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SPRING SCHOOL ON SUPERSTRING THEORY AND RELATED TOPICS

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Phenomenological aspects of string theory

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Please note: These are preliminary notes intended for internal distribution only.

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Phenomenological aspects

of

String Theory

Hierarchy problem: why gravity is so weak compared to the other interactions?

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

- Supersymmetry: protection of hierarchy due to cancellations between fermions and bosons

$$\Rightarrow m_{\text{susy}} \sim \text{TeV}$$

- TeV strings: low UV cutoff

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

- Split supersymmetry: unknown solution

  live with the hierarchy

$$\Rightarrow m_0 \text{ heavy, fermions light}$$

$\longrightarrow$ all of them testable at LHC

• Heterotic string:

Natural framework for susy and unification

However mismatch between string and GUT scales

$M_s = gM_P \simeq 50M_{\text{GUT}}$

• 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

$\Rightarrow$ 2 new scenaria besides ‘conventional’

low energy susy Standard Model

- low string scale
- split supersymmetry

OUTLINE

I) Low string scale /

strong gravity at low energies

II) High SUSY breaking scale: Split SUSY

III) Non compact extra dimensions

and localized gravity

I) Low string scale / strong gravity at low energies

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

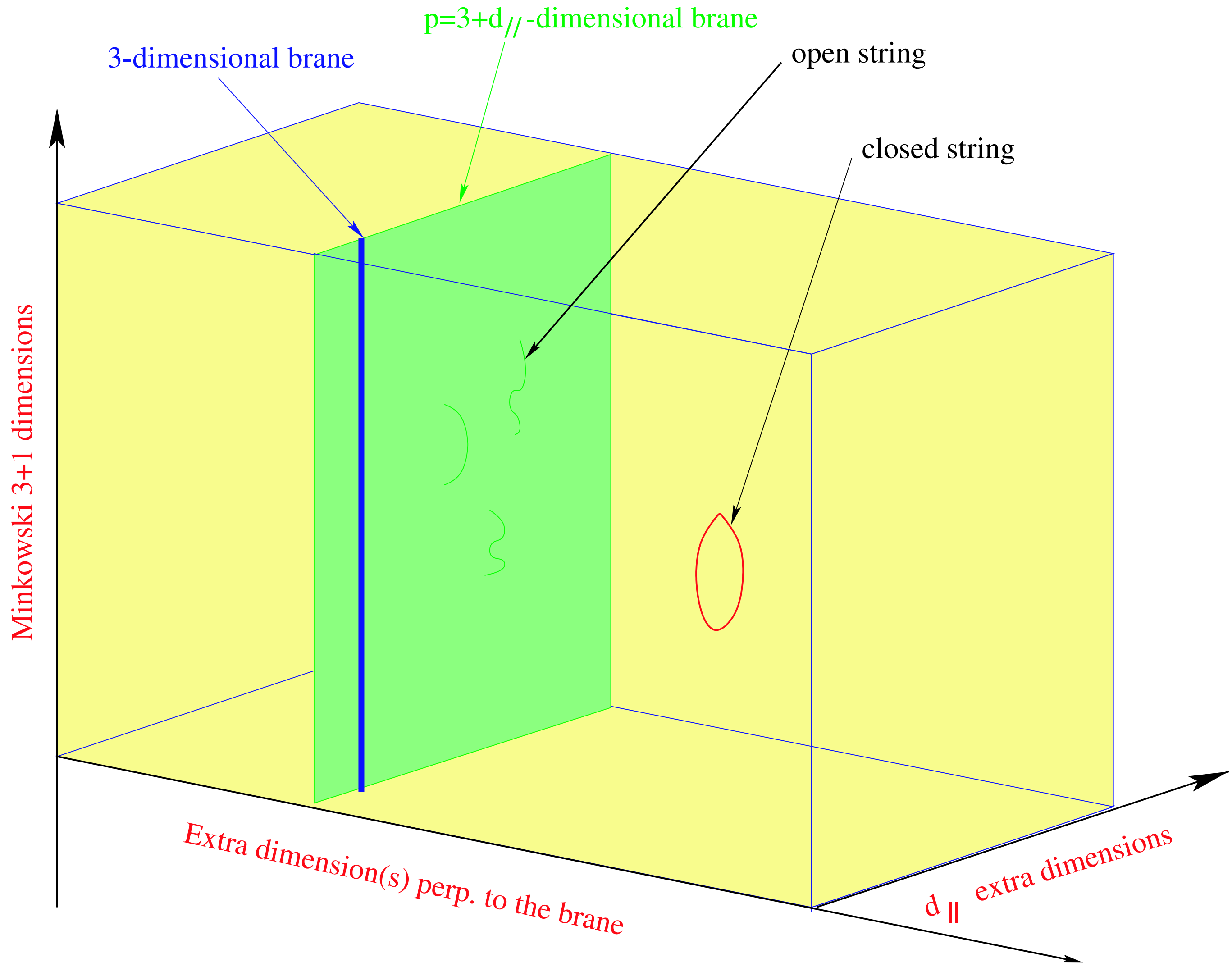
- Framework
- Experimental predictions

  particle accelerators, microgravity experiments
- SUSY in the bulk

  SUSY breaking, non-linear SUSY on the brane
- Electroweak symmetry breaking
- A D-brane embedding of the Standard Model

  unification, proton stability, Right-neutrinos

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 $R_\perp$

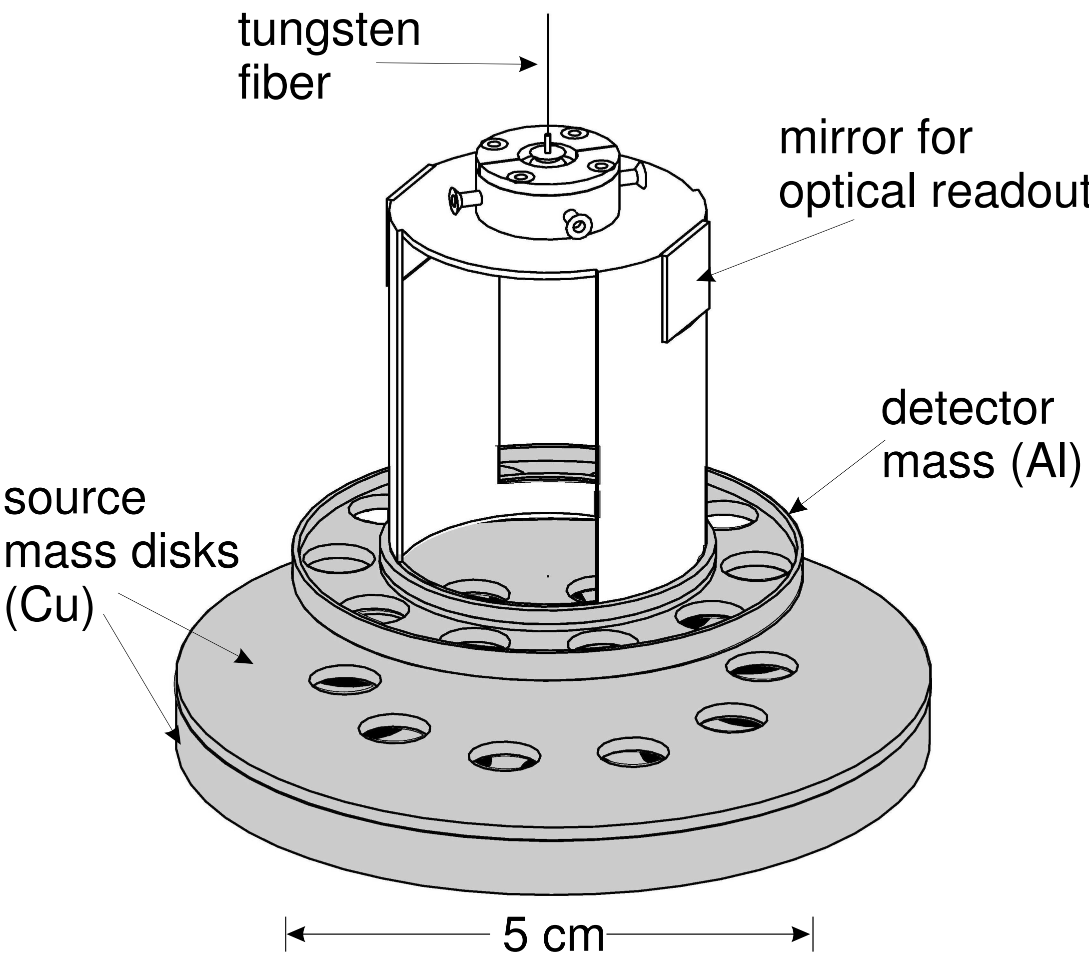
$M_s \sim 1$ TeV $\Rightarrow R_\perp \sim .1 - 10^{-13}$ mm $(n = 2-6)$

- 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



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

Supernova constraints

cooling due to graviton production

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

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

$\nearrow$

$\sim$ 10 MeV

$\Rightarrow$ production rate:

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

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

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

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}	-	-

Experimental predictions

- particle accelerators

- Large TeV dimensions

  seen by gauge interactions

- Extra large hidden dimensions transverse

  $\Rightarrow$ strong gravity

- massive string vibrations

- microgravity experiments

- gravity modifications at short distances

  new submillimeter forces

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)

⇒ 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

⇒ pair production of KK modes (universal dims)

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

Servant-Tait '02

Massive string vibrations ⇒ indirect effects

virtual exchanges ⇒ effective interactions

Actual limits: Matter fermions on

branes ⇒ $M_s \gtrsim 500$ GeV

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

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

High energies ⇒

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

Giddings-Thomas, Dimopoulos-Landsberg '01

Matter fermions: open strings ending

- on the same set of branes

$\Rightarrow$ dimension-8 effective operators

$\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2 \;\Rightarrow\; M_s \gtrsim 500$ GeV

Cullen-Perelstein-Peskin '00

virtual graviton exchange: $\frac{g^4}{M_s^4}(\bar{\psi}\partial\psi)^2$

- on different set of branes

$\Rightarrow$ dimension-6 effective operators

$\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2 \;\Rightarrow\; M_s \gtrsim 2-3$ TeV

I.A.-Benakli-Laugier '00

- 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

Scherk-Schwarz (SS) SUSY breaking

Scherk-Schwarz '79, Rohm '84, Fayet '85

Ferrara-Kounnas-Porrati-Zwirner '88, I.A. '90

Periodicity up to R-symmetry transformation

$\Phi(y+2\pi R) = U\Phi(y) \qquad U = e^{2\pi i Q} \qquad \Rightarrow$

KK-momentum: $p = \frac{m+Q}{R} \Rightarrow$ mass-shifts

R-symmetry: discrete internal rotation $U^N = 1$

$\Rightarrow Q$ quantized in units of $1/N$

Closed strings: modular invariance $\Rightarrow$

windings $n \to n$, $Q \to Q-n$

Open strings: $R_\parallel \Rightarrow$ like in field theory

$R_\perp \Rightarrow$ brane supersymmetry

I.A.-Dudas-Sagnotti '98

Brane supersymmetry breaking

I.A.-Dudas-Sagnotti, Aldazabal-Uranga '99

Stable configurations of branes with orientifolds

- absence of tachyons
- bulk susy breaking suppressed by $R_\perp$

	D	$\bar{\text{D}}$	O	$\bar{\text{O}}$
RR charge	$+$	$-$	$-$	$+$
tension	$+$	$+$	$-$	$-$
linear SUSY	Q_e	Q_o	Q_e	Q_o
NL SUSY	Q_o	Q_e		

