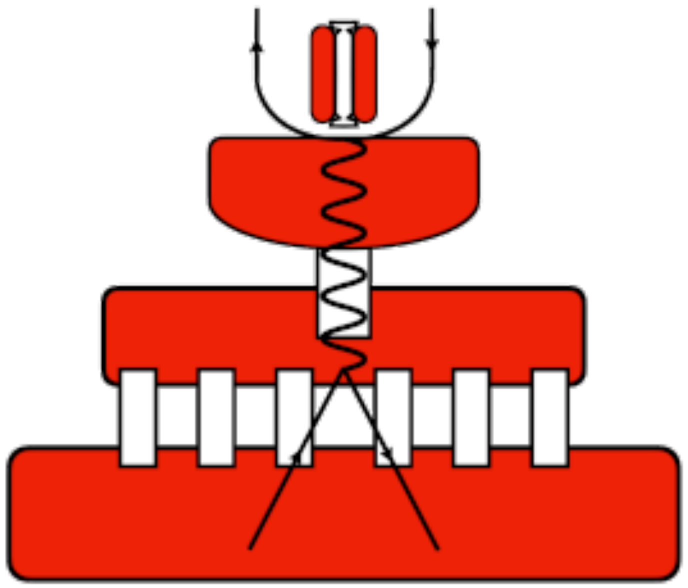
Light HNLs in beam-dump experiments



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EPFL, Lausanne

KAON-2019 @ Perugia 13.09.2019

Overview

- Generic HNLs: production and decay
- See-saw mechanism and HNLs
- HNLs and baryon asymmetry of the Universe

Generic HNLs: production and decay

HNLs (heavy neutral leptons)

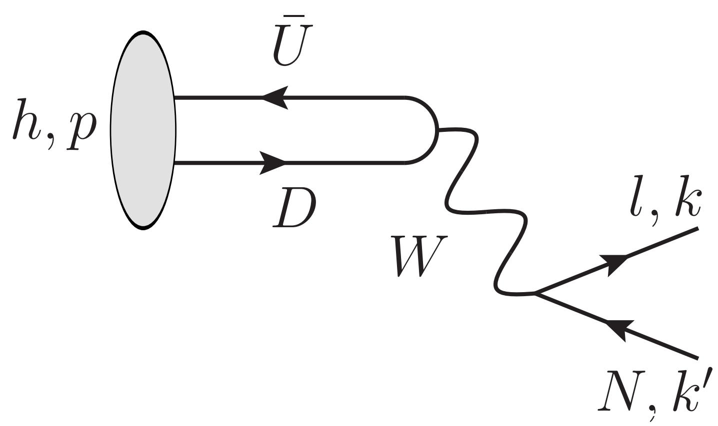
- Neutral singlet fermions. Mixing with neutrinos

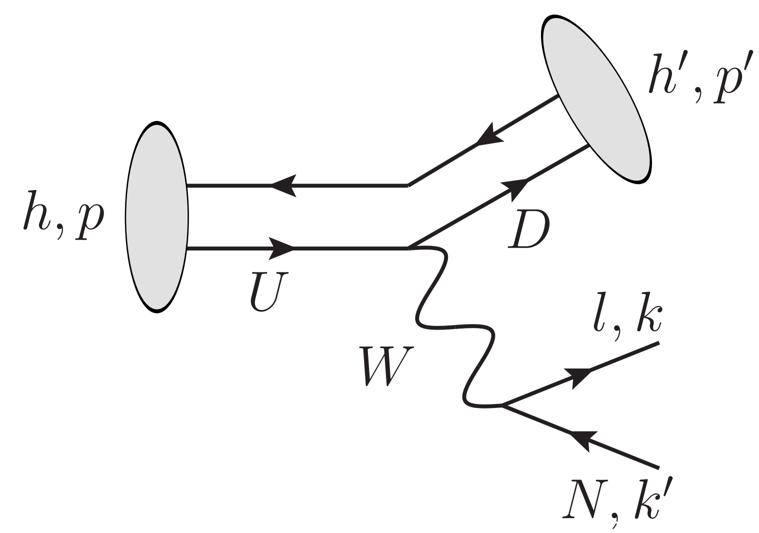
$$\nu_{L_\alpha} = U^{PMNS}_{\alpha i} \nu_i + U_\alpha N,$$

