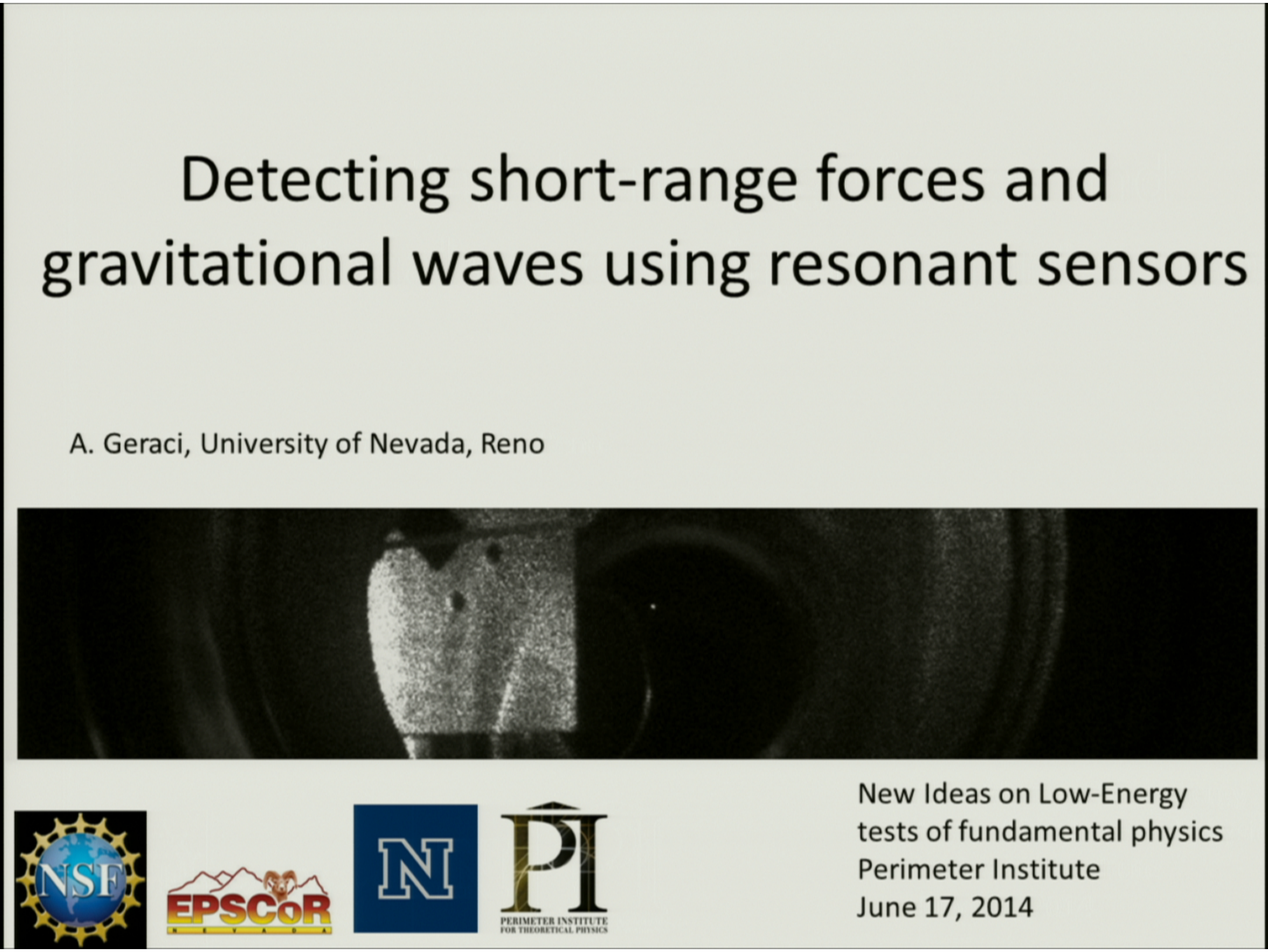
Title: New methods for detecting short-range forces and gravitational waves using resonant sensors

Date: Jun 17, 2014 02:00 PM

URL: http://pirsa.org/14060019

Abstract: <span>High-Q resonant sensors enable ultra-sensitive force and field detection. In this talk I will describe three applications of these sensors in searches for new physics. First I will discuss our experiment which uses laser-cooled optically trapped silica microspheres to search for violations of the gravitational inverse square law at micron distances [1]. I will explain how similar sensors could be used for gravitational wave detection at high frequencies [2]. Finally I will describe a new method for detecting short-range spin-dependent forces from axion-like particles based on nuclear magnetic resonance in hyperpolarized Helium-3. The method can potentially improve previous experimental bounds by several orders of magnitude and can probe deep into the theoretically interesting regime for the QCD axion [3]. [1] A.Geraci, S. Papp, and J. Kitching, Phys. Rev. Lett. 105, 101101 (2010), [2] A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 110, 071105 (2013), [3] A. Arvanitaki and A. Geraci, arxiv: 1403.1290 (2014).</span>

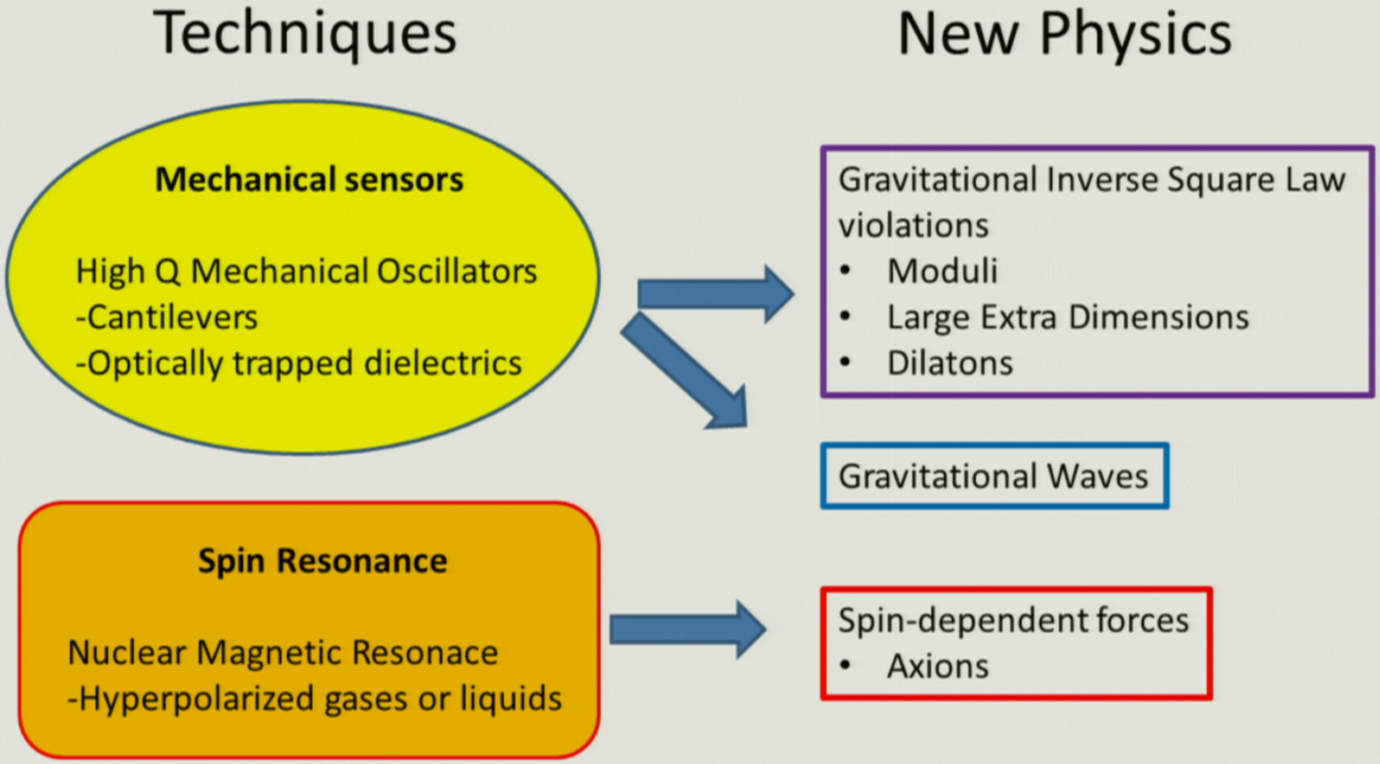


# Detecting short-range forces and gravitational waves using resonant sensors

A. Geraci, University of Nevada, Reno

New Ideas on Low-Energy
tests of fundamental physics
Perimeter Institute
June 17, 2014

# Resonant Sensors



## Techniques

## New Physics

**Mechanical sensors**

High Q Mechanical Oscillators
-Cantilevers
-Optically trapped dielectrics

**Spin Resonance**

Nuclear Magnetic Resonace
-Hyperpolarized gases or liquids

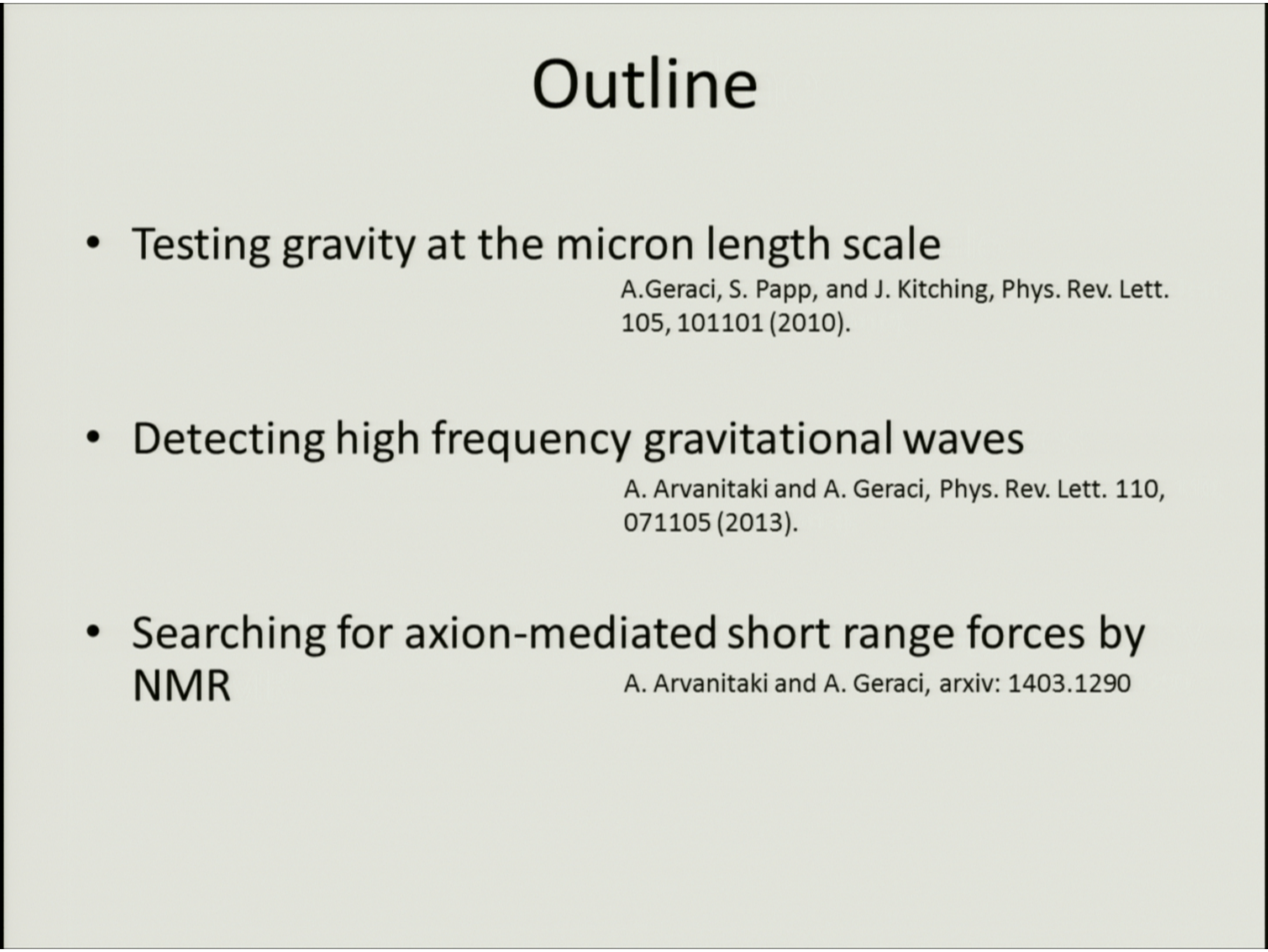
Gravitational Inverse Square Law violations

- Moduli
- Large Extra Dimensions
- Dilatons

Gravitational Waves

Spin-dependent forces

- Axions



# Outline

- Testing gravity at the micron length scale

  A.Geraci, S. Papp, and J. Kitching, Phys. Rev. Lett. 105, 101101 (2010).

- Detecting high frequency gravitational waves

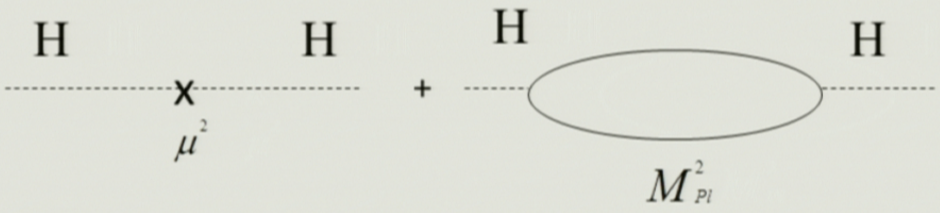
  A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 110, 071105 (2013).

