The Levitated Sensor Detector for high-frequency gravitational wave detection

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Ultra high-frequency gravitational waves: where to next? CERN Dec. 4-8, 2023
Levitated optomechanics - brief introduction

- Ashkin, Bell Labs, 1970s  
  Optical tweezers → biology, biophysics
- Ashkin (76) Levitation in high vacuum

1. Polarisable neutral glass particles act as high field seekers - trapped in laser focus
2. When particle is approximately spherical, acts as 3 decoupled harmonic oscillators.
3. Characteristic length scale 10’s nanometers to 10’s microns.
4. High Q factors ~ $10^{12}$ → excellent force sensors
5. Can reduce the effective motional ‘temperature’ of such objects through feedback schemes
(Ground) state of the art:

Dynamical backaction: Measurement based cooling:
Fundamental limitation: thermal noise

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

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

\[
\frac{1}{2} k \langle x^2 \rangle = \frac{1}{2} k_B T
\]

\[
F_{\text{min}} = \left( \frac{4 k k_B T b}{Q \omega_0} \right)^{1/2}
\]
Improving sensitivity

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

Levitate the force sensor!

CM motion decoupled from environment – no clamping, materials losses
Projected Force sensitivity

\[ F_{\min} = \left(4k_B T \gamma m\right)^{1/2} \quad (1) \]

20 zN/Hz^{1/2} Gieseler, Novotny, Quidant (Nature Phys. 2013)


Photon recoil heating

Seen recently by Novotny group
V. Jain et. al., PRL 116, 243601 (2016)
Trap loading

\[ a \propto \frac{1}{R^2} \]

\(~10^7 \text{ g for } R=150\text{nm}\!\)
Trapping instabilities

• **Radiometric forces**

Trap instabilities arise from uneven heating of the sphere surface.

Important when mean free path $\sim$ object size

Crooke’s Radiometer
Radiometric forces

\[ F_T = \frac{\pi r^2 \eta \sqrt{\frac{\alpha R_g}{MT}} \Gamma_i}{\frac{P}{P_0} + \frac{F_0}{P}} \]

1% temp gradient across surface
R=1.5 \mu m, I=2 \times 10^9 W/m^2

Heating rate > gas damping rate \implies Particle loss \implies Need feedback!

Ranjit et.al., PRA 91, 051805(R) (2015).
3D feedback cooling of a nanosphere

Needed to stabilize the particle, damp and cool it
Mitigate photon recoil heating

\[ F_{\text{min}} = \sqrt{\frac{4kK_BTB}{\omega_0Q}} \]
\[ Q_{\text{eff}} = \frac{Q_0\Gamma_0}{\Gamma_0 + \Gamma_{\text{cool}}} \]
\[ T_{\text{eff}} = \frac{T_0\Gamma_0}{\Gamma_0 + \Gamma_{\text{cool}}} \]

Ranjit et.al., PRA 91, 051805(R) (2015).
Calibrated zN force sensitivity

Standing wave trap with counter-propagating beams

zeptonewton sensitivity in a standing wave trap w/ 3-D laser feedback cooling –

Gravitational waves

One of last predictions of GR to be tested
Discovered by LIGO Sep 2015 !!
Sources:
- Inspirals of astrophysical objects
- Inflation, Phase transitions, etc.

Dark Matter

• Zwicky detected its influence on cluster motions in the mid-1930s, Rubin detected it in galaxy rotation curves in the 1960s
• Its nature and origin is one of the most vexing problems in physics and astronomy
• One of strongest hints of physics beyond the Standard Model

Galactic Rotation Curves: much more gravity than from ordinary matter

Gravitational Lensing: “Bullet” cluster – separation of lensing from visible matter

Also: Structure formation, Cosmic Microwave background, ...

The Dark Sector

- New particles, fields, and forces may be lurking undetected because of their extremely weak coupling to ordinary matter.

- ~95% of the energy content of our universe is unknown to us!


