I. Antoniadis

CERN

How to Detect

Extra-dimensions

OUTLINE

- Motivations
- Framework low string scale /

  strong gravity at low energies

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

- Exp predictions for particle accelerators
- SUSY breaking / SUSY in the bulk

  and new short range forces radion force

- Gauge bosons in the bulk

  strong forces at very short distances

- Status of microgravity experiments

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

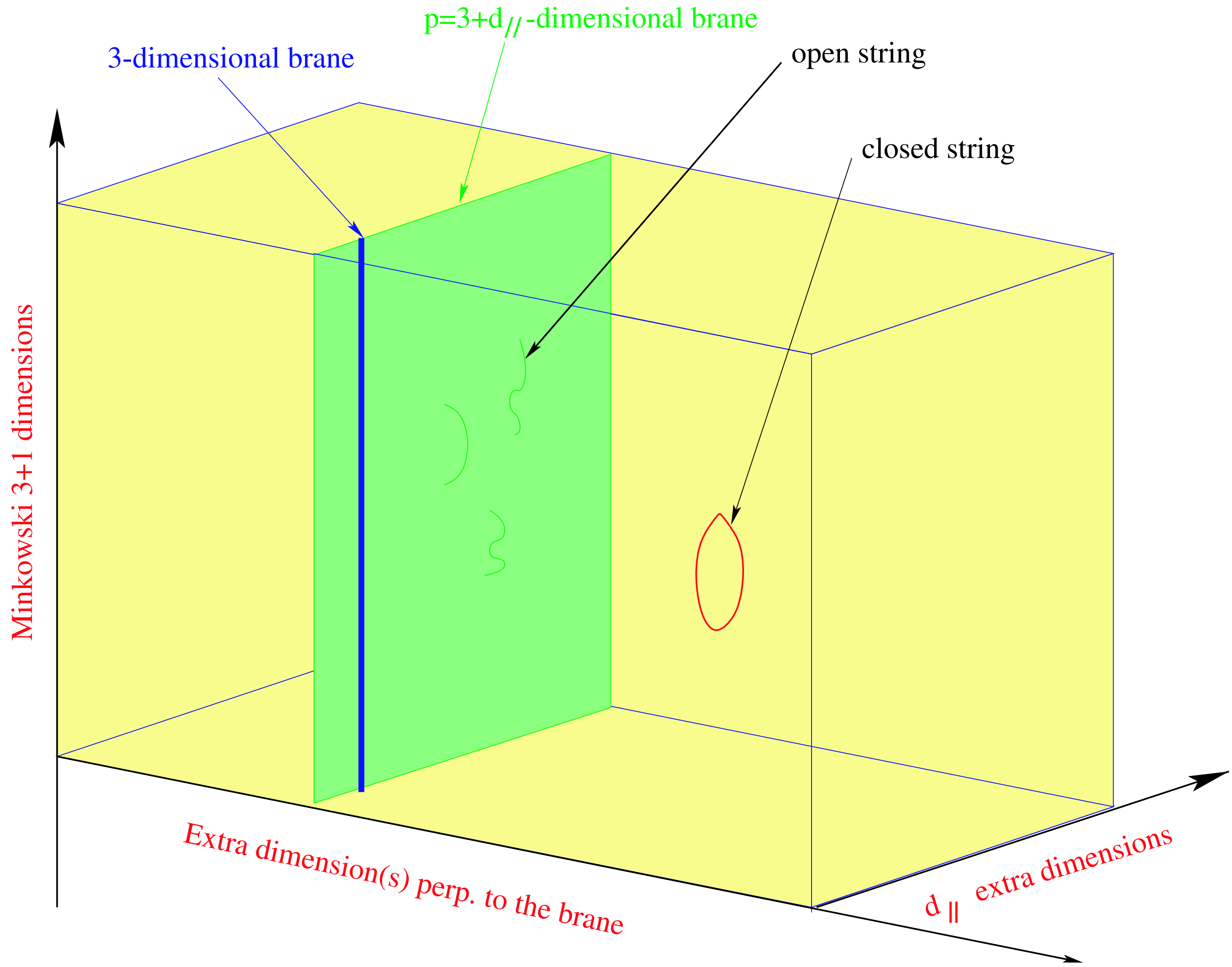
Natural separation of

global SUSY from gravity

$\swarrow \qquad\qquad\qquad \searrow$

D-branes/open strings $\qquad$ closed strings

Braneworld



two types of compact extra dimensions:

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

I.A. '90

- transverse ($\perp$): can be as large as 0.1 mm

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 $R_\perp$

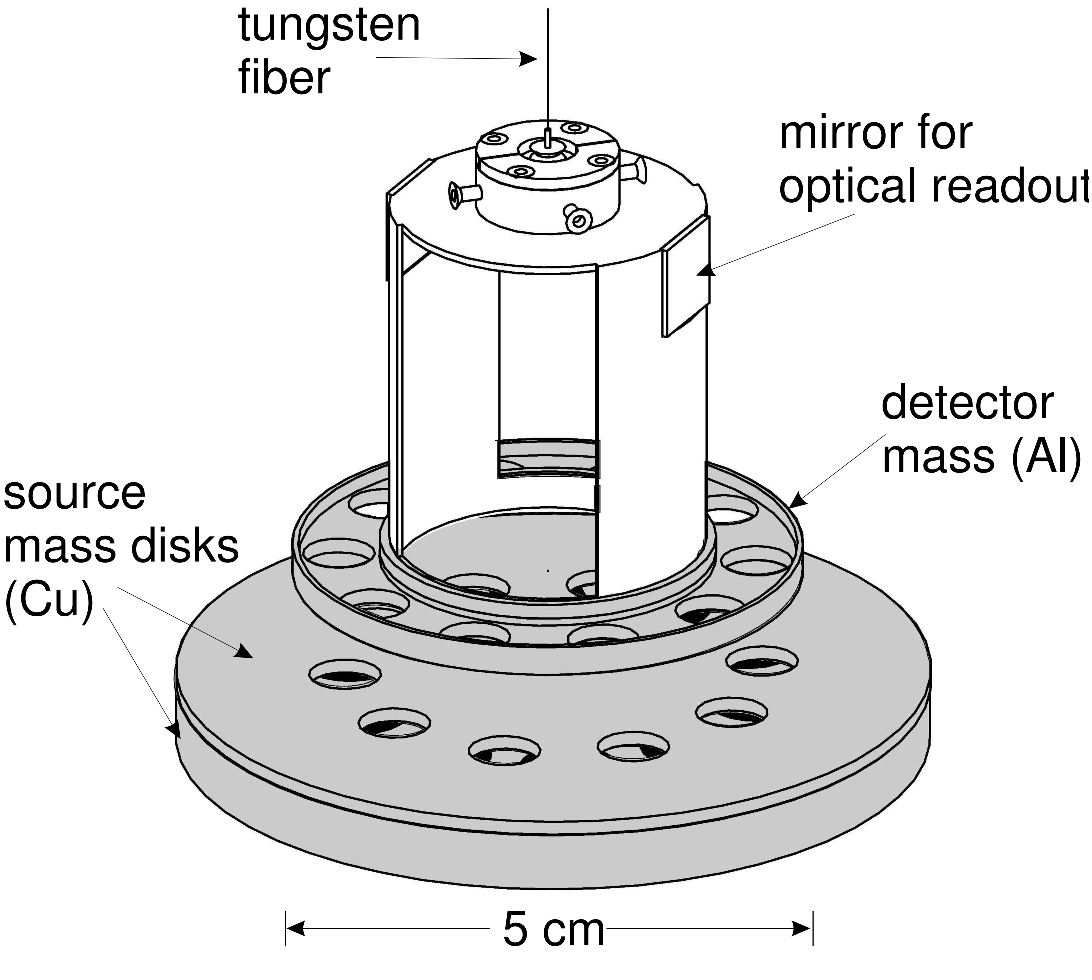
$M_s \sim 1$ TeV $\Rightarrow R_\perp \sim .1 - 10^{-13}$ mm $(n = 2-6)$

- 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 $< R_\perp$

Adelberger et al. '04



$R_\perp \lesssim 130\ \mu\text{m}$ at 95% CL

Supernova constraints

cooling due to graviton production

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

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

~ 10 MeV

$\Rightarrow$ production rate:

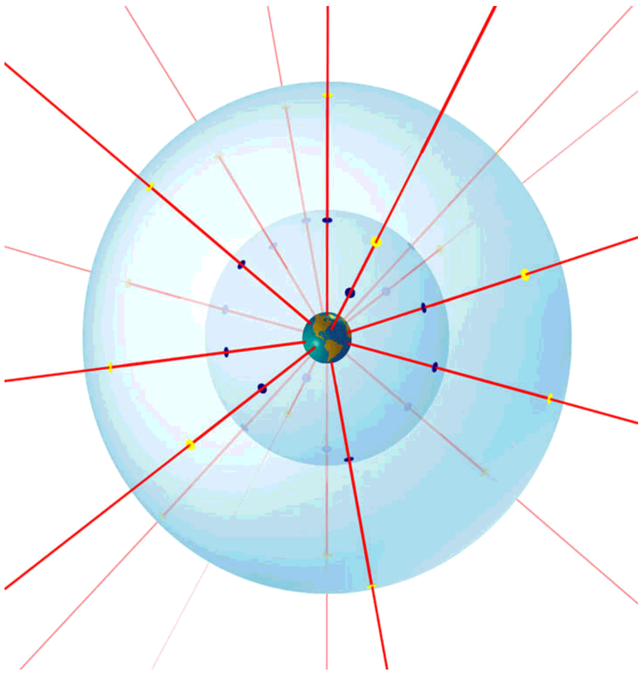
$$P_{\text{gr}} \sim \frac{1}{M_p^2}(TR_\perp)^n \sim \frac{T^n}{M_*^{(2+n)}}$$

