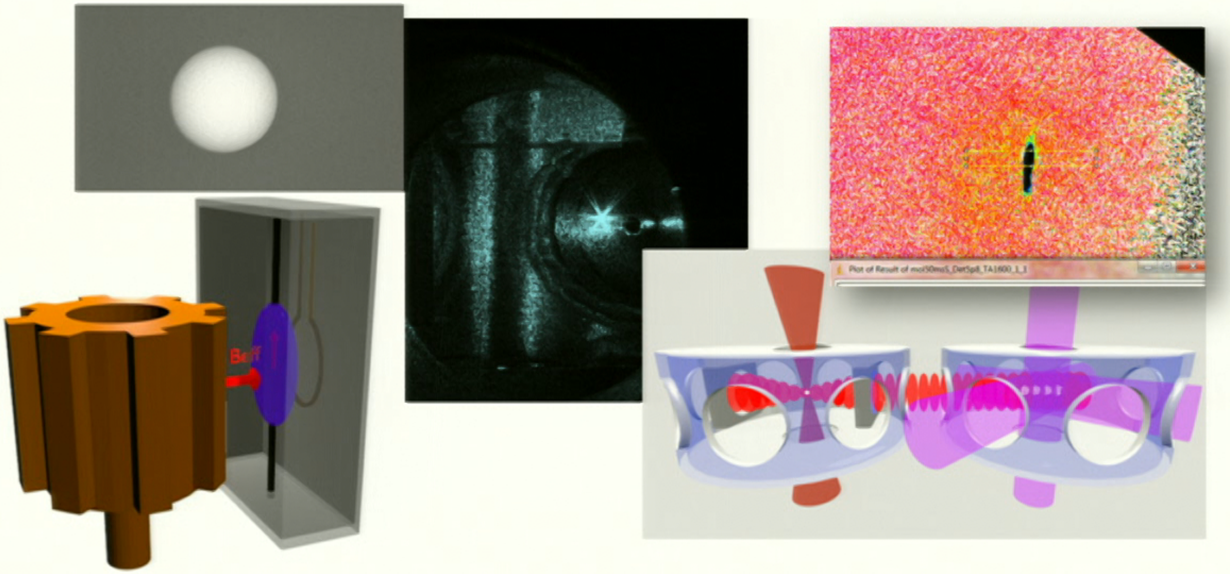
Title: Hunting for axions and new short-range forces with AMO-based sensors

Date: Apr 19, 2017 02:00 PM

URL: http://pirsa.org/17040001

Abstract: <p>We normally think of large accelerators and large-scale cosmic events when we consider the frontiers of elementary particle physics, pushing to understand the universe at higher and higher energy scales. However, several tabletop low-energy experiments are posed to discover a wide range of new physics beyond the Standard model, where feeble interactions require precision measurements rather than high energies. In our experiments, high-Q resonant sensors enable ultra-sensitive force and field detection. In this talk I will describe two applications of these sensors in searches for new physics, based on techniques in atomic-molecular-and optical (AMO) physics. First, I will discuss an experiment which uses laser-cooled optically trapped silica nanospheres to search for corrections to Newtonian gravity at micron distances with zeptonewton sensitivity. Finally, I will discuss the Axion Resonant InterAction Detection Experiment (ARIADNE), a new precision magnetometry experiment using laser-polarized 3-He gas to search for a notable dark-matter candidate: the QCD axion. </p>

Hunting for axions and new short-range forces with AMO-based sensors



A. Geraci, University of Nevada Reno

Colloquium, Perimeter Institute, Apr 19, 2017

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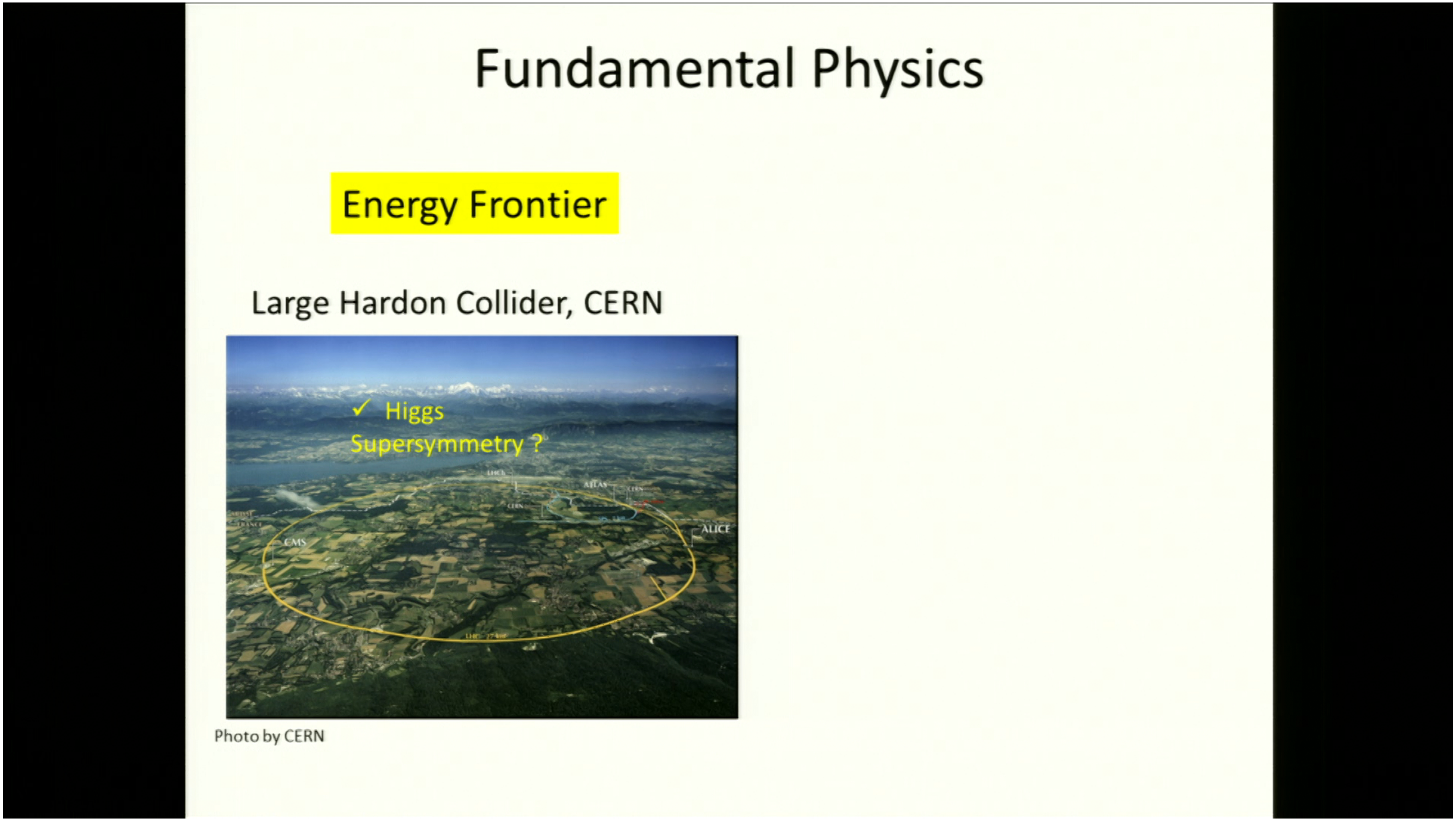
ibs Institute for Basic Science
University of Nevada, Reno
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS
INDIANA UNIVERSITY
LELAND STANFORD JUNIOR UNIVERSITY 1891



Fundamental Physics

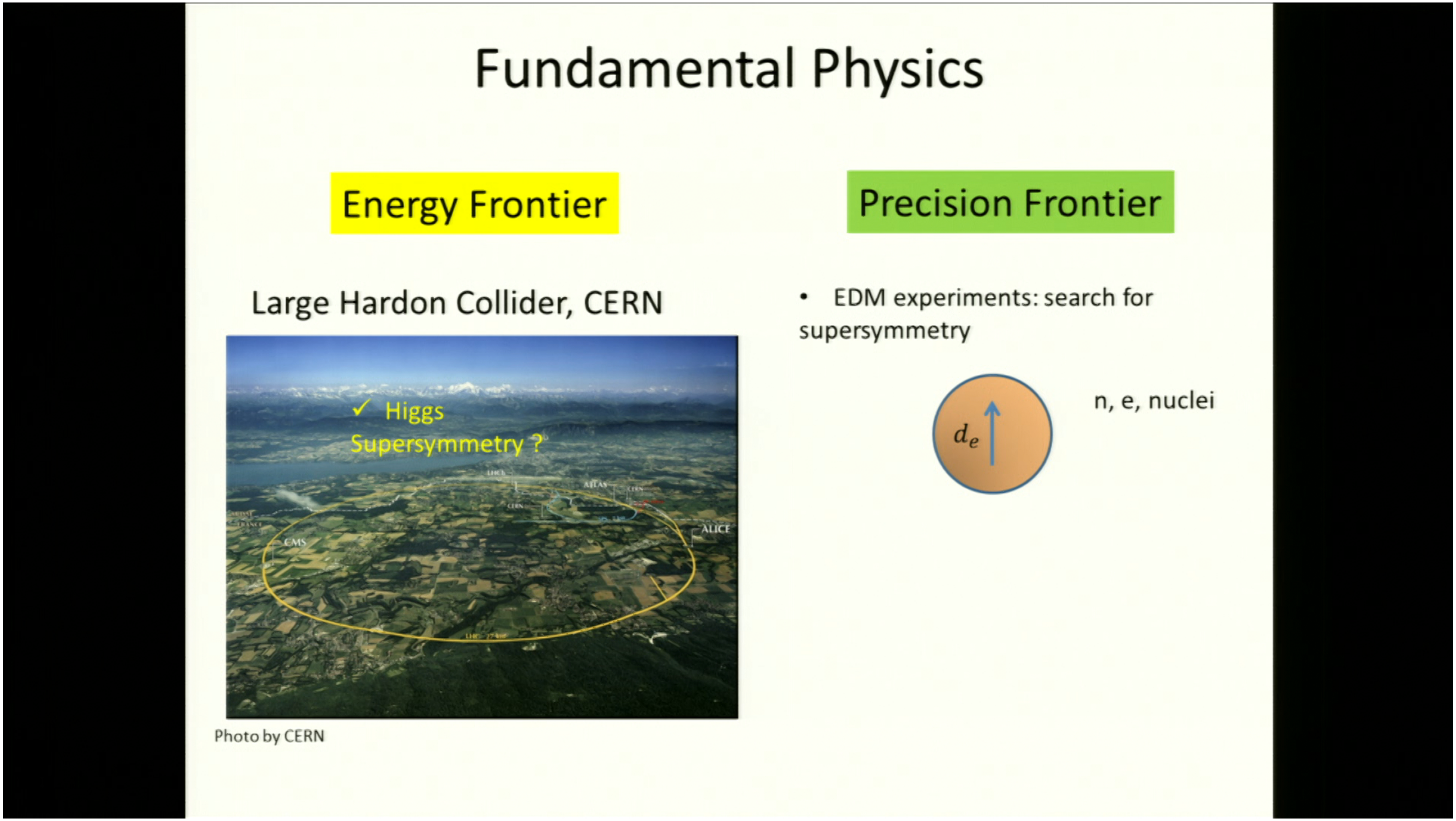
Energy Frontier

Large Hardon Collider, CERN

✓ Higgs

Supersymmetry ?

Photo by CERN



Fundamental Physics

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Large Hardon Collider, CERN

Photo by CERN

Precision Frontier

- EDM experiments: search for supersymmetry

n, e, nuclei

Fundamental Physics

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Large Hardon Collider, CERN

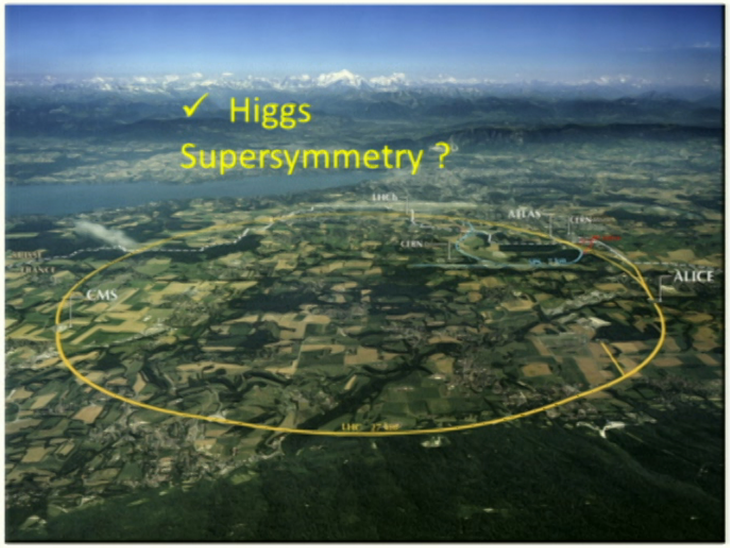
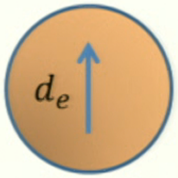


Photo by CERN

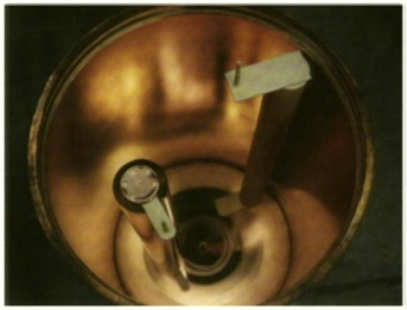
Precision Frontier

- EDM experiments: search for supersymmetry



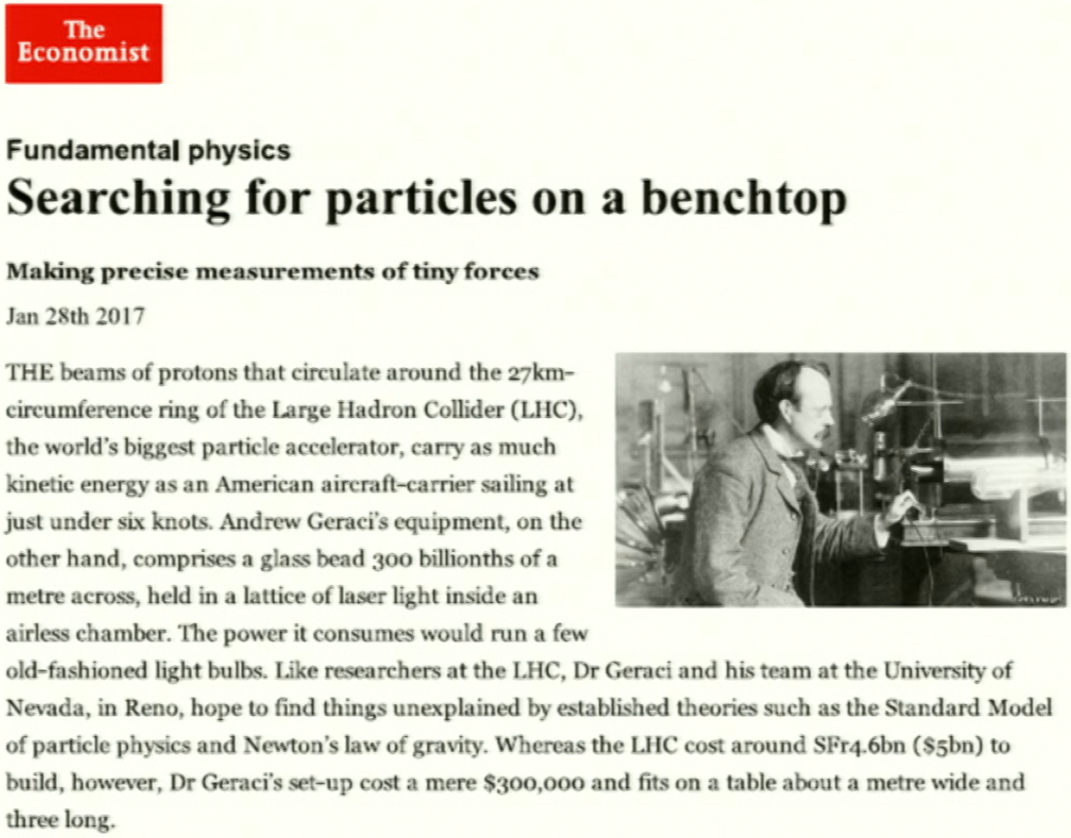
n, e, nuclei

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



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

Tabletop fundamental physics



The Economist

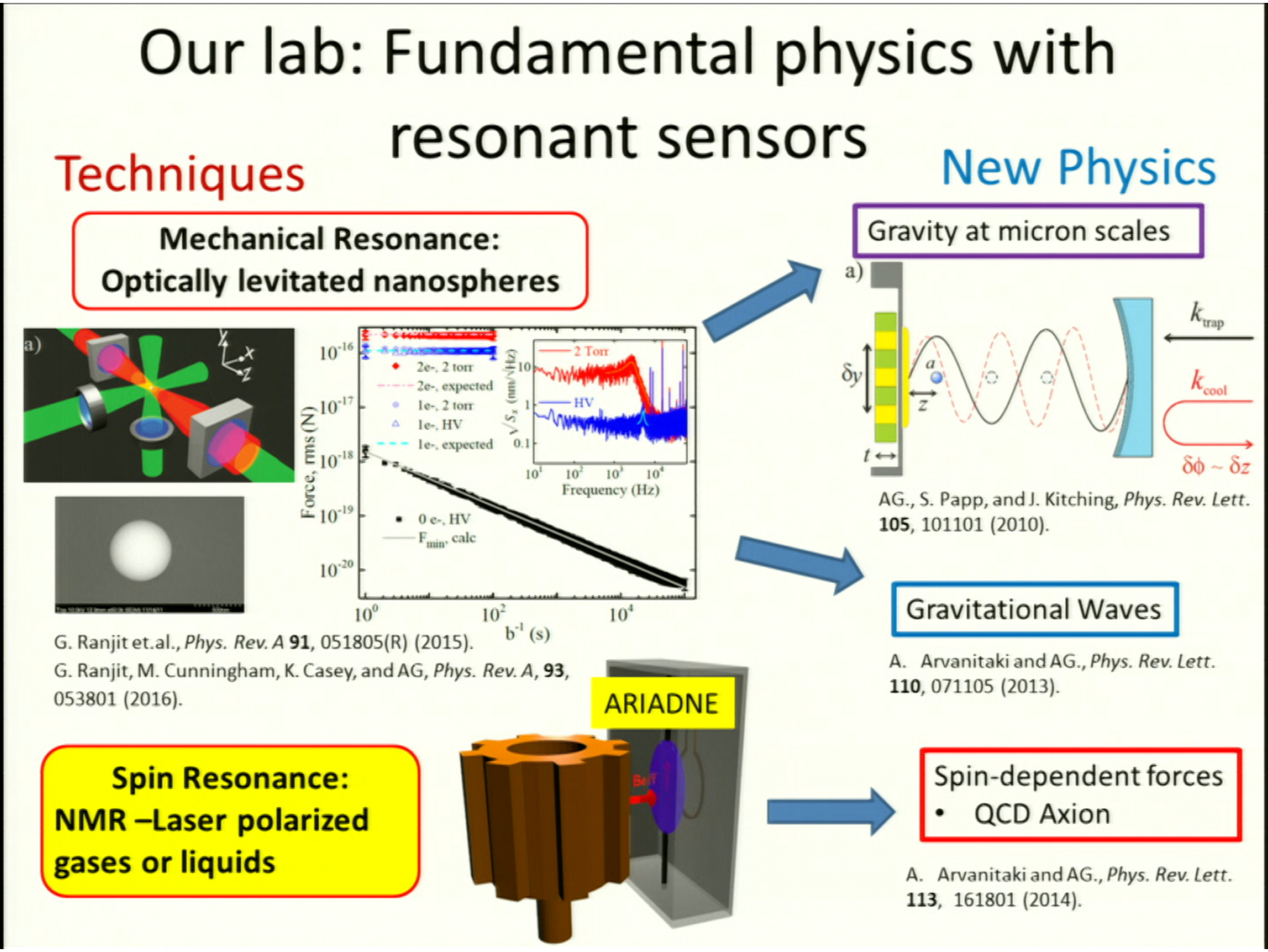
Fundamental physics

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.



Our lab: Fundamental physics with resonant sensors

Techniques

Mechanical Resonance:
Optically levitated nanospheres

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

Spin Resonance:
NMR –Laser polarized gases or liquids

New Physics

Gravity at micron scales

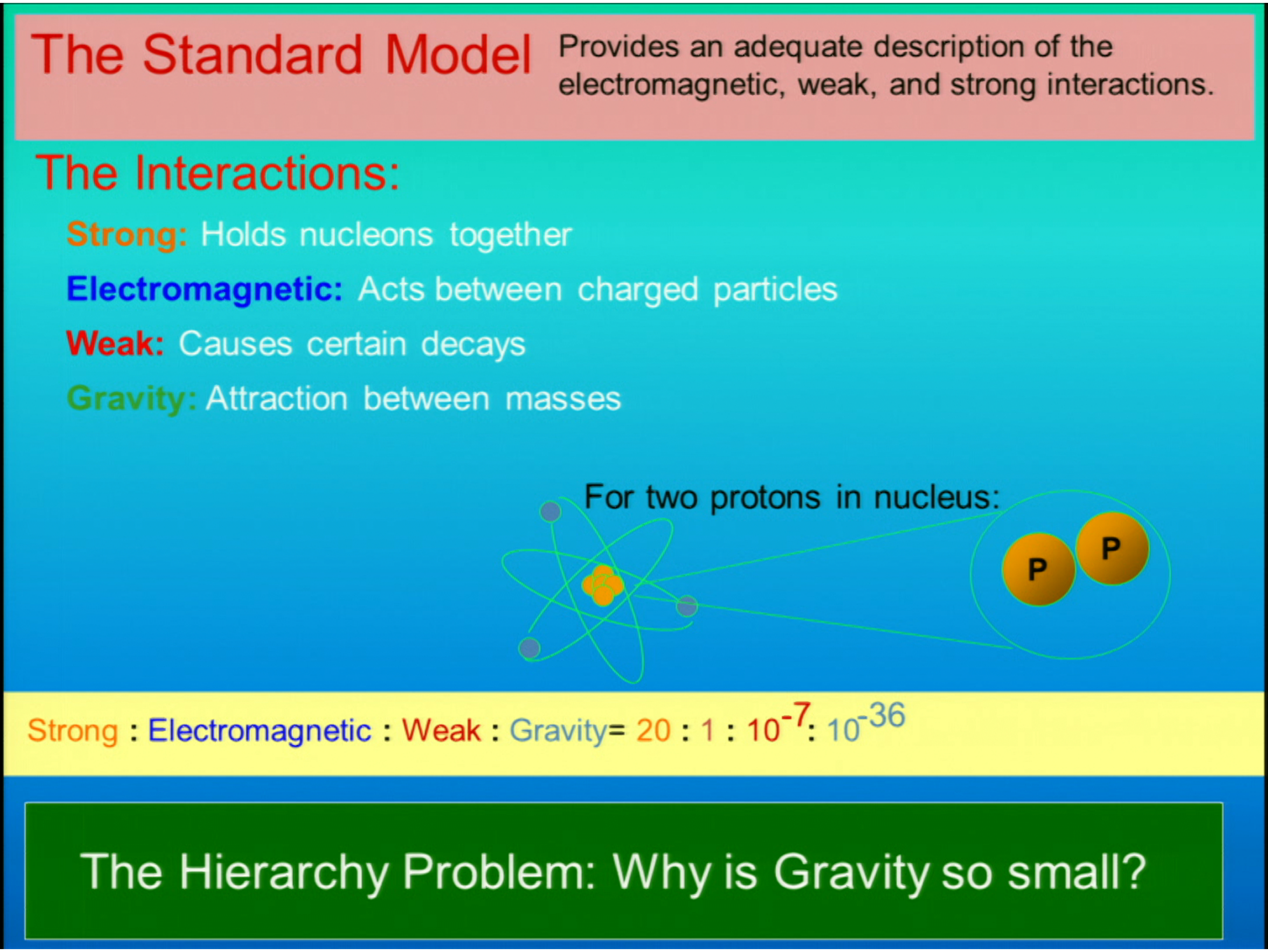
AG., S. Papp, and J. Kitching, *Phys. Rev. Lett.* **105**, 101101 (2010).

