Baryogenesis from dark matter annihilation

Jean Racker

Instituto de Física corpuscular (IFIC), Universidad de Valencia-CSIC

ICHEP 2014 - Valencia
Overview of some explanations for $\Omega_{DM} \sim 5 \Omega_B$

Baryogenesis from DM annihilations
   ♦ Main ingredients
   ♦ A mechanism for TeV scale baryogenesis
   ♦ A model that connects the baryon asymmetry, DM, and neutrino masses

Based on [JR, N. Rius, arXiv:1406.6105]
The content of the Universe

- Dark Energy: 68.3%
- Dark Matter: 26.8%
- Ordinary Matter: 4.9%

(Planck)
The coincidence problem (not the subject of this talk)

\[
\begin{align*}
\rho & \text{ [GeV cm}^{-3}] \\
\rho_{\text{radiation}} & \\
\rho_{\text{matter}} & \\
\rho_{\Lambda} & \\
T & \text{ [GeV]} \\
T_0 &
\end{align*}
\]

(figure from [Arkani-Hamed, Hall, Kolda, Murayama, 2000])

\[
\Omega_\gamma : \Omega_B : \Omega_{DM} : \Omega_\Lambda \sim 10^{-3} : 1 : 5 : 14
\]
Baryonic content: Asymmetric matter and antimatter domains should be larger than \( \sim \) the visible Universe (cosmic diffuse \( \gamma \)-ray background).

[Cohen, De Rújula, Glashow, 1998]

DM content: ? (only known from its gravitational influence). Hint:

\[
\Omega_\chi \equiv \frac{\rho_\chi}{\rho_{\text{cr}}} \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_{\chi}^2}{g_X^4}
\]

\( M_\chi \sim M_{\text{weak}} \sim 10^2 - 10^3 \text{ TeV}, \quad g_\chi \sim g_{\text{weak}} \sim 0.65 \quad \rightarrow \quad \Omega_\chi \sim 0.25 \)

WIMP miracle

Why \( \Omega_B \sim \Omega_{DM} \)?
Asymmetric Dark Matter

$\Omega_{DM}$ is due to a DM particle-antiparticle asymmetry.

1) **Generation** of a DM and/or B asymmetry

2) **Transfer** of asymmetries between DM and B sectors
   
   Transfer stops and asymmetries freeze at $T_f$ when
   
   $$\Gamma_{DM\leftrightarrow B} < H$$
   
   $$\mu_{DM}(T_f) \simeq \mu_B(T_f) \Rightarrow \begin{cases} 
   n_{DM}(T_f) \sim n_B(T_f) & \text{if } M_{DM} \ll T_f \\
   n_{DM}(T_f) \sim e^{-M_{DM}/T_f} n_B(T_f) & \text{if } M_{DM} \gtrsim T_f 
   \end{cases}$$

3) **Annihilation** of the symmetric component

- $n_{DM}(T_f) \sim n_B(T_f)$ and $\Omega_{DM} \sim 5 \Omega_B \implies M_{DM} \sim 5 \text{ GeV}$
  - dark QCD + mechanism for $\Lambda_{dQCD} \sim \Lambda_{QCD}$ [Y. Bai, P. Schwaller, 2013]

- WIMP miracle is a coincidence
Baryomorphosis
Mechanism to transform an initial $B$-asymmetry into a thermal WIMP-like density.

1) An initial asymmetry is built into $\Sigma$

2) Transfer of the $\Sigma$-asymmetry to “annihilons”: $\Sigma \rightarrow \phi_B \hat{\phi}_B \ldots$ at $T_d \ll m_\phi$ (when $\phi_B, \hat{\phi}_B$ are decoupled from the thermal bath)

3) Annihilation of the asymmetry in $\phi_B, \hat{\phi}_B$ via $\mathcal{O} = \lambda_B \phi_B \hat{\phi}_B \hat{H}^\dagger \hat{H}$:

$$n_{\phi_B}(T_d) \sim \frac{H(T_d)}{\langle \sigma v \rangle}$$

4) The remaining $\phi_B$ and $\hat{\phi}_B$ decay to SM baryons

[J. McDonald, 2010]
Baryogenesis for WIMPs

The B-asymmetry is generated in the late decay of a meta-stable WIMP after its thermal freeze out. Consider at least two WIMP-like particles:

- $\chi$: stable $\rightarrow$ DM
- $\chi_B$: meta-stable with $CP$ and $B$ decays $\rightarrow$ the B-asymmetry inherits the would-be miracle abundance from the WIMP parent (up to a suppression factor $\epsilon_{CP}$)

$$\frac{\Omega_B}{\Omega_{DM}} = \epsilon_{CP} \frac{m_p}{m_{\chi_B}} \frac{\Omega^{t\rightarrow\infty}_{\chi_B}}{\Omega_{DM}}$$

[Y. Cui, R. Sundrum, 2012]
Anthropic reasoning

A way to realize many values of $\frac{\Omega_{DM}}{\Omega_B}$
(e.g. Axion DM with Peccei-Quinn transition before inflation)

\[ + \]

Anthropic reasoning

- $\frac{\Omega_{DM}}{\Omega_B} \gg 1 \implies$ The largest objects that can cool and fragment are too small to make stars efficiently
- $\frac{\Omega_{DM}}{\Omega_B} \ll 1 \implies$ Slow growth of structure ($\Lambda$ could become dominant before structure formation)
Wimpy Baryogenesis

During the annihilation $\chi\chi \rightarrow L\Psi$, $\bar{L}\bar{\Psi}$ of WIMP-like DM, the Sakharov’s conditions may be satisfied. [Y. Cui, L. Randall, B. Shuve, 2012]

$$\frac{dY_{\Delta L}}{dz} \sim \epsilon \frac{dY_{\chi}}{dz} - Y_{\Delta L} \left[ \frac{\gamma_{\Psi}}{n_{eq}^L H} \right] - Y_{\Delta \Psi} \left[ \frac{\gamma_{\Psi,\bar{\Psi}}}{n_{eq}^\Psi H} \right] = \text{source} - \text{washes outs}$$

$Y_X \equiv n_X/s$, $z \equiv M_\chi/T$

$$|A(L\Psi \rightarrow \chi\chi)|^2 \sim |A(\bar{L}\bar{\Psi} \rightarrow \chi\chi)|^2$$

$n_L > n_{\bar{L}} \Rightarrow \int d\pi f_L f_{eq}^L |A(L\Psi \rightarrow \chi\chi)|^2 > \int d\pi f_{\bar{L}} f_{eq}^{\bar{L}} |A(\bar{L}\bar{\Psi} \rightarrow \chi\chi)|^2$

$n_\Psi > n_{\bar{\Psi}} \Rightarrow \int d\pi f_\Psi f_{eq}^\Psi |A(L\Psi \rightarrow \chi\chi)|^2 > \int d\pi f_{\bar{\Psi}} f_{eq}^{\bar{\Psi}} |A(\bar{L}\bar{\Psi} \rightarrow \chi\chi)|^2$

$$\downarrow$$

$\gamma(L\Psi \rightarrow \chi\chi) > \gamma(\bar{L}\bar{\Psi} \rightarrow \chi\chi)$
\[ \epsilon \Rightarrow \text{washouts} \]

\[ \chi \xrightarrow{S_1} L \rightleftharpoons \Psi \]

\[ \chi \xrightarrow{S_1} \bar{\Psi} \rightarrow \bar{L} \xrightarrow{S_2} \Psi \]

\[ \epsilon \sim \lambda^2, \quad \frac{\Gamma_\Psi}{H} \bigg|_{T=M_\chi} \sim \lambda^4 \frac{M_P}{M_\chi} \]
$L \Psi \leftrightarrow \bar{L} \bar{\Psi}$ washouts

\[ \frac{\Gamma_{\text{decay (anni.)}}}{H(T = M)} = \text{const.}, \quad \epsilon = \text{const.}, \quad \lambda^2 = 2 \times 10^{-4} \]
$L \psi \leftrightarrow \overline{L} \overline{\psi}$

washouts

\[
\frac{\Gamma_{\text{decay (anni.)}}}{H(T = M)} = \text{const}., \quad \epsilon = \text{const}., \quad \lambda^2 = 2 \times 10^{-4}
\]
There is a crucial point for this mechanism to work:

\[
\frac{dY_{\Delta L}}{dz} \sim -Y_{\Delta L} \left[ \gamma \left( \frac{L\Psi \rightarrow \bar{L}\bar{\Psi}}{n_{eq}^L H} \right) \right] - Y_{\Delta \Psi} \left[ \gamma \left( \frac{L\Psi \rightarrow \bar{L}\bar{\Psi}}{n_{eq}^\Psi H} \right) \right] + \ldots
\]

