Helicitogenesis: WIMPy baryogenesis with sterile neutrinos

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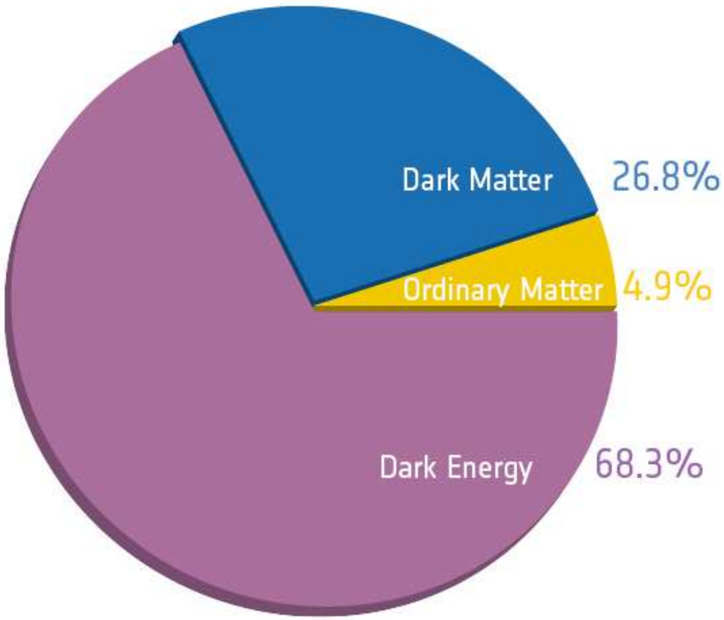
Content of the talk

Motivations and brief description of a model that:

- Incorporates a mechanism for low scale thermal baryogenesis ($T \lesssim 10^5$ TeV).
- Complements previous studies on requirements for baryogenesis from dark matter annihilation.
- It's a simple extension of the SM -new fields are all singlets- where sterile neutrinos play a role on determining the abundance of dark matter, baryon asymmetry and neutrino masses.

Based on [JR, Nuria Rius, JHEP 1411 (2014) 163]

The content of the Universe



(Planck)

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 8{,}6 \times 10^{-11}$$

- Baryonic content: Asymmetric
  matter and antimatter domains should be larger than $\sim$ the visible Universe (cosmic diffuse γ-ray background) .
  [Cohen, De Rújula, Glashow, 1998]
- DM content: ? (only known from its gravitational influence). Hint:

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

$$M_\chi \sim M_{\rm weak} \sim 10^2 - 10^3 \text{ TeV}, \; g_\chi \sim g_{\rm weak} \sim 0{,}65 \quad \longrightarrow \quad \Omega_\chi \sim 0{,}25$$

WIMP miracle

Both need physics beyond the SM to be explained

Baryogenesis

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:

$$\frac{H(T=M)}{\text{Interaction rates}} \quad \propto \quad f(M_i/M, \text{couplings})\ \frac{M}{M_{\mathrm{P}}}$$

Thermal Baryogenesis

The baryon -or lepton- asymmetry is generated in the decay or scattering of heavy particles thermally produced.

To be more specific we start considering type I leptogenesis:
The singlet Majorana neutrinos of the type I seesaw can generate a lepton asymmetry when decaying in the primitive Universe.

$$\boxed{Y_B^f = -\kappa\, \epsilon\, \eta} \qquad \text{(constant } \epsilon\text{)}$$

- $\kappa = \frac{28}{79} Y_{N_1}^{eq}(T \gg M_1) \sim 10^{-3}$
- $\epsilon = \frac{\gamma(N_1 \to H\ell) - \gamma(N_1 \to \bar{H}\bar{\ell})}{\gamma(N_1 \to H\ell) + \gamma(N_1 \to \bar{H}\bar{\ell})}$
- $\eta = efficiency\ , \qquad 0 \leq |\eta| \leq 1.$

Overview [Nuria Rius, on Tuesday]

$\eta \quad \longrightarrow \quad$ from Boltzmann equations

$$\frac{\mathrm{d}Y_N}{\mathrm{d}z} = -\frac{1}{zHs}\left(\frac{Y_N}{Y_N^{eq}} - 1\right) 2\gamma_D$$

$$\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = -\epsilon\frac{\mathrm{d}Y_N}{\mathrm{d}z} \; - \; \frac{1}{z}\left\{Y_{\Delta L}\left[\frac{\gamma_D^{eq}}{n_\ell^{eq}H} + \frac{\gamma_{N_2}^{eq}}{n_\ell^{eq}H}\right] + Y_{\Delta h}\left[\frac{\gamma_D^{eq}}{n_h^{eq}H} + \frac{\gamma_{N_2}^{eq}}{n_h^{eq}H}\right]\right\}$$

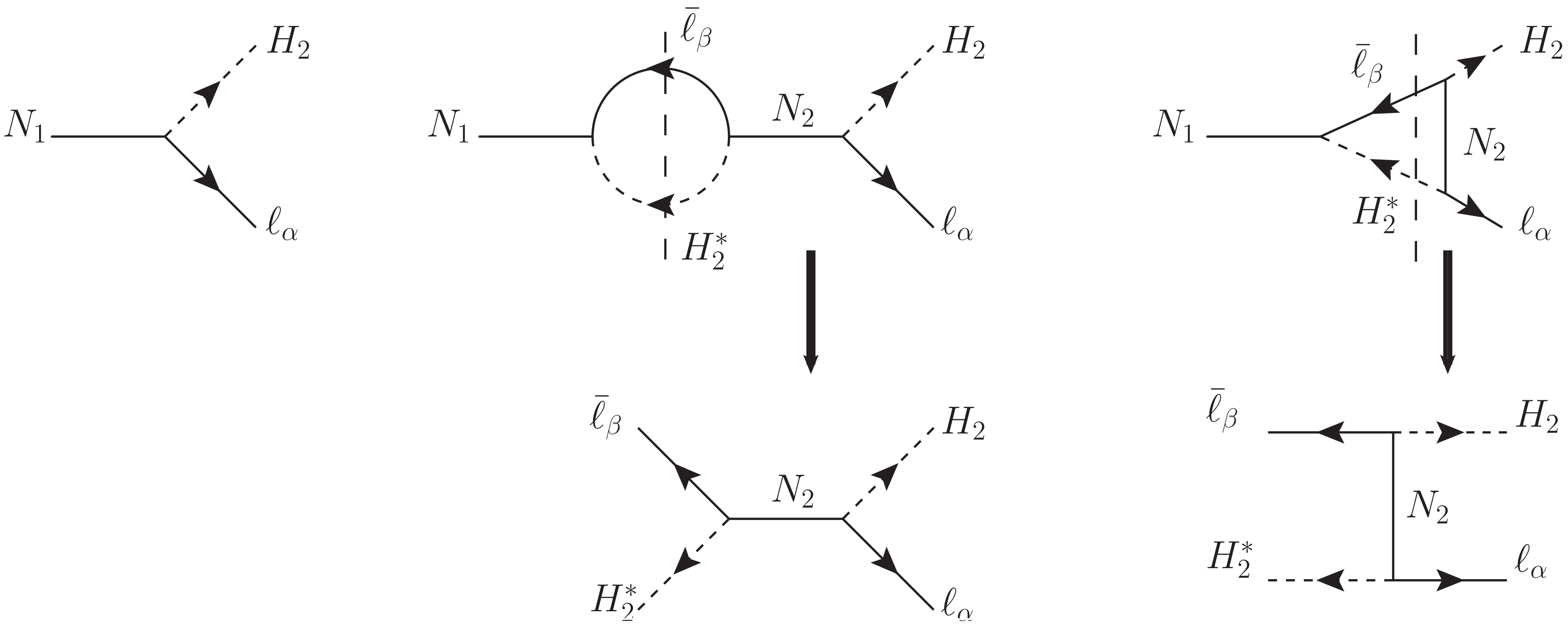
$$= \textbf{source} - \textbf{w a s h o u t s}$$