Gravitational Waves

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

Spin-dependent forces
- QCD Axion

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



The Standard Model

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

The Interactions:

Strong: Holds nucleons together

Electromagnetic: Acts between charged particles

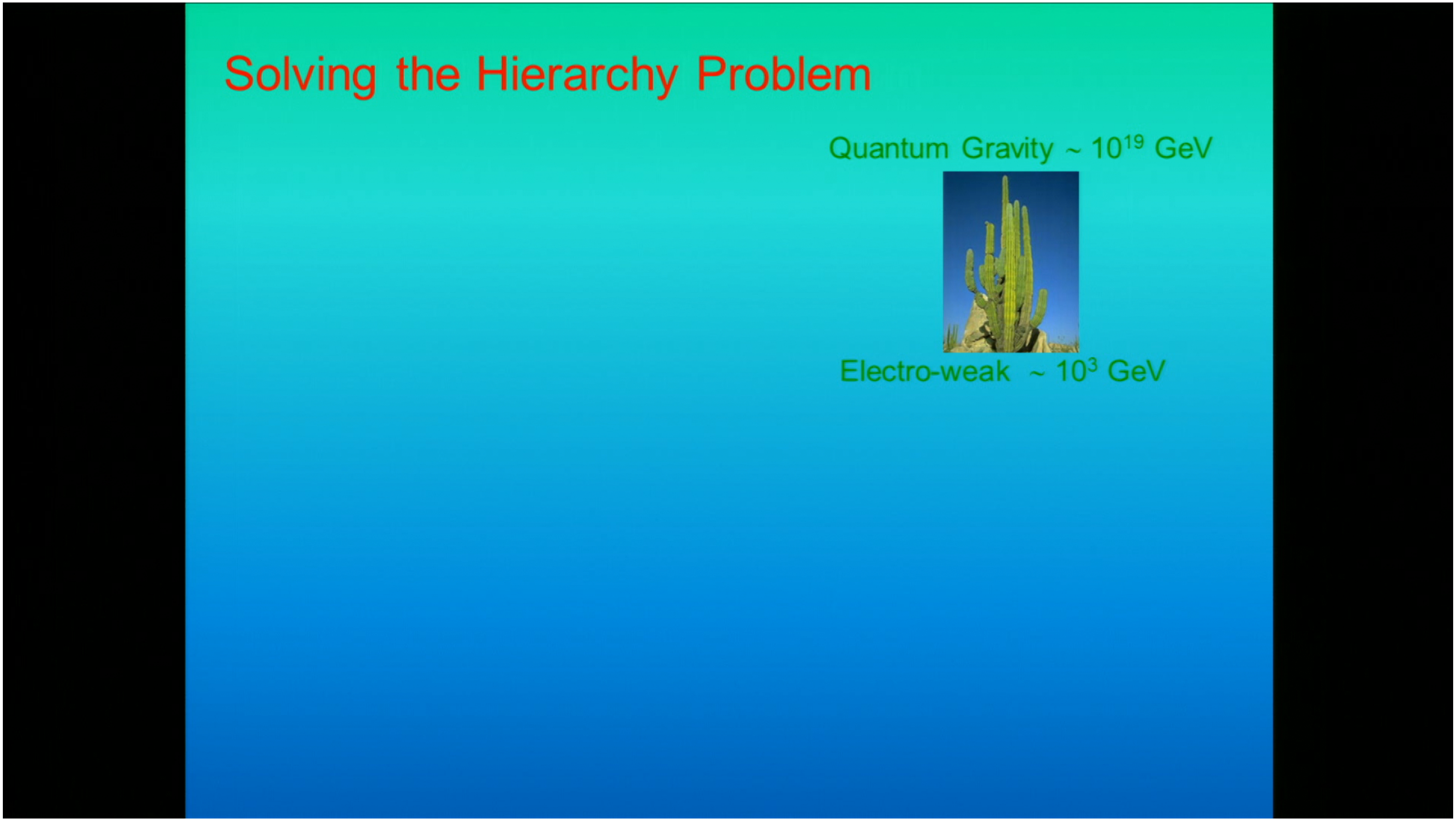
Weak: Causes certain decays

Gravity: Attraction between masses

For two protons in nucleus:

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

The Hierarchy Problem: Why is Gravity so small?



Solving the Hierarchy Problem

Quantum Gravity ~ 10^{19} GeV

Electro-weak ~ 10^{3} GeV

Solving the Hierarchy Problem

Quantum Gravity ~ 10^{19} GeV

Electro-weak ~ 10^{3} GeV

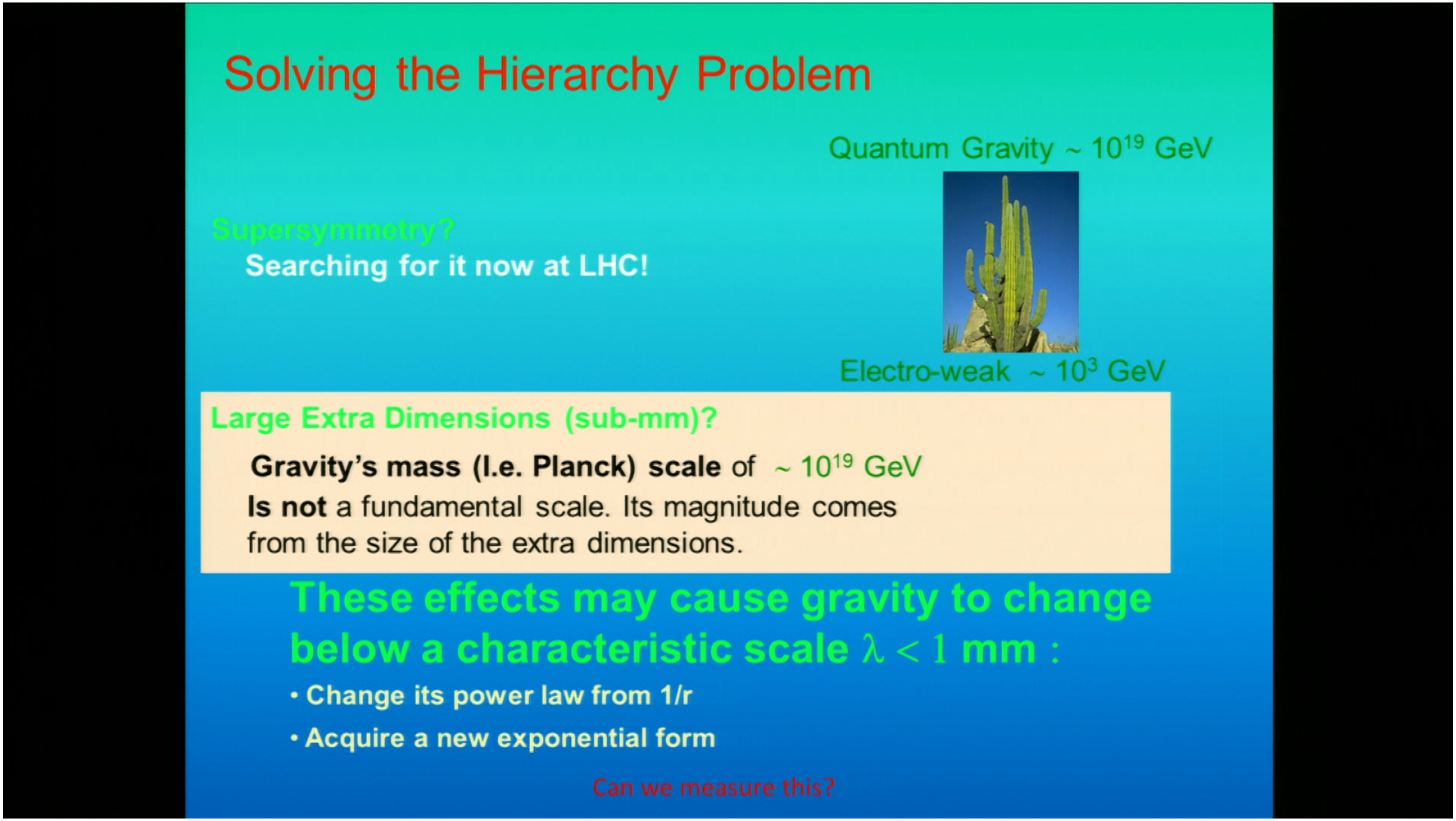
Supersymmetry?

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.



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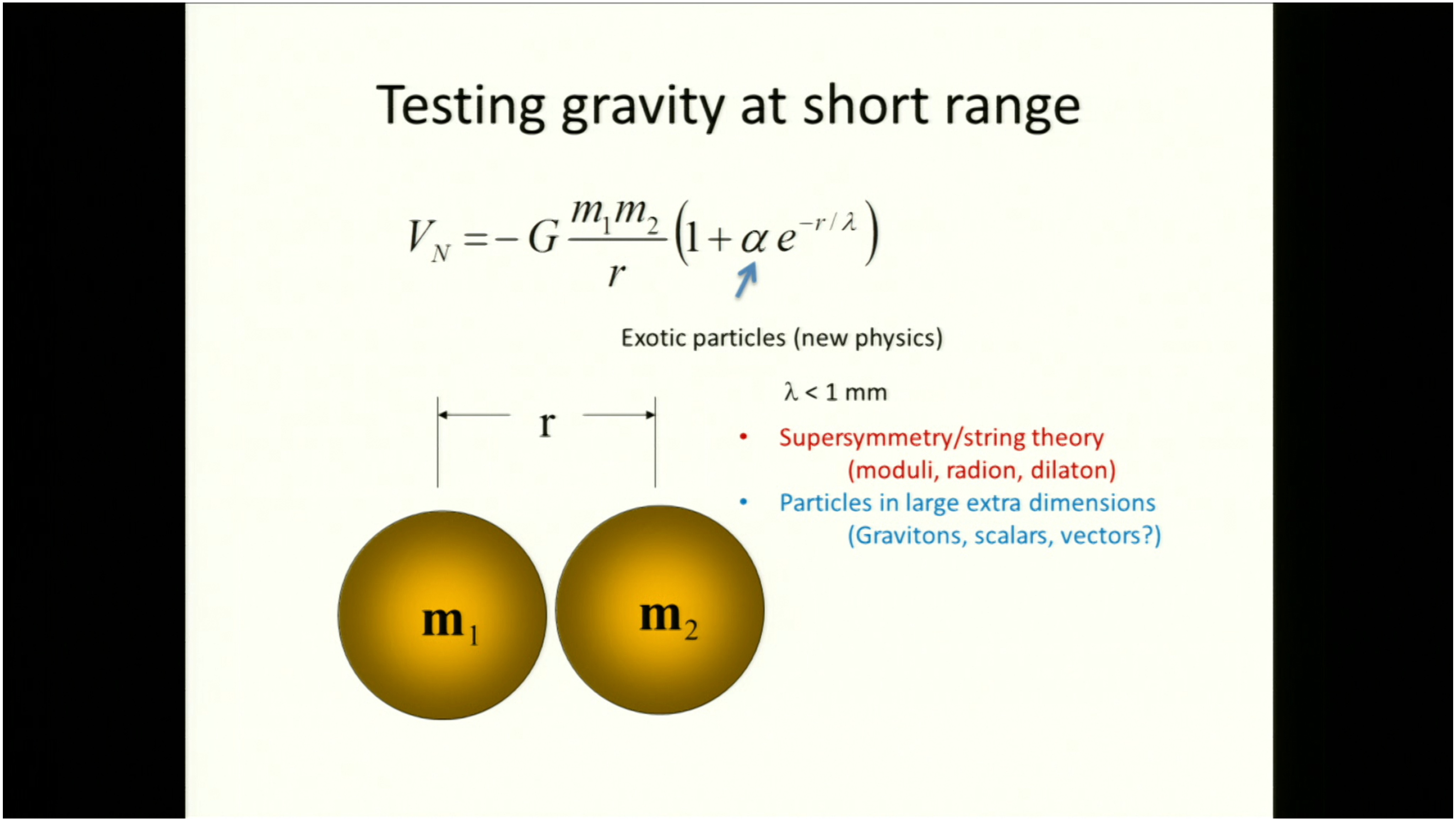
Is not a fundamental scale. Its magnitude comes
from the size of the extra dimensions.

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?



Testing gravity at short range

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

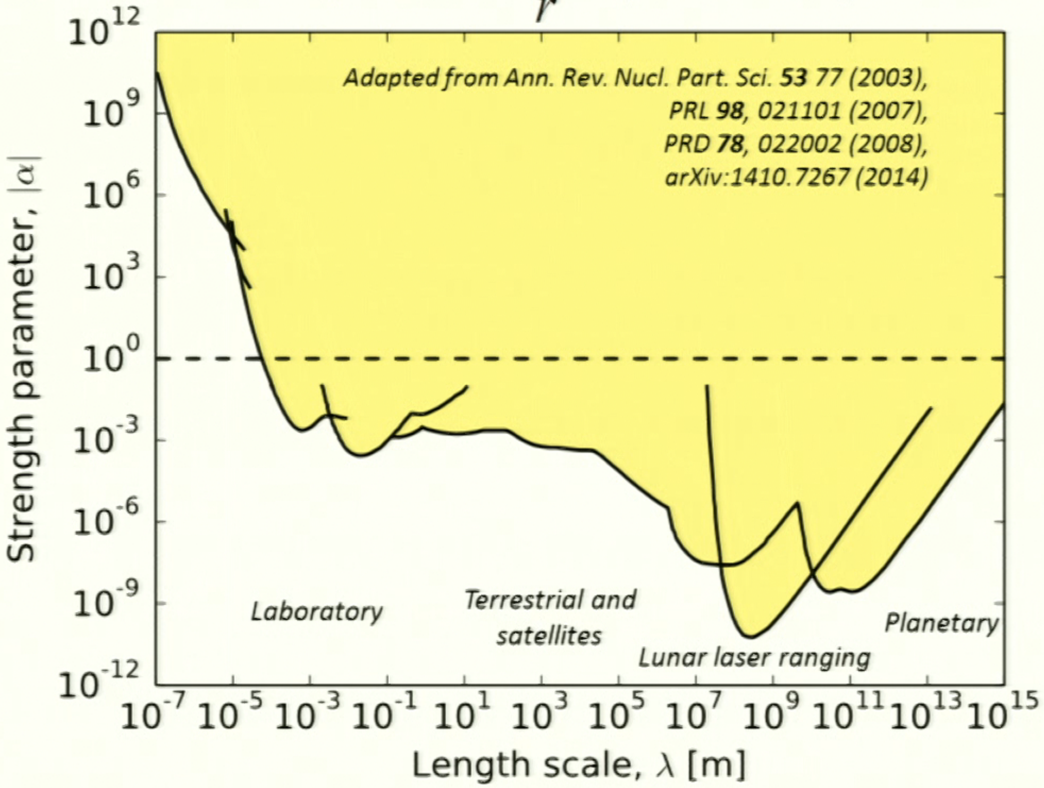
Exotic particles (new physics)

$\lambda < 1$ mm

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

Landscape for ISL corrections

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

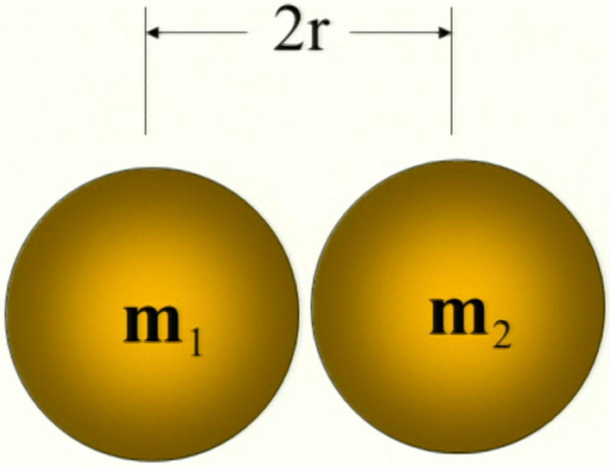


Adapted from Ann. Rev. Nucl. Part. Sci. ***53*** *77 (2003),*
PRL ***98****, 021101 (2007),*
PRD ***78****, 022002 (2008),*
arXiv:1410.7267 (2014)

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

Experimental challenge: scaling of gravitational force

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



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

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

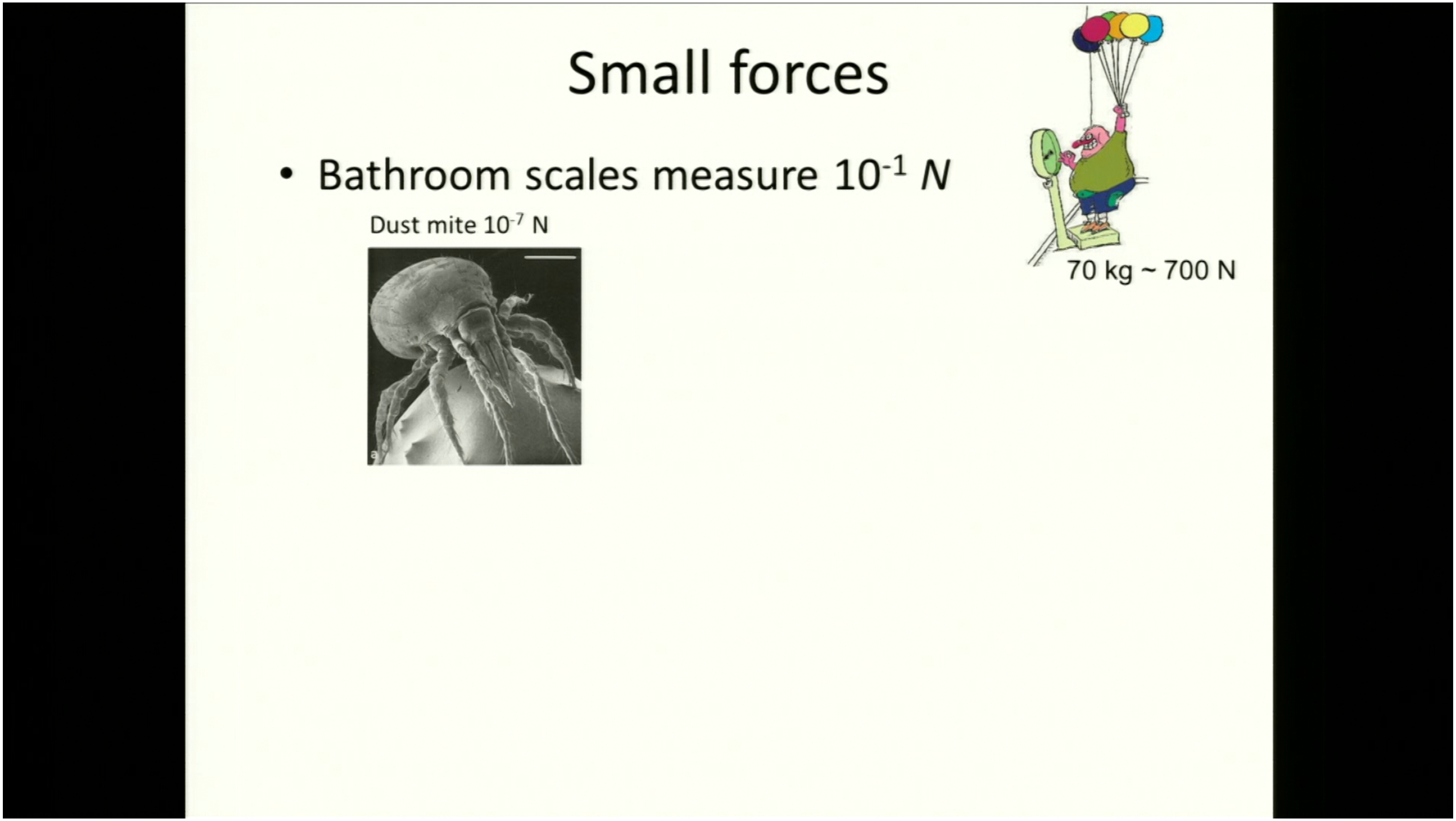
In the range of experimental interest:

