Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Leptogenesis from low energy CP-violation

Jessica Turner

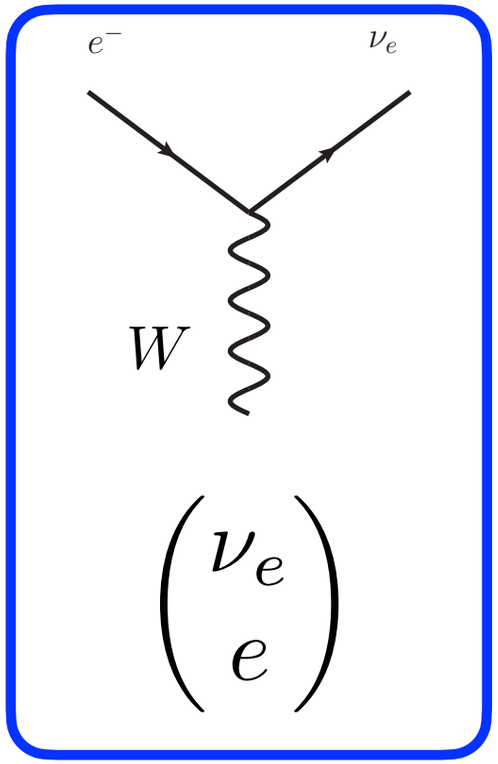
IFIRSE seminar

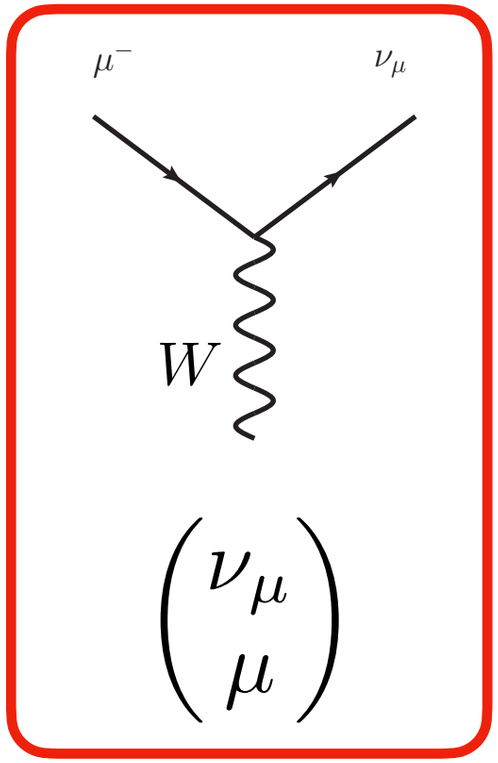
19 August 2020

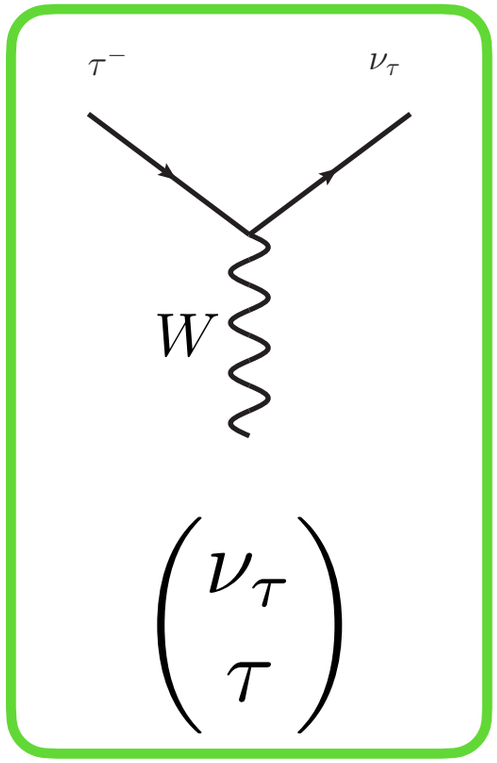
Outline

- Neutrino masses and mixing
- Measuring the baryon asymmetry
- Sakharov's conditions
- Leptogenesis: a bridge between neutrino masses and the BAU
- Leptogenesis from low energy CP-violation

Neutrino Masses and Mixing





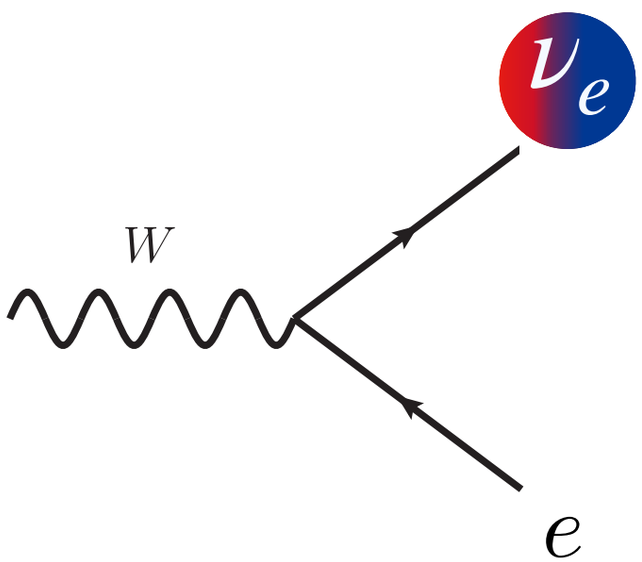


Neutrinos are part of the SU2L doublets and flavour associated with the charge lepton.

The neutrino flavour interacts with charged leptons of the same flavour.

Neutrino Oscillations

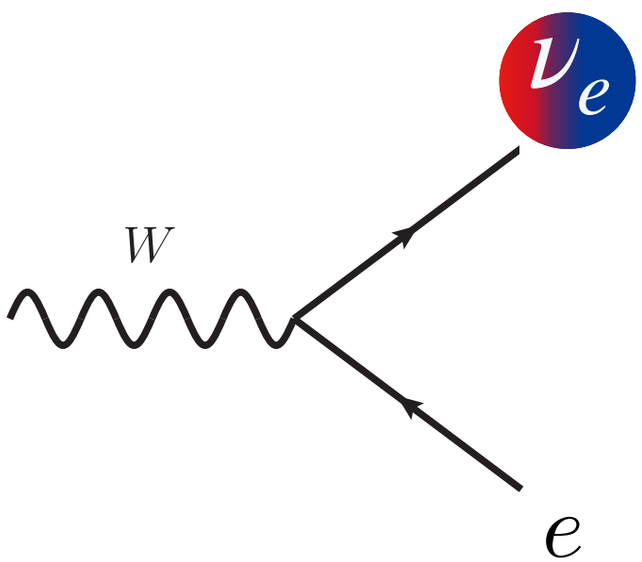
production



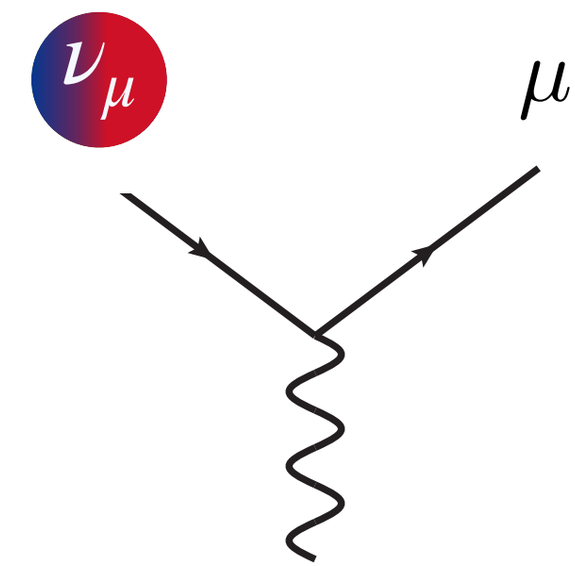
Super-Kamiokande 1998
SNO 2002

Neutrino Oscillations

production



detection



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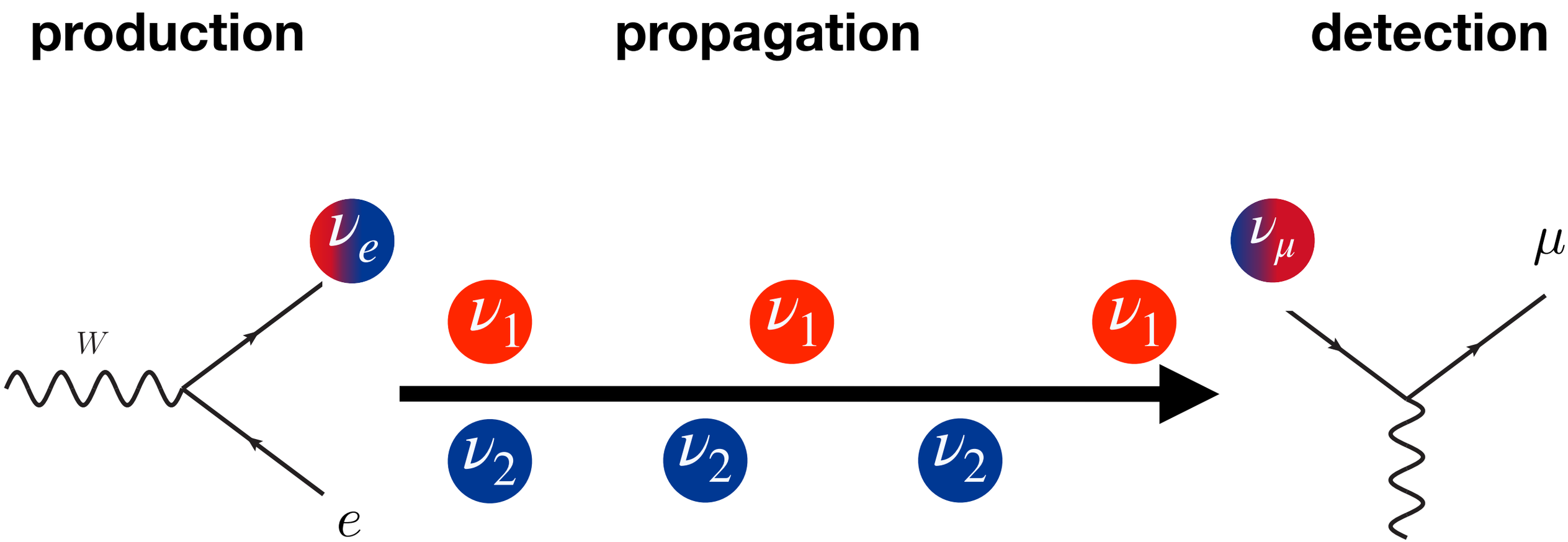
Neutrino Oscillations



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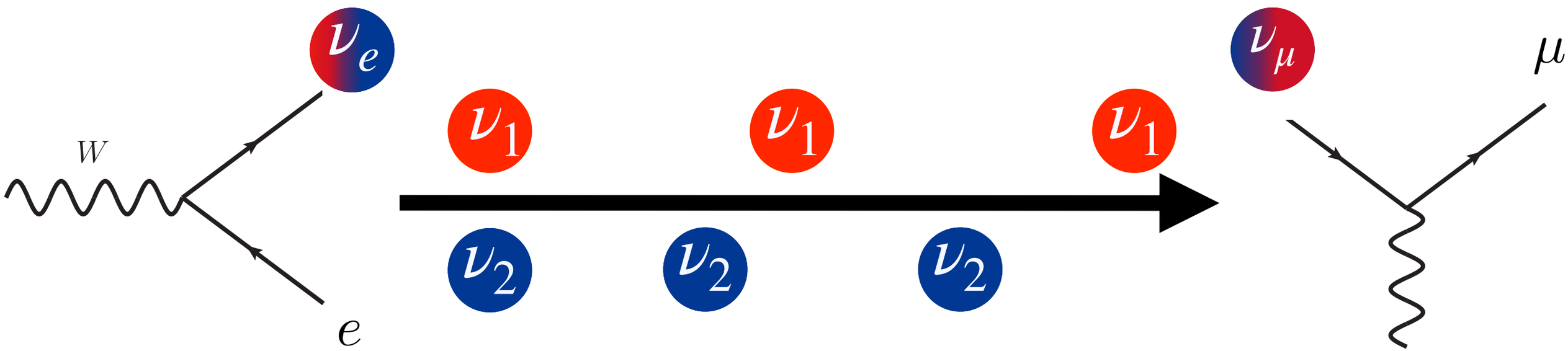
Neutrino Oscillations

production **propagation** **detection**



$$|\nu(t)\rangle = e^{-i\mathcal{H}t} = -\sin(\theta)e^{-iE_1 t}|\nu_1\rangle + \cos(\theta)e^{-iE_2 t}|\nu_2\rangle$$

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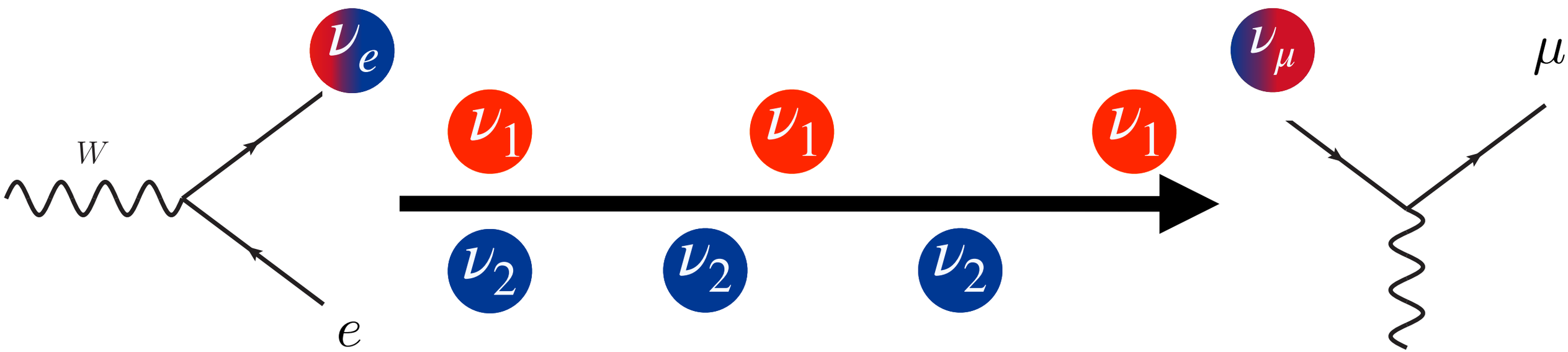
Neutrino Oscillations

production **propagation** **detection**



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Neutrinos are relativistic

$$E_i \simeq E + \frac{m_i^2}{E} \implies E_i - E_j \simeq \frac{\Delta m_{ij}^2}{2E}$$

In the simplified two neutrino case:

$$\boxed{P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2\left(2\theta\right)\sin^2\frac{\left(\Delta m^2_{ij} L\right)}{2E}}$$

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$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavour states

PMNS matrix

mass states

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Energy of neutrino

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Energy of neutrino

baseline distance between production and detection

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flavour states

PMNS matrix

mass states

In the simplified two neutrino case:

mass squared splitting

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2\left(2\theta\right)\sin^2\frac{\left(\Delta m^2_{ij} L\right)}{2E}$$

mixing angle parametrises misalignment of bases

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flavour states

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mass states

- Neutrinos have (non-degenerate) masses
- Neutrinos mix i.e. PMNS matrix is a non-identity matrix

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If neutrinos Dirac fermions, PMNS: 3 mixing angles + 1 phase

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$41.1 \leq \theta_{23}(^\circ) \leq 51.3 \qquad 8.22 \leq \theta_{13}(^\circ) \leq 8.98 \qquad 31.61 \leq \theta_{12}(^\circ) \leq 36.27$$

$$144 \leq \delta(^\circ) \leq 357$$

nu-fit data 4.1

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nu-fit data 4.1

If neutrinos Majorana fermions, PMNS: 3 mixing angles + 3 phases

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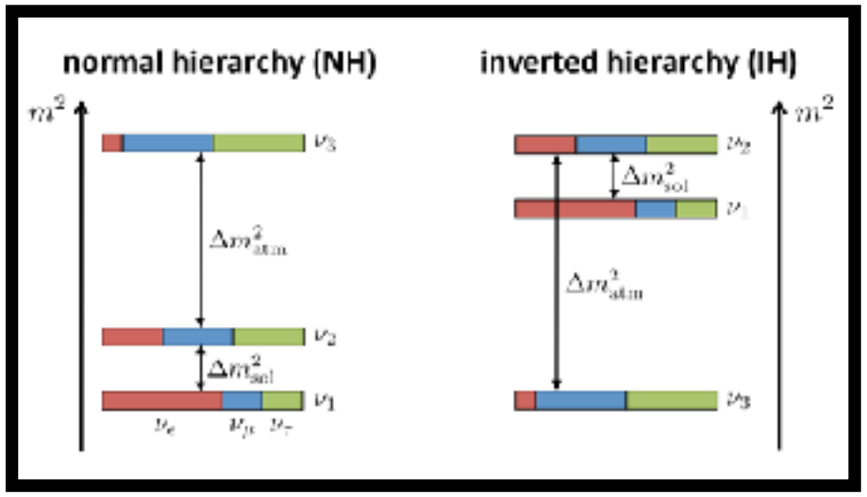
Majorana nature of neutrinos not observable at oscillation experiments

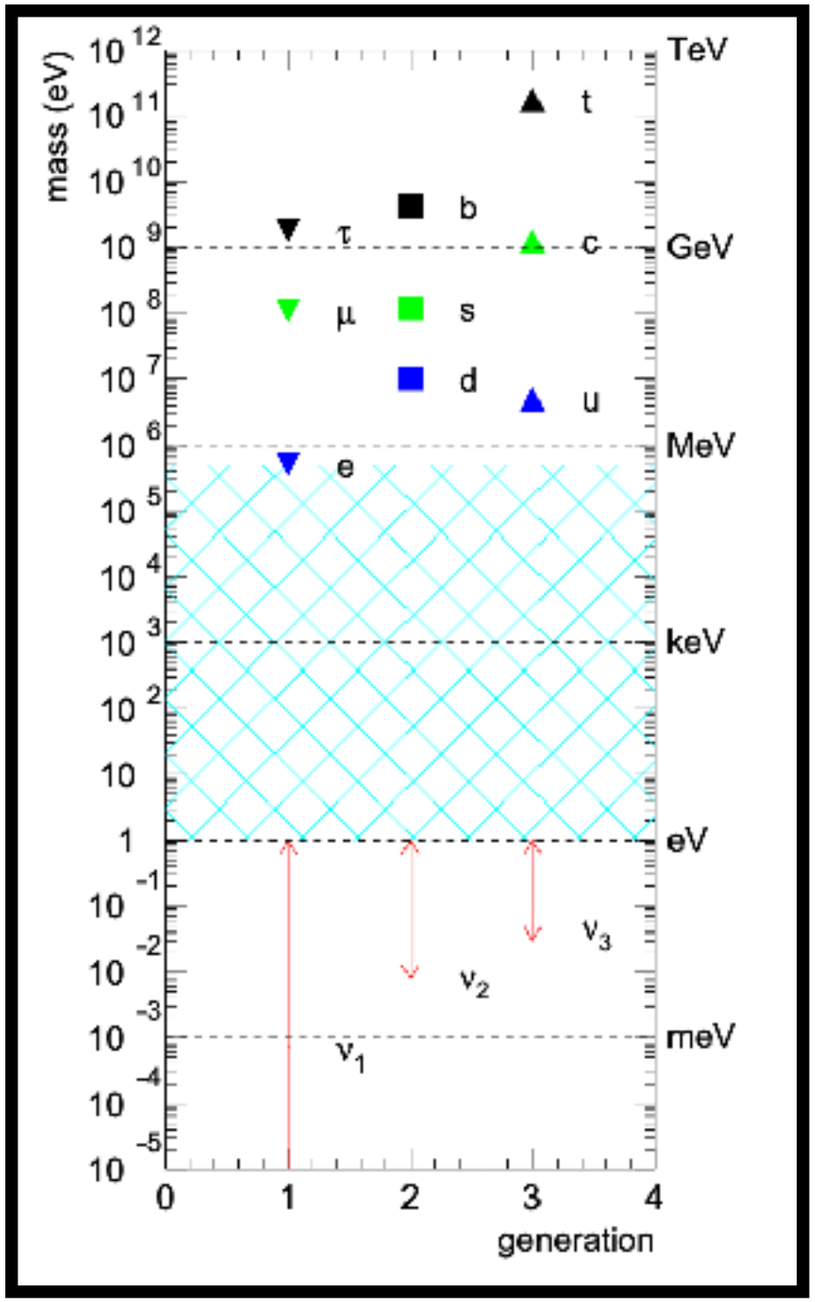
- Mass ordering?
- Precise PMNS structure?
- CP-violation?
- Dirac or Majorana?
- Absolute mass scale?

