Neutrino Mass

and

Extra Dimensions

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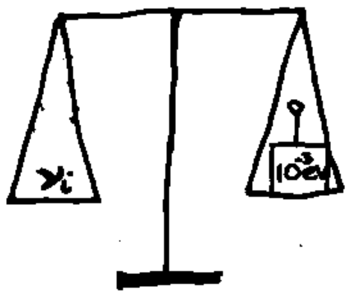
Introduction

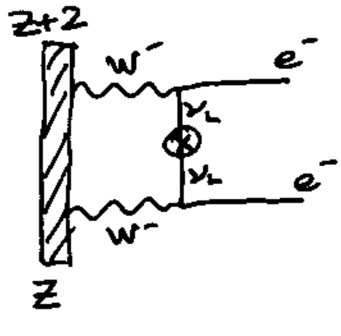
Neutrinos have mass:



But, are neutrinos Majorana or Dirac in nature?

<u>Experiment</u> Look for lepton number violation:

e.g. neutrinoless double β decay ($0\nu\beta\beta$)



<u>Theory</u> Seesaw mechanism is elegant and simple, but can also have natural Dirac mass!

① Majorana

At low energies (IR) lepton number is violated by an irrelevant op. (dim. 5) :

E<M $\qquad \mathcal{L} = \mathcal{L}_{SM} + \frac{\lambda_M}{M} \nu_L \nu_L H H$

$$\langle H \rangle \sim v \quad \Rightarrow \quad m_\nu = \lambda_M \frac{v^2}{M} = \lambda_M v \cdot \underbrace{\frac{v}{M}}_{\text{extra suppression}}$$

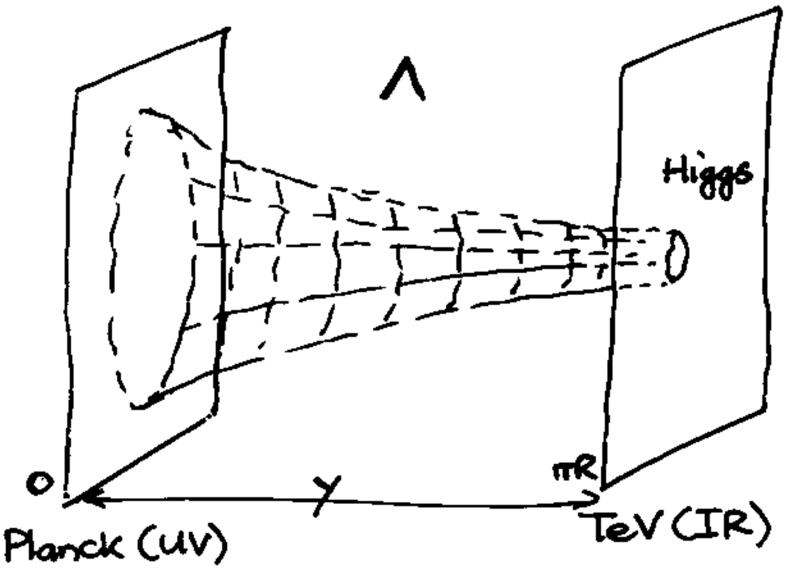
$\Rightarrow$ naturally small provided $M \gg v$

E=M $\quad$ Introduce RH neutrino ν_R with mass term

$$\mathcal{L} = M \nu_R \nu_R + h.c.$$

Seesaw mechanism $\quad (\nu_L \, \nu_R) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \Rightarrow \quad m_\nu = \frac{m^2}{M}, \quad \underbrace{M}_{\text{RH neutrin decouple fo } E<M}$

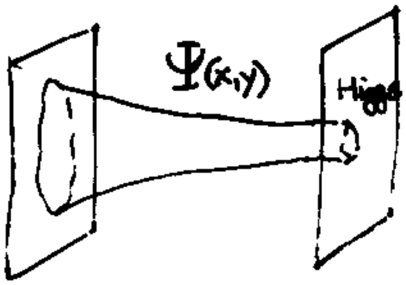
Warped Extra Dimensions [Randall, Sundrum (1999)]



