

Title: Fundamental Physics with Optically Levitated Dielectric Objects

Date: Jun 17, 2013 11:00 AM

URL: <http://pirsa.org/13060013>

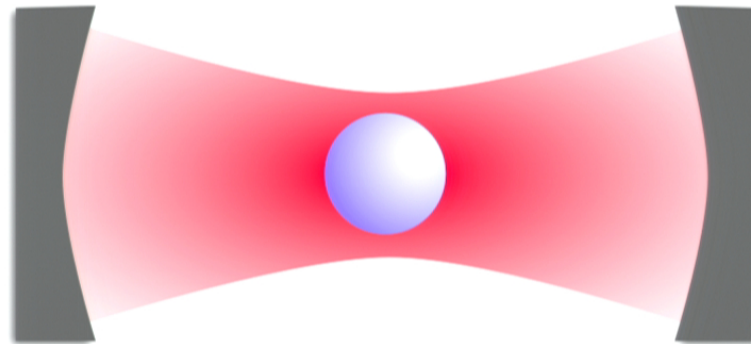
Abstract: In the past few years, optical cooling and manipulating of macroscopic objects, such as micro-mirrors and cantilevers has developed into an active field of research. In mechanical systems, the oscillator is attached to its suspension, a thermal contact that limits the motion isolation. On the 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

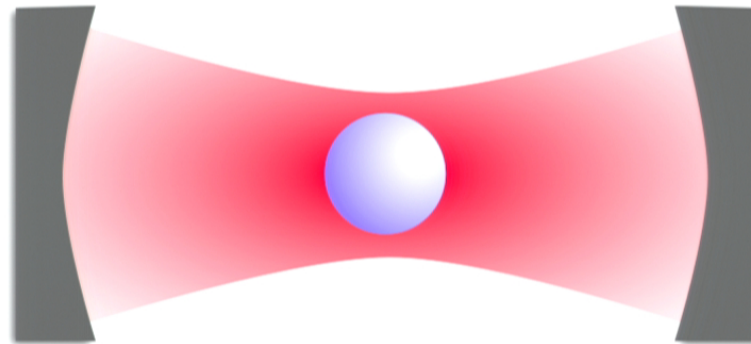
Ashkin et al. (1970,1971,1976)



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

Optical Trapping of Dielectrics

Ashkin et al. (1970,1971,1976)



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

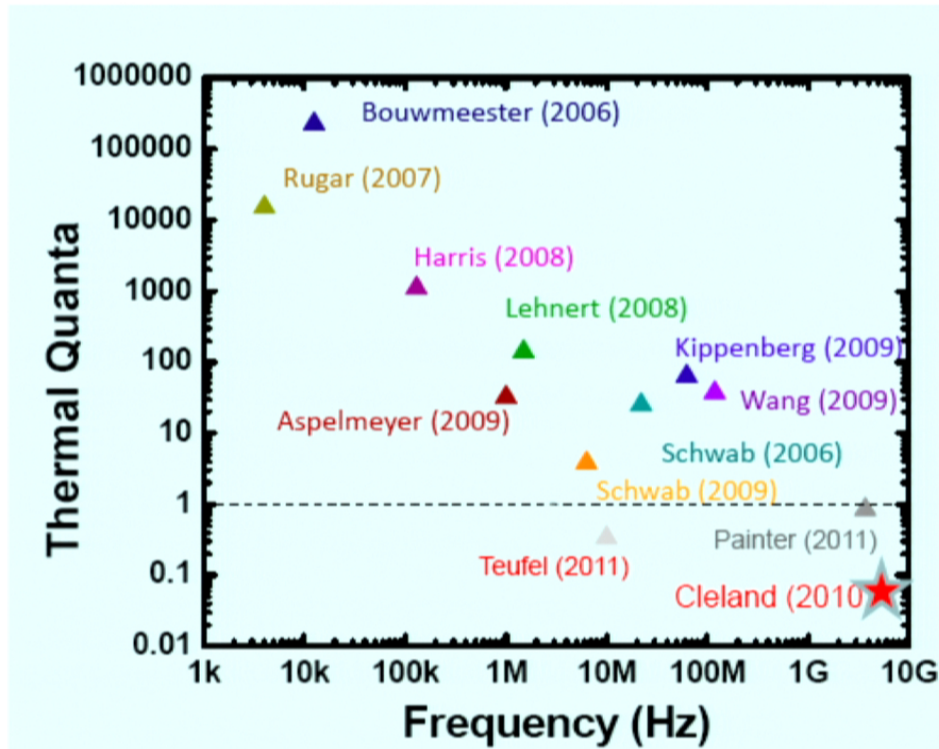
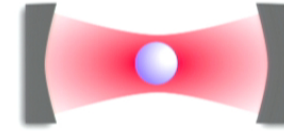
- Quality factor, $\omega_{\text{mech}} / \Gamma_{\text{loss}}$, larger than 10^{12} even at room temperature
- Internal modes decoupled from CM for small objects
- CM motion controlled by the intensity of light

Optical Trapping Applications

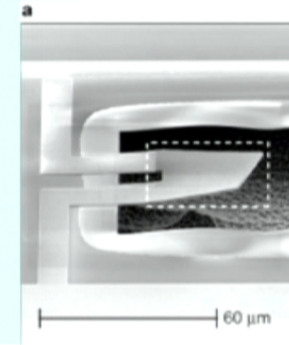
- Atom Interferometry (Nobel Prize 1997, 2001, 2005, 2012)
- Biology
- Quantum Computing

Towards the Quantum Regime

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

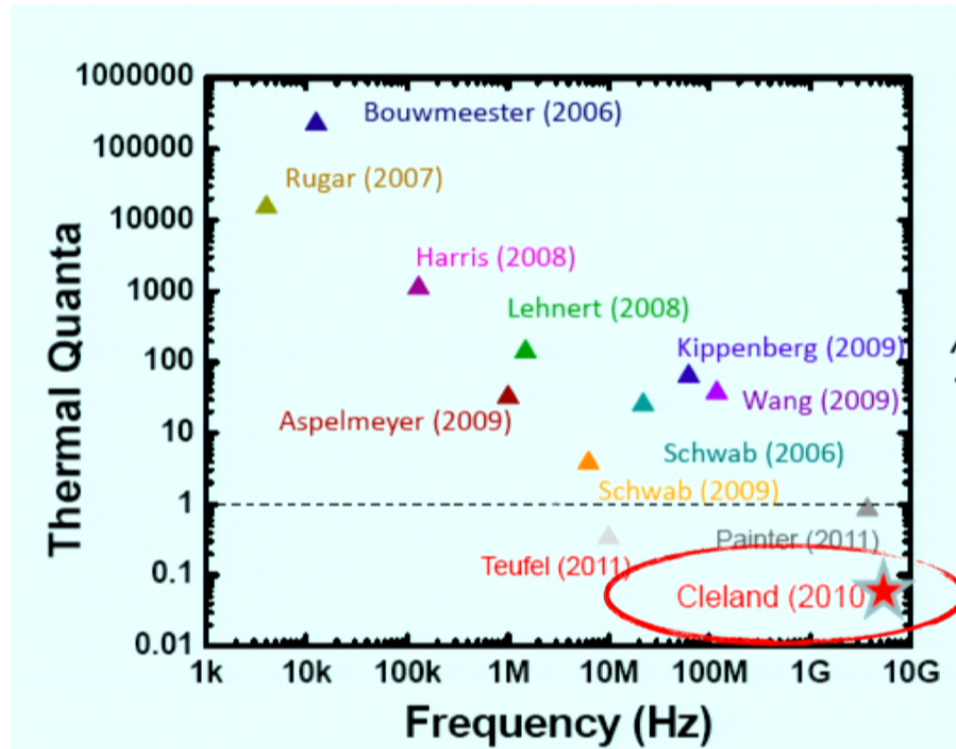
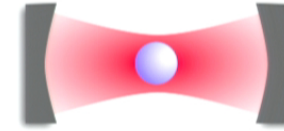


