Leptogenesis from Low Energy CP Violation

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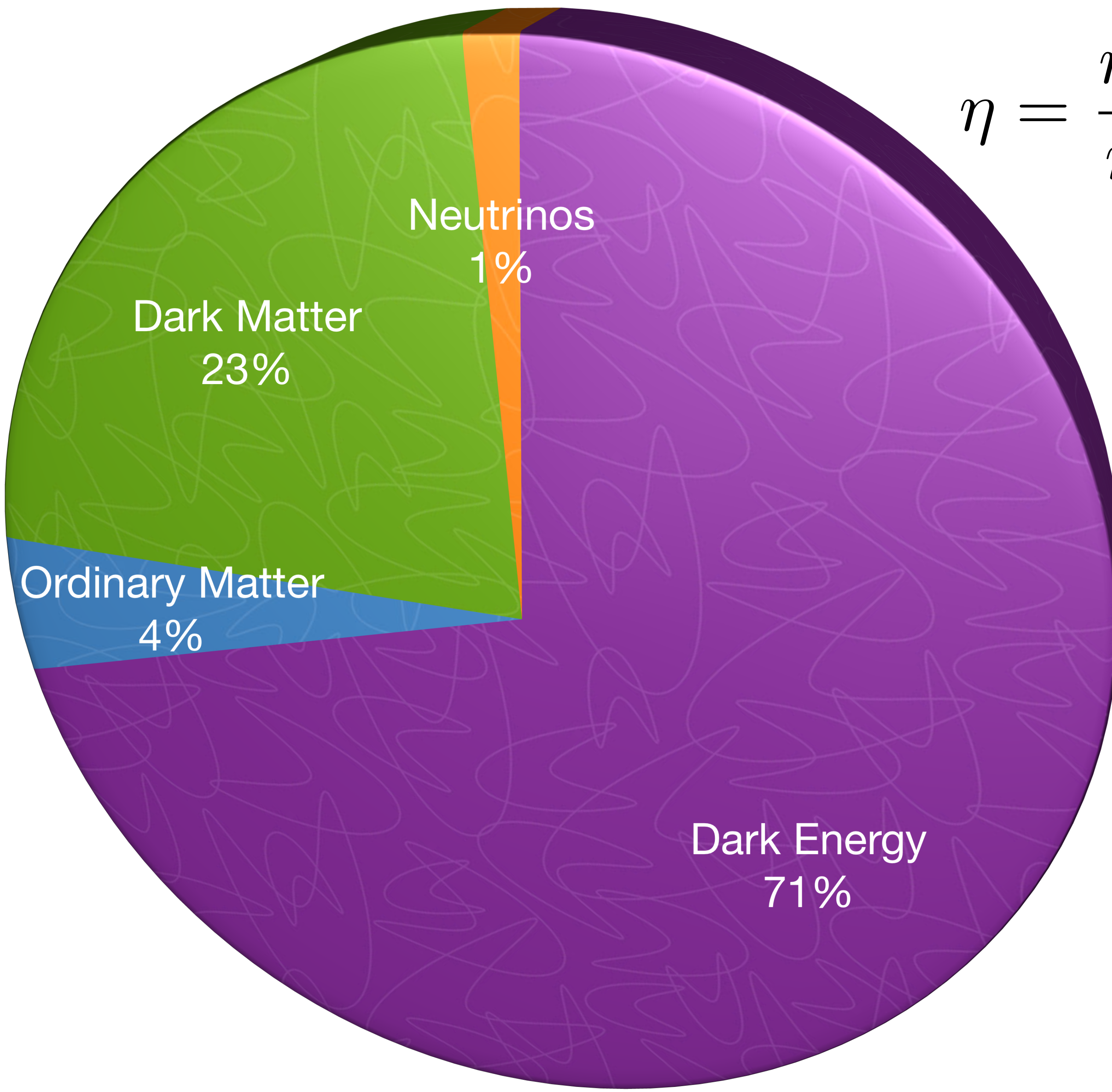
Fermilab

NTN Workshop on NSIs

Fermilab

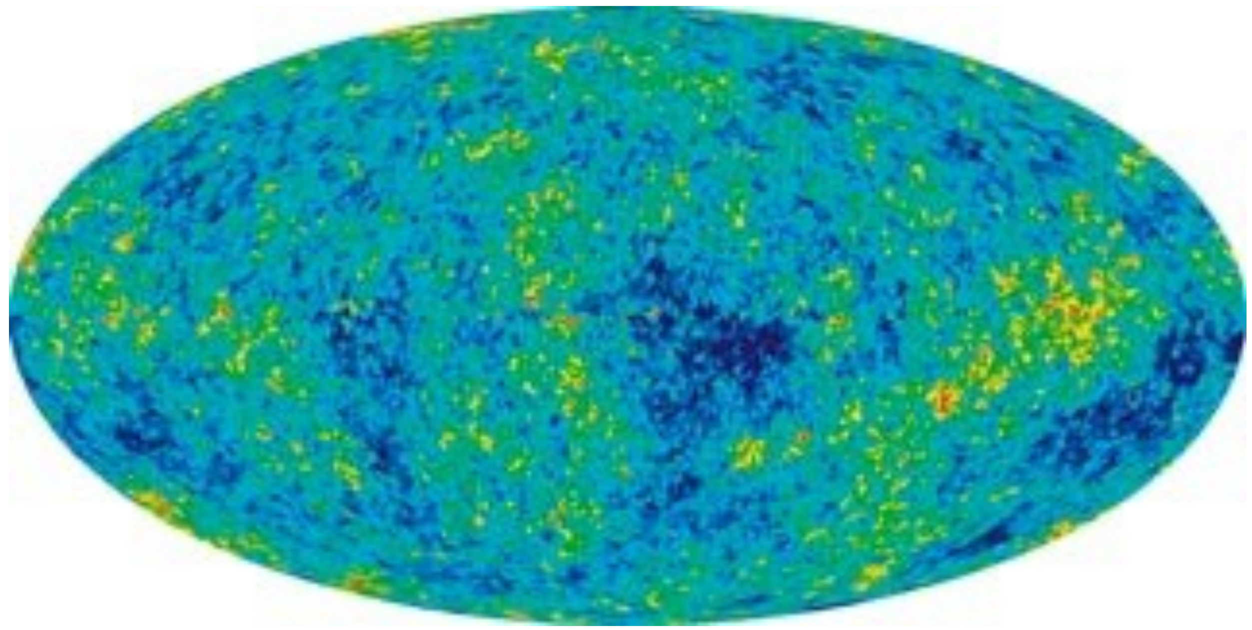
Energy Budget of the Universe

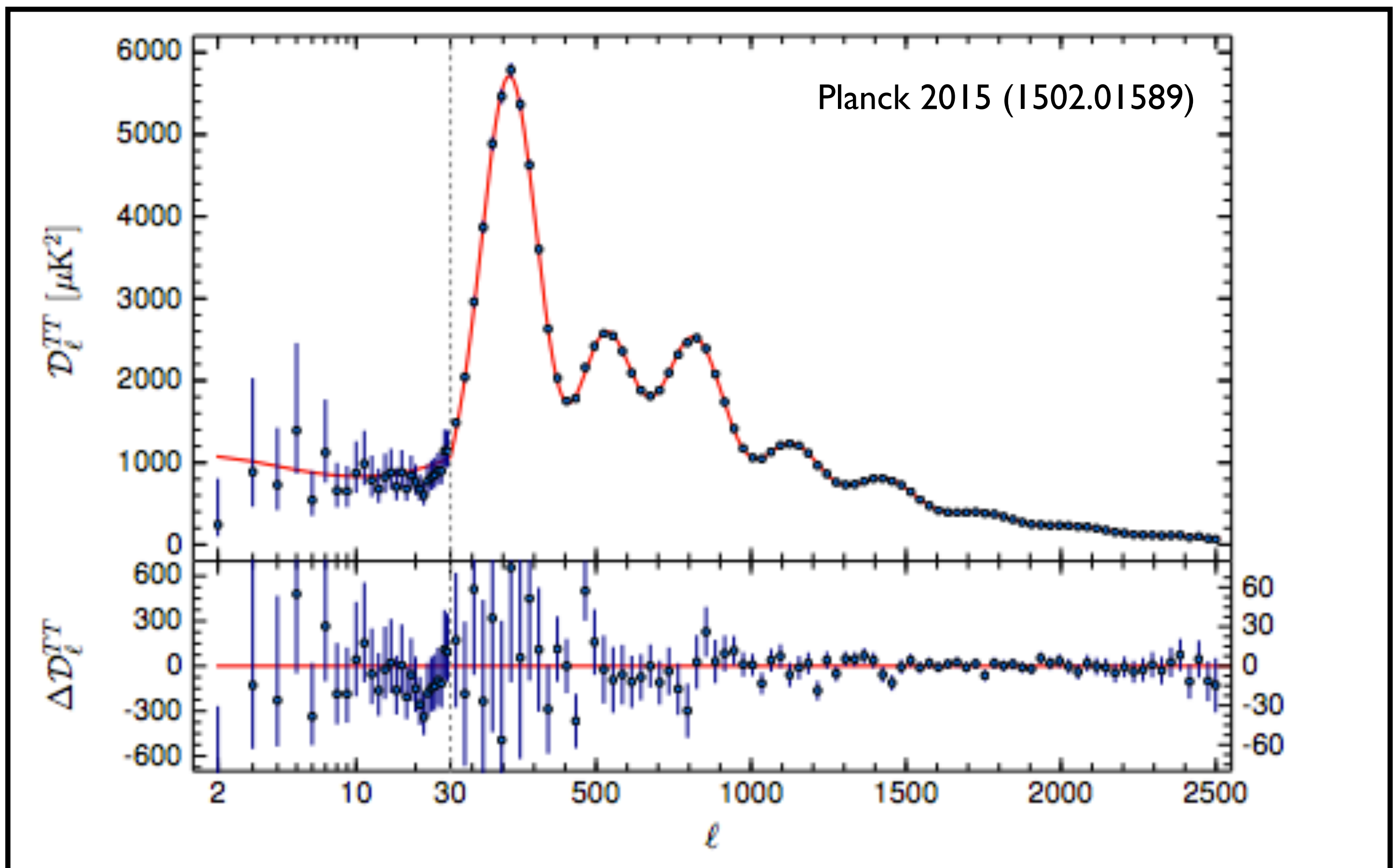


$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Cosmic Microwave Background