r~10 μm **;** $F_N \sim 10^{-21} N$

Small forces

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

70 kg ~ 700 N



Small forces

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

Dust mite 10^{-7} N

70 kg ~ 700 N

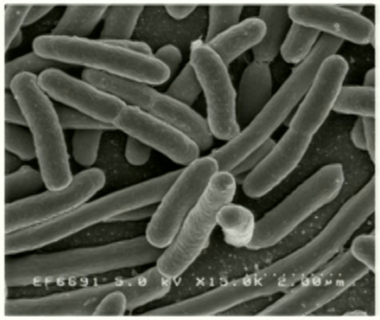
Small forces

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

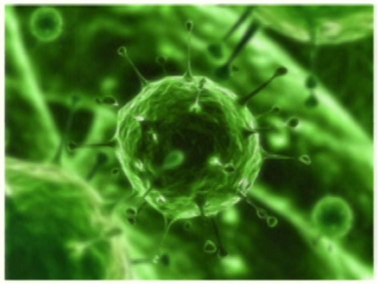
70 kg ~ 700 N

Dust mite 10^{-7} N

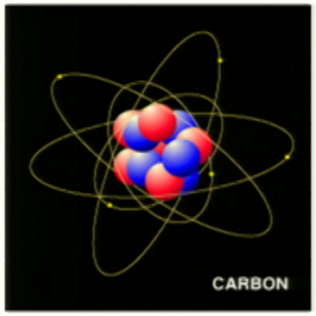
E. coli 10^{-15} N

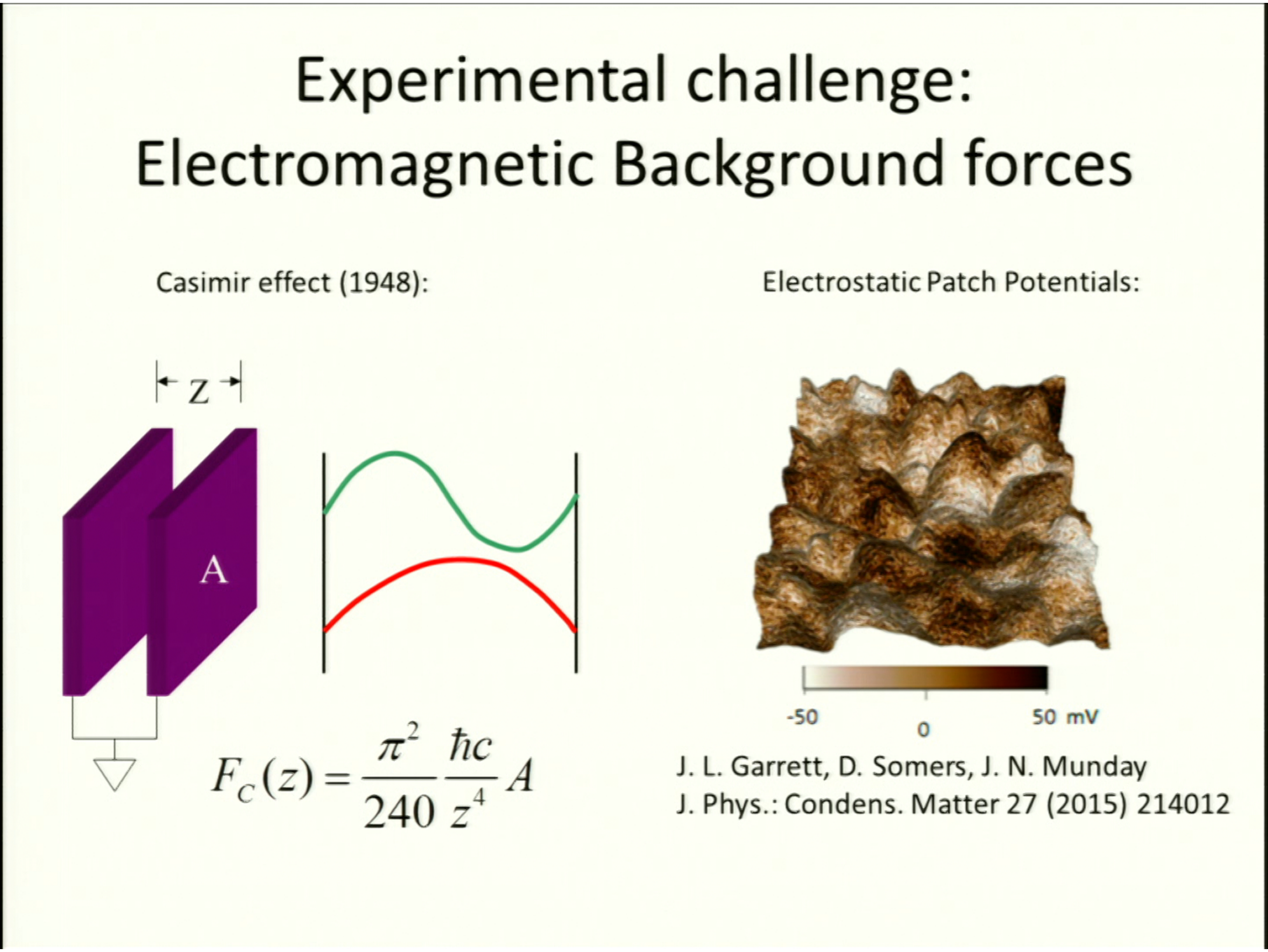


Virus 10^{-19} N



Carbon atom 10^{-25} N





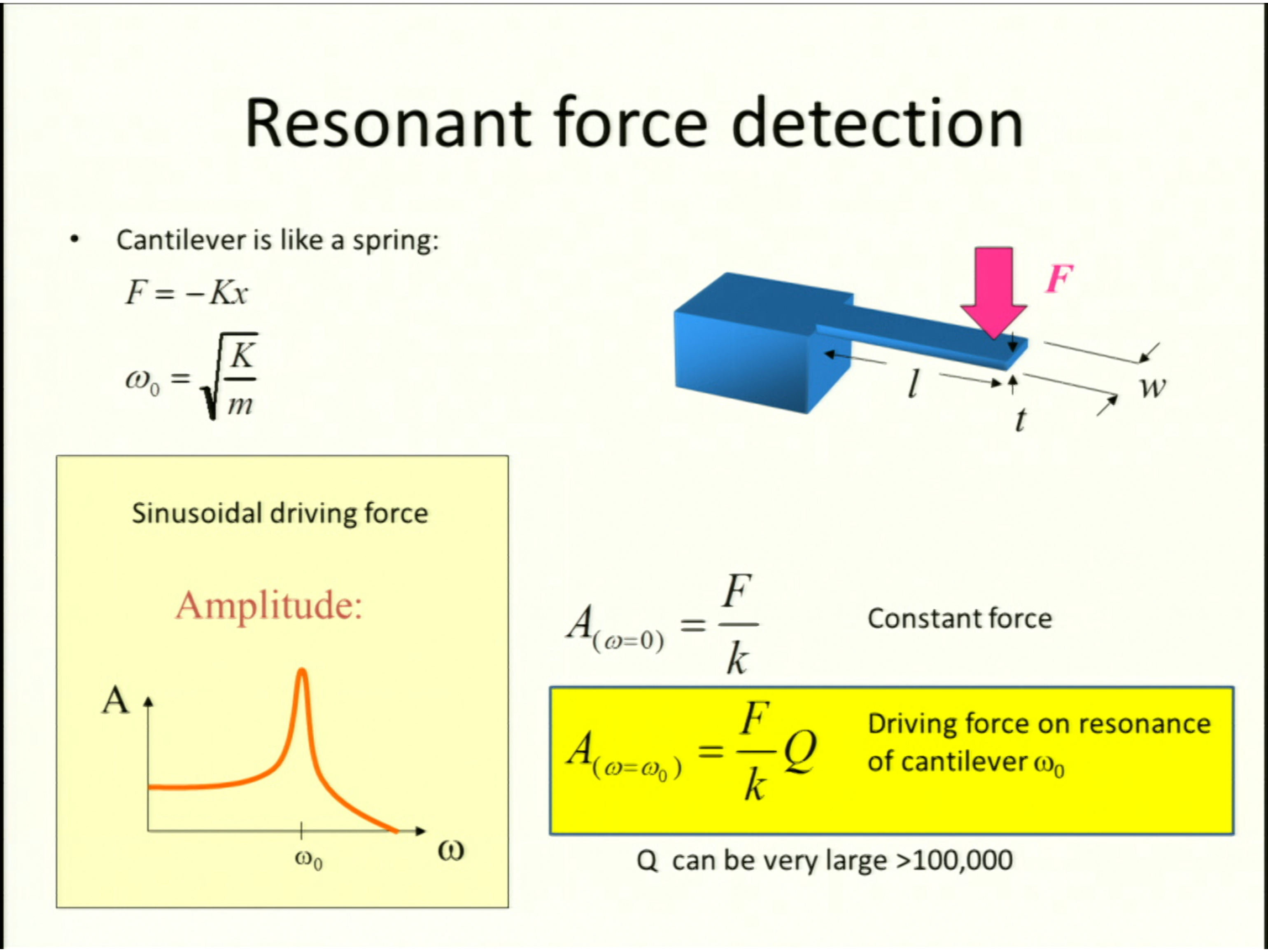
Experimental challenge: Electromagnetic Background forces

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



Resonant force detection

- Cantilever is like a spring:

$$F = -Kx$$

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

Sinusoidal driving force

Amplitude:

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

Constant force

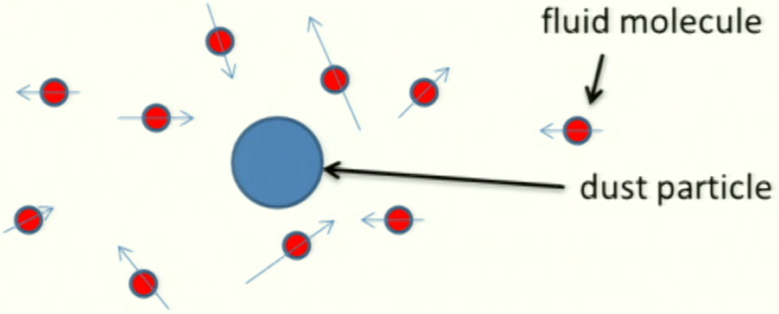
$$A_{(\omega=\omega_0)} = \frac{F}{k}Q$$

Driving force on resonance of cantilever ω_0

Q can be very large >100,000

Fundamental limitation: thermal noise

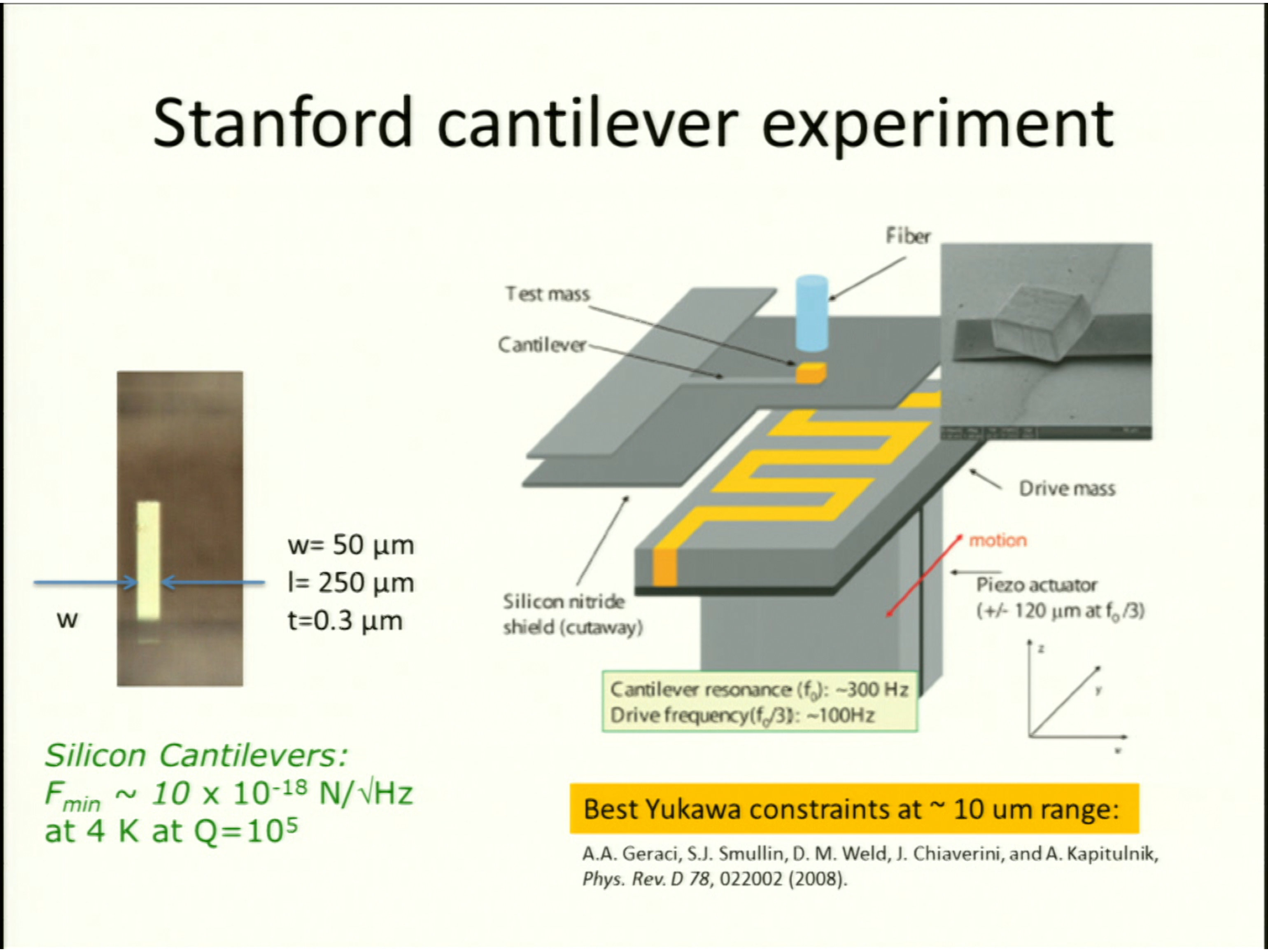
Brownian motion – random “kicks” given to particle due to thermal bath



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

$$\frac{1}{2}k\left\langle x^2\right\rangle=\frac{1}{2}k_BT \quad\Longrightarrow\quad \boxed{F_{\min}=\left(\frac{4kk_BTb}{Q\omega_0}\right)^{1/2}}$$

Stanford cantilever experiment



w= 50 μm
l= 250 μm
t=0.3 μm

Cantilever resonance (f_0): ~300 Hz
Drive frequency(f_0/3): ~100Hz

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

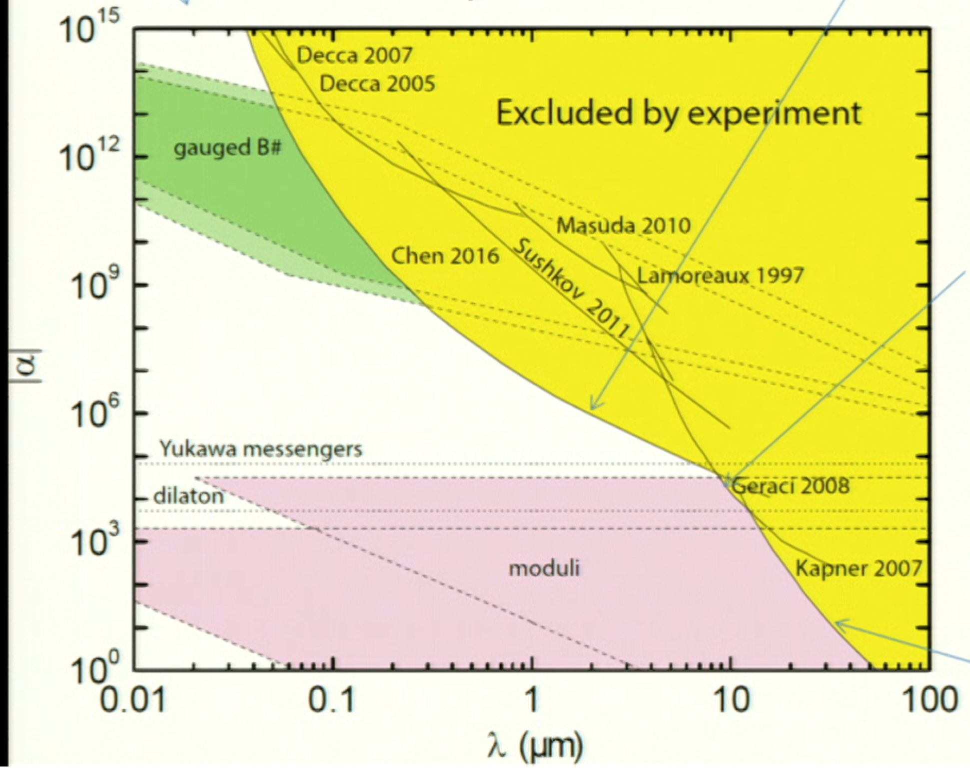
Best Yukawa constraints at ~ 10 um range:

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

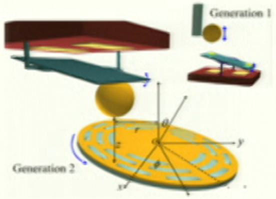
Force-distance parameter space (2017)

Casimir measurements (Riverside)

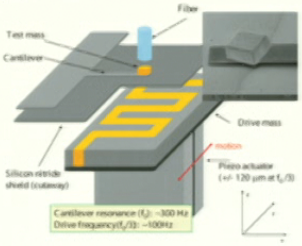
$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$

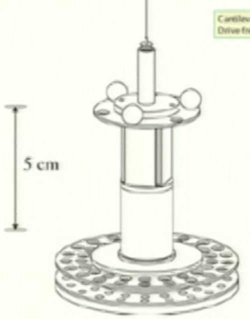


Casimir measurements (Indiana)



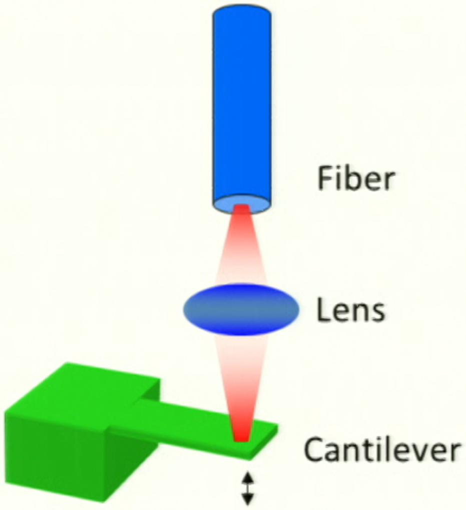
Cantilevers (Stanford)





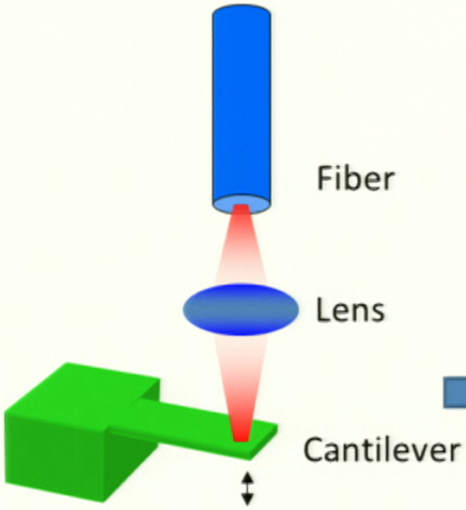
Torsion balance experiments (U Washington)

Improving the sensitivity

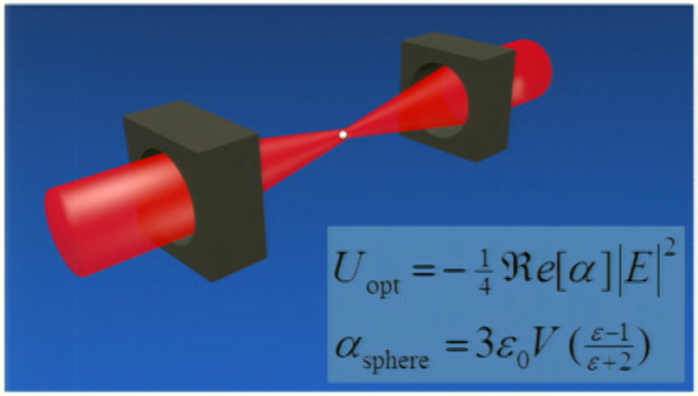


Limitations on Q: Clamping, surface imperfections, internal materials losses

Improving the sensitivity



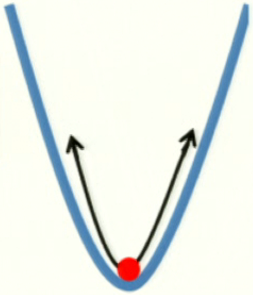
Levitate the force sensor!



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

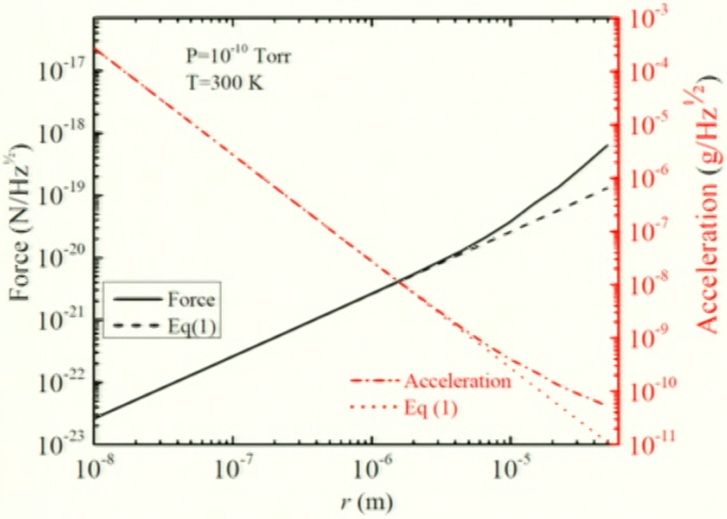
$$\alpha_{\text{sphere}} = 3\varepsilon_0 V\left(\tfrac{\varepsilon-1}{\varepsilon+2}\right)$$

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



CM motion decoupled from environment – no clamping, materials losses

Projected sensitivity

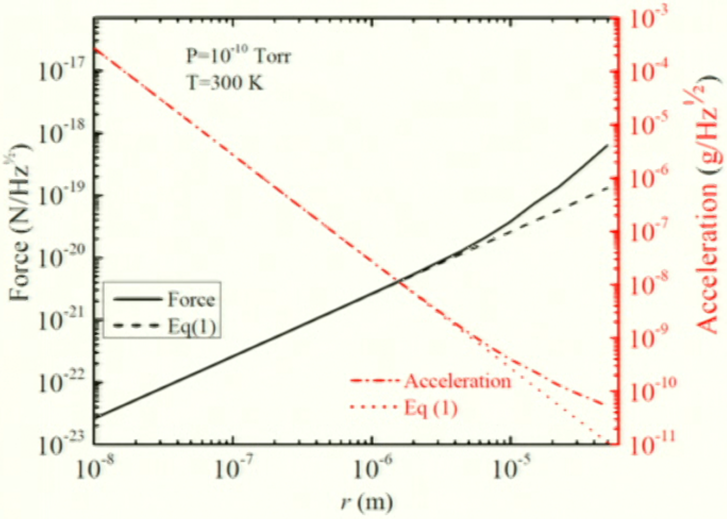


$$F_{\min} = \left(4k_B T\,\gamma\, m\right)^{1/2} \quad (1)$$

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

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

Projected sensitivity



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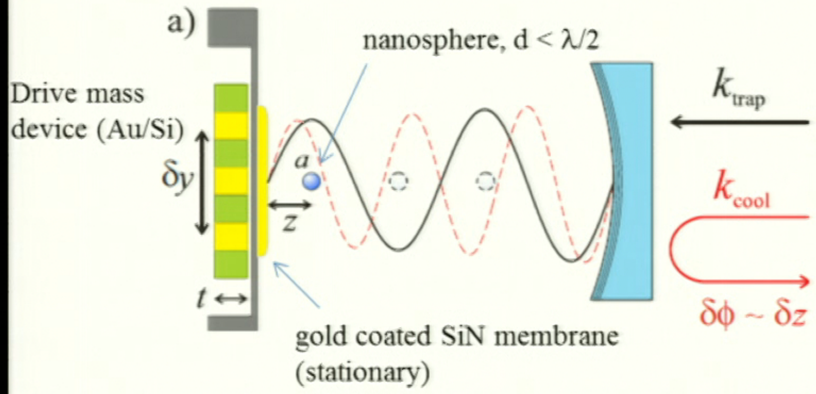
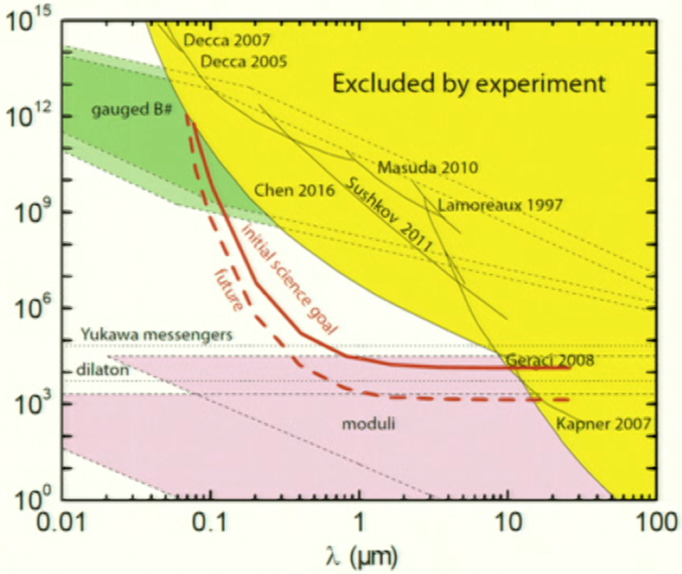


