Leptogenesis from Oscillations of Heavy Neutrinos with Large Mixing Angles

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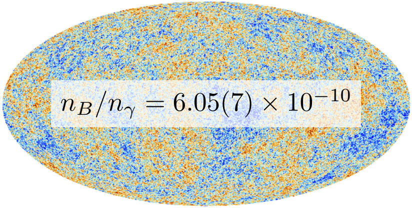
based on 1606.6690 and 1609.xxxx with Marco Drewes, Björn Garbrecht and Dario Gueter

DESY 2016, 28. September

from the BSM to-do list:

Baryon asymmetry of the universe

WMAP, Planck and Big bang nucleosynthesis:

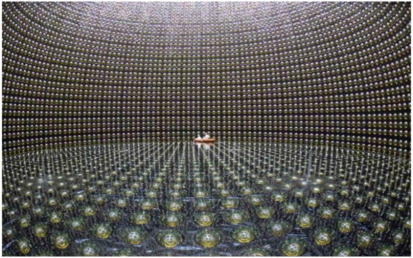


$$n_B/n_\gamma = 6.05(7) \times 10^{-10}$$

Neutrino masses

Nobel prize 2015

Kajita, McDonald



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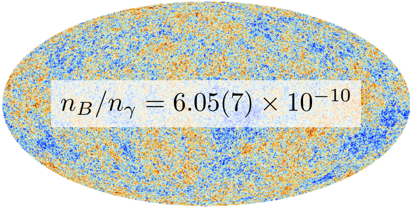

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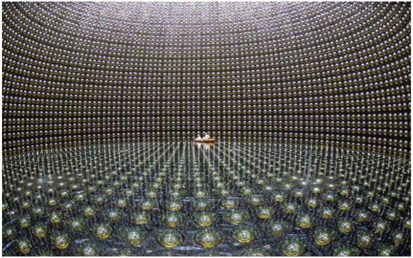
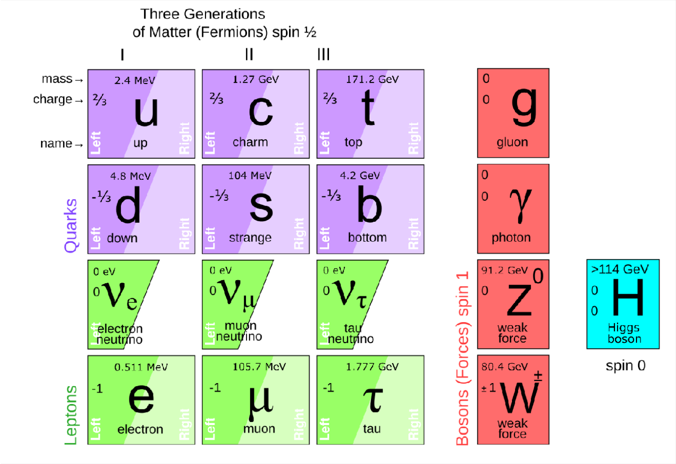


Is there a way to explain both?

Standard Model



Neutrino Masses $\to$ Seesaw Mechanism

- Dirac Mass $m_D = vY^\dagger$
- Right handed neutrino (RHN) Majorana mass M_M

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} \\ \overline{N_R} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L & N_R \end{pmatrix}$$