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

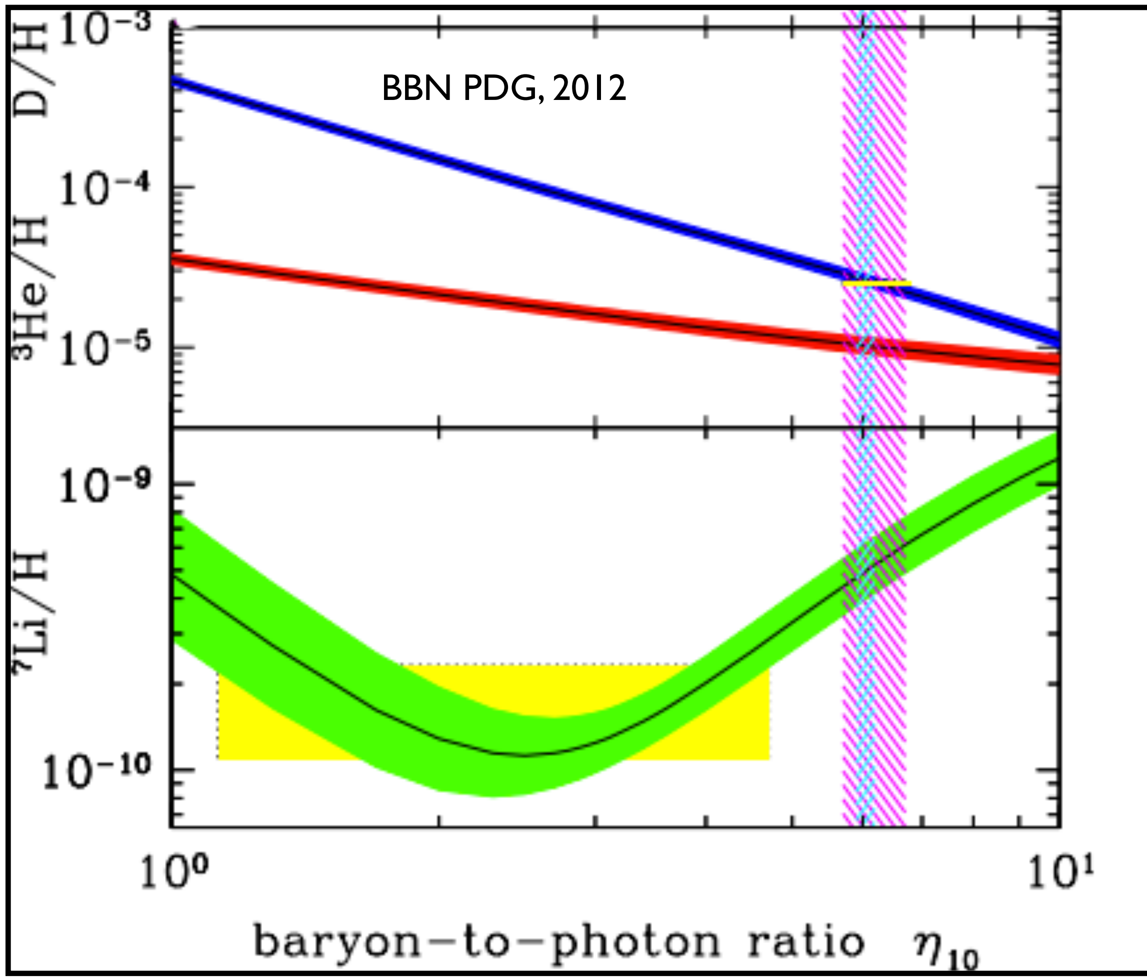




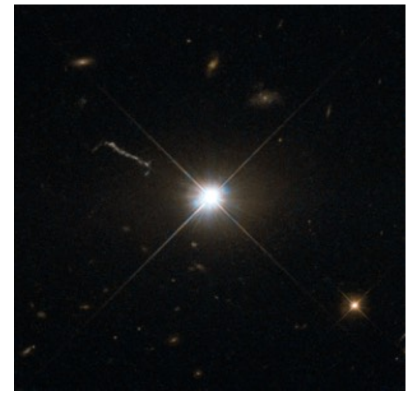
η_{CMB} = (6.23 ± 0.17) × 10^{-10}

Big Bang Nucleosynthesis

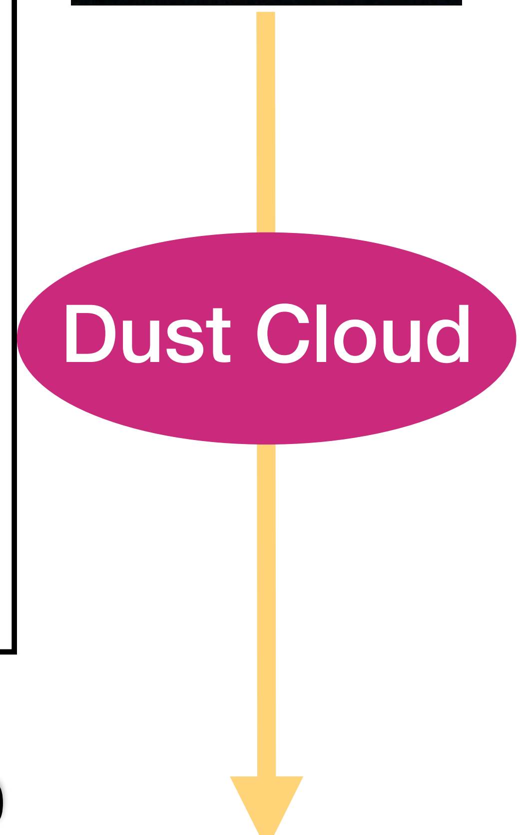
$T \sim 1\,\mathrm{MeV}$

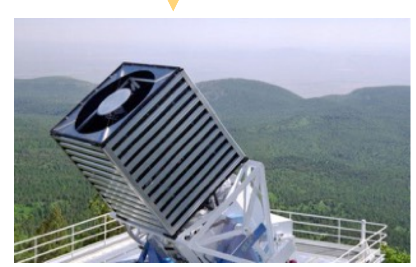


$\eta_{BBN} = (6.08 \pm 0.06) \times 10^{-10}$



bright quasar 3C 273:
Hubble Space
Telescope





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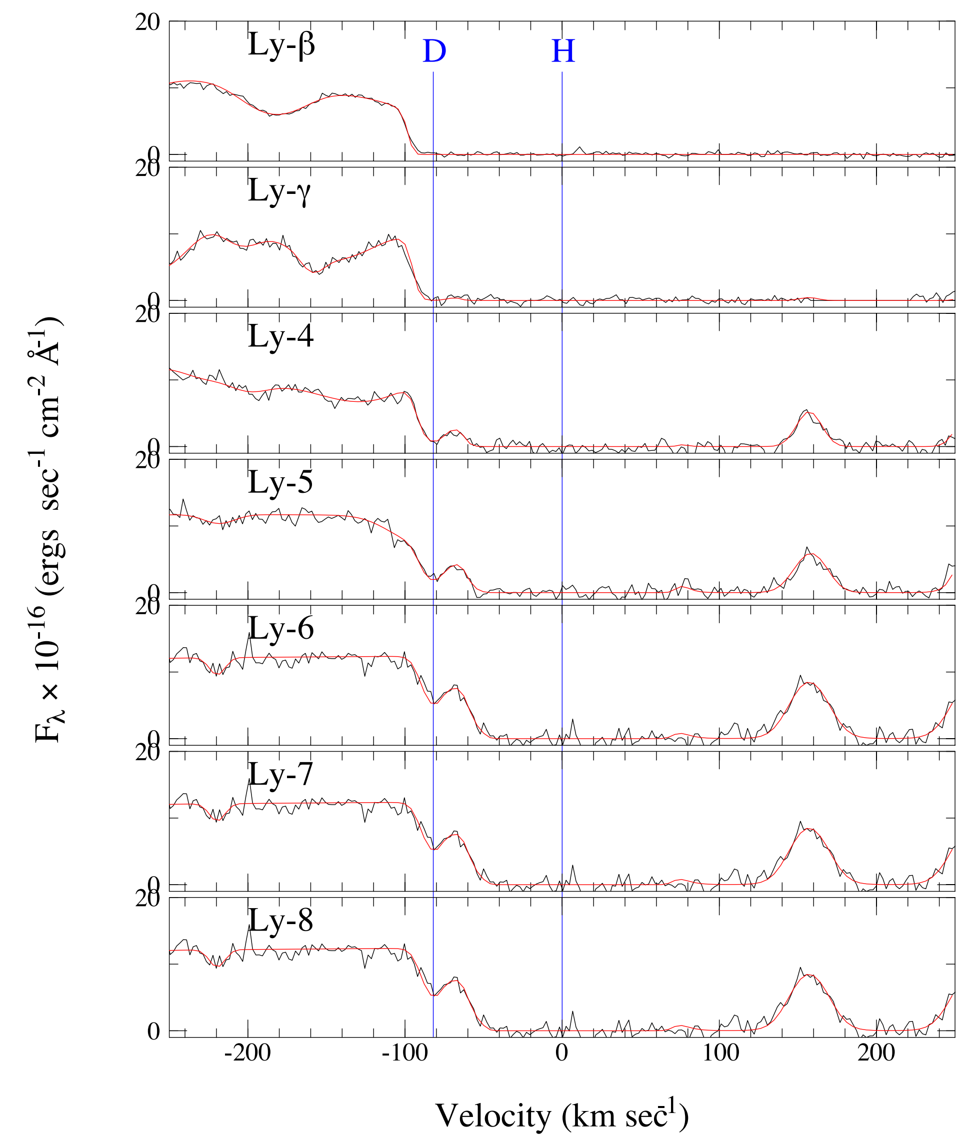


Sakharov's Conditions

Kuzmin, Rubakov and Shaposhnikov

Baryon and Lepton Number Violation

Insufficient CP Violation

Gavela, Hernandez, Orloff, Pene; Huet and Sather

Kajantie, Laine, Rummukainen, Shaposhnikov

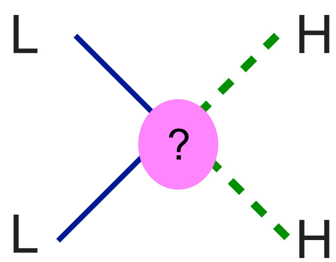
No departure from thermal equilibrium

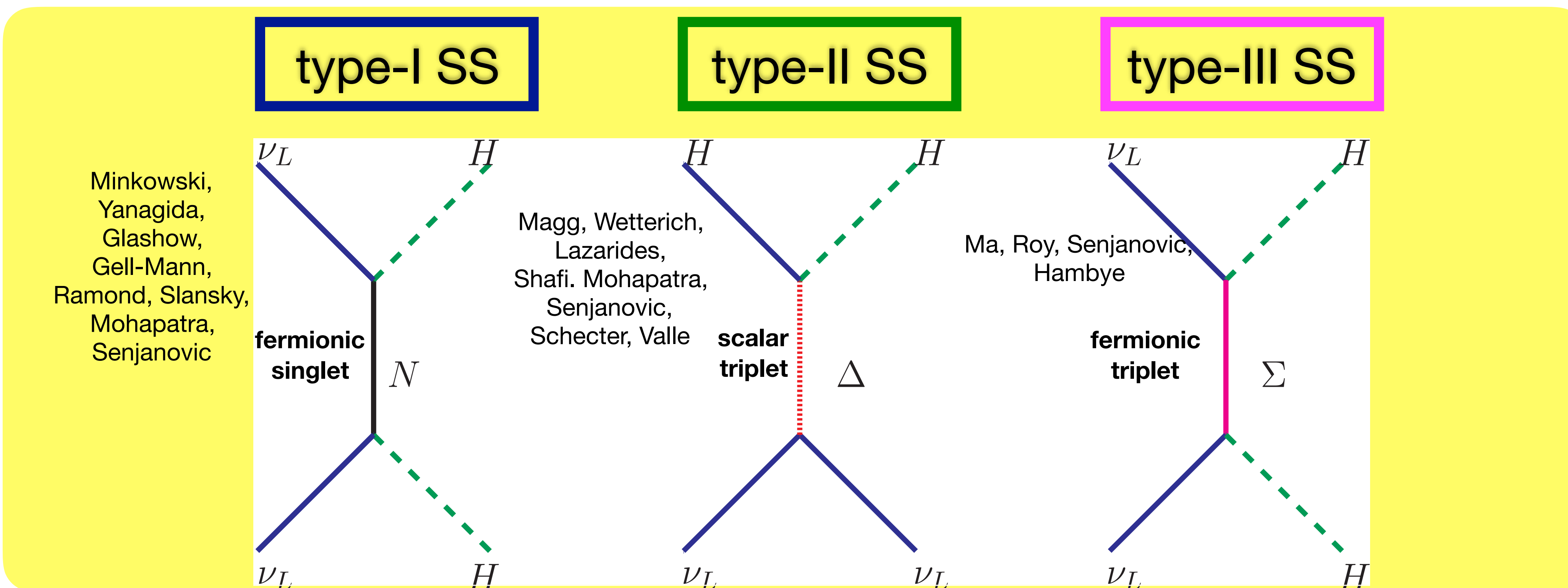
Leptogenesis: Motivation

SU(2) invariant mass term for neutrinos

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

lepton number violating





See talks by Mu Chun Chen, Anil Thapa, Sudip Jana

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

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

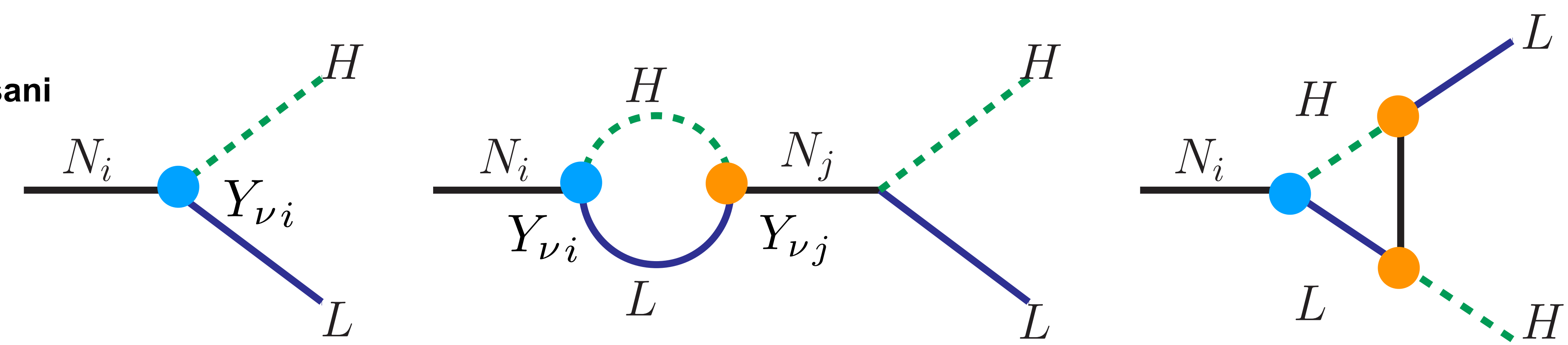
$$m_\nu = \frac{Y_\nu^2 v^2}{M_N} \sim 0.1\,\mathrm{eV}$$

