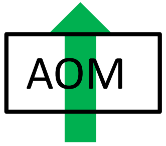
3D feedback cooling of a nanosphere

Needed to stabilize the particle, damp and cool it
Mitigate photon recoil heating

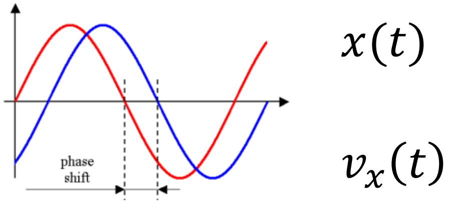








780 nm



$x(t)$

$v_x(t)$

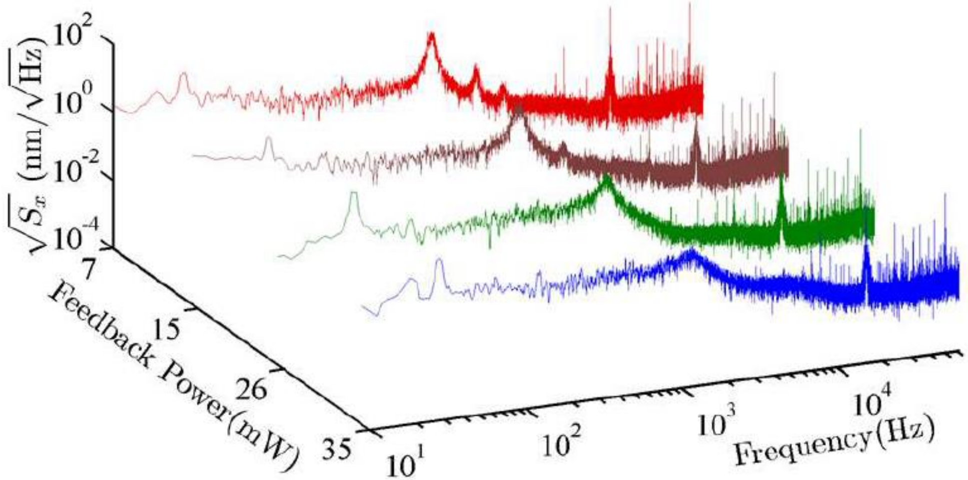
$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

$$Q_{eff} = \frac{Q_0 \Gamma_0}{\Gamma_0 + \Gamma_{cool}}$$

$$T_{eff} = \frac{T_0 \Gamma_0}{\Gamma_0 + \Gamma_{cool}}$$

Ranjit et.al., PRA 91, 051805(R) (2015).

Varying feedback power

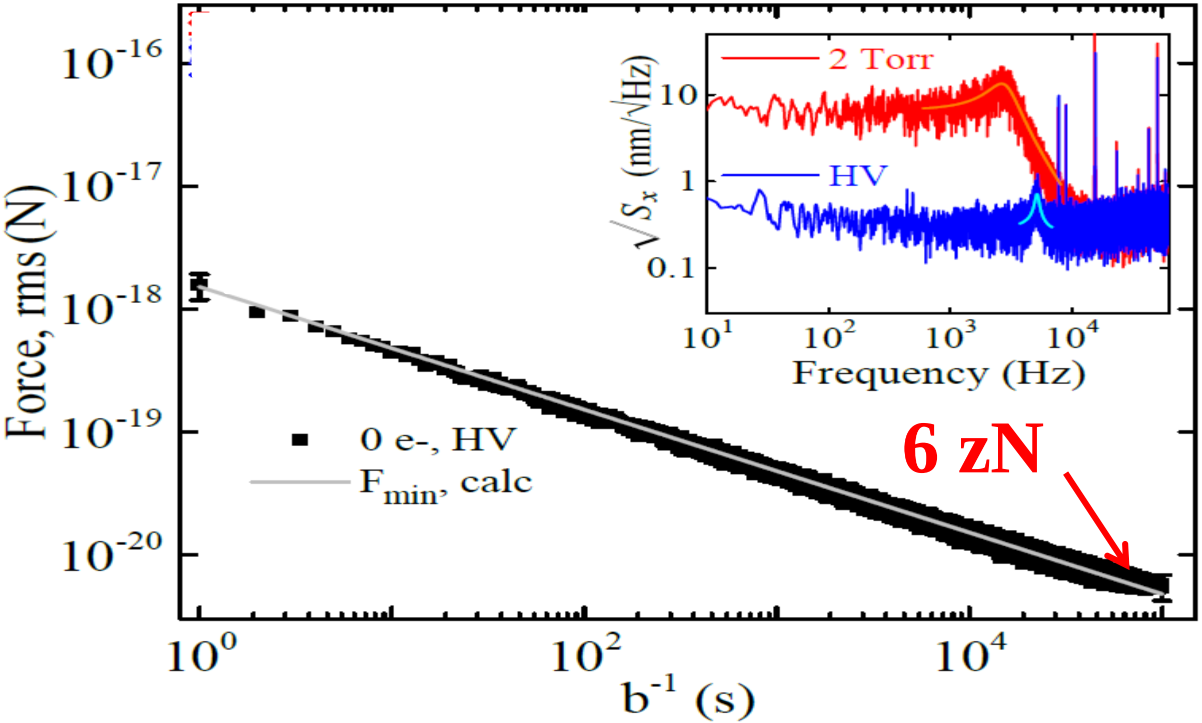


High Vacuum -- Can decrease cooling rate by > 1 order of magnitude and maintain stable trap

→ Gas contributes to loss mechanisms near 100 mTorr - 1 Torr range

Ranjit et.al., PRA 91, 051805(R) (2015).

