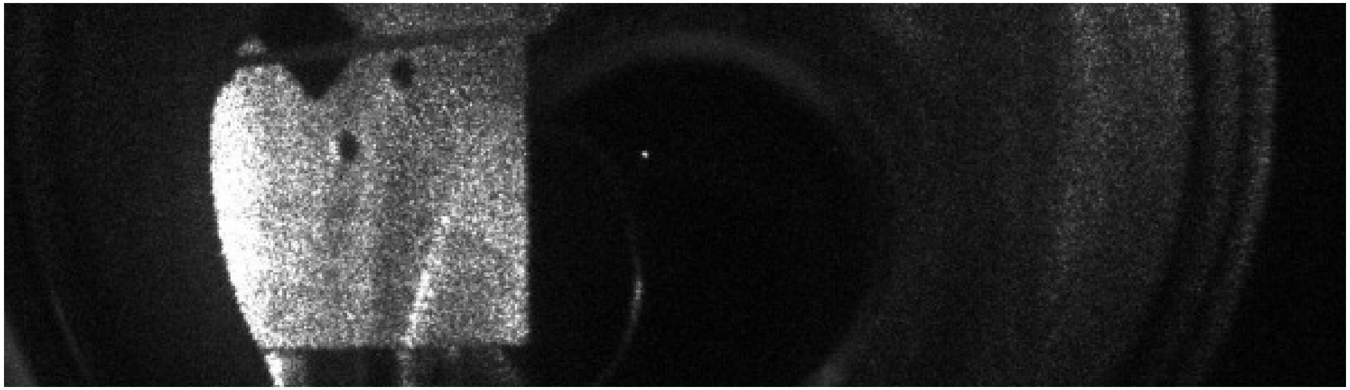
Detecting short-range forces and gravitational waves using resonant sensors

A. Geraci, University of Nevada, Reno



Frontiers of New Physics:
Colliders and Beyond
ICTP
June 27, 2014

Resonant Sensors

Techniques

Mechanical sensors

High Q Mechanical Oscillators
-Cantilevers
-Optically trapped dielectrics

Spin Resonance

Nuclear Magnetic Resonace
-Hyperpolarized gases or liquids

New Physics

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).

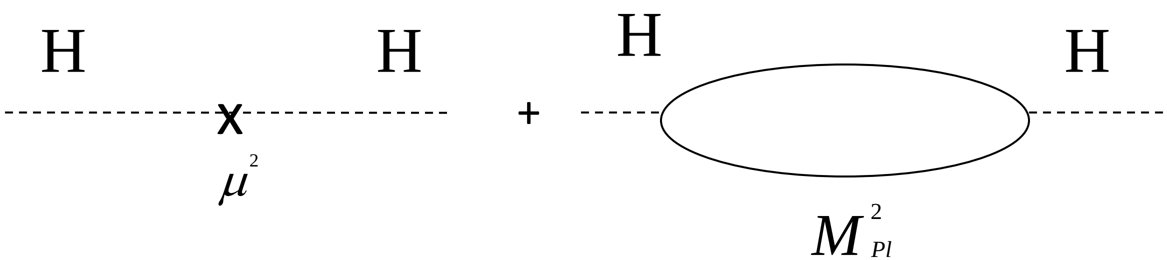
- Searching for axion-mediated short range forces by NMR

  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_{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

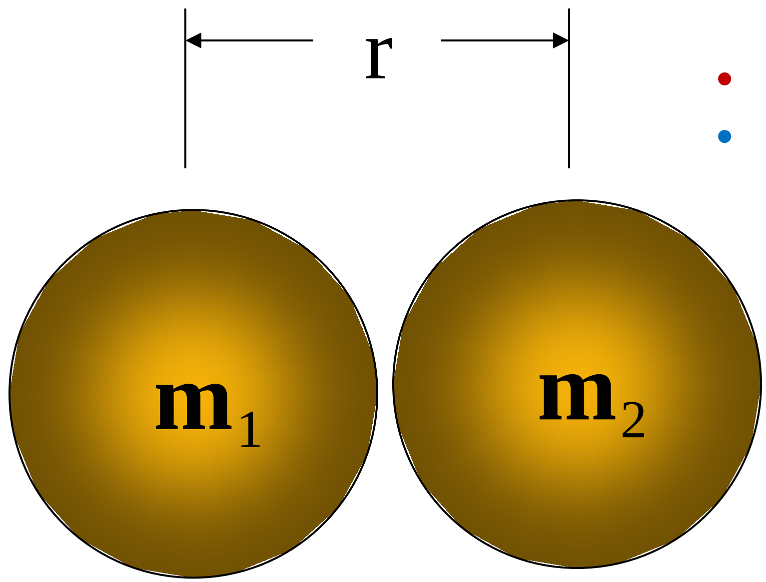
Testing gravity at short range

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

Exotic particles (new physics)

$\lambda < 1$ mm

- Supersymmetry
- Large extra dimensions



Experimental challenge: scaling of gravitational force

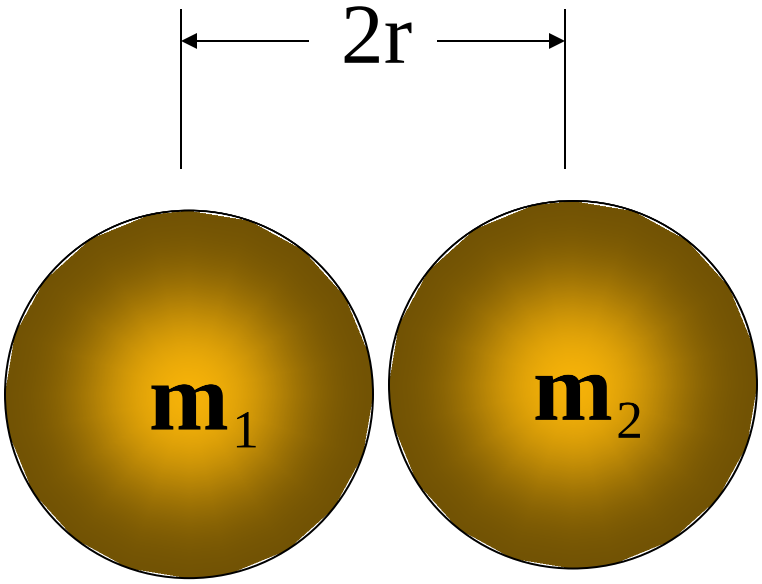
$$V_N = -G\frac{m_1 m_2}{r}$$

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

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

In the range of experimental interest:

r~10 μm ; $F_N \sim 10^{-21} N$

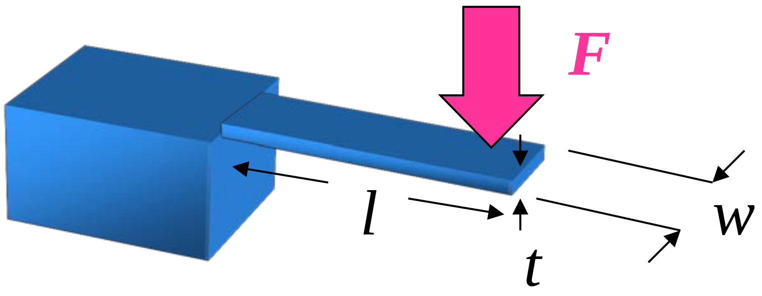


Resonant force detection

- Cantilever is like a spring:

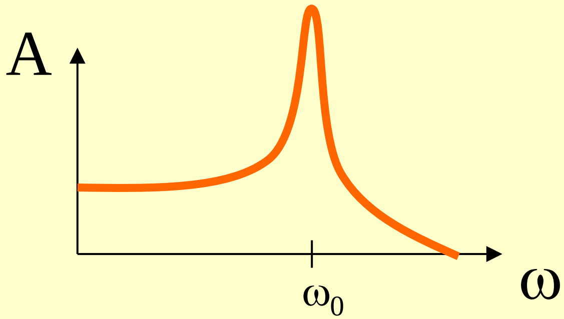
$$F = -Kx$$

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



Sinusoidal driving force

Amplitude:



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

Constant force

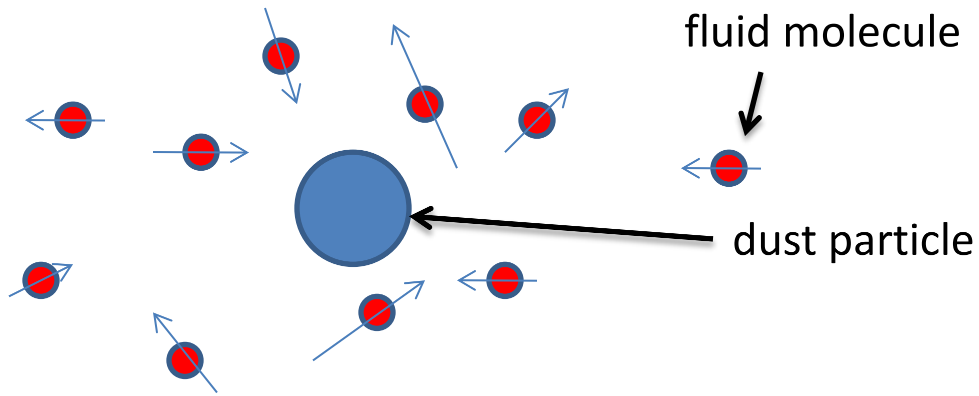
$$A_{(\omega=\omega_0)} = \frac{F}{k}Q$$

Driving force on resonance of cantilever ω_0

Q can be very large >100,000

Fundamental limitation: thermal noise

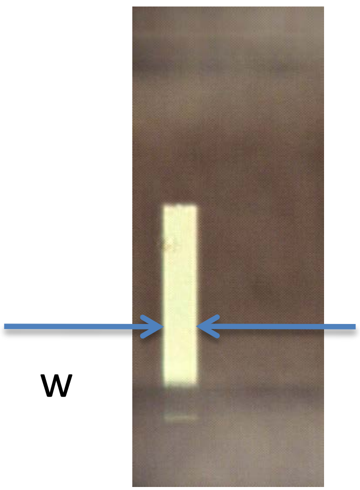
Brownian motion – random “kicks” given to particle due to thermal bath



