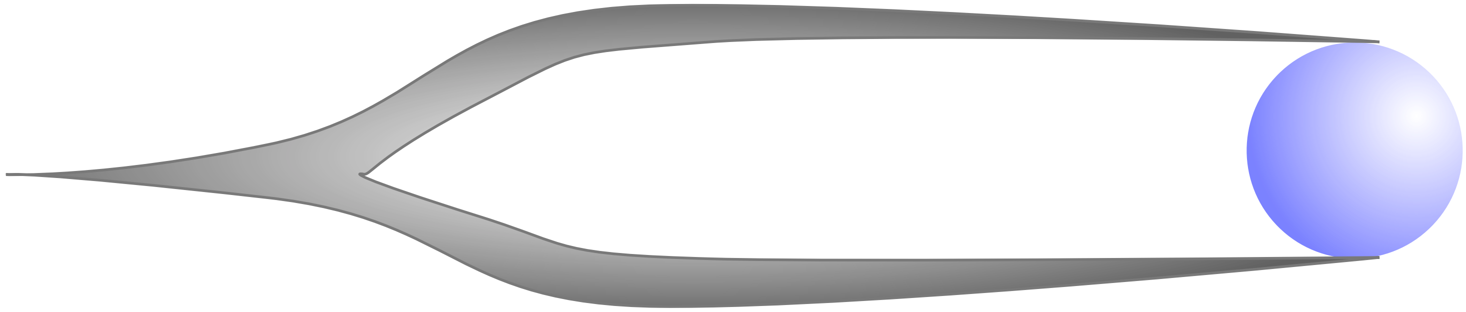
FUNDAMENTAL PHYSICS WITH OPTICALLY LEVITATED OBJECTS

Asimina Arvanitaki
Stanford University

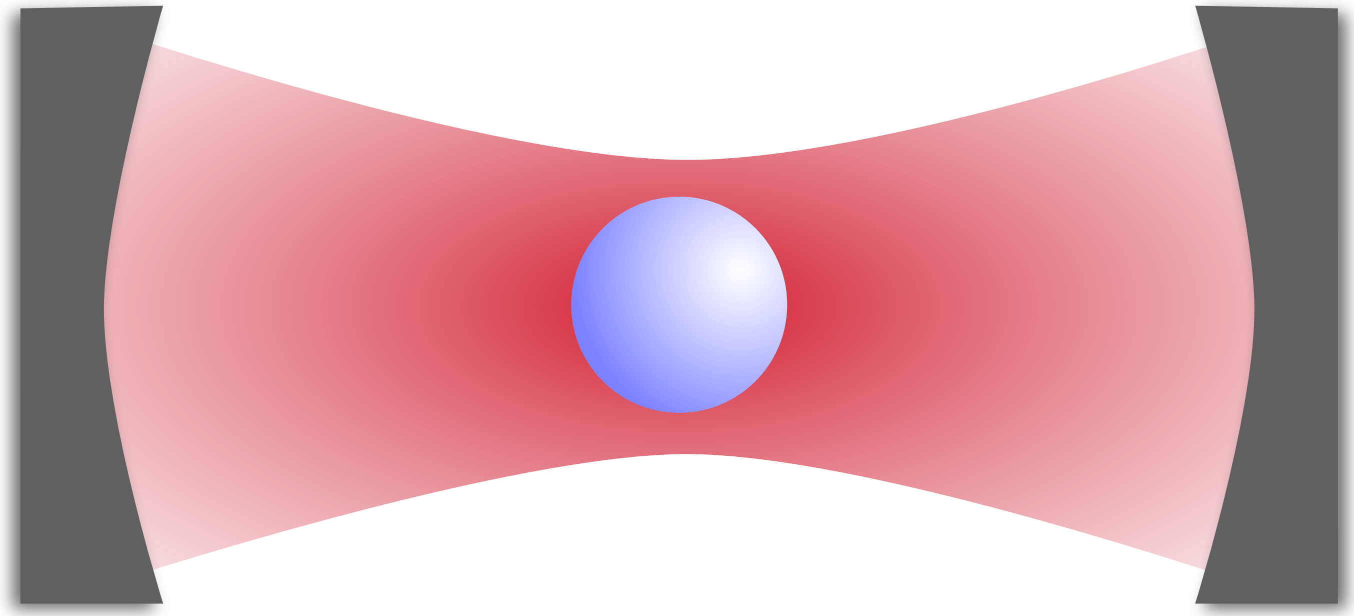
with
Andrew Geraci (experiment)
and
Sergei Dubovsky (theory)

Optical Trapping of Dielectrics



Optical Trapping of Dielectrics

Ashkin et al. (1970,1971,1976)



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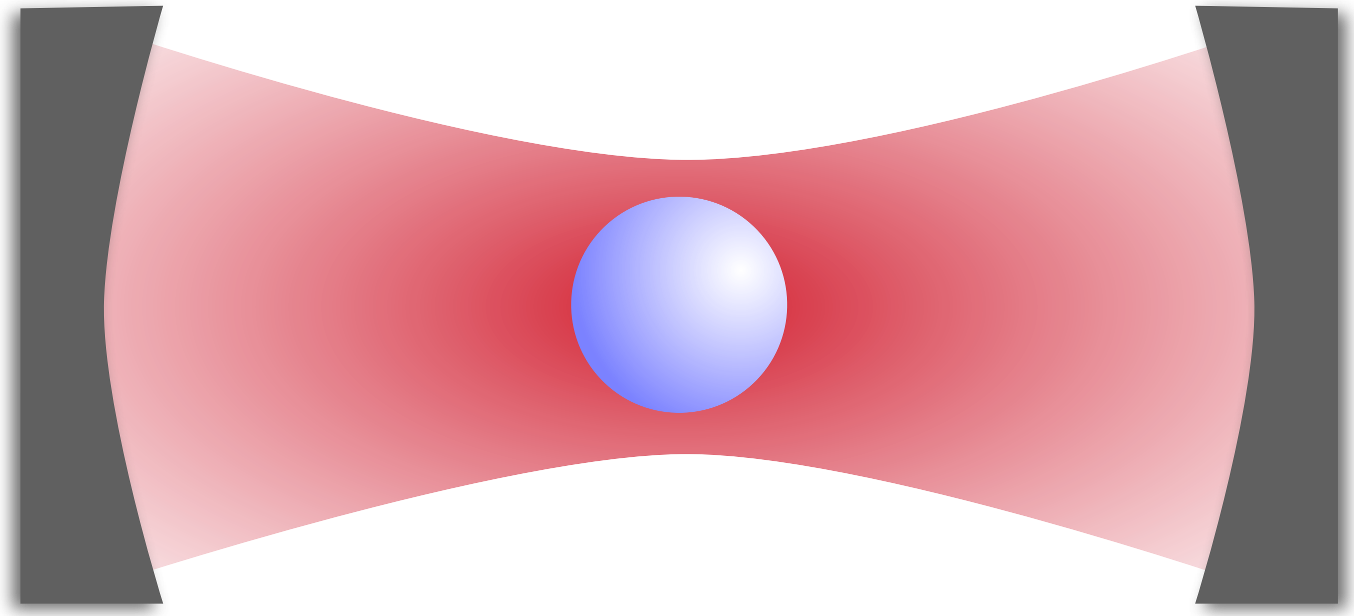


$$\text{Force} \propto -\nabla E^2 \equiv -kx$$

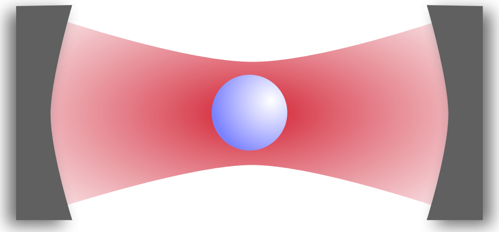
- Quality factor, $\omega_{\text{mech}} / \Gamma_{\text{loss}}$, larger than 10^{12} even at room temperature
- Internal modes decoupled from CM for small objects
- CM motion controlled by the intensity of light

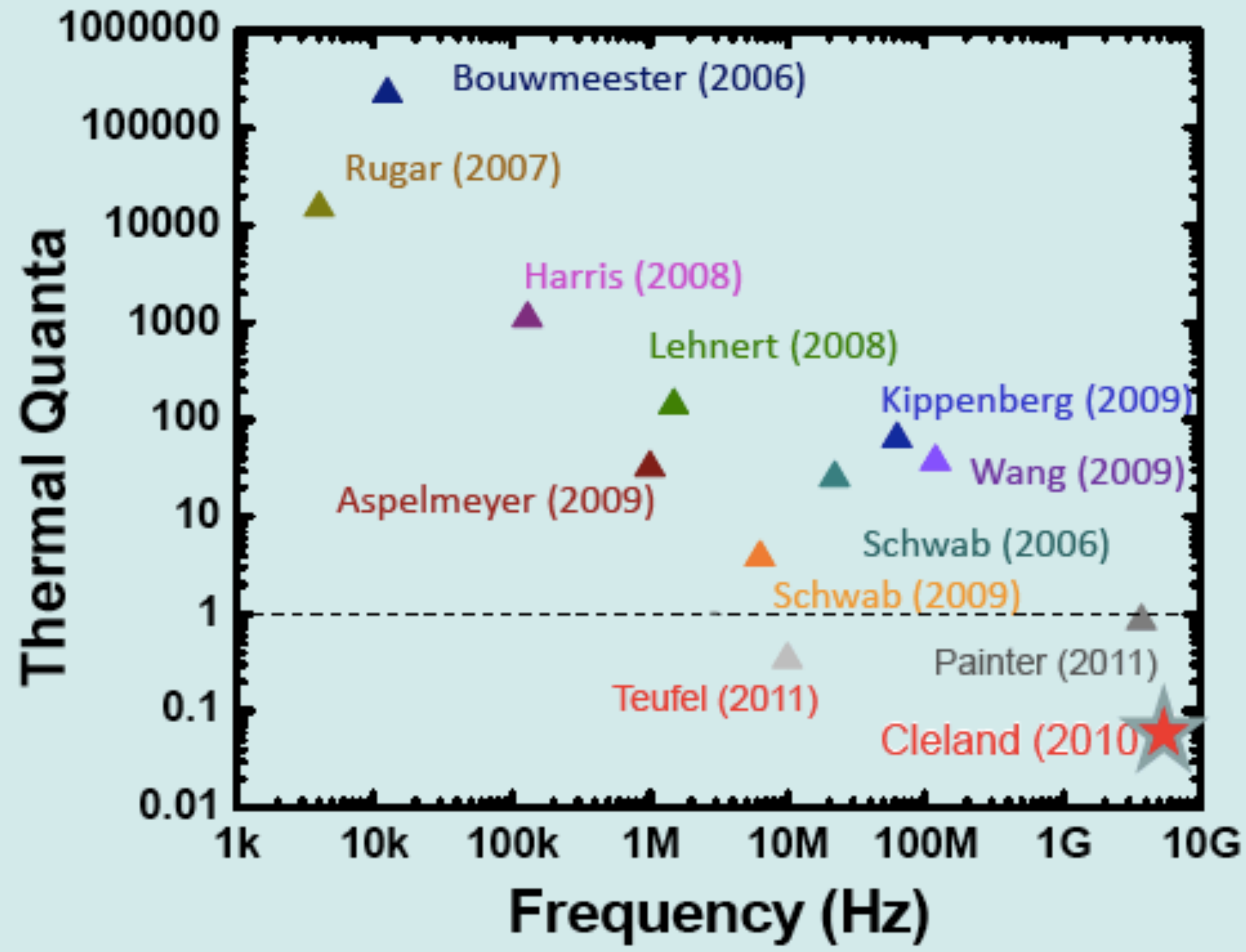
Optical Trapping Applications

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

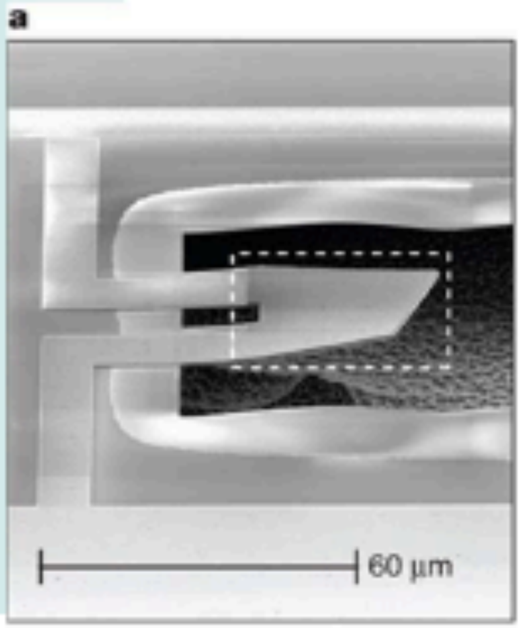
Towards the Quantum Regime

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

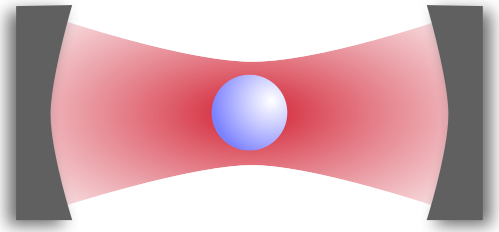




A. D. O'Connell et.al.
10.1038/nature08967



Towards the Quantum Regime



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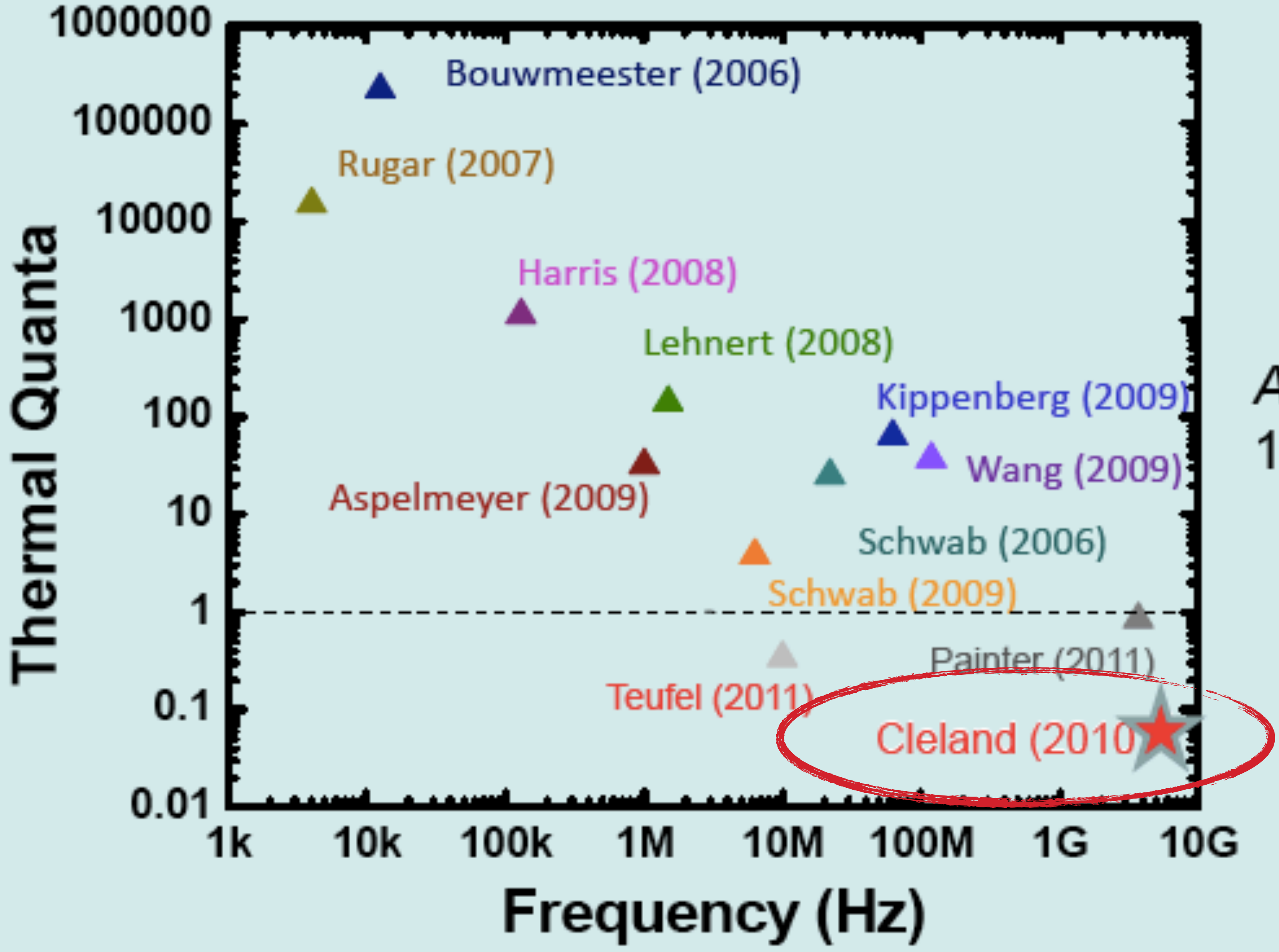

