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Neutrinos as Probes of Extra Dimensions

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(NuFact'00 - Monterey, CA, May '00)

Introduction

Conventional view:

- neutrinos probe short-distance physics at scale $M \lesssim M_{GUT} \sim 10^{16}$ GeV
- RHD neutrino = SM singlet, not protected from acquiring large mass

  $$\Rightarrow \quad m_\nu \sim \frac{v^2}{M} \qquad \text{(see-saw)}$$
- probe New Physics but in an indirect way (via coefficients of higher-dim. operators)

  ⇒ learn about scale of New Physics, but not its nature

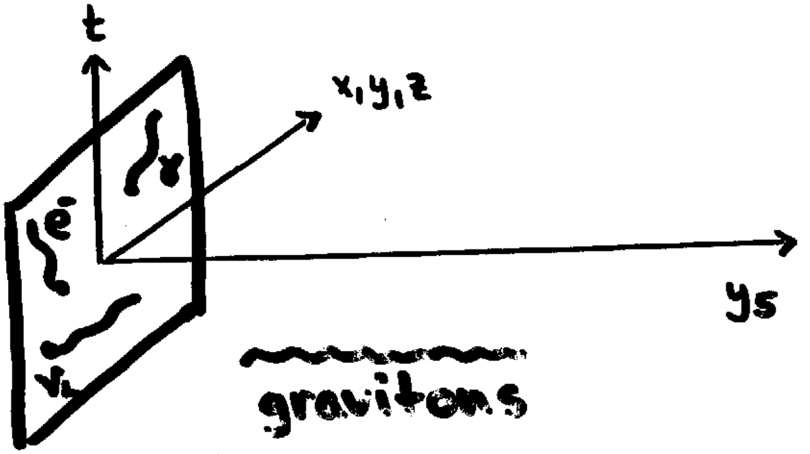
Neutrino physics in extra dimension models can be quite different from conventional picture:

- * natural to have (infinitely) many sterile neutrinos
- * natural to have light Dirac neutrinos without see-saw
- * natural to have mixing matrix without hierarchy (unlike CKM)
- * natural to have different numbers of LHD and RHD neutrinos

etc.

Large extra dimensions

A^2DD: extra spatial dimensions could be macroscopic ($\lesssim 1$ mm) if all SM fields were confined to a 4D slice ("brane") of a higher-dim. space ("bulk")



"brane world"

← usually compact (S^1, S^1/Z_2 ...)

- all particles carrying SM charges are confined to brane
- gravity lives in bulk

⇒ weakness of gravity is consequence of volume suppression

RHD neutrinos

⇒ Planck scale is derived, effective 4D parameter:

$$M_P^2 = M_*^{2+n}\, V_n$$

compact volume

fundamental
scale of gravity

⇒ modification of Newton's law at scales $< R_n$

$R_n \lesssim 1\,\text{mm}$ possible

- want $M_* \sim$ TeV to eliminate hierarchy problem (gravity ~ weak scale)

$n = 1$ excluded

$n = 2$: $R_n \sim 1\,\text{mm}$!

$n > 2$: can have some R_n large

- sterile particle (SM singlet) is not confined to brane and thus lives in bulk:

RHD neutrino $\Leftrightarrow$ bulk fermion

(Arkani-Hamed et al.)
(Dienes et al.)

- consequences:
  - coupling to SM neutrino is suppressed by same volume factor as gravit. coupling:

$$\Rightarrow \quad m_\nu^D \sim v \cdot \frac{M_*}{M_P} \quad \text{like see-saw}$$

  - bulk fermion has Kaluza-Klein excitations with spacings

$$\Delta m \sim \frac{1}{R_n} \gtrsim 10^{-3}\,\text{eV}$$

↳ mixing with SM neutrinos !