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

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

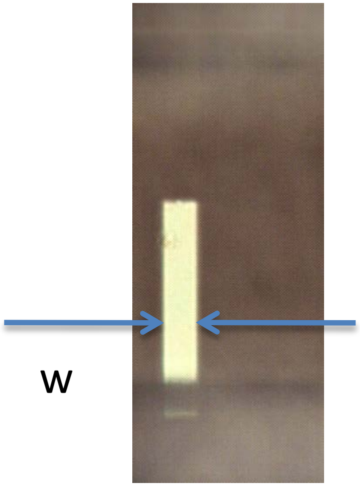
Fundamental limitation: thermal noise



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

Fundamental limitation: thermal noise



w

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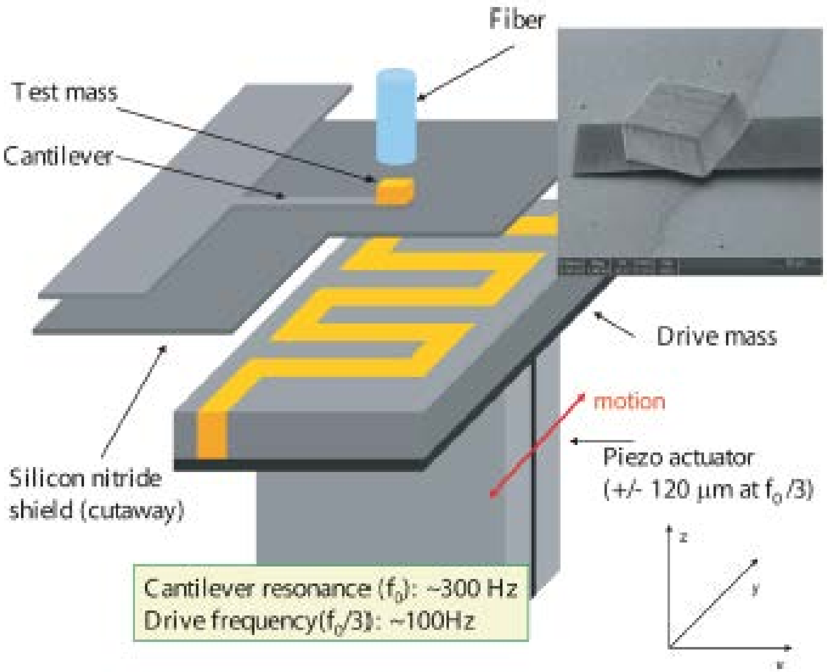


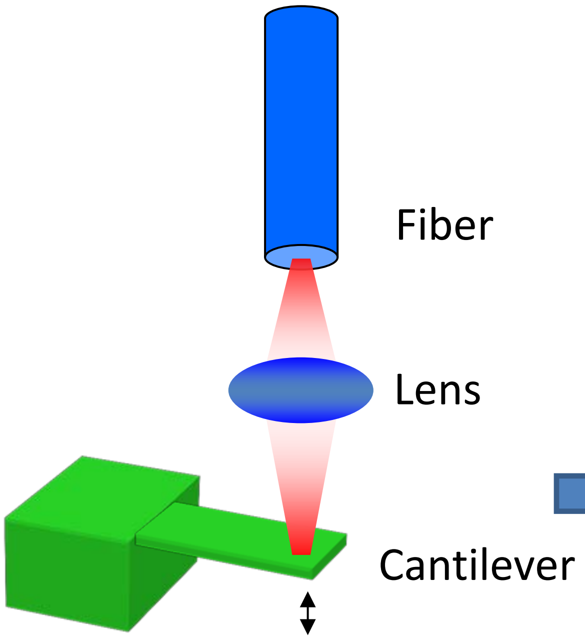
Best Yukawa constraints at ~ 10 um range:

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

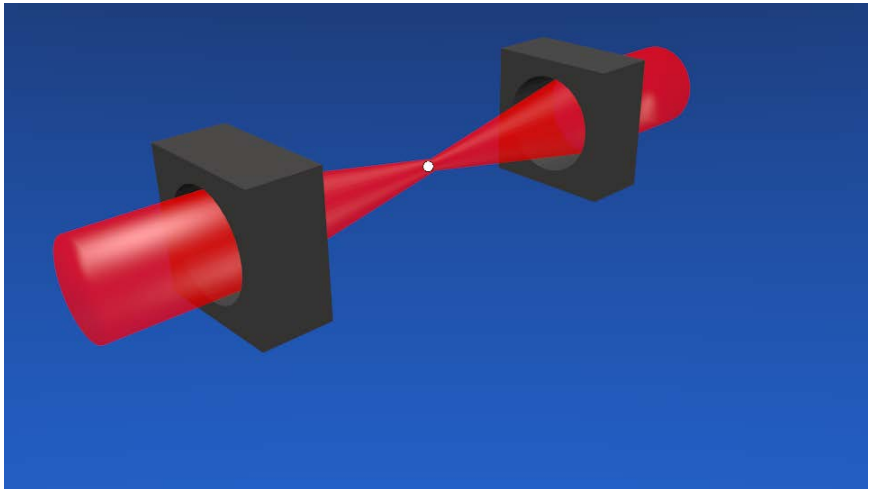
$$F_{\min} = \sqrt{\frac{4k\, k_B T b}{\omega_0 Q}}$$

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

Improving Q?



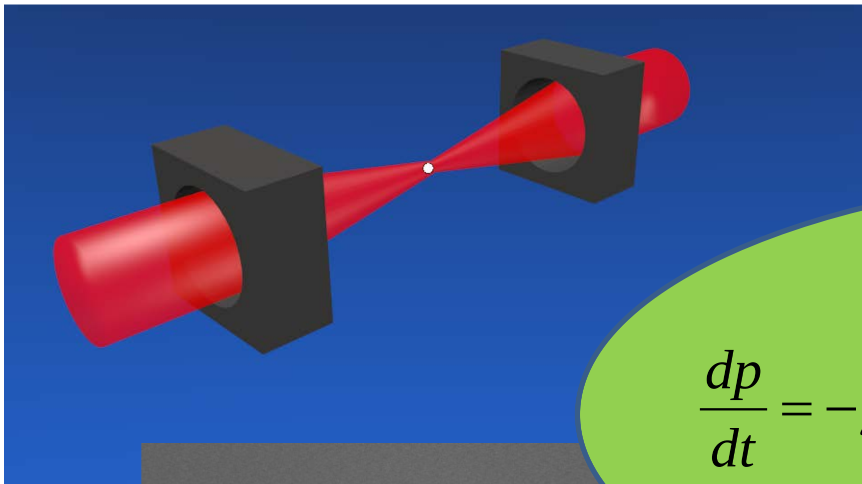
Levitate the force sensor!

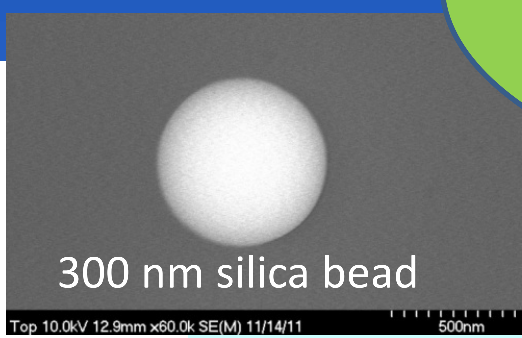


Limitations on Q: Clamping, surface imperfections, internal materials losses

CM motion decoupled from environment –
no clamping, materials losses

Optically-levitated sensors





Pressure-limited damping

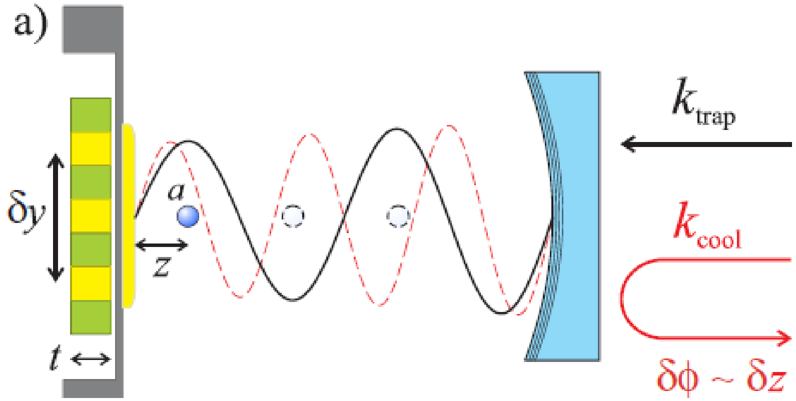
$$\frac{dp}{dt} = -\gamma_g \frac{p}{2} \qquad \frac{\gamma_g}{2} = \left(\frac{8}{\pi}\right)\frac{P}{\bar{v} r \rho}$$

P=10^{-10} Torr, r=0.15 μm, $\omega/2\pi$=10 kHz, Q=10^{12} !

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

Q ~ 10^{12}
T ~ 300 → F ~ 10^{-21} N/Hz$^{1/2}$
$\omega_0/2\pi$ ~ 10^5
m ~ $10^{-(14\text{-}17)}$ kg