Zeptonewton force sensing



6 zN

G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Sensitivity

$$S_{F,x} = 1.63 \pm .37 \text{ aN}/\sqrt{\text{Hz}}$$

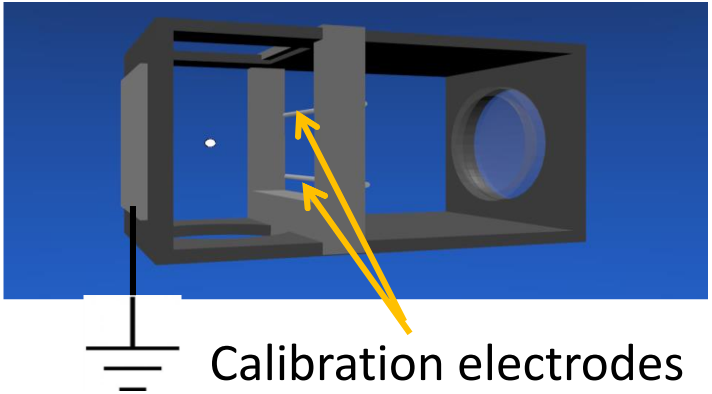
Zeptonewton force sensing

Electrostatic Calibration

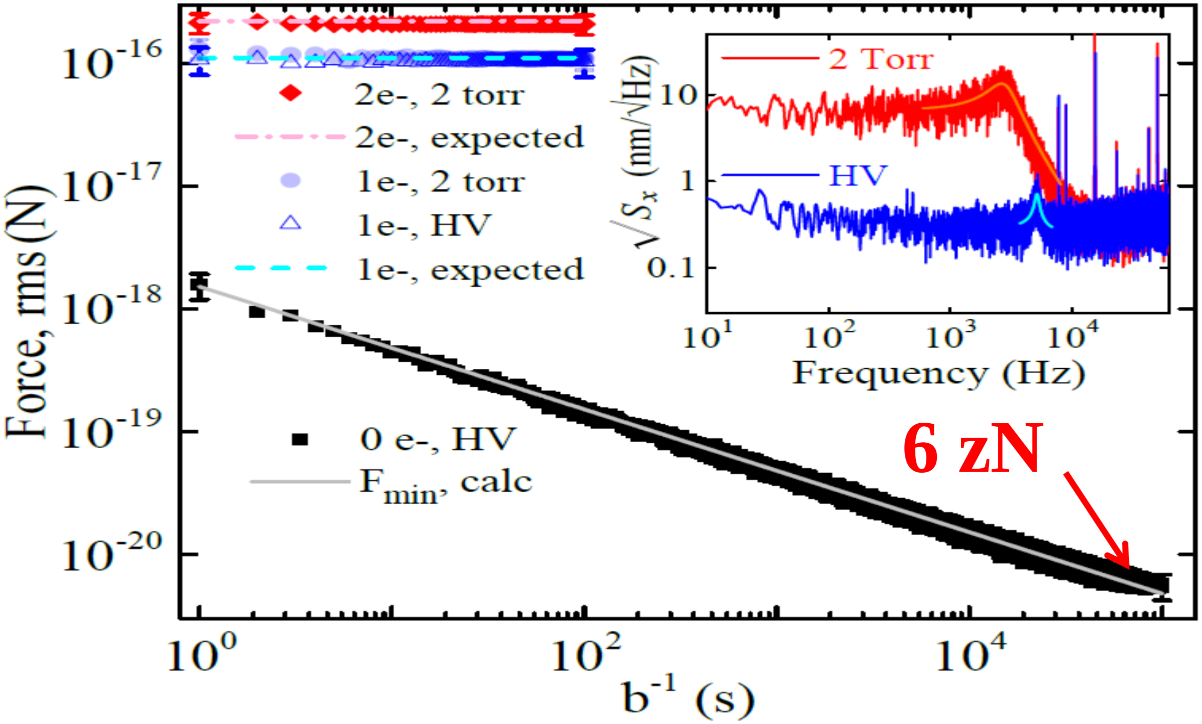
90% of beads are neutral

Neutral beads stay neutral

Charge stays constant over days



Calibration electrodes



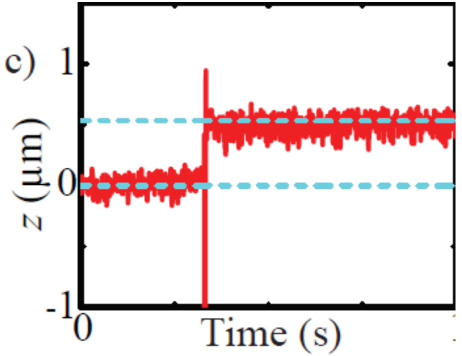
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Sensitivity