  - bulk neutrino more like graviton than like a SM fermion

Concrete model: (Dvali, Smirnov)

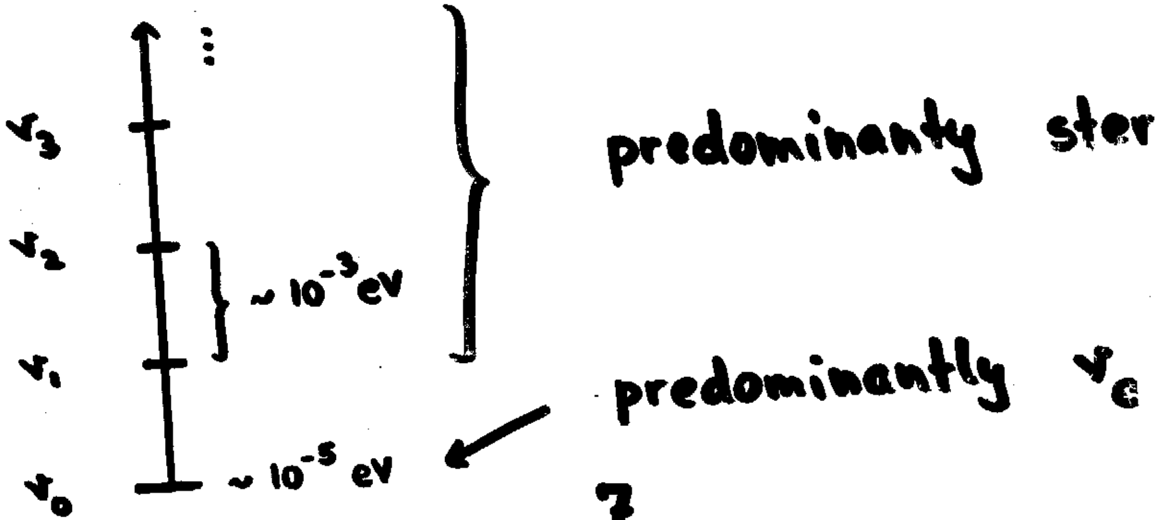
- assume $M_* \sim 1\,\text{TeV}$ and $n \geq 2$ but one dimension (size R) much larger than others

- coupling of bulk states to SM neutrino gives Dirac mass term:

$$m_D = \underset{\substack{\uparrow \\ O(1)\text{ Yukawa coupling}}}{h}\; v\, \frac{M_*}{M_P} \sim h \cdot 6 \cdot 10^{-5}\,\text{eV}$$

- KK Dirac masses: $m_n = \frac{n}{R} \gg m_D$

$\Rightarrow$ diagonalize mass matrix



$$\Rightarrow \quad \nu_e \sim \nu_0 + \xi \sum_{n \geq 1} \frac{1}{n} \nu_n$$

coherent superposition of mass eigenstates with increasing mass and decreasing mixing, where

$$\xi = \sqrt{2}\, \frac{m_D}{m_1} \ll 1$$

* explain solar neutrinos in terms of $\nu_e \to \nu_s$ where ν_s is (predominantly) the first excited bulk mode:

$$\Delta m^2 = \frac{1}{R^2} \sim (4-10) \cdot 10^{-6}\ \mathrm{eV}^2$$

$$\Rightarrow \quad R \sim (0.06 - 0.1)\ \mathrm{mm} \quad !$$

$$\sin^2 2\Theta = 4\xi^2 \sim (0.7 - 1.5) \cdot 10^{-3}$$

⇒ requires small mixing angle solution !

* resonance conversion in sun (MSW):

