Neutrino Theory

Neutrino Theory: Mass, Interactions, Unification

Oleg Popov
Seoul National University of Science and Technology

opopo001@ucr.edu

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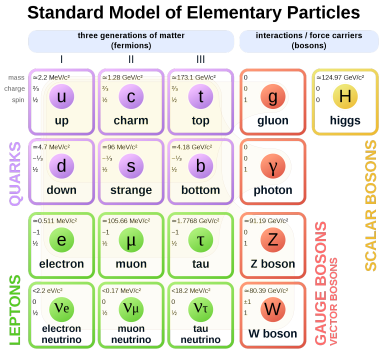
Overview

Introduction/Motivation

- (Naturally) small neutrino masses
- Connection with dark matter existence
- Lepton mixing
- Unification

Standard Model



Gauge symmetry group $\mathbb{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}^Y = \bar{u} Y_u Q H + \bar{Q} Y_d d H + \text{h.c.} \tag{1}$$

$$\langle h^0 \rangle = v \rightarrow \quad m_f = Y_f v \tag{2}$$

Requirements for neutrino mass

- Majorana or Dirac type?
- Tree level or radiative?
- New particles? (scalar, fermionic, vector)
- New gauge sectors? $(U(1), SU(2), SU(N))$

Possible effects/ Ways to test

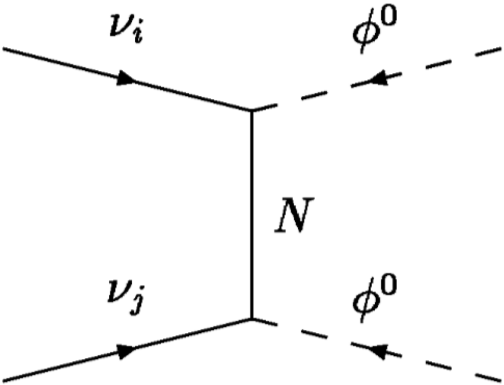
- Collider (LHC,ILC, FCC)
- Dark matter
- Grand unified theories
- Neutrino mixing
- Leptogenesis (CPV)
- Neutrinoless N$-$pole beta decay($0\nu n\beta$)
- GW via scalar sector

Tree level, Majorana

Weinberg Operator 1979: $\frac{LHLH}{\Lambda} = \frac{(l^- H^+ - \nu H^0)(l^- H^+ - \nu H^0)}{\Lambda}$

Add $N_R \sim (1,1,0)$ under $\mathbb{G}_{SM}$

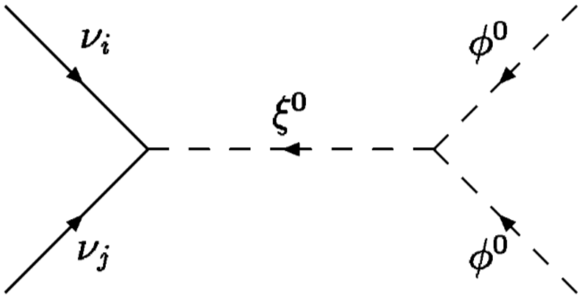
$$\mathcal{L}_{new} = \bar{N} Y_D LH + m_N N_R N_R + \text{h.c.}$$



Seesaw-I

Add[1980] $\xi = (\xi^{++}, \xi^{+}, \xi^{0}) \sim (1,3,1)$ under $\mathbb{G}_{SM}$

$$\mathcal{L}_{new} = YL\xi L + \text{h.c.} - \mu H\xi H \to m_\nu = Y\left\langle \xi^0 \right\rangle = -2\frac{Y\mu v^2}{M_\xi}$$

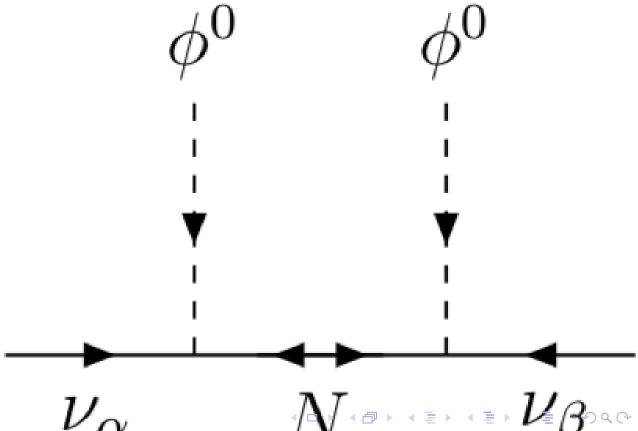


Seesaw-III

Weinberg Operator 1979: $\frac{LHLH}{\Lambda} = \frac{(l^- H^+ - \nu H^0)(l^- H^+ - \nu H^0)}{\Lambda}$

Add $N_R \sim (1,1,0)$ under $\mathbb{G}_{SM}$

$$\mathcal{L}_{new} = \bar{\Sigma} Y_D L H + m_N \Sigma_R \Sigma_R + \text{h.c.}$$