Model I: DO or $\bar{\text{D}}\bar{\text{O}}$

local charge conservation, brane SUSY (locally)

Model II: $\bar{\text{D}}$O or D$\bar{\text{O}}$

brane SUSY breaking (linear), NL SUSY

Example: $I = S^1/\mathbb{Z}_2$ with SS SUSY breaking

O8 ——————— πR ——————— $\bar{\text{O}}$8

RR charge: -8 +8

- SS SUSY breaking: 16 D9 branes along I

  $\Rightarrow SO(32)$ with fermion mass-shifts

- Model I: 8 D8 branes on O8

  8 $\bar{\text{D}}$8 branes on $\bar{\text{O}}$8

  $\Rightarrow SO(16) \times SO(16)$ 'SUSY'

- Model II: 8 $\bar{\text{D}}$8 branes on O8

  8 D8 branes on $\bar{\text{O}}$8

  $\Rightarrow SO(16)\times SO(16)$ with fermions in the sym

  $(136, 1) + (1, 136)$ $136 = 135 + 1 \leftarrow$ 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 $\equiv \ln R_\perp$

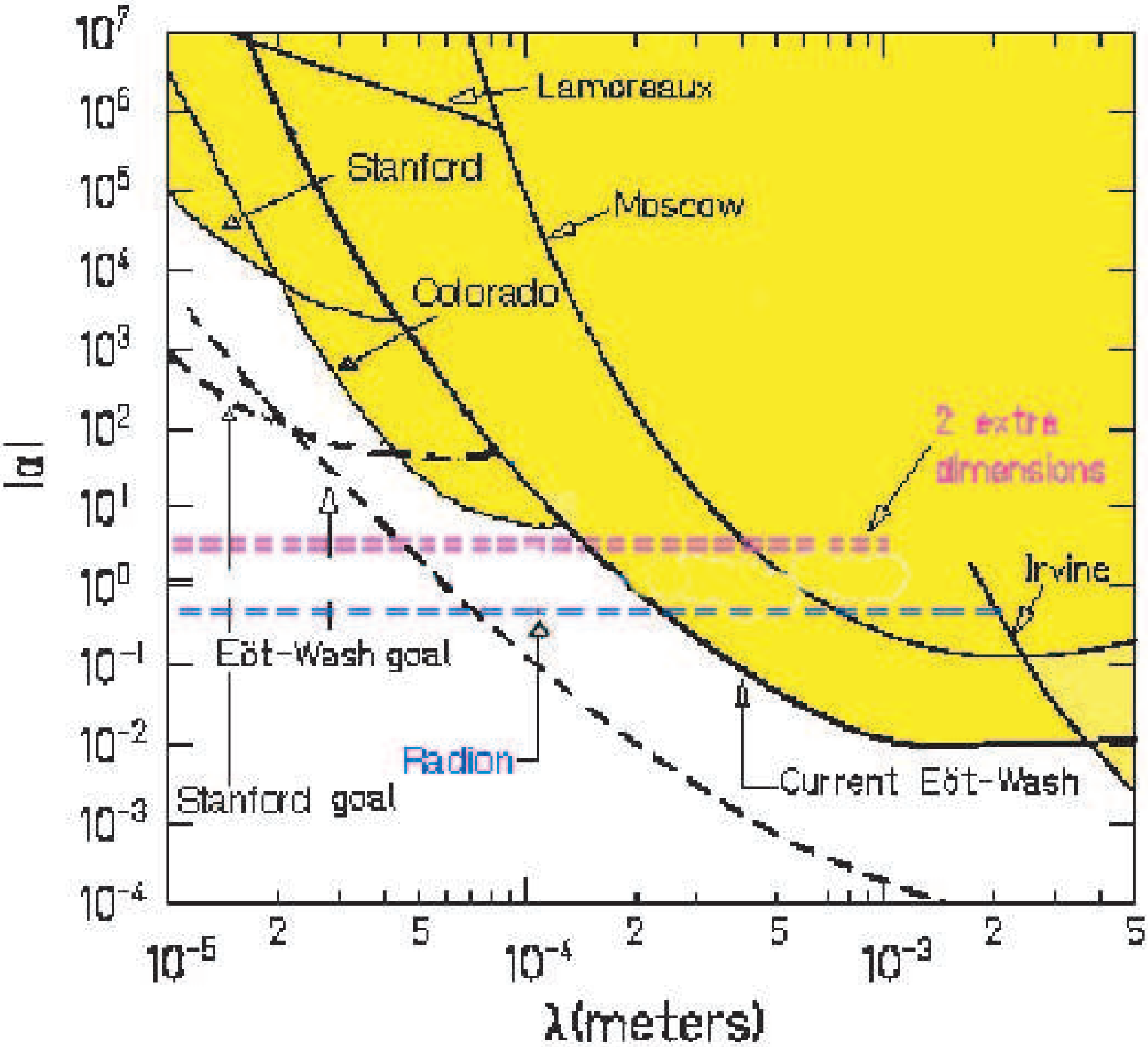
mass: $(\text{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range

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

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



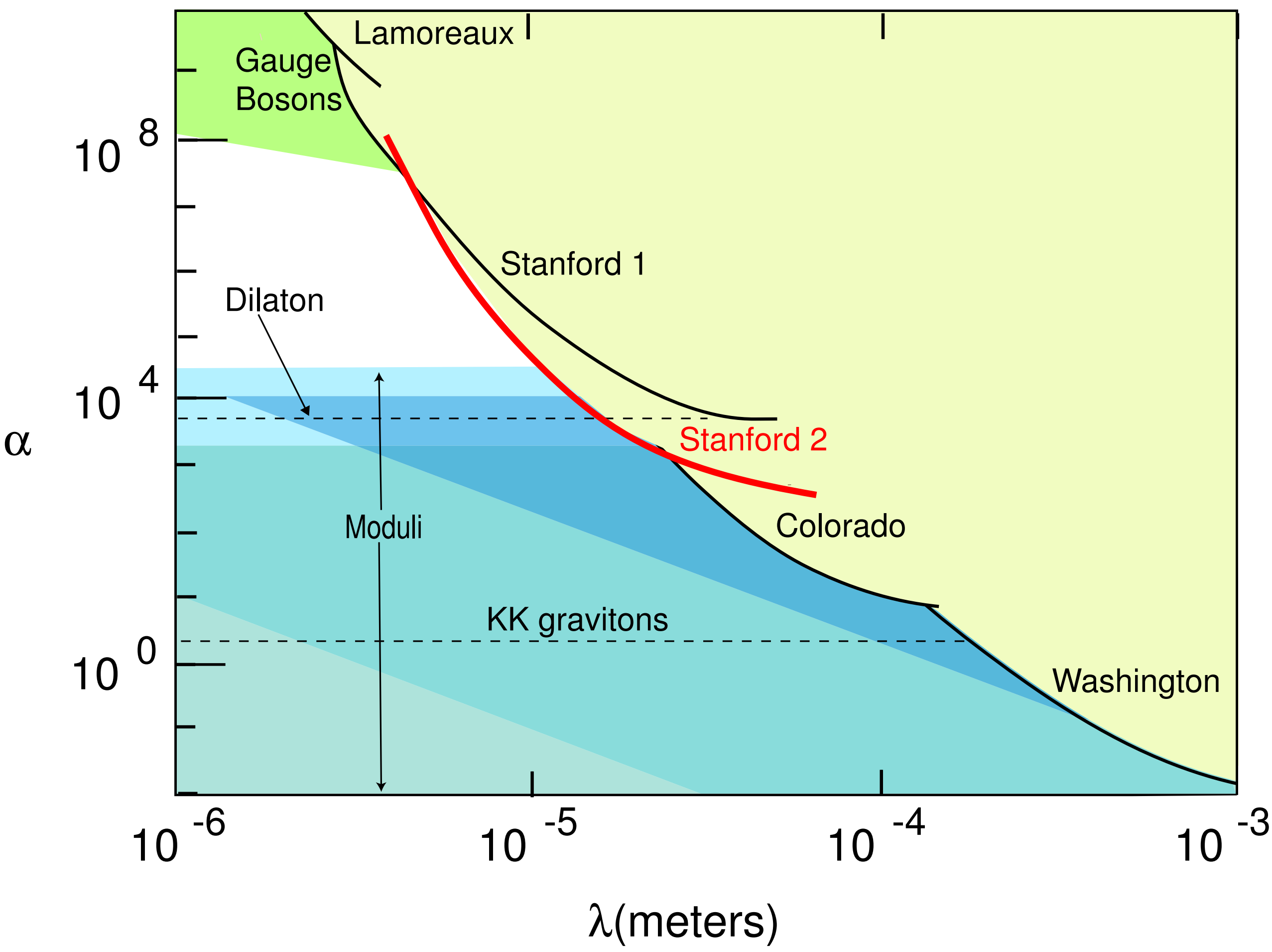
Radion $\Rightarrow M_* \gtrsim$ 3 - 4.5 TeV 95% CL (n=2-6)