A. D. O'Connell et.al.
10.1038/nature08967

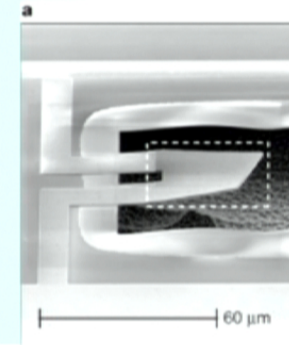


Towards the Quantum Regime

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



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

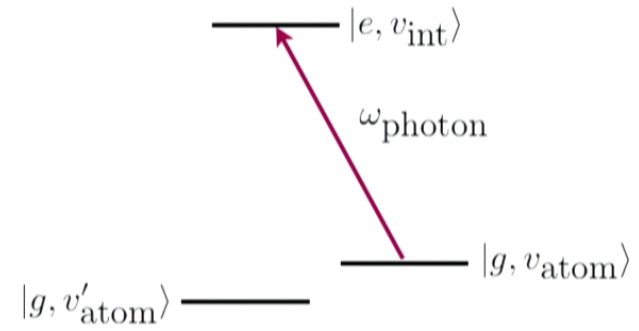


10^9 atoms in a quantum superposition of states

Optical Cooling

Doppler cooling

For an atom

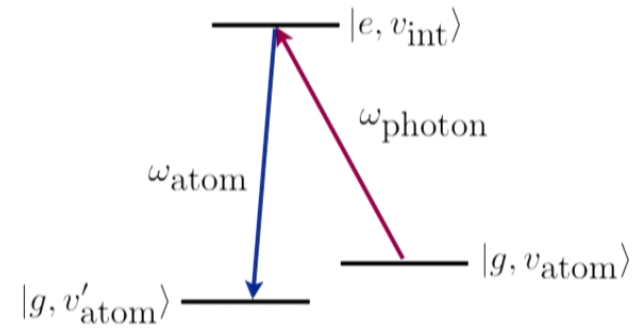
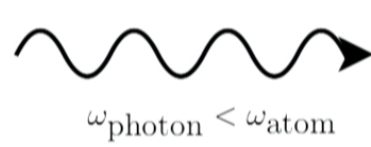


$$v'_{\text{atom}} < v_{\text{atom}}$$

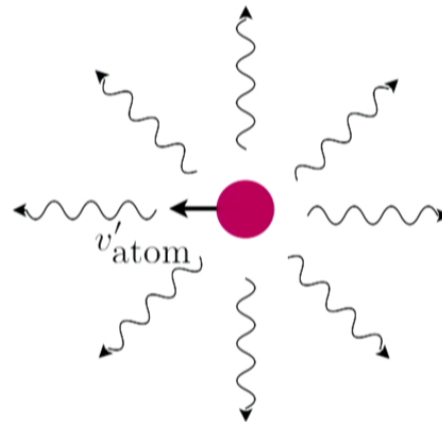
Optical Cooling

Doppler cooling

For an atom



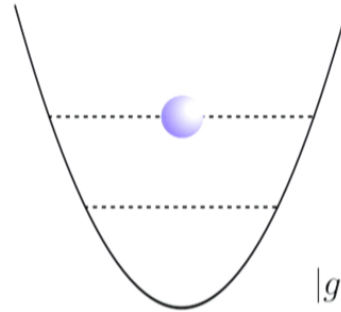
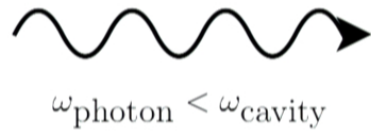
$v'_{\text{atom}} < v_{\text{atom}}$



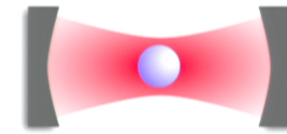
Spontaneous emission

Optical Cavity Cooling

For a trapped oscillating
dielectric



$|g, n_{\text{vib}} - 1\rangle$



$|e, n_{\text{vib}} - 1\rangle$

ω_{photon}

$|g, n_{\text{vib}}\rangle$

Outline

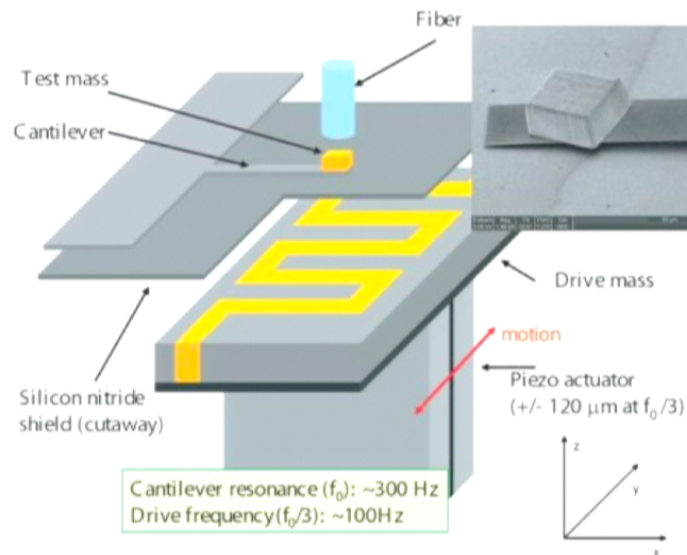
- Short Distance Tests of Gravity
- Gravitational Wave Detection
 - Sources of High-Frequency Gravitational Waves
- Future Prospects

Short Distance Tests of Gravity

Motivated by:

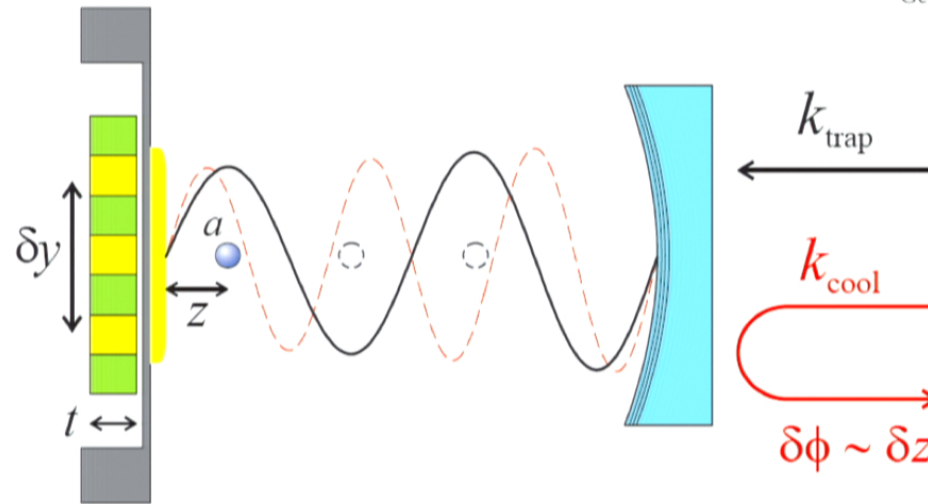
- Large Extra Dimensions
- Supersymmetry
- Moduli, Dilaton, etc.

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



Short Distance Tests of Gravity

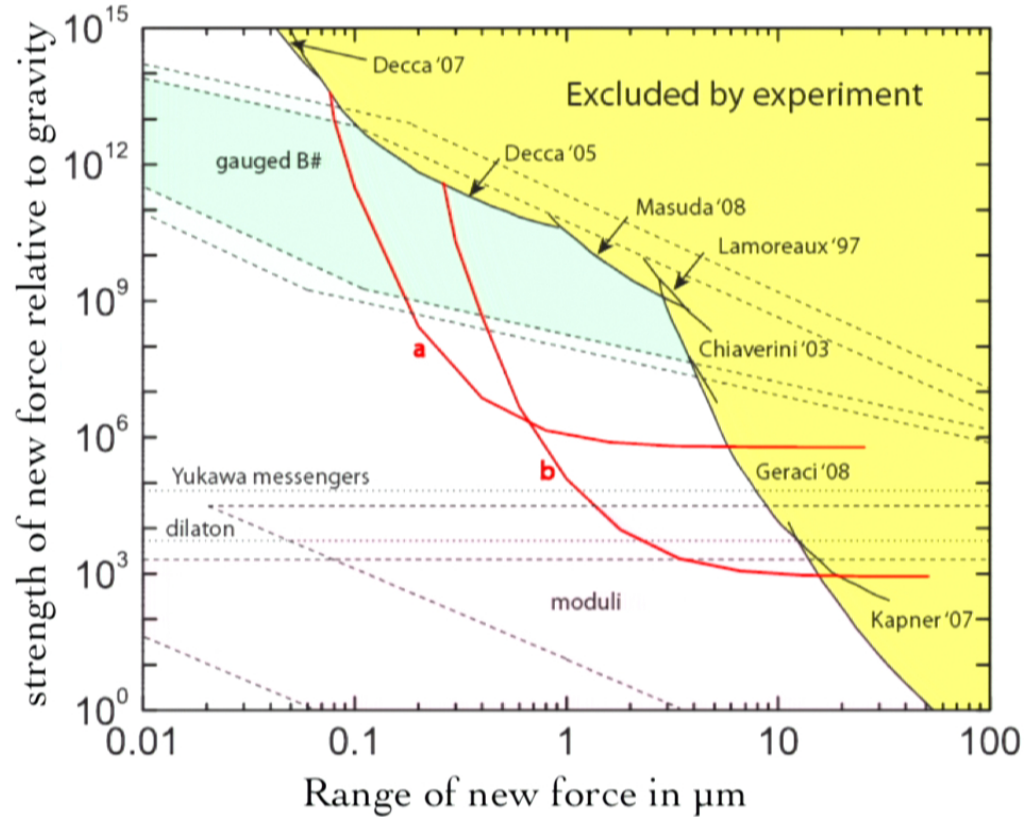
Geraci et al. (2010)