Leptogenesis via Decays

Fukugida, Yanagida

Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani

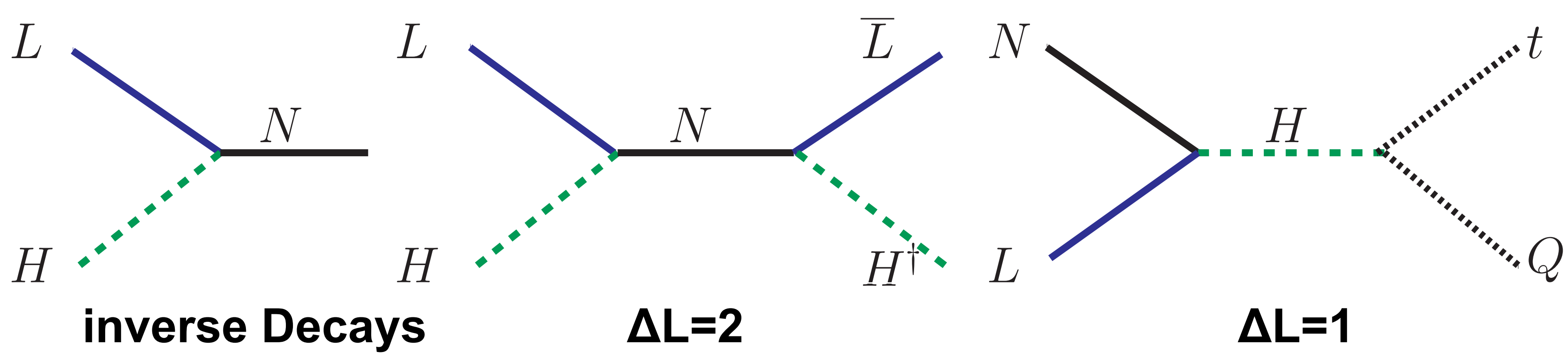


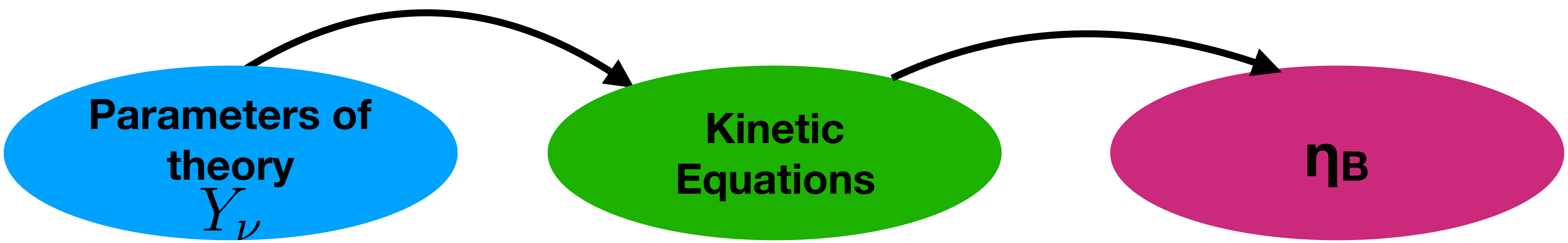
Decay Asymmetry

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

Basic Mechanism

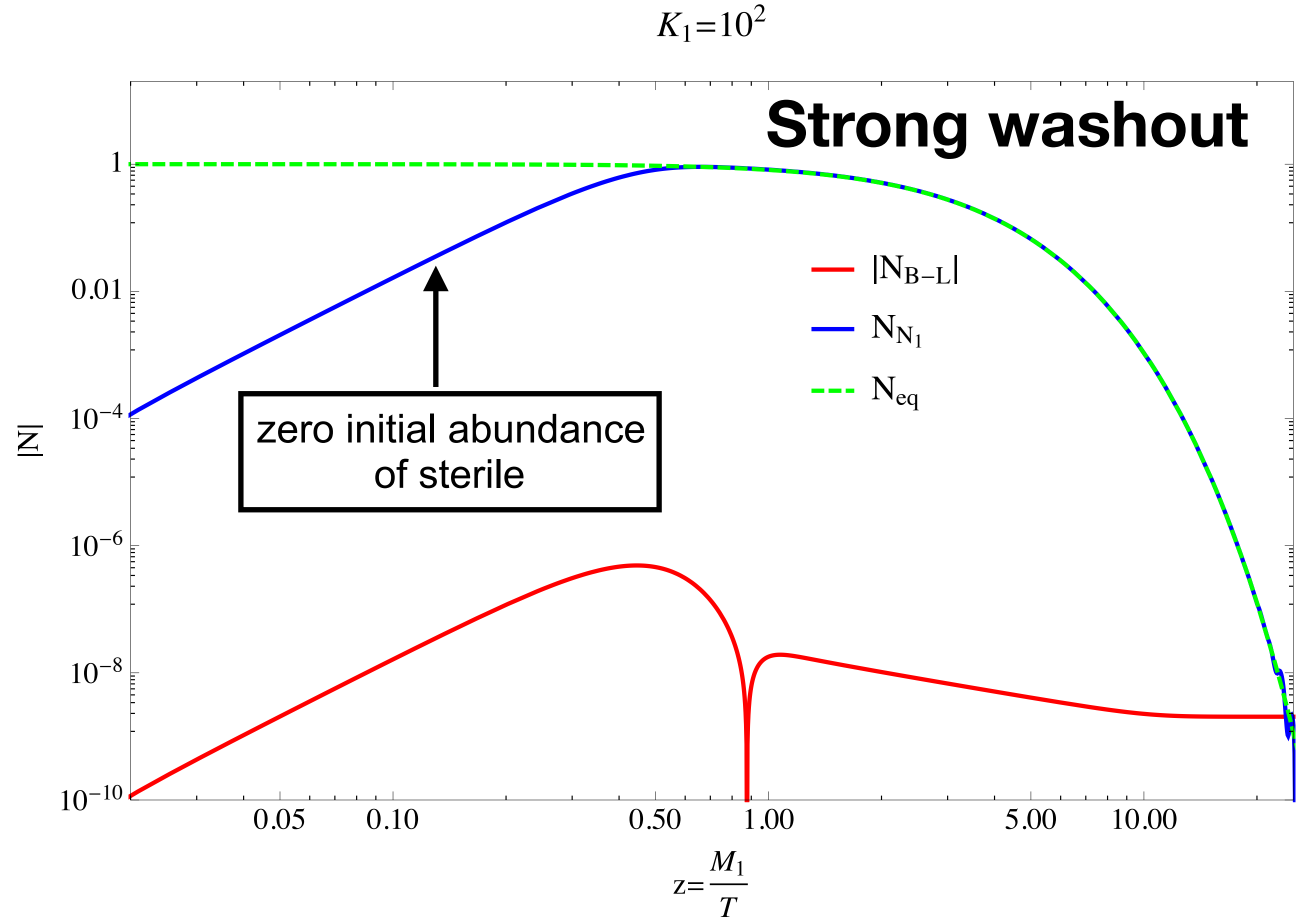
Washout and Scattering processes

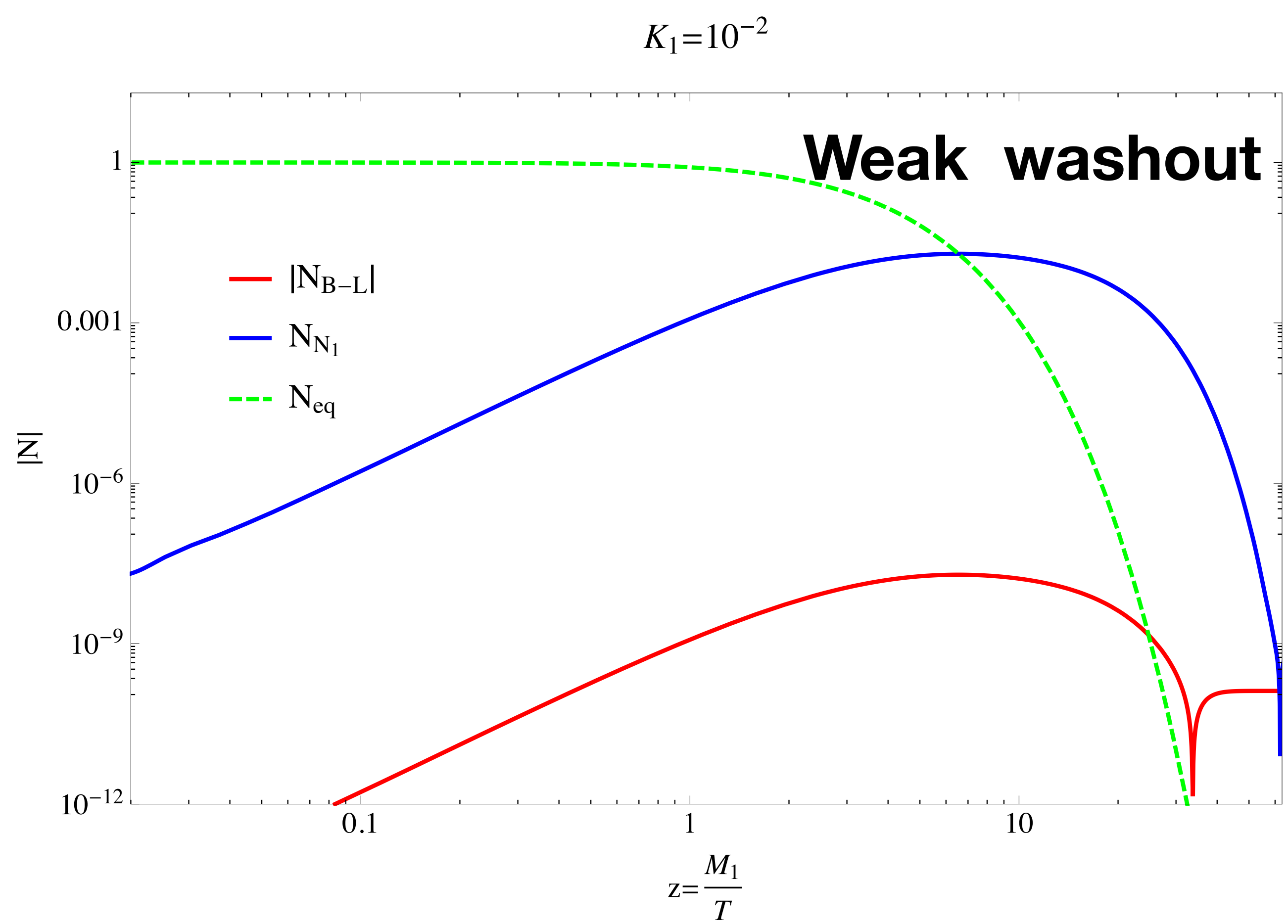




$$\frac{dn_{N_i}}{dz} = -\,D_i(n_{N_i} - n_{N_i}^{\rm eq}),$$

$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3}\left(\epsilon^{(i)} D_i(n_{N_i} - n_{N_i}^{\rm eq}) - W_i n_{B-L}\right).$$


K1=10^2
Strong washout
|N_B−L|
N_N1
N_eq
zero initial abundance
of sterile
|N|
1
0.01
10^−4
10^−6
10^−8
10^−10
0.05
0.10
0.50
1.00
5.00
10.00
z=M1/T


K1=10^−2
Weak washout
|N_B−L|
N_N1
N_eq
|N|
1
0.001
10^−6
10^−9
10^−12
0.1
1
10
z=M1/T

Model Parameter Space

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

- U_{PMNS}: **Neutrino Oscillation constraints** → **3 mixing angles, 3 phases**
- $\sqrt{m}$: **sum of neutrino masses and neutrino oscillation** → **3 parameters**
- R^T: **Complex, orthogonal matrix** → **6 real parameters**
- $\sqrt{M}$: **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.

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

Leptogenesis via oscillations

Flavour effects can lower scale

Minimal Leptogenesis

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

Pilaftsis, Underwood, Millington, Teresi

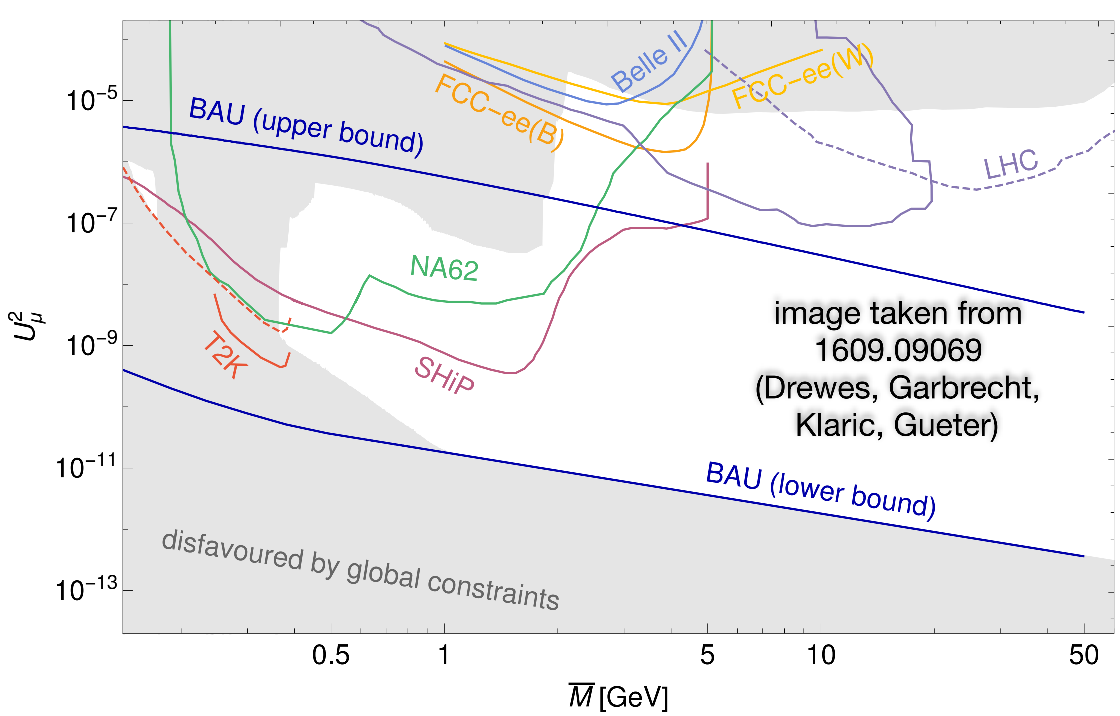
Resonant Leptogenesis

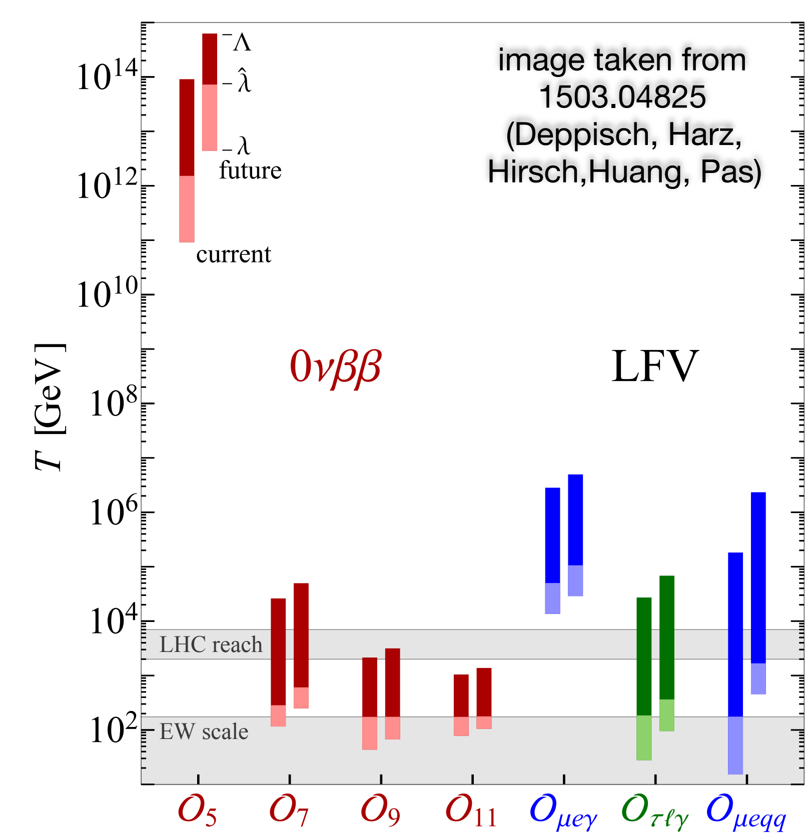
- **small neutrino masses ⟺ BAU**
- **minimal: 2RHN**
- **neutrino data, NDBD, LFV and LNV, cosmology in meson decays, collider searches**

- **Minimal models fairly tuned (1401.2459)**

- **small neutrino masses ⟺ BAU**
- **minimal: 2RHN**
- **Easily embedded in GUT models**
- **falsifiable**

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





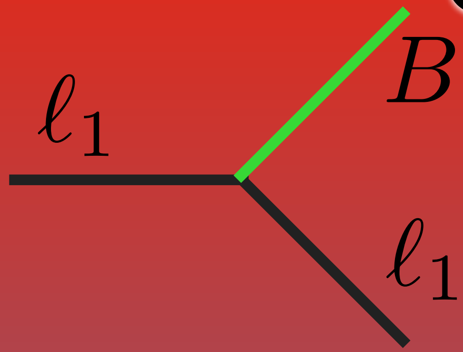
Intermediate Scale Leptogenesis

arXiv:1804.05066

Flavour Effects

$\Gamma_\ell < H$

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



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

Flavour Effects

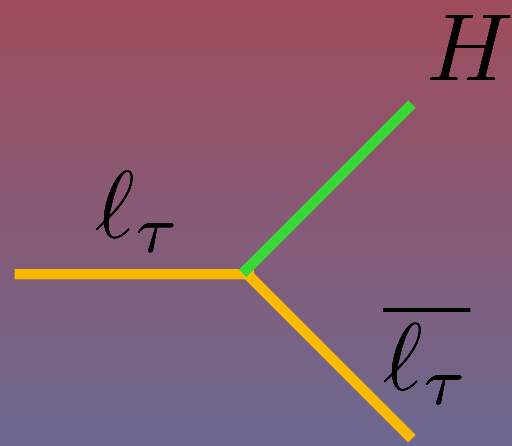
$$T \gtrsim 10^{13}\,\mathrm{GeV}$$

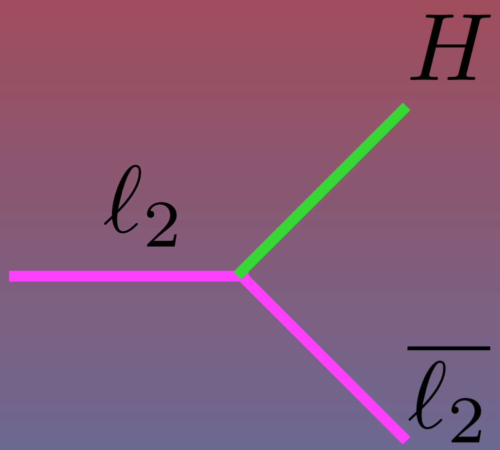
$$\Gamma_\ell < H$$

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

SM Yukawa couplings

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





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

Flavour Effects

$$\Gamma_\ell < H$$

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

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

SM Yukawa couplings

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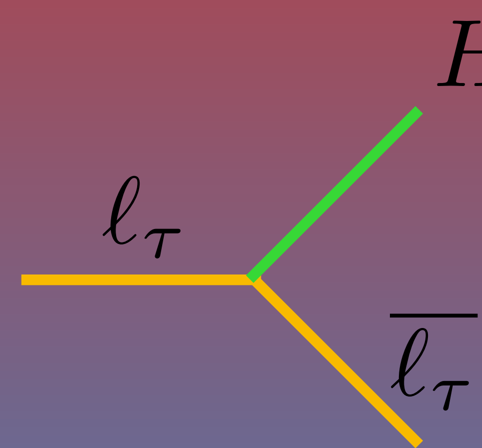
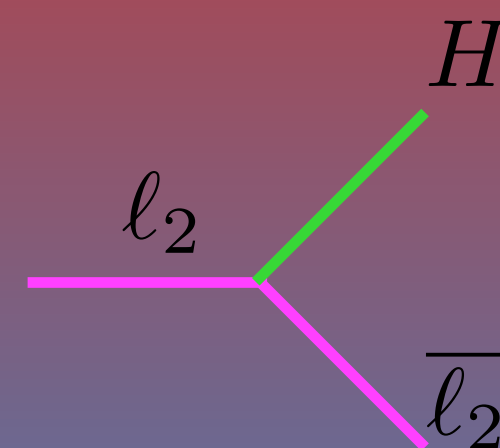
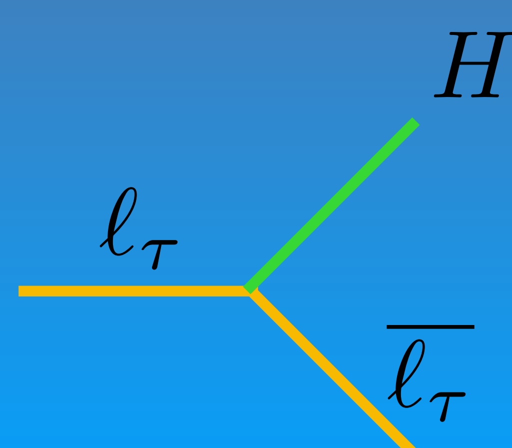