- Searching for axion-mediated short range forces by NMR

  A. Arvanitaki and A. Geraci, arxiv: 1403.1290

# Physics beyond the Standard Model

- One reason to expect: hierarchy problem
Standard Model, as is, requires extreme fine tuning



$M_{\text{Planck}}$

$M_{\text{electro-weak}}$

Possible Solutions:

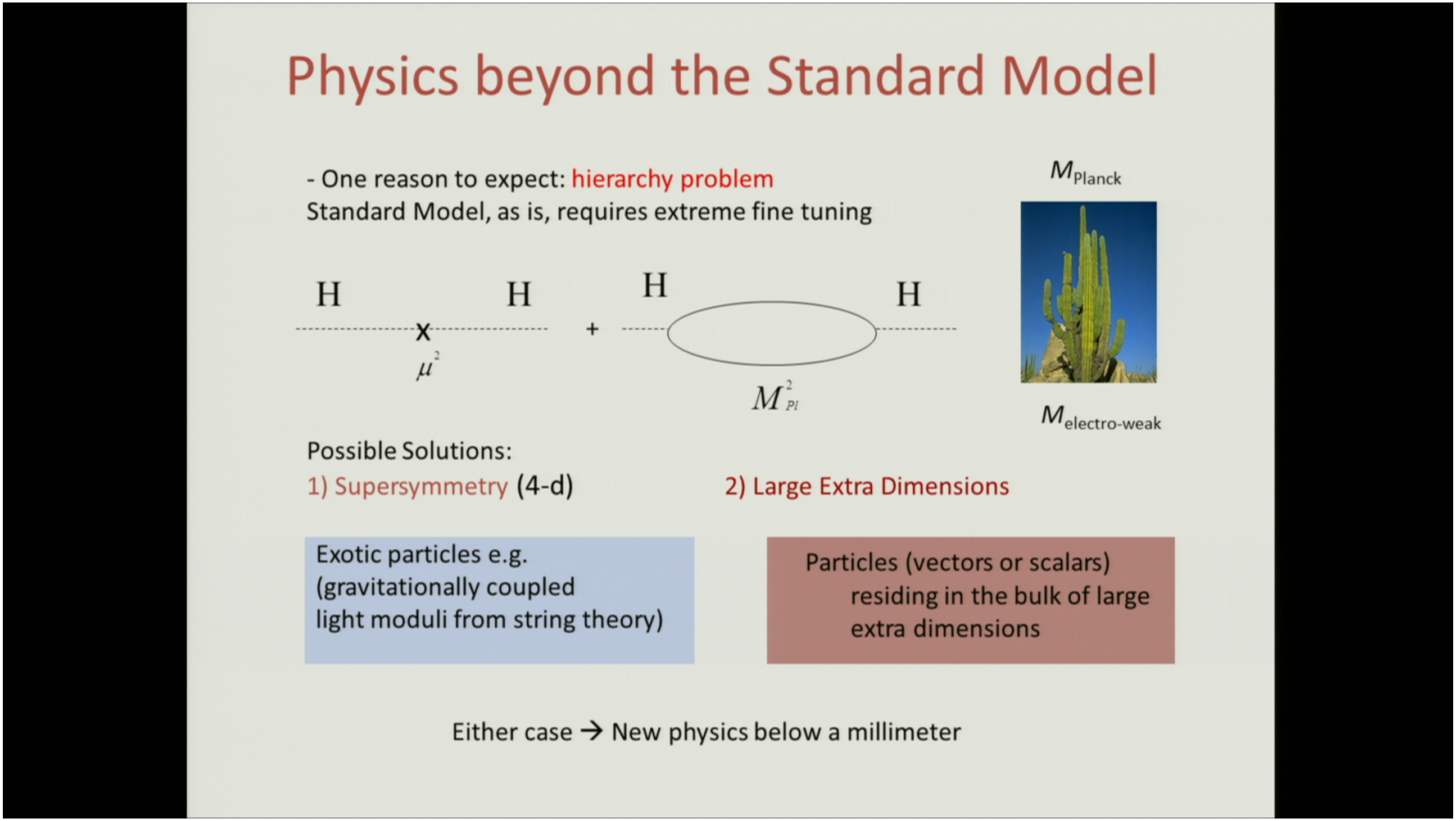
1) Supersymmetry (4-d)

Exotic particles e.g.
(gravitationally coupled
light moduli from string theory)

2) Large Extra Dimensions

Particles (vectors or scalars)
residing in the bulk of large
extra dimensions

Either case → New physics below a millimeter



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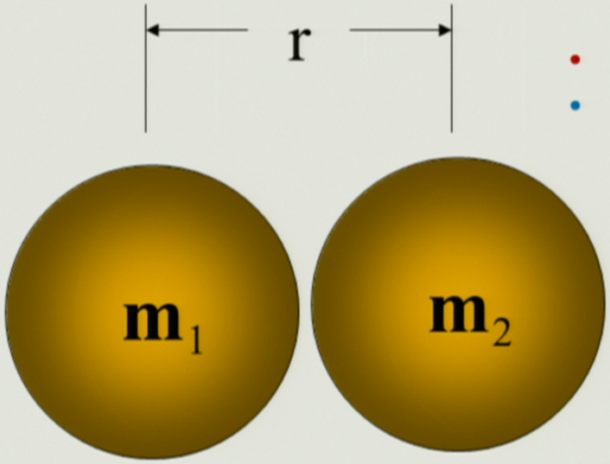
# Testing gravity at short range

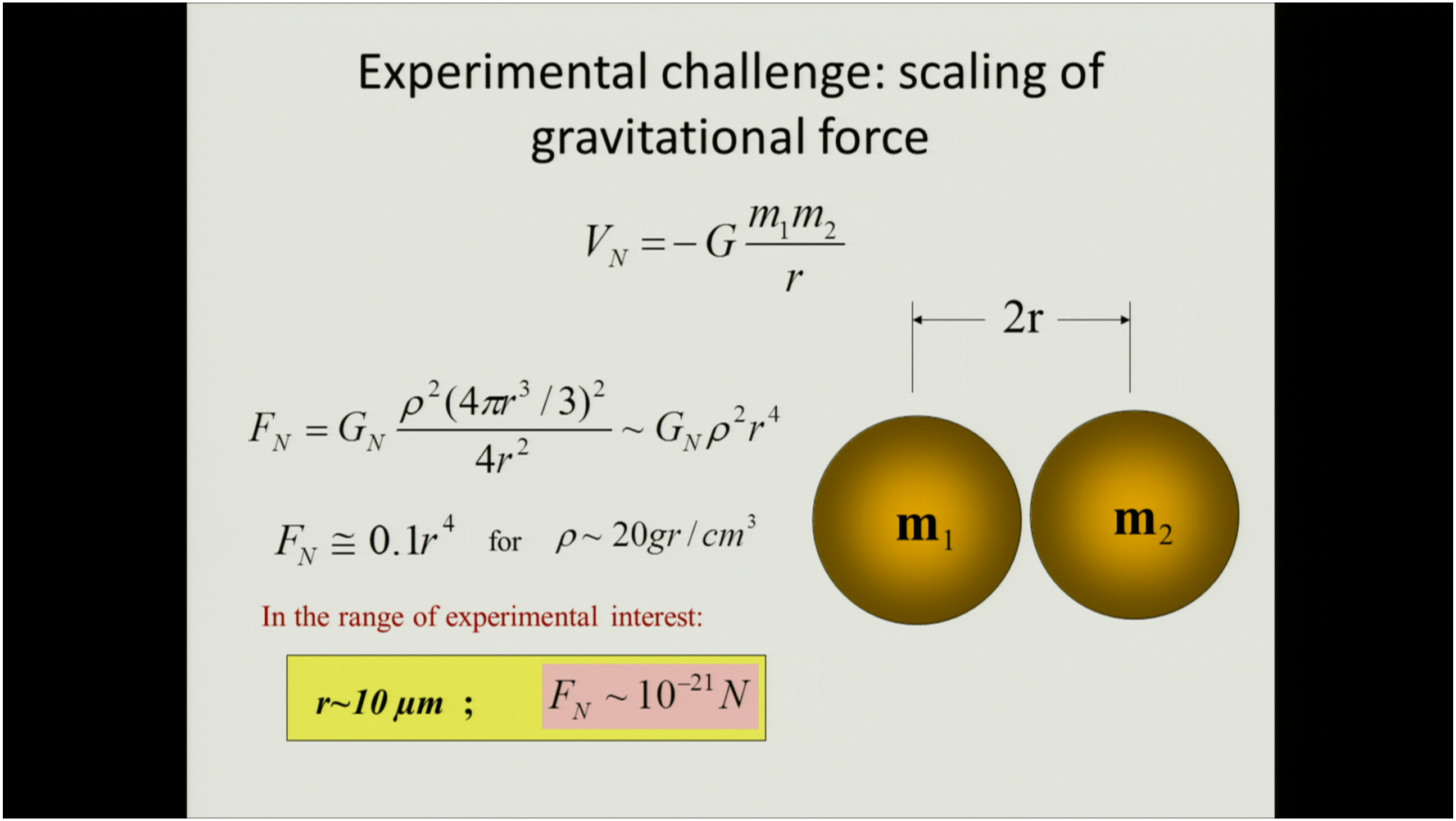
$$V_N = -G\frac{m_1 m_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$

Exotic particles (new physics)

$\lambda < 1$ mm

- Supersymmetry
- Large extra dimensions





# Experimental challenge: scaling of gravitational force

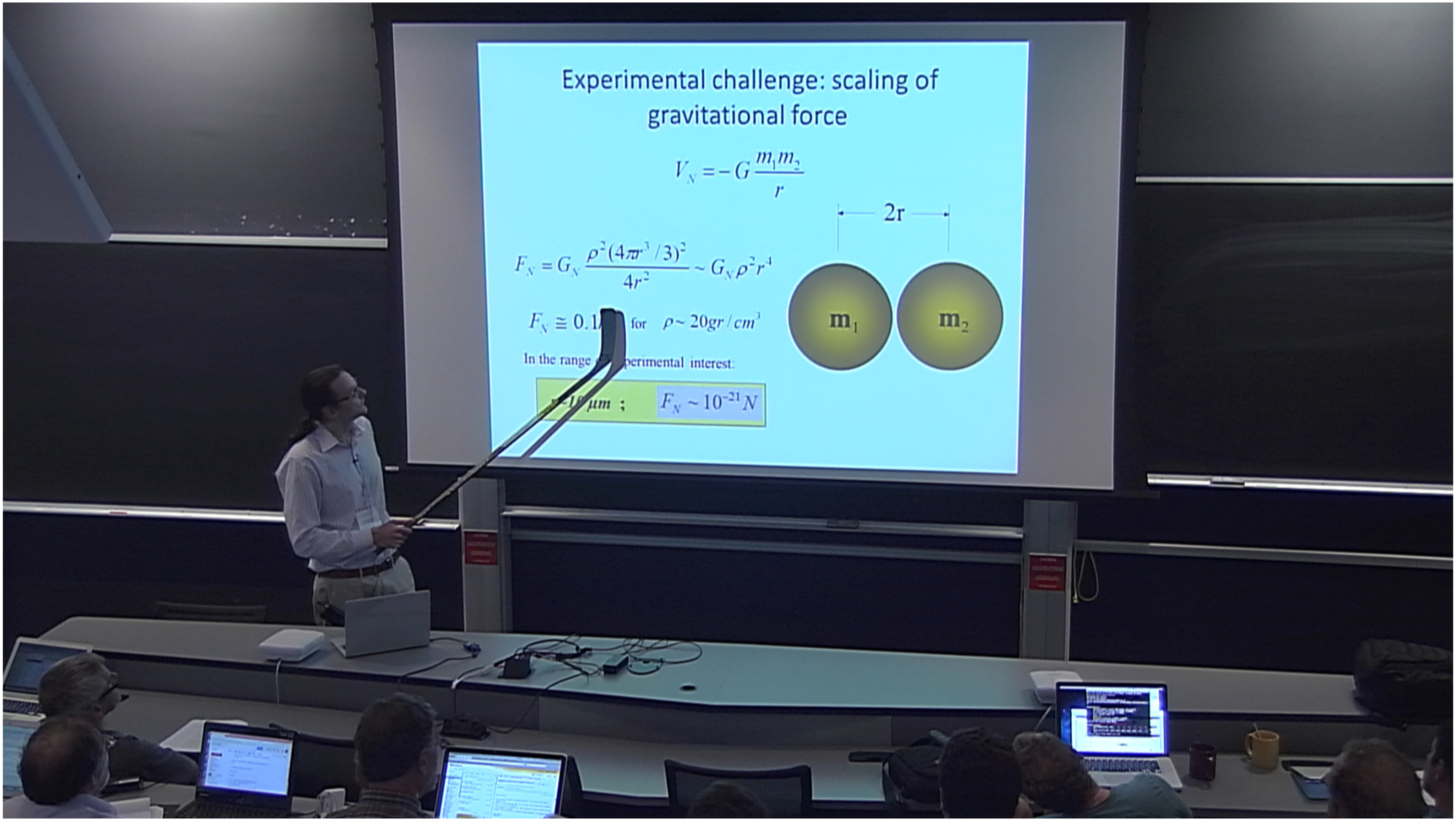
$$V_N = -G\frac{m_1 m_2}{r}$$

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

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

In the range of experimental interest:

***r~10 µm ;*** $F_N \sim 10^{-21} N$



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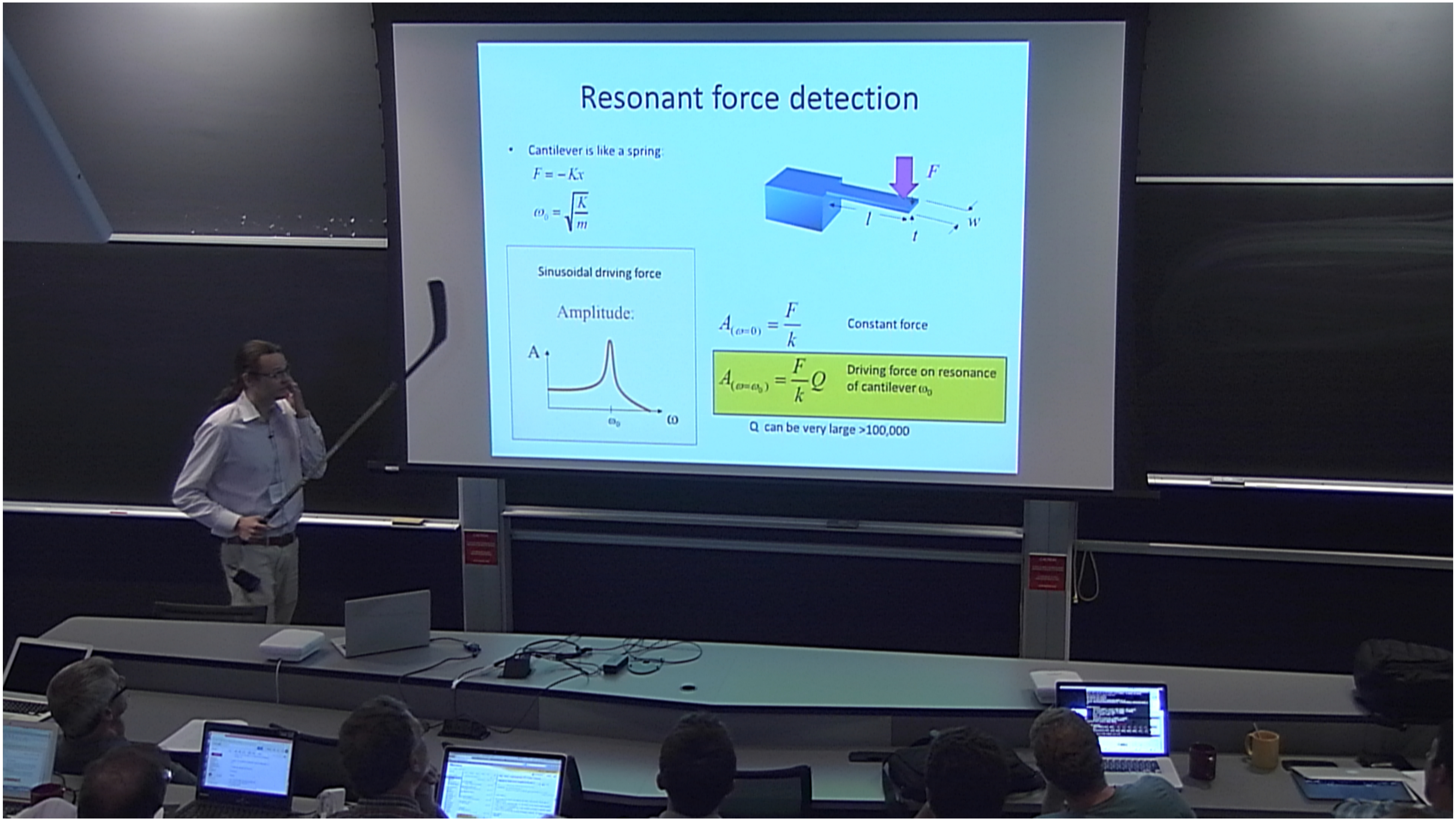

# Resonant force detection

- 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 $\omega_0$

Q can be very large >100,000

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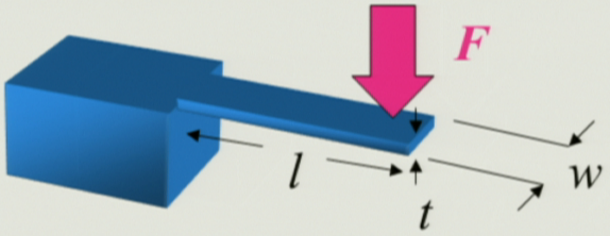

Sinusoidal driving force

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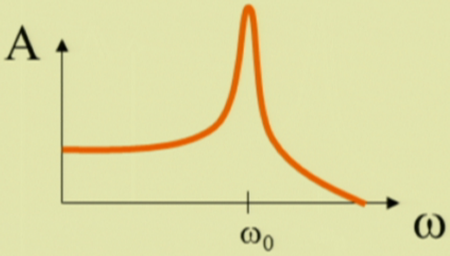

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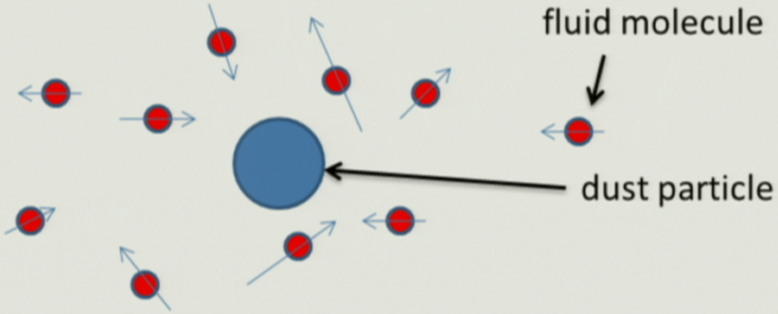
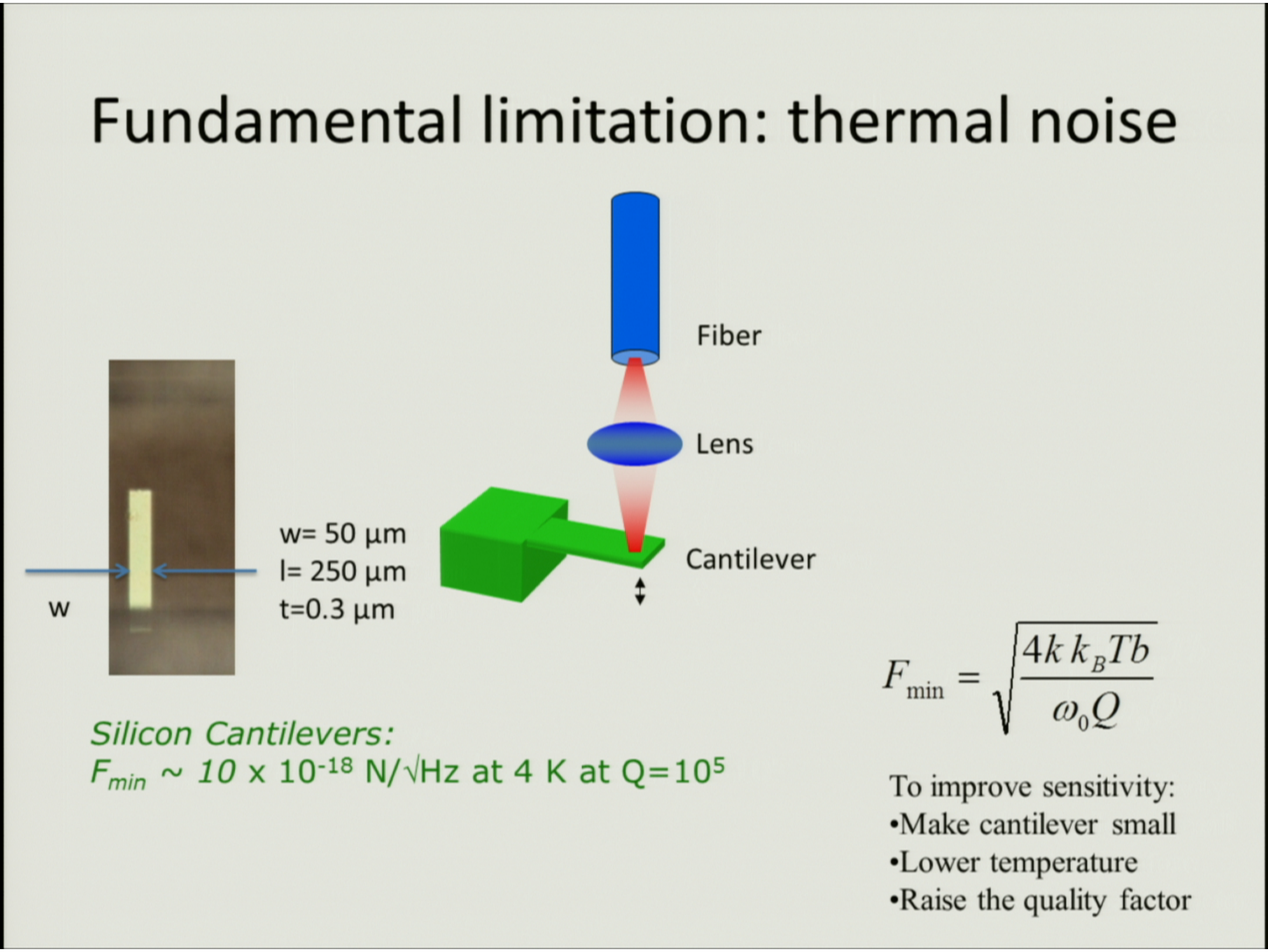
# Fundamental limitation: thermal noise

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



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

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



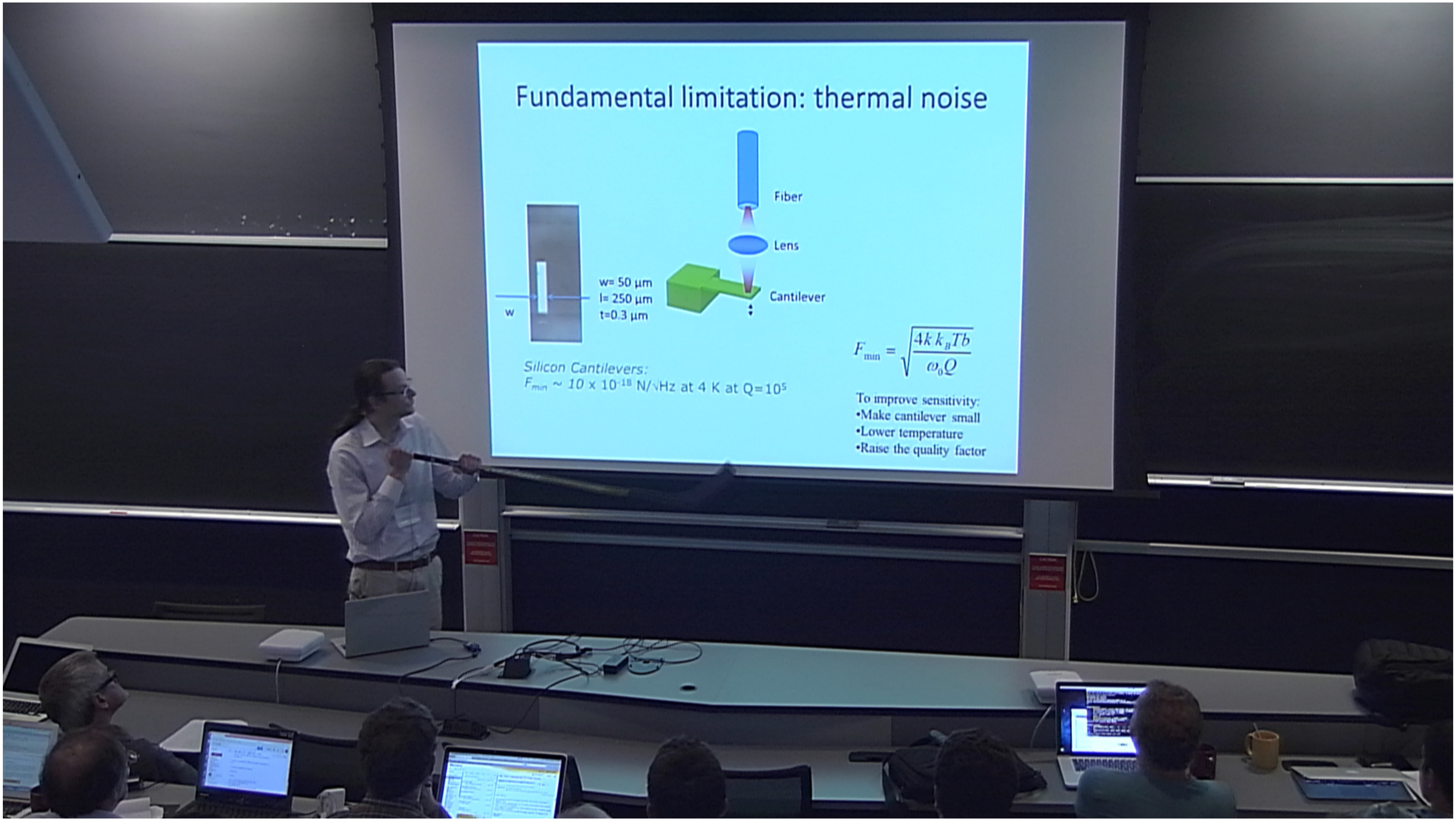
# Fundamental limitation: thermal noise

w= 50 µm
l= 250 µm
t=0.3 µm

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

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

To improve sensitivity:
- Make cantilever small
- Lower temperature
- Raise the quality factor



