

Dark Matter and WIMPy Baryogenesis in Scotogenic Model

Based on arXiv:1806.04689 with
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Outline

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

The Standard Model

Standard Model of Elementary Particles

three generations of matter (fermions)				
	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
charge	$2/3$	$2/3$	$2/3$	0
spin	$1/2$	$1/2$	$1/2$	1
QUARKS	u up	c charm	t top	g gluon
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
	$-1/3$	$-1/3$	$-1/3$	0
	$1/2$	$1/2$	$1/2$	1
	d down	s strange	b bottom	γ photon
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7758 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$
	-1	-1	-1	0
	$1/2$	$1/2$	$1/2$	1
	e electron	μ muon	τ tau	Z Z boson
	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$
	0	0	0	± 1
	$1/2$	$1/2$	$1/2$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
				GAUGE BOSONS
				SCALAR BOSONS

The Standard Model

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- The SM has been very successful in describing the elementary particles and their interaction except gravity.

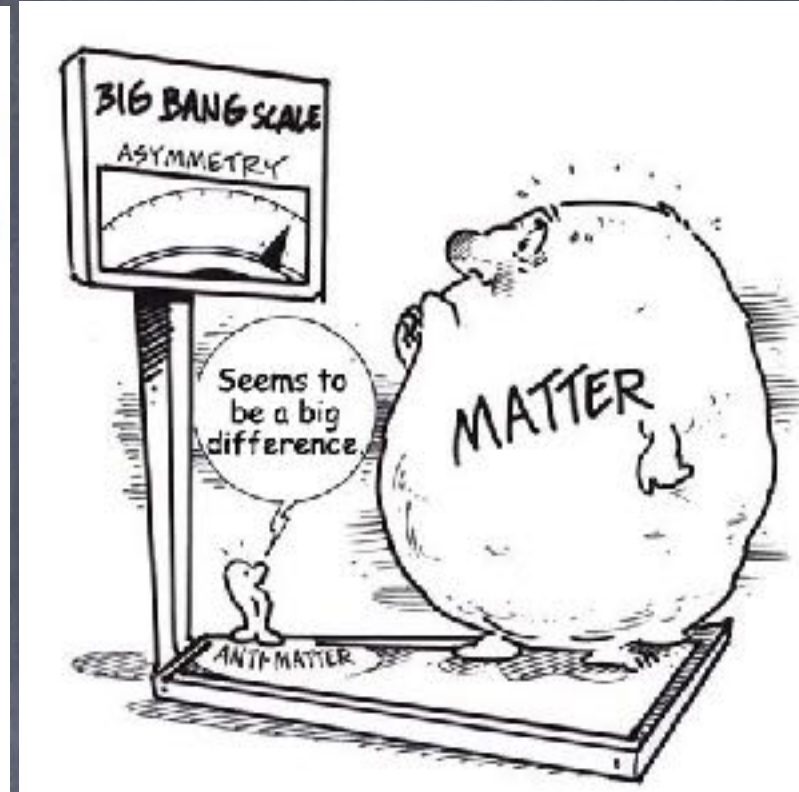
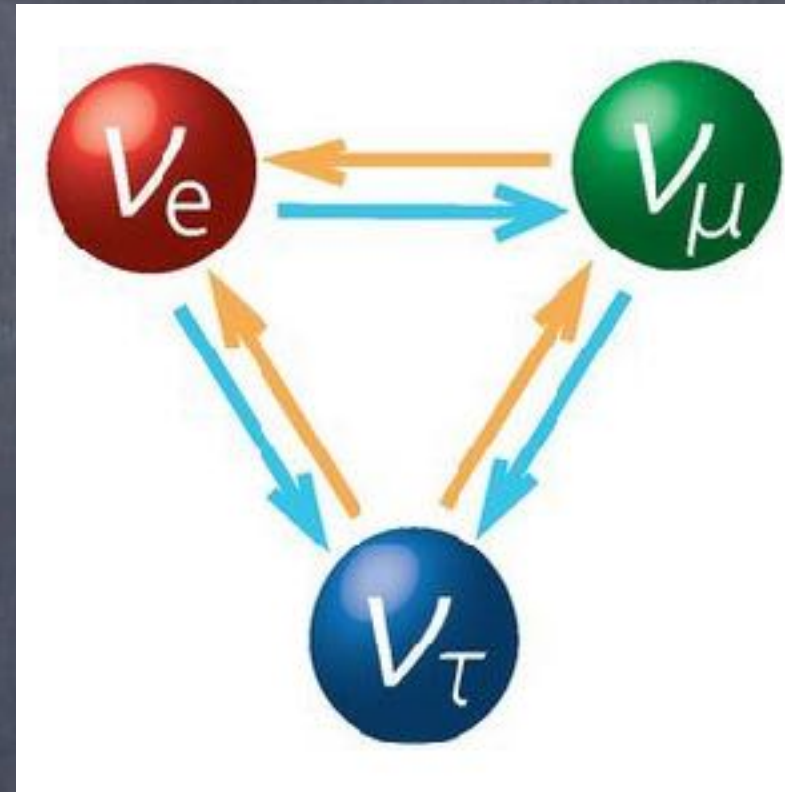
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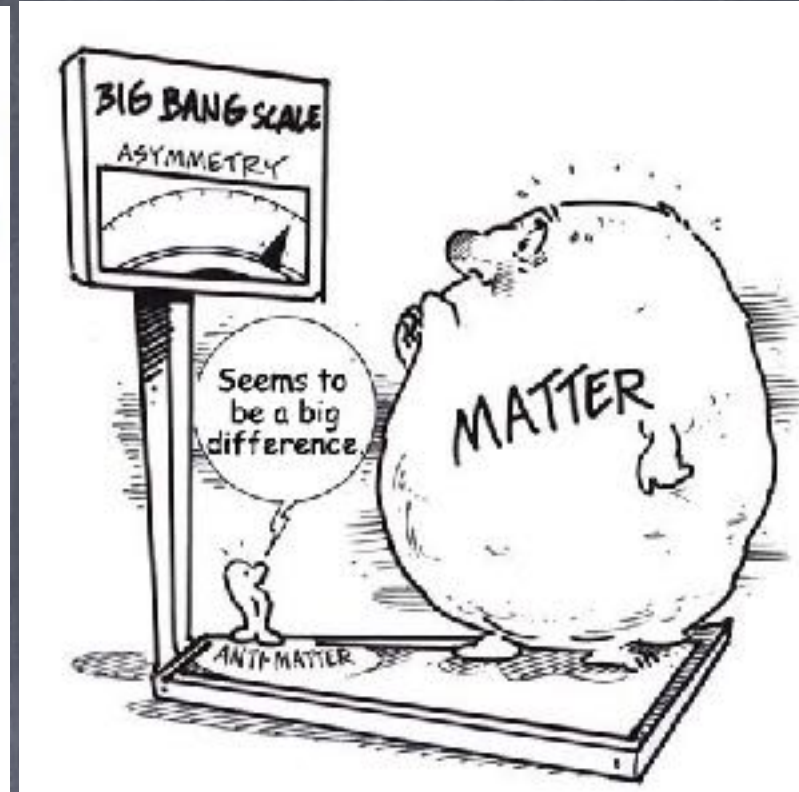
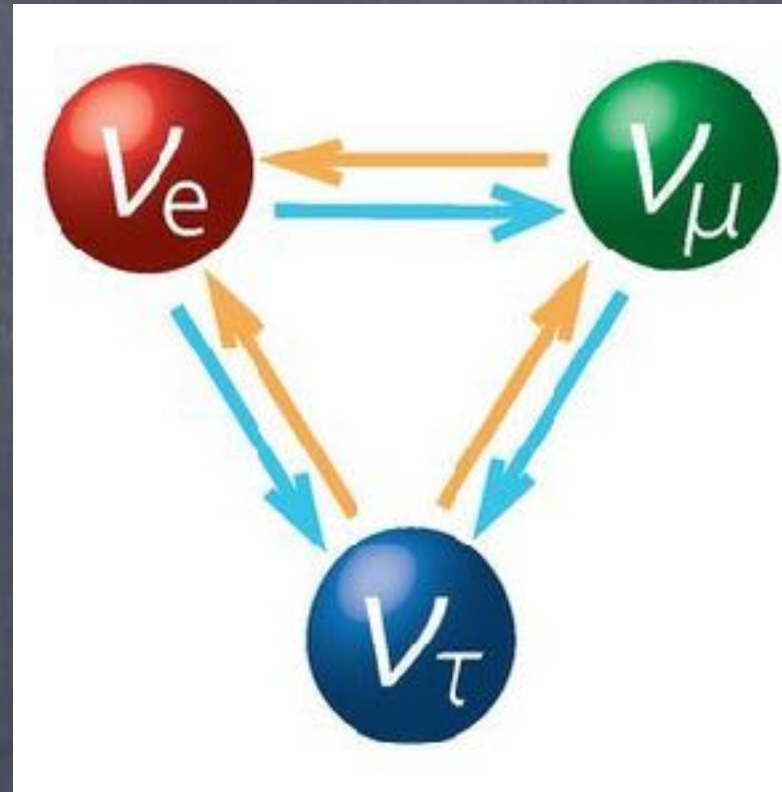
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- The last missing piece of the SM, the Higgs boson was also discovered a few years back at the LHC (2012).
- Since then the LHC results have only been able to confirm the validity of the SM again and again, with no convincing signatures of new physics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

