Dark Matter Stability and Dirac Neutrinos using only SM Symmetries

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- Does it has at least the symmetries to ensure DM stability?

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- **Automatic Symmetries:** Lepton number $U(1)_L$ and Baryon number $U(1)_B$ are automatically conserved in SM
- $U(1)_B$ and $U(1)_L$ conservation has important consequences
  - **Baryon number conservation: Proton stability**
  - **Lepton number conservation: Dirac neutrinos**

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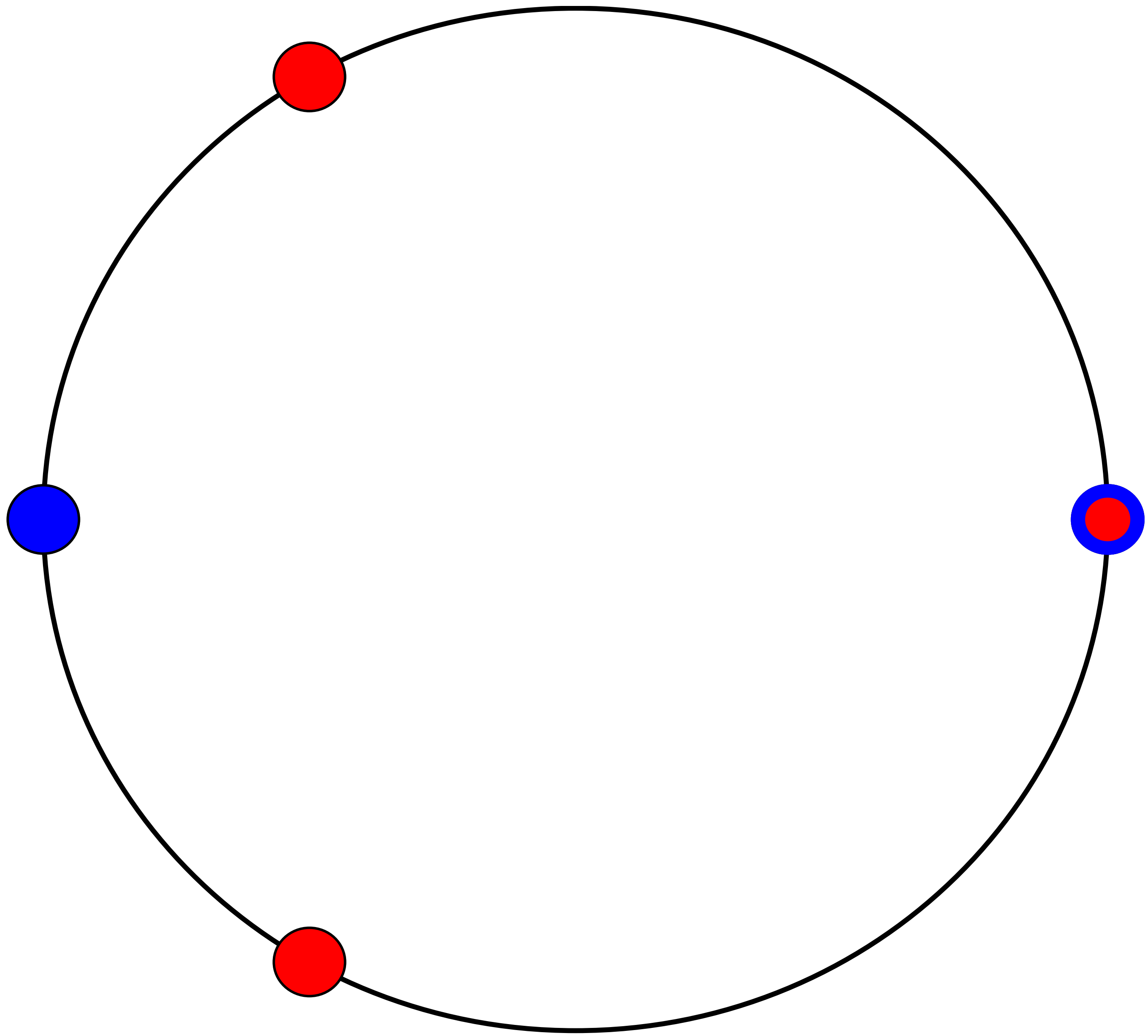
  - **Usual Choice:** Explicitly break $U(1)_L \to Z_2$ in UV completions (seesaw or loop) of Weinberg Operator