- $\mathscr{M}(K \to eN) = U_e \cdot \mathscr{M}(K \to e\nu)$

HNL production

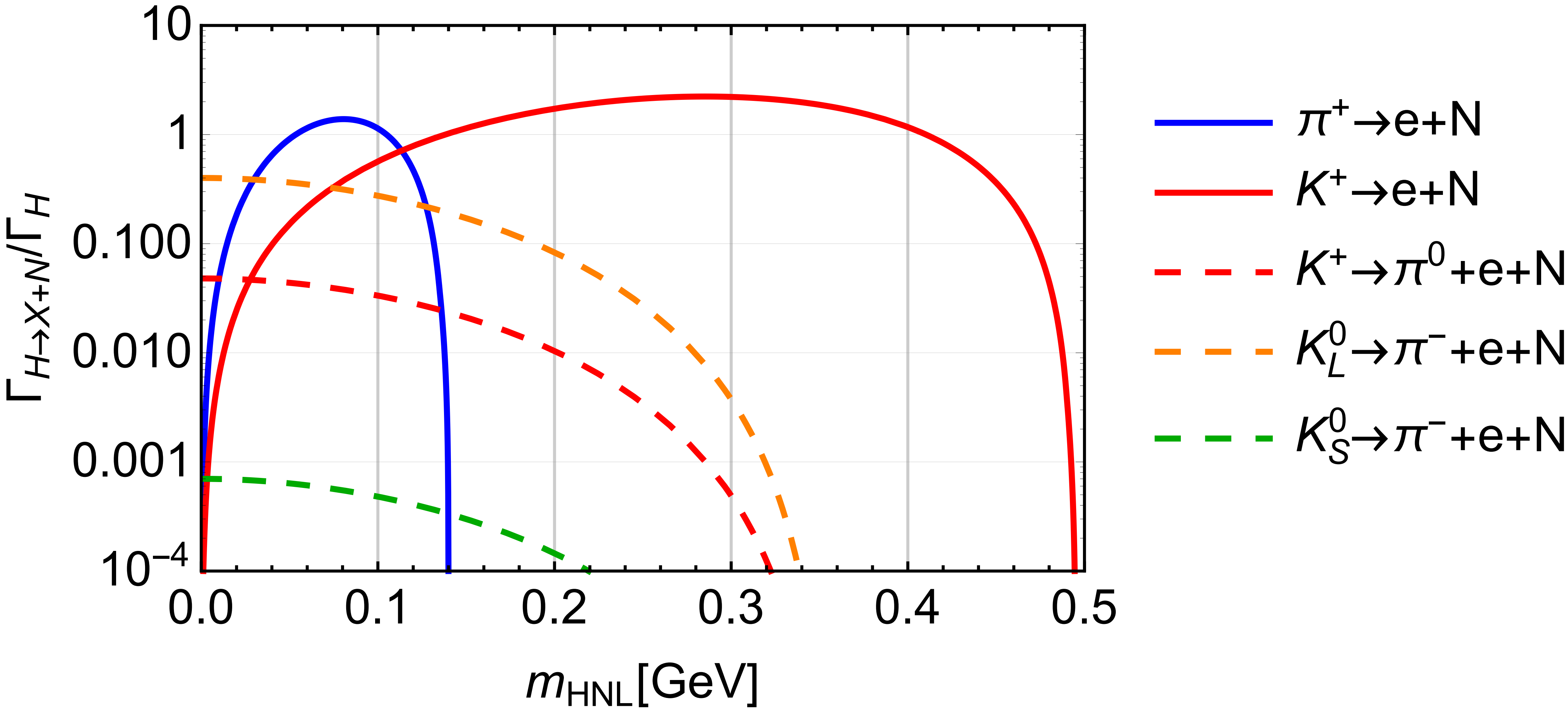
Leptonic and semileptonic meson decays





- HNL production and decay have been studied in many works, see e.g. Gorbunov, Shaposhnikov 0705.1729 and its update Bondarenko et al, 1805.08567