$$\sum_{i=1}^{3} m_i \leq 0.2\,\mathrm{eV}$$ PDG

$$m_\nu < 1.1\,\mathrm{eV}\,(90\%\,\mathrm{C.L})$$ KATRIN

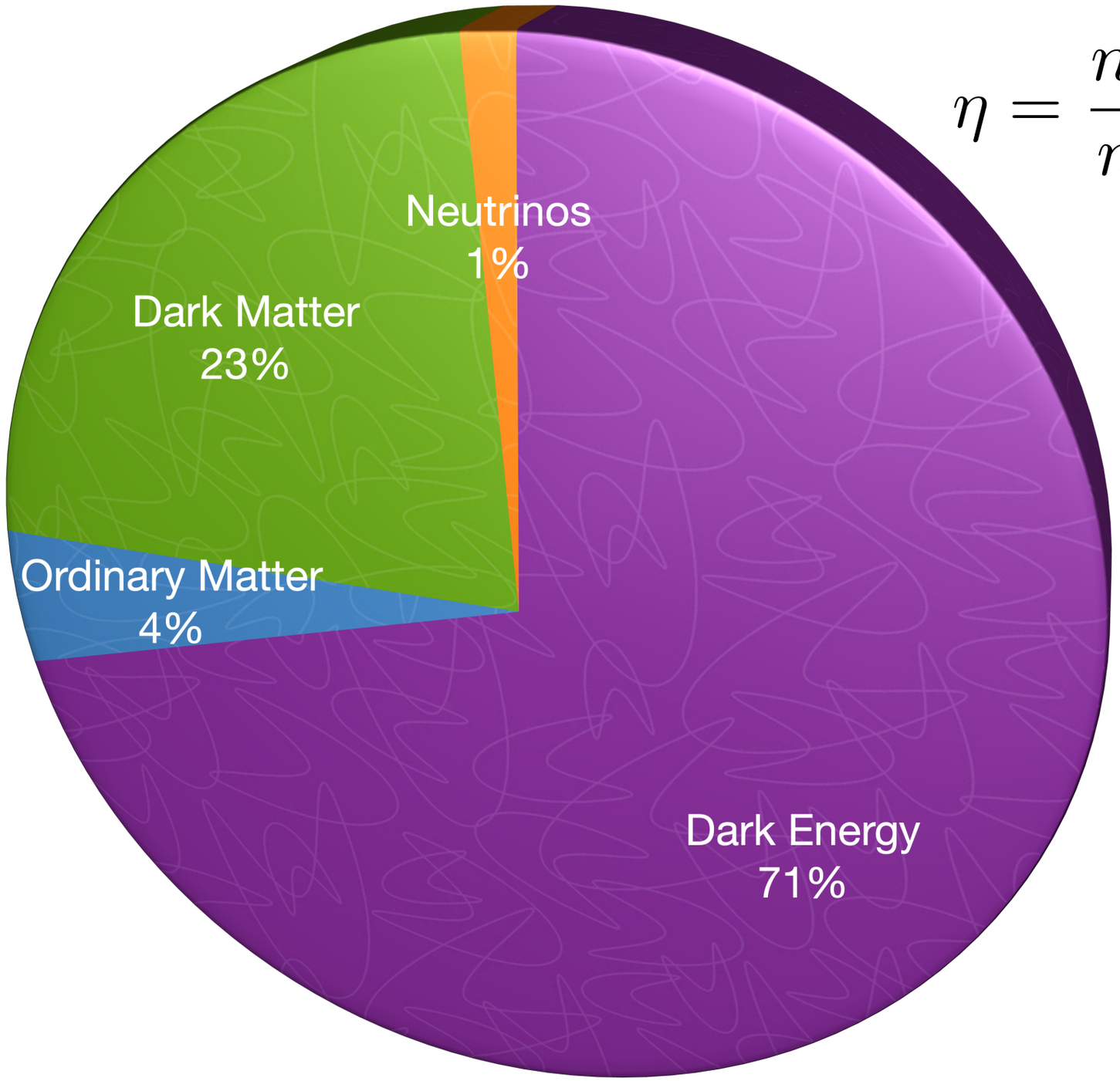
It is clear neutrinos much lighter than other known fermions





The Matter Anti-Matter Asymmetry

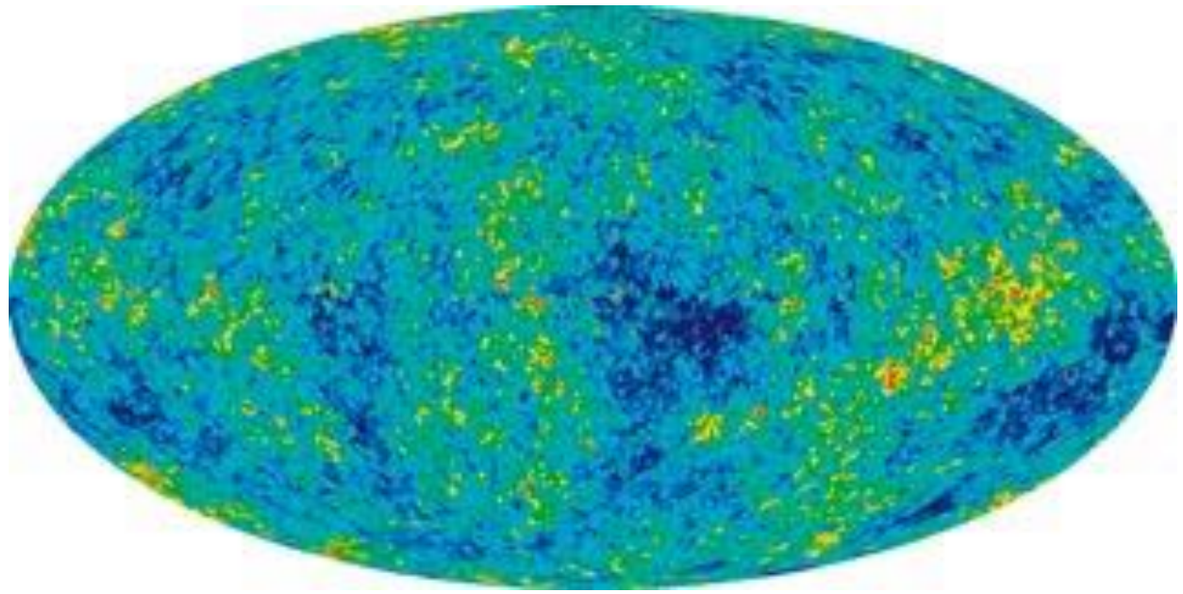
Universe's Energy Budget

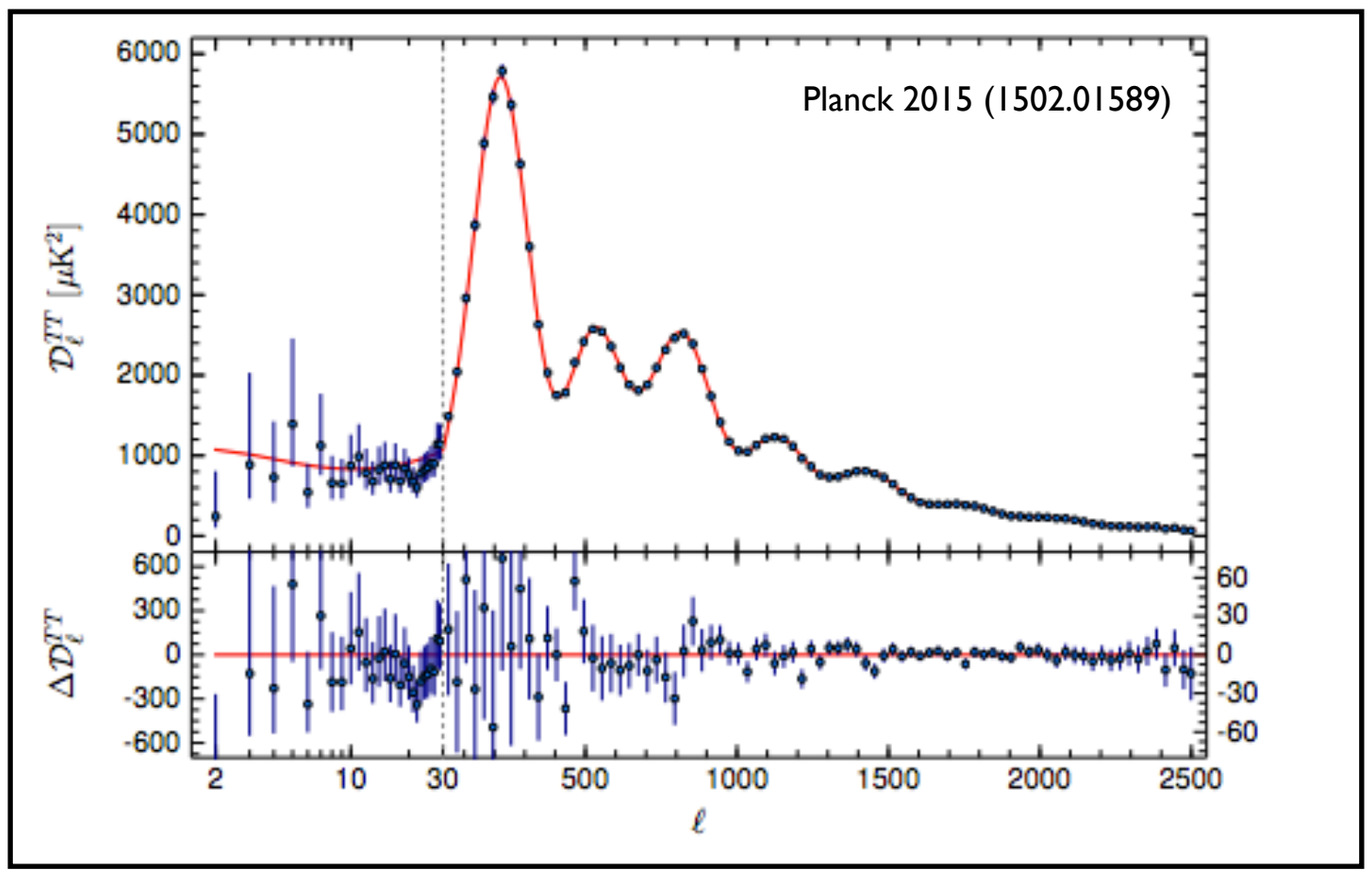


$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Cosmic Microwave Background

$T \sim 0.26\,\mathrm{eV}$

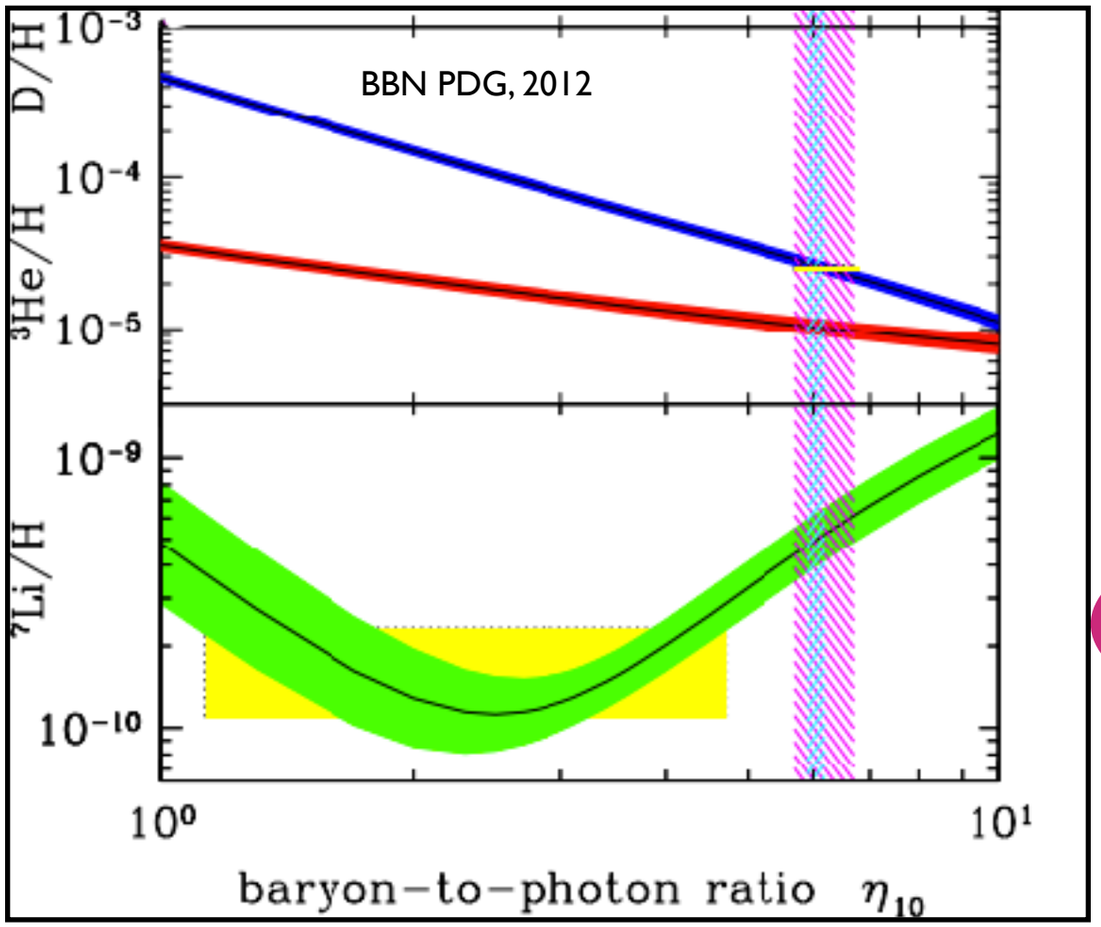




$$\eta_{\mathrm{CMB}} = (6.23 \pm 0.17) \times 10^{-10}$$

Big Bang Nucleosynthesis

$T \sim 1\,\mathrm{MeV}$

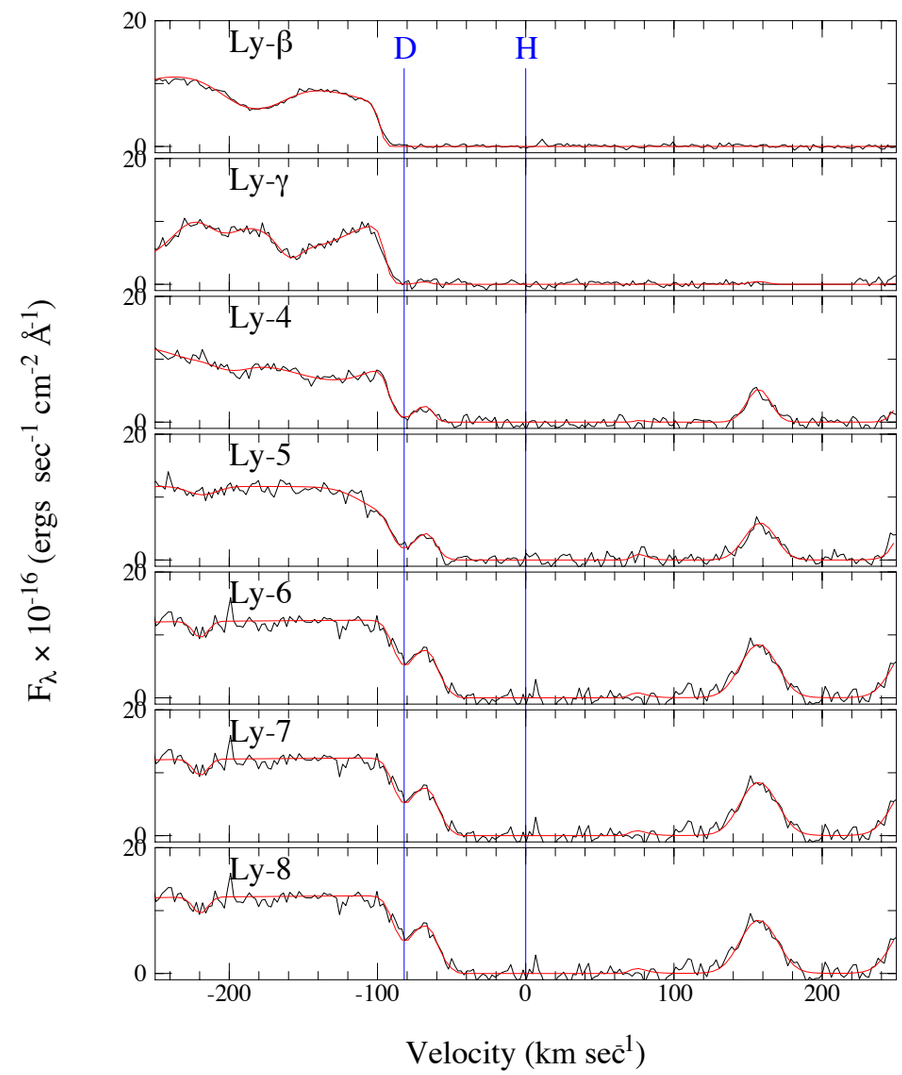


$$\eta_{\mathrm{BBN}} = (6.08 \pm 0.06) \times 10^{-10}$$

bright quasar 3C 273: Hubble Space Telescope

Dust Cloud

0302006



Sakharov's Conditions

☑ **Baryon and Lepton Number Violation**

Kuzmin, Rubakov and Shaposhnikov

☒ **Insufficient CP-violation**

Gavela, Hernandez, Orloff, Pene; Huet and Sather

☒ **No departure from thermal equilibrium**

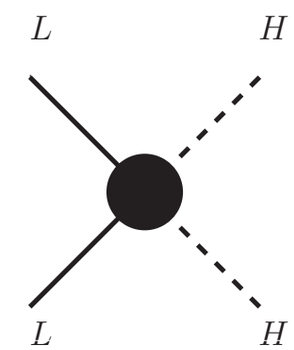
Kajantie, Laine, Rummukainen, Shaposhnikov

* assumes CPT conserved

- SU2L invariant term mass term for neutrinos

Weinberg

$$-\mathcal{L}_{d=5} = \lambda \frac{L.HL.H}{M}$$



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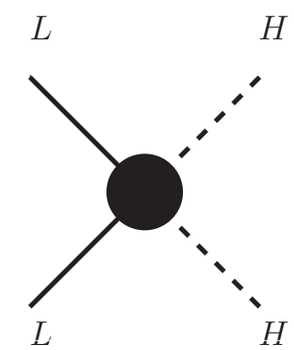

- How can we ultraviolet complete this operator at tree-level?