Nature of Neutrinos

Lepton Number Breaking Pattern **[Hirsch, RS, Valle '17]**

- If $U(1)_L$ is conserved: Neutrinos are Dirac
  - Accidental Symmetry of SM: New physics beyond SM need not conserve it
- If $U(1)_L$ is broken: Symmetry breaking pattern will determine the nature of neutrinos
  - $U(1)_L$ symmetry only admits Z_M subgroups i.e. cyclic groups of m elements
  - If x is a non-identity group element of Z_M, then $x^{M+1} \equiv x$
  - The Z_M groups only admit one-dimensional irreducible representations
  - Conveniently represented by using the n-th roots of unity, $\omega = Exp[2\pi I/M]$ where $\omega^M = 1$

Residual Subgroups



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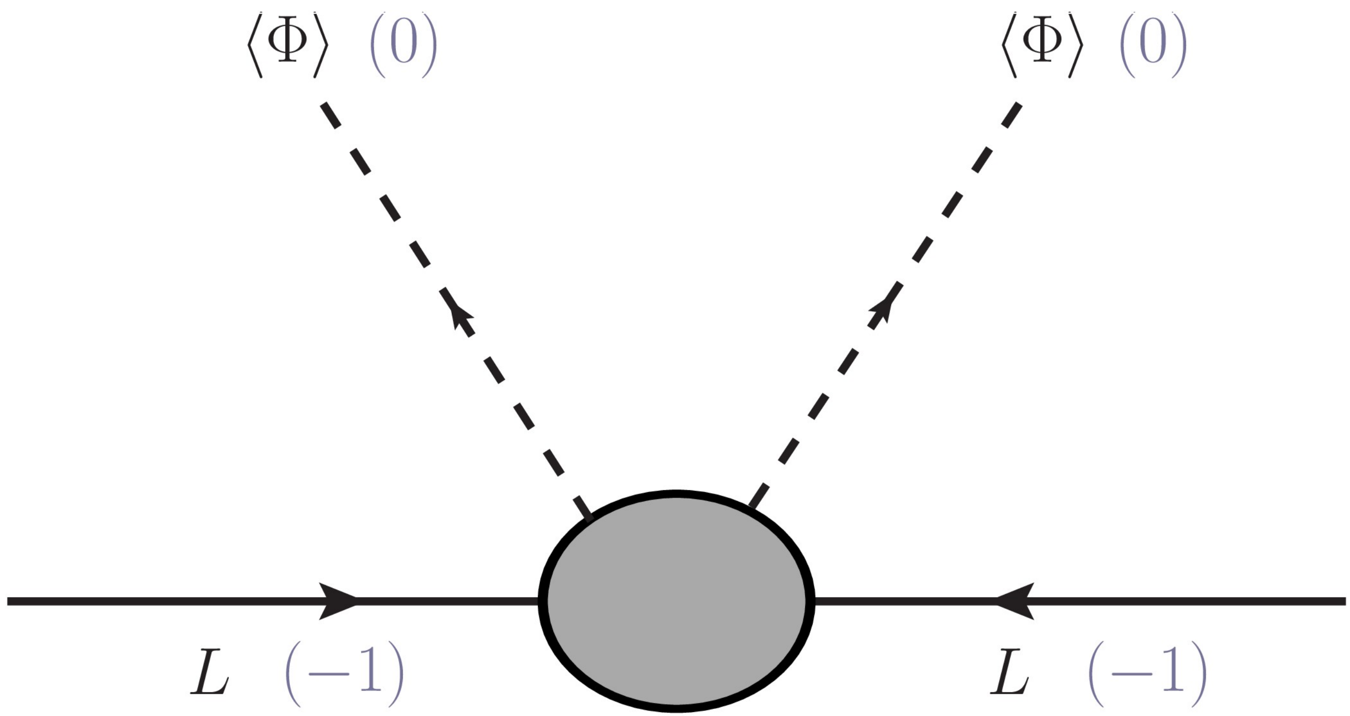
- From symmetry point of view: **Dirac neutrinos are more natural !!!**

Majorana Neutrinos: Weinberg Operator

- Weinberg Operator: Provides "effective" description of how Majorana neutrino mass can be generated **[S. Weinberg '79]**



- Breaks $U(1)_L \to \mathcal{Z}_2$
  - Both reps of $\mathcal{Z}_2$ satisfy the Majorana condition
  - **All UV completions of Weinberg operator will always lead to Majorana neutrinos**