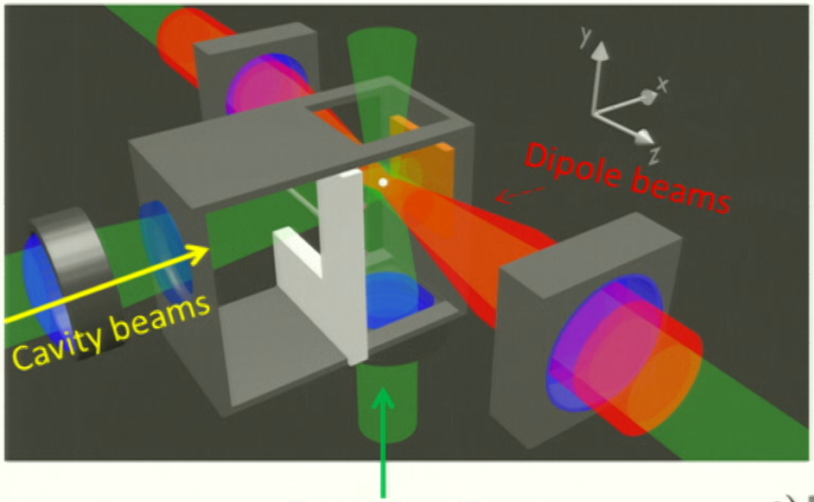
AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett.* **105**, 101101 (2010)

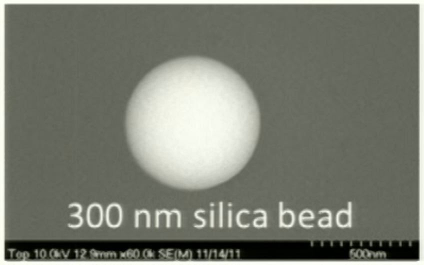
Projected Reach

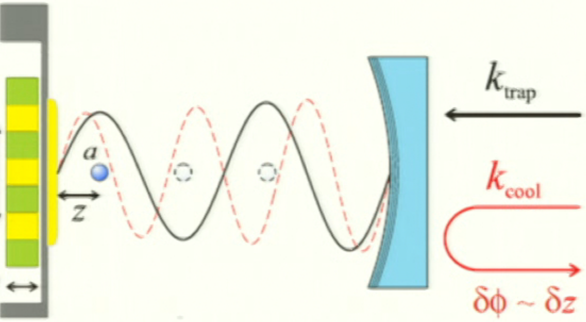


Experimental Setup

Combined cavity/dipole trap







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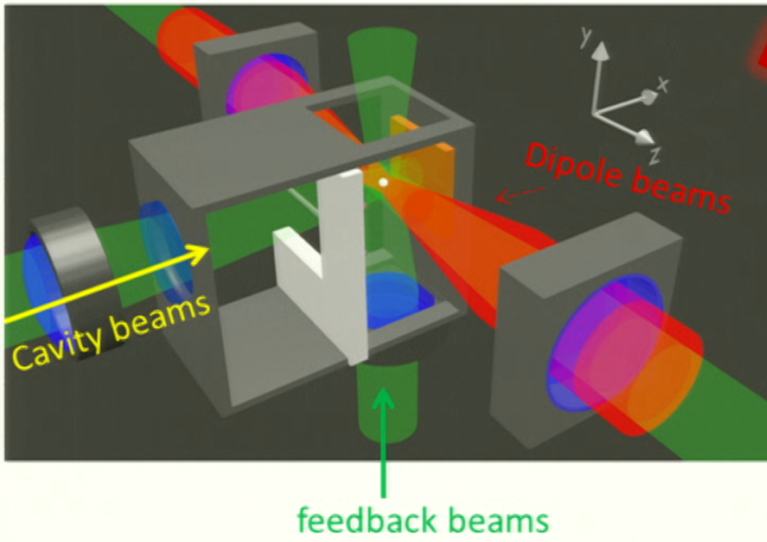
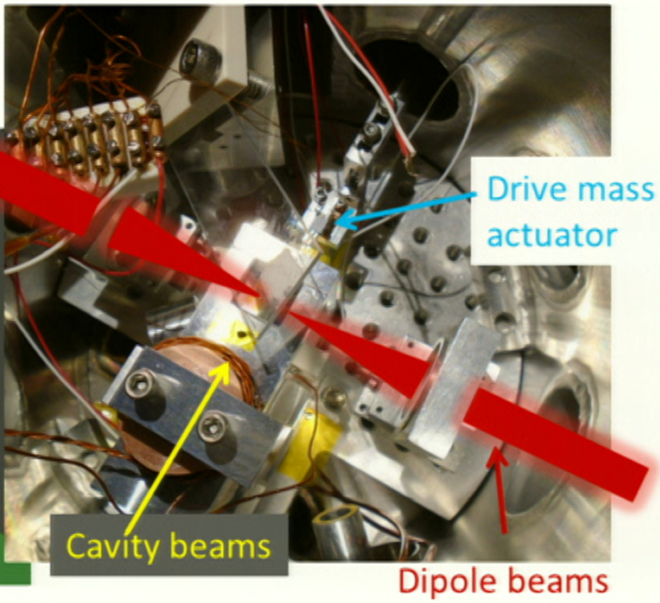
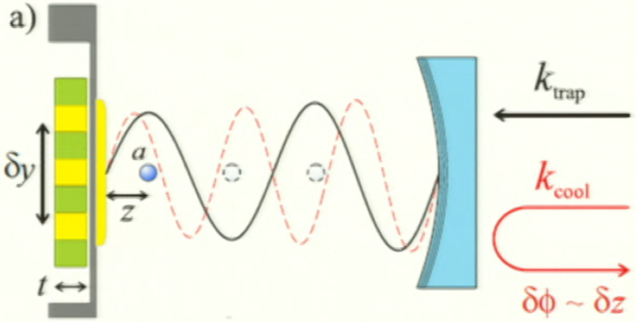


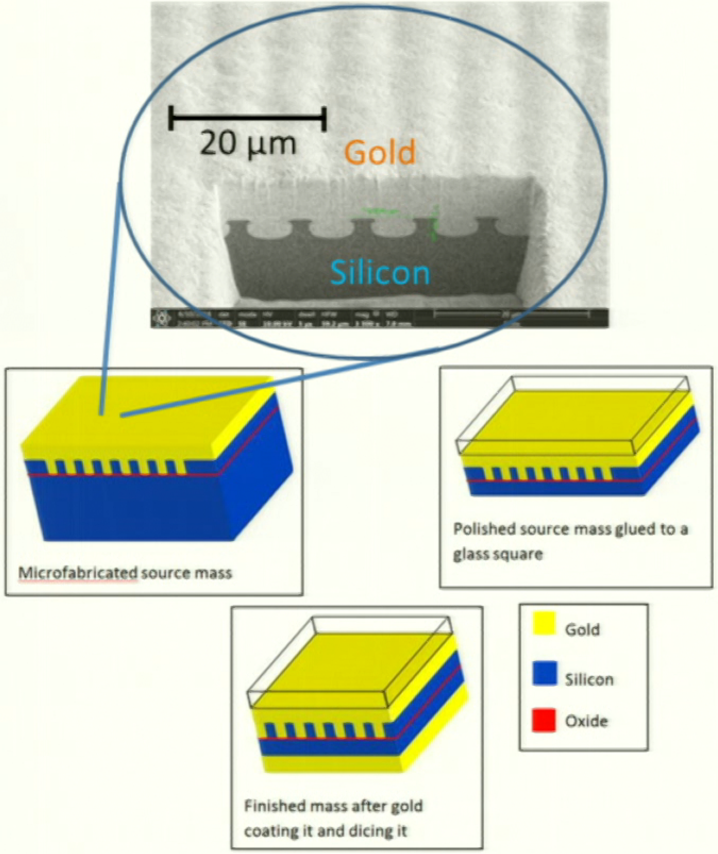




AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett.* **105**, 101101 (2010)
G. Ranjit et.al., PRA 91, 051805(R) (2015).
G. Ranjit et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Drive Mass fabrication

Buried drive mass technique – eliminates corrugation

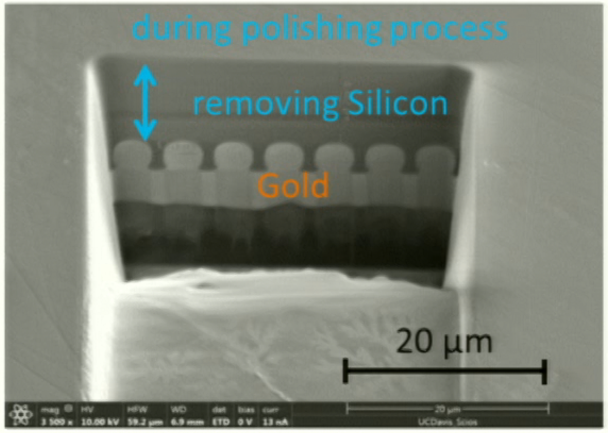


Microfabricated source mass

Polished source mass glued to a glass square

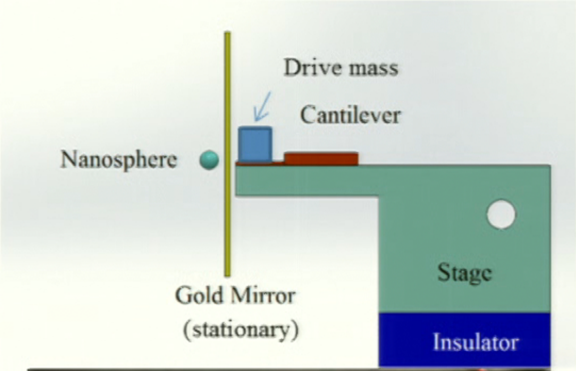
Finished mass after gold coating it and dicing it

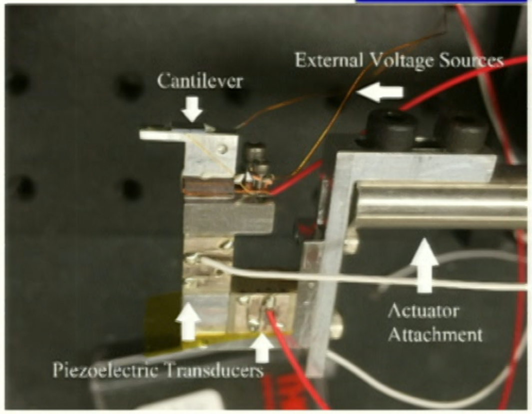
🟨 Gold
🟦 Silicon
🟥 Oxide



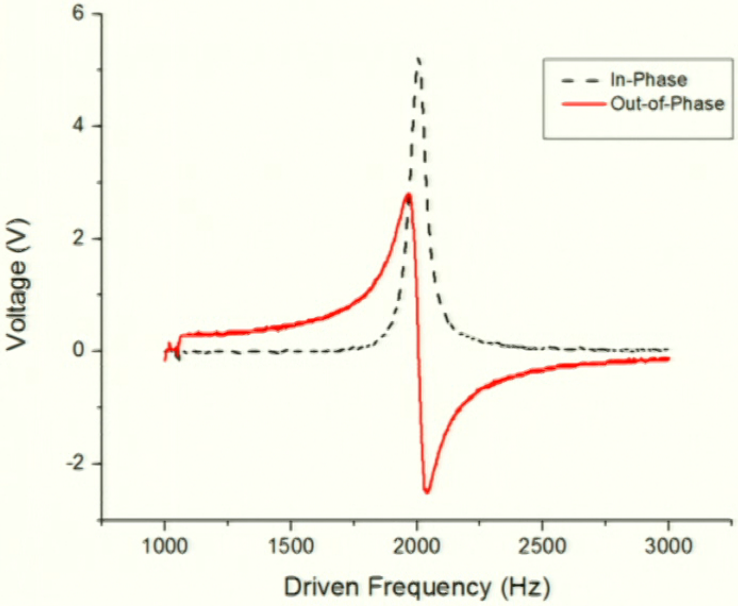
MEMS actuator

- Device for positioning drive mass

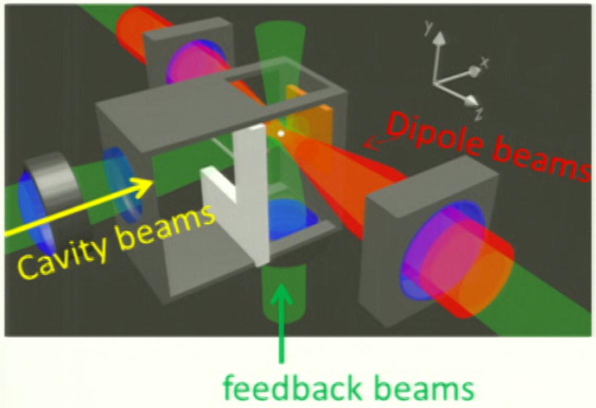


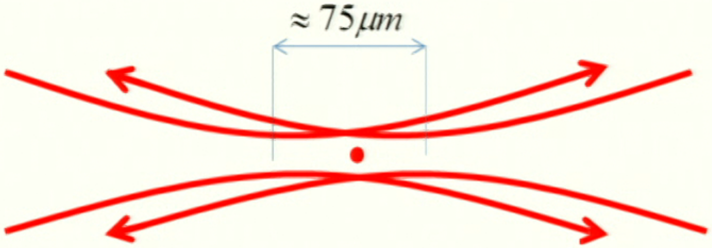


100V DC, 10V AC
~5 um displacement

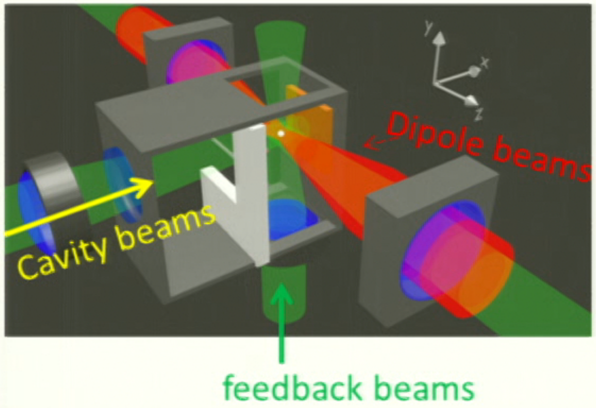


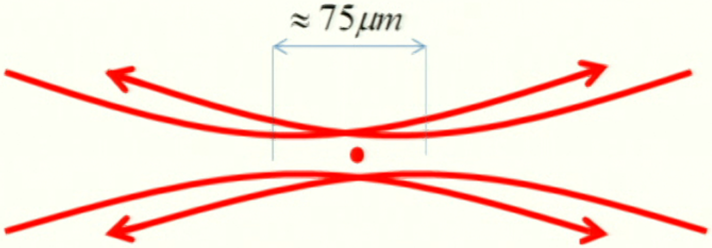
Standing wave optical trap

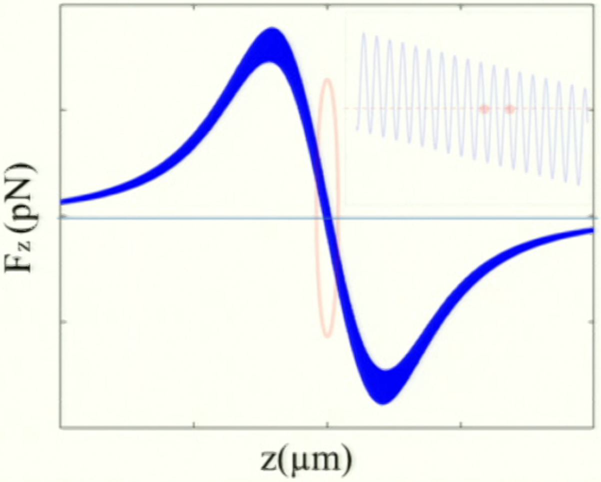




Standing wave optical trap







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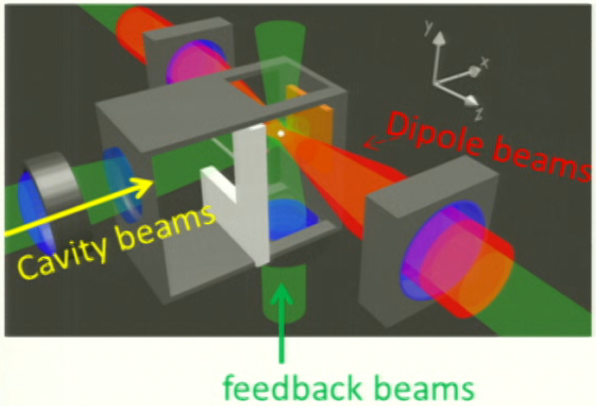
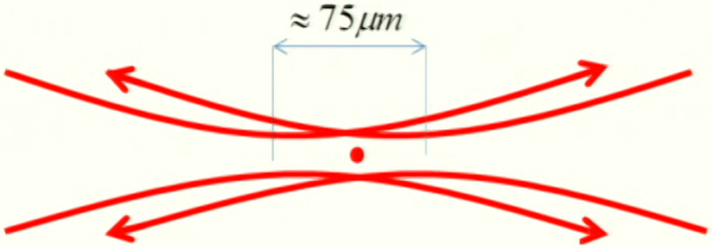
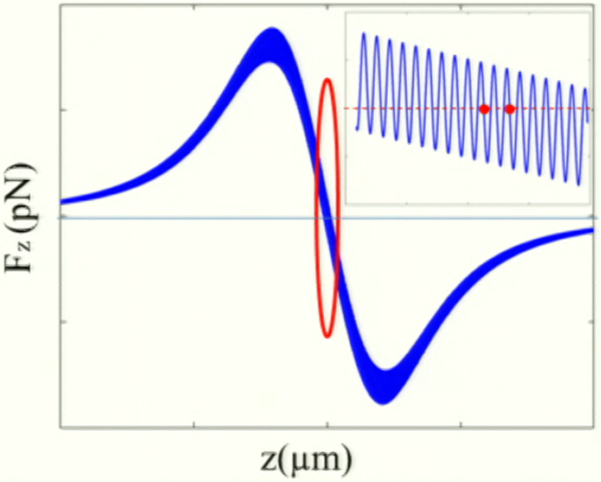
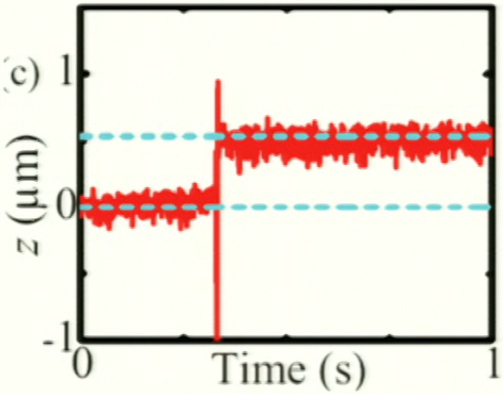


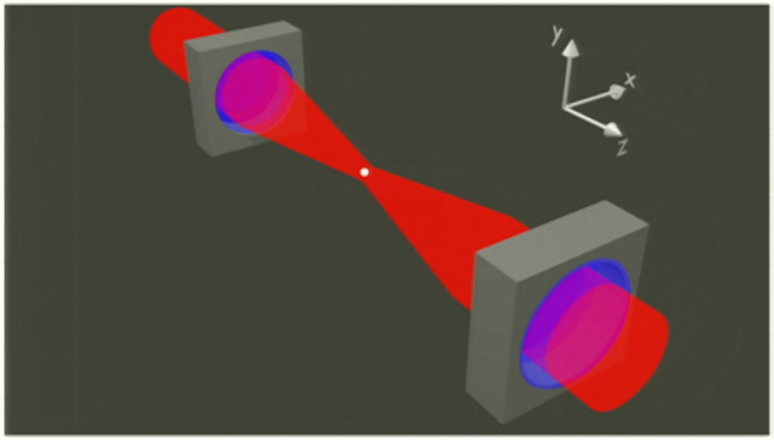


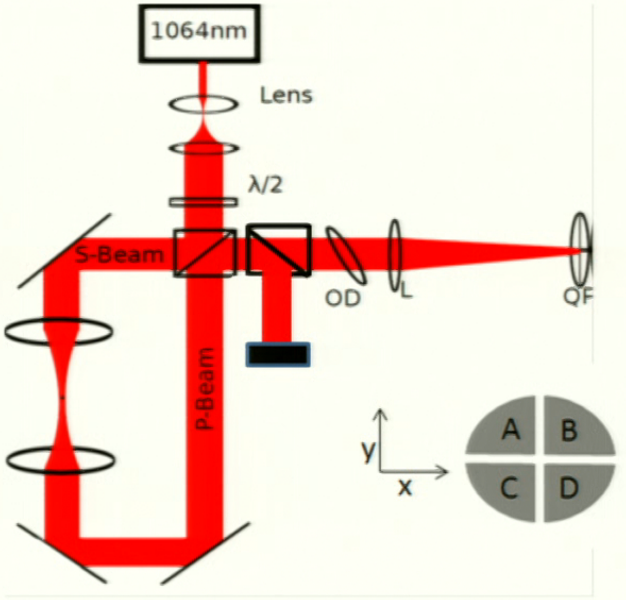


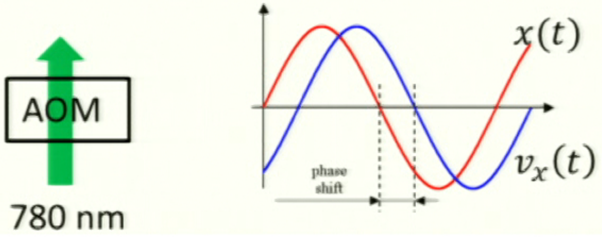


3D feedback cooling of a nanosphere

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







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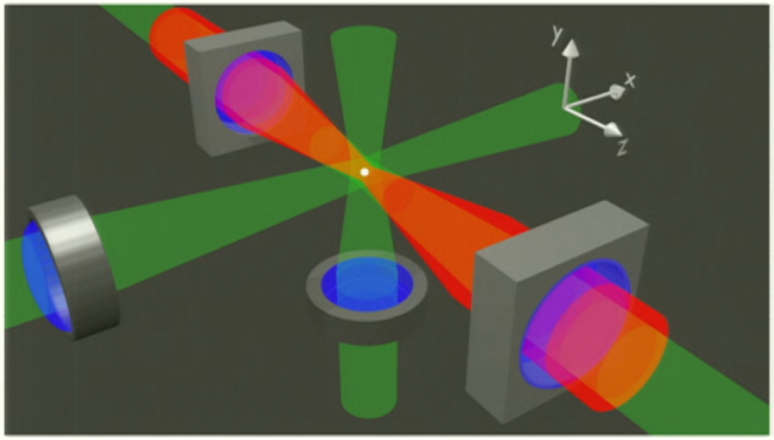

