

# Flavour matters in Leptogenesis

claim: single-flavour approximation (usual Boltzmann Eqns for total lepton number) is unreliable

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## 1. review:

- the baryon asymmetry, two neutrino mass differences and the seesaw
- thermal leptogenesis from  $N_1$  decay,  $M_1 \ll M_{2,3}$

## 2. why flavour matters

- $N_1$  production *and* decay involve light leptons
- lepton flavours are distinguishable (sum probabilities not amplitudes...)

## 3. how flavour matters

- phenomenology “no” leptogenesis bound on neutrino mass scale  
mild changes in  $\{M_1, \Gamma\}$  where leptogenesis works
- models: baryon asym can change by orders of magnitude, in specific models

## Introduction: why make the BAU in the seesaw?

the Universe contains a matter excess:  $6 \pm 1$  baryons for every  $10^{10}$  photons (WMAP).  
 $\Rightarrow$  must generate BAU after inflation, before nucleosynthesis ( $\tau_U \sim \text{sec}$ )  
*and* maintain proton lifetime  $\gtrsim 10^{33}$  years

Required ingredients:      baryon number violation  
                                         C and CP violation  
                                         non-equilibrium dynamics

Sakharov

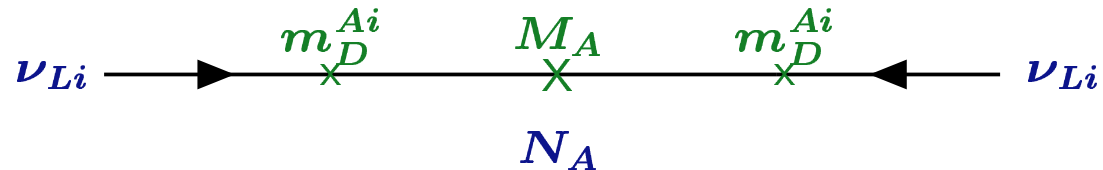
present in SM ...but... not make BAU ...  $\Rightarrow$  need (“motivated”) New Physics.

- ★ the seesaw, which naturally explains small neutrino masses, also gives attractive mechanism to make baryon asym: leptogenesis...
- ★ non-perturbative  $\mathcal{B} + \mathcal{L}$  (SM) + perturbative  $\mathcal{L}$  (seesaw) =  $\mathcal{B}$  for baryogenesis but not proton decay

## The See-Saw in three generations

- in the charged lepton (“flavour”) and  $N(= \nu_R)$  mass bases, at large energy scale  $\gg M_i$ :

$$\mathcal{L}_{leptons} = \mathbf{h}_\alpha \bar{e}_{R\alpha} \ell_\alpha \cdot \phi + \lambda_{J\alpha} \bar{N}_J \ell_\alpha \cdot \phi - \frac{1}{2} \bar{N}_J M_J N_J^c$$



- at the weak scale, get effective light neutrino mass matrix

$$\begin{aligned} \frac{1}{2}[m_\nu] &= \lambda^T M^{-1} \lambda \langle \phi^0 \rangle^2 \\ &\sim \frac{m_t^2}{10^{14} \text{GeV}} \sim .1 \text{eV} \end{aligned}$$



# The Baryon Asymmetry by Thermal Leptogenesis ( $N_1$ decay)

Suppose that  $M_1 \sim 10^9 \text{ GeV} \ll M_2, M_3$  (simple kinematics  $\leftrightarrow$  algebra...)

After inflation, vacuum energy density is transferred to a hot thermal soup at  $T_{reheat}$  (made of particles with gauge interactions). Then...

- $TE$  dynamics: from U expansion  $\leftrightarrow$  rates  $\lesssim H$ . The lightest  $N_1$  produced in the thermal soup after inflation by scatterings ( $qt^c \rightarrow N\ell_\alpha$ ) and inverse decays ( $\phi\ell_\alpha \rightarrow N$ ). At  $T \lesssim M_1$ ,  $N_1$  decays.

- $CP$ : Lepton asym. in flavour  $\alpha$  due to  $CP$  in  $N_1$  interactions ( $\rightarrow \lambda$  complex):

$$\epsilon^{\alpha\alpha} = \frac{\Gamma(N_1 \rightarrow \phi\ell_\alpha) - \Gamma(\bar{N}_1 \rightarrow \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N \rightarrow \phi\ell) + \Gamma(\bar{N}_1 \rightarrow \bar{\phi}\bar{\ell})} \quad (\text{recall } N_1 = \bar{N}_1)$$

- $\mathcal{L}, \mathcal{B} + \mathcal{L} : \mathcal{L}$  due to  $M, \lambda$ . Non-perturbative SM processes (sphalerons): lepton asym.  $\rightarrow$  baryon asym.

