Torsion balances and low-energy tests of gravity

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Fundamental Principles?

All objects fall at the same acceleration, regardless of mass or composition

<u>Equivalence Principle:</u> Uniform gravitational field is locally equivalent to an accelerated reference frame

Standard (Newtonian) picture: $m_i = m_g$

Gravitational Inverse Square Law $$V = -\frac{Gm_1m_2}{r}$$

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But weak long-range forces that appear as EP violation?

Gravitational Inverse Square Law $V = -\frac{Gm_1 m_2}{r}$

But tested at short distance scales?

5^{th} force

Long history of "discoveries" of an apparent fifth force

[Fischbach et al. '86,…]

No reason to think such a force cannot exist

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Scalar

$$y\phi\bar{N}N \qquad y\phi\bar{e}e$$

$$b\phi|H|^2, \qquad g^2|\phi|^2|H^2|$$

Vector

$$g_{B-L}X_\mu\bar{\psi}\gamma^\mu\psi$$

Naturalness?

$$V(r) = \pm\frac{y^2}{4\pi}\frac{q_i q_S}{r}e^{-r/\lambda}, \qquad \lambda = 1/m_\phi$$

EP Violation

If force couples to e.g. Baryons, then $q \approx m/m_N$
why does this violate EP? Binding energy!

$$F \approx g_{B-L}^2 \Delta_{B-L} \left(\frac{A_S - Z_S}{A_S} \right) \frac{M_S M_{A_i}}{m_N^2} \frac{1}{R^2}$$

$$\Delta_{B-L} = Z_1/A_1 - Z_2/A_2$$

EPV force due to vector exchange between source and test masses 1,2

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EPV force due to vector exchange between source and test masses 1,2

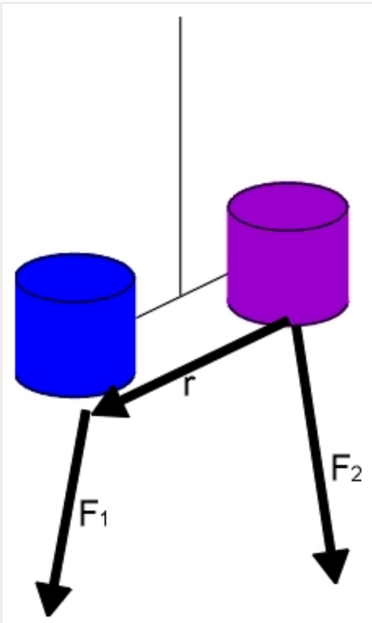
$$V(r) = -\frac{G m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

$$\alpha \approx \frac{y^2}{4\pi} \frac{M_{\rm pl}^2}{m_N^2}$$

$$\tilde{\alpha} = \frac{y^2 M_{\rm pl}}{4\pi u} \left(\frac{q}{\mu} \right)_i \left(\frac{q}{\mu} \right)_S$$

Test body mass in units of atomic mass units u

Torsion Balance



[Eotvos]

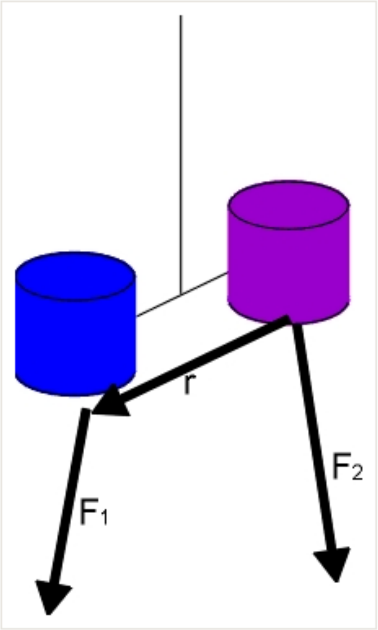
Sensitive to torque along the fiber

$$\tau = \frac{(\vec{F}_1 \times \vec{F}_2) \cdot r_{12}}{|\vec{F}_1 + \vec{F}_2|}$$

