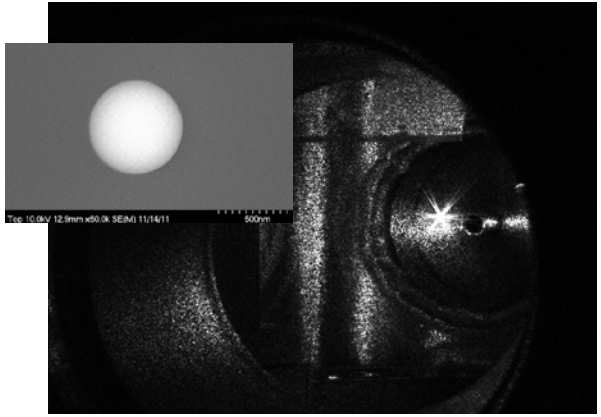
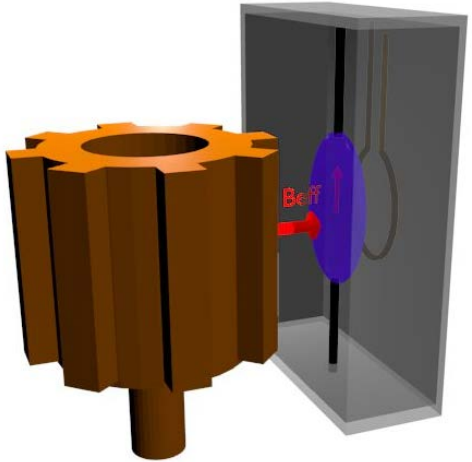
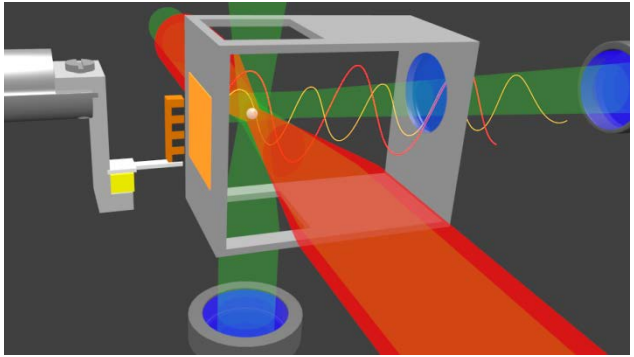
Hunting for new forces, Axions, and ultra-light Dark Matter with AMO-based sensors







Sensitivity frontier
KITP Workshop April 17, 2018

A. Geraci, Northwestern University

Our lab has moved!

University of Nevada, Reno

Northwestern University

Center for Fundamental Physics (CFP)

Northwestern University

Center for Fundamental Physics (CFP)

Jerry Gabrielse group

- g-2 of electron

Predicted: $\mu/\mu_B = -1.001\,159\,652\,181\,78\,(77)$
Measured: $\mu/\mu_B = -1.001\,159\,652\,180\,73\,(28)$

- electron EDM

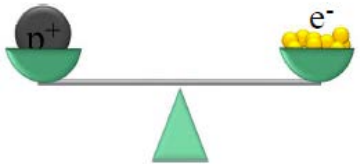
ACME $|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$

- Test of CPT with antihydrogen

Brian Odom group

- Single molecule spectroscopy of trapped molecular ions

Does m_p/m_e Change in Time?

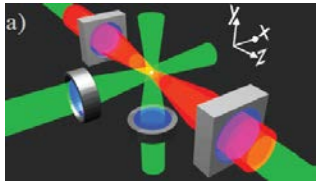


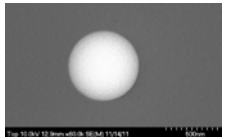
A search is underway for a fourth faculty member

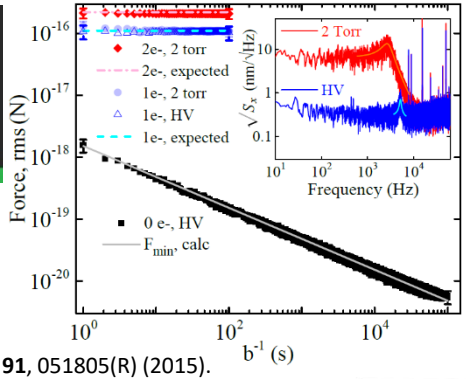
Our lab: fundamental physics with resonant sensors

Techniques

Mechanical Resonance:
Optically levitated nanospheres

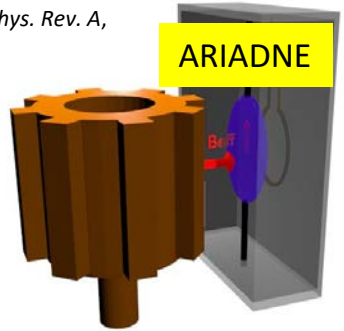






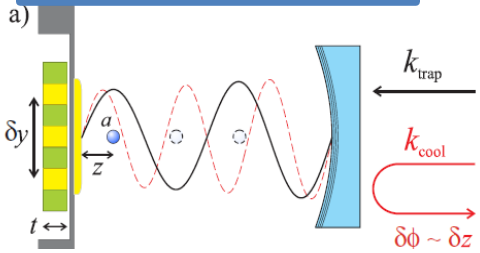
G. Ranjit et.al., *Phys. Rev. A* **91**, 051805(R) (2015).
G. Ranjit, M. Cunningham, K. Casey, and AG, *Phys. Rev. A*, **93**, 053801 (2016).

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).

Outline

- Testing gravity at short-range with optically levitated nanospheres

- Searching for axions and (ultra-)light Dark Matter

  The ARIADNE axion experiment

  Ultralight Scalar fields with interferometers

The Standard Model

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

The Interactions:

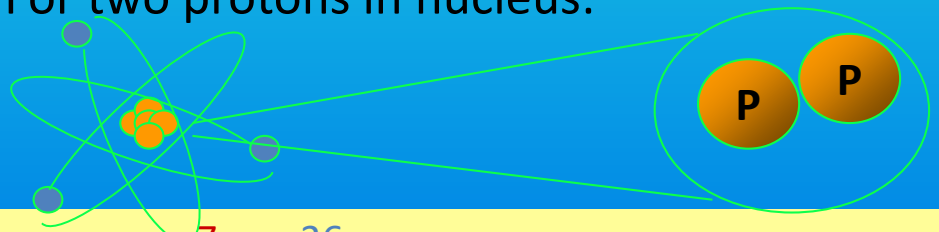
Strong: Holds nucleons together

Electromagnetic: Acts between charged particles

Weak: Causes certain decays

Gravity: Attraction between masses

For two protons in nucleus:



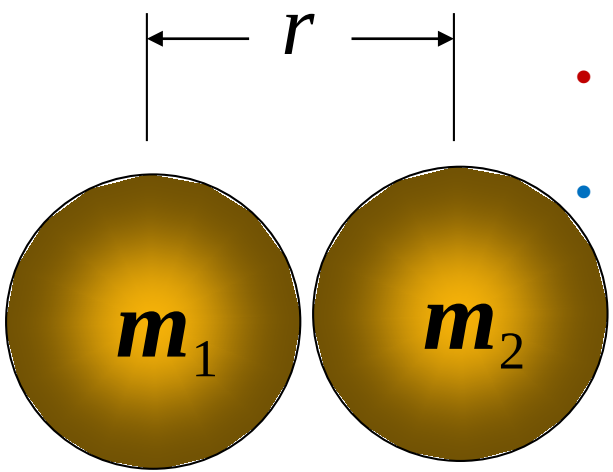
Strong : Electromagnetic : Weak : Gravity= 20 : 1 : 10^{-7} : 10^{-36}

The Hierarchy Problem: Why is Gravity so small?

Testing gravity at short range

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

Exotic particles (new physics)

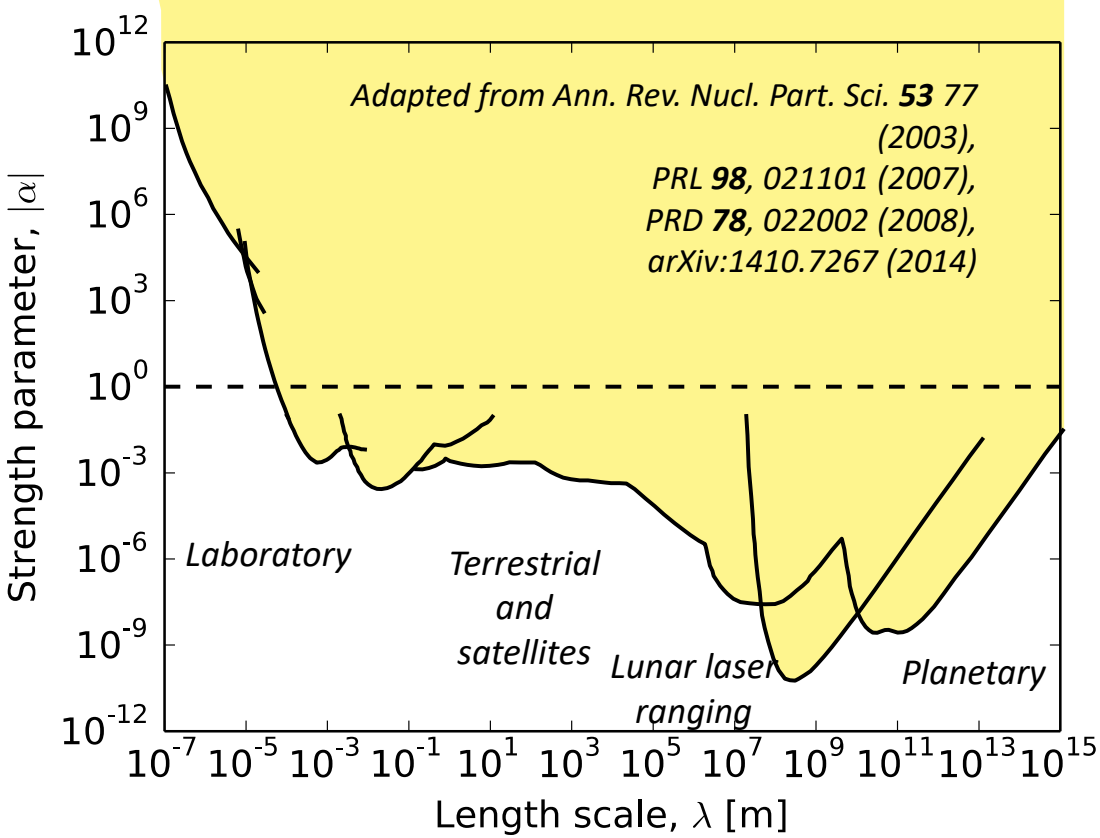


$\lambda < 1$ mm

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

Landscape for 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

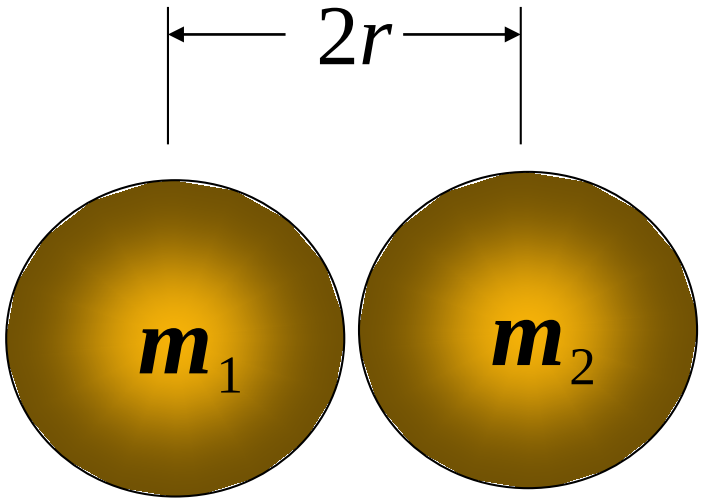
$$V_N = -G\frac{m_1 m_2}{r}$$

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

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

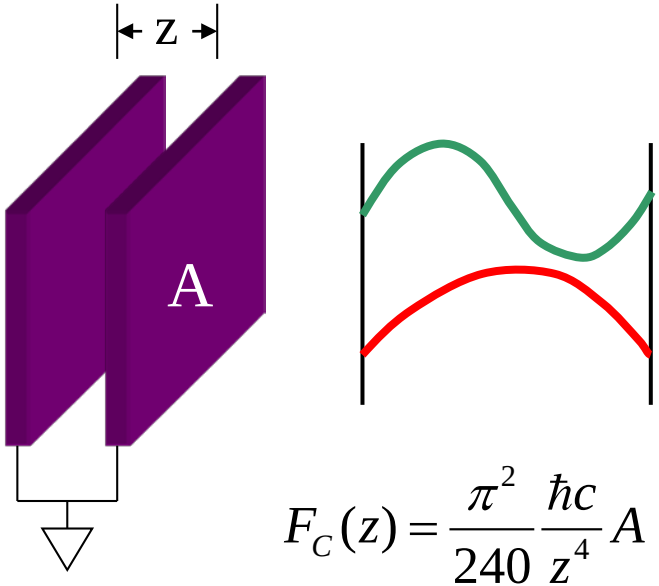
In the range of experimental interest:

r~10 μm ; $F_N \sim 10^{-21} N$



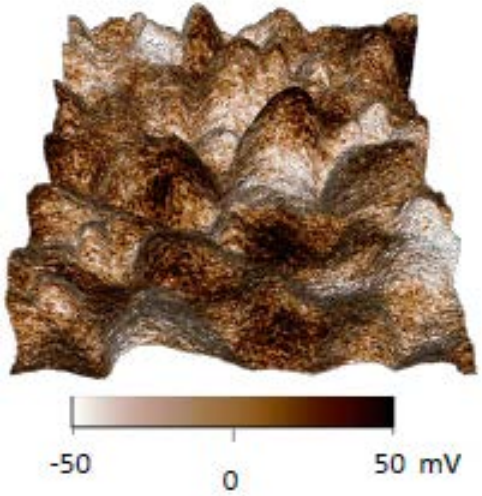
Experimental challenge: electromagnetic background forces

Casimir effect (1948):



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

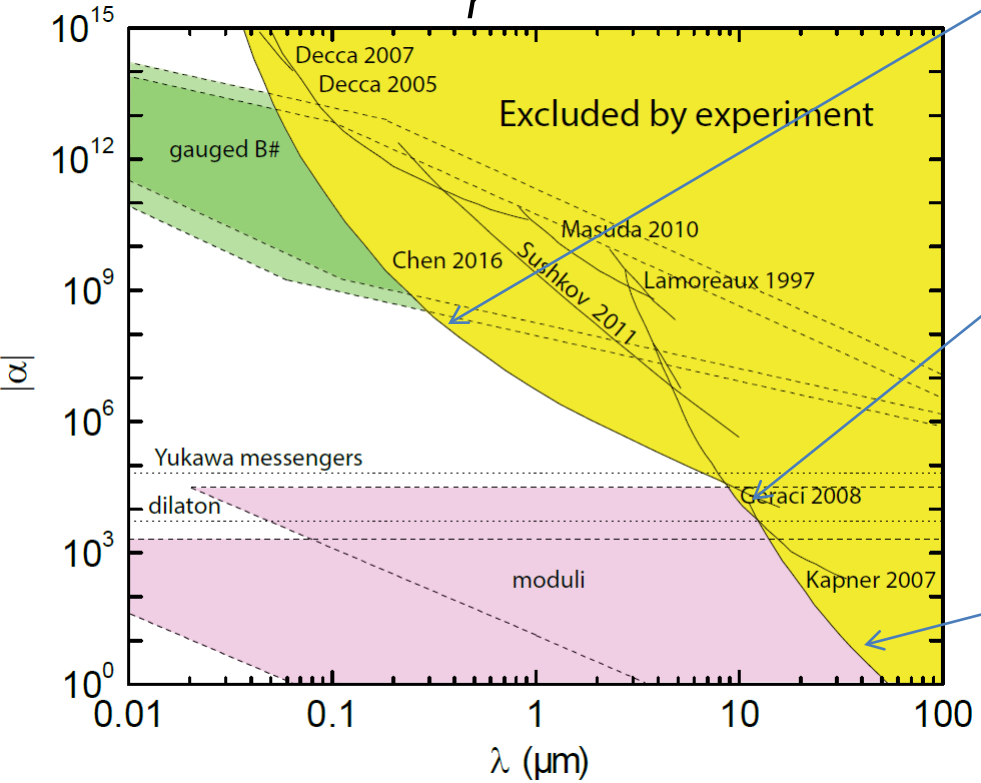
Electrostatic Patch Potentials:



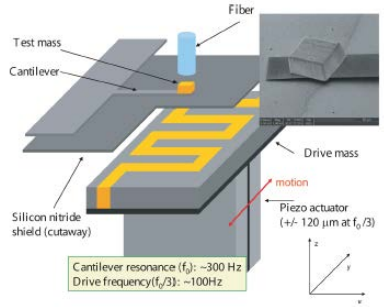
J. L. Garrett, D. Somers, J. N. Munday
J. Phys.: Condens. Matter 27 (2015) 214012

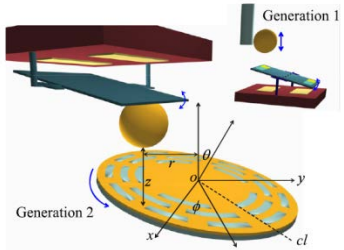
Force-distance parameter space

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



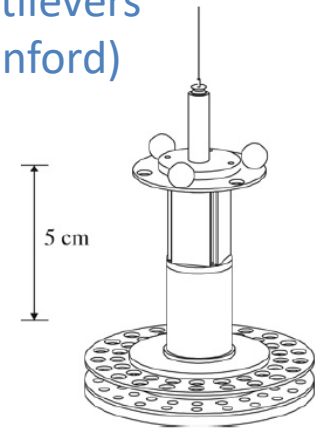
Casimir measurements (Indiana)





Cantilevers (Stanford)

Torsion balance experiments (U Washington)

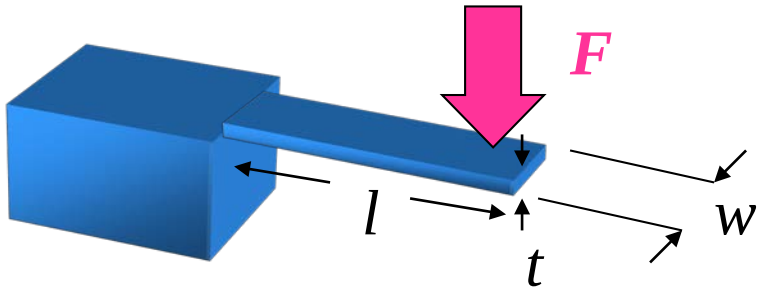


Resonant force detection

- Cantilever is like a spring:

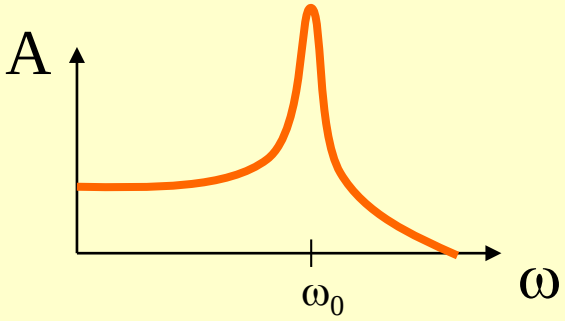
$$F = -Kx$$

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



Sinusoidal driving force

Amplitude:



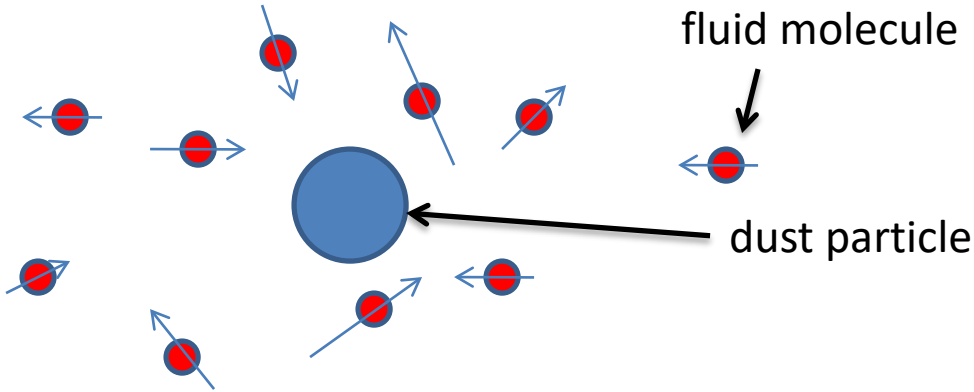
$$A_{(\omega=0)} = \frac{F}{k}$$ Constant force

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

Q can be very large >100,000

Fundamental limitation: thermal noise

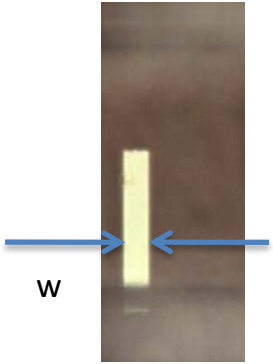
Brownian motion – random "kicks" given to particle due to thermal bath



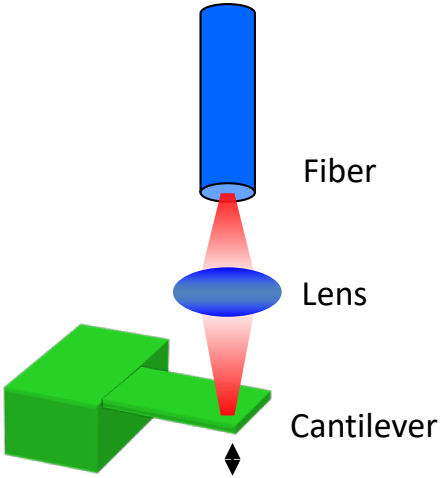
- Random "kicks" are given to cantilever due to finite T of oscillator

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

Example: Silicon microcantilevers



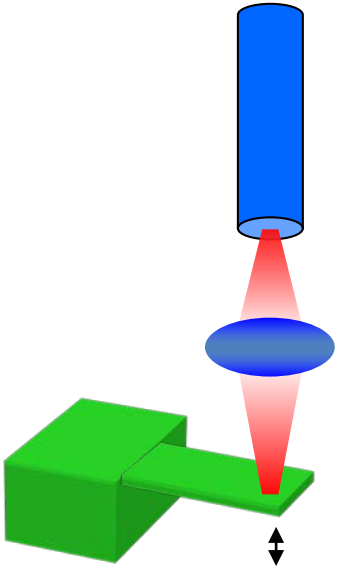
w= 50 µm
l= 250 µm
t=0.3 µm



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

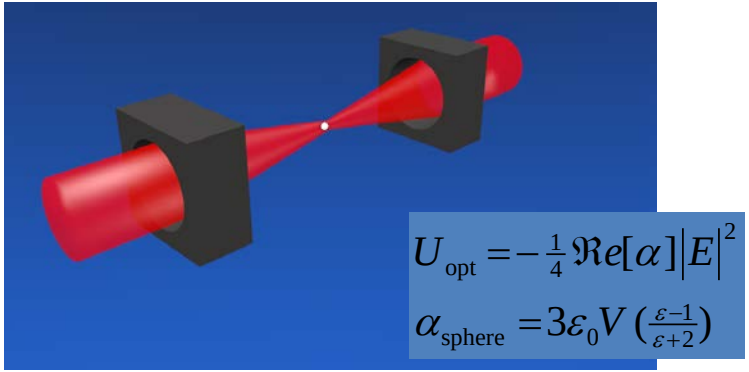
Silicon Cantilevers:
F_{min} ~ *10* x 10^{-18} N/√Hz at 4 K at Q=10^5

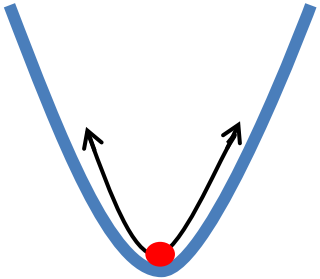
Improving sensitivity



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

Levitate the force sensor!





CM motion decoupled from environment – no clamping, materials losses

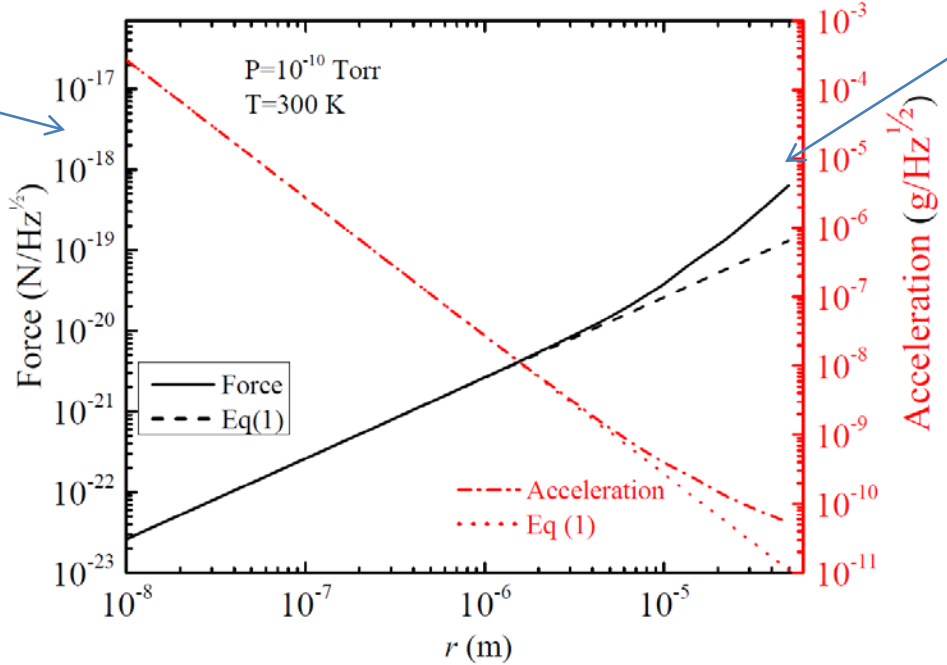
Projected force sensitivity

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

Cantilevers

Photon recoil heating

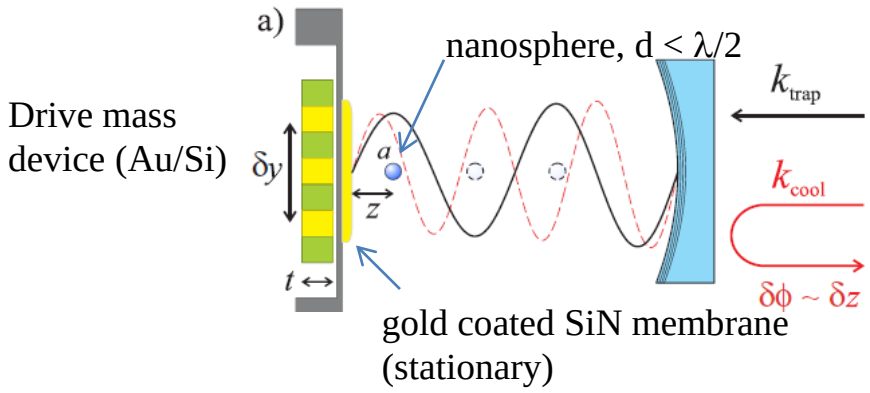
Seen recently by Novotny group V. Jain et. al., PRL 116, 243601 (2016)

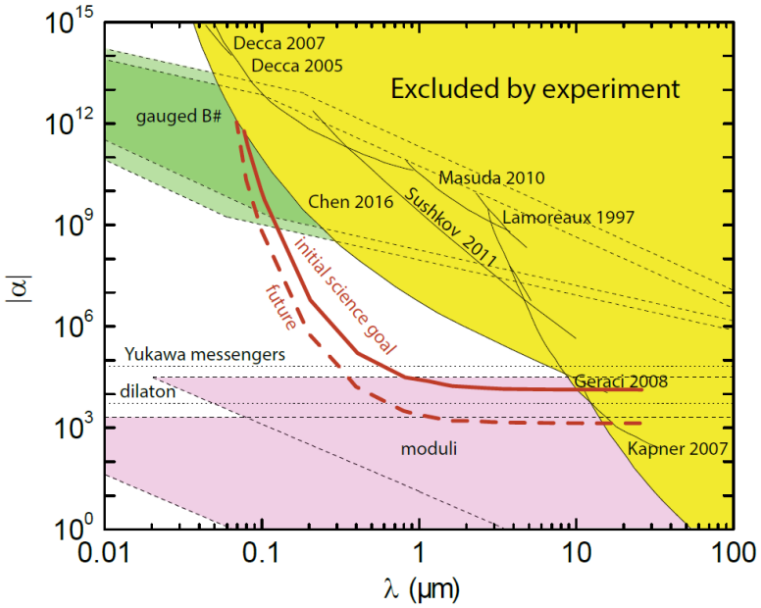


20 zN/Hz$^{1/2}$ Gieseler, Novotny, Quidant (Nature Phys. 2013)

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

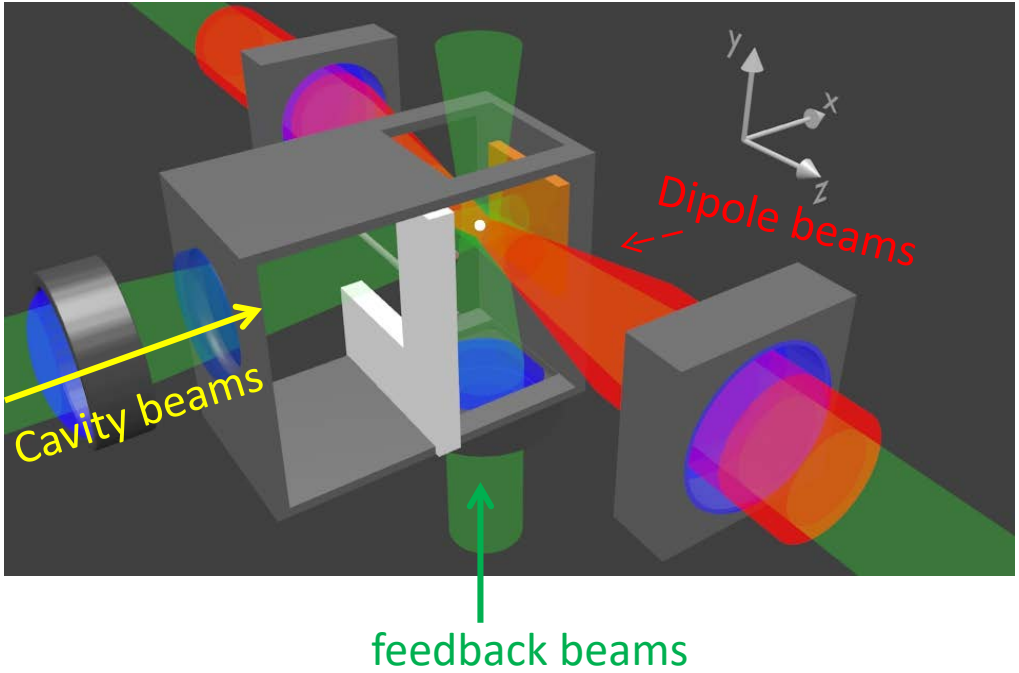
Projected sensitivity

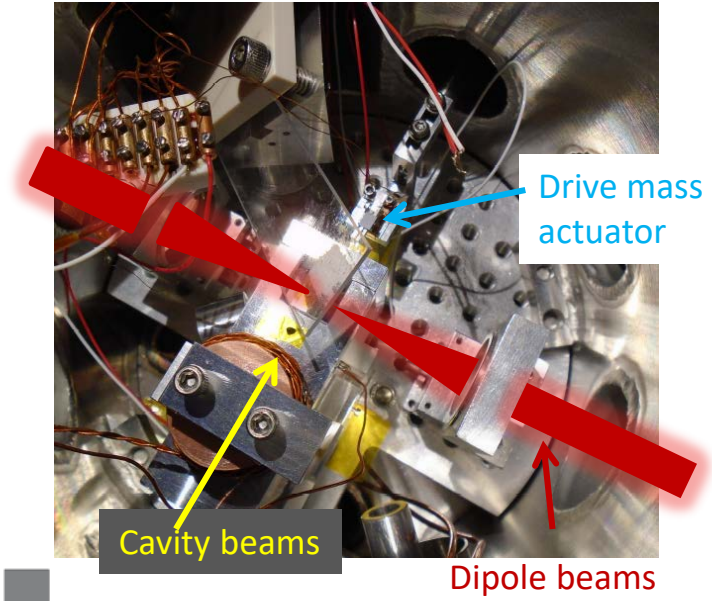


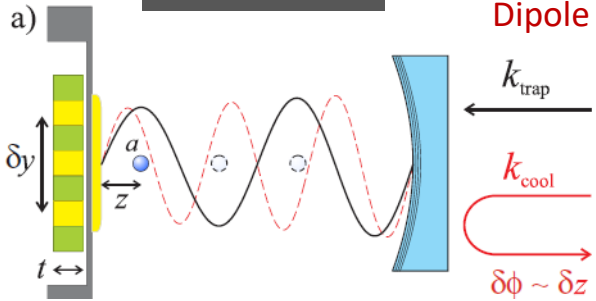


AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Experimental Setup

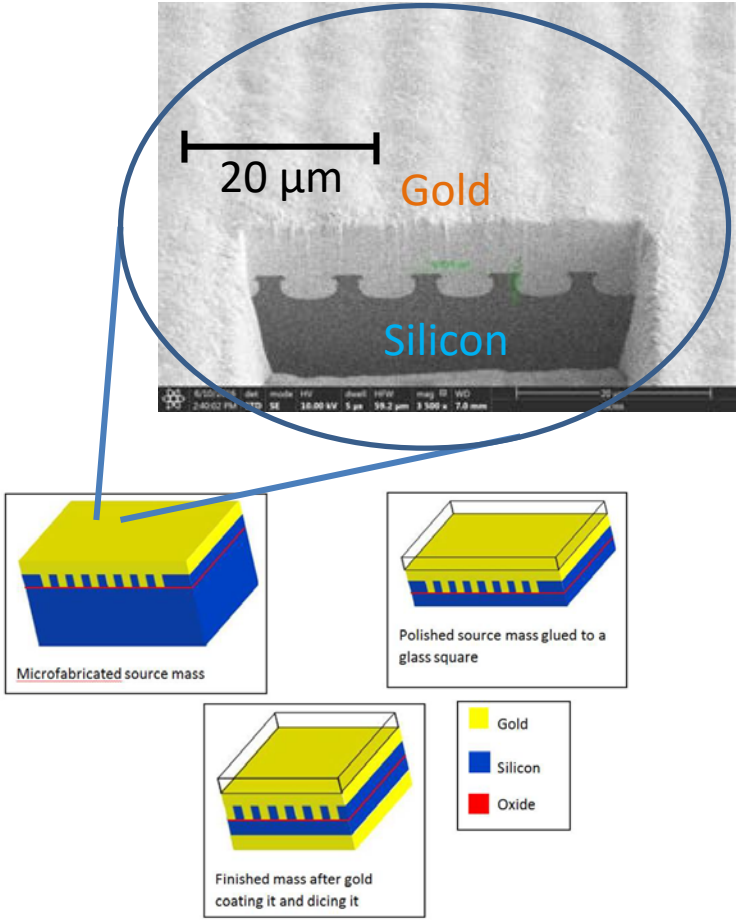




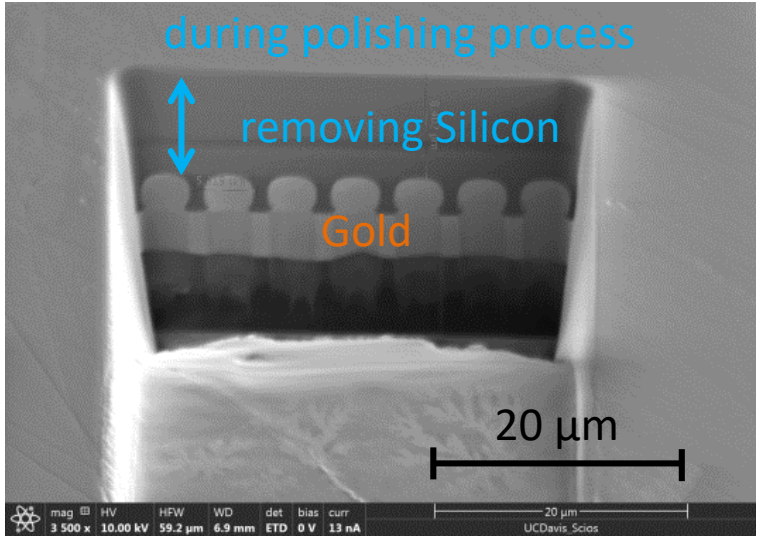


AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)
G. Ranjit et.al., PRA 91, 051805(R) (2015).
G. Ranjit et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Drive Mass fabrication

