Baryon asymmetry and neutrino physics

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Based on

JHEP 1010 (2010) 036: J. F. Kamenik (Ljubljana), M. Nemevsek (Ljubljana)

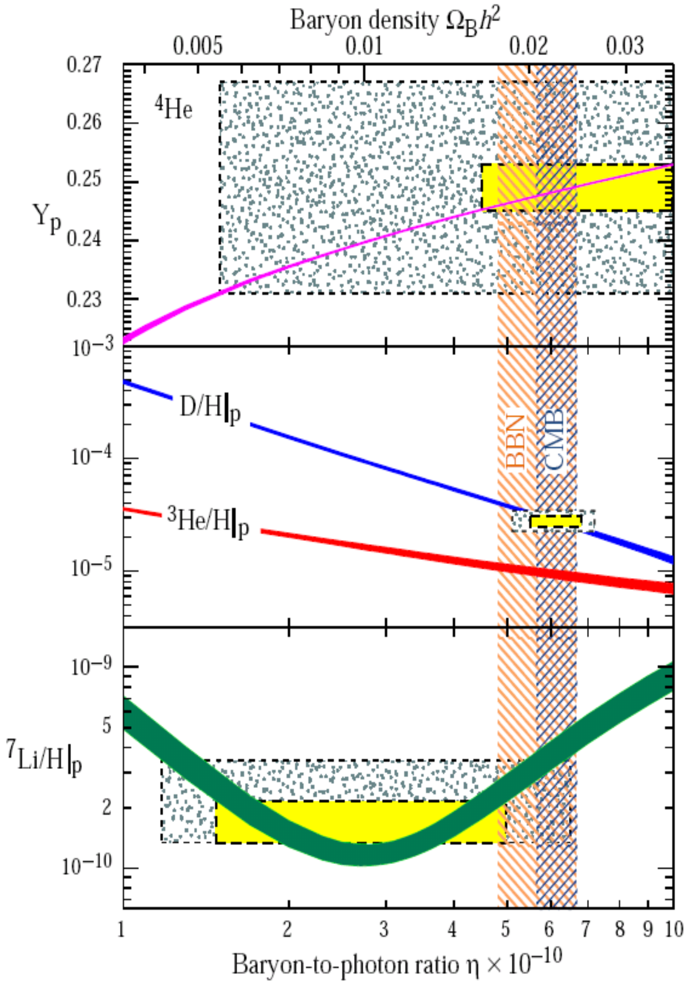
JCAP 1402 (2014) 013: E. Nardi (LNF-Frascati), Sheng Fong (Sao Paulo, U.), E. Peinado (LNF-Frascati)

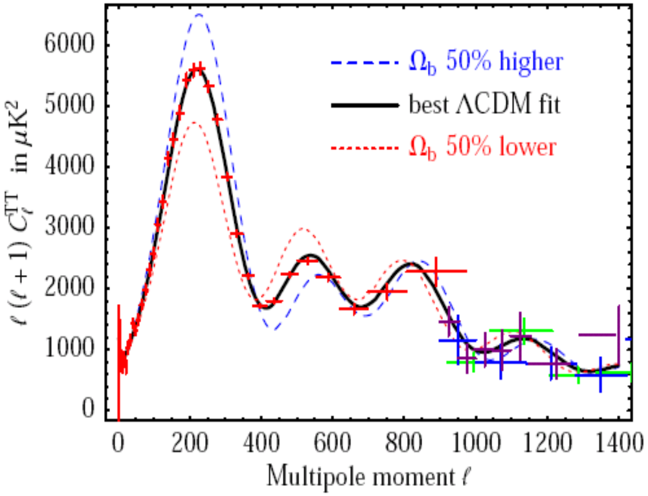
[arXiv: arXiv:1401.4347]: M. Dhen (ULB), T. Hambye (ULB)

Introduction

Baryon asymmetry

The cosmic Baryon Asymmetry (BA) is derived from measurements of light elements abundances (D, ^{3}He, ^{4}He, ^{7}Li) and the CMB





$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq (6.21 \pm 0.16) \times 10^{-10}$$

$$\eta = 2.74 \times 10^{-8} \Omega_B h^2$$

$$Y_{\Delta_B} = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{\eta}{7.04}$$

$$\boxed{Y_{\Delta_B} \simeq (8.75 \pm 0.23) \times 10^{-11}}$$

7-year WMAP, arXiv:1001.4538

Origin of the BA

☐ Could be an initial condition?... A crucial ingredient of ΛCDM is inflation... Any primordial B asymmetry would be diluted.

☐ The origin of the Baryon Asymmetry should be dynamic (Baryogenesis):

Sakharov Conditions

Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32-35

❶ The Baryon Asymmetry generating interations must violate B.

❷ The Baryon Asymmetry generating interactions must break CP.

❸ The Baryon Asymmetry generating interactions must departure -at some point- from Thermodynamical Equilibrium.

Any model satisfying these conditions -in principle- constitutes a framework for baryogenesis

Baryogenesis in the SM

Qualitatively

- B is broken at the non-perturbative level (sphalerons processes)
- CP violation is provided by the CKM quark mixing matrix
- Departure from TEQ provided by the electro-weak phase transition.

