Laboratoire de Physique Théorique-Orsay

Leptogenesis

- ☞ Motivation, Requirements, Framework
- ☞ Neutrino mass $\rightarrow$ new physics, explains also baryogenesis?
- ☞ Seesaw mechanisms
- ☞ Leptogenesis and Consequences : some phenomenology
- ☞ Leptogenesis at low scales, how difficult?
- ☞ How to Disentangle between seesaws? Collider Physics?

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NuFlavour , 8-10 June 2009, Cosener's House

Observations : Neutrino masses and BAU

☞ **Need dynamical mechanism to generate** Baryon Asymmetry of the Universe η_B:

Primordial abundances of light elements + CMB Anisotropies sensitive to η_B

$$\eta_B^{\text{BBN}} = \frac{n_B}{n_\gamma}\Big|_{\text{BBN}} \approx (4.7 - 6.5) \times 10^{-10}, \; \eta_B^{\text{CMB}} = \frac{n_B}{n_\gamma}\Big|_{\text{CMB}} \approx (6.21 \pm 0.16) \times 10^{-10}$$

Baryo(Lepto)genesis requirements

Sakharov '67 [a]

1. **B**aryon (**L**epton) number violation
2. **C** & CP Violation
3. **O**ut of equilibrium processes

$$n_{B(L)} \neq n_{\bar{B}(\bar{L})}$$

[a] 4th constraint : $B - L$ must be violated if baryogenesis occurs > EW scale

☞ **Need a high scale to generate** small neutrino masses and mixings:

Recent data: atmosphere, Solar, Terrestrial expts.

Atmospheric ν and Reactor Data

$\Delta m^2_{\rm atm}({\rm eV}^2)$	$\theta_{\rm atm}$	θ_{13}
$2.6 \pm 0.2\,(0.6) \times 10^{-3}$	$43.3\,^{+4.3}_{-3.8}$	$0\,^{+5.2}_{-0.0}$

Solar ν

$\Delta m^2_{\rm sol}({\rm eV}^2)$	$\theta_{\rm sol}$
$7.9\,^{+0.27}_{-0.28} \times 10^{-5}$	33.7 ± 1.3

Absolute mass scale ν

Oscillations	$m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 5 \times 10^{-2}$ eV
Cosmology	$\sum_i m_{\nu_i} <\sim 1$ eV
Tritium	$m_{\nu_e} \lesssim 2.2$ eV

- Majorana nature? **Lepton Number Violation** ➡ $(0\nu\beta\beta)$
- Low energy mixing and **Additional CP phases?**
  - Dirac CP Phase δ ➡ first need to know θ_{13} with good accuracy
  - Majorana phases $\alpha_{1,2}$: no direct information ➡ $(0\nu\beta\beta)$?

Little history

- 1985: Kuzmin, Rubakov & Shaposhnikov, following the discovery of fast $B + L$ violation at $T > T_{\rm EW}$
  "On the anomalous electroweak baryon number nonconservation in the early universe"
- 1986: Fukugita &Yanagida, basic idea of leptogenesis
  "Baryogenesis without grand unification"
- 1992-1996: a few remarkable works opened the way to quantitative leptogenesis, e.g.
  Luty ('92), "Baryogenesis via leptogenesis",
  Covi, Roulet,Vissani ('96), "CP violating decays in leptogenesis scenarios"
- 1993: Farrar, Shaposhnikov, EW baryogenesis?
  "Baryon asymmetry of the Universe in the MSM"
- 1994: Gavela,Hernandez, Orloff, Pene IMPOSSIBLE!
  "Standard model CP violation and baryon asymmetry"
- $>$ SK (2000): Evidence for neutrino oscillations + EW baryogenesis fails in SM and MSSM, fuel the interest on leptogenesis : a flourishing study begins

➡ **Need a high scale to generate** **small neutrino masses and mixings**

➡ **Need dynamical mechanism to generate** **BAU**

↓

AIM: find models that are simultaneously consistent with Neutrino masses and BAU

- Favourite option: new physics at high scale M
- What is this new physics? How does it manifest?
- At which scale? Which implications for low energy phenomenology?

$m_\nu \neq 0 \Rightarrow$ New Physics

- Lepton symmetry is accidental $\Longrightarrow$ Non-renormalisable operators dim 5, 6 ...

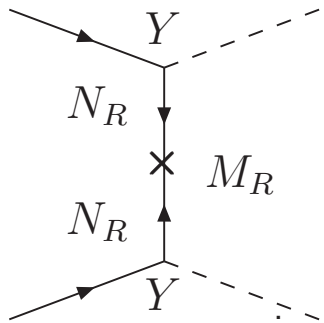
SM $\equiv$ Effective theory of a larger one at a scale Λ

