

Physics from extra dimensions

I. Antoniadis

CERN

- ① Motivations and mass hierarchy
- ② Strings, branes and extra dimensions
- ③ Main accelerator signatures
- ④ Short distance forces and microgravity experiments

BSM physics: driven by 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 $\Lambda \sim \text{TeV}$

- 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
- explicit model building is not necessary at this moment

Framework of type I string theory \Rightarrow D-brane world

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

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

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

calculability $\Rightarrow R_{\parallel} \simeq l_{\text{string}}$; R_{\perp} arbitrary

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

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

$$M_s \sim 1 \text{ TeV} \Rightarrow R_{\perp}^n = 10^{32} l_s^n \quad \text{small } M_s/M_P \Rightarrow \text{extra-large } R_{\perp}$$

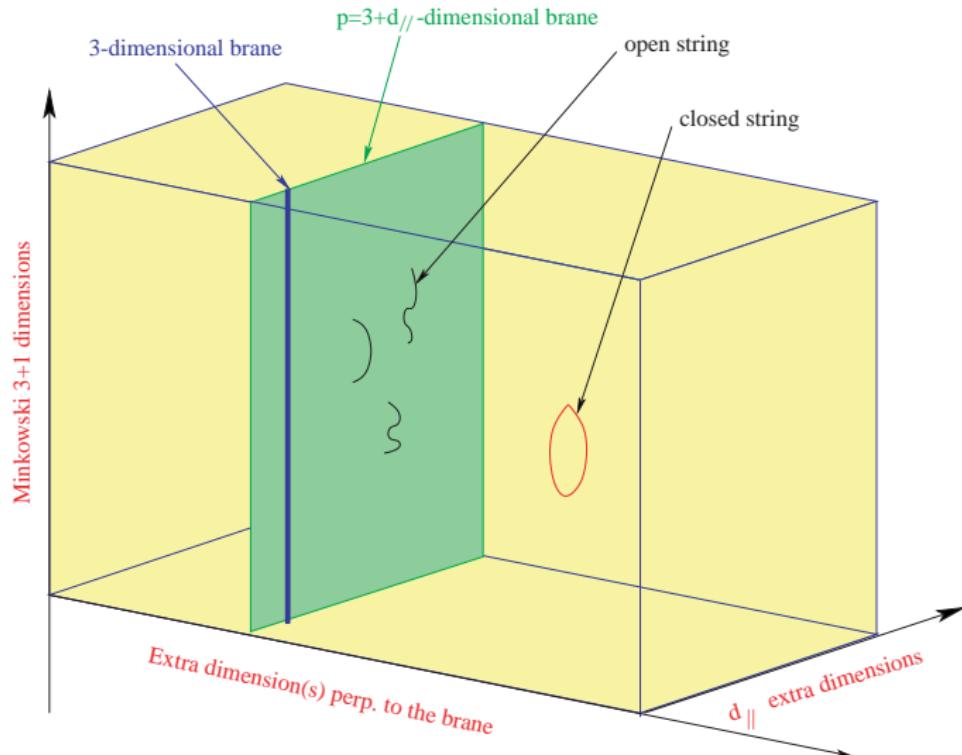
$$R_{\perp} \sim .1 - 10^{-13} \text{ mm for } n = 2 - 6 \quad [5]$$

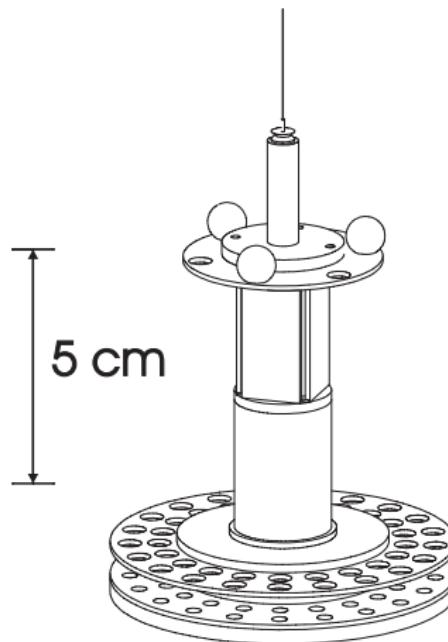
distances $< R_{\perp}$: gravity $(4+n)$ -dim \rightarrow strong at 10^{-16} cm [9]

Braneworld

2 types of compact extra dimensions:

- parallel (d_{\parallel}): $\lesssim 10^{-16}$ cm (TeV) [10]
- transverse (\perp): $\lesssim 0.1$ mm (meV) [14]





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

- dark-energy length scale $\approx 85 \mu\text{m}$ [3] [21]

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

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

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

Two length scales:

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

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

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

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

\Rightarrow Gravity modification at large (cosmological) and short distances ?