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

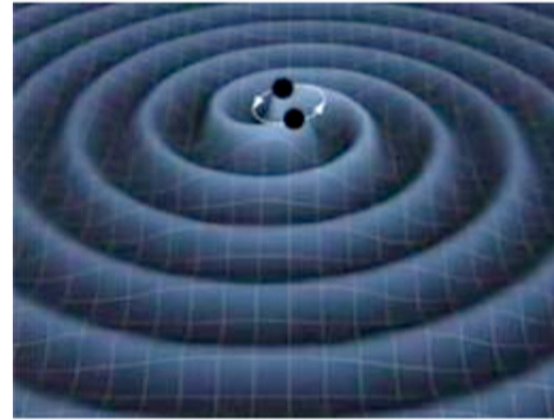
Short Distance Tests of Gravity

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



More than 10^6 improvement at $< 1 \mu\text{m}$

Gravitational Wave Detection



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

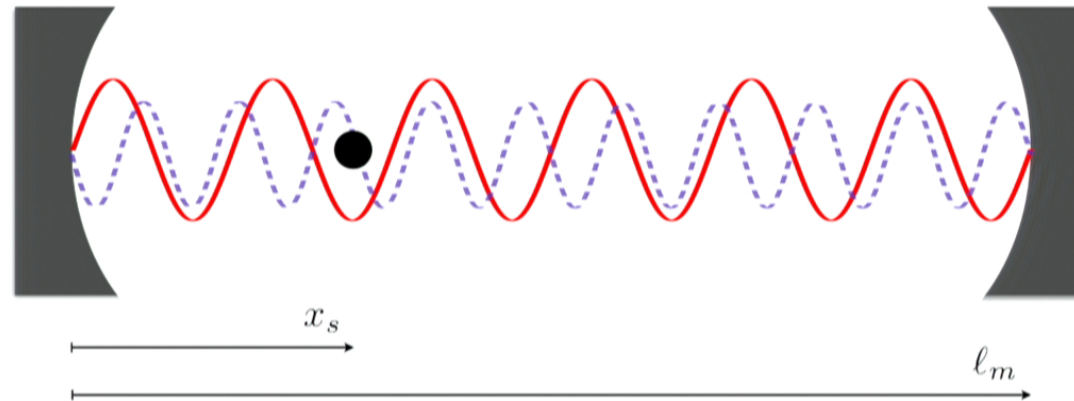
Gravitational Wave Detection



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

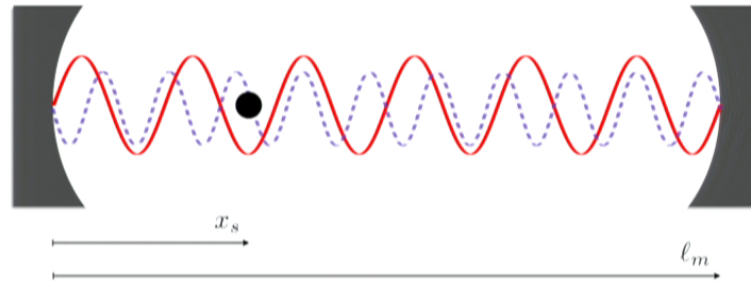
Gravitational Wave Detection

AA and Geraci (2012)



- Fused silica sphere ($r = 150 \text{ nm}$) or disk ($d=500 \text{ nm}$, $r=75 \text{ }\mu\text{m}$) 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



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

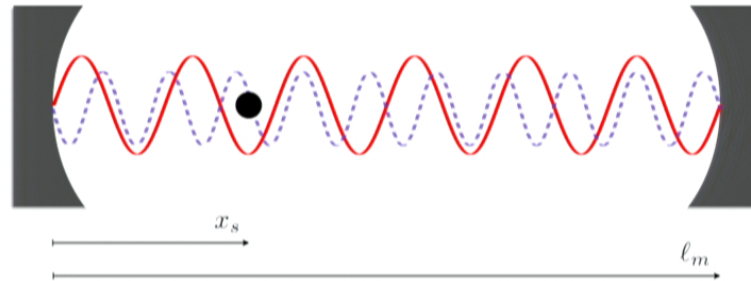
- Changes the physical position of the laser antinode:

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

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

$$\delta X_s = \frac{1}{2} x_s h$$

Gravitational Wave Detection



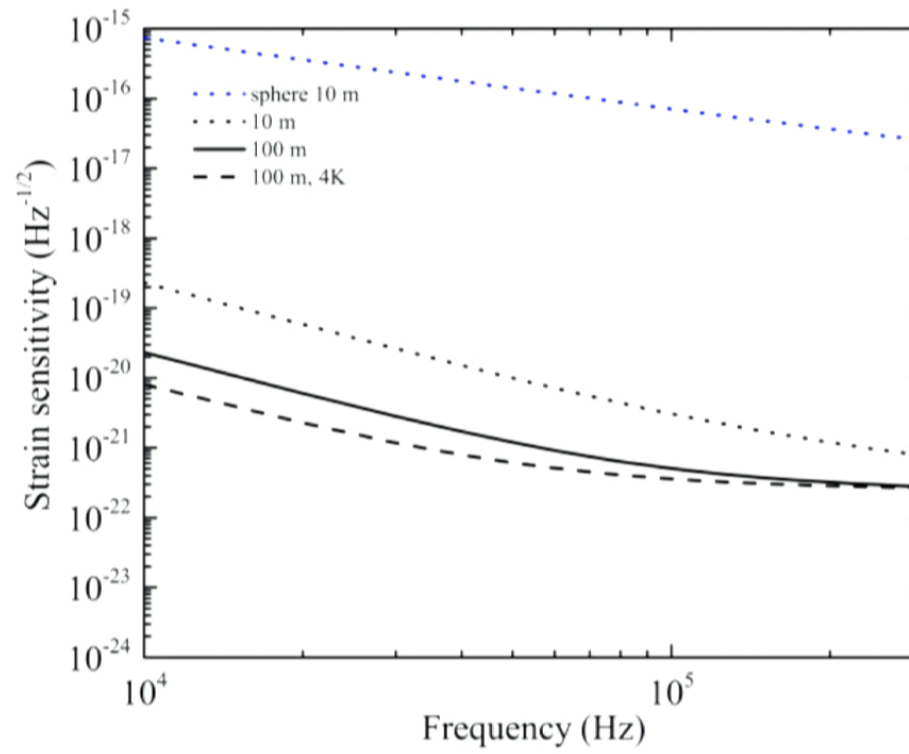
$$\Delta X = \frac{1}{2}(x_s - \ell_m)h$$

- Laser intensity changes resonant frequency of the sensor:
Tunable resonant GW detector

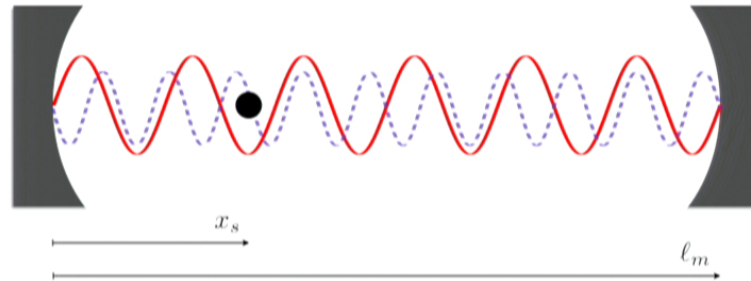
- $$h = \frac{1}{\omega_{GW}L} \sqrt{\frac{4T}{\omega_{GW}mQ}} \sim \frac{10^{-22}}{\sqrt{\text{Hz}}} \quad \text{for a disk in a 100 m cavity}$$

