B-L breaking patterns, Dirac neutrinos and Dark Matter

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Outline

-Neutrino physics

- Smallness of neutrino mass ✓
- Dirac or Majorana? ✓
- Flavour structure
- Interactions with matter
- ...

-Dark Matter

- Cosmological implications
- Particle composition of DM ✓
- Stability of DM components ✓
- ...

Can we connect these pieces?

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: Types I, II and III, inverse, linear…
- Typically leads to Majorana neutrinos → **Not necessarily!**
- If neutrinos are Dirac, **an extra symmetry is needed** to forbid the tree level neutrino mass.

Dirac seesaw:
SCC, Ma, Srivastava, Valle 1606.04543
SCC, Srivastava, Valle 1606.06904, 1706.00210, 1802 05722, 1804.03181

Majorana seesaw:
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
- **Dirac scenario is as rich as the Majorana one**

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 an extra symmetry** to protect ‘Diracness’.

Dark matter problem

- Galactic rotation profiles
- Large scale structure
- Galaxy clusters gravitational mass
- CMB

…

- Negative experimental result (yet)
- Stability of the DM candidate sometimes **needs an extra symmetry**

New symmetries needed

- Dirac neutrinos need a symmetry to protect Diracness
- Dirac seesaw needs a symmetry to forbid tree-level mass term
- Dark matter requires a new symmetry for stabilization

Can we use less than 3 symmetries?

Quarticity Z_4 symmetry

- This symmetry is closely related with lepton number conservation: **discrete version of lepton number or B-L**
- 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

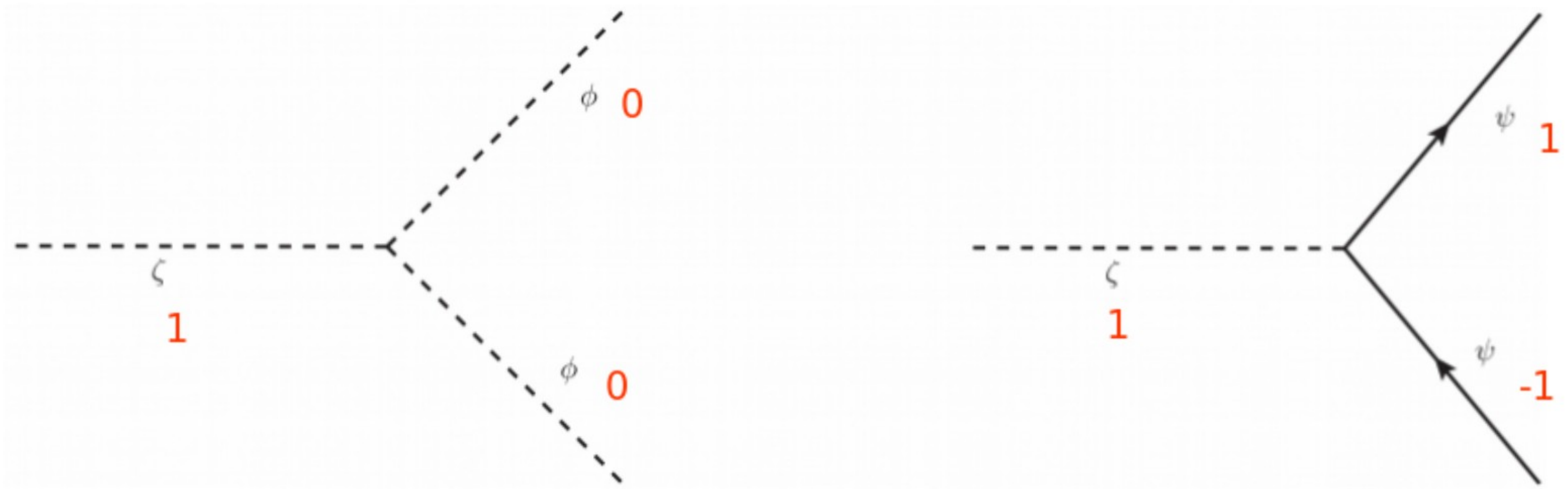
Dirac neutrinos

- 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.

