Leptogenesis and Low-Energy Leptonic CP Violation

Jessica Turner

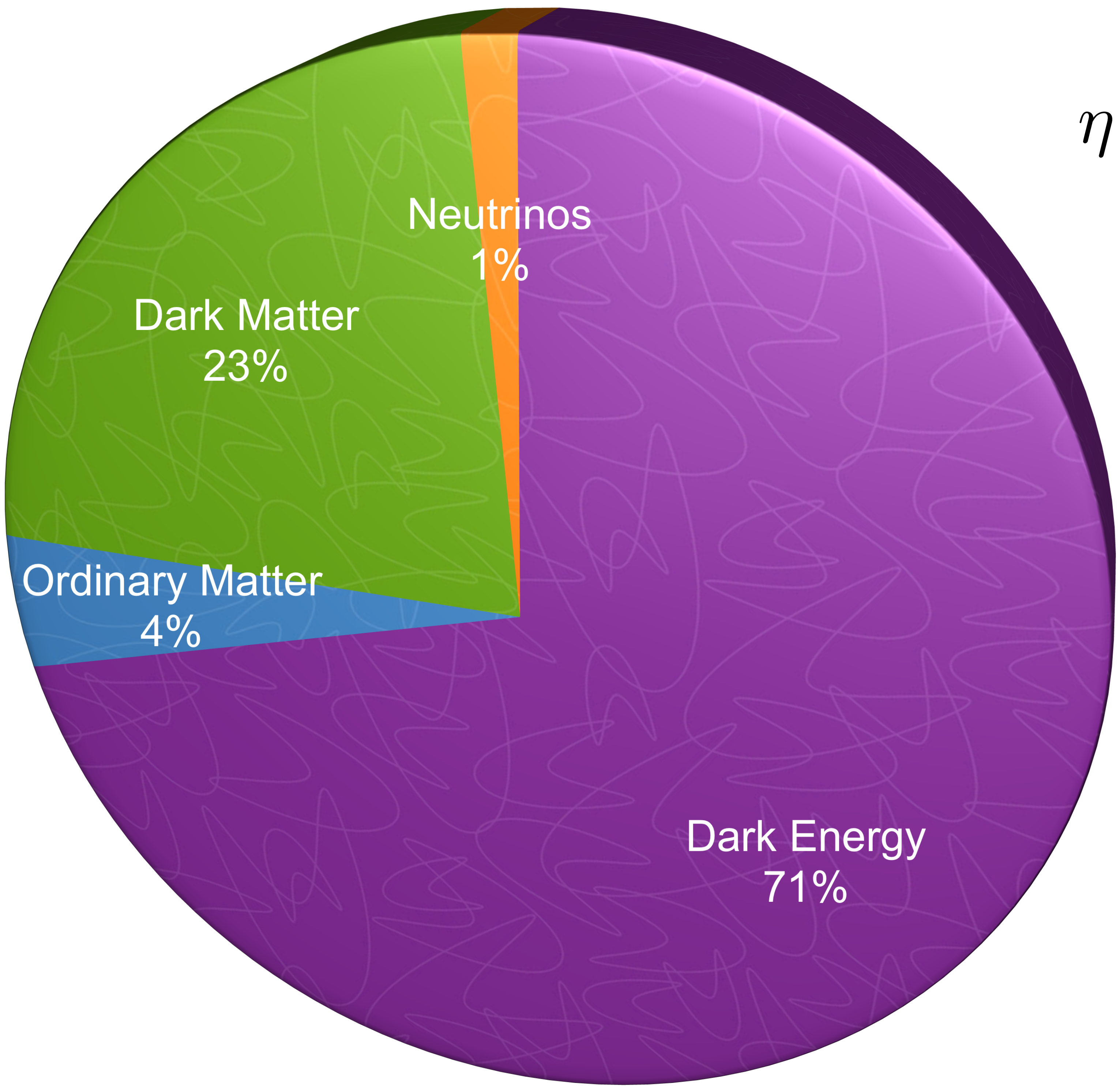
Prospects of Neutrino Physics 2019

Kavli IPMU

Work in collaboration with K. Moffat, S. Pascoli, S.T. Petcov.

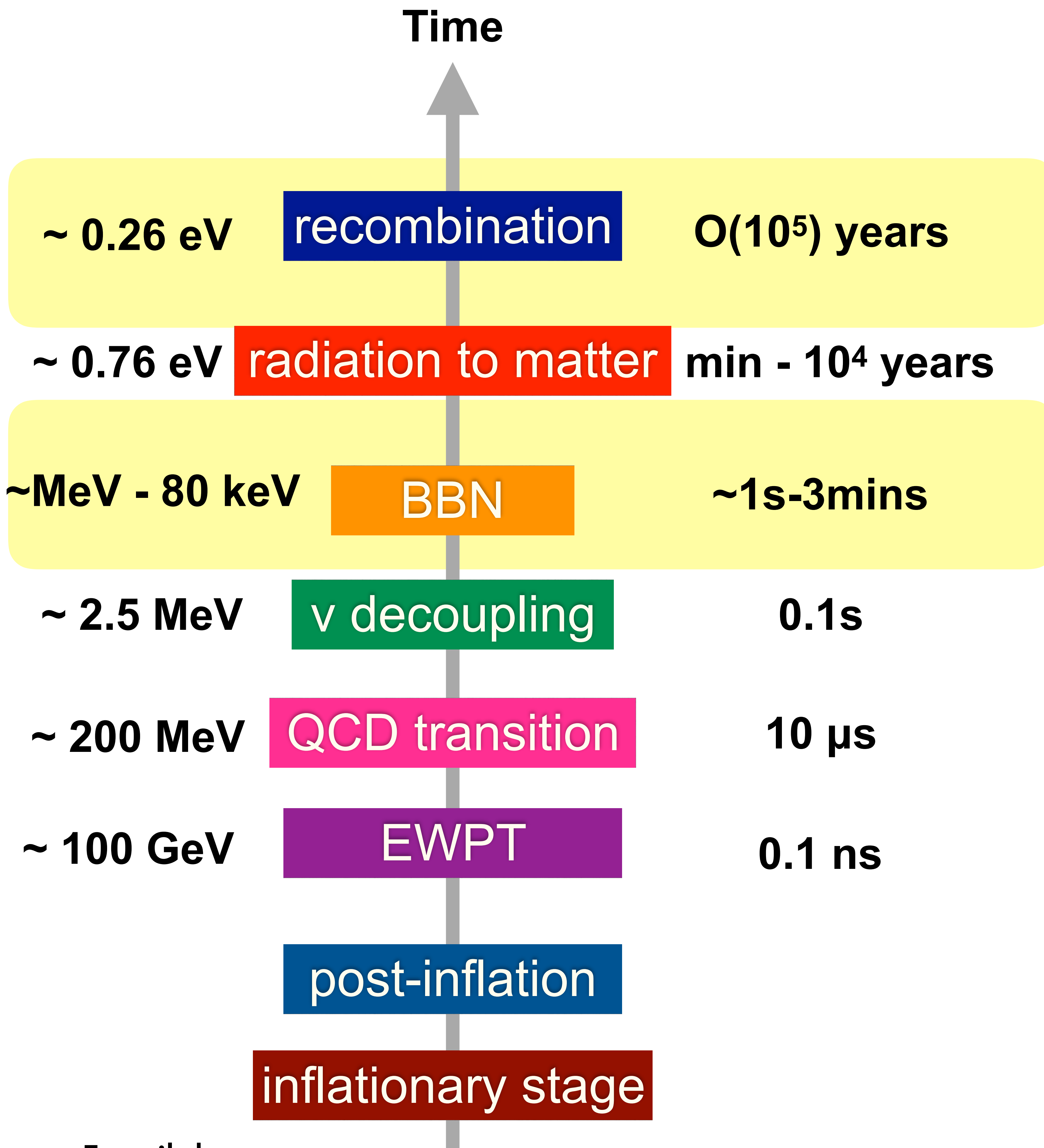
Fermilab

Energy Budget of the Universe



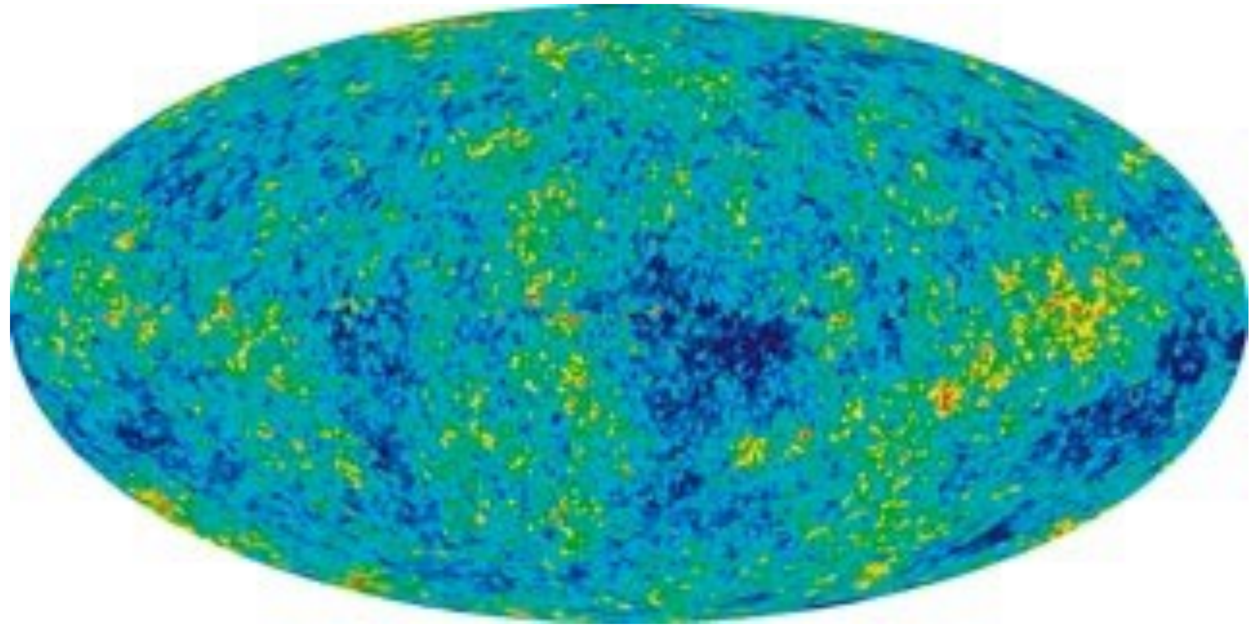
$$\eta = \frac{n_B - n_{\overline{B}}}{\eta_\gamma}$$