Problems in the SM



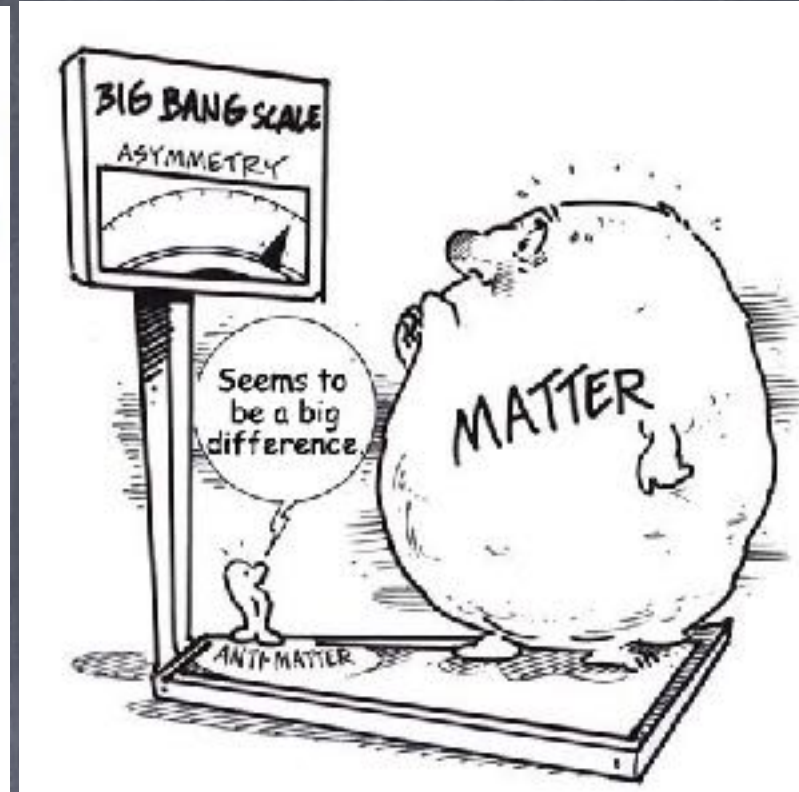
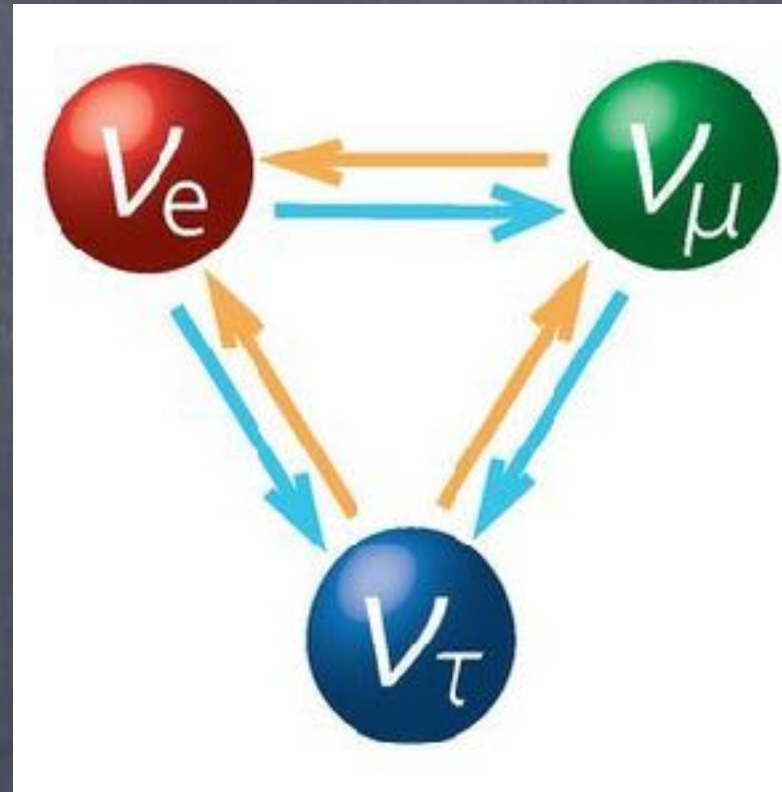
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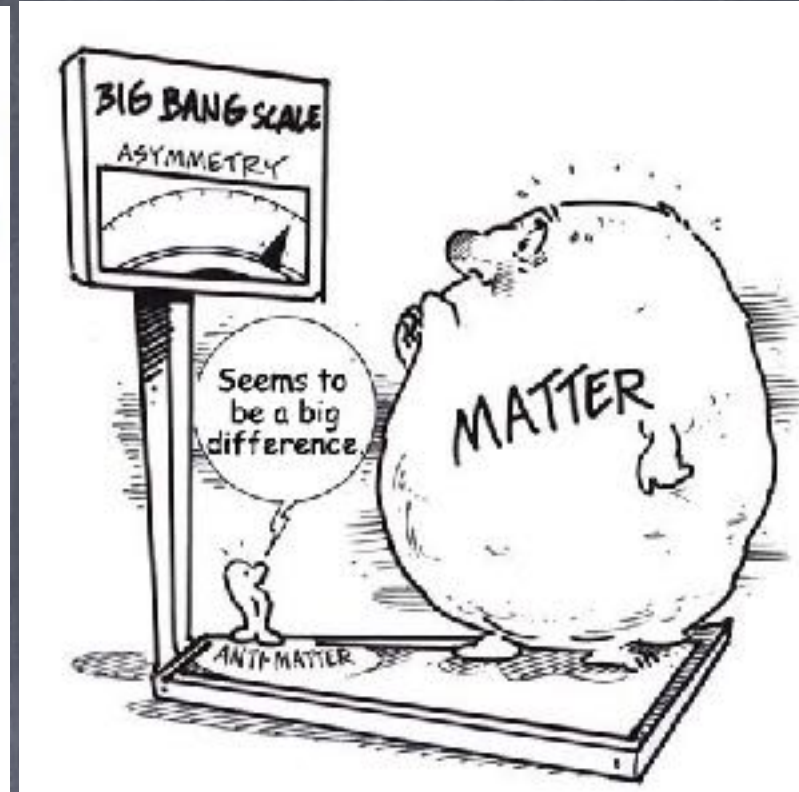
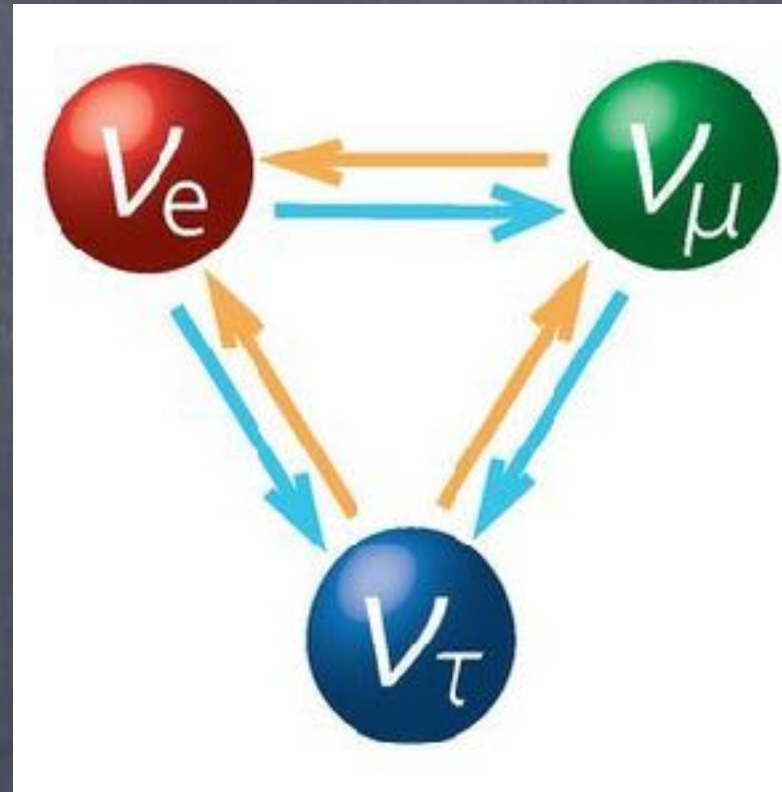
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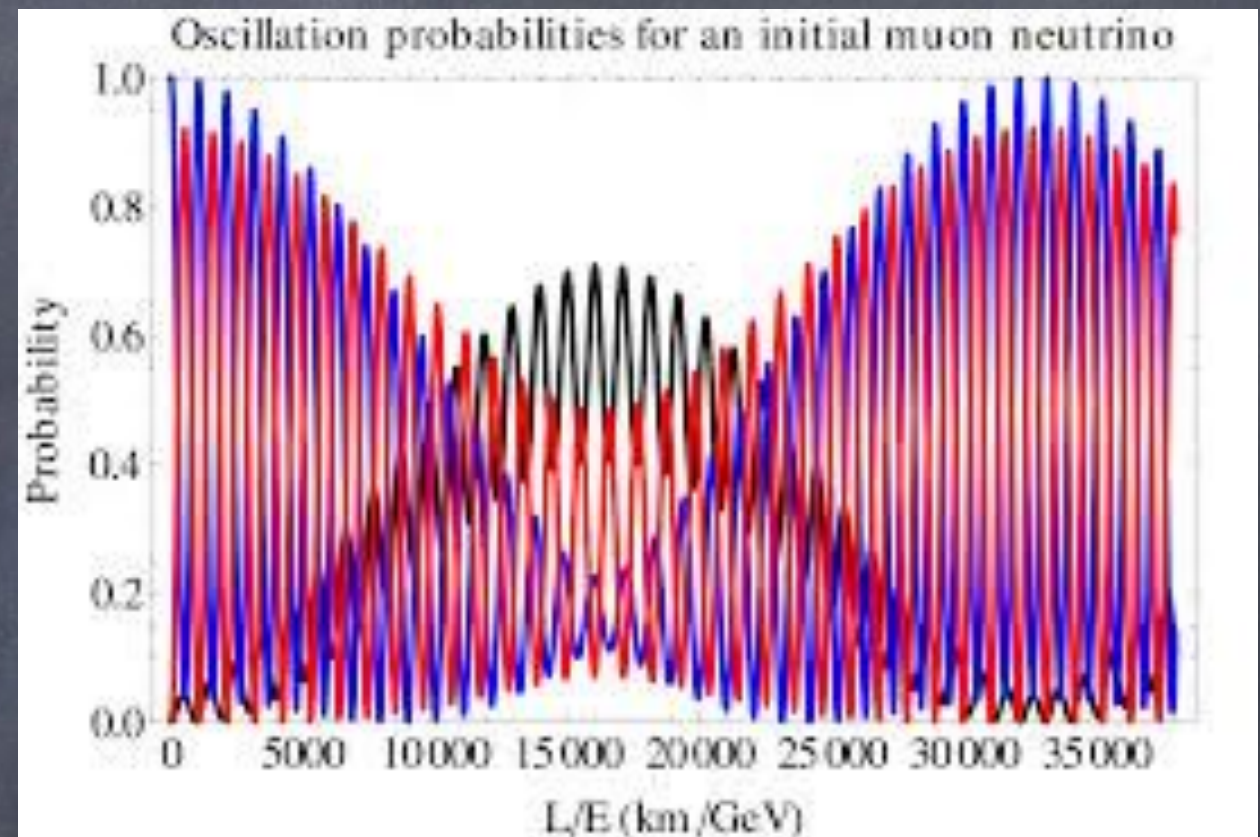
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- SM cannot explain the observed baryon asymmetry



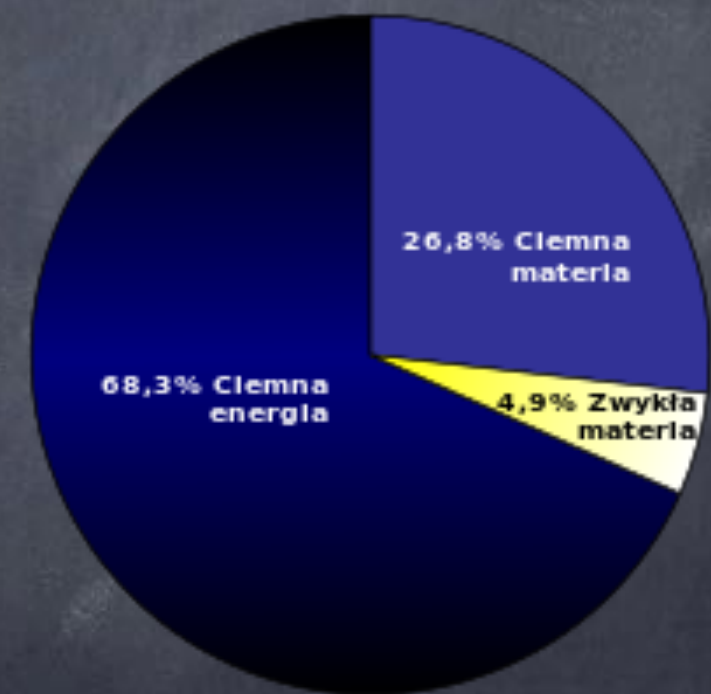
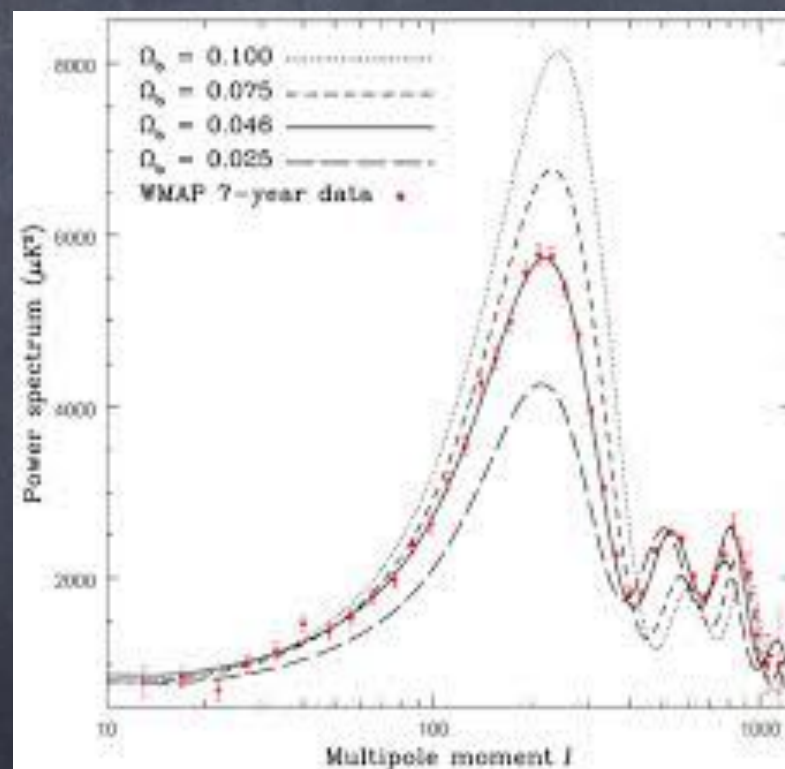
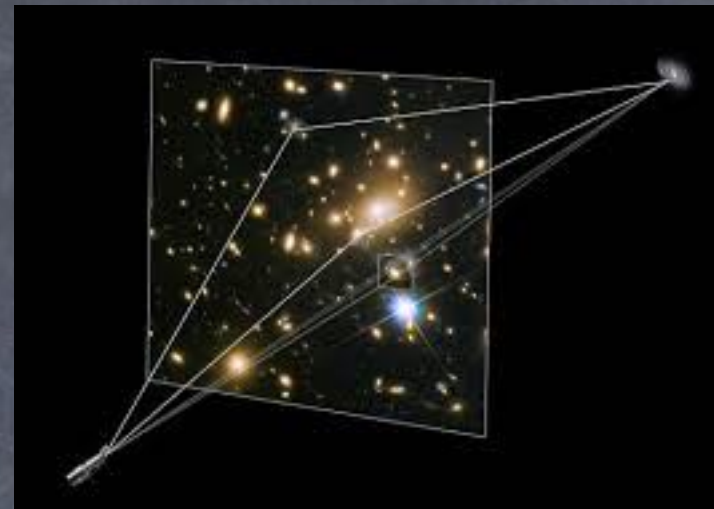
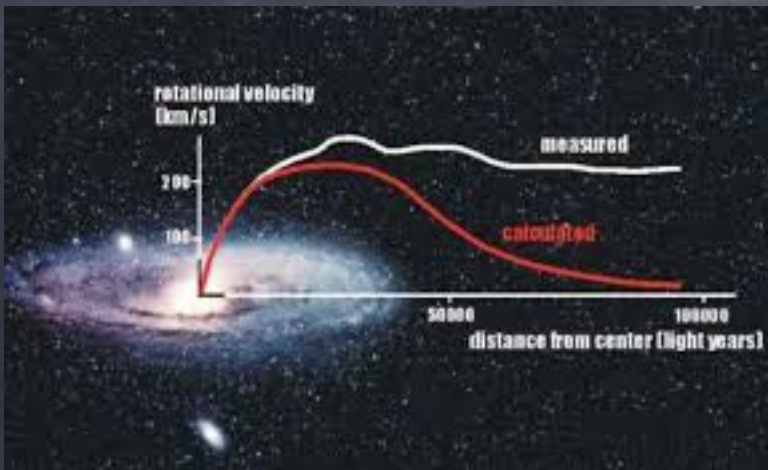
Neutrino Mass and Mixing

