# Testing the low scale seesaw and leptogenesis

Juraj Klarić (TU München)

based on 1606.6690 and 1609.09069 with Marco Drewes, Björn Garbrecht and Dario Gueter

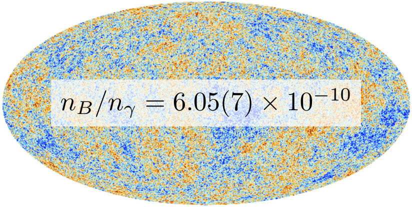
Neutrinos in Cosmology, in Astro- Particle- and Nuclear physics

EMFCSC, Erice, Sicily, 17. September 2017

# Some of the missing pieces of the standard model:

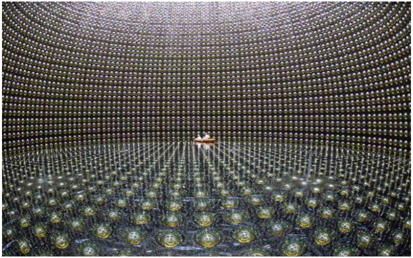
## BAU baryon asymmetry of the universe

WMAP, Planck and Big bang nucleosynthesis:




## Neutrino masses

Nobel prize 2015
Kajita, McDonald



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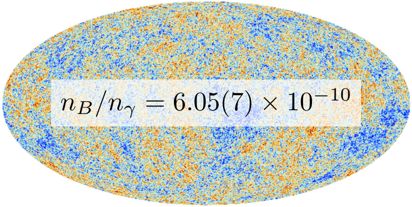


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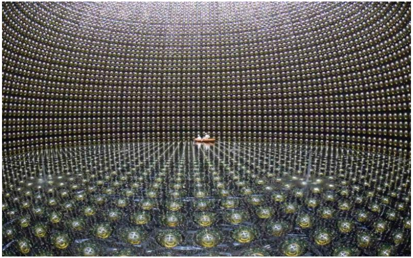
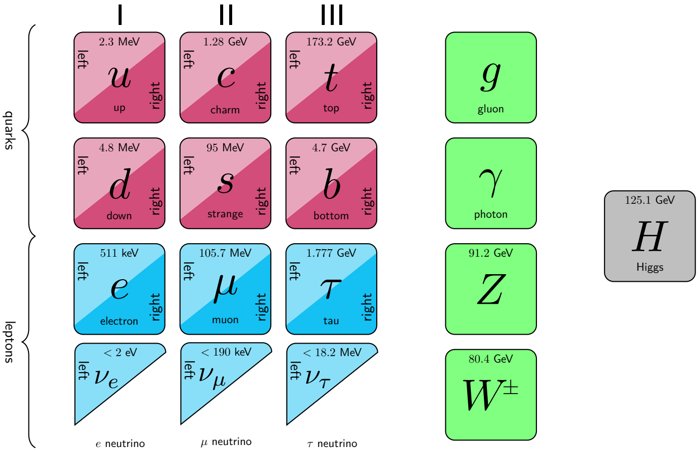


*Is there a way to explain both?*

# Standard Model



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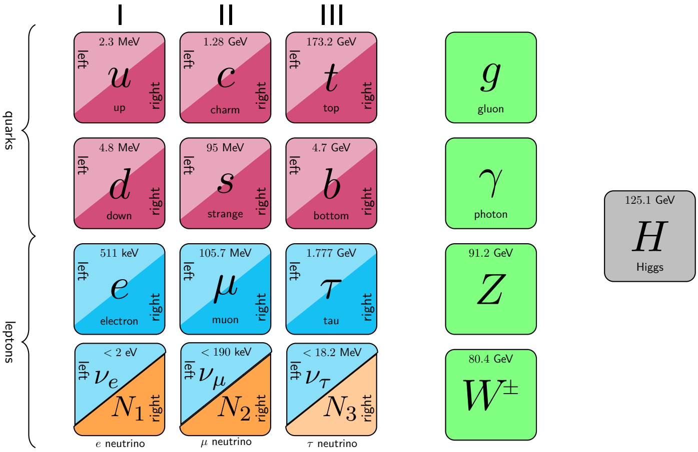

# BAU baryon asymmetry of the universe

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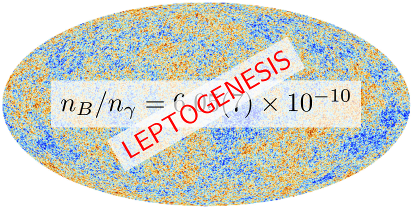


