

Naturally Light Dirac Neutrinos from Left-Right Symmetric Models

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Talk based on:

“Naturally Light Dirac and Pseudo-Dirac Neutrinos from Left-Right Symmetry”

K.S. Babu, Xiao-Gang He, Minxian Su and Anil Thapa (to appear)

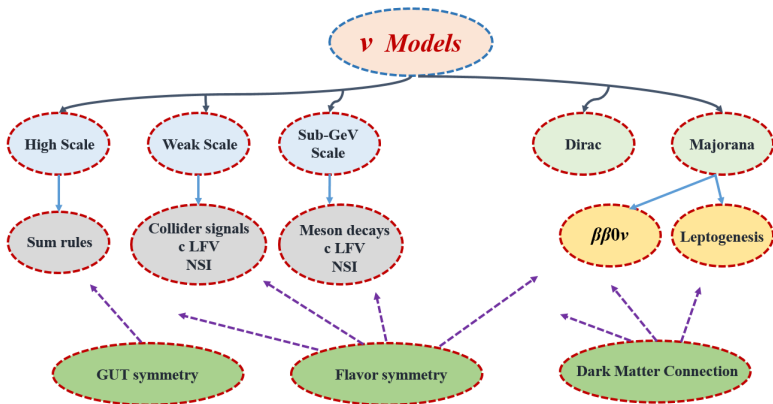
Current knowledge of neutrino oscillations

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	0.269 \rightarrow 0.343	$0.304^{+0.013}_{-0.012}$	0.269 \rightarrow 0.343
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	31.27 \rightarrow 35.86	$33.45^{+0.78}_{-0.75}$	31.27 \rightarrow 35.87
	$\sin^2 \theta_{23}$	$0.570^{+0.018}_{-0.024}$	0.407 \rightarrow 0.618	$0.575^{+0.017}_{-0.021}$	0.411 \rightarrow 0.621
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	39.6 \rightarrow 51.8	$49.3^{+1.0}_{-1.2}$	39.9 \rightarrow 52.0
	$\sin^2 \theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	0.02034 \rightarrow 0.02430	$0.02240^{+0.00062}_{-0.00062}$	0.02053 \rightarrow 0.02436
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	8.20 \rightarrow 8.97	$8.61^{+0.12}_{-0.12}$	8.24 \rightarrow 8.98
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	107 \rightarrow 403	286^{+27}_{-32}	192 \rightarrow 360
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \rightarrow +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \rightarrow -2.412$	
with SK atmospheric data	$\sin^2 \theta_{12}$	$0.304^{+0.012}_{-0.012}$	0.269 \rightarrow 0.343	$0.304^{+0.013}_{-0.012}$	0.269 \rightarrow 0.343
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	31.27 \rightarrow 35.86	$33.45^{+0.78}_{-0.75}$	31.27 \rightarrow 35.87
	$\sin^2 \theta_{23}$	$0.573^{+0.016}_{-0.020}$	0.415 \rightarrow 0.616	$0.575^{+0.016}_{-0.019}$	0.419 \rightarrow 0.617
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	40.1 \rightarrow 51.7	$49.3^{+0.9}_{-1.1}$	40.3 \rightarrow 51.8
	$\sin^2 \theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	0.02032 \rightarrow 0.02410	$0.02238^{+0.00063}_{-0.00062}$	0.02052 \rightarrow 0.02428
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	8.20 \rightarrow 8.93	$8.60^{+0.12}_{-0.12}$	8.24 \rightarrow 8.96
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	120 \rightarrow 369	282^{+26}_{-30}	193 \rightarrow 352
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \rightarrow +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \rightarrow -2.414$	

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou (2020)

Roadmap for Neutrino Models



Dirac Neutrino Models

- ▶ Neutrinos may be Dirac particles without lepton number violation
- ▶ Oscillation experiments cannot distinguish Dirac neutrinos from Majorana neutrinos
- ▶ Spin-flip transition rates (early universe, stars) are suppressed by small neutrino mass:

$$\Gamma_{\text{spin-flip}} \approx \left(\frac{m_\nu}{E}\right)^2 \Gamma_{\text{weak}}$$

- ▶ Neutrinoless double beta decay discovery would establish neutrinos to be Majorana particles
- ▶ If neutrinos are Dirac, it would be nice to understand the smallness of their mass
- ▶ Models exist which explain the smallness of Dirac m_ν
- ▶ “Dirac leptogenesis” can explain baryon asymmetry