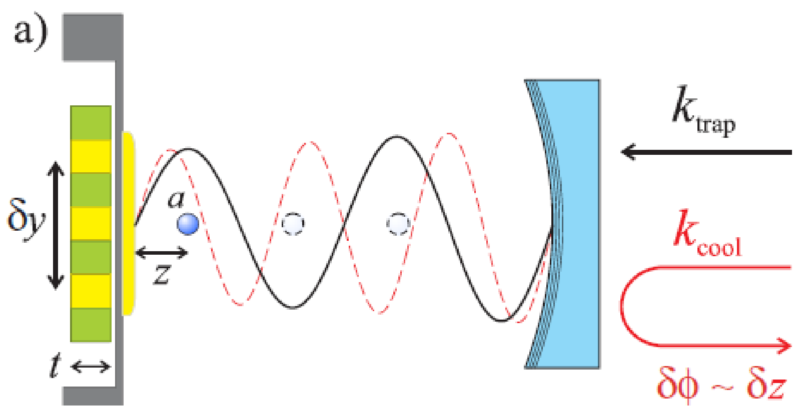
Micron-scale gravity test experiment

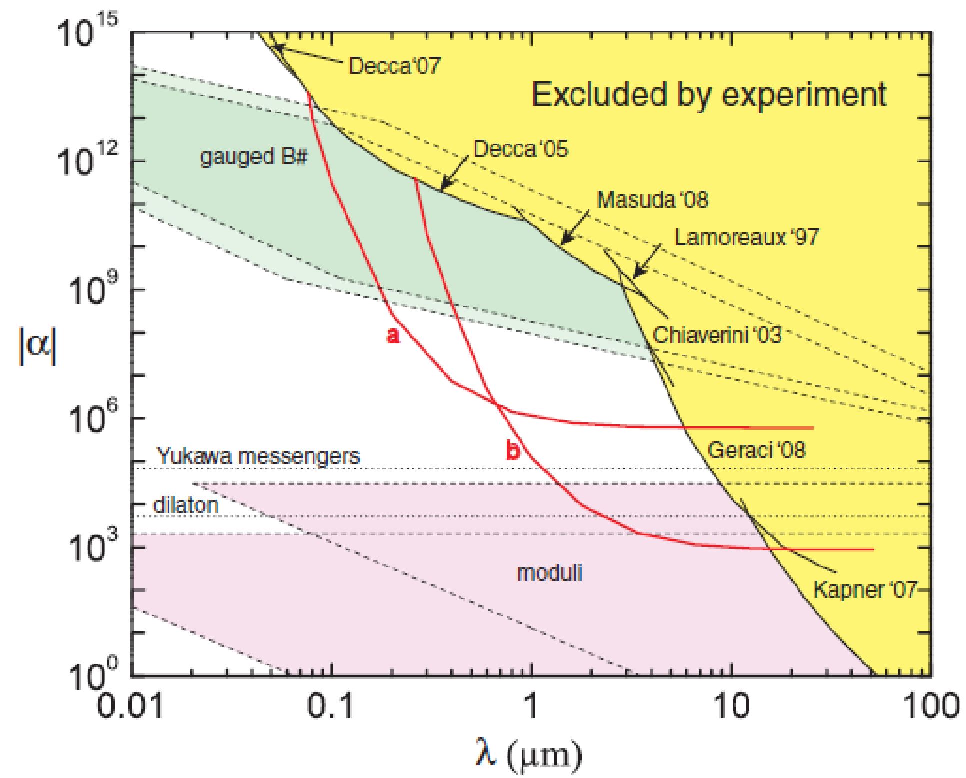


A. A. Geraci, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Micron-scale gravity test experiment

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

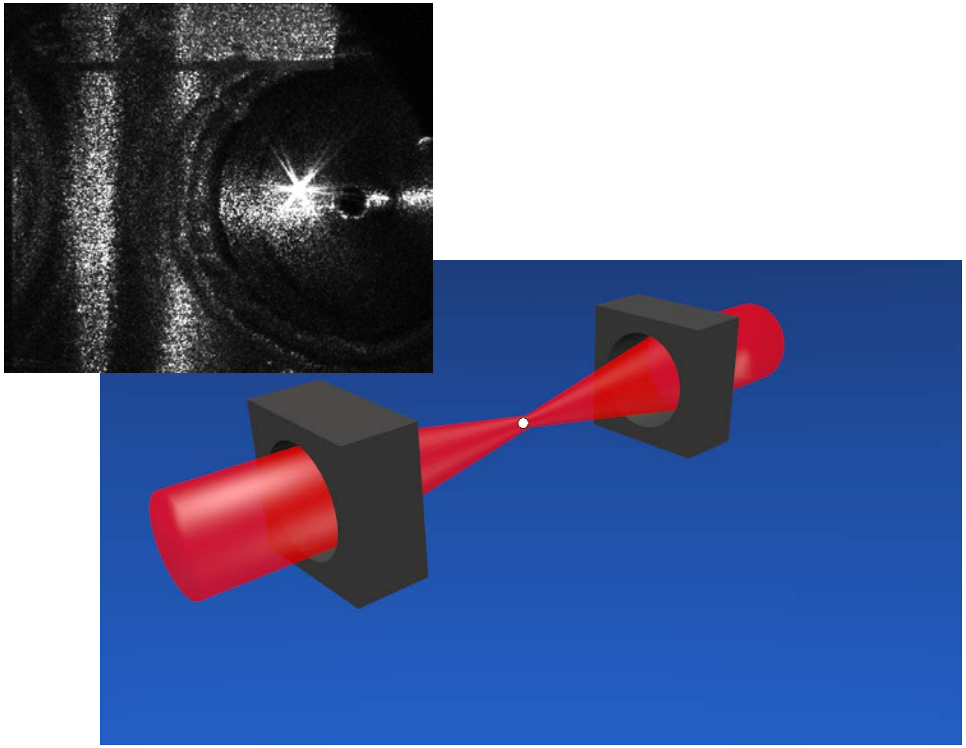




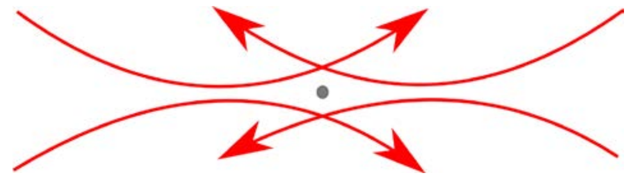
10^6 improvement possible at 1μm length scale

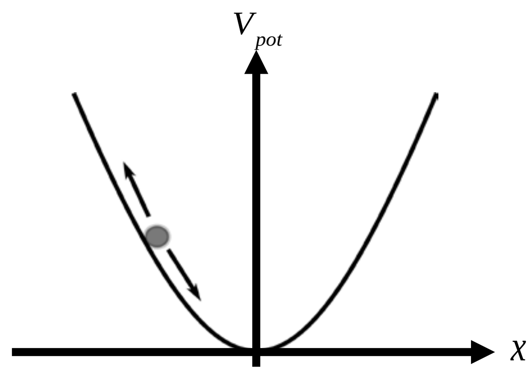
A. A. Geraci, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Dual beam dipole trap



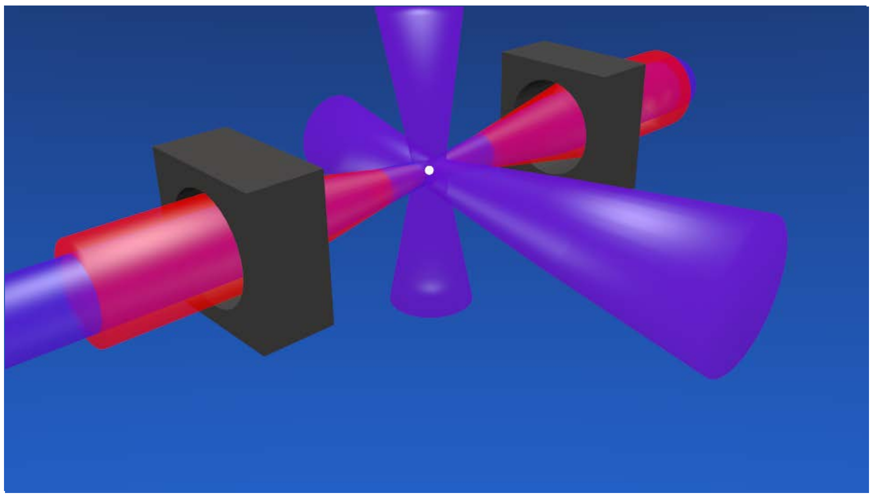
Our Trap Configurations

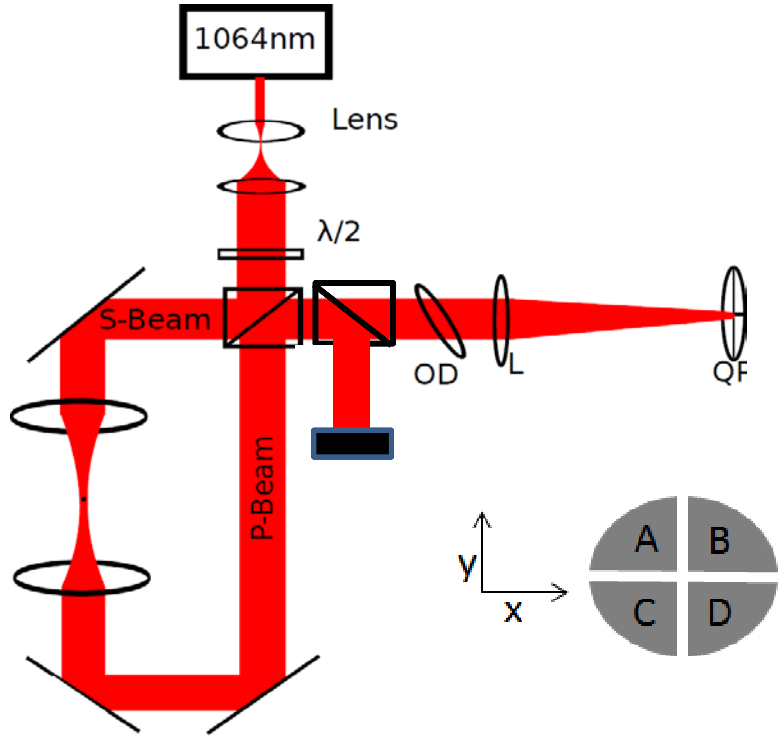




- Trap frequency ~10 kHz
- High Q-factor > 10^{12}
- Need cooling!

Laser cooling of a microsphere

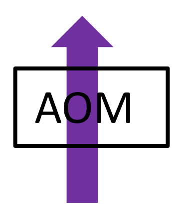


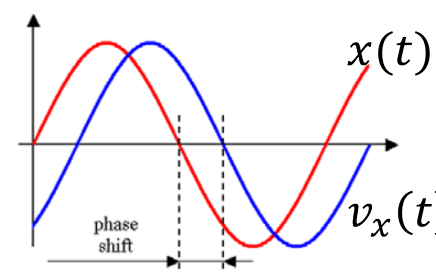


$$F_{\min} = \sqrt{\frac{4kK_B TB}{\omega_0 Q}}$$

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

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





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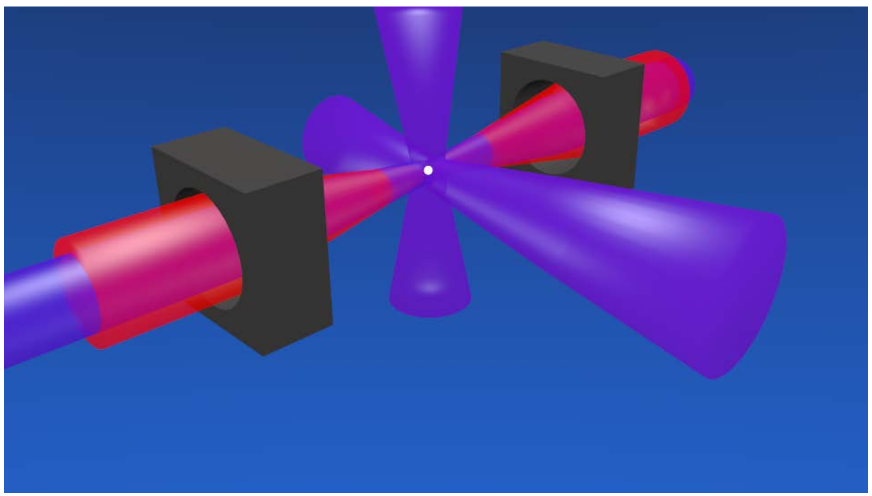


