Heavy neutral leptons in cosmology

Mikhail Shaposhnikov

Why heavy neutral leptons?

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The best way to get massive neutrinos!

Minkowski, Yanagida, Gell-Mann, Ramond, Slansky, Glashow, Mohapatra, G. Senjanovic + too many names to write, the whole domain of neutrino physics

Most general renormalizable (see-saw) Lagrangian

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

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

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- $\mathcal{N} = \mathbf{3}$: All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).

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- $\mathcal{N} > \mathbf{3}$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

HNL and neutrino masses

Notations: M_D - Dirac mass, M - Majorana mass, F - Yukawa coupling, v - Higgs vev

One flavour see-saw formula: extremely small mixing angles

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \frac{F^2 v^2}{M} = U^2 M \quad \Longrightarrow \quad U^2 = \frac{m_\nu}{M} \simeq 10^{-10} \frac{GeV}{M}$$

However, we need at least 2 HNL to explain atmospheric and solar mass differences.

Consequence: instead of equality we have only the lower bound!

$$U^2 > \frac{m_\nu}{M} \simeq 10^{-10} \frac{GeV}{M}$$

Physics of large mixing angles – symmetry

MS '06; Kersten and Smirnov '07:

Consider SM + one extra massive Dirac spinor Ψ, which is singlet with respect to SM.

$$L = L_{SM} + \bar{\Psi} i \partial_\mu \gamma^\mu \Psi - F_\alpha \, \bar{L}_\alpha \Psi H - M \, \bar{\Psi}\Psi + h.c.,$$

Symmetry: lepton number conservation. For any F_α and M all active neutrinos are massless.

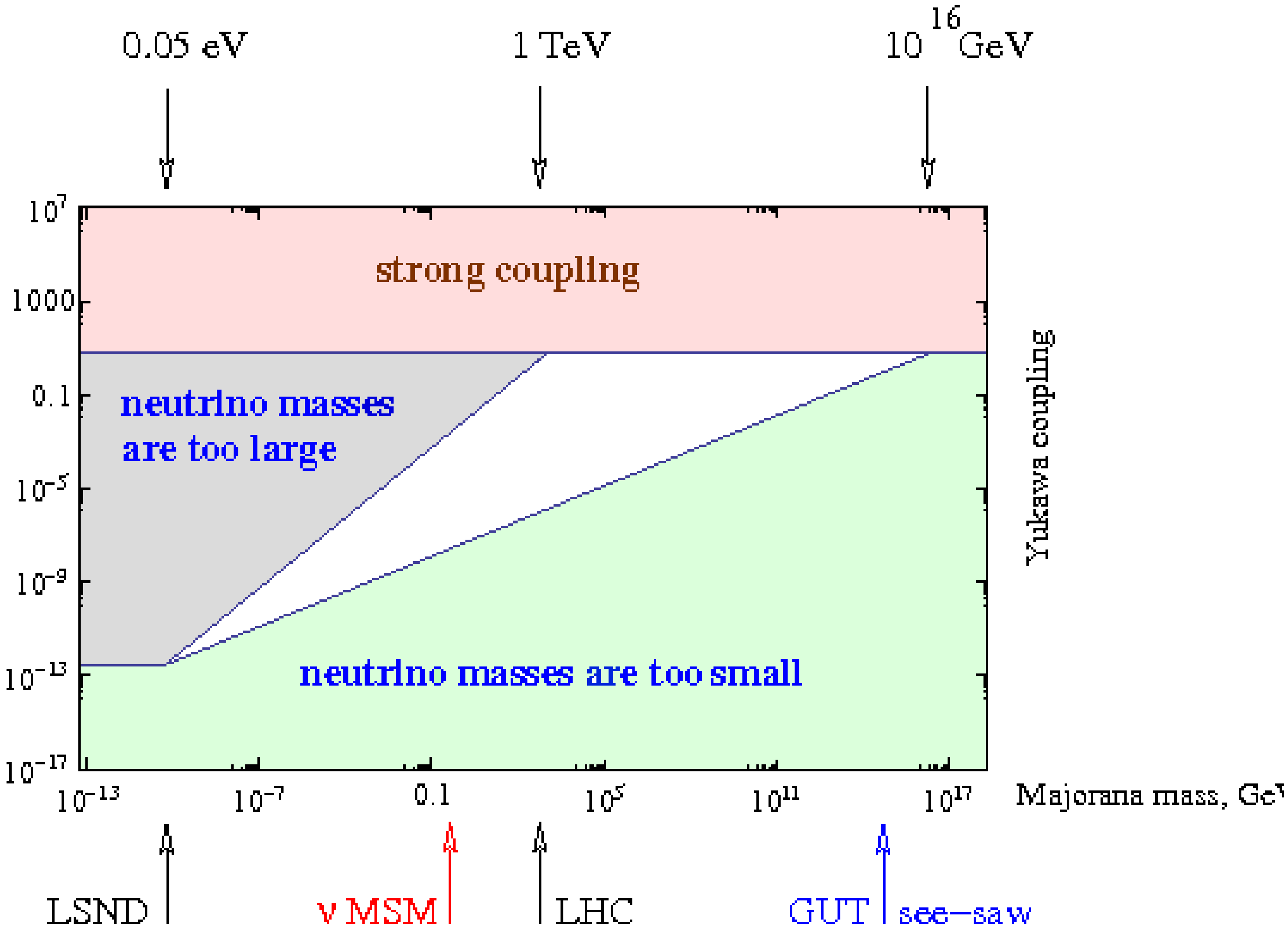
Small symmetry breaking terms $\Longrightarrow$ small active neutrino masses :

