UNIVERSITY OF LIVERPOOL

Asymmetric Dark Matter from Leptogenesis

A Lower Mass Bound on Neutrino Mass for Leptogenesis from Dark Matter with large coupling Hierarchy

Henry McKenna, Juri Smirnov, Martin Gorbahn

Research Questions

1. Can we break the Davidson Ibarra bound (10^9 GeV) with Asymmetric Dark Matter and Leptogenesis?

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

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.

Constraints on mass and coupling

- 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

UNIVERSITY OF LIVERPOOL

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 $M_N \lesssim 10^7$ 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 either couples 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

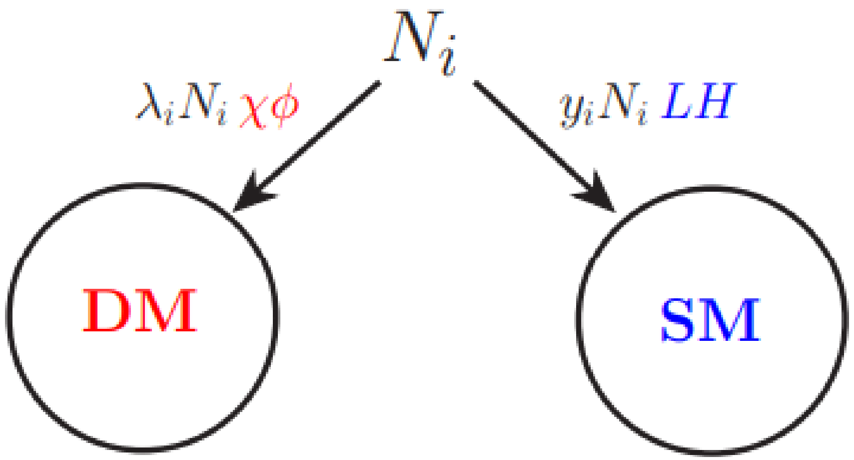
- This Model has been studied by Falkowski, Ruderman, and Volansky (Arxiv 1101.4936)

- 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

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

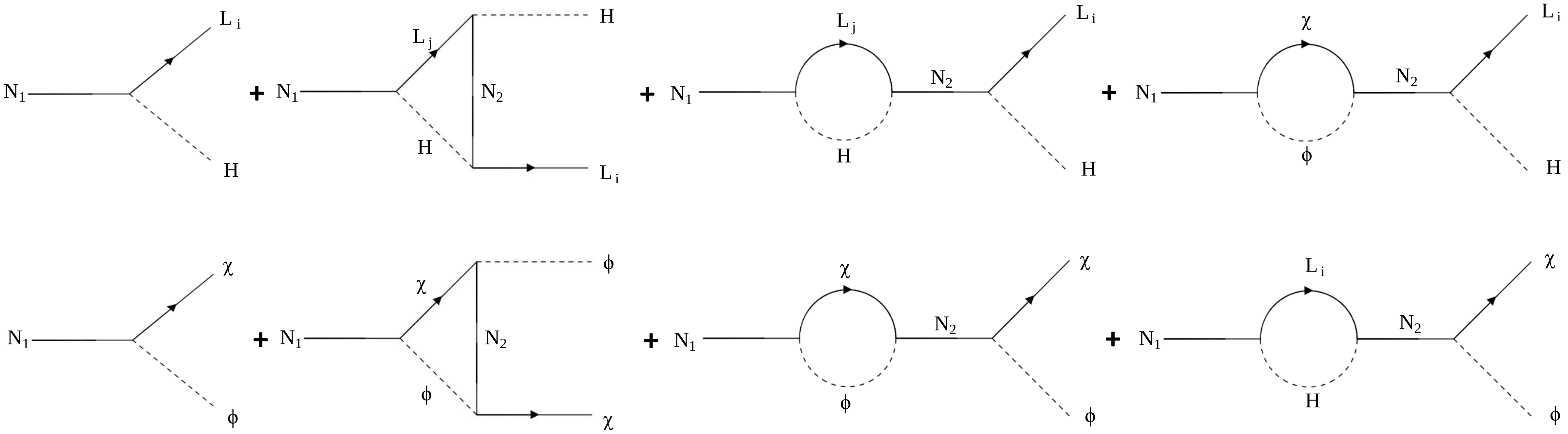
Asymmetric dark matter from Leptogenesis