Adelberger et al. '04

an order of magnitude improvement

on bounds in the range 6-20 μm

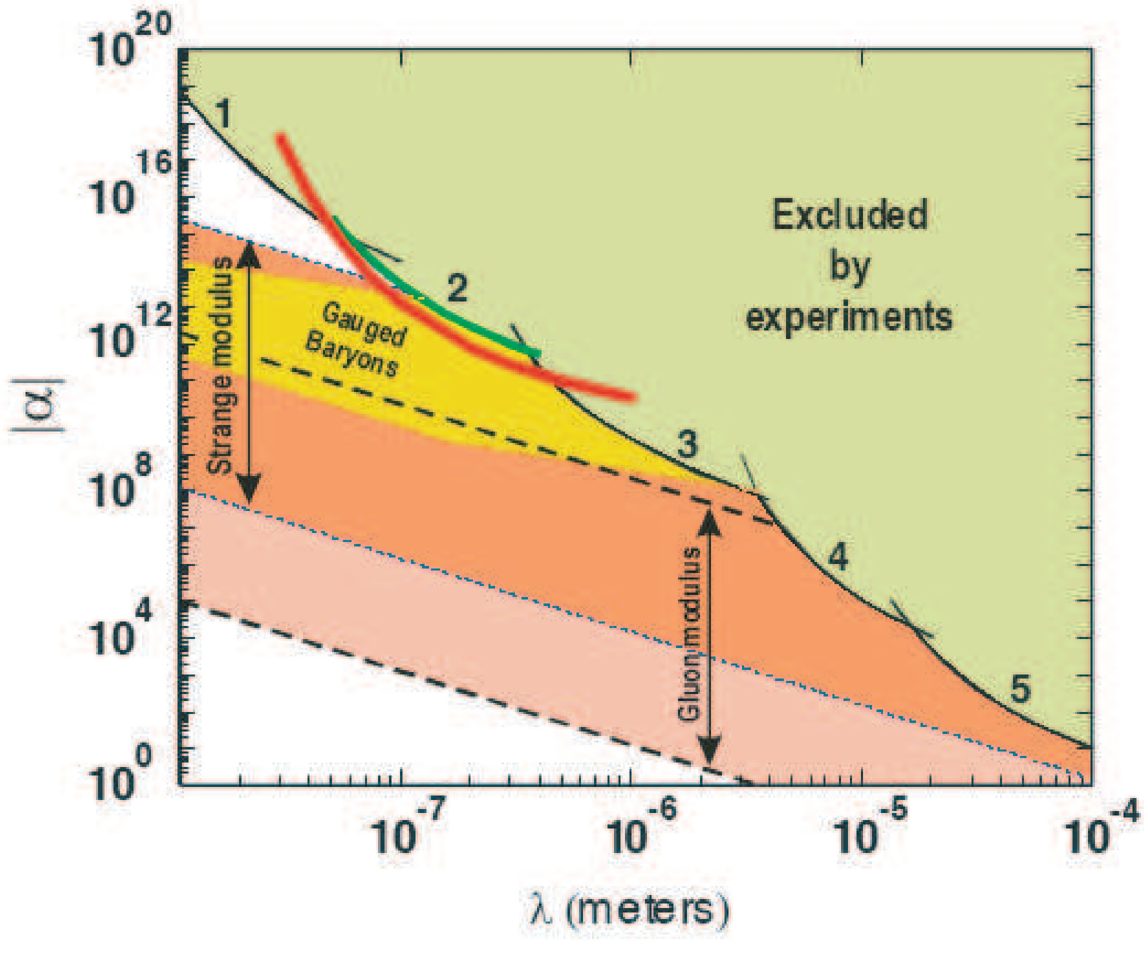
Smullin-Geraci-Weld-Chiaverini-Holmes-Kapitulnik '05



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.

Non-linear SUSY on the brane $\Rightarrow$

(nearly) massless goldstino χ

Dudas-Mourad, Pradisi-Riccioni '01

Standard realization of Volkov-Akulov $\Rightarrow$

universal coupling to stress-tensor

$$\mathcal{L}_\chi = -\frac{i}{2}\chi\sigma^\mu \overleftrightarrow{\partial}_\mu \bar{\chi} + i\kappa^2(\chi\overleftrightarrow{\partial}^\mu \sigma^\nu \bar{\chi})T_{\mu\nu}$$

κ: goldstino decay constant

But not the most general

e.g. a new 4-fermion operator not fixed by NL SUSY

Brignole-Feruglio-Zwirner '97, I.A.-Benakli-Laugier '01

General analysis of goldstino couplings

to SM fields in D-brane models

I.A.-Tuckmantel '04

Matter on intersection of two brane stacks:

$$\frac{1}{2\kappa^2} = T_1 + T_2 \qquad T_i = \frac{M_s^4}{4\pi^2 g_i^2}N_i$$

$$\delta\mathcal{L}_\chi = i\sqrt{2}\kappa F_{\mu\nu} f\sigma^\mu\partial^\nu\bar{\chi} + 2\kappa D_\mu\phi(f\partial^\mu\chi) + \text{h.c.}$$
$$+ 2\kappa^2(\partial_\mu\chi f_1)(\partial^\mu\bar{\chi}\bar{f}_2) + \mathcal{O}(\kappa^3)$$

F: gauge fields, f: Weyl fermions, ϕ: scalars

- universal coefficients independent of brane-angles
- 3rd term: fixes the field theory ambiguity of 4-fermion operator
- 1st term: hypercharge + fermion singlet
- 2nd term: higgs + lepton doublets

  preserves lepton number if $L(\chi) = -1$

I.A.-Tuckmantel-Zwirner '04

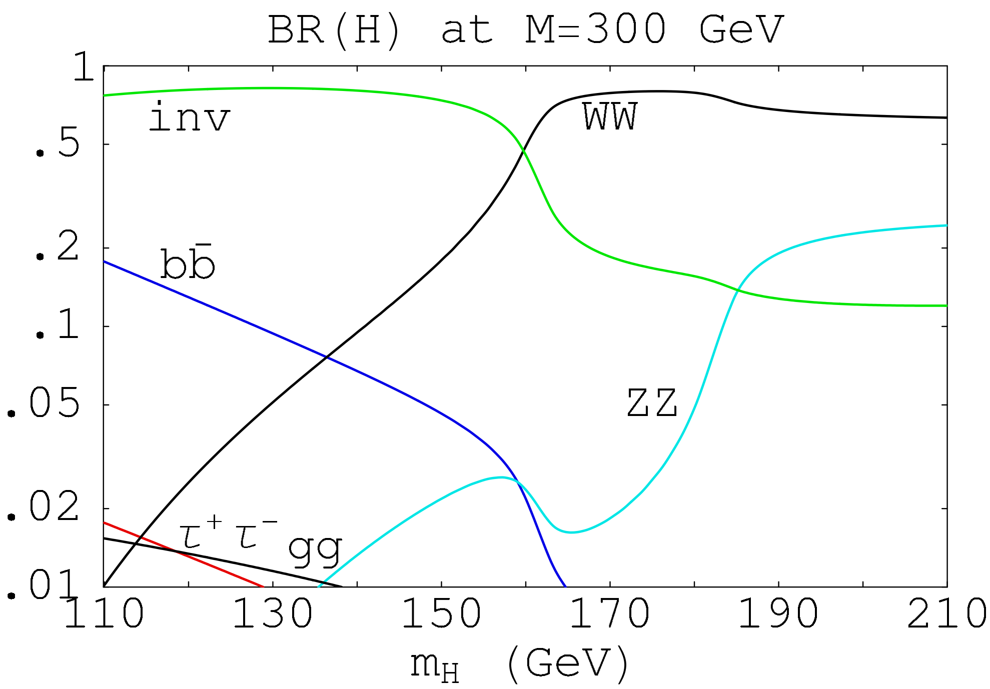
$Z, H \to \nu\chi \quad W^\pm \to l^\pm\chi \Rightarrow$

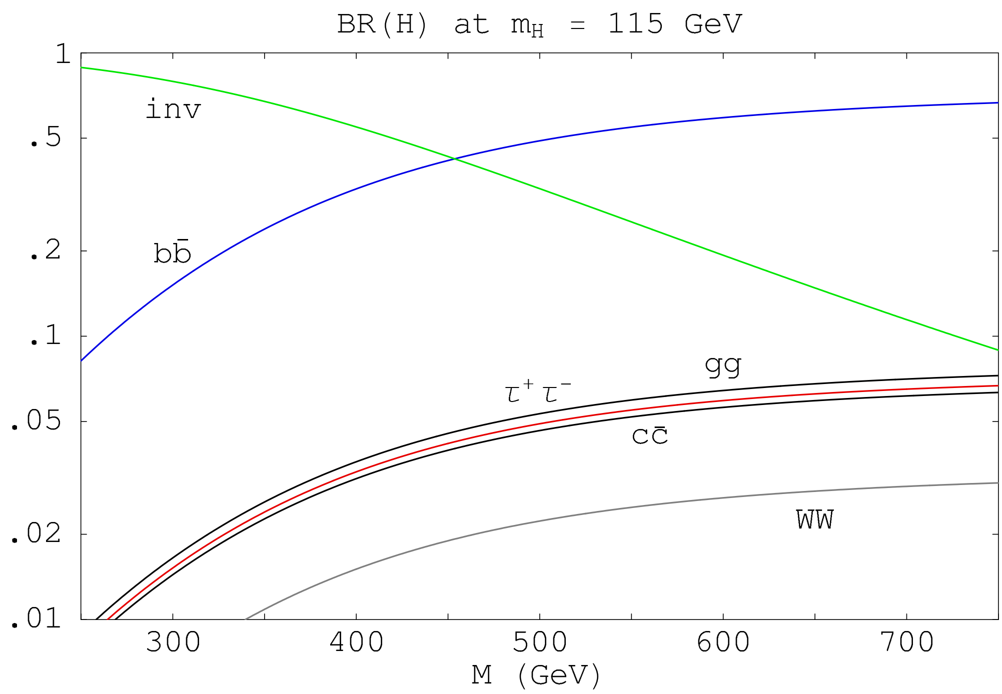
- bounds: $M_s \gtrsim 500$ GeV (e.g. invisible Z width)

- signal: invisible Higgs decay

dominant or non-negligible in a large range of (M_s, M_H)

$M_s \simeq 2M$


BR(H) at M=300 GeV
inv
WW
bb̄
ZZ
τ+τ− gg
mH (GeV)
1
.5
.2
.1
.05
.02
.01
110
130
150
170
190
210


BR(H) at mH = 115 GeV
inv
bb̄
gg
τ+τ−
cc̄
WW
M (GeV)
1
.5
.2
.1
.05
.02
.01
300
400
500
600
700

Origin of EW symmetry breaking?