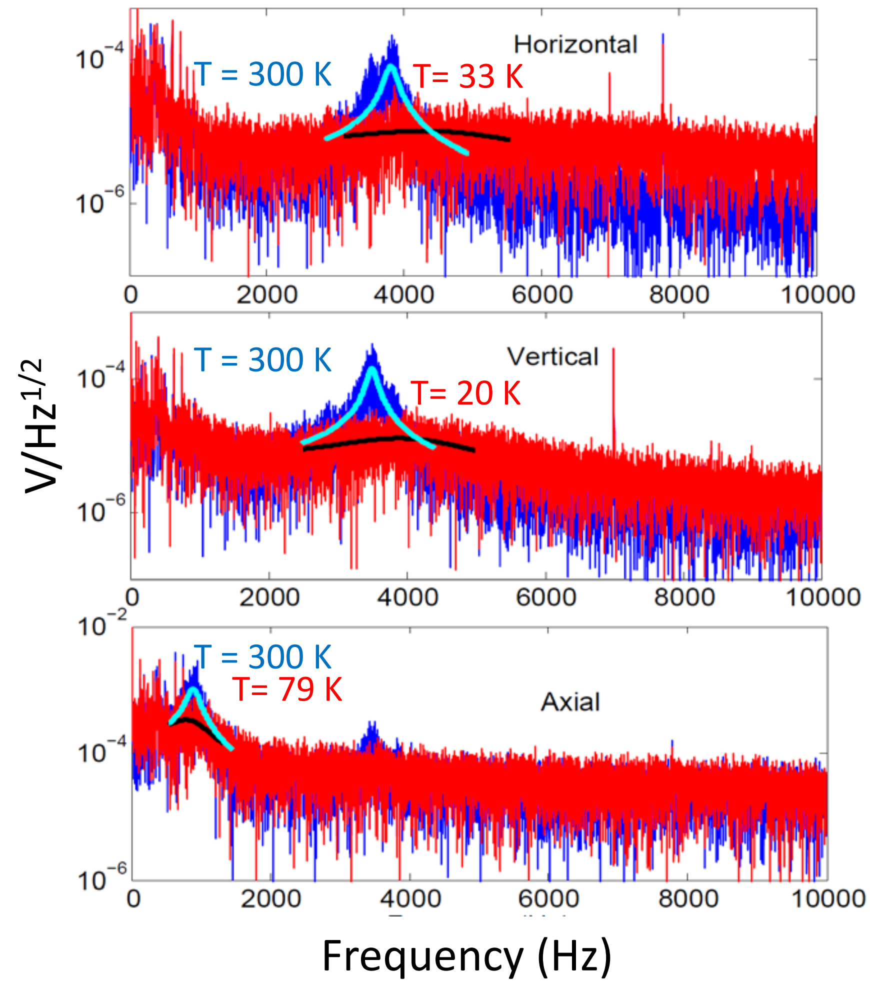
Q = 38
T = 300K

$$F_{\min} \sim 50 \times 10^{-17} N / \sqrt{Hz}$$

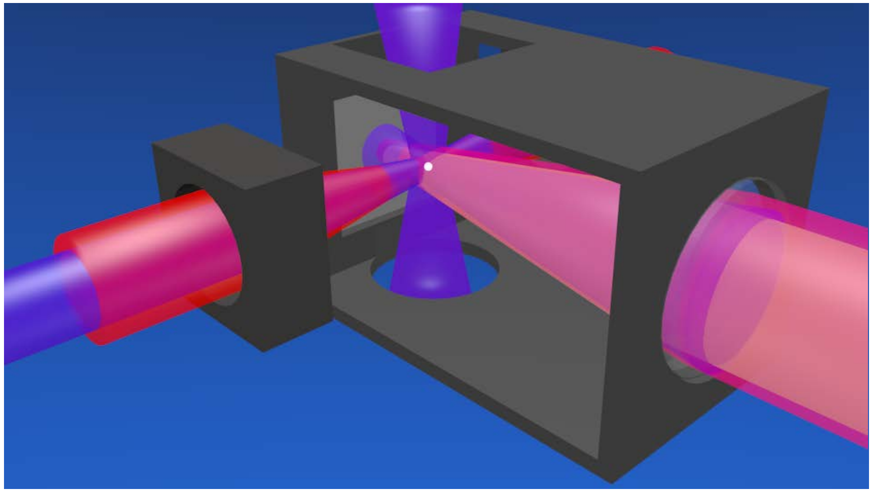
Goal at UHV: $F_{\min} \sim 10^{-21} N / \sqrt{Hz}$

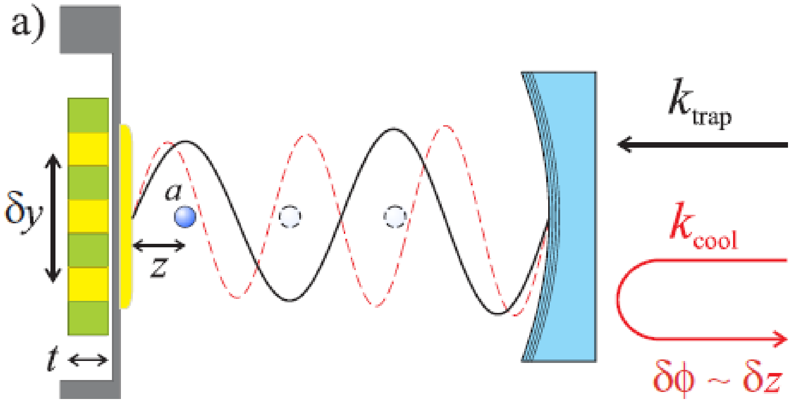
Preliminary

3D Feedback cooling at 2 mbar



Cavity Trapping and cooling

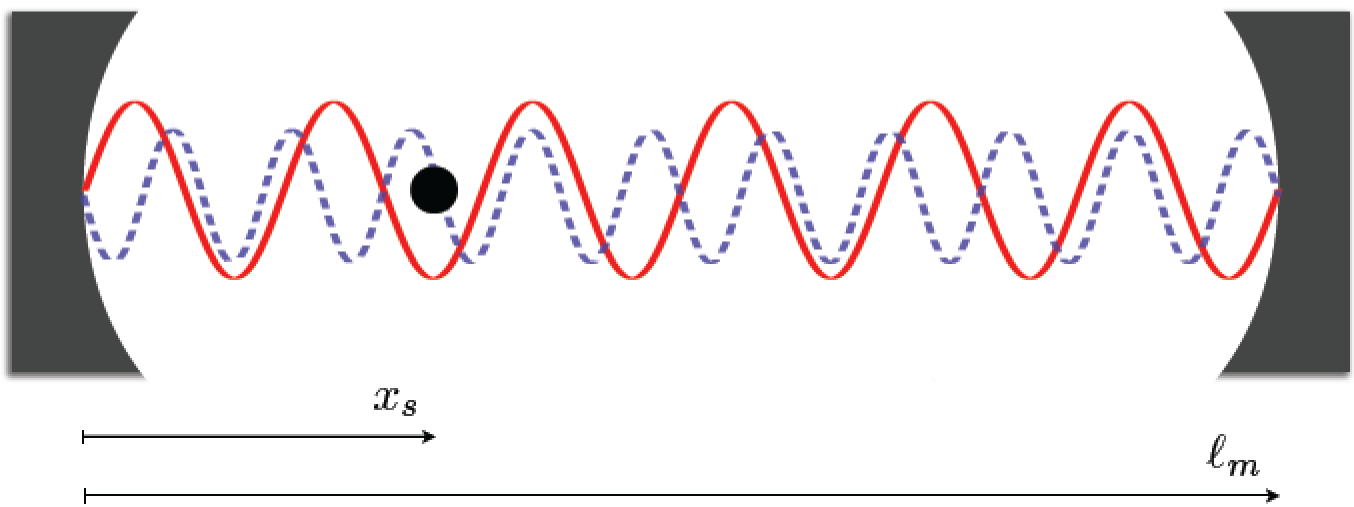




1596nm beam to trap a bead at its antinode

1064nm beam to cavity cool the CM of bead

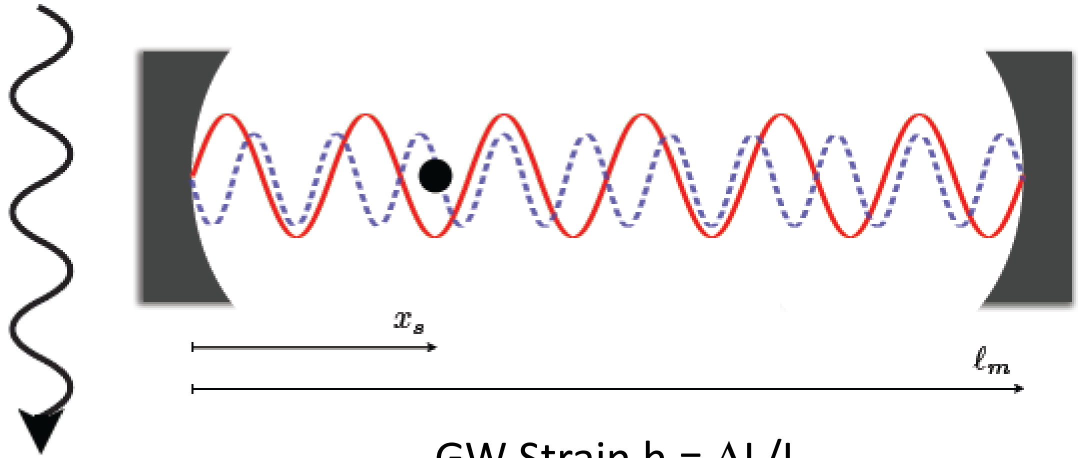
Gravitational Wave Detection



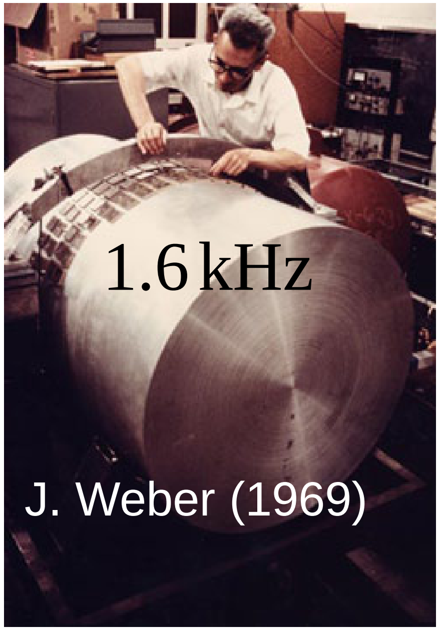
- Fused silica sphere (r = 150nm) or disc (t = 500nm, r = 75 μm)
  In an optical cavity of size 10-100 m
- One laser to trap, one to cool and measure sensor position

