Dirac neutrinos and Dark Matter

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Outline

Roadmap to Dirac neutrino mass

UV-complete Models

Connection to flavour

Dark Matter stability.

Introduction: neutrino masses

- Neutrinos are massless in the Standard Model
  - There is no right-handed neutrino.
- However, neutrino masses are well established by oscillation experiments
  - Entering the precision era (~2% error in θ_{13})

Why so small masses?

Are neutrinos Dirac or Majorana?

Introduction: seesaw mechanism

- Most popular answer is the seesaw mechanism.

- Smallness of neutrino masses is related to the heaviness of messenger fields.
  - Many variants: Type I, II and III, inverse seesaw...
  - Typically leads to Majorana neutrinos

Minkowski 1977
Gellman-Ramond-Slansky
Mohapatra-Senjanovc 1980
Schechter-Valle 1980 / 1982
Mohapatra-Valle 1986
And many others...

Introduction: Why Dirac Neutrinos?

- Black box theorem: neutrinoless double beta decay implies Majorana mass term
  - No experimental signature (yet).
- Both possibilities are open Dirac & Majorana
- ν_R may be needed for UV completion just as in some Majorana seesaws

Schechter-Valle 1982

Introduction: Dirac vs Majorana

- We denote a fermion as ‘Majorana fermion’ when it is indistinguishable from its own antiparticle.
- Conserved charges are key in determining if a fermion is Dirac or Majorana.
- All fermions in the SM (except for neutrinos) have non-zero electric charge → Dirac fermions.
- Symmetries of mass terms play a key role.
    - Dirac mass terms conserve Abelian symmetries: $\overline{\Psi}\,\Psi$
    - Majorana mass terms break them (except in special cases): $\overline{\Psi^c}\,\Psi$

Ingredients for Dirac Neutrinos

- Majorana mass terms must be forbidden.
- Not only tree-level terms but also all effective higher order operators leading to Majorana mass.
- This requires extra symmetry.
- One possibility is Z_4 Quarticity symmetry.

Quarticity Z_4 symmetry

- This symmetry is closely related with lepton number conservation: discrete lepton number
- Must be an exact symmetry
- All leptons transform as z ($z^4 = 1$).
  - $\Psi_i \sim z$.
- All scalars carrying a vev transform as the identity: Z_4 must not be spontaneously broken.
  - If $\langle X \rangle \neq 0 \rightarrow X \sim 1$

SCC, Ma, Srivastava, Valle 1606.04543

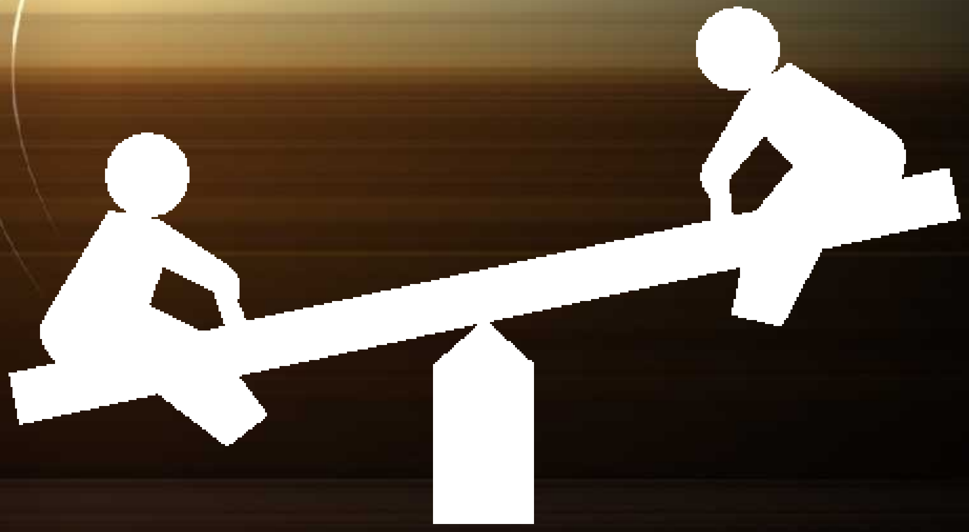
Dirac neutrinos

- All leptons transform as z and scalars with vev as the identity.
  - $\Psi_i \sim z$,   If $\langle X \rangle \neq 0 \rightarrow X \sim 1$.
- Fermions must appear in pairs due to Lorentz symmetry:
  - $\overline{\Psi}_i^c \Psi_j \sim z^2$
  - $\overline{\Psi}_i \Psi_j \sim 1$
- Therefore
  - $\overline{\Psi}_i^c X^n Y^m \ldots \Psi_j \sim z^2 \rightarrow$ Majorana mass terms are forbidden
  - $\overline{\Psi}_i X^n Y^m \ldots \Psi_j \sim 1 \rightarrow$ Dirac mass terms are allowed by Z_4.