$$\Delta L = f_\alpha \, \bar{L}_\alpha \Psi^c H - m \, \bar{\Psi}\Psi^c + h.c.,$$

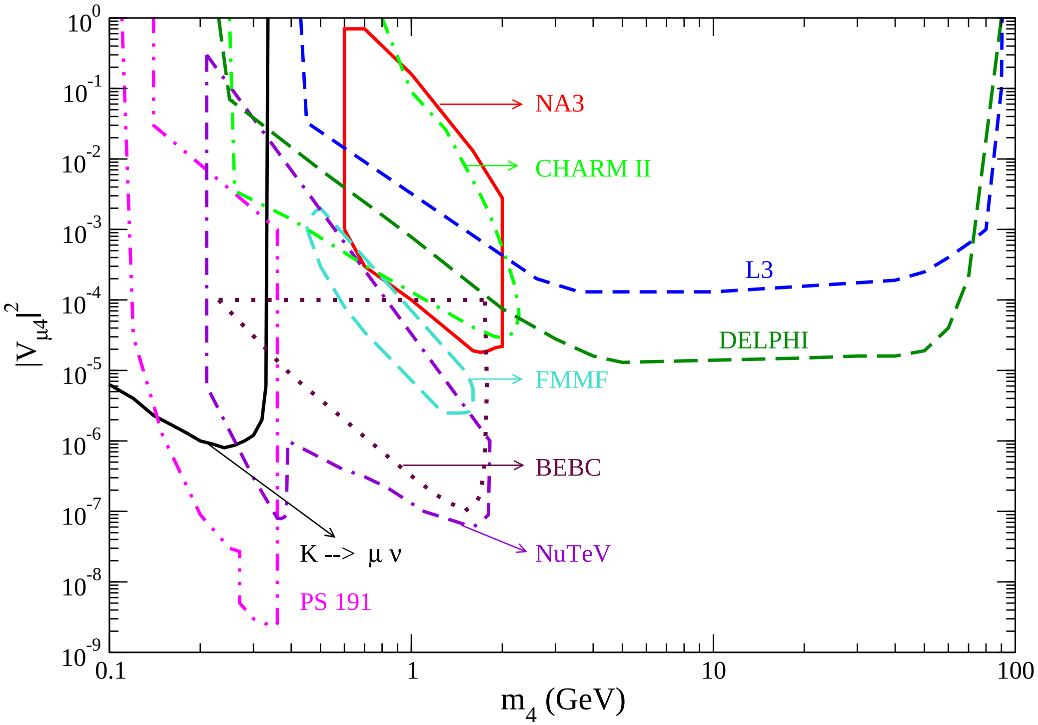
Active neutrino masses:

$$m_\nu \simeq \frac{F v^2 \times f}{M} + \frac{F^2 v^2 \times m}{M^2}$$

$$Y^2 = Trace[F^\dagger F]$$



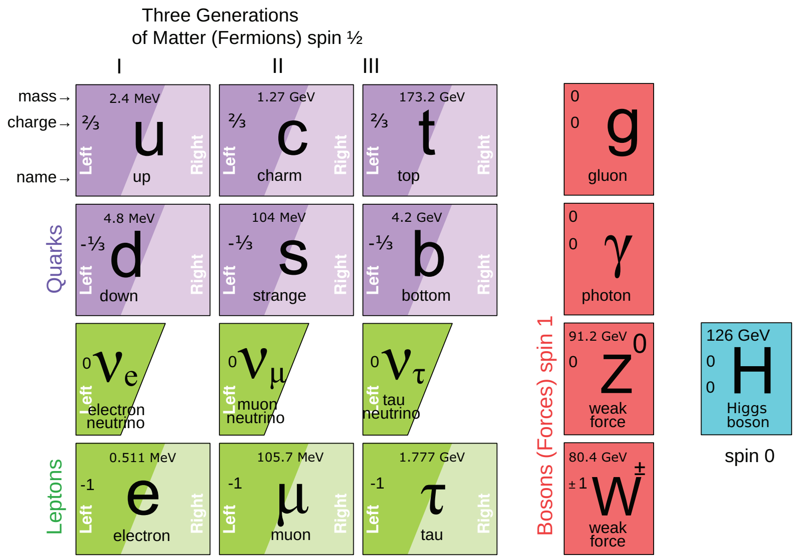
Survey of constraints on HNL

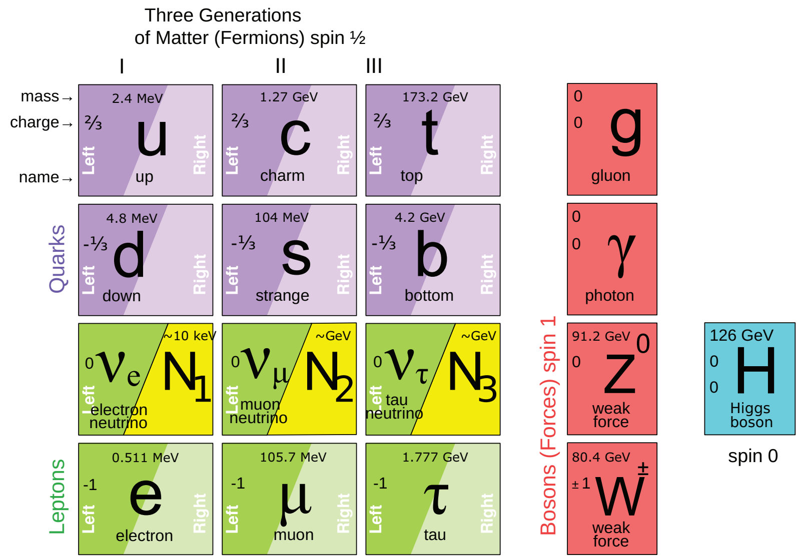


From arXiv:0901.3589, Atre et al

Any increase of experimental sensitivity may lead to discovery of HNL responsible for active neutrino masses!

$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM





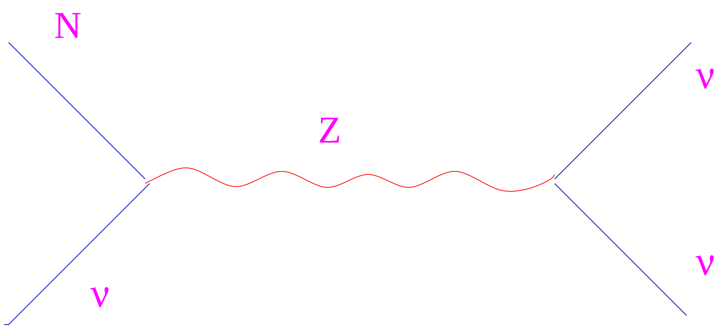
N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter (has been discovered in X-rays? $M_1 \simeq 7$ keV, Bulbul et al., Boyarsky et al)

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

Dark Matter candidate: N_1

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

For one flavour:

$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\ \text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

$$\theta_1 = \frac{m_D}{M_N}$$

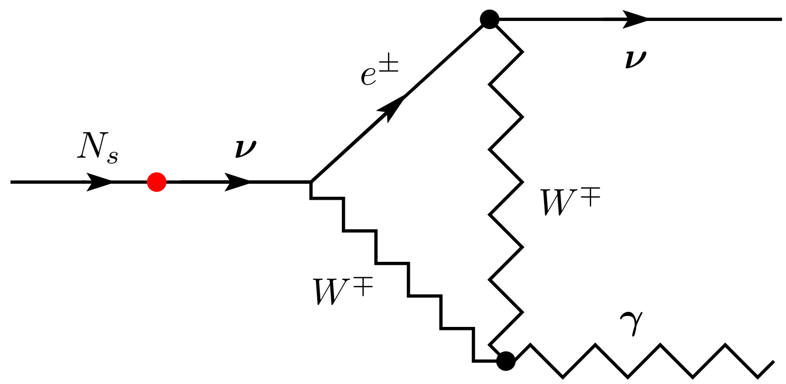
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$

