

Leptogenesis from Oscillations of Heavy Neutrinos with Large Mixing Angles

Juraj Klarić (TU München)

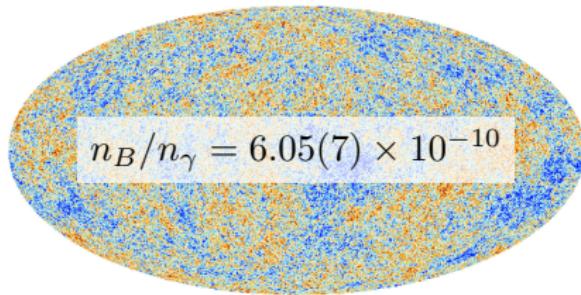
based on 1606.6690 and 1609.xxxx with Marco Drewes, Björn Garbrecht and Dario Gueter

TeVPA, CERN 2016, 12. September

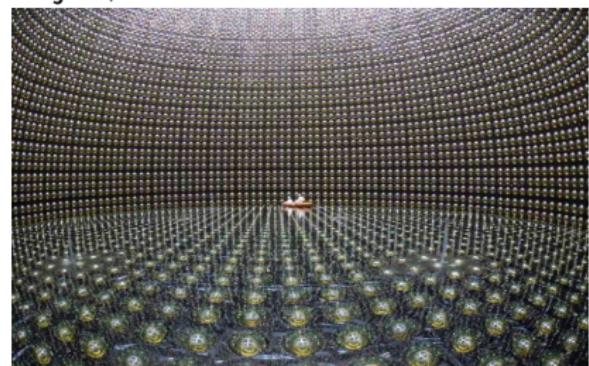
from the BSM to-do list:

Baryon asymmetry of the universe

WMAP, Planck and Big bang nucleosynthesis:



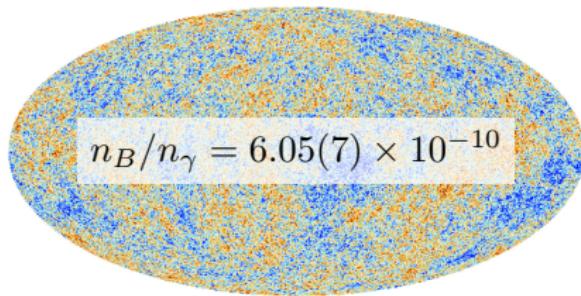
Neutrino masses
Nobel prize 2015
Kajita, McDonald



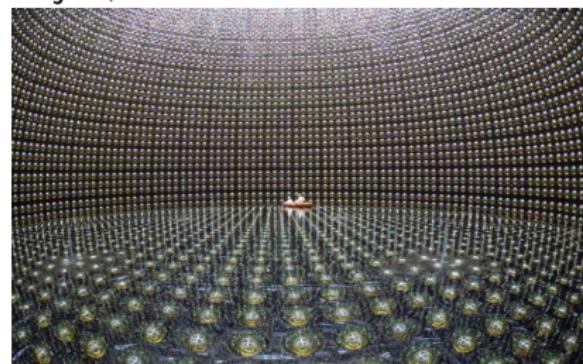
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Is there a way to explain both?

Standard Model

Three Generations of Matter (Fermions) spin $\frac{1}{2}$						Bosons (Forces) spin 1	
	I	II	III				
mass \rightarrow	2.4 MeV	1.27 GeV	171.2 GeV				
charge \rightarrow	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$				
name \rightarrow	u Left up Right	c Left charm Right	t Left top Right				
Quarks	d Left down Right	s Left strange Right	b Left bottom Right				
	0 eV ν_e Left electron neutrino Right	0 eV ν_μ Left muon neutrino Right	0 eV ν_τ Left tau neutrino Right				
Leptons	e Left electron Right	μ Left muon Right	τ Left tau Right				
	0.511 MeV	105.7 MeV	1.777 GeV				
	-1	-1	-1				

