Fundamental Physics

Energy Frontier

Large Hadron Collider, CERN

- EDM experiments: search for supersymmetry

Precision Frontier

- Dark Matter: Axion Dark Matter Experiment (ADMX) uses $\mu$-wave cavity

Photo by CERN

http://www.phys.washington.edu/groups/admx/home.html
EDM experiments

Searching for extra CP Violation

- Neutrons
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

- Atoms
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto

- Ions-Muons
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- $|d_e| < 8.7 \times 10^{-29} \text{ e cm} \ (\text{ThO Molecule, ACME})$

- $(199\text{Hg}) < 7.4 \times 10^{-30} \text{ e cm}$, Seattle
  $\rightarrow < 1.2 \times 10^{-26} \text{ e cm}$ for nedm (95%)

- $n_{\text{edm}}$ (direct, trapped Ultracold Neutrons) $< 3.6 \times 10^{-26} \text{ e cm}$ (95%)

EDM measurements probing physics beyond energy scale of LHC

Adapted from “EDM Searches”, K. Kurch, PSI

ACME Collaboration: Science 1248213 (2013)
Fundamental physics

Searching for particles on a benchtop

Making precise measurements of tiny forces

Jan 28th 2017

The beams of protons that circulate around the 27km-circumference ring of the Large Hadron Collider (LHC), the world’s biggest particle accelerator, carry as much kinetic energy as an American aircraft-carrier sailing at just under six knots. Andrew Geraci’s equipment, on the other hand, comprises a glass bead 300 billionths of a metre across, held in a lattice of laser light inside an airless chamber. The power it consumes would run a few old-fashioned light bulbs. Like researchers at the LHC, Dr Geraci and his team at the University of Nevada, in Reno, hope to find things unexplained by established theories such as the Standard Model of particle physics and Newton’s law of gravity. Whereas the LHC cost around SFr4.6bn ($5bn) to build, however, Dr Geraci’s set-up cost a mere $300,000 and fits on a table about a metre wide and three long.
Goal of these lectures

• Focus on small-scale (i.e. non-accelerator, non-large scale DM detectors) experiments
• Give particle physics students sense of experimental techniques available, newly developing techniques, what they may be useful for
• Generate new ideas for experiments in the future?!
Syllabus

- Introduction
- New (scalar) forces
- Gravitational Waves and Ultralight Dark Matter
- New (spin-dependent) forces
  (relation to axions, EDMS, Cosmic DM experiments)
Outline for Lectures

• Lecture 1 –
  New (scalar) Forces
  Background/Motivation
  Gravitational experiments
  Principles of Force sensing
  New Techniques:
    → Optical levitation
    → Atomic-based sensors
    → Matter-wave interferometry
Outline for Lectures

• Lecture 2 –
  -Gravitational waves

    New Techniques:
    → Levitated sensors
    → Atom interferometry

  -Ultralight scalar field dark matter
Outline for Lectures

• Lecture 3 –
  New (spin-dependent) forces
    Background
    Torsion balance tests
    Magnetometry
    New techniques: (ARIADNE)
    Relation to axions, EDM experiments, Cosmic DM experiments
Syllabus for Lectures

• Lecture 1 – New (scalar) Forces

  Background/Motivation
  Gravitational experiments
  Principles of Force sensing
  New Techniques:
  ➔ Optical levitation
  ➔ Matter-wave interferometry
The Hierarchy Problem: Why is Gravity so small?

For two protons in nucleus:

**Strong**: Holds nucleons together

**Electromagnetic**: Acts between charged particles

**Weak**: Causes certain decays

**Gravity**: Attraction between masses

The Interactions:

- **Strong**: Holds nucleons together
- **Electromagnetic**: Acts between charged particles
- **Weak**: Causes certain decays
- **Gravity**: Attraction between masses

The Standard Model Provides an adequate description of the electromagnetic, weak, and strong interactions.
Solving the Hierarchy Problem

Supersymmetry?
Searching for it now at LHC!

Quantum Gravity $\sim 10^{19}$ GeV

Electro-weak $\sim 10^3$ GeV

Large Extra Dimensions (sub-mm)?

