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CERN

Physics and Signatures

of

Extra Dimensions

TeV Particle Astrophysics

Venice, 27-31 August 2007

OUTLINE

- Motivations
- Framework of low scale strings

  large extra dimensions, low scale gravity
- Exp predictions for particle accelerators

  strong gravity, TeV dimensions, string effects
- D-brane embedding of the Standard Model

  unification, proton stability, Right-neutrinos
- SUSY in the bulk ⇒ short-range forces

  and microgravity experiments

  radion force, gauge bosons in the bulk

Hierarchy problem: why gravity is so weak

compared to the other interactions?

Quantum theory: all particle masses $\nearrow M_P \sim 10^{19}$ GeV

- TeV strings: low UV cutoff

$$\Rightarrow M_s \sim \text{TeV}$$

- Framework of type I string theory

$\Rightarrow$ D-brane world

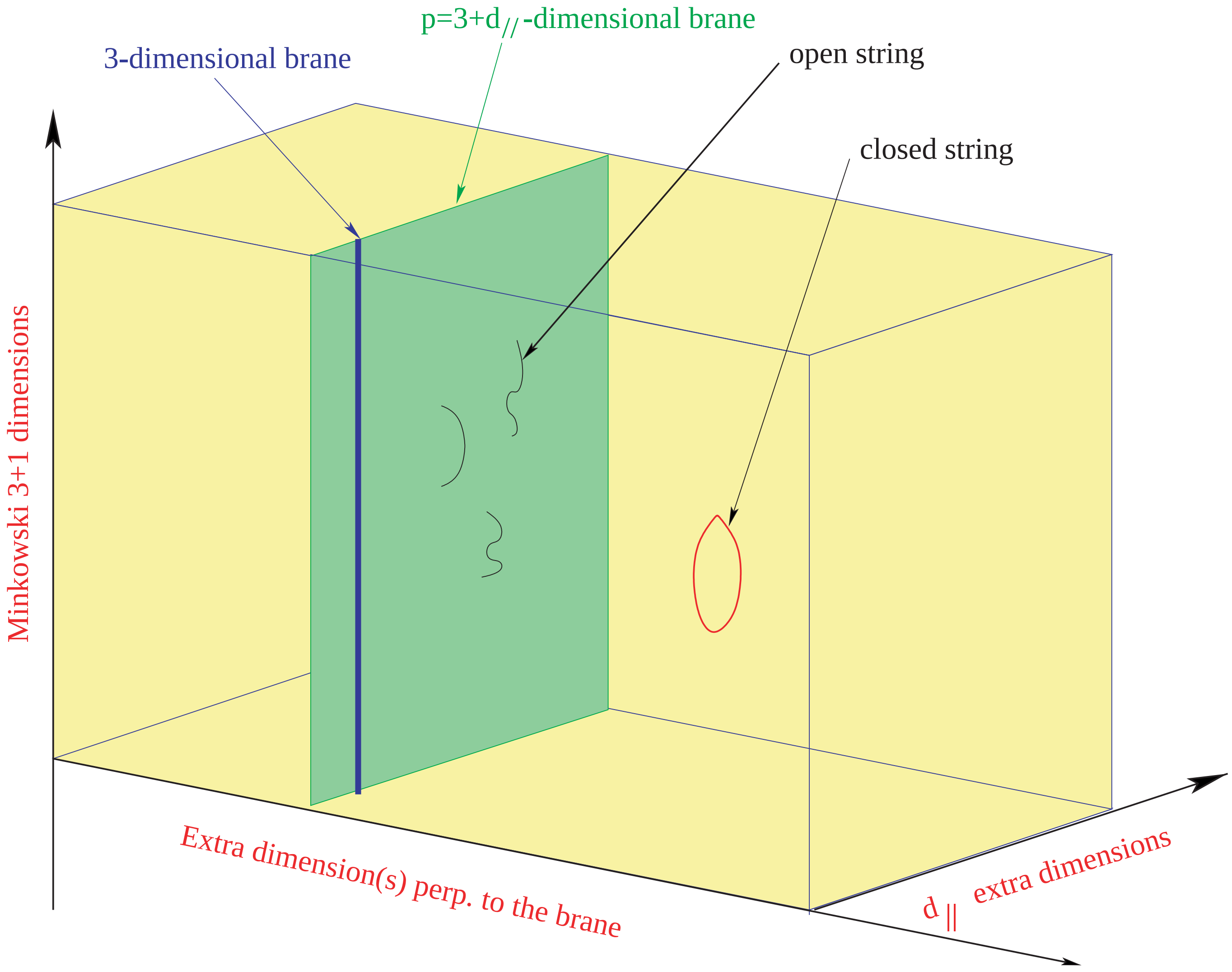
Natural separation of

global SUSY from gravity

$\swarrow$ $\searrow$

D-branes/open strings closed strings

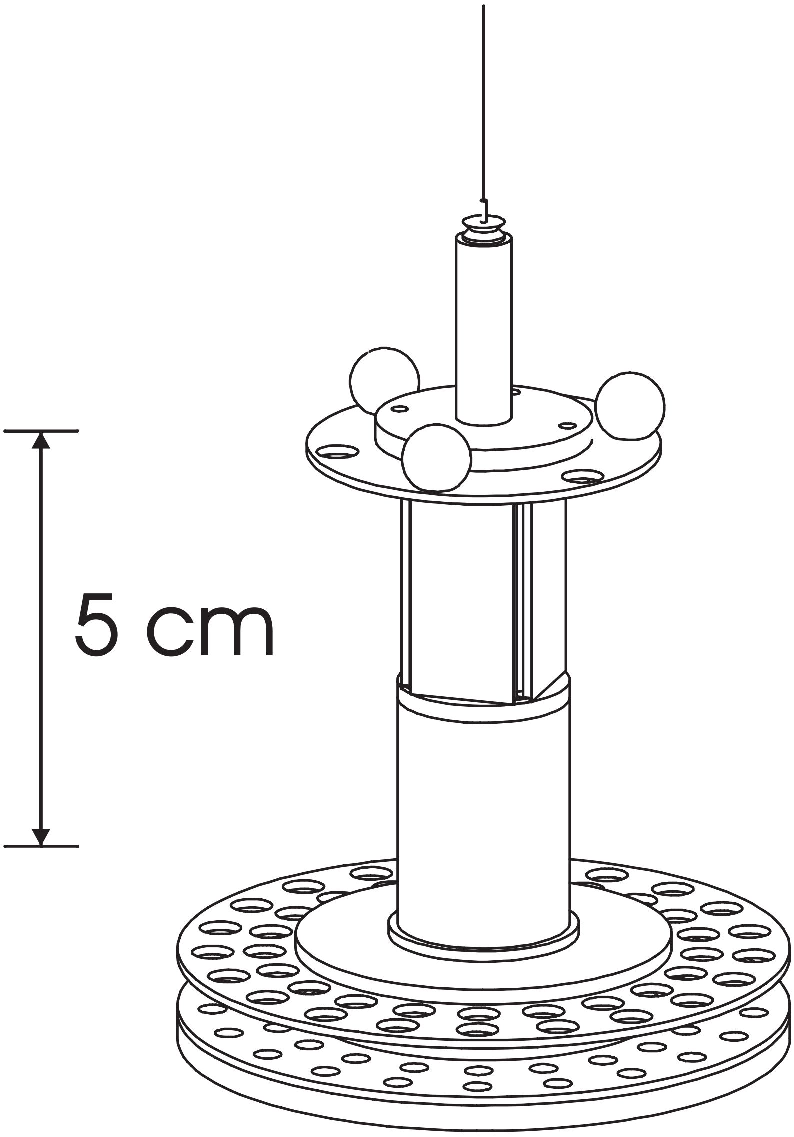
Braneworld



two types of compact extra dimensions:

- parallel ($d_{\|}$): can be as large as 10^{-16} cm (TeV^{-1})