# Fundamental limitation: thermal noise

w= 50 µm
l= 250 µm
t=0.3 µm

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

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

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- Make cantilever small
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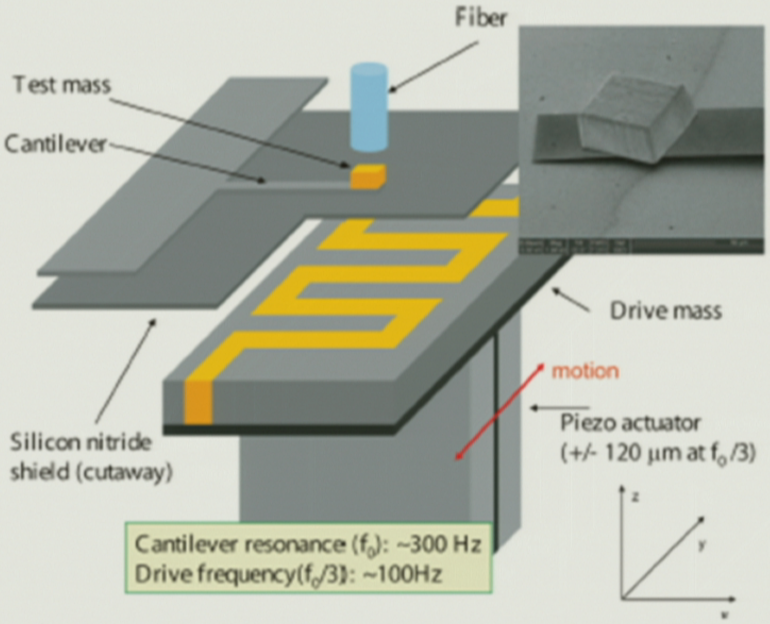
# Stanford Cantilever experiment

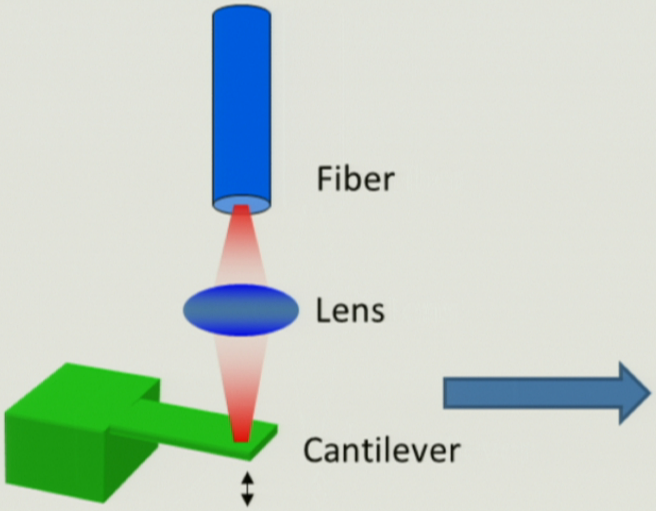


Cantilever resonance ($f_0$): ~300 Hz
Drive frequency($f_0$/3): ~100Hz

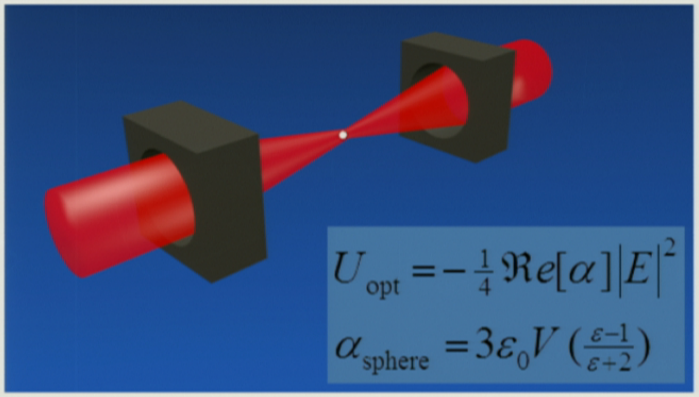
Best Yukawa constraints at ~ 10 um range:

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

# Improving Q?



Levitate the force sensor!



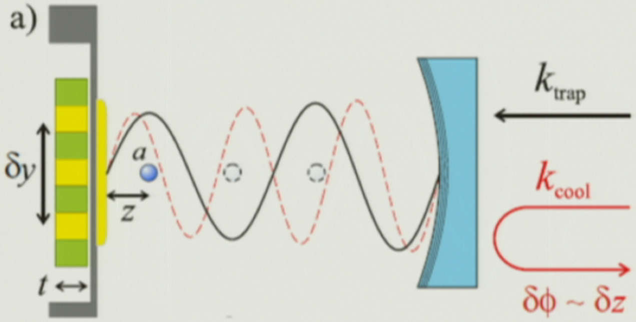
$$U_{\mathrm{opt}} = -\tfrac{1}{4}\Re e[\alpha]\left|E\right|^2$$

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

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

CM motion decoupled from environment –
no clamping, materials losses

# Micron-scale gravity test experiment



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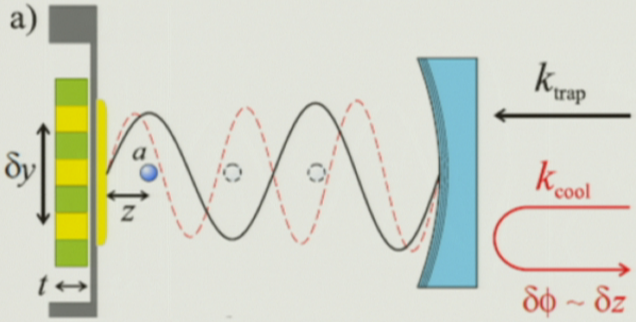

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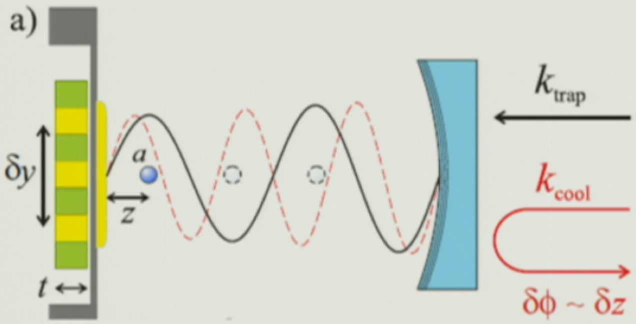
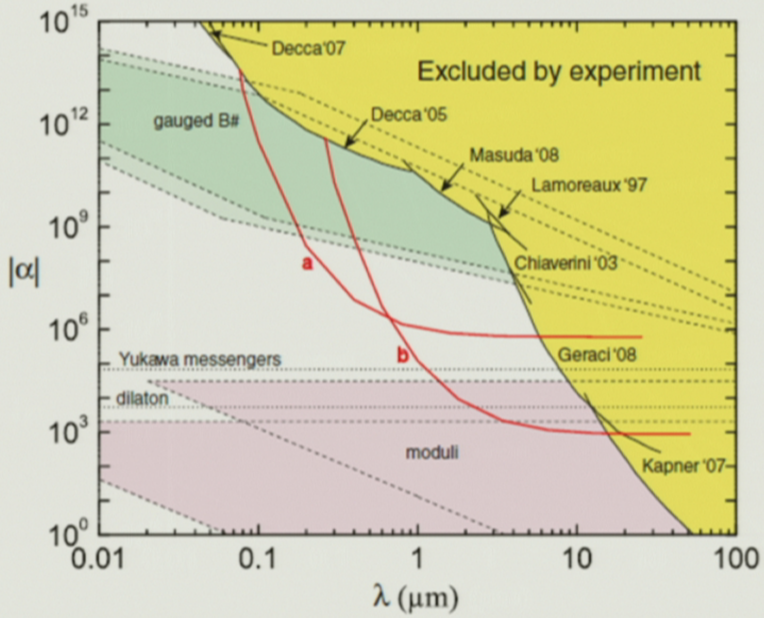
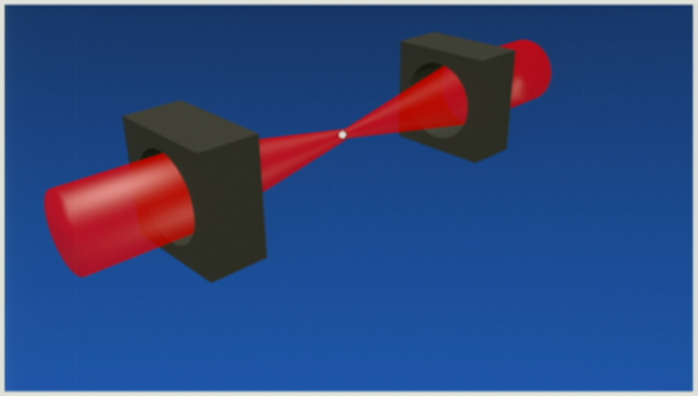




$10^6$ improvement possible at 1μm length scale

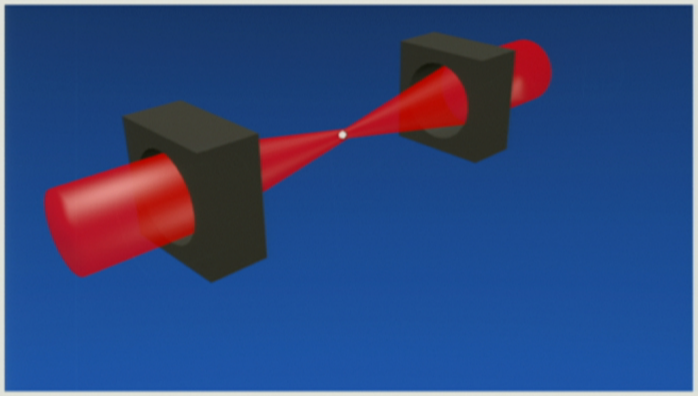
A. A. Geraci, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

