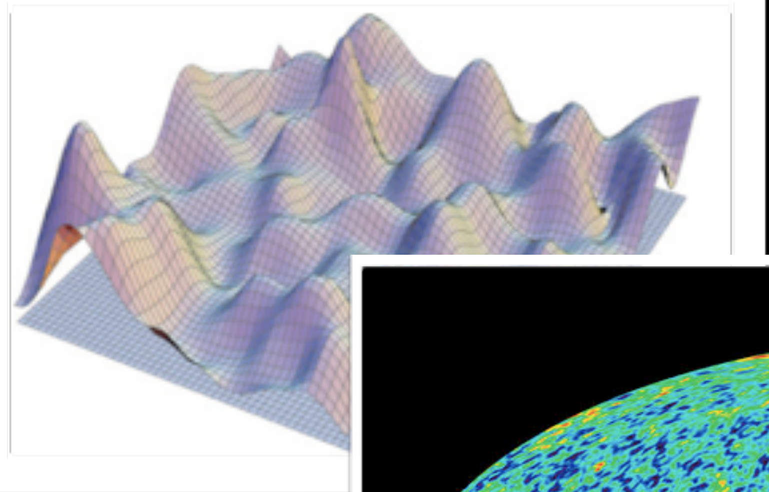
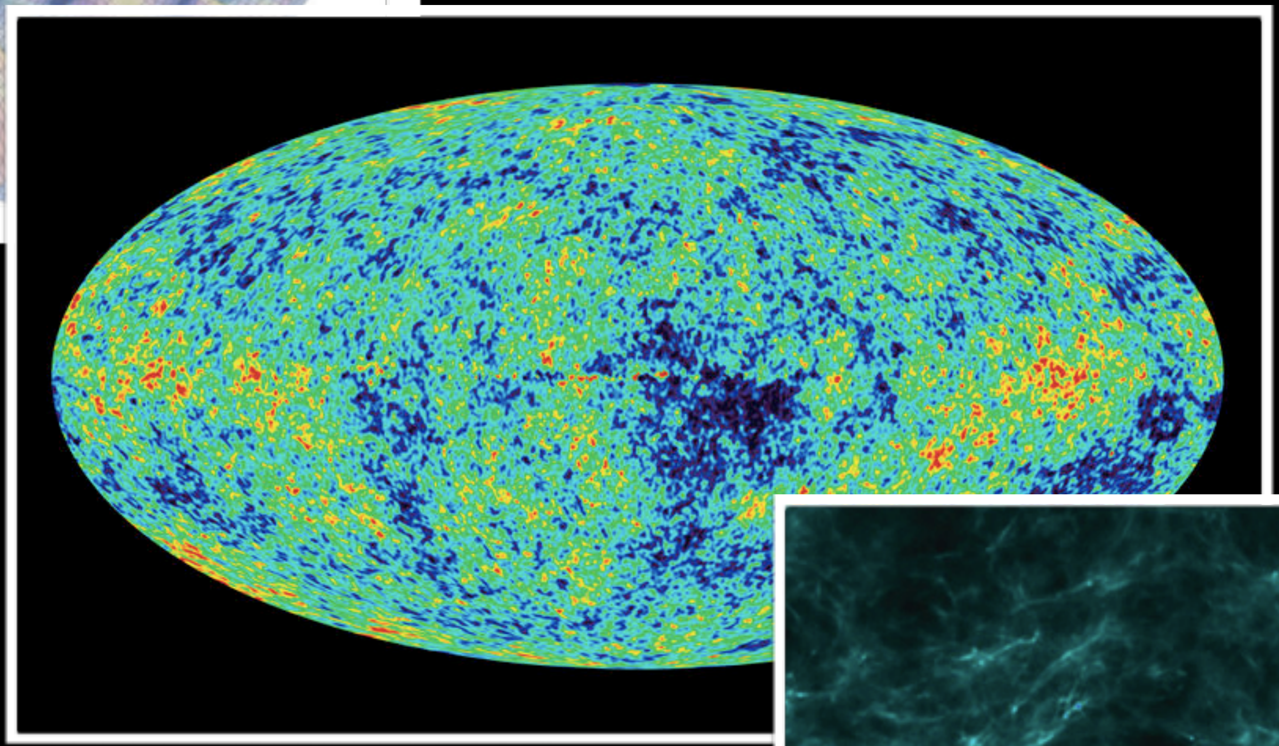
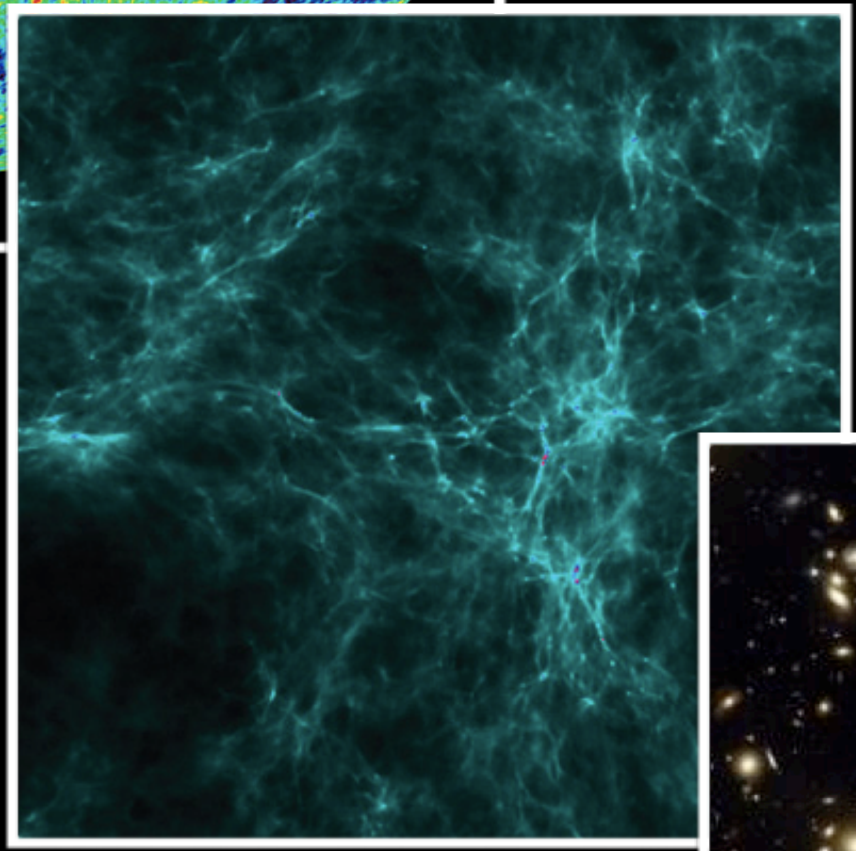
Triplet seesaw model: from inflation to asymmetric DM and leptogenesis







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- C.A., J.O.Gong and N.Sahu, arXiv:1206.0009 [hep-ph]
- C.A. and N.Sahu, Nucl.Phys.B854, arXiv:1108.3967 [hep-ph]

The heavy triplet scalar model: $\Delta(3,2)$ under $SU(2)_L \times U(1)_Y$ + SM + Dark Matter

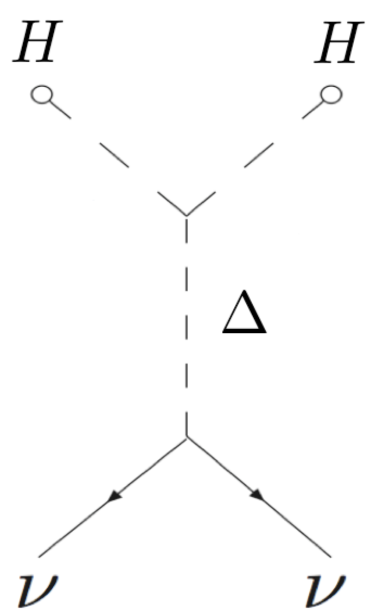
$$V_J(\Delta, H) = M_\Delta^2 \Delta^\dagger \Delta + \frac{\lambda_\Delta}{2}(\Delta^\dagger \Delta)^2 - M_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2 + \lambda_{\Delta H} H^\dagger H \Delta^\dagger \Delta + \frac{1}{\sqrt{2}}\left[\mu_H \Delta^\dagger H H + \text{h.c.}\right]$$