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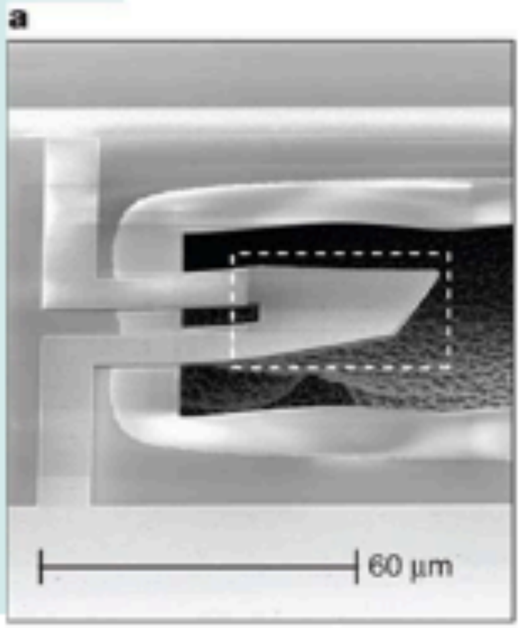
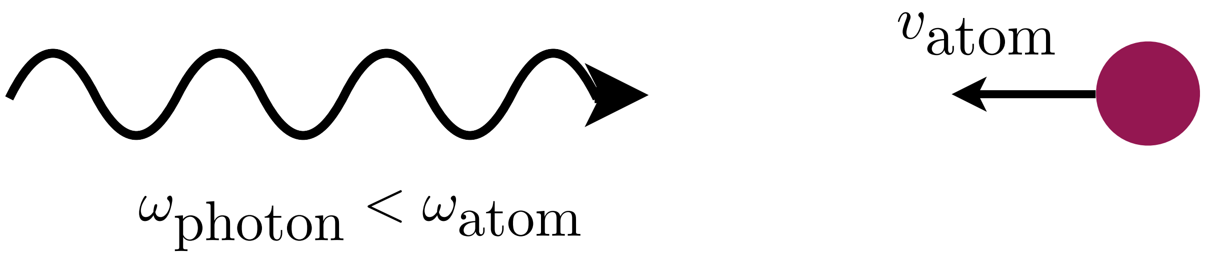


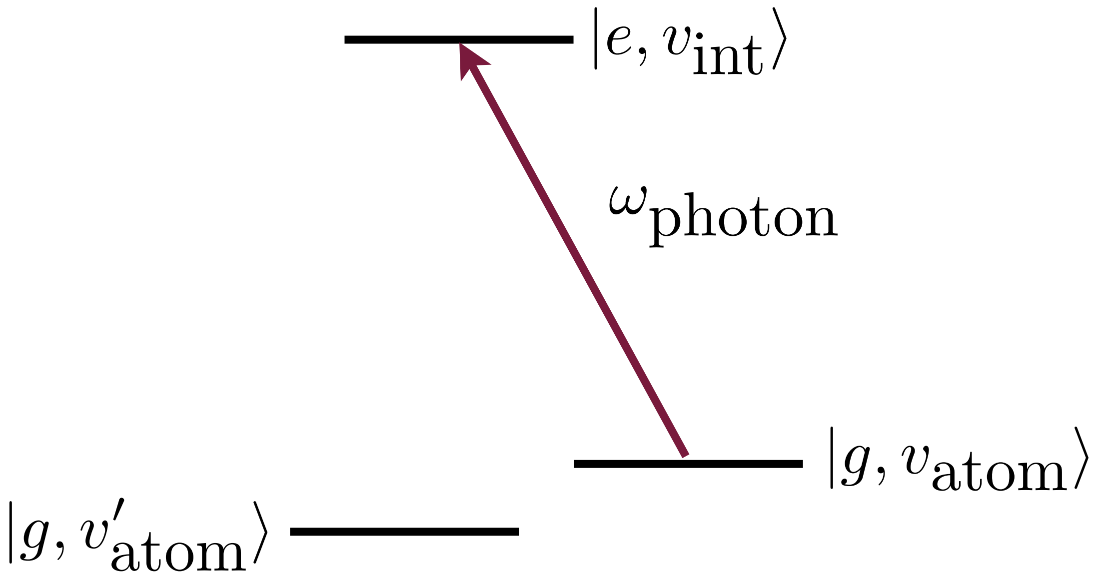
10^9 atoms in a quantum superposition of states

Optical Cooling

Doppler cooling

For an atom





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

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Doppler cooling

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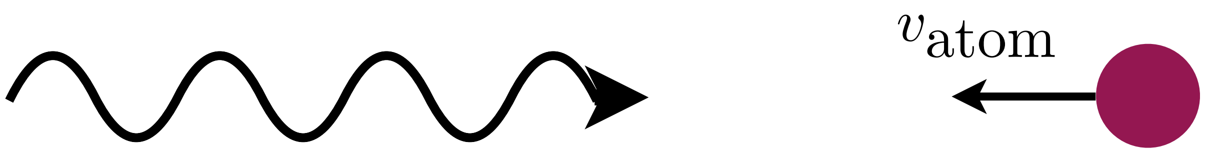
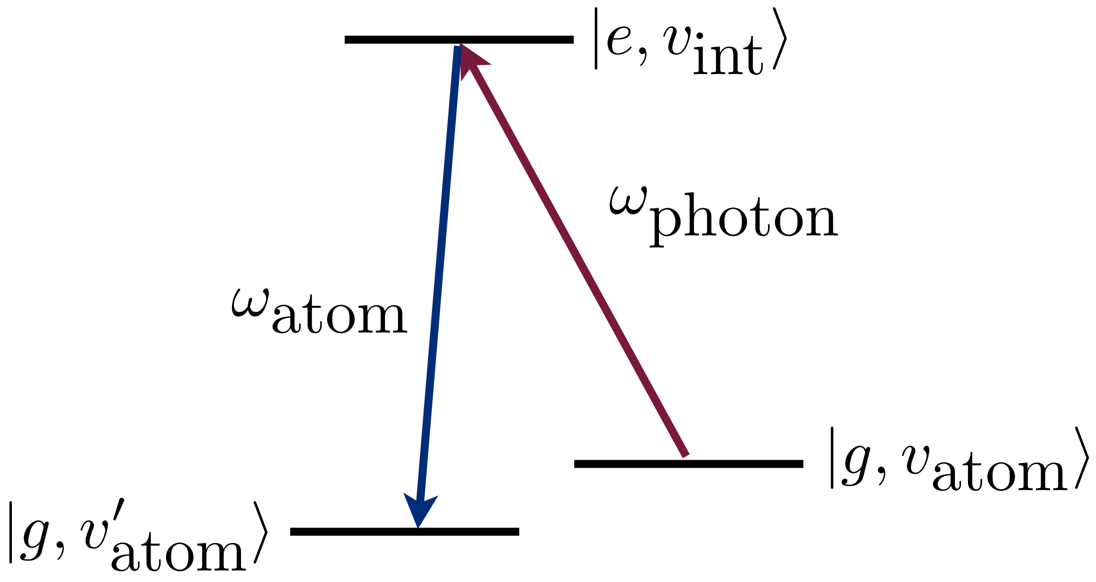


$\omega_{\text{photon}} < \omega_{\text{atom}}$



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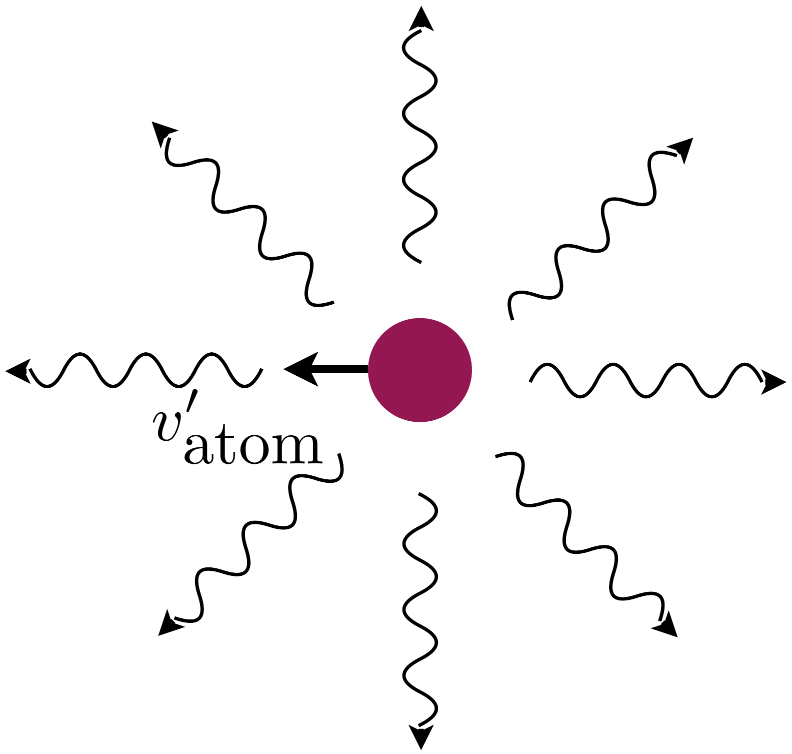
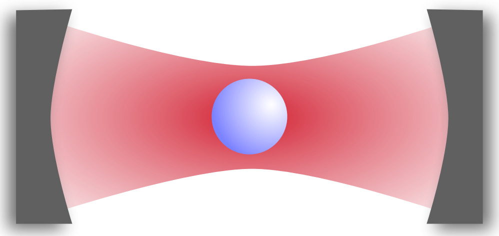
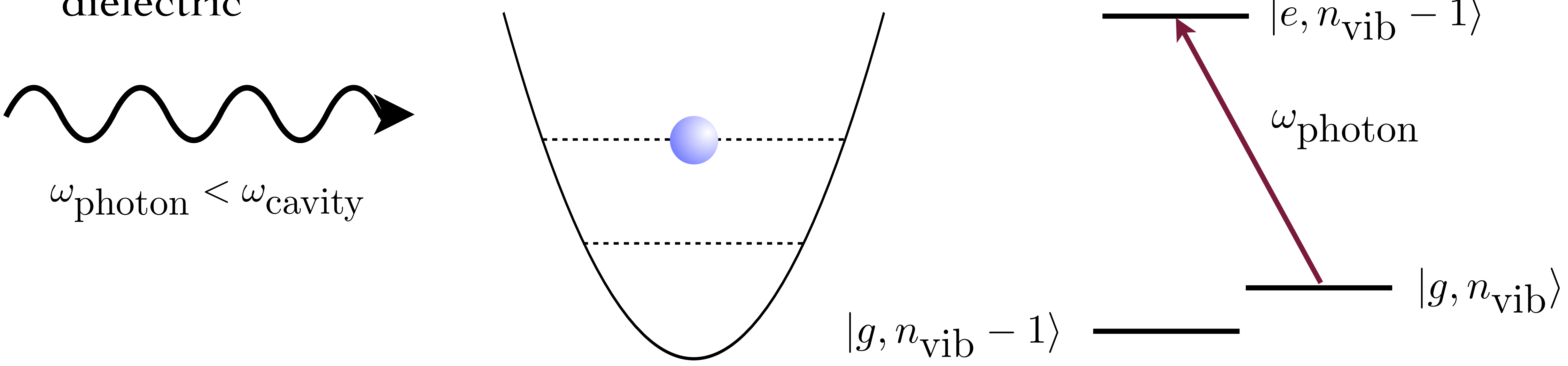


Spontaneous emission

Optical Cavity Cooling



For a trapped oscillating dielectric



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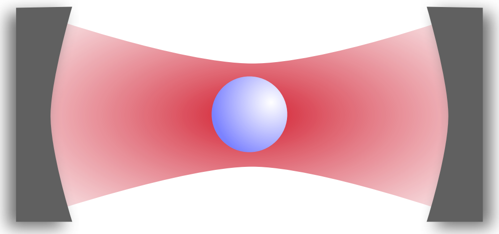

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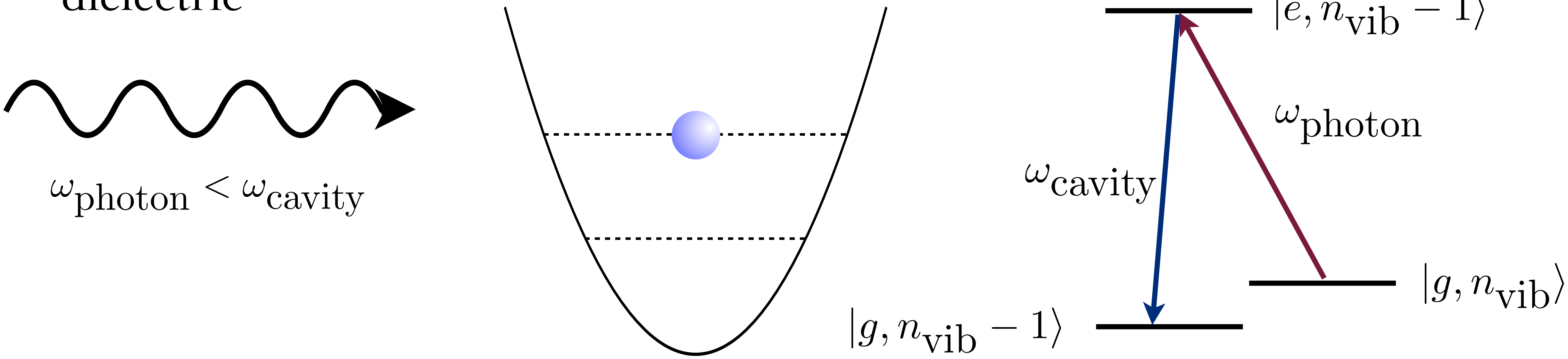
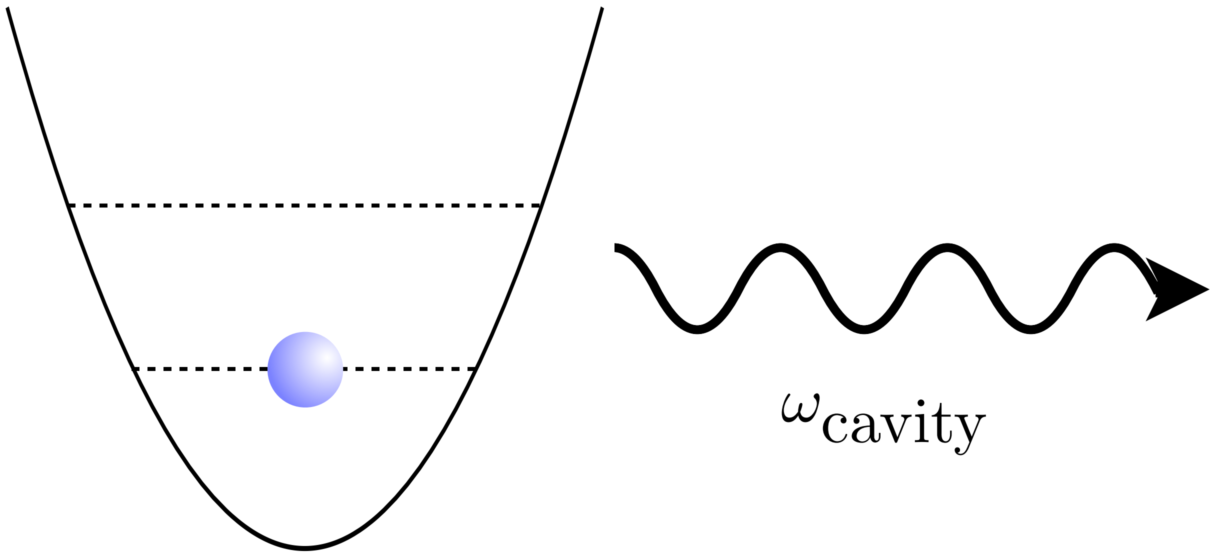


