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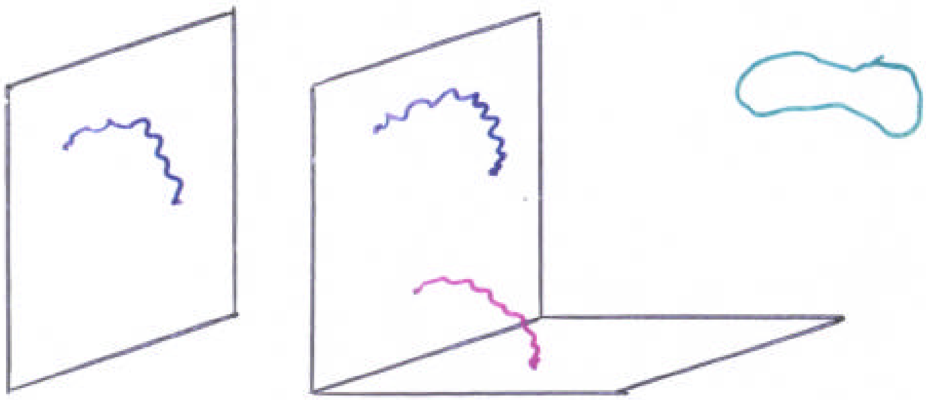
# D-brane models with large extra dimensions

OUTLINE

- Introduction : type I strings and D-branes
- Localization of matter : couplings + bounds
- Brane susy breaking : evading the NS tadpoles
  effective field theory
  submm forces
- U(1) masses

Type I strings provide a perturbative framework for model building with low string scale

- gravity : closed strings (bulk)
- gauge interactions : on D-branes



A particularly attractive possibility :

- bulk is susy
- brane susy breaking

Discrete choice :

(1) Standard Model on non-susy branes

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

I.A. - Arkani Hamed - Dimopoulos - Dvali

(2) SM on a susy brane $\Rightarrow$

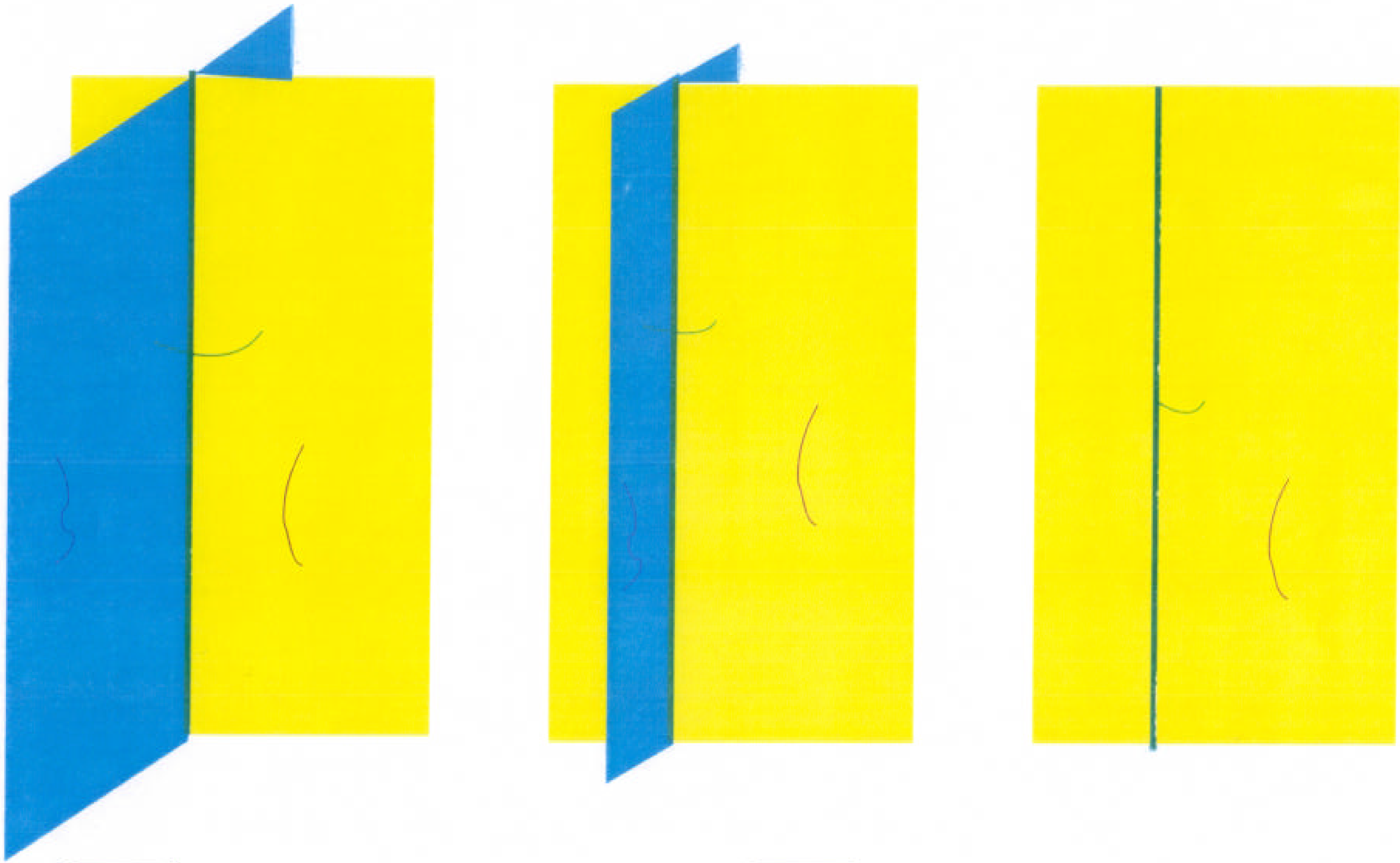
- replace hidden sector of susy by non susy branes $\Rightarrow M_{SUSY}\big|_{hidden} = M_s$
- mediation by gravitational interactions

