Neutrino Mass Theory

K.S. Babu

Oklahoma State University

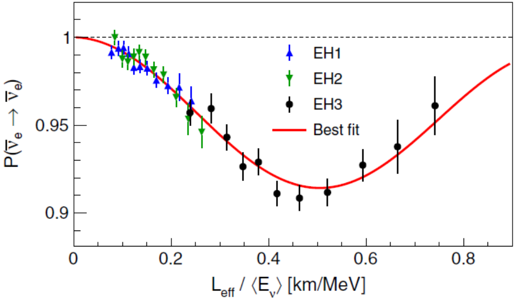
Neutrino '26
University of California, Irvine
June 22 – 26, 2026

Oscillating Neutrinos

- Neutrinos oscillate among flavors:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

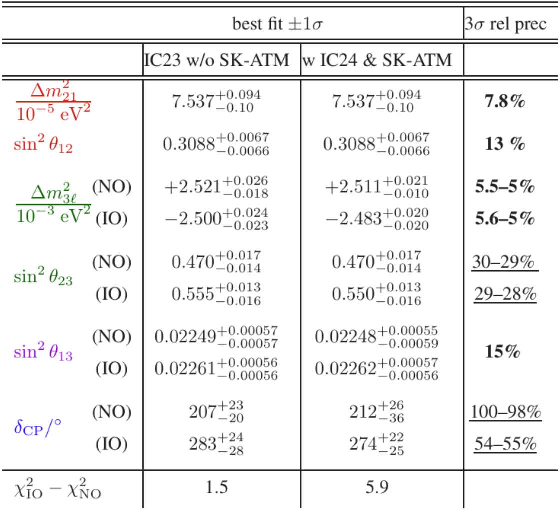
- Oscillatory behavior observed in Daya Bay $\overline{\nu}_e$, KamLand $\overline{\nu}_e$, SuperKamiokande atmospheric ν_μ and IceCube-DeepCore data



Daya Bay (2015)