with $\quad Y_x \equiv \dfrac{n_x}{s}\,, \qquad z \equiv \dfrac{M_1}{T}\,, \qquad N \equiv N_1$.

Source = CP violation $\times$ L violation $\times$ departure from eq.

Washouts = asymmetries $(Y_{\Delta L},\; Y_{\Delta h})$ $\times$ rates (γ/Hn).

$\epsilon \quad \propto \quad$ CP odd phase $\quad \times \quad$ CP even phase

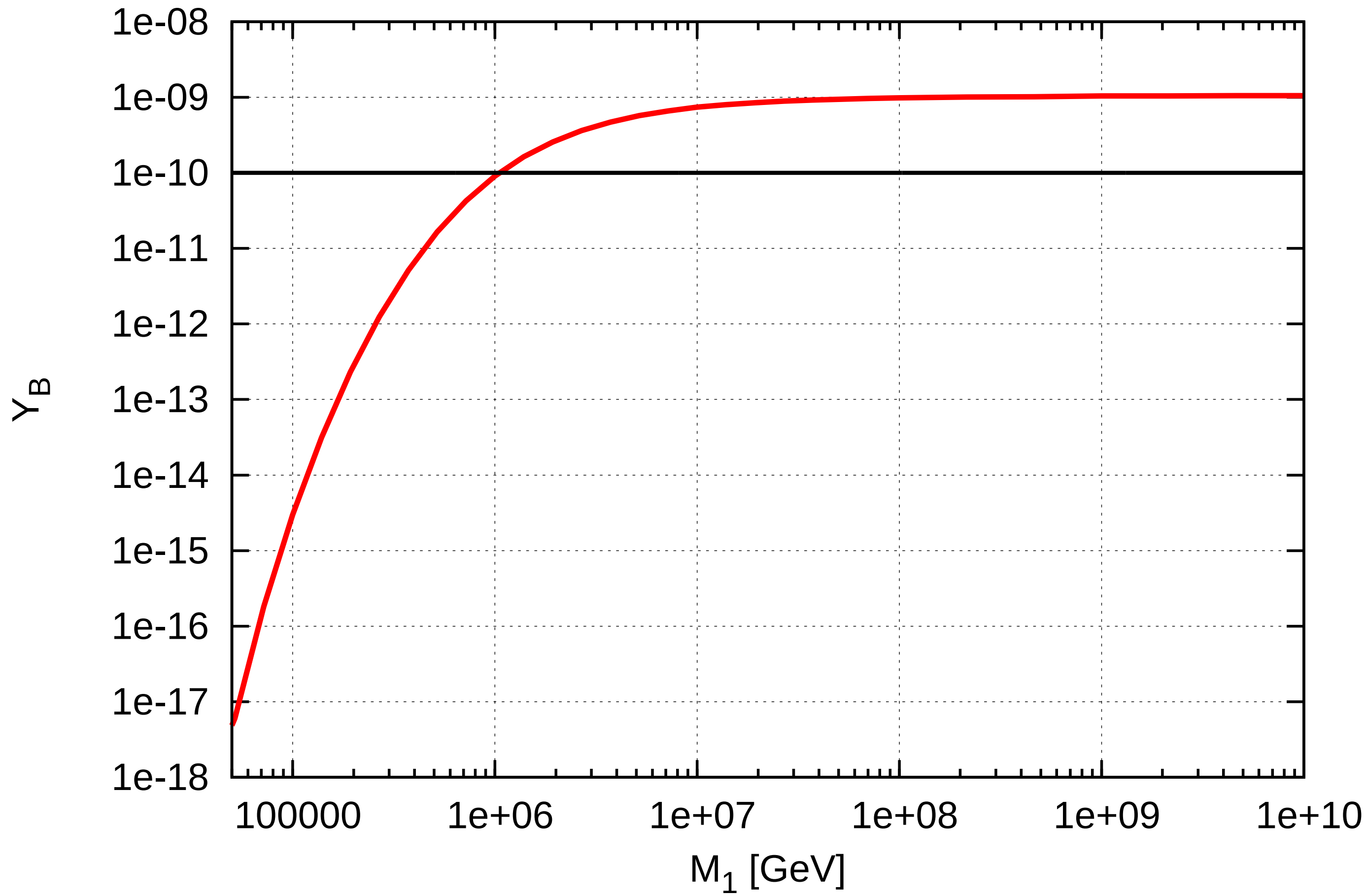


$$\epsilon \quad \Longrightarrow \quad \ell\, h \leftrightarrow \overline{\ell h}$$

strength $\quad \longrightarrow \quad \dfrac{\Gamma(\ell\, h \leftrightarrow \overline{\ell h})}{H(T=M)} \propto \left(\dfrac{M}{M_2}\right)^2 \; \dfrac{m_P\, (\lambda^\dagger \lambda)^2_{22}}{M}$

