Common Origin of Visible & Dark Matter: An Overview

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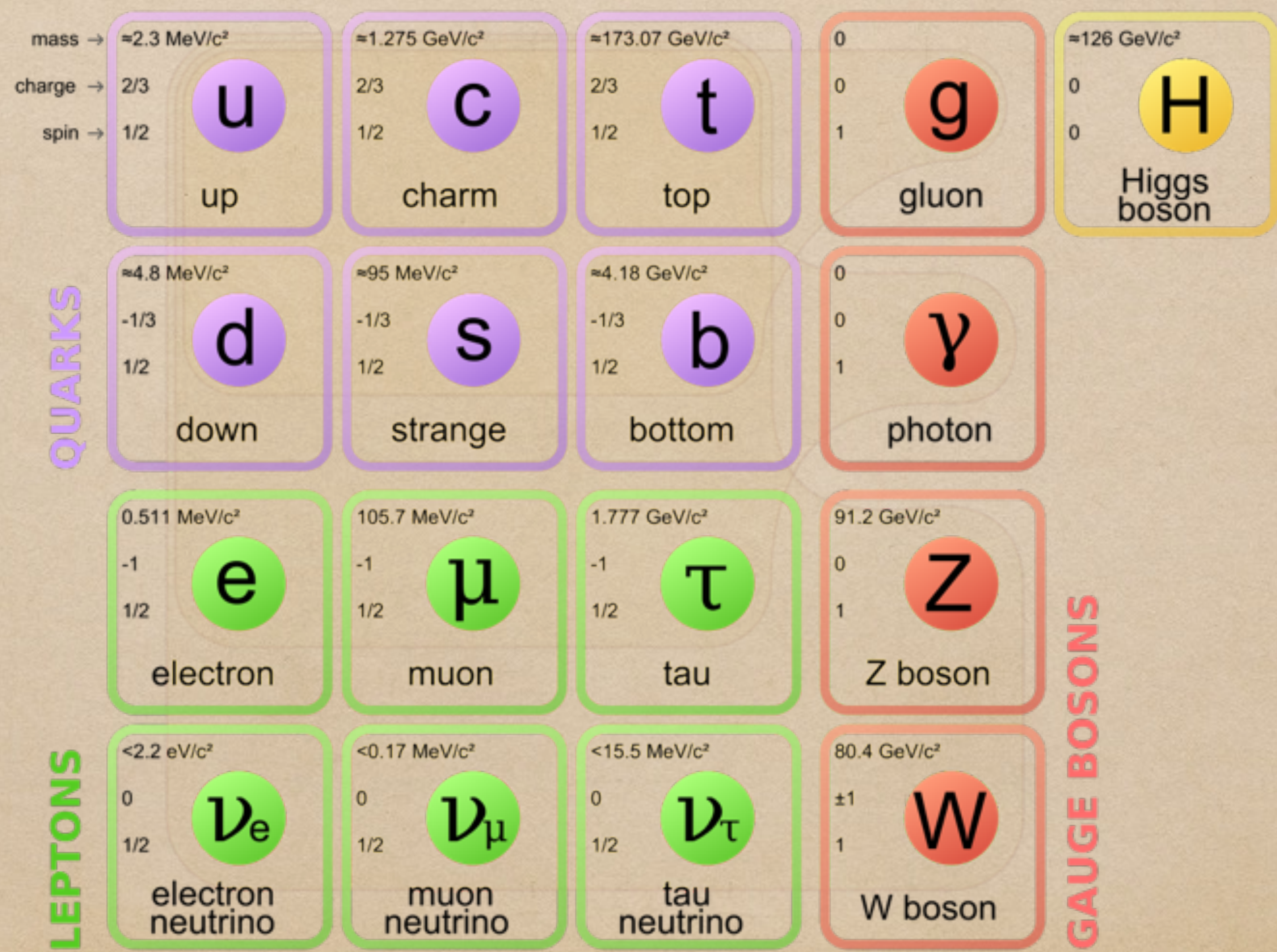
Outline

- Introduction
- Dark Matter (DM)
- Baryon Asymmetry of Universe (BAU)
- Towards a Common Origin of DM & BAU
    1. Asymmetric DM
    2. WIMPy Baryogenesis
    3. Others
- Conclusion

The Standard Model



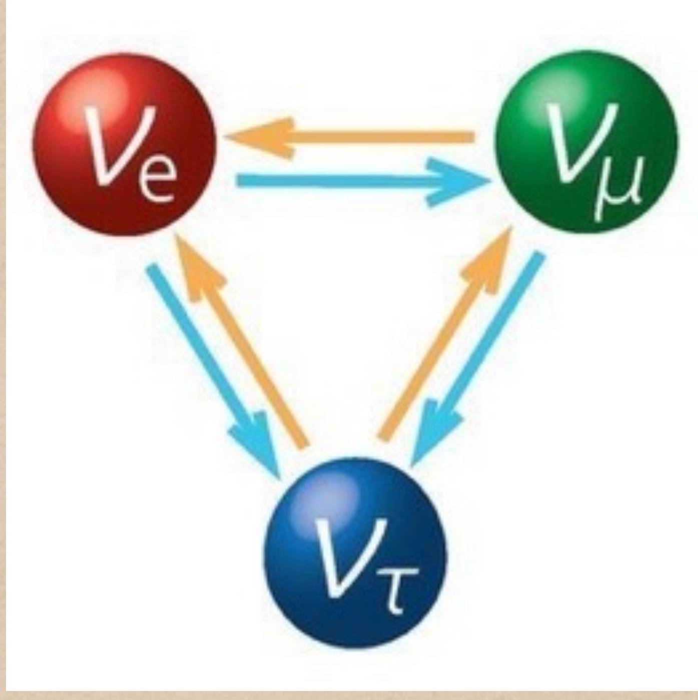
The Standard Model

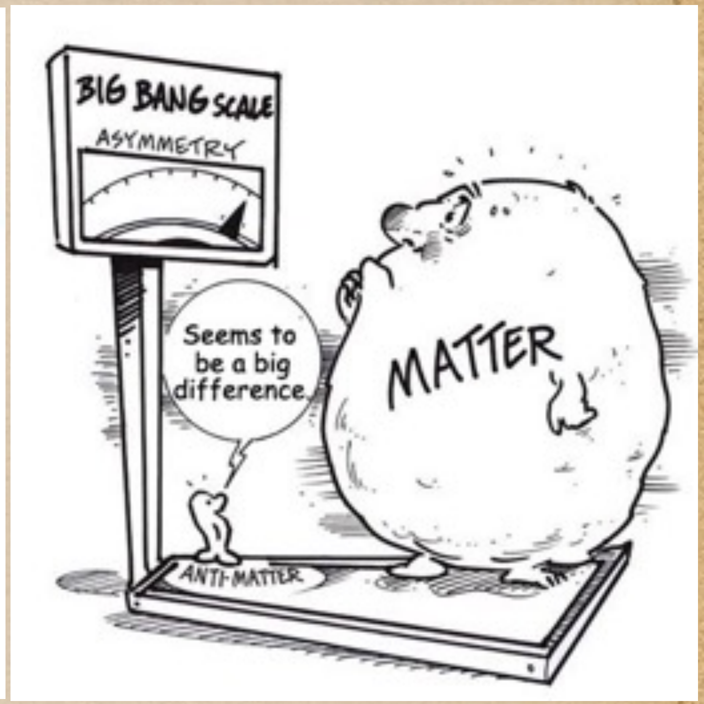
- The SM has been very successful in describing the elementary particles and their interactions except gravity.
- The last missing piece of the SM, the Higgs boson was also discovered a few years back at the LHC (2012).
- Since then the LHC results have only been able to confirm the validity of the SM 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

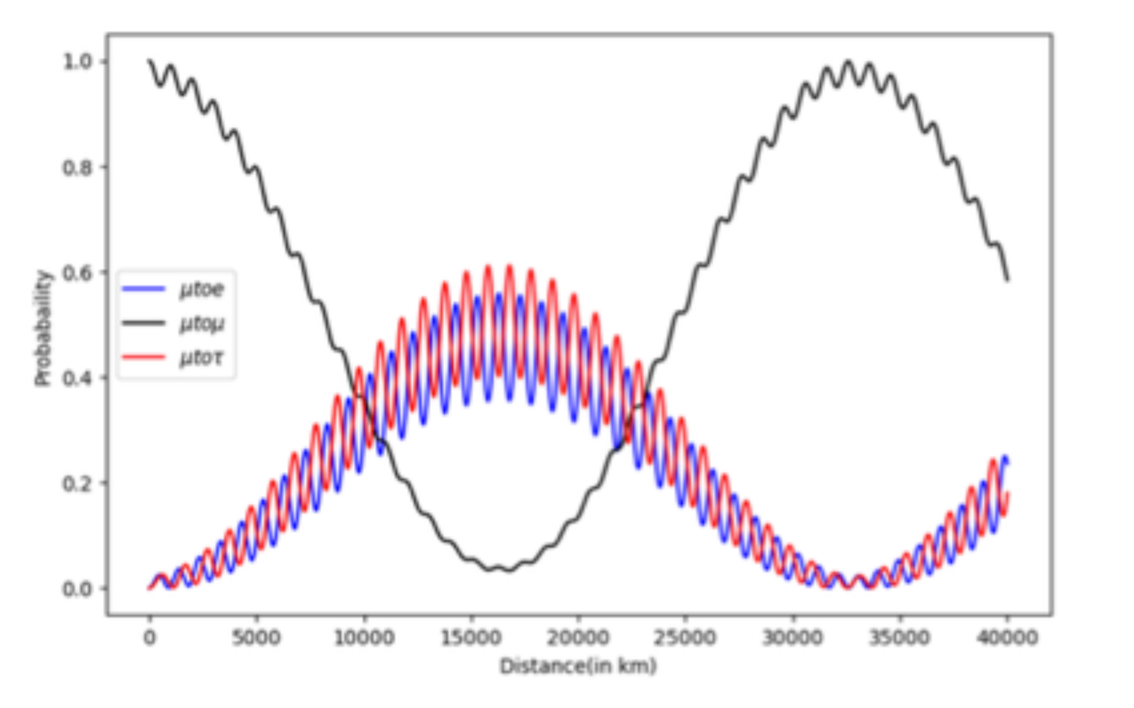




Neutrino Mass & Mixing

Plenary talk by K S Babu

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

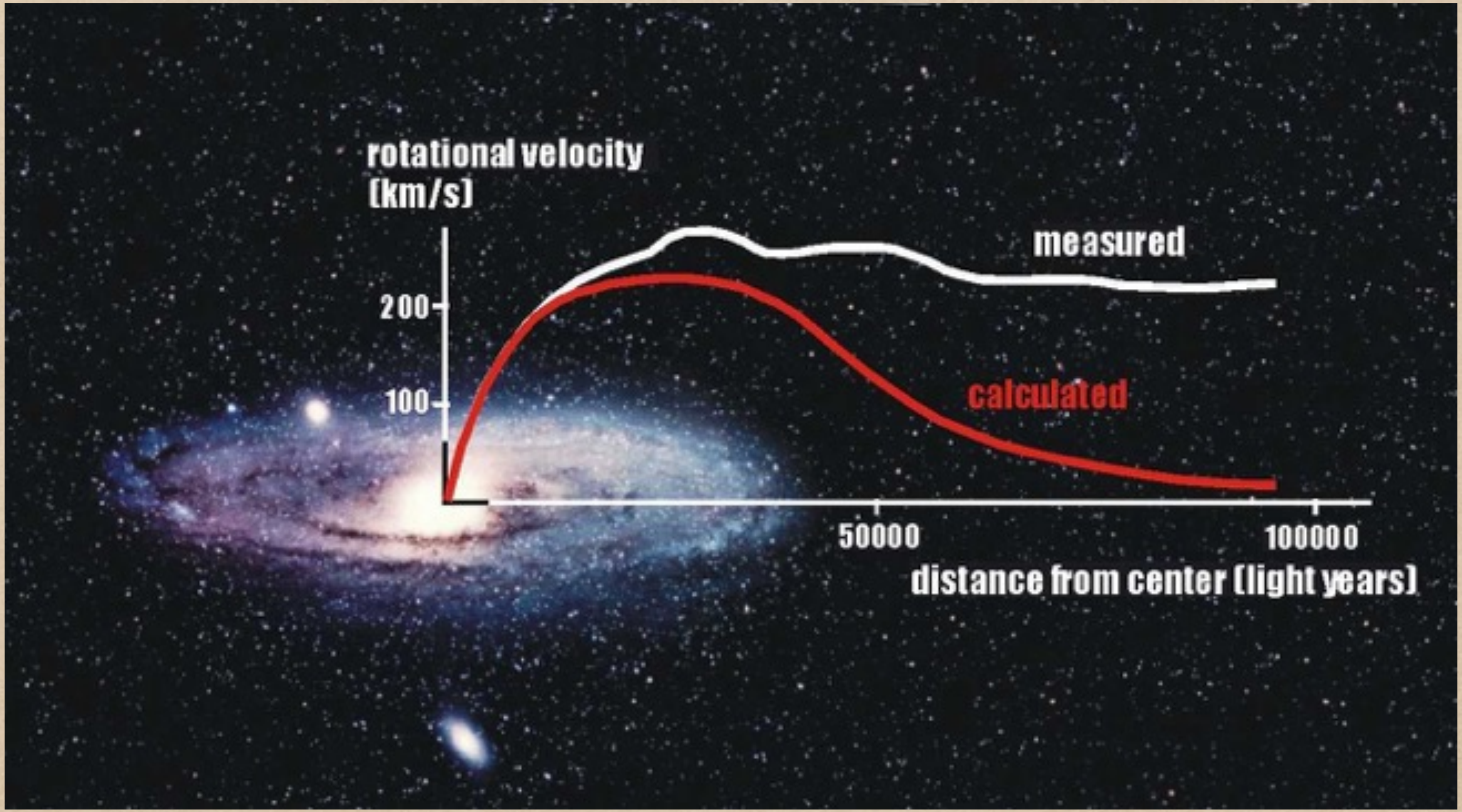


$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2 \frac{\Delta m^2_{ij} L}{4E} + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin \frac{\Delta m^2_{ij} L}{2E}$$

Dark Matter: Evidence

- In 1932, Oort found that the gravitational potential provided by the visible stars was not enough to keep the stars bound to the Galactic plane. Since the galaxy is stable and not losing stars, there has to be more matter to keep the stars bound to the galaxy.
- The other claim that some mysterious form of matter (Dark Matter) must dominate in Galaxy clusters was made by Fritz Zwicky in 1933. He found that the radial velocities of galaxies in a cluster are almost a factor of 10 larger than expected from the summed mass of all galaxies in the cluster.
- Vera Rubin and her collaborators later observed galaxy rotation curves (1970's), another astrophysical evidence suggesting the presence of Dark Matter.

