Title: Fundamental Physics with Optically Levitated Dielectric Objects

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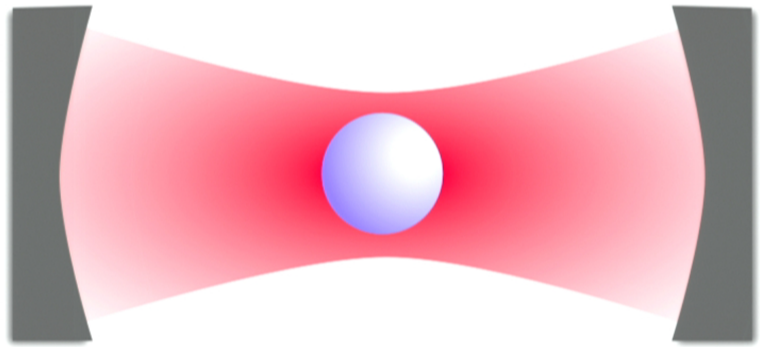
Abstract: In the past few years, optical cooling and manipulating of macroscopic objects, such as micro-mirrors and cantilevers has developed into an active field of research. In mechanical systems, the oscillator is attached to its suspension, a thermal contact that limits the motion isolation. On the other hand, when these small objects are levitated using the radiation pressure force of lasers, the excellent thermal isolation even at room temperatures helps produce very sensitive force detectors, and eventually quantum transducers for quantum computation purposes. These new techniques may have a variety of applications for fundamental physics such as short distance tests of gravity and gravitational wave detection at high frequencies. In addition, there are several proposals suggesting that optically levitated dielectrics can be cooled to the ground state of the center of mass motion, opening the exciting possibility of creating macroscopic matter-wave interferometers.

Fundamental Physics with Optically Levitated Objects

Asimina Arvanitaki
Stanford University

Optical Trapping of Dielectrics

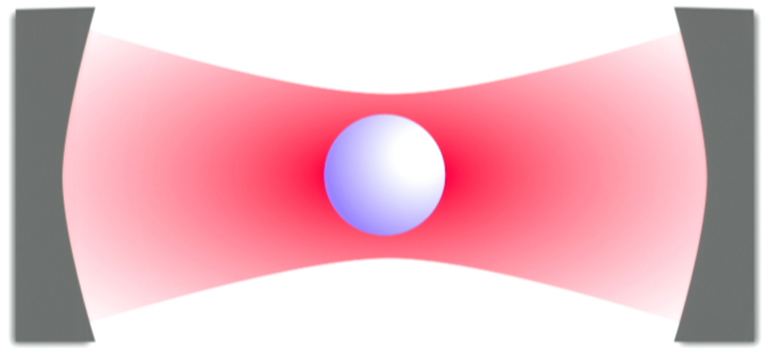
Ashkin et al. (1970,1971,1976)



$$\text{Force} \propto -\nabla E^2 \equiv -kx$$

Optical Trapping of Dielectrics

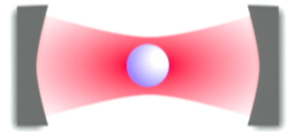
Ashkin et al. (1970,1971,1976)



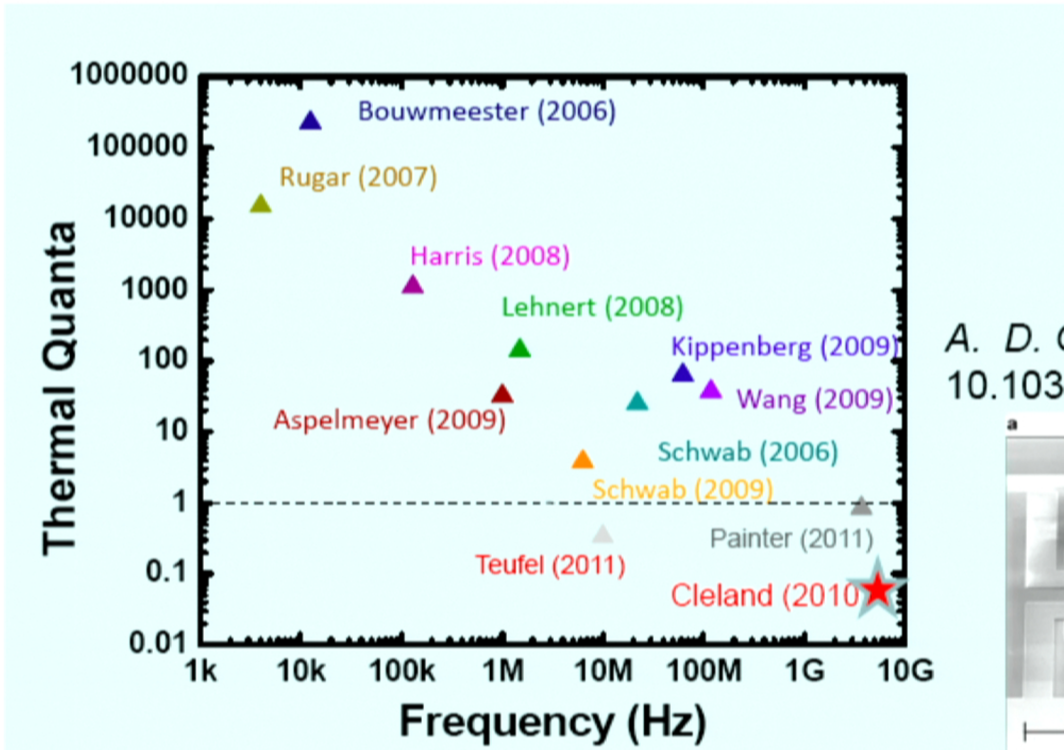
$$\text{Force} \propto -\nabla E^2 \equiv -kx$$

- Quality factor, $\omega_{mech} / \Gamma_{loss}$, larger than 10^{12} even at room temperature
- Internal modes decoupled from CM for small objects
- CM motion controlled by the intensity of light

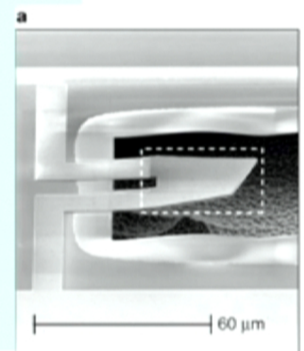
Towards the Quantum Regime



$E_{CM} = (n_{thermal} + 1/2)\omega_{CM}$



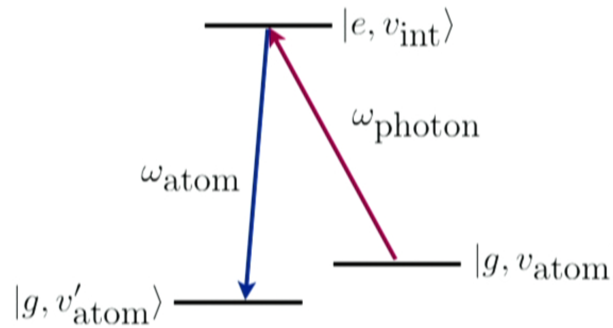
A. D. O'Connell et.al.
10.1038/nature08967



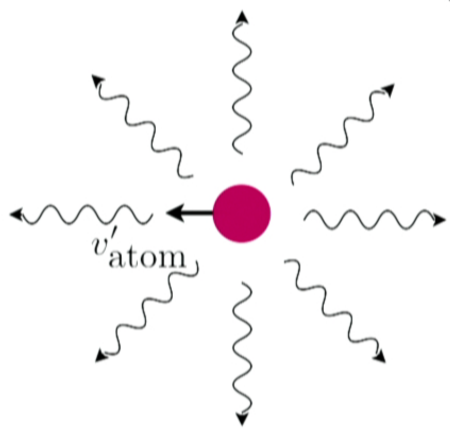
Optical Cooling

Doppler cooling

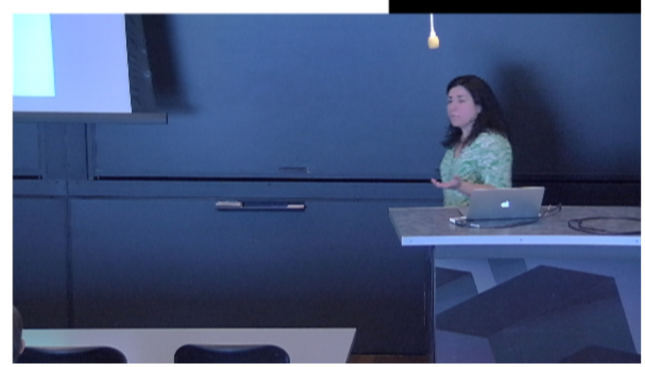
For an atom



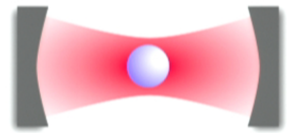
$v'_{\text{atom}} < v_{\text{atom}}$



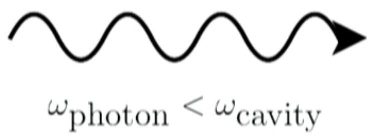
Spontaneous emission

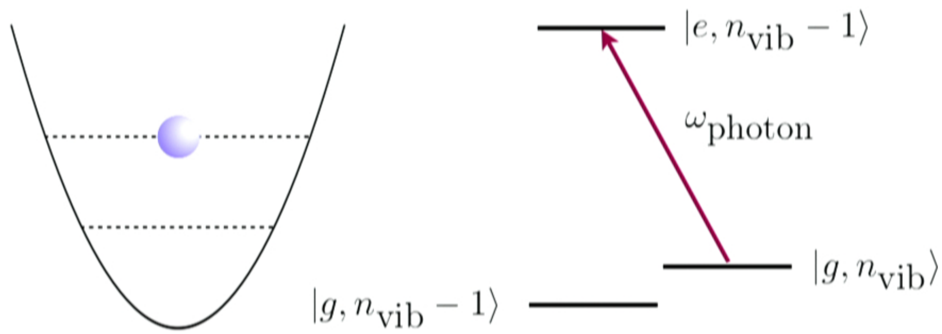


Optical Cavity Cooling



For a trapped oscillating dielectric





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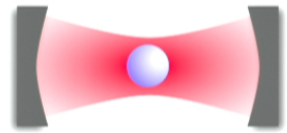