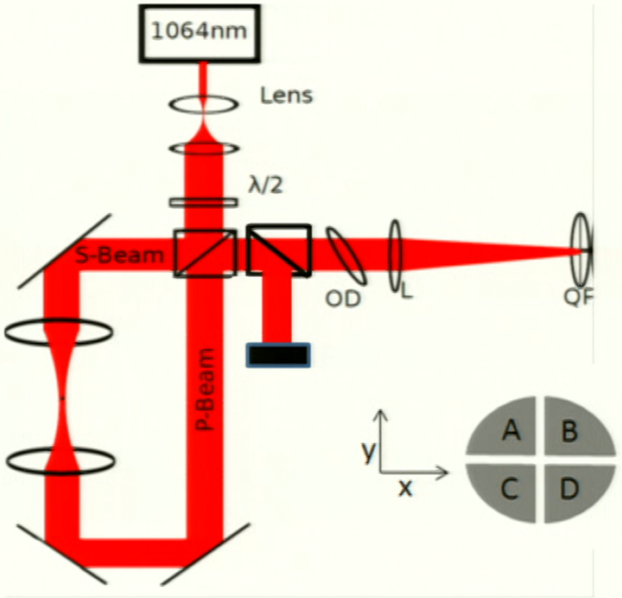

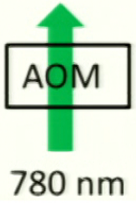

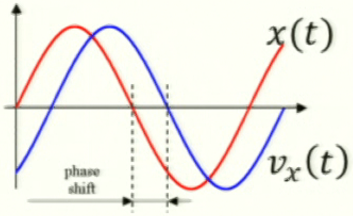

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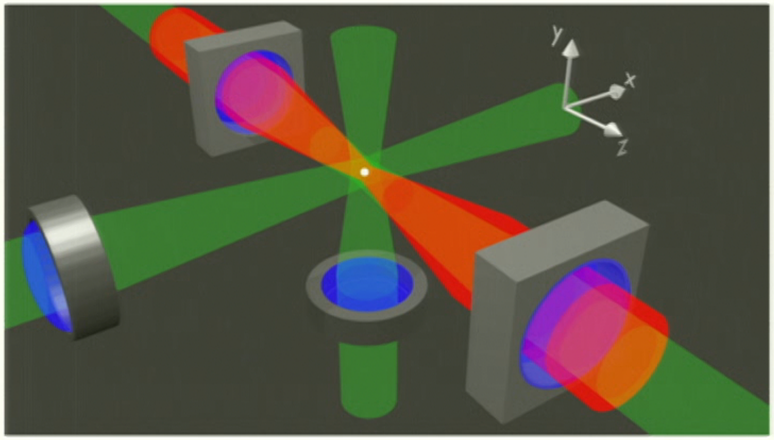
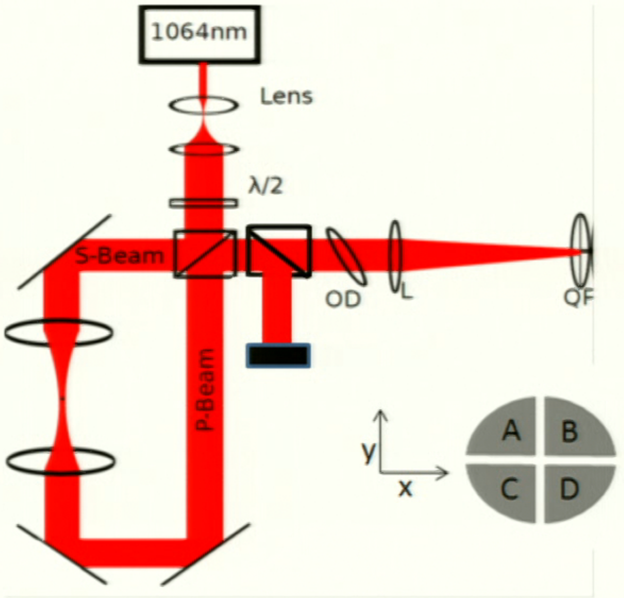
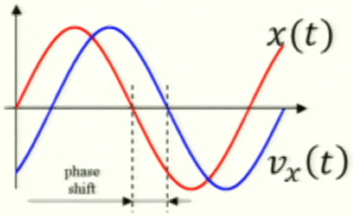


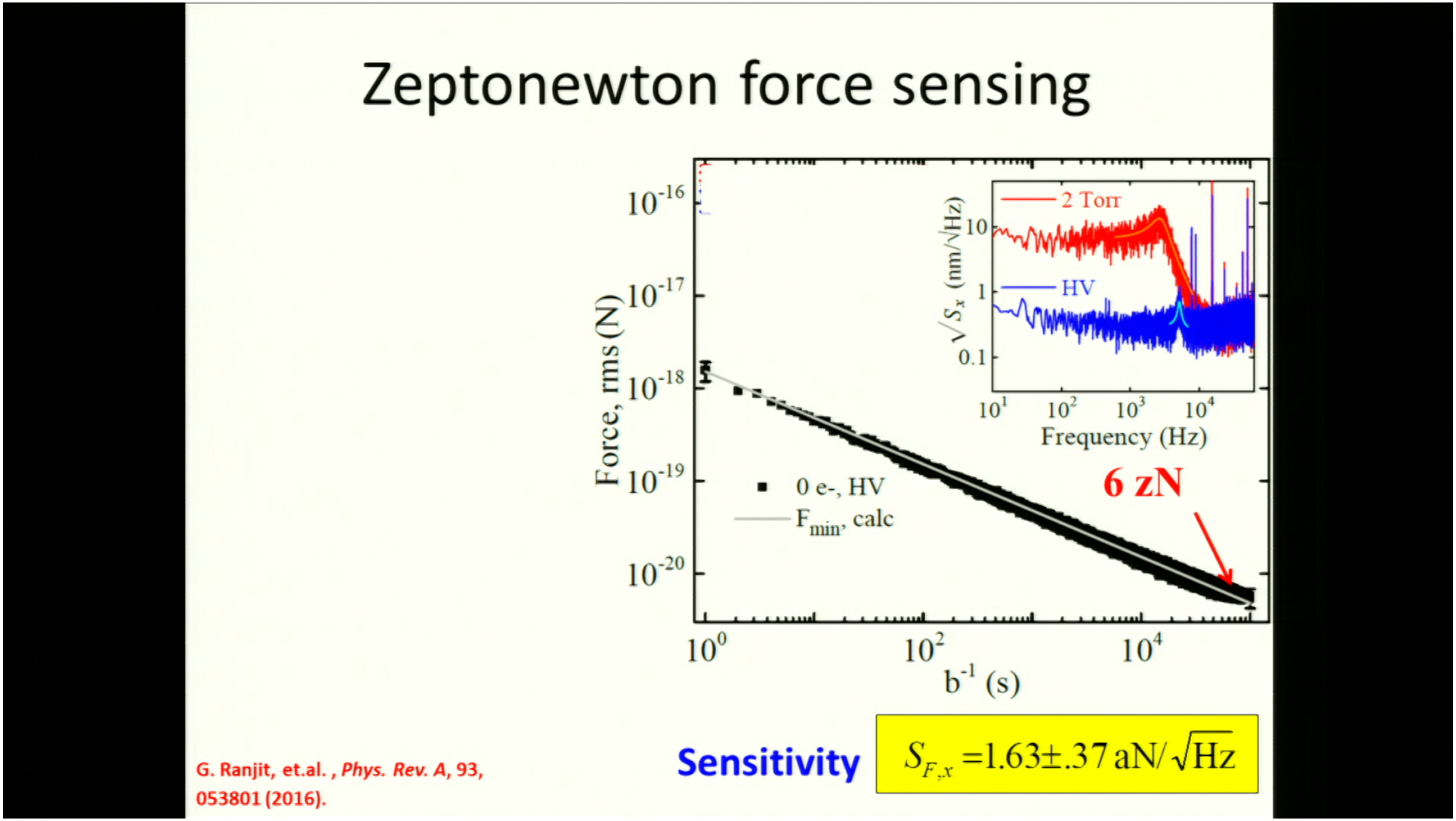


$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

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

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





Zeptonewton force sensing

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

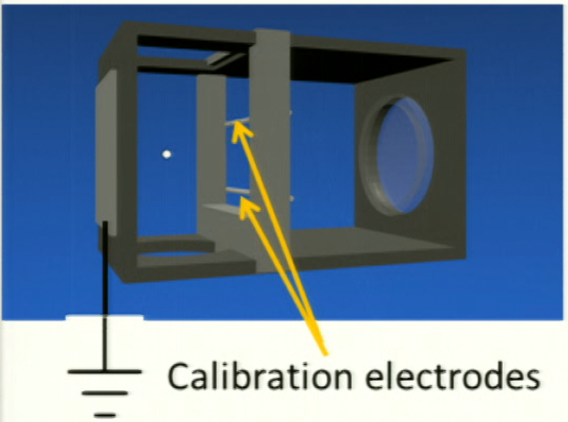
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

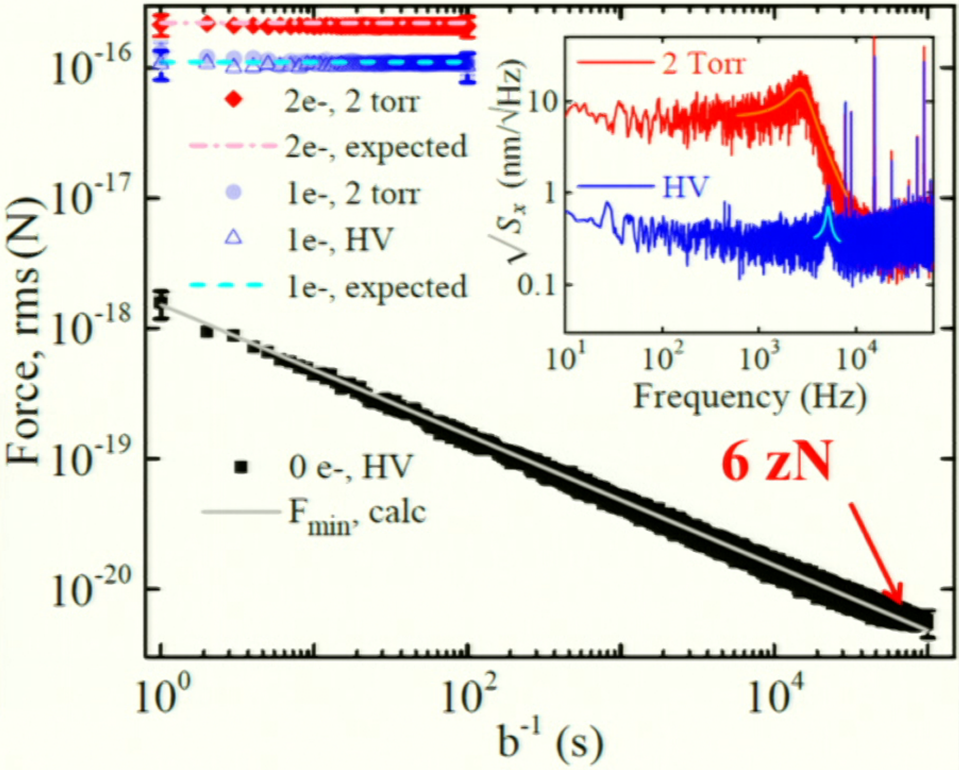
Zeptonewton force sensing

Electrostatic Calibration

90% of beads are neutral

Neutral beads stay neutral
Charge stays constant over days





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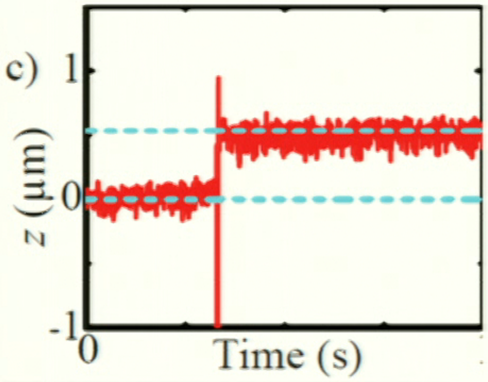
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Zeptonewton force sensing

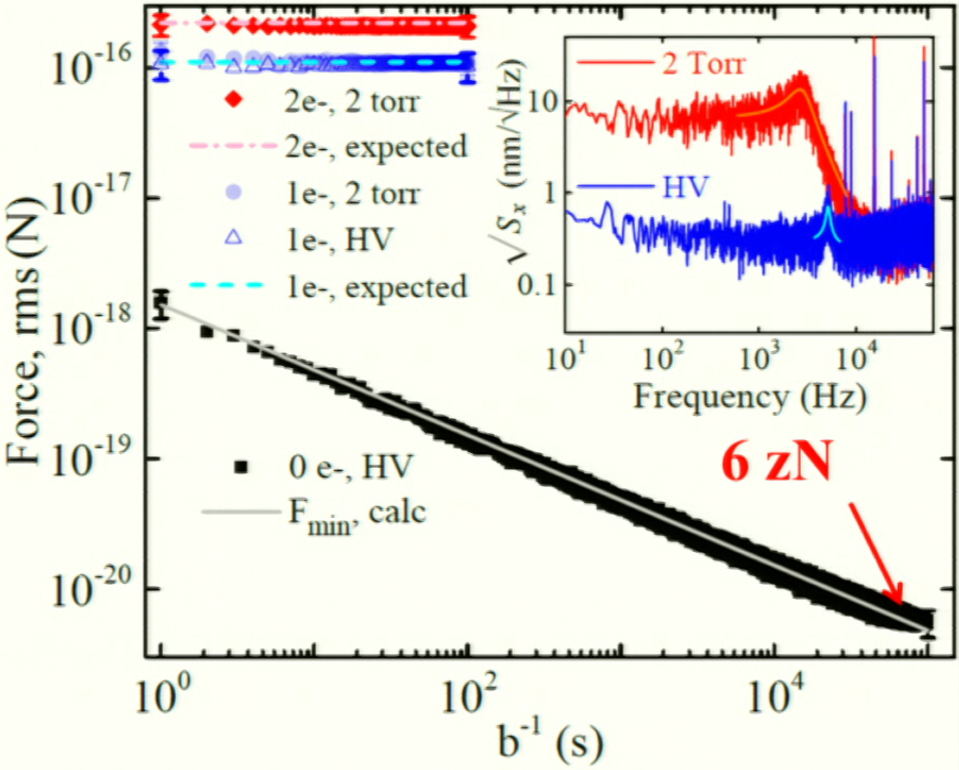
Optical lattice calibration



Useful for neutral objects

Method consistent with electric field approach

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



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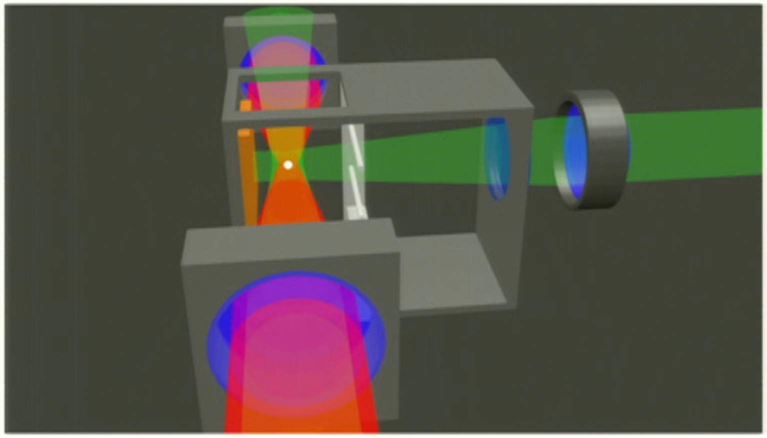
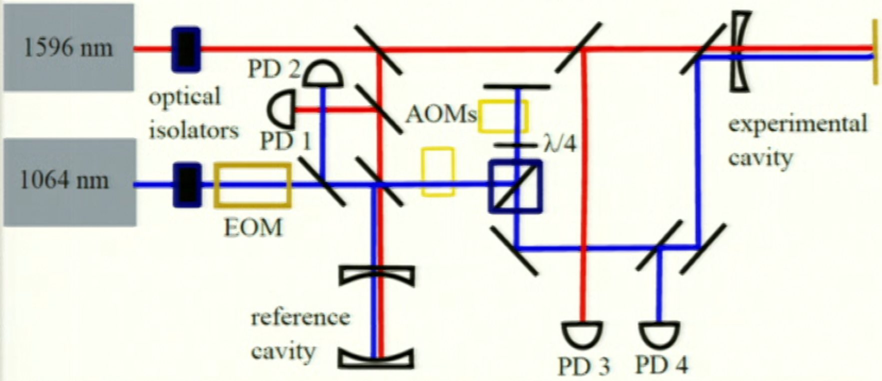
Next: Cavity Trapping and cooling



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



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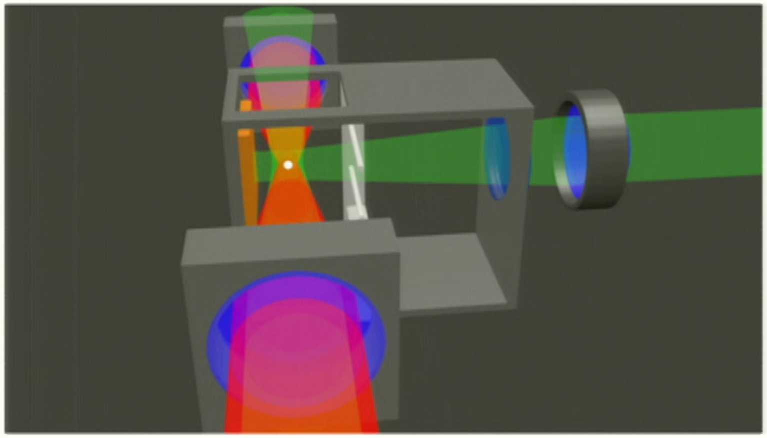

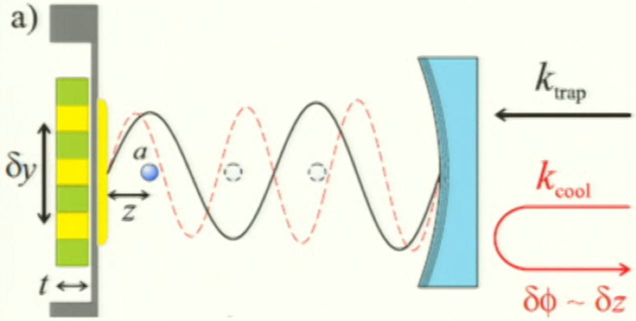

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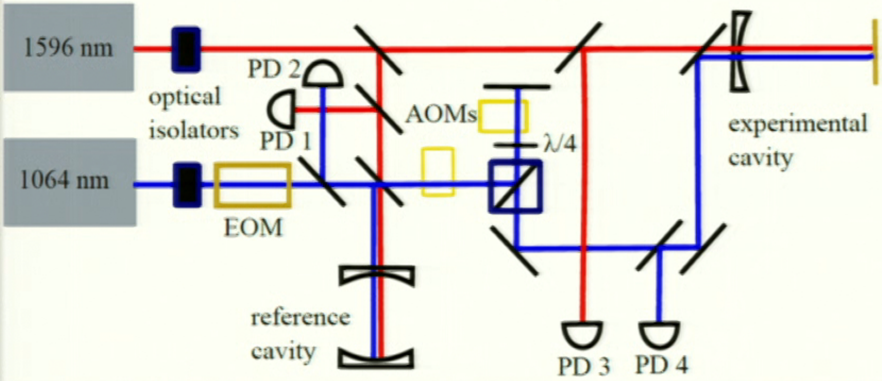
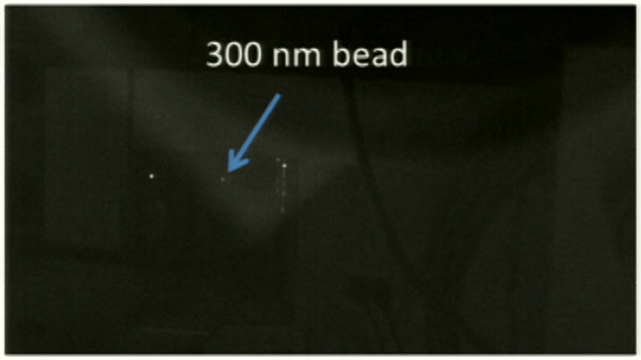
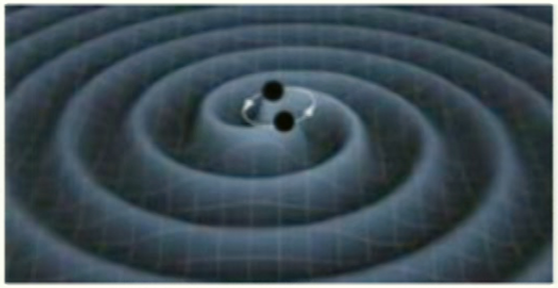
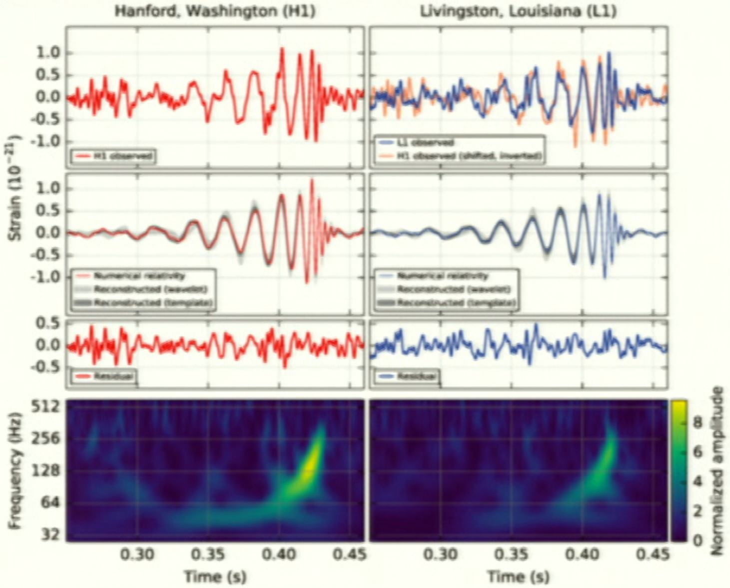




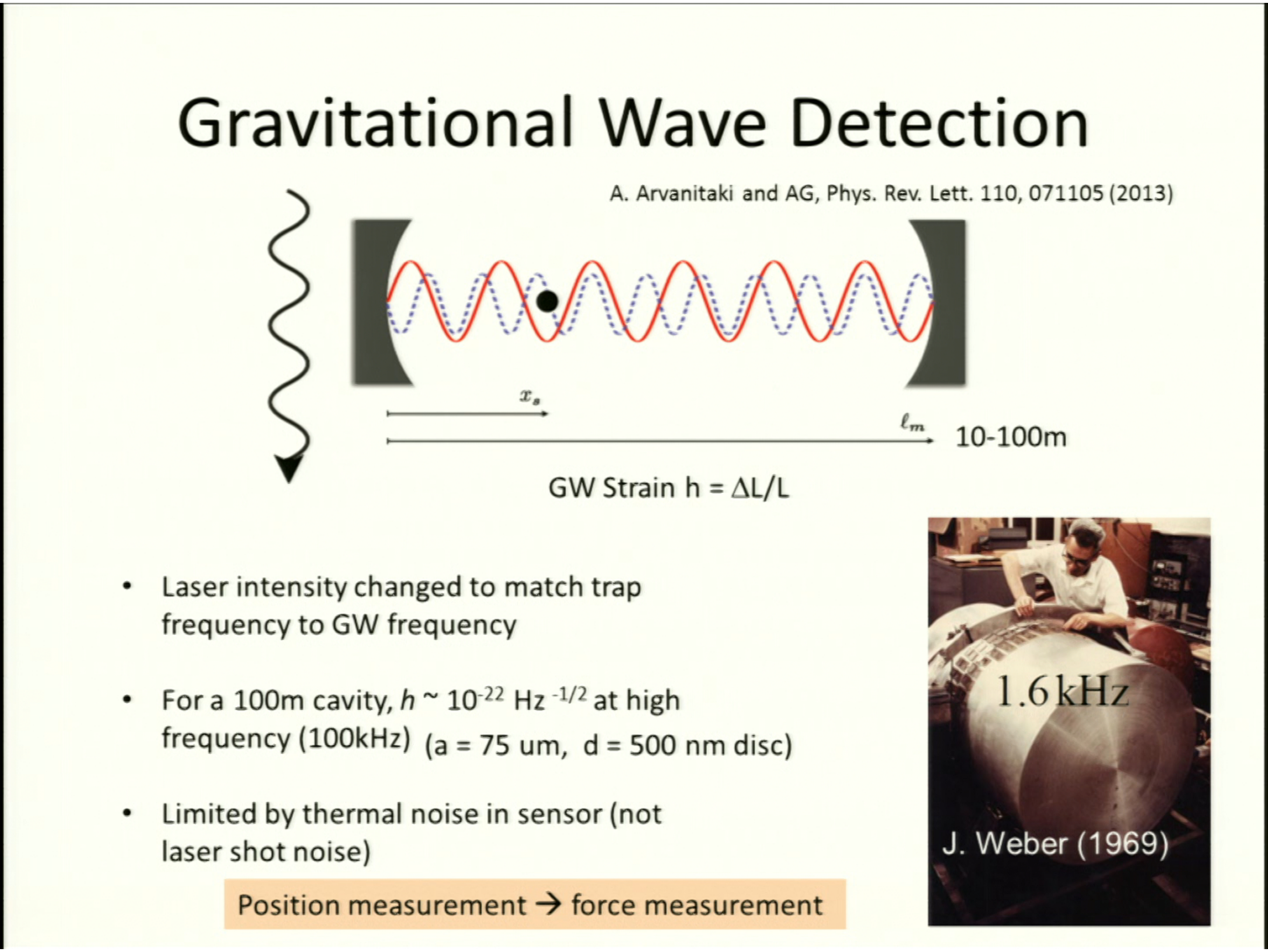
Gravitational waves





- Just discovered by LIGO Sep 2015 !!
- Sources:
  - Inspirals of astrophysical objects
  - Inflation, Phase transitions, etc.