Dick, Lindner, Ratz, Wright (2000)

Dirac Seesaw Models

- ▶ Dirac seesaw can be achieved in Mirror Models

Lee, Yang (1956); Foot, Volkas (1995); Berezhiani, Mohapatra (1995), Silagadze(1997)

- ▶ Mirror sector is a replica of Standard Model, with new particles transforming under mirror gauge symmetry:

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L; \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}; \quad L' = \begin{pmatrix} \nu' \\ e' \end{pmatrix}_L; \quad H' = \begin{pmatrix} H'^+ \\ H'^0 \end{pmatrix}$$

- ▶ Effective dimension-5 operator induces small Dirac mass:

$$\frac{(LH)(L'H')}{\Lambda} \Rightarrow m_\nu = \frac{v v'}{\Lambda}$$

- ▶ $B - L$ may be gauged to suppress Planck-induced Weinberg operator $(LLHH)/M_{\text{Pl}}$ that would make neutrino pseudo-Dirac particle

Dirac Neutrinos from Left-Right Symmetry

- ▶ In left-right symmetric models with a “universal seesaw”, neutrinos are naturally Dirac particles
- ▶ Gauge symmetry is extended to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$
- ▶ These models are motivated on several grounds:
 - ▶ Provide understanding of Parity violation
 - ▶ Better understanding of smallness of Yukawa couplings
 - ▶ Requires right-handed neutrinos to exist
 - ▶ Provide a solution to the strong CP problem via Parity

Davidson, Wali (1987); Babu, He (1989); Babu, Mohapatra (1990); Craig, Garcia Garcia, Koszegi, McCune (2020); Babu, He, Su, Thapa (2022)

Left-Right Symmetry

- ▶ Fermion transformation:

$$Q_L (3, 2, 1, 1/3) = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad Q_R (3, 1, 2, 1/3) = \begin{pmatrix} u_R \\ d_R \end{pmatrix},$$

$$\Psi_L (1, 2, 1, -1) = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \Psi_R (1, 1, 2, -1) = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}.$$

- ▶ Vector-like fermions are introduced to realize seesaw for charged fermion masses:

$$P(3, 1, 1, 4/3), \quad N(3, 1, 1, -2/3), \quad E(1, 1, 1, -2).$$

- ▶ Higgs sector is very simple:

$$\chi_L (1, 2, 1, 1) = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R (1, 1, 2, 1) = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$$

- ▶ $\langle \chi_R^0 \rangle = \kappa_R$ breaks $SU(2)_R \times U(1)_X$ down to $U(1)_Y$, and $\langle \chi_L^0 \rangle = \kappa_L$ breaks the electroweak symmetry with $\kappa_R \gg \kappa_L$

Seesaw for charged fermions

- ▶ Yukaw interactions:

$$\mathcal{L} = y_u (\bar{Q}_L \tilde{\chi}_L + \bar{Q}_R \tilde{\chi}_R) P + y_d (\bar{Q}_L \chi_L + \bar{Q}_R \chi_R) N \\ + y_\ell (\bar{\Psi}_L \chi_L + \bar{\Psi}_R \chi_R) E + h.c.$$

- ▶ Vector-like fermion masses:

$$\mathcal{L}_{\text{mass}} = M_{p^0} \bar{P} P + M_{N^0} \bar{N} N + M_{E^0} \bar{E} E$$

- ▶ Seesaw for charged fermion masses:

$$M_F = \begin{pmatrix} 0 & Y_{\kappa_L} \\ Y_{\kappa_R}^\dagger & M \end{pmatrix} \Rightarrow m_f = \frac{Y^2_{\kappa_L \kappa_R}}{M}$$

- ▶ There is no seesaw for neutrinos, since there is no corresponding singlet fermion
- ▶ Dirac neutrino masses arise via two-loop diagrams

