Leptogenesis United

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based on 2008.13771 and 2103.16545 in collaboration with M.E. Shaposhnikov and I. Timiryasov

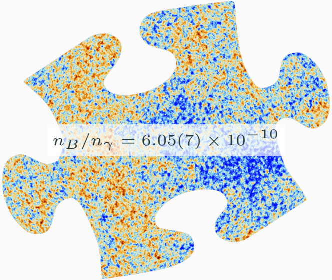
University of Manchester, May 21st 2021

Outline

Introduction

Some puzzles for physics beyond the Standard Model

BAU baryon asymmetry of the universe



Neutrino masses

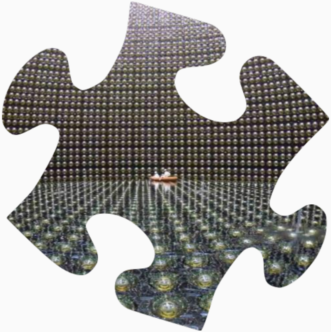


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

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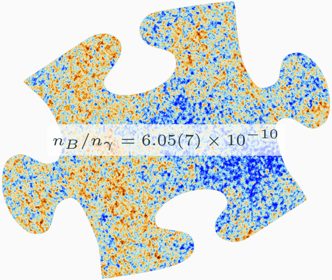

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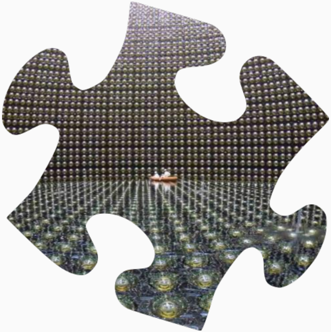

Is there a way to explain both?

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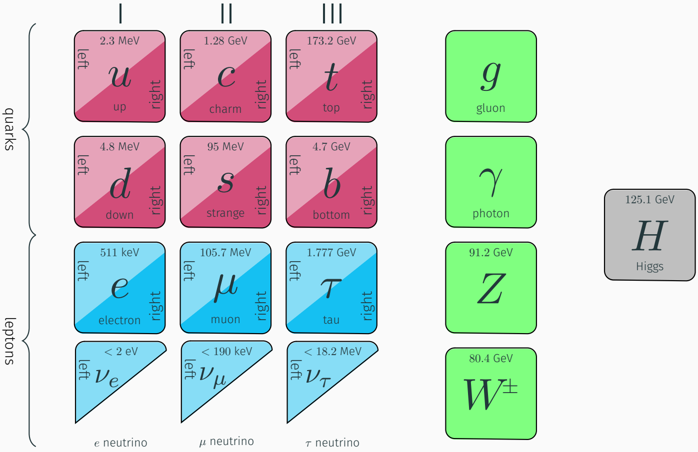
Standard Model



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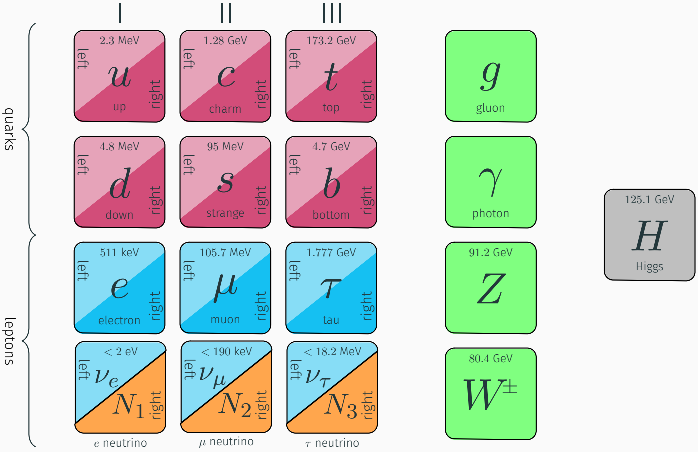

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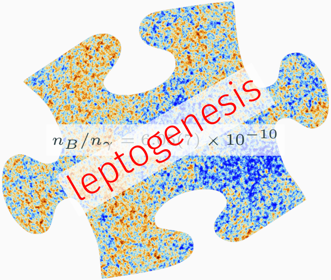