Quantitatively

- CP violation to small ✘
- Succesful baryogenesis requires strongly $1^{\underline{st}}$ order phase transition $\Rightarrow$

$m_h < 40$ GeV while LHC: $m_h \simeq 125$ GeV **CMS, ATLAS** ✘

The SM fails at the quantitative level

Explanation of $Y_{\Delta B}$ requires BSM physics

Possible approaches

A large number of mechanisms (models) for baryogenesis exist. Among them two of the most widely studied are:

EW baryogenesis **(Cohen, Kaplan, Nelson, PLB,245,561)**

EW baryogenesis models “cure” the SM pitfalls via extended scalar sectors

$$V_{\text{SM}}(\Phi) \longrightarrow V(S_i,\Phi_i) \Rightarrow \begin{cases} \text{Strongly } 1^{\underline{\text{st}}} \text{ order EWPT: relaxing } m_h^{\text{max}} \\ \text{Additional CP violating sources} \end{cases}$$

SM+S, 2HDMs, MSSM... **EWB testable at the LHC!**

Leptogenesis: **(Fukugita, Yanagida, PLB,174,45)**

$$Y_{\Delta_L} \to Y_{\Delta_B}$$

$B+L$ violating EW sphalerons interactions

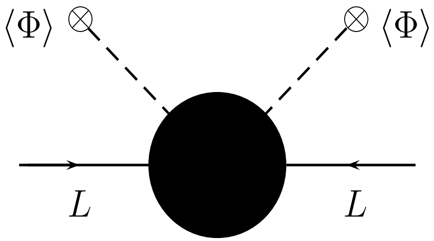
$$\mathcal{O}_{B+L} = \prod_{i=1,2,3} (q_{L_i} q_{L_i} q_{L_i} \ell_{L_i})$$

Qualitatively (quantitatively in some cases) viable in models of Majorana neutrino masses. Linked with the origin of neutrino masses!

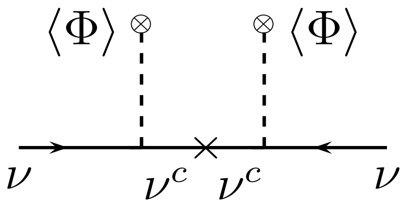
Neutrino masses

Model independent approach: induced by $\mathcal{O}_5 \sim LL\Phi\Phi \Rightarrow \Delta L = 2$

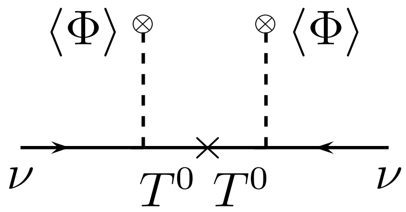
S. Weinberg, Phys. Rev. D **22**, 1694 (1980)



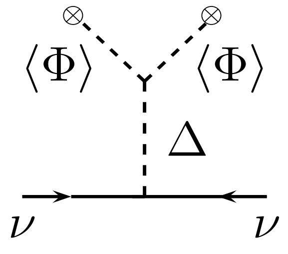
Tree-level UV completions



Type-I



Type-III



Type-II

Minkowski, 1977

Mohapatra & Senjanovic, 1980

Schechter & JWFV, 1980 ...

Foot, Lew, He & Joshi, 1989

Schechter, JWFV, 1980 ...

Leptogenesis: “standard” case

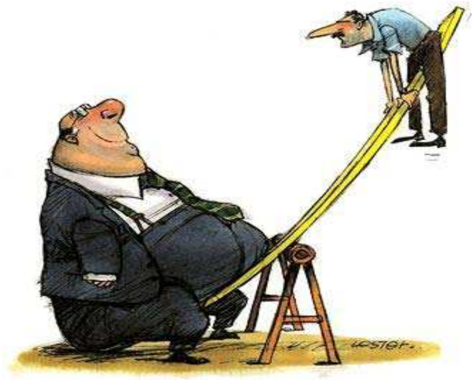
Type-I seesaw

All these realizations satisfy (at least qualitatively) the Sakharov conditions.

Standard seesaw Add new fermionic EW singlets, N_R to the SM

$$\mathcal{L} = -\lambda^*_{i\alpha}\bar{\ell}_i N_{R\alpha}\tilde{H} - \frac{1}{2}\bar{N}_{R\alpha} m_{R\alpha} N^c_{R\alpha} + \text{h.c}$$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$



Diagonalization yields 3 heavy masses for the fermionic EW singlets M_i and 3 light masses m_i (Assumming $m_R \gg m_D$).

$$M_\nu^{\text{eff}} = -m_D m_R^{-1} m_D^T$$

The smallness of light neutrinos masses is due to the suppression of the heavy R-H neutrino masses

The standard seesaw model is the framework for standard leptogenesis

Tracking asymmetries

Relevant dynamics in non thermal equilibrium

Distribution function f_ψ determined by Boltzmann equation

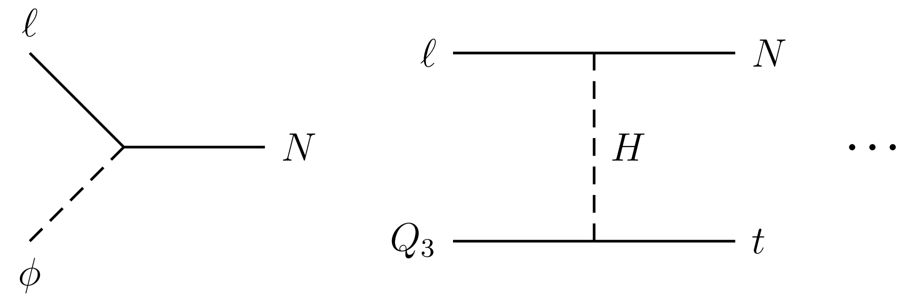
$Y_\psi = n_\psi/s$, conservation of s/V_C

$$E\frac{\partial f_\psi}{\partial t} - \underbrace{\frac{\dot{R}}{R}|\vec{p}|^2\frac{\partial f_\psi}{\partial E}}_{\textbf{Expansion}} = \underbrace{C[f]}_{\textbf{Dynamics}}$$