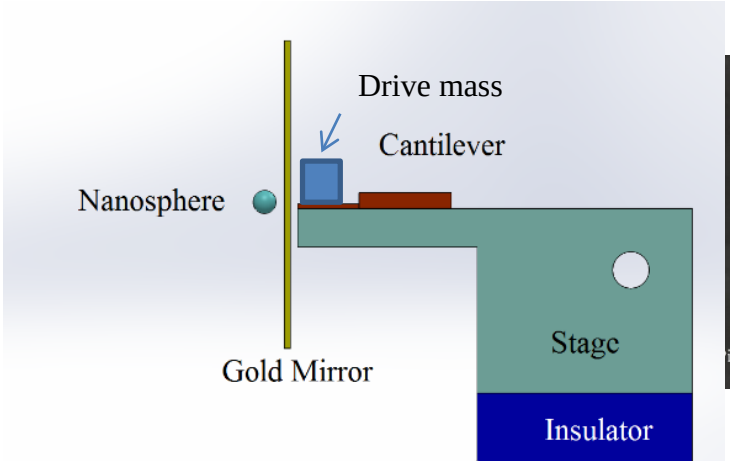


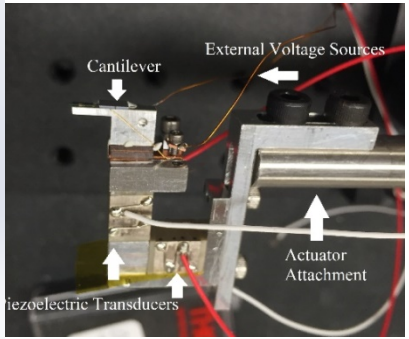
Buried drive mass technique – eliminates corrugation



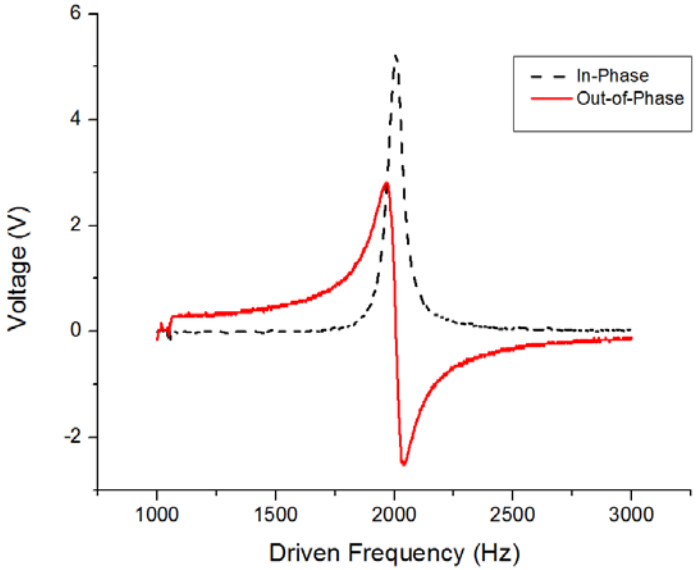
MEMS actuator

- Device for positioning drive mass

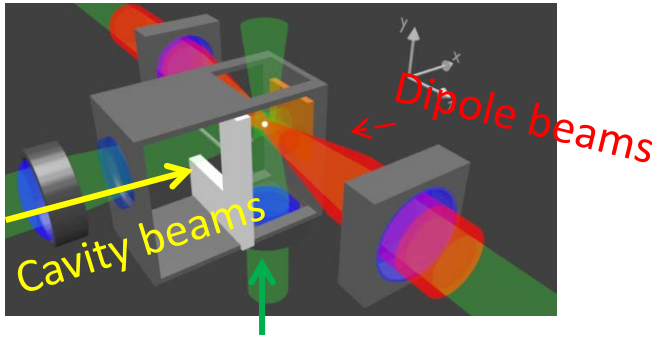


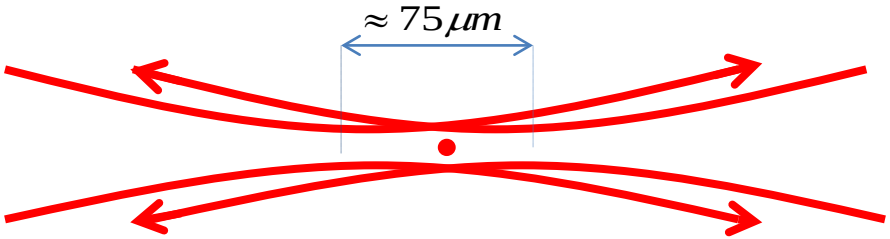


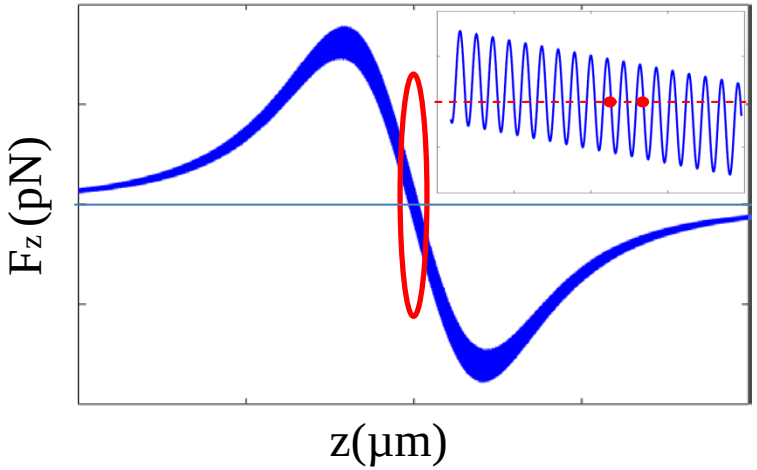
100V DC, 10V AC
~5 um displacement

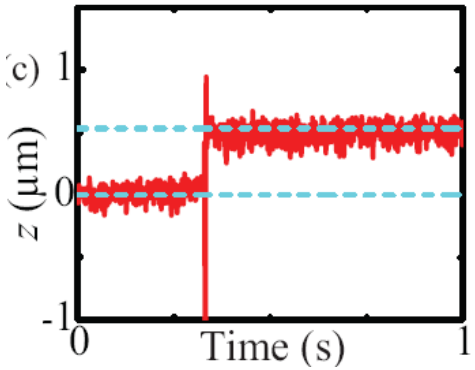


Standing wave optical trap

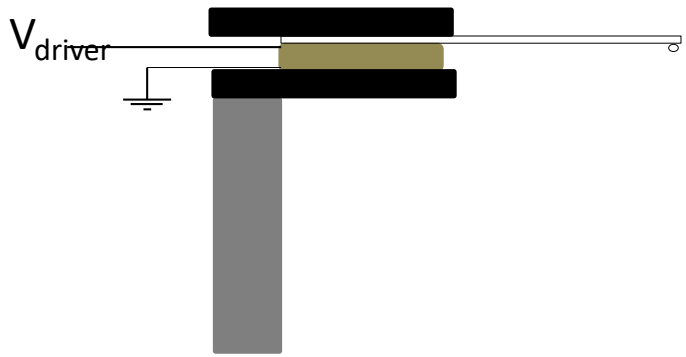


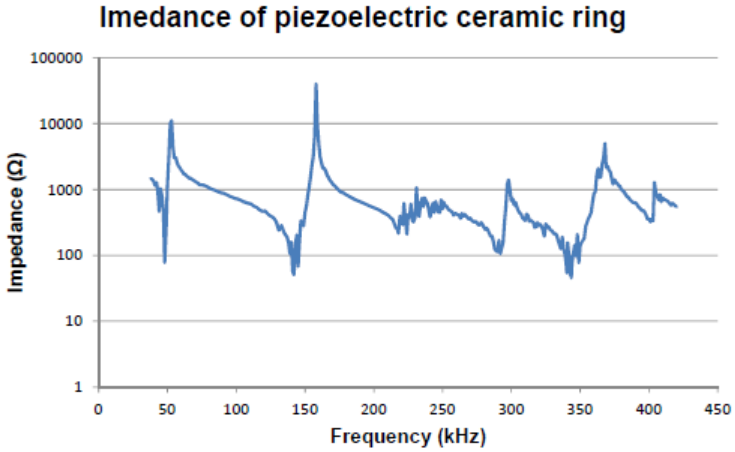






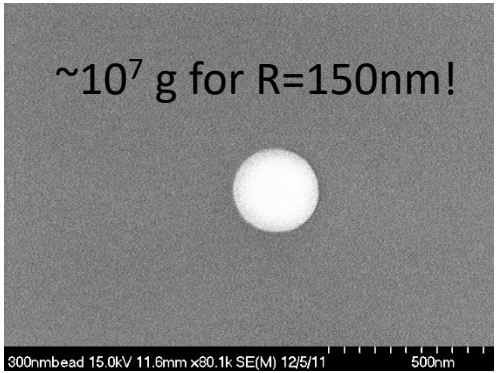
Trap loading



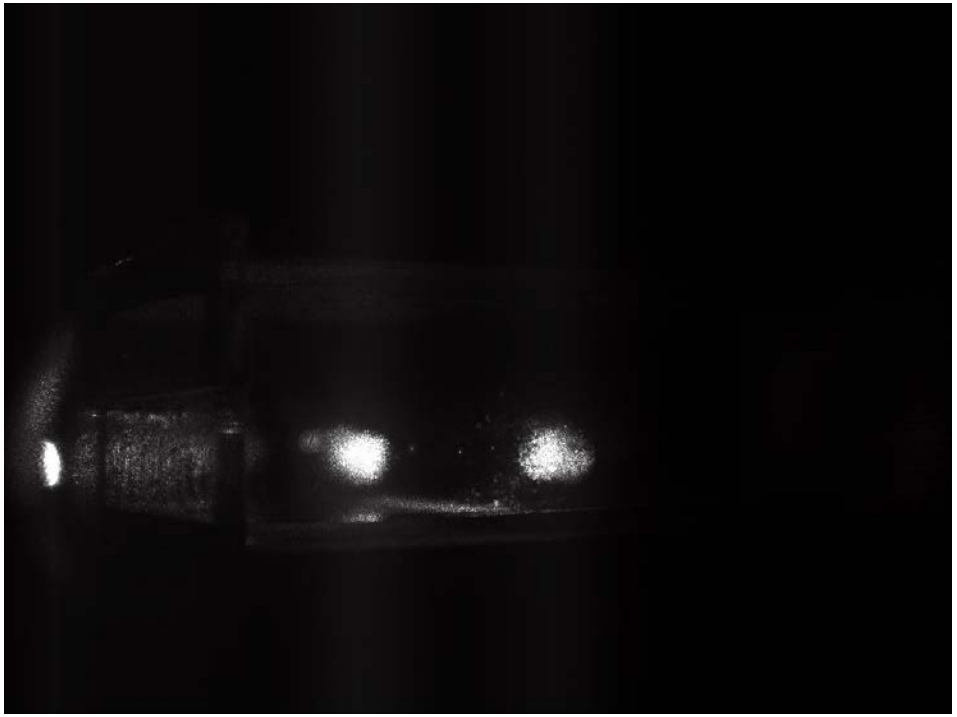


- Acceleration required to release a nanometer-sized sphere from a substrate

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



Loading optical trap



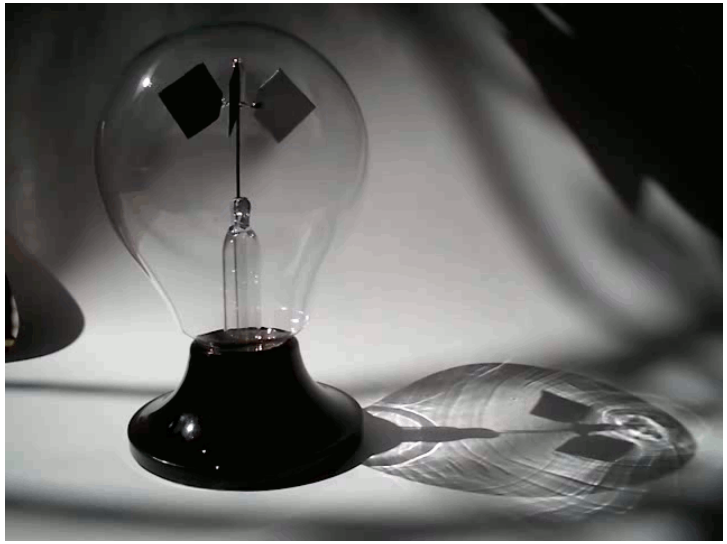
Optical dipole trap lasers

Trapping instabilities

- **Radiometric forces**

Trap instabilities arise from uneven heating of the sphere surface

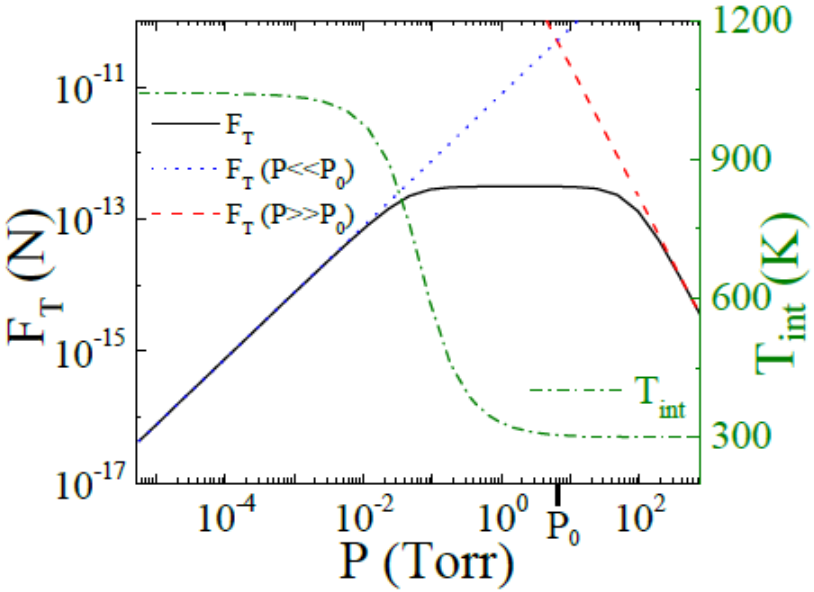
Important when mean free path ~ object size

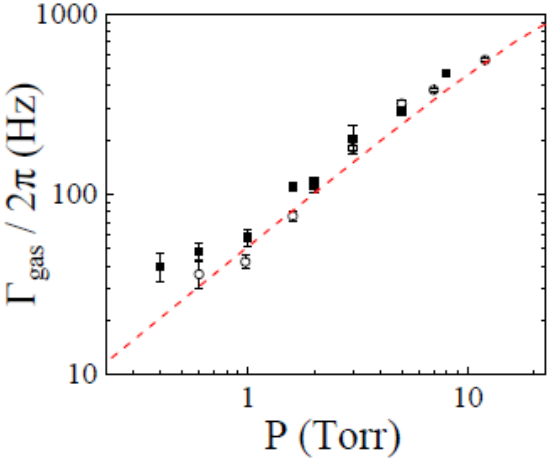


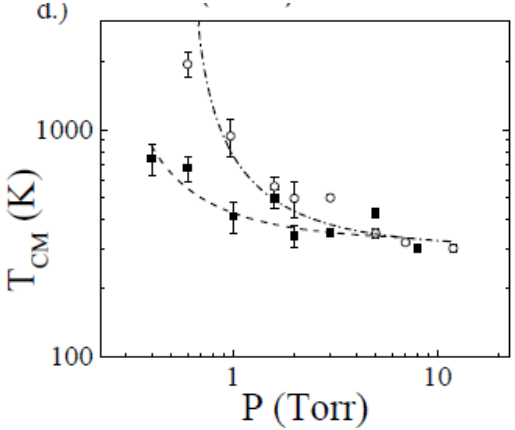
Crooke's Radiometer

Radiometric forces

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







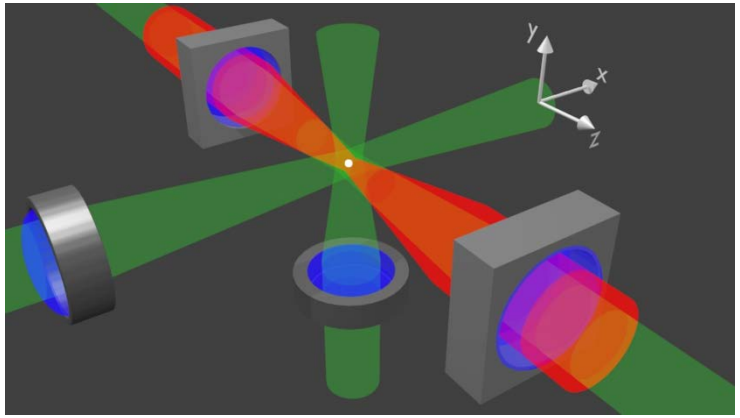
1% temp gradient across surface
R=1.5 μm, I=2 x 10^9 W/m^2

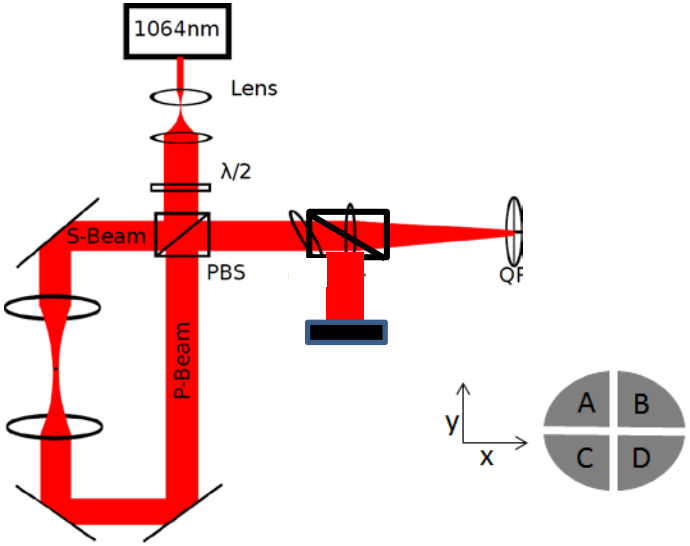
Ranjit et.al., PRA 91, 051805(R) (2015).