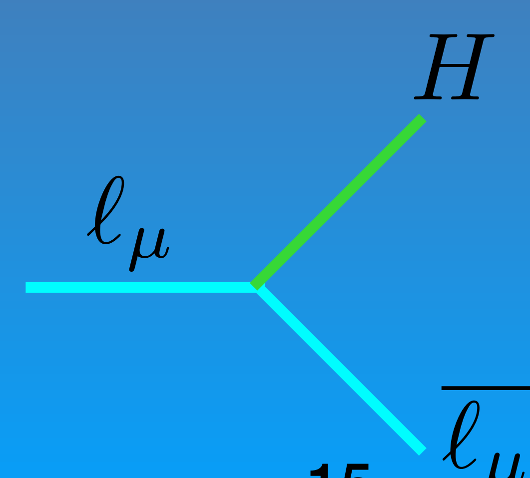


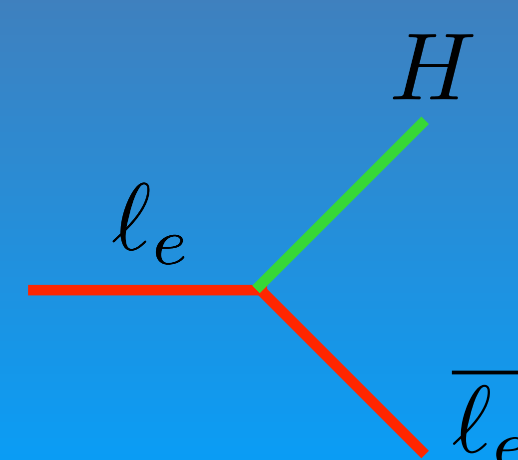
$$\Gamma_\tau \propto h_\tau^2 T > H$$

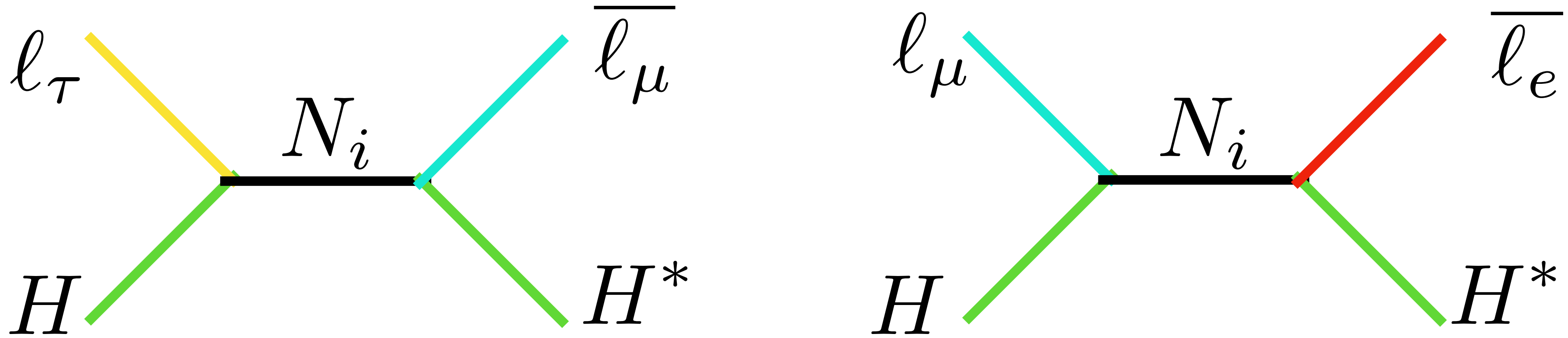
$$T \sim 10^9\mathrm{GeV}$$

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









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*

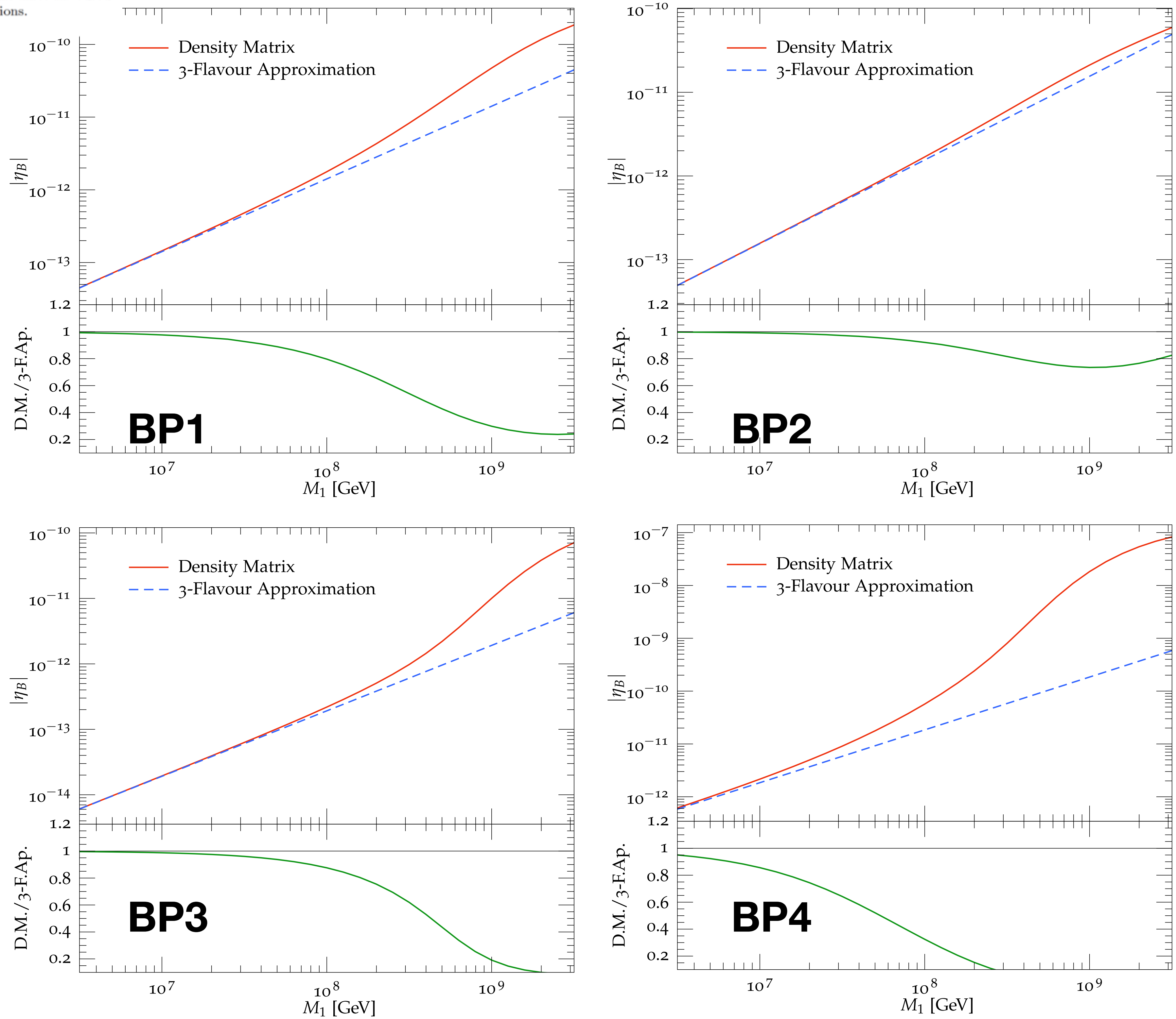
*K. Moffat, S. Pascoli, S. T. Petcov, H. Schulz, JT

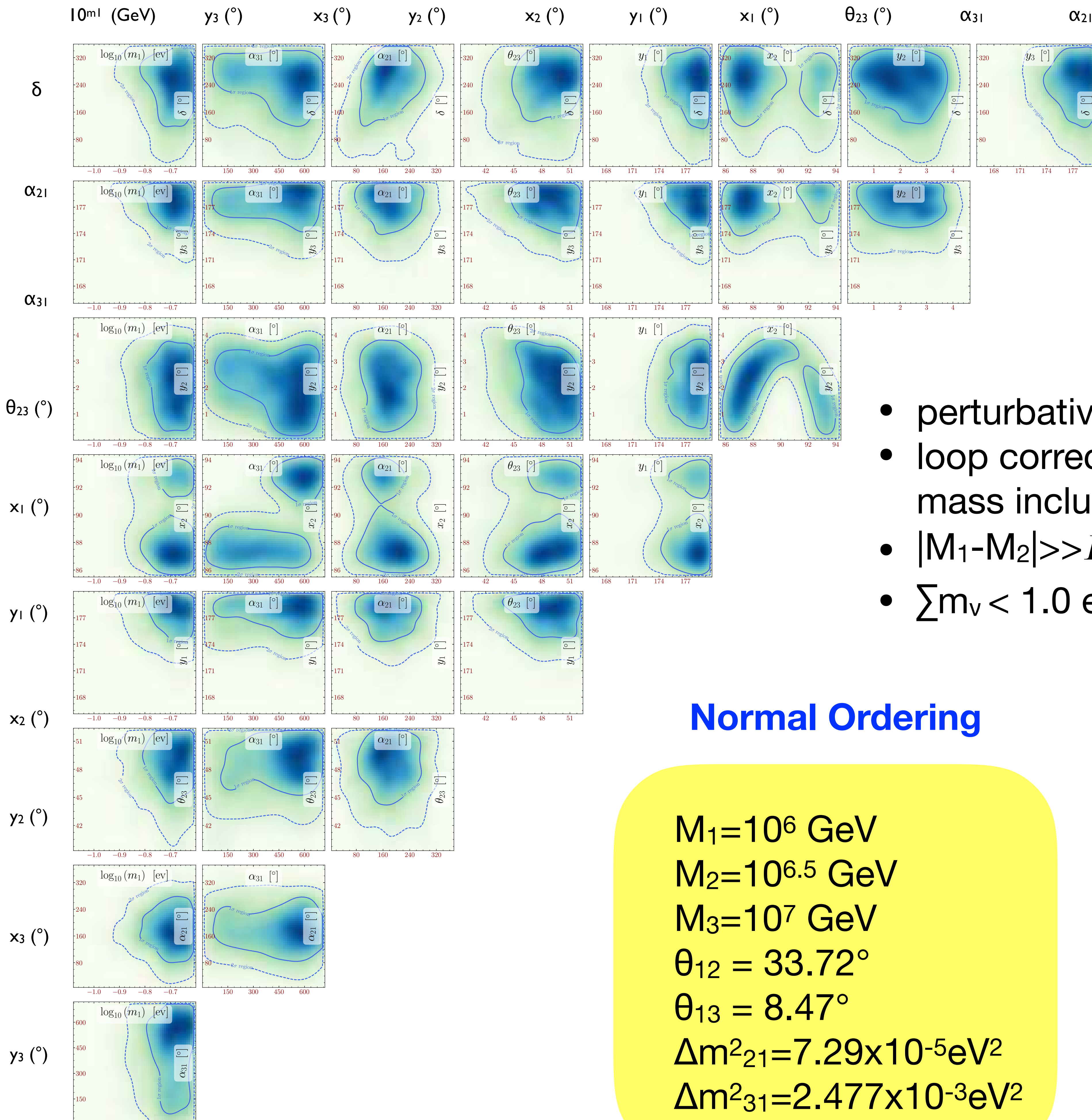
DME versus Classical BE

arXiv:1804.05066

	δ	α_{21}	α_{31}	$x_1(^\circ)$	$y_1(^\circ)$	$x_2(^\circ)$	$y_2(^\circ)$	$x_3(^\circ)$	$y_3(^\circ)$
BP1	π	0	0	10	45	15	25	65	35
BP2	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	20	0	45	25	75	15
BP3	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	60	10	45	90	65	0
BP4	$\frac{3\pi}{2}$	$\frac{\pi}{2}$	0	5	180	5	90	65	135

TABLE II. Benchmark points used to test the three-flavoured equations against the density matrix equations.



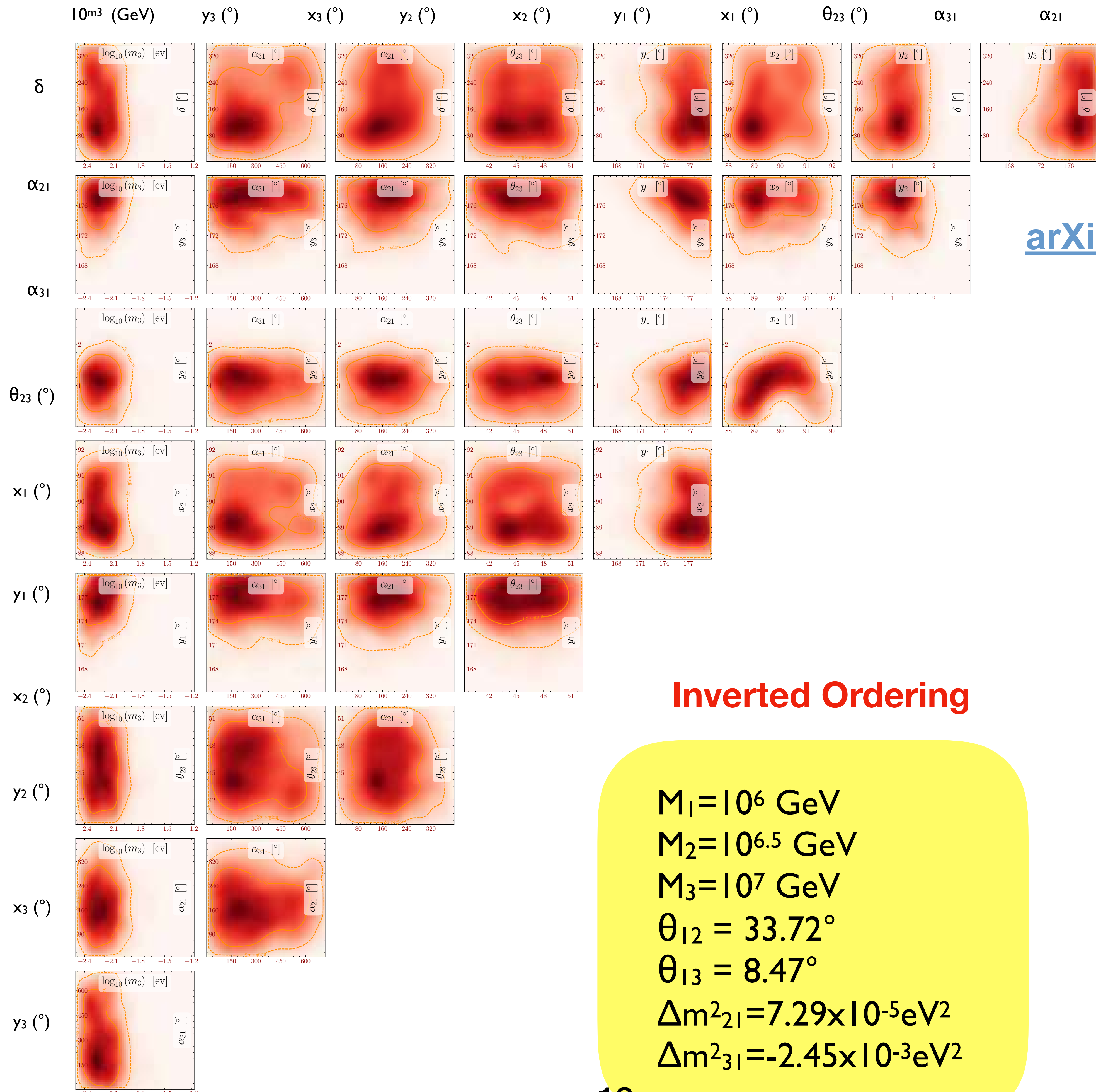


Applied nested sampling algorithm: MultiNest

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

Normal Ordering

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



arXiv:1804.05066

Inverted Ordering

$M_1 = 10^6$ GeV

$M_2 = 10^{6.5}$ GeV

$M_3 = 10^7$ GeV

$\theta_{12} = 33.72°$

$\theta_{13} = 8.47°$

$\Delta m^2_{21} = 7.29 \times 10^{-5} \mathrm{eV}^2$

$\Delta m^2_{31} = -2.45 \times 10^{-3} \mathrm{eV}^2$

Leptogenesis via low energy CPV

arXiv:1809.08251

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*

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])

