Leptogenesis in natural low-scale seesaw mechanisms

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Baryon asymmetry of the Universe (BAU)

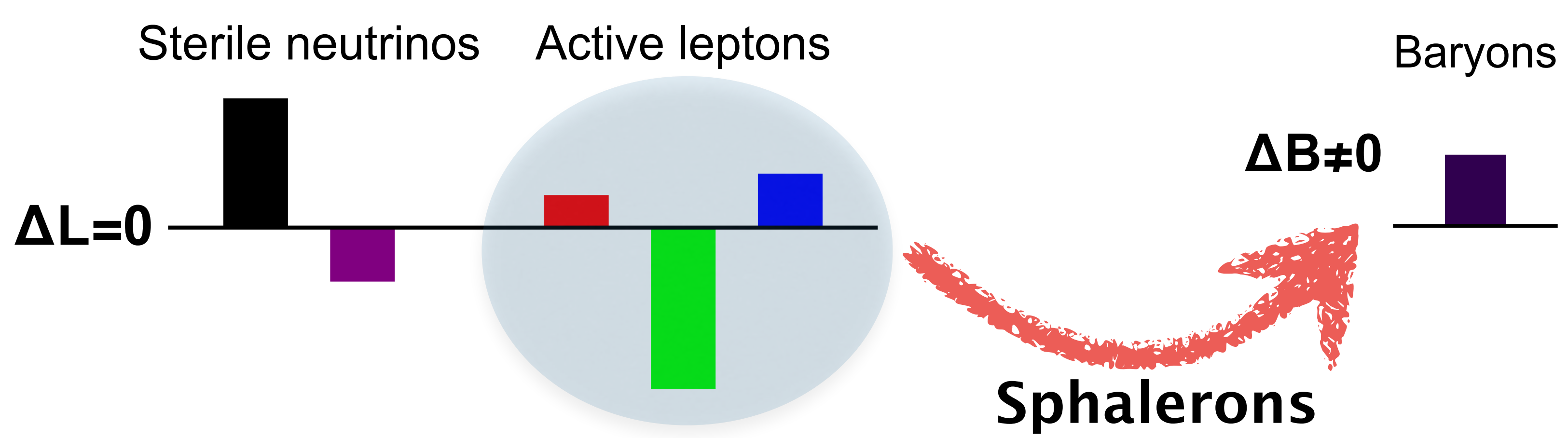
The Universe is matter dominated, the Standard Model cannot account for the BAU

$$Y_{\Delta B} = (8.6 \pm 0.01) \times 10^{-11}$$

ARS MECHANISM: low scale leptogenesis from neutrino oscillations

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, [hep- ph/9803255]
T. Asaka and M. Shaposhnikov, [hep-ph/0505013]
M. Shaposhnikov, [arXiv:0804.4542 [hep-ph]]
T. Asaka and H. Ishida, [arXiv:1004.5491 [hep-ph]]
T. Asaka, S. Eijima and H. Ishida, [arXiv:1112.5565 [hep-ph]]
L. Canetti, M. Drewes and M. Shaposhnikov, [arXiv:1204.4186 [hep-ph]]
L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, [arXiv:1208.4607 [hep-ph]]

- **Complex Yukawa** couplings as a source of $\not{C}P$
- **Matter and temperature** effects in the **primordial plasma**
- The **total lepton number** is **conserved** during oscillations



Naturalness argument

Need a pair of **degenerate** (RH or sterile) neutrinos (minimal setup): fine-tuning or **symmetry**

Approximate lepton number at the origin of mass degeneracy

$$M = \underbrace{M_0}_{\Delta L = 0} + \underbrace{\Delta M}_{\Delta L \neq 0}$$

$$||\Delta M|| \ll ||M_0||$$ ➔ **degenerate pseudo-Dirac pairs of sterile neutrinos**

Minimal setup: SM + 2 sterile fermions with opposite lepton number

Field content: $\overbrace{\nu_L + N_1}^{L=1} + \overbrace{N_2}^{L=-1}$

$$M_0 = \begin{pmatrix} 0 & vy & 0 \\ vy & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}$$

$m_\nu = 0$

$M_1 = M_2 = \Lambda$

"Lepton number conserving" mass spectrum

(some) Minimal mechanisms

$$M_0 = \begin{pmatrix} 0 & vy & 0 \\ vy & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}$$

Basis: (ν_L, N_1^c, N_2^c)

L=1

L=-1

Need to perturb M_0 to generate $m_\nu \neq 0$ and $\Delta M_{heavy} \neq 0$

Add small $\Delta L=2$ operators (assume $\varepsilon, \zeta, \zeta' \ll 1$)

$$\Delta M_{linear} = \begin{pmatrix} 0 & 0 & \epsilon vy \\ 0 & 0 & 0 \\ \epsilon vy & 0 & 0 \end{pmatrix} \qquad \Delta M_{ISS} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \zeta\Lambda \end{pmatrix} \qquad \Delta M_{loop} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \zeta'\Lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Toy model (one active neutrino)

	ISS	Linear	Loop
m_ν	$\zeta y^2 \frac{v^2}{\Lambda}$	$2\epsilon y^2 \frac{v^2}{\Lambda}$	$\zeta' y^2 \frac{v^2}{\Lambda} f\left(\frac{\Lambda^2}{M_W^2}\right)$
ΔM^2_{32}	$2\zeta\Lambda^2$	$4\epsilon v^2 y^2$	$2\zeta'\Lambda^2$