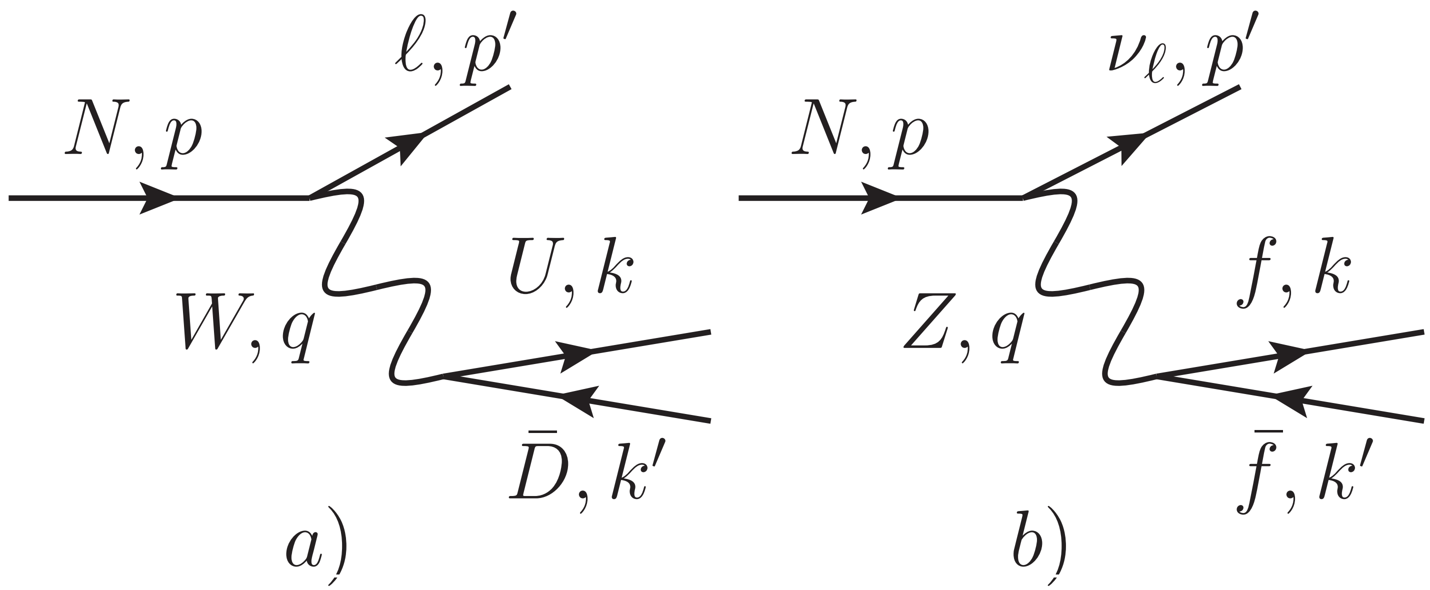
HNL production



Bondarenko et al, 1805.08567

$$U_e^2 = 1,\ U_\mu^2 = U_\tau^2 = 0$$

HNL decays



Bondarenko et al, 1805.08567

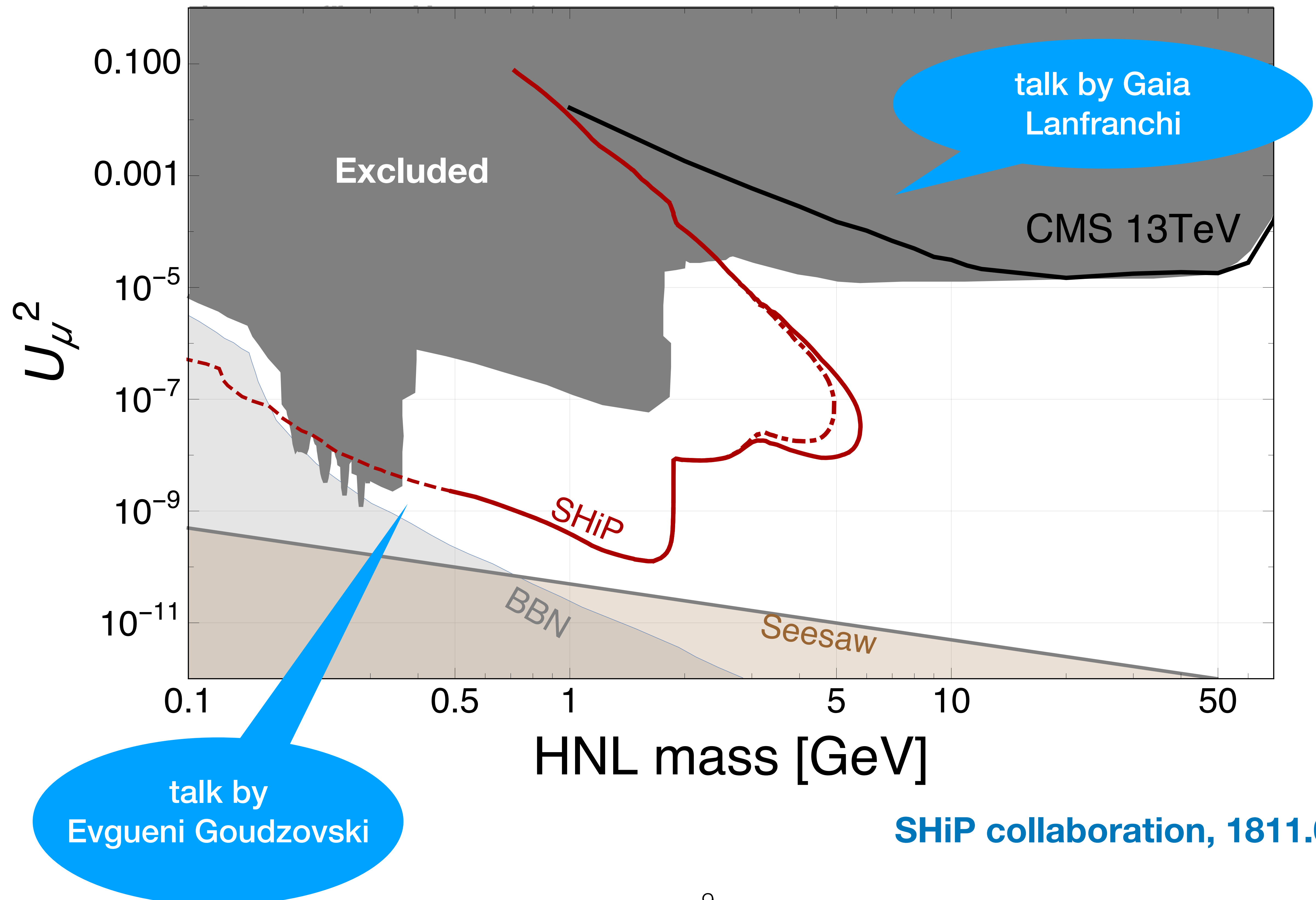
Open-source implementation:
https://github.com/f-thiele/cHNLdecay

HNL decays

Channel	Opens at [MeV]	Relevant from [MeV]	Relevant up to [MeV]	Max BR [%]	Reference in [67]
$N \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$	$\sum m_\nu \approx 0$	$\sum m_\nu \approx 0$	—	100	(3.5)
$N \to \nu_\alpha e^+ e^-$	1.02	1.29	—	21.8	(3.4)
$N \to \nu_\alpha \pi^0$	135	136	3630	57.3	(3.7)
$N \to e^- \pi^+$	140	141	3000	33.5	(3.6)
$N \to \mu^- \pi^+$	245	246	3000	19.7	(3.6)
$N \to e^- \nu_\mu \mu^+$	106	315	—	5.15	(3.1)
$N \to \mu^- \nu_e e^+$	106	315	—	5.15	(3.1)
$N \to \nu_\alpha \mu^+ \mu^-$	211	441	—	4.21	(3.4)
$N \to \nu_\alpha \eta$	548	641	2330	3.50	(3.7)
$N \to e^- \rho^+$	770	780	4550	10.4	(3.8)
$N \to \nu_\alpha \rho^0$	770	780	3300	4.81	(3.9)
$N \to \mu^- \rho^+$	875	885	4600	10.2	(3.8)
$N \to \nu_\alpha \omega$	783	997	1730	1.40	(3.9)
$N \to \nu_\alpha \eta'$	958	1290	2400	1.86	(3.7)