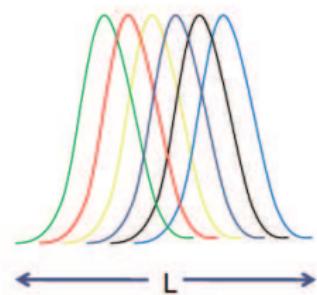
More general framework: large number of species

N particle species \Rightarrow lower quantum gravity scale : $M_*^2 = M_p^2/N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

Pixel of size L containing N species storing information:



localization energy $E \gtrsim N/L \rightarrow$ [18]

Schwarzschild radius $R_s = N/(LM_p^2)$

no collapse to a black hole : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

$M_* \simeq 1 \text{ TeV} \Rightarrow N \sim 10^{32} \text{ particle species !}$

2 ways to realize $N = 10^{32}$ lowering the string scale

- ① Large volume compactifications SM on D-branes [3]

$N = R_\perp^n I_s^n$: number of KK modes up to energies of order $M_* \simeq M_s$

- ② $N \sim$ effective number of string modes contributing to the BH bound

Dvali-Lüst '09, Dvali-Gomez '10

$$N_s = \frac{1}{g_s^2} \text{ with } g_s \simeq 10^{-16} \quad \text{SM on NS5-branes}$$

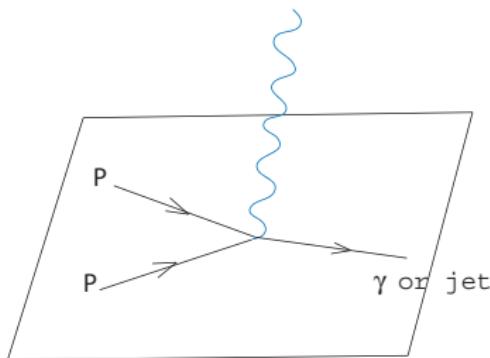
I.A.-Pioline '99, I.A.-Dimopoulos-Giveon '01

in this case gravity does NOT become strong at M_s

Both ways are compatible with the general string relation:

$$M_p^2 = \frac{1}{g_s^2} V_6 M_s^8 \quad V_6 : \text{internal 6d compactification volume}$$

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
⇒ KK resonances of SM gauge bosons [4] I.A. '90

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

- string physics and possible strong gravity effects

Massive string vibrations ⇒ e.g. resonances in dijet distribution [15] [17]

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

higher spin excitations of quarks and gluons with strong interactions

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

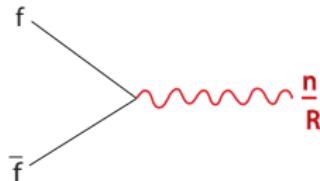
production of micro-black holes? [18]

Giddings-Thomas, Dimopoulos-Landsberg '01

Localized fermions (on 3-brane intersections) [4] [14]

⇒ single production of KK modes

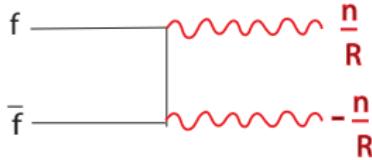
I.A.-Benakli '94



- strong bounds indirect effects: $R^{-1} \gtrsim 3 \text{ TeV}$
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

⇒ pair production of KK modes (universal dims)

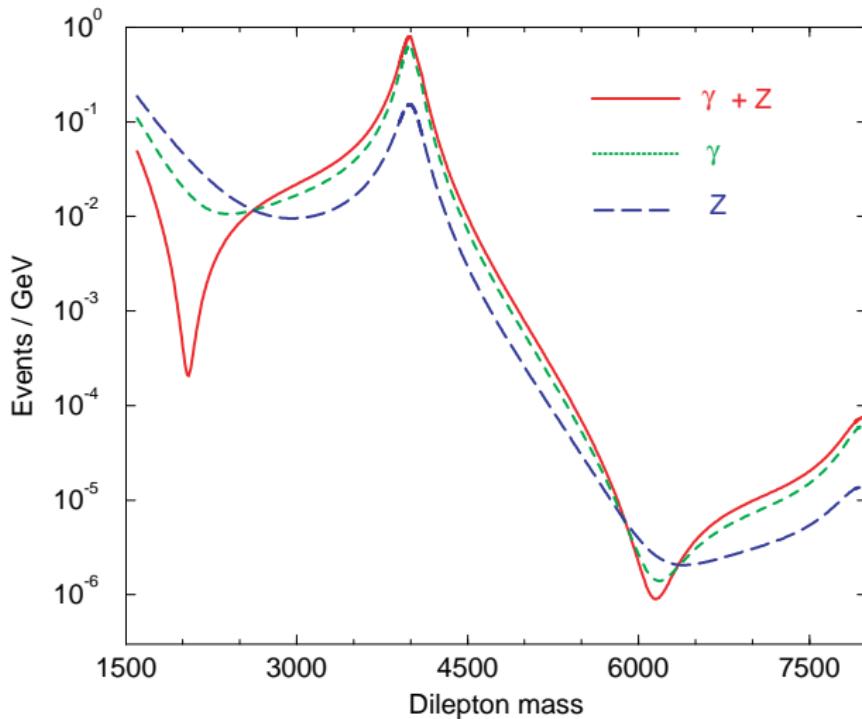


- weak bounds $R^{-1} \gtrsim 300\text{-}500 \text{ GeV}$
- no resonances
- lightest KK stable ⇒ dark matter candidate