- $\epsilon \quad \longleftrightarrow \quad \ell\, h \leftrightarrow \overline{\ell h}$
- If $M \searrow$ and you decrease $(\lambda^\dagger\lambda)_{22}$ to keep $\frac{\Gamma}{H}$ const $\rightarrow \; \epsilon \searrow$

  If $M \searrow$ and you keep $\epsilon = $ const. $\rightarrow \frac{\Gamma(\ell\, h \leftrightarrow \overline{\ell h})}{H(T=M)} \nearrow$
- $\dfrac{\gamma_{N_2}}{n_\ell^{eq} H} \propto \dfrac{T}{M} \quad \left(\text{or } \dfrac{T^3}{M^3}\right) \qquad \text{for } T \ll M$



$$\frac{\Gamma_N}{H(T{=}M)} = 1 \qquad \frac{M_2}{M_1} = 10 \qquad (\lambda^\dagger\lambda)_{22} = 2 \times 10^{-4}$$

$$(\implies \epsilon = \text{ const. })$$

Two problems to lower the energy scale

$$\epsilon \quad \sim \quad \frac{3}{16\pi}\frac{\lambda^2_{\alpha 2}}{M_2} M_1 \qquad \text{(hierarchical)}$$

- Connection with light neutrino masses:

  Type I seesaw: $\epsilon \quad \sim \quad \frac{3}{16\pi}\frac{m_i}{v^2}M_1 \qquad \text{(type I seesaw)}$

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

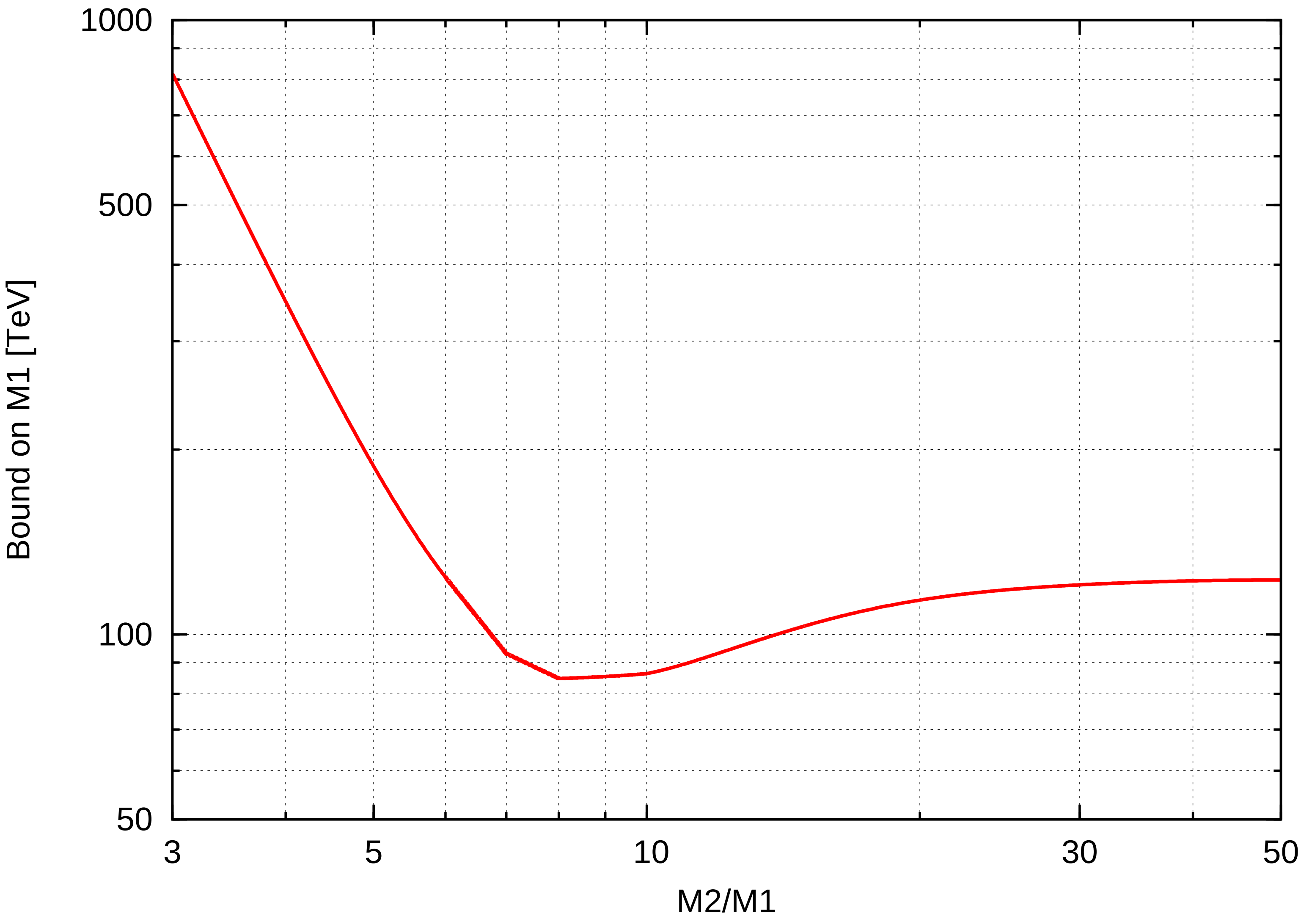
  Some alternatives: Inverse seesaw, radiative seesaws, ...

- Even with no connection to neutrino masses:

  Washout processes inherent to the existence of CP violation

$$\text{washouts} \quad \propto \quad \left(\frac{\lambda^2_{\alpha 2}}{M_2}\right)^2$$

large ϵ $\rightarrow$ large $\lambda_{\alpha 2}$ $\rightarrow$ too much washout at LE $\rightarrow$ How low?



