Implications of low-scale strings to LHC and the early Universe

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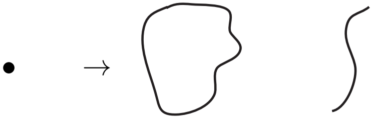
String theory: Quantum Mechanics + General Relativity

point particle $\rightarrow$ extended objects



particles $\equiv$ string vibrations

- quantum gravity
- framework of unification of all interactions
- "ultimate" theory: · ultraviolet finite
  · no free parameters

mass scale (tension): $M_{\rm string} \leftrightarrow$ size: $l_{\rm string}$

rigid string : known particles (massless)

vibrations : infinity of massive particles

Main predictions of String Theory

$\rightarrow$ inspirations for BSM physics

Consistency of the Theory $\Rightarrow$

- Spacetime supersymmetry   but arbitrary breaking scale
- Extra dimensions of space   six or seven in M-theory
- Brane-world description of our Universe

  matter and gauge interactions may be localised in less dimensions

  p-brane: extended in p spatial dimensions

  $p = 0$: particle, $p = 1$: string,...

  $\Rightarrow$ Two types of new dimensions:

  1. longitudinal: along the brane-world $\Rightarrow$ $R_{\parallel} \lesssim 10^{-16}$ cm
  2. transverse: only gravitational signal $\Rightarrow$ $R_{\perp} \lesssim 0.1$ mm

- Landscape of vacua

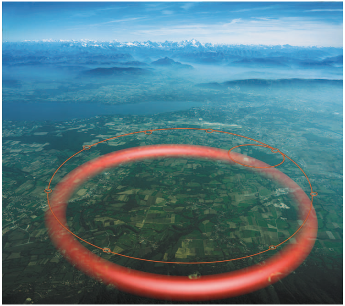
Connect string theory to the real world

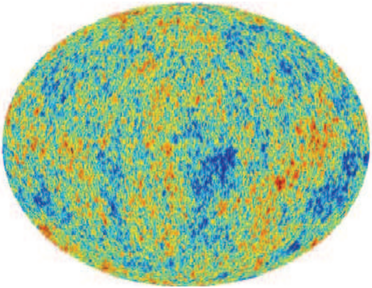
- Is string theory a tool for strong coupling dynamics

  or a theory of fundamental forces?

- If theory of Nature can string theory describe

  both particle physics and cosmology?





Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

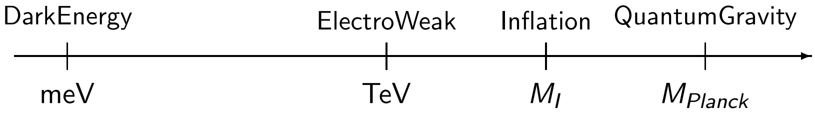
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_{Planck} :



At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale M_s

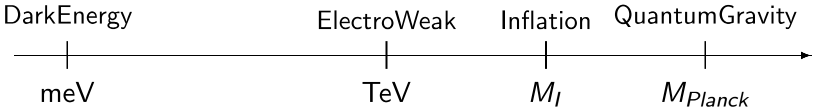
Before 1994: $M_s \simeq M_{\rm Planck} \sim 10^{18}$ GeV $\quad l_s \simeq 10^{-32}$ cm $\quad$ After 1994:

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV
- physical motivations $\Rightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV (hierarchy problem)

Problem of scales



1. possible connections
   - M_I could be near the EW scale, such as in Higgs inflation

     but large non minimal coupling to explain
   - M_{Planck} could be emergent from the EW scale

     in models of low-scale gravity and TeV strings

   What about M_I? can it be at the TeV scale?

   Can we infer M_I from cosmological data? [25]