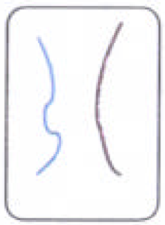
$$\Rightarrow M_{SUSY}\big|_{us} \sim M_s^2/M_P$$

$\Rightarrow M_s \sim 10^{11}$ GeV (intermediate scale)

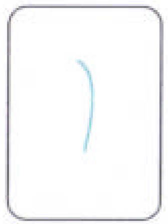
Benakli

Burgess - Ibanez - Quevedo



 live on // Dbranes

gauge and matter fields.

 live on Dbranes intersections

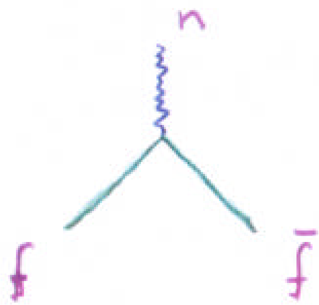
matter fields only.

# Couplings

(a) 


$$= g\,\delta_{n_1+n_2+n_3}$$ ← momentum conservation

Fourrier Tranform : $\int dy\, F^2_{\mu\nu}(x,y)$

(b) 


$$= g\,\delta^{-n^2 \frac{l_s^2}{R^2}} \xrightarrow[R>>l_s]{} g$$

$\delta > 1$

FT : $$e^{-\frac{y^2}{2 l_s^2 \ln\delta}} \xrightarrow[l_s\to 0]{} \delta(y)$$

⇒ Gaussian distribution of charge with width

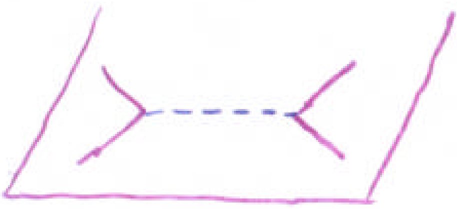
$$\sigma = \sqrt{\ln\delta}\; l_s$$ ← "brane thickness"

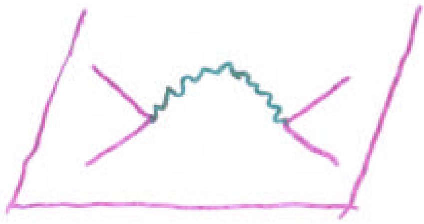
Exchange of massive string modes $\Rightarrow$