Example model: Dirac Type I seesaw

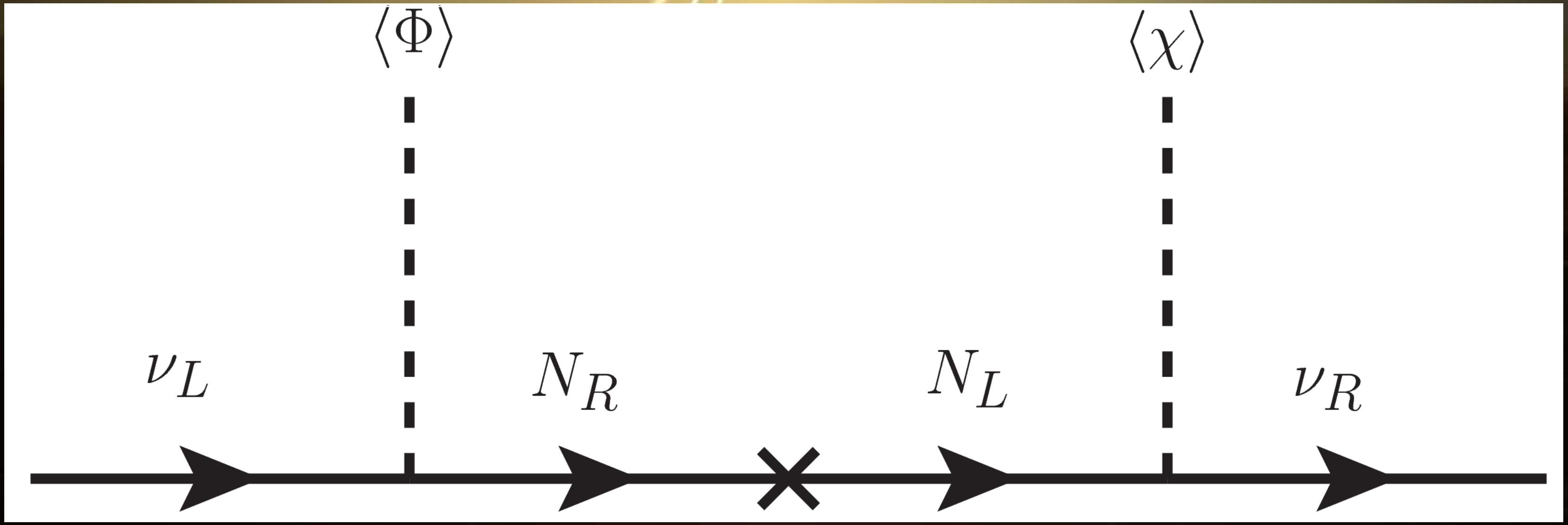
- Quarticity symmetry is imposed to ensure Diracness of neutrinos.

- Heavy neutral Dirac fermion, singlet under $SU(2)_L$ is introduced: N_L and N_R → seesaw!



Example model: Dirac Type I seesaw

- A new $SU(2)_L$ singlet scalar with non-zero vev is needed for neutrino mass: χ → coupling between $\overline{N}_L\ \chi\ \nu_R$
- Leading order contribution to neutrino masses:



Example model: Dirac Type I seesaw

- An extra symmetry is needed to forbid the tree level term $\bar{L}\,\Phi^c\,\nu_R$.
- A simple Z_2 can do the job → simple model 1606.04543
- Bigger symmetry groups can lead to flavour predictions: $\Delta(27)$ 1606.06904, A_4 1706.00210.

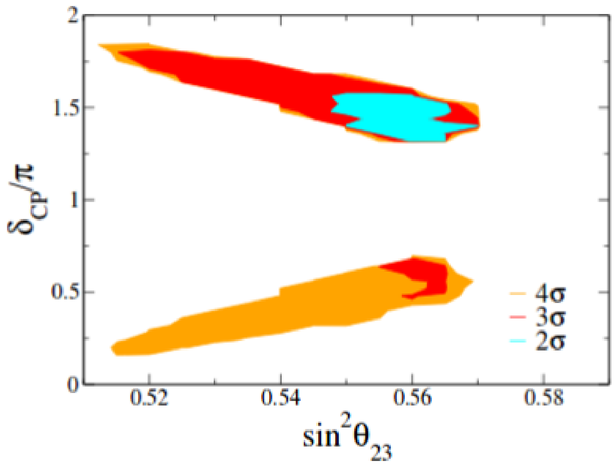


Figure 1: Allowed regions at 2, 3 and 4σ in the plane θ_{23}-δ_{CP} within the model, given the current global neutrino oscillation analysis.

SCC, Ma, Srivastava, Valle 1606.04543

SCC, Srivastava, Valle 1606.06904

SCC, Srivastava, Valle 1706.00210

Plot extracted from Srivastava, Ternes, Tórtola, Valle 1711.10318

Connection with dark matter

- There can be a connection between the Diracness of neutrinos and DM stability.

- The Quarticity symmetry can also stabilize a dark matter candidate.

