Small Scale experiments for fundamental physics

ICTP Summer School on Particle Physics, June 12-15

A. Geraci, University of Nevada, Reno

Fundamental Physics

Energy Frontier

Large Hardon Collider, CERN

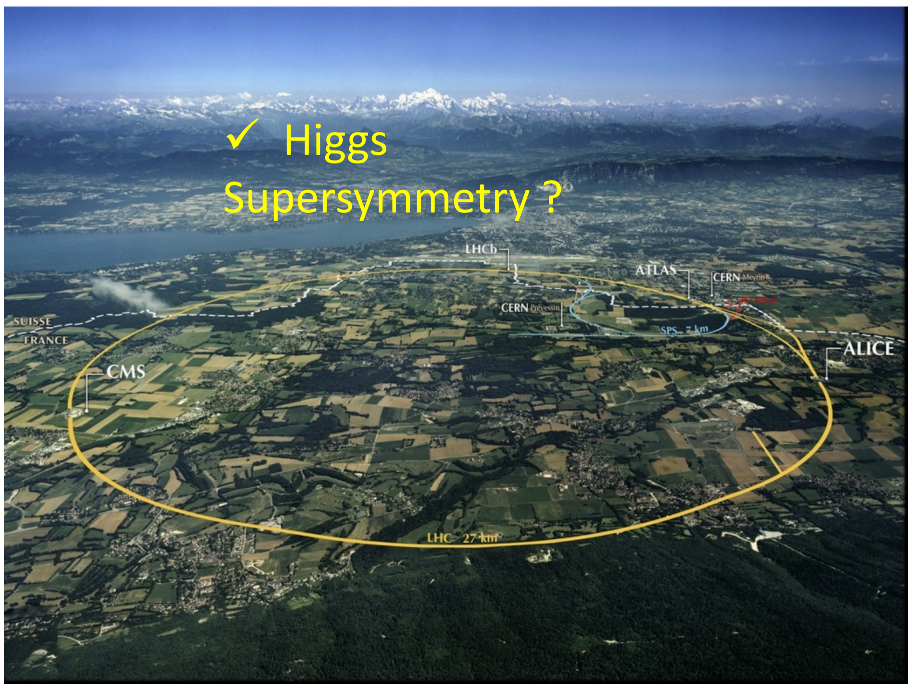
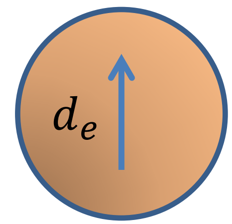


Photo by CERN

Precision Frontier

- EDM experiments: search for supersymmetry



n, e, nuclei

- Dark Matter: Axion Dark Matter Experiment (ADMX) uses μ-wave cavity

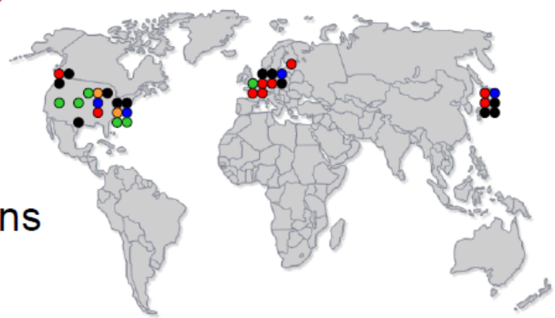
http://www.phys.washington.edu/groups/admx/home.html

EDM experiments

Searching for extra CP Violation

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons (~200)
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
- Molecules (~50)
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
- Atoms (~100)
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto
- Ions-Muons (~200)
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids (~10)
  - GGG@Indiana
  - ferroelectrics@Yale



Adapted from "EDM Searches", K. Kurch, PSI

- |de|<8.7×10−29 e cm (ThO Molecule, ACME)
- (199Hg) < 7.4x10-30e cm, Seattle
  → < 1.2x10-26 e cm for nedm (95%)
- n_{edm} (direct, trapped Ultrac-cold Neutrons) < 3.6x10-26 e cm (95%)

EDM measurements probing physics beyond energy scale of LHC

ACME Collaboration: Science 1248213 (2013)
Mercury experiment: Phys. Rev. Lett. 116, 161601 (2016)
Neutron EDM: Phys. Rev. D 92, 092003 (2015)

Tabletop fundamental physics

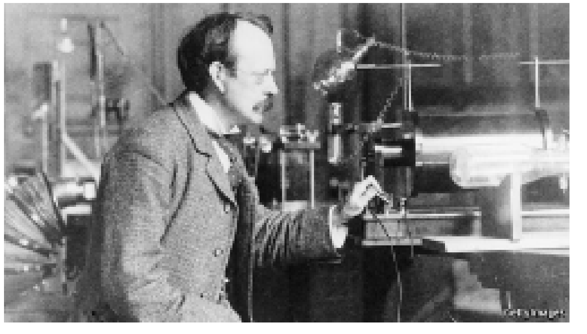
The Economist

Fundamental physics

Searching for particles on a benchtop

Making precise measurements of tiny forces

Jan 28th 2017



THE beams of protons that circulate around the 27km-circumference ring of the Large Hadron Collider (LHC), the world's biggest particle accelerator, carry as much kinetic energy as an American aircraft-carrier sailing at just under six knots. Andrew Geraci's equipment, on the other hand, comprises a glass bead 300 billionths of a metre across, held in a lattice of laser light inside an airless chamber. The power it consumes would run a few old-fashioned light bulbs. Like researchers at the LHC, Dr Geraci and his team at the University of Nevada, in Reno, hope to find things unexplained by established theories such as the Standard Model of particle physics and Newton's law of gravity. Whereas the LHC cost around SFr4.6bn ($5bn) to build, however, Dr Geraci's set-up cost a mere $300,000 and fits on a table about a metre wide and three long.

Goal of these lectures

- Focus on small-scale (i.e. non-accelerator, non-large scale DM detectors) experiments
- Give particle physics students sense of experimental techniques available, newly developing techniques, what they may be useful for
- Generate new ideas for experiments in the future?!

Syllabus

- Introduction
- New (scalar) forces
- Gravitational Waves and Ultralight Dark Matter
- New (spin-dependent) forces

(relation to axions, EDMS, Cosmic DM experiments)

Outline for Lectures

- Lecture 1 –

New (scalar) Forces

Background/Motivation

Gravitational experiments

Principles of Force sensing

New Techniques:

→ Optical levitation

→ Atomic-based sensors

→ Matter-wave interferometry

Outline for Lectures

- Lecture 2 –

-Gravitational waves

New Techniques:

→ Levitated sensors

→ Atom interferometry

-Ultralight scalar field dark matter

Outline for Lectures

- Lecture 3 –

  New (spin-dependent) forces

  Background

  Torsion balance tests

  Magnetometry

  New techniques: (ARIADNE)

  Relation to axions, EDM experiments, Cosmic DM experiments

Syllabus for Lectures

- Lecture 1 –

New (scalar) Forces

Background/Motivation

Gravitational experiments

Principles of Force sensing

New Techniques:

→ Optical levitation

→ Matter-wave interferometry

The Standard Model

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

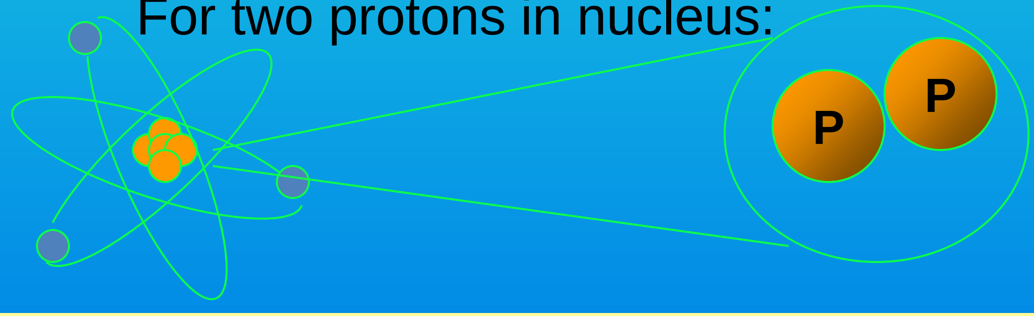
The Interactions:

Strong: Holds nucleons together

Electromagnetic: Acts between charged particles

Weak: Causes certain decays

Gravity: Attraction between masses



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

The Hierarchy Problem: Why is Gravity so small?

Solving the Hierarchy Problem

Quantum Gravity ~ 10^{19} GeV

Electro-weak ~ 10^{3} GeV

Supersymmetry?

Searching for it now at LHC!

Large Extra Dimensions (sub-mm)?

Gravity's mass (I.e. Planck) scale of ~ 10^{19} GeV

Is not a fundamental scale. Its magnitude comes from the size of the extra dimensions.

These effects may cause gravity to change below a characteristic scale $\lambda < 1$ mm :

- **Change its power law from 1/r**
- **Acquire a new exponential form**

Can we measure this?

1) Light Moduli

Moduli: Massless scalar particles generic in string theory
- describe the shape and size
 of (small OR large) extra dimensions

Moduli must become massive to avoid conflict with experiment

Mass may come from Supersymmetry breaking

Gravity-Mediated (high scale 10^{11} GeV)	Gauge Mediated (scale can be low ~30 TeV)
↓	↓
Moduli at EW scale	Moduli are light (mm^{-1}) →
	Observable signatures!

S.Dimopoulos, G.Giudice, Phys.Lett. B379 (1996)

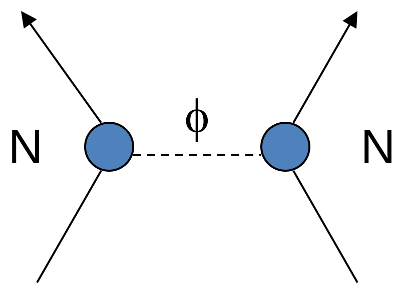
Standard Model Couplings

May depend on moduli

- Yukawa couplings → masses of quarks, leptons $\sim \lambda_{ij}(\phi)\bar{u}_i Q_j H_u$

- Gauge couplings → W,Z bosons, gluons $\sim \lambda_g \frac{\phi}{M} G^a_{\mu\nu} G^{\mu\nu a}$

e.g. 2 nucleons can exchange gluon modulus:



$$\longrightarrow \quad V = -\frac{G_N m_1 m_2}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$

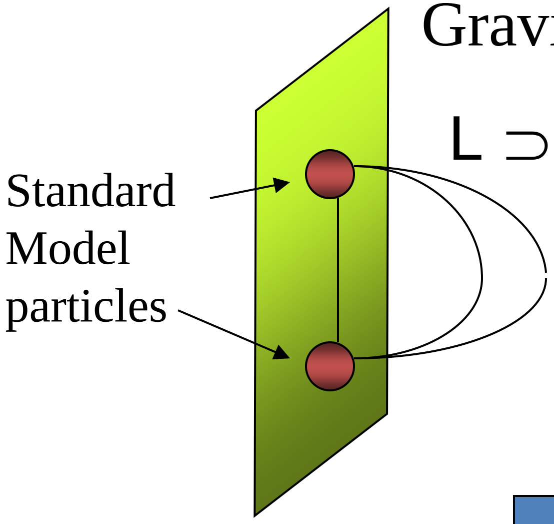
range $$\lambda(\mathrm{mm}) \approx 0.8 \ \frac{(100\,\mathrm{TeV})^2}{F}\left(\frac{M\ \lambda_g^{-1}}{5\times 10^{17}\ \mathrm{GeV}}\right)$$

Strength relative to gravity $$\alpha \ \propto \left(\frac{5\times 10^{17}\ \mathrm{GeV}}{M}\right)^2 \lambda_g^2$$

2) Large Extra Dimensions

N. Arkani-Hamed, S. Dimopoulos, G.Dvali, Phys.Lett. B429 (1998)

Standard Model fields confined to a "brane", except gravity



Gravity is "diluted" by the volume of extra space

$$L \supset \int d^4x d^n y \, M_*^{2+n} \sqrt{G} R \longrightarrow \int d^4 x \, M_{Pl}^2 \sqrt{G} R$$

$$V_n M_*^{2+n} = M_{Pl}^2$$

Now M* can be closer to weak scale at ~TeV

No more fine-tuning problem

For $V_n \sim L^n$, taking n=2, L can be 1mm for $M_* \sim$ TeV

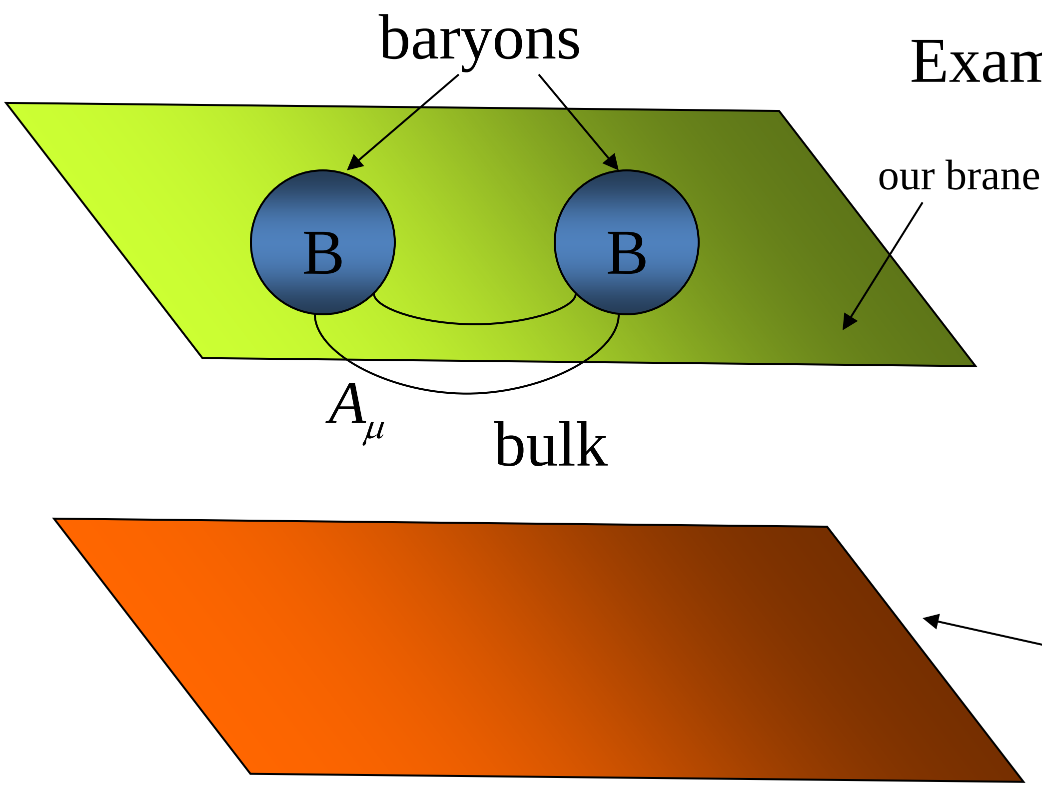
--Newton's law changed below radius of compactification

$$F(r) = \frac{G^{(4)} m_1 m_2}{r^2} \longrightarrow \frac{G^{(4+n)} m_1 m_2}{r^{2+n}}$$

Gauge particles in the bulk

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys.Rev. **D59** (1999)

1) can mediate forces 10^6 x gravity
2) range of zero mode not limited by the radius of compact dimensions (so n>2 still accessible to tabletop)



Example – gauged baryon #

$$\frac{F_{\text{gauge}}}{F_{\text{gravity}}} = \frac{g_4^{\;2}}{G_N m^2_{\text{nucleon}}}$$

$$\approx \frac{M_*^2}{m^2_{\text{nucleon}}} \approx 10^6 - 10^8$$

$$m_{A_\mu} \approx g_4 M_* \approx (\text{mm}^{-1})$$

other brane --
gauge symmetry broken spontaneously
by some “Higgs” field with vev ~ M*

Scalars in Bulk

"Yukawa Messengers"

N. Arkani-Hamed, S. Dimopoulos, PRD 65, 052003 (2002)

- Also can get sub-mm range from SUSY breaking
- Coupling much stronger than moduli, and independent fundamental scale M*

effective coupling to the zero mode $\rho\, ff\chi_0$ $\rho = \frac{v}{M_{\mathrm{Pl}}} \approx 10^{-16}$

but compare to gravity:

$$\frac{\rho^2}{G_N m_{\mathrm{nucleon}}^2} \approx 10^6$$

- quite strong
- independent of "n"
- Independent of M*

Both vectors and scalars in the bulk can also produce a Yukawa-potential:

$$V = -\frac{G_N m_1 m_2}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$

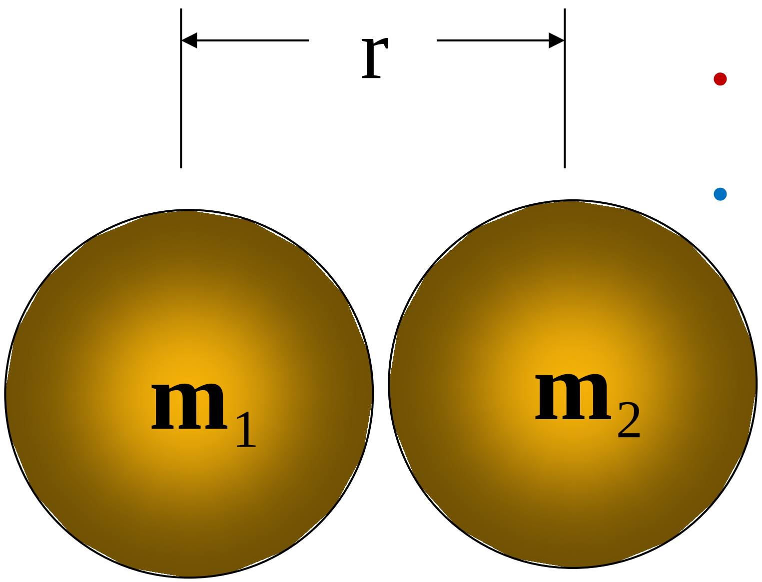
$\alpha > 0$ attractive (scalar)

$\alpha < 0$ repulsive (vector)

Testing gravity at short range

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

Exotic particles (new physics)

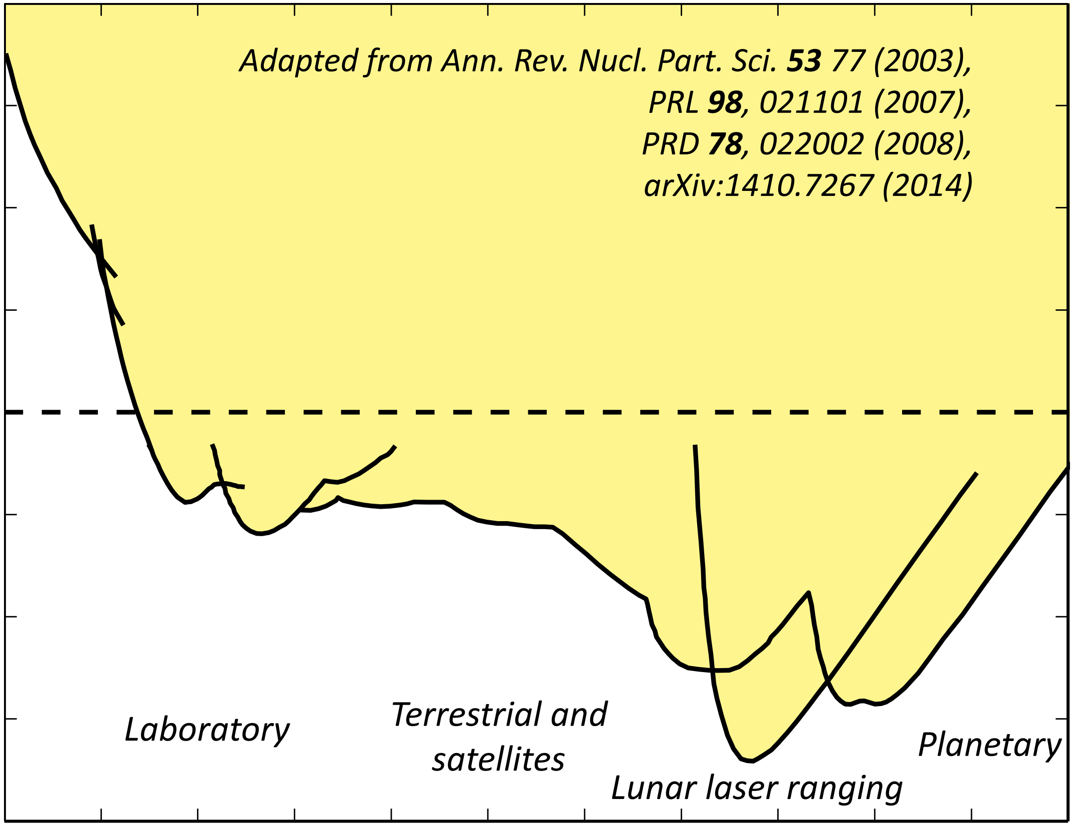


$\lambda < 1$ mm

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

Landscape for ISL corrections

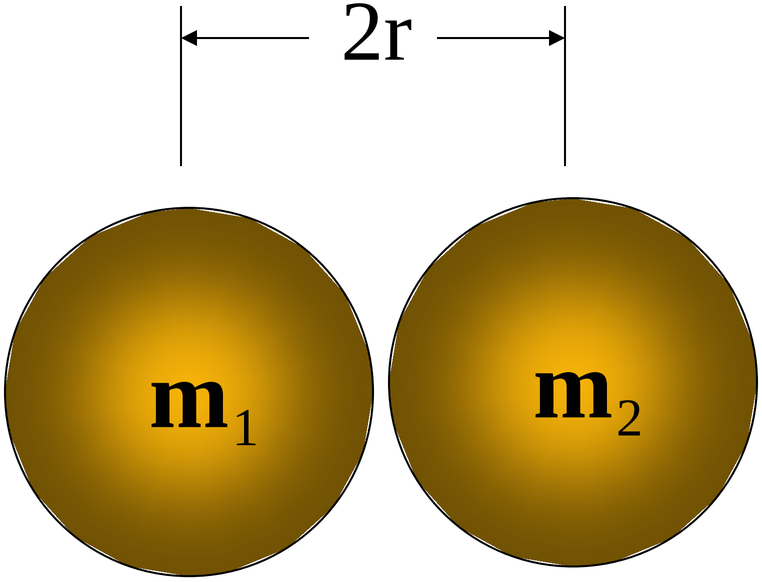
$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$



