Leptogenesis

Juraj Klarić

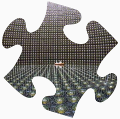
Neutriverse, December 1st 2022

Overview

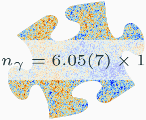
Introduction

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



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

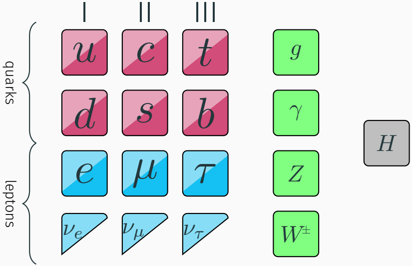
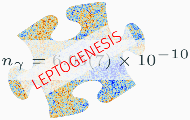


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Neutrino masses

[Minkowski 1977...]

The Baryon Asymmetry of the Universe



[Fukugita/Yanagida '86...]

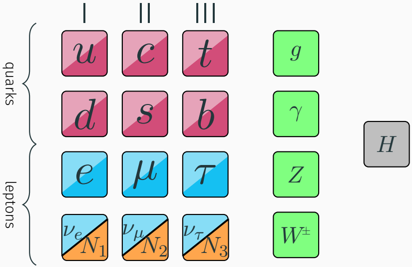


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

The seesaw mechanism

The neutrino masses

- the observed neutrino masses are surprisingly small

$$m_\nu \lesssim 1\,\mathrm{eV}$$

- if the masses are even partly Dirac $\rightarrow$ right-handed neutrinos (RHN) exist

$$\mathcal{L} \supset \frac{1}{2}\overline{\nu_L} m_D \nu_R$$

- RHN are SM gauge singlets
- they can be their own antiparticles $\rightarrow$ they *can*[1] have a Majorana mass term M_M
- the full mass matrix:

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

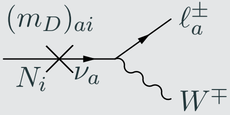
[1]“Everything not forbidden is compulsory.” - Murray Gell-Mann

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

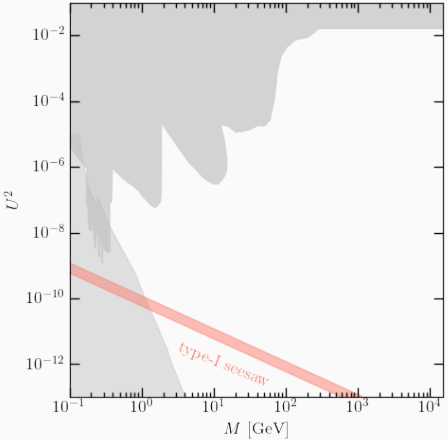
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

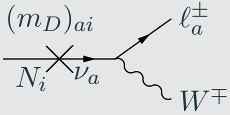
[see talks by Vedran and Matthias]

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

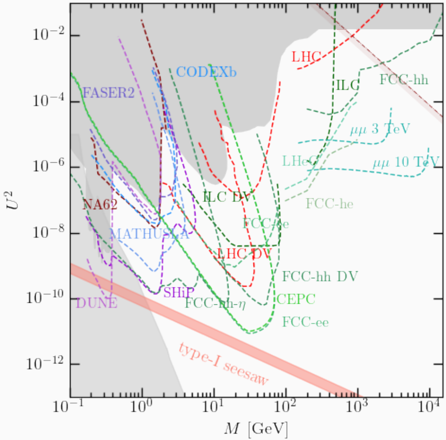
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

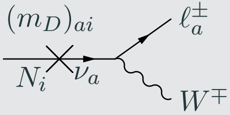
[see talks by Vedran and Matthias]

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

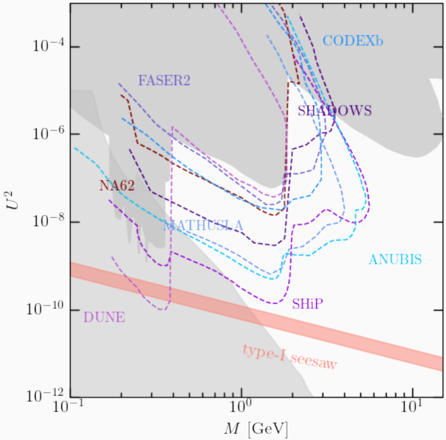
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

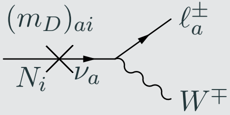
[see talks by Vedran and Matthias]

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

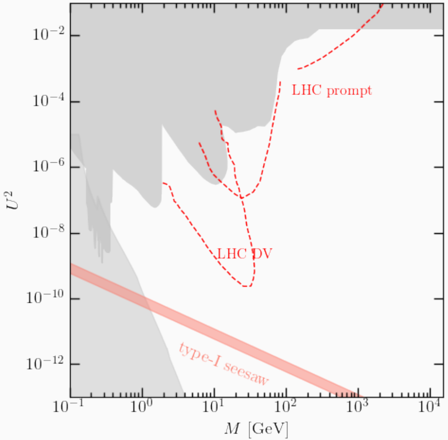
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

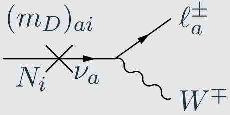
[see talks by Vedran and Matthias]

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

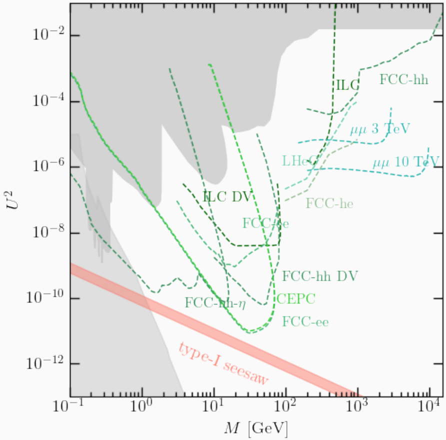
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

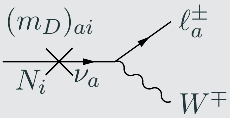
[see talks by Vedran and Matthias]

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

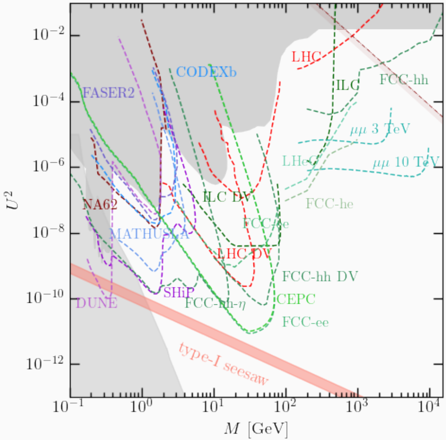
HNL mixing



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

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$

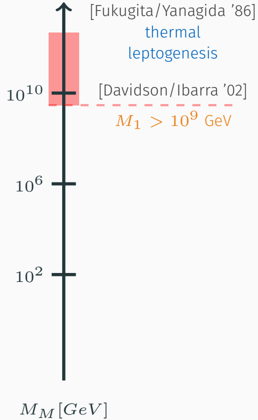


[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

[see talks by Vedran and Matthias]

