Dirac Neutrinos via Lepton Quarticity and Self-Interacting Dark Matter

DOI: 10.1103/PhysRevD.109.055036

S. Mahapatra [1] V. Thounaujam [2] **Sujit K. Sahoo** [2] N. Sahu [2]

[1]Sungkyunkwan University [2]IIT Hyderabad

Introduction

- We put forward a connetion between Dirac nature of neutrinos and self-interacting dark matter. We have explored a $Z_4 \otimes Z_4'$ discrete symmetry. Wherein the cyclic symmetry Z_4 has been considered as a descrete manifestation of the Lepton number symmetry and the other Z_4' forbids the tree-level neutrino mass generation and the combination of these two discrete symmetries ensure the stability of DM.
- The sub-eV Dirac neutrino mass is produced through a type-I seesaw mechanism. As a consequence of its light mass, the model also features additional relativistic degrees of freedom $\Delta N_{\rm eff}$.
- Our setup also facilitates the realization of self-interacting dark matter with a light mediator that can alleviate small-scale anomalies of the ΛCDM while being consistent with the latter at large scales, as suggested by astrophysical observations.

Lepton Quarticity Model

Fields	Z_4	Z_4'	Fields	Z_4	Z_4'
$\overline{L}_L$	z^3	z'^3	ν_R	z	1
l_R	z	1	η	1	z'^2
Φ	1	z'	χ	z	z'
$N_{L,R}$	z	z'^2	S	z^2	z'^2

Table 1. Particle contents of the model with their charges.

The relevant Lagrangian,

$$-\mathcal{L} \supset f_{ij}\overline{L}_{L_i}\tilde{\Phi}N_{R_j} + g_{ij}\overline{N}_{L_i}\eta\nu_{R_j} + M_{ij}\overline{N}_{L_i}N_{R_j} + y_\chi\overline{\chi^c}\chi S + m_\chi\overline{\chi}\chi \; - \; V(\Phi,\eta,S),$$

where the scalar potential is given by,

$$V(\Phi,\eta,S) \;=\; -\mu_h^2(\Phi^\dagger\Phi) + \lambda_h(\Phi^\dagger\Phi)^2 - \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}(\Phi^\dagger\Phi)\eta^2 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{hS}}{2}(\Phi^\dagger\Phi)S^2 + \frac{\lambda_{\eta S}}{4}\eta^2 S^2.$$

Role of Z_4: Forbiding Majorana mass term for N_R and ν_R.
Role of Z_4': The seesaw neutrino mass generation by preventing tree-level coupling between ν_R and ν_L and the stability of DM is ensured.

Type-I Dirac Seesaw

The mass matrix in the basis of $(\overline{\nu_L}\;\; \overline{N_L})$ and $(\nu_R\;\; N_R)^T$ is given as:

$$M_{\nu N} = \begin{pmatrix} 0 & \mathbf{m} \\ \mathbf{m'} & M_N \end{pmatrix}$$

Diagonalizing the above mass matrix we obtain the light neutrino mass matrix as:

$$M_\nu = \mathbf{m}\, M_N^{-1}\, \mathbf{m'};\;\; \mathbf{m} = \mathbf{f}\, v/\sqrt{2}, \mathbf{m'} = \mathbf{g}\, u$$

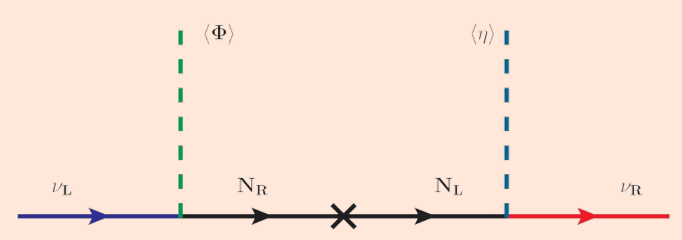


Figure 1. Dirac seesaw for neutrino mass generation.

