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Linking Asymmetric Dark Matter and Leptogenesis

A Testable Framework for Neutrino Mass and the Matter-Antimatter Asymmetry

Henry McKenna, Juri Smirnov, Martin Gorbahn

Research Questions

1. Is it possible to break the Davidson Ibarra bound (10^9 GeV) from Asymmetric Dark Matter with Leptogenesis?

2. If so, how low can this bound go?

3. Can it be tested?

Three major problems in physics

- Dark Matter

- Baryon asymmetry of the Universe

  Observations such as Baryon to photon ratio show imbalance between Baryonic matter and anti-matter.

  $$\eta_B = \frac{n_B}{n_\gamma} = (6.19 \pm 0.15) \times 10^{-10}$$ [1]

  but..............SM processes generate an equal amount of matter and antimatter.

- Neutrino mass

  In SM - neutrinos are massless.

  but........observations of neutrino oscillation - neutrinos must have mass.

[1] Nakamura R et al. Int J of Mod Phys E. 2017;26:1741003.

Baryogenesis

It is unknown why there is no anti-matter in the observable universe

Needs physics beyond the Standard Model.

Baryogenesis is the process in early dynamic universe producing baryon asymmetry

Sakharov (1967) stated the following conditions:

- Baryon number (B) must be violated
- Charge (C) and Charge-Parity (CP) symmetry must be violated
- There must be departure from thermal equilibrium.

Leptogenesis

- See-Saw type I mechanism generates neutrino mass
- Lepton number is violated – extension to SM
- Generation of an asymmetry in the lepton sector
- Transferred to the Baryon sector - Sphaleron process.
- Sphalerons violate Baryon number (B) and Lepton number (L) but conserve $B-L$.

Seesaw mechanism

- Type I See-Saw mechanism

$$\mathcal{L}_{seesaw\ mass} = (\nu_L^T N_R^T) \begin{pmatrix} 0 & \lambda v_H \\ \lambda v_H & M_{N,R} \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

- From seesaw – constraints on mass is $m_{\nu,L} \simeq \frac{(\lambda v)^2}{m_{\nu,R}}$

- $m_{\nu,L}$ is fixed to small range, v is fixed, $m_{\nu,R} \propto \lambda^2$

- Dirac mass is given by $m_D = \lambda v$

Constraints on mass and coupling

- See-Saw Type I Leptogenesis achievable but constrained
- To generate the correct asymmetry - needs a large value of λ.
- As light left neutrino's mass is fixed – requires $m_{\nu,R} \propto \lambda^2$
- Increasing λ^2 requires $m_{\nu,R}$ to be increased

Constraints on mass and coupling

- From Davidson & Ibarra - lowest bound on heavy neutrino mass required to generate observed asymmetry as 10^9 GeV [2] .

- Large RHN mass contributes to the Electroweak Hierarchy problem

- This tension is alleviated is if RHN mass is $M_{N_1} \lesssim 10^7$ GeV also called the Vessani bound [3]

[2] Davidson S, Ibarra A. Physics Letters B. 2002;535:25-32.

[3] Vissani F. *Physical Review D* 57.11 (1998): 7027.

Asymmetric Dark Matter (ADM)

$$\Omega \equiv \rho/\rho_c$$

$$\Omega_{DM} \simeq 5\Omega_{VM}$$

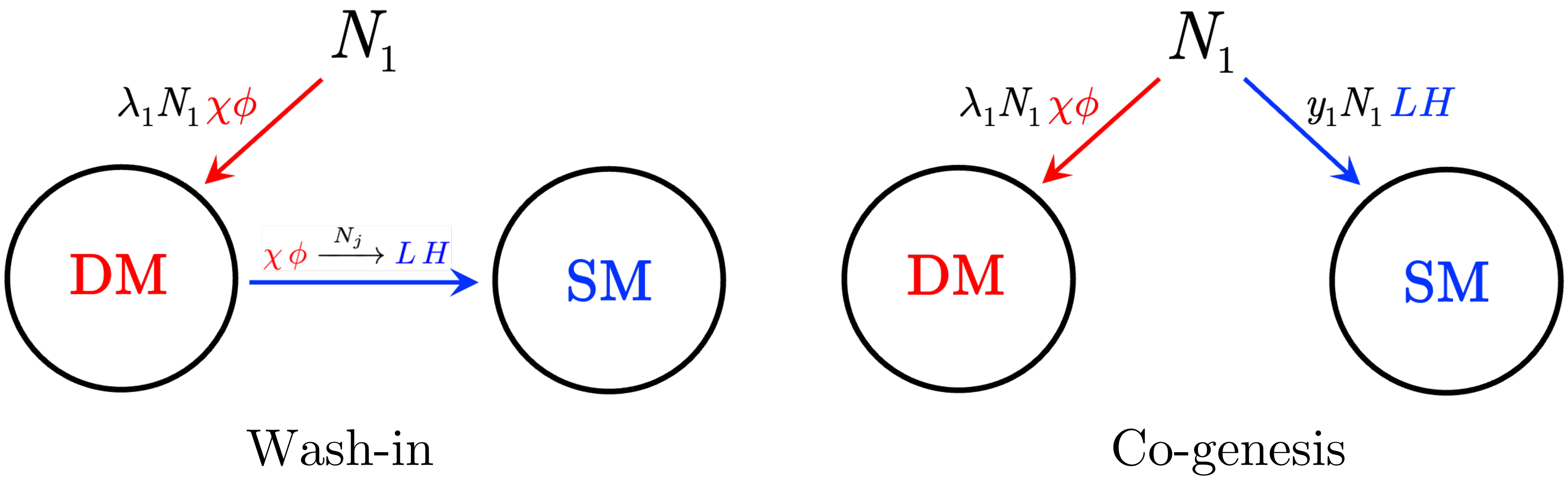
- If dark matter couples the the Standard model (SM) resulting in ADM, then there are two possible connections.
- It could couple to the Baryonic sector or the Leptonic sector.
- Here, the focus is on DM coupling to the Leptonic Sector via Leptogenesis.

Asymmetric dark matter from Leptogenesis

- This Model has been studied by Falkowski, Ruderman, and Volansky (Arxiv 1101.4936)
- Idea is to generate asymmetry in visible sector and Dark sector simultaneously from same mediator or Bridge particle
- Visible sector generated via Standard Leptogenesis with the exception of new dark mediator in loop
- They showed that for $\frac{\Gamma_{N_j}}{\Gamma_{N_1}} \simeq \frac{M_{N_j}}{M_{N_1}}$, then $M_{N_1} \gtrsim 10^9$ GeV, so did not break bound
- Did not explore the case where $\frac{\Gamma_{N_j}}{\Gamma_{N_1}} \gg \frac{M_{N_j}}{M_{N_1}}$
- We explore two scenarios that arise following this assumption

Falkowski, A., Ruderman, J.T., Volansky, T., JHEP; *2011*(5):1-32

Asymmetric dark matter from Leptogenesis



$$-\mathcal{L} \supset \frac{1}{2} M_{N_i} \overline{N_i^c} N_i + \lambda_i N_i \chi\phi + y_{i\alpha} N_i L_\alpha H + h.c.$$

Fields		SU(2)	$U(1)_Y$
Fermions	N_i	1	0
	χ	1	0
	L	2	-1
Scalars	ϕ	1	0
	H	2	1

Falkowski, A., Ruderman, J.T., Volansky, T., JHEP; *2011*(5):1-32

Boltzmann equations

- With the addition of the dark fermion χ and dark scalar ϕ, we now have

$$\frac{dY_{N_1}}{dz} = -z\frac{\Gamma_{N_1}}{H_1}\frac{K_1(z)}{K_2(z)}\left(Y_{N_1} - Y_{N_1}^{eq}\right) + (2 \leftrightarrow 2)$$

$$\frac{dY_{\Delta\chi}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_\chi \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right] - \frac{\Gamma_{N_2}}{H_1}\left[2\mathrm{Br}_\chi^2 I_W(z) Y_{\Delta\chi}\right]$$

$$\frac{dY_{\Delta l}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_l \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right] - \frac{\Gamma_{N_2}}{H_1}\left[\mathrm{Br}_l\mathrm{Br}_\chi I_{T_+}(z)(Y_{\Delta l} + Y_{\Delta\chi}) + \mathrm{Br}_l\mathrm{Br}_\chi I_{T_-}(z)(Y_{\Delta l} - Y_{\Delta\chi})\right]$$

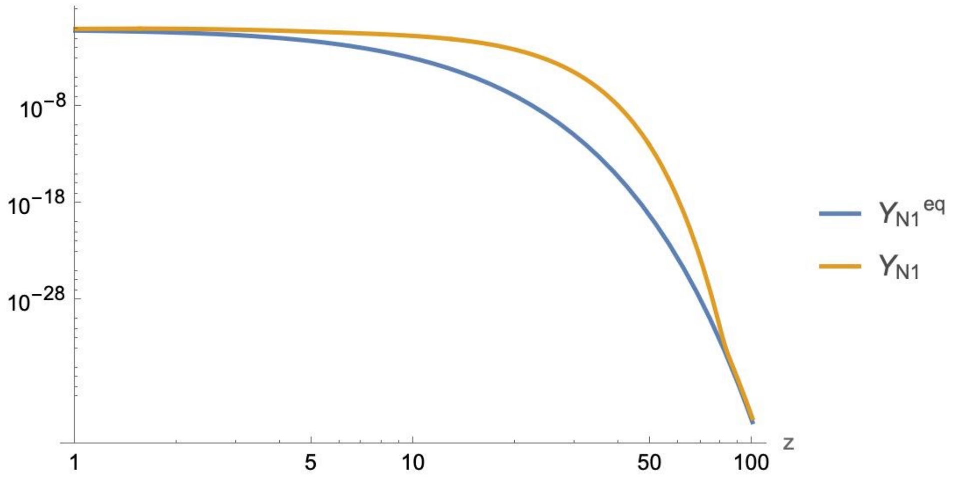
where $K_i(z)$ is the Modified Bessel function of the i$^{\text{th}}$ kind, Br_χ and Br_l are the branching ratios,

- $I_{T+,T\_,W}$ are the thermally averaged cross section excluding couplings, Y_i is the Yield
- Negligible terms have been removed
- Can generate asymmetry in two sectors through lepton portal.