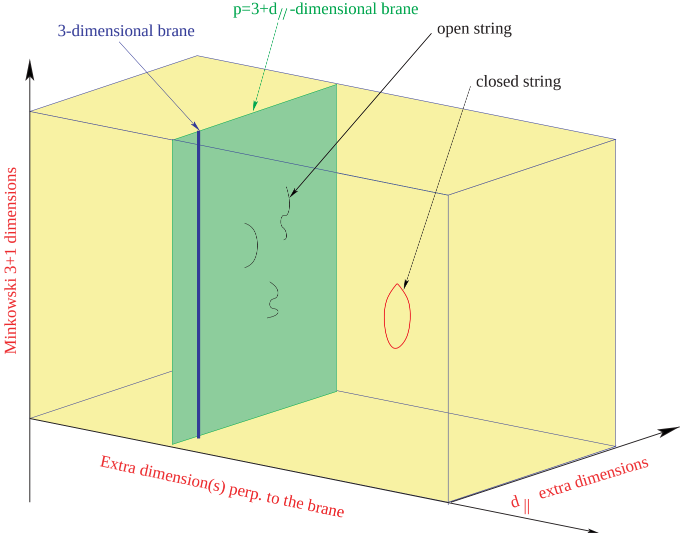
I.A.-Patil '14 and '15

2. they are independent

Braneworld

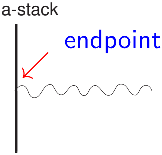
2 types of compact extra dimensions:

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



D-brane spectrum

Generic spectrum: N coincident branes $\Rightarrow U(N)$

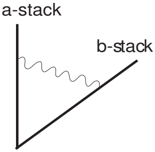


endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$ $U(1)_a$ charge: $+1$ or -1

$\Rightarrow$ "baryon" number

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

• stretched between two stacks $\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$



non-oriented strings $\Rightarrow$ also:

- orthogonal and symplectic groups $SO(N), Sp(N)$

- matter in antisymmetric + symmetric reps

Minimal Standard Model embedding

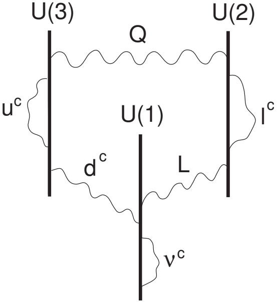
General analysis using 3 brane stacks [21]

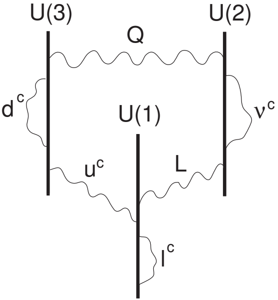
$$\Rightarrow \; U(3) \times U(2) \times U(1)$$

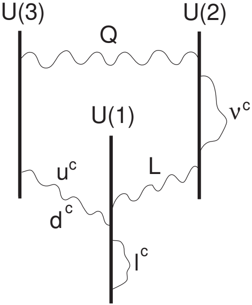
antiquarks u^c, d^c $(\bar{3}, 1)$:

antisymmetric of $U(3)$ or bifundamental $U(3) \leftrightarrow U(1)$

$\Rightarrow$ 3 models: antisymmetric is u^c, d^c or none

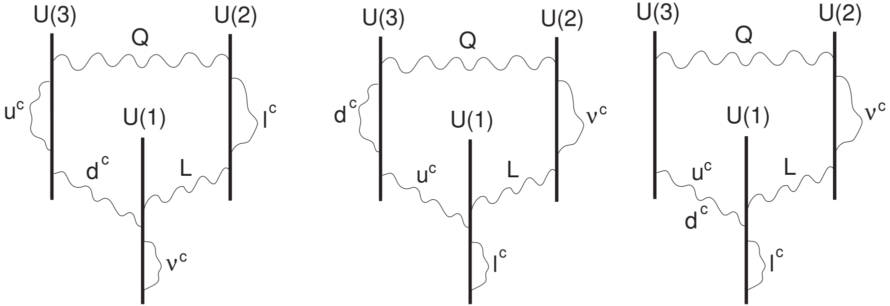






Model A | **Model B** | **Model C**

	Model A	Model B	Model C
Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,-1)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$



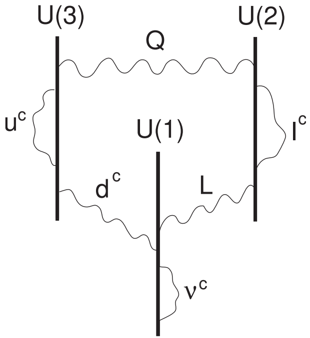
Model A **Model B** **Model C**

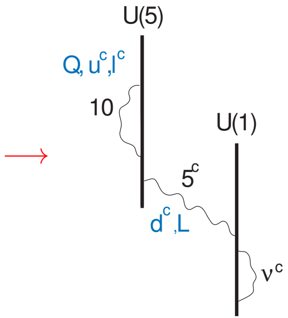
$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2 \qquad Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

$$\sin^2\theta_W = \left.\frac{1}{2+2\alpha_2/3\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{3}{8} \qquad \left.\frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$