Dark matter stability

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

Dark matter stability



Quarticity Z4 symmetry

- Connection between the Diracness of neutrinos and DM stability.
- Deeply related with lepton number (or B-L).
- Dirac seesaw needs an extra symmetry → Open door for flavour symmetries

SCC, Srivastava, Valle 1606.06904

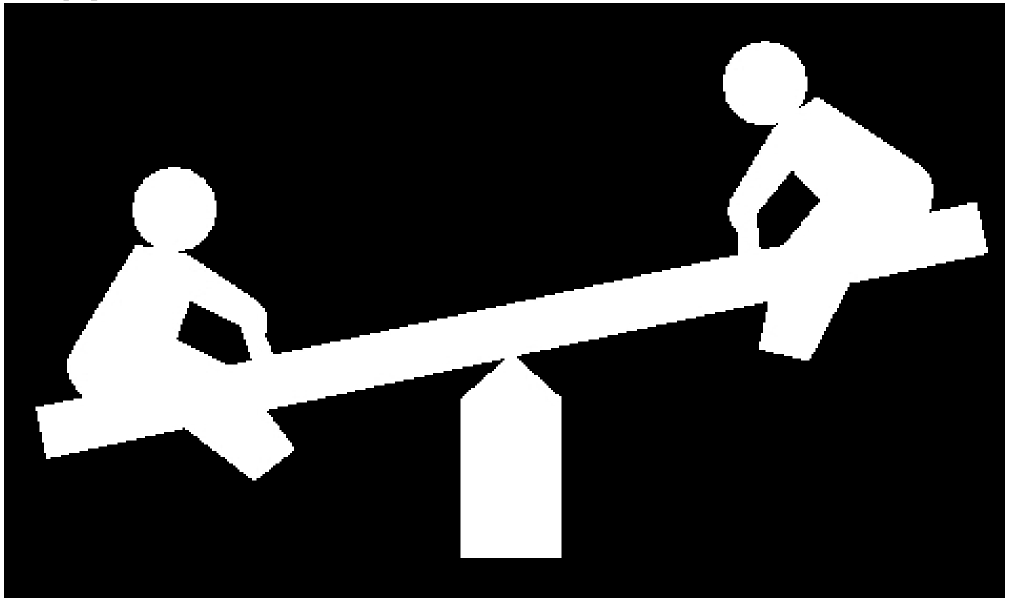
SCC, Ma, Srivastava, Valle 1606.04543

SCC, Srivastava, Valle 1706.00210

Example model: Dirac Type I seesaw

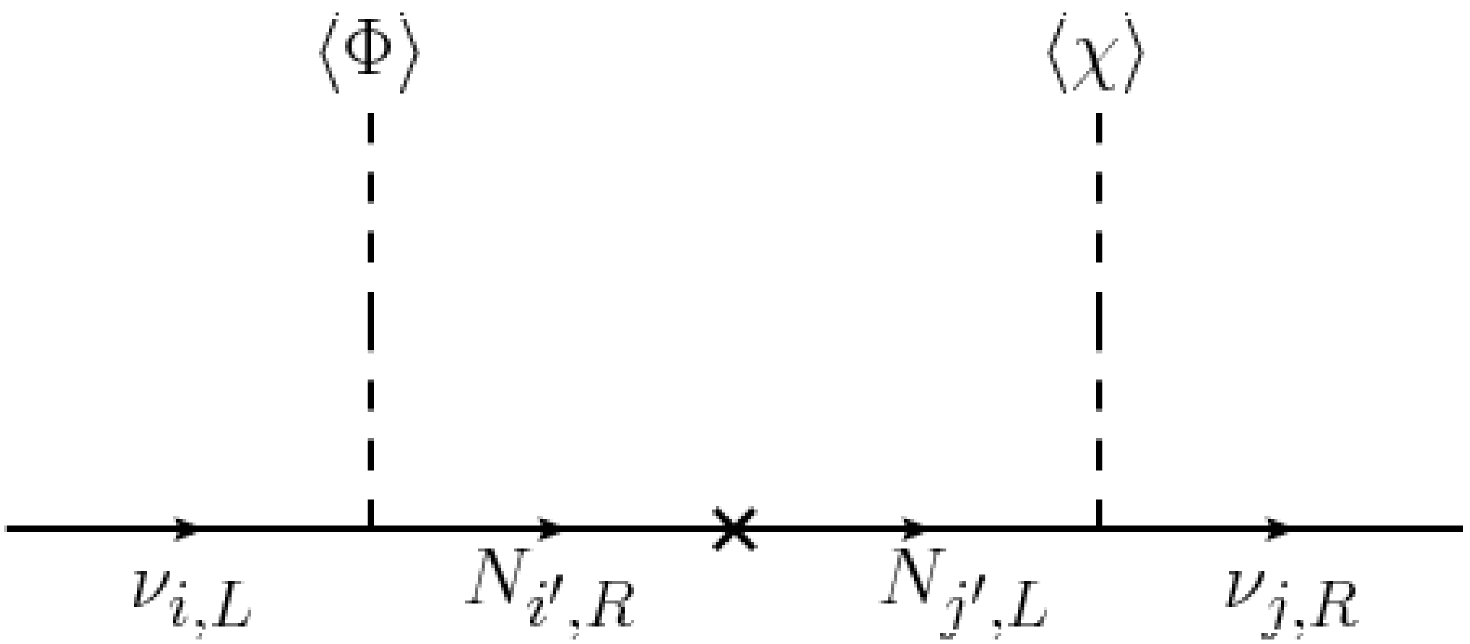