- **Main background:** Thermal motion in the trap

GW sensitivity



Gravitational Wave Detection



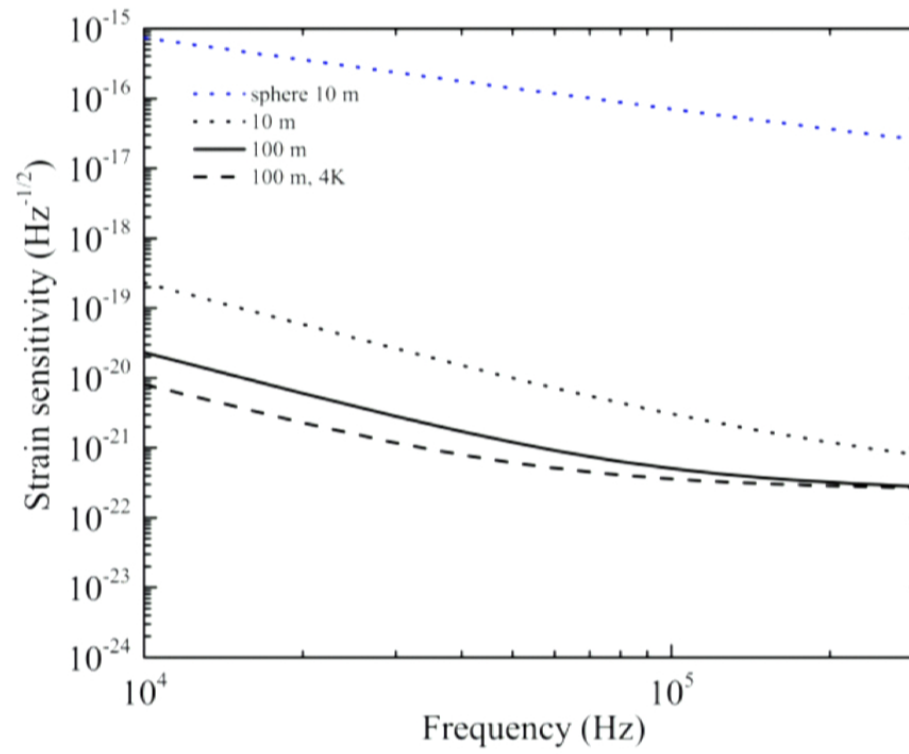
$$\Delta X = \frac{1}{2}(x_s - \ell_m)h$$

- Laser intensity changes resonant frequency of the sensor:
Tunable resonant GW detector

- $$h = \frac{1}{\omega_{GW}L} \sqrt{\frac{4T}{\omega_{GW}mQ}} \sim \frac{10^{-22}}{\sqrt{\text{Hz}}} \quad \text{for a disk in a 100 m cavity}$$

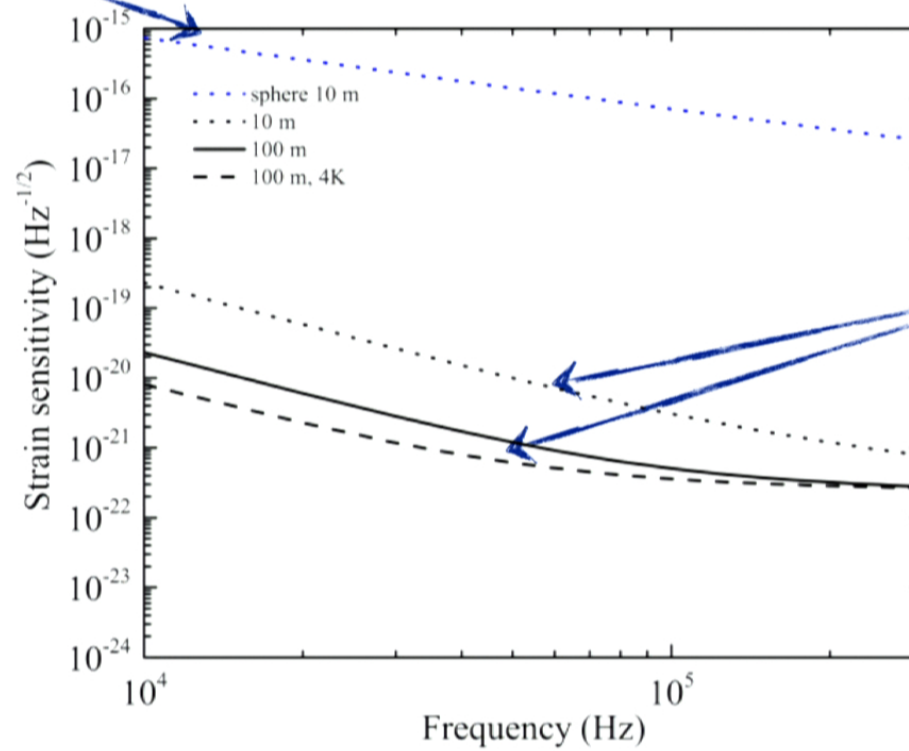
- **Main background:** Thermal motion in the trap