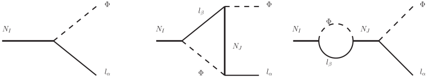


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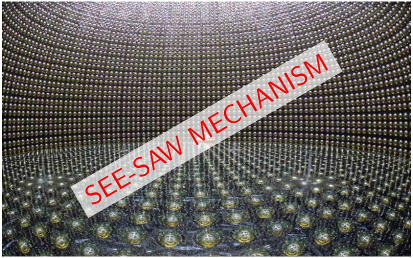



$$m_\nu = -v^2 Y^\dagger M_M^{-1} Y^*$$

# Seesaw Mechanism

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

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

## Active neutrino masses

$$m_\nu = -m_D M_M^{-1} m_D^T$$

## Mixing with RHN

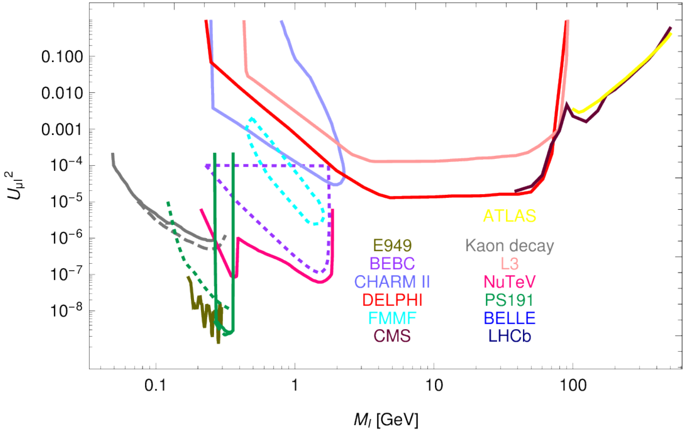
$$|U_{ai}|^2 = \left| \left( m_D M_M^{-1} \right)_{ai} \right|^2$$

# Constraints on RHN parameters

- Direct constraints - past experiments
- Seesaw constraints - neutrino oscillation data
  radiatively corrected Casas-Ibarra parametrization

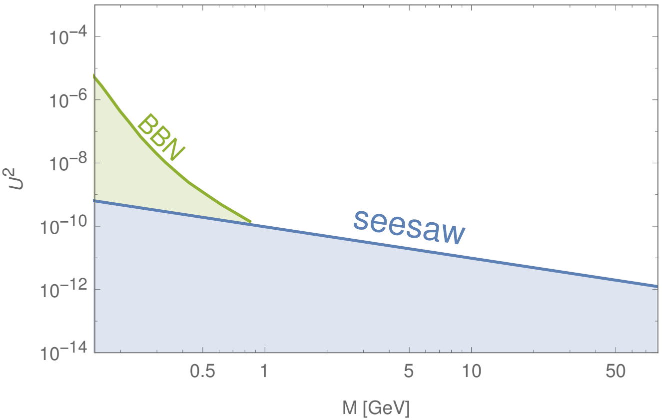
  [Lopez-Pavon/Molinaro/Petcov 1506.05296]
- Cosmological constraints - BBN $\tau_N < 0.1$s
- Indirect constraints
  - neutrinoless double $\beta$ decay
  - lepton universality
  - CKM universality
  - electroweak precision data
  - $LFV$ in rare lepton decays:
    - $\mu \to e\gamma$
    - $\tau \to e\gamma$
    - $\tau \to \mu\gamma$

# Direct constraints

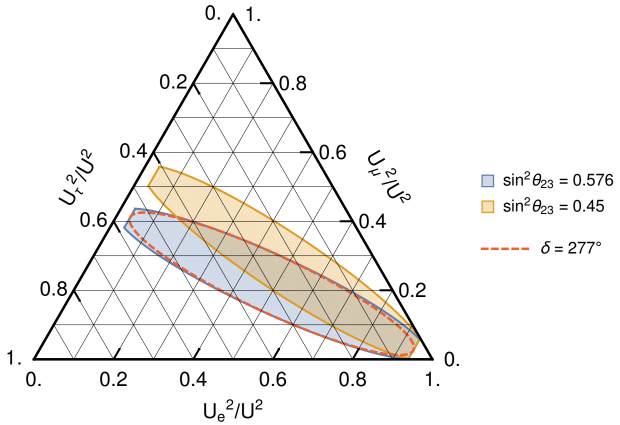



[Plot from arXiv:1502.00477]