$$\frac{dY_\psi}{dz} = \underbrace{\bar{C}[f]}_{\textbf{Dynamics}}$$

BEQs for standard leptogenesis

$$\frac{dY_N}{dz} \propto (\gamma_D + \gamma_{\text{Sca}})$$



$$\frac{d}{dz}Y_{\Delta(B-L)} = S + W$$

$S \propto \epsilon_N$: processes capable of producing $B-L$

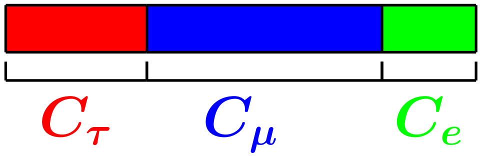
W: processes capable of erasing $B-L$

$z = M_N/T$

Lepton flavor: a sketch

$\boxed{\textbf{SM lepton Yukawa reactions are slow: } \Gamma_i \ll H}$

$$\ell \; = \sum_i C_i \, \ell_i$$



$\boxed{\Gamma_i \gg H \textbf{ and } \Gamma_i \gg \Gamma_{\textbf{Coherence}}}$

ℓ_τ

$$\ell \; = \; \sum_i C_i \, \ell_i$$

Possible T regimes

- $\boxed{10^{12}\text{ GeV} \lesssim T \lesssim 10^{13}\text{ GeV}}$ h_b and h_τ Yukawa interactions are in TEQ
- $\boxed{10^{9}\text{ GeV} \lesssim T \lesssim 10^{12}\text{ GeV}}$ Also EW sphalerons are in TEQ
- $\boxed{10^{8}\text{ GeV} \lesssim T \lesssim 10^{11}\text{ GeV}}$ Second Yukawa generation enter into TEQ
- $\boxed{T \ll 10^{8}\text{ GeV}}$ All SM Yukawa interactions and EWS are in TEQ

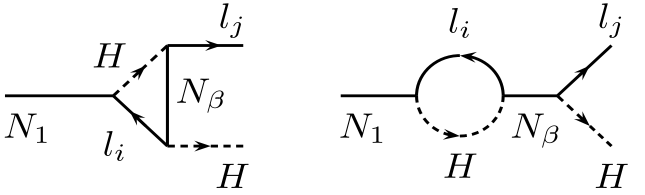
Standard leptogenesis

The fermionic singlet mass spectrum: $M_1 \ll M_{2,3}$. The lepton asymmetry proceeds via N_{R1} out-of-equilibrium and CP violating decays

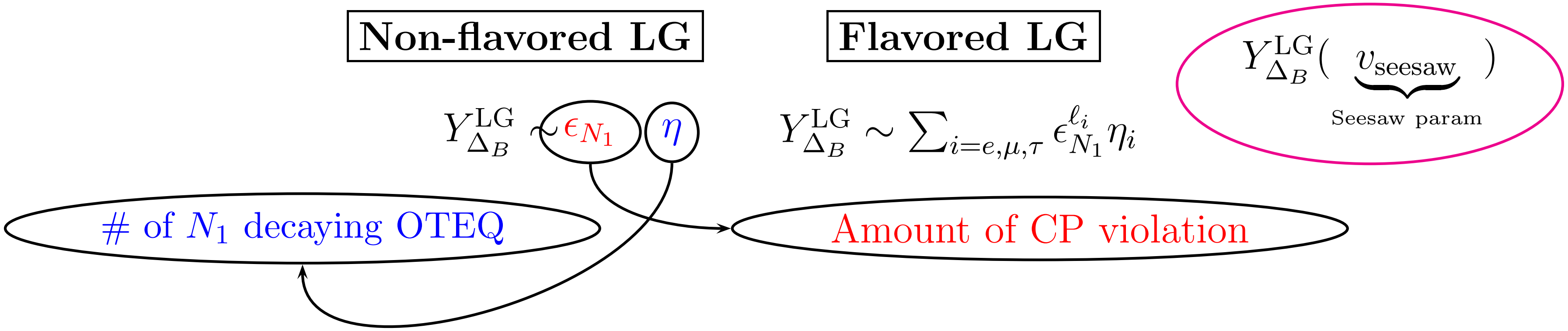
$$\Gamma_D = \Gamma(N_{R1} \to \ell\tilde{H}, \bar{\ell}\tilde{H}^\dagger) = \frac{M_1^2}{8\pi v^2}\sum_{i=e,\mu,\tau}\tilde{m}_{i1} \qquad \boxed{\tilde{m}_{i\alpha} \propto \lambda^*_{i\alpha}\lambda_{i\alpha}}$$

- Majorana mass term m_R is a L violating source $(\Delta L = 2)$.
- $\lambda_{i\alpha} \longrightarrow$ contain new physical CPV phases. CPV asymmetries arise at the one-loop level

$$\boxed{\epsilon^{\ell_i}_{N_1} = \frac{\Gamma_i - \bar{\Gamma}_i}{\Gamma_i + \bar{\Gamma}_i}}$$



- Departure from thermal equilibrium provided by the expansion. $\Gamma_D \lesssim H(z = M/T = 1)$



Non-flavored LG

Flavored LG

$$Y^{\mathrm{LG}}_{\Delta_B}\sim \epsilon_{N_1}\,\eta$$

$$Y^{\mathrm{LG}}_{\Delta_B}\sim \sum_{i=e,\mu,\tau}\epsilon^{\ell_i}_{N_1}\eta_i$$

