New Searches for Subgravitational Forces

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with
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New Era in Fundamental Physics

Energy Frontier
LHC
Nature of Electroweak Symmetry Breaking
(Higgs, Naturalness, New Symmetries/Dimensions)
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Energy Frontier
LHC
Nature of Electroweak Symmetry Breaking
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Precision Frontier
Atom Interferometry
Strong CP Solution, Nature of CC/DM
(Axions, Naturalness, New Forces, Violations of GR)

Rapidly advancing - Gaining 10 in sensitivity per year
Atomic Interferometer

Currently under construction at Stanford
Outline

Motivation for New Forces

Atom Interferometry

Fifth Force Experiments

- Deviations in Newtonian Gravity
- Equivalence Principle Violating Forces

Outlook
Many suggestions for fifth forces

\[ \delta V(r) = \alpha \frac{G_N M m}{r} \exp(-r/\lambda) \]

One Precision Frontier: Short Distance Gravity

Parameterization of new force

\[ \alpha = \left( \frac{m_p}{M_{Pl}} \right)^{\frac{1}{2}} \]

\[ \lambda = \frac{\hbar}{m_\phi c} \]

- \(\alpha\): Strength relative to gravity
- \(\lambda\): Range (i.e. Compton wavelength)
Moduli Mediated Forces

In Supersymmetry some particles only get mass from supersymmetry breaking

\[ m_\phi \sim \frac{m^2_{\text{susy}}}{M_{\text{Pl}}} \]

If \( m_{\text{susy}} \sim 1 \text{ TeV} \implies \lambda = \frac{\hbar}{m_\phi c} \sim 1 \text{ mm} \)

Generically have gravitational size couplings to matter

\[ \mathcal{L}_{\text{int}} = \alpha^{\frac{1}{2}} \frac{m_p}{M_{\text{Pl}}} \phi \bar{p}p \]
Large Extra Dimensions

\[ V(r) \sim \frac{1}{r} \rightarrow \frac{L^n}{r^{n+1}} \]

**Strength**

\[ E \sim \frac{1}{r} \]

**Gravity**

\[ M_{Planck} \]

**EM + QCD**

\[ M_{Weak} \]
Large Extra Dimensions

\[ V(r) \sim \frac{1}{r} \rightarrow \frac{L^n}{r^{n+1}} \]

\[ E \sim \frac{1}{r} \]

\[ M_{\text{Planck}} \]

\[ M_{\text{Weak}} \]
Basic Idea

All forces start out equal at weak scale

EM & QCD live in 4 dimensions,
gravity lives in more and dilutes

High scale physics is just a mirage

Gravity is different at a new scale: mm to fm
Composite Gravity

The Cosmological Constant

\[ \Lambda_{CC} \simeq \frac{\hbar c}{(50 \mu m)^4} \]

\[ \Lambda_{CC} = \bigcirc + \bigcirc \bigcirc + \cdots \simeq \frac{\hbar c}{\epsilon^4} \]
Composite Gravity

The Cosmological Constant \( \Lambda_{\text{CC}} \approx \frac{\hbar c}{(50 \, \mu\text{m})^4} \)

\[
\Lambda_{\text{CC}} = \bigcirc + \bigcirc + \ldots \sim \frac{\hbar c}{\epsilon^4}
\]

Cosmological expansion driven by coupling to gravity

\[
h_{\mu\nu} \bigcirc \uparrow L \bigcirc \quad \Lambda_{\text{CC}} \sim \frac{\hbar c}{L^4}
\]
Composite Gravity

The Cosmological Constant \[ \Lambda_{CC} \sim \frac{\hbar c}{(50 \mu m)^4} \]

\[ \Lambda_{CC} = \bigcirc + \bigcirc + \ldots \sim \frac{\hbar c}{\epsilon^4} \]

Cosmological expansion driven by coupling to gravity

\[ h_{\mu\nu} \quad \bigcirc \quad \uparrow \downarrow \quad L \quad \Lambda_{CC} \sim \frac{\hbar c}{L^4} \]

If the graviton is composite with a size 50\mu m

no coupling to small loops \[ \bigcirc \quad \bigcirc \quad \bigcirc \quad \bigcirc \quad \bigcirc \quad L < \epsilon \]
Composite Gravity

The Cosmological Constant
\[ \Lambda_{CC} \approx \frac{\hbar c}{(50 \, \mu m)^4} \]

\[ \Lambda_{CC} = \bigcirc + \bigcirc + \ldots \sim \frac{\hbar c}{\epsilon^4} \]

Cosmological expansion driven by coupling to gravity

If the graviton is composite with a size 50\,\mu m

no coupling to small loops  \[ L < \epsilon \]

No known theory does this

Motivates looking at short distance gravity
Neutrinos in the Standard Model mediate a very tiny, unscreenable force

\[ V_\nu \approx \frac{G_F^2}{16\pi^2} \frac{e^{-m_\nu c r/\hbar}}{r^5} \]

\[ \frac{\hbar}{m_\nu c} \sim 1 \text{ mm} \]

\[ \sim 10^{-15} V_N (r \sim 100 \mu\text{m}) \]