Table from 1811.00930
[67] = Bondarenko et al, 1805.08567

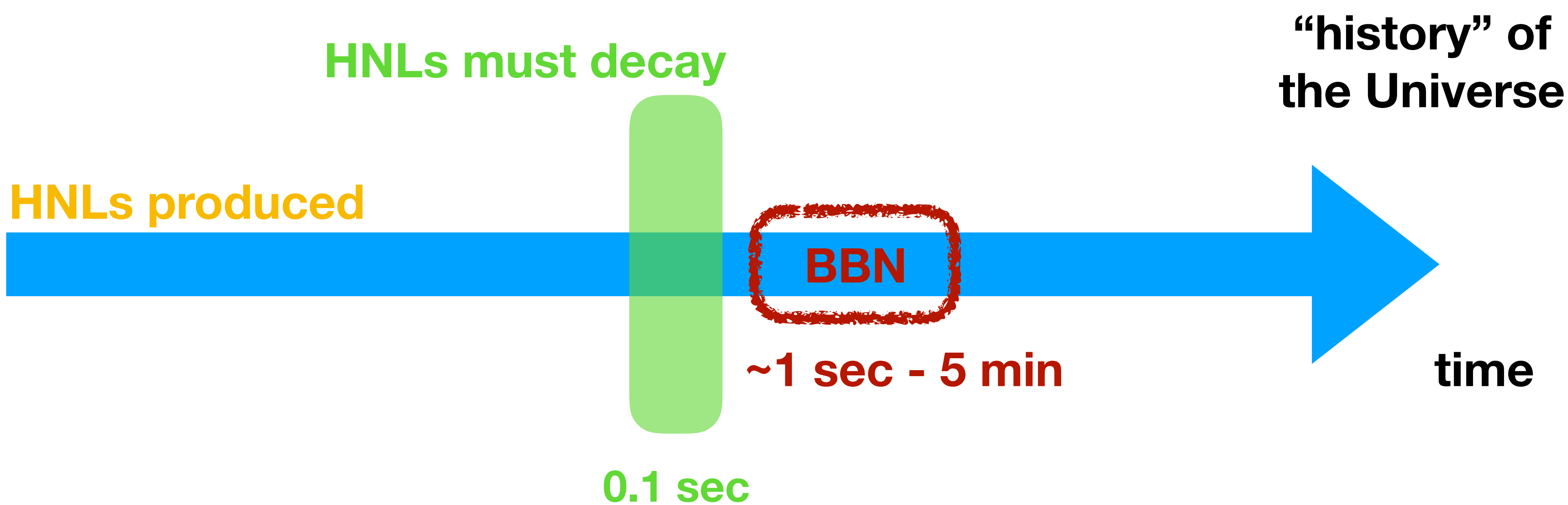
Constraints on mass and mixing



SHiP collaboration, 1811.00930

BBN constraint

HNLs will be thermally produced in the early Universe due to mixing with active neutrinos. Their decays could potentially spoil primordial nucleosynthesis.



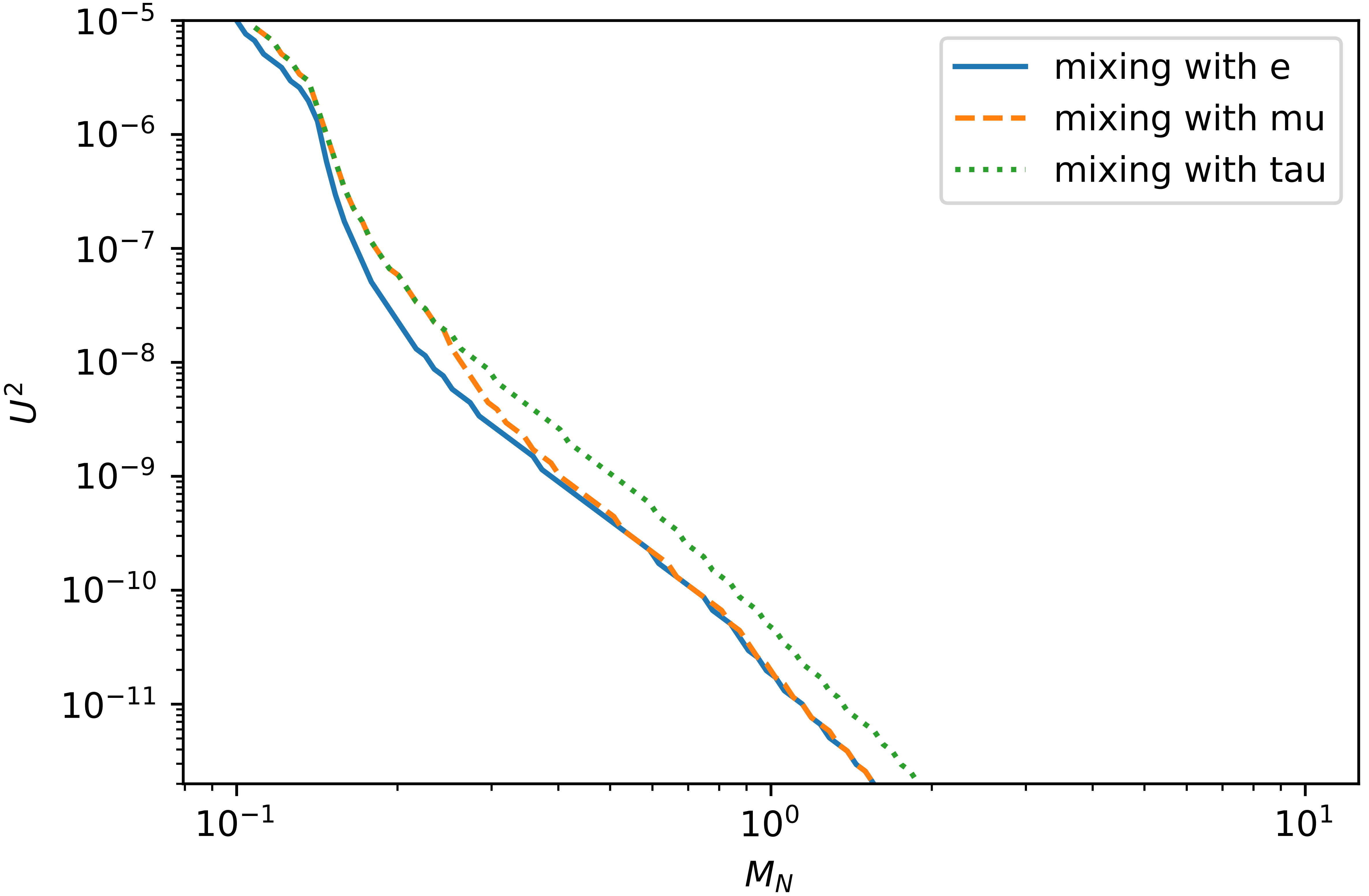
BBN constraint:

$$\frac{1}{\Gamma_{tot}} < 0.1 \; sec$$

Dolgov et al, hep-ph/0002223

Accurate consideration below π mass: Ruchayskiy, Ivashko, 1202.2841

BBN constraint



See-saw mechanism and HNLs

See-saw mechanism for neutrino masses

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

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

At least 2 HNLs to be compatible with oscillation data

N_I are RH neutrinos (~HNLs), $I = 1,2,...$

Φ is the SM Higgs doublet, L_α are the SM lepton doublets

$F_{\alpha I}$ are new Yukawa couplings, M_{IJ} is the mass matrix of RH neutrinos

Neutrino masses:

$$M_\nu = -M_D M_M^{-1} M_D^T,$$

$$[M_D]_{\alpha I} = F_{\alpha I}\langle\Phi\rangle$$

Mixing with N_I

$$\nu_{L_\alpha} = U_{\alpha i}^{PMNS}\nu_i + \Theta_{\alpha I}N_I^c,$$

$$\Theta_{\alpha I} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_I}$$

See-saw mechanism with 2 HNLs

- 6 parameters: two masses, Dirac phase, 1 Majorana phase, two more parameters (a complex angle ω)

- If one wants to be technically natural, 2 HNLs have to be nearly degenerate in mass

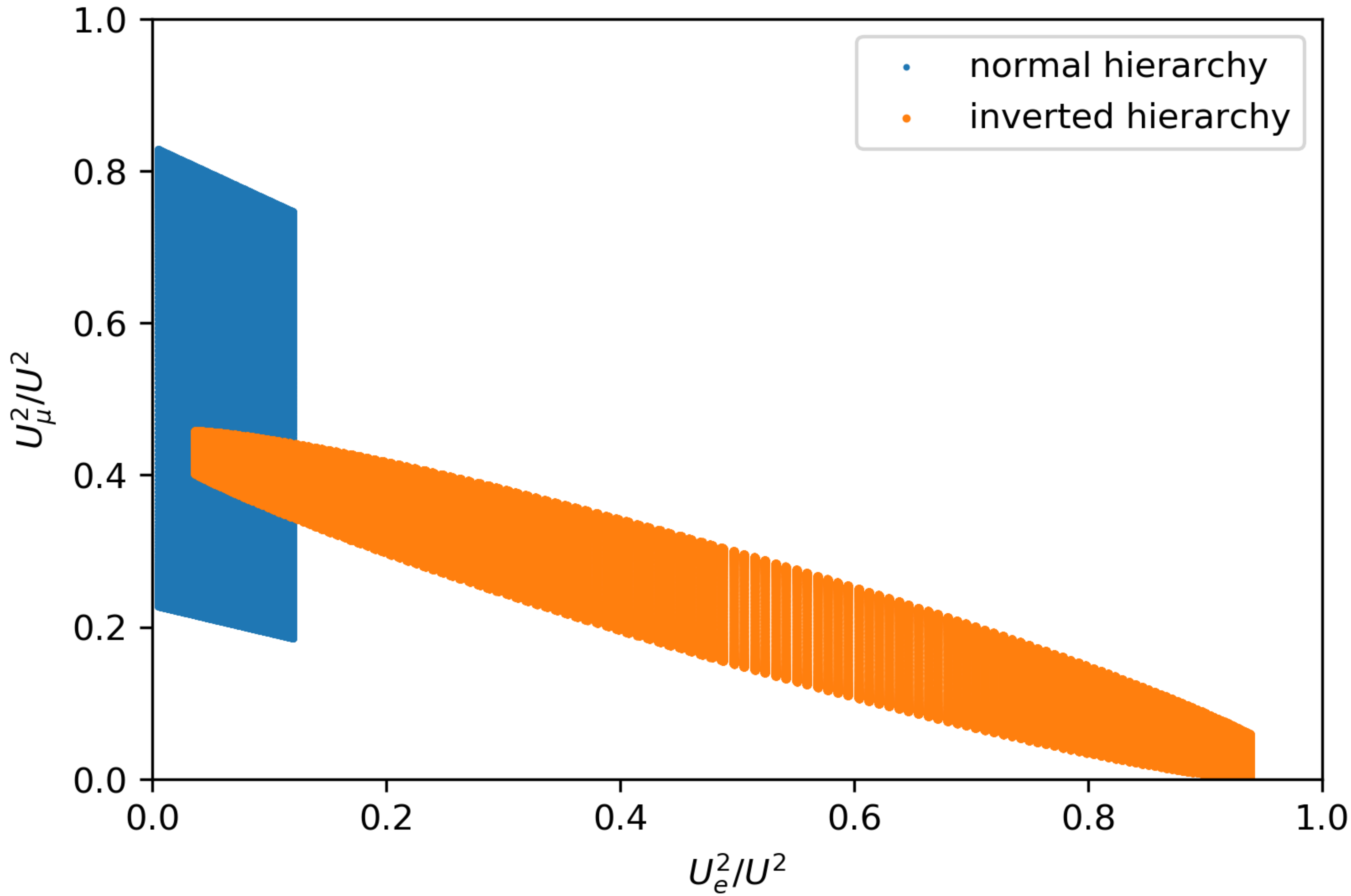
Shaposhnikov 2006
Kersten, Smirnov 2007
Moffat, Pascoli, Weiland [1712.07611]
Drewes ,Klarić, Klose [1907.13034]