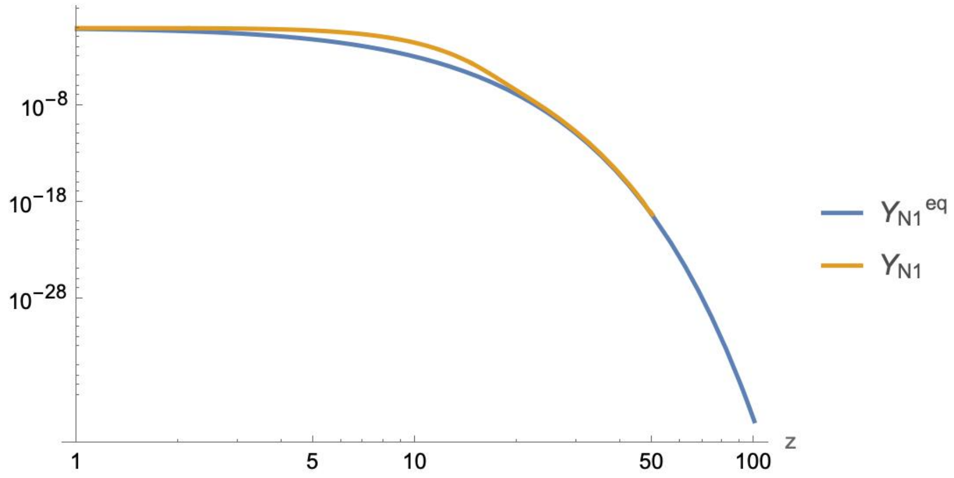
Hierarchical scenario

- If hierarchy present such that (with $\lambda_1 \ll \lambda_2$), N_1 departure from thermal equilibrium can be significant

$$\frac{dY_{N_1}}{dz} = -z\frac{\Gamma_{N_1}}{H_1}\frac{K_1(z)}{K_2(z)}\left(Y_{N_1} - Y_{N_1}^{eq}\right) \qquad \frac{dY_{\Delta a}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_a \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right]$$



Small Couplings: $\frac{\Gamma_{N1}}{H_1} = 0.022$



Large Couplings: $\frac{\Gamma_{N1}}{H_1} = 0.1$

$$\Gamma_{N_1} = \frac{2(y^\dagger y)_{11} + |\lambda_1|^2}{16\pi} M_{N_1}$$

Hierarchical scenario

- If hierarchy present such that (with $\lambda_1 \ll \lambda_2$), N_1 departure there is from thermal equilibrium can be significant

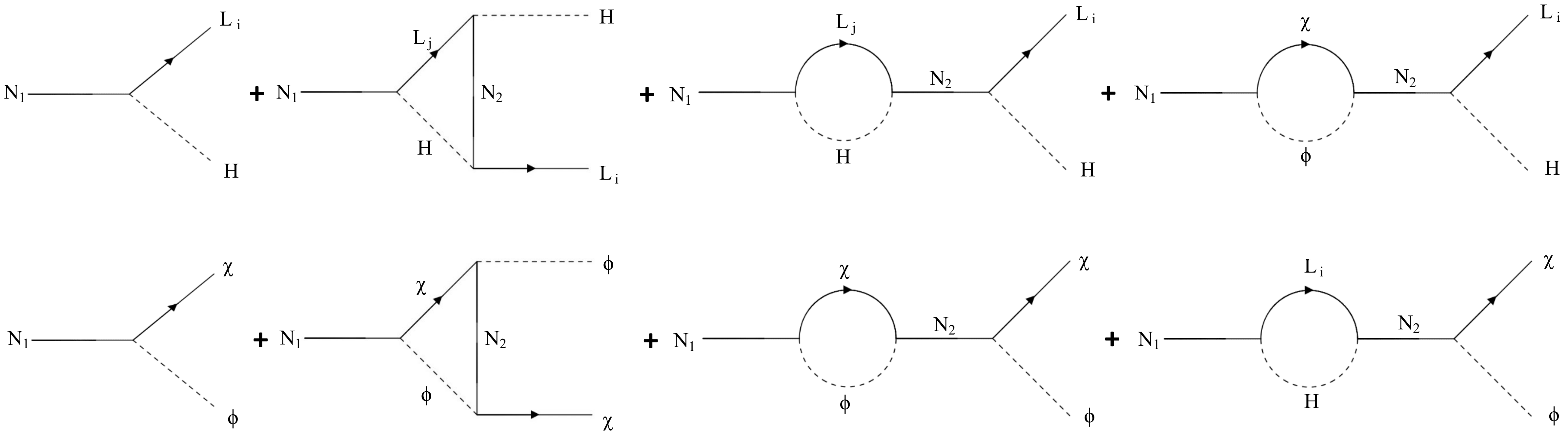
$$\frac{dY_{N_1}}{dz} = -z\frac{\Gamma_{N_1}}{H_1}\frac{K_1(z)}{K_2(z)}\left(Y_{N_1} - Y_{N_1}^{eq}\right) \qquad \frac{dY_{\Delta a}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_a \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right]$$

$$\Gamma_{N_1} = \frac{2\,(y^\dagger y)_{11} + |\lambda_1|^2}{16\pi} M_{N_1}$$

- With $M_{N1} \lesssim M_{N2}$, large λ_2 allows

$$\epsilon_L \simeq \frac{M_1}{M_2}\frac{\text{Im}\left[3(y^\dagger y)_{12}^2 + (y^\dagger y)_{12}\,\lambda_1^* \lambda_2\right]}{8\pi(2\,(y^\dagger y)_{11} + |\lambda_1|^2)} \qquad \epsilon_\chi \simeq \frac{M_1}{M_2}\frac{\text{Im}\left[(\lambda_1^*\lambda_2)^2 + (y^\dagger y)_{12}\,\lambda_1^*\lambda_2\right]}{8\pi(2(y^\dagger y)_{11} + |\lambda_1|^2)}$$

Hierarchical scenario



$$\epsilon_L \simeq \frac{M_1}{M_2} \frac{\mathrm{Im}\left[3(y^\dagger y)_{12}^2 + (y^\dagger y)_{12}\, \lambda_1^* \lambda_2\right]}{8\pi(2\,(y^\dagger y)_{11} + |\lambda_1|^2)}$$

$$\epsilon_\chi \simeq \frac{M_1}{M_2} \frac{\mathrm{Im}\left[(\lambda_1^* \lambda_2)^2 + (y^\dagger y)_{12}\, \lambda_1^* \lambda_2\right]}{8\pi(2(y^\dagger y)_{11} + |\lambda_1|^2)}$$

