Baryogenesis in the νMSM: recent developments

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Outlook

- Baryogenesis with GeV-scale right-handed neutrinos
- Freeze-out of the baryon number in low scale leptogenesis models
- A new study of the parameter space

Leptogenesis with light right-handed neutrinos

Neutrino flavour oscillations are impossible in the minimal SM.

Extension with right-handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_I \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha \tilde{\Phi} N_I - \frac{M_{IJ}}{2} \bar{N}_I^c N_J + h.c.$$

- Leptogenesis by *M. Fukugita and T. Yanagida, 1986*
  Out of equilibrium decays of very heavy RH neutrino.
  Mass scale $\sim 10^{15}$ GeV. Might be lowered in resonant leptogenesis.
  The assymetry in lepton sector is communicated to to the baryon sector by sphaleron processes.
- Baryogenesis via neutrino oscillations. RH neutrinos with masses below the EW scale. *E. Akhmedov, V. Rubakov, A. Smirnov, 1998*
  Sphaleron freeze-out is important.
  Testable!

nuMSM

It was shown that two almost degenerate in mass RH neutrinos are enough for successful baryogenesis.

T. Asaka and M. Shaposhnikov, 2005

The third RH neutrino can be a DM candidate

νMSM

νMSM — an extension of the SM with three RH neutrinos.
Active neutrino masses, DM and BAU can be addressed simultaneously.

Canetti, Drewes, Frossard, Shaposhnikov, 2013

Testable!

Baryogenesis in the nuMSM

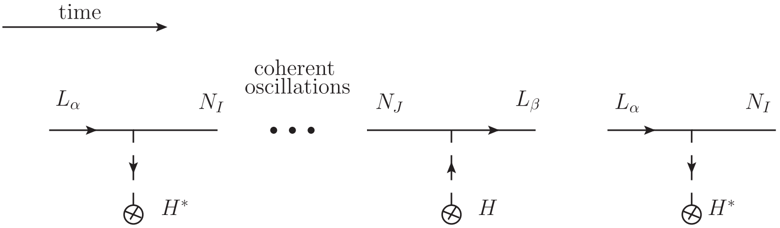
$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_I \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha \tilde{\Phi} N_I - \frac{M_{IJ}}{2} \bar{N}_I^c N_J + h.c.$$

A fermion number for HNLs coincides with helicity.
naive see-saw $F \sim 10^{-7} - 10^{-8}$

Sakharov conditions

- Violation of Standard Model lepton number.
  Majorana mass violates the total lepton number, but this is suppressed as M_N^2/T^2. scattering processes $L_\alpha \to N_I$ through the Yukawa interactions violate SM lepton number
- CP violation. Phases in $F_{\alpha I}$.
- Deviation from equilibrium. N_I are out of equilibrium at temperatures when sphalerons are active.

Baryogenesis in the nuMSM



$Y_{\Delta L_1} = 0$	$Y_{\Delta L_1} > 0$	$Y_{\Delta L_1} > 0$
$Y_{\Delta L_2}, Y_{\Delta L_3} = 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$
$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} \neq 0$

the figure by Shuve and Yavin, 2014

Baryogenesis in the nuMSM

$$-F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}N_I - \frac{M_{IJ}}{2}\bar{N}_I^c N_J + h.c.$$

Experimentally observed values of active neutrino mass differences and mixings should be reproduced

$$F = \frac{i}{v_0}U^{PMNS}m_\nu^{1/2}\Omega m_N^{1/2},$$

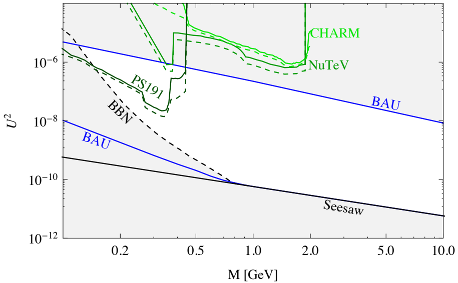
$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix} \quad \text{for NH}$$