- transverse ($\perp$): can be as large as 0.1 mm

Adelberger et al. '06



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

- dark-energy length scale $\approx 85\mu$m

Dimensions of finite size: $p-3$ parallel

$n = 9-p$ transverse

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

$$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_\perp^n$$

↖

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

small M_s/M_P $\Rightarrow$ extra-large $R_\perp$

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

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

- weak string coupling: $g_s = \alpha$
- gravity strong at $M_* \sim M_s << M_P$

  10^{30} stronger than thought previously!

  deviations from Newton's law at distances $< R_\perp$

Supernova constraints

cooling due to graviton production

e.g. $NN \to NN +$ graviton

number of gravitons: $\sim (TR_\perp)^n$ $\qquad T >> R_\perp^{-1}$

$\nearrow$

~ 10 MeV

$\Rightarrow$ production rate:

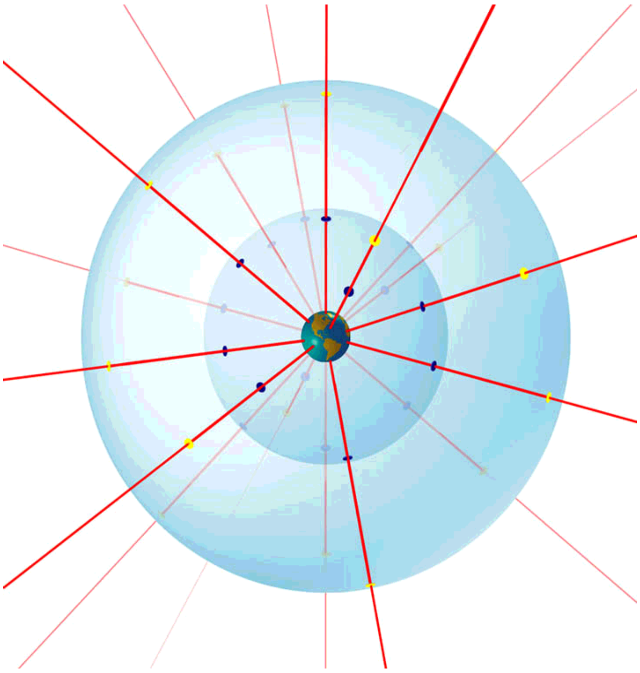
$$P_{\text{gr}} \sim \frac{1}{M_p^2}(TR_\perp)^n \sim \frac{T^n}{M_*^{(2+n)}}$$

$$P_{\text{gr}} < P_\nu \quad \Rightarrow \quad M_*\Big|_{n=2} \gtrsim 50 \text{ TeV}$$