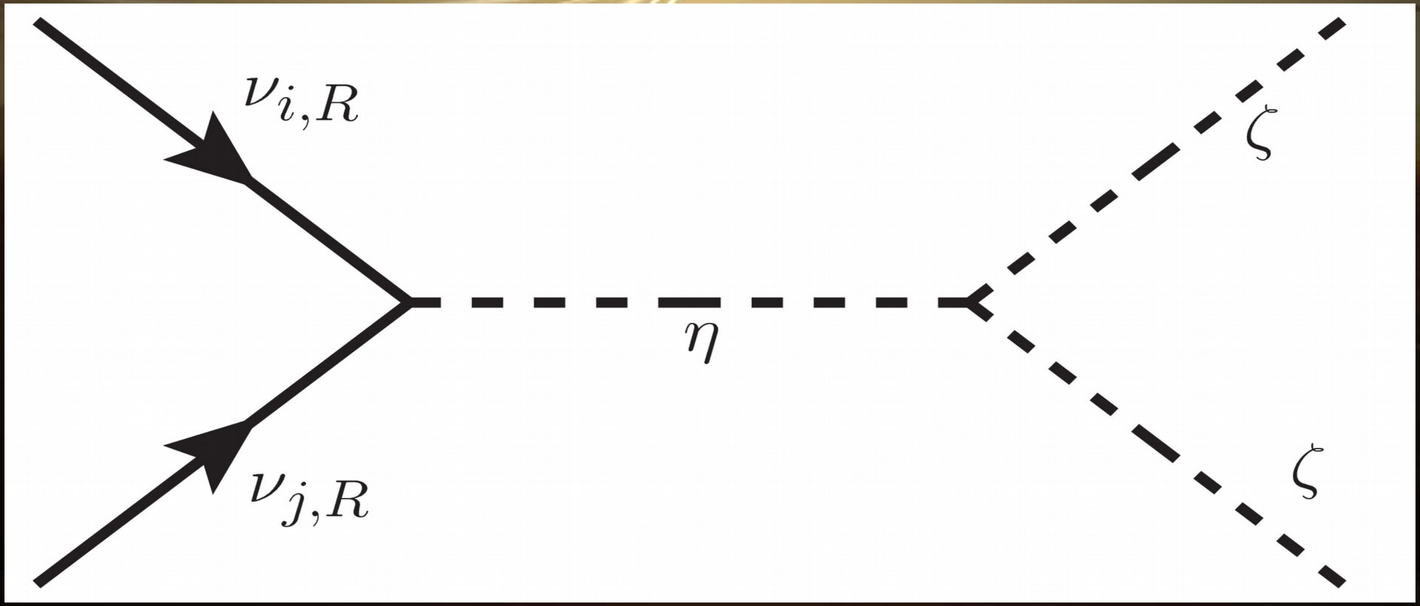
- Deep connection between Dirac neutrinos and dark matter.

Dark matter Stability

- Reminder: All leptons transform as z and all scalars with vev transform as the identity.
  - $\Psi_i \sim z$, If $\langle X \rangle \neq 0 \rightarrow X \sim 1$
- Up to this point, all Lorentz invariant structures transform as even powers under Z_4.
- A new scalar ζ transforming as z will be stable:
  - $\zeta\, (\overline{\Psi}_i^c\ \Psi_j)^n (\overline{\Psi}_k\ \Psi_l)^m X^p \ldots \sim z^{odd} \rightarrow$ ζ cannot decay

Dirac Type I seesaw

- The 'dark sector' of the model also includes a real scalar $\eta \sim z^2$ which connects the dark and the visible sectors:



Dirac seesaw roadmap

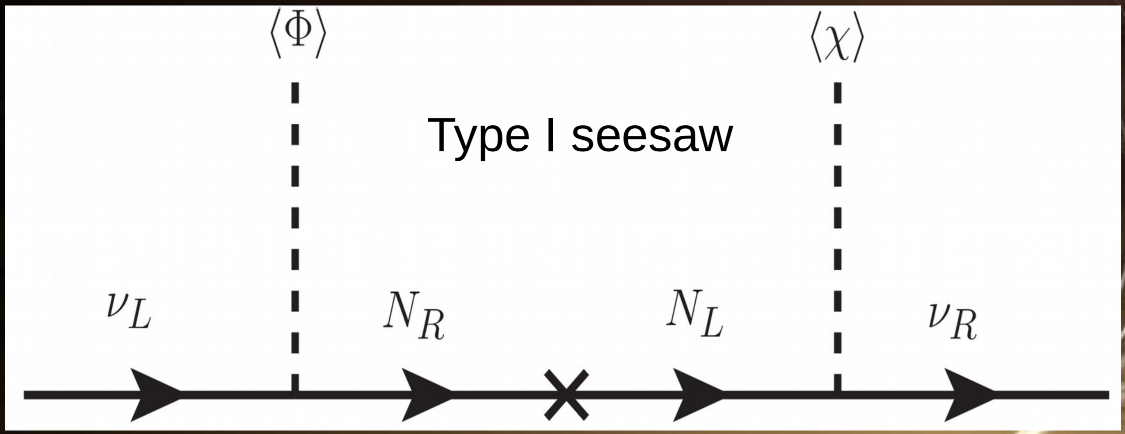
- Other Dirac seesaws can be realized.
- We recently described all the possible dimension 5 operators leading to Dirac neutrino masses → 1802.05722.
- We study the generic operator $\bar{L}\, X\, Y\, \nu_R$.
- If X transforms as an n-plet under $SU(2)_L$, then Y transforms as either n+1 or n-1.
    - For example if X is a singlet then Y must be a doublet.