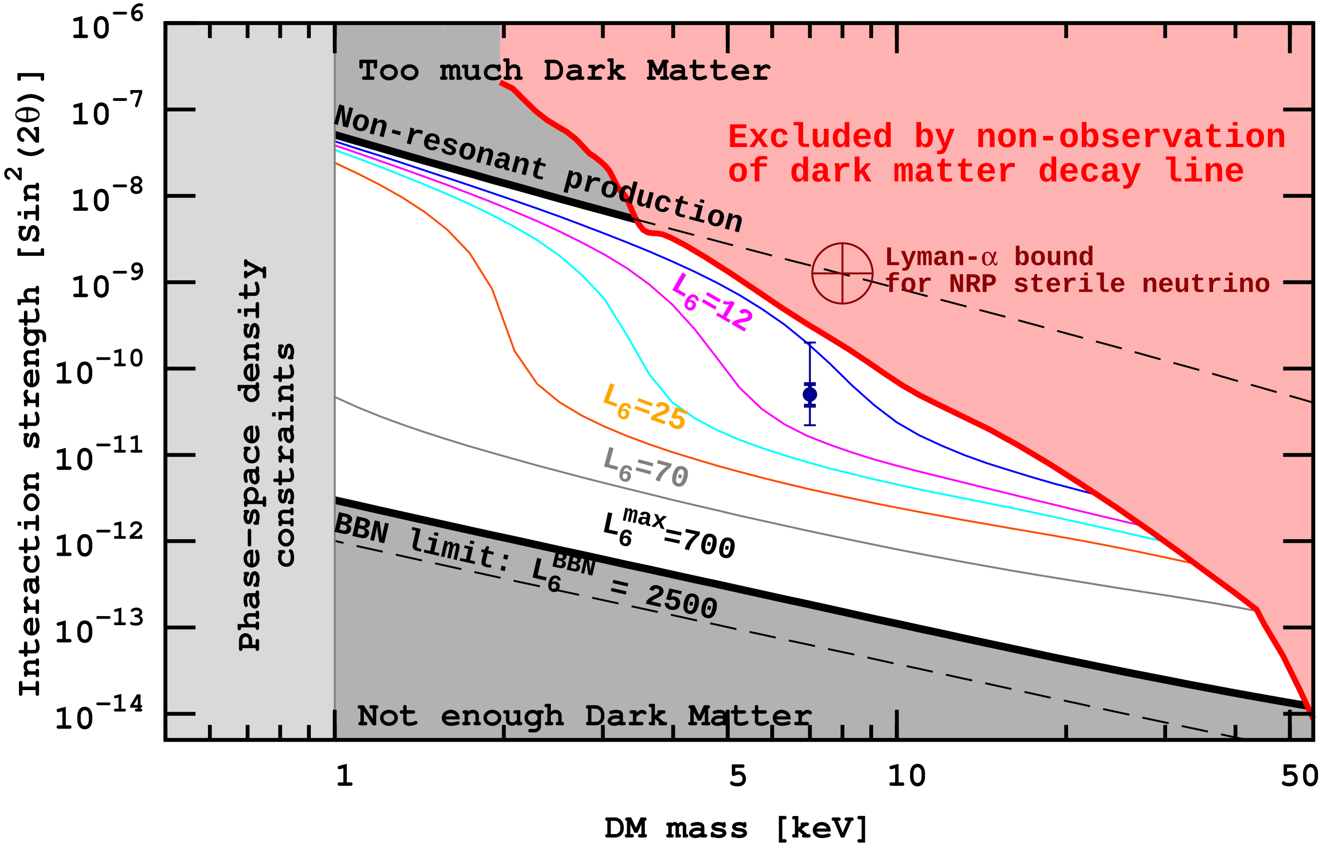


Radiative decay width:

$$\Gamma_{\mathrm{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256 \cdot 4\pi^4}\ \sin^2(2\theta)\,M_s^5$$

Constraints on DM HNL N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). seen yet