Neutrino masses

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 $\to$ 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 $\to$ they *can*[1] have a Majorana mass term M_M
- the full mass matrix:

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

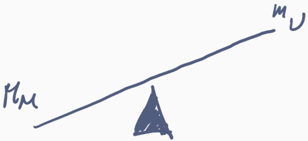
[1] "Everything not forbidden is compulsory." - Murray Gell-Mann

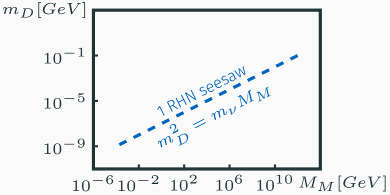
The seesaw relation

Active neutrino masses

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

- m_D and M_M are related through the seesaw formula
- for $m_D \sim 1\,\text{GeV} \to M_M \sim 10^{10}\,\text{GeV}$
- but for $m_D \sim 10^{-5}\,\text{GeV} \to M_M \sim 1\,\text{GeV}$

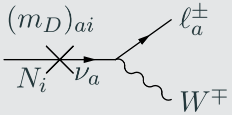




[Minkowski 1977...]

Mixing between heavy and light neutrinos

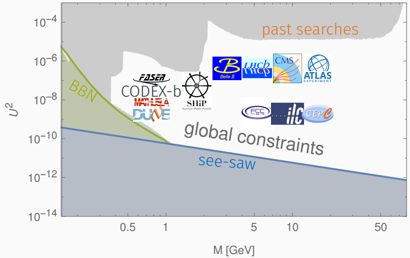
Mixing with RHN



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

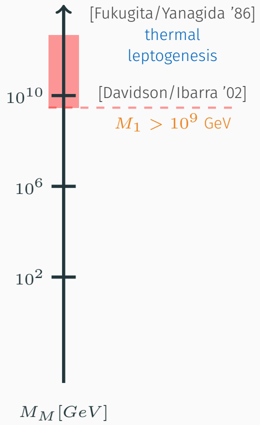
$$U^2 = \sum_{a,i} U_{ai}^2$$

GeV range is especially interesting!



The low-scale leptogenesis mechanisms

Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

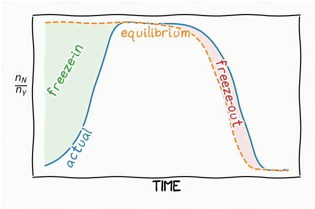
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

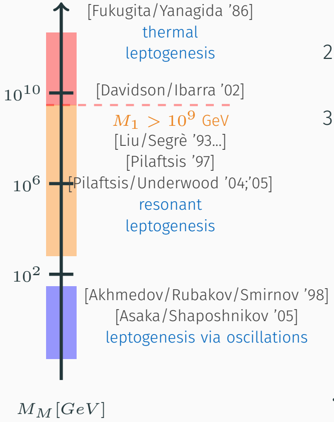
3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



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

Leptogenesis mechanisms



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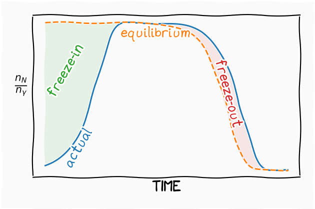

- for hierarchical RHN $M_1 \gtrsim 10^9 GeV$
- leptogenesis works in a wide range of RHN masses

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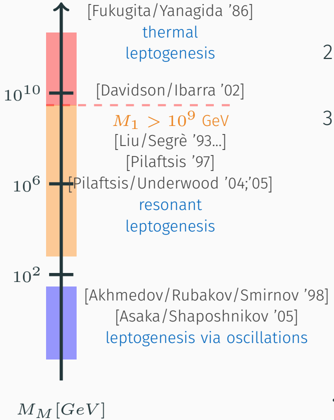

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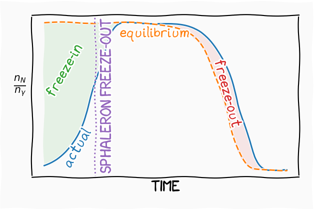