Restoring torque $-\kappa\theta$

Differential (horizontal) acceleration $\Delta a \sim \frac{\kappa\theta}{m r_{12}}$

Torsion Balance



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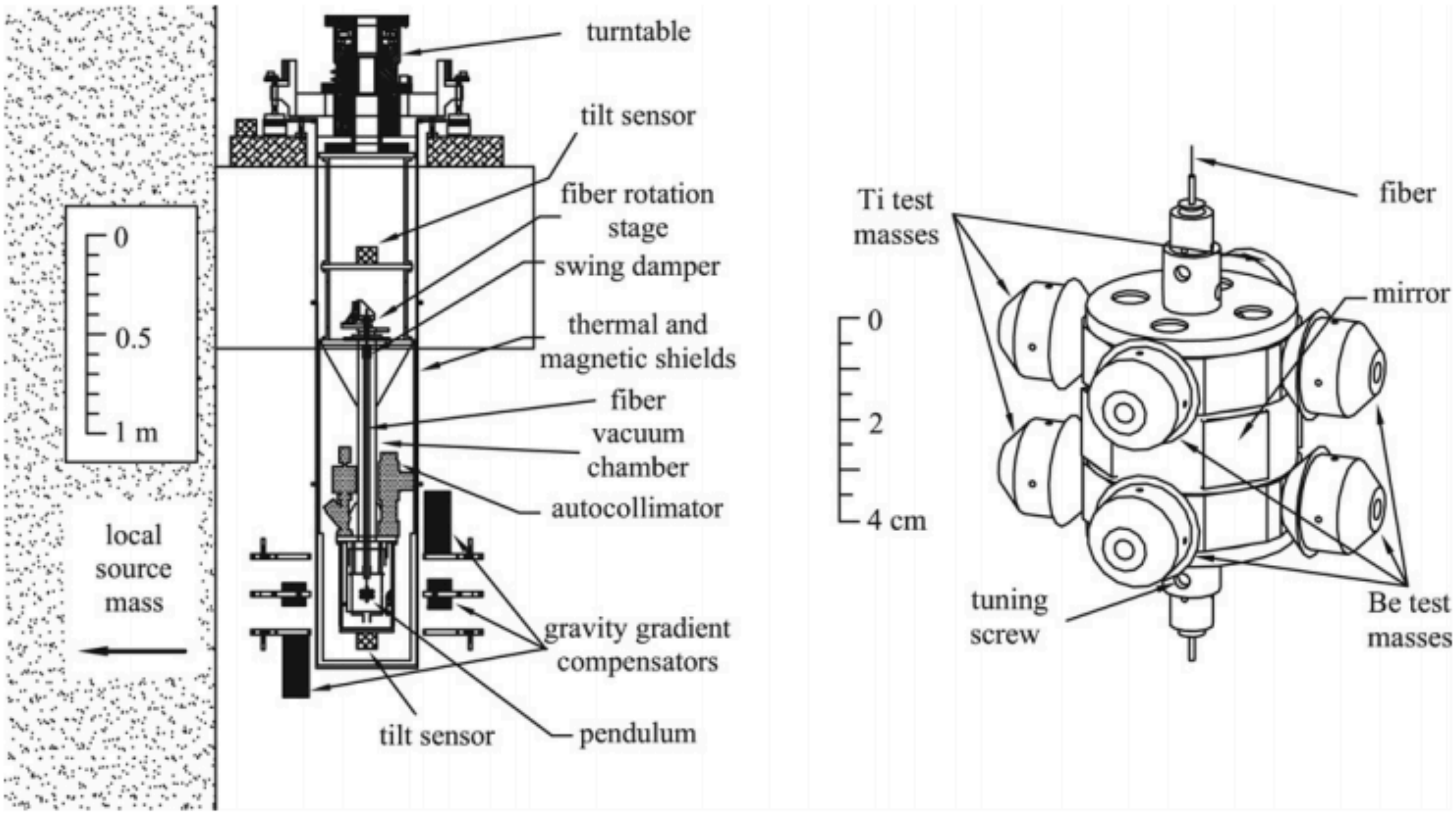
Occurs if EP is violated and local vertical forces F1, F2 are different in direction (not magnitude) – sensitive to the angle between forces!