[8]

$SU(5)$ GUT





- Gravitational radiation in the bulk $\Rightarrow$ missing energy

  present LHC bounds: $M_* \gtrsim 4 - 9$ TeV

- Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution [16]

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

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 7$ TeV

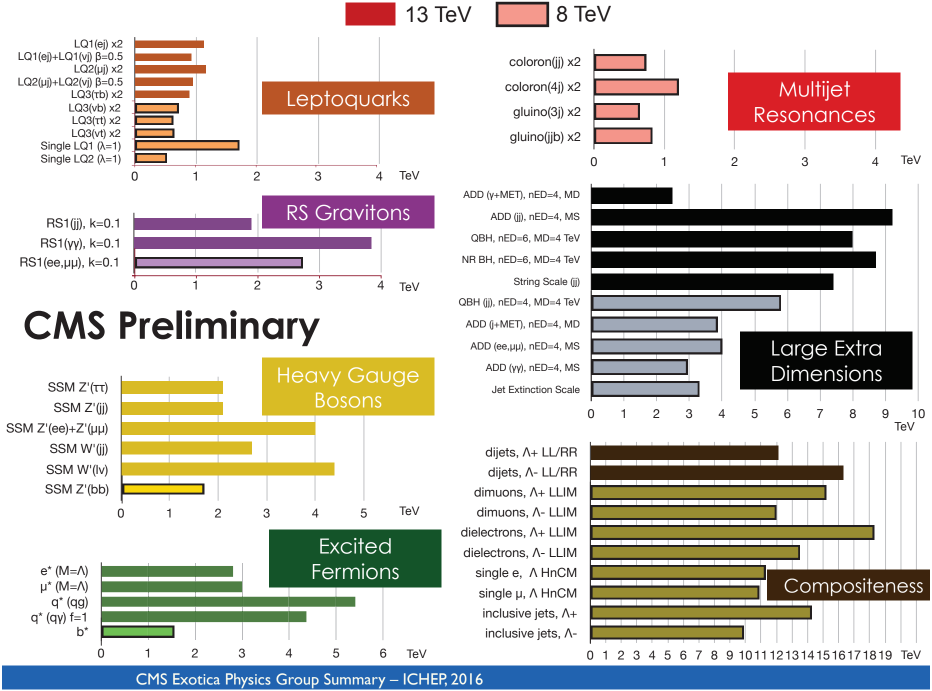
- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

  $$M_k^2 = M_0^2 + k^2/R^2 \;\; ; \;\; k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions)

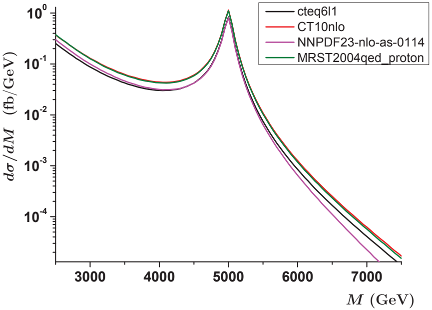
- extra $U(1)$'s and anomaly induced terms

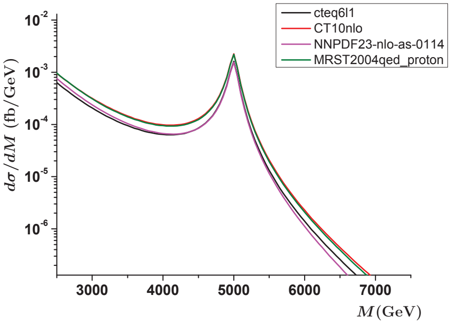
  masses suppressed by a loop factor from M_s [19]


13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
0 1 2 3 4 TeV
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
0 1 2 3 4 TeV
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
0 1 2 3 4 5 6 7 8 9 10 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
0 1 2 3 4 5 TeV
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
0 1 2 3 4 5 6 TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor ’14





