Can we predict the sign and magnitude of baryon asymmetry from particle physics experiments?

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- We want to explain baryon to photon ratio:

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10}$$

Sakharov conditions

Baryon number violation

CP-non-conservation

Departure from thermal equilibrium: automatic, provided by the Universe expansion

Technology is highly elaborated nowadays: take a specific Lagrangian, embed it into expanding Universe, and make a computation. However, to have a prediction, we should know the theory to start with.

SM baryogenesis

First candidate - the Standard Model: everything is known (all parameters, CP-violation, mechanism of baryon number non-conservation). No true computation has been done for asymmetry, but we are convinced that it does not work:

CP-violation

Relevant measure of CP violations baryogenesis: the combination (MS' 86).

$$D \sim G_F^6 s_1^2 s_2 s_3 sin\delta m_t^4 m_b^4 m_c^2 m_s^2 \sim 10^{-20} \ll 10^{-10}$$

A number of attempts to find amplification :

* enhancement by the time factor $M_P/M_W \sim 10^{16}$, Chern-Simons condensate of gauge fields (MS' 86,87) - does not work (Ambjorn, Laursen, MS' 89)

* enhancement by the time factor $M_P/M_W \sim 10^{16}$, Z-condensation on the bubble walls (Nasser, Turok ' 94) - does not work, there are no bubble walls, as followed from the later works

* enhancement by the temperature effects (similar to enhancement of CP-violation in K-decays) (Farrar, MS '93) - does not work due to coherence lost in particle collisions in the plasma (Gavela, Hernandez, Orloff, Pene, Quimbay ' 94; Huet, Sather' 94)

Deviations from thermal equilibrium

* Too small, there is no electroweak phase transition for Higgs masses exceeding 73 GeV (Kajantie, Laine, Rummukainen, MS ' 96). This gives an extra suppression factor. This limit was superseded at LEP in 1997.

BAU tells that there is physics beyond the SM!

Neutrinos and baryogenesis

What kind of new physics? In 1998 neutrino oscillations are discovered meaning that neutrinos have non-zero masses.

Effective field theory approach: low energy Lagrangian can contain all sorts of higher-dimensional SU(3)xSU(2)xU(1) invariant operators, suppressed by some unknown scale Λ,

$$L = L_{\mathrm{SM}} + \sum_{n=5}^{\infty} \frac{O_n}{\Lambda^{n-4}}$$

Majorana neutrino mass: from five-dimensional Weinberg operator

$$O_5 = A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi} \right) \left(\phi^\dagger L_\beta^c \right)$$

Neutrino mass matrix:

$$M_\nu \sim A_{\alpha\beta} \frac{v^2}{\Lambda}$$

Important questions:

What is the physics behind non-renormalizable terms?

What is the value of Λ ?

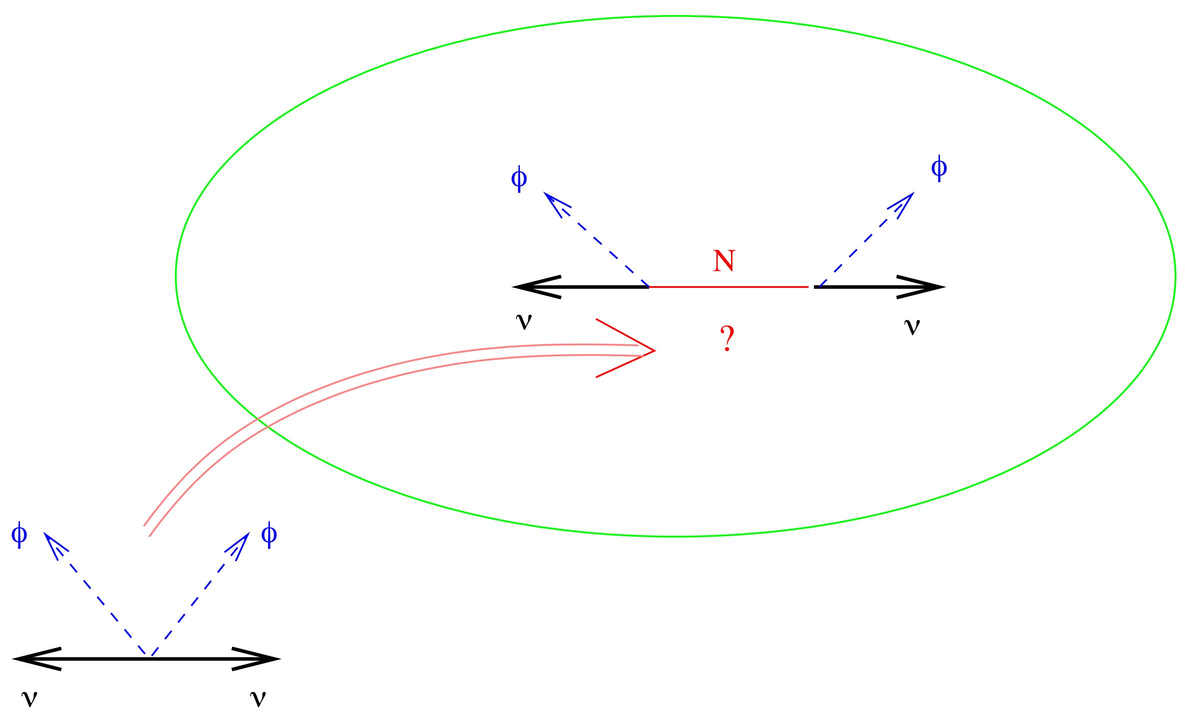
Two options:

1. Origin of neutrino masses - existence of new unseen particles; complete theory is renormalisable
2. There are no new particles, we have just these 5-dimensional operators

New unseen particles

- Higgs triplet with hypercharge 2 - direct contribution to neutrino mass. Will not be considered.