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



$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \frac{\Delta m_{ij}}{4E} + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \frac{\Delta m_{ij}}{2E}$$

Dark Matter: Evidences



Credits:

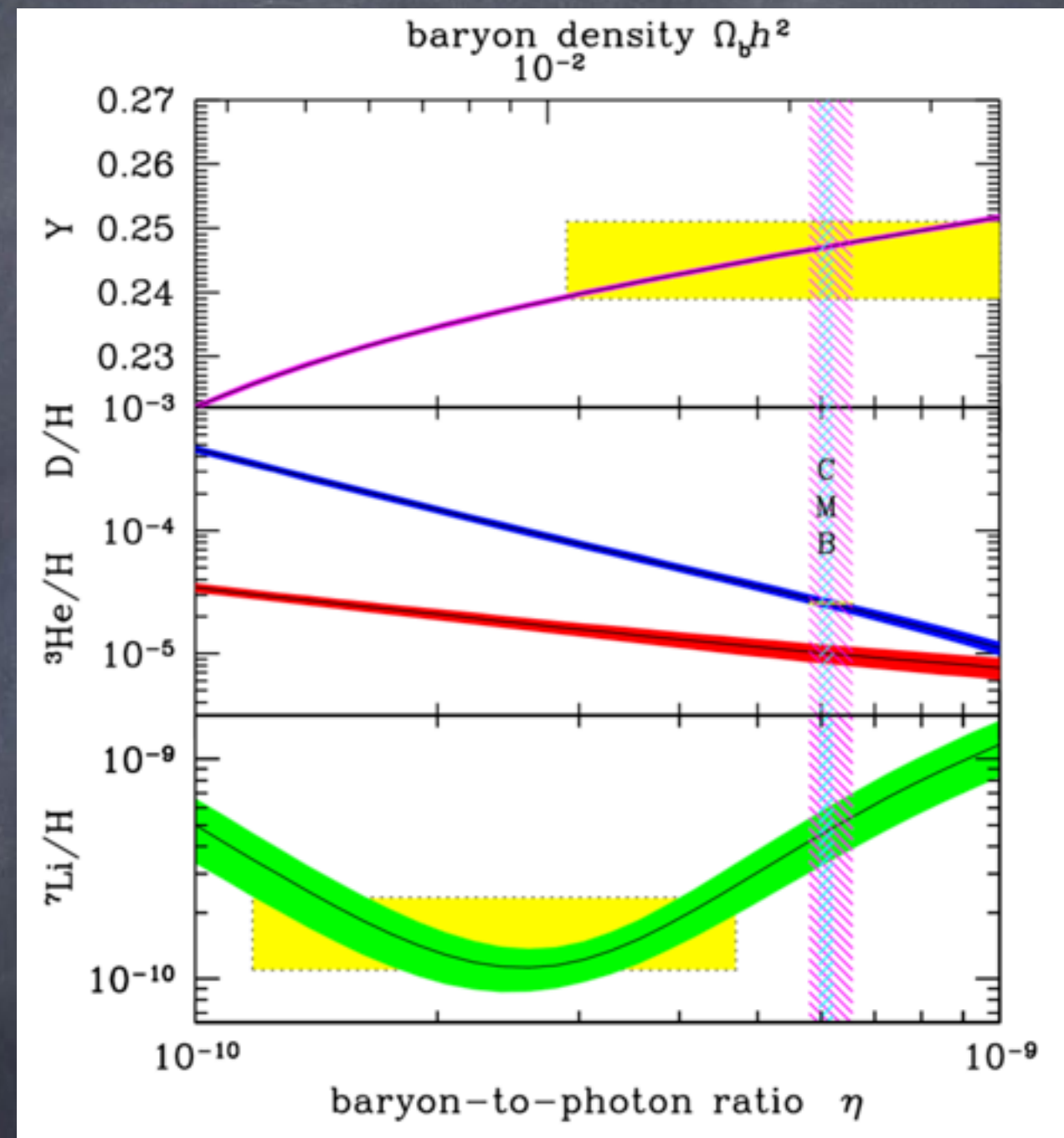
HST, Chandra, DE Survey, WMAP

Baryon Asymmetry of the Universe

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

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

- 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

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- Departure from thermal equilibrium.

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- Typically, seesaw models explaining neutrino mass and mixing can also play 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 provide a common framework to explain neutrino mass, mixing and baryon asymmetry of the Universe.

Baryogenesis & Dark Matter

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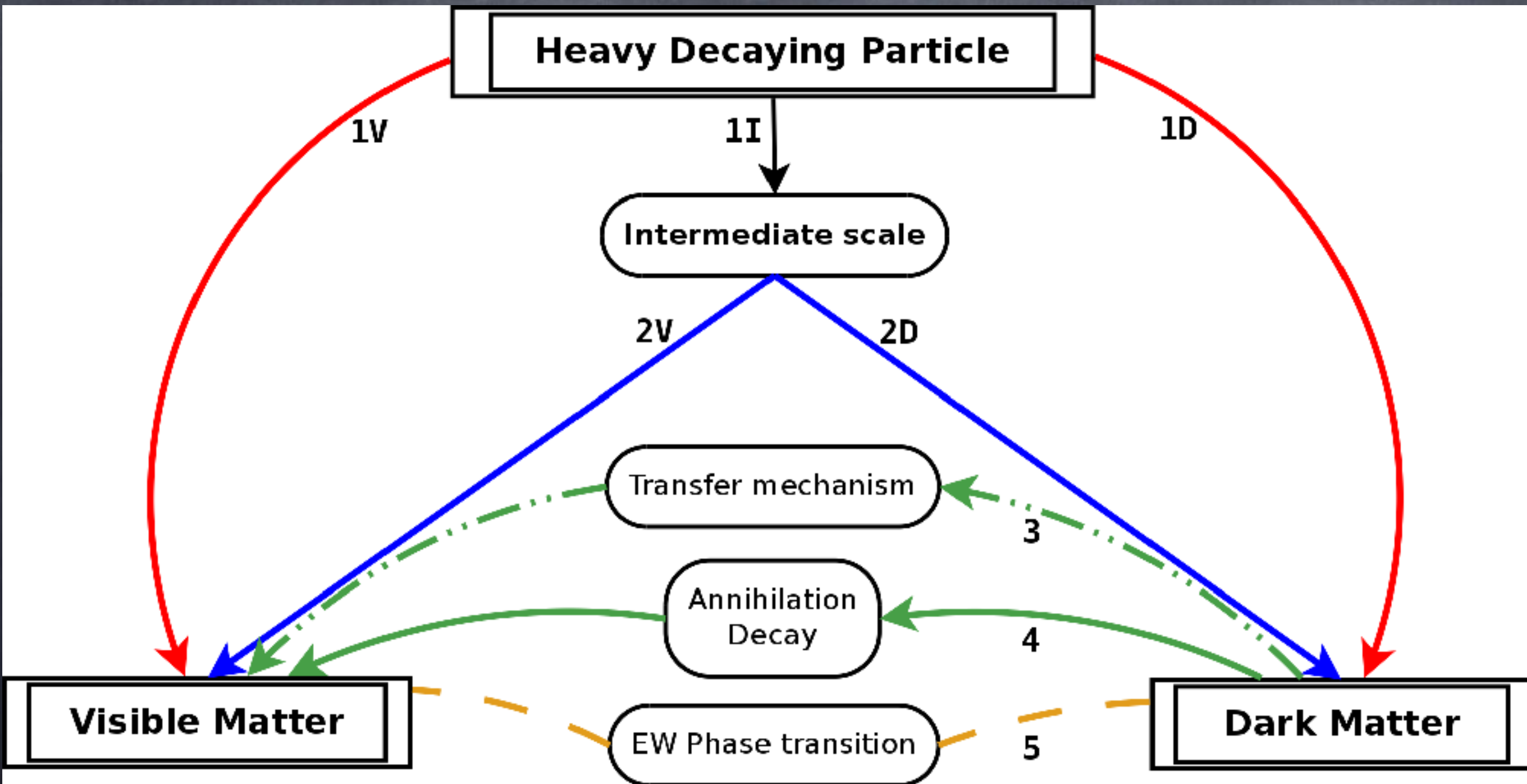
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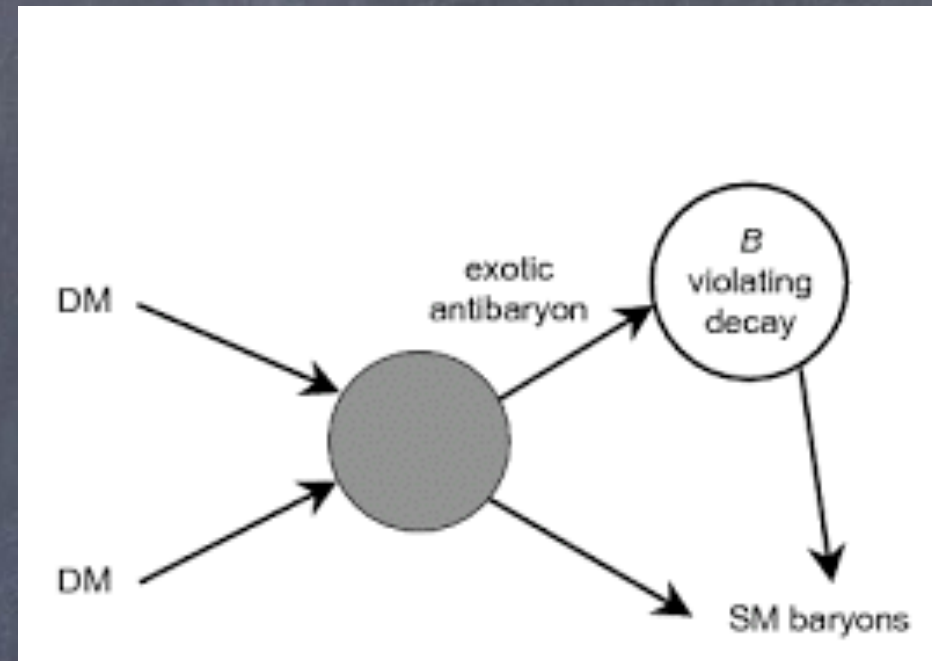
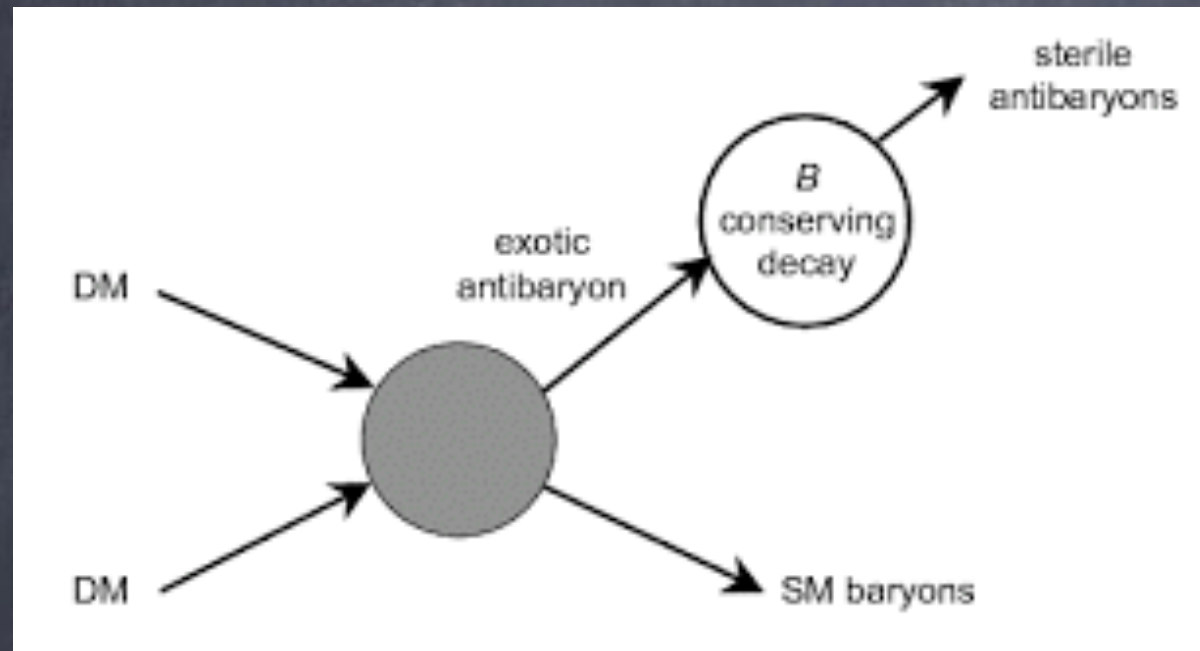
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- Asymmetric DM, WIMPy Baryogenesis etc are some of the scenarios proposed so far.
- While generic implementations of these scenarios tightly relate BAU & DM abundances, there exists other implementations too where the connections may be loose.