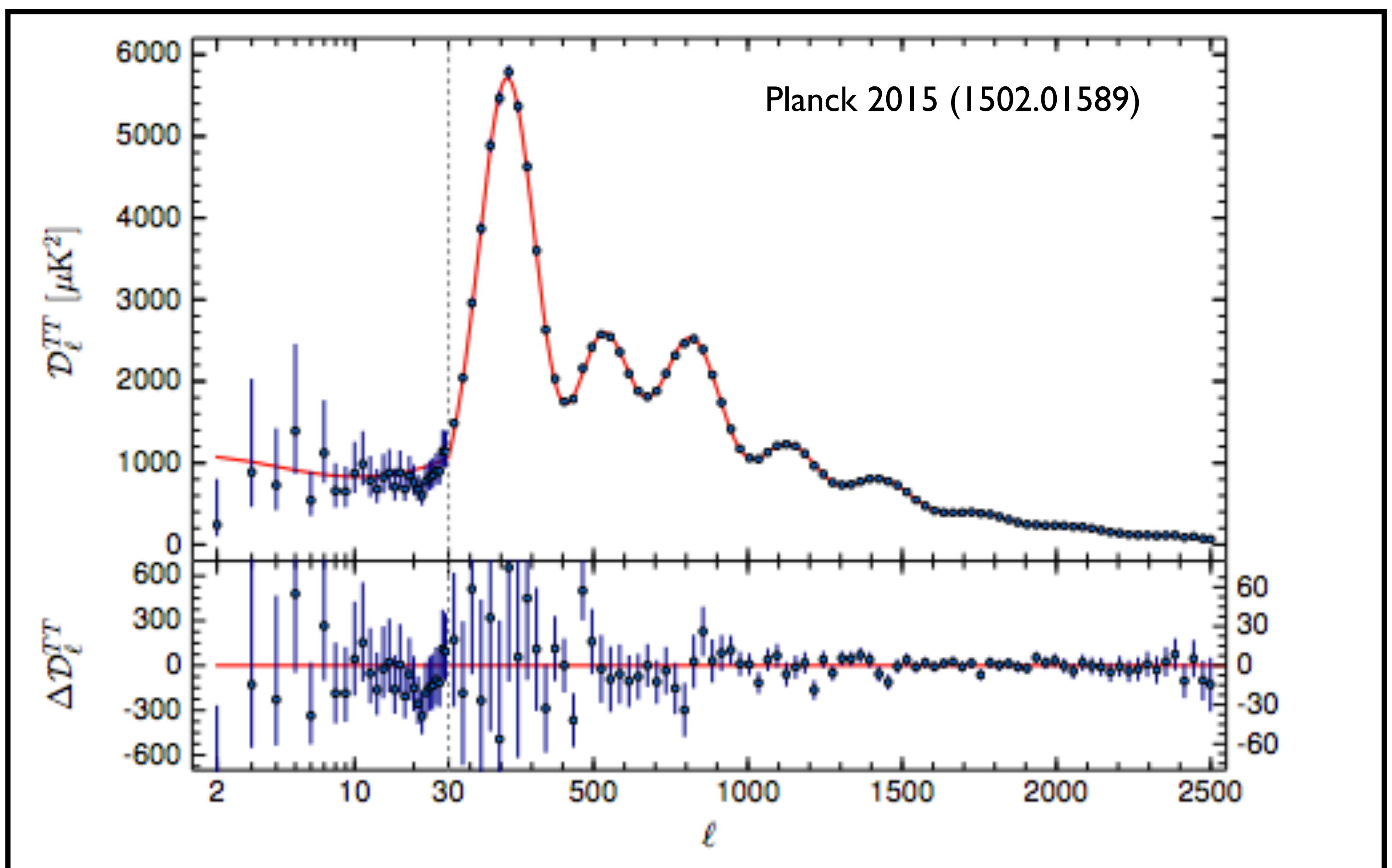
Measuring the Baryon Asymmetry



Cosmic Microwave Background

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

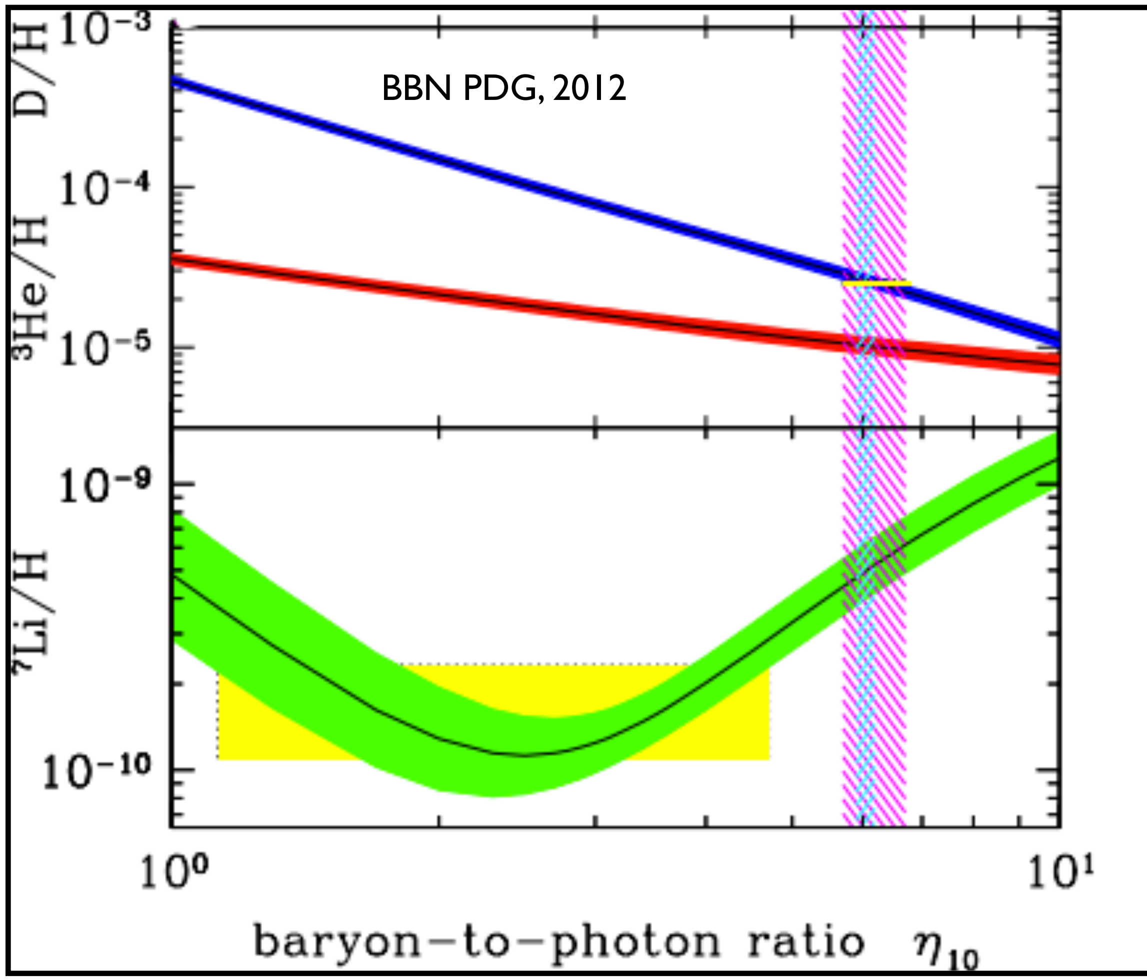




$$\eta_{\mathrm{CMB}} = (6.23 \pm 0.17) \times 10^{-10}$$

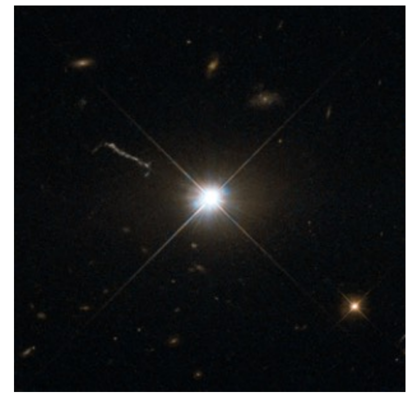
Big Bang Nucleosynthesis

$T \sim 1.0\,\mathrm{MeV}$

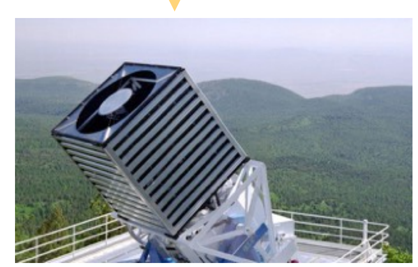


$$\eta_{\mathrm{BBN}} = (6.08 \pm 0.06) \times 10^{-10}$$

bright quasar 3C 273: Hubble Space Telescope



Dust Cloud



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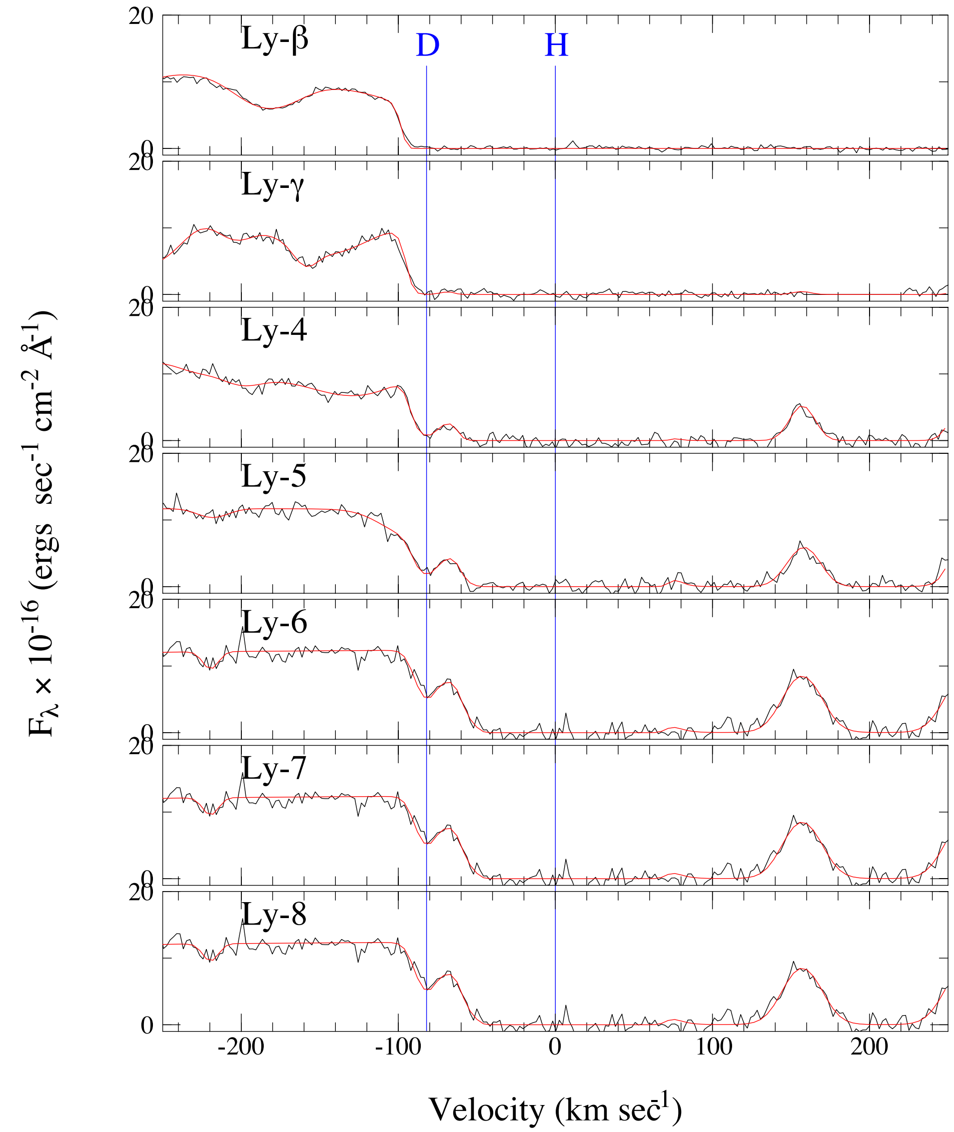
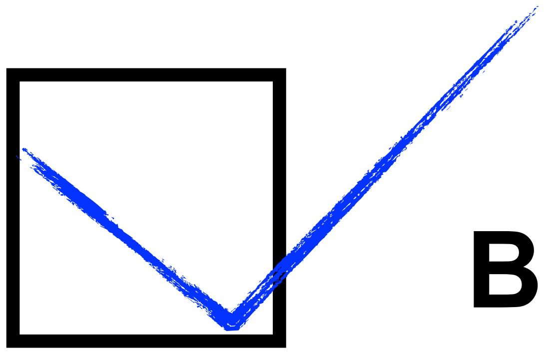


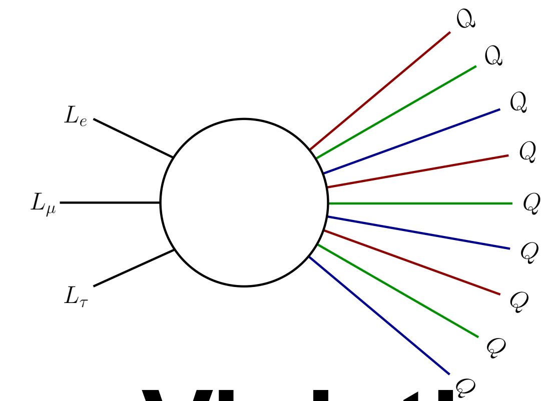
Sakharov Conditions*

*Only necessary if QFT is CPT conserving
Dolgov, Zeldovich & Cohen, Kaplan

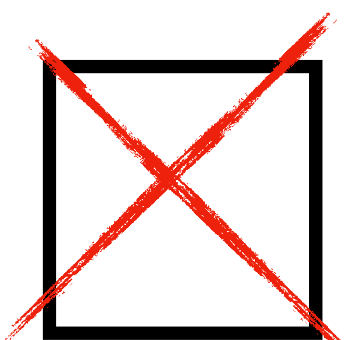


Kuzmin, Rubakov and Shaposhnikov

B+L violating sphalerons →

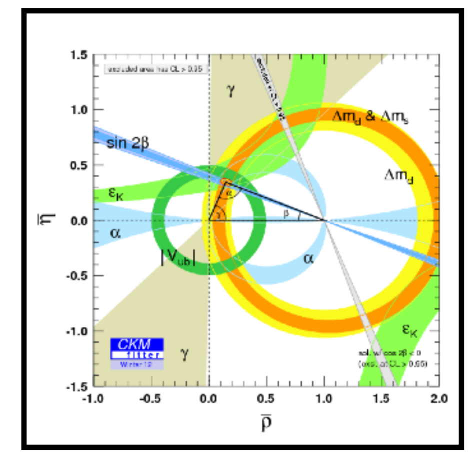


Baryon and Lepton Number Violation

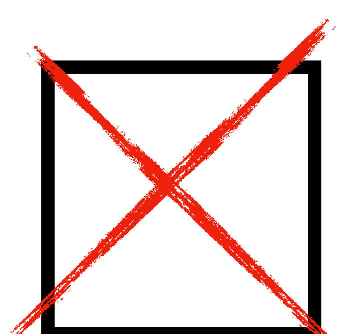


Gavela, Hernandez, Orloff, Pene; Huet and Sather

CPV phase of CKM →

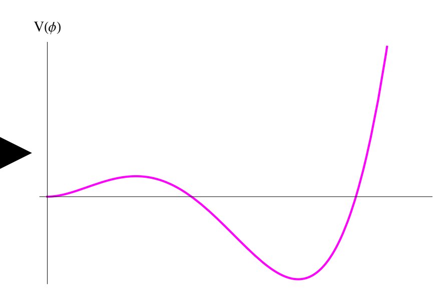


Insufficient CP Violation



Kajantie, Laine, Rummukainen, Shaposhnikov

SM EWPT crossover not 1st order PT →

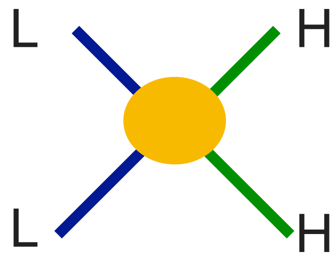


No departure from thermal equilibrium

Nice overview by Takehiko Asaka yesterday

Seesaw Mechanism

- Most theories of leptogenesis assume neutrinos are Majorana (of course there are exceptions*)

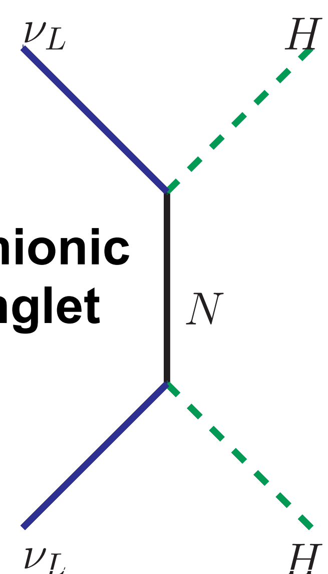


$$-\mathcal{L}_{D=5} = \lambda \frac{L.H L.H}{M} = \frac{\lambda v^2}{M} \nu_L^T C^\dagger \nu_L$$

type-I SS

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

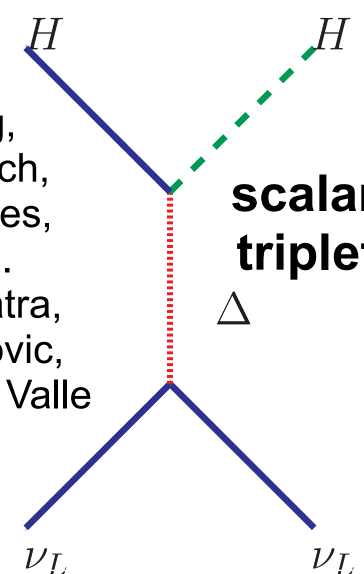
fermionic singlet



type-II SS

Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

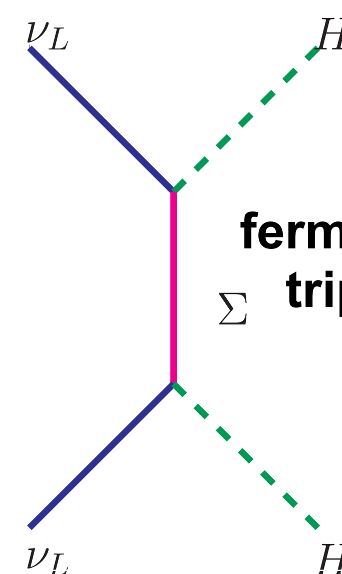
scalar triplet



type-III SS

Ma, Roy, Senjanovic, Hambye

fermionic triplet



$$\mathcal{L} = -Y_\nu \overline{N} L H - \frac{1}{2} \overline{N^C} M_N N$$

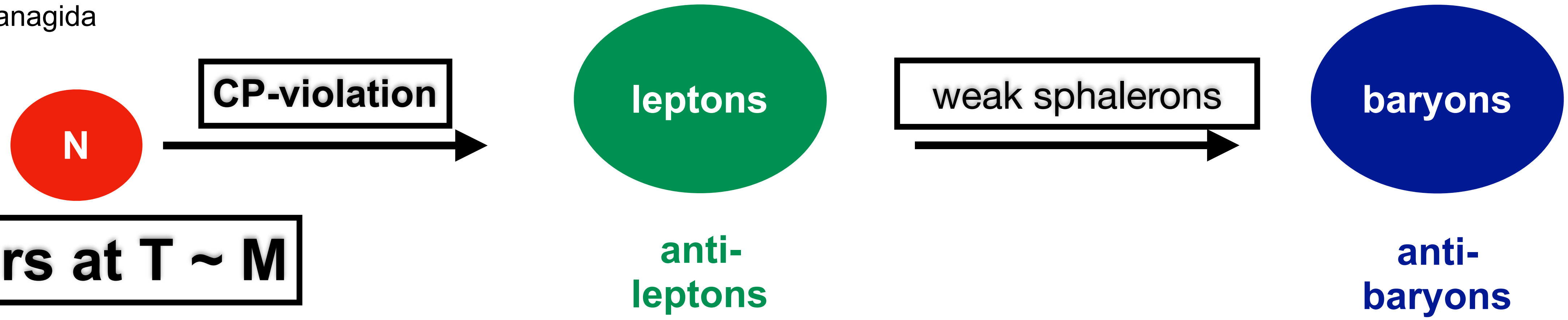
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v^2}{M_N} \sim 0.1\,\text{eV}$$