[JR, JCAP 1403 (2014) 025]

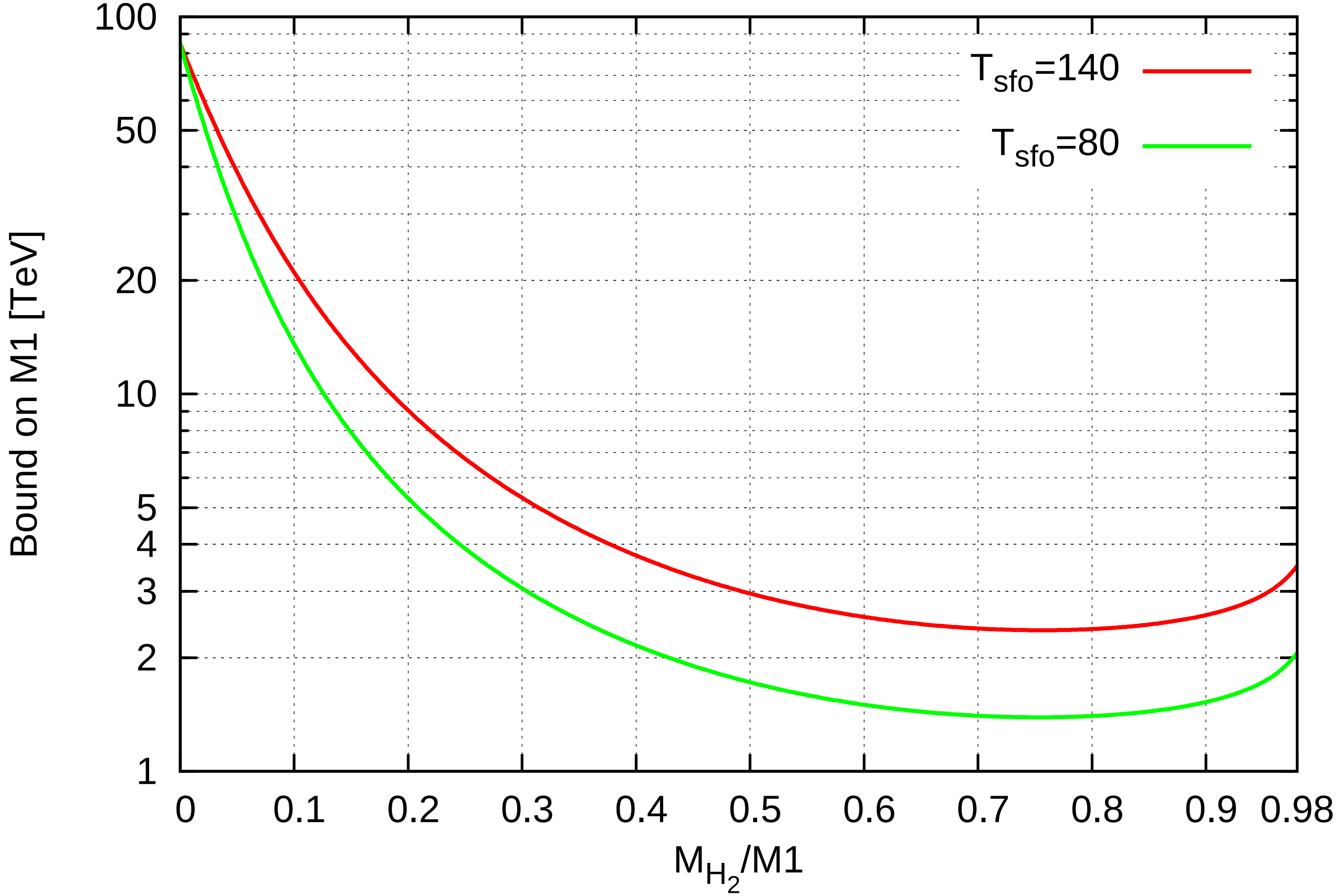
Motivations for baryogenesis at low energy scales

- Experimental accessibility
- Some supergravity models require $T_{rh} \lesssim 10^5 \ - \ 10^7$ GeV
- Hierarchy problem if $M \gtrsim 10^7$ GeV
- Baryogenesis at $T \gtrsim \mathrm{few\ TeV's}$ could become disfavored, e.g. if some lepton number violating processes are observed at the LHC

Ways for thermal baryogenesis from particle decays -or annihilations- at low energy

- Initial thermal density $+$ late decay
- Quasi-degenerate particles (resonant leptogenesis)
- Massive decay products
  $\Longrightarrow$ Boltzmann suppression $\propto e^{-M_{H_2}/T}$ of the washouts
  [Y. Cui, L. Randall, B. Shuve, 2012]
  [JR, 2014]

For other scenarios $\rightarrow$ M. Drewes and the PhD Forum on Cosmology talks.



Bound on M1 [TeV]
100
50
20
10
5
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.98
M_{H_2}/M1
T_{sfo}=140
T_{sfo}=80

There is a crucial point for this mechanism to work:

$$\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = -\frac{1}{z}\left\{Y_{\Delta L}\,\frac{\gamma_{N_2}^{eq}}{n_\ell^{eq} H} + Y_{\Delta H_2}\,\frac{\gamma_{N_2}^{eq}}{n_{H_2}^{eq} H}\right\} + \ldots$$