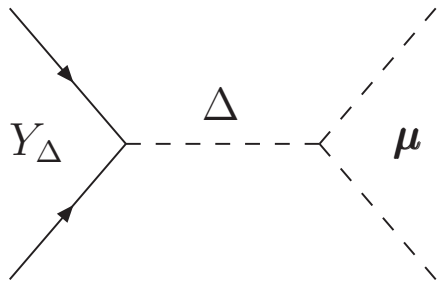
$$\mathcal{O}_5 = \frac{C_{d=5}}{\Lambda}\left\{(\phi\ell)^{\mathrm{T}}(\phi\ell)\right\} \xrightarrow{\langle\phi\rangle=v} \quad m_\nu \sim C_{d=5}^2 v^2/\Lambda \quad \Rightarrow \quad \Lambda \in [\text{TeV}, \quad M_{\text{GUT}}]$$

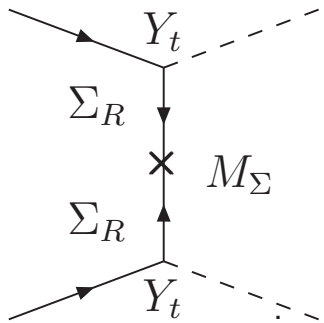
Typically 3 possible ways to generate $m_\nu \neq 0$:

- See-saw mechanism: towards GUT $\rightarrow SO(10), \cdots$ can be achieved via
  1. type I with RH neutrino exchange
  2. type II with scalar triplet exchange
  3. type III with fermionic triplet exchange
- Radiative corrections $\rightarrow$ MSSM or various extensions $+\not{R}_p$, Zee model...
- Extra dimensions $\rightarrow$ alternative to the see-saw

3 ways to generate tree level $\mathcal{O}^{d=5}$: Seesaw I, II, III







type I (fermionic singlet)

$$\mathbf{m}_\nu = -\frac{v^2}{2}\, Y_N^T \frac{1}{M_N}\, Y_N$$

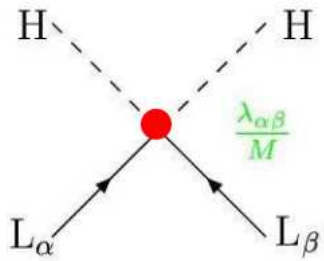
type II (scalar triplet)

$$\mathbf{m}_\nu = -2v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$$

type III (fermionic triplet)

$$\mathbf{m}_\nu = -\frac{v^2}{2}\, Y_\Sigma^T \frac{1}{M_\Sigma}\, Y_\Sigma$$

☞ $\mathcal{O}^{d=5}$ **is common to *all* models of Majorana neutrinos**



Leptogenesis

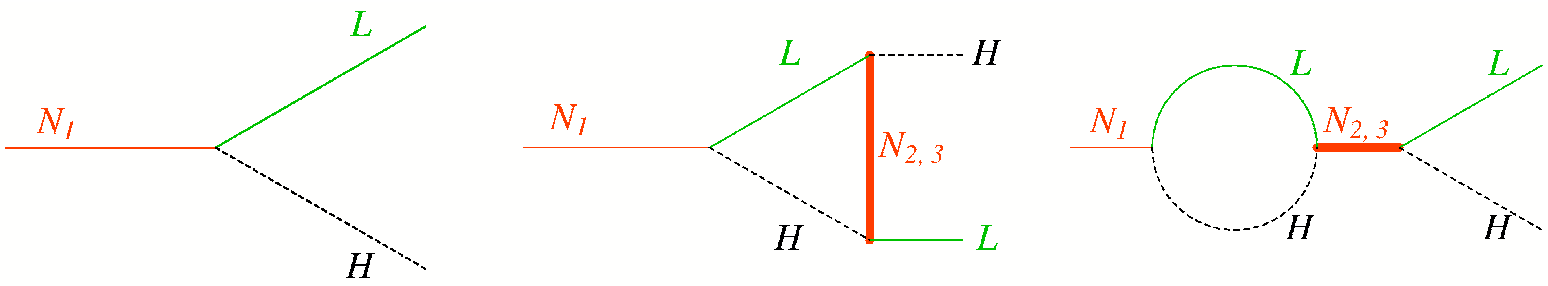
Basic Leptogenesis Mechanism (Seesaw type I)

Fukugita and Yanagida '86

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda^{\nu}_{Jk} \bar{L}_k \nu_{R_J} H - \frac{1}{2} \bar{\nu}_{R_J} M_{R_J} \nu^c_{R_J} + h_\alpha H^c \bar{e}_{R_\alpha} \ell_\alpha$$

1. CP violating decay of a heavy particle through an L-violating interaction can produce a lepton asymmetry
2. Lepton asymmetry transformed into *BAU* through sphaleron interactions:
   $B+L$-current is anomalous but $B-L$ and $1/3B - L_\alpha$ currents are not

$$\eta_B = -\left(\frac{24+4n_H}{42+9n_H}\right)\eta_L$$



1) L violation ← N_i Majorana

2) C & CP asymmetry: $\epsilon_1 = \sum_\alpha \epsilon_{\alpha\alpha} = \frac{\sum_\alpha \left(\Gamma(N_1 \to H\ell_\alpha) - \Gamma(\bar{N}_1 \to \bar{H}\bar{\ell}_\alpha)\right)}{\sum_\alpha \left(\Gamma(N_1 \to H\ell_\alpha) + \Gamma(\bar{N}_1 \to \bar{H}\bar{\ell}_\alpha)\right)}$

