Creating Matter-Antimatter Asymmetry from Dark Matter Annihilations in Scotogenic Scenarios

Based on arXiv:1806.04689 with
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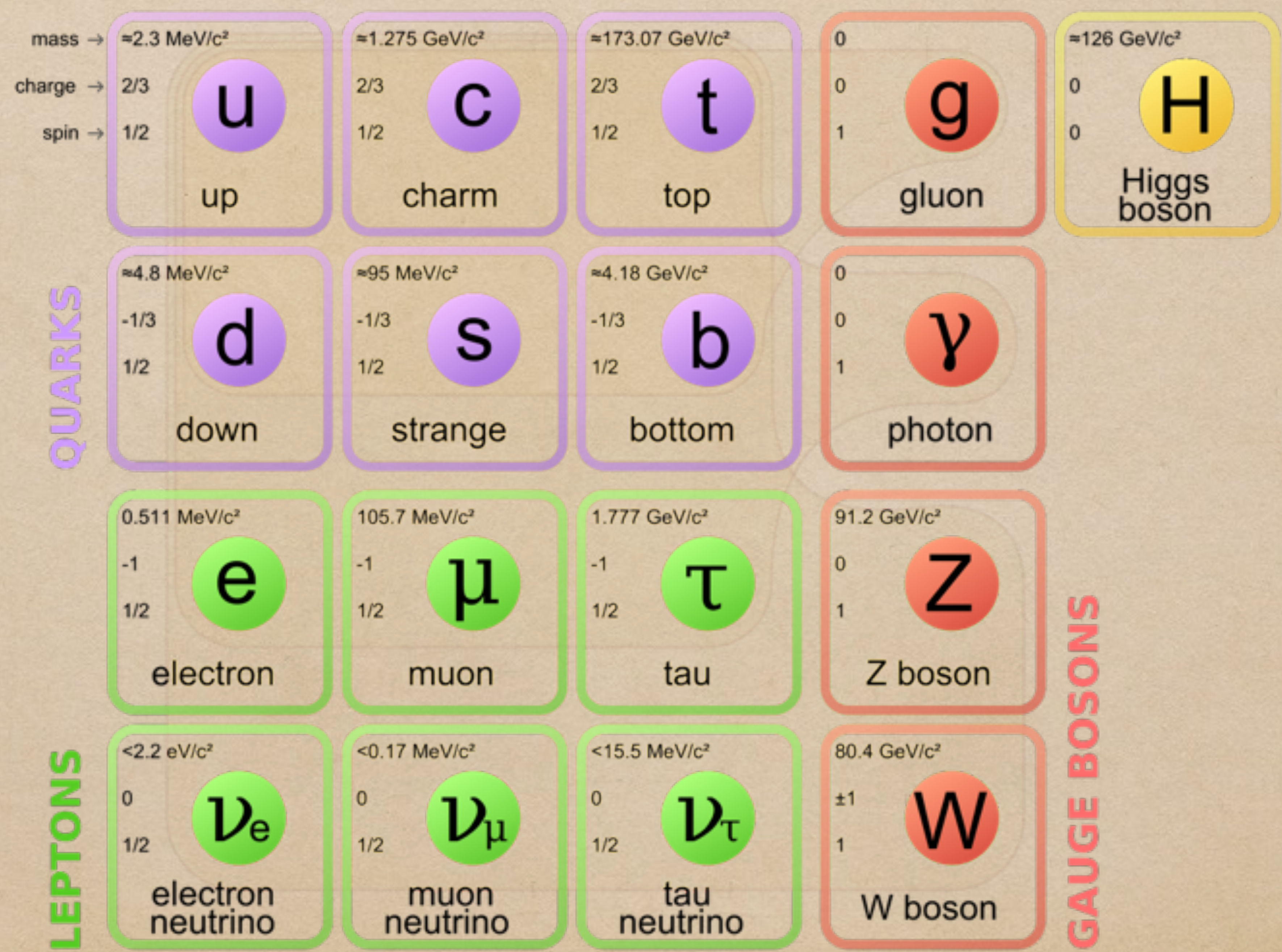
Outline

- Introduction
- Dark Matter (DM)
- Baryon Asymmetry of Universe (BAU)
- Towards a Common Origin of DM & BAU
- Baryogenesis from DM annihilation in Scotogenic Model
- Conclusion

The Standard Model



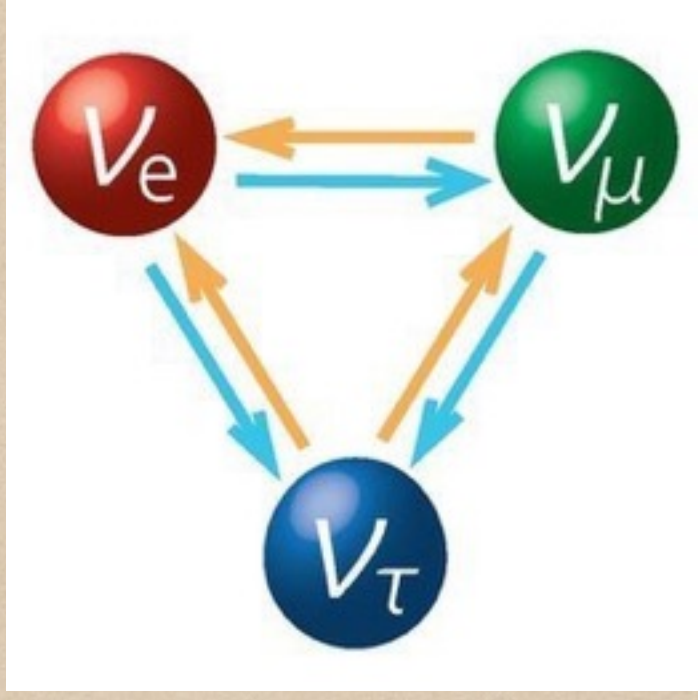
The Standard Model

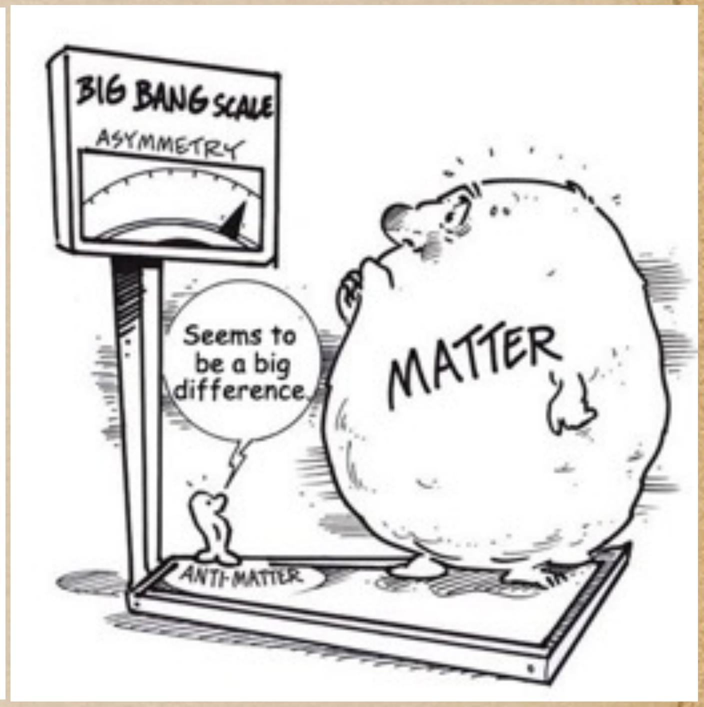
- The SM has been very successful in describing the elementary particles and their interactions except gravity.
- The last missing piece of the SM, the Higgs boson was also discovered a few years back at the LHC (2012).
- Since then the LHC results have only been able to confirm the validity of the SM again and again, with no convincing signatures of new physics around the TeV scale.

But, there are

Problems in the SM

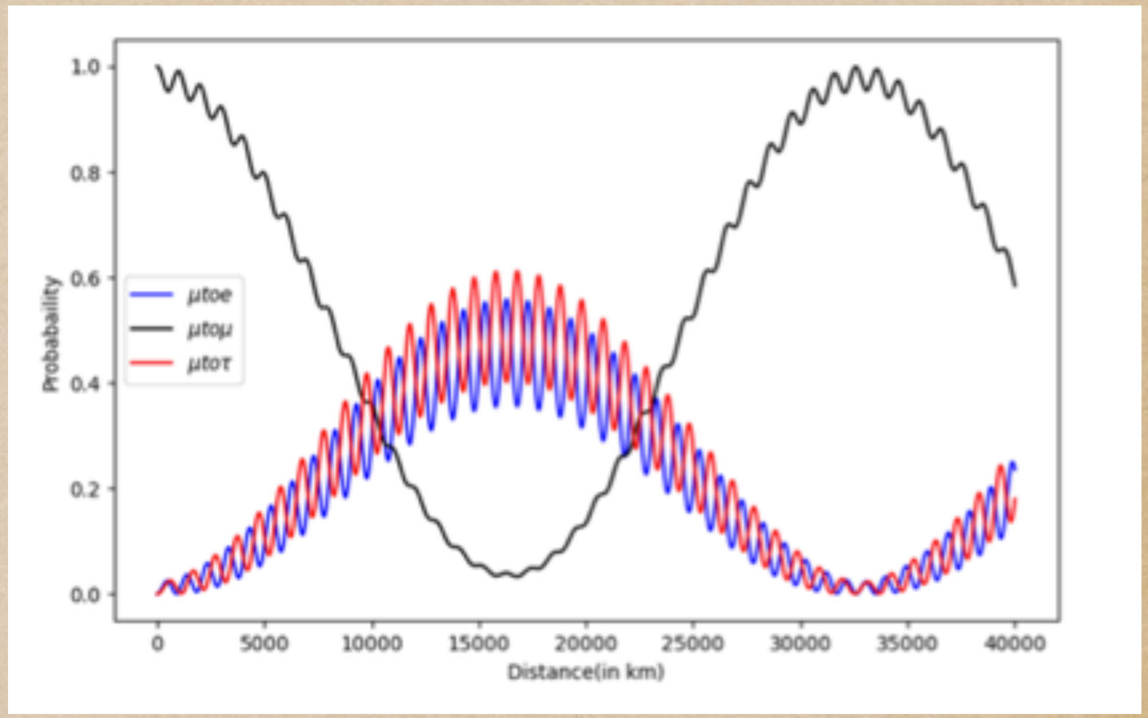
- SM can not explain the observed neutrino mass and mixing.
- SM does not have a dark matter candidate.
- SM can not explain the observed baryon asymmetry





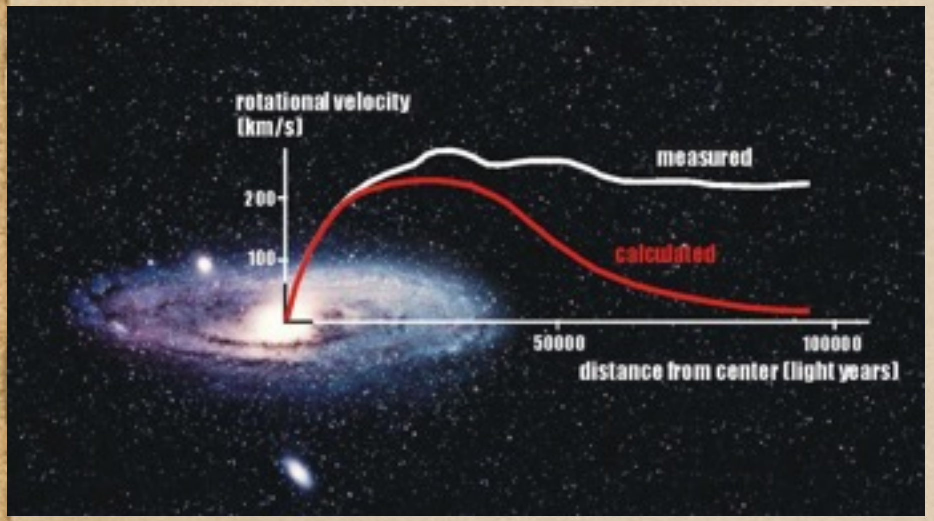
Neutrino Mass & Mixing

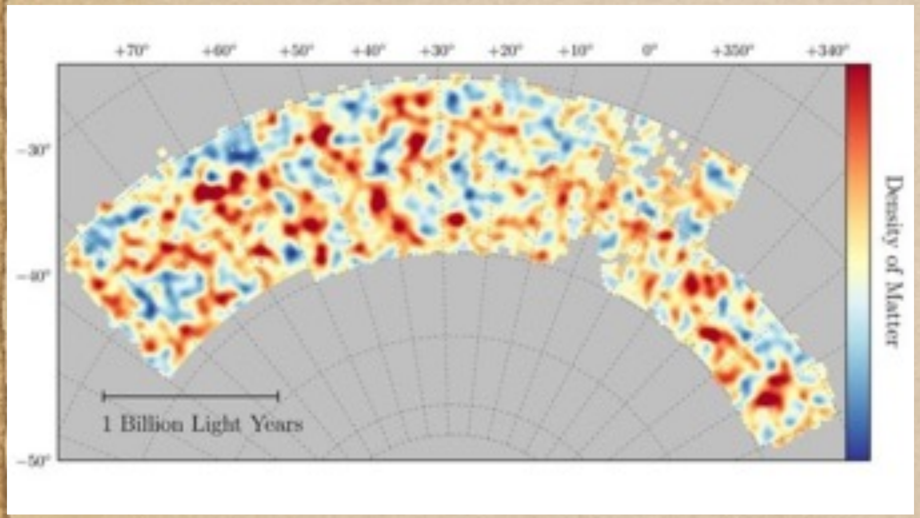
- Neutrinos can oscillate from one flavour to another, experimentally verified by the Super Kamiokande and Sadbury Neutrino Observatories (Physics Nobel 2015).

