Theoretical motivations for short-range interactions

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1. TeV strings and large extra dimensions

   I.A. '90, I.A.-Arkani Hamed-Dimopoulos-Dvali '98
2. Gravity modifications at short distances
3. Extra light particles and short-range forces
4. Anomaly driven signatures of extra $U(1)$'s

   I.A.-Boyarsky-Ruchayskiy '06, '07

Beyond Einstein's Gravity: Why?

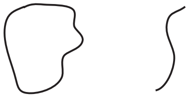
- Quantum Mechanics
- Unification of all fundamental forces

Quantum Mechanics + Special Relativity $\Rrightarrow$ Quantum Field Theory

Standard Model of electroweak + strong interactions

Quantum Mechanics + General Relativity $\Rrightarrow$ String Theory

point particle $\longrightarrow$ extended objects

$\bullet \quad \longrightarrow$  $\Rrightarrow$ particles $\equiv$ string vibrations

Framework for unification of all interactions

Mass scale: String tension $M_s \leftrightarrow$ string size: l_s

Experiment: Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho$ $\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

$\Rightarrow$ Gravity modification at large (cosmological) and short distances ? [7]

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics $m_H \sim$ UV cutoff Λ

why gravity is so weak compared to the other interactions? $\Lambda = M_P$

Possible answer (alternative to supersymmetry): Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$

large extra dimensions, warped dimensions, DGP localized gravity

- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

Experimentally testable framework:

- spectacular model independent predictions
- radical change of high energy physics at the TeV scale

Type I string theory $\Rightarrow$ D-brane world

I.A.-Arkani Hamed-Dvali-Dimopoulos '98

- gravity: closed strings propagating in $4+6$ extra dims
- gauge interactions: open strings with their ends attached on D-branes

Dimensions of finite size: n transverse $6-n$ parallel

calculability $\Rightarrow R_{\|} \simeq l_{\rm string}$; $R_{\perp}$ arbitrary

$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$ $\alpha = g_s$: weak string coupling [30]

Planck mass in $4+n$ dims: M_*^{2+n}

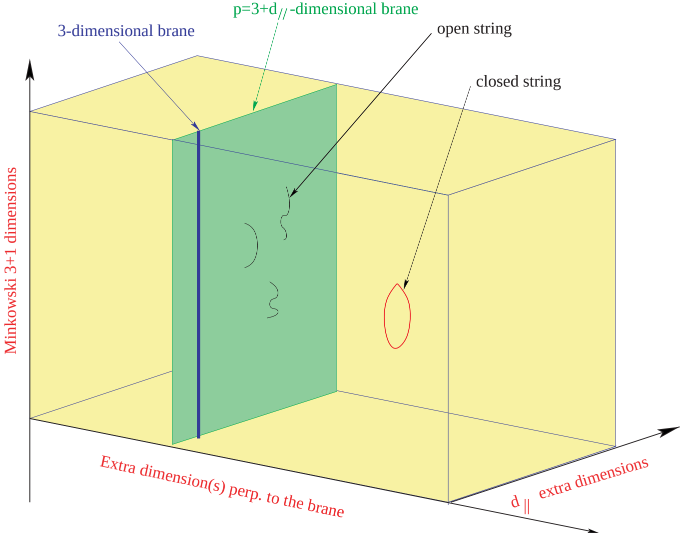
$M_s \sim 1$ TeV $\Rightarrow R_{\perp} \sim .1 - 10^{-13}$ mm $(n = 2-6)$ [7]

distances $< R_{\perp}$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm [8]

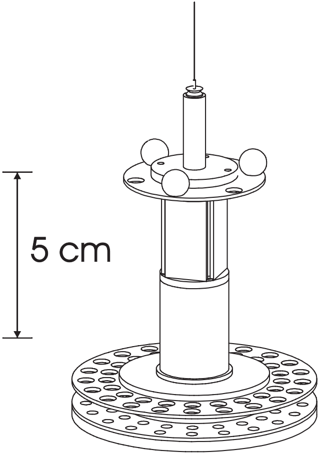
Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [28]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