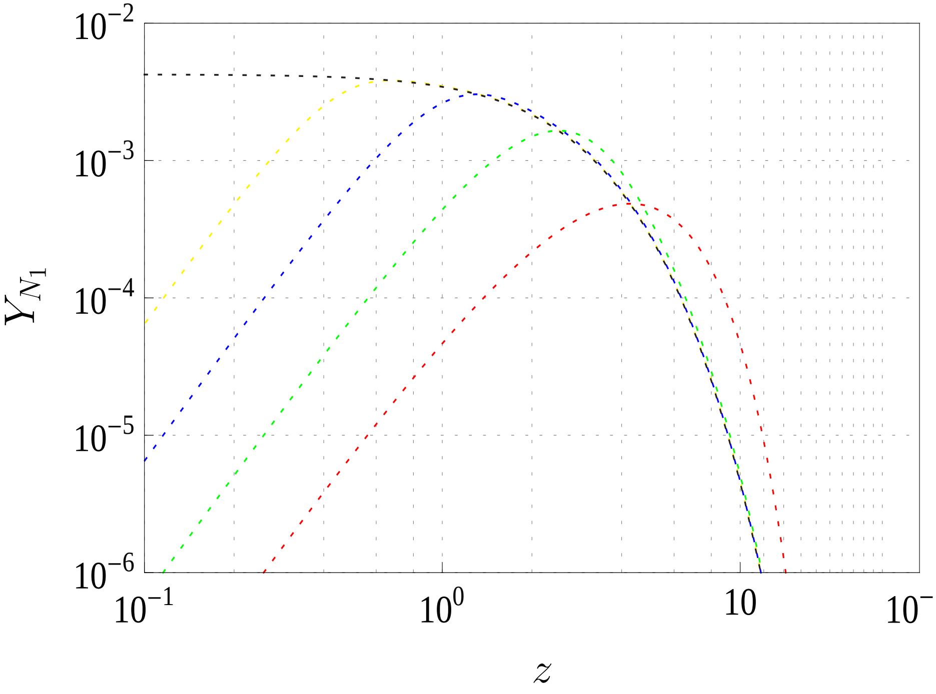
$$Y^{\mathrm{LG}}_{\Delta_B}(\underbrace{v_{\text{seesaw}}}_{\text{Seesaw param}})$$

\# of N_1 decaying OTEQ

Amount of CP violation

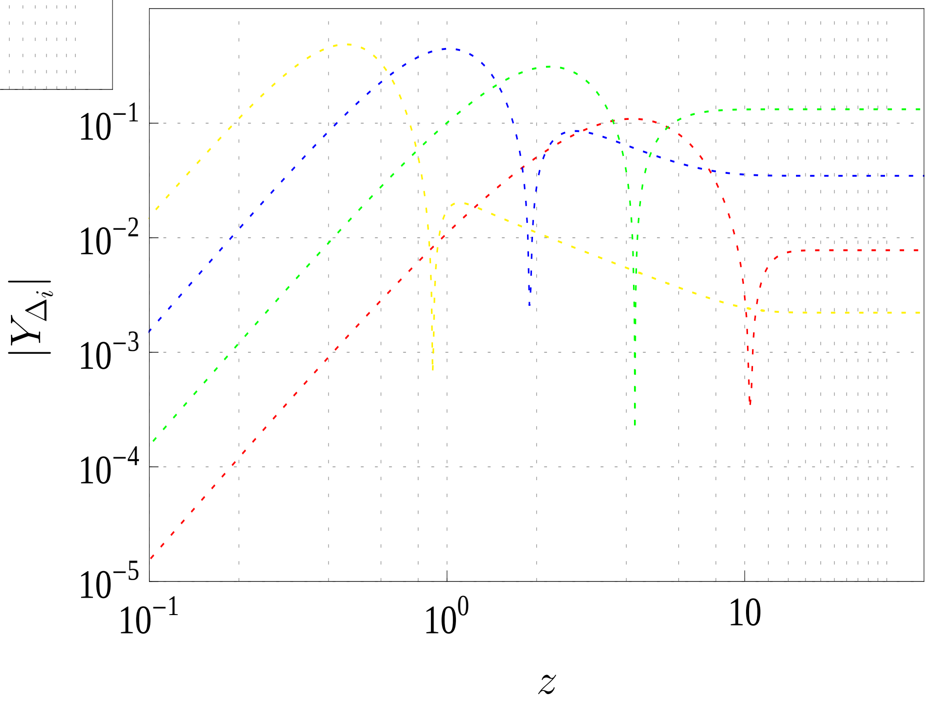
General picture

A general picture is given by numerical integration of the kinetic equations:



Populating the heat bath with RHNs for different $\tilde{m}$

Generation of the $B-L$ asymmetry for different $\tilde{m}$



Leptogenesis in type-III seesaw

Type-III seesaw

In type-III seesaw neutrino masses are generated via the interchange of fermionic EW triplets

$$\mathcal{L} = \overline{T}^A_\alpha \gamma^\mu D_\mu T^A_\alpha - \lambda^*_{i\alpha}\overline{\ell}_i \tau^A T^A_\alpha \widetilde{H} - \frac{1}{2}\overline{T}^A_\alpha M_{T_\alpha}(T^A_\alpha)^C + \text{h.c.}$$

$$T_\alpha = \begin{pmatrix} T^0_\alpha & \sqrt{2}T^+_\alpha \\ \sqrt{2}T^-_\alpha & -T^0_\alpha \end{pmatrix}$$

T^0_α responsible for ν masses

$$\boldsymbol{m_\nu}^{\text{eff}} = -v^2 \boldsymbol{\lambda} \cdot \boldsymbol{\hat{M}_T}^{-1} \cdot \boldsymbol{\lambda}^T$$

The new CP violating sources in $\boldsymbol{\lambda}$ induce CP violating T_α decays: ☞

- Hierarchical T_α spectrum $\omega_\beta = M^2_{T_\beta}/M^2_{T_\alpha} \gg 1$

$$\epsilon^{\ell_j}_{T_\alpha} \lesssim 10^{-5}\left(\frac{M_{T_\alpha}}{10^{10}\ \text{GeV}}\right)\left(\frac{m_3}{1\ \text{eV}}\right)\frac{\widetilde{m}_{j\alpha}}{\widetilde{m}_\alpha}$$