Neutrino Masses → Seesaw Mechanism

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

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

Active neutrino masses

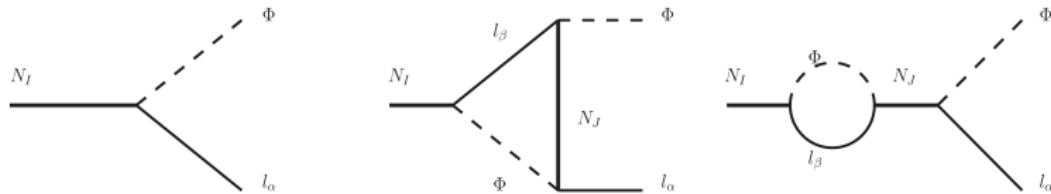
$$m_\nu = -v^2 Y^\dagger M_M^{-1} Y^*$$

Mixing with RHN

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

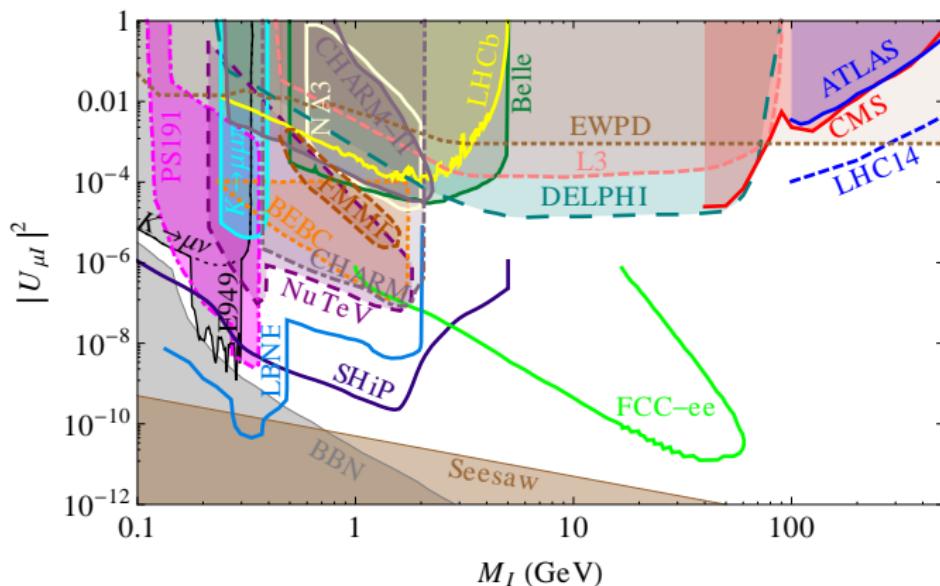
Baryon Asymmetry → Leptogenesis

- Majorana RHN allow for CP and lepton number violation:



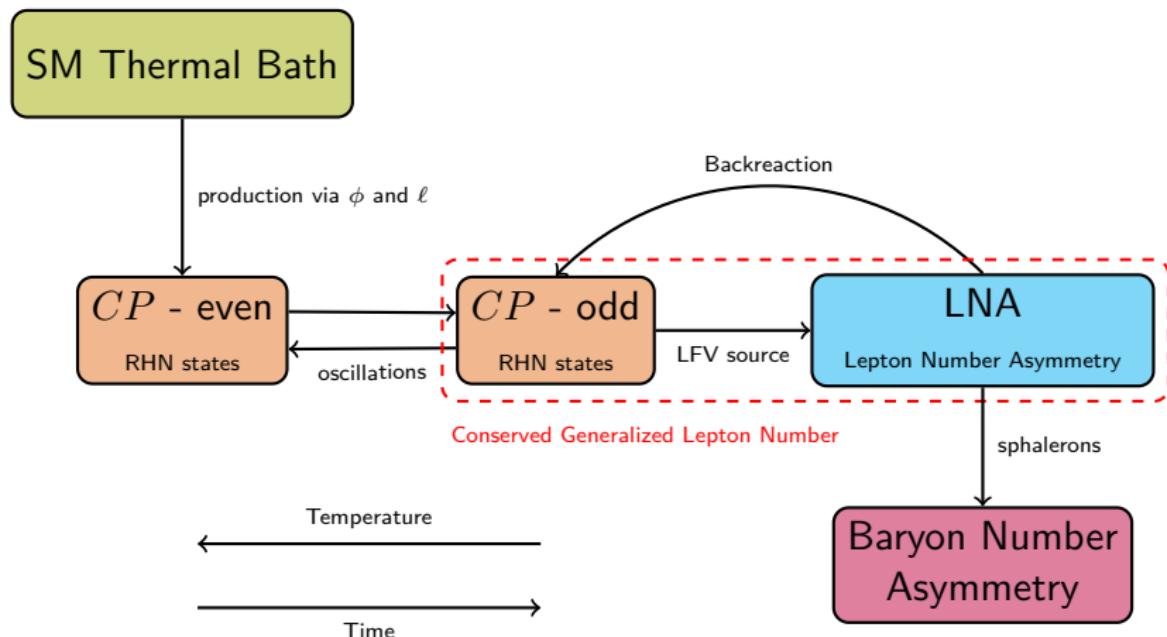
$$\Gamma(N \rightarrow \ell + \overline{\Phi}) \neq \Gamma(N \rightarrow \bar{\ell} + \Phi)$$