$$S_{F,x} = 1.63 \pm .37\ \text{aN}/\sqrt{\text{Hz}}$$

Zeptonewton force sensing

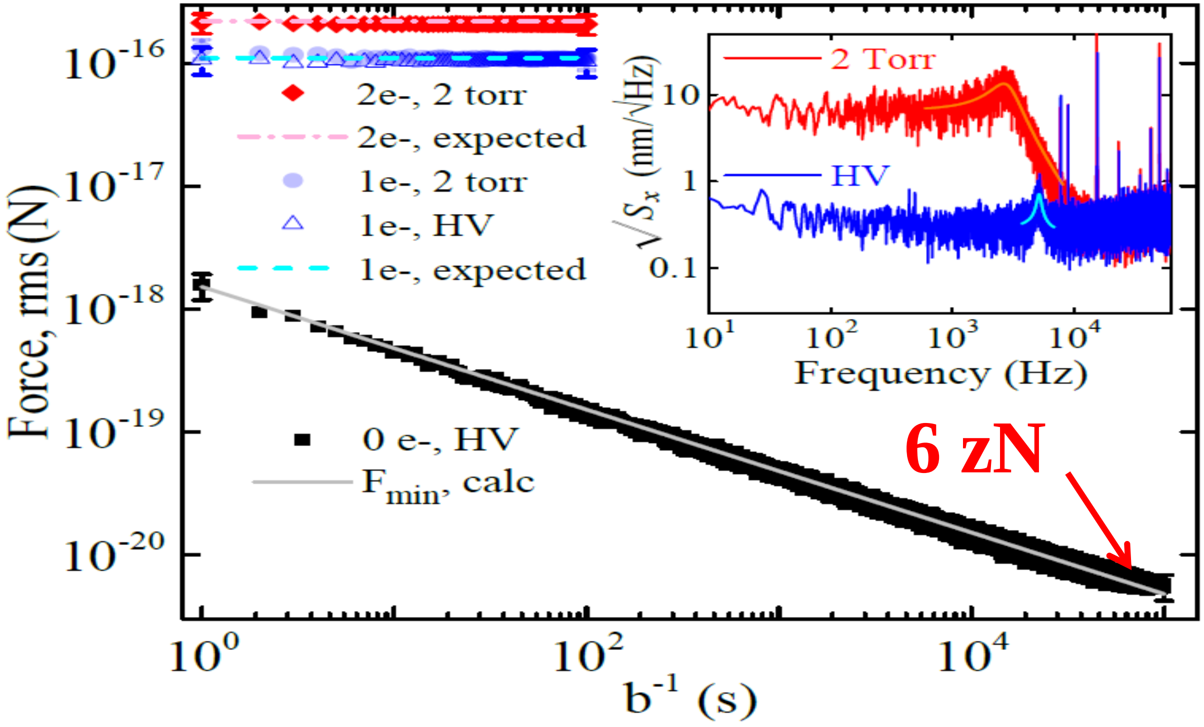
Optical lattice calibration



Useful for neutral objects

Method consistent with electric field approach

G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

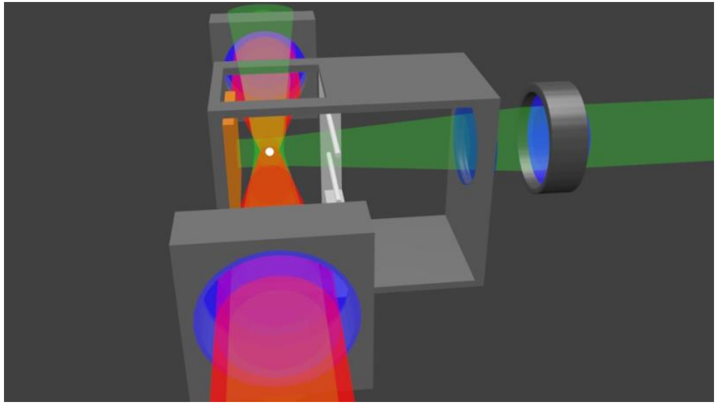


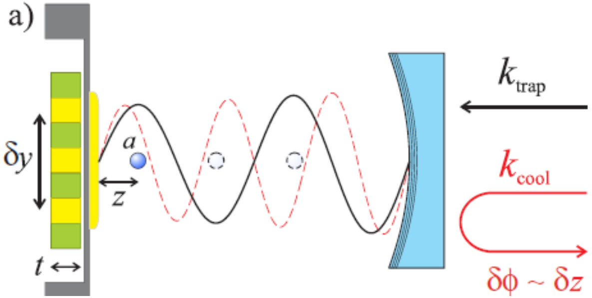
6 zN

Sensitivity

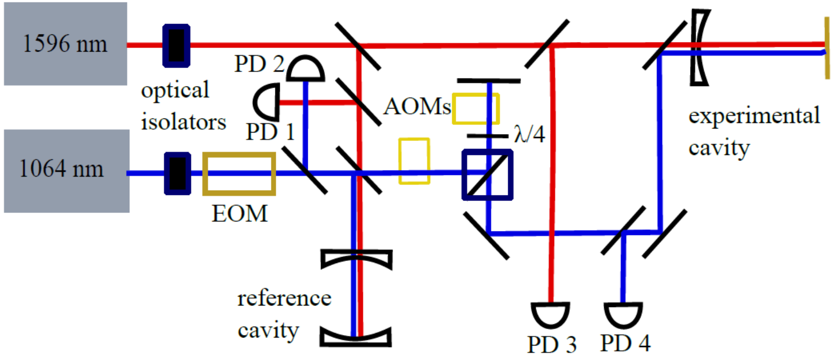
$$S_{F,x} = 1.63 \pm .37 \text{ aN}/\sqrt{\text{Hz}}$$

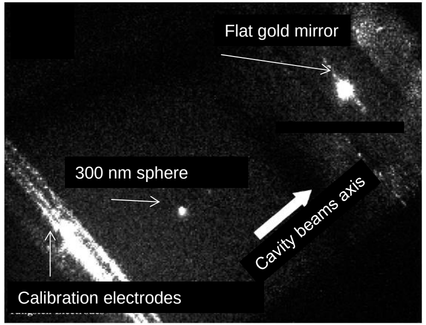
Next: Cavity Trapping and cooling





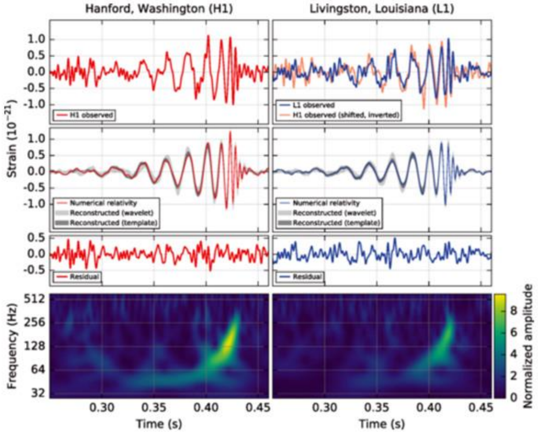