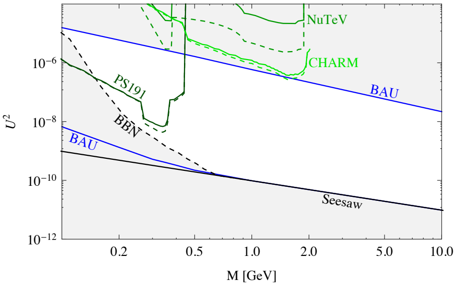
Casas and Ibarra, 2001

Important parameter

$$X_\omega = \exp(\mathrm{Im}\,\omega). \tag{1}$$

Baryogenesis in the nuMSM





Canetti, Drewes, Frossard, Shaposhnikov, Phys.Rev. D87 (2013)

However, several effects have to be accounted for.

Freeze-out of the baryon number

In leptogenesis baryon asymmetry is reprocessed from lepton asymmetry by electroweak sphalerons

$$B = \chi(T)(L - B)$$

The equilibrium formula for baryon asymmetry **is valid as long as the sphaleron rate exceeds that of the lepton asymmetry production during all stages of BAU generation**.

This is the case for high scale leptogenesis

M. Fukugita and T. Yanagida, Phys. Lett. B174 (1986)

But this is definitely not the case for the low-scale leptogenesis

Structure of kinetic equations

The production of lepton asymmetry is described by a set of kinetic equations.

In the Higgs phase, kinetic equations generically can be written as:

$$\dot{n}_{\nu_\alpha} = f_\alpha(\mathbf{n}_N, n_{\nu_\alpha}),$$
$$\dot{\mathbf{n}}_N = g(\mathbf{n}_N, n_{\nu_\alpha}),$$

n_{ν_α} $(\alpha = e, \mu, \tau)$ are asymmetries of number densities of left-handed neutrinos,
$\mathbf{n}_N$ is a matrix of number densities and correlations of HNLs and ant-HNLs.

This system is far from being realistic:

- no charged fermions;
- no sphaleron processes which are fast at temperatures above $T_{sph} \simeq 131.7$ GeV

M. D'Onofrio, K. Rummukainen and A. Tranberg, Phys. Rev. Lett. 113 (2014)

Structure of kinetic equations

At temperatures of low scale leptogenesis all SM species are in equilibrium:
$\mu_{\nu_\alpha} = \mu_{e_{L,\alpha}} = \mu_{e_{R,\alpha}} = \mu_\alpha$
Only n_{ν_α} are changing due to interactions with HNLs:
$[\dot{n}_{\nu_\alpha}]_{HNLs} = [\dot{n}_\alpha]_{HNLs}$

Also $[\dot{n}_\alpha]_{HNLs} = [\dot{n}_{\Delta_\alpha}]_{HNLs}$, where $n_{\Delta_\alpha} = n_\alpha - n_B/3$
($B - L$ is preserved by sphalerons)

$$\dot{n}_{\Delta_\alpha} = f_\alpha(\mathbf{n}_N, \mu_\alpha),$$
$$\dot{\mathbf{n}}_N = g_I(\mathbf{n}_N, \mu_\alpha).$$

The neutrality of the electroweak plasma implies a non-trivial relation between the chemical potentials and the asymmetries

$$\mu_\alpha = \omega_{\alpha\beta}(T) n_{\Delta_\beta} + \omega_B(T) n_B,$$

ω – susceptibility matrices.

Susceptibilities

Thermodynamical potential

$$\Omega(\mu, T) =$$
$$\frac{1}{24}\left(8T^2\mu_B^2 + 8T^2\mu_B\mu_Y + 6\mu_1^2T^2 + 6\mu_2^2T^2 + 6\mu_3^2T^2 + 22T^2\mu_T^2 + \right.$$
$$\left. 22T^2\mu_Y^2 - 8\mu_1T^2\mu_Y - 8\mu_2T^2\mu_Y - 8\mu_3T^2\mu_Y + 3\langle\Phi\rangle^2\mu_T^2 - 6\langle\Phi\rangle^2\mu_T\mu_Y + 3\phi^2\mu_Y^2\right)$$

with

$$\mu_Y \equiv ig_1B_0, \quad \mu_T \equiv ig_2A_0^3.$$

S. Yu. Khlebnikov and M. E. Shaposhnikov, Phys. Lett. B387 (1996)

Number densities of conserved charges

$$-\frac{\partial(\Omega/\mathcal{V})}{\partial\mu_\alpha} = n_\alpha, \quad -\frac{\partial(\Omega/\mathcal{V})}{\partial\mu_B} = n_B,$$