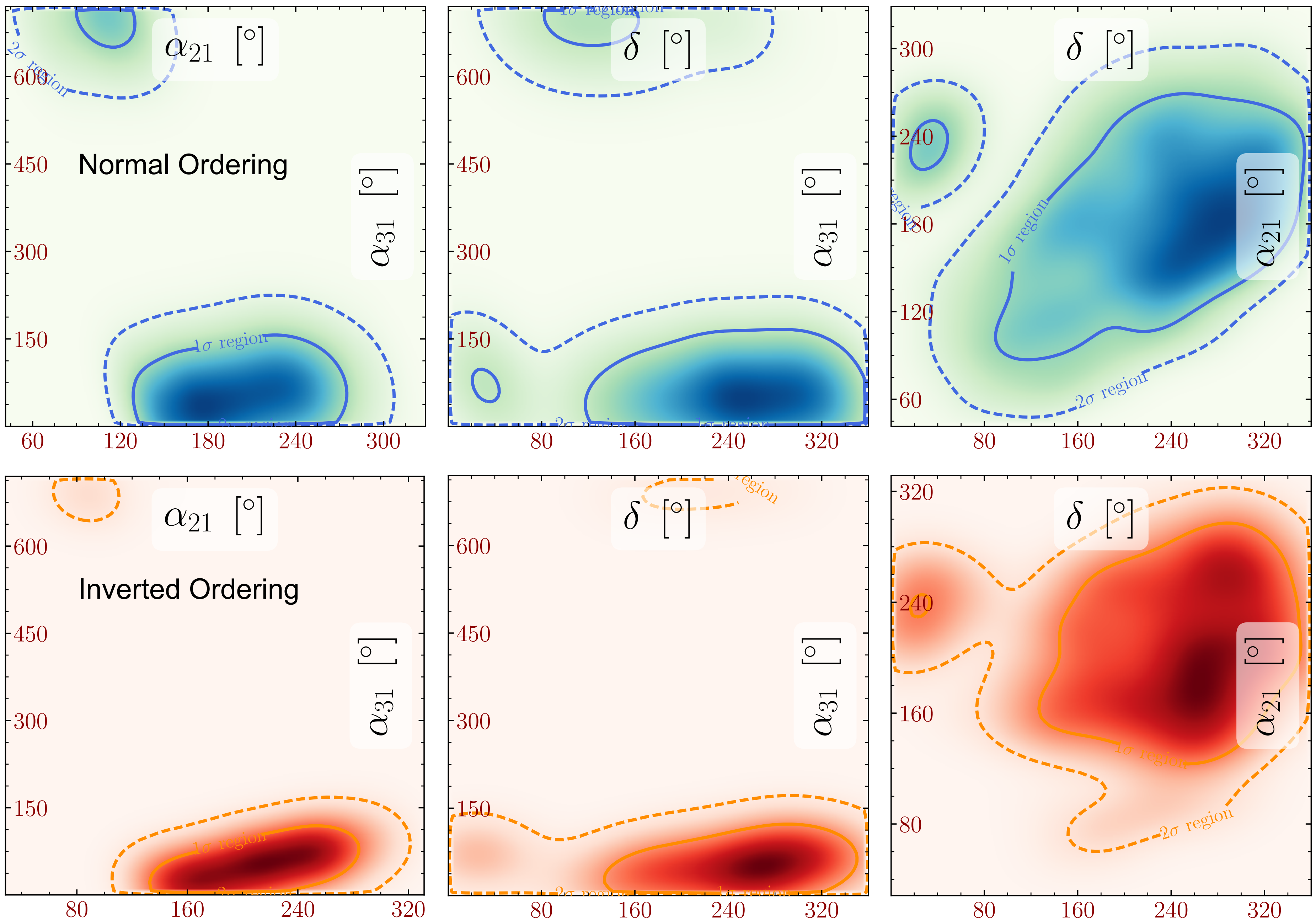
1809.08251 revisits this question using modern numerical machinery: density matrix equations + MultiNest* for effective PS exploration

Leptogenesis from Leptonic CP Violation

$T<10^9$ GeV

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

* Can be lowered to m1=0.05 eV



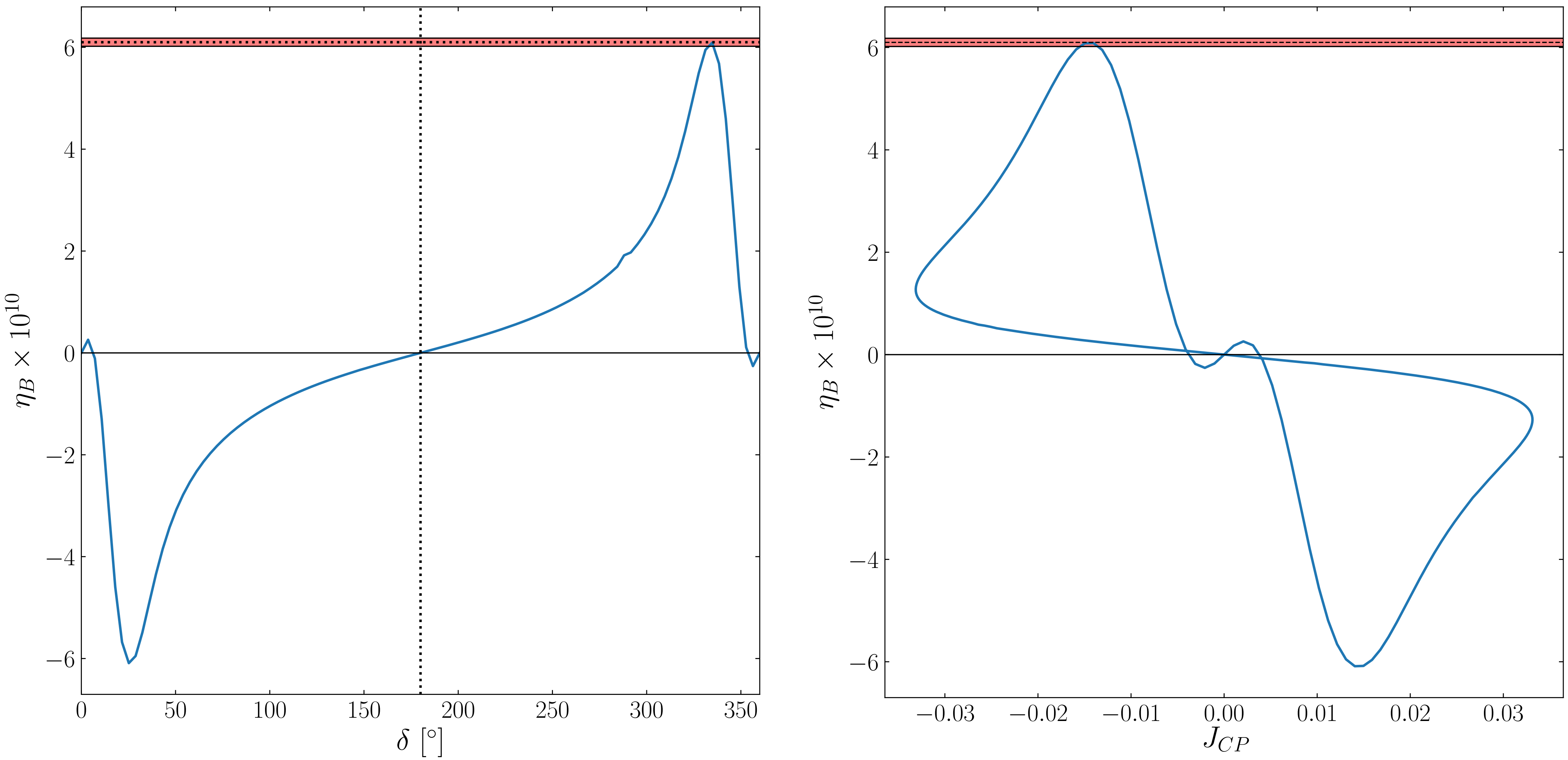
R matrix CP conserving and low energy observable fixed at best fit values NuFit.

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

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

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

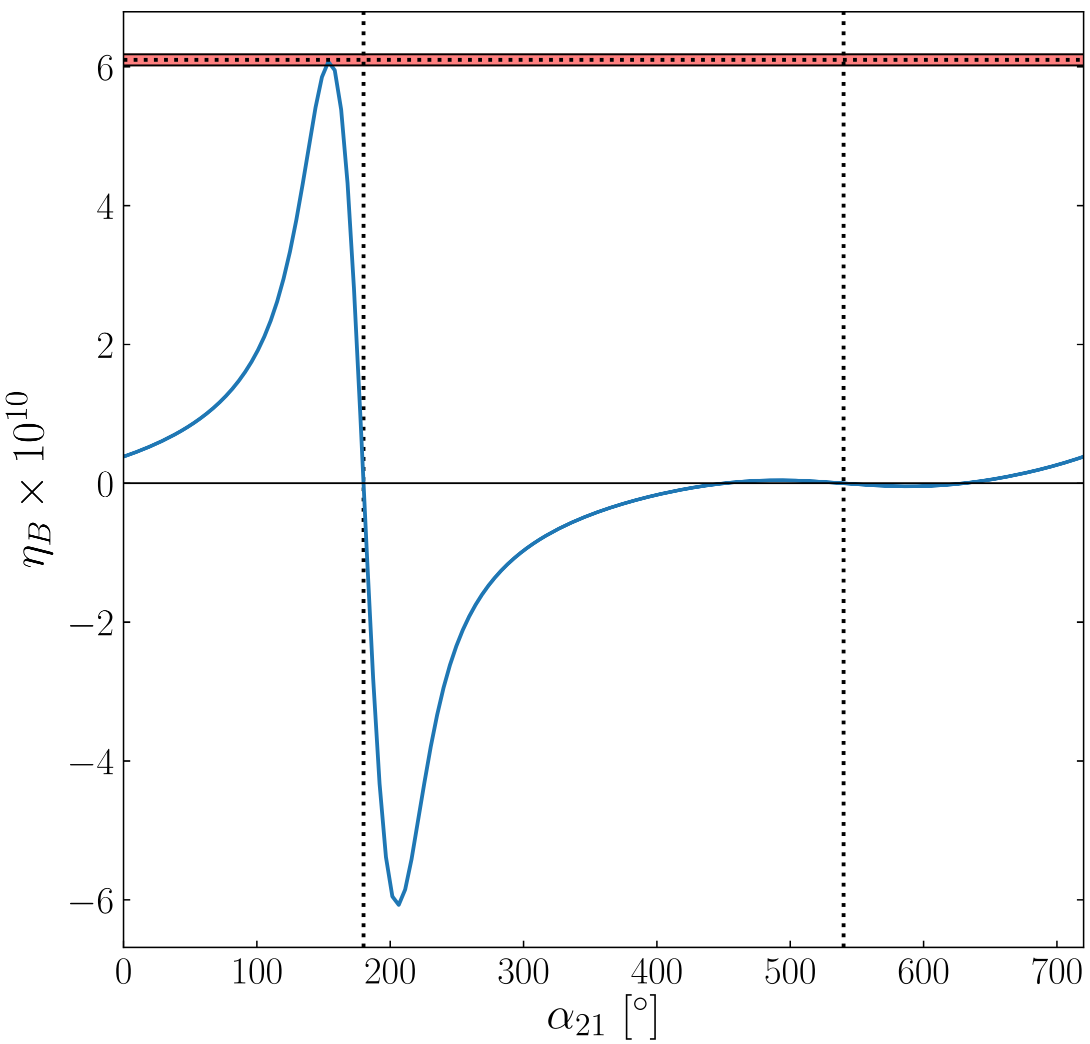


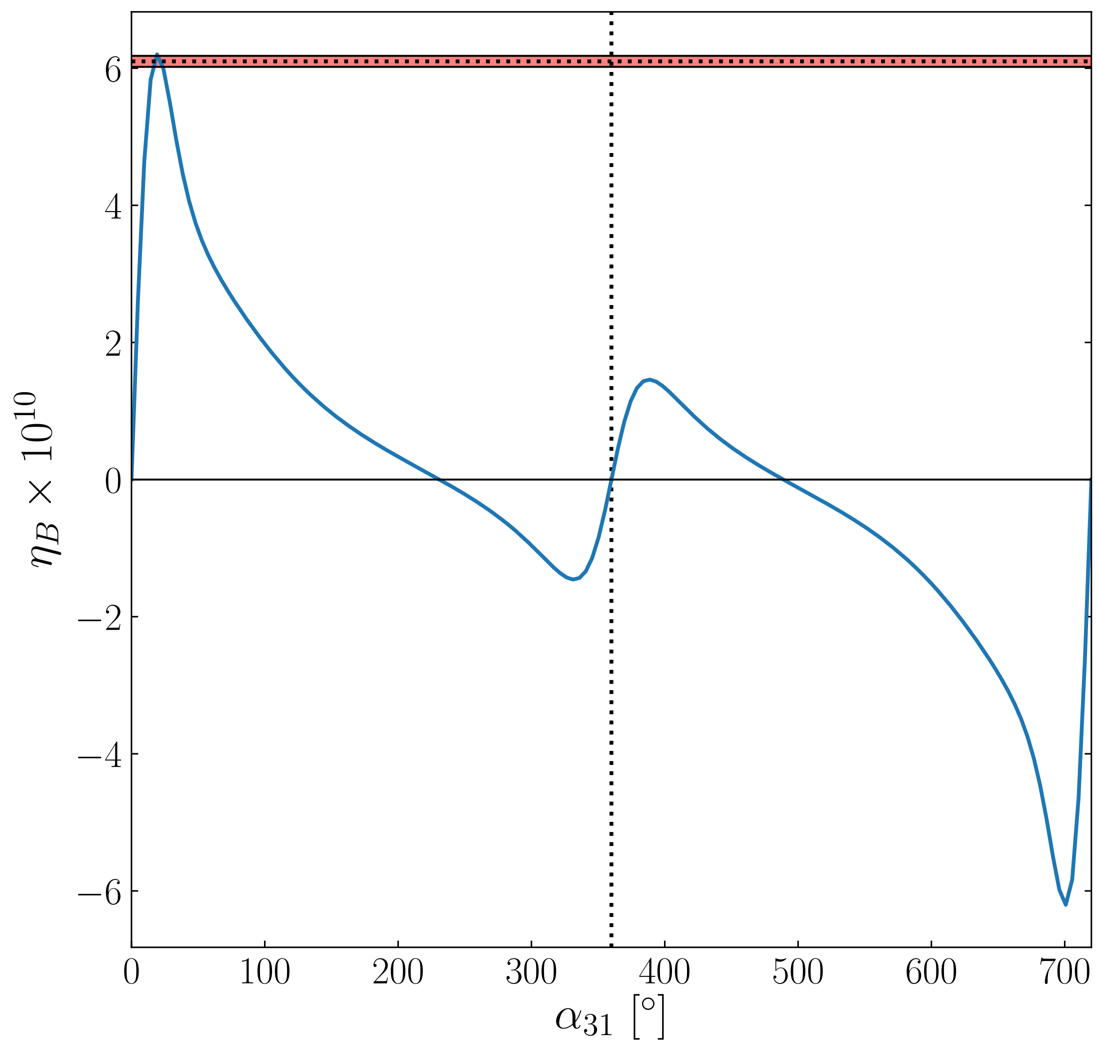
$$M_1 = 7.0 \times 10^8\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$$

Pure Dirac phase leptogenesis requires minimally M_1~10^8 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_1~10^6 GeV