1596nm beam to trap a bead at its antinode → localization
1064nm beam to cavity cool the CM of bead → position readout





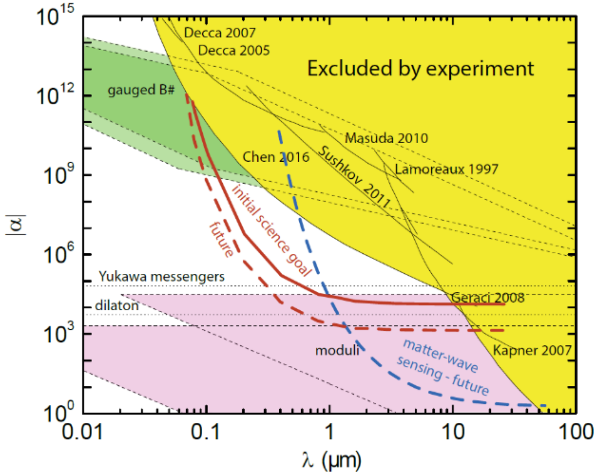
Future prospects

- Gravitational waves



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **116**, 061102 (2016).

- Quantum limited sensing



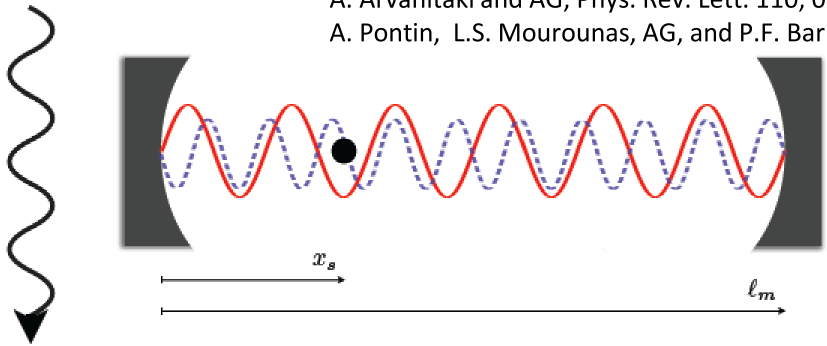
A. Arvanitaki and AG, Phys. Rev. Lett. 110, 071105 (2013)
A. Pontin, L.S. Mourounas, AG, and P.F. Barker, New J. Phys. 20 023017 (2018).

A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).

- Applications in nuclear physics?

