Neutrino mass models: Seesaw and DM

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Outline

- Type I seesaw with three RHNs for the generation of neutrino mass and its connection to dark matter physics.

- Dodelson-Widrow/Shi-Fuller Mechanism for keV RHN DM:

  Application to the RHN sector realizing a heavy DM from the Ladau-Zener production.

- Scotogenic Model of Ma:

  Extension with Majoron – PNGB of $U(1)_{B-L}$.

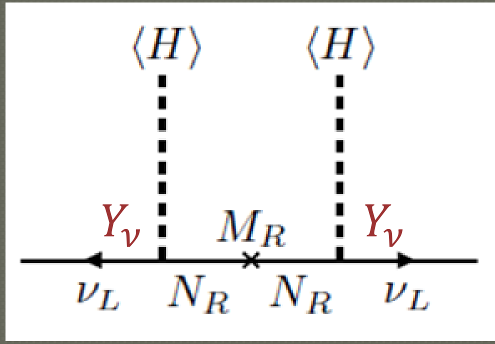
- Neutrino portal DM:

  Freeze-in and energetic neutrino signals

Type I Seesaw

- Singlet Majorana fermion N coupling to the neutrino Yukawa term:

$$\mathcal{L}_\nu = Y_\nu LHN + \frac{1}{2} M_N NN + h.c. \quad \Rightarrow \quad m_\nu = Y_\nu \frac{\langle H\rangle^2}{M_N} Y_\nu^T$$

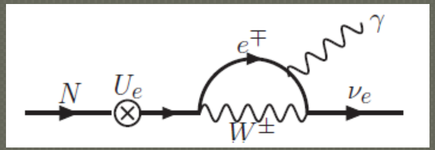


- Typical size of the Yukawa for seesaw:

$$Y_\nu \sim \frac{\sqrt{m_\nu M_N}}{\langle H\rangle} \sim 10^{-6} \sqrt{\frac{m_\nu}{0.05\text{eV}} \frac{M_N}{\text{TeV}}}$$

- Two masses for atmospheric and solar neutrinos → one RHN can be cosmologically stable:

$$\Gamma_{N\to LH} = \frac{Y_\nu^2 M_N}{8\pi} \sim \frac{1}{10^{28}\text{sec}} \left(\frac{Y_\nu}{10^{-27}}\right)^2 \frac{M_N}{\text{TeV}}$$

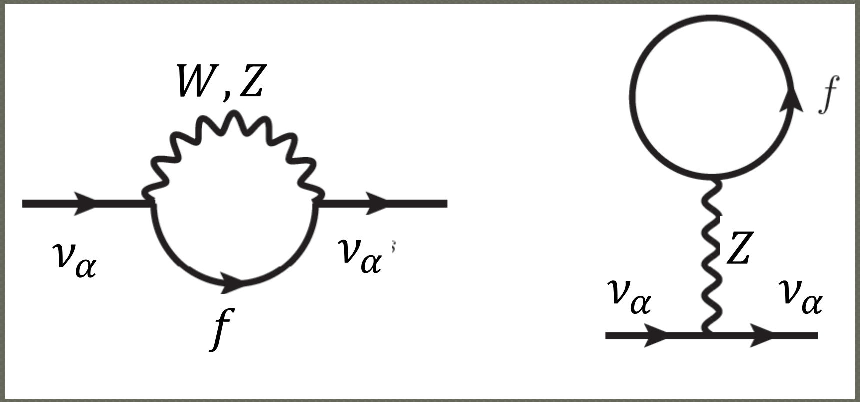


$$\Gamma_{N\to\nu\gamma} = \frac{9\alpha G_F^2}{265\pi^4} \theta^2 M_N^5 \sim \frac{1}{10^{28}\text{sec}} \left(\frac{\theta}{3\times 10^{-4}}\right)^2 \left(\frac{M_N}{\text{keV}}\right)^5 \qquad \theta = \frac{Y_\nu \langle H\rangle}{M_N}$$

Dodelson-Widrow/Shi-Fuller Mechanism

keV sterile neutrino DM

- Neutrino propagation in thermal background (MSW effect) of $f = \alpha, \nu_\alpha, q$ where $\alpha = e, \mu, \tau$.



$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$i \frac{d}{dt} \begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = H \begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix}$$

$$H = \left(\mathrm{p} + \frac{m_1^2 + m_2^2}{2\mathrm{p}} + \frac{V(t, \mathrm{p})}{2} \right) I + \frac{1}{2} \begin{pmatrix} V(t, \mathrm{p}) - \Delta c_{2\theta} & \Delta s_{2\theta} \\ \Delta s_{2\theta} & \Delta c_{2\theta} - V(t, \mathrm{p}) \end{pmatrix}$$

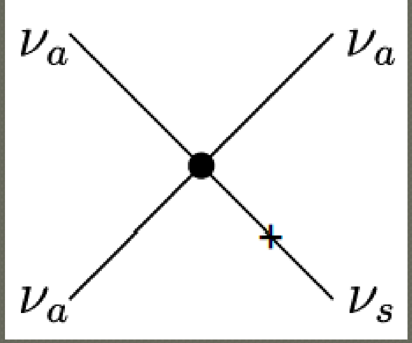
$$s_{2\theta_m}^2 = \frac{\Delta^2 \mathrm{s}_{2\theta}^2}{\Delta^2 s_{2\theta}^2 + \left(\Delta c_{2\theta} - V_\alpha(T, \mathrm{p}) \right)^2} \quad \text{where } \Delta = \frac{m_2^2 - m_1^2}{2\mathrm{p}}$$

Thermal medium effect

- Sterile neutrino ($\nu_s = N$) production through the ν_a-ν_s mixing in the plasma: thermal effect of the total number density ($n_a + n_{\bar{a}}$) and lepton asymmetry ($\mathcal{L}_a = (n_a - n_{\bar{a}})/s$).