Higgs physics constraint $\longrightarrow$ $M_\Delta = 10^8$ GeV

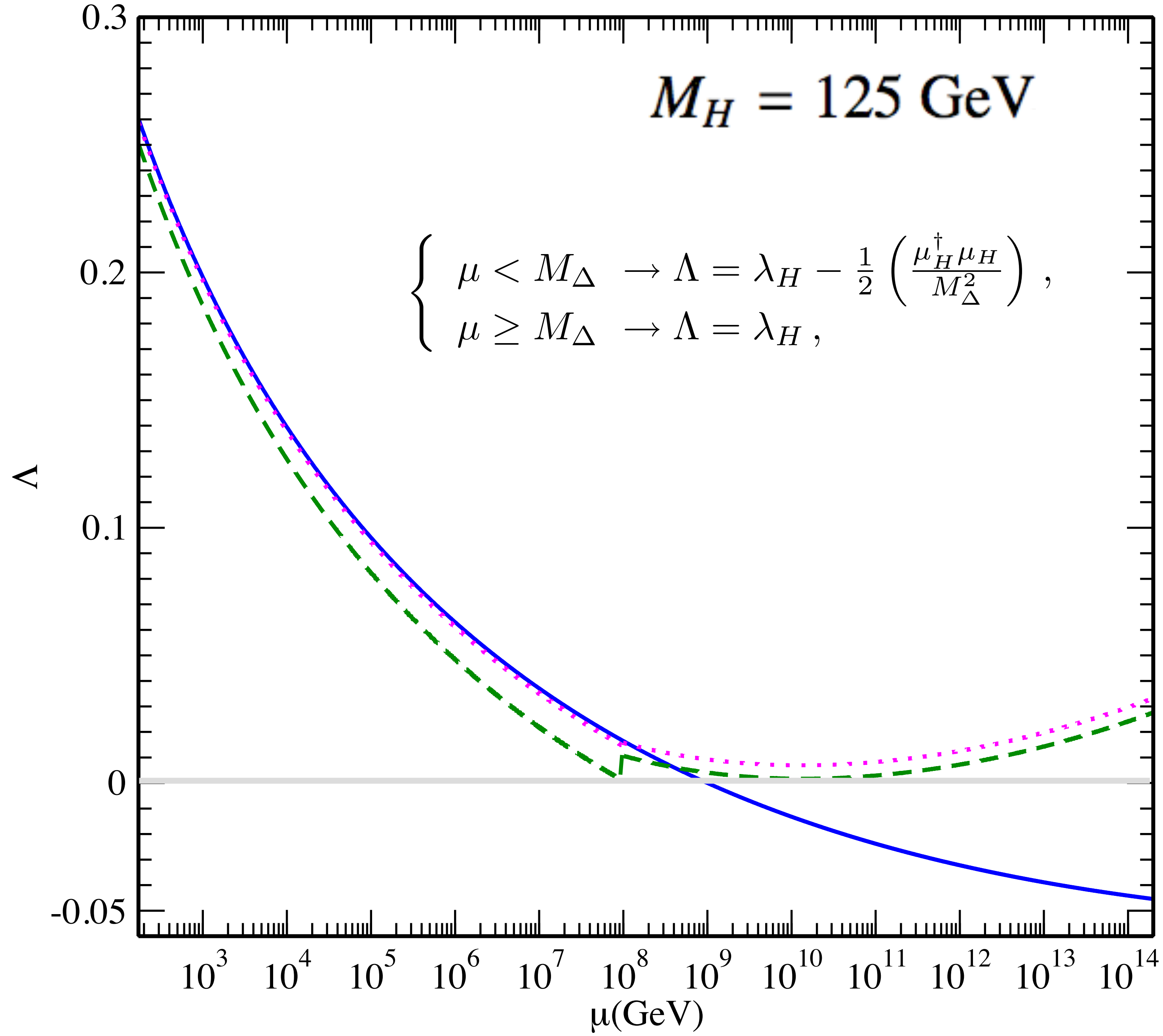
Neutrino/Visible matter sector

$$-\mathcal{L} \supset \frac{1}{\sqrt{2}}\left[f_L \Delta L L + \text{h.c.}\right]$$

$$(\Delta L = 2)$$



$$M_\nu = \sqrt{2} f_L \langle \Delta \rangle = f_L f_H \frac{-v^2}{M_\Delta}$$



type II seesaw, i.e.: Valle, Schechter '80; Cheng, Li '80; Lazarides, Shafi, Wetterich '81.

Asymmetric Dark Matter: Inert doublet with Z_2 flavour symmetry

$(2,-1) \quad SU(2)_L \times U(1)_Y$

Scalar DM

$$\chi = \begin{pmatrix} \chi^+ \\ \frac{S+iA}{\sqrt{2}} \end{pmatrix}$$

$$\langle \chi \rangle = 0$$

$$V(\Delta, H, \chi) = M_\chi^2 \chi^\dagger \chi + \lambda_\chi (\chi^\dagger \chi)^2 + [\mu_\chi \Delta^\dagger \chi\chi + \text{h.c.}] + \lambda_3 |H|^2 |\chi|^2 + \lambda_4 |H^\dagger \chi|^2 + \frac{\lambda_5}{2} [(H^\dagger \chi)^2 + \text{h.c.}]$$

- U(1) global symmetry (Peccei-Quinn like) for $\lambda_5 \to 0$
- small mass splitting (keV)

$$\Delta M^2 \equiv M_S^2 - M_A^2 = \lambda_5 v^2 \,.$$

- coupling is complex, CP net asymmetry generated via out of equilibrium process $\Delta \to \chi\chi$
- Wash out processes, asymmetry may get erased

Fermionic DM

$$\psi \equiv (\psi_{\rm DM}, \psi_-)$$

$$-\mathcal{L} \supset \overline{\psi} i \gamma^\mu \mathcal{D}_\mu \psi + M_D \overline{\psi}\psi + \frac{1}{\sqrt{2}} \left[f_\psi \Delta \psi\psi + \text{h.c.} \right]$$

$$\mathcal{M} = \begin{pmatrix} M_D & m/2 \\ m/2 & M_D \end{pmatrix}$$

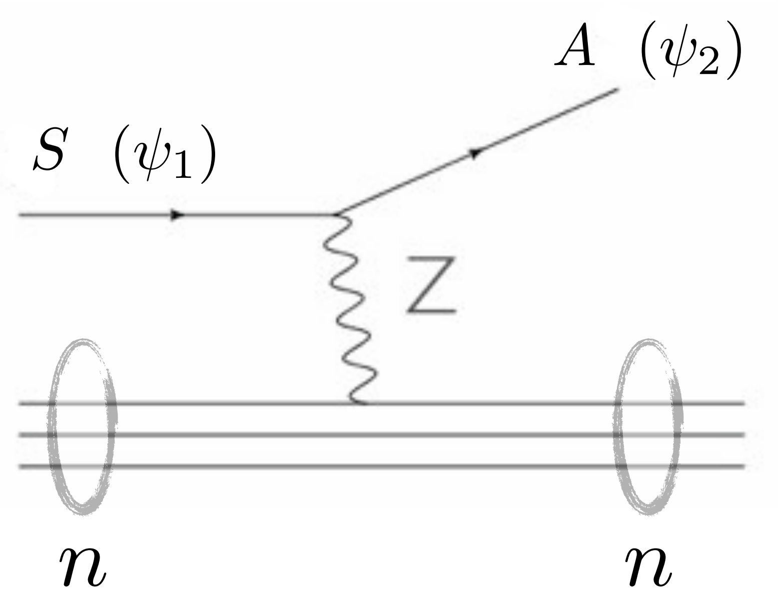
$$m = \sqrt{2} f_\psi \langle \Delta \rangle = f_H f_\psi \frac{-v^2}{M_\Delta} \sim \mathcal{O}(100)\ \text{keV}$$

- coupling is complex, CP net asymmetry generated via out of equilibrium process $\Delta \to \psi\psi$
- No wash out processes, asymmetry is not erased
- Hierarchy between Majorana masses of DM and neutrinos

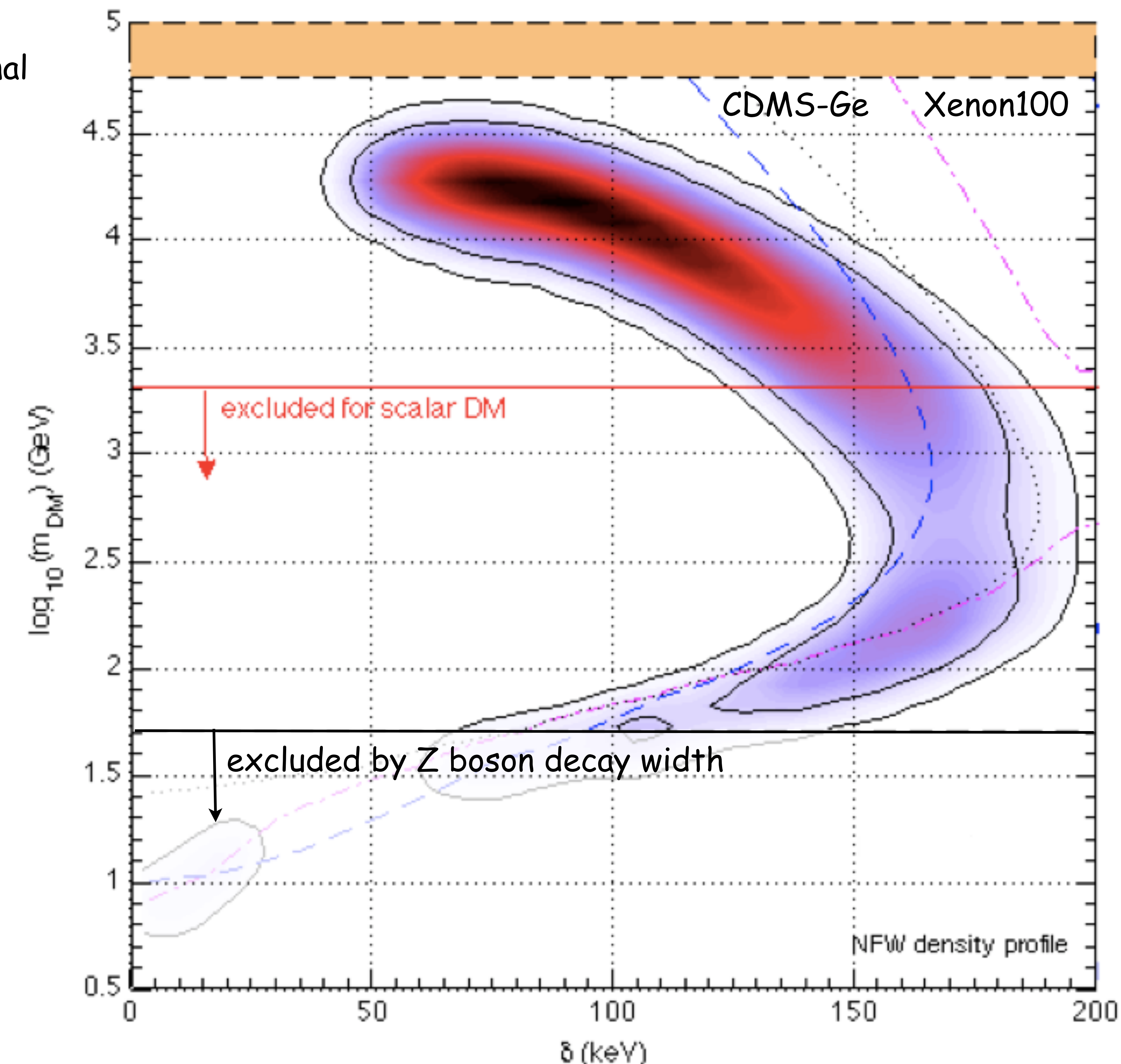
$$R \equiv \frac{M_\nu}{m} = \frac{f_L}{f_\psi} \approx \mathcal{O}(10^{-5})$$

Direct detection constraints on DM

(i) the DM has non zero hypercharge, the interaction with the Z should be off diagonal not to be excluded by direct detection
(ii) inelastic scattering off nucleus



$$v_{min} = c\sqrt{\frac{1}{2M_N E_R}}\left(\frac{M_N E_R}{\mu_n} + \delta\right)$$



- Scalar DM candidate excluded as explanation of DAMA by Xenon100
- Fermionic candidate allowed between 45 GeV and ~ 250 GeV