Neutrality conditions read

$$\frac{\partial(\Omega/\mathcal{V})}{\partial\mu_Y} = 0, \quad \frac{\partial(\Omega/\mathcal{V})}{\partial\mu_T} = 0.$$

Susceptibilities

$$\mu_\alpha = \omega_{\alpha\beta}(T) n_{\Delta_\beta} + \omega_B(T) n_B,$$

with susceptibilities

$$\omega(T) = \frac{1}{T^2} \begin{pmatrix} a & b & b \\ b & a & b \\ b & b & a \end{pmatrix}, \quad a = \frac{22\left(15x^2+44\right)}{9\left(17x^2+44\right)}, \quad b = \frac{8\left(3x^2+22\right)}{9\left(17x^2+44\right)}$$

and

$$\omega_B(T) = \frac{1}{T^2}\frac{4\left(27x^2+77\right)}{9\left(17x^2+44\right)},$$

where $x = \langle\Phi\rangle/T$ – Higgs vev devided by temperature.

S. Eijima, M. Shaposhnikov and I.T., 2017

In the same way for sphalerons:

$$n_{B^{eq}} = -\chi(T)\sum_\alpha n_{\Delta_\alpha}, \quad \chi(T) = \frac{4\left(27(\langle\Phi\rangle/T)^2+77\right)}{333(\langle\Phi\rangle/T)^2+869},$$

Standard approach (approach 1)

While sphalerons are active, $T > 130$ GeV

$$\mu_\alpha(T) = \omega_{\alpha\beta}(T) n_{\Delta_\beta} + \omega_B(T) n_{B^{eq}}(T),$$

Below freeze out, $T < 130$ GeV

$$\mu_\alpha(T) = \omega_{\alpha\beta}(T) n_{\Delta_\beta} + \omega_B(T) n_{B^{eq}}(T_{sph}),$$

$$n_{B^{eq}} = -\chi(T) \sum_\alpha n_{\Delta_\alpha}$$

Separate kinetic equation for n_B (approach 2)

V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys.Lett. 155B (1985)

Kinetic equation for n_B

S. Yu. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. B308 (1988)

Y. Burnier, M. Laine and M. Shaposhnikov, JCAP 0602 (2006) 007

$$\dot{n}_B = -\Gamma_B (n_B - n_{B^{eq}}),$$

$$\Gamma_B = 9 \frac{869 + 333(\phi/T)^2}{792 + 306(\phi/T)^2} \cdot \frac{\Gamma_{diff}(T)}{T^3},$$

The Chern-Simons diffusion rate in a pure gauge theory:

M. D'Onofrio, K. Rummukainen and A. Tranberg, Phys. Rev. Lett. 113 (2014)

$$\Gamma_{diff} \simeq \begin{cases} T^4 \cdot \exp\left(-147.7 + 0.83\, T/\mathrm{GeV}\right), & \text{broken phase,} \\ T^4 \cdot 18\, \alpha_W^5, & \text{symmetric phase.} \end{cases}$$