Active neutrino masses

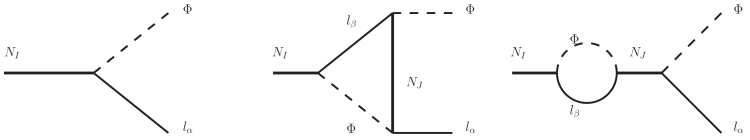
$$m_\nu = -v^2 Y^\dagger M_M^{-1} Y^*$$

Mixing with RHN

$$|U_{ai}|^2 = \left| \left(vY^\dagger M_M^{-1} \right)_{ai} \right|^2$$

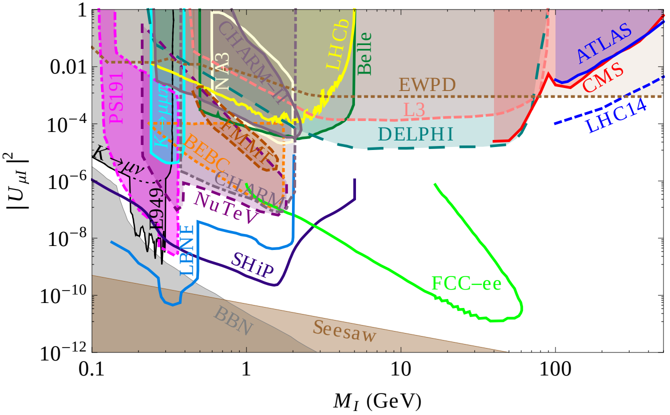
Baryon Asymmetry $\rightarrow$ Leptogenesis

- Majorana RHN allow for CP and lepton number violation:



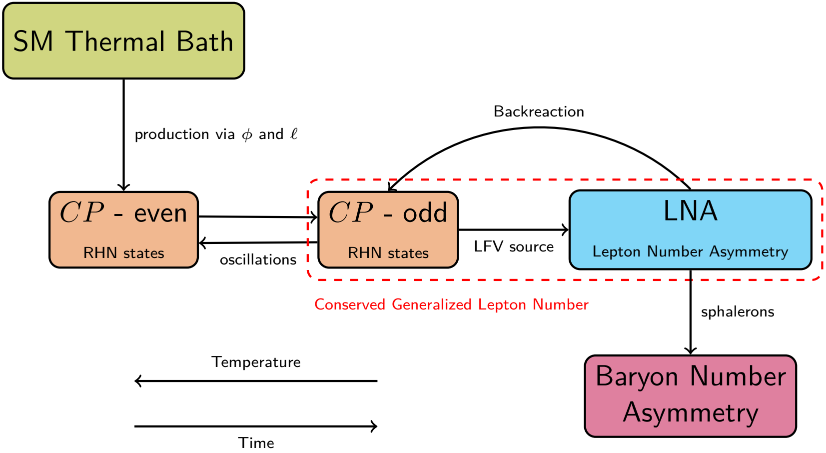
$$\Gamma(N \rightarrow \ell + \overline{\Phi}) \neq \Gamma(N \rightarrow \overline{\ell} + \Phi)$$

GeV mass and large mixing angles



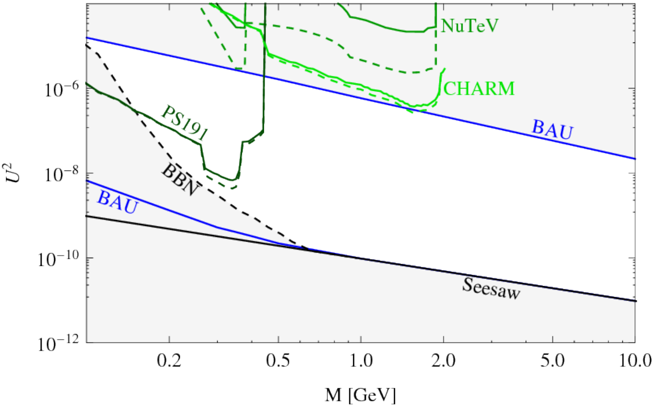
[Plot from arXiv:1504.04855]

Leptogenesis via Neutrino Oscillations



[Akhmedov/Rubakov/Smirnov PhysRevLett.81.1359]

Leptogenesis with two RHN



[Canetti/Drewes/Fossard/Shaposhnikov 1208.4607]

Goals of the present work:

- derive the density matrix equations from first principles
- include the more recent calculations of rates
  [Anisimov/Besak/Bödeker 1012.3784]
  [Garbrecht/Glowna/Schwaller 1303.5498]
- include spectator effects
  [Barbieri/Creminelli/Strumia/Tetradis hep-ph/9911315]
  [Garbrecht/Schwaller 1404.2915]
- resolve seemingly contradicting results from other groups
  [Hernandez/Kekic/Lopez-Pavon/Racker/Ruis 1508.03676]
  [Abada/Arcadi/Domcke/Lucente 1507.06215]
- improve the analytical understanding of *oscillatory* and *overdamped* production regimes