The *low-scale* leptogenesis mechanisms

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

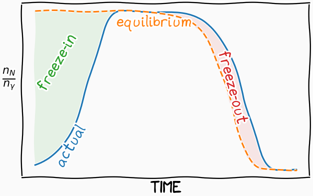
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

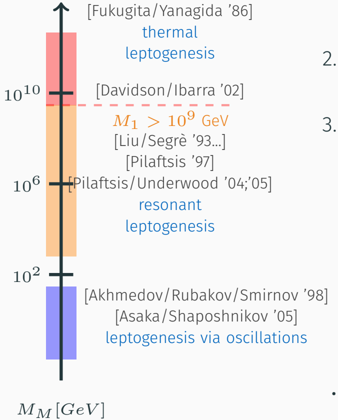
3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

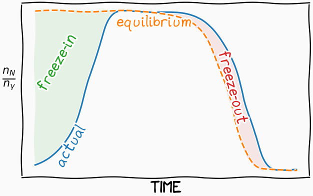
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

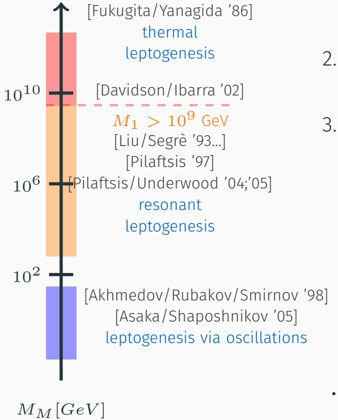
3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

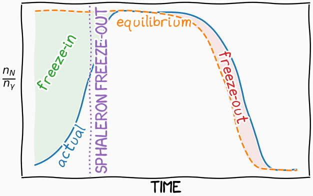
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

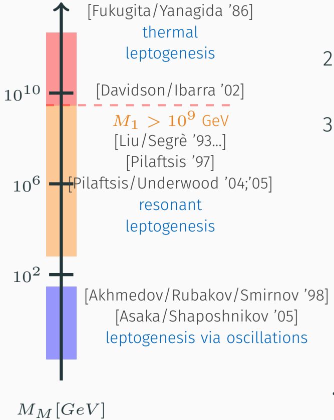
3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

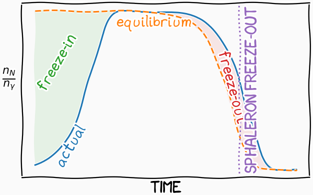
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

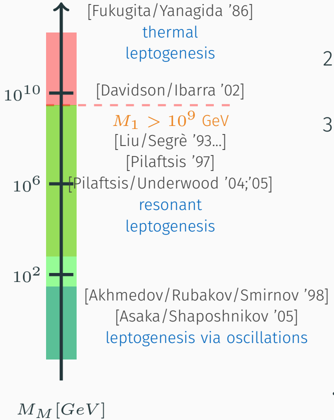
3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

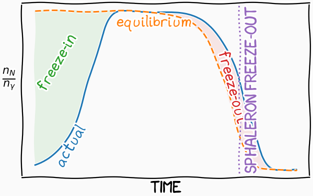
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

3. Deviation from thermal equilibrium

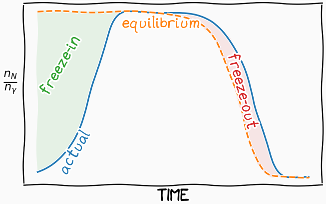
   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

Thermal leptogenesis

- the BAU is mainly produced in the decays of RHN
- as the universe expands, cools down to $T \leq M_M$ the RHN become non-relativistic and begin to decay



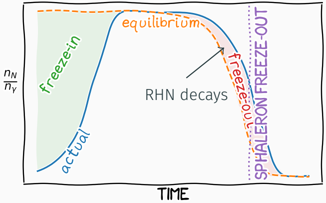
The lepton asymmetries follow the equation

$$\frac{dY_{\ell_a}}{dz} = -\epsilon_a \frac{\Gamma_N}{Hz}(Y_N - Y_N^{\text{eq}}) - W_{ab} Y_{\ell_b}$$

The key quantity determining the BAU is the decay asymmetry

$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}}$$

- the BAU is mainly produced in the decays of RHN
- as the universe expands, cools down to $T \leq M_M$ the RHN become non-relativistic and begin to decay



The lepton asymmetries follow the equation

$$\frac{dY_{\ell_a}}{dz} = -\epsilon_a \frac{\Gamma_N}{Hz}(Y_N - Y_N^{\mathrm{eq}}) - W_{ab} Y_{\ell_b}$$

The key quantity determining the BAU is the decay asymmetry

$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}}$$

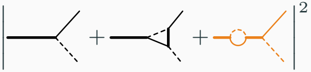
- for hierarchical neutrinos, the decay asymmetry is limited by the Davidson-Ibarra bound

$$|\epsilon| \lesssim \frac{3M_1 m_\nu}{8\pi v^2}$$

[Davidson/Ibarra 2002]

- however, if we carefully look at the diagrams

$$\Gamma_{N\to\ell\bar{\phi}} \sim$$



we find that the wave-function diagram becomes enhanced for $M_2 \to M_1$

$$\epsilon = \frac{1}{8\pi}\frac{\mathrm{Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}}\frac{M_1 M_2}{M_1^2 - M_2^2}$$

[Kuzmin 1970]

In the context of *leptogenesis*:

[Liu/Segrè/Flanz/Paschos/Sarkar/Weiss/Covi/Roulet/Vissani/Pilaftsis/Underwood/Buchmüller/Plumacher...]

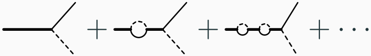
This enhancement is known as resonant leptogenesis.

Resonant Leptogenesis and RHN oscillations

- the decay asymmetry ϵ appears divergent for $M_2 \to M_1$
- this divergence is unphysical, it needs to be regulated

$$\epsilon = \frac{1}{8\pi} \frac{\mathrm{Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}} \frac{M_1 M_2}{M_1^2 - M_2^2 + A^2}$$

- in the degenerate limit perturbation theory breaks down

$\Gamma_N \supset$ 

- to resolve this we have to go beyond the S-matrix formalism, RHN are unstable particles $\to$ no asymptotic states!

Evolution equations for resonant leptogenesis

- another way of describing the same process is to use density matrix equations
- instead of number densities, we include correlations of the RHN flavours:

RHN density matrix

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

Active lepton equations

$$\frac{\mathrm{d}Y_\ell}{\mathrm{d}z} = S_\ell(n) - W Y_\ell$$

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

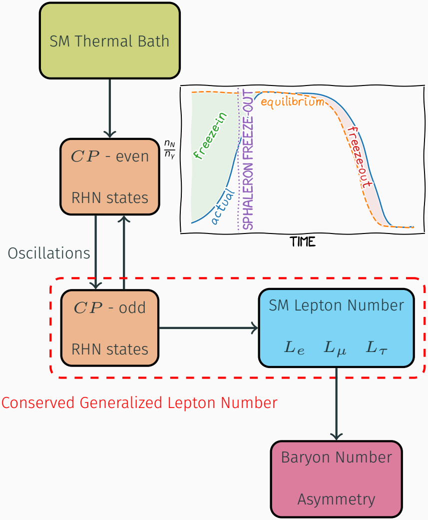
Resonant leptogenesis - summary

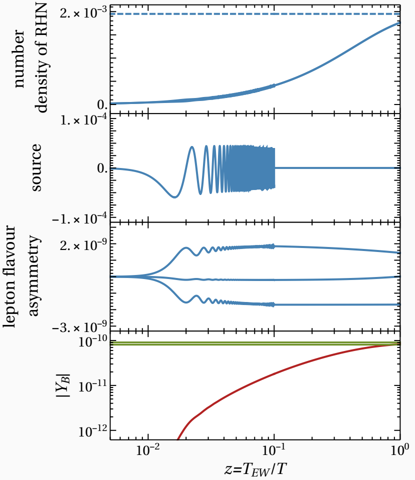
- resonant leptogenesis allows RHN below $10^9\,\mathrm{GeV}$
  - can be relaxed down to $\sim 10^7$ GeV with flavour effects
- we run into conceptual problems for $M_2 \to M_1$
- these issues can be resolved with non-perturbative methods
  - resonant leptogenesis can be described through RHN oscillations