Gravitational Wave Detection

A. Arvanitaki and AG, Phys. Rev. Lett. 110, 071105 (2013)
A. Pontin, L.S. Mourounas, AG, and P.F. Barker, New J. Phys. 20 023017 (2018)

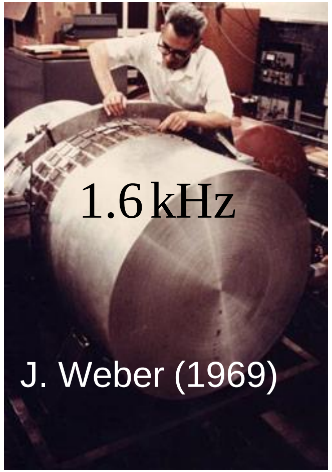


10-100m

GW Strain h = ΔL/L

- Laser intensity changed to match trap frequency to GW frequency
- For a 100m cavity, *h* ~ 10^{-22} Hz $^{-1/2}$ at high frequency (100kHz) (a = 75 um, d = 500 nm disc)
- Limited by thermal noise in sensor (not laser shot noise)

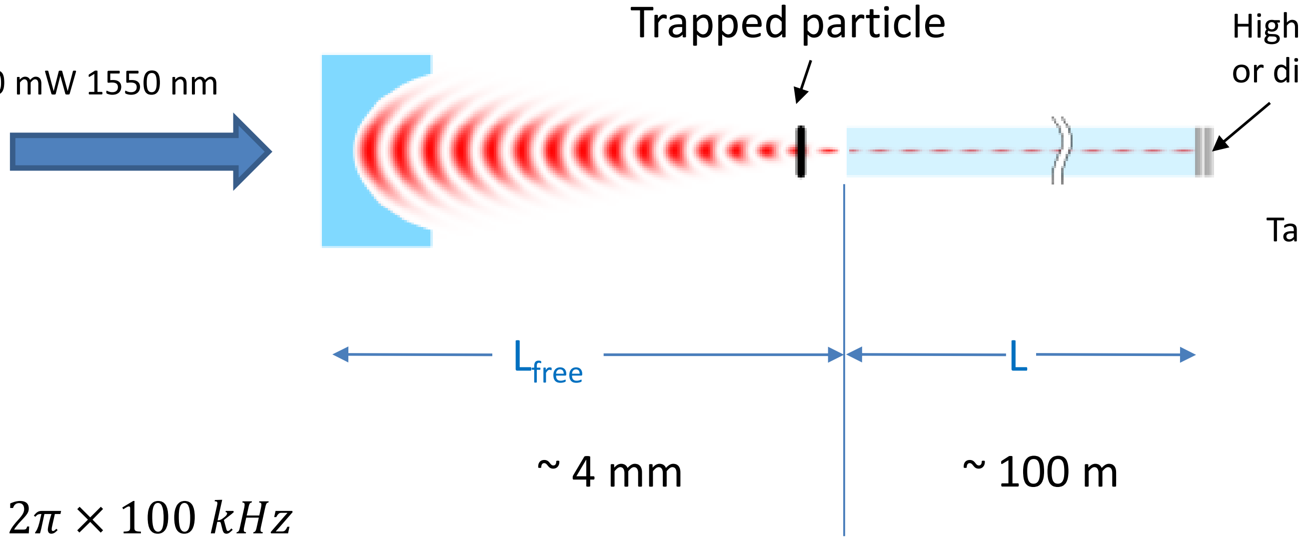
Position measurement → force measurement



1.6 kHz

J. Weber (1969)

Fiber based FP Cavity



60 mW 1550 nm

Trapped particle

High reflectivity mirror
or distributed bragg reflector

Target finesse ~10

~ 4 mm

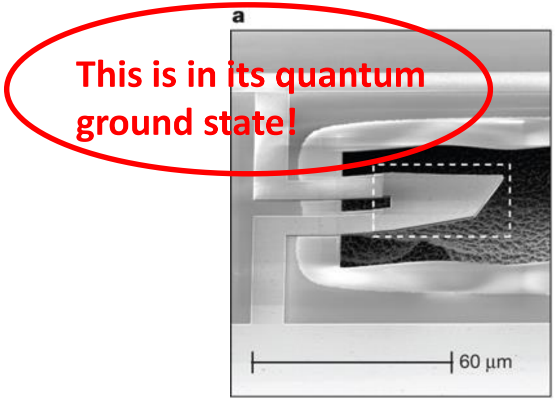
~ 100 m

$$\omega = 2\pi \times 100\ kHz$$

$\kappa = 2\pi$ x 51 kHz

A. Pontin, L.S. Mourounas, AG, and P.F. Barker, arXiv:1706.10227New. J. Phys (2018), accepted

Quantum “Mechanics”

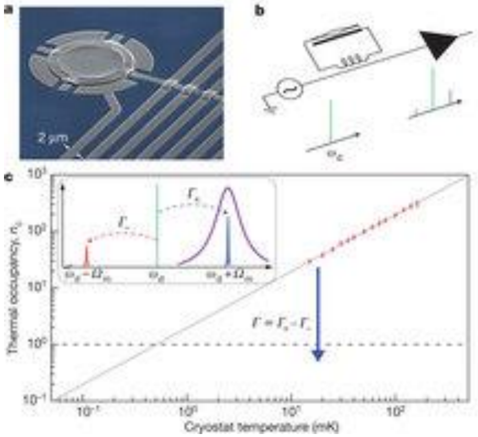


This is in its quantum ground state!