$M_s = 5$ TeV: dijet at LHC14 $\gamma +$ jet

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

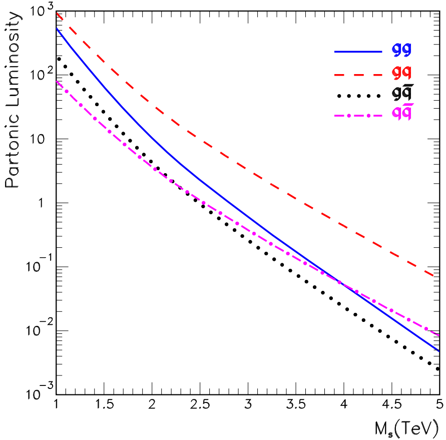
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV

are dominated by *gq*, *gg*

$\Rightarrow$ model independent

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



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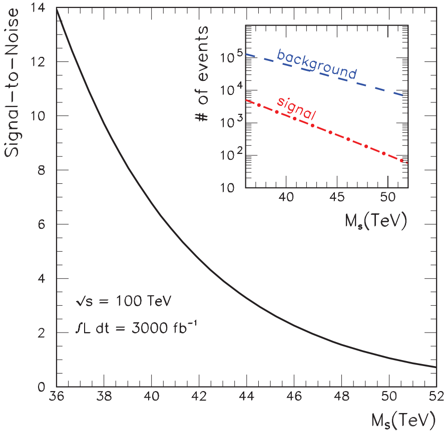
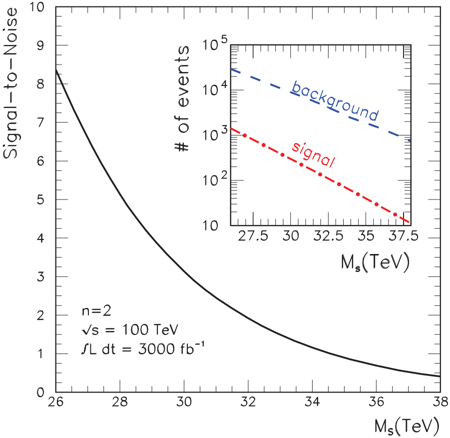




[14]

Extra $U(1)$'s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

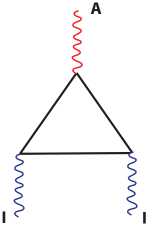
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

$M_{NA} \simeq g_A M_s V_2 \leftarrow$ (6d$\rightarrow$4d) internal space $\Rightarrow M_{NA} \geq M_A$

or massless in the absence of such anomalies [21]

Green-Schwarz anomaly cancellation



$= k_I^A \sim \mathrm{Tr}\, Q_A Q_I^2 \;\rightarrow$ axion θ : $\delta A = d\Lambda \quad \delta\theta = -m_A \Lambda$

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

cancel the anomaly

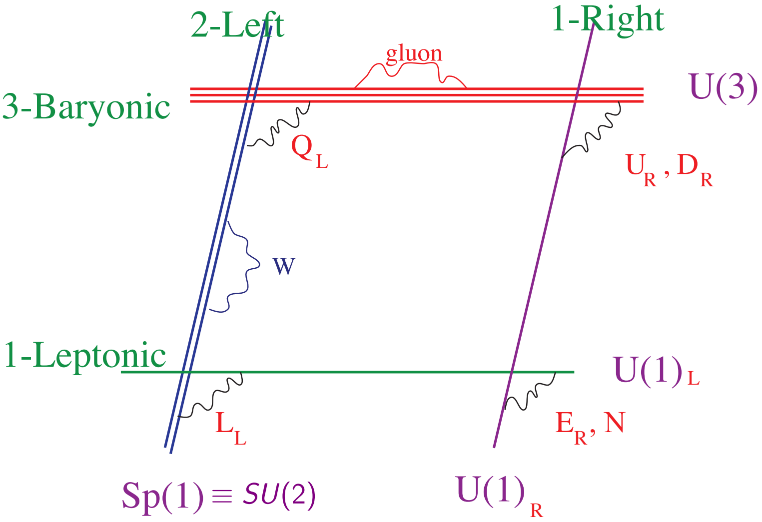
D-brane models: $U(1)_A$ gauge boson acquires a mass

but global symmetry remains in perturbation theory [23]

GS anomaly cancellation $\Rightarrow$ extra scalars and axion-like particles (ALP)

- coupled to gauge kinetic terms
- lighter than the string scale (masses loop-factor suppressed)

Standard Model on D-branes : SM^{++}



$U(1)^3 \Rightarrow$ hypercharge $(Y = \frac{1}{2}(R - L) + \frac{1}{6}B) + B, L$

global symmetries

- B and L become massive due to anomalies

  Green-Schwarz terms

- 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: $\frac{\langle H \rangle^2}{M_s} LL$

  (M_s) $\sim$ GeV

- $B, L \Rightarrow$ extra Z's [7]