Evolution Equations

RHN density matrix

$$\frac{\mathrm{d}n}{\mathrm{d}z} = -\frac{\mathrm{i}}{2}\left[H, n\right] - \frac{1}{2}\left\{\Gamma, n - n^{\mathrm{eq}}\right\} - \tilde{\Gamma} q_\ell$$

Active lepton equations

$$\frac{\mathrm{d}q_\ell}{\mathrm{d}z} = \frac{S_\ell(n)}{T} - W q_\ell + \tilde{W} q_N$$

- Density matrix of the RHN $n = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}$
- Effective Hamiltonian H of the RHN $\sim M^2$
- Production rate $\Gamma \sim Y^2$
- Source term S_ℓ of the active neutrinos
- Washout term W

Evolution Equations

RHN density matrix

$$\frac{\mathrm{d}n}{\mathrm{d}z} = -\frac{\mathrm{i}}{2}[H, n] - \frac{1}{2}\{\Gamma, n - n^{\mathrm{eq}}\} - \tilde{\Gamma} q_\ell$$

Active lepton equations

$$\frac{\mathrm{d}q_\ell}{\mathrm{d}z} = \frac{S_\ell(n)}{T} - W q_\ell + \tilde{W} q_N$$

Temperature (time) scales

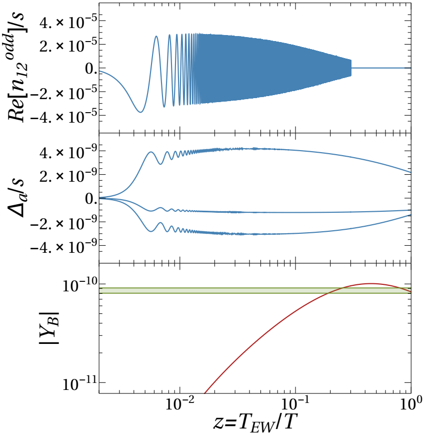
$$T_{\mathrm{osc}} = \sqrt[3]{T_{\mathrm{com}}\left(M_{11}^2 - M_{22}^2\right)}$$

$$T_{\mathrm{eq}} = T_{\mathrm{com}} \gamma_{\mathrm{av}} \mathrm{Tr}\left(Y Y^\dagger\right)$$

- Possible to solve numerically
- Approximations needed for parameter scans

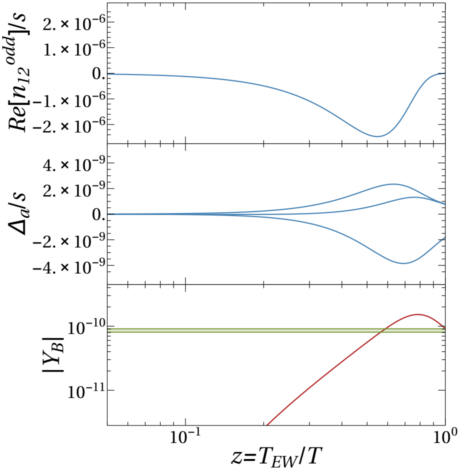
Oscillatory regime: $T_{\rm osc} \gg T_{\rm eq}$

- typical for small mixing angles
- oscillations begin long before relaxation to equillibrium
- almost all lepton flavour asymmetry produced during first few oscillations
- lepton number asymmetry produced through flavour asymmetric washout