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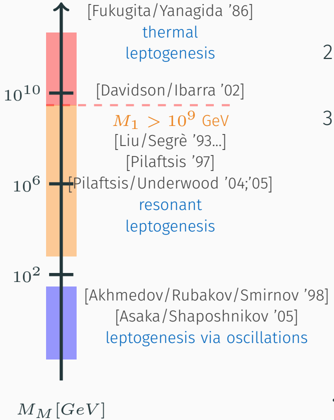

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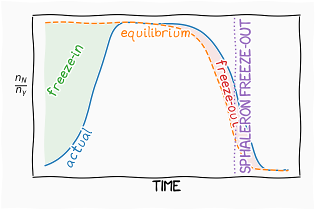

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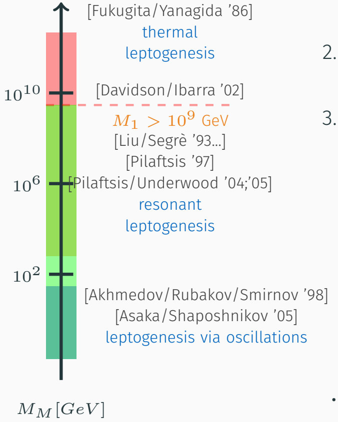

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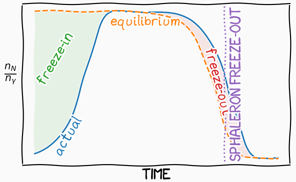
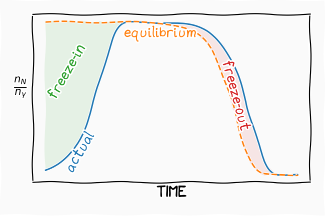


- for hierarchical RHN $M_1 \gtrsim 10^9 GeV$
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

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

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

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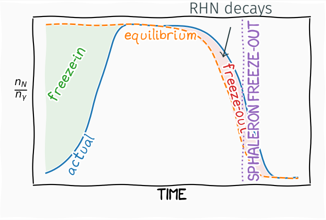

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Resonant leptogenesis

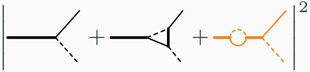
- for hierarchical neutrinos, the decay asymmetry is limited by the Davidson-Ibarra bound

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

  [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...]

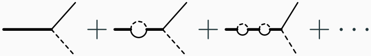
This enhancement is known as resonant leptogenesis.

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

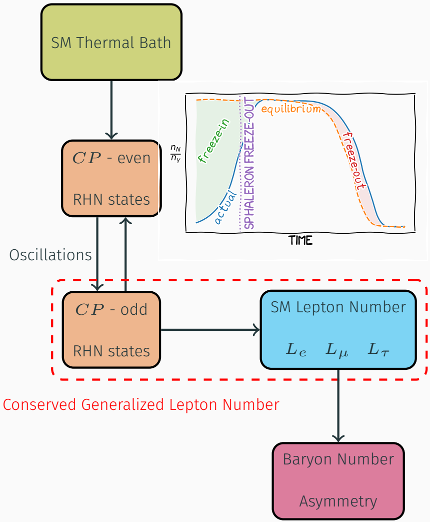
Resonant leptogenesis - summary

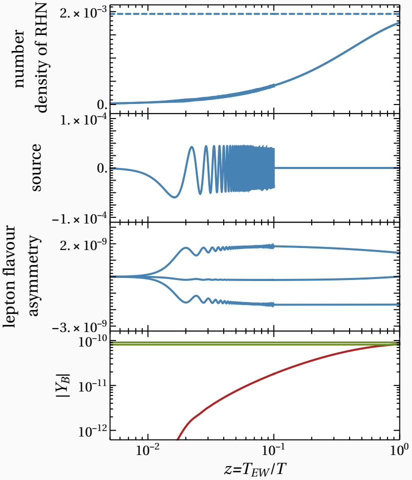
- resonant leptogenesis allows RHN below $10^9\,\mathrm{GeV}$
- we run into conceptual problems for $M_2 \to M_1$
- these issues can be resolved with non-perturbative methods
  - resonant leptogenesis can be described through RHN oscillations