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

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

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

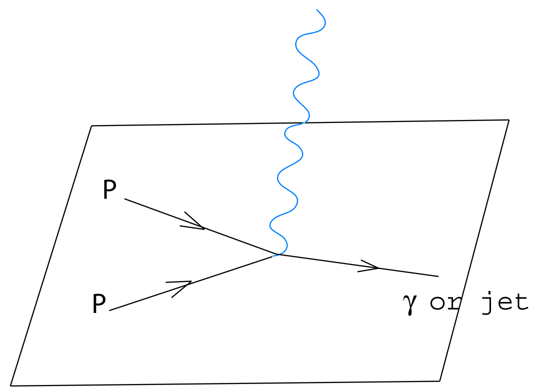
$\Rightarrow$ strong gravity at the TeV

Gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

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

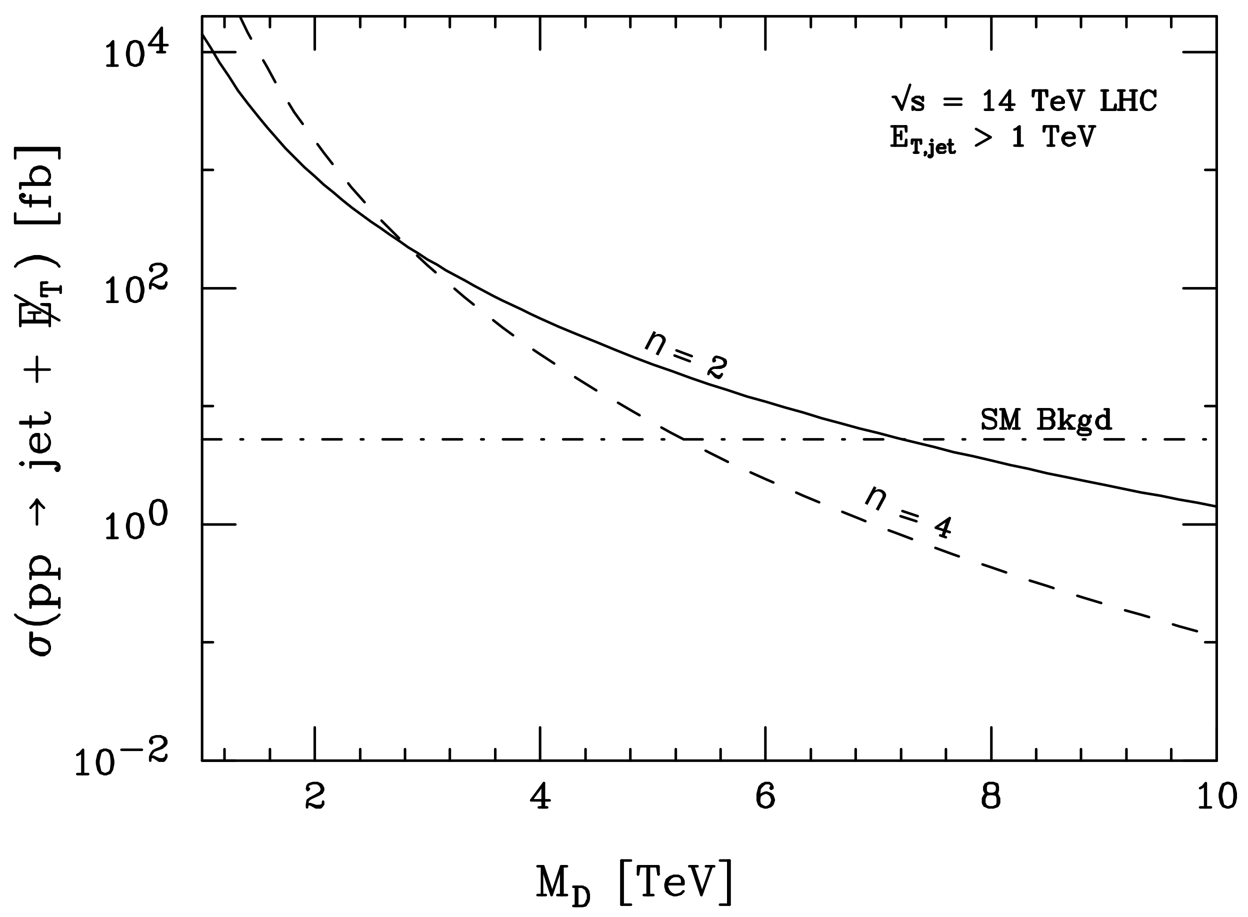
LHC: 10^{30} massive gravitons of intensity 10^{-30} each



Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Giudice-Rattazzi-Wells '98



no observation $\Rightarrow$

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

- more dimensions $\Rightarrow$ 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

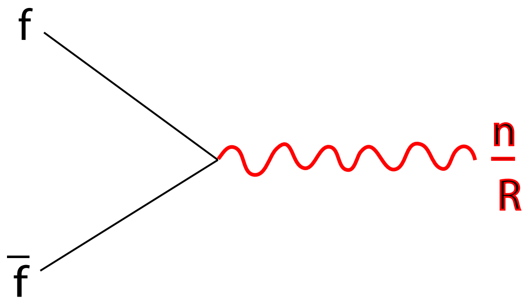
$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

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

Localized fermions (on 3-brane intersections)