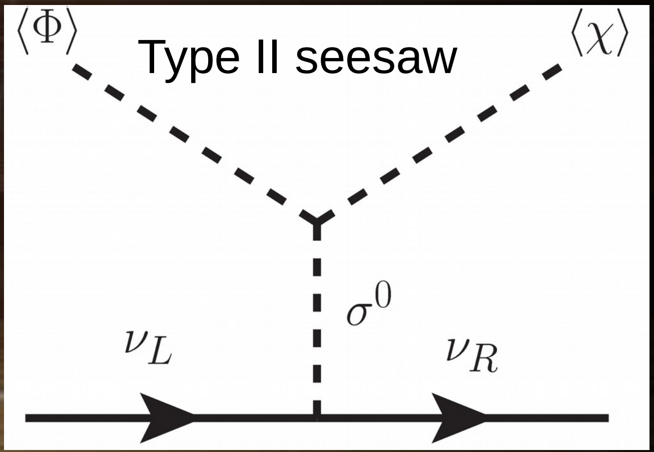
SCC, Srivastava, Valle 1802 05722

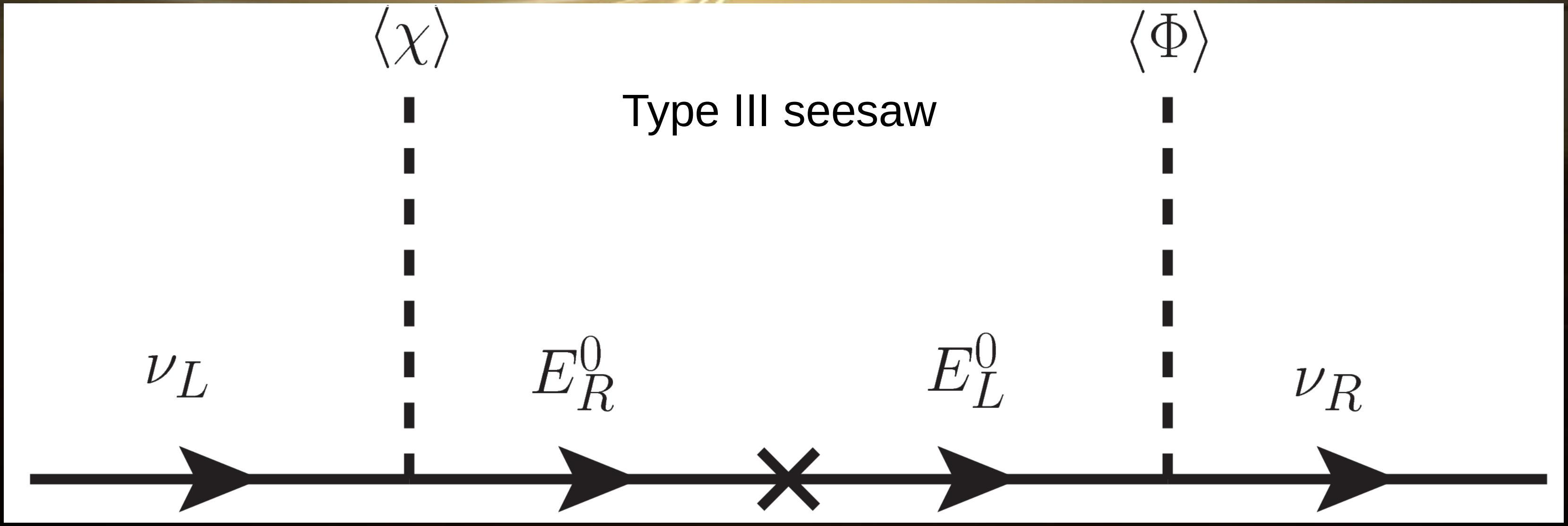
Dirac seesaw roadmap

- Restricting to singlets, doublets and triplets, there are only three different operators:
- $\bar{L}\,\chi\,\Phi^{c}\,\nu_R$ → Type I, II and III Dirac analogues.
- $\bar{L}\,\Phi^{c}\,\Delta_0\,\nu_R$ → Two 'Type III like' and one 'Type II like'.
- $\bar{L}\,\Phi\,\Delta_{-2}\,\nu_R$ → Identical $SU(2)_L$ contractions as the previous one.