# Seesaw and BBN constraints

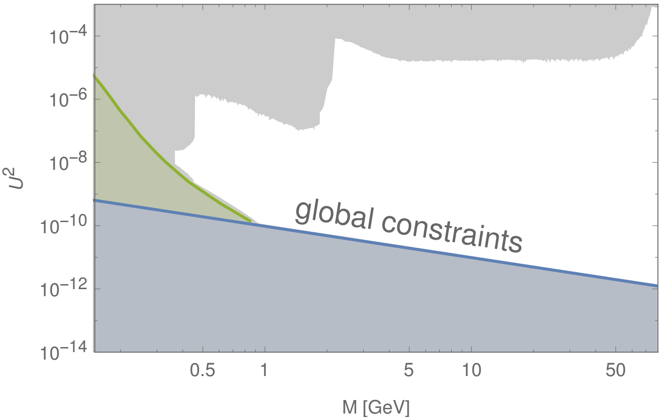


# Constraints on flavour patterns: Inverted hierarchy




[Drewes/Garbrecht/Gueter/JK 1609.09069]

# Global constraints: Inverted hierarchy



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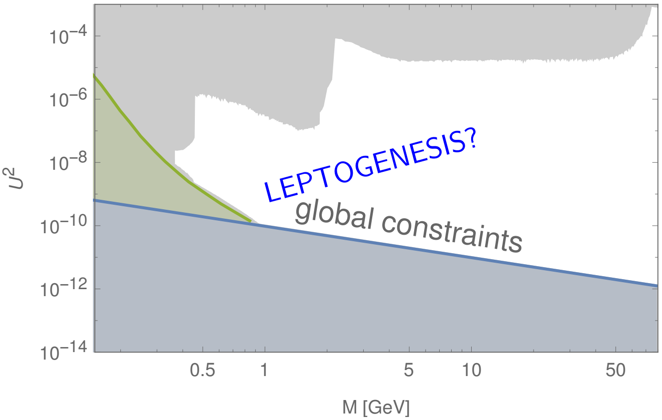
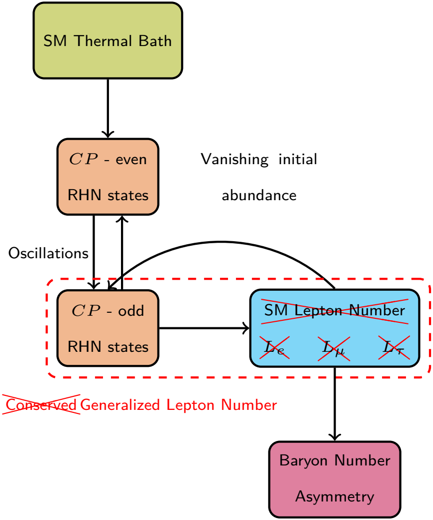
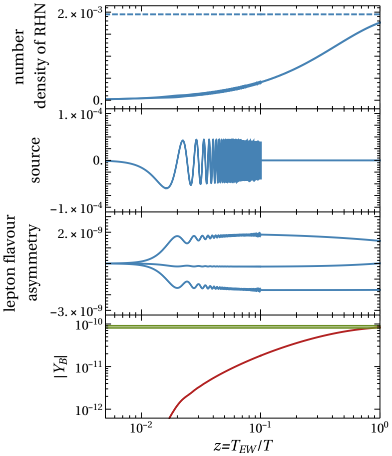


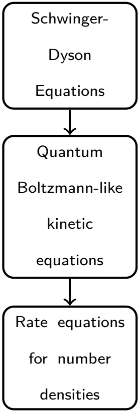
# Leptogenesis via Neutrino Oscillations



# Goals of this work:

- derivation of the **density matrix** equations from **first principles** [Drewes/Garbrecht/Gueter/JK 1606.06690]
- use the more recent **calculations of rates** [Anisimov/Besak/Bödeker 1012.3784] [Garbrecht/Glowna/Schwaller 1303.5498]
- inclusion of **spectator effects** [Barbieri/Creminelli/Strumia/Tetradis hep-ph/9911315] [Garbrecht/Schwaller 1404.2915]
- **analyitical approximations** for different regimes [Drewes/Garbrecht/Gueter/JK 1606.06690]
- explore parameter space/ phenomenological implications [Hernández/Kekic/López-Pavón/Racker/Salvado 1606.06719] [Drewes/Garbrecht/Gueter/JK 1609.09069]
- *violation of generalized lepton number* [Hambye/Teresi 1606.00017] [Eijima/Shaposhnikov 1703.06085] [Laine/Ghiglieri 1703.06087]