Dodelson-Widrow '93 + Shi-Fuller '98

- The $\nu_a \to \nu_s$ transition rate:



$$\Gamma(\nu_a \to \nu_s\!: \mathrm{p}, T) = \frac{\Gamma_a}{4} s^2_{2\theta_m}$$

$$s^2_{2\theta_m} = \frac{\Delta^2 s^2_{2\theta}}{\Delta^2 s^2_{2\theta} + \left(\Delta c_{2\theta} - V_\alpha(T, \mathrm{p})\right)^2}$$

$$\Gamma_a(\mathrm{p}) \approx G_F^2 \mathrm{p} T^4$$

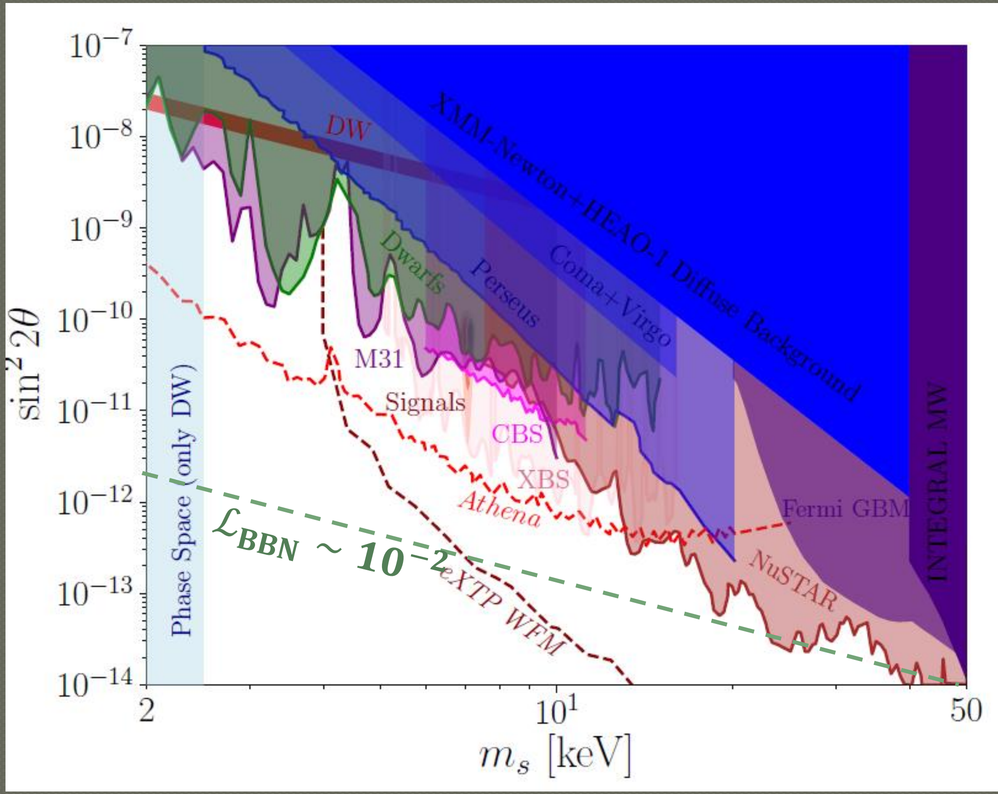
$$V_a(T, \mathrm{p}) = V_a^T + V_a^L$$

$$\sim -G_F^2\, \mathrm{p}\, T^4 + G_F\, \mathcal{L}_a T^3$$

Resonance conversion

Abazajian, et.al, 0101524

Summary plots



$\mathcal{L}_{BBN}$

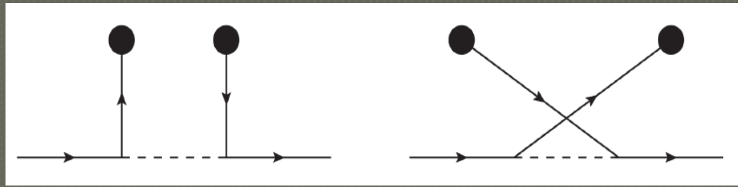
Abazajian, 2102.10183

Boyarsky et.al., 1807.07938

Heavy sterile neutrino DM

- The Model: $-\mathcal{L}_N = \frac{y_{ij}}{2} N_i N_j \phi + \frac{M_i}{2} N_i N_i + \frac{\lambda_{\phi H}}{4} |\phi|^2 |H|^2 + \frac{\lambda_\phi}{4} |\phi|^4 + h.c.$
- Assume $y_{11} \ll y_{12} \ll y_{22}$ to make N_1 DM, and N_2 (& ϕ) in thermal equilibrium.
- It leads to the thermal Hamiltonian:

$$H \approx \mathrm{p}\, I + \frac{1}{2\mathrm{p}} \begin{pmatrix} M_1^2 + 2\delta M_{11}^2 & 2\delta M_{12}^2 \\ 2\delta M_{12}^2 & M_2^2 + 2\delta M_{22}^2 \end{pmatrix}$$



$$\delta M_{ij}^2 \approx \frac{1}{16} y_{il} y_{jl}^* T^2$$

$$\tan 2\theta_m \approx \frac{4\delta M_{12}^2}{M_1^2 - M_2^2 - 2\delta M_{22}^2} \quad \Rightarrow \text{Resonace at } T_{\text{res}} \approx 2\sqrt{2}\frac{\sqrt{M_1^2 - M_2^2}}{|y_{22}|}$$

EJC, Kadota, Yun, work in progress

Landau-Zener production

- Adiabaticity condition:

$$\gamma_{\rm ad} \equiv \frac{\left|\frac{d\theta_T}{dt}\right|}{|\Delta H_T|} \approx \left(\frac{HT}{4\delta M_{12}^2}\right)_{\rm res} \approx \frac{3.3\sqrt{g_*}}{|y_{12}y_{22}^*|}\frac{T_{\rm res}}{M_{pl}} \gg 1$$

- Non-adiabatic $N_2 \to N_1$ transition (Landau-Zener):

$$P(N_2 \to N_1) = 1 - e^{-\frac{\pi}{2}\frac{1}{\gamma_{\rm ad}}} \approx \frac{\pi}{2}\frac{1}{\gamma_{\rm ad}}$$

- N_1 DM number density:

$$n_{N_1} = P(N_2 \to N_1)\, n_{N_2}^{\rm eq}$$

$$\boxed{\Rightarrow |y_{12}||y_{22}|^2\frac{M_1}{M_2} \approx 10^{-25} \text{ with } M_1 > M_2}$$

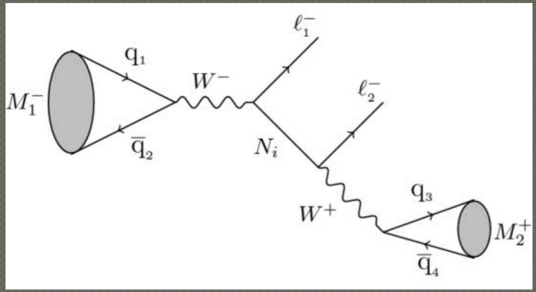
- Stability requirement:

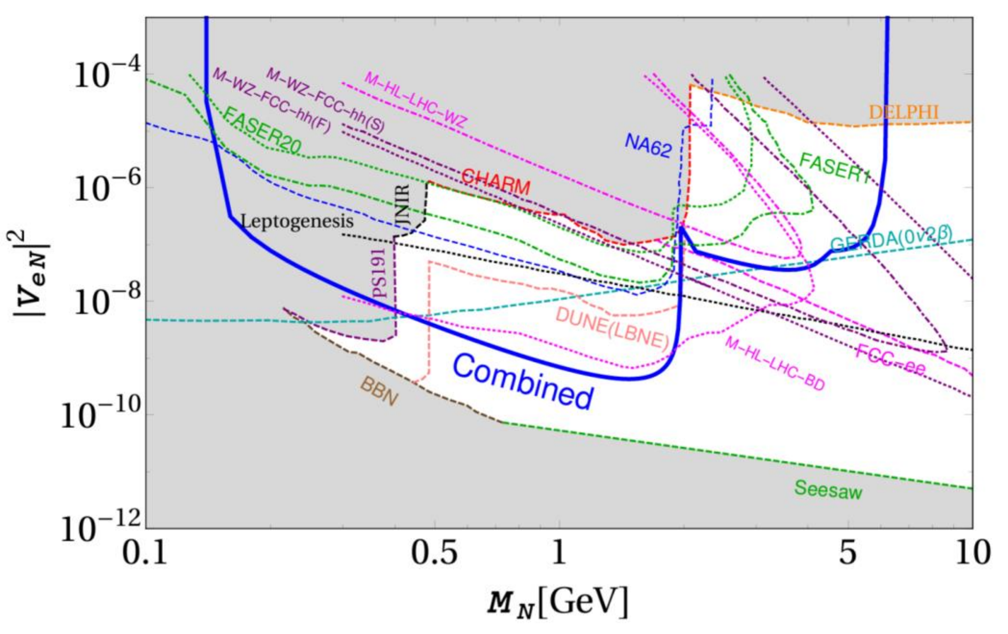
$$\boxed{\Gamma_{N_1\to\phi\nu} \approx \frac{|y_{12}|^2}{8\pi}\frac{m_\nu}{M_2}M_1 > \tau_U^{-1} \Rightarrow |y_{12}|\sqrt{\frac{M_1}{M_2}} < 10^{-15}}$$