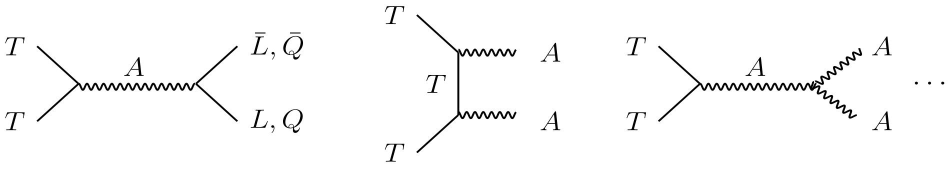
Succesful leptogenesis only possible for $M_T \gtrsim 10^{10}$ GeV

- Quasi-degenerate T_α spectrum $\sqrt{\omega_\beta} \sim 1 + \Gamma_\beta/M_\alpha$

Wave function piece resonantly enhanced
Sucessful leptogenesis $M_T \sim \mathcal{O}(\text{TeV})$

BEQs

Gauge reactions drive the T distribution close to a thermal equilibrium



Precise determination of the lepton asymmetry requires solution of BEQs

$$\frac{dY_{T_\alpha}}{dz_\alpha} = -\frac{1}{sHz_\alpha}\left[\left(\frac{Y_{T_\alpha}}{Y^{\rm Eq}_{T_\alpha}}-1\right)\gamma_{D_\alpha} + \left(\frac{Y^2_{T_\alpha}}{\left(Y^{\rm Eq}_{T_\alpha}\right)^2}-1\right)\gamma_{A_\alpha}\right]$$

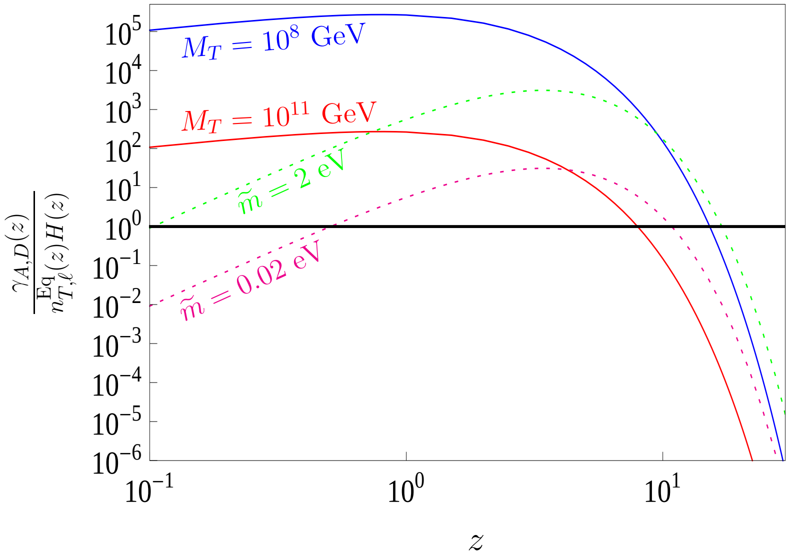
$$\frac{dY_{\Delta_i}}{dz_\alpha} = -\frac{1}{sHz_\alpha}\left[\left(\frac{Y_{T_\alpha}}{Y^{\rm Eq}_{T_\alpha}}-1\right)\epsilon^{\ell_i}_{T_\alpha} + \frac{K_{i\alpha}}{2Y^{\rm Eq}_\ell}\sum_{j=e,\mu,\tau} C^\ell_{ij}Y_{\Delta_j}\right]\gamma_{D_\alpha}$$

Flavor projectors: $K_{i\alpha} = \frac{\tilde{m}_{i\alpha}}{\tilde{m}_\alpha}$

$$Y_{\ell_i} = \sum_{i=e,\mu\tau} C^\ell_{ij}Y_{\Delta_i}$$

The generation of a L asymmetry proceeds according to:

$$\frac{\gamma_A}{n^{\rm Eq}_T H} \lesssim 1 \Rightarrow \begin{cases} \frac{\gamma_D}{n^{\rm Eq}_\ell H} \lesssim 1 & \text{ID decoupled} \\ \frac{\gamma_D}{n^{\rm Eq}_\ell H} \gtrsim 1 & \text{ID still active} \\ \frac{\gamma_A}{\gamma_D} \sim \frac{g^4}{M_T\tilde{m}} & \end{cases}$$



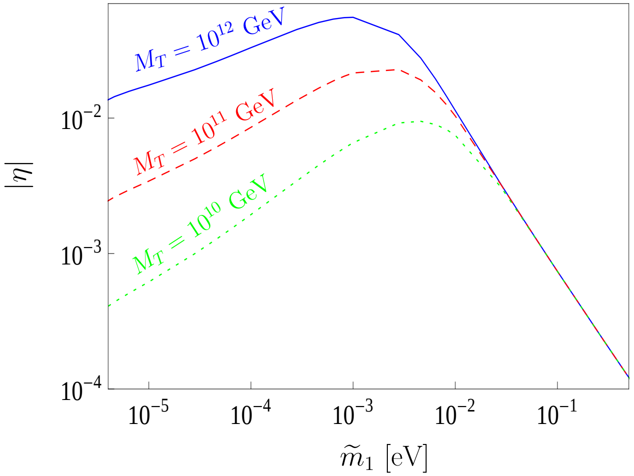
Lepton asymmetry: aligned case

In the case of a hierarchical triplet spectrum the asymmetry is determined by the lightest triplet (T_1):

$$Y_{\Delta_{B-L}} = 3 \times \sum_{i=e,\mu,\tau} \epsilon_{T_1}^{\ell_i} Y_T^{\text{Eq}} \eta_i$$

$\eta_{i\alpha}$: Efficiency in flavor ℓ_i ([0,1])

Compared with the standard case due to the couplings with $A = W_a, B$ there are several differences:



Small $\tilde{m}$

- 🟥 η strongly depends on M_T
- 🟥 $M_T \lesssim 10^{12} \Rightarrow \eta_{III} \ll \eta_I$

