Dark Matter and WIMPy Baryogenesis in Scotogenic Model

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Based on arXiv:1806.04689 (to appear in JHEP)
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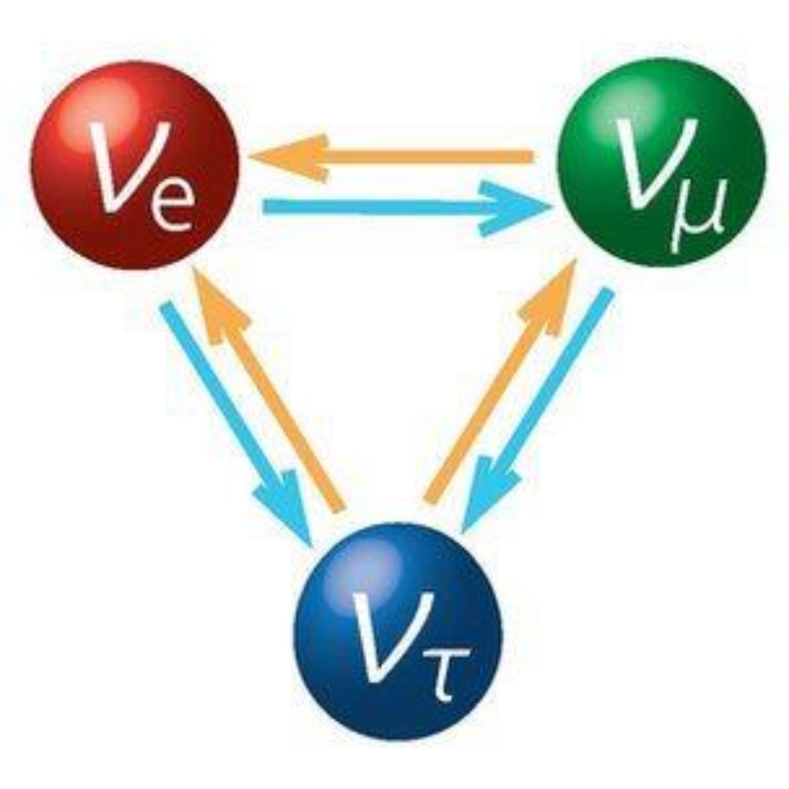
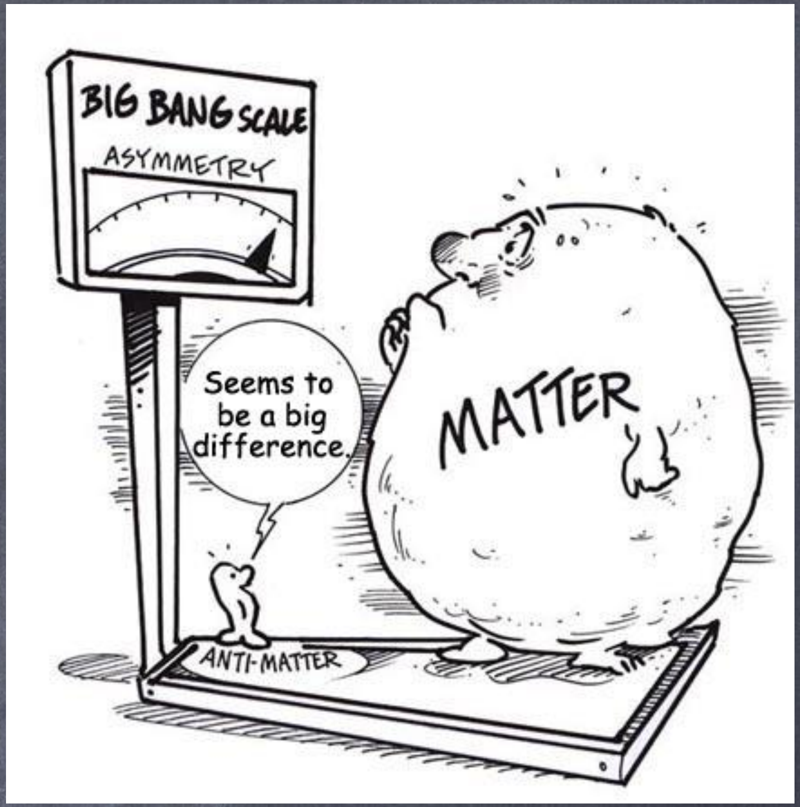
Problems in the SM



- SM cannot explain the neutrino mass and mixing
- SM does not have a dark matter candidate.
- SM cannot explain the observed baryon asymmetry



Aims of this work

- We show how those 3 problems can be resolved in a model.
- For the generation of tiny neutrino masses, we consider "Scotogenic Model" where neutrino masses are radiatively generated at 1-loop.
- Scotogenic model contains dark matter candidate.
- But, there is some trouble to achieve vanilla leptogenesis in minimal Scotogenic model and it can not explain why dark matter and baryon abundances are close to each other.
- We show how baryon asymmetry and dark matter can simulataneously be accommodated through the mechanism of WIMPy baryogenesis in Scotogenic model.

Why WIMPy Baryogenesis ?

(Cui, Randall & Shuve '11)

- Motivated by the fact that the observed BAU and DM abundance are of the same order

$$\Omega_{DM} \approx 5\Omega_B$$

- It makes WIMP DM abundance related with Baryon Asymmetry.

- Dark matter particle freezes out to generate its own relic abundance and then an asymmetry in the baryon sector is produced from DM annihilations.

- WIMP annihilation satisfies Sakharov conditions :

  - WIMP annihilation violate B or L.

  - WIMP couplings to SM violate CP.

  - Cooling of the Universe provides the departure from thermal equilibrium.

WIMPy Baryogenesis: General Framework

- Generation of baryon asymmetry through DM X annihilation

$$\frac{dY_X}{dx} = -\frac{2s(x)}{xH(x)}\langle\sigma_{ann}v\rangle\left[Y_X^2 - (Y_X^{eq})^2\right],$$

$$\frac{dY_{\Delta B}}{dx} = \frac{\epsilon s(x)}{xH(x)}\langle\sigma_{ann}v\rangle\left[Y_X^2 - (Y_X^{eq})^2\right] - \frac{s(x)}{xH(x)}\langle\sigma_{washout}v\rangle\frac{Y_{\Delta B}}{2Y_\gamma}\prod_i Y_i^{eq}$$

$$Y_{\Delta B}(x) \approx -\frac{\epsilon}{2}\int_0^x dx'\frac{dY_X(x')}{dx'}exp\left[-\int_{x'}^x \frac{dx''}{x''}\frac{s(x'')}{2Y_\gamma H(x\quad '')}\langle\sigma_{washout}v\rangle\prod_i Y_i^{eq}(x'')\right]$$

- Requiring the wash-out process to freeze out before WIMP freezes out, the final asymmetry is

$$Y_{\Delta B}(\infty) \approx -\frac{\epsilon}{2}\int_{x_{washout}}^{\infty} dx'\frac{dY_X(x')}{dx'} = \frac{\epsilon}{2}\left[Y_X((x_{washout}) - Y_X(\infty)\right]$$

Scotogenic Model

E. Ma 2006

- Extension of the SM by 3 RHN & 1 Scalar Doublet, odd under Z_2 symmetry, and invented as an alternative to canonical seesaw.
- No tree level neutrino masses but they are radiatively generated at 1-loop.
- The lightest Z_2 odd neutral particle can be a DM candidate.
- Scalar DM resembles inert Doublet DM (hep-ph/0603188,0512090,0612275).
- Lightest RHN DM (arXiv:1710.03824).