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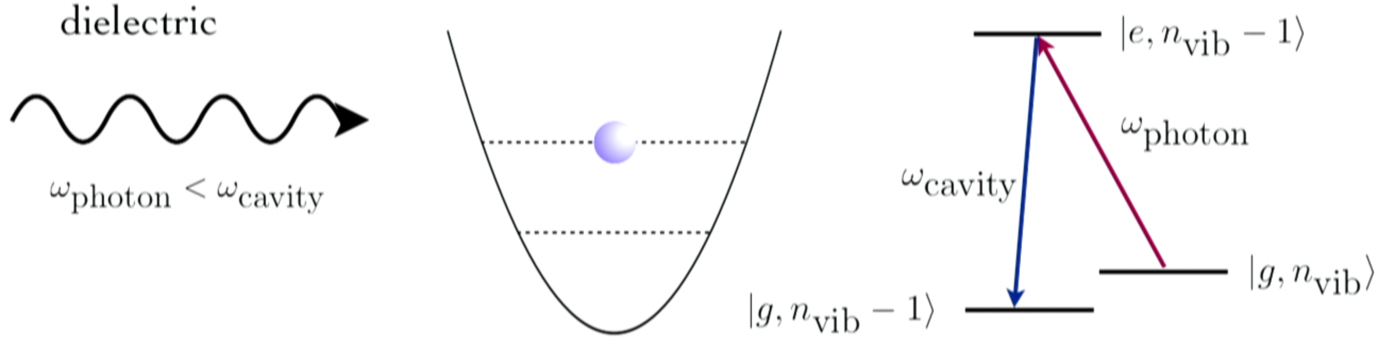
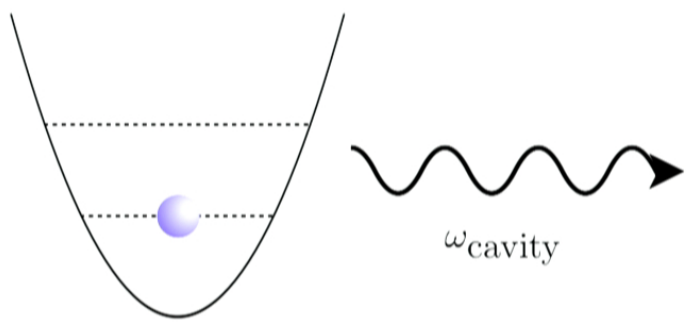




Photon is re-emitted at the frequency of the cavity tuned laser

Outline

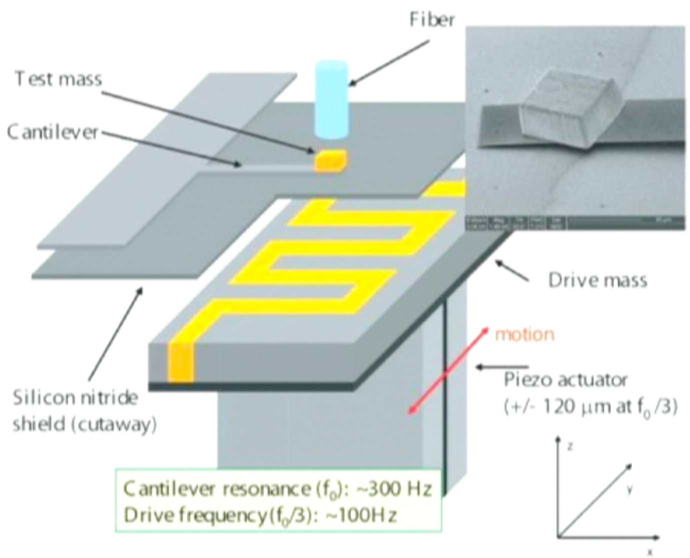
- Short Distance Tests of Gravity
- Gravitational Wave Detection
  - Sources of High-Frequency Gravitational Waves
- Future Prospects

Short Distance Tests of Gravity

Motivated by:

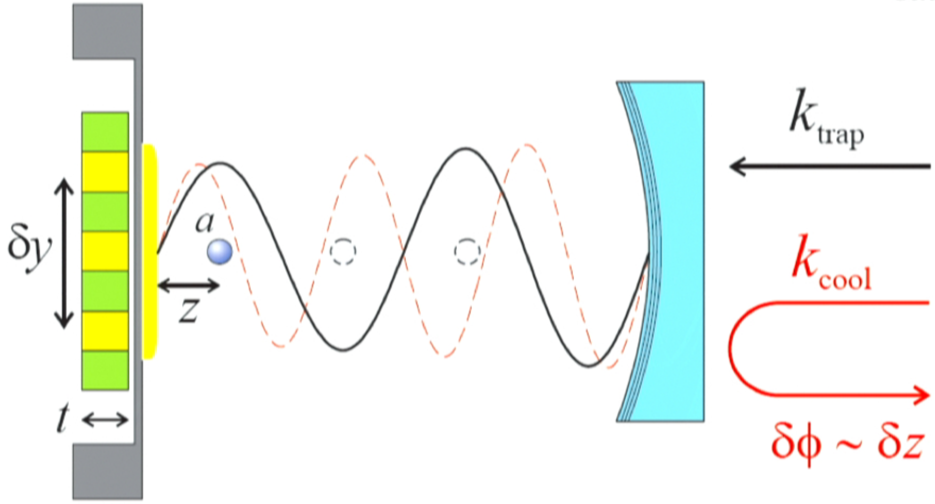
- Large Extra Dimensions
- Supersymmetry
- Moduli, Dilaton, etc.

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



Short Distance Tests of Gravity

Geraci et al. (2010)



- Resonant force detection
  - Oscillation frequency of the test mass matches the frequency of the trapped sensor
- Sensitive to forces as small as 10^{-21} N/(Hz)$^{1/2}$
  - Sensitivity proportional to $\sqrt{\frac{T_{CM}}{Q}}$

Short Distance Tests of Gravity

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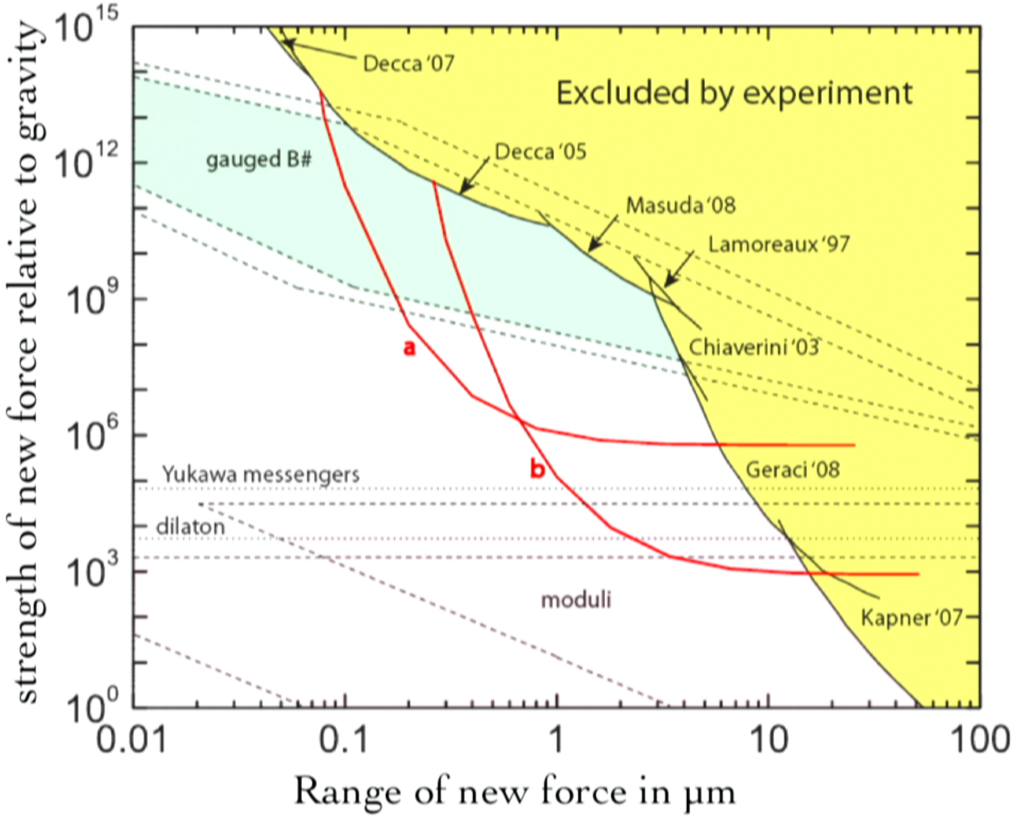
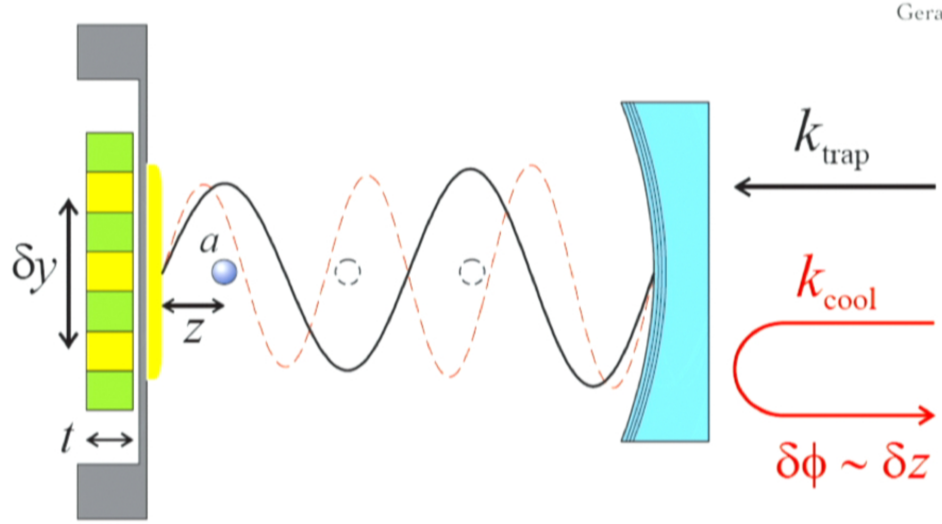