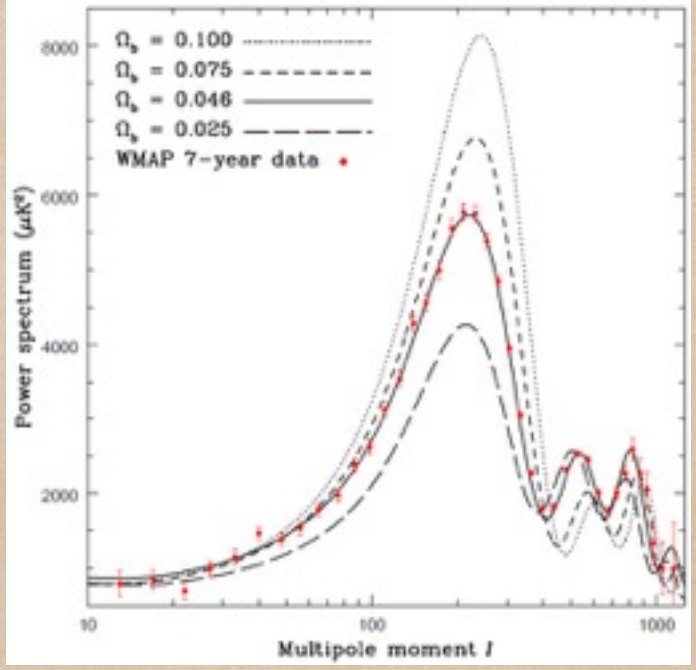


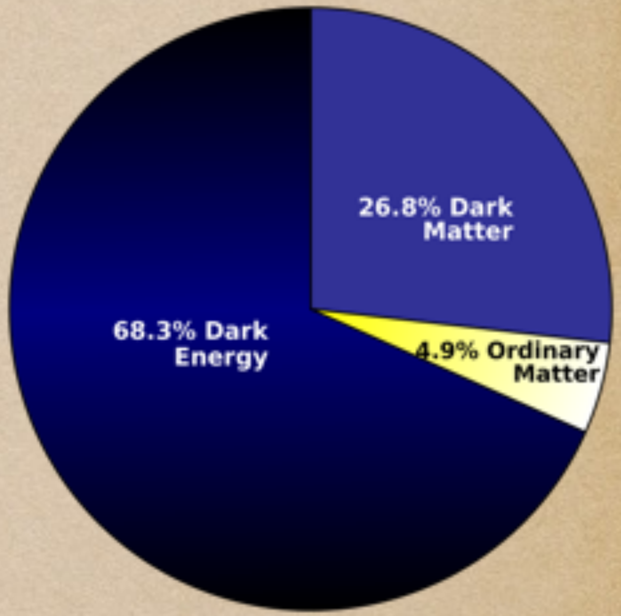
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2 \frac{\Delta m^2_{ij} L}{4E} + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin \frac{\Delta m^2_{ij} L}{2E}$$

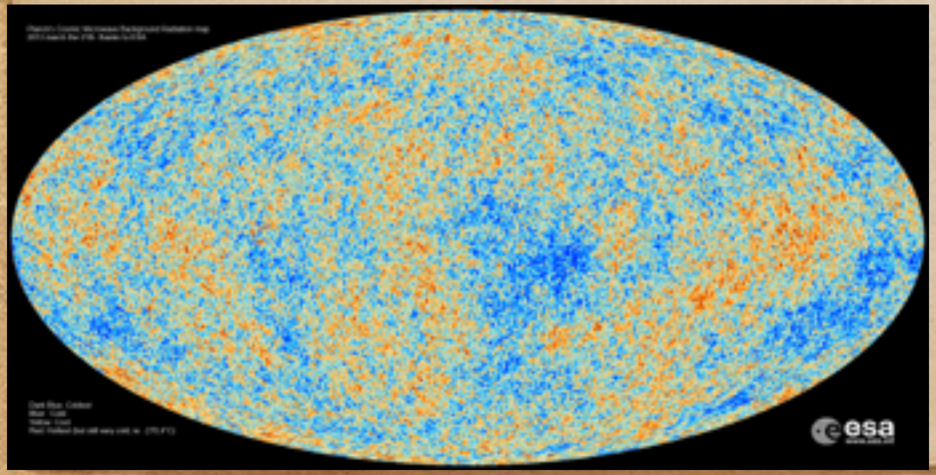
Dark Matter: Evidences











Credits:

HST, Chandra, DE Survey, WMAP, Planck

Dark Matter: 10 Point Test

- Does it match the appropriate relic abundance?
- Is it cold?
- Is it electromagnetic and color neutral?
- Is it consistent with Big Bang Nucleosynthesis?
- Does it leave stellar evolution unchanged?
- Is it compatible with constraints on self-interactions?
- Is it consistent with direct dark matter searches?
- Is it compatible with gamma-ray searches?
- Is it compatible with other astrophysical bounds?
- Can it be probed experimentally?

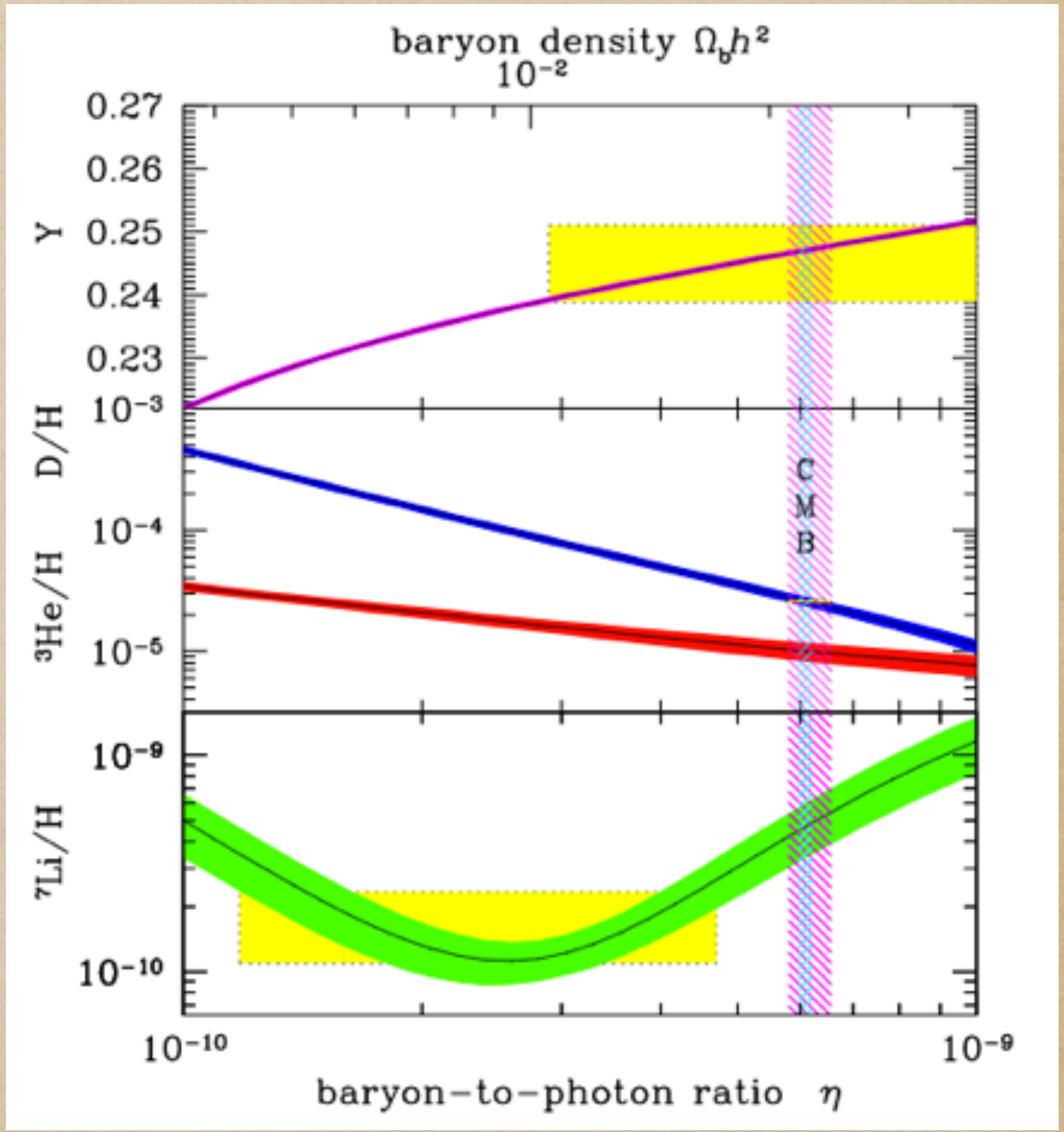
Taoso, Bertone & Masiero 2008

Baryon Asymmetry of the Universe

- The observed BAU is often quoted in terms of baryon to photon ratio

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10}$$

- The prediction for this ratio from Big Bang Nucleosynthesis (BBN) agrees well with the observed value from Cosmic Microwave Background Radiation (CMBR) measurements (Planck, arXiv: 1502.01589).



Particle Data Group 2017

Sakharov's Conditions

Three basic ingredients necessary to generate a net baryon asymmetry from an initially baryon symmetric Universe (Sakharov 1967):

- Baryon Number (B) violation $X \to Y + B$
- C & CP violation.

$$\Gamma(X \to Y + B) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) \neq \Gamma(\overline{X} \to \overline{q_L} + \overline{q_L}) + \Gamma(\overline{X} \to \overline{q_R} + \overline{q_R})$$

- Departure from thermal equilibrium.

Baryogenesis

- The SM fails to satisfy Sakharov's conditions: insufficient CP violation in the quark sector & Higgs mass is too large to support a strong first order electroweak phase transition (Electroweak Baryogenesis).
- Additional CP violation in lepton sector (not yet discovered) may play a role through the mechanism of Leptogenesis (Fukugita & Yanagida 1986).
- Typically, seesaw models explaining neutrino mass and mixing can also play a role in creating a lepton asymmetry through out of equilibrium CP violating decay of heavy particles, which later gets converted into baryon asymmetry through electroweak sphalerons.
- Leptogenesis provides a common framework to explain neutrino mass, mixing and baryon asymmetry of the Universe.

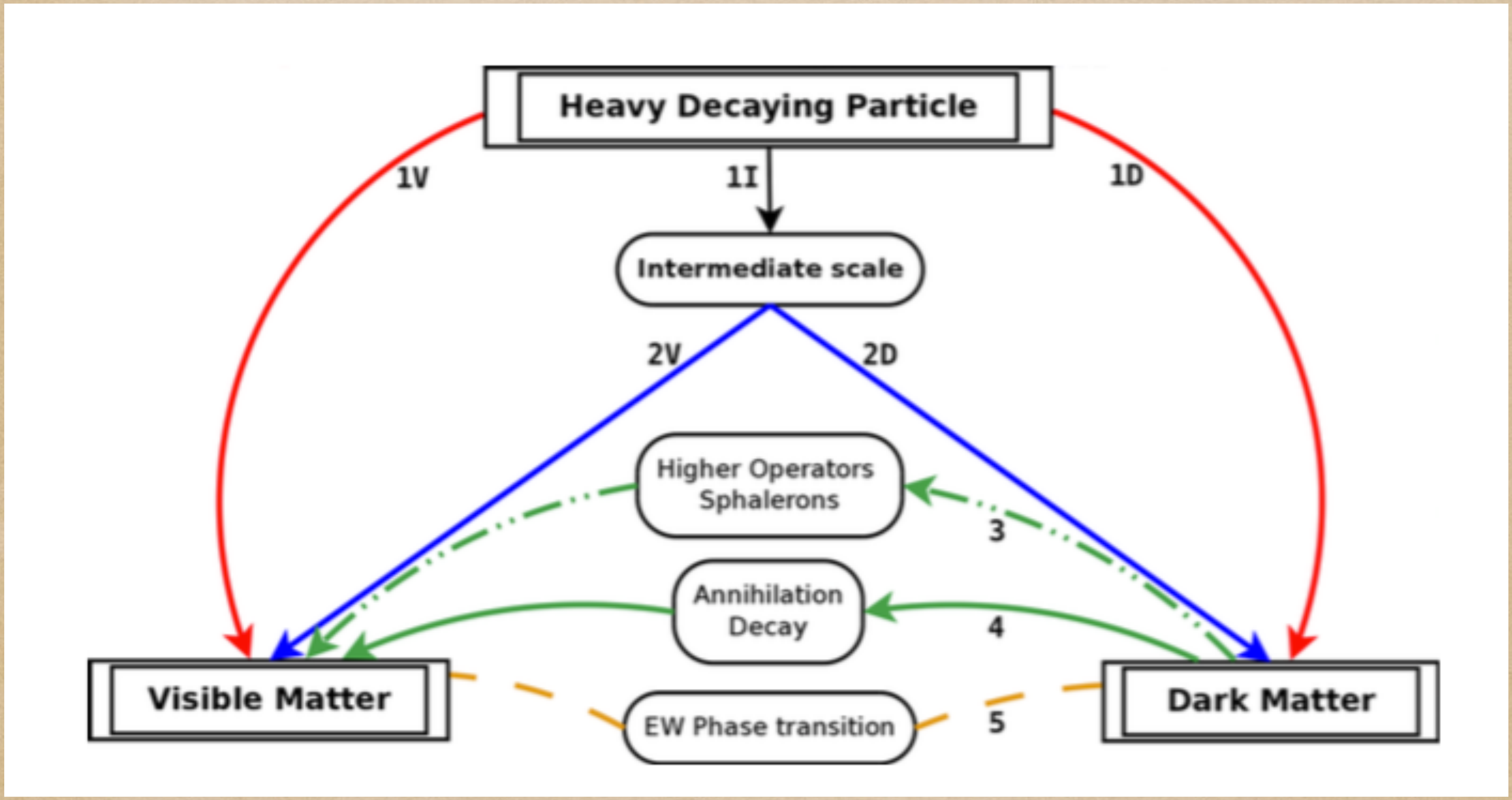
Baryogenesis & Dark Matter

- The observed BAU and DM abundance are of the same order

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

- Although this could be just a coincidence, it has motivated several studies trying to relate their origins.
- Asymmetric DM, WIMPy Baryogenesis etc are some of the scenarios proposed so far.
- While generic implementations of these scenarios tightly relate BAU & DM abundances, there exist other implementations too where the connections may be loose.