Issues:

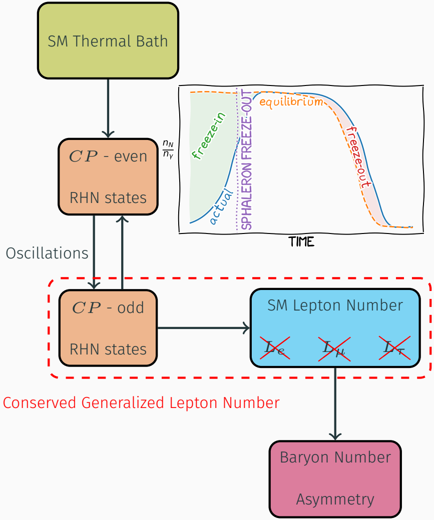
- existing studies typically assume non-relativistic RHN and neglect relativistic effects
- non-thermal initial conditions still require solving the full density matrix equations
- RHN decays require $M \gtrsim T$ $\to$ not clear what happens for $M \lesssim 130\,\mathrm{GeV}$

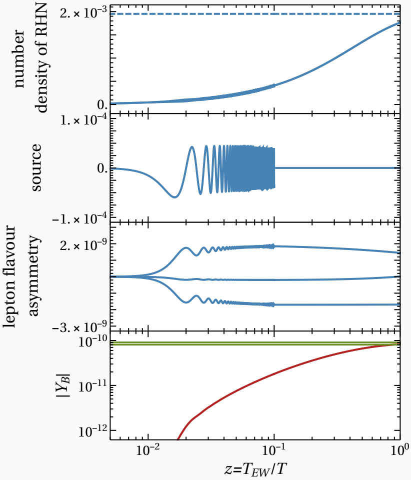
Leptogenesis through Neutrino Oscillations



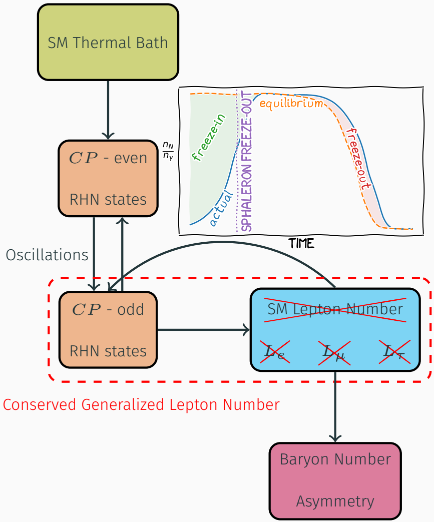


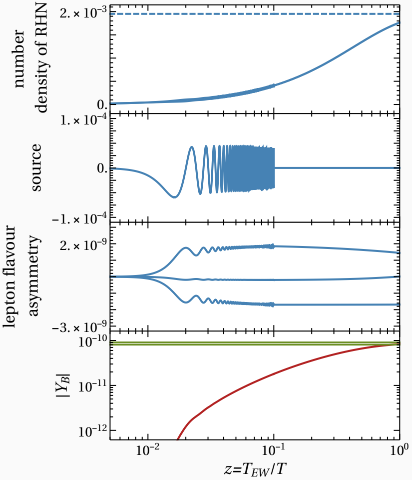
Leptogenesis through Neutrino Oscillations



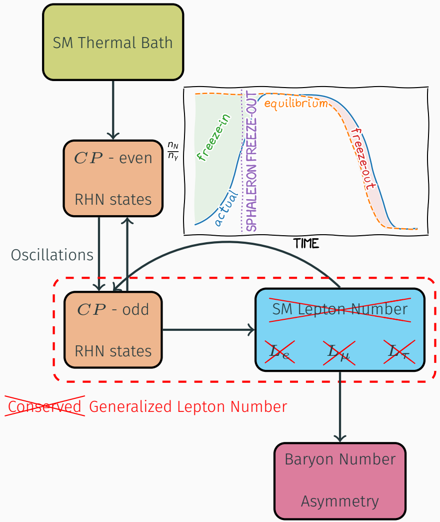


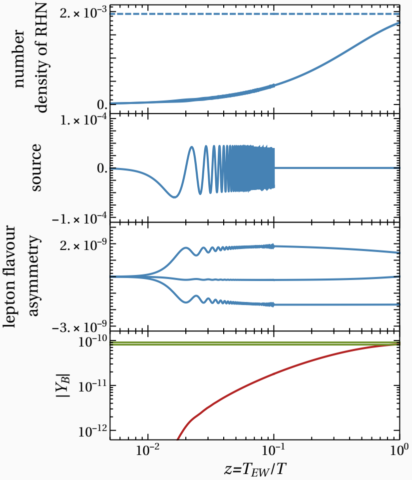
Leptogenesis through Neutrino Oscillations





Leptogenesis through Neutrino Oscillations





Evolution Equations

System of kinetic equations

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\Gamma_\alpha\right] f_N\left(1-f_N\right) \quad + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\tilde{\Gamma}_\alpha\left(\bar{\rho}_N-\rho_N\right)\right],$$

$$i\frac{d\rho_N}{dt} = \left[H_N,\rho_N\right] - \frac{i}{2}\left\{\Gamma,\rho_N-\rho_N^{eq}\right\} - \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

$$i\frac{d\bar{\rho}_N}{dt} = -\left[H_N,\bar{\rho}_N\right] - \frac{i}{2}\left\{\Gamma,\bar{\rho}_N-\rho_N^{eq}\right\} + \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

- equations very similar to those used for resonant leptogenesis
- notably there are twice as many equations for the RHN $\rightarrow$ helicity taken into account $(\rho_N\,,\rho_{\bar{N}})$
- temperature dependence of the equilibrium distributions often neglected

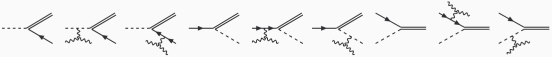
Leptogenesis through Neutrino Oscillations - differences

Compared to resonant leptogenesis, there exist a few important differences:

- initial conditions are crucial, all BAU is generated during RHN equilibration
- it is important to distinguish between the helicities of the RHN, as it carries an approximately conserved lepton number
- the decay of the RHN equilibrium distribution can typically be neglected $\dot{Y}_N^{\mathrm{eq}} \approx 0$

Rates for leptogenesis

- one of the major challenges is to estimate the coefficients H_N and Γ_N
- unlike resonant leptogenesis, where it is often assumed that the rates are dominated by RHN decays, the main contribution comes from thermal effects