# Dual beam dipole trap

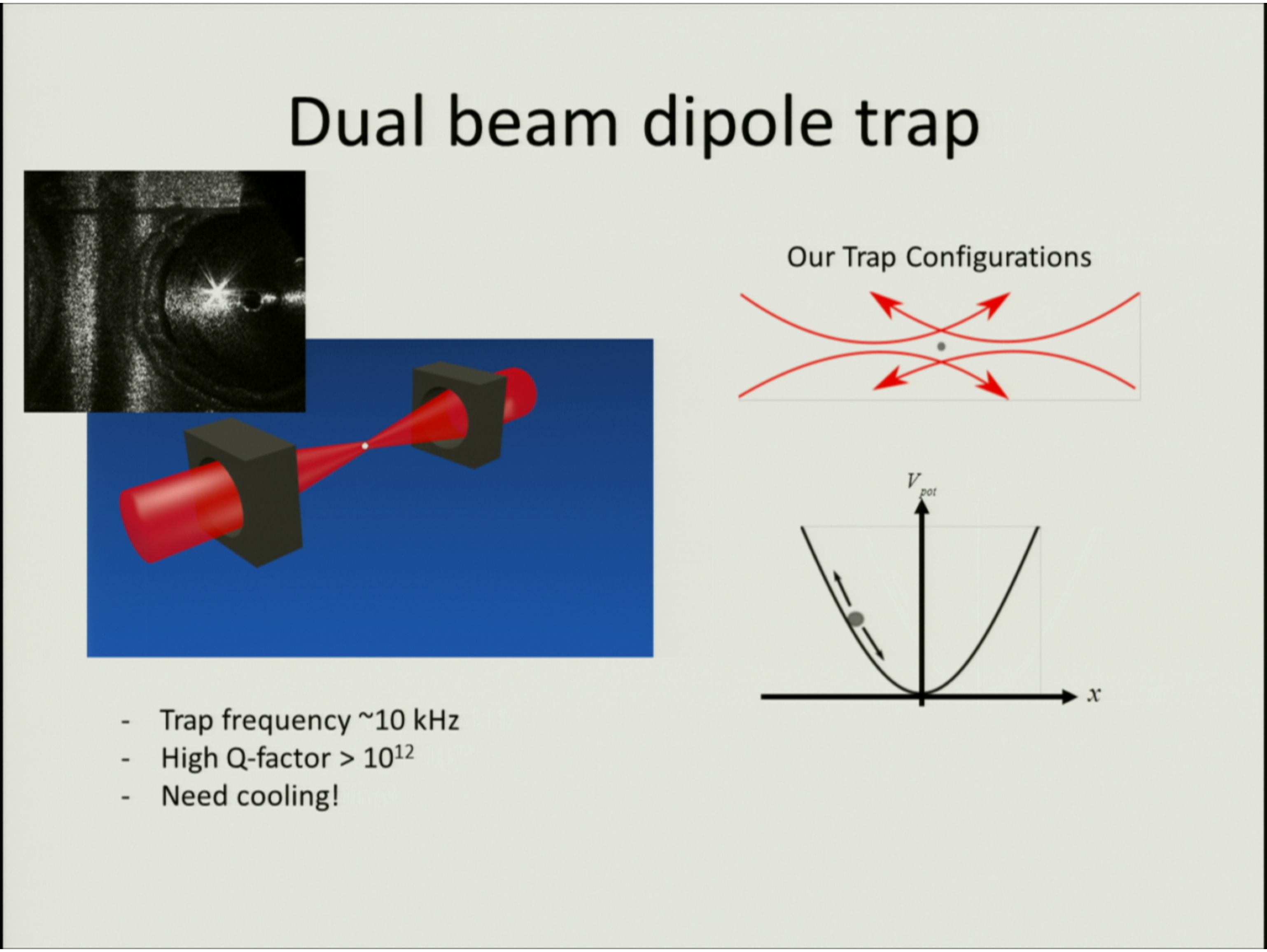


Optical trap loading

# Dual beam dipole trap



Optical trap loading

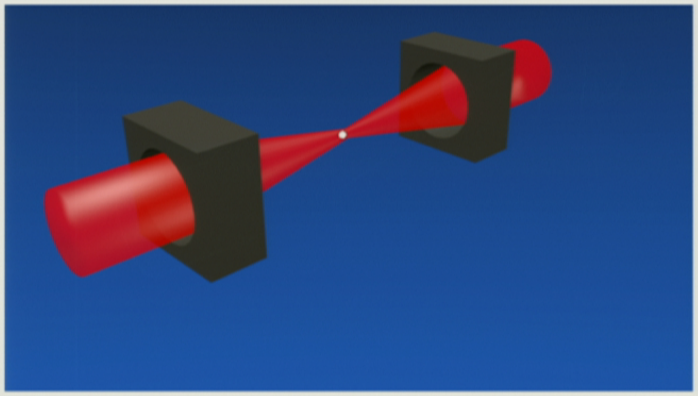


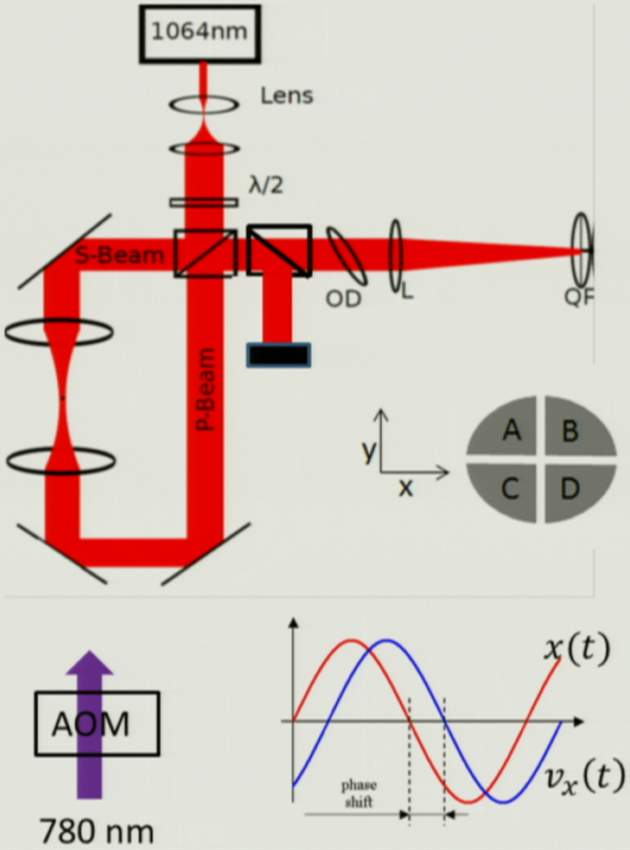
# Dual beam dipole trap

Our Trap Configurations

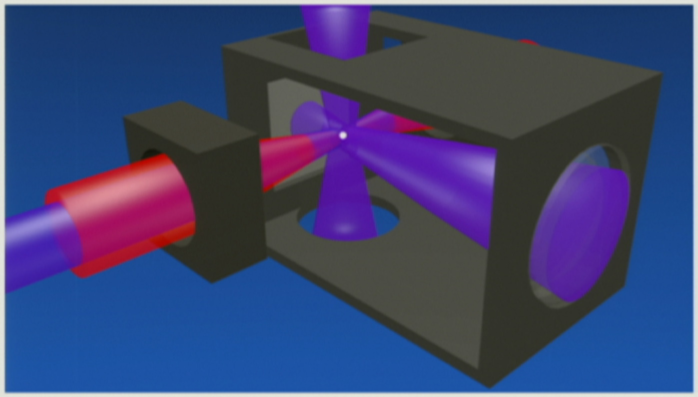
- Trap frequency ~10 kHz
- High Q-factor > $10^{12}$
- Need cooling!

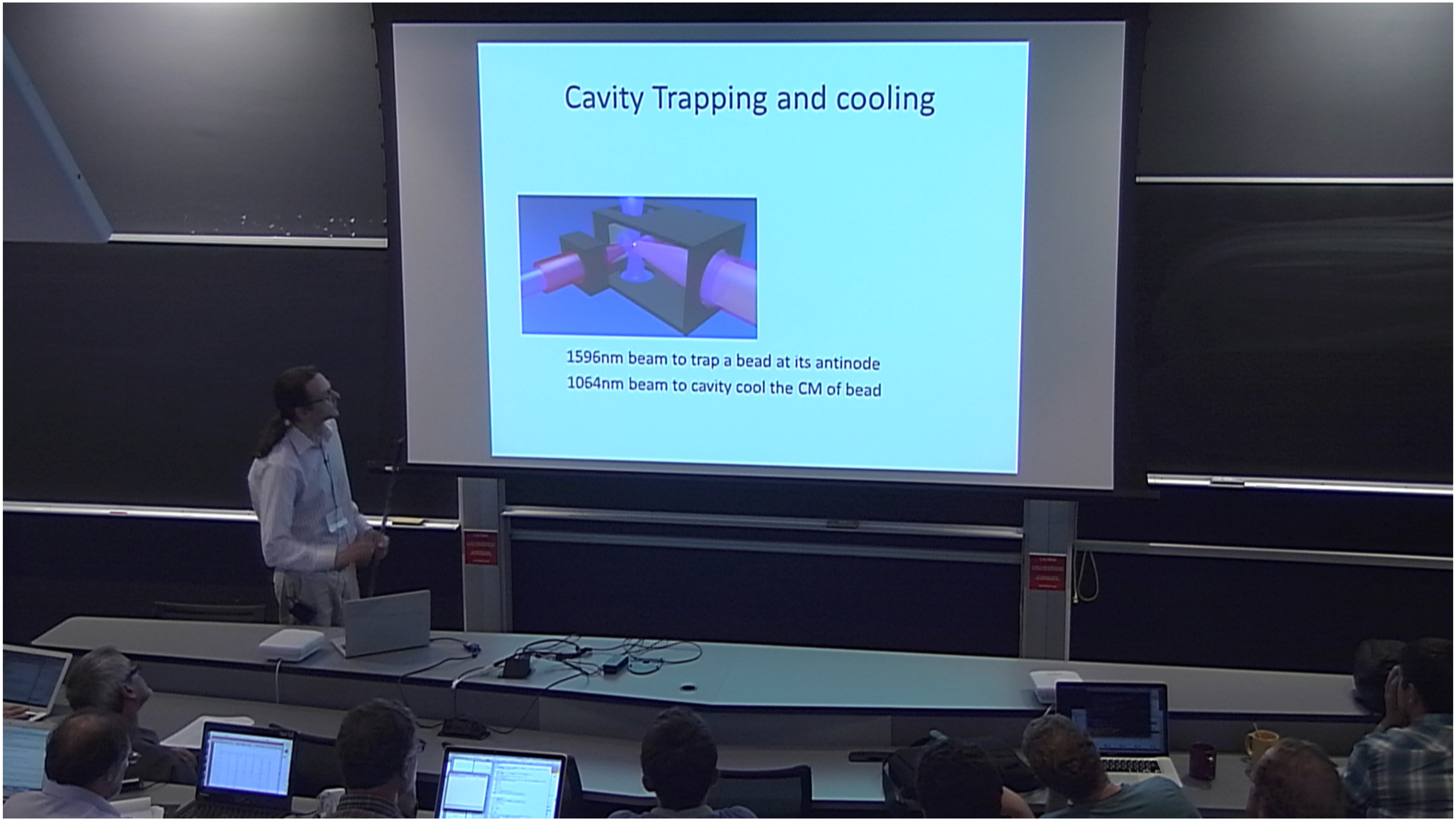
# Laser cooling of a microsphere





# Cavity Trapping and cooling

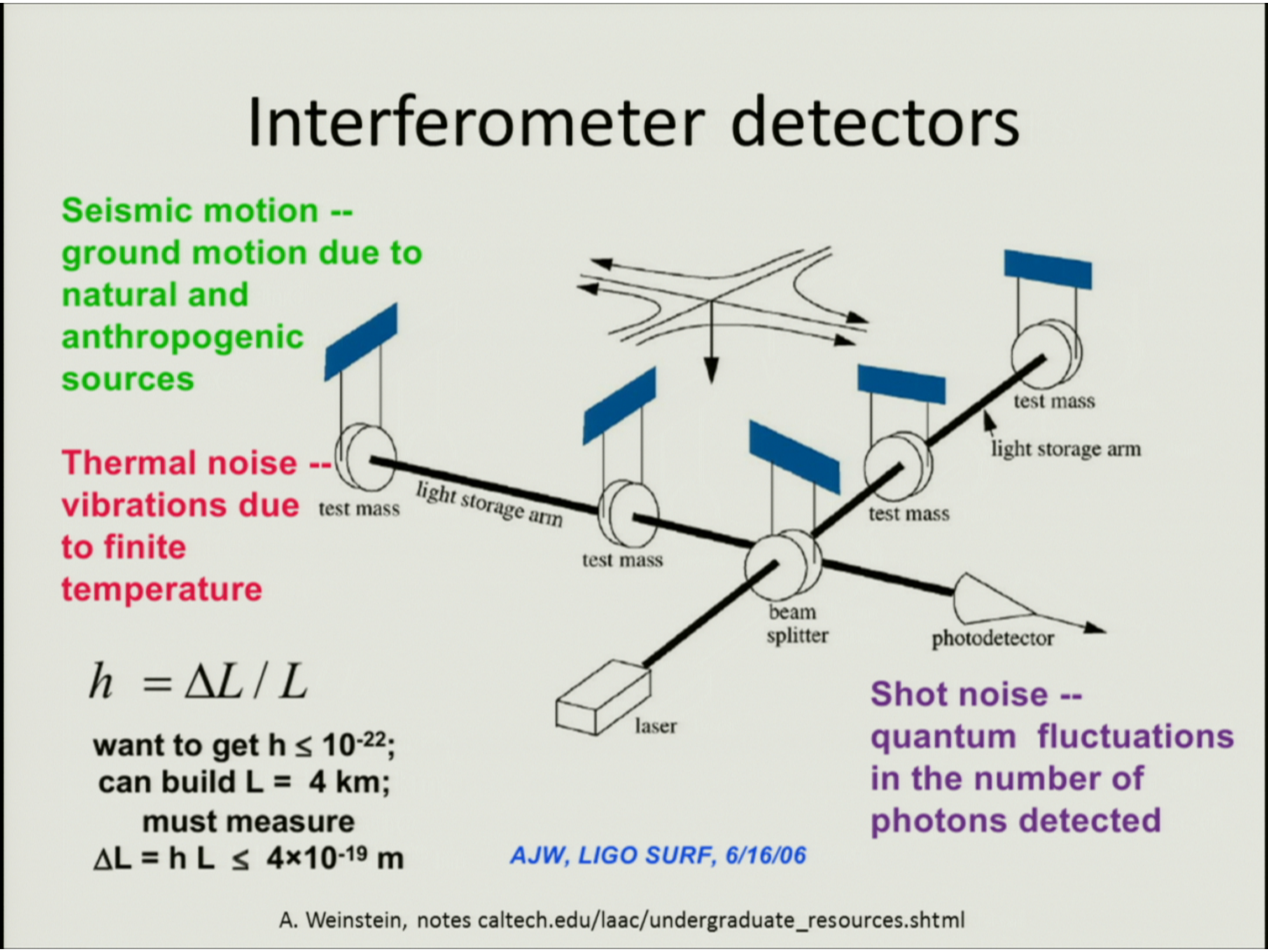




# Cavity Trapping and cooling

1596nm beam to trap a bead at its antinode

1064nm beam to cavity cool the CM of bead



# Interferometer detectors

**Seismic motion -- ground motion due to natural and anthropogenic sources**

**Thermal noise -- vibrations due to finite temperature**

$$h = \Delta L / L$$

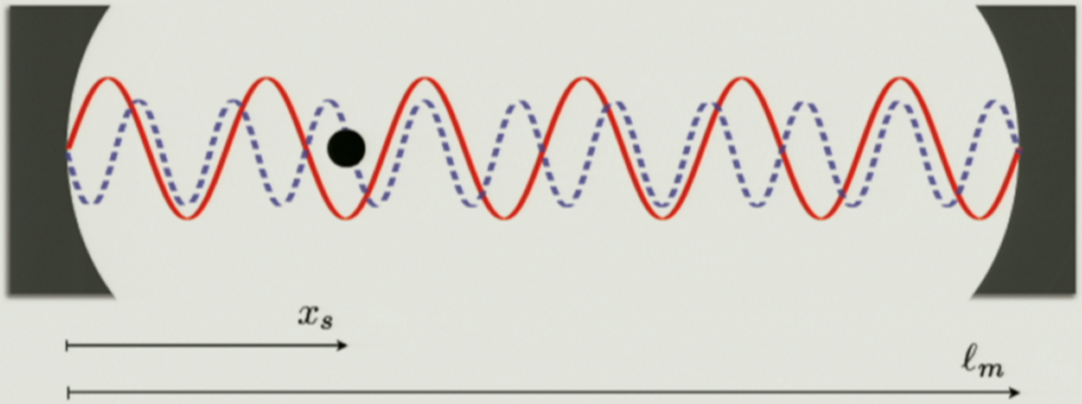
**want to get $h \leq 10^{-22}$;**
**can build L = 4 km;**
**must measure**
**$\Delta L = h\,L \leq 4\times10^{-19}$ m**