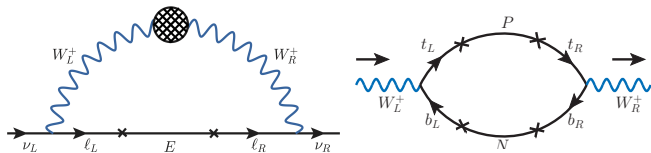
Matter Content from $SU(5)_L \times SU(5)_R$

$$\psi_{L,R} = \begin{bmatrix} D_1^c \\ D_2^c \\ D_3^c \\ e \\ -\nu \end{bmatrix}_{L,R} \quad \chi_{L,R} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & U_3^c & -U_2^c & -u_1 & -d_1 \\ -U_3^c & 0 & U_1^c & -u_2 & -d_2 \\ U_2^c & -U_1^c & 0 & -u_3 & -d_3 \\ u_1 & u_2 & u_3 & 0 & -E^c \\ d_1 & d_2 & d_3 & E^c & 0 \end{bmatrix}_{L,R},$$

- ▶ All left-handed SM fermions are in $\{(10, 1) + (\bar{5}, 1)\}$, while all right-handed SM fermions are in $\{(1, 10) + (1, \bar{5})\}$
- ▶ There is ν_R in the theory, but no seesaw for neutrino sector
- ▶ Small Dirac neutrino masses arise as two-loop radiative corrections
- ▶ We have evaluated the flavor structure of the two-loop diagrams and shown consistency with neutrino data

Two-loop Dirac Neutrino Masses

- ▶ Higgs sector is very simple: $\chi_L(1, 2, 1, 1/2) + \chi_R(1, 1, 2, 1/2)$
- ▶ $W_L^+ - W_R^+$ mixing is absent at tree-level in the model
- ▶ $W_L^+ - W_R^+$ mixing induced at loop level, which in turn generates Dirac neutrino mass at two loop **Babu, He (1989)**



- ▶ Flavor structure of two loop diagram needs to be studied to check consistency
- ▶ Oscillation date fits well within the model regardless of Parity breaking scale **Babu, He, Su, Thapa (2022)**

Loop Integrals

$$M_{\nu D} = \frac{-g^4}{2} y_t^2 y_b^2 y_\ell^2 \kappa_L^3 \kappa_R^3 r \frac{M_P M_N M_{E_\ell}}{M_{W_L}^2 M_{W_R}^2} I_{E_\ell}$$

$$I_{E_\ell} = \int \int \frac{d^4 k d^4 p}{(2\pi)^8} \frac{3M_{W_L}^2 M_{W_R}^2 + (p^2 - M_{W_L}^2)(p^2 - M_{W_R}^2)}{k^2(p+k)^2(k^2 - M_N^2)(p+k)^2 - M_P^2 p^2 (p^2 - M_{E_\ell}^2)(p^2 - M_{W_L}^2)(p^2 - M_{W_R}^2)}$$

$$\begin{aligned} G_1 = & \frac{3}{(r_3 - 1)(r_4 - 1)(r_4 - r_3)} \left[-\frac{\pi^2}{6} (r_1 + r_2)(r_3 - 1)(r_3 - r_4)(r_4 - 1) \right. \\ & + r_3 r_4 (r_4 - r_3) \left(r_1 F \left[\frac{1}{r_1}, \frac{r_2}{r_1} \right] + r_2 F \left[\frac{1}{r_2}, \frac{r_1}{r_2} \right] + F[r_1, r_2] \right) \\ & - (r_4 - 1) r_4 \left(r_1 F \left[\frac{r_3}{r_1}, \frac{r_2}{r_1} \right] + r_2 F \left[\frac{r_3}{r_2}, \frac{r_1}{r_2} \right] + r_3 F \left[\frac{r_1}{r_3}, \frac{r_2}{r_3} \right] \right) \\ & + (r_3 - 1) r_3 \left(r_1 F \left[\frac{r_4}{r_1}, \frac{r_2}{r_1} \right] + r_2 F \left[\frac{r_4}{r_2}, \frac{r_1}{r_2} \right] + r_4 F \left[\frac{r_1}{r_4}, \frac{r_2}{r_4} \right] \right) \\ & + (r_3 - r_4)(r_3 - 1)(r_4 - 1) \left(r_2 Li_2 \left[1 - \frac{r_1}{r_2} \right] + r_1 Li_2 \left[1 - \frac{r_2}{r_1} \right] \right) \\ & + r_3 r_4 (r_3 - r_4) \left(Li_2[1 - r_1] + Li_2[1 - r_2] + r_1 Li_2 \left[\frac{r_1 - 1}{r_1} \right] + r_2 Li_2 \left[\frac{r_2 - 1}{r_2} \right] \right) \\ & + r_4 (r_4 - 1) \left(r_3 Li_2 \left[1 - \frac{r_1}{r_3} \right] + r_3 Li_2 \left[1 - \frac{r_2}{r_3} \right] + r_1 Li_2 \left[1 - \frac{r_3}{r_1} \right] + r_2 Li_2 \left[1 - \frac{r_3}{r_2} \right] \right) \\ & \left. - r_3 (r_3 - 1) \left(r_4 Li_2 \left[1 - \frac{r_1}{r_4} \right] + r_4 Li_2 \left[1 - \frac{r_2}{r_4} \right] + r_1 Li_2 \left[1 - \frac{r_4}{r_1} \right] + r_2 Li_2 \left[1 - \frac{r_4}{r_2} \right] \right) \right]. \end{aligned} \tag{1}$$