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{1}{3} \frac{n_\ell - n_{\bar{\ell}}}{n_\gamma}$$

( caveat: there are many other leptogenesis scenarios!)



## non-equilibrium, washout and $\eta$

produce  $N_1$  by same  $(CP, \Psi) \lambda_{1\alpha} N \ell_\alpha \phi$  vertex as they decay through:  $\Gamma_{prod} \simeq \Gamma_{decay}$ .

Can show:  $\Gamma_{dec} \frac{8\pi \langle \phi_0 \rangle^2}{M_1^2} \equiv \tilde{m} > m_1$  . "Expect"  $\tilde{m} \gtrsim m_{sol} \Rightarrow \Gamma_{decay} \gg H(T = M)$

1. for  $\Gamma_{prod}, \Gamma_{decay} < H$ , make  $n_N < n_\gamma$  and a lepton anti-asymmetry  $-Y_L$ . When  $n_N$  decay, they make  $+Y_L$  asymmetry. Incomplete cancellation because anti-asymmetry partially washed out while waiting around.
2.  $\Gamma_{prod}, \Gamma_{decay} > H$ ,  $\Rightarrow$  make (maximal) thermal density  $n_N \simeq n_\gamma$ , but, when  $T$  drops below  $M_1$ , decay "in equilibrium"

- The lepton asym produced in  $N$  decay does not survive until *after* inverse decays are "out of equilibrium"

$$\Gamma_{ID}(\phi \ell \rightarrow N) \simeq \Gamma_{decay} e^{-M_1/T} \lesssim H$$

- At temperature where  $\Gamma_{ID} = H$ , have  $n_N/n_\gamma \simeq e^{-M/T} \simeq H/\Gamma_{dec}$ , so

$$Y_B \sim \frac{1}{3} \frac{n_\ell - n_{\bar{\ell}}}{n_N} \frac{n_N}{n_\gamma} \sim \frac{1}{3} \epsilon \eta \frac{1}{g_*} \quad \eta \sim H/\Gamma \sim .1 \div .01 \quad (\text{no flavour})$$



## just a yoctosecond—what about flavour?

1. produce the (maximal) thermal density  $n_N \simeq n_\gamma$  if ( $M_1 \lesssim T$ , and) production rate, e.g.  $\sum_\alpha \Gamma(q_L t_R \rightarrow \phi \rightarrow \ell_\alpha N)$  is fast enough ( $\tau_{prod} < \tau_U$ ):

$$\Gamma_{prod} \sim \sum_\alpha \frac{h_t^2 |\lambda_{\alpha 1}|^2}{4\pi} T > H, \quad \Rightarrow \quad \frac{[\lambda^\dagger \lambda]_{11}}{4\pi} > \frac{10T}{m_{pl}} \Big|_{T=M_1}$$

Suppose that, as “expected”, this condition is satisfied.

2. The lepton asym in flavour  $\alpha$  (produced from  $N$  decay) can survive after Inverse Decays from flavour  $\alpha$  turn off ( $\tau_{ID} > \tau_U$ )

$$\Gamma_{\alpha\alpha} \equiv \Gamma(\ell_\alpha \phi \rightarrow N_1) \simeq \frac{|\lambda_{\alpha 1}|^2 M_1 e^{-M_1/T}}{8\pi} < \frac{10T^2}{m_{pl}}$$

At temperature  $T_\alpha$  when Inverse Decays from flavour  $\alpha$  turn off,

$$\frac{n_N}{n_\gamma}(T_\alpha) \simeq e^{-M_1/T_\alpha} \simeq \frac{H}{\Gamma_{\alpha\alpha}} \equiv \eta_\alpha$$

so

$$Y_B \sim \frac{1}{3} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \frac{n_N(T_\alpha)}{n_\gamma} \sim \frac{H}{3g_*} \sum_\alpha \frac{\epsilon_{\alpha\alpha}}{\Gamma_{\alpha\alpha}} \neq \frac{H}{3g_*} \frac{\sum_\alpha \epsilon_{\alpha\alpha}}{\sum_\beta \Gamma_{\beta\beta}}$$



## Flavour is irrelevant—its obvious, no?

1. Production, decay of  $N_1$  are controlled by  $\lambda$ ; charged lepton Yukawas  $h_e, h_\mu, h_\tau$  are  $\ll 1$ , a small correction in perturbation theory?