# 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 $\Gamma \sim Y^2 T$
- Source term $S_\ell$ of the active neutrinos
- Washout term $W$

# Evolution Equations

## RHN density matrix

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## Active lepton equations

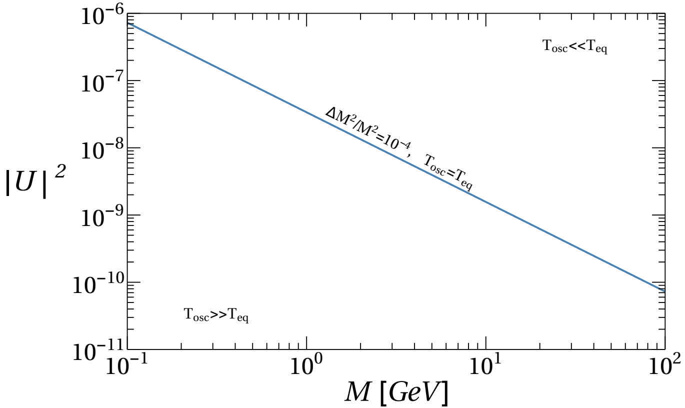
$$\frac{\mathrm{d}q_\ell}{\mathrm{d}z} = \frac{S_\ell(n)}{T} - W q_\ell + \tilde{W} q_N$$

## Temperature (time) scales

$$T_{\mathrm{osc}} = \sqrt[3]{T_{\mathrm{com}}\left(M_{11}^2 - M_{22}^2\right)}$$
$$T_{\mathrm{eq}} = T_{\mathrm{com}} \gamma_{\mathrm{av}} \mathrm{Tr}\left(Y Y^\dagger\right)$$

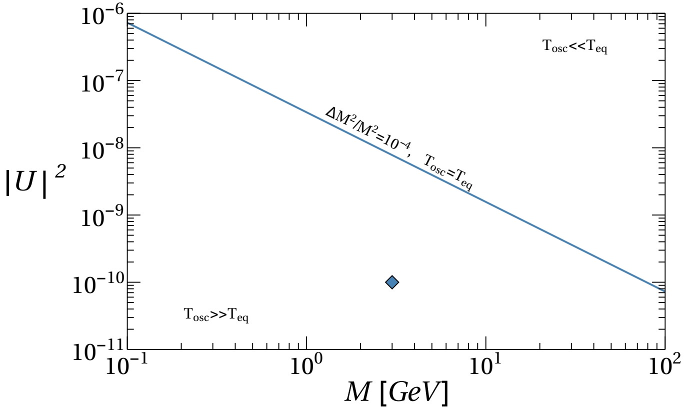
- Possible to solve numerically
- Approximations needed for parameter scans

# Temperature scales and observables




[Drewes/Garbrecht/Gueter/JK 1606.06690]

# Temperature scales and observables

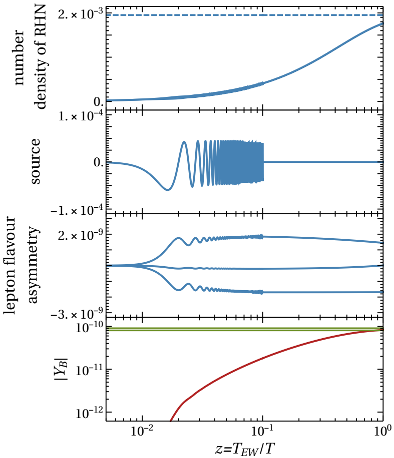



[Drewes/Garbrecht/Gueter/JK 1606.06690]

# Oscillatory regime: $T_{\text{osc}} \gg T_{\text{eq}}$ (small mixing angles)

- **oscillations** begin long before relaxation to equillibrium
- almost all lepton flavour asymmetry produced during first few oscillations
- lepton number asymmetry produced only through **flavour asymmetric washout**

[Drewes/Garbrecht/Gueter/JK 1606.06690]



