Warped Leptogenesis with Dirac Neutrino Masses

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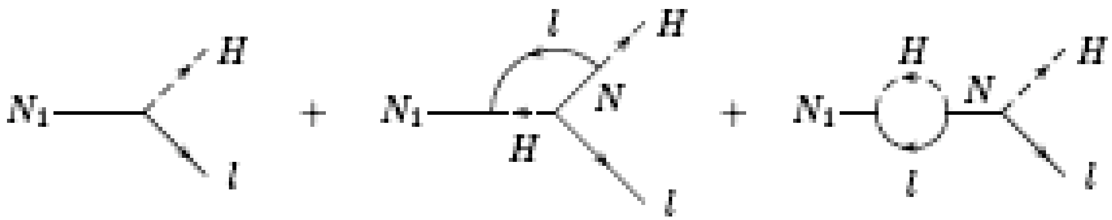
Outline

- Introduction
- Dirac neutrino masses with lepton number violation
- Warped leptogenesis
- Conclusion

Introduction

Leptogenesis [Fukugita, Yanagida 86]

Majorana neutrino decay ➡ Lepton asymmetry



$$\epsilon = \frac{\Gamma(N_1 \to lH^\dagger) - \Gamma(N_1 \to l^c H)}{\Gamma(N_1 \to lH^\dagger) + \Gamma(N_1 \to l^c H)} \simeq \delta_{eff} \frac{|\lambda_2|^2}{8\pi} \frac{M_1}{M_2}$$

where $\delta_{eff} = \frac{\mathrm{Im}(\lambda_1^* \lambda_2)^2}{|\lambda_1|^2 |\lambda_2|^2}$ $\quad M_1 \ll M_2$

Usual values: $M_1 \sim 10^{10}\mathrm{GeV}$ $\quad \epsilon \sim 10^{-8}$ $\quad g_* \sim 10^2$

$$\Rightarrow \quad Y_B \simeq -\frac{1}{3} Y_L \simeq \frac{\epsilon}{g_*} \sim 10^{-10}$$

Alternative scenario:

Approximately degenerate Majorana masses $M_{2,1} = M \pm \delta m$ $\delta m \ll M$

$$\epsilon \simeq \frac{\delta_{eff}}{32\pi} \frac{|\lambda_2|^2}{(\delta m/M)} \simeq 10^{-8}$$

$$\Gamma_{1,2} \ll M_2 - M_1$$

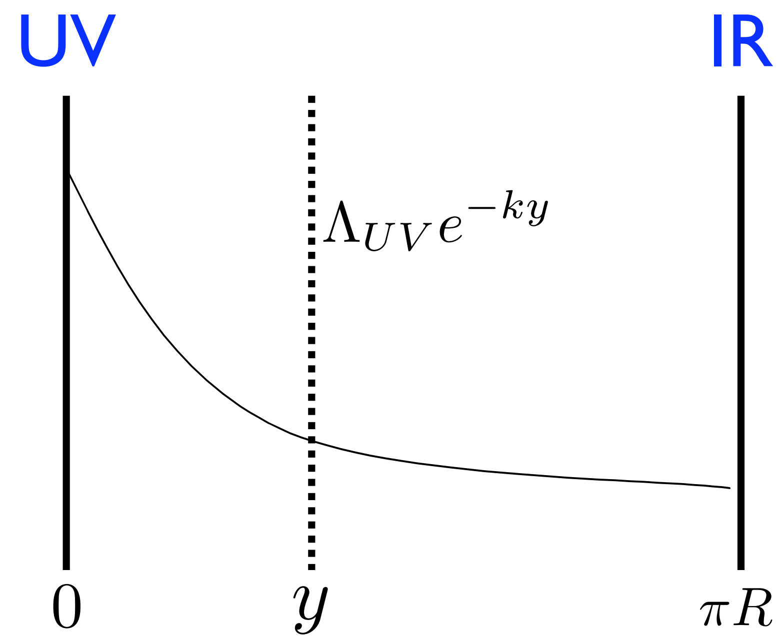
[$\Gamma \sim \Delta M$ in Pilaftsis 99; Pilaftsis, Underwood 03]

Values: $|\lambda_2| \sim 10^{-7}$ $\delta m/M \sim 10^{-9}$ $\delta_{eff} \sim 0.1$

$$\Rightarrow \quad Y_B \simeq -\frac{1}{3} Y_L \simeq \frac{\epsilon}{g_*} \sim 10^{-10}$$

How can this be achieved?