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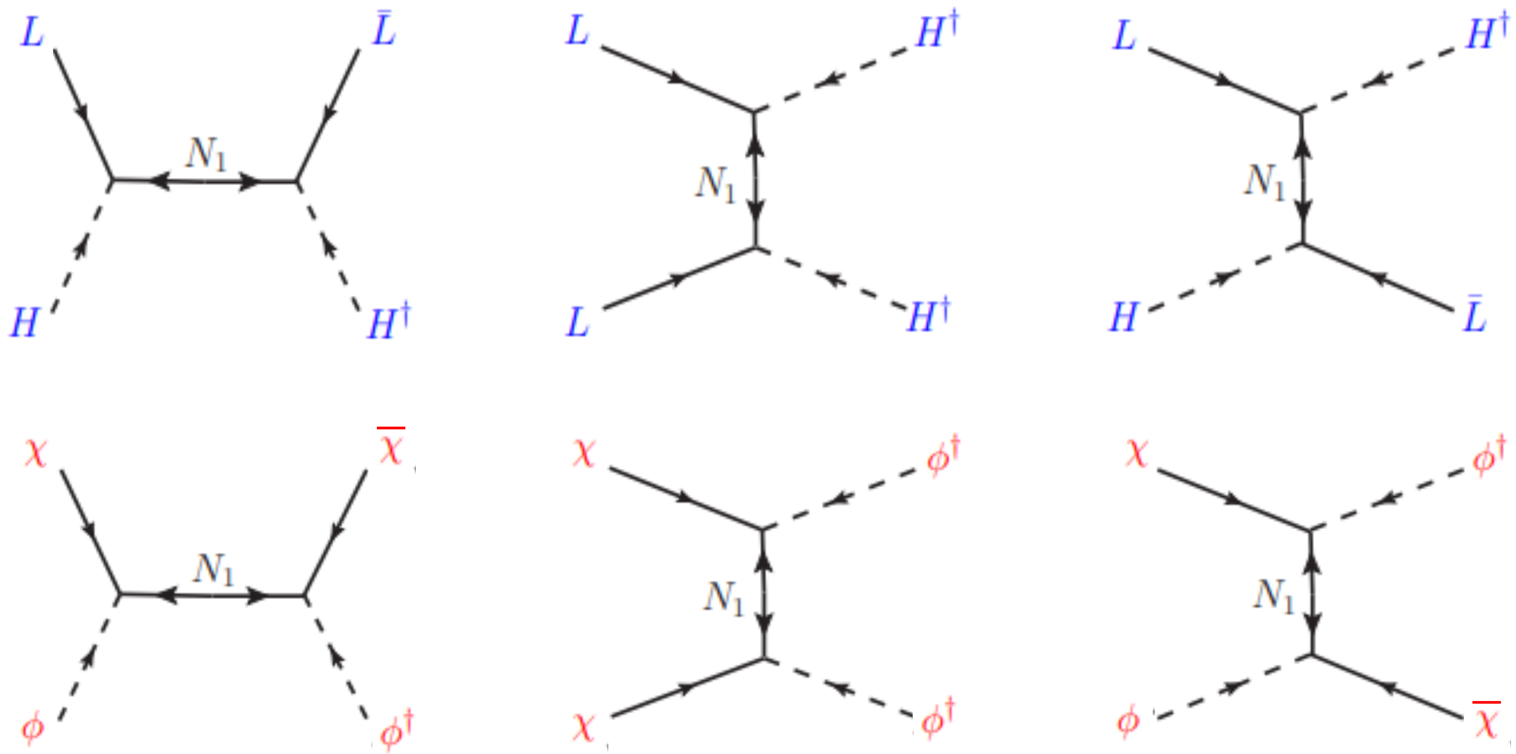
Washout Processes

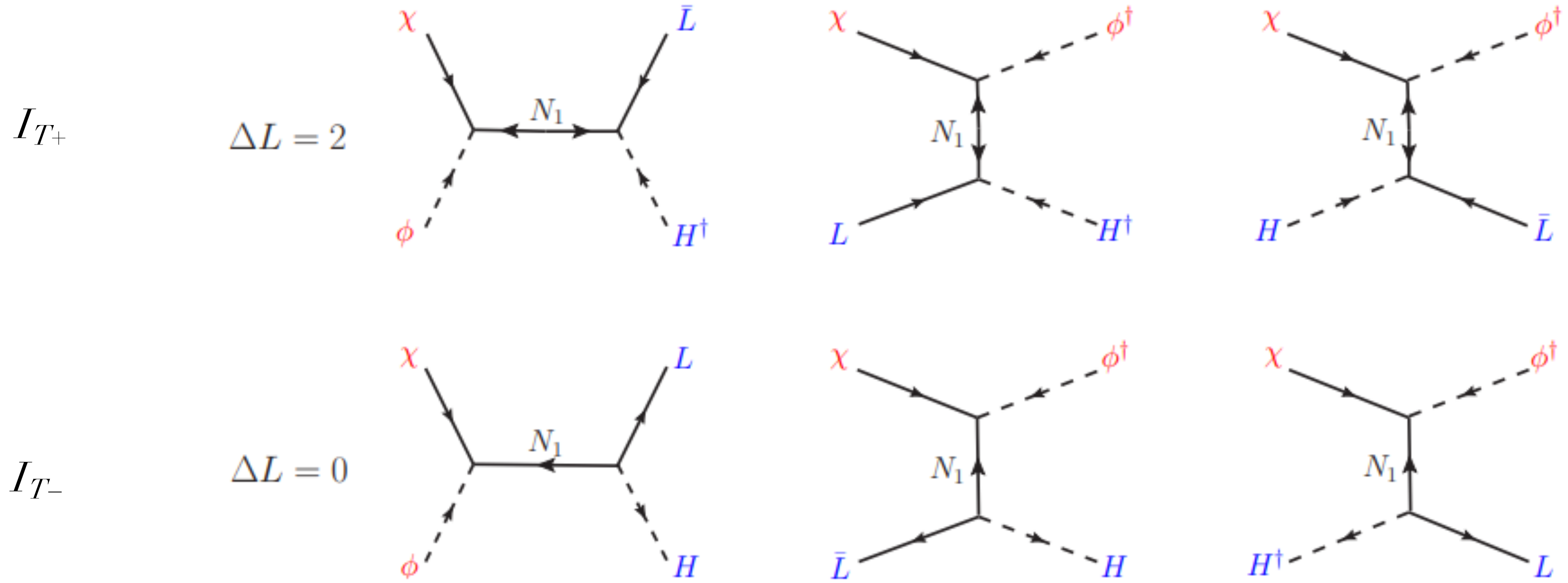
- Washout processes reduce asymmetries
- The I_W washout terms in Boltzmann come from these diagrams.
- If the couplings are too large, then these processes become more dominant and actively reduce asymmetry generated.



Transfer

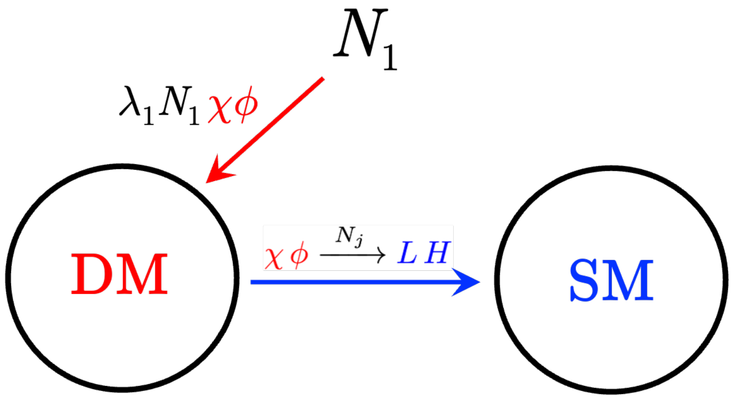
- The I_{T+}, I_{T-} washout terms in Boltzmann come from these diagrams.

- If the couplings are too large, then these processes become more dominant and actively reduce asymmetry generated.



Falkowski, A., Ruderman, J.T., Volansky, T., JHEP; *2011*(5):1-32

Wash In



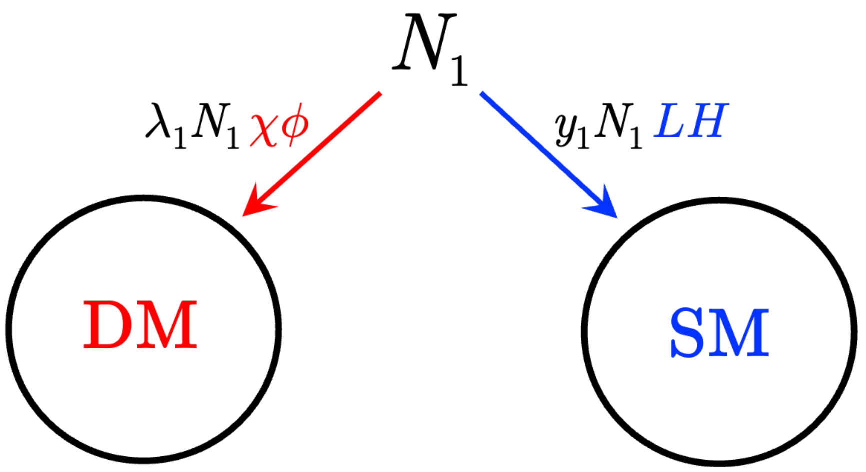
$$\frac{dY_{N_1}}{dz} = -z\frac{\Gamma_{N_1}}{H_1}\frac{K_1(z)}{K_2(z)}\left(Y_{N_1} - Y_{N_1}^{eq}\right) + (2 \leftrightarrow 2)$$

$$\frac{dY_{\Delta\chi}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_\chi \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right] - \frac{\Gamma_{N_2}}{H_1}\left[2\mathrm{Br}_\chi^2 I_W(z) Y_{\Delta\chi}\right]$$

$$\frac{dY_{\Delta l}}{dz} = -\frac{\Gamma_{N_2}}{H_1}\left[\mathrm{Br}_l\mathrm{Br}_\chi I_{T_+}(z)(Y_{\Delta l} + Y_{\Delta\chi}) + \mathrm{Br}_l\mathrm{Br}_\chi I_{T_-}(z)(Y_{\Delta l} - Y_{\Delta\chi})\right]$$