Baryogenesis & Dark Matter: Common Origin



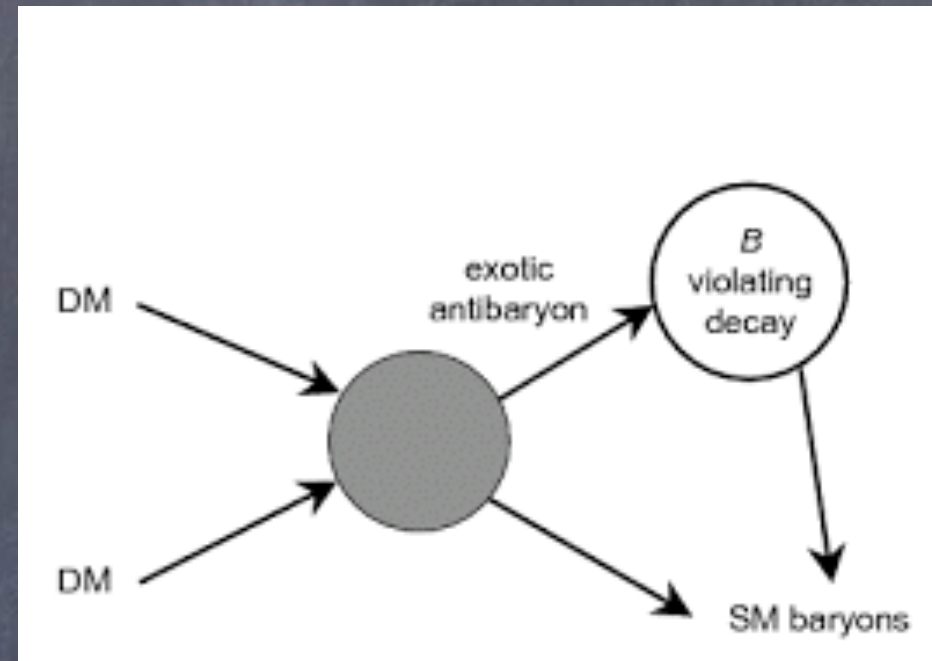
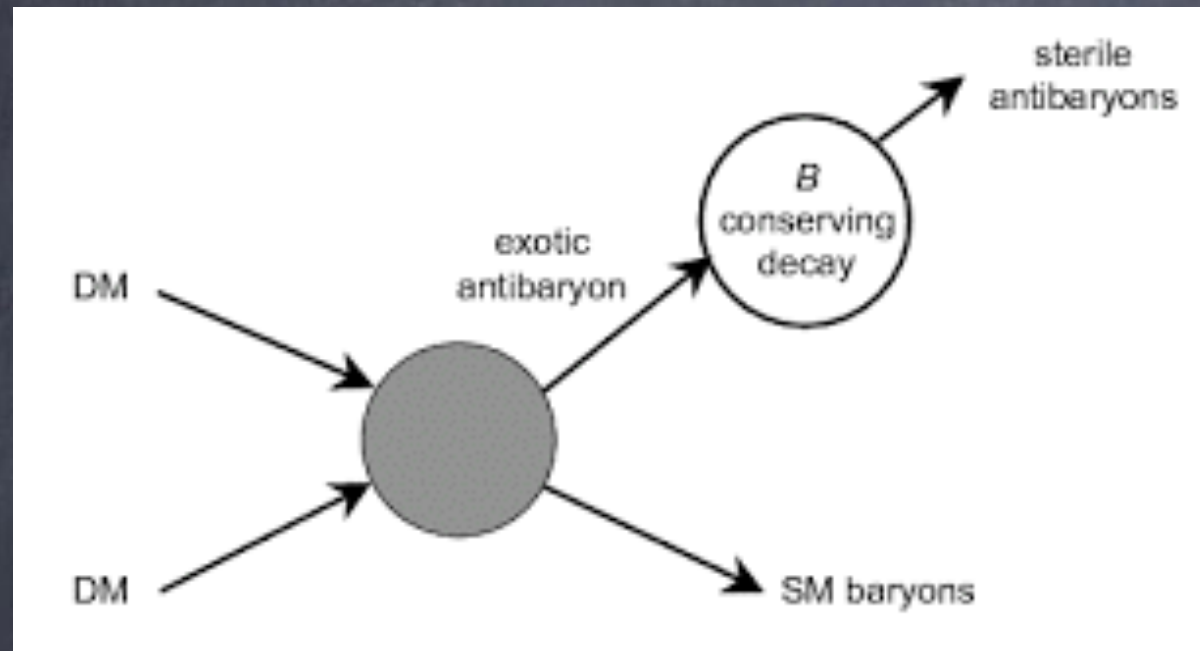
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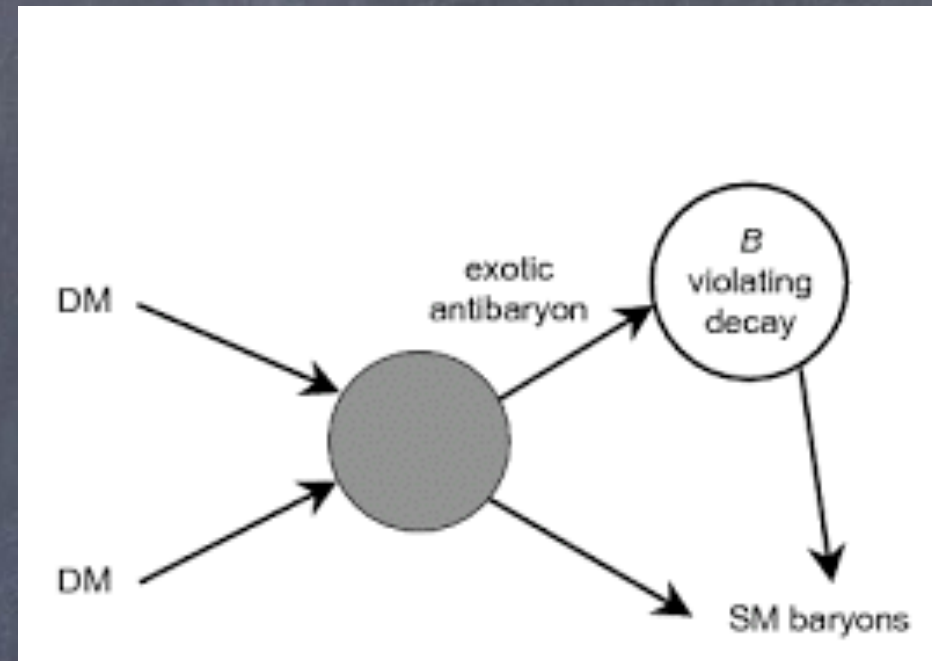
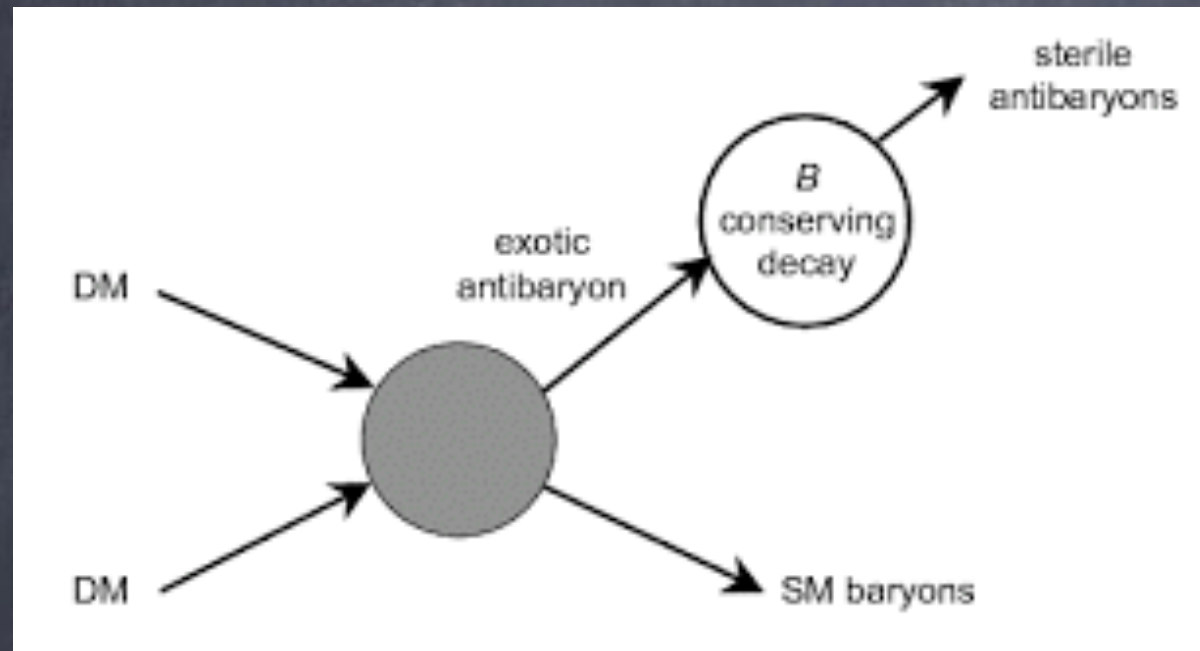
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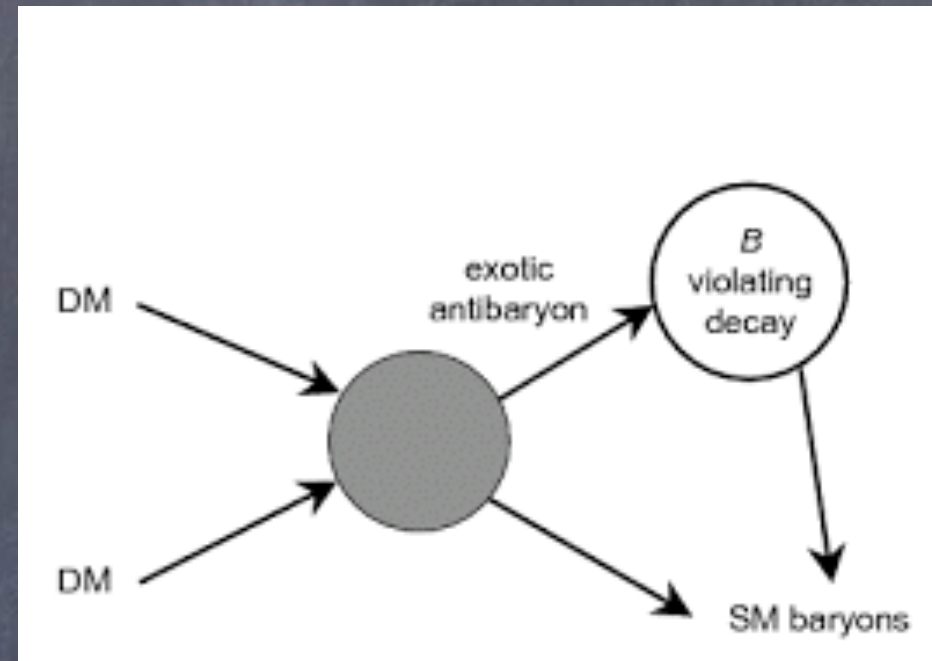
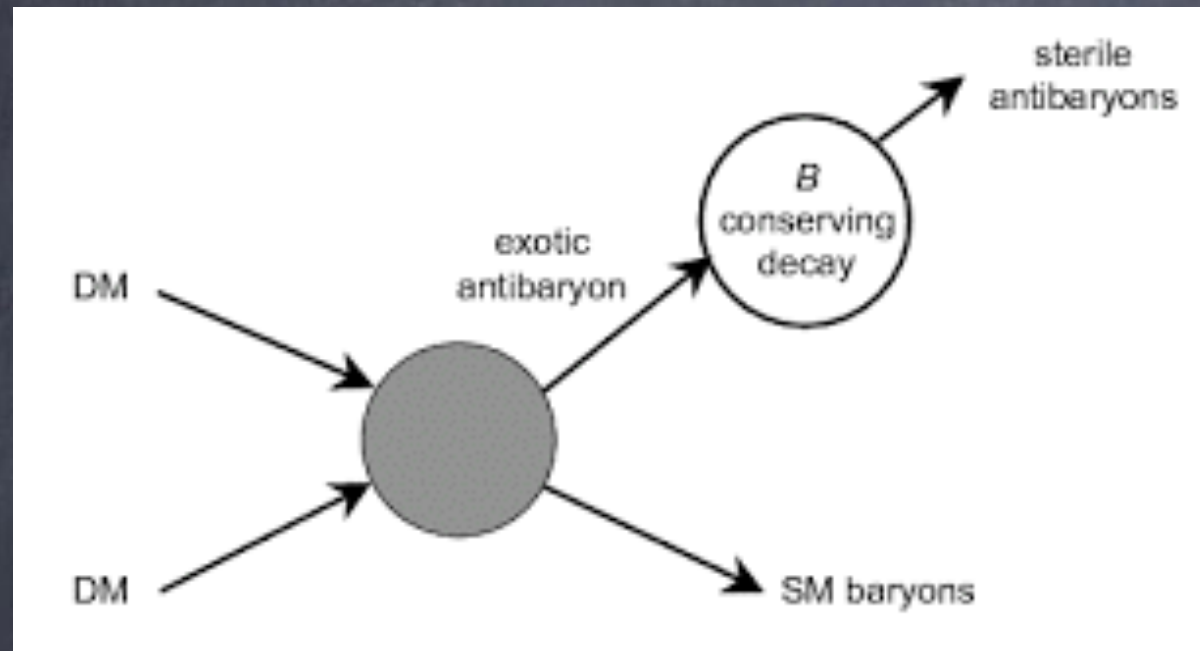
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1. WIMP annihilation violate B or L .
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3. Cooling of the Universe provides the departure from thermal equilibrium.