Relative angle between forces can come from difference in centrifugal (inertial mass) and gravitational forces (gravitational mas) = test of EP violation!

Key systematic: gravitational gradients

Twist measured, e.g. by reflecting a light from a mounted mirror

Eot-Wash Setup



Turntable to achieve relative rotation between test masses and source to achieve a sinusoidal signal ~ mHz. Reduce frequency-dependent noises

Test Bodies and Source

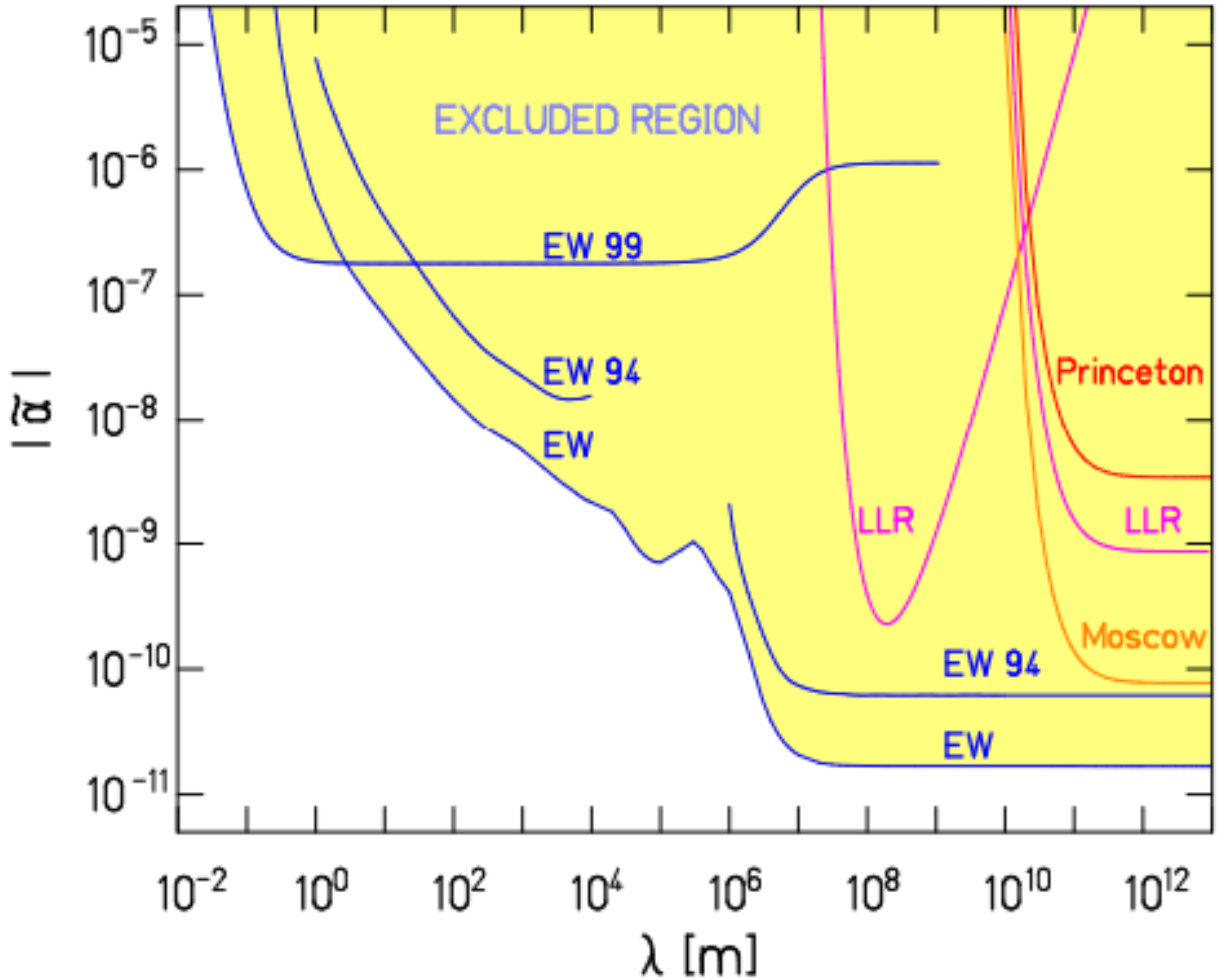
Non-magnetic conducting solids [Adelberger et al, '09]