- Mixings $|U_\alpha|^2 = |\Theta_{\alpha 1}|^2 + |\Theta_{\alpha 2}|^2$

- **Not all values of $|U_\alpha|^2$ are compatible with oscillation data!**

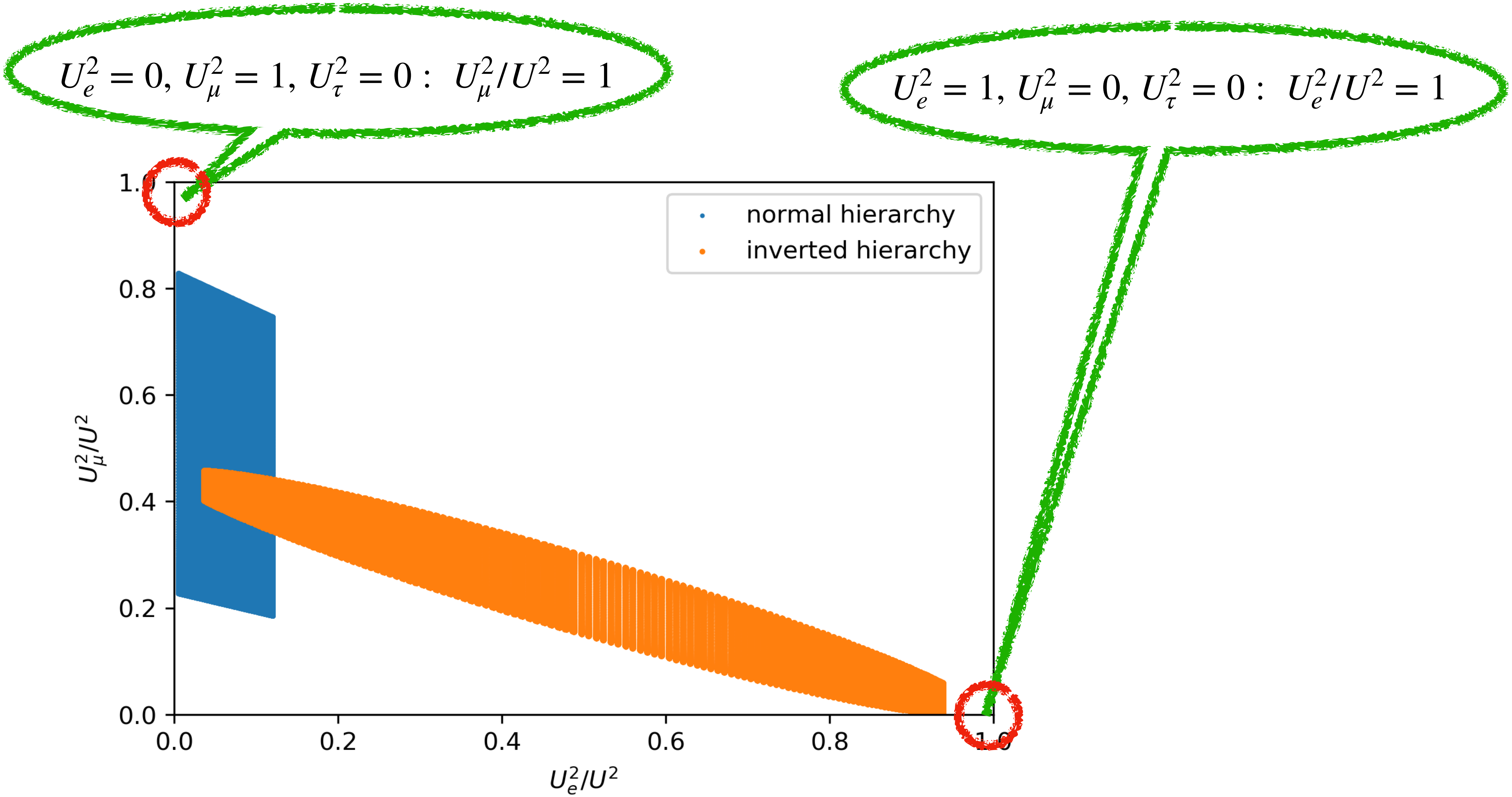
- There are lower bounds on $U^2 = \Sigma_\alpha |U_\alpha|^2$ and $|U_\alpha|^2$