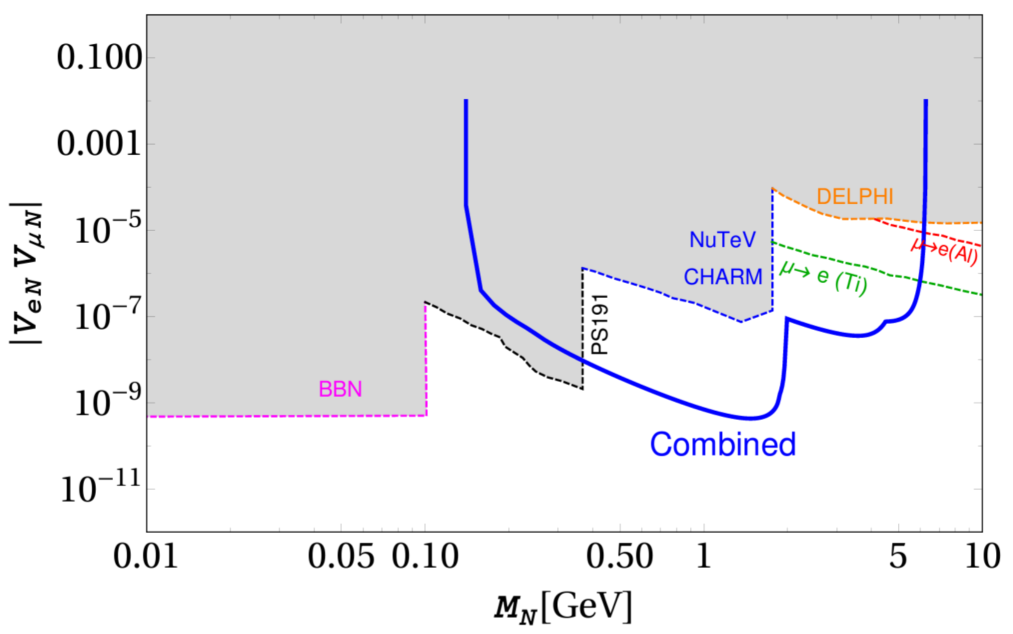
Requiring a big hierarchy

- Favorable parameter space for $M \sim M_1 \gtrsim M_2$
  - $y_{22} \gtrsim 10^{-3} \left(\frac{M}{\mathrm{GeV}}\right)^{\frac{1}{5}}$ for thermalization
  - $y_{12} \lesssim 10^{-19} \left(\frac{\mathrm{GeV}}{M}\right)^{\frac{2}{5}}$ ($< 10^{-15}$ for stability)
  - $T_{\mathrm{res}} \lesssim 2\ \mathrm{TeV} \left(\frac{M}{\mathrm{GeV}}\right)^{\frac{4}{5}}$

GeV HNL searches in meson decays







EJC, Das, Mandal, Mitra, Sinha, 1908.09562

Scotogenic Model of Ma

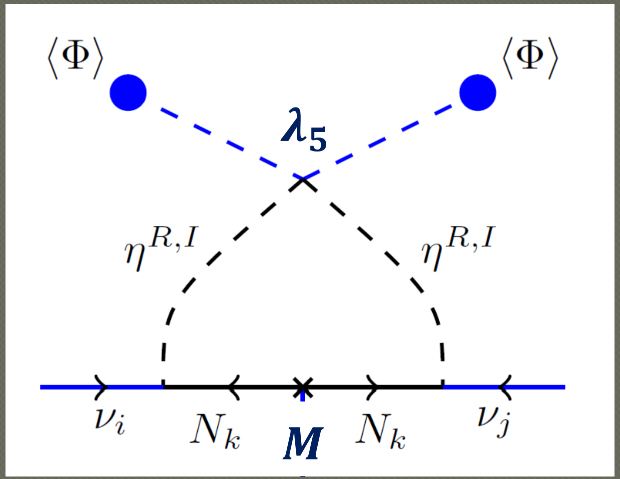
Scotogenic Model

Ma, 0601225

- Radiative neutrino mass generation with dark matter candidates: Z_2-odd RHN N and a $SU(2)_W$ inert doublet η

$$-\mathcal{L} \ni \lambda_5 \left(\Phi^\dagger \eta\right)^2 + Y_\nu L \eta N + \frac{1}{2} M N N + h.c$$

$$\boxed{m_\nu = \frac{\lambda_5 v_\Phi^2}{32\pi^2 m_\eta^2} Y_\nu M f_1(x) Y_\nu^T \quad (x = M^2/m_\eta^2)}$$

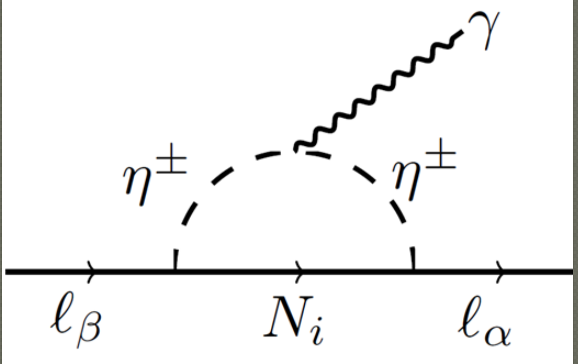


$$m_\nu \sim \lambda_5 \, Y_\nu^2 \frac{\widetilde{\Lambda}}{32\pi^2} \rightarrow \lambda_5 Y_\nu^2 \sim 10^{-10} \text{ for } \widetilde{\Lambda} \sim 300\text{GeV}$$