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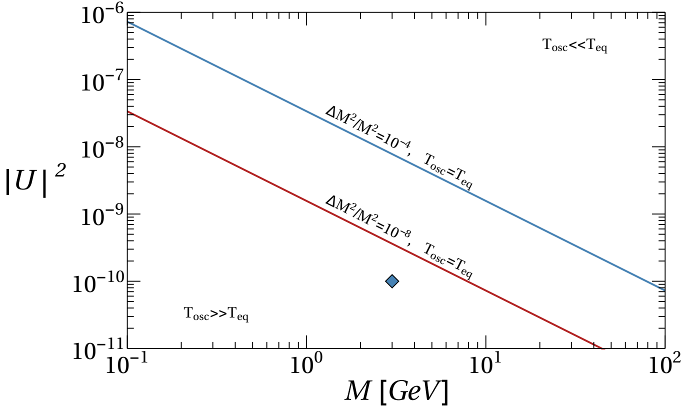


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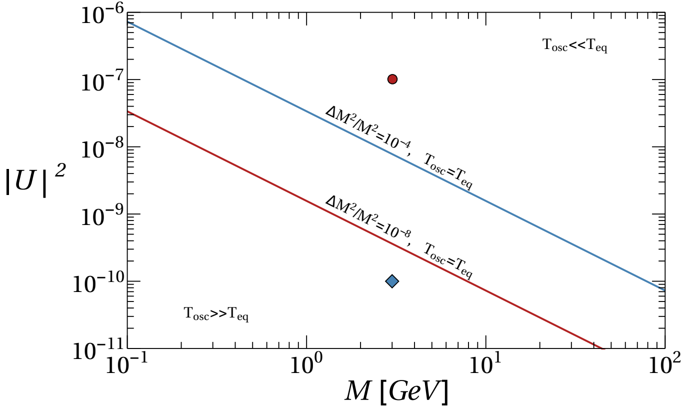
# Temperature scales and observables

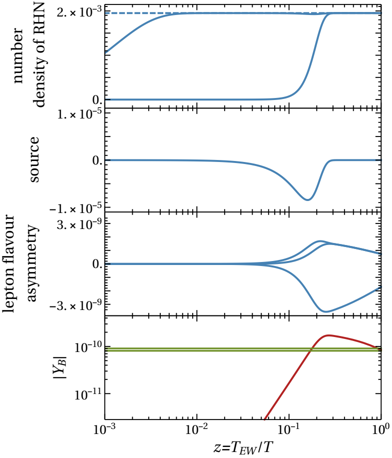



[Drewes/Garbrecht/Gueter/JK 1606.06690]

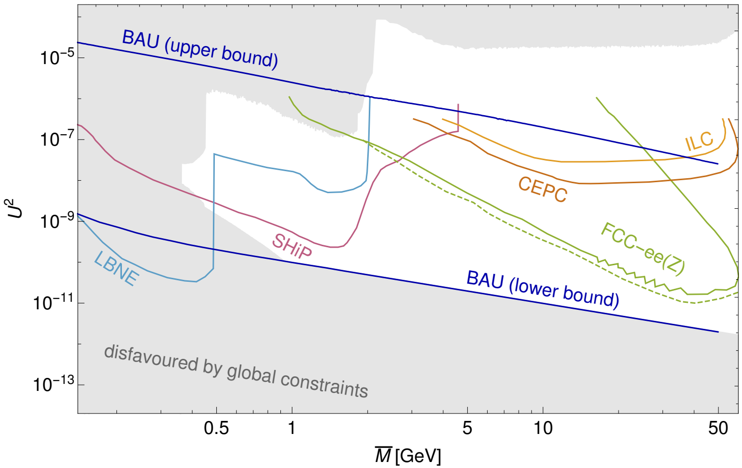
# Overdamped regime: $T_{\rm osc} \ll T_{\rm eq}$ (large mixing angles)

- naively for $T_{\rm osc} < T_{\rm eq}$, already in equilibrium
- requirement of reproducing the neutrino masses only allows **one interaction eigenstate** to equilibrate
- mixing between interaction eigenstates $\rightarrow$ equilibration
- approximate $B - L$ can postpone the production of BAU, **preventing** too much **washout**

[Drewes/Garbrecht/Gueter/JK 1606.06690]



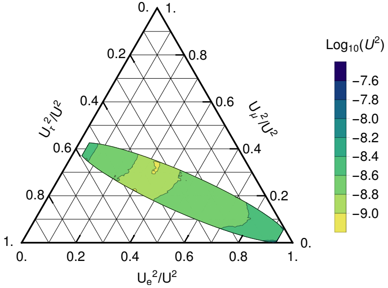
# Results: Inverted hierarchy




[Drewes/Garbrecht/Gueter/JK 1609.09069]