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





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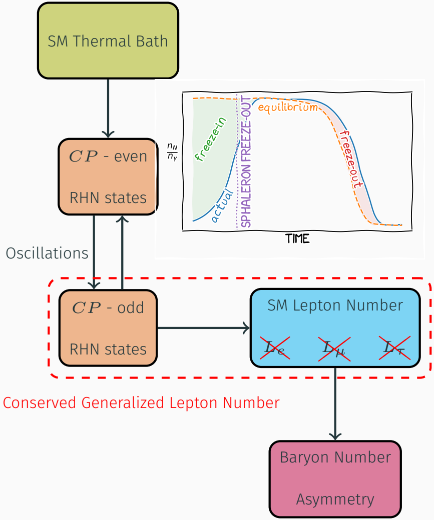

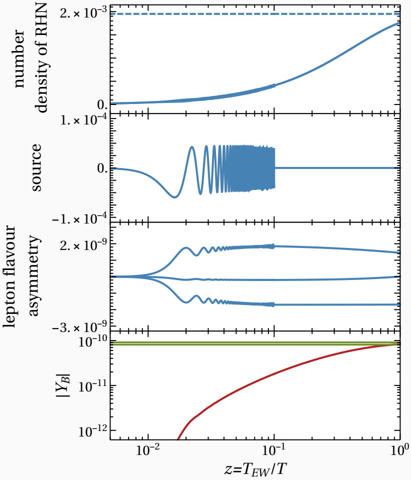

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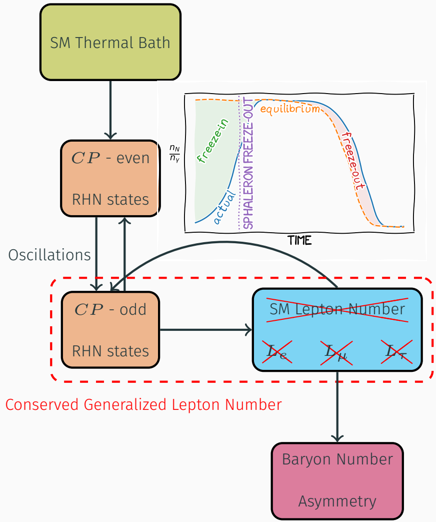

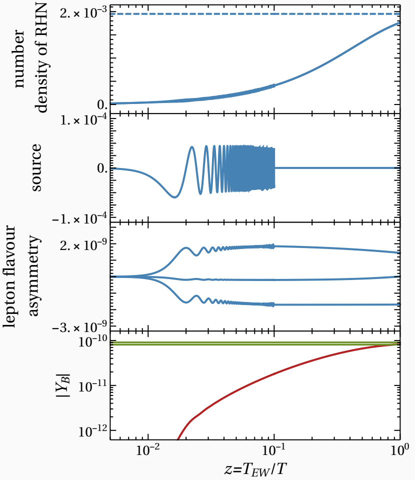

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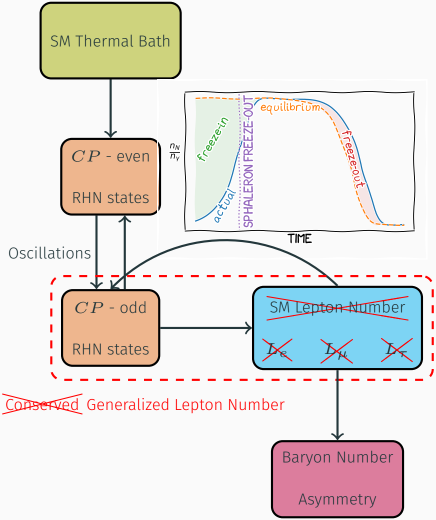
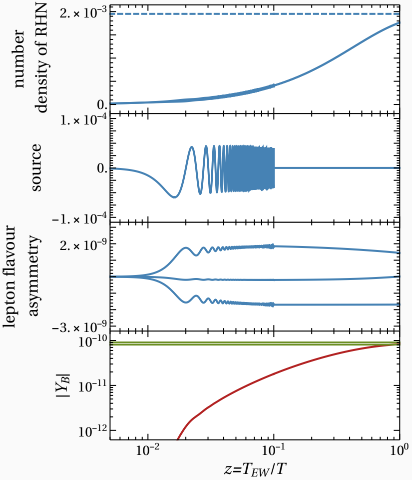