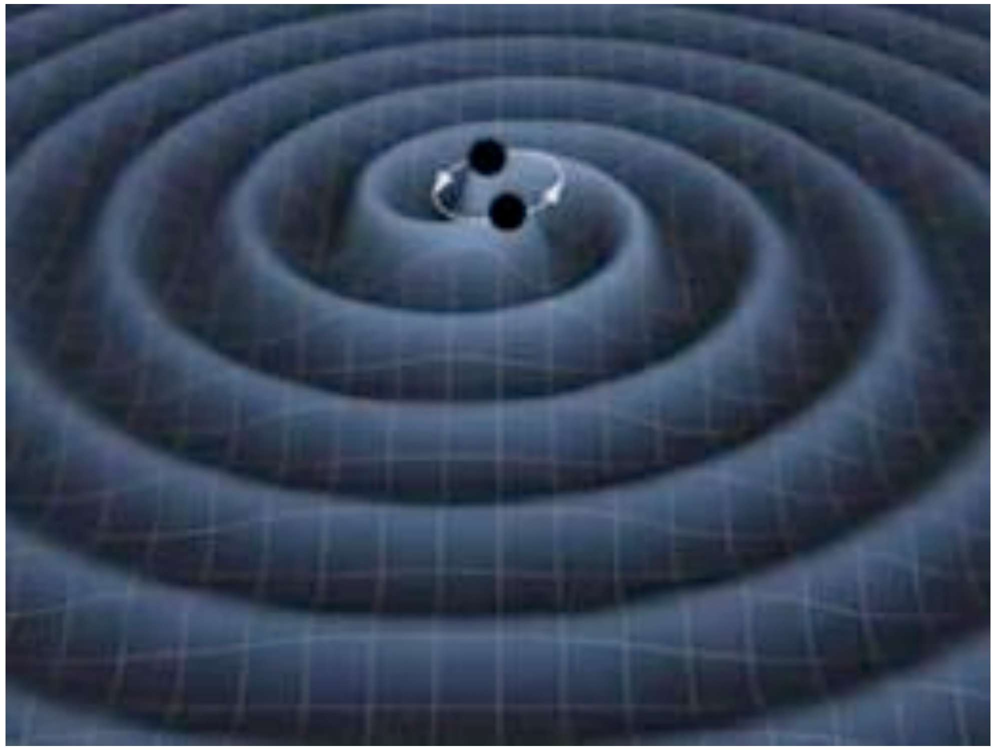


Photon is re-emitted at the frequency of the cavity tuned laser

Outline

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

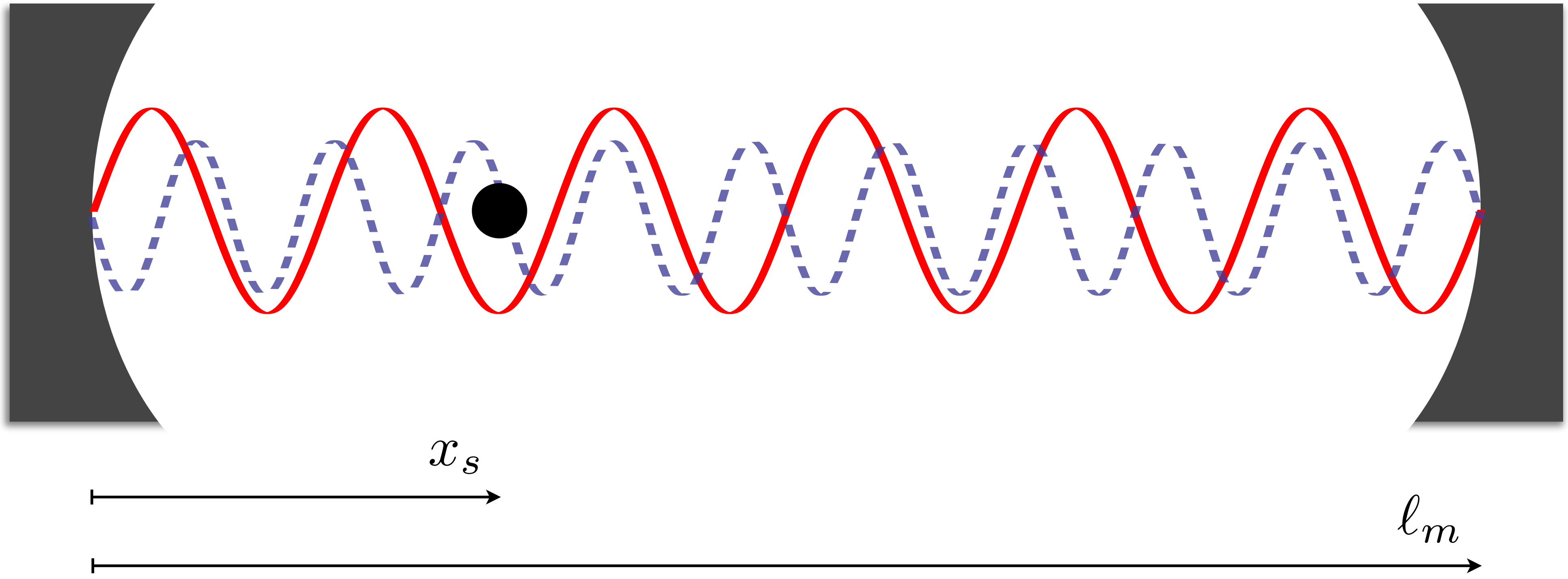
Gravitational Wave Detection



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

Gravitational Wave Detection

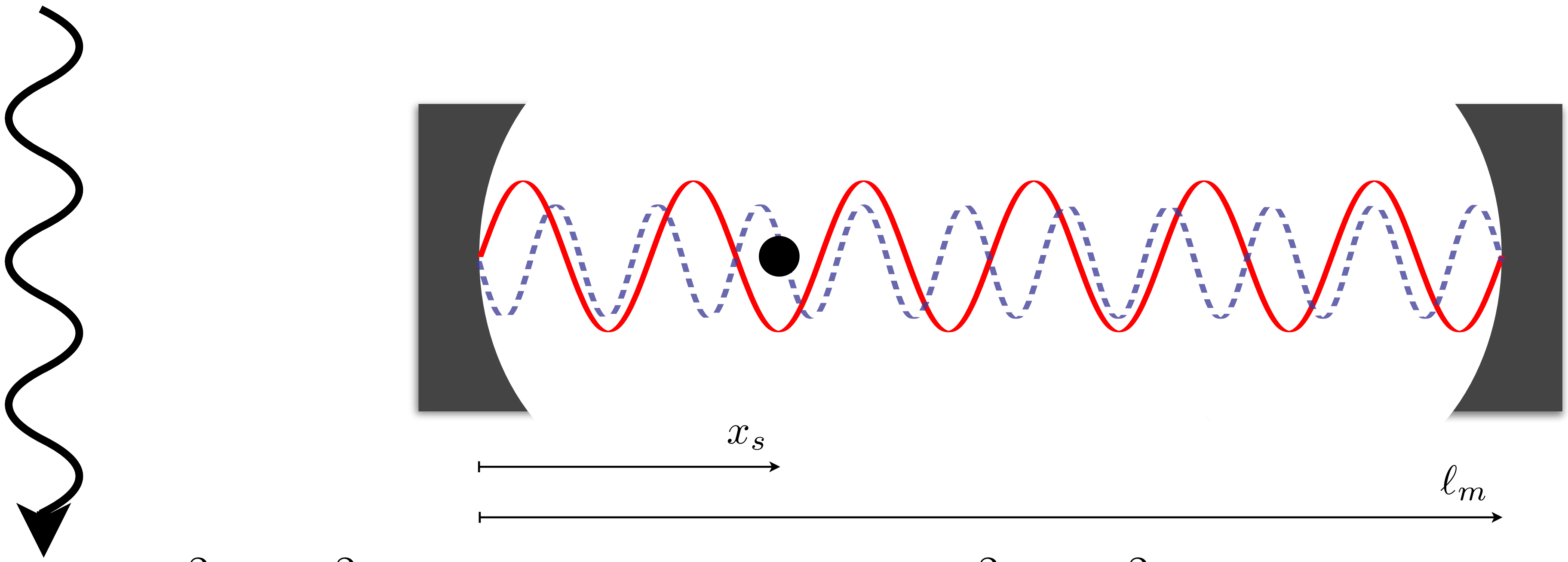
AA and Geraci (2012)



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

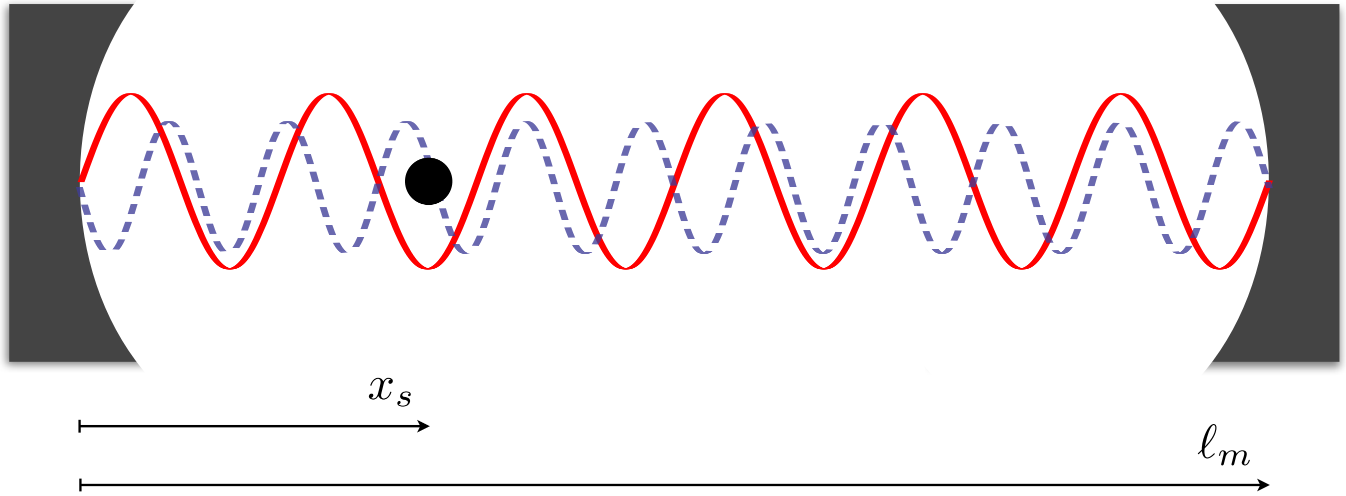
- One laser to hold, one to cool and one to measure the position

Gravitational Wave Detection



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

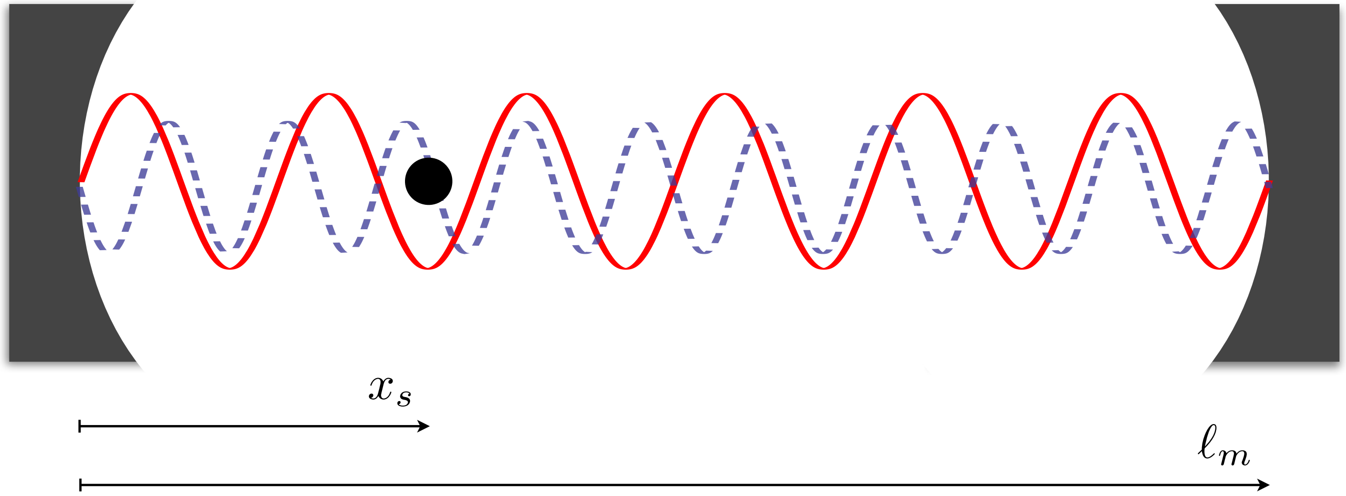
Gravitational Wave Detection



Gravitational wave changes the physical distance between masses

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

Gravitational Wave Detection



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

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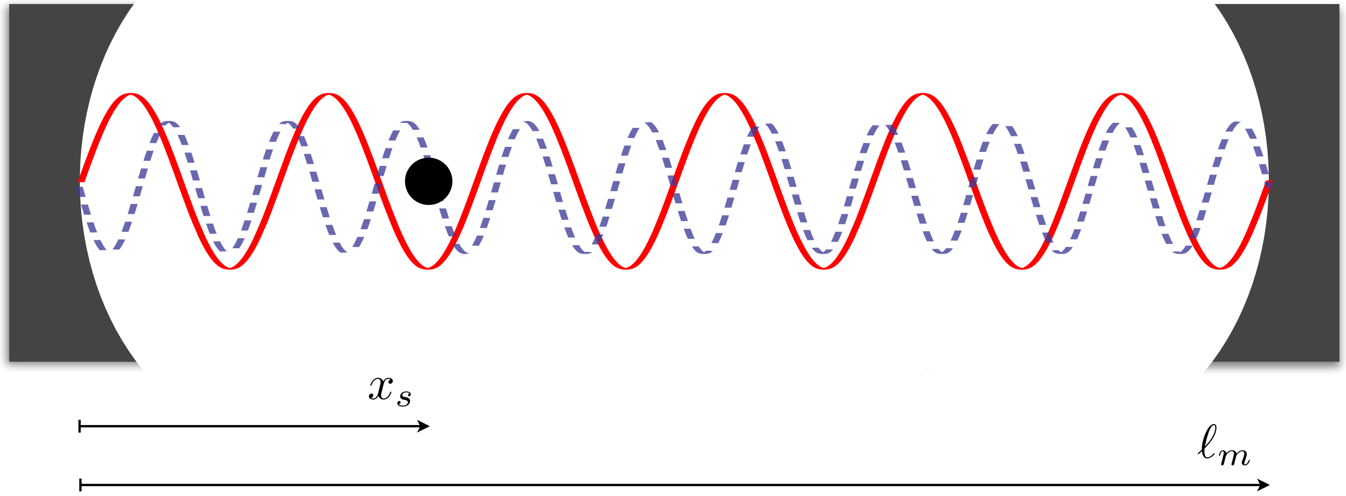

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$$\delta X_{\mathrm{S}} = \frac{1}{2}x_s h$$

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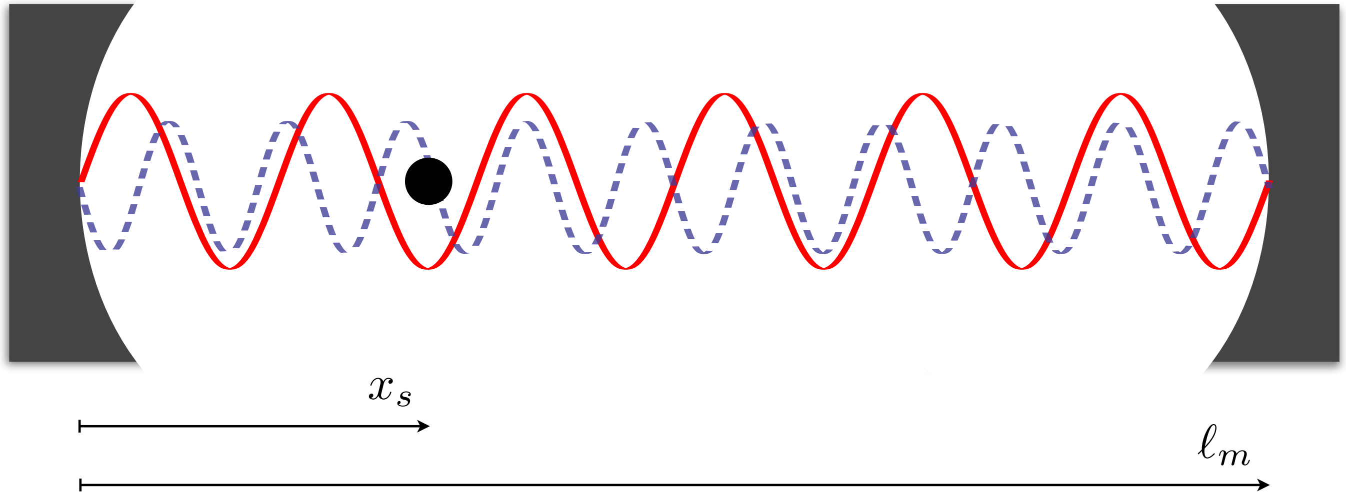

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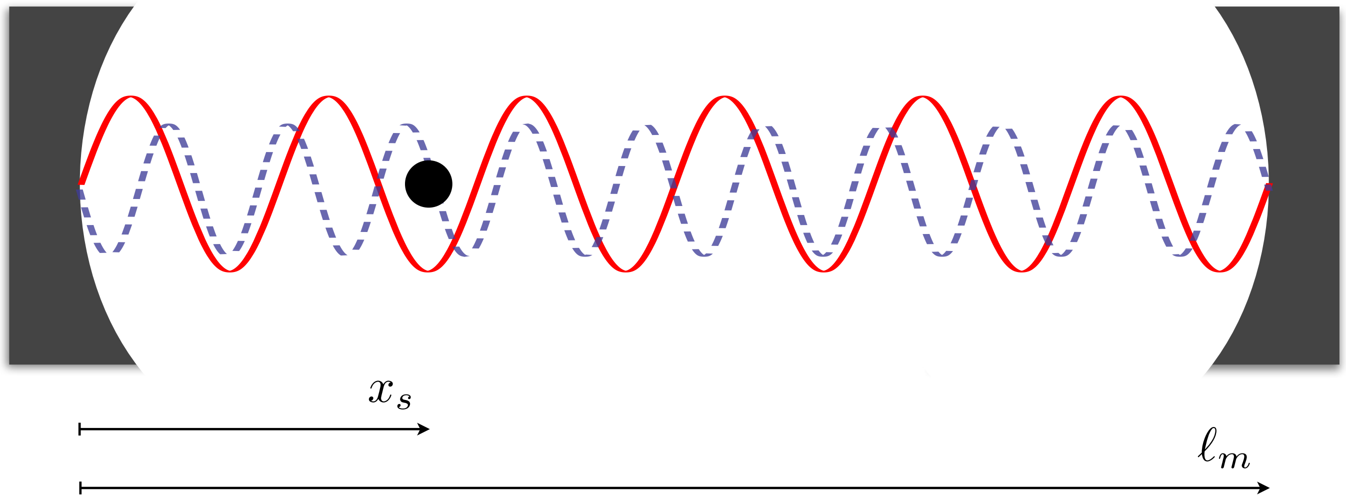
- Sensor position changes with respect to the trap minimum:

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

Gravitational Wave Detection



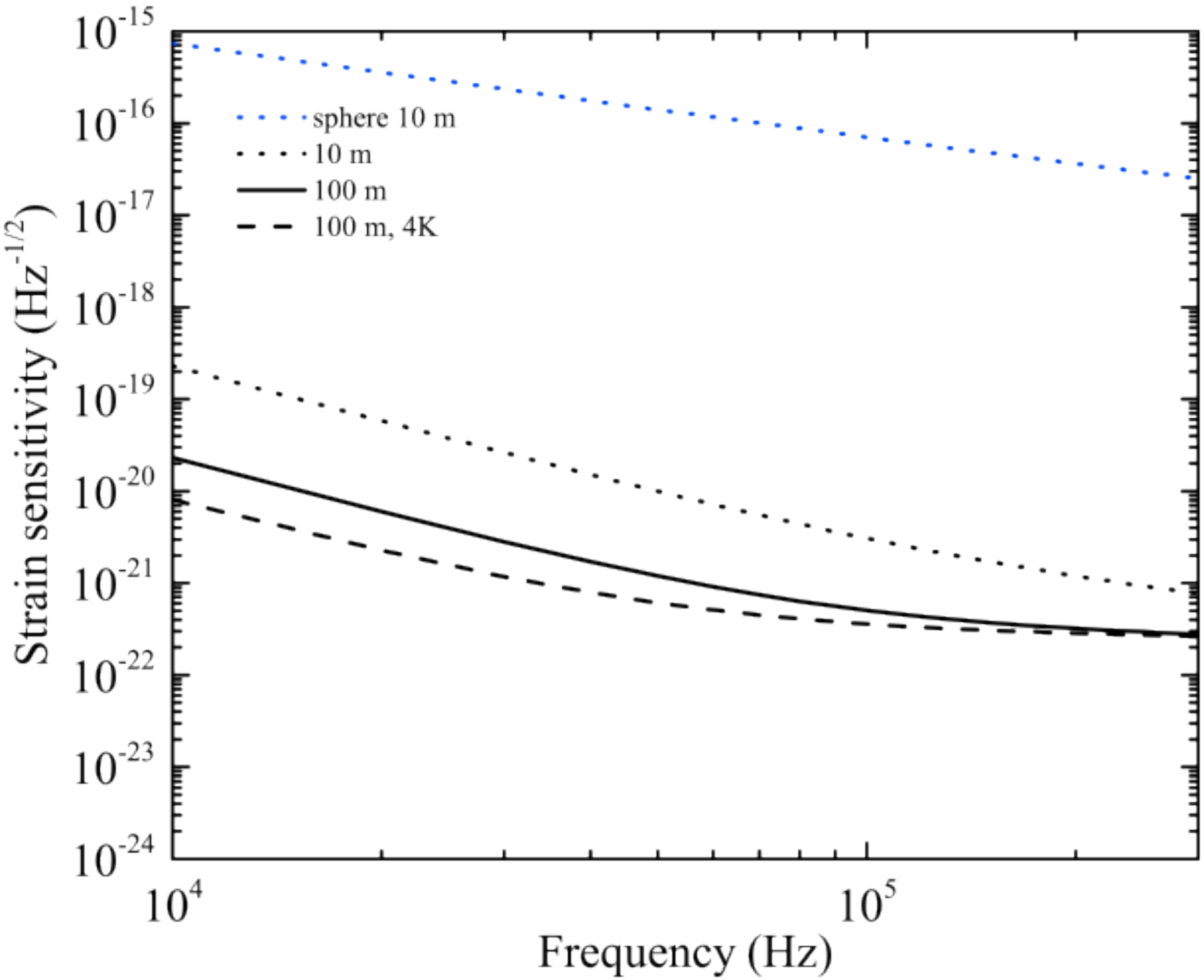
$$\Delta X = \frac{1}{2}(x_s - \ell_m)h$$

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

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

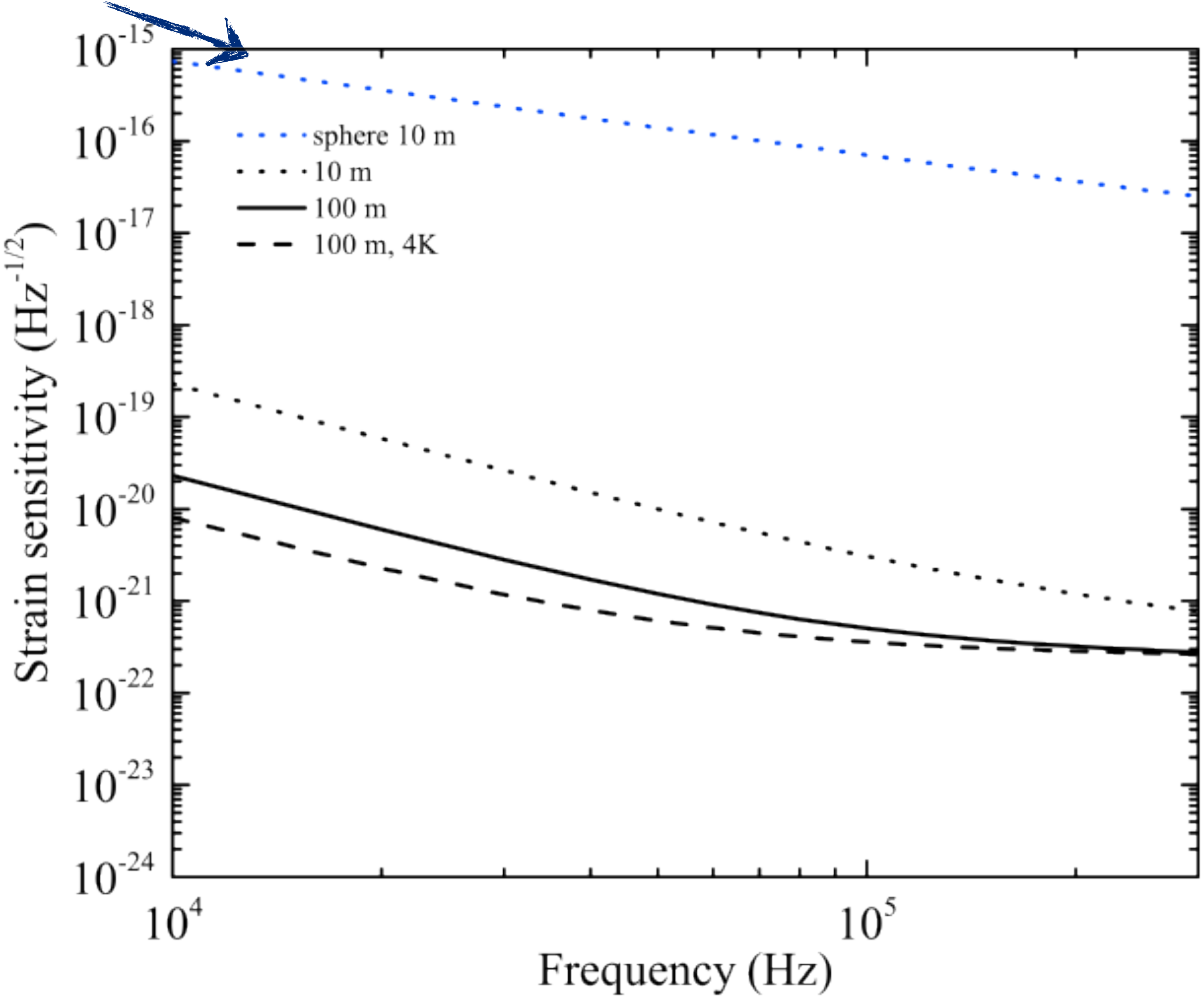
- Main background: Thermal motion in the trap

GW sensitivity



GW sensitivity

150 nm sphere



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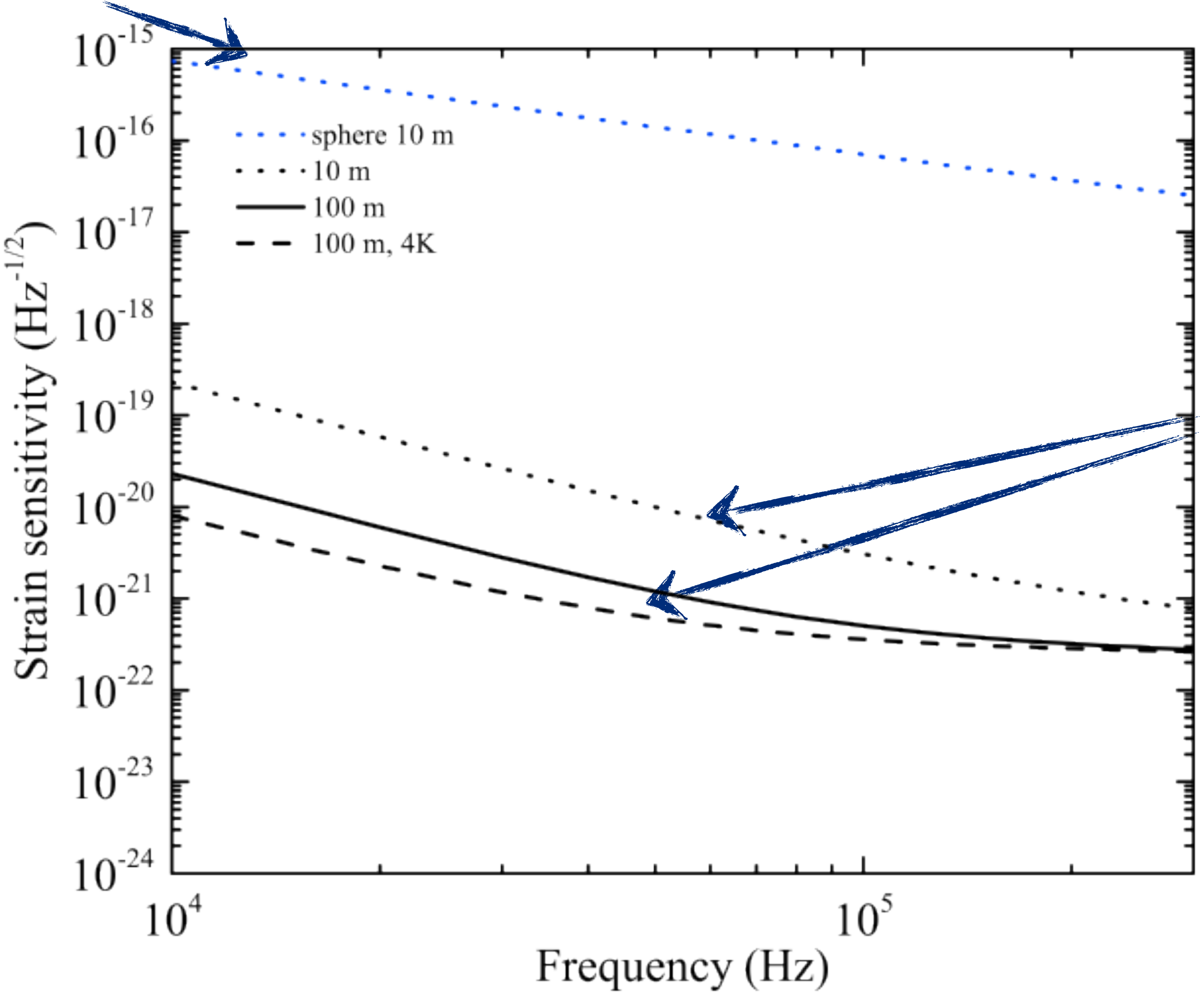
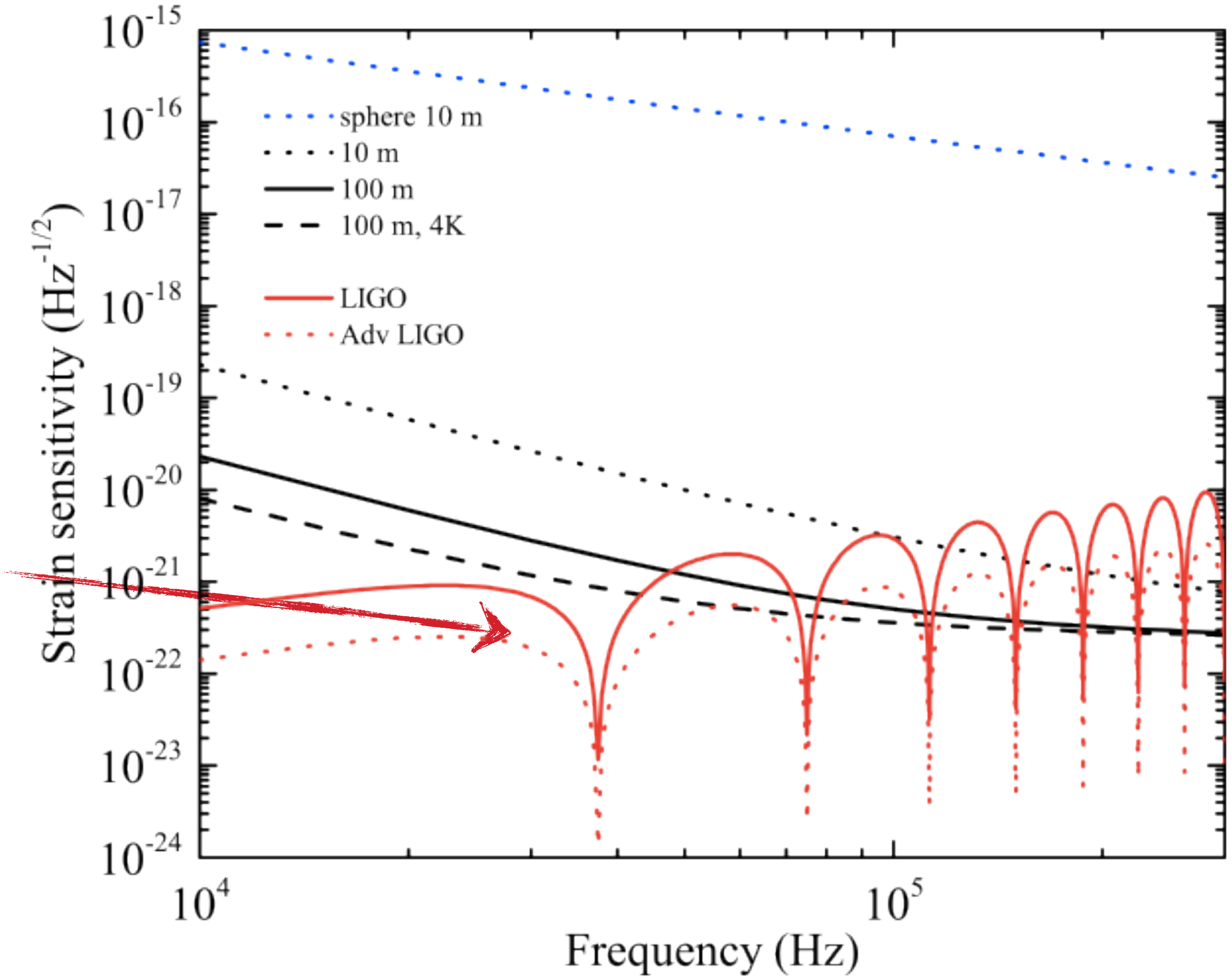


500 nm × (75 μm)^2
disk

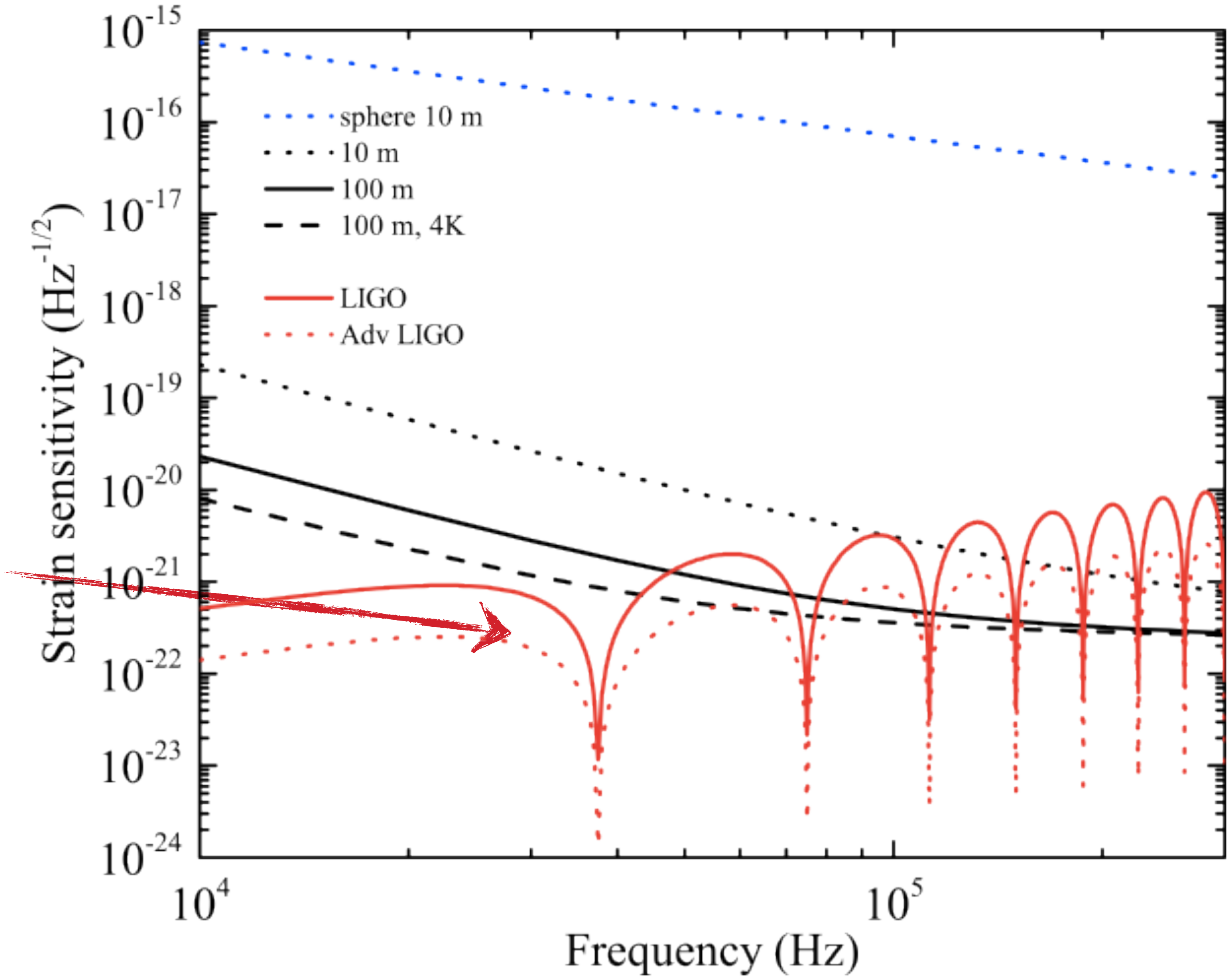
Radical change in sensitivity between the two geometries due to difference in mass and in light scattering properties