$$\Rightarrow \quad M_s \gtrsim 10 \text{ TeV}$$

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 $r \lesssim .1$ mm

Hidden submillimeter dimensions

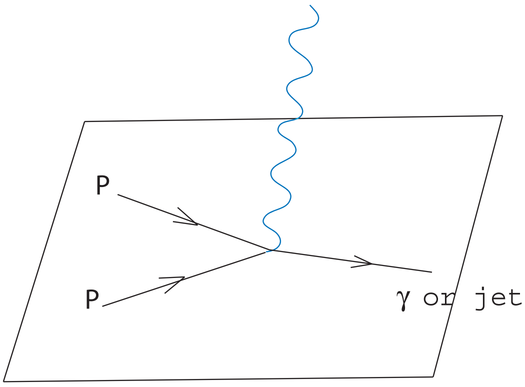
$\Rightarrow$ strong gravity at the TeV

Gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

$\Rightarrow$ high energy: huge number of particles produced

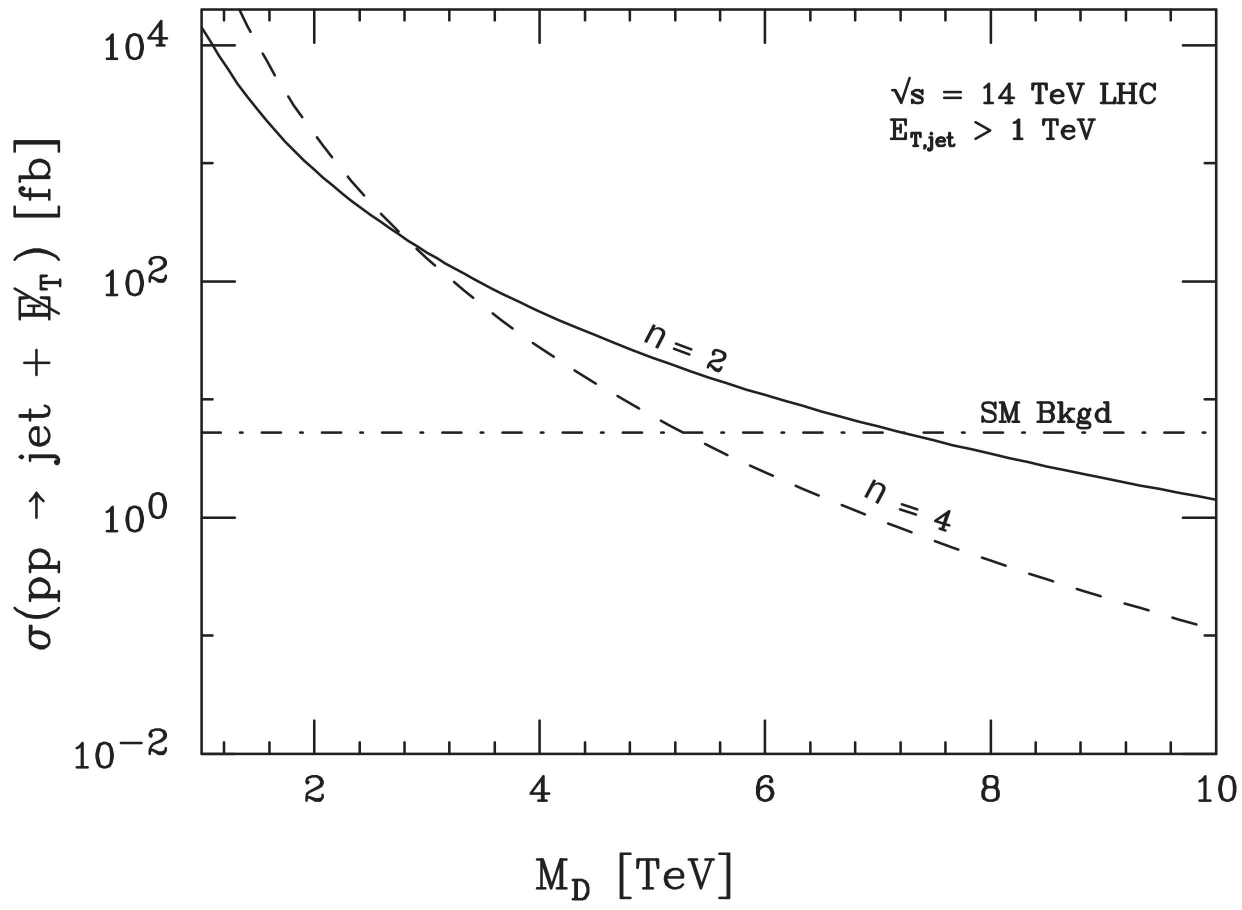
LHC: 10^{30} massive gravitons of intensity 10^{-30} each



Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Giudice-Rattazzi-Wells '98



no observation ⇒

$R_\perp \lesssim 10^{-2} - 10^{-12}$ mm ($n = 2 - 6$); 95% CL

- more dimensions ⇒ weaker limits

Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
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}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_s \Rightarrow$

R^{-1} first scale of new physics I.A. '90

increasing the energy

- could happen for some of the internal dims
- explain coupling constant ratios g_2/g_3
- susy breaking
- fermion masses displace light generations

Massive tower of Kaluza Klein modes

for Standard Model particles

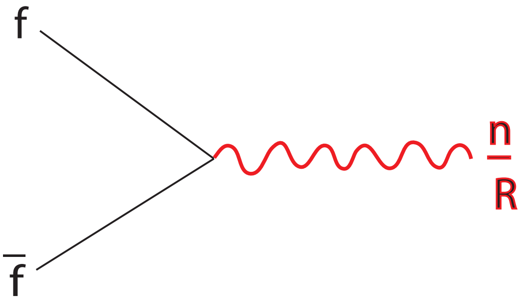
$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

$\Rightarrow$ excited states of photon, $W^{\pm}$, Z, gluons

Localized fermions (on 3-brane intersections)

$\Rightarrow$ single production of KK modes

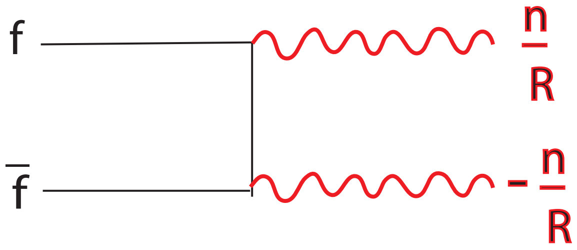
I.A.-Benakli '94



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

Otherwise KK momentum conservation

$\Rightarrow$ pair production of KK modes (universal dims)

