

Testing the low scale seesaw and leptogenesis

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based on

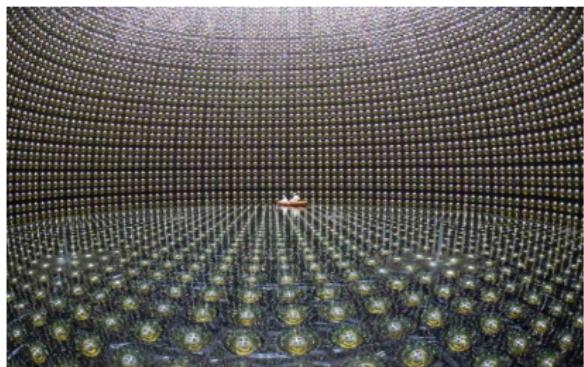
1606.06690, 1609.09069, 1611.04769 and 1611.08504

with M.Drewes, B.Garbrecht and J.Klarić

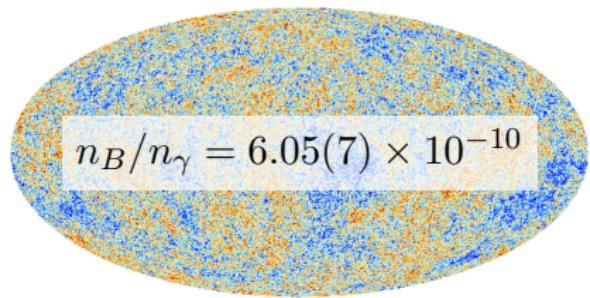
CosPA 2016, 1 December

Remaining puzzles of the universe

Neutrino masses

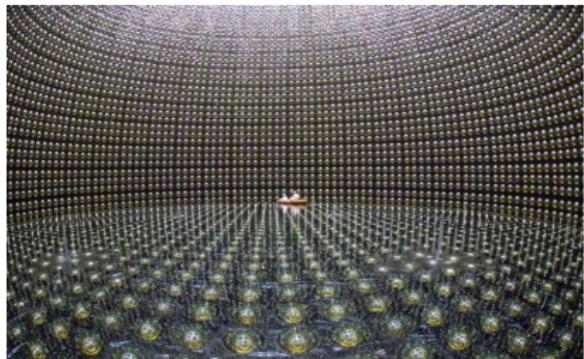


Baryon asymmetry of the
universe (BAU)



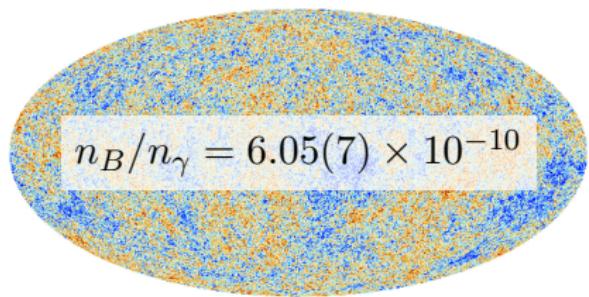
Remaining puzzles of the universe

Neutrino masses



No neutrino mass term in the SM

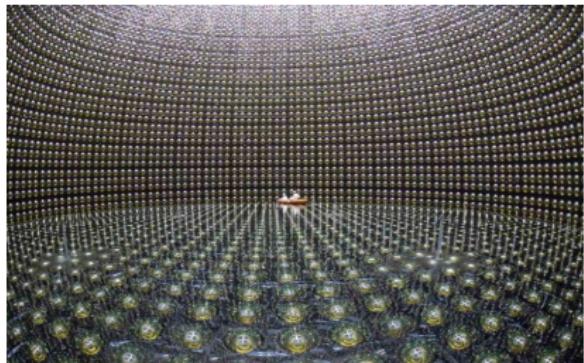
Baryon asymmetry of the universe (BAU)



CP violation too weak in SM

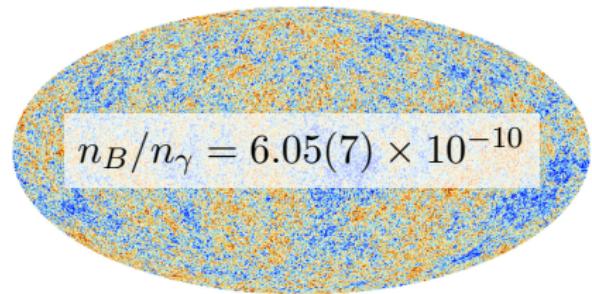
Remaining puzzles of the universe

Neutrino masses



No neutrino mass term in the SM

Baryon asymmetry of the universe (BAU)