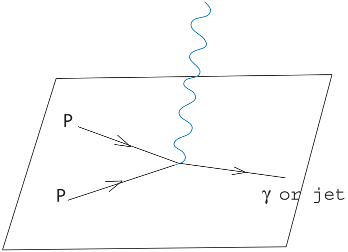
Adelberger et al. '06



$R_\perp \lesssim 45\ \mu$m at 95% CL

- dark-energy length scale $\approx 85\mu$m [3] [5] [10]

Gravitational radiation in the bulk $\Rightarrow$ missing energy



Collider bounds on $R_\perp$ in mm			
	$n=2$	$n=4$	$n=6$
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}

Other accelerator signatures

- Large TeV dimensions   seen by SM gauge interactions

  $\Rightarrow$ KK resonances of SM gauge bosons [26]   I.A. '90

$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \dots$$

  if lightest KK stable (e.g. KK-parity) $\Rightarrow$ dark matter candidate [27]

  Servant-Tait '02

- string physics and possible strong gravity effects

  Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution [29]

$$M_j^2 = M_0^2 + M_s^2\, j \quad ; \quad \text{maximal spin} : j + 1$$

  higher spin excitations of quarks and gluons with strong interactions

  Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08

  production of micro-black holes? [30]

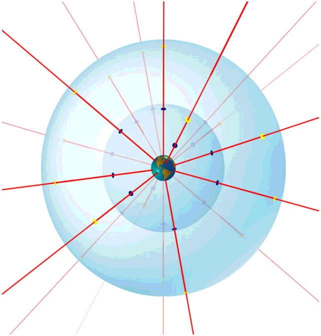
  Giddings-Thomas, Dimopoulos-Landsberg '01

microgravity experiments

- change of Newton's law at short distances [17]
  detectable only in the case of two large extra dimensions
- new short range forces
  light scalars and gauge fields if SUSY in the bulk
  or broken by the compactification on the brane
  I.A.-Dimopoulos-Dvali '98, I.A.-Benakli-Maillard-Laugier '02
  such as radion and lepton number
  volume suppressed mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\to$ mm range
  can be experimentally tested for any number of extra dimensions [12]
  - Light $U(1)$ gauge bosons: no derivative couplings
    $\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim 10^6$ [19]

Gravity modification at submillimeter distances

Newton's law: force decreases with area



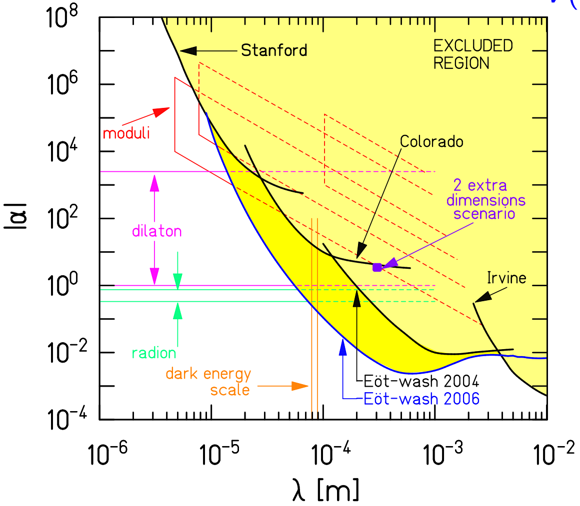
3d: force $\sim 1/r^2$

(3+n)d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r << .1$ mm

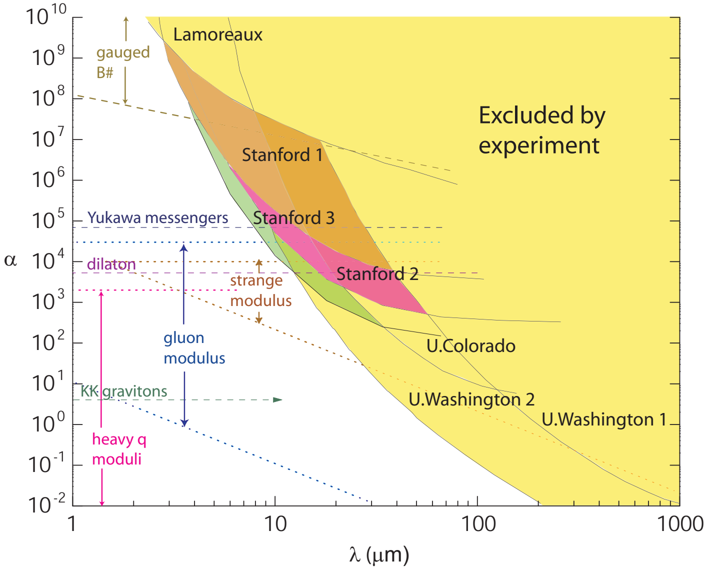
Experimental limits on short distance forces