Galaxy Rotation Curve



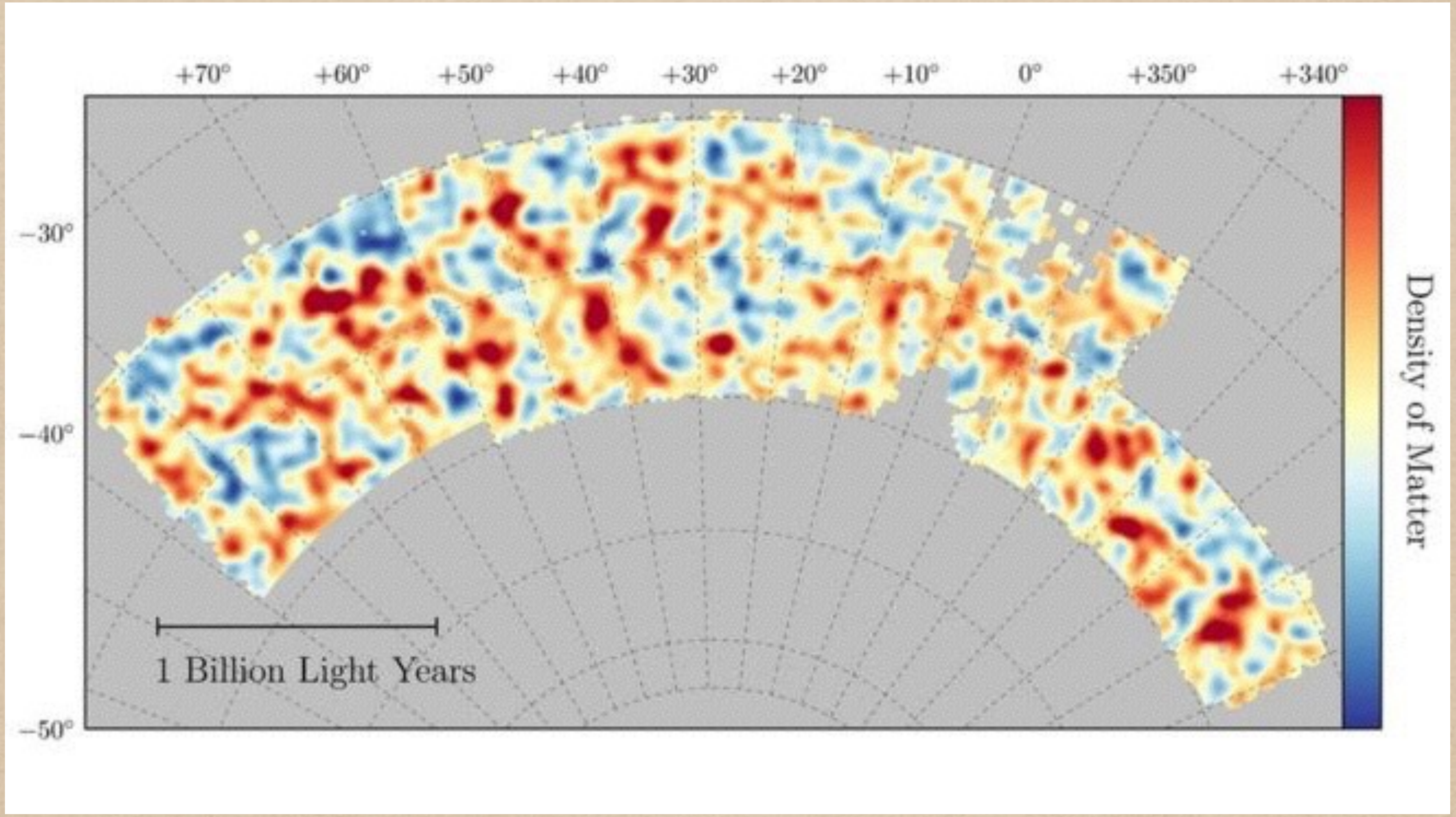
For small r: $\frac{mv^2(r)}{r} = \frac{GM(r)m}{r^2}, \;\; M(r) = \frac{4}{3}\pi\rho r^3 \quad v(r) \propto r$

For large r: $v(r) \propto \frac{1}{\sqrt{r}}$

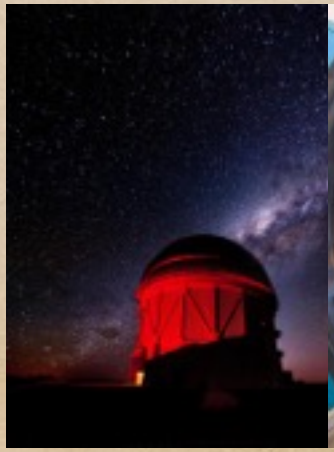
Gravitational Lensing

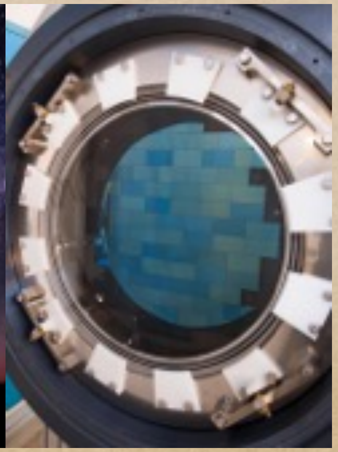
Abel S1063 Cluster, Hubble Space Telescope