- Singlet Majorana fermions - type I see-saw



Assume: minimal see-saw model with 2 or 3 Majorana fermions (HNLs, or heavy neutral leptons) gives rise simultaneously to neutrino masses and baryon asymmetry of the Universe.

Can we compute BAU with the use of available now or in the future experimental information?

Two generic cases will be considered:

(i) Standard see-saw, superheavy HNLs with GUT scale masses

(ii) Relatively light HNLs, with masses in the GeV region

For generic situation, the question of the predictivity of BAU can be solved by parameter counting.

See-Saw leptogenesis

Most general renormalisable see-saw Lagrangian with Majorana neutrinos:

Minkowski; Yanagida; Gell-Mann, Ramond, Slansky; Glashow, Mohapatra, Senjanovic

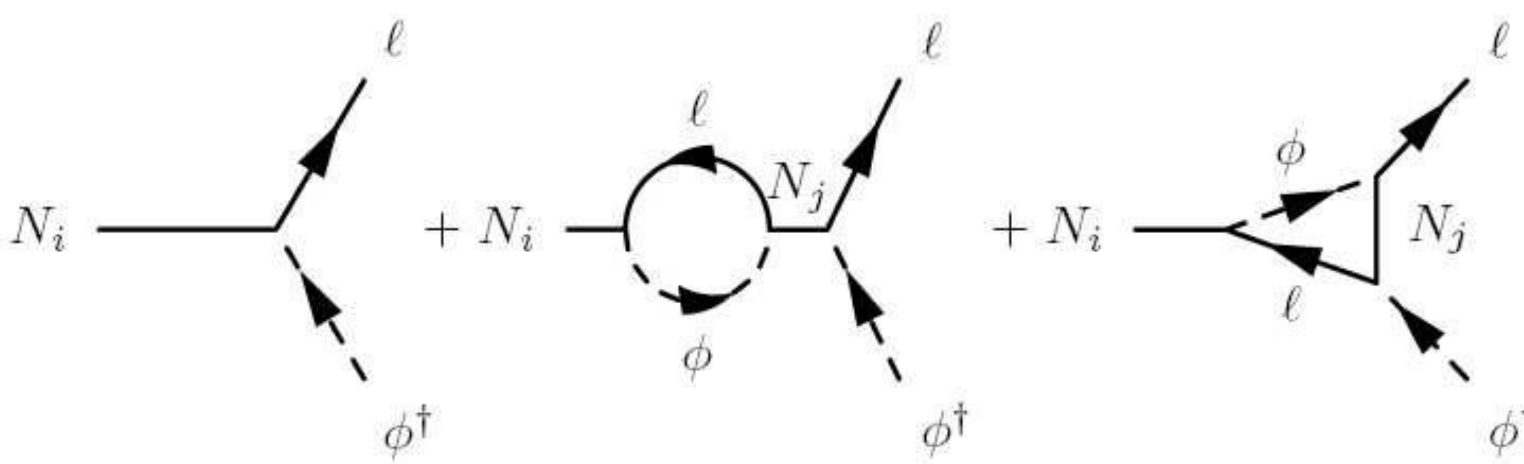
$$L_{\nu MSM} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Counting "high energy" parameters, 3 HNLs:
3 Majorana masses of new neutral fermions N, 15 new Yukawa couplings in the leptonic sector (3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases), 18 new parameters in total.

Counting "very low energy" parameters, 3 HNLs:

3 Majorana masses of active neutrinos, 3 mixing angles in PMNS matrix, 1 Dirac phase and 2 Majorana phases, 9 parameters in total, 6 of them can be measured in active neutrino oscillations

The mechanism: leptogenesis with superheavy Majorana neutrinos (Fukugita, Yanagida) : HNLs go out of thermal equilibrium, decay, and produce lepton asymmetry at temperatures $T \sim 10^{10}\ GeV$. Then the lepton number is converted into baryon asymmetry by sphalerons which are active until $T \simeq 130\ GeV$. The resulting baryon asymmetry is just a numerical factor of order one smaller than the lepton asymmetry.



In general, baryon asymmetry depends on all high-energy parameters of the model. There are 18 of them. In the very best case we can only determine 9 combinations of them via the see-saw formula in low energy neutrino experiments. Therefore, neither amplitude no sign of baryon asymmetry can be predicted.

Question: Can we chose high energy parameters in such a way that we are consistent with low energy neutrino experiments and produce the necessary baryon asymmetry?

Answer: Yes, the freedom is pretty large: baryon asymmetry is just one number, and we have 9 parameters to play with!

