Sub-millimeter tests of the gravitational $1/r^2$ law:
a search for "large extra dimensions"

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Outline

- motivation
- previous work
- new results from the Eöt-Wash group
What might be special about gravity at ≤ 1mm?

- mass scale of gravity
  \[ M_p = \sqrt{\frac{k_c}{G}} \sim 10^{16}\,\text{TeV} \]
  can be unified with mass scale of particle physics
  \[ M_{\text{part}} \sim 1\,\text{TeV} \]
  if 2 of the extra dimensions are large and have size \( \sim 1\,\text{mm} \)

- cosmological constant from distant supernovae
  \[ \Lambda \sim 3\,\text{keV/cm}^3 \]
  corresponds to a length of \( \sim 0.1\,\text{mm} \)

- essentially nothing is known about gravity at small separations \( \leq 1\,\text{mm} \)

These notions have sparked a flowering of ideas in theory & experiment.
The hierarchy problem

• mass scale of gravity

\[ V_N(r) = G \frac{m m}{r} = \frac{kc}{M_p^2} \frac{m m}{r} \]

\[ M_p = \sqrt{\frac{kc}{G}} \sim 10^{16} \text{ TeV} \]

• mass scale of particle physics

\[ M_{\text{SM}} \sim 1 \text{ TeV} \]

• Arkani-Hamed et al. solution to the problem


assume that:

• gravity propagates in all of the 7 extra dimensions of string theory

• SM particles are confined to a 4-dim "brane"

• some of the 7 extra dimensions are "large" while the remainder are "curled up" at the Planck scale

\[ R_0 = \sqrt{\frac{G \hbar c^3}{k}} = 1.6 \times 10^{-33} \text{ cm} \]
extra dimension

our 'brane'

gravitons: has no free ends, not stuck to brane

fermions, gluons, photons, weak bosons, etc stuck to brane
• Suppose there are n "large" extra dimensions of size \( R^* \)

• then at distances \( r \ll R^* \)
  gravity would obey Gauss' law in \( n+2 \) space dimensions

\[
V_{4+n}(r) = \frac{(k_C)^{n+1}}{(M^*)^{n+2} C^{2n}} \frac{mm}{r^{n+1}}
\]

where \( M^* \) is the true mass scale of gravity

• while at distances \( r \gg R^* \)
  gravity obeys the usual Gauss' law in 3 dimensions

\[
V_4(r) = \frac{k_C}{M^2} \frac{mm}{r}
\]

and now \( M^2 \) is no longer a fundamental scale

• equating \( V_{4+n}(R) = V_4(R) \) we find

\[
(M^*)^{n+2} = \left( \frac{k_C}{CR^*} \right)^n M^2
\]

\[
R^* = \frac{k_C}{M^* C^2} \left( \frac{M^2}{M^*} \right)^{2/n}
\]

by picking \( R^* \) and \( n \) can make \( M^* = M_{SM} \)
"Solving" hierarchy problem by setting $M^* = 1 \text{ TeV}$ we find

for $n=1$

$R^* \sim 10^{15} \text{ cm}$

\[\uparrow\text{ ruled out by astronomical observations of orbit precessions}\]

for $n=2$

$R^* \sim 2 \text{ mm}$

\[\uparrow\text{ not inconsistent with existing data! why not?}\]

gravity is very, very weak.

for $n > 2$

$R^*$ so small it cannot be detected in mechanical experiments

but may be detected in collider experiments
Figure 2.13: Constraints on the coupling constant $\alpha$ as a function of the range $\lambda$ from composition-independent experiments. The dark shaded area indicates the status as of 1981, and the lighter region gives the current limits. Note that only the most sensitive results are exhibited in each regime in $\lambda$, and that all limits are quoted at the $2\sigma$ level. For references to the earlier experiments which contribute to the curves, see [Talmadge, 1988] and [DeRujula, 1986].

$2\sigma$ limits on inverse-square law violating interaction of the form

$$V(r) = \alpha \frac{G m m}{r} e^{-r/\lambda}.$$
\[ V(r) = -G \frac{m m'}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

- **dilaton** - theory argument by Kaplan & Wise hep-ph 000811
- **axion** - region allowed by neutron EOM + astrophysical constraints

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Mark II short-range instrument

torsion pendulum

upper attractor

t he 10 holes in the lower attractor are "out of phase" with the holes in the upper attractor.

this cancels Newtonian gravity torque by a factor of \( \sim 20 \), but has little effect on torque from short-range force.

measure \( z \)-dependence of torque signals at 10w, 20w and 30w.
Eötvös Mark II short-range instrument
PENDULUM

NOT LEVEL, CAPACITANCE CHANGES UNDER ROTATION

HORIZON

DIFFERENTIAL CAPACITOR PLATES (NOT NECESSARILY LEVEL)

LEVEL, CAPACITANCE UNCHANGED UNDER ROTATION
Centering Runs at $z = 0.237$ mm

Harmonic Amplitude [urad]

Offset [mm]

- $10\omega$
- $30\omega$
- $20\omega$
capacitance measurement of the separation
Calibration

- Gravitational force between spheres is simple to calculate.

- Large sphere separation eliminates effects from short-range interactions

- $2\omega$ torque = $4.007 \pm 0.001 \times 10^{-7}$ dyne-cm
\( a(2\omega) = 11.557 \pm 0.010 \mu\text{rad} \)
signal at a separation of 237 μm
Slope = 1.0230 ± 0.0002
Eötvös Wash Mark II short-range constraints

2 large extra dimensions scenario predicts
\[ \alpha = 3 \leftarrow \text{compactification on sphere} \]
\[ \alpha = 4 \leftarrow \text{torus} \]

Our Mark II results are inconsistent with
\[ \alpha \geq 3 \text{ for } \lambda \geq 190 \mu m \]
at 95\% confidence \[ \Rightarrow M^* \geq 3.5 \text{ TeV} \]
95% confidence constraints on $|\alpha|$ for $\lambda$ in mm:

$\lambda [\text{mm}]$

New analysis combining results from Mark II and Mark III instruments:

$\alpha < 3$ for $\lambda = 150 \mu\text{m}$ — 2 large extra dim. scenario

$\alpha < 1$ for $\lambda = 300 \mu\text{m}$

Upper limit on size of the largest extra dimension.
to "bounce" mode damper

we hope to probe down to \( \lambda < 50 \mu m \)

with this instrument
"I had a better grasp of things when physics dealt mostly with falling bodies."
preliminary 26-hole data

26\omega twist [nrad*10]

In Phase
Out of Phase

separation [mm]
Some improvements in the 44-hole instrument

- better cancellation of Newtonian gravity
- bigger Yukawa signal
  - higher densities \( Mo + Mo \rightarrow \rho \rho_n \) \( 4.5 \times \) greater
  - power pushed into fundamental
- \( 2 \times \) thinner conducting membrane
- "bounce mode" damper \( 6 \times \) reduction in mean bounce
- \( 6 \times \) lower torque noise
- Minimum separation \( 2 \times \) closer
  
  have data at \( z = 98 \mu m \)
  
  with prototype system
44-hole pendulum with 22-fold azimuthal symmetry

design goal: probe down to $\lambda \sim 50 \mu m$