Scotogenic model

- Highly constrained parameter space
- Lepton flavor violation:

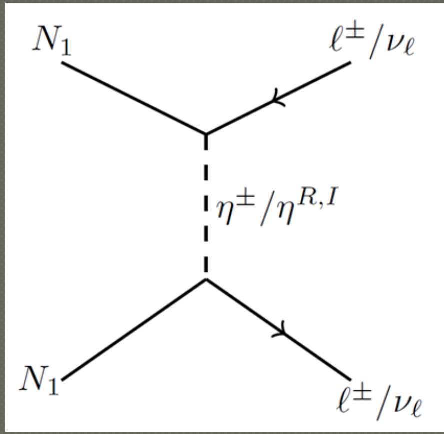
$$\Gamma(\mu \to e\gamma) = \frac{\alpha_{em} m_\mu^5}{16\, m_\eta^4} \left| \frac{1}{16\pi^2} \left(Y_\nu f_2(x) Y_\nu^\dagger \right)_{\mu e} \right|^2$$



$B(\mu \to e\gamma) < 4.3\ 10^{-13} \Rightarrow |Y_\nu|^2_{\mu e} \lesssim 6\ 10^{-5}$ for $M, m_\eta \sim 300\mathrm{GeV}$

- DM abundance (freeze-out):

$$\langle \sigma v \rangle = \frac{\left(Y_\nu^\dagger Y_\nu \right)_{11}}{4\pi M_1^2} f_3(x)$$



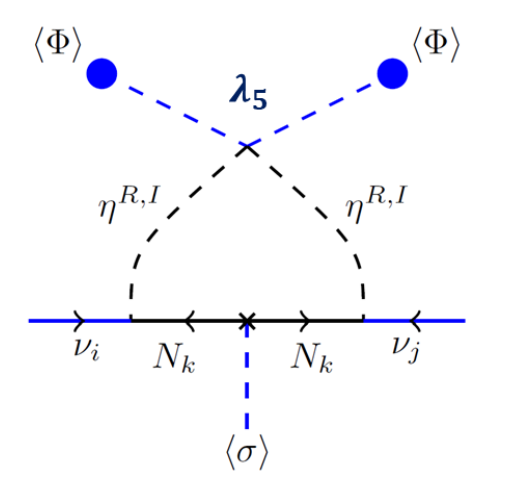
$$\Omega_{N_1} h^2 \sim 0.1\ \frac{2\ 10^{-9}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \Rightarrow \left(Y_\nu^\dagger Y_\nu \right)_{11} \sim 10^{-2} \text{ for } M_1 \sim 300\mathrm{GeV}$$

Scotogenic Model with Majoron

- Scotogenic Model extended with $U(1)_{B-L}$:

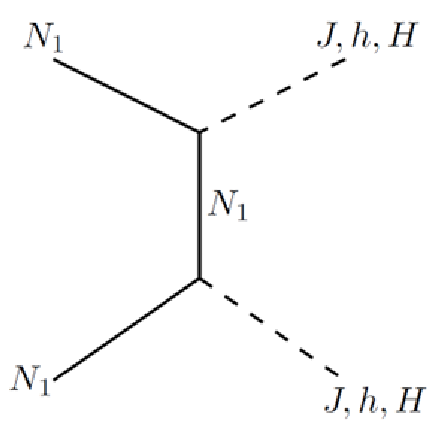
$$-\mathcal{L} \ni \lambda_5\left(\Phi^\dagger\eta\right)^2 + Y_\nu L\eta N + \frac{1}{2} y_N \sigma N N + h.c.$$
$$+(\lambda_{\Phi\sigma}|\Phi|^2 + \lambda_{\eta\sigma}|\eta|\text{^}2)|\sigma|\text{^}2 + \cdots$$

$$\langle\sigma\rangle = \frac{1}{\sqrt{2}}(v_\sigma + \rho + i\,J) \qquad M_N = y_N v_\sigma$$



- Supposed to change the DM property due to the new coupling y_N:

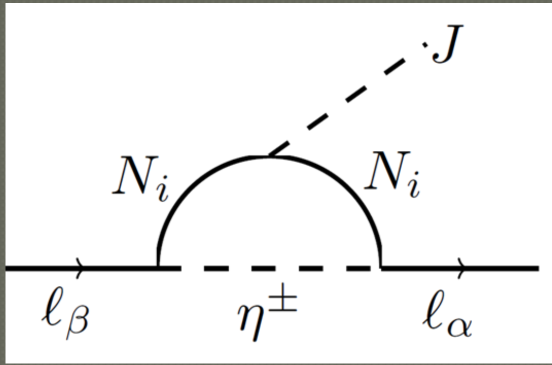
$$\langle\sigma v\rangle \sim \frac{|y_N|^2}{4\pi M_N^2} \;\Rightarrow\; |y_N|^2 \sim 10^{-2} \text{ for } M_N \sim 300\text{GeV}$$