*Dirac Leptogenesis, Dick, Lindner, Wright, Ratz & Murayama, Pierce

Mechanism

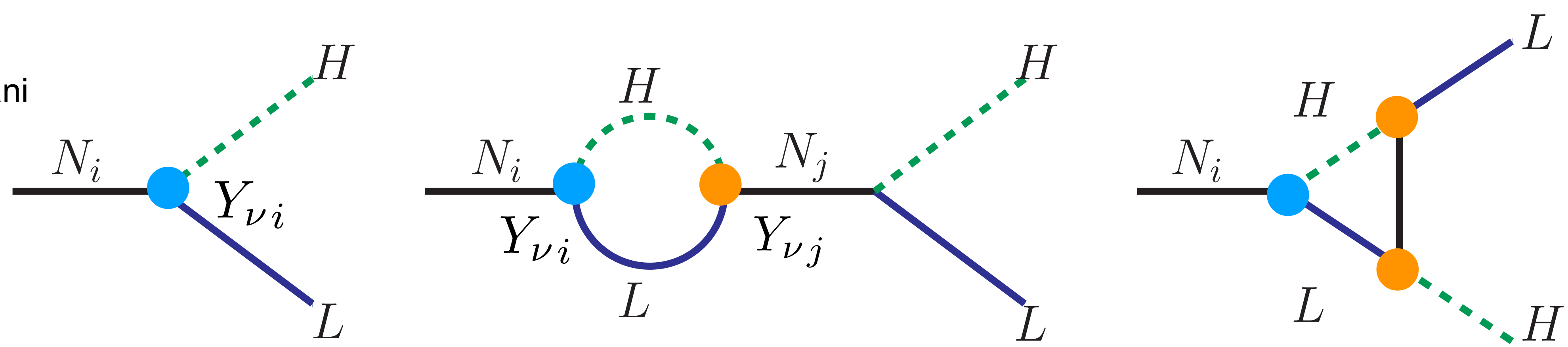
Fukugida, Yanagida



occurs at T ~ M

Decay asymmetry from interference between tree and loop level diagrams

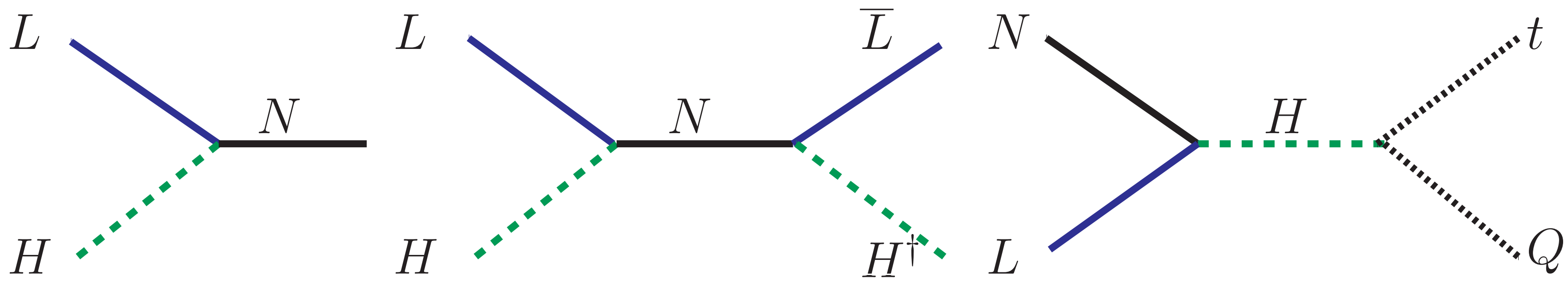
Covi, Roulet, Vissani



Decay Asymmetry

$$\epsilon = \frac{\Gamma\left(N_1 \to HL\right) - \Gamma\left(N_1 \to H^\dagger \overline{L}\right)}{\Gamma\left(N_1 \to HL\right) + \Gamma\left(N_1 \to H^\dagger \overline{L}\right)}$$

Washout and Scattering processes

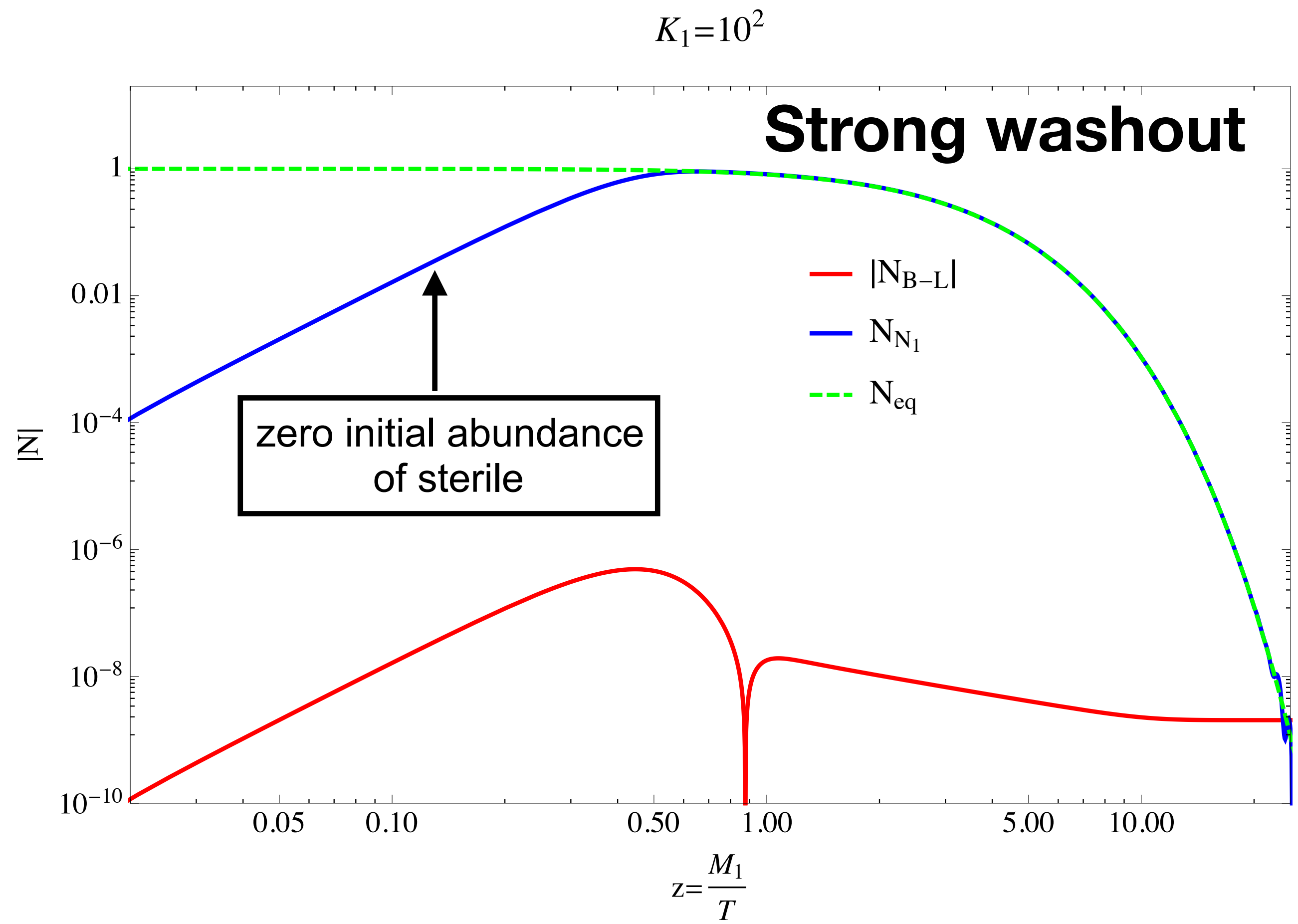


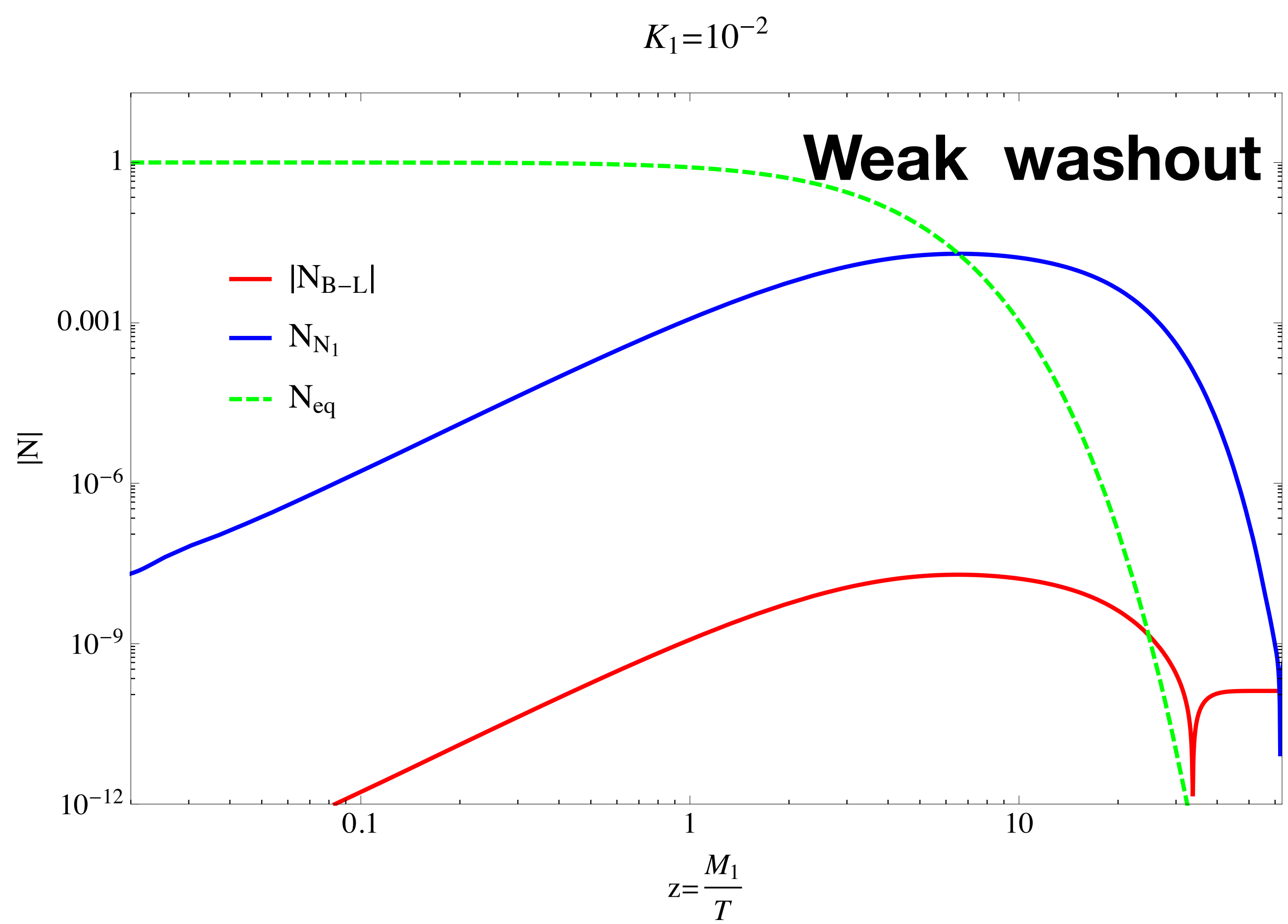
inverse Decays ΔL=2 ΔL=1

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

$$\frac{dN_{B-L}}{dz} = \epsilon_1 D_1(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W_1 N_{B-L}$$

$$\Gamma_i \equiv \Gamma_i \left(N_i \to \phi^\dagger l_i\right) \qquad D_i \equiv \frac{\Gamma_i + \overline{\Gamma}_i}{Hz}. \qquad W_i \equiv \frac{1}{2}\frac{\Gamma_i^{\mathrm{ID}} + \overline{\Gamma}_i^{\mathrm{ID}}}{Hz}.$$


$K_1=10^2$
Strong washout
zero initial abundance of sterile
$|N_{B-L}|$
N_{N_1}
N_{eq}
|N|
$z=\frac{M_1}{T}$