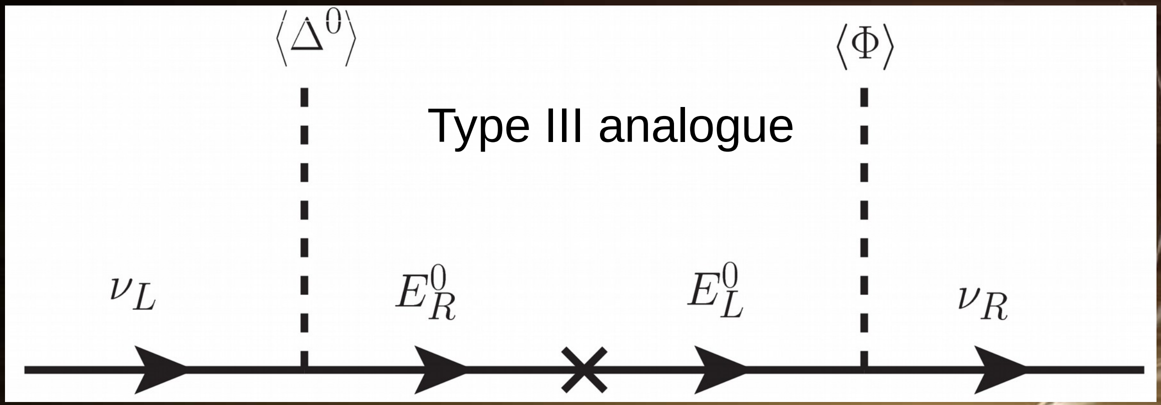
$$\overline{L}\,\chi\,\Phi^c\,\nu_R$$

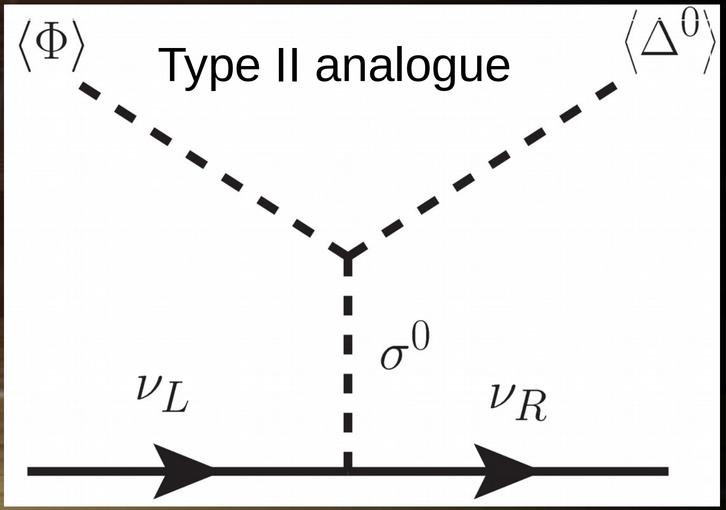


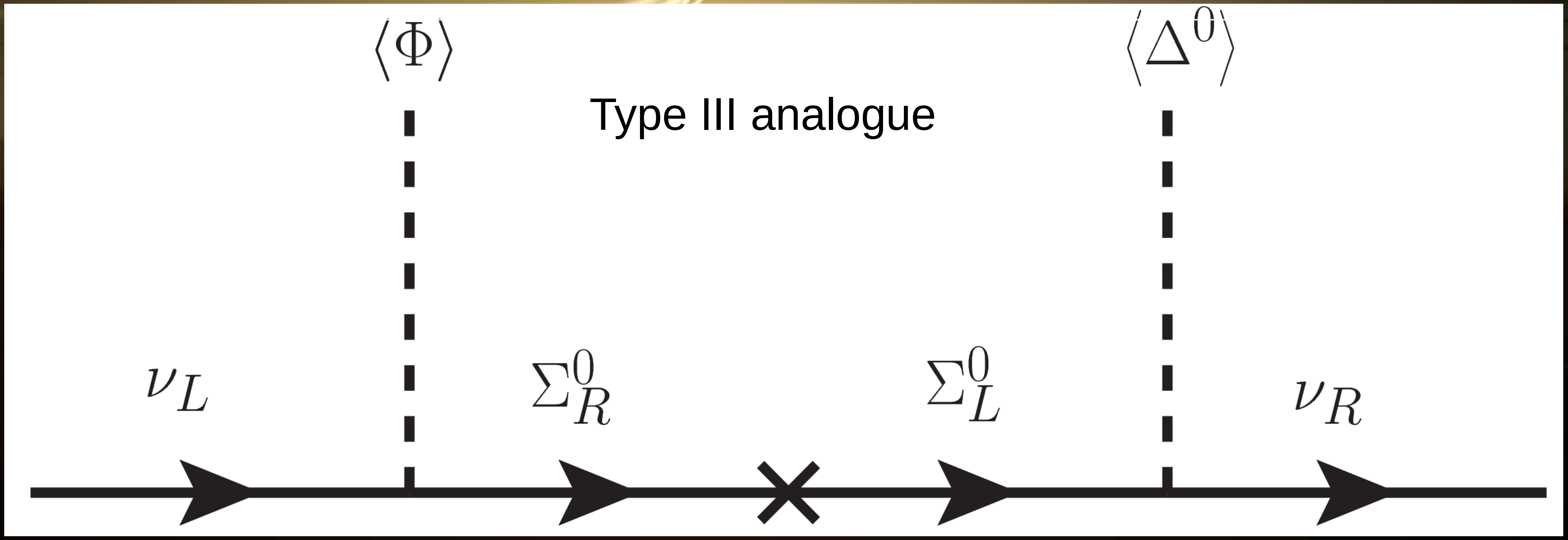




$\bar{L}\,\Delta_0\,\Phi^c\,\nu_R$ or $\bar{L}\,\Delta_{-2}\,\Phi\,\nu_R$







Higher dimension operators

- We also recently studied dimension 6 operators: 1804.03181
- The number of new models is quite big so I won't go into details.