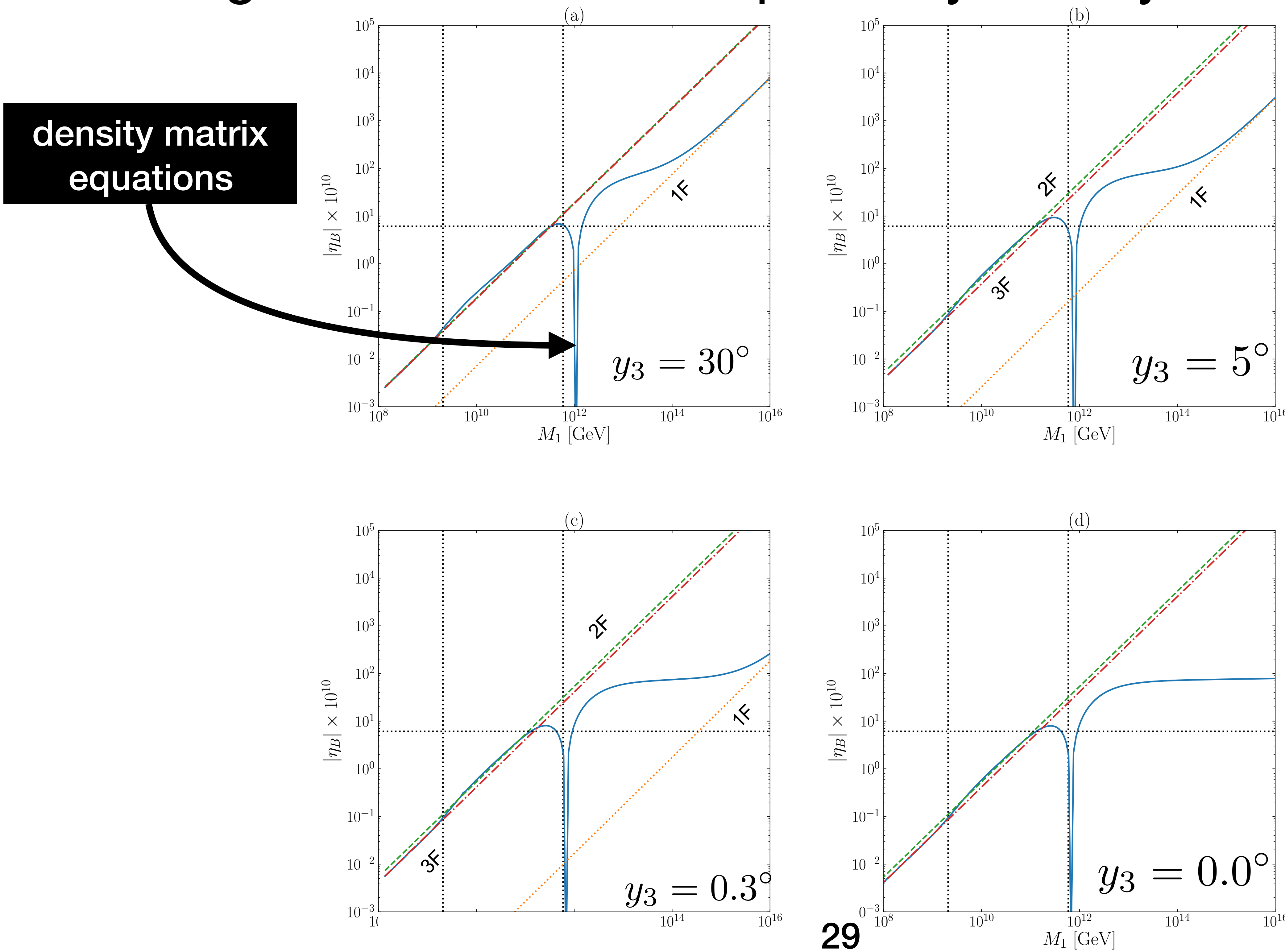
Mini summary: non-resonant thermal leptogenesis can explain BAU using only low scale phases at $M_1 \sim 10^6$ GeV

Leptogenesis from Leptonic CP Violation

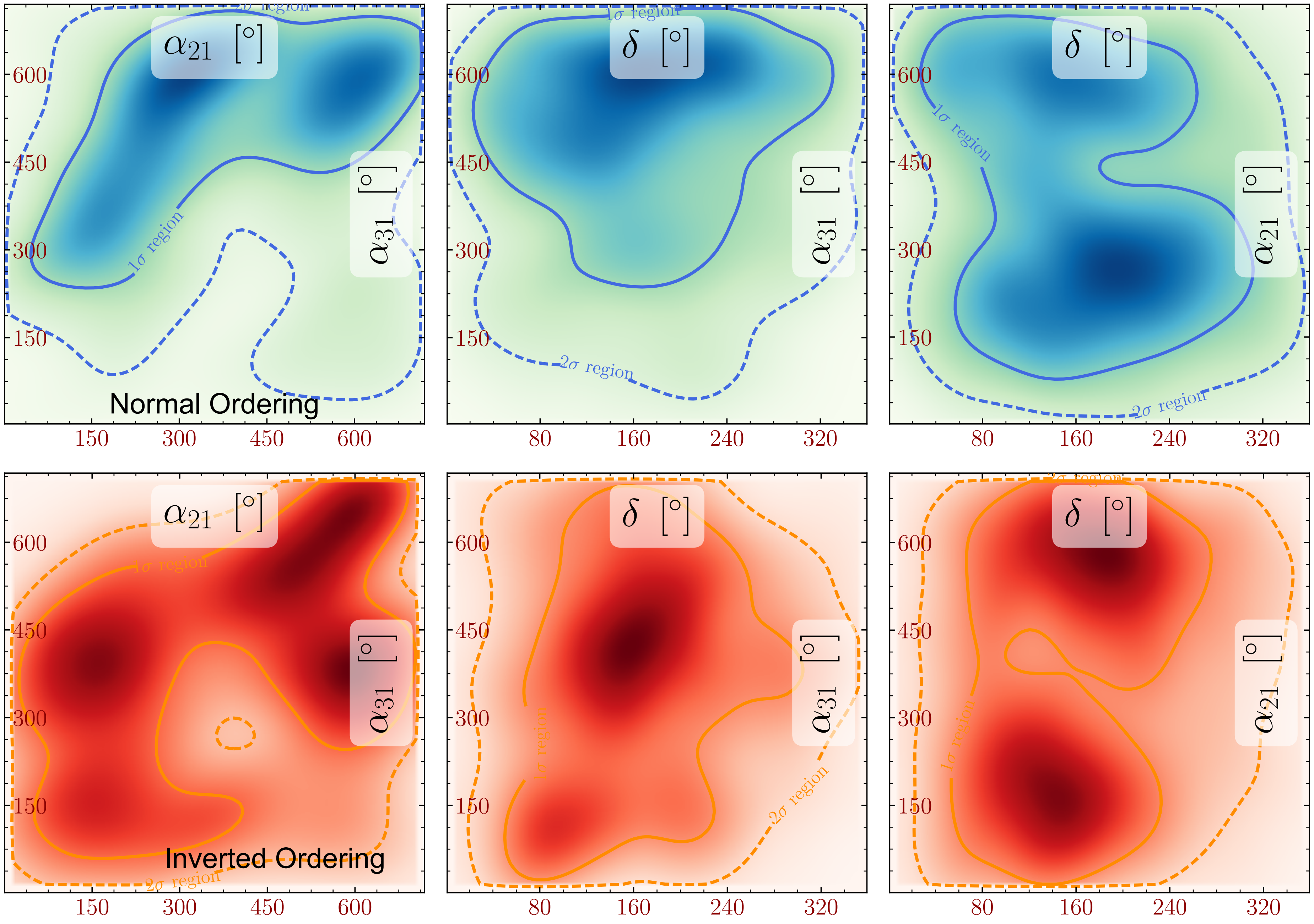
$T>10^{12}$ GeV

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.