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

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

Asymmetric dark matter from Leptogenesis



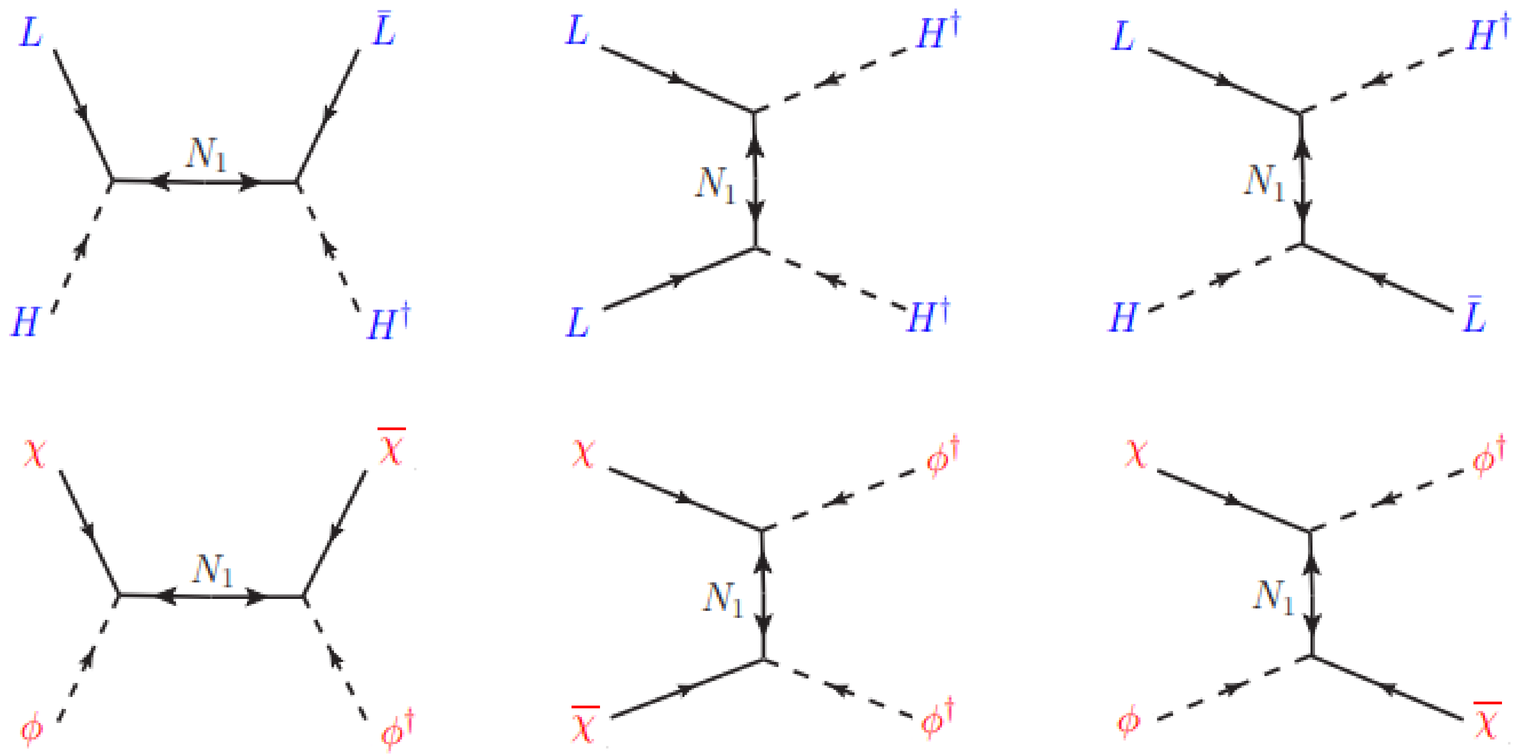
$$\epsilon_L \simeq \frac{M_1 M_2}{M_2^2 - M_1^2} \frac{\mathrm{Im}\left[2(y_1^\dagger y_2)^2 + y_1^\dagger y_2 \lambda_1^\star \lambda_2\right]}{16\pi(y_1^\dagger y_1 + |\lambda_1|^2)}$$

$$\epsilon_\chi \simeq \frac{M_1 M_2}{M_2^2 - M_1^2} \frac{\mathrm{Im}[2(\lambda_1^* \lambda_2)^2 + (y_1^\dagger y_2)\lambda_1^* \lambda_2)]}{16\pi(y_1^\dagger y_1 + \lambda_1^2)}$$

Washout Processes

- 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.

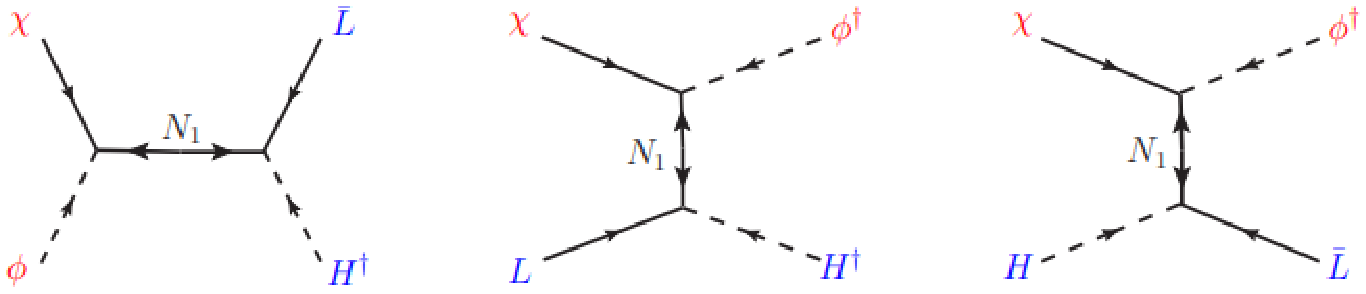


Transfer

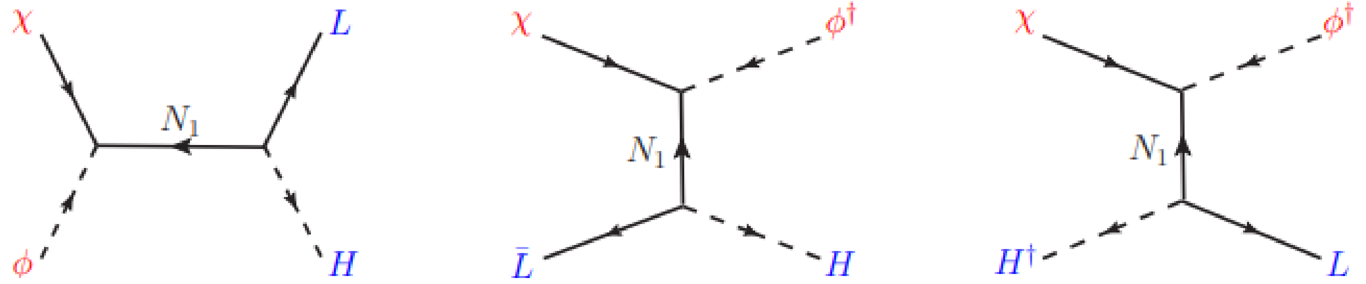
- The I_{T+}, I_{T-} washout terms in Boltzmann come from these diagrams.