- Flavor oscillations requires neutrinos to have nonzero masses

Current knowledge of 3-neutrino oscillations

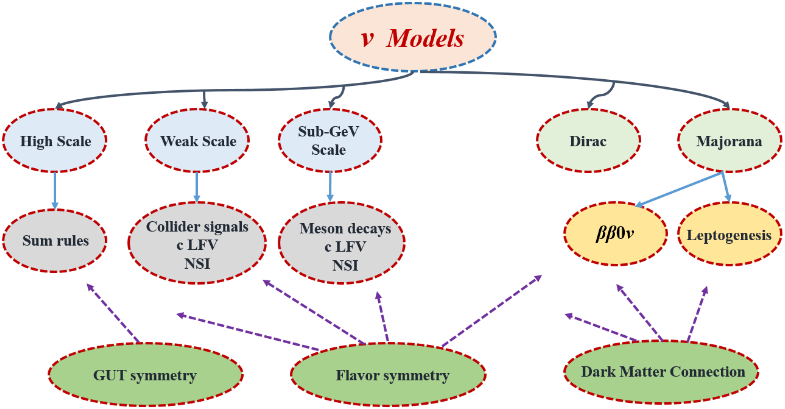


		best fit $\pm 1\sigma$		3σ rel prec
		IC23 w/o SK-ATM	w IC24 & SK-ATM	
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$		$7.537^{+0.094}_{-0.10}$	$7.537^{+0.094}_{-0.10}$	**7.8%**
$\sin^2\theta_{12}$		$0.3088^{+0.0067}_{-0.0066}$	$0.3088^{+0.0067}_{-0.0066}$	**13 %**
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	(NO)	$+2.521^{+0.026}_{-0.018}$	$+2.511^{+0.021}_{-0.010}$	**5.5–5%**
	(IO)	$-2.500^{+0.024}_{-0.023}$	$-2.483^{+0.020}_{-0.020}$	**5.6–5%**
$\sin^2\theta_{23}$	(NO)	$0.470^{+0.017}_{-0.014}$	$0.470^{+0.017}_{-0.014}$	30–29%
	(IO)	$0.555^{+0.013}_{-0.016}$	$0.550^{+0.013}_{-0.016}$	29–28%
$\sin^2\theta_{13}$	(NO)	$0.02249^{+0.00057}_{-0.00057}$	$0.02248^{+0.00055}_{-0.00059}$	**15%**
	(IO)	$0.02261^{+0.00056}_{-0.00056}$	$0.02262^{+0.00057}_{-0.00056}$	
$\delta_{\mathrm{CP}}/^\circ$	(NO)	207^{+23}_{-20}	212^{+26}_{-36}	100–98%
	(IO)	283^{+24}_{-28}	274^{+22}_{-25}	54–55%
$\chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$		1.5	5.9	

From talk by Gonzalez-Garcia, Neutrino '26

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro, Schwetz, Zhou (2024)

Roadmap for Neutrino Mass Models



ν Models

High Scale

Weak Scale

Sub-GeV Scale

Dirac

Majorana

Sum rules

Collider signals
c LFV
NSI

Meson decays
c LFV
NSI

ββ0ν

Leptogenesis

GUT symmetry

Flavor symmetry

Dark Matter Connection

“Fermi Theory” of neutrino mass

- Neutrino masses are zero in the Standard Model. Observed oscillations require new physics beyond Standard Model

- Neutrino masses and oscillations can be explained in terms of the effective $d = 5$ Weinberg operator

$$\mathcal{O}_1 = \frac{\kappa_{ab}}{2}(L^i_a L^j_b) H^k H^l \epsilon_{ik}\epsilon_{jl}$$

- $M_\nu = \kappa v^2 \Rightarrow \kappa^{-1} \sim (10^{14} - 10^{15})\ \mathrm{GeV}$ can explain oscillation data

- EFT description cannot be the end goal, especially when the coefficients of operators are measured. Without UV completion important phenomena would be missed (e.g. Leptogenesis)

- What if neutrinos are Dirac particles? $\mathcal{O}_1$ is then the wrong description. Only experiments can decide nature of neutrino mass

- What if neutrino masses arose from $d = 7$ operators or $d = 9$ operators in a fundamental theory, and not through $\mathcal{O}_1$?

Seesaw Mechanism

- ν_L has a right-handed partner ν_R

- In addition to the usual "Dirac mass" connecting ν_L with ν_R, there is also a large mass connecting ν_R with its conjugate $(\nu^c)_L$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- M_R is not protected by any symmetry, and can be very large. $\Rightarrow$

$$m_\nu^{\mathrm{light}} = \frac{m_D^2}{M_R}$$

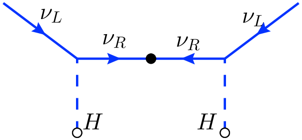
- For $m_D \sim 100$ GeV, $M_R \sim 10^{15}$ GeV, light neutrino mass of 10^{-2} eV is obtained. $M_R \sim 10^{15}$ GeV is close to the scale of grand unification

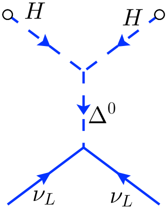
Minkowski (1977)
Yanagida (1979)
Glashow (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra & Senjanovic (1980)

Varieties of Seesaw

- $\nu_L - \nu_R$ seesaw is termed "Type-I" seesaw. Here one integrates out a heavy fermion, the ν_R
- A second "Type-II" seesaw can be realized by integrating out scalars:

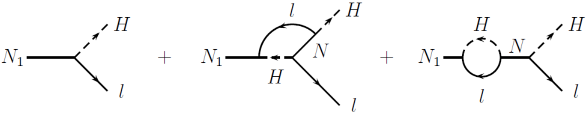
$$m_\nu^{\mathrm{light}} \sim Y \left(\frac{\mu v^2}{M_\Delta^2} \right)$$