- If $\Gamma(N_1 \to L\ H) \simeq 0$, $\epsilon_L \simeq 0$, then can have asymmetry generation via wash-in from the dark sector.
- Successful Baryogenesis possible if $M_{N_1} \geq 10^9$ GeV

Co-genesis

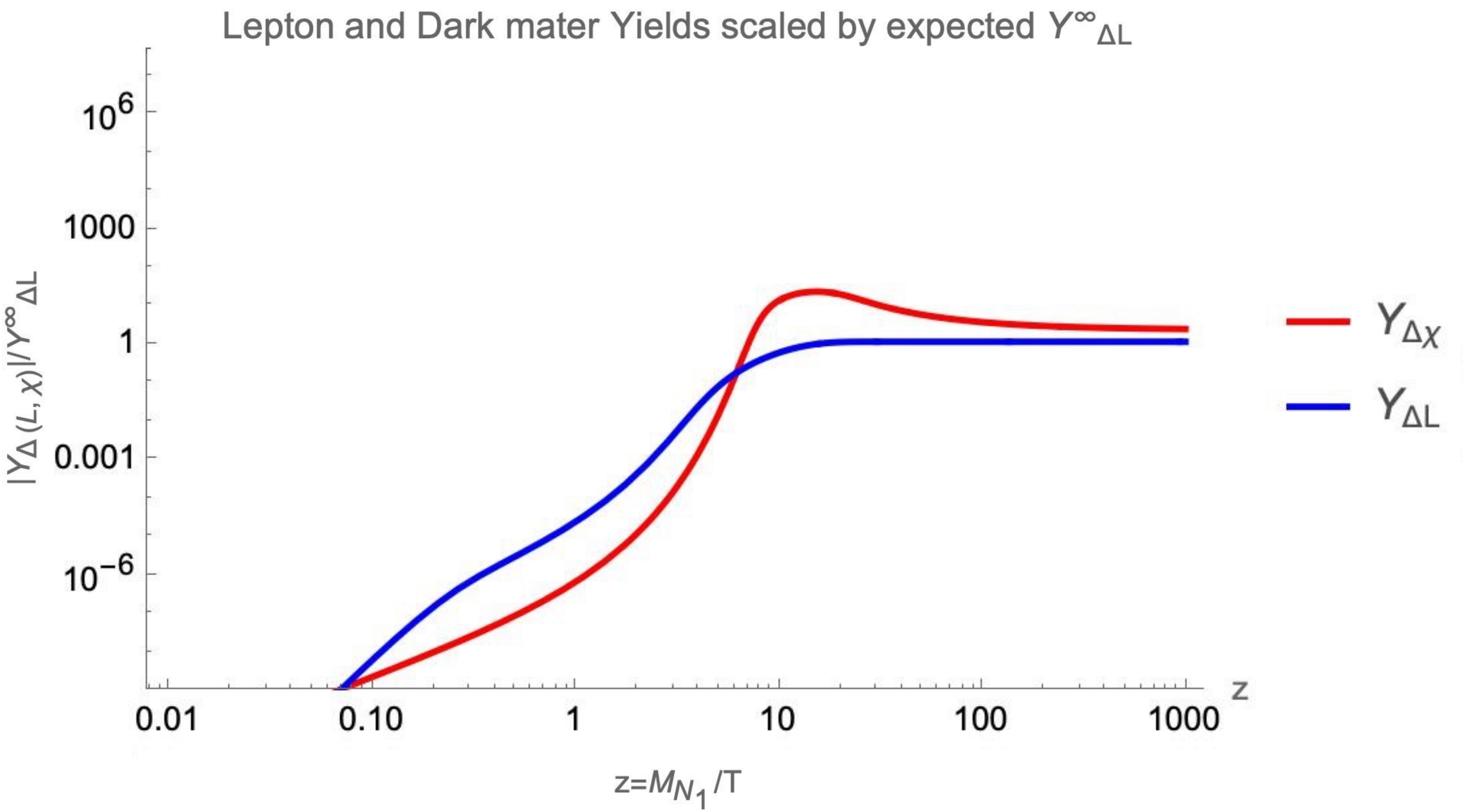


- With $\epsilon_L \neq 0$ and. $\lambda_1 \ll \lambda_2$ can have significant boost to lepton asymmetry generation

$$\epsilon_L \simeq \frac{M_1}{M_2} \frac{\text{Im}\left[3(y^\dagger y)^2_{12} + (y^\dagger y)_{12}\, \lambda_1^* \lambda_2\right]}{8\pi(2\,(y^\dagger y)_{11} + |\lambda_1|^2)}$$

- Successful Baryogenesis possible for $M_{N_1} < 10^9$ GeV

How low can you go with $\lambda_1 \ll \lambda_2$?



- With M_{N1} ~10^7 GeV, M_{N2} ~10^8 GeV, $|\lambda_1| \sim 10^{-6}$, $|\lambda_2| \sim 10^{-2}$, $|y_1| \approx 10^{-6}$, $|y_2| \approx 10^{-4}$; the observed asymmetry can be produced, with DM mass of $m_\chi \approx 0.33$ GeV

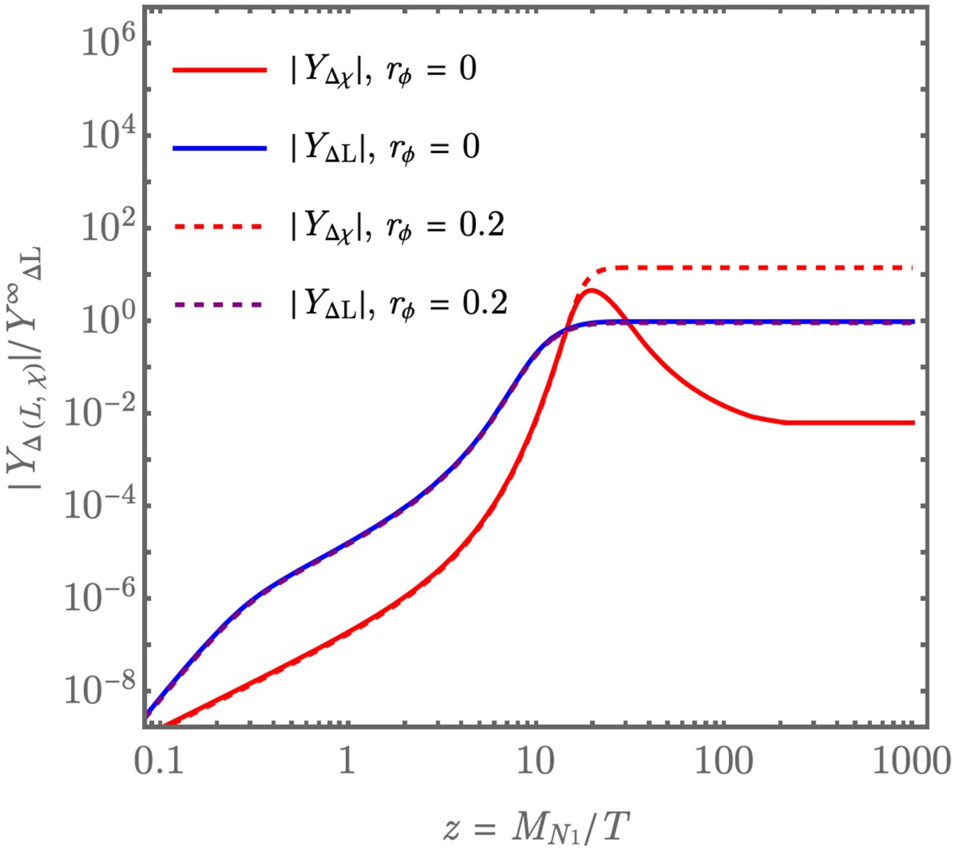
Is a lower bound achievable with $\lambda_1 \ll \lambda_2$?