- Small correction to  $\epsilon$ . But *not* to dynamics: timescale for leptogenesis is  $H^{-1}$  (Sahkarov). All faster interactions should be resummed, eg, into thermal masses. Compare rates for  $h_\tau, h_\mu$  to  $H$

$$\Gamma_\tau \simeq 10^{-2} h_\tau^2 T > H \text{ for } T < 10^{12} \text{ GeV}, \quad \Gamma_\mu > H \text{ for } T < 10^9 \text{ GeV}$$

If the  $h_\tau, h_\mu$  are in equilibrium, flavour defines distinguishable mass eigenstates.

(If  $\Gamma(N \rightarrow \phi\ell) > \Gamma_\tau$  should also be included in determination of mass eigenstates)

Blanchet  
diBari Raffelt

- leptons enter in  $N_1$  production and decay, distinguishable in between  $\leftrightarrow$  sum probabilities not amplitudes.

2. lepton asym is a Trace in flavour space, basis-independent, can calculate the asym in the flavour combination into which  $N_1$  decays

Sure, in field theory, can work in any basis. BUT— in any basis *other* than the flavour basis,  $h_\alpha$  put additional fast terms in the Boltzmann Eqns.

## outline (again)

### 1. review:

- the baryon asymmetry, the seesaw and two neutrino mass differences
- thermal leptogenesis from  $N_1$  decay,  $M_1 \ll M_{2,3}$

### 2. why flavour matters

- distinguishable leptons appear in production/decay of  $N_1 \Rightarrow$  should evolve flavoured asymmetries.
- and physics *is* basis independent ??

### 3. how it matters

- phenomenology      no leptogenesis bound on neutrino mass scale  
                                 mild changes in allowed  $\{M_1\Gamma\}$  parameter space
- models: baryon asym can change by orders of magnitude, in specific models

## pheno consequences 1 - single flavour “old” vs flavoured

“single flavour” approx, successful thermal leptogenesis  $\Rightarrow$  light  $\nu$  mass scale  $\lesssim .1$  eV.

“flavoured”: more  $\mathcal{CP}$ , so no bound. Models can be tuned to work for  $m_\nu \lesssim$  few eV (cosmo)

“single flavour”: no model-indep connection between  $\mathcal{CP}$  for leptogenesis and MNS phases.

“flavoured”: still no sensitivity of baryon asym. to MNS phases (but can say things in classes of models:Petcov)

There is an envelope, in space of parameters leptogenesis depends on  $(M_1, \Gamma, \epsilon\dots)$  where leptogenesis *can* work.

Including flavour gives envelope more dimensions  $(M_1, \epsilon_{\alpha\alpha}, \Gamma_{\alpha\alpha})$ , little changes to “interesting” regions of the envelope projected onto  $M_1, \Gamma$  space ( not move lower bound on  $T_{reheat}$ )

Antusch+..  
Blanchet+..

Josse-Michaux+...

## consequences for models...to estimate $Y_B$

single flavour analytic approximation :  $Y_B \simeq \frac{\epsilon\eta}{9g_*}$

$$\eta \simeq \frac{1}{\Gamma/H + H/6\Gamma} \Big|_{T=M_1} \simeq \begin{cases} H/\Gamma & \Gamma \gg H \\ \Gamma/H & \Gamma \ll H \end{cases} \Rightarrow \text{calculate } \Gamma, \epsilon = \frac{\Gamma(N_1 \rightarrow H\ell) - \Gamma(\bar{N}_1 \rightarrow \bar{H}\bar{\ell})}{\Gamma(N \rightarrow H\ell) + \Gamma(\bar{N}_1 \rightarrow \bar{H}\bar{\ell})}$$

**model predictions with flavour** :  $\epsilon^{ee}, \epsilon^{\mu\mu}, \epsilon^{\tau\tau}, \Gamma^{ee}, \Gamma^{\mu\mu}, \Gamma^{\tau\tau}$