$\Rightarrow$ single production of KK modes

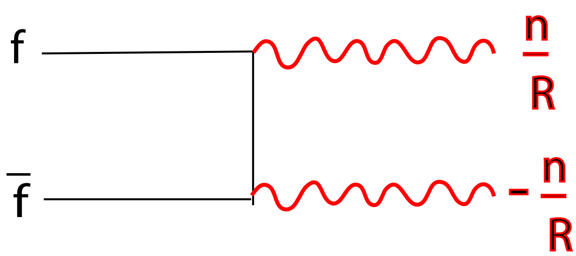
I.A.-Benakli '94



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

Otherwise KK momentum conservation

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

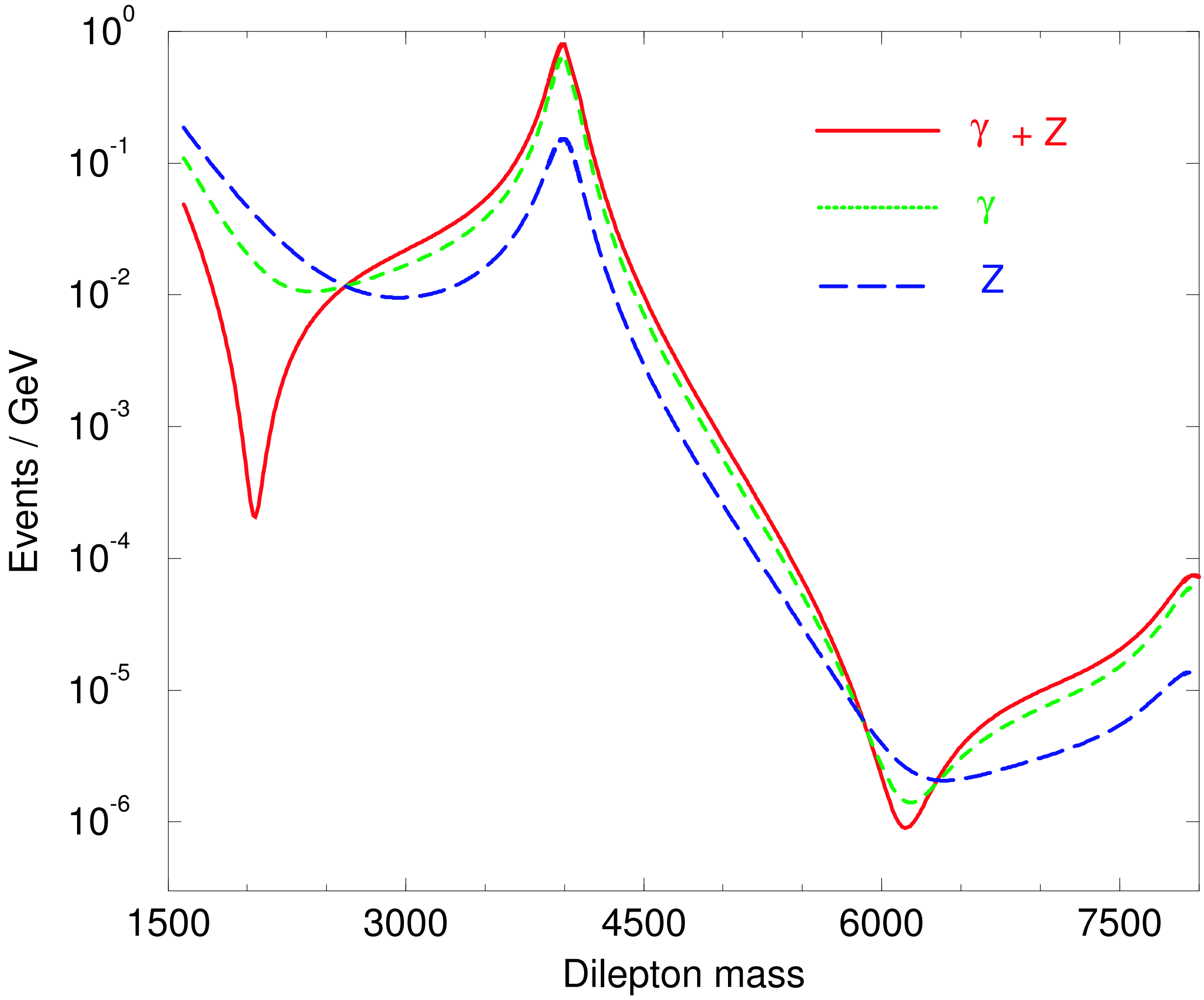


- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable $\Rightarrow$ dark matter candidate

Servant-Tait '02

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

$R^{-1} = 4$ TeV



- no observation in dijets

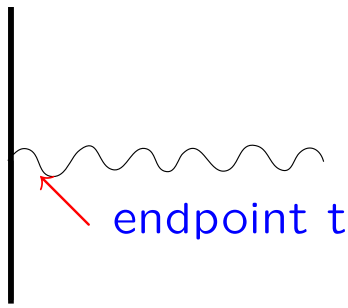
$$\Rightarrow R^{-1} \gtrsim 20 \text{ TeV} \ ; \ 95\% \text{ CL}$$

- more than one dimension $\Rightarrow$ stronger limits

Generic spectrum

N coincident branes $\Rightarrow U(N)$

a-stack



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

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

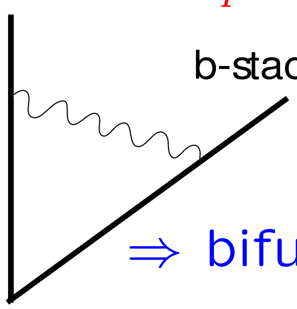
$U(1)$: "baryon" number

- open strings from the same stack $\Rightarrow$
  adjoint gauge multiplets of $U(N_a)$