GeV mass and large mixing angles



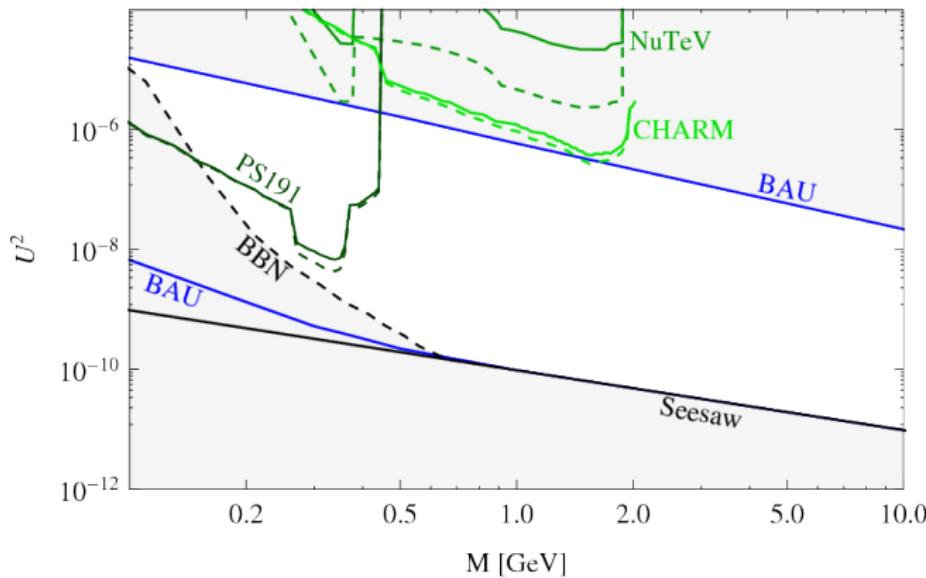
[Plot from arXiv:1504.04855]

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

$$\frac{dn}{dz} = -\frac{i}{2} [H, n] - \frac{1}{2} \{ \Gamma, n - n^{\text{eq}} \} - \tilde{\Gamma} q_\ell$$

Active lepton equations

$$\frac{dq_\ell}{dz} = \frac{S_\ell(n)}{T} - W q_\ell + \tilde{W} q_N$$

- 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

$$\frac{dn}{dz} = -\frac{i}{2} [H, n] - \frac{1}{2} \{ \Gamma, n - n^{\text{eq}} \} - \tilde{\Gamma} q_\ell$$

Active lepton equations

$$\frac{dq_\ell}{dz} = \frac{S_\ell(n)}{T} - W q_\ell + \tilde{W} q_N$$

Temperature (time) scales

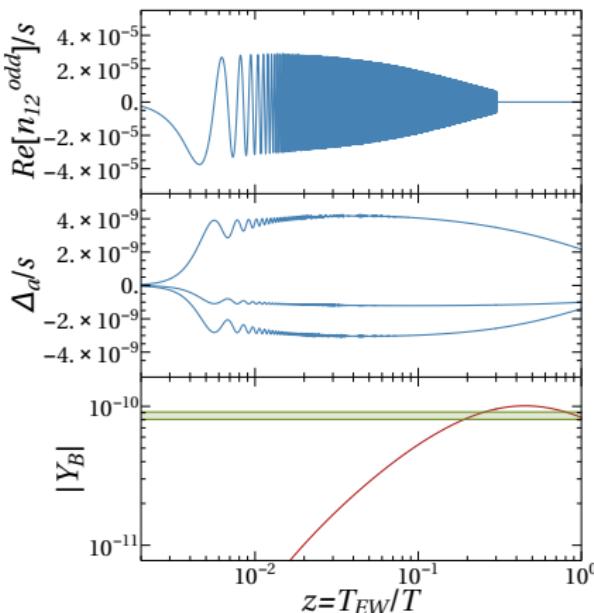
$$T_{\text{osc}} = \sqrt[3]{T_{\text{com}} (M_{11}^2 - M_{22}^2)}$$