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

I_{T+} $\Delta L = 2$

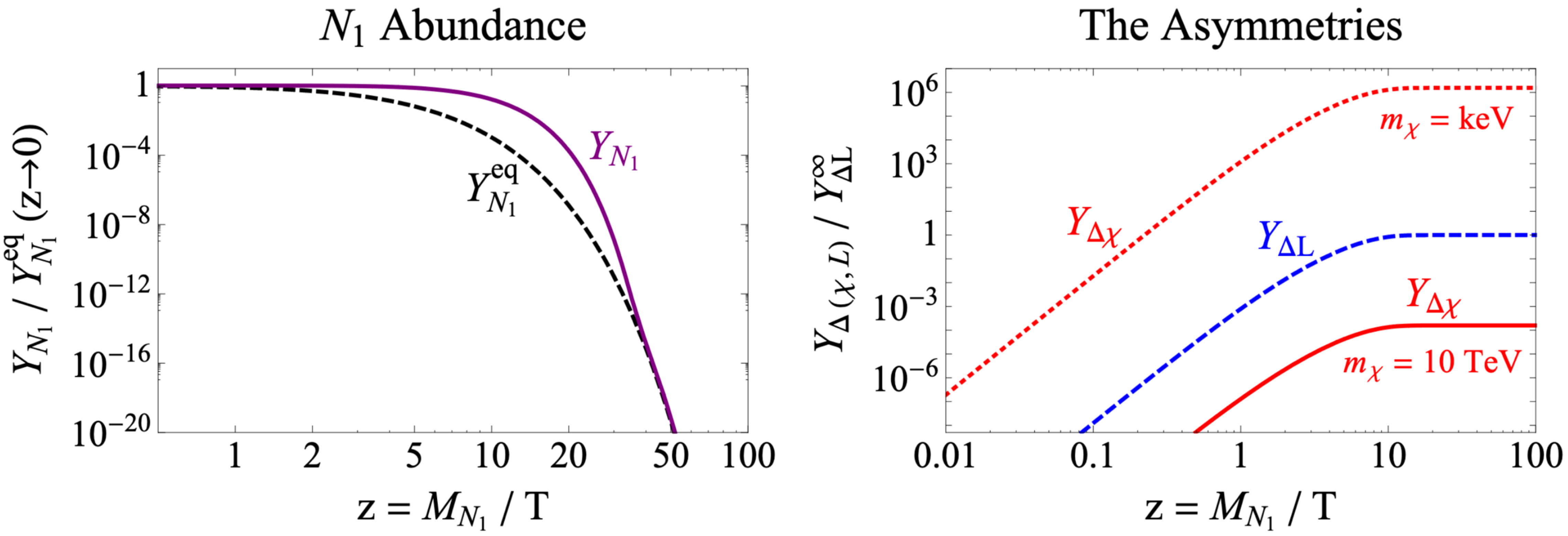


I_{T-} $\Delta L = 0$



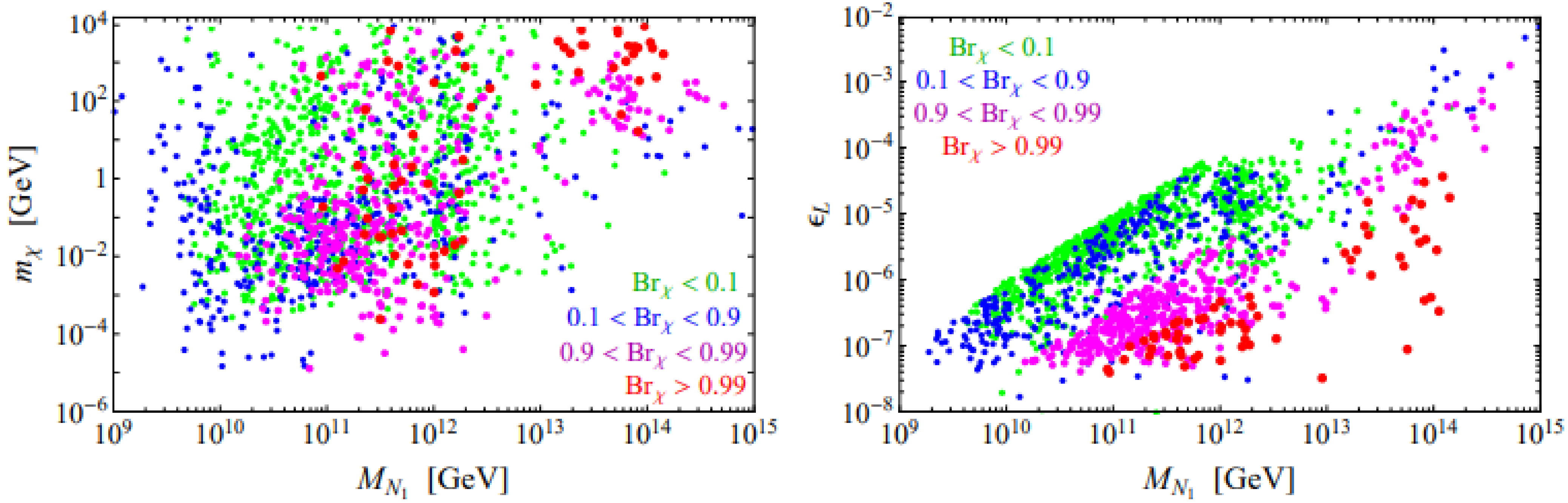
Falkowski, A., Ruderman, J.T., Volansky, T., JHEP; *2011*(5):1-32