Gravity’s mass (i.e. Planck) scale of $\sim 10^{19}$ GeV

Is **not** a fundamental scale. Its magnitude comes from the size of the extra dimensions.

These effects may cause gravity to change below a characteristic scale $\lambda < 1$ mm:

- Change its power law from $1/r$
- Acquire a new exponential form

Can we measure this?
1) Light Moduli

Moduli: Massless scalar particles generic in string theory
- describe the shape and size
  of (small OR large) extra dimensions

Moduli must become massive to avoid conflict with experiment

Mass may come from Supersymmetry breaking

Gravity-Mediated
(high scale $10^{11}$ GeV)

Moduli at EW scale

Gauge Mediated
(scale can be low ~30 TeV)

Moduli are light (mm$^{-1}$) → Observable signatures!

Standard Model Couplings

- Yukawa couplings $\rightarrow$ masses of quarks, leptons $\sim \lambda_{ij}(\phi)\bar{u}_iQ_jH_u$
- Gauge couplings $\rightarrow$ W,Z bosons, gluons $\sim \lambda_g\frac{\phi}{M}G^a_{\mu\nu}G^{\mu\nu a}$

e.g. 2 nucleons can exchange gluon modulus:

\[ V = -\frac{G_N m_1 m_2}{r}(1 + \alpha e^{-\frac{r}{\lambda}}) \]

range $\lambda$(mm) $\approx 0.8 \frac{(100\text{ TeV})^2}{F} \left( \frac{M \lambda_g^{-1}}{5 \times 10^{17}\text{ GeV}} \right)$

Strength relative to gravity $\alpha \propto \left( \frac{5 \times 10^{17}\text{ GeV}}{M} \right)^2 \lambda_g^2$
2) Large Extra Dimensions


Standard Model fields confined to a “brane”, except gravity

Gravity is “diluted” by the volume of extra space

\[ L \supset \int d^4xd^n y M_*^{2+n} \sqrt{G}R \quad \rightarrow \quad \int d^4x M_{pl}^2 \sqrt{G}R \]

\[ V_n M_*^{2+n} = M_{pl}^2 \]

Now \( M_* \) can be closer to weak scale at \( \sim \text{TeV} \)

No more fine-tuning problem

For \( V_n \sim L^n \), taking \( n=2 \), \( L \) can be \( 1 \text{mm} \) for \( M_* \sim \text{TeV} \)

--Newton’s law changed below radius of compactification

\[ F(r) = \frac{G(4)m_1m_2}{r^2} \quad \rightarrow \quad \frac{G(4+n)m_1m_2}{r^{2+n}} \]
Gauge particles in the bulk


1) can mediate forces $10^6 \times$ gravity
2) range of zero mode not limited by the radius of compact dimensions (so $n>2$ still accessible to tabletop)

Example – gauged baryon 

$$F_{\text{gauge}} \propto g_4^2 \quad \frac{F_{\text{gauge}}}{F_{\text{gravity}}} = \frac{g_4^2}{G_N m_{\text{nucleon}}^2}$$

$$\approx \frac{M^2_*}{m_{\text{nucleon}}^2} \approx 10^6 - 10^8$$

$$m_{A_\mu} \approx g_4 M_* \approx (\text{mm}^{-1})$$

---

Our brane --

---

gauge symmetry broken spontaneously by some “Higgs” field with vev $\approx M^*$
Scalars in Bulk

“Yukawa Messengers”


- Also can get sub-mm range from SUSY breaking
- Coupling much stronger than moduli, and independent fundamental scale M*

$$\rho \ll \chi_0$$

but compare to gravity:

$$\rho^2 \approx 10^6$$

Effective coupling to the zero mode

$$\rho = \frac{\nu}{M_{Pl}} \approx 10^{-16}$$

- quite strong
- independent of “n”
- Independent of M*

Both vectors and scalars in the bulk can also produce a Yukawa-potential:

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

$$\alpha > 0 \text{ attractive (scalar)}$$

$$\alpha < 0 \text{ repulsive (vector)}$$
Testing gravity at short range

\[ V_N = -G \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

Exotic particles (new physics)