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



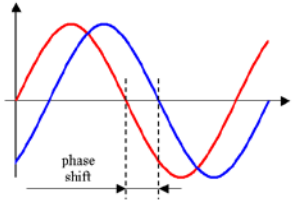


$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

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

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

780 nm

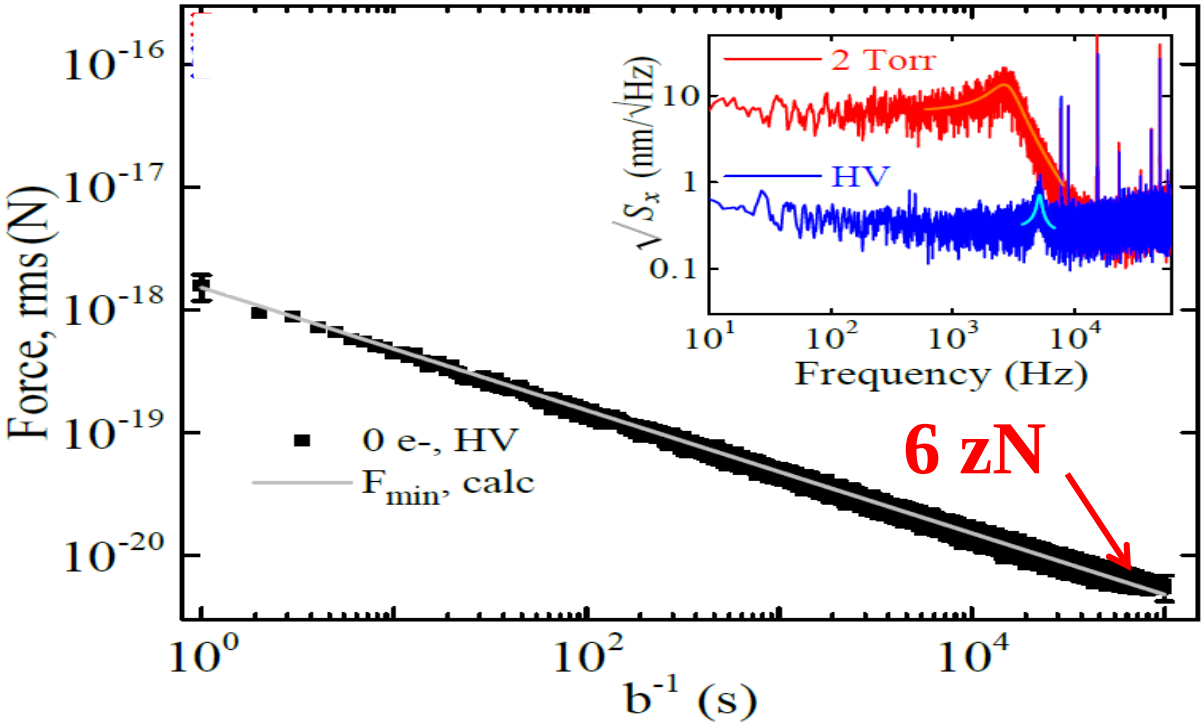


$x(t)$

$v_x(t)$

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

Zeptonewton force sensing



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

Sensitivity

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

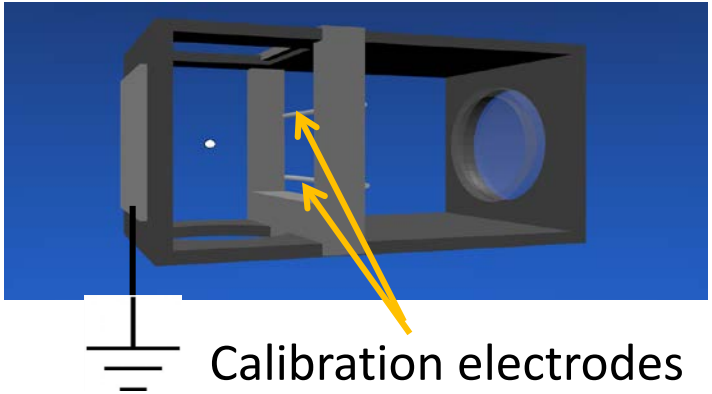
Zeptonewton force sensing

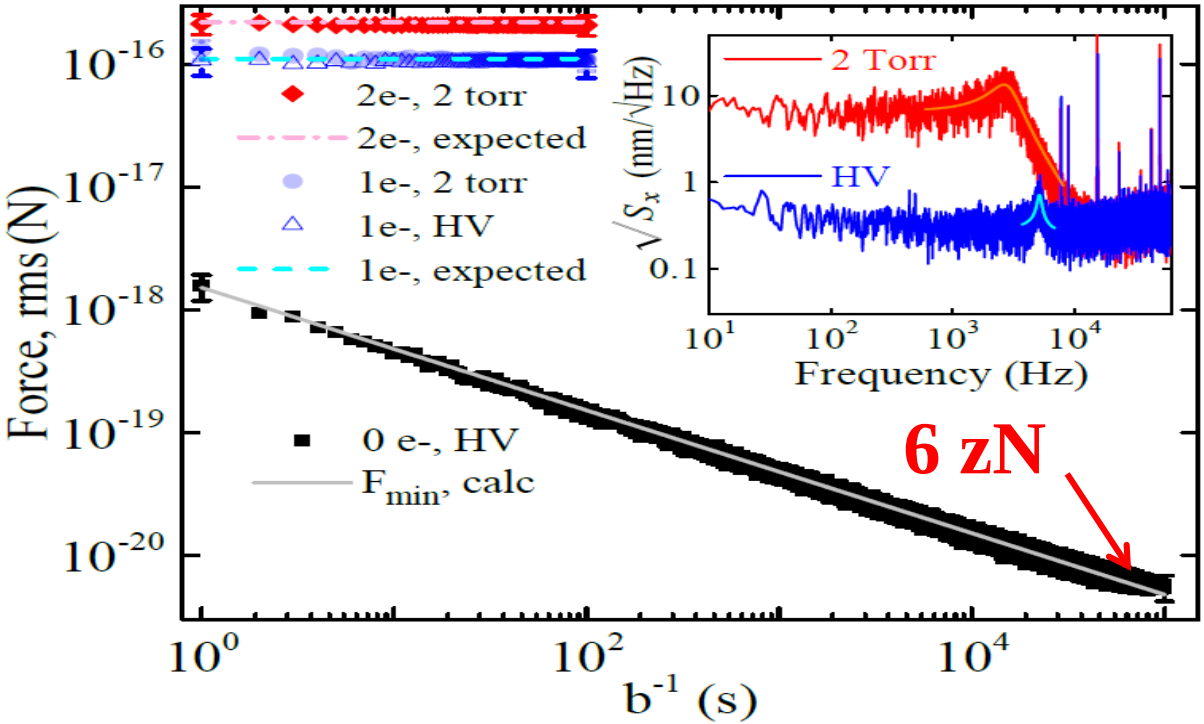
Electrostatic Calibration

90% of beads are neutral

Neutral beads stay neutral

Charge stays constant over days





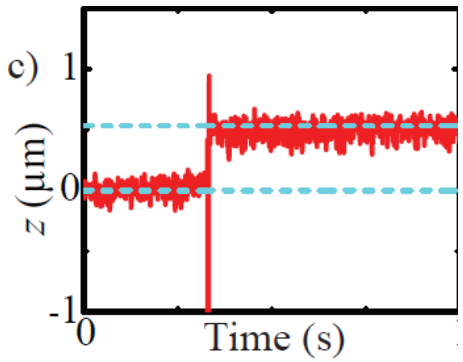
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Sensitivity

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

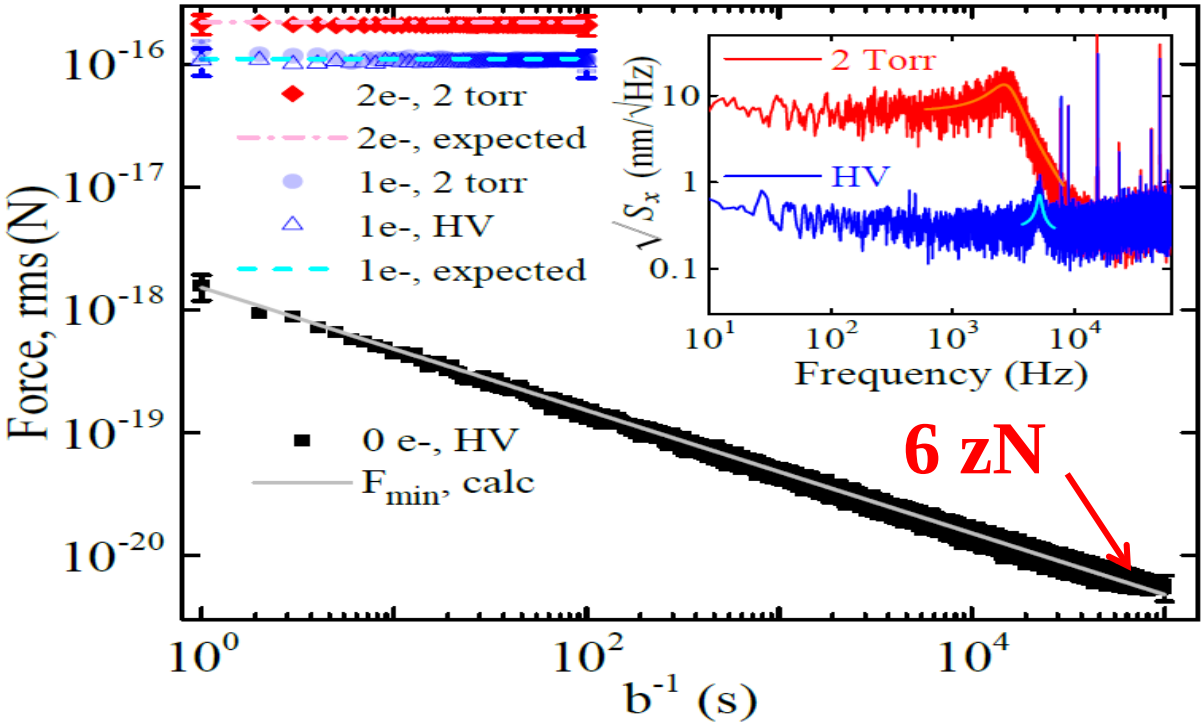
Zeptonewton force sensing

Optical lattice calibration



Useful for neutral objects

Method consistent with electric field approach

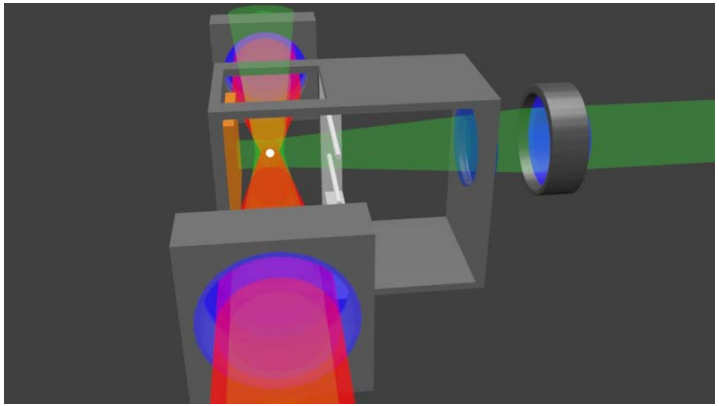


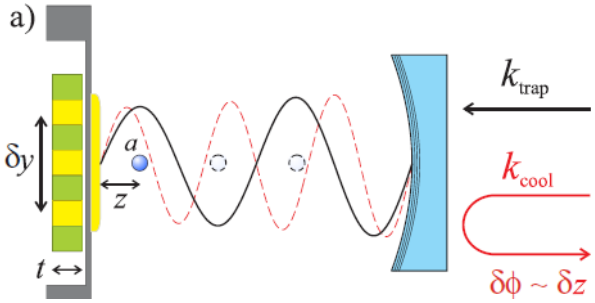
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Sensitivity

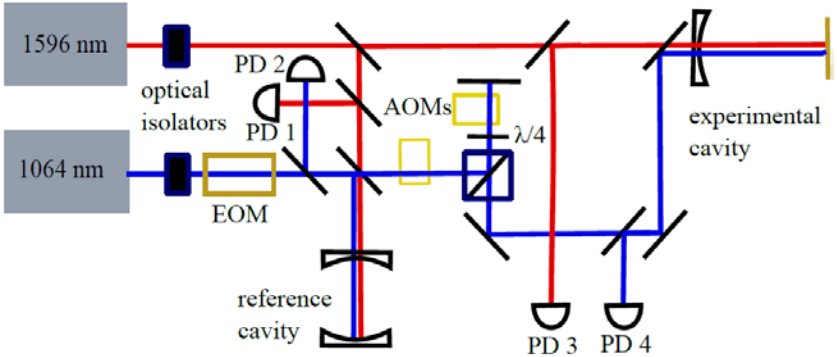
$$S_{F,x} = 1.63 \pm .37 \text{ aN}/\sqrt{\text{Hz}}$$

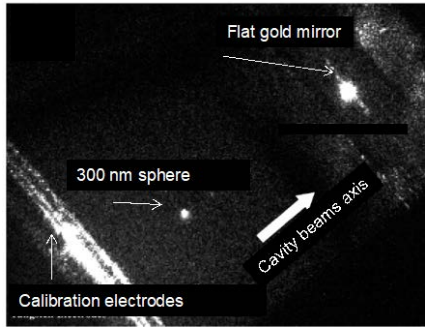
Next: Cavity Trapping and cooling





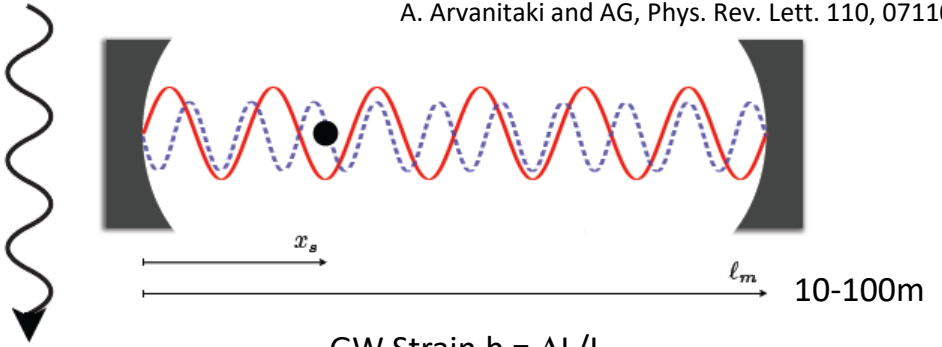
1596nm beam to trap a bead at its antinode → localization
1064nm beam to cavity cool the CM of bead → position readout





Gravitational Wave Detection

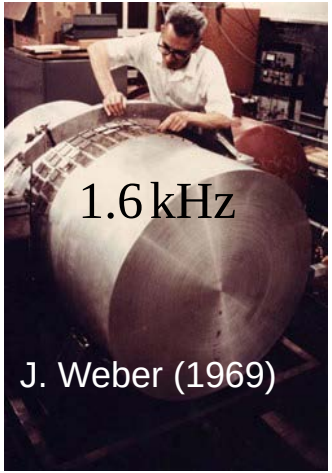
A. Arvanitaki and AG, Phys. Rev. Lett. 110, 071105 (2013)



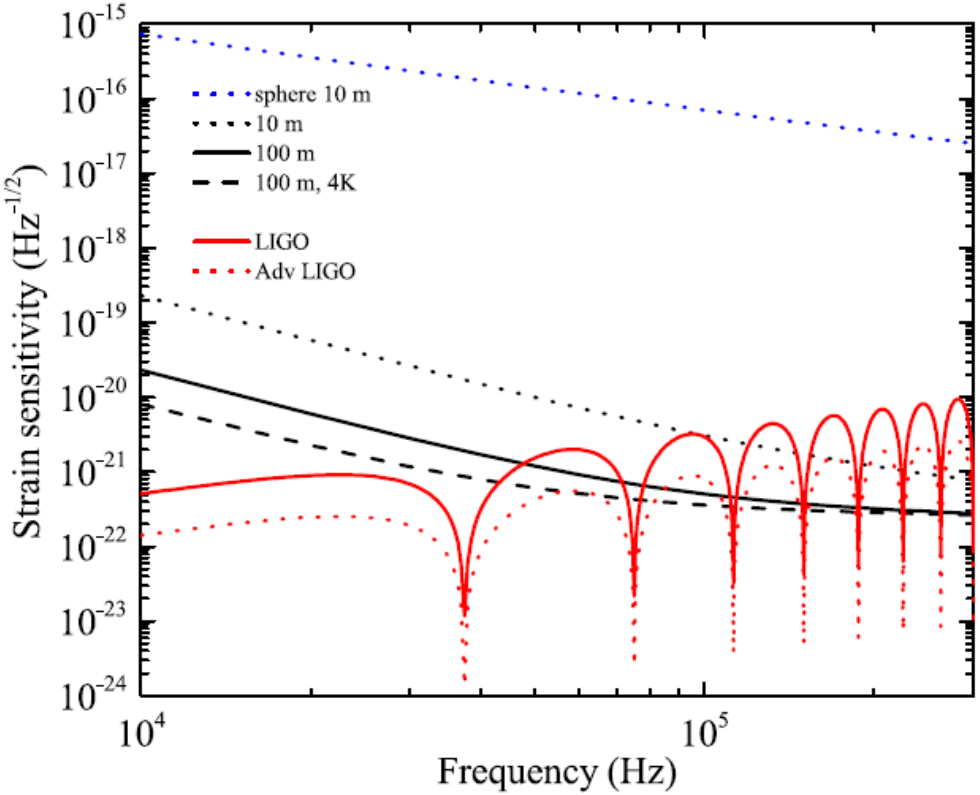
GW Strain h = ΔL/L

- Laser intensity changed to match trap frequency to GW frequency
- For a 100m cavity, $h \sim 10^{-22}$ 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