Evolution of Yield



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

Bound on Mass with no Hierarchy: $\lambda_1 \simeq \lambda_2$



From Falkowski, the bound is found to be $M_{N1} > 10^9$ GeV, same as Davidson Ibarra bound

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

Recent Research

Falkowski study did not break Davidson Ibarra bound in paper,

but certain parameters were not explored

Can this bound be lower?

- Large hierarchy in couplings not investigated
- Would $\lambda_1 \ll \lambda_2$ result in lower bound?
- If so, why? How?

UNIVERSITY OF LIVERPOOL

Boltzmann equations

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

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

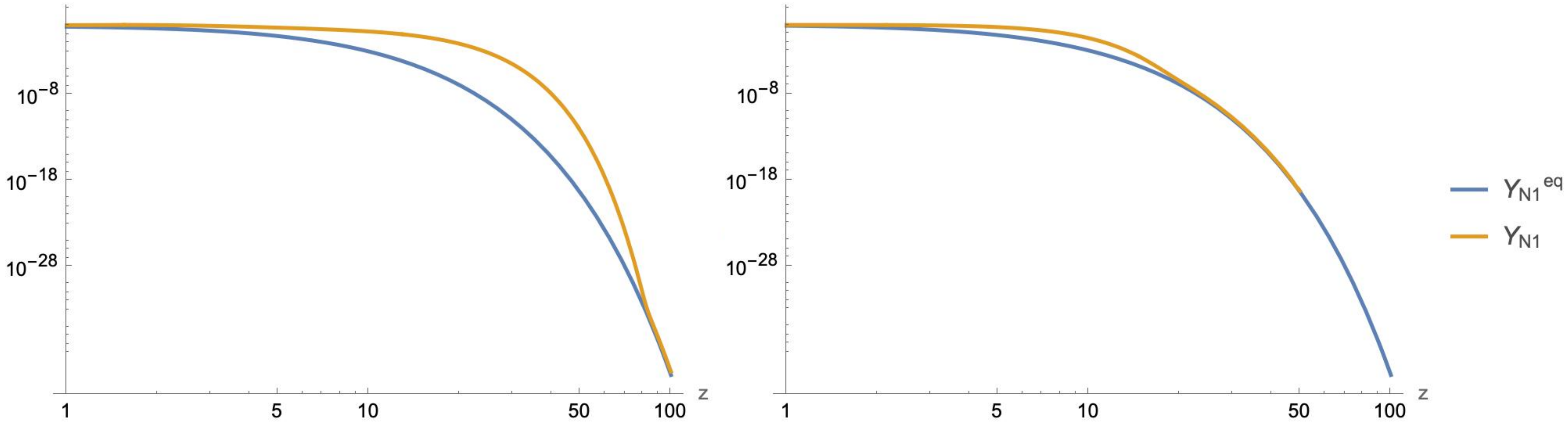
$$\frac{dY_{\Delta\chi}}{dz} = \frac{\Gamma_{N_1}}{H_1}\left[\epsilon_\chi \frac{zK_1(z)}{K_2(z)}(Y_{N_1} - Y_{N_1}^{eq})\right] - \frac{\Gamma_{N_2}}{H_1}\left[2\mathrm{Br}_\chi^2 I_W(z) Y_{\Delta\chi}\right]$$

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

where $K_i(z)$ is the Modified Bessel function of the ith 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.

Departure from Thermal Equilibrium



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

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

Problem with increasing couplings

- If you increase the couplings (with $\lambda_1 \simeq \lambda_2$), you reduce the how much N_1 and N_2 departure from thermal equilibrium you get