$E_1^R \sim 0.4 - 0.8$ MeV

$E_2^R \sim 1.6 - 3.2$ MeV

$E_3^R \sim 3.6 - 7.2$ MeV

$\vdots$

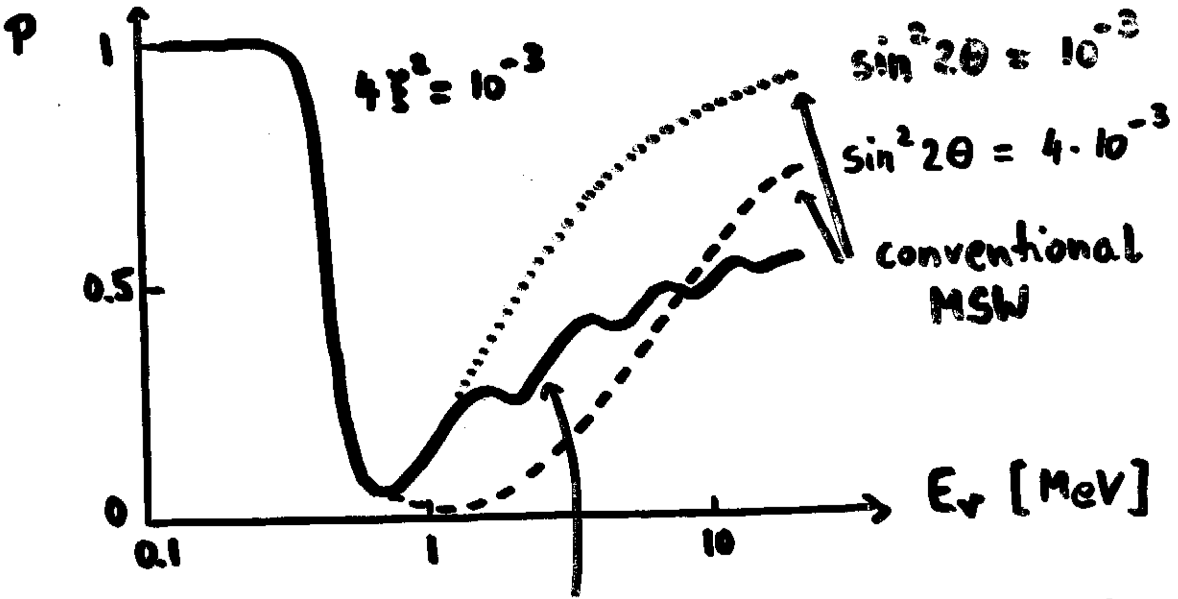
$E_n^R = n^2 E_1^R$

$E_{pp} < 0.42$ MeV

$E_{Be} = 0.86$ MeV

$\vdots$

⇒ characteristic modulation of survival probability as function of E_ν



conversion into bulk states

* Limitations:

- difficult to explain more than one neutrino anomaly at same time

(Mohapatra et al.)

- constraints from universality
  ⇒ how severe ?

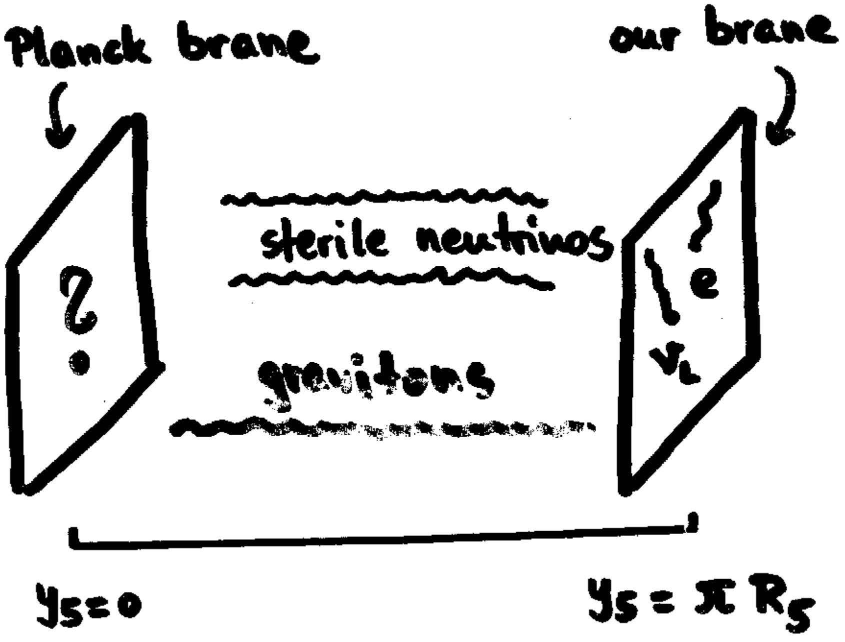
(Das, Kong)

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$$

Warped extra dimensions

RS: extra dimension of few × Planck size (small), but non-factorizable geometry

$$ds^2 = e^{-2ky_5}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - dy_5^2$$



S^1/Z_2 compactification of 5th dim.