- Quarticity symmetry is imposed to ensure Diracness of neutrinos.

- 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 $\overline{L}\,\Phi^c\,\nu_R$.
- A simple Z_2 can do the job $\rightarrow$ simple model 1606.04543
- Bigger symmetry groups can lead to flavour predictions: $\Delta(27)$ 1606.06904, A_4 1706.00210.

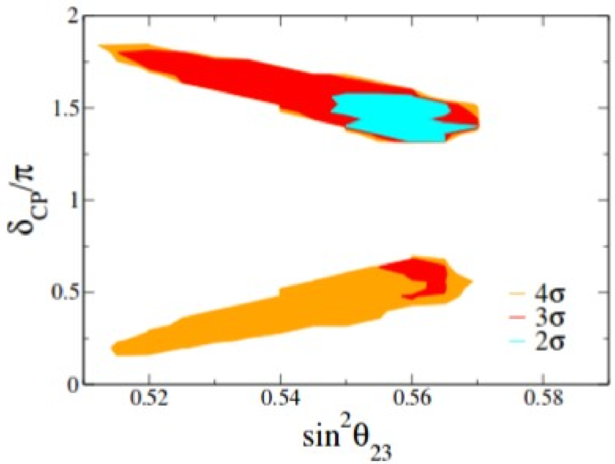


Figure 1: Allowed regions at 2, 3 and 4σ in the plane θ_{23}-δ_{CP} within the model, given the current global neutrino oscillation analysis.