Scalar potential for inflation

$$S_J = \int d^4x\,\sqrt{-g}\left[\frac{R}{2} + \left(\xi_H H^\dagger H + \xi_\Delta \Delta^\dagger \Delta + c.c.\right) R - |\mathcal{D}_\mu H|^2 - |\mathcal{D}_\mu \Delta|^2 - V_J(H,\Delta)\right]$$

Jordan frame

(i) conformal transformation $\Omega^2 = 1 + 2\xi_\Delta|\Delta|^2 + 2\xi_H|H|^2$ → Einstein frame

(ii) redefinition of the three degrees of freedom (h, δ and θ) -> (φ, r and θ)

(iii) large field limit

$$V(r,\varphi,\theta) = \frac{\lambda_H/2 + \lambda_{H\Delta}r^2 + \lambda_\Delta r^4/2}{4(\xi_H + \xi_\Delta r^2)^2}\left(1 - e^{-2\varphi/\sqrt{6}}\right)^2 + \frac{M_H^2 + M_\Delta^2 r^2}{2(\xi_H + \xi_\Delta r^2)} e^{-2\varphi/\sqrt{6}}\left(1 - e^{-2\varphi/\sqrt{6}}\right)$$
$$+ \frac{\mu_H r\cos\theta}{2(\xi_H + \xi_\Delta r^2)^{3/2}} e^{-\varphi/\sqrt{6}}\left(1 - e^{-2\varphi/\sqrt{6}}\right)^{3/2}.$$

(i) the quartic term is dominant for $M_\Delta \simeq \mu_H < 10^{-6}$, because the mass terms are already suppressed by an additional exponential factor

(ii) note that a similar constraint on the lepton number violating term arises from Higgs physics

(iii) r is an heavy field, it does not contribute to inflation but sets quickly to its minimum

(iv) study of the minimum of the potential depending only on r

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non minimal couplings to gravity
Salopek, Bond and Bardeen '89

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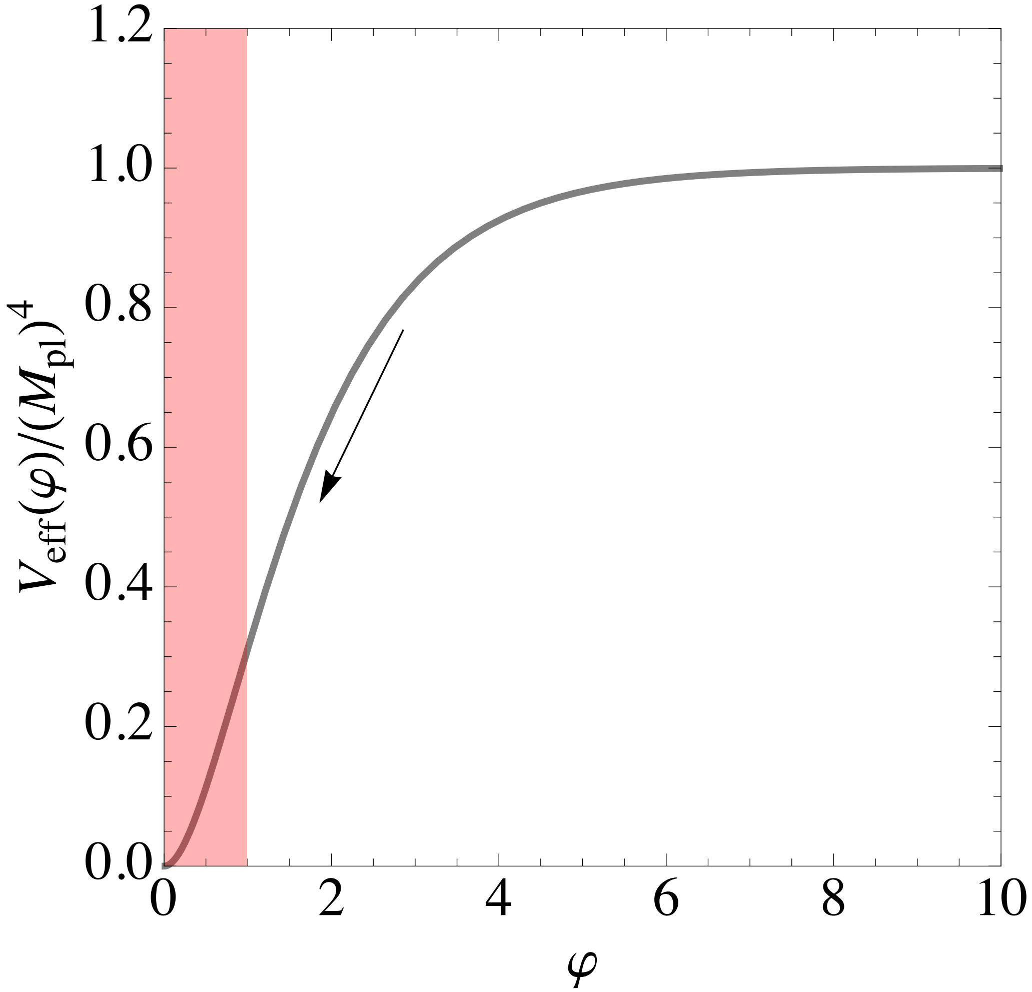
Slow-roll inflationary phase

$$V(\varphi) = V_0 \left(1 - e^{-2\varphi/\sqrt{6}}\right)^2$$

- Effective final potential is equivalent to Higgs inflation (Bezrukov and Shaposnikov '07)
- V_0 depends on the minimum in which rolls $r = \frac{\delta}{h}$

Mixed Inflaton	Pure Higgs Inflaton	Pure Triplet Inflaton
$r^2 = (\lambda_{H\Delta}\xi_H - \lambda_H\xi_\Delta)/(\lambda_{H\Delta}\xi_\Delta - \lambda_\Delta\xi_H)$	$r^2 \to 0$	$r^2 \to \infty$
$V_0^{(\mathrm{mixed})} = \frac{\lambda_\Delta\lambda_H - \lambda_{H\Delta}^2}{8(\lambda_\Delta\xi_H^2 + \lambda_H\xi_\Delta^2 - 2\lambda_{H\Delta}\xi_\Delta\xi_H)}$	$V_0^{(H)} = \frac{\lambda_H}{8\xi_H^2}$	$V_0^{(\Delta)} = \frac{\lambda_\Delta}{8\xi_\Delta^2}$



$$N = \int_e^\star \frac{V}{V'} d\varphi = \frac{3}{4}\left[e^{2\varphi_\star/\sqrt{6}} - e^{2\varphi_e/\sqrt{6}} - \frac{2}{\sqrt{6}}(\varphi_\star - \varphi_e)\right]$$

$\Delta N_\star = 55.6$

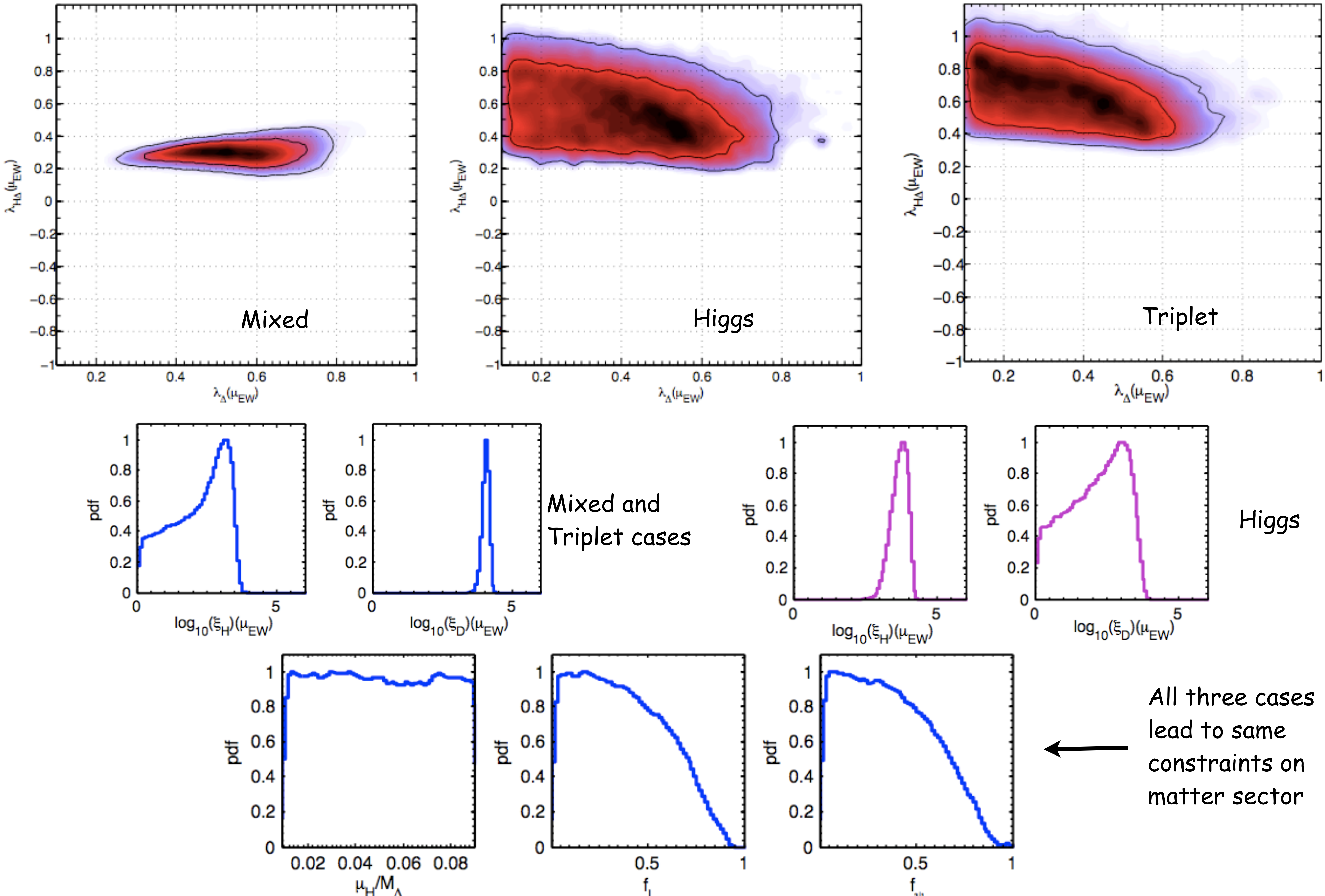
$\epsilon(\varphi_e) = 1$

$$\begin{cases} \varphi_e = -\frac{\sqrt{6}}{2}\log\left(2\sqrt{3} - 3\right) = 0.940 \\ \varphi_\star = 5.36 \end{cases}$$

$$\mathcal{P}_\mathcal{R}(k_0) = \frac{V(\varphi_\star)}{12\pi^2}\left(\frac{\partial N}{\partial \varphi_\star}\right)^2 = \frac{V(\varphi_\star)}{24\pi^2\epsilon(\varphi_\star)} = (2.43 \pm 0.11) \times 10^{-9}$$