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

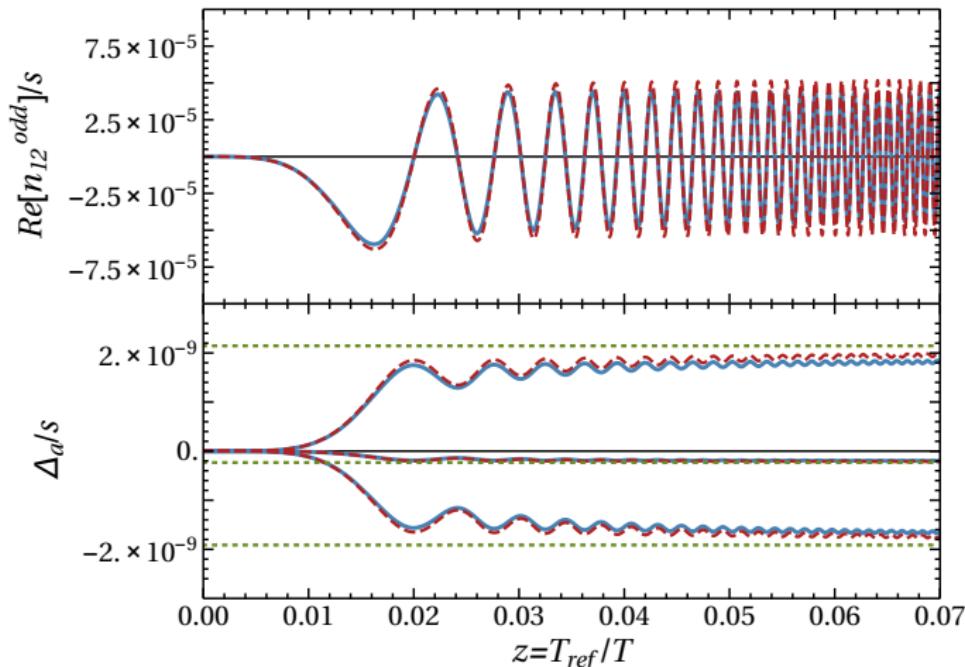
- Possible to solve numerically
- Approximations needed for parameter scans

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

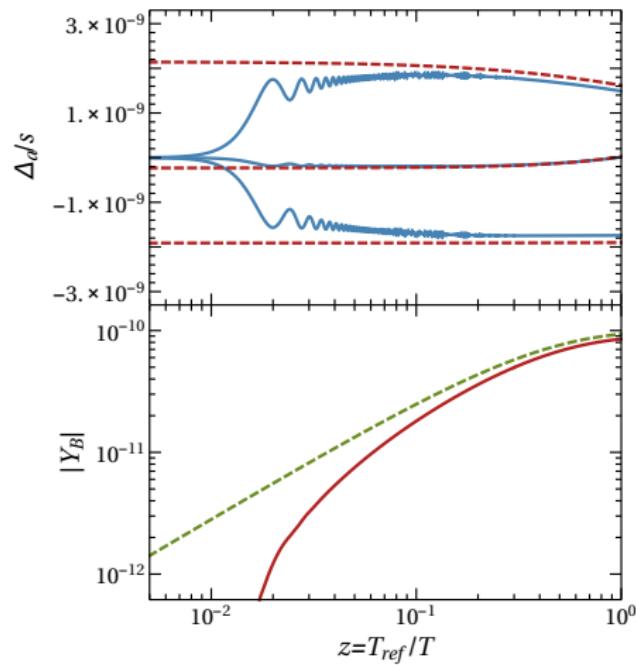
- typical for small mixing angles
- oscillations begin long before relaxation to equilibrium
- almost all lepton flavour asymmetry produced during first few oscillations
- lepton number asymmetry produced through flavour asymmetric washout