Warped Extra Dimension ➡ Explain hierarchies



"Slice of AdS_5"

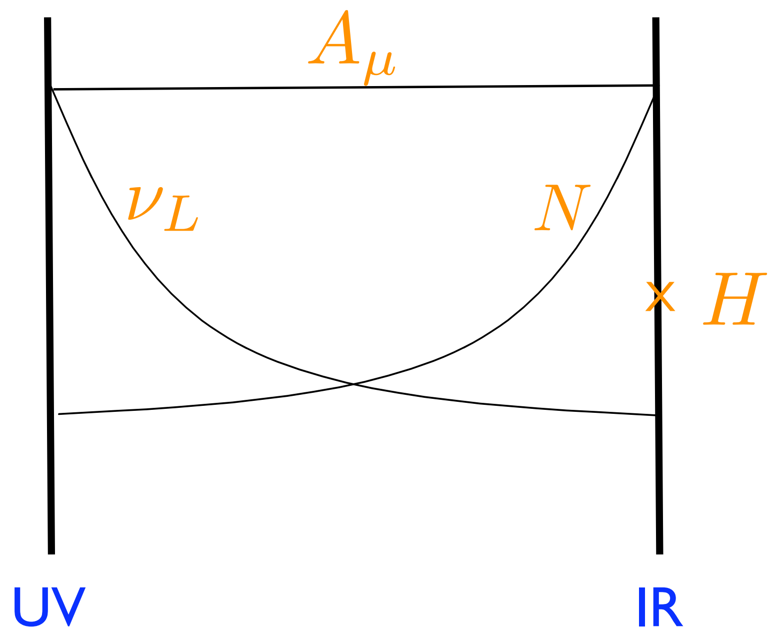
[Randall,Sundrum 99]

k=AdS curvature scale

5D metric : $$ds^2 = e^{-2ky} dx^2 + dy^2$$

Neutrino mass hierarchy

[Grossman, Neubert 99; TG 03]