Dirac Neutrinos and DM Stability from Lepton Number

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- **The dark sector participates in the loop**
  - The lightest particle being stable, a good DM candidate
- **We aim to accomplish all this with Lepton Number**
  - No extra explicit or accidental symmetries

Lepton Number of Right Handed Neutrinos

- Baryon and Lepton number of all SM particles are fixed
- What is the Lepton number of Right Handed Neutrinos?
  - B and L symmetries are anomalous
  - Only B – L combination can be anomaly free if lepton number carrying right handed neutrinos are added to SM
- Vector solution : Add three right handed neutrinos with B–L charges of (-1,-1,-1)

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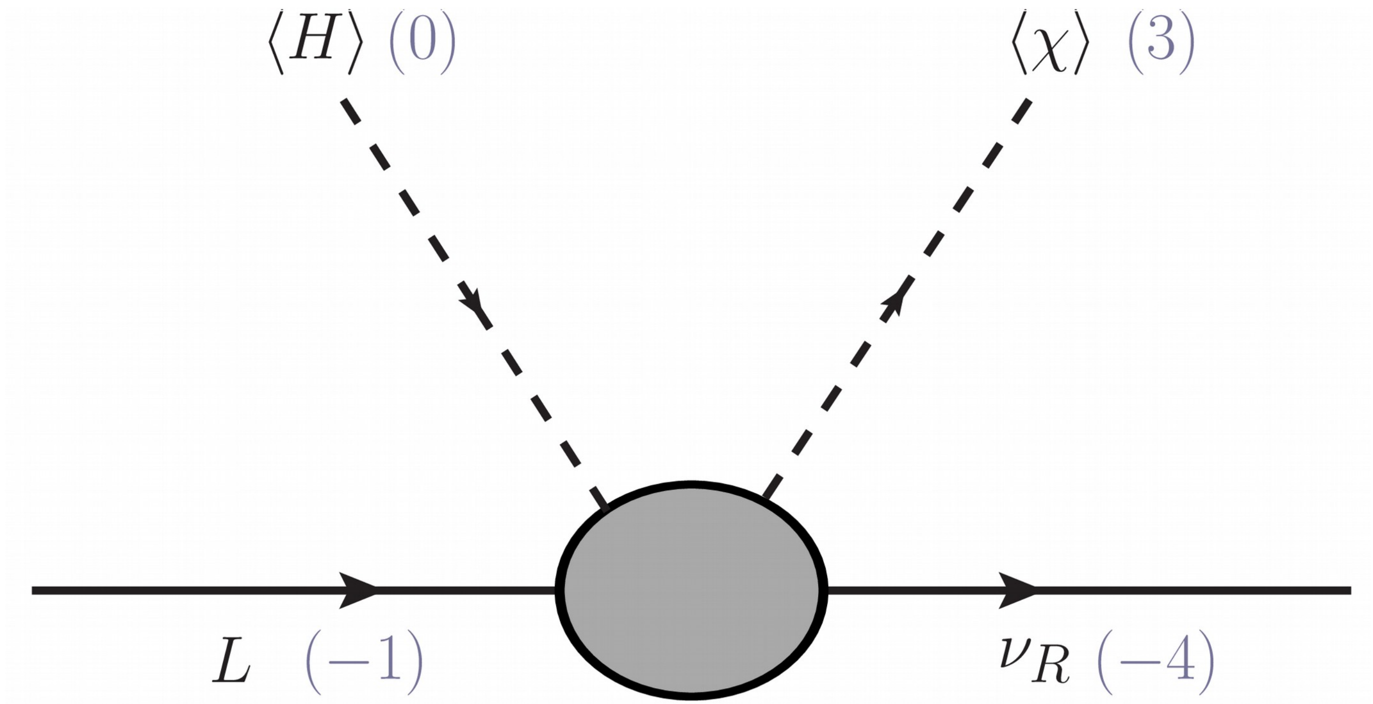
- **New Chiral Solution: Right handed neutrinos with B – L charges of (-4,-4,5)** **[Ma, RS '14, Pollard, Ma, RS, Reza '15]**
  - Yukawa term $L\tilde{\Phi}\nu_R$ automatically forbidden
  - Paves way for "naturally small" Dirac neutrino masses: **Dirac neutrino mass mechanisms**
    [RS et.al '15,'16,'17'18'19, Several other]

Generalized Weinberg Operator

- Neutrino Mass can be generated at dim-5 level

[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS ‘18,’19]