- \( \lambda < 1 \text{ mm} \)
  - Supersymmetry/string theory (moduli, radion, dilaton)
  - Particles in large extra dimensions (Gravitons, scalars, vectors?)
Landscape for ISL corrections

\[ V_N = -G \frac{m_1 m_2}{r} \left(1 + \alpha e^{-r/\lambda} \right) \]


Experimental challenge: scaling of gravitational force

\[ V_N = -G \frac{m_1 m_2}{r} \]

\[ F_N = G_N \frac{\rho^2 (4\pi r^3 / 3)^2}{4r^2} \sim G_N \rho^2 r^4 \]

\[ F_N \approx 0.1 r^4 \text{ for } \rho \sim 20 \text{ gr/cm}^3 \]

In the range of experimental interest:

\[ r \sim 10 \mu m ; \quad F_N \sim 10^{-21} N \]
Small forces

• Bathroom scales measure $10^{-1} N$
  
  - Dust mite $10^{-7} N$
  - E. coli $10^{-15} N$
  - Virus $10^{-19} N$
  - Carbon atom $10^{-25} N$

• AFM measures $10^{-11} N$

70 kg ~ 700 N
Experimental challenge: Electromagnetic Background forces

Casimir effect (1948):

Electrostatic Patch Potentials:

\[ F_C(z) = \frac{\pi^2}{240} \frac{\hbar c}{z^4} A \]

J. L. Garrett, D. Somers, J. N. Munday
UW Torsion Balance Experiments

Best yukawa constraints at ~ 10 µm – 5 mm range

1x Gravity tested at ~50 µm

Kapner et. al., PRL 98, 021101 (2007)
C.D. Hoyle et. al., PRL 86, 1418 (2001)


Future: Cryogenic torsion balance experiments with improved sensitivity!
Micro- and nano- resonators

Kapitulnik group, Stanford

Best yukawa constraints at ~ 10 um range:


Next generation apparatus

Yukawa phase space

\[ V_N = -G \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

Cantilevers (Stanford)

Torsion oscillators (Colorado, IU)

Casimir Measurements

Torsion balance experiments (U Washington)
Resonant force detection

- Cantilever is like a spring:

\[ F = -Kx \]

\[ \omega_0 = \sqrt{\frac{K}{m}} \]

\[ A_{(\omega=0)} = \frac{F}{k} \quad \text{Constant force} \]

\[ A_{(\omega=\omega_0)} = \frac{F}{k}Q \quad \text{Driving force on resonance of cantilever } \omega_0 \]

Q can be very large >100,000
Dissipation

\[ E = \frac{1}{2} m \dot{x}^2 + \frac{1}{2} k x^2 \]

Energy stored in oscillation
Dissipation

\[ E = \frac{1}{2} mx^2 + \frac{1}{2} kx^2 \quad \text{Energy stored in oscillation} \]

\[ Q \equiv 2\pi \frac{E}{\delta E} \quad \text{Energy stored in oscillation} / \text{energy dissipated in 1 cycle} \]
Dissipation

\[ E = \frac{1}{2} m\dot{x}^2 + \frac{1}{2} kx^2 \]

Energy stored in oscillation

\[ Q \equiv 2\pi \frac{E}{\delta E} \]

Energy stored in oscillation / energy dissipated in 1 cycle

\[ m\ddot{x} = -kx - \gamma\dot{x} \]

\[ Q \approx \frac{\sqrt{mk}}{\gamma} \]

Plays crucial role in force detection
Cantilever response

\[ \ddot{x} + \omega_0^2 x + \gamma \dot{x} = \frac{F(t)}{m} \]

For a harmonic driving force: \( F(t) = f_0 e^{-i\omega t} \)

\[ -\omega^2 \dot{x} + \omega_0^2 x - i\gamma \omega x = \frac{f_0}{m} \]
Cantilever response

\[ \ddot{x} + \omega_0^2 x + \gamma \dot{x} = \frac{F(t)}{m} \]