CP violation too weak in SM

⇒ need to go beyond SM

Extending the SM by two or more RH neutrinos

SM				nuMSM			
Quarks	mass → charge → name →	mass → charge → name →	Quarks	mass → charge → name →	mass → charge → name →	Leptons	
Left down	2.4 MeV $\frac{2}{3}$ u	1.27 GeV $\frac{2}{3}$ c	Left top	171.2 GeV $\frac{2}{3}$ t	Left up	2.4 MeV $\frac{2}{3}$ u	Left electron
Right	Right	Right	Right	Right	Right	104 MeV $-\frac{1}{3}$ s	0 eV $0 \bar{\nu}_e$ electron neutrino
Left strange	4.8 MeV $-\frac{1}{3}$	4.2 GeV $-\frac{1}{3}$ b	Left bottom	4.2 GeV $-\frac{1}{3}$ b	Left down	104 MeV $-\frac{1}{3}$ s	0 eV $0 \bar{\nu}_\mu$ muon neutrino
Right	Right	Right	Right	Right	Right	4.8 MeV $-\frac{1}{3}$ d	0 eV $0 \bar{\nu}_\tau$ tau neutrino
Leptons	Leptons	Leptons	Leptons	Leptons	Leptons	Leptons	Leptons
Left electron	0.511 MeV -1 e	105.7 MeV -1 μ	Left tau	1.777 GeV -1 τ	Left sterile neutrino	0.511 MeV -1 e	Left electron
Right neutrino	Right neutrino	Right neutrino	Right neutrino	Right neutrino	Right sterile neutrino	105.7 MeV -1 μ	Right muon
						1.777 GeV -1 τ	Right tau

RH neutrinos could solve the puzzle

Extending the minimal SM by two or more RH neutrinos

- Neutrino masses by the **seesaw mechanism** [Yanagida]
- BAU via **leptogenesis** [Yanagida, Fukugita]
- third RH neutrino could be **DM candidate**

Neutrino masses via seesaw mechanism

Add RH neutrinos (SM singlets) ν_R to SM

$$\mathcal{L} \supset \ell_L Y^\dagger \nu_R \tilde{\Phi} - \frac{1}{2} \overline{\nu_R^c} M_M \nu_R + \text{h.c.}$$

Two sets of Majorana mass states after EW symmetry breaking

$$\nu \simeq U_\nu (\nu_L + \theta \nu_R^c)$$

- light neutrinos
- mostly **active** doublet
- light masses:
 $m_\nu \simeq v^2 Y^\dagger M_M^{-1} Y^*$

$$N \simeq \nu_R + \theta^T \nu_L^c$$

- heavy neutrinos
- mostly **sterile** singlets
- heavy masses:
 $M_N \simeq M_M \gg m_\nu$

$\Rightarrow N$ only interact via small mixing

$$U_{ai}^2 \equiv |\theta_{ai}|^2 \ll 1$$

Evolution equations

RH neutrino density matrix

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

SM lepton doublet equations

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

- “time”: $z = T_{\text{EW}}/T$
- Density matrix
 $\mathbf{n} = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}$
- Effective Hamiltonian
 $\mathbf{H} \sim M^2$
- Production rate $\mathbf{\Gamma} \sim Y^2$
- Source term S_ℓ
- Washout term \mathbf{W}
- Feedback terms $\tilde{\mathbf{\Gamma}}, \tilde{\mathbf{W}}$

Evolution equations

RH neutrino density matrix

$$\frac{d\textcolor{blue}{n}}{dz} = -\frac{i}{2} [\textcolor{red}{H}, \textcolor{blue}{n}] - \frac{1}{2} \{\textcolor{brown}{\Gamma}, \textcolor{blue}{n} - n^{\text{eq}}\} - \tilde{\Gamma} q_\ell$$