GW Strain Sensitivity



Size scale: 100 m LIGO

GW sources at high-frequency

- Astrophysical Sources

  Natural upper bound on GW frequency

  inverse BH size ~ 30 kHz

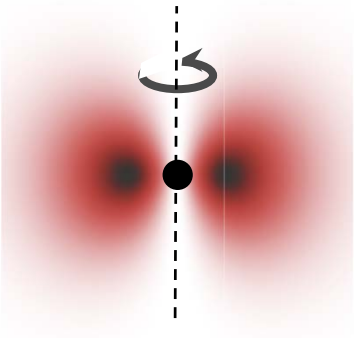
- Beyond standard model physics

  - QCD Axion → Annihilation to gravitons in cloud around Black holes

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

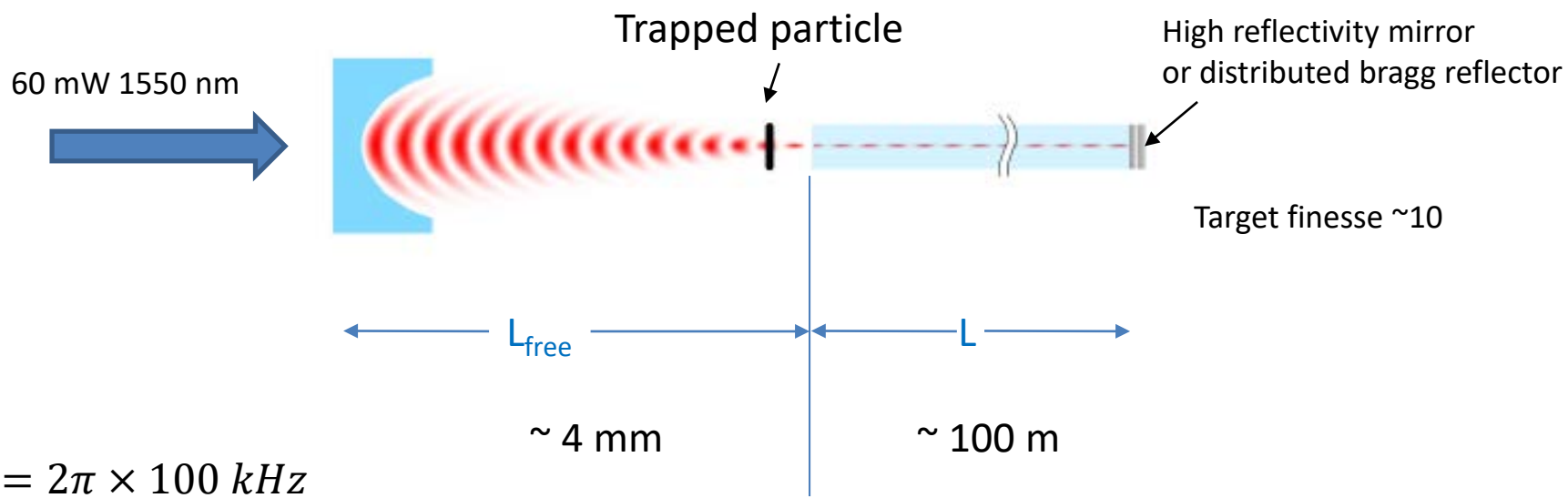
A. Arvanitaki *et al.* PRD 83, 044026 (2011)

Black hole superradiance



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

Fiber based FP Cavity



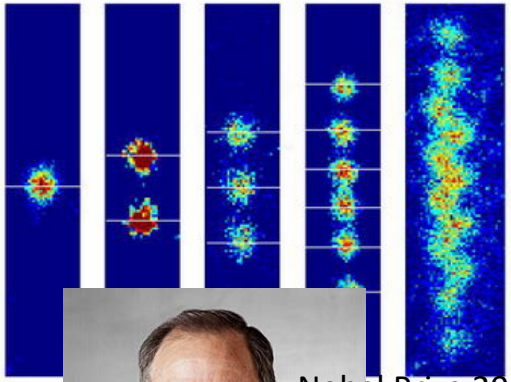
$\omega = 2\pi \times 100\ kHz$

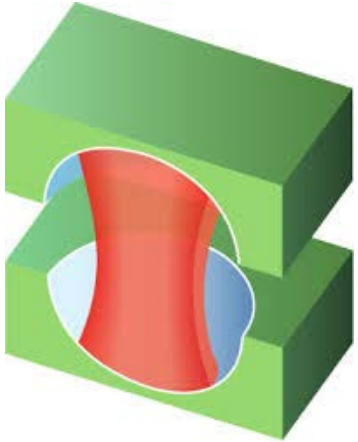
$\kappa = 2\pi$ x 51 kHz

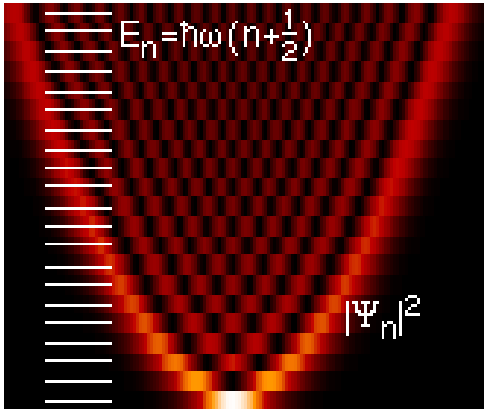
A. Pontin, L.S. Mourounas, AG, and P.F. Barker, arXiv:1706.10227New. J. Phys (2018), accepted

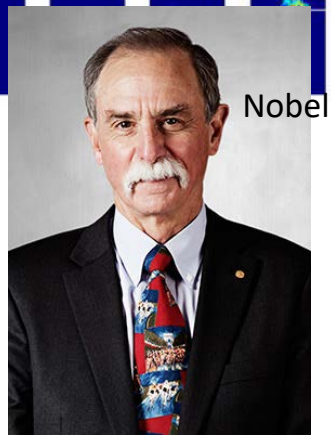
Quantum Regime

High fidelity quantum control:
Internal states | ↑>, | ↓>
motional states
Long coherence times









Nobel Prize 2012

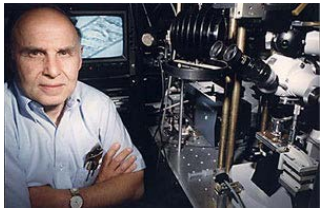
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

https://commons.wikimedia.org/wiki/File:QHarmonicOscillator.png#/media/File:QHarmonicOscillator.png

Levitated optomechanics

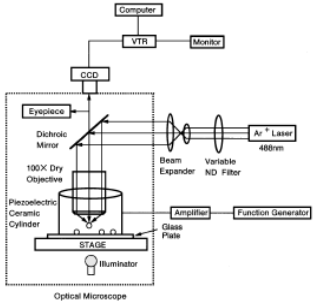
- Ashkin, Bell Labs, 1970s
- Ashkin (76) Levitation in high vacuum

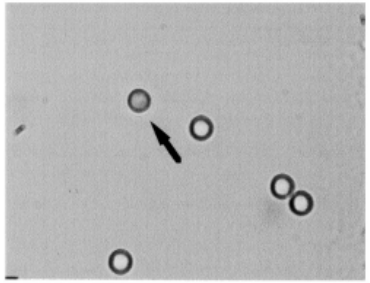
Optical tweezers → biology, biophysics



- Omori (97)

r=1.5,2,2.5 µm





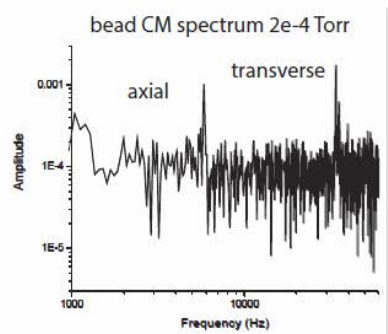
(a)

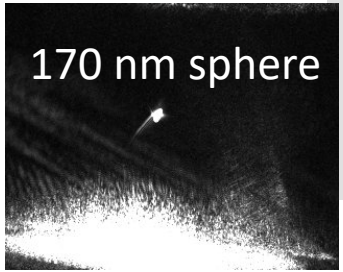
- Recently → proposals/experiments for ground state cooling

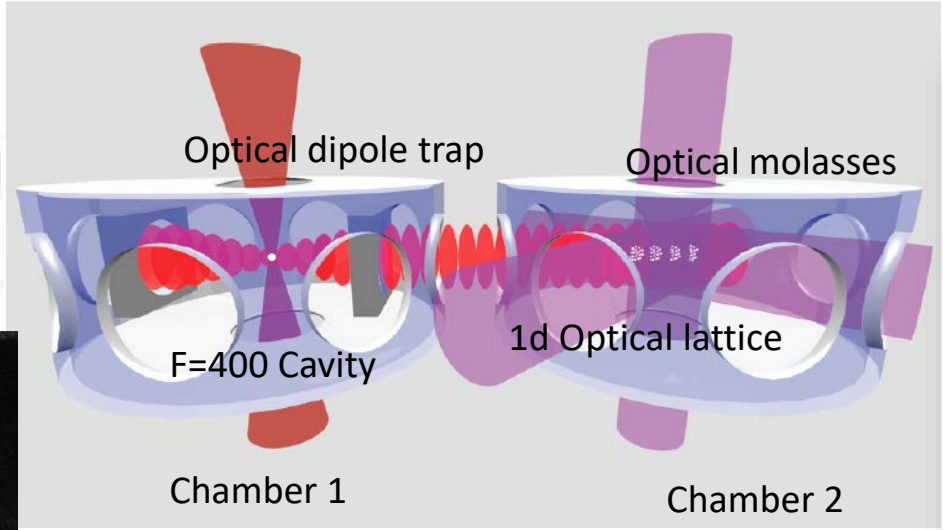
D.E. Chang *et. al.*, PNAS (2009)

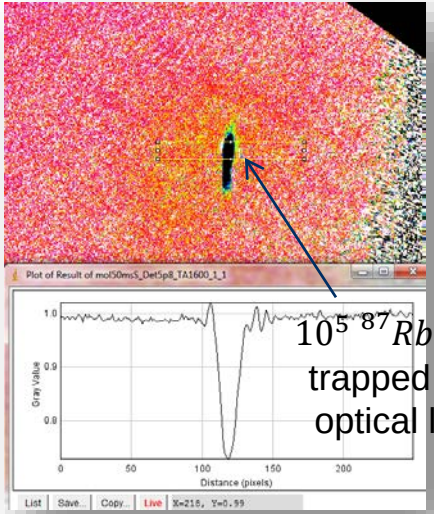
O. Romero-Isart et.al. New J. Phys. (2010)

Sympathetic cooling with cold atoms









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

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

Ground state cooling from room temp

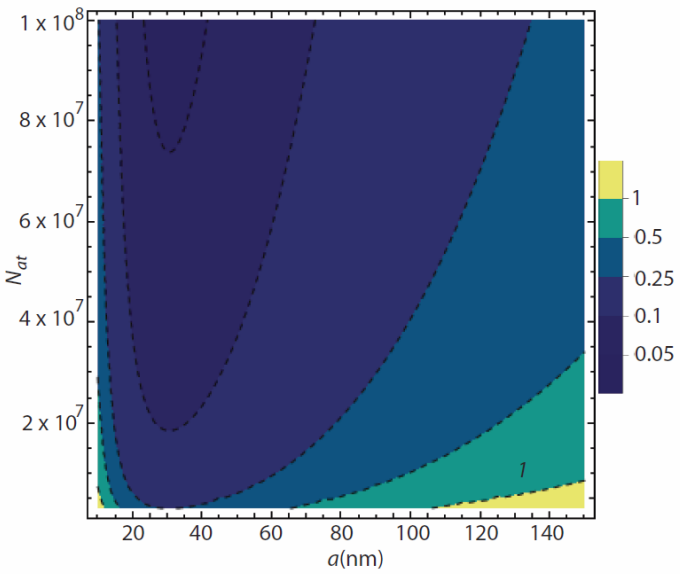
opto-mechanical coupling

$$\Gamma_{\text{cool}} = \gamma_{\text{at}}^{\text{cool}} \frac{g^2}{\Delta_m^2 + (\gamma_{\text{at}}^{\text{cool}}/2)^2}$$

Cooling rate

Mechanical detuning

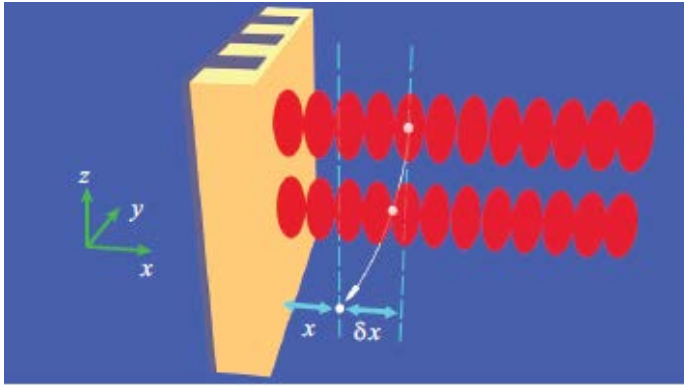
Atom cooling rate

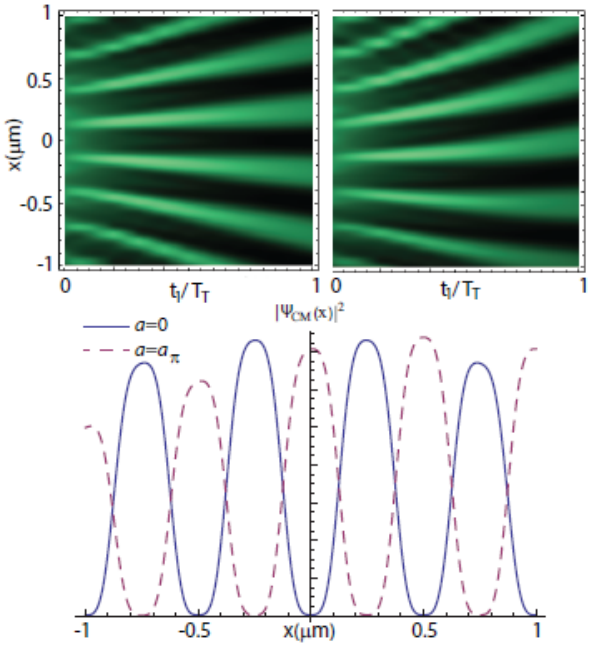


- No ultra-high finesse cavity required (no resolved sideband limit)

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

Matter-wave interferometry

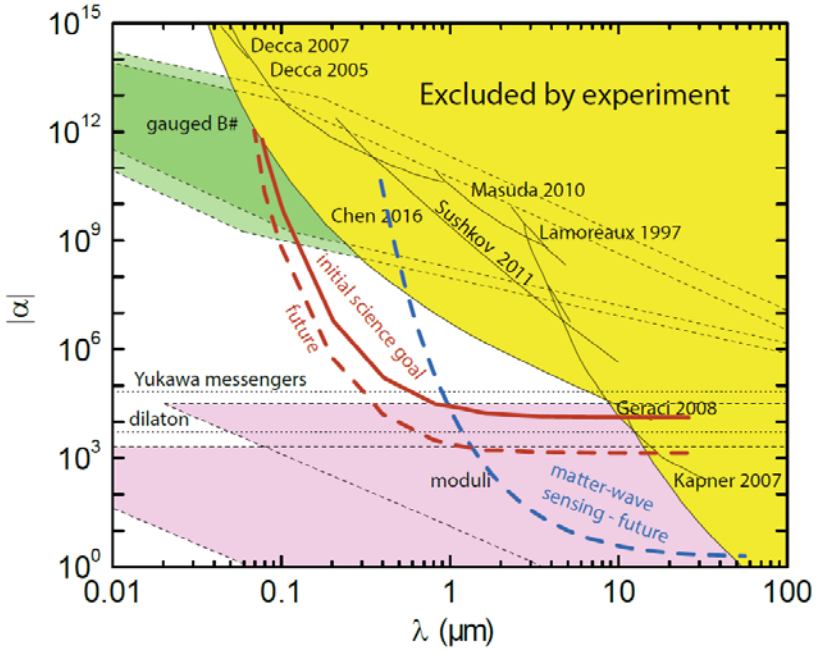




O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, J. I. Cirac
Phys. Rev. Lett. 107, 020405 (2011).
Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht,, Nat. Commun. 5, 4788 (2014).
A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).

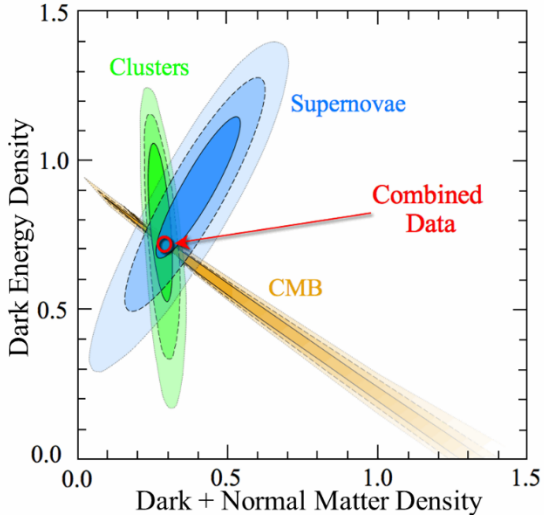
ng acceleration
sensing

Projected reach-
nanosphere matter-wave interferometer

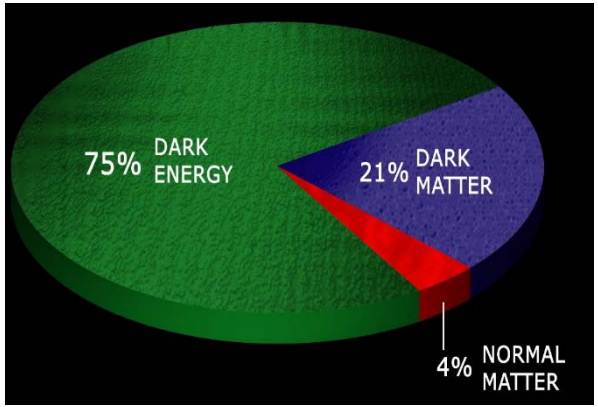


A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).

The Dark Sector



Evidence supporting a universe of dark matter and energy. Image: Kowalski *et al,* Astrophys. J. **686,** 794 (2008).