- DM stability requires $M_{N_1} > m_\phi > m_\chi$

- If $M_{N_1} \gg m_\phi$, then increasing λ_2 results in unstable DM due to strong washout

- If $M_{N_1} \gtrsim m_\phi$, then the washout effects can be Boltzmann supressed

Effect of washout suppression from $m_\phi = 0.2\times M_{N1}$



- With $M_{N1} \simeq 4\times10^6$ GeV, $M_{N2} \simeq 5.5\times10^6$ GeV, $|\lambda_1|=1.4\times10^{-6}$, $|\lambda_2|=2\times10^{-2}$, $|y_1|\approx1.4\times10^{-6}$, $|y_2|\approx1.5\times10^{-4}$; the observed asymmetry can be produced, with ϕ and DM mass for $r_\phi = 0$ of $m_\phi > m_\chi \simeq 383$ GeV and for $r_\phi = 0.2$ of $m_\phi \simeq 8.1\times10^5$ GeV and $m_\chi \simeq 0.17$ GeV

Finding new bound from $\lambda_1 \ll \lambda_2$ and Washout suppression

- The washout suppression from the mass of ϕ results in more asymmetry in χ

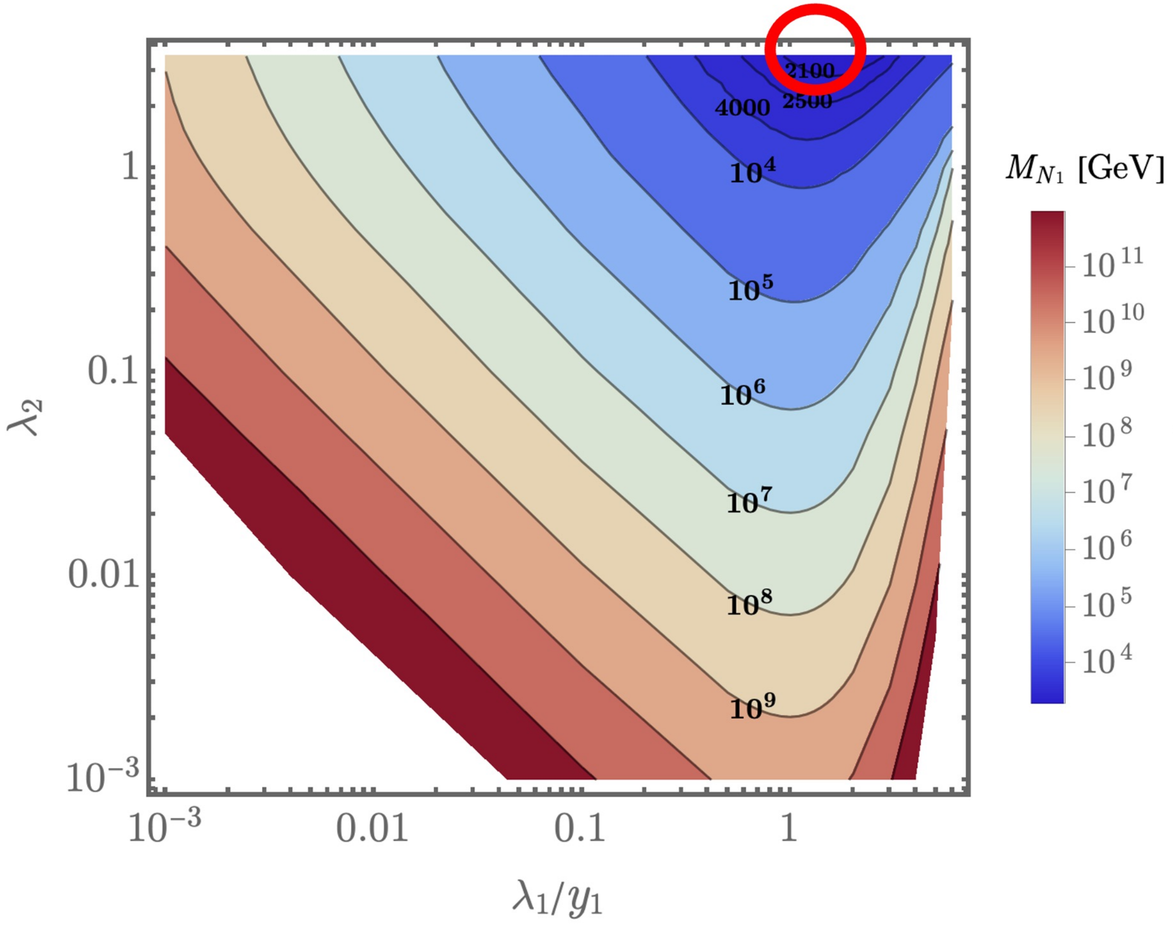
- This allows the coupling λ_2 to be increased, thus allowing more asymmetry in L

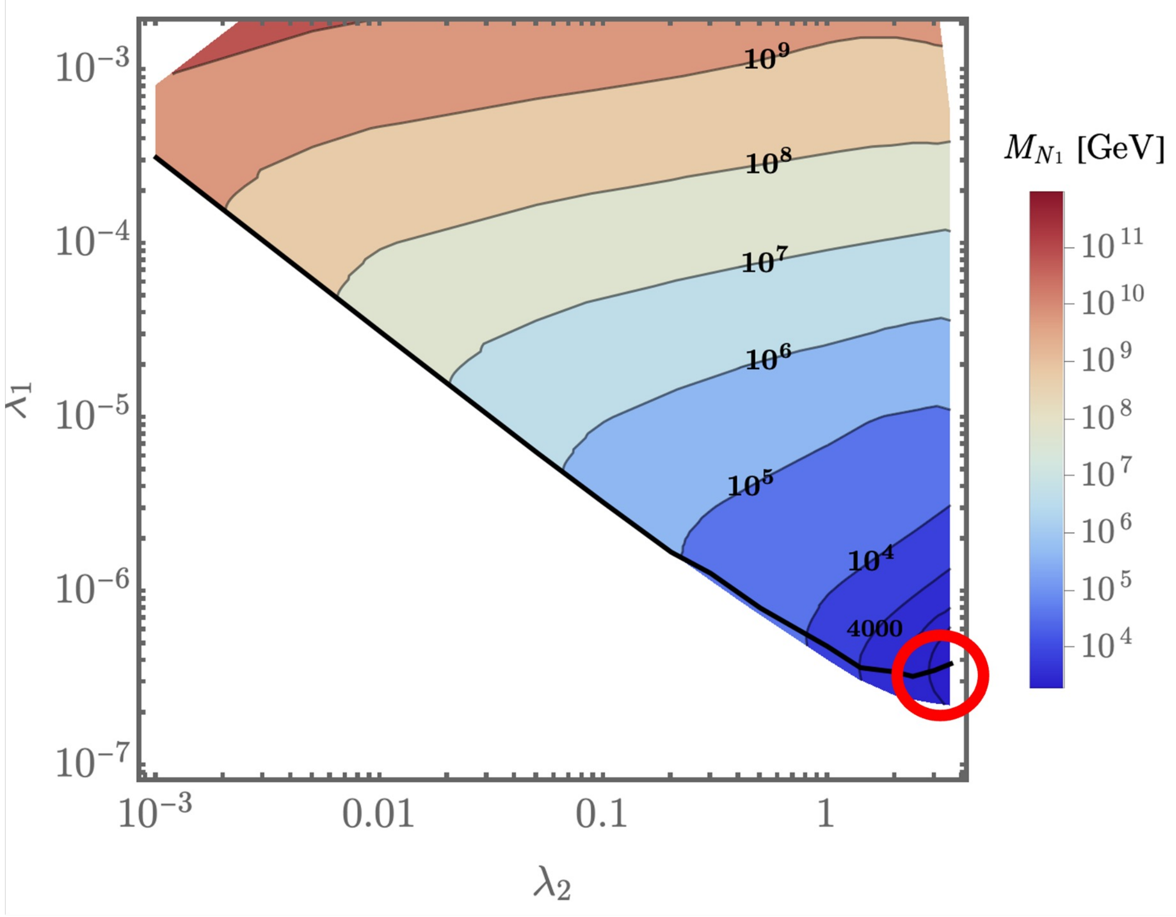
- The constraint on λ_2 is no longer washout, but instead perturbation theory

- Lower bound of $M_{N\mathbf{1}}$ determined at the point when $m_\phi > m_\chi$ is no longer true

- New bound is about $M_{N1} \geq 2$ TeV

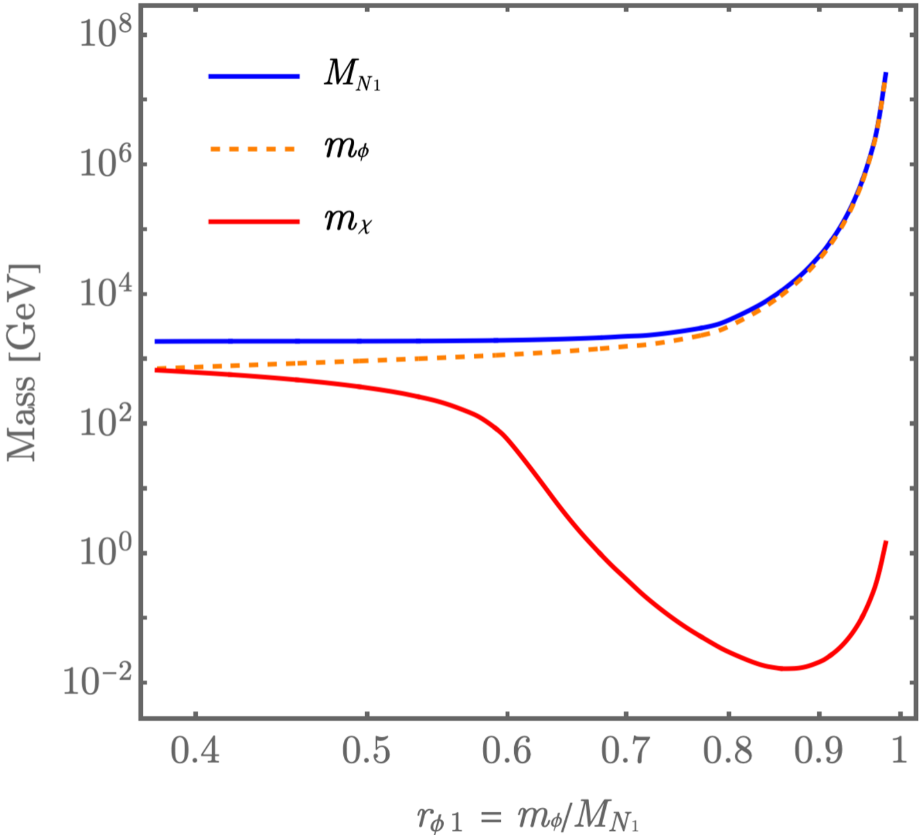
Effect on parameters on bound





- The mass gap set to $M_{N2}/M_{N1} \simeq 1.35$, $|y_1| \approx \sqrt{M_{N1}} \cdot 6.8 \times 10^{-10}/\sqrt{\text{GeV}}$, $|y_2| \approx \sqrt{M_{N2}} \cdot 6.5 \times 10^{-8}/\sqrt{\text{GeV}}$