V_0 normalized at the pivot scale of WMAP7

Constraints on the couplings (RGes from EW to Unitarity scale)

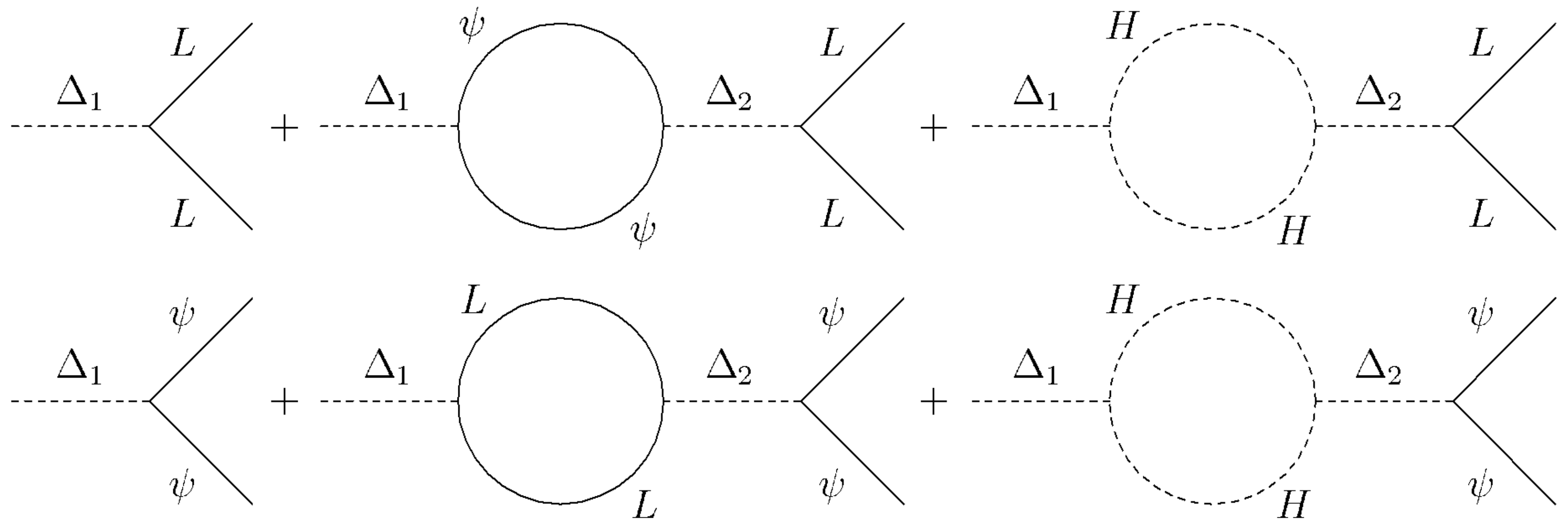


Generation of the asymmetries

triplet leptogenesis: Hambye, Radial, Strumia '05 and Chun, Scopel '07

- tree level decay channels $\Delta \to LL \quad \Delta \to HH \quad \Delta \to \psi\psi$

- to generate CP asymmetries needed at least 2 triplets -> decay of the lightest mass eigenstate: $\zeta_1^+ \; \zeta_1^-$



$$\epsilon_L = 2\left[\mathrm{Br}(\zeta_1^- \to \ell\ell) - \mathrm{Br}(\zeta_1^+ \to \ell^c\ell^c)\right]$$

$$\epsilon_\psi = 2\left[\mathrm{Br}\left(\zeta_1^- \to \psi_{\rm DM}\psi_{\rm DM}\right) - \mathrm{Br}\left(\zeta_1^+ \to \psi^c_{\rm DM}\psi^c_{\rm DM}\right)\right] \equiv \epsilon_{\rm DM}$$

- 5 free parameters, considering the DM mass, while the triplet mass is fixed at 10^8 GeV and the neutrino mass at 0.05 eV

$$\sum_j \epsilon_j = 0 \qquad \sum_j B_j = 1 \qquad |\epsilon_j| \leq 2\, B_j \qquad \Gamma_1 = \frac{M_1}{8\pi}\left(|f_{1H}|^2 + |f_{1\psi}|^2 + |f_{1L}|^2\right)$$

Boltzmann equations for out of equilibrium decay

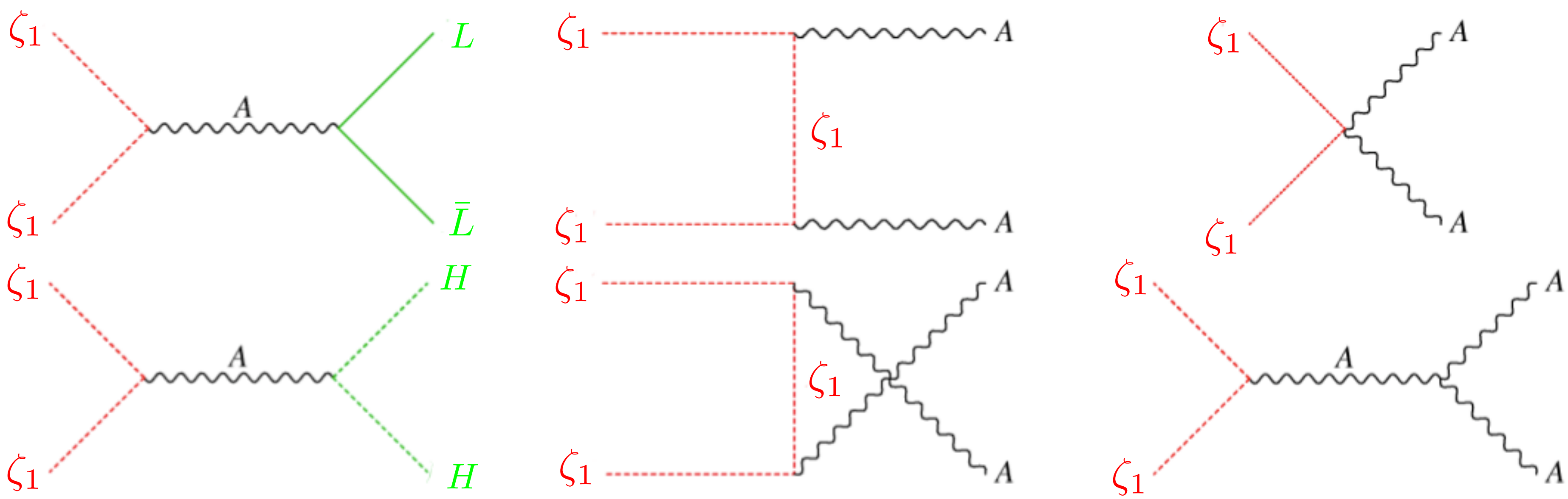
- Defining the triplet number density and the asymmetries (efficiency factors) as:

$$X_\zeta = n_{\zeta_1^-}/s \equiv n_{\zeta_1^+}/s,$$

$$\eta_i = \frac{Y_i}{\epsilon_i \, X_\zeta\big|_{T \gg M_1}}$$

$$Y_\zeta = (n_{\zeta_1^-} - n_{\zeta_1^+})/s$$

- The relevant processes contributing to triplet leptogenesis consist in:
  - (i) decays and inverse decays
  - (ii) scattering $\Delta L = 2$ such as $LL \to \zeta_1 \to HH$.
  - (iii) scattering $\Delta\zeta_1 = 2$ such as:

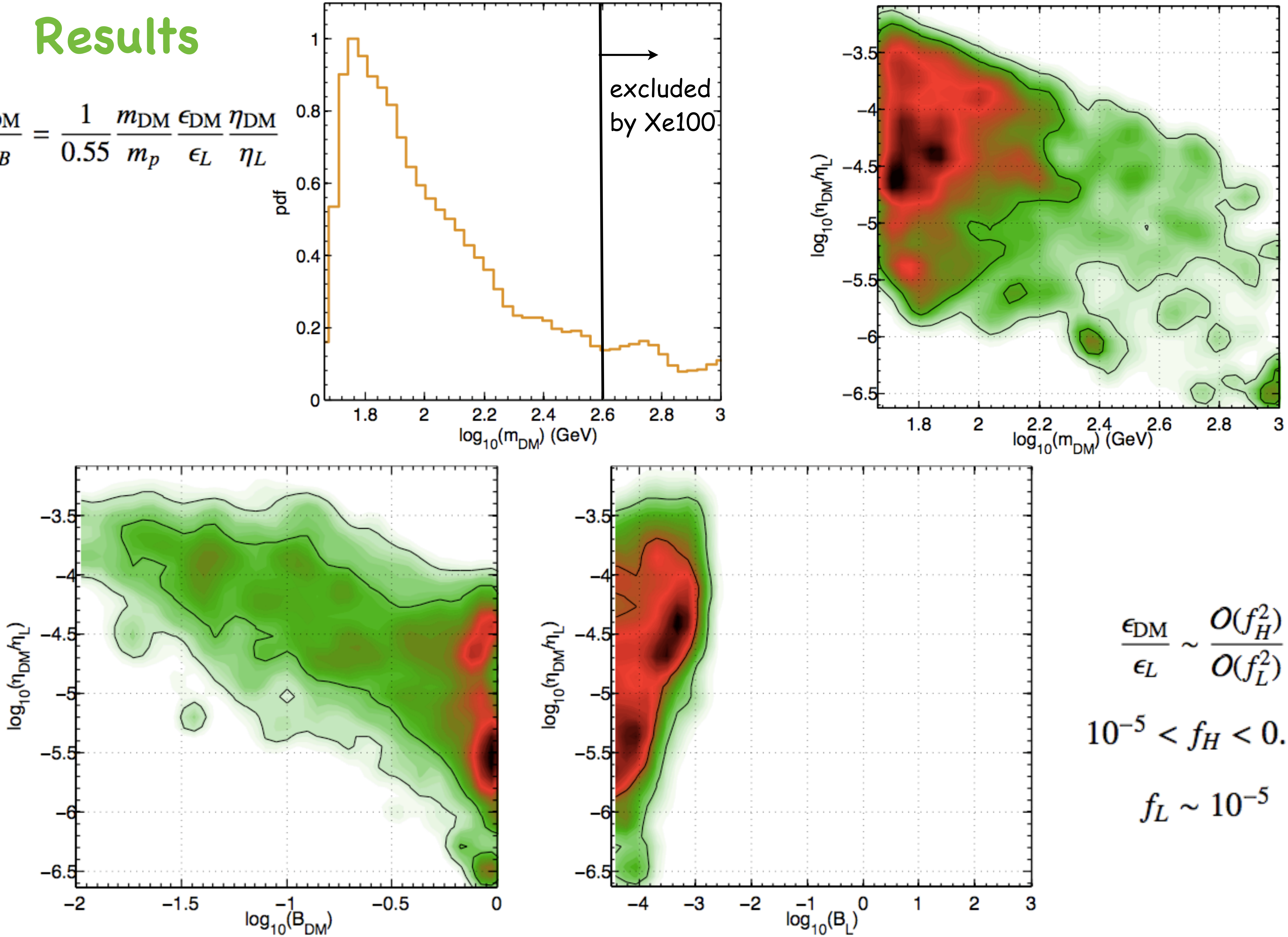


- Asymmetry transferred to baryon sector via SU(2) sphalerons
- Parameter space sampled via Markov-Chain Monte Carlo techniques, with a likelihood demanding:

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{1}{0.55}\frac{m_{DM}}{m_p}\frac{\epsilon_{DM}}{\epsilon_L}\frac{\eta_{DM}}{\eta_L} \qquad \bar{\eta}_b \pm \sigma_{\eta b} = (6.15 \pm 0.25) \times 10^{-10} \qquad 2Y_\zeta + \sum_j Y_j = 0$$

Results

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{1}{0.55}\frac{m_{DM}}{m_p}\frac{\epsilon_{DM}}{\epsilon_L}\frac{\eta_{DM}}{\eta_L}$$



$$\frac{\epsilon_{DM}}{\epsilon_L} \sim \frac{\mathcal{O}(f_H^2)}{\mathcal{O}(f_L^2)}$$

$$10^{-5} < f_H < 0.1$$

$$f_L \sim 10^{-5}$$

Summary

- Presented phenomenology of a heavy triplet extension of the SM

  - triplet at 10^8 GeV scale prevents vacuum instability due to Higgs quartic coupling running negative with a Higgs at 125 GeV;

  - allowing non minimal couplings to gravity, the triplet mixed with the Higgs behaves as inflaton;

  - the low energy effective theory generates neutrino masses via type-II seesaw;

  - fermionic asymmetric DM candidate is allowed, with inelastic scattering of nucleus as direct detection signature;

  - out of equilibrium decay of the triplet generates both the baryon and DM asymmetries via leptogenesis route.

- Future prospects

  - the triplet is heavy, therefore the quartic couplings are not measurable at LHC; to distinguish between the 3 cases of inflation a proper numerical treatment is due, including the multi field dynamics;

  - the scale of the triplet can be lowered at TeV scale in order to lead to visible signatures at LHC, i.e. via dilepton signals.

  - careful study of oscillations - gauge interactions interplay for arising the asymmetry

Thanks for your attention!

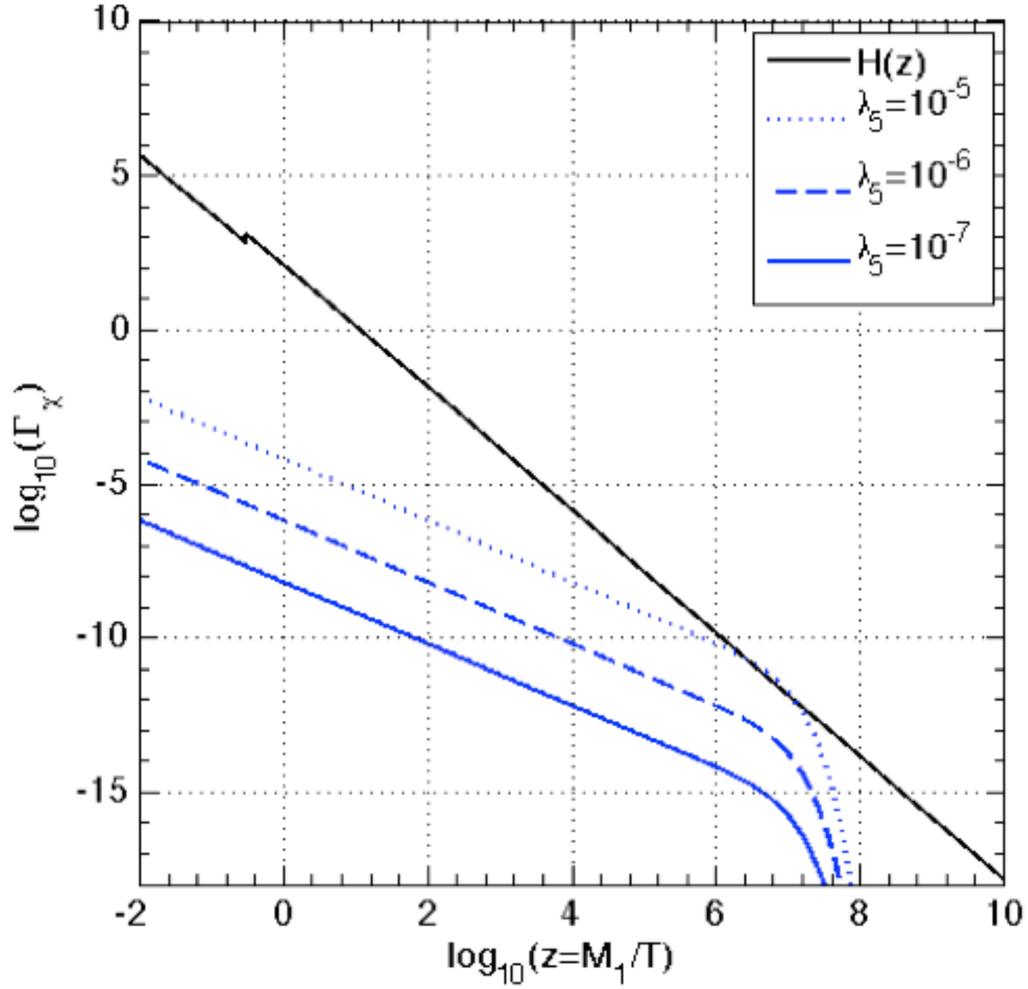
Back-up slides

Wash-out processes

(1) DM number violating processes

$$\chi\chi \;\rightarrow\; \Delta \;\rightarrow\; HH$$
$$\chi\chi \;\rightarrow\; H^\dagger H^\dagger$$
$$\chi\chi \rightarrow H \rightarrow \bar{f}f$$

For $\lambda_5 \lesssim 10^{-5}$ these processes remain out of equilibrium



(2) Oscillations

$$|\chi_0\rangle = \frac{1}{\sqrt{2}}(S+iA)$$
$$|\bar{\chi}_0\rangle = \frac{1}{\sqrt{2}}(S-iA)$$

$$P_{|\chi_0\rangle\rightarrow|\bar{\chi}_0\rangle} \simeq \frac{1}{2}\left[1-\cos\left(\frac{\Delta M^2(t-t_{\rm EW})}{2E}\right)\right]$$

$$t-t_{\rm EW} \sim 4\times10^{-10}{\rm s}\left(\frac{T}{100{\rm GeV}}\right)\left(\frac{{\rm keV}^2}{\Delta M^2}\right)$$

To preserve the asymmetry the DM should freeze out before it starts oscillate:

$$M_{\chi_0} \gtrsim x_f T_{\rm EW} \gtrsim 2\ {\rm TeV}$$

Renormalization group equations with heavy triplet (I)

Schmidt '07; Gogoladze, Okada and Shafi '08

$$\beta_X = dX/d\ln\mu$$

Our contribution is the addition of the RG for the DM and for the non minimal couplings to gravity

- Above the mass scale of the triplet:

$$16\pi^2\beta_{\lambda_H} = 12\lambda_H^2 + 6\lambda_{H\Delta}^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda_H + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2g_2^2 + g_2^4\right) + \left(12\lambda_H Y_t^2 - 12Y_t^4\right)$$

$$16\pi^2\beta_{\lambda_\Delta} = -\left(\frac{36}{5}g_1^2 + 24g_2^2\right)\lambda_\Delta + \frac{108}{25}g_1^4 + 18g_2^4 + \frac{72}{5}g_1^2g_2^2 + 14\lambda_\Delta^2 + 4\lambda_{\Delta H}^2$$
$$+ 4\lambda_\Delta \mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right) - 8\mathrm{Tr}\left(f_L^\dagger f_L f_L^\dagger f_L + f_\psi^\dagger f_\psi f_\psi^\dagger f_\psi\right)$$

$$16\pi^2\beta_{\lambda_{\Delta H}} = -\left(\frac{9}{2}g_1^2 + \frac{33}{2}g_2^2\right)\lambda_{\Delta H} + \frac{27}{25}g_1^4 + 6g_2^4 + \left(8\lambda_\Delta + 6\lambda_H + 4\lambda_{\Delta H} + 6Y_t^2\right)\lambda_{\Delta H}$$
$$+ 2\mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)\lambda_{\Delta H} - 4\mathrm{Tr}\left(f_L^\dagger f_L f_L^\dagger f_L + f_\psi^\dagger f_\psi f_\psi^\dagger f_\psi\right)$$

$$16\pi^2\beta_{g_1} = \frac{47}{10}g_1^3$$

$$16\pi^2\beta_{g_2} = -\frac{5}{2}g_2^3$$

$$16\pi^2\beta_{f_L} = 3\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)f_L - \frac{3}{2}\left(\frac{3}{5}g_1^2 + 3g_2^2\right)f_L + \left[\mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)\right]f_L$$

$$16\pi^2\beta_{f_\psi} = 3\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)f_\psi - \frac{3}{2}\left(\frac{3}{5}g_1^2 + 3g_2^2\right)f_\psi + \left[\mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)\right]f_\psi$$

$$16\pi^2\beta_{\mu_H} = \left(\lambda_H - 4\lambda_{\Delta H} - \frac{27}{10}g_1^2 - \frac{21}{2}g_2^2 + 6Y_t^2\right)\mu_H + \left[\mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right)\right]\mu_H$$