Scotogenic Model

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij}N_iN_j + (Y_{ij}\overline{L}\tilde{\Phi}_2 N_j + h.c)$$

$$V(\Phi_1,\Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}\Big|\Phi_1|^4 + \frac{\lambda_2}{2}\Big|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$

$$+\lambda_4|\Phi^\dagger\Phi|^2 + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2) + h.c\right\}$$

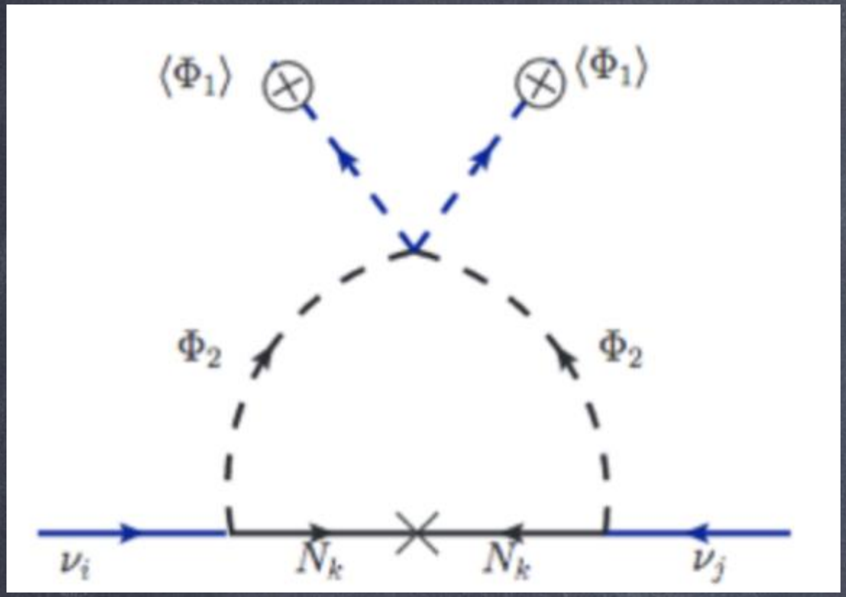
$$m_h^2 = \lambda_1 v^2 \qquad m_{H\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2,$$

$$m_H^2(= m_R^2) = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$$

$$m_A^2(= m_I^2) = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2$$

Scotogenic Model

1- loop neutrino mass :



$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik} Y_{jk} M_k}{16\pi^2} \left(\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right)$$

Requiring m_I^2-$m_R^2 = \lambda_5 v^2 \ll m_{R(I)}^2$ &

m_R^2+$m_I^2 \approx M_k^2$

$$(m_\nu)_{ij} \approx \sum_k \frac{\lambda_5 v^2}{32\pi^2} \frac{Y_{ik} Y_{jk}}{M_k} = \sum_k \frac{m_A^2 - m_H^2}{32\pi^2} \frac{Y_{ik} Y_{jk}}{M_k}$$

Seesaw scale is reduced by $\frac{\lambda_5}{32\pi^2}$, and M_k can be O(TeV)

Dark Matters in Scotogenic Model

- Lightest heavy RH neutrino (Ma '06, Ahriche, Jueid, Nasri, '17)

$$\Omega_{N_1} h^2 \sim \frac{3\times 10^{-26} cm^3 s^{-1}}{<\sigma_{N_1 N_1 \to L\bar{L}} v_r>}$$

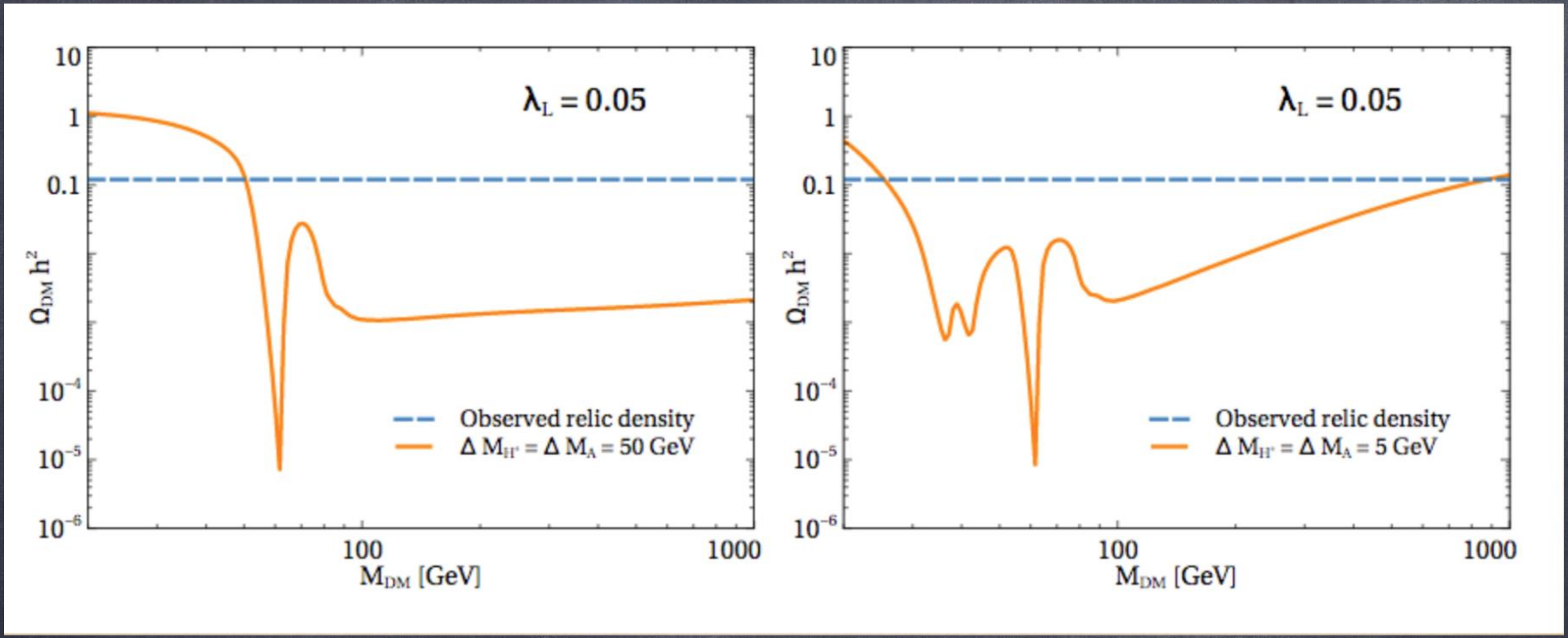
- Direct detection : for SI scattering

$$\sigma_{det}(N_1 + \mathcal{N} \to N_1 + \mathcal{N}) = \frac{\tilde{y}^2_{hN_1\bar{N}_1}(m_{\mathcal{N}} - \frac{7}{9}m_{\mathcal{B}})^2 m_{\mathcal{N}}^2 M_1^2}{4\pi v^2 m_h^4 (m_{\mathcal{N}} + M_1)^2}$$

- N_1 with 10 < M< 700 GeV can satisfy the relic abundance
- It can be probed at LHC with 300 fb^{-1} (arXiv:1710.03824)

- η_R can be a dark matter
- It resembles inert Doublet DM (hep-ph/0603188, 0512090, 0612275)
  - The fact that η_I must be slightly heavier is a natural condition for coannihilation
  - $\eta_{R(I)}\eta_{R(I)} \to L\bar{L}$ dominant contributions to relic abundance.