DM mass range



- With $M_{N2}/M_{N1} = 1.41$, $|\lambda_1| \simeq \sqrt{M_{N1}} \cdot 6.8 \times 10^{-10}/\sqrt{\text{GeV}}$, $|\lambda_2| = 1$, $|y_1| \approx \sqrt{M_{N1}} \cdot 6.8 \times 10^{-10}/\sqrt{\text{GeV}}$, $|y_2| \approx \sqrt{M_{N2}} \cdot 6.5 \times 10^{-8}/\sqrt{\text{GeV}}$

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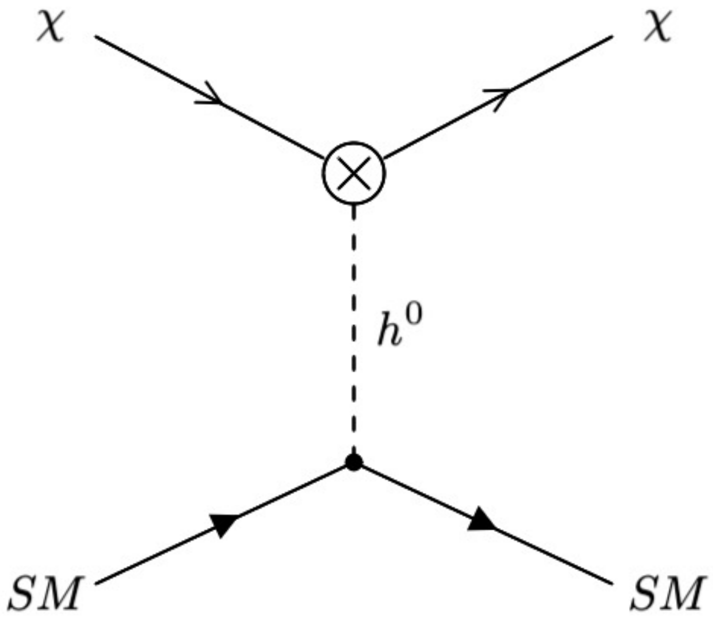
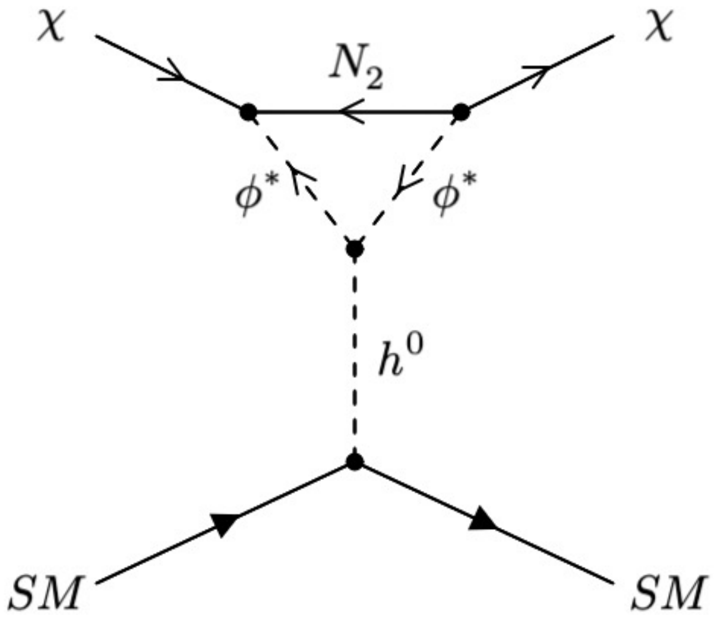
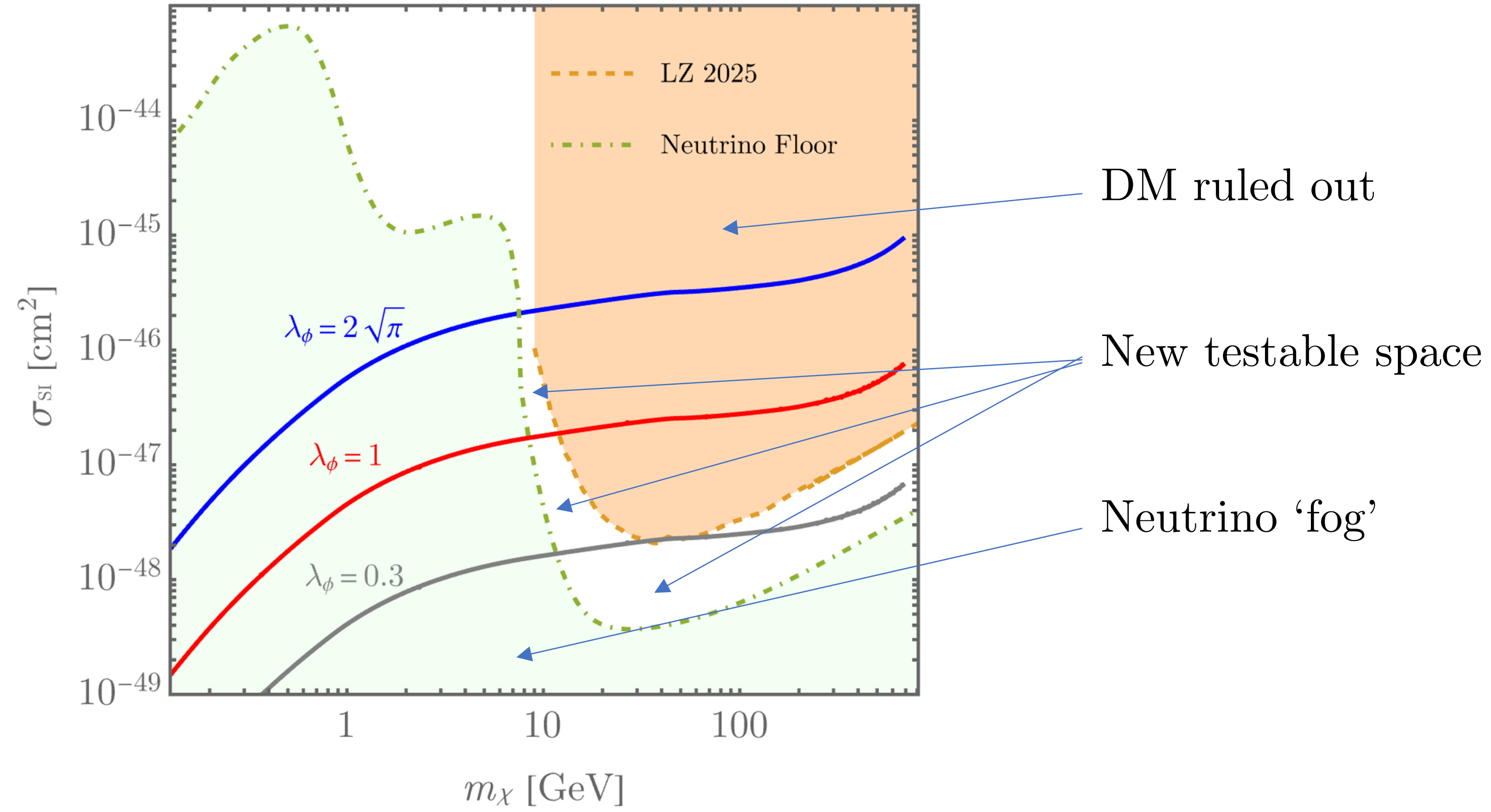
Direct Detection Scattering





- $\mathcal{L} \supset \lambda_\phi \; \phi^* \phi \; H^\dagger H$ will generate after EWSB: $\mathcal{L} \supset \lambda_\phi v \; h^0 \; \phi^* \phi$
- Leads to spin independent direct detection (for $M_{N_1} \simeq 2$ TeV)
- After Electroweak Symmetry Breaking, the Higgs gains a vev and leading to this scattering process. This can be tested via direct detection