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

$$\downarrow$$

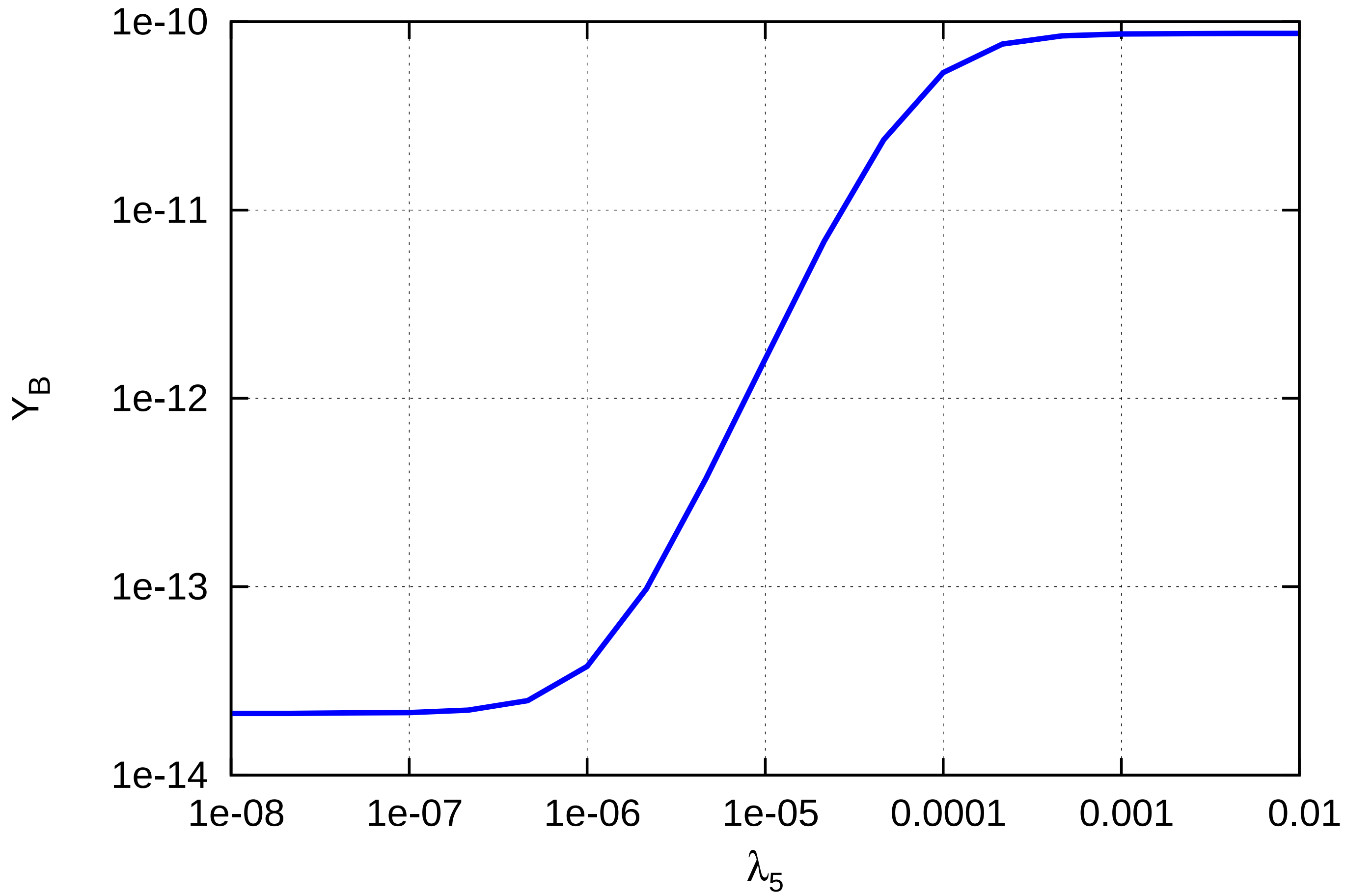
relation among $Y_{\Delta H_2}$ and $Y_{\Delta L}$

$$\downarrow$$

If $Y_{\Delta H_2} = c\,Y_{\Delta L} \longrightarrow$ the mechanism does not work $\quad (c = \mathrm{const.})$

$Y_{\Delta H_2}$ must vanish exponentially without erasing -or canceling- $Y_{\Delta L}$

$$\text{fast } H_2 a_1 \leftrightarrow a_2 a_3 \implies \mu_{H_2} = \sum_i \mu_i \implies Y_{\Delta H_2} \propto e^{-M_{H_2}/T}\ (m_i \ll M_{H_2})$$



λ_5 is the coupling of $H_2H_2 \leftrightarrow HH$ (Inert Doublet Model)

[JR, arXiv:1410.5482]

Alternatively, take a Majorana fermion as the massive particle $(Y_\Delta = 0)$ [JR, Nuria Rius, 2014]

$$\downarrow$$

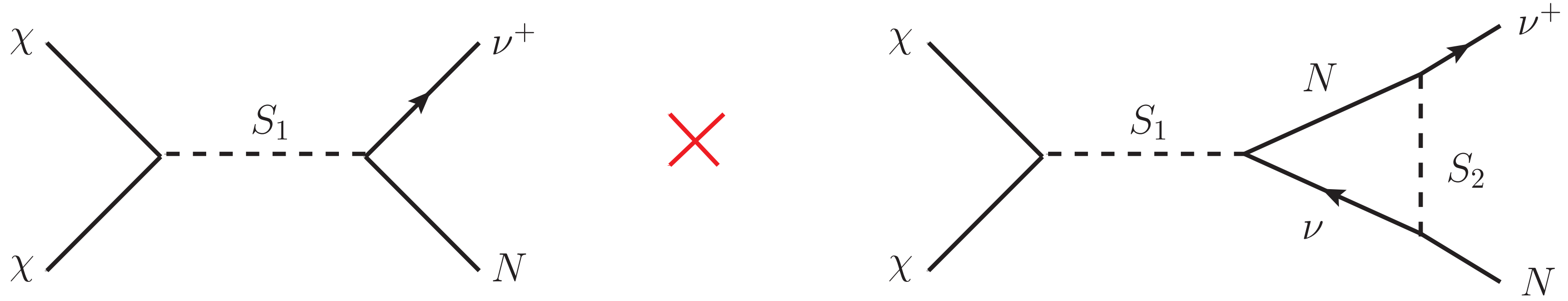
implementation in a model of Wimpy Baryogenesis:

$$\downarrow$$

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

Wimpy Baryogenesis via helicitogenesis

Step 1: Generation of helicity asymmetry



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

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

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

$\hat{\rho}_\nu$ diagonal in $\{\nu^+, \nu^-\}$ $\longrightarrow$ evolution equation for $Y_{\Delta\nu} \equiv Y_{\nu^+} - Y_{\nu^-}$

Step 2: Transfer of helicity asymmetry

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

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

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

$$m_\nu < \text{ few} \times 10\,\text{GeV} \quad + \quad h_\nu \gtrsim 2 \times 10^{-7} \quad \Longrightarrow \quad m_i \gtrsim \text{few} \times 0{,}01\,\text{eV} \,!$$

$$(Y_{\Delta\nu} \neq 0) \quad + \quad (Y_{\Delta\nu} \to Y_{\Delta L} \neq 0) \quad \Longrightarrow \quad \text{light } \nu \text{ masses !}$$

N and ν decay into SM particles $\Rightarrow$ no need for extra -Z_4- discrete symmetries and a sector decoupled from SM fields at low T .

$$M_\chi,\ M_{S_a},\ M_N \sim (1-10)\ \mathrm{TeV}$$

Large $\sim O(1)$	Small $< O(10^{-2}-10^{-3})$
$\frac{M_N}{M_\chi}$	$\frac{m_\nu}{M_\chi}$
$\lambda_a\, S_a \bar{N} P_R \nu$	$\lambda_{\nu a}\, S_a \bar{\nu} P_R \nu$
$\lambda_{\chi a}\, S_a \bar{\chi} P_R \chi$	$h_N\, \tilde{H} \bar{\ell} P_R N$

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

	χ	N	ν	S_a	ℓ, e_r
L	$1/2$	0	1	1	1

Light neutrino masses via a double seesaw.