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

Gravitational Wave Detection



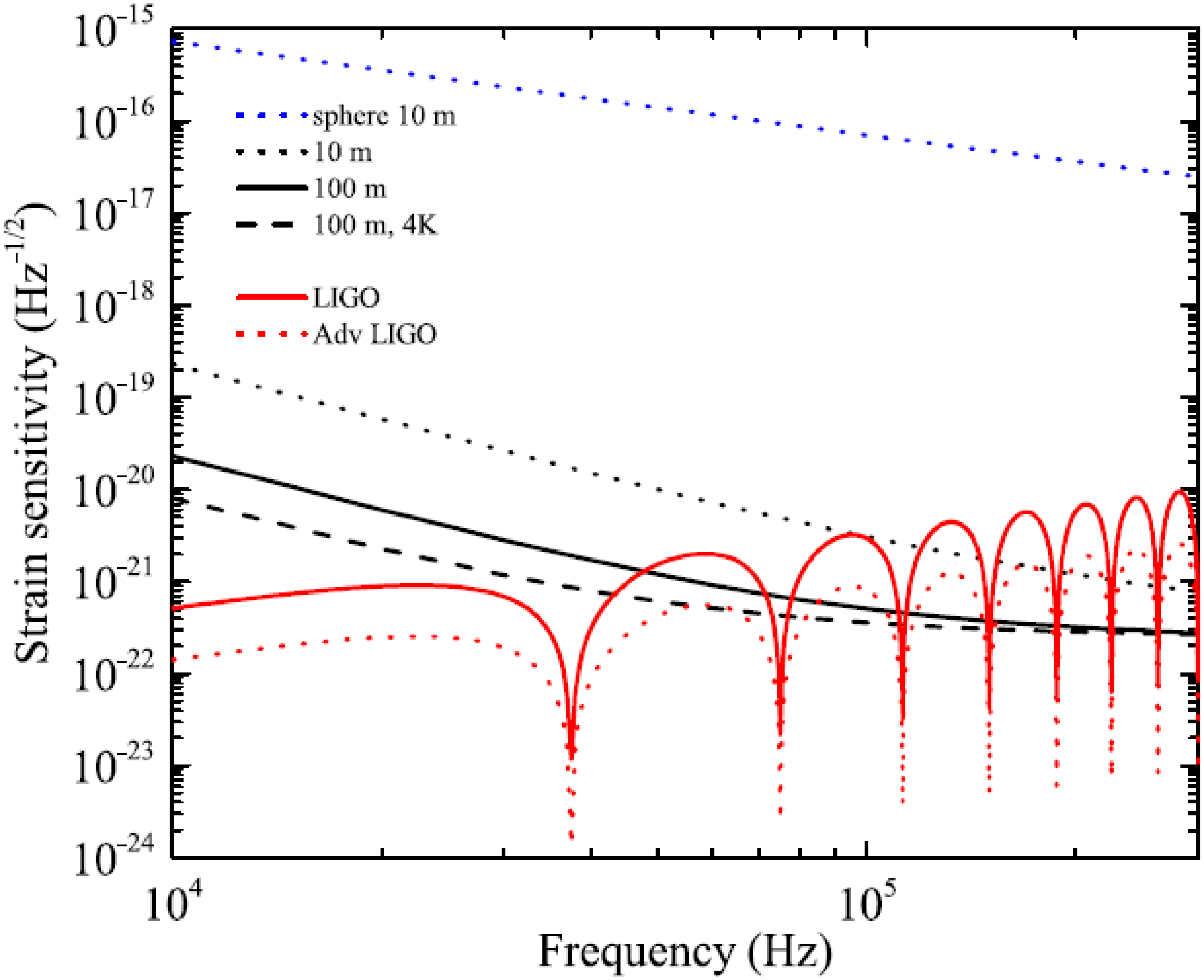
GW Strain h = ΔL/L



- 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

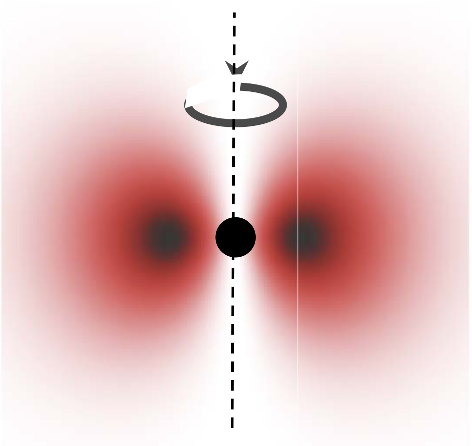
- Astrophysical Sources
  Natural upper bound on GW frequency
  inverse BH size ~ 30 kHz

- 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?

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

Axions

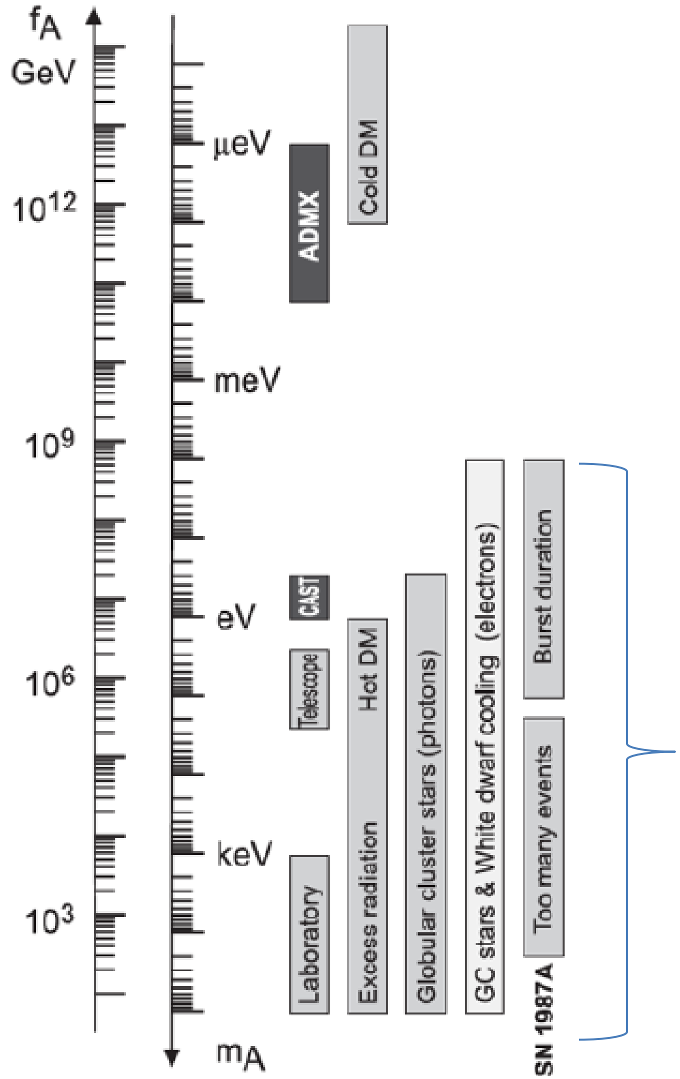
- Light pseudoscalar particles in many theories Beyond Standard model
- Peccei-Quinn Axion (QCD) solves strong CP-problem
- Dark matter candidate

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

→ 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).

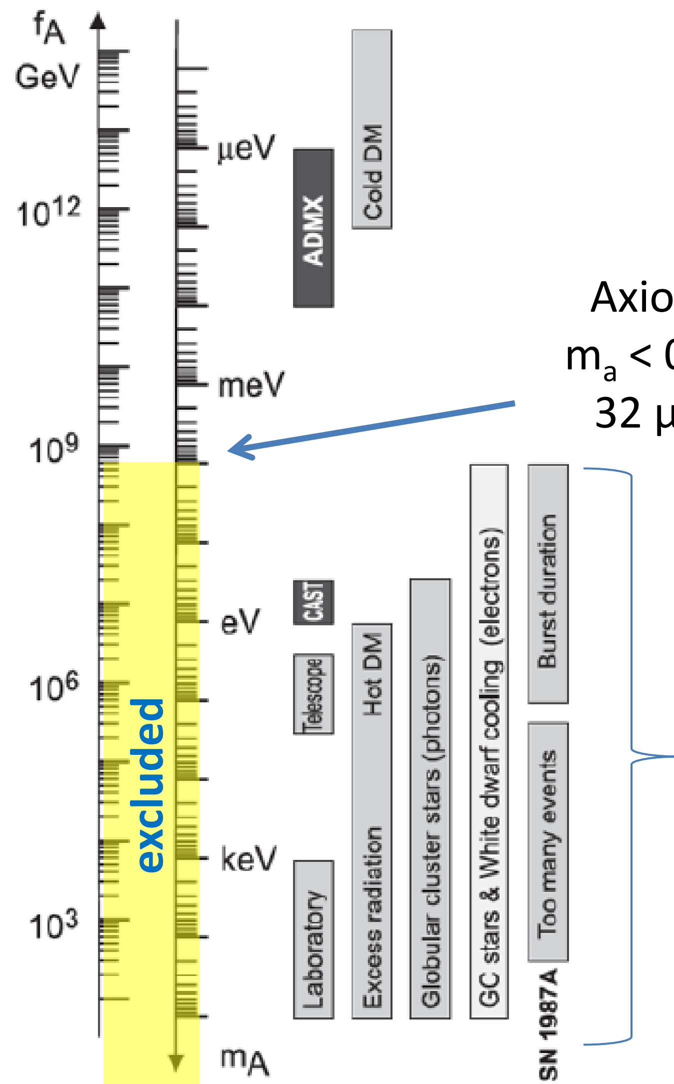
QCD Axion parameter space



Lab and Astrophysical bounds

QCD Axion parameter space

Axion decay constant
10^9 GeV < f_a



Axion mass
m_a < 0.006 eV
32 μm < λ_a

Lab and Astrophysical bounds

QCD Axion parameter space

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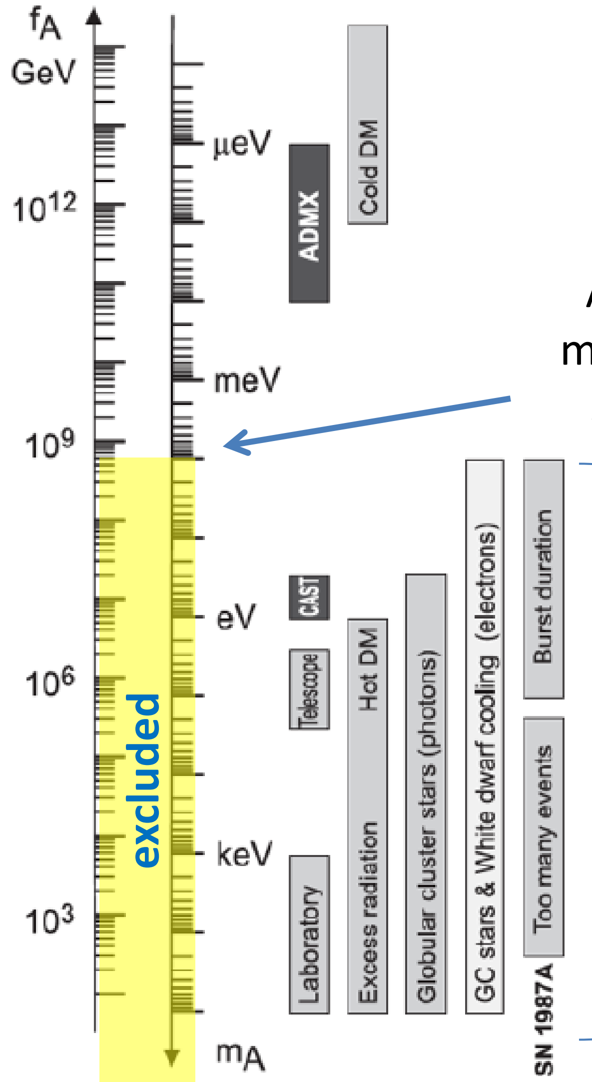
10^9 GeV < f_a < 10^{17} GeV