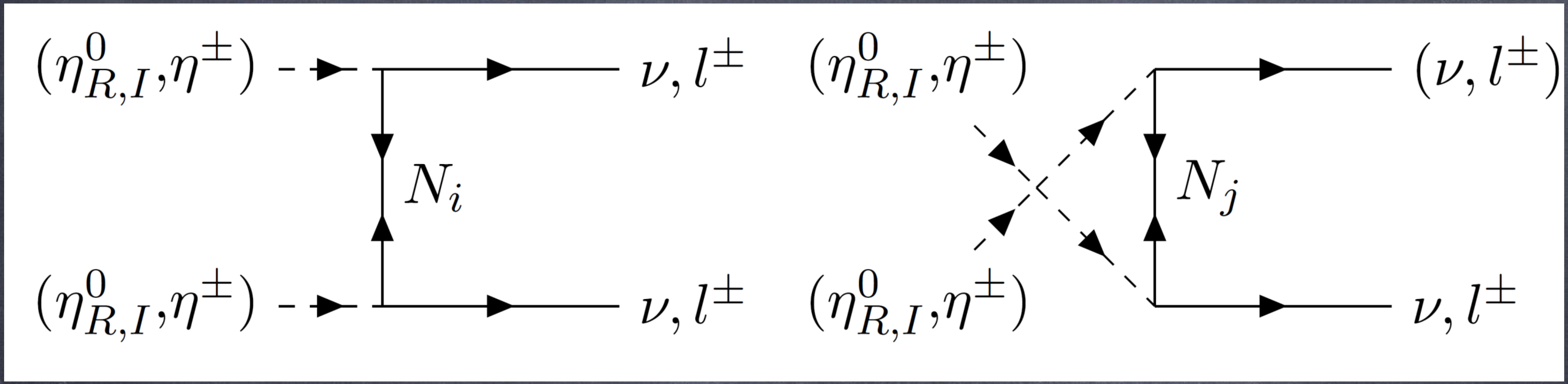
Relic density of Scalar Doublet Dark Matter



- There exist 2 distinct mass regions for tiny mass splitting satisfying the correct DM relic abundance

WIMPy Leptogenesis in Scotogenic Model

- We propose that the (co-)annihilation of scalar DM can produce a lepton number asymmetry



- Simultaneously achieved both Relic density of DM and ΔB

- CP violating asymmetry

$$\epsilon = \sum_{\alpha\beta} \epsilon_{\alpha\beta} = \sum_{\alpha,\beta} \frac{4\gamma_1^{eq}(DMDM \to L_\alpha L_\beta)}{2\sum_{\rho\omega}\gamma_0^{eq}(DMDM \to L_\rho L_\omega)}$$

$$= \sum_{\alpha,\beta} \frac{\int_{s_{min}}^{\infty} ds \frac{2\lambda(s, m_{i_1}^2, m_{i_2}^2)}{s} \sigma_{1\alpha\beta} \sqrt{s} K_1(\sqrt{s}/T)}{\sum_{\rho\omega} \int_{s_{min}}^{\infty} ds \frac{2\lambda(s, m_{i_1}^2, m_{i_2}^2)}{s} \sigma_{0\rho\omega} \sqrt{s} K_1(\sqrt{s}/T)}$$

- Leading contribution to the asymmetry

$$\epsilon_{\alpha\beta} = \sum_{i,j} \frac{4\Im[Y_{\alpha i}^* Y_{\beta i}^* Y_{\alpha j} Y_{\alpha j}]}{2\sum_{k\rho\omega} |Y_{\rho k} Y_{\omega k}|^2} \frac{\lambda_\eta}{16\pi} v \qquad m_{N_i} \simeq m_{N_j} \simeq m_{N_k}$$

$$\varepsilon \approx \lambda_\eta \sin\phi \frac{v}{8\pi}$$

WIMPy Leptogenesis in Scotogenic Model

- Solving Boltzmann Eqs.

$$\frac{dY_\eta}{dz} = -\frac{2zs}{H(M_\eta)}\langle\sigma v\rangle_{\eta\eta\to SMSM}\left(Y_\eta^2 - (Y^{eq})_\eta^2\right)$$

$$\frac{dY_{\Delta L}}{dz} = \frac{2zs}{H(M_\eta)}\left[\epsilon\langle\sigma v\rangle_{\eta\eta\to LL}\left(Y_\eta^2 - (Y_\eta^{eq})^2\right)\right]$$

$$-Y_{\Delta L}Y_l^{eq}\left[\langle\sigma v\rangle_{NN->LL}^{wo} + \langle\sigma v\rangle_{\eta\eta\to LL}\right]$$

$$-Y_{\Delta L}Y_{DM}\left[\langle\sigma v\rangle_{\eta L\to\eta\bar{L}}^{wo}\right] - \frac{1}{2}Y_{\Delta L}\left[\langle\sigma v\rangle_{\eta N\to SM\bar{L}}\right]$$

$$H = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{M_{DM}^2}{M_{Pl}},$$

$$s = g_*\frac{2\pi^2}{45}\left(\frac{M_{DM}}{z}\right)^3$$

- We have considered wash-out processes erasing the asymmetry produced

$\Delta L = 1$: $N\eta_{R,I}(\eta^\pm) \to LZ(W^\pm)$ $\Delta L = 2$: $NN \to LL$, $L\eta \to \bar{L}\eta$

Numerical Analysis for Minimal Scotogenic Model

- We implement the model in SARAH 4 and extract the thermally averaged annihilation rates from MicrOMEGAS 4.3 while solving BE.

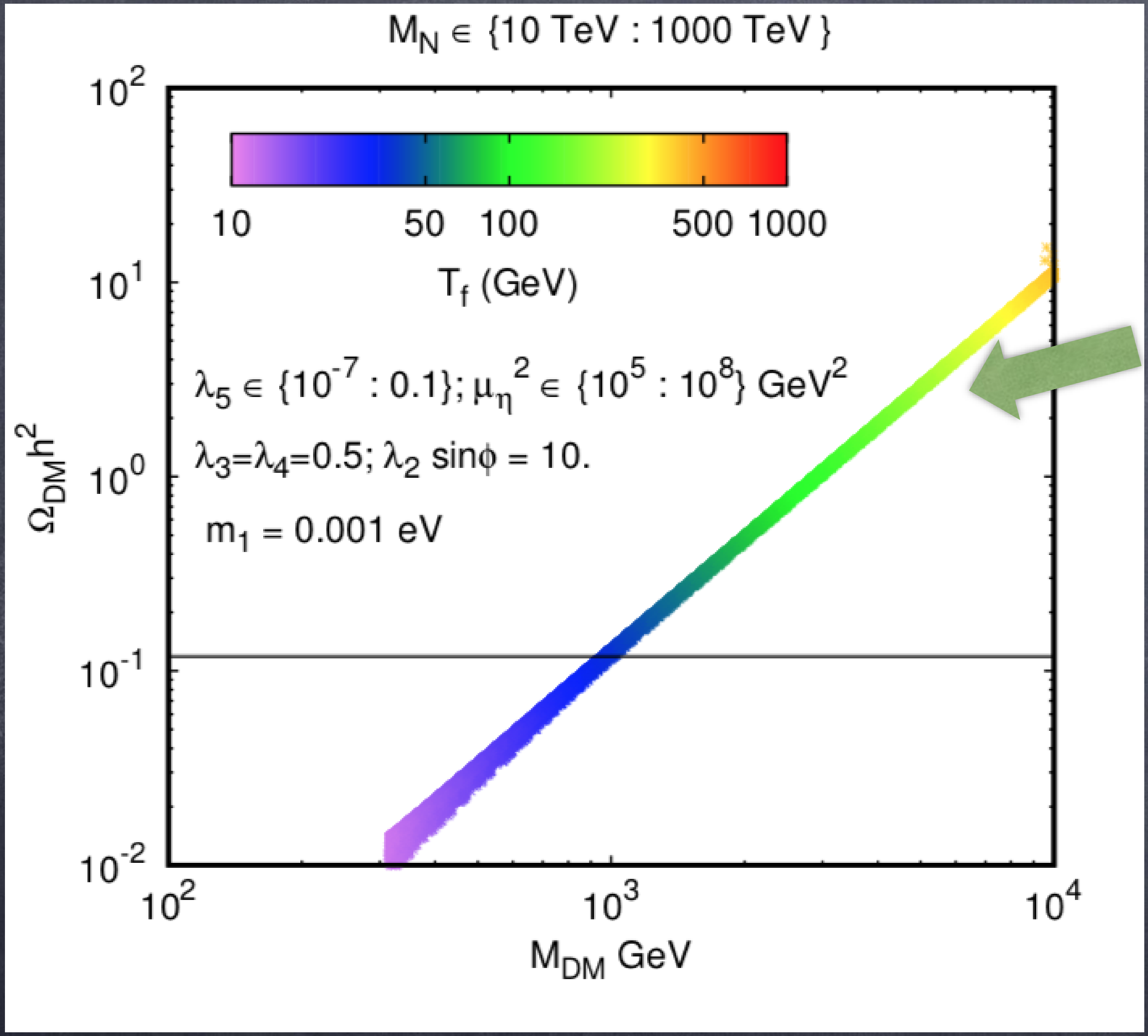
- In order to implement the constraints from neutrino mass and mixing angles, we use the Casas-Ibarra parameterization and use SPheno 3.1.