- R is general complex matrix with 8 independent parameters.
- It plays a crucial role in tuning the f and g.

$$\mathbf{f} = \frac{\sqrt{2}}{v}\left(V_{lL}\sqrt{\hat{M}_\nu}\; R\; \sqrt{\hat{M}_N}\right)$$

$$\mathbf{g} = \frac{1}{u}\left(\sqrt{\hat{M}_N}\; R^{-1}\; \sqrt{\hat{M}_\nu} V_{lR}^\dagger\right).$$

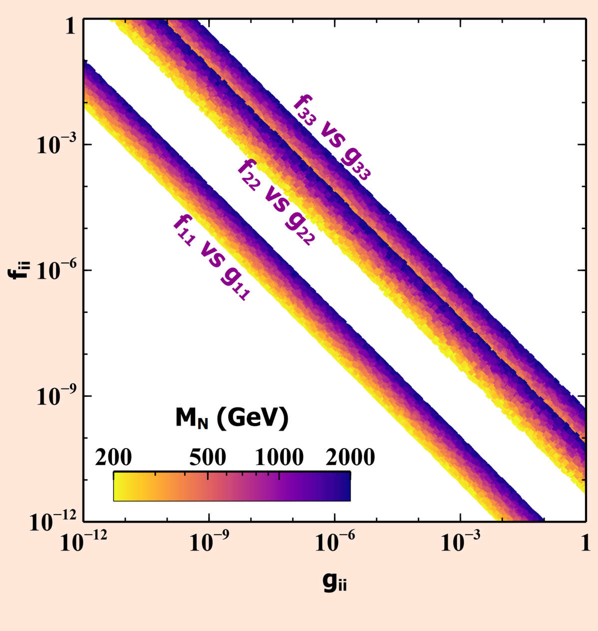


Figure 2. Dirac seesaw for neutrino mass generation.

Self-interacting DM

- The non-relativistic DM self-interacting potential is described as $V(r) = \frac{y_\chi^2}{4\pi r}e^{-M_S r}$
- The thermally averaged DM annihilation to meiators is $\langle\sigma v\rangle = \frac{3}{4}\frac{y_\chi^4}{16\pi M_\chi^2}v^2\sqrt{1-\frac{M_S^2}{M_\chi^2}}$.
- FOPT (first-order phase thansition) assists in extablishing the correct relic.

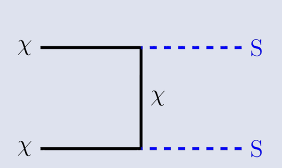


Figure 3. DM annihilation.

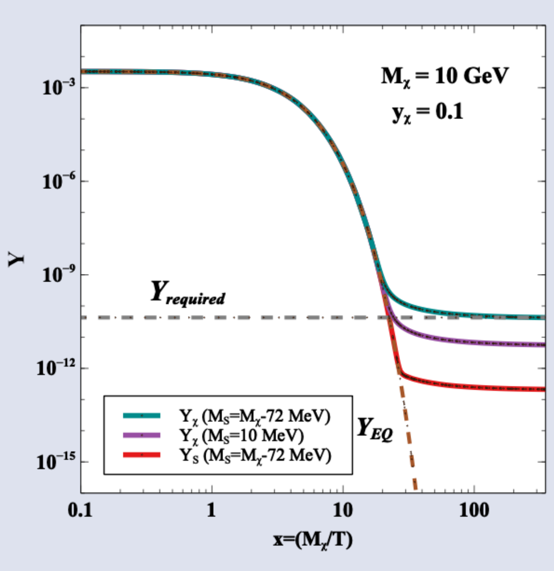
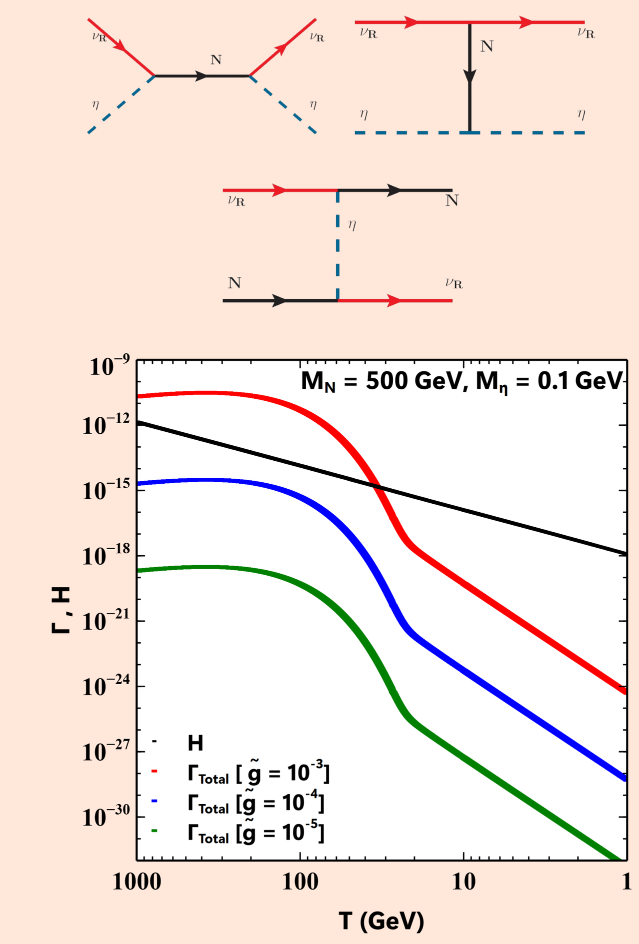