- Since $\chi \sim 3$, its vev breaks $U(1)_{B-L} \to \mathcal{Z}_{3m}; m \in \mathbb{Z}^+$
  - The exact residual subgroup depends on UV completion

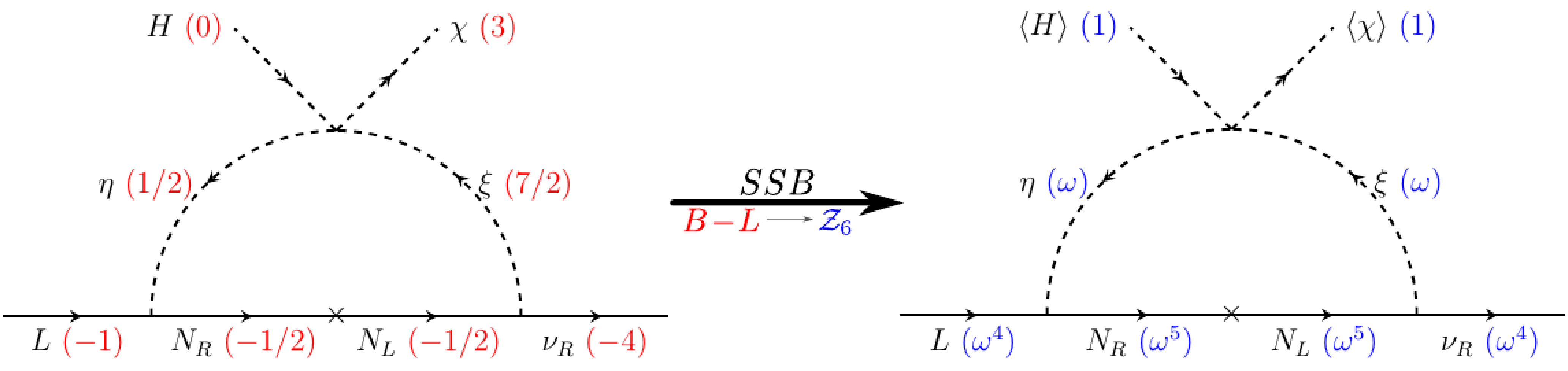
UV Completion

- One loop completion: Dark Sector particles in the loop *a la* Scotogenic models

  [C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS '18,'19]

- The Residual $\mathcal{Z}_{3m}$ subgroup should protect Diracness and Dark Matter stability
  - Exact subgroup fixed by the smallest B-L charge in model
  - If SM leptons have smallest charge then $U(1)_{B-L} \rightarrow \mathcal{Z}_3$
  - Turns out $\mathcal{Z}_3$ is too small **[C.Bonilla,E.Peinado,RS '19]**
    - Cannot insure DM stability on its own
- Break $U(1)_{B-L} \rightarrow \mathcal{Z}_6$
  - Can be achieved if the particles running in loop carry half integral B-L charges

UV Completion



(a) $U(1)_{B-L}$ charge assignment.

(b) Residual $\mathcal{Z}_6$ charge assignment.

[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS '18,'19]

- Here $\omega = e^{2\pi I/6}; \omega^6 = 1$ is the 6th root of unity.
- All particles carrying fractional B-L charges belong to Dark Sector
  - **Lightest Dark Sector particle will be Stable Dark Matter Candidate**