CP from the complexity of the λ^ν Yukawa matrix

3) Out-of-equilibrium decay of N_1 ← $\frac{\Gamma_{N_1}}{H(T=M_1)} \ll 1$

$\eta_L \propto K\ \epsilon_1$ is produced

4) Sphalerons act: $\Delta L \to \Delta B$

To see if it works , Solve B.E

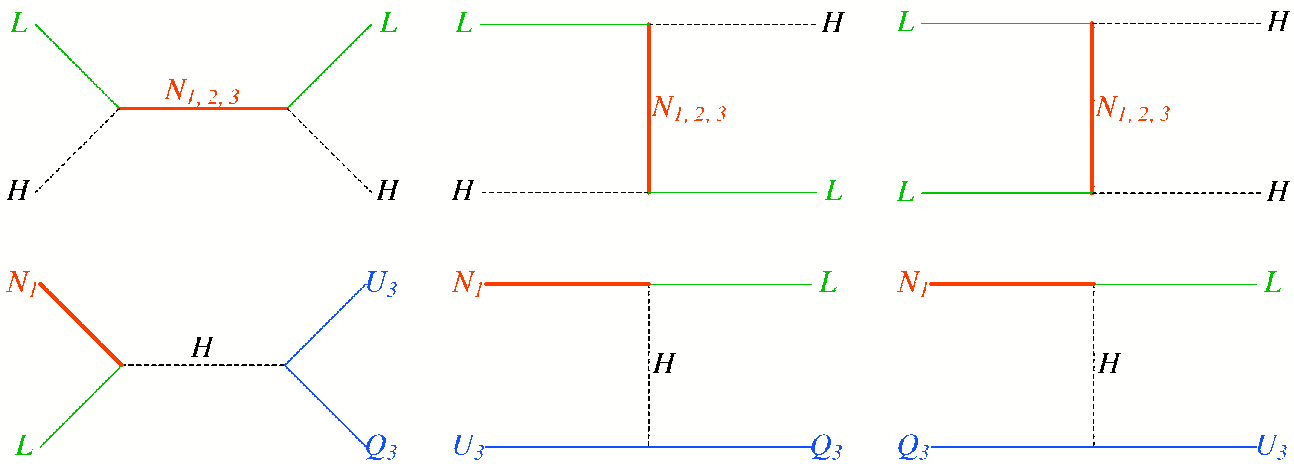
Boltzmann Equations 1 Flavour Approx

Lightest N_1 produced in the thermal bath after inflation

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(M_1)}\left(\frac{Y_{N_1}}{Y_N^{eq}} - 1\right)(\gamma_{D_1} + \gamma_{S_1})$$

$$\frac{dY_L}{dz} = -\frac{z}{sH(M_1)}\left[\epsilon_1\gamma_{D_1}\left(\frac{Y_{N_1}}{Y_N^{eq}} - 1\right) - \gamma_W \frac{Y_L}{Y_L^{eq}}\right]$$

* $Y_{N_1} \equiv \frac{n_{N_1}}{s}$ is N_1 abundance, $Y_L \equiv \frac{n_\ell - n_{\bar{\ell}}}{s} = \sum_\alpha Y_L^{\alpha\alpha}$ is total lepton asymmetry
* $z = \frac{M_1}{T}$, s: entropy density, ϵ_1: CP-asymmetry
* $\gamma_{D_1}, \gamma_{S_1}$: interaction rates for the decay and scattering $\Delta L = 1$
* γ_W = function ($\gamma_{D_1}, \gamma_{S_1}$, $\Delta L = 2$) washout factor