- We include dark matter direct detection constraints arising from Z boson mediated process $\eta_R n \to \eta_I\, n$

$$\sigma_n^0 = \frac{G_F^2}{2\pi}\mu_n^2 \simeq 7.44 \times 10^{-39}\mathrm{cm}^2$$

- Considering the typical kinetic energy of dark matter to be 100 keV, one can forbid such process if $\delta = m_{\eta_I} - m_{\eta_R} > 100$ keV.

Results for Minimal Scotogenic Model



DM is overproduced

Since EW sphaleron process is effective at T>150 GeV, baryon asymmetry should be achieved only if $T_f \sim \frac{M_{DM}}{20} > 150\ GeV$

All points satisfying $\delta = m_{\eta_I} - m_{\eta_R} > 100$ keV

Results for Minimal Scotogenic Model

- It is not possible to produce the correct lepton asymmetry above the electroweak phase transition from scalar DM annihilation while satisfying correct DM relic, neutrino mass constraints, and DM direct detection mediated by Z boson.

- Correct lepton asymmetry requires order one Yukawa which at the same time requires small λ_5 achieving tiny neutrino mass, but in conflict with DM direct detection.

→

Minimal Extension of Scotogenic Model

We extend the scotogenic model by introducing a complex singlet scalar which results in the scalar potential

$$V = \mu_H^2 H^\dagger H + \mu_\eta^2 \eta^\dagger \eta + \mu_\chi^2 \chi^* \chi + \frac{1}{4}\mu_4^2[\chi^2 + (\chi^*)^2]$$

$$+\mu(\eta^\dagger H \chi + H^\dagger \eta \chi^*) + \frac{1}{2}\lambda_H (H^\dagger H)^2 + \frac{1}{2}\lambda_\eta (\eta^\dagger \eta)^2$$

$$+\frac{1}{2}\lambda_\chi (\chi^* \chi)^2 + \lambda_4 (\eta^\dagger \eta)(H^\dagger H) + \lambda_5 (\eta^\dagger H)(H^\dagger \eta)$$

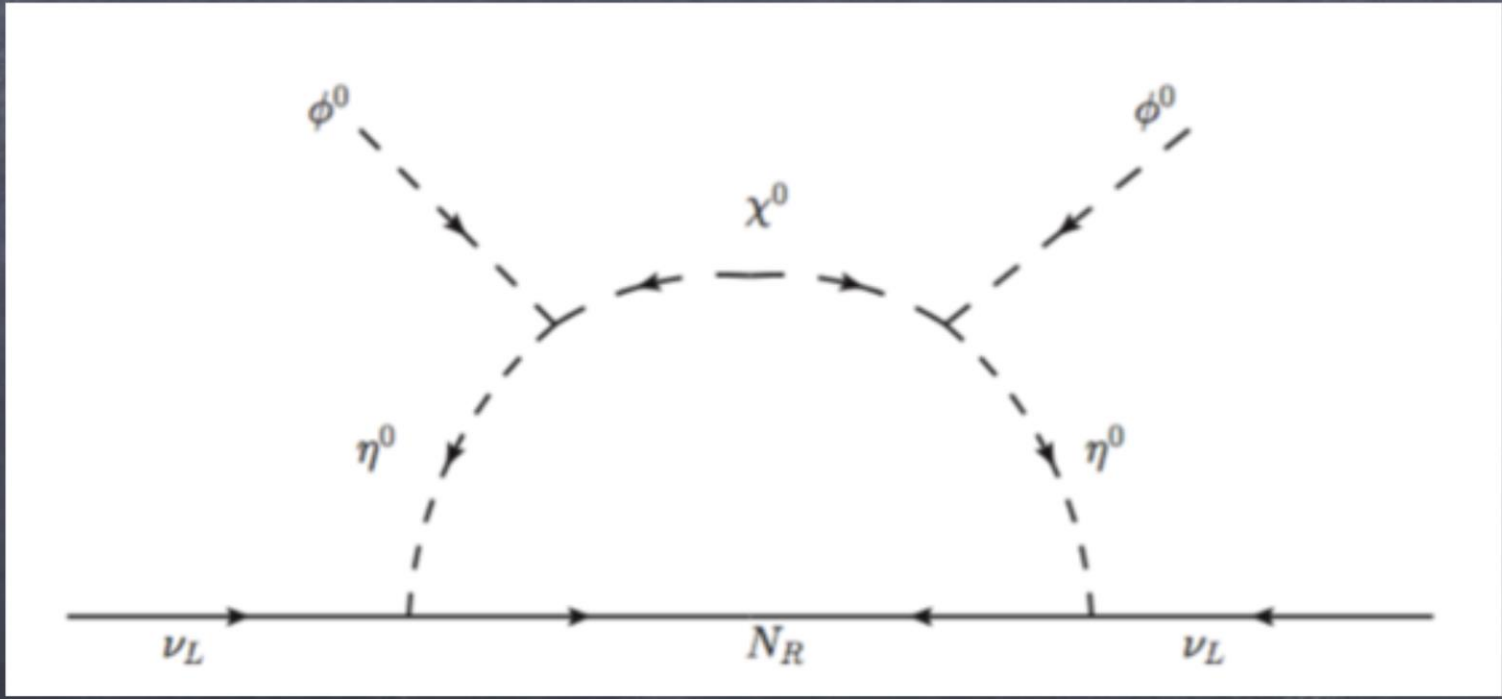
$$+\lambda_6 (\chi^* \chi)(H^\dagger H) + \lambda (\chi^* \chi)(\eta^\dagger \eta)$$

The motive behind the extension is to decouple DM mass splitting from the generation of neutrino masses so that we could resolve the tension between tiny neutrino mass and the constraint coming from the inelastic scattering mediated by Z boson.

Mass spectrum

Thanks to the trilinear term, η can mix with χ.

$$m_H^2 = \lambda_H v^2, \quad m_{\eta^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_4 v^2 \qquad M_{R,I}^2 = \begin{pmatrix} \mu_\eta^2 + (\lambda_4 + \lambda_5)v^2/2 & \mu v/\sqrt{2} \\ \mu v/\sqrt{2} & \mu_\chi^2 + \lambda_6 v^2/2 \pm \mu_4^2 \end{pmatrix}$$