Question: Can we get baryon asymmetry just from low energy CP-violating phases? To make sense of this question, consider Casas-Ibarra parametrisation of the matrix of Yukawa couplings:

$$F = \frac{1}{v} U_{PMNS} \sqrt{m_\nu} R \sqrt{M}$$

Here R is complex orthogonal matrix depending on 3 complex angles. Make these angles real or some of them pure imaginary to get rid of high-energy complex phases (ad-hoc choice).

Answer: Yes, the freedom is still pretty large! (Moffat, Pascoli, Petcov Turner '18)

Question: Can we get baryon asymmetry just from low energy Dirac phase (i.e. put all Majorana phases to zero)?

Answer: Yes, the freedom is still pretty large! (Moffat, Pascoli, Petcov Turner '18)

Question: Can we get baryon asymmetry if low energy CP phases are zero?

Answer: Yes, no problem!

Let us decrease the number of parameters: assume that only 2 HNLs exist

Counting "high energy" parameters, 2 HNLs:

2 Majorana masses of new neutral fermions N, 9 new Yukawa couplings in the leptonic sector (2 Dirac neutrino masses, 4 mixing angles and 3 CP-violating phases), 11 new parameters in total.

Counting "very low energy" parameters, 2 HNLs:

2 Majorana masses of active neutrinos (one is almost massless), 3 mixing angles in PMNS matrix, 1 Dirac phase and 1 Majorana phases, 7 parameters in total, 6 of them can be measured in active neutrino oscillations

Still, 11>7 and therefore, neither amplitude no sign of baryon asymmetry can be predicted.

Question: Can we chose high energy parameters in such a way that we are consistent with low energy neutrino experiments and produce the necessary baryon asymmetry?

Answer: Yes, the freedom is pretty large: baryon asymmetry is just one number, and we have 4 parameters to play with!

Question: Can we get baryon asymmetry just from low energy CP-violating phases?

Answer: Yes, the freedom is still pretty large (3 parameters)! (Moffat, Pascoli, Petcov Turner '18)

Question: Can we get baryon asymmetry just from low energy Dirac phase (i.e. put all Majorana phases to zero)?

Answer: Yes, the freedom is still pretty large (2 parameters)! (Moffat, Pascoli, Petcov Turner '18)

Question: Can we get baryon asymmetry if low energy CP phases are zero?

Answer: Yes, no problem!