More than 10^6 improvement at <1 μm

Short Distance Tests of Gravity

Geraci et al. (2010)



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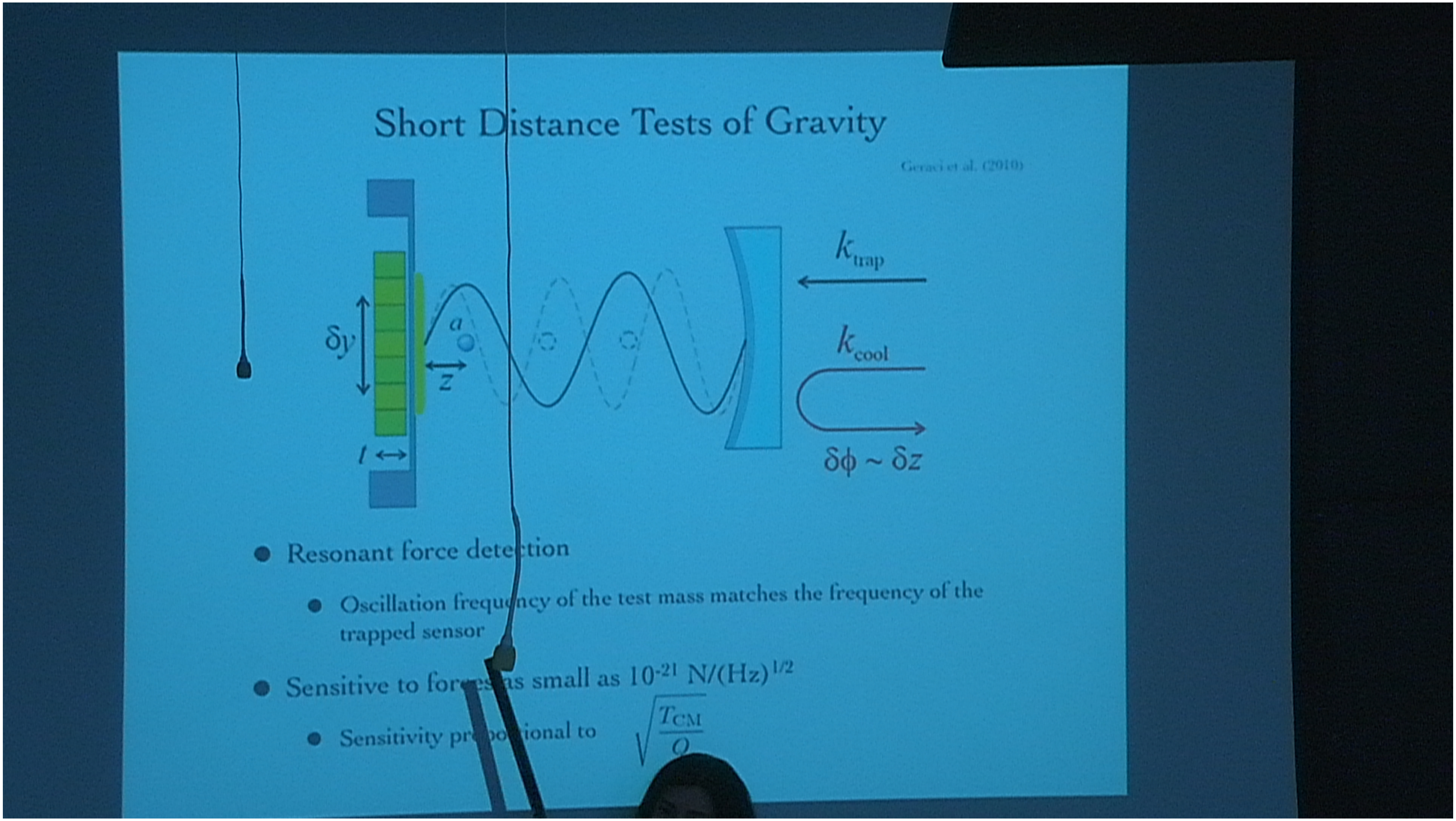
Short Distance Tests of Gravity
Geraci et al. (2010)
k_{trap}
k_{cool}
$\delta\phi \sim \delta z$
δy
a
z
t
Resonant force dete tion
Oscillation frequ ncy of the test mass matches the frequency of the trapped sensor
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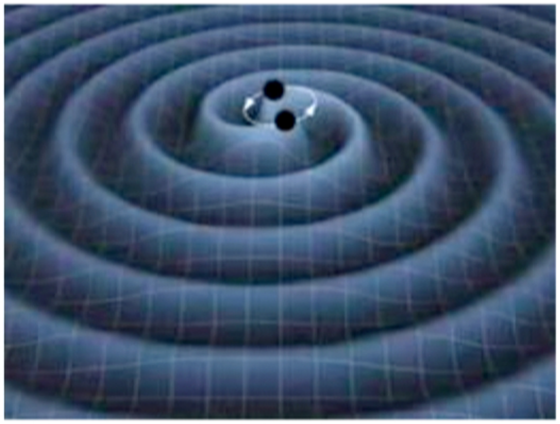
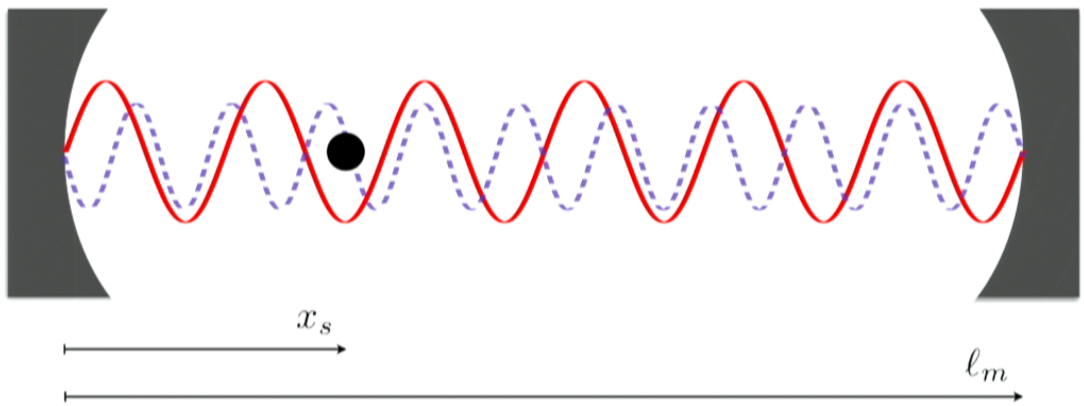
Gravitational Wave Detection



- Last piece of General Relativity
- Sources:
  - Inspirals of astrophysical objects
  - Inflation, Phase transitions, etc.

Gravitational Wave Detection

AA and Geraci (2012)

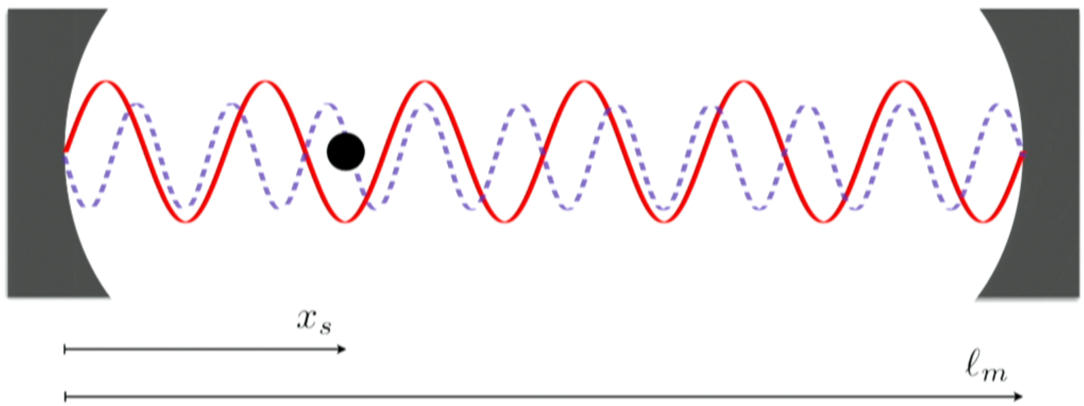


- Fused silica sphere (r = 150 nm) or disk (d=500 nm, r=75 μm) sensor in optical cavity of 10-100 m in size