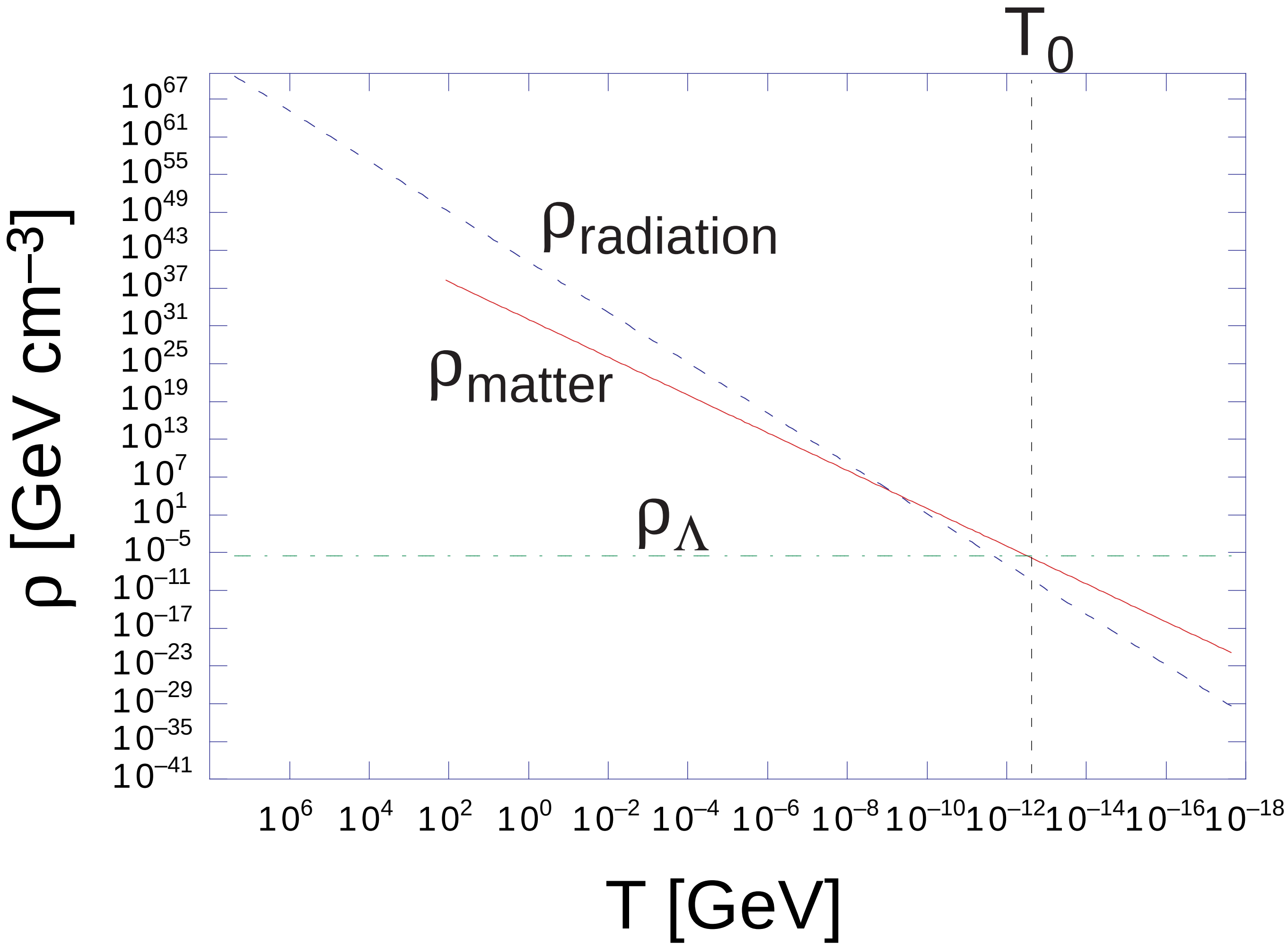
Summary and outlook

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

  [Francisco José Domínguez González, JR, Work in progress].

Additional slides ...

The coincidence problem

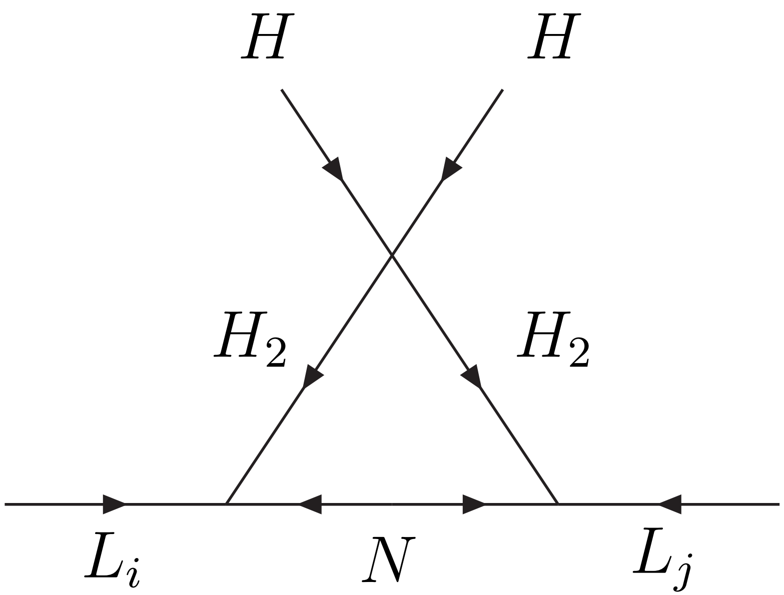


(figure from [Arkani-Hamed, Hall, Kolda, Murayama, 2000])

$$\Omega_\gamma \ : \ \Omega_B \ : \ \Omega_{DM} \ : \ \Omega_\Lambda \quad \sim \quad 10^{-3} \ : \ 1 \ : \ 5 \ : \ 14$$