GW sensitivity compared to LIGO



Current and Advanced LIGO

GW sensitivity compared to LIGO



Current and Advanced LIGO

LIGO: 4 km cavity

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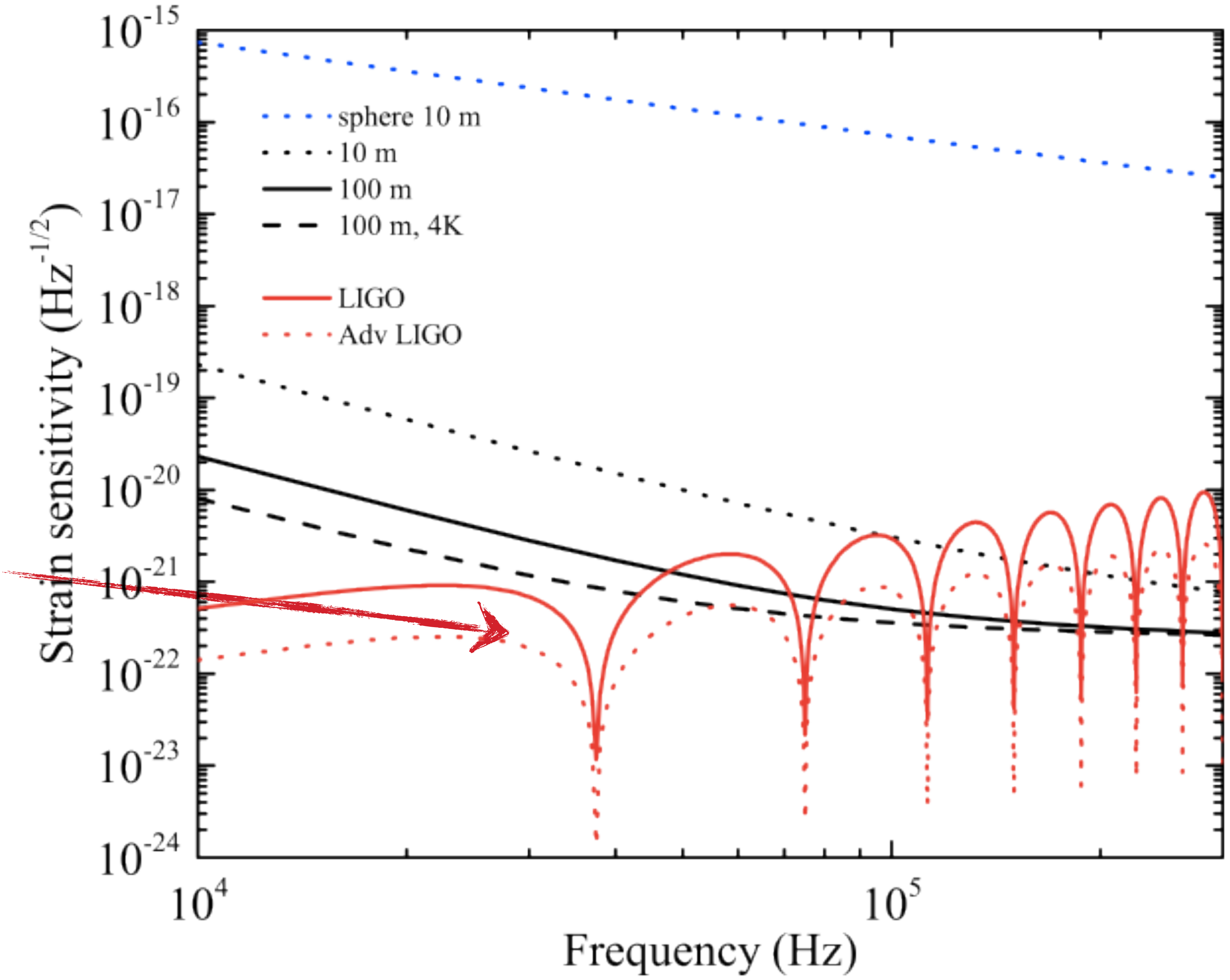


Current and Advanced LIGO

LIGO: 4 km cavity

Current setup: 100 m cavity

GW Sources in the High Frequency Regime

- Astrophysical Sources:

Natural upper bound on GW frequency

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

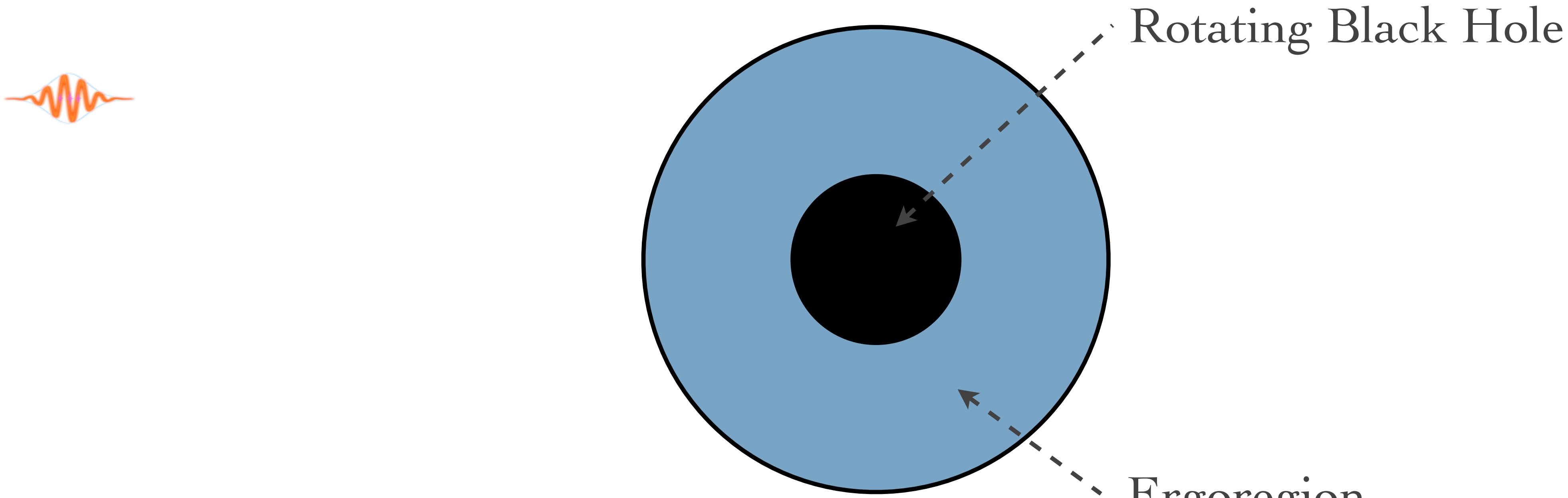
- Beyond-the-Standard Model Sources:

AA and Dubovsky (2010)

Black Hole Super-radiance

Black Hole Superradiance

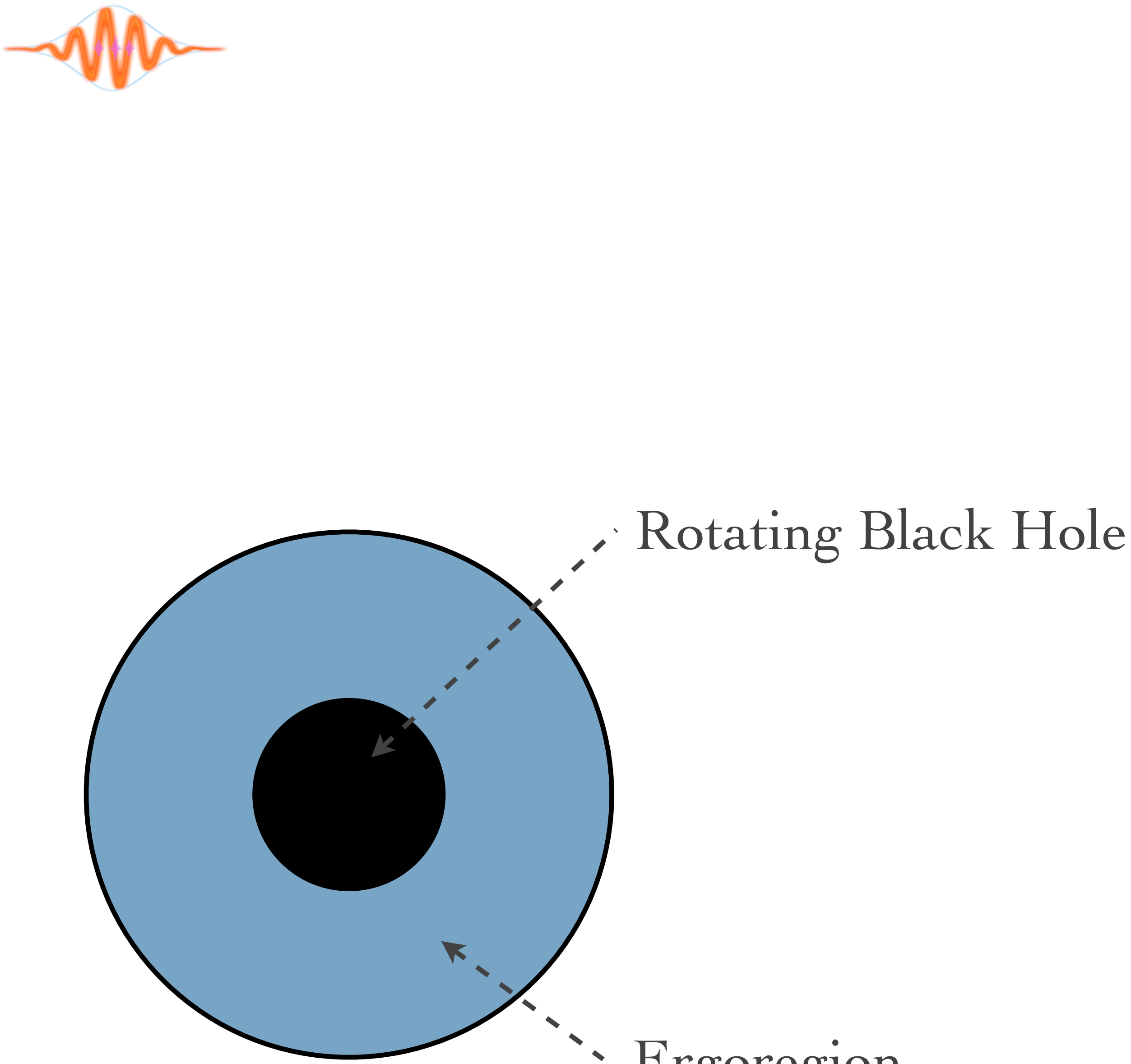
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

Penrose Process



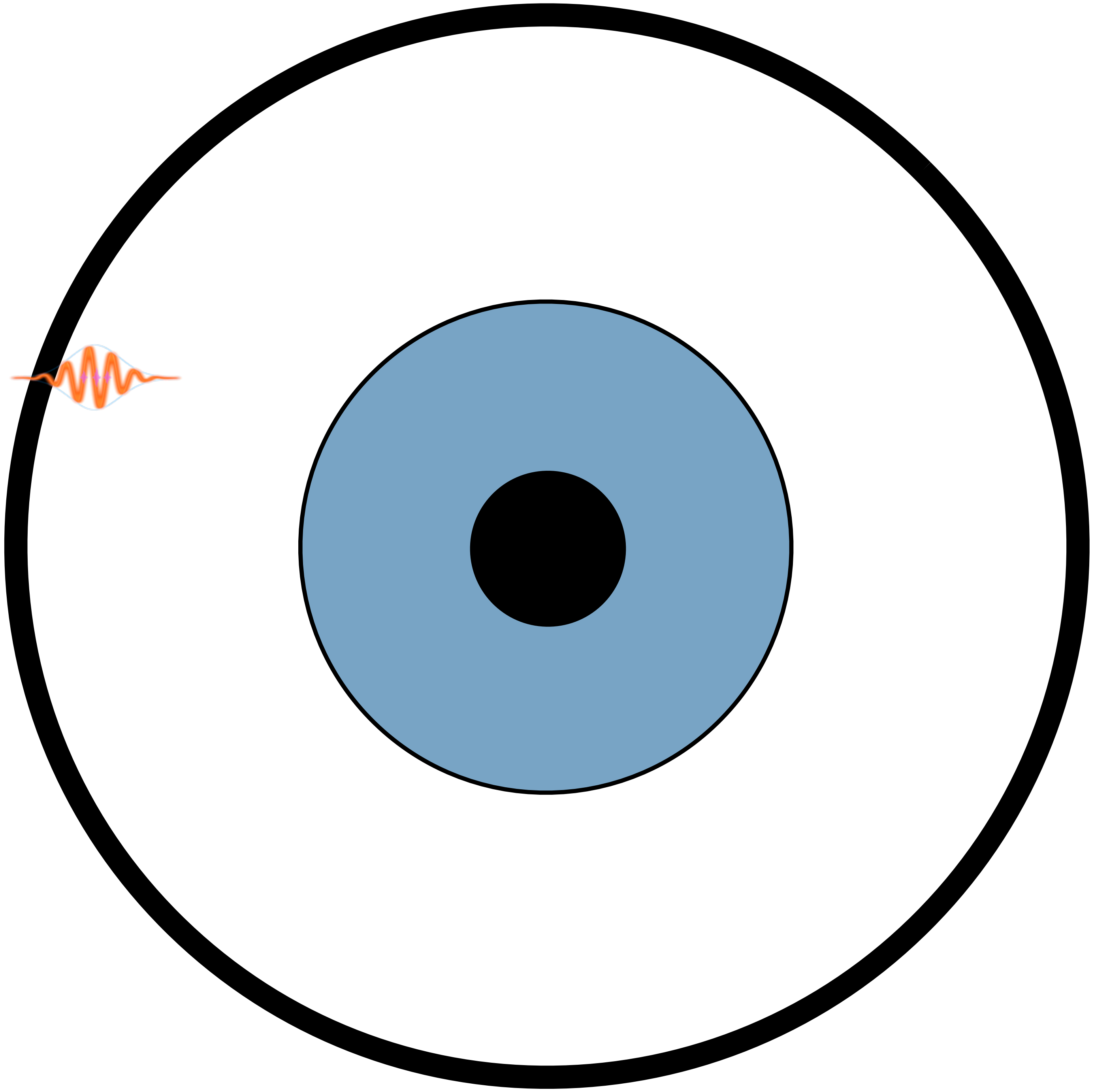
Rotating Black Hole

Ergoregion

Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

Press & Teukolsky 1972



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

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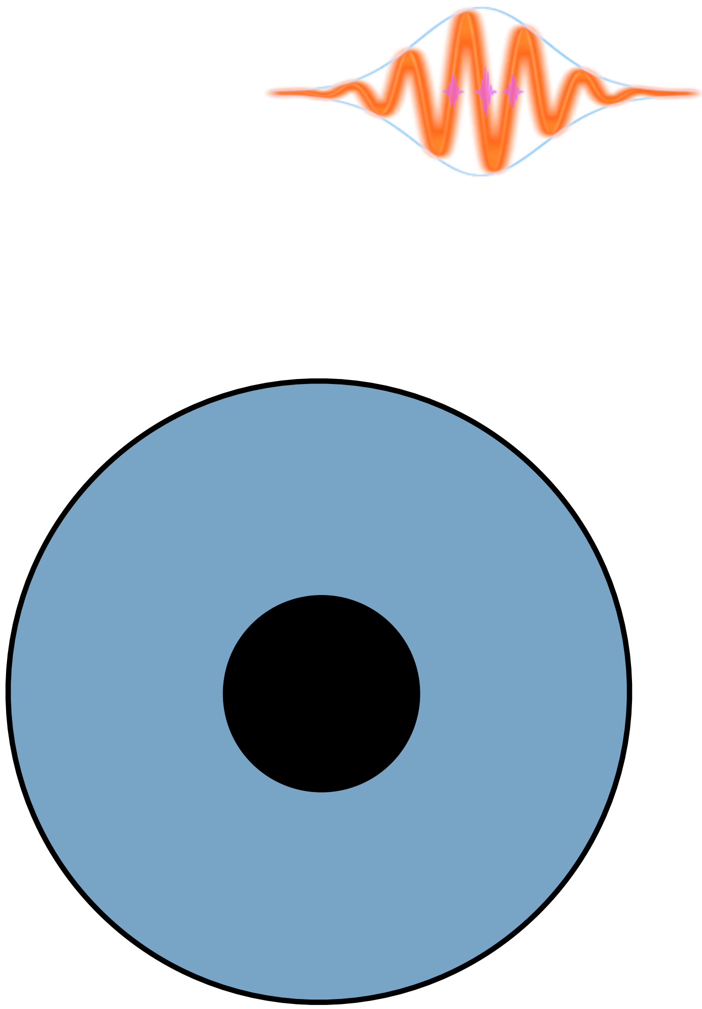