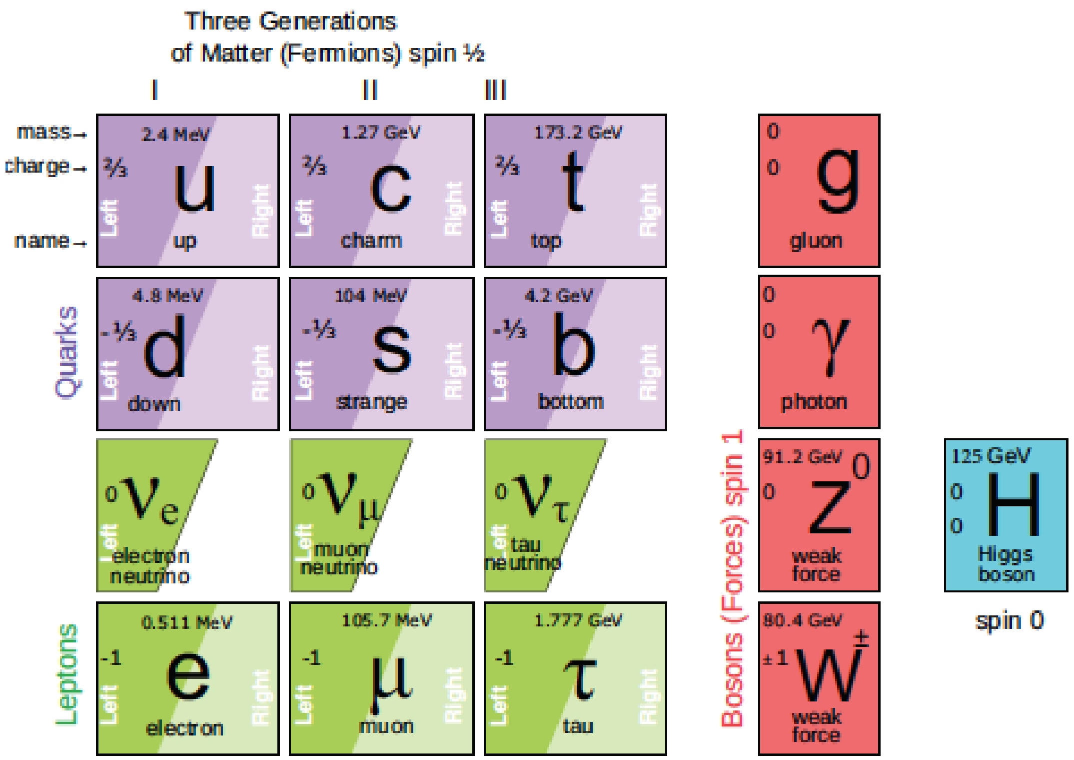
Conclusions for see-saw leptogenesis

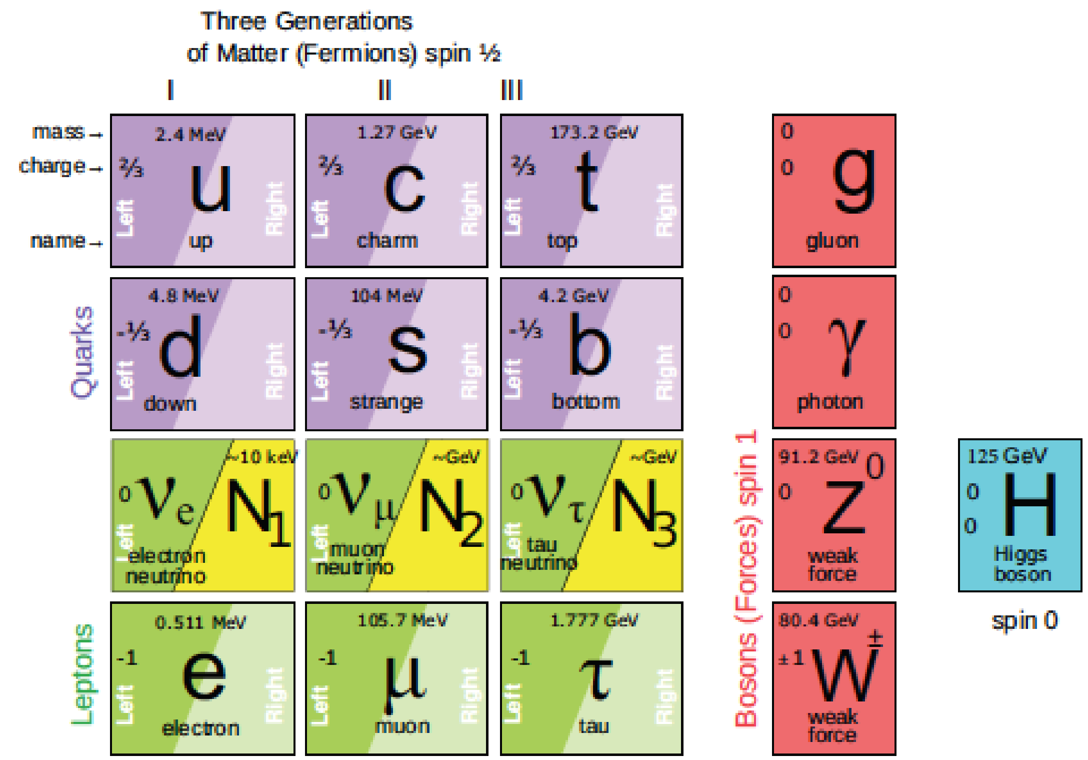
- It is impossible to find the sign and amplitude of BAU in see-saw models, as we do not (and will not) have an access to essential information about high scales experimentally.

- BAU can be explained with low energy Dirac phase only, but there are no convincing arguments why other phases should vanish.

Low scale leptogenesis

HNL masses are similar to SM quark and lepton masses: SM-> NuMSM





Role of the Higgs boson: break the symmetry and inflate the Universe

Role of N_1 with mass in keV region: dark matter.

Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Yukawa couplings:

- KeV scale DM sterile neutrino N1: $F \sim 10^{-13}$ to have sufficiently large lifetime
- GeV scale N2 and N3: $F \sim 10^{-6}$ to explain neutrino masses

Note: the SM does not provide any explanation of the origin and magnitude of Yukawa couplings of quarks and charged leptons, they are all taken from experiment and scatter from $f_t \sim 1$ for the top quark to $f_e \sim 10^{-5}$ for electron.

Leptogenesis with GeV HNLs

Creation of baryon asymmetry is a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation. One need to deal with resummations, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc.

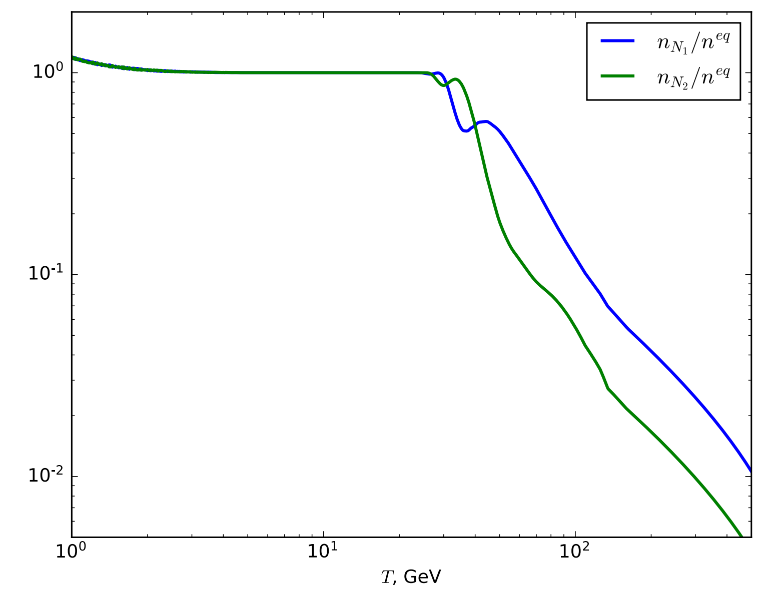
Initial idea: Akhmedov, Rubakov, Smirnov ‘98

Formulation of kinetic theory and demonstration that NuMSM can explain simultaneously neutrino masses, dark matter, and baryon asymmetry of the Universe: Asaka, M.S. ’05