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

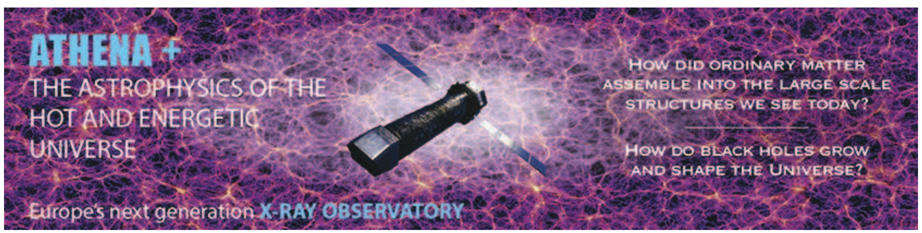
Searches for HNL in space

- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

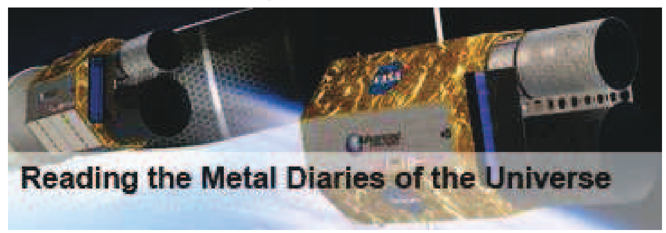
Astro-H

LOFT

Athena+



Origin/Xenia



Baryon asymmetry

- CP-violation - OK due to new complex phases in Yukawa couplings
- Lepton number violation - OK due to HNL couplings and due to Majorana masses
- Deviations from thermal equilibrium: OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Note:

- there is no electroweak phase transition for the Higgs mass 126 GeV
- For masses of N in the GeV region they decay at temperatures ~ 1 GeV. These decays cannot be used for baryogenesis, as they occur below the sphaleron freeze-out temperature

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.

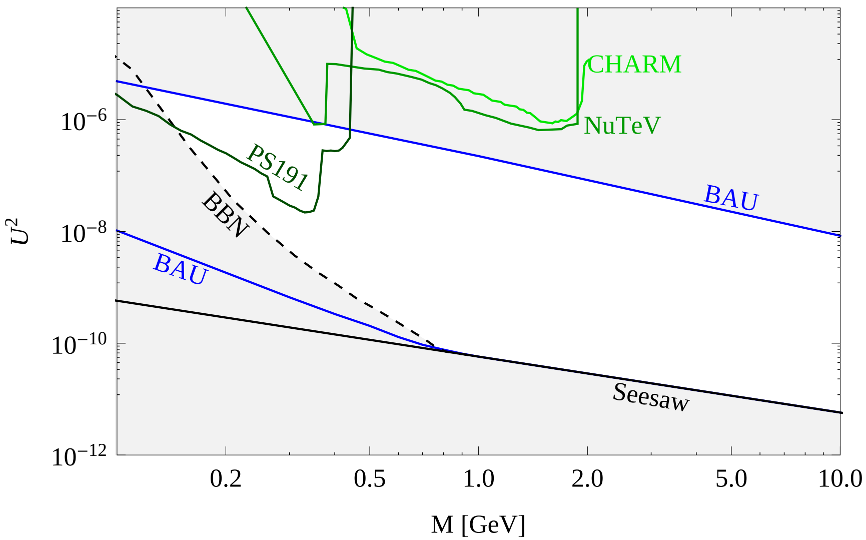
Qualitatively:

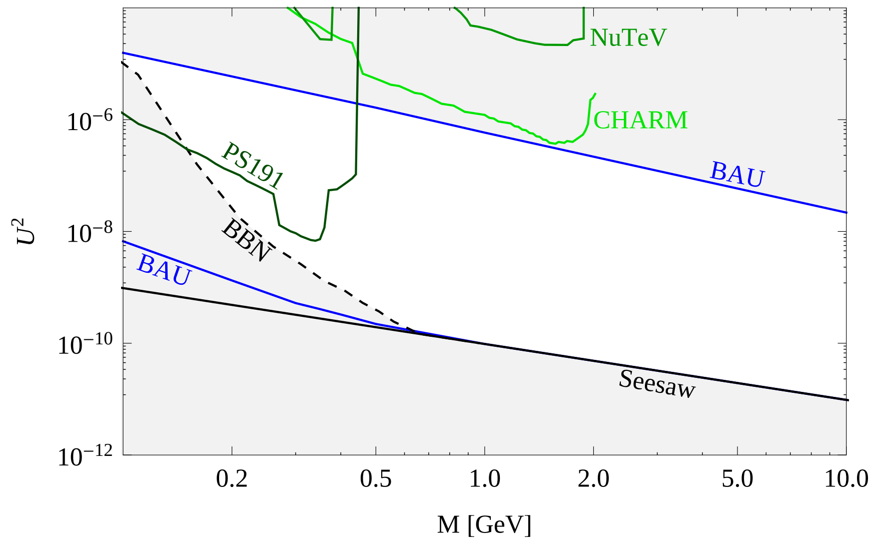
- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen





Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

Sakharov condition

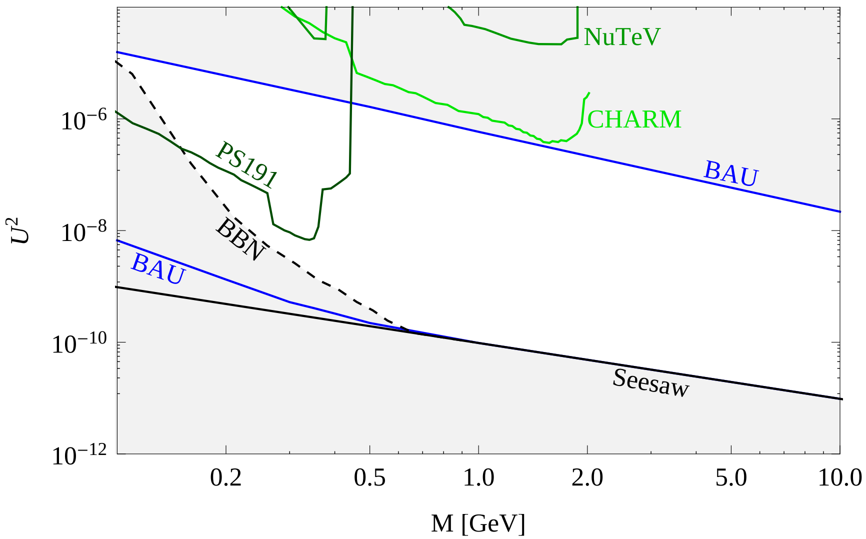
Rate of HNL equilibration $\Gamma \simeq \kappa F^2 T$ must be smaller than the rate of the Universe expansion at the sphaleron freeze-out $T = T_{sph} \simeq 130$ GeV, $H \simeq T^2/M_0$, $M_0 \sim M_{Pl}$ ($\kappa \simeq 3 \times 10^{-6}$ - some number following from solution of kinetic equations in the early universe):

$$\kappa F^2 \left(1 - \frac{M^2}{M_W^2}\right)^2 T_{sph} < \frac{T_{sph}^2}{M_0}$$

Numerically, $F < 8 \times 10^{-6}$, and

$$U^2 < 2 \times 10^{-6} \left(\frac{GeV}{M}\right)^2 \left(1 - \frac{M^2}{M_W^2}\right)^2$$

Sakharov condition



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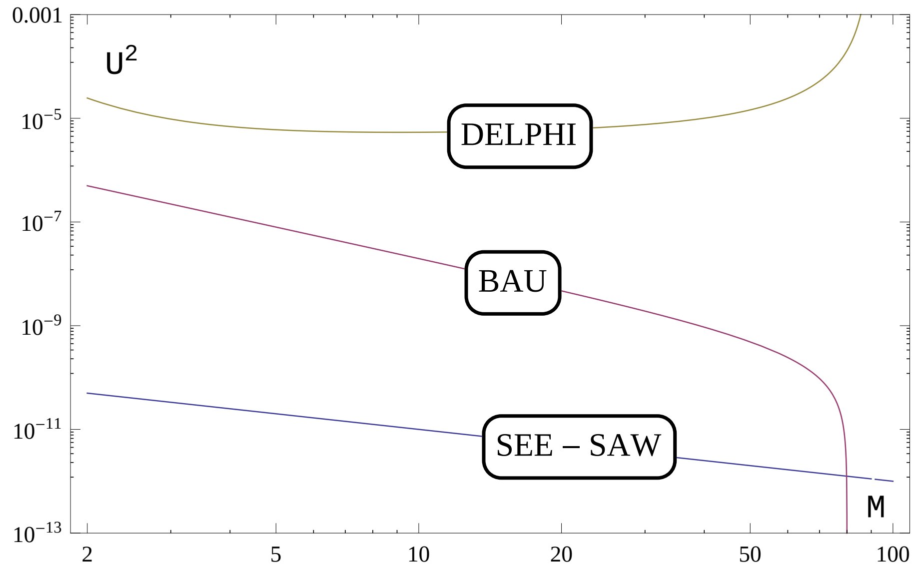
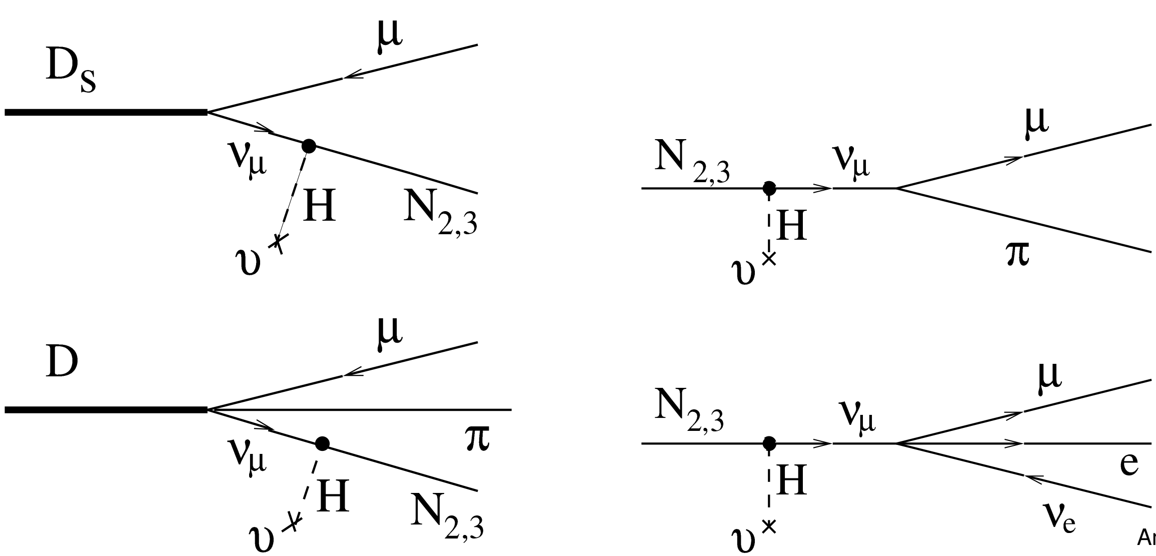