BH superradiance

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



Axion mass
m_a < 0.006 eV
32 μm < λ_a

Lab and Astrophysical bounds

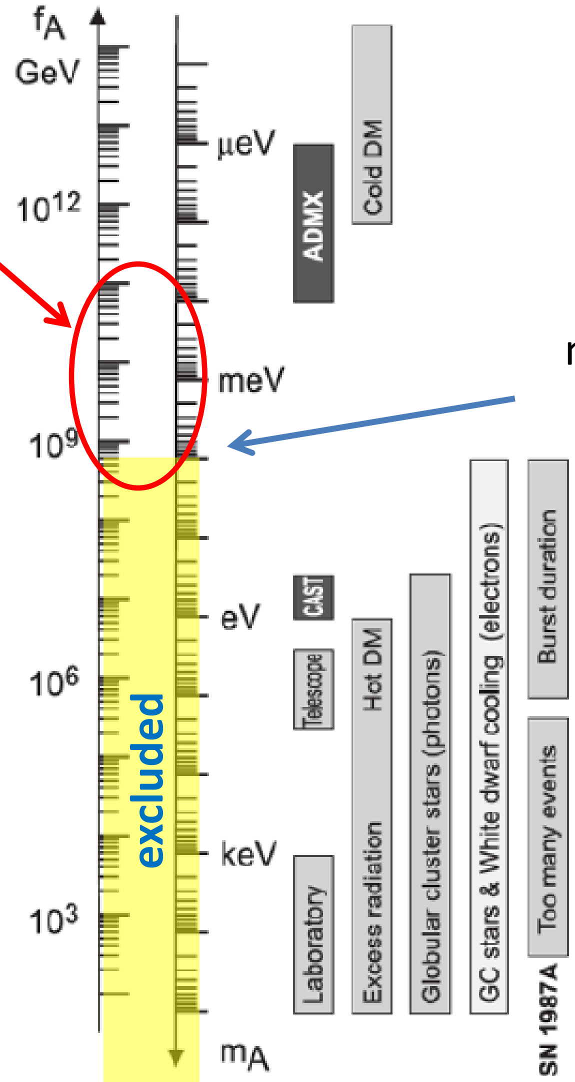
QCD Axion parameter space

- No existing experiments

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

BH superradiance

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



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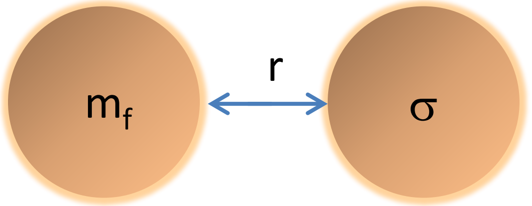
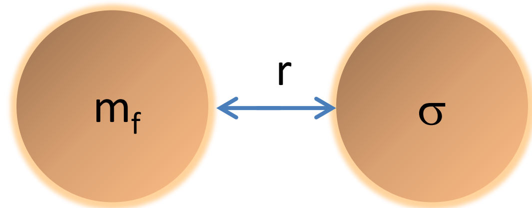
Spin-dependent forces



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



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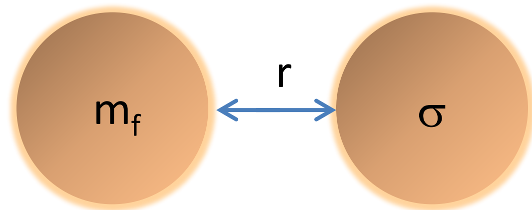
$$B_{\text{eff}} = \frac{1}{\gamma_f}\frac{\hbar g_s g_p}{4\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right)e^{-r/\lambda_a}$$

gyromagnetic ratio

Spin-dependent forces



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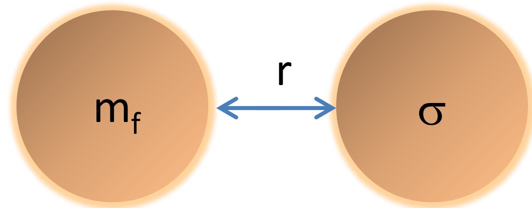
gyromagnetic ratio

Coupling constants

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

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

Spin-dependent forces



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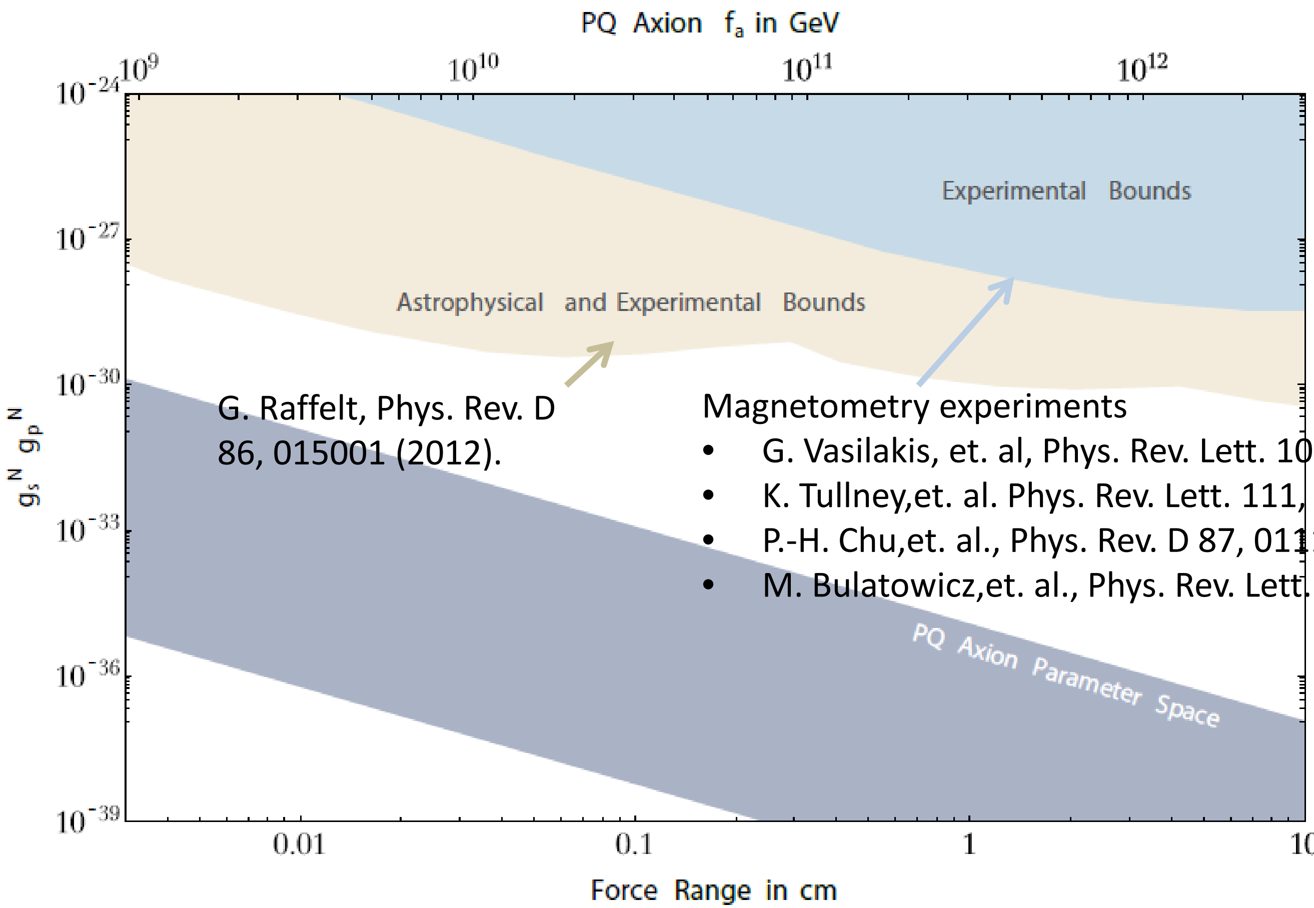
$$g_p = \frac{C_f m_f}{f_a} = C_f 10^{-9}\left(\frac{m_f}{1\text{GeV}}\right)\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

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

Constraints on spin dependent forces

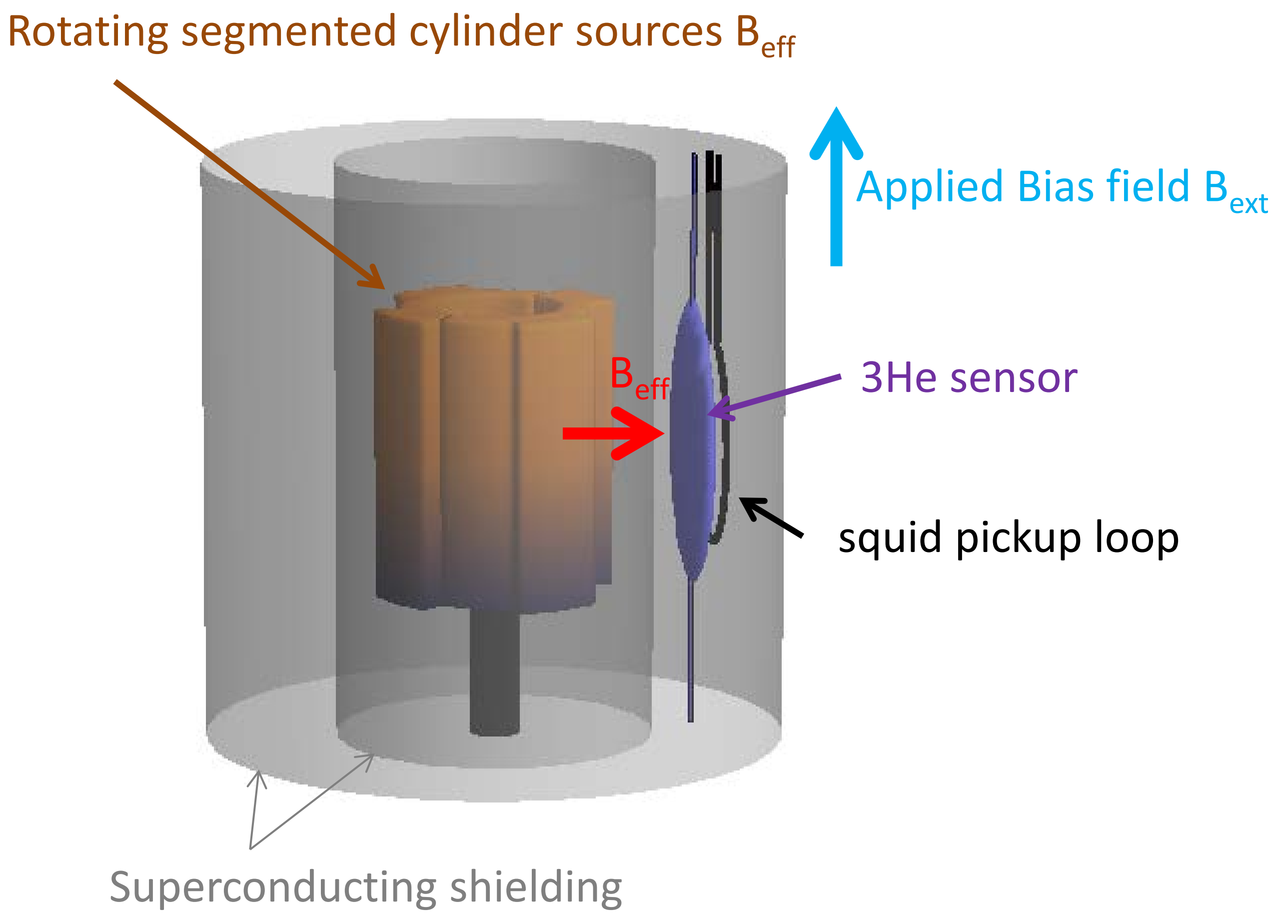


G. Raffelt, Phys. Rev. D 86, 015001 (2012).

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).