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



Gravitational Wave Detection

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

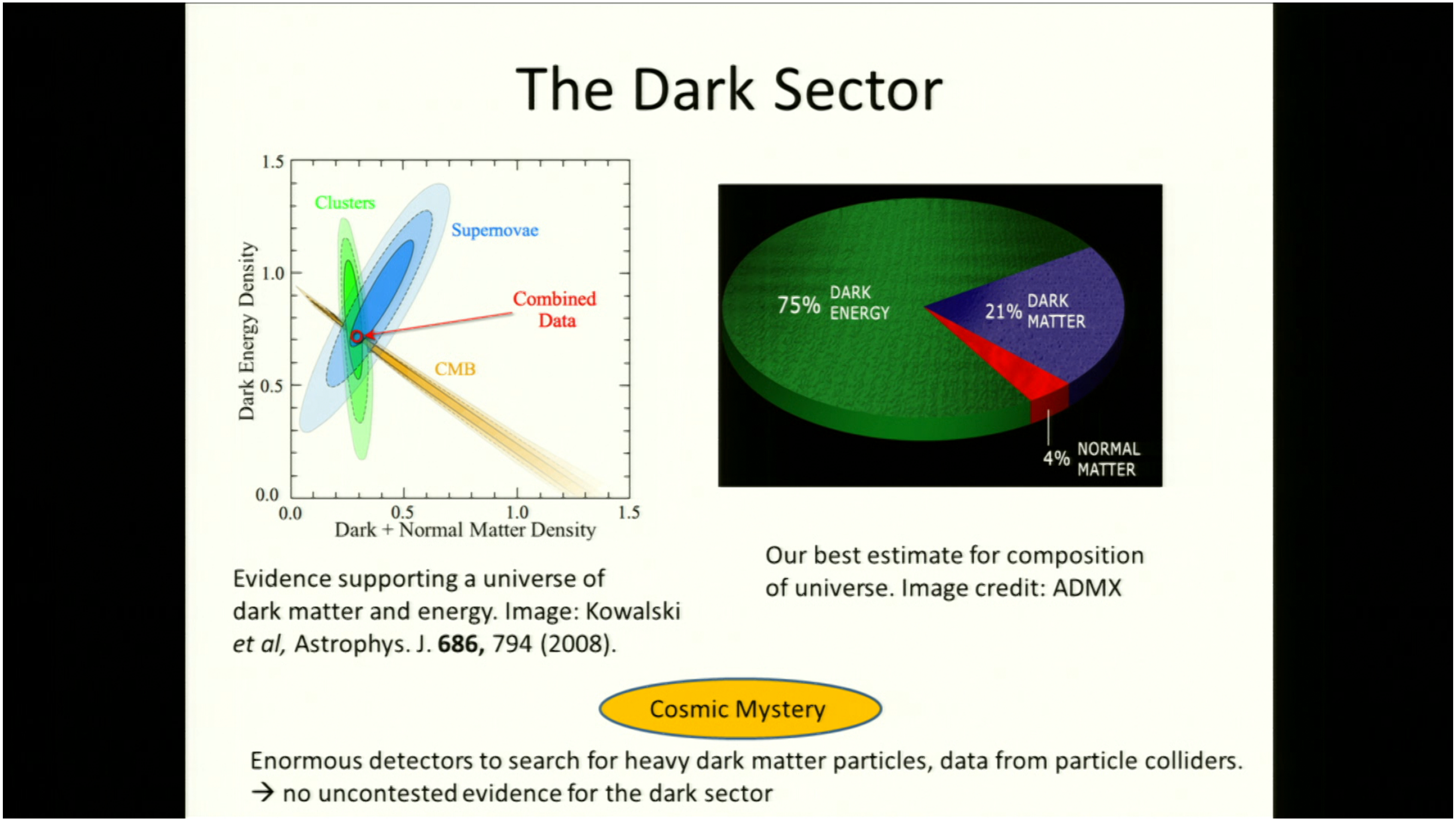
GW Strain h = ΔL/L

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

Position measurement → force measurement

1.6 kHz

J. Weber (1969)



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

- 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).

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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).

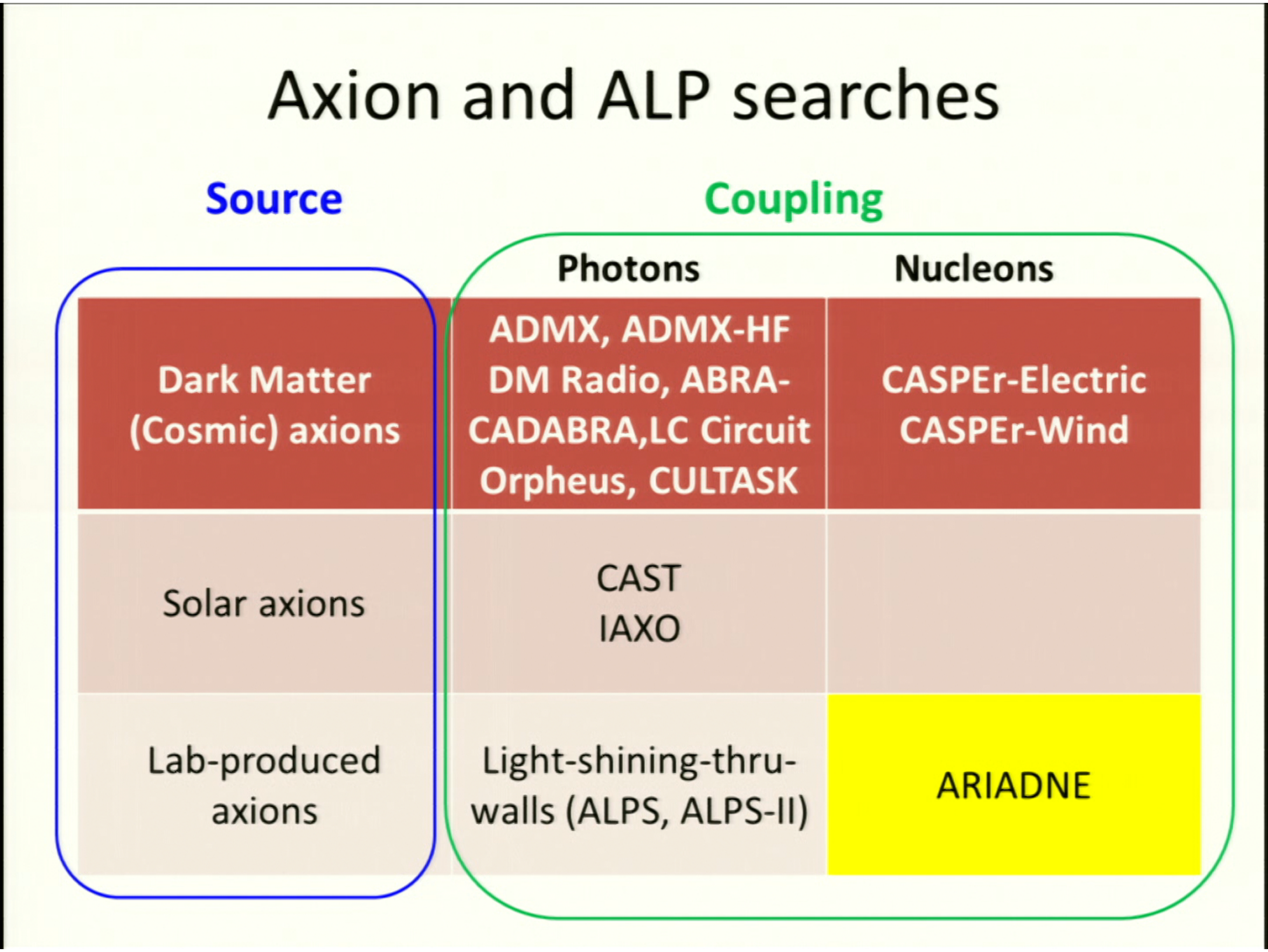
The Axion Resonant InterAction Detection Experiment (ARIADNE)

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

Mark Cunningham (UNR)
Mindy Harkness (UNR)
Jordan Dargert (UNR)
Chloe Lohmeyer (UNR)
Asimina Arvanitaki (Perimeter)
Aharon Kapitulnik (Stanford)
Eli Levenson-Falk (Stanford)
Sam Mumford (Stanford)
Josh Long (IU)
Chen-Yu Liu (IU)
Mike Snow (IU)
Erick Smith (IU)
Justin Shortino (IU)
Mofan Zhang (IU)
Andrew Rusch (IU)
Yannis Semertzidis (CAPP)
Yun Shin (CAPP)
Yong-Ho Lee (KRISS)

A. Geraci, University of Nevada Reno

Axion and ALP searches

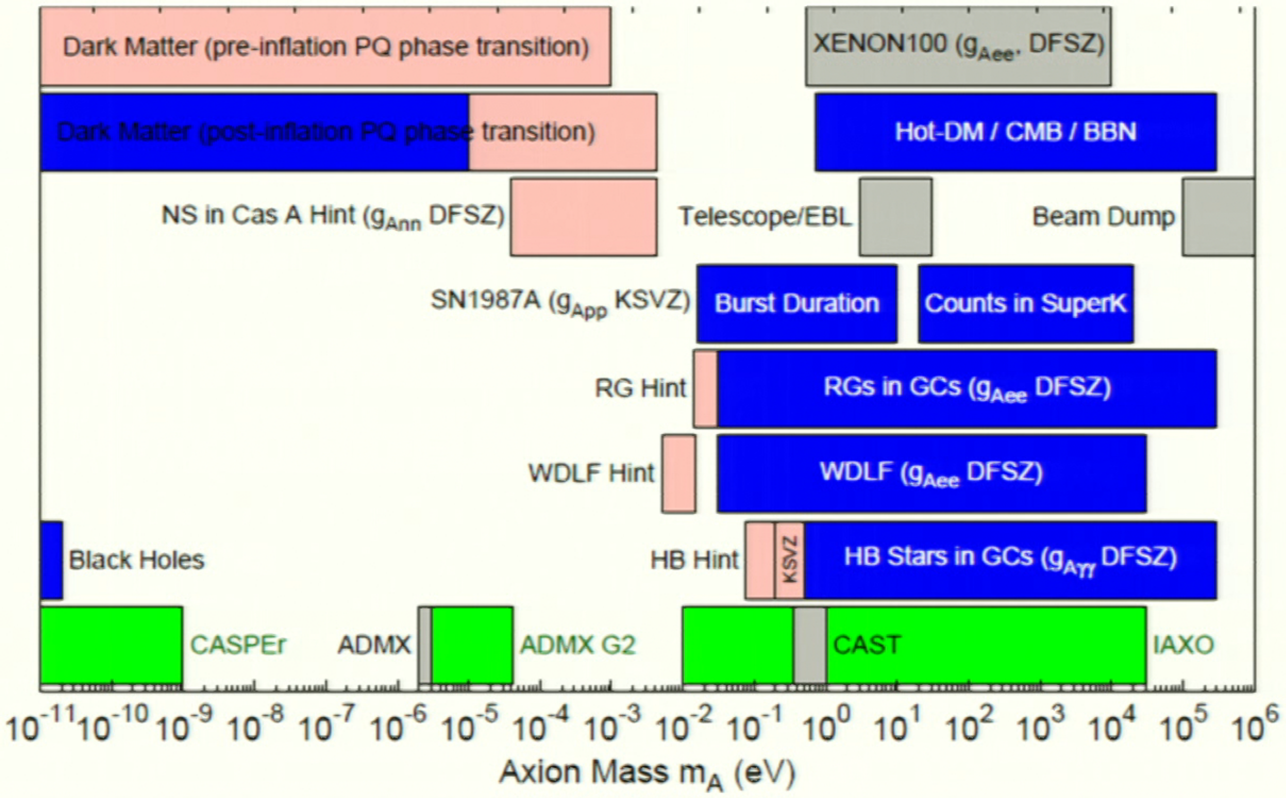


Source

Coupling

	Photons	**Nucleons**
Dark Matter (Cosmic) axions	ADMX, ADMX-HF DM Radio, ABRA-CADABRA,LC Circuit Orpheus, CULTASK	CASPEr-Electric CASPEr-Wind
Solar axions	CAST IAXO	
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE

QCD Axion parameter space



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

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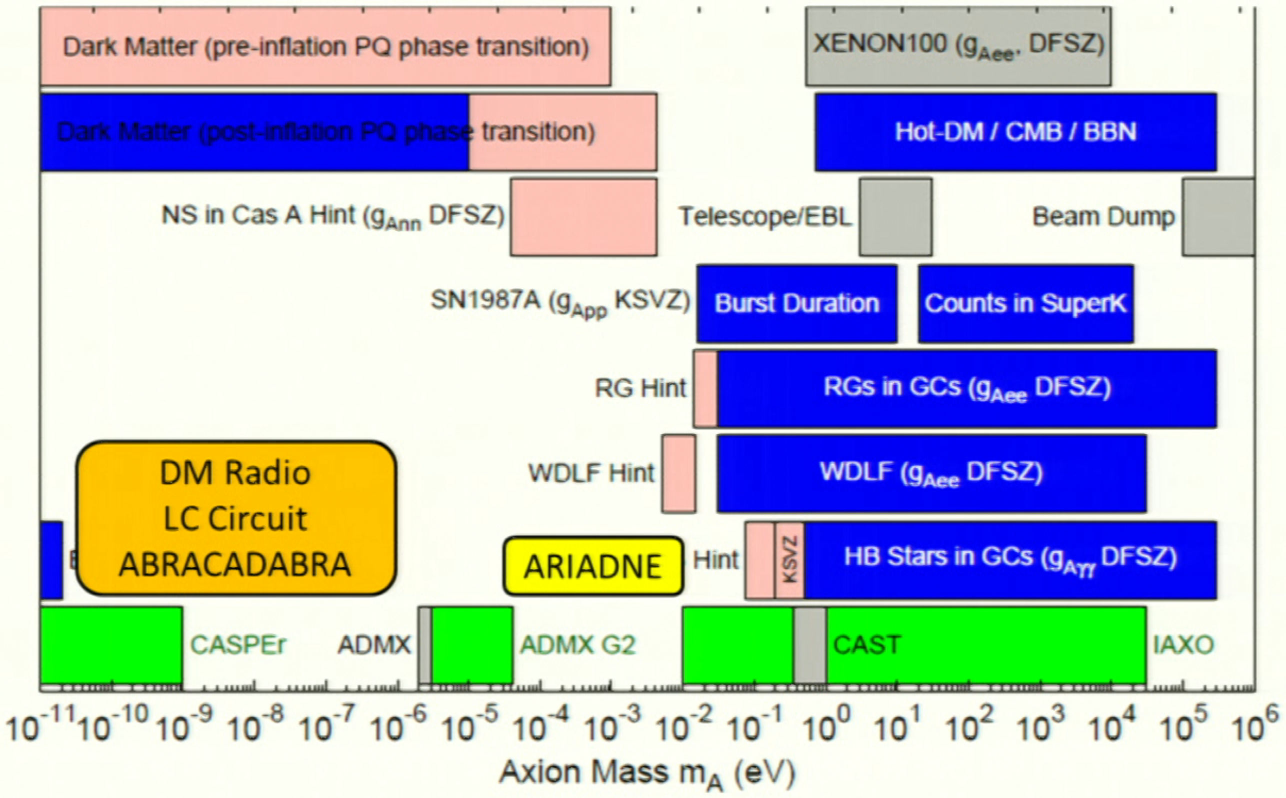


Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion-exchange between nucleons

- Scalar coupling ∝ θ_{QCD}

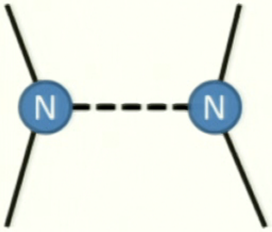
$$\mathcal{L} \supset \frac{\theta_{QCD}}{f_a}\mu \; a\bar{\psi}\psi$$

- Pseudoscalar coupling

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

In the non-relativistic limit:

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



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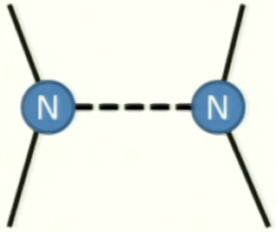
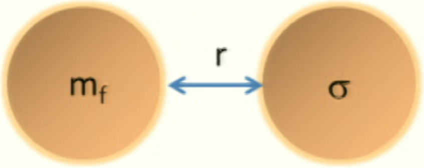
Axion acts a force mediator between nucleons



$(g_s^N)^2$	$g_s^N g_P^N$	$(g_p^N)^2$
Monopole-monopole	Monopole-dipole	dipole-dipole

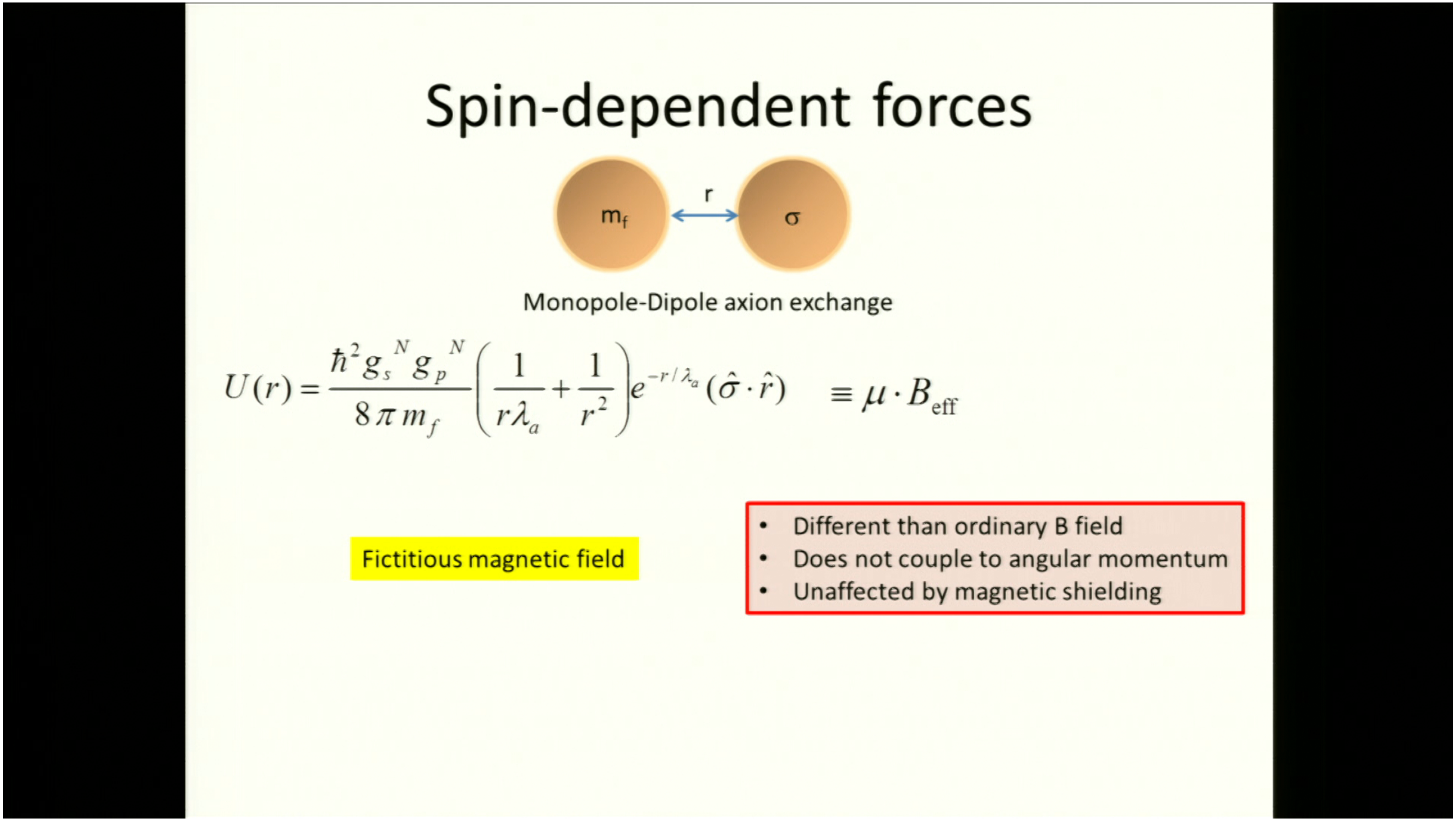
Spin-dependent forces



Monopole-Dipole axion exchange

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

Fictitious magnetic field



Spin-dependent forces

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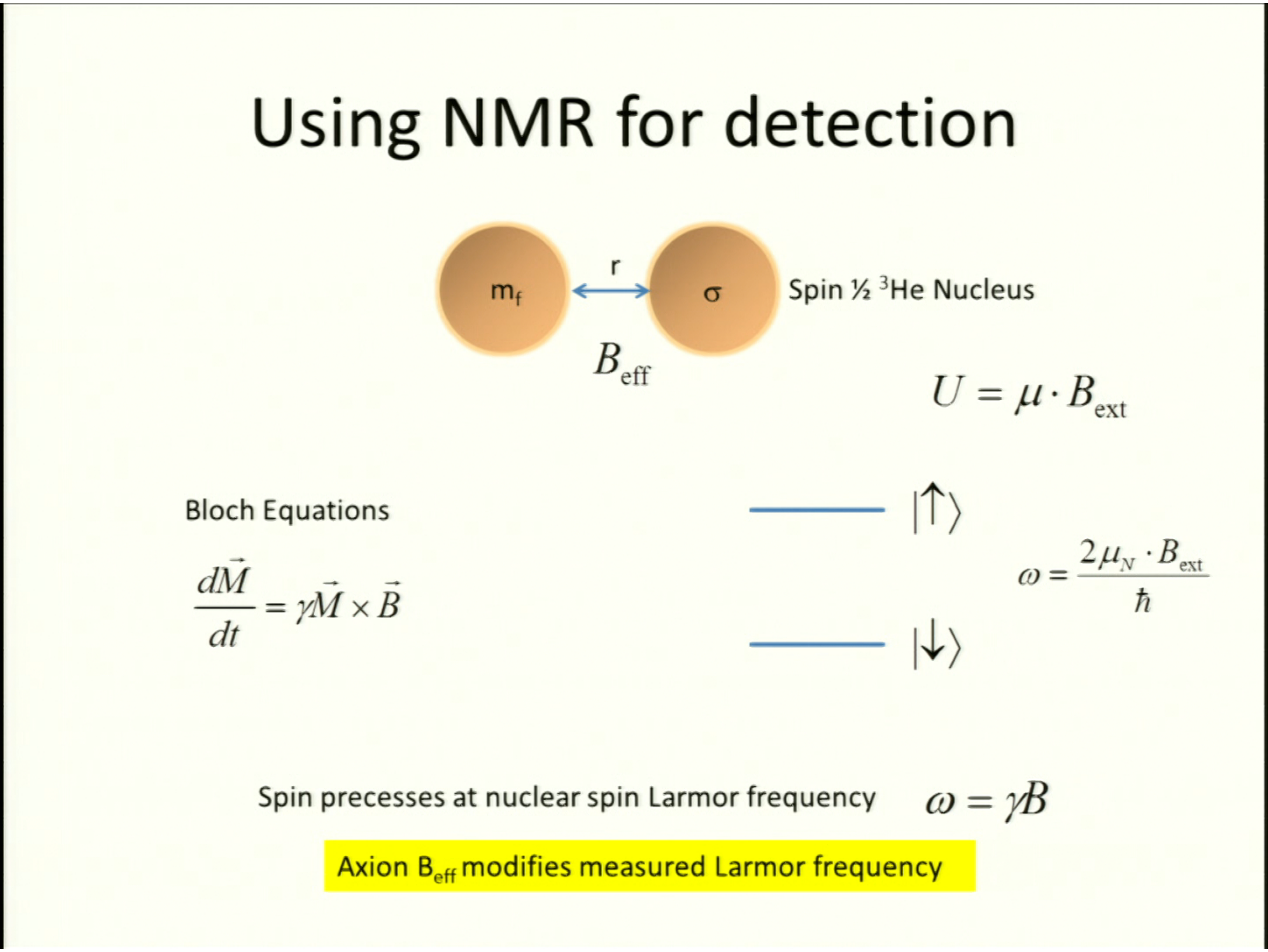
Fictitious magnetic field