SM lepton doublet equations

$$\frac{dq_\ell}{dz} = \frac{\textcolor{brown}{S}_\ell(n)}{T} - \textcolor{teal}{W} q_\ell + \tilde{W} q_N$$

Temperature (time) scales

$$\begin{aligned}\textcolor{red}{T}_{\text{osc}} &= \sqrt[3]{T_{\text{com}} (M_{11}^2 - M_{22}^2)} \\ \textcolor{brown}{T}_{\text{eq}} &= T_{\text{com}} \gamma_{\text{av}} \text{Tr} (YY^\dagger)\end{aligned}$$

- Possible to solve numerically
- Approximations useful for parameter scans

Sakharov conditions

B violation

- Sphalerons violate $B + L$ but conserve $B - L$ for $T \gtrsim 140$ GeV (BUT suppressed for low T)
- L gets transferred to B

C and CP violation

- CP violating parameters in Yukawa couplings

Non-equilibrium

- Non-equilibrium production of RH neutrinos in thermal bath
- Electroweak phase transition

Leptogenesis scenarios

Thermal leptogenesis [Yanagida, Fukugita]

BAU is generated via **CP violating decays** of superheavy RH neutrinos for $M_i \gg v$

- Equilibrate \rightarrow freeze out (**non-equilibrium**) \rightarrow decay long before sphalerons freeze out (**CP violation**)
- Lepton asymmetry L partly converted into BAU by sphalerons (**B violation**)
- L violation suppressed at low temperature $T \ll M_i$
 $\rightarrow B$ preserved from being washed out

Disadvantage: Requires $M_i > 10^9$ GeV

Leptogenesis scenarios

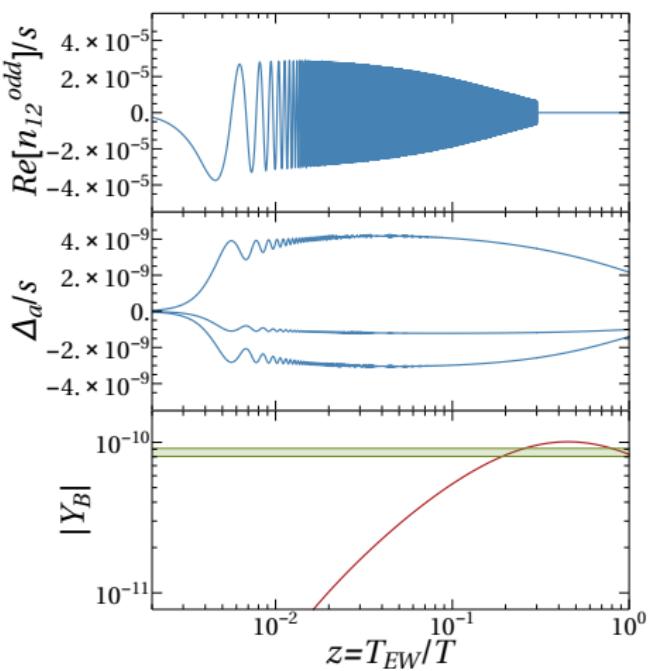
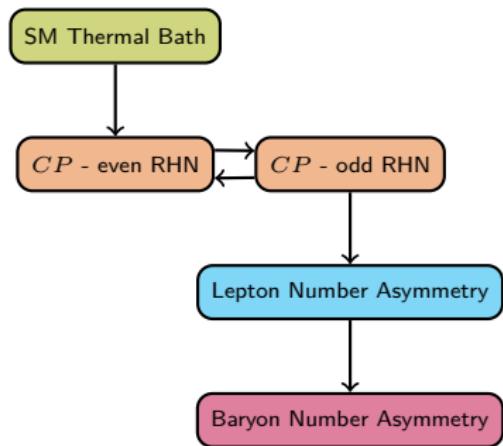
Baryogenesis via neutrino oscillations [Akhmedov, Rubakov, Smirnov]

BAU is generated via **CP violating oscillations** of RH neutrinos for $M_i < v$ (fully relativistic treatment)