Early time approximations $T \approx T_{\text{osc}} \gg T_{\text{eq}}$

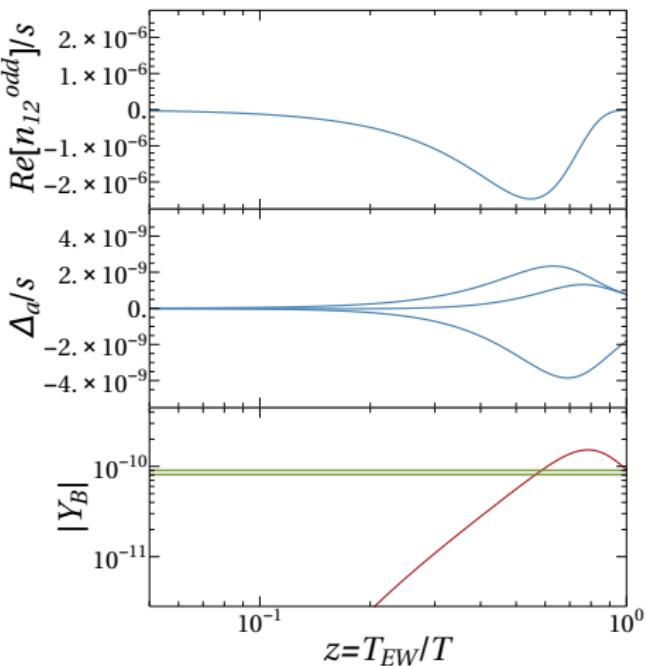


Late time approximations, $T \ll T_{\text{osc}}$



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

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



Approximations when $T_{\text{osc}} \ll T_{\text{eq}}$

RHN evolution

$$\frac{dn_{ij}}{dz} = - \left(\frac{i}{2} [H, n] + \frac{1}{2} \{\Gamma, n - n^{\text{eq}}\} \right)_{ij}$$

- for early times
 $H \ll \Gamma$
- identify overdamped degrees of freedom and neglect their derivatives

- solve the algebraic equations to express them in terms of the undamped degrees of freedom
- solve the remaining differential equation(s)