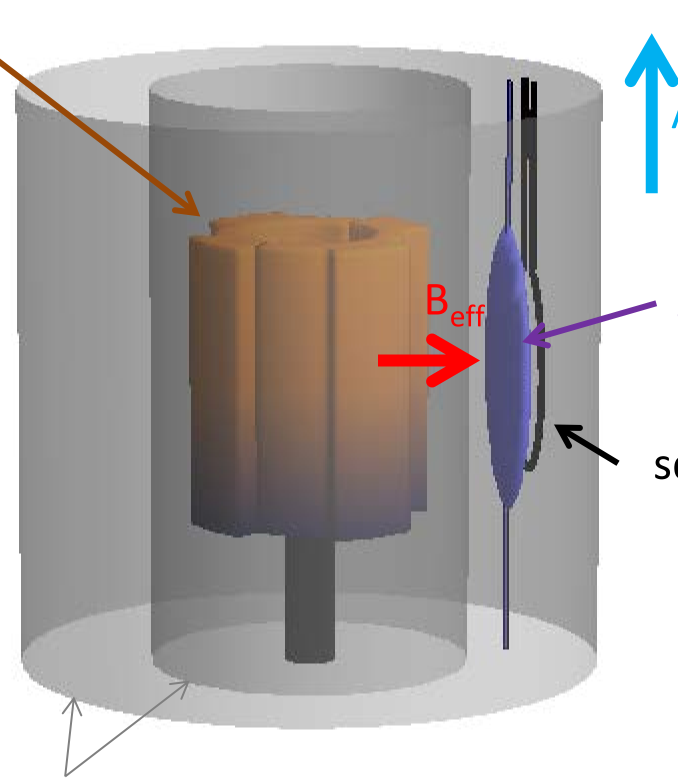
Concept for new experiment



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

A. Arvanitaki and A. Geraci, arxiv: 1403.1290

Concept for new experiment



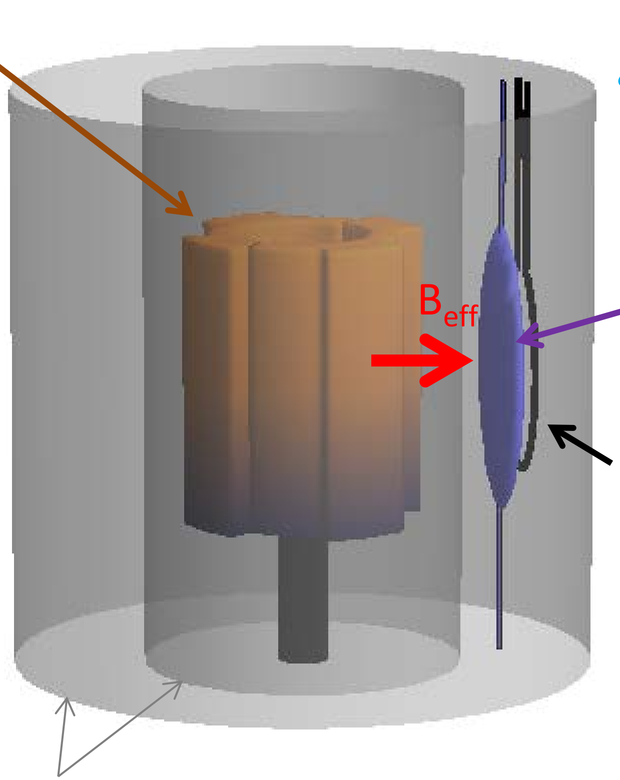
$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

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

Spin density

A. Arvanitaki and A. Geraci, arxiv: 1403.1290

Concept for new experiment



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Spin density

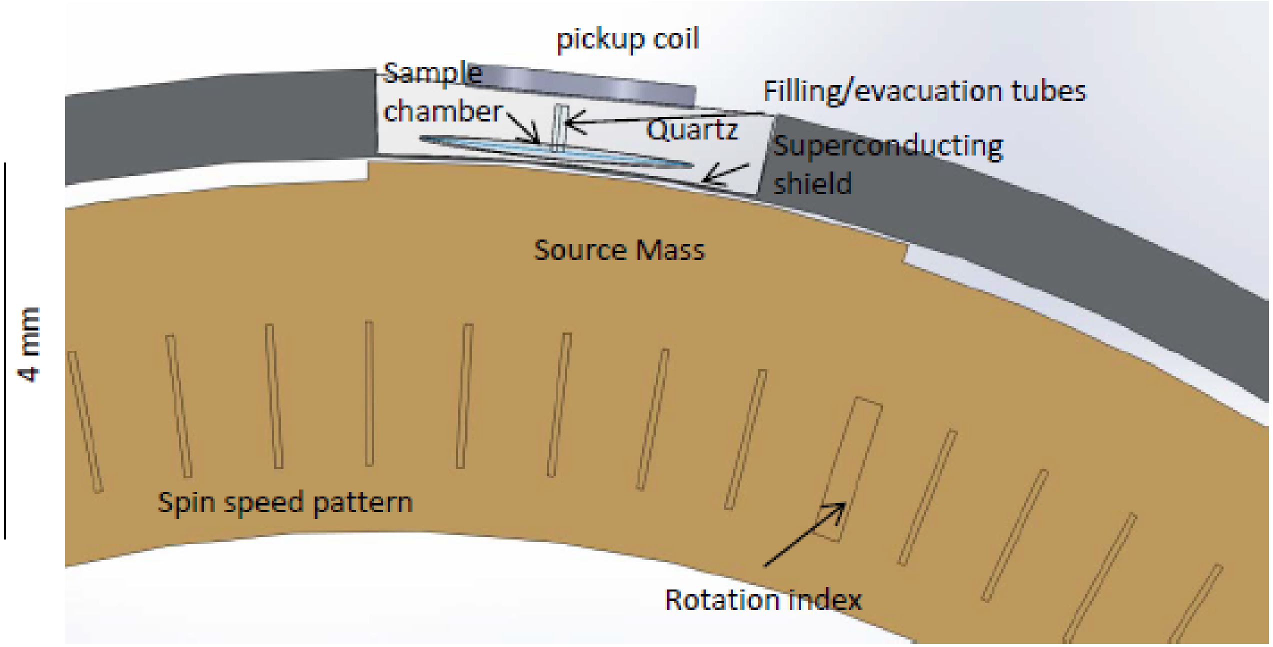
Limit: Transverse spin projection noise

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

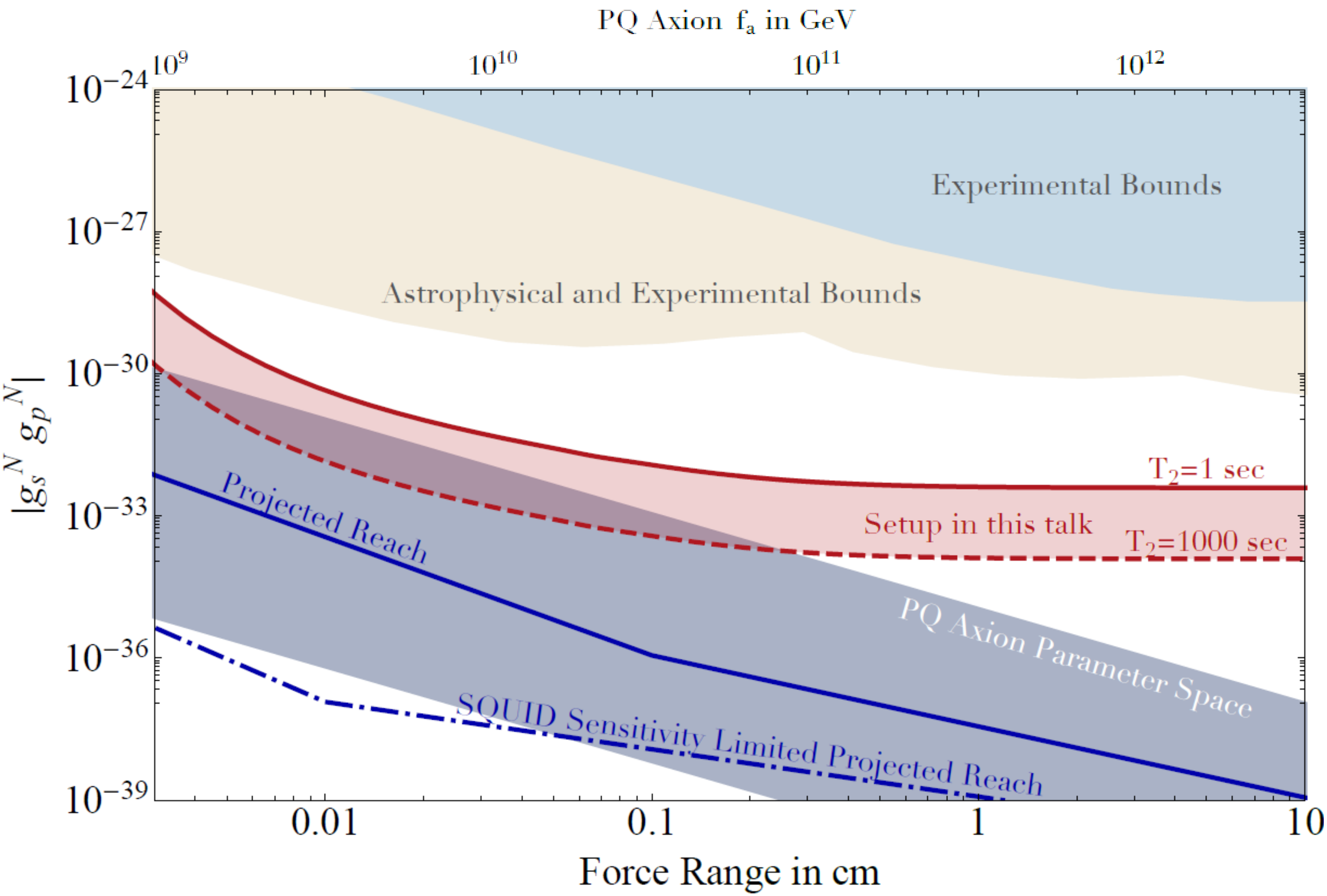
A. Arvanitaki and A. Geraci, arxiv: 1403.1290