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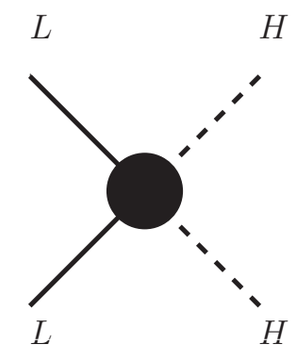

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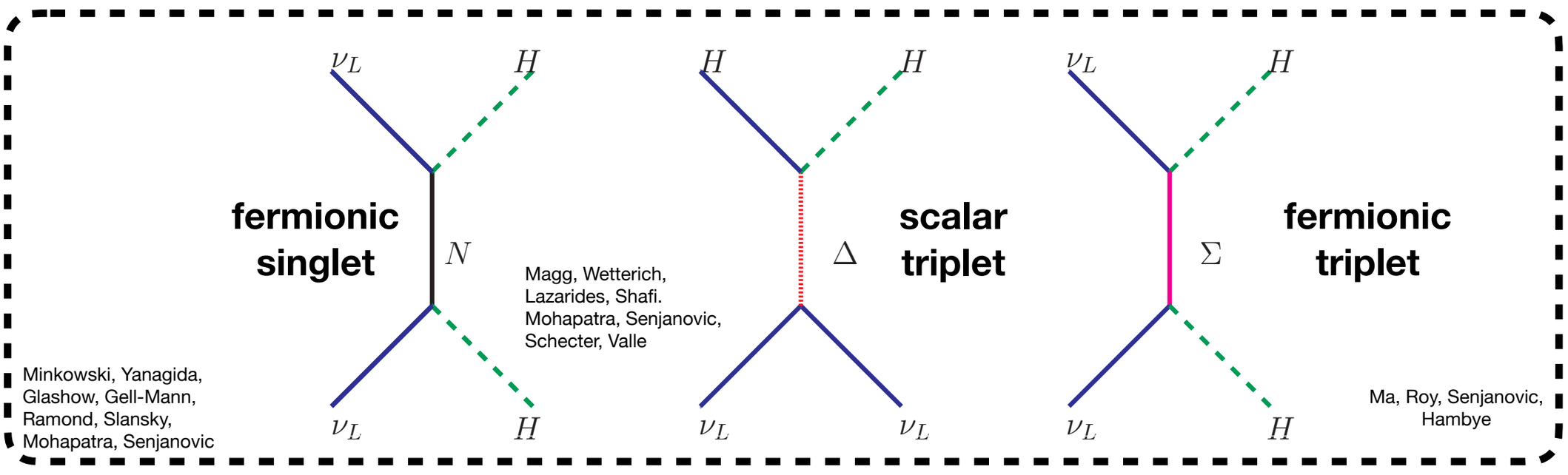

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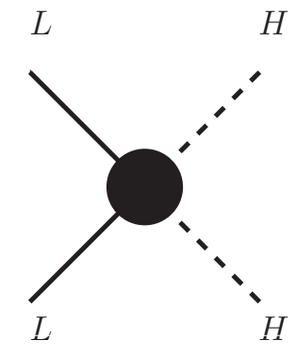

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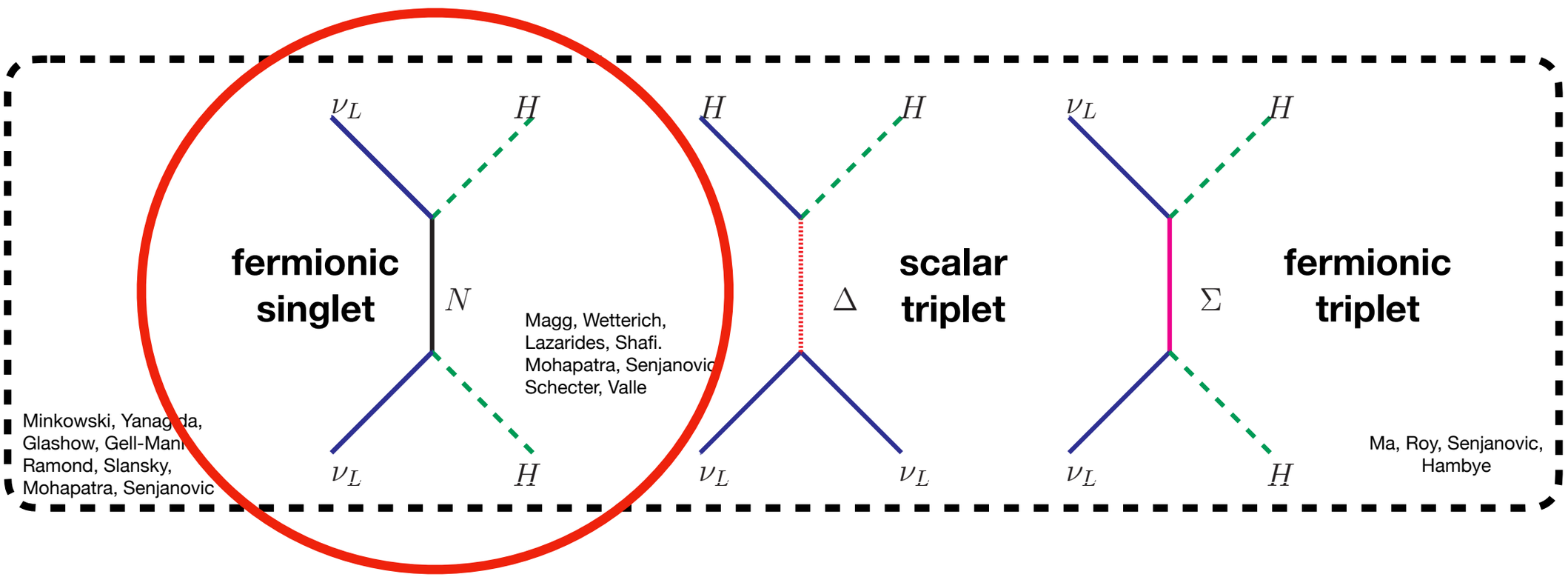
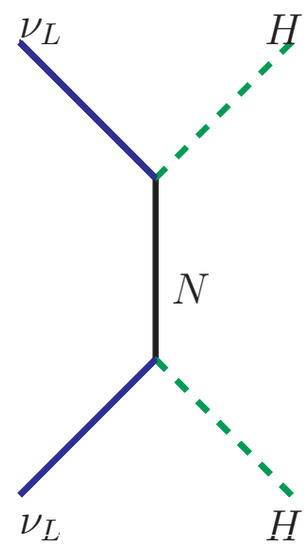


We will focus on this possibility for the remainder of the talk

- Type-I seesaw mechanism



$$\mathcal{L} = Y_\nu \overline{L} \tilde{\Phi} N - \frac{1}{2} M_N \overline{N^c} N$$

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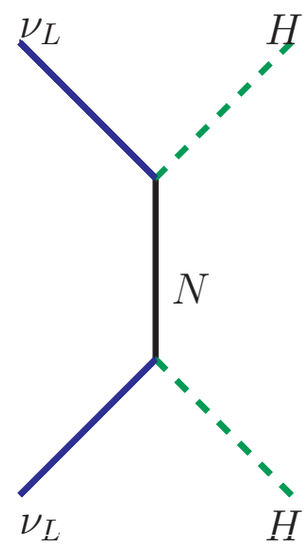

$$\mathcal{L} = Y_\nu \overline{L} \tilde{\Phi} N - \frac{1}{2} M_N \overline{N^c} N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_D = Y_\nu v$$

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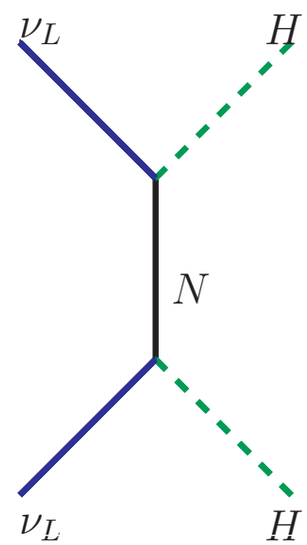

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$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \xrightarrow[\text{of mass matrix}]{\text{find eigenvalues}} m_\nu = \frac{Y_\nu^2 v^2}{M_N} \sim 0.1\,\mathrm{eV}$$

$$m_D = Y_\nu v$$

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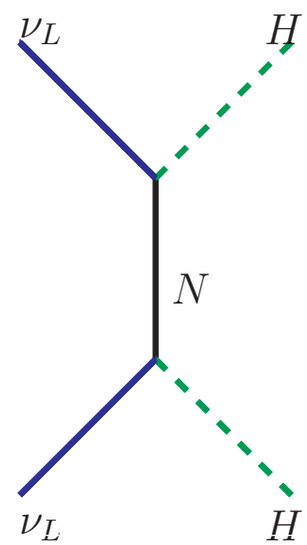

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Seesaw mechanism qualitatively satisfies Sakharov's conditions!

Thermal leptogenesis

Fukugida, Yanagida

Thermal leptogenesis

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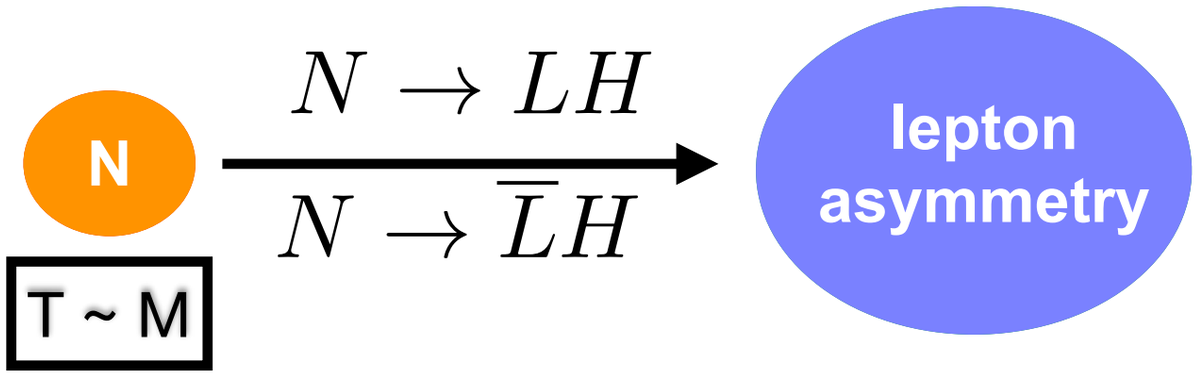

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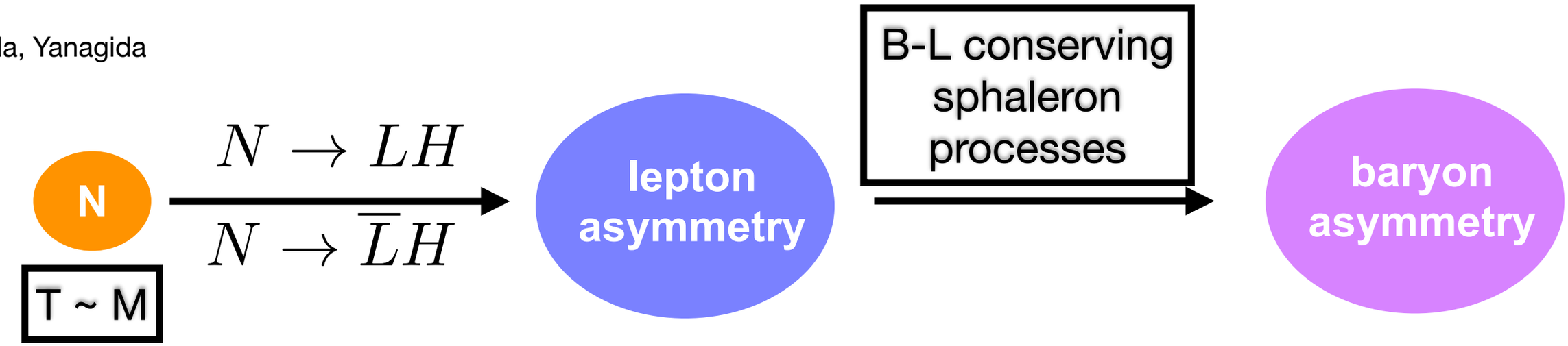

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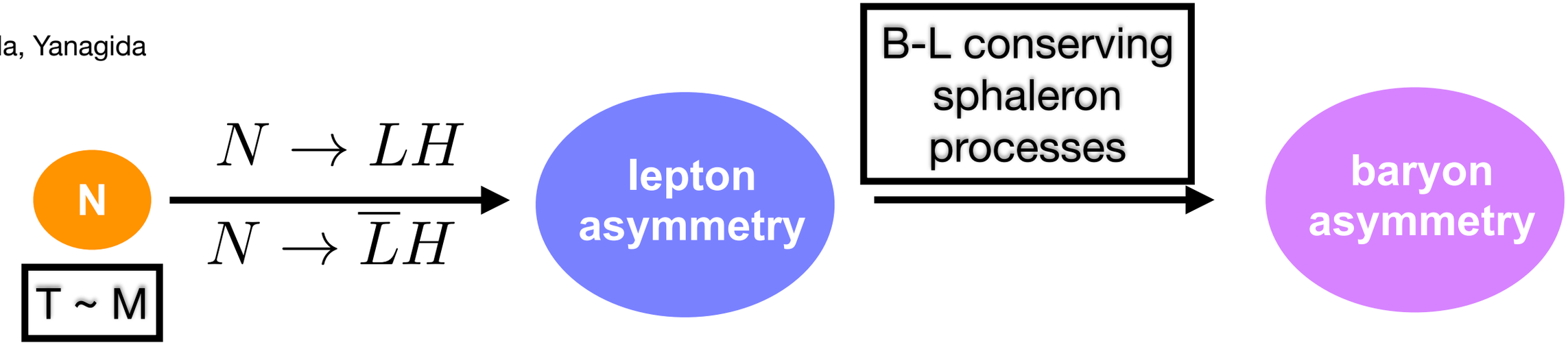
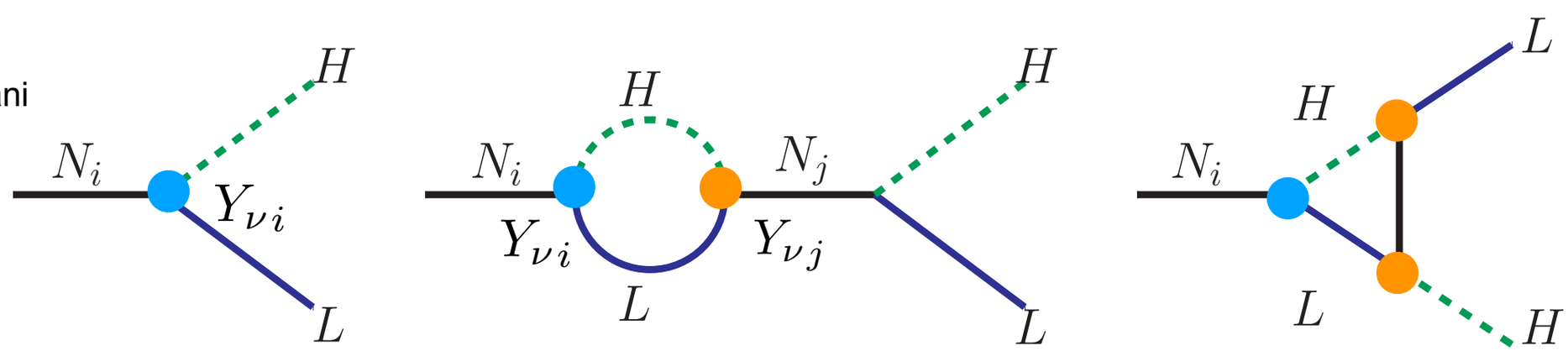


Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani

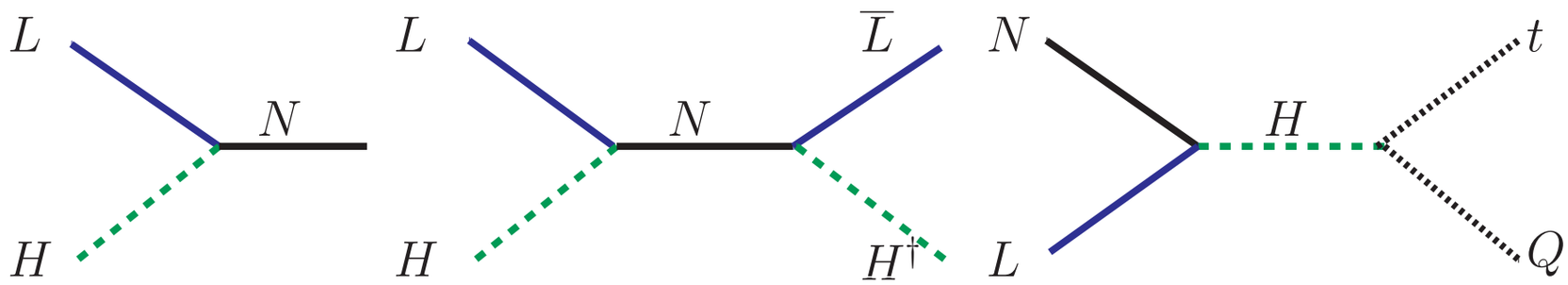


Decay Asymmetry

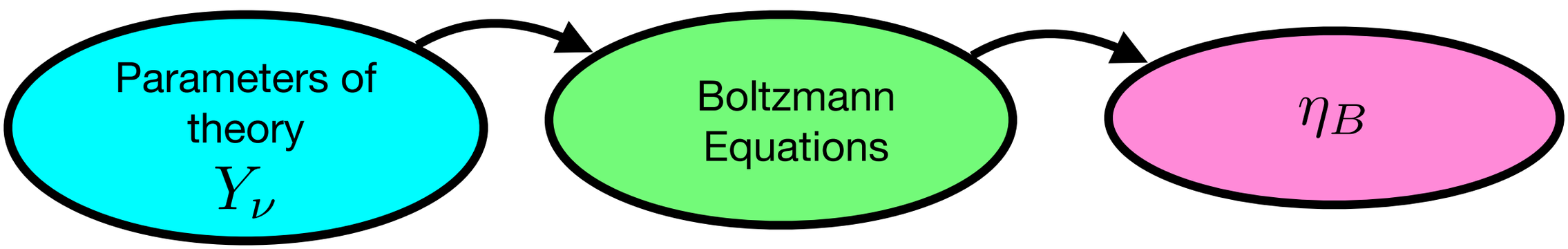
$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$$