$M_1 = m_\nu$

$M_{2,3} \simeq \Lambda$

Viable mechanisms (minimal setup)

Toy model

	ISS	Linear	Loop
m_ν	$\zeta y^2 \frac{v^2}{\Lambda}$	$2\epsilon y^2 \frac{v^2}{\Lambda}$	$\zeta' y^2 \frac{v^2}{\Lambda} f\left(\frac{\Lambda^2}{M_W^2}\right)$
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Requirements

Neutrino data

$$m_\nu \gtrsim \sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}\ \text{eV}$$

Successful leptogenesis

Need a pair of

$$y < \sqrt{2} \times 10^{-7}$$ out of equilibrium

$$100\ \text{MeV} \leq M_{2,3} \lesssim 20\ \text{GeV}$$ relativistic

BBN bound

$$\Delta M_{32} \lesssim 100\ \text{keV}$$ degenerate

sterile neutrinos

Only ISS: too large mass splitting or too small neutrino masses
Only linear: no mass splitting when Higgs VEV v=0

The minimal framework

Linear + inverse seesaw perturbations

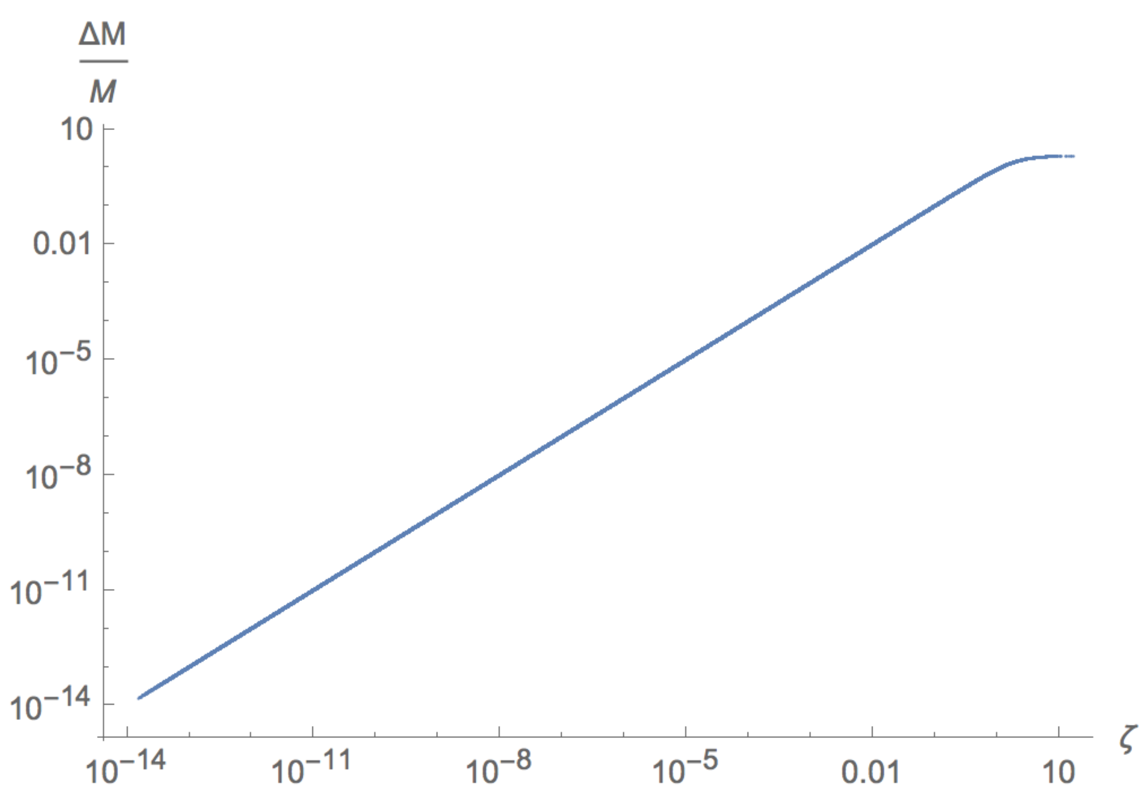
SM + 2 RH neutrinos with opposite lepton number