- stretched between two stacks

a-stack in p dims

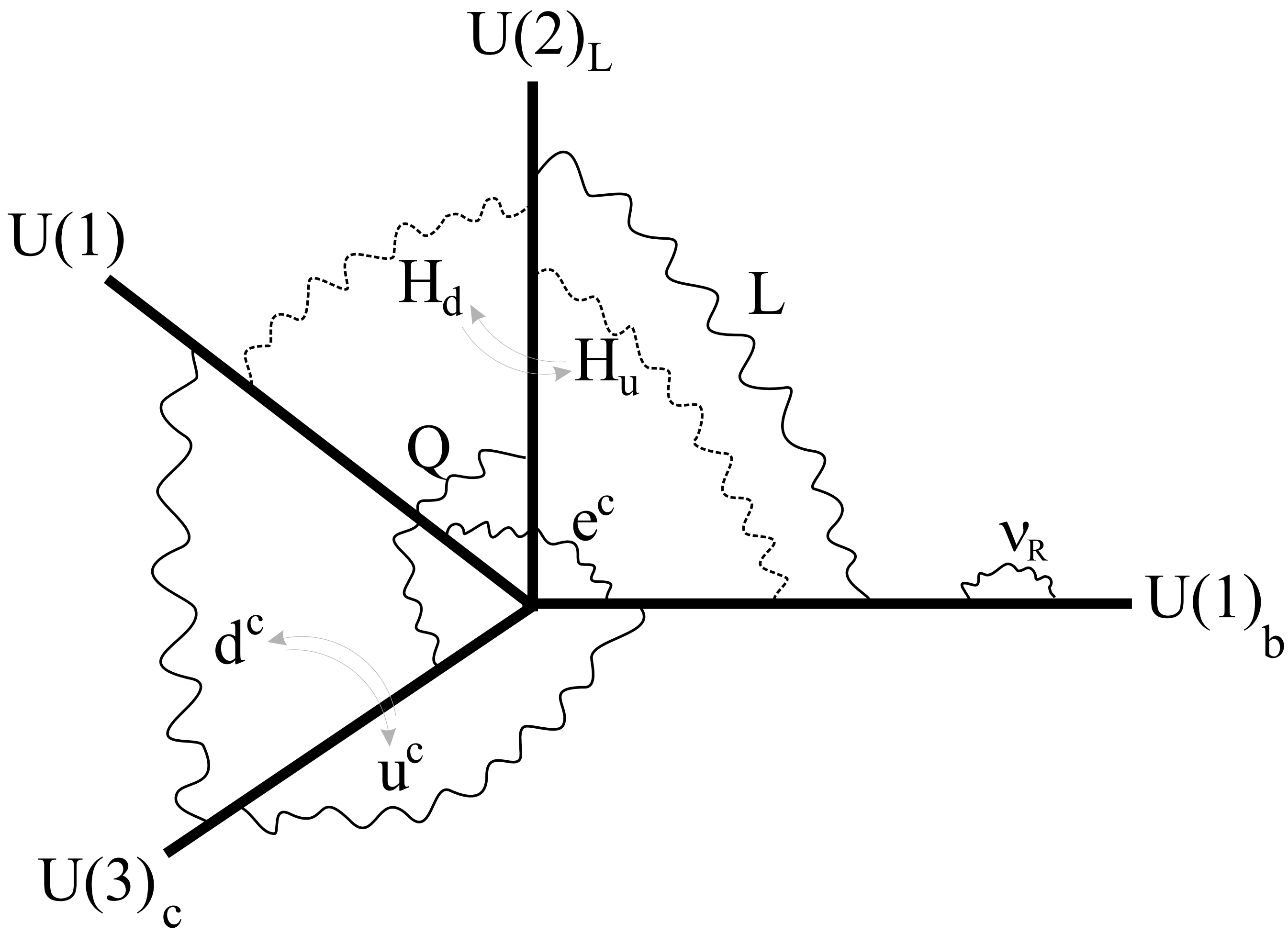
b-stack in p' dims



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

in $p \cap p'$ dims

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

- global SUSY:

- No need to be there at least for hierarchy

- New ways of breaking

  using extra dimensions

  branes at angles/internal magnetic fields

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

  very weakly broken

- New forces at submm scales

  e.g. radion, graviphoton

- Non linear realization on branes

  SM + (light) goldstino

Energy density: Λ_{bulk}, Λ_{brane}

generic non-SUSY string model $\Rightarrow$

$\Lambda_{\text{bulk}} \sim M_s^{4+n} \Rightarrow \Lambda_{\text{brane}} \sim M_s^{4+n} R_\perp^n \sim M_s^2 M_P^2$

analog in softly broken SUSY: $m^2_{\text{SUSY}} \Lambda^2_{UV}$

quadratic divergence to Λ

vanishing if bulk is (approximately) SUSY

$\Lambda_{\text{brane}} \sim M_s^4 \Rightarrow \Lambda_{\text{bulk}} \sim M_s^4 / R_\perp^n$