Material	ρ (g/cm^3)	Z/μ	N/μ	B/μ
Be	1.9	0.44384	0.55480	0.99865
PE	1.0	0.57034	0.42854	0.99888
MM	2.1	0.49813	0.50250	1.00063
Al	2.7	0.48181	0.51887	1.00068
Ti	4.5	0.45961	0.54147	1.00108
EC	7.7	0.46610	0.53504	1.00114
Cu	9.0	0.45636	0.54475	1.00112
Pt	21.4	0.39984	0.60034	1.00018
Au	19.3	0.40108	0.59909	1.00017
Pb	11.3	0.39572	0.60440	1.00012

Depends on force range of interest and other more detailed systematics

Attractor	R_A (m)	Z/μ	N/μ	B/μ	$\tilde{\psi}_A^0$ (deg)	$g_\perp^{max}$ (m/s^2)	
Depleted uranium	1	0.39	0.61	1.00	−32	9.2×10^{-7}	
Local topography	$5 - 2 \times 10^4$	0.50	0.50	1.00	−55	7.2×10^{-5}	
Entire earth	5×10^7	0.49	0.51	1.00	−44	1.7×10^{-2}	Ref. [14]
Sun	2×10^{11}	0.86	0.14	0.99	−81	5.9×10^{-3}	
Galaxy	3×10^{20}					1.9×10^{-10}	
Galactic DM	3×10^{20}					4.8×10^{-11}	Ref. [15]

Torsion constraints on B-L force



Dark Matter Detection

Use similar torsion experiment to directly detect dark matter!

Light bosonic DM (m < eV) acts as a random classical field

$$\phi = \phi_0 \cos(mt) \qquad \rho_{\rm dm} \sim \frac{0.4\ {\rm GeV}}{{\rm cm}^3} \sim m^2 \phi_0^2$$

$$\lambda_{\rm coh} \sim \frac{1}{mv}, \quad \tau_{\rm coh} \sim \frac{1}{mv^2}, \ \text{with } v \sim 10^{-3}$$

Effects are locally coherent over 10^6 oscillations

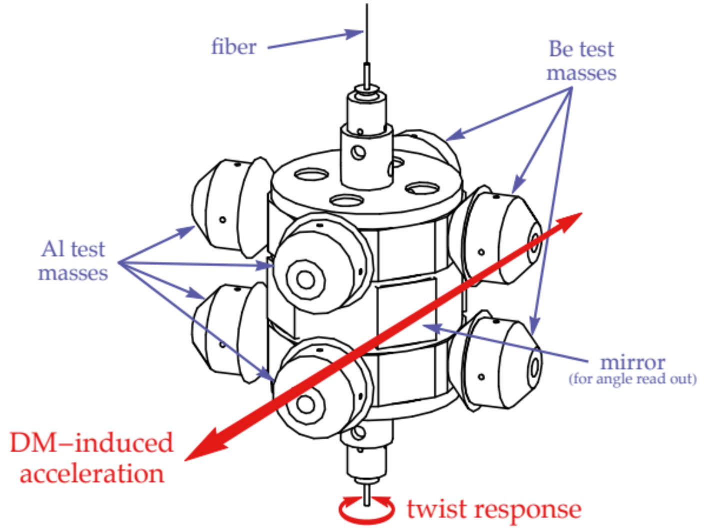
If the DM coupled in the same way as a fifth force, will produce a time-oscillating EPV

[Graham et al. ’15]