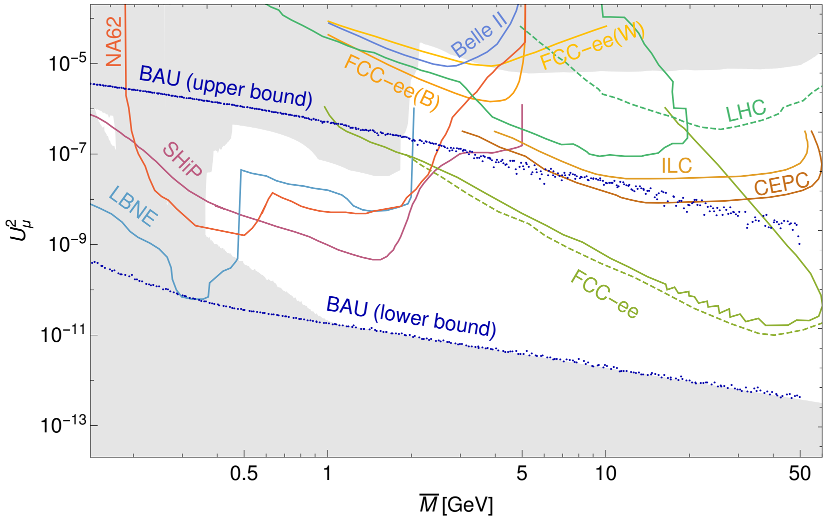


Overdamped regime: $T_{\mathrm{osc}} \ll T_{\mathrm{eq}}$

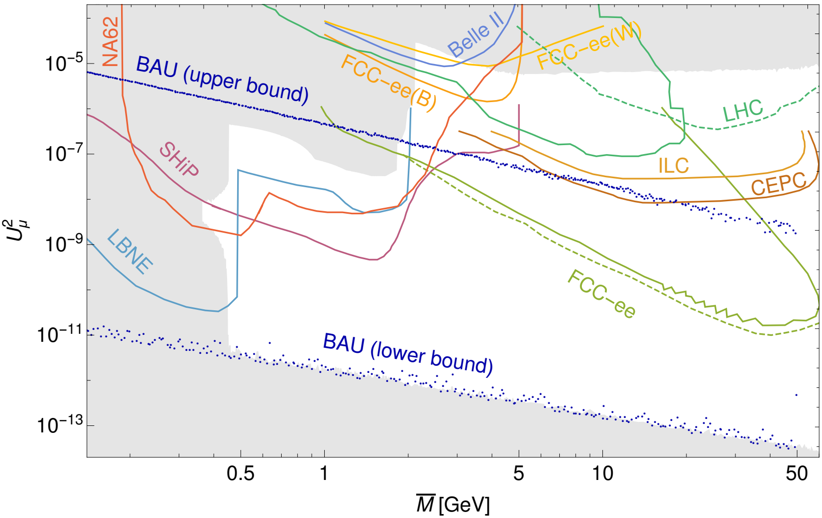
- typical scenario for large mixing angles
- naively for $T_{\mathrm{osc}} < T_{\mathrm{eq}}$, already in equilibrium - no leptogenesis
- known neutrino data constrain the parameters so that $T_{\mathrm{eq}} \gg T_{\mathrm{osc}}$ is only valid for one RHN!



Results: Normal Hierarchy



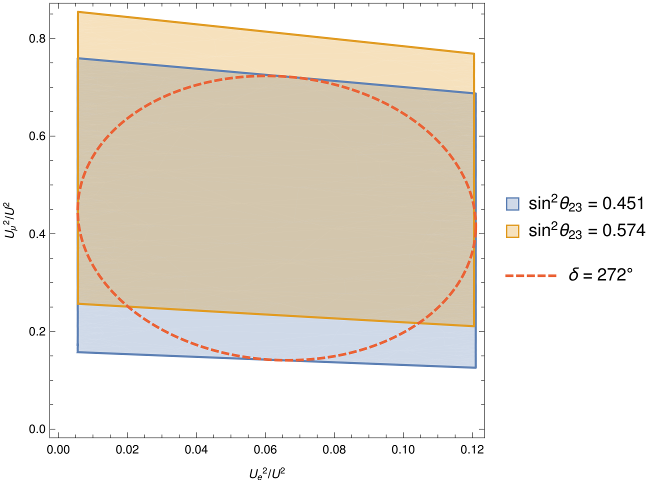
Results: Inverse Hierarchy



What can leptogenesis tell us about the RHN?