Experimental search for HNL

- Production
  - via intermediate (hadronic) state

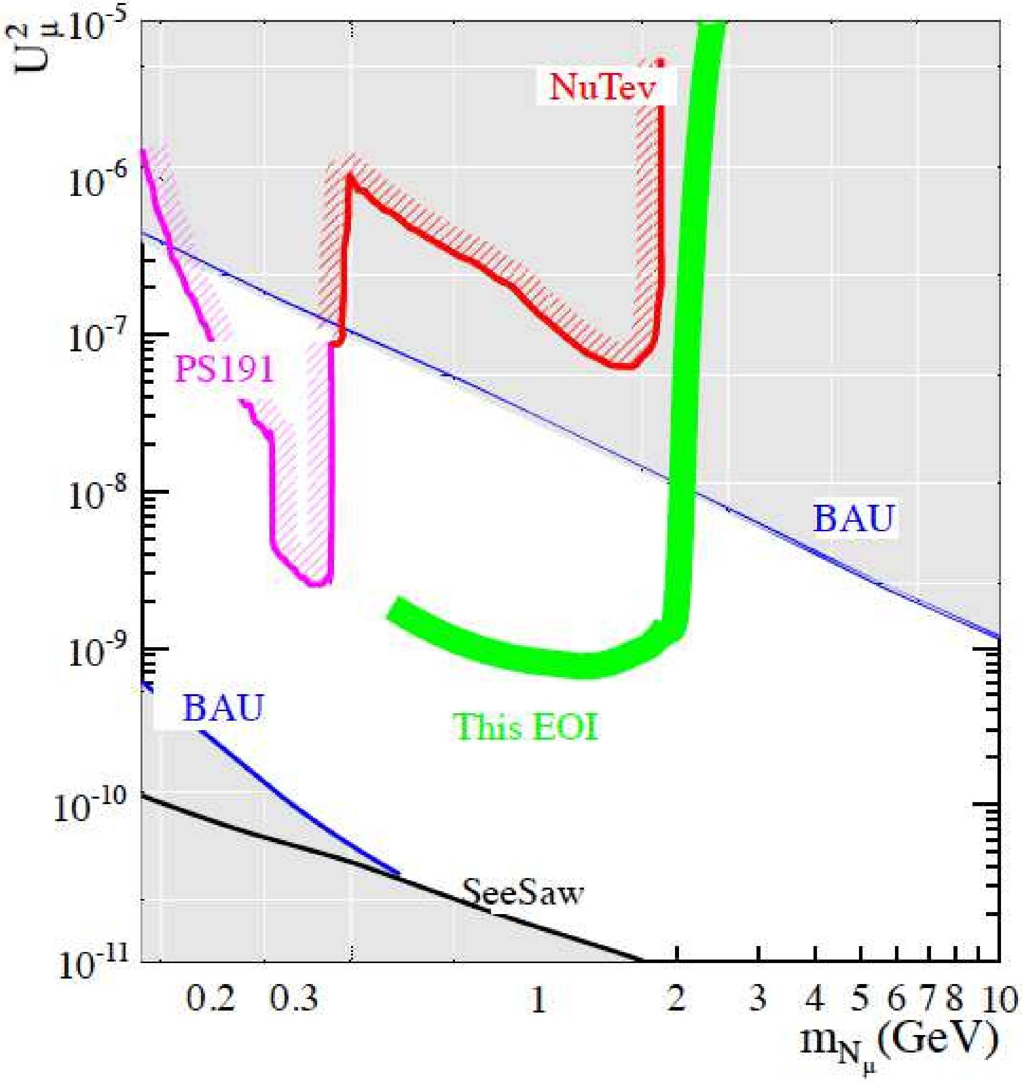
    $\boldsymbol{p + \text{target} \to \text{mesons} + \ldots}$, and then hadron$\to N + \ldots$.
  - via Z-boson decays: $e^+e^- \to Z \to \nu N$
- Detection
  - Subsequent decay of N to SM particles