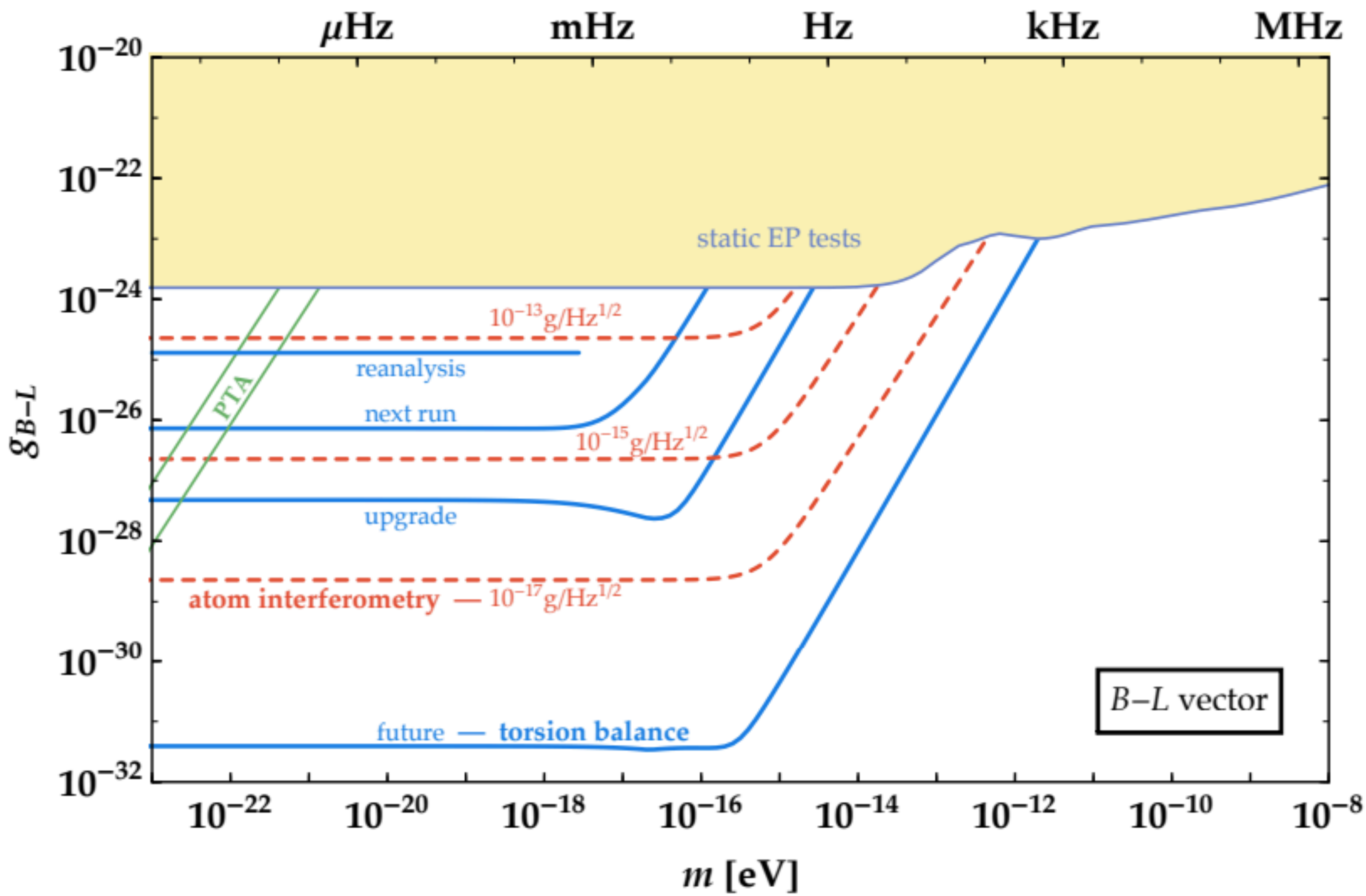
Static vs. Oscillating EP Violation

(1) Reduce systematics (e.g. gravitational gradients) since signal is oscillating at a frequency set by fundamental physics. Also annual modulation

(2) DM exerts a force on test body in a random direction (e.g. direction of B-L ”electric field”). No $O(10^{-3})$ suppression from searches for a vertical force sourced by the Earth in this case.