The first term decouples exponentially, but what about the second?

\[
\downarrow
\]

relation among \( Y_{\Delta \Psi} \) and \( Y_{\Delta L} \)

\[
\downarrow
\]

If \( Y_{\Delta \Psi} = c \, Y_{\Delta L} \quad \longrightarrow \quad \text{the mechanism does not work} \quad (c = \text{const.})
\]

\( Y_{\Delta \Psi} \) must vanish exponentially without erasing -or canceling- \( Y_{\Delta L} \)

\[
\text{fast } \Psi a_1 \leftrightarrow a_2 a_3 \quad \longrightarrow \quad \mu_\Psi = \sum_i \mu_i \quad \Longrightarrow \quad Y_{\Delta \Psi} \propto e^{-M_\Psi/T} \quad (m_i \ll M_\Psi)
\]

Alternatively, take a real scalar or Majorana fermion as the massive particle \( (Y_\Delta = 0) \) \quad [JR, N. Rius, arXiv:1406.6105]
Wimpy Baryogenesis via helicitogenesis

Step 1: Generation of helicity asymmetry

\[-\mathcal{L} = \lambda_a S_a \bar{N} P_R \nu + \lambda_a^* S_a \bar{\nu} P_L N + \ldots\]

\[\epsilon \equiv \frac{\gamma (\chi \chi \rightarrow \nu^+ N) - \gamma (\chi \chi \rightarrow \nu^- N)}{\gamma (\chi \chi \rightarrow \nu^+ N) + \gamma (\chi \chi \rightarrow \nu^- N)} = a \left( \frac{m_\nu}{M_\chi} \right)^0 + b \left( \frac{m_\nu}{M_\chi} \right)^1 + \ldots\]

\[a \propto \text{Im} \left[ (\lambda_1 \lambda_2^*)^2 \right] + \ldots, \quad b \left( \frac{m_\nu}{M_\chi} \right) \propto \text{Im} \left[ m_\nu M_\nu \lambda_1^2 \right] + \ldots\]

\[\hat{\rho}_\nu \text{ diagonal in } \{\nu^+, \nu^-\} \rightarrow \text{evolution equation for } Y_{\Delta \nu} \equiv Y_{\nu^+} - Y_{\nu^-}\]
Step 2: Transfer of helicity asymmetry

\[ Y_{\Delta \nu} \xrightarrow{\text{Yukawas}} Y_{\Delta L} \xrightarrow{\text{sphalerons}} Y_B \]

- \( \gamma (\ell_\alpha \nu^- \rightarrow Q_3 \bar{t}) \): \( Y_{\Delta \nu} \rightarrow Y_{\Delta L} \) with the "correct" sign
- \( \gamma (\ell_\alpha \nu^+ \rightarrow Q_3 \bar{t}) \): washout

\[
\frac{\gamma (\ell_\alpha \nu^+ \rightarrow Q_3 \bar{t})}{\gamma (\ell_\alpha \nu^- \rightarrow Q_3 \bar{t})} = O \left( \frac{(m_\nu/T)^2}{2} \right)
\]

- \( m_\nu < \text{few} \times 10 \text{ GeV} \)
- \( h_\nu \gtrsim 2 \times 10^{-7} \)
- \( Y_{\Delta \nu} \neq 0 \)
- \( Y_{\Delta \nu} \rightarrow Y_{\Delta L} \neq 0 \)

\[ \Rightarrow m_i \gtrsim \text{few} \times 0.01 \text{ eV} \]

\( \Rightarrow \) light \( \nu \) masses!
\[ M_\chi, \ M_{S_a}, \ M_N \sim (1 - 10) \text{ TeV} \]

<table>
<thead>
<tr>
<th>Large</th>
<th>( \sim O(1) )</th>
<th>Small</th>
<th>( &lt; O(10^{-2} - 10^{-3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{M_N}{M_\chi} )</td>
<td>( \lambda_a S_a \bar{N} P_R \nu )</td>
<td>( \frac{m_\nu}{M_\chi} )</td>
<td>( \lambda_{\nu a} S_a \bar{\nu} P_R \nu )</td>
</tr>
<tr>
<td>( \lambda_{\chi a} S_a \bar{\chi} P_R \chi )</td>
<td>( h_N \bar{H} \ell P_R N )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A \( U(1)_L \) \((U(1)_{B-L})\) makes this pattern natural:

\[
\begin{array}{c|c|c|c|c|c}
\chi & N & \nu & S_a & \ell, e_r \\
L & 1/2 & 0 & 1 & 1 & 1 \\
\end{array}
\]
Summary and outlook

- A mechanism for thermal baryogenesis at low energies: massive decay or annihilating products which do not store asymmetry.