For a harmonic driving force: \( F(t) = f_0 e^{-i\omega t} \)

\[-\omega^2 \ddot{x} + \omega_0^2 x - i\gamma \omega x = \frac{f_0}{m} \]

Susceptibility:

\[ \chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m} \left( \frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma} \right) \]

DC: \( \omega \to 0, x = \frac{f_0}{k} \)

\[ \lim_{\omega \to \infty} \chi(\omega) = -\frac{1}{m\omega^2} \]
Cantilever response

\[ \chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m} \left( \frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma} \right) \]

Steady state \( x(t) \) in presence of driving force

\[ f_0 \cos(\omega t) \]

\[ x(t) = \text{Re}\left[ \chi(\omega) f_0 e^{-i\omega t} \right] \]

\[ = \text{Re}\left[ \chi(\omega) |f_0 e^{-i\omega t} e^{i\phi} | \right] \]

\[ = f_0 |\chi(\omega)| \cos(\omega t - \phi(\omega)) \]
Cantilever response

\[ \chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m} \left( \frac{1}{-\omega^2 + \omega_0^2 - i\omega\gamma} \right) \]

Steady state \( x(t) \) in presence of driving force

\[ f_0 \cos(\omega t) \]

\[ x(t) = \text{Re} \left[ \chi(\omega) f_0 e^{-i\omega t} \right] \]
\[ = \text{Re} \left[ |\chi(\omega)| f_0 e^{-i\omega t} e^{i\phi} \right] \]
\[ = f_0 |\chi(\omega)| \cos(\omega t - \phi(\omega)) \]

\[ |\chi(\omega)| = \frac{1}{m} \frac{1}{\sqrt{\left( \omega^2 - \omega_0^2 \right)^2 + \omega^2 \gamma^2}} \]

\[ \tan \phi(\omega) = \frac{\omega \gamma}{\omega_0^2 - \omega^2} \]
Cantilever response

\( \chi(\omega) = \frac{x(\omega)}{f(\omega)} = \frac{1}{m} \left( \frac{1}{\omega^2 + \omega_0^2 - i \omega \gamma} \right) \)

Steady state \( x(t) \) in presence of driving force

\[
 f_0 \cos(\omega t) \\
 x(t) = \text{Re} \left[ \chi(\omega) f_0 e^{-i\omega t} \right] \\
 = \text{Re} \left[ |\chi(\omega)| f_0 e^{-i\omega t} e^{i\phi} \right] \\
 = f_0 |\chi(\omega)| \cos(\omega t - \phi(\omega))
\]

\[
|\chi(\omega)| = \frac{1}{m} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + \omega^2 \gamma^2}}
\]

\[
\tan \phi(\omega) = \frac{\omega \gamma}{\omega_0^2 - \omega^2}
\]

Amplitude:

\[
A(f) = A_{dc} \sqrt{\frac{f_0^2}{\left( f_0^2 - f^2 \right)^2 + \frac{f_0^2 f^2}{Q^2}}}
\]
Dissipation

\[ \frac{dW}{dt} = F(t)\dot{x}(t) \]

Steady-state dissipated power:

\[ P = \frac{1}{2} \omega f_0^2 |\chi(\omega)| \sin \phi(\omega) = \frac{1}{2} f_0^2 \omega \text{Im}[\chi(\omega)] \]

\[ \text{Im}[\chi(\omega)] = \frac{1}{m} \frac{\omega \gamma}{(\omega^2 - \omega_0^2)^2 + (\omega \gamma)^2} \]

On resonance:

\[ P = \frac{1}{2} f_0^2 \frac{1}{m \gamma} \]
Fundamental limitation: thermal noise

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

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

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

\[
F_{\text{min}} = \left( \frac{4 k k_B T b}{Q \omega_0} \right)^{1/2}
\]
Fundamental limitation: thermal noise