Limits on B-L Dark Matter



EP violation vs. ISL

EP: compare acceleration of two different materials, sensitive to deviations $r \lesssim \lambda \lesssim \infty$

ISL: compare force at two different lengths, sensitive to deviations $r_1 \lesssim \lambda \lesssim r_2$

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EP: compare acceleration of two different materials, sensitive to deviations $r \lesssim \lambda \lesssim \infty$

ISL: compare force at two different lengths, sensitive to deviations $r_1 \lesssim \lambda \lesssim r_2$

Dominant 5$^{\text{th}}$ force constraint depends on the mass range of interest

Any motivation for effects that deviate ISL without violating EP?

Extra Dimensions

ISL modified if there are extra dimensions – must be compact

String theory has many extra dimensions, perhaps $R < O(10^{-31}\ \text{cm})$. But can they be larger?

SM particles propagate in extra dimensions, yields a KK tower of states

$$m_{\text{KK}}^2 \sim \frac{n^2}{R^2}$$

Naively constrains $R<O(10^{-17}\ \text{cm})$, unless we live on a Brane!

Large Extra Dimensions

Attempt to address Hierarchy Problem: why is v/Mpl<<1?

Solution: Gravity is not intrinsically weak, and there is only one fundamental scale [Arkani-Hamed, Dimopolous, Dvali '98,…]

Gravity only appears weak due to large extra dimensions!

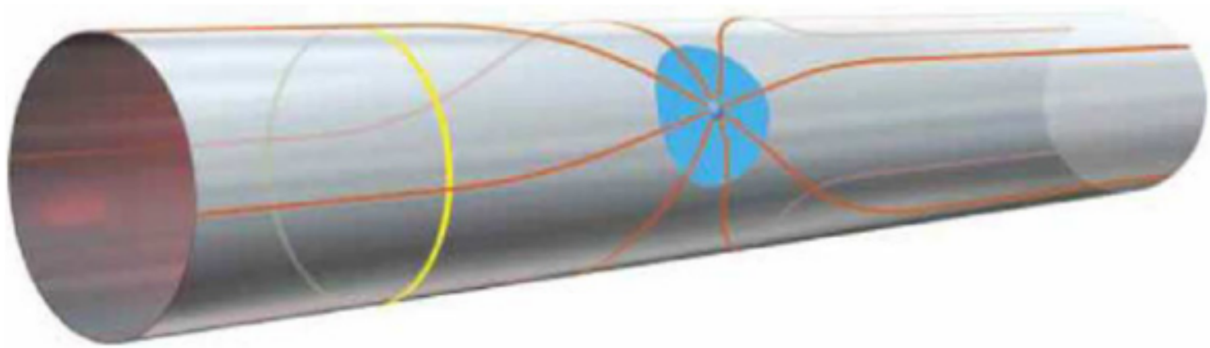
Simple example: d extra dimensions of size R

$$V(r) = \frac{m_1 m_2}{M_{\rm pl}^2}\frac{1}{r} \qquad r \gtrsim R$$

$$V(r) = \frac{m_1 m_2}{M^{2+d}}\frac{1}{r^{d+1}} \qquad r \lesssim R$$

$$M_{\rm pl}^2 = M^{2+d} R^d \approx (10^{19}\ {\rm GeV})^2$$

Large Extra Dimensions



$$M_{\rm pl}^2 = M^{2+d} R^d \approx (10^{19}\ \text{GeV})^2 \qquad M \approx \text{TeV}$$