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:

r~10 μm ;	$F_N \sim 10^{-21} N$

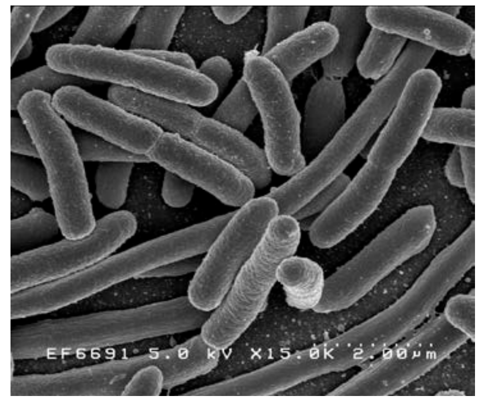
Small forces

70 kg ~ 700 N

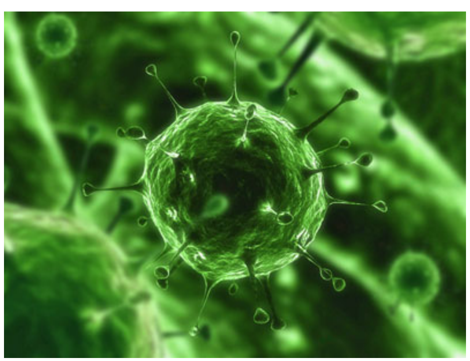
- Bathroom scales measure 10^{-1} *N*

Dust mite 10^{-7} N

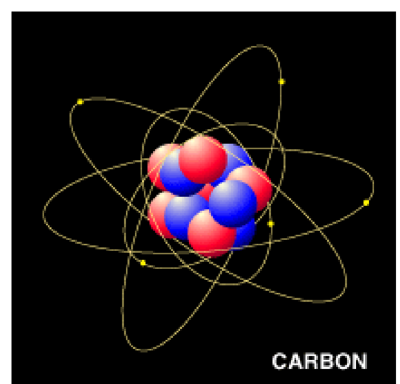
E. coli 10^{-15} N



Virus 10^{-19} N



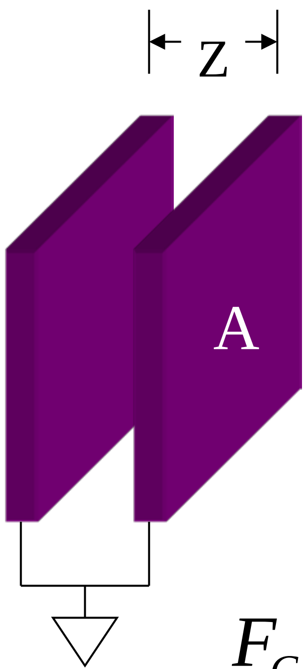
Carbon atom 10^{-25} N

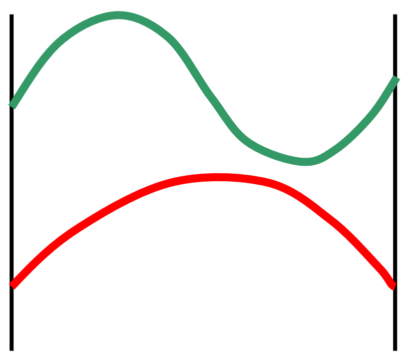


- AFM measures 10^{-11} *N*

Experimental challenge:
Electromagnetic Background forces

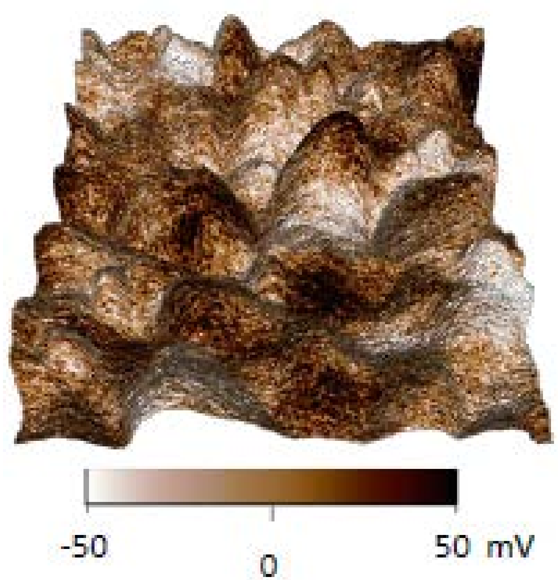
Casimir effect (1948):





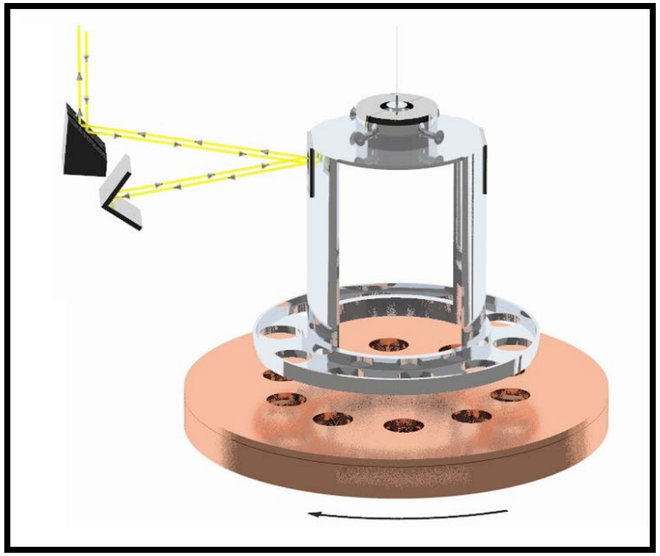
$$F_C(z) = \frac{\pi^2}{240}\frac{\hbar c}{z^4}A$$

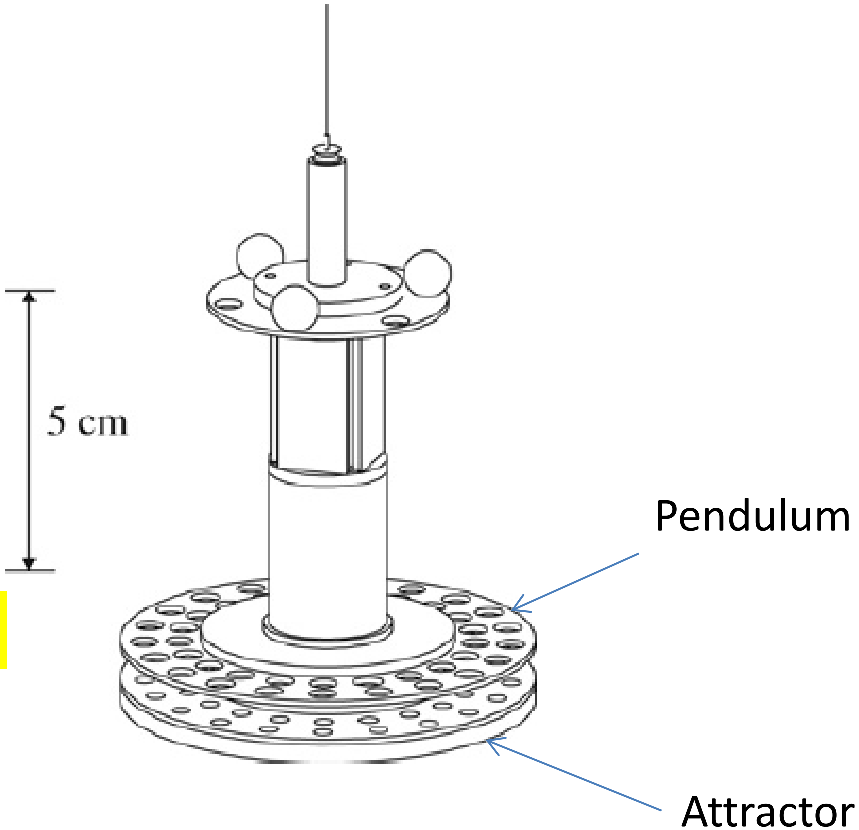
Electrostatic Patch Potentials:



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

UW Torsion Balance Experiments





Best yukawa constraints at ~ 10 μm – 5 mm range

1x Gravity tested at ~50 μm

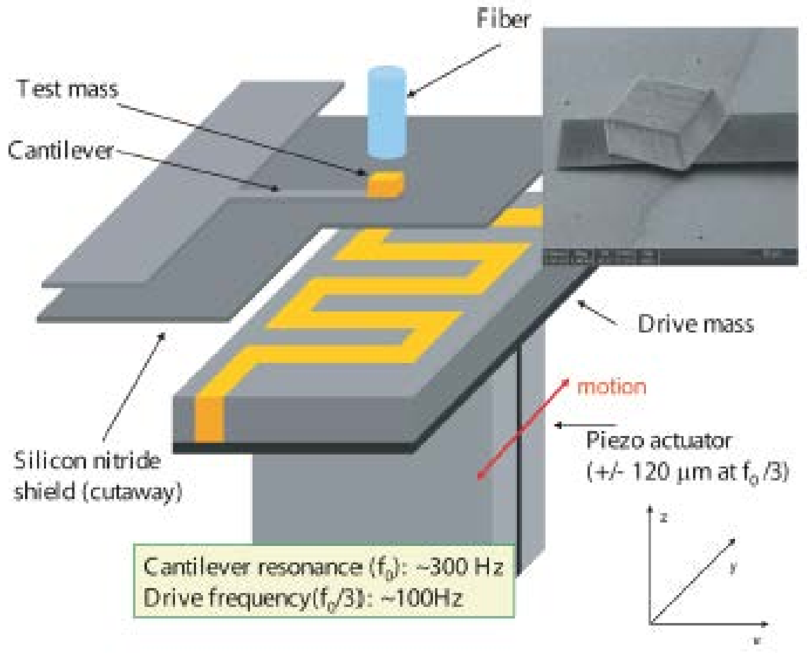
Kapner et. al., PRL 98, 021101 (2007)
C.D. Hoyle et. al., PRL 86, 1418 (2001)

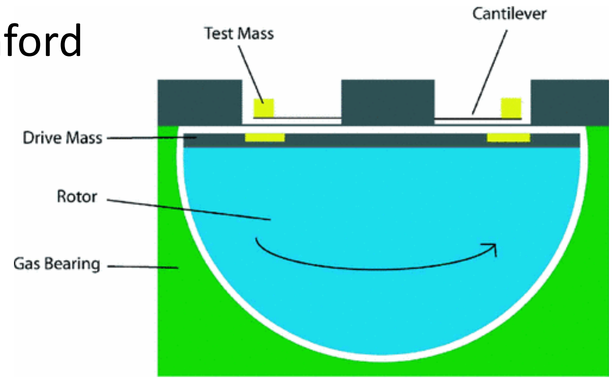
Review: E.G. Adelberger et. al. Progress in Particle and Nuclear Physics 62, 102 (2009)

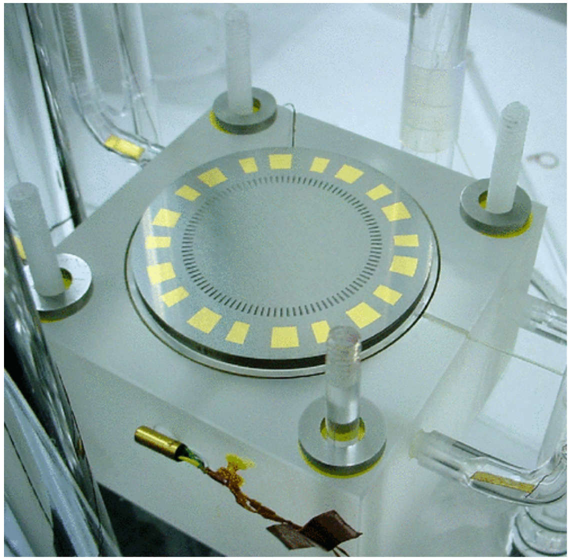
Future: Cryogenic torsion balance experiments with improved sensitivity!

Micro- and nano- resonators

Kapitulnik group, Stanford







A.A. Geraci, S.J. Smullin, D. M. Weld, J. Chiaverini, and A. Kapitulnik, *Phys. Rev. D 78*, 022002 (2008).

Best yukawa constraints at ~ 10 um range:

D. M. Weld, J. Xia, B.Cabrera, and A. Kapitulnik Phys. Rev. D **77**, 062006 (2008)

Next generation apparatus
~10-100 x sensitivity

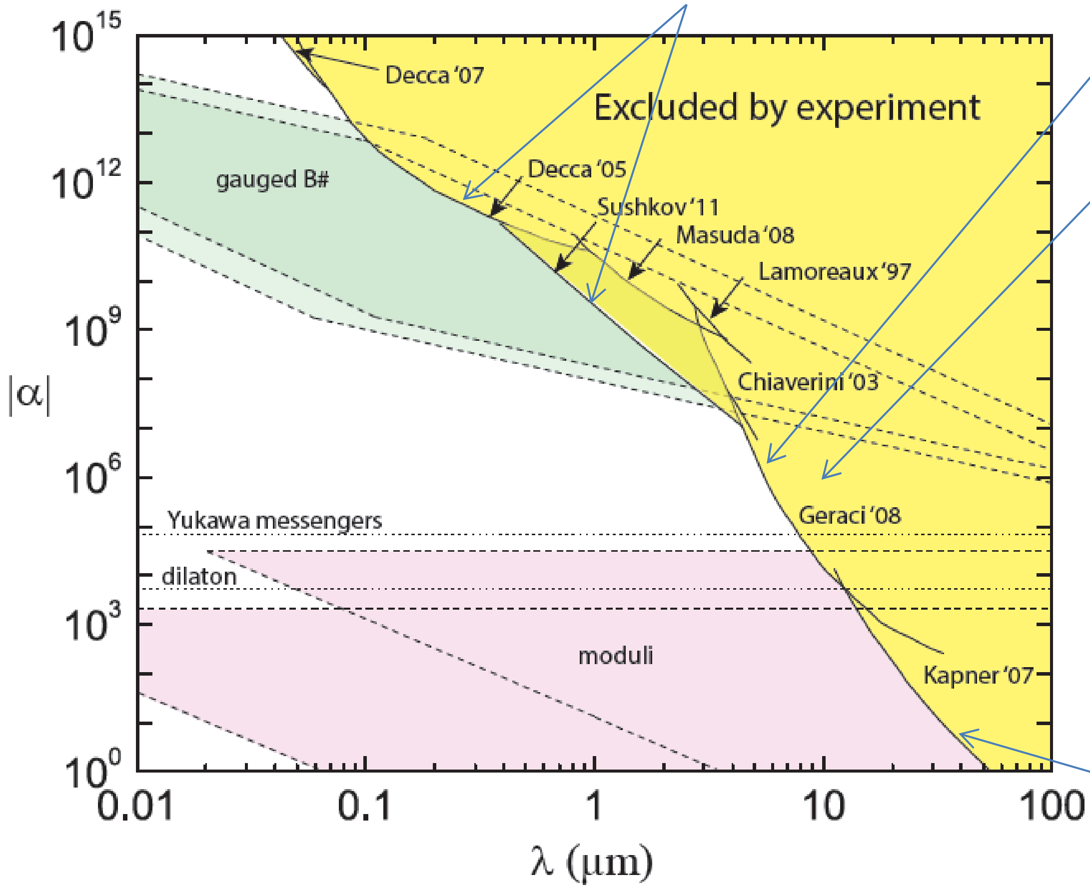
Yukawa phase space

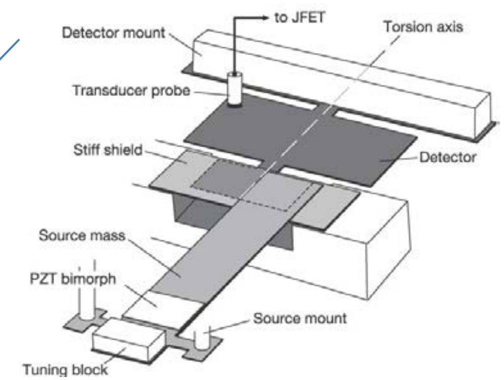
$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$

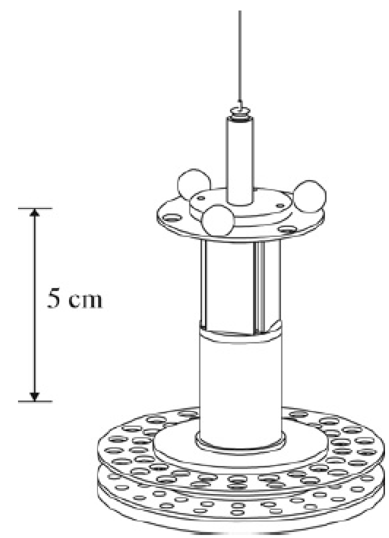
Casimir Measurements

Cantilevers (Stanford)

Torsion oscillators (Colorado,IU)







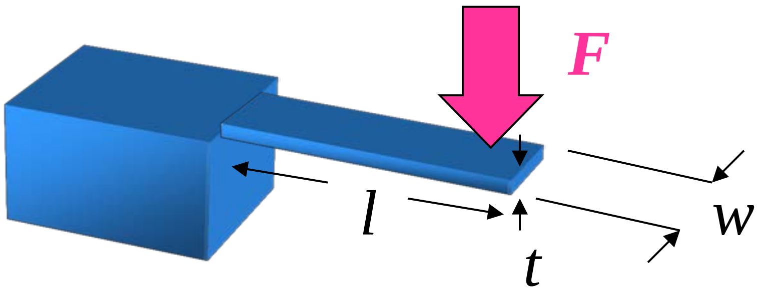
Torsion balance experiments (U Washington)

Resonant force detection

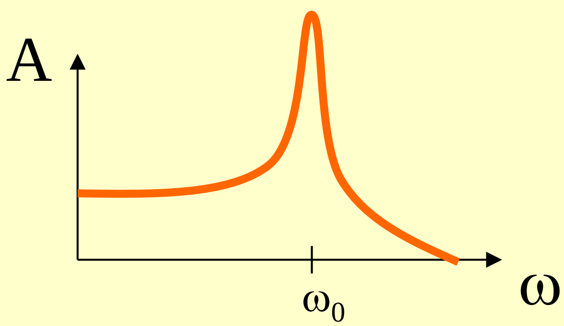
- Cantilever is like a spring:

$$F = -Kx$$

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



Amplitude:

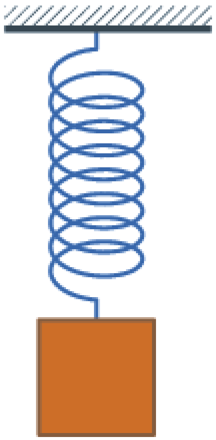


$$A_{(\omega=0)} = \frac{F}{k}$$ Constant force

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

Q can be very large >100,000

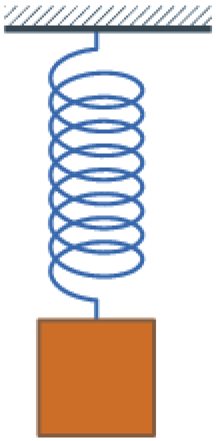
Dissipation



$$E = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2$$

Energy stored in oscillation

Dissipation



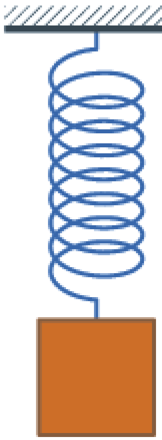
$$E = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2$$