Approximations when $T_{\text{osc}} \ll T_{\text{eq}}$

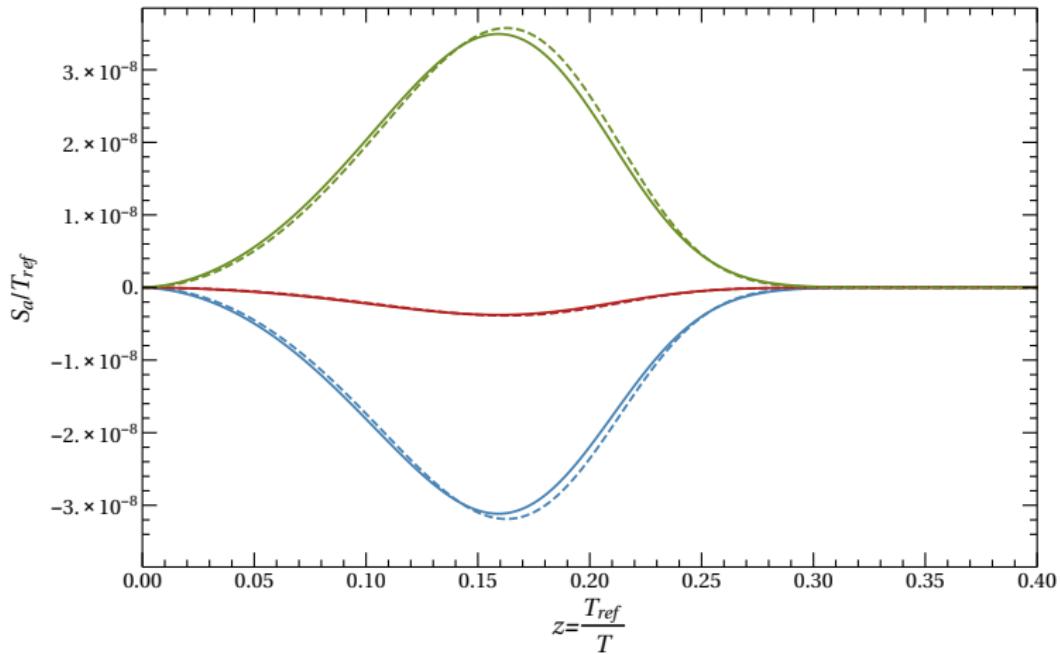
RHN evolution

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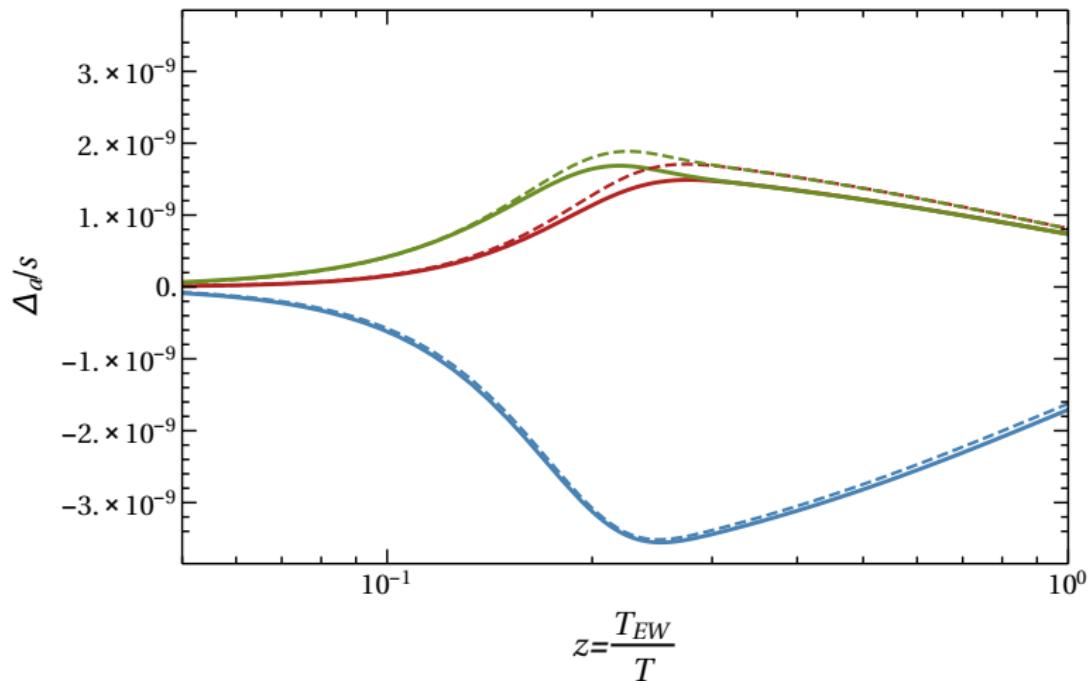
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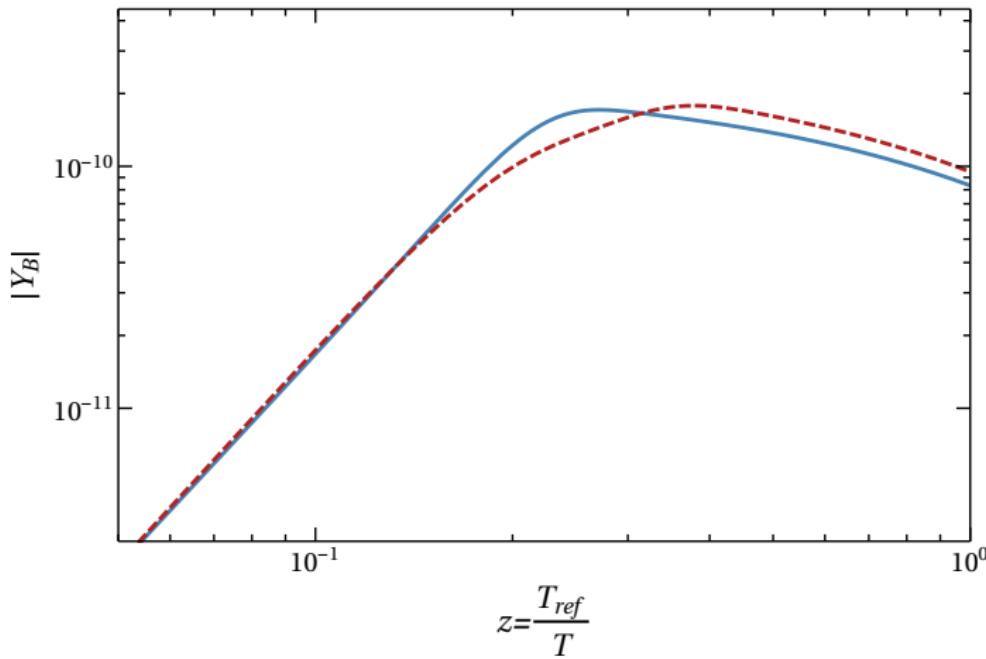
Approximate solutions for $T_{\text{osc}} \ll T_{\text{eq}}$



