Mass hierarchies in string theory and holography

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SUPERFIELDS - Sixth Joint Seminar

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1. Motivations and mass hierarchy
2. Strings, branes and extra dimensions
3. Gravity scale and number of species
4. Low string coupling and little strings at a TeV

   I.A.-Dimopoulos-Giveon '01 + with Arvanitaki '11
5. Main accelerator signatures

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 $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ large extra dimensions, warped dimensions

- 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 $\Rightarrow R_{\parallel} \simeq l_{\rm string}$; $R_{\perp}$ arbitrary

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

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

small M_s/M_P : extra-large $R_{\perp}$

$M_s \sim 1$ TeV $\Rightarrow R_{\perp}^n = 10^{32}\ l_s^n$ [8]

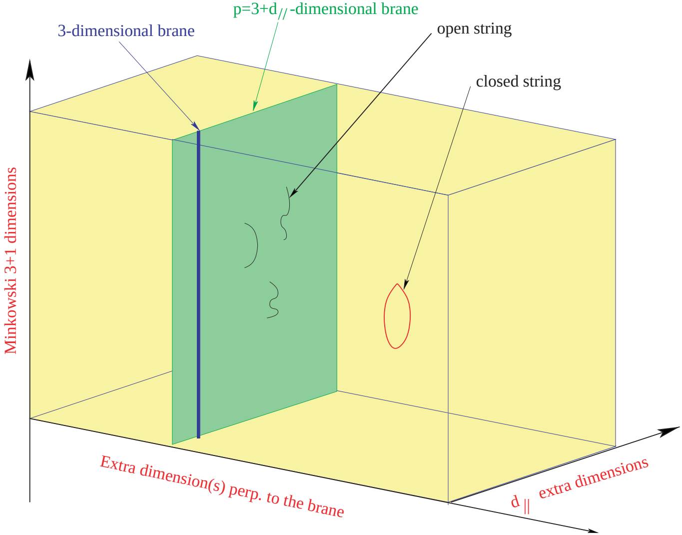
$R_{\perp} \sim .1 - 10^{-13}$ mm for $n = 2-6$ [5]

distances $< R_{\perp}$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm [6]

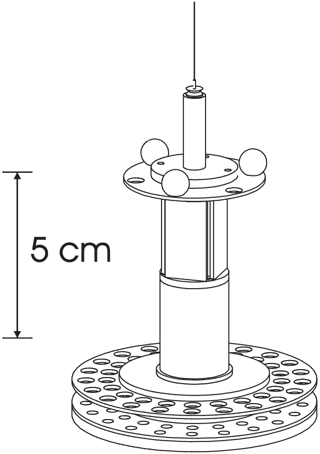
Braneworld

2 types of compact extra dimensions:

- parallel ($d_\parallel$): $\lesssim 10^{-16}$ cm (TeV) I.A. '90
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



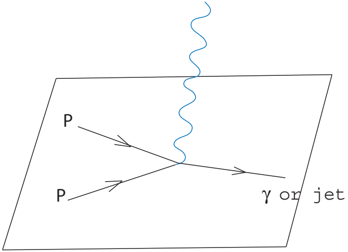
Adelberger et al. '06



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

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

Gravitational radiation in the bulk ⇒ 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}

Black hole production

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

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

Comparison with Regge excitations : $M_n = M_s\sqrt{n} \Rightarrow$

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach M_{BH} [3]

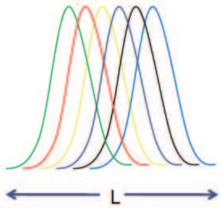
More general framework: large number of species

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 $E \gtrsim N/L \rightarrow$

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

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

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

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

1. Large volume compactifications SM on D-branes

   $N = R_\perp^n\, l_s^n$: 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

   $N_s = \frac{1}{g_s^2}$ with $g_s \simeq 10^{-16}$ 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:

$$M_p^2 = \frac{1}{g_s^2}\, V_6\, M_s^8$$

V_6 : internal $6d$ compactification volume puzzle as $g_s \to 0$:

- M_* remains finite $\Rightarrow$ Quantum Gravity effects in a free theory

  $M_*^2 = M_p^2/N \simeq M_s^2/(g_s^2 N) \sim M_s^2$ since $N \simeq 1/g_s^2$

- forward 4pt amplitude does not decouple

  e.g. $\sum_{\text{string states } X} |q\bar{q} \to X|^2 \sim g_s^2 \times N \sim \mathcal{O}(1)$ at M_*

solution: log corrections $N(M_*) \sim 1/(g_s \ln g_s)^2$ $M_* \sim M_s |\ln g_s|$

string density of states: $N(M_*) \sim \left(\frac{M_*}{M_s}\right)^{-d} e^{\beta M_*/M_s}$

$d = 4\,;\ \beta = 2\sqrt{2}\pi$ for closed superstrings

$M_*^2 = \frac{M_s^2}{g_s^2 N} v_6 \leftarrow$ 6d volume in string units

$$\Rightarrow \frac{1}{g_s \sqrt{N}} = \frac{1}{\beta} \ln N - \frac{d}{\beta} \ln \ln N + \ldots$$

What is LST ? Decouple gravity from NS5-branes

Analogy from D3-branes : decouple gravity $\Rightarrow M_s \to \infty$, g_s fixed

$\to$ (conformal) Field Theory (CFT)

simplest case: 4d $\mathcal{N} = 4$ super Yang Mills $SU(N)$

parameters: number of branes N, gauge coupling g_{YM}

NS-5 branes: M_s finite, $g_s \to 0 \to$ (little) String Theory without gravity

simplest case: 6d LST (chiral IIA or non-chiral IIB)

massless sector: 6d $SU(N)$ of vectors (IIA) or tensors (IIB)

at a non-trivial fixed point

parameters: number of branes N, string scale M_s

How to study LST ? Using gauge/gravity duality

Gravity background : near horizon geometry (holography) Maldacena '98

Analogy from D3-branes : $AdS_5 \times S^5$

parameters: AdS radius $r_{AdS} M_s$, $g_s \leftrightarrow N, g_{YM}$

supergravity validity: $r_{AdS} M_s >> 1$, $g_s << 1 \Rightarrow$ large N, $g_{YM}^2 N$

$\rightarrow$ model independent part : AdS_5

NS-5 branes : $(\mathcal{M}_6 \otimes R_+) \times SU(2) \equiv S^3$

$\uparrow$ linear dilaton background in 7d flat string-frame metric $\Phi = -\alpha|y|$

Aharony-Berkooz-Kutasov-Seiberg '98

parameters: M_s, α (or S^3 radius) $\leftrightarrow N$

sugra validity: small $\alpha \Rightarrow$ large N

compactify to $d = 4\,(\mathcal{M}_6 \rightarrow \mathcal{M}_4) \Rightarrow g_{YM} \sim$ 2d volume

$\rightarrow$ model independent part : linear dilaton

Put gravity back but weakly coupled

"cut" the space of the extra dimension $\Rightarrow$ gravity on the brane

Analogy from D-branes $\rightarrow$ 2 possibilities:

- flat space $\Rightarrow$ large extra dimensions AADD '98
- curved space from gravity back reaction $\Rightarrow$ slice of AdS_5

RS, H. Verlinde '99

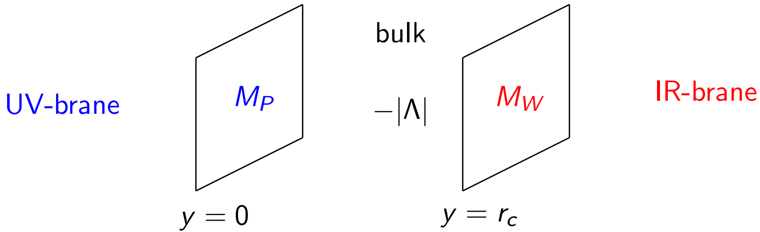
NS-5 branes : linear dilaton on an interval $y \in [0, r_c]$

$$S_{bulk} = \int d^4x\, dy \sqrt{-g}\, e^{-\Phi} \left(M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda \right)$$

$$S_{vis(hid)} = \int d^4x \sqrt{-g}\, e^{-\Phi} \left(L_{SM(hid)} - T_{vis(hid)} \right)$$

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [16]

RS models : $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $\quad k^2 \sim \Lambda/M_5^3$



- fine-tuned tensions: $T = -T' = 24M^3k$
- exponential hierarchy: $M_W = M_P e^{-2kr_c}$ $\quad M_P^2 \sim M_5^3/k$