- White noise background due to finite $T$ of oscillator

\[ S_X(\omega) = |\chi(\omega)|^2 S_F \]
Fundamental limitation: thermal noise

- White noise background due to finite T of oscillator

\[
S_x(\omega) = |\chi(\omega)|^2 S_F
\]

\[
\langle x^2 \rangle = \frac{1}{k^2} \int_0^\infty S_F \left( \frac{A(f)}{A_{dc}} \right)^2 df
\]

\[
S_F^{1/2} = \left( \frac{2}{\pi Qf_0} \right)^{1/2} k\chi_{rms}
\]

\[
A(f) = A_{dc} \frac{f_0^2}{\sqrt{(f_0^2 - f^2)^2 + \frac{f_0^2 f^2}{Q^2}}}
\]
Fundamental limitation: thermal noise

- White noise background due to finite T of oscillator

\[
S_X(\omega) = |\chi(\omega)|^2 S_F
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\langle x^2 \rangle = \frac{1}{k^2} \int_0^\infty S_F \left( \frac{A(f)}{A_{dc}} \right)^2 df
\]

\[
S_F^{1/2} = \left( \frac{2}{\pi Q f_0} \right)^{1/2} k x_{rms}
\]

\[
\frac{1}{2} k \langle x^2 \rangle = \frac{1}{2} k_B T \quad \Rightarrow \quad S_F^{1/2} = \left( \frac{4k k_B T}{Q \omega_0} \right)^{1/2}
\]

\[
F_{\text{min}} = S_F^{1/2} B^{1/2}
\]

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

• In equilibrium, thermal fluctuations are related to dissipation:

\[
S_{F}^{1/2} = \left(\frac{4kk_{B}T}{Q\omega_{0}}\right)^{1/2}
\]

\[
S_{F} = 4k_{B}Tm\Gamma
\]

\[
\Gamma = \omega_{0} / Q
\]

e.g. Johnson noise in a resistor:

\[
S_{V} = 4k_{B}T R
\]
Fluctuation-Dissipation theorem

- In equilibrium, thermal fluctuations are related to dissipation:

\[ S_F^{1/2} = \left( \frac{4k_B T}{Q \omega_0} \right)^{1/2} \]

\[ S_F = 4k_B T m \Gamma \]

\[ \Gamma = \frac{\omega_0}{Q} \]

e.g. Johnson noise in a resistor:

\[ S_V = 4k_B T R \]

FDT:

\[ S_X = 2k_B T \frac{\text{Im}[\chi(\omega)]}{\omega} \]

\[ \text{Im}[\chi(\omega)] = \frac{1}{m} \frac{\omega \gamma}{(\omega^2 - \omega_0^2)^2 + (\omega \gamma)^2} \]

\[ S_X(\omega) = |\chi(\omega)|^2 S_F \]
Fundamental limitation: thermal noise

Silicon Cantilevers:
\[ F_{\text{min}} \sim 10 \times 10^{-18} \text{ N/}\sqrt{\text{Hz}} \text{ at } 4 \text{ K at } Q=10^5 \]

To improve sensitivity:
- Make cantilever small
- Lower temperature
- Raise the quality factor
Displacement detection

Cantilever is only moving few angstroms

Interferometer signal

\[ \frac{2\pi d}{\lambda} \]

Can detect \(10^{-12} \text{ m/Hz}^{1/2} \) (µW)
Displacement detection

Cantilever is only moving few angstroms

Interferometer signal

$\frac{2\pi d}{\lambda}$

Can detect $10^{-12} \text{ m/Hz}^{1/2} (\mu W)$

Other methods: capacitance, QPD, high finesse optical cavity
Silicon Cantilevers:

\[ F_{\text{min}} \sim 10 \times 10^{-18} \text{ N/} \sqrt{\text{Hz}} \]

at 4 K at \( Q = 10^5 \)

Stanford cantilever experiment

Best Yukawa constraints at ~ 10 µm range:

A.A. Geraci, S.J. Smullin, D. M. Weld, J. Chiaverini, and A. Kapitulnik, 
Advances in cryogenic nano-oscillators

Significantly improved sensitivities (higher frequencies)

Schliesser group, Copenhagen

Painter group, Caltech

Si:
freq=5 GHz
Q_m=5X10^{10}
mass =136 fg
T=60 mK

Regal group, JILA

SiN:
freq=1.5 MHz
Q_m=2X10^8
mass=10 ng
T=30 mK

Also nanotubes:


~ 10 \text{ zN}/\sqrt{\text{Hz}}
Improving the sensitivity

Levitate the force sensor!