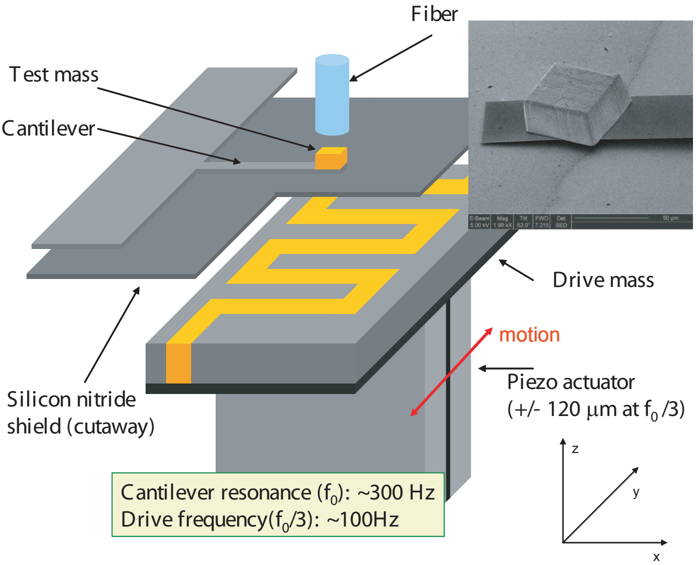
$V(r) = -G\,\frac{m_1 m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$



Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL Adelberger et al. '06 improved bounds in the range 5-15 μm

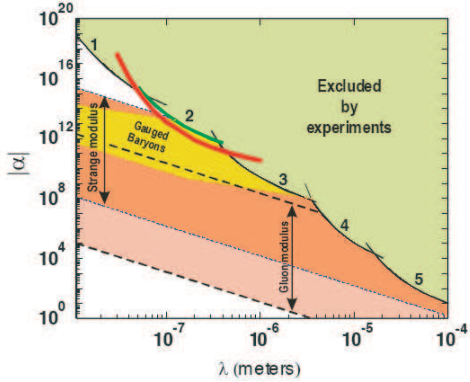
Geraci-Smullin-Weld-Chiaverini-Kapitulnik '08

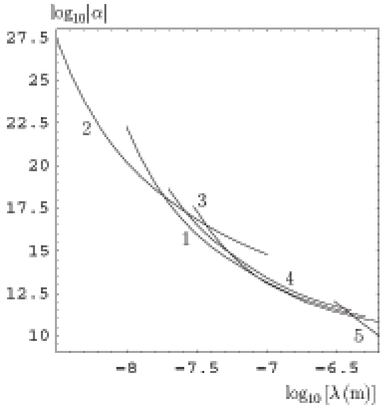



Fiber
Test mass
Cantilever
Drive mass
motion
Piezo actuator
(+/- 120 μm at f_0 /3)
Silicon nitride
shield (cutaway)
z
y
x
Cantilever resonance (f_0): ~300 Hz
Drive frequency(f_0/3): ~100Hz

improved bounds from the Casimir effect in the range ∼10-100 nm

Decca-Fischbach et al '07, '08

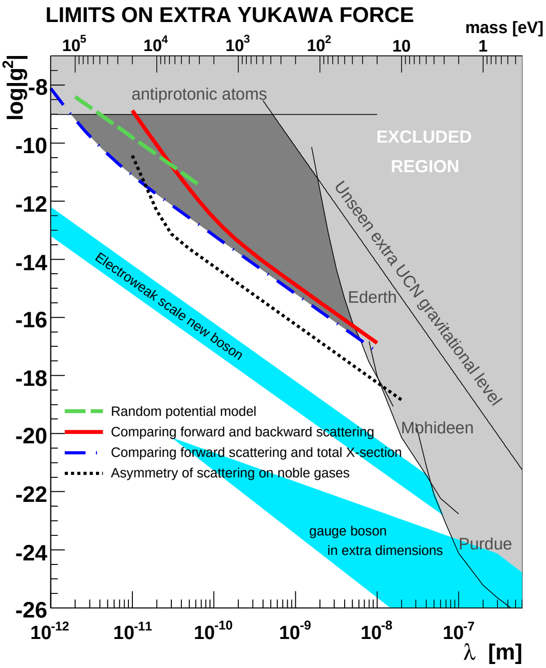




5: Colorado 4: Stanford 3: Lamoureaux 1: Mohideen et al.