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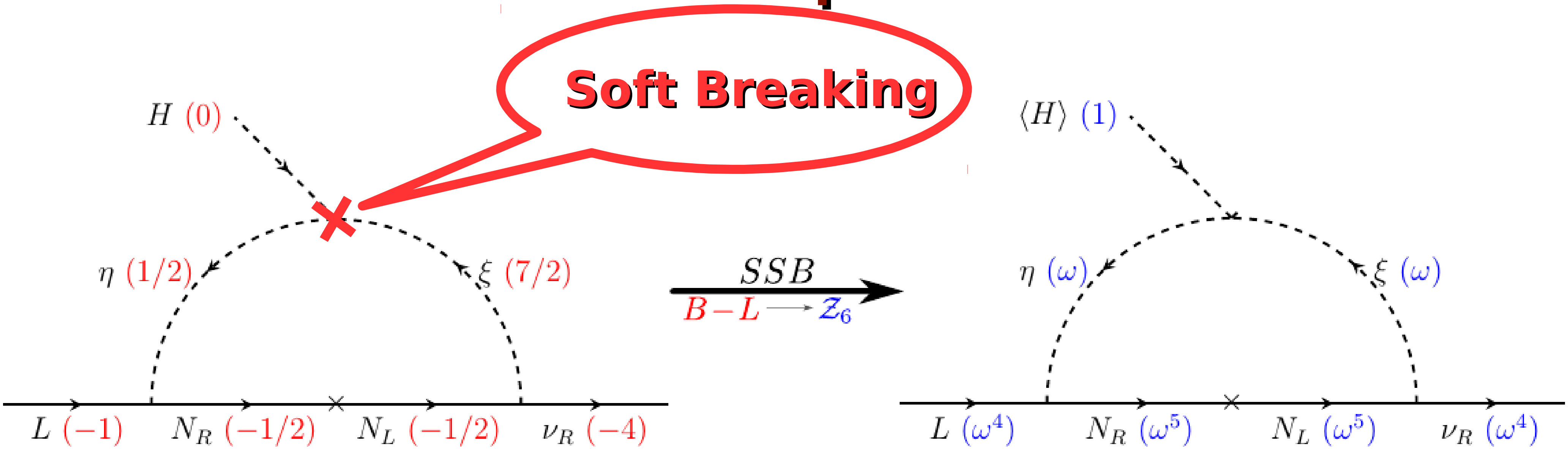

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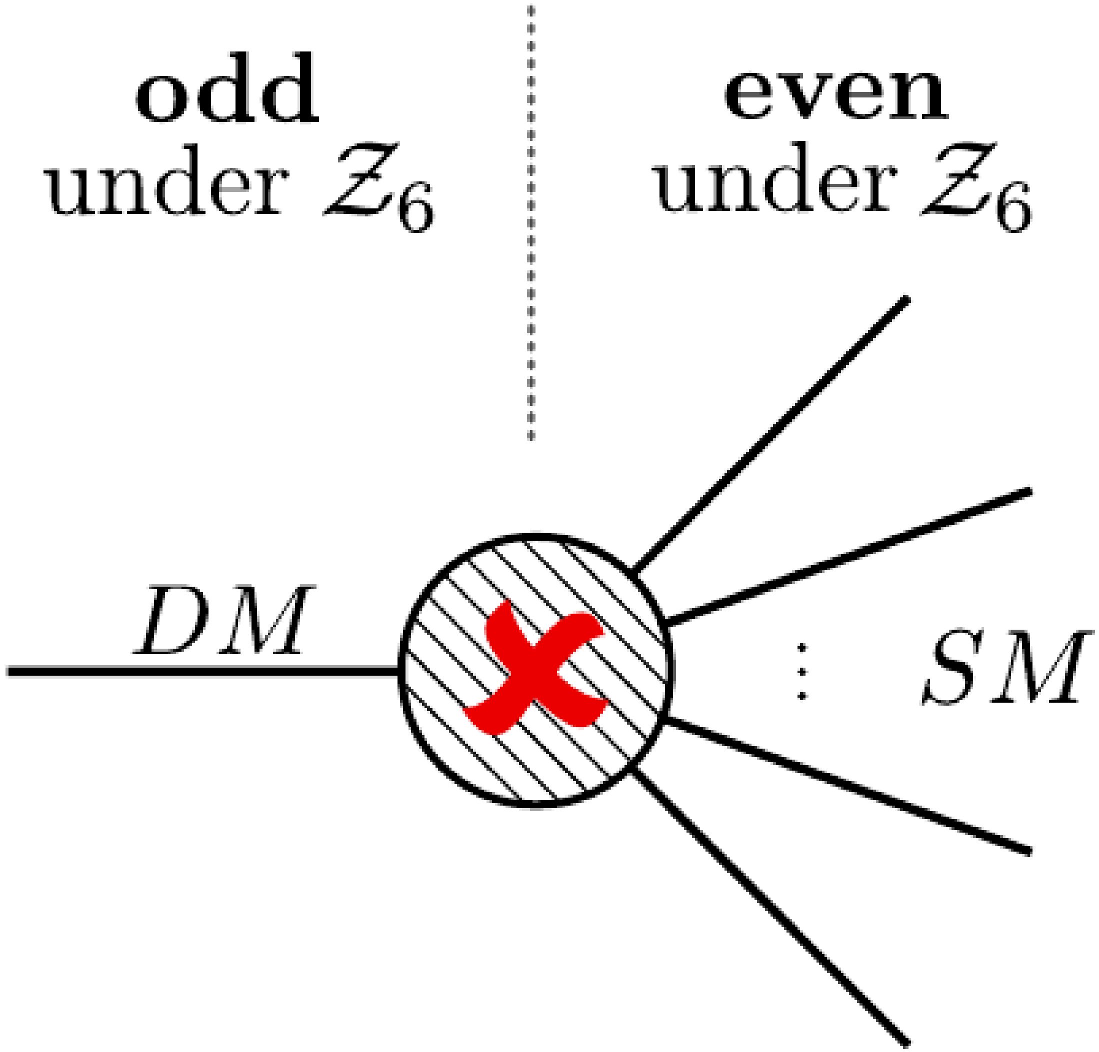
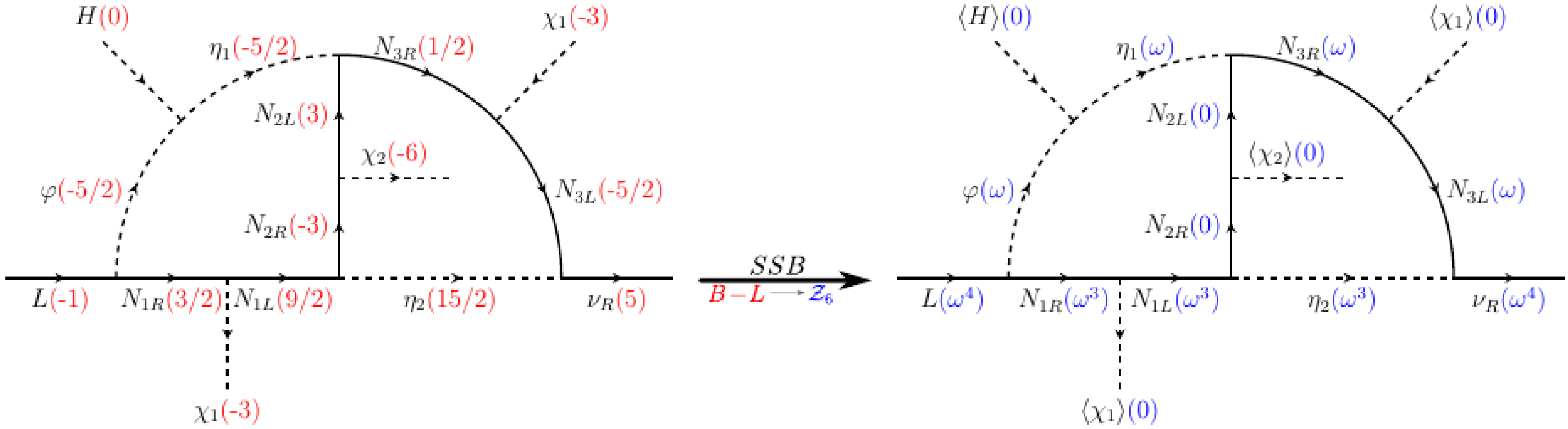