Energy stored in oscillation

$$Q \equiv 2\pi \frac{E}{\delta E}$$

Energy stored in oscillation / energy dissipated in 1 cycle

Dissipation



$$E = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2$$

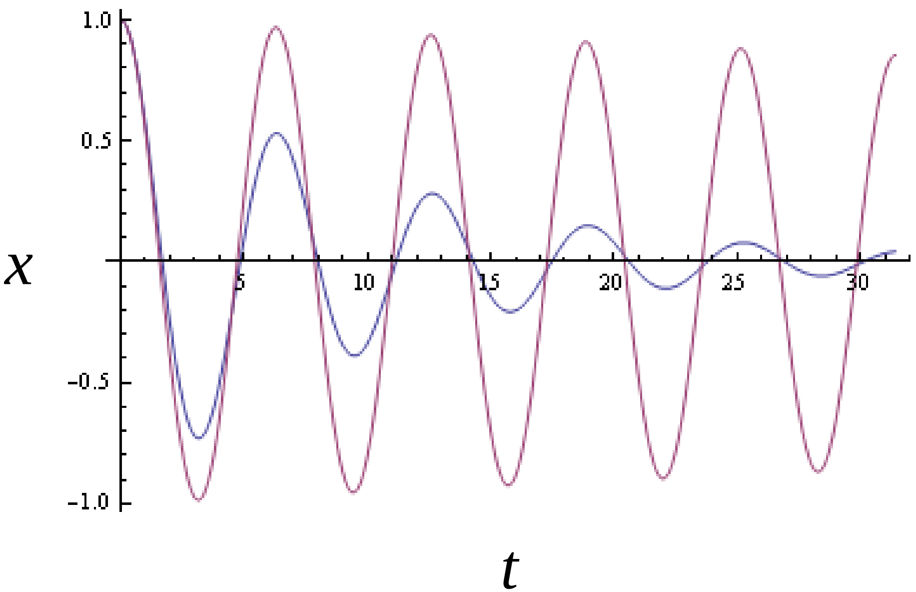
Energy stored in oscillation

$$Q \equiv 2\pi \frac{E}{\delta E}$$

Energy stored in oscillation / energy dissipated in 1 cycle

$$m\ddot{x} = -kx - \gamma\dot{x}$$

$$Q \cong \frac{\sqrt{mk}}{\gamma}$$



Plays crucial role in force detection

Cantilever response

$$\ddot{x} + \omega_0^2 x + \gamma\dot{x} = \frac{F(t)}{m}$$

For a harmonic driving force: $F(t) = f_0 e^{-i\omega t}$

$$-\omega^2 \ddot{x} + \omega_0^2 x - i\gamma\omega x = \frac{f_0}{m}$$

Cantilever response

$$\ddot{x}+\omega_0^2 x+\gamma\dot{x}=\frac{F(t)}{m}$$

For a harmonic driving force: $F(t)=f_0 e^{-i\omega t}$

$$-\omega^2\ddot{x}+\omega_0^2 x-i\gamma\omega x=\frac{f_0}{m}$$

Susceptibility:

$$\chi(\omega)=\frac{x(\omega)}{f(\omega)}=\frac{1}{m}\left(\frac{1}{-\omega^2+\omega_0^2-i\omega\gamma}\right)$$

$$\text{DC}:\omega\rightarrow 0, x=\frac{f_0}{k}$$

$$\lim_{\omega\rightarrow\infty}\chi(\omega)=-\frac{1}{m\omega^2}$$

Cantilever response

$$\chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m}\left(\frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma}\right)$$

Steady state *x(t)* in presence of driving force

$$f_0 \cos(\omega t)$$

$$\begin{aligned} x(t) &= \mathrm{Re}\left[\chi(\omega) f_0 e^{-i\omega t}\right] \\ &= \mathrm{Re}[\left|\chi(\omega)\right| f_0 e^{-i\omega t} e^{i\phi}] \\ &= f_0 \left|\chi(\omega)\right| \cos(\omega t - \phi(\omega)) \end{aligned}$$

Cantilever response

$$\chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m}\left(\frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma}\right)$$

Steady state *x(t)* in presence of driving force

$$f_0 \cos(\omega t)$$

$$\begin{aligned} x(t) &= \mathrm{Re}\left[\chi(\omega) f_0 e^{-i\omega t}\right] \\ &= \mathrm{Re}[|\chi(\omega)| f_0 e^{-i\omega t} e^{i\phi}] \\ &= f_0 |\chi(\omega)| \cos(\omega t - \phi(\omega)) \end{aligned}$$

$$|\chi(\omega)| = \frac{1}{m}\frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \omega^2\gamma^2}}$$

$$\tan\phi(\omega) = \frac{\omega\gamma}{\omega_0^2 - \omega^2}$$

Cantilever response

$$\chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m}\left(\frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma}\right)$$

Steady state *x(t)* in presence of driving force

$$f_0 \cos(\omega t)$$

$$x(t) = \mathrm{Re}\left[\chi(\omega) f_0 e^{-i\omega t}\right]$$

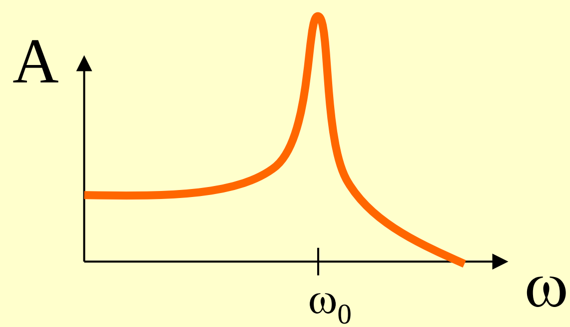
$$= \mathrm{Re}[|\chi(\omega)| f_0 e^{-i\omega t} e^{i\phi}]$$

$$= f_0 |\chi(\omega)| \cos(\omega t - \phi(\omega))$$

$$|\chi(\omega)| = \frac{1}{m}\frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \omega^2\gamma^2}}$$

$$\tan\phi(\omega) = \frac{\omega\gamma}{\omega_0^2 - \omega^2}$$

Amplitude:



$$A(f) = A_{dc}\frac{f_0^{\,2}}{\sqrt{(f_0^{\,2} - f^{\,2})^2 + \frac{f_0^{\,2} f^{\,2}}{Q^2}}}$$

Dissipation

$$\frac{dW}{dt} = F(t)\dot{x}(t)$$

Steady-state dissipated power:

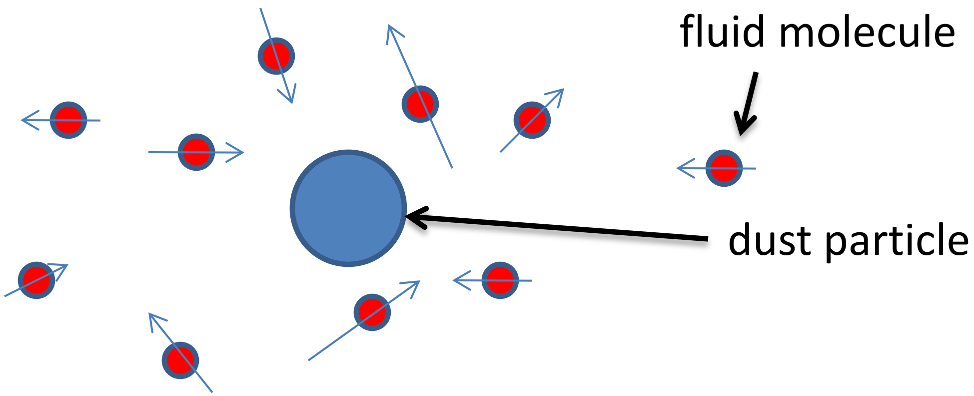
$$P = \frac{1}{2}\omega\, f_0^2 \left|\chi(\omega)\right| \sin\phi(\omega) = \frac{1}{2}\, f_0^2 \omega\, \mathrm{Im}[\chi(\omega)]$$

$$\mathrm{Im}[\chi(\omega)] = \frac{1}{m} \frac{\omega\gamma}{(\omega^2 - \omega_0^2)^2 + (\omega\gamma)^2}$$

On resonance: $$P = \frac{1}{2}\, f_0^2 \frac{1}{m\gamma}$$

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

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

Fundamental limitation: thermal noise

- White noise background due to finite T of oscillator

$$S_X(\omega) = |\chi(\omega)|^2 S_F$$

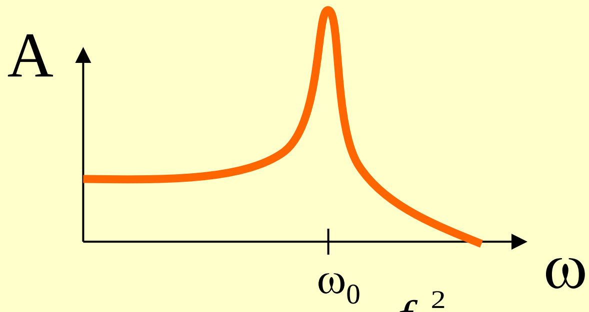
Fundamental limitation: thermal noise

- White noise background due to finite T of oscillator

$$S_X(\omega) = \left|\chi(\omega)\right|^2 S_F$$

$$\left\langle x^2 \right\rangle = \frac{1}{k^2}\int_0^\infty S_F \left(\frac{A(f)}{A_{dc}}\right)^2 df$$

$$S_F^{1/2} = \left(\frac{2}{\pi Q f_0}\right)^{1/2} k x_{rms}$$



$$A(f) = A_{dc}\frac{f_0^{\,2}}{\sqrt{(f_0^{\,2} - f^{\,2})^2 + \frac{f_0^{\,2} f^{\,2}}{Q^2}}}$$

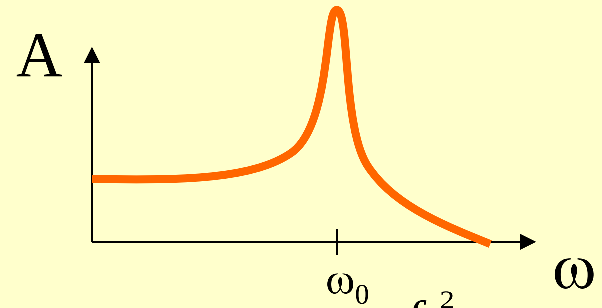
Fundamental limitation: thermal noise

- White noise background due to finite T of oscillator

$$S_X(\omega) = |\chi(\omega)|^2 S_F$$

$$\langle x^2 \rangle = \frac{1}{k^2} \int_0^\infty S_F \left(\frac{A(f)}{A_{dc}} \right)^2 df$$

$$S_F^{1/2} = \left(\frac{2}{\pi Q f_0} \right)^{1/2} k x_{rms}$$



$$A(f) = A_{dc} \frac{f_0^2}{\sqrt{(f_0^2 - f^2)^2 + \frac{f_0^2 f^2}{Q^2}}}$$

$$\frac{1}{2} k \langle x^2 \rangle = \frac{1}{2} k_B T \Rightarrow S_F^{1/2} = \left(\frac{4 k k_B T}{Q \omega_0} \right)^{1/2}$$

$$F_{min} = S_F^{1/2} B^{1/2} \Rightarrow F_{\min} = \left(\frac{4 k k_B T b}{Q \omega_0} \right)^{1/2}$$

Fluctuation-Dissipation theorem

- In equilibrium, thermal fluctuations are related to dissipation:

$$S_F^{1/2} = \left(\frac{4kk_B T}{Q\omega_0} \right)^{1/2}$$

$$S_F = 4k_B T\, m\Gamma$$

$$\Gamma = \omega_0 / Q$$

e.g. Johnson noise in a resistor: $S_V = 4k_B T\, R$

Fluctuation-Dissipation theorem

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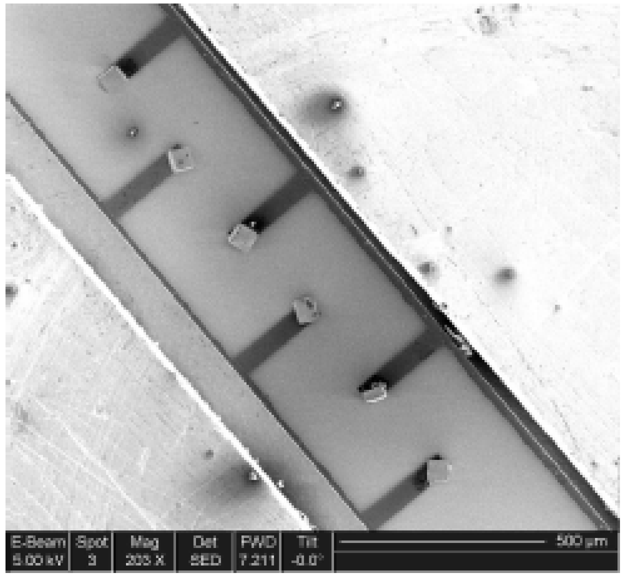
$$\Gamma = \omega_0 / Q$$

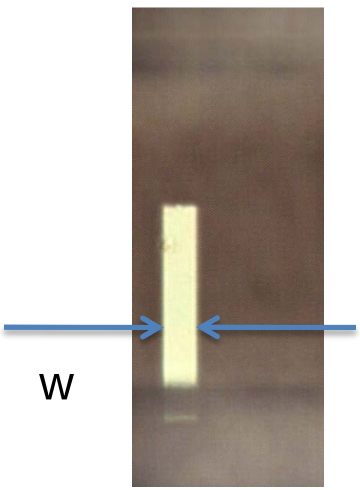
e.g. Johnson noise in a resistor: $S_V = 4 k_B T \, R$

FDT: $S_X = 2k_B T \frac{\mathrm{Im}[\chi(\omega)]}{\omega}$ $\quad \mathrm{Im}[\chi(\omega)] = \frac{1}{m} \frac{\omega\gamma}{(\omega^2 - \omega_0^2)^2 + (\omega\gamma)^2}$

$$S_X(\omega) = \left|\chi(\omega)\right|^2 S_F$$

Fundamental limitation: thermal noise





w= 50 µm
l= 250 µm
t=0.3 µm

$$F_{\min} = \left(\frac{4kk_B Tb}{Q\omega_0} \right)^{1/2}$$

$$F_{\min} = (k_B TB)^{1/2} (E\rho)^{1/4} \left(\frac{wt^2}{lQ} \right)^{1/2}$$

To improve sensitivity:

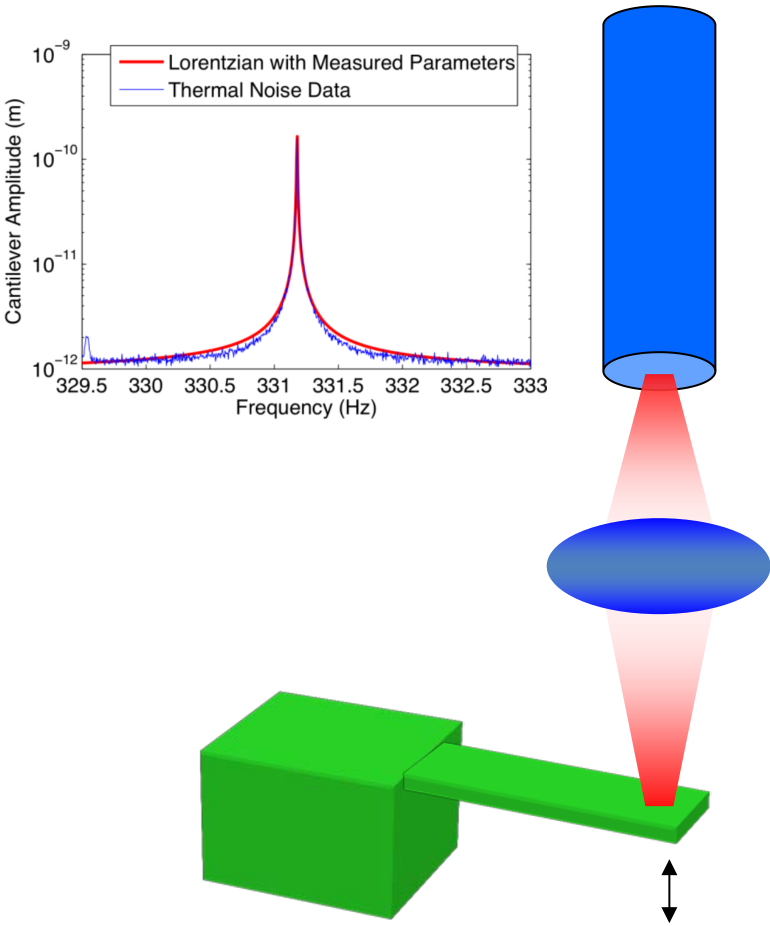
- Make cantilever small
- Lower temperature
- Raise the quality factor

Silicon Cantilevers:

F_{min} ~ 10 x 10^{-18} N/√Hz at 4 K at $Q=10^5$

Displacement detection

Cantilever is only moving few angstroms



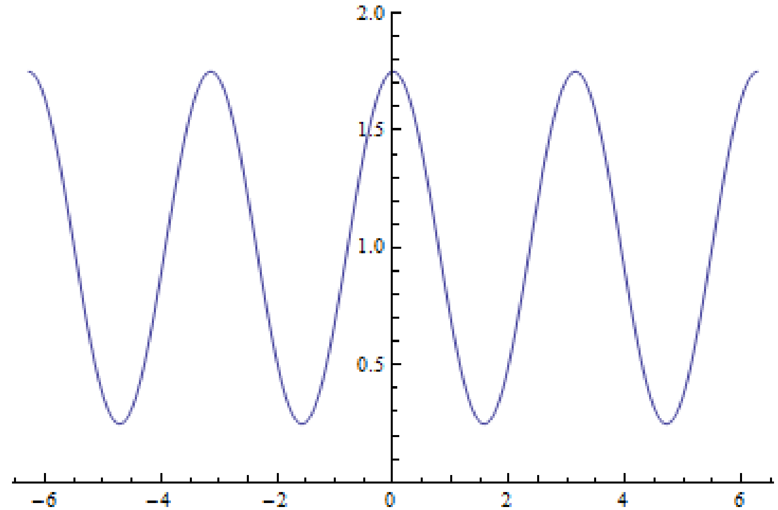
Fiber

Lens

Cantilever

Interferometer signal

V

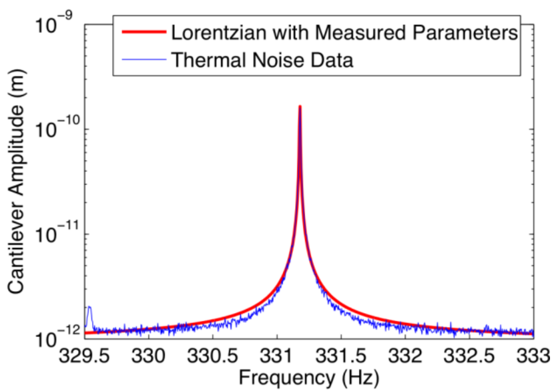


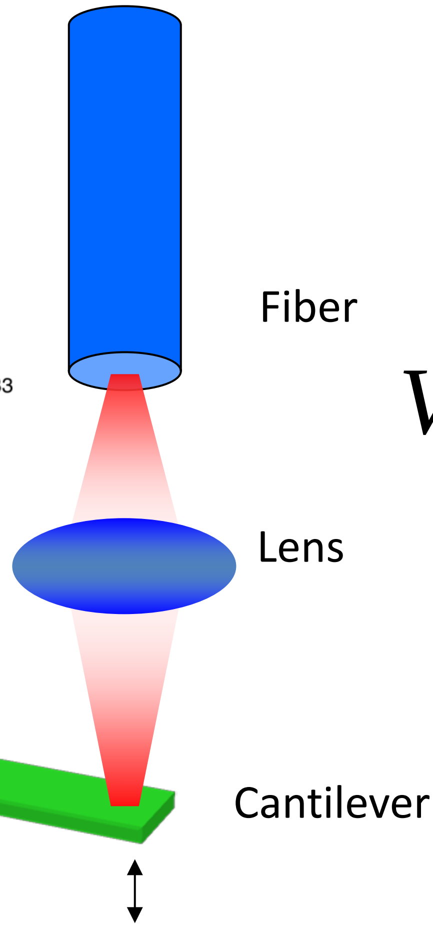
$$\frac{2\pi d}{\lambda}$$

Can detect 10^{-12} m/Hz$^{1/2}$ (μW)