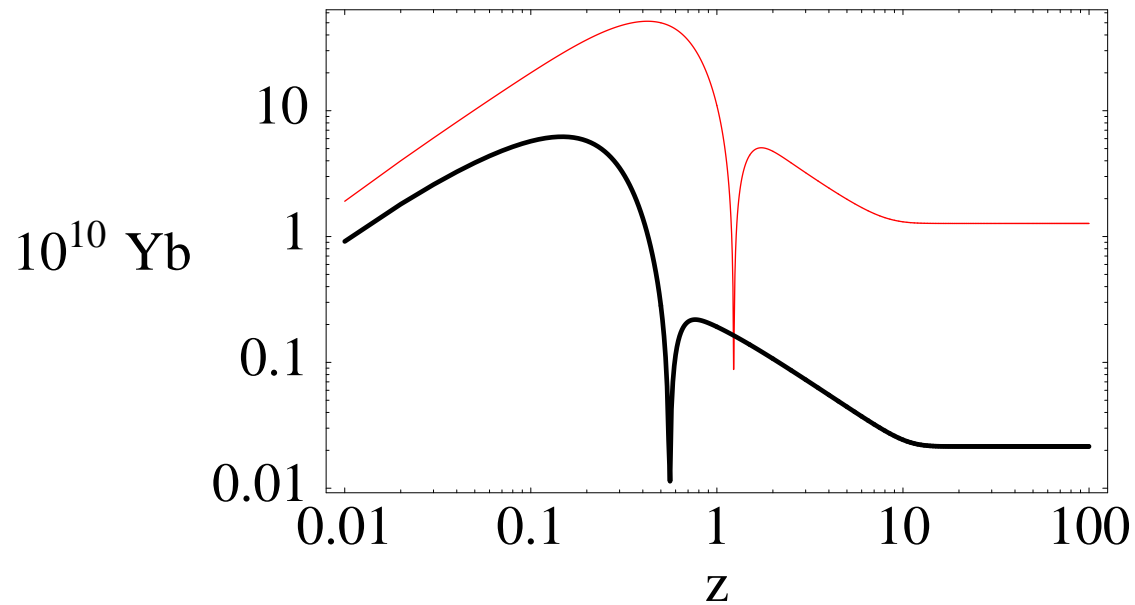
1. “strong washout” of at least one flavour:  $\Gamma_\tau \gg \Gamma \gg H$

$$Y_B \simeq \frac{1}{9g_*} \sum_{\alpha} \epsilon^{\alpha\alpha} \eta^{\alpha} \quad \eta^{\alpha} \simeq \frac{1}{\Gamma^{\alpha\alpha}/H + H/6\Gamma^{\alpha\alpha}}$$

2. weak washout all flavours:  $\tilde{m}^{\alpha\alpha} < m_*$  (assume no initial asymmetry)

$$Y_B \simeq 5 \times 10^{-3} \frac{\tilde{m}}{m_*} \sum_{\alpha} \epsilon^{\alpha\alpha} \frac{\tilde{m}^{\alpha\alpha}}{m_*} \quad (Y_N \propto \tilde{m}; \quad CP \text{ in scatt.} \rightarrow \epsilon^{\alpha\alpha} \tilde{m}^{\alpha\alpha})$$

## useful enhancement factor...



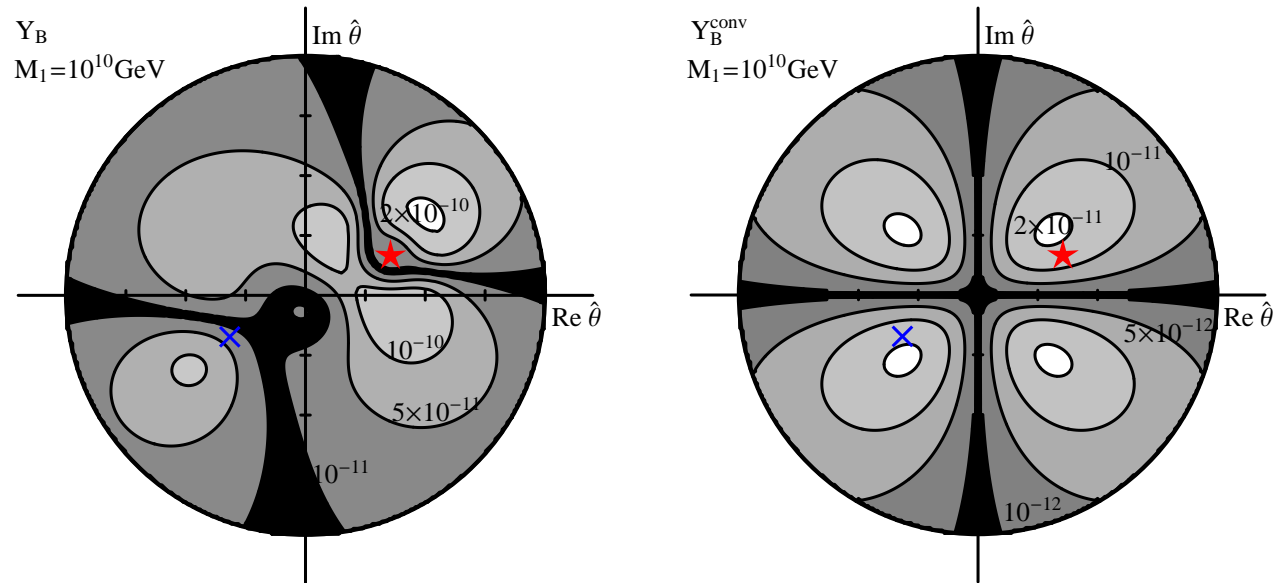
The baryon to entropy ratio, as a function of “time”, **in flavoured** and unflavoured calculation.