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Superradiance for a Massive Boson

Penrose Process

Damour et al; Zouros & Eardley;
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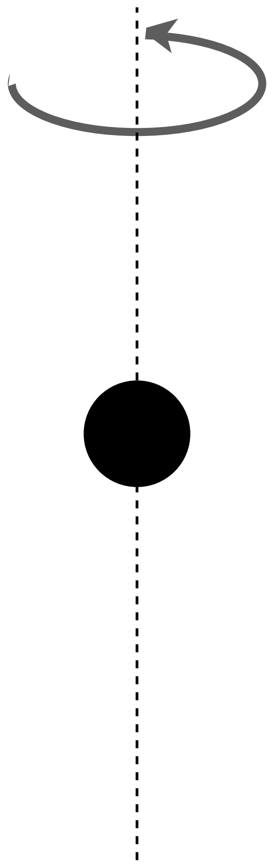

Particle Compton Wavelength comparable to the size of the Black Hole

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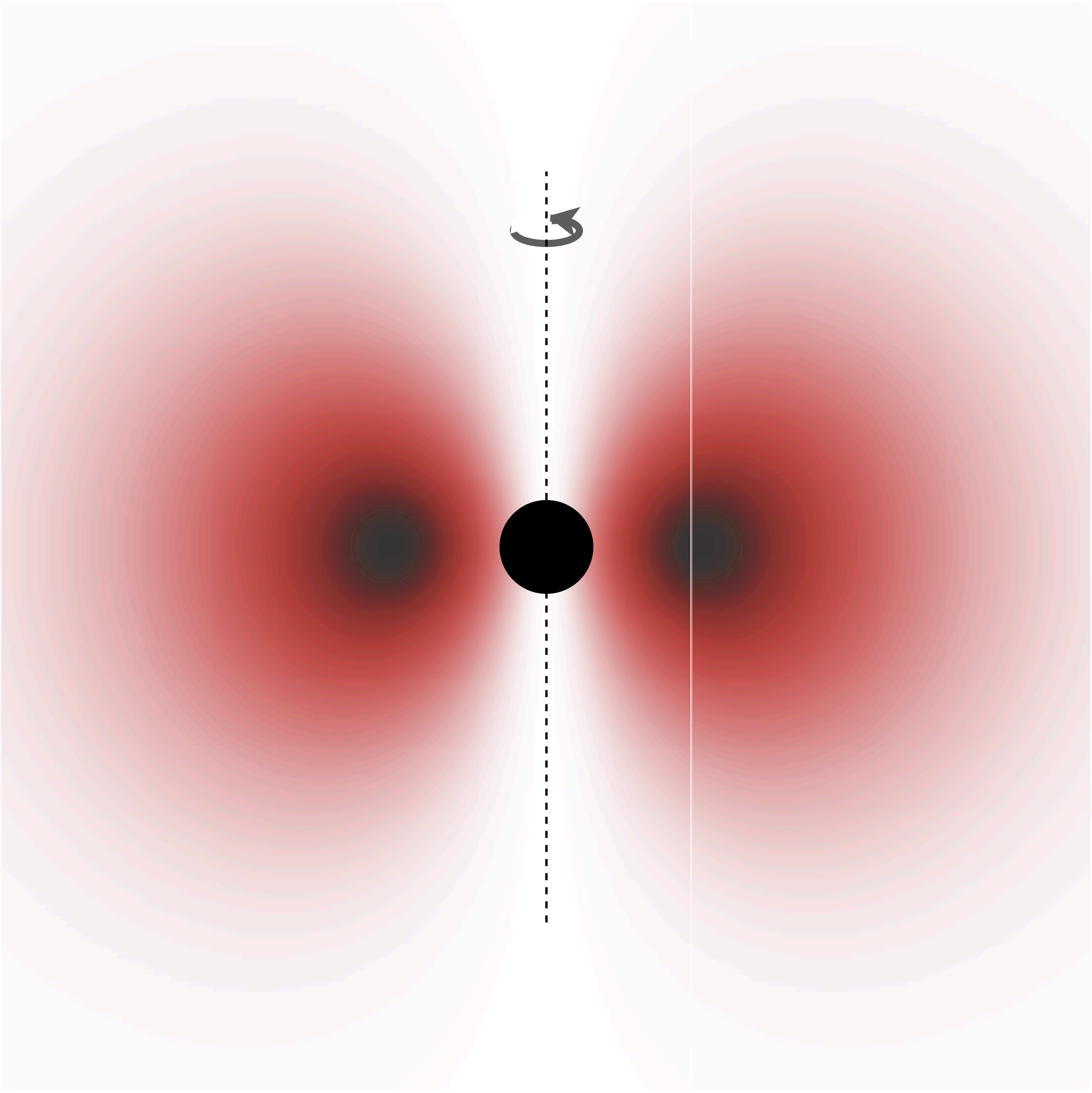

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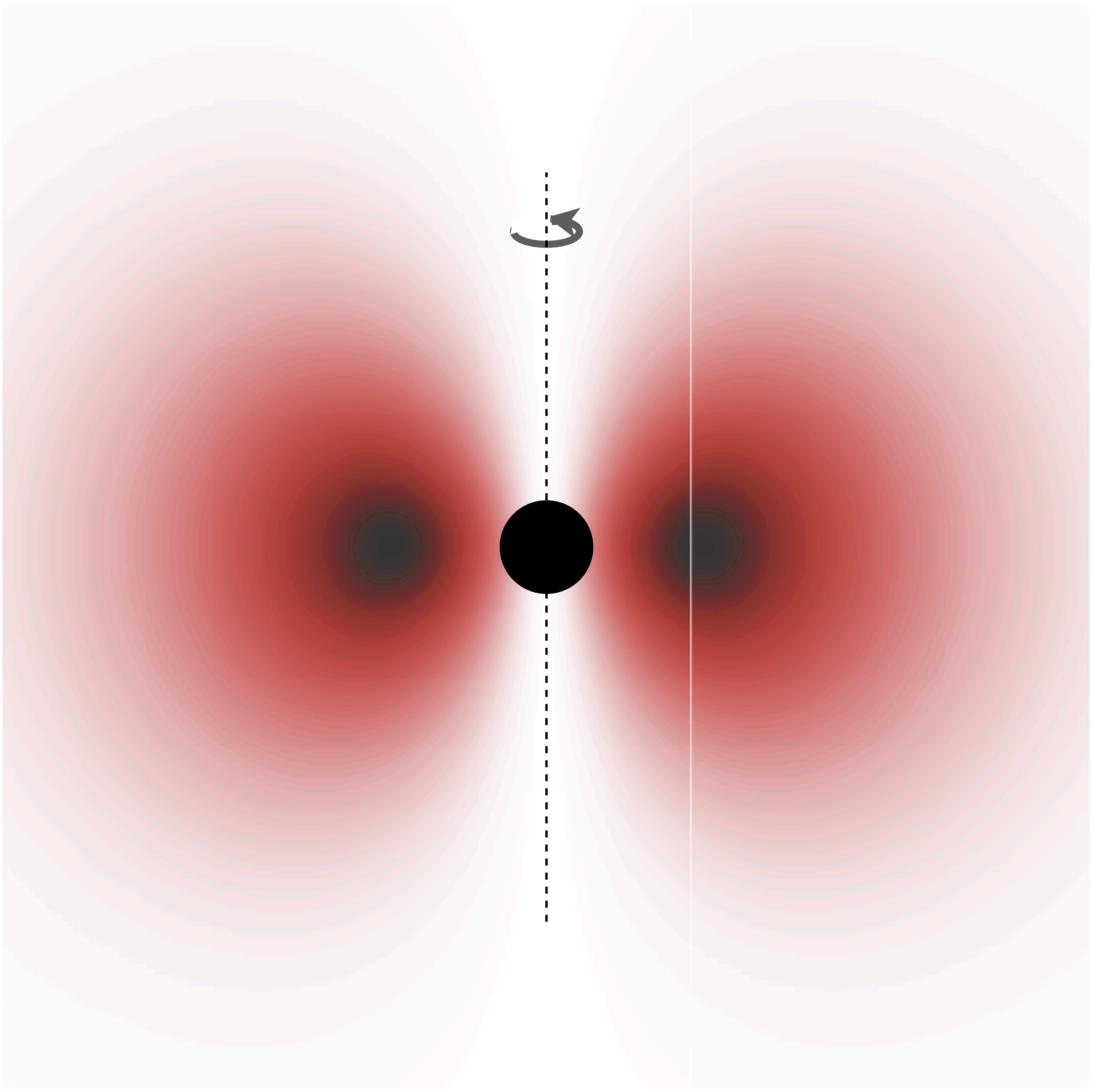

Gravitational Atom in the Sky

The Strong CP Problem

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

Non-zero electric dipole moment for the neutron

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

Solution:
$\theta_{\rm QCD}$ is a dynamical field, an axion

Axion mass from QCD:

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

f_a : axion decay constant

Evolution of Superradiance for an Axion

Superradiance instability time (100 sec minimum)

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

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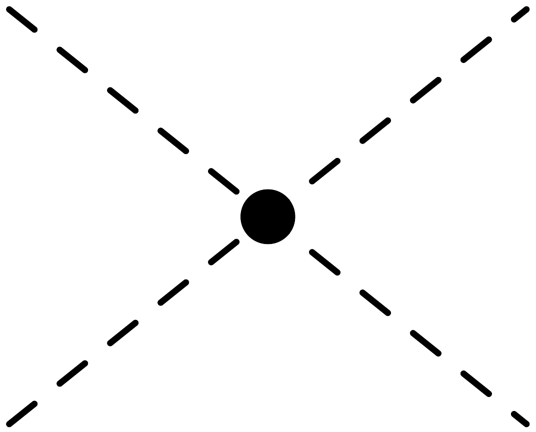
Axion self-interactions



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Superradiance instability time (100 sec minimum)

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Gravity wave transitions of axions between levels

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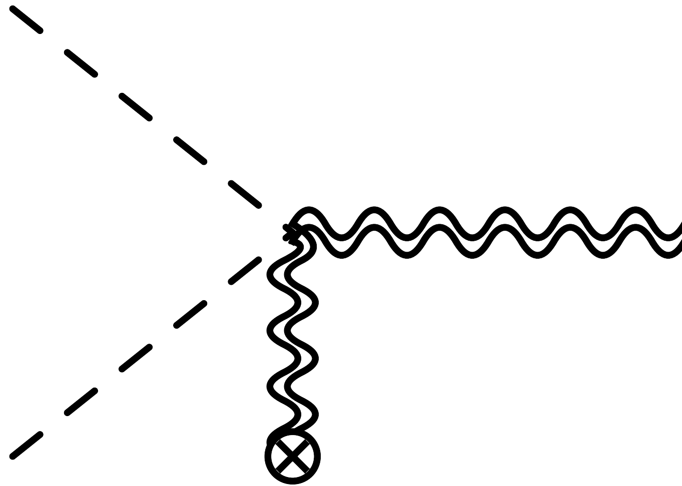
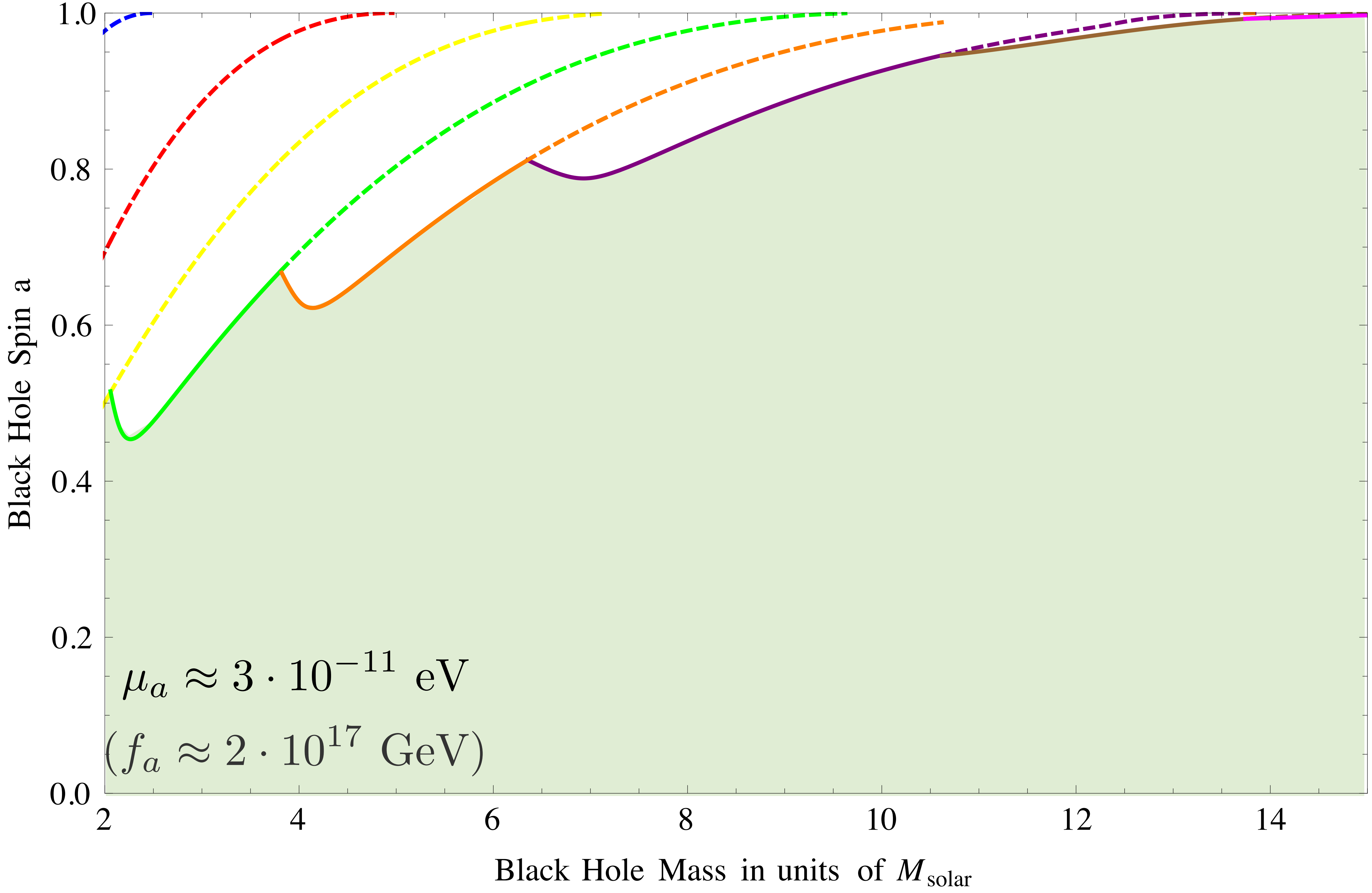
Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations



Spin Gap for the QCD Axion



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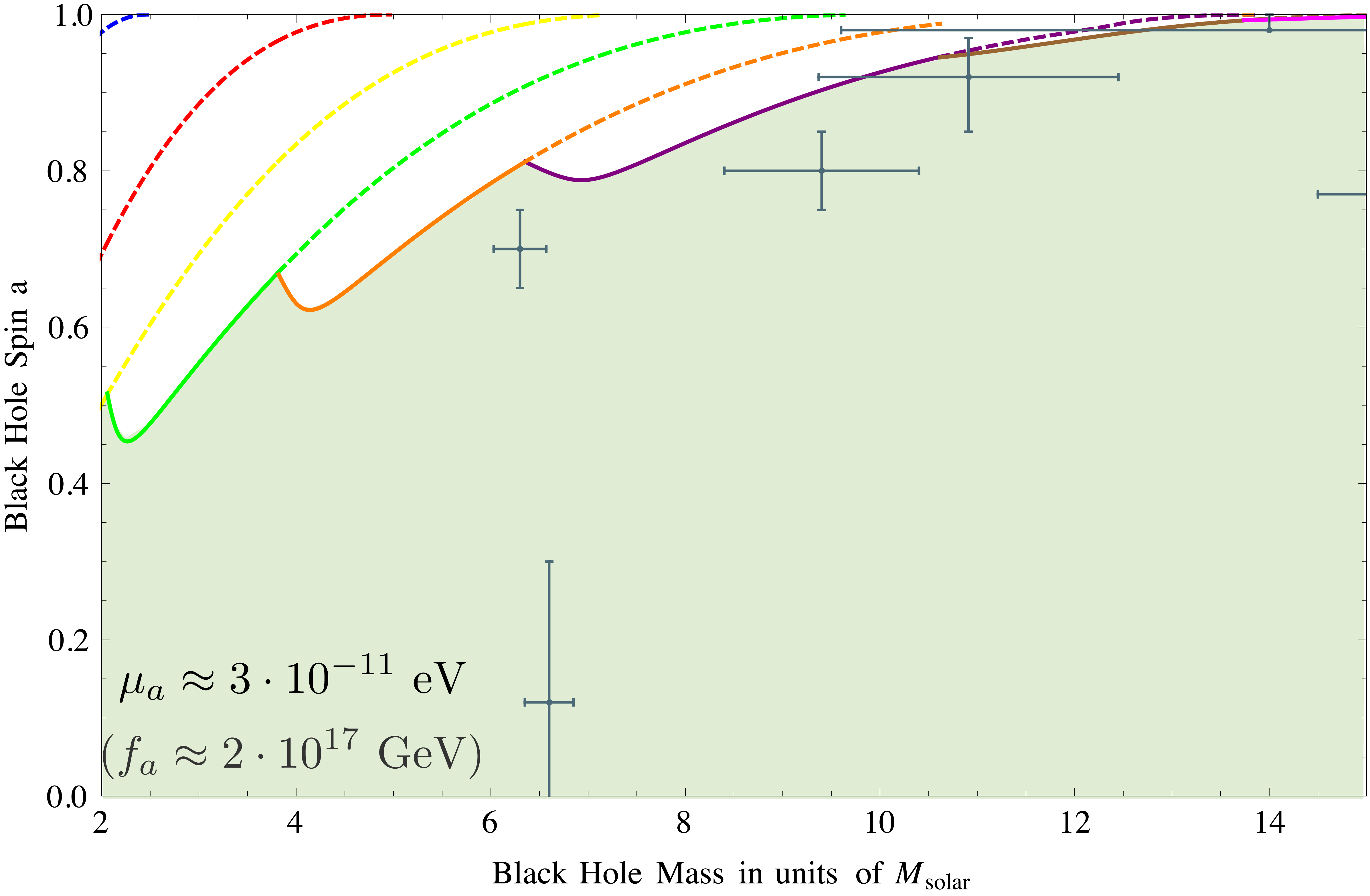

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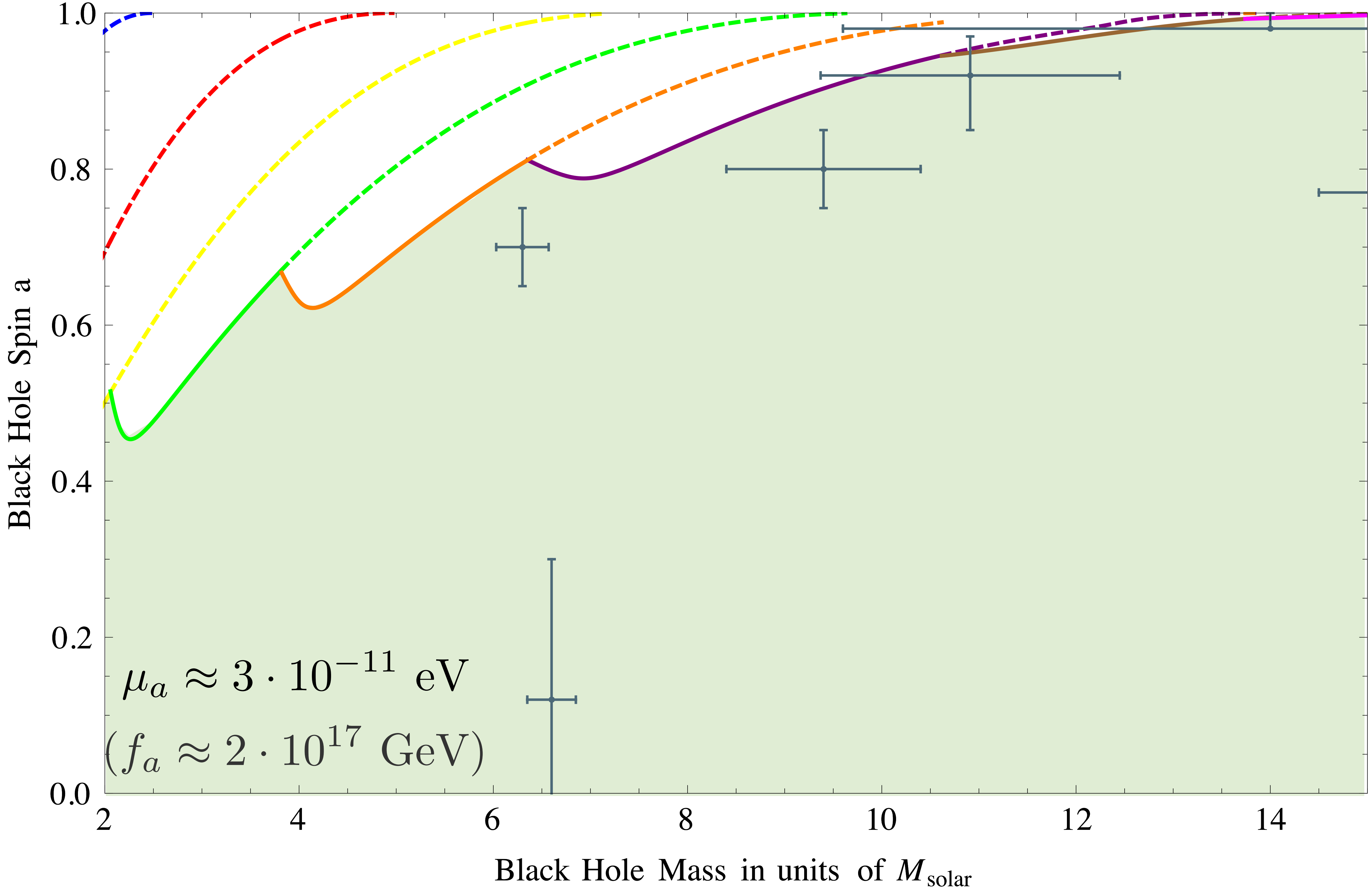
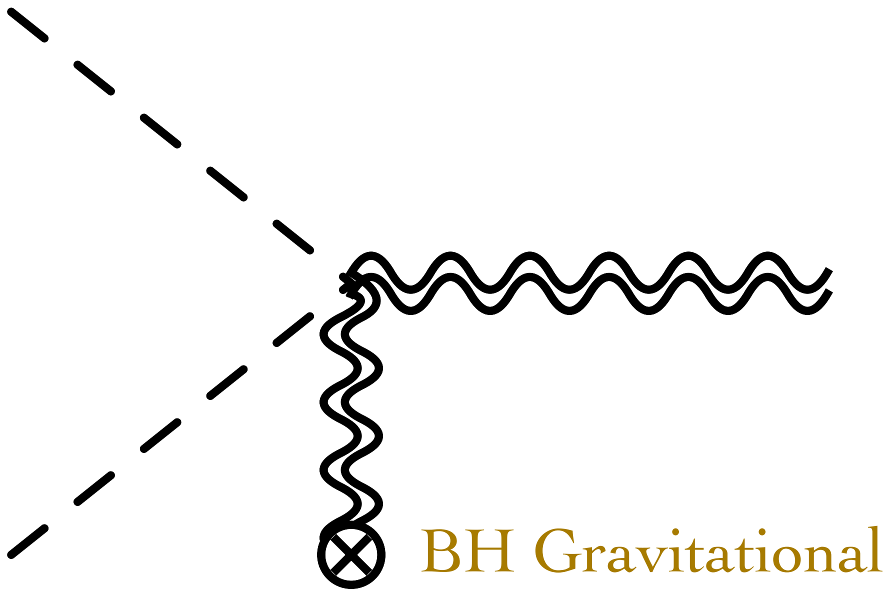


Possible to probe the QCD axion down to f_a ~few × 10^{16} GeV

Signals from annihilations



BH Gravitational field

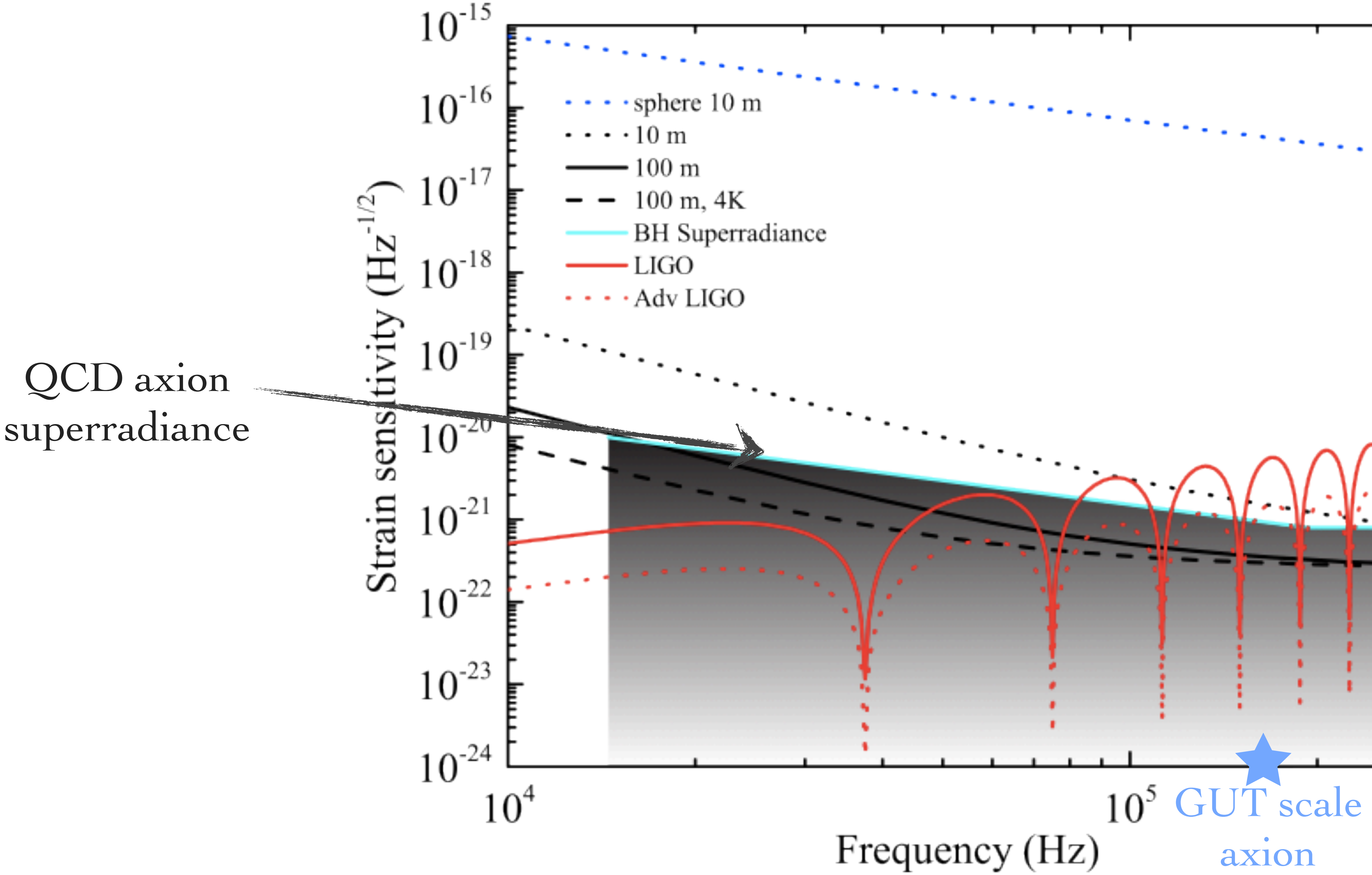
$\omega_{\text{graviton}} = 2\ m_{\text{axion}}$

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

$$h \sim 10^{-19}\left(\frac{\alpha}{\ell}\right)^7 \epsilon\left(\frac{10\ \text{kpc}}{r}\right)\left(\frac{M_{BH}}{2\times M_\odot}\right)$$

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

GWs from the QCD axion at high frequencies



Distance to the source: 10 kpc

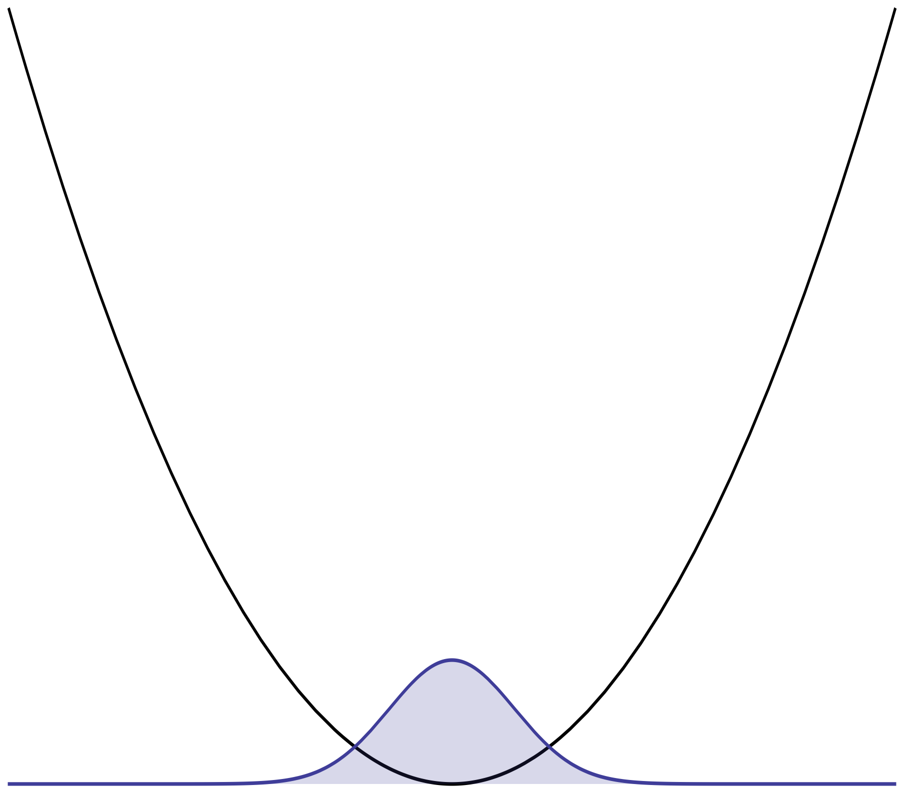
Prospects of GW detection with optically trapped sensors

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

Outline

- Gravitational Wave Detection
  - Sources of High-Frequency Gravitational Waves
- Future Prospects: Towards an interferometer of macroscopic objects

Towards the Schroedinger Cat State



- Feasible goal: Ground state cooling of the CM motion of $10^{8\text{-}9}$ atoms

Towards the Schroedinger Cat State

- Feasible goal: Ground state cooling of the CM motion of $10^{8\text{-}9}$ atoms

- Can we put the wave-function of 10^9 atoms in a superposition of spatially separated states?

Sources of Decoherence

- Black Body radiation emission
- Collisions with gas molecules
- Interaction with diffraction grating, holding light, etc.