Prediction: possible new forces at submm scales

e.g. radion $\equiv \ln R_\perp$

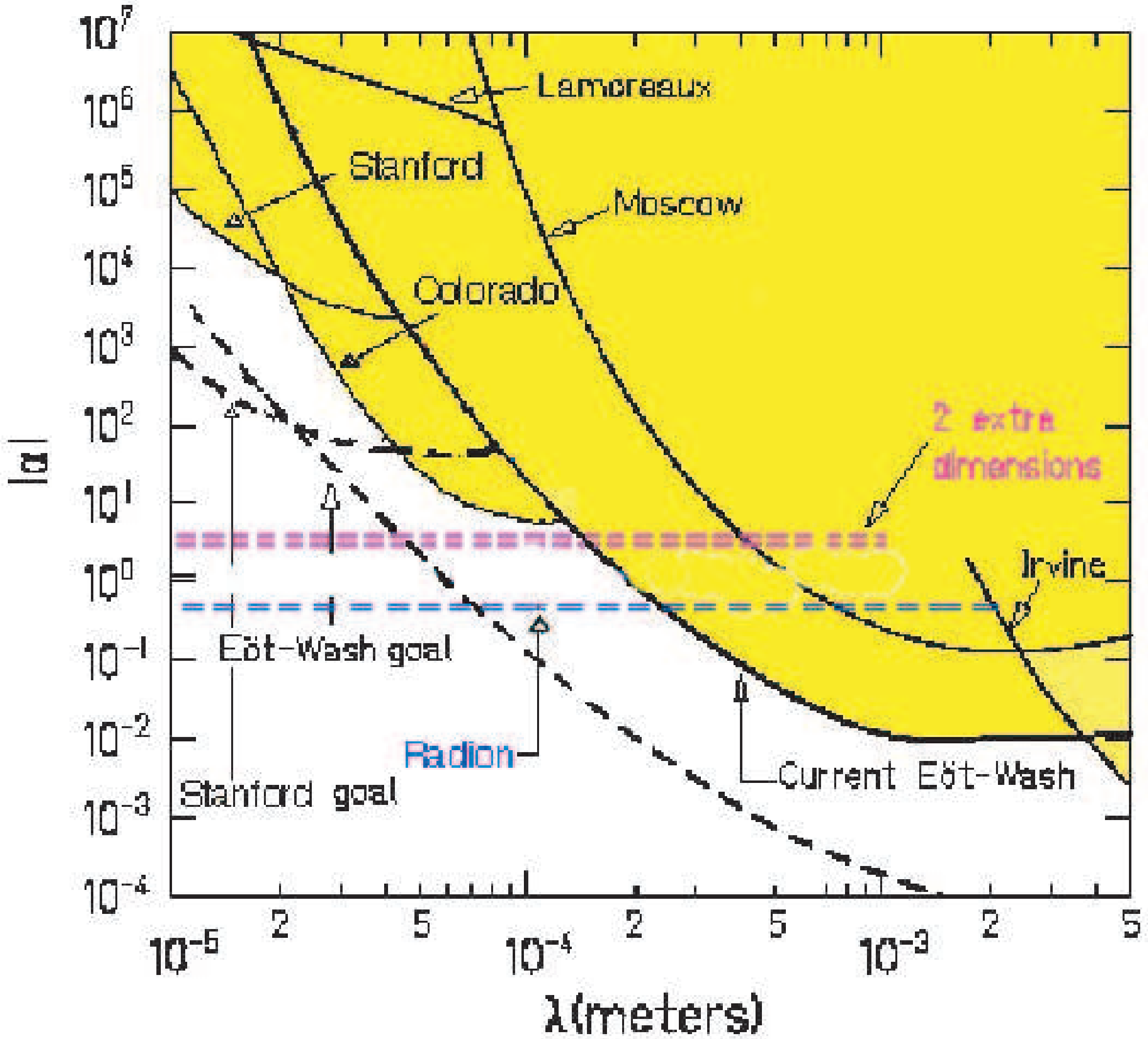
mass: $(\text{TeV})^2 / M_P \sim 10^{-4}$ eV $\rightarrow$ mm range

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

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

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

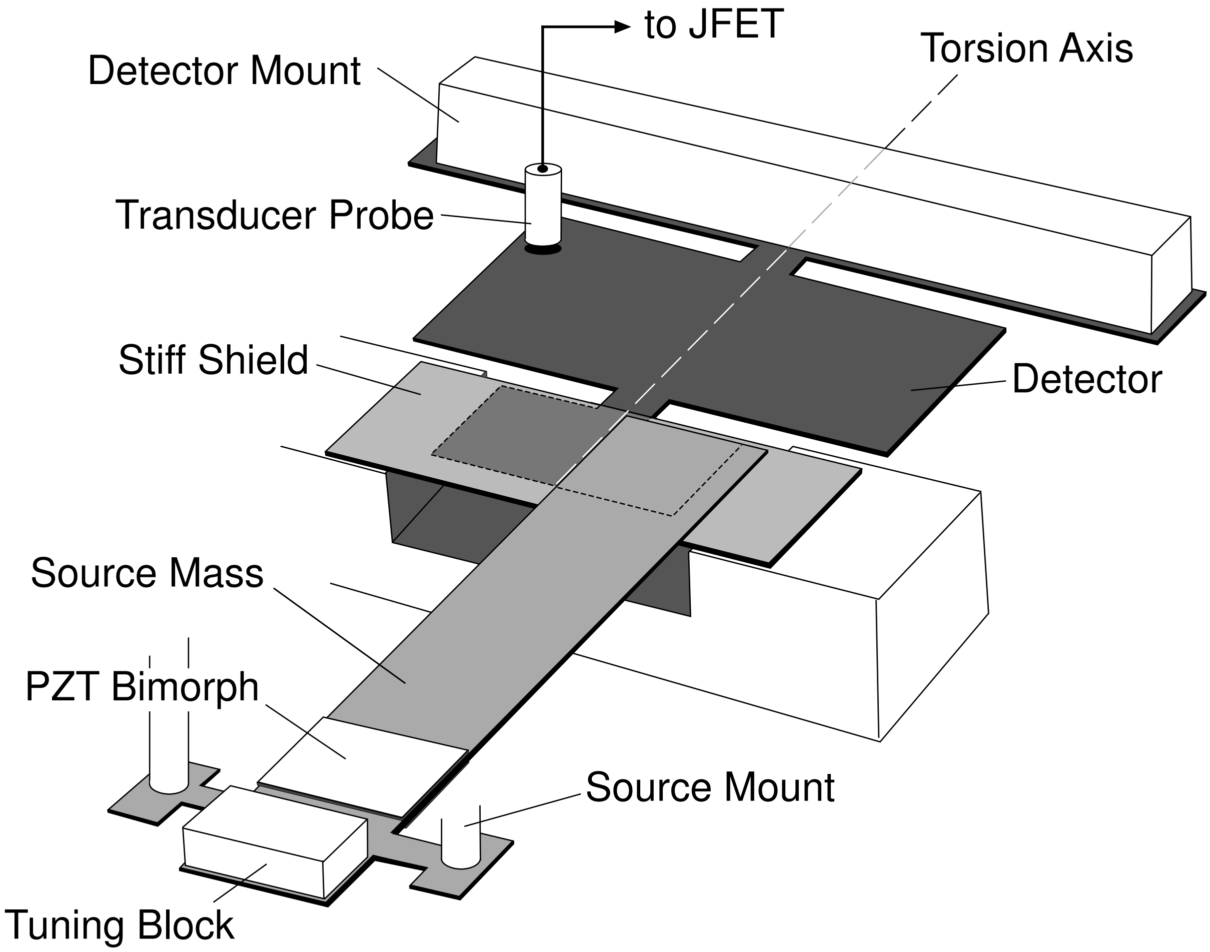
$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Radion $\Rightarrow M_* \gtrsim$ 3 - 4.5 TeV 95% CL (n=2-6)