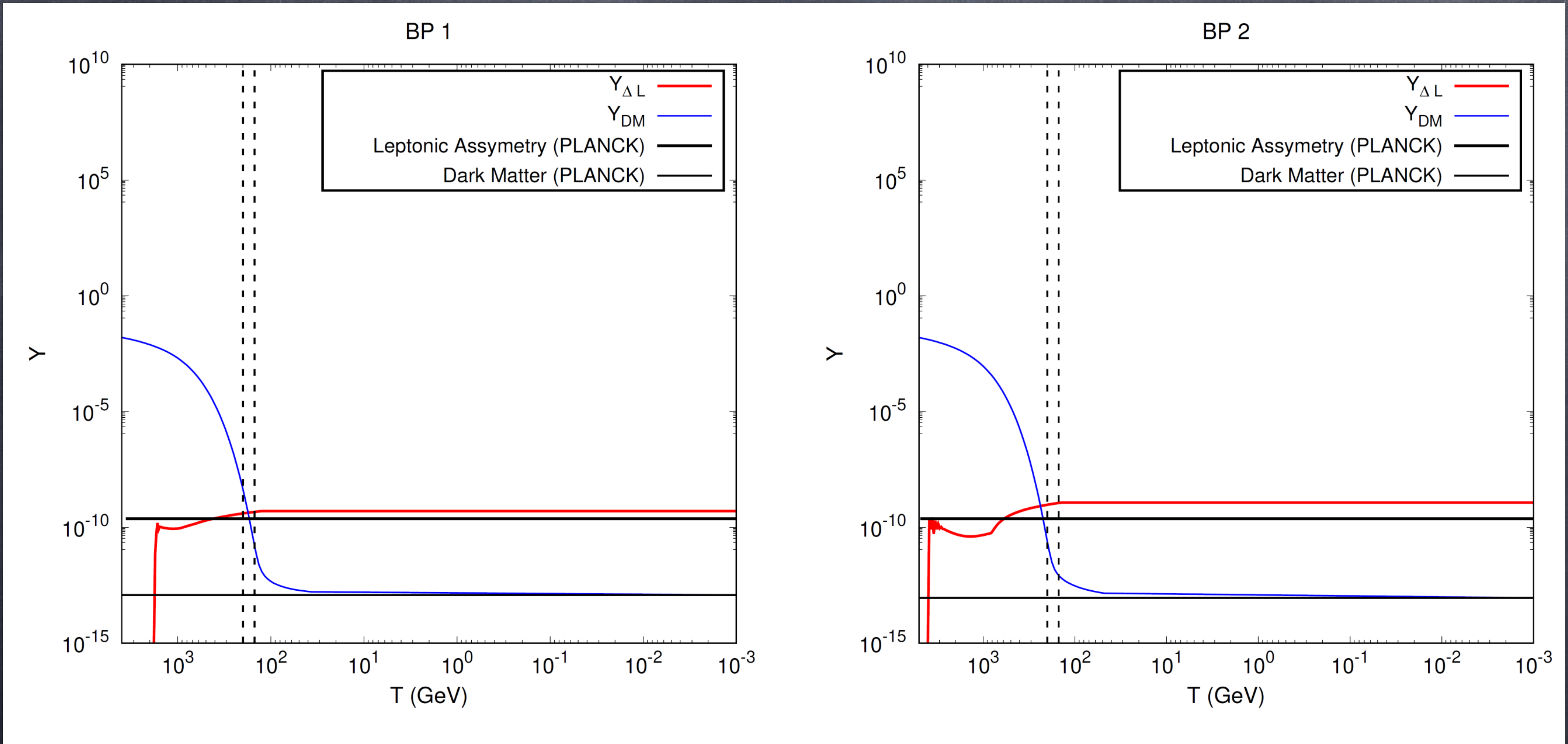
$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik}Y_{jk}M_k}{16\pi^2}\left(\frac{\cos^2\theta_R m^2_{\phi^R_\alpha}}{m^2_{\phi^R_\alpha} - M_k^2}\ln\frac{m^2_{\phi^R_\alpha}}{M_k^2} - \frac{\cos^2\theta_I m^2_{\phi^I_\alpha}}{m^2_{\phi^I_\alpha} - M_k^2}\ln\frac{m^2_{\phi^I_\alpha}}{M_k^2}\right), \ \alpha = 1, 2.$$

Numerical results

We could find parameter space achieving both relic density and baryon asymmetry by solving BEs.

BP1
$m_{\phi_1^R} = 3.612\ \text{TeV}, m_{\phi_2^R} = 4.\ \text{TeV}, m_{\phi_1^I} = 3.612\ \text{TeV}, m_{\phi_2^I} = 4\ \text{TeV}, m_{\phi^\pm} = 4\ \text{TeV},$ $\mu_\eta = 4.\ \text{TeV}, \mu_\chi = 3.61\ \text{TeV}, \mu = 9.\ \text{GeV}, \mu_4 = 80\ \text{keV},$ $\lambda_6 = 1.64,\ M_k = 10.0\ \text{TeV}\ (k = 1, 2, 3).$
BP2
$m_{\phi_1^R} = 4.804\ \text{TeV}, m_{\phi_2^R} = 5\ \text{TeV}, m_{\phi_1^I} = 4.804\ \text{TeV}, m_{\phi_2^I} = 5\ \text{TeV}, m_{\phi^\pm} = 5\ \text{TeV},$ $\mu_\eta = 5.\ \text{TeV}, \mu_\chi = 4.8\ \text{TeV}, \mu = 9.\ \text{GeV}, \mu_4 = 80\ \text{keV},$ $\lambda_6 = 2.59,\ M_k = 12.5\ \text{TeV}\ (k = 1, 2, 3).$

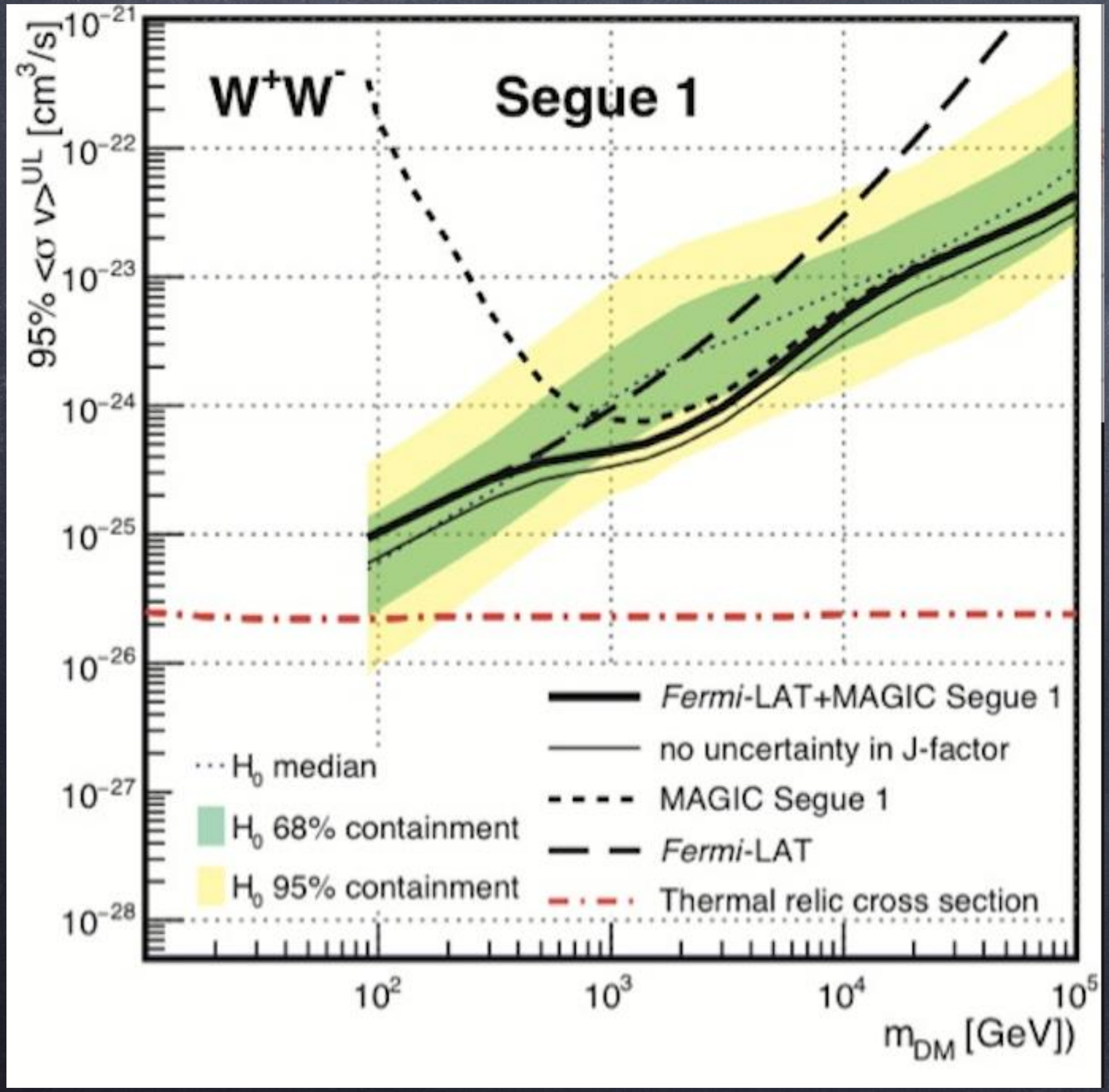
Prediction of Y as a function of T



Comoving number densities for lepton asymmetry and dark matter as a function of temperature for BP1 (left) and BP2 (right) . The largest value of Yukawa couplings are of order O(1) i.e $Y_{ij} \approx 0.2$. The vertical lines denote the range of electroweak phase transition temperature.