$K_1=10^{-2}$
Weak washout
$|N_{B-L}|$
N_{N_1}
N_{eq}
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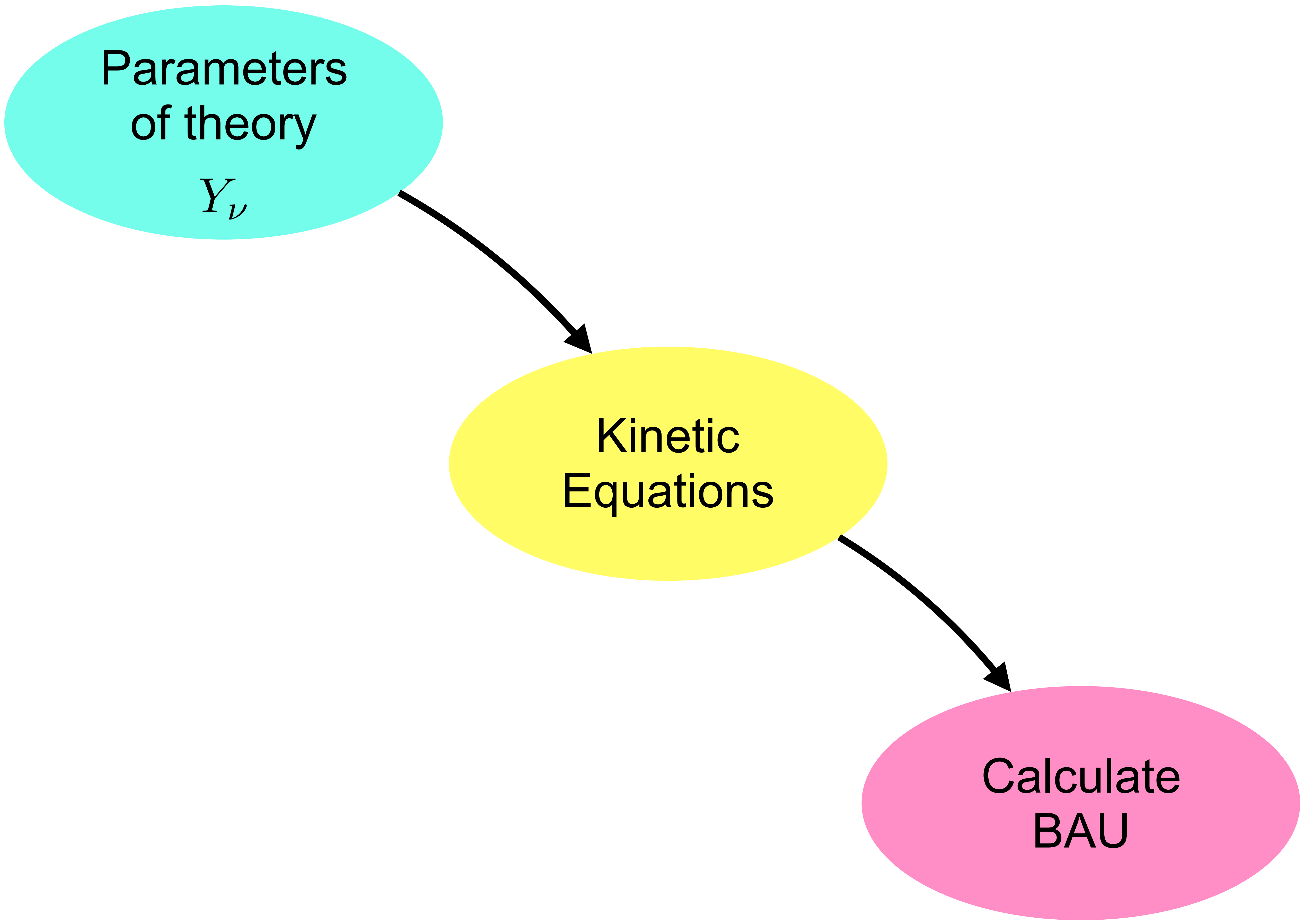
$z=\frac{M_1}{T}$


Parameters of theory
Y_ν
Kinetic Equations
Calculate BAU

Model Parameter Space

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

Model Parameter Space

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

Neutrino Oscillation constraints

3 mixing angles
3 phases

sum of neutrino masses and neutrino oscillation

3 parameters

Complex, orthogonal matrix

6 real parameters

Unconstrained

3 masses
ensure at least mild hierarchy

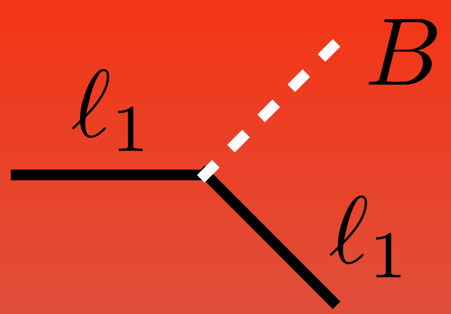
$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{\omega_i} = \cos \omega_i, \; s_{\omega_i} = \sin \omega_i, \; \omega_i = x_i + i y_i$$

η_B is a function of up to 18 parameters

Flavour Effects in Kinetic Equations

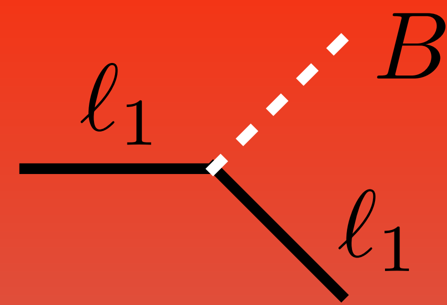
$T \gtrsim 10^{13}\,\mathrm{GeV}$



$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle \quad \Gamma_\ell < H$$

Flavour Effects in Kinetic Equations

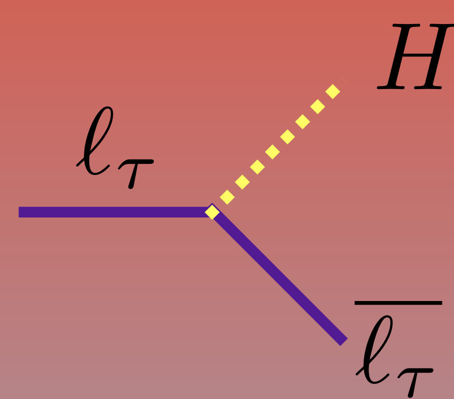
$T \gtrsim 10^{13}\,\mathrm{GeV}$

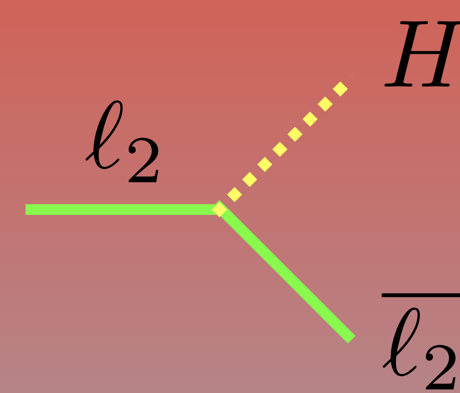


$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle \quad \Gamma_\ell < H$$

SM Yukawa coupling

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

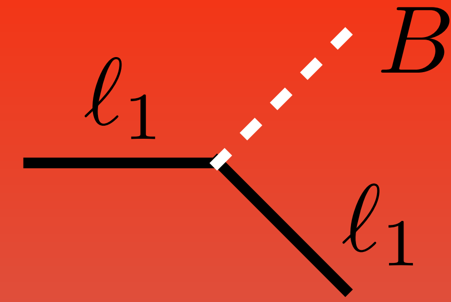




$$\Gamma_\tau \propto h_\tau^2 T > H$$

Flavour Effects in Kinetic Equations

$T \gtrsim 10^{13}\,\mathrm{GeV}$



$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle \quad \Gamma_\ell < H$$

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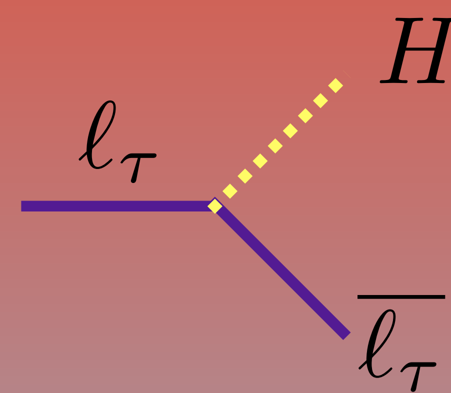
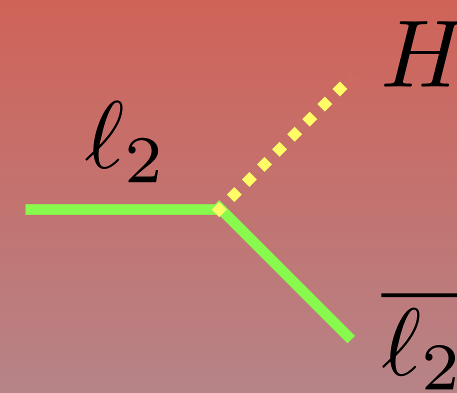
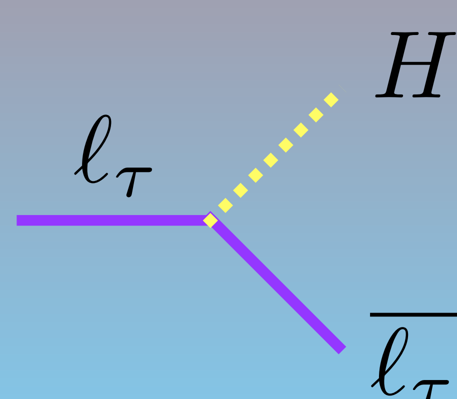
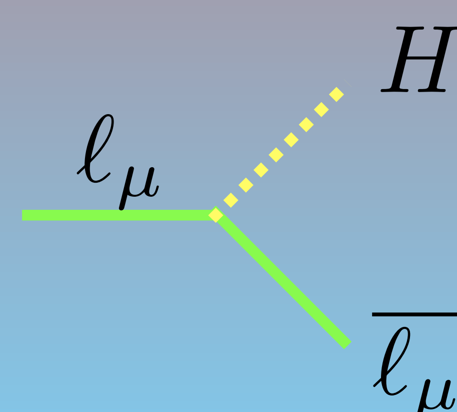


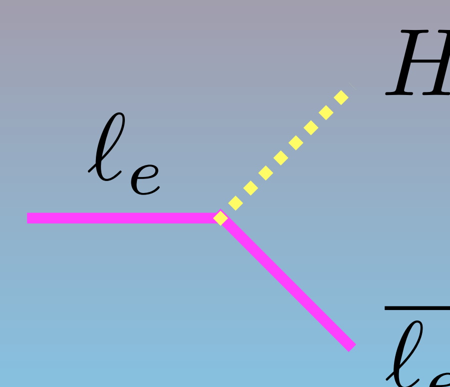


$$\Gamma_\tau \propto h_\tau^2 T > H$$

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



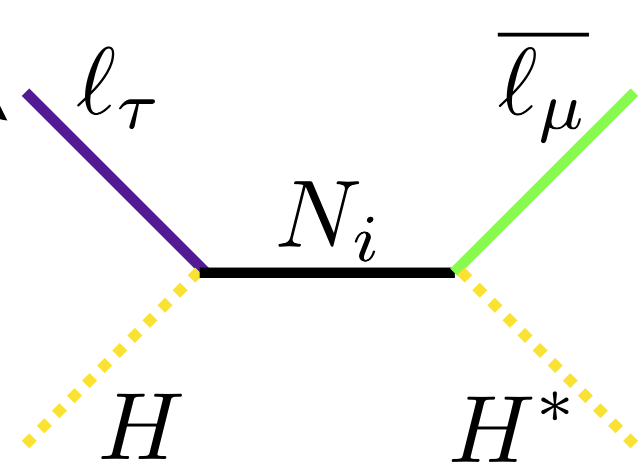


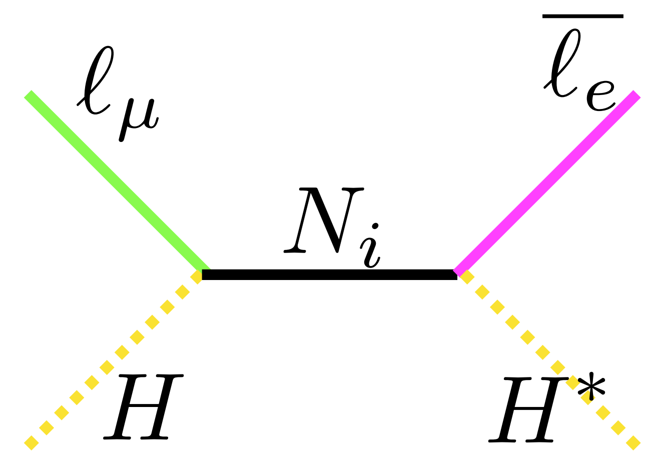


$$\Gamma_\mu \propto h_\mu^2 T > H$$

Why bother with flavour effects?

represent off-diagonal components of density matrix equations





Similar to inclusion of spectator effects, we gain protection for the lepton asymmetry

T < 10^9 GeV, three flavours become distinct

Density matrix equation which account for lepton flavour oscillation (pictured above) are needed.