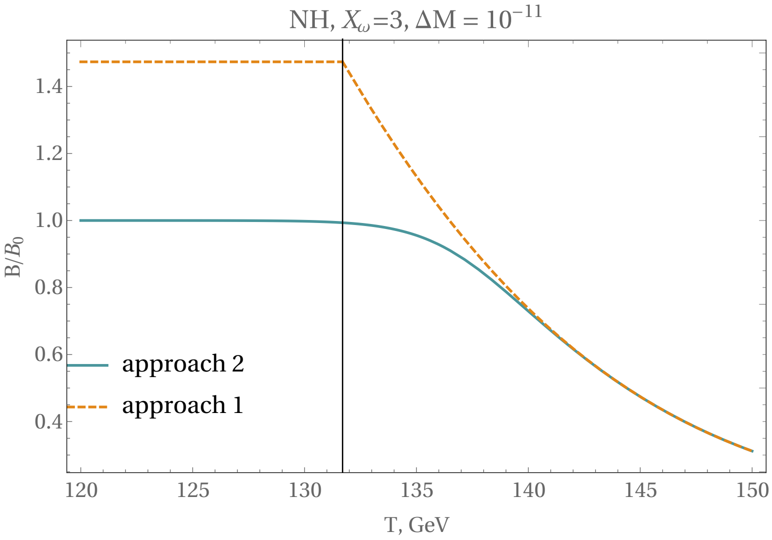
Numerical analysis

1. **Approach 1**. A scenario of an instantaneous B freeze out. Baryon number density $n_B(T) = n_{B^{eq}}(T)$ for all temperatures above T_{sph} and $n_B(T) = n_{B^{eq}}(T_{sph})$ for all $T < T_{sph}$.

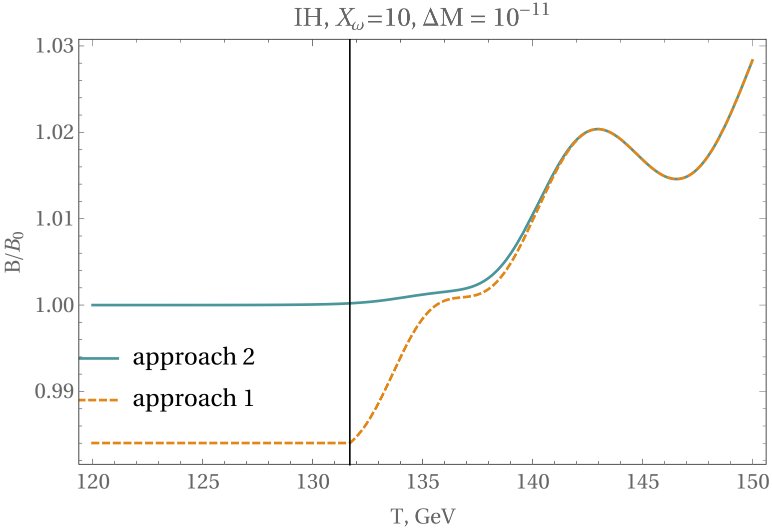
2. **Approach 2**. An approach with the separate kinetic equation for n_B. In this case one can follow the n_B during the freeze out, but at the cost of adding a new scale into the problem.

We found that lepton asymmetry is the same in both approaches.

n_B/n_B^0 as function of temperature. NH.

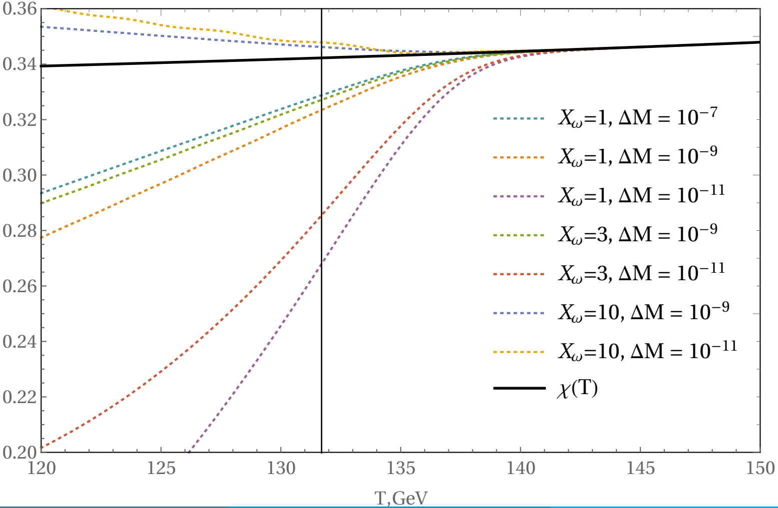


n_B/n_B^0 as function of temperature. IH.