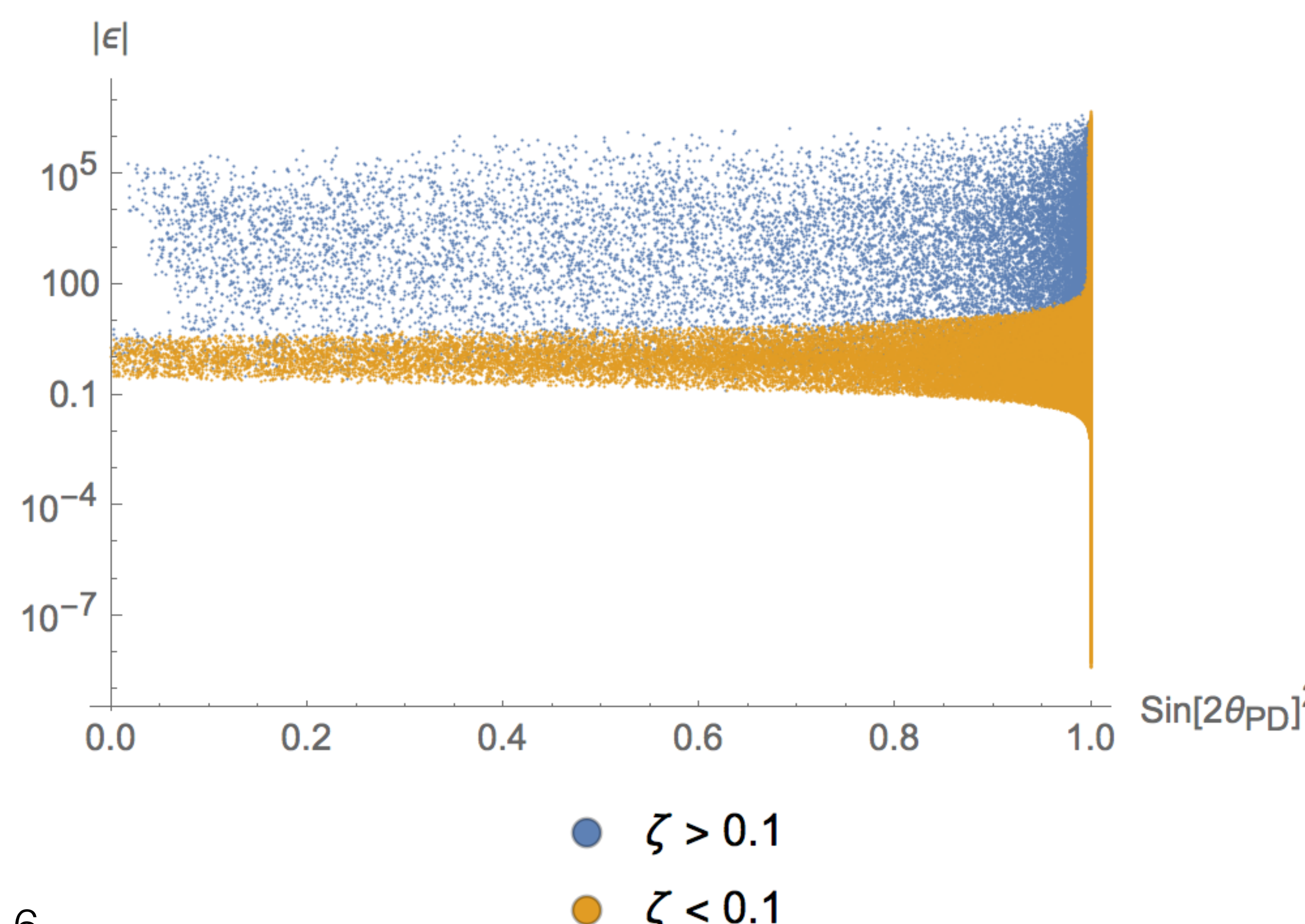
"Minimal flavour seesaw"

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez, [arXiv:0906.1461 [hep-ph]]

$$\mathcal{M} = \begin{pmatrix} 0 & vY & \epsilon v Y' \\ vY^T & 0 & \Lambda \\ \epsilon v Y'^T & \Lambda & \zeta\Lambda \end{pmatrix}$$

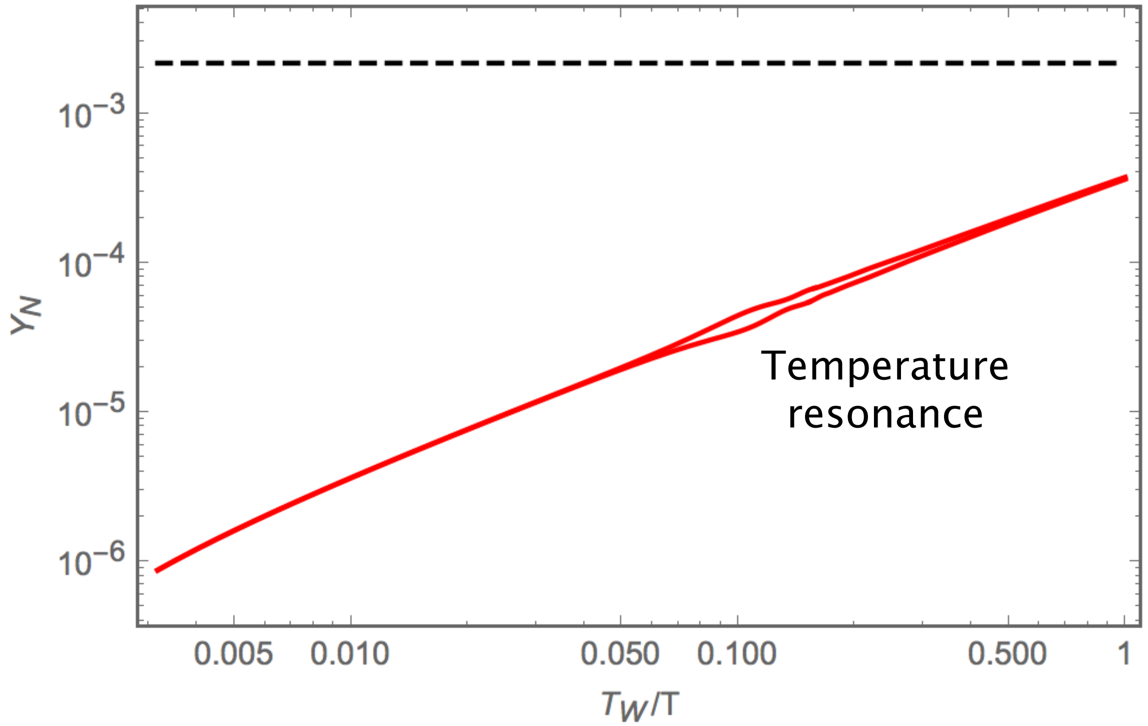
Sterile neutrino oscillations
$\zeta \ll 1 \Rightarrow$ small mass splitting
$\varepsilon \ll 1 \Rightarrow$ large mixing angle