little hierarchy: $m_W/M_s \lesssim \mathcal{O}(10^{-1})$

string tree-level: $m_W = 0$ or $\mathcal{O}(M_s)$

possible solution: radiative breaking

I.A.-Benakli-Quiros '00

$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

$\mu^2 = 0$ at tree but becomes < 0 at one loop

non susy vacuum

simplest case: one Higgs from the same brane

$\Rightarrow$ tree-level V same as susy: $\lambda = \frac{1}{8}(g^2 + g'^2)$

D-terms

$\mu^2 = -g^2 \varepsilon^2 M_s^2 \leftarrow$ effective UV cutoff

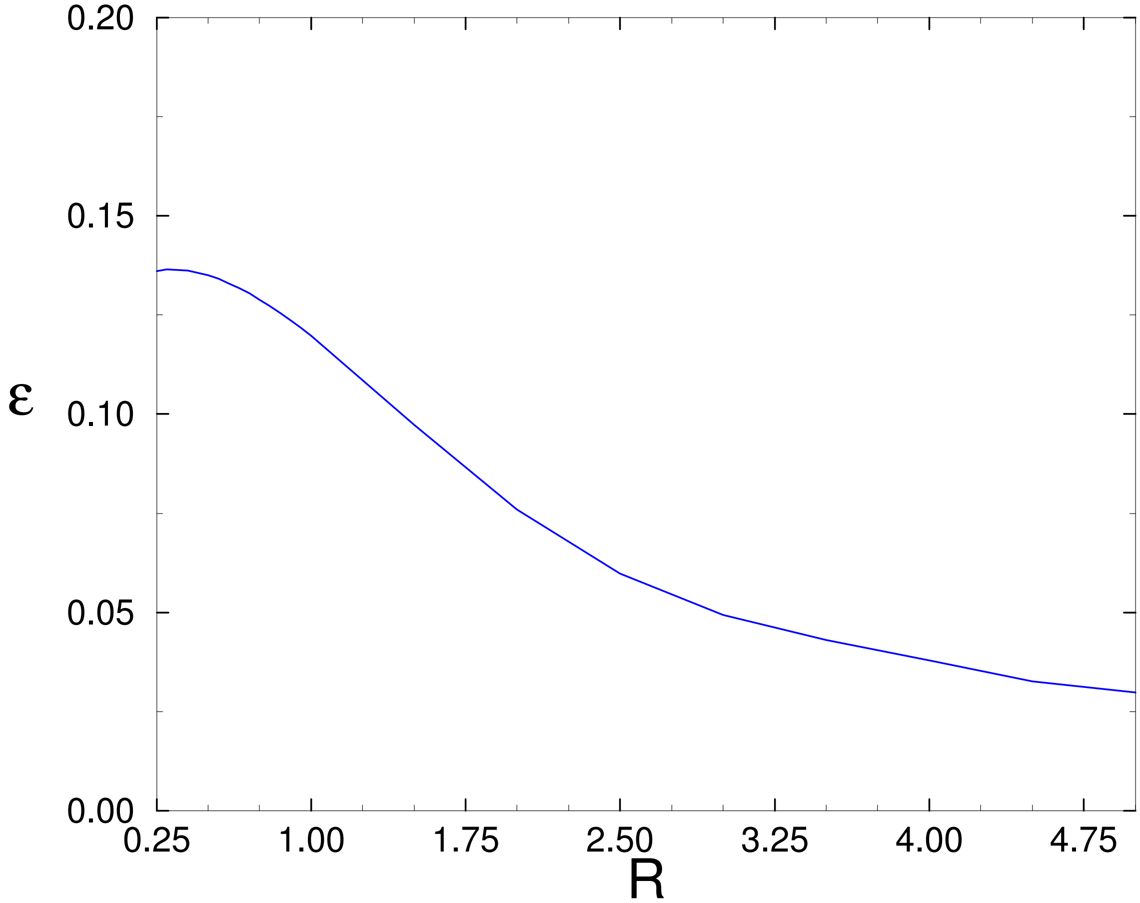
$\nwarrow$

loop-factor estimated by a toy model computation

UV $\qquad\qquad\qquad\qquad$ $e^{-\pi l}$

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2}\int_0^{\infty} dl\, l^{3/2}\,\frac{\theta_2^4}{16 l^4 \eta^{12}}\left(il + \frac{1}{2}\right)\sum_n n^2 e^{-2\pi n^2 R^2 l}$$

IR $\qquad\qquad\qquad\qquad$ 1



$R \to \infty :\ \varepsilon(R) M_s \sim \varepsilon_\infty / R$ $\qquad$ $\varepsilon_\infty \simeq 0.008$

UV cutoff: $M_s \to 1/R$

$R \to 0 :\ \varepsilon(R) \simeq 0.14$ $\qquad$ large transverse dim

- $M_H = M_Z$ at tree

  same as MSSM for $\tan\beta, m_A \to \infty$

- $M_s = M_H/(\sqrt{2}g\varepsilon)$

Low-energy SM radiative corrections

top quark sector

$M_H \sim 120$ GeV

$\Rightarrow$

$M_s \sim$ a few TeV

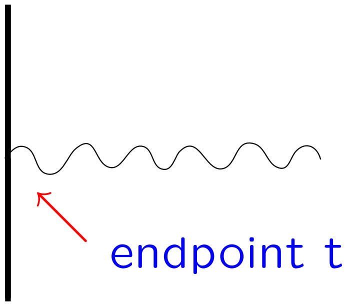
A D-brane embedding of the Standard Model

I.A.-Kiritsis-Tomaras '00

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

N coincident branes $\Rightarrow U(N)$

a-stack



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

$U(1)$ coupling: $g_N/\sqrt{2N}$ with unit charge of $\mathbf{N}$

non-abelian generators: $\text{Tr}T^aT^b = \frac{1}{2}\delta^{ab}$

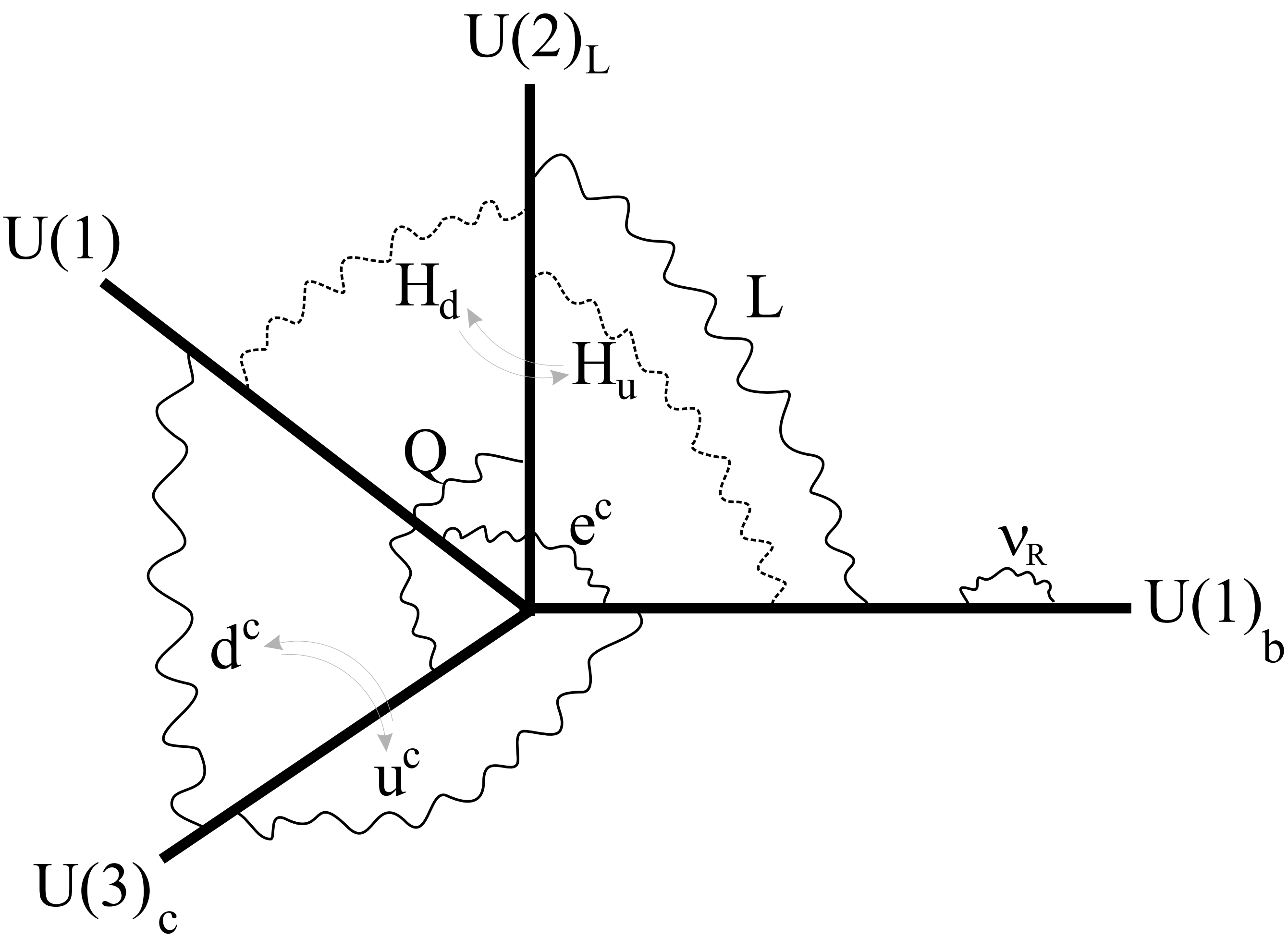
abelian: $T_{U(1)} = \mathbb{1}_{N\times N}$

$\Rightarrow$ gauged "baryon" number

minimal choice: $U(3) \times U(2) \times U(1)$

color branes (g_3) weak branes (g_2)

Standard Model on D-branes



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

- PQ-type symmetry $\Rightarrow$ electroweak axion

can be explicitly broken by moving slightly away from the orbifold point

Green-Schwarz anomany cancellation:

shifting of axions $\Rightarrow$ $U(1)_A$ become massive

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

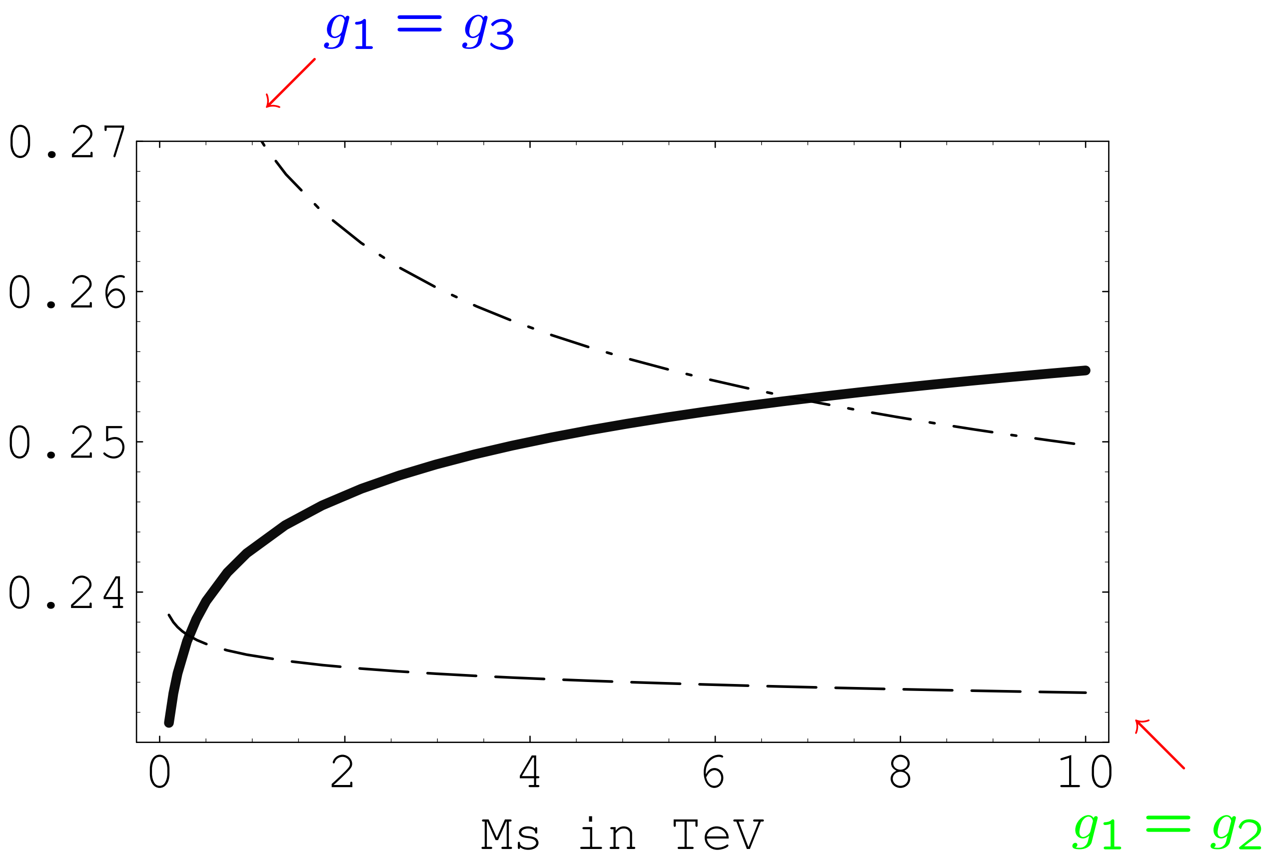
$$-\frac{1}{4g_A^2}F_A^2 - \frac{1}{2}(da + MA)^2 + \frac{a}{M}k_I^A \mathrm{tr} F_I \wedge F_I$$