- hierarchy explained by induced metric on our brane: $g_{\mu\nu} \sim e^{-k\pi R_5} = \dfrac{v}{M_{Pl}} \sim 10^{-1}$

  if $kR_5 \sim 12$
  $\uparrow$ curvature

⇒ no volume suppression for gravitons, so $M_* \sim M_p$ fundamental gravity scale

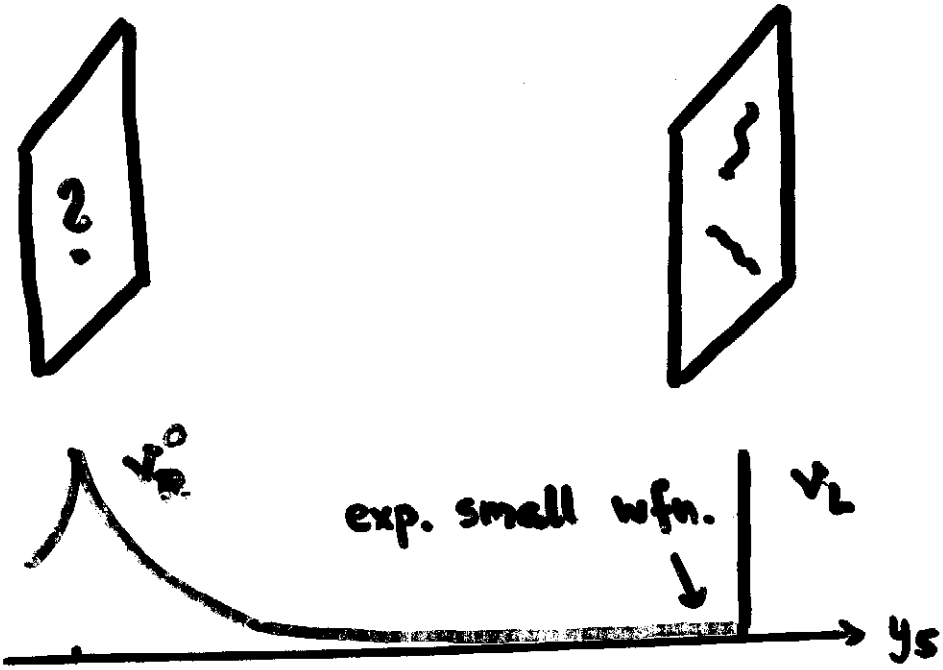
$$\Downarrow$$

How to get small neutrino masses ?

(Grossman + MN)

* RS branes = domain walls and can support fermion zero modes

Z_2 symmetry:
- no LHD zero mode
- RHD zero mode localized on Planck brane !



Consequences:

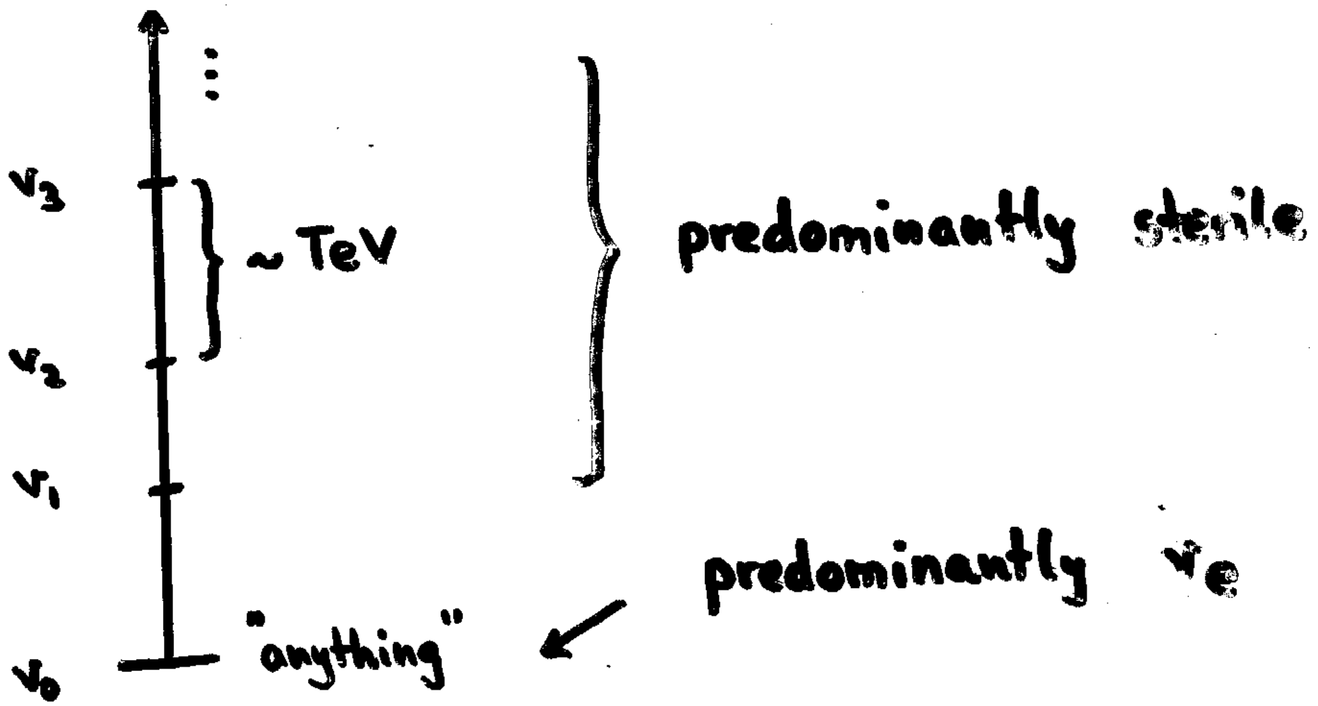
* lightest state gets Dirac mass

$$m_\nu \sim v \left(\frac{v}{M_P}\right)^{\underbrace{\frac{m_5}{k}-\frac{1}{2}}_{\text{parameter !}}}$$

⇒ generalized see-saw relation

⇒ get $m_\nu \sim 10^{-5} - 10$ eV for $\frac{m_5}{k} \sim 1.1 - 1.5$

* infinite tower of massive neutrinos with level spacing $\Delta m \sim$ TeV



Minimal model: (Grossman + MN)

- 2 bulk fermions → 2 RHD zero modes
- yields:

$$\left.\begin{array}{l} m_{\nu_1} = 0 \\ m_{\nu_2} \text{ superlight} \end{array}\right\} \Delta m^2_{12} \sim v^2 \left(\frac{v}{M_P}\right)^{2\frac{m_1}{k}-1}$$

$$\left.\begin{array}{l} m_{\nu_2} \text{ superlight} \\ m_{\nu_3} \text{ light} \end{array}\right\} \Delta m^2_{23} \sim v^2 \left(\frac{v}{M_P}\right)^{2\frac{m_2}{k}-1}$$

⇒ naturally large hierarchy !

mixing matrix: no small parameter

⇒ no hierarchy (unlike CKM) !

- prefers LMA solar solution
- likes large atmospheric mixing
- naturally predicts large (max.! $\cancel{CP}$

⟿ great scenario for ν factory !

Further predictions:

$$\nu_e = \cos\theta_e \underset{\substack{\uparrow \\ \text{light state}}}{\nu_0} + \overset{\text{TeV-scale states}}{\swarrow} \dots$$

* invisible Z^0 width:

$$3 - N_\nu^{\text{eff}} = \sin^2\theta_e + \sin^2\theta_\mu + \sin^2\theta_\tau$$

$$= 0.015 \pm 0.008$$

$$\Rightarrow \quad |\theta_i| \lesssim 0.1$$

* universality:

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \underset{\substack{\text{SM} \\ \downarrow}}{} 1.233 \cdot 10^{-4} \; \frac{\cos^2\theta_e}{\cos^2\theta_\mu}$$

$$= (1.230 \pm 0.004) \cdot 10^{-4}$$

$\Rightarrow$ similar bound

- theory:

$|\theta_i| \sim 0.1$ natural, but cannot be much smaller

$\Downarrow$

expect to see deviations at level not much below current sensitivity !

Conclusions

- extra dimension models are full of surprises → shows our ignorance about physics beyond weak scale

- neutrino physics in extra dim. models can be very different from conventional lore

  RHD neutrino probes bulk geometry

- models make predictions that can be tested at ν factory and other collider experiments

⇓

go explore the "brane world" ...