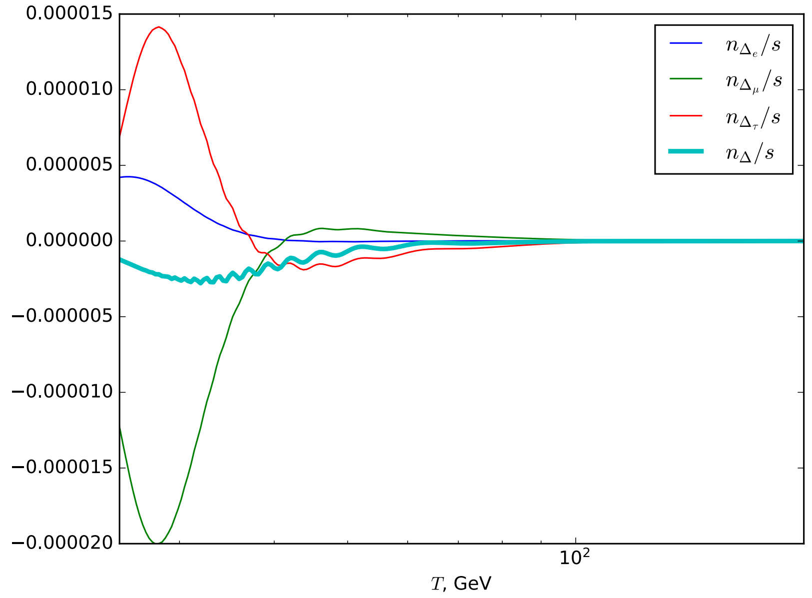
Analysis of baryon asymmetry generation in the NuMSM: Asaka, M.S., Canetti, Drewes, Frossard; Abada, Arcadia, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, Racker, J. Salvado; Drewes, Garbrech, Guetera, Klariç; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine,…

Time evolution

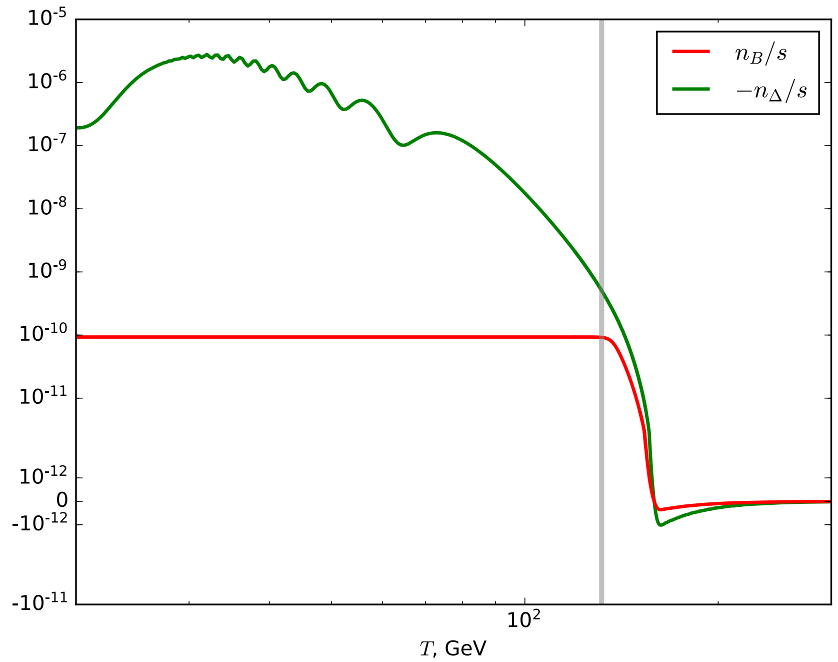
HNL densities



Lepton asymmetries



Baryon asymmetry



Dark Matter HNL N1 decouples from see-saw formula and leptogenesis: Yukawa are too small

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- Dream scenario. Both HNLs N2 and N3 are discovered, their masses and decay branching ratios to electron, muon and tau flavours are found, and CP-violation in their decays is observed. 3 phases must be determined (at least 1 in HNL decays, 2 others can come from "very low energy" neutrino data). This determines all NuMSM parameters. The amplitude and sign of baryon asymmetry is predicted, and all "very low energy parameters" are fixed. The model is tested by the comparison with "very low energy" neutrino data.

More realistic scenario. From baryogenesis: masses of HNLs N2 and N3 are close to each other

$$\Delta M/M \sim 10^{-1} - 10^{-13}$$

and thus their mass splitting may not be resolved at experiments. They will look like a single particle. Then only part of the NuMSM parameters which can be determined experimentally (mass and decay branching ratios to electron, muon and tau flavours). If CP-violating effects are tiny, they also are not seen experimentally. So, we can determine only 1+3=4 “low energy” parameters. One can show that 2 combinations of these 4 parameters have no influence on “very low energy” neutrino parameters.

The amplitude and sign of baryon asymmetry cannot be predicted as it depends essentially on HNL mass difference and “low energy” CP-violating phase.

For active neutrino masses, the theory is equivalent to NuMSM with degenerate N2 and N3 and is characterised by 9 instead of 11 parameters ($\Delta M = M_2 - M_3$ and one CP-phase are out). 7 of them propagate to “very low energies” (only 2 combinations of them determined experimentally).