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

- Which reduces how much asymmetry is generated

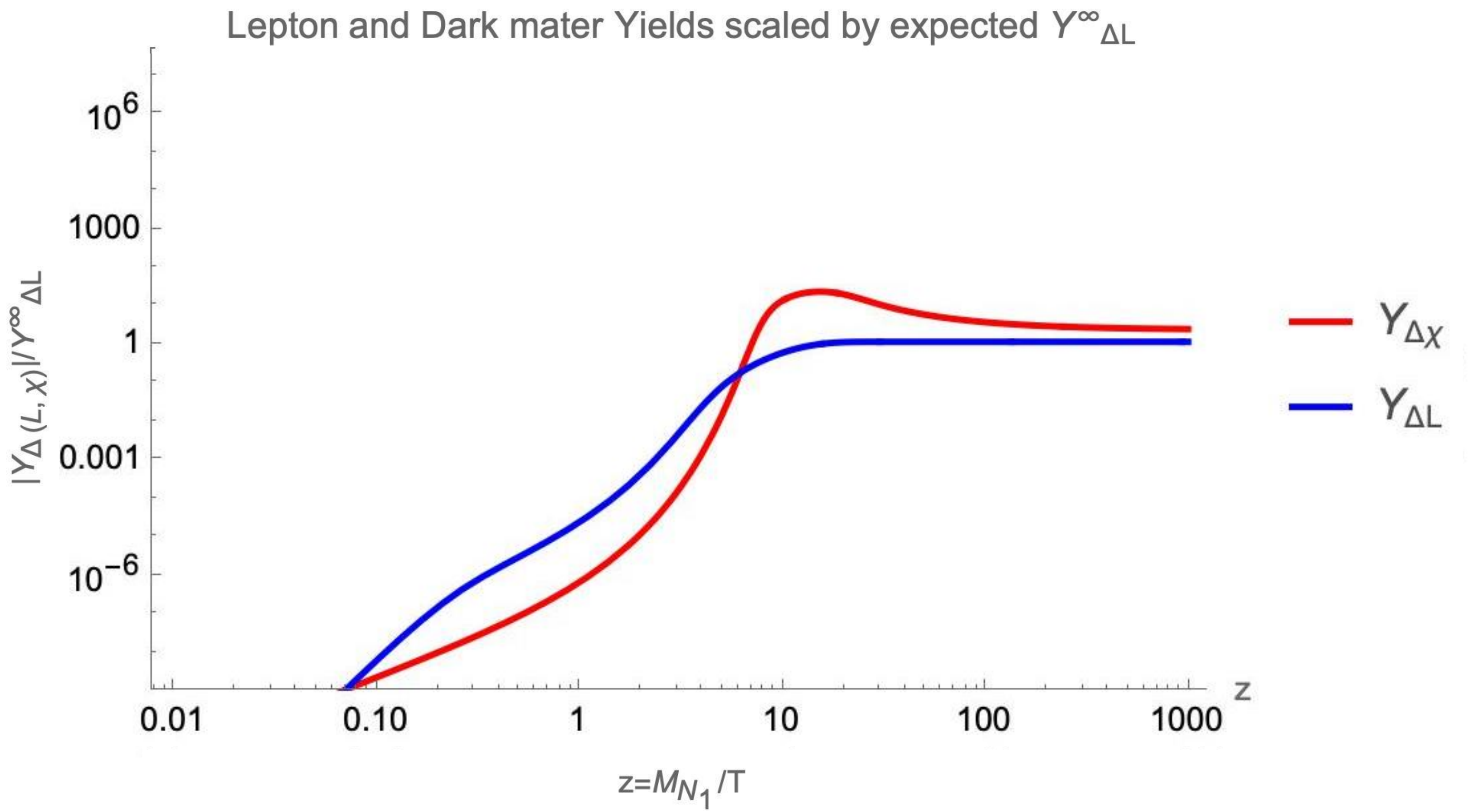
$$\Gamma_{N_1} = \frac{(y^\dagger y)_{11} + |\lambda_1|^2}{16\pi} M_{N_1}$$

Have your cake and eat it too

- But, if you have a hierarchy $\lambda_1 \ll \lambda_2$, can have N_1 have large departure from equilibrium as λ_1 can be small
- N_2 will have small departure with large coupling λ_2 but will allow the asymmetry parameter to be larger
- Have main contribution to asymmetry from N_1 decays

$$\epsilon_L \simeq \frac{M_1 M_2}{M_2^2 - M_1^2} \frac{\mathrm{Im}\left[2(y_1^\dagger y_2)^2 + y_1^\dagger y_2 \lambda_1^\star \lambda_2\right]}{16\pi(y_1^\dagger y_1 + |\lambda_1|^2)}$$

Lower Bound with Large Hierarchy: $\lambda_1 \ll \lambda_2$?