Deviation from equilibrium

The ratio $r(T) = -B/(\sum_\alpha \Delta_\alpha)$ as function of temperature. In the equilibrium with respect to sphalerons $r(T) = \chi(T)$.

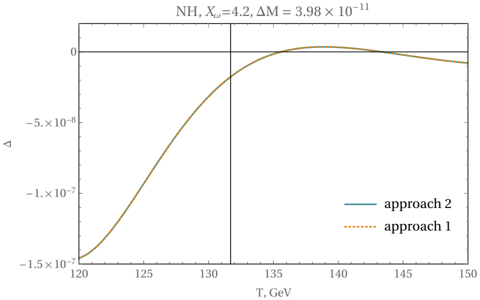


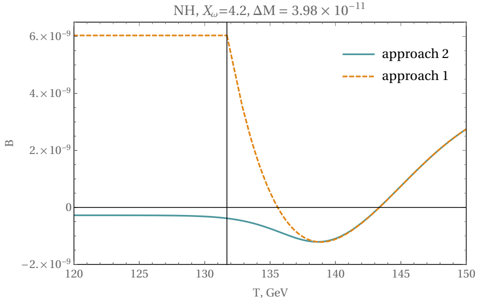
Two step freeze out

In contrast to the instantaneous freeze-out assumption, the baryon number freeze-out occurs in two steps:

1. deviation from the equilibrium value at temperatures around 140 GeV;
2. the final freeze-out at temperatures around $T_{sph} \simeq 131.7$ GeV.
   If a sufficient portion of lepton asymmetry was generated in the transition period, the deviation between two approaches can be significant.

Large deviation





Improvement of the instantaneous freeze-out approach

Instead of using

$$B = \chi(T_{sph}) \sum_\alpha \Delta_\alpha(T_{sph}),$$

One can solve

$$\frac{d(n_B(T))}{dT}\frac{dT}{dt} = -\Gamma_B(T)\left(n_B(T) + \chi(T)\sum_\alpha n_{\Delta_\alpha}(T)\right),$$

with the source $\sum_\alpha n_{\Delta_\alpha}(T)$ calculated within the instantaneous freeze out approach (**approach 1**).

Results of this procedure perfectly agree with those obtained within the **approach 2**.

Improvement of the instantaneous freeze-out approach

- Transition period between departure from equilibrium and final freeze out is important.
- If one wants to ensure that the resulting BAU is correct for all parameter sets, it is necessary to solve the kinetic equation for baryon number.

Baryogenesis in the nuMSM: recent improvements

Progress in theoretical understanding

- Accurate computation of relevant rates

Ghiglieri and Laine, 1605.07720

Eijima and Shaposhnikov, 1703.06085

- Fermion number violating processes were included

Eijima and Shaposhnikov, 1703.06085

Ghiglieri and Laine, 1703.06087

Antusch et al., 1710.03744

- The role of sphaleron processes was clarified

Eijima, Shaposhnikov, I.T., 1709.07834

Studies of the parameter space

Several groups performed scans of the parameter space

Canetti, Drewes,Frossard, Shaposhnikov, 1208.4607

Hernández, Kekic, López-Pavón, Racker, Salvado, 1606.06719

Drewes, Garbrecht, Gueter and Klaric, 1606.06690

Eijima, Shaposhnikov, I.T., 180x.xxxxx

Parameter space of baryogenesis in the νMSM

M, GeV	$\log_{10}(\Delta M/\text{GeV})$	$\text{Im}\omega$	$\text{Re}\omega$	δ	η
$[0.1 - 10]$	$[-11, -5]$	$[-7, 7]$	$[0, 2\pi]$	$[0, 2\pi]$	$[0, 2\pi]$

Parameters of the theory: common mass; mass difference; $\text{Im}\omega$; $\text{Re}\omega$; Dirac and Majorana phases.