- Wimpy baryogenesis via helicitogenesis: a model that connects DM, BAU, and $\nu$ masses.

- Phenomenology: exploit the $S_a - H$ mixing and the $Z'$ interaction in the $U(1)_{B-L}$ case.

- The TeV-scale-baryogenesis mechanism is more general, e.g., it can be implemented in the inert doublet model with two inert Higgses.
Additional slides ...
The matter-antimatter asymmetry of the Universe

Observations:

(a) The Universe is globally asymmetric: the amount of antimatter is negligible with respect to the amount of matter.
   ♦ Cosmic rays from the sun.
   ♦ Planetary probes.
   ♦ Galactic cosmic rays.
   ♦ BESS-Polar experiment $\Rightarrow \frac{\overline{He}}{He} < 1 \times 10^{-7}$.
   ♦ Absence of strong $\gamma$-ray flux from nucleon-antinucleon annihilations in clusters of Galaxies (like Virgo cluster).

$\Rightarrow$ Matter and antimatter domains should be larger than 20 Mpc. [Steigman, 1976]

Actually they must be larger than $\sim$ the visible Universe (cosmic diffuse $\gamma$-ray background). [Cohen, De Rújula, Glashow, 1998]
(b) Baryon density

♦ Big Bang Nucleosynthesis. The abundances of the light elements D, $^3$He, $^4$He, and $^7$Li depend mainly on one parameter, $n_B/n_\gamma$.

♦ CMB anisotropies.

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 8.6 \times 10^{-11}$$
Sakharov’s conditions
Basic requirements to dynamically generate a baryon asymmetry:

- Baryonic number \((B)\) violation
- \(C\) and \(CP\) Violation
- Departure from thermal equilibrium

In thermal baryogenesis from the decay of a particle with mass \(M:\)

\[
\frac{H(T = M)}{\text{Interaction rates}} \propto f(M_i/M, \text{couplings}) \frac{M}{M_P}
\]
Two types of washouts

\[ N \rightarrow \ell h, \ \bar{\ell}h \quad \Rightarrow \quad \ell h, \ \bar{\ell}h \rightarrow N \]

\[ \gamma(\ell h \rightarrow N) = \int d\pi f_\ell f_h |A(N \rightarrow \ell h)|^2 \]

Assume kinetic equilibrium:

\[ f_x(E) = \frac{n_x}{n_{eq}} f^eq_x(E) \]

\[ \gamma(\ell h \rightarrow N) = \frac{n_\ell}{n_{eq}} \frac{n_h}{n_{eq}} \gamma_D^{eq}, \quad \gamma(\bar{\ell}h \rightarrow N) = \frac{n_{\bar{\ell}}}{n_{eq}} \frac{n_{\bar{h}}}{n_{eq}} \gamma_D^{eq} \]

\[ \gamma(\ell h \rightarrow N) - \gamma(\bar{\ell}h \rightarrow N) = n_{\Delta \ell} \frac{\gamma_D^{eq}}{n_\ell^{eq}} + n_{\Delta h} \frac{\gamma_D^{eq}}{n_h^{eq}} \]

(at first order in the n-asymmetries and zeroth order in \( \epsilon \))
\[ \gamma_D^{eq}(z) = n_N^{eq}(z) \frac{K_1(z)}{K_2(z)} \frac{1}{2} \Gamma_N \]

with \( \Gamma_N = \frac{(\lambda^\dagger \lambda)_{11} M}{8 \pi} \) and \( \mathcal{L} = \lambda_{\alpha i} \bar{\ell}_\alpha P_R N_i \tilde{h} + \ldots \)

strength \[ \frac{\Gamma_N}{H(T = M)} \approx \frac{\sqrt{g_*}}{40} \frac{m_P (\lambda^\dagger \lambda)_{11}}{M} \]