WIMPy Baryogenesis: General Framework

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

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

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

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

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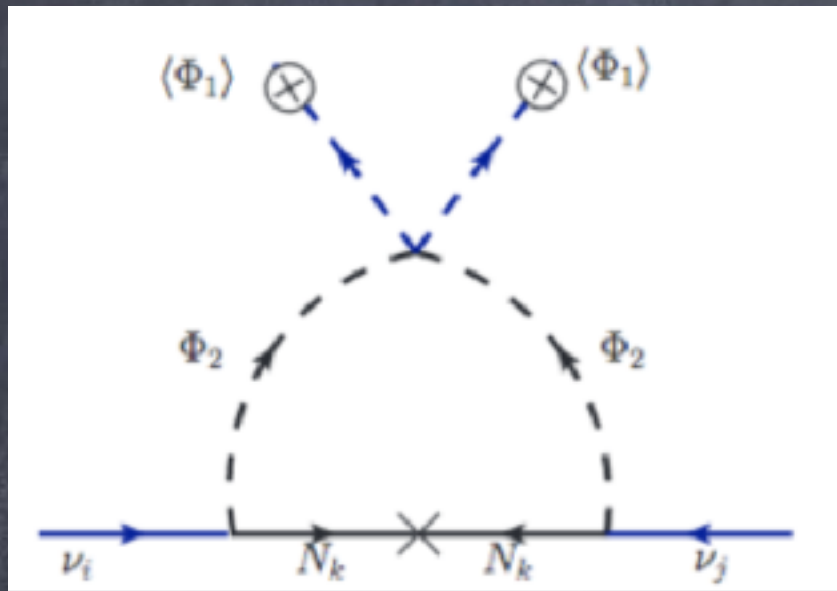
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- Lightest RHN DM (1710.03824).
- Neutrino Mass arises at one-loop level.

Scolotogenic Model

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

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



$$m_h^2 = \lambda_1 v^2$$

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

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

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

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

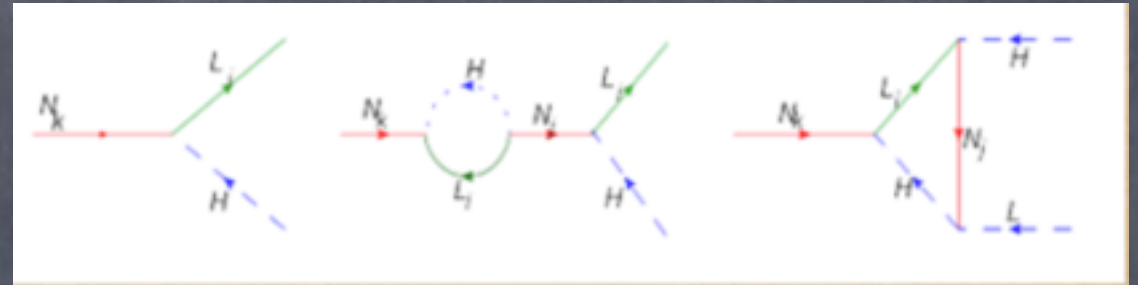
Which under the approximation $m_H^2 + m_A^2 \approx M_k^2$ boils down to

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

Vanilla Leptogenesis in Scotogenic Model

- Right handed neutrino decays out of equilibrium (Fukugida & 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 , leaves to a lepton asymmetry.

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

- At least two N 's are required to generate an asymmetry due to the presence of interference between tree and one loop diagram namely, vertex diagram (Fukugida & 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 baryons asymmetry through electroweak sphalerons (Khlebnikov & Shaposhnikov '88).

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

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

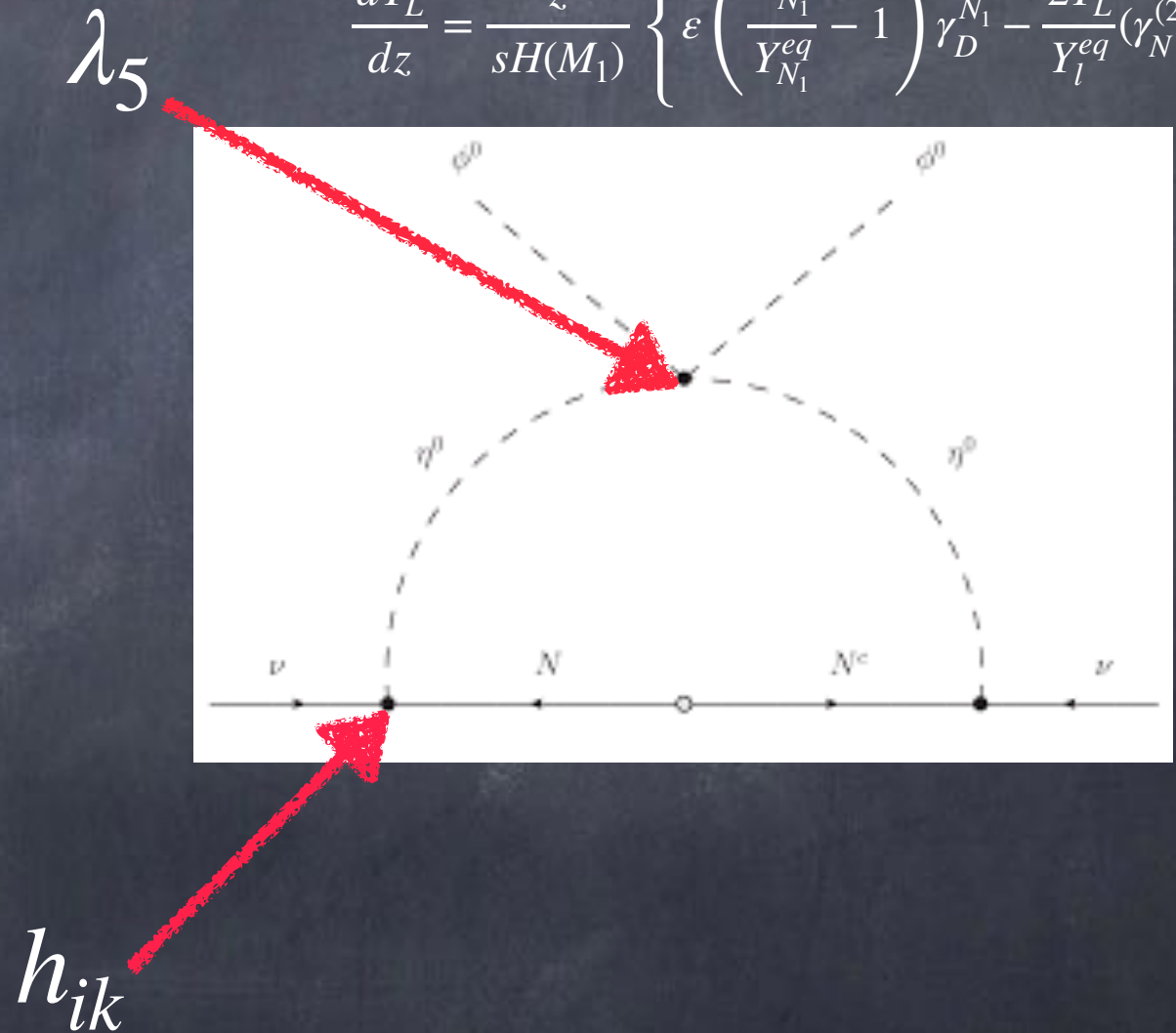
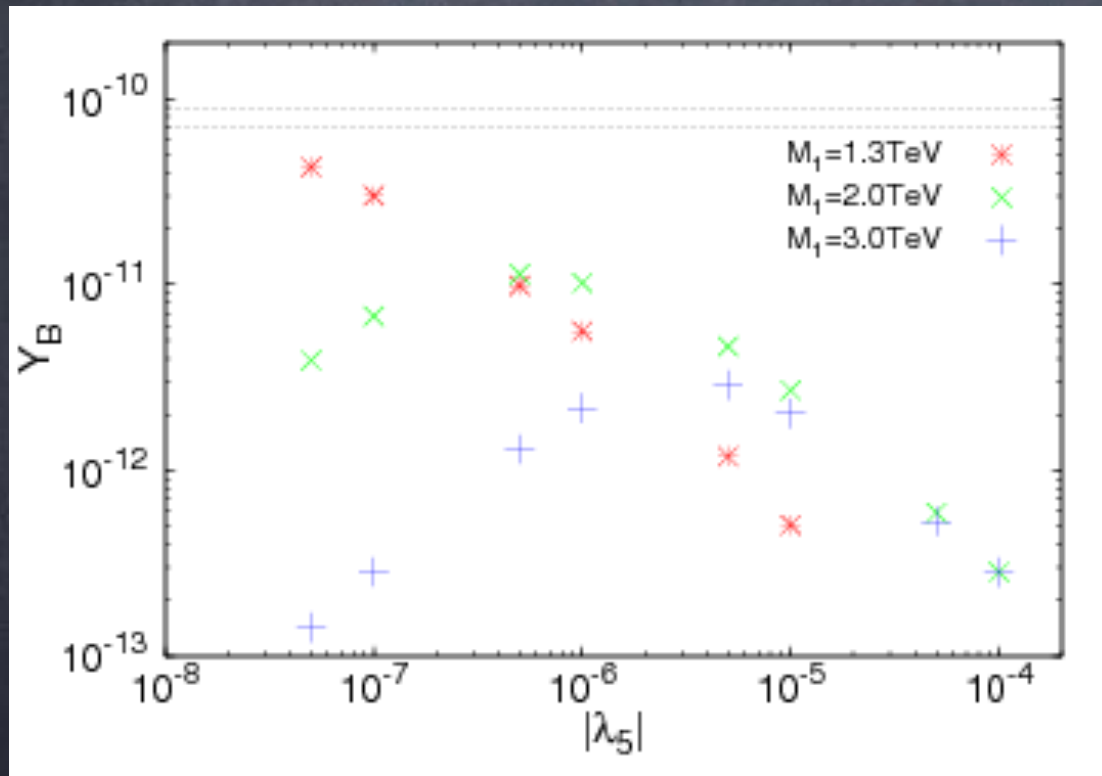
Leptogenesis in Scotogenic Model

1207.2594

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

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

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

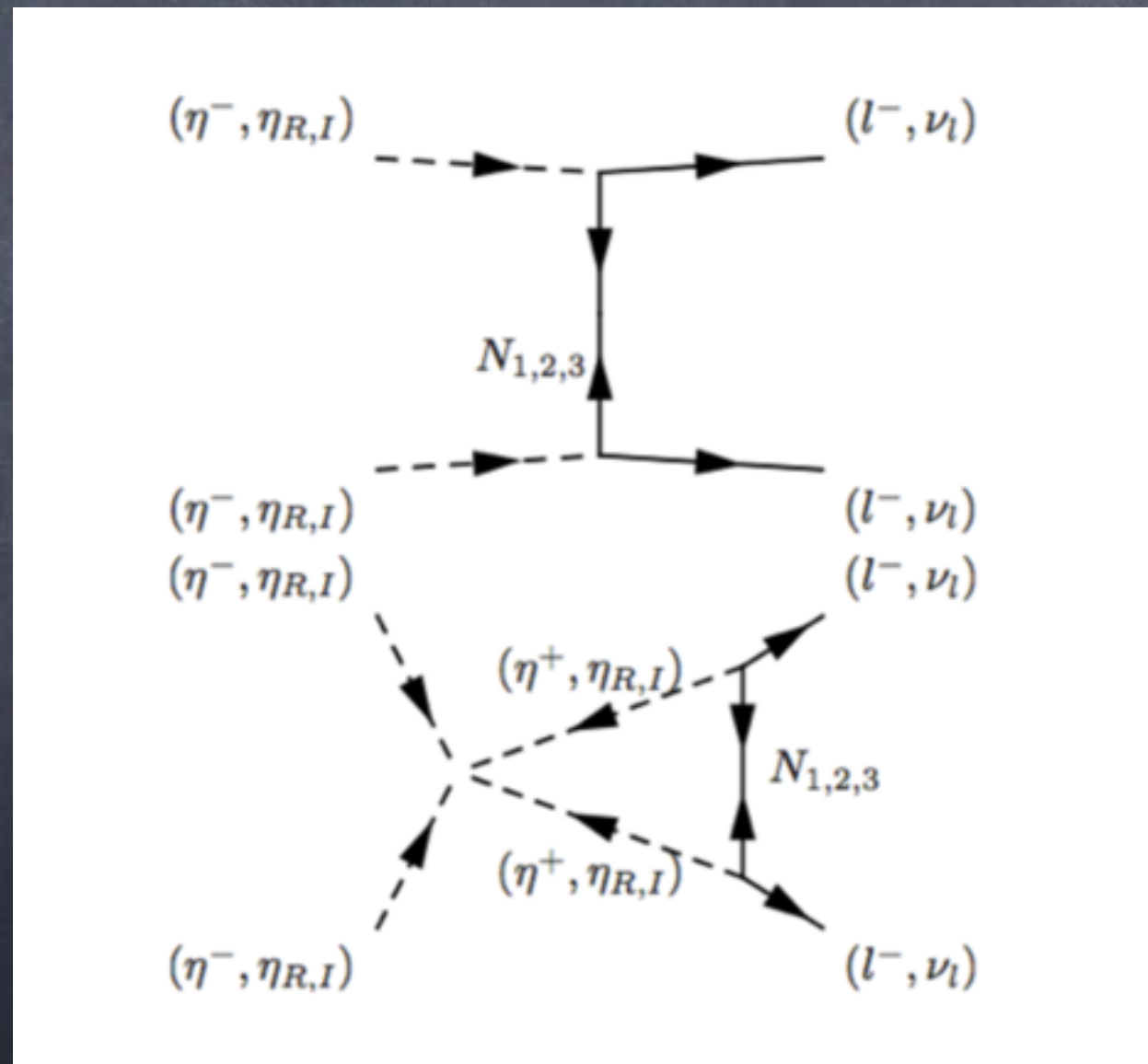


Leptogenesis in Scotogenic Model

- Smaller values of λ_5 requires larger Yukawa h_{ij} for correct neutrino mass and vice versa.
- Large Yukawa results in more wash-outs. Small Yukawa 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)