Probing our scenario

- Since the particle spectrum of the model remains heavy, around 5 TeV or more, their direct production at the 14 TeV LHC remains suppressed.



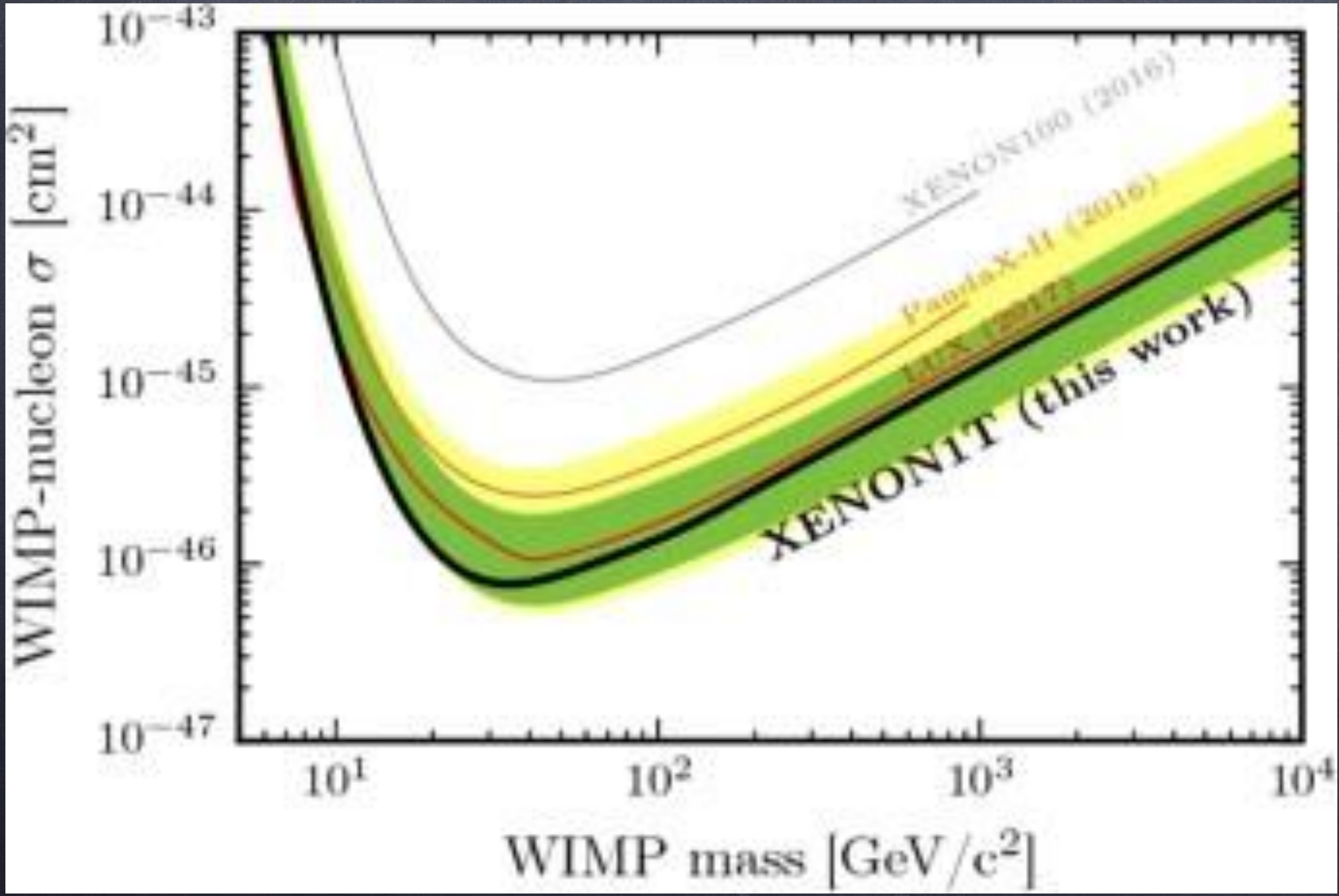
$$\langle \sigma v \rangle_{DMDM \to W^+ W^-} =$$

$$2.83 \times 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1} (BP1)$$

$$3.24 \times 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1} (BP2)$$

Probing our scenario

- The prospects at the direct dark matter detection experiments remain weak.



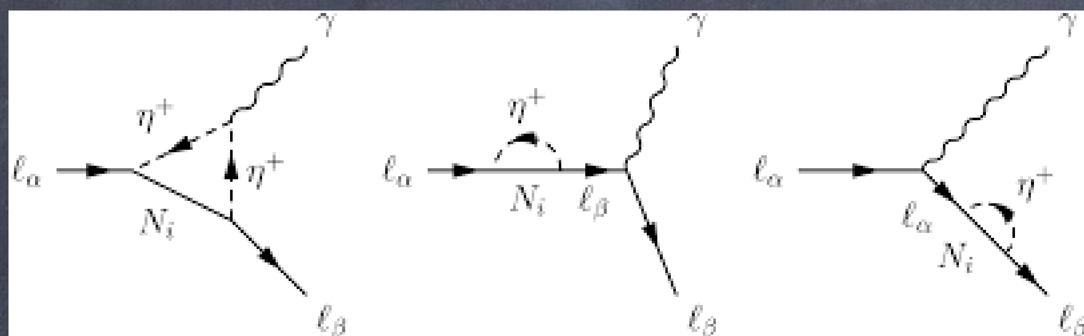
$$\sigma^{SI}_{DMn} =$$

$3.527 \times 10^{-47}\,\mathrm{cm}^2$ *BP1*

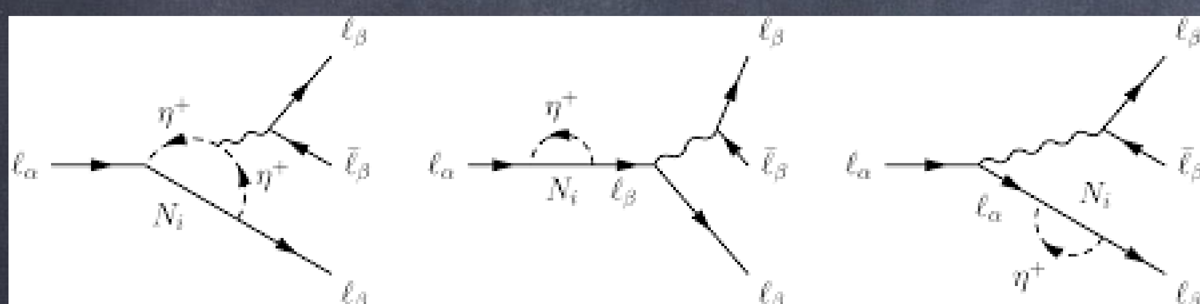
$2.508 \times 10^{-47}\,\mathrm{cm}^2$ *BP2*