Adelberger et al. '04

Long-Chan-Churnside-Gulbis-Varney-Price '03



Light $U(1)$ gauge bosons

I.A.-Kiritsis-Rizos '02

$U(1)$ anomalies $\Rightarrow$ Green-Schwarz mechanism

$\delta A = d\Lambda \quad \Rightarrow \quad \delta a = -M\Lambda$

gauge field   axion

$$-\frac{1}{4g_A^2} F_A^2 - \frac{1}{2}(da + MA)^2 + \frac{a}{M} k_I^A \, \mathrm{Tr} F_I \wedge F_I$$

cancel the anomaly

$\Rightarrow \quad U(1)_A$ mass: $\quad m_A = g_A M$

- a: Poincaré dual of a 2-form

  from RR closed string sector

- $U(1)_A$ global symmetry remains

  (in perturbation)

ex. Baryon and Lepton number needed to prodect proton decay and neutrino masses

$$m_A = g_A \, M$$

small mass $\Rightarrow$ small coupling

$\Rightarrow$ A in the bulk and a on the brane:

localized mass

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

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

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

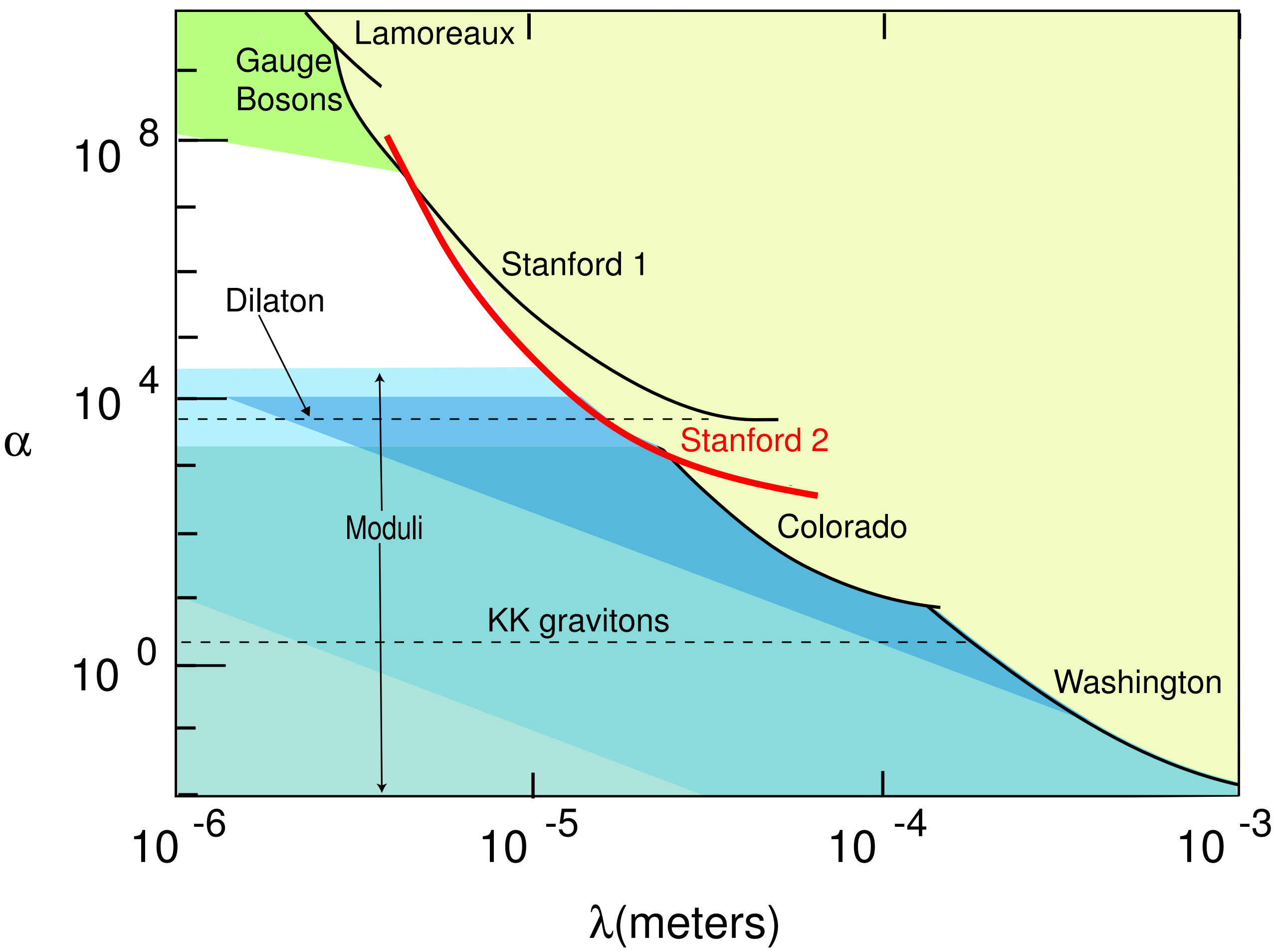
m_{proton}/M_P

supernova $\Rightarrow$ dim of the bulk ≥ 4

an order of magnitude improvement

on bounds in the range 6-20 μm

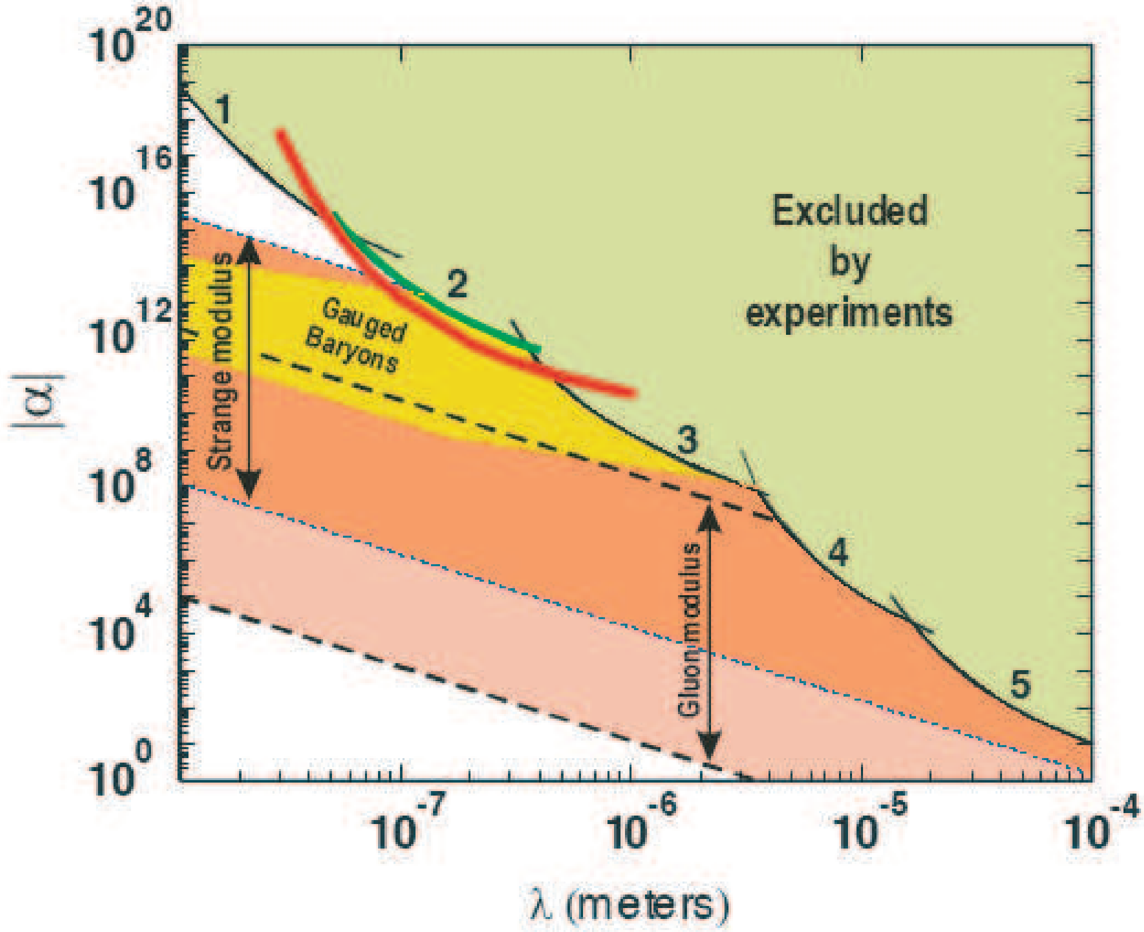
Smullin-Geraci-Weld-Chiaverini-Holmes-Kapitulnik '05



an order of magnitude improvement

on bounds in the range 200 nm

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



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