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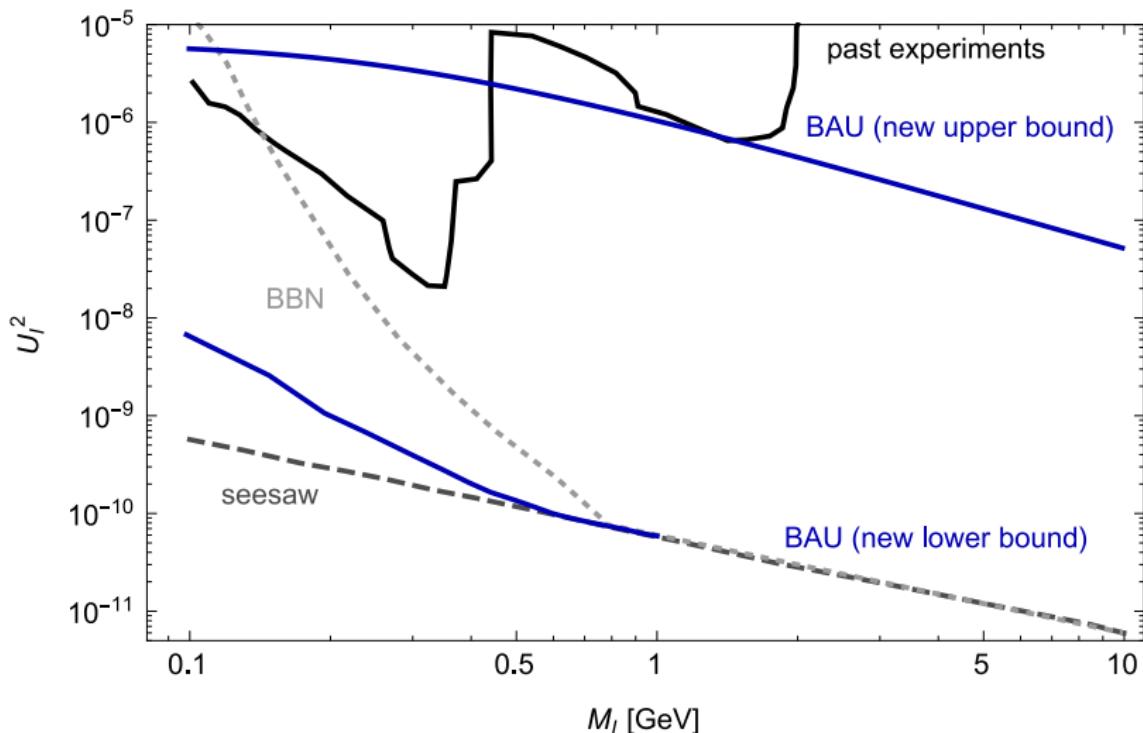


Search for maximal mixing angles

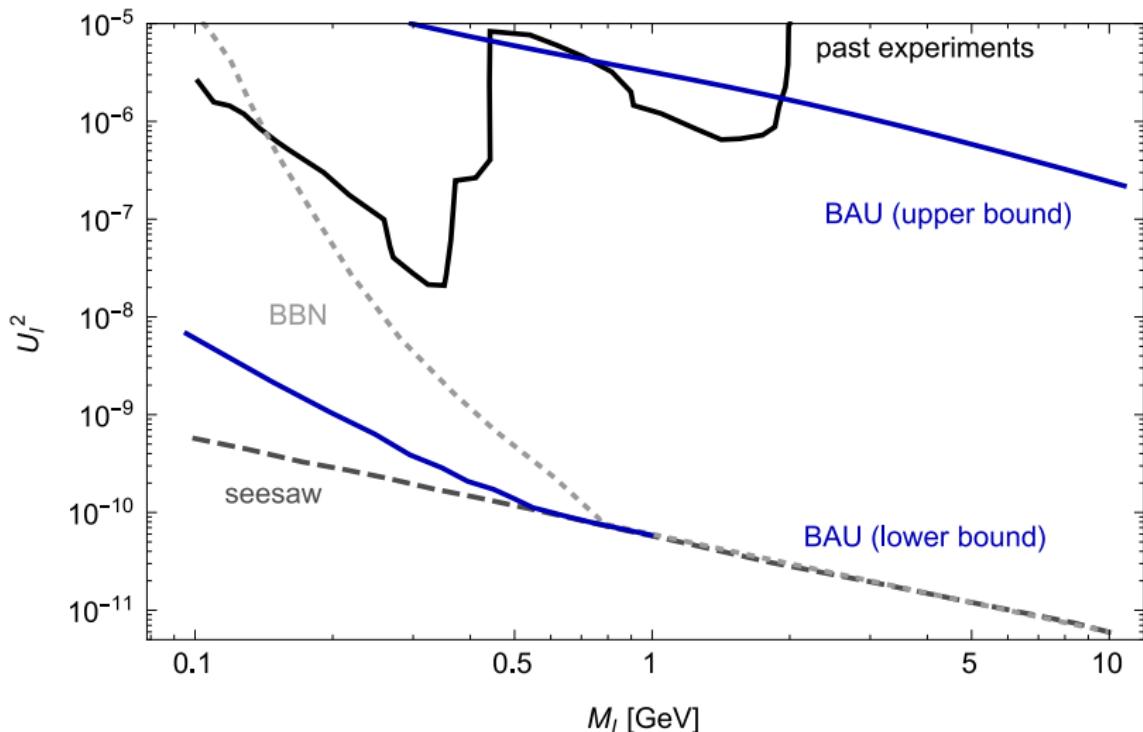
- complete scan is numerically demanding
- use the symmetries of the problem instead
- by keeping $T_{\text{osc}} : T_{\text{eq}}$ constant, only the time-scale and amplitude of the solutions change
- time dependence $|Y_B(z)|$ can tell us how to “tune” ΔM^2 to find the correct BAU