# Flavour patterns from leptogenesis: Inverted hierarchy

- large mixing angles require a **flavour asymmetric washout**, which corresponds to a flavour asymmetric mixing
- together with **seesaw constraints** this imposes constraints on the mixing patterns for **large mixing angles**

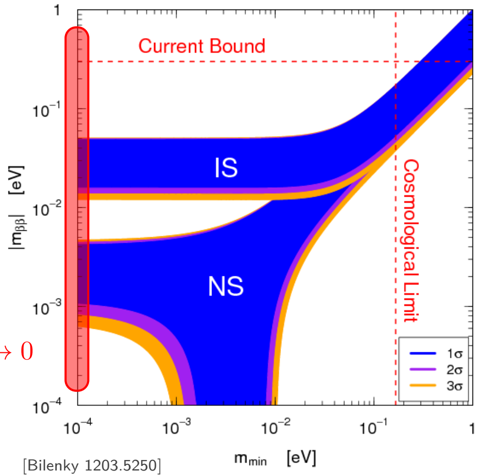



$\bar{M} = 30\,\mathrm{GeV}$

[Drewes/Garbrecht/Gueter/JK 1609.09069]

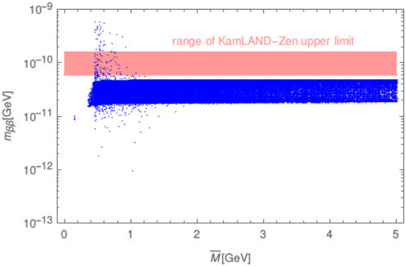
# Leptogenesis and neutrinoless double $\beta$ decay

$m_{\text{min}} \to 0$




[Bilenky 1203.5250]

# Leptogenesis and neutrinoless double $\beta$ decay




[Eijima/Drewes 1606.06221,

Hernández/Kekic/López-Pavón/Salvado 1606.06719]

- RHN can contribute to $m_{\beta\beta}$
- large mass splitting is required to have an observable effect (not always compatible with leptogenesis)
- some leptogenesis scenarios can already be excluded by current results

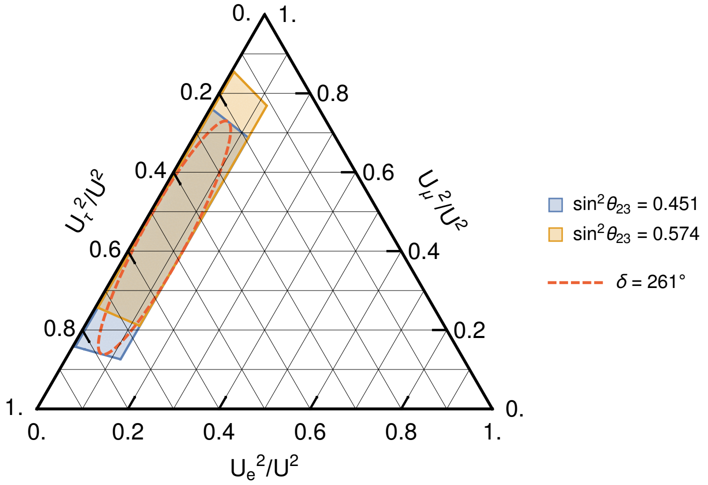
# Full Testability?

- full testability requires a complete determination of the RHN parameters
- in principle possible from a measurement of all mixing angles and masses
- leptogenesis requires degenerate masses - hard to resolve in experiments
- remaining parameters could be probed by:
  - neutrinoless double $\beta$ decay requires large $\Delta M$ and $U^2$

    [Eijima/Drewes 1606.06221,Hernández/Kekic/López-Pavón/Salvado 1606.06719]
  - $CP$ violation requires $\Delta M$ comparable to the decay width
  - lepton number violation requires $\Delta M$ comparable to the decay width