- Below the mass scale of the triplet, the triplet is integrated out, effective theory with

$$\Lambda = \lambda_H - \frac{1}{2}\left(\frac{\mu_H^\dagger \mu_H}{M_\Delta^2}\right) \qquad 16\pi^2\beta_{g_1} = \frac{41}{10}g_1^3 \qquad 16\pi^2\beta_{g_2} = -\frac{19}{6}g_2^3$$

Renormalization group equations with heavy triplet (II)

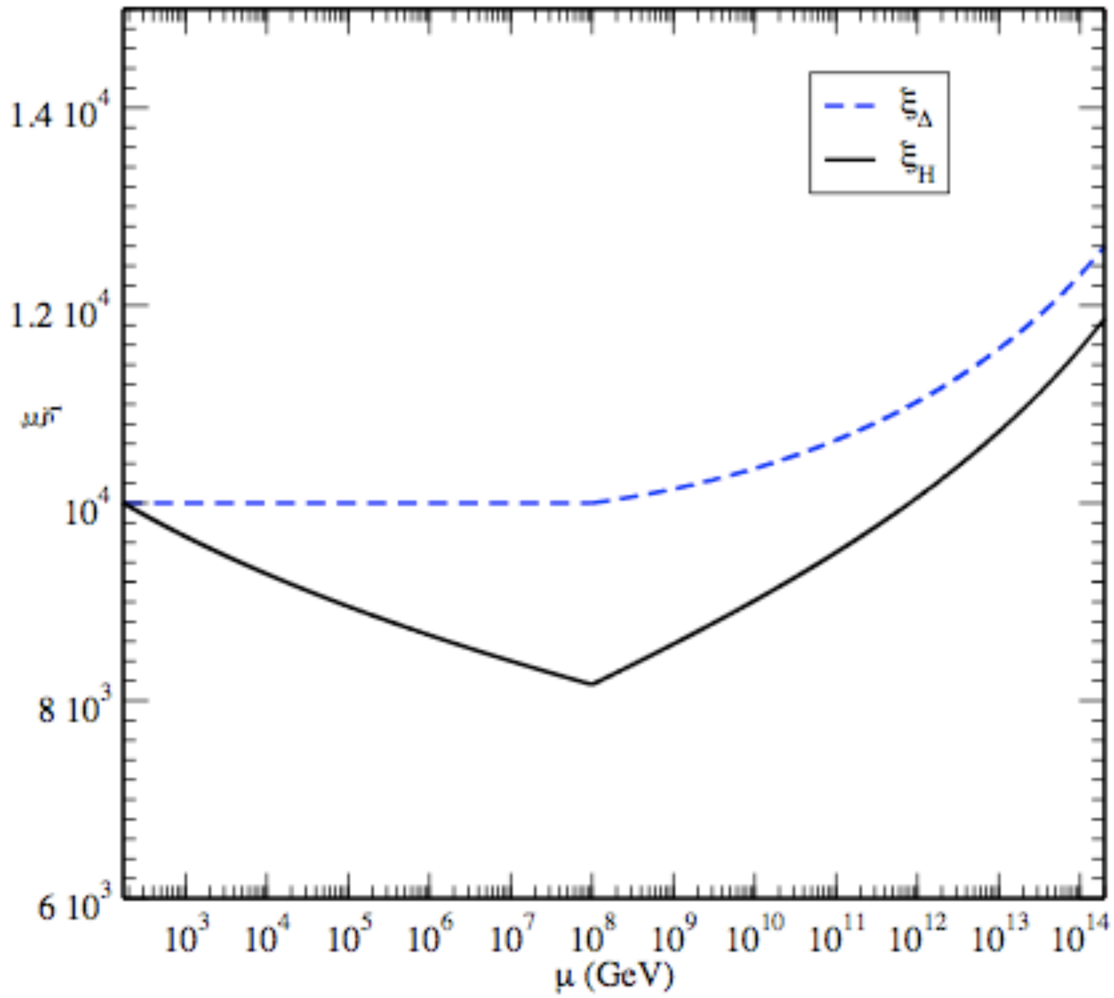
- the triplet is a singlet under SU(3) therefore the running of g_3 and Y_t are not modified

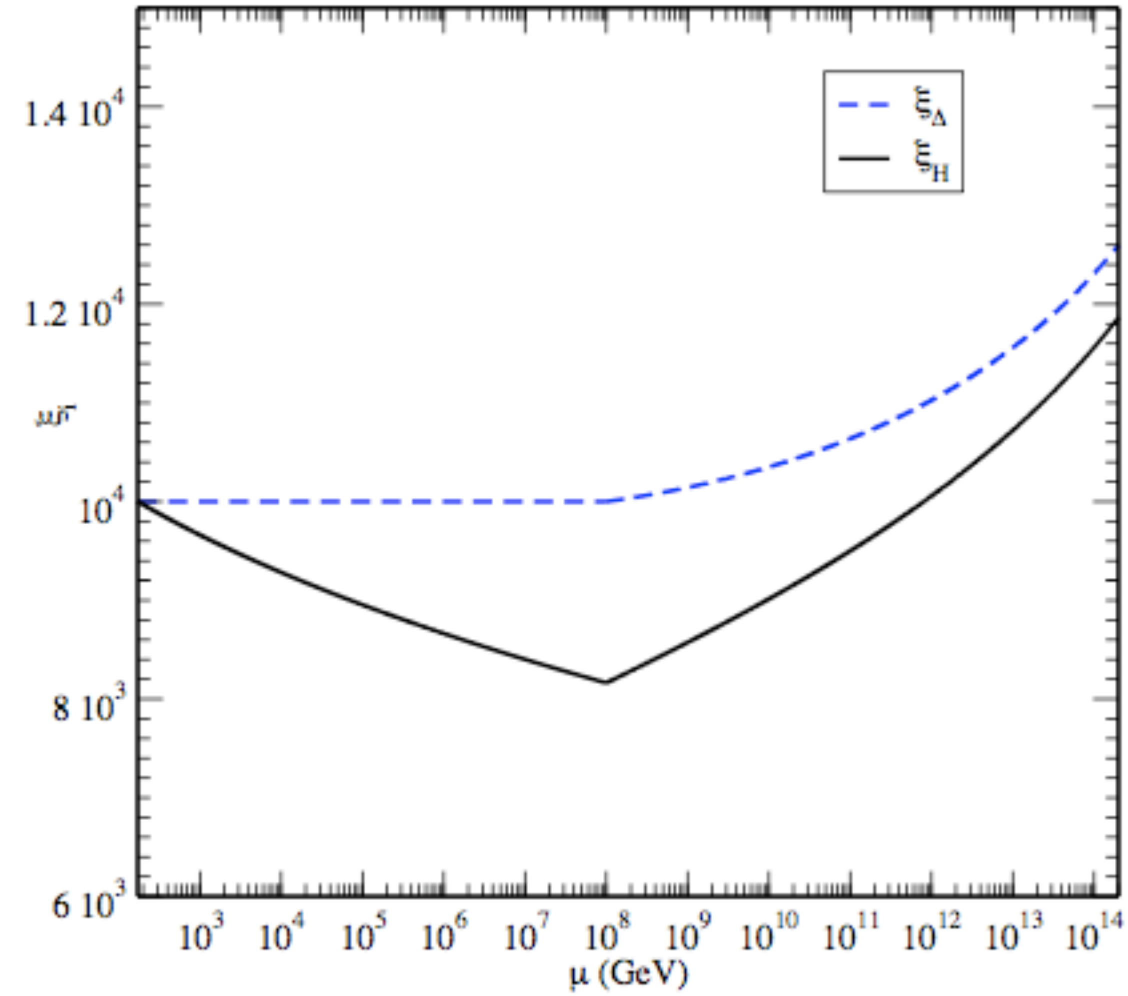
$$16\pi^2\beta_{Y_t} = \frac{9}{2}Y_t^3 - \left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2\right)Y_t \qquad 16\pi^2\beta_{g_3} = -7\,g_3^3$$

- non minimal coupling to gravity $\quad \gamma_X \equiv -X^{-1}dX/d\ln\mu \qquad \beta_{\xi_{ij}} = \left(\xi_{mn} - \frac{1}{6}\delta_{mn}\right)\gamma_{ij}^{kl}$

$$16\pi^2\beta_{\xi_H} = \left(\xi_H + \frac{1}{6}\right)\left(-\frac{9}{20}g_1^2 - \frac{9}{4}g_2^2 + \frac{3}{2}\lambda_H + 3Y_t^2\right) + 3\left(\xi_\Delta + \frac{1}{6}\right)\left(\lambda_{H\Delta} + \frac{\mu_H^2}{M_\Delta^2}\right)$$

$$16\pi^2\beta_{\xi_\Delta} = 2\left(\xi_H + \frac{1}{6}\right)\lambda_{H\Delta} + \left(\xi_\Delta + \frac{1}{6}\right)\left[4\lambda_\Delta + \frac{1}{2}\frac{\mu_H^2}{M_\Delta^2} + \mathrm{Tr}\left(f_L^\dagger f_L + f_\psi^\dagger f_\psi\right) - \frac{9}{5}g_1^2 - 6g_2^2\right]$$