The long path to leptogenesis via oscillations

- first idea proposed in [Akhmedov/Rubakov/Smirnov '98]
- further developed in [Asaka/Shaposhnikov '05]
  - importance of back-reaction terms
- further clarifications
  - fermion number violating (FNV) terms

  [Shaposhnikov '08; Canneti/Drewes/Frossard/Shaposhnikov '12]
- plasma neutrality (susceptibilities/spectators) [Shuve/Yavin '14]
- improved rate calculations

  [Anisimov/Besak/Bödeker '10; Besak/Bödeker '12]
- more systematic derivation of FNV terms

  [Ghiglieri/Laine '17; Eijima/Shaposhnikov '17]
- gradual sphaleron freeze-out

  [Ghiglieri/Laine '17; Eijima/Shaposhnikov/Timiryasov '17]

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

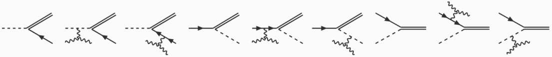
Leptogenesis through Neutrino Oscillations - differences

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

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

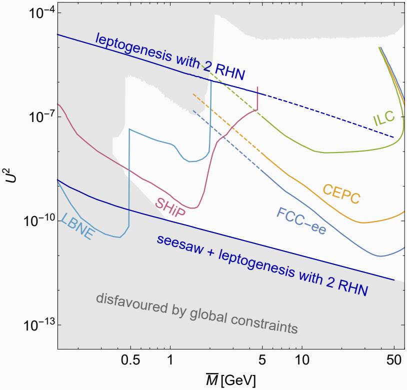
Fermion number violating

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

[Ghiglieri/Laine 2017, Eijima/Shaposhnikov 2017]

The parameter space of leptogenesis

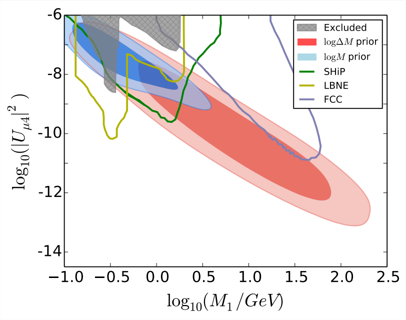
Parameter space of low-scale leptogenesis



[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 $\mathcal{O}(50)$ GeV?

Parameter space of low-scale leptogenesis



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

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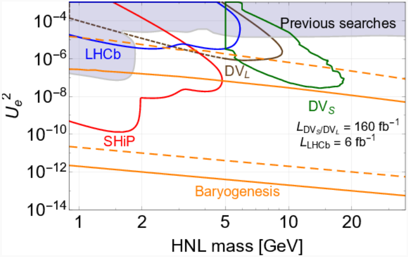
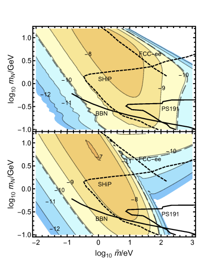


including the FNV and FNC rates
[Eijima/Shaposhnikov/Timiryasov '18]
[Boiarska et. al. '19]

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

Resonant leptogenesis

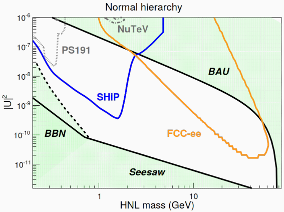
- early estimates lead to successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood '05]
- *different* GeV-scale mechanism proposed in [Hambye/Teresi '16; '17]



- results not fully consistent with the density-matrix treatment at the O(10) GeV scale?

Leptogenesis through 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 $T \sim 150\,\text{GeV}$, $M \sim 80\,\text{GeV}$
- early estimate [Blondel/Graverini/Serra/Shaposhnikov 2014]



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

A quantitative study is necessary!