Thermal leptogenesis

Washout and scattering processes



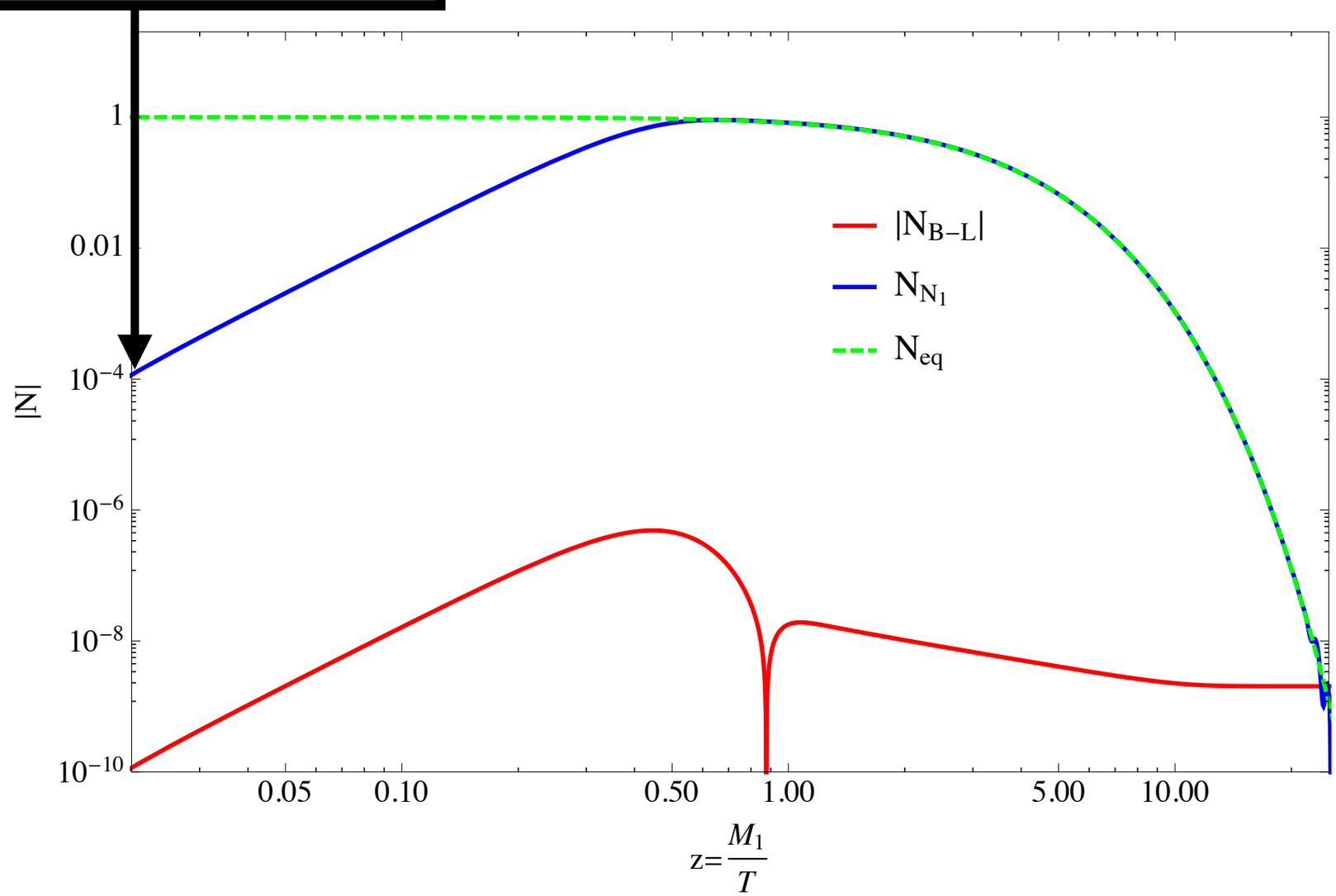
inverse Decays ΔL=2 ΔL=1

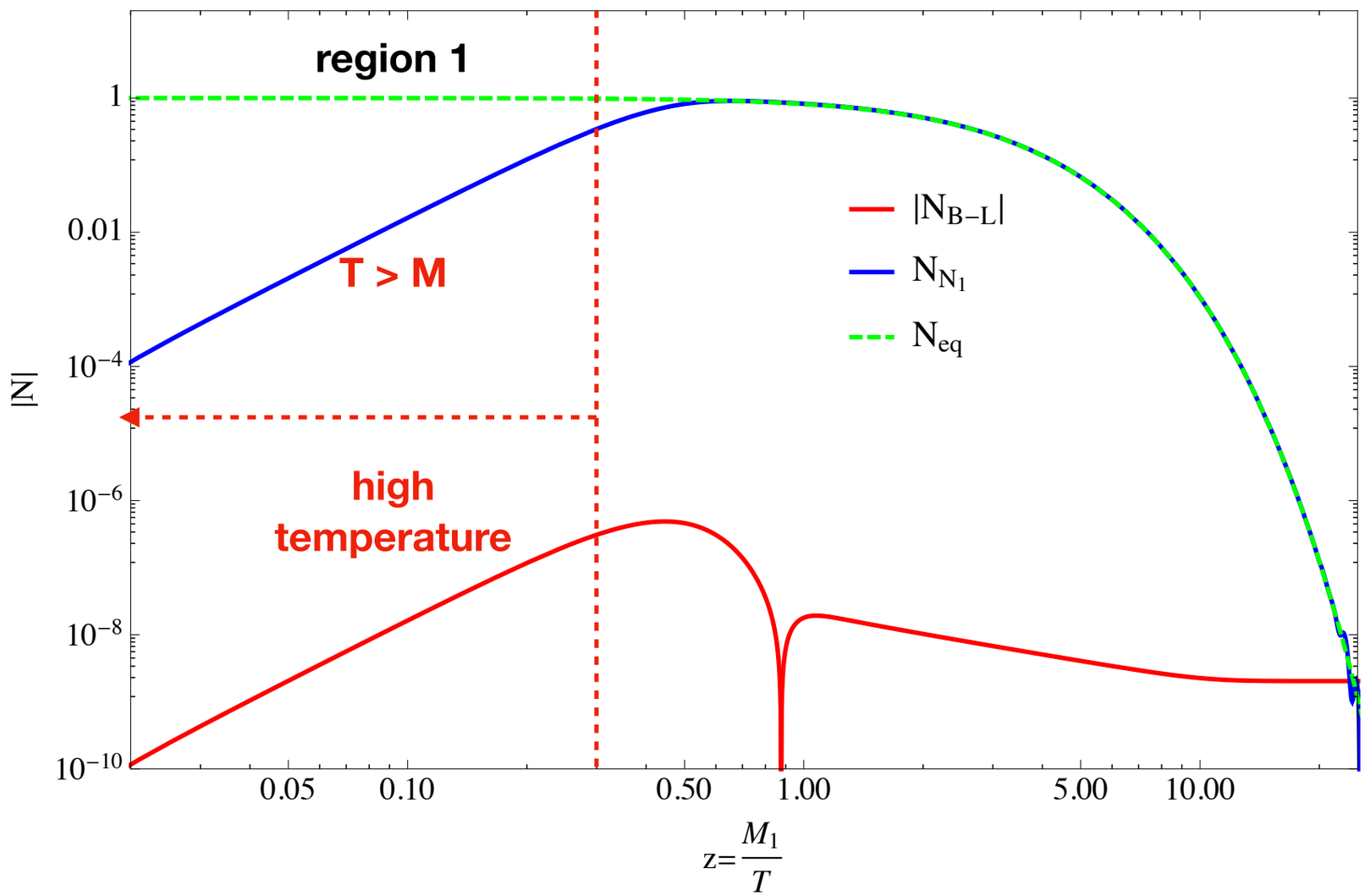


$$\frac{dn_{N_i}}{dz} = - D_i(n_{N_i} - n_{N_i}^{\rm eq}),$$

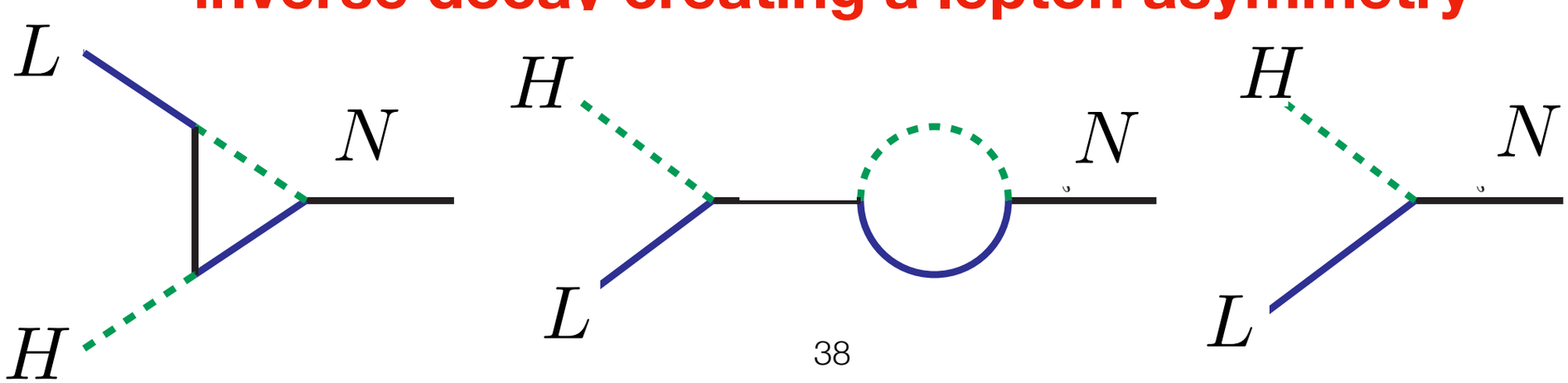
$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3} \Big(\underbrace{\epsilon^{(i)} D_i(n_{N_i} - n_{N_i}^{\rm eq})}_{\textbf{source}} - \underbrace{W_i n_{B-L}}_{\textbf{sink}} \Big) .$$

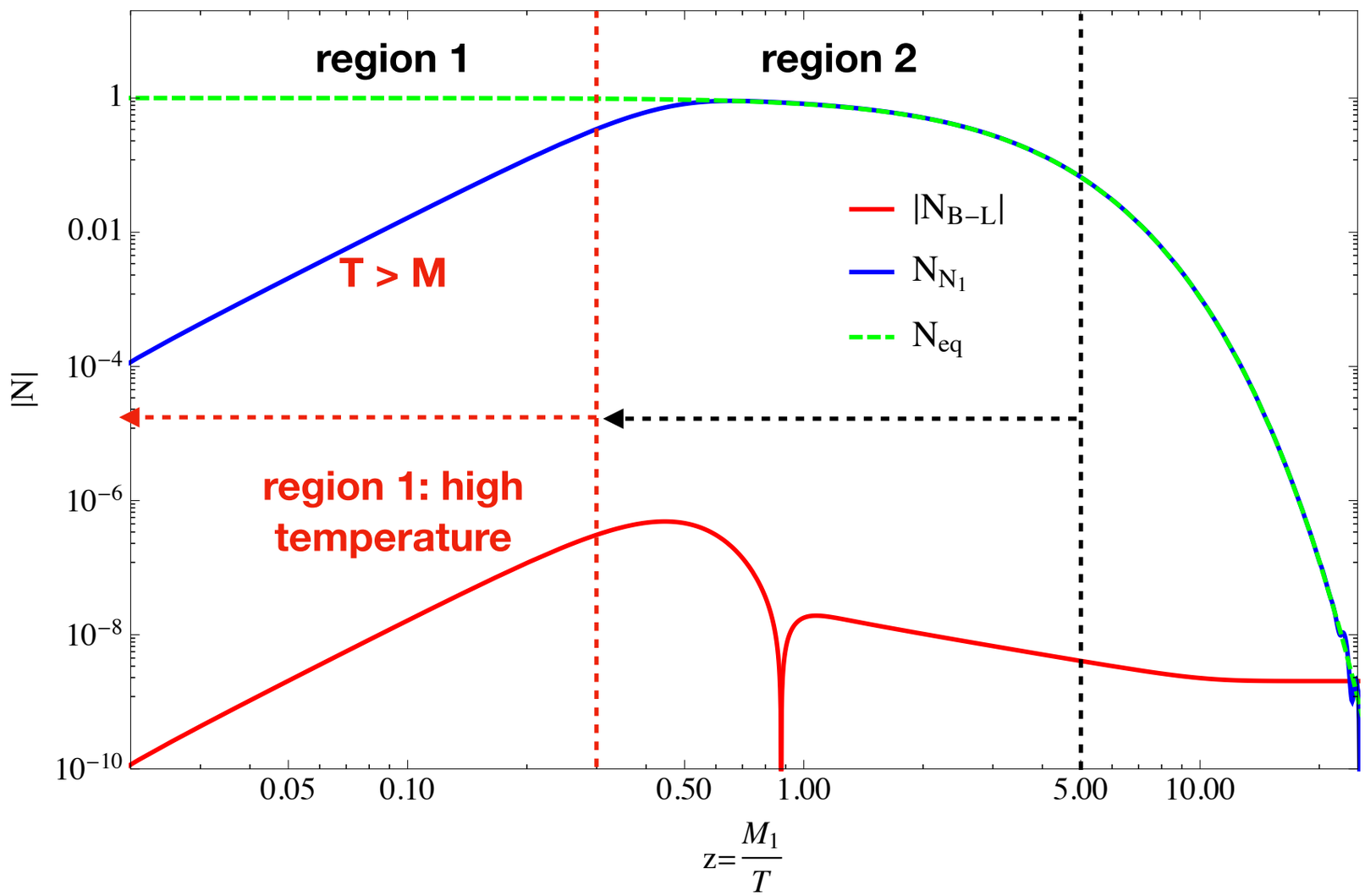
assume zero initial abundance of RHNs





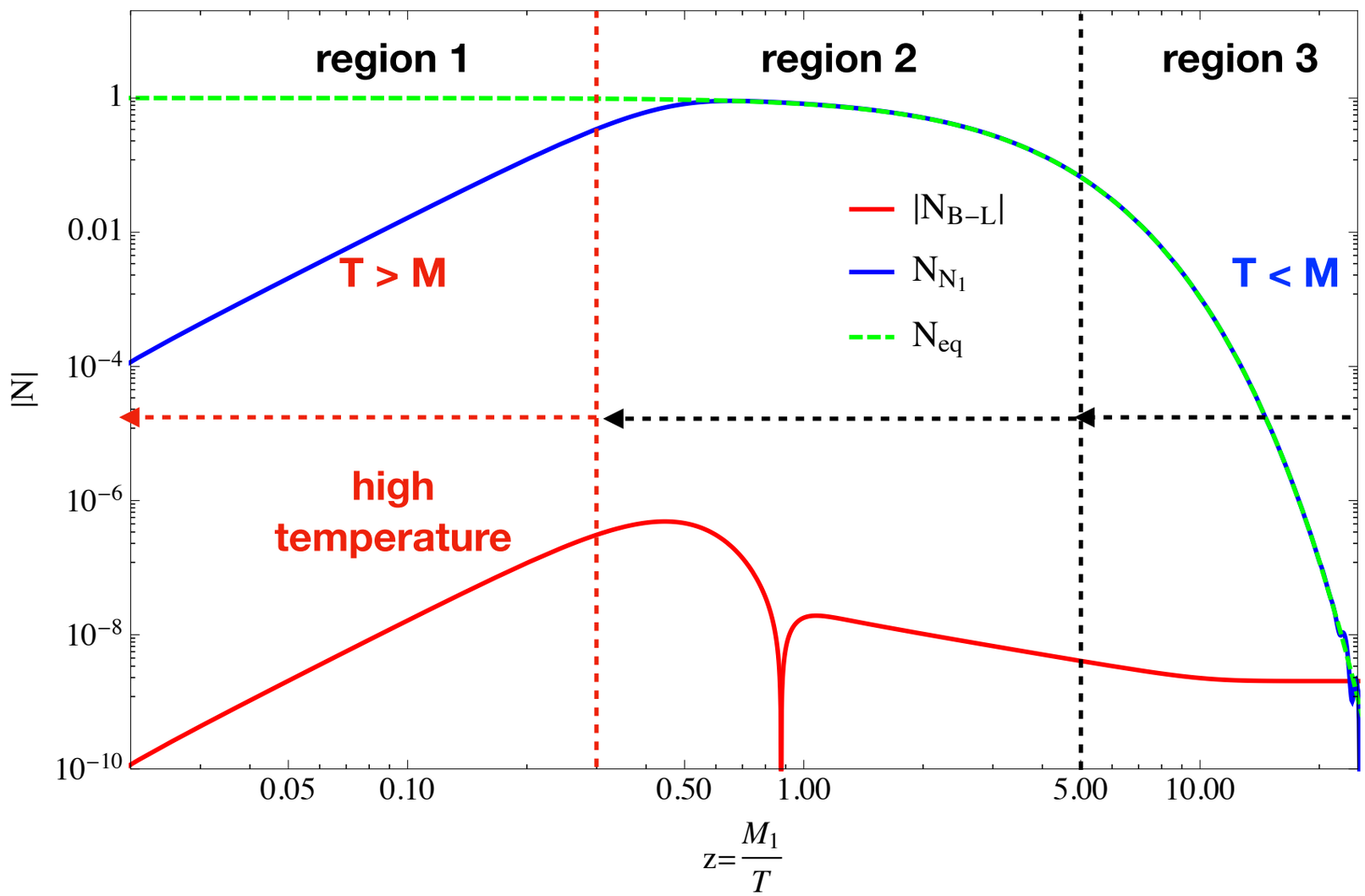
Region 1: leptons and Higgs have enough energy to inverse decay creating a lepton asymmetry





<u>Region 2</u>: At T ~ M, RHN reach equilibrium abundance and lepton asymmetry is produced from decays, inverse decays and washout

Notice the number density of lepton asymmetry can change sign.



<u>Region 3:</u> At T < M, RHN abundance is depleted. Lepton asymmetry freezes out.

Parameter Space

Casas, Ibarra

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

Parameter Space

Casas, Ibarra

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

low-energy scale: 3 phases, 3 mixing angles and 3 masses

Parameter Space

Casas, Ibarra

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

low-energy scale: 3 phases, 3 mixing angles and 3 masses

high-energy scale: 3 phases, 3 mixing angles and 3 masses

Parameter Space

Casas, Ibarra

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

low-energy scale: 3 phases, 3 mixing angles and 3 masses

high-energy scale: 3 phases, 3 mixing angles and 3 masses

Without any symmetry constraints 18 parameters in total.