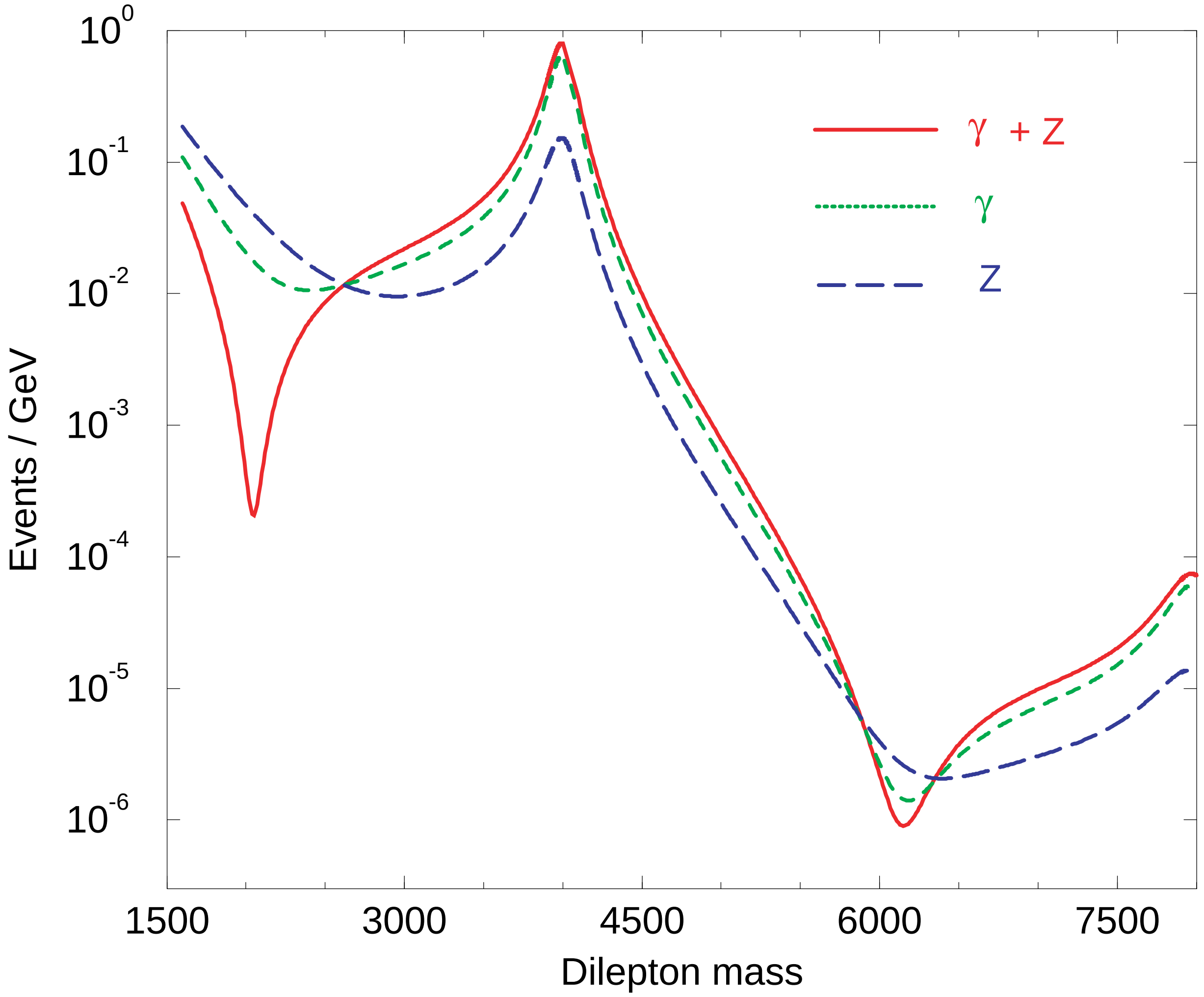


- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable $\Rightarrow$ dark matter candidate

Servant-Tait '02

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

$R^{-1} = 4$ TeV



- no observation in dijets

$$\Rightarrow R^{-1} \gtrsim 20 \text{ TeV} \ ; \ 95\% \text{ CL}$$

- more than one dimension $\Rightarrow$ stronger limits

Massive string vibrations ⇒ indirect effects

virtual exchanges ⇒ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes ⇒ $M_s \gtrsim 500$ GeV

dim-8: $\frac{g^2}{M_s^4}(\bar\psi\partial\psi)^2$ Cullen-Perelstein-Peskin '00

- brane intersections ⇒ $M_s \gtrsim 2-3$ TeV

dim-6: $\frac{g^2}{M_s^2}(\bar\psi\psi)^2$ I.A.-Benakli-Laugier '00

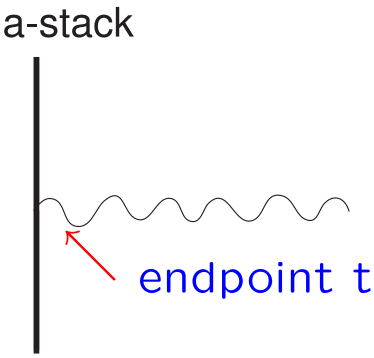
High energies ⇒

- direct production: string physics
- strong gravity: production of micro-black holes?

Giddings-Thomas, Dimopoulos-Landsberg '01

Generic spectrum

N coincident branes $\Rightarrow U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$