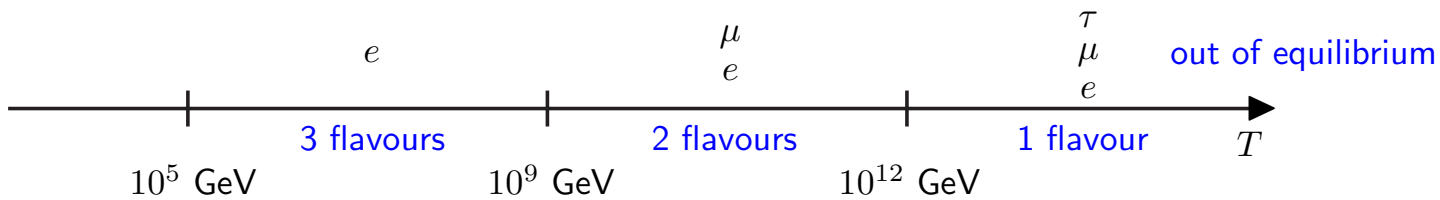


First results: Constraints in 1 Flavour Approx

- $M_1 << M_2 << M_3$ ➡ $|\epsilon_1| \leq \frac{3\sqrt{2}}{16\pi} M_1 \frac{\sqrt{m_1^2+m_2^2+m_3^2}}{v^2}$
  - If **degenerate** light ν ➡ $\epsilon_1 = 0$
  - If **hierarchical** light ν ➡ $|\epsilon_1| \leq \frac{3\sqrt{2}}{16\pi} M_1 \frac{\sqrt{\Delta m^2_{\rm atm}}}{v^2}$ [Davidson, Ibarra]
  - $\lambda \sim \mathcal{O}(1)$ & $\kappa \sim 1$ and $\eta_B^{\rm WMAP}$ ➡ $M_1 \gtrsim 6.4 \times 10^8$ GeV
  - $\eta_{B-L}^{\rm max}$ ➡ $m \lesssim 0.15$ eV [Buchmuller, Di Bari, Plumacher]
- Quasi-degenerate $M_J^2 - M_I^2 << M_J^2 \simeq M_I^2$ ➡ $|\epsilon_1| \neq 0$ ➡ $m \lesssim 1$ eV [Hambye et al]
- $M_1 = M_2 = M_3$ ➡ $\epsilon_1 = 0$

Why should we worry about flavour?

- Thermal leptogenesis at $T \simeq M_1$ when $\Gamma_{N_1} < H(M_1)$
- One flavour approximation: correct when the interactions mediated by charged lepton Yukawa are out of equilibrium
- $\Gamma_\alpha \simeq 5 \times 10^{-3} h_\alpha^2 \; T$



- One flavour approx valid for $M_1 > 10^{12}$ GeV,
  below, solve FLAVOURED Boltzmann eqs to generate $Y_{L_{\alpha\beta}}$
- diagonal terms ($\alpha\alpha$): lepton asymmetries stored in each flavour
- off-diagonal terms encode the quantum correlations between the flavour asymmetries

One flavour

$$\frac{dY_L^{\alpha\alpha}}{dz} = -\frac{z}{sH(M_1)}\left[\epsilon_{\alpha\alpha}\gamma_{D_1}\left(\frac{Y_{N_1}}{Y_N^{eq}}-1\right)-\gamma_W^{\alpha\alpha}\frac{Y_L^{\alpha\alpha}}{Y_L^{eq}}\right],$$

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1\to H\ell_\alpha)-\Gamma(\bar{N}_1\to\bar{H}\bar{\ell}_\alpha)}{\Gamma(N_1\to H\ell_\alpha)+\Gamma(\bar{N}_1\to\bar{H}\bar{\ell}_\alpha)}$$

Sum over flavour

$$\begin{aligned}
\sum_\alpha \frac{dY_L^{\alpha\alpha}}{dz} &= -\frac{z}{sH(M_1)}\Big[\underbrace{(\epsilon_{ee}+\epsilon_{\mu\mu}+\epsilon_{\tau\tau})}_{\epsilon_1}\gamma_{D_1}\left(\frac{Y_{N_1}}{Y_N^{eq}}-1\right) \\
&- \frac{1}{Y_L^{eq}}\underbrace{\left(\gamma_W^{ee}Y_L^{ee}+\gamma_W^{\mu\mu}Y_L^{\mu\mu}+\gamma_W^{\tau\tau}Y_L^{\tau\tau}\right)}_{\neq(\gamma_W^{ee}+\gamma_W^{\mu\mu}+\gamma_W^{\tau\tau})Y_L}\Big], \\
&\neq -\frac{z}{sH(M_1)}\left[\epsilon_1\gamma_{D_1}\left(\frac{Y_{N_1}}{Y_N^{eq}}-1\right)-\gamma_W\frac{Y_L}{Y_L^{eq}}\right] \quad \text{(One Flav Approx)}
\end{aligned}$$

Flavoured B.E

$Y_{\Delta\alpha} \Rightarrow B/3 - L_\alpha$ asymmetry in lepton flavour α

Baryonic asymmetry: $Y_{\mathcal{B}} \simeq \frac{12}{37} \sum_\alpha Y_{\Delta\alpha} \simeq -1.26 \times 10^{-3} \sum_\alpha \epsilon_\alpha \, \eta_\alpha$

N_1 Abundance: $Y'_{N_1}(z) = -\kappa \left(D(z) + S(z)\right) \left(Y_{N_1}(z) - Y^{eq}_{N_1}(z)\right), \quad z = M_1/T$

$Y_{\Delta\alpha}$ asymmetry:

$$Y_{\Delta\alpha}{}'(z) = -\epsilon_\alpha \kappa \left(D(z) + S(z)\right) \left(Y_{N_1}(z) - Y^{eq}_{N_1}(z)\right) - \kappa_\alpha W(z) \sum_\beta A_{\alpha\beta} Y_{\Delta\beta}(z)$$

Y_L Abundance: $Y_{L_\alpha} = A_{\alpha\beta} Y_{\Delta\beta}; \quad A = -\begin{pmatrix} -151/179 & 20/179 & 20/179 \\ 25/358 & -344/537 & 14/537 \\ 25/358 & 14/537 & -344/537 \end{pmatrix}$