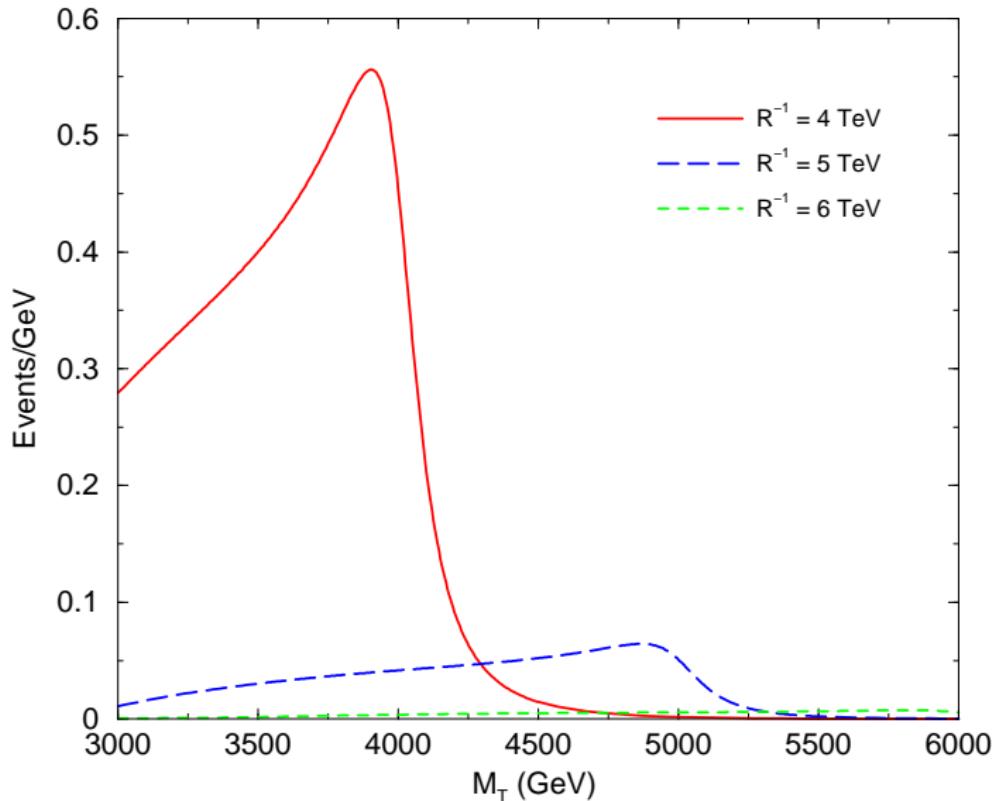
Servant-Tait '02

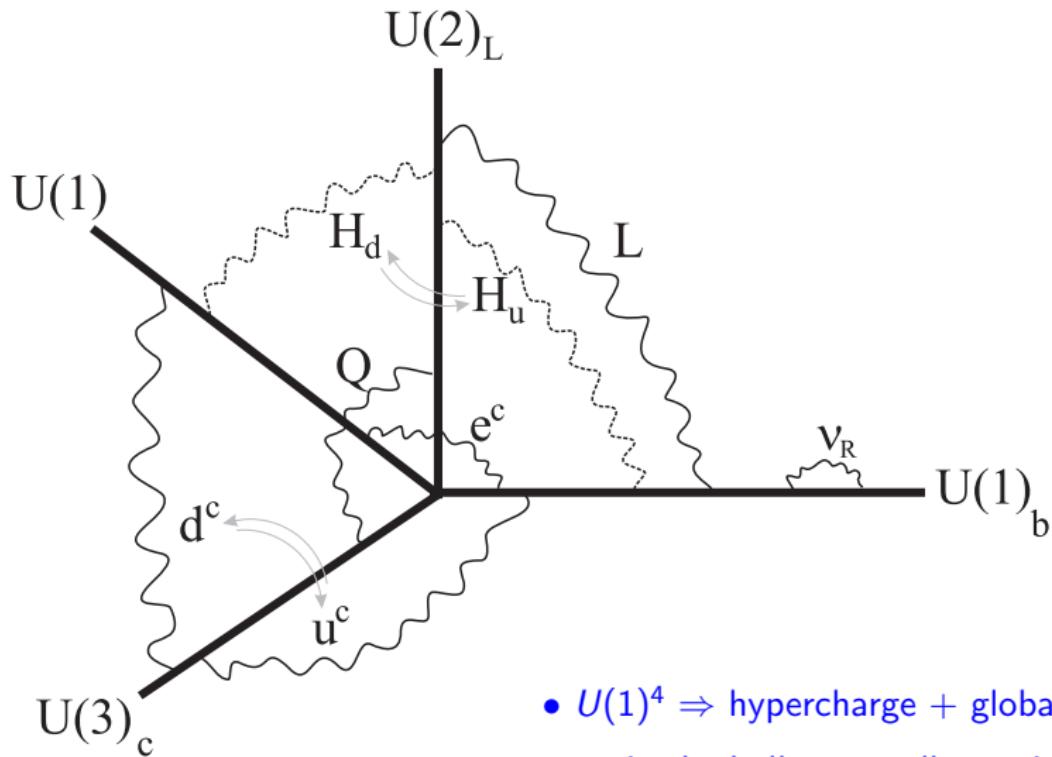
$R^{-1} = 4 \text{ TeV}$

I.A.-Benakli-Quiros '94, '99



KK W-production at LHC in the $l\nu$ channel [11]