Neutron scattering: bounds in the range $\sim$ 1pm - 1nm [10]

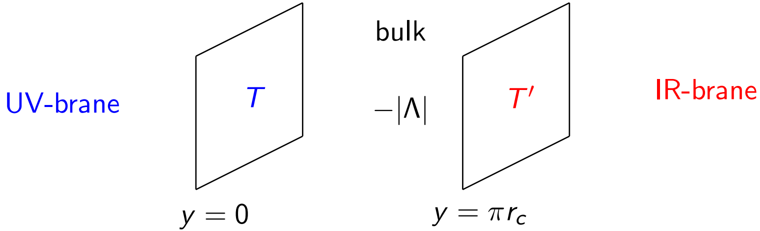
Nesvizhevsky-Pignol-Protasov '07



Randal Sundrum models

spacetime = slice of AdS_5 our universe = 4d flat boundary

$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$



- fine-tuned tensions: $T = -T' = 24M^3k^2$ $\Lambda = -24M^3k^2$
- exponential hierarchy: $M_W = M_P e^{-2\pi k r_c}$ $M_P^2 \sim M^3/k$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

- main prediction: spin-2 resonances at the TeV scale

  $m_n = c_n\, k\, e^{-2\pi k r_c}$ $\quad c_n \simeq (n + 1/4)$ for large n

- gravitational potential: $\frac{1}{r} + \frac{1}{k^2 r^3} \leftarrow$ deviations $(r_c \to \infty)$

  $k^{-1} \lesssim 0.1$ mm $\Rightarrow M > 10^8$ GeV, $T^{1/4} > 1\ \mathrm{TeV}$ [10]

Extra $U(1)$'s: present in many SM extensions

- GUTs with rank > 4

- general feature of string compactifications

  e.g. in D-brane models: $U(N)$ groups   away from orientifolds

1. X couples to Standard Model fermions $\Rightarrow$

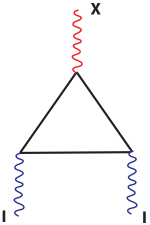
   standard LHC signals   e.g. Z'-type or extra short-range force

2. All Standard Model fermions neutral under $X \Rightarrow$ hidden?

   No if anomaly driven signatures

challenging case: new physics at 'high' energy but X light

naive expectation from decoupling ⇒ double suppression: coupling + mass



e.g. X coupling to SM gauge bosons:

loop factor $\times$ E^2/M_f^2

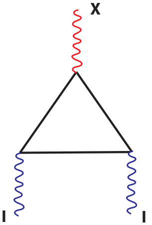
← dim-6 effective operator $F_X F_I F_I$

exception: non trivial anomaly cancellation

→ new dimensionless coupling

⇒ $U(1)_X$ may couple to SM gauge bosons with no mass suppression

Green-Schwarz anomaly cancellation mechanism



$= k_I^X \sim \mathrm{Tr} Q_X Q_I^2 \;\rightarrow$ axion θ : $\delta X = d\Lambda \quad \delta\theta = -m_X \Lambda$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2}(d\theta + m_X X)^2 + \frac{\theta}{m_X} k_I^X \, \mathrm{Tr}\, F_I \wedge F_I$$

cancel the anomaly

Two $U(1)$'s: $U(1)_X \times U(1)_A$ $\qquad$ X anomalous, A anomaly free

$\Rightarrow$ also possible Chern-Simons terms: I.A.-Kiritsis-Tomaras '00

Coriano-Irges-Kiritsis '05, Anastasopoulos-Bianchi-Dudas-Kiritsis '06

$$\mathcal{L} = -\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{1}{2}(D\theta_X)^2 - \frac{\kappa}{m_X} D\theta_X \wedge A \wedge F_A + \dots \qquad D = d + m_X X$$