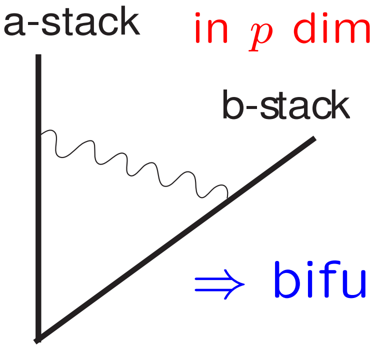
$U(1)_a$ charge: $+1$ or -1

$U(1)$: "baryon" number

- open strings from the same stack

  $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$

- open strings stretched between two stacks



in p dims

in p' dims

$\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$

in $p \cap p'$ dims

A D-brane embedding of the Standard Model

I.A.-Kiritsis-Tomaras '00

I.A.-Kiritsis-Rizos-Tomaras '02

- oriented strings ⇒

  need at least 4 brane-stacks

- existence of bulk with large dimensions ⇒

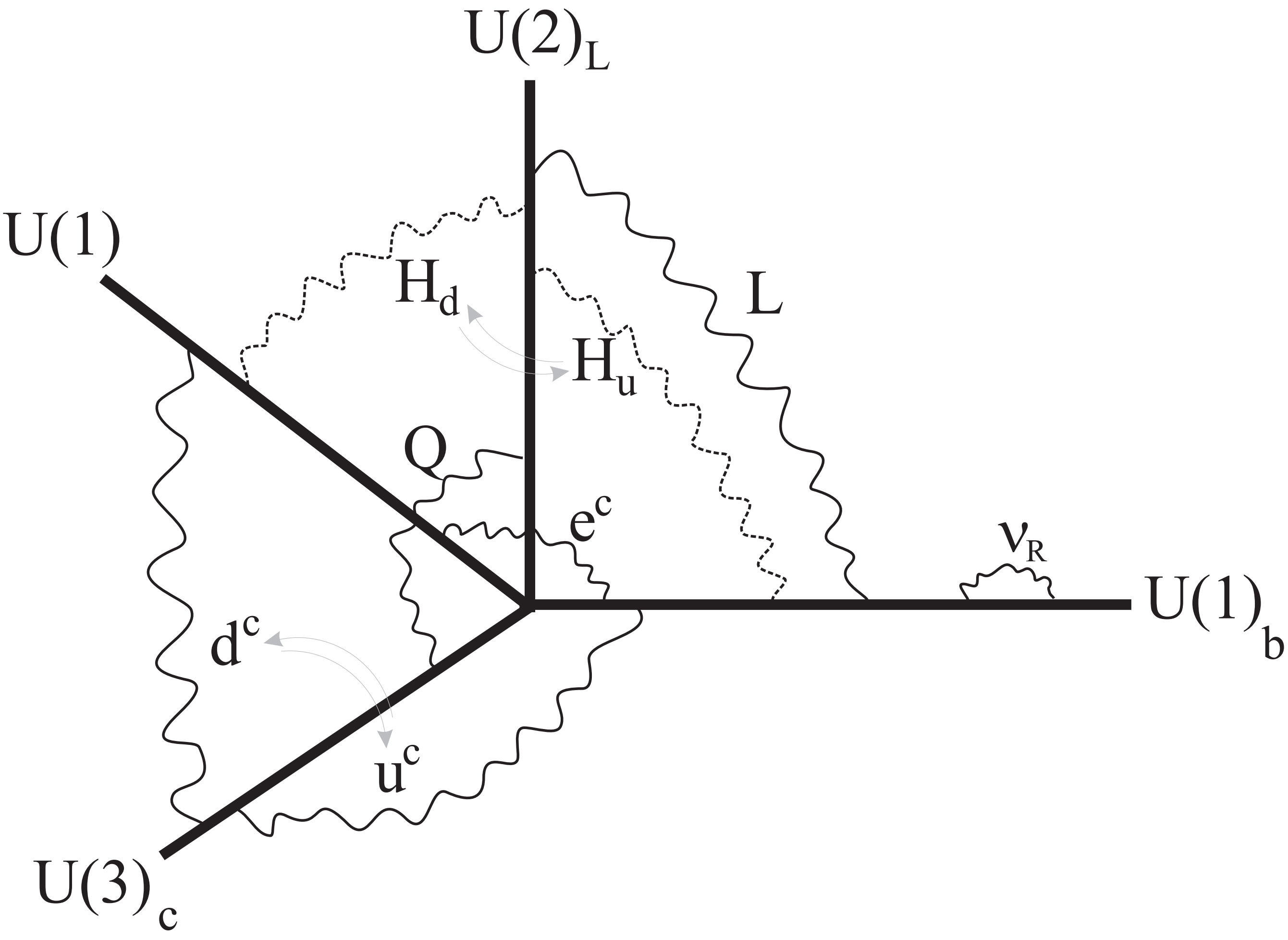
  minimal choice: $U(3)\times U(2)\times U(1)\times U(1)_{bulk}$

  color branes (g_3)　　　weak branes (g_2)

- also for non-oriented strings

  with Baryon and Lepton number symmetries

Standard Model on D-branes



- $g_2^2/g_3^2 = R/l_s \Rightarrow$ KK modes for $SU(2)_L$
- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- $U(1)$ on top of $U(2)$ or $U(3) \Rightarrow$ prediction for $\sin^2\theta_W$
- ν_R in the bulk $\Rightarrow$ small neutrino masses

The remaining three $U(1)$'s : anomalous

Green-Schwarz anomaly cancellation $\Rightarrow$

- they become massive (absorb three axions)
- the global symmetries remain in perturbation

