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MeV Scale SIMP Dark Matter, Neutrino Mass and Leptogenesis

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Outline

- Model
- Relic Abundance and Self Interaction
- Neutrino Mass
- Leptogenesis

Model

- WIMP Dark Matter with mass above a few GeV is severely constrained from experiments.
- DM with mass around the MeV range still remains a viable option.
- Several other observations – Missing Satellite Problem, Too big to fail, Core-cusp problem.
- Can be addressed by introducing Strongly Interacting Massive Particle (SIMP) Dark Matter.

- A simple model of SIMP.
- Standard Model extended with 3 right-handed neutrinos (N_1, N_2, N_3) and two scalars (ϕ, δ).
- N_1, N_2, N_3 needed for neutrino mass and leptogenesis.
- A discrete Z_2 symmetry is introduced for stability of DM.
- The scalar ϕ is odd under this symmetry and is the DM candidate.
- Scalar δ plays multiple roles – DM mass, $3 \rightarrow 2$ DM annihilation process, important role in leptogenesis.

- Vacuum expectation values of the scalar fields

$$\langle H \rangle = v_H , \quad \langle \delta \rangle = v_\delta$$

- The scalar potential

$$\mathrm{V} = \frac{\lambda_{11}}{4!}\phi^4 + \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_{12}}{4}\phi^2\delta^2 + \frac{\mu_\delta^2}{2}\delta^2 + \frac{\mu_{22}}{3!}\delta^3 + \frac{\lambda_{22}}{4!}\delta^4 + \frac{\mu_{21}}{2}\phi^2\delta + \frac{\lambda_{13}}{2}\phi^2 H^\dagger H + \mu_{23}\delta H^\dagger H + \frac{\lambda_{23}}{2}\delta^2 H^\dagger H + \mu_H^2 H^\dagger H + \lambda_{33}\left[H^\dagger H\right]^2 .$$

- Higgs invisible decay BR restricts $\lambda_{13} < \mathcal{O}(10^{-2})$.

- DM mass

$$M_\phi^2 = \left(\frac{\lambda_{12}}{2}v_\delta^2 + 2\lambda_{13}v_H^2 + \mu_{12}v_\delta + 2\mu_\phi^2\right) .$$

- For couplings $\lambda_{11}, \lambda_{12} \sim 1$, the DM mass must be in the MeV range for correct relic density.

- We need to choose $v_\delta \sim \text{MeV}$ and $\lambda_{13} \leq 10^{-6}$.

- This tiny coupling also helps evade the direct detection constraints.

- The Higgs scalar mass-squared matrix (H^0, δ) is given as

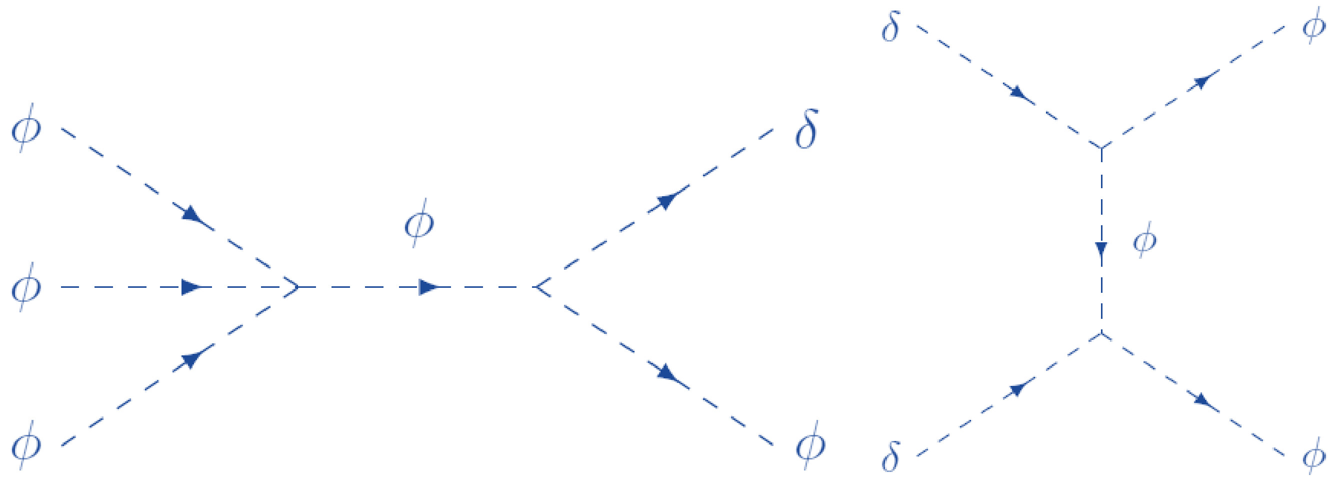
$$M_H^2 = \begin{bmatrix} \frac{1}{2}\lambda_{22}v_\delta^2 + 2\lambda_{23}v_H^2 + 6\mu_{22}v_\delta + 2\mu_\delta^2 & -\frac{v_\delta}{3\sqrt{2}v_H}\left(\lambda_{22}v_\delta^2 + 18\mu_{22}v_\delta + 12\mu_\delta^2\right) \\ -\frac{v_\delta}{3\sqrt{2}v_H}\left(\lambda_{22}v_\delta^2 + 18\mu_{22}v_\delta + 12\mu_\delta^2\right) & 4\lambda_{33}v_H^2 \end{bmatrix}.$$