Our best estimate for composition of universe. Image credit: ADMX

Cosmic Mystery

Enormous detectors to search for heavy dark matter particles, data from particle colliders.
→ no uncontested evidence for the dark sector

Axions

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP problem $\theta_{QCD} < 10^{-10}$
- Dark matter candidate

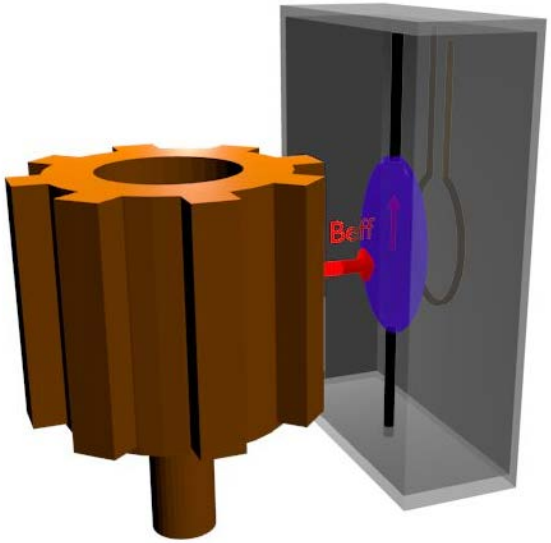
Experiments: e.g. ADMX, CAST, LC circuit, Casper

- Also mediates spin-dependent forces between matter objects at short range (down to 30 µm)

→ Can be sourced locally

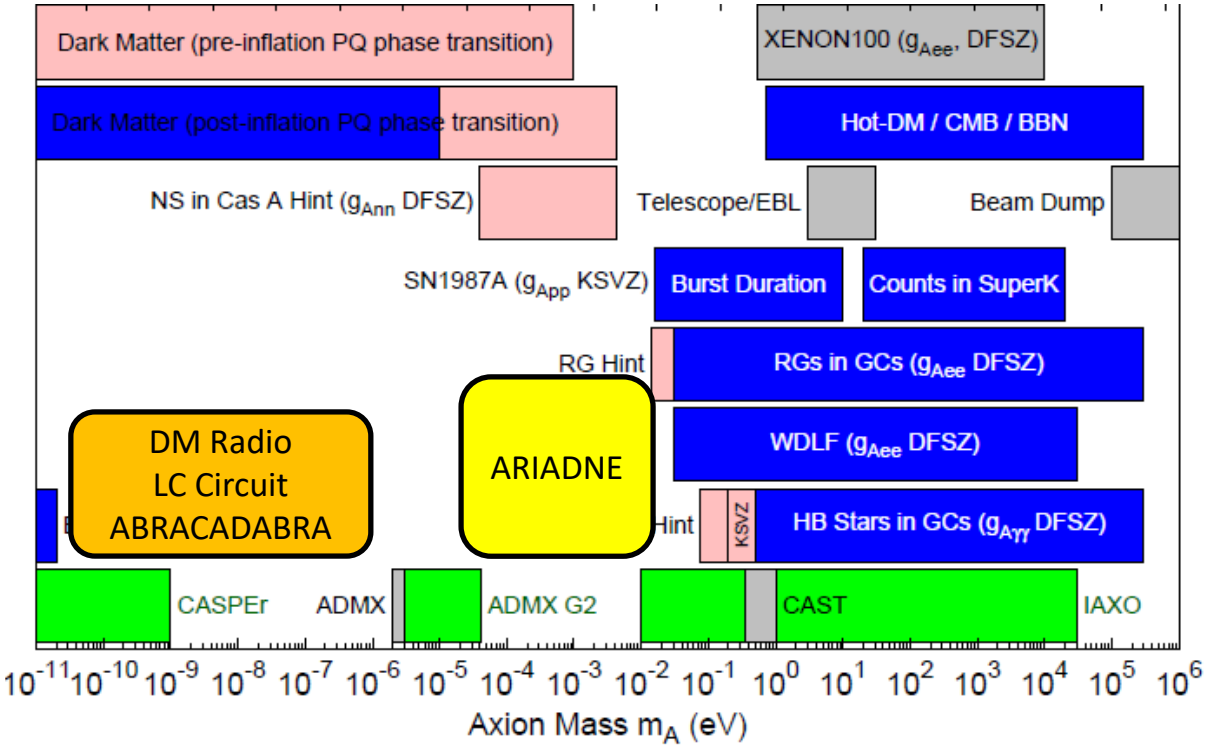
- R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978);
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

The Axion Resonant InterAction Detection Experiment (ARIADNE)



Mindy Harkness (UNR)
Jordan Dargert (UNR)
Chloe Lohmeyer (Northwestern)
Asimina Arvanitaki (Perimeter)
Aharon Kapitulnik (Stanford)
Eli Levenson-Falk (Stanford)
Sam Mumford (Stanford)
Alan Fang (Stanford)
Josh Long (IU)
Chen-Yu Liu (IU)
Mike Snow (IU)
Erick Smith (IU)
Justin Shortino (IU)
Inbum Lee (IU)
Evan Weisman (IU)
Yannis Semertzidis (CAPP)
Yun Shin (CAPP)
Yong-Ho Lee (KRISS)

QCD Axion parameter space



Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion and ALP searches

Source	Coupling: Photons	Coupling: Nucleons
Dark Matter (Cosmic) axions	ADMX, HAYSTACK, DM Radio, LC Circuit, MADMAX, ABRACADABRA	CASPEr
Solar axions	CAST IAXO	
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE

Axion-exchange between nucleons

- Scalar coupling $\propto \theta_{\mathrm{QCD}}$

$$\mathcal{L} \supset \frac{\theta_{QCD}}{f_a}\mu\ a\bar{\psi}\psi$$

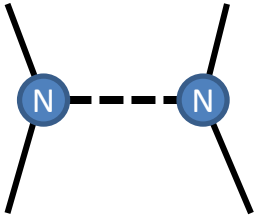
- Pseudoscalar coupling

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma_5\psi$$

In the non-relativistic limit:

$$\mathcal{L} \supset \frac{\vec{\nabla} a}{f_a}\cdot\vec{\sigma}$$

Axion acts a force mediator between nucleons

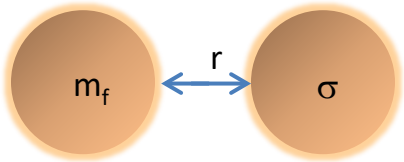


$(g_s^N)^2$ Monopole-monopole

$g_s^N g_P^N$ Monopole-dipole

$(g_p^N)^2$ dipole-dipole

Spin-dependent forces



Monopole-Dipole axion exchange

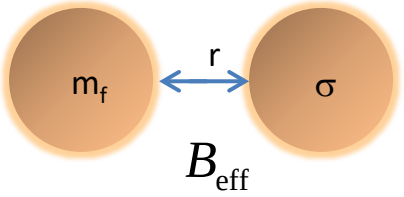
$$U(r) = \frac{\hbar^2 g_s{}^N g_p{}^N}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r}) \quad \equiv \mu \cdot B_{\text{eff}}$$

$m_a < 6$ meV → $\lambda_a > 30$ μm

Fictitious magnetic field

- Different than ordinary B field
- Does not couple to angular momentum
- Unaffected by magnetic shielding

Using NMR for detection

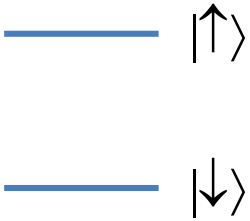


Spin ½ ^{3}He Nucleus

$$U = \mu \cdot B_{\text{ext}}$$

Bloch Equations

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$

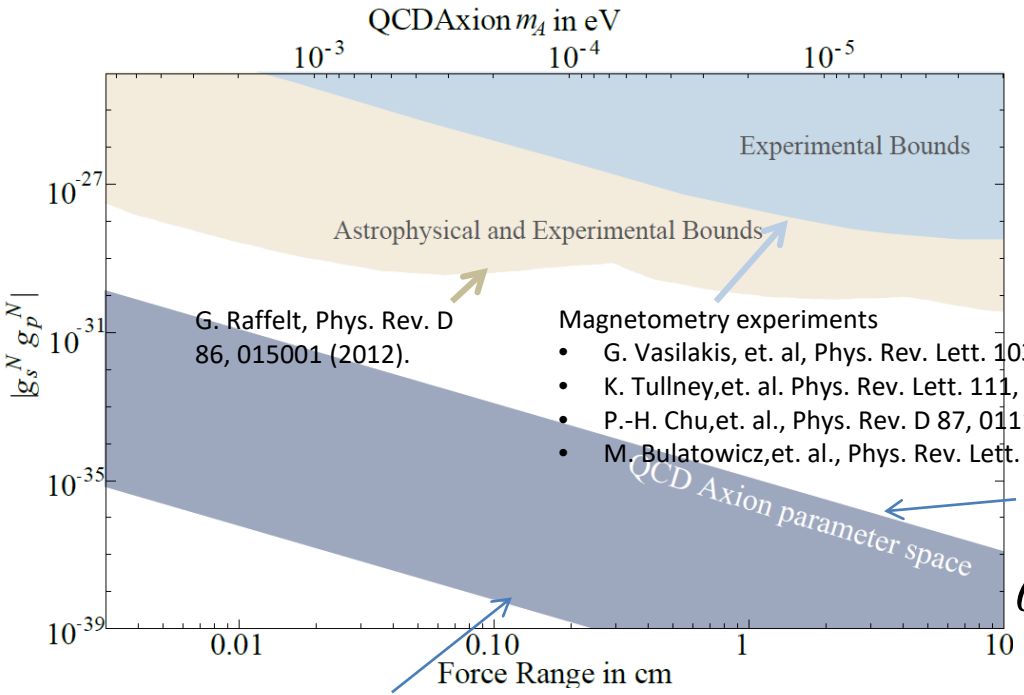


$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

Spin precesses at nuclear spin Larmor frequency $\omega = \gamma B$

Axion B_{eff} modifies measured Larmor frequency

Constraints on spin dependent forces



G. Raffelt, Phys. Rev. D 86, 015001 (2012).

Magnetometry experiments

- G. Vasilakis, et. al, Phys. Rev. Lett. 103, 261801 (2009).
- K. Tullney,et. al. Phys. Rev. Lett. 111, 100801 (2013)
- P.-H. Chu,et. al., Phys. Rev. D 87, 011105(R) (2013).
- M. Bulatowicz,et. al., Phys. Rev. Lett. 111, 102001 (2013).

nEDM bound

$$\theta_{QCD} < 10^{-10}$$

Standard Model lower bound

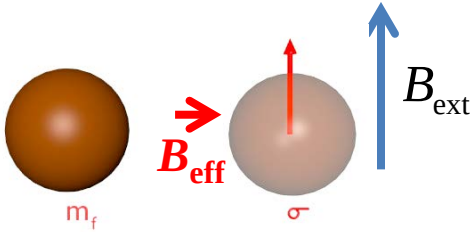
$$\theta_{QCD} > 10^{-16}$$

ARIADNE: uses resonant enhancement

Oscillate the mass at Larmor frequency

$$B_{\text{eff}} = B_{\perp}\cos(\omega t)$$

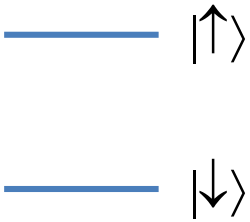
Spin ½ ^{3}He Nucleus



$$U = \mu \cdot B_{\text{ext}}$$

Bloch Equations

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$



$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

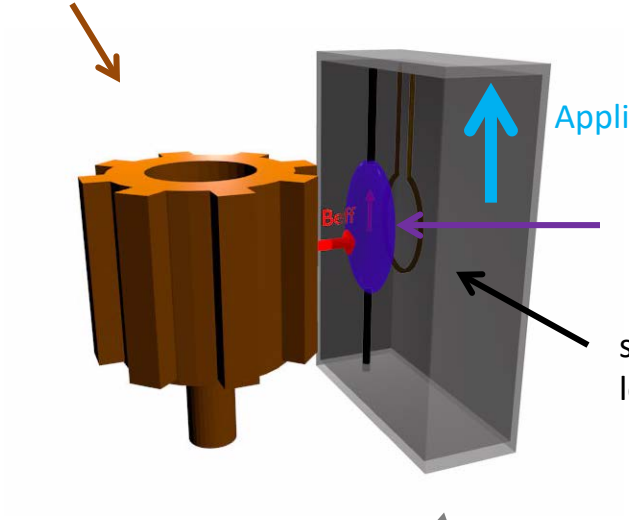
Time varying Axion B_{eff} drives spin precession → produces transverse magnetization

Amplitude is resonantly enhanced by Q factor ~ ωT_2.

Can be detected with a SQUID

Concept for ARIADNE

Unpolarized (tungsten) segmented cylinder sources B_{eff}



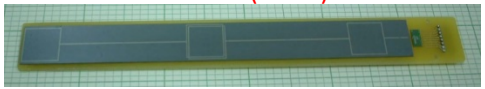
Applied Bias field B_{ext}

$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

Laser Polarized ^{3}He gas senses B_{eff} (Indiana U)

squid pickup loop

Y.-H. Lee (KRISS)



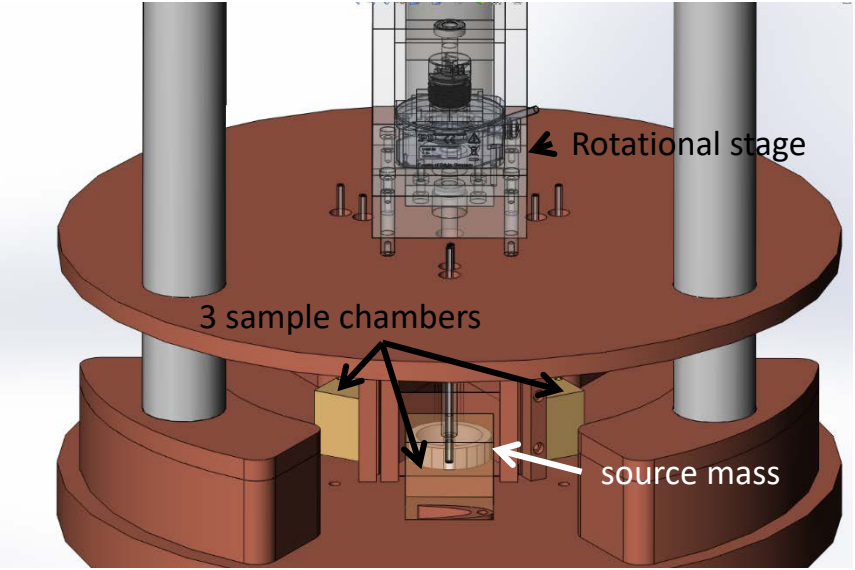
Superconducting shielding (Stanford)

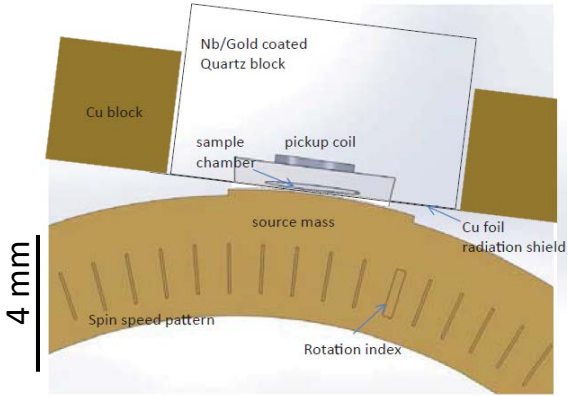
Limit: Transverse spin projection noise

$$B_{\min} \approx p^{-1}\sqrt{\frac{2\hbar}{n_s \mu^3_{\text{He}} \gamma V T_2}} = 10^{-20}\frac{T}{\sqrt{Hz}} \times \left(\frac{1}{p}\right)\left(\frac{1\ \text{cm}^3}{V}\right)^{1/2}\left(\frac{10^{21}\ \text{cm}^{-3}}{n_s}\right)^{1/2}\left(\frac{1000\ \text{sec}}{T_2}\right)^{1/2}$$

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

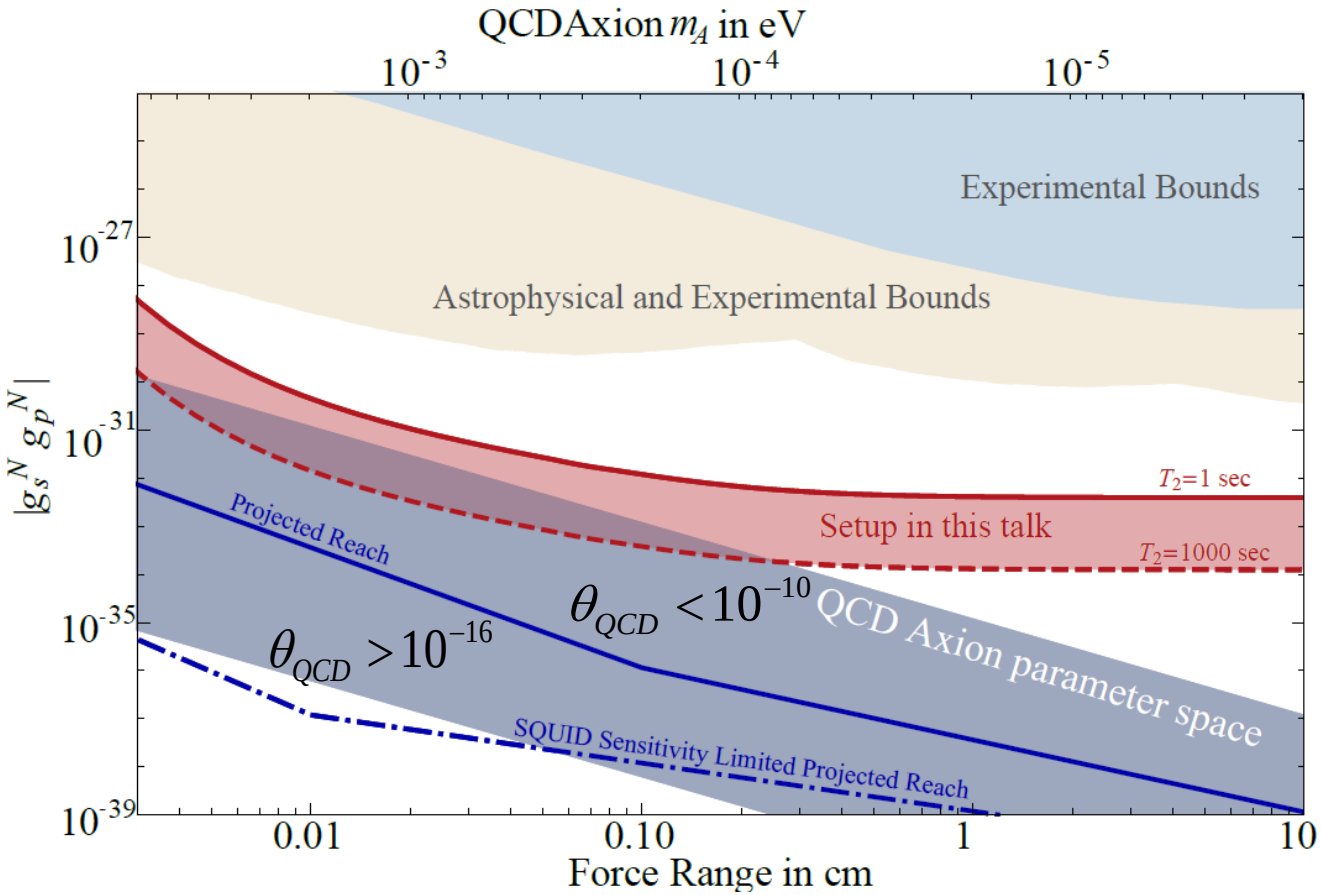
Experimental parameters





11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

Sensitivity



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

Experimental challenges

Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients	3×10^{-6} T/m	Limits T_2 to ~ 100 s Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at $\omega_{\rm rot}$
External vibrations	5×10^{-20} T/$\sqrt{\rm Hz}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\rm patch}}{0.1{\rm V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\rm Hz}$	Assuming $1\mu\Phi_0/\sqrt{\rm Hz}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\rm T}{\sqrt{\rm Hz}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})$T/$\sqrt{\rm Hz}$	f is SC shield factor (100 Hz)
Barnett Effect	$10^{-22}(\frac{10^8}{f})$ T	Can be used for calibration above 10 K
Magnetic Impurities in Mass	$10^{-25} - 10^{-17}(\frac{\eta}{1{\rm ppm}})(\frac{10^8}{f})$ T	η is impurity fraction (see text)
Mass Magnetic Susceptibility	$10^{-22}(\frac{10^8}{f})$ T	Assuming background field is 10^{-10} T Background field can be larger if $f > 10^8$

