Neutrino Masses from Little Seesaws

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Based on: H.D., R. Kitano, G. Kribs, and H. Murayama, hep-ph/0502176.

H.D. and P. Huber, hep-ph/0504265.

Weak Interactions and Neutrinos 2005

The Standard Model:

- Effective field theory, cutoff scale Λ.

- Global symmetries broken at Λ.

- Protect $(B, L) \Rightarrow$ Large Λ:

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- Protect $(B, L) \Rightarrow$ Large Λ:

★ $\tau_p \gtrsim 10^{33}$ *years* $\rightarrow \Lambda \gtrsim 10^{16}$ *GeV* $(\not{B})$.

★ $m_\nu \lesssim 0.1$ *eV* $\rightarrow \Lambda \gtrsim 10^{14}$ *GeV* $(\not{L})$.

- QFT, SM probed up to $\sqrt{s} \lesssim 1$ TeV.

$\Lambda \gtrsim 1$ *TeV: Avoid big extrapolation, may resolve hierarchy.*

Arkani-Hamed, Dimopoulos, Dvali (1998)
Randall, Sundrum (1999)

- Lowering Λ:

$(B, L) \Rightarrow$ *Gauged (anomaly free) symmetries.*

Protecting $(B,\, L)$

- Quarks: Z_A^q ; Leptons: Z_B^ℓ.

H.D., R. Kitano, G. Kribs, H. Murayama, hep-ph/0502176.

Higgs uncharged under $Z_A^q \times Z_B^\ell$ (IR symmetries).

- Anomaly cancellation:

$9a = 0$, mod A $SU(2)$

$3b = 0$, mod B $SU(2)$, gravity

	Q	u^c	d^c	L	e^c
Z_A^q	a	$-a$	$-a$	0	0
Z_B^ℓ	0	0	0	b	$-b$

Choose (a, b) = (1, 1); $Z_9^q \times Z_3^\ell$.

Protecting (B, L)

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Choose (a, b) = (1, 1); $Z^q_9 \times Z^\ell_3$.

$\not{B}$, $\not{L}$: $\quad O \sim Q^9 L^3/\Lambda^{14}$

Multi-nucleon $\tau > \tau_p \Rightarrow \Lambda \gtrsim 200$ *GeV.* *Safe!*

Majorana Neutrinos

★ $m_\nu \, \nu_L \nu_L \quad \rightarrow \not{Z}_3^\ell$ *spontaneously.*

★ Scalar χ , $Z_3^\ell(\chi) = +1$, $\langle\chi\rangle \neq 0$:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + c\,\chi(LH)^2/\Lambda^2 + \ldots, \qquad (c \sim 1)$$

$$\langle H \rangle = v \rightarrow y_\chi \, \chi \, \nu \, \nu \quad ; \quad y_\chi \equiv c(v/\Lambda)^2.$$

★ Important Constraint: $0\nu\beta\beta \oplus \chi \rightarrow y_\chi < 3 \times 10^{-5} \Rightarrow \Lambda > 30$ TeV.

PDG 2004

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PDG 2004

$$m_\nu = y_\chi \langle\chi\rangle = c\,(0.06 \text{ eV}) \left(\frac{\langle\chi\rangle}{2 \text{ keV}}\right) \left(\frac{30 \text{ TeV}}{\Lambda}\right)^2$$

[$\Delta m^2_{\text{atm}} \simeq (0.06)^2 \, \text{eV}^2$]

Phenomenology

- *Discrete Symmetry Breaking $\rightarrow$ Domain Walls:*

$\Delta T/T \lesssim 10^{-5}$: $\langle \chi \rangle \lesssim 400$ keV $\rightarrow \Lambda \lesssim 400$ TeV. *Upper Bound on Λ!*

Frustrated Network: Dark Energy; $w = -2/3$.

- *BBN ($T_{BBN} \sim 1$ MeV):*

$m_\nu \gtrsim 10^{-4}$ eV: $\nu\nu \leftrightarrow \chi\chi, \ldots \quad \Rightarrow \Delta N_\nu = 8/7$. *Allowed.* Cyburt *et al.* (2004)

- *$\Delta B \rightarrow 0$ from $\not{L}$ via $m\chi^3$:*

Thermal below $T_* \sim 300$ GeV $\left(\frac{m}{300 \text{ keV}}\right)^{2/3}$: $\Rightarrow \quad m \lesssim 300$ keV.

- *CMB:*

ν's free stream at decoupling, $T \sim 1$ eV.

Chacko et al. (2003)

χ's shift acoustic peaks: $\Delta l_k = -29.3 \qquad (k \gg 1)$ $\quad (\Delta l_k|_{SM} = -23.3$, *Planck Experiment*)

Dirac Neutrinos

★ Introduce ν_R^i, $i = 1, 2, \ldots, n_R$; $Z_9^q \times Z_3^\ell$ *exact.*

★ Forbid $HL\nu_R$ with new gauged symmetries.