[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS ‘18,’19]

Two Loop Model

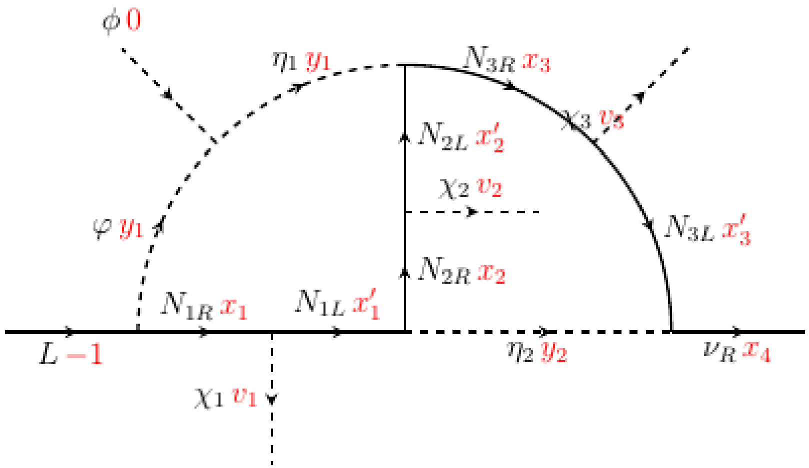


(a) $U(1)_{B-L}$ charge assignment.

(b) Remnant $\mathcal{Z}_6$ charge assignment.