Table 1: Table of estimated systematic error and noise sources, as discussed in the text. The projected sensitivity of the device is $3 \times 10^{-19}(\frac{1000{\rm s}}{T_2})$ T/$\sqrt{\rm Hz}$

- Design/Simulation Work: Magnetic gradient reduction strategy
- Experimental testing in progress: Vibration tests, Shielding factor *f* test thin-film SC

Superconducting Magnetic Shielding

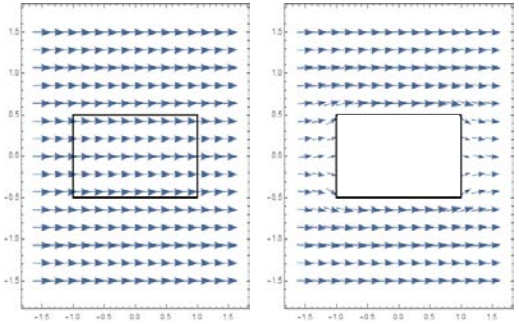
→ Essential to avoid Johnson noise

Meissner Effect

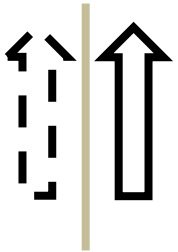
- No magnetic flux across superconducting boundary

Method of Images

- Make “image currents” mirrored across the superconducting boundary



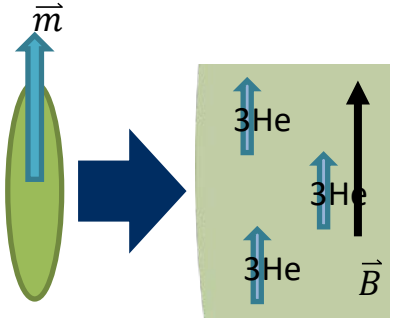
$T > T_c$ $T < T_c$



Dipole with image

The Problem of Unwanted Images

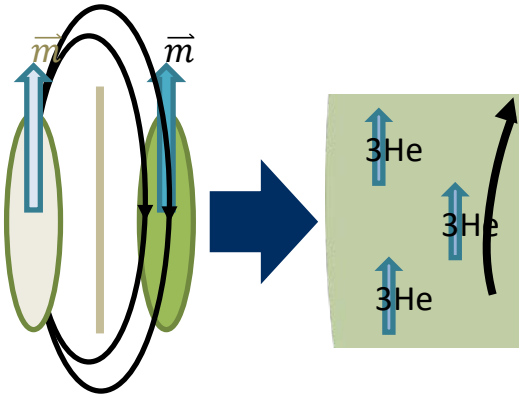
- ARIADNE uses magnetized spheroid
  - Constant interior field



- $B_{in} = \text{const.}$
- $\overrightarrow{B_{in}} \parallel \overrightarrow{m_i}$

- Magnetic shielding introduces "image spheroid"
  Interior field varies

→ variations in nuclear Larmor frequency

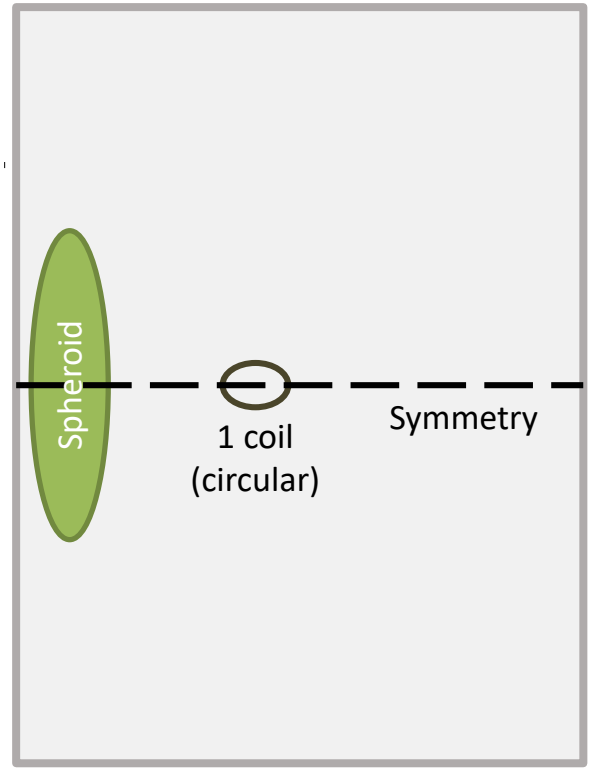


- $B_{in} \neq \text{const.}$
- $\overrightarrow{B_{in}} \nparallel \overrightarrow{m_i}$

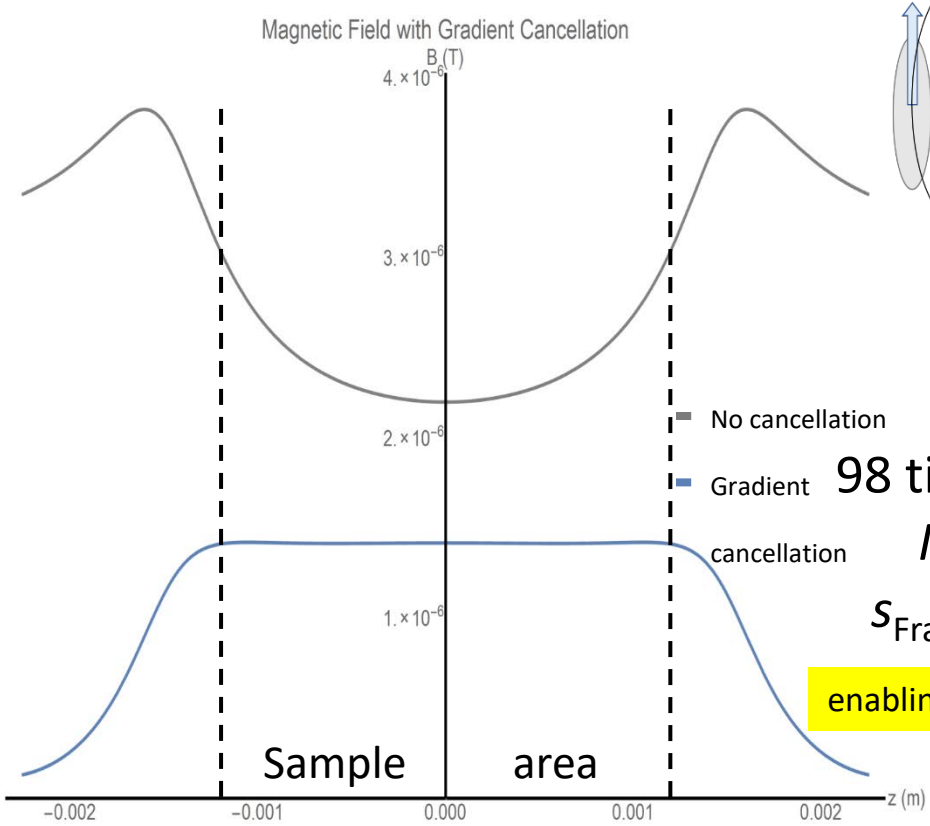
But want to drive entire sample on resonance

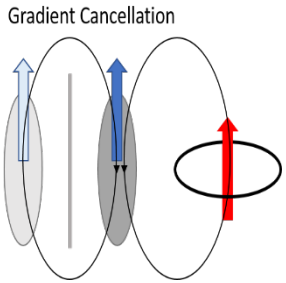
Flattening Solution

- 1 coil – simple configuration
- Expected field from spheroid ~1 μT
  - I on the 0.1 – 1 A range



Gradient Cancellation





98 times flatter

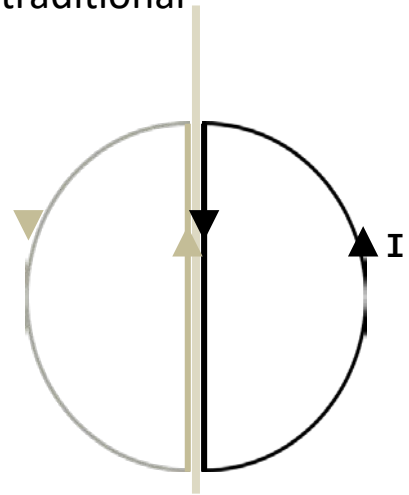
I = 1.6 A

s_{Frac} = 0.17%

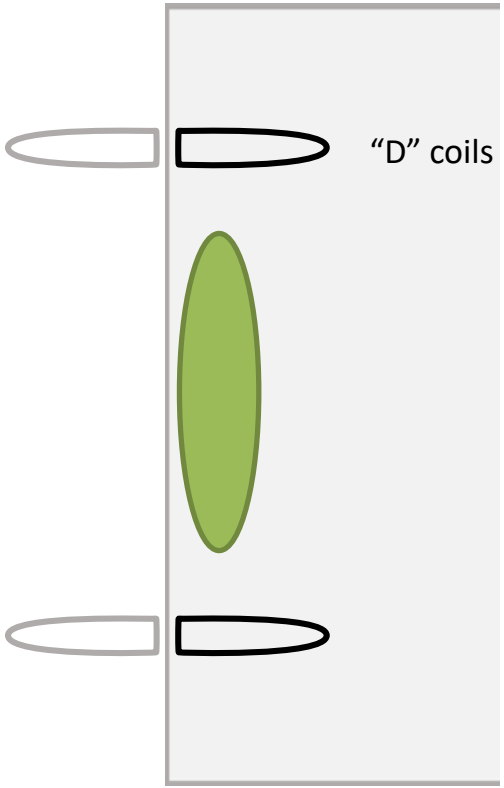
enabling T_2 of ~100 s

Tuning Solution – “D” Coils

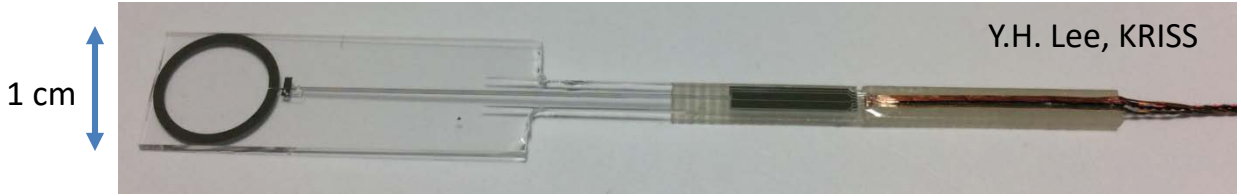
- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils
- “D” coils look like Helmholtz coils when their images are included
- Inner straight-line currents cancel
- Outer currents do not

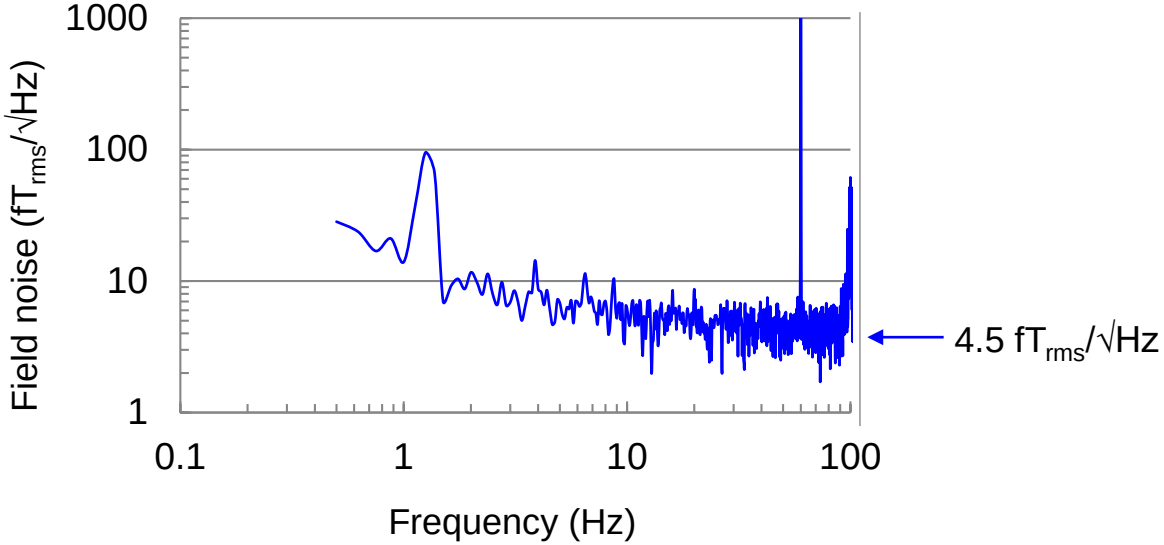


One “D” coil and image (bird’s eye view)



SQUID Magnetometers

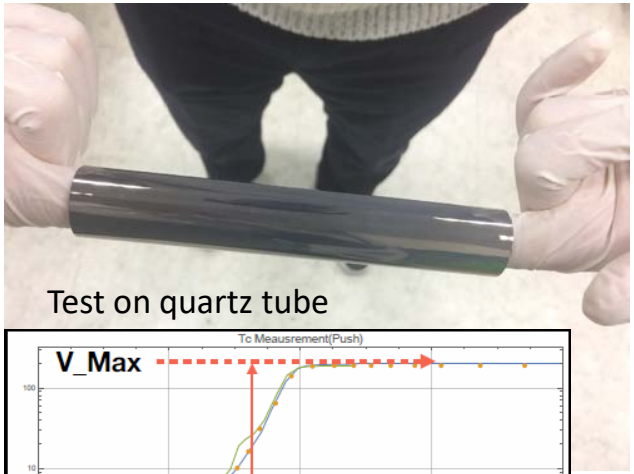


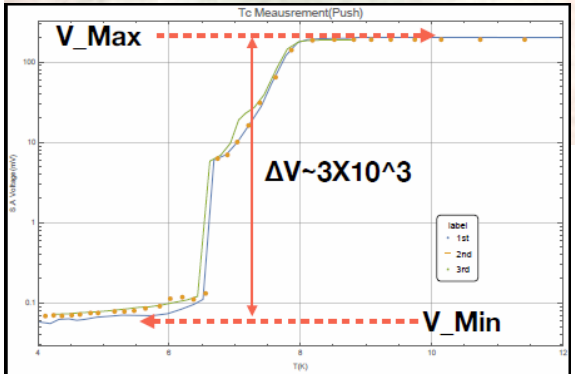


Measured inside a magnetically shielded room (without Nb tube)

Nb sputtering tests

Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov
CAPP/IBS



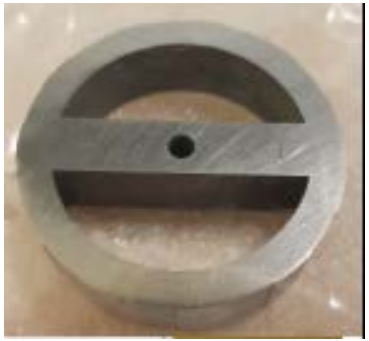


Thickness of deposition : ~ 1um
Tc = 7.3K

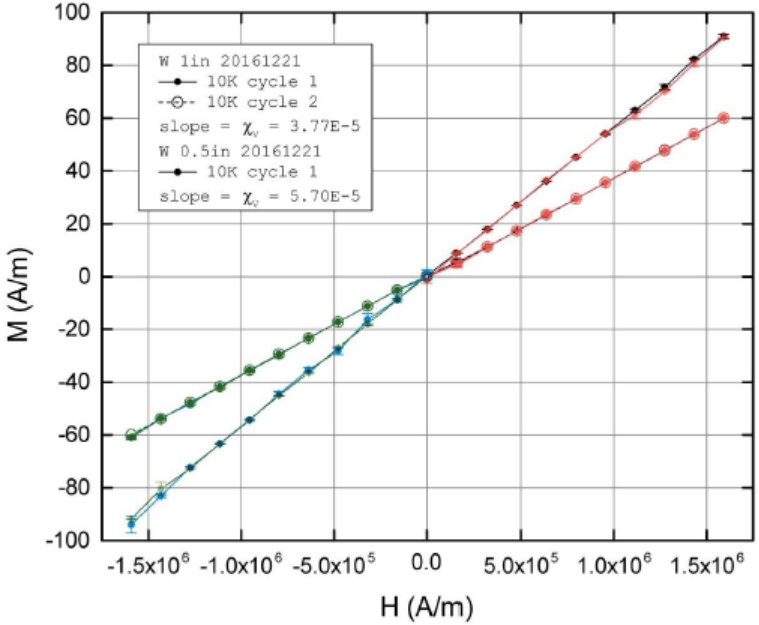
Work in progress on optimizing Tc and adhesion