Baryogenesis via leptogenesis and type-I seesaw

- In the early history of the universe, a lepton asymmetry may be dynamically generated in the decay of N Fukugita, Yanagida (1986)
- N being a Majorana fermion can decay to $L + H$ as well as $\overline{L} + H^*$



- Three Sakharov conditions can be satisfied: B violation via electroweak sphaleron, C and CP violation in Yukawa couplings of N, and out of equilibrium condition via expanding universe
- Lepton asymmetry in decay of N_1 (with $M_1 \ll M_{2,3}$):

$$\varepsilon_1 \simeq \frac{3}{16\pi} \frac{1}{(f_\nu f_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(f_\nu f_\nu^\dagger)_{i1}^2\right] \frac{M_1}{M_i}$$

- $\varepsilon \sim 10^{-6}$ can explain observed baryon asymmetry of the universe
- Indirect tests in Majorana nature of ν and in CP violation in oscillations

Dirac Neutrino Mass Models

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

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

- 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. I shall describe left-right symmetric theories and unified theories with Parity symmetry where this happens.

Left-Right Symmetric Models

- Gauge symmetry is extended to:

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Pati, Salam (1974); Mohapatra, Pati (1975); Mohapatra, Senjanovic (1979)

- Fermions transform in a left-right symmetric manner:

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

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

- Note the natural appearance of the right-handed neutrino
- Under Parity symmetry $Q_L \leftrightarrow Q_R$, $\Psi_L \leftrightarrow \Psi_R$, $W_L \leftrightarrow W_R$

Dirac Neutrinos from Left-Right Symmetry

- Higgs sector for symmetry breaking is very simple:

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

- $\langle H_R^0 \rangle = \kappa_R$ breaks $SU(2)_R \times U(1)_{B-L}$ down to $U(1)_Y$, and $\langle H_L^0 \rangle = \kappa_L$ breaks the electroweak symmetry with $\kappa_R \gg \kappa_L$
- Parity symmetry is spontaneously broken.
- Vector-like fermions are introduced to realize "universal seesaw" for charged fermion masses: Davidson, Wali (1987)

$$U(3,1,1,4/3), \quad D(3,1,1,-2/3), \quad E(1,1,1,-2)\ .$$

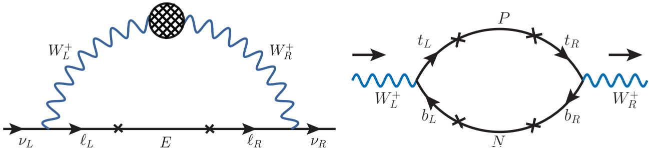
- Seesaw for charged fermion masses (no seesaw for neutrinos):

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

- Parity can solve strong CP probelm in this setup without axion Babu, Mohapatra (1989)

Two-loop Dirac Neutrino Masses

- Neutrino masses arise as quantum corrections
- $W_L^+ - W_R^+$ mixing is absent at tree-level in the model
- $W_L^+ - W_R^+$ mixing induced at loop level, which in turn generates small Dirac neutrino mass at two loop Babu, He (1989)



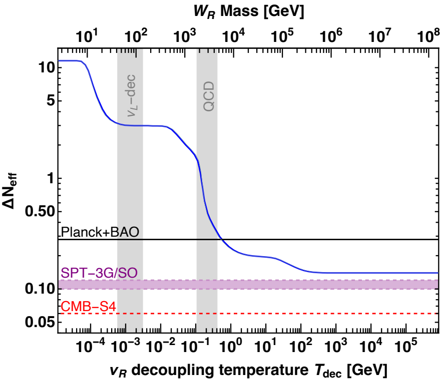
- Flavor structure of two loop diagram needs to be studied to check consistency
- Oscillation date fits well within the model regardless of Parity breaking scale Babu, He, Su, Thapa (2022)