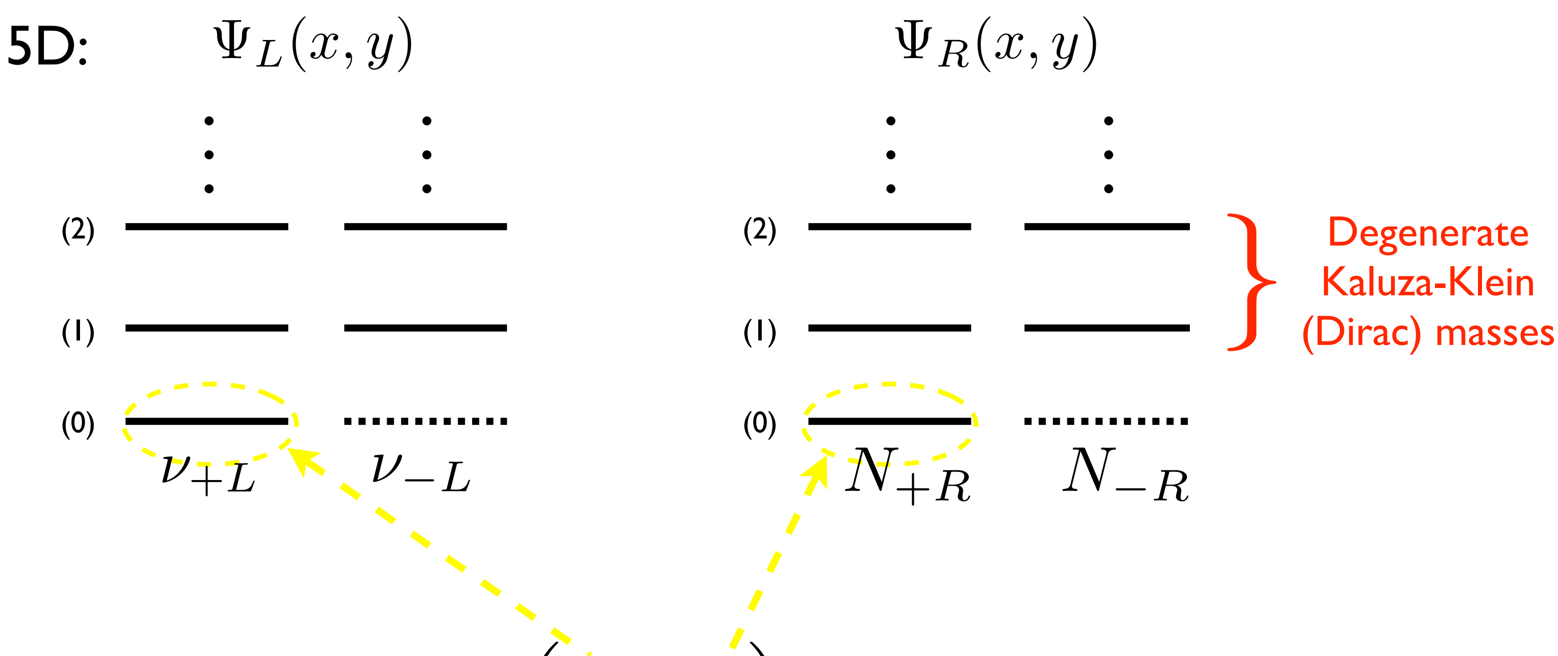


$$\psi^{(0)} \sim e^{(\frac{1}{2}-c)ky}$$

c = bulk mass parameter

$$S_\Psi = \int d^4x dz \sqrt{-g} \left(\bar{\Psi} e^M_A \gamma^A D_M \Psi + \underbrace{M_\Psi}_{c\,k sgn(z)} \bar{\Psi}\Psi \right)$$

Embed 4D fermions into 5D:



4D: $\psi_\nu(x) = \begin{pmatrix} \nu_{+L} \\ N_{+R} \end{pmatrix}$

Neutrino mass spectrum

$$\frac{1}{2}(N_+^{(0)}, N_+^{(1)}, N_-^{(1)}, \dots)\begin{pmatrix} 0 & 0 & 0 & \dots \\ 0 & 0 & D_1 & \dots \\ 0 & D_1 & 0 & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix}\begin{pmatrix} N_+^{(0)} \\ N_+^{(1)} \\ N_-^{(1)} \\ \vdots \end{pmatrix}$$

⇒ $$0, \pm D_1, \pm D_2, \dots$$

↑ Becomes massive Dirac neutrino after EWSB

Kaluza-Klein Dirac mass:

$$D_n \simeq \left(n + |c_R + \frac{1}{2}| - \frac{3}{4}\right) \underbrace{\pi k e^{-\pi k R}}_{\text{TeV}}$$

5D Yukawa interaction

$$\int d^4x\, dy \sqrt{-g}\, Y_\nu^{5D} \bar{\Psi}_L(x,y)\Psi_R(x,y)H(x,y)$$

$\rightarrow H^{(0)}(y) \sim e^{bky}$ b=Higgs bulk mass parameter

4D Yukawa couplings:

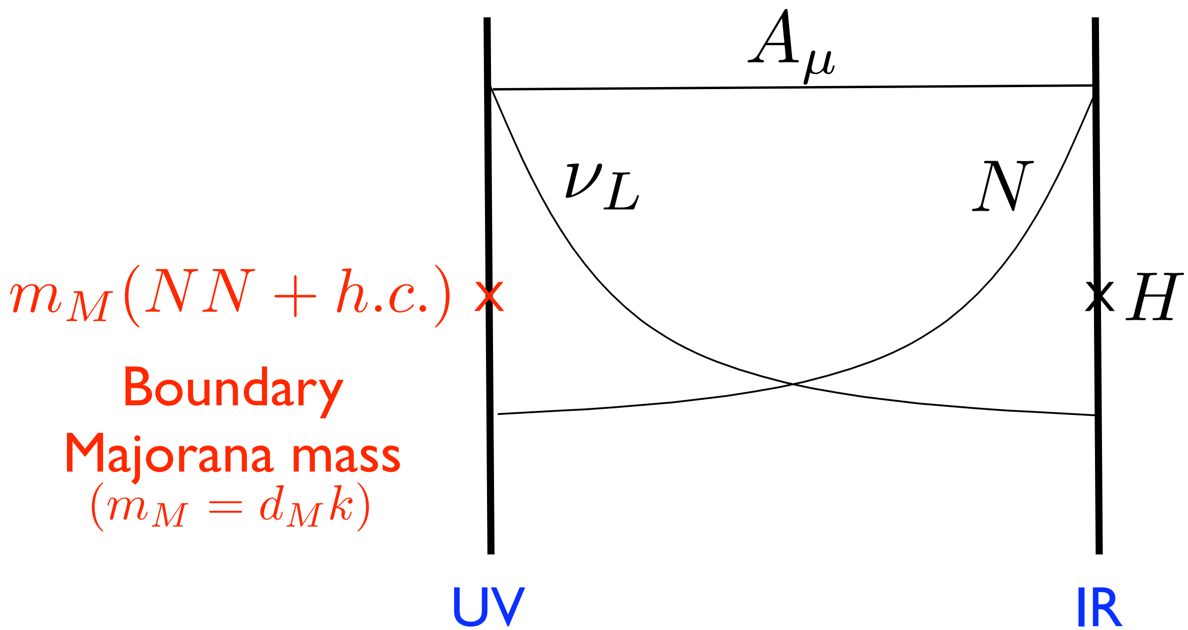
$$Y_\nu \simeq (Y_\nu^{5D}\sqrt{k}) \frac{\sqrt{(c_L - \frac{1}{2})(\frac{1}{2} - c_R)(b-1)}}{(b - c_L - c_R)} e^{(\frac{1}{2} - c_L)\pi k R}$$

dimensionless parameter ***O(1)***

[For $b > 1, c_L > 1/2, c_R < 1/2, b > c_L + c_R$]

For $1.3 \leq c_L \leq 1.6$ obtain $10^{-5}\,\mathrm{eV} \leq m_\nu \leq 0.25\,\mathrm{eV}$

Add lepton number violation [TG 03]



➡ Introduces tiny mass splitting in Dirac states

Neutrino mass spectrum with UV Majorana mass:

$$\frac{1}{2}(N_+^{(0)}, N_+^{(1)}, N_-^{(1)}, \dots) \begin{pmatrix} A_{00} & A_{01} & 0 & \dots \\ A_{01} & A_{11} & D_1 & \dots \\ 0 & D_1 & 0 & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix} \begin{pmatrix} N_+^{(0)} \\ N_+^{(1)} \\ N_-^{(1)} \\ \vdots \end{pmatrix}$$

with $A_{nm} = \frac{d_M}{2\pi R} f_{N+}^{(m)}(0) f_{N+}^{(n)}(0)$

Obtain $m_0 \sim \frac{d_M}{2}(1-2c_R)ke^{-(1-2c_R)\pi kR}$ $\quad (c_R \leq -1/2)$

➡ Neutrinos are still predominantly Dirac

Kaluza-Klein mass: $\frac{\delta m_n}{D_n} \sim d_M e^{-2(c_R+1)\pi kR}$ $\quad (c_R \leq -1/2)$

➡ Tiny mass splitting in Kaluza-Klein states!

Model predictions

Inputs $\pi k R = 34.5$ ➡ $k e^{-\pi k R} \sim \text{TeV}$

$$d_M \sim 0.1 \quad Y_\nu^{5D}\sqrt{k} \sim 0.1$$

Bulk masses: $(c_N, c_L, c_{eR}, b) = (-0.8, 1.75, 1.2, 1.39)$

Output

$Y_B \sim 10^{-10}$ Baryon asymmetry

$\lambda_e \sim 10^{-6}$ electron Yukawa coupling

$\lambda_{\nu_e} \sim 10^{-19}$ electron neutrino Yukawa coupling $m_{\nu_e} \sim 10^{-8}\,\text{eV}$ $(\Delta m_M \sim 10^{-11}\,\text{eV})$