cancel the anomaly

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

a: Poincaré dual of a 2-form B_2 $\qquad da = *dB_2$

$\sin^2\theta_W(M_s)$



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

for $M_s \sim$ a few TeV

R-neutrinos: open strings in the bulk $H'L\nu_R$

Arkani Hamed-Dimopoulos-Dvali-March Russell '98

Dienes-Dudas-Gherghetta '98

- $\int d^{4+n}x\, \bar\nu \not\partial \nu \qquad \nu = (\nu_R, \nu_R^c) \;\Rightarrow$

$$R_\perp^n \int d^4x \sum_m \left\{ \bar\nu_{Rm} \not\partial \nu_{Rm} + \bar\nu^c_{Rm} \not\partial \nu^c_{Rm} + \frac{m}{R_\perp} \nu_{Rm} \nu^c_{Rm} + c.c. \right\}$$

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

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

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

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

- $m = 0$: Dirac neutrino masses

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

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

II) High SUSY breaking scale: Split SUSY

Arkani Hamed-Dimopoulos '04

- Motivations
- Framework

  Type I string theory with magnetized D9 branes

- Spectrum — with S.Dimopoulos
- gauge coupling unification

  Non abelian

  Standard Model embedding with $\sin^2\theta_W = \frac{3}{8}$ at M_{GUT}

- Mass scales
- Gaugino masses
- Split extended supersymmetry

  with K.Benakli, A.Delgado, M.Quirós, M.Tuckmantel

Physics beyond the Standard Model $\leftrightarrow$

stabilization of mass hierarchy?

- SUSY
- Extra dimensions
- Low string scale
- Compositeness
- Little Higgs

However actual precision tests + bounds $\Rightarrow$

already some degree of fine tuning a few % !

Need very clever theory beyond the SM

OR

Live with the hierarchy

still unknown explanation perhaps related to the cosmological constant problem

Split Supersymmetry: raise SUSY breaking scale

but keep SUSY main predictions:

unification + dark matter candidate $\Rightarrow$

keep all MSSM fermions light

but let squarks and sleptons become heavy

TeV physics: SM with a ‘fine tuned’ light Higgs

+ gauginos + a pair of higgsinos

All MSSM ‘problems’ solved:

FCNC, B/L violation, CP, nb of parameters,...

Arkani Hamed-Dimopoulos, Giudice-Romanino ’04

Main signatures of split susy:

- squarks superheavy $\Rightarrow$ long lived gluino

$$\tau_g \simeq \left(3 \times 10^{-2}\text{s}\right)\left(\frac{m_0}{10^9\text{GeV}}\right)^4\left(\frac{1\,\text{TeV}}{m_g}\right)^5$$

$\Rightarrow$ displaced vertices

late decays captured near the detector, etc

- susy unification of 5 couplings at m_0:

$$\Delta\mathcal{L} = \sqrt{2}g_u H^\dagger \tilde{W}\psi_u + \sqrt{2}g_d H\tilde{W}\psi_d +$$

$$\frac{1}{\sqrt{2}}g'_u H^\dagger \tilde{B}\psi_u - \frac{1}{\sqrt{2}}g'_d H\tilde{B}\psi_d - \frac{\lambda}{2}(H^\dagger H)^2$$

higgsinos (ψ_u, ψ_d)

susy relations: $g_u = g\sin\beta,\ g_d = g\cos\beta,\ g'_u = g'\sin\beta$

$g'_d = g\cos\beta,\ \lambda = \frac{1}{4}(g^2 + g'^2)\cos^2 2\beta$

$\Rightarrow$ 5 relations in terms of one parameter

General framework

- Type I string theory compactified in 4d
  on 6d Calabi-Yau

$\Rightarrow$ $N=2$ SUSY in the bulk, $N=1$ on branes

- Magnetic fluxes on 2-cycles

$\Rightarrow$ SUSY breaking

Dirac quantization: $H = \frac{m}{nA} \equiv \frac{p}{A}$

H: constant magnetic field

m: units of magnetic flux

n: brane wrapping

A: area of the 2-cycle

Spin-dependent mass shifts for all charged states

$[p_i, p_j] = iqH\epsilon_{ij}$ $\quad$ q: charge

$\Rightarrow$ Landau spectrum

6d $\rightarrow$ 4d on T^2 with abelian magnetic field H

$\delta M^2 = (2k+1)|qH| + 2qH \cdot \Sigma \leftarrow$ spin operator

$k = 0, 1, 2, \ldots$: Landau level

Landau multiplicity: mn

- spin-0: $\Sigma = 0 \Rightarrow$ mass gap

- spin-1/2: $\Sigma = \pm 1/2 \Rightarrow$ chiral 0-mode

$k = 0 \quad : \quad \delta M^2 = |qH| \pm qH$

$\Rightarrow \quad \delta M^2 = 0 \quad$ for $\Sigma = -1/2$ $(qH > 0)$

- spin-1: $\Sigma = \pm 1 \Rightarrow$ tachyon

Nielsen-Olesen instability

$k = 0 \quad : \quad \delta M^2 = |qH| \pm 2qH$

$\Rightarrow \quad \delta M^2 = -qH \quad$ for $\Sigma = -1$ $(qH > 0)$

Exact open string description:

$q \longrightarrow q_L + q_R$ endpoint charges

$qH \longrightarrow \theta_L + \theta_R$; $\theta_{L,R} = \arctan q_{L,R} H \alpha'$

weak field limit $\Rightarrow$ field theory

H constant $\Rightarrow$ $F_{kl} = \epsilon_{kl} H$ $A_k = -\frac{1}{2} F_{kl} x^l$

world-sheet boundary action:

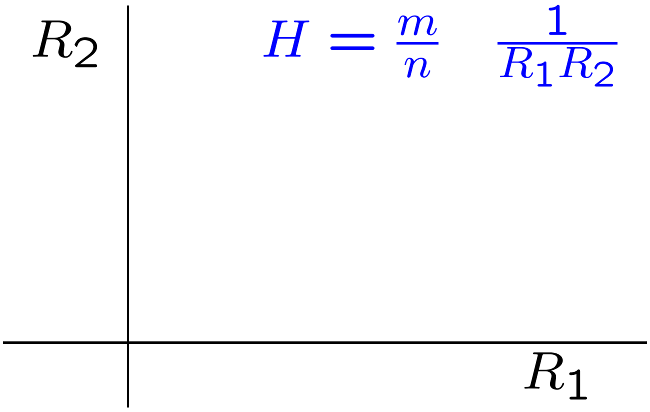
$$q \int A_k \partial x^k = -H \int \left(q_L x^k \overleftrightarrow{\partial} x^l \Big|_{\sigma=0} + q_R x^k \overleftrightarrow{\partial} x^l \Big|_{\sigma=\pi} \right)$$

internal rotation current

$\Rightarrow$ frequency shift by $\theta_{L,R}$: $\tan \theta_{L,R} = q_{L,R} H$

T-dual representation: branes at angles

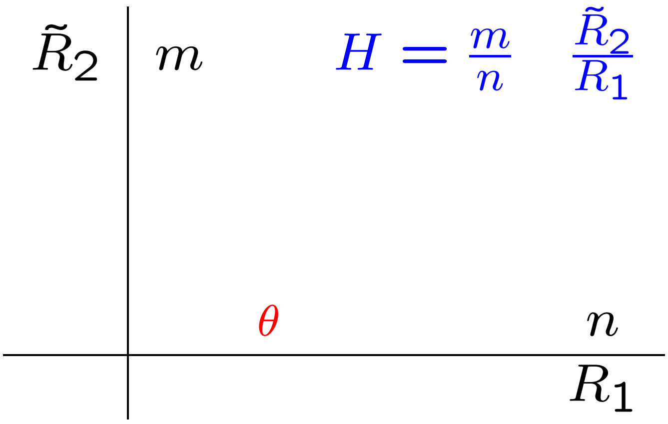
magnetized D9-brane wrapped on T^2



$$H = \frac{m}{n} \quad \frac{1}{R_1 R_2}$$

$$R_2 \to \alpha'/R_2 \equiv \tilde{R}_2 \quad \Rightarrow$$ D8-brane

wrapped around a direction of angle θ in T^2



$$H = \frac{m}{n} \quad \frac{\tilde{R}_2}{R_1} = \tan\theta$$

m, n : wrapping numbers

$(T^2)^3$ generalization: H_I with $I = 1, 2, 3$

$$\delta M^2 = \sum_I \{(2k_I + 1)|qH_I| + 2qH_I\Sigma_I\}$$

- spin-1/2: one chiral 0-mode

$\delta M^2 = 0$ for $k_I = 0$ and $\Sigma_I = -1/2$ $(qH_I > 0)$

- spin-1: tachyon can be avoided Bachas 95

$$\begin{array}{ccccccc} & |H_1| & + & |H_2| & - & |H_3| & > 0 \\ & |H_1| & - & |H_2| & + & |H_3| & > 0 \\ - & |H_1| & + & |H_2| & + & |H_3| & > 0 \end{array}$$

massless scalar ⇔ partial brane susy restoration

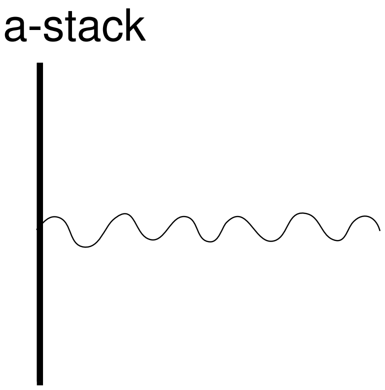
Angelantonj-I.A.-Dudas-Sagnotti 00

$$\theta_1 + \theta_2 + \theta_3 = 0$$

Generic spectrum

Turn on H_I^a in several $U(1)_a$ directions

$\Rightarrow$ Gauge group: $\prod_a U(N_a) \leftarrow SU(N_a) \times U(1)_a$



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

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

- Neutral strings: adjoint representations

  $\Rightarrow$ massless gauge supermultiplets

- Charged strings $\Rightarrow$ massless chiral fermions same stack: antisymmetric or symmetric

$$\text{multiplicities}: \begin{cases} A: & \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a + 1\right) \\ S: & \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a - 1\right) \end{cases}$$

different stacks: bifundamentals

$$\text{multiplicities}: \begin{cases} (N_a, N_b): & \prod_I (m_I^a n_I^b + n_I^a m_I^b) \\ (N_a, \bar{N}_b): & \prod_I (m_I^a n_I^b - n_I^a m_I^b) \end{cases}$$