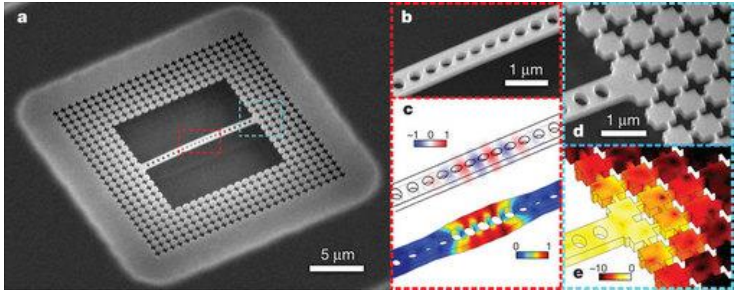
Quantum ground state and single-phonon control of a mechanical resonator
A. D. O’Connell et.al.
Nature 464, 697 (2010).

$$k_B T << \hbar\omega$$

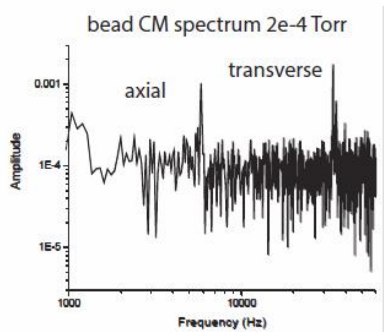
Sideband cooling of micromechanical motion to the quantum ground state
J. D. Teufel,[1] *et.al.* Nature 475, 359 (2011).

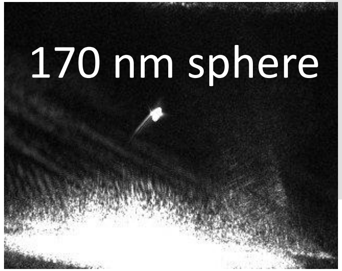


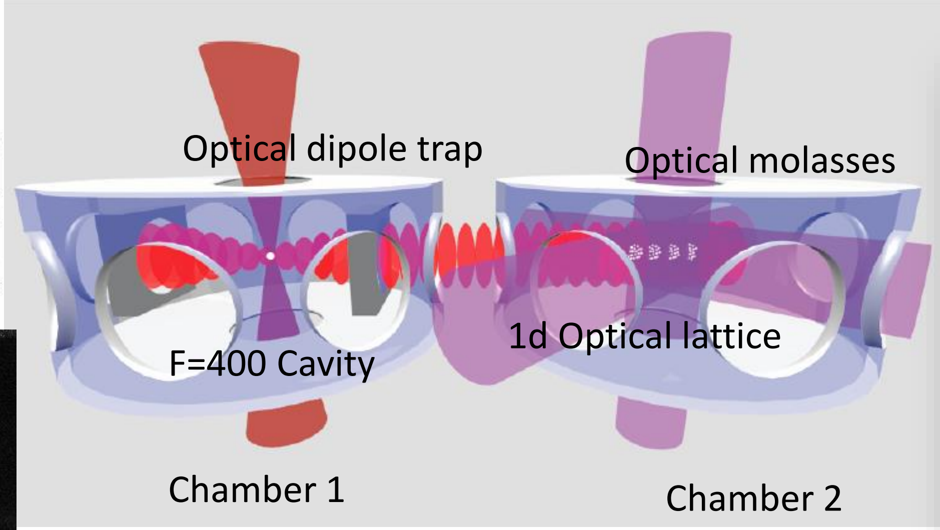
Laser cooling of a nanomechanical oscillator into its quantum ground state
Jasper Chan,[1] *et.al.* Nature 478, 89–92(2011)