- If \( M \downarrow \), just decrease \( (\lambda^\dagger \lambda)_{11} \) to keep \( \frac{\Gamma_N}{H(T = M)} \) constant.
- \( \epsilon \) is -basically- independent of \( (\lambda^\dagger \lambda)_{11} \).
- \( \gamma_D^{eq}(T) \propto e^{-M/T} \)
\[ Y^i_N = 0 \quad \text{blue} \quad Y^i_N = Y^i_N^{eq} \]

\[ \frac{\Gamma_N}{H(T=M)} = \frac{\tilde{m}_1}{m_*} \]

\[ \tilde{m}_1 \equiv \frac{(\lambda^\dagger \lambda)_{11}}{M_1} v^2 \rightarrow \text{contribution of } N_1 \text{ to } \sum_i m_{\nu_i}. \]

\[ m_* \equiv \frac{16}{3\sqrt{5}} \pi^{5/2} \sqrt{g_*} \frac{v^2}{m_P} \sim 10^{-3} \text{ eV} \]

\[ \eta \text{ is maximum for } \tilde{m}_1 \sim m_* \sim 10^{-3} \text{ eV} \quad !! \]
Thermal baryogenesis at low energies

We keep exemplifying with leptogenesis from sterile neutrino decays.

If \((\lambda^\dagger \lambda)_{11} \sim (\lambda^\dagger \lambda)_{22}\), what would be the scale of leptogenesis?:

\[
Y_B^f = \kappa \epsilon \frac{1}{(\lambda^\dagger \lambda)_{11}} 10^{-17} M_1 [\text{GeV}] \quad (\eta \sim \frac{m_*}{\bar{m}})
\]

\[
10^{-10} \sim 10^{-3} 10^{-1} (\lambda^\dagger \lambda)_{22} \quad \frac{1}{(\lambda^\dagger \lambda)_{11}} 10^{-17} M_1 [\text{GeV}]
\]

\[
\implies M_1 \sim 10^{11} \text{GeV} \quad \text{actually} \quad M_1 \gtrsim 10^{11} \text{GeV}
\]
Two problems to lower the energy scale

\[ \epsilon \sim \frac{3}{16\pi} \frac{\lambda_{\alpha_2}^2}{M_2} M_1 \]  
(hierarchical)

- Connection with light neutrino masses:
  - Type I seesaw: \( \epsilon \sim \frac{3}{16\pi} \frac{m_i}{v^2} M_1 \) (type I seesaw)

  \[ |\epsilon| \leq \epsilon_{\text{max}}^{\text{DI}} = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1) \implies M_1 \gtrsim 10^9 \text{ GeV} \quad (\eta \leq 1) \]

Some alternatives: Inverse seesaw, radiative seesaws, ...

- Even with no connection to neutrino masses:
  - Washout processes inherent to the existence of CP violation:

  \[ \text{washouts} \propto \left( \frac{\lambda_{\alpha_2}^2}{M_2} \right)^2 \]

  large \( \epsilon \rightarrow \) large \( \lambda_{\alpha_2} \rightarrow \) too much washout at LE \( \rightarrow \) How low?
[JR, JCAP 1403 (2014) 025]
Motivations for baryogenesis at low energy scales

- Experimental accessibility
- Some supergravity models require $T_{rh} \lesssim 10^5 - 10^7$ GeV
- Many models of physics BSM incorporate particles with $M \sim O(1)$ TeV
- Baryogenesis at $T \gtrsim \text{few TeV}'s$ could become severely disfavored, e.g. if some lepton number violating processes are observed at the LHC
Ways for thermal Baryogenesis at low energies

1) Initial thermal density + late decay

If the $N_1$ are produced at $T \gg M_1$ by a process different from the Yukawa interactions, then $\lambda_{\alpha_1}$ can be chosen small enough to have the $N_1$ decay at $T \ll M_2$.

⇒ It is possible to have large $\lambda_{\alpha_2}$ and consequently a big $\epsilon$, but at the same time small washouts at the moment the $N_1$ start to decay and produce the BAU.