Our best estimate for composition of universe. Image credit: ADMX
**Dark Matter**

Possible Dark Matter Mass Range:
- **Axions**: $\sim 10^{-2} \text{eV to } 10^{11} \text{eV}$
- **WIMPs**: $\sim 10^{-1000} \text{GeV}$
- **PBHs**: $10^{-22}$

Dimensions:
- **Hubble**
- **Particle-like**
- **Planck**

**Possible Mass Ranges**:
- $10^{-22}$ to $10^{-21}$
- $10^{-21}$ to $10^{-20}$
- $10^{-20}$ to $10^{-19}$
- $10^{-19}$ to $10^{-18}$
- $10^{-18}$ to $10^{-17}$
- $10^{-17}$ to $10^{-16}$
- $10^{-16}$ to $10^{-15}$
- $10^{-15}$ to $10^{-14}$
- $10^{-14}$ to $10^{-13}$
- $10^{-13}$ to $10^{-12}$
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- $10^{-11}$ to $10^{-10}$
- $10^{-10}$ to $10^{-9}$
- $10^{-9}$ to $10^{-8}$
- $10^{-8}$ to $10^{-7}$
- $10^{-7}$ to $10^{-6}$
- $10^{-6}$ to $10^{-5}$
- $10^{-5}$ to $10^{-4}$
- $10^{-4}$ to $10^{-3}$
- $10^{-3}$ to $10^{-2}$
- $10^{-2}$ to $10^{-1}$
- $10^{-1}$ to $10^{0}$
- $10^{0}$ to $10^{1}$
- $10^{1}$ to $10^{2}$
- $10^{2}$ to $10^{3}$
- $10^{3}$ to $10^{4}$
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- $10^{26}$ to $10^{27}$
- $10^{27}$ to $10^{28}$

**Range Breakdown**:
- **Wave-like**
- **Particle-like**
- **1eV/c^2**
Novel gravitational wave detector for > 10 kHz

- Laser intensity changed to match trap frequency to GW frequency
- For a 10m cavity, $h \sim 10^{-22}$ Hz $^{-1/2}$ at high frequency (100kHz)
- Limited by thermal noise in sensor (not laser shot noise) $\Rightarrow$ much better at high frequency!

Frequency landscape for gravitational waves

Distance to source: 1 kpc
(within our galaxy)

Axions:

Distance to source: 10 kpc
(within our galaxy)

PBHs:
1-meter Levitated Sensor Detector (LSD) prototype

The LSD Collaboration --  Experiment: AG(PI), Nancy Aggarwal (co-I), George Winstone (PD), Shelby Klomp (G), Aaron Wang (G), Peter J. Pauzauskie (UW), Greg Felsted (UW, G) Theory: Jacob Sprague (G), Shane Larson (co-I), Vicky Kalogera (co-I)
Levitated object optimization: disc/plate vs sphere

SiO₂ spheres

SiO₂ disks & NaYF hexagons

SiN/SiO₂/SiN stacks

Ideal sensor: high mass, high frequency, low photon recoil

• High-index end caps with low-index spacer
• Increased mass and internal reflections

• Less isotropic scattering reduces photon recoil noise

Optical trapping of NaYF hexagonal prisms

Hexagonal plate “stands up” with normal vector to face along the axis of the standing wave trap

Axial frequency (z-) highest due to intensity gradient along optical lattice

Figure of merit $\eta$ for GW detection

$$h_{\text{limit}} = \frac{4}{\omega_0^2} \sqrt{\frac{k_B T_{CM} \gamma_g b}{M}} \left[ 1 + \frac{\gamma_{sc}}{N_i \gamma_g} \right] H(\omega_0)$$

Ideal sensor: high mass, high frequency, low photon recoil

Thermal noise dominated

$$\eta_{\text{thermal}} \equiv \omega_0^2 \sqrt{M \rho l}$$

Photon recoil noise dominated

$$\eta_{\text{recoil}} = \omega_0^{3/2} \sqrt{M / \gamma_{sc}}$$

Future goal: Laser refrigeration of NaYF material

- Particles could withstand higher intensities
  → Pathway for MHz trapping frequencies → high bandwidth accelerometers and gravitational wave detectors

Search Range for the Levitated Sensor Detector (LSD)

Source modeling: Next talk by Jacob Sprague:

Summary

• Calibrated zeptonewton force sensing with optically levitated nanospheres
  → new approach for high frequency gravitational waves
  **Geometric methods to mitigate recoil heating, improve sensitivity**
  **Materials allow solid-state cooling** → **higher frequency detectors**

• Source modeling in process - PBHs, BH superradiance (axions, vector bosons)

• Future outlook: network of detectors planned: GOLDEN (Gravitational wave Observatory Levitated DEtector Network (UC Davis – N. Aggarwal, University College London – P. Barker, others?))
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