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

\[ U_{\text{opt}} = -\frac{1}{4} \Re[\alpha]|E|^2 \]
\[ \alpha_{\text{sphere}} = 3\varepsilon_0 V \left( \frac{\varepsilon - 1}{\varepsilon + 2} \right) \]

CM motion decoupled from environment – no clamping, materials losses
Optically-levitated sensors

Decoupled from environment – no clamping, materials losses!

Pressure-limited damping

\[
\frac{dp}{dt} = -\gamma_g \frac{p}{2}
\]

\[
\frac{\gamma_g}{2} = \left( \frac{8}{\pi} \right) \frac{P}{\bar{v}r\rho}
\]

P=10^{-10} Torr, r=0.2 \mu m, \omega/2\pi=100 kHz, Q=10^{12}!

\[
F_{\text{min}} = \left( \frac{4kk_B T_b}{Q \omega_0} \right)^{1/2}
\]

Q \sim 10^{12}
T \sim 300 \quad \rightarrow \quad F \sim 10^{-21} \text{ N/Hz}^{1/2}

\omega_0/2\pi \sim 10^5
m \sim 10^{-(14-17)} \text{ kg}
Optical Trapping

Optical forces on objects due to radiation pressure

Light incident on a totally reflecting mirror:

\[ F_{rad} = 2 \frac{P}{c} \]

\[ F_{rad} = \frac{2 \cdot 1 W}{3 \cdot 10^8 \text{ m/s}} = 6.67 \text{ nN} \]
Optical Trapping

Optical forces on objects due to radiation pressure

Light incident on a totally reflecting mirror:

\[ F_{rad} = 2 \frac{IA}{c} \]

\[ F_{rad} = \frac{2 \cdot 1W}{3 \cdot 10^8 \text{ m/s}} = 6.67 nN \]

Scattering Force

Imparted by traveling wave

\[ F_{scat} = \hbar k R_{scat} \]
Optical Trapping

\[ F = \frac{IA}{c} 2 \sin\left(\frac{\theta}{2}\right) \]

- Force arising from refraction of light
Optical Trapping

Ray Optics Approximation
\( (R \gg \lambda) \)

- When photons strike bead, they are refracted and momentum changes
  - Forces
    - Scattering force occurs along the axial direction
      - Axial component of \( F_a + F_b \)
    - Gradient force is along direction of increasing intensity

Ashkin
Rayleigh Approximation
\((R<<\lambda)\)

- Glass bead treated as induced dipole
- Scattering force
  - Electric field oscillates in time
  - Sphere acts as oscillating electric dipole
  - Radiates secondary (scattering) waves in all directions
  - Changes magnitude and direction of energy flux of electromagnetic field
  - Field due to momentum changes in electromagnetic field due to scattering by dipole

\[
F_{\text{Scat}}(\vec{r}) = \left(\frac{n}{c}\right)C_{\text{scat}} I(\vec{r})\hat{z} = \frac{128\pi^5 R^6}{3c\lambda_0^4} \left(\frac{m^2 - 1}{m^2 + 2}\right)^2 n_{md}^5 I(\vec{r})\hat{z}
\]

- Gradient Force

\[
\vec{F}_{\text{grad}}(\vec{r}, t) = \nabla[\vec{p}(\vec{r}, t) \cdot \vec{E}(\vec{r}, t)] = \frac{2\pi n_{md} R^3}{c} \left(\frac{m^2 - 1}{m^2 + 2}\right)^2 \nabla I(\vec{r})
\]
Optical Cavity

• An arrangement of mirrors that forms a standing wave of light waves.