Baryogenesis & Dark Matter: Common Origin



Boucenna & Morisi 2014

Asymmetric DM

Zurek, 1308.0338; Petraki & Volkas, 1305.4939

- Similar to baryons, there exists an asymmetry in DM as well, both of which have common origin (Nussinov 1985; Gelmini, Hall, Lin 1987; Kaplan, Luty, Zurek 2009).

- If they have similar number densities

$$n_{DM} - n_{\bar{DM}} \approx n_B - n_{\bar{B}}$$

then $\rho_{DM} \approx 5\rho_B$ implies $M_{DM} \approx 5 m_p \approx 5\ \text{GeV}$

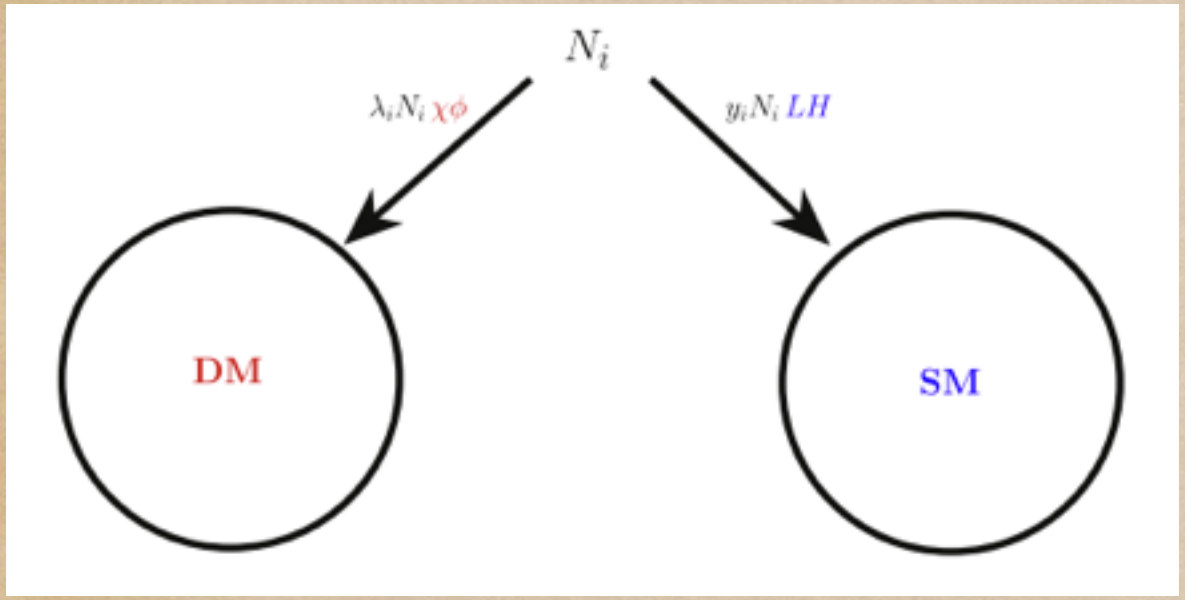
- However, if the process producing DM asymmetry decouples early or different asymmetries are generated in DM and visible sectors, then DM mass can be different from what this simple relation dictates.

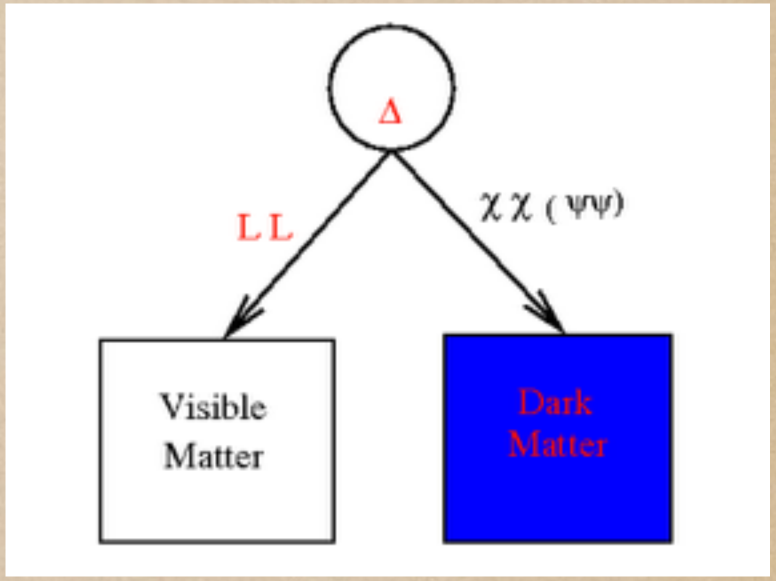
ADM: Basic Framework

- Asymmetry generated in either of the sectors followed by transfer into the other or simultaneous generation.
- Freeze-out of the processes involved.
- If the DM sector was thermalised while asymmetry generation, then the symmetric part should annihilate away leaving the remnant asymmetric part (similar to electron-positron annihilation before H recombination).

Asymmetry Generation

- Simultaneous generation: Cogenesis e.g. Out of equilibrium decay (Falkowski et al 2011, Arina & Sahu 2011 etc.)





Comments (ADM)

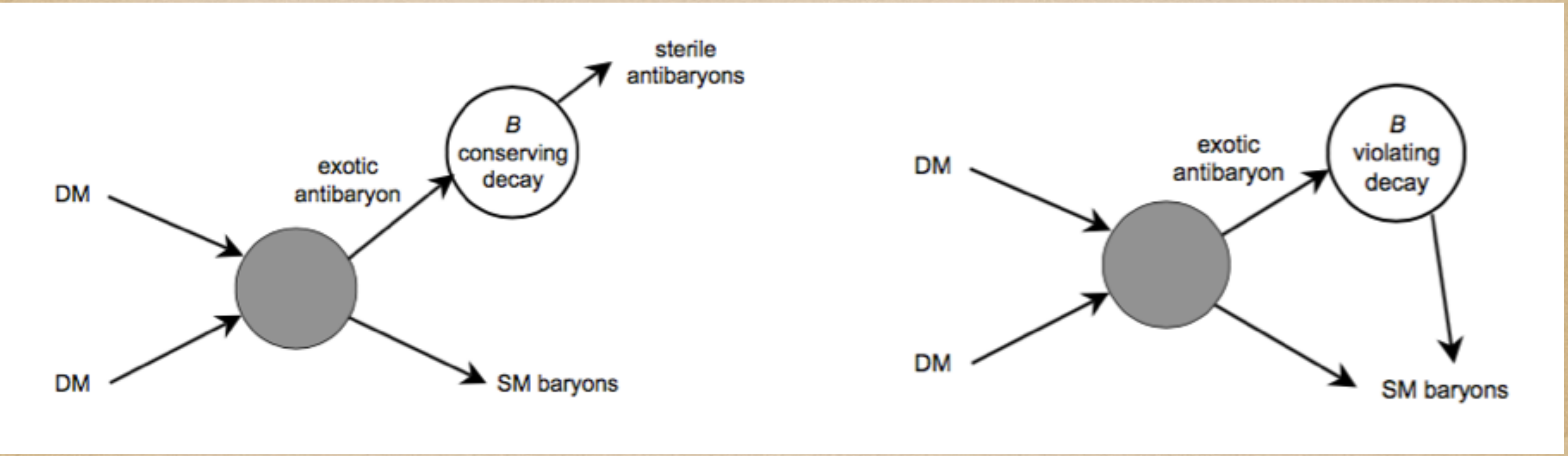
- Apart from decay, cogenesis can occur through Affleck-Dine mechanisms (1105.4612).
- Electroweak baryogenesis: sphalerons can couple to both SM & DM (Barr 1992, 0909.2034). (Tight precision constraints on chiral extensions of SM).
- Darkogenesis: Dark sphalerons generate asymmetry in the dark sector which then gets transferred to the visible sector via a connecting sector (1008.1997).
- Hidden sector ADM (1005.1655).
- Wide range of DM masses possible in all such scenarios.

Comments (ADM)

- Composite ADM (Gudnason, Boucenna, Kouvaris, Sannino 2006).
- KITANO-LOW Model(Kitano & Low 2006).
- Hylogenesis Model (Davoudiasl et al 2010).
- Xogenesis (Buckley & Randall 2011).

WIMPy Baryogenesis

Cui, Randall & Shuve 2011



1. WIMP annihilations violate B or L.
2. WIMP couplings to SM have CP violations.
3. Cooling of the Universe provides the departure from thermal equilibrium.

WIMPy Baryogenesis: General Framework

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

DM X annihilating into baryons

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

Integrating the 2nd equation gives

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

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

Assuming the wash-out process to freeze-out before WIMP freezes out, we can have the final asymmetry as

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

WIMPy Baryogenesis: General Framework

- For wash-out freeze-out to precede WIMP freeze-out, one must have the following quantity less than unity at the time of wash-out freeze-out.

$$\frac{\Gamma_{\text{washout}}(x)}{\Gamma_{\text{WIMP}}(x)} \approx \frac{\langle \sigma_{\text{washout}} v \rangle \prod_i Y_i^{\text{eq}}(x)}{4 \langle \sigma_{\text{ann}} v \rangle Y_X^{\text{eq}}(x) Y_\gamma}$$

- This can be made sure for every process washing out the baryon asymmetry if

1. One of the baryon states is heavier than dark matter so $\frac{\prod_i Y_i^{\text{eq}}(x)}{Y_X^{\text{eq}}(x) Y_\gamma} \ll 1$.
2. The baryon-number-violating coupling is small so $\langle \sigma_{\text{washout}} v \rangle \ll \langle \sigma_{\text{ann}} v \rangle$.

- The second scenario is difficult to realise because same couplings decide both the cross sections.

Scotogenic Model

E Ma 2006

- Extension of the SM by 3 RHN & 1 Scalar Doublet, odd under the a built-in Z_2 symmetry.
- The lightest of the Z_2 odd particles, if EM neutral is a DM candidate.
- Scalar DM resembles inert doublet DM (hep-ph/0603188, 0512090, 0612275).
- Lightest RHN DM (1710.03824).
- Neutrino Mass arises at one-loop level.

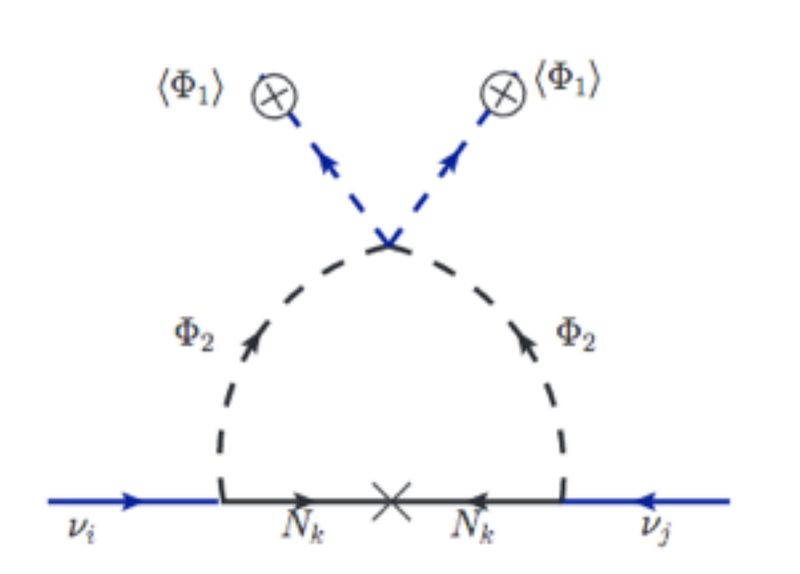
Scotogenic Model

E Ma 2006

$$V(\Phi_1,\Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\}$$

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij}N_iN_j + \left(Y_{ij}\,\bar{L}_i\tilde{\Phi}_2N_j + \text{h.c.}\right)$$

$$m_h^2 = \lambda_1 v^2,$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2,$$
$$m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)v^2 = m_{H^\pm}^2 + \frac{1}{2}(\lambda_4+\lambda_5)\,v^2,$$
$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3+\lambda_4-\lambda_5)v^2 = m_{H^\pm}^2 + \frac{1}{2}(\lambda_4-\lambda_5)\,v^2.$$