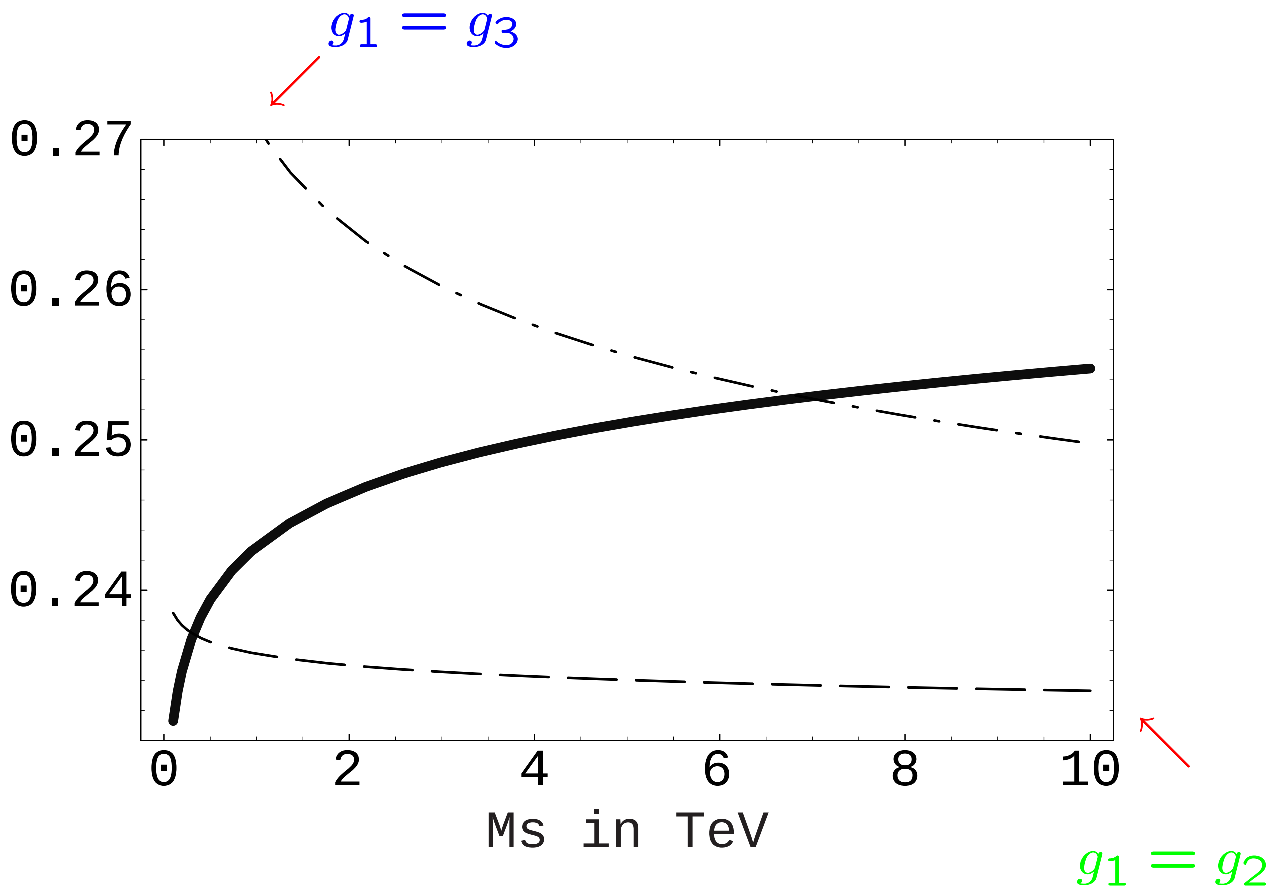
- Baryon number $\Rightarrow$ proton stability
- Lepton number $\Rightarrow$ protect small neutrino masses

no Lepton number $\Rightarrow \frac{1}{M_s} LLHH$

$\Rightarrow$ Majorana mass: $\frac{\langle H \rangle^2}{M_s} LL$

$\sim$ GeV

$\sin^2\theta_W(M_s)$



$\Rightarrow$ correct prediction for $\sin^2\theta_W$

for $M_s \sim$ a few TeV

R-neutrinos: open strings in the bulk

Arkani Hamed-Dimopoulos-Dvali-March Russell '98

Dienes-Dudas-Gherghetta '98

- $\int d^{4+n}x\ \bar{\nu}\partial\!\!\!/\nu \qquad \nu = (\nu_R, \nu_R^c)\ \Rightarrow$

$$R_\perp^n \int d^4x \sum_m \{\bar{\nu}_{Rm}\partial\!\!\!/\nu_{Rm} + \bar{\nu}^c_{Rm}\partial\!\!\!/\nu^c_{Rm} + \tfrac{m}{R_\perp}\nu_{Rm}\nu^c_{Rm} + c.c.\}$$

- $S_{int} = g_s \int d^4x H(x)L(x)\nu_R(x, y = 0)$

$\langle H\rangle = v \ \Rightarrow$ mass-terms: $\frac{g_s v}{R_\perp^{n/2}} \sum_m \nu_L \nu_{Rm}$

$\frac{g_s v}{R_\perp^{n/2}} << \frac{1}{R_\perp} \ \Leftrightarrow\ g_s v << R_\perp^{n/2-1} \ \Rightarrow$