$$\epsilon_{ee} = 2.5 \times 10^{-6}, \quad \epsilon_{\mu\mu} = -2 \times 10^{-6}, \quad \epsilon_{\tau\tau} = 10^{-7}$$

$$M_1 = 10^{10} \text{ GeV}$$

$$\frac{\Gamma_{ee}}{H} \simeq 10, \quad \frac{\Gamma_{\mu\mu}}{H} \simeq 30, \quad \frac{\Gamma_{\tau\tau}}{H} \simeq 30$$

## useful factors of 10...



$Y_B$  in the 2RHN model, hierarchical  $\nu_L$ .  
 LHS flavoured leptogenesis, RHS “single flavour approx”.  
 (1,2) texture zero      (1,3) texture zero  
 (in plane of complex angle of R matrix)

## Summary

thermal leptogenesis is an attractive, minimal mechanism to make the Baryon asymmetry of the Universe.

When the interaction rates of the charged lepton Yukawas are faster than the leptogenesis rates, lepton flavours are distinguishable and asymmetry production should be studied flavour by flavour (or put the charged lepton Yukawas in the Boltzmann Equations).

Resulting “flavoured” Boltzmann Equations are different, and the solutions are different:

- allowed phenomenological parameter space mildly affected
  - 1) leptogenesis works for degenerate light neutrinos
- baryon asymmetry  $Y_B$  obtained in specific models can be (?is?) enhanced
  - 1) cancellations reduced:  $Y_B \propto \sum_{\alpha} \epsilon^{\alpha\alpha} f(\Gamma^{\alpha\alpha})$
  - 2) flavoured  $\epsilon^{\alpha\alpha}$  can be bigger than  $\epsilon$

## Eqns for $Y_L^{\alpha\beta}$ in field theory?

Should be able to do Field Theory in any basis we like. Consider eqns of motion for

$$Y_L^{\alpha\beta} \propto \frac{\int d^3k \langle a_{\ell\alpha}^\dagger a_{\ell\beta} - a_{\ell\beta}^\dagger a_{\ell\alpha} \rangle}{s}$$

in flavour basis, diagonal elements are  $(n_{\ell\alpha} - n_{\ell\alpha}^-)/s$ , off-diagonals encode quantum correlations, and are driven rapidly to zero by charged lepton yukawas when these are in equilibrium.

So at  $T \lesssim 10^9$  GeV, in flavour basis, and *only* in flavour basis, the Boltzmann Eqns are:

$$\frac{sH(M_1)}{z} \frac{d}{dz} \begin{bmatrix} Y_L^{ee} & \cdot & \cdot \\ \cdot & Y_L^{\mu\mu} & \cdot \\ \cdot & \cdot & Y_L^{\tau\tau} \end{bmatrix} = \gamma \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \begin{bmatrix} \epsilon^{ee} & \cdot & \cdot \\ \cdot & \epsilon^{\mu\mu} & \cdot \\ \cdot & \cdot & \epsilon^{\tau\tau} \end{bmatrix} - \frac{1}{Y_L^{eq}} \begin{bmatrix} \gamma^{ee} & \cdot & \cdot \\ \cdot & \gamma^{\mu\mu} & \cdot \\ \cdot & \cdot & \gamma^{\tau\tau} \end{bmatrix} \begin{bmatrix} Y_L^{ee} & \cdot & \cdot \\ \cdot & Y_L^{\mu\mu} & \cdot \\ \cdot & \cdot & Y_L^{\tau\tau} \end{bmatrix}$$

Same as previous flavoured. Take Trace to get eqn for total  $Y_L$ —take it in any basis? (eg direction into which  $N_1$  decays? This give the usual BEs) **NO**. Dropped from BE  $\sim -|h_\alpha|^2 T Y_L^{\alpha\beta}$  terms that drive off-diagonals to zero.