- One laser to hold, one to cool and one to measure the position

Gravitational Wave Detection

AA and Geraci (2012)



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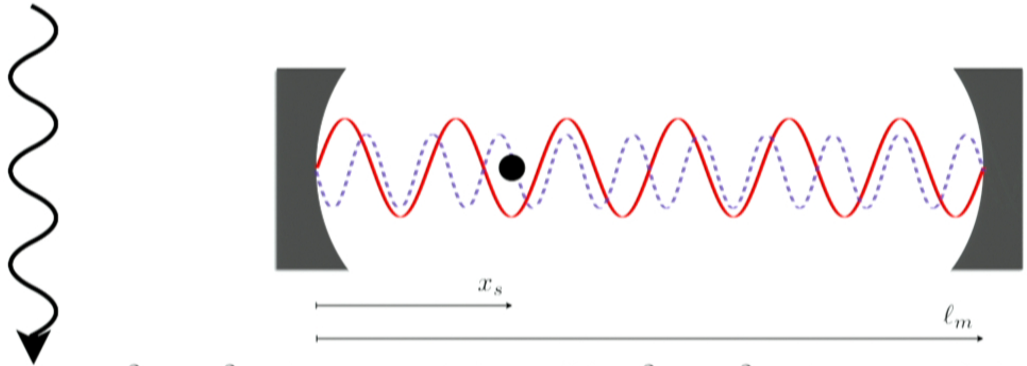
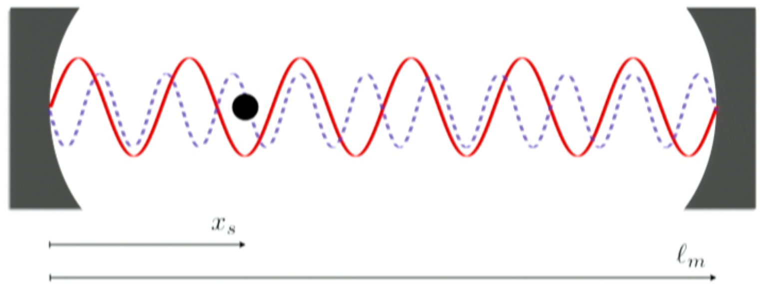


$$ds^2 = dt^2 - (1 + h\cos(\omega(t-y)))dx^2 - dy^2 - (1 - h\cos(\omega(t-y)))dz^2$$

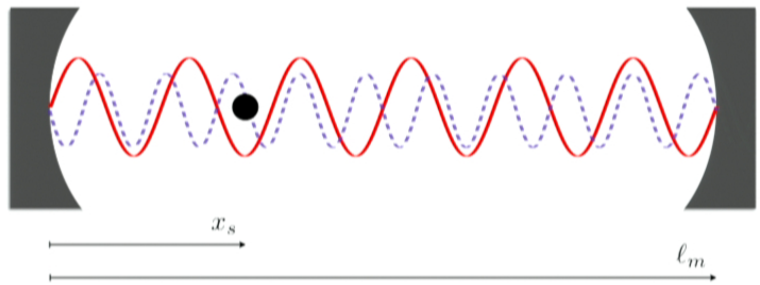
Gravitational Wave Detection



Gravitational wave changes the physical distance between masses

$$L = L_0 \, (1 + h \cos \omega t)$$

Gravitational Wave Detection

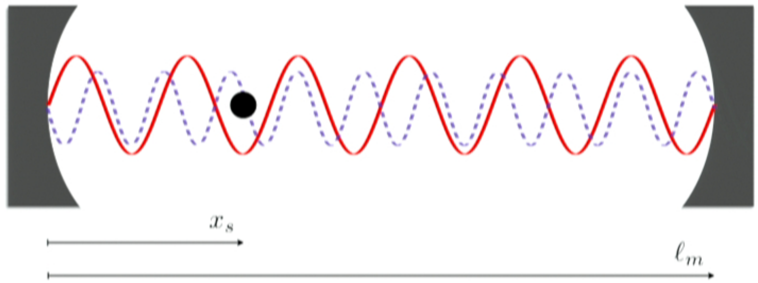


Gravitational wave changes the physical distance between masses
$L=L_0\,(1+h\cos\omega t)$

- Changes the physical position of the laser antinode:

$$\delta X_{\min} = \frac{1}{2}\ell_m h$$

Gravitational Wave Detection



Gravitational wave changes the physical distance between masses

$L = L_0 (1 + h \cos\omega t)$

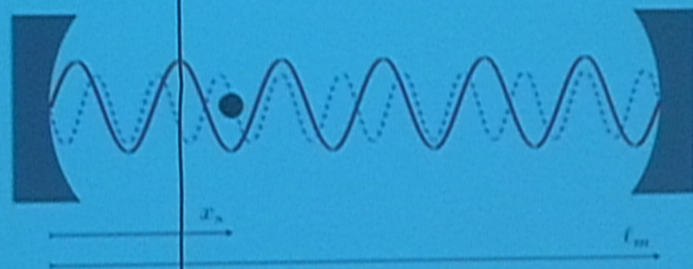
- Changes the physical position of the laser antinode:

$$\delta X_{\min} = \frac{1}{2}\ell_m h$$

- Changes the physical distance between the sensor and the mirror:

$$\delta X_{\mathrm{S}} = \frac{1}{2}x_s h$$

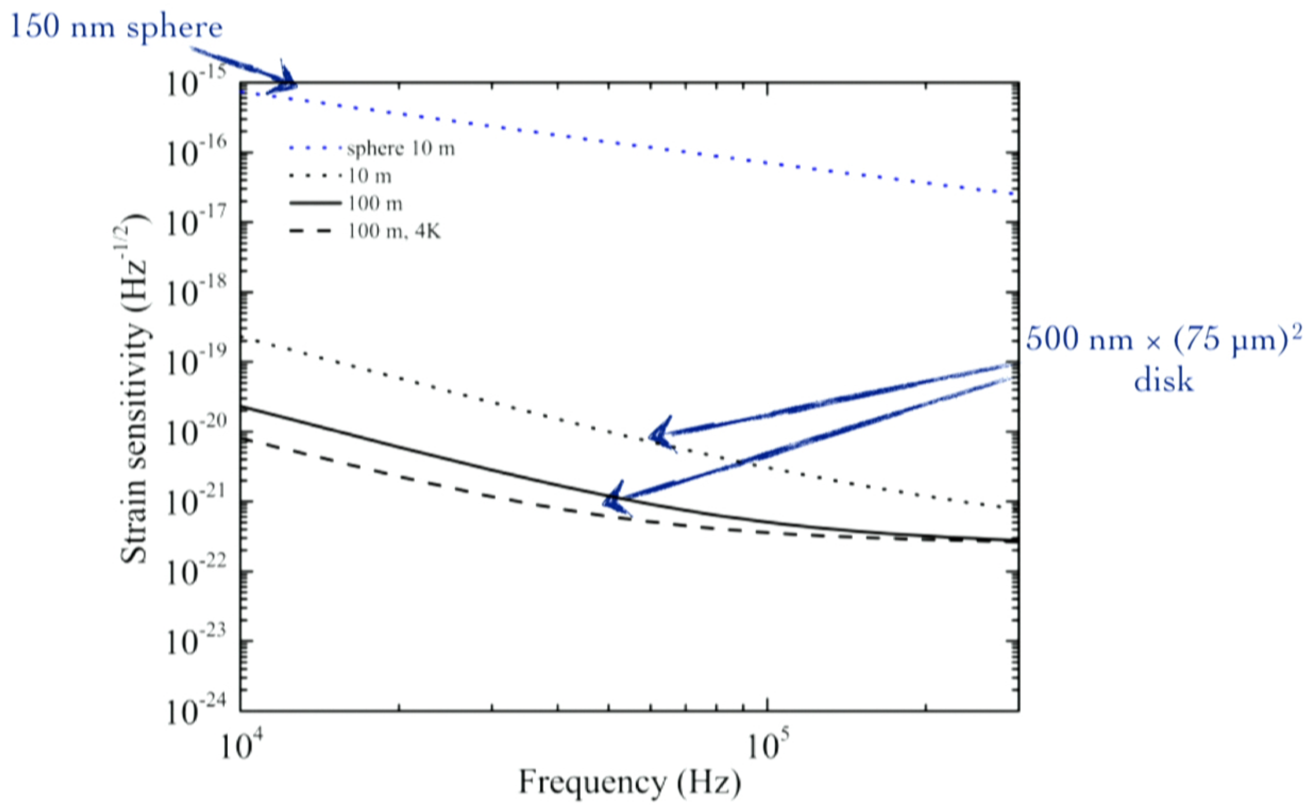
Gravitational Wave Detection



$$\Delta X = \frac{1}{2}(x_s - \ell_m)h$$

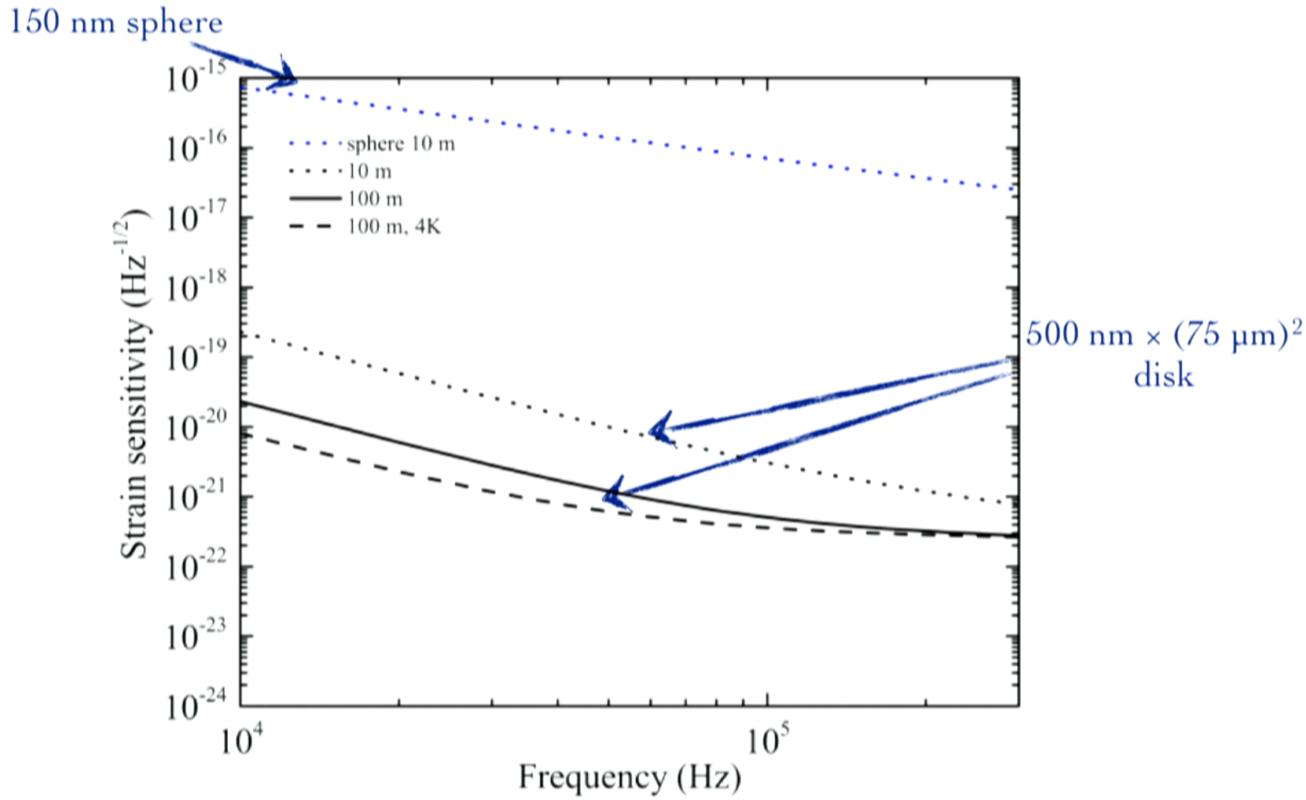
- Laser intensity changes resonant frequency of the sensor: Tunable resonant GW detector
- For a 100 m cavity h ~10^{-22} $Hz^{-1/2}$ sensitivity and increases linearly with the cavity size
- Main background: Thermal motion in the trap

GW sensitivity



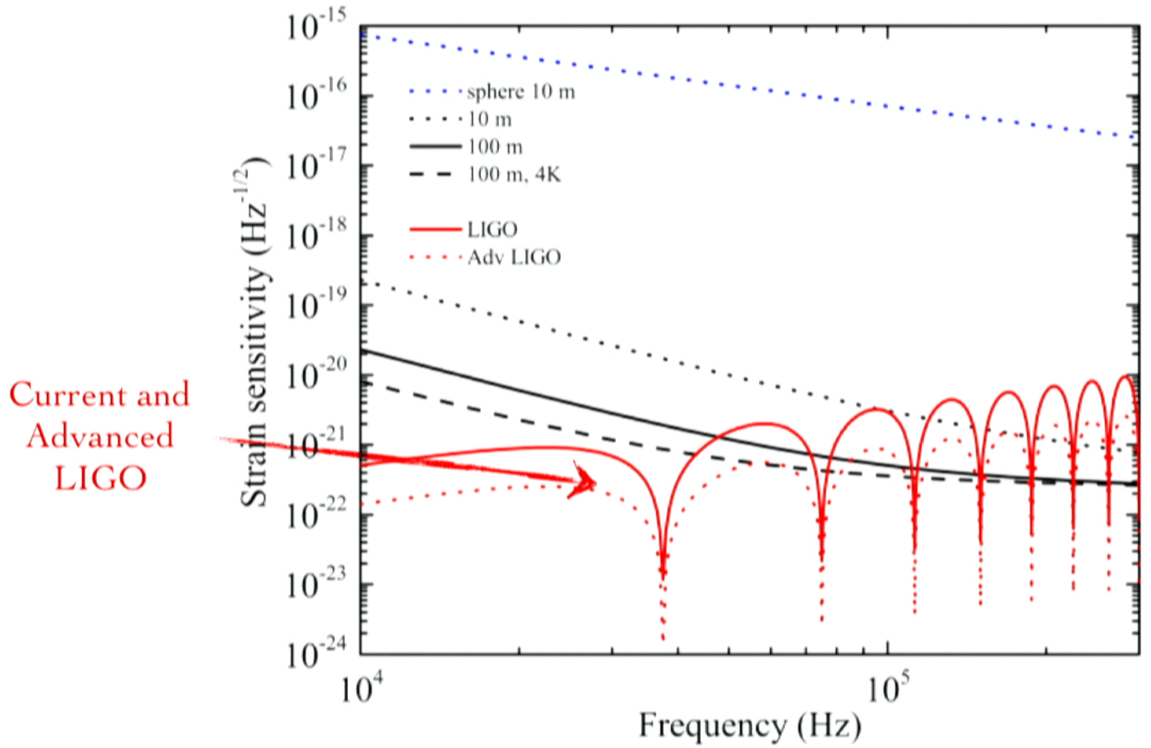
Radical change in sensitivity between the two geometries due to difference in mass and in light scattering properties

GW sensitivity



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

GW sensitivity compared to LIGO



GW sensitivity compared to LIGO

	Resonant sensors in optical cavities	Laser interferometry with optical cavities
Main sources of noise at high frequencies	Thermal motion of sensor in the trap	Laser shot noise
Displacement sensitivity required to detect $h \sim 10^{-22}$ $Hz^{-1/2}$	10^{-15} m/(Hz)$^{1/2}$	10^{-18} m/(Hz)$^{1/2}$
Internal thermal noise	Sensor behaves as a refractive object no surface effects	Mirror reflects light surface thermal motion important

GW Sources in the High Frequency Regime

- Astrophysical Sources:

  Natural upper bound on GW frequency

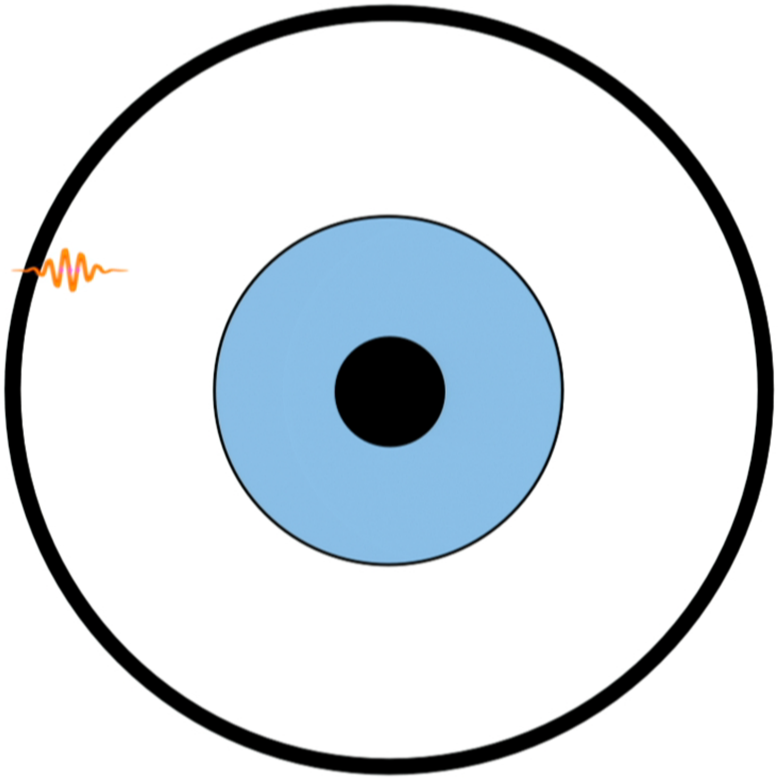
$$\frac{1}{\text{Minimum Black Hole Size}} \sim 30 \text{ kHz}$$

- Beyond-the-Standard Model Sources: AA and Dubovsky (2010)

  Black Hole Super-radiance

Black Hole Bomb

Press & Teukolsky 1972



Photons reflected back and forth from the black hole
and through the ergoregion

Gravitational Atom in the Sky

Away from the Black Hole: Newtonian Potential

The gravitational Hydrogen Atom

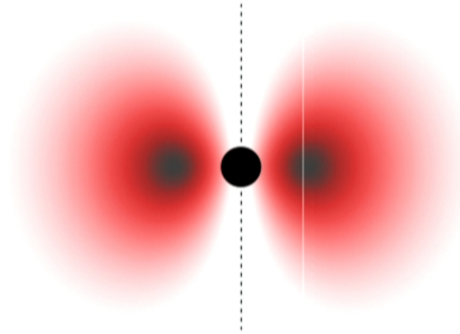
$$\alpha_{EM} = \frac{e^2}{4\pi} \quad \longrightarrow \quad \alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$$

$$E_{\rm binding} = -\frac{\alpha_{EM}^2 m_e}{2n^2} \quad \longrightarrow \quad E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$$

fermions $\longrightarrow$ bosons

Occupation number

$1 \longrightarrow 10^{75}$



Superradiance Parametrics

Superradiance Condition

$$\omega_{\rm axion} < m\,\Omega_+$$

$$\mu_a + E_{\rm binding} < m\frac{a}{2R_g(1+\sqrt{1-a^2})}$$

m : magnetic quantum number

a : BH spin, between 0 and 1

Superradiance Rate

$\tau_{sr} \sim 0.6 \times 10^7\ R_g$ for $R_g\,\mu_a \sim 0.4$

When $R_g\,\mu_a >> 1$,

$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g\,\mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