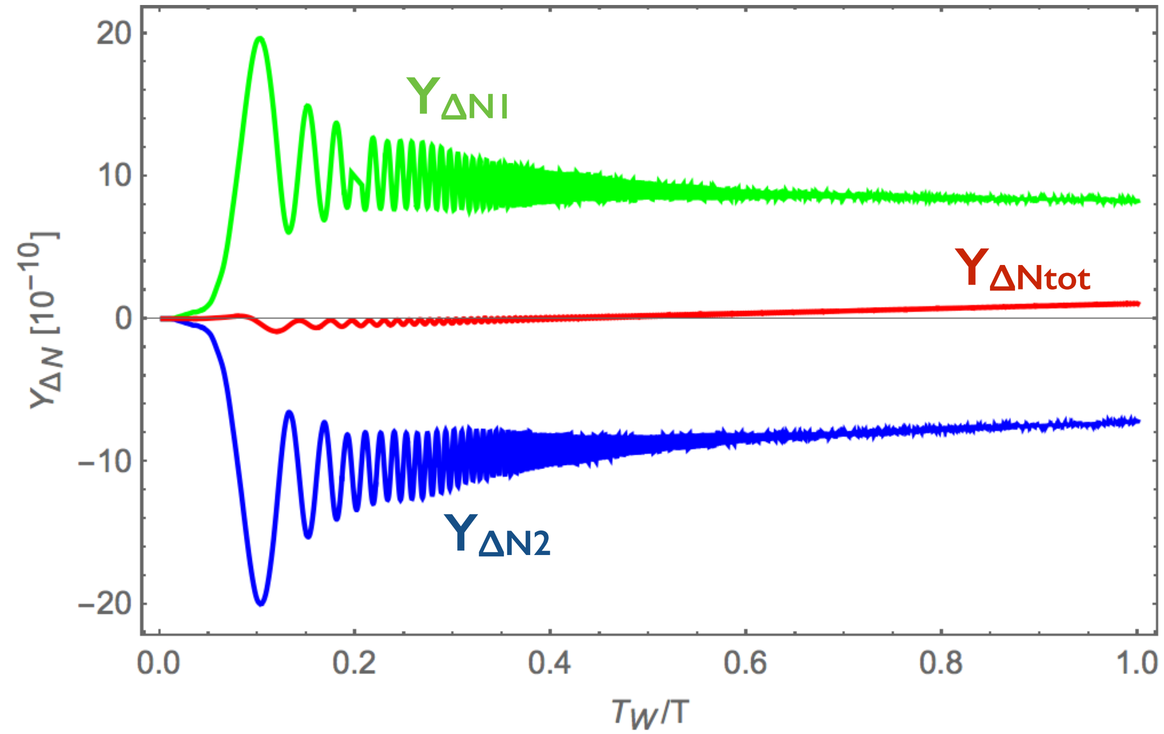


Evolution (numerical solution)