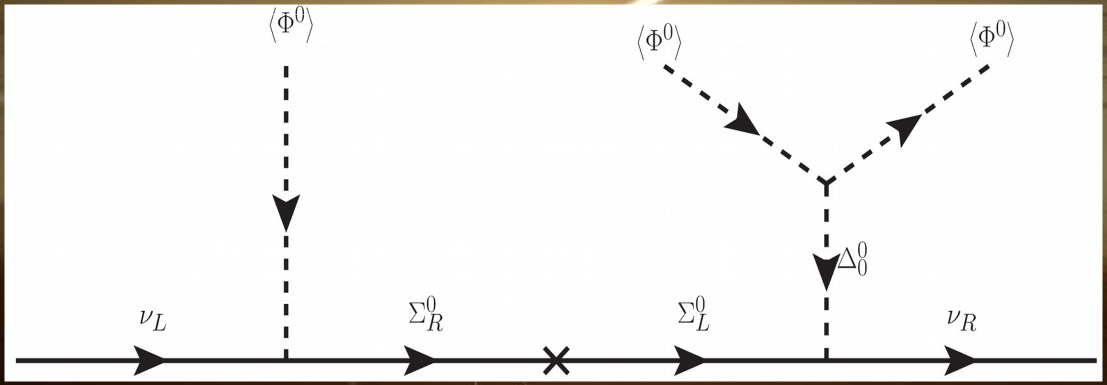
X	Y	Z	Operator	Diagrams	X	Y	Z	Operator	Diagrams
1	**1**	**2**	$L\,\chi\,\chi\,\Phi\,\nu_R$	10	**2**	**2**	**2**	$L\,\Phi\,\Phi\,\Phi\,\nu_R$	15
1	**2**	**3**	$\bar{L}\,\chi\,\bar{\Phi}\,\Delta_0\,\nu_R$	16	**1**	**1**	**2**	$\bar{L}\,\bar{\chi}\,\chi\,\bar{\Phi}\,\nu_R$	15
1	**2**	**3**	$\bar{L}\,\chi\,\Phi\,\Delta_{-2}\,\nu_R$	16	**2**	**3**	**3**	$\bar{L}\,\bar{\Phi}\,\bar{\Delta}_0\,\Delta_0\,\nu_R$	31
2	**3**	**3**	$\bar{L}\,\bar{\Phi}\,\Delta_0\,\Delta_0\,\nu_R$	16	**2**	**3**	**3**	$\bar{L}\,\bar{\Phi}\,\bar{\Delta}_{-2}\,\Delta_{-2}\,\nu_R$	26
2	**3**	**3**	$\bar{L}\,\Phi\,\Delta_0\,\Delta_{-2}\,\nu_R$	27					

Table I. Possible $SU(2)_L$ assignments for the scalars X, Y, Z; the allowed operators and number of associated UV-complete models in each case. Here $\bar{\Phi}$ denotes either $\Phi^\dagger$ or Φ^c, depending on the particular $SU(2)_L$ contractions. Note that the hypercharge of $\bar{\Phi}$ has the opposite sign than the hypercharge of Φ. Similar notation is used for other scalar multiplets.

SCC, Srivastava, Valle 1804.03181

Higher dimension operators

- The most interesting ones are the induced types.
- Inducing the vev of the external χ or Δ leads to a 'doubly suppressed' neutrino mass.



- Type III-like sesaw, accessible scale
- Collider phenomenology

Take-home ideas

- Neutrinos can be Dirac – open possibility
  - A new symmetry to protect Diracness is needed.
- Seesaw mechanism is compatible with Dirac neutrino masses.
  - A rich zoo of possibilities – just like in Majorana case.
- There can be a deep connection between the Dirac nature of neutrinos and dark matter stability.

Thank you for your attention

- Questions?

- References:

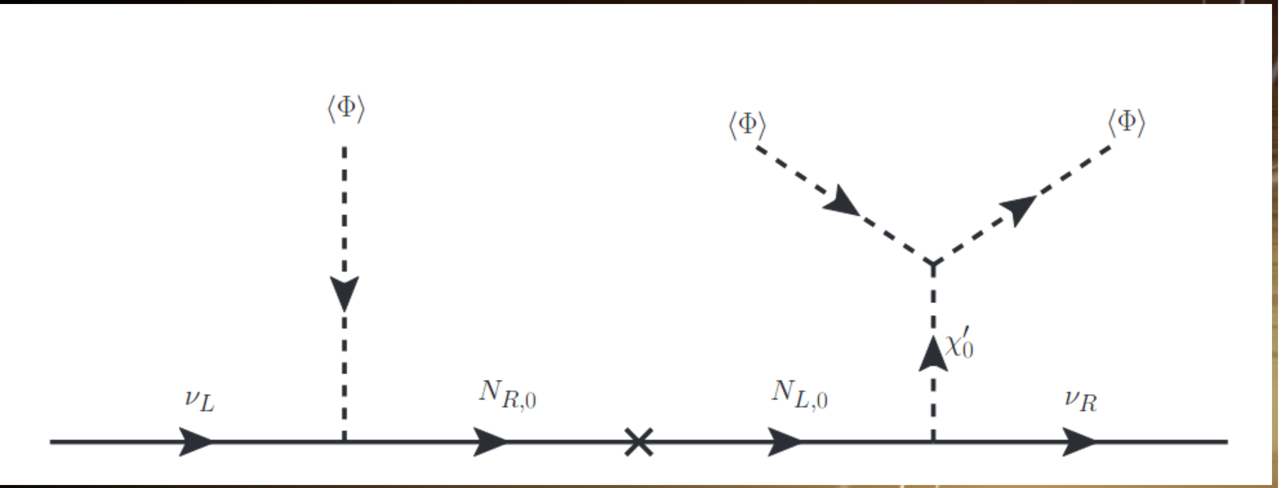
- **Dirac Neutrinos and Dark Matter Stability from Lepton Quarticity.** SCC, Ernest Ma, Rahul Srivastava, José W.F. Valle. Phys.Lett. B767 (2017) 209-213.
- **CP violation from flavor symmetry in a lepton quarticity dark matter model.** SCC, Rahul Srivastava, José W.F. Valle. Phys.Lett. B761 (2016) 431-436.

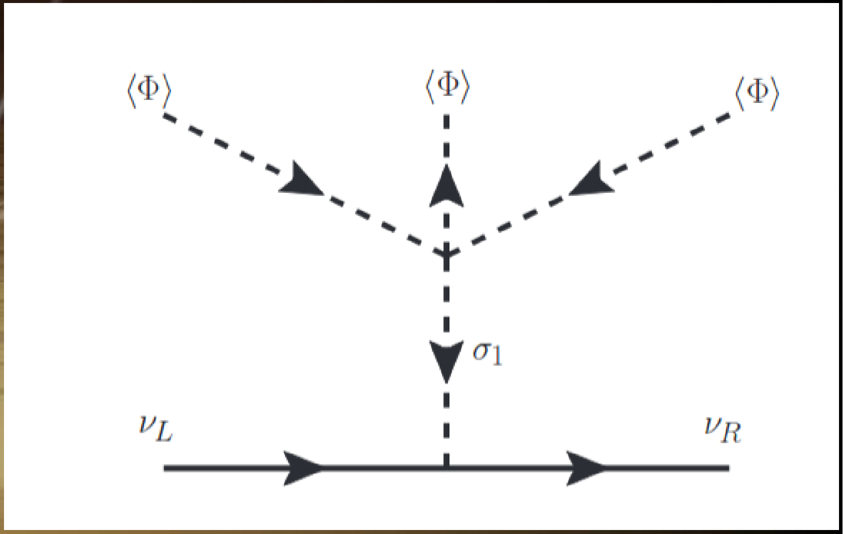
- **Generalized Bottom-Tau unification, neutrino oscillations and dark matter: predictions from a lepton quarticity flavor approach.** SCC, Rahul Srivastava, José W.F. Valle. Phys.Lett. B773 (2017) 26-33.

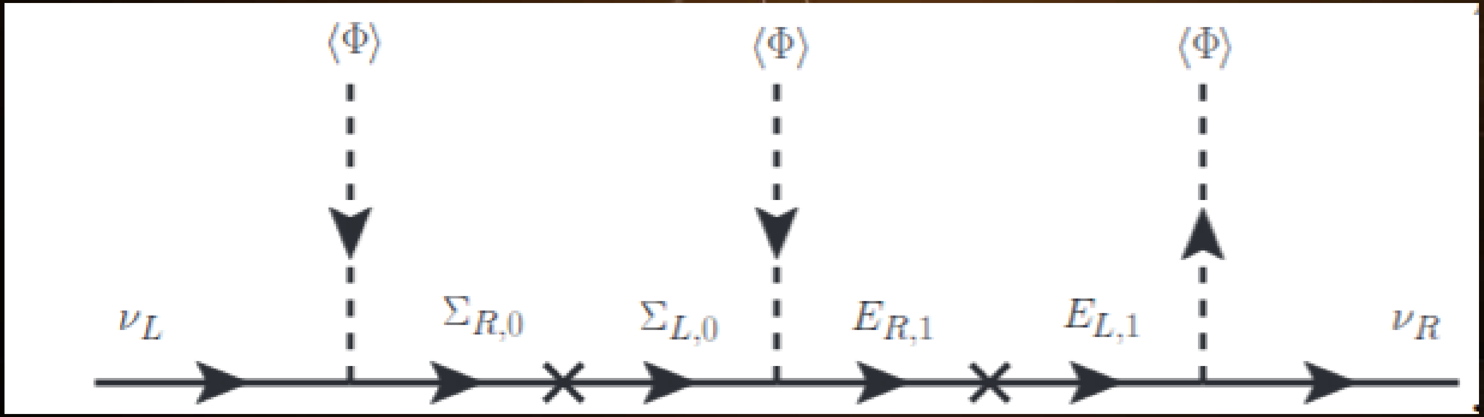
- **Seesaw roadmap to neutrino mass and dark matter.** SCC, Rahul Srivastava, José W.F. Valle. Phys.Lett. B781 (2018) 122-128

- **Seesaw Dirac neutrino mass through dimension-6 operators.** SCC, Rahul Srivastava, José W.F. Valle.