## Boltzmann Equations

- the lightest  $N_1$  is produced in the thermal soup after inflation by scatterings ( $qt^c \rightarrow N\ell_\alpha$ ) and inverse decays ( $H\ell_\alpha \rightarrow N$ ). At  $T \lesssim M_1$   $N_1$  decays.
- CP violation in  $N_1$  interactions :  $\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \rightarrow H\ell_\alpha) - \Gamma(N_1 \rightarrow \bar{H}\bar{\ell}_\alpha)}{\Gamma(N \rightarrow H\ell) + \Gamma(N_1 \rightarrow \bar{H}\bar{\ell})} \rightarrow \text{asym. in } n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}$
- non-perturbative SM processes: lepton asymmetry  $\rightarrow$  baryon asymmetry

described by Boltzmann Eqns for  $N_1$  and lepton asymmetry number densities ( $z = \frac{M_1}{T}$  is time var.):

$$\frac{dY_N}{dz} = -\frac{z}{sH} \left( \frac{Y_N}{Y_N^{eq}} - 1 \right) \gamma$$

$Y_N = n_N/s$  ( $s =$  entropy density) pushed to equilibrium by  $\gamma(z)$ , which describes thermally averaged  $N$  decays (D), scatterings (S), inverse decays(ID). summed on flavour  $\alpha$

$$\frac{d}{dz} \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{s} \equiv \frac{dY_L^{\alpha\alpha}}{dz} = \frac{z}{sH(M)} \left[ \left( \frac{Y_N}{Y_N^{eq}} - 1 \right) \epsilon^{\alpha\alpha} \gamma - \gamma^{\alpha\alpha} \frac{Y_L^{\alpha\alpha}}{Y_\ell^{eq}} \right]$$

asym  $Y_L^{\alpha\alpha}$  produced by out-of-equilibrium  $N$ s, washed out by same processes D, ID, S.

NB tension:  $\gamma \gg Hs$  to ensure  $Y_N \sim Y_N^{EQ}$  at  $T \gtrsim M_1$ . But  $\gamma \ll Hs$  to minimise washout of  $Y_L^{\alpha\alpha}$ .

(for afictionados: calculate matrix elements in  $T = 0$  field theory. include CP in  $N$  scattering.)

## So Boltzmann Eqns for total lepton number are...

Recall that for  $Y_L^{\alpha\alpha} = (n_{\ell\alpha} - n_{\bar{\ell}\alpha})/s$

$$\frac{d}{dz} Y_L^{ee} = \frac{z}{sH} \left[ \gamma \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon^{ee} - \frac{Y_L^{ee}}{Y_\ell^{eq}} \gamma^{ee} \right], \quad \text{with } \epsilon^{\alpha\alpha} = \frac{\Gamma_{N \rightarrow H\ell\alpha} - \Gamma_{N \rightarrow \bar{H}\bar{\ell}\alpha}}{\Gamma_{N \rightarrow H\ell} + \Gamma_{N \rightarrow \bar{H}\bar{\ell}}}$$

Sum up the flavoured BEs:

$$\begin{aligned} \sum_{\alpha} \frac{d}{dz} Y_L^{\alpha\alpha} &= \frac{z}{sH} \left[ \gamma \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \underbrace{(\epsilon^{ee} + \epsilon^{\mu\mu} + \epsilon^{\tau\tau})}_{\epsilon} - \frac{1}{Y_\ell^{eq}} \underbrace{(\gamma^{ee} Y_L^{ee} + \gamma^{\mu\mu} Y_L^{\mu\mu} + \gamma^{\tau\tau} Y_L^{\tau\tau})}_{\neq \gamma Y_L} \right] \\ &= \frac{z}{sH} \left[ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon \gamma - \frac{\gamma^{ee} Y_L^{ee} + \gamma^{\mu\mu} Y_L^{\mu\mu} + \gamma^{\tau\tau} Y_L^{\tau\tau}}{Y_\ell^{eq}} \right] \end{aligned}$$

Compare to the usual “single flavour” approx = consider lepton number, neglect flavour

$$\frac{dY_L}{dz} = \frac{z}{sH(M)} \left[ \left( \frac{Y_N}{Y_N^{eq}} - 1 \right) \epsilon \gamma - (\gamma^{ee} + \gamma^{\mu\mu} + \gamma^{\tau\tau}) \frac{Y_L^{ee} + Y_L^{\mu\mu} + Y_L^{\tau\tau}}{Y_\ell^{eq}} \right]$$

NOT the same.