Radiative seesaw

E.g. Inert Doublet Model



Leptogenesis: Different ways for baryogenesis at the TeV scale

Or no seesaw: Dirac leptogenesis

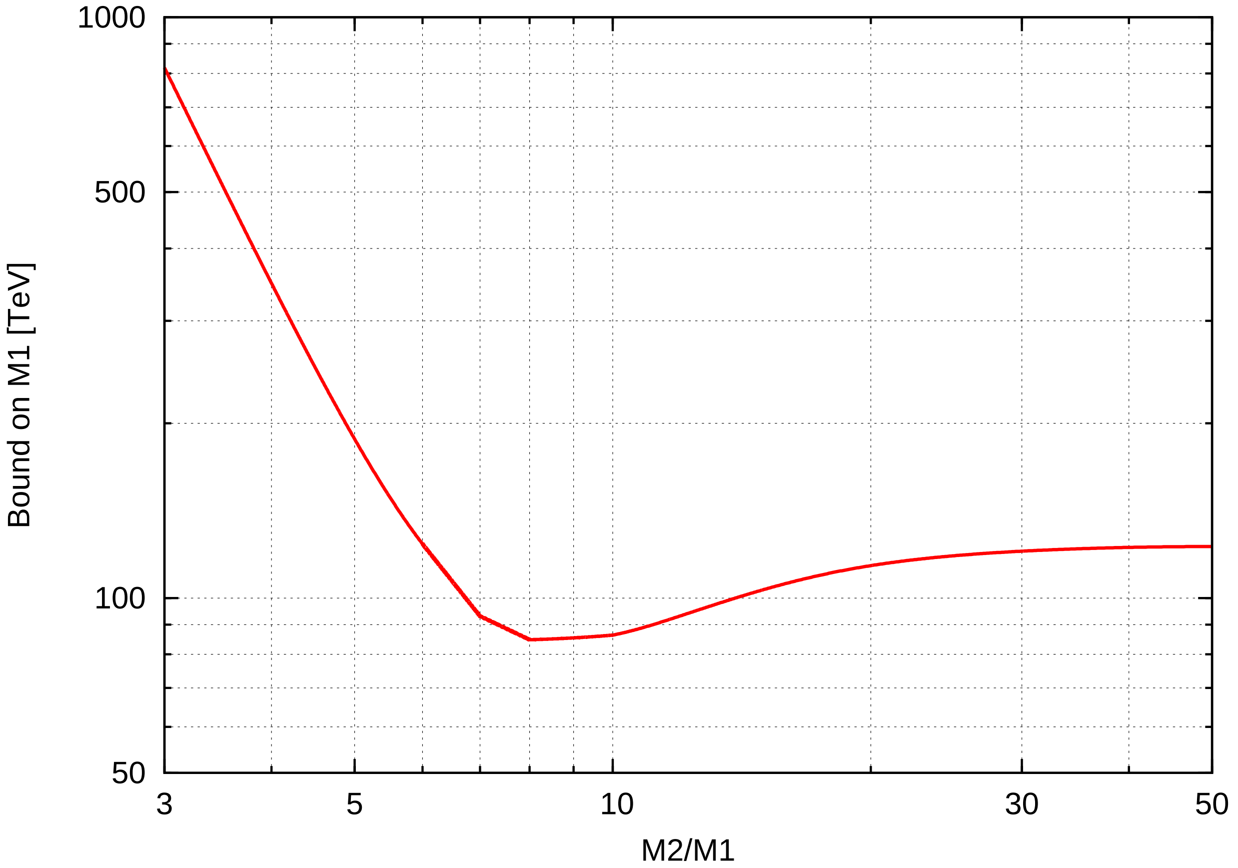
$$\begin{array}{ccc} \text{L-asymmetry in } \psi_L & = & -\text{ L-asymmetry in } \psi_R \\ \downarrow \text{ (sphal)} & & \downarrow \\ \text{B-asymmetry} & & \text{part stored in } N_R \text{ until } T \ll T_{sfo} \end{array}$$

Note: This works because neutrino masses are very tiny

Ways for thermal Baryogenesis at low energies

L-violating CP asymmetry

$$\epsilon \;\propto\; \lambda_{\alpha 2}^2 \,\frac{M_1}{M_2}, \qquad \text{washouts} \;\propto\; \left[\lambda_{\alpha 2}^2 \,\frac{M_1}{M_2}\right]^2$$



[JR, 2014]

L-conserving CP asymmetry

$\epsilon_\alpha \;\propto\; \lambda^2_{\beta 2} \left(\frac{M_1}{M_2}\right)^2$, washouts $\propto \left[\lambda^2_{\beta 2} \left(\frac{M_1}{M_2}\right)^2\right]^2$.

Inverse seesaw

Particle content: SM + ν_{R_i}, s_{L_i} (singlet fermions).

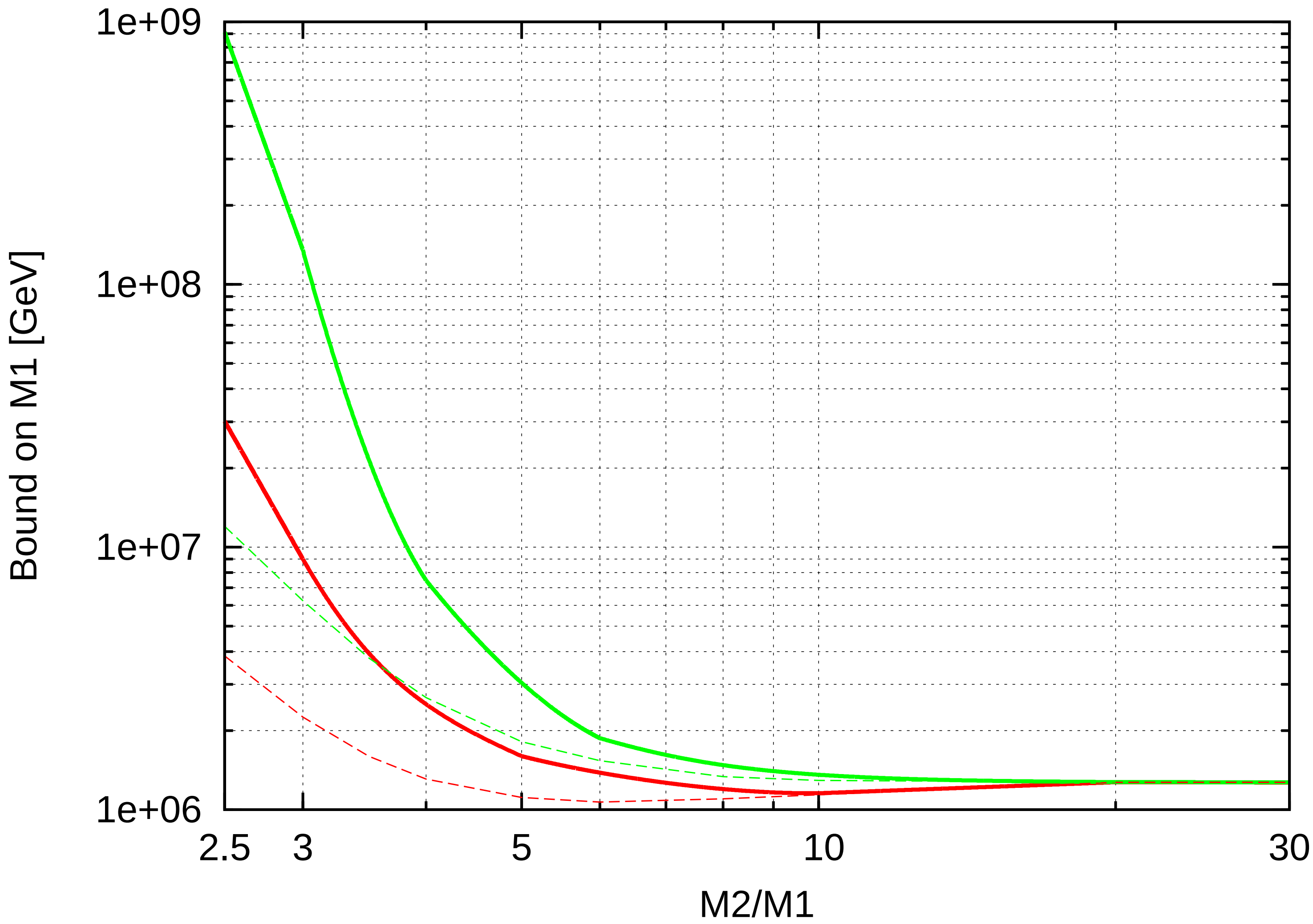
The mass matrix of the neutral sector in the basis ν_L, ν_R^c, s_L is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = m_D M^{T^{-1}} \mu M^{-1} m_D^T \sim m_D \left(\frac{\mu}{M}\right)\left(\frac{m_D}{M}\right) \quad (m_D, \mu \ll M)$$