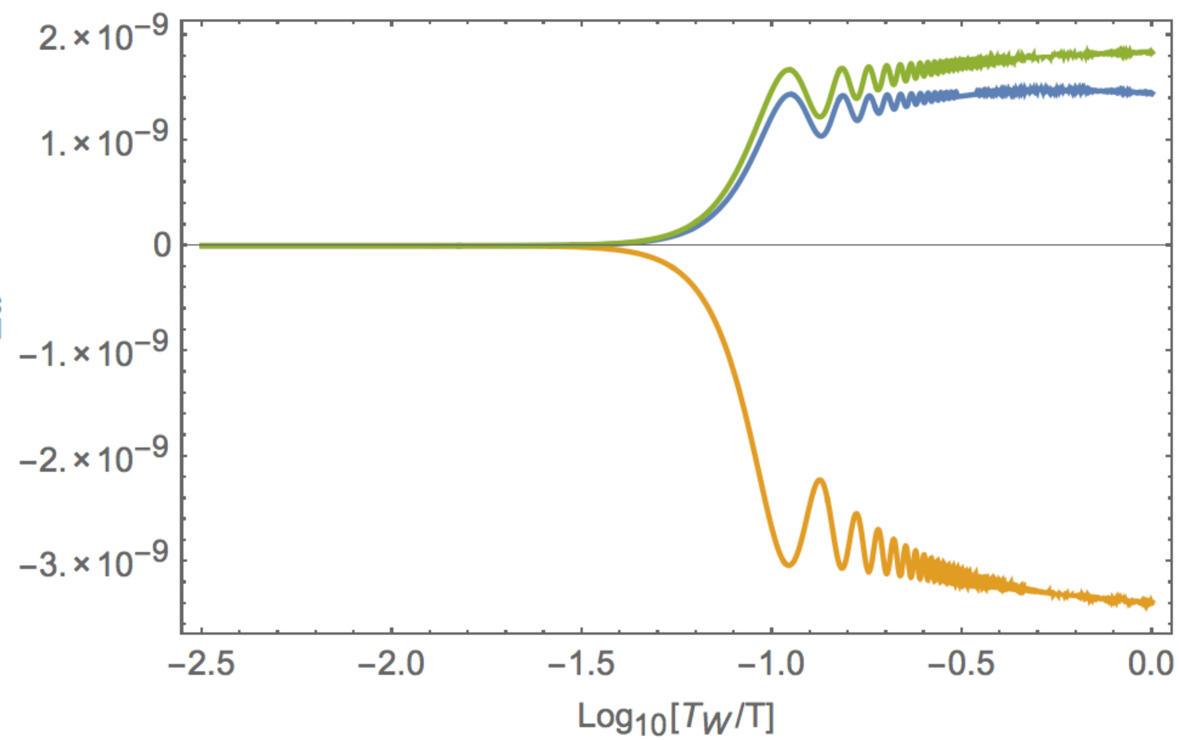
Sterile neutrino abundances



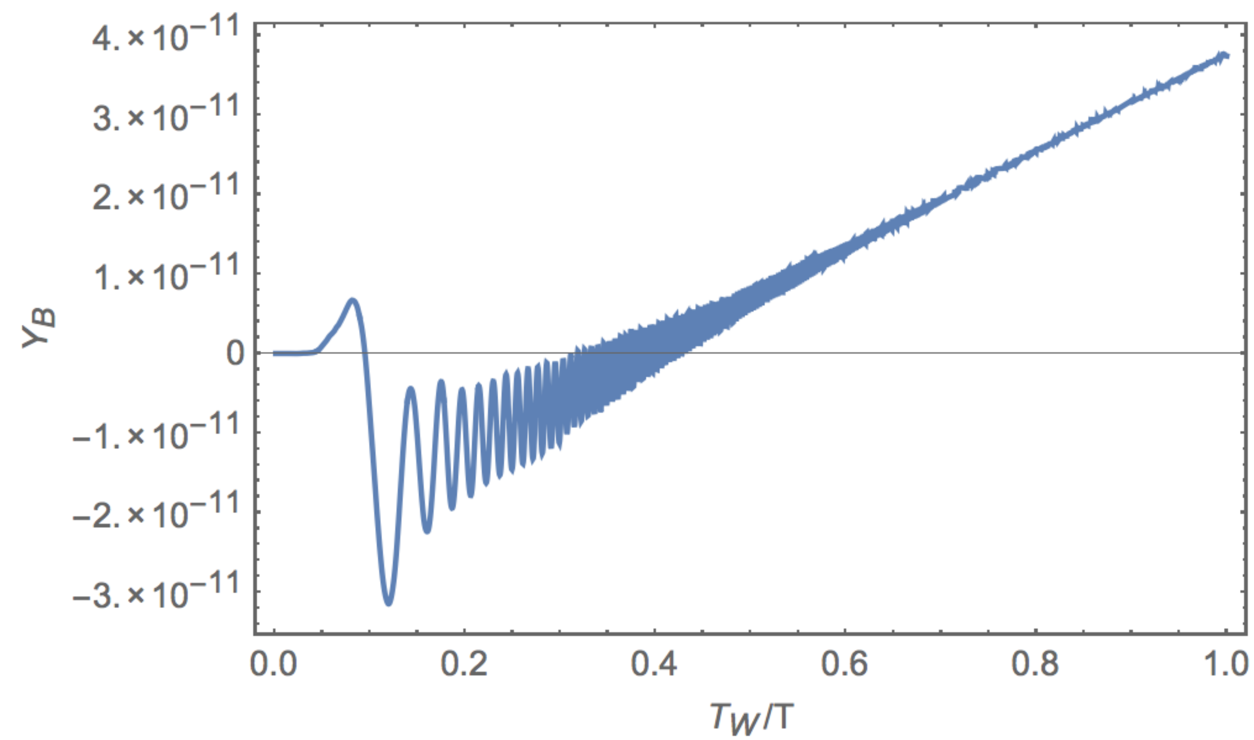
Sterile neutrino asymmetry



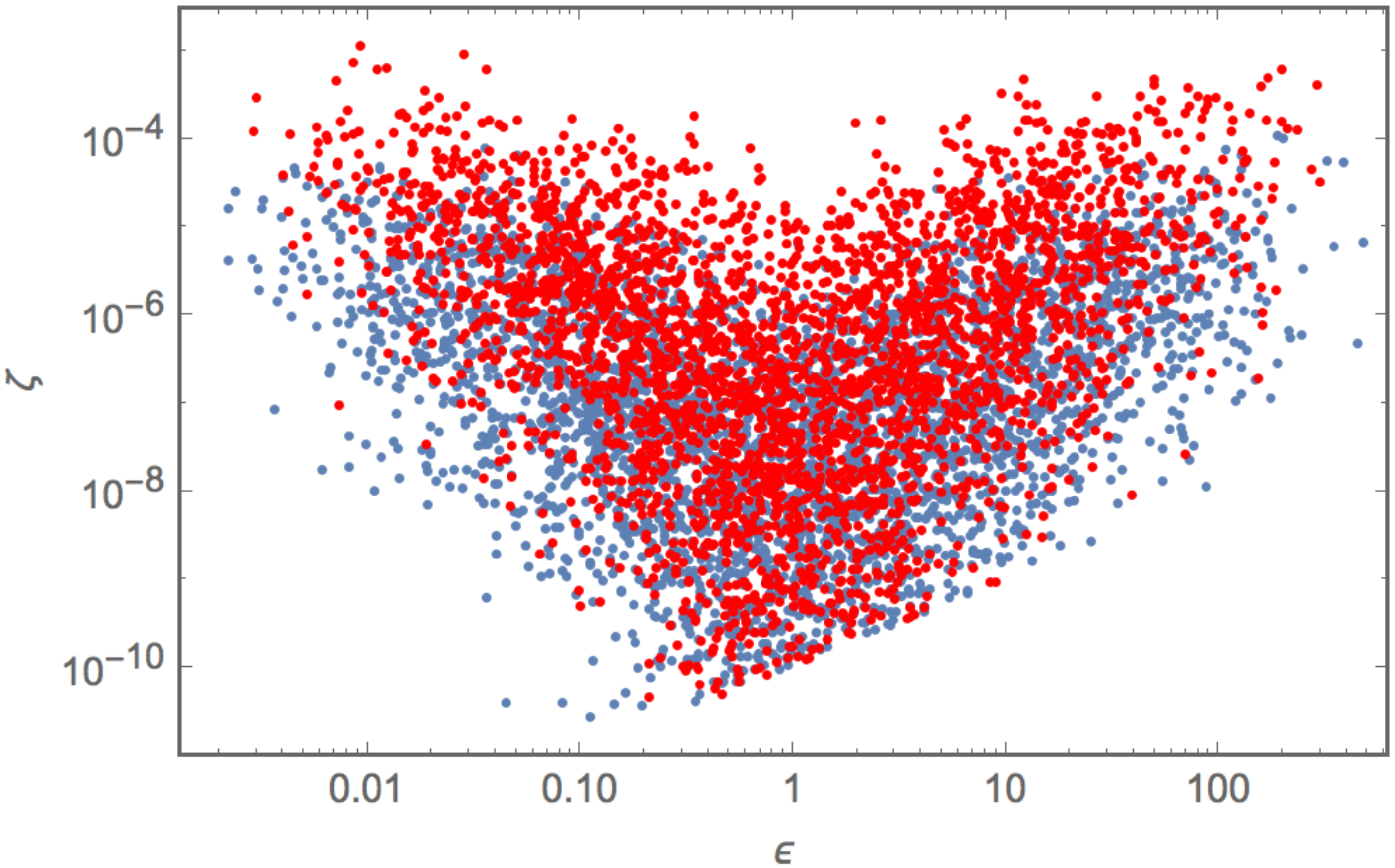
Lepton flavour asymmetry



Baryon asymmetry



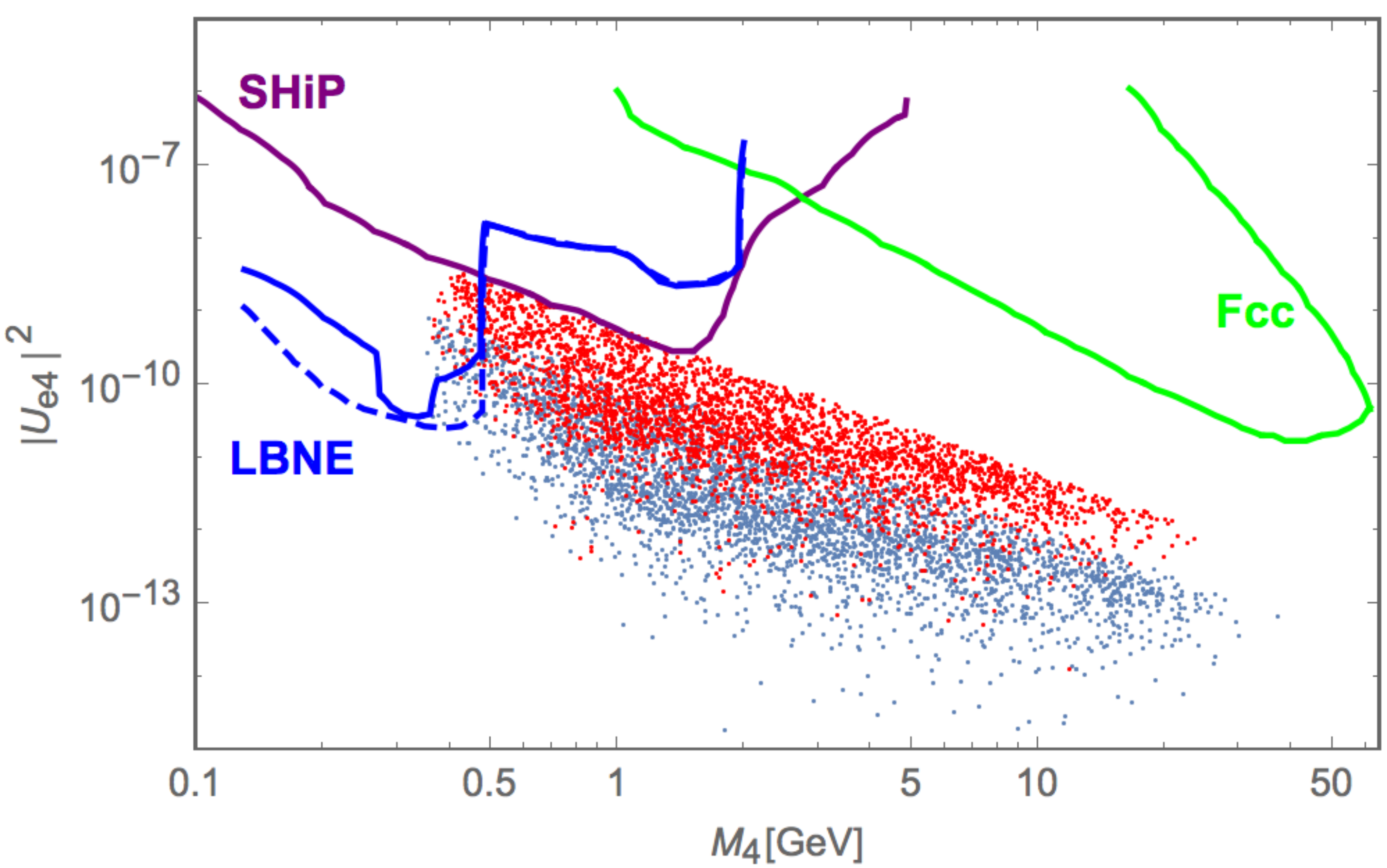