Akmedov, Rubakov, Smirnov, Hernandez, Kekic, Lopez-Pavon, Racker, Salvado,Drewes,Garbcreht, Klaric, Gueter

Leptogenesis via oscillations

Flavour effects can lower the scale

Minimal Leptogenesis

~ eV ~ 0.1 GeV ~50 GeV ~10^5 GeV ~10^7 GeV ~10^{14} GeV

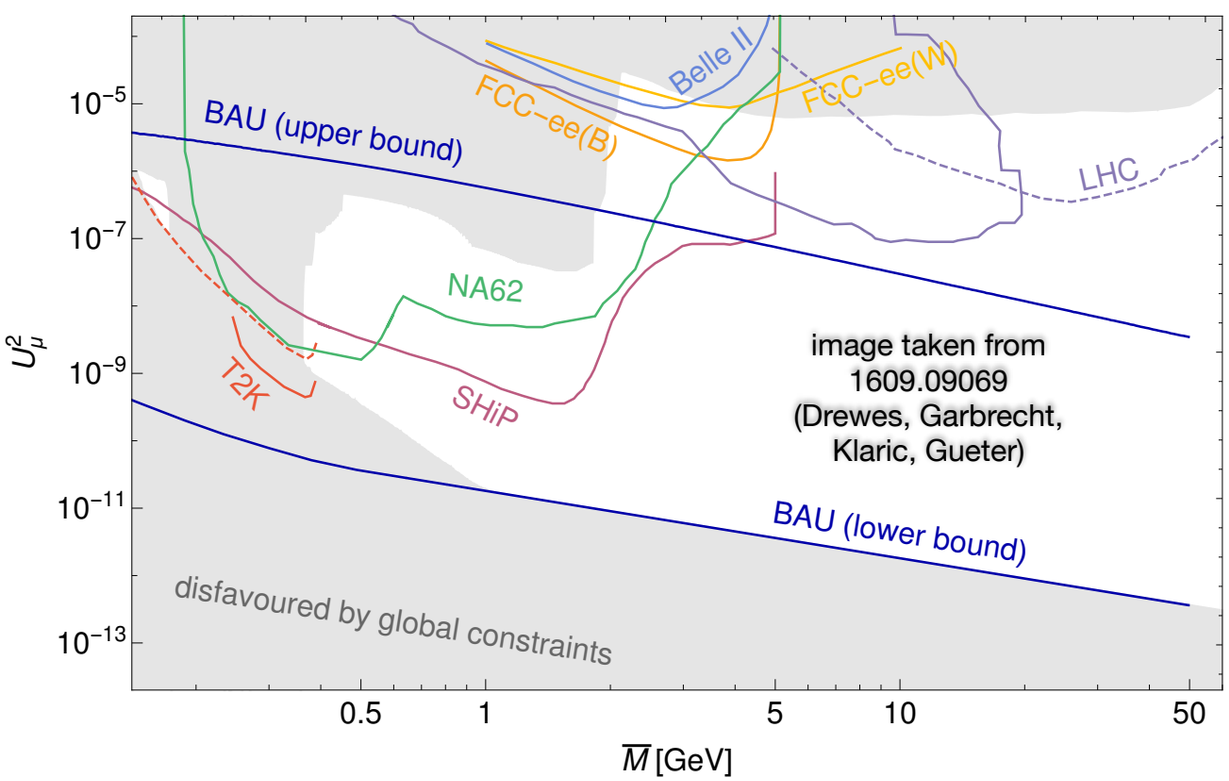
Pilaftsis, Underwood, Millington, Teresi

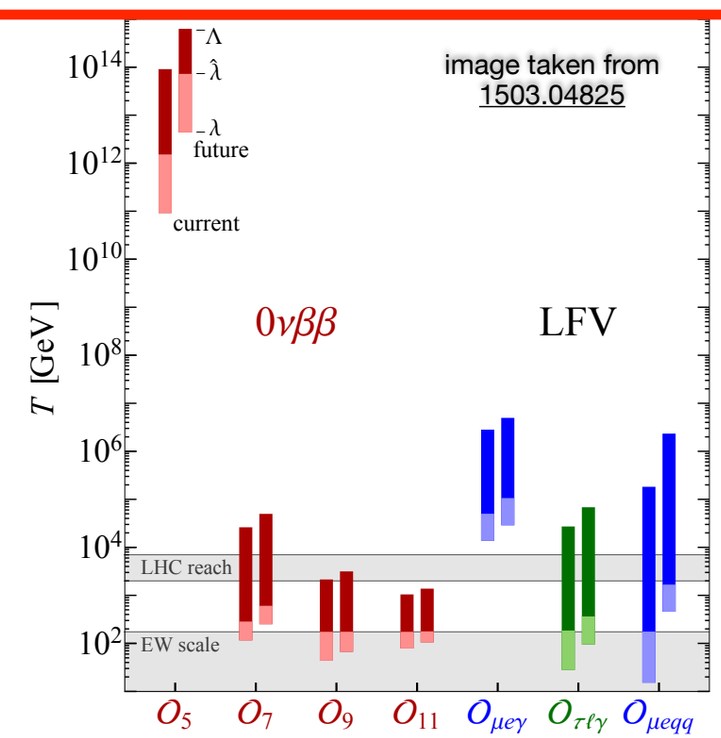
Resonant Leptogenesis

- **small neutrino masses ⟺ BAU**
- **minimal: 2RHN**
- **neutrino data, NDBD, LFV and LNV, cosmology in meson decays, collider searches**

- **small neutrino masses ⟺ BAU**
- **minimal: 2RHN**
- **Easily embedded in GUT models**
- **falsifiable**
- **Can induce the EW scale**

- **Scale too high can exacerbate Higgs fine tuning**
- **RHNs too heavy to produce**





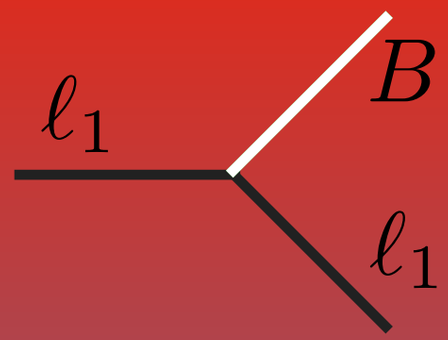
Intermediate Scale Leptogenesis

1804.05066

In collaboration with K. Moffat, S. Pascoli, S.Petcov and H.Schulz

Flavour Effects

$$T \gtrapprox 10^{13}\mathrm{GeV}$$

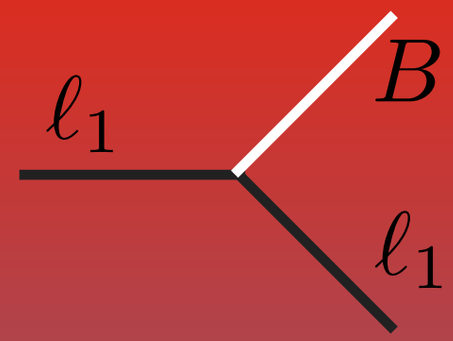


$$\Gamma_\ell < H$$

$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle$$

Flavour Effects

$$T \gtrapprox 10^{13}\mathrm{GeV}$$



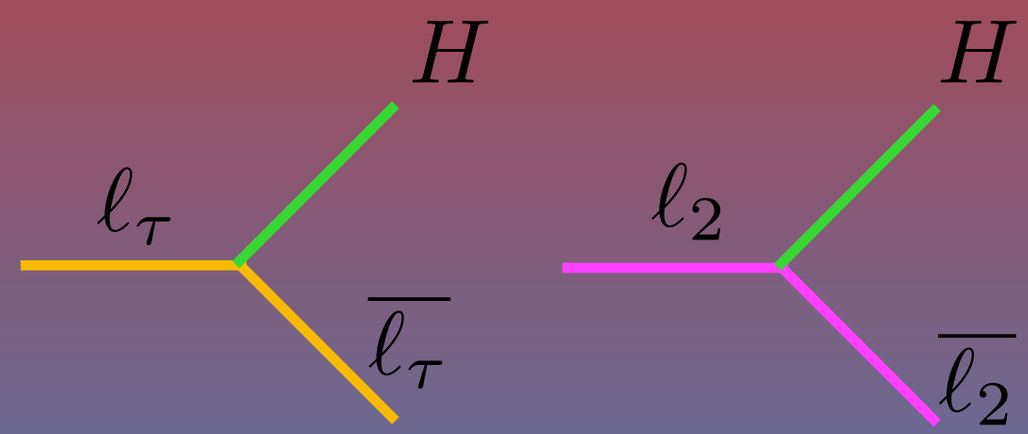
$$\Gamma_\ell < H$$

$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle$$

SM Yukawa couplings

$$\Gamma_\tau \propto h_\tau^2 T > H$$

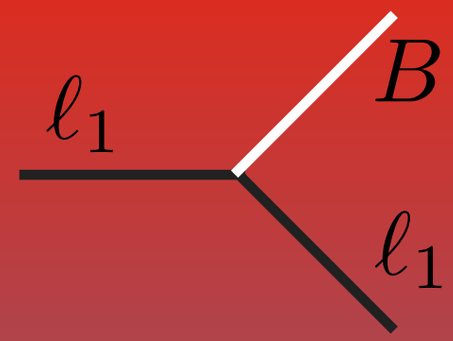
$$T \sim 10^{11}\mathrm{GeV}$$



Flavour Effects

$$\Gamma_\ell < H$$

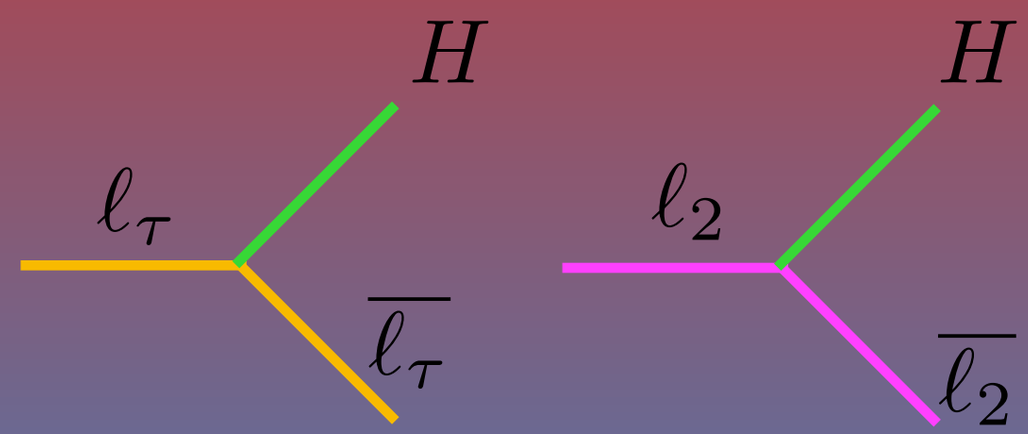
$T \gtrapprox 10^{13}\mathrm{GeV}$



$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle$$

SM Yukawa couplings

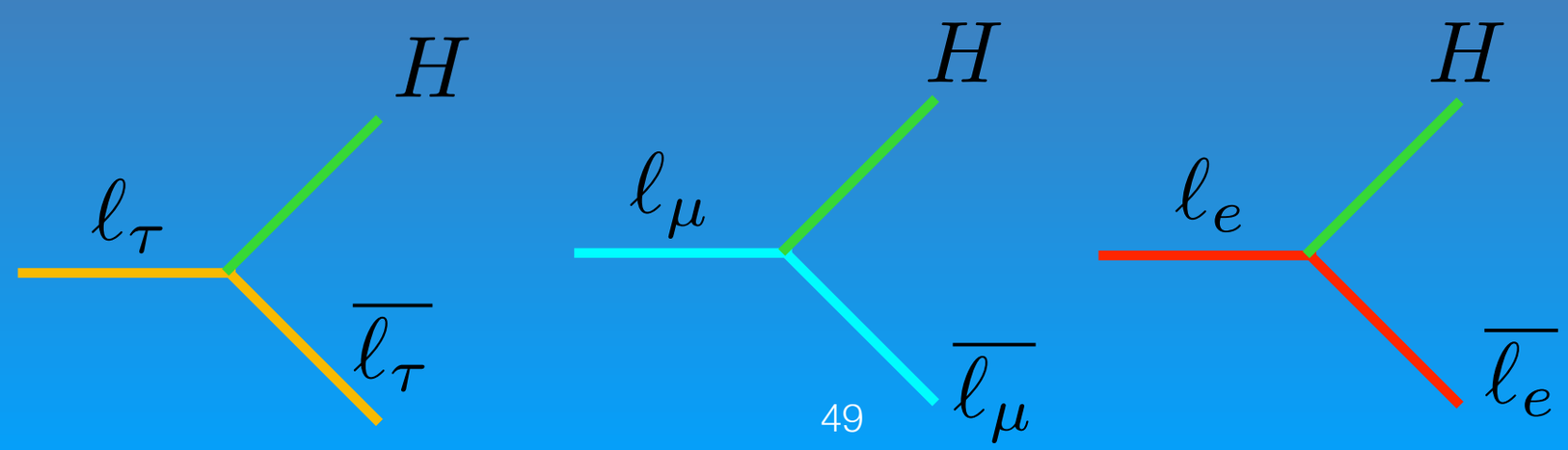
$T \sim 10^{11}\mathrm{GeV}$



$$\Gamma_\tau \propto h_\tau^2 T > H$$

$T \sim 10^{9}\mathrm{GeV}$

$$\Gamma_\tau \propto h_\mu^2 T > H$$



Density Matrix Equations

$$\frac{dn_{N_i}}{dz} = - D_i(n_{N_i} - n_{N_i}^{\rm eq})$$

$$\frac{dn_{\alpha\beta}}{dz} = \sum_i \left(\epsilon_{\alpha\beta}^{(i)} D_i(n_{N_i} - n_{N_i}^{\rm eq}) - \frac{1}{2} W_i \left\{ P^{0(i)}, n \right\}_{\alpha\beta} \right)$$

$$- \frac{\Im(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta} - \frac{\Im(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta},$$

Promote lepton asymmetry number density to matrix:

$$N = \begin{pmatrix} N_{\tau\tau} & N_{\tau\mu} & N_{\tau e} \\ N_{\mu\tau} & N_{\mu\mu} & N_{\mu e} \\ N_{e\tau} & N_{e\mu} & N_{ee} \end{pmatrix}$$

Density Matrix Equations

$$\frac{dn_{N_i}}{dz} = - D_i(n_{N_i} - n_{N_i}^{\rm eq})$$

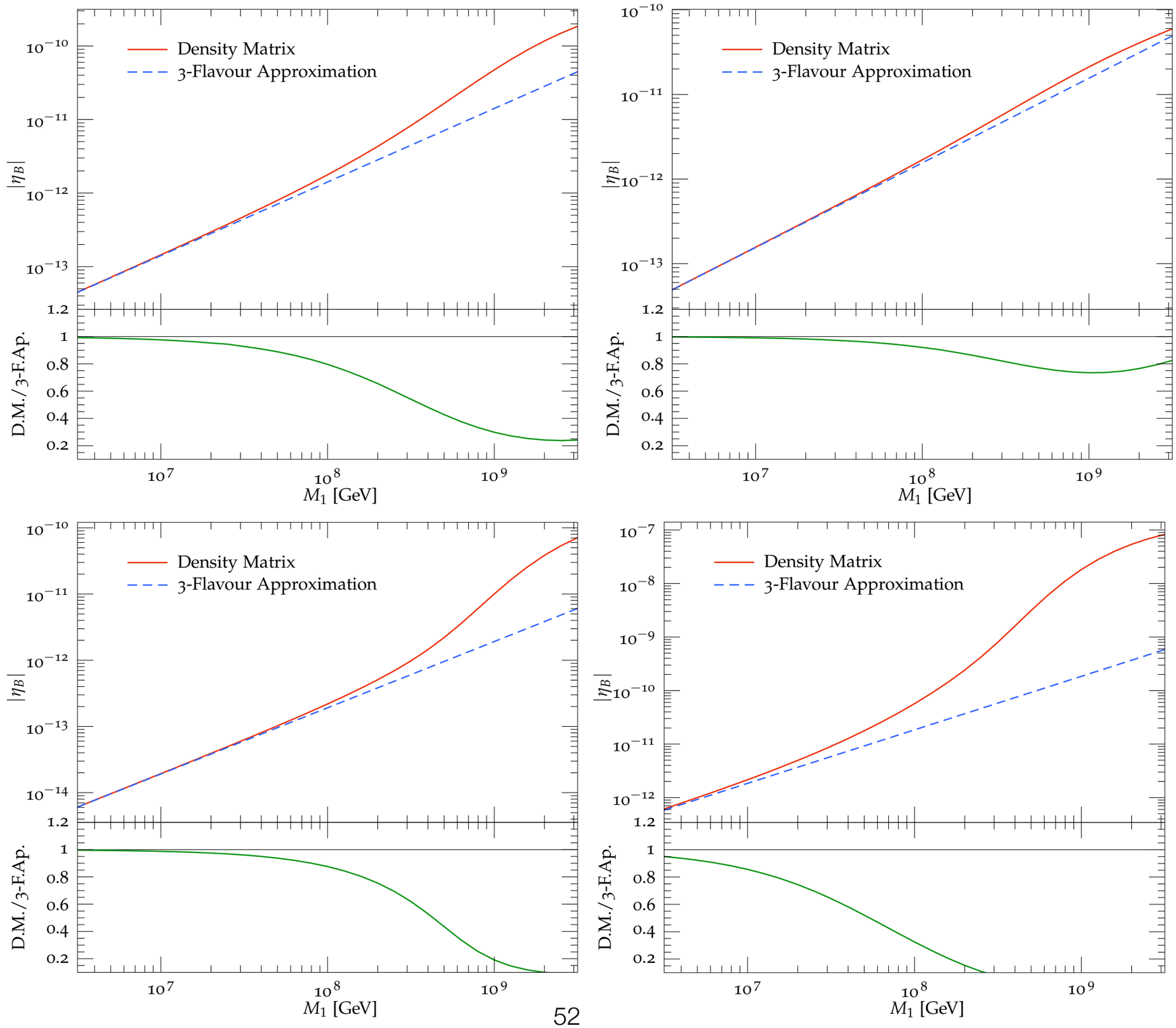
$$\frac{dn_{\alpha\beta}}{dz} = \sum_i \left(\epsilon_{\alpha\beta}^{(i)} D_i(n_{N_i} - n_{N_i}^{\rm eq}) - \frac{1}{2} W_i \left\{ P^{0(i)}, n \right\}_{\alpha\beta} \right)$$

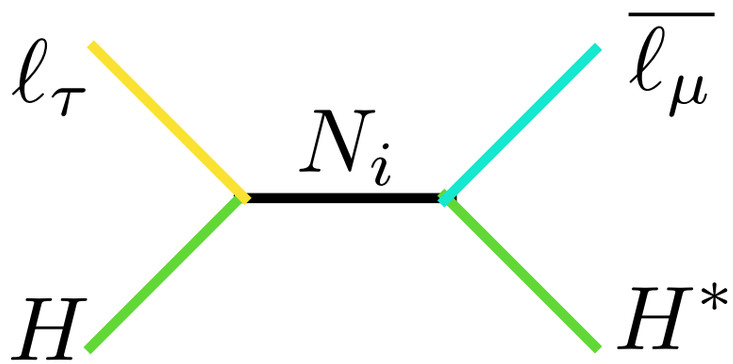
$$- \frac{\Im(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta} - \frac{\Im(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta},$$

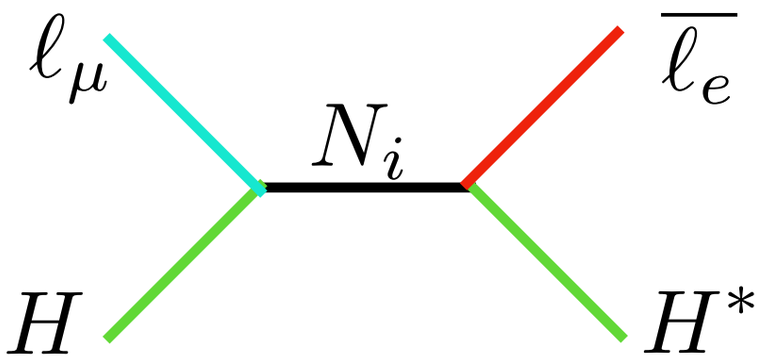
"Classical" BE ignore off-diagonal components of matrix and only take the trace of the matrix

$$N = \begin{pmatrix} N_{\tau\tau} & N_{\tau\mu} & N_{\tau e} \\ N_{\mu\tau} & N_{\mu\mu} & N_{\mu e} \\ N_{e\tau} & N_{e\mu} & N_{ee} \end{pmatrix}$$

DME versus Classical BE







Represent off-diagonal components of density matrix

Similar to inclusion of spectator effects, protection of lepton asymmetry

Era of leptonenesis occurs T < 10^9 GeV, three flavours become distinct

Density matrix equations account for flavour oscillations

1804.05066 we demonstrate **non-resonant** thermal leptogenesis can be lowered to T~ 10^6 GeV

Leptogenesis via low energy CPV

1809.08251

In collaboration with K. Moffat, S. Pascoli and S.Petcov

Leptogenesis from low energy CPV

S. Pascoli, S.T. Petcov and A. Riotto (0609125, 0611338)

All CPV stems from low energy phases. This implies the "high scale" phases of the R-matrix must be CP conserving*

