Fundamental Physics with Optically Levitated Objects

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with
Andrew Geraci (experiment)
and
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Optical Trapping of Dielectrics
Optical Trapping of Dielectrics


Force $\propto -\nabla E^2 \equiv -kx$
Optical Trapping of Dielectrics

- 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

Force $\propto -\nabla E^2 \equiv -kx$

Optical Trapping Applications

- Biology
- Quantum Computing
Towards the Quantum Regime

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

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

10^9 atoms in a quantum superposition of states
Optical Cooling
Doppler cooling

For an atom

\[ \omega_{\text{photon}} < \omega_{\text{atom}} \]

\[ v'_{\text{atom}} < v_{\text{atom}} \]
Optical Cooling

Doppler cooling

For an atom

\[ \omega_{\text{photon}} < \omega_{\text{atom}} \]

\[ v'_{\text{atom}} < v_{\text{atom}} \]

Spontaneous emission
Optical Cavity Cooling

For a trapped oscillating dielectric

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

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

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

$\omega_{\text{photon}}$
Optical Cavity Cooling

For a trapped oscillating dielectric

\[ \omega_{\text{photon}} < \omega_{\text{cavity}} \]

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

- 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

AA and Geraci (2012)
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

$L = L_0 \left(1 + h \cos \omega t\right)$
Gravitational Wave Detection

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

- Changes the physical position of the laser antinode:
  \[ \delta X_{\text{min}} = \frac{1}{2} \ell_m h \]
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:
  \[ \delta X_{\text{min}} = \frac{1}{2} \ell_m h \]

- Changes the physical distance between the sensor and the mirror:
  \[ \delta X_S = \frac{1}{2} x_s h \]
Gravitational Wave Detection

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

- Changes the physical position of the laser antinode:
  \[ \delta X_{\text{min}} = \frac{1}{2} \ell_m \hbar \]

- Changes the physical distance between the sensor and the mirror:
  \[ \delta X_s = \frac{1}{2} x_s \hbar \]

- Sensor position changes with respect to the trap minimum:
  \[ \Delta X = \frac{1}{2} (x_s - \ell_m) \hbar \]
Gravitational Wave Detection

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

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

- Main background: Thermal motion in the trap

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

![GW sensitivity graph](image)
GW sensitivity

150 nm sphere
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

Current and Advanced LIGO

LIGO: 4 km cavity
GW sensitivity compared to LIGO

Current setup: 100 m cavity

LIGO: 4 km cavity

Current and Advanced LIGO
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:

  Black Hole Super-radiance

  AA and Dubovsky (2010)
Black Hole Superradiance

Penrose Process

Ergoregion: Region where even light has to be rotating
Black Hole Superradiance

Penrose Process

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
Black Hole Bomb

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

Press & Teukolsky 1972
Superradiance for a Massive Boson

Particle Compton Wavelength comparable to the size of the Black Hole
Superradiance for a Massive Boson

Particle Compton Wavelength comparable to the size of the Black Hole
Superradiance for a Massive Boson

Penrose Process

Gravitational Atom in the Sky
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:
\( \theta_{\text{QCD}} \) 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 time (100 sec minimum)
Evolution of Superradiance for an Axion

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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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Axion self-interactions

Gravity wave transitions of axions between levels
Evolution of Superradiance for an Axion

Superradiance instability time (100 sec minimum)

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
Spin Gap for the QCD Axion

\[ \mu_a \approx 3 \cdot 10^{-11} \text{ eV} \]
\[ (f_a \approx 2 \cdot 10^{17} \text{ GeV}) \]
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Possible to probe the QCD axion down to \( f_a \approx \text{few} \times 10^{16} \text{ GeV} \)
Signals from annihilations

\[ \omega_{\text{graviton}} = 2 \, m_{\text{axion}} \]

**BH Gravitational field**

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

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

signal duration > years and \( \epsilon \sim 10^{-5} \)
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 $10^{-21}$ $1/\text{Hz}^{1/2}$ above $\sim30$ 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 $10^{8-9}$ atoms
Towards the Schroedinger Cat State

- Feasible goal: Ground state cooling of the CM motion of $10^{8-9}$ 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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- Black Body radiation emission \( \lambda_{BB} \gg \delta x \)
- Collisions with gas molecules
- Interaction with diffraction grating, holding light, etc.
Decoherence from BB emission

Romero-Isart (2011)

\[ \lambda_{BB} \gg \delta x \]

For a 50 nm sphere with 0.1 nm separation
Decoherence from BB emission

$\lambda_{BB} >> \delta x$

For a 50 nm sphere with 0.1 nm separation

100 ms is a long time

There may be a setup that actually works...

Romero-Isart (2011)
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

Black Hole Mass in $\log_{10} \frac{M_{BH}}{M_{\odot}}$ for $\mu_a r_g = 1$

Distance to the source: 20 Mpc

$6g$ level $\rightarrow 5g$ level
Signals from annihilations

Black Hole Mass in $\log_{10} \frac{M_{BH}}{M_{\odot}}$ for $\mu_a \times r_g = 1$

Distance to the source: 20 Mpc