Large $\tilde{m}$

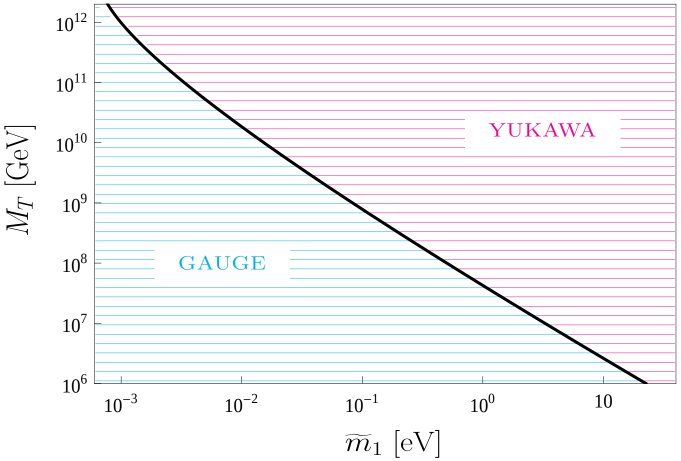
- 🟥 $\eta \neq \eta(M_T) \Rightarrow$ as in standard leptogenesis
- 🟥 There is a $\tilde{m}_{\text{min}}$ for which $\gamma_A < \gamma_D$

Gauge region

- At gauge decoupling ID are decoupled too

Yukawa region

- ID are active when $\gamma_A / n_T^{\text{Eq}} H \lesssim 1$



Including flavor I

The inclusion of flavor should have an impact on the final asymmetry. Numerical results for a representative “point”

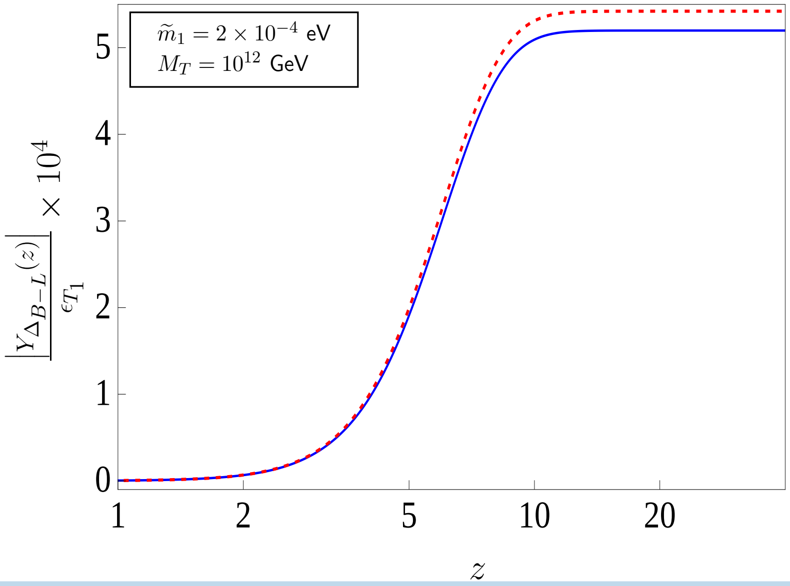
★ $K_{11} = 0.99$ ($K_{\tau 1} = 1 - K_{11}$), $\epsilon_{T_1}^{\ell_1} = -0.1 \times \epsilon_{T_1}$, $\epsilon_{T_1}^{\ell_\tau} = 1.1 \times \epsilon_{T_1}$ with $\epsilon_{T_1} = 10^{-5}$

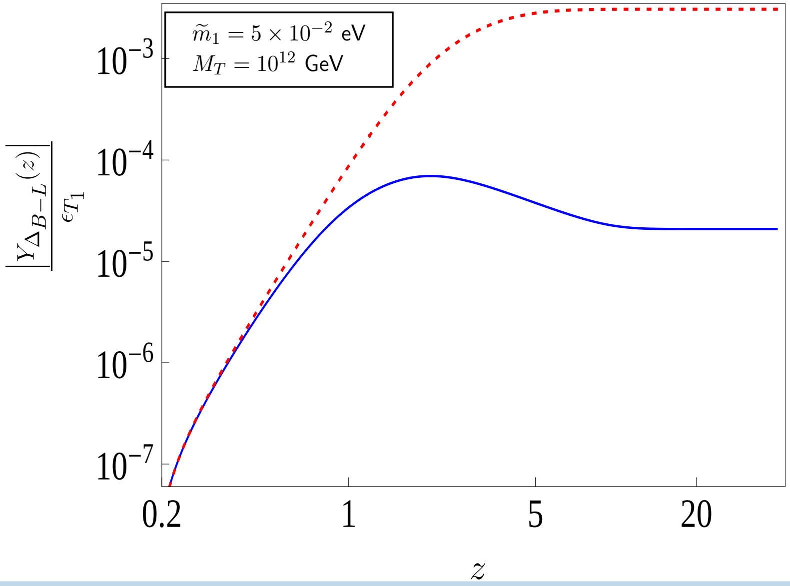
Gauge “region”

Yukawa “region”

The T_1 abundance is efficiently diminished by γ_A. Flavor effects are tiny (∼5% for ★)