Gravitational Lensing

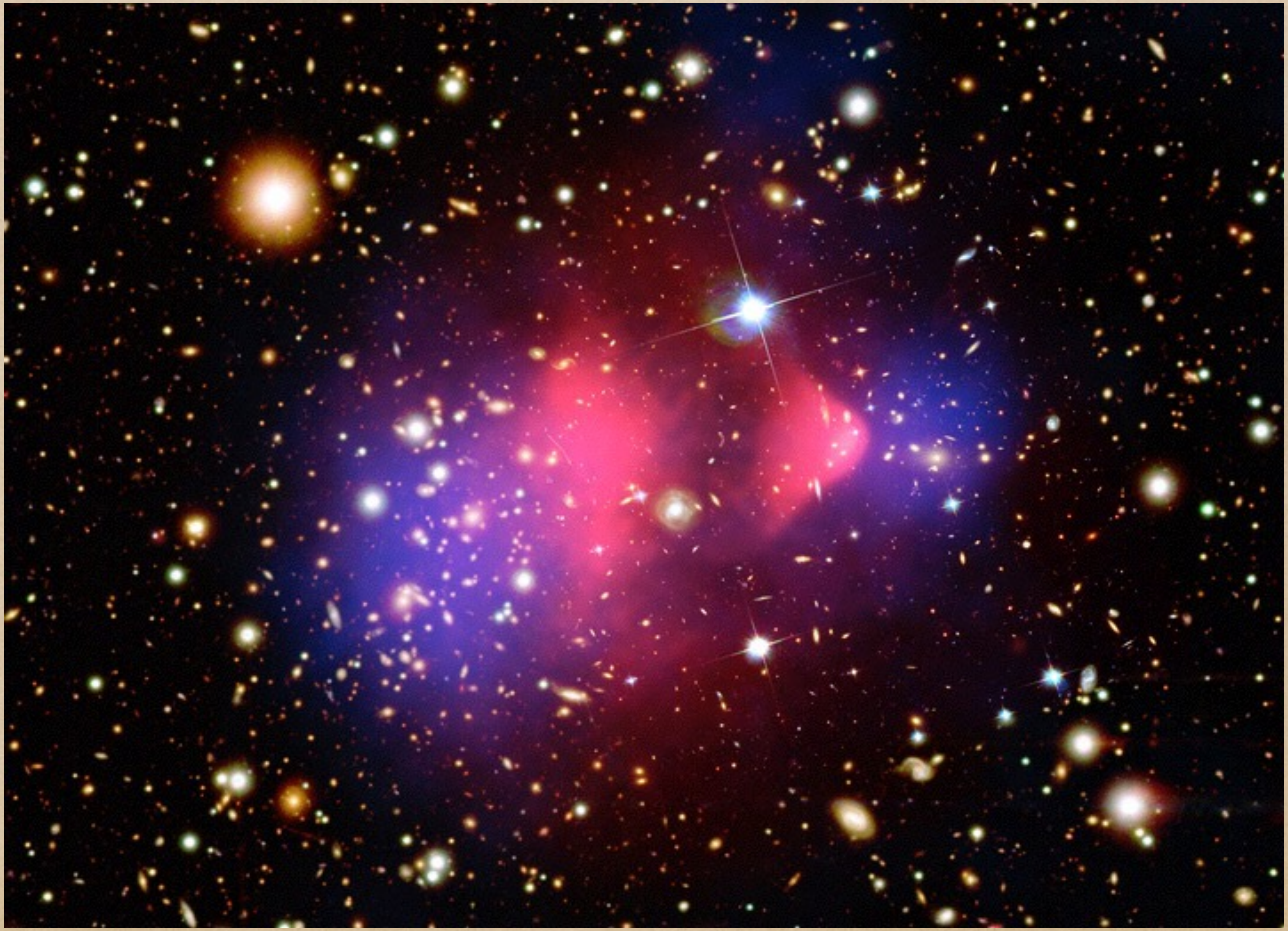


DES Survey 2017

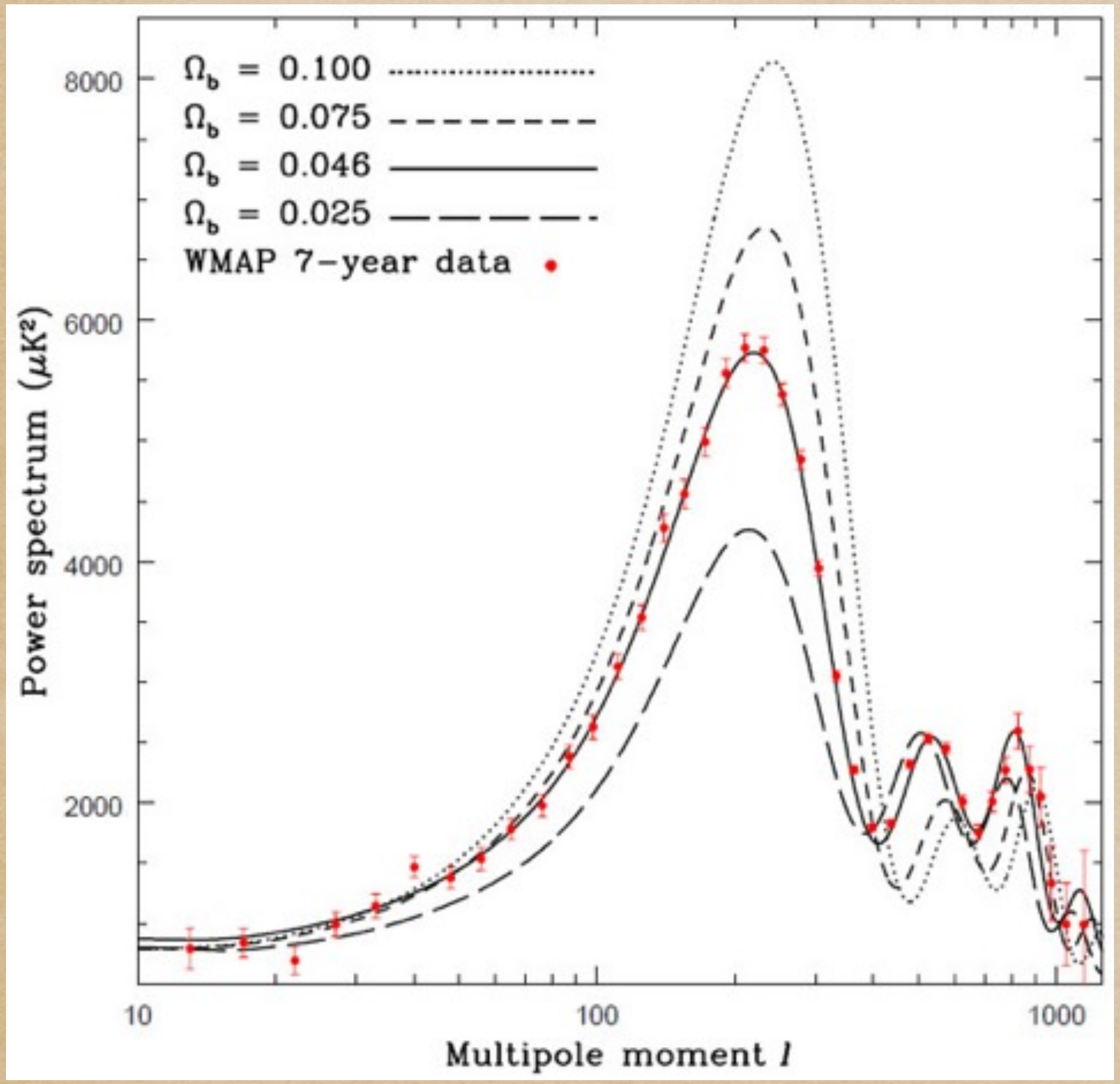


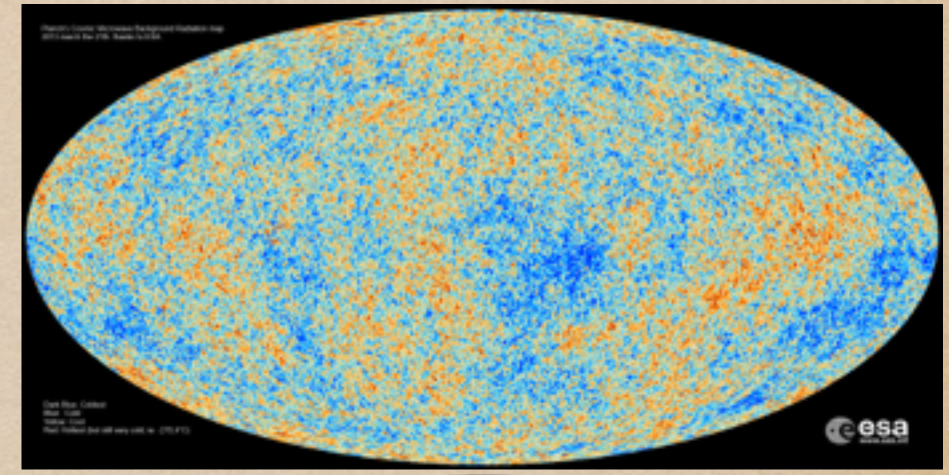


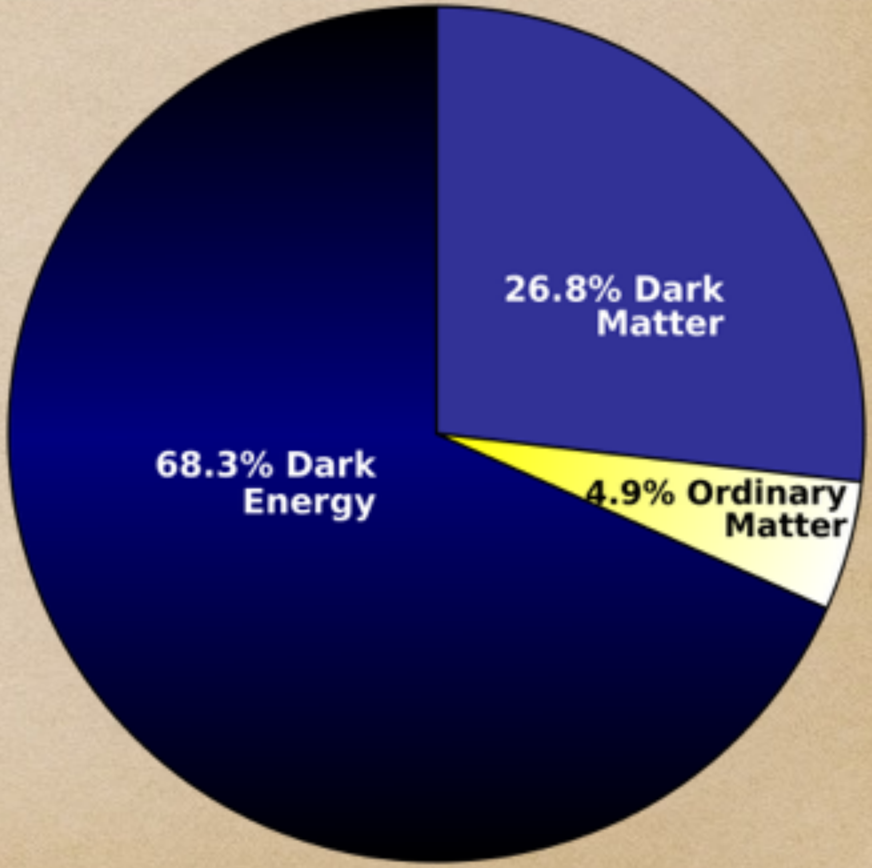
Bullet Cluster



Evidence from CMBR







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?

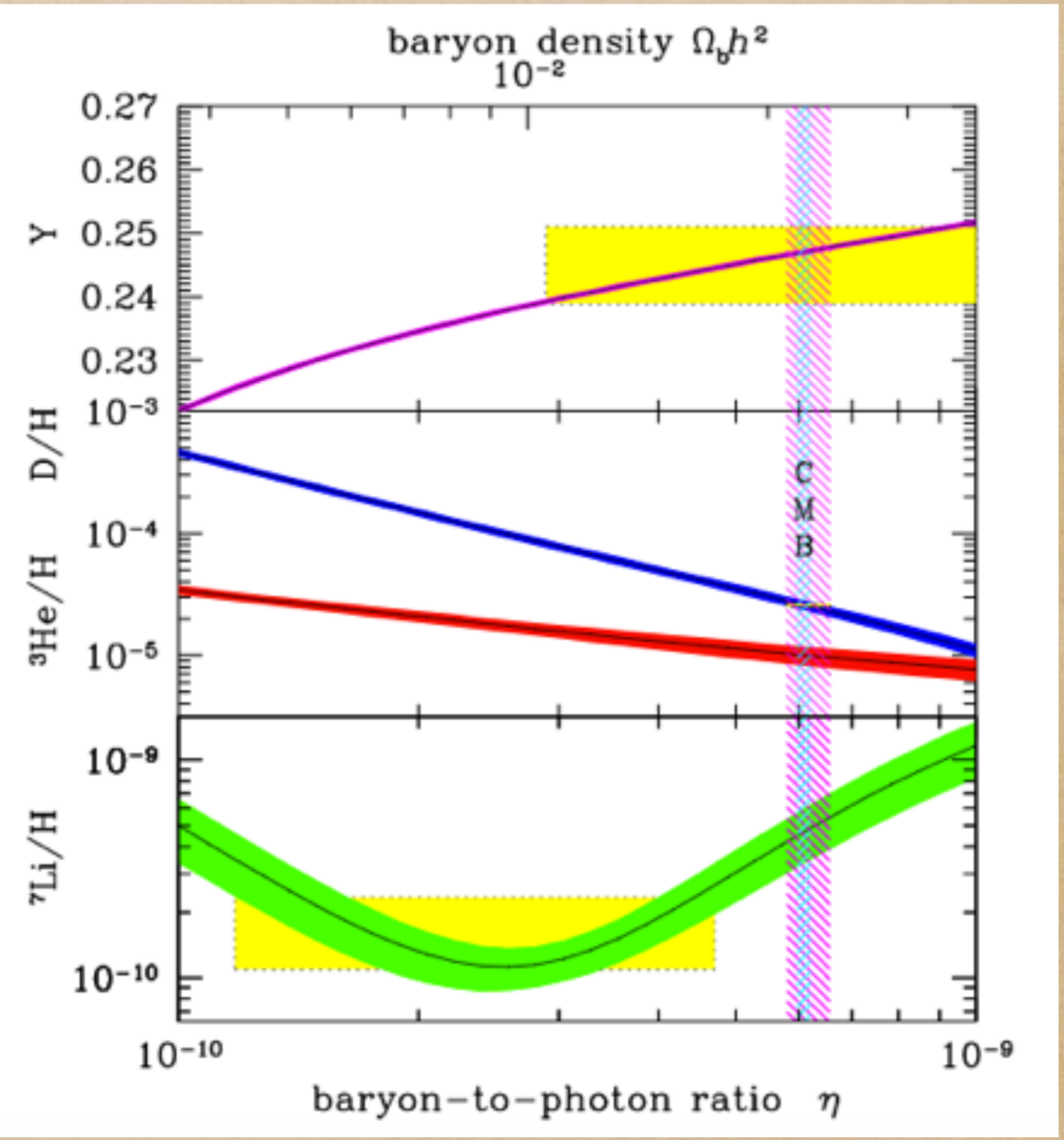
Taoso, Bertone & Masiero 2008

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 $X \rightarrow Y + B$
- C & CP violation.

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

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

- Departure from thermal equilibrium.

Baryogenesis

See Bhupal's talk, WG V

- 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 provide a common framework to explain neutrino mass, mixing and baryon asymmetry of the Universe.

Baryogenesis & Dark Matter

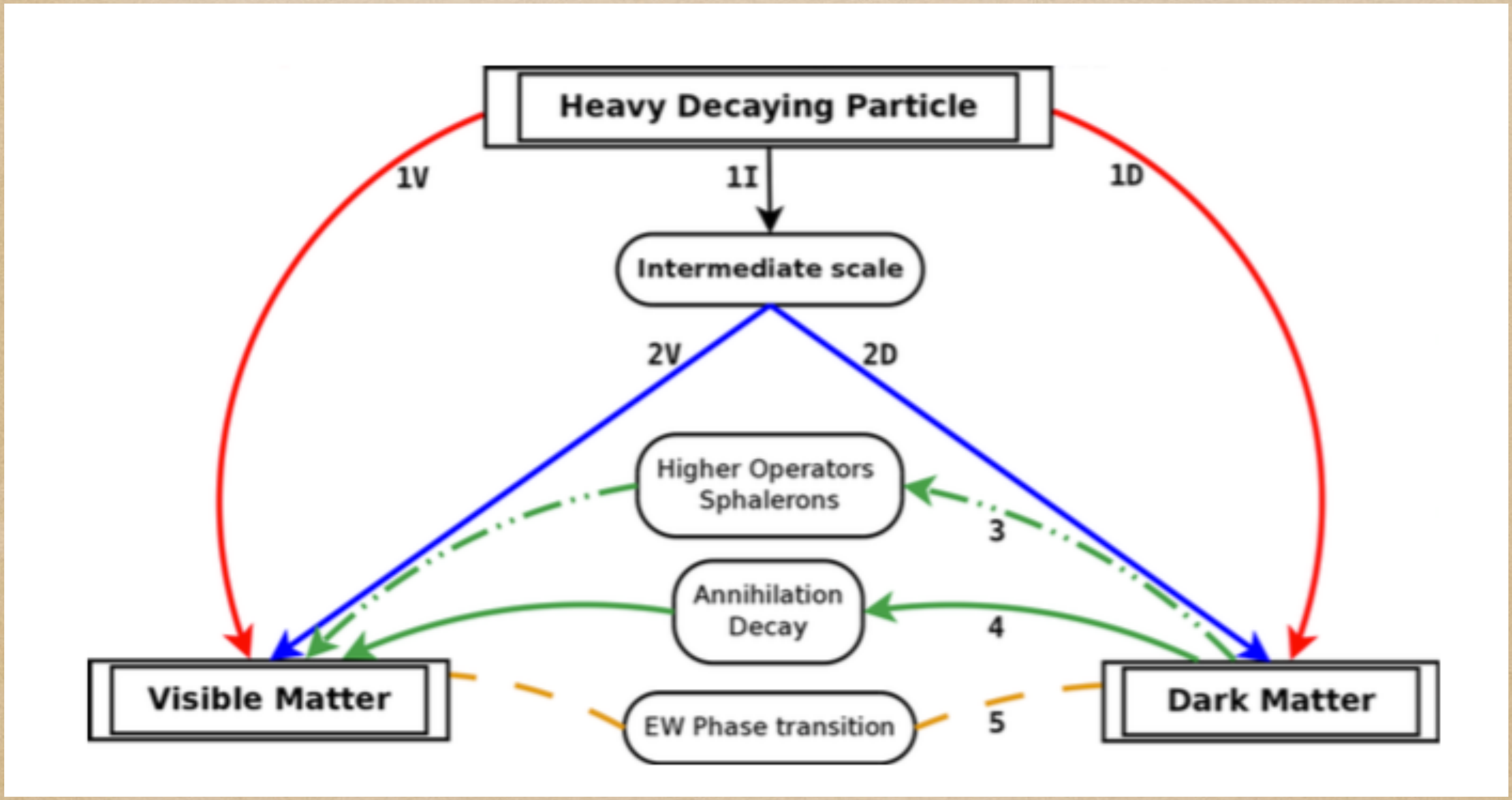
- The observed BAU and DM abundance are of the same order

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

- 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 ADM tightly relates BAU & DM abundances, the other scenarios try to connect their origins within a unified framework.
- Since many neutrino mass models typically accommodate leptogenesis, one can also relate neutrino and DM

→ Narendra's Talk WG III+V

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 $M_{DM} \approx 5m_p \approx 5 \text{ GeV}$

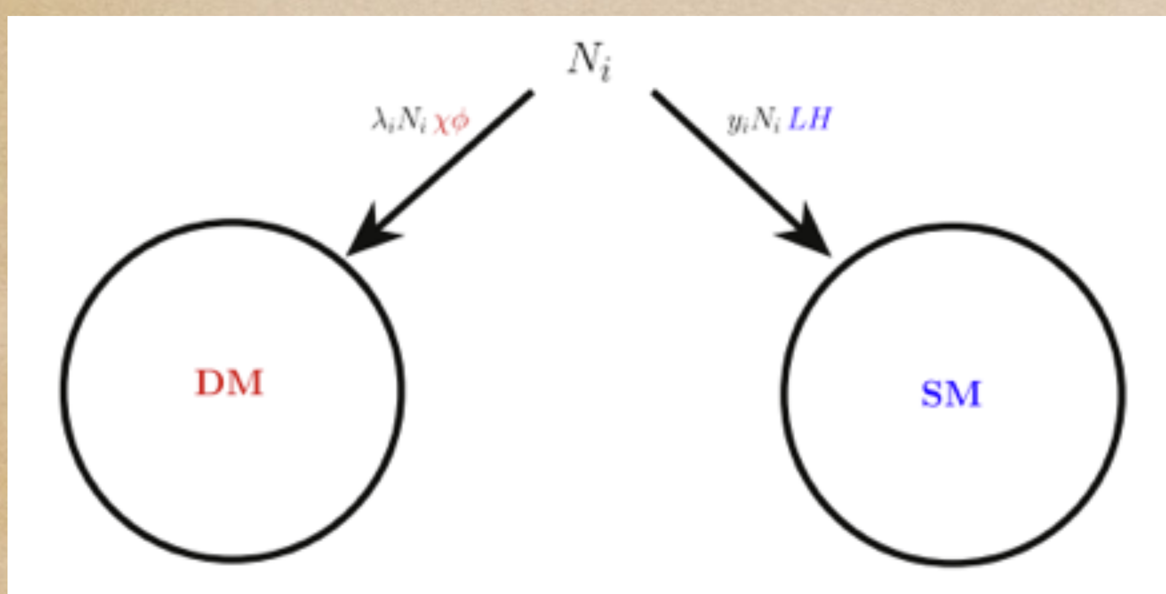
- However, if the process producing DM asymmetry decouples early or different asymmetries are generated in DM and visible sectors, then DM mass can be different from what this simple relation dictates.