TeV Leptogenesis from DM annihilation

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



The Boltzmann Equations

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

$$\begin{aligned} \frac{dY_{\Delta L}}{dz} = & \frac{2zs}{H(M_{DM})} \left[\epsilon \langle \sigma v \rangle_{DMDM \rightarrow LL} (Y_{DM}^2 - (Y_{DM}^{eq})^2) \right] \\ & - Y_{\Delta L} Y_l^{eq} [\langle \sigma v \rangle_{DMDM \rightarrow LL}^{wo} + \langle \sigma v \rangle_{DMDM \rightarrow LL}] \\ & - Y_{\Delta L} Y_{DM} [\langle \sigma v \rangle_{DML \rightarrow DM\bar{L}}^{wo}] - \frac{1}{2} Y_{\Delta L} [\langle \sigma v \rangle_{DMDM \rightarrow SM\bar{L}}] \end{aligned}$$

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

Wash-out



$$\Delta L = 1 \quad N\eta_{R,I}(\eta^\pm) \rightarrow LZ(W^\pm)$$

$$\Delta L = 1 \quad NN \rightarrow \eta\eta, L\eta L \rightarrow \bar{L}\eta$$

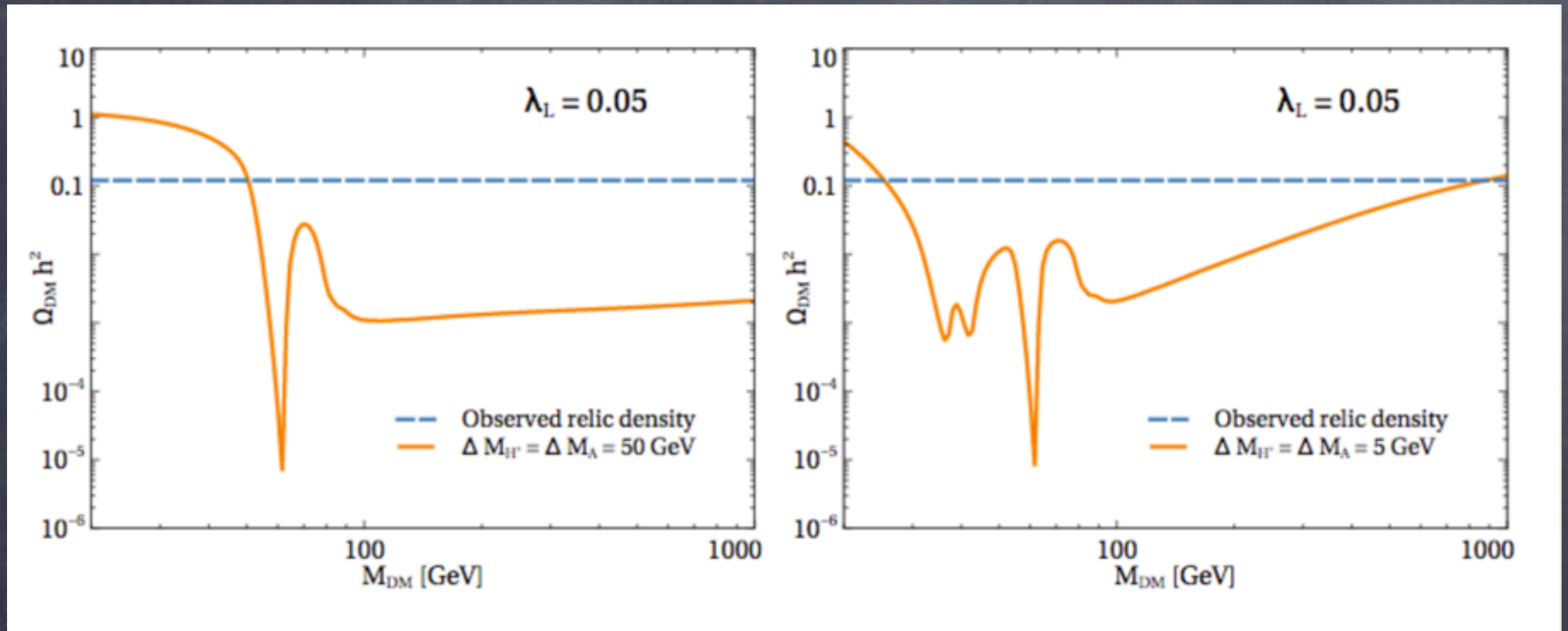
$$\epsilon = \frac{\langle \sigma v \rangle_{DM \rightarrow LL}^1}{\langle \sigma v \rangle_{DM \rightarrow LL}^0} \simeq \lambda \sin \phi \hat{\epsilon}$$

$$\hat{\epsilon} = \frac{1+x}{8\pi^2 x} \left[\ln \left(-\frac{(1+x)}{2x} \right)^2 + 2\text{Li}_2 \left(\frac{1}{2} \left(3 + \frac{1}{x} \right) \right) \right. \\ \left. - 2\text{Li}_2 \left(\frac{(x-1)^2}{(1+x)^2} \right) + 2\text{Li}_2 \left(\frac{1+x(2-3x)}{(1+x)^2} \right) \right. \\ \left. - 2\text{Li}_2 \left(3 - \frac{2}{1+x} \right) + 4\text{Li}_2 \left(\frac{2-1-x}{1+x} \right) \right]$$

$$x = \frac{M_{\text{DM}}^2}{M_N^2}$$

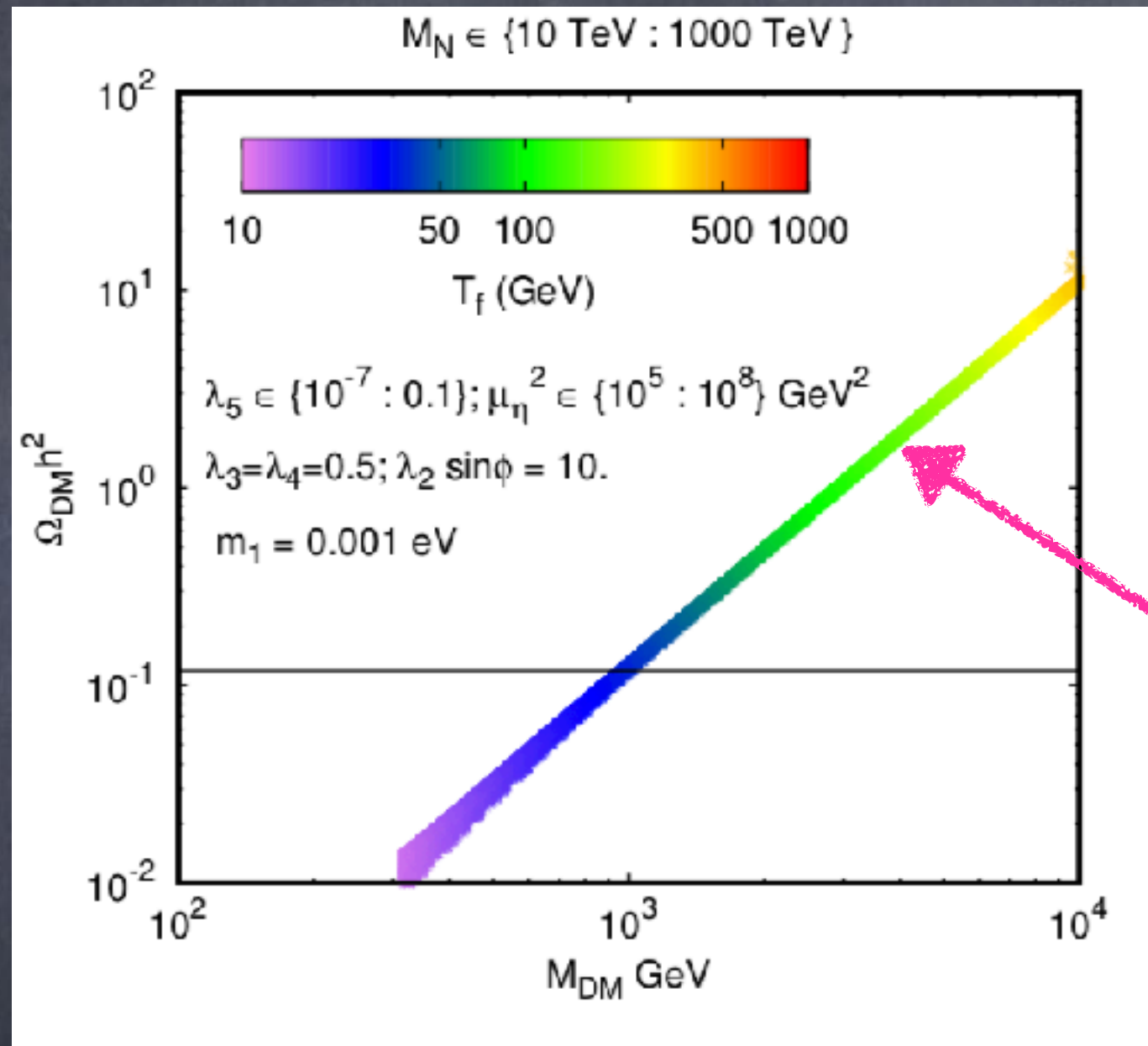
$$\text{Li}_2(y) = \sum_{k=1}^{\infty} \frac{y^k}{k^2}$$

Scalar Doublet Dark Matter



- There exist 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



DM
Overproduced

Summary of 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 annihilation 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 a lower bound on

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

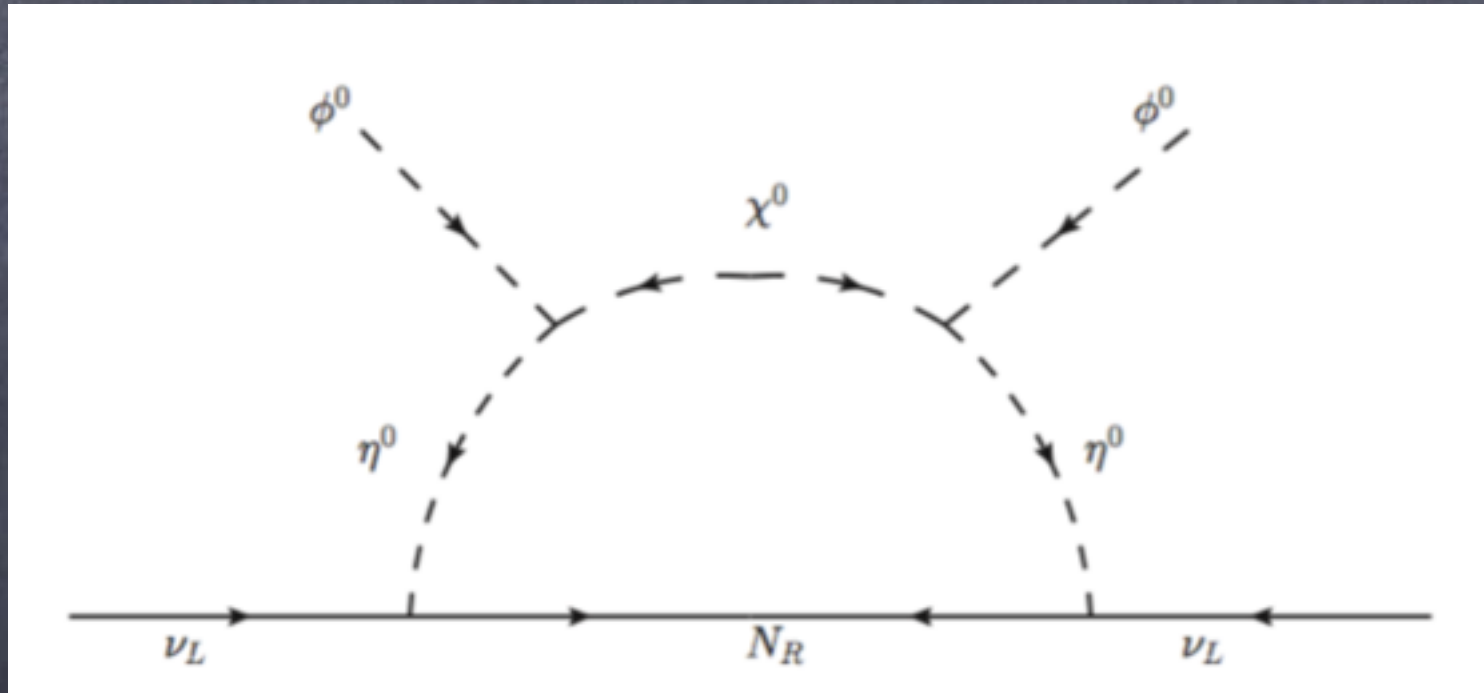
Minimal Extension

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

$$\begin{aligned} V = & \mu_H^2 H^\dagger H + \mu_\eta^2 \eta^\dagger \eta + \mu_\chi^2 \chi^* \chi + \frac{1}{4} \mu_4^2 [\chi^2 + (\chi^*)^2] \\ & + \mu (\eta^\dagger H \chi + H^\dagger \eta \chi^*) + \frac{1}{2} \lambda_H (H^\dagger H)^2 + \frac{1}{2} \lambda_\eta (\eta^\dagger \eta)^2 \\ & + \frac{1}{2} \lambda_\chi (\chi^* \chi)^2 + \lambda_4 (\eta^\dagger \eta) (H^\dagger H) + \lambda_5 (\eta^\dagger H) (H^\dagger \eta) \\ & + \lambda_6 (\chi^* \chi) (H^\dagger H) + \lambda (\chi^* \chi) (\eta^\dagger \eta) \end{aligned}$$