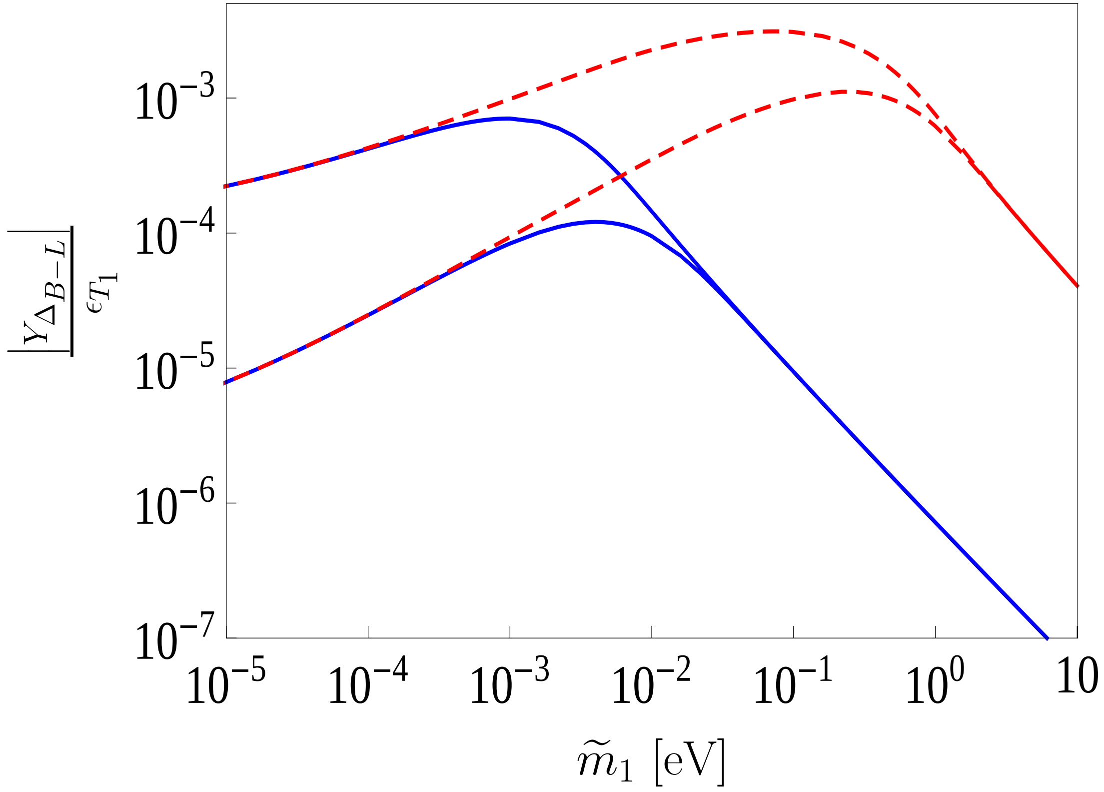
At $z_1 \gg 1$ the dynamics of T_1 is entirely determined by γ_D. Flavor effects are sizable (a factor $\sim 10^2$ for ★)





Including flavor II

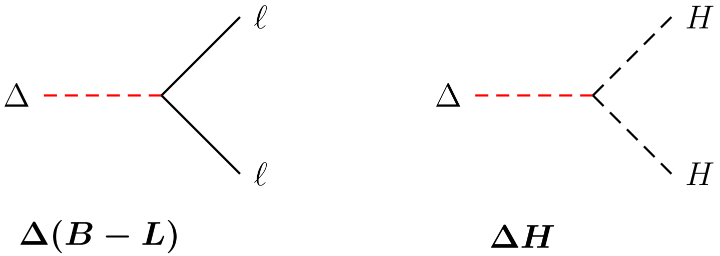
Flavor effects are relevant as long as leptogenesis takes place within the “Yukawa region”. The minimum $\tilde{m}$ for which flavor effects become relevant depends upon M_T.



Further developments

Type-II: some remarks (A)

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \underbrace{Y\ell\ell\Delta}_{\Delta(B-L)} + \underbrace{\mu HH\Delta}_{\Delta H}$$



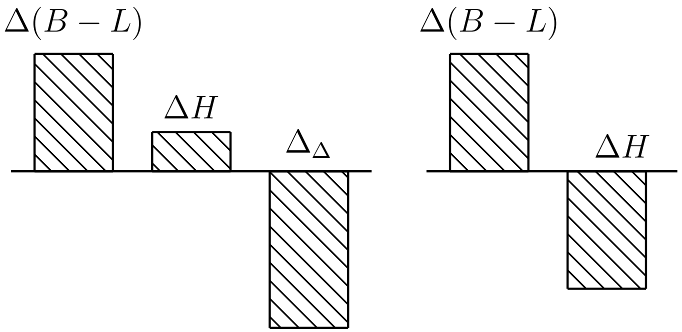
$\Delta \neq \Delta^\dagger$

Asymmetry in Δ

For $T > 10^{15}$ GeV all SM reactions: $\Gamma_{\text{SM}} \ll H$

Asymmetries tracked with Boltzmann equations

Hypercharge neutrality of the heat bath



For $T < 10^{13}$ GeV lepton flavor plays a role

Type-II: some remarks (B)