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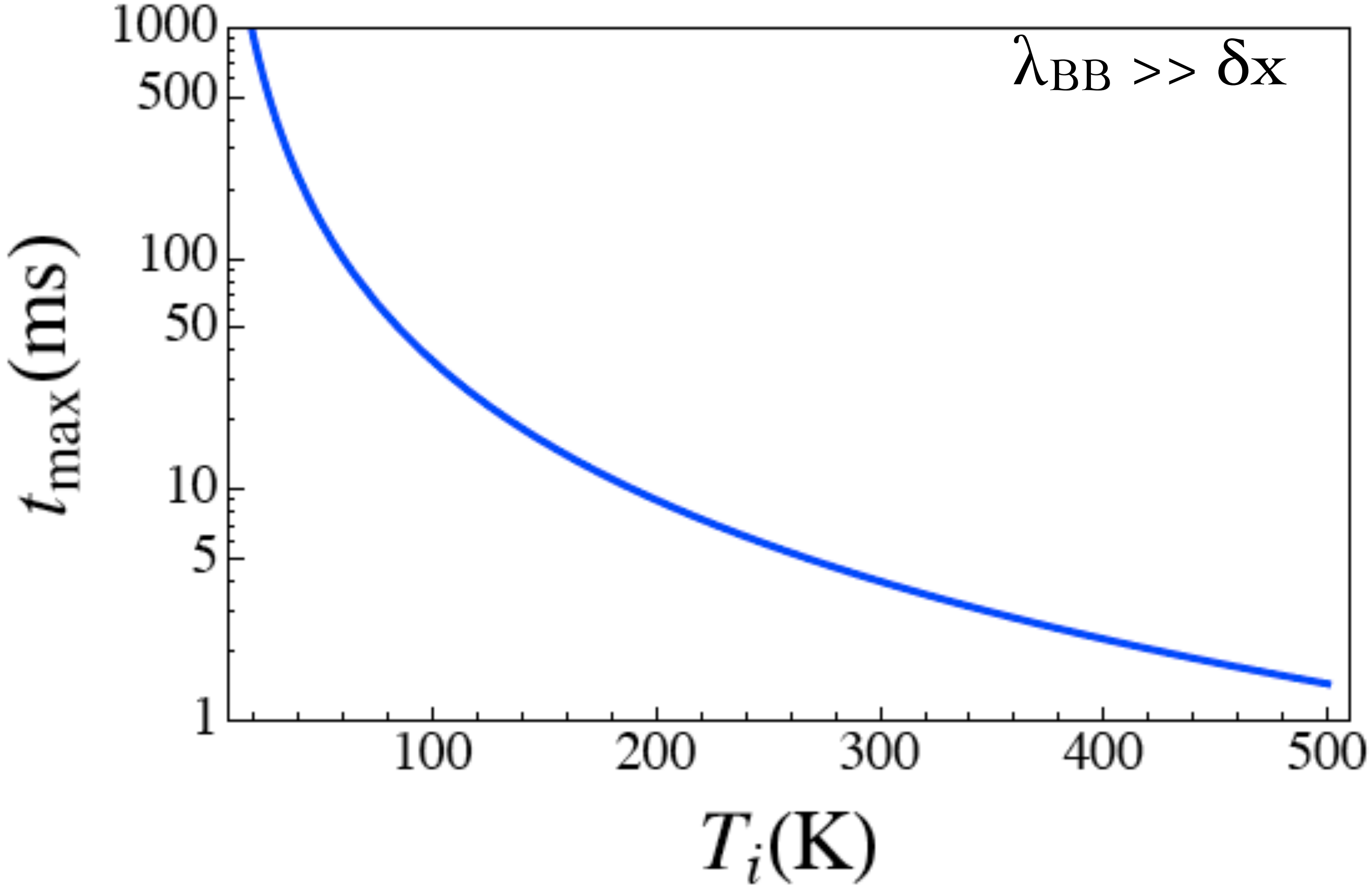
Decoherence from BB emission

Romero-Isart (2011)



For a 50 nm sphere with 0.1 nm separation

Decoherence from BB emission

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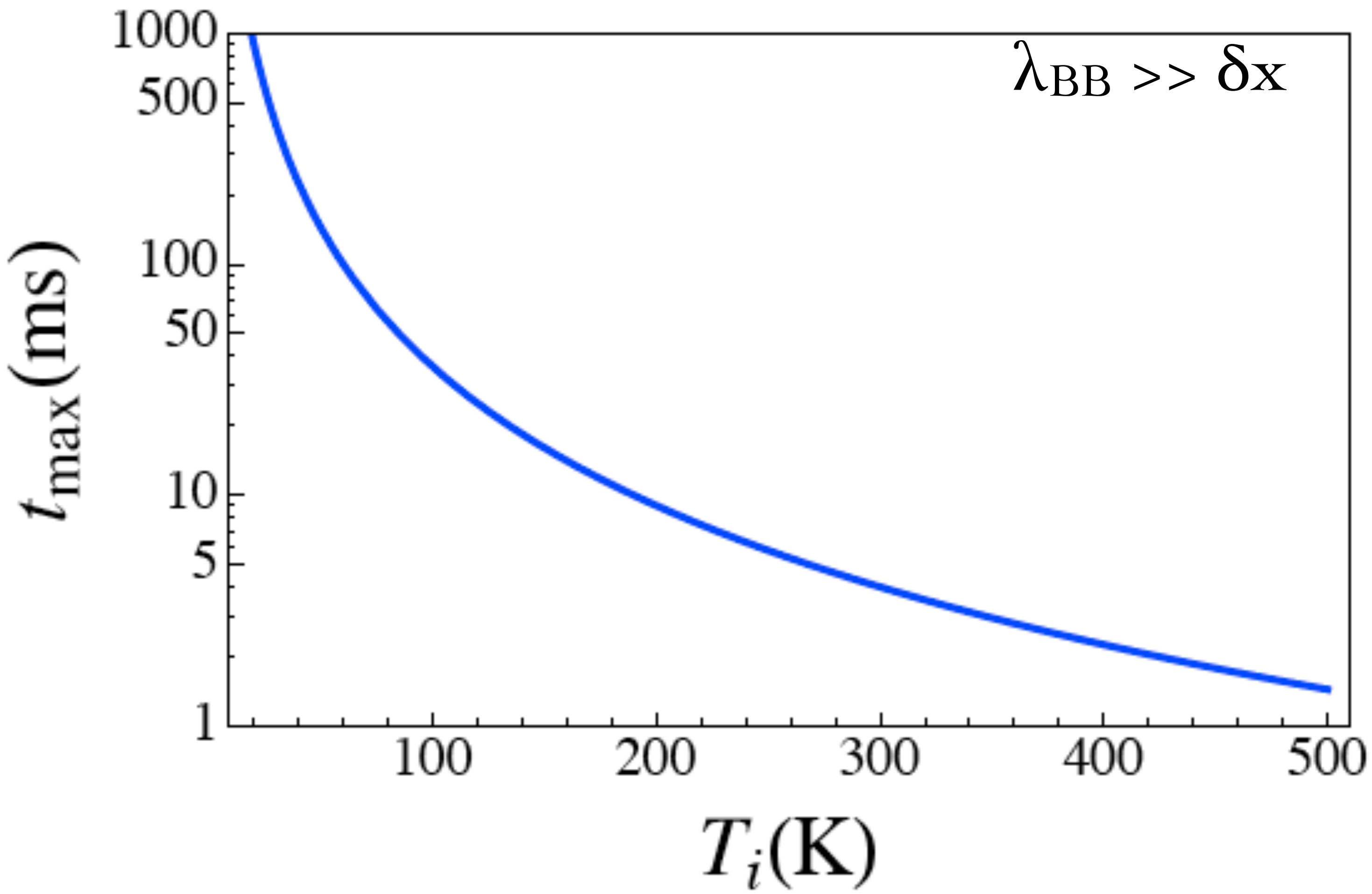


For a 50 nm sphere with 0.1 nm separation

100 ms is a long time

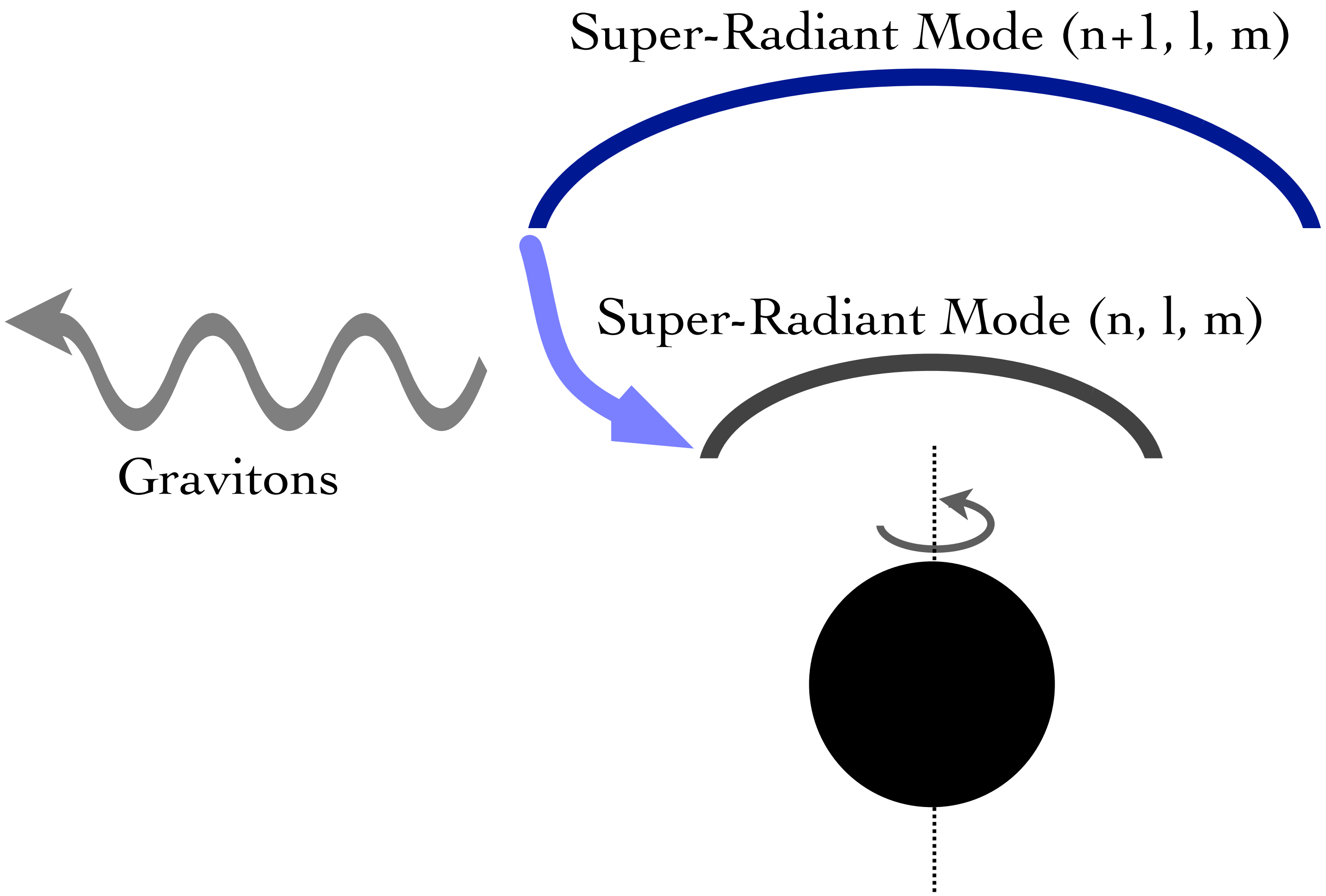
There may be a setup that actually works...

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

Gravity Wave Transitions



Super-Radiant Mode (n+1, l, m)

Super-Radiant Mode (n, l, m)

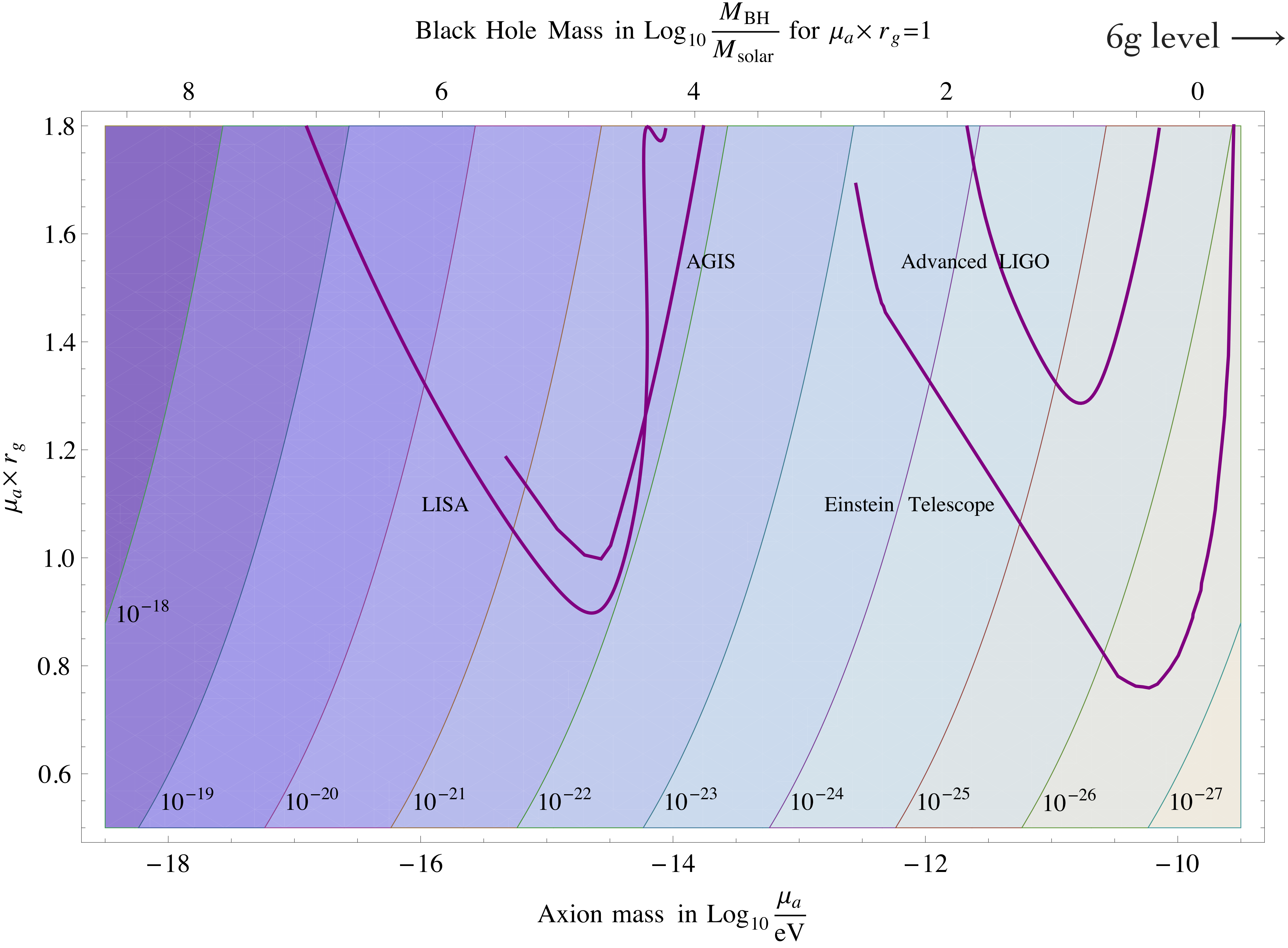
Gravitons

signal duration ~ 1 day-1 year

QCD axion observable at high frequency gravity wave detectors

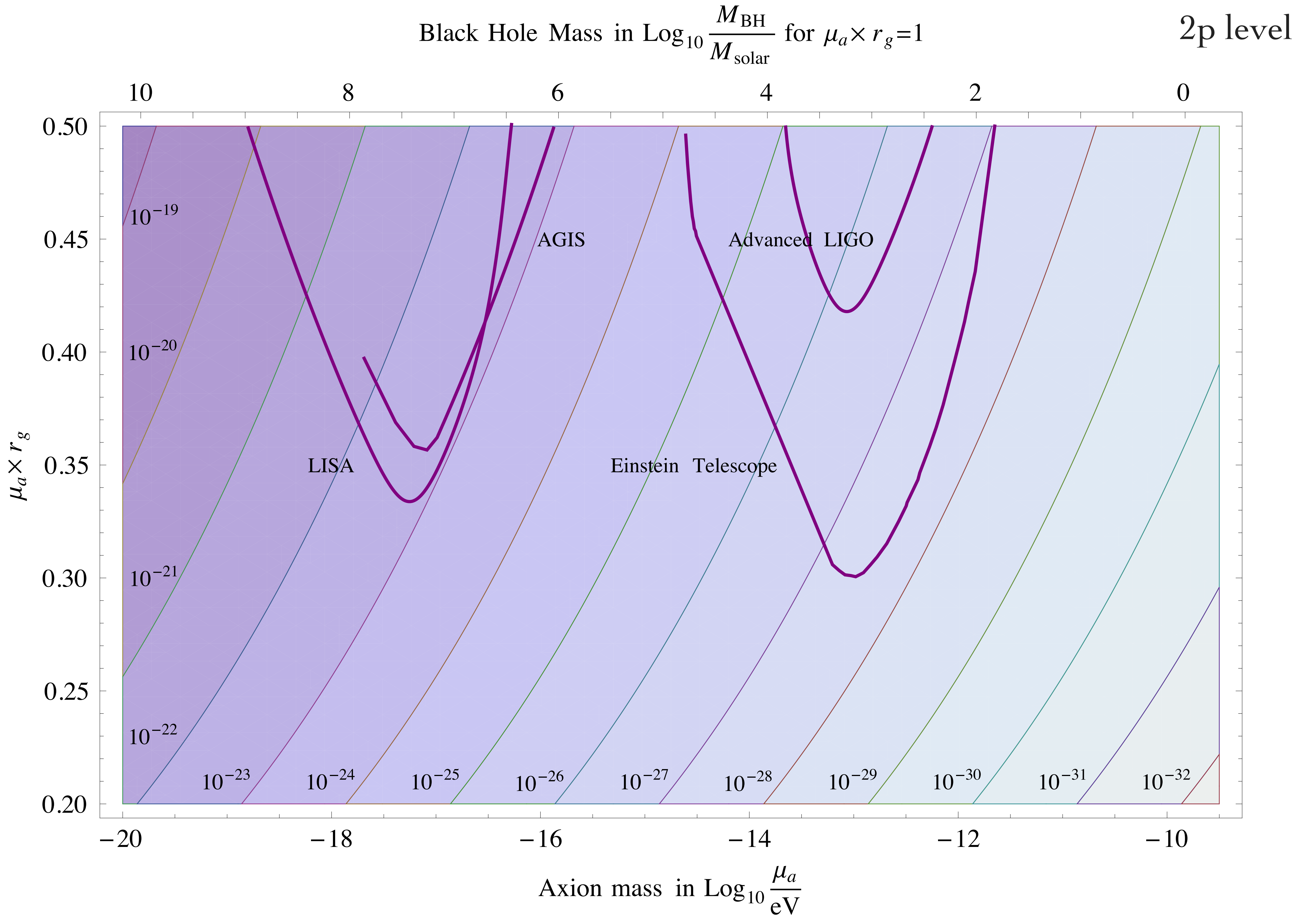
Gravity Wave Transitions

6g level ⟶ 5g level



Distance to the source: 20 Mpc

Signals from annihilations



Distance to the source: 20 Mpc