Naturally Light Dirac Neutrinos from Left-Right Symmtric Models

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Talk based on:

"Naturally Light Dirac and Pseudo-Dirac Neutrinos from Left-Right Symmetry"

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Current knowledge of neutrino oscillations

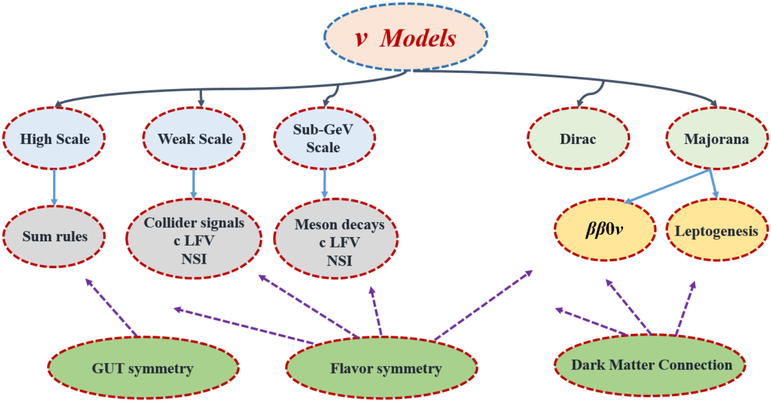
NuFIT 5.0 (2020)

		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	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{\rm CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

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:

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

- 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

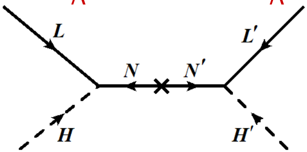
  Lee, Yang (1956); Foot, Volkas (1995); Berezhiani, Mohapatra (1995), Silagadze(1997)

- 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:

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



- $B - L$ may be gauged to suppress Planck-induced Weinberg operator $(LLHH)/M_{\rm Pl}$ 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) – universal seesaw
Babu, He (1989) – Dirac neutrino
Babu, Mohapatra (1990) – solution to strong CP problem via parity
Babu, Dutta, Mohapatra (2018) – R_{D^*} solution
Craig, Garcia Garcia, Koszegi, McCune (2020) – flavor constraints
Babu, He, Su, Thapa (2022) – neutrino oscillations

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:

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

- Seesaw for charged fermion masses:

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

- $\theta_{QCD} = 0$ due to Parity; ArgDet$(M_U M_D) = 0$; induced $\overline{\theta} = 0$ at one-loop; small and finite $\overline{\theta}$ arises at two-loop
- There is no seesaw for neutrinos, since there is no corresponding singlet fermion

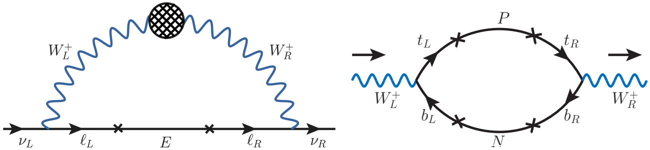
Matter Content from $SU(5)_L \times SU(5)_R$

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

- 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

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

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

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

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)
$\Delta m^2_{21} (10^{-5}\ \mathrm{eV}^2)$	6.82 - 8.04	7.42	7.32	7.35	7.30
$\Delta m^2_{23} (10^{-3}\ \mathrm{eV}^2)$(IH)	2.410 - 2.574	-	-	2.48	2.52
$\Delta m^2_{31} (10^{-3}\ \mathrm{eV}^2)$(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°	296°
δ_{CP} (NH)	105 - 405	199°	200°	-	-
$m_{\mathrm{light}}\ (10^{-3})$ eV		0.66	0.17	0.078	4.95
M_{E_1}/M_{W_R}		917	321.3	639	3595
M_{E_2}/M_{W_R}		0.650	19.3	1.54	5.03
M_{E_3}/M_{W_R}		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 with $N_{\rm eff}$ in Cosmology

- Dirac neutrino models of this type will modify $N_{\rm eff}$ by about 0.14

$$\Delta N_{\rm eff} \simeq 0.027 \left(\frac{106.75}{g_\star \left(T_{\rm dec} \right)} \right)^{4/3} g_{\rm eff}$$