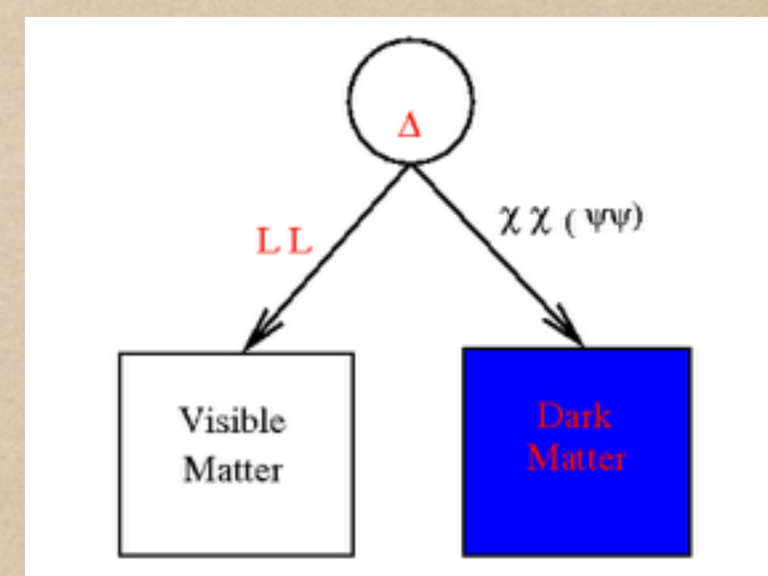
ADM: Basic Framework

- 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.)



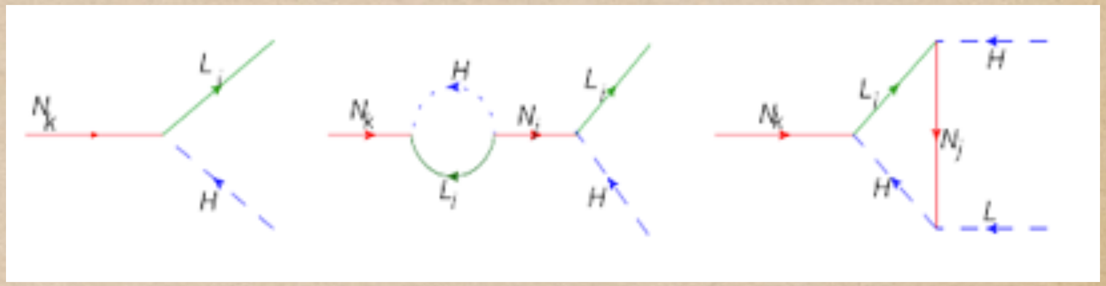


See Bhupal's talk, WG V

Leptogenesis & ADM

- 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.

Leptogenesis & ADM

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

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

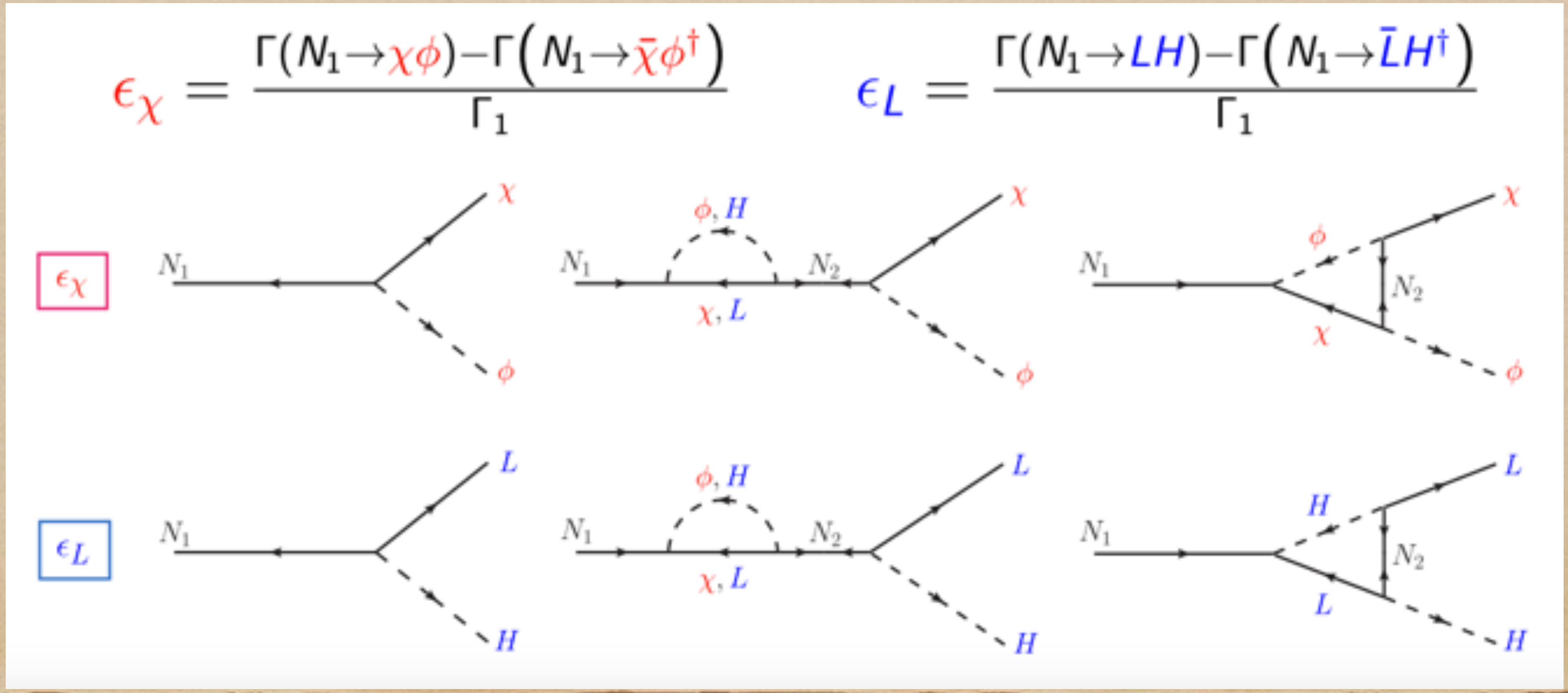
- The same right handed neutrinos also generate light neutrino masses through Type I seesaw mechanism $-M_\nu = M_D M_N^{-1} M_D^T, M_D = Y\langle H\rangle$

Type I Seesaw Leptogenesis & ADM

- Type I seesaw with ADM (Falkowski et al 2011).

$$-\mathcal{L} \supset \frac{1}{2}M_i N_i^2 + y_i N_i l h + \lambda_i N_i \chi \phi + h.c.$$

- Right handed neutrinos can decay into both SM and DM sectors generating asymmetry simultaneously.



Type I Seesaw Leptogenesis & ADM

- The asymmetries can be calculated to be

$$\epsilon_\chi \simeq \frac{M_1}{M_2}\frac{1}{16\pi(y_1^2+\lambda_1^2)}\left(2\lambda_1^2|\lambda_2|^2\sin\left(2\phi_\chi\right)+y_1y_2\lambda_1|\lambda_2|\sin\left(\phi_l+\phi_\chi\right)\right) ,$$

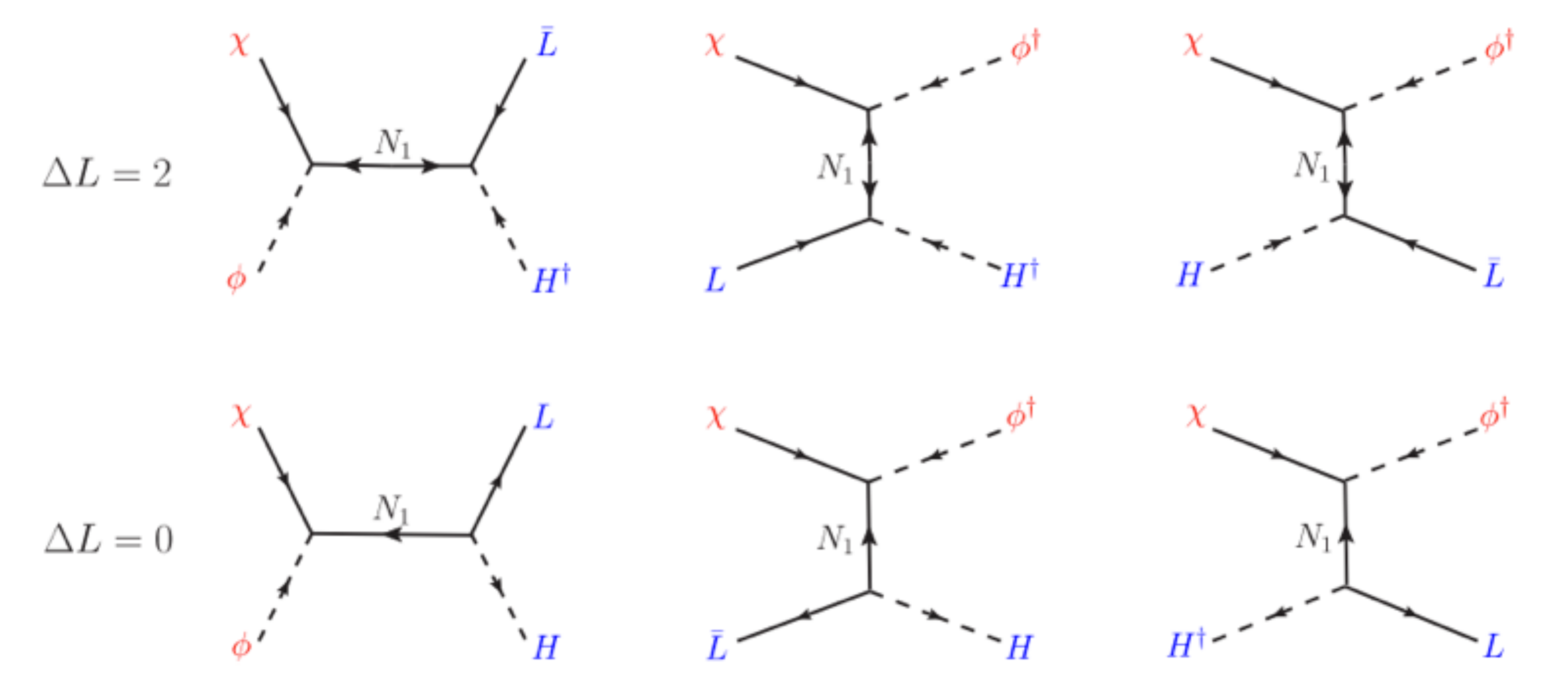
$$\epsilon_l \simeq \frac{M_1}{M_2}\frac{1}{16\pi(y_1^2+\lambda_1^2)}\left(2y_1^2|y_2|^2\sin\left(2\phi_l\right)+y_1y_2\lambda_1|\lambda_2|\sin\left(\phi_l+\phi_\chi\right)\right) .$$

- Depending on the Yukawa couplings relating the right handed neutrinos to SM & DM sectors, the asymmetry generated can be similar or very different.

$$\frac{\epsilon_l}{\epsilon_\chi} \simeq \frac{2r\sin(2\phi_l)+\sin(\phi_l+\phi_\chi)}{2r^{-1}\sin(2\phi_\chi)+\sin(\phi_l+\phi_\chi)} , \qquad r=\frac{y_1|y_2|}{\lambda_1|\lambda_2|} .$$