*AJW, LIGO SURF, 6/16/06*

**Shot noise -- quantum fluctuations in the number of photons detected**

A. Weinstein, notes caltech.edu/laac/undergraduate_resources.shtml

# Gravitational Wave Detection

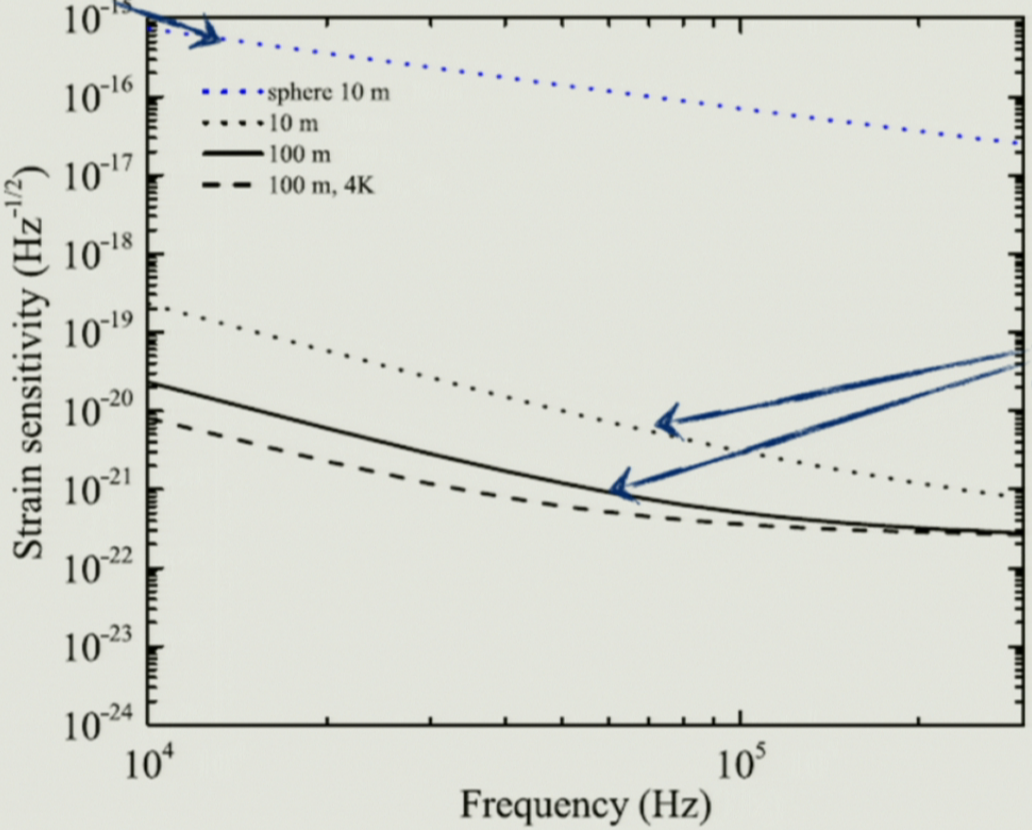


- Fused silica sphere (r = 150nm) or disc (t = 500nm, r = 75 µm)
  In an optical cavity of size 10-100 m
- One laser to trap, one to cool and measure sensor position

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

# GW Strain Sensitivity

150 nm sphere



500 nm × (75 μm)$^2$ disk

Differing sensitivity between the two geometries
due to difference in mass and in light scattering properties

# GW sources at high-frequency

- Astrophysical Sources

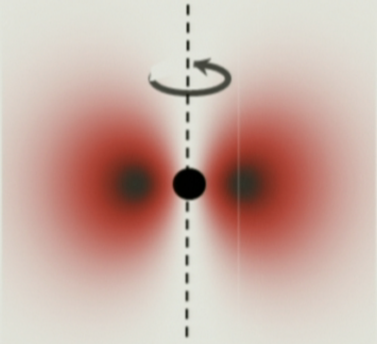
  Natural upper bound on GW frequency
  inverse BH size ~ 30 kHz

- 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?

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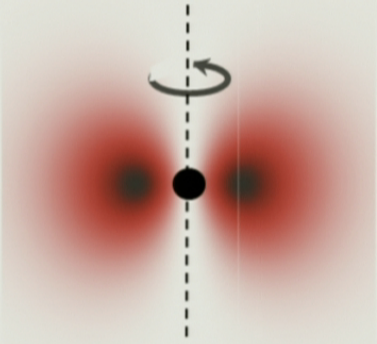

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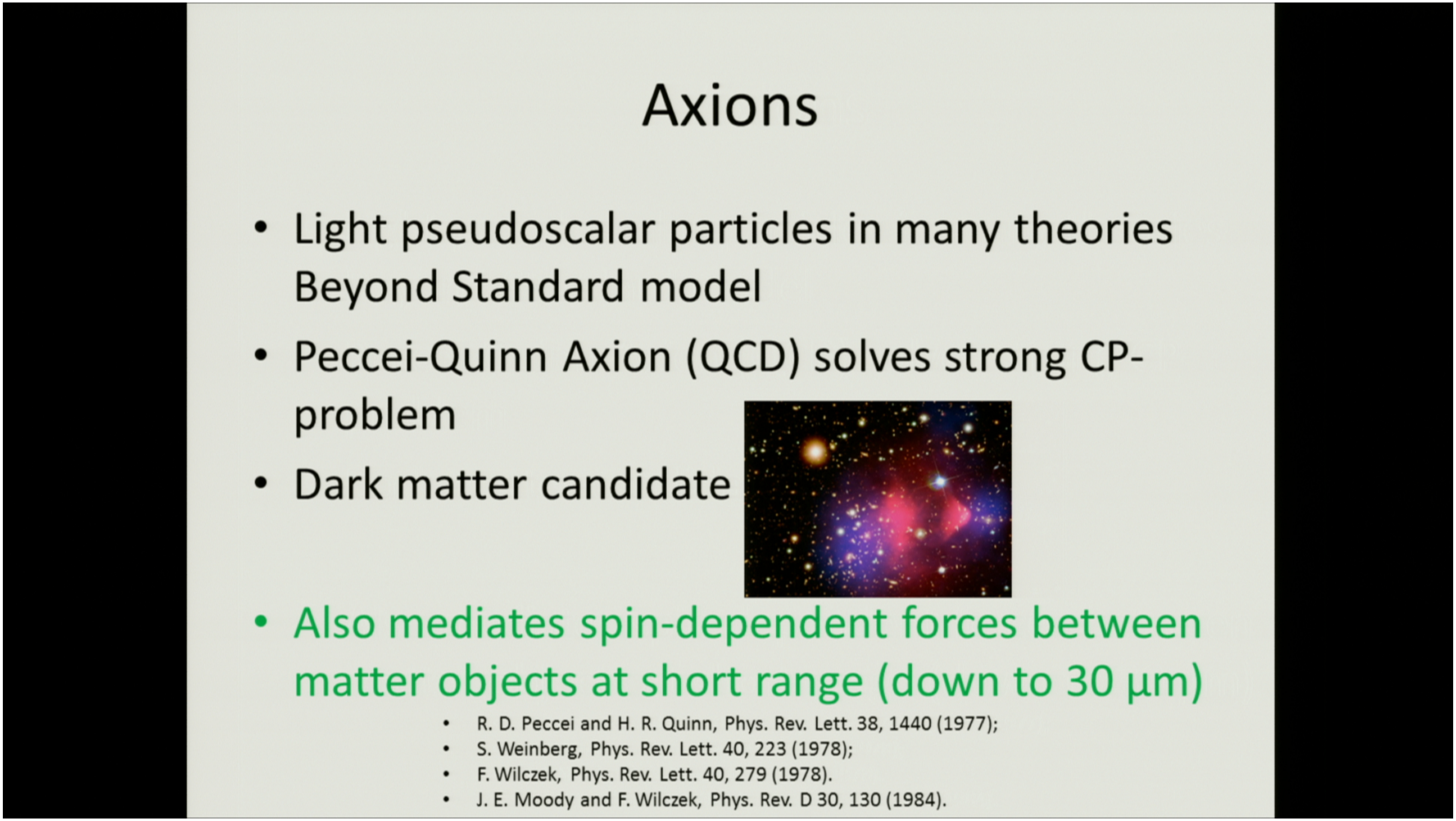
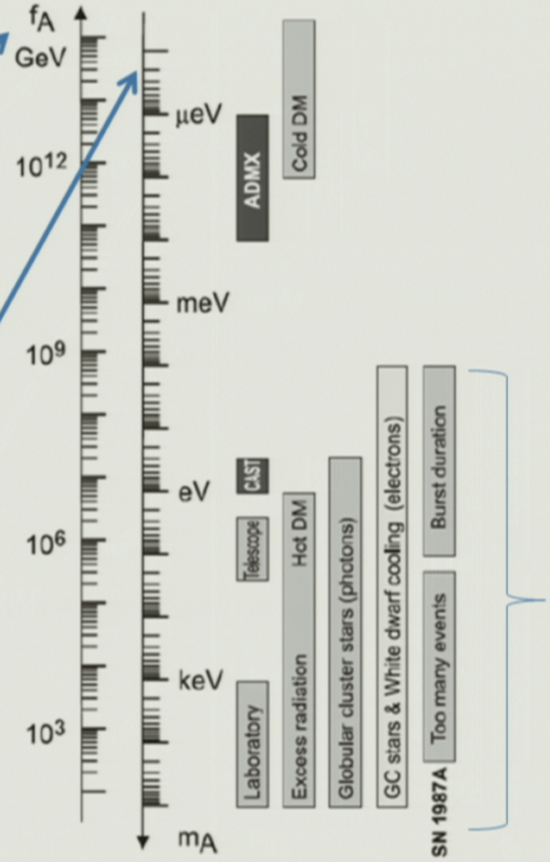


# Axions

- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP-problem
- Dark matter candidate
- Also mediates spin-dependent forces between matter objects at short range (down to 30 μm)
  - 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).

# QCD Axion parameter space



Axion decay constant
$10^9$ GeV < $f_a$ < $10^{17}$ GeV

BH superradiance

Axion mass
$3 \times 10^{-11}$ eV < $m_a$ < 0.006 eV
32 μm < $\lambda_a$ < 1.5 km

Lab and Astrophysical bounds

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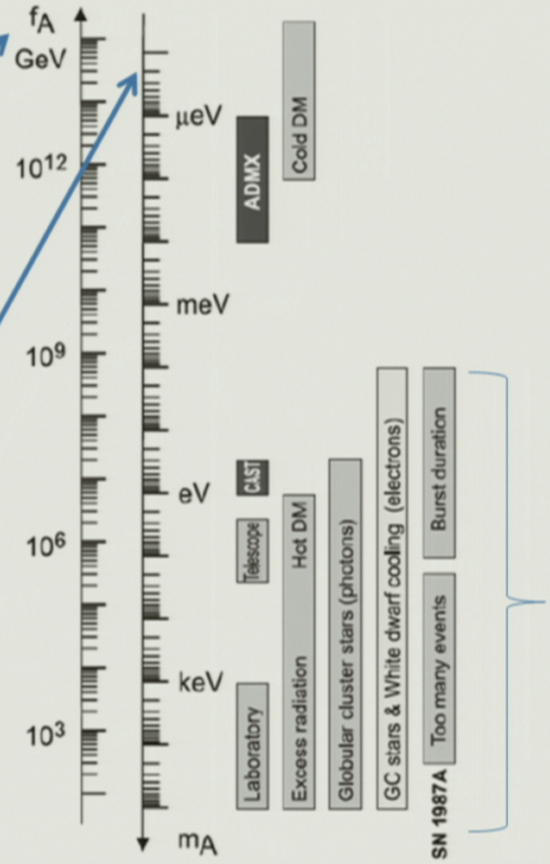

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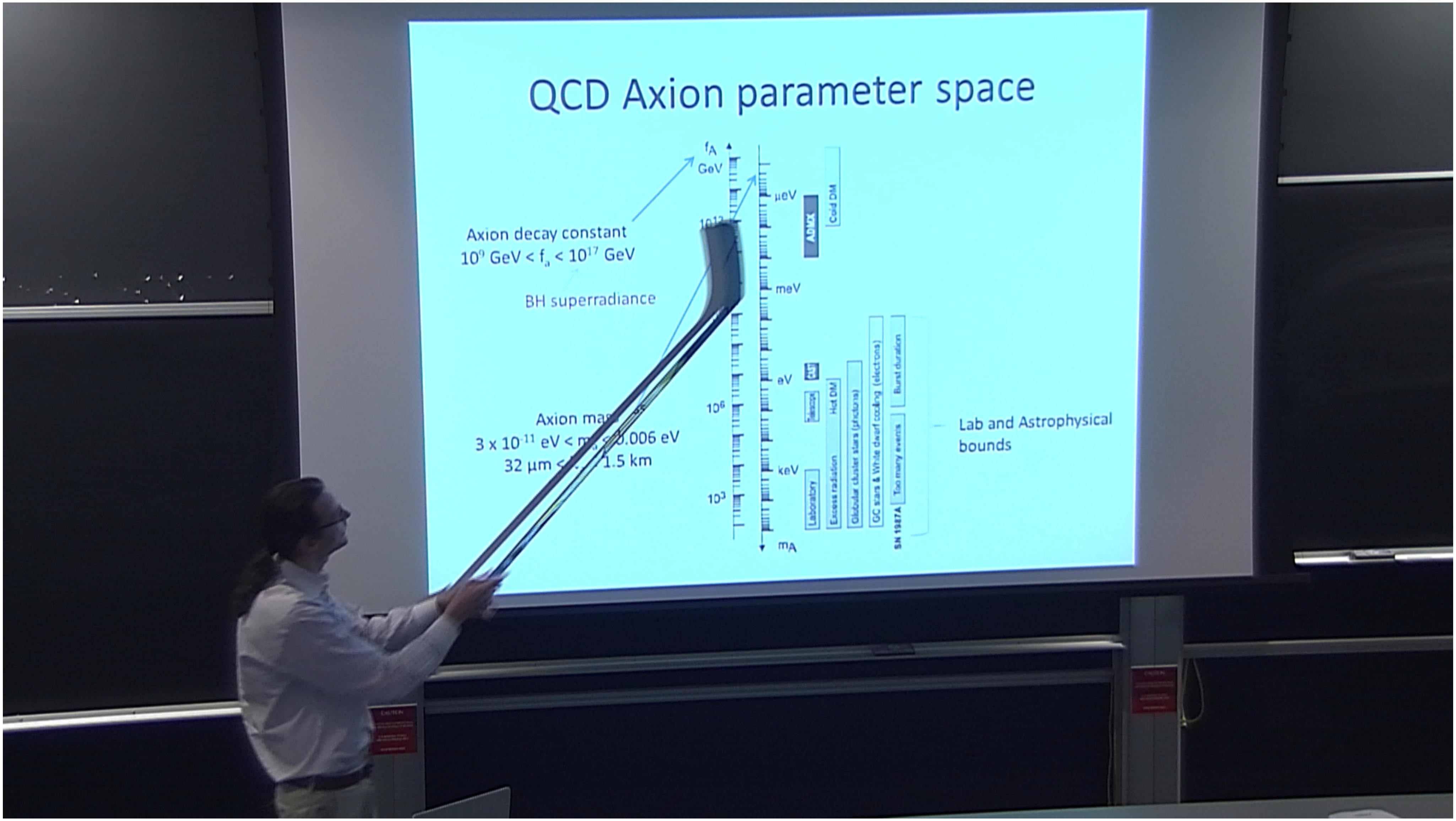