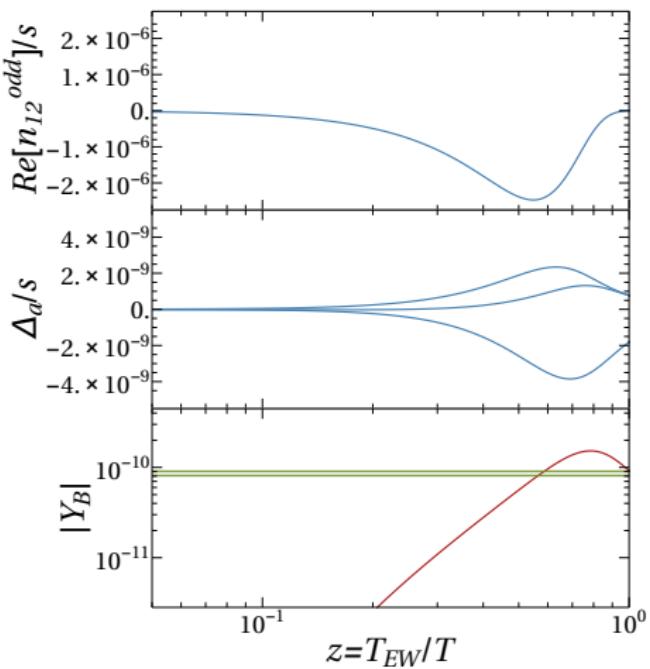
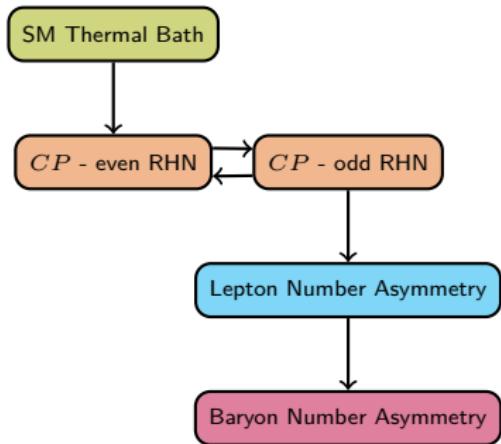
- Generation of flavour asymmetries L_a for $a = e, \mu, \tau$
 \leftrightarrow BUT L violation suppressed $\rightarrow L \equiv \sum_a L_a = 0$
- Flavour asymmetric decays of L_a into N_i via Y_{ia} create net lepton number $L \neq 0$ (**CP violation**)
- Lepton number partly transferred into baryon number due to sphalerons (**B violation**)
- RH neutrinos must not equilibrate before sphaleron freeze out
 \rightarrow Baryon number freezes in (**non-equilibrium**)

Advantage: GeV scale makes it experimentally testable

Oscillatory regime \rightarrow small mixing angles



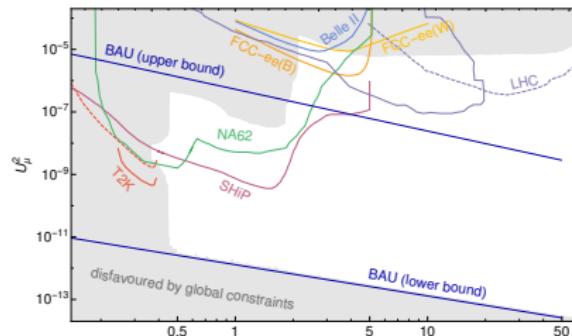
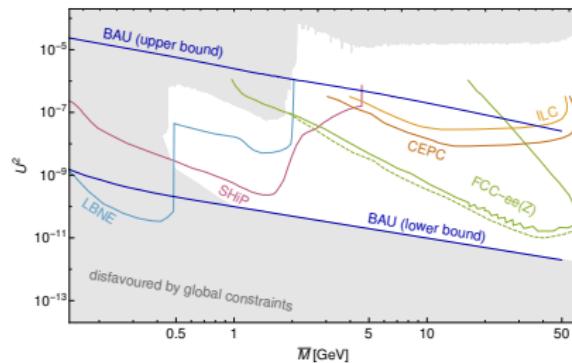
Overdamped regime \rightarrow large mixing angles



Testability of low scale Leptogenesis for $n = 2$

Heavy neutrinos N_i with masses below the electroweak scale can be searched for at directly:

- **blue lines:** viable leptogenesis parameter space (for inverted hierarchy)
- **coloured lines:** reach of some future experiments
- **grey area:** constraints from past experiments