Physical Masses

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



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

Bechmark points

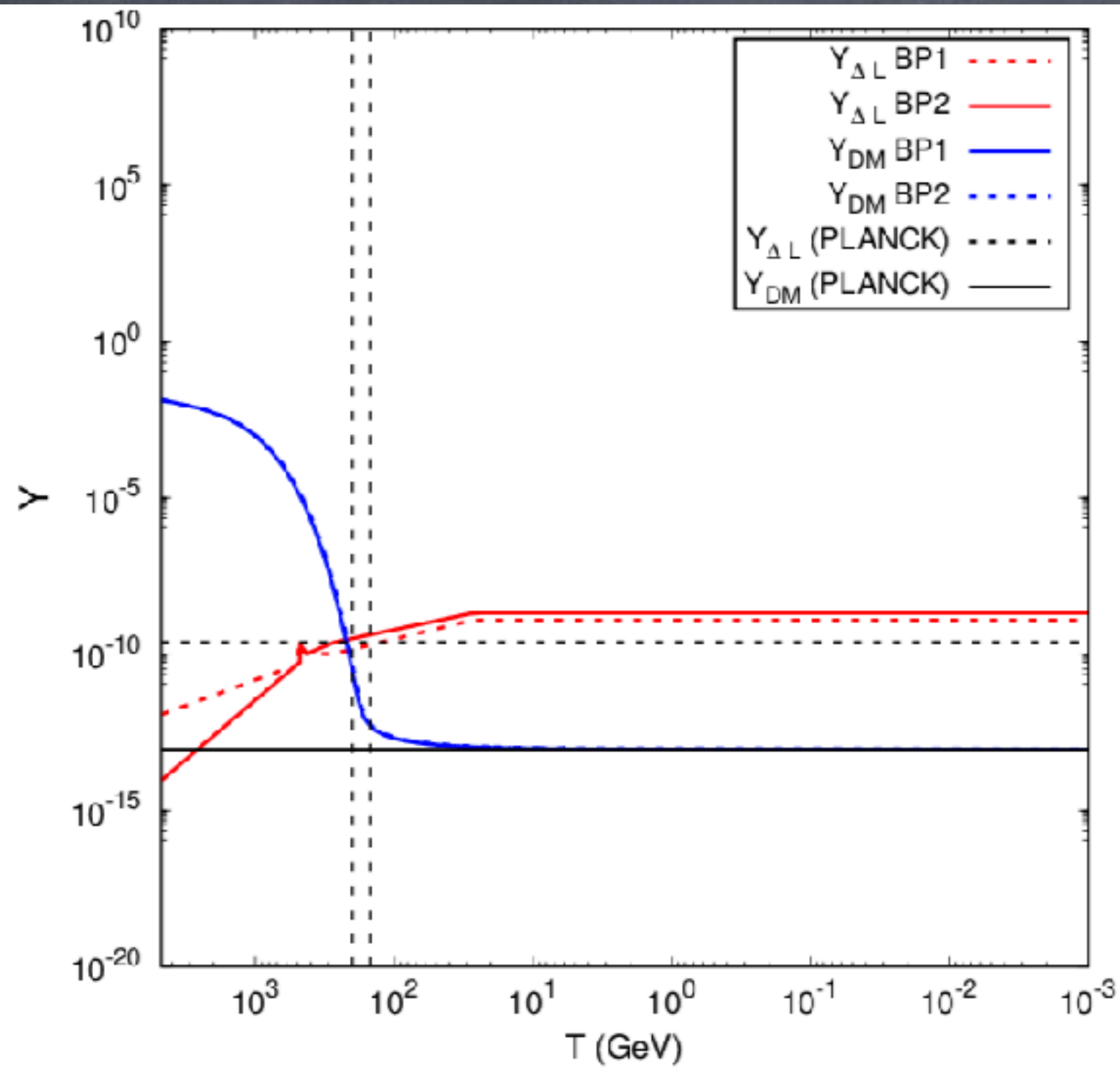
BP1

$$m_{\phi_1^R} = 4.89 \text{ TeV}, m_{\phi_2^R} = 4.90 \text{ TeV}, m_{\phi_1^I} = 4.89 \text{ TeV}, m_{\phi_2^I} = 4.90 \text{ TeV}, m_{\phi^\pm} = 4.89 \text{ TeV}, \mu_\eta = 4.89 \text{ TeV},$$
$$\mu_\chi = 4.89 \text{ TeV}, \mu = 234.14 \text{ GeV}, \mu_4 = 24.64 \text{ GeV}, \lambda_4 = 2.24 \times 10^{-3}, \lambda_5 = 1.53 \times 10^{-4}, \lambda_6 = 5.95 \times 10^{-5},$$
$$M_k = 15.02 \text{ TeV} (k = 1, 2, 3)$$

BP2

$$m_{\phi_1^R} = 4.78 \text{ TeV}, m_{\phi_2^R} = 4.79 \text{ TeV}, m_{\phi_1^I} = 4.78 \text{ TeV}, m_{\phi_2^I} = 4.79 \text{ TeV}, m_{\phi^\pm} = 4.78 \text{ TeV}, \mu_\eta = 4.78 \text{ TeV},$$
$$\mu_\chi = 4.79 \text{ TeV}, \mu = 212.43 \text{ GeV}, \mu_4 = 27.74 \text{ GeV}, \lambda_4 = 1.37 \times 10^{-4}, \lambda_5 = 3.48 \times 10^{-5}, \lambda_6 = 3.55 \times 10^{-4},$$
$$M_k = 17.79 \text{ TeV} (k = 1, 2, 3).$$

Results



Testability

Testability

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

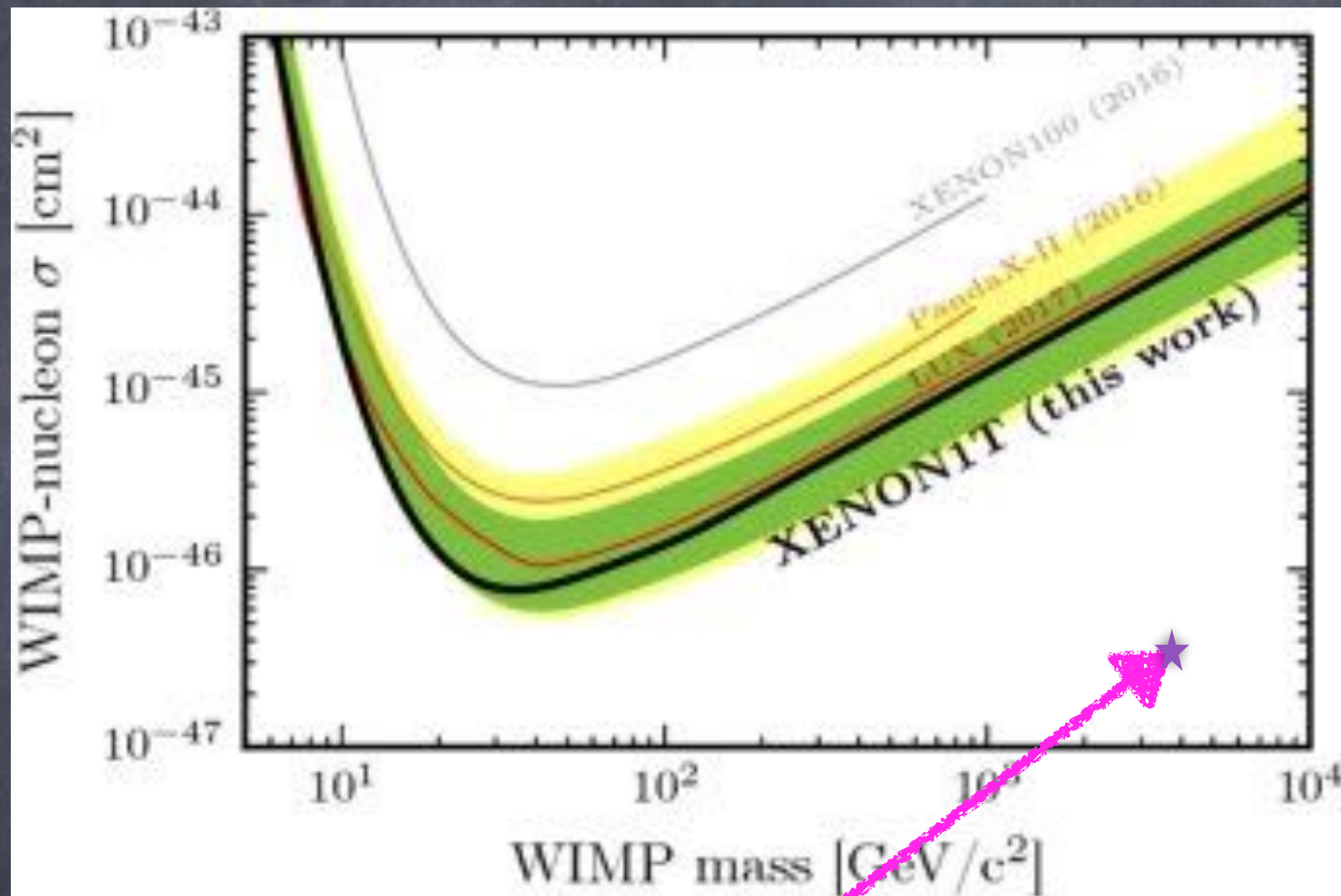
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- Since the particle spectrum of the model remains heavy, around 5 TeV or more, their direct production at the 14 TeV LHC remains suppressed.
- The model can however be tested at rare decay experiments looking for the lepton flavour violation.
- The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