Tests with $N_{\rm eff}$ in Cosmology

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

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

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



Pseudo-Dirac Neutrinos

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- If $M_R \ll m_D$, neutrino becomes pseudo-Dirac
  Wolfenstein (1980); Petcov (1982); Valle, Singer (1983)
- $M_R = 0$ is realized in models of Dirac neutrino. Non-renormalizable operators induced by gravity can provide small M_R:
  Eg: $LLHHS/M_{\rm Pl}^2$ (S carries B-L chare of $+2$)
- Active-sterile mass splitting strongly constrained by solar neutrino data: $\delta m_{as}^2 \leq 10^{-11}$ eV^2
- For $\langle S \rangle = (10^4 - 10^{14})$ GeV, $\delta m_{as}^2 = (10^{-12} - 10^{-21})$ eV^2 is realized
- Oscillations average out, and the flux of active neutrinos will be depleted by half
- Testable in high energy neutrino events at IceCube with identified source Beacom, Bell, Hooper, Learned, Pakvasa, Weiler (2004)

Astrophysical Tests of Pseudo-Dirac Neutrinos

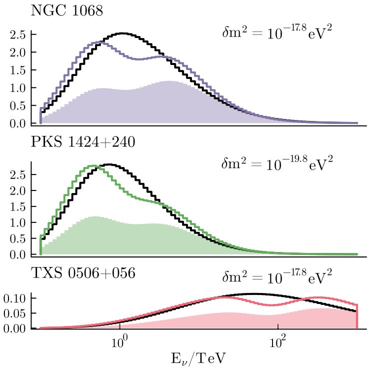


Figure: Calculated event distributions for the three most significant sources under the SM (black) and the pseudo-Dirac (filled color) hypotheses.

Carloni, Martinez-Soler, Arguelles, Babu, Dev (2023)

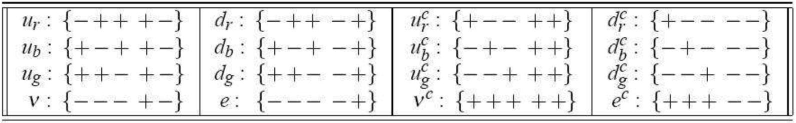
Sensitivity from galactic neutrinos: $\delta m^2_{as} = (10^{-13.6} - 10^{-12.3})\,\mathrm{eV}^2$
MacDonald, Carloni, Arguelles, Martinez-Soler, Batista (2026)

Grand Unification: A Refresher

- Unifies strong, weak and electromagnetic forces into a single force
- Leads to gauge coupling unification
- Unifies quarks, leptons, antiquarks and antileptons neatly into common GUT multiplets
- Explains electric charge quantization
- Right-handed neutrinos are required in most GUTs leading to seesaw mechanism as well as baryogenesis
- Predictive setup for quark and lepton masses
- Testable in its hallmark prediction of proton decay

Unification of Forces & Matter in SO(10)

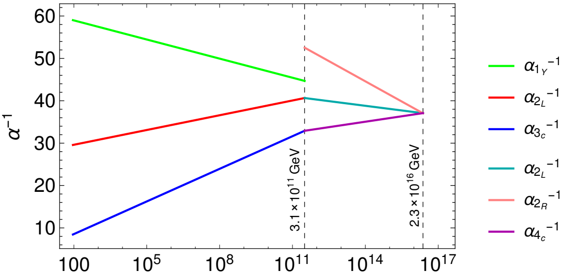
16 members of a family fit into a spinor of $SO(10)$



$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u^c_r : \{+--\ ++\}$	$d^c_r : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u^c_b : \{-+-\ ++\}$	$d^c_b : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u^c_g : \{--+\ ++\}$	$d^c_g : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

First 3 spins refer to color, last two are weak spins

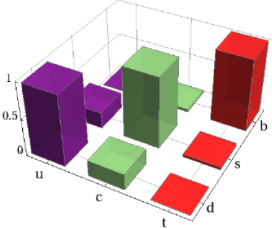
$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$