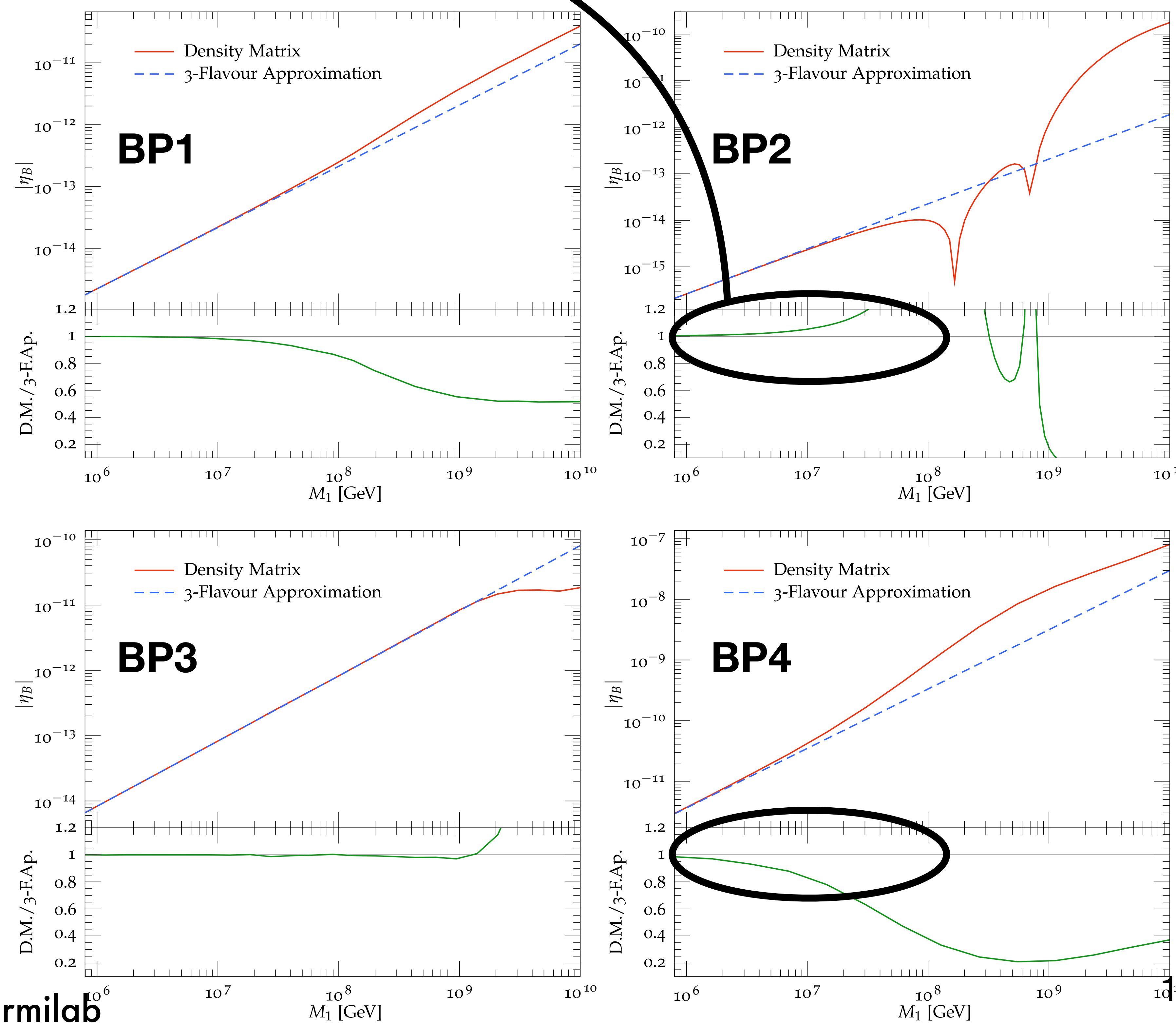
In 1804.05066 we* demonstrated non-resonant thermal leptogenesis can be lowered to T~10^6 GeV

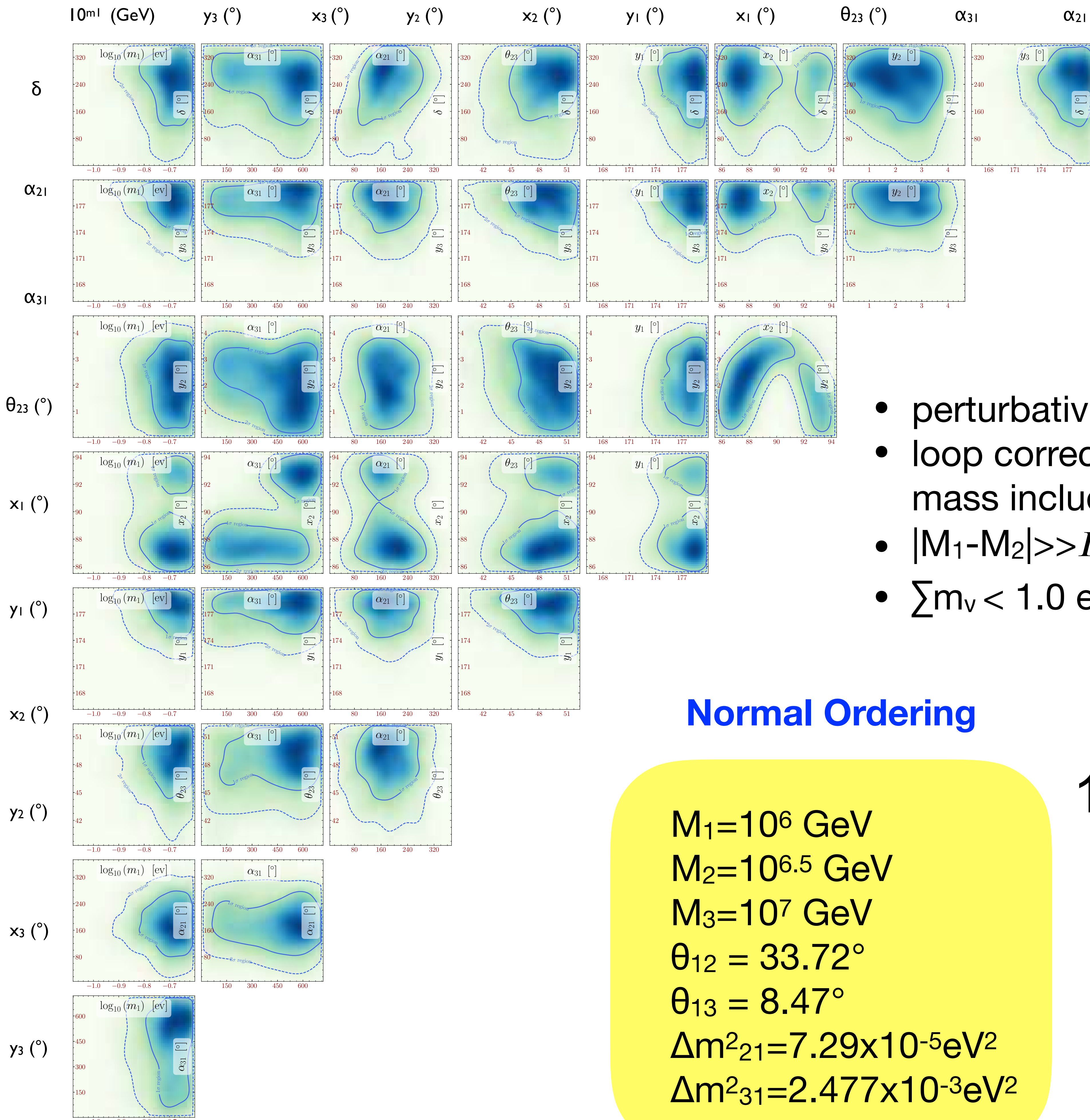
*K. Moffat, S. Pascoli, S.T. Petcov, H. Schulz, JT

1804.05066

	$\delta(^\circ)$	$\alpha_{21}(^\circ)$	$\alpha_{31}(^\circ)$	$x_1(^\circ)$	$y_1(^\circ)$	$x_2(^\circ)$	$y_2(^\circ)$	$x_3(^\circ)$	$y_3(^\circ)$
BP1	180	0	0	100	45	150	25	45	35
BP2	270	90	180	10	60	55	25	70	-15
BP3	330	40	220	0	100	-1	10	1	-75
BP4	320	450	450	15	180	-90	2	144	-175

Inclusion of flavour effects can result in ~5-10% effect for M1~10^6-10^7 GeV





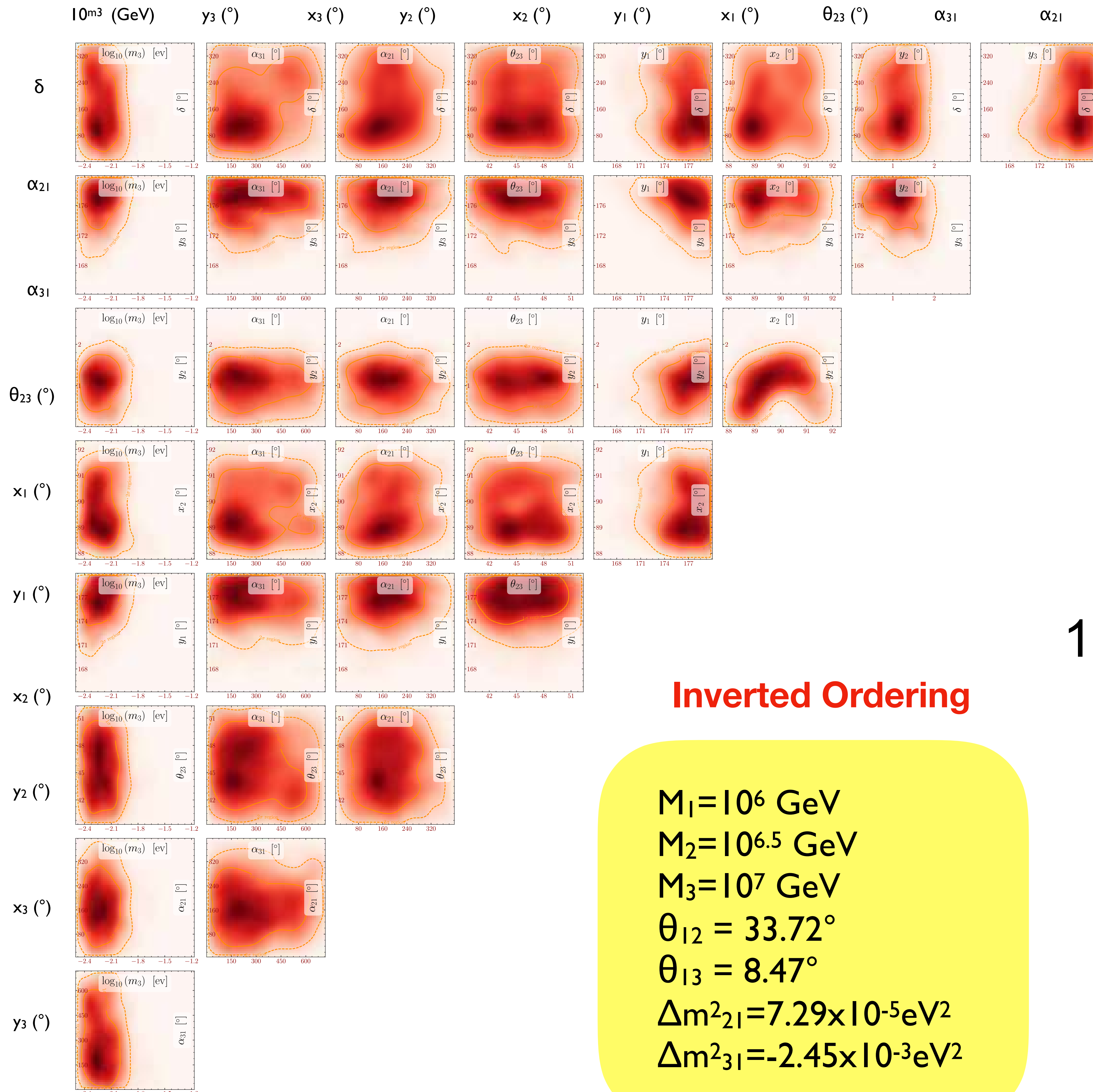
Applied nested sampling algorithm: MultiNest

- perturbativity
- loop corrections to neutrino mass included
- $|M_1 - M_2| >> \Gamma_1$
- $\sum m_\nu < 1.0$ eV

Normal Ordering

1804.05066

$M_1 = 10^6$ GeV
$M_2 = 10^{6.5}$ GeV
$M_3 = 10^7$ GeV
$\theta_{12} = 33.72°$
$\theta_{13} = 8.47°$
$\Delta m^2_{21} = 7.29 \times 10^{-5} eV^2$
$\Delta m^2_{31} = 2.477 \times 10^{-3} eV^2$



1804.05066

Inverted Ordering

$M_1 = 10^6$ GeV
$M_2 = 10^{6.5}$ GeV
$M_3 = 10^7$ GeV
$\theta_{12} = 33.72°$
$\theta_{13} = 8.47°$
$\Delta m^2_{21} = 7.29 \times 10^{-5} eV^2$
$\Delta m^2_{31} = -2.45 \times 10^{-3} eV^2$

Leptogenesis from Leptonic CP Violation

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*.

From CP invariance conditions on N_i implies entries of R-matrix are **purely real** or **imaginary**.

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

$$\epsilon_1 = 0$$

*models that include 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])

Leptogenesis from Leptonic CP Violation

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

In the high energy limit (T > 5 x 10^{12} GeV) low energy phase could not be connected with leptogenesis since:

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to \ell H) - \Gamma(N_1 \to H^\dagger \overline{L})}{\Gamma(N_1 \to \ell H) + \Gamma(N_1 \to H^\dagger \overline{L})}$$

$$\propto \sum_j \mathrm{Im}(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

zero if R real or purely imaginary

In the low(er) energy limit (T < 10^{10} GeV) low energy phase could not be connected with leptogenesis because decay asymmetry is too small.