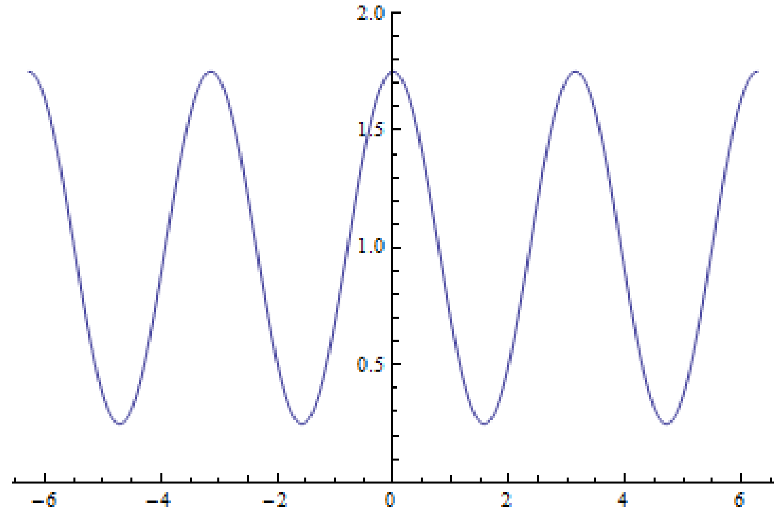
Displacement detection

Cantilever is only moving few angstroms





Interferometer signal



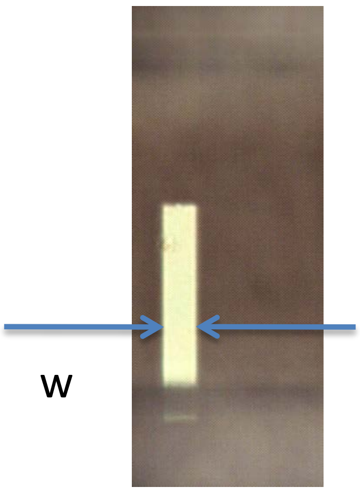
V

$$\frac{2\pi d}{\lambda}$$

Can detect 10^{-12} m/Hz$^{1/2}$ (μW)

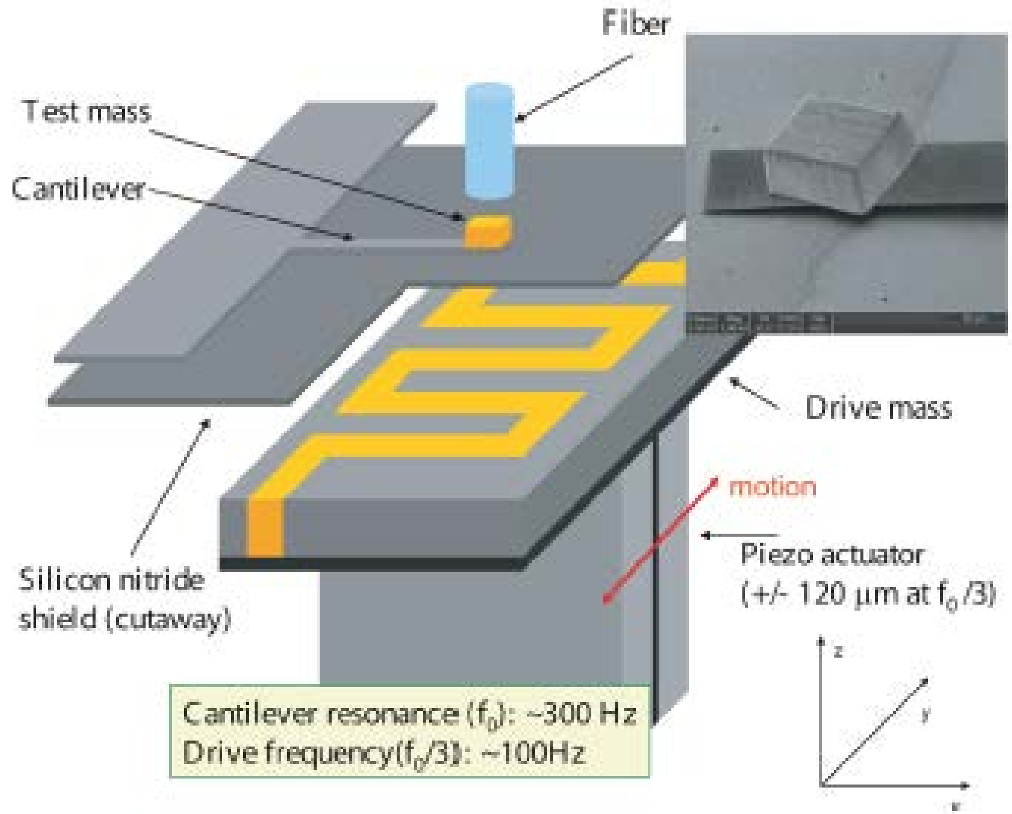
Other methods: capacitance, QPD, high finesse optical cavity

Stanford cantilever experiment



w= 50 μm
l= 250 μm
t=0.3 μm

Silicon Cantilevers:
F_{min} ~ *10* x 10^{-18} N/√Hz
at 4 K at Q=10^5

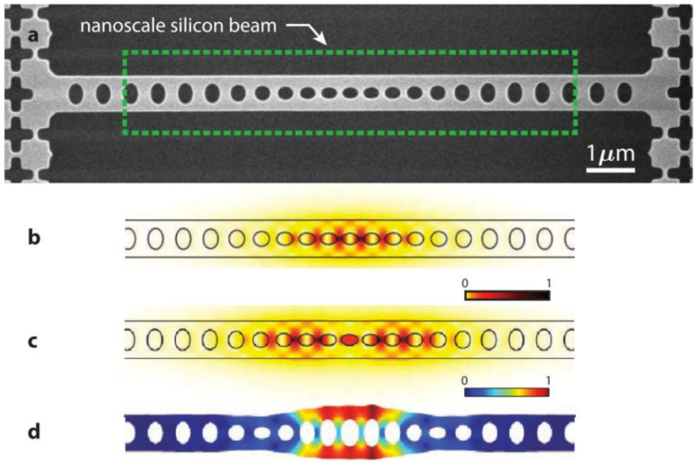


Best Yukawa constraints at ~ 10 um range:

A.A. Geraci, S.J. Smullin, D. M. Weld, J. Chiaverini, and A. Kapitulnik, *Phys. Rev. D 78*, 022002 (2008).

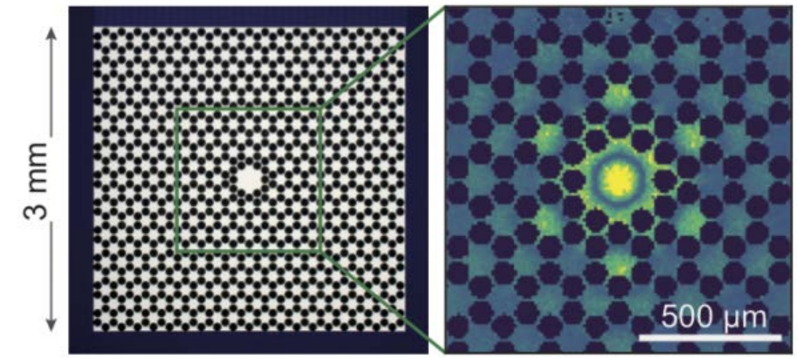
Advances in cryogenic nano-oscillators

Significantly improved sensitivities (higher frequencies)

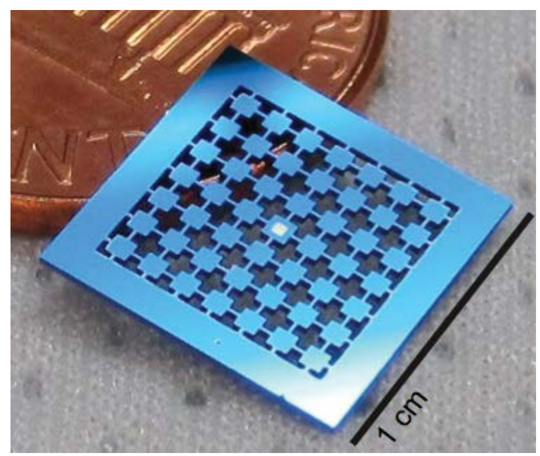


Painter group, Caltech

Si:
freq=5 GHz
Q_m=5X10^{10}
mass =136 fg
T=60 mK



Schliesser group, Copenhagen



Regal group, JILA

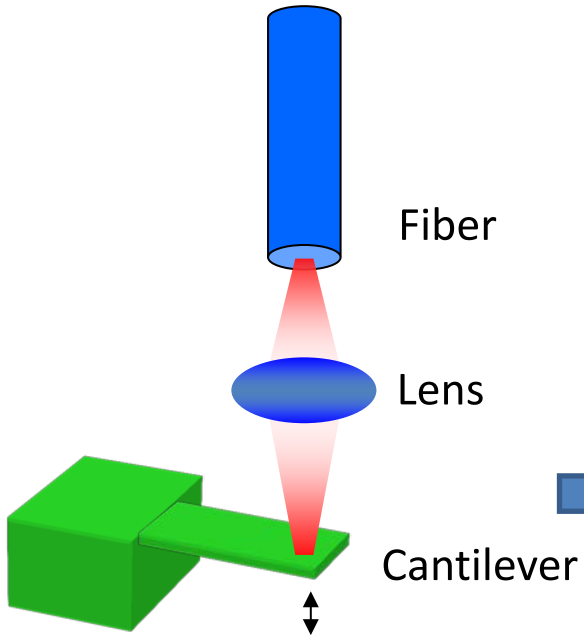
SiN:
freq=1.5 MHz
Q_m=2X10^8
mass=10 ng
T=30 mK

Also nanotubes:

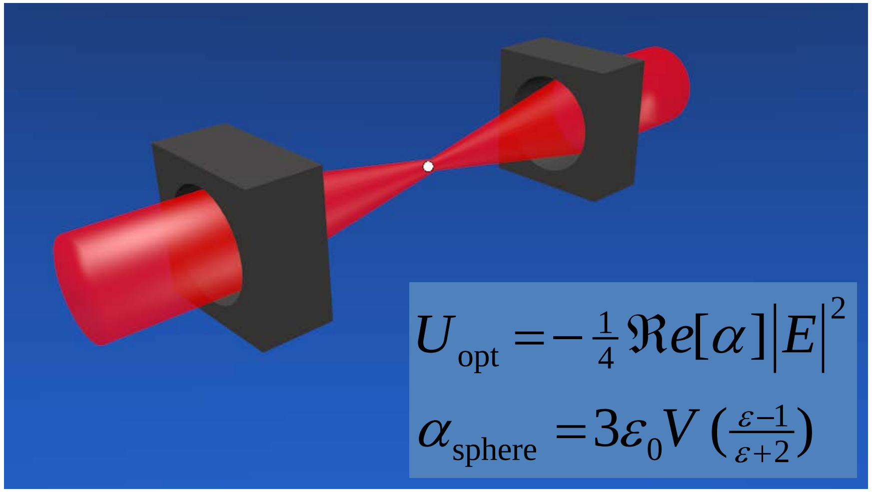
J. Moser, J. Guttinger, A. Eichler, M. J. Esplandiu, D. E. Liu, M. I. Dykman, and A. Bachtold, Nat. Nanotechnol. **8**, 493 (2013).

$\sim 10\ \text{zN}/\sqrt{\text{Hz}}$

Improving the sensitivity



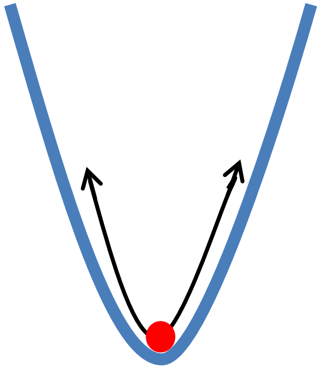
Levitate the force sensor!



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

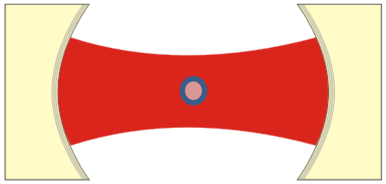
$$\alpha_{sphere} = 3\varepsilon_0 V\left(\tfrac{\varepsilon-1}{\varepsilon+2}\right)$$

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



CM motion decoupled from environment – no clamping, materials losses

Optically-levitated sensors



Decoupled from environment – no clamping, materials losses!

Pressure-limited damping

$$\frac{dp}{dt} = -\gamma_g \frac{p}{2} \qquad \frac{\gamma_g}{2} = \left(\frac{8}{\pi}\right)\frac{P}{\bar{v} r \rho}$$

P=10^{-10} Torr, r=0.2 μm, $\omega/2\pi$=100 kHz, Q=10^{12} !

$$F_{\min} = \left(\frac{4 k k_B T b}{Q \omega_0}\right)^{1/2}$$

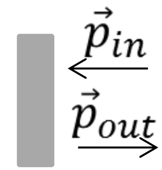
Q ~ 10^{12}
T ~ 300
$\omega_0/2\pi$ ~ 10^5
m ~ $10^{-(14-17)}$ kg

→ F ~ 10^{-21} N/Hz$^{1/2}$

Optical Trapping

Optical forces on objects due to radiation pressure

Light incident on a totally reflecting mirror:



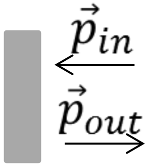
$$F_{rad} = 2\frac{P}{c}$$

$$F_{rad} = \frac{2 \cdot 1W}{3 \cdot 10^8 m/s} = 6.67nN$$

Optical Trapping

Optical forces on objects due to radiation pressure

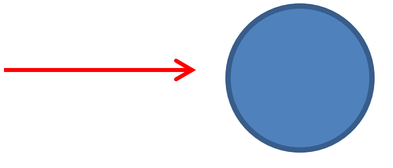
Light incident on a totally reflecting mirror:



$$F_{rad} = 2\frac{IA}{c}$$

$$F_{rad} = \frac{2 \cdot 1W}{3 \cdot 10^8 m/s} = 6.67nN$$

Dielectric sphere

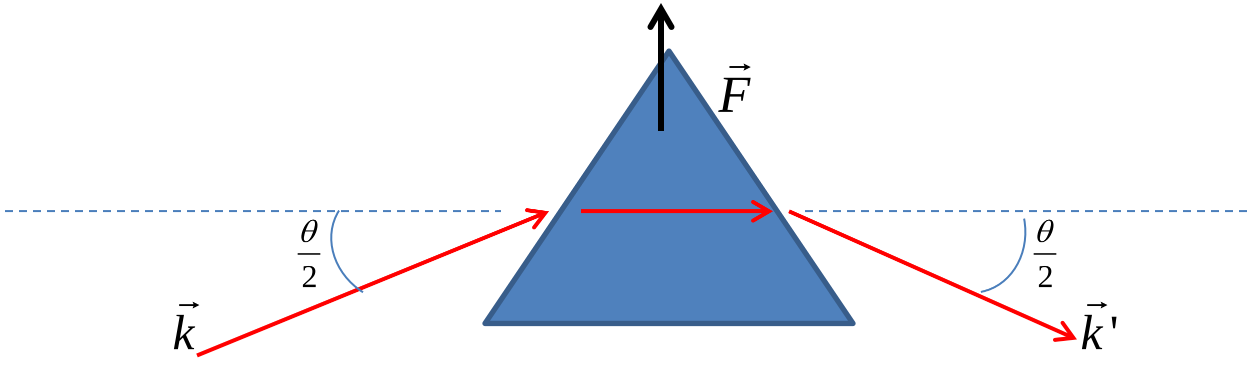


Scattering Force

Imparted by traveling wave

$$F_{scat} = \hbar k R_{scat}$$

Optical Trapping



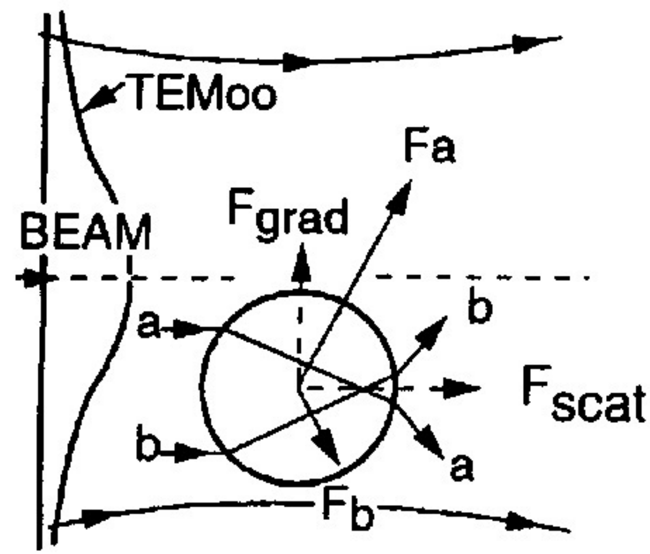
$$F = \frac{IA}{c} 2\sin(\frac{\theta}{2})$$

- Force arising from refraction of light

Optical Trapping

Ray Optics Approximation
(R>>λ)

- When photons strike bead, they are refracted and momentum changes
  - Forces
    - Scattering force occurs along the axial direction
      - Axial component of F_a+F_b
    - Gradient force is along direction of increasing intensity



Ashkin

Rayleigh Approximation (R<<λ)

- Glass bead treated as induced dipole
- Scattering force
  - Electric field oscillates in time
  - Sphere acts as oscillating electric dipole
  - Radiates secondary (scattering) waves in all directions
  - Changes magnitude and direction of energy flux of electromagnetic field
  - Field due to momentum changes in electromagnetic field due to scattering by dipole

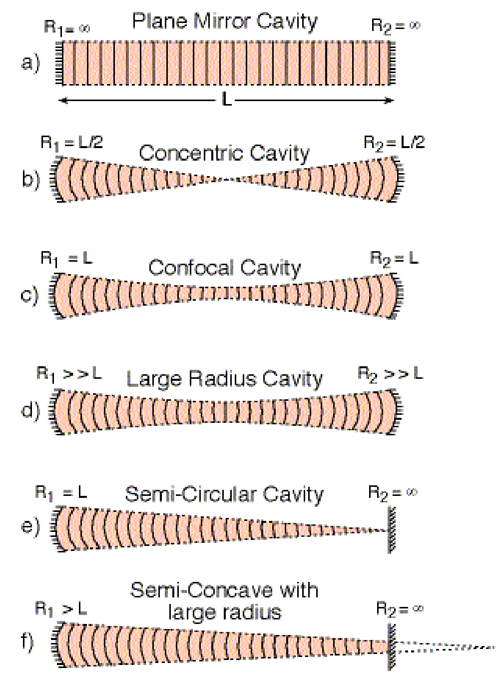
$$F_{Scat}(\vec{r}) = \left(\frac{n}{c}\right) C_{scat} I(\vec{r})\hat{z} = \frac{128\pi^5 R^6}{3c\lambda_0^4}\left(\frac{m^2-1}{m^2+2}\right)^2 n_{md}^5 I(\vec{r})\hat{z}$$

- Gradient Force

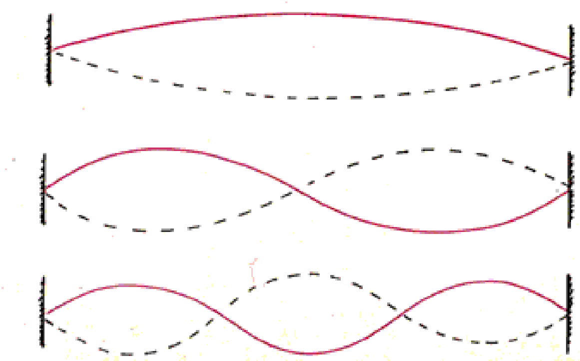
$$\vec{F}_{grad}(\vec{r},t) = \vec{\nabla}[\vec{p}(\vec{r},t) \bullet \vec{E}(\vec{r},t)] = \frac{2\pi n_{md} R^3}{c}\left(\frac{m^2-1}{m^2+2}\right)^2 \vec{\nabla} I(\vec{r})$$

Optical Cavity

- An arrangement of mirrors that forms a standing wave of light waves.
- Cavity Resonance Condition
  - Length between mirrors must be an integer multiple of one half the laser wavelength.
  - $L = m\left(\frac{\lambda}{2}\right)$
  - Standing wave

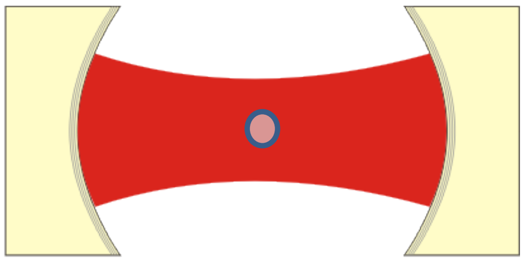


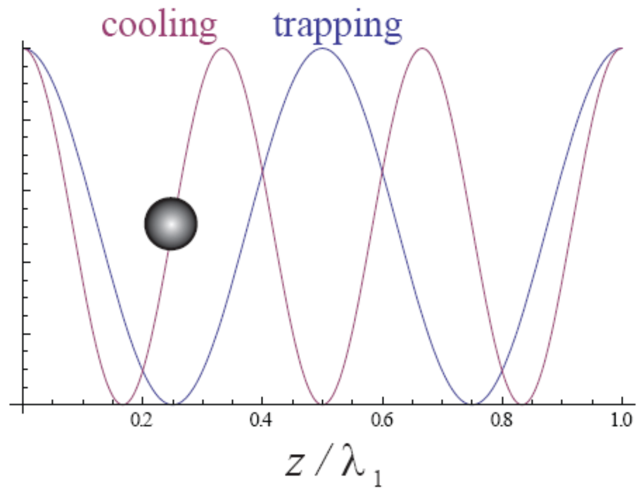
http://perg.phys.ksu.edu/vqm/laserweb/ch-8/f8s1t1p1.htm