★ Generate small m_ν from infrared symmetry breaking.

(I) Discrete Gauge Symmetries: Z_{3n}^R

	ν_R^1	ν_R^2	ν_R^3	H_R
Z_{3n}^R	n	n	n	-1
Z_3^ℓ	-1	-1	-1	0

$$\mathcal{L}^R = \lambda^{\alpha i} \, (H_R/\Lambda)^n \, (HL^\alpha)\nu_R^i$$

BBN Constraint: $\Delta N_\nu \lesssim 1$

- R-sector diluted $\mathcal{O}(10)$ below $T_{QCD} \sim 200$ MeV.

1 MeV $\leq T \leq T_{QCD}$: $\langle H_R \rangle \gg 1$ MeV or $\Lambda \gg 1$ TeV.

$\therefore$ *Discrete symmetry excluded by domain walls or else hierarchic.*

(II) A New Continuous Symmetry: $\mathrm{U(1)_R}$

- ν_R^i charged under $\mathrm{U}(1)_R$: $Q = (q_1, \cdots, q_{n_R})$.

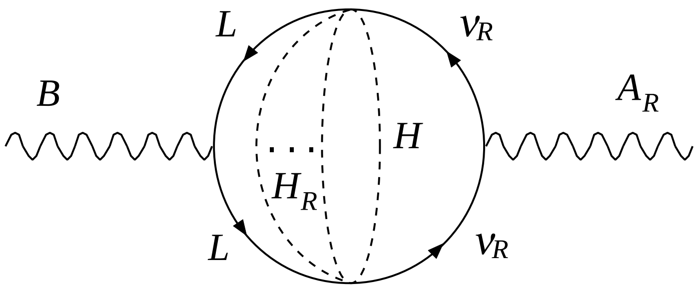
- Anomaly free: $\sum_i q_i = 0 \quad ; \quad \sum_i q_i^3 = 0$.

	ν_R^1	ν_R^2	ν_R^3	ν_R^4
Q_R	$+1$	-1	$+1$	-1
Z_3^ℓ	-1	-1	-1	0

- $\mathcal{L}^R = \lambda^{\alpha i} \left(\frac{H_R^{(*)}}{\Lambda} \right)^n (H L^\alpha) \nu_R^i$: $Q(H_R) = -1/n$.

- Dirac $m_\nu \simeq 0.1$ eV: $m_A \sim g_R \langle H_R \rangle \gtrsim 1$ eV *(Short range force)*.

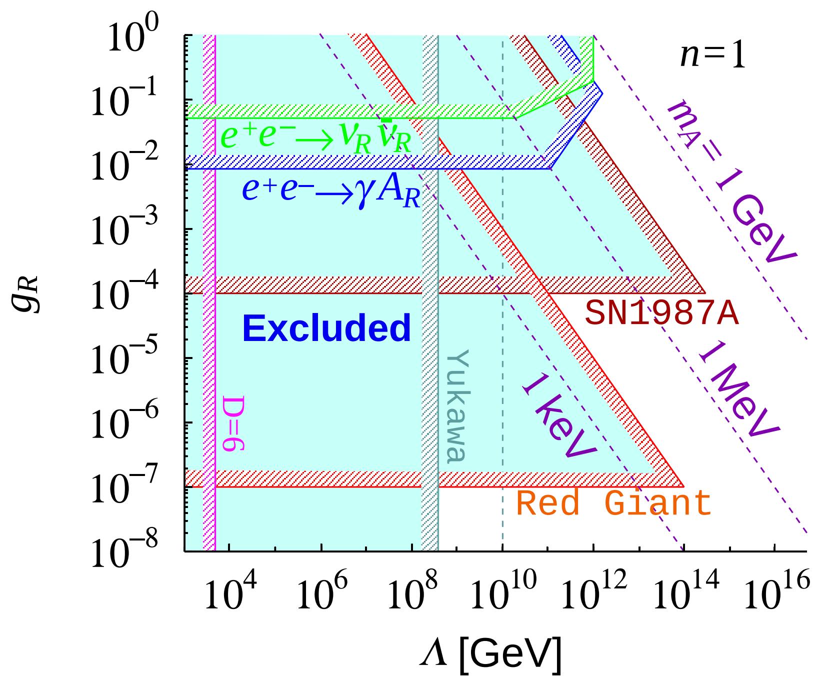
- $\mathrm{U}(1)_Y$–$\mathrm{U}(1)_R$ *kinetic mixing:*