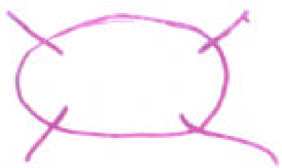
4-fermion effective operators

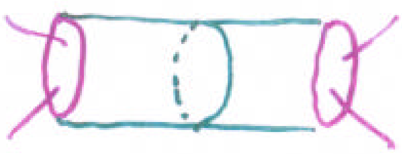
type I string theory : dominant compared to

virtual graviton emission









disk $\Rightarrow$ $g_s$ 1-loop $\Rightarrow$ $g_s^2$

$\Rightarrow$ loop factor enhancement

$\Rightarrow$ probe string physics

I. A. - Accomando - Benakli '99

Cullen - Perelstein - Peskin '00

Matter fermions : open strings ending

- on the same set of branes

$\Rightarrow$ dim-8 effective operators

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

Cullen-Perelstein-Peskin

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

- on different sets of branes

$\Rightarrow$ dim-6 eff. operators

$$-\frac{g^2}{M_I^2}(\bar\psi\gamma\psi)^2 \Rightarrow M_I \gtrsim 2\text{-}3 \text{ TeV}$$

I.A.-Benakli-Laugier '00

Brane susy breaking in

type I string theory

Stable configurations of antibranes

with branes or orientifolds

non-dynamical branes

with no localized degrees of freedom

and +ve or −ve tension

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

⇒ Interesting model building

Simplest model 10D $\mathrm{IIB}/\Omega$ Sugimoto

| | | | RR-charge | tension |
|---|---|---|---|---|
| * $\Omega = +1$ $\Rightarrow$ | 16 | $O_-9$ | $-$ | $-$ |
| | 16 | $D9$ | $+$ | $+$ |

open sector : antisymmetrization $\Rightarrow$ $SO(32)$ susy

| | | | | |
|---|---|---|---|---|
| * $\Omega = -1$ $\Rightarrow$ | 16 | $O_+9$ | $+$ | $+$ |
| | 16 | $\bar{D}9$ | $-$ | $+$ |

open sector: $\Omega$ symmetrizes bosons but

antisymmetrizes fermions

$\Rightarrow$ $Sp(32)$ with fermions in the antisym rep

brane susy breaking $\bar{D}O_+$

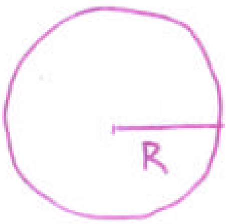
Evading the NS tadpoles:

introduce a small $\cancel{\text{susy}}$ in the bulk

by Scherk-Schwarz boundary conditions

I.A. - Benakli - Laugier

- S-S on $S^1/\mathbb{Z}_2$




$y \to -y \Rightarrow$


periodicity under $y \to y + 2\pi R$

bosons: periodic

$\mathbb{Z}_2$ even : $\phi_e(x^\mu, y) = \sum_n \phi_e^{(n)}(x^\mu) \cos \frac{n}{R} y$

$\mathbb{Z}_2$ odd : $\phi_o = \sum_n \phi_o^{(n)}(x^\mu) \sin \frac{n}{R} y$

fermions : antiperiodic

$\mathbb{Z}_2$-even : $\quad \psi_e = \sum_n \psi_e^{(n)}(x^\mu) \cos \frac{n+\frac{1}{2}}{R} y$

$\mathbb{Z}_2$-odd : $\quad \psi_o = \sum_n \psi_o^{(n)}(x^\mu) \sin \frac{n+\frac{1}{2}}{R} y$