Suppose that all 7 “very low energy” parameters are fixed by experiments (neutrino oscillations and neutrino less double beta decay). So, we get 7 equations for 5 unknowns, meaning that we have 2 consistency relations which must be satisfied in the NuMSM.

Forget about Dark Matter and use all 3 HNLs for baryon asymmetry and neutrino mass generation

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- Dream scenario. All three HNLs are discovered, and their decay branching ratios to electron, muon and tau flavours are found. Several CP-violating effects are found (6), fixing all the phases. All “low energy” parameters are found, the amplitude and sign of baryon asymmetry is predicted. We also get 9 consistency relations with “very low energy” neutrino data.

- More realistic scenario. Some of “low energy” parameters are not determined (such as CP-violation phases). The amplitude and sign of baryon asymmetry can not be predicted. However, we get several consistency relations with “very low energy” neutrino data.

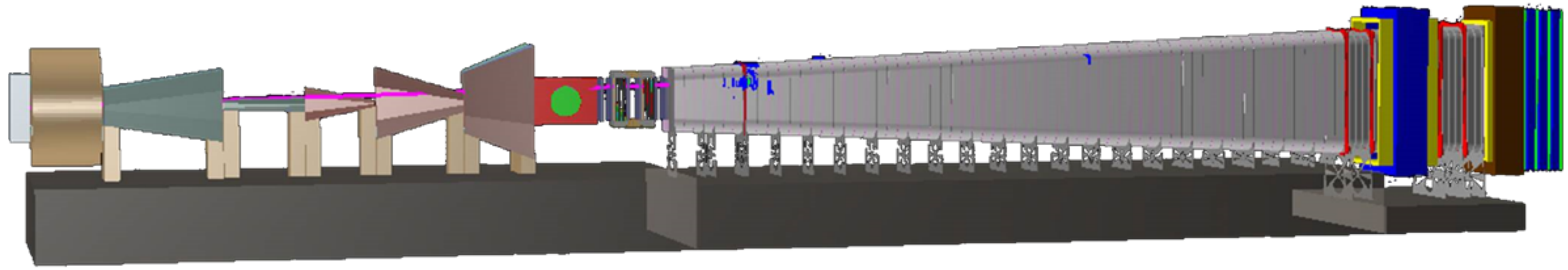
Experimental challenges of HNL searches:

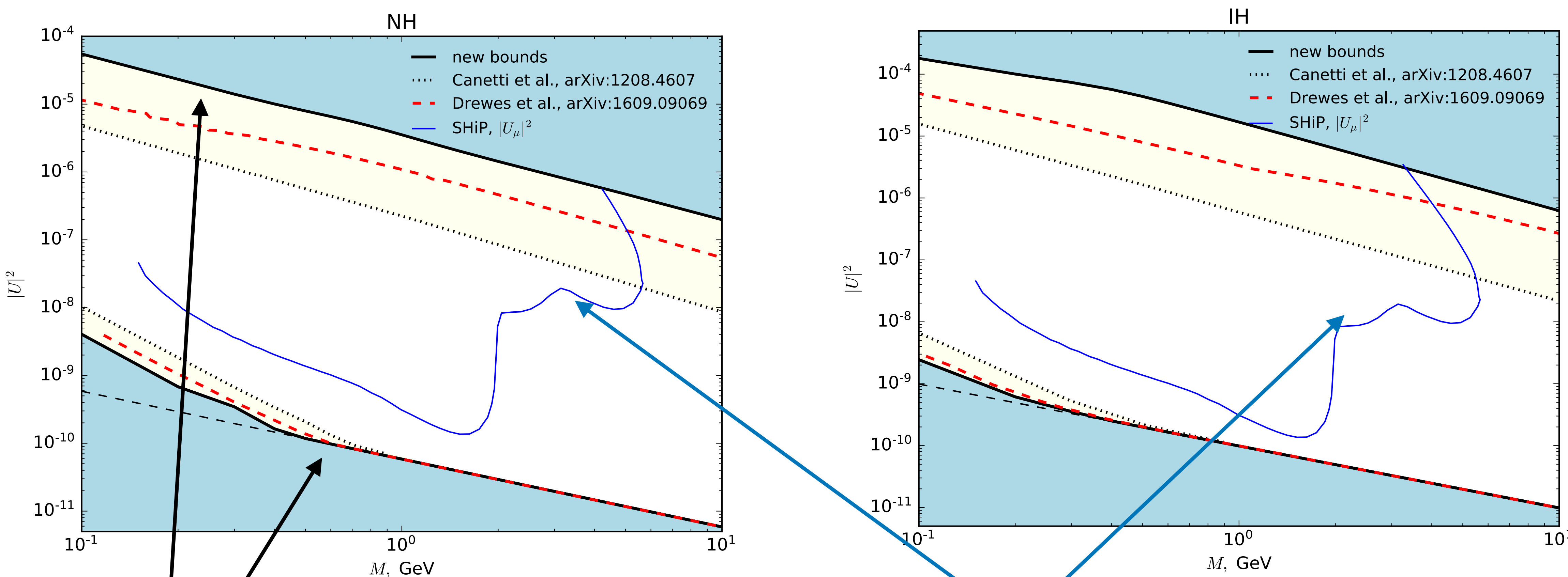
HNL production and decays are highly suppressed – dedicated experiments are needed:

- Mass below ~ 5 GeV - Intensity frontier, CERN SPS: NA62 in beam dump mode, SHiP
- Mass below ~ 5 GeV - Energy frontier, LHC: MATHUSLA
- Mass above ~ 5 GeV - FCC in e+e– mode in Z-peak, LHC

Generic purpose experiments to search for all sorts of relatively light dark sector particles (dark photons, hidden scalars, etc).