GW sensitivity



GW sensitivity

150 nm sphere

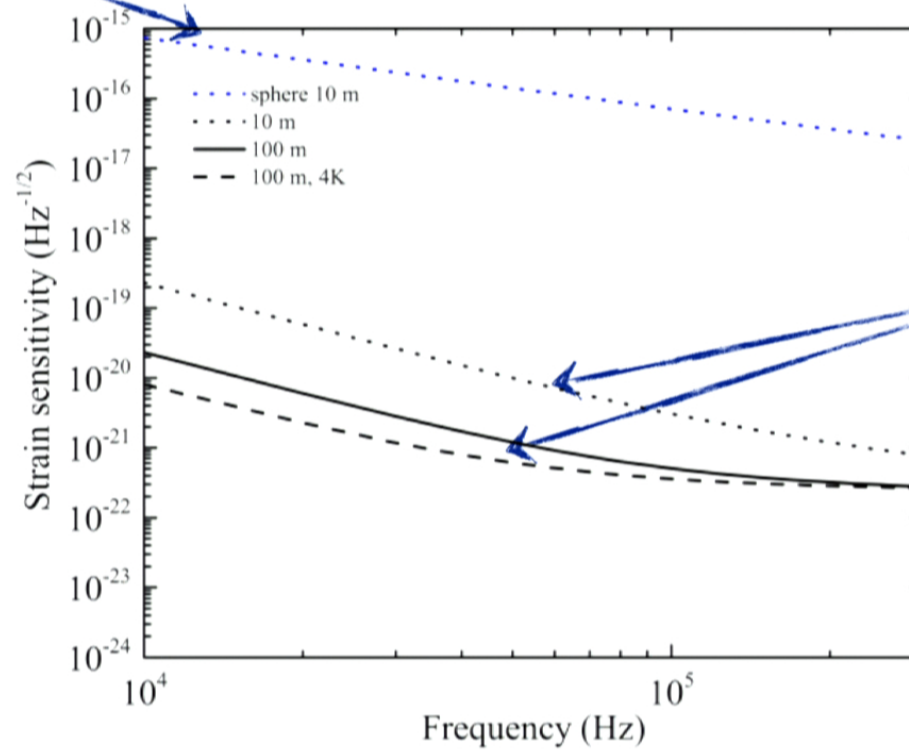


500 nm $\times$ (75 μm)²
disk

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

GW sensitivity

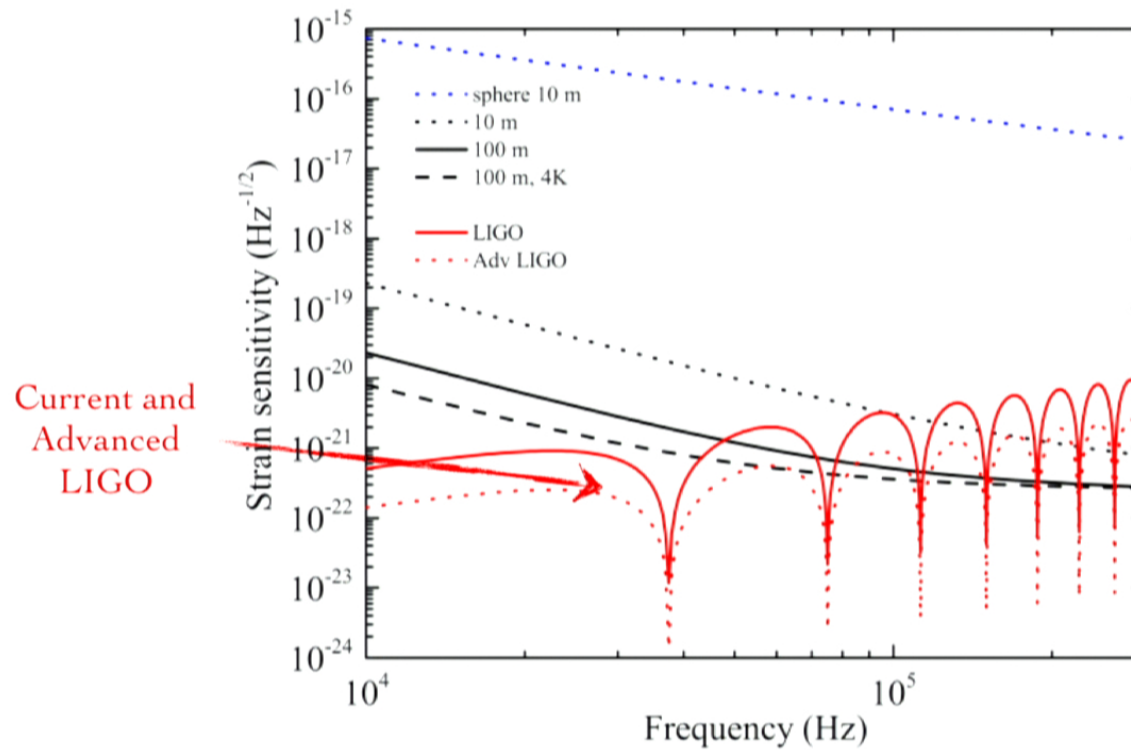
150 nm sphere



$500 \text{ nm} \times (75 \text{ } \mu\text{m})^2$
disk

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 $h \sim 10^{-22} \text{ Hz}^{-1/2}$	$10^{-15} \text{ m}/(\text{Hz})^{1/2}$	$10^{-18} \text{ m}/(\text{Hz})^{1/2}$
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



GW Sources in the High Frequency Regime

- Astrophysical Sources:

Natural upper bound on GW frequency

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

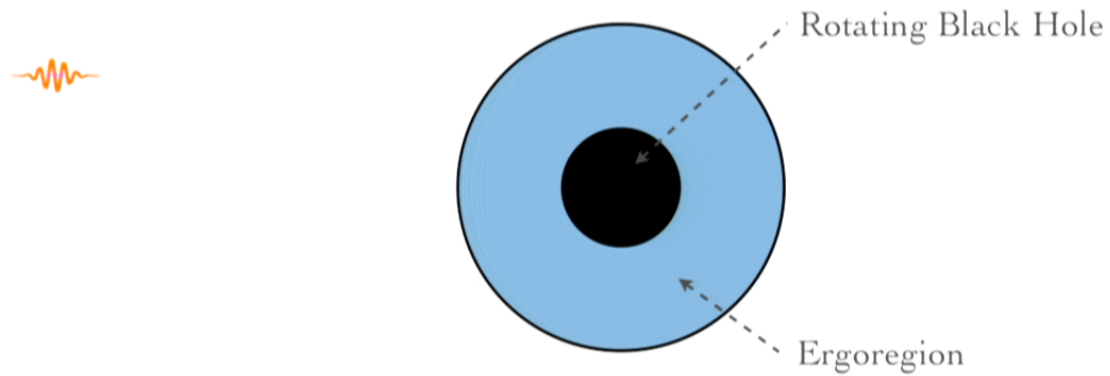
- Beyond-the-Standard Model Sources:

AA and Dubovsky (2010)

Black Hole Super-radiance

Black Hole Superradiance

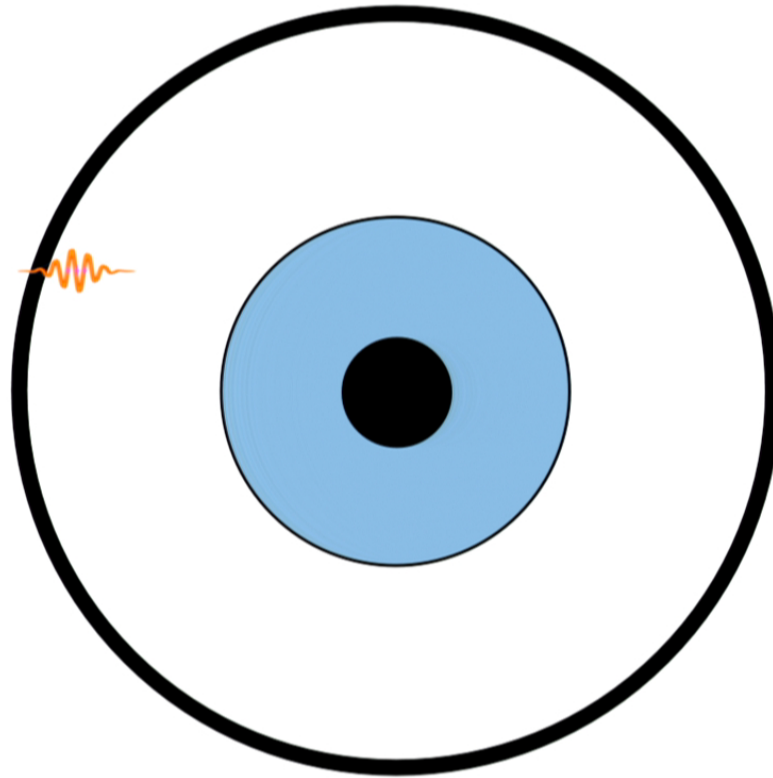
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Bomb