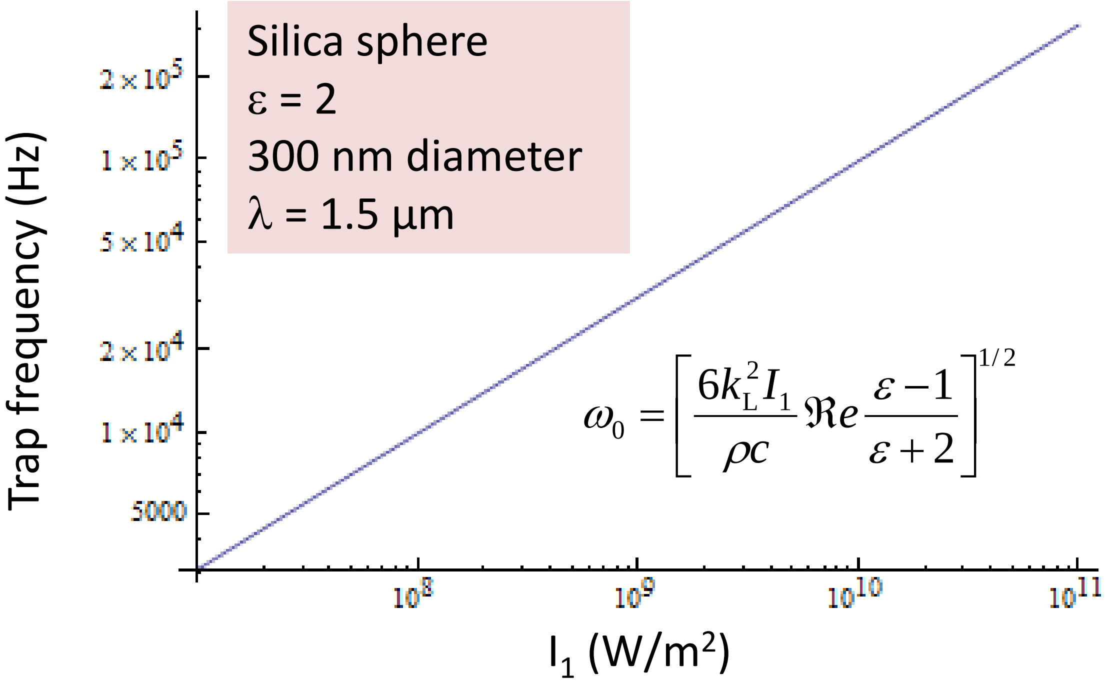


http://www.watervalley.net/users/bolen/page5.html

Standing-wave trap

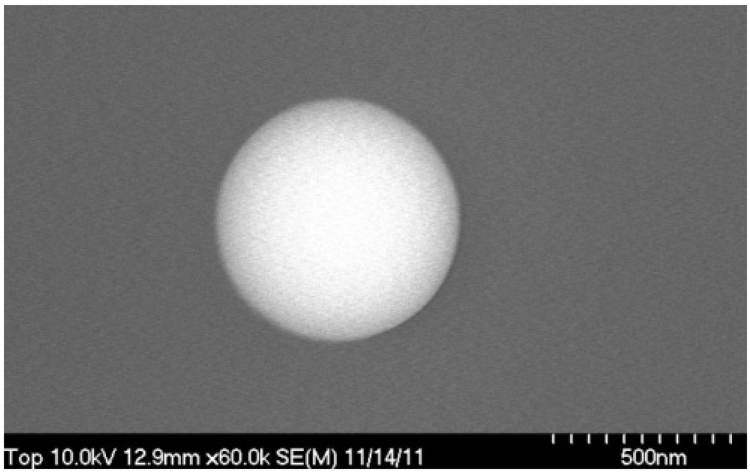






Silica sphere
$\varepsilon = 2$
300 nm diameter
$\lambda = 1.5$ µm

$$\omega_0 = \left[\frac{6k_L^2 I_1}{\rho c}\Re e\frac{\varepsilon - 1}{\varepsilon + 2}\right]^{1/2}$$



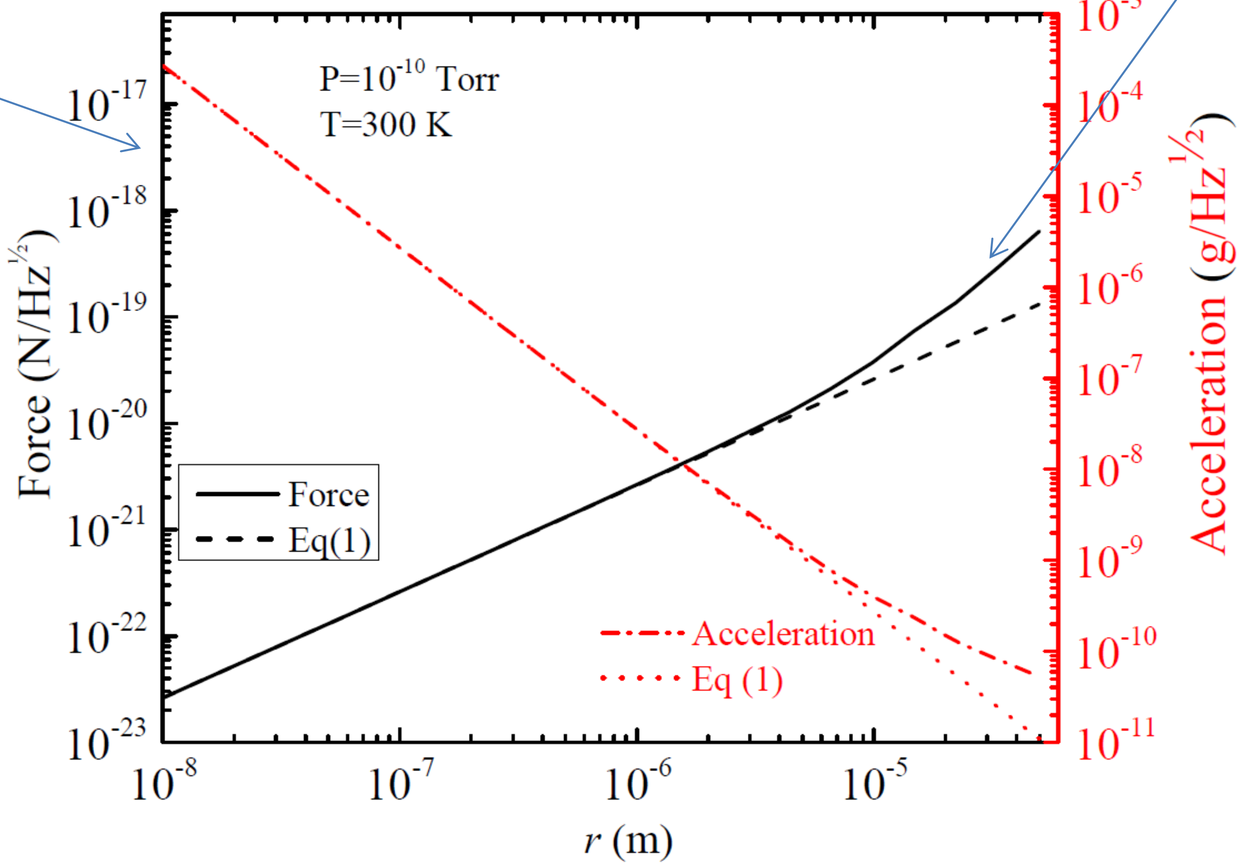
Projected sensitivity

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

Photon recoil heating

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

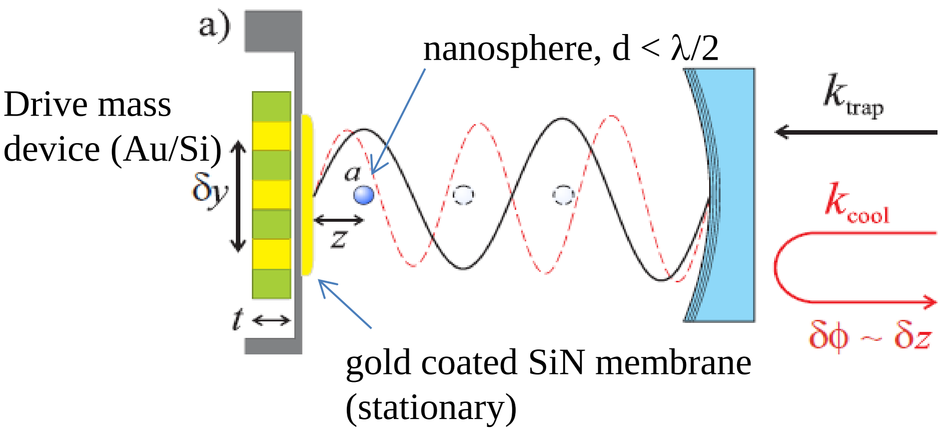
Cantilevers



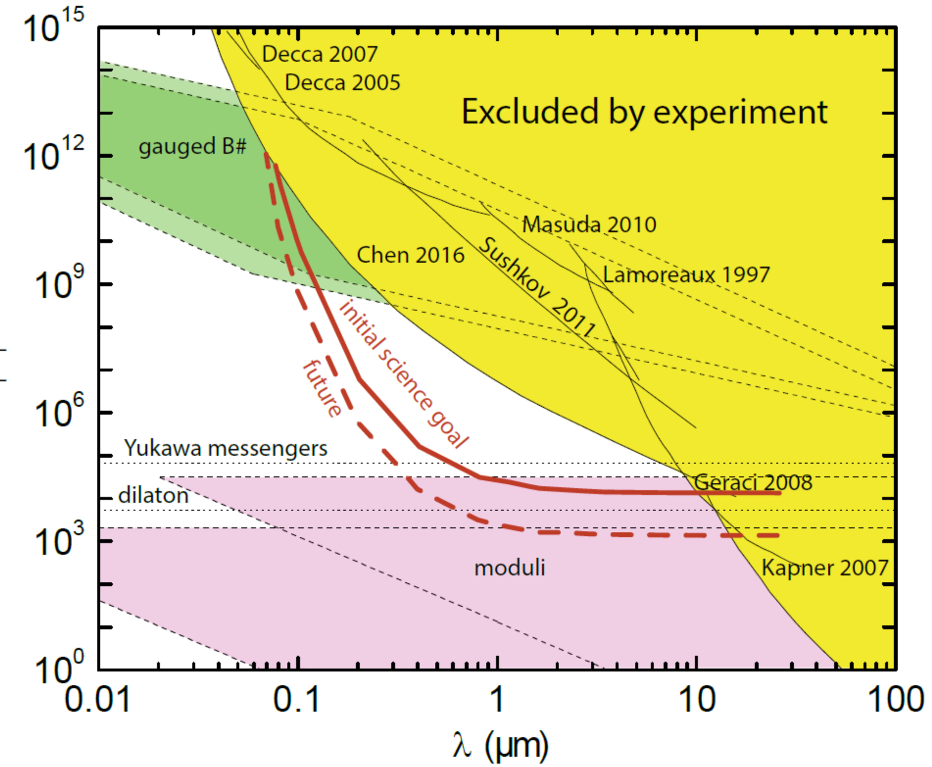
20 zN/Hz$^{1/2}$ Gieseler, Novotny, Quidant (Nature Phys. 2013)

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

Projected sensitivity



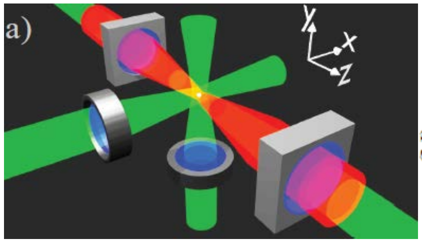
Projected Reach

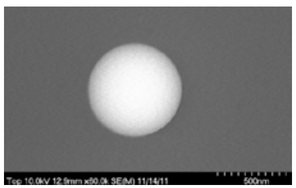


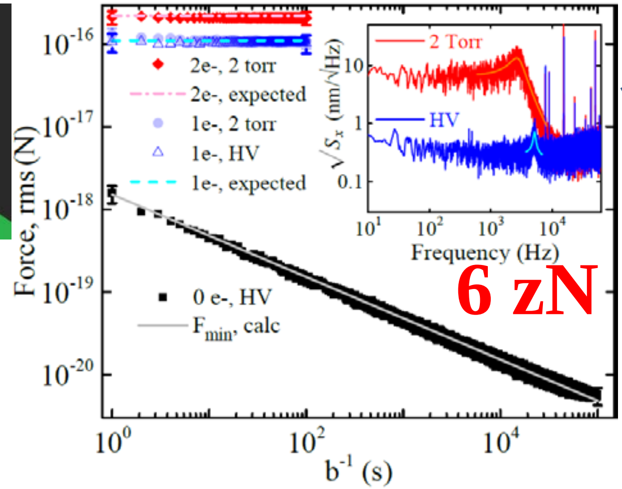
AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Optically-levitated micro-particles

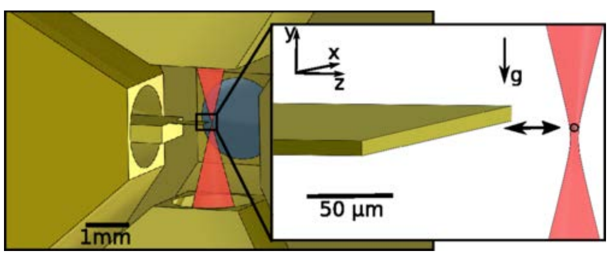
High Q Mechanical Resonance:
Optically levitated microspheres







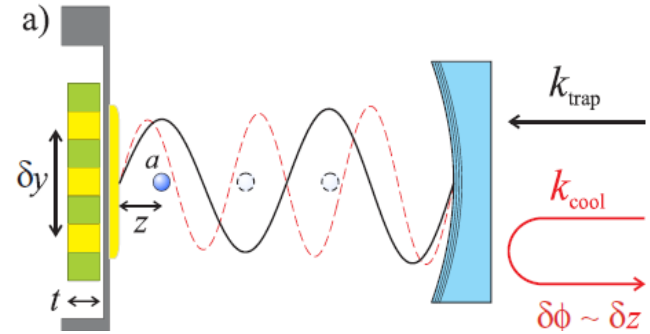
G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).
G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).



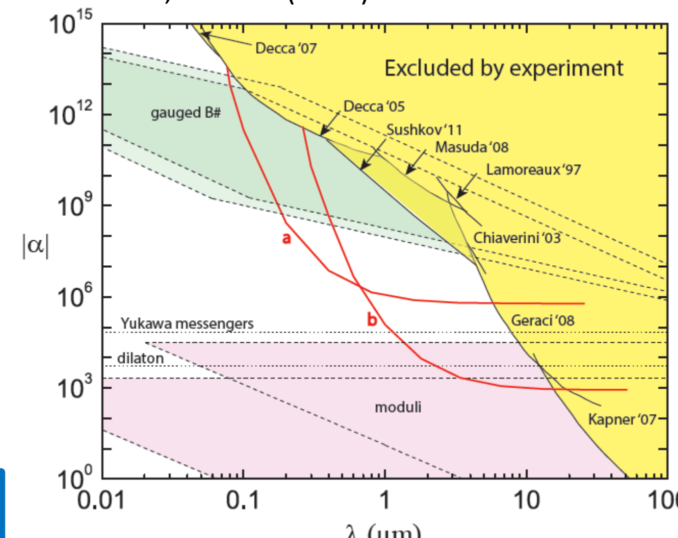
A. D. Rider, D. C. Moore, C. P. Blakemore, M. Louis, M. Lu, and G. Gratta *Phys. Rev. Lett.* **117**, 101101 (2016)

New Physics

Gravity at micron scales



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

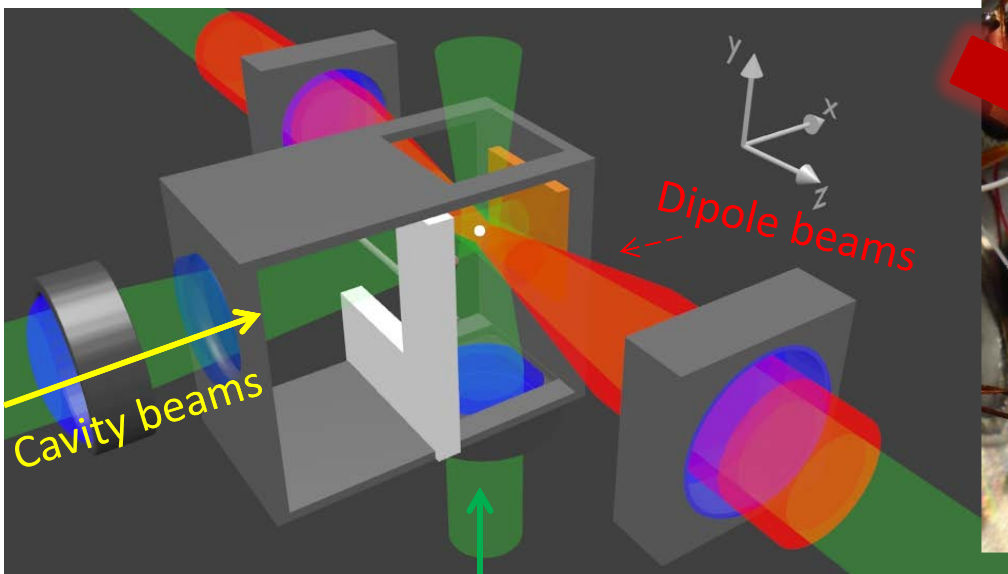


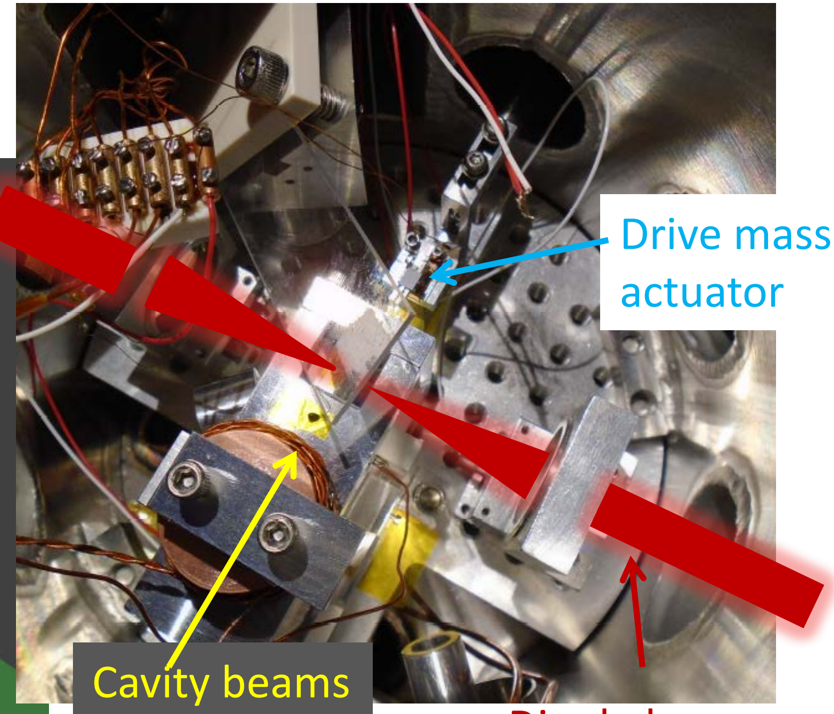
Gravitational Waves

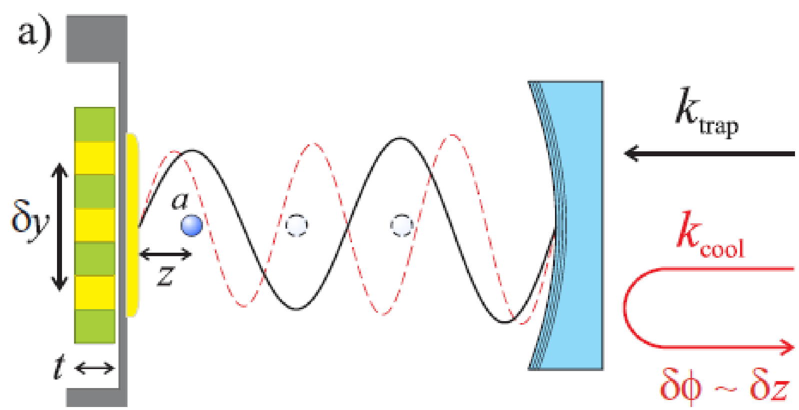
A. Arvanitaki and AG., *Phys. Rev. Lett.* **110**, 071105 (2013).