R-matrix entries purely real or imaginary:

$$R^*_{ij} = R_{ij}\rho_i^N \rho_j^\nu \qquad i,j \in \{1,2,3\}\,.$$

They found low scale CPV could explain the observed BAU:

$$10^{10} \lesssim M(\mathrm{GeV}) \lesssim 10^{12}$$

Upper bound was placed as in the one-flavoured regime

$$\epsilon_1 = 0$$

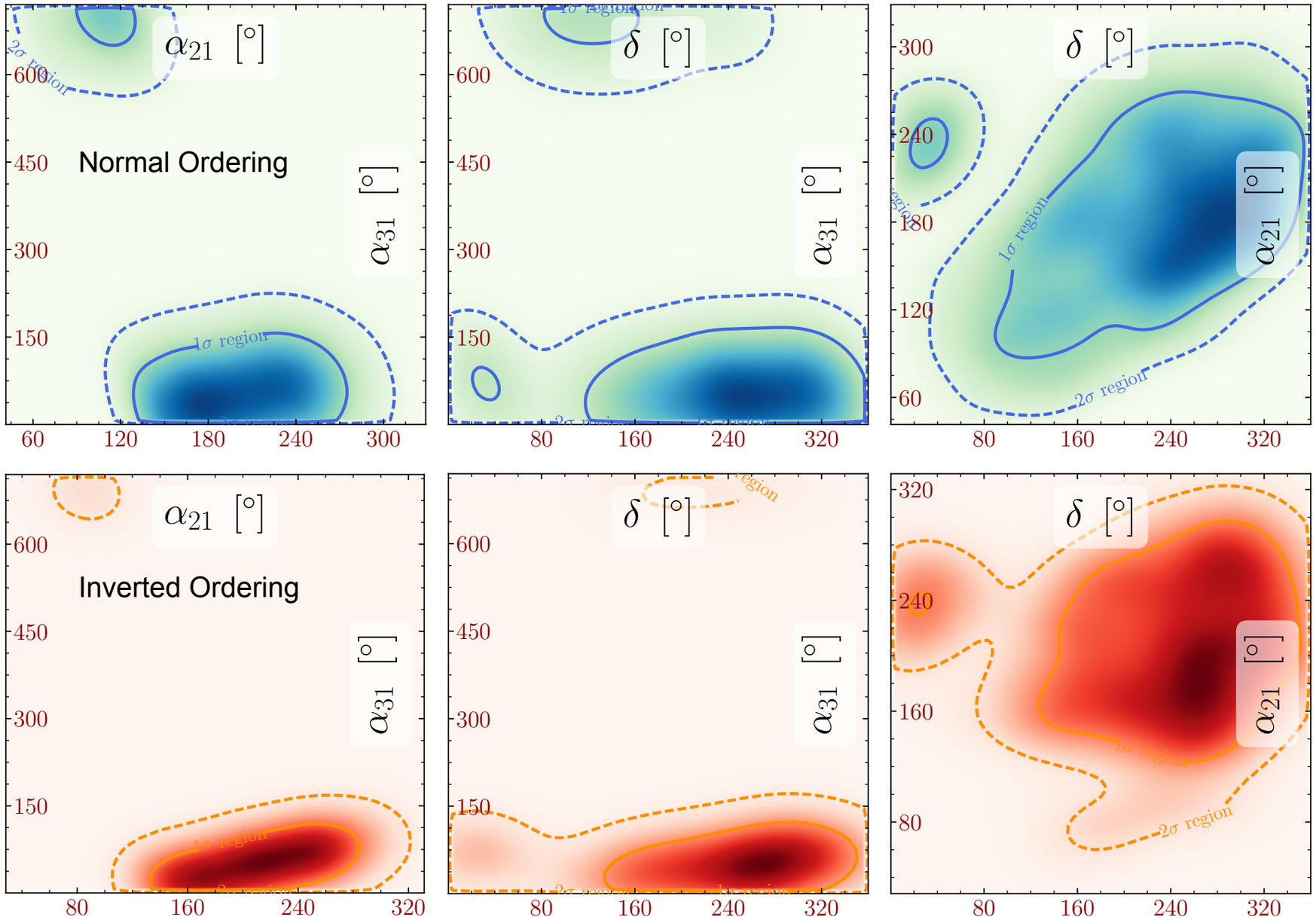
*not entirely ad hoc, models that include such a feature have been studied in the context of flavour and generalised CP symmetries (1203.4435 [Petcov etal], 1506.06788 [Mohapatra etc], 1602.03873 [Ding etal], 1602.04206 [Hagedorn etal])

1809.08251 revisits this question using modern numerical machinery: density matrix equations + MultiNest* for effective PS exploration

Leptogenesis from Leptonic CP Violation

$T < 10^9$ GeV

$m_1 = 0.21\,\mathrm{eV}$



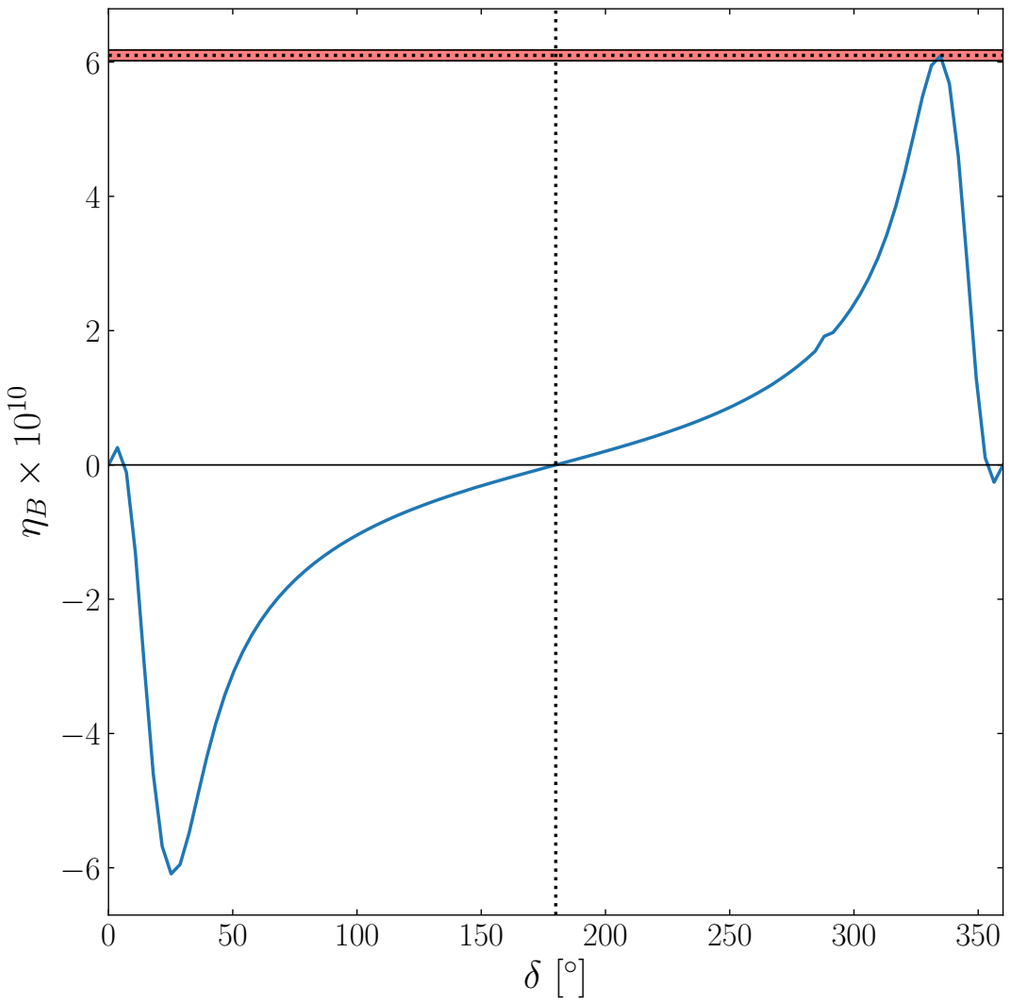
R matrix CP conserving and low energy observable fixed at best fit values NuFit.

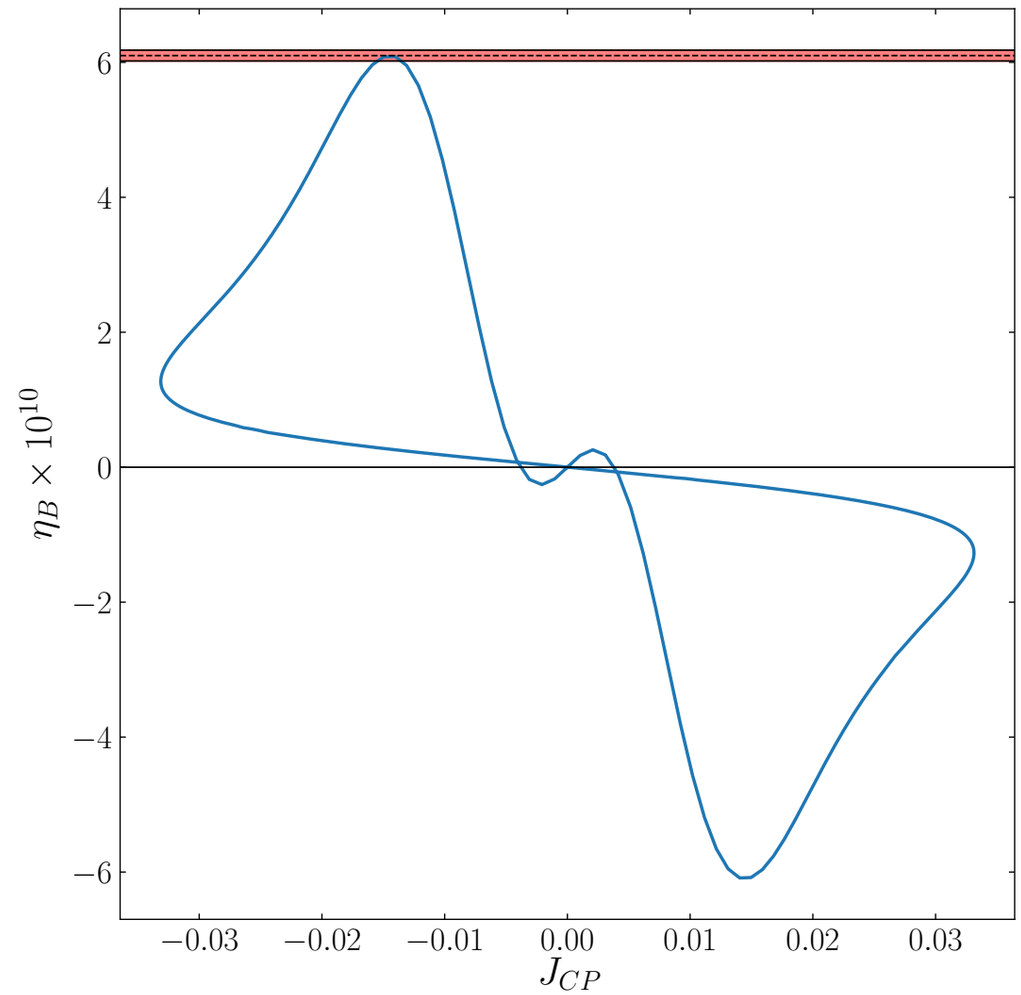
$$M_1 = 3.16 \times 10^6\,\mathrm{GeV},\ M_2 = 3.5 M_1,\ M_3 = 3.5 M_2$$

Lowest mass for non-resonant low scale CPV from Dirac and Majorana phases ~10^6 GeV. At this scale all low energy phases.

Pure Dirac CP Violation

$$J_{CP} \equiv \Im\left[U_{e1}U_{\mu 2}U_{e2}^{*}U_{\mu 1}^{*}\right]$$





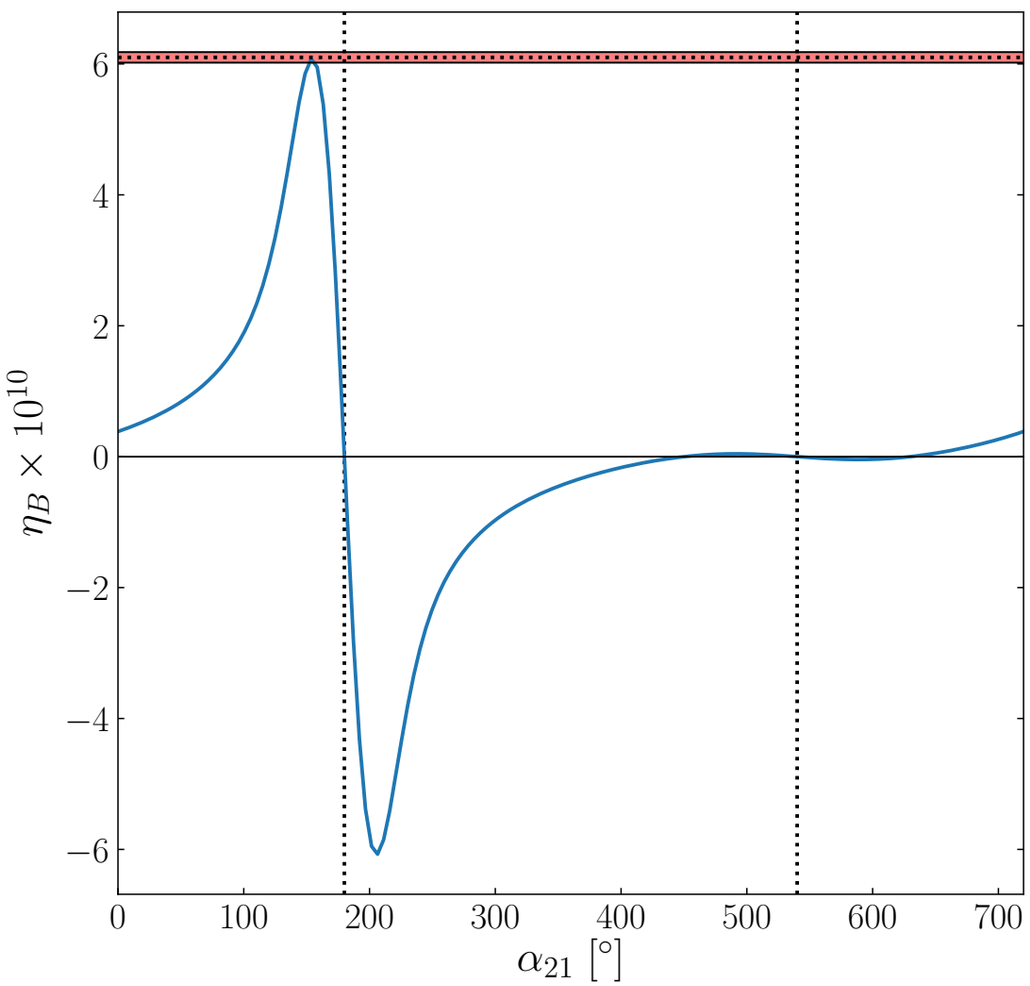
$$M_1 = 7.0 \times 10^8\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

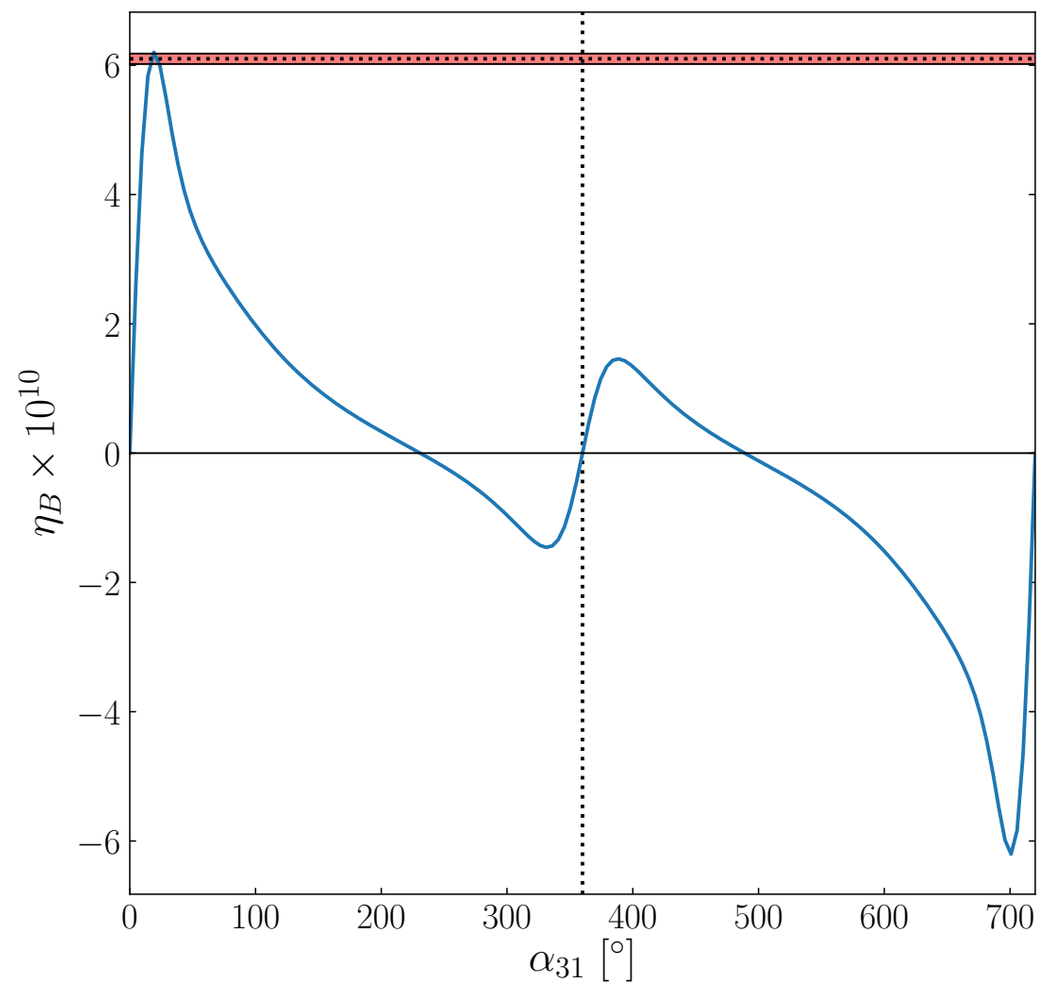
Pure Dirac phase leptogenesis requires minimally $M_1 \sim 10^8$ GeV scale is higher than Majorana only as we are $\sin\theta_{13}$ penalised

$m_1 = 0.21\,\mathrm{eV}$

Pure Majorana CP Violation

$$J_{CP} \equiv \Im\left[U_{e1}U_{\mu 2}U_{e2}^{*}U_{\mu 1}^{*}\right]$$





$$M_1 = 3.71 \times 10^6\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

Pure Majorana phase leptogenesis requires minimally $M_1 \sim 10^6$ GeV

Mini summary: non-resonant thermal leptogenesis can explain BAU using only low scale phases at $M_1 \sim 10^6$ GeV