Washout parameters: $\kappa_\alpha \equiv \frac{\Gamma_{N1\,\ell_\alpha}}{H(M_{N_1})} = \lambda_{1\,\alpha} \lambda^\star_{1\,\alpha} \frac{v^2}{M_1 m^*} \equiv \frac{\tilde{m}_\alpha}{m^*}$

$\kappa = \sum_\alpha \kappa_\alpha \equiv \frac{\tilde{m}}{m^*}$, $m^* \simeq 1.08 \times 10^{-3}$ eV

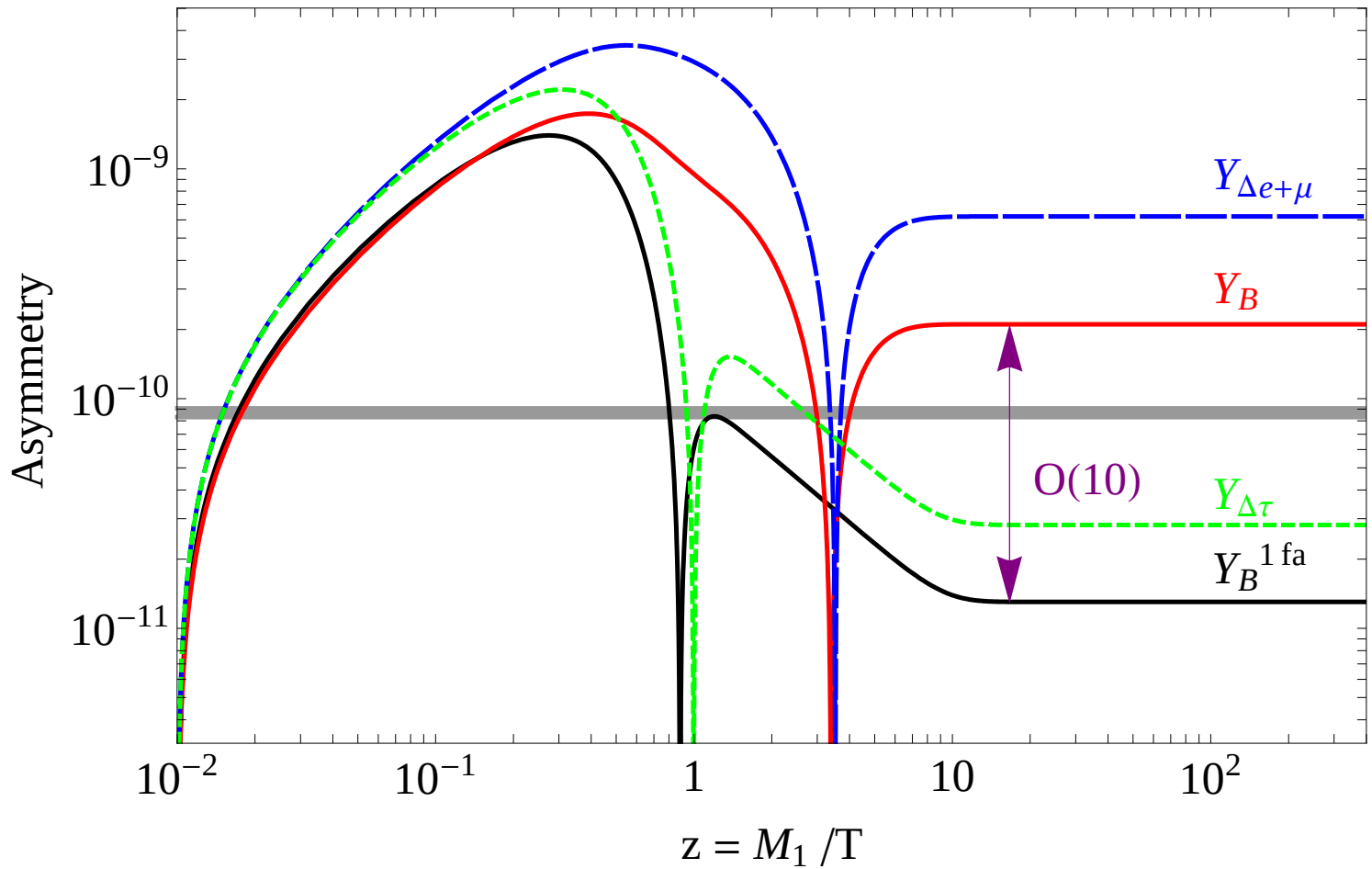
The CP-asymmetry:

$$\epsilon_\alpha = \frac{\Gamma_{N1\,\ell_\alpha} - \Gamma_{N1\,\bar{\ell}_\alpha}}{\sum_\alpha \left(\Gamma_{N1\,\ell_\alpha} + \Gamma_{N1\,\bar{\ell}_\alpha}\right)} = \frac{1}{(8\pi)} \frac{1}{[\lambda\lambda^\dagger]_{11}} \sum_j \mathrm{Im}\left\{(\lambda_{1\alpha})(\lambda\lambda^\dagger)_{1j}(\lambda^*_{j\alpha})\right\} g\left(\frac{M_j^2}{M_1^2}\right)$$