Exotic $U(1)$ anomaly induced couplings

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

Non trivial anomaly cancellation $\rightarrow$ new **dimensionless** couplings

mixed $U(1)$ anomalies

$\Rightarrow Z'$ may couple to SM gauge bosons with no mass suppression

$$A \wedge X \wedge F_X \qquad A \equiv Z'\,,\ X \equiv W, Y$$

2 axionic phases: $A \rightarrow \theta_A$, $X \rightarrow \theta_X$ $\equiv$ SM Higgs $\Rightarrow$ [20]

$$D\theta_A \wedge D\theta_X \wedge F_X \rightarrow \quad \mathcal{L}_{\text{eff}} = c_1 D\theta_A \frac{H^\dagger DH}{|H|^2} F_Y + c_2 D\theta_A \frac{HF_W DH^\dagger}{|H|^2}$$

D'Hoker-Farhi type terms

$$c_2 \rightarrow AW^+W^- \qquad c_1 \rightarrow AZY \quad (AZ\gamma, AZZ) \quad \text{vertices}$$

$$\Gamma(Z' \to ZZ) = \frac{c_1^2 \sin^2\theta_W M_{Z'}^3}{192\pi M_Z^2}\left(1 - \frac{4M_Z^2}{M_{Z'}^2}\right)^{5/2}$$

$$\Gamma(Z' \to W^+W^-) = \frac{c_2^2 M_{Z'}^3}{48\pi M_W^2}\left(1 - \frac{4M_W^2}{M_{Z'}^2}\right)^{5/2}$$

$$\Gamma(Z' \to Z\gamma) = \frac{c_1^2 \cos^2\theta_W M_{Z'}^3}{96\pi M_Z^2}\left(1 - \frac{M_Z^2}{M_{Z'}^2}\right)^3\left(1 + \frac{M_Z^2}{M_{Z'}^2}\right)$$

[7]

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

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

- Large extra dimensions SM on D-branes

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

- $M_s \sim TeV \Rightarrow$ low inflation scale

  allowed by the data since cosmological observables are dimensionless

  in units of the effective gravity scale

I.A.-Patil '14

Cosmological observables

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations $\mathcal{R}$)

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22$$

ϵ ← $-\dot{H}/H^2$

Power spectrum of primordial tensor anisotropies $\mathcal{P}_t = 2\frac{H^2}{\pi^2 M_*^2}$

$\Rightarrow$ tensor to scalar ratio $r = \mathcal{P}_t/\mathcal{P}_{\mathcal{R}} = 16\epsilon$

measurement of $\mathcal{A}$ and $r \Rightarrow$ fix the scale of inflation

$$H \text{ in terms of } M_* \quad : \quad \frac{H}{M_*} = \left(\frac{\pi^2 \mathcal{A}\, r}{2 \times 10^{10}}\right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$$

- M_* **may be different than** M_{Planck} **at the time of inflation**

Effective Planck mass and the scale of inflation

I.A.-Patil '14, '15

Explicit realisation:

Flat extra dimensions: obstruction due to the de Sitter bound:

$$M^2_{\mathrm{spin}\,2} \geq 2H^2 \qquad \mathrm{Higuchi}\,'87$$

$\Rightarrow$ no KK-excitations with mass less than Hubble scale

Kleban-Mirbabayi-Porrati '15

However in warped extra dimensions:

KK-modes couple much stronger than 0-mode

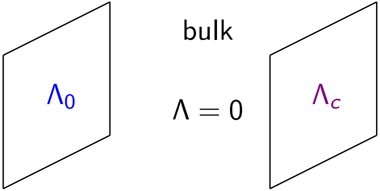
5D brane-world realisation: empty bulk with two boundary dS branes [30]

$$ds^2 = \frac{(1 - H|y|)^2}{H^2\tau^2}\left(-d\tau^2 + dx_1^2 + dx_2^2 + dx_3^2\right) + dy^2$$