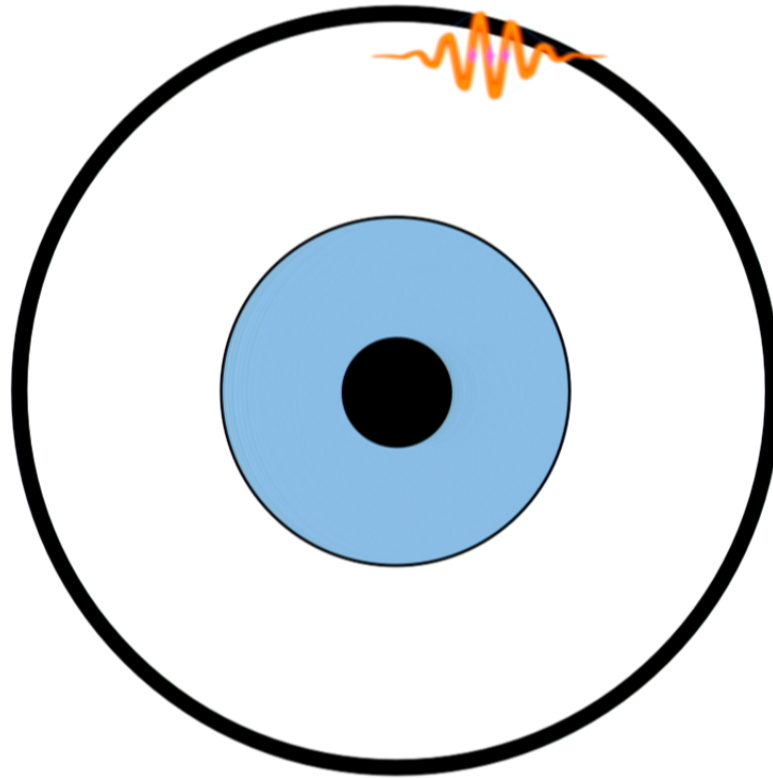
Press & Teukolsky 1972



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

Black Hole Bomb

Press & Teukolsky 1972

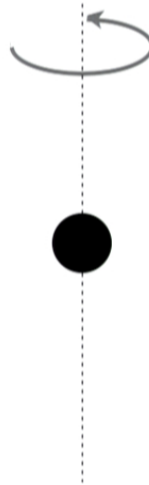


Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a Massive Boson

Penrose Process

Damour et al; Zouros & Eardley;
Detweiler; Gaina

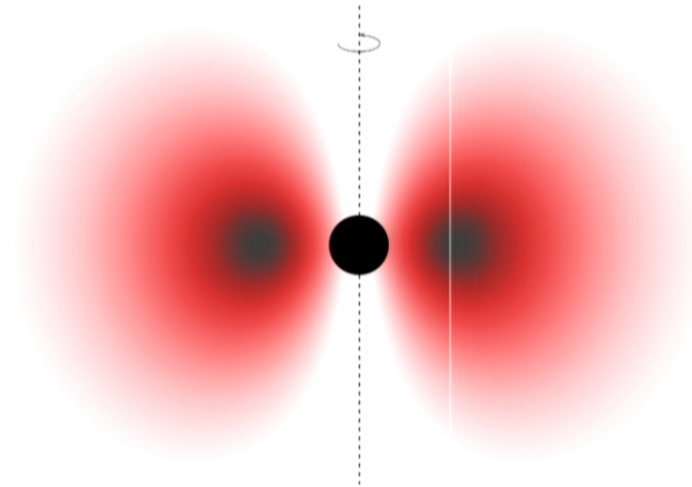


Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance for a Massive Boson

Penrose Process

Damour et al; Zouros & Eardley;
Detweiler; Gaina



Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

Away from the Black Hole: Newtonian Potential

The gravitational Hydrogen Atom

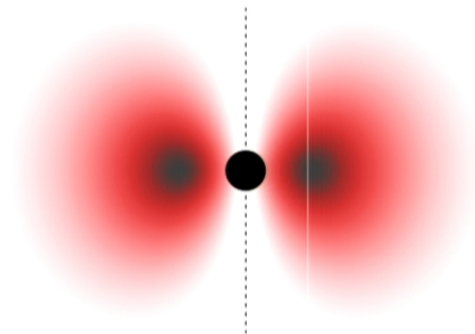
$$\alpha_{EM} = \frac{e^2}{4\pi} \longrightarrow \alpha = G_N M_{\text{BH}} \mu_a = R_g \mu_a$$

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

fermions $\longrightarrow$ bosons

Occupation number

$$1 \longrightarrow 10^{75}$$



Gravitational Atom in the Sky

Away from the Black Hole: Newtonian Potential

The gravitational Hydrogen Atom

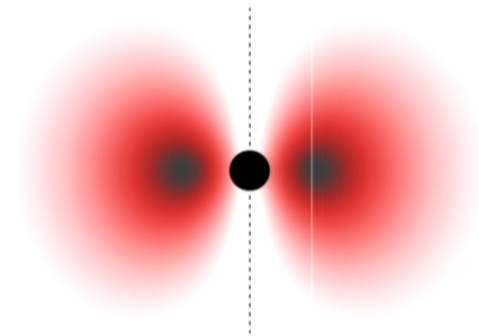
$$\alpha_{EM} = \frac{e^2}{4\pi} \longrightarrow \alpha = G_N M_{\text{BH}} \mu_a = R_g \mu_a$$

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

fermions $\longrightarrow$ bosons

Occupation number

$$1 \longrightarrow 10^{75}$$



Superradiance Parametrics

Superradiance Condition

$$\omega_{\text{axion}} < m \Omega_+$$

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

m : magnetic quantum number

a : BH spin, between 0 and 1

Superradiance Rate

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

When $R_g \mu_a \gg 1$,

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

When $R_g \mu_a \ll 1$

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

Superradiance Parametrics

Superradiance Condition

$$\omega_{\text{axion}} < m \Omega_+$$

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

m : magnetic quantum number

a : BH spin, between 0 and 1

Superradiance Rate

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

When $R_g \mu_a \gg 1$,

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

When $R_g \mu_a \ll 1$

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

Superradiance Parametrics

Superradiance Condition

$$\omega_{\text{axion}} < m \Omega_+$$

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

m : magnetic quantum number

a : BH spin, between 0 and 1

Superradiance Rate

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

When $R_g \mu_a \gg 1$,

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

When $R_g \mu_a \ll 1$

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

The Strong CP Problem

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

Non-zero electric dipole moment for the neutron

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

Solution:

θ_{QCD} is a dynamical field, an axion

Axion mass from QCD:

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

f_a : axion decay constant

The Strong CP Problem

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

Non-zero electric dipole moment for the neutron

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

Solution:

θ_{QCD} is a dynamical field, an axion

Axion mass from QCD:

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

f_a : axion decay constant

The Strong CP Problem

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

Non-zero electric dipole moment for the neutron

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

Solution:

θ_{QCD} is a dynamical field, an axion

Axion mass from QCD:

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

f_a : axion decay constant

Evolution of Superradiance for an Axion

Superradiance instability

Evolution of Superradiance for an Axion

Superradiance instability

Black Hole Accretion $\tau_{\text{accretion}} \sim 10^8 \text{ years}$

Evolution of Superradiance for an Axion

Superradiance instability

Black Hole Accretion $\tau_{\text{accretion}} \sim 10^8$ years

Axion self-interactions

Gravity wave transitions of axions between levels



Evolution of Superradiance for an Axion

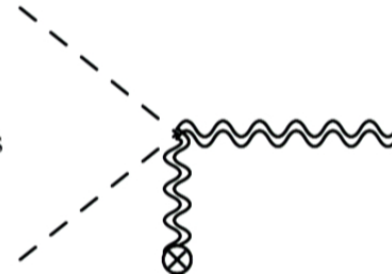
Superradiance instability

Black Hole Accretion $\tau_{\text{accretion}} \sim 10^8$ years

Axion self-interactions

Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations



Evolution of Superradiance for an Axion

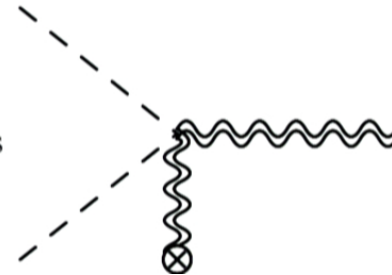
Superradiance instability

Black Hole Accretion $\tau_{\text{accretion}} \sim 10^8 \text{ years}$

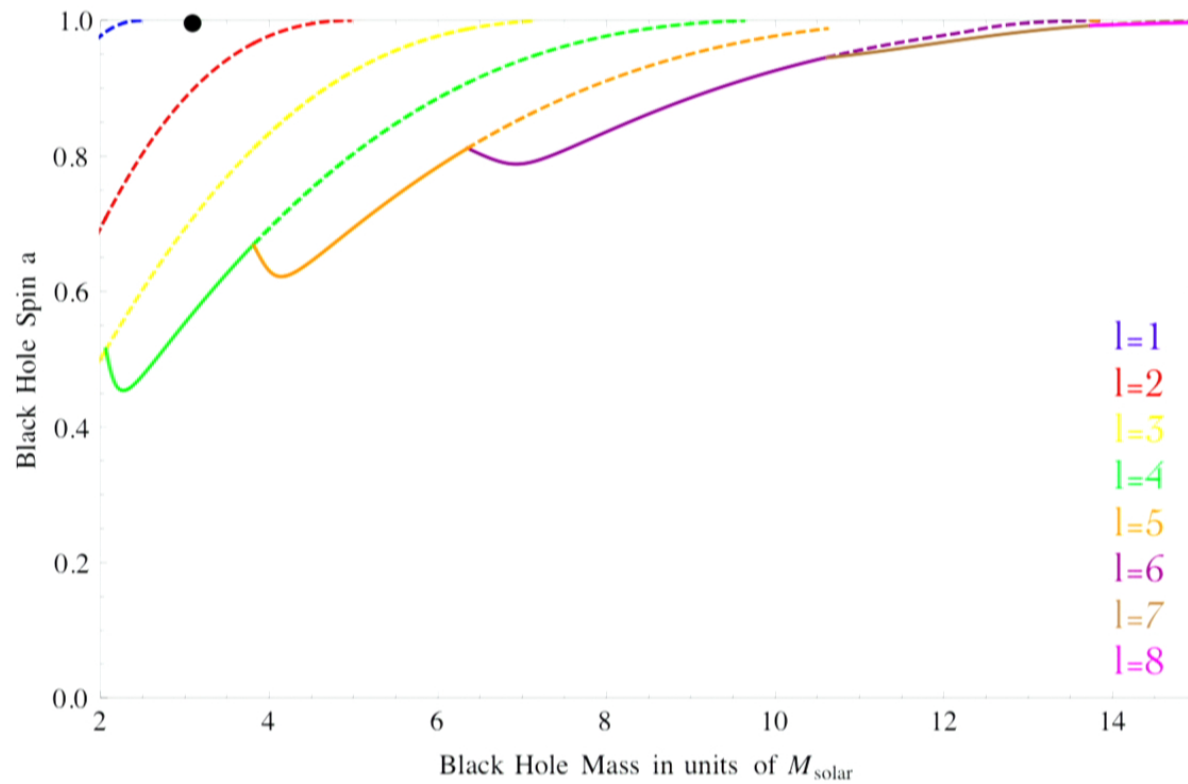
Axion self-interactions

Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations



Evolution of Superradiance

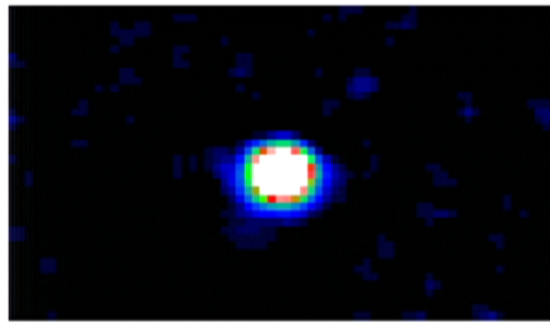


Maximum superradiance rate for level with min. l , max. m

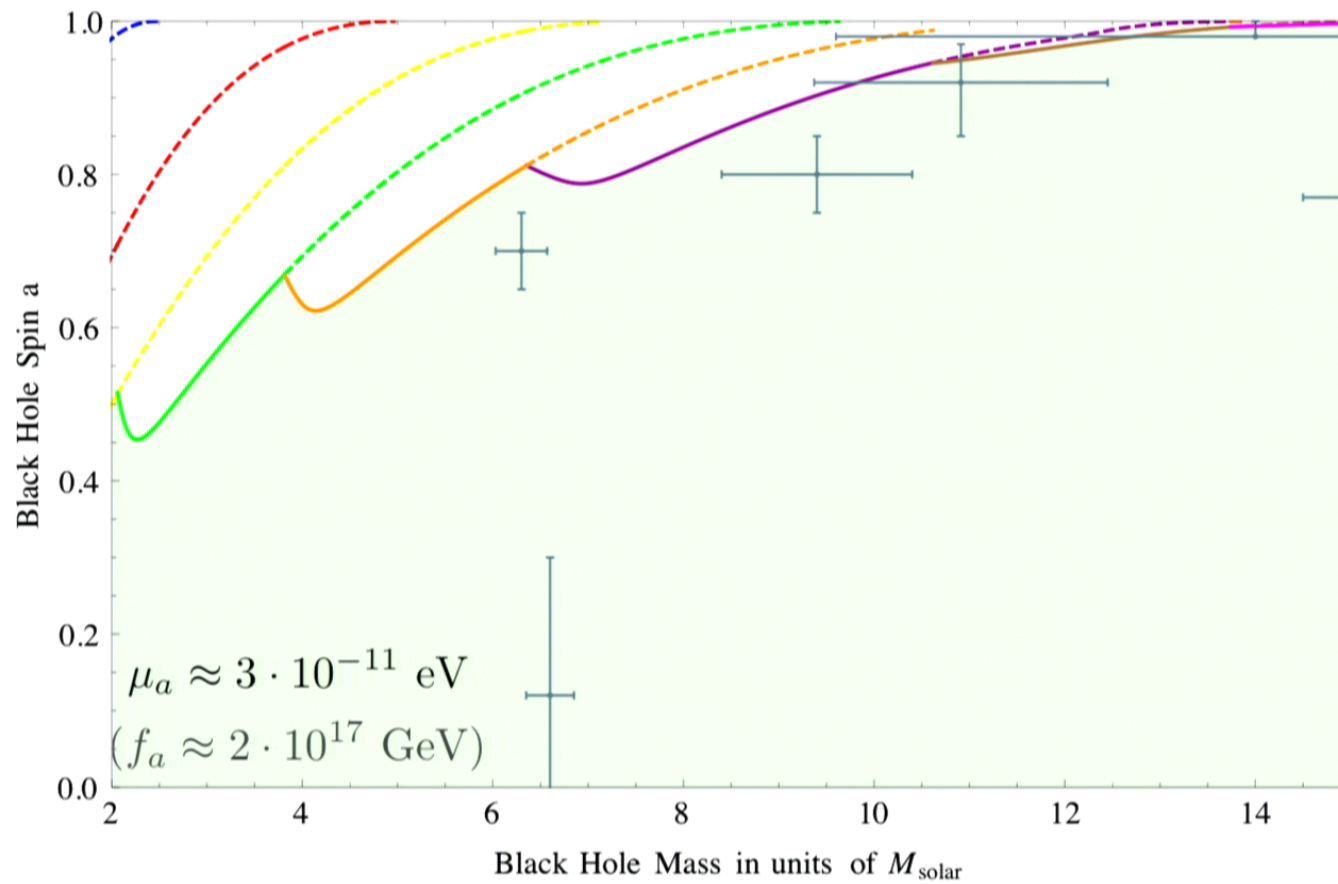
Bose Einstein Condensate in a Trap

The effect of attractive self-interactions

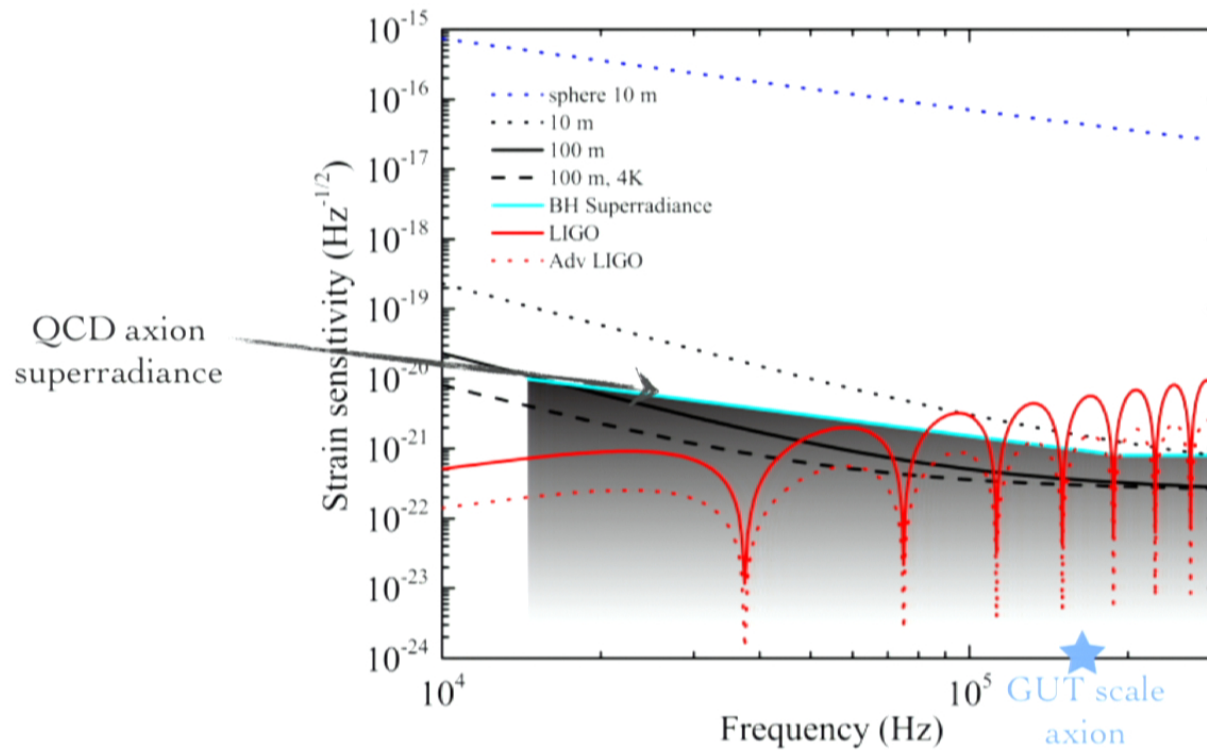
$$E_{\text{trap}} \sim E_{\text{inter.}}$$