Figure 4. Direct detection of DM.

Thermal and Non-thermal production of ν_R



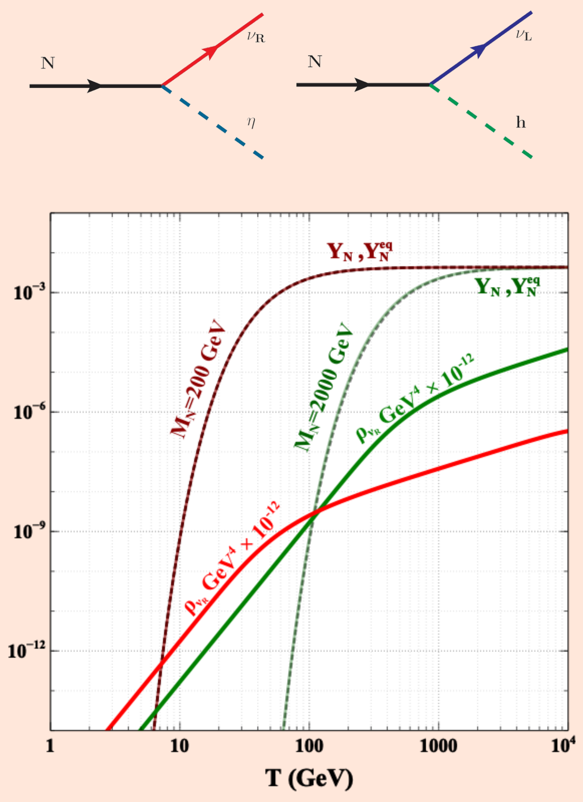


Figure 5. Evolution of ν_R energy density.

Estimating $\Delta N_{\rm eff}$

the total radiation energy density can be written as,

$$\Delta N_{\rm eff} \;=\; N_{\nu_R} \times \left.\frac{\rho_{\nu_R}}{\rho_{\nu_L}}\right|_{\rm T=T_{CMB}}$$

$$10^{-3} \leq \tilde{g} < \sqrt{4\pi} \qquad\qquad 10^{-12} < \tilde{g} < 10^{-3}$$

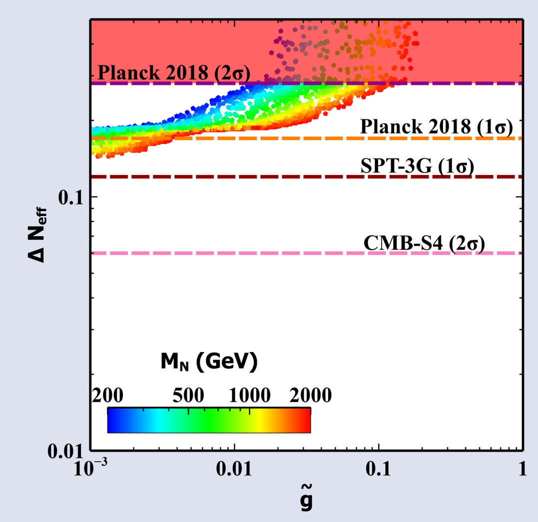


Figure 6. Thermal production of ν_R.