$|y| < 1/H$: avoid Riddler horizon $\qquad a(y) = 1 - H|y| > 0$

dS brane

$H = \kappa_5^2 \Lambda_0 / 6$



$y = 0$ $\qquad$ $y = y_c$

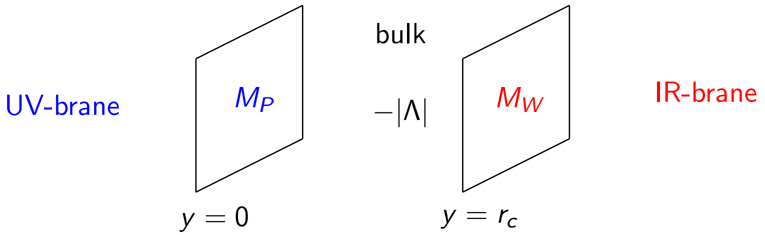
dS brane

$H_c = \frac{H}{a_c}\Lambda_c = -\frac{\Lambda_0}{a_c}$

$|y_c| = \frac{6(\Lambda_0 + \Lambda_c)}{\kappa_5^2 \Lambda_0 \Lambda_c}$

Randal Sundrum models

spacetime = slice of AdS$_5$: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $k^2 \sim \Lambda/M_5^3$



- fine-tuned tensions: $T = -T' = 24M_5^3 k$
- exponential hierarchy: $M_W = M_P e^{-2kr_c}$ $M_P^2 \sim M_5^3/k$ $M_5 \sim M_{GUT}$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

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

spectrum and couplings

4d Planck mass: $M_{Pl} \sim 1/(2H\kappa_5^2)$ y_c large

Spectrum:

0-mode (4d graviton): wave function $\phi_0 \sim (2H)^{1/2} e^{-2z}$ $z \equiv -\ln a(y) > 0$

KK-modes: $m_n^2 = H_y^2 \left(\frac{9}{4} + \pi^2 \frac{n^2}{z_c^2}\right)$ $H_y \equiv H/a(y)$: Hubble constant at y

wave functions $\phi_n \sim \frac{H}{2m_n}\left(\frac{H}{z_c}\right)^{1/2} e^{-z/2}\left[3\sin\left(\frac{n\pi z}{z_c}\right) + \frac{2\pi n}{z_c}\cos\left(\frac{n\pi z}{z_c}\right)\right]$

$\Rightarrow$ KK-modes couple much stronger than 0-mode at y_c:

$$|\phi_n|/|\phi_0| = \frac{\pi n}{\sqrt{2} z_c^{3/2}} \frac{H_c}{m_n} e^{3z_c/2}$$

similar result for bulk scalars

Power spectrum

0-mode as before:

$$\mathcal{P}_0 = \frac{2}{\pi^2}\frac{H_c^2}{M_{Pl}^2}$$

KK-modes:

$$\mathcal{P}_n = \mathcal{P}_0 \frac{\pi^2 n^2}{2z_c^3} e^{3z_c} \left(\frac{H_c}{m_n}\right)^3 \left(\frac{k}{a_{dS} H_c}\right)^3 \simeq \mathcal{P}_0 \frac{\pi^2 n^2}{2z_c^3} \left(\frac{H_c}{m_n}\right)^3 e^{3(z_c - N)}$$

N: number of e-foldings — Riotto '02

$$\mathcal{P}_0 \lesssim \mathcal{P}_n \Rightarrow e^N \lesssim e^{z_c}/z_c$$

$$\mathcal{P}_{\rm KK} = \sum_n^{m_n < M_5} \mathcal{P}_n = \mathcal{P}_0\, e^{3(z_c - N)} \frac{1}{2\pi} \ln \frac{M_5 z_c}{\pi H_c}$$

$$\gtrsim \mathcal{P}_0 \Rightarrow N \lesssim z_c$$

Power spectrum

Allowed range of parameters:

$$M_{Pl}^2 \simeq \frac{M_5^3}{H_c} e^{z_c} \Rightarrow e^{z_c} \simeq \frac{M_{Pl}^2 H_c}{M_5^3} \lesssim \frac{M_{Pl}^2}{M_5^2} \quad H_c \lesssim M_5$$

$$e^{N_{\min}} = 10^{13} \times \frac{H_c}{1\,\mathrm{GeV}} \lesssim e^{z_c}$$

$\Rightarrow$ 1 TeV $\lesssim H_c \lesssim 10^8$ GeV and 1 TeV $\lesssim M_5 \lesssim 10^{10}$ GeV

Conclusions

String phenomenology:

Consistent framework for particle physics and cosmology

Challenge of scales: at least three very different (besides M_{Planck})

electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

Low scale gravity and strings at the (multi-)TeV scale:

offer connection of scales and spectacular new physics to discover

Inflation scale: cannot be determined from observation of B-modes

unknown gravity scale at the time of inflation