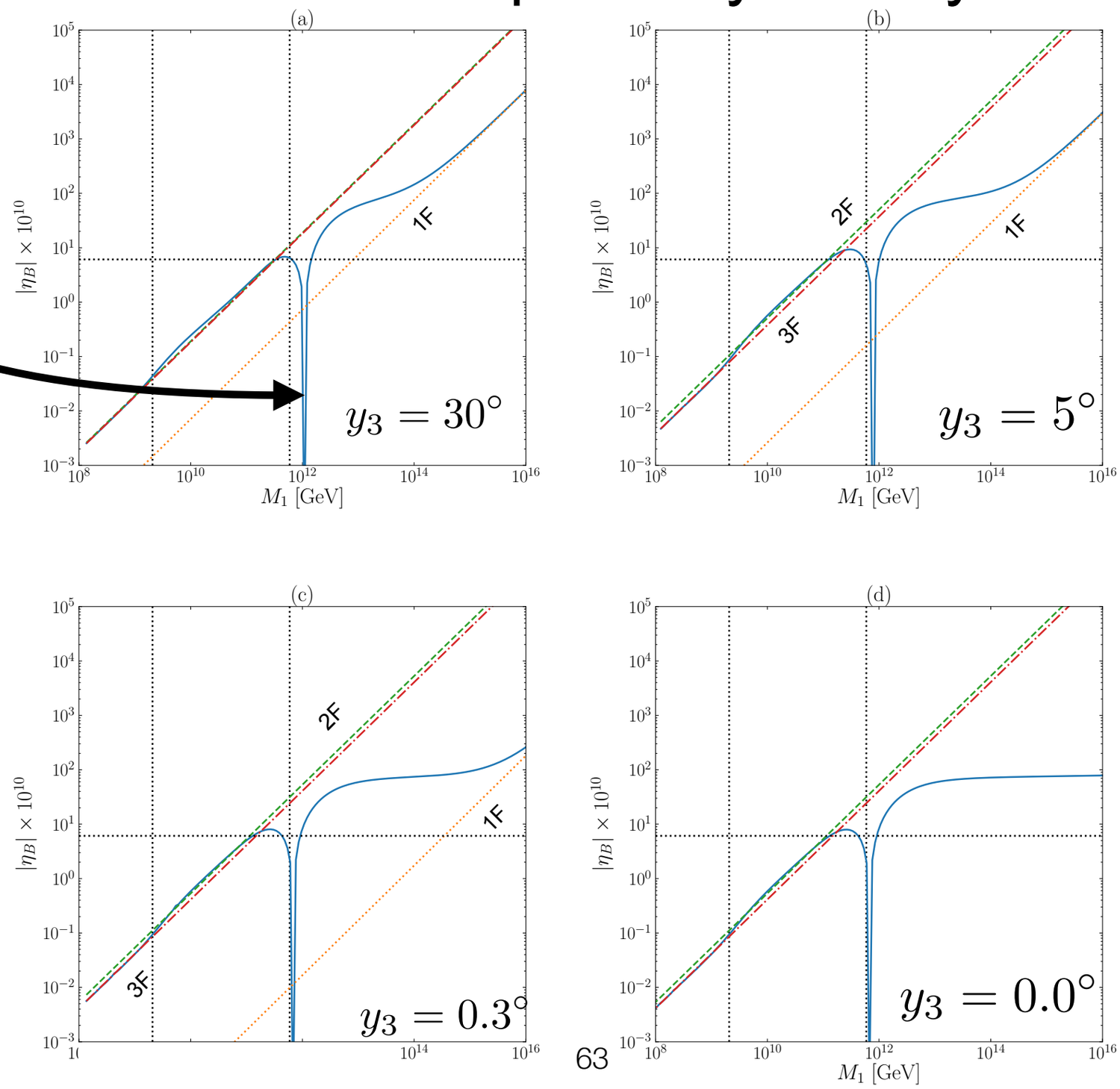
Leptogenesis from Leptonic CP Violation

$T > 10^{12}$ GeV

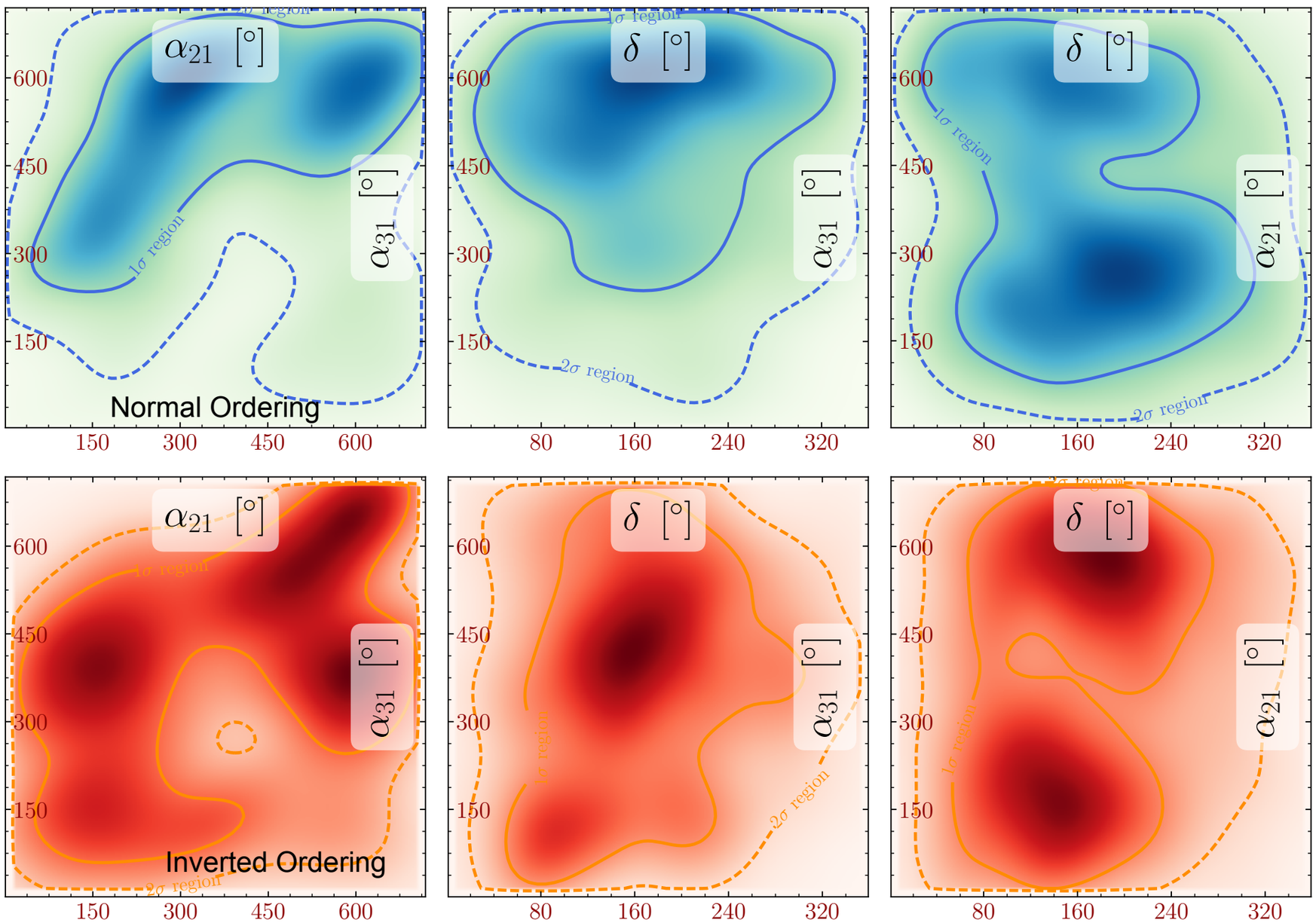
Before in very high energy regime ("one flavoured") not possible to produce the BAU from low phases

Although ϵ = 0, the washout terms are still flavour dependent and can generate sufficient lepton asymmetry.

density matrix equations



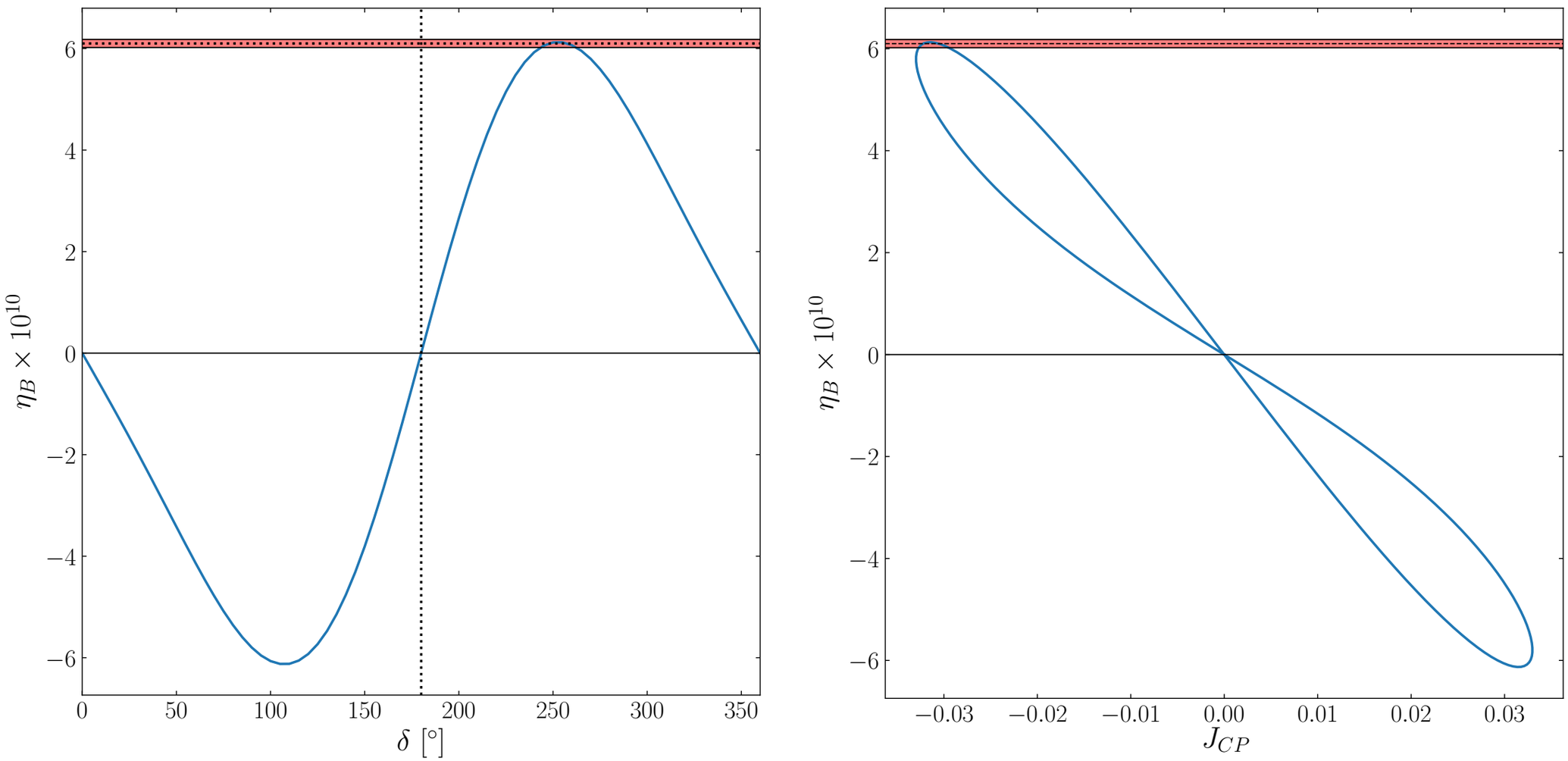
Leptogenesis from low-scale CP-Violation



$$M_1 = 10^{13}\,\mathrm{GeV},\ M_2 = 3.5 M_1,\ M_3 = 3.5 M_2$$

Pure Dirac CP Violation

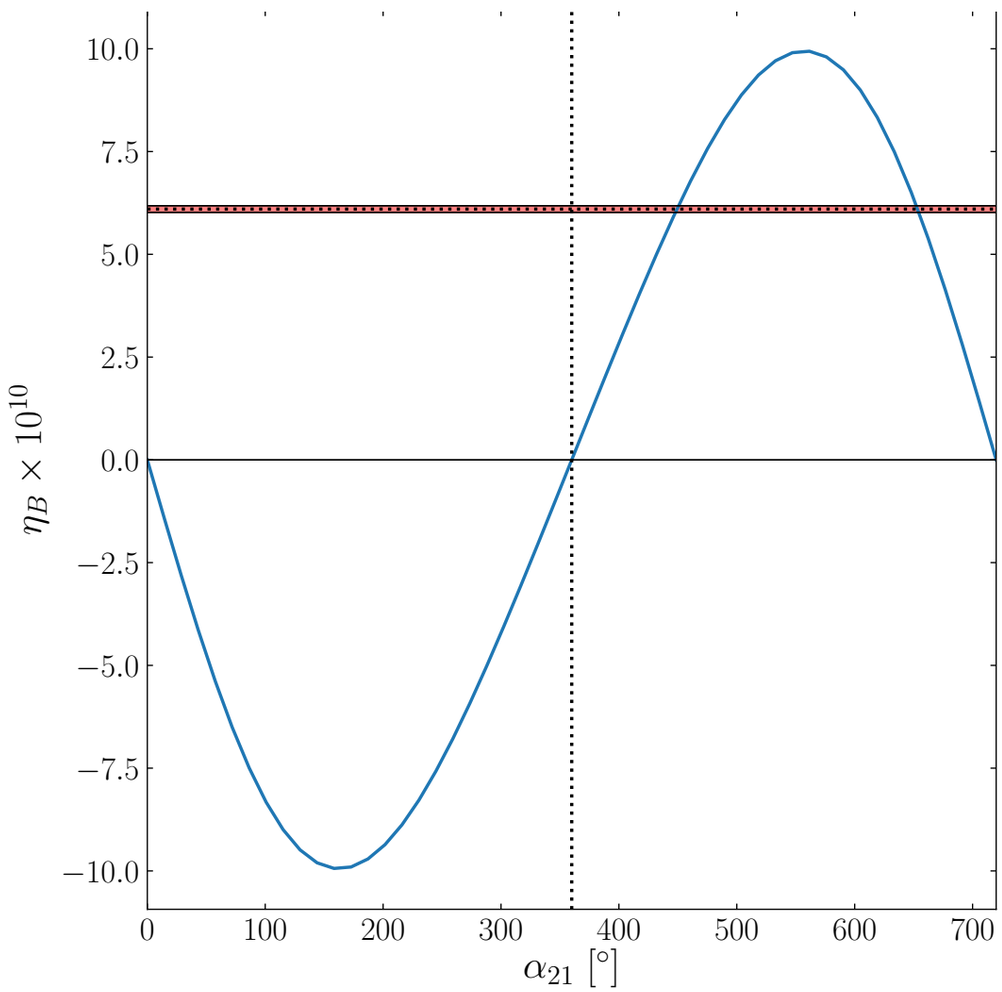
$$J_{CP} \equiv \Im\left[U_{e1}U_{\mu 2}U_{e2}^{*}U_{\mu 1}^{*}\right]$$

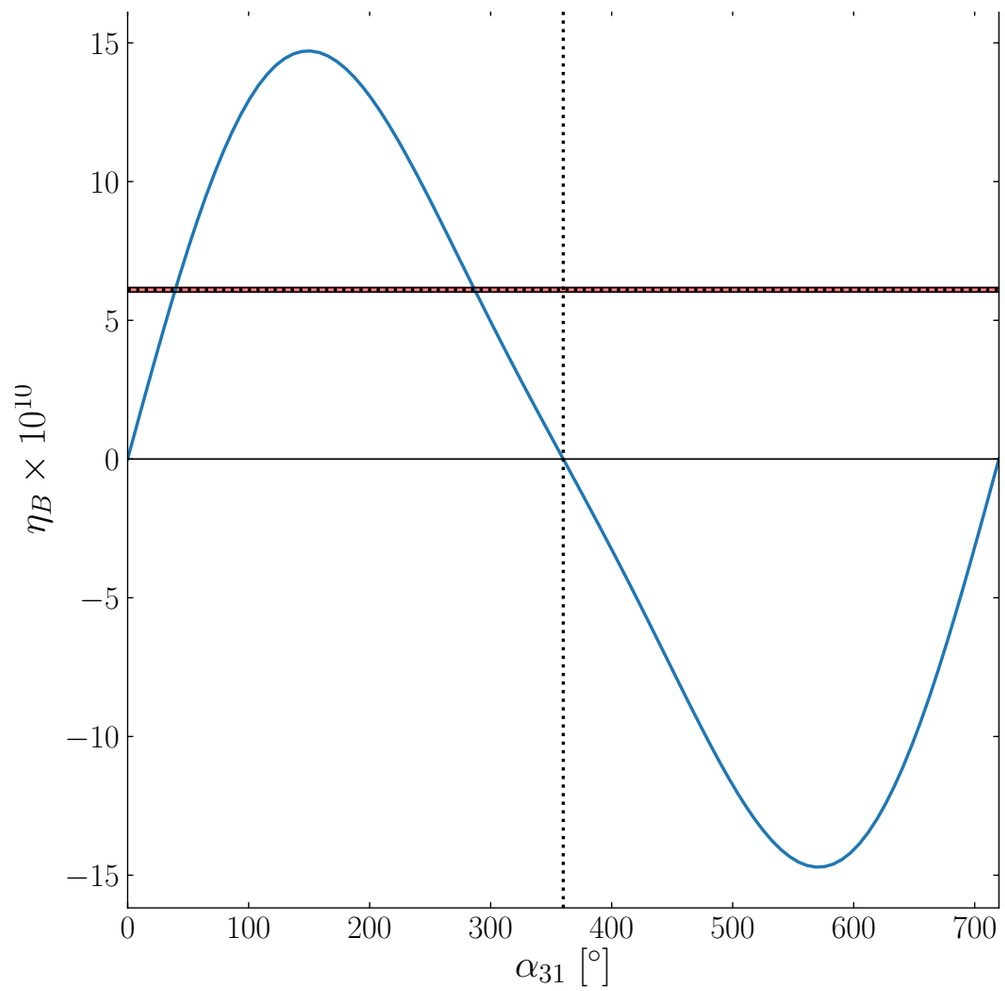


$$M_1 = 10^{13}\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

Pure Majorana CP Violation

$$J_{CP} \equiv \Im\left[U_{e1}U_{\mu 2}U_{e2}^{*}U_{\mu 1}^{*}\right]$$





$$M_1 = 10^{13}\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

Mini summary: non-resonant thermal leptogenesis can explain BAU using only low scale phases at $M_1 > 10^{12}$ GeV

Conclusions

- Thermal leptogenesis is a very plausible mechanism to explain the BAU.
- The scale can be lowered (but still non-resonant) using a mild hierarchy of RHN, flavour effects and broad PS exploration.
- Low scale leptonic phases can produce the BAU over many (10^6 - 10^{13} GeV) orders of magnitude.

"The observation of low-scale leptonic Dirac CP violation, in combination with the positive determination of the Majorana nature of the massive neutrinos,
would make more plausible, but will not be a proof of, the existence of high or intermediate-scale thermal leptogenesis. These remarkable discoveries would indicate, in particular, that thermal leptogenesis could produce the BAU
with the requisite CP violation provided by the Dirac CP-violating phase in the neutrino mixing matrix."

Thank you!