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

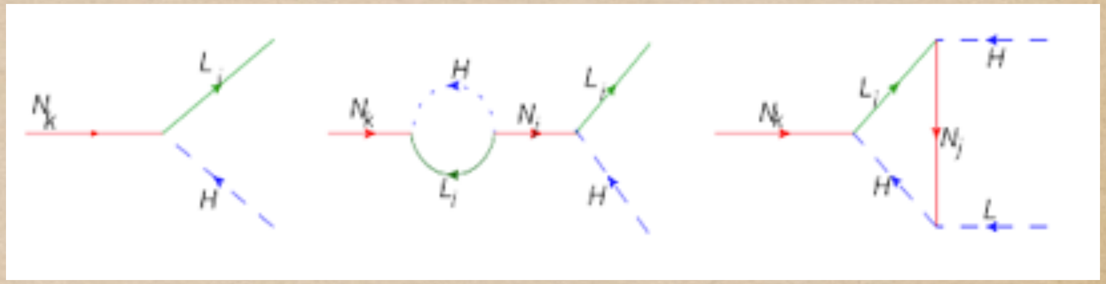
which under the approximation $m_H^2 + m_A^2 \approx M_k^2$ boils down to

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

Vanilla Leptogenesis in Scotogenic Model

- Right handed neutrino decays out of equilibrium (Fukugita & Yanagida 1986)

$$Y_{ij}\bar{L}_i\tilde{H}N_j + \frac{1}{2}M_{ij}N_iN_j$$



- CP violation due to phases in Yukawa couplings Y, leads to a lepton asymmetry.

$$\epsilon_{N_k} = -\sum_i \frac{\Gamma(N_k \to L_i + H^*) - \Gamma(N_k \to L_i + H)}{\Gamma(N_k \to L_i + H^*) + \Gamma(N_k \to L_i + H)}$$

- At least two N are required to generate an asymmetry due to the presence of interference between tree and one loop diagrams namely, vertex diagram (Fukugita & Yanagida'86) and self energy diagram (Liu & Segre'93). For one N, the complex phase can be rotated away.

Vanilla Leptogenesis in Scotogenic Model

- The asymmetry freezes out at $T \ll M_i$
- The lepton asymmetry gets converted into baryon asymmetry through electroweak sphalerons (Khlebnikov & Shaposhnikov'88, Harvey & Turner'90).

$$\frac{n_{\Delta B}}{s} = -\frac{28}{79}\frac{n_{\Delta L}}{s}$$

- The same right handed neutrinos also generate light neutrino masses at one-loop, along with scalar dark matter going inside the loop.

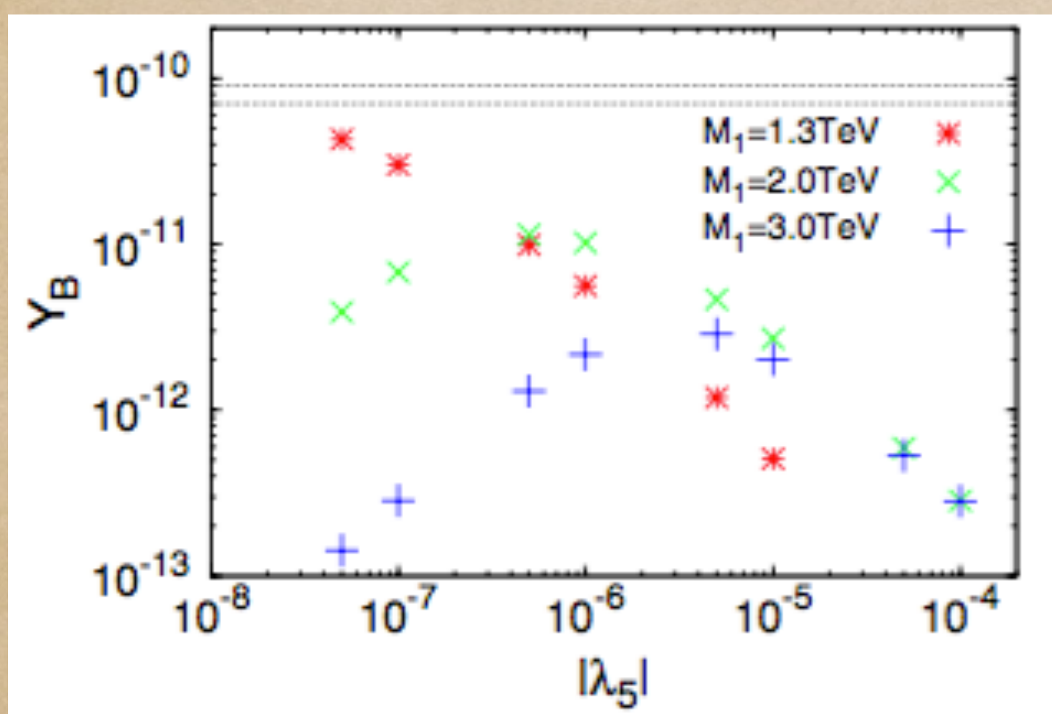
Vanilla Leptogenesis in Scotogenic Model

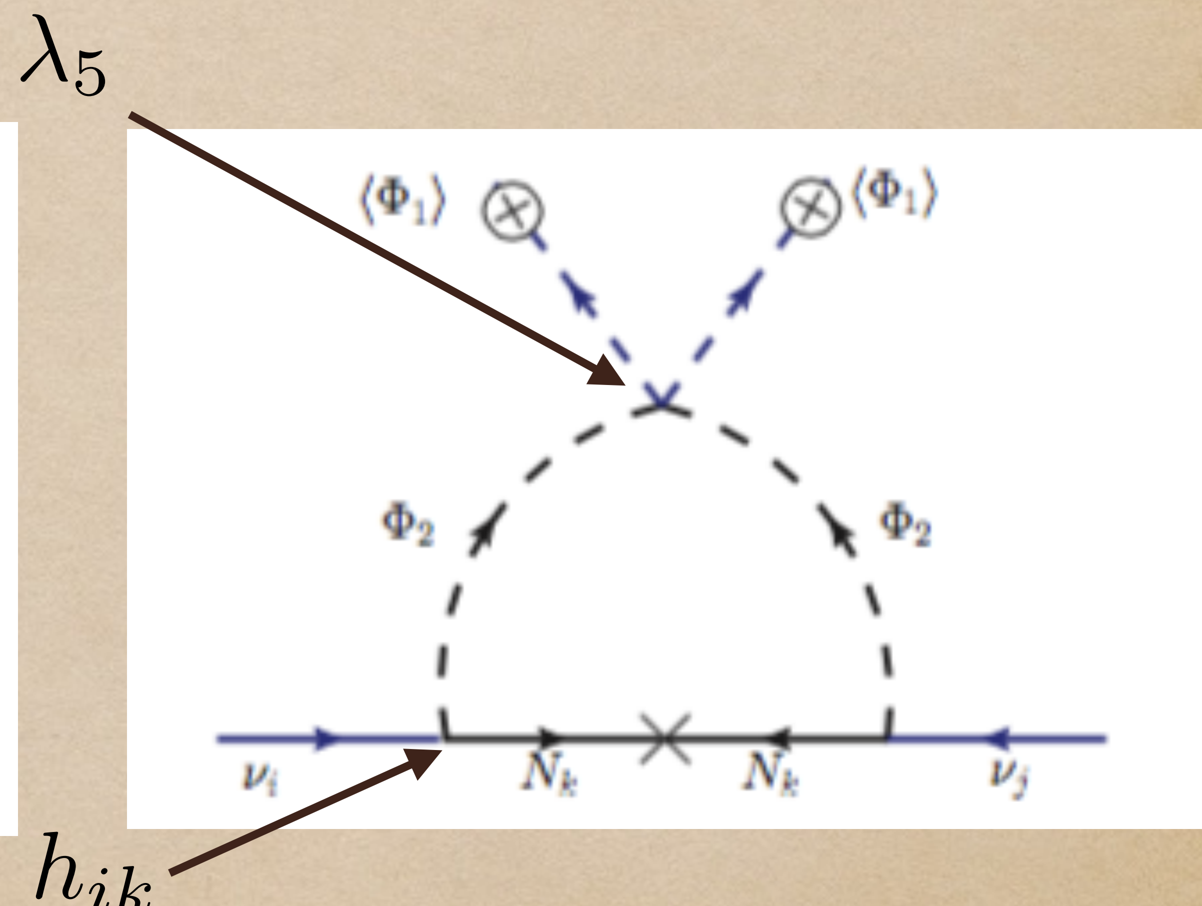
1207.2594

$$\varepsilon = \frac{1}{16\pi[\frac{3}{4} + \frac{1}{4}(1 - \frac{M_\eta^2}{M_i^2})^2]} \sum_{i=2,3} \frac{\mathrm{Im}[(\sum_{k=e,\mu,\tau} h_{k1} h_{ki}^*)^2]}{\sum_{k=e,\mu,\tau} h_{k1} h_{k1}^*} \times G\left(\frac{M_i^2}{M_1^2}, \frac{M_\eta^2}{M_1^2}\right)$$

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(M_1)}\left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right)\left\{\gamma_D^{N_1} + \sum_{i=2,3}(\gamma_{N_1N_i}^{(2)} + \gamma_{N_1N_i}^{(3)})\right\},$$

$$\frac{dY_L}{dz} = \frac{z}{sH(M_1)}\left\{\varepsilon\left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right)\gamma_D^{N_1} - \frac{2Y_L}{Y_\ell^{\mathrm{eq}}}(\gamma_N^{(2)} + \gamma_N^{(13)})\right\},$$

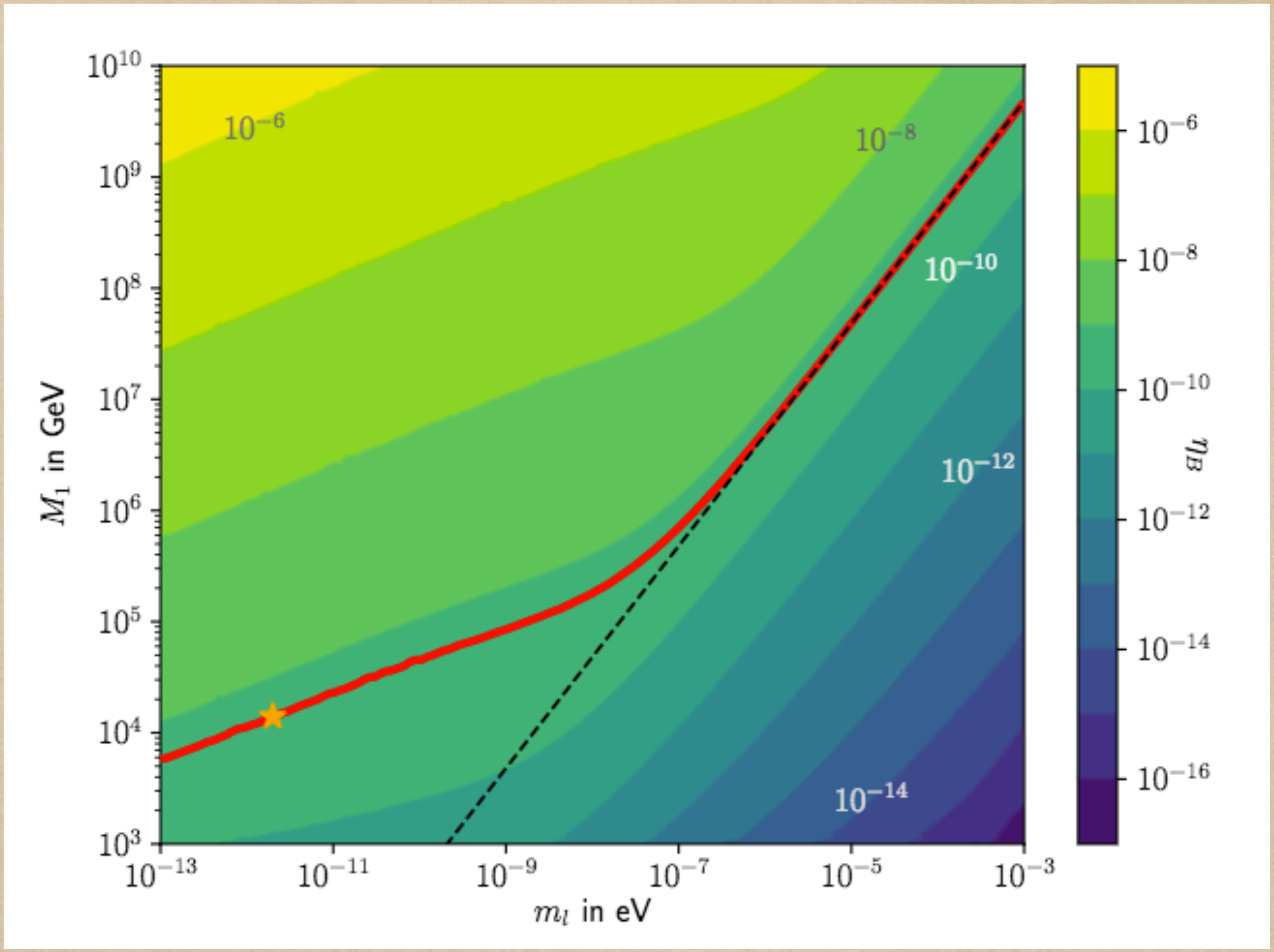




Vanilla Leptogenesis in Scotogenic Model

- Smaller value of λ_5 requires larger Yukawa h_{ij} for correct neutrino mass and vice versa.
- Large Yukawa results in more wash-outs. Small Yukawas will produce small asymmetry.
- For TeV scale RHN, one requires very small values of λ_5 to satisfy neutrino mass and baryon asymmetry requirements.
- Such small values of λ_5 leads to large inelastic scattering of DM, ruled out by data.
- TeV scale leptogenesis is not possible for hierarchical RHN, unless the lightest RHN is heavier than 10 TeV (1804.09660).
- Resonant leptogenesis can work (Pilaftsis 1997, B Dev et al 2013).