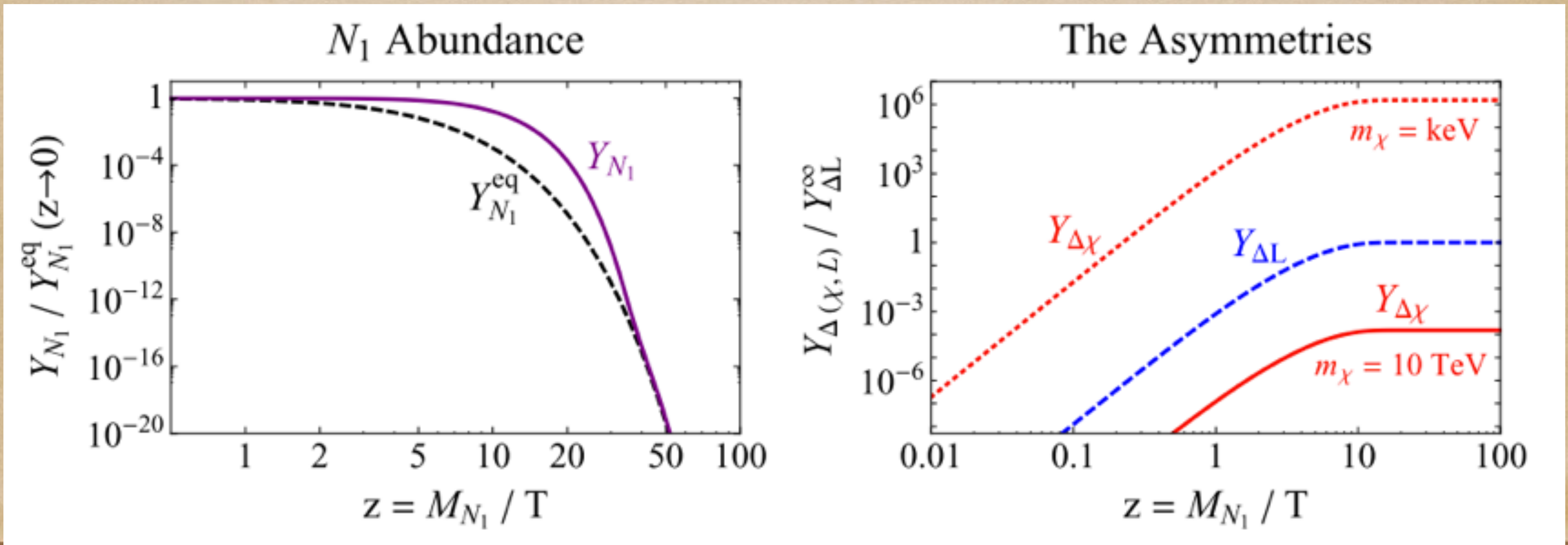
Boltzmann Equations: Type I Lepto+ADM

$$
\begin{aligned}
\frac{sH_1}{z} Y'_{N_1} &= -\gamma_D \left(\frac{Y_{N_1}}{Y_N^{\rm eq}} - 1 \right) + (2 \leftrightarrow 2)\,, \\
\frac{sH_1}{z} Y'_{\Delta\chi} &= \gamma_D \left[\epsilon_\chi \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1 \right) - \frac{Y_{\Delta\chi}}{2Y_\chi^{\rm eq}} \,{\rm Br}_\chi \right] + (2 \leftrightarrow 2 \text{ washout} + \text{transfer})\,, \\
\frac{sH_1}{z} Y'_{\Delta l} &= \gamma_D \left[\epsilon_l \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1 \right) - \frac{Y_{\Delta l}}{2Y_l^{\rm eq}} \,{\rm Br}_l \right] + (2 \leftrightarrow 2 \text{ washout} + \text{transfer})\,.
\end{aligned}
$$



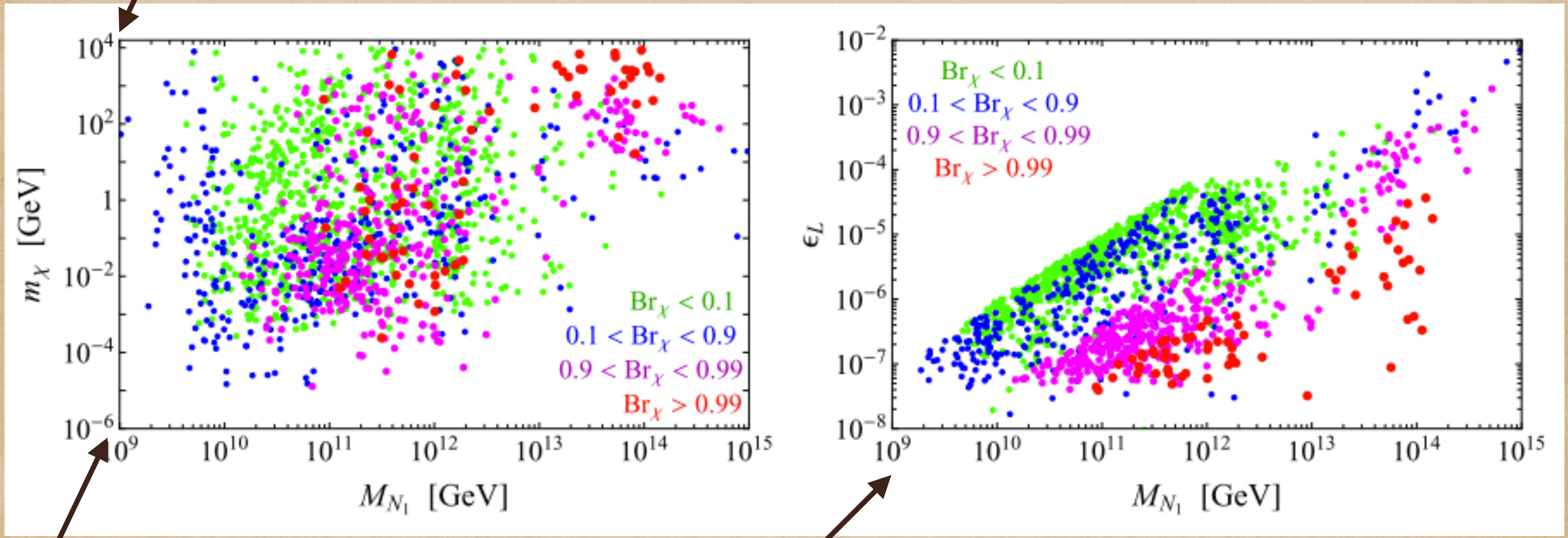
Weak Wash-out & Narrow Width Regime

- In this regime $\Gamma_{N_1} \mathrm{Br}_{l,\chi}/H \ll 1, \Gamma_{N_1} \ll M_{N_1}$
- Assuming initial condition $Y_{N_1} = Y_{N_1}^{\mathrm{eq}}$ the final asymmetries are $Y_{\Delta x}^{\infty} = \epsilon_x Y_{N_1}^{\mathrm{eq}}(0)$. Final Asymmetries are determined just by decay asymmetries $\frac{Y_{\Delta L}^{\infty}}{Y_{\Delta \chi}^{\infty}} \approx \frac{\epsilon_L}{\epsilon_\chi} \approx \frac{y_1 y_2}{\lambda_1 \lambda_2}$



Parameter Scan

Upper Limit from requirement of sufficient annihilation of symmetric part

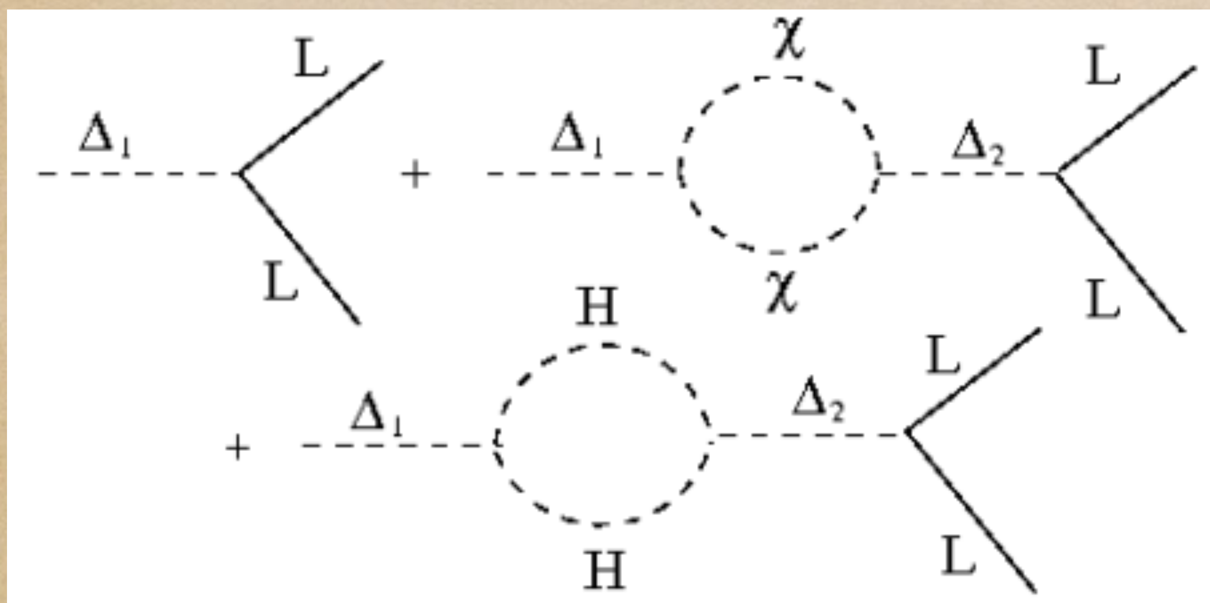


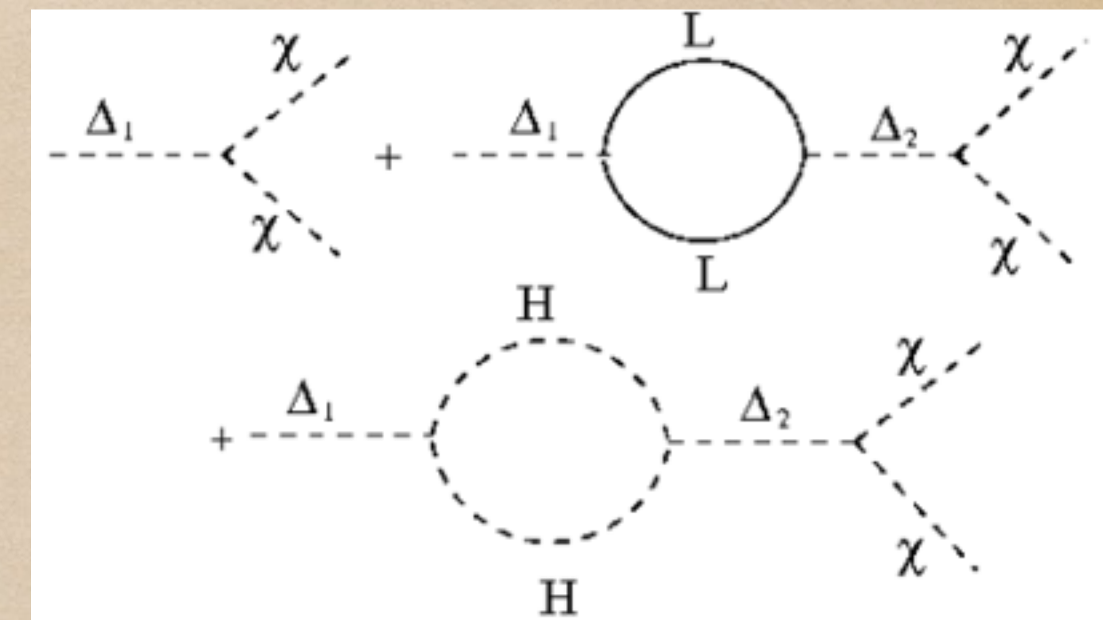
Lower limit from perturbativity of decay asymmetry

Similar to Davidson Ibarra bound in leptogenesis with hierarchical N's

Type II Seesaw Leptogenesis + ADM

Arina & Sahu 2011





$$\epsilon_L = \frac{\mathrm{Im}\left(\mu_{1\chi}\mu_{2\chi}^*\left[1+\frac{\mu_{1H}\mu_{2H}^*}{\mu_{1\chi}\mu_{2\chi}^*}\right]\sum_{\alpha\beta} f_{1\alpha\beta}f_{2\alpha\beta}^*\right)}{8\pi^2(M_2^2-M_1^2)}\left[\frac{M_1}{\Gamma_1}\right],$$

$$\epsilon_\chi = \frac{\mathrm{Im}\left(\mu_{1\chi}\mu_{2\chi}^*\left[\frac{\mu_{1H}\mu_{2H}^*}{M_1^2}+\sum_{\alpha\beta} f_{1\alpha\beta}f_{2\alpha\beta}^*\right]\right)}{8\pi^2(M_2^2-M_1^2)}\left[\frac{M_1}{\Gamma_1}\right],$$

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{1}{\mathcal{S}_{\rm DM}}\frac{m_{\rm DM}}{m_p}\frac{\epsilon_{\rm DM}}{\epsilon_L}\frac{\eta_{\rm DM}}{\eta_L}$$