Abada etal  
Nardi etal

where  $z = \frac{M_1}{T}$  is a time var,  $\gamma^{\alpha\alpha} = \gamma_D^{\alpha\alpha} + \gamma_{\Delta L=1}^{\alpha\alpha}$  is  $N \leftrightarrow H\ell_\alpha$  and  $qt^c \leftrightarrow N\ell_\alpha$  etc rates

## pheno consequences 1 - no bound on $m_\nu$

In “single flavour” approx, successful thermal leptogenesis  $\Rightarrow m_\nu \leq .1$ . Recall:

$$Y_B \simeq 10^{-3} \epsilon \eta \quad (\eta = H/\Gamma)$$

For degenerate  $\nu_L$  ( $m_\nu > m_{atm}$ ):  $\Gamma$  increases ( $\Gamma \geq C m_\nu \Rightarrow \eta$  decreases),  $\epsilon$  decreases:

$$\sum_{\alpha} \epsilon^{\alpha\alpha} \leq \frac{3M_1 \Delta m_{atm}^2}{8\pi v^2 m_\nu}$$

$\Rightarrow$  there is a  $m_\nu \simeq 0.1$  eV above which cannot get big enough  $Y_B$ .

With flavour, more  $C\mathcal{P}$ : Individual flavour asyms can grow with light  $\nu$  mass scale  $m_\nu$ :

$$\epsilon^{\alpha\alpha} \leq \frac{3M_1 m_\nu}{8\pi v^2} \sqrt{\frac{\Gamma_\alpha}{\Gamma}}$$

Partial decay rates  $\Gamma(N \rightarrow \phi l_\alpha)$  still increase, but

$$Y_B \simeq 10^{-3} \sum_{\alpha} \epsilon_{\alpha\alpha} \eta_{\alpha} \quad \left( \eta_{\alpha} = \frac{H}{\Gamma(N \rightarrow \phi l_{\alpha})} \right)$$

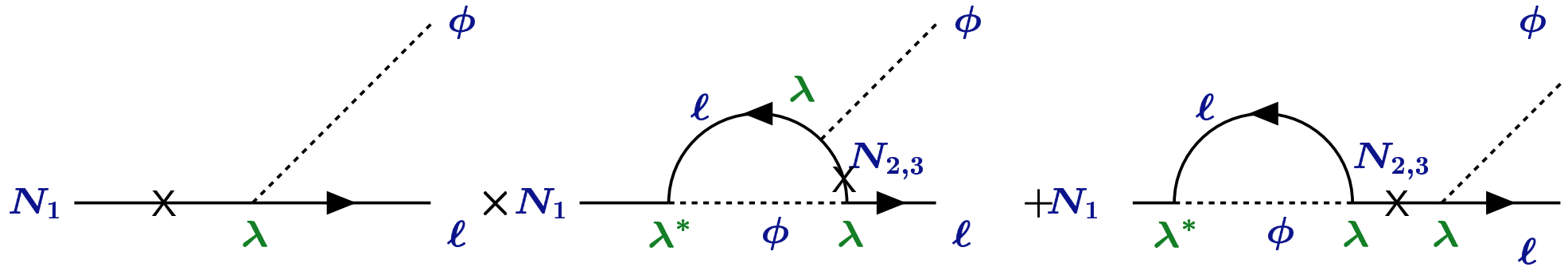
can stay same.  $\Rightarrow$  no leptogenesis bound  $m_\nu \lesssim .1$  eV

(caveat when  $\Gamma(N \rightarrow \phi l) \gg \Gamma_\tau$ , Blanchet diBari Raffelt get  $m_\nu < 2$  eV)

## Thermal Leptogenesis with $M_1 \ll M_{2,3}$ : $C\mathcal{P}$ and $\epsilon^{\alpha\alpha}$

- $C\mathcal{P}, \mathcal{X}$ : generate lepton asymmetry in flavour  $\alpha$  due to  $C\mathcal{P}$  in  $N_1$  interactions:

$$\epsilon^{\alpha\alpha} = \frac{\Gamma(N_1 \rightarrow H\ell_\alpha) - \Gamma(\bar{N}_1 \rightarrow \bar{H}\bar{\ell}_\alpha)}{\Gamma(N \rightarrow H\ell) + \Gamma(\bar{N}_1 \rightarrow \bar{H}\bar{\ell})} \quad (\text{recall } N_1 = \bar{N}_1)$$