Vanilla Leptogenesis in Scotogenic Model

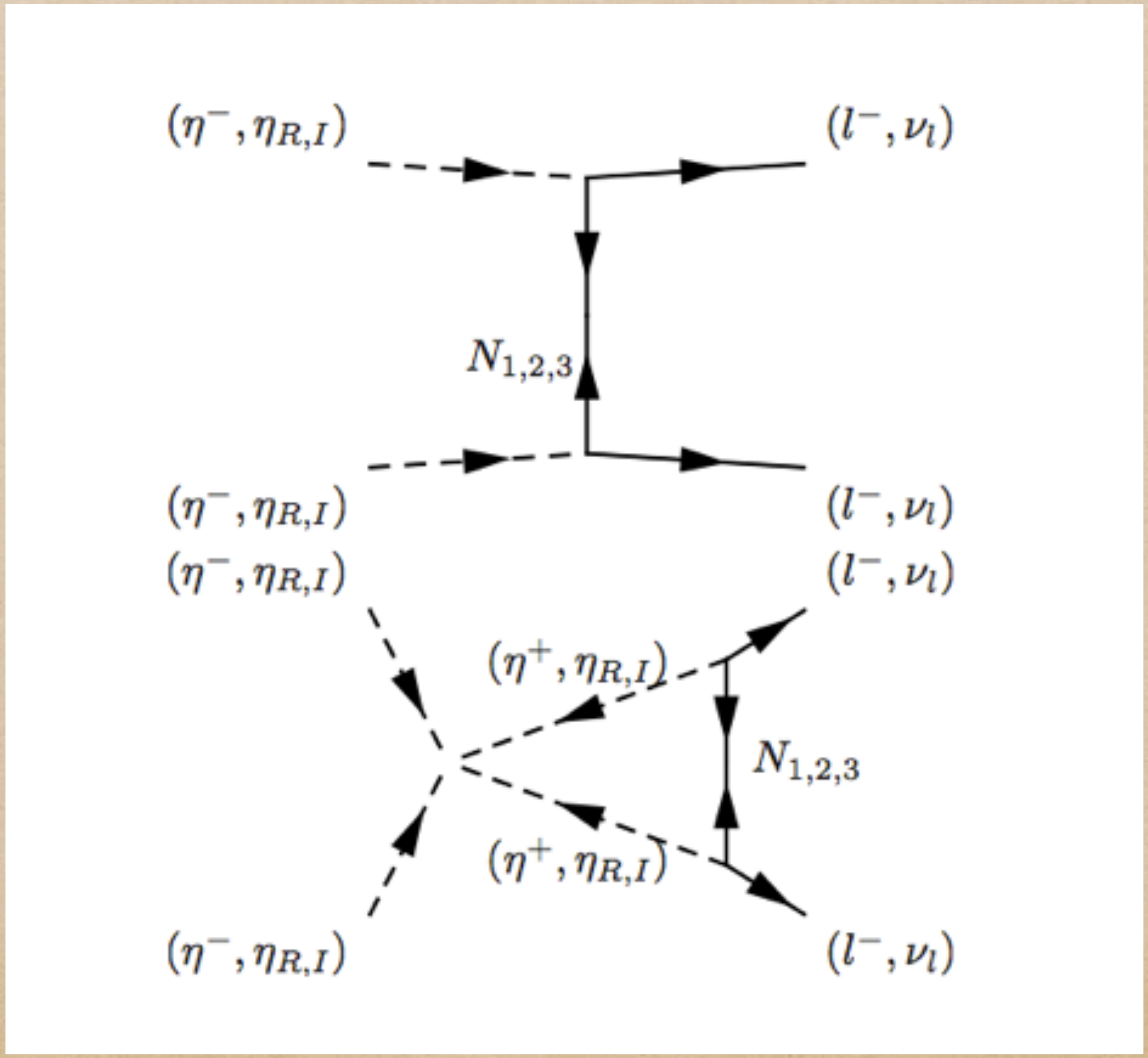


1804.09660

The required asymmetry can be generated even if the RHN mass is around tens of TeV, much lower than the usual bound for type I seesaw: $M_1 > 10^9$ GeV. (Davidson & Ibarra 2002)

TeV scale Leptogenesis from DM annihilation

The annihilation of scalar DM can produce a leptonic asymmetry through the following processes



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The Boltzmann Equations

$$\frac{dY_{\rm DM}}{dz} = \frac{-2zs}{H(M_{\rm DM})}\langle\sigma v\rangle_{{\rm DMDM}\to SMSM}\left(Y_{\rm DM}^2 - (Y_{\rm DM}^{\rm eq})^2\right),$$

$$\frac{dY_{\Delta L}}{dz} = \frac{2zs}{H(M_{\rm DM})}\Big[\epsilon\langle\sigma v\rangle_{{\rm DMDM}\to LL}\left(Y_{\rm DM}^2 - (Y_{\rm DM}^{\rm eq})^2\right)$$
$$- Y_{\Delta L}Y_l^{\rm eq}\left[\langle\sigma v\rangle^{\rm wo}_{{\rm DMDM}\to LL} + \langle\sigma v\rangle_{{\rm DMDM}\to LL}\right]$$
$$- Y_{\Delta L}Y_{\rm DM}\left[\langle\sigma v\rangle^{\rm wo}_{{\rm DM}L\to{\rm DM}\bar{L}}\right] - \frac{1}{2}Y_{\Delta L}\left[\langle\sigma v\rangle^{\rm wo}_{{\rm DMDM}\to SM\bar{L}}\right]\Big]$$

$$H = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{M_{\rm DM}^2}{M_{\rm Pl}}, \qquad s = g_*\frac{2\pi^2}{45}\left(\frac{M_{\rm DM}}{z}\right)^3$$

WO →

$\Delta L = 1$ washout: $N\,\eta_{R,I}(\eta^{\pm}) \to L\,Z(W)$.

$\Delta L = 2$ washout: $NN \to LL$, $L\,\eta \to \bar{L}\,\eta$.

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

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

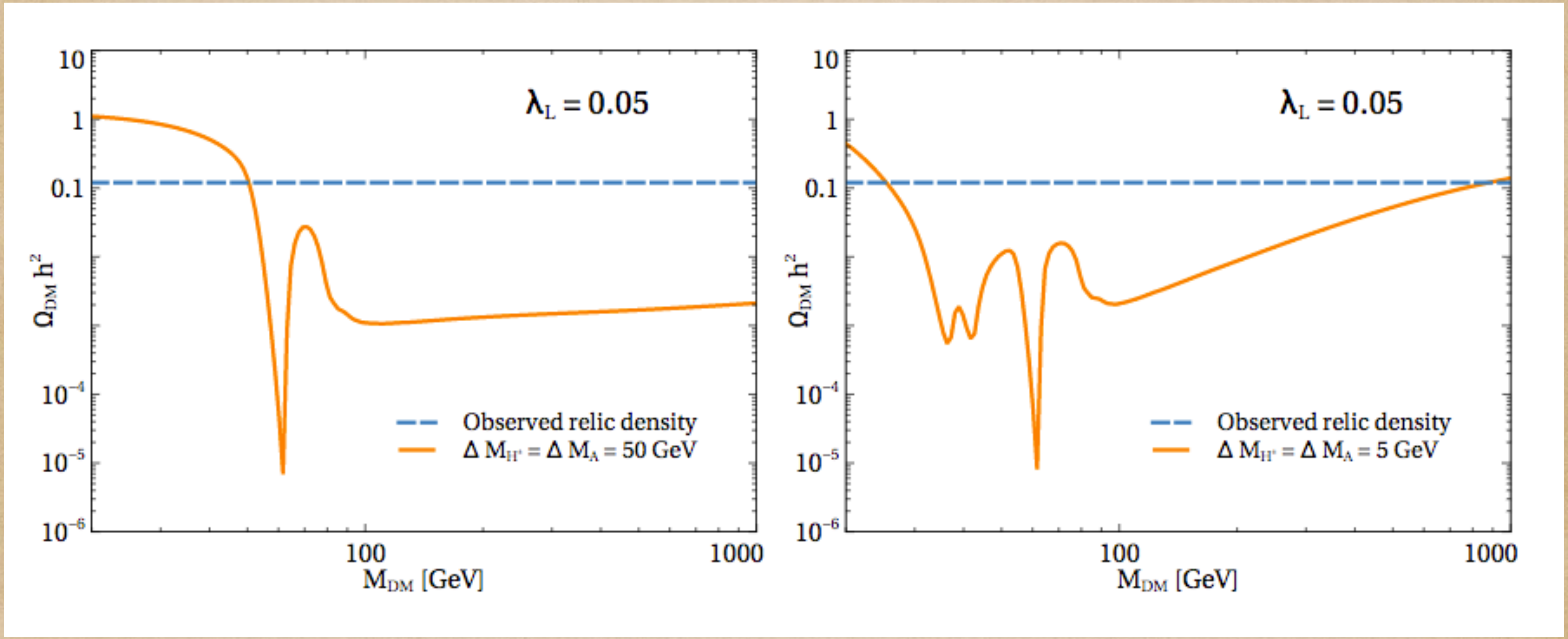
$$- 2\mathrm{Li}_2\left(\frac{(x-1)^2}{(1+x)^2}\right) + 2\mathrm{Li}_2\left(\frac{1+x(2-3x)}{(1+x)^2}\right)$$