- the requirement of explaining the seesaw mechanism imposes constraints on the flavour patterns of the RHN
- large mixing angles require a flavour asymmetric washout, which corresponds to a flavour asymmetric mixing
- together this imposes constraints on the mixing patterns for large mixing angles
- if heavy neutral leptons are found at a future experiment we can assess if they can be the common origin of both the neutrino mass and the baryon asymmetry of the universe

Flavour patterns from the seesaw: Normal Hierarchy



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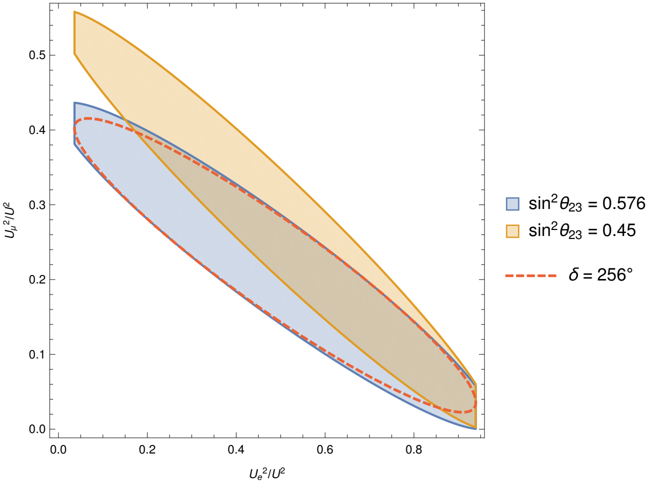
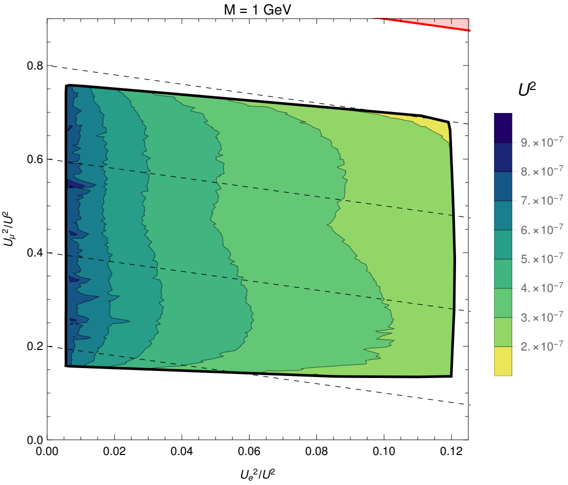
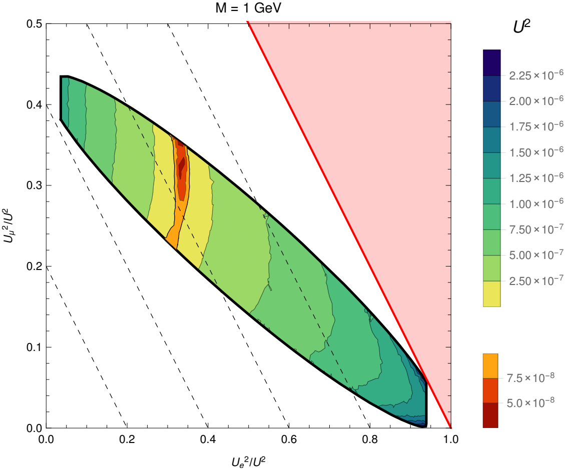


Flavour patterns from leptogenesis: Normal Hierarchy



Flavour patterns from leptogenesis: Inverted Hierarchy



Conclusions

- adding GeV-scale RHNs to the standard model can explain both the observed neutrino masses and the Baryon Asymmetry of the Universe
- working leptogenesis in reach of future experiments (SHiP, FCC-ee, NA62)
- found analytic approximations for *oscillatory* and *overdamped* regimes
- eliminated several uncertainties from previous calculations
- found that the baryon asymmetry of the Universe can be explained with larger mixing angles than previous studies have shown
- found constraints on the flavour patterns of the RHN with large mixing angles