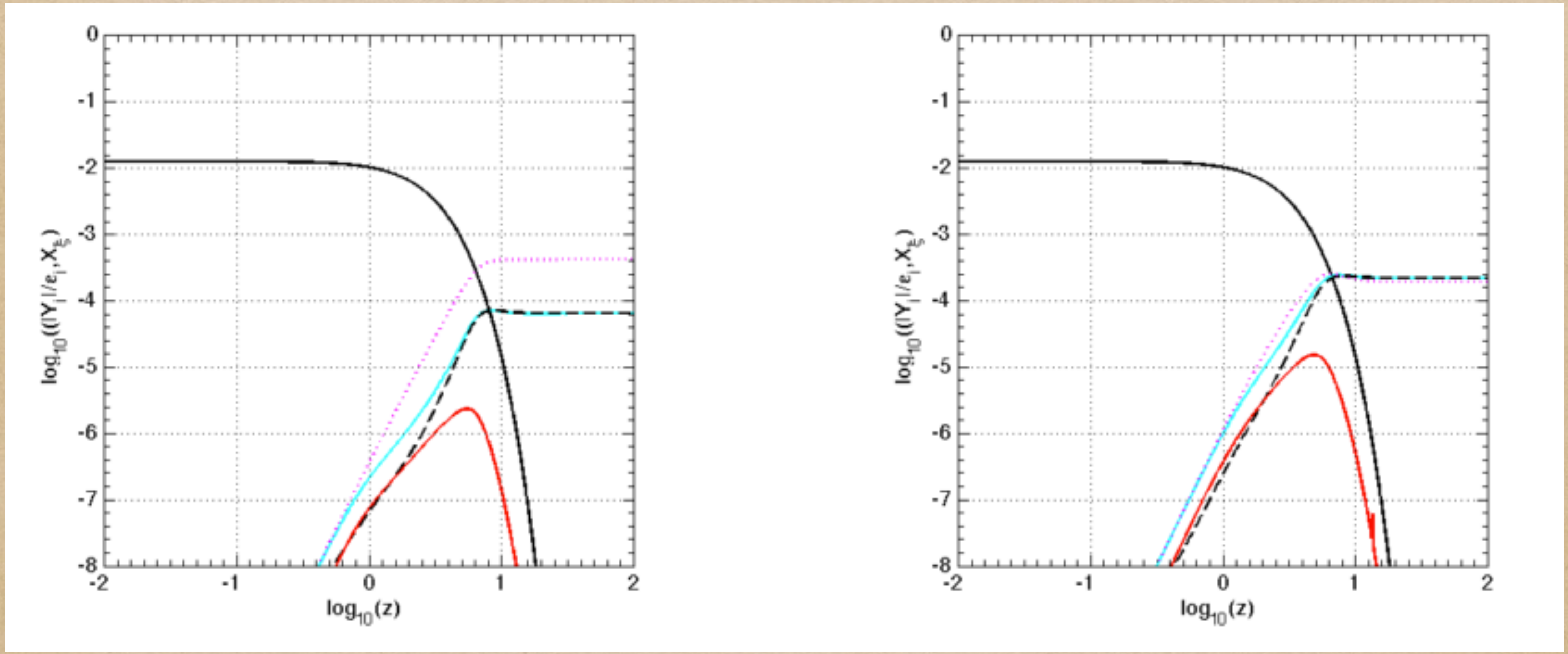
Sphaleron conversion factor

$$Y_B = -\mathcal{S}_{DM} Y_L$$

Type II Seesaw Leptogenesis + ADM

Arina & Sahu 2011

Yield for leptons (cyan solid), DM (dotted magneta), Higgs (dashed black), Δasymmetry (solid red), Δ abundance (black solid)



$m_{DM} = 86 \text{ GeV}, \epsilon_L = 2.6 \times 10^{-6}$

$\epsilon_{DM} = 1.1 \times 10^{-8}, r \equiv \dfrac{\Omega_{DM}}{\Omega_b} = 4.75$

$m_{DM} = 2 \text{ TeV}, \epsilon_L = 7 \times 10^{-7}$

$\epsilon_{DM} = 1.2 \times 10^{-9}, r \equiv \dfrac{\Omega_{DM}}{\Omega_b} = 5.4$

Comments (ADM)

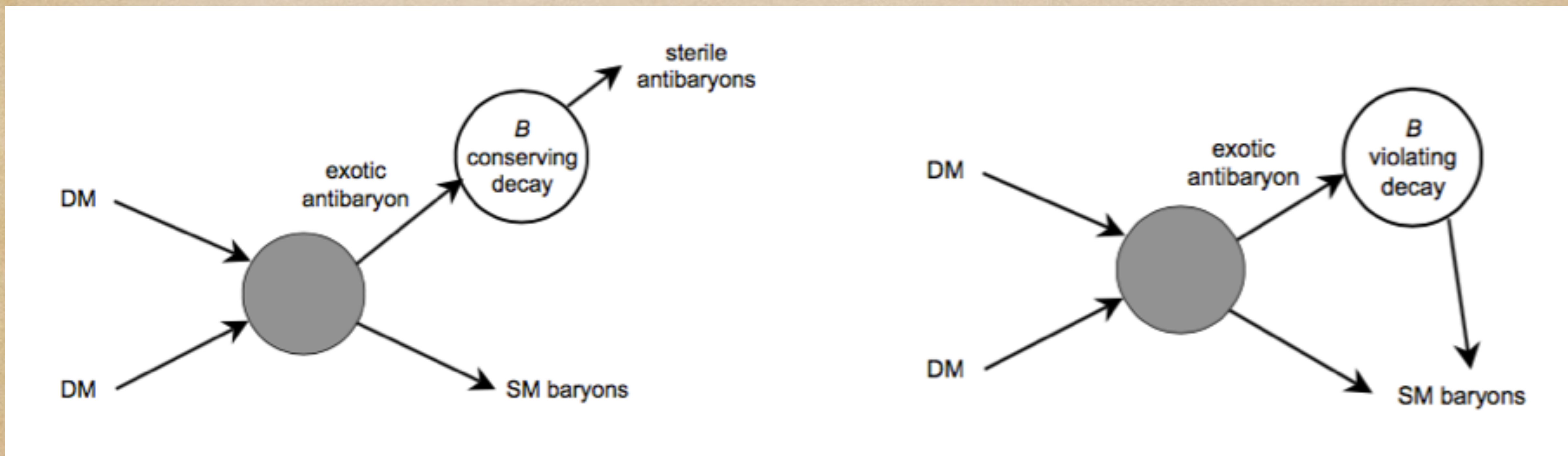
- Apart from decay, cogenesis can occur through Affleck-Dine mechanisms (1105.4612).
- Electroweak baryogenesis: sphalerons can couple to both SM & DM (Barr 1992, 0909.2034). (Tight precision constraints on chiral extensions of SM).
- Darkogenesis: Dark sphalerons generate asymmetry in the dark sector 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

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

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 followingquantity 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.

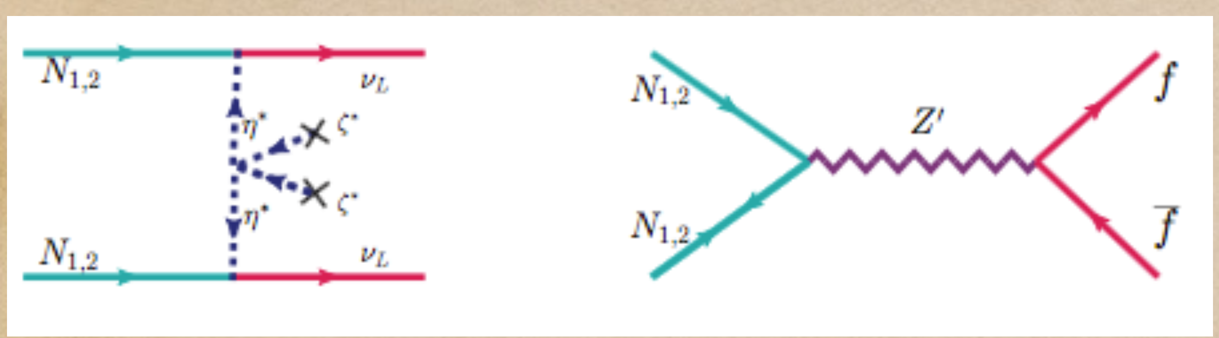
TeV Scale WIMPy Leptogenesis

Dasgupta, Hati, Patra & Sarkar 2016

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{3}, \mathbf{2}, \ 1/6)$	$1/3$
	u_R	$(\mathbf{3}, \mathbf{1}, \ 2/3)$	$1/3$
	d_R	$(\mathbf{3}, \mathbf{1}, \ -1/3)$	$1/3$
	$\ell_L \equiv (\nu, \ e)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	-1
	e_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	-1
	N_1	$(\mathbf{1}, \mathbf{1}, \ 0)$	-4
	N_2	$(\mathbf{1}, \mathbf{1}, \ 0)$	-4
	N_3	$(\mathbf{1}, \mathbf{1}, \ 0)$	5
Scalars	H	$(\mathbf{1}, \mathbf{2}, \ 1/2)$	0
	η	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	3
	ζ	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	3
	χ	$(\mathbf{1}, \mathbf{1}, \ 0)$	8
	ξ	$(\mathbf{1}, \mathbf{1}, \ 0)$	-1

$$\mathcal{L} = y_u \overline{q_L} \widetilde{H} u_R + y_d \overline{q_L} H \, d_R + y_e \overline{\ell_L} H e_R + y_\nu \overline{\ell_L} \eta \, N_{1,2} + \sum_{\alpha,\beta=1,2} h_{\alpha\beta} \overline{N_\alpha^c} \chi N_\beta + \sum_{\alpha,\beta=1,2} h_{3\alpha} \xi \overline{N_\alpha^c} N_3 . \quad (3)$$

$$V(H, \eta, \zeta, \chi, \xi) = \sum_{X=H,\eta,\xi} \left[\mu_X^2 |X|^2 + \lambda_X |X|^4 \right] + \sum_{\substack{X \neq Y \\ X,Y=H,\eta,\zeta,\chi,\xi}} \lambda_{XY} |X|^2 |Y|^2 - \left[\lambda'' (\zeta^\dagger \eta)^2 + \text{h.c.} \right] .$$

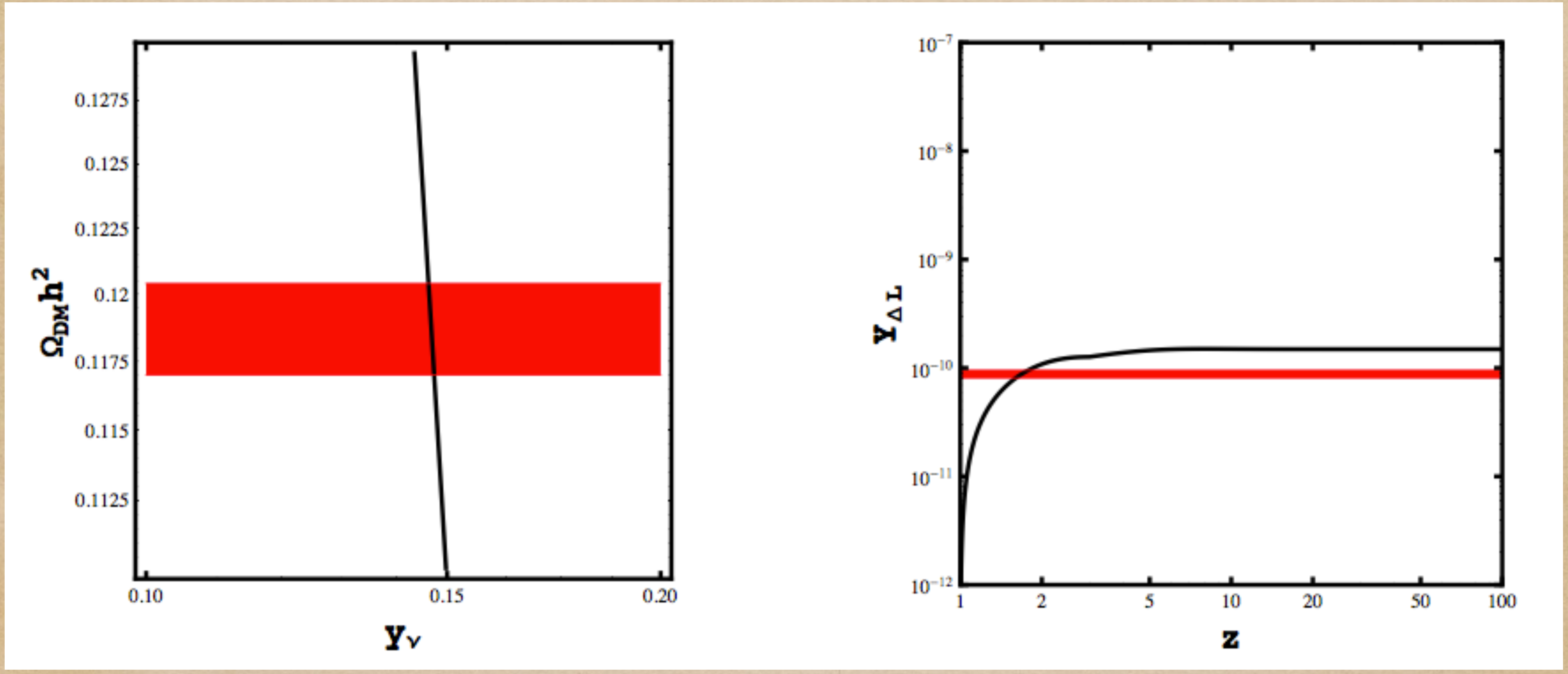


$$zH(z)s(z) \frac{dY_{DM}}{dz} = -(\gamma^{CPV} + \gamma^{CPC}) \left(\frac{Y_{DM}^2}{(Y_{DM}^{eq})^2} - 1 \right)$$

$$zH(z)s(z) \frac{dY_{\Delta L}}{dz} = (\varepsilon \gamma^{CPV}) \left(\frac{Y_{DM}^2}{(Y_{DM}^{eq})^2} - 1 \right), \\ - \gamma^{CPC} \left(\frac{Y_{DM}^2}{(Y_{DM}^{eq})^2} - 1 \right) - \frac{Y_{\Delta L} Y_{DM}}{Y_{\Delta L}^{eq} Y_{DM}^{eq}} \gamma_{WO},$$