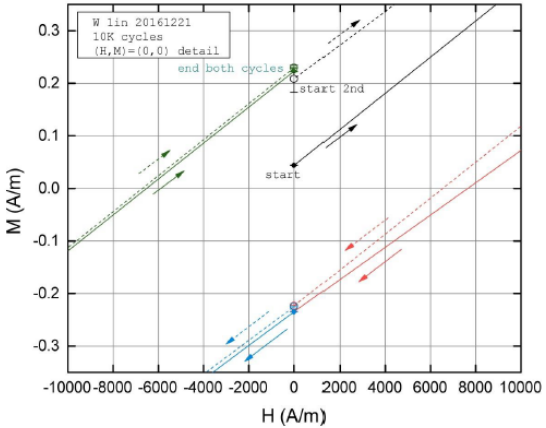
Tungsten Source Mass Prototype

11 segments, 3.8 cm diameter Tungsten
Sprocket prototype, Wire EDM



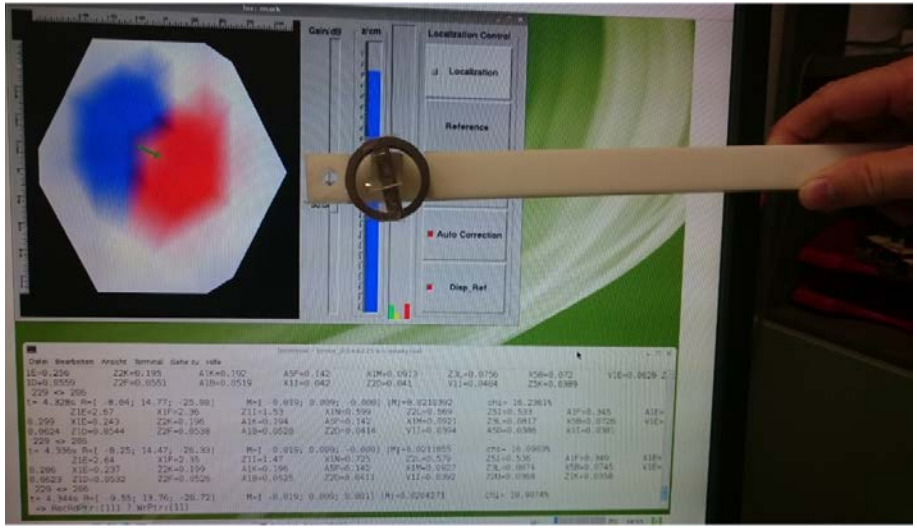
Magnetic impurity testing in Tungsten
using commercial SQUID magnetometer -- Indiana





Magnetic impurities below 0.4 ppm

Residual magnetization

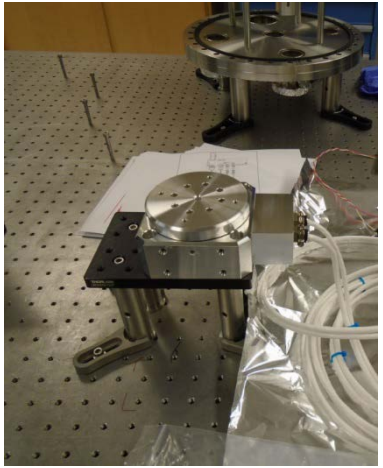


Nov 2017 In collaboration with Lutz Trahms, PTB, SQUID measurements in shielded room

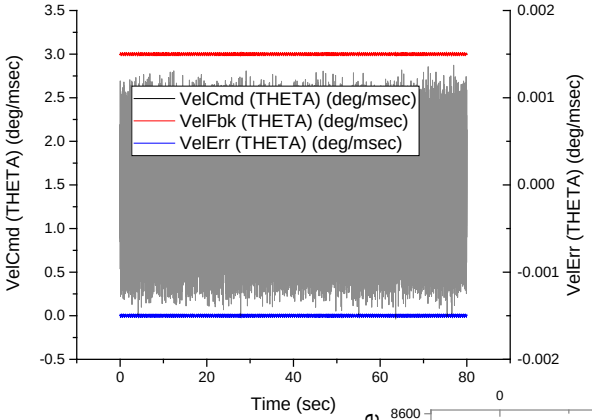
- after degaussing, field approx. 2pT near surface in range of noise
- Johnson noise < 1-2 pT, agreeing with expectations
- Looks promising for target shielding factor of Nb film!

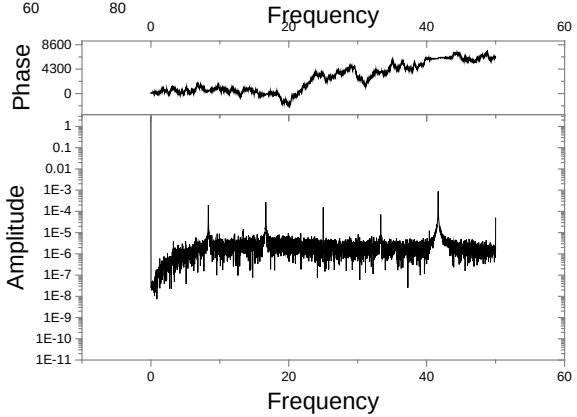
Speed stability test - direct drive stage

- Optical encoder
- Current feedback control



Stage speed stability error – unloaded, in air





Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T2 > 100s

Ultra-light scalar Dark Matter

- Dark Matter mass scales:

  $>10^{-22}$ eV (size of dwarf galaxies)

➢ Ultralight DM looks like coherent field rather than particle

$$\phi(\boldsymbol{r}, t) = \phi_0 \cos\left(\omega_\phi t - \boldsymbol{k}_\phi \cdot \boldsymbol{r} + \ldots\right).$$

$$\phi_0 = \hbar\sqrt{2\rho_{\mathrm{DM}}}/(m_\phi c)$$

➢ Techniques for detecting oscillating scalar DM:

- Atomic clocks
- Bar detectors
- Torsion Balances
- Atom Interferometers

Asimina Arvanitaki, Savas Dimopoulos, and Ken Van Tilburg, Phys. Rev. Lett. **116**, 031102 (2016)
Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, Phys. Rev. D 91, 015015 (2015)
Asimina Arvanitaki, Peter W. Graham, Jason M. Hogan, Surjeet Rajendran, and Ken Van Tilburg
Phys. Rev. D 97, 075020 (2018)
Peter W. Graham, David E. Kaplan, Jeremy Mardon, Surjeet Rajendran, William A. Terrano
Phys. Rev. D 93, 075029 (2016)

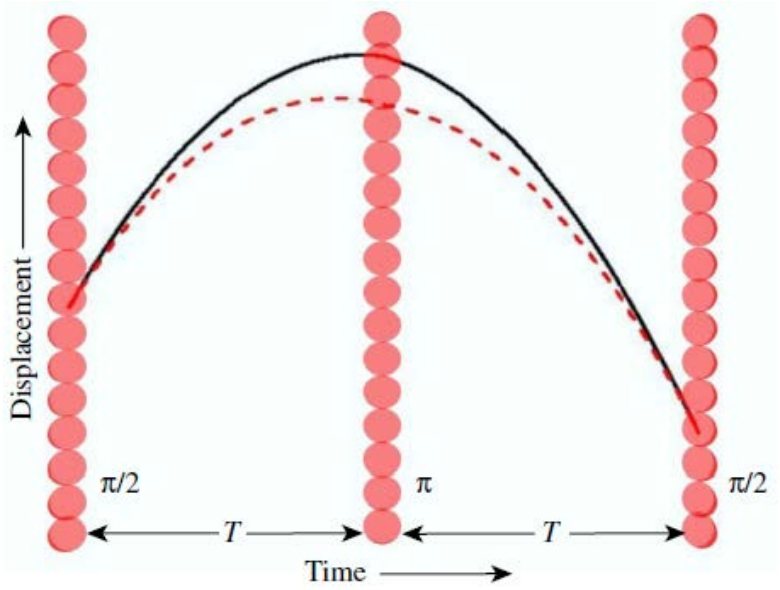
Time-varying acceleration of earth and masses of atoms

$$\frac{\Delta g_n}{g} = \frac{\Delta M_\oplus}{M_\oplus}$$
$$= \left(\frac{2\rho_{\rm DM}\hbar^3}{m_\phi^2 c \Lambda_n^2}\right)^{n/2} \times \frac{1}{2^{(n-1)}} \cos(n\omega_\phi t - n\boldsymbol{k}_\phi \cdot \boldsymbol{r} + \ldots)$$

$$g(t) = g_0[1 + \delta_g \cos(\omega t + \theta_0)],$$

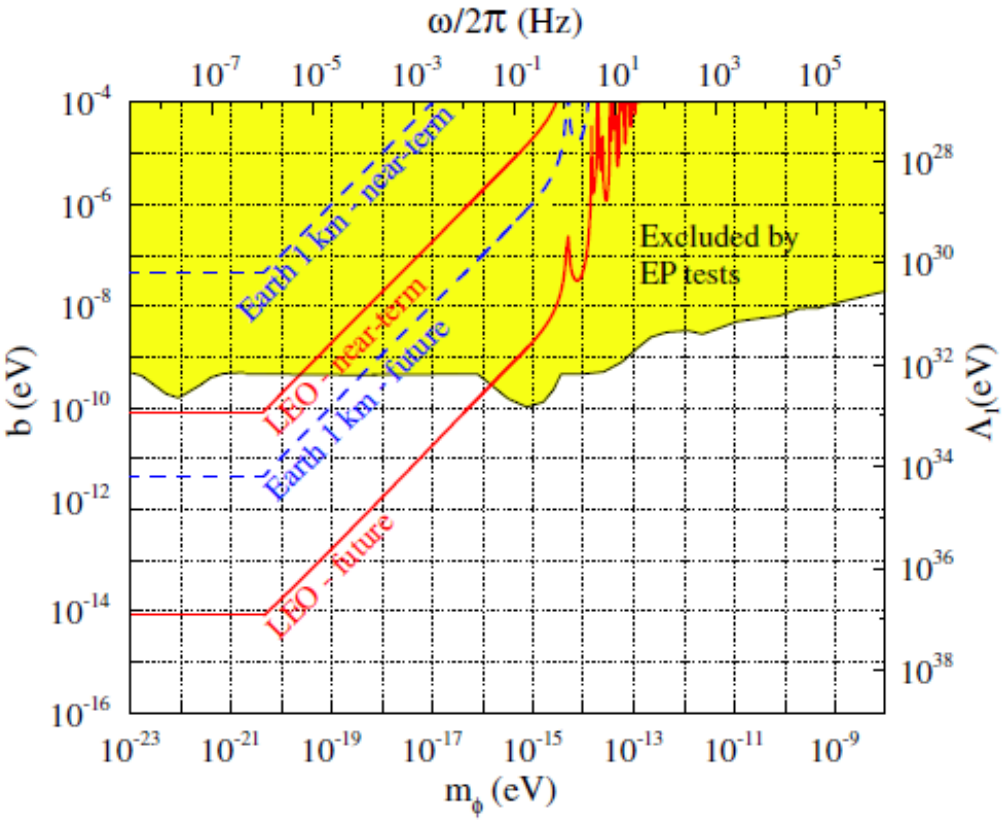
$$m(t) = m_0[1 + \delta_m \cos(\omega t + \theta_0)]$$

Atom inteferometry



Signal: $\phi = kgT^2$

Sensitivity - higgs portal search



AG and Andrei Derevianko, *Phys. Rev. Lett. 117, 261301 (2016).*

Conclusions

AMO-based methods at the sensitivity frontier

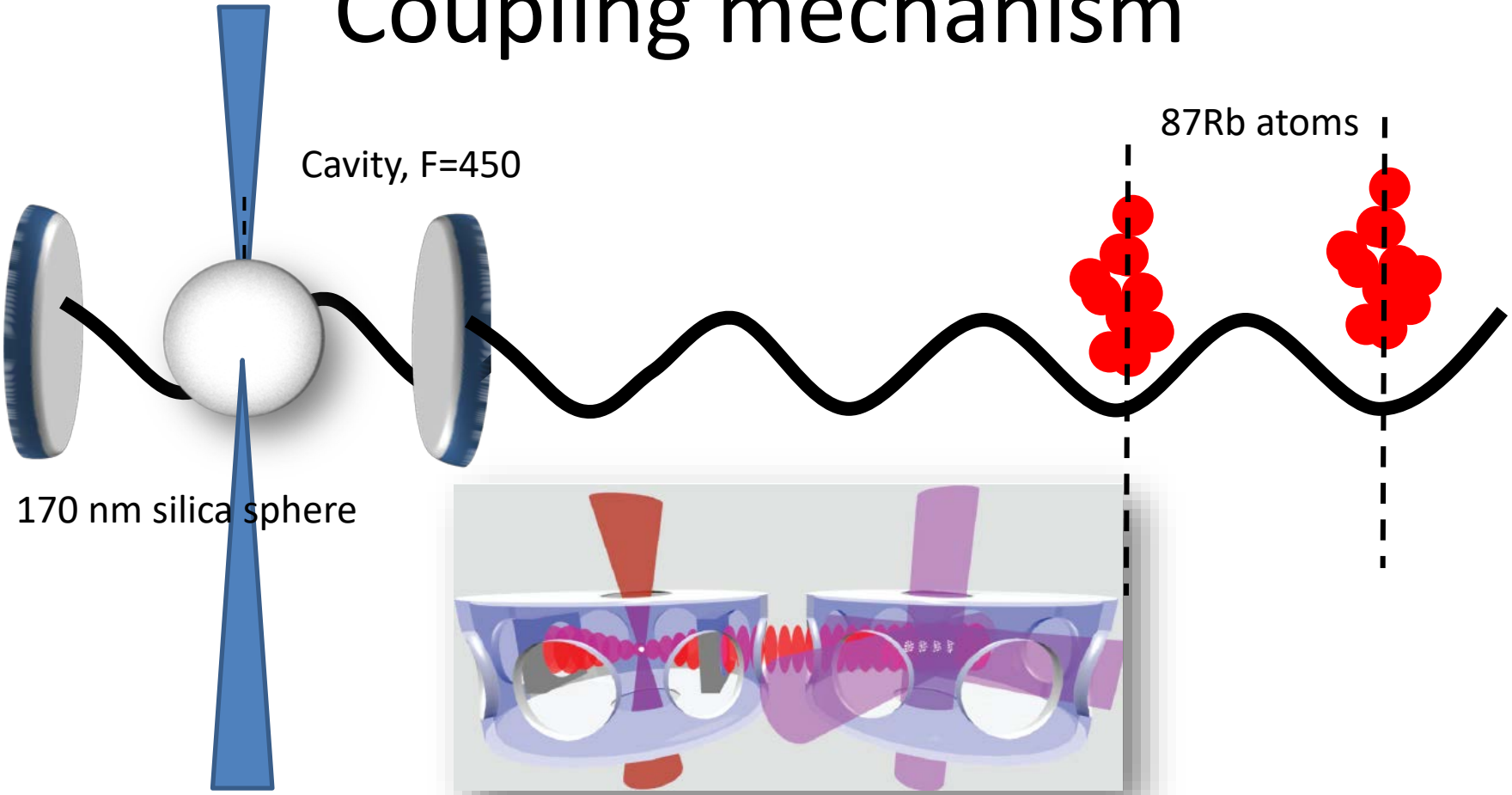
- Calibrated zeptonewton force sensing with optically levitated nanospheres
  - → Micron-distance gravity tests
  - → High frequency gravitational waves
- ARIADNE → New resonant NMR method
  - Gap in experimental QCD axion searches
    - $0.1\ \text{meV} < m_a < 10\ \text{meV}$
  - Complementary to cavity-type (e.g. ADMX) experiments
  - No need to scan mass, indep. of local DM density
- Ultralight DM with atom interferometers

Acknowledgements

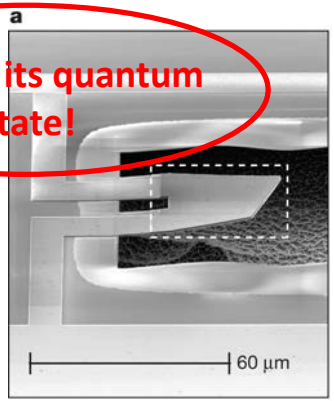
PHY-1205994
PHY-1506431
PHY-1506508
1510484, 1509176

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).

Coupling mechanism



Quantum "Mechanics"

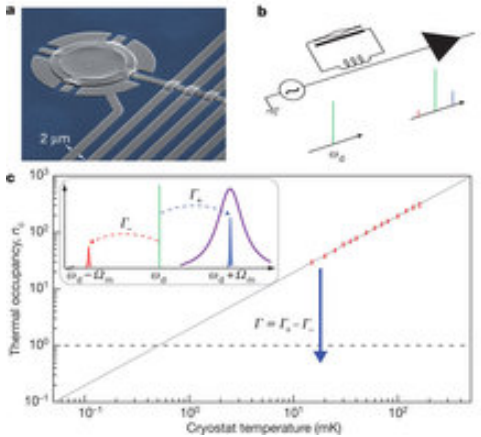


This is in its quantum ground state!

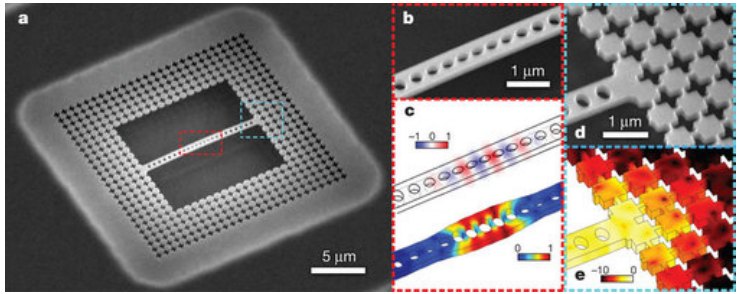
Quantum ground state and single-phonon control of a mechanical resonator
A. D. O'Connell et.al.
Nature 464, 697 (2010).

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

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)



Quantum Regime

Ground state cooling of solid-state mechanical resonators

- Cryogenic cooling
- Feedback cooling
- Passive back-action cooling