Sensitivity

Experimental parameters:
10 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

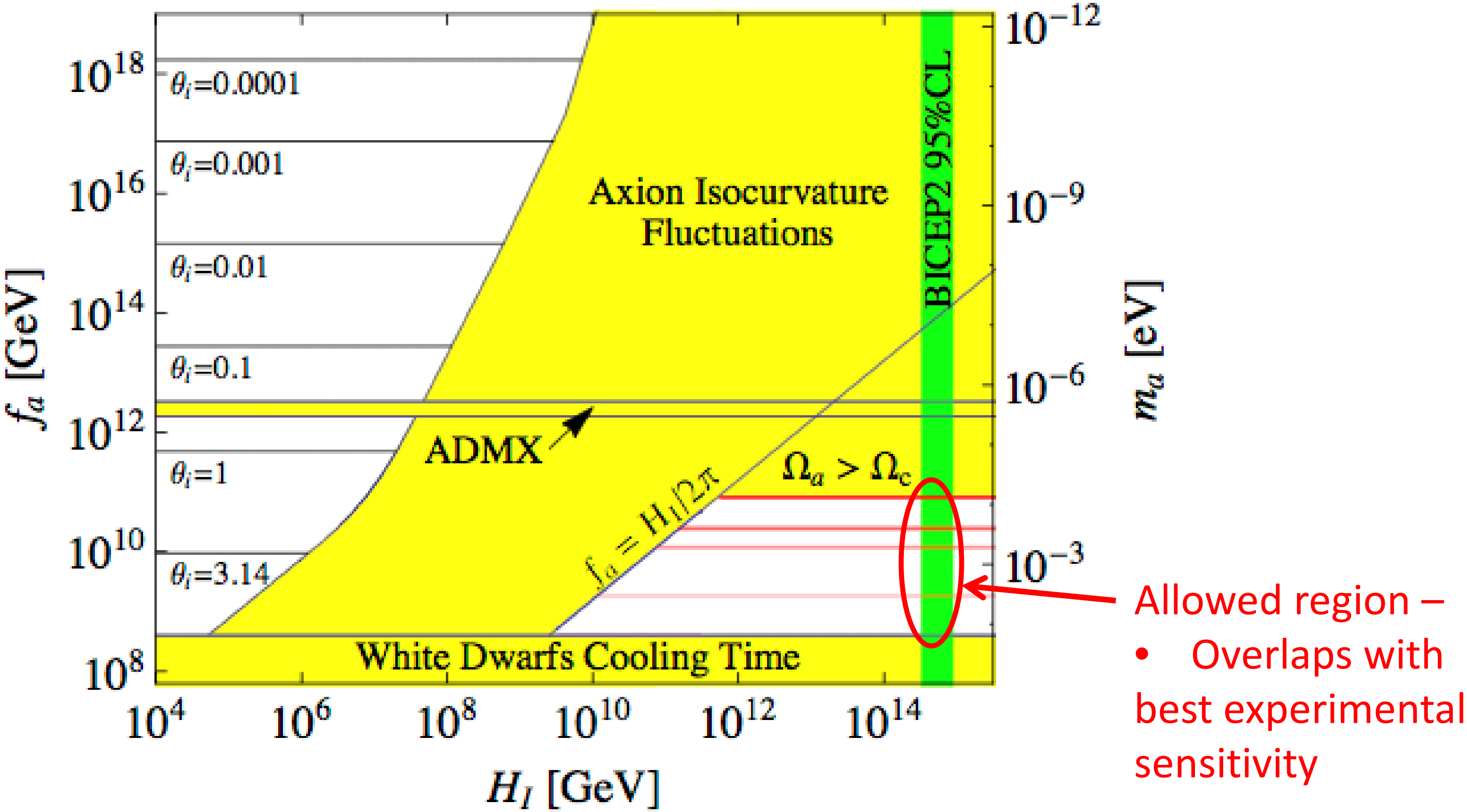


A. Arvanitaki and A. Geraci, arxiv: 1403.1290

Experimental challenges

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

Axion Cosmology in light of Inflationary scale

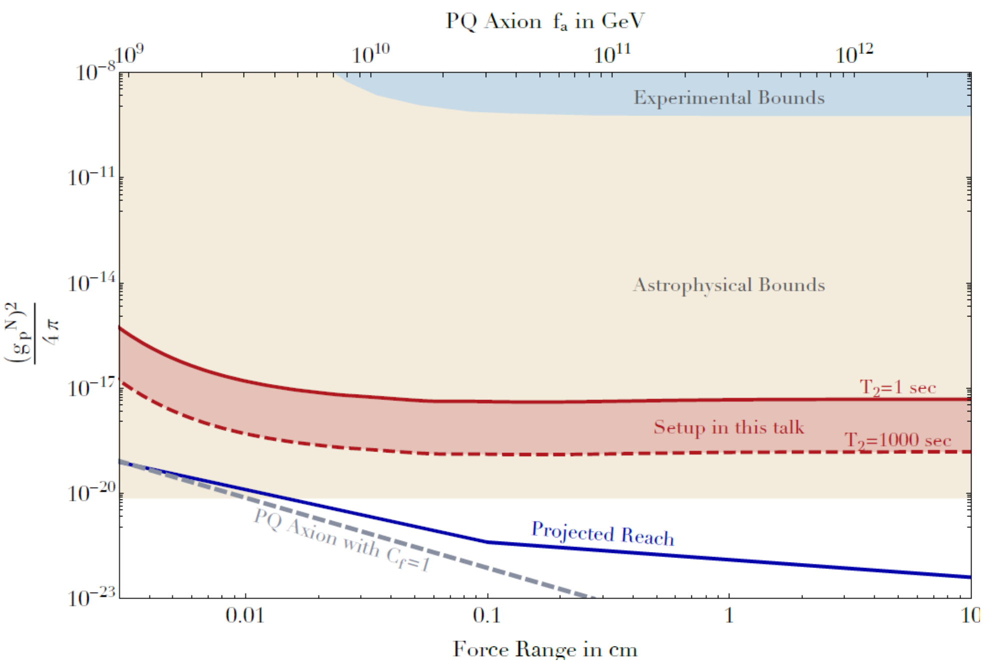


from: Luca Visinelli and Paolo Gondolo, arxiv: 1403.4594v2

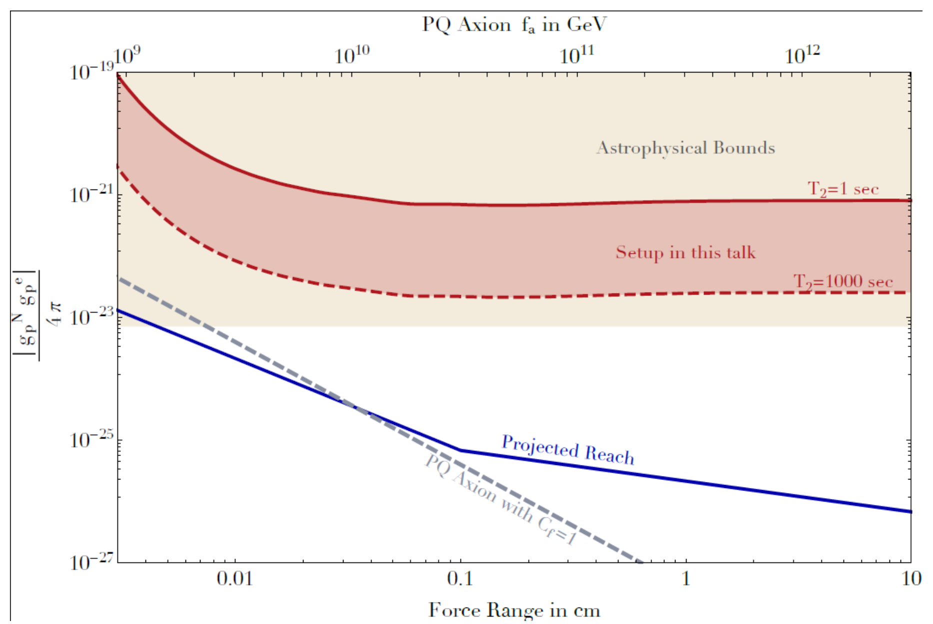
Dipole-Dipole axion forces

- Spin-polarized source mass
- May be competitive with astrophysical bounds
- Magnetic shielding requirements more stringent

Nuclear spin



Electron spin



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 (even if axion is not dark matter)
- Plans for Experiment: Axion Resonant InterAction DetectioN Experiment (ARIADNE)

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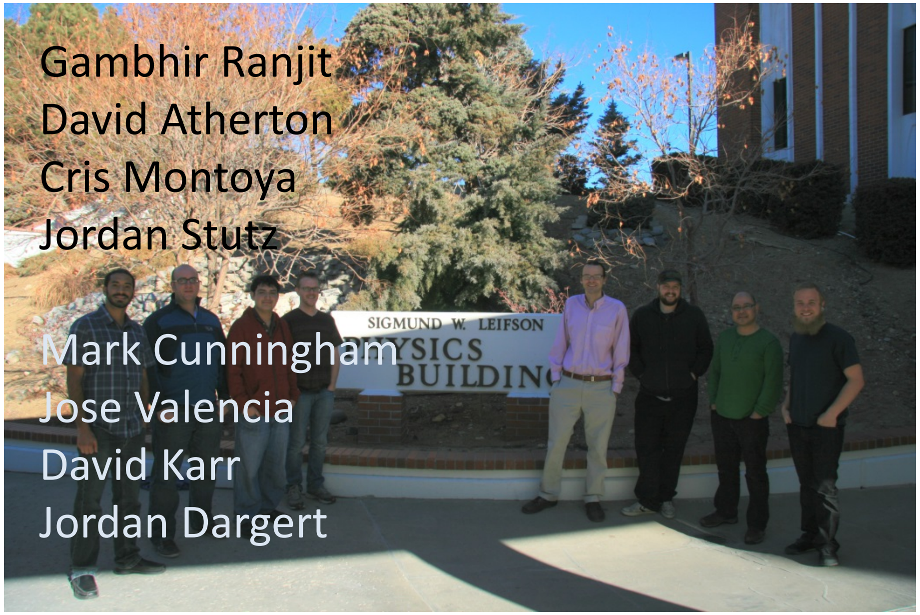
Acknowledgements

Research team:



Gambhir Ranjit
David Atherton
Cris Montoya
Jordan Stutz

Mark Cunningham
Jose Valencia
David Karr
Jordan Dargert

Collaborators:

Asimina Arvanitaki (Perimeter)
John Kitching (NIST)
Mike Snow (Indiana)
Aharon Kapitulnik (Stanford)
Eli Levenson-Falk (Stanford)
Josh Long (Indiana)
Chen-Yu Liu (Indiana)

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