SCC, Ma, Srivastava, Valle 1606.04543

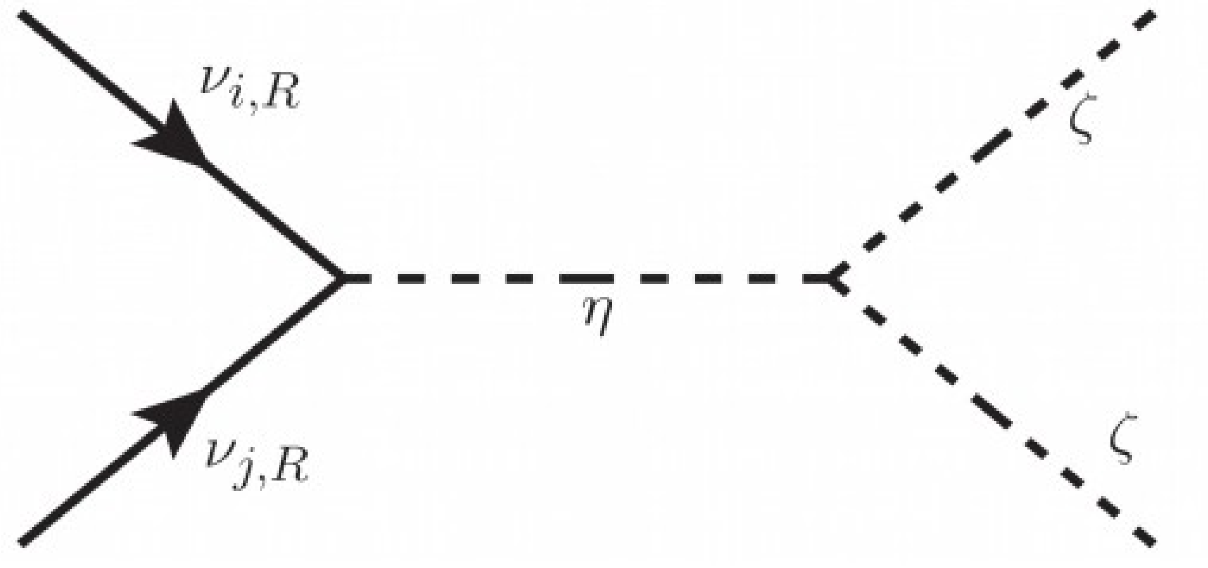
SCC, Srivastava, Valle 1606.06904

SCC, Srivastava, Valle 1706.00210

Plot extracted from Srivastava, Ternes, Tórtola, Valle 1711.10318

Dark sector

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



Higgs portal to the dark sector

- The Higgs boson can decay into two DM particles (invisible decay)
- Nuclear recoil mediated by the Higgs boson

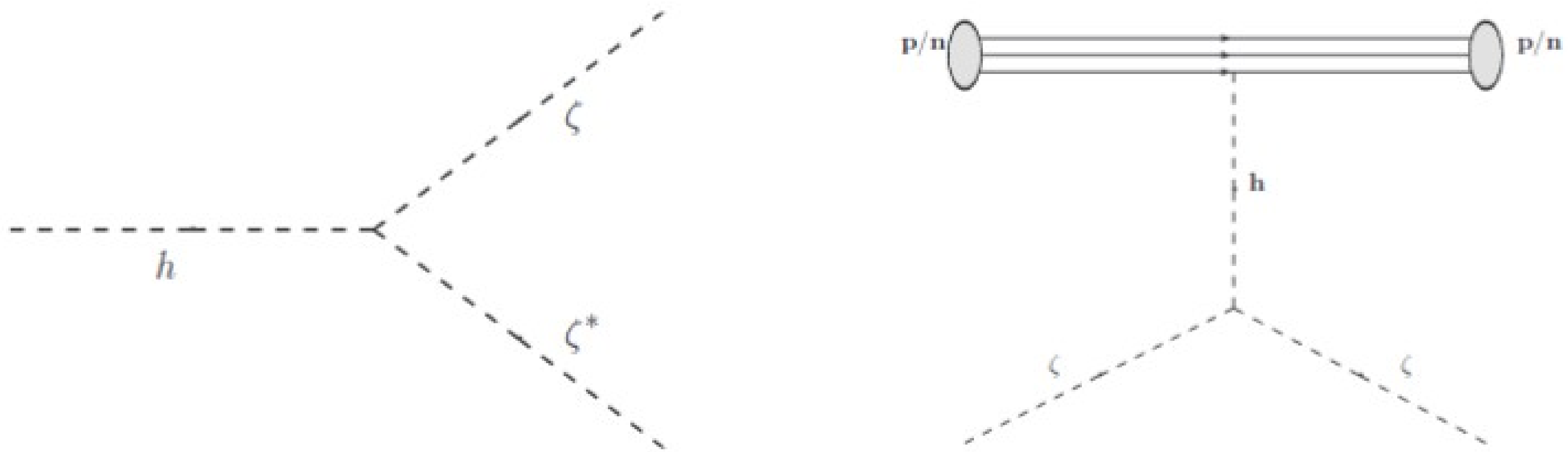


Figure 3. The diagrams for invisible Higgs decay to two dark matter particles and direct detection of dark matter through Higgs mediated nuclear recoil.