Experimental Setup

Combined cavity/dipole trap



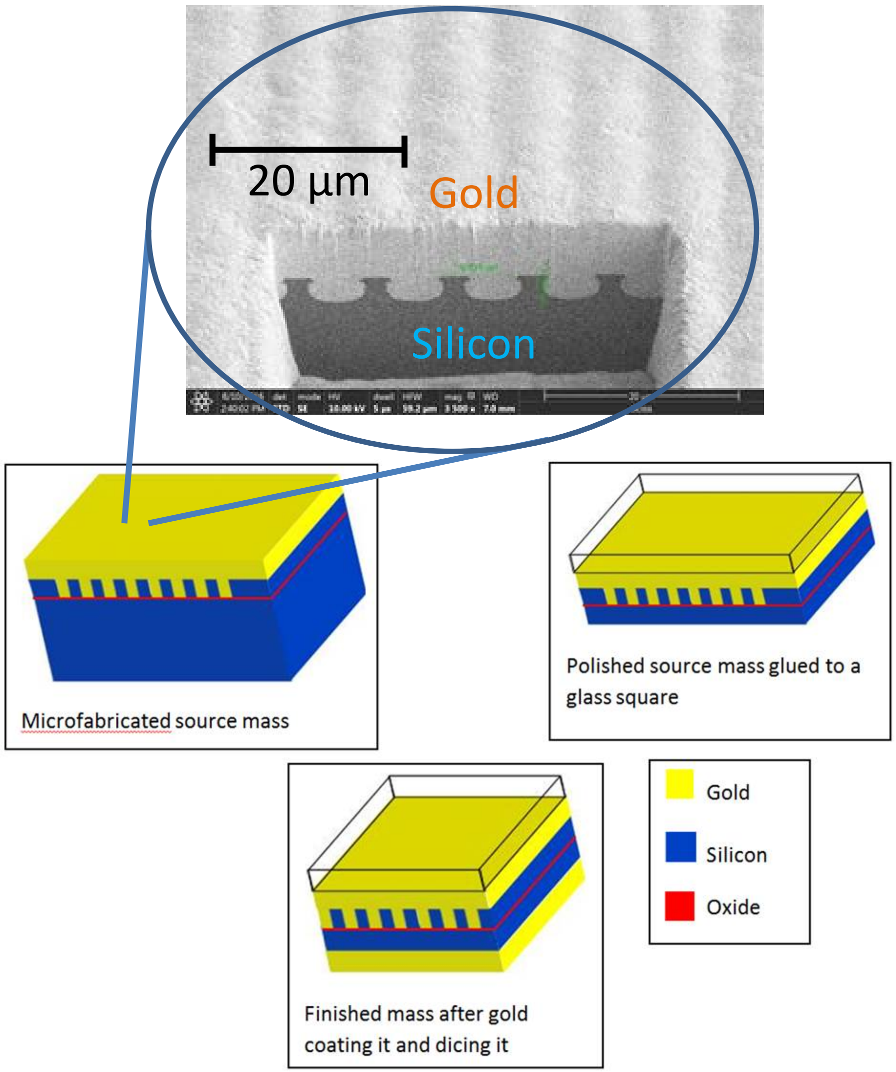


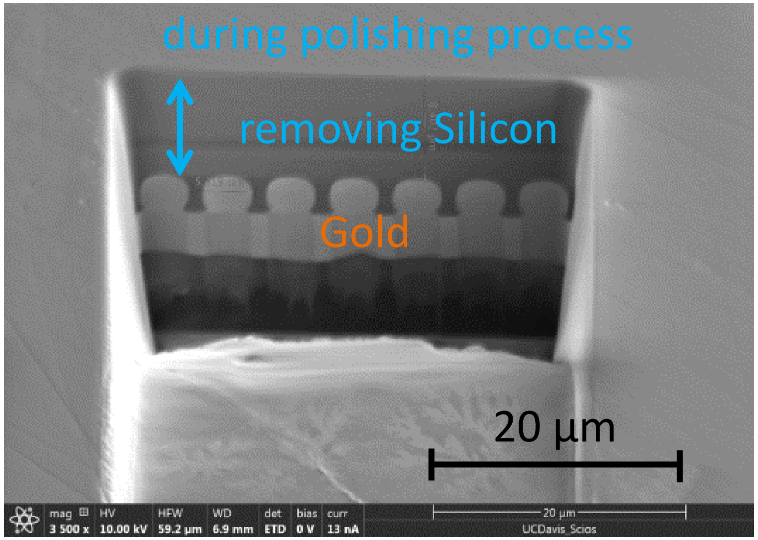


AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)
G. Ranjit et.al., PRA 91, 051805(R) (2015).
G. Ranjit et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Drive Mass fabrication

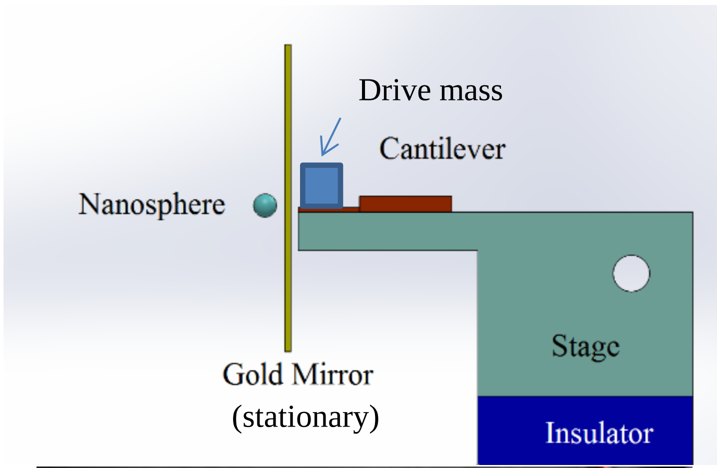
Buried drive mass technique – eliminates corrugation

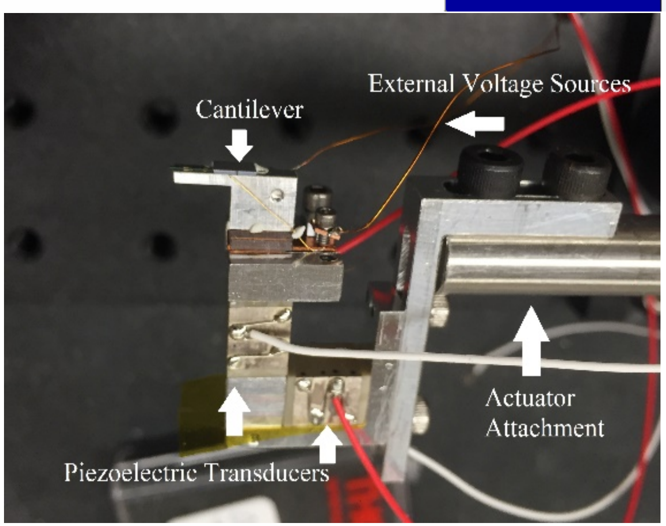




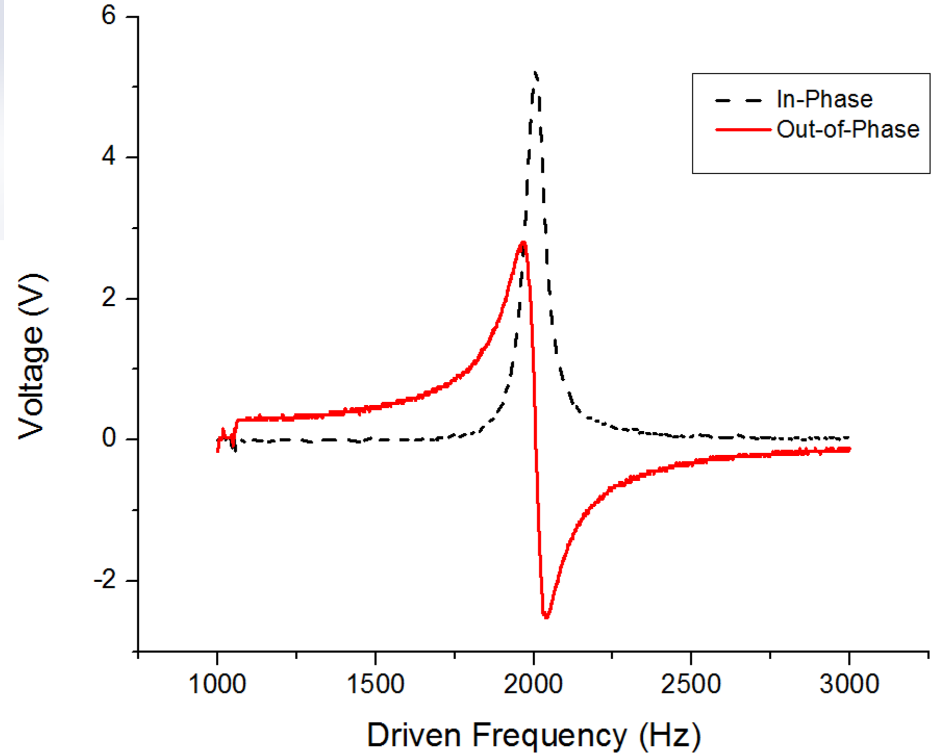
MEMS actuator

- Device for positioning drive mass

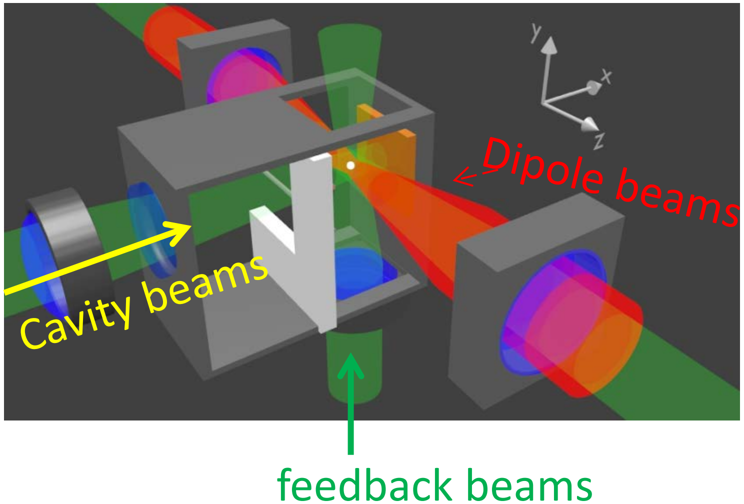


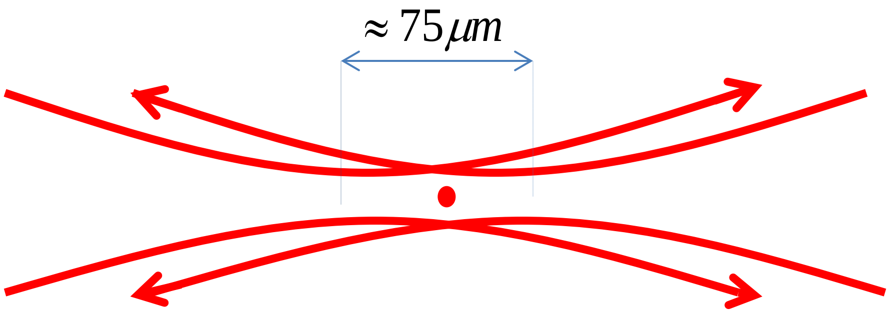


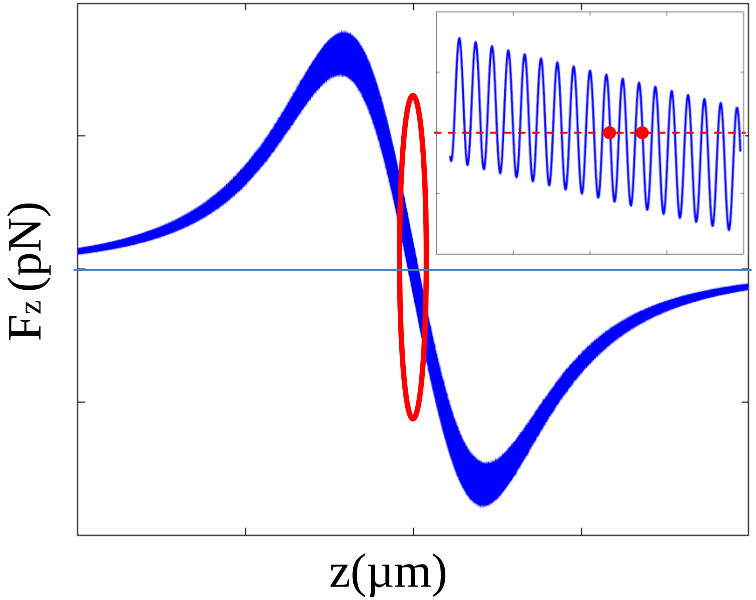
100V DC, 10V AC
~5 um displacement

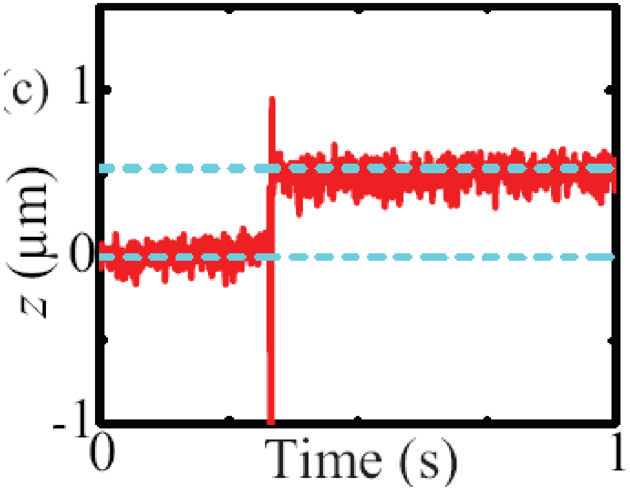


Standing wave optical trap



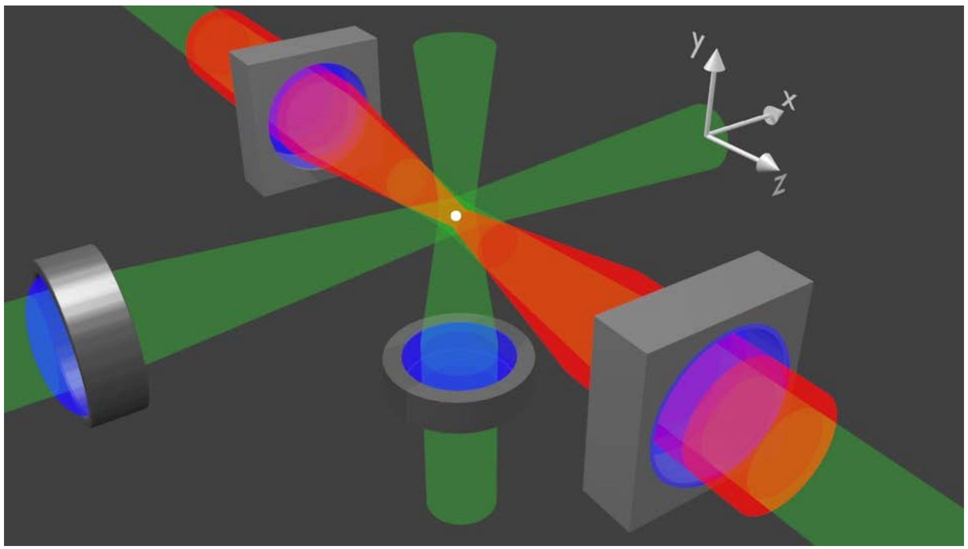


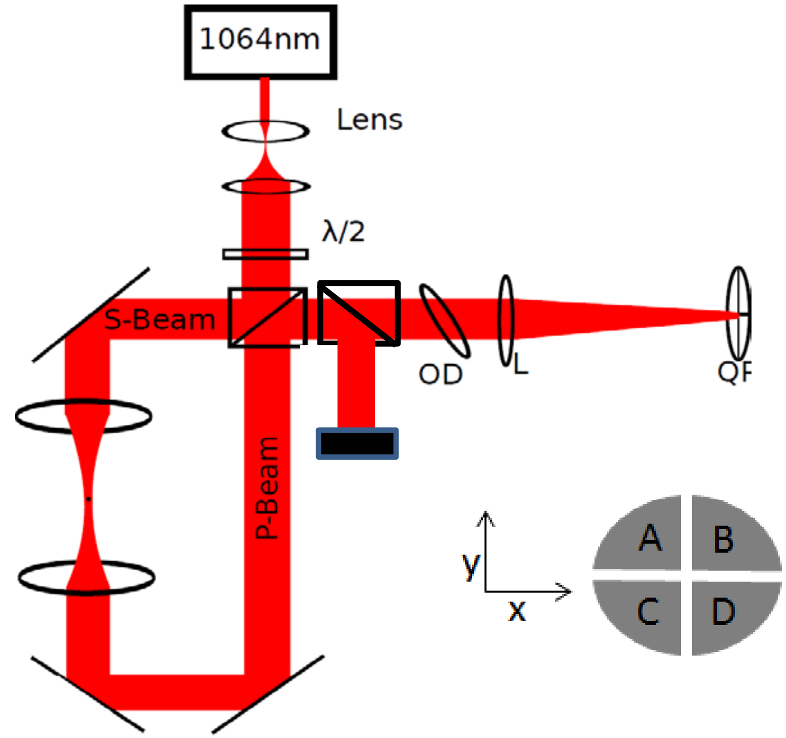




3D feedback cooling of a nanosphere

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

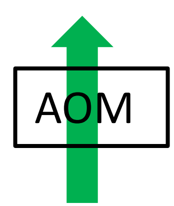




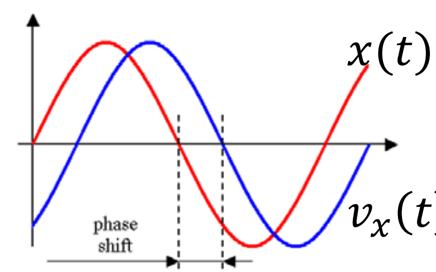
$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

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

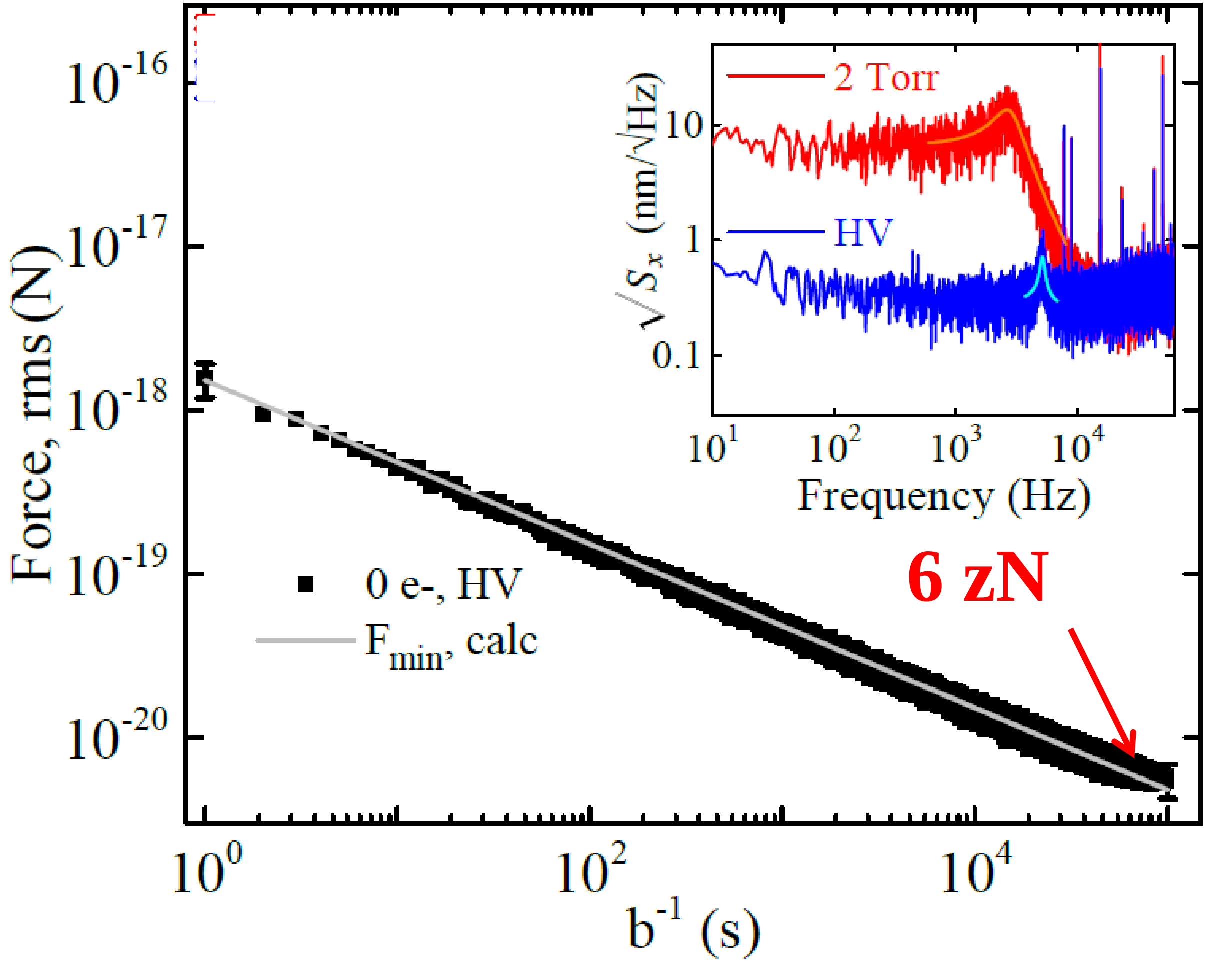
$$T_{eff} = \frac{T_0 \Gamma_0}{\Gamma_0 + \Gamma_{cool}}$$