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



Using NMR for detection

Spin ½ ^{3}He Nucleus

$$B_{\text{eff}}$$

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

Bloch Equations

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

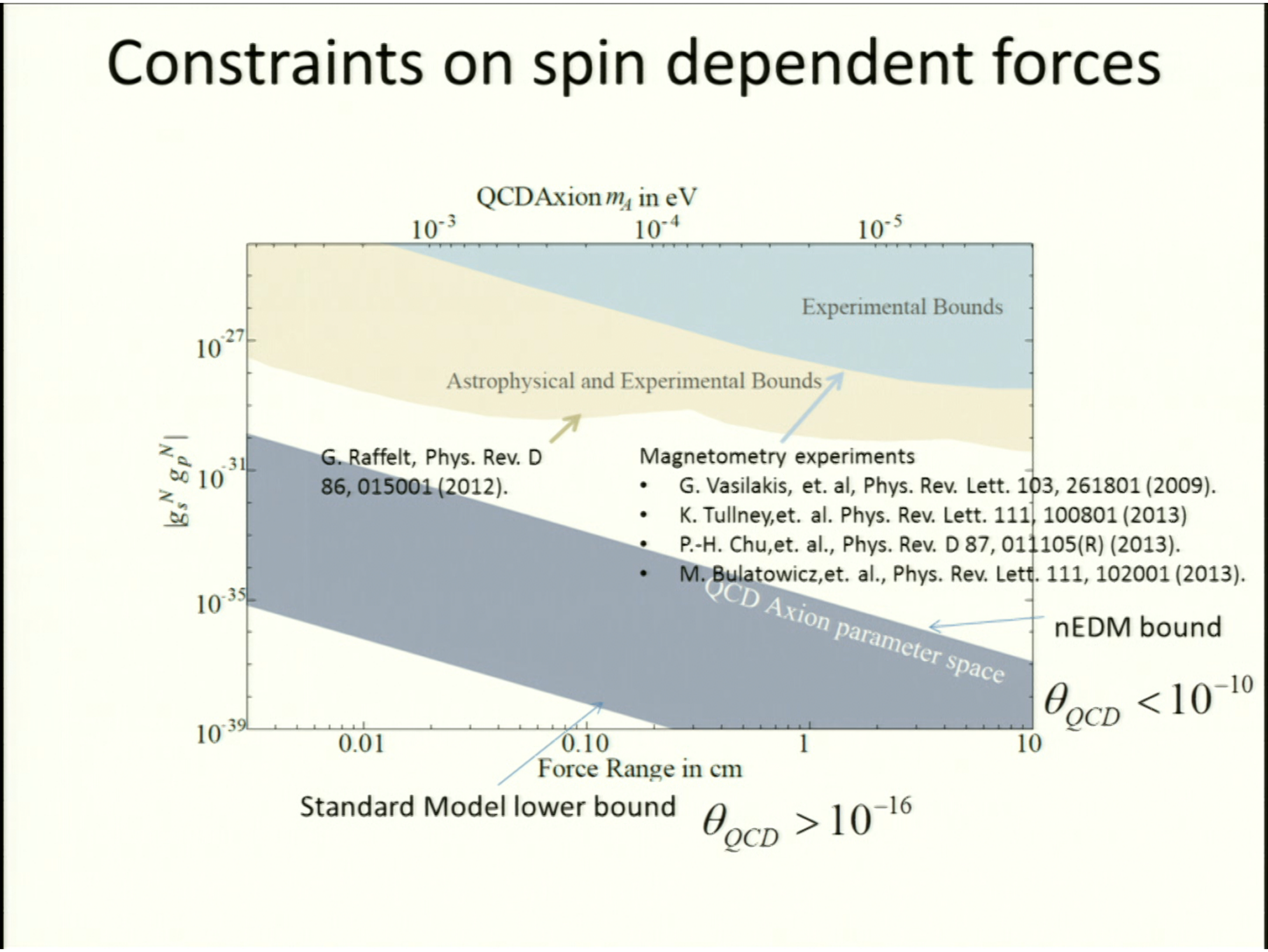
$$|\uparrow\rangle$$

$$|\downarrow\rangle$$

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

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

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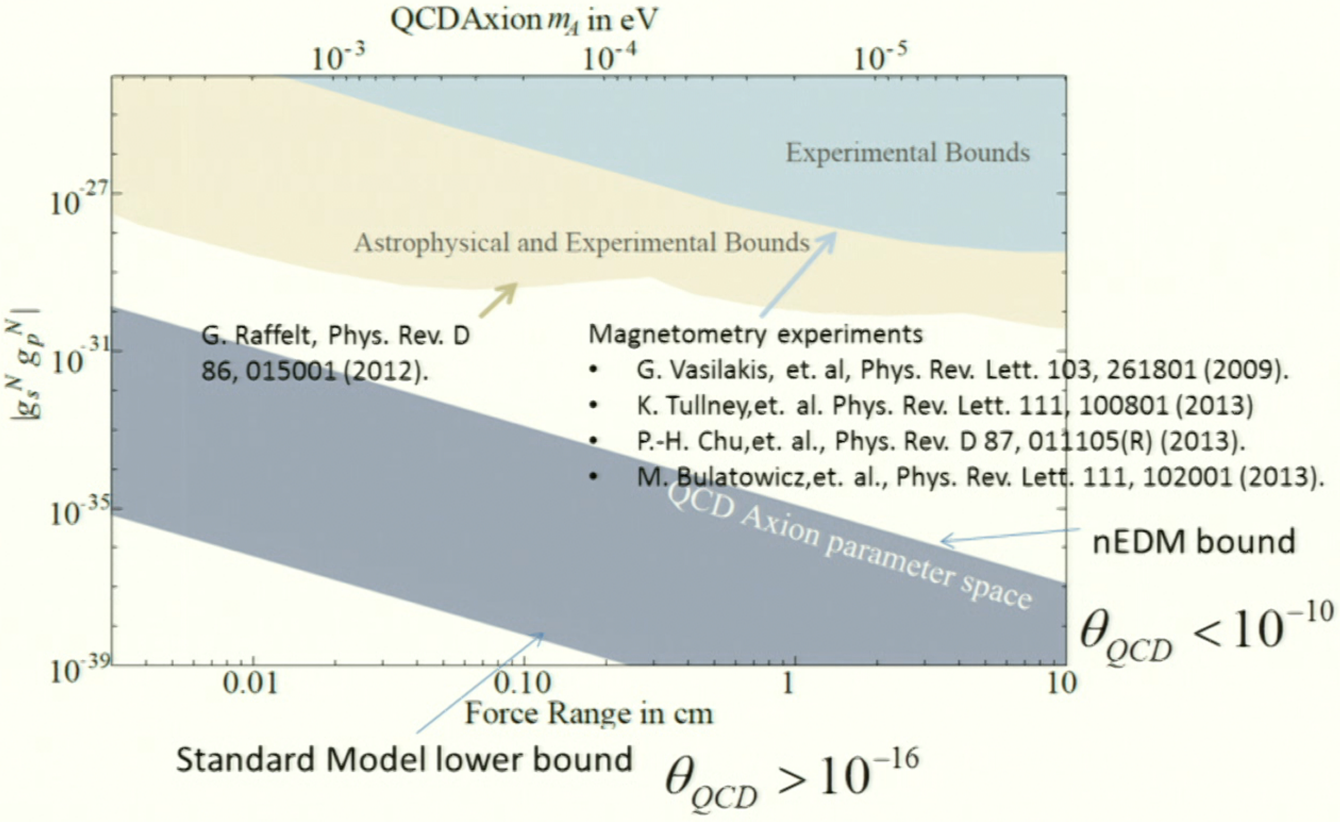

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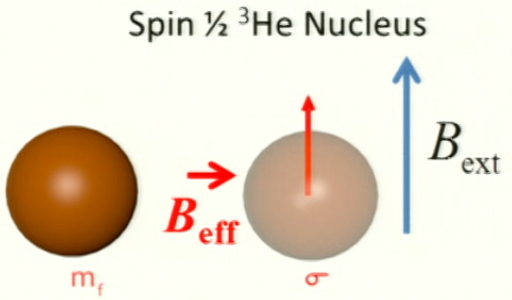
ARIADNE: uses resonant enhancement

Oscillate the mass at Larmor frequency

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



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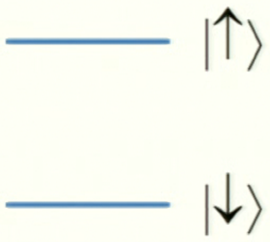
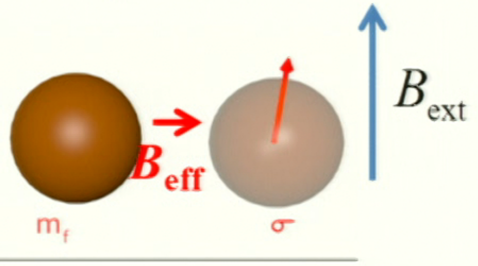


$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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

ARIADNE: uses resonant enhancement

Spin ½ ^{3}He Nucleus



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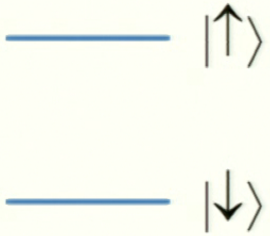

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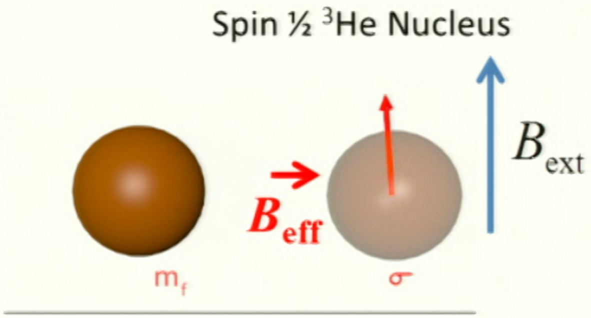

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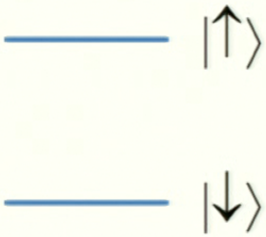
$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$



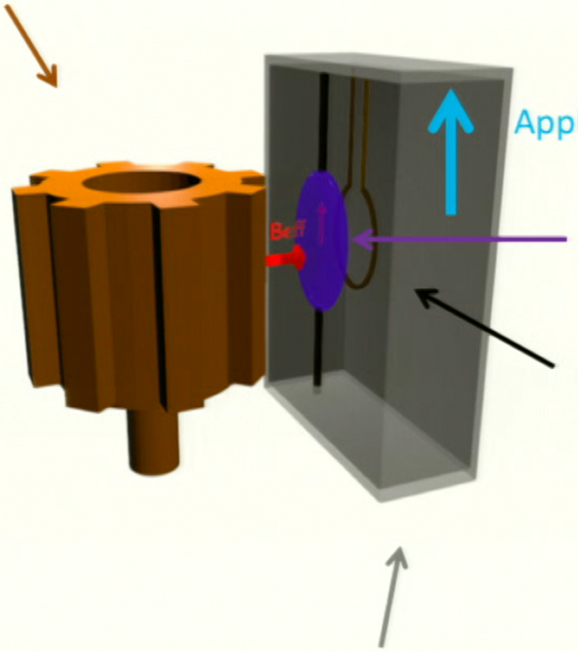
$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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}

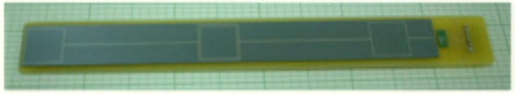
Applied Bias field B_{ext}

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

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

squid pickup
loop

Y.-H. Lee (KRISS)



Superconducting shielding (Stanford)

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

Concept for ARIADNE

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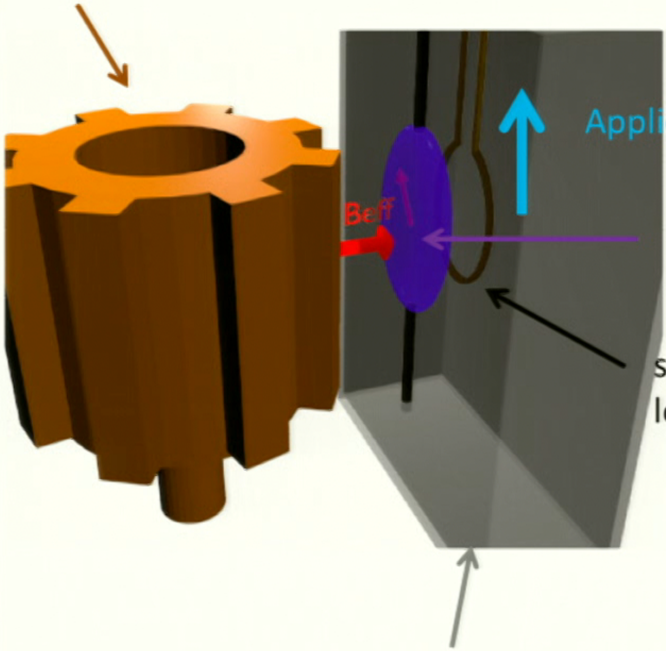

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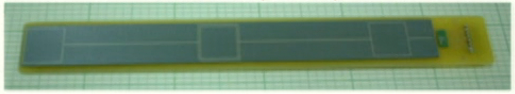

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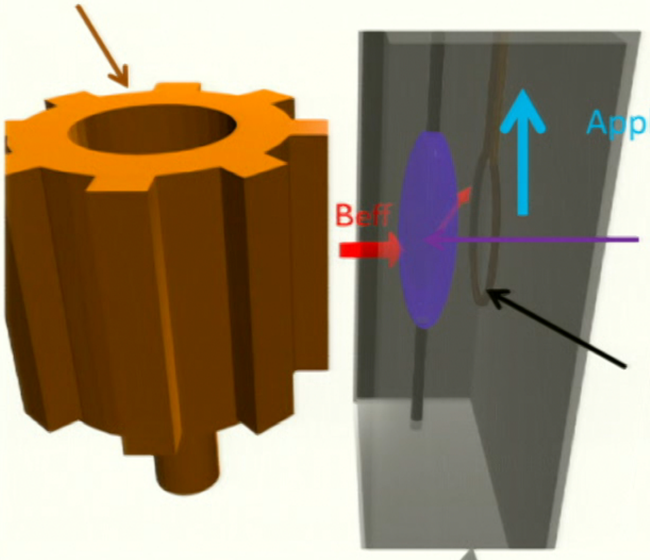

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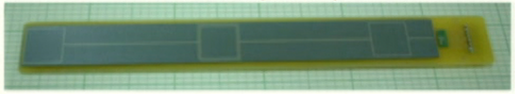


Superconducting shielding (Stanford)

Limit: Transverse spin projection noise

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

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

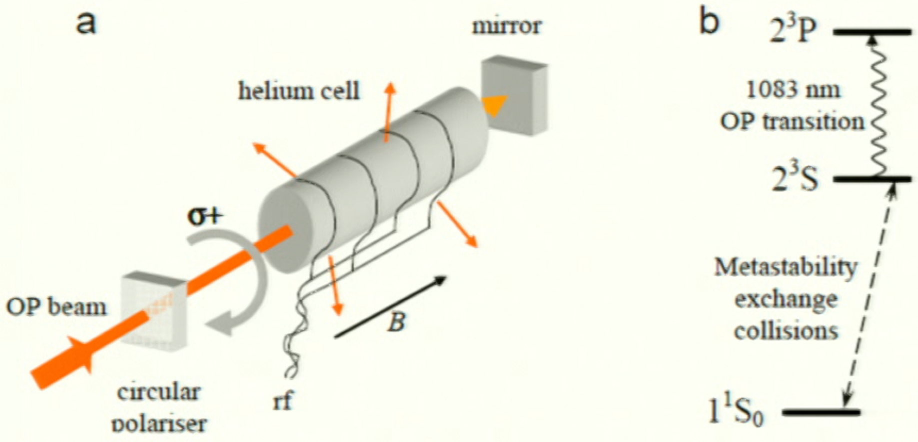
Hyperpolarized ^{3}He

- Ordinary magnetic fields cannot be used to reach near unity polarization

$$\exp[-\mu_N B / k_B T]$$

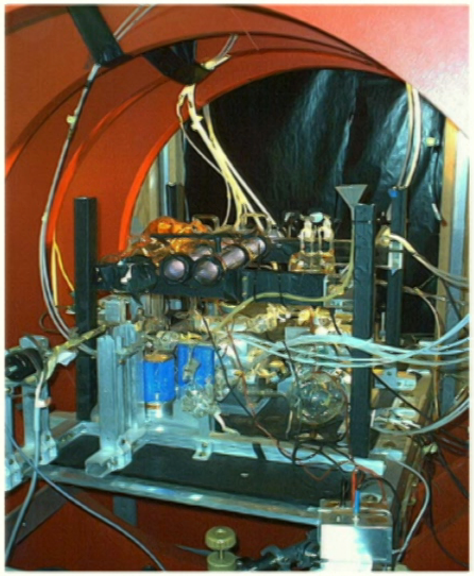
Optical pumping techniques

- Metastability exchange optical pumping



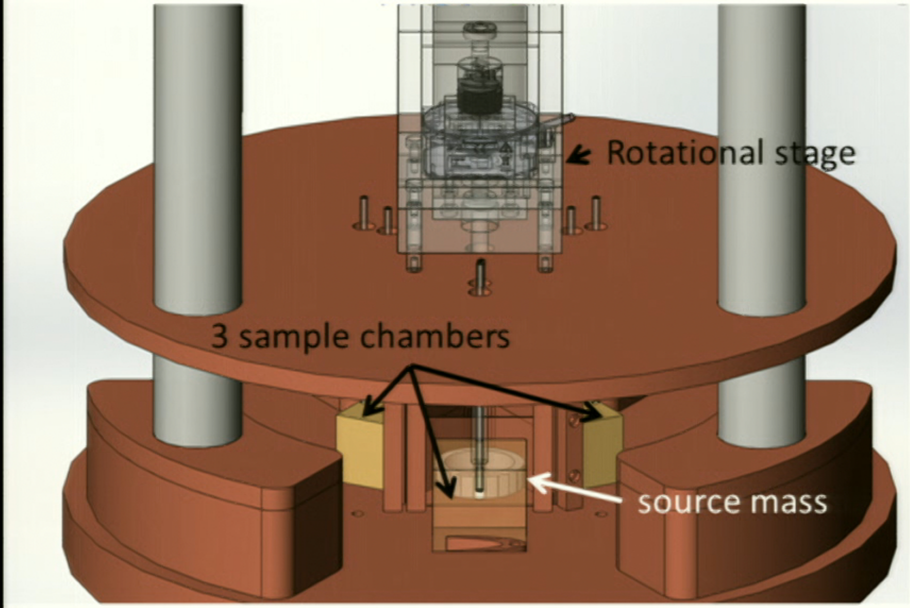
M Batz, P-J Nacher and G Tastevin, Journal of Physics: Conference Series **294** (2011) 012002

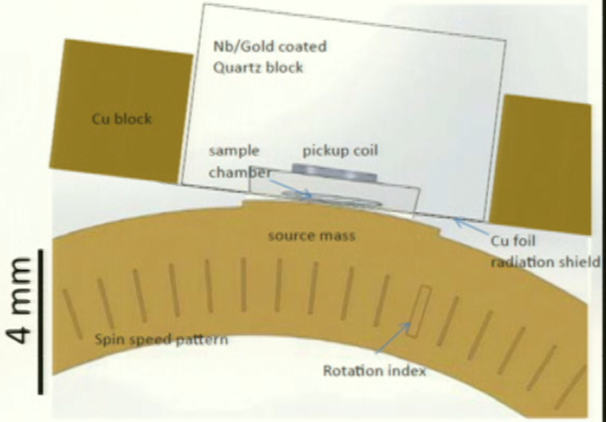
Indiana U. MEOP apparatus



Rev. Sci. Instrum. 76, 053503 (2005)