Example model: Dirac Type I seesaw

- Quarticity symmetry ensures both Diracness and DM stability (higgs portal, WIMP DM).

- Needs an extra symmetry to forbid tree level mass term and therefore having natural small masses implementing a Dirac seesaw. This extra symmetry can be a flavour symmetry.

Chiral anomaly free B-L

- B-L already in SM as an ‘accidental symmetry’
- Exotic charges under B-L for ν_R forbid the tree level mass term.
- Neutrino masses come from a loop with extra vev insertions and extra intermediate chiral fermions.
- The charges of the new particles must cancel the triangular anomalies.

Cepedello, SCC, Peinado, Srivastava 1901.06402, 1812.01599

Chiral anomaly free B-L

- The charges of the scalars with vev will determine the breaking pattern of B-L
  - If $U(1)_{B-L}$ breaks spontaneously to an even Z_n then we can have an stable scalar DM candidate.
  - If the lightest particle in the loop is an scalar and has an odd charge under Z_n it will be stable due to Lorentz invariance and Z_n.
  - If neutrinos **do not** transform as **n** or **0** under the remnant Z_{2n} (note this is not possible with $Z_2 \rightarrow$ minimum group is Z_4) they are automatically Dirac particles.

Chiral anomaly free B-L

- One symmetry to rule them all:
  - Neutrinos are Dirac fields
  - Stability of Dark matter
  - Small neutrino masses via loops

Example model: B-L → Z_6

- The charges of the particles in the example model are given by

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$	$\mathcal{Z}_6$
Fermions	L_i	$(\mathbf{2}, -1/2)$	-1	ω^4
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	$(\omega^4, \omega^4, \omega^4)$
	N_{L_l}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
	N_{R_l}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
Scalars	H	$(\mathbf{2}, 1/2)$	0	1
	χ	$(\mathbf{1}, 0)$	3	1
	η	$(\mathbf{2}, 1/2)$	$1/2$	ω
	ξ	$(\mathbf{1}, 0)$	$7/2$	ω

- One can check that triangular anomalies are cancelled (including gravity)

Example model: B-L → Z_6

•1-loop neutrino masses and symmetry breaking pattern:

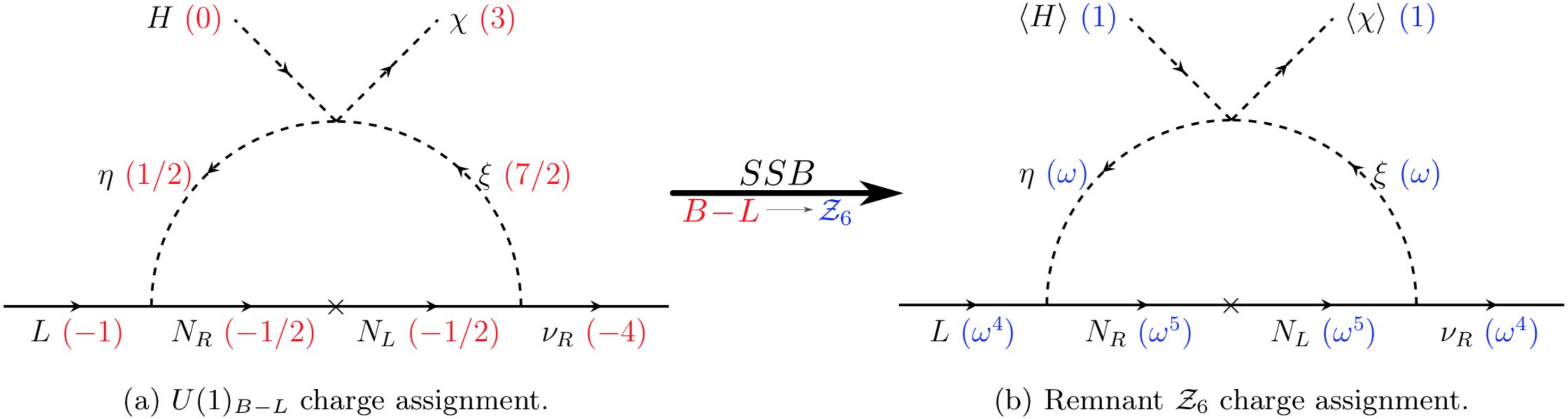


Figure 2: Charge assignment for the example model and its spontaneous symmetry breaking pattern.

•The lightest scalar in the loop -for example η_1- will be stable. Easy to check in the right diagram after SSB.

Take-home ideas

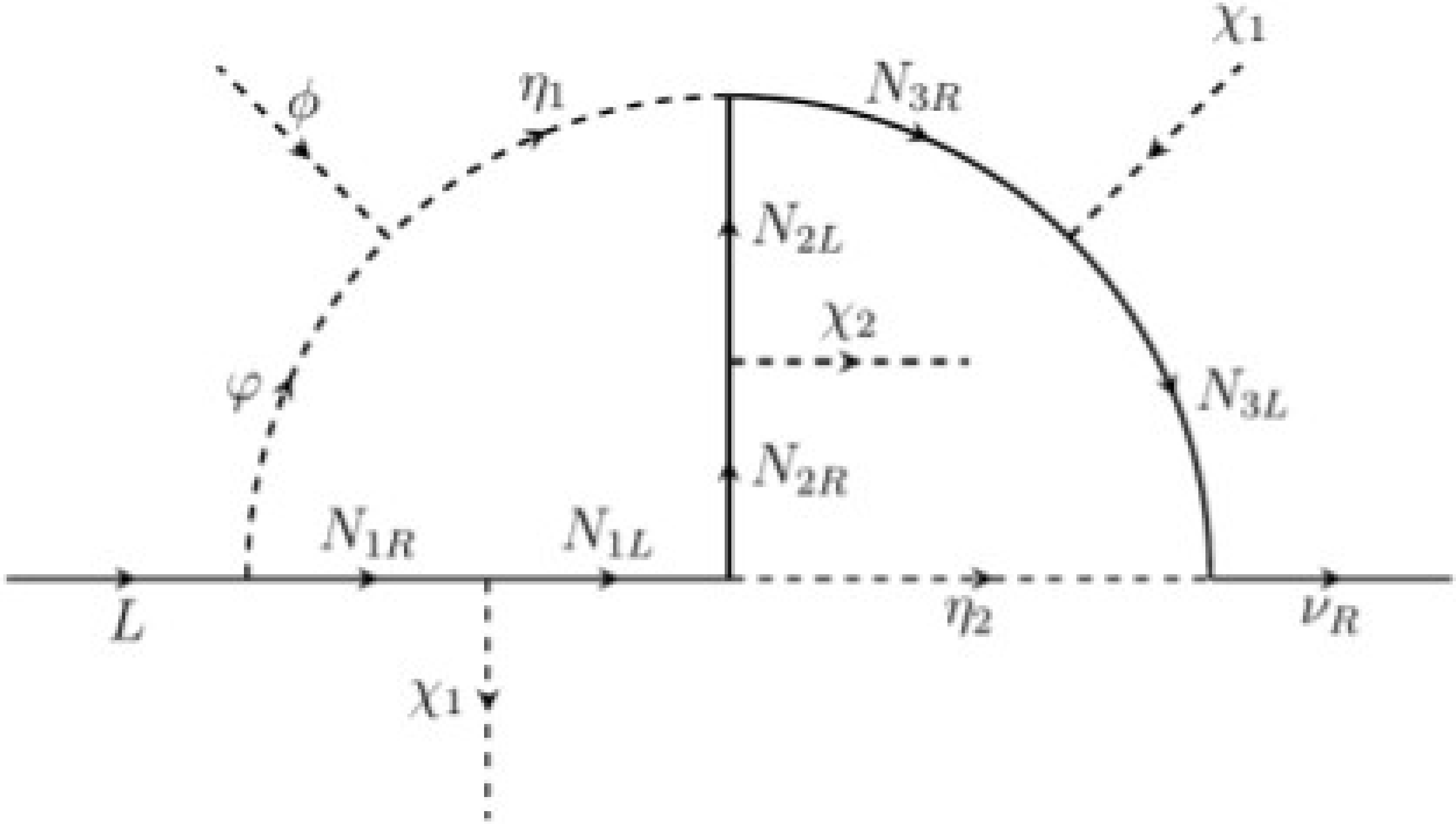
- Neutrinos can be Dirac – open possibility
  - A new symmetry to protect Diracness is needed → Lepton number (or B-L) is a natural option.
  - **Seesaw mechanism is compatible with Dirac neutrino masses**.
- There can be a deep **connection between Diracness and dark matter stability** → Example: Quarticity symmetry
- Chiral, anomaly-free B-L can lead to smallness of neutrino mass, Dirac neutrinos and stable DM **without the need of extra symmetries (explicit or accidental)**.