780 nm



Zeptonewton force sensing



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

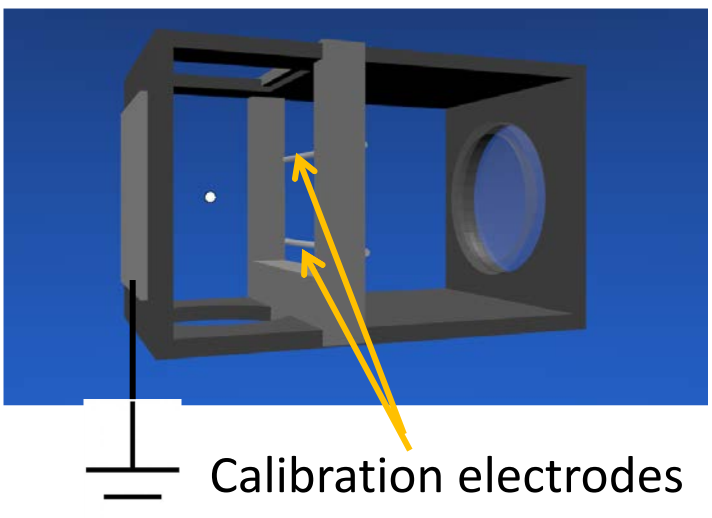
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

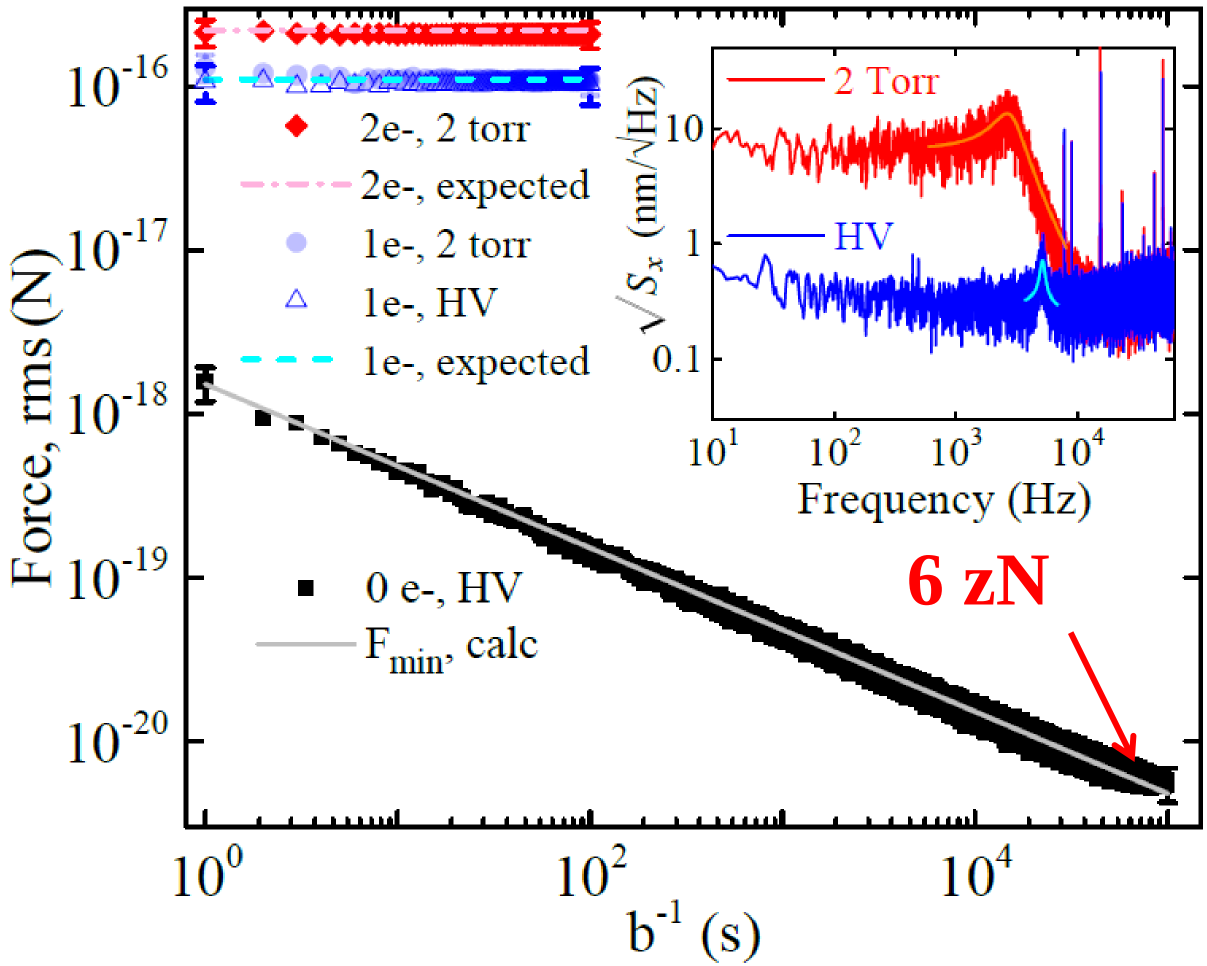
Zeptonewton force sensing

Electrostatic Calibration

90% of beads are neutral

Neutral beads stay neutral
Charge stays constant over days



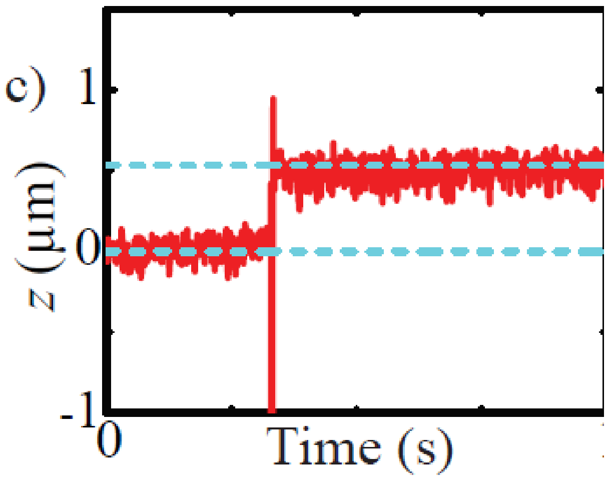


G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

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

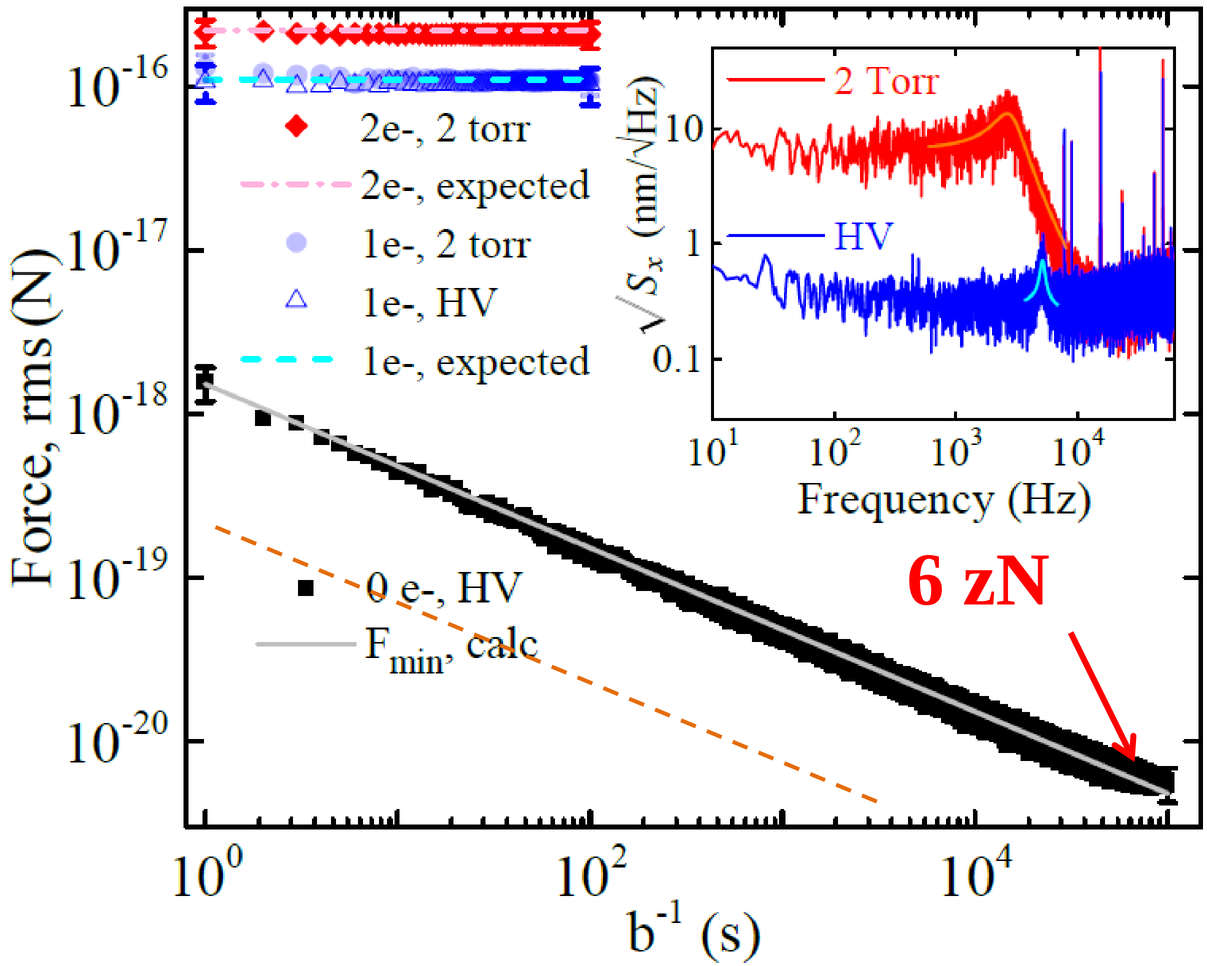
Zeptonewton force sensing

Optical lattice calibration



Useful for neutral objects

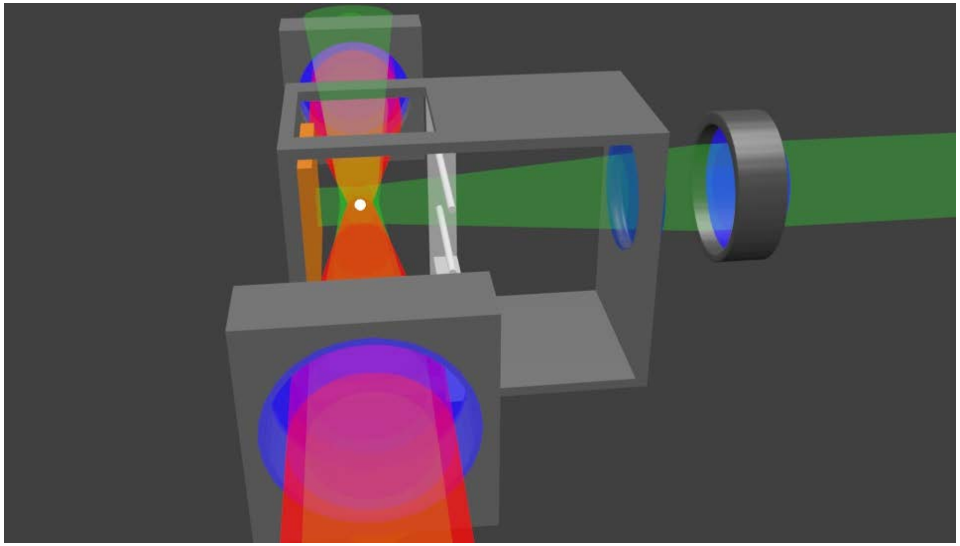
Method consistent with electric field approach

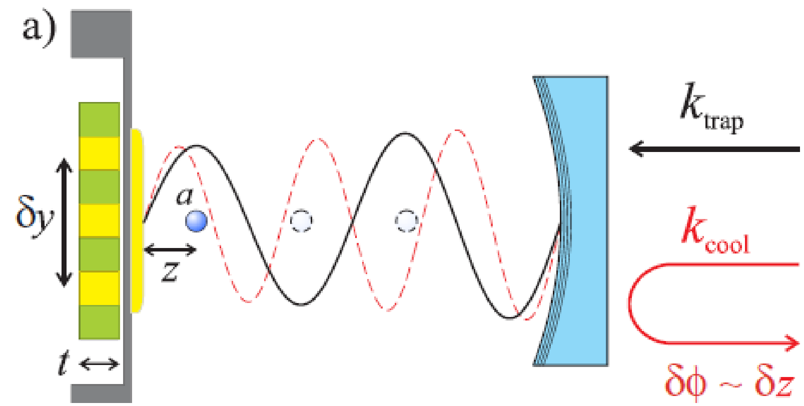


Sensitivity $S_{F,x} = 1.63 \pm .37\ \mathrm{aN}/\sqrt{\mathrm{Hz}}$

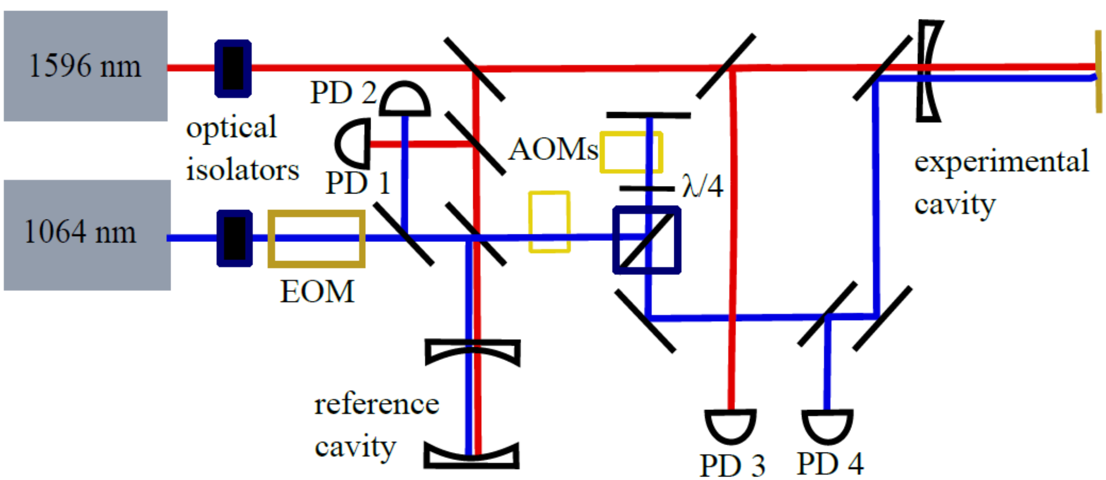
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Next: Cavity Trapping and cooling



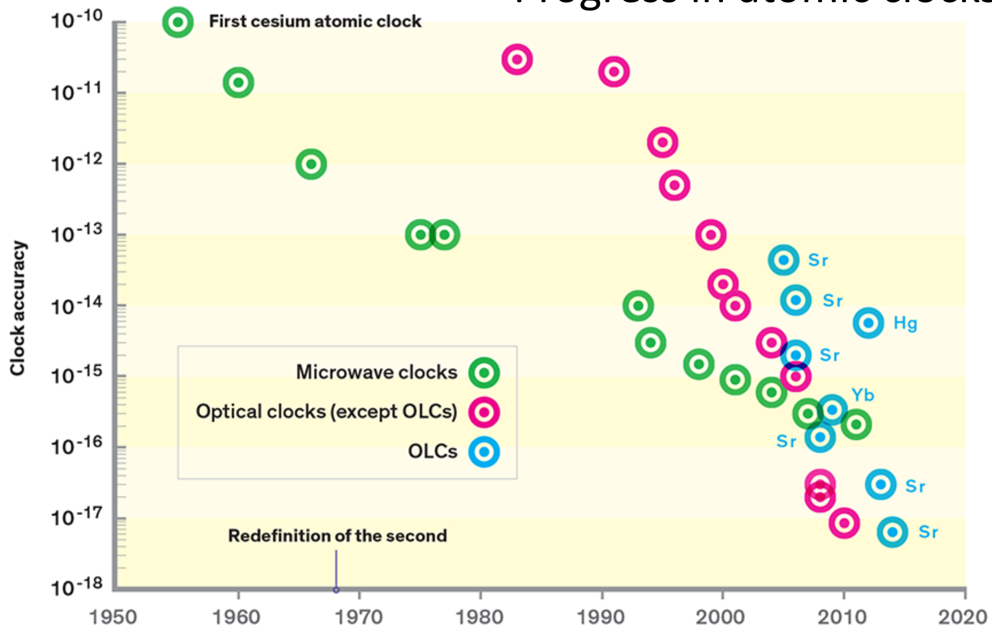


1596nm beam to trap a bead at its antinode → localization
1064nm beam to cavity cool the CM of bead → position readout



AMO- based techniques

Progress in atomic clocks

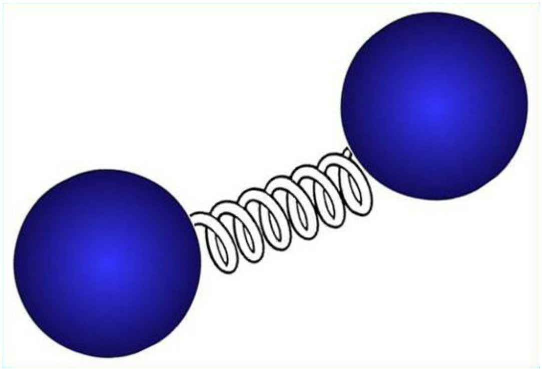


A molecular quantum clock, a device that precisely measures the vibrations of this spring,

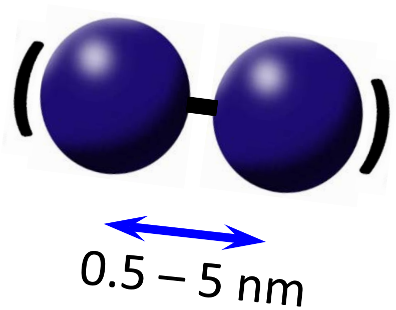
-Time variation of electron-to-proton mass ratio

-Test if unknown forces - besides electromagnetism and Newtonian gravity - modify the vibrations of the spring at the nanometer length scale.