See-saw mechanism with 2 HNLs: Mixings



* no constraints on δ phase were assumed

See-saw mechanism with 2 HNLs: Examples of mixings



* no constraints on δ phase were assumed

HNLs and baryon asymmetry of the Universe

Baryon asymmetry of the Universe (BAU)

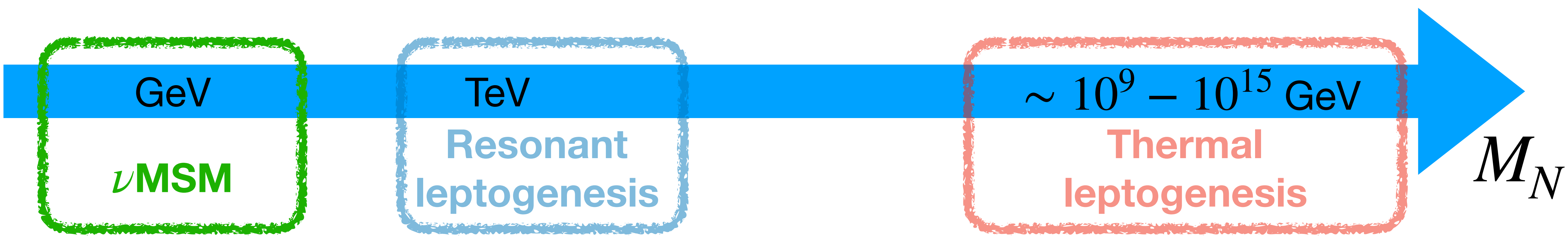
$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}$$