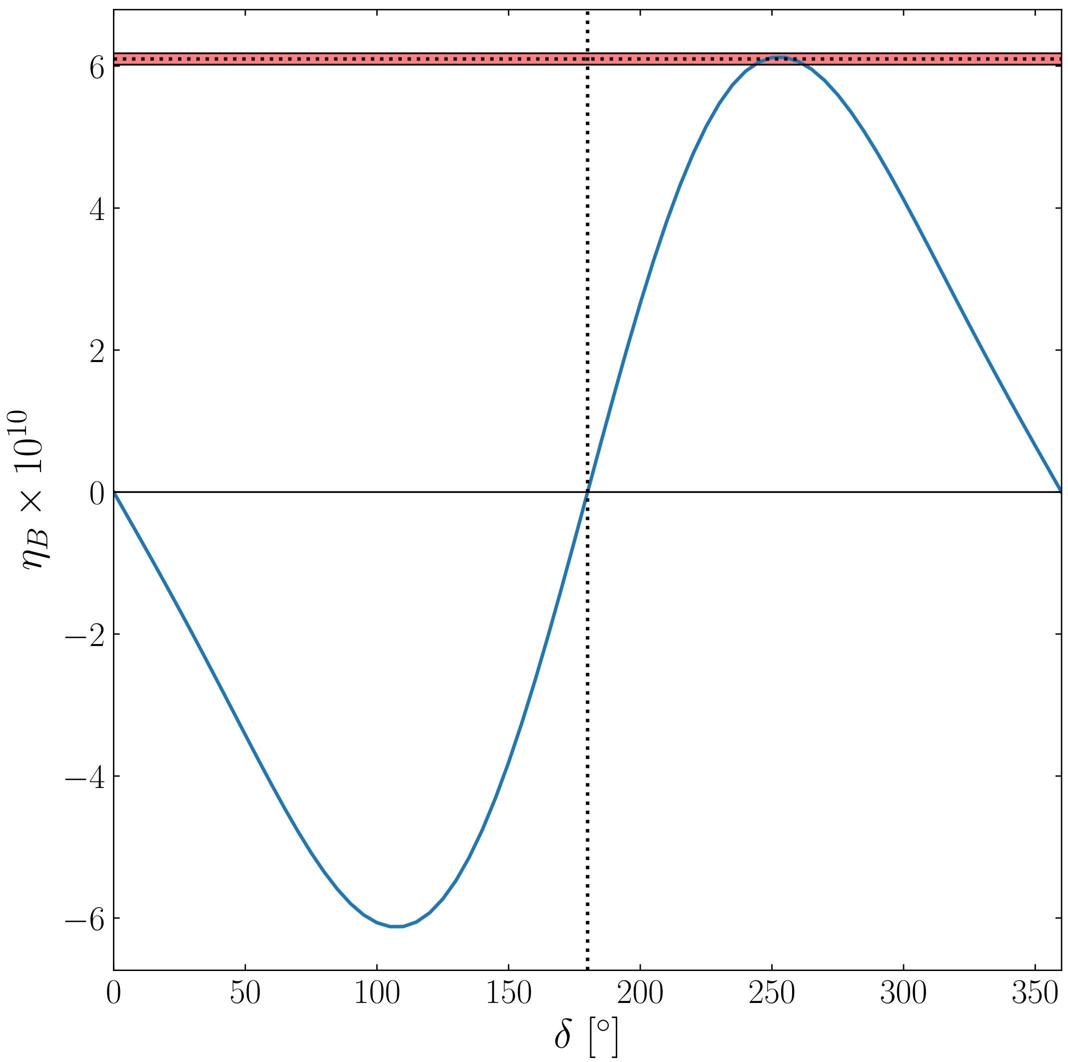


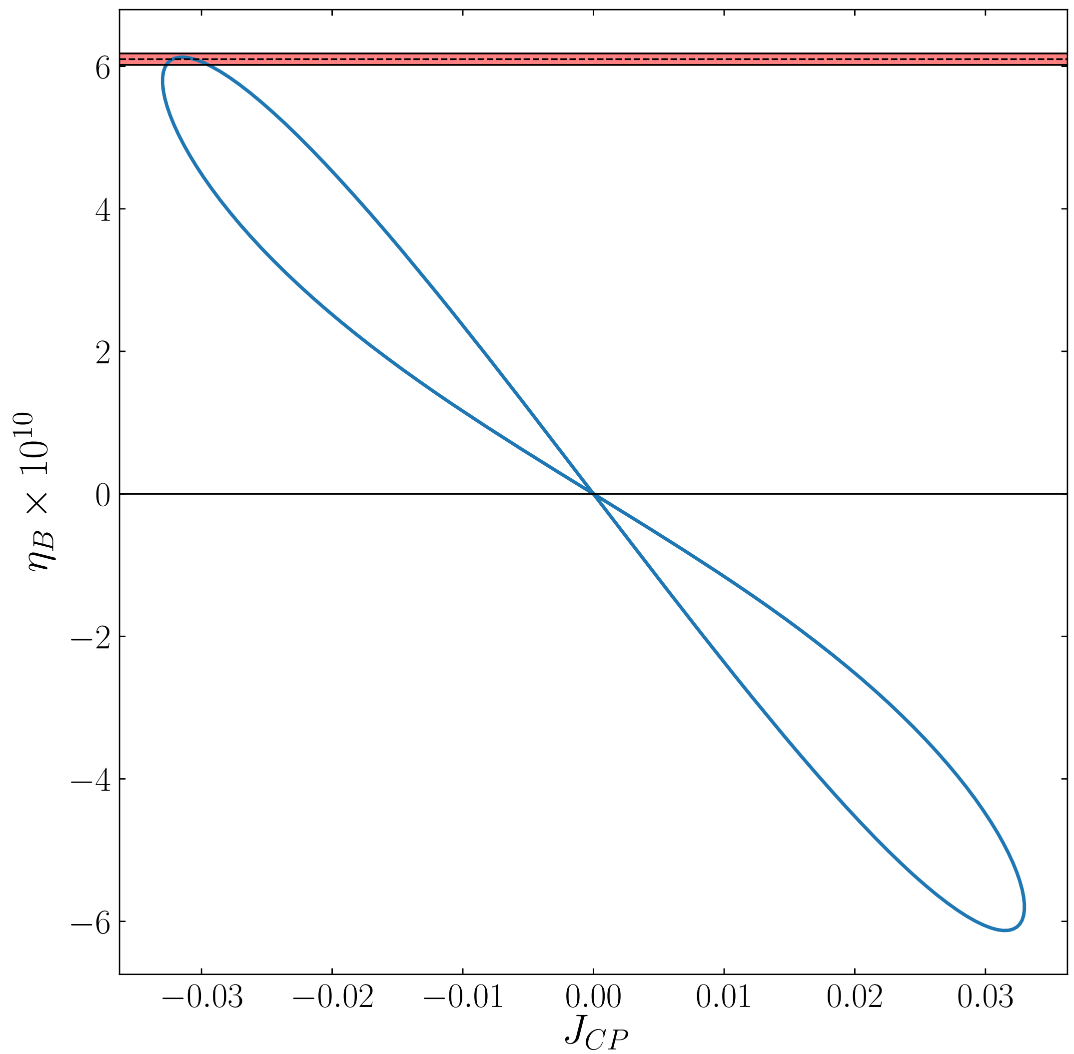
Leptogenesis from Leptonic CP Violation



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

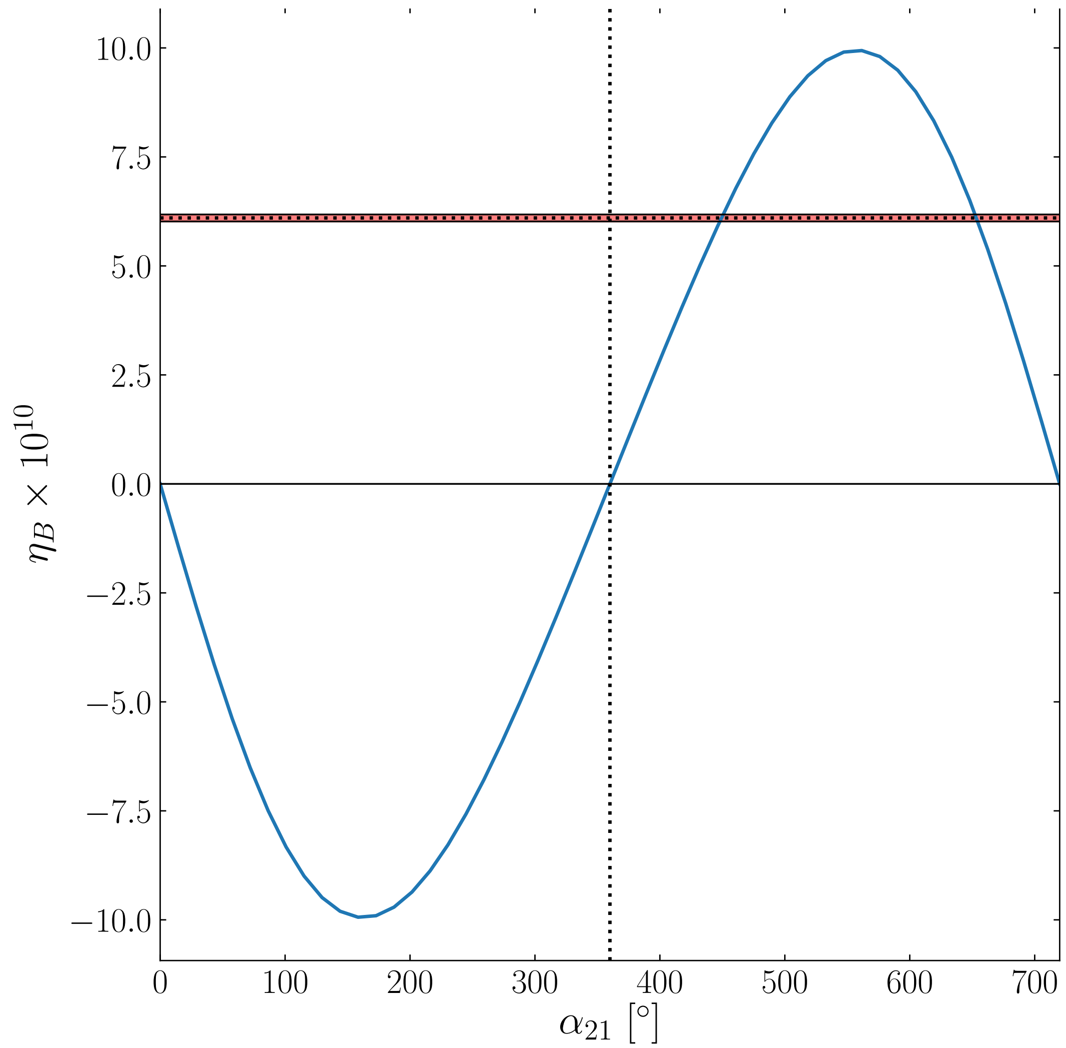
Pure Dirac CPV

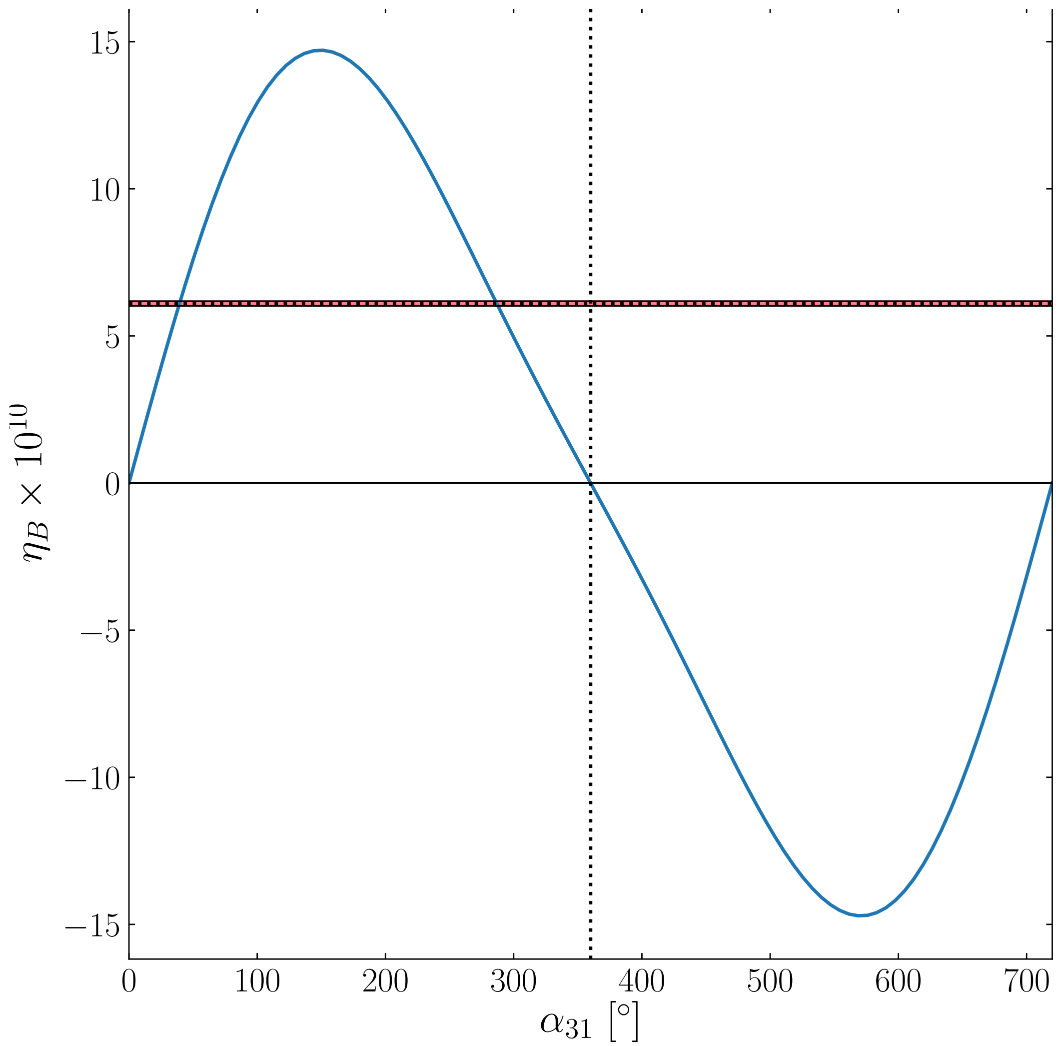




$$M_1 = 10^{13}\,\text{GeV},\; M_2 = 3.5 M_1,\; M_3 = 3.5 M_2$$

Pure Majorana CPV





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

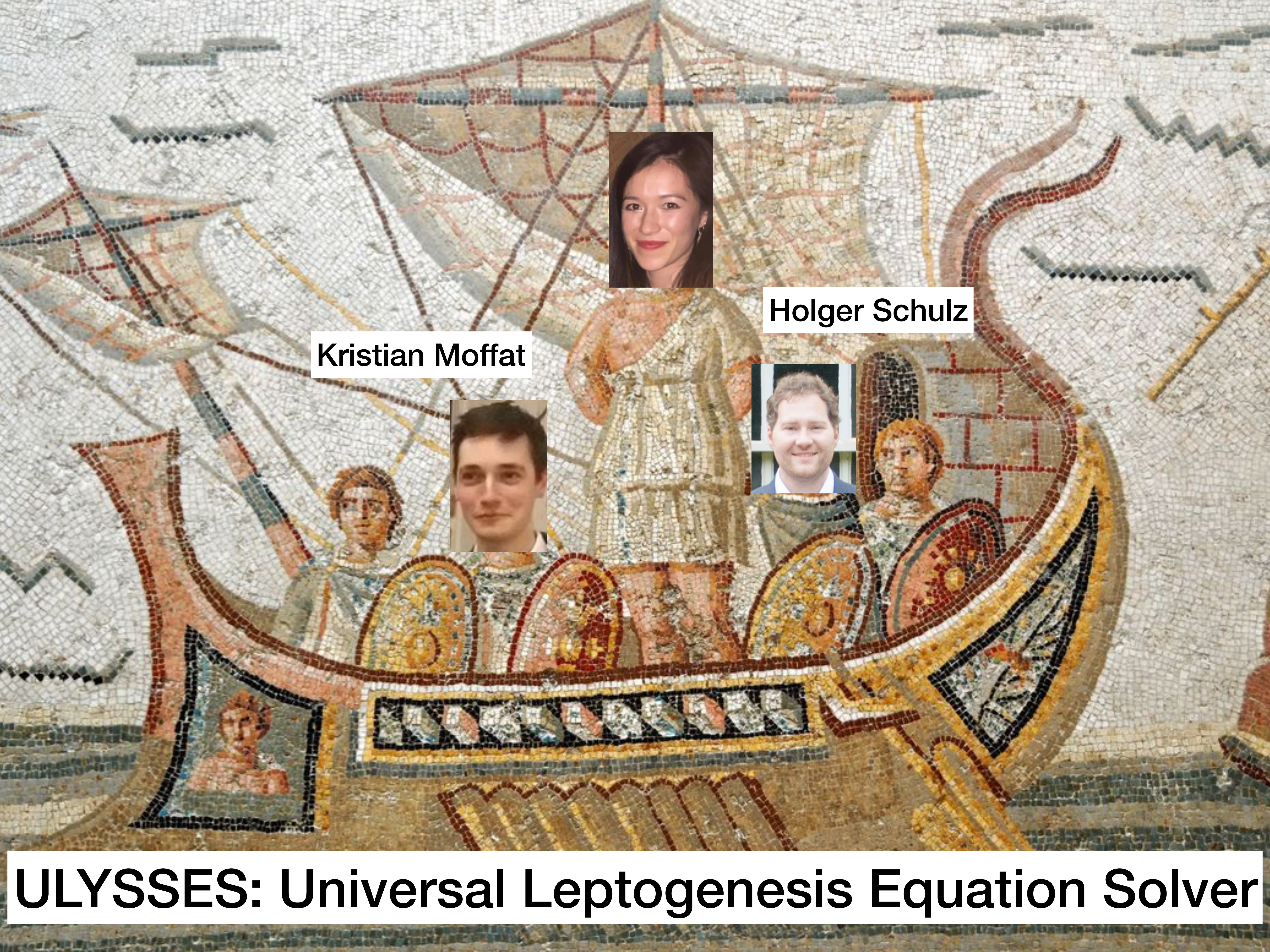
Mini summary: **non-resonant thermal leptogenesis can explain BAU using only low scale phases at $M_1 > 10^{12}$ GeV**

Conclusions

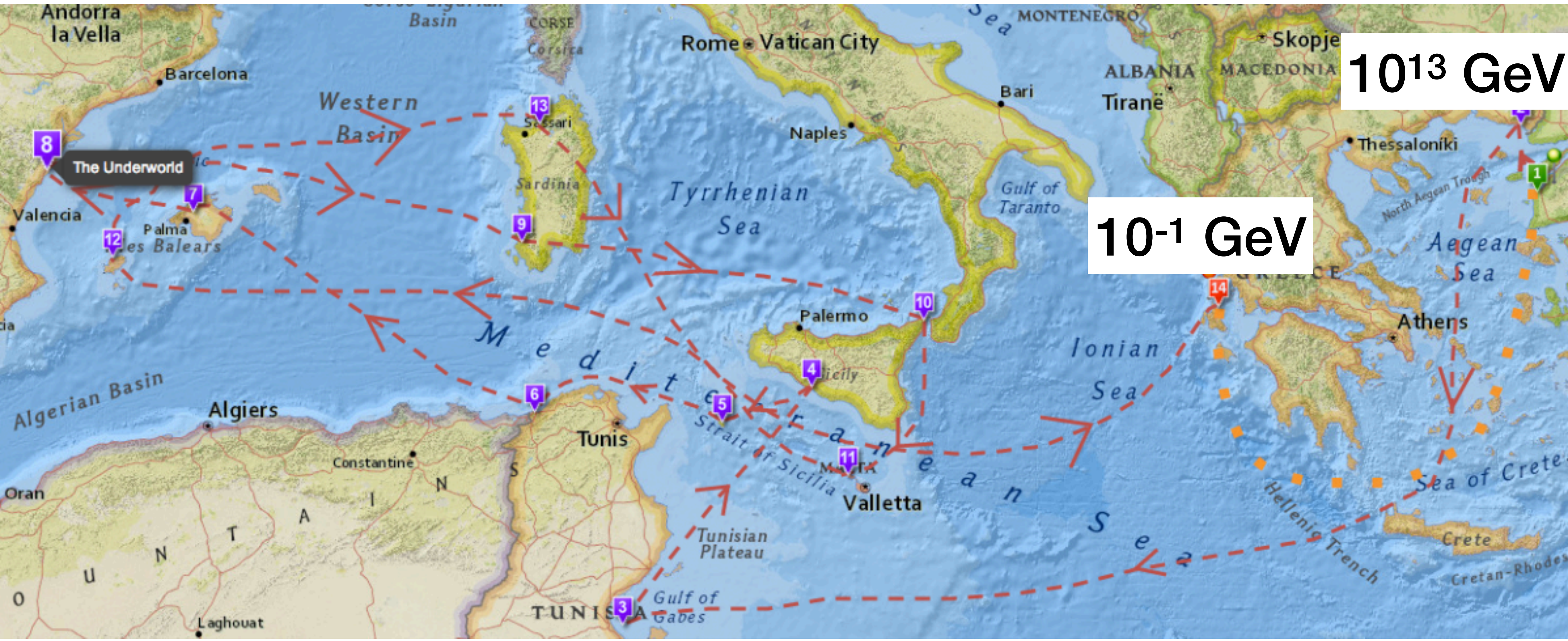
- Thermal leptogenesis is a very plausible mechanism to explain the BAU.
- The scale can be lowered (but still non-resonant) using a mild hierarchy of RHN, flavour effects and broad PS exploration.
- Low scale leptonic phases can produce the BAU over many (10^6 - 10^{13} GeV) orders of magnitude.

“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.”