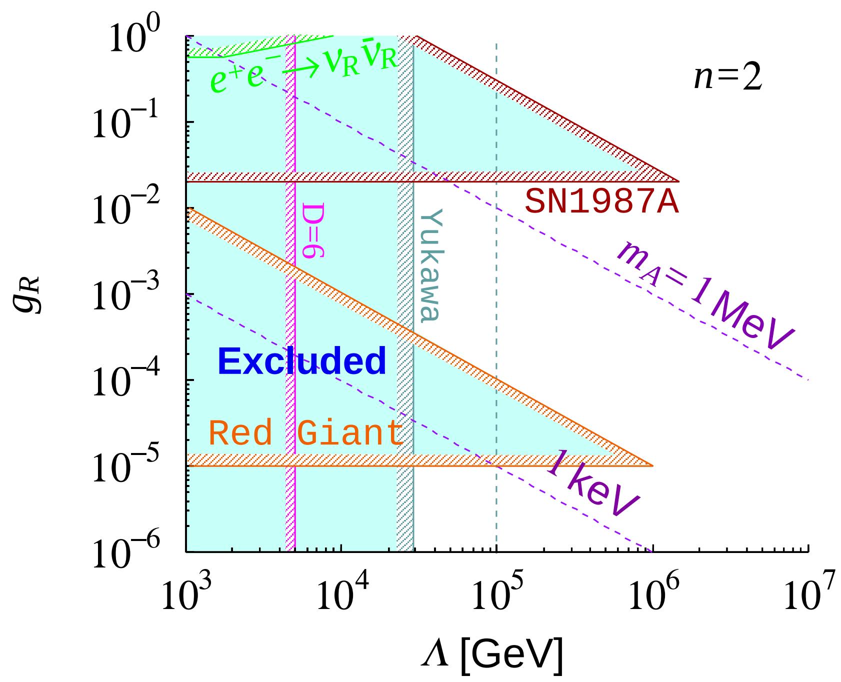


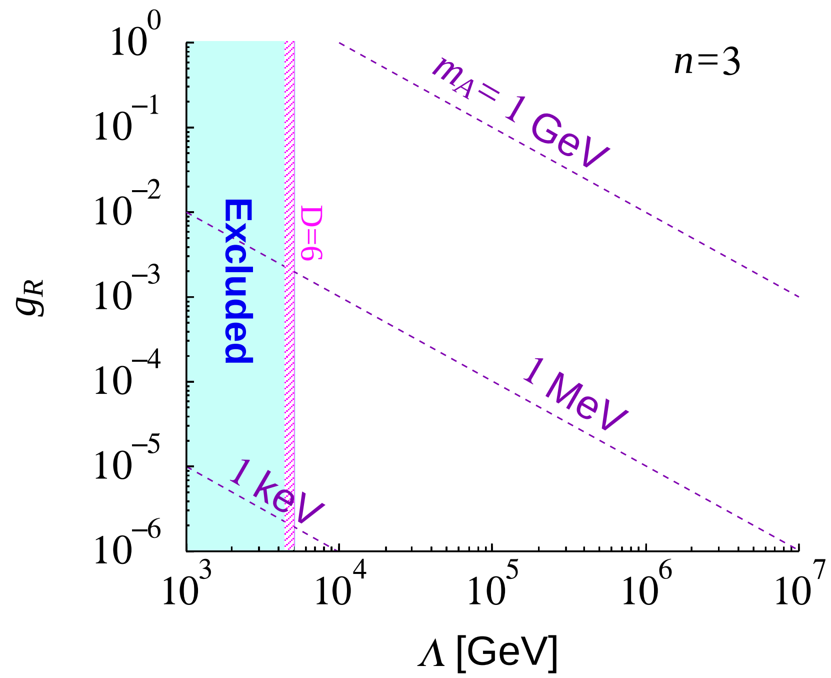
$$\mathcal{L}^A = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F^R_{\mu\nu}F^{R\mu\nu} - 2\,\varepsilon F_{\mu\nu}F^{R\mu\nu}) \quad ; \quad \varepsilon \ll 1$$

Diagonalized: $Q_f\,\bar\psi \not{A} \psi \to Q_f\,\bar\psi \not{A} \psi + \varepsilon\, Q_f\,\bar\psi \not{A}_R \psi$.

$$\varepsilon(\Lambda) = 0 \quad ; \quad \varepsilon_{rad} \sim g_Y g_R/(16\pi^2)^{2+n}$$







Phenomenology:

- $(g-2)_e$: $\varepsilon \lesssim 3\times 10^{-5}$
- *BBN;* $\Delta N_\nu \lesssim 1$: $e^+e^- \to \nu_R\bar{\nu}_R$; $e^+e^- \to \gamma A_R$, ...
- *Astrophysics: Red giant and supernova cooling*

Supernova Signatures

★ SN: $\Delta t_{\text{cool}} \sim 10$ s; $R_{\nu-\text{sphere}} \simeq 50$ km; $n_\nu \sim T_{\text{SN}}^3 \sim (30\,\text{MeV})^3$.