- The mixing is proportional to $\frac{v_\delta}{v_H}$ and hence extremely small.

- We require $m_\delta \sim \text{MeV}$, hence $\lambda_{23} \leq 10^{-6}$.

Relic Abundance and Self Interaction

- SIMP dark matter usually comprises of $3\phi \to 2\phi$ or $4\phi \to 2\phi$.
- We explore an assisted annihilation process.
- We consider $m_\phi < m_\delta < 2m_\phi$, so the important diagrams contributing to the DM relic density



The Boltzmann's equations for the evolution of the number density

$$\frac{dY_\phi}{dx} = -\frac{xs^2}{3H(m_\phi)} \langle \sigma v^2 \rangle_{3\to 2} (Y_\phi^3 - Y_\phi Y_\delta Y_\phi^{eq}) + \frac{xs}{H(m_\phi)} \langle \sigma v \rangle_{2\to 2} (Y_\phi^2 - Y_\delta^2)$$

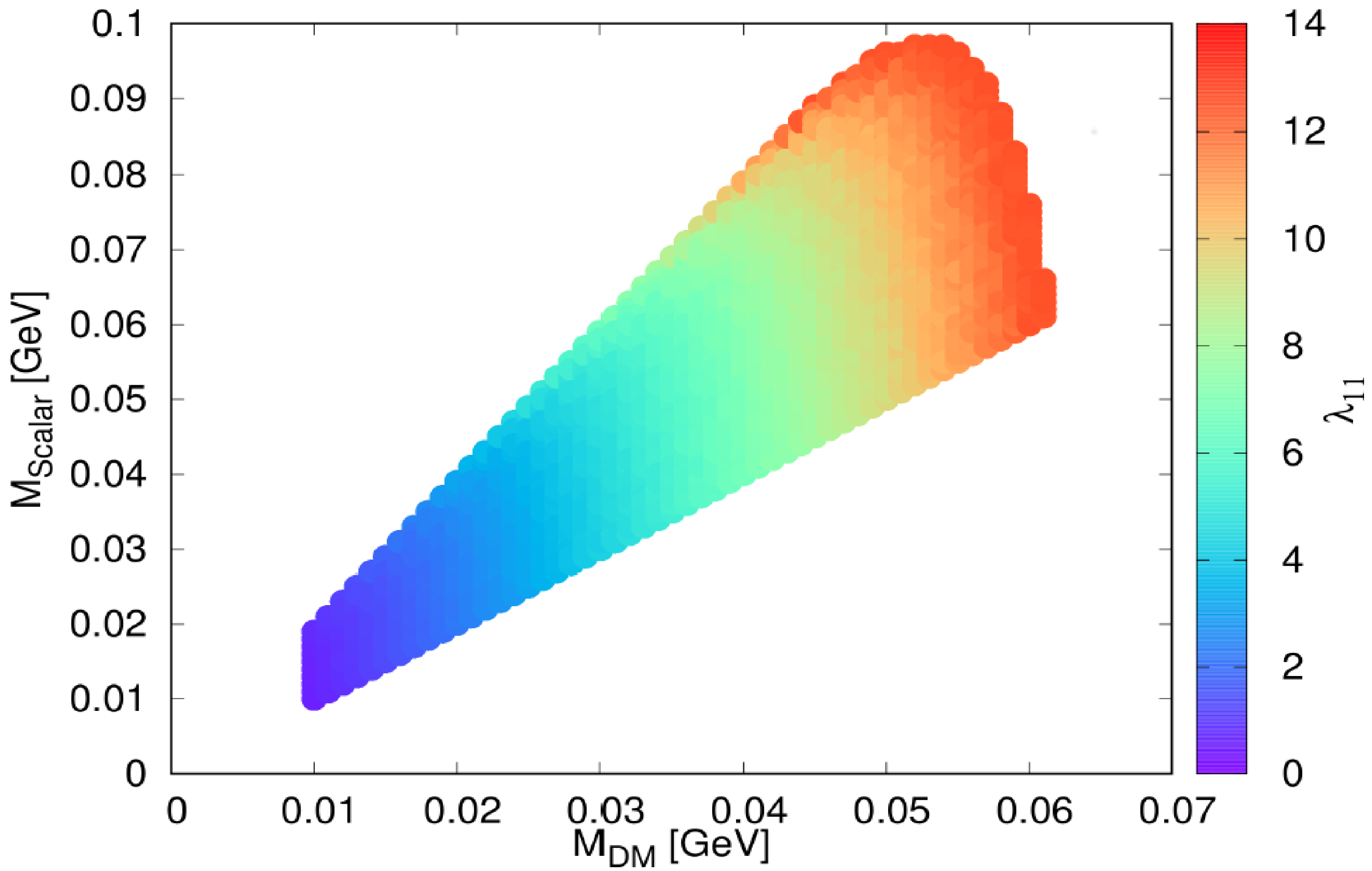
$$\frac{dY_\delta}{dx} = +\frac{xs^2}{6H(m_\phi)} \langle \sigma v^2 \rangle_{3\to 2} (Y_\phi^3 - Y_\phi Y_\delta Y_\phi^{eq}) - \frac{xs}{H(m_\phi)} \langle \sigma v \rangle_{2\to 2} (Y_\phi^2 - Y_\delta^2),$$

where

$Y_i = n_i/s$, $x = m_\phi/T$ and $H(m_\phi) = \sqrt{\frac{\pi^2 g^*}{90}} \frac{m_\phi^2}{M_{pl}}$.

$$\langle \sigma_{3\to 2} v^2 \rangle = \frac{\lambda_{11}^2 \mu_{\rm eff}^2}{64\pi m_\phi^3} \sqrt{\left(1 - \frac{(m_\phi + m_\delta)^2}{9m_\phi^2}\right)\left(1 - \frac{(m_\delta - m_\phi)^2}{9m_\phi^2}\right)} \frac{1}{64 m_\phi^4},$$