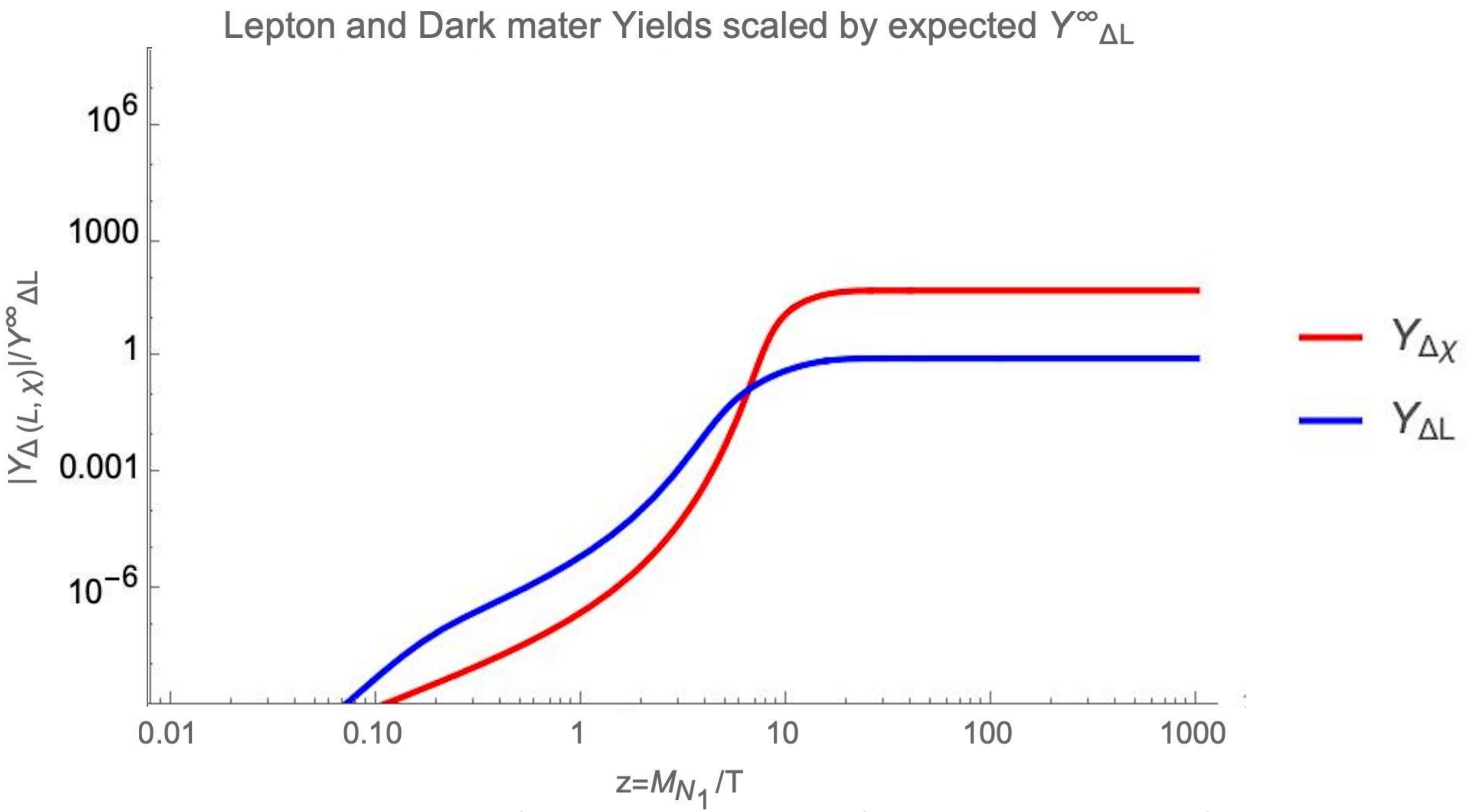


- With M_{N1}=4*10^7 GeV, M_{N2}=10^8 GeV, $|\lambda_1|$=5*10^{-6}, $|\lambda_2|$=2.5*10^{-2}, $|y_1| \approx 6*10^{-6}$, $|y_2| \approx 5*10^{-4}$; the observed asymmetry can be produced, with DM mass of $m_\chi \approx 0.33$ GeV

Washout suppression (more cake?)

- The main issue with lowering the bound further is due to the washout from the dark asymmetry.
- The asymmetry dictates the dark matter mass, if it is too low then the χ will become more massive than N_1 and thus be unstable
- However, we can supress the dark washout by setting the mass of $m_\phi \sim 0.2\ M_{N1}$.
- This supresses the dark washout enough such that we can increase the λ_2 coupling enough to allow a lower bound, lower than 10^7 GeV