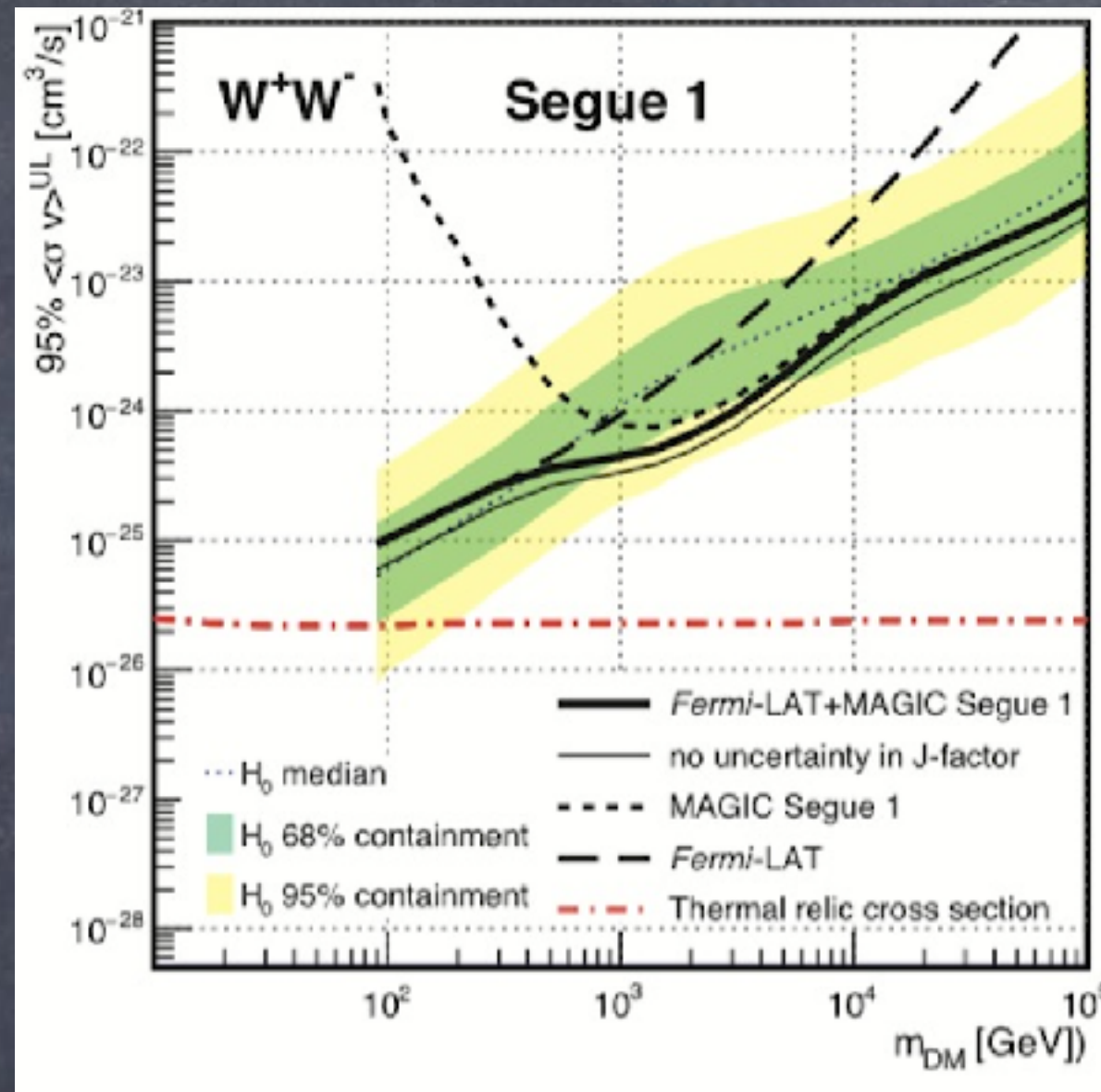
Direct Detection



$$\sigma_{DMn}^{SI} = 3.527 \times 10^{-47} \text{cm}^2 \quad \text{BP1}$$

$$\sigma_{DMn}^{SI} = 2.508 \times 10^{-47} \text{cm}^2 \quad \text{BP2}$$

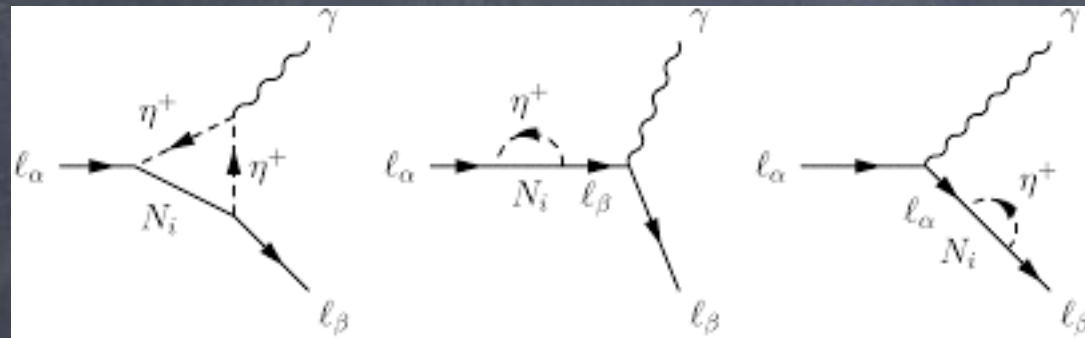
Indirect Detection



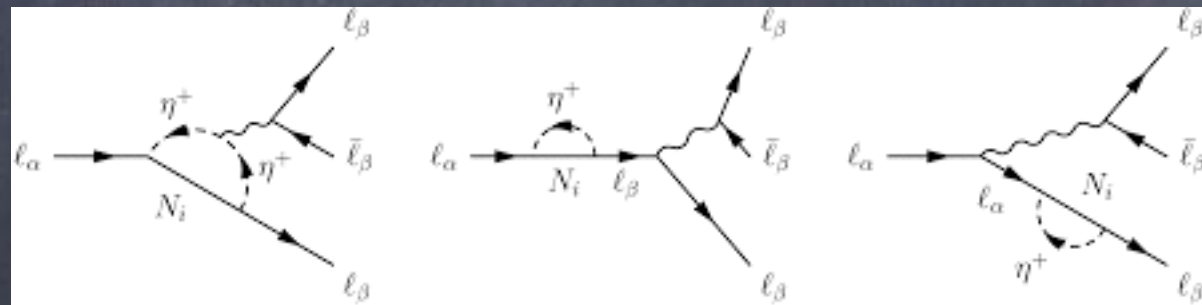
$$\langle \sigma v \rangle_{DMDM \rightarrow W^+W^-} = 2.83 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \quad (\text{BP1})$$

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

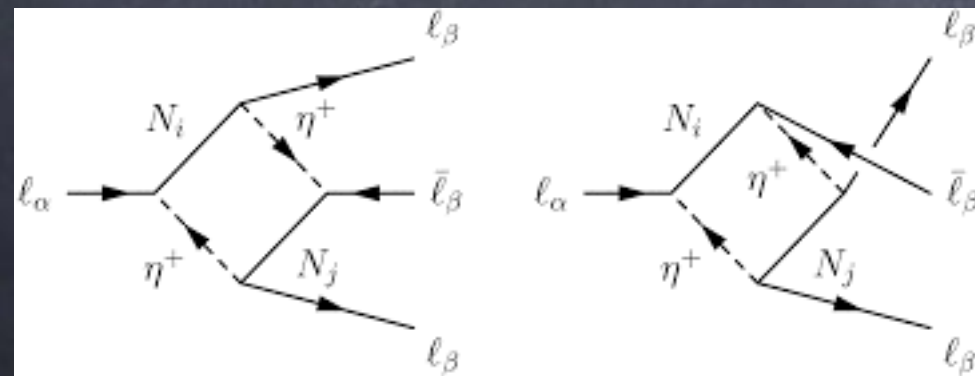
Lepton Flavor Violation



$$l_\alpha \rightarrow l_\beta \gamma$$

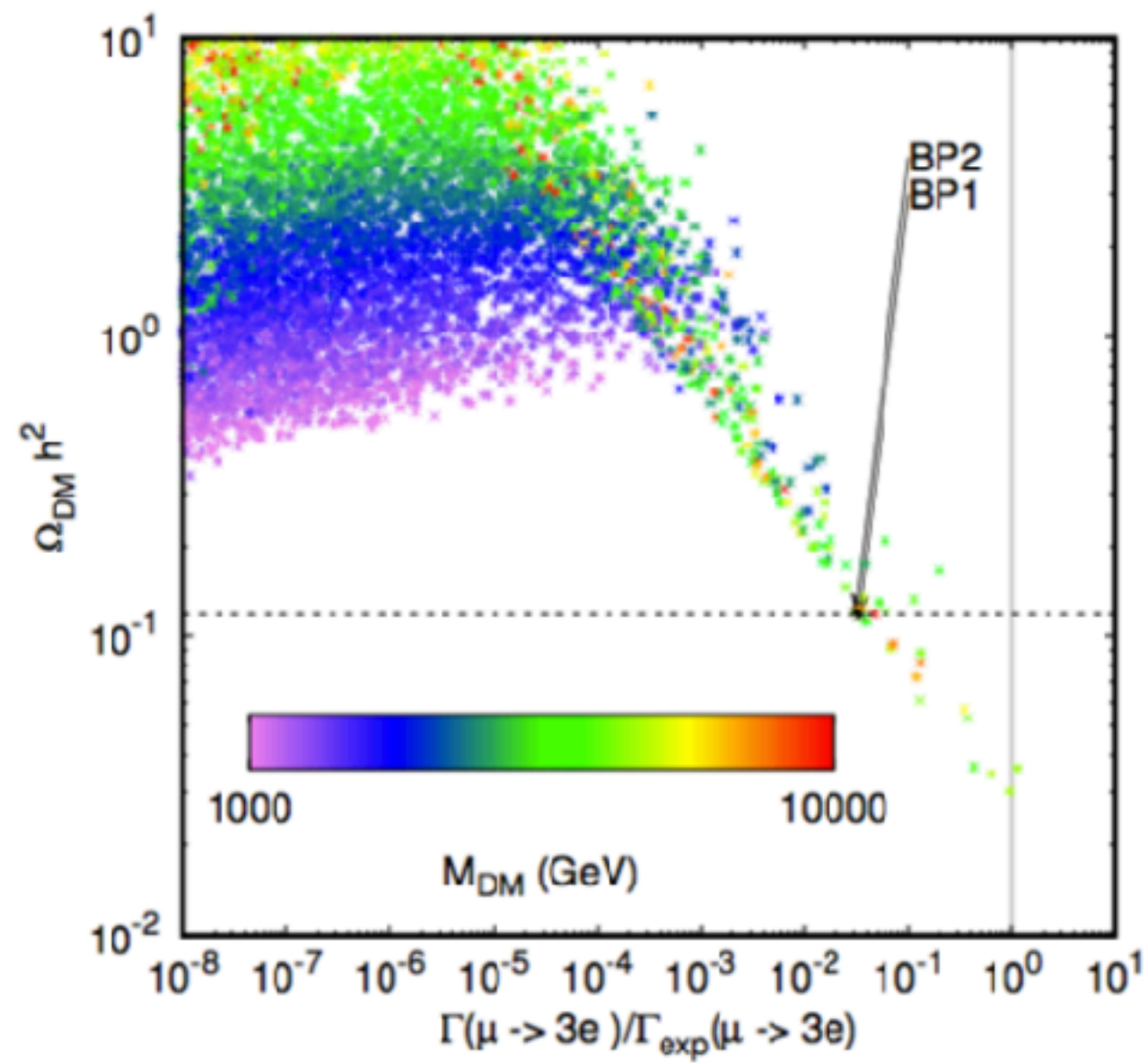
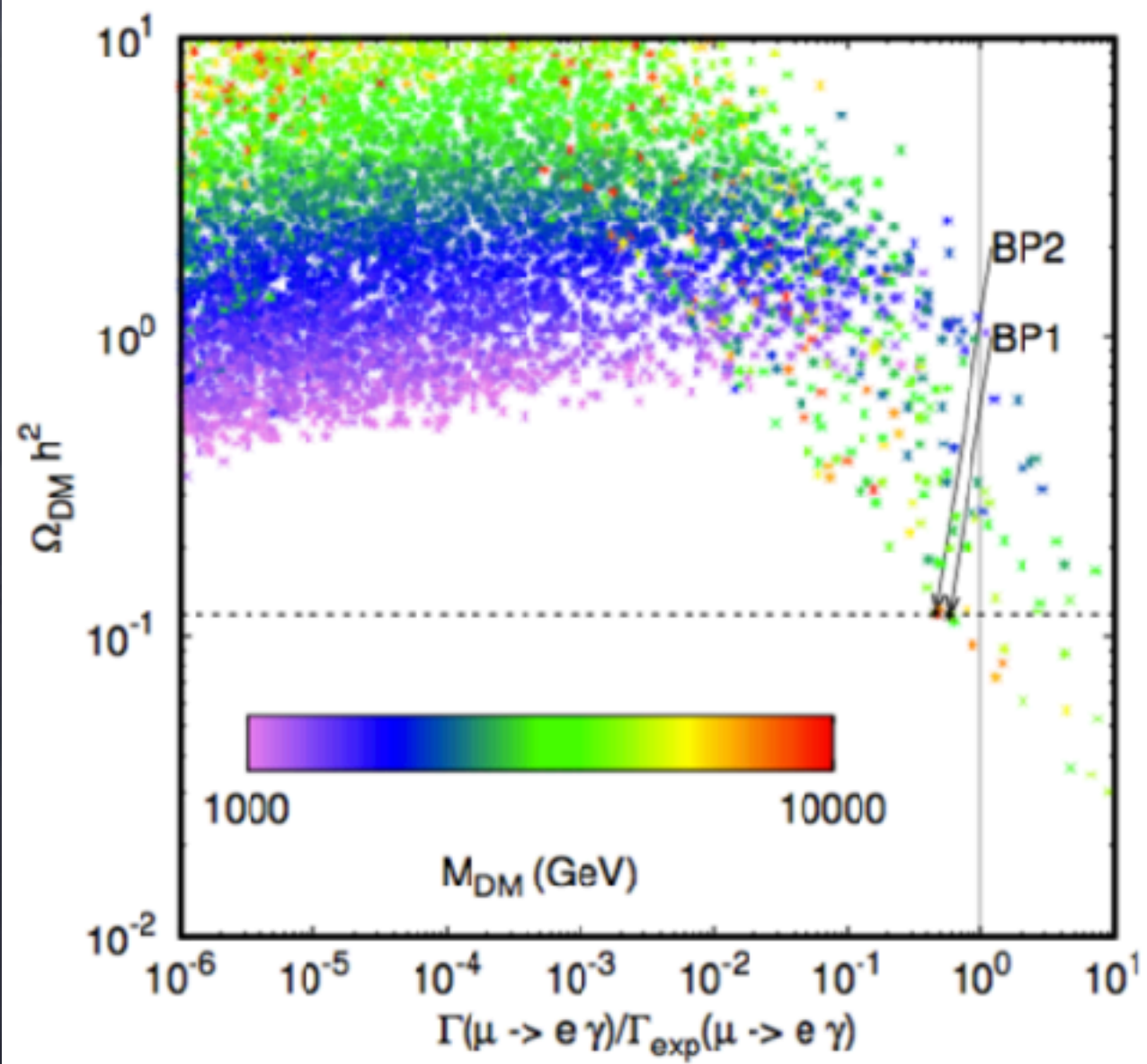


$$l_\alpha \rightarrow 3l_\beta$$



Lepton Flavor Violation

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



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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 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