- $m \neq 0$: masses for KK ν_m unaffected

- $m = 0$: Dirac neutrino masses

$$m_\nu \simeq \frac{g_s v}{R_\perp^{n/2}} \simeq v\frac{M_s}{M_p}$$

$\simeq 10^{-3} - 10^{-2}$ eV for $M_s \simeq 1 - 10$ TeV

- global SUSY: no need to be there

at least for hierarchy

- SUGRA: probably unbroken in the bulk $\Rightarrow$

very weakly broken

New forces at submm scales

e.g. radion, gauge fields

Radion $\equiv \ln V_\perp$

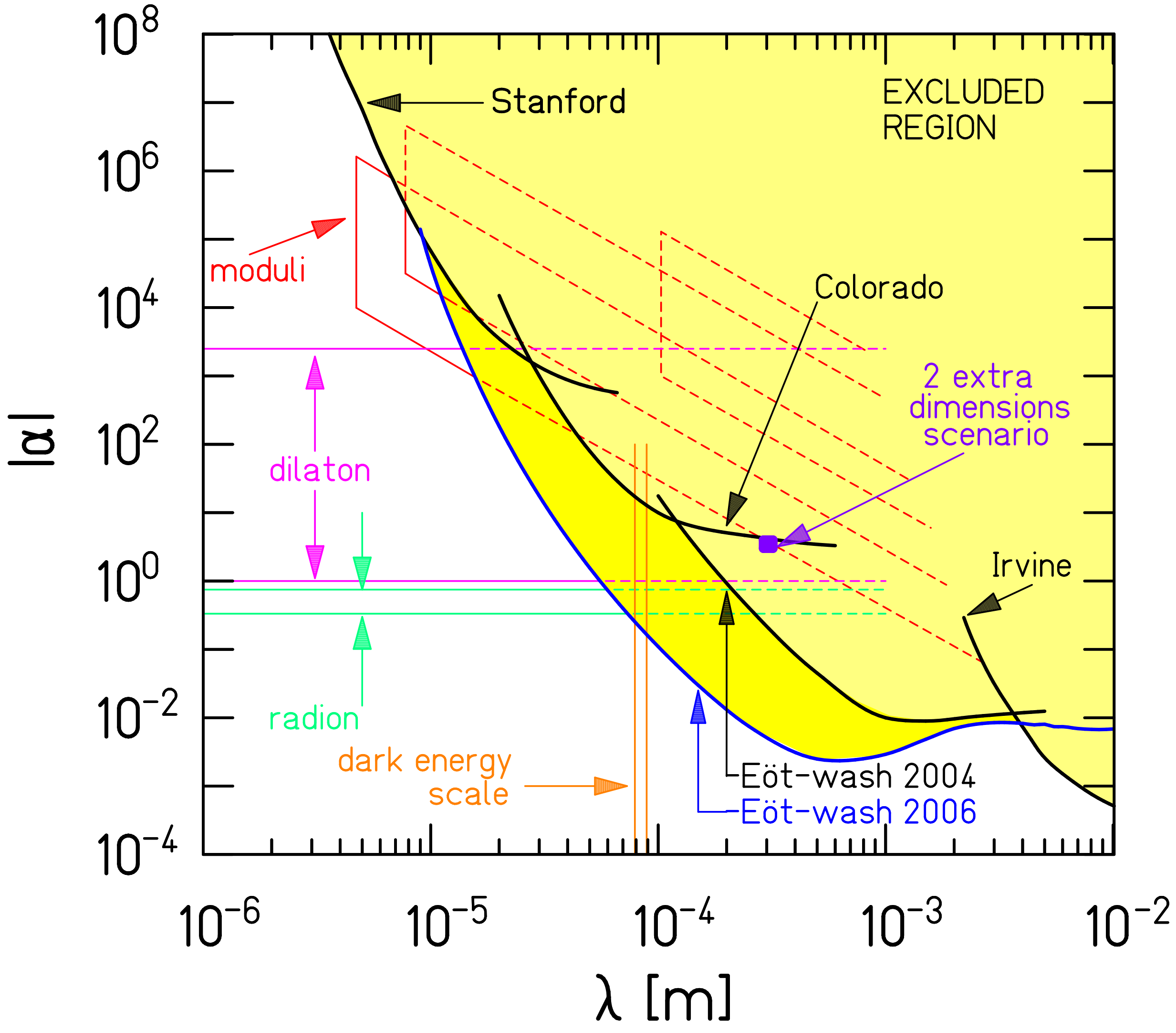
mass: $(\text{TeV})^2/M_P \sim 10^{-4}$ eV $\to$ mm range

coupling: $\frac{1}{m}\frac{\partial m}{\partial \ln V_\perp} = \sqrt{\frac{n}{n+2}} \times$ gravity