- $U(1)^4 \Rightarrow$ hypercharge + global symmetries
- ν_R in the bulk \Rightarrow small neutrino masses [11]

Massive string vibrations

indirect effects: virtual exchanges \Rightarrow effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes $\Rightarrow M_s \gtrsim 500$ GeV dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$
- brane intersections $\Rightarrow M_s \gtrsim 2 - 3$ TeV dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$

Cullen-Perelstein-Peskin, I.A.-Benakli-Laugier '00

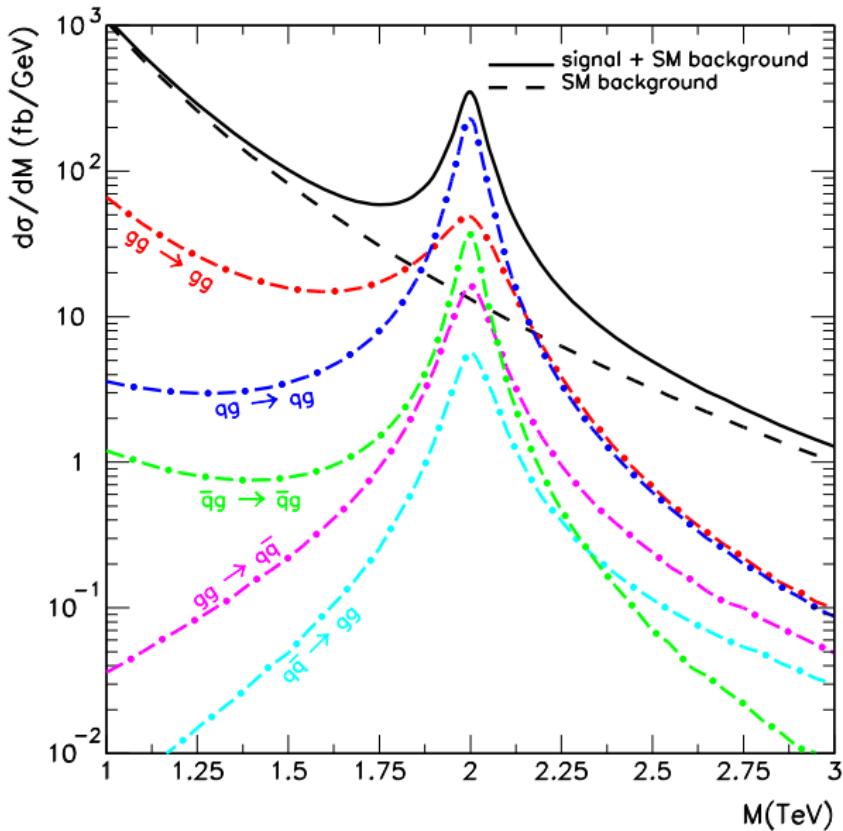
High energies \Rightarrow direct production: string physics

Universal deviation from Standard Model in jet distribution

$M_s = 2 \text{ TeV}$

Width = 15-150 GeV

Anchordoqui-Goldberg-
Lüst-Nawata-Taylor-
Stieberger '08 [10]



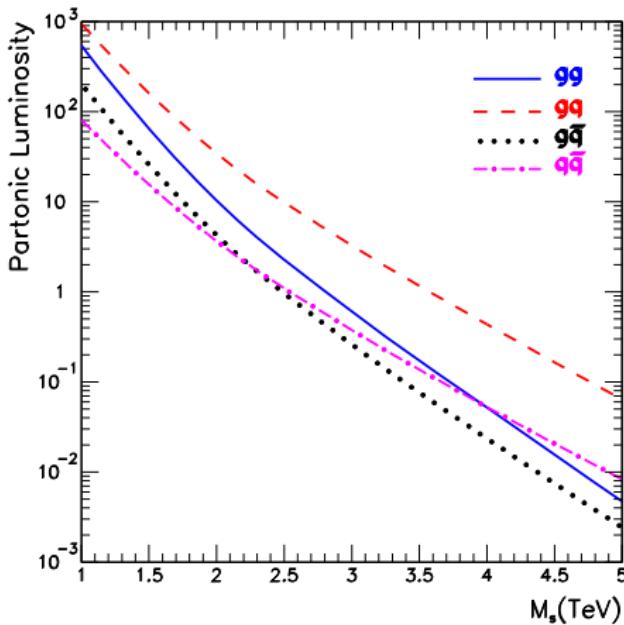
Tree level superstring amplitudes involving at most 2 fermions and gluons:
model independent for any compactification, # of susy's, even none
no intermediate exchange of KK, windings or graviton emmission
Universal sum over infinite exchange of string (Regge) excitations [10]