Seesaw variations

$$\mathcal{M}_{\nu N} = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix},$$

Seesaw[1979] $m_\nu = -m_D^2 / m_N$

Seesaw variations

$$\mathscr{M}_{\nu n} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & m_1 & m_N \\ 0 & m_N & m_2 \end{pmatrix}$$

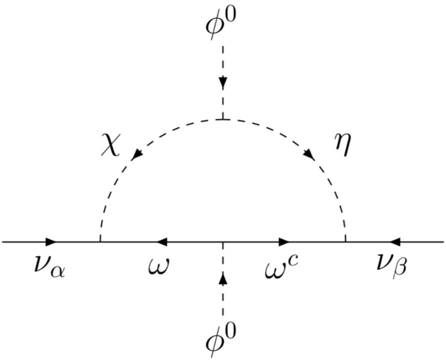
Inverse Seesaw[1986] $m_\nu = m_D^2 m_2/(m_N^2 - m_1 m_2)$

Seesaw variations

$$\mathscr{M}_{\nu N} = \begin{pmatrix} 0 & m_D & m'_D \\ m_D & 0 & m_N \\ m'_D & m_N & 0 \end{pmatrix}$$

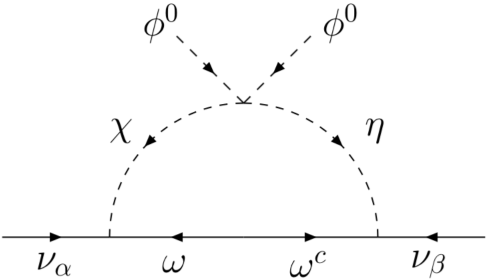
Linear Seesaw $m_\nu = -2 m_D m_{D'} / m_N$

Radiative neutrino mass, Majorana



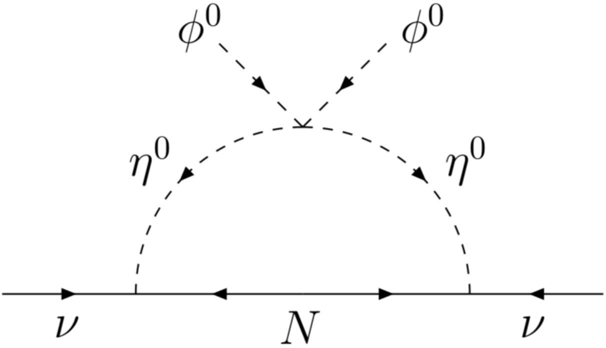
Zee[1986]

Radiative neutrino mass, Majorana



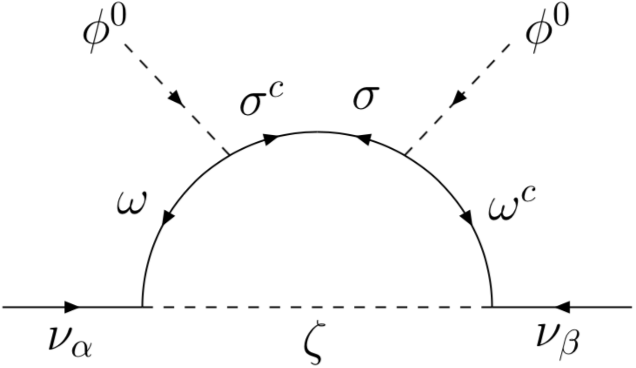
Ma[2006]

Scotogenic radiative neutrino mass

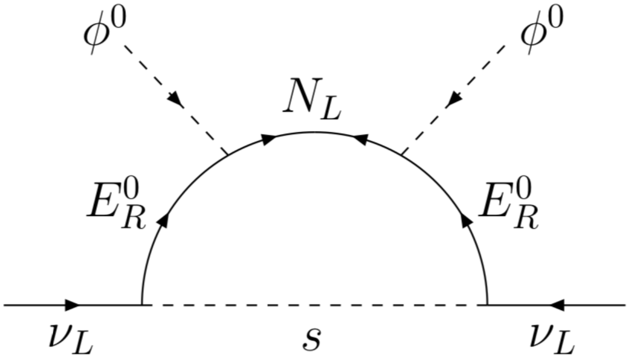


Add $\mathbb{Z}_2$ symmetry under which $\eta \sim (1, 2, 1/2)$ and N_R are ood

Radiative neutrino mass, Majorana



Fraser,Ma,OP[2014]



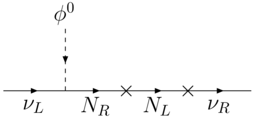
Add $\mathbb{Z}_2$ symmetry under which real singlet scalar and $E_{L,R} \sim (1, 2, 1/2)$ and $N_L \sim (1, 1, 0)$ are odd

Dirac neutrinos

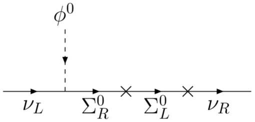
- Add $N_R \sim (1, 1, 0)$ under G_{SM}
- N_R MUST transfor under some other symmetry non-trivially
- New symmetry S is discrete, global, gauged, dark?