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

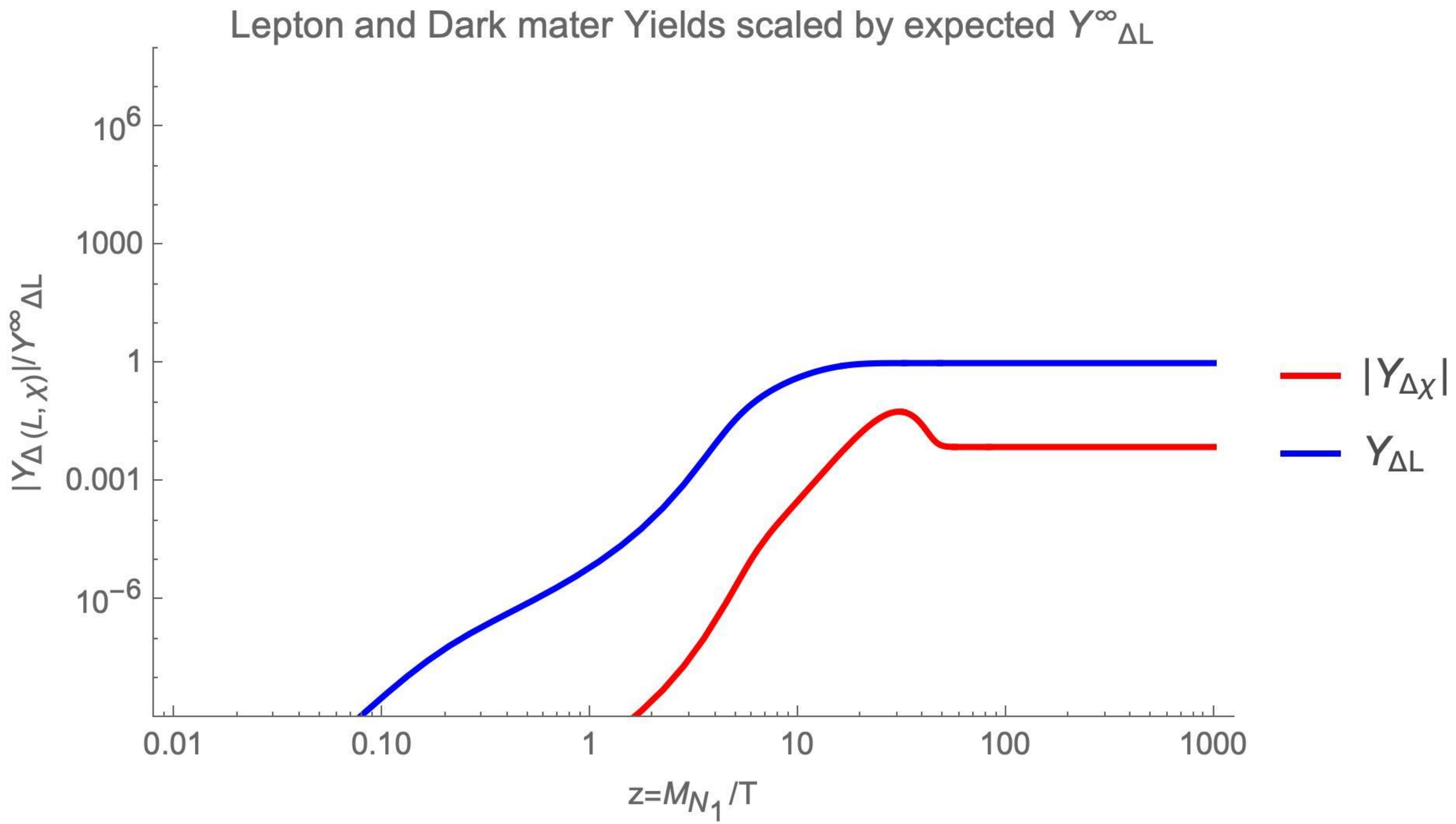


- With M_{N1}=4*10^7 GeV, M_{N2}=10^8 GeV, $m_\phi \approx$ 8*10^8 GeV, $|\lambda_1|$=5*10^{-6}, $|\lambda_2|$=2.5*10^{-2}, $|y_1|\approx$6*10^{-6}, $|y_2|\approx$5*10^{-4}; the observed asymmetry can be produced, with DM mass of $m_\chi \approx$ 0.04 GeV

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_{N1} determined at the point when $m_\phi > m_\chi$ is no longer true
- New bound is about $M_{N1} \geq 50$ TeV

New Lower Bound with Large Hierarchy: $\lambda_1 \ll \lambda_2$?



- With M_{N1}=50 TeV, M_{N2}=125 TeV, m_ϕ=22 TeV, $|\lambda_1|=1.6 \times 10^{-7}$, $|\lambda_2|=1$, $|y_1| \approx 2*10^{-7}$, $|y_2| \approx 1.6*10^{-5}$; the observed asymmetry can be produced, mass of dark matter χ is 341 GeV

Conclusions

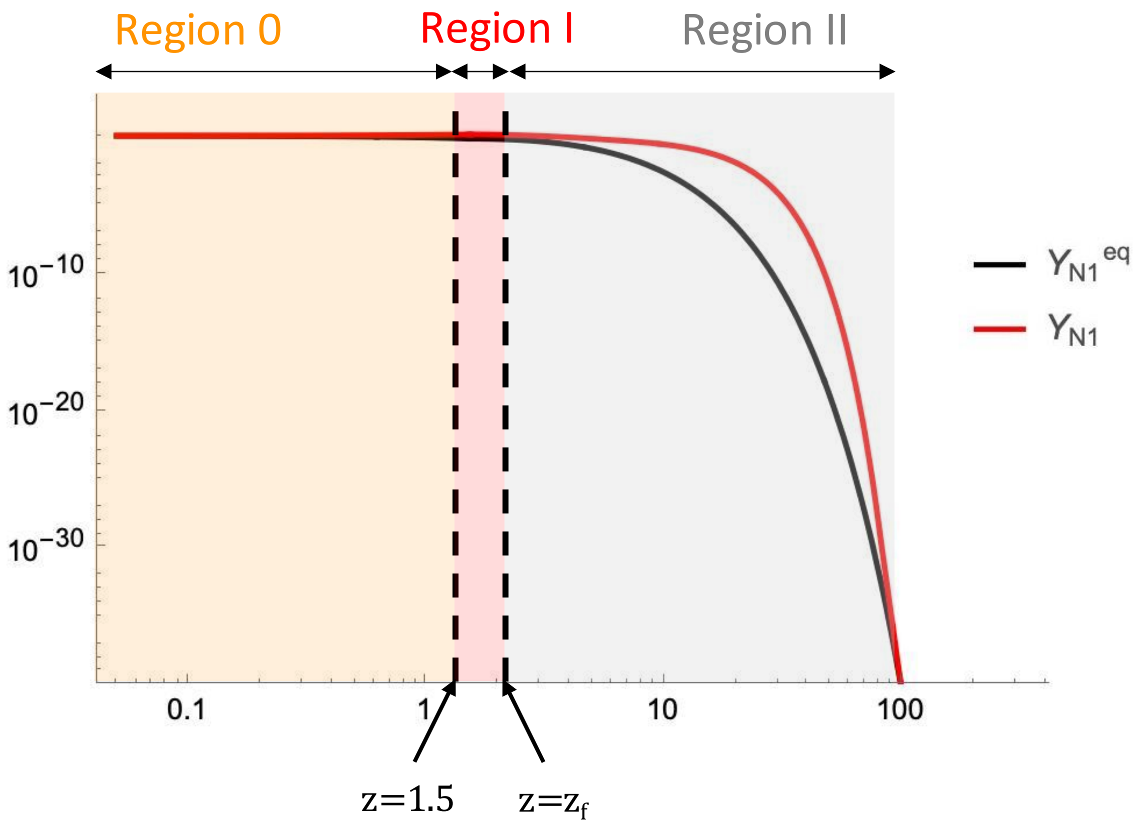
1. Bound can be lower than Davidson Ibarra and Falkowski with large hierarchy
2. Bound is about 50 TeV, any lower and Dark matter becomes unstable
3. Maybe testable from electroweak precision observables*

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

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 ($1.5 < z < z_f$):