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

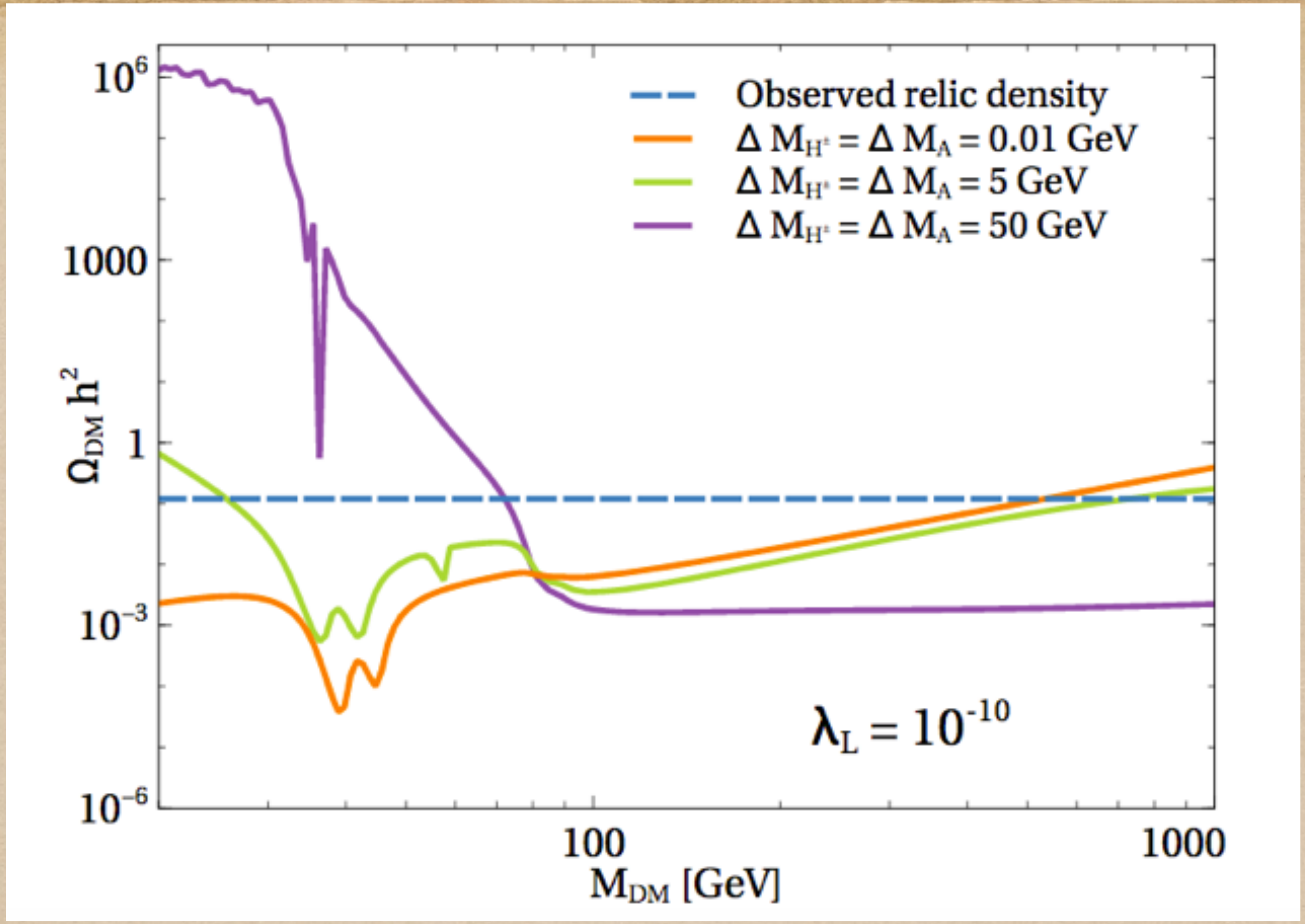
$$x = \frac{M^2_{DM}}{M^2_N}$$

$$\mathrm{Li}_2(y) = \sum_{k=1}^{\infty} \frac{y^k}{k^2}$$

Scalar Doublet Dark Matter

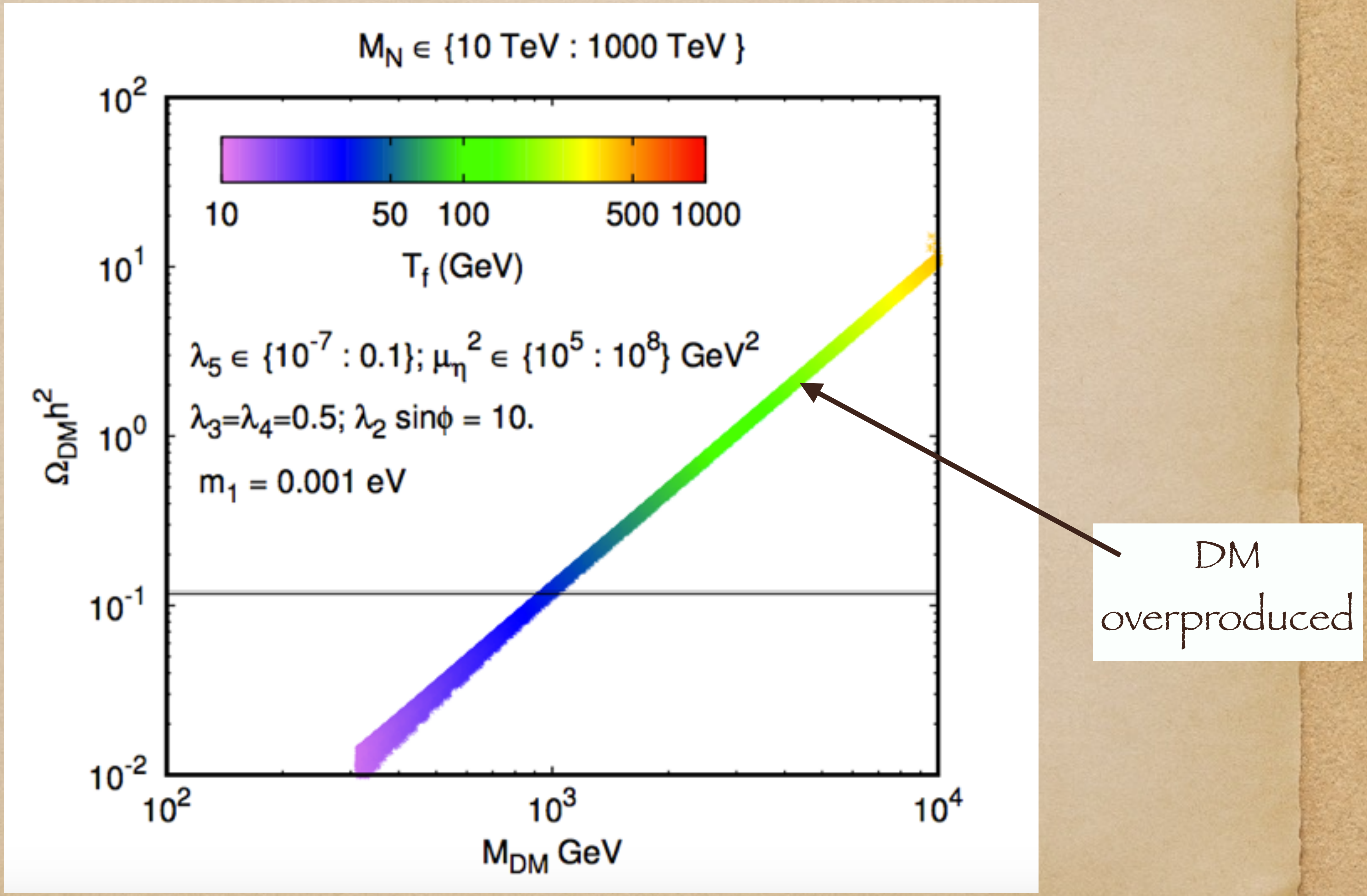


There exists two distinct mass regions satisfying the correct DM relic abundance.



Clearly, DM is overproduced in the high mass regime, if the mass splitting is kept low!

Results: Minimal Scotogenic Model



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Summary of Results: Minimal Scotogenic Model

- It is not possible to produce the correct lepton asymmetry above the electroweak phase transition from scalar DM annihilations while satisfying correct DM relic and neutrino mass constraints.

- While correct lepton asymmetry requires order one Yukawa which at the same time requires small λ_5 from neutrino mass point of view, DM direct detection gives an lower bound on

$$\lambda_5 \approx 1.65 \times 10^{-7} \left(\frac{\delta}{100 \text{ keV}} \right) \left(\frac{M_{\text{DM}}}{100 \text{ GeV}} \right)$$

Minimal Extension

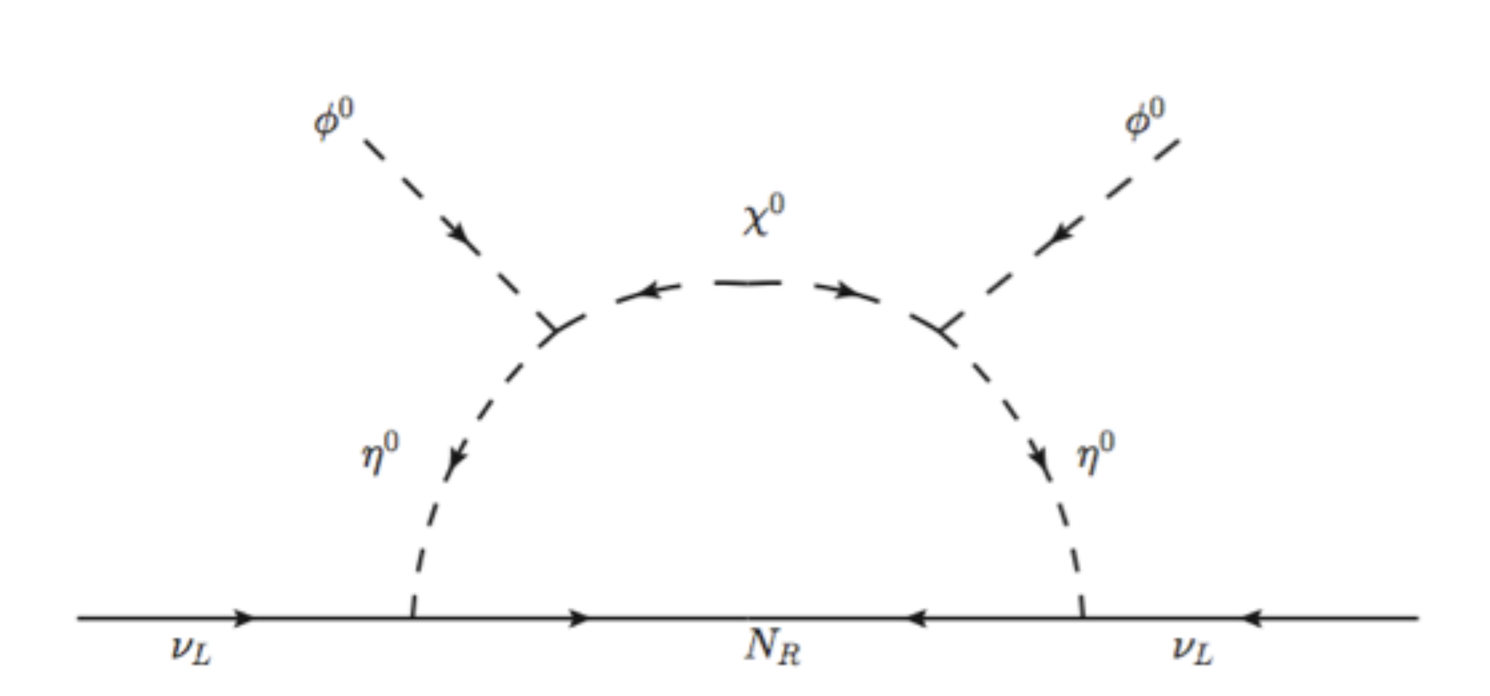
The scotogenic model can be extended by a complex singlet scalar which results in the scalar potential

$$V = \mu_H^2 H^\dagger H + \mu_\eta^2 \eta^\dagger \eta + \mu_\chi^2 \chi^* \chi + \frac{1}{2}\mu_4^2 \left[\chi^2 + (\chi^*)^2\right]$$
$$+ \mu(\eta^\dagger H \chi + H^\dagger \eta \chi^*) + \frac{1}{2}\lambda_H (H^\dagger H)^2 + + \frac{1}{2}\lambda_\eta (\eta^\dagger \eta)^2$$
$$+ \frac{1}{2}\lambda_\chi (H \chi^* \chi)^2 + \lambda_4 (\eta^\dagger \eta)(H^\dagger H) + \lambda_5 (\eta^\dagger H)(H^\dagger \eta)$$
$$+ \lambda_6 (\chi^* \chi)(H^\dagger H) + \lambda_7 (\chi^* \chi)(\eta^\dagger \eta)$$

Physical Masses

$$m_h^2 = \lambda_H v^2, m_{\eta^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_4 v^2$$

$$M_{R,I}^2 = \begin{pmatrix} \mu_\eta^2 + (\lambda_4+\lambda_5)v^2/2 & \mu v/\sqrt{2} \\ \mu v/\sqrt{2} & \mu_\chi^2 + \lambda_6 v^2/2 \pm mu_4^2 \end{pmatrix}$$



$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik}Y_{jk}M_k}{16\pi^2}\left(\frac{\cos^2\theta_R m^2_{\phi_1^R}}{m^2_{\phi_1^R} - M_k^2}\ln\frac{m^2_{\phi_1^R}}{M_k^2} + \frac{\sin^2\theta_R m^2_{\phi_2^R}}{m^2_{\phi_2^R} - M_k^2}\ln\frac{m^2_{\phi_2^R}}{M_k^2} - \frac{\cos^2\theta_I m^2_{\phi_1^I}}{m^2_{\phi_1^I} - M_k^2}\ln\frac{m^2_{\phi_1^I}}{M_k^2} - \frac{\sin^2\theta_I m^2_{\phi_2^I}}{m^2_{\phi_2^I} - M_k^2}\ln\frac{m^2_{\phi_2^I}}{M_k^2}\right)$$

Benchmark

BP1

$m_{\phi_1^R} = 4.8902136$ TeV, $m_{\phi_2^R} = 4.90106233$ TeV, $m_{\phi_1^I} = 4.890212$ TeV, $m_{\phi_2^I} = 4.90105859$ TeV, $m_{\phi^\pm} = 4.8929958$ TeV,

$\mu_\eta = 4.89$ TeV, $\mu_\chi = 4.89$ TeV, $\mu = 234.14$ GeV, $\mu_4 = 24.64$ GeV, $\lambda_4 = 2.24 \times 10^{-3}$, $\lambda_5 = 1.53 \times 10^{-4}$,

$\lambda_6 = 5.95 \times 10^{-5}$, $M_k = 15.02$ TeV $(k = 1, 2, 3)$.