Lepton Flavor Violation in Scotogenic Model

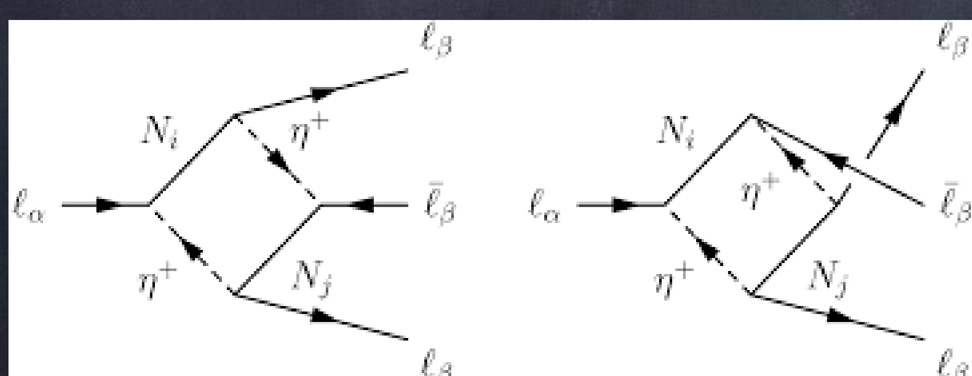
The model can be probed by rare decay experiments concerned with the lepton flavour violation.



$$l_\alpha \to l_\beta \gamma$$



$$l_\alpha \to 3l_\beta$$



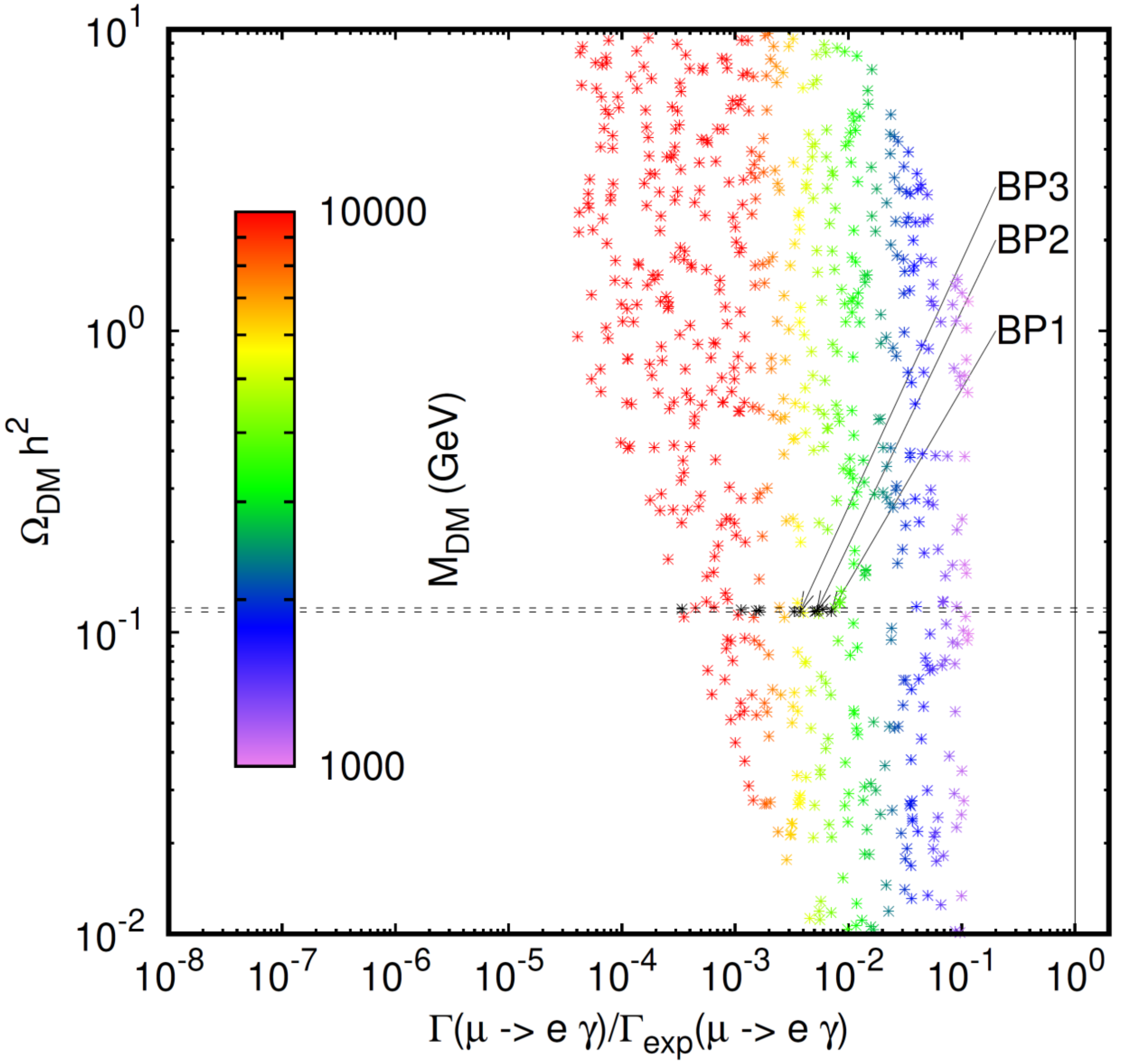
arXiv:1312.2840,1412.2545

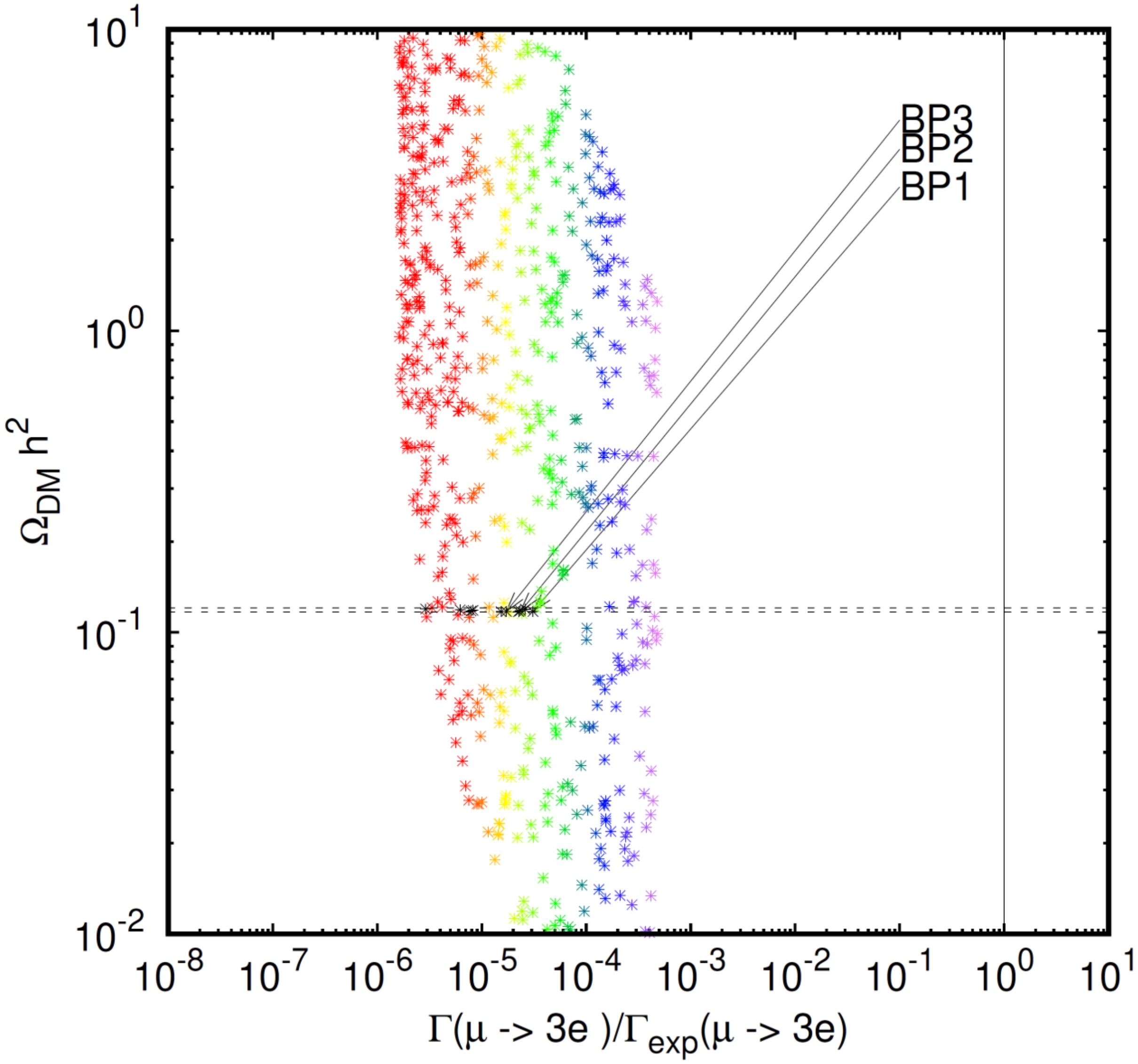
Lepton Flavor Violation in Scotogenic Model