$\Rightarrow$ Generic spectrum of split SUSY:

- massless gauginos
- massive squarks and sleptons
- massless Higgs $\Leftrightarrow$ non chiral susy intersection
  two Higgs multiplets

Gauge couplings

I.A.-Dimopoulos '04

$$SU(N_a): \quad \frac{1}{\alpha_{N_a}} = \frac{V}{g_s} \prod_I |n_I^a| \sqrt{1 + (H_I^a \alpha')^2}$$

g_s: string coupling

V: compactification volume in string units

$U(1)$ DBI action on T^2:

$$\sqrt{\det(\delta_{ij} + F_{ij}\alpha')} = \sqrt{1 + (H\alpha')^2}$$

$$\det(\delta_{ij} + F_{ij}\alpha') = \det\begin{pmatrix} 1 & H\alpha' \\ -H\alpha' & 1 \end{pmatrix}$$

$$U(1)_a: \quad \alpha_{U(1)_a} = \frac{\alpha_{N_a}}{2N_a}$$

non-abelian generators: $\mathrm{Tr}T^aT^b = \frac{1}{2}\delta^{ab}$

abelian: $T_{U(1)} = \mathbb{1}_{N\times N} \leftarrow$ **N** has unit charge

Gauge couplings

I.A.-Dimopoulos '04

$$SU(N_a): \quad \frac{1}{\alpha_{N_a}} = \frac{V}{g_s} \prod_I |n_I^a| \sqrt{1 + (H_I^a \alpha')^2}$$

g_s: string coupling

V: compactification volume in string units

$$U(1)_a: \quad \alpha_{U(1)_a} = \frac{\alpha_{N_a}}{2N_a}$$

Non abelian unification conditions:

(i) $\prod_I |n_I^a|$ independent of a

follows from absence of chiral symmetric reps

no color sextets and weak triplets $\Rightarrow \prod_I n_I^a = 1$

$$\text{(ii)} \ |H_I^a| \begin{cases} \text{independent of } a \\ << M_s^2 = \alpha'^{-1} \end{cases}$$

$\Rightarrow$ more quantitative analysis

$$\frac{1}{\alpha_{N_a}} = \frac{V}{g_s} \prod_I \sqrt{1 + (H_I^a \alpha')^2}$$

1% error in $\alpha_3 = \alpha_2 \quad \Rightarrow \quad H_I^a \alpha' \lesssim 0.1$

$\Rightarrow V = \prod_I V_I \gtrsim 10^3$

too high to keep strings weakly coupled?

$\alpha_{\text{GUT}} \simeq 1/25 \to g_s \gtrsim \mathcal{O}(10)$

can be partly relaxed if $H_I^3 = H_I^2$ for some I:

it follows from the absence of chiral $(\bar{3}, 2)$

no antiquark doublets

$\Rightarrow$ keep $g_s \lesssim \mathcal{O}(1)$

Minimal Standard Model embedding

New possibilities using intersecting branes

- no large dimensions for low string scale
- no need for B or L conservation
- but need $\sin^2\theta_W = \frac{3}{8}$

General analysis using 3 brane stacks

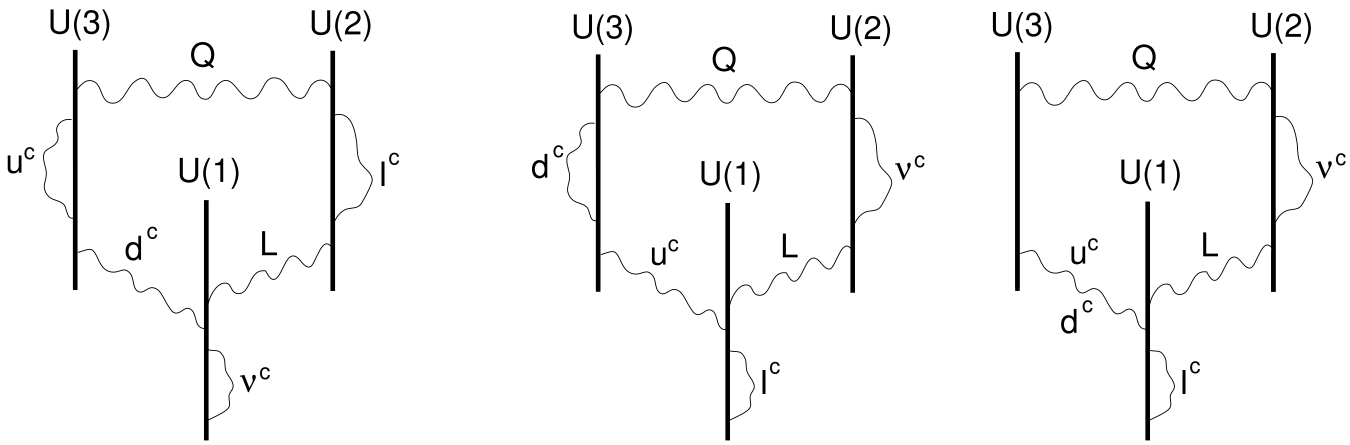
$\Rightarrow$ $U(3) \times U(2) \times U(1)$

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**
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	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_0$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$

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

$$\text{Model A} \quad : \quad \sin^2\theta_W = \frac{1}{2+2\alpha_2/3\alpha_3}\bigg|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

$$\text{Model B, C} \quad : \quad \sin^2\theta_W = \frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\bigg|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$

$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$$

$$\frac{1}{\alpha_Y} = \frac{2c_1^2}{\alpha_1} + \frac{4c_2^2}{\alpha_2} + \frac{9c_3^2}{\alpha_3}$$

$$\sin^2\theta_W = \frac{\alpha_Y}{\alpha_2+\alpha_Y} = \frac{1}{\alpha_2/\alpha_Y+1}$$

$$= \frac{1}{1+4c_2+2c_1^2\alpha_2/\alpha_1+6c_3^2\alpha_2/\alpha_3}$$

- Higgs can be easily implemented

  massless $\Rightarrow$ susy intersection

  $H_1, H_2 \,:\, U(2) \leftrightarrow U(1)$ like L

	Model A	**Model B, C**
H_1	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_{H_1})_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_1},1)_{-1/2}$
H_2	$(\mathbf{1},\mathbf{2};0,1,\varepsilon_{H_2})_{1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_2},-1)_{1/2}$

- 2 extra $U(1)$'s

\- One combination can be $B-L$

$$(\varepsilon_d = \varepsilon_L = \varepsilon_\nu = -\varepsilon_{H_1} = \varepsilon_{H_2})$$

$$B-L = -\tfrac{1}{6}Q_3 + \tfrac{1}{2}Q_2 - \tfrac{\varepsilon_d}{2}Q_1$$

broken by a SM singlet VEV at high scale

or survive at low energies

\- The other/both is/are anomalous

Mass scales

- $M_{\text{GUT}} \simeq$ smallest compactification scale

  $\simeq 10^{16}$ GeV

- smallest $H_I^a \alpha' \sim 0.1 \Rightarrow$

  $M_s \simeq 3 \times M_{\text{GUT}}$

- $m_{\text{susy}} \sim$ largest scalar mass m_0

  : free parameter

branes: $m_0^2 \sim \delta H^a \equiv \epsilon_1 H_1^a + \epsilon_2 H_2^a + \epsilon_3 H_3^a$

brane intersections: $m_0^2 \sim \delta H^{ab} \equiv \delta H^a - \delta H^b$

"natural" scale: $m_0 \sim M_{\text{GUT}}$

but can be much smaller stable due to SUSY

Gaugino masses: protected by R-symmetry

However problem with SUGRA:

- keep R-symmetry at low energies
- generate light gaugino masses

Two possible solutions:

(1) brane susy $\Rightarrow$ generate $m_{1/2}$ from $m_{3/2}$

one gravitational loop: 1 handle + 1 boundary

$$\Rightarrow m_{1/2} \sim g_s^2 \frac{m_{3/2}^3}{M_s^2}$$ I.A.-Taylor '04

(2) keep gravity subdominant $\Rightarrow$

generate $m_{1/2}$ from brane α'-corrections

two gauge loops: 3 boundaries

$$\Rightarrow m_{1/2} \sim g_s^2 \frac{m_0^4}{M_s^3}$$ I.A.-Narain-Taylor '05

gauginos: open strings

$\Rightarrow$ at least one boundary $h \geq 1$

$N = 2$ superconformal charge:

3/2 units for each (chiral) gaugino

± 1 unit for each 2d supercurrent T_F

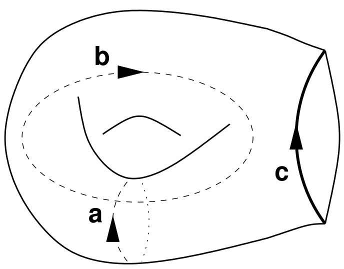
$\Rightarrow$ at least 3 T_F insertions

lowest "genus": $g + h/2 = 3/2$

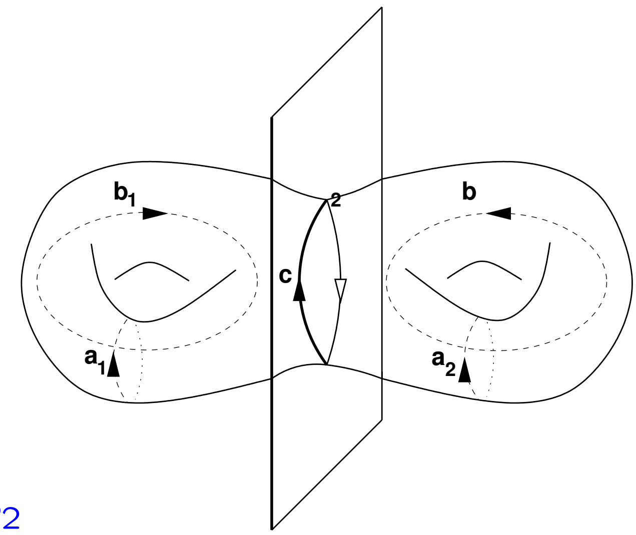
independently of the source of SUSY breaking!