The Strong CP Problem

$$L_{\mathrm{SM}} \supset \frac{g_s^2}{32\pi^2}\theta_{\mathrm{QCD}} G^a \tilde{G}^a$$

Non-zero electric dipole moment for the neutron

Experimental bound: $\theta_{\mathrm{QCD}} < 10^{-10}$

Solution:

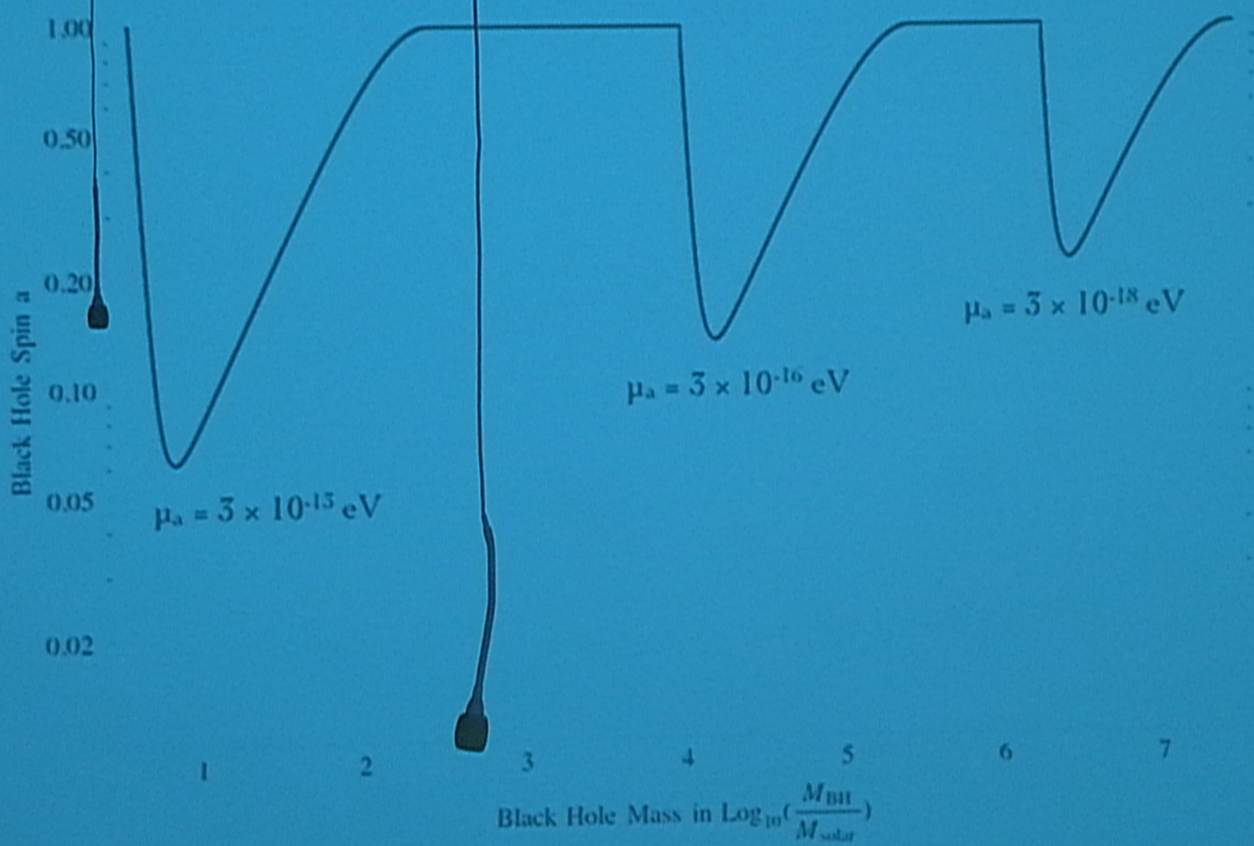
θ_{QCD} is a dynamical field, an axion

Axion mass from QCD:

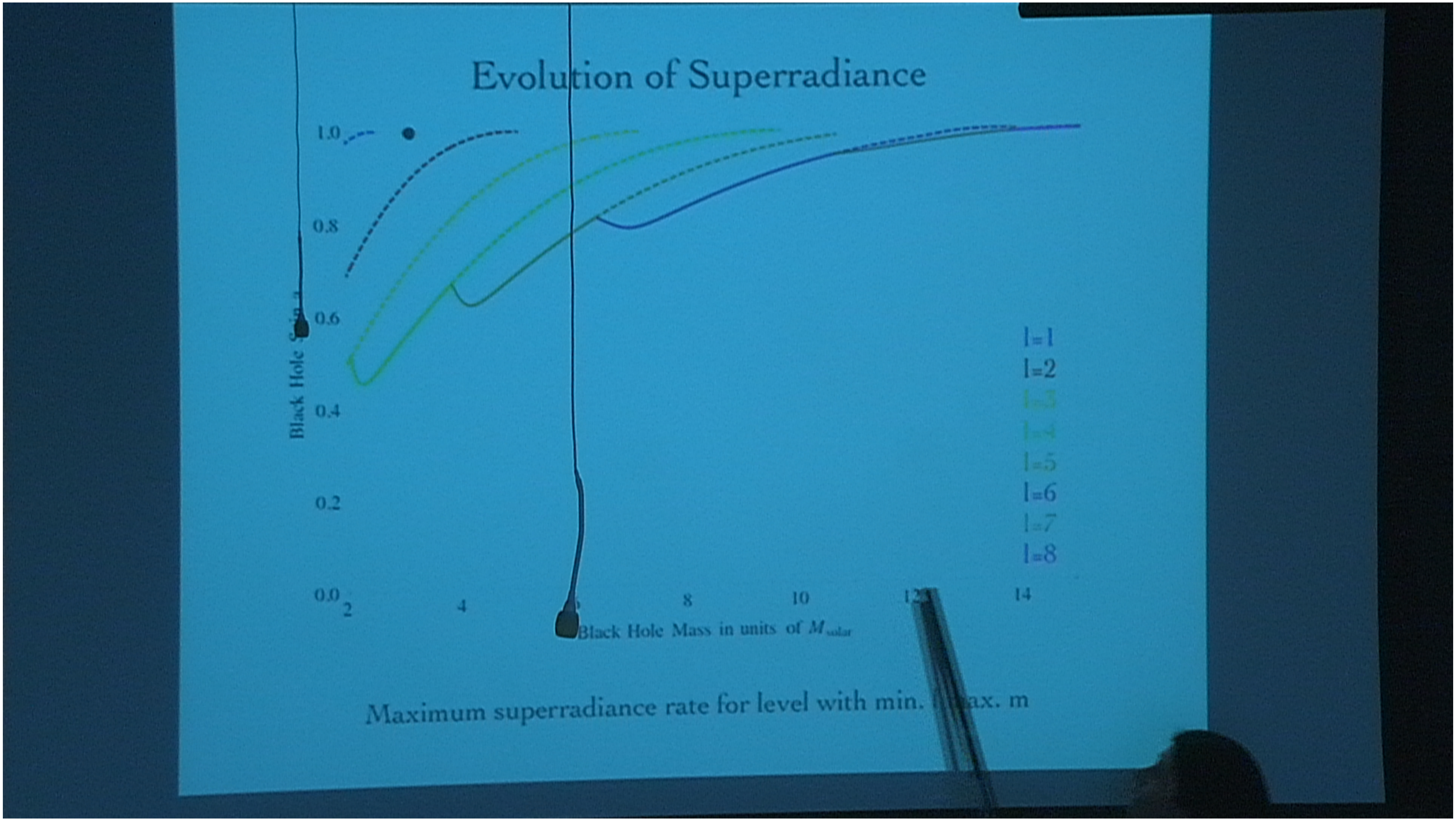
$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