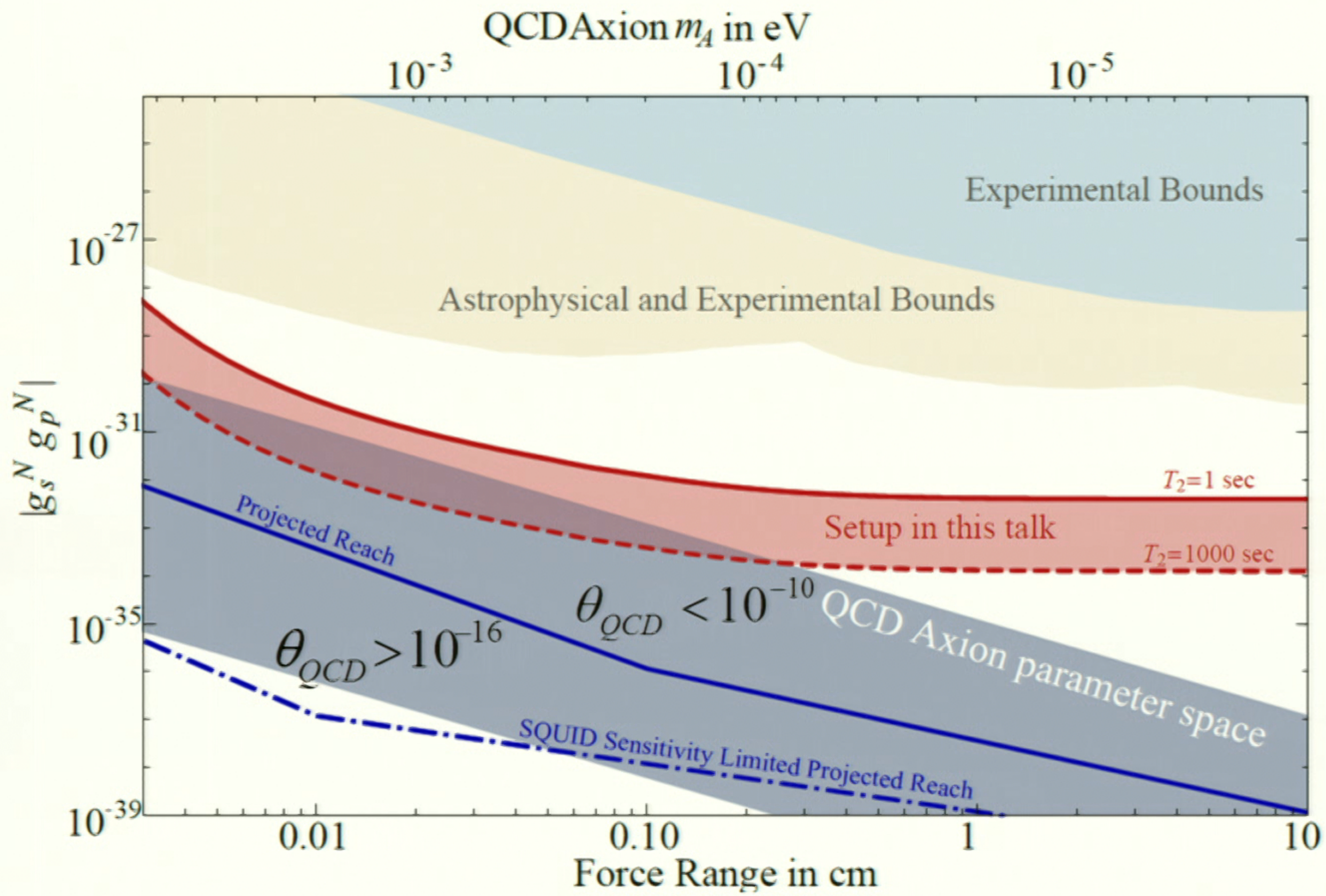
Experimental parameters





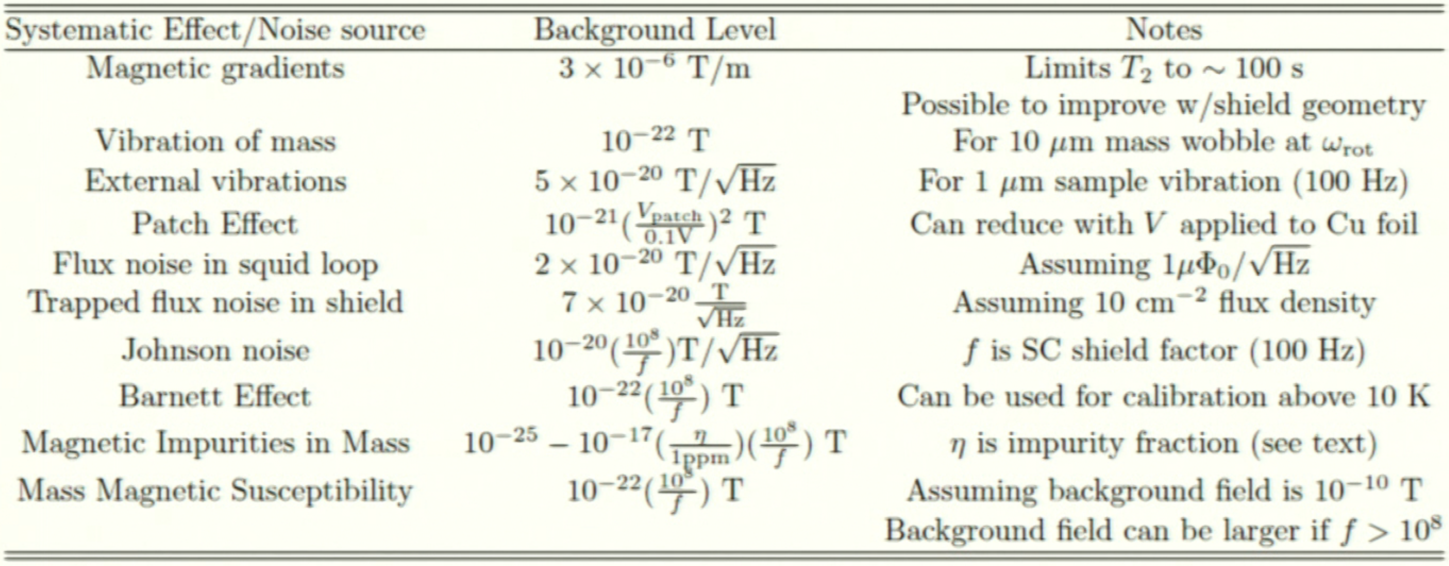
11 segments
100 Hz nuclear spin precession frequency
2×10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 µm volume
Separation 200 µm
Tungsten source mass (high nucleon density)

Sensitivity



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

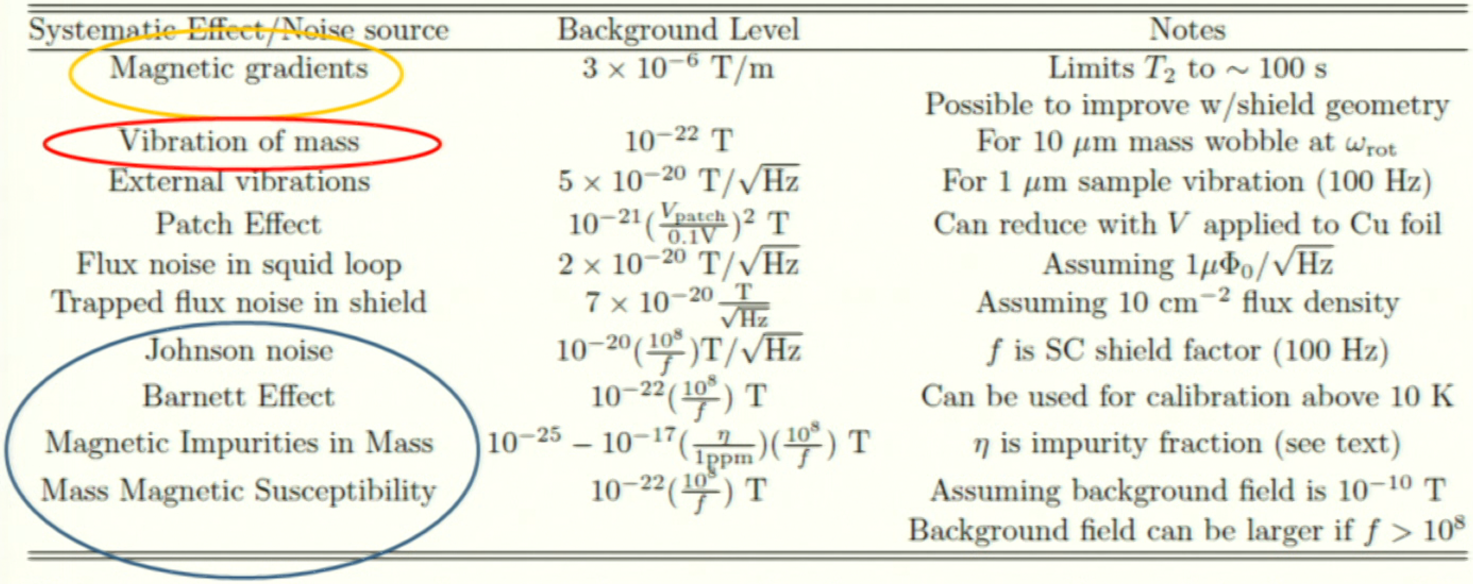
Experimental challenges



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 ω_{rot}
External vibrations	5×10^{-20} T/$\sqrt{\mathrm{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\mathrm{patch}}}{0.1\mathrm{V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\mathrm{Hz}}$	Assuming $1\mu\Phi_0/\sqrt{\mathrm{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})\mathrm{T}/\sqrt{\mathrm{Hz}}$	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	$10^{-25} - 10^{-17}(\frac{\eta}{1\mathrm{ppm}})(\frac{10^8}{f})$ 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 $3 \times 10^{-19}(\frac{1000\mathrm{s}}{T_2})$ T/$\sqrt{\mathrm{Hz}}$

Experimental challenges



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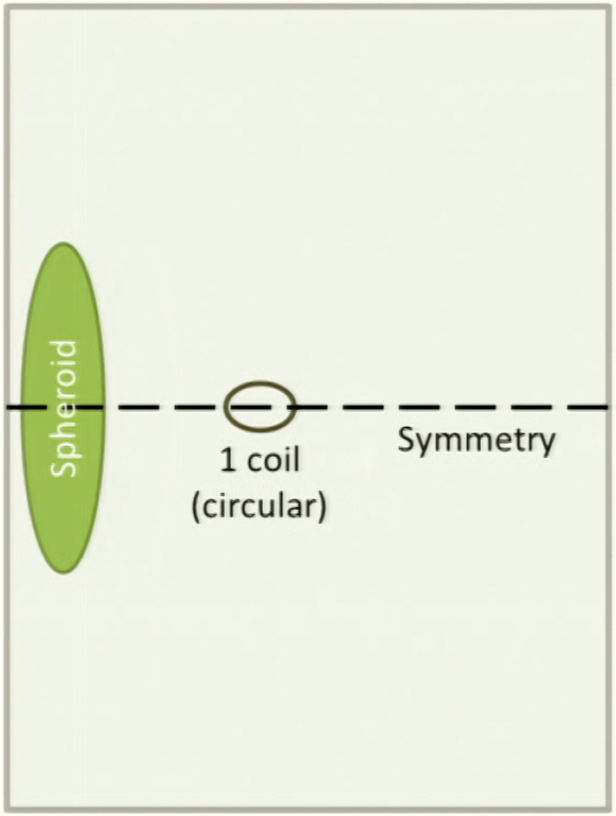
- Design/Simulation Work: Magnetic gradient reduction strategy
- Experimental testing in progress: Vibration tests, Shielding factor *f* test thin-film SC

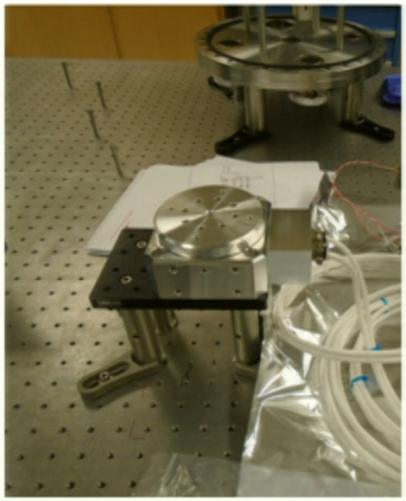
Flattening Solution

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

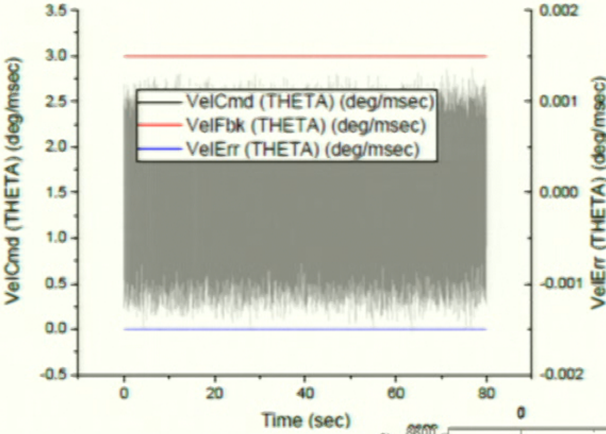


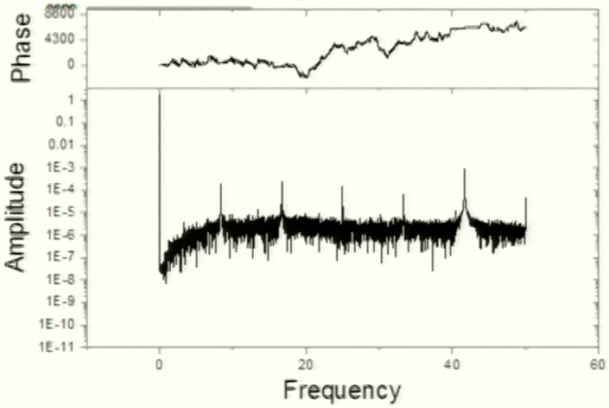
Speed stability test - direct drive stage

- Optical encoder
- Current feedback control



Stage speed stability error – unloaded, in air

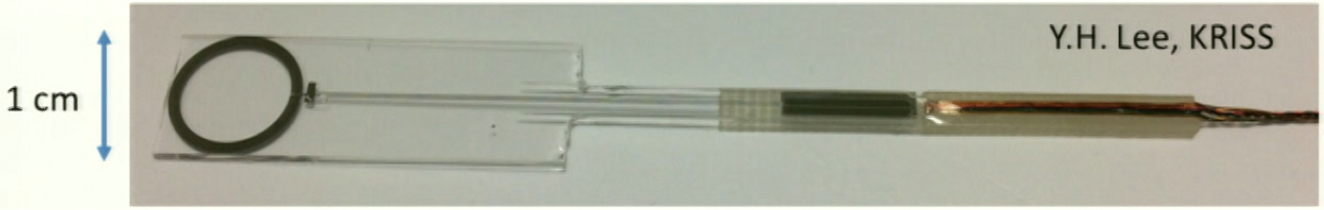


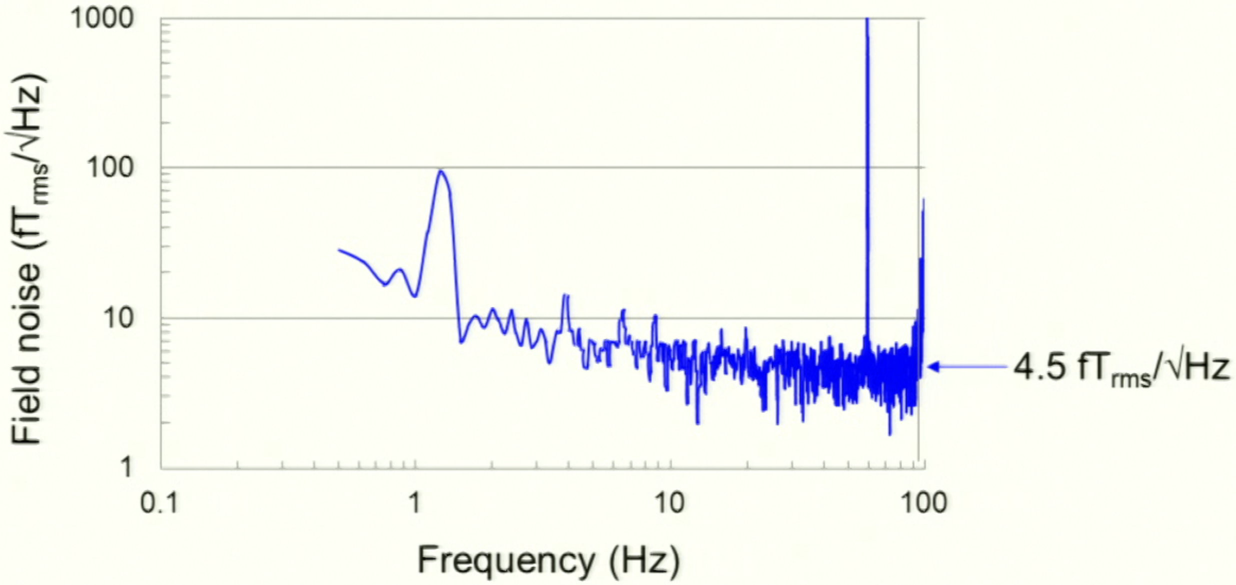


Rotation speed control
8.3 Hz ~ 1 part in 10000
RMS ~ 1 part in 3000

Allows utilization of T2 > 100s

SQUID Magnetometers



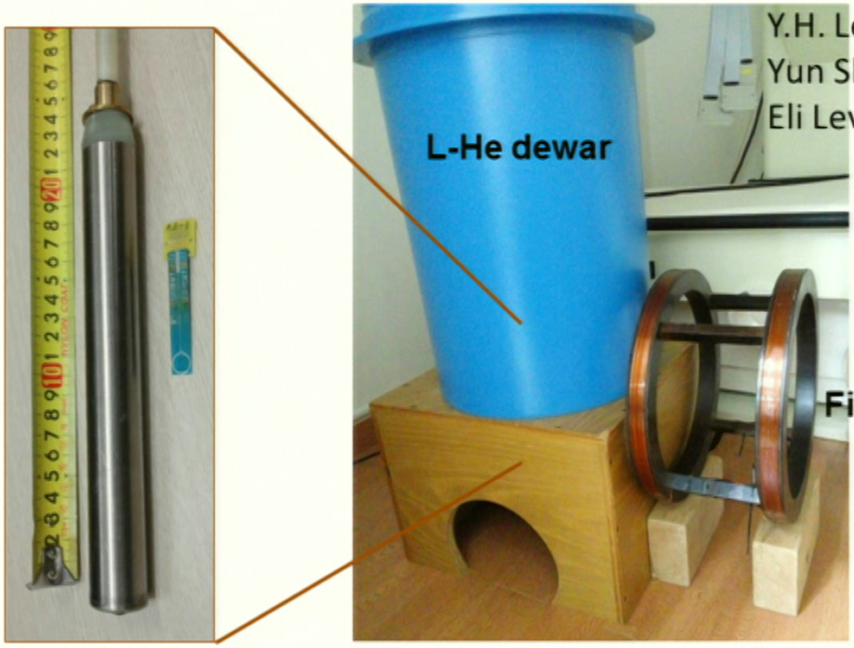


Measured inside a magnetically shielded room (without Nb tube)

Preliminary test of superconductive shielding

Y.H. Lee, KRISS,
Yun Shin (CAPP)
Eli Levenson-Falk (Stanford)

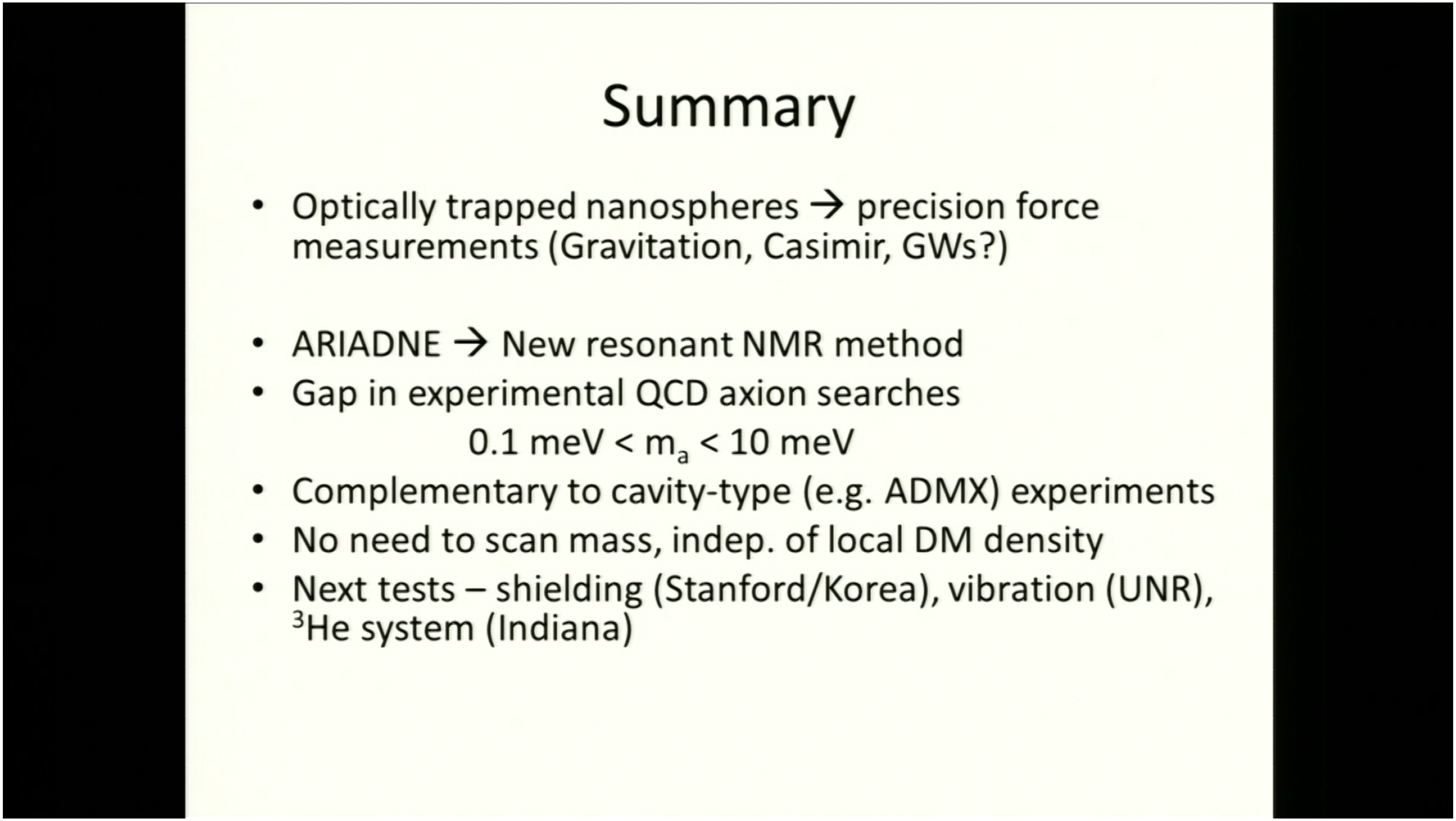
Nb tube:
23 mm ID
1 mm thick
Length 200 mm



Applied field: 10-100 μT_{pp} range (at 8 Hz)

SQUID magnetometer: Near the center of Nb tube
Shielding factor: ≒(0.5-3) $\times 10^9$ for transverse field

Goal: 10^8 with thin film Nb SC shield – tests planned May 2017



Summary

- Optically trapped nanospheres → precision force measurements (Gravitation, Casimir, GWs?)

- ARIADNE → New resonant NMR method
- Gap in experimental QCD axion searches

  $0.1\ \mathrm{meV} < m_a < 10\ \mathrm{meV}$
- Complementary to cavity-type (e.g. ADMX) experiments
- No need to scan mass, indep. of local DM density
- Next tests – shielding (Stanford/Korea), vibration (UNR), ^{3}He system (Indiana)

Acknowledgements

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PHY-1509176
1510484, 1509176

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Cris Montoya (G) Chethn Galla (G) Chloe Lohmeyer(UG) Kirsten Casey (UG) Bella Rodriguez(UG) Gambhir Ranjit (PD)

Not pictured: Apryl Witherspoon (UG), Ohidul Mojumder (UG), Hannah Mason (UG)