$$\mu_{eff} = \mu_{12} + \frac{\lambda_{12} v_\delta}{2}.$$

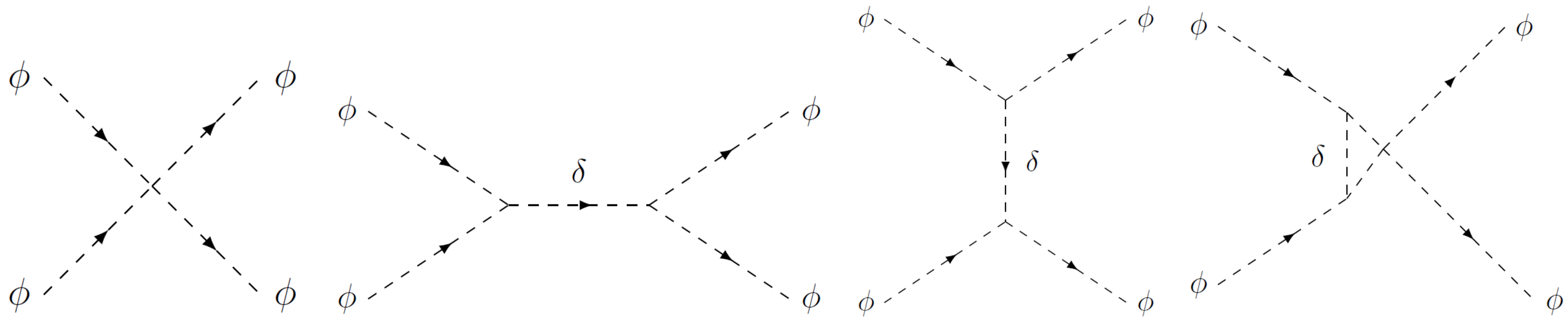


Relic Density Plot

Observations from Galaxy clusters put severe constraints on the self-scattering cross-section of DM

$\sigma_{\rm self}/m_\phi ({\rm cm}^2/{\rm g})$	Observations
$\sim (1.7 \pm 0.7) \times 10^{-4}$	Bright cluster galaxies in the 10 kpc core of Abell 3827 [60]
~ 0.1	Cores in clusters [61, 62]
~ 1.5	Abell 3827 subhalos [63]
~ 1	Abell 520 cluster [64–66]
$\lesssim 1$	Halo shapes and Bullet cluster [67, 68]