Thank you for your attention

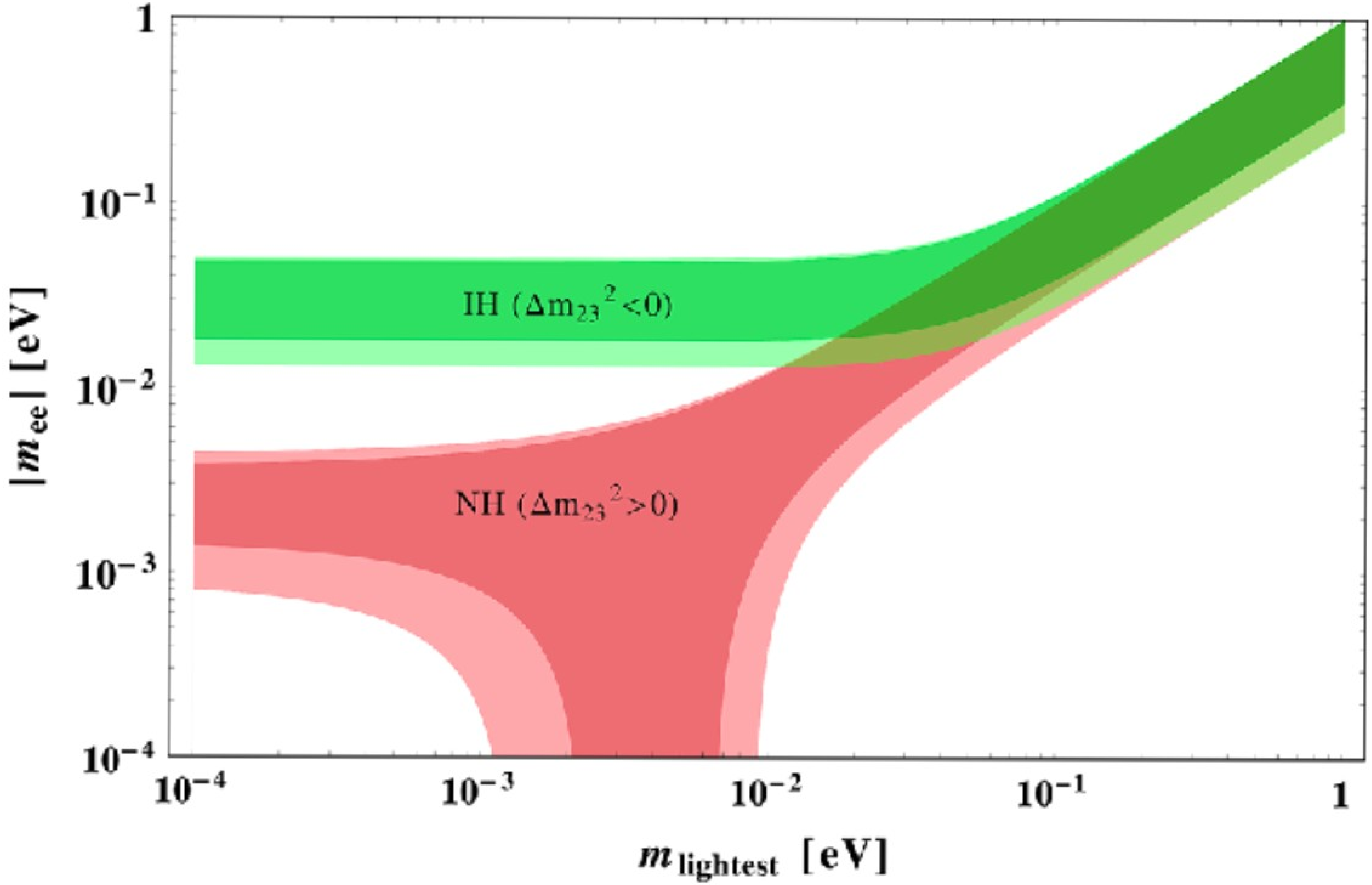
- Questions?