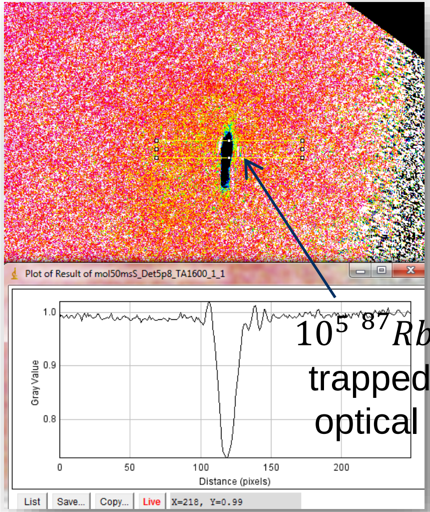


Sympathetic cooling of a nanoparticle via cold atoms




170 nm sphere



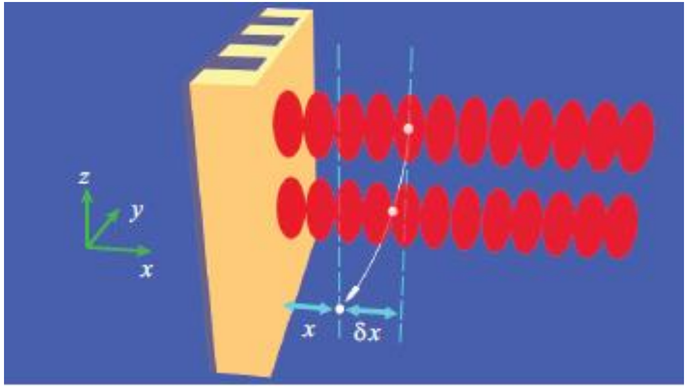

Plot of Result of mol50msS_Det5p8_TA1600_1_1

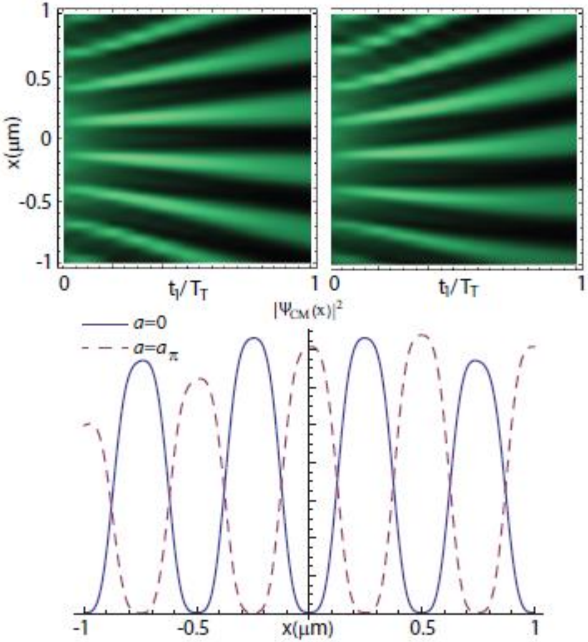
X=218, Y=0.99

10^5 ^{87}Rb atoms trapped in an optical lattice

G. Ranjit, et.al. Phys. Rev. A 91, 013416 (2015).

Matter-wave interferometry



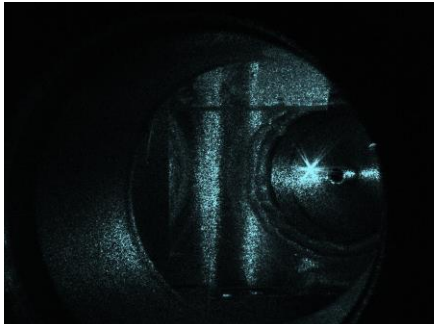


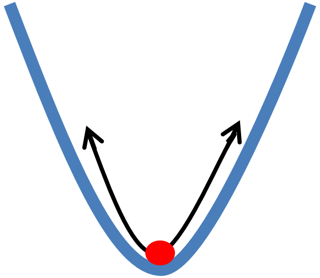
O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, J. I. Cirac Phys. Rev. Lett. 107, 020405 (2011).
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht,, Nat. Commun. 5, 4788 (2014).
A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).

ng acceleration sensing

Nuclear physics applications?

- Other uses for zeptonewton force sensing
- Rare decays





M. Dietrich, A.G.

β -decay

$$\Delta v = \frac{\Delta p}{m} \sim 10^{-4} m/s \left(\frac{\Delta p}{1\ MeV}\right) \left(\frac{10^{-17} kg}{m}\right)$$

Detectable above thermal noise for 100 nm particle at 3 mK

Conclusions

- Calibrated zeptonewton force sensing with optically levitated nanospheres
  - → Micron-distance gravity tests
  - → Casimir forces in new regimes
  - → High frequency gravitational waves
  - → Other applications??
- Quantum Regime
  - → Source for matter wave interferometry
  - → Testing quantum behavior at the macro-scale

S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A.G., P.F. Barker, M. S. Kim, and G. Milburn, Phys. Rev. Lett. **119**, 240401 (2017)