Diagrams contributing to the self-scattering

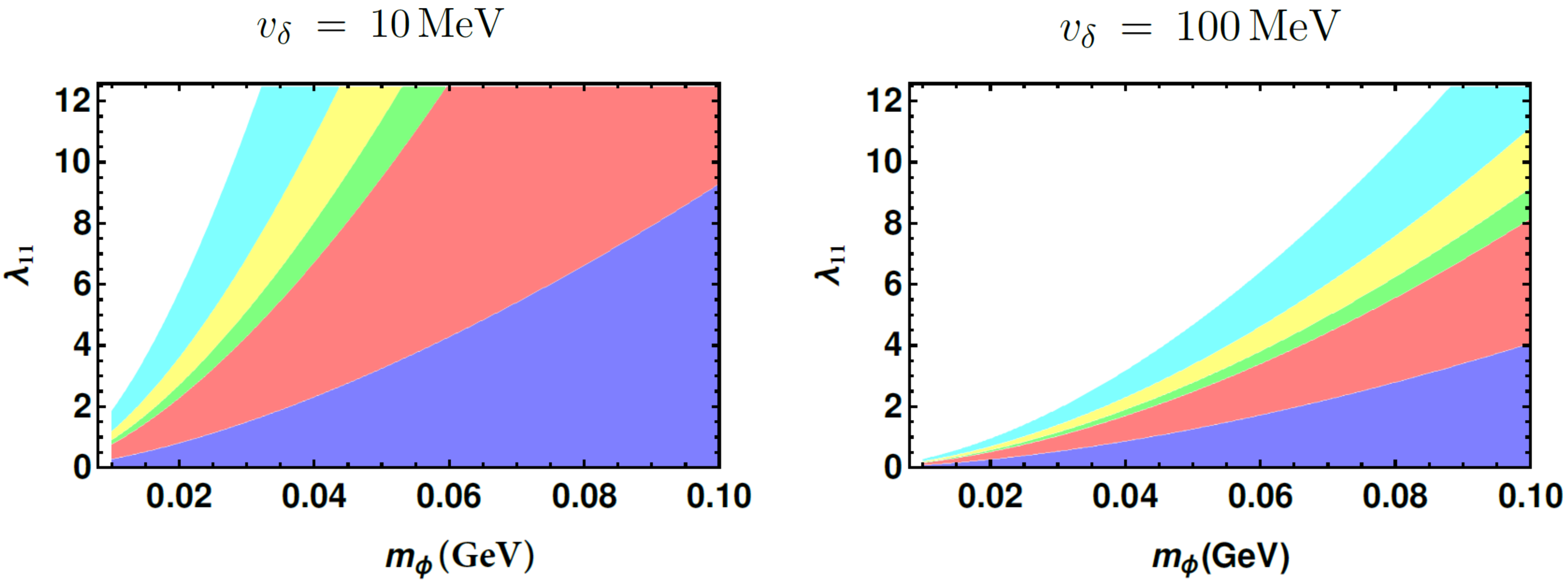


Self-scattering cross-section

$$\sigma_{\text{self}} = \frac{1}{64\pi m_\phi^2} |\mathcal{M}|^2$$

where $i\mathcal{M} = i\left(\lambda_{11} + \mu_{\text{eff}}^2 \frac{1}{(s - m_\delta^2)} + \mu_{\text{eff}}^2 \frac{1}{(t - m_\delta^2)} + \mu_{\text{eff}}^2 \frac{1}{(u - m_\delta^2)}\right)$

$$\mu_{eff} = \mu_{12} + \frac{\lambda_{12} v_\delta}{2}$$



$\sigma_{\rm self}/m_\phi \lesssim 0.1$ cm^2/g (blue), 0.1 cm^2/g $\lesssim \sigma_{\rm self}/{\rm