$$\epsilon \propto M_1$$

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

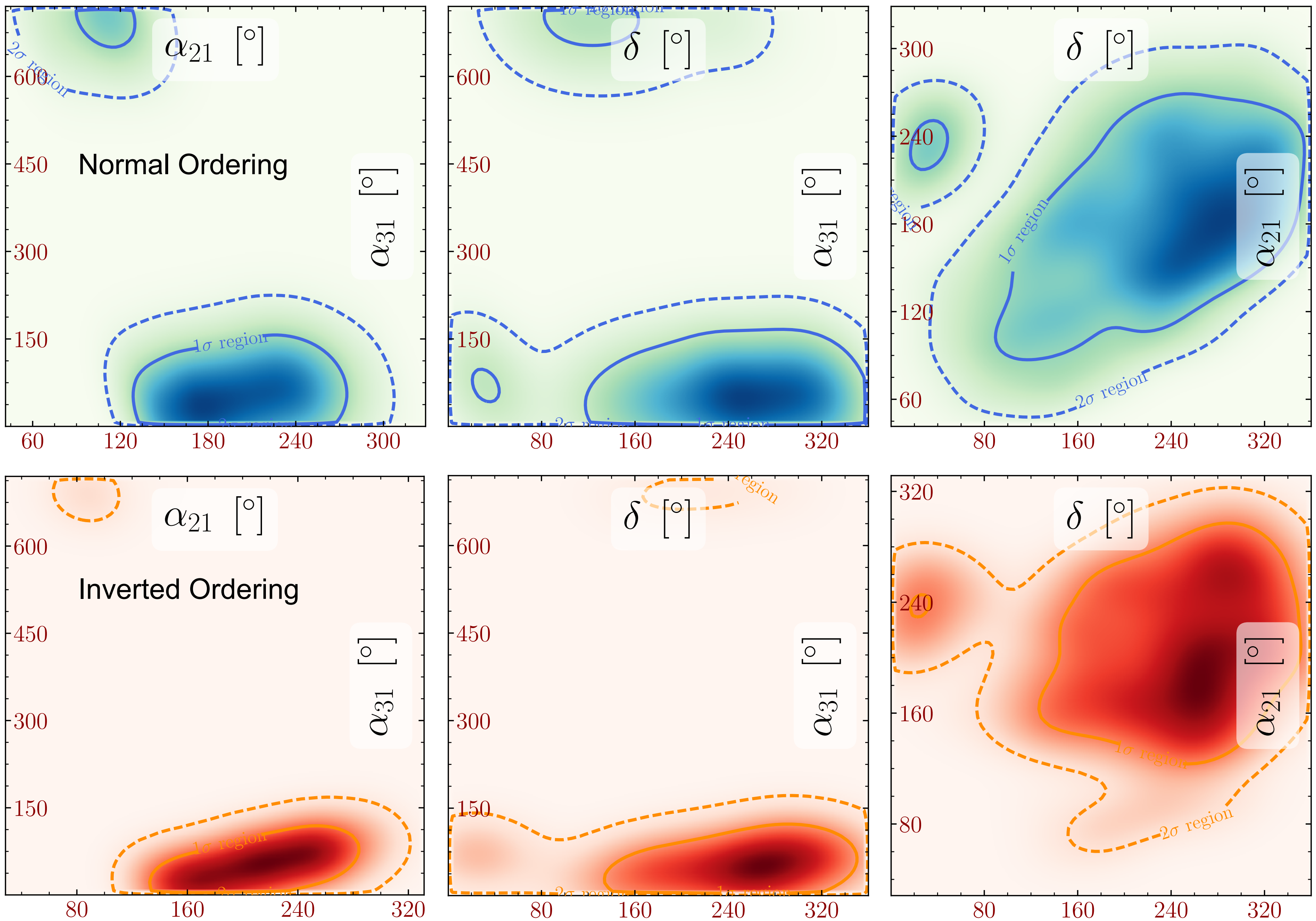
* 0809.3437

Leptogenesis from Leptonic CP Violation

$T<10^9$ GeV

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

* Can be lowered to m1=0.05 eV



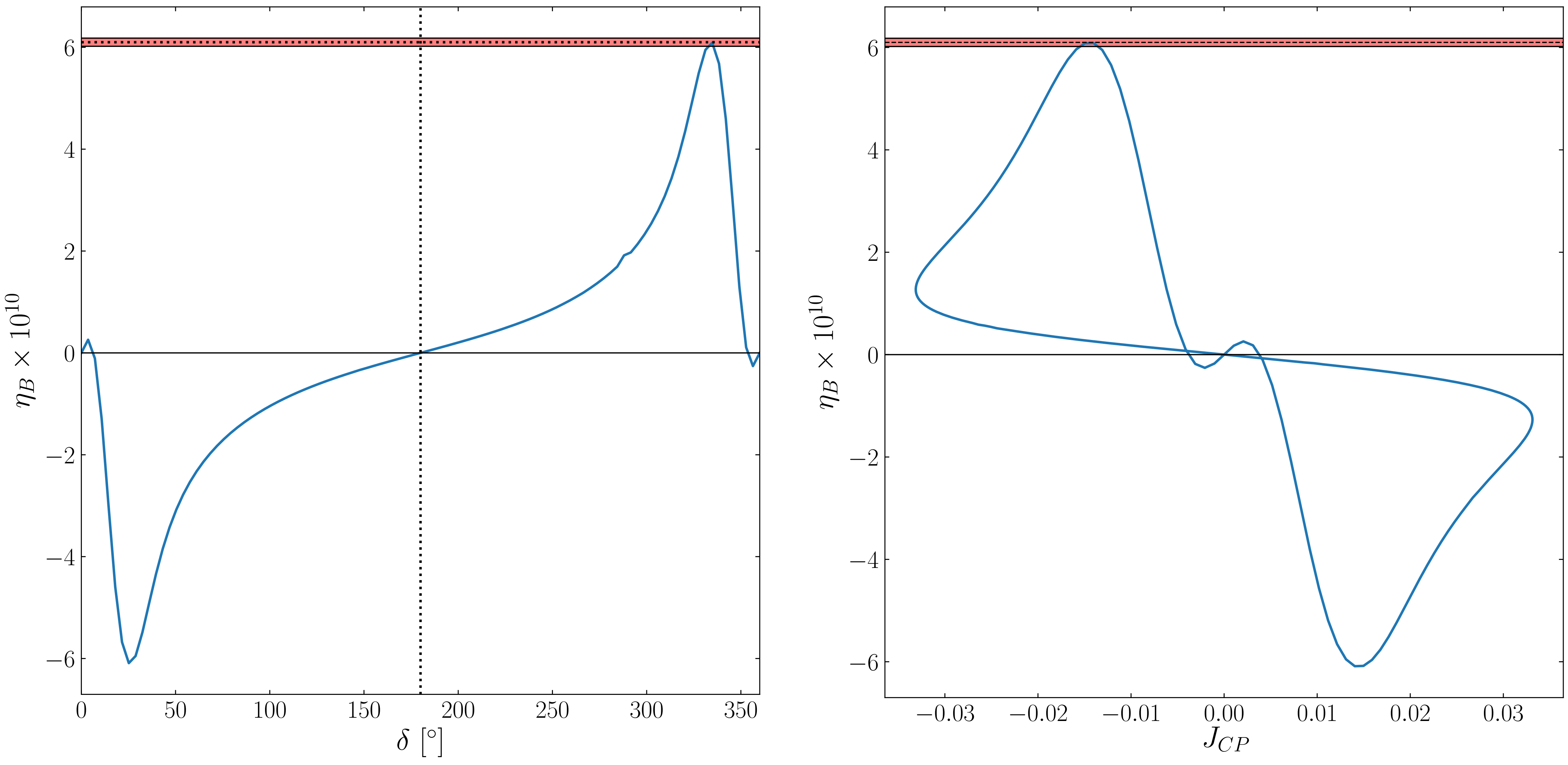
R matrix CP conserving and low energy observable fixed at best fit values NuFit.

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

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

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

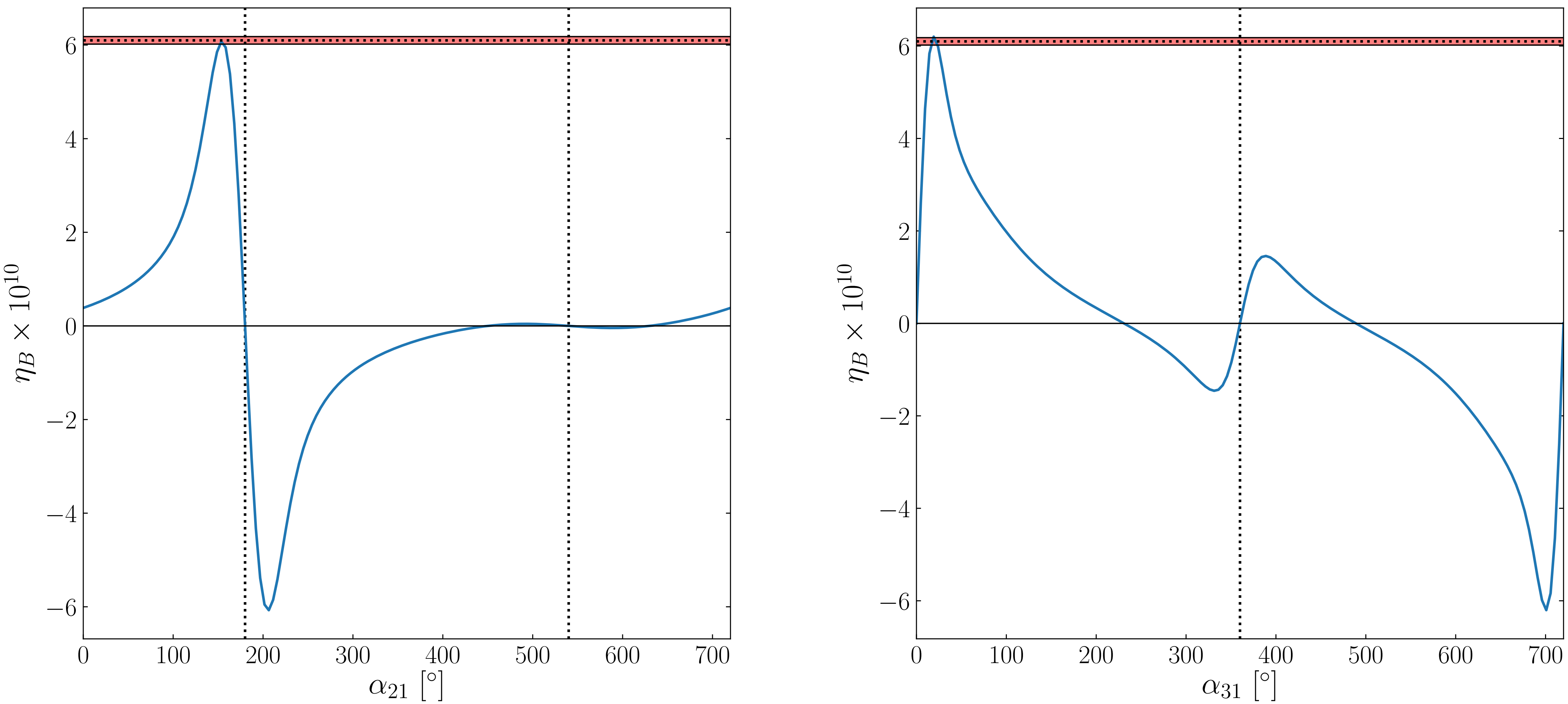


$$M_1 = 7.0 \times 10^8\,\mathrm{GeV},\; M_2 = 3.5 M_1,\; M_3 = 3.5 M_2$$

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 CPV



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

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

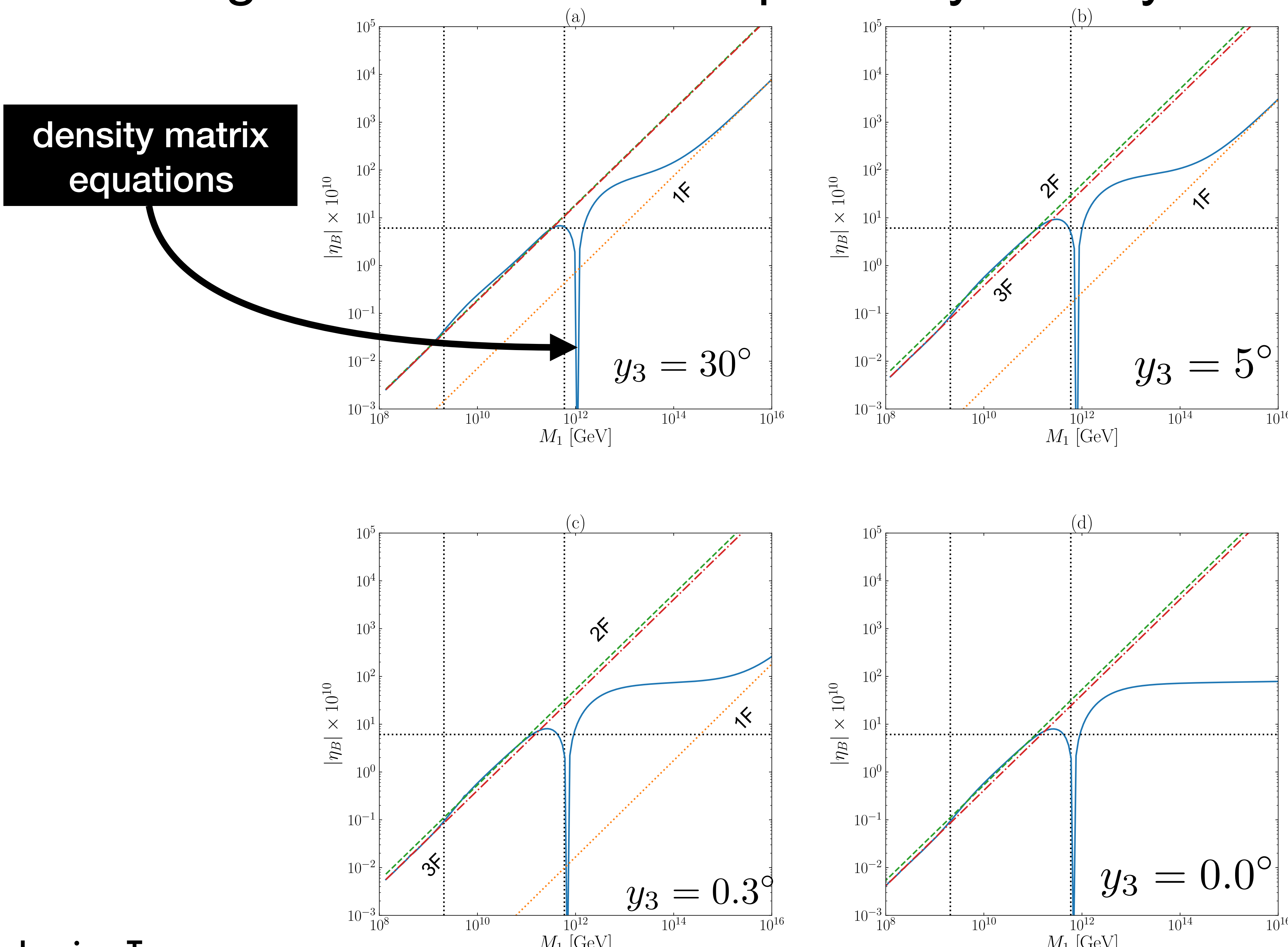
Mini summary: non-resonant thermal leptogenesis can explain BAU using only low scale phases at $M_1 \sim 10^6$ GeV

Leptogenesis from Leptonic CP Violation

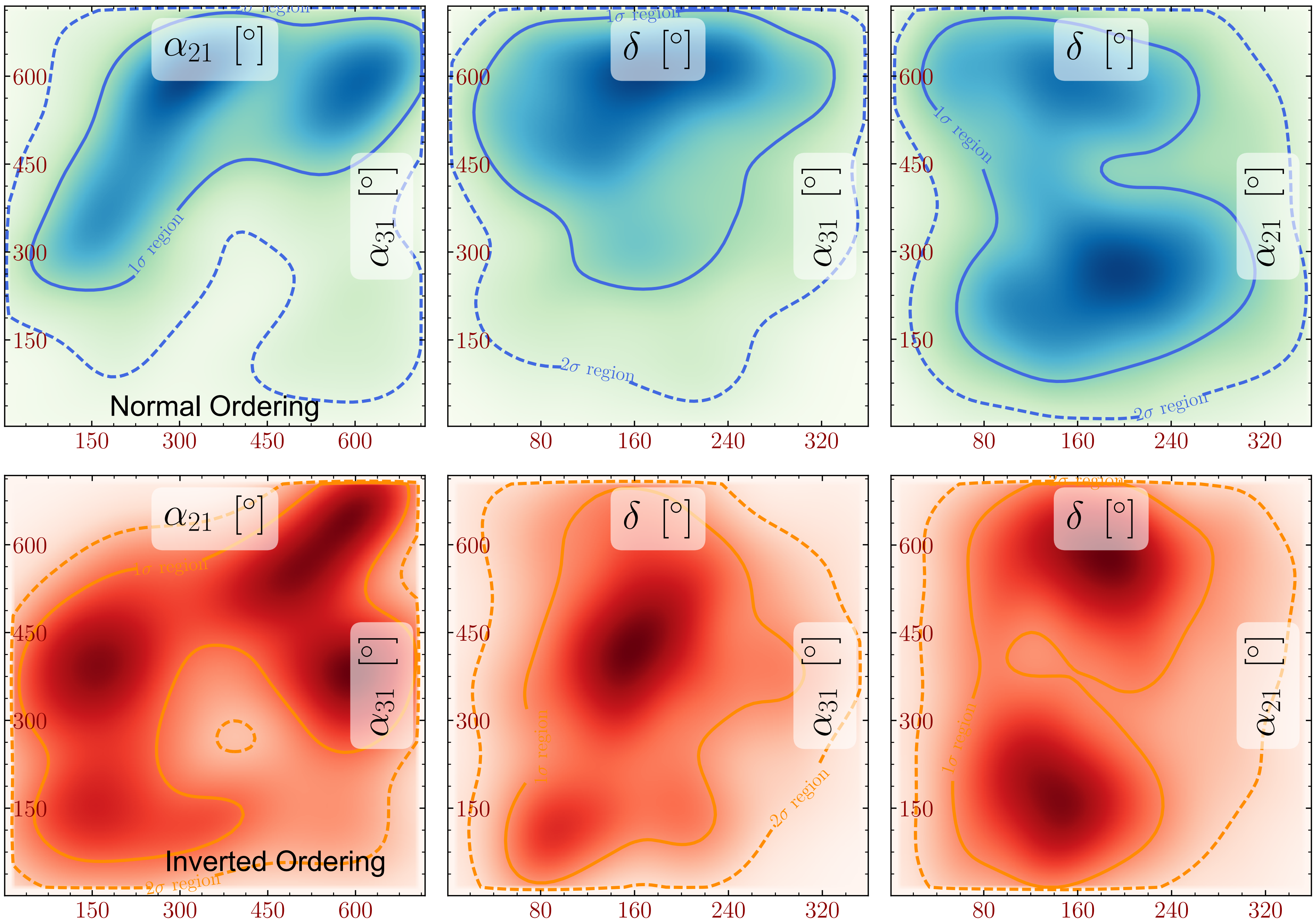
$T > 10^{12}$ GeV

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.