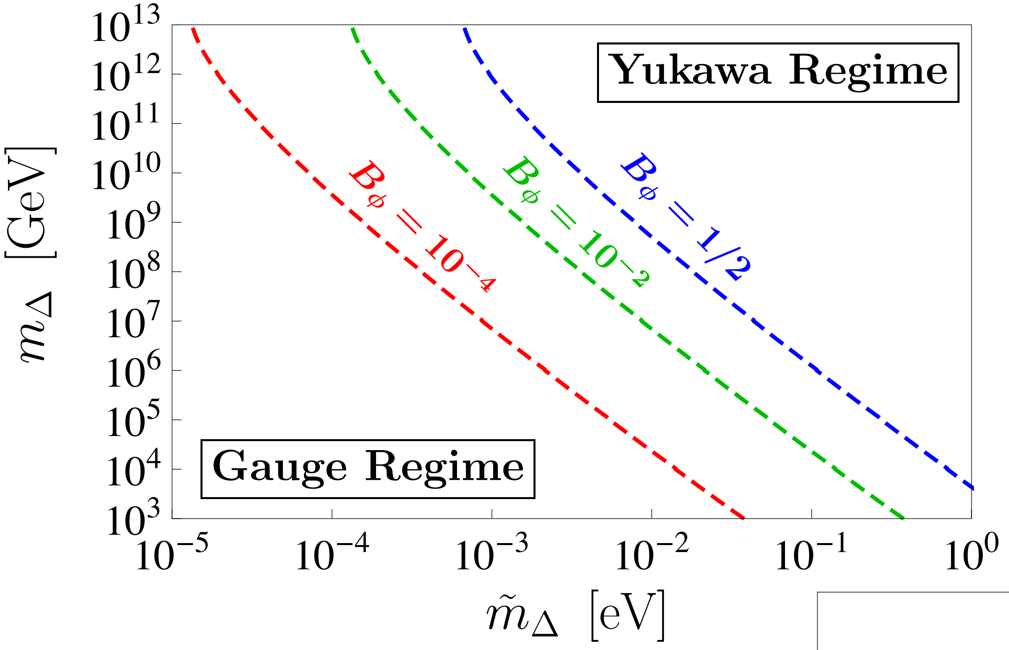
Introduction

Leptogenesis: “standard” case

Leptogenesis in type-III seesaw

Further developments
- Type-II: some remarks (A)
- Type-II: some remarks (B)
- Cloistered baryogenesis

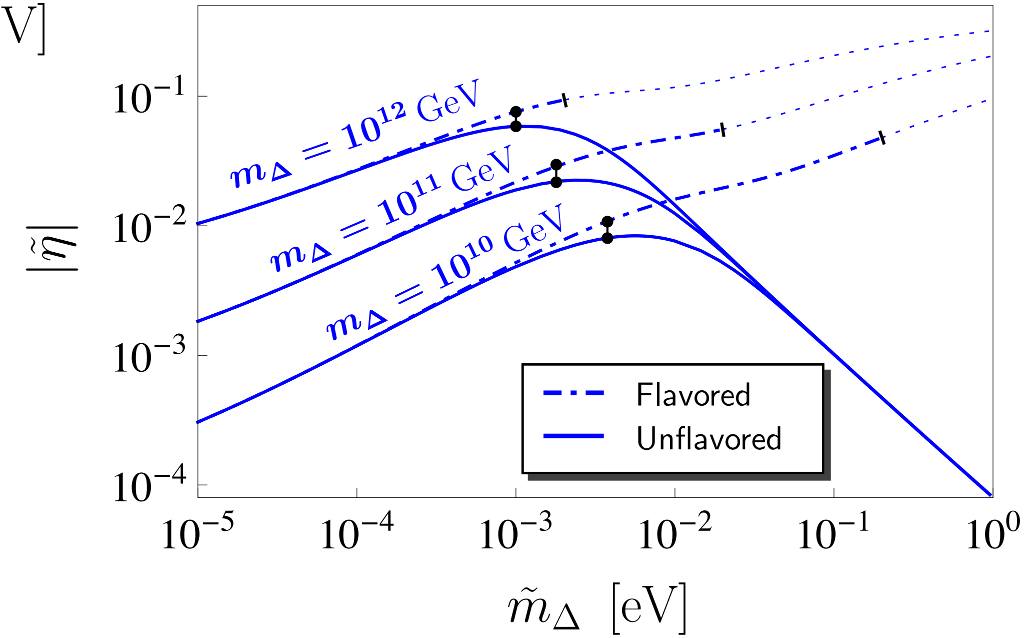
Conclusions



$$\gamma_D \propto \tilde{m}_\Delta \frac{m_\Delta}{\sqrt{B_\phi(1-B_\phi)}}$$

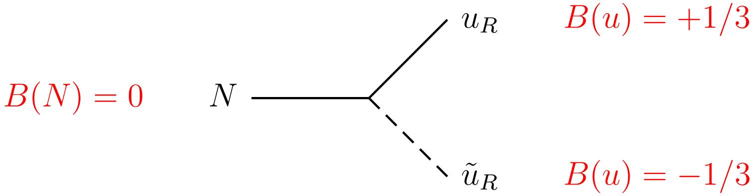
$$B_\phi + B_\ell = 1$$

$$B_\phi = 0.5$$

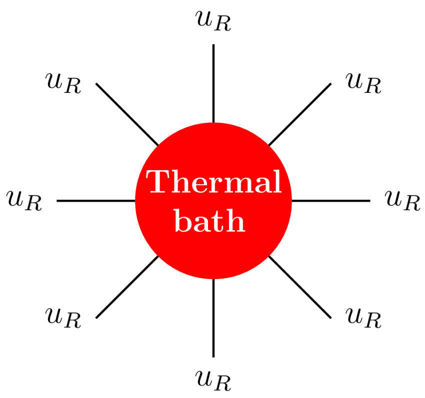


Cloistered baryogenesis

RHNs coupled with RH up-type quarks. Gauge invariance requires a new colored scalar $\tilde{u}$:



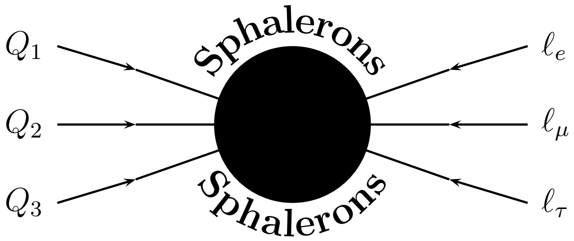
$\boxed{\Delta B = 0}$



A fraction of B_u goes into SM d.o.f

In particular Q_L

$\tilde{u}$ is chemically decoupled



In the heat bath

$\Delta B_{\tilde{u}} \neq \Delta B_{\text{SM}}$

$\boxed{\Delta B \neq 0}$

Baryogenesis via B conserving decays provided one of the states is chemically decoupled

Conclusions

Final remarks

- The baryon asymmetry of the Universe certainly calls for BSM physics.

- Leptogenesis is probably among the best motivated scenarios where this puzzle can be addressed:
  - ✔ Tree-level seesaw models provide natural playgrounds.
  - ✔ They have been throughout analyzed

    .

- Testability... Evidence might weakness or favor the case for leptogenesis.