Efficiency η_α: need to solve B.E

Enhancing η_B

$\alpha = 1 \equiv$ ("$e + \mu$") $\rightarrow$ strong washout $\alpha = 2 \equiv (\tau) \rightarrow$ weak washout



Significant enhancement of BAU compared to One Flavour Approximation

Consequences of treatment of flavours

With **Yukawa couplings**: $\lambda = \frac{1}{v}\sqrt{M_N}\, R\, \sqrt{m_\nu}\, U^\dagger$ [Casas-Ibarra]

CP asymmetry

$$\varepsilon_1 = -\frac{3\, m_{N_1}}{8\,\pi\, v_2^2}\, \frac{\mathrm{Im}\left[\sum_\beta m_{\nu_\beta}^2\, {R_{1\beta}}^2\right]}{\sum_\delta m_{\nu_\delta}\, |R_{1\delta}|^2}$$

$$\varepsilon_{1,\alpha} = -\frac{3\, m_{N_1}}{8\,\pi\, v_2^2}\, \frac{\mathrm{Im}\left[\sum_{\beta\rho} m_{\nu_\beta}^{1/2}\, m_{\nu_\rho}^{3/2}\, (U_{\mathrm{MNS}})^*_{\alpha\beta} (U_{\mathrm{MNS}})_{\alpha\rho}\, R_{1\beta}\, R_{1\rho}\right]}{\sum_\delta m_{\nu_\delta}\, |R_{1\delta}|^2}$$

1 flav approx: if light ν are **degenerate** ($m_i \simeq \bar{m}$) ➡ $\epsilon_1 = 0$

flavoured: $\epsilon_1 = \sum_\alpha \epsilon_{1,\alpha} = 0$; individual $\epsilon_{1,\alpha} \leq \frac{3M_1\bar{m}}{8\pi v^2}$ grows with absolute scale $\bar{m}$

ϵ_α have opposite sign but are weighted by different washout factors

➡ **Can have successful leptogenesis in the case of degenerate light neutrino spectrum**

➡ **Additional sources of CP violation**

Sources of CP violation R and U_{MNS}! Crucial: $R \neq 1$

Input parameters - **Yukawa couplings** λ:

$$\lambda = \frac{1}{v}\sqrt{M_N}\, R\, \sqrt{m_\nu}\, U^\dagger$$ [Casas-Ibarra]

BAU from **flavoured** leptogenesis: $\left(R(\theta_i),\ M_1,\ m_1,\ \theta_{13},\ \delta,\ \varphi_1,\ \varphi_2\right)$

Flavoured BAU (3 ν_R): not sensitive to phases in U [Davidson, Garayoa, Palorini, Rius]

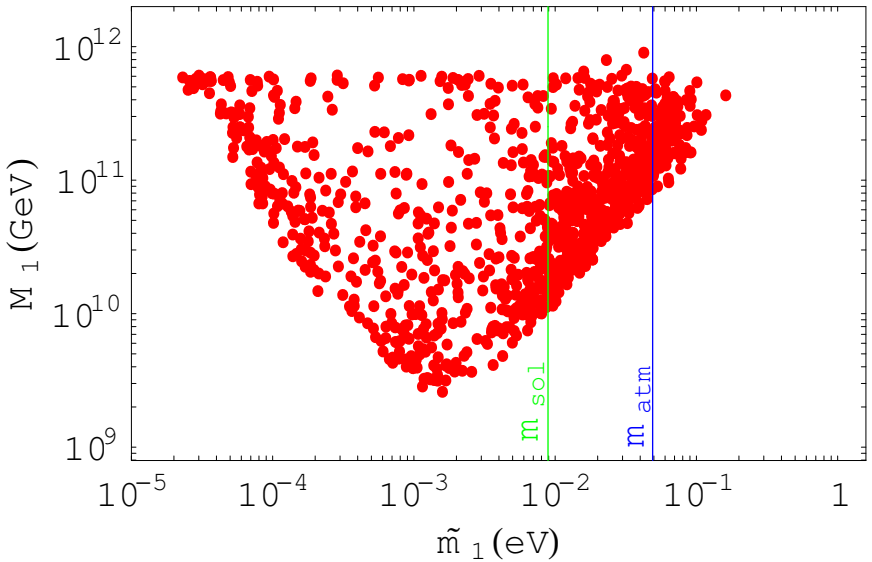
η_B accounted for with R phases (any value of $\theta_{13},\ \delta,\ \varphi_1,\ \varphi_2$)
even if U phases measured, η_B can have any value