$$|U|^2 \equiv \sum_{\alpha I} |\Theta_{\alpha I}|^2 = \frac{1}{2M} \left[(m_2 + m_3) \left(X_\omega^2 + X_\omega^{-2} \right) + \mathcal{O}\left(\frac{\Delta M}{M} \right) \right],$$

Kinetic equations

$$i\,\frac{d\rho_{\nu_\alpha}}{dt} = -i\,\Gamma_{\nu_\alpha}\,\rho_{\nu_\alpha} + i\,\mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}\,\rho_{\bar{N}}],$$

$$i\,\frac{d\rho_{\bar{\nu}_\alpha}}{dt} = -i\,\Gamma^*_{\nu_\alpha}\,\rho_{\bar{\nu}_\alpha} + i\,\mathrm{Tr}[\tilde{\Gamma}^*_{\nu_\alpha}\,\rho_{N}],$$

$$i\,\frac{d\rho_N}{dt} = [H_N, \rho_N] - \frac{i}{2}\,\{\Gamma_N, \rho_N\} + i\,\sum_\alpha \tilde{\Gamma}^\alpha_N \rho_{\bar{\nu}_\alpha},$$

$$i\,\frac{d\rho_{\bar{N}}}{dt} = [H^*_N, \rho_{\bar{N}}] - \frac{i}{2}\,\{\Gamma^*_N, \rho_{\bar{N}}\} + i\,\sum_\alpha (\tilde{\Gamma}^\alpha_N)^*\,\rho_{\nu_\alpha}.$$

Matrices of density ρ depend on momenta. A complicated system.
A simplification: integrated system $\rho(k,t) = n(t) f(k)$, $f(k) = 1/(e^{E(k)/T} + 1)$

$$\begin{aligned}
\dot{n}_{\Delta_\alpha} &= -\mathrm{Re}\,\overline{\Gamma}_{\nu_\alpha}\,\mu_\alpha + 2i\mathrm{Tr}[(\mathrm{Im}\,\overline{\tilde{\Gamma}}_{\nu_\alpha})n_+] - \mathrm{Tr}[(\mathrm{Re}\,\overline{\tilde{\Gamma}}_{\nu_\alpha})N_-],\\
\dot{n}_+ &= -i[\mathrm{Re}\,\overline{H}_N, n_+] + \frac{1}{2}[\mathrm{Im}\,\overline{H}_N, n_-] - \frac{1}{2}\{\mathrm{Re}\,\overline{\Gamma}_N, n_+\} - \frac{i}{4}\{\mathrm{Im}\,\overline{\Gamma}_N, n_-\}\\
&\quad - \frac{i}{2}\sum(\mathrm{Im}\,\overline{\tilde{\Gamma}}^\alpha_N)\mu_\alpha - S^{eq},\\
\dot{n}_- &= 2[\mathrm{Im}\,\overline{H}_N, n_+] - i[\mathrm{Re}\,\overline{H}_N, n_-] - i\{\mathrm{Im}\,\overline{\Gamma}_N, n_+\} - \frac{1}{2}\{\mathrm{Re}\,\overline{\Gamma}_N, n_-\}\\
&\quad - \sum(\mathrm{Re}\,\overline{\tilde{\Gamma}}^\alpha_N)\mu_\alpha.
\end{aligned}$$

Errors of order of 50%

T. Asaka, S. Eijima and H. Ishida, 2012
J. Ghiglieri and M. Laine, 2018

Numerical studies

Production of BAU in the νMSM is described by a set of 11 ordinary differential equations (which are stiff).

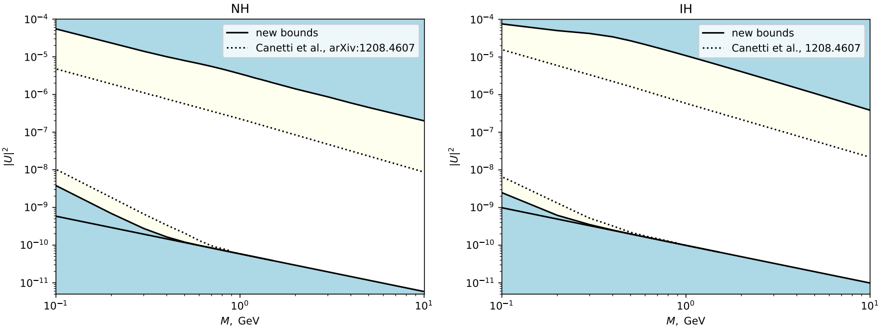
Previously the equations were solved using Mathematica.