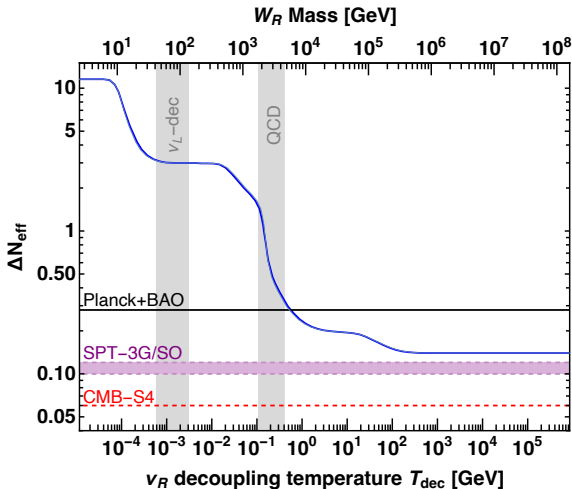
Neutrino Fit in Two-loop Dirac Mass Model

Oscillation parameters	3σ range NuFit5.1	Model prediction			
		BP I (NH)	BP II (NH)	BP III (IH)	BP IV (IH)
$\Delta m_{21}^2 (10^{-5} \text{ eV}^2)$	6.82 - 8.04	7.42	7.32	7.35	7.30
$\Delta m_{23}^2 (10^{-3} \text{ eV}^2)$ (IH)	2.410 - 2.574	-	-	2.48	2.52
$\Delta m_{31}^2 (10^{-3} \text{ eV}^2)$ (NH)	2.43 - 2.593	2.49	2.46	-	-
$\sin^2 \theta_{12}$	0.269 - 0.343	0.324	0.315	0.303	0.321
$\sin^2 \theta_{23}$ (IH)	0.410 - 0.613	-	-	0.542	0.475
$\sin^2 \theta_{23}$ (NH)	0.408 - 0.603	0.491	0.452	-	-
$\sin^2 \theta_{13}$ (IH)	0.02055 - 0.02457	-	-	0.0230	0.0234
$\sin^2 \theta_{13}$ (NH)	0.02060 - 0.02435	0.0234	0.0223	-	-
δ_{CP} (IH)	192 - 361	-	-	271 $^\circ$	296 $^\circ$
δ_{CP} (NH)	105 - 405	199 $^\circ$	200 $^\circ$	-	-
$m_{\text{light}} (10^{-3}) \text{ eV}$		0.66	0.17	0.078	4.95
M_{E_1}/M_{WR}		917	321.3	639	3595
M_{E_2}/M_{WR}		0.650	19.3	1.54	5.03
M_{E_3}/M_{WR}		0.019	1.26	0.054	2.94

- ▶ Ten parameters to fit oscillation data
- ▶ Both normal ordering and inverted ordering allowed
- ▶ Dirac CP phase is unconstrained
- ▶ Left-right symmetry breaking scale is not constrained

Tests in N_{eff} in Cosmology

- ▶ Dirac neutrino models will modify N_{eff} by about 0.14
- ▶ Can be tested in CMB measurements: $N_{\text{eff}} = 2.99 \pm 0.17$ (Planck+BAO)
- ▶ Present data sets a lower limit of 7 TeV on W_R mass



Conclusions

- ▶ Neutrino may very well be Dirac particles
- ▶ A left-right symmetric scenario is presented which is motivated on several other grounds
- ▶ Neutrinos may be pseudo-Dirac particles at a more fundamental level
- ▶ N_{eff} in cosmology can test these models