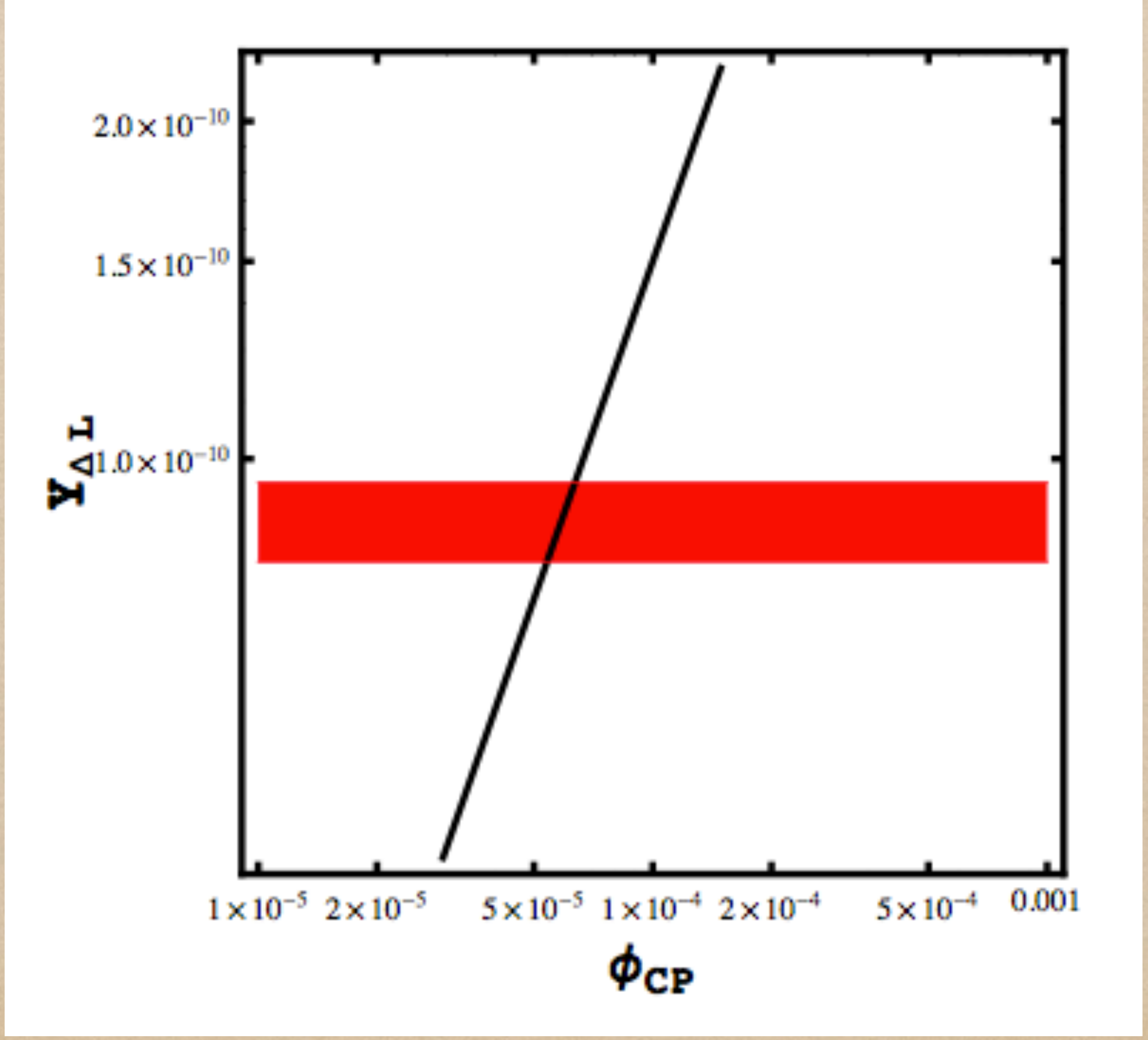
TeV Scale WIMPy Leptogenesis

Dasgupta, Hati, Patra & Sarkar 2016



TeV Scale WIMPy Leptogenesis

Dasgupta, Hati, Patra & Sarkar 2016



Other Scenarios

- There are models where DM is neither asymmetric nor its annihilations lead to baryon asymmetry.
- However, the presence of DM can play a role in generating neutrino mass and baryogenesis.
- Or, the presence of a seesaw mechanism for neutrino mass also can generate DM and baryon asymmetry.
- Scotogenic model, Dirac neutrino mass model, B violating models, DM assisted EW Baryogengesis are a few of such frameworks where this can happen.
- There are other scenarios too which can address these three problems simultaneously.

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 particle, if EM neutral is a DM candidate.
- Scalar DM resembles inert doublet DM (hep-ph/0603188, 0512090, 0612275, 1404.5261).
- Lightest RHN DM (1710.03824)

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

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

- Connection to Vacuum Stability (1501.03700, 1503.03085).
- Lepton portal limit (1703.08674).
- Thermal and Non-thermal source of IDM (1706.05034).
- Lightest RHN decay as a source of leptogenesis (1207.2594, 1308.1840).

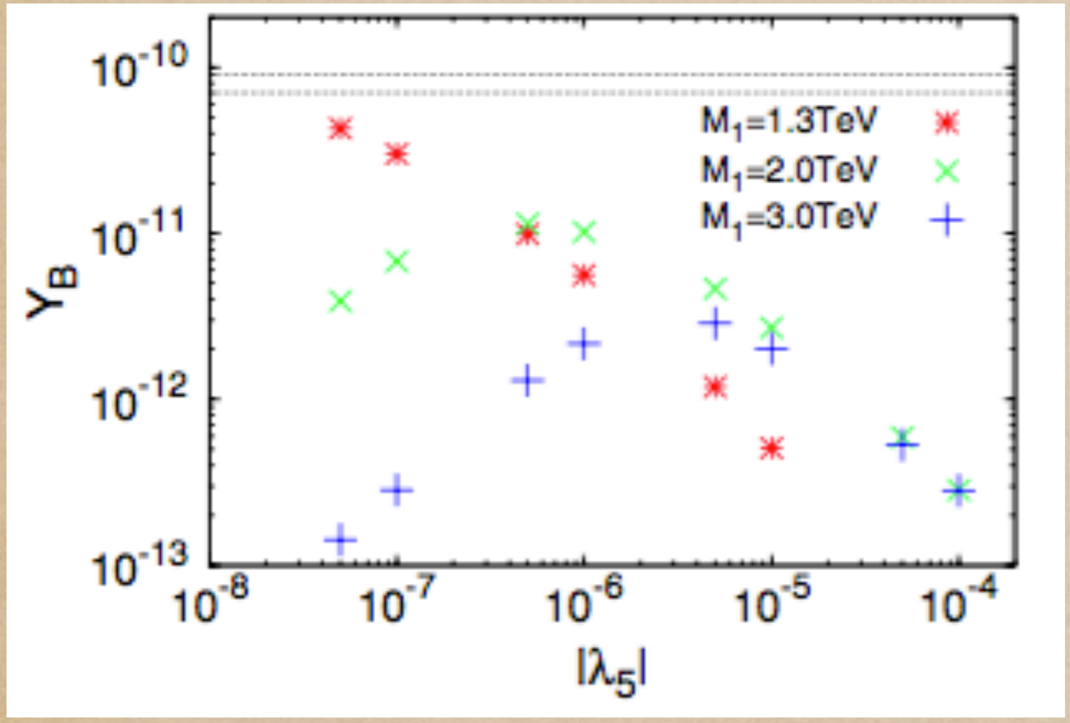
Leptogenesis in Scotogenic Model

1207.2594

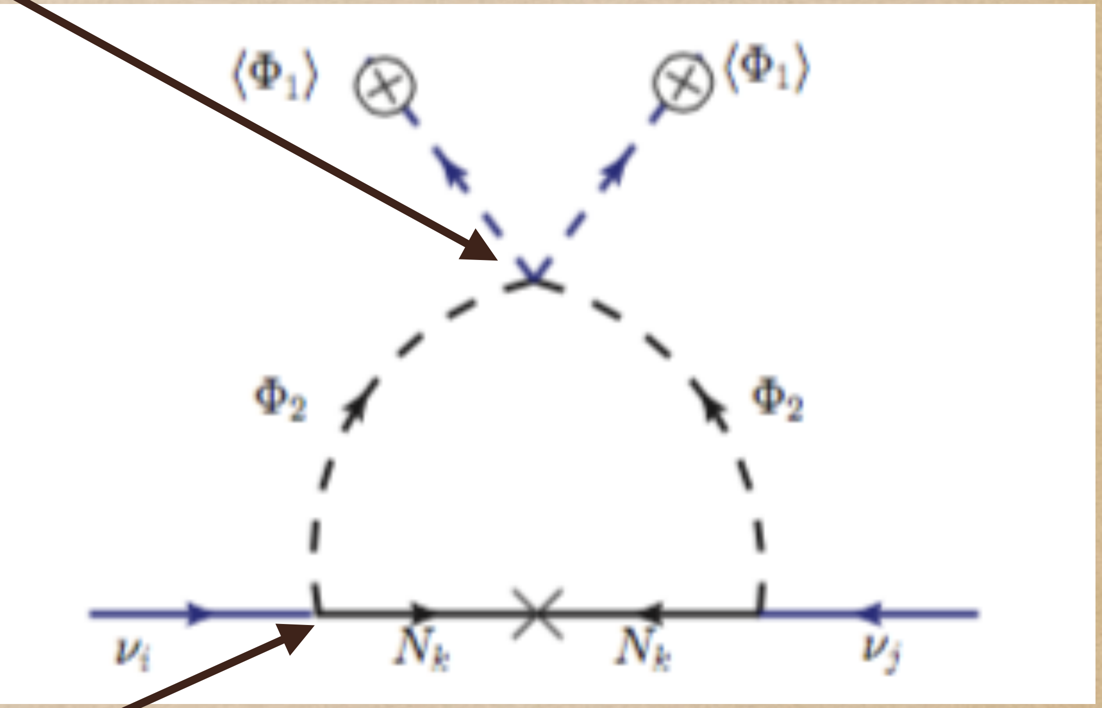
$$\varepsilon = \frac{1}{16\pi[\frac{3}{4} + \frac{1}{4}(1 - \frac{M_\eta^2}{M_1^2})^2]} \sum_{i=2,3} \frac{\mathrm{Im}[(\sum_{k=e,\mu,\tau} h_{k1} h_{ki}^*)^2]}{\sum_{k=e,\mu,\tau} h_{k1} h_{k1}^*} \times G\left(\frac{M_i^2}{M_1^2}, \frac{M_\eta^2}{M_1^2}\right)$$

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

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



λ_5



h_{ik}

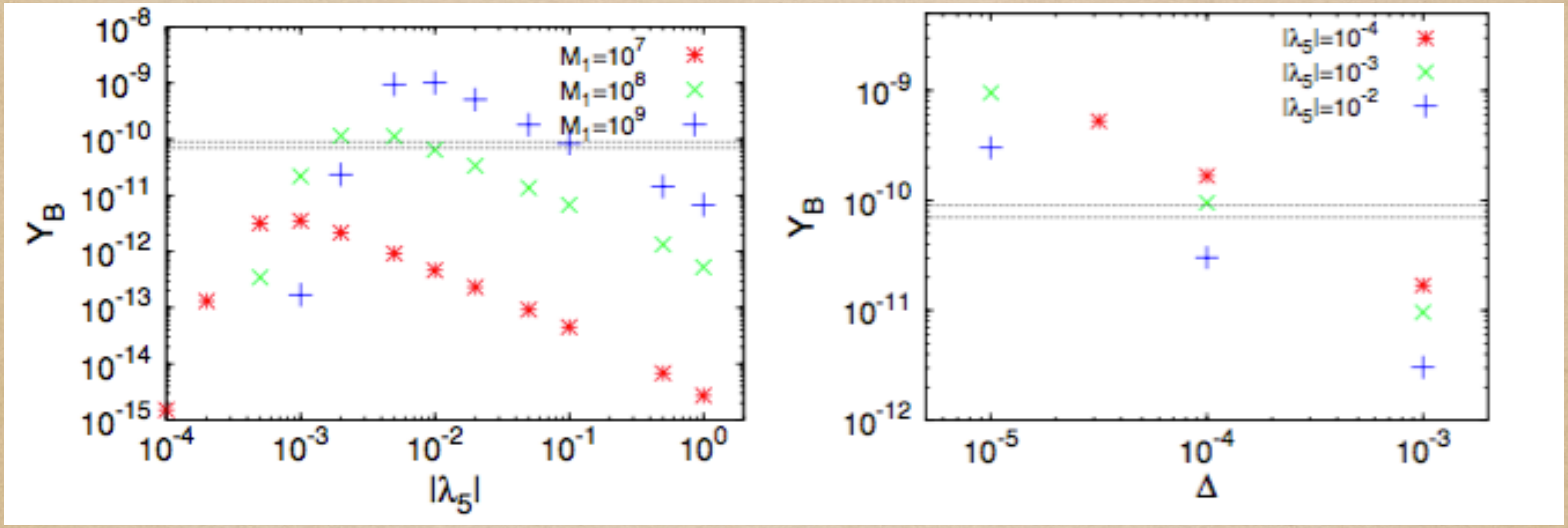
Leptogenesis in Scotogenic Model

1207.2594

- 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.
- Resonant leptogenesis can work (Pilaftsis 1997, B Dev et al 2013).