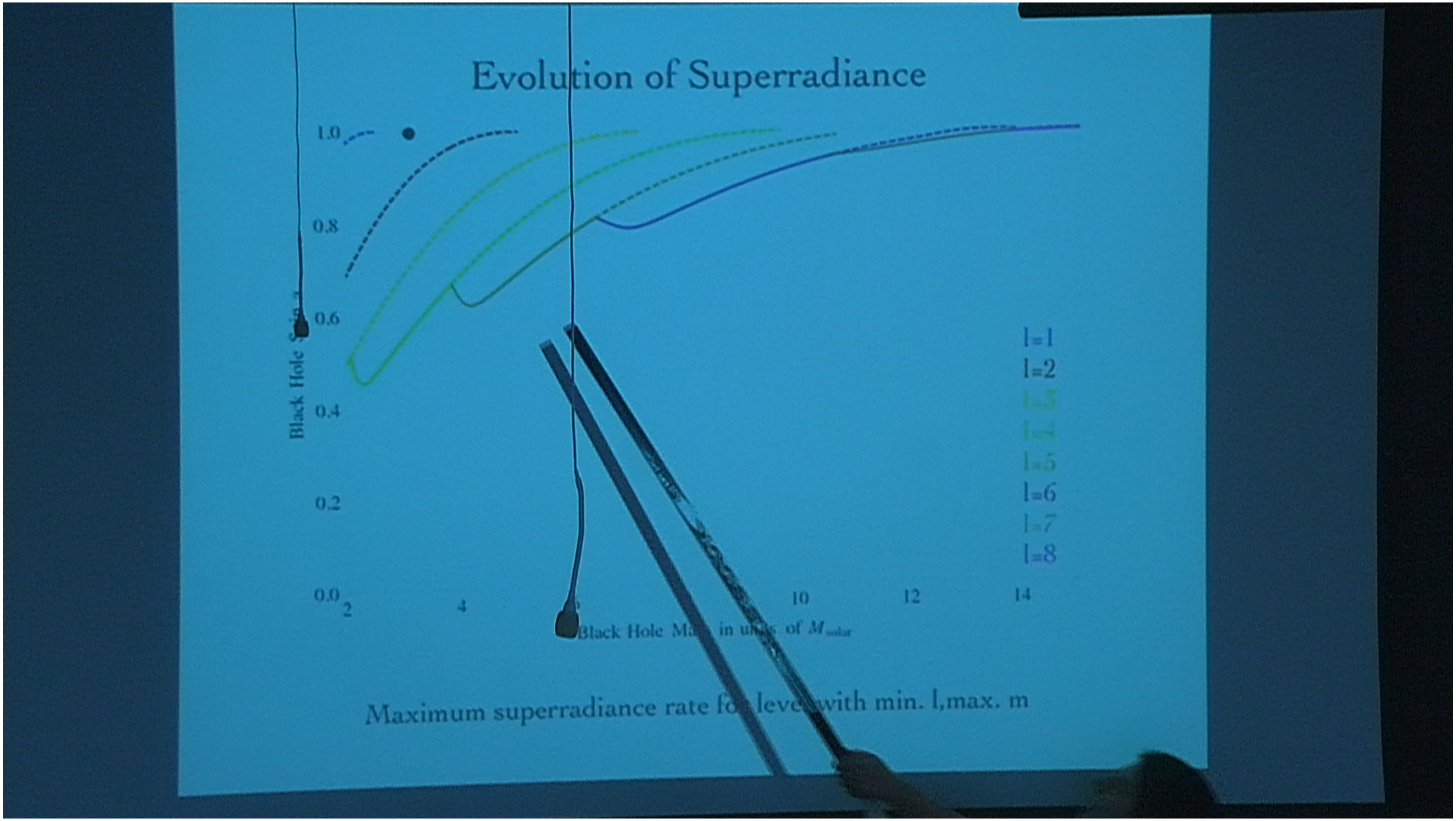
$\mathrm{f_a}$: axion decay constant

Signals from Superradiance



Gaps in the mass vs spin plot


Evolution of Superradiance
1.0
0.8
0.6
0.4
0.2
0.0
Black Hole
2
4
8
10
14
Black Hole Mass in units of M_{solar}
l=1
l=2
l=6
l=8
Maximum superradiance rate for level with min.


Evolution of Superradiance
1.0
0.8
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2
4
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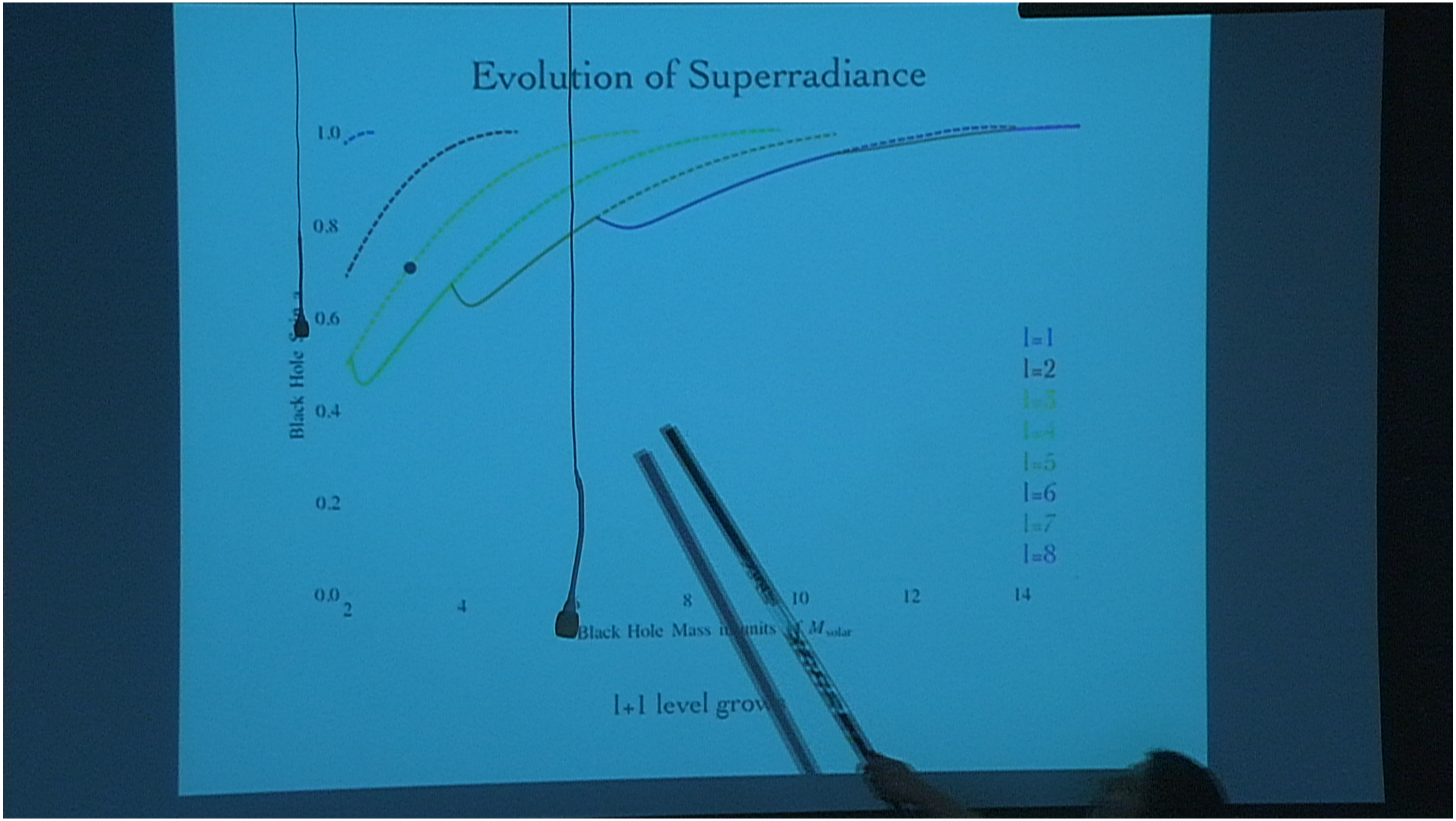
12
14
Black Hole Mass in units of M_{solar}
l=1
l=2
l=6
l=8
Maximum superradiance rate for level with min. l,max. m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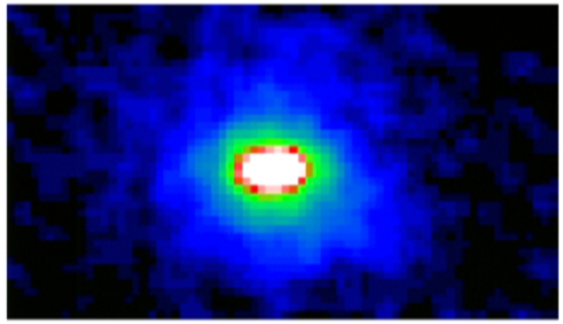
Black Hole Mass
l=1
l=2
l=3
l=4
l=5
l=6
l=7
l=8
l+1 level grow