How to improve the bounds or to discover HNL?

Fixed target SPS: SHIP

SHiP
Search for Hidden Particles



FCC-ee for 10^{12} Z

very preliminary

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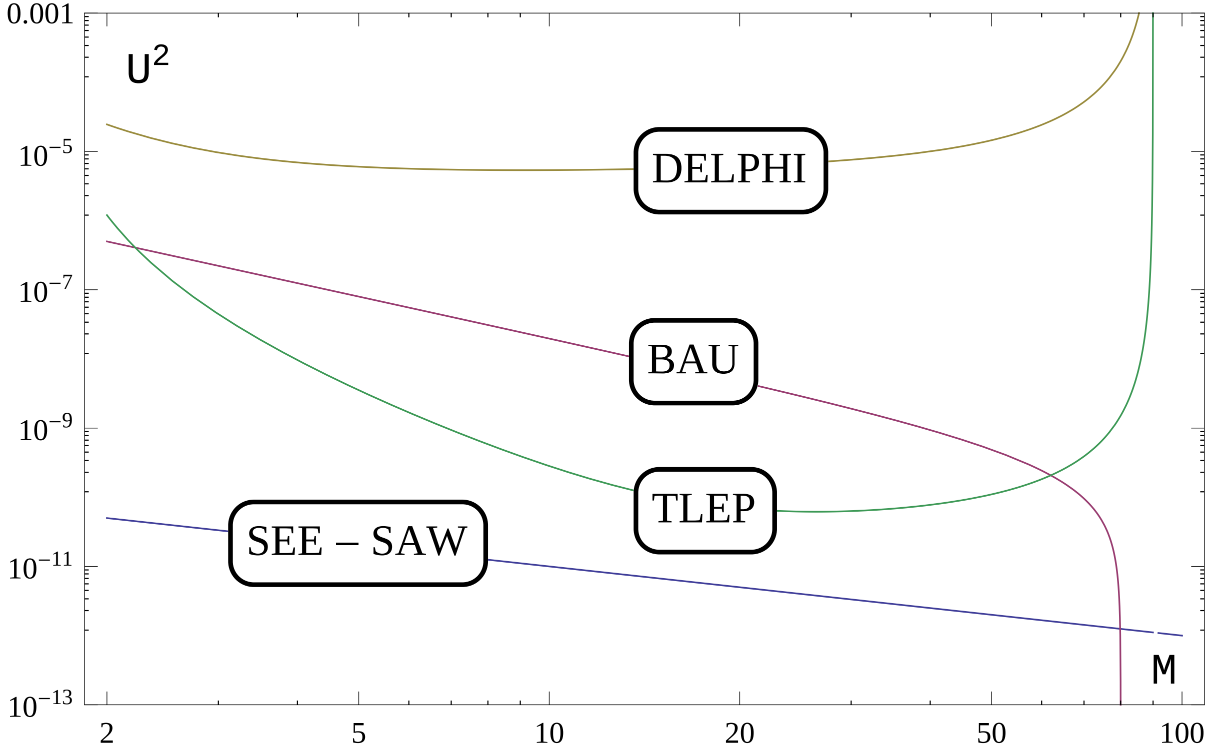

Conclusions

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites - Astro H
  - proton fixed target experiment - SHIP, $\boldsymbol{M \lesssim 2}$ GeV
  - collider experiments at FCC-ee in Z-peak, $\boldsymbol{M \gtrsim 3}$ GeV