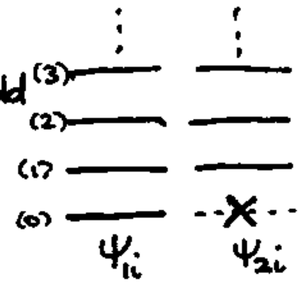
Metric: $$\boxed{ds^2 = \overbrace{e^{-2ky}}^{\text{warp factor}} dx^2 + dy^2} \rightarrow \text{slice of } AdS_5 \quad (\Lambda < 0)$$

where k = AdS curvature scale ($k \sim M_P$)

Fermions in the bulk [TG, Pomarol (2000)]



$$\Psi_i(x,y) = \begin{pmatrix} \psi_{1i} \\ \bar{\psi}_{2i} \end{pmatrix} \overset{\text{orbifold}}{\Longrightarrow}$$



$$S_{bulk} = -i \int d^4x\, dy \sqrt{-g} \left[\bar{\Psi}_i \Gamma^M D_M \Psi_i + \underbrace{c_i k\, \varepsilon(y) \bar{\Psi}_i \Psi_i}_{\text{bulk mass term}} \right]$$

Zero mode $\psi_{1i}^{(0)}(y) \sim \frac{1}{N_0} e^{(\frac{1}{2} - c_i)ky}$

Cases (i) $c_i > \frac{1}{2}$ ⇒ localised towards Planck brane

(ii) $c_i < \frac{1}{2}$ ⇒ " " TeV brane

② Dirac

Introduce RH neutrino that does <u>not</u> decouple

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda_D \nu_L \nu_R H$$

$$\langle H \rangle \sim v \quad \Rightarrow \quad m_\nu = \overbrace{\lambda_D v}^{\text{no suppression!}}$$

Requires: (i) $\Delta m_\nu^2 \sim 10^{-4} eV^2 \Rightarrow \lambda_D \sim 10^{-13}$!

(ii) No dim 3 relevant operator : $M \nu_R \nu_R$

$\longrightarrow$ Impose global lepton number symmetry

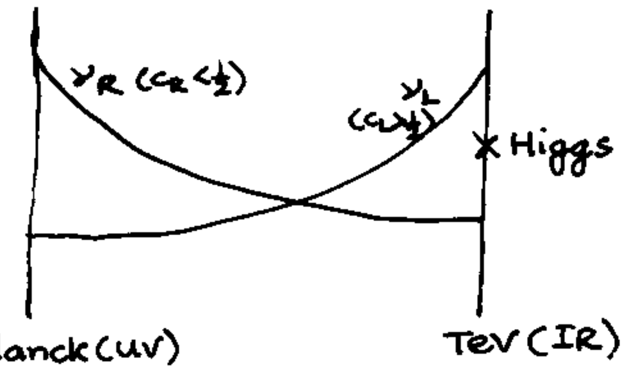
But, badly violated in the UV $\rightarrow$ quantum gravity

$\Rightarrow M = M_P$!

How can (i) and (ii) be natural ?

$\rightarrow$ use warped extra dimensions !

Dirac neutrino mass [Grossman, Neubert (2000)]

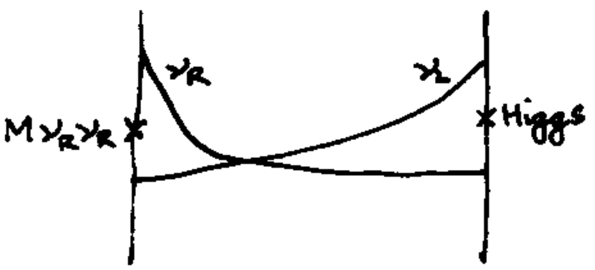


Tiny wavefunction overlap $\Rightarrow$ $\lambda_D \ll 1$!

But, at Planck brane expect global lepton number to be violated

$\Rightarrow$ neutrino no longer Dirac!