Relevant Boltzmann equations (I)

$$X_\zeta \equiv n_{\zeta_1^-}/s = n_{\zeta_1^+}/s \qquad X_j = n_j/s \qquad j = L, H, \psi$$

$$Y_\zeta = (n_{\zeta_1^-} - n_{\zeta_1^+})/s \qquad Y_j = (n_j - n_{\bar{j}})/s$$

$$\Gamma_D = \Gamma_1 \frac{K_1(z)}{K_2(z)}$$

$$\Gamma_A = \frac{\gamma_A}{n_{\zeta_1}^{eq}}$$

$$\Gamma_{ID}^j = \Gamma_D \frac{X_\zeta^{eq}}{X_j^{eq}} \quad \text{and} \quad B_j = \frac{\Gamma_j}{\Gamma_1}$$

$$\Gamma_S = \gamma_S / n_{\zeta_1}^{eq}$$

$$\frac{dX_\zeta}{dz} = -\frac{\Gamma_D}{zH(z)}\left(X_\zeta - X_\zeta^{eq}\right) - \frac{\Gamma_A}{zH(z)}\left(\frac{X_\zeta^2 - X_\zeta^{eq\,2}}{X_\zeta^{eq}}\right)$$

$$\frac{dY_\zeta}{dz} = -\frac{\Gamma_D}{zH(z)} Y_\zeta + \sum_j \frac{\Gamma_{ID}^j}{zH(z)} 2 B_j Y_j$$

$$\frac{dY_j}{dz} = 2\left\{\frac{\Gamma_D}{zH(z)}\left[\epsilon_j (X_\zeta - X_\zeta^{eq})\right] + B_j \left(\frac{\Gamma_D}{zH(z)} Y_\zeta - \frac{\Gamma_{ID}^j}{zH(z)} 2Y_j\right) - \sum_k \frac{\Gamma_S^k}{zH(z)} \frac{X_\zeta^{eq}}{X_k^{eq}} 2Y_k\right\}$$

$$Y_B = -\frac{8n + 4m}{14n + 9m} Y_L = -0.55 Y_L$$

Transfer the asymmetry from the lepton sector to the baryon sector

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

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

$$\Gamma_1 = \frac{1}{8\pi}\frac{|m_\nu| M_1^2}{\langle H\rangle^2 \sqrt{B_L B_H}}$$

Relevant Boltzmann equations (II)

Triplet mass eigenstates

$$\frac{1}{2}\Delta_a^\dagger \left(\mathcal{M}_+^2\right)_{ab} \Delta_b + \frac{1}{2}(\Delta_a^*)^\dagger \left(\mathcal{M}_-^2\right)_{ab} \Delta_b^*$$

$$\mathcal{M}_\pm^2 = \begin{pmatrix} M_1^2 - iC_{11} & -iC_{12}^\pm \\ -iC_{21}^\pm & M_2^2 - iC_{22} \end{pmatrix}$$

$$C_{ab}^+ = \Gamma_{ab} M_b = \frac{1}{8\pi}\left(\mu_{aH}\mu_{bH}^* + \mu_{a\chi}\mu_{b\chi}^* + M_a M_b \sum_{\alpha\beta} f_{a\alpha\beta}^* f_{b\alpha\beta}\right)$$

$$\zeta_{1,2}^+ = A_{1,2}^+\Delta_1 + B_{1,2}^+\Delta_2$$

$$\Gamma_A = \frac{\gamma_A}{n_{\zeta_1}^{eq}}$$

Scattering interaction that produce a wash out of the asymmetry mainly due to gauge interactions

$$\gamma(\zeta_1^+\zeta_1^- \to \bar{f}f) = \frac{M_1^4\left(6g_2^4 + 5g_Y^4\right)}{128\pi^5 z}\int_{x_{\min}}^\infty dx\,\sqrt{x}K_1(z\sqrt{x})r^3$$

$$\gamma(\zeta_1^+\zeta_1^- \to H^\dagger H) = \frac{M_1^4\left(g_2^4 + g_Y^4/2\right)}{512\pi^5 z}\int_{x_{\min}}^\infty dx\,\sqrt{x}K_1(z\sqrt{x})r^3$$

$$\gamma(\zeta_1^+\zeta_1^- \to W^aW^b) = \frac{M_1^4 g_2^4}{64\pi^5 z}\int_{x_{\min}}^\infty dx\,\sqrt{x}K_1(z\sqrt{x})\left[r\left(5 + \frac{34}{x}\right) - \frac{24}{x^2}(x-1)\log\left(\frac{1+r}{1-r}\right)\right]$$

$$\gamma(\zeta_1^+\zeta_1^- \to BB) = \frac{3M_1^4 g_Y^4}{128\pi^5 z}\int_{x_{\min}}^\infty dx\,\sqrt{x}K_1(z\sqrt{x})\left[r\left(1 + \frac{4}{x}\right) - \frac{4}{x^2}(x-2)\log\left(\frac{1+r}{1-r}\right)\right]$$

$$\gamma(\zeta_1^+\zeta_1^- \to \bar{\psi}\psi) = \frac{M_1^4\left(6g_2^4 + 5g_Y^4\right)}{128\pi^5 z}\int_{x_{\min}}^\infty dx\,\sqrt{x}K_1(z\sqrt{x})r^3$$

$$H(z) = H(T = M_1)/z^2$$

$$r = \sqrt{1 - 4/x}$$

$$x = \hat{s}/M_1^2$$

Details on the inflationary potential (I)

Transformation due to the conformal factor

$$\tilde{g}_{\mu\nu} = \Omega^2 g^J_{\mu\nu}$$

$$V(H,\Delta) = \frac{V_J(H,\Delta)}{\Omega^4}$$

Field redefinition

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h \end{pmatrix} \qquad \Delta = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ \delta e^{i\theta} & 0 \end{pmatrix} \quad \Bigg\} \longrightarrow \quad \varphi = \sqrt{\frac{3}{2}}\log\left(1+\xi_\Delta\delta^2+\xi_H h^2\right), \quad r = \frac{\delta}{h}$$

Slow roll inflation

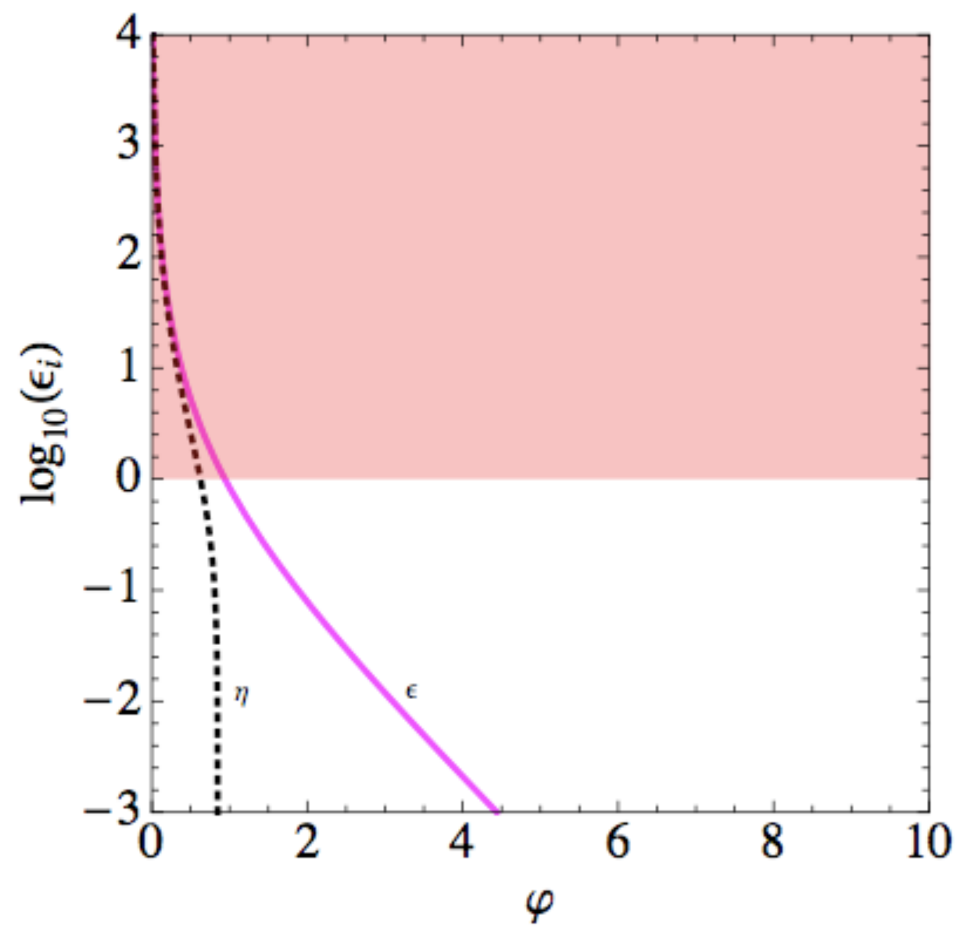
$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = \frac{4}{3}\frac{e^{-4\varphi/\sqrt{6}}}{\left(1-e^{-2\varphi/\sqrt{6}}\right)^2}$$

$$\eta = \frac{V''}{V} = -\frac{4}{3}e^{-2\varphi/\sqrt{6}}\frac{1-2e^{-2\varphi/\sqrt{6}}}{\left(1-e^{-2\varphi/\sqrt{6}}\right)^2}$$

$$\frac{\partial N}{\partial\varphi_\star} = \frac{\sqrt{6}}{4}\left(e^{2\varphi_\star/\sqrt{6}}-1\right) = 48.3\,.$$

$$n_{\mathcal{R}} = 1-2\epsilon+2\eta-\frac{2}{(\partial N/\partial\varphi_\star)^2} = 0.965$$

$$\xi_{\rm eff} = \frac{\sqrt{\lambda_{\rm eff}}}{\sqrt{96\pi^2\epsilon(\varphi_\star)\mathcal{P}_{\mathcal{R}}(k_0)}} = 48646.2\sqrt{\lambda_{\rm eff}} \sim 5\times10^4\sqrt{\lambda_{\rm eff}}$$



Details on the inflationary potential (II)

$$V_{\varphi\text{-indep}} = \frac{\lambda_H/2 + \lambda_\Delta/2r^4 + \lambda_{H\Delta}r^2}{4(\xi_H + \xi_\Delta r^2)^2}$$

$$\lambda_{H\Delta} + \sqrt{\lambda_H\lambda_\Delta} > 0$$
$$\lambda_H > 0$$
$$\lambda_\Delta > 0$$

1. Case mixed inflation

$$r^2 = (\lambda_{H\Delta}\xi_H - \lambda_H\xi_\Delta)/(\lambda_{H\Delta}\xi_\Delta - \lambda_\Delta\xi_H)$$

$$V_{\varphi\text{-indep}} \equiv V_0^{(\text{mixed})} = \frac{\lambda_\Delta\lambda_H - \lambda_{H\Delta}^2}{8\,(\lambda_\Delta\,\xi_H^2 + \lambda_H\,\xi_\Delta^2 - 2\lambda_{H\Delta}\xi_\Delta\xi_H)}$$

$$\left.\begin{array}{l} V_0^{(\text{mixed})} > 0 \\ dV^2/dr^2|_{r^2=r_0^2} > 0 \end{array}\right\}$$

$$\lambda_H\lambda_\Delta - \lambda_{H\Delta}^2 > 0,$$
$$\xi_H\lambda_{H\Delta} - \xi_\Delta\lambda_H < 0,$$
$$\xi_\Delta\lambda_{H\Delta} - \xi_H\lambda_\Delta < 0.$$