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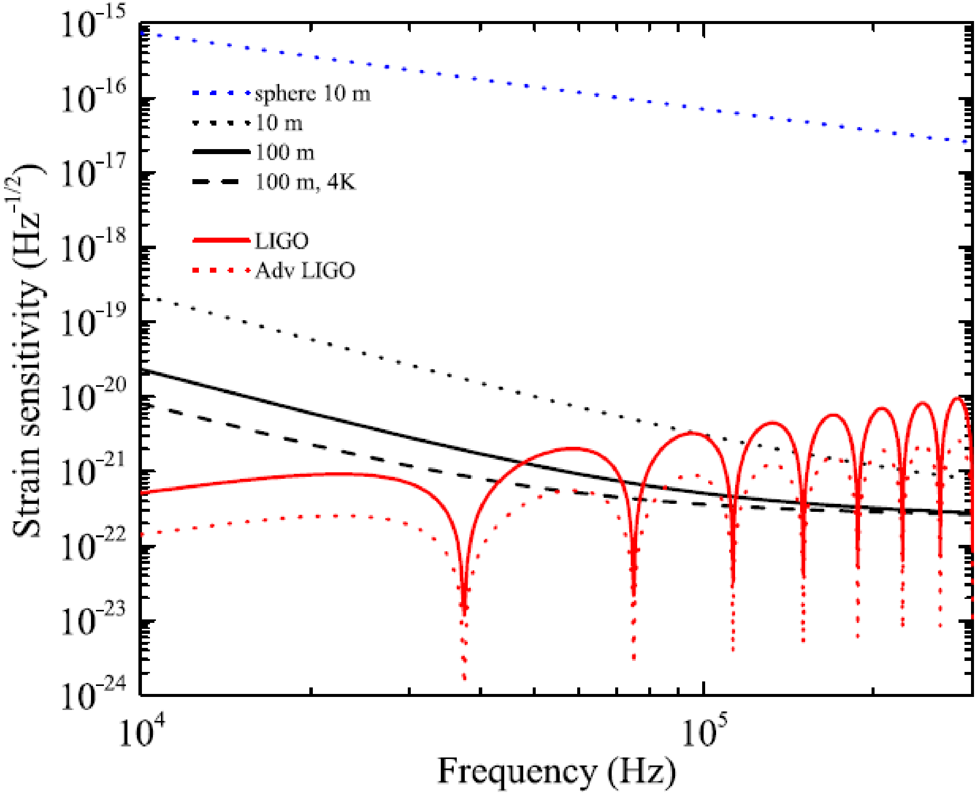
PHY-1506431
PHY-1506508
1510484, 1509176

Back row (L to R): Cris Montoya (G), William Eom (UG), Jason Lim (UG), Harry Fosbinder-Elkins (UG), Mindy Harkness (UG), Andrew Geraci (PI)
Front row (L to R): Ryan Danenberg (UG), Kathleen Wright (UG), Isabella Rodriguez (UG), Chloe Lohmeyer (G), Ohidul Mojumder (UG), Jordan Dargert (G), Chethn Galla (G), Colin Bradley (UG).

GW Strain Sensitivity



100 m

Size scale:

LIGO

GW sources at high-frequency

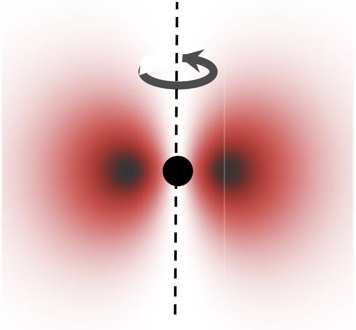
- Astrophysical Sources
  Natural upper bound on GW frequency
  inverse BH size ~ 30 kHz

- Beyond standard model physics
  - QCD Axion → Annihilation to gravitons in cloud around Black holes

A. Arvanitaki *et. al*, PRD, 81, 123530 (2010)

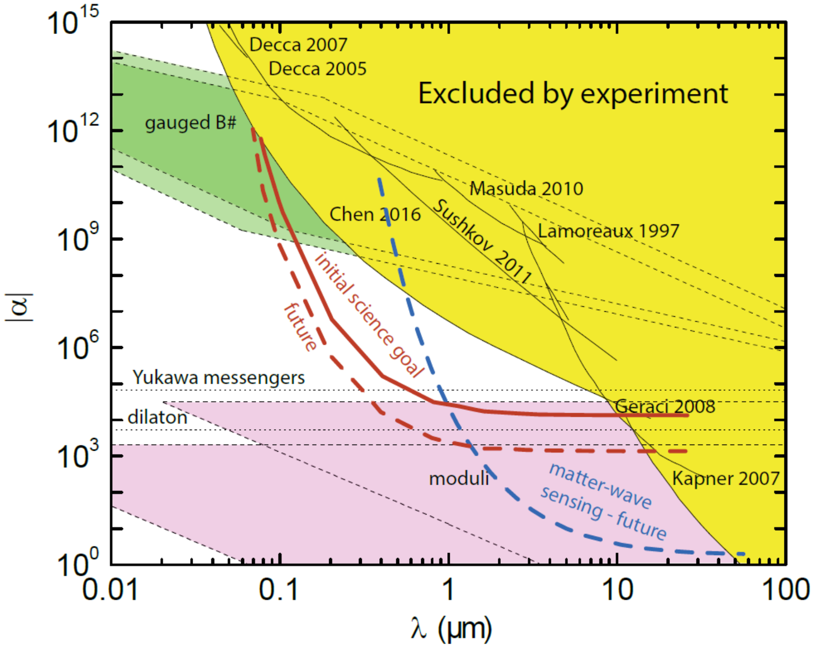
A. Arvanitaki *et al.* PRD 83, 044026 (2011)

Black hole superradiance



- String cosmology R. Brustein et. al. Phys. Lett. B, 361, 45 (1995)
- The unknown?

Projected reach- nanosphere matter-wave interferometer



A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).