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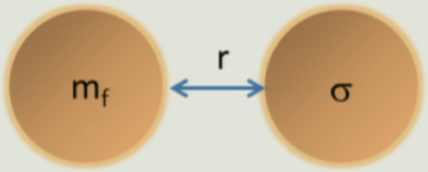
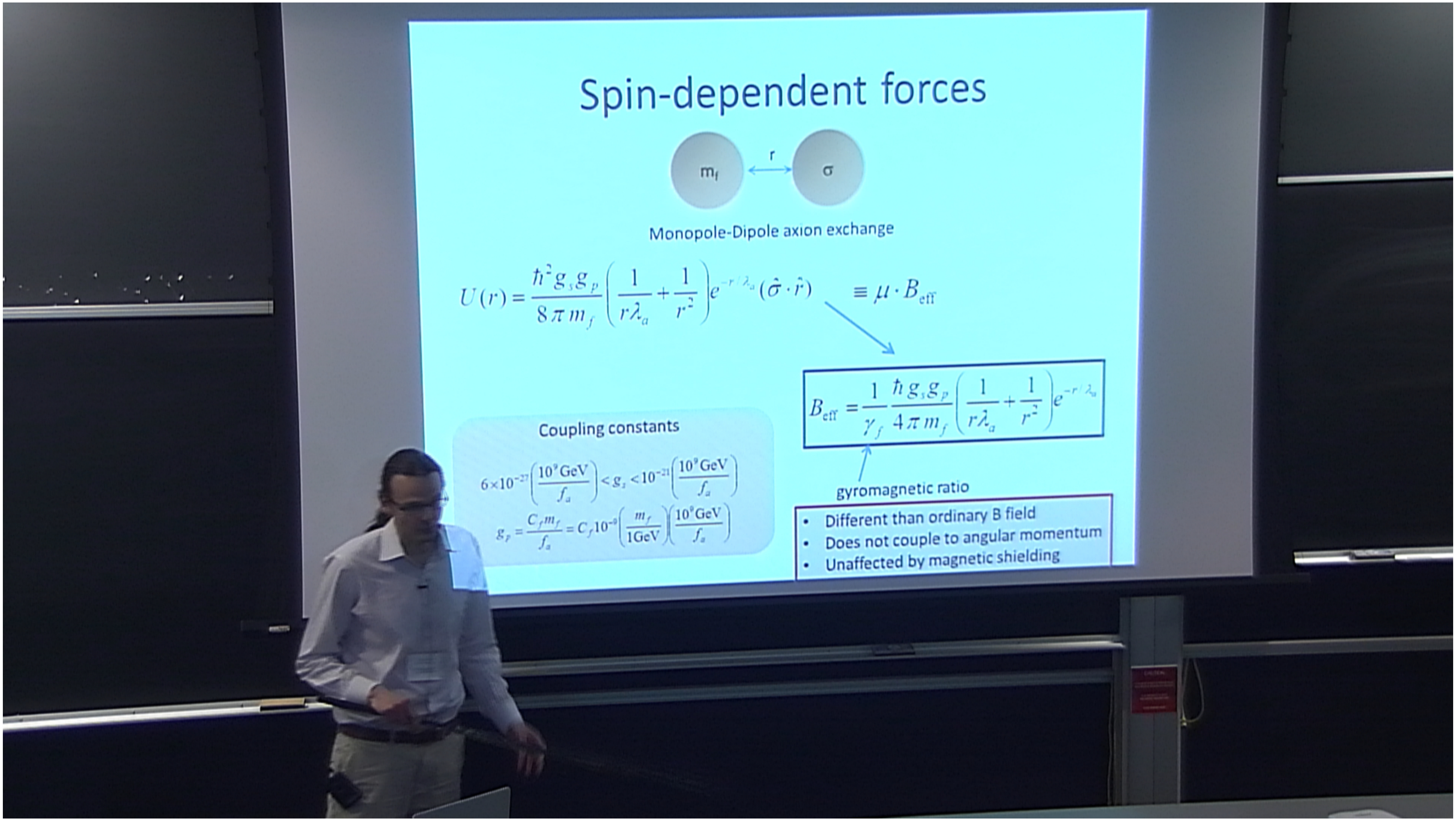
Lab and Astrophysical bounds

# Spin-dependent forces



Monopole-Dipole axion exchange

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



# Spin-dependent forces

Monopole-Dipole axion exchange

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

$$\boxed{B_{\mathrm{eff}}=\frac{1}{\gamma_f}\frac{\hbar g_s g_p}{4\pi m_f}\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)e^{-r/\lambda_a}}$$

gyromagnetic ratio

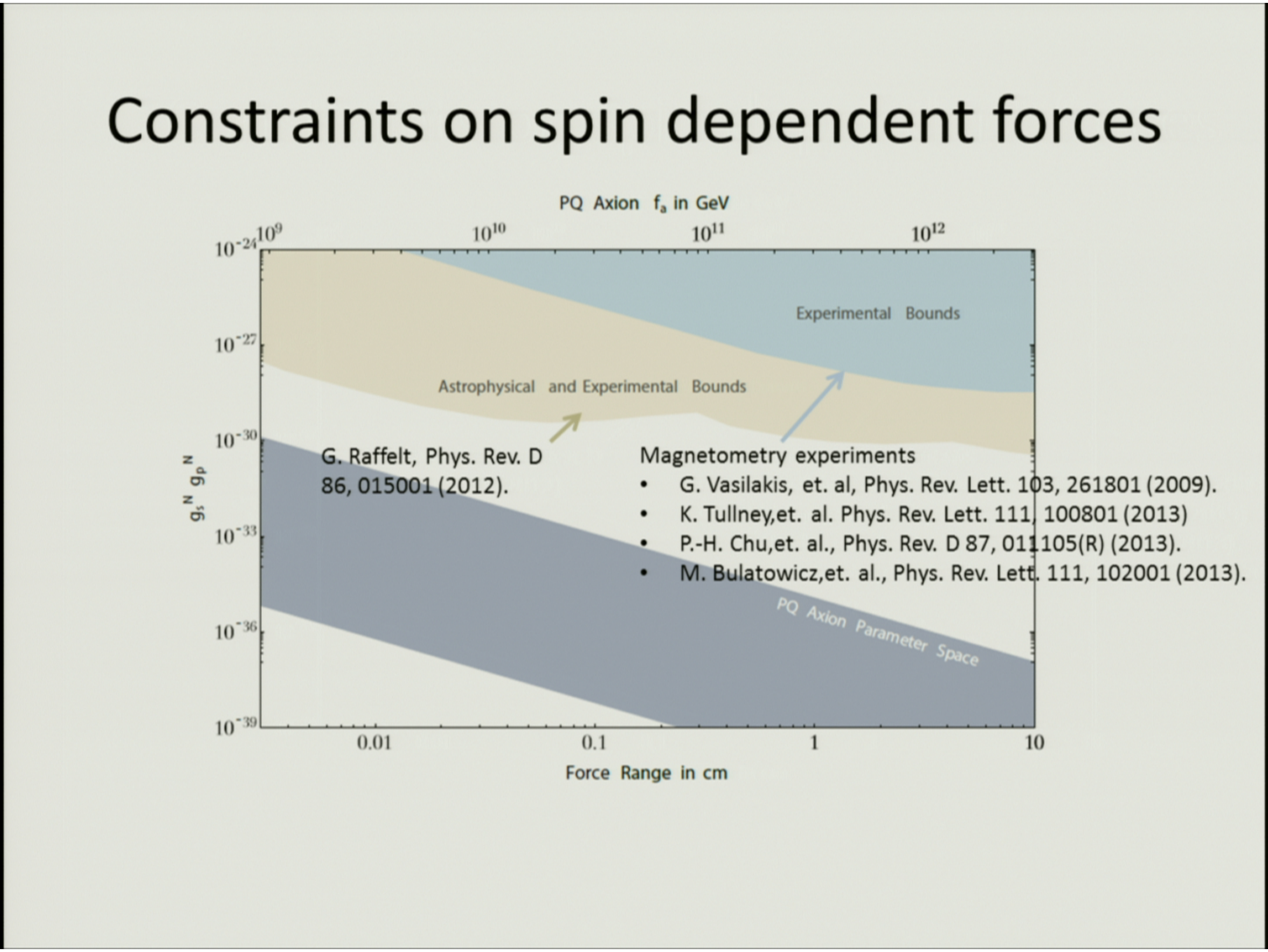
**Coupling constants**

$$6\times10^{-27}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)<g_s<10^{-21}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

$$g_p=\frac{C_f m_f}{f_a}=C_f 10^{-9}\left(\frac{m_f}{1\mathrm{GeV}}\right)\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

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

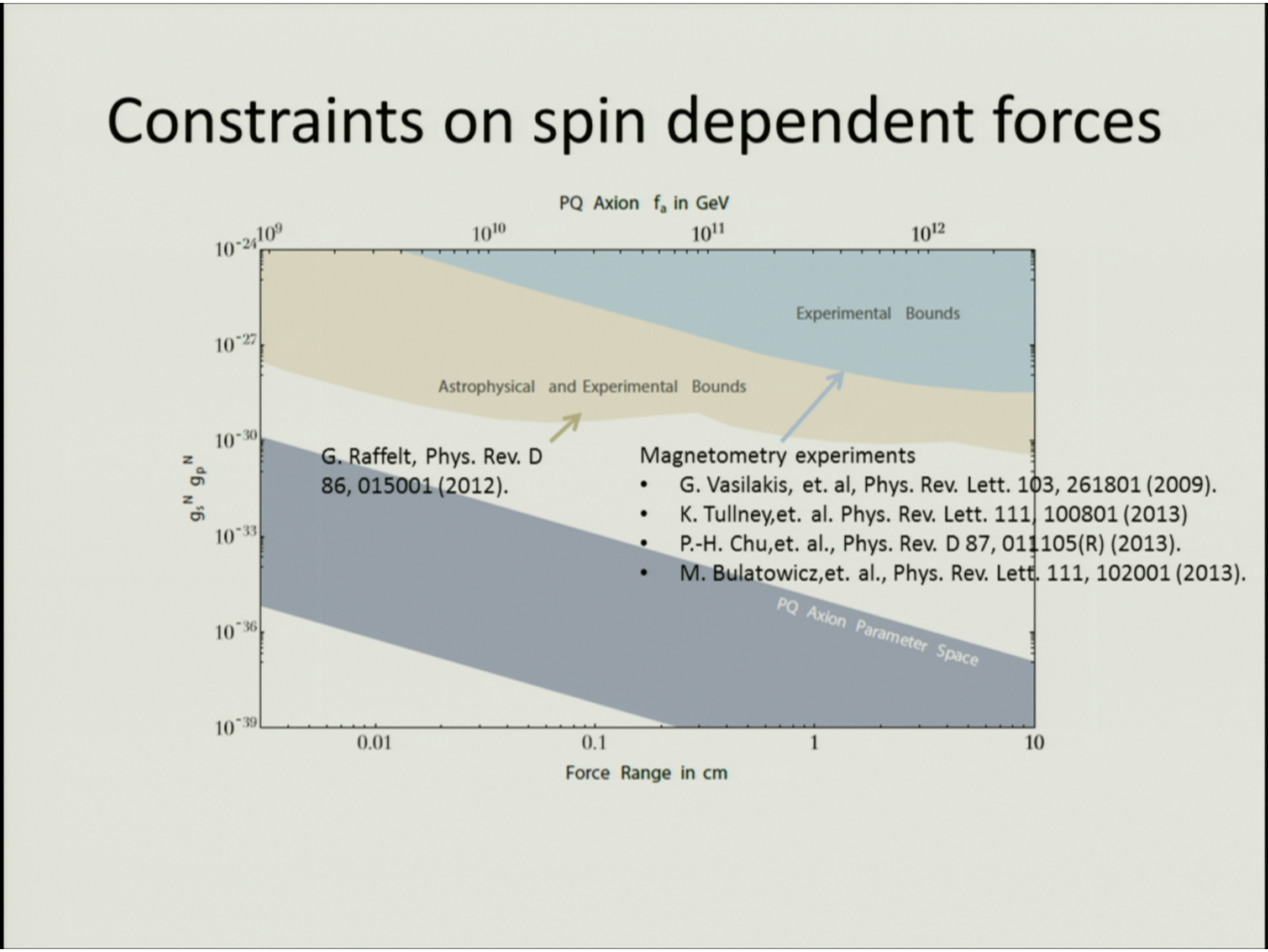
# Constraints on spin dependent forces



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).