Disparity in Quark & Lepton Mixings

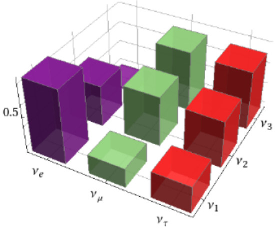
- **Quark Mixings**

$$V_{CKM} \sim \begin{bmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{bmatrix}$$



- **Leptonic Mixings**

$$U_{PMNS} \sim \begin{bmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{bmatrix}$$



Yukawa Sector of Minimal $SO(10)$

$$16 \times 16 = 10_s + 120_a + 126_s$$

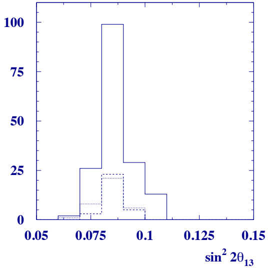
- At least two Higgs fields needed for family mixing
- Symmetric 10_H and $\overline{126}$ is the minimal model

$$W_{SO(10)} = 16^T \left(Y_{10}\, 10_H + Y_{126} \overline{126}_H \right) 16 \ .$$

$$\begin{aligned}
M_U &= v_u^{10} Y_{10} + v_u^{126} Y_{126} \\
M_D &= v_d^{10} Y_{10} + v_d^{126} Y_{126} \\
M_E &= v_d^{10} Y_{10} - 3 v_d^{126} Y_{126} \\
M_{\nu_D} &= v_u^{10} Y_{10} - 3 v_u^{126} Y_{126} \\
M_R &= Y_{126} V_R
\end{aligned}$$

Minimal Yukawa sector of SO(10)

- 12 parameters plus 7 phases to fit 18 observed quantities
- This setup fits all obsevables quite well
- Large neutrino mixings coexist with small quark mixings
- θ_{13} prediction turned out to be correct



Babu, Mohapatra (1993); Bajc, Senjanovic, Vissani (2001); (2003); Fukuyama, Okada (2002); Goh, Mohapatra, Ng (2003); Bajc, Melfo, Senjanovic, Vissani (2004); Bertolini, Malinsky, Schwetz (2006); Babu, Macesanu (2005); Dutta, Mimura, Mohapatra (2007); Aulakh et al (2004); Bajc, Dorsner, Nemevsek (2009); Joshipura, Patel (2011); Dueck, Rodejohann (2013); Ohlsson, Penrow (2019); Babu, Bajc, Saad (2018); Babu, Saad (2021)

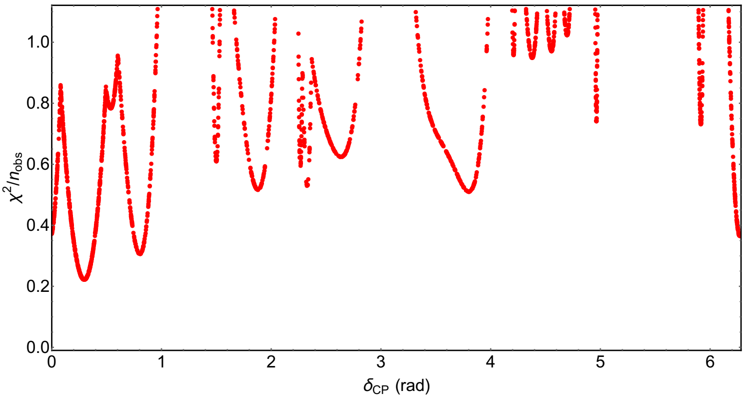
Best fit values for fermion masses and mixings