Resonant Leptogenesis in Scotogenic Model

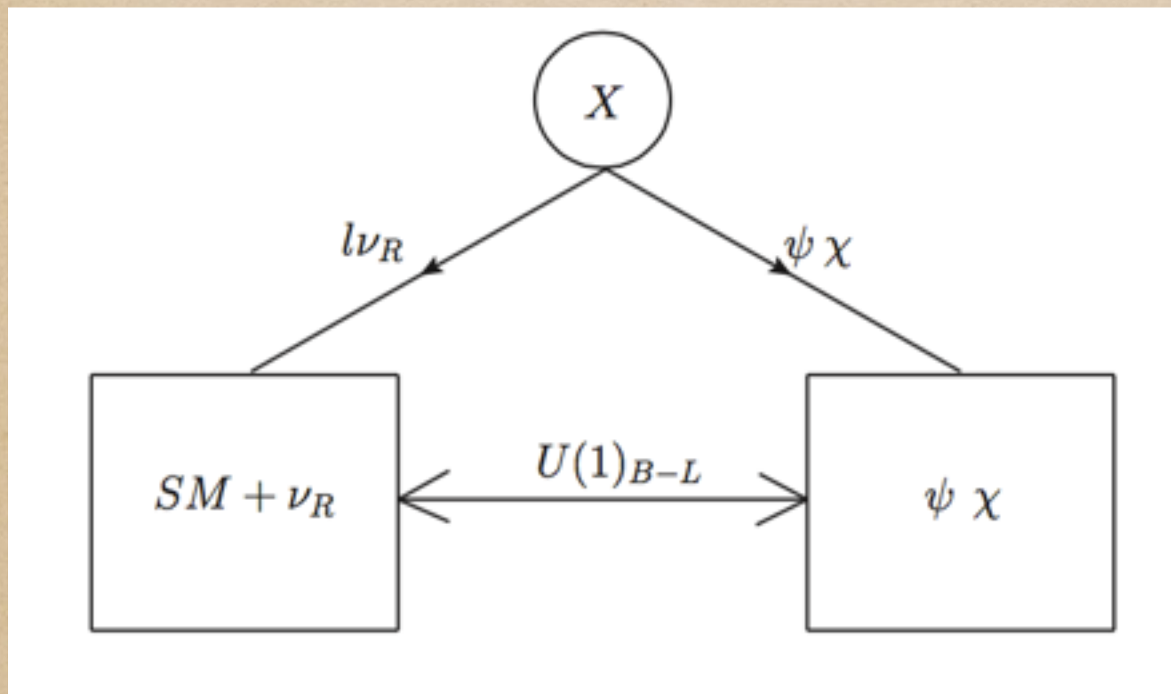
1207.2594



- Lightest RHN mass more than 80 TeV cam give successful leptogenesis (non-degenerate RHN) (1308.1840).
- TeV scale leptogenesis (non-resonant) is possible if lightest RHN has some initial abundance on top of its equilibrium value (1308.1840).
- Scotogenic Dirac Leptogenesis is also possible (1608.03872).

DM Assisted Dirac Leptogenesis

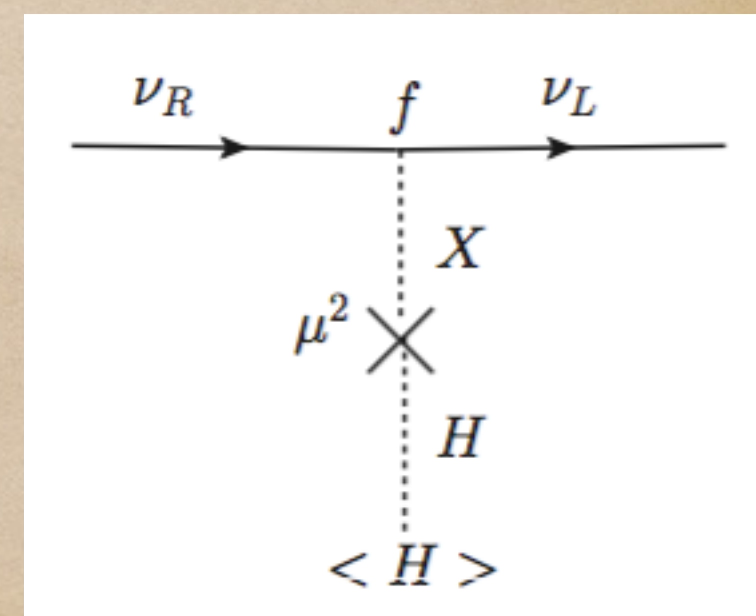
N Sahu et al; 1712.02960

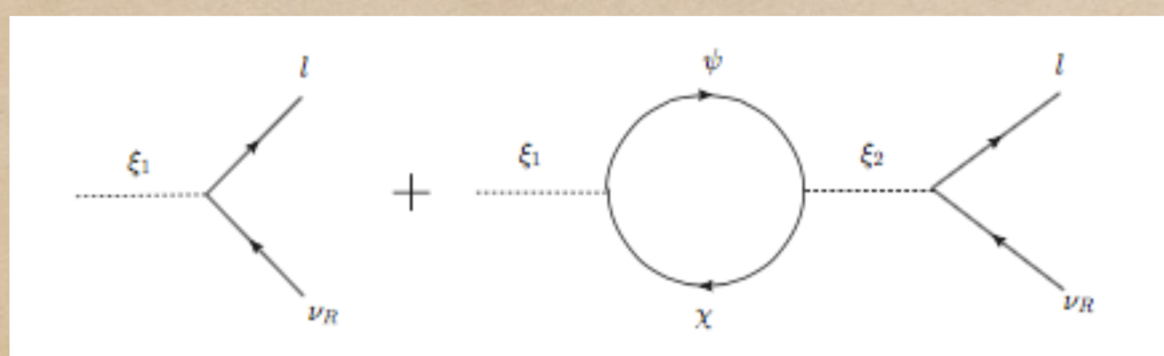


Parameter	$U(1)_{B-L}$	$U(1)_D$	Z_2
$X=(X^+,X^0)^T$	0	0	-
ν_R	-1	0	-
$\psi=(\psi^0,\psi^-)^T$	-1	1	+
χ	-1	1	-

$$\mathcal{L}_{soft} = -\mu^2 H^\dagger X + \text{h.c.}$$

- High scale leptogenesis. Two copies of X required.





DM Assisted Dirac Leptogenesis

N Sahu et al; 1712.02960

- CP Violating decay of mother particle creates an equal and opposite amount of asymmetry in left and right sector fermions in the exact B-L symmetry limit.
- These CP asymmetries don't equilibrate due to smallness of neutrino Dirac mass. The left-sector asymmetry then gets converted into Baryon asymmetry through sphalerons (Dick, Lindner, Ratz & Wright 2000).
- In the model presented in 1712.02960, the asymmetry in dark sector fermion does not survive due to soft symmetry breaking interactions.
- The symmetric part of DM survives due to smallness of dark gauge interactions.
- In the non-thermal limit, the DM can be produced from the decay of the scalar.

TeV Scale Baryogenesis & DM

Allahverdi, Dev & Dutta; 1712.02713

- B-violating interactions through TeV scale color triplet scalars X (Y=4/3) & singlet Majorana fermion (DM) that coupled only to RH quarks.

$$\mathcal{L} \supset \left(\lambda_{\alpha i} X^{*}_{\alpha} \psi u^{c}_{i} + \lambda'_{\alpha i j} X_{\alpha} d^{c}_{i} d^{c}_{j} + \frac{m_{\psi}}{2} \bar{\psi}^{c} \psi + \text{H.c.}\right) + m^{2}_{X_{\alpha}} |X_{\alpha}|^{2} + (\text{kinetic terms}) .$$

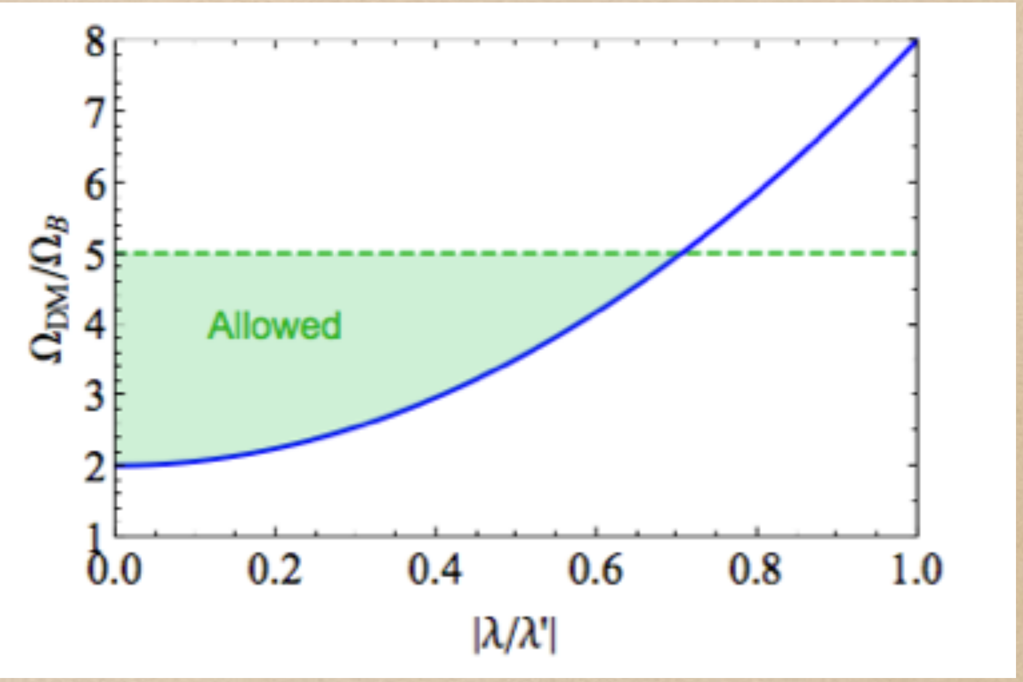
- These interactions can lead to DM decay $\psi \to p + e^{-} + \bar{\nu}_{e}$ as well proton decay $p \to \psi + e^{+} + \nu_{e}$, both of which can be avoided for this mass window $m_{p} - m_{e} \leq m_{\psi} \leq m_{p} + m_{e}$

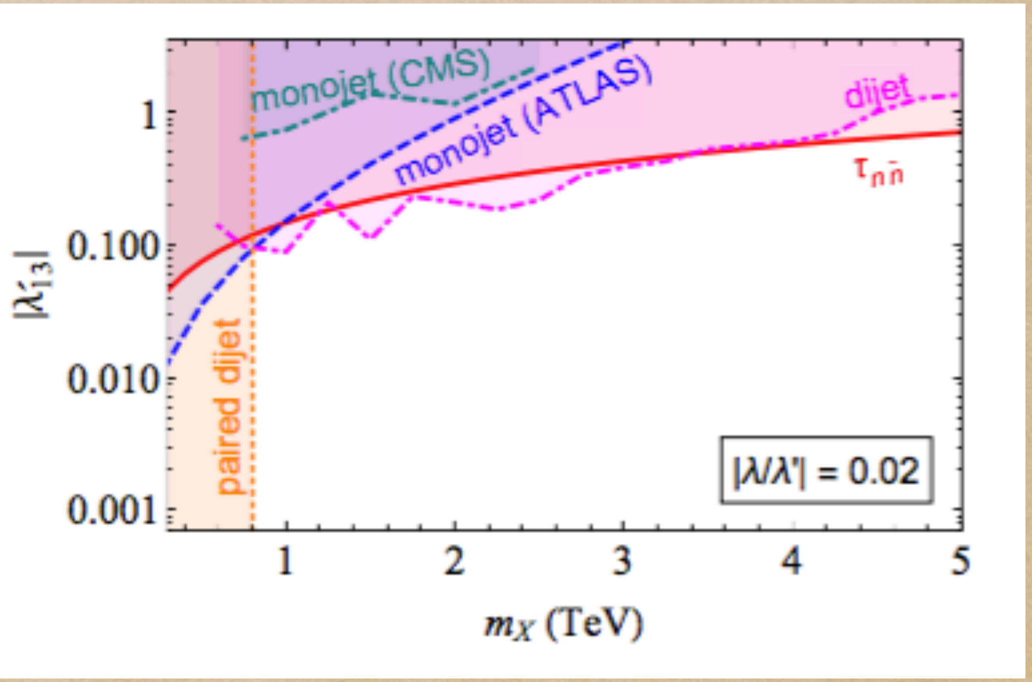
- Late time decay of moduli to X and DM, then then X giving rise to baryon asymmetry finally decides the DM-Baryon coincidence.

TeV Scale Baryogenesis & DM

Allahverdi, Dev & Dutta; 1712.02713

- Since the asymmetry is generated directly in the Baryon sector, it can happen well below the sphaleron temperature: post-sphaleron baryogengesis (Babu, Mohapatra & Nasri 2006).
- The model also predicts observable neutron-antineutron oscillations & monojet signal at the LHC.





Conclusion

- There are different scenarions (ADM, WIMPy, Others) that can relate DM with baryon asymmetry.
- The exact relation (strong/weak) depends upon the particular scenario or the model implementation.
- Such scenarios 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.

Future Outlook

- Low scale cogenesis that evades Davidson-Ibarra bounds and does not require unnatural fine-tuned mass splitting between masses of RNH (or decaying particle).
- Production of DM and lepton asymmetry from a common decay. Less free parameters.
- Connection to Inflaton?
- Effects of CPT Violation and connection to flavour physics.
- Post-sphaleron baryogenesis and DM?
- Cogenesis through oscillation (ARS Mechanism)?
- What if DM is an artefact of modified gravity and baryon asymmetry is just an initial condition (1606.05344)?