Still futuristic, but something to aim for!
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Space-time Interferometry
Mach-Zehnder Interferometer

10m Stanford Interferometer
Kasevich & Hogan

\[ \Delta x \sim 1 \text{ m} \]
\[ c\tau = 10^8 \text{ m} \]
\[ A_{AI} \sim 10^8 \text{ m}^2 \]
\[ A_{Ligo} \sim 10^7 \text{ m}^2 \]

Mach-Zehnder Inteferometer

Time is a big lever-arm in area
Raman Transitions

Two photon transition

Fine Split
1 eV

Hyperfine Split
$10^{-5}$ eV

$\Delta p \sim 1$ eV
$\Delta E \sim 0$
Rabi Oscillations
Effectively 2 state oscillations

\[ i \frac{d}{dt} \begin{pmatrix} |1\rangle \\ |2\rangle \end{pmatrix} = \begin{pmatrix} 0 & \Omega_{\text{Rabi}}/2 \\ \Omega_{\text{Rabi}}/2 & 0 \end{pmatrix} \begin{pmatrix} |1\rangle \\ |2\rangle \end{pmatrix} \]
Mirrors and beamsplitters are lasers.

Atom Interferometry

\[ O_1 = \frac{1}{2} (1 + \cos \phi) \]
\[ O_2 = \frac{1}{2} (1 - \cos \phi) \]

\( t = 0 \)
\( t = T \)
\( t = 2T \)

\( \frac{\pi}{2} \) pulse
\( \pi \) pulse
\( \frac{\pi}{2} \) pulse

Mirrors and beamsplitters are lasers.
Difference of Phases

\[ \hbar \Phi = [V(0) - V(\nu_r T)] \Delta T \]
Slowly changing potentials

For optical transitions and Rb

$$\Delta x = v_r T \sim 1 \text{ mm}$$

$$V(x) = V_0 + V' x(t) + V'' x^2(t)$$

$$\phi = \Delta V \ T \quad \Delta V \sim V' \Delta x$$

$$\phi \sim F \ v_r T \ T \sim \text{Force} \cdot \text{Area}$$

Interferometers are accelerometers

for $$V'' \Delta x / V' \ll 1$$
Quickly changing potentials

Consider Yukawa potential

\[ V(x) = V_0 \exp(-x/\lambda) \]

For \( \Delta x \gg \lambda \) measures potential differences

\[ \Delta \Phi \sim V_0 \ T \quad V_0 \sim m \ a \ \lambda \]

Insensitive to momentum imparted
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Outlook
The “Gyroscope” Configuration

Launch vertically but shine lasers horizontally
Measures the force in laser’s direction
Free motion in horizontal direction
Ballistic motion - time and height the same

\[ h = gT^2 \]
Experimental Set-up

First measure “null”
Experimental Set-up

Lasers shine horizontally towards test mass

Move test mass in and out and measure its gravity

\[ L \]

\[ w \]

\[ x_N \]

\[ \Phi_{\text{Near}} \]

\[ \Phi_{\text{Null}} \]
Experimental Set-up

Lasers shine horizontally towards test mass

Move test mass in and out and measure its gravity
Precision

\[ \Phi = k a T^2 = \frac{h}{\lambda} \frac{a}{g} \]

Dimensions of experiment

\[ \lambda \sim 500 \text{ nm} \quad a \sim G_N \rho w \sim 10^{-8} g \quad h \sim 10 \text{ cm} \]

Signal Size \quad Resolution

\[ \Phi \sim 10^{-2} \quad \delta \Phi \sim 10^{-1} \]
Precision

\[ \Phi = k\alpha T^2 = \frac{h}{\lambda} \frac{a}{g} \]

Dimensions of experiment

\[ \lambda \sim 500 \text{ nm} \quad a \sim G_N \rho \omega \sim 10^{-8} g \quad h \sim 10 \text{ cm} \]

Signal Size

\[ \Phi \sim 10^{-2} \]

Resolution

\[ \delta \Phi \sim 10^{-1} \]

\[ N_{\text{atoms}} \sim 10^6 \quad N_{\text{bunches}} \sim 10^6 \]

Ultimate Resolution

\[ \frac{\frac{1}{\sqrt{N_b N_a}} \delta \Phi}{\Phi} \sim 10^{-5} \]
Measurement Strategy

$G_N$ unknown $\iff$ Normalization of $V(x)$ unknown

Must measure at two distances
Measurement Strategy

\( G_N \) unknown \( \implies \) Normalization of \( V(x) \) unknown

Must measure at two distances

\[
\lambda \lesssim L \\
\lambda \gtrsim L
\]
Measurement Strategy

$G_N$ unknown $\implies$ Normalization of $V(x)$ unknown

Must measure at two distances
Measurement Strategy

\( G_N \) unknown \( \implies \) Normalization of \( V(x) \) unknown

Must measure at two distances
Limits on Resolution

Newtonian Prediction

Atoms initially held in laser trap
Wide wave packet

\[ \Delta x \sim 100 \, \mu m \]
Limits on Resolution
Newtonian Prediction

Limits on source mass geometry
\[ V \sim m a x (1 + O(x/L)) \]  Planar Geometry

Uncertainty in the position looks like new force

Systematic
\[ \delta V/V \sim 10^{-6} \]