m}_\phi \lesssim 1$ cm^2/g (red), 1 cm^2/g $\lesssim \sigma_{\rm self}/{\rm m}_\phi \lesssim$ 1.5 cm^2/g (green), 1.5 cm^2/g $\lesssim \sigma_{\rm self}/{\rm m}_\phi \lesssim 3$ cm^2/g (yellow) and 3 cm^2/g $\lesssim \sigma_{\rm self}/{\rm m}_\phi \lesssim$ 10 cm^2/g (cyan).

Neutrino Mass

- Neutrino part of the Lagrangian

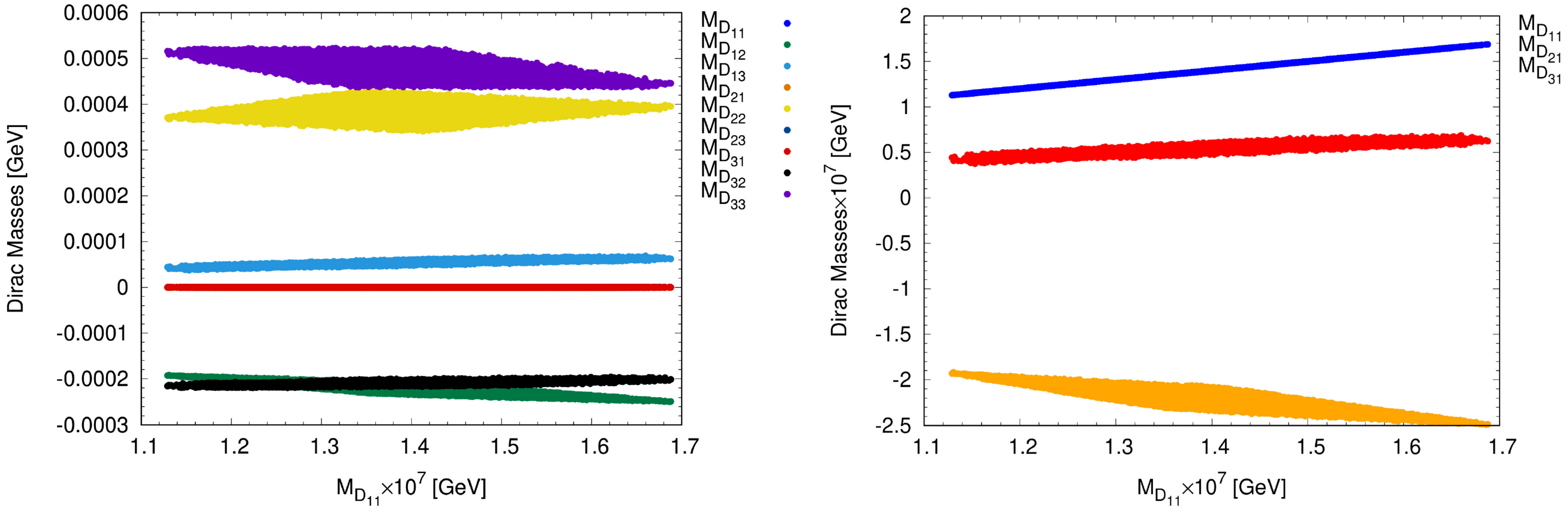
$$\mathcal{L}_Y \supset \left[Y_{D_{ij}} L_i^T i\sigma_2 H N_j + \frac{1}{2} M_{N_{ij}} \overline{N_i^c} N_j + \frac{1}{2} f_{ij} \overline{N_i^c} N_j \delta \right] + \text{H.C.}$$