2. Case pure Higgs inflation

$$r^2 \to 0$$

$$V_{\varphi\text{-indep}} \equiv V_0^{(H)} = \frac{\lambda_H}{8\xi_H^2}$$

$$\xi_H\lambda_{H\Delta} - \xi_\Delta\lambda_H > 0,$$
$$\xi_\Delta\lambda_{H\Delta} - \xi_H\lambda_\Delta < 0.$$

3. Case pure triplet inflation

$$r^2 \to \infty:$$

$$V_{\varphi\text{-indep}} \equiv V_0^{(\Delta)} = \frac{\lambda_\Delta}{8\xi_\Delta^2}$$

$$\xi_H\lambda_{H\Delta} - \xi_\Delta\lambda_H < 0,$$
$$\xi_\Delta\lambda_{H\Delta} - \xi_H\lambda_\Delta > 0.$$

Details on the inflationary potential (III)

$$\frac{\mathcal{L}}{\sqrt{-\tilde{g}}} = -\frac{1}{2}\left[1 + \frac{1+r_0^2}{6(\xi_H + \xi_\Delta r_0^2)}\right](\partial_\mu\varphi)^2 - \frac{1}{2}\frac{r_0^2}{\xi_H + \xi_\Delta r_0^2}\left(1 - e^{-2\varphi/\sqrt{6}}\right)(\partial_\mu\theta)^2 - V(\varphi,\theta)$$

Assuming quartic dominant, the quadratic term is negligible:

$$\frac{V_M}{V_\lambda} \sim M_\Delta^2 r_0^2 e^{-2\varphi/\sqrt{6}}\frac{\xi_{\rm eff}}{\lambda_{\rm eff}} \sim M_\Delta^2\, 10^{-2}\frac{10^9}{\xi_{\rm eff}} r_0^2 \sim 10^7 M_\Delta^2 \frac{r_0^2}{\xi_{\rm eff}}$$

$$\varphi \sim 5$$

$$e^{-2\varphi/\sqrt{6}} \sim 10^{-2}$$

$$\lambda_{\rm eff}/\xi_{\rm eff}^2 \sim 10^{-9}$$

Assuming quartic dominant, the other term is made negligible demanding positivity of the potential:

$$\frac{V_\mu}{V_\lambda} \sim \mu_H e^{-\varphi/\sqrt{6}}\frac{1}{\lambda_{\rm eff}/\xi_{\rm eff}^2}\frac{r_0}{\xi_{\rm eff}^{3/2}} \sim 10^8 \mu_H \frac{r_0}{\xi_{\rm eff}^{3/2}}$$

$$V \sim 10^{-10}\left(1 - e^{-2\varphi/\sqrt{6}}\right)^2 + \frac{r_0}{2\xi_{\rm eff}^{3/2}}\mu_H \cos\theta e^{-\varphi/\sqrt{6}}\left(1 - e^{-2\varphi/\sqrt{6}}\right)^{3/2}$$

$$\mu_H \frac{r_0}{\xi_{\rm eff}^{3/2}} \lesssim 10^{-10} e^{\varphi/\sqrt{6}}\left(1 - e^{-2\varphi/\sqrt{6}}\right)^{1/2}$$

$$\frac{V_\mu}{V_\lambda} \sim 10^8 \mu_H \frac{r_0}{\xi_{\rm eff}^{3/2}} \lesssim 10^{-2}$$

Numerical estimation:

	N_0	$\partial N/\partial\varphi_\star$	$\partial N/\partial\chi_\star$
$r_0 = 1, \xi_{\rm eff} = 10^4, \mu_H = 10^{-7}, \varphi_\star = 5, \chi_\star = 10^{-3}$	42.0850	35.9478	-2.98106
the same as above but $\varphi_\star = 5.5$	64.3191	54.2294	-5.24260
the same as above but $\chi_\star = 10^{-3.5}$	42.0884	35.9508	-8.89659
$r_0 = 10, \xi_{\rm eff} = 10^3, \mu_H = 10^{-9}, \varphi_\star = 5, \chi_\star = 10^{-3}$	42.1880	36.0828	-1.07484×10^{-3}
the same as above but $\varphi_\star = 5.5$	64.5161	54.4816	-1.98455×10^{-3}
the same as above but $\chi_\star = 10^{-3.5}$	42.1880	36.0828	-3.39071×10^{-4}
$r_0 = 10^2, \xi_{\rm eff} = 50, \mu_H = 10^{-11}, \varphi_\star = 5, \chi_\star = 10^{-3}$	42.1785	36.0711	-4.19220×10^{-7}
the same as above but $\varphi_\star = 5.5$	64.4986	54.4600	-9.66338×10^{-7}
the same as above but $\chi_\star = 10^{-3.5}$	42.1785	36.0711	-3.55271×10^{-8}

More on the model

Scalar DM

$$V(\Delta, H, \chi) = M_\Delta^2 \Delta^\dagger \Delta + \lambda_\Delta (\Delta^\dagger \Delta)^2 + M_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + M_\chi^2 \chi^\dagger \chi + \lambda_\chi (\chi^\dagger \chi)^2 + [\mu_H \Delta^\dagger H H + \mu_\chi \Delta^\dagger \chi \chi + \text{h.c.}] + \lambda_3 |H|^2 |\chi|^2 + \lambda_4 |H^\dagger \chi|^2 + \frac{\lambda_5}{2}[(H^\dagger \chi)^2 + \text{h.c.}],$$

$$M_\chi^2 > 0 \qquad \lambda_L \equiv \lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_\chi \lambda_H}$$

$$M_{\chi^\pm}^2 = M_\chi^2 + \lambda_3 \frac{v^2}{2},$$

$$M_h^2 = 2\lambda_H v^2,$$

$$\lambda_5 = \frac{2 M_S \delta}{v^2}$$

$$M_S^2 = M_\chi^2 + (\lambda_3 + \lambda_4 + \lambda_5)\frac{v^2}{2},$$

$$M_A^2 = M_\chi^2 + (\lambda_3 + \lambda_4 - \lambda_5)\frac{v^2}{2}.$$

Fermionic DM

$$-\mathcal{L} \supset M_\Delta^2 \Delta^\dagger \Delta + M_D \overline{\psi}\psi + \frac{1}{\sqrt{2}}[\mu_H \Delta^\dagger H H + f_{\alpha\beta} \Delta L_\alpha L_\beta + g \Delta \psi \psi + \text{h.c.}]$$

$$\frac{1}{\sqrt{2}} g \Delta \psi \psi \equiv \frac{1}{\sqrt{2}} g \overline{\psi^c} i \tau_2 \Delta \psi = -\frac{1}{2} g [\sqrt{2}(\overline{\psi^c_-} \psi_- \Delta^{++}) + (\overline{\psi^c_-} \psi_{\rm DM} + \overline{\psi^c_{\rm DM}} \psi_-)\Delta^+ - \sqrt{2}(\overline{\psi^c_{\rm DM}} \psi_{\rm DM} \Delta^0)],$$

$$-\mathcal{L}_{\rm DMmass} = M_D [\overline{(\psi_{\rm DM})_L} (\psi_{\rm DM})_R + \overline{(\psi_{\rm DM})_R} (\psi_{\rm DM})_L] + m[\overline{(\psi_{\rm DM})^c_L} (\psi_{\rm DM})_L + \overline{(\psi_{\rm DM})^c_R} (\psi_{\rm DM})_R].$$

$$\mathcal{D}_\mu = \partial_\mu + i\sqrt{\frac{3}{5}} g_1 B_\mu + i g_2 t.W_\mu$$

Covariant derivative with GUT charge normalization

Triplet VEV

$$\langle \Delta \rangle = -\mu_H \frac{v^2}{\sqrt{2} M_\Delta^2}$$

$$v = \langle H \rangle = 246 \text{ GeV}$$

$$\langle \Delta \rangle < \mathcal{O}(1) \text{ GeV}$$

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta} = \frac{1 + 2x^2}{1 + 4x^2} \approx 1$$

$$x = \langle \Delta \rangle / v$$

The wash out processes for scalar DM

(1) DM number violating processes

$$\hat{\sigma}(\chi\chi \to \Delta \to HH) = \frac{1}{8\pi}\frac{|\mu_\chi|^2|\mu_H|^2}{(\hat{s}-M_1^2)^2}$$

$$\hat{\sigma}_\chi = \frac{\lambda_5^2}{32\pi}$$

$$\gamma_\chi = \frac{T}{64\pi^4}\int_{\hat{s}_{\min}}^{\infty} d\hat{s}\sqrt{\hat{s}}K_1\left(\frac{\sqrt{\hat{s}}}{T}\right)\hat{\sigma}_\chi$$

$$n_\chi^{\rm eq} = \frac{g_{\rm dof}M_\chi^2 T}{2\pi^2}K_2\left(\frac{M_\chi}{T}\right)$$

$$\Gamma_\chi = (\gamma_\chi/n_\chi^{\rm eq})$$

(2) Oscillations

$$|\chi_0\rangle = \frac{1}{\sqrt{2}}(S+iA)$$
$$|\bar{\chi}_0\rangle = \frac{1}{\sqrt{2}}(S-iA)$$

$$\left|\phi(x,t)\right\rangle = \frac{1}{\sqrt{2}}\left[e^{-i(E_S t-k_S x)}|S\rangle + i\,e^{+i(E_A t-k_A x)}|A\rangle\right]$$

$$E_S = \sqrt{k_S^2+M_S^2} \qquad E_A = \sqrt{k_A^2+M_A^2}$$

$$P_{|\chi_0\rangle\to|\bar{\chi}_0\rangle} = \left|\left\langle\bar{\chi}_0|\phi(x,t)\right\rangle\right|^2$$

$$P_{|\chi_0\rangle\to|\bar{\chi}_0\rangle} = \frac{1}{4}\left[2 - e^{-i[(E_S-E_A)t-(k_A-k_S)x]} - e^{+i[(E_S-E_A)t-(k_A-k_S)x]}\right]$$