ULYSSES: Universal Leptogenesis Equation Solver


Holger Schulz
Kristian Moffat
ULYSSES: Universal Leptogenesis Equation Solver

Scale Odyssey



Step 1: Installation

```
pip3 install ulysses --user
```

Step 2: Pick a point

```
delta 31.713030
a21 130.953483
a31 649.655874
x1 -72.335979
y1 170.549206
x2 86.969063
y2 2.223559
x3 -1.862141
y3 178.312158
m -0.942835
t12 33.630000
t23 46.633046
t13 8.520000
M1 6.500000
M2 7.200000
M3 7.900000
```

point.txt

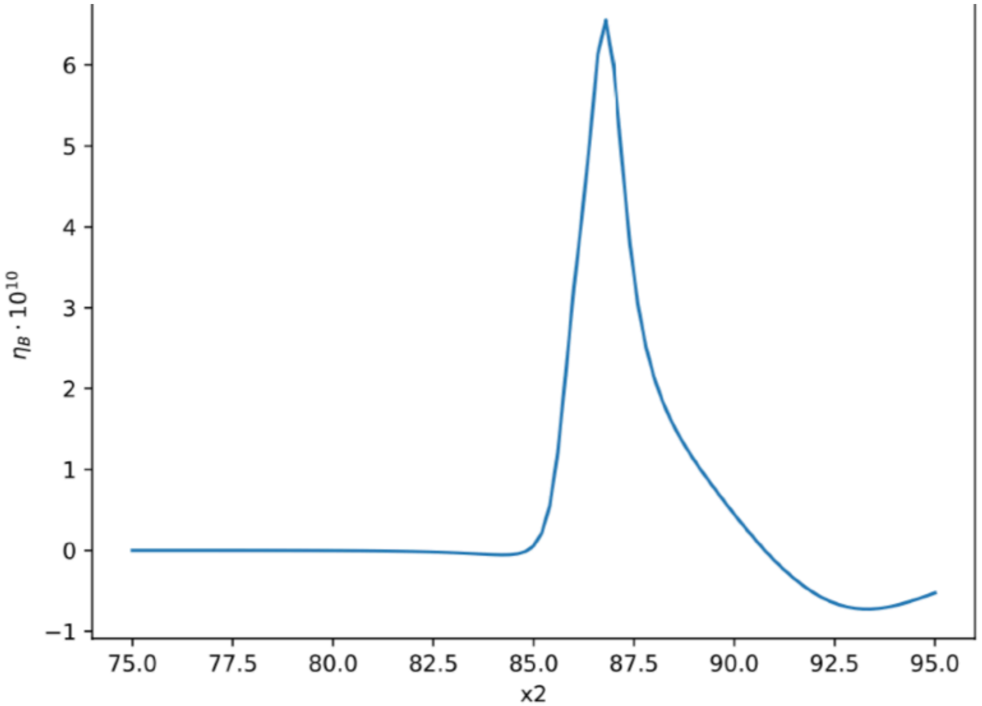
Step 2: Pick a mechanism

```
ulc-calc -m 3DME point.txt
```

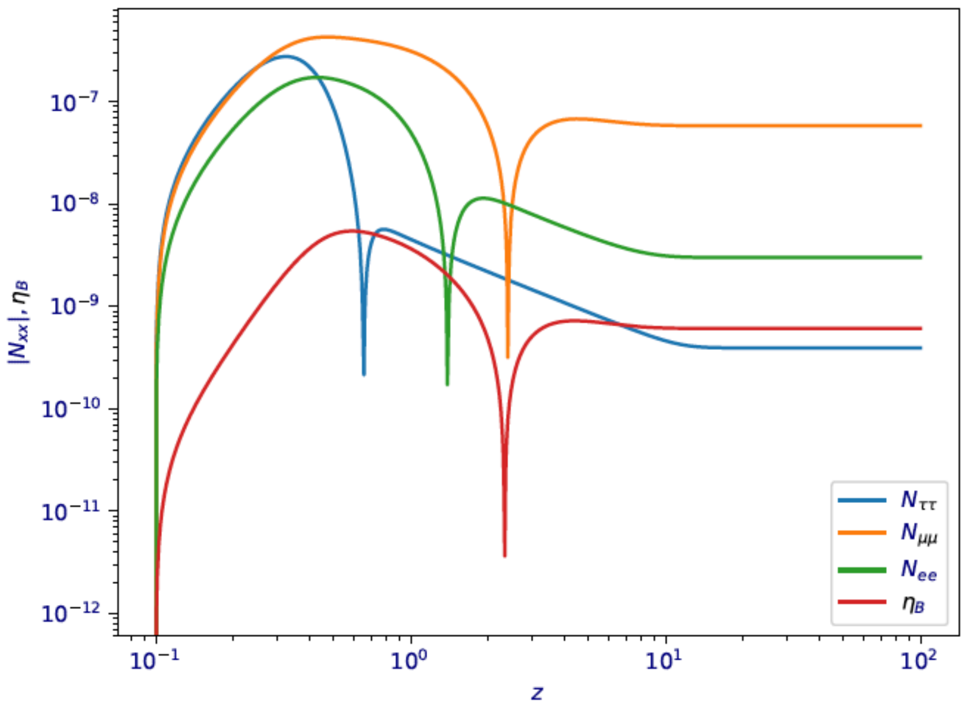
Density matrix equations with 3 decaying steriles

Step 3: Output etaB and plots

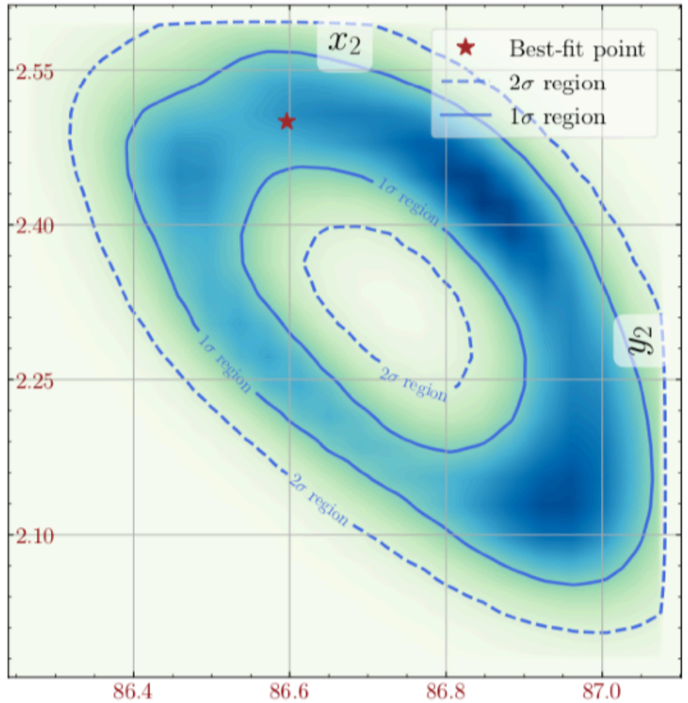
```
ulc-scan -m 3DME scan_x2.txt -o scan_x2.pdf -n 40
```




```
ulc-calc -m 3DME point.txt -o evolution.pdf
```



Step 4: uls-nest a multidimensional likelihood scanner based on MultiNest. Computationally expensive so we use MPI implementation




```
mpirun -np 256 uls-nest -m 3DME scan_x2_y2.ranges -o 2Dscan --loop --mn-points 10(
```

Thank you for your attention

Back up slides

Formulae

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

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

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

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

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

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

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

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

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N1} - N^{\mathrm{eq}}_{N_1})$$

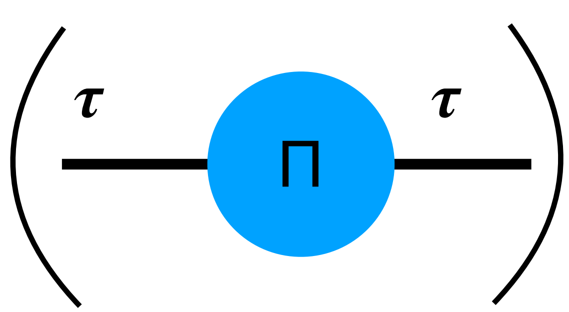
$$\frac{dN_{N_2}}{dz} = -D_2(N_{N2} - N^{\mathrm{eq}}_{N_2})$$

$$\frac{dN_{N_3}}{dz} = -D_3(N_{N3} - N^{\mathrm{eq}}_{N_3})$$

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

washout projects along different directions of flavour space

CP-asymmetry promoted to matrix

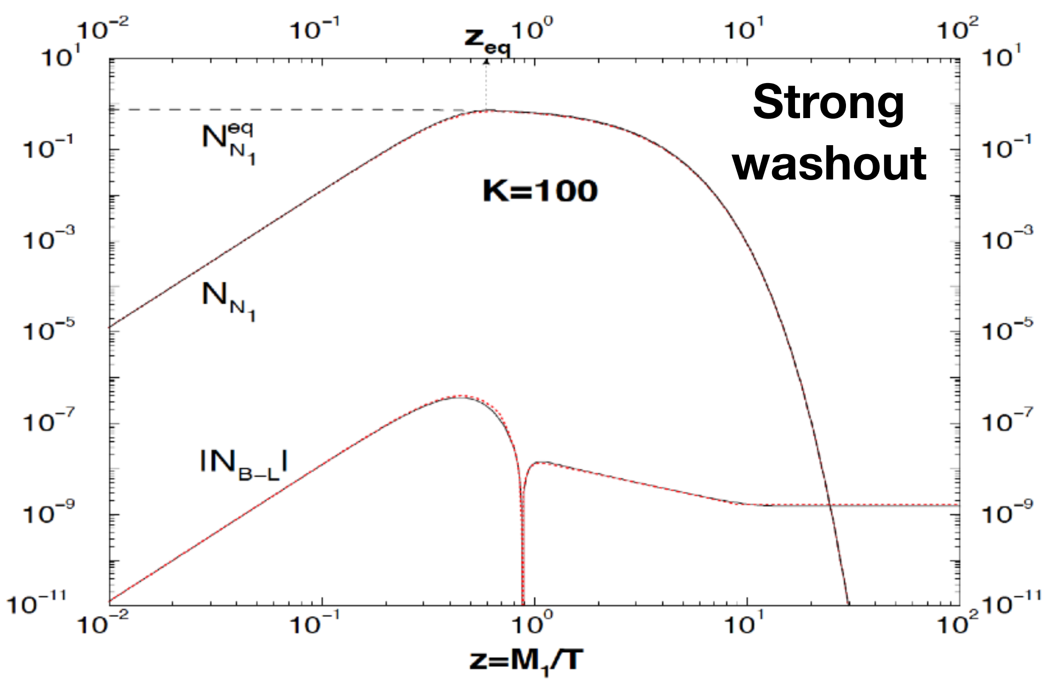
Im 

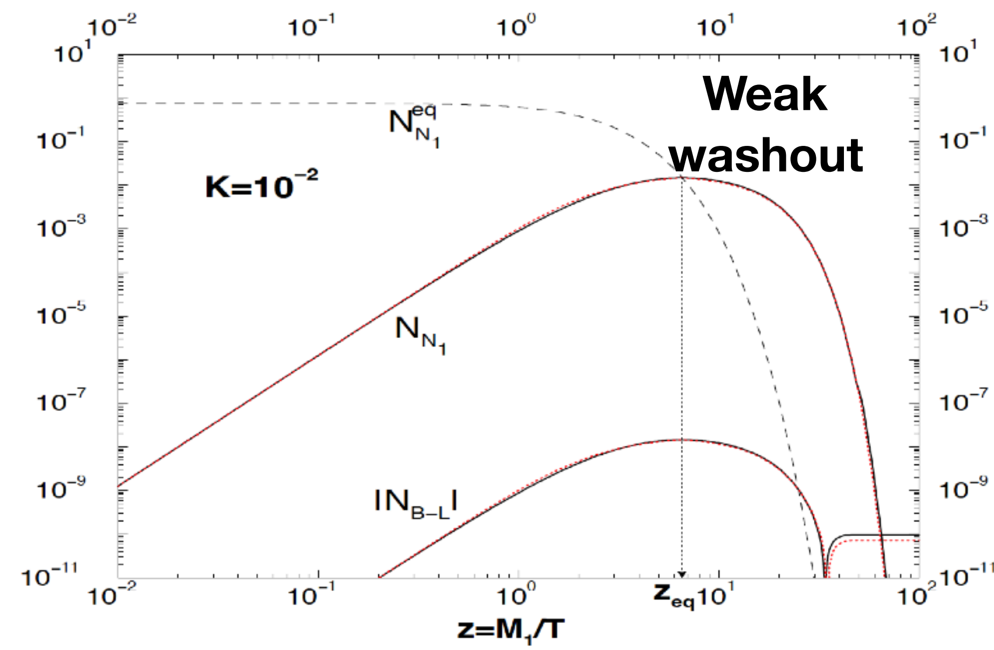
= thermal width

Self-energy of tau/muon controls flavour effects

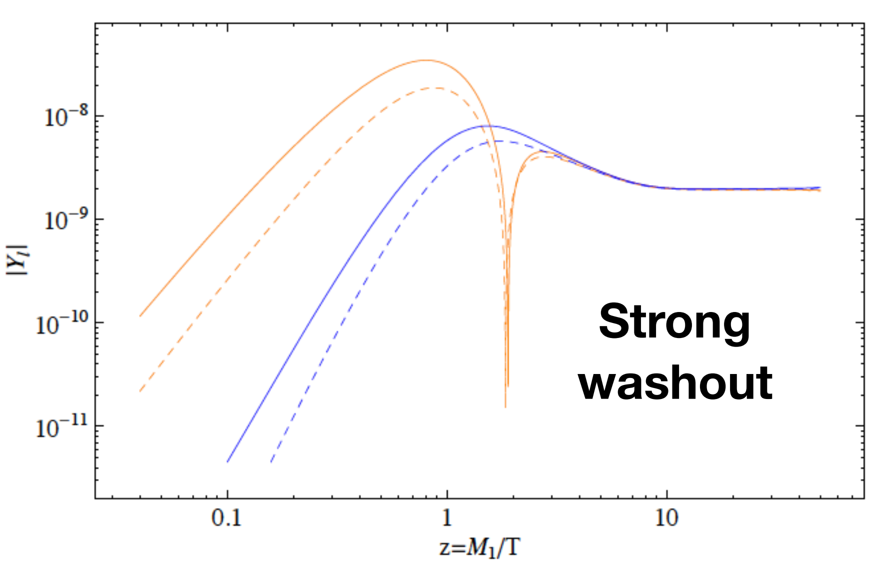
Semi-Classical Justification

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



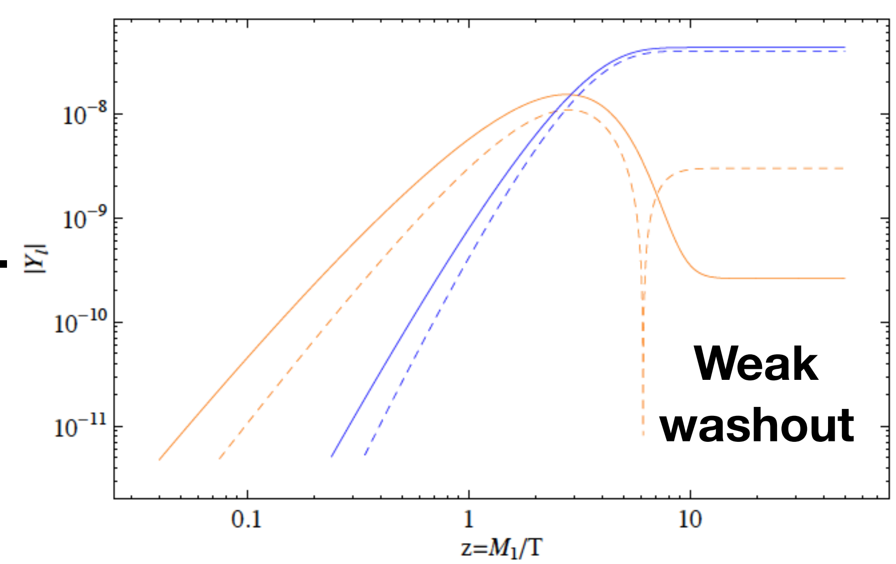


Plots from 1002.1326. Garbrecht etal

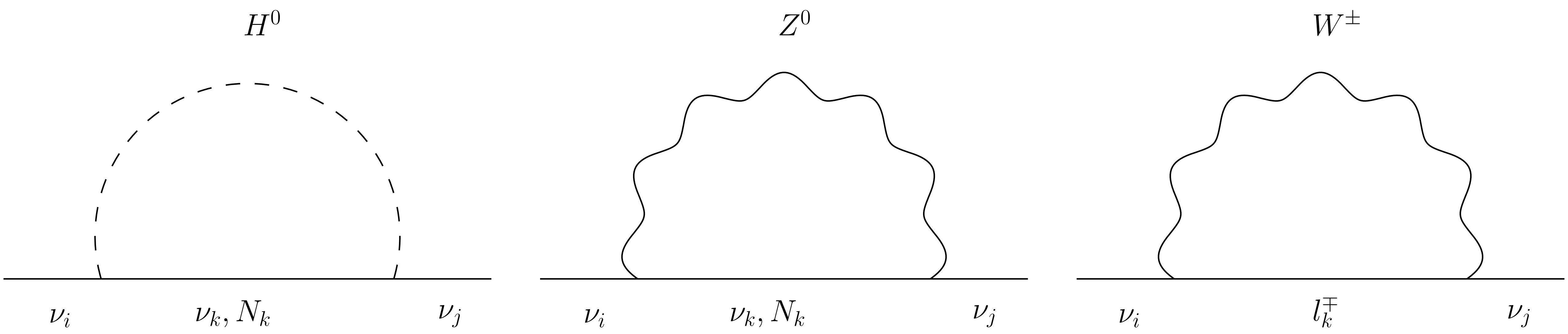


Strong washout FDFT effects negligible.
Weak washout FDFT important.

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

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

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

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

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

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

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

Fine Tuning

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