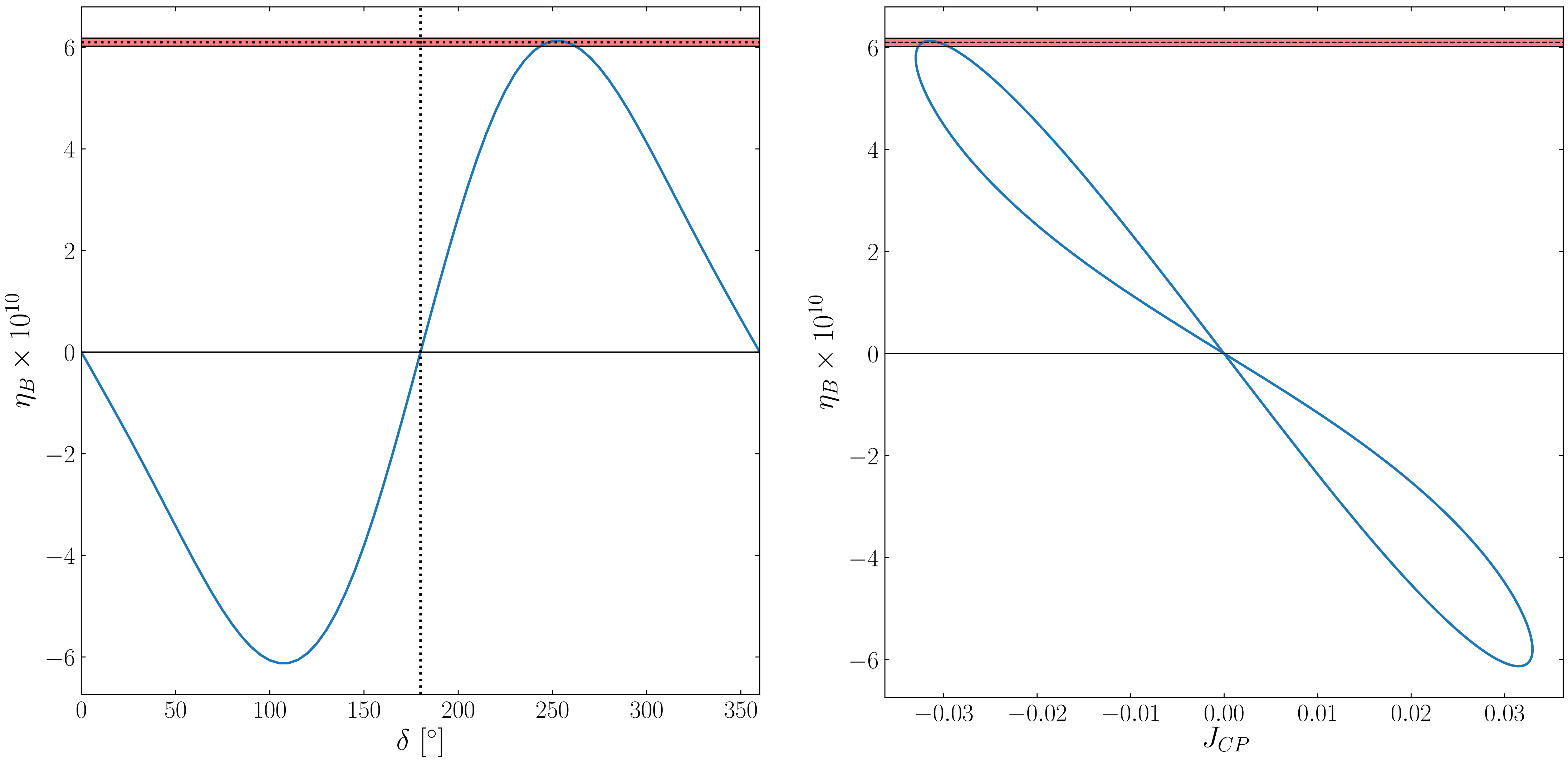


Leptogenesis from Leptonic CP Violation



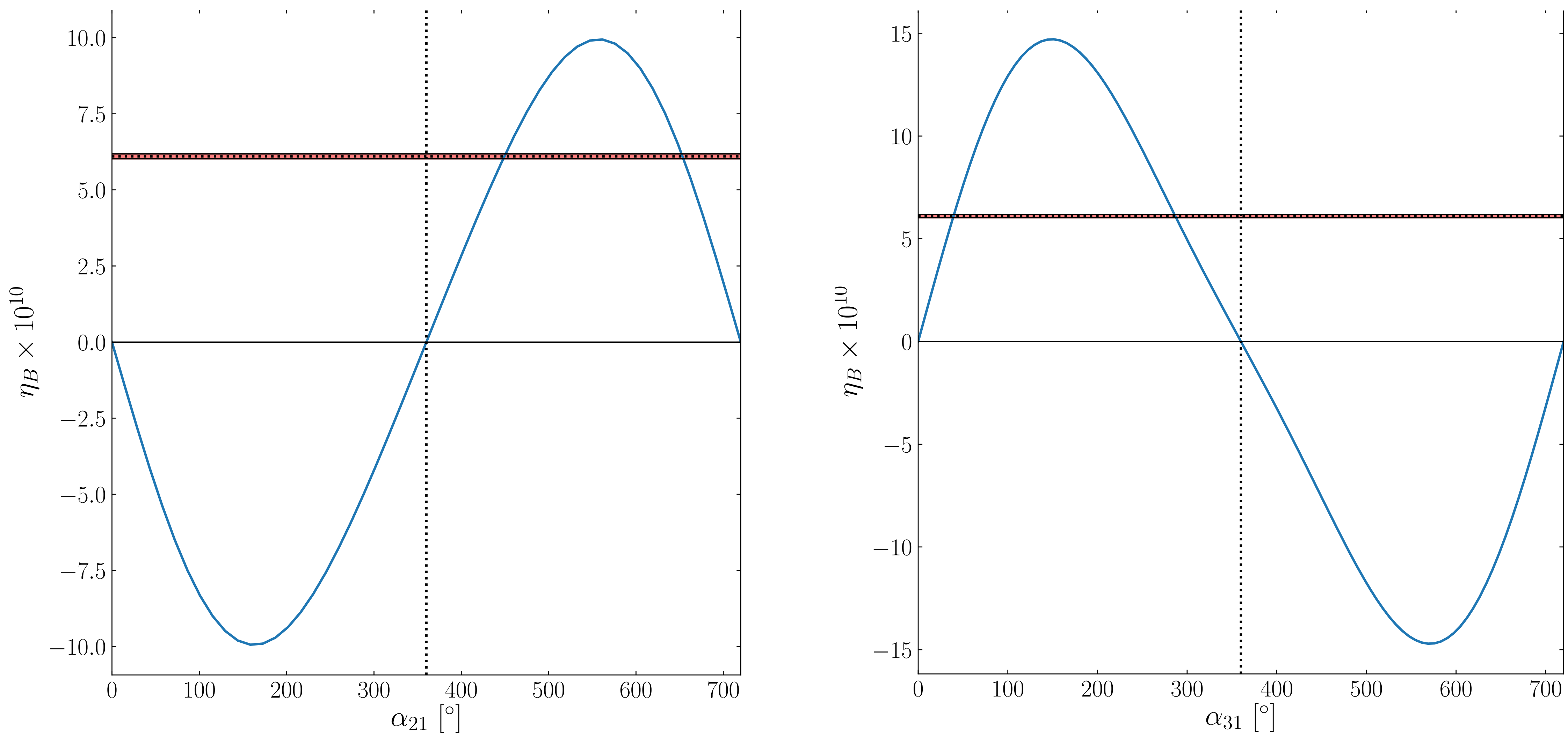
$$M_1 = 10^{13}\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

Pure Dirac CPV



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

Pure Majorana CPV



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

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."

Back Up Slides

Abada, Ibarra, Simone, Riotto, Garbrecht, Di Bari, Millington

Density Matrix Equations

*We are justified in using “semi-classical” equations rather than first principles derived NE-QFT equations given we are in the strong washout regime

$$\frac{\mathrm{Im}(\Lambda_\tau)}{Hz} = 4.85 \times 10^{-8}\frac{M_{PL}}{M_1}$$
$$\frac{\mathrm{Im}(\Lambda_\mu)}{Hz} = 1.69 \times 10^{-10}\frac{M_{PL}}{M_1}$$

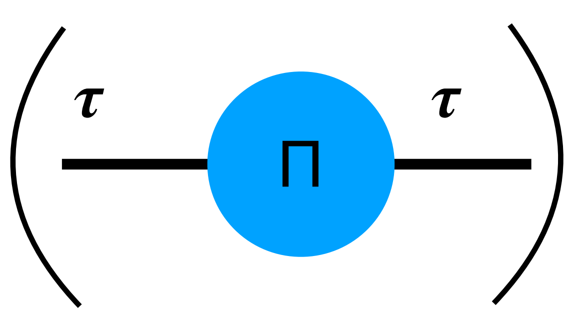
$$N = \begin{pmatrix} N_{\tau\tau} & N_{\tau\mu} & N_{\tau e} \\ N_{\mu\tau} & N_{\mu\mu} & N_{\mu e} \\ N_{e\tau} & N_{e\mu} & N_{ee} \end{pmatrix}$$

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N1} - N_{N_1}^{\mathrm{eq}})$$
$$\frac{dN_{N_2}}{dz} = -D_2(N_{N2} - N_{N_2}^{\mathrm{eq}})$$
$$\frac{dN_{N_3}}{dz} = -D_3(N_{N3} - N_{N_3}^{\mathrm{eq}})$$

$$\begin{aligned}\frac{dN_{\alpha\beta}}{dz} =& \epsilon^{(1)}_{\alpha\beta} D_1(N_{N1} - N_{N_1}^{\mathrm{eq}}) - \frac{1}{2}W_1\left\{P^{0(1)}, N\right\} \\ &+ \epsilon^{(2)}_{\alpha\beta} D_2(N_{N2} - N_{N_2}^{\mathrm{eq}}) - \frac{1}{2}W_2\left\{P^{0(2)}, N\right\} \\ &+ \epsilon^{(3)}_{\alpha\beta} D_3(N_{N3} - N_{N_3}^{\mathrm{eq}}) - \frac{1}{2}W_3\left\{P^{0(3)}, N\right\} \\ &- \frac{\mathrm{Im}(\Lambda_\tau)}{Hz}\left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, \left[\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, N\right]\right]_{\alpha\beta} \\ &- \frac{\mathrm{Im}(\Lambda_\mu)}{Hz}\left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, \left[\begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, N\right]\right]_{\alpha\beta},\end{aligned}$$