[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS; Coming Soon]

General Two Loop Model



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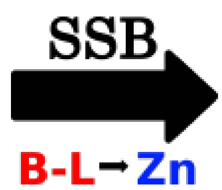
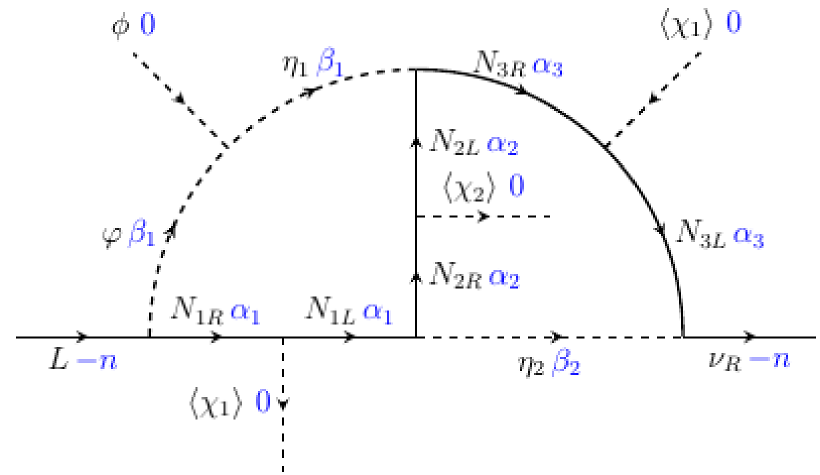


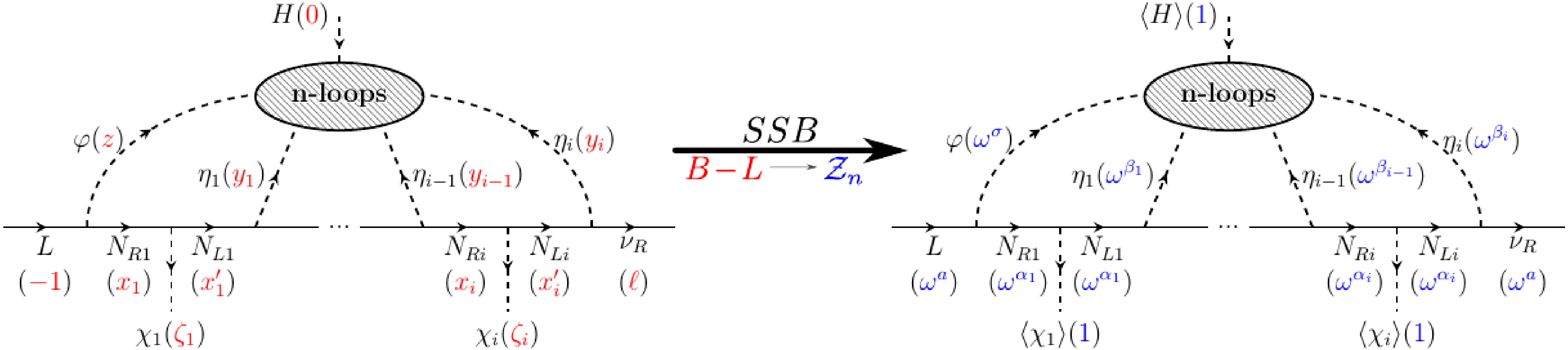


(b) General remnant $\mathcal{Z}_n$ charge assignament.

Figure 1: General charge assignment for a given topology and its spontaneous symmetry breaking

[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS; Coming Soon]

Completely General N Loop Formalism



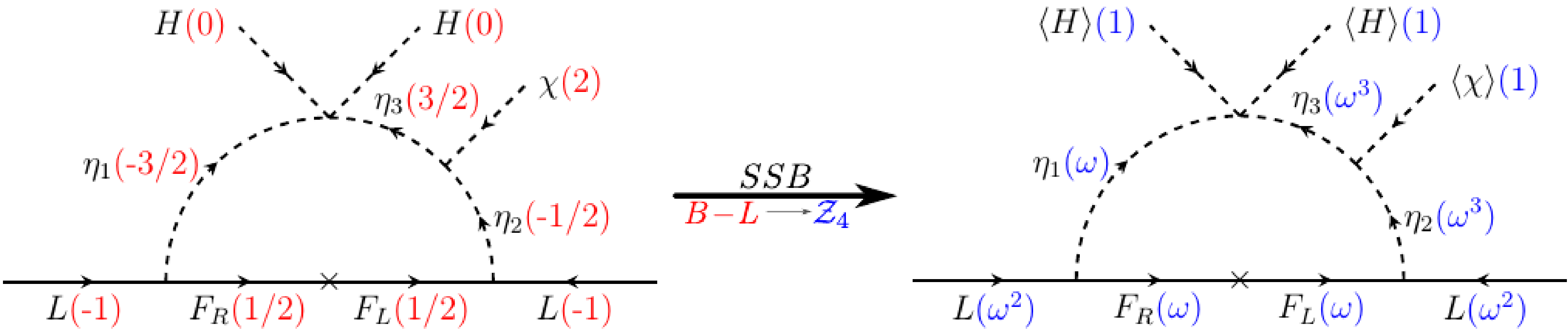
(a) General $U(1)_{B-L}$ charge assignment.