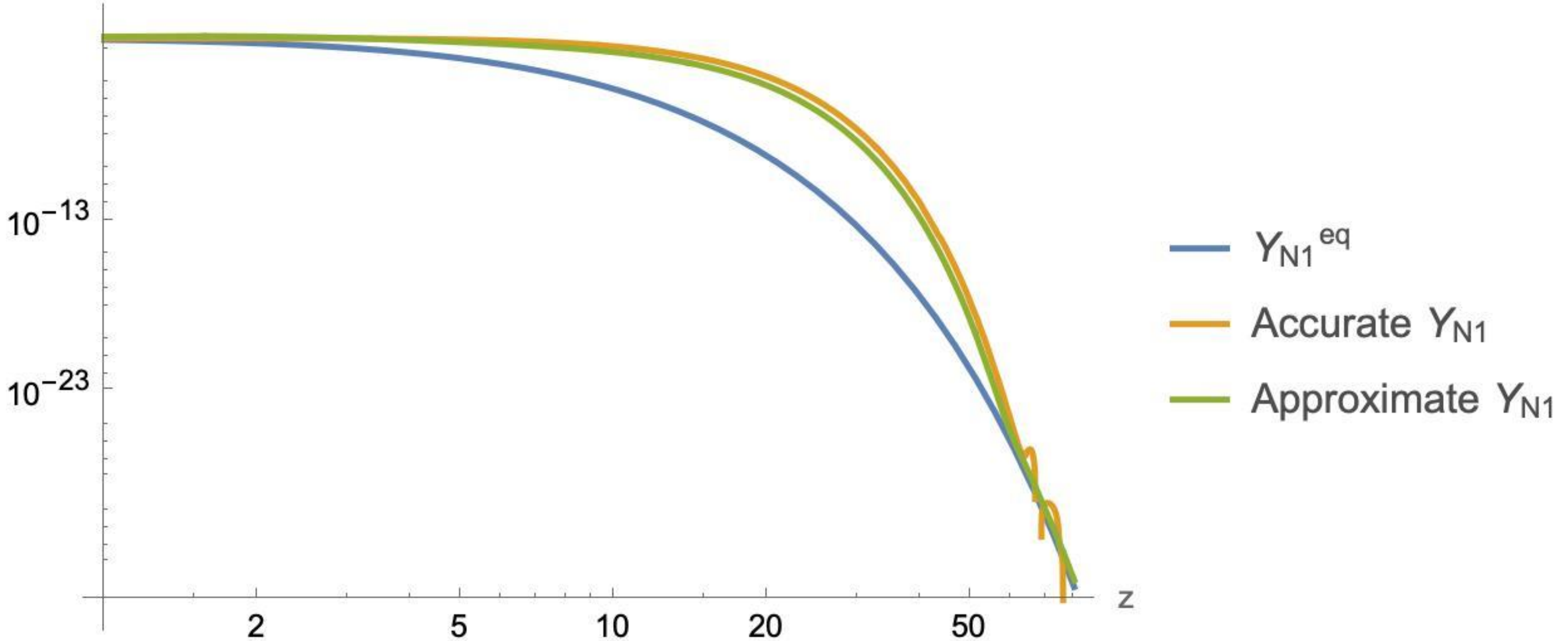
$$Y_{N1}^{eq} = Ae^{-z}z^{\frac{3}{2}}$$
$$Y_{N1} = Ae^{-z}z^{\frac{3}{2}} - A\frac{H_1}{\Gamma_{N1}}\frac{3}{2}e^{-z}z^{-\frac{1}{2}} + A\frac{H_1}{\Gamma_{N1}}e^{-z}z^{\frac{1}{2}}$$

- Region II ($z_f < z$):

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

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

Seesaw mechanism

- Could come from type 1 seesaw 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

$$m_{\nu,L} \simeq \frac{(\lambda v)^2}{m_{\nu,R}}$$

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

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

CP violation

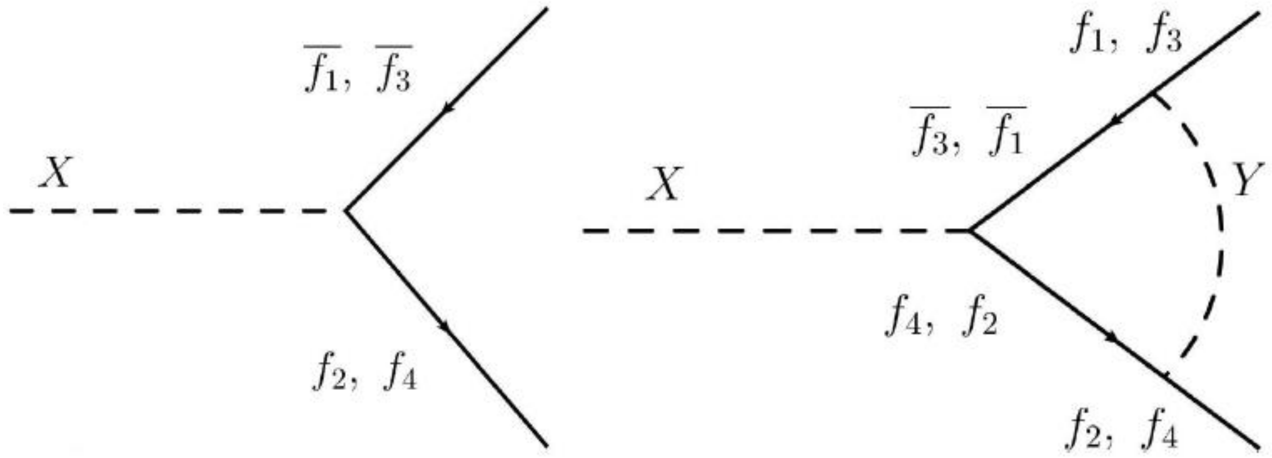
In order to generate CP violation it is necessary for mixing between tree level and one loop Interactions.

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

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

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