Tree Dirac case

- Insert a Dirac fermion singlet N which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $\bar{\nu}_R N_L$ term.

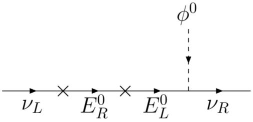


- Insert a Dirac fermion triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$ which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ and $SU(2)_L \times U(1)$ together spontaneously to obtain the dimension-three $\bar{\nu}_R \Sigma^0_L$ term.

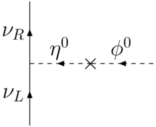


Dirac case

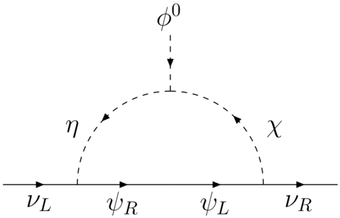
- Insert a Dirac fermion doublet (E^0, E^-) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $(\bar{E}^0 \nu_L + E^+ e^-)$ term.

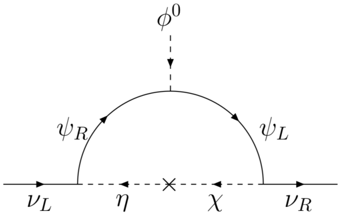


- Insert a scalar doublet (η^+, η^0) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-two $(\eta^- \phi^+ + \bar{\eta}^0 \phi^0)$ term.



Dirac case





$U(1)_{B-L} case$

- Add 3 $N_R \sim (1,1,0)$ which carry $L = (1,1,1)$
- Add 3 $N_R \sim (1,1,0)$ which carry $L = (4,4,-5)$
- Other variations are possible
- Makes $U(1)_{B-L}$ anomaly free.
- $U(1)_{B-L}$ can global or gauged
- Global: softly or spontaneously broken(Majorana, Dirac)
- Gauged: spontaneously broken(Majorana, Dirac)

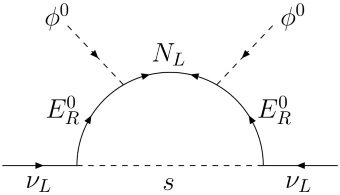
Scotogenic model in $SU(6)$ GUT*

Simple case: Extend $SU(5)$ to $SU(6)$ to incude BSM particles needed

$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

$\underline{6}^*_F \times \underline{15}_F \times \underline{6}^*_S$, $\underline{15}_F \times \underline{15}_F \times \underline{15}_S$ $SU(6)$ Yukawas

Anomaly free combinations: $\underline{5}^*_F + \underline{10}_F$ for $SU(5)$, $\underline{6}^*_F + \underline{6}^*_F + \underline{15}_F$ for $SU(6)$. New $SU(6)$ $\underline{21}_S$ scalar is added to obtain 2'nd Higgs doublet ($\mathbb{Z}_2 \sim -$) with new interactions $\underline{6}^*_F \times \underline{6}^*_F \times \underline{21}_S$, $\underline{15}^*_S \times \underline{15}^*_S \times \underline{21}_S \times \underline{21}_S$



Scotogenic model in $SU(7)$ GUT†

Less simple case: Extend $SU(5)$ to $SU(7)$ to incude BSM particles needed

$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

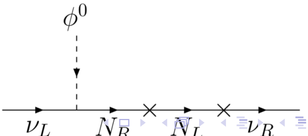
$\underline{7}^*_F \times \underline{21}_F \times \underline{7}^*_S$, $\underline{21}_F \times \underline{21}_F \times \underline{35}_S$ $SU(7)$ Yukawas

Anomaly free combination for $SU(7)$: $\underline{7}^*_F + \underline{7}^*_F + \underline{7}^*_F + \underline{21}_F$.

New $\underline{28}_S$ scalar needed to accomodate $SU(2)_N$ doublet, with new interactions:$\underline{7}^*_F \times \underline{7}^*_F \times \underline{28}_S$, $\underline{21}^*_S \times \underline{21}^*_S \times \underline{28}_S \times \underline{28}_S$

- Insert a Dirac fermion singlet N which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ sc

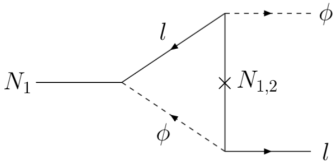
  by the dimension-three $\bar{\nu}_R N_L$ term.

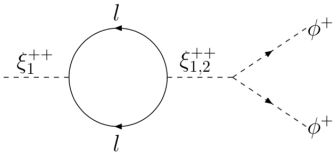


Connection to GW signals

- Neutrino mass requires new scalars or gauge bosons
- Strong first order phase transition (BSM gauge symmetry)
- Strong first order phase transition gives GW
- Some possible models: LR models, $SU(N)$ scotognic symmetry

Leptogenesis





Summary

- Neutrino masses can be Majorana or Dirac
- Tree or radiative
- Reuire BSM fields and symmetries (globa or gauged)
- Connection with DM
- Connection with GW
- Leptogenesis

Thank you!