Oriented case

(1) $g = 1$ $h = 1$ from mirror involution of $g = 2$



$\longleftarrow$

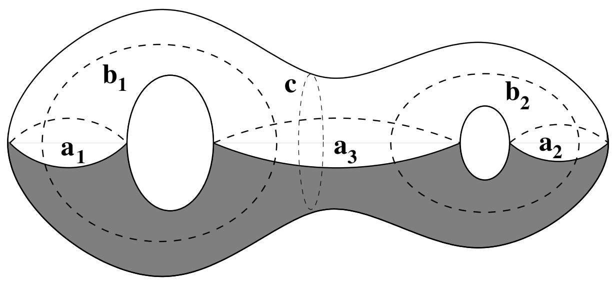


$a_1 \leftrightarrow a_2$

$b_1 \leftrightarrow -b_2$

(1) $g = 0$ $h = 3$ from mirror involution of $g = 2$

$\longleftarrow$



$a_i \leftrightarrow a_i$

$b_i \leftrightarrow -b_i$

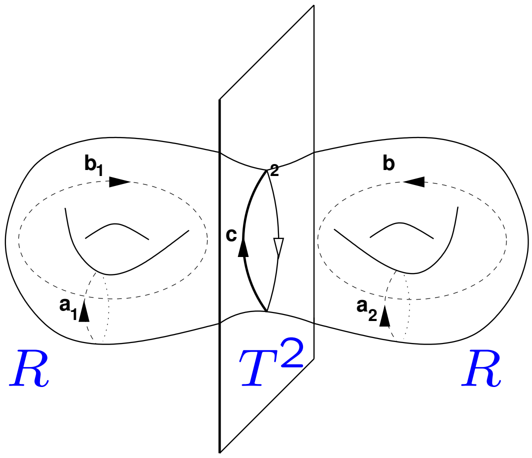
Topological partition function F_g

genus g

computes $N = 2$ SUSY F-terms

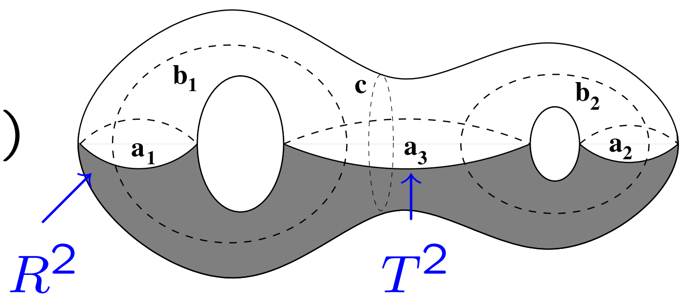
$$W^{2g}_{N=2} \quad \rightarrow \quad R^2\, T^{2g-2}$$

- graviphoton vertex T = (gaugino)^2
- graviton vertex = (gauge field)^2

(1) 

$\Rightarrow \quad \lambda\lambda\, R$

or SUSY breaking

(2) 

$\Rightarrow \quad \lambda\lambda\, F^2$

Invariant period matrix: $\Omega = \begin{pmatrix} \tau & -il \\ -il & -\bar{\tau} \end{pmatrix}$

$\tau_1 + i\tau_2$: modulus of the torus (handle)

l : radius of the hole

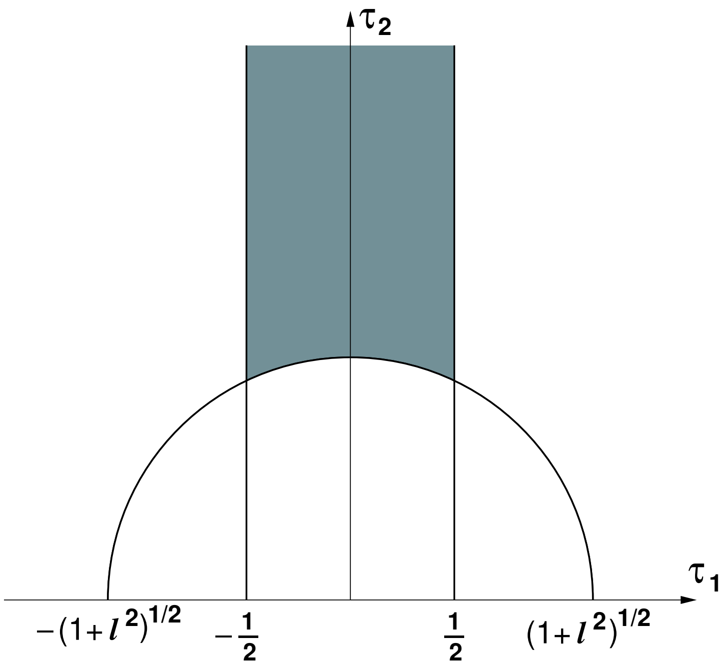
Modular transformations

$T: \quad \tau \to \tau + 1 \qquad l \to l$

$S: \quad \tau \to -\frac{\bar{\tau}}{|\tau|^2 - l^2} \qquad l \to \frac{l}{|\tau|^2 - l^2}$ ← $\det \Omega$

Fundamental domain:

$|\tau_1| \leq 1/2 \qquad |\tau|^2 \geq 1 + l^2 \qquad l \geq 0$



SS radius $R \to \infty$ $(m_{3/2} \sim 1/R \to 0)$ $\Rightarrow$ $\tau_2 \to \infty$

$$m_{1/2} \sim g_s^2 \int d\tau_2 \frac{dl}{(e^{2\pi l} - 1)} \frac{\Gamma}{(\tau_2 + l)^2} \sum_m \frac{mR^2}{(\tau_2 - l)^{3/2}} e^{-\dfrac{m^2 \pi R^2}{\tau_2 - l}}$$

integration measure ↗ (first factor); 4d non-compact coordinates ↗ (second factor); SS partition function $\times \partial X_{SS}$ ↗ (third factor)

possible divergence in $l \sim 0$ cancels by Γ $\Rightarrow$

$\int dl$ convergent

$$\Rightarrow m_{1/2} \sim g_s^2 \int \frac{d\tau_2}{\tau_2^{7/2}} \sum_m mR^2 e^{-\dfrac{m^2 \pi R^2}{\tau_2}}$$

$$\sim \frac{g_s^2}{R^3} \sim g^4 m_{3/2}^3 \qquad g_s \sim g^2$$

- anomaly mediation:

$$m_{1/2} \sim g^2 m_{3/2} \qquad g^2 \sim g_s$$

• power of g_s does not match

one loop correction always vanishes

by $N = 2$ superconformal charge

• higher loops behave $\sim m_{3/2}^3$

no linear term - dl integral converges

- hierarchy between gaugino and scalar masses

Sherk-Schwarz along an interval $\perp$ branes

$\Rightarrow m_{3/2} \sim 1/R$

gravity strength $\Rightarrow R^{-1} = \frac{2}{\alpha_G^2}\frac{M_s^3}{M_p^2} \sim 10^{13}$ GeV

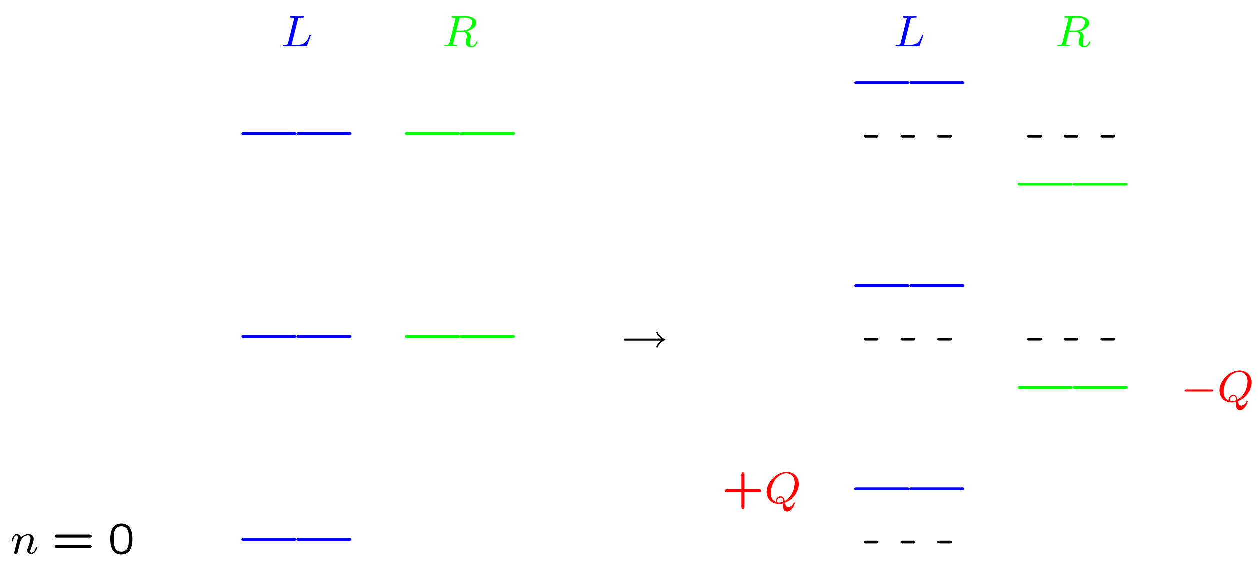
- $m_{1/2} \sim g_s^2 \frac{m_{3/2}^3}{M_s^2} \sim 1$ TeV

  if every loop-factor $\sim 10^{-2}$

- $m_0 \gtrsim g_s \frac{m_{3/2}^2}{M_s} \sim 10^8$ GeV

Break SUGRA keeping R-symmetry

SS breaking on $S^1/\mathbb{Z}_2 \perp$ brane $\Rightarrow$ 3/2-KK states



- generic shift Q $\Rightarrow$ Majorana masses, $\not R$

  $E << Q/R \Rightarrow$ 4d non-SUSY

  $Q/R < E < 1/R \Rightarrow$ 4d SUGRA

  $E >> 1/R \Rightarrow$ 5d SUGRA

- $Q = 1/2 \Rightarrow$ pairing $|n+Q\rangle_L$ with $|n+1-Q\rangle_R$

  $\Rightarrow$ Dirac masses, unbroken R-symmetry

  no intermediate regime $\Rightarrow$ no 4d SUGRA description

Effective QFT description: D-breaking

magnetic field $H \sim \langle \mathrm{D} \rangle$-term of $U(1)$

$\langle \mathrm{D} \rangle \sim m_0^2$ $U(N)$ brane stack

gaugino masses: protected by R-symmetry

broken by string corrections

$\Rightarrow$ higher-dim effective operators:

$F_{(0,3)} \int d^2\theta \mathcal{W}^2 \mathrm{Tr} W^2$ $\langle \mathcal{W} \rangle = \theta \langle \mathrm{D} \rangle$

↖

topological partition function at genus-0 with 3 holes

I.A.-Narain-Taylor '05

$\Rightarrow \; m_{1/2} \sim \epsilon^2 \frac{m_0^4}{M_s^3}$ ϵ^2: 2-loop factor

$\sim$ TeV for $m_0 \sim 10^{13} - 10^{14}$ GeV

Simple toroidal models

gauge multiplets: $N = 4$ (or $N = 2$) SUSY

$\Rightarrow$ Dirac gaugino masses without $\not{R}$

$\int d^2\theta \mathcal{W} \mathrm{Tr} W A \;\Rightarrow\; m_D \sim \epsilon \frac{m_0^2}{M_s}$ 1-loop factor

$N = 2$ vector $=$ $N = 1$ vector W $+$ chiral A

they can still be consistent with unification

I.A.-Benakli-Delgado-Quirós-Tuckmantel '05

	$M_{\rm GUT}$	m_0	m_D	$m_{1/2}$
$N = 4$	M_P	$10^{16} - 10^{17}$	10^{13}	10^6
$N = 2$	10^{18}	10^{13}	10^7	10^{-5}
$N = 2/2$ higgses	10^{16}	$10^{13} - 10^{14}$	10^9	10^2