Parton luminosities in pp above TeV

are dominated by gq, gg

⇒ model independent

$gq \rightarrow gq, gg \rightarrow gg, gg \rightarrow q\bar{q}$



Black hole production

String-size black hole energy threshold : $M_{\text{BH}} \simeq M_s/g_s^2$ [7]

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: $r_H \sim l_s = M_s^{-1}$
- black hole mass: $M_{\text{BH}} \sim r_H^{d-3}/G_N \quad G_N \sim l_s^{d-2} g_s^2$

weakly coupled theory \Rightarrow strong gravity effects occur much above M_s, M_*

$$g_s \sim 0.1 \text{ (gauge coupling)} \quad \Rightarrow \quad M_{\text{BH}} \sim 100M_s$$

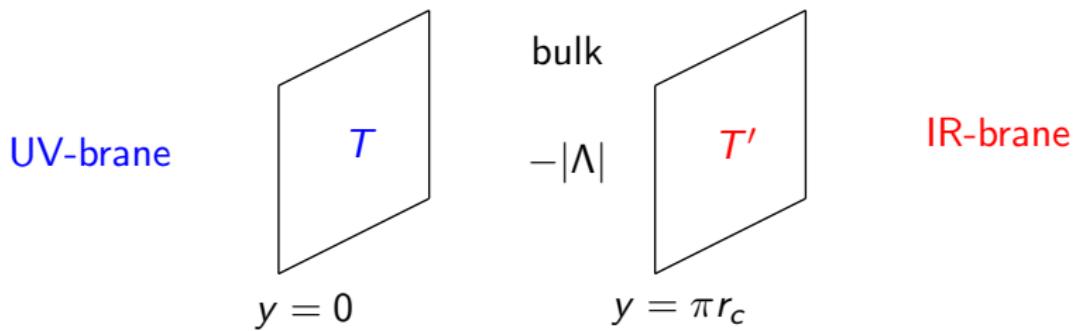
Comparison with Regge excitations : $M_j = M_s \sqrt{j} \Rightarrow$

production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach M_{BH}

Randal Sundrum models

spacetime = slice of AdS₅ 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

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

weakly coupled for $m_n < M e^{-2\pi k r_c} \Rightarrow k < M$

- viable models: Standard Model gauge bosons in the bulk,
fermions near the UV-brane, Higgs on the IR-brane
- AdS/CFT duals to strongly coupled 4d field theories

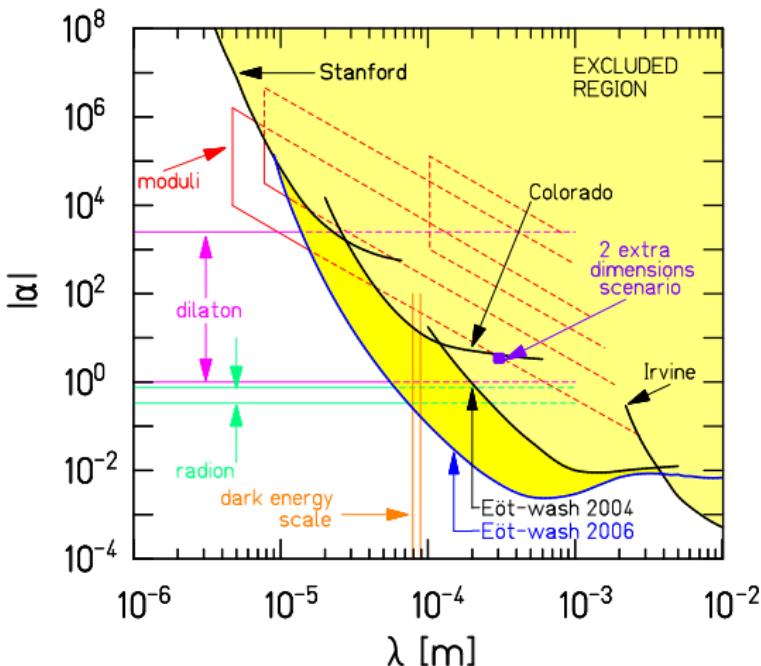
composite Higgs models, technicolor-type $g_{YM} = M/k > 1$ [10]

microgravity experiments

- change of Newton's law at short distances [5]
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: $(\text{TeV})^2/M_P \sim 10^{-4}$ eV \rightarrow mm range
- can be experimentally tested for any number of extra dimensions
- Light $U(1)$ gauge bosons: no derivative couplings
 - \Rightarrow for the same mass much stronger than gravity: $\gtrsim 10^6$