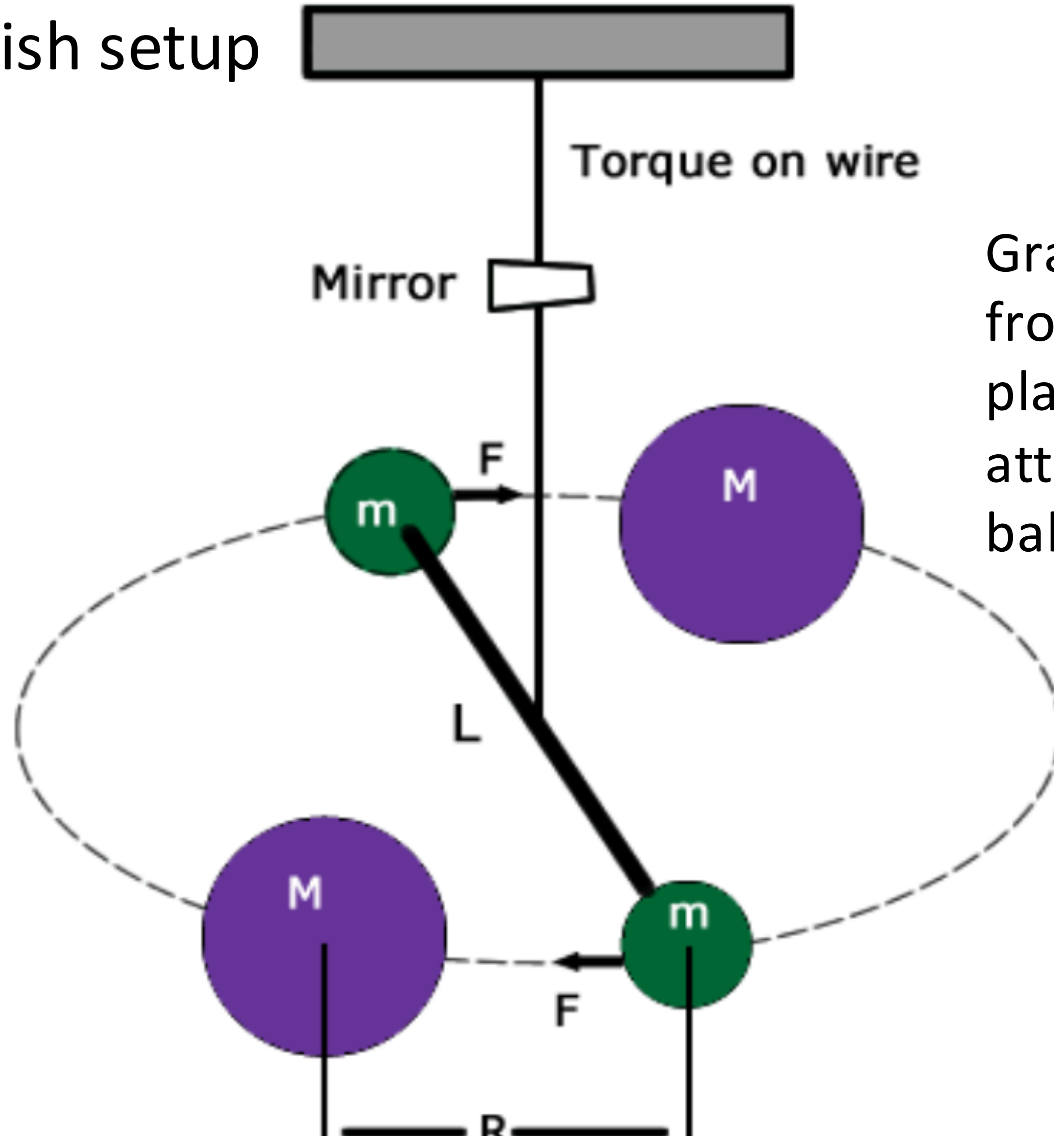
$$d = 1 \Rightarrow R \approx 100\ \text{AU}$$

$$d = 2 \Rightarrow R \approx 0.1\ \text{mm}$$

Can never completely rule out LED framework, but still important to test gravity on short distance scales

Torsion Balance

Cavendish setup



Gravitational torque from source masses placed near a test mass attached to torsion balance bars

General Constraints on ISL

Amalgamation over all length scales

[Murata, Tanaka, '14]