Spin Independent cross section parameter space



- Blue line with perturbative maximum

Conclusions

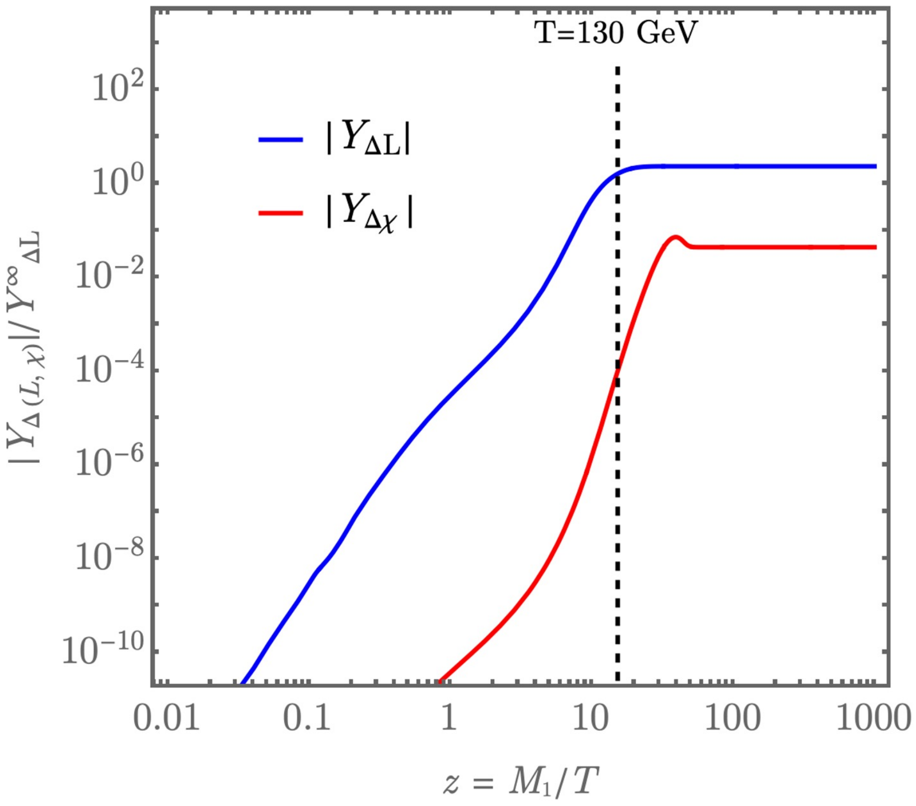
1. Bound can be lower than Davidson Ibarra and Falkowski with large hierarchy

2. Bound is about 2 TeV, any lower and Dark matter becomes unstable

3. Testable via direct detection

* Akhmedov, Evgeny, et al. JHEP 2013.5 :1-33.

Asymmetry generation close to bound

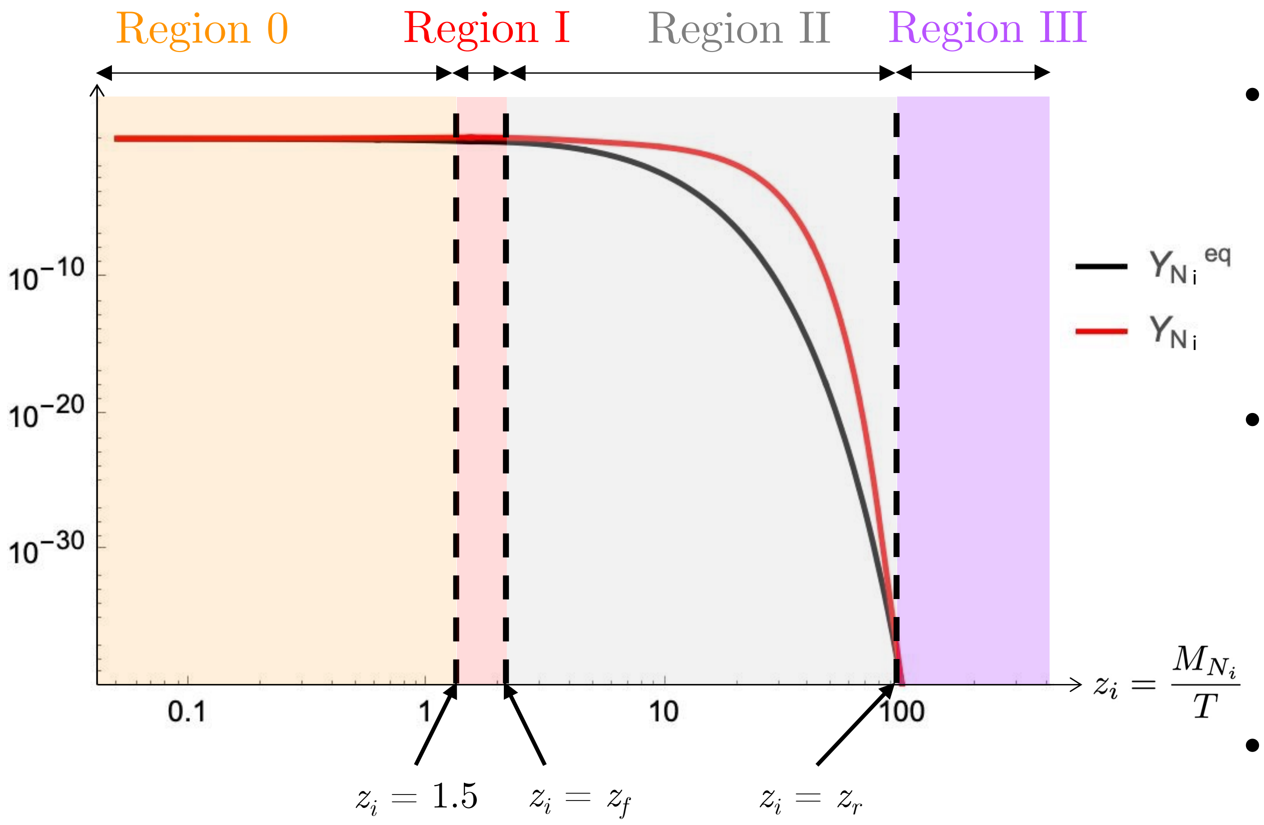


- Here the evolution of the asymmetries for DM mass close to the low point in the neutrino fog.
- With $M_{N1} \simeq 2.0$ TeV, $M_{N2} \simeq 2.7$ TeV, $m_\phi \simeq 1.2$ TeV, $|\lambda_1| \approx 10^{-8}$, $|\lambda_2| = \sqrt{4\,\pi}$, $|y_1| \approx 10^{-8}$, $|y_2| \approx 10^{-6}$, with DM mass of $m_\chi \simeq 56$ GeV

Any Questions?

Backup Slides

Analytical Approximation to $Y_{N1}{}^{eq}$ and Y_{N1}



- Region 0 ($z < 1.5$):

$$Y_{N1}{}^{eq} = a\,z + b$$

$$Y_{N1} = Y_{N1}{}^{eq};$$

$$z_f = \frac{H_1}{2\Gamma_{N1}} \cdot \left(1 - \sqrt{1 - 6\frac{\Gamma_{N1}}{H_1}}\right) \simeq \frac{3}{2} + \frac{9}{4}\frac{\Gamma_{N1}}{H_1}$$

- Region I ($1.5 < z < z_f$):

$$Y_{N1}{}^{eq} = Ae^{-z} z^{\frac{3}{2}}$$

$$Y_{N1} = Ae^{-z} z^{\frac{3}{2}} - A\frac{H_1}{\Gamma_{N1}}\frac{3}{2} e^{-z} z^{-\frac{1}{2}} + A\frac{H_1}{\Gamma_{N1}} e^{-z} z^{\frac{1}{2}}$$