[Ghiglieri/Laine 2017]

Two main types of rates:

Fermion number conserving

$$\Gamma_+ \sim Y^2 T \sim H$$

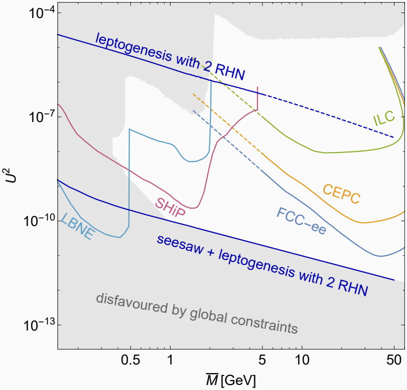
Fermion number violating

$$\Gamma_- \sim Y^2 \frac{M^2}{T} \ll H$$

[Ghiglieri/Laine 2017, Eijima/Shaposhnikov 2017]

The parameter space of leptogenesis

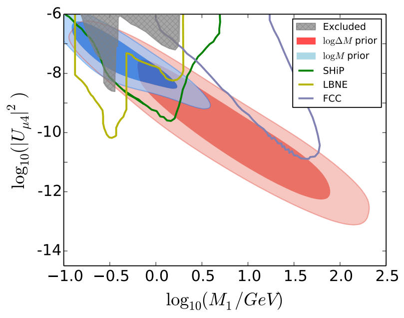
Parameter space of low-scale leptogenesis



[Drewes/Garbrecht/Gueter/JK '16]

- several systematic studies over the past years
- leptogenesis is within reach of future experiments
- why do they often stop around $\mathcal{O}(50)\,\mathrm{GeV}$?

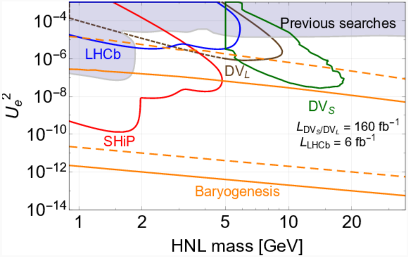
Parameter space of low-scale leptogenesis



prior dependent Bayesian study
[Hernández/Kekic/López-Pavón/Racker/Salvado '16]

- several systematic studies over the past years
- leptogenesis is within reach of future experiments
- why do they often stop around $\mathcal{O}(50)\,\mathrm{GeV}$?

Parameter space of low-scale leptogenesis



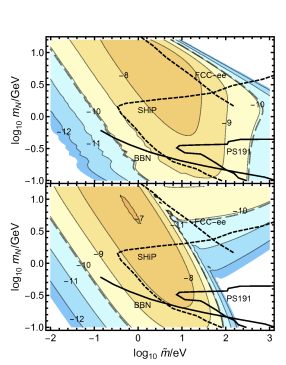
including the FNV and FNC rates
[Eijima/Shaposhnikov/Timiryasov '18]
[Boiarska et. al. '19]

- several systematic studies over the past years
- leptogenesis is within reach of future experiments
- why do they often stop around $\mathcal{O}(50)\,\mathrm{GeV}$?

What lies beyond $\mathcal{O}(50)$ GeV?

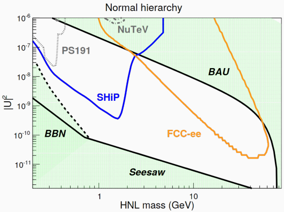
Resonant leptogenesis

- early estimates lead to successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood '05]
- Higgs decay leptogenesis mechanism proposed in [Hambye/Teresi '16; '17]



Leptogenesis via oscillations

- for $M_M > M_W$ new channels open up
- large equilibration rates for both FNV and FNC processes
- generically we have $\Gamma_N/H \gtrsim 30$ for $T \sim 150\,\mathrm{GeV}$, $M \sim 80\,\mathrm{GeV}$
- early estimate [Blondel/Graverini/Serra/Shaposhnikov 2014]



- Baryogenesis window closes at $M_M \sim 80\,\mathrm{GeV}$?

A quantitative study is necessary!

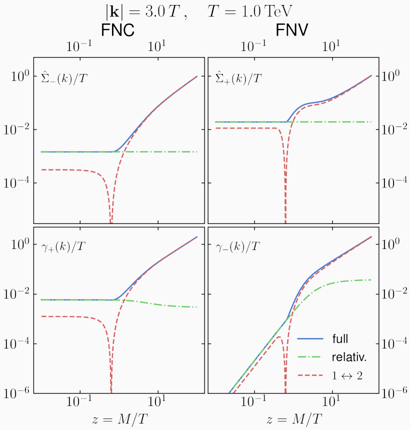
Study of the parameter space

- we use a single set of equations for both leptogeneses
    - for $M \gg T$ we recover resonant leptogenesis
    - for $M \ll T$ we recover leptogenesis via oscillations
- we separate the freeze-in and freeze-out regimes
    - for thermal initial conditions freeze-out is the only source of BAU: "resonant" leptogenesis dominates
    - for vanishing initial conditions with $\dot{Y}_N^{eq} \to 0$ freeze-in is the only source of BAU: LG via oscillations dominates
- biggest challenge: rates!
    - so far estimates of the rates only exist for $M \ll T$ and $M \gg T$
    - we combine the two by *extrapolating* the relativistic rate and adding it to the non-relativistic decays
- we perform a comprehensive numerical scan over the parameters between $100\,\mathrm{MeV} < M_M < 10\,\mathrm{TeV}$

Extrapolating the rates to the non-relativistic regime

- helicity-dependent rates unknown outside of the relativistic regime
- we extrapolate the relativistic rate
- combine this result with the $1 \leftrightarrow 2$ rate

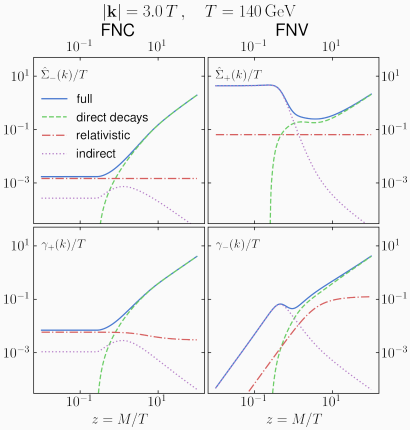
Symmetric phase of the SM:



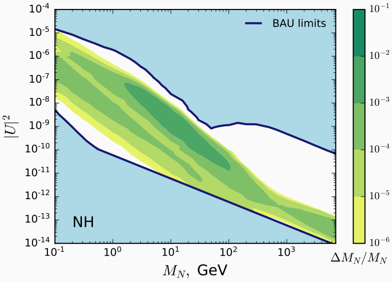
Extrapolating the rates to the non-relativistic regime

- helicity-dependent rates unknown outside of the relativistic regime
- we extrapolate the relativistic rate
- combine this result with the $1 \leftrightarrow 2$ rate
- in the broken phase the situation is more involved
- large FNV contribution from mixing with light neutrinos
- indirect contribution is enhanced when $M_N \sim g^2 T$

Broken phase of the SM:



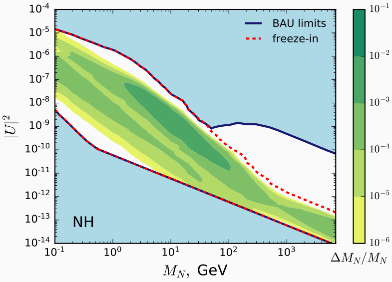
Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the “source” term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

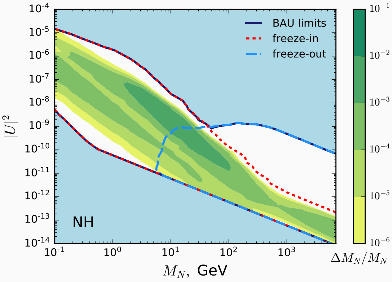
Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\rm eq}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\rm eq}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

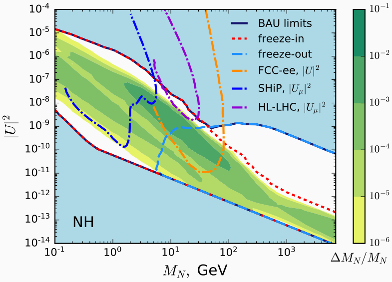
Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

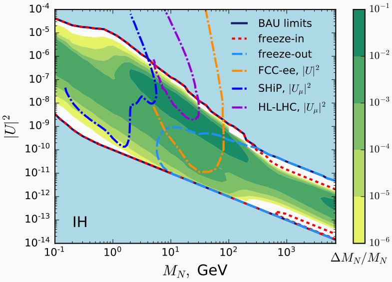
Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the “source” term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

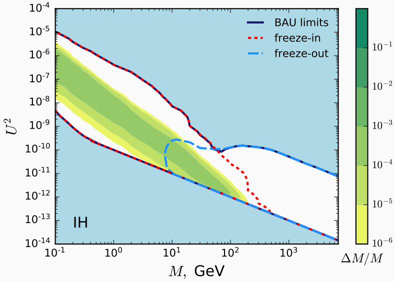
Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\rm eq}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\rm eq}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

Results



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

Leptogenesis with 3 RHNs

How is $3 \neq 2$?: Dimensionality of the parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

+ 2 RHN masses

2 parameters

3 Heavy Neutrinos

+ 3 RHN masses

3 parameters

How is $3 \neq 2$?: Dimensionality of the parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

+ 2 RHN masses
+ 1 *complex* $(\times 2)$ angle

3 parameters

3 Heavy Neutrinos

+ 3 RHN masses
+ 3 *complex* $(\times 2)$ angles

6 parameters

How is $3 \neq 2$?: Dimensionality of the parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

- 2 RHN masses
- 1 *complex* $(\times 2)$ angle
- **2 light neutrino masses**

---

5 parameters

3 Heavy Neutrinos

- 3 RHN masses
- 3 *complex* $(\times 2)$ angles
- **2 $+ 1$ light neutrino masses**

---

9 parameters

How is $3 \neq 2$?: Dimensionality of the parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

+ 2 RHN masses
+ 1 *complex* $(\times 2)$ angle
+ **2 light neutrino masses**
+ **3 PMNS angles**
+ 1 CP phase δ
+ 1 Majorana phase α

11 (6 free) parameters

3 Heavy Neutrinos

+ 3 RHN masses
+ 3 *complex* $(\times 2)$ angles
+ **$2 + 1$ light neutrino masses**
+ **3 PMNS angles**
+ 1 CP phase δ
+ 2 Majorana phases $\alpha_{1,2}$

18 (13 free) parameters

Large mixing angles and approximate B-L symmetry

- large U^2 require cancellations between different entries of the Yukawa matrices F
- this cancellation can be associated with an approximate lepton number symmetry

  [Shaposhnikov hep-ph/0605047, Kersten Smirnov 0705.3221, Moffat Pascoli Weiland 1712.07611]
- symmetry broken by small parameters $\epsilon, \epsilon', \mu, \mu'$

Pseudo-Dirac pairs

$$N_s = \frac{N_1 + iN_2}{\sqrt{2}}\,, N_w = \frac{N_1 - iN_2}{\sqrt{2}}$$

B-L parametrisation

$$M_M = \bar{M}\begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

$$F = \frac{1}{\sqrt{2}}\begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}$$

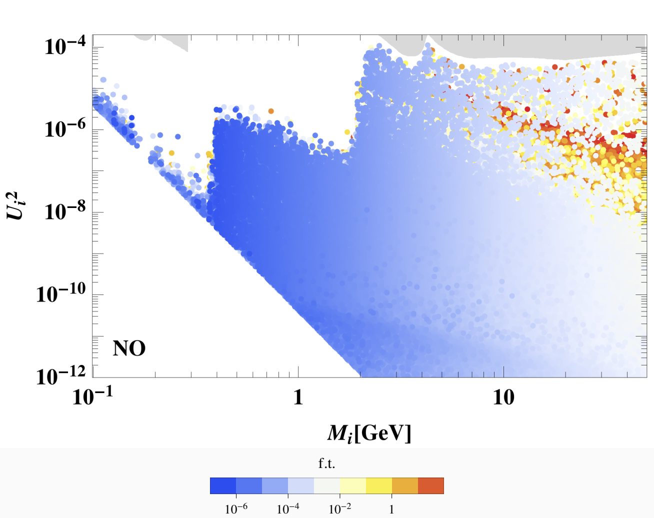
Fine tuning

- if present, symmetries are manifest to all orders in p.t.
- in the case of a large B-L breaking, radiative corrections can cause large neutrino masses
- we can use the size of radiative corrections to the light neutrino masses to quantify tuning

Fine Tuning

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

Results: Leptogenesis with 3 RHN (Normal Ordering)



[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

How is $3 \neq 2$?: Leptogenesis

- asymmetry can be generated even without washout

  [Akhmedov/Rubakov/Smirnov hep-ph/9803255]

- large hierarchy in the washout is possible

  [Canetti/Drewes/Garbrecht 1404.7144]

- level crossing between the heavy neutrinos

  [Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

How is $3 \neq 2$?: Leptogenesis

- asymmetry can be generated even without washout

  [Akhmedov/Rubakov/Smirnov hep-ph/9803255]

  - Sakharov II: CP
  - more CP phases than in the case with two RHN

- large hierarchy in the washout is possible

  [Canetti/Drewes/Garbrecht 1404.7144]

  - Sakharov III: non-equilibrium

- level crossing between the heavy neutrinos

  [Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

  - Sakharov II: CP

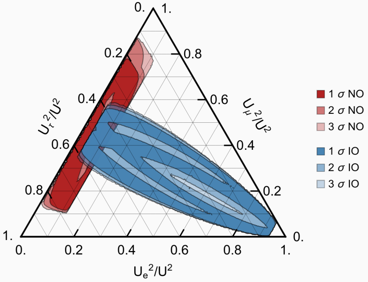
Hierarchy in the washout

- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

$$\mathfrak{f} \equiv \frac{\Gamma_a}{\Gamma} \sim \frac{U_a^2}{U^2}$$

- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible

2 RHNs:



[Snowmass White Paper 2203.08039]

[Drewes/Garbrecht/Gueter/JK 1609.09069]

[Caputo/Hernandez/Lopez-Pavon/Salvado 1704.08721]