Observables	**SUSY**			**non-SUSY**		
(masses in GeV)	Input	Best Fit	Pull	Input	Best Fit	Pull
$m_u/10^{-3}$	0.502±0.155	0.515	0.08	0.442±0.149	0.462	0.13
m_c	0.245±0.007	0.246	0.14	0.238±0.007	0.239	0.18
m_t	90.28±0.89	90.26	-0.02	74.51±0.65	74.47	-0.05
$m_b/10^{-3}$	0.839±0.17	0.400	-2.61	1.14±0.22	0.542	-2.62
$m_s/10^{-3}$	16.62±0.90	16.53	-0.09	21.58±1.14	22.57	0.86
m_b	0.938±0.009	0.933	-0.55	0.994±0.009	0.995	0.19
$m_e/10^{-3}$	0.3440±0.0034	0.344	0.08	0.4707±0.0047	0.470	-0.03
$m_\mu/10^{-3}$	72.625±0.726	72.58	-0.05	99.365±0.993	99.12	-0.24
m_τ	1.2403±0.0124	1.247	0.57	1.6892±0.0168	1.688	-0.05
$\lvert V_{us}\rvert/10^{-2}$	22.54±0.07	22.54	0.02	22.54±0.06	22.54	0.06
$\lvert V_{cb}\rvert/10^{-2}$	3.93±0.06	3.908	-0.42	4.856±0.06	4.863	0.13
$\lvert V_{ub}\rvert/10^{-2}$	0.341±0.012	0.341	0.003	0.420±0.013	0.421	0.10
δ°_{CKM}	69.21±3.09	69.32	0.03	69.15±3.09	70.24	0.35
$\Delta m^2_{21}/10^{-5}(eV^2)$	8.982±0.25	8.972	-0.04	12.65±0.35	12.65	-0.01
$\Delta m^2_{31}/10^{-3}(eV^2)$	3.05±0.04	3.056	0.02	4.307±0.059	4.307	0.006
$\sin^2\theta_{12}$	0.318±0.016	0.314	-0.19	0.318±0.016	0.316	-0.07
$\sin^2\theta_{23}$	0.563±0.019	0.563	0.031	0.563±0.019	0.563	0.01
$\sin^2\theta_{13}$	0.0221±0.0006	0.0221	-0.003	0.0221±0.0006	0.0220	-0.16
δ°_{CP}	224.1±33.3	240.1	0.48	224.1±33.3	225.1	0.03
χ^2	-	-	7.98	-	-	7.96

Babu, Saad (2021)

Dirac CP phase

Multiple χ^2 minima make δ_{CP} prediction difficult



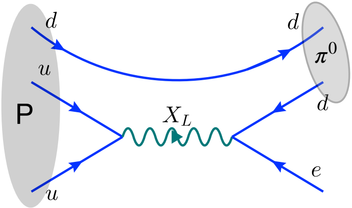
Babu, Bajc, Saad (2018)

Proton Decay in GUTs

- Packing quarks, leptons, antiquarks and antileptons into same multiplets of $SO(10)$ implies baryon number is violated

- Dominant decay of proton in $SO(10)$ is

$$p \to e^{+}\pi^{0}$$

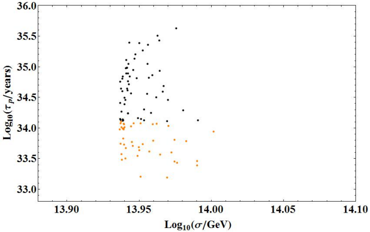


- Non-observation of proton decay has ruled out minimal $SU(5)$ GUT, but not $SO(10)$ GUT

- Proton lifetime scales as fourth power of the superheavy X gauge boson mass

Proton decay predictions

- Proton decay branching ratios determined by neutrino oscillation fits
- Mediated by superheavy gauge bosons
- Lifetime has large range, $\tau_p \approx (10^{32} - 10^{36})$ yrs.
- Testable in forthcoming experiments via rate and branching ratios



Prediction of branching ratios

$$\Gamma(p \to \pi^0 e^+) \to 47\%$$
$$\Gamma(p \to \pi^0 \mu^+) \to 1\%$$
$$\Gamma(p \to \eta^0 e^+) \to 0.20\%$$
$$\Gamma(p \to \eta^0 \mu^+) \to 0.00\%$$
$$\Gamma(p \to K^0 e^+) \to 0.16\%$$
$$\Gamma(p \to K^0 \mu^+) \to 3.62\%$$
$$\Gamma(p \to \pi^+ \overline{\nu}) \to 48\%$$
$$\Gamma(p \to K^+ \overline{\nu}) \to 0.22\%$$