BAU with Real R

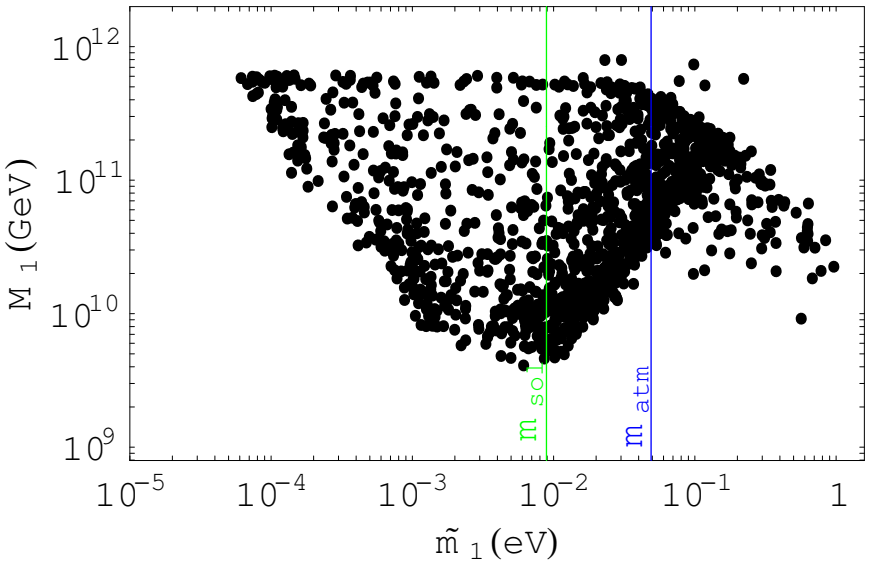
SM: feasible [Pascoli ,Petcov, Riotto, Branco, Gonzalez-Felipe, Joaquim. . .]
Disfavoured in SUSY seesaw (T_{RH}) [Antusch, Teixeira . . .]

* Implication for M_ν: Lower bound on N_1 mass

- Allowed parameter space M_1 -$\tilde{m} = \sum_\alpha \kappa_\alpha$ compatible with $5.2 \times 10^{-10} \lesssim 7.04 \times Y_{\mathcal{B}} \lesssim 7.2 \times 10^{-10}$



One Flavour approx

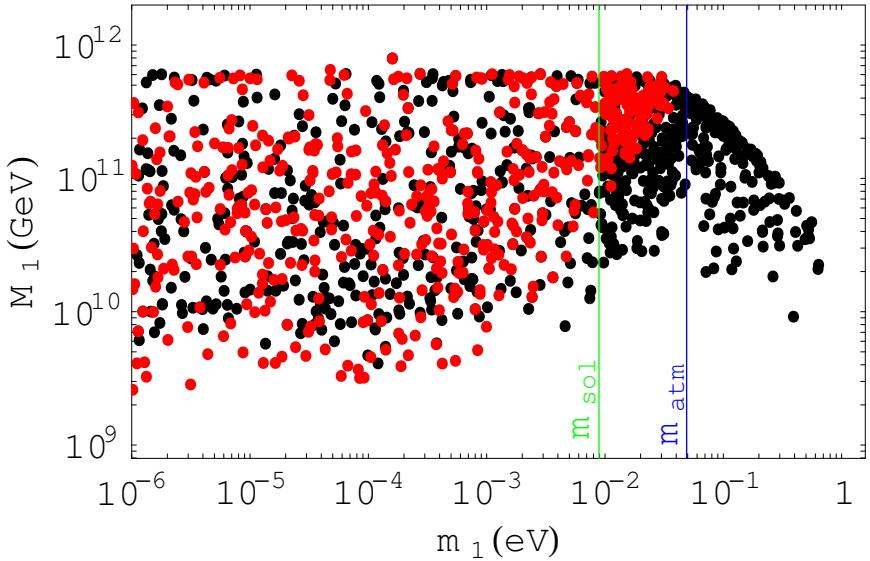


Full flavour treatment

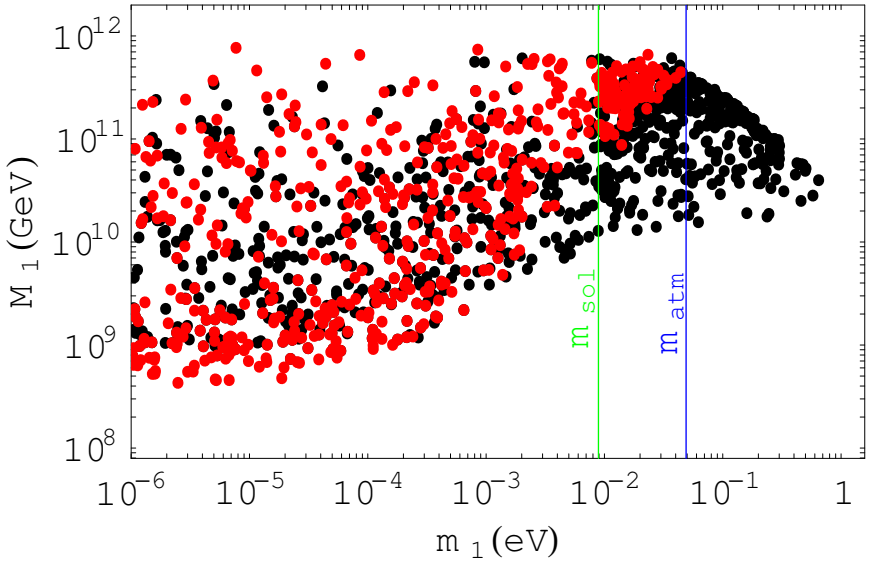
$$M_{N_1} \gtrsim \begin{cases} 6 \times 10^8 \text{ GeV} & \text{in the thermal case} \\ 4 \times 10^9 \text{ GeV} & \text{in the dynamical case} \end{cases}$$

Flavours open a wider range for $\tilde{m}_1$ (extremely small values allowed)

* Implication for lightest neutrino mass m_1



Dynamical



Thermal

There is **NO BOUND** on absolute scale of light neutrinos from the requirement of successful leptogenesis!