Formulae

$$D_1(z) = \frac{\Gamma_1(T)}{Hz} = K_1 z \langle \frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)} \rangle$$

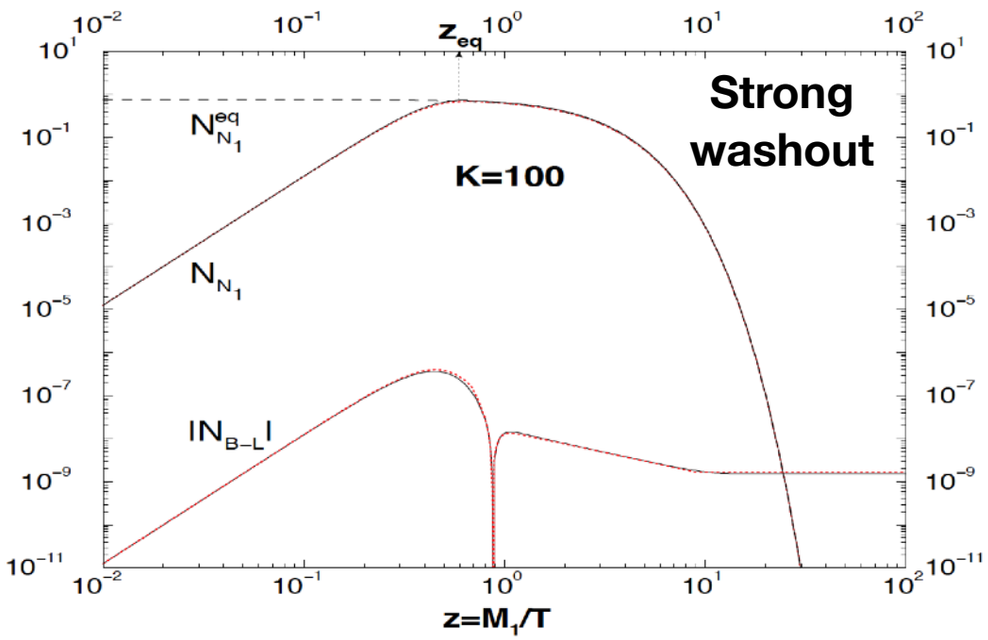
$$N_1^{eq} = \frac{1}{2} z^2 K_2(z)$$

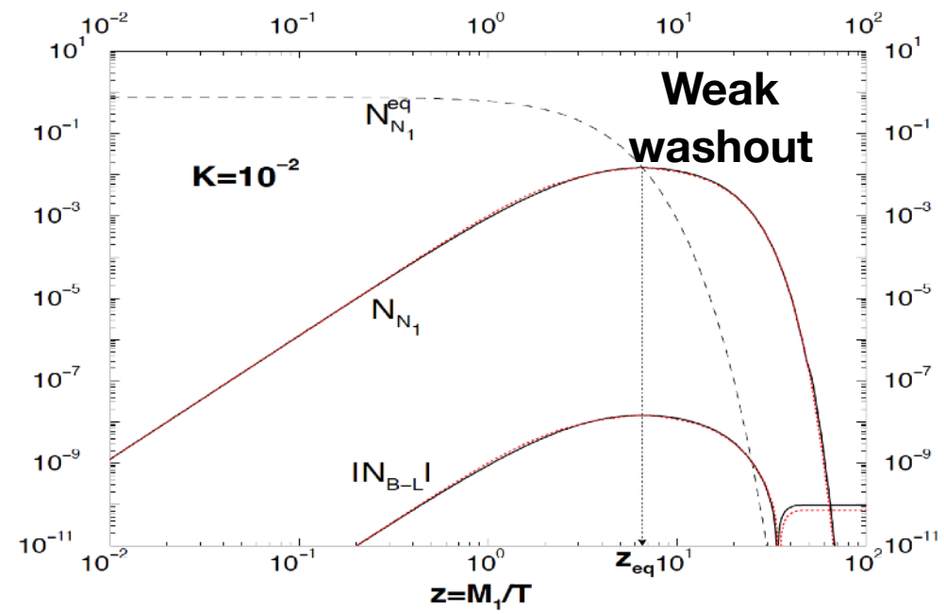
$$W_1(z) = \frac{1}{2} \frac{\Gamma_1^{ID}}{Hz} = \frac{1}{4} K_1 \mathcal{K}_\infty z^3$$

$$\eta_B(T = T_{rec}) = \frac{28}{29} \frac{N_{B-L}^f}{N_\gamma} \frac{g_*(T = T_{rec})}{g_*(T = T_{lep})} \simeq 0.96 \times 10^{-2} N_{B-L}^f$$

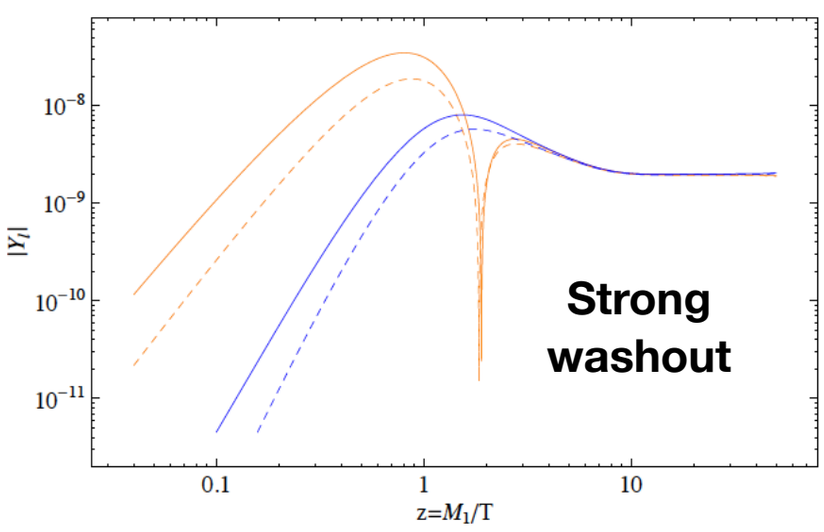
Semi-Classical Justification

$$\mathcal{K}_1 = \frac{\Gamma_1 + \overline{\Gamma_1}}{Hz} = \frac{m_1}{m^*} = \frac{(m_D^\dagger m_D)_{11}}{M_1}\frac{1}{10^{-3}\mathrm{eV}} = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1}\frac{1}{10^{-12}\mathrm{GeV}}$$



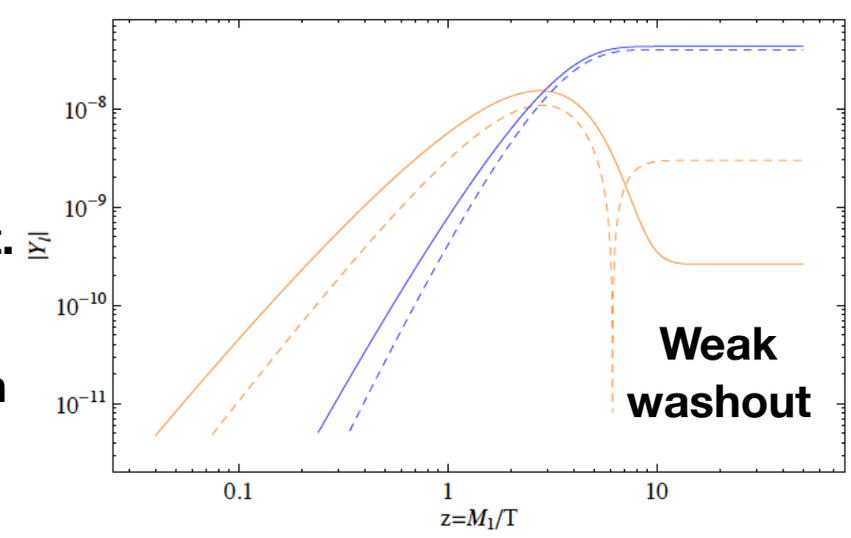


Plots from 1002.1326. Garbrecht etal

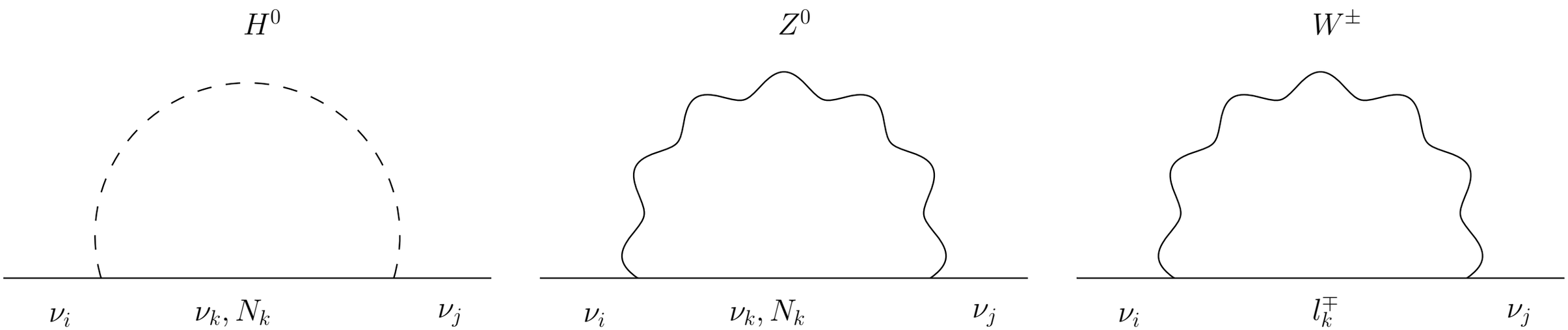


Strong washout FDFT effects negligible.
Weak washout FDFT important.

Luckily for us, we are always in the strong washout regime!



Parametrisation: Radiative Corrections



$$m_\nu = m^{\text{tree}} + m^{\text{1-loop}}.$$

$$Y = \frac{1}{v} m_D = \frac{1}{v} U \sqrt{\hat{m}_\nu} R^T \sqrt{f(M)^{-1}},$$

contains loop contributions

Light Neutrino Mass

$$m^{\text{tree}} \approx m_D M^{-1} m_D^T \qquad m_\nu = m^{\text{tree}} + m^{\text{1-loop}}$$

$$m^{\text{1-loop}} =$$

$$- m_D \left(\frac{M}{32\pi^2 v^2} \left(\frac{\log\left(\frac{M^2}{m_H^2}\right)}{\frac{M^2}{m_H^2} - 1} + 3 \frac{\log\left(\frac{M^2}{m_Z^2}\right)}{\frac{M^2}{m_Z^2} - 1} \right) \right) m_D^T,$$

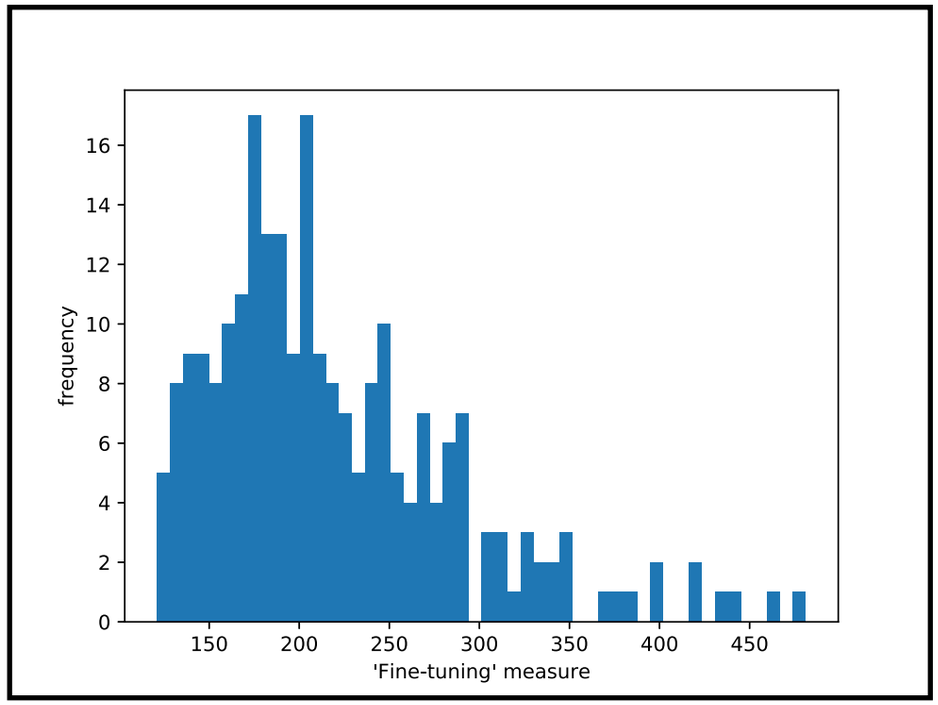
$$= -\frac{1}{32\pi^2 v^2} m_D \text{diag}\left(g\left(M_1\right), g\left(M_2\right), g\left(M_3\right)\right) m_D^T,$$

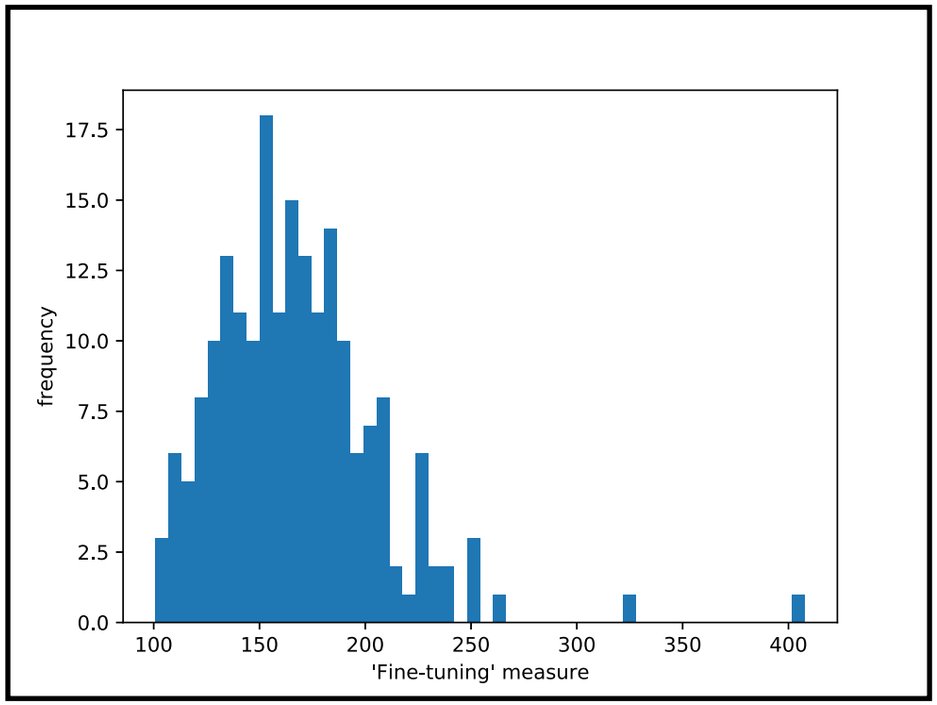
$$g\left(M_i\right) \equiv M_i \left(\frac{\log\left(\frac{M_i^2}{m_H^2}\right)}{\frac{M_i^2}{m_H^2} - 1} + 3 \frac{\log\left(\frac{M_i^2}{m_Z^2}\right)}{\frac{M_i^2}{m_Z^2} - 1} \right),$$

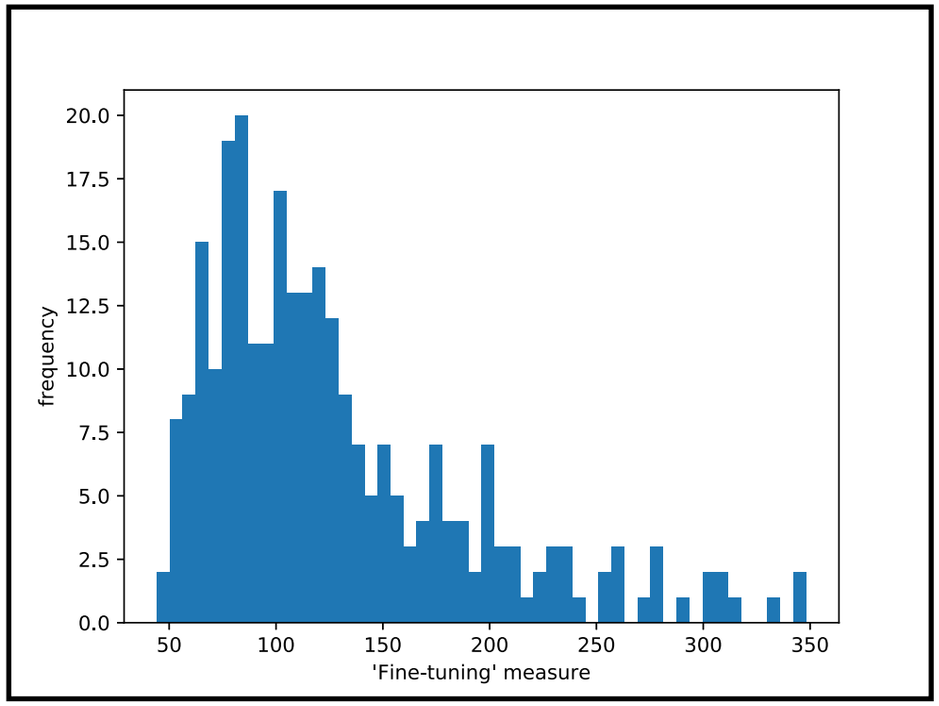
$$f(M) \equiv M^{-1} - \frac{M}{32\pi^2 v^2} \left(\frac{\log\left(\frac{M^2}{m_H^2}\right)}{\frac{M^2}{m_H^2} - 1} + 3 \frac{\log\left(\frac{M^2}{m_Z^2}\right)}{\frac{M^2}{m_Z^2} - 1} \right) = \text{diag}\left(\frac{1}{M_1}, \frac{1}{M_2}, \frac{1}{M_3}\right) - \frac{1}{32\pi^2 v^2} \text{diag}\left(g\left(M_1\right), g\left(M_2\right), g\right.$$

Fine Tuning

$$\text{F.T.} \equiv \frac{\sum_{i=1}^{3} \text{SVD}[m^{\text{1-loop}}]_{\text{i}}}{\sum_{i=1}^{3} \text{SVD}[m_\nu]_{\text{i}}}$$







CP Conditions

CP-conjugate neutrino fields (light and heavy)

$$U_{CP} N_i(x) U_{CP}^\dagger = i\rho_i^N N_i(x') ,$$
$$U_{CP} \nu_i(x) U_{CP}^\dagger = i\rho_i^\nu \nu_i(x') ,$$

CP-invariance of R-matrix follows from the above and CI parametrisation:

$$R_{ij}^* = R_{ij} \rho_i^N \rho_j^\nu , \quad i,j \in \{1,2,3\} .$$

High scale baryon asymmetry from low scale phases

$$n_{B-L}(z_f) = \int_{z_0}^{z_f} e^{-\int_{z'}^{z_f} W_1(z'')dz''} \left(\mathrm{Tr}\epsilon^{(1)} D_1(z')(n_{N_1}(z') - n_{N_1}^{eq}(z')) + W_1(z')\lambda(z') \right) dz',$$

Analytic solution

$$\lambda(z) \equiv 2 \int_{z_0}^{z} dz' \Re \left[C_{1\tau^\perp} C_{1\tau}^* \frac{\Im(\Lambda_\tau)}{Hz'} n_{\tau\tau^\perp}(z') \right].$$

For CP-conserving R-matrix: $\mathrm{Tr}\epsilon^{(1)} = 0$

$$n_{B-L}(z_f) = \int_{z_0}^{z_f} e^{-\int_{z'}^{z_f} W_1(z'')dz''} W_1(z')\lambda(z')dz'.$$

solution isn't vanishing due to off-diagonal lepton asymmetry! If you didn't solve the density matrix equations you would miss this piece!