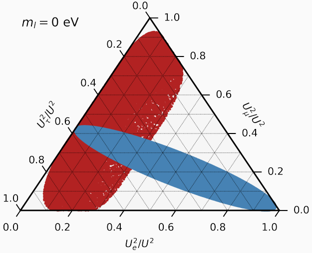
Hierarchy in the washout

- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

$$\mathfrak{f} \equiv \frac{\Gamma_a}{\Gamma} \sim \frac{U_a^2}{U^2}$$

- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible

3 RHNs:



[Drewes/Georis/JK 230x.xxxx]

[Chrzaszcz/Drewes/Gonzalo/Harz/Krishnamurthy/Weniger 1908.02302]

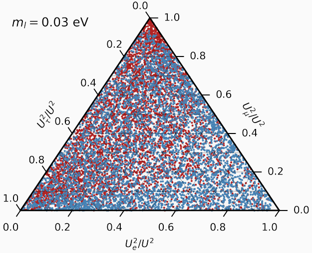
Hierarchy in the washout

- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

$$\mathfrak{f} \equiv \frac{\Gamma_a}{\Gamma} \sim \frac{U_a^2}{U^2}$$

- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible

3 RHNs:

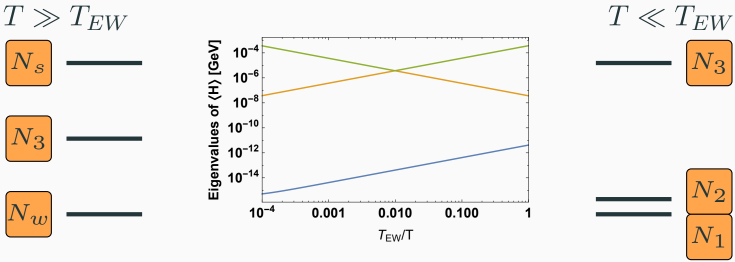


[Drewes/Georis/JK 230x.xxxx]

[Chrzaszcz/Drewes/Gonzalo/Harz/Krishna-murthy/Weniger 1908.02302]

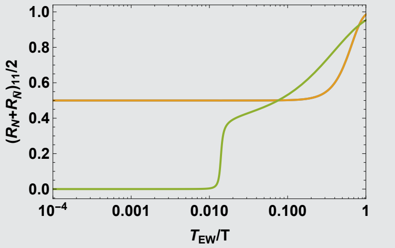
Enhancement due to level crossing

- in the $B - L$ symmetric limit two heavy neutrinos form a pseudo-Dirac pair
- the “3rd” heavy neutrino can be heavier than the pseudo-Dirac pair
- for $T \gg T_{EW}$, the pseudo-Dirac pair also has a thermal mass

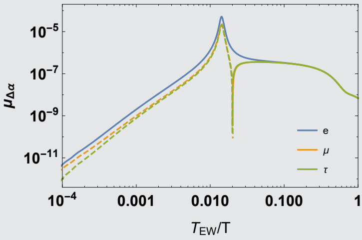


Enhancement due to level crossing

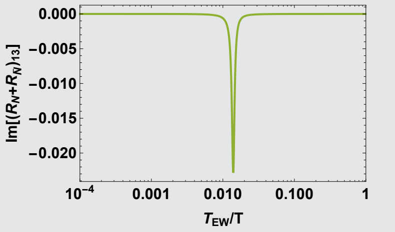
Heavy Neutrino Densities



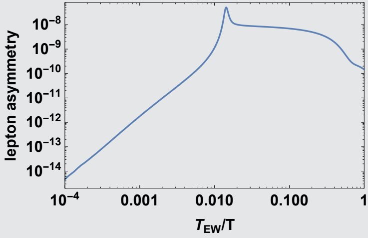
Lepton flavour asymmetries



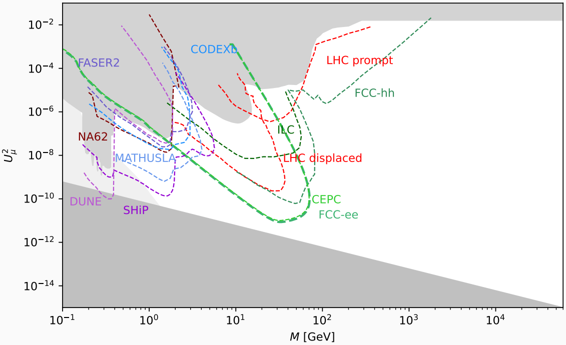
Heavy Neutrino correlations



Lepton number asymmetry



Results: Beyond the EW scale with 3 RHNs

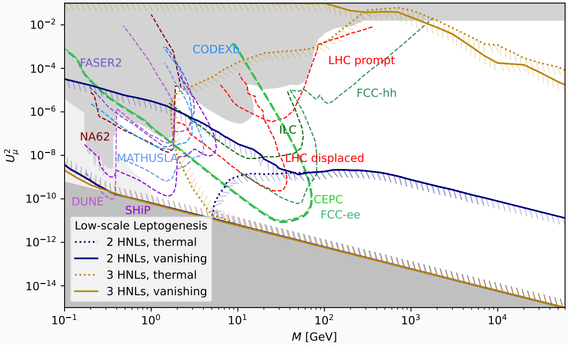


[Snowmass White Paper 2203.08039]

leptogenesis lines from [Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
- both freeze-in and freeze-out leptogeneses already testable at existing experiments
- the maximal value of U^2 depends on m_1

Results: Beyond the EW scale with 3 RHNs

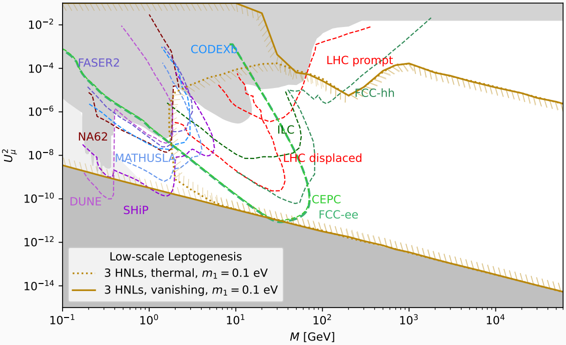


[Snowmass White Paper 2203.08039]

leptogenesis lines from [Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
- both freeze-in and freeze-out leptogeneses already testable at existing experiments
- the maximal value of U^2 depends on m_1

Results: Beyond the EW scale with 3 RHNs

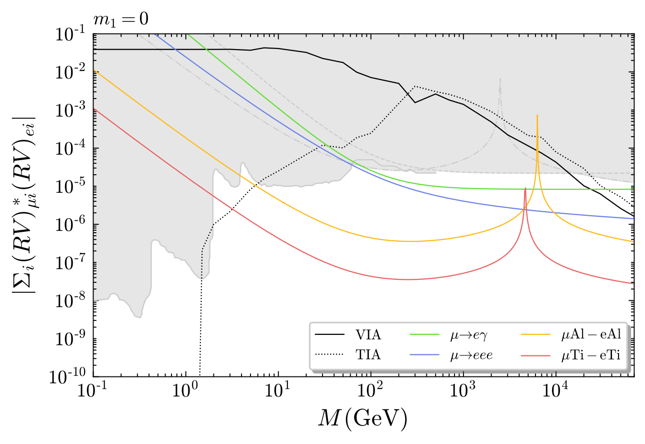


[Snowmass White Paper 2203.08039]

leptogenesis lines from [Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
- both freeze-in and freeze-out leptogeneses already testable at existing experiments
- the maximal value of U^2 depends on m_1