susy parameter : antiperiodic

$$\delta \phi = \psi \eta$$

periodic $\qquad$ anti-periodic

- $y=0$ : $\eta_o = 0 \Rightarrow$ half of susy remains : $\eta_e$

- $y=\pi R$ : $\eta_e = 0 \Rightarrow$ " : $\eta_o$

No zero mode of $\eta \Rightarrow$

susy is broken globally

SS ⇒ ~~SUSY~~ : $\quad Q_e \qquad\qquad\qquad\qquad Q_o$

$0 \longmapsto\!\!\longrightarrow\!\!\dashv \pi R$

Orientifolds: $\quad O(-,-) \qquad\qquad\qquad \bar{O}(+,-)$

RR-charge $\quad$ tension

D-branes: $\quad D(+,+) \qquad\qquad\qquad \bar{D}(-,+)$

SUSY (linear) $\quad Q_e \qquad\qquad\qquad Q_o$

Non-linear $\quad Q_o \qquad\qquad\qquad Q_e$

Model I: · local charge conservation

· brane SUSY (locally) $\quad Q_e$

Model II: $\quad O\,\bar{D} \qquad\qquad\qquad \bar{O}\,D$

· brane SUSY breaking

but Non-linear SUSY $\quad Q_e$

· only global charge conservation

## Example with 8-branes

- bulk : $S^1/\mathbb{Z}_2$ with SS breaking

$$0 \longmapsto \pi R$$

$$O_- \qquad\qquad\qquad \bar{O}_-$$

RR charge: $-16$ $\qquad\qquad +16$

- Model I : $\left.\begin{array}{l} 16 \; D_8 \text{ on } O_- \\ 16 \; \bar{D}_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16) \times SO(16)$

"SUSY"

- Model II : $\left.\begin{array}{l} 16 \; \bar{D}_8 \text{ on } O_- \\ 16 \; D_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16) \times SO(16)$

with fermions in symmetric reps : $(136, 1) + (1, 136)$

$$136 = 135 + \underset{\substack{\uparrow \\ \text{Goldstino}}}{1}$$

Non-linear susy on the brane

$\Rightarrow$ massless Goldstino $\chi$

Sen, Dudas-Mourad, Pradisi-Riccioni

$$\mathcal{L}_{eff} = -\frac{1}{4V^4}\left(\chi \overleftrightarrow{\partial}_\mu \sigma^\nu \chi\right)\left(f \overleftrightarrow{\partial}_\nu \sigma^\mu f\right) + \frac{2C_f}{V^4}\left(f\partial^\mu \chi\right)\left(f\partial_\mu \chi\right)$$

fixed by susy

model dependent

Brignole-Feruglio-Zwirner

Matter fermions on the same set of branes $\Rightarrow$

- $\frac{V^4}{2} = \underset{\substack{\uparrow \\ \text{number of branes}}}{N} \cdot T \leftarrow$ tension $\qquad T_{3\text{-brane}} = \frac{M_s^4}{(2\pi)^2 g_s}$

- $C_f = \begin{cases} 1 & f, \chi \text{ : same internal helicity} \\ 0 & \quad " \qquad \text{different} \quad " \end{cases}$

I.A.-Benakli-Laugier

No SUSY in our world (brane)

but it may exist a mm away!

to protect the hierarchy against grav. corrections

Prediction: possible new forces at submm scales

e.g. light scalars:

$$\frac{(\text{TeV})^2}{M_p} \sim 10^{-4}\,\text{eV} = 1\ \text{mm}^{-1}$$

radion - modulus $\equiv \ln r$

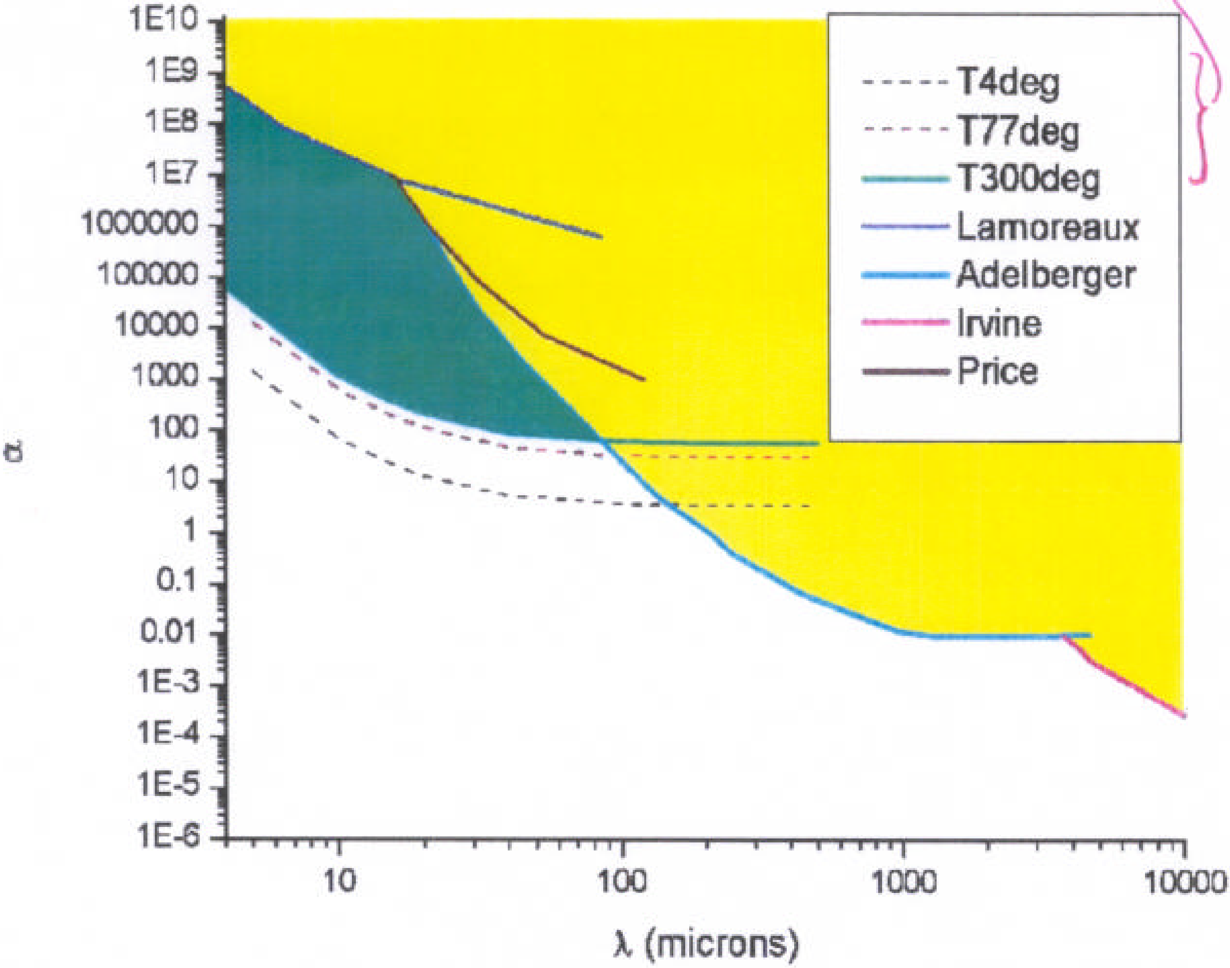
coupling to matter relative to gravity:

$$\frac{1}{m}\frac{\partial m}{\partial \ln r} = \sqrt{\frac{2n}{n+2}} \sim \mathcal{O}(1)$$

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

I.A. - Benakli - Maillard

Kapitulnik et al.



# U(1) masses in type I models

I.A. - Kiritsis - Rizos '02

4d U(1) anomalies ⇒ Green-Schwarz mechanism

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

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

cancel the anomaly

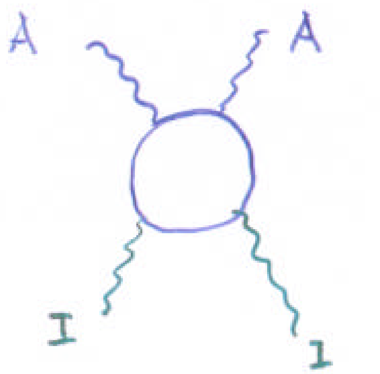
⇒ $U(1)_A$ mass : $M_A = g_A M$

a: Poincaré dual of a 2-form

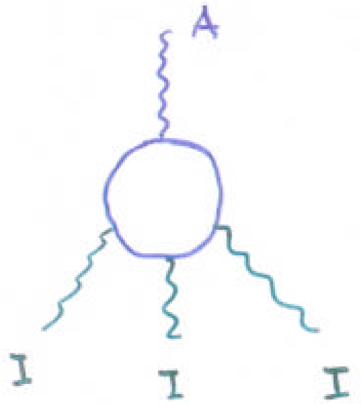
from RR closed string sector

$U(1)_A$ global symmetry remains (in perturbation)