- $M_{1\text{min}} \sim 2500 \ (2000) \ \text{GeV}$ for $T_{sfo} = 140 \ (80) \ \text{GeV}$ \ (L).
- $M_{1\text{min}} \gtrsim O(1) \ \text{GeV}$ \ (B)

Note: The interaction that creates the $N_1$ must decouple before they decay.
\[ M_1 = 2.5 \text{ TeV} \quad M_2 = 10M_1 \quad T_{sfo} = 140 \text{ GeV} \]
\[ (\lambda^\dagger \lambda)_{11} = 2 \times 10^{-15} \quad (\lambda^\dagger \lambda)_{22} = 2 \times 10^{-5} \]
2) Degenerate neutrinos

\[ M_2 - M_1 \sim \frac{\Gamma_{N_2}}{2} \quad \Rightarrow \quad |\epsilon| \sim \frac{1}{2} \frac{\text{Im} \left[ (\lambda^\dagger \lambda)^2_{21} \right]}{(\lambda^\dagger \lambda)_{11} (\lambda^\dagger \lambda)_{22}} \leq \frac{1}{2} \]

\[ \Gamma_{N_1, N_2} \ll \Delta M \ll M_1 \quad \Rightarrow \quad |\epsilon| \propto \frac{(\lambda^\dagger \lambda)_{22}}{\delta} \]

\[ \delta \equiv \frac{\Delta M}{M_1} \quad \Delta M \equiv M_2 - M_1 \]
$$\delta \equiv \frac{M_2 - M_1}{M_1}, \quad r = \frac{\text{smallest Yukawa coupling}}{\text{largest Yukawa coupling}}$$

$$\delta \times r \lesssim 10^{-8} \quad \text{for} \quad M_1 \sim 4 \text{ TeV}$$

$$\delta \times r \lesssim 3 \times 10^{-9} \quad \text{for} \quad 250 \text{ GeV} \lesssim M_1 \lesssim 1 \text{ TeV}$$
3) Massive decay products

In baryogenesis from annihilations, \( \chi \chi \rightarrow \psi u \), it is possible to take \( m_\psi > m_\chi \) \( \Rightarrow \) Boltzmann suppression \( \propto e^{-m_\psi / T} \) of the washouts without reducing the CP asymmetry.

[Y. Cui, L. Randall, B. Shuve, 2012]

In decays, e.g. taking a massive \( H_2 \) in \( N_1 \rightarrow H_2 \ell \), like in the inert doublet model, there are two opposite effects:

- Boltzmann suppression of the washouts (but not as much as for annihilations, since \( m_{H_2} < M_1 \)).

- Phase space suppression of the CP asymmetry

\[ \downarrow \quad \text{SM} + H_2 + N_i, \text{ with } H_2 \text{ and } N_i \text{ odd under a } Z_2 \]
Bound on $M_1$ [TeV]

$T_{sfo}=140$

$T_{sfo}=80$

[JR, JCAP 1403 (2014) 025]
Boundary on $M_1$ [GeV]

- $\mu_2 \gg \Gamma_{N_2}$
- $\mu_2 \ll \Gamma_{N_2}$

Note: This is for 2 flavors. The bound can be up to a factor $\sim 4$ smaller for 3 flavors.

[JR, M. Peña, N. Rius, 2012]
Ways to have Baryogenesis at low energy scales

■ Mass degeneracy:

\[ M_2 - M_1 \sim \frac{\Gamma N_2}{2}, \quad |\epsilon| \sim \frac{1}{2} \frac{\text{Im} [(\lambda^\dagger \lambda)^2_{21}]}{\text{Im} [(\lambda^\dagger \lambda)_{11}(\lambda^\dagger \lambda)_{22}]} \leq \frac{1}{2} \]

Note: However in the type I seesaw the mixing between active and sterile neutrinos is:

\[ \text{mixing} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{M}} \ll 1. \]

■ Three body decays: It’s more easy to satisfy the o.e.c. [T. Hambye, 2002].

■ Hierarchy of couplings:

\( \star \) Take \( \lambda_{\alpha_1} \) as small as necessary.

E.g. \( \lambda_{\alpha_1} \sim 10^{-7} \) to have \( \Gamma \sim H(T = M_1) \) for \( M_1 = 1 \) TeV.

\( \star \) Take \( \lambda_{\alpha_2} \) much larger to have enough CP violation.

■ See also [Fong, Gonzalez-Garcia, Nardi, Peinado, 2013].
Massive decay products provide an interesting way to lower the energy scale of baryogenesis.

The inert doublet model can explain simultaneously neutrino masses, DM and the BAU at the TeV scale, without resorting to degenerate heavy neutrinos (for initial thermal abundance of $N$ or with some fine tuning among phases).