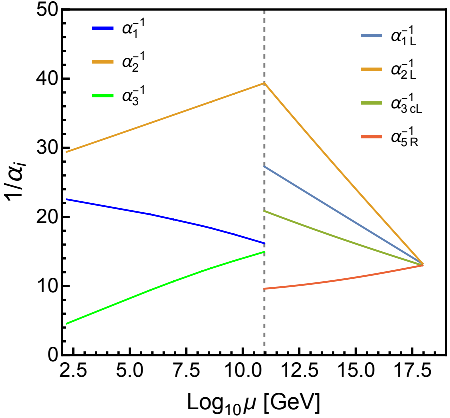
Babu, Khan (2015)
Nemesvek, Bajc, Dorsner (2009)

Parity Symmetric Unification

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

- Based on $SU(5)_L \times SU(5)_R$ gauge symmetry
- Fermions of universal seesaw model fit nicely into $SU(5)_L \times SU(5)_R$ representations
- 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 normal seesaw for neutrino sector
- Small *Dirac neutrino masses* arise as a type-II Dirac seesaw

Gauge Coupling Unification

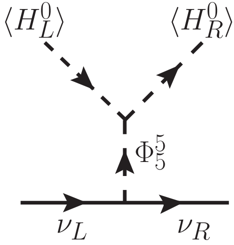


- $M_I = 9.02 \times 10^{10}$ GeV, $M_G = 8.0 \times 10^{17}$ GeV, $\alpha_G^{-1} = 13.18$
- Intermeidte symmetry: $SU3)_{cL} \times SU(2)_L \times U(1)_L \times SU(5)_R$

Type-II Dirac Seesaw for Neutrino Masses

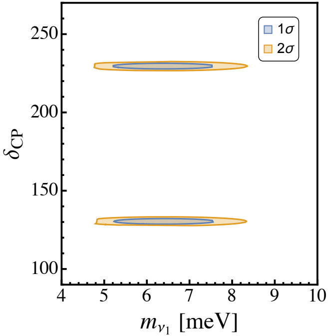
- Neutrinos are naturally light Dirac particles
- A type-II Dirac seesaw makes them light
- A Higgs doublet with mass of order M_G for $\Phi(5,5^*)$ acquires an induced VEV
- The neutrino Dirac Yukawa coupling is

$$Y_\nu \sim \frac{M_I}{M_G} \sim 10^{-7}$$



Predictions for Neutrino Parameters

- 1 parameter in $\mathcal{M}_d$ should fit 3 light down-quark masses
- Leads to 2 predictions in neutrino oscillations
- δ_{CP} and lightest neutrino mass m_1 are predicted:



$$\begin{aligned} \delta_{CP} &= (130.4 \pm 1.2)^\circ \text{ or } (229.6 \pm 1.2)^\circ \\ m_{\nu_1} &= (4.8 - 8.4)\ \mathrm{meV} \end{aligned}$$

Radiative neutrino mass generation

- An alternative to seesaw is radiative neutrino mass generation, where neutrino mass is absent at tree level, but arises via quantum loop corrections
- The smallness of neutrino mass is explained by loop and chiral suppression
- Loop diagrams may arise at 1-loop, 2-loop or 3-loop levels
- New physics scale typically near TeV and thus accessible to LHC
- Further tests in observable LFV processes and as nonstandard neutrino interaction (NSI) in oscillations

Effective $\Delta L = 2$ Operators

$$\begin{aligned}
\mathcal{O}_1 &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \\
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km} \\
\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl} \\
\mathcal{O}_7 &= L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm} \\
\mathcal{O}_8 &= L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij} \\
\mathcal{O}_9 &= L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_1' &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} H^{*m} H_m
\end{aligned}$$