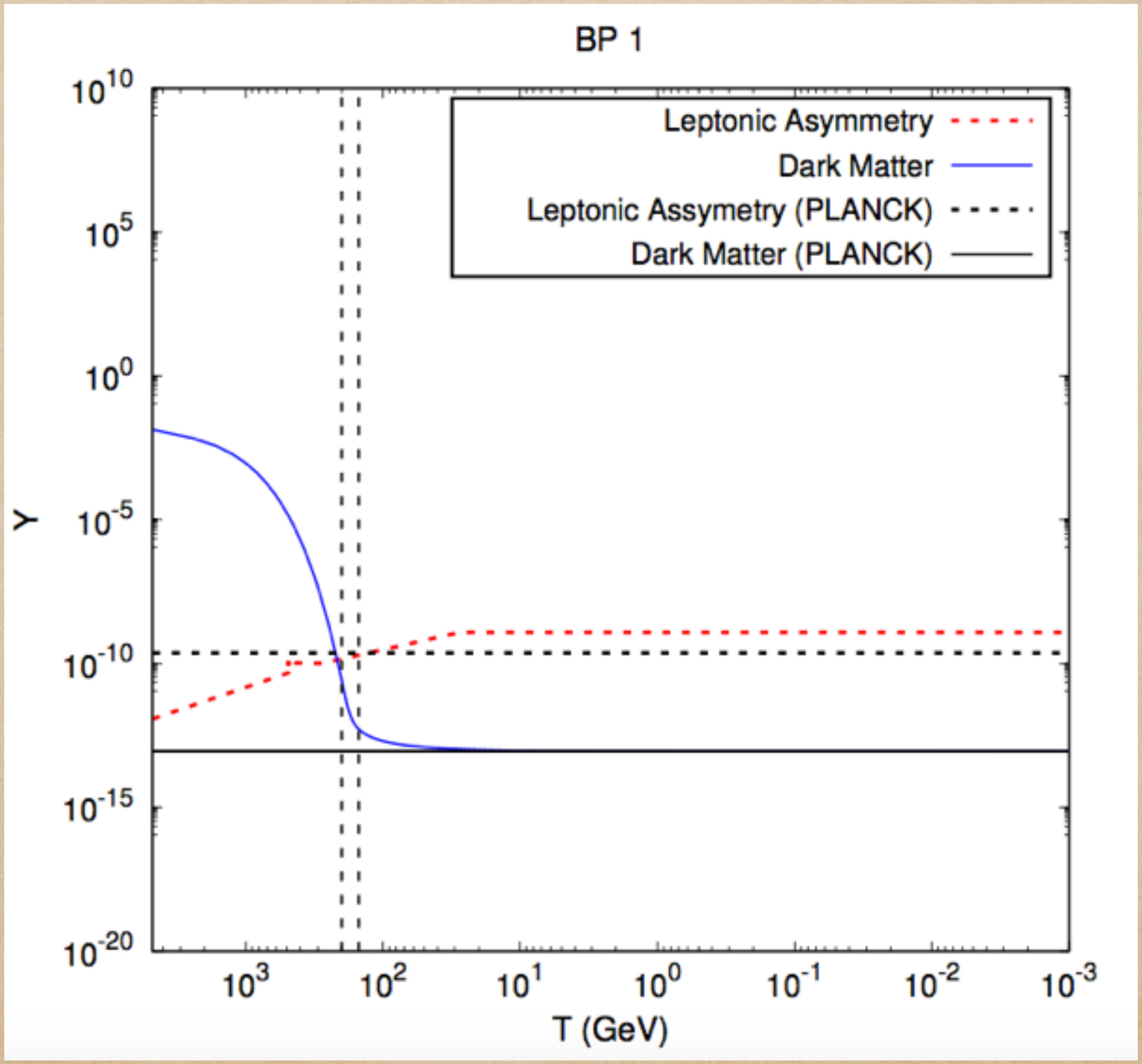
BP2

$m_{\phi_1^R} = 4.78171586$ TeV, $m_{\phi_2^R} = 4.79263107$ TeV, $m_{\phi_1^I} = 4.78171462$ TeV, $m_{\phi_2^I} = 4.79262652$ TeV, $m_{\phi^\pm} = 4.78405012$ TeV,

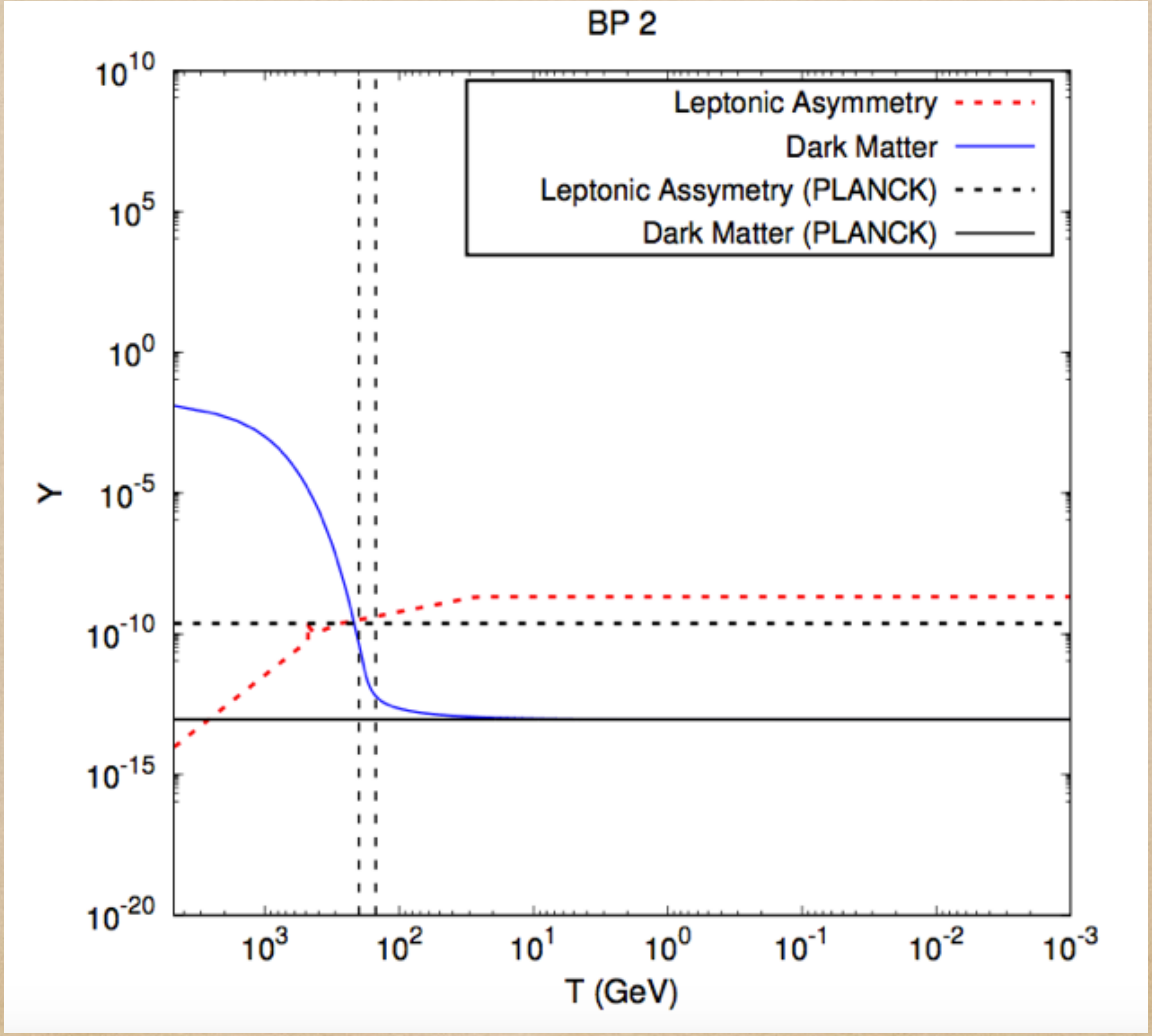
$\mu_\eta = 4.78$ TeV, $\mu_\chi = 4.79$ TeV, $\mu = 212.43$ GeV, $\mu_4 = 27.74$ GeV, $\lambda_4 = 1.37 \times 10^{-4}$, $\lambda_5 = 3.48 \times 10^{-5}$,

$\lambda_6 = 3.55 \times 10^{-4}$, $M_k = 17.79$ TeV $(k = 1, 2, 3)$.

Results


BP 1
Leptonic Asymmetry
Dark Matter
Leptonic Assymetry (PLANCK)
Dark Matter (PLANCK)
Y
10^10
10^5
10^0
10^-5
10^-10
10^-15
10^-20
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
T (GeV)

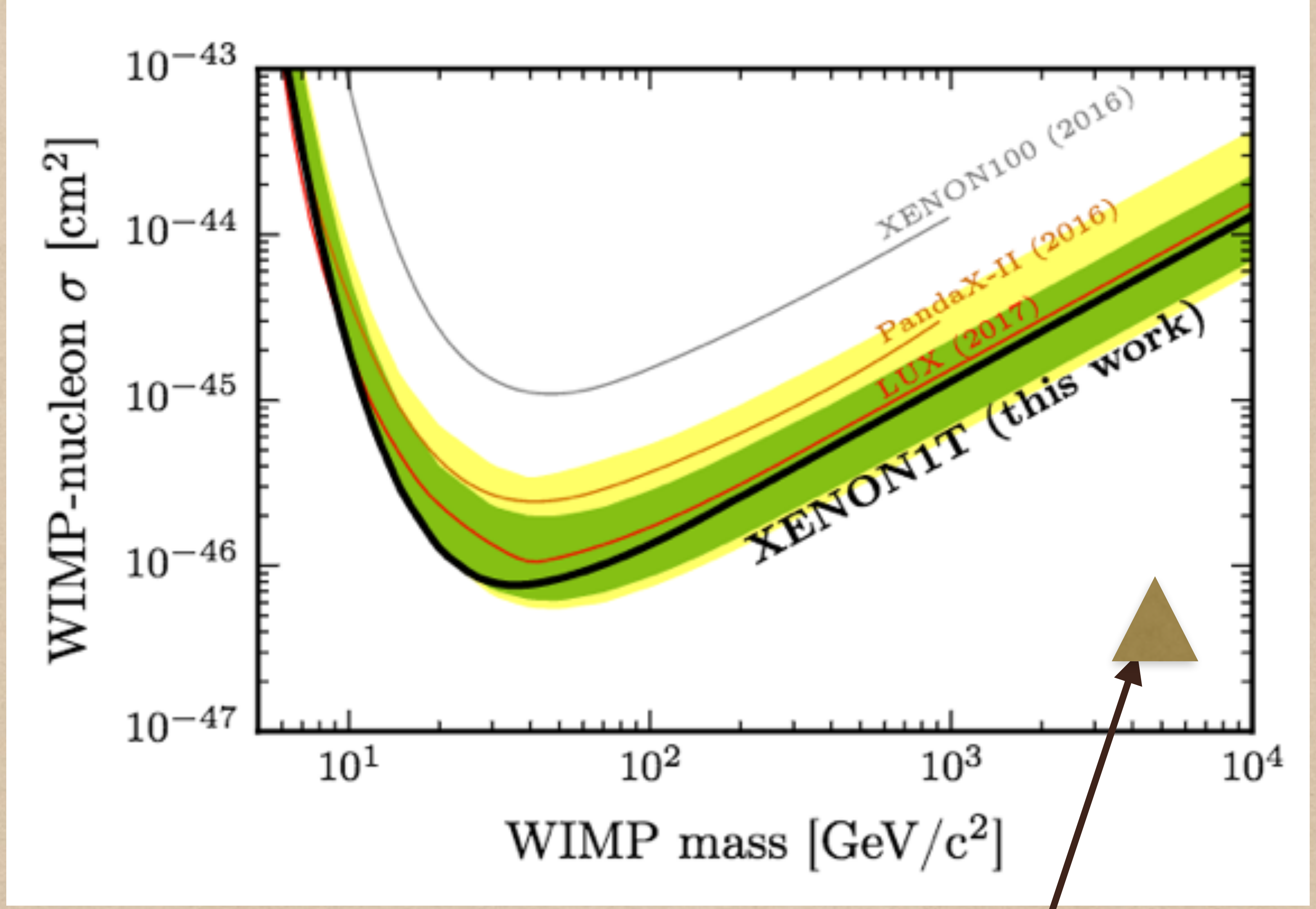
Results


BP 2
Leptonic Asymmetry
Dark Matter
Leptonic Assymetry (PLANCK)
Dark Matter (PLANCK)
Y
T (GeV)
10^10
10^5
10^0
10^-5
10^-10
10^-15
10^-20
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3

Testability

- Since the particle spectrum of the model remains heavy, around 5 TeV or more, their direct production at 14 TeV LHC remains suppressed.
- The model can however be tested at rare decay experiments looking for lepton flavour violation.
- The prospects at direct/indirect dark matter detection experiments remain weak.

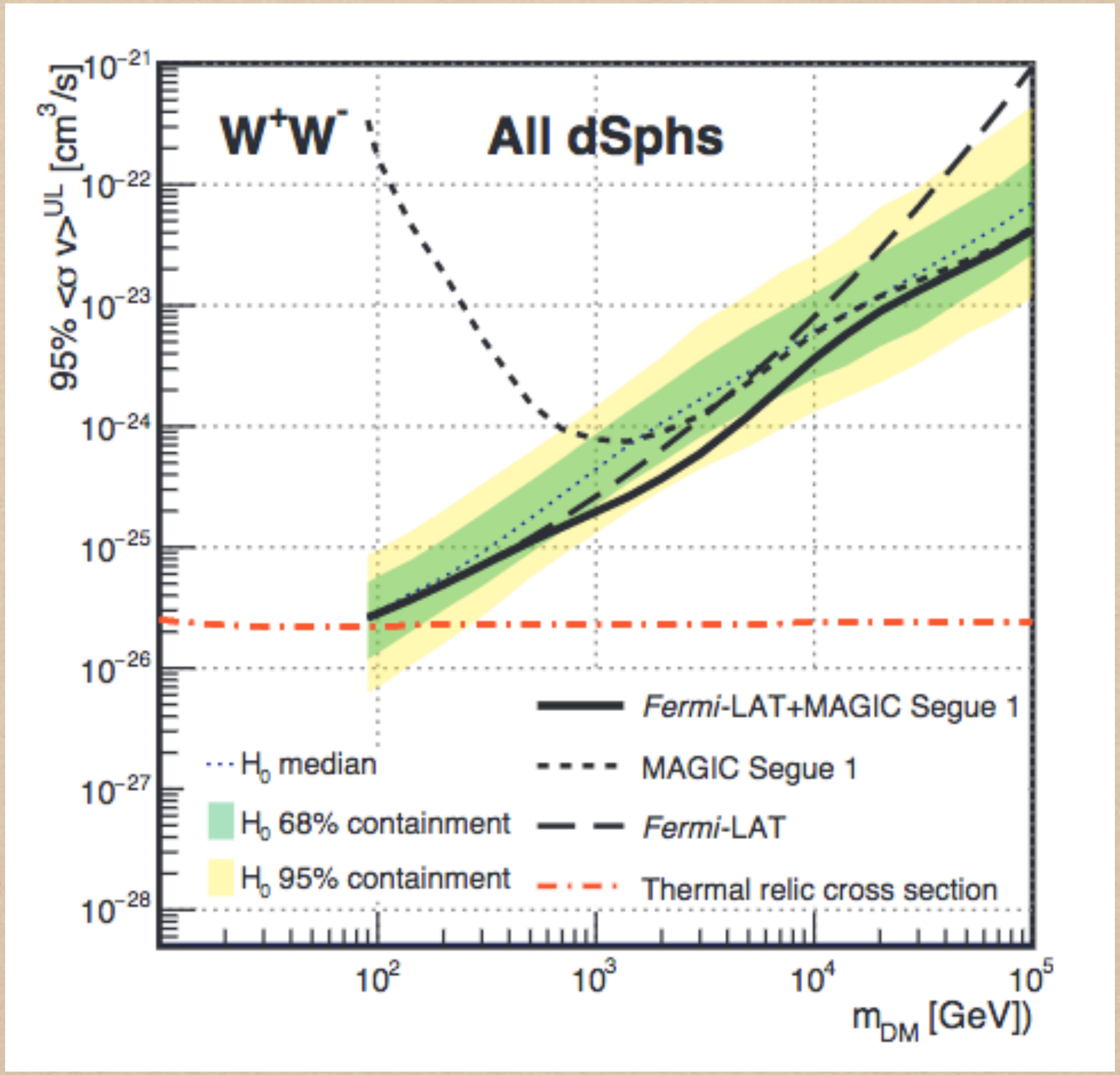
Direct Detection



$$\sigma^{\rm SI}_{\rm DM\ n} = 3.527 \times 10^{-47}\ {\rm cm}^2 ({\rm BP1})$$
$$\sigma^{\rm SI}_{\rm DM\ n} = 2.508 \times 10^{-47}\ {\rm cm}^2 ({\rm BP2})$$