• Cavity Resonance Condition
  – Length between mirrors must be an integer multiple of one half the laser wavelength.
  
  \[ L = m \left( \frac{\lambda}{2} \right) \]
  
  – Standing wave
Standing-wave trap

Silica sphere
\( \varepsilon = 2 \)
300 nm diameter
\( \lambda = 1.5 \) \( \mu \text{m} \)

\[ \omega_0 = \left[ \frac{6k_L^2I_1}{\rho c} \Re \frac{\varepsilon - 1}{\varepsilon + 2} \right]^{1/2} \]
Projected sensitivity

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

Cantilevers

Photon recoil heating

Seen recently by Novotny group

V. Jain et. al., PRL 116, 243601 (2016)

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

Projected sensitivity

Optically-levitated micro-particles

High Q Mechanical Resonance:
Optically levitated microspheres

Gravity at micron scales

Gravitational Waves


Experimental Setup

Combined cavity/dipole trap

G. Ranjit et.al., PRA 91, 051805(R) (2015).
Drive Mass fabrication

Buried drive mass technique – eliminates corrugation during polishing process.
MEMS actuator

- Device for positioning drive mass

100V DC, 10V AC
~5 um displacement
Standing wave optical trap
3D feedback cooling of a nanosphere

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

\[ F_{\text{min}} = \sqrt{\frac{4kK_B T_B}{\omega_0 Q}} \]
\[ Q_{\text{eff}} = \frac{Q_0 \Gamma_0}{\Gamma_0 + \Gamma_{\text{cool}}} \]
\[ T_{\text{eff}} = \frac{T \Gamma_0}{\Gamma_0 + \Gamma_{\text{cool}}} \]
Zeptonewton force sensing

Sensitivity

\[ S_{F,x} = 1.63 \pm 0.37 \text{ aN/\sqrt{Hz}} \]

Zeptonewton force sensing

**Electrostatic Calibration**

90% of beads are neutral
Neutral beads stay neutral
Charge stays constant over days

\[ \text{Sensitivity} = 37.6 \pm 3.1 \text{ Hz/aN} \]

Zeptonewton force sensing

Optical lattice calibration

Useful for neutral objects
Method consistent with electric field approach

Sensitivity

1596 nm beam to trap a bead at its antinode \( \rightarrow \) localization
1064 nm beam to cavity cool the CM of bead \( \rightarrow \) position readout

Next: Cavity Trapping and cooling
A molecular quantum clock, a device that precisely measures the vibrations of this spring,
- Time variation of electron-to-proton mass ratio
- Test if unknown forces - besides electromagnetism and Newtonian gravity - modify the vibrations of the spring at the nanometer length scale.

(Sr Molecular clock)
Nanometer-Scale Mass-Dependent Forces with Ultracold Molecules

\[ V = -\frac{GM^2}{r} \left(1 + Ae^{-r/\lambda}\right) \]

0.5 – 5 nm

A < 10^{21} @ 1 nm!

Experiment: Vibrational spectroscopy of molecular isotopes
Theory: Born-Oppenheimer and mass-dependent corrections

Y. Kamiya et al., PRL 114, 161101 (2015)
E. Adelberger et al., ARNPS 53, 77 (2003)
Atomic Bose-Einstein condensates

D. M. Harber, J. M. Obrecht, J. M. McGuirk, and E. A. Cornell, PRA 72, 033610 2005

Casimir-Polder force measurements

Cornell group, JILA
Atom interferometers

Probing Dark Energy with Atom Interferometry
C. Burrage, E. J. Copeland, E. A. Hinds
JCAP 1503 (2015) 03, 042

Search for Chameleons (screened within matter, only shell contributes, except for atoms!)

P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, J. Khoury

Benjamin Elder, Justin Khoury, Philipp Haslinger, Matt Jaffe, Holger Müller, Paul Hamilton, PRD 94, 044051 (2016).
Matter-wave interferometry

Projected reach-nanosphere matter-wave interferometer
Summary

• Rich possibilities for new science
  ✓ Tests of gravity
  ✓ Dark Sector Physics
  ✓ Beyond the Standard Model

• Diverse set of techniques from researchers of varying backgrounds and expertise
  – Atomic, Molecular, Optical Physics
  – Condensed matter and low-temperature physics
  – Torsion balances/precision mechanical measurements