Role of N_2 and N_3

Relaxing the assumption of $M_3 \gg M_2 \gg M_1$

- **Impact of N_2**

  $M_{N_{2,3}} < T_{\rm RH}$, L-asymmetry from $N_{2,3}$ survives N_1 leptogenesis

  - **N_1- decoupling** ($Y_{N_2} \gg Y_{N_1}$) [Di Bari, Vives, Blanchet ...]
  - **strong N_1- coupling** (N_1 decoherence effects project L-asymmetry from N_2 onto direction protected against N_1 washout) [Barbieri et al, Nardi, Strumia, ...]

- **Lowering the seesaw scale: resonant leptogenesis**

  Resonant enhancement of CP asymmetry if $M_{N_2} - M_{N_1} = \Gamma_2/2$: $\varepsilon_{\rm CP} \sim \mathcal{O}(1)$

  [Pilaftsis, Underwood, Branco, Buras, Sarkar, Paschos, Flanz, Broncano, Plumacher ...]

  Viable BAU **independently** of M_{N_i} $\rightarrow$ **low scale leptogenesis**

  [Ma, Hambye, Frigerio, Sarkar, Albright, Riotto,Babu,Isidori ...]

SUSY leptogenesis

- **SUSY-Seesaw:** small qualitative and quantitative differences

$$Y_{\text{B-L}}^{\text{MSSM}} \approx -\eta \left[\tfrac{1}{2}(\varepsilon_1 + \tilde{\varepsilon}_1) Y_{N_1}^{\text{eq}} + \tfrac{1}{2}(\varepsilon_{\tilde{1}} + \tilde{\varepsilon}_{\tilde{1}}) Y_{\tilde{N}_1}^{\text{eq}} \right]$$

flavours: correct T by $(1 + \tan^2\beta)$ factor in general

but *gravitino problem*: constraints on $\boldsymbol{T_{\mathrm{RH}}}$ $\rightarrow$ can compromise viable BAU

T_{RH} **bounded from above (gravitino problem)** $\Rightarrow$ **upper bound on** $\boldsymbol{m_{N_1}}$
(due to dramatic loss of efficiency when $m_{N_1} \gg T_{\mathrm{RH}}$ [Giudice et al ('03)])

- **"new mechanisms":**
  - **Affleck-Dine** (BAU from coherent oscillations of B, L charged flat directions of $V_{\text{SUSY}}^{\text{scalar}}$)
  - **Soft leptogenesis** (unavoidable but subdominant in the SUSY-seesaw) $\not{L}$ and $\not{C}\not{P}$ from $\mathcal{L}_{\tilde{N}}^{\text{soft}}$
    [Grossman et al., D'Ambrosio et al,. . .]

Leptogenesis beyond type I see-saw

- **Type II ($SU(2)_L$ triplet + singlet)**

- New sources of lepton asymmetry (and neutrino masses)
- The CP asymmetry ε_T increases with m_ν
- Less severe lower bound on M_T and M_R

[Frère, Hambye, Raidal, Strumia, Chun, Akhmedov, Lavignac, Frigerio, Antusch, ...]

- **Type III (fermionic triplet)**

- Decay rate $\Gamma_{FT} > \Gamma_N$
- The asymmetry $\varepsilon_{FT} < \varepsilon_N$ (cancellations in the loops)
- Ignoring flavour effects, stricter bound on M_{FT} ($\sim 10^{10}$ GeV) [Hambye, Senjanovic, ...]

Other leptogenesis mechanisms

▶ **Dirac leptogenesis** [Akhmedov, Rubakov, Smirnov, Dick, Leidner, Ratz, Wright...]

- Dirac neutrinos with $Y_\nu \sim 10^{-11}$ (from soft symmetry breaking)
- No L-violation
- Lepton asymmetry: decays of new heavy particles producing L for f_L and $-L$ for f_R
- Charged fermions quickly equilibrate

$$\nu_L \text{ and } \nu_R \text{ in equilibrim for } T < T_{\text{EW}} \; (Y_\nu \sim 10^{-11})$$

- Sphalerons: part of L stored in ν_L converted into B

Phenomenological consequences: no $(0\nu\beta\beta)$ decay!

Open Questions

- **Is there a way to disprove leptogenesis?**
- **If seesaw leptogenesis, how to disentangle between seesaws? Collider Physics?**
- **Is it realistic to envisage a bridge between high and low energy CP phases?**
- **How natural is a real R matrix?** CP exact symm in the RH sector
- **Do LFV processes provide any additional constraints?**