$\Rightarrow$ can be experimentally tested for all $n \geq 2$

I.A.-Benakli-Maillard-Laugier '02

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



Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL

Adelberger et al. '06

Light $U(1)$ gauge bosons

$$m_A = g_A\, M$$

small mass $\Rightarrow$ small coupling

$\Rightarrow$ A in the bulk with localized mass

$g_A \sim 1/\sqrt{V_\perp}$

$$\Rightarrow m_A \gtrsim M_s^2/M_P \;\simeq\; 10^{-4}\,\text{eV}$$

A propagates in part of the bulk

$\Rightarrow$ new submm forces

$g_A \sim 1/\sqrt{V_\perp} \gtrsim M_s/M_P \sim 10^{-16}$

$\Rightarrow\ \gtrsim\ 10^6 - 10^8 \times$ gravity

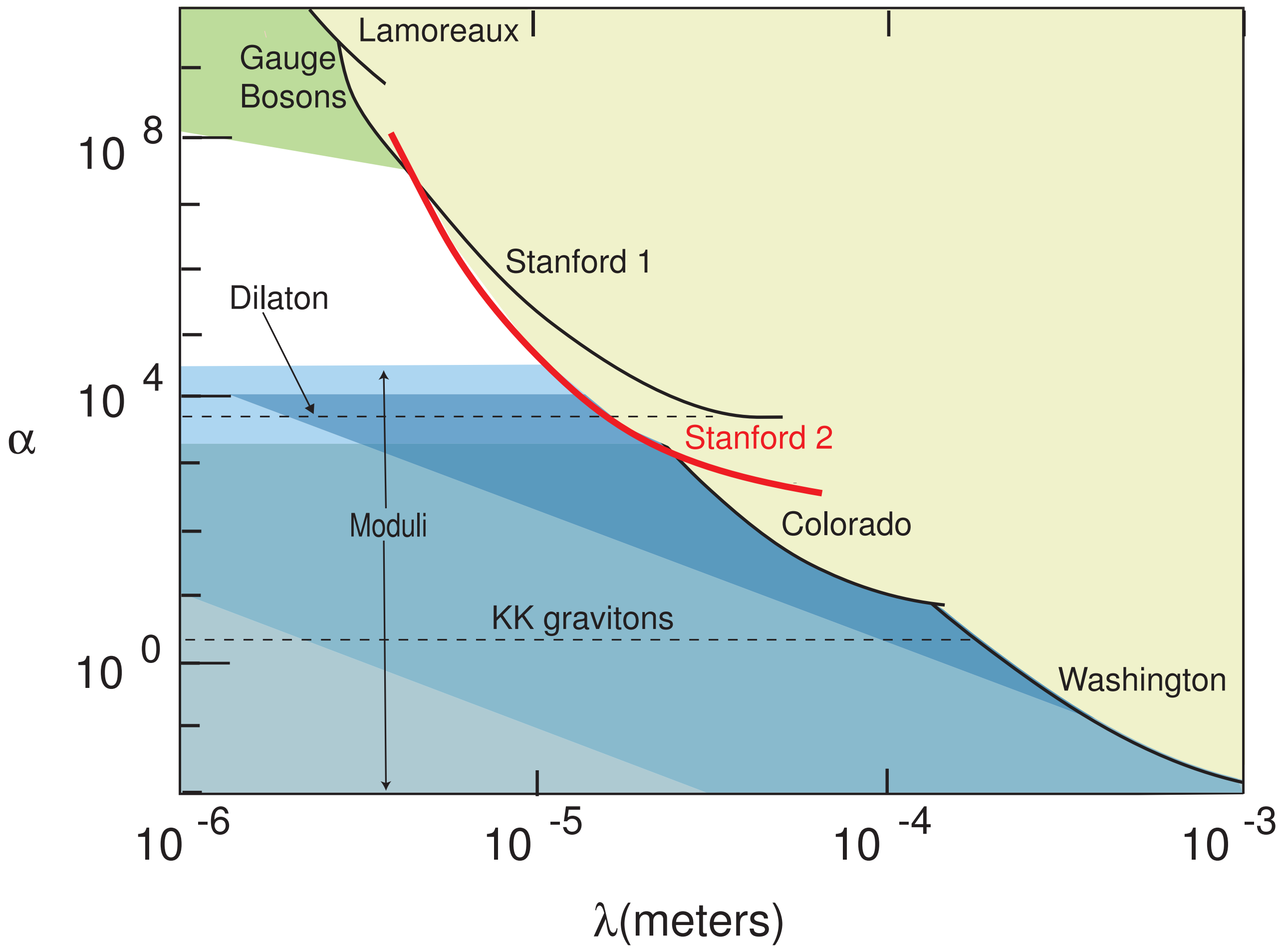
m_{proton}/M_*

supernova $\Rightarrow$ dim of the bulk ≥ 4

an order of magnitude improvement

on bounds in the range 6-20 μm

Smullin-Geraci-Weld-Chiaverini-Holmes-Kapitulnik ’05

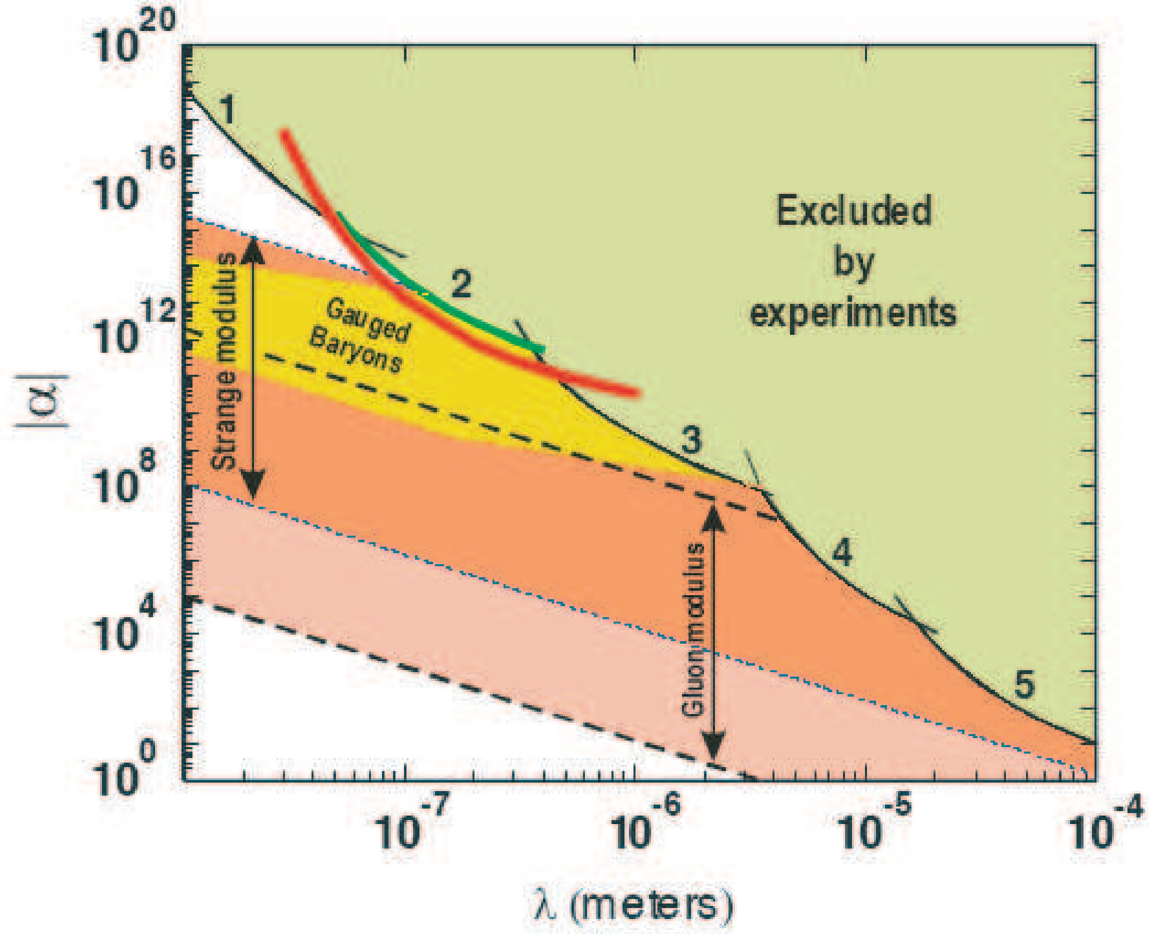


Casimir effect: an order of magnitude improvement

on bounds in the range 10-200 nm

Decca-López-Chan-Fischbach-Krause-Jamell ’05

Decca et al. ’07



5: Colorado

4: Stanford

3: Lamoureaux

1: Mohideen et al.

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

LHC: will explore the physics beyond
the Standard Model