EJC, Roy, Mandal, Mitra, 2303.02681

Constraints

- New LFV mode: $\mu \to eJ$



$$\Gamma(\mu \to eJ) = \frac{m_\mu}{32\pi}\left|\frac{m_\mu}{16\pi^2 v_\sigma}\left(Y_\nu f_4(x) Y_\nu^\dagger\right)_{\mu e}\right|^2$$

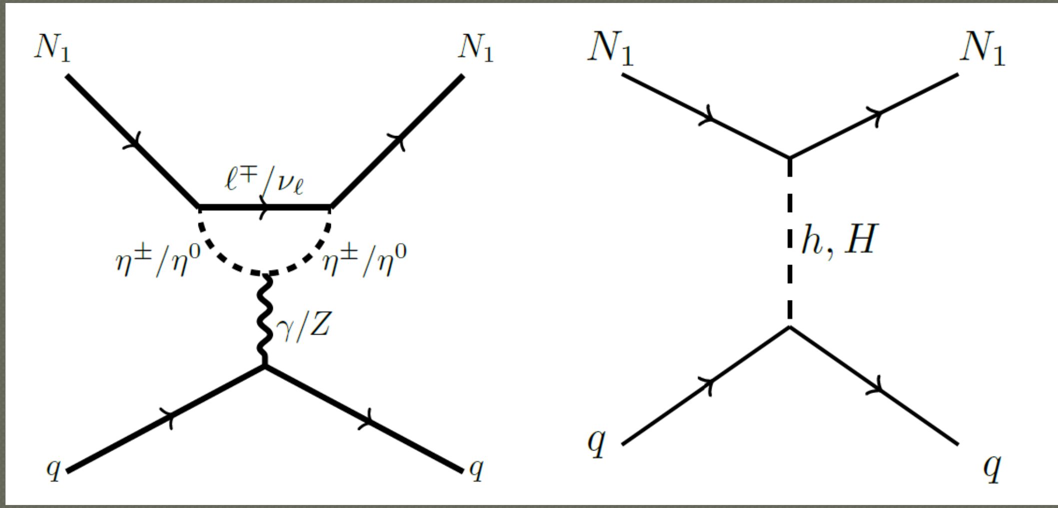
$B(\mu \to eJ) < 10^{-5} \Rightarrow |Y_\nu|^2_{\mu e} \lesssim 2\ 10^{-5}$ for $M_N, m_\eta, v_\sigma \sim 300\mathrm{GeV}.$

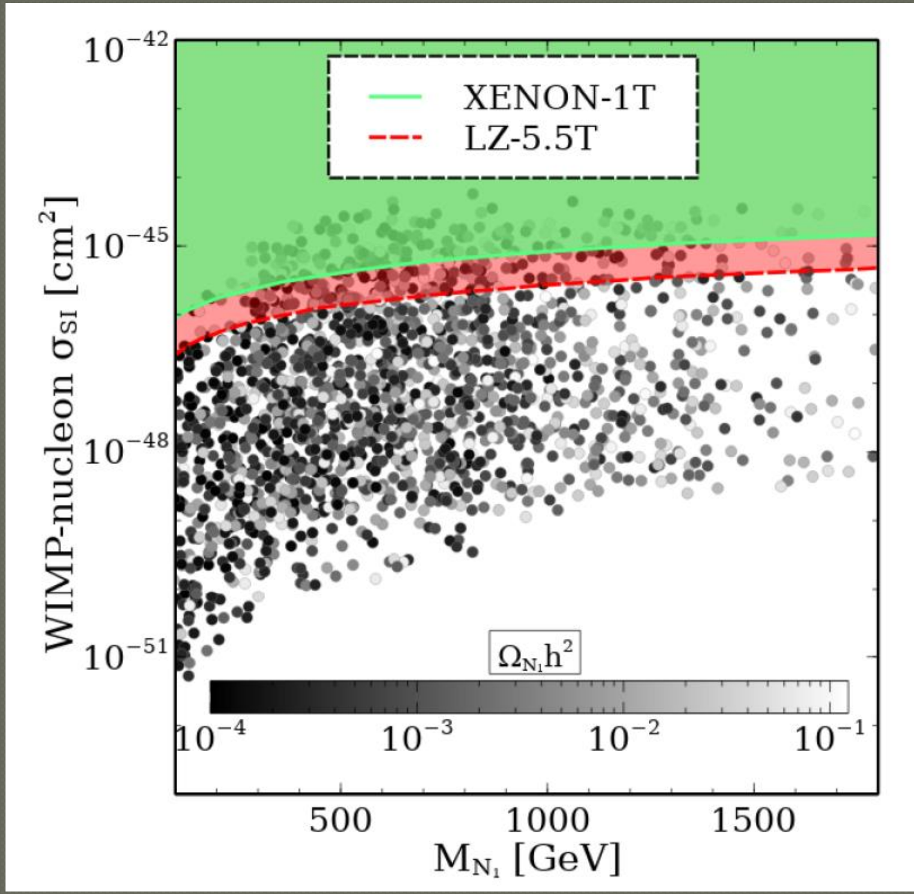
- Additional stellar cooling process of Majoron emission:

Electron cooling: $\left[\frac{m_e}{16\pi^2 v_\sigma}\left(Y_\nu f_4(x) Y_\nu^\dagger\right)_{ee}\right] < 2\ 10^{-13} \to \left|Y_\nu\right|^2_{ee} < 10^{-5}$

Muon cooling: $\left[\frac{m_\mu}{16\pi^2 v_\sigma}\left(Y_\nu f_4(x) Y_\nu^\dagger\right)_{\mu\mu}\right] < 2\ 10^{-10} \to \left|Y_\nu\right|^2_{\mu\mu} < 10^{-4}$

Direct detection of DM





Nb) Majoron may drive a successful leptogenesis.

EJC, Jung, 2311.09005

Neutrino portal DM

Neutrino portal DM

- The model with Z_2 odd singlets in the dark sector:

$$-\mathcal{L} = y_\nu LHN + \frac{1}{2}MNN + \lambda N\chi\phi + \kappa\phi^2|H|^2 + h.c.$$

- The standard freeze-out WIMP DM can be realized through the sizable RHN coupling.

Pospelov, Ritz, Voloshin, 0711.4866

Freeze-in Neutrino Portal

- Considering feeble couplings; $y_\nu, y_\nu\lambda, \kappa \ll 10^{-7}\left(\frac{m_\chi}{\mathrm{TeV}}\right)$, N, χ, ϕ are never thermalized, but DM χ/ϕ can be produced from thermal particles (freeze in).
- Freeze-in channels: 1) $HH \to \phi\phi \to \nu\chi\nu\chi$

  2) $LH \to N, NN \to \chi\chi/\phi\phi \to \chi\chi/\nu\chi\nu\chi$

  3) $LH \to N \to \phi\chi \to \nu\chi\chi$
- Energetic neutrinos produced at the final stage $\phi \to \nu\chi$ can contribute to DR and may be detectable today.

Bandyopadhyay, EJC, Mandal, 2005.13933

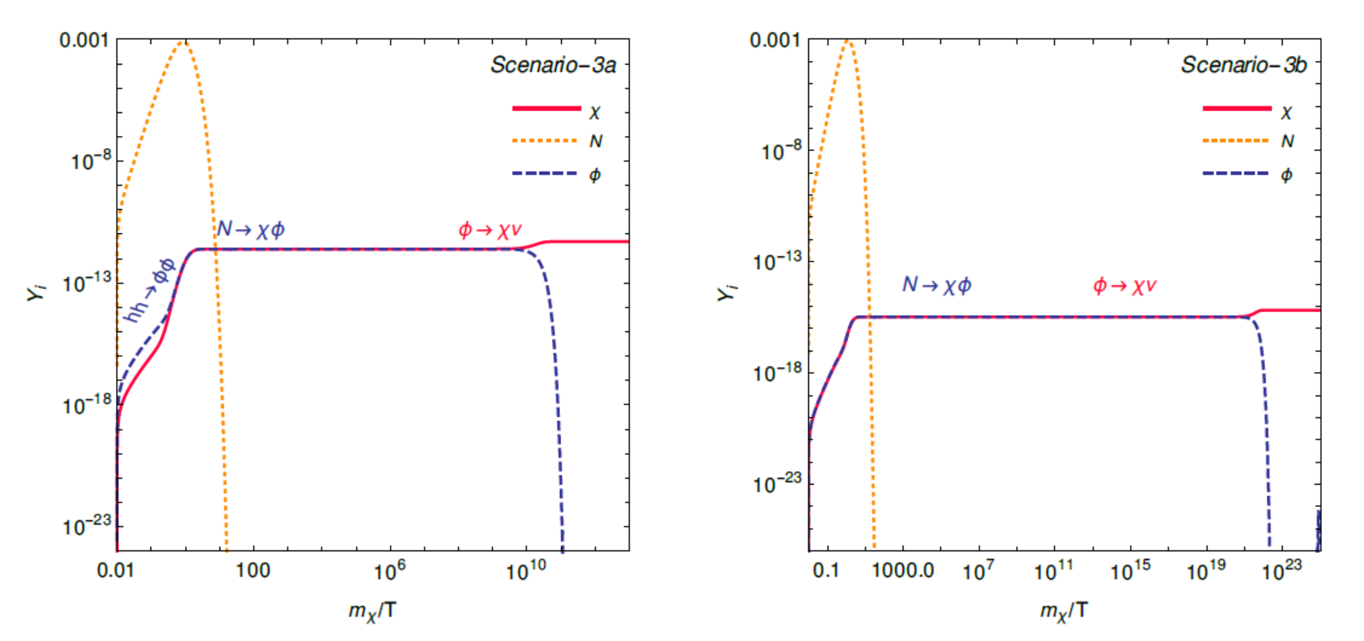
DM genesis

Scenario 3)