Experimental limits on short distance forces

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

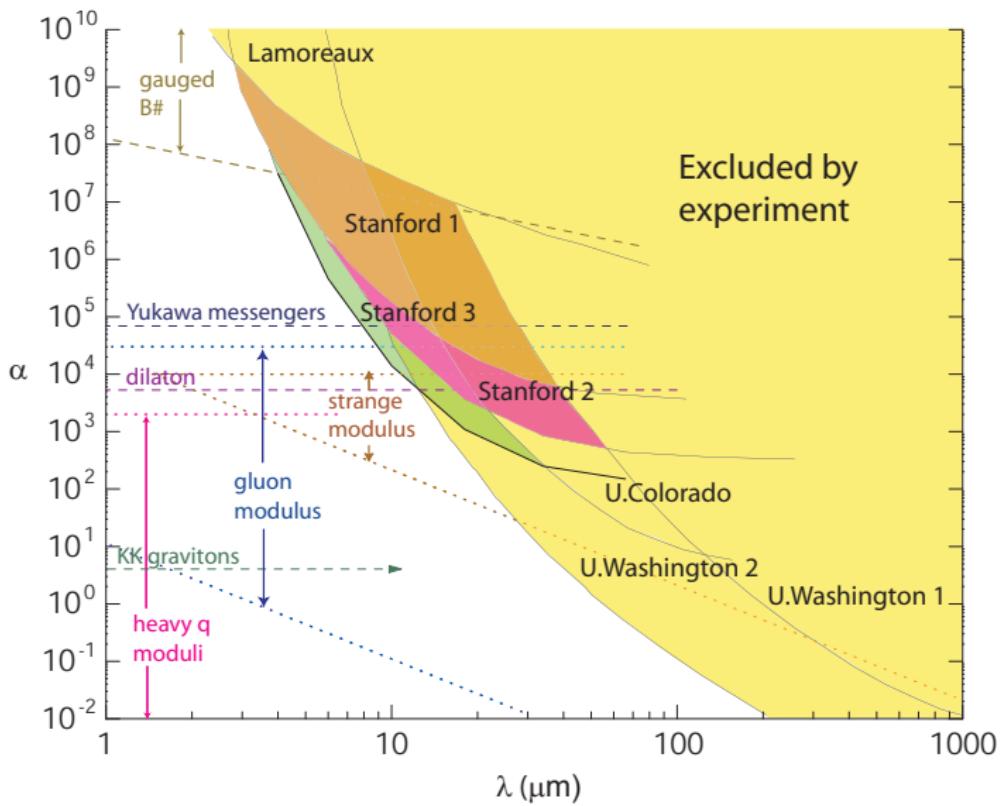


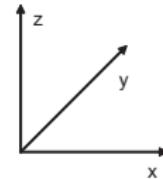
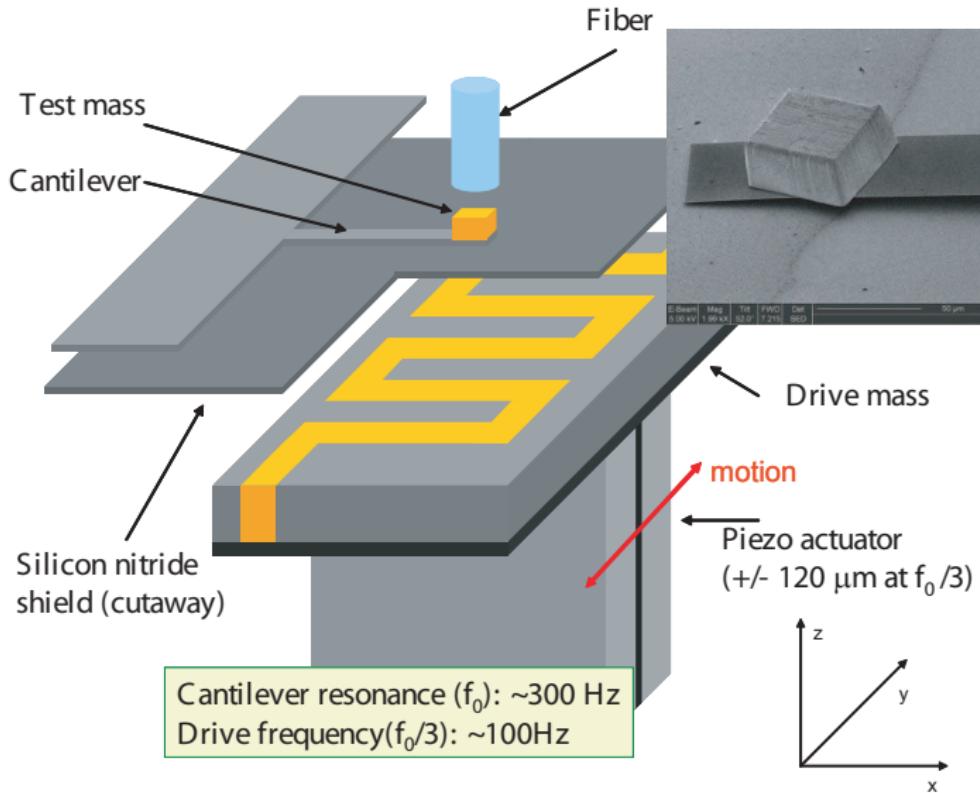
$\text{Radion} \Rightarrow M_* \gtrsim 6 \text{ TeV} \quad 95\% \text{ CL}$