$\lambda_{1,2} \sim 10^{-7}$ massive Kaluza-Klein coupling

$\frac{\delta m}{M_{1,2}} \sim 10^{-9}$ Kaluza-Klein mass splitting

Sakharov conditions

L violation UV Majorana mass term

CP violation $\lambda_1^{(1)}, \lambda_2^{(1)}$ have different phases [Pilaftsis 99]

Out of equilibrium decay

$$\Gamma \leq H \quad \Rightarrow \quad \lambda_{1,2} \leq \sqrt{8\pi\sqrt{g_*}\frac{M_{2,1}}{M_P}} \simeq 3 \times 10^{-7}$$

$\lambda_{1,2} \geq 10^{-8}$ for $T_D \geq 10^2\,\mathrm{GeV}$

4D Dual Interpretation: AdS/CFT correspondence

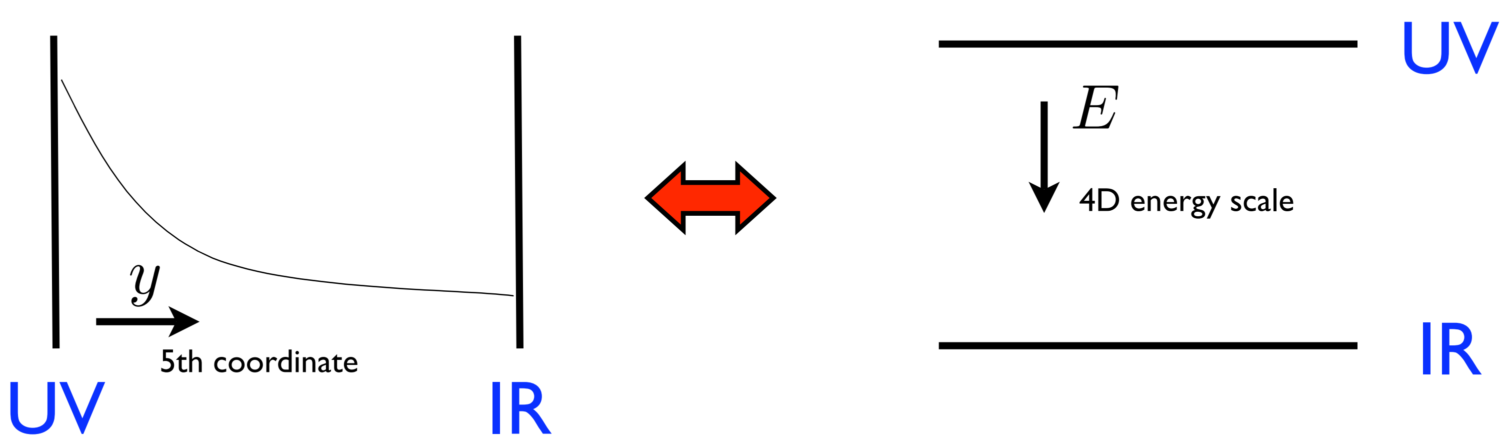
[Maldacena, 97 ;Gubser, Klebanov, Polyakov, 98; Witten 98]

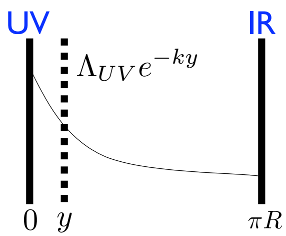
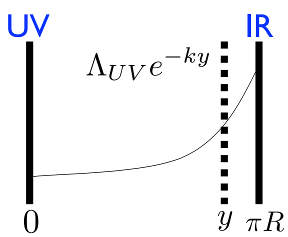
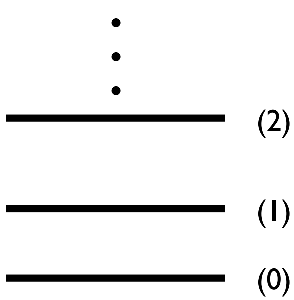
Type IIB string theory on AdS5 x S5	⟷ DUAL	$\mathcal{N}$=4 SYM in 4D