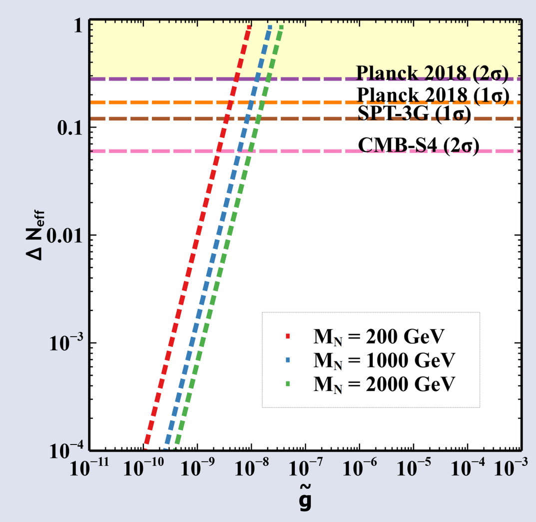


Figure 7. Non-thermal production of ν_R.

Direct detection of DM

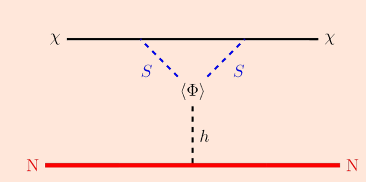


Figure 8. DM direct detection.

The DM-quark interaction of the form $C_q^{tri}\,\overline{q}q\overline{\chi}\chi$, with

$$C_q^{tri} = \frac{y_\chi^2}{16\pi^2 M_h^2 M_\chi}\left[\frac{\lambda_{hs}}{2}L\left(\frac{M_\chi^2}{M_S^2}\right)\right]m_q$$

Here $L(x) = (1 + x^{-1})ln(1 + x) - 1$

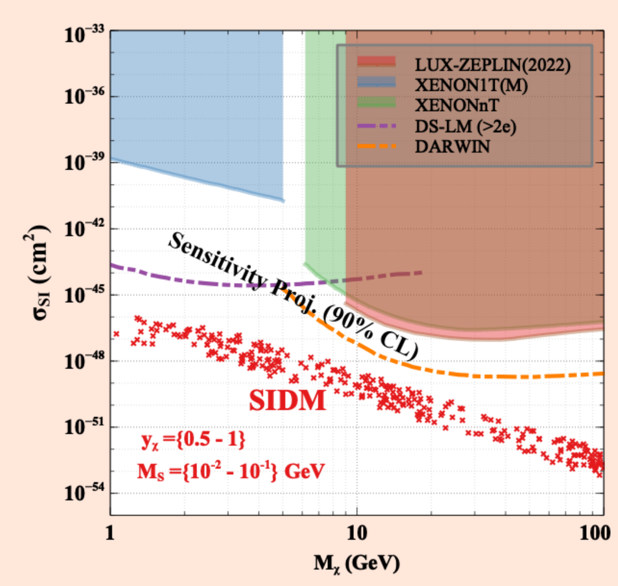


Figure 9. Indirect detection of DM.

Conclusion

- We introduce a compelling model that combines self-interacting dark matter and Dirac mass for neutrinos, utilizing a discrete Z_4 symmetry known as 'Lepton quarticity'.
- The self-interaction of DM is facilitated by a light scalar S. We emphasize that achieving the correct relic density of SIDM can be accomplished through the thermal freeze-out mechanism by tuning the mediator mass to a higher value in the early Universe. This adjustment addresses the issue of under-abundance resulting from excessive annihilation to S. Subsequently, the mass of S can decrease to its present value after a phase transition that occurs well after the establishment of the DM relic density.
- We demonstrate that direct dark matter search experiments do not place stringent constraints on the model parameters. Additionally, $\Delta N_{\rm eff}$ provides a further cosmological probe for the model.

References

1. Centelles Chuliá, Salvador and Ma, Ernest and Srivastava, Rahul and Valle, José W. F. (2017), Dirac Neutrinos and Dark Matter Stability from Lepton Quarticity, 1606.04543.
2. Adhikary, Amit and Borah, Debasish and Mahapatra, Satyabrata and Saha, Indrajit and Sahu, Narendra and Thounaojam, Vicky (2024), Rescuing thermally under-abundant dark matter with a first-order phase transition, 2405.17564.
3. Biswas, Anirban and Borah, Debasish and Nanda, Dibyendu, Light Dirac neutrino portal dark matter with observable $\Delta N_{\rm eff}$ (2021), 2103.05648.

Sujit Kumar Sahoo, ph21resch11008@iith.ac.in