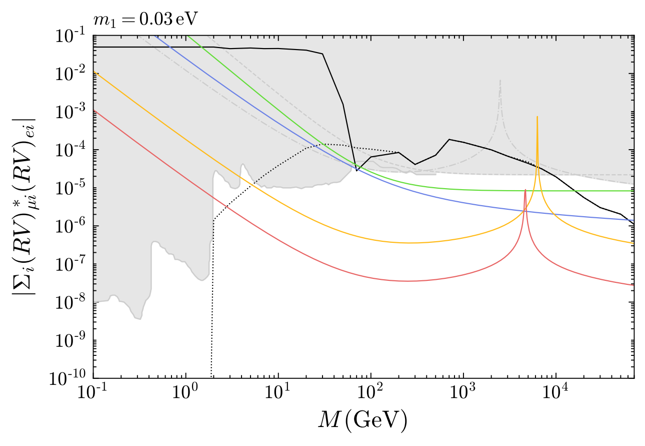
Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

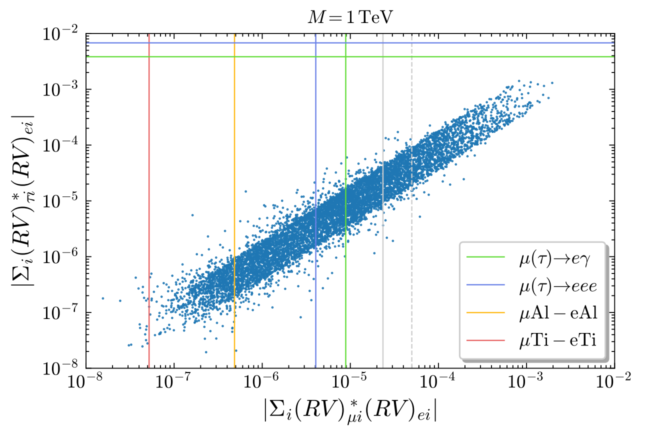
Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

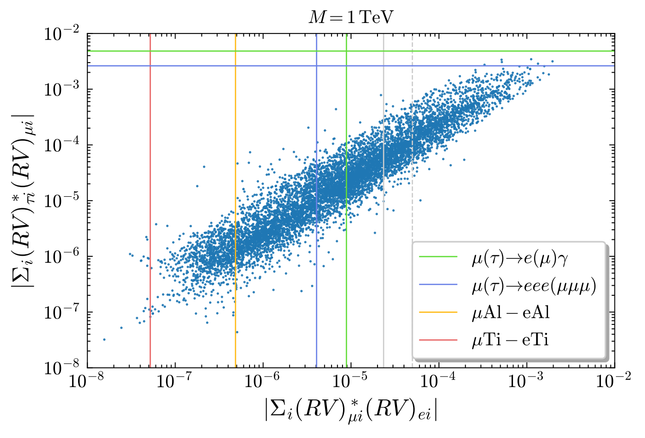
Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

Indirect probes: Charged LFV



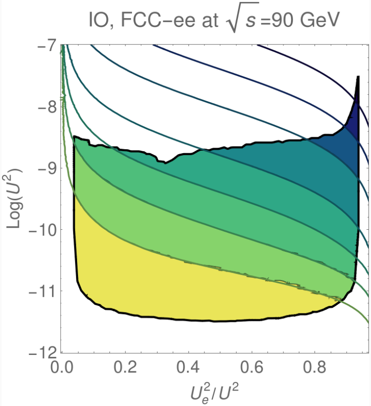
[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

From discovery to tests

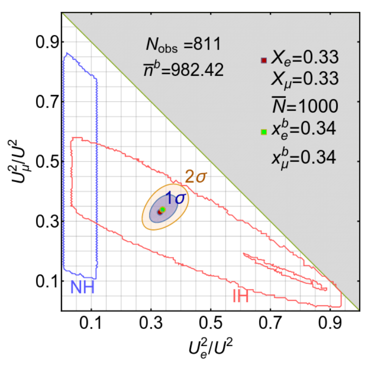
Measuring flavor ratios at experiments

$M_N = 30$ GeV @ FCC-ee



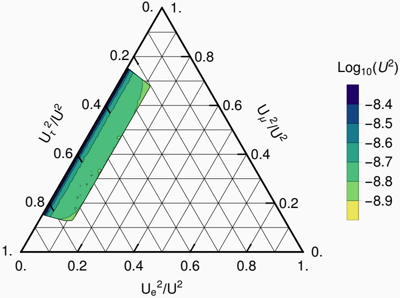
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

$M_N = 1$ GeV @ SHiP

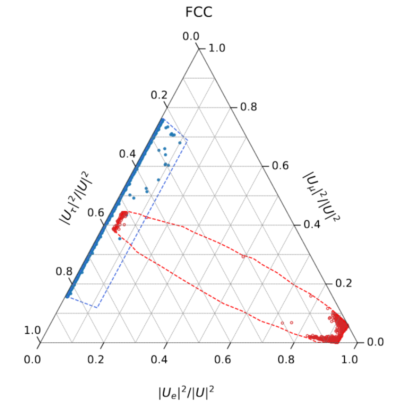


[Snowmass HNL WP 2203.08039]

Flavor constraints from leptogenesis



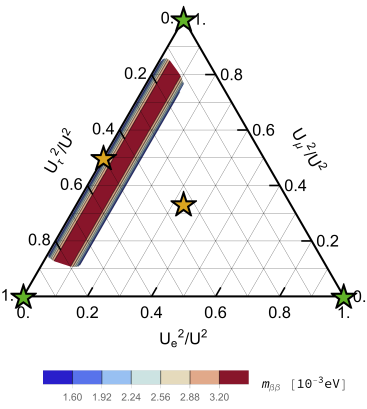
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]



$$\Delta M/M = 10^{-2}$$

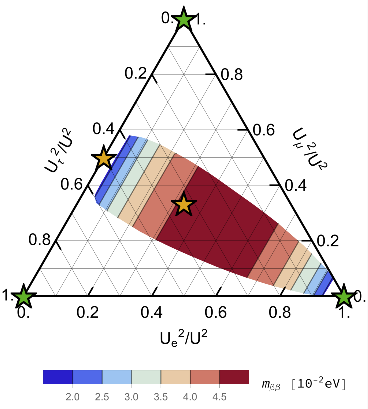
[Hernandez/Lopez-Pavon/Rius/Sandner 2207.01651]

Complementarity with neutrinoless double beta decay



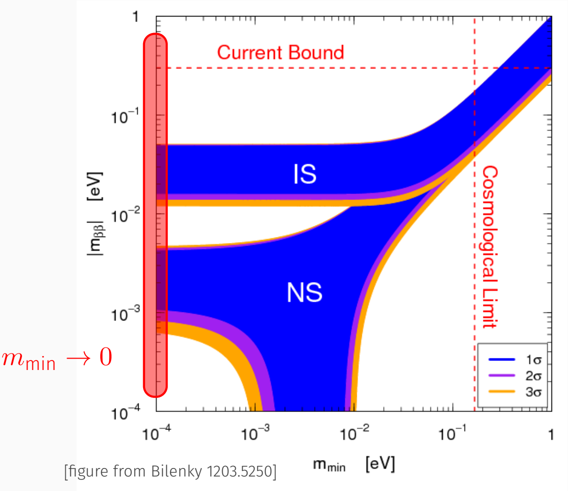
- $m_{\beta\beta}$ is a complementary probe of the flavor mixing ratios for $M_N \gg 100 MeV$
- excluding $m_{\beta\beta}$ limits allowed flavour ratios