(b) General residual $\mathcal{Z}_n$ charge assignment.

Figure 1: General charge assignment for any topology and its spontaneous symmetry breaking pattern.

[C.Bonilla,S.C.Chulia,R.Cepedello,E.Peinado,RS ‘18]

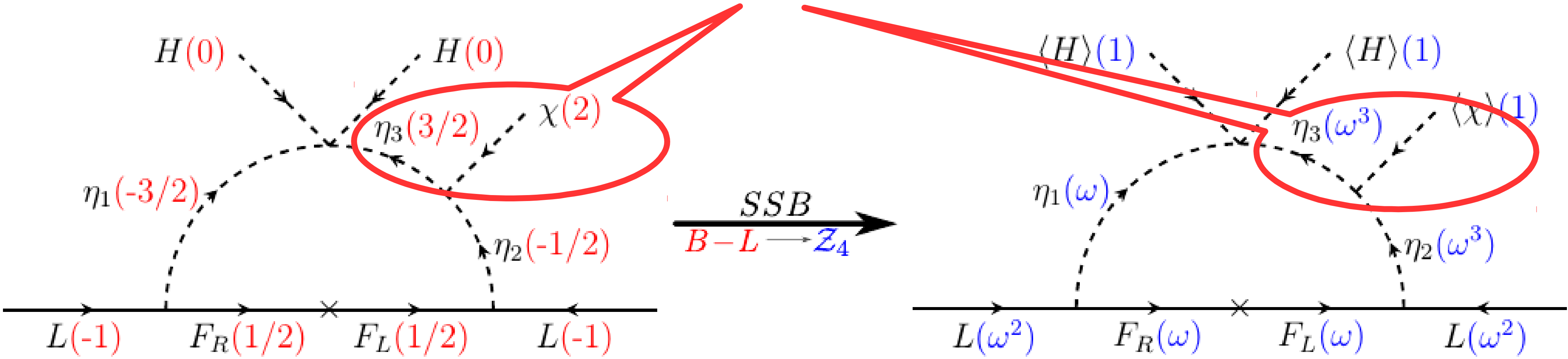
B-L Scotogenic for Majorana Neurinos



[S.C.Chulia,R.Cepedello,E.Peinado,RS '19]

B-L Scotogenic for Majorana Neurinos

Hard Breaking: Remove these fields



[S.C.Chulia,R.Cepedello,E.Peinado,RS ‘19]

Conclusions

- **Nature of Neutrinos and Dark matter are two of the most important open questions**
- **We definitely need additional particles beyond those in SM to account for Dark Matter as well as mass of neutrinos**
- **However, I hope I convinced you that the symmetries present in SM are enough to**
  - Account for Dark Matter stability
  - Protect Diracness of neutrinos
  - Explain the smallness of neutrino mass
- **The Dirac nature of neutrinos and Dark Matter Stability are intimately related**
  - Guaranteed by the same Residual Subgroup of B-L

Conclusions

- **The relation between Diracness and Dark Matter Stability is even deeper**
  - Also holds true for Dirac Seesaw Mechanisms **[S.C.Chulia,E. Ma, RS, J.W.F.Valle ‘16] [SCC, RS, JWFV, ‘17,’18, ‘19]**
  - The relation actually holds independent of the mass generation mechanism for Dirac neutrinos **[S.C.Chulia,RS, J.W.F.Valle ‘18]**
- **For certain special cases, the formalism discussed here can also be adopted for Majorana neutrinos** **[S.C.Chulia,R.Cepedello,E.Peinado,RS ‘19]**
  - Leads to a Scotogenic like mechanism

Thank You