ν_{R_i}, s_{L_i} combine to form quasi-Dirac fermions with mass $\sim M$.

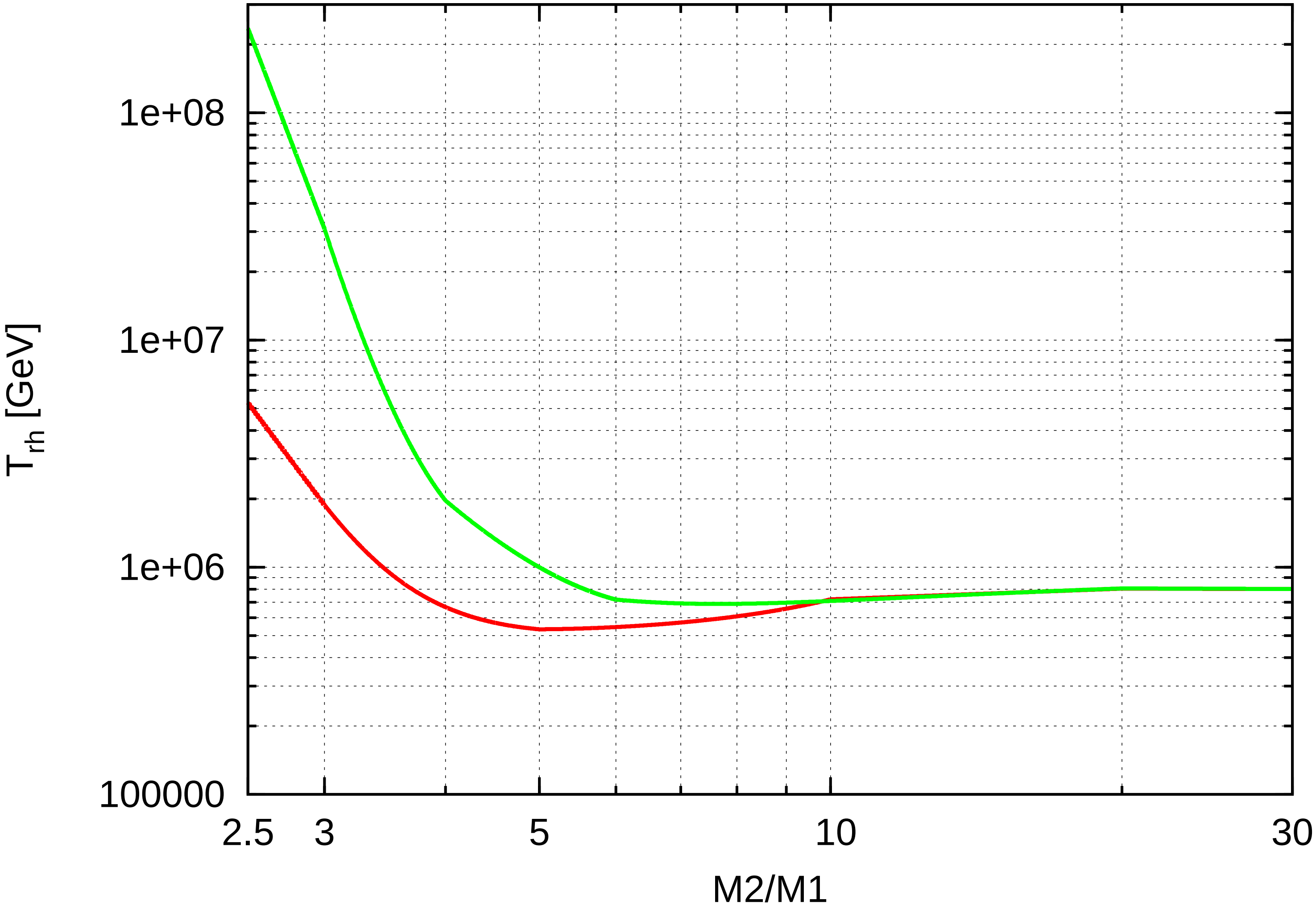
$$\text{mixing} \;\sim\; \frac{m_D}{M} \;\sim\; \sqrt{\frac{m_\nu}{\mu}}$$



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

[JR, M. Peña, N. Rius, 2012]

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



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

Note: The Upper bound on T_{rh} from gravitino overproduction can be satisfied

Some proposed ways for thermal baryogenesis at TeV scales:

- **Mass degeneracy**:

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

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**:
  - 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.
  - Take $\lambda_{\alpha 2}$ much larger to have enough CP violation.

- See also [Fong, Gonzalez-Garcia, Nardi, Peinado, 2013].