In fact [Huber, Shafi (2003)]



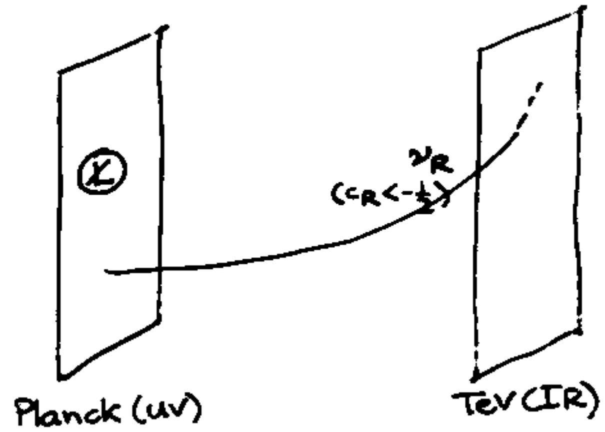
$\Rightarrow$ $m_\nu \sim \frac{v^2}{M}$, M

i.e. usual seesaw mechani:

But, can we still have a Dirac neutrino?

Yes!

Consider RH neutrino localised on TeV brane [T.G. (2004)]



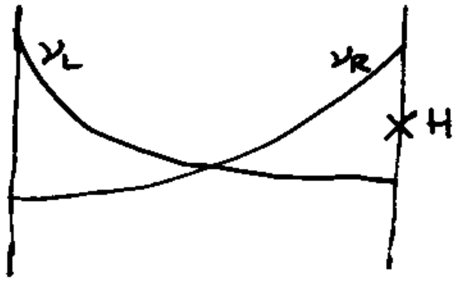
$$S_{total} = S_{bulk} + \int d^4x \int dy \; \underbrace{i \frac{b_M}{2} \delta(y) \left(\bar{\Psi}_R^c \Psi_R + h.c. \right)}_{\text{boundary Majorana mass}}$$

Majorana mass: $m_0 \sim \frac{b_M}{2} (1-2c_R) \, k e^{-(1-2c_R)\pi k R}$

$$\sim \frac{b_M}{2} \underbrace{\left(\frac{TeV}{M_P} \right)}_{\text{huge suppression for } c_R < -\frac{1}{2}}^{1-2c_R} \cdot M_P \longrightarrow 0 \quad \text{as } c_R \to -\infty$$

$\Longrightarrow$ RH neutrino does <u>not</u> decouple

But we still need to generate a mass:



Consider Yukawa interaction:

$$S_y = \int d^4x \int dy \underbrace{\lambda_5}_{\text{5D Yukawa coupling}} \nu_L(x,y)\, \nu_R(x,y)\, H(x)\, \delta(y-\pi R)$$

$$\Rightarrow \quad \lambda_4 \simeq \lambda_5 k \sqrt{(c_L-\tfrac{1}{2})(\tfrac{1}{2}-c_R)}\; e^{(\frac{1}{2}-c_L)\pi k R} \qquad (c_L > \tfrac{1}{2}, c_R <$$

$$\Rightarrow \quad \lambda_4 \simeq 10^{-13} \quad \text{for } c_L \sim 1{\cdot}36$$

Actually, to obtain realistic fermion mass spectrum $\Rightarrow$ delocalise Higgs

e.g. $c_H = 0{\cdot}5$; $c_L = 1{\cdot}32$; $c_{e_R} = 0{\cdot}2$; $c_{\nu_R} = -2$

or $c_H = 0{\cdot}11$; $c_L = 1{\cdot}32$; $c_{e_R} = 1$; $c_{\nu_R} \simeq -2{\cdot}5$

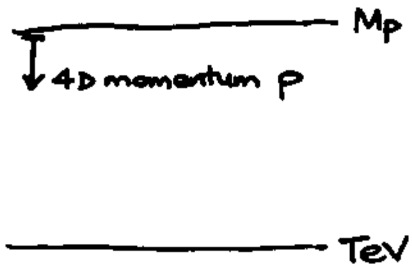
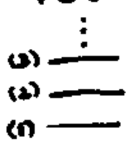
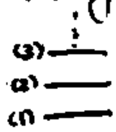
Thus, have

natural Dirac mass in presence of Planck scale lepton number violation!