AdS/CFT dictionary

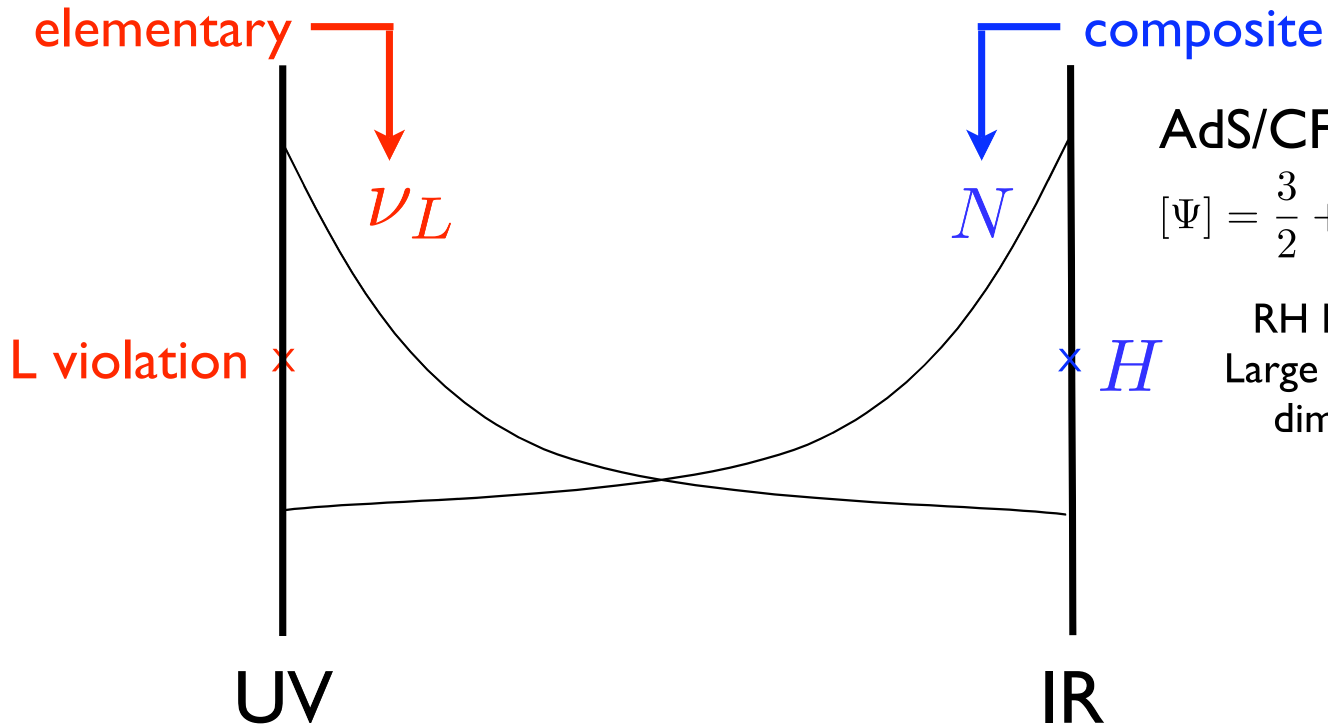
[Arkani-Hamed, Randall, Porrati 00; Rattazzi, Zaffaroni 00]

5D AdS ⟺ Large N, strongly coupled 4D CFT



Boundary value of bulk field $\text{e.g }\Phi(x,z)\Big\vert_{UV} = \phi(x)$	Source of CFT operator O $\mathcal{L} = \phi(x)\mathcal{O}$
Bulk masses $\text{e.g. } m_\Phi^2$	dimension of O $\text{e.g. } \dim \mathcal{O} = 2 + \sqrt{4 + m_\Phi^2/k^2}$
 UV localized field	elementary "source" state
 IR localized field	CFT bound state
Kaluza-Klein tower 	Tower of resonances $\sum_{n=0}^{\infty} \frac{d_n^2}{p^2 + m_n^2}$

Warped leptogenesis



AdS/CFT:

$$[\Psi] = \frac{3}{2} + \gamma_\Psi \leftrightarrow ck\bar{\Psi}\Psi$$

RH Neutrino:
Large anomalous dimensions

Elementary sector: Lepton number violated

→ L violation by irrelevant operators →

CFT sector: Preserves global lepton number

Conclusion

- Neutrino Dirac mass hierarchy is natural in a warped extra dimension
- Lepton number violation leads to tiny mass splittings
- Leptogenesis can occur at the TeV scale!