(Sr Molecular clock)

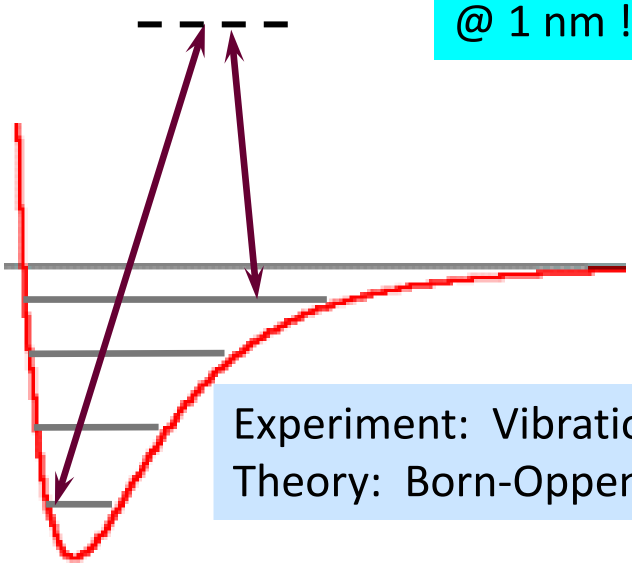


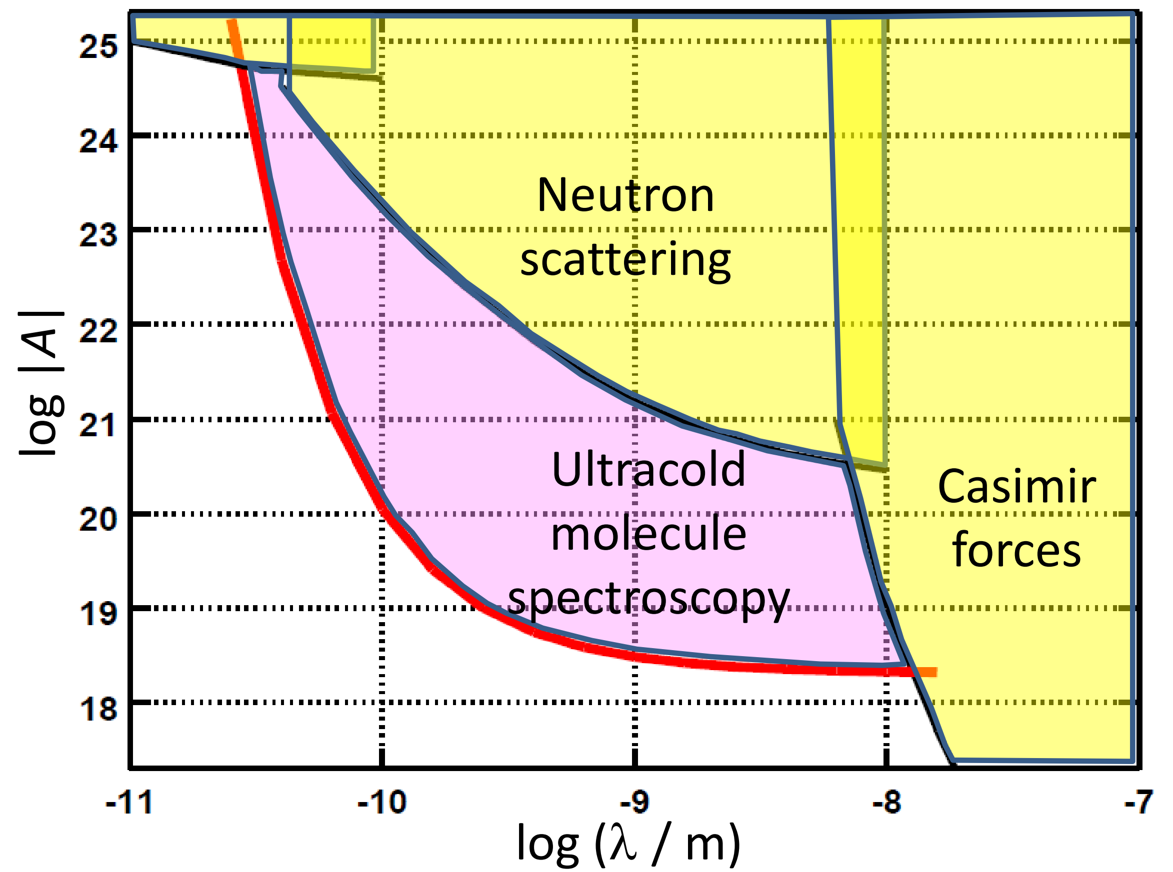
Nanometer-Scale Mass-Dependent Forces with Ultracold Molecules



$$V = -\frac{GM^2}{r}\left(1 + Ae^{-r/\lambda}\right)$$

$A < 10^{21}$ @ 1 nm !





Experiment: Vibrational spectroscopy of molecular isotopes
Theory: Born-Oppenheimer and mass-dependent corrections

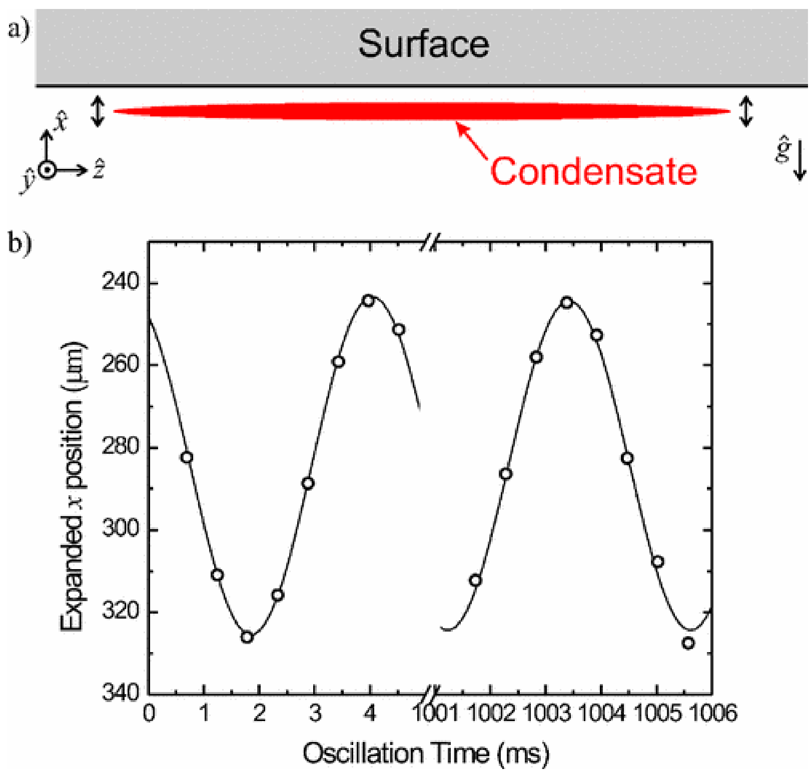
Slide: T. Zelevinsky

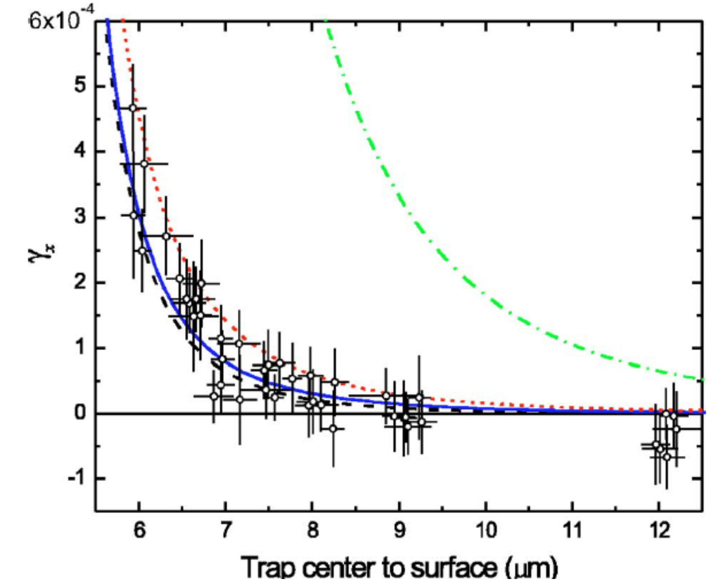
Y. Kamiya *et al.*, *PRL* **114**, 161101 (2015)

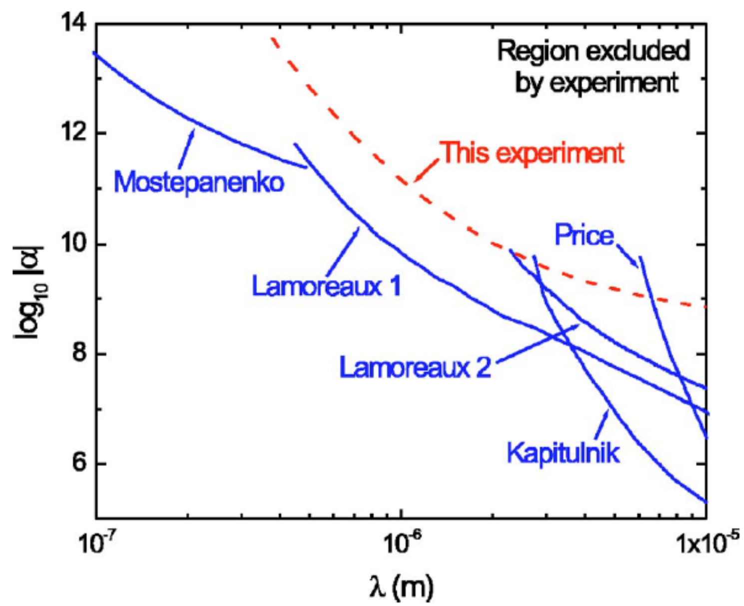
E. Adelberger *et al.*, *ARNPS* **53**, 77 (2003)

Atomic Bose-Einstein condensates

Casimir-Polder force measurements



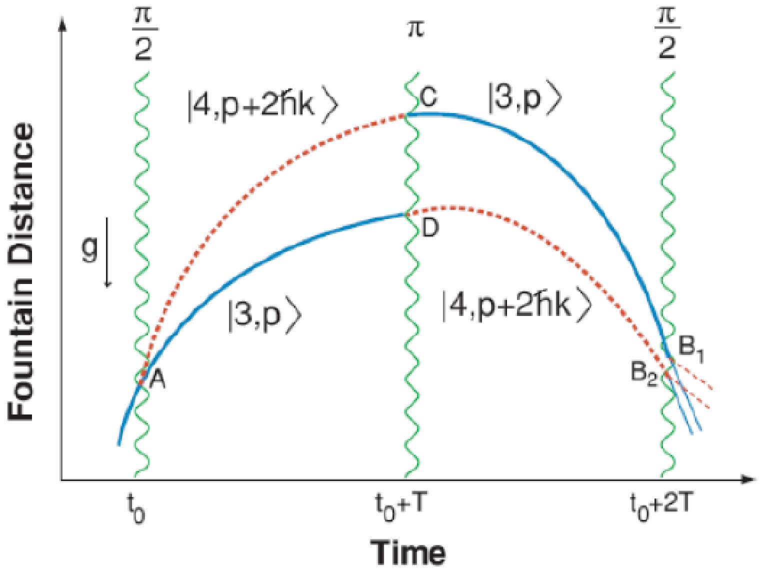


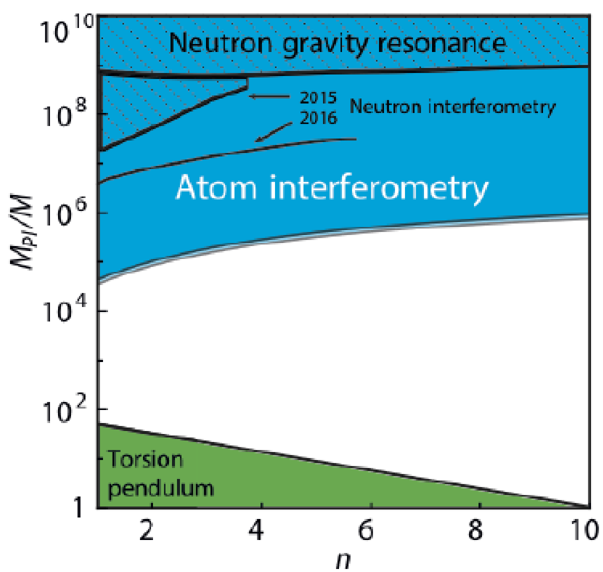


D. M. Harber, J. M. Obrecht, J. M. McGuirk, and E. A. Cornell, PRA **72**, 033610 2005

Cornell group, JILA

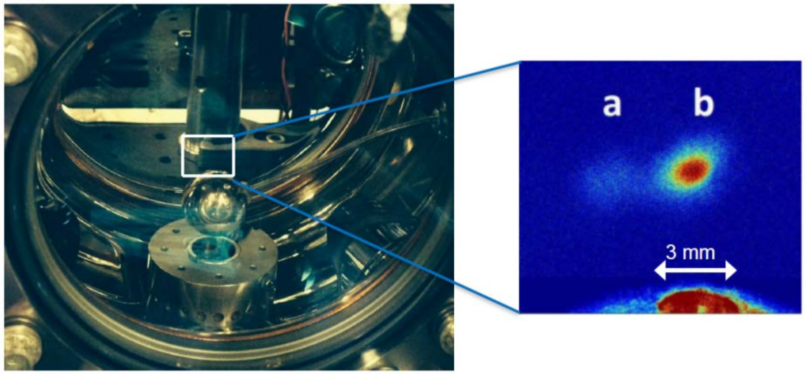
Atom interferometers





Probing Dark Energy with Atom Interferometry
C. Burrage, E. J. Copeland, E. A. Hinds
JCAP 1503 (2015) 03, 042

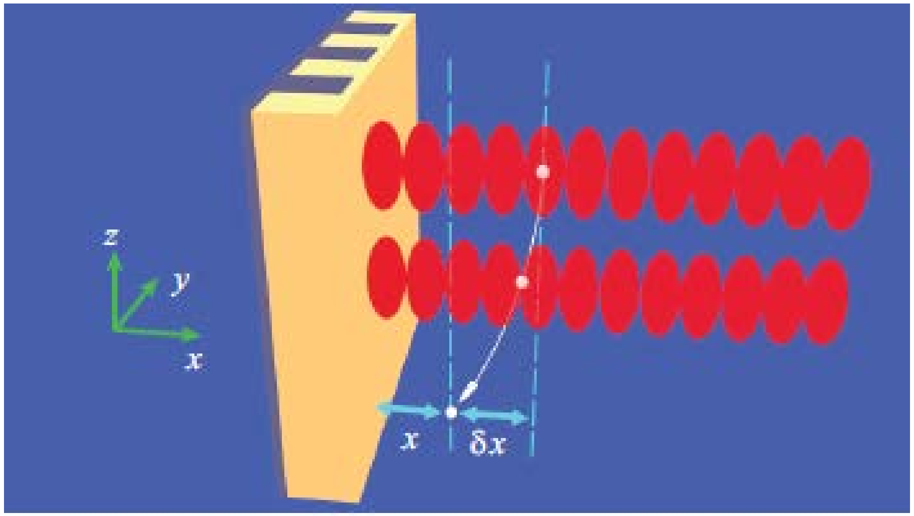
Search for Chameleons (screened within matter, only shell contributes, except for atoms!)

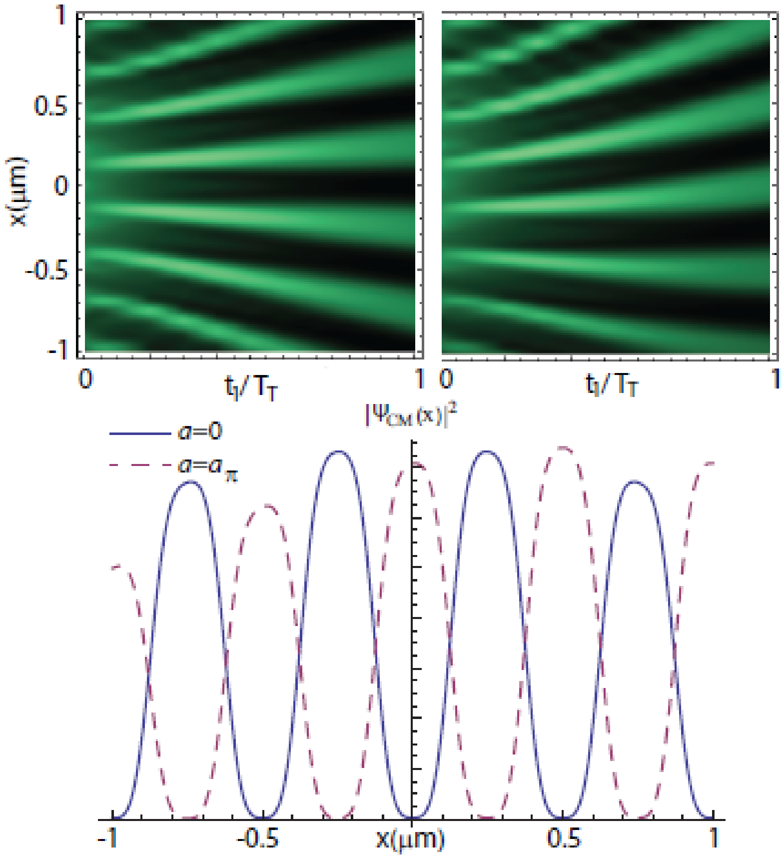


P. Hamilton, M. Jaffe, P. Haslinger,
Q. Simmons, H. Müller, J. Khoury
Science 349, 849 (2015).

Benjamin Elder, Justin Khoury, Philipp Haslinger, Matt Jaffe,
Holger Müller, Paul Hamilton, PRD 94, 044051 (2016).

Matter-wave interferometry

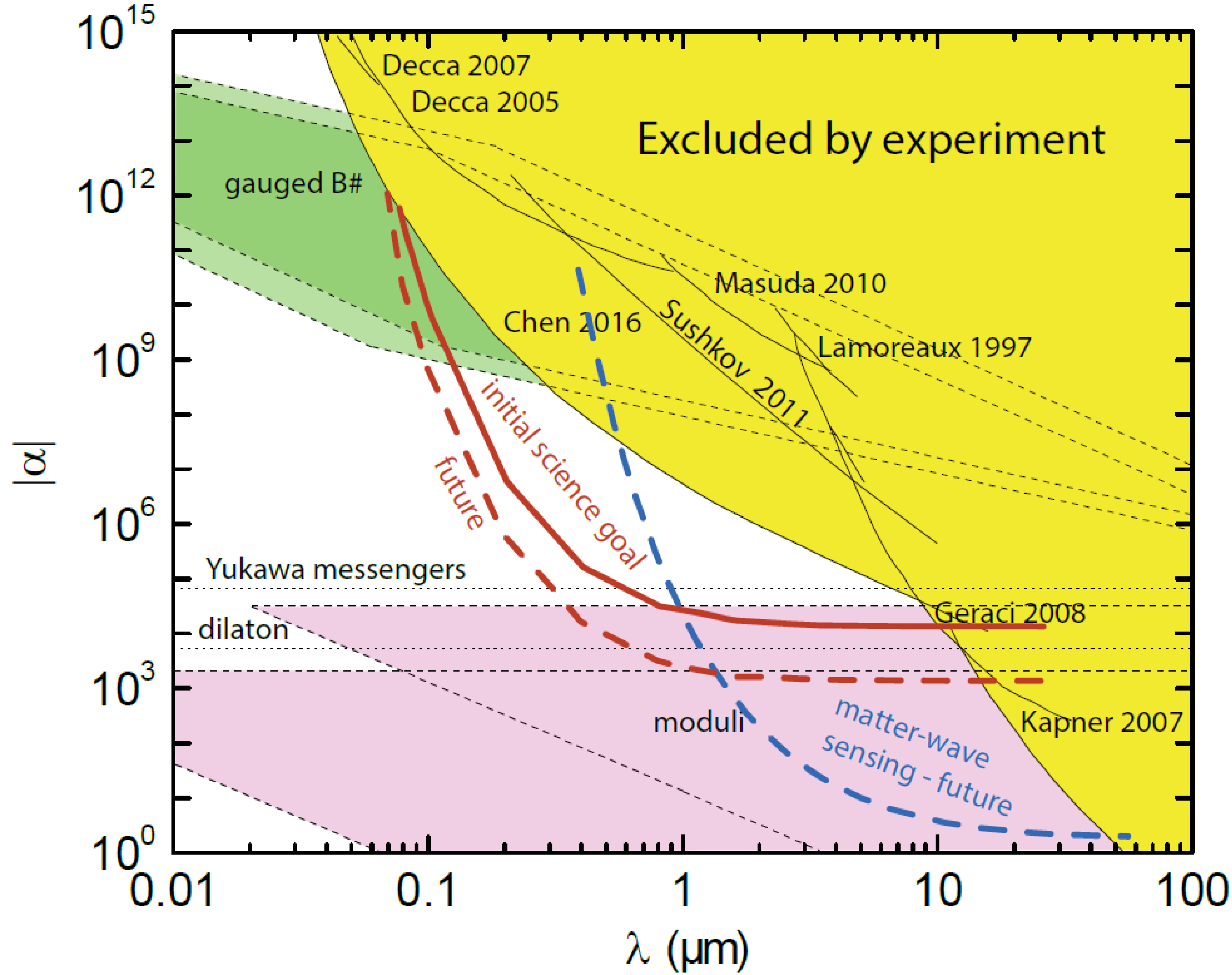




ng acceleration sensing

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

Projected reach- nanosphere matter-wave interferometer



Summary

- Rich possibilities for new science
  - ✓ Tests of gravity
  - ✓ Dark Sector Physics
  - ✓ Beyond the Standard Model
- Diverse set of techniques from researchers of varying backgrounds and expertise
  - Atomic, Molecular, Optical Physics
  - Condensed matter and low-temperature physics
  - Torsion balances/precision mechanical measurements