$M_5 \sim M_{GUT}$

- 4d gravity localized on the UV-brane, but KK gravitons on the IR

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

  $m_n = c_n\, k\, e^{-2kr_c} \sim \text{TeV} \qquad c_n \simeq (n + 1/4)$ for large n

  $\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels

  weakly coupled for $k < M_5$

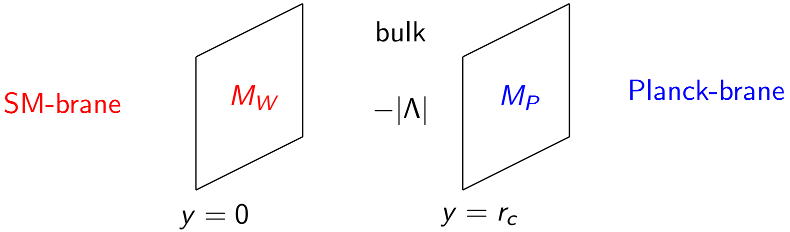
- viable models: SM gauge bosons in the bulk, Higgs on the IR-brane

- AdS/CFT duals to strongly coupled 4d field theories

  composite Higgs models, technicolor-type $\quad g_{YM} = M_5/k > 1$ [13]

LST : $\Phi = -\alpha|y|$; $ds^2 = e^{\frac{2}{3}\alpha|y|}(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2)$ ← Einstein frame

$z \sim e^{\alpha y/3}$ ⇒ polynomial warp factor + log varying dilaton



- exponential hierarchy: $g_s^2 = e^{-\alpha|y|}$ $\quad M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$
- 4d graviton flat, KK gravitons localized near SM
- SM particles cannot be in the bulk

  bulk gauge bosons: exp suppressed couplings

LST KK graviton phenomenology

- KK spectrum : $m_n^2 = \left(\frac{n\pi}{r_c}\right)^2 + \frac{\alpha^2}{4}$; $n = 1, 2, \ldots$

  $\Rightarrow$ mass gap + dense KK modes $\alpha \sim 1$ TeV $r_c^{-1} \sim 30$ GeV

- couplings : $\frac{1}{\Lambda_n} \sim \frac{1}{(\alpha r_c) M_5}$

  $\Rightarrow$ extra suppression by a factor $(\alpha r_c) \simeq 30$

- width : $1/(\alpha r_c)^2$ suppression ~ 1 GeV

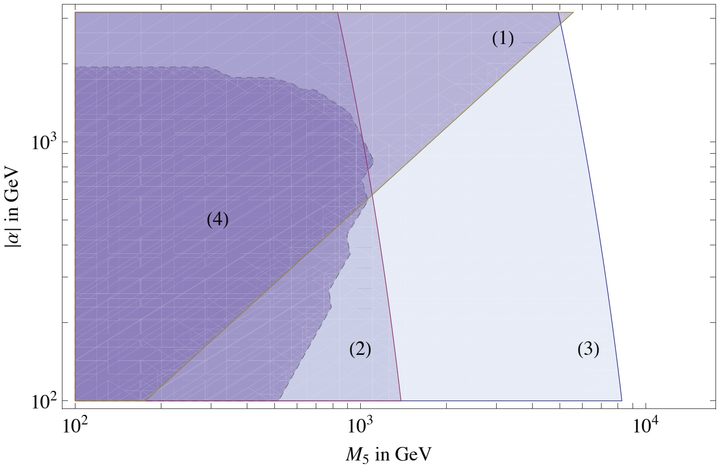
  $\Rightarrow$ narrow resonant peaks in di-lepton or di-jet channels

- extrapolates between RS and flat extra dims ($n = 1$)

  $\alpha \gtrsim (0.1\,\mathrm{mm})^{-1} \sim 10^{-2}$ eV from microgravity experiments

  $\Rightarrow$ distinct experimental signals

Bounds on the LST parameter space



exclusion by (1) perturbativity (2) Tevatron with 5.4 fb^{-1} data

(3) LHC 14 TeV with 10 fb^{-1} (4) diphoton at Tevatron 5.4 fb^{-1}

Conclusions

Mass hierarchy $\Rightarrow$ testing strings at the TeV ?

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Several realizations with different signatures

  flat large extra dimensions, exp warped metrics,

  tiny string coupling and linear dilaton background

- Stimulus for micro-gravity experiments and accelerator searches

But: - unification has to be dropped

- physics is radically changed above string scale