$$Y_B(z, \Delta M^2, M) = \frac{M_0}{M} \left(\frac{\Delta M^2}{\Delta M_0^2} \right)^{1/3} Y_B \left[z \left(\frac{\Delta M_0^2}{\Delta M^2} \right)^{1/3}, \Delta M_0^2, M_0 \right]$$

Results: Normal Hierarchy



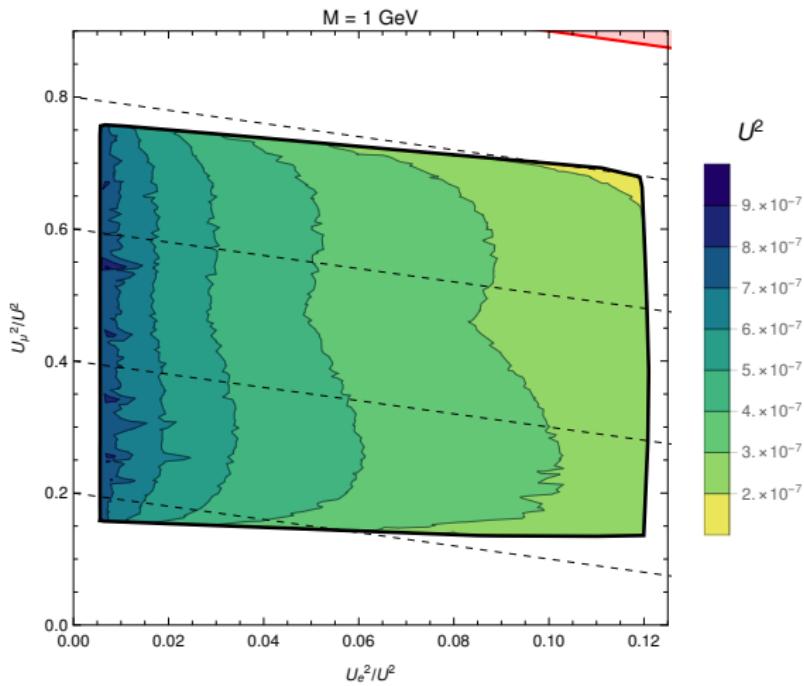
Results: Inverse Hierarchy



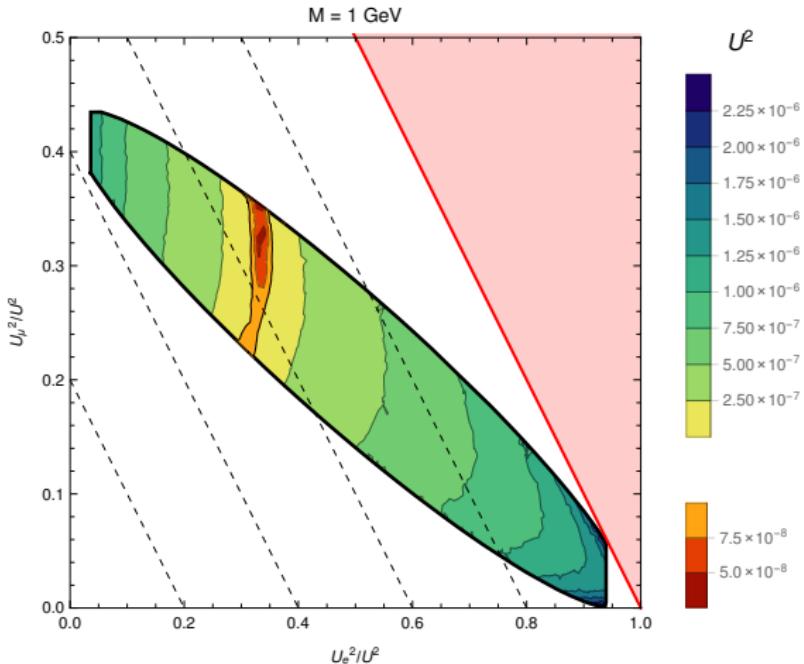
What can leptogenesis tell us about the RHN?

- 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 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 both present (LHCb, BELLE II) and future experiments (SHiP, FCC-ee)
- 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