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13} [25]	6×10^{-14} [26]
$\tau \to e\gamma$	3.3×10^{-8} [39]	$\sim 3 \times 10^{-9}$ [40]
$\tau \to \mu\gamma$	4.4×10^{-8} [39]	$\sim 3 \times 10^{-9}$ [40]
$\mu \to eee$	1.0×10^{-12} [28]	$\sim 10^{-16}$ [27]
$\tau \to \mu\mu\mu$	2.1×10^{-8} [41]	$\sim 10^{-9}$ [40]
$\tau^- \to e^-\mu^+\mu^-$	2.7×10^{-8} [41]	$\sim 10^{-9}$ [40]
$\tau^- \to \mu^-e^+e^-$	1.8×10^{-8} [41]	$\sim 10^{-9}$ [40]
$\tau \to eee$	2.7×10^{-8} [41]	$\sim 10^{-9}$ [40]
$\mu^-, \mathrm{Ti} \to e^-, \mathrm{Ti}$	4.3×10^{-12} [42]	$\sim 10^{-18}$ [35]
$\mu^-, \mathrm{Au} \to e^-, \mathrm{Au}$	7×10^{-13} [43]	
$\mu^-, \mathrm{Al} \to e^-, \mathrm{Al}$		$10^{-15} - 10^{-18}$
$\mu^-, \mathrm{SiC} \to e^-, \mathrm{SiC}$		10^{-14} [32]

arXiv:1312.2840,1412.2545

Predictions of relic density *vs.* LFV





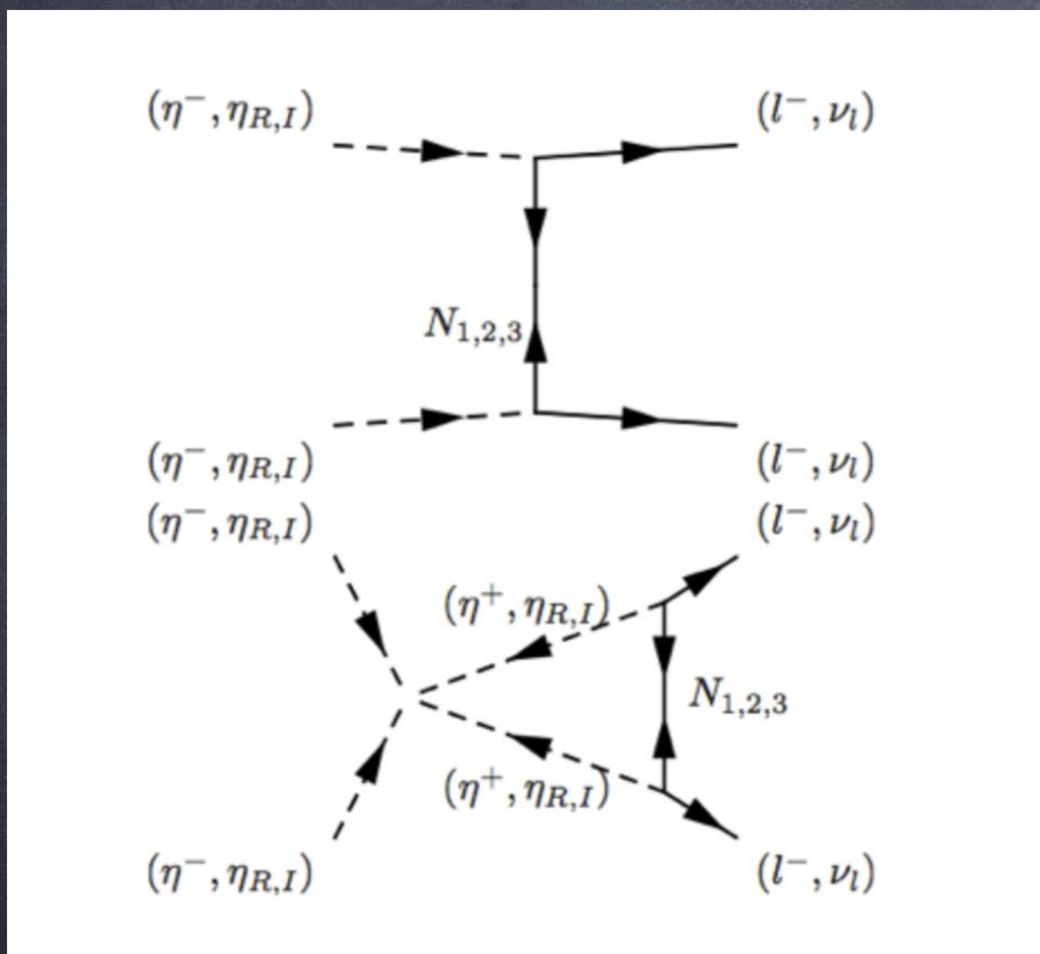
Predictions for LFV processes in our model for varying MDM and their correlations with the DM relic abundance. The vertical (horizontal) line corresponds to experimental limit for LFV processes (DM density).

Conclusion

- Scenarios relating DM and baryon abundance are more constrained than individual DM or baryogenesis models and have implications in a wide range of experiments starting from particle physics, cosmology & astrophysics.
- We show here the WIMPy baryogenesis cannot be realized in minimal scotogenic model.
- With a minimal extension by a scalar singlet, scotogenic model can accommodate successful leptogenesis from DM annihilation while keeping the scale of leptogenesis as low as 5 TeV

Thank You

$$\epsilon = \frac{\langle \sigma v \rangle^{1}_{DMDM \to LL}}{\langle \sigma v \rangle^{0}_{DMDM \to LL}} \simeq \lambda \sin\phi \bar{\epsilon}$$



$$\bar{\epsilon} = \frac{1+x}{8\pi^2 x}\left[\ln\left(-\frac{(1+x)}{2x}\right)^2 + 2\mathrm{Li}_2\left(\frac{1}{2}\left(3+\frac{1}{x}\right)\right)\right.$$

$$-2\mathrm{Li}_2\left(\frac{(x-1)^2}{(1+x)^2}\right) + 2\mathrm{Li}_2\left(\frac{1+x(2-3x)}{(1+x)^2}\right)$$

$$\left.-2\mathrm{Li}_2\left(3-\frac{2}{1+x}\right) + 4\mathrm{Li}_2\left(\frac{2-1-x}{1+x}\right)\right]$$

$$x = \frac{M_{\mathrm{DM}}^2}{M_N^2} \qquad \mathrm{Li}_2(y) = \sum_{k=1}^{\infty}\frac{y^k}{k^2}$$