- Neutrino mass is generated by Type-I seesaw mechanism with

$$M_{D_{ij}} = Y_{D_{ij}} v_H \,, \quad M_{R_{ij}} = M_{N_{ij}} + f_{ij} v_\delta$$

- The lightest RHN mass is chosen to be a few MeV as a requirement for successful leptogenesis.

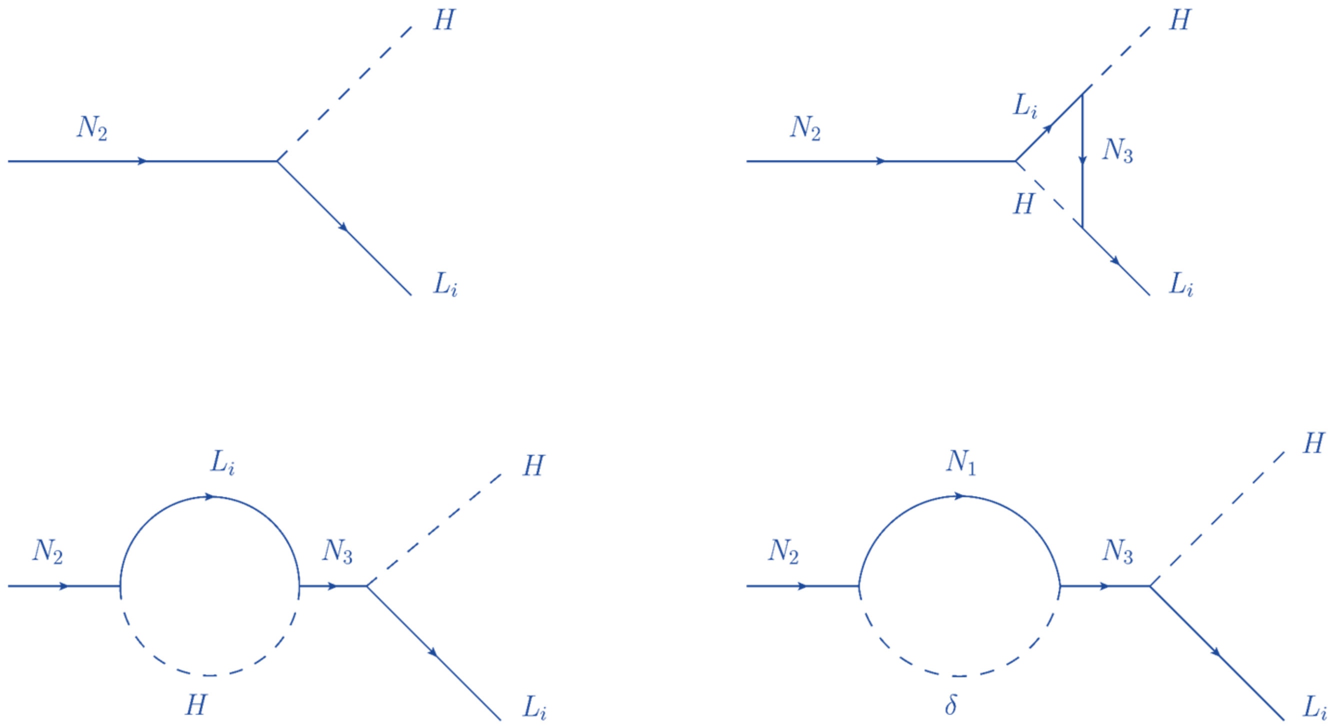
- Other two RHNs are around 10 TeV mass.