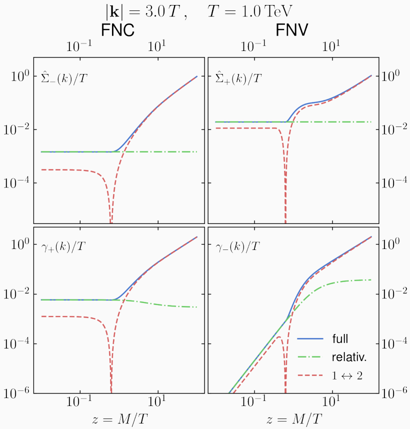
Study of the parameter space

- 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 $0.1\text{GeV} < M_M < 10\,\text{TeV}$

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

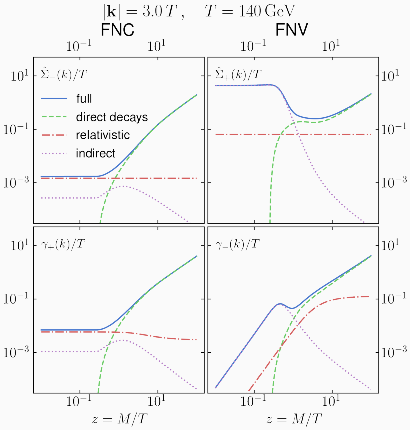
Symmetric phase of the SM:



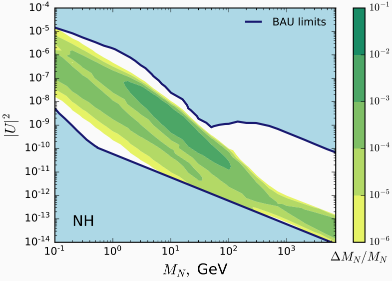
Extrapolating the rates to the non-relativistic regime

- 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



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- 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 $Y_N(0) = Y_N^{\text{eq}}$
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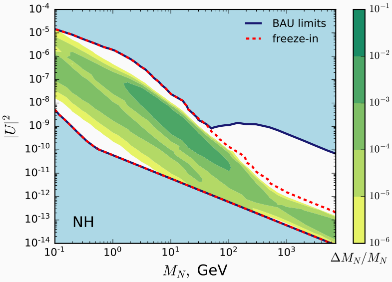

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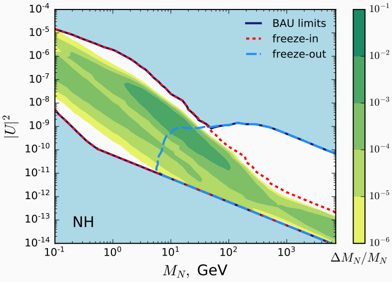

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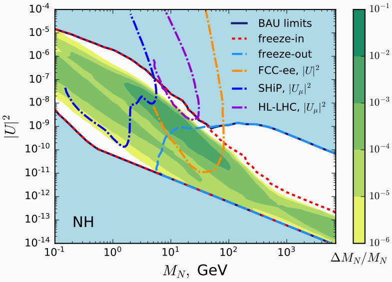

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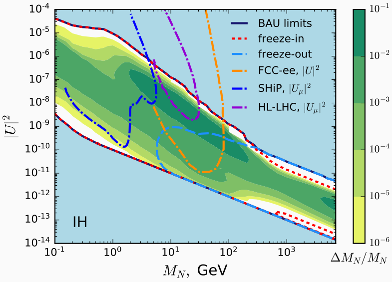

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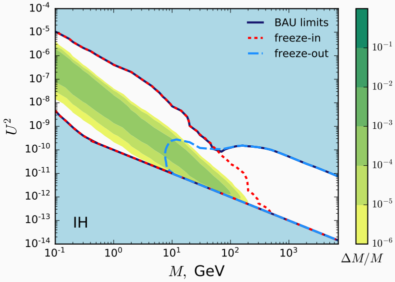