Babu & Leung (2001)

de Gouvea & Jenkins (2008)

Angel & Volkas (2012)

Cai, Herrero-Garcia, Schmidt, Vicente, Volkas (2017)

Lehman (2014) – all $d = 7$ operators

Li, Ren, Xiao, Yu, Zheng (2020); Liao, Ma (2020) – all $d = 9$ operators

Operator $\mathcal{O}_2$ and the Zee model

- Introduce a singly charged scalar and a second Higgs doublet to standard model:

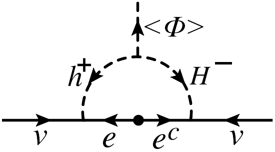
$$\mathcal{L} \quad = \quad f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + \mu H^a \Phi^b h^- \epsilon_{ab} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$$

Zee (1980)

- Neutrino mass arises at one-loop.



- A minimal version of this model in which only one Higgs doublet couples to a given fermion sector with a Z_2 symmetry yields: Wolfenstein (1980)

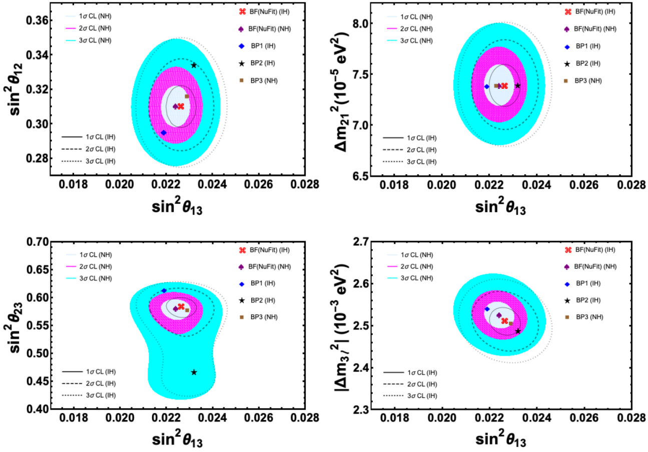
$$m_\nu = \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}, \quad m_{ij} \simeq \frac{f_{ij}}{16\pi^2} \frac{(m_i^2 - m_j^2)}{\Lambda}$$

It requires $\theta_{12} \simeq \pi/4 \rightarrow$ ruled out by solar + KamLAND data.

Koide (2001); Frampton *et al.* (2002); He (2004)

Neutrino oscillations in the Zee model

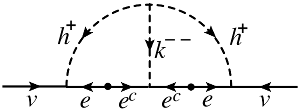
Neutrino oscillation data can be fit to the Zee model consistently without assuming the Z_2 symmetry



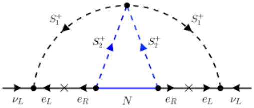
Babu, Dev, Jana, Thapa (2019)

Other Radiative Neutrino Mass Models

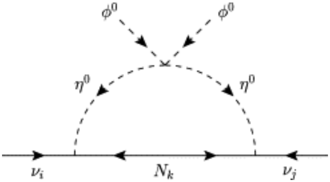
Zee-Babu Model: Neutrino mass arises at two-loops



Krauss-Nasri-Trodden (KNT) Model: ν-mass via 3-loop diagrams



Scotogenic Model of Ma: Dark matter mediates neutrino mass generation



New particles in loops cannot be too heavy, leading to potential signals

Conclusions

- EFT description alone in neutrino sector is inadequate; we may miss important phenomena such as leptogenesis
- Higher symmetries such as left-right and GUT provide powerful tools to interconnect neutrino sector with quark sector
- Models of neutrino mass based on GUTs have correlated predictions for proton decay
- Neutrino may very well be Dirac particles; interesting models of Dirac neutrino exist
- Various $d = 7$ and $d = 9$ lepton number violating EFT operators can lead to interesting radiative neutrino mass models

Thank You!