Hierarchy in M_D to satisfy the oscillation data.

Leptogenesis

Lepton asymmetry given as $\epsilon_2 = -\sum_i \left[\frac{\Gamma(N_2 \to \bar{l}_i H^*) - \Gamma(N_2 \to l_i H)}{\Gamma_{tot}(N_2)} \right]$



Total decay width of N_2 considering both channels

$$\Gamma_{\rm tot}(N_2) = \frac{(Y^\dagger_{D_{2i}} Y_{D_{2i}}) + |f_{12}|^2}{4\pi} M_{N_2}$$

The CP asymmetry is

$$\epsilon_2 = \frac{1}{8\pi} \left([g_V(x) + g_S(x)]\mathcal{T}_{23} + g_S(x)\mathcal{S}_{23} \right) ,$$

where $g_V(x) = \sqrt{x}\{1 - (1+x)\ln[(1+x)/x]\}$, $g_S(x) = \sqrt{x}/(1-x)$

$$\mathcal{T}_{23} = \frac{\mathrm{Im}[(Y_{D_{2i}} Y^\dagger_{D_{3i}})^2]}{(Y^\dagger_{D_{2i}} Y_{D_{2i}}) + |f_{21}|^2}, \quad \mathcal{S}_{23} = \frac{\mathrm{Im}[(Y_{D_{2i}} Y^\dagger_{D_{3i}})(f_{21} f^\dagger_{31})]}{(Y^\dagger_{D_{2i}} Y_{D_{2i}}) + |f_{21}|^2}$$

with $x = M^2_{N_3}/M^2_{N_2}$.

In the case when $M_{N_2} \simeq M_{N_3}$, the self energy correction term can significantly enhance the CP asymmetry.

This is known as resonant leptogenesis.

The CP asymmetry in this case approximately becomes

$$\epsilon_2 \simeq -\frac{1}{16\pi}\left[\frac{M_{N_3}}{v^2}\frac{Im[(Y_D^* m_\nu Y_D^\dagger)_{22}]}{(Y_D^\dagger Y_D)_{22}+|f_{21}|^2} + \frac{Im[(Y_D Y_D^\dagger)_{23}(f_{21} f_{31}^\dagger)]}{(Y_D^\dagger Y_D)_{22}+|f_{21}|^2}\right] R$$

where $R \equiv |M_{N_2}|/(|M_{N_3} - M_{N_2}|)$ is the resonant factor.

In absence of the second term, one would need $R \sim 10^{6-7}$ to generate the required asymmetry. This means $M_{N_3} - M_{N_2} \approx 10^{-2}\,\mathrm{GeV}$ which is highly fine tuned.

Look at the second term $\frac{Im[(Y_D Y_D^\dagger)_{23}(f_{21} f_{31}^\dagger)]}{(Y_D^\dagger Y_D)_{22} + |f_{21}|^2}$.

The coupling f_{21} is constrained by the out-of-equilibrium condition

$$\Gamma_{N_2} < H|_{T=M_{N_2}}$$

which gives

$$\sqrt{|f_{21}|^2} < 3 \times 10^{-4} \sqrt{M_{N_2}/10^9 (\mathrm{GeV})} \ .$$

f_{31} has no such constraints and can enhance the asymmetry.

Can help alleviate the fine tuning.