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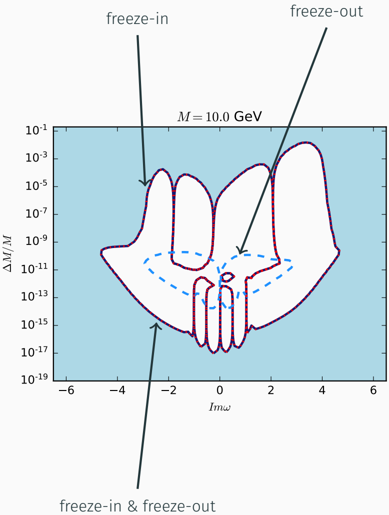
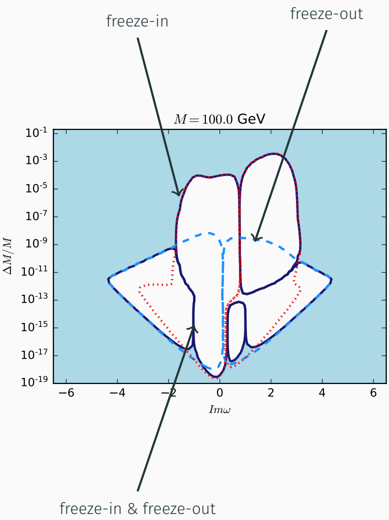


- slices of the parameter space for fixed M, $\mathrm{Re}\omega$ and phases in the PMNS matrix
- both mechanisms contribute at all masses
- large ΔM region is highly sensitive to initial conditions
- freeze-out leptogenesis requires small mass splitting $\Delta M/M \lesssim 10^{-}8$

Slices of the parameter space



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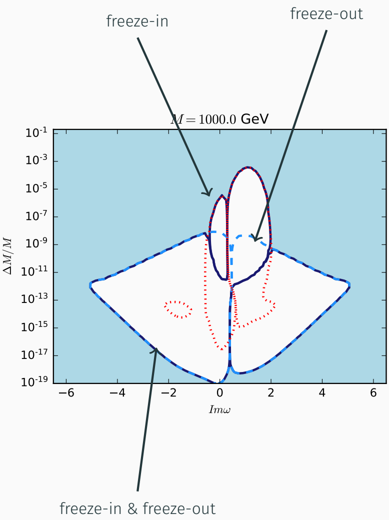

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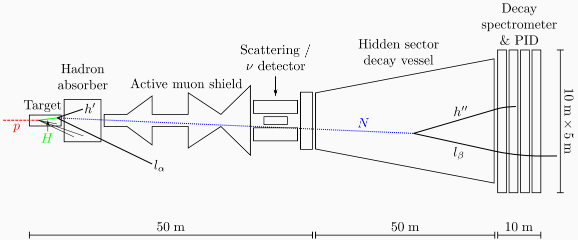
Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two regimes of the same mechanism
- freeze-out leptogenesis is already possible for GeV-scale heavy neutrinos
- freeze-in leptogenesis 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

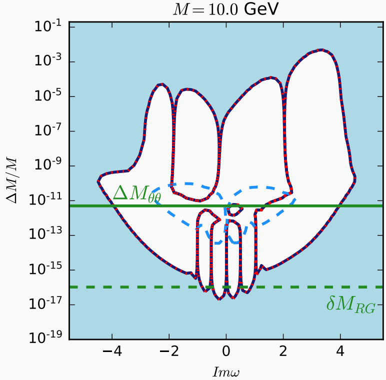
Thank you!

Example of an IF experiment: SHiP



- RHN can be produced in D and B meson decays
  [Gorbunov/Shaposhnikov 2007]
- GeV-scale RHN are very long lived—they decay into charged particles in the vacuum vessel
- SHiP can be very sensitive to HNLs [SHiP collaboration 2018]

Tuned parameters?



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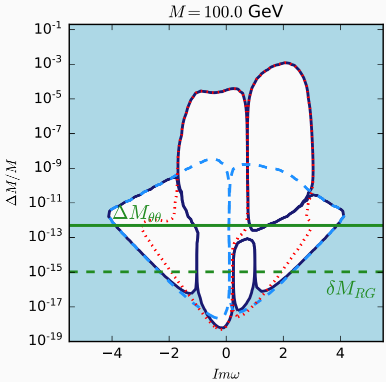

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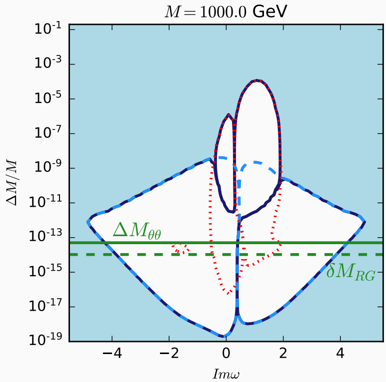

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