- 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.
- **Scotogenic dark matter and Dirac neutrinos using only Standard Model symmetries** Ricardo Cepedello, SCC, Eduardo Peinado, Rahul Srivastava 1812.01599



ϕ
η_1
N_{3R}
χ_1
N_{2L}
χ_2
φ
N_{3L}
N_{2R}
N_{1R}
N_{1L}
L
η_2
ν_R
χ_1



1
10−1
10−2
10−3
10−4
|mee| [eV]
IH (Δm23² <0)
NH (Δm23² >0)
10−4
10−3
10−2
10−1
1
mlightest [eV]

$$
\begin{aligned}
[SU(3)_c]^2\, U(1)_{B-L} &\rightarrow \sum_q (B-L)_{q_L} - \sum_q (B-L)_{q_R} \\
[SU(2)_L]^2\, U(1)_{B-L} &\rightarrow \sum_l (B-L)_{l_L} + 3 \sum_q (B-L)_{q_L} \\
[U(1)_Y]^2\, U(1)_{B-L} &\rightarrow \sum_{l,q} \left[Y_{l_L}^2\, (B-L)_{l_L} + 3\, Y_{q_L}^2\, (B-L)_{q_L} \right] - \sum_{l,q} \left[Y_{l_R}^2\, (B-L)_{l_R} + 3\, Y_{q_R}^2\, (B-L)_{q_R} \right] \\
U(1)_Y\, [U(1)_{B-L}]^2 &\rightarrow \sum_{l,q} \left[Y_{l_L}\, (B-L)_{l_L}^2 + 3\, Y_{q_L}\, (B-L)_{q_L}^2 \right] - \sum_{l,q} \left[Y_{l_R}\, (B-L)_{l_R}^2 + 3\, Y_{q_R}\, (B-L)_{q_R}^2 \right] \\
[U(1)_{B-L}]^3 &\rightarrow \sum_{l,q} \left[(B-L)_{l_L}^3 + 3\, (B-L)_{q_L}^3 \right] - \sum_{l,q} \left[(B-L)_{l_R}^3 + 3\, (B-L)_{q_R}^3 \right] \\
[\text{Gravity}]^2\, [U(1)_{B-L}] &\rightarrow \sum_{l,q} \left[(B-L)_{l_L} + 3\, (B-L)_{q_L} \right] - \sum_{l,q} \left[(B-L)_{l_R} + 3\, (B-L)_{q_R} \right]
\end{aligned}
$$