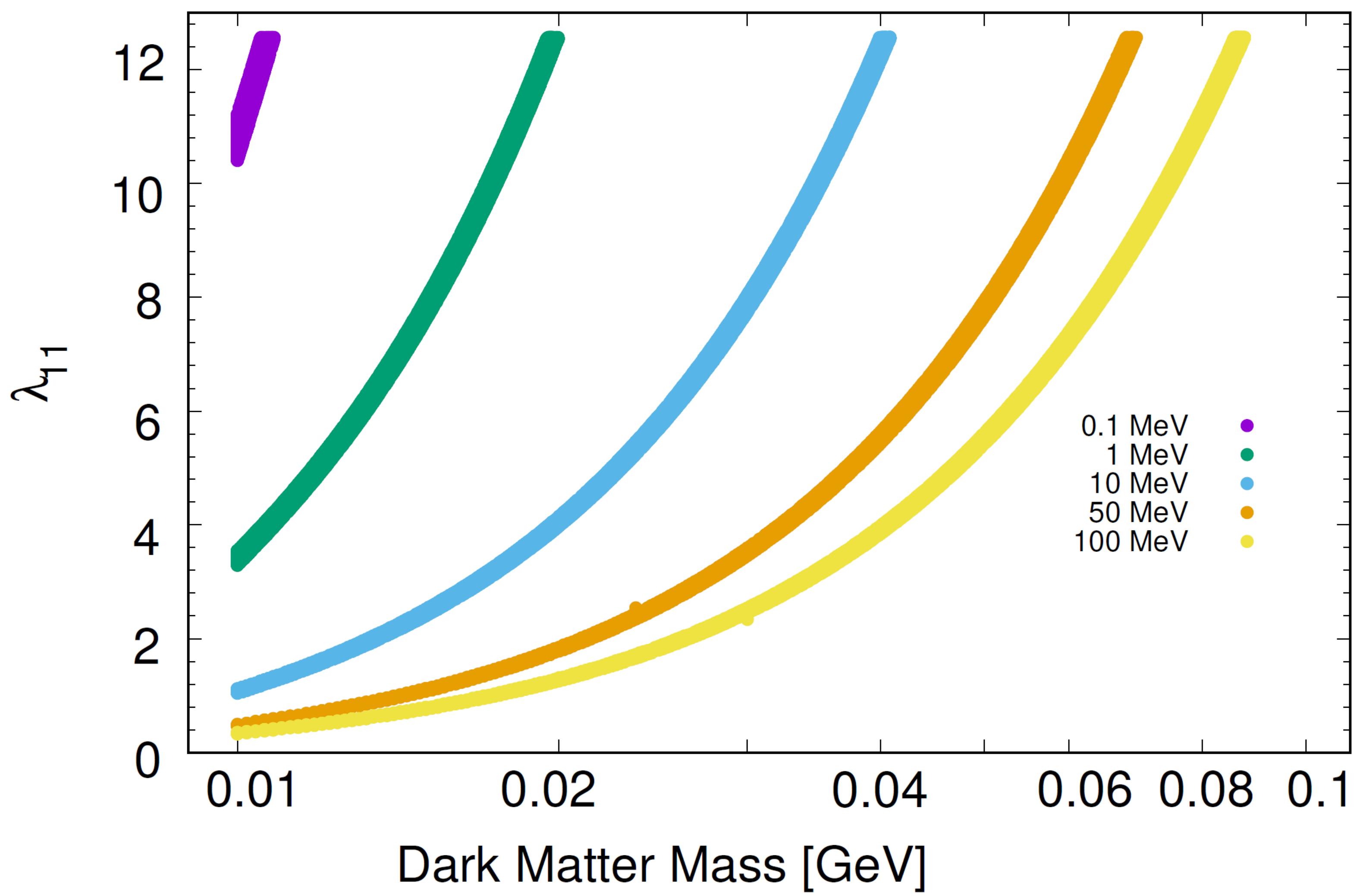
Lepton asymmetry can be obtained quite naturally in this case.

Summary

- Overview of a simple model of SIMP DM.
- The SM was augmented with three RHN and two scalar.
- A discrete Z_2 symmetry protected the DM candidate from decaying.
- We could explain the observed relic density, neutrino mass and the baryon asymmetry of the universe through leptogenesis.
- Several other details are discussed in the paper.

Thank You!

Backup Slides



Relic Density for various v_δ

The mean free path for scattering of DM is given as

$$\lambda_{\rm scatt} = \frac{\sigma_{\rm self}}{m_\phi}\rho\, v,$$

where $\sigma_{\rm self}$, ρ, v and m_ϕ are the self-scattering cross-section, density, velocity and mass of DM.

Study of galaxy clusters provide values of density and velocity of DM at the core while $\lambda_{\rm scatt}$ is around the size of the galaxy cluster.

This provides limits for $\sigma_{\rm self}/m_\phi$.