Bose Einstein Condensate in a Trap

The effect of attractive self-interactions

$E_{\text{trap}} \sim E_{\text{inter.}}$

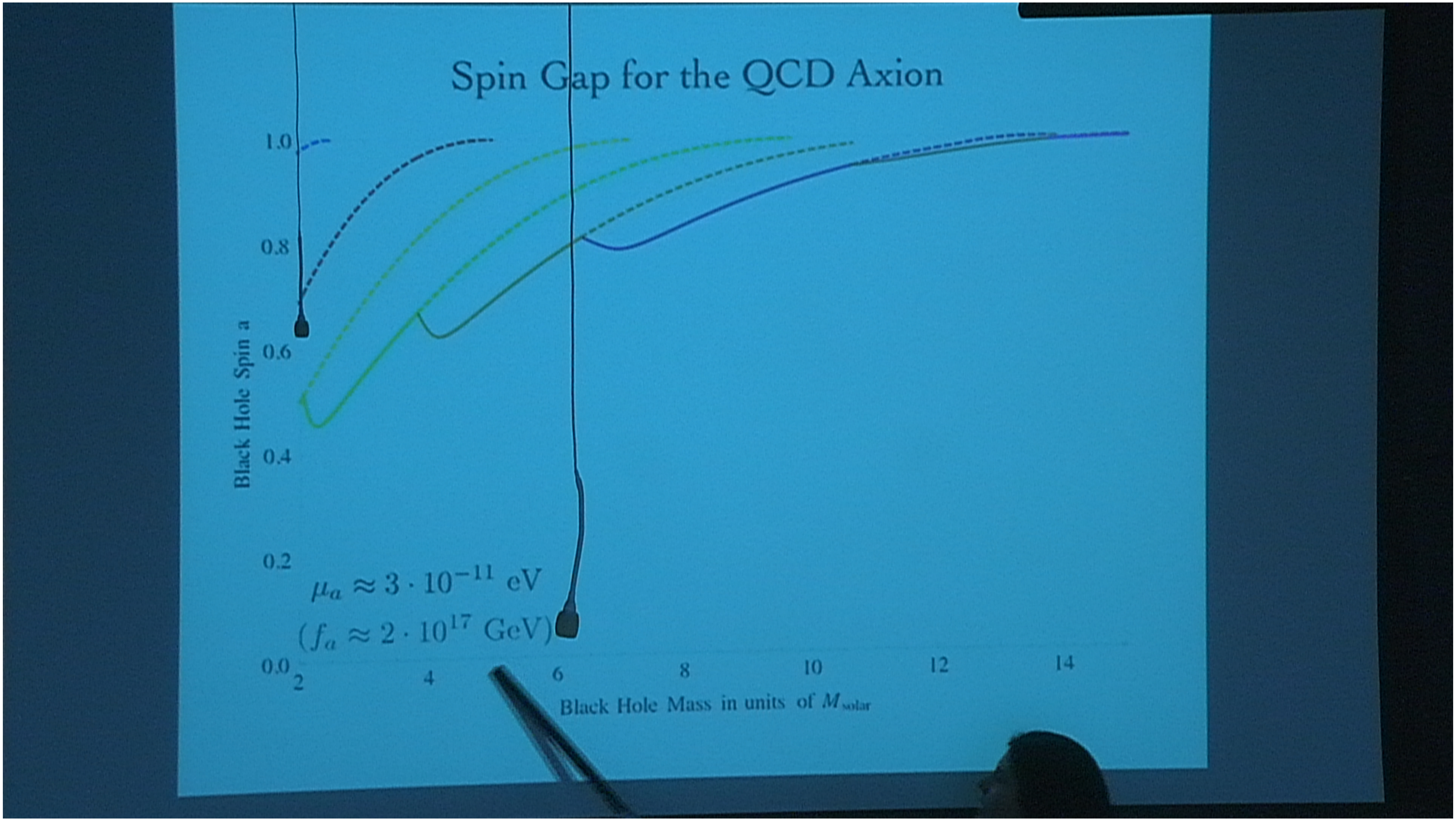


The Bosenova

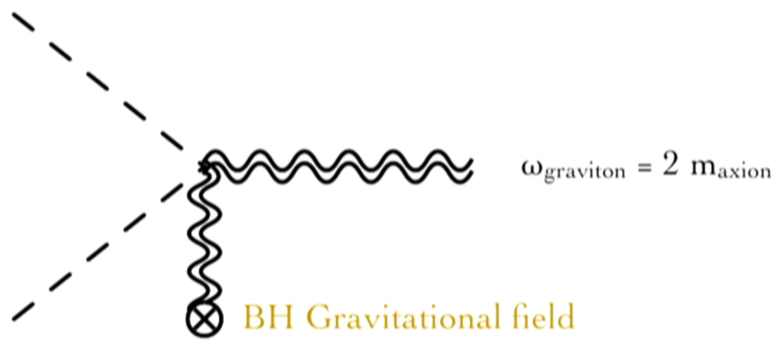
Happens when $$\frac{M_{\text{cloud}}}{M_{\text{BH}}} \sim \frac{f_a^2}{M_{\text{Planck}}^2}\frac{l^4}{\alpha^2} \sim 10^{-4}$$

Repeats 10-100 times

Wait 10^3-10^4 τ_{sr} to stop superradiating


Spin Gap for the QCD Axion
Black Hole Spin a
1.0
0.8
0.6
0.4
0.2
0.0
$\mu_a \approx 3 \cdot 10^{-11}$ eV
($f_a \approx 2 \cdot 10^{17}$ GeV)
2
4
6
8
10
12
14
Black Hole Mass in units of M_{solar}

Signals from annihilations

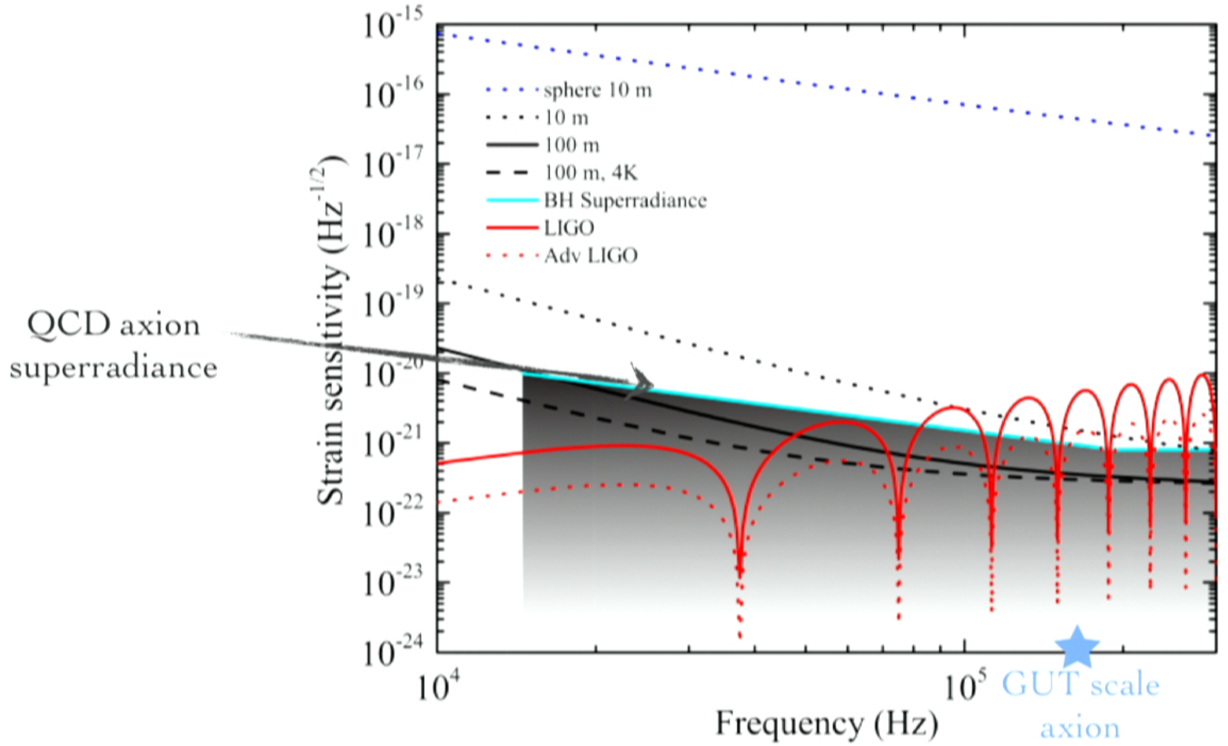


$$f = 145\ \mathrm{kHz}\left(\frac{2\times 10^{16}\ \mathrm{GeV}}{f_a}\right)$$

$$h \sim 10^{-19}\left(\frac{\alpha}{\ell}\right)\epsilon\left(\frac{10\ \mathrm{kpc}}{r}\right)\left(\frac{M_{BH}}{2\times M_\odot}\right)$$

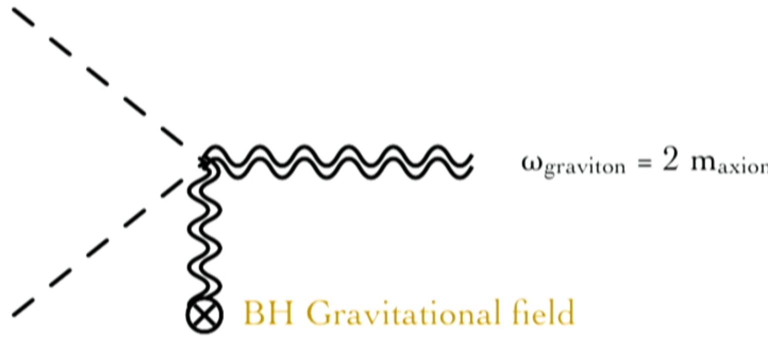
signal duration > years and $\varepsilon \sim 10^{-3}$

GWs from the QCD axion at high frequencies



Distance to the source: 10 kpc

Signals from annihilations



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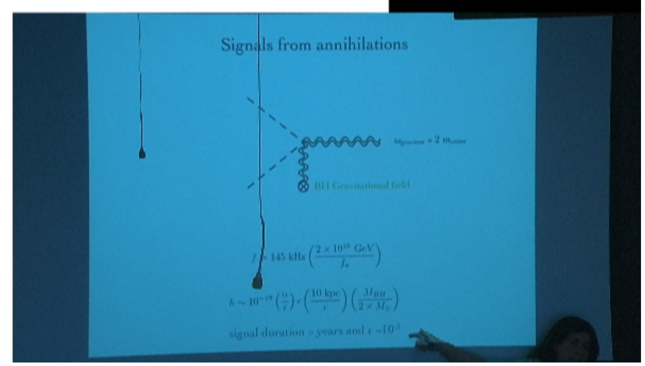

Prospects of GW detection with optically trapped sensors

- Sensitivity better than 10^{-21} $1/\mathrm{Hz}^{1/2}$ above ~30 kHz
- Relatively small size enables GW array antenna design
- Possibility to use full LIGO arms: 40 times more sensitive
- Improved GW sensitivity in new regime for GW astronomy

Conclusions

- Optical trapping and cooling provides new precision tool
    - Short distance tests of gravity
    - GW detection in the high frequency regime
- Quantum Mechanics pushed to a new regime