Complementarity with neutrinoless double beta decay



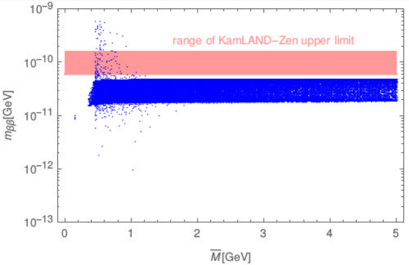
- $m_{\beta\beta}$ is a complementary probe of the flavor mixing ratios for $M_N \gg 100 MeV$
- excluding $m_{\beta\beta}$ limits allowed flavour ratios

Leptogenesis and neutrinoless double β decay



[figure from Bilenky 1203.5250]

HNL contribution to neutrinoless double β decay

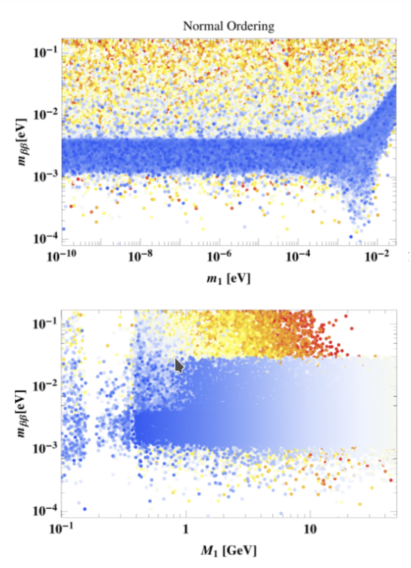


[Eijima/Drewes 1606.06221,

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

HNL contribution to neutrinoless double β decay

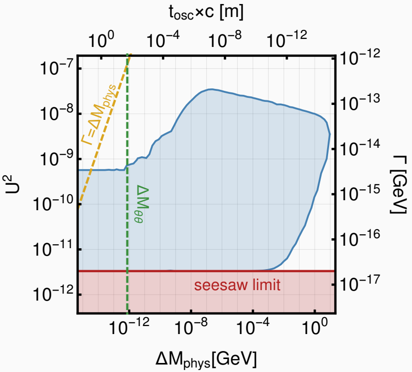


- RHN can contribute to $m_{\beta\beta}$
- large mass splitting is required to have an observable effect (not always compatible with leptogenesis)
- some leptogenesis scenarios can already be excluded by current results

[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

Measuring the mass splitting in model with 2 HNLs

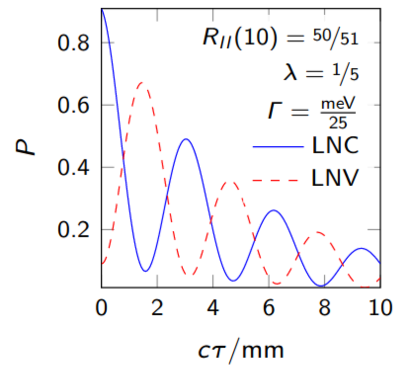
Normal Ordering:



$M = 30$ GeV

[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

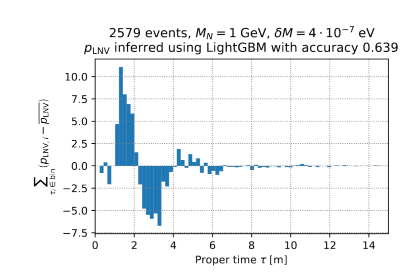
- large range of ΔM consistent with leptogenesis
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
- Higgs vev contribution to RHN mass difference $\Delta M_{\theta\theta}$ practically implies lower limit on the mass splitting



[Antusch/Hajer/Rosskopp 2210.10738]

- large range of ΔM consistent with leptogenesis
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
- Higgs vev contribution to RHN mass difference $\Delta M_{\theta\theta}$ practically implies lower limit on the mass splitting

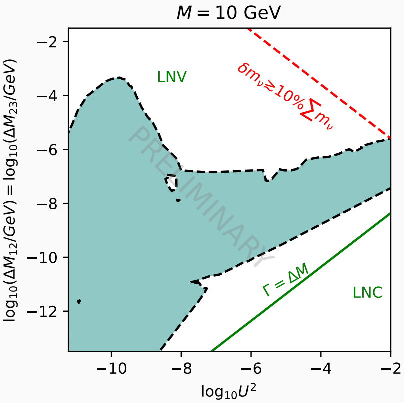
Measuring the mass splitting in model with 2 HNLs



[Tastet/Timiryasov 1912.05520]

- large range of ΔM consistent with leptogenesis
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
- Higgs vev contribution to RHN mass difference $\Delta M_{\theta\theta}$ practically implies lower limit on the mass splitting

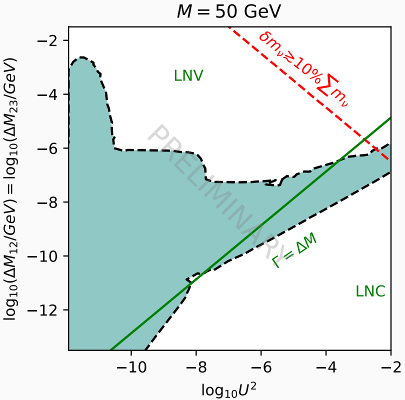
Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 230x.xxxx]

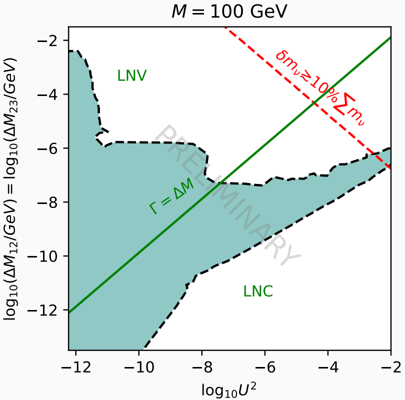
Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 230x.xxxx]

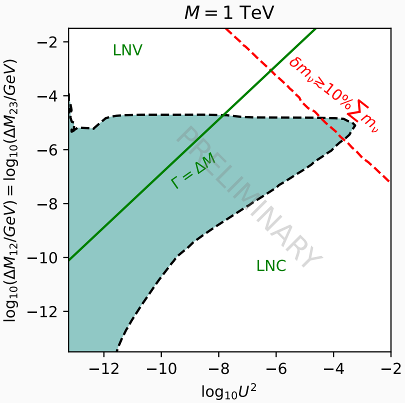
Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 230x.xxxx]

Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 230x.xxxx]

Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two regimes of the same mechanism
- freeze-out is already possible for GeV-scale RHNs
- freeze-in remains important at the TeV-scale and beyond
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- leptogenesis is testable at planned future experiments
    - there is synergy between high-energy and high-intensity experiments!
    - together they will cover a large portion of the low-scale leptogenesis parameter space

Thank you!