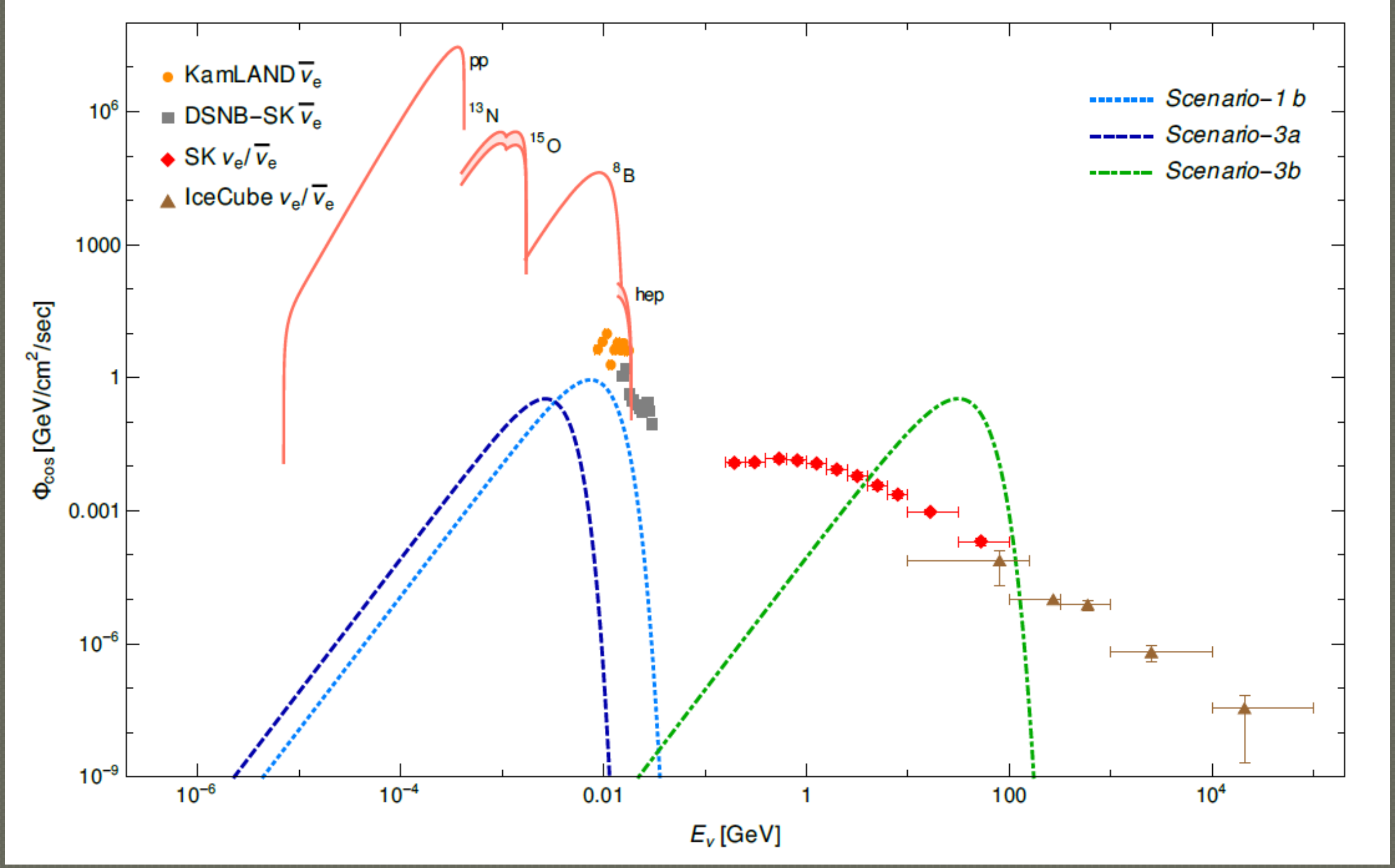
Scenario	Masses in GeV			Couplings		
	m_χ	m_N	m_ϕ	y_ν	κ	λ
3a	100	341	241	10^{-7}	10^{-12}	6.1×10^{-11}
3b	1.0×10^6	2.05×10^6	1.05×10^6	10^{-5}	10^{-12}	2.4×10^{-11}

$\tau_\phi = 10^{10}\ sec$

$4\ 10^{12}\ \mathrm{sec} \gtrsim t_{eq}$



Energetic cosmic neutrinos



$E_0 \sim 62$ GeV, $\tau \sim 10^{11}$sec

$E_0 \sim 100$ GeV, $\tau \sim 10^{10}$sec

$E_0 \sim 49$ TeV, $\tau \sim 4\ 10^{12}$sec

$$\boxed{E_\nu = E_0/(1+z)}$$

$$\boxed{E_0 = \frac{m_\phi^2 - m_\chi^2}{2m_\phi}}$$

Conclusion

- Connecting origins of neutrino mass and dark matter.
- DM may arise from thermal effect in the RHN sector with self (Yukawa) interaction.
- To allow RHN DM in Scotogenic Model, it can be readily extended with majoron (driving leptogenesis?).
- Freeze-in may work in the framework of neutrino portal DM, which leads to ultra-relativistic neutrino signals.