Adelberger et al. '06

improved bounds in the range 5-15 μm

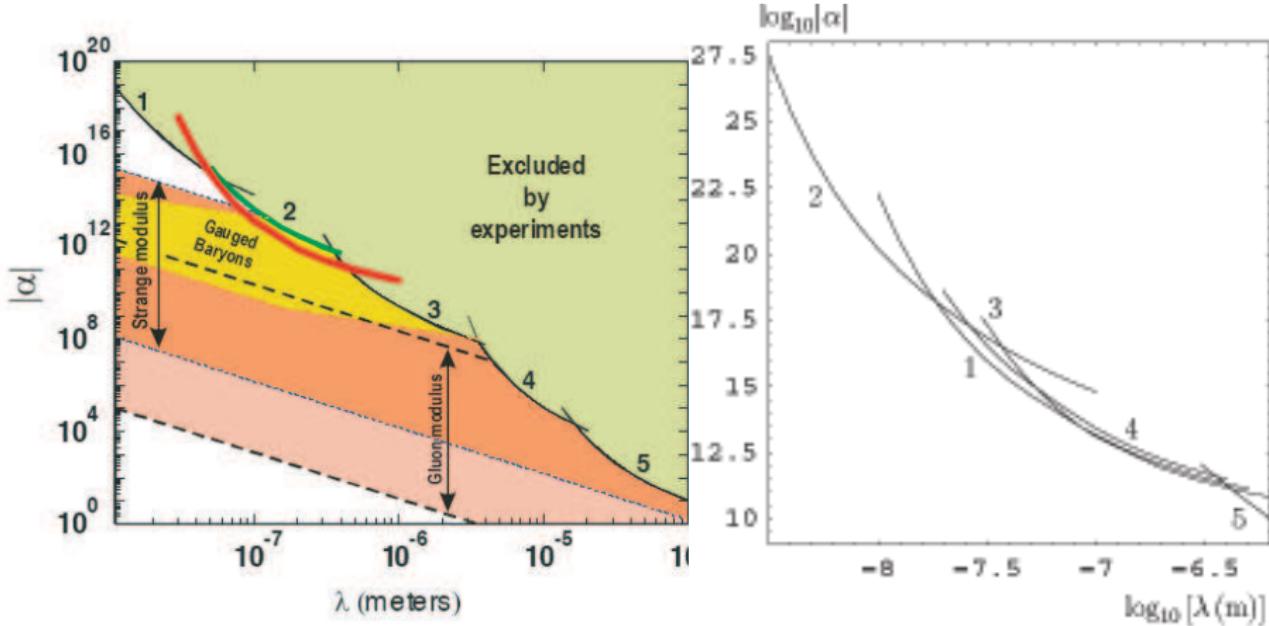
Geraci-Smullin-Weld-Chiaverini-Kapitulnik '08