- Dark matter: higgsinos?

no vector-like couplings up to 50 TeV

$\Delta m \gtrsim 100$ keV $\Rightarrow m_D \lesssim 10^5$ GeV

EW symmetry breaking $\Rightarrow \Delta m \sim \mathcal{O}(\frac{m_W^2}{m_D})$

$\Rightarrow$ - $N = 2/1$ higgs ok

- $N = 4/1$ higgs or $N = 2/2$ higgses:

with $m_D = 0$ for Binos

- Higgsino mass

- $\int d^2\theta \mathcal{W}^2 \bar{D}^2 \bar{H}_1 \bar{H}_2 \Rightarrow \mu \sim \epsilon \frac{m_0^4}{M_s^3} \sim m_{1/2}$

$\psi_1 \psi_2$ ok for $N = 2/2$ higgses

- or free parameter : $N = 4$ or $N = 2/1$ higgs

DM constraints $\Rightarrow m_{1/2} \gtrsim \mu$

- $m_{1/2} \sim \mu \Rightarrow$ LSP: higgsino + Bino

only for $N = 2/2$ higgses

- $m_{1/2} >> \mu \Rightarrow$ LSP=higgsino $\mu \simeq 1.1$ TeV

• gauginos lifetime:

$$\tau_g \simeq \left(\frac{m_0}{10^{13}\text{GeV}}\right)^4 \left(\frac{10^2\text{GeV}}{m_g}\right)^5 \tau_{\text{universe}} \Rightarrow$$

$N = 1$ split susy:

$m_0 \lesssim 10^{13} - 10^{15}$ GeV for $m_g \sim 0.1 - 10$ TeV

$N = 2$: ok

$N = 4$: replace m_0 with M_s for one pair

of gauginos $\Rightarrow \tau_g \sim 0.1\tau_{\text{universe}}$

• low energy signals:

charged higgsinos

decays $\rightarrow$ leptons + LSP, neutralinos

II) Non-compact extra dimensions

and localized gravity

- no problem with fixing the size moduli
- new approach to the hierarchy problem
- gravity modification at large distances

\- curved space: Randall-Sundrum '99

\- flat space : Dvali-Gabadadze-Porrati '00

more attractive for string theory realization spacetime = slice of AdS_5

our universe = 4d flat boundary

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \qquad \Lambda = -24M^3k^2$$

UV-brane $\rightarrow$ $0 \leq y \leq \pi r_c \leftarrow$ IR-brane

- fine-tuned tensions: $T = -T' = 24M^3k^2$
- IR-brane can move to infinity: $r_c \rightarrow \infty$

$$M_P^2 = M^3 \, \frac{1-e^{-2\pi k r_c}}{k} \leftarrow \text{internal volume } V$$

finite V even in the non-compact limit $\Rightarrow$

- always 4d gravity on the brane

  localized on the UV-brane

  potential: $\frac{1}{r} + \frac{1}{k^2 r^3} \leftarrow$ deviations ($r_c \rightarrow \infty$)

  $k^{-1} \lesssim 0.1$ mm $\Rightarrow M > 10^8$ GeV, $T^{1/4} > 1$ TeV

Two Einstein-Hilbert actions

in $4+n$ and 4 dimensions

$$M^{2+n}\int d^4x d^n y \mathcal{R}^{(4+n)} + M_P^2 \int d^4x \mathcal{R}^{(4)}\Big|_{y=0}$$

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

$y = 0$: p^{2-n} $M^{2+n}\, r_c^n$ p^2

$\Rightarrow$ $M^{2+n}\, p^2\, (\, p^{-n} + r_c^n\,)$

short distances: $p^{-1} << r_c \Rightarrow$ 4d p^2

large distances: $p^{-1} >> r_c \Rightarrow$ $(4+n)$d p^{2-n}

$\nearrow$

crossover scale

However: “brane thickness” $w \Rightarrow$

important effects

$n = 1$: $M_P^2 = M^3\, r_c$

$r_c \gtrsim 10^{28}$ cm $\Rightarrow$ $M \lesssim 100$ MeV

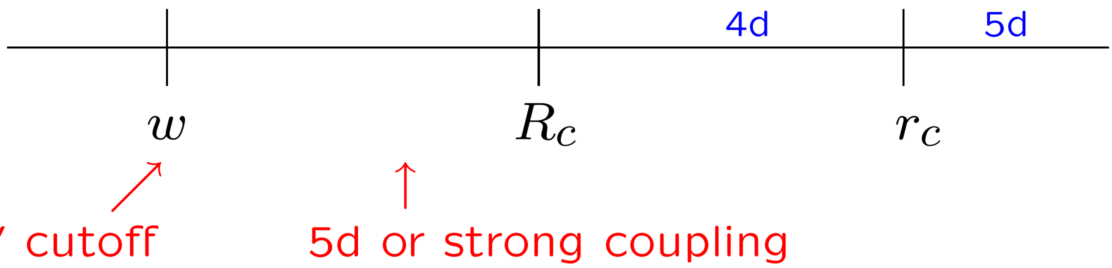
dark energy $\Rightarrow r_c \simeq 10^{28}$ cm

or $M^{-1} \sim 1$ mm ?   DGP

Moreover: new crossover scale $R_c \sim \sqrt{w r_c}$

Kiritsis-Tetradis-Tomaras '01

or $\sim r_c^{3/5} w^{2/5}$ Luty-Porrati-Rattazzi, Rubakov '03

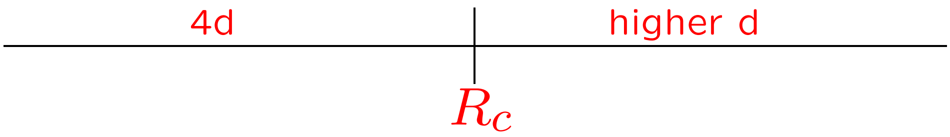


$r_c \sim 10^{28}$ cm $\Rightarrow R_c \sim 10^{-4} - 10$ m !

$n \geq 2$: UV divergences in the bulk $\Rightarrow$

$w = 0$: always 4d behavior on the 'brane'

$w \neq 0$: crossover scale becomes $R_c = w \left(\frac{r_c}{w}\right)^{n/2}$



2-pt function at $y = 0$: $G(p) = \dfrac{D(p)}{1 + r_c^n \, p^2 \, D(p)}$

$$D(p) = \int \frac{d^n k}{k^2 + p^2} \sim \begin{cases} n = 1 : & 1/p \\ n \geq 2 : & w^{2-n} \end{cases}$$

UV divergent

$w \sim l_P \quad \Rightarrow \quad R_c \sim M^{-1}(M_P/M)^{n/2}$

$M \sim 1$ TeV $\Rightarrow$ $R_c \sim 10^{8(n-2)}$ cm

$\gtrsim 10^{28}$ cm $\Rightarrow n \geq 6$

string realization of localized gravity?

- what is its strength? $M_P >> M_s$?

- what is its width w ?

I.A.-Minasian-Vanhove '02

string corrections to $\mathcal{R}$

- Heterotic: vanishing in perturbation theory

I.A.-Gava-Narain '92

- Open strings: 4d SUSY corrections vanish

in the decompactification limit

- Closed type II strings: 4d localized terms in

non-trivial non-compact Calabi-Yau manifolds

- M-theory: 5d localization

strong coupling limit of type IIA

10d effective action:

$$\int_{M_{10}} \left\{ \frac{M_s^8}{g_s^2} \mathcal{R}^{(10)} + M_s^2 f(g_s) R \wedge R \wedge R \wedge R \wedge e \wedge e \right\}$$

IIA

$$f(g_s) = -\frac{2}{3g_s^2}\zeta(3) \pm \frac{2\pi^2}{9} + \text{non-perturbative}$$

IIB

$$M_{10} \Rightarrow M_4 \times \mathrm{CY}_6 \qquad \int_{\mathrm{CY}_6} R \wedge R \wedge R = \chi \quad \Rightarrow$$

Euler number

$$\frac{M_s^8}{g_s^2} \int_{M_4 \times \mathrm{CY}_6} \mathcal{R}^{(10)} + \chi f(g_s) M_s^2 \int_{M_4} \mathcal{R}^{(4)}$$

- It preserves $N = 2$ SUSY
- In general $\chi = \sum_I \chi_I$ localized at y_I

$\chi_I = \pm 4 \times$ (nb of $N = 2$ vectors - nb of hypers)

• strength of the localized term

$$M_P^2 = \chi f(g_s) M_s^2 \qquad f(g_s) = \frac{c_0}{g_s^2} + c_1 + \cdots$$

while $M^2 = M_s^2 / g_s^{1/2} \Rightarrow$

$M_P >> M \quad \Rightarrow \quad g_s \to 0$ or χ large

• width of the localized term

$$M_P \equiv l_P^{-1} \to \infty \quad : \quad \text{expect} \quad w \sim \frac{l_P^\nu}{l_s^{\nu-1}} \to 0$$

$\Rightarrow \nu > 0$

computation in orbifolds $\Rightarrow \quad \nu = 1$

difficulty for computing ν:

• $c_0 \neq 0 \Rightarrow l_P \sim g_s l_s \quad \Rightarrow \quad w = 0$ in perturbation

• orbifolds: $c_0 = 0$ but need $\chi \to \infty$

$$\chi = \sum_{\text{fixed points}} \chi_I \quad ; \quad \mathbb{Z}_N\text{-orbifold: } \chi_I \sim N$$

Summary of the results $(c_0 \neq 0)$

$M_P \sim (\chi/g_s)^{1/2} M_s$ $\quad w \sim l_P$ $\quad R_c \sim g_s l_s^4 / l_P^3$

width $\quad$ crossover scale

$M_s \sim 1$ TeV $\Rightarrow$ $R_c \sim g_s \times 10^{32}$ cm

$|\chi| \sim g_s \times 10^{16}$

- $\chi \sim \mathcal{O}(1) \Rightarrow g_s \sim 10^{-16}$

  $R_c \sim 10^{16}$ cm $\quad$ excluded

- $R_c \gtrsim 10^{28}$ cm $\Rightarrow$ $g_s \gtrsim 10^{-4}$; $|\chi| \gtrsim 10^{24}$!

IIA CY : need hypermultiplets

IIB CY and orbifolds : need vector multiplets

Open problems

localization of gauge fields:

e.g. put D3-branes where gravity is localized

Effective field theory: UV - IR correlation

appearance of ghosts Dubovsky-Rubakov '02

String theory realization:

consistent framework to address the problems

SUSY preserving $\Rightarrow$ stable

- gravity and matter source localization
- effective UV cutoff(s)
- gravity force among D-brane sources
- model building

Conclusions

Hierarchy problem $\Rightarrow$

- susy GUTs
- low string scale $\searrow$
- split susy $\nearrow$

D-brane models

Low scale strings $\Rightarrow$ large extra dimensions

- spectacular effects in accelerators
- gravity modification at short distances
- new framework of EW symmetry breaking

Split susy

fine-tuned low energy world

but new susy phenomenology

LHC will show the way