6d $U(1)$ anomalies $\Rightarrow$ a $\begin{cases} \text{2-form } b \\ \text{axion dual to a 4-form} \end{cases}$




$\Rightarrow$ 2-form : $\quad b \wedge \mathrm{tr}\, F_I^2 + (db)^2$




$\Rightarrow$ 0-form : $\quad a\, \mathrm{tr}\, F^3 + (da + MA)^2$

- 2-form $\Rightarrow$ no $U(1)_A$ mass

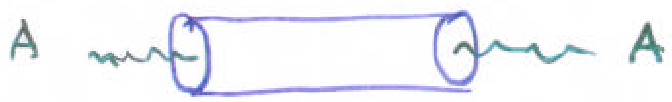
- 0-form $\Rightarrow$ $U(1)_A$ mass

Compactification to 4d $\Rightarrow$

- no anomaly but still $U(1)_A$ mass
- all $k_I$ must vanish

1-loop string computation in orientifolds

$\Rightarrow$ contact term from the annulus




- $N=4$ sectors $\to$ 0
- $N=2$ $\Rightarrow$ 6 d masses localized in 4 dims

  non vanishing $\longleftrightarrow$ 6d anomalies
- $N=1$ $\to$ 4d masses localized in 6 dims

$$M_A^2 = \frac{1}{\pi^3} \sum_{\substack{N=1 \\ \text{sectors } k}} (\mathrm{Tr}\, \gamma_k \lambda)^2 \, \mathrm{Str}_k \Big[ \underbrace{\tfrac{1}{12} - s^2}_{-\frac{3}{2} N_V + \frac{1}{2} N_C} \Big]_{\text{closed channel}}$$

4d helicity

$N=2$ sectors : $\mathrm{Str}[\ ]_{\text{closed}} \to V_2\, \mathrm{Str}[\ ]_{\text{open}}$

$\Rightarrow$ explicit realizations for

| $(A, a)$ | sectors | $m_A$ | $g_A$ |
|---|---|---|---|
| (brane, brane) | $N=1$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ |
| (bulk, brane) | $N=1$ | $1/\sqrt{V_A}$ | $1/\sqrt{V_A}$ |
| (brane, bulk) | $N=2$ | $1/\sqrt{V_a}$ | $\mathcal{O}(1)$ |
| (bulk, bulk) | $N=2$ | $\sqrt{V_a/V_A}$ | $1/\sqrt{V_A}$ |

(brane, bulk) : exp excluded

A light with $g_A \sim \mathcal{O}(1)$

(bulk, brane) : new sub mm forces

$$g_A \sim M_s/M_p \sim 10^{-16} \sim 10^{6} - 10^{8} \times \text{gravity} \leftarrow \frac{m_{proton}}{M_p}$$

supernova $\Rightarrow$ dim of bulk $\geq 4$

(bulk, bulk): large KK mass-shifts $\Rightarrow$ unobservable forces

· all cases : $M_A \lesssim g_s M_s$ up to $M_s^2/M_P$

$\Rightarrow$ new effects in accelerators

production of $U(1)_A$ + possible KK

· Model building : extra conditions for $U(1)_Y$

to remain massless

anomaly free in all 6d limits

e.g. part of non-abelian groups

· Brane ~~susy~~ models :

$D\bar{O}$ , $\bar{D}O$ : annulus is not affected

$\Rightarrow$ "susy" result remains

$D\bar{D}$ : extra contributions easy to compute

## Other properties

- Electroweak symmetry breaking

$$\mu^2 = - \varepsilon^2 g^2 M_s^2$$

calculable loop factor suppression

- B global symmetry

$\Rightarrow$ protect proton decay

- L global symmetry

$\Rightarrow$ no lepton number violation

  - R-neutrinos in the bulk

- alternatives of gauge couplings unification