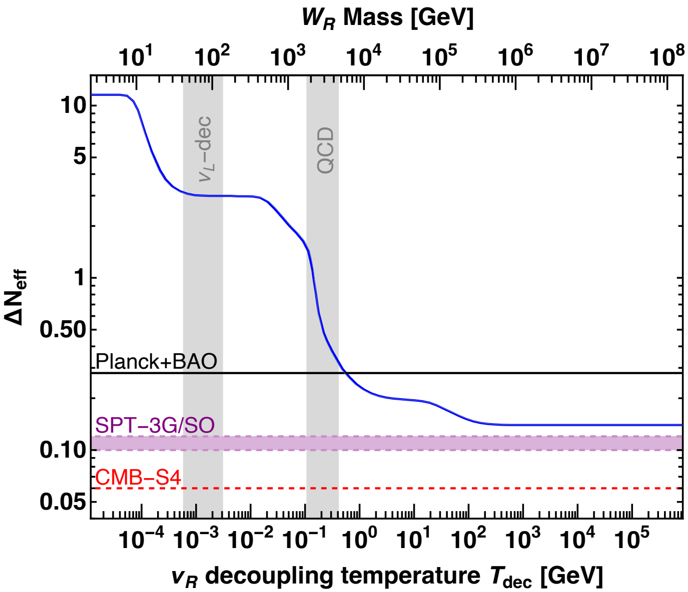
$$g_{\rm eff} = (7/8) \times (2) \times (3) = 21/4$$

- Can be tested in CMB measurements: $N_{\rm eff} = 2.99 \pm 0.17$ (Planck+BAO)

$$G_F^2 \left(\frac{M_{W_L}}{M_{W_R}} \right)^4 T_{\rm dec}^5 \approx \sqrt{g^*(T_{\rm dec})} \, \frac{T_{\rm dec}^2}{M_{\rm Pl}}$$

$$T_{\rm dec} \simeq 400 \ {\rm MeV} \left(\frac{g_* \left(T_{\rm dec} \right)}{70} \right)^{1/6} \left(\frac{M_{W_R}}{5 \ {\rm TeV}} \right)^{4/3}$$

- Present data sets a lower limit of 7 TeV on W_R mass



W_R Mass [GeV]
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
ΔN_{eff}
10
5
1
0.50
0.10
0.05
ν_L–dec
QCD
Planck+BAO
SPT–3G/SO
CMB–S4
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
ν_R decoupling temperature T_{dec} [GeV]

Pseudo-Dirac Neutrinos

- In any model with Dirac neutrinos, quantum gravity corrections could induce tiny Majorana masses via Weinberg operator
- The active-sterile neutrino mass splitting should obey $|\delta m^2| < 10^{-12}$ eV^2 from solar neutrino data – de Gouvea, Huang, Jenkins (2009)
- $B - L$ may be gauged in rder to control the small amount of Majorana mass. $(LLHH/M_{\rm Pl})$ won't be allowed due to $B - L$, but $(LLHH\varphi)/M_{\rm Pl}^2$ may be allowed – if φ has $B - L$ of $+2$
- In the current model $(\psi_R\psi_R\chi_R\chi_R)/M_{\rm Pl}$ is more important (if allowed), but $B - L$ gauging could forbid this operator, but may permit $(\psi_R\psi_R\chi_R\chi_R\varphi)/M_{\rm Pl}^2$
- Pseud-Dirac nature of neutrinos may be tested with high energy astrophysical neutrinos via (L/E)-dependent flavor ratios – Beacom, Bell, Hooper, Learned, Pakvasa, Weiler (2003)
- For $\langle\chi_R\rangle \sim \langle\varphi\rangle \sim 10^5$ GeV, $\Delta m^2 \approx 10^{-16}$ eV^2

IceCube Flavor Ratios for Pseudo-Dirac Neutrinos

- Flavor ratio at source from pion decay: $(\frac{1}{3},\ \frac{2}{3},\ 0)$
- For Dirac neutrinos these ratios become at detector $(\frac{1}{3},\ \frac{1}{3},\ \frac{1}{3})$
- For pseudo-Dirac neutrinos at the detector we have:

$$P_\beta = \frac{1}{3} + \delta P_\beta$$

$$\delta P_\beta = -\frac{1}{3}\left[|U_{\beta 1}|^2\chi_1 + |U_{\beta 2}|^2\chi_2 + |U_{\beta 3}|^2\chi_3\right]$$

$$\chi_j = \sin^2\left(\frac{\Delta m_j^2 L}{4E}\right)$$

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
- $N_{\rm eff}$ in cosmology can test these models
- IceCube can potentially distinguish a Dirac neutrino from a pseudo-Dirac neutrino via (L/E)-dependent flavor ratios