Viable solutions



LNV parameters

Normal Hierarchy

Inverted Hierarchy



Sterile fermions phenomenology

C. Adams et al., arXiv:1307.7335 [hep-ex]

S. Alekhin et al., arXiv:1504.04855 [hep-ph]

Backup

Analytical solution

$$Y_B = \frac{\pi^{3/2}}{32\, 3^{1/3}\Gamma(5/6)} \sin^3\phi \frac{M_0}{T_{\rm EW}} \frac{M_0^{4/3}}{\Delta M_{23}^{4/3}} \left(F^\dagger_{I\alpha} \delta_\alpha F_{\alpha I} \right)$$

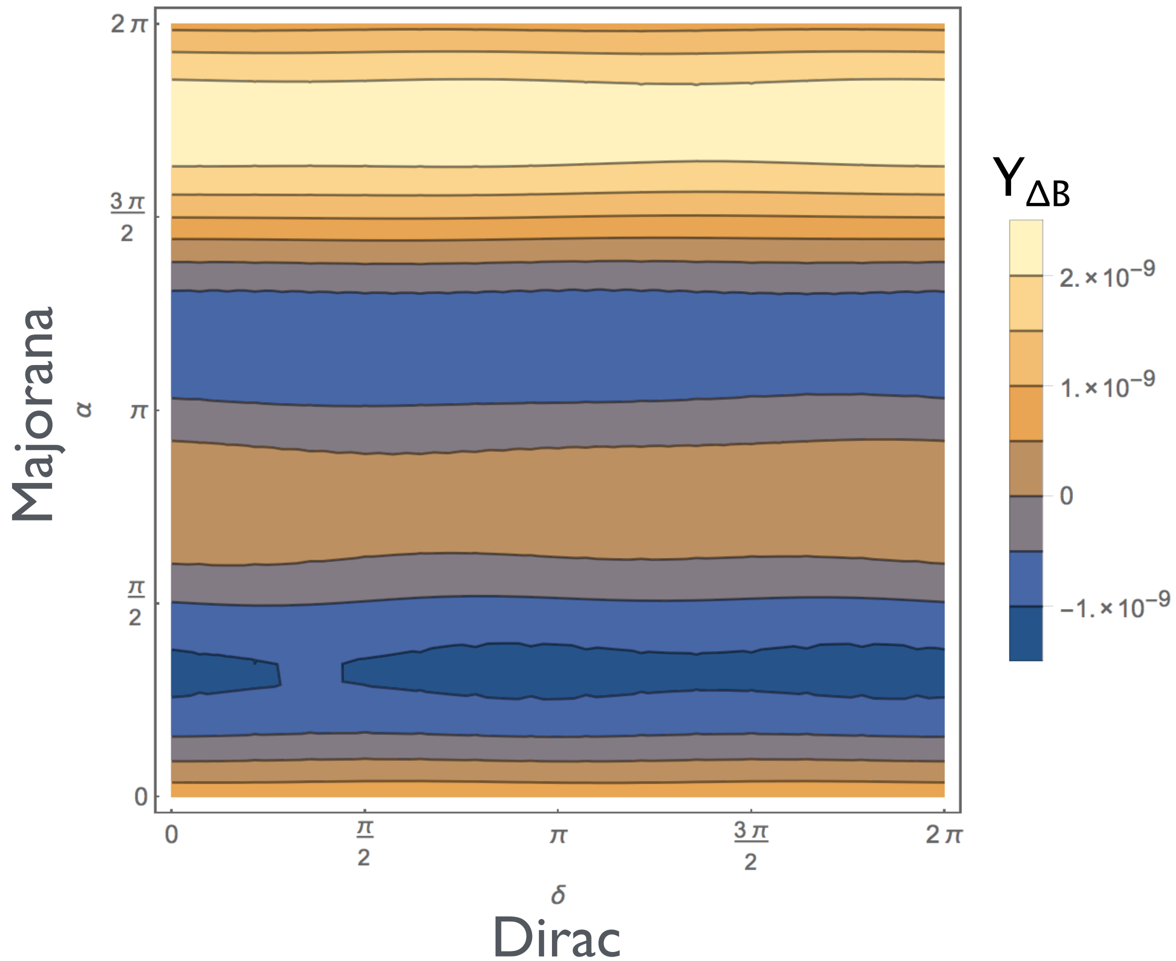
$$\mathcal{L} \ni F_{\alpha I}\, \overline{\ell^\alpha_L}\, \widetilde{H}\, N_I + h.c.$$