arXiv:1705.06655

Indirect Detection

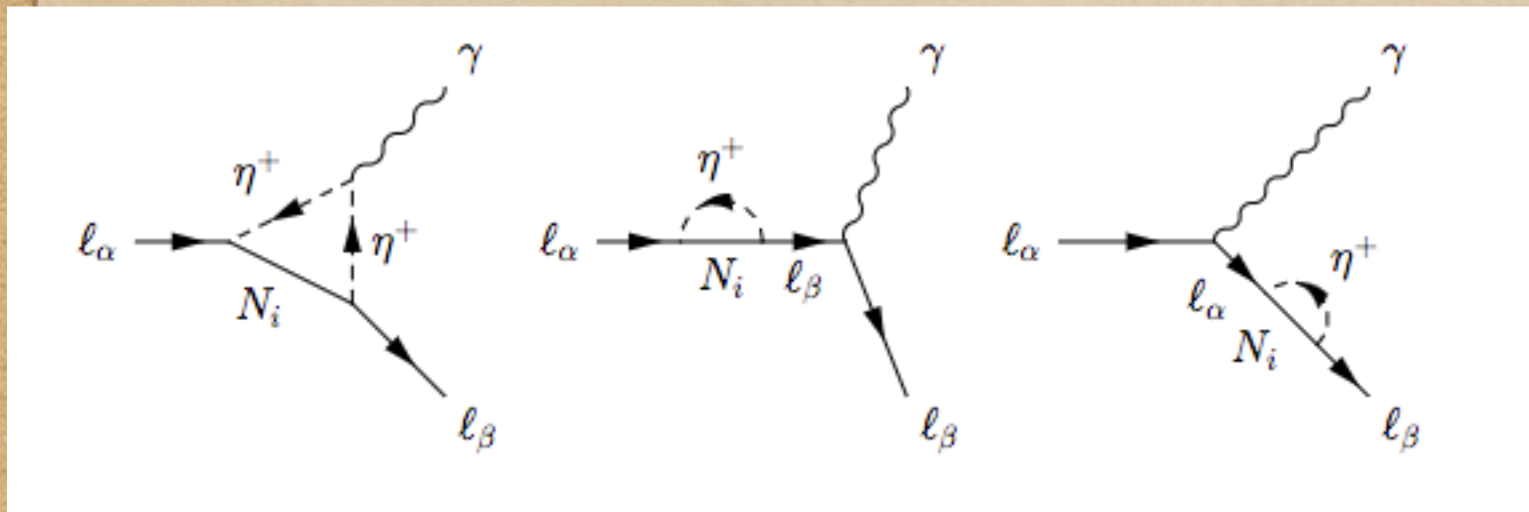


$$\langle \sigma v \rangle_{\mathrm{DMDM} \to \mathrm{W}^+\mathrm{W}^-} = 2.83 \times 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1} (\mathrm{BP1})$$

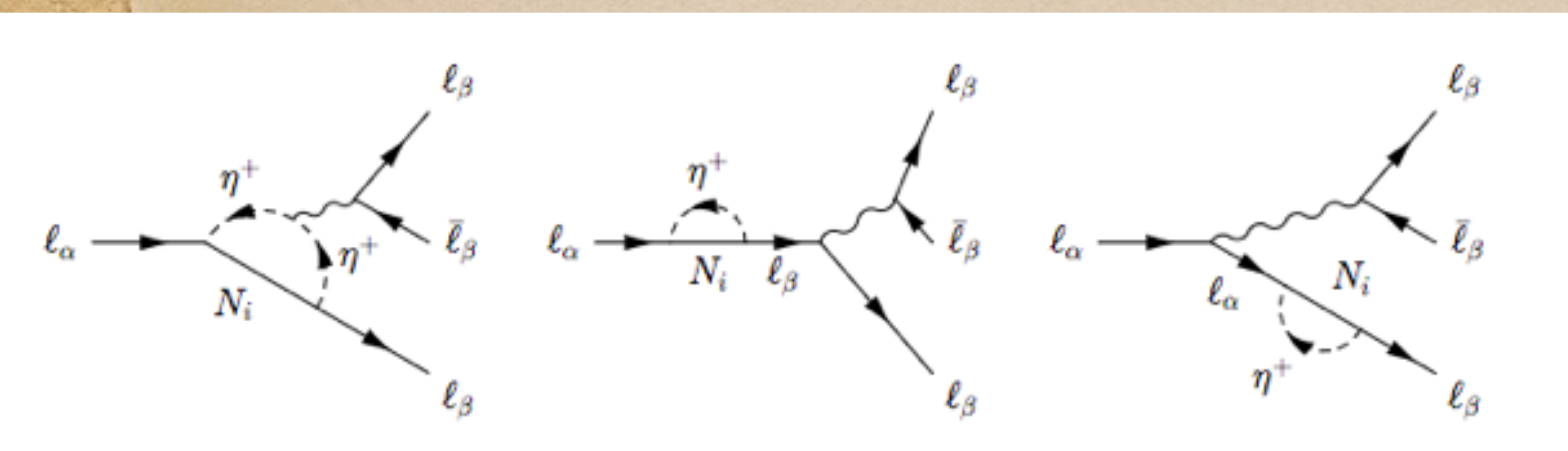
$$\langle \sigma v \rangle_{\mathrm{DMDM} \to \mathrm{W}^+\mathrm{W}^-} = 3.24 \times 10^{-28} \mathrm{cm}^3 \mathrm{s}^{-1} (\mathrm{BP2})$$

arXiv:1601.06590

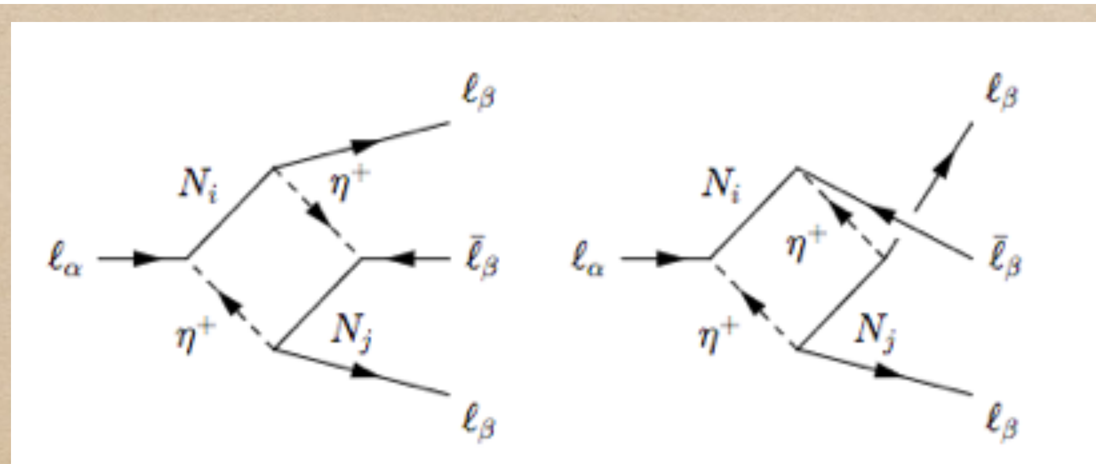
Lepton flavour violation



$\mu \to e\gamma$



$\mu \to 3e$

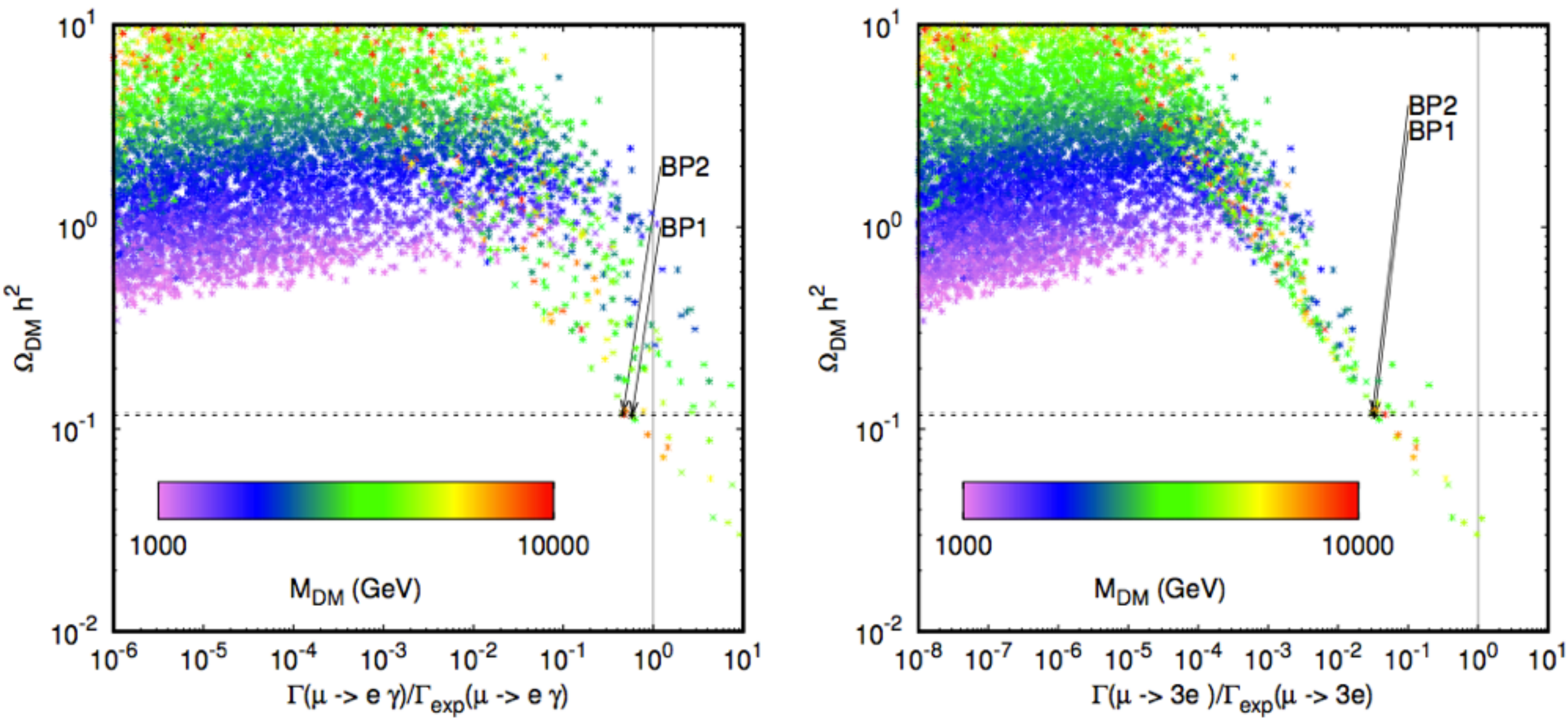


arXiv:1312.2840,1412.2545

Lepton Flavour Violation

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



$\Omega_{DM}\, h^2$
BP2
BP1
1000
10000
M_{DM} (GeV)
$\Gamma(\mu \to e\,\gamma)/\Gamma_{exp}(\mu \to e\,\gamma)$
$\Gamma(\mu \to 3e)/\Gamma_{exp}(\mu \to 3e)$

1806.04689

More recent updates

- …Radiative Neutrino Masses, keV-Scale Dark Matter and Viable Leptogenesis with sub-TeV New Physics, arXiv:1806.06864 (Implementation of ARS type leptogenesis in scotogenic model).
- Scalar Dark Matter, GUT baryogenesis and Radiative neutrino mass, arXiv:1806.08204 (GUT scale leptogenesis a la Fukugita-Yanagida in scotogenic model).

Conclusion

- Scenarios relating DM and baryon abundance are more constrained than individual DM or baryogenesis models and can have implications in a wide range of experiments starting from particle physics, cosmology & astrophysics.
- It is so constrained that leptogenesis from DM annihilation can not be realised 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 that can be probed at rare decay experiments.

Thank You