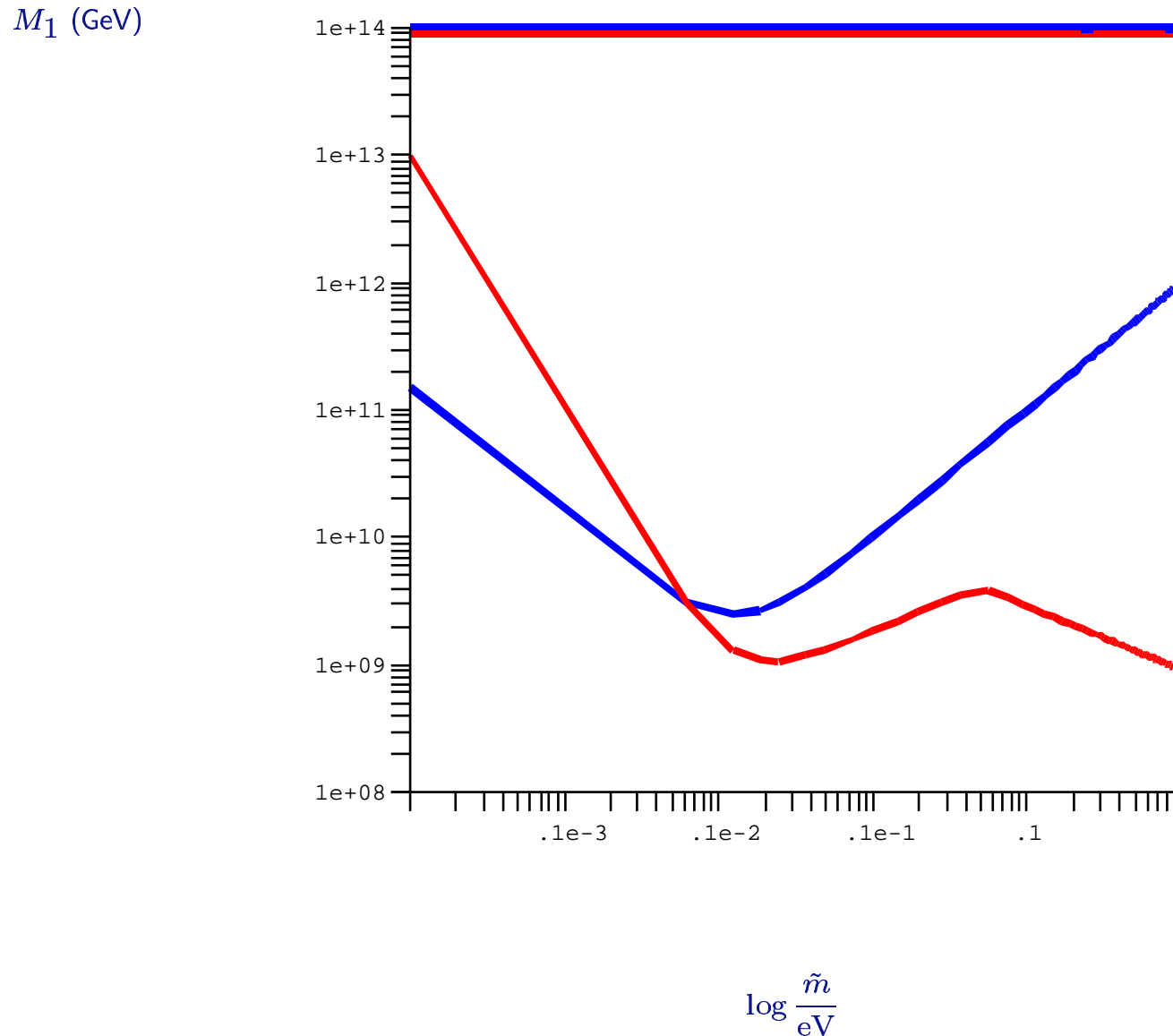


Can show :

$$\sum_{\alpha} \epsilon^{\alpha\alpha} < \frac{3}{8\pi} \frac{(m_3 - m_1)M_1}{\langle H_u \rangle^2} \sim 10^{-6} \frac{M_1}{10^9 \text{ GeV}} \Rightarrow M_1 \gtrsim 10^9 \text{ GeV}$$

# phenomenological consequences

There is an envelope, in space of parameters leptogenesis depends on :  $M_1$ ,  $\tilde{m}$ ,  $\epsilon$ , where leptogenesis *can* work.



$$\tilde{m} \propto \Gamma(N \rightarrow HL)$$