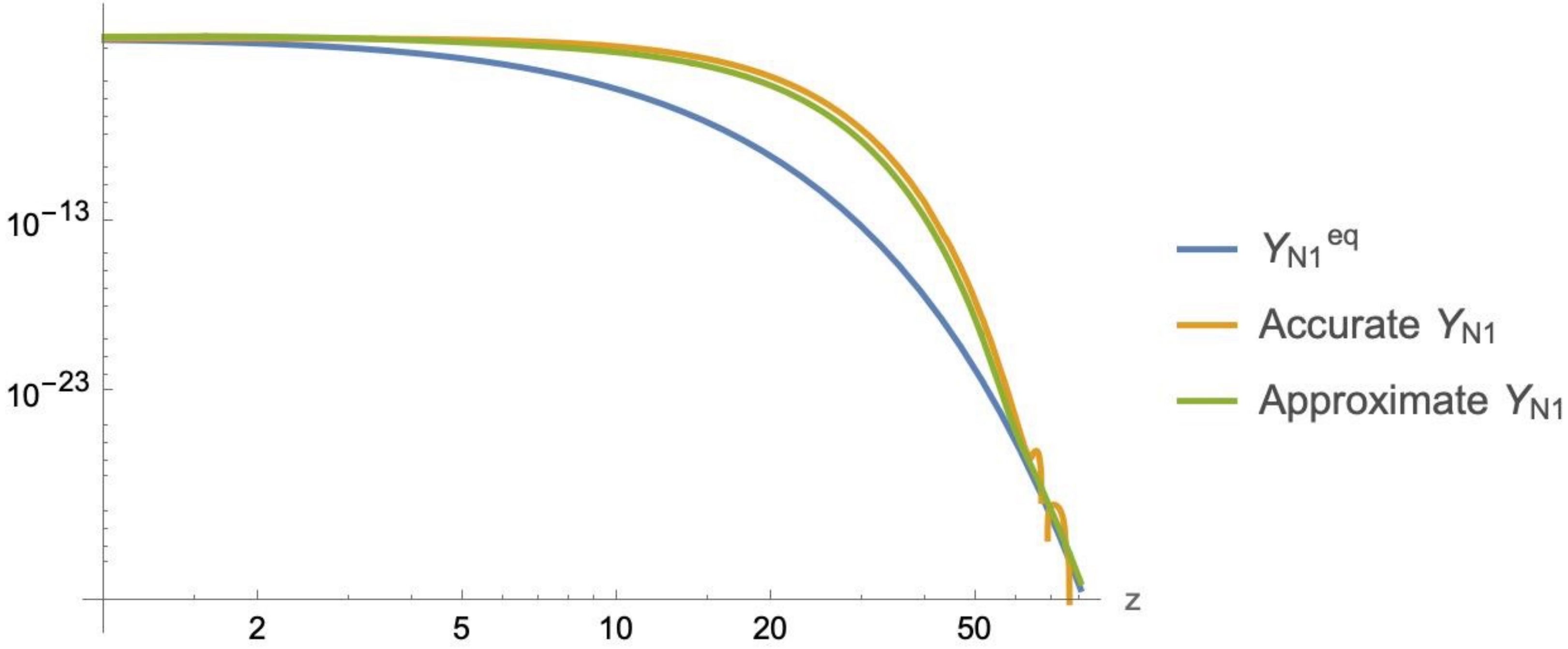
- Region II ($z_f < z$):

$$Y_{N1}{}^{eq} = Ae^{-z} z^{\frac{3}{2}} z_f^{2} \frac{\Gamma}{2\,H_1} - z_f - z^2 \frac{\Gamma}{2\,H_1}$$

$$Y_{N1} = Ae^{-z} z^{\frac{3}{2}} + A\,\frac{H_1}{\Gamma_{N1}}\, e^{\left(\frac{\Gamma}{2\,H_1} - z_f - z^2\frac{\Gamma}{2\,H_1}\right)} \cdot \left(z_f^{\frac{1}{2}} - \frac{3}{2} z_f^{-\frac{1}{2}}\right)$$

Analytical Approximation

- To observe how Boltzmann solution behaves, used analytical approximations and compared to accurate numerical solutions.



CI Parameterisation

$$(y^\dagger y) = \frac{1}{v_{ew}^2} M_N R^\dagger R\, M_N \qquad R = -i\,\mathcal{U} m_\nu^{\frac{1}{2}} \mathcal{O} M_N^{-\frac{1}{2}}$$

- $\mathcal{U}$ is the PNMS matrix, $\mathcal{O}$ is an arbitrary complex orthogonal matrix, M_N is 3x3 or 2x2 diagonal heavy neutrino mass matrix, m_ν is the light neutrino mass matrix
- CI parameterisation, when done carefully, allows flexibility in yukawa couplings
- Can also have hierarchy in yukawa couplings

Boltzmann equations

For number density (n_χ) of a particle χ

$$\frac{dn_\chi}{dt} + 3Hn_\chi = C(\chi)$$

Collision term is

$$\begin{aligned} C(\alpha_1) \equiv & \int d\Pi_{\alpha 1} \cdots d\Pi_{\alpha n} d\Pi_{\beta 1} \cdots d\Pi_{\beta m} (2\pi)^4 \delta^4(p_{\beta 1} + \cdots + p_{\beta m} - p_{\alpha 1} - \cdots - p_{\alpha n}) \\ & \times \left[(f_{\alpha 1} \cdots f_{\alpha n}) |\mathcal{M}(\alpha \to \beta)|^2 - f_{\beta 1} \cdots f_{\beta m} |\mathcal{M}(\beta \to \alpha)|^2 \right], \\ & \equiv (r_{\beta 1} \cdots r_{\beta m} - r_{\alpha 1} \cdots r_{\alpha n}) \Gamma(\alpha \to \beta) \end{aligned}$$

The CP violation is given by

$$\epsilon_{\alpha \to \beta} = \frac{\Gamma(\alpha \to \beta) - \Gamma(\beta \to \alpha)}{\Gamma(\alpha \to \beta) + \Gamma(\beta \to \alpha)}$$

Neutrino mass

- In SM - neutrinos are massless
- Neutrino oscillation → neutrinos must have mass
- ? Dirac or Majorana.
- Dirac mass - neutrinos couple to scalar boson ? SM Higgs (conserves L number)
- Majorana mass -neutrinos become their own anti-particle (violates L number)

Lepton violation

- Lowest Dimension operator is Dim 5 Weinberg operator

- $-\mathcal{L}_M = \frac{\lambda}{\mathrm{M}} L^T \cdot H\, C^\dagger L \cdot H = \frac{\lambda {v_H}^2}{M} \nu_L^T C^\dagger \nu_L$

- Violates lepton number

CP violation

In order to generate CP violation it is necessary for mixing between tree level and one loop Interactions.

$$\mathcal{L} = g_1 X \bar{f}_1 f_2 + g_2 X \bar{f}_3 f_4 + g_3 Y \bar{f}_1 f_3 + g_4 Y \bar{f}_2 f_4 + H.c.$$

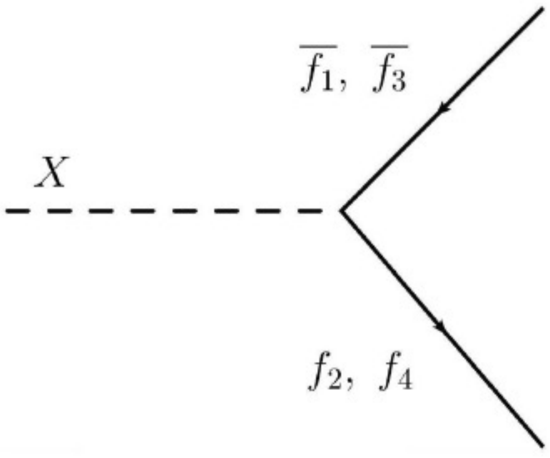
$$g_1 X \bar{f}_1 f_2 \overset{CP}{\rightarrow} g_1 X \bar{f}_2 f_1$$

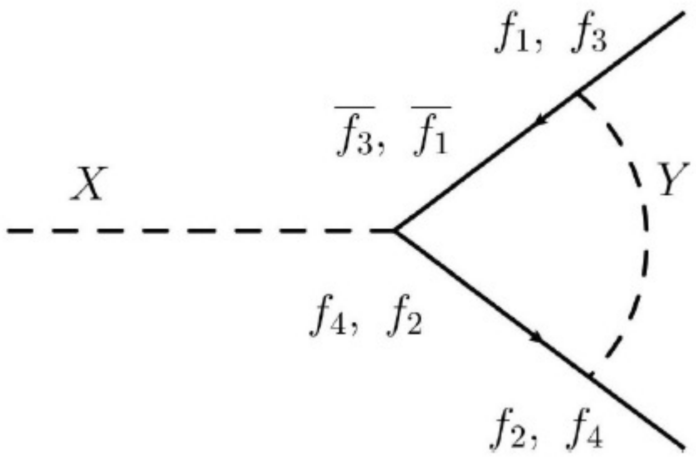
CP transformation

$$g_1 X \bar{f}_1 f_2 \overset{H.c.}{\rightarrow} g_1^* X \bar{f}_2 f_1$$

Hermitian conjugation

CP violation





$$\Gamma(X \to \bar{f}_1 f_2) = |g_1|^2 I_{tree} + g_1 g_2^* g_3 g_4^* I_{int} + (g_1 g_2^* g_3 g_4^* I_{int})^* + |g_2|^2 |g_3|^2 |g_4|^2 I_{loop} + \cdots$$

$$\Gamma(\bar{X} \to \bar{f}_2 f_1) = |g_1|^2 I_{tree} + g_1^* g_2 g_3^* g_4 I_{int} + (g_1^* g_2 g_3^* g_4 I_{int})^* + |g_2|^2 |g_3|^2 |g_4|^2 I_{loop} + \cdots$$

$$\Delta\Gamma = 4 Im(g_1 g_2^* g_3 g_4^*) Im(I_{int})$$

Freeze Out

- Majority of asymmetry generated at higher temperatures - washout process reduces asymmetry as temperature decreases.
- Washout process would completely remove the asymmetry but the asymmetry instead freezes out after departure from thermal equilibrium before it disappears.
- Freeze out occurs when the interaction or decay rate is less than the Hubble expansion rate and it departs from equilibrium.
- So, the weaker the interaction rate the earlier freeze out occurs.

Asymmetric Dark Matter from Leptogenesis

- Introduction
- Leptogenesis & Asymmetric Dark Matter
- Boltzmann equations
- Numerical solution
- Mapping to model
- Some results
- Conclusions