Canetti, Drewes,Frossard, Shaposhnikov, 1208.4607

A full scan was impossible.

We have implemented an efficient numerical procedure reducing integration time by $3-4$ orders of magnitude.

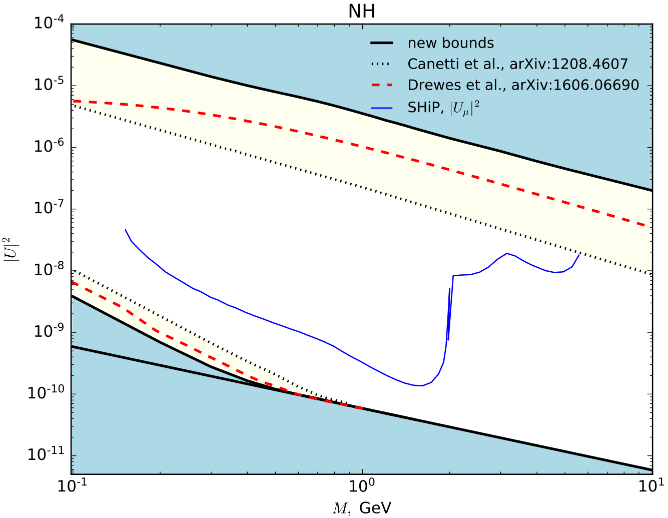
Parameter space of baryogenesis in the νMSM



Why the allowed regions have changed?

- Accurate computation of the rates (note also that after the Higgs discovery the values of the crossover temperature, sphaleron freeze-out temperature etc. were updated)
- Significant numerical improvement: system of 11 coupled ODE can now be solved more than 10^{3} times faster.
- In ref. Canetti et al., 1208.4607 Dirac and Majorana CP-phases δ and η were fixed to some (non-optimal) values. This has reduced the allowed region in 1208.4607.
- Fast code allows to perform a thorough parameter scan.

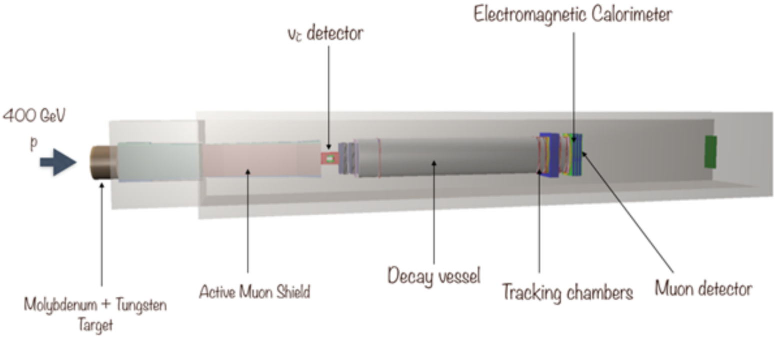
Parameter space of baryogenesis in the νMSM



blue line: SHiP Collaboration, Sensitivity of the SHiP experiment towards heavy neutral leptons, arXiv:180x.xxxxx , also Fig. 1 of 1805.08567

Direct detection in the SHiP experiment

SHiP – search for hidden particles. Fixed target experiment at CERN SPS. Production of HNLs in decays of D and B mesons.



Also NA62, MATHUSLA, (DUNE, FCC-ee - ?)

Conclusions and outlook

- It seems that all effects important for the baryogenesis in the νMSM have been understood:
  - An accurate derivation of rates
  - Neutrality of plasma
  - Fermion number violating processes
  - Freeze-out of sphalerons
- Efficient numerical methods of calculation of BAU in the νMSM were implemented