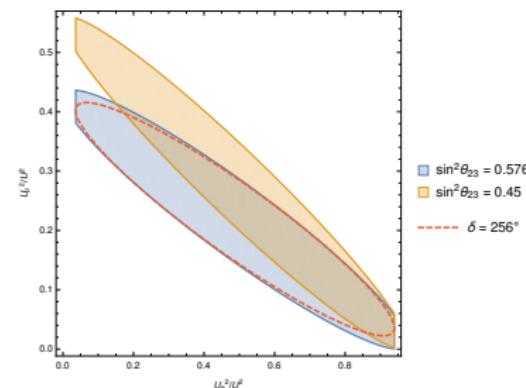
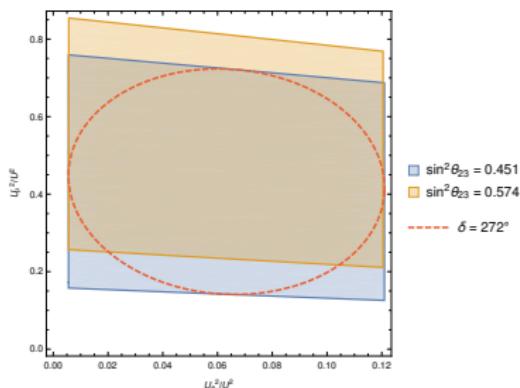
High mass resolution: U_{ai}^2

- U_{a1}^2 and U_{a2}^2 can be measured independently (e.g. at SHiP)
- Model not uniquely identified due to degeneracy in model parameters
- A possible (independent) measurement of the Dirac phase δ (DUNE or NO ν A) in the future will break this degeneracy
⇒ $0\nu\beta\beta$ decay rate predictable
⇒ Neutrino mass generation and baryogenesis fully testable

Low mass resolution: U_a^2

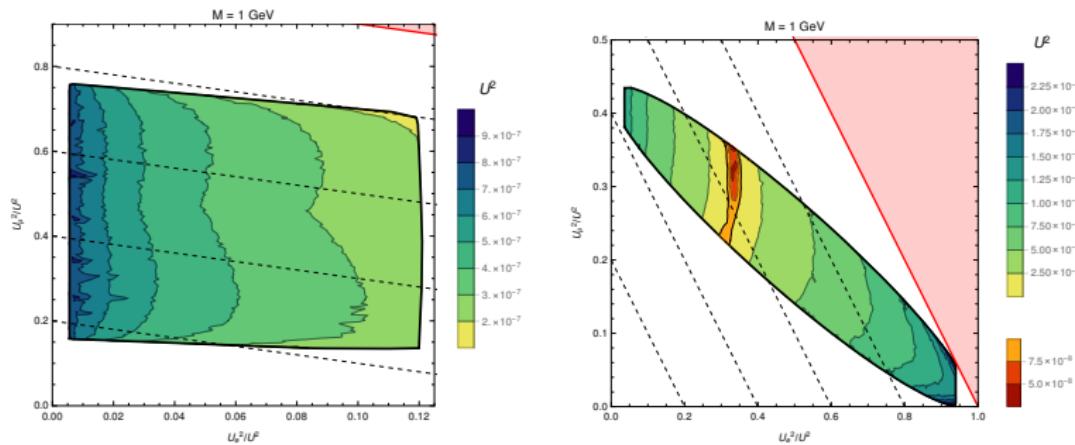
- U_{a1}^2 and U_{a2}^2 cannot be measured independently but the sum $U_a^2 = \sum_{i=1,2} U_{ai}^2$
- No constraints on ΔM and $0\nu\beta\beta$
- Just certain ratios of U_a^2/U^2 are allowed

⇒ Powerful test of the seesaw mechanism



Low mass resolution: U_a^2

Requirement of fulfilling the experimentally observed BAU further restricts the model:



Conclusions

- A measurement of the Dirac phase δ would allow to make testable predictions for the couplings of the heavy neutrinos to individual SM flavours.
- Heavy neutrinos with masses below M_W are experimentally detectable in near future experiments
- In case of an experimentally discovered, all model parameters can be reconstructed from measurements of δ and the mixings U_{ai}^2

The low scale seesaw is a fully testable mechanism of neutrino mass generation and baryogenesis.