Spin Gap for the QCD Axion

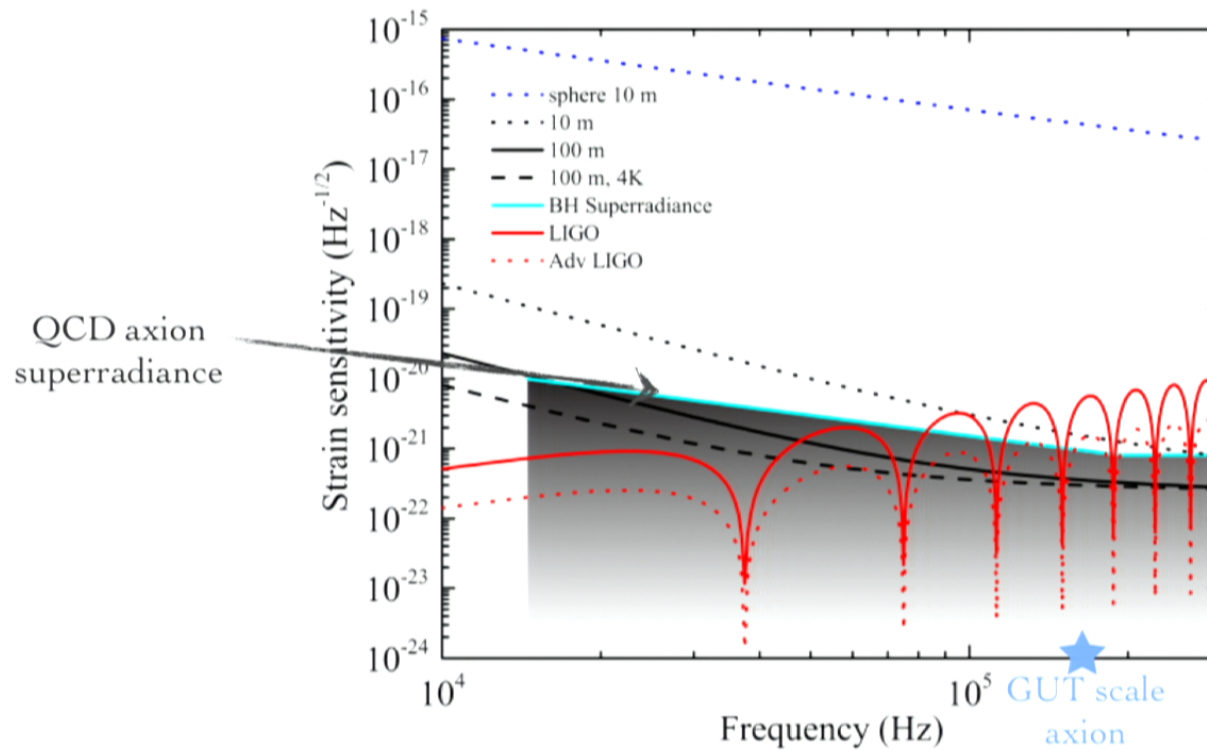


GWs from the QCD axion at high frequencies



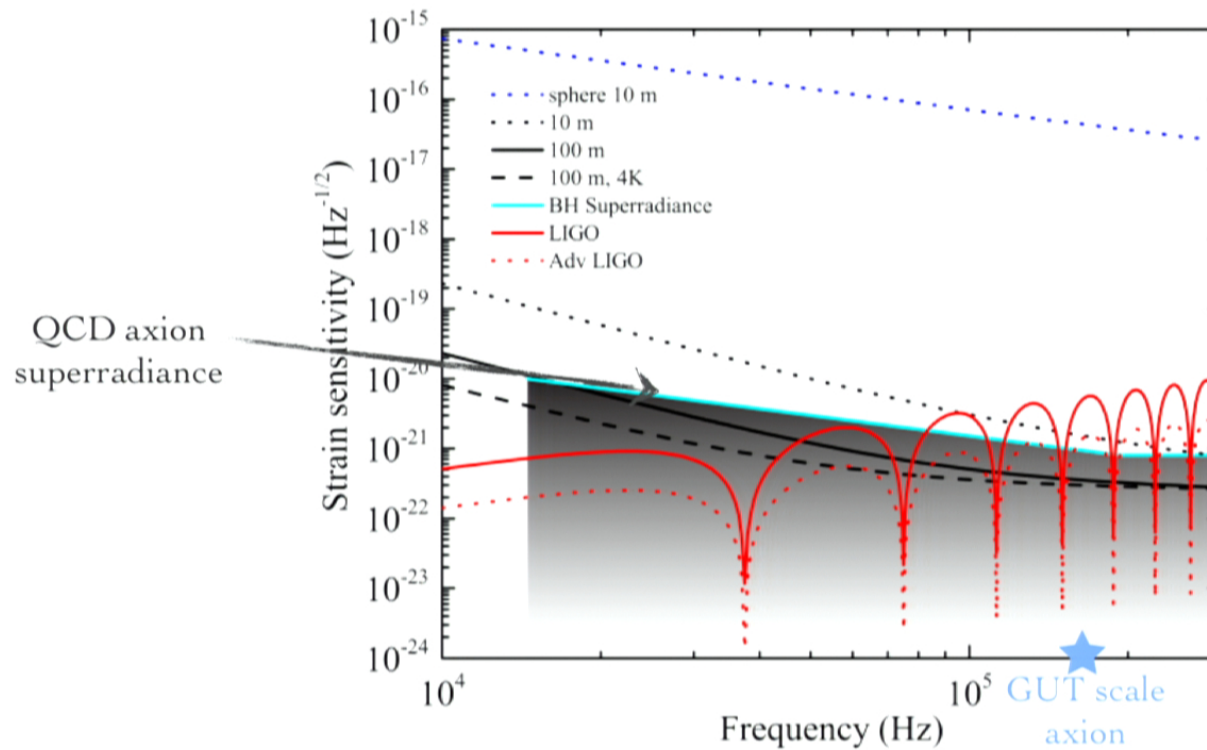
Distance to the source: 10 kpc

GWs from the QCD axion at high frequencies



Distance to the source: 10 kpc

GWs from the QCD axion at high frequencies



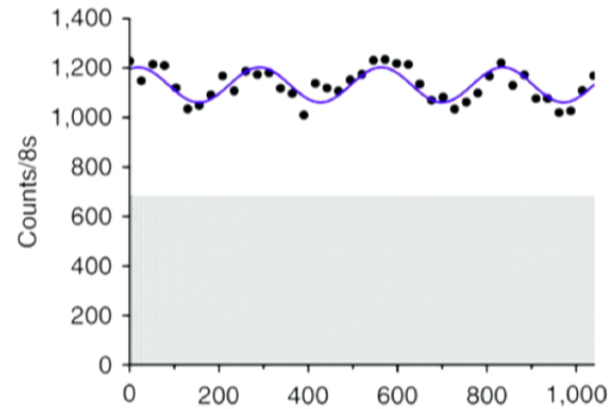
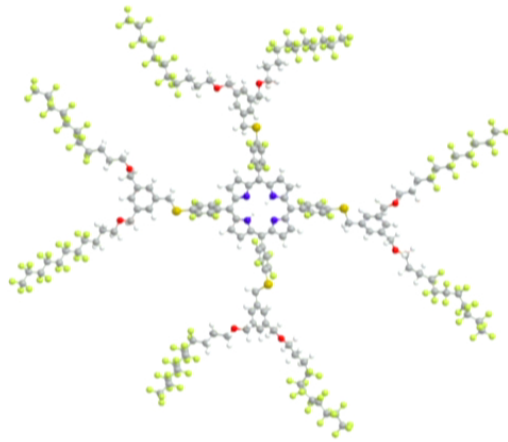
Distance to the source: 10 kpc

Prospects of GW detection with optically trapped sensors

- Sensitivity better than $10^{-21} \text{ 1/Hz}^{1/2}$ above $\sim 30 \text{ kHz}$
- Relatively small size enables GW array antenna design
- Improved GW sensitivity in new regime for GW astronomy

Towards the Schroedinger Cat State

Gerlich et al. (2011)



- Largest object to interfere so far:
 $\text{C}_{168}\text{H}_{94}\text{F}_{152}\text{O}_8\text{N}_4\text{S}_4$ (430 atom organic molecule)
- Limited by thermal dispersion of the initial wave function