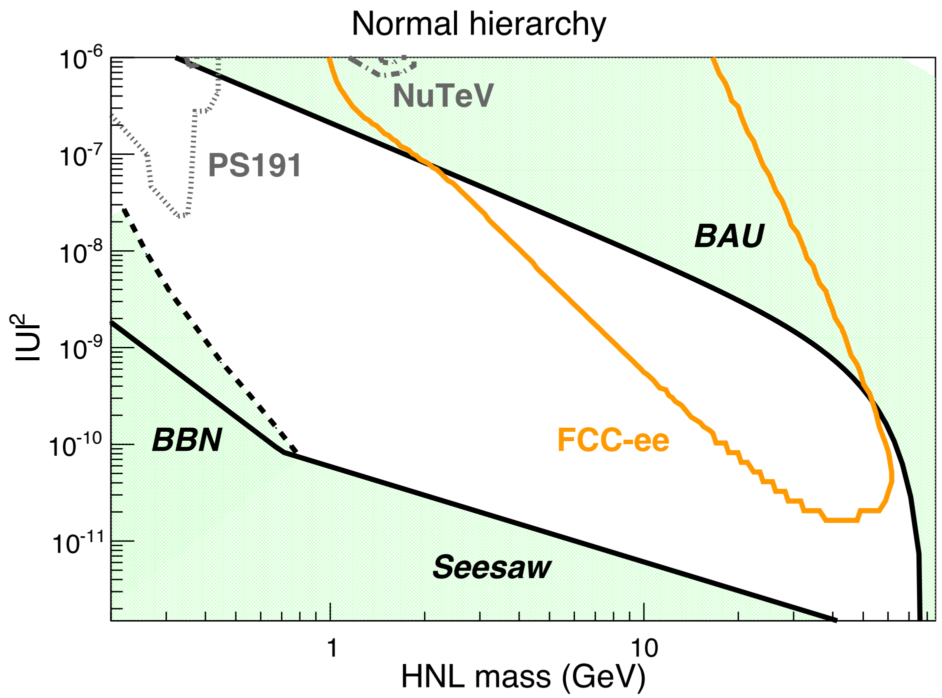
SHiP
Search for Hidden Particles



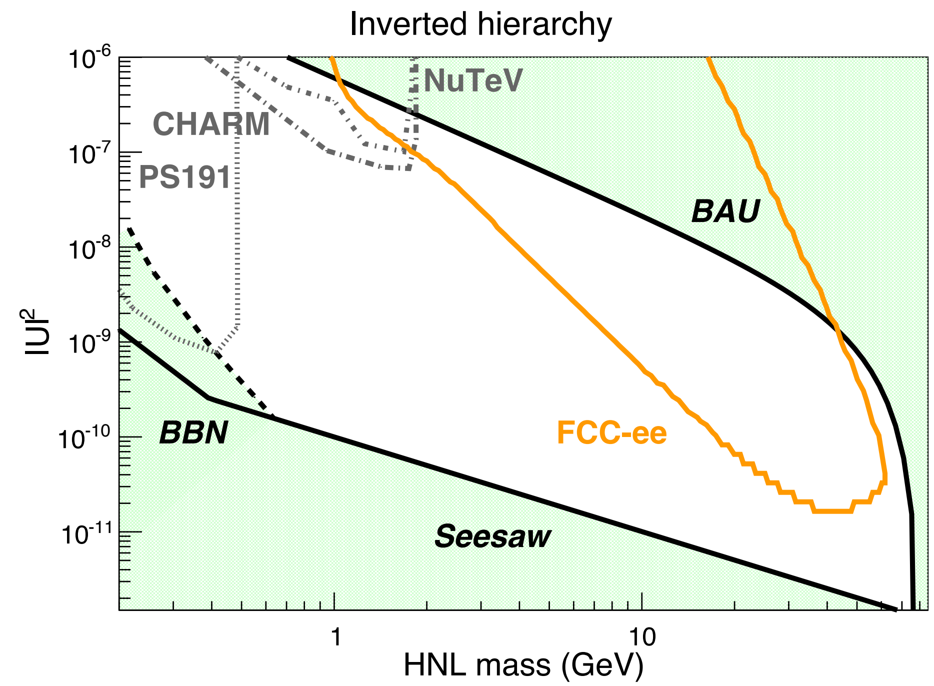


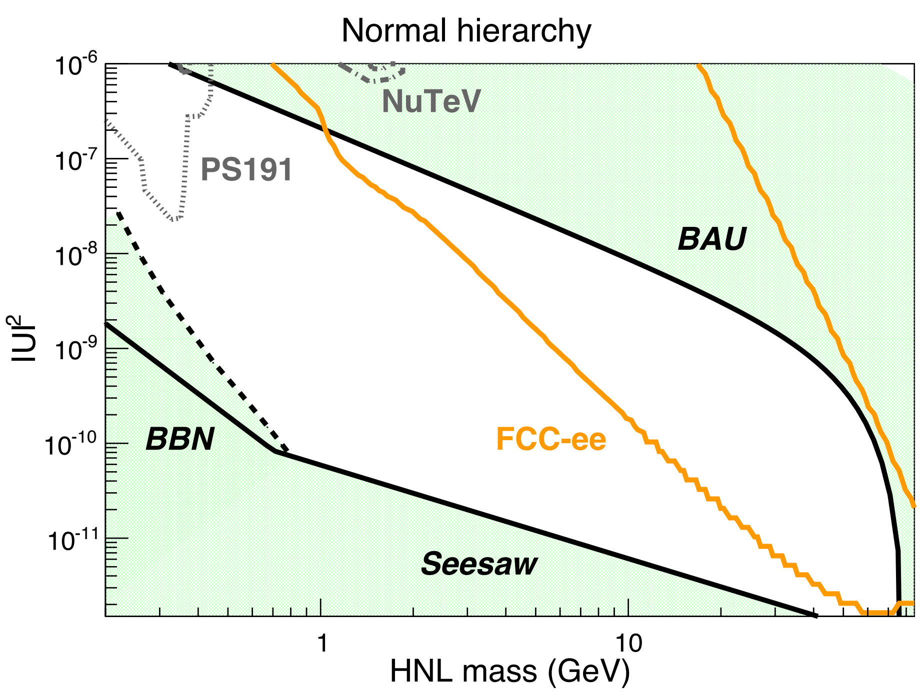
SHiP collaboration

Eijima, M.S., Timiryasov

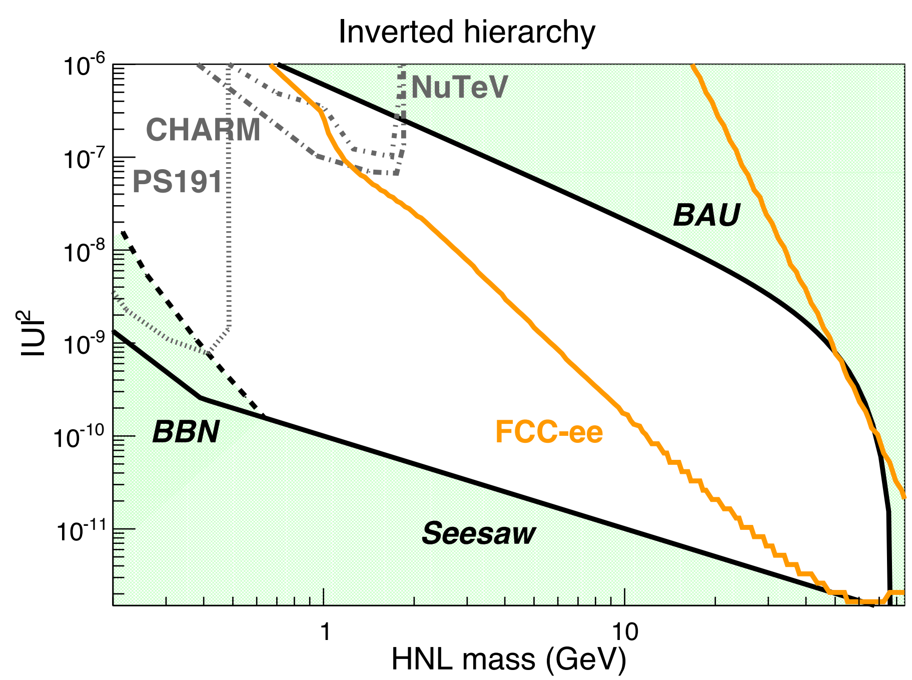


Decay length 10-100 cm, 10^{12} Z^0





Decay length 10-100 cm, 10^{13} Z^0



Blondel, Graverini, Sera, M.S.

There are no new particles just 5-dimensional operators.

$$O_5 = A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi} \right) \left(\phi^\dagger L_\beta^c \right)$$

The theory is not renormalisable, but, perhaps, asymptotically safe

Idea (Bezrukov, Gorbunov, MS '11): the 5-dimensional operator itself

$$L_5 = \frac{1}{\Lambda(|\phi|)} A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi}\right) \left(\phi^\dagger L^c_\beta\right)$$

can lead to production of lepton asymmetry due to non-trivial time dependence of the Higgs field, as, for example, in the Higgs inflation: initially ϕ is large $\phi \sim M_P$, then it oscillates with decreasing amplitude and heats the Universe. Baryon asymmetry can be computed entirely in terms of low-energy neutrino parameters and function $\Lambda(|\phi|)$. The amplitude cannot be predicted, but the sign of BAU is related to low-energy phases in neutrino mixing matrix via CP-violating trace,

$$\mathrm{Tr}(AA^\dagger AYYA^\dagger YY) \propto y_\tau^4 A_{3\beta} A^*_{\alpha\beta} A_{\alpha 3} A^*_{33}$$

where Y is the charged lepton Yukawa matrix (y_τ is the tau Yukawa). Numerically, one can get the correct amplitude of BAU for reasonable $\Lambda(|\phi|)$

Conclusions

- With some luck from experimental sight we will be able to fix all parameters in neutrino physics and predict baryon asymmetry of the Universe (better to say make a postdiction and verify the consistency of the theory).

Search for HNLs!