# Conclusions

- adding GeV-scale RHNs to the standard model can explain both the observed **neutrino masses** and the **BAU**
- the seesaw mechanism gives constraints on **RHN mixing patterns** (stronger if $\delta$ is measured!)
- testable leptogenesis within reach offuture experiments (SHiP, LBNE , FCC, ILC, CEPC)
- large mixing angles + leptogenesis $\rightarrow$ even stronger predictions on the flavour patterns
- while complete determination of the RHN parameters is possible in principle, it requires extreme experimental sensitivity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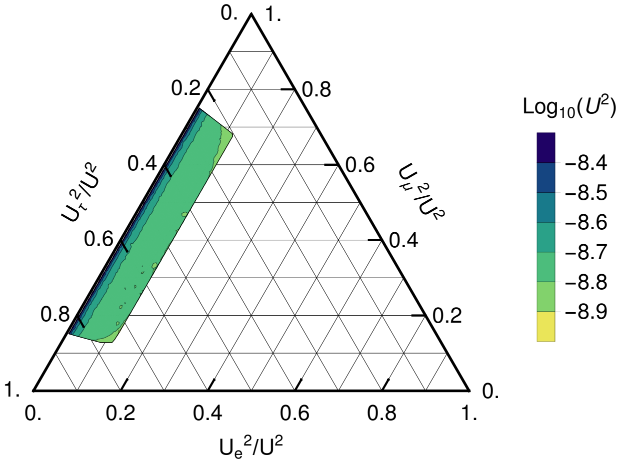
$U_\tau^2/U^2$
$U_\mu^2/U^2$
$U_e^2/U^2$
$\sin^2\theta_{23} = 0.451$
$\sin^2\theta_{23} = 0.574$
$\delta = 261°$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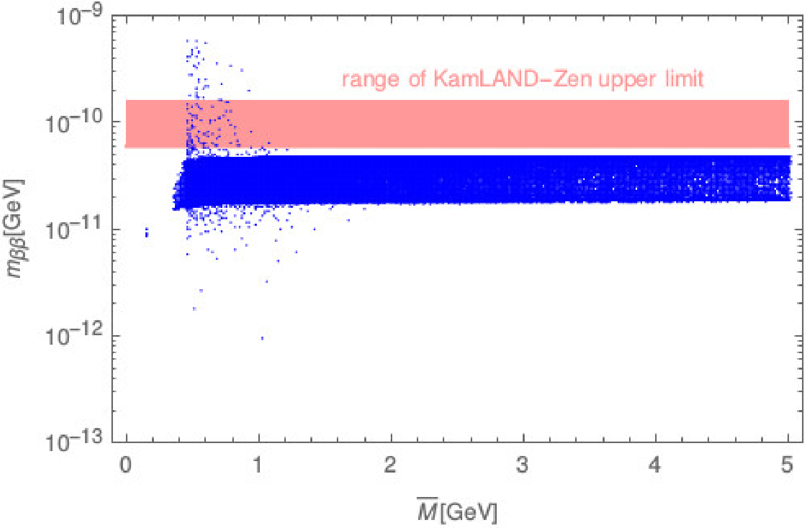
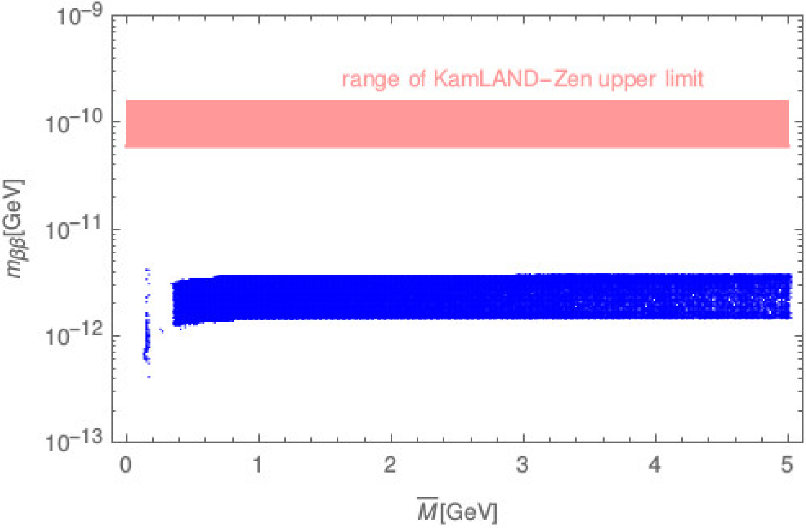
$U_\tau{}^2/U^2$
$U_\mu{}^2/U^2$
$U_e{}^2/U^2$
$\mathrm{Log}_{10}(U^2)$
−8.4
−8.5
−8.6
−8.7
−8.8
−8.9




[Eijima/Drewes 1606.06221]

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