Backup slide: more dim 6 examples







Backup slide: A4 model

Fields	$SU(2)_L$	A_4	Z_4	Fields	$SU(2)_L$	A_4	Z_4
$\bar{L}_i$	**2**	**3**	$\mathbf{z}^3$	$\nu_{e,R}$	**1**	**1**	$\mathbf{z}$
$\bar{N}_{i,L}$	**1**	**3**	$\mathbf{z}^3$	$\nu_{\mu,R}$	**1**	$\mathbf{1}'$	$\mathbf{z}$
$N_{i,R}$	**1**	**3**	$\mathbf{z}$	$\nu_{\tau,R}$	**1**	$\mathbf{1}''$	$\mathbf{z}$
$l_{i,R}$	**1**	**3**	$\mathbf{z}$	$d_{i,R}$	**1**	**3**	$\mathbf{z}$
$\bar{Q}_{i,L}$	**2**	**3**	$\mathbf{z}^3$	$u_{i,R}$	**1**	**3**	$\mathbf{z}$
Φ_1^u	**2**	**1**	**1**	χ_i	**1**	**3**	**1**
Φ_2^u	**2**	$\mathbf{1}'$	**1**	η	**1**	**1**	$\mathbf{z}^2$
Φ_3^u	**2**	$\mathbf{1}''$	**1**	ζ	**1**	**1**	$\mathbf{z}$
Φ_i^d	**2**	**3**	**1**				

Table I. Charge assignments for leptons, quarks, scalars (Φ_i^u, Φ_i^d and χ_i) as well as "dark matter sector" (ζ and η). Here $\mathbf{z}$ is the fourth root of unity, i.e. $\mathbf{z}^4 = 1$.

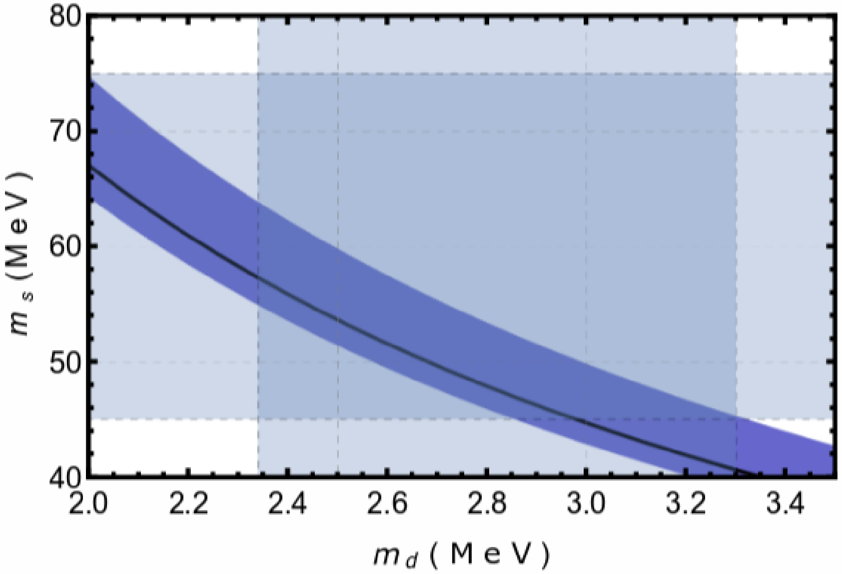
$$M_l = \begin{pmatrix} 0 & a_l\alpha & b_l \\ b_l\alpha & 0 & a_l r \\ a_l & b_l r & 0 \end{pmatrix}$$

$$M_{\nu,N} = \begin{pmatrix} 0 & 0 & 0 & a'_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & a'_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & a'_3 \\ y'_1 u_1 & y'_2 u_1 & y'_3 u_1 & M & 0 & 0 \\ y'_1 u_2 & \omega y'_2 u_2 & \omega^2 y'_3 u_2 & 0 & M & 0 \\ y'_1 u_3 & \omega^2 y'_2 u_3 & \omega y'_3 u_3 & 0 & 0 & M \end{pmatrix}$$

Backup slide: A4 model

$$M_u = \begin{pmatrix} y_1^u v_1^u + y_2^u v_2^u + y_3^u v_3^u & 0 & 0 \\ 0 & y_1^u v_1^u + \omega\, y_2^u v_2^u + \omega^2\, y_3^u v_3^u & 0 \\ 0 & 0 & y_1^u v_1^u + \omega^2\, y_2^u v_2^u + \omega\, y_3^u v_3^u \end{pmatrix}$$

$$M_d = \begin{pmatrix} 0 & a_d\alpha & b_d \\ b_d\alpha & 0 & a_d r \\ a_d & b_d r & 0 \end{pmatrix}$$



$$\frac{m_\tau}{\sqrt{m_e m_\mu}} = \frac{m_b}{\sqrt{m_s m_d}}$$