$\rightarrow$ unitary gauge: $-\frac{1}{4}F_A^2 - \frac{1}{4}F_X^2 + \frac{m_X^2}{2}X^2 - \kappa\, X \wedge A \wedge F_A + \dots$

$A = \gamma \Rightarrow$ axion alternatives I.A.-Boyarsky-Ruchayskiy '06, '07

$\left[A \equiv Z, W \Rightarrow\right.$ LHC physics I.A-Boyarsky-Espahbodi-Rucharsky-Wells '09$\left.\right]$

$X \wedge A \wedge F_A \Rightarrow XA$ mixing in the presence of magnetic field $F_A \neq 0$

linearly polarized photon gets a mass $\Rightarrow$ axion behavior, interesting effects

2 parameters: mass m_X, C-S coupling $\kappa \leftarrow$ dimensionless

$X_\mu \leftrightarrow$ axion: $a \equiv \theta_X$ with mass $m_a = m_X$ and decay constant $f_a \equiv \frac{m_X}{\kappa}$

however without axion constraint $m_a f_a = m_\pi f_\pi$

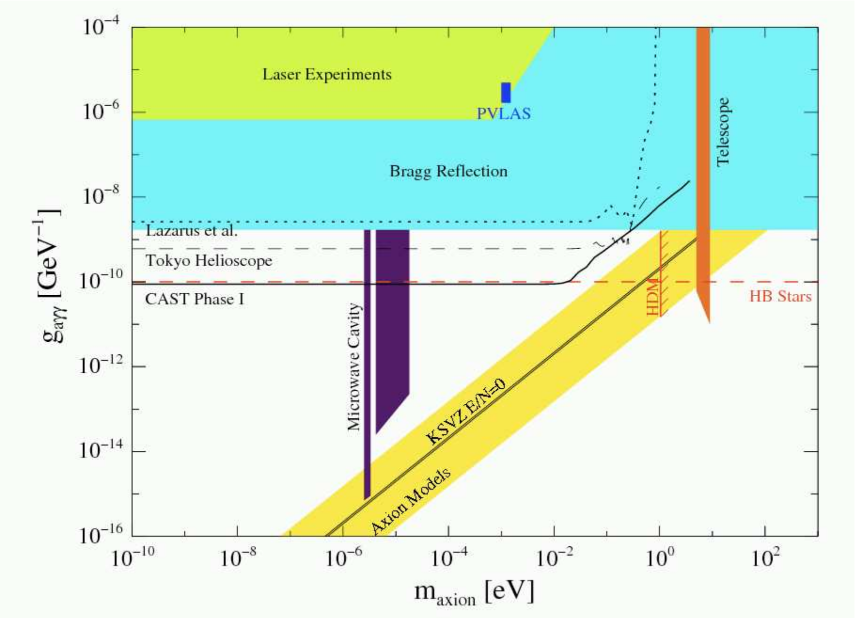
astrophysical constraints $\Rightarrow m_X/\kappa \gtrsim 10^{10}$ GeV

can be evaded if X-current conserved at stellar energies

longitudinal X production is then suppressed by $(m_X/E)^2$

same as QED with photon mass

Experimental bounds on Axion Like Particles



for instance massive fermions with $m_f \lesssim$ keV $\leftarrow$ stellar energies

$$\Rightarrow \kappa m_X \lesssim 10^{-10}\ \text{eV}$$

$\star$ notice $\mathcal{L}$ effective up to a scale $\Lambda \lesssim m_X/\kappa$ (unitarity bound)

- can accommodate PVLAS type data

- $m_X \lesssim$ eV: κ small may be obtained from millicharged keV fermions f

Conclusions

Short-distance modification of gravity and/or new short-range interactions:

- Well motivated theoretical proposals

  with many testable experimental predictions

  new resonances, missing energy, new forces

- Micro-gravity experiments: complementary to particle accelerators

  look for new forces at short distances

  higher dim graviton, scalars, gauge fields, axion alternatives

- Ultra Cold Neutron experiments - GRANIT: very promising

  new techniques to probe fundamental physics at short distances