Stochastic
\[ \frac{\delta V}{\sqrt{N_b V}} \sim 10^{-9} \]

\[ \delta x \sim 1 \mu m \]
Casimir / van der Waal’s Force

\[ V(r) = \frac{\alpha_0}{r^4} \]

\( \alpha_0 \) polarizability \( \sim 20 \text{ Å}^3 \)

Put in shield to keep environment constant

30 \( \mu \text{m} \) shield bends by 1 nm
**Coriolis Force**

\[
\phi_{\text{Cor}} = m \omega v_l v_r T^2 \sim 10^3
\]

Methods of actively reducing it by \(10^{-5}\)

Is common mode noise - up to jitter and vibrations

Stochastic with bunches \(10^{-3}\)

still need \(\delta v_{\text{vib}} \lesssim 10^{-4} \text{ m/s}\)

good vibration isolation
Preliminary Reach

\[ \log[\frac{\lambda}{1\text{ m}}] \]

\[ \log[\alpha] \]
Equivalence Principle

New forces often violate EP

Way of distinguishing from Gravity

Useful for long distances
Equivalence Principle

New forces often violate EP
Way of distinguishing from Gravity
Useful for long distances

New force couples to $Z$ & $(A - Z)$ as

$$F \sim (1 + c)Z + (1 - c)(A - Z)$$
Equivalence Principle

New forces often violate EP

Way of distinguishing from Gravity

Useful for long distances

New force couples to $Z$ & $(A - Z)$ as

$$F \sim (1 + c)Z + (1 - c)(A - Z)$$

Introduce $\zeta \equiv Z/A$  Proton fraction of nucleus

$$a = \frac{F}{m} \sim a_0(1 + c\zeta)$$

Composition dependent force
Multiple Isotopic Species

Use composition dependent force
Perform differential measurements

\[ \Delta \Phi = \Phi_1 - \Phi_2 \]

Different isotopes at \textit{same} time

\[ \Delta \Phi \propto a_1 - a_2 \sim a_0 c (\zeta_1 - \zeta_2) \]

Want to maximize isotopic differences

\[ \delta \zeta_{\text{Rb}} \sim 1\% \quad \delta \zeta_{\text{Li}} \sim 7\% \]

\[ \delta \zeta_{\text{He}} \sim 25\% \quad \delta \zeta_{\text{H}} \sim 50\% \]
Co-Location

Electronically identical

Nuclear moments differ, atoms see slightly different potential

Changes to a null experiment
Backgrounds

Coriolis is greatly reduced

Uncontrolled gravitational sources are not a problem
easier environment to find

Casimir is important at 0.1 mm
Double differential measurement as before
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Improvements

Consider the phase

\[ \frac{\Phi}{\Delta \Phi_{\text{res}}} \sim p a T^2 N_{\text{atom}}^{\frac{1}{2}} N_{\text{bunch}}^{\frac{1}{2}} \]

Can’t make signal bigger

Big cost to make taller drop towers

Number of bunches
sets length of experiment
Large Momentum Transfer

\[ \Phi \sim p a T^2 N_{\text{atom}}^{\frac{1}{2}} N_{\text{bunch}}^{\frac{1}{2}} \]

changing the frequency to walk up momentum

\[ \Delta p \sim 10^2 \text{ eV} \]

2 orders of magnitude improvement on long ranged forces

no gain on short ranged forces

\[ \Delta x \sim 10 \text{ cm} \]
Improvements

\[ \Phi \sim \rho a T^2 N^{\frac{1}{2}}_{\text{atom}} N^{\frac{1}{2}}_{\text{bunch}} \]

Could do more atoms...

\[ |\psi\rangle \sim (|1\rangle + |2\rangle)^{N_{\text{Atom}}} \]

Resolution goes as \( N^{-\frac{1}{2}}_{\text{Atom}} \)
Could do more atoms...

\[ |\psi\rangle \sim (|1\rangle + |2\rangle)^{N_{\text{Atom}}} \]

Resolution goes as \( N_{\text{Atom}}^{-\frac{1}{2}} \)

\[ |\psi\rangle \sim (|1\rangle)^{N_{\text{Atom}}} + (|2\rangle)^{N_{\text{Atom}}} \]

Resolution goes as \( N_{\text{Atom}}^{-1} \)

known as Heisenberg Statistics

\( 10^3 \) Gain!
Other experiments

Equivalence Principle
   Hogan, Kasevich

Precision GR
   Dimopoulos, Graham, Hogan, Kasevich
gr-qc/0610047

Gravity Waves
   Dimopoulos, Graham, Hogan, Kasevich, Rajendran

Electric Neutrality of Atoms
   Arvanitaki, Dimopoulos, Geraci, Hogan, Kasevich
Atom Interferometry

New method for searching for beyond the SM physics

Many possibilities for future improvements

Need creativity for new methods of searching