washout projects along different directions of flavour space

CP-asymmetry promoted to matrix

Im 

= thermal width

Self-energy of tau/muon controls flavour effects

Formulae

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

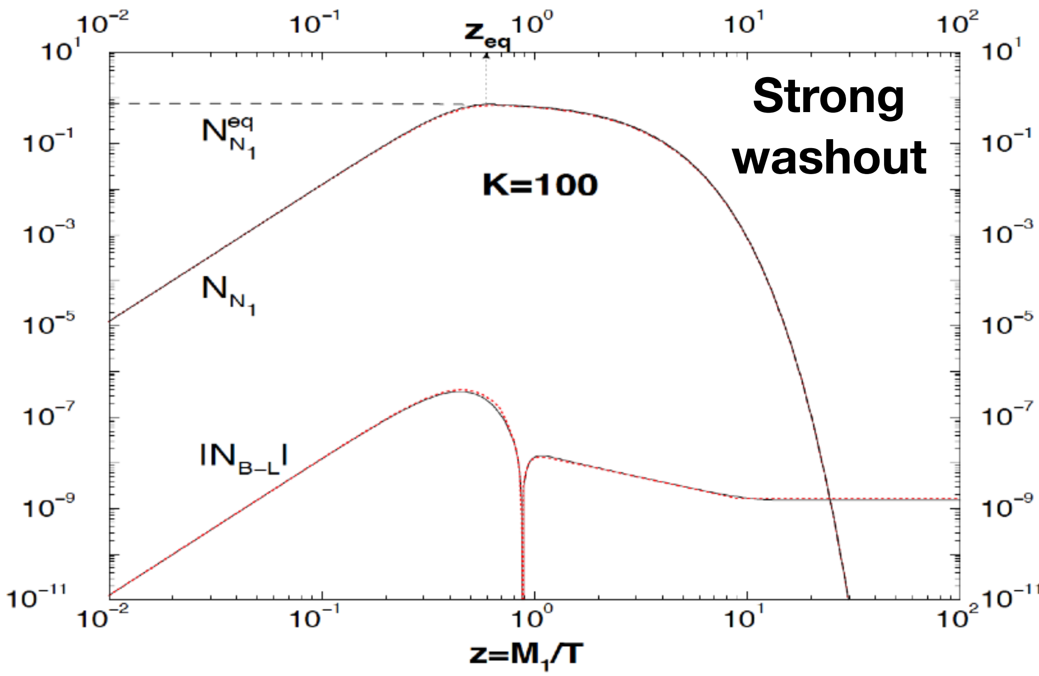
$$N_1^{eq} = \frac{1}{2} z^2 K_2(z)$$

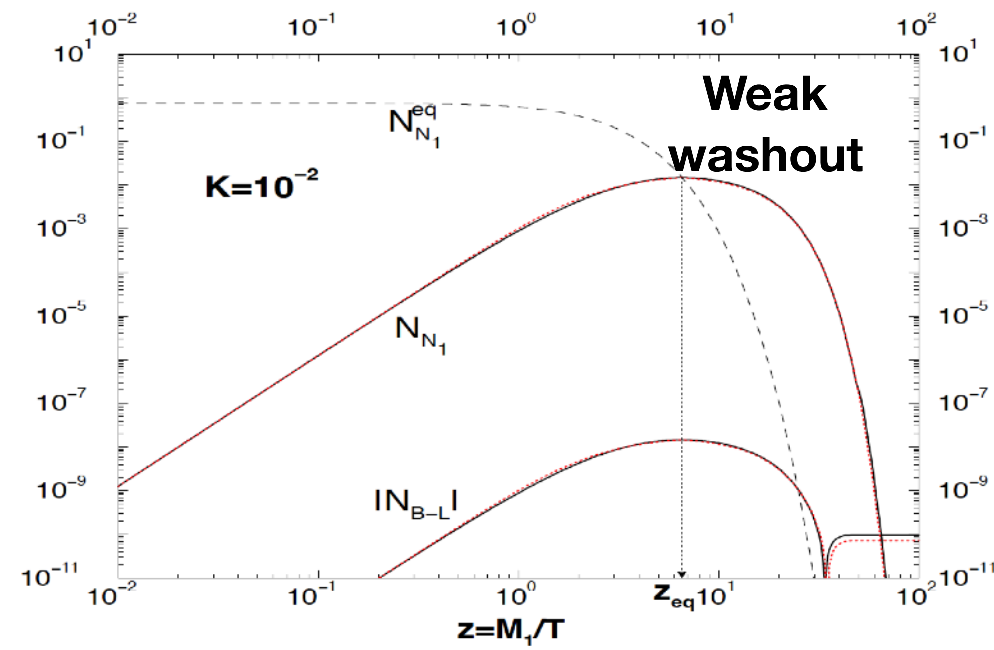
$$W_1(z) = \frac{1}{2} \frac{\Gamma_1^{ID}}{Hz} = \frac{1}{4} K_1 \mathcal{K}_\infty z^3$$

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

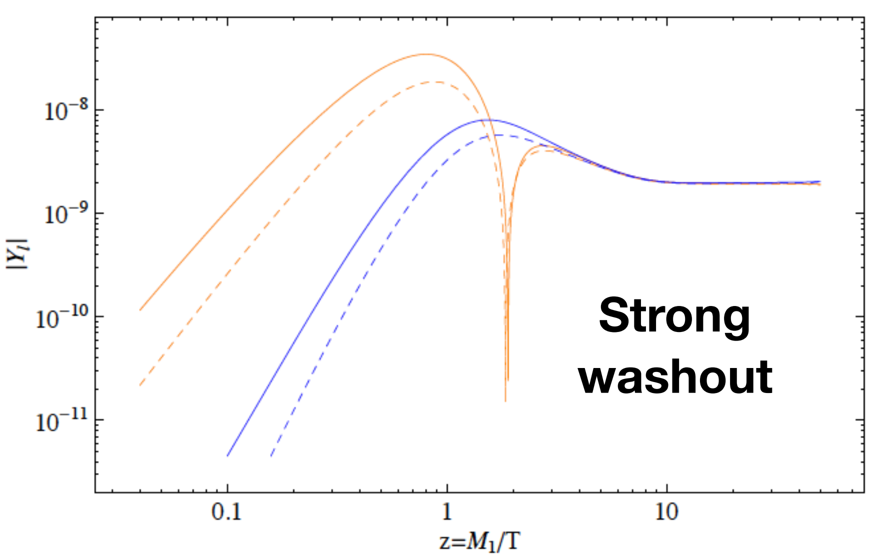
Semi-Classical Justification

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



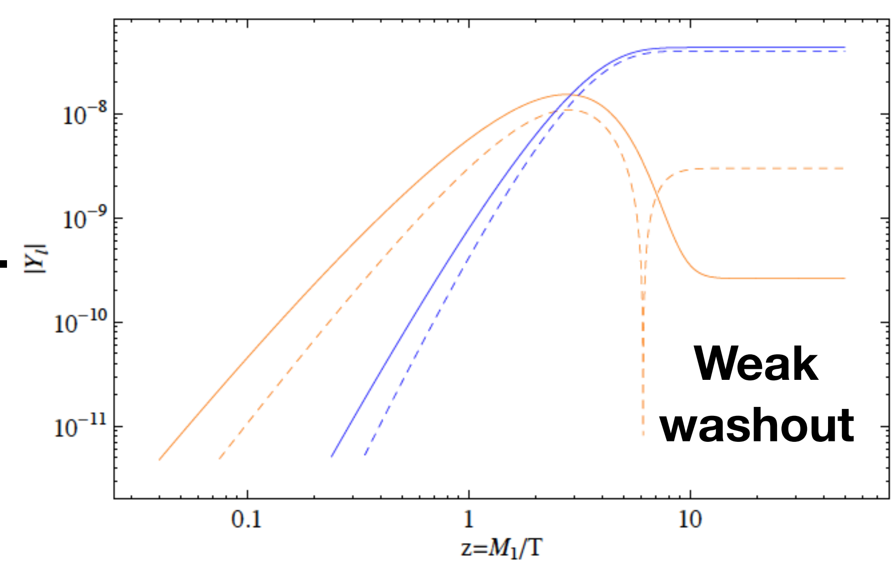


Plots from 1002.1326. Garbrecht etal



Strong washout FDFT effects negligible.
Weak washout FDFT important.

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



Light Neutrino Mass

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

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

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

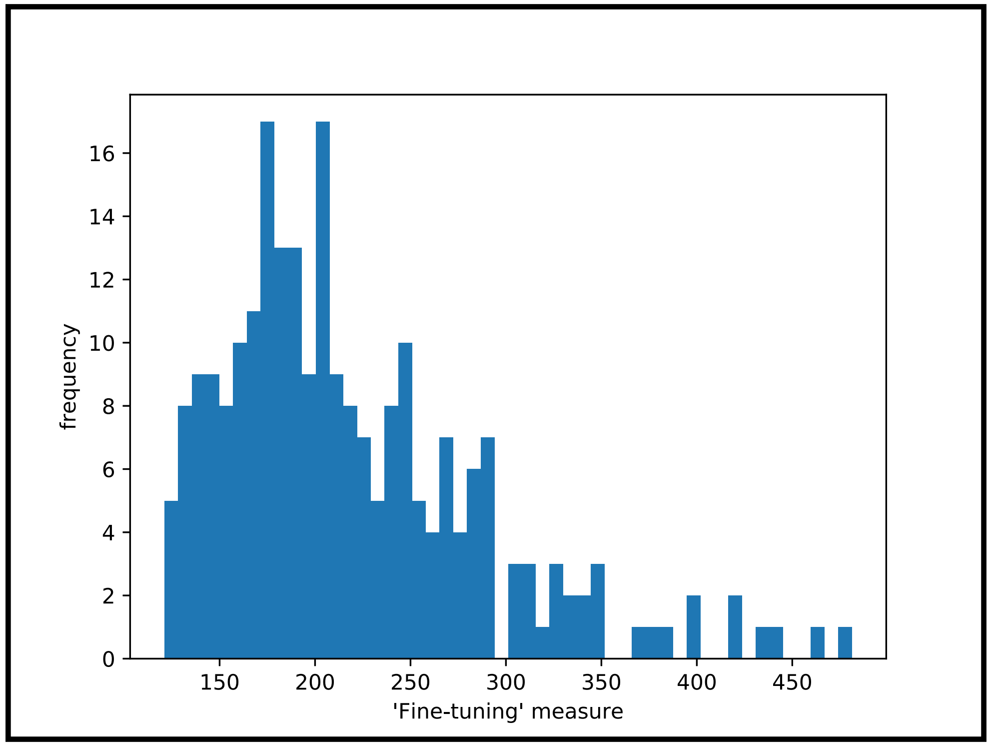
$$= -\frac{1}{32\pi^2 v^2} m_D \text{diag}\left(g\left(M_1\right), g\left(M_2\right), g\left(M_3\right)\right) m_D^T,$$

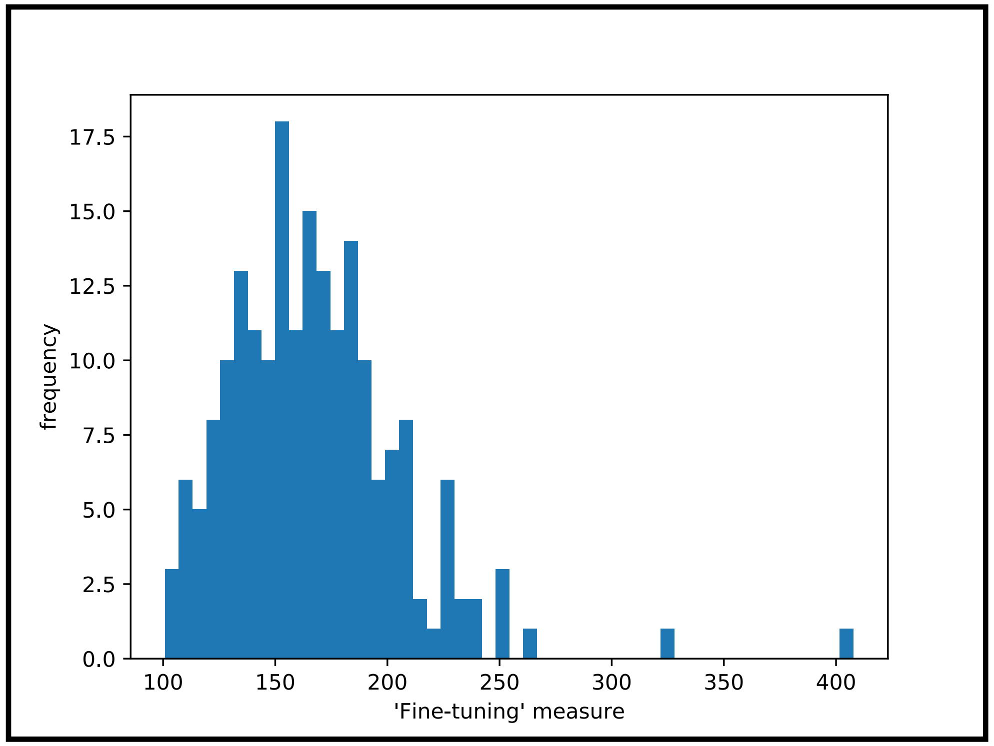
$$g\left(M_i\right) \equiv M_i \left(\frac{\log\left(\frac{M_i^2}{m_H^2}\right)}{\frac{M_i^2}{m_H^2} - 1} + 3\frac{\log\left(\frac{M_i^2}{m_Z^2}\right)}{\frac{M_i^2}{m_Z^2} - 1} \right),$$

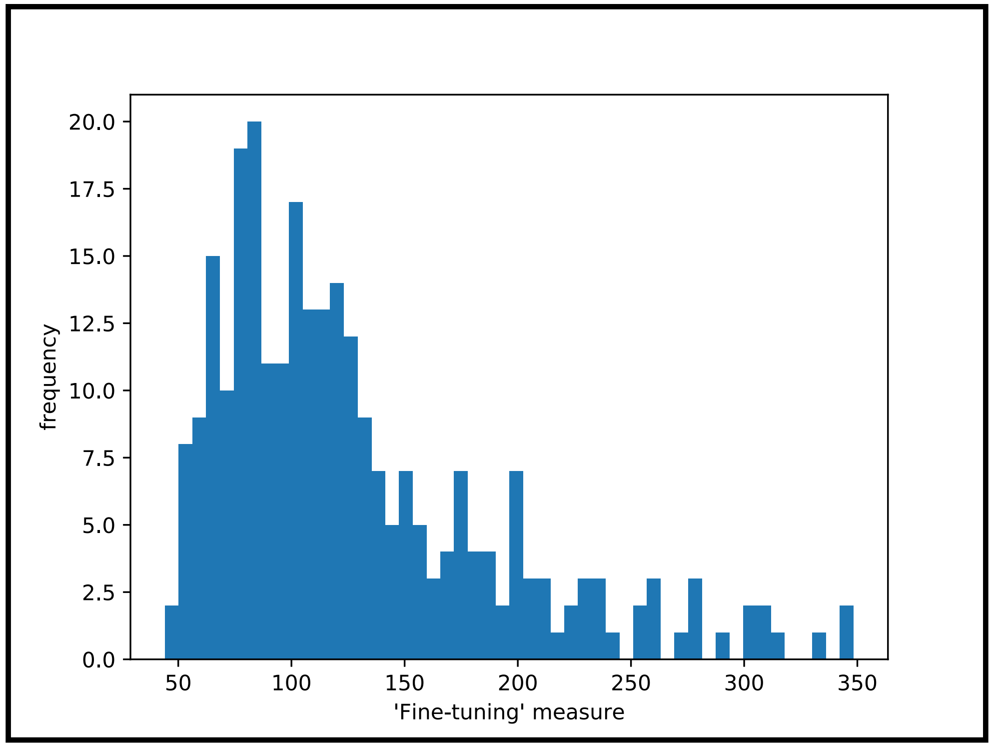
$$f(M) \equiv M^{-1} - \frac{M}{32\pi^2 v^2} \left(\frac{\log\left(\frac{M^2}{m_H^2}\right)}{\frac{M^2}{m_H^2} - 1} + 3\frac{\log\left(\frac{M^2}{m_Z^2}\right)}{\frac{M^2}{m_Z^2} - 1} \right) = \text{diag}\left(\frac{1}{M_1}, \frac{1}{M_2}, \frac{1}{M_3}\right) - \frac{1}{32\pi^2 v^2}\text{diag}\left(g\left(M_1\right),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

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 Conserving R Matrix Conditions

$$C\overline{\nu}_i^T = \nu_i ,$$

$$C\overline{N}_i^T = N_i ,$$

CP transformation

±i

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

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

The above condition impose CP invariance on heavy and light Majorana neutrinos respectively. But we are only interested in the case where CP is conserved the R matris. This implies

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