H.D., P. Huber, hep-ph/0504265

★ $\chi \leftrightarrow \nu\,\nu$: $\Gamma_\chi \sim y_\chi^2 T_{\text{SN}} \gtrsim (10^{-8}\ \text{s})^{-1} \Rightarrow \Gamma_\chi^{-1} \lesssim 1$ m.

★ *Thermal Bose-Einstein* χ-gas inside ν-sphere: $n_\chi \sim n_\nu \sim T_{\text{SN}}^3$.

★ $T_{\text{SN}} \gg \langle\chi\rangle \rightarrow$ Symmetry restoration; $\langle\chi\rangle = 0$: Phase transition at $T_c \sim \langle\chi\rangle$.

★ ν's and χ's radiated from surface of ν-sphere.

$\therefore$ *SN core radiates a two-component* ν*-flux:*

(1) Thermal Fermi-Dirac ν's.

(2) From χ-gas decays, $\langle E\rangle \approx \langle E_{\text{thermal}}\rangle/2$.

Additional astrophysical signatures:
H. Goldberg, G. Perez, I. Sarcevic,
hep-ph/0505221.

Assumptions:

- $T_{\bar{\nu}_e} = 4.8\,\text{MeV},\ T_{\nu_x} = 4.8\,\text{MeV},\ \eta^D_{\bar{\nu}_e} = 0.66$ (flavor ratio); $x = \mu, \tau$.

Keil, Raffelt, Janka 2002

- $P_{\bar{e}\bar{e}} = \cos^2\theta_{12},\ E_{\text{SN}} = 3 \times 10^{53}$ erg, $D_{\text{SN}} = 10$ kpc.

Estimate: $\sim$ 10000 events in 22.5 kt fiducial mass, Super-Kamiokande.

Results

- Number of events needed to confirm bi-modal distribution at 3σ:

$T_{\bar{\nu}_e}, T_{\bar{\nu}_x} \geq 3.8$ MeV
Normalization N

Hierarchy	Normal	Inverted	
$P_{\bar{e}\bar{e}}$	$\cos^2\theta_{12}$	$\cos^2\theta_{12}$	0
Perfect knowledge	538	152	294
N unknown	1107	678	682
$(N, T_{\bar{\nu}_e})$ unknown	1157	709	682
$(N, T_{\bar{\nu}_e}, T_{\bar{\nu}_x})$ unknown	10502	7397	709
$(N, T_{\bar{\nu}_e}, T_{\bar{\nu}_x}, \eta^D_{\bar{\nu}_e})$ unknown	13449	7432	709

- Establishing the Bose-Einstein χ-gas: $10^5 - 10^6$ events.

$\Rightarrow$ *Megaton water Čerenkov detector.*

Some Speculations

- Lowering cutoff $\Lambda \rightarrow$ *Low scale phase transition.*

- QCD *chiral symmetry breaking* in the SM:

$\Lambda_{\text{QCD}} \sim 100$ MeV, no new degrees of freedom.

$$(\bar{q}_L q_R L)(HL)/\Lambda^3 \quad \text{Allowed}$$

- $\langle \bar{q}_L q_R \rangle \sim (100\,\text{MeV})^3$, $\langle H \rangle \sim 100$ GeV, $\Lambda \sim 1$ TeV: $m_\nu \sim 0.1$ eV.

- This requires new symmetries: $m_u = 0$.

$\therefore$ *QCD explanation of $m_\nu \neq 0$ and a solution to strong CP!*

Concluding Remarks

- Lowering the cutoff scale Λ:

$Z_9^q \times Z_3^\ell$ to protect B and L.

- Small $m_\nu \neq 0$ from *Little Seesaws*:

Spontaneous IR (sub-GeV) symmetry breaking.

- Majorana m_ν from $\not{Z}_3^\ell$:

Domain walls: $\Lambda \lesssim 400$ *TeV*, $0\nu\beta\beta \oplus \chi$, $\Delta N_\nu^{BBN} \simeq 1$.

- Dirac m_ν with new symmetries:

(i) Discrete symmetry: Domain wall problem unless $\Lambda \gtrsim 10^8$ *GeV (hierarchic).*

(ii) $U(1)_R$ *broken by* $\langle H_R \rangle \neq 0$*: Light* (H_R, A_R), ν_R, *U(1) kinetic mixing,* $\Lambda \gtrsim 10$ *TeV* $(g_R \sim 1)$.

- Supernova:

Low energy ν-flux from scalar gas: Super-Kamiokande.

Bose-Einstein scalar gas: Megaton detector.

Symmetry restoration, phase transition.

The End