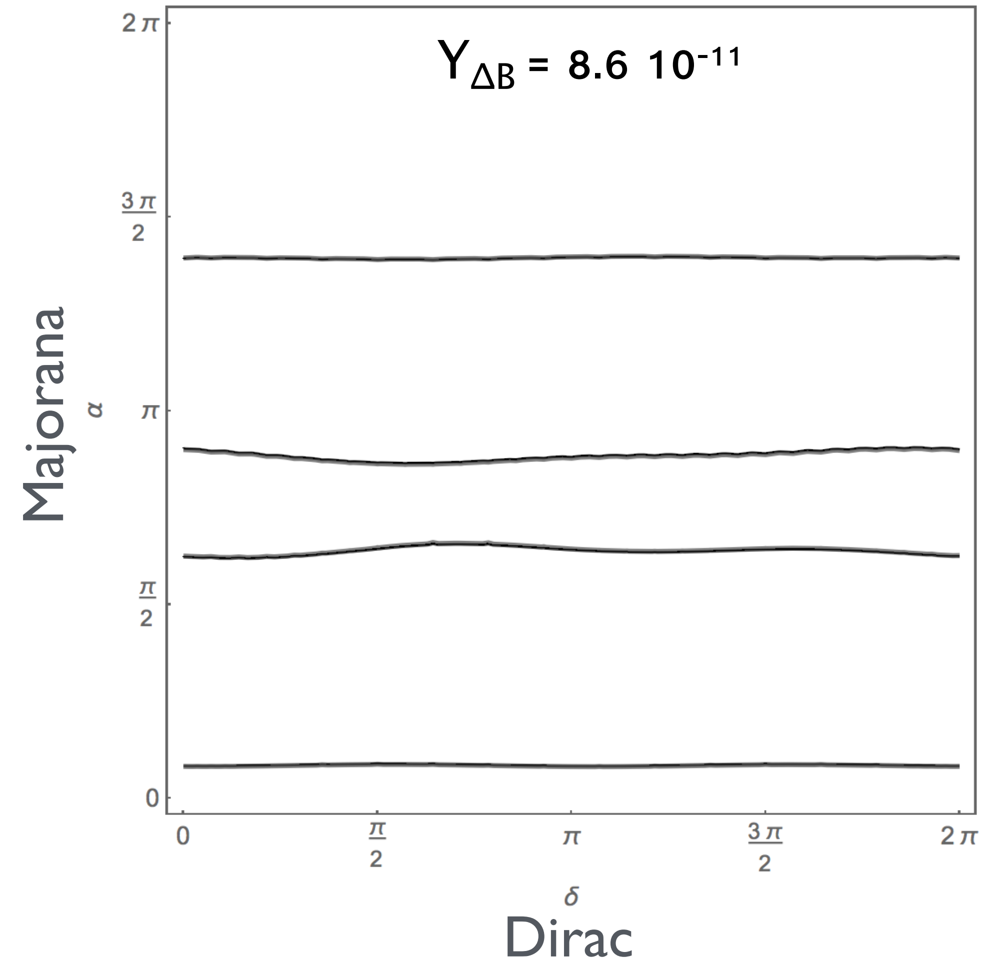
$$\delta_\alpha = \sum_{I>J} \mathrm{Im} \left[F_{\alpha I} \left(F^\dagger F \right)_{IJ} F^\dagger_{J\alpha} \right]$$

$$H = \frac{T^2}{M_0}$$

$$\frac{N_C h_t^2}{64\pi^3} = \frac{\sin\phi}{8}$$

Dirac and Majorana phase dependence





Strong dependence on **Majorana** phase

Weak dependence on **Dirac** phase

$$\mathcal{M} = \begin{pmatrix} 0 & vY & \epsilon v Y' \\ vY^{\mathrm{T}} & 0 & \Lambda \\ \epsilon v Y'^{\mathrm{T}} & \Lambda & \zeta\Lambda \end{pmatrix}$$

3 complex phases

U_{PMNS} with one massless ν

2 complex phases

Dirac
+
Majorana