Dual 4D interpretation

[Maldacena (1998)
Arkani Hamed, Porrati, Randall (2001)
Rattazzi, Zaffaroni (2001)]

Using AdS/CFT correspondence :

5D warped extra dimension	$\xleftrightarrow{\text{DUAL}}$	4D strongly coupled CFT at large N
	$\longleftrightarrow$	
UV bdy value of bulk field $\Phi(x, y=0) \equiv \Phi(x)$	$\longleftrightarrow$	source of CFT operators $\mathcal{O}$ $\mathcal{L} = \lambda\, \Phi(x)\, \mathcal{O}(x)$
Bulk mass m_Φ	$\longleftrightarrow$	dim $\mathcal{O}$
Kaluza-Klein tower 	$\longleftrightarrow$	Resonances of large N gauge theory 
Zero mode near Planck brane	$\longleftrightarrow$	elementary state added to CFT
Zero mode near TeV brane	$\longleftrightarrow$	bound state of CFT

Dual interpretation of Dirac neutrino [TG (2004)]

M_P — $\not{L}$ (lepton number violation)

$\downarrow$ 4d momentum p

CFT with <u>no</u> relevant ops.

TeV — Conformal symmetry spontaneously broken.

RH neutrino dual 4D Lagrangian:

$$\mathcal{L} = \mathcal{L}_{CFT} + \xi\, k^{\frac{1}{2}+c_R}\, \underbrace{\bar{\Psi}_R}_{\text{elem. field}}\, \overbrace{\mathcal{O}_R}^{\text{CFT op.}} + \text{h.c.} \qquad (c_R < -\tfrac{1}{2})$$

where $\dim \mathcal{O}_R = \frac{3}{2} + |c_R - \frac{1}{2}|$

In limit $c_R \to -\infty$, mixing term $\to 0$ (irrelevant

$\Rightarrow$ RH neutrino is a CFT bound state of size TeV^{-1} !

$\xleftrightarrow{\text{TeV}^{-1}}$

$= \nu_R$!

Also: Arkani-H[amed], Grossman (1998)

$\longrightarrow$ Not sensitive to UV violation of lepton number

$$\nu_R = \psi^{(0)}_{\mathcal{O}_R} - b_M \overbrace{\left(\frac{\mu}{M_P}\right)^{1/2 - c_R}}^{\text{Decouples as } c_R \to -\infty} \Psi_R$$

$$\Rightarrow \mathcal{L}_{Majorana} \simeq \underbrace{b_M \cdot k \left(\frac{\mu}{k}\right)^{\frac{1}{2}-c_R}}_{} \nu_R \nu_R$$

Dimension 3 mass term becomes highly irrelevant in IR!

LH neutrino dual 4D Lagrangian :

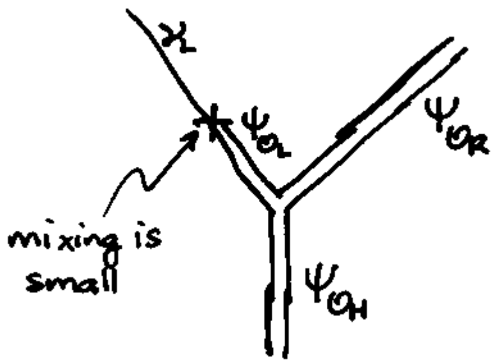
$$\mathcal{L} = \mathcal{L}_{CFT} + i\bar{\Psi}_L \bar{\sigma}\cdot\partial\Psi_L + \xi\, k^{\frac{1}{2}-c_L} \underbrace{\bar{\Psi}_L}_{\text{elem. field}} \overbrace{\mathcal{O}_L}^{\text{CFT op.}} + \text{h.c.} \qquad (c_L >$$

where $\dim \mathcal{O}_L = \frac{3}{2} + |c_L + \frac{1}{2}|$

In limit $c_L \to +\infty$, mixing term $\to 0$

$\Rightarrow$ LH neutrino is an elementary state

Dirac mass:



$$\mathcal{L}_{Yukawa} = \left(\frac{\mu}{k}\right)^{c_L-\frac{1}{2}} \nu_L \nu_R H +$$

$\Rightarrow$ tiny Yukawa coupling

Conclusion

Composite
RH neutrino, ν_R
at TeV scale

Planck scale
lepton number
violation

$\boxed{\text{Natural Dirac mass}}$

Open questions

- Dirac leptogenesis
  - → "Neutrinogenesis" Dirk, Lindner, Ratz, Wright (2000)
- How does compositeness affect early universe cosmology?