improved bounds from Casimir effect in the nm range

Decca-Fischbach et al '07, '08

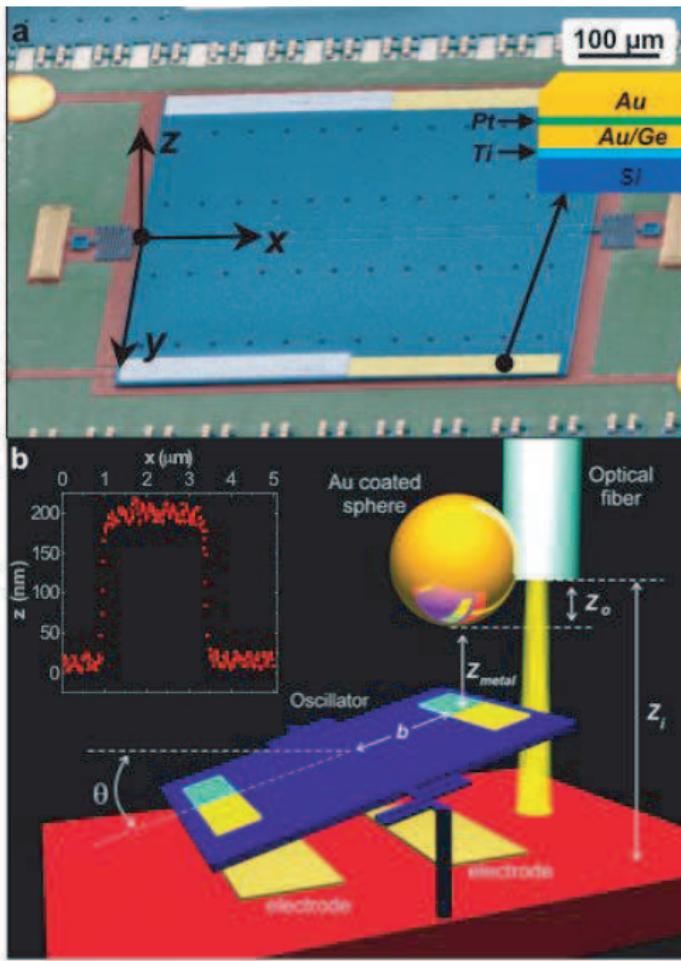


5: Colorado

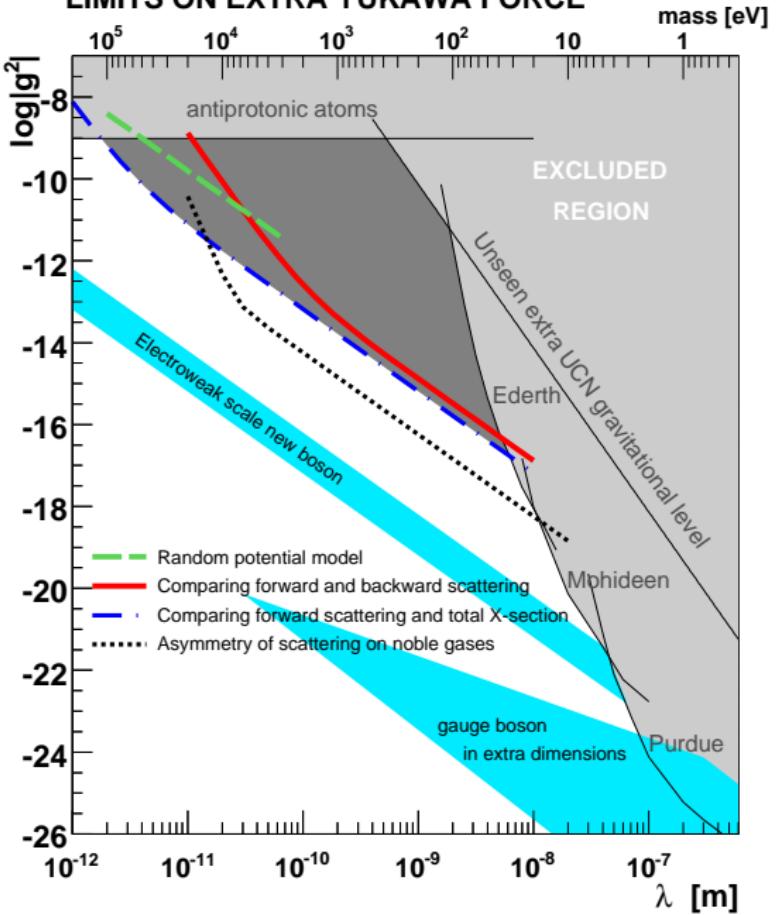
4: Stanford

3: Lamoureux

1: Mohideen et al.



LIMITS ON EXTRA YUKAWA FORCE

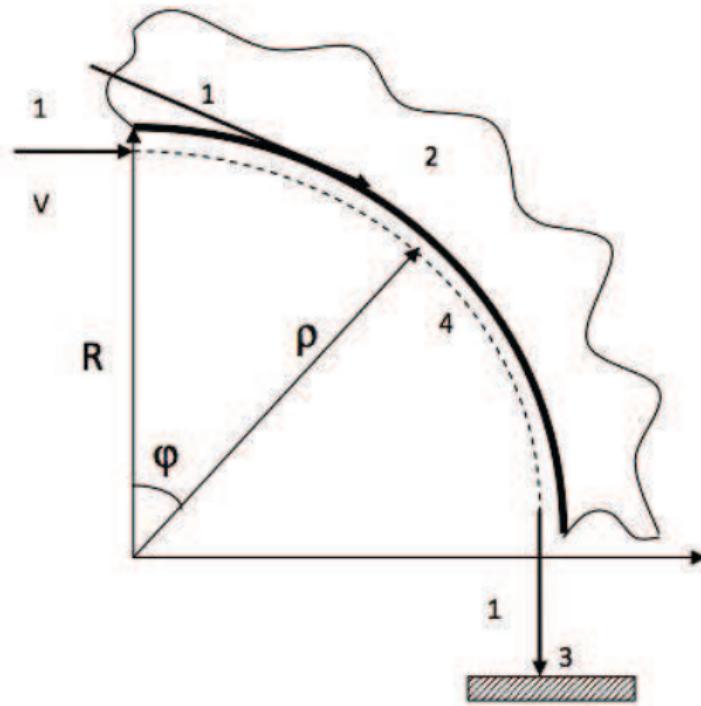


Neutron scattering:
bounds in the range
 $\sim 1\text{pm} - 1\text{nm}$ [21]

Nesvizhevsky-Pignol-
Protasov '07

Neutron whispering gallery

Centrifugal quantum states of neutrons



Conclusions

TeV strings and large extra dimensions: Physical reality or imagination?

- Well motivated theoretical framework
 - with many testable experimental predictions
 - new resonances, missing energy
- Stimulus for micro-gravity experiments
 - look for new forces at short distances
 - higher dim graviton, scalars, gauge fields

But: - unification has to be dropped

- physics is radically changed above string scale

LHC: will explore the physics beyond the Standard Model