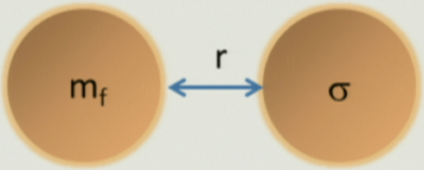
# Constraints on spin dependent forces

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).

# Spin-dependent forces



Monopole-Dipole axion exchange

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

$$\boxed{B_{\text{eff}}=\frac{1}{\gamma_f}\frac{\hbar g_s g_p}{4\pi m_f}\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)e^{-r/\lambda_a}}$$

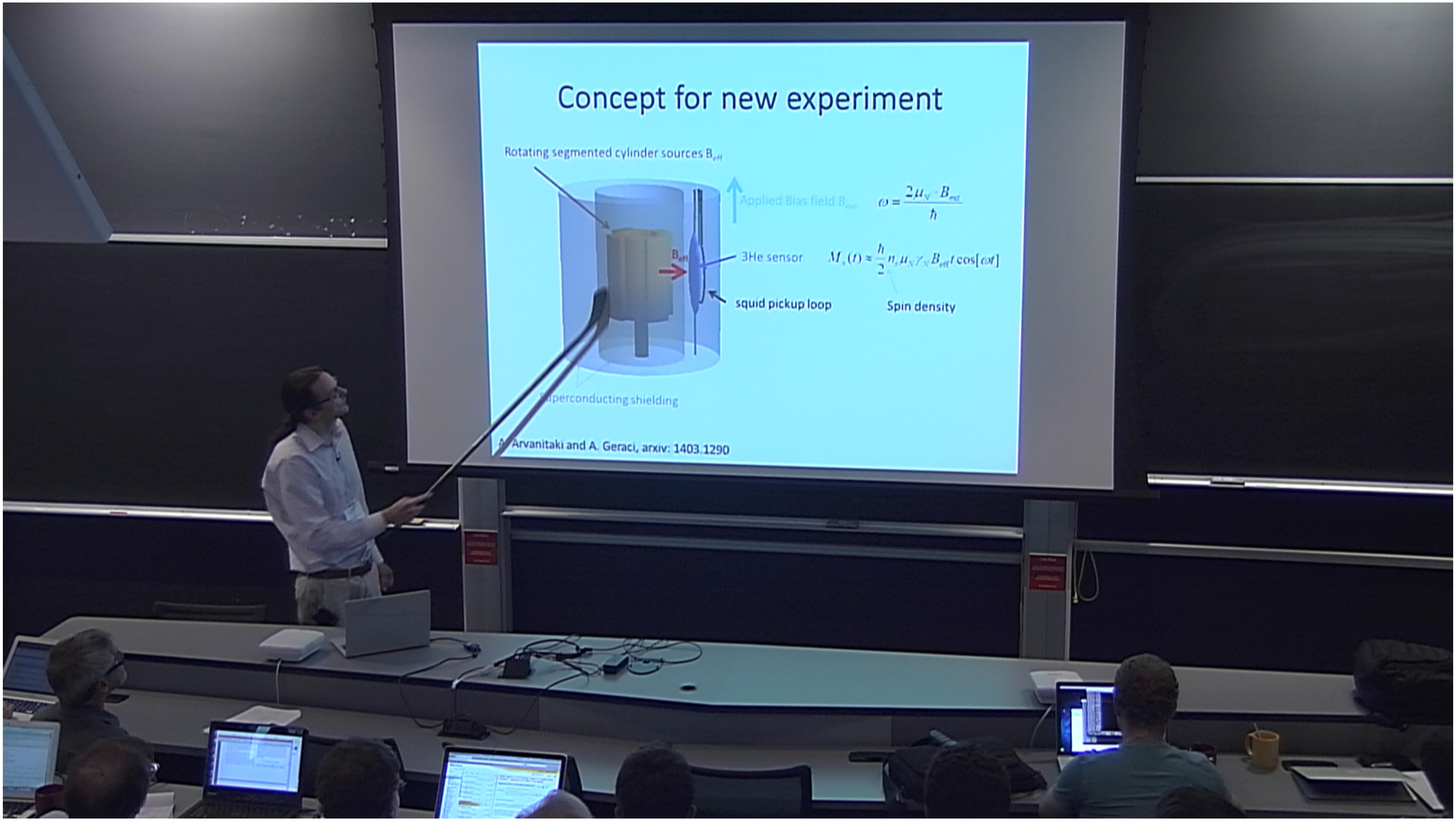
gyromagnetic ratio

**Coupling constants**

$$6\times10^{-27}\left(\frac{10^9\,\text{GeV}}{f_a}\right)<g_s<10^{-21}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

$$g_p=\frac{C_f m_f}{f_a}=C_f 10^{-9}\left(\frac{m_f}{1\text{GeV}}\right)\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

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



# Concept for new experiment

Rotating segmented cylinder sources $B_{eff}$

Applied Bias field $B_{ext}$

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

$B_{eff}$

3He sensor

$$M_x(t) \approx \frac{\hbar}{2} n_s \mu_N \gamma_N B_{eff} t \cos[\omega t]$$

squid pickup loop

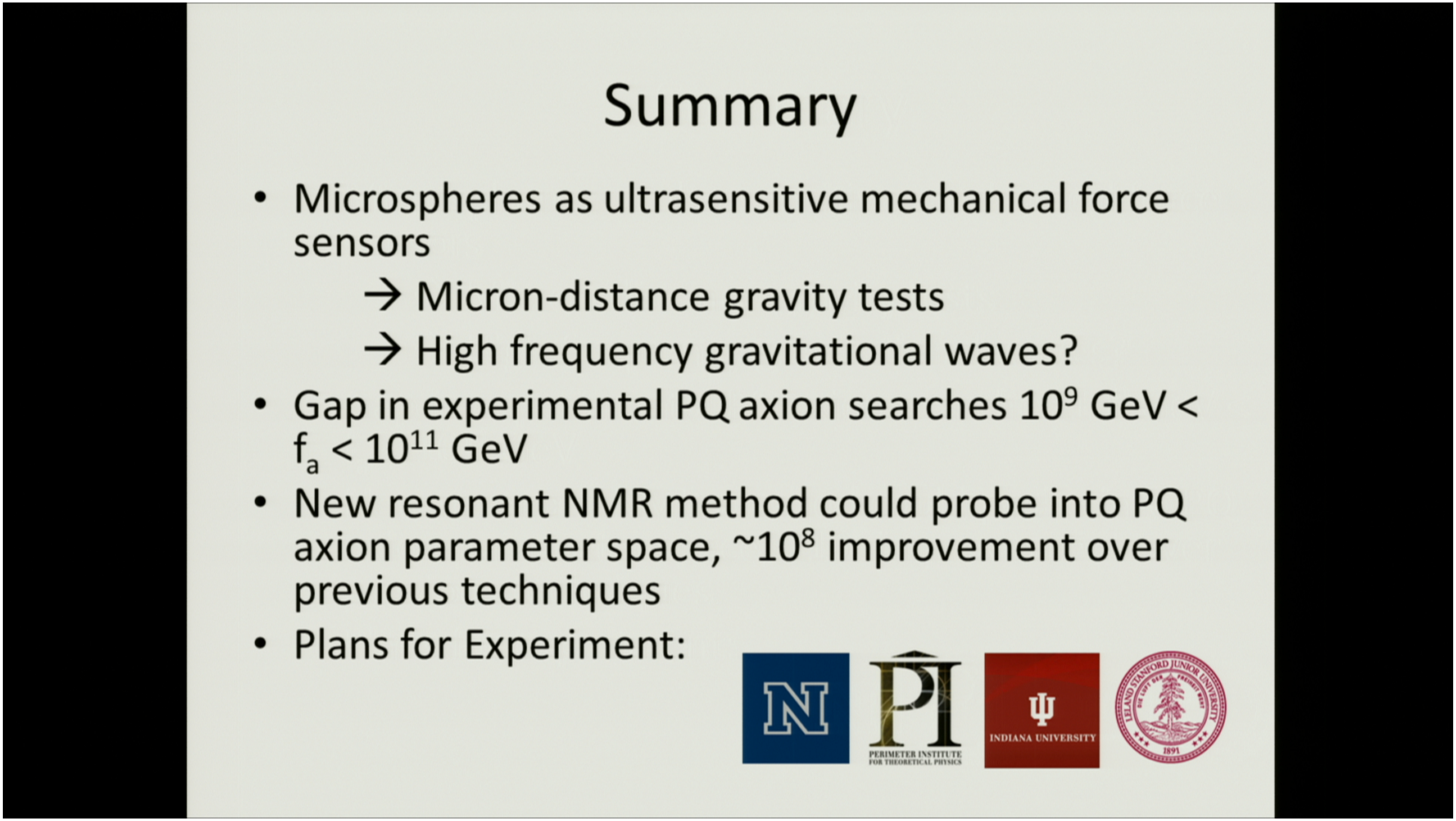
Spin density

Superconducting shielding

A. Arvanitaki and A. Geraci, arxiv: 1403.1290

# Experimental challenges

- Magnetic gradients
- Nonlinearities
- Barnett Effect
- Trapped magnetic flux
- Vibration isolation
- Magnetic noise from thermal currents



# Summary

- Microspheres as ultrasensitive mechanical force sensors
  - → Micron-distance gravity tests
  - → High frequency gravitational waves?
- Gap in experimental PQ axion searches $10^9$ GeV < $f_a < 10^{11}$ GeV
- New resonant NMR method could probe into PQ axion parameter space, ~$10^8$ improvement over previous techniques
- Plans for Experiment:

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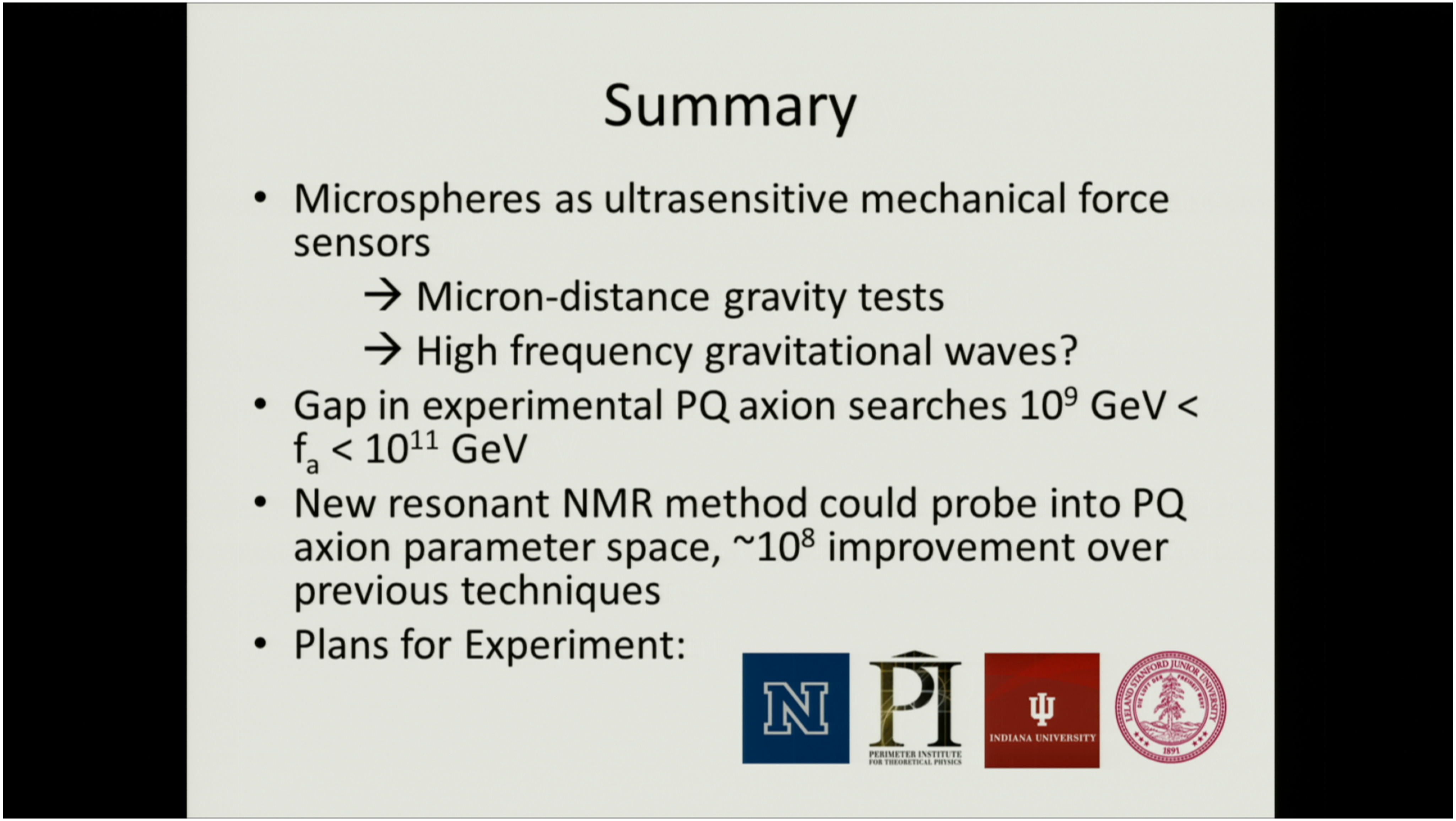

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