see, e.g.   hep-ph/1204.4186

Leptogenesis

Lepton asymmetry -> baryon asymmetry
by the sphaleron processes

Kuzmin, Rubakov
Shaposhnikov 1986



Asaka, Shaposhnikov 2005

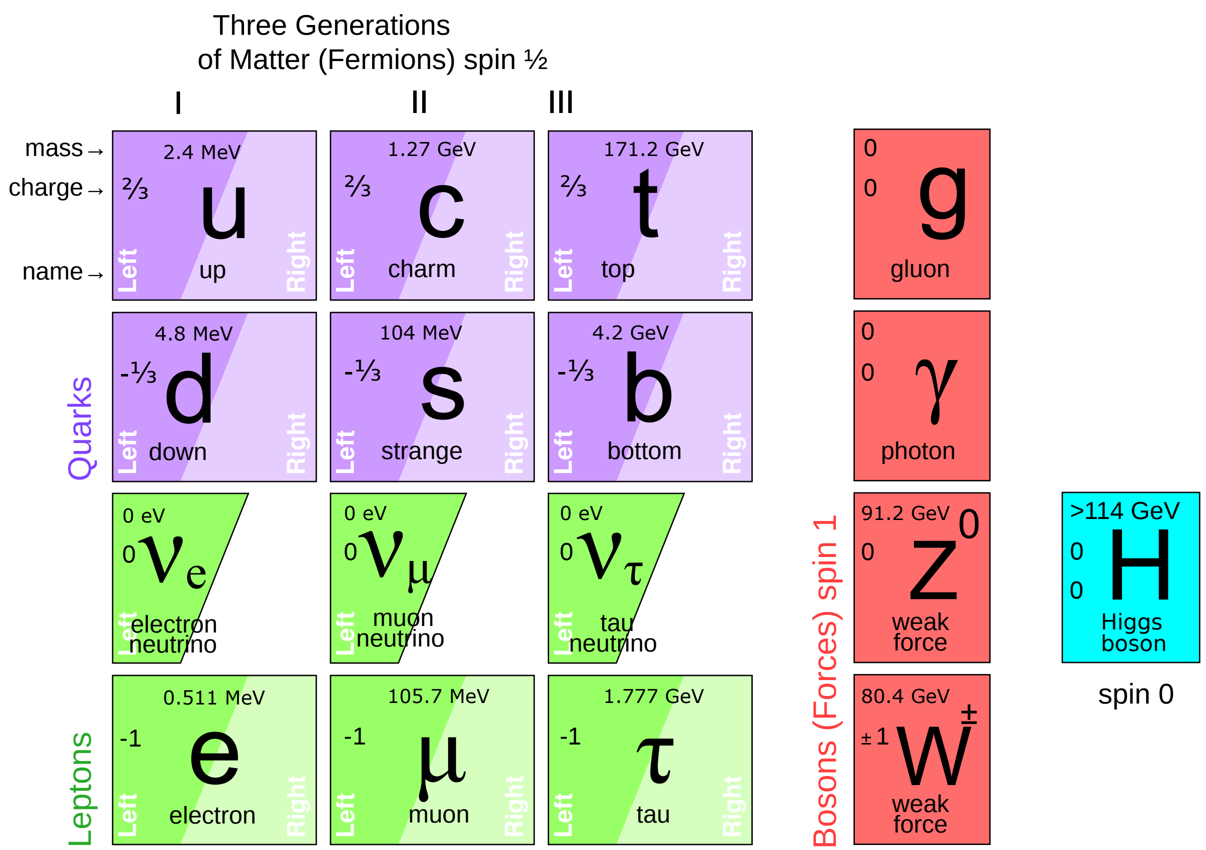
Pilaftsis, Underwood 2003

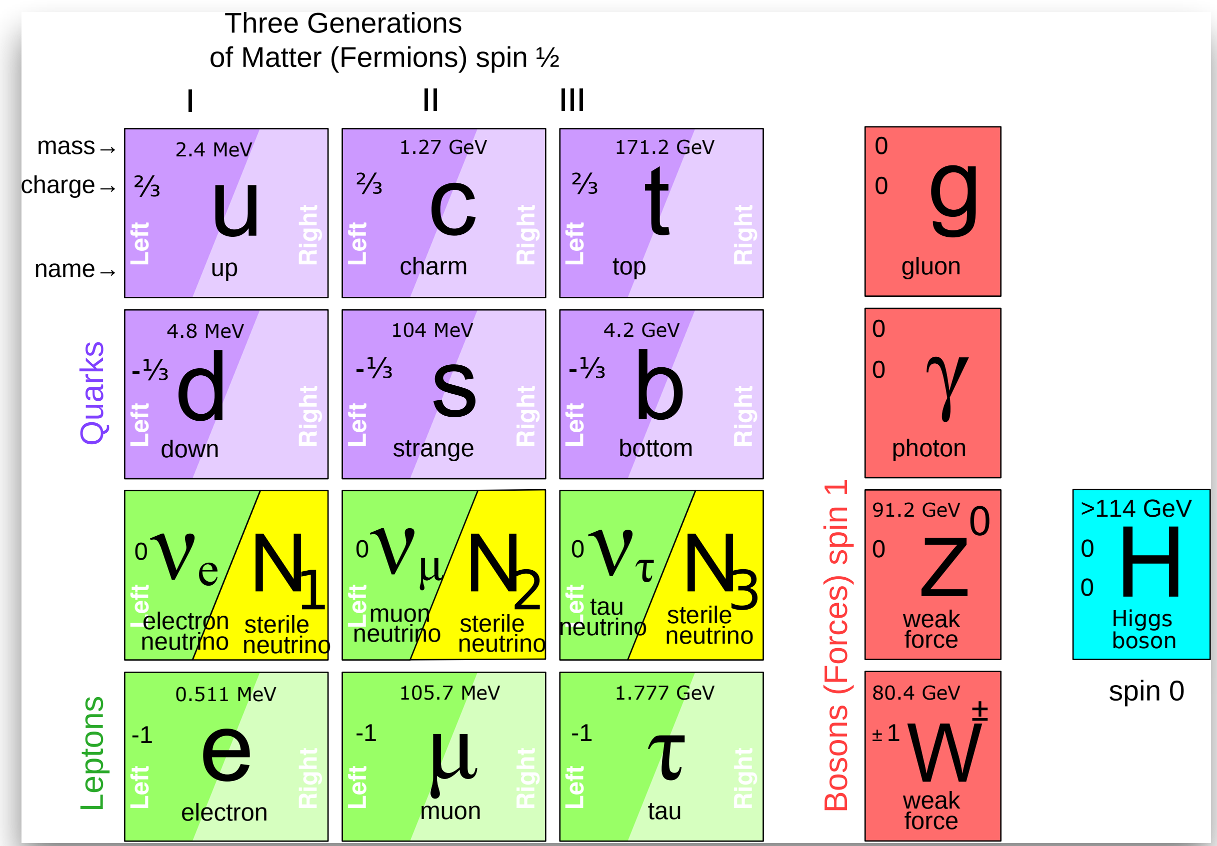
Fukugita, Yanagida 1986

2 right-handed neutrinos (HNLs) with almost degenerate mass M_N

νMSM (neutrino Minimal Standard Model)

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005





N_1 DM candidate $m \sim few \times keV$

N_2, N_3 } ν masses via see-saw, BAU, DM production — $m \sim 0.1 - 10\, GeV$, almost degenerate

Akhmedov, Rubakov, Smirnov, 1998
Asaka,Shaposhnikov 2005

HNLs in the νMSM

- 6 parameters: two masses, Dirac phase, 1 Majorana phase, two more parameters (a complex angle ω)
- Degenerate in mass (leptogenesis requirement)
- Mixings $|U_\alpha|^2 = |\Theta_{\alpha 1}|^2 + |\Theta_{\alpha 2}|^2$
- Not all values of $|U_\alpha|^2$ are compatible with oscillation data!
- There are lower bounds on $U^2 = \Sigma_\alpha |U_\alpha|^2$ and $|U_\alpha|^2$ from see-saw
- **Upper bounds from BAU**

BAU in the νMSM

- Initial idea: Akhmedov, Rubakov, Smirnov

- Formulation of kinetic theory: Asaka, Shaposhnikov.

- Analysis of baryon asymmetry generation in the νMSM: Asaka, Shaposhnikov, Canetti, Drewes, Frossard; Abada, Arcadi, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, Racker, J. Salvado; Drewes, Garbrech, Guetera, Klariç; Hambye, Teresi; Eijima, IT; Ghiglieri, Laine,...

BAU in the νMSM

- Generation of asymmetry is described by a system of kinetic equations: (3 + 4 + 4) differential equations

- Recent improvements

  Incorporated in Eijima, Shaposhnikov, IT

  - Accurate computation of rates

    1012.3784, 1202.1288, 1403.2755, 1605.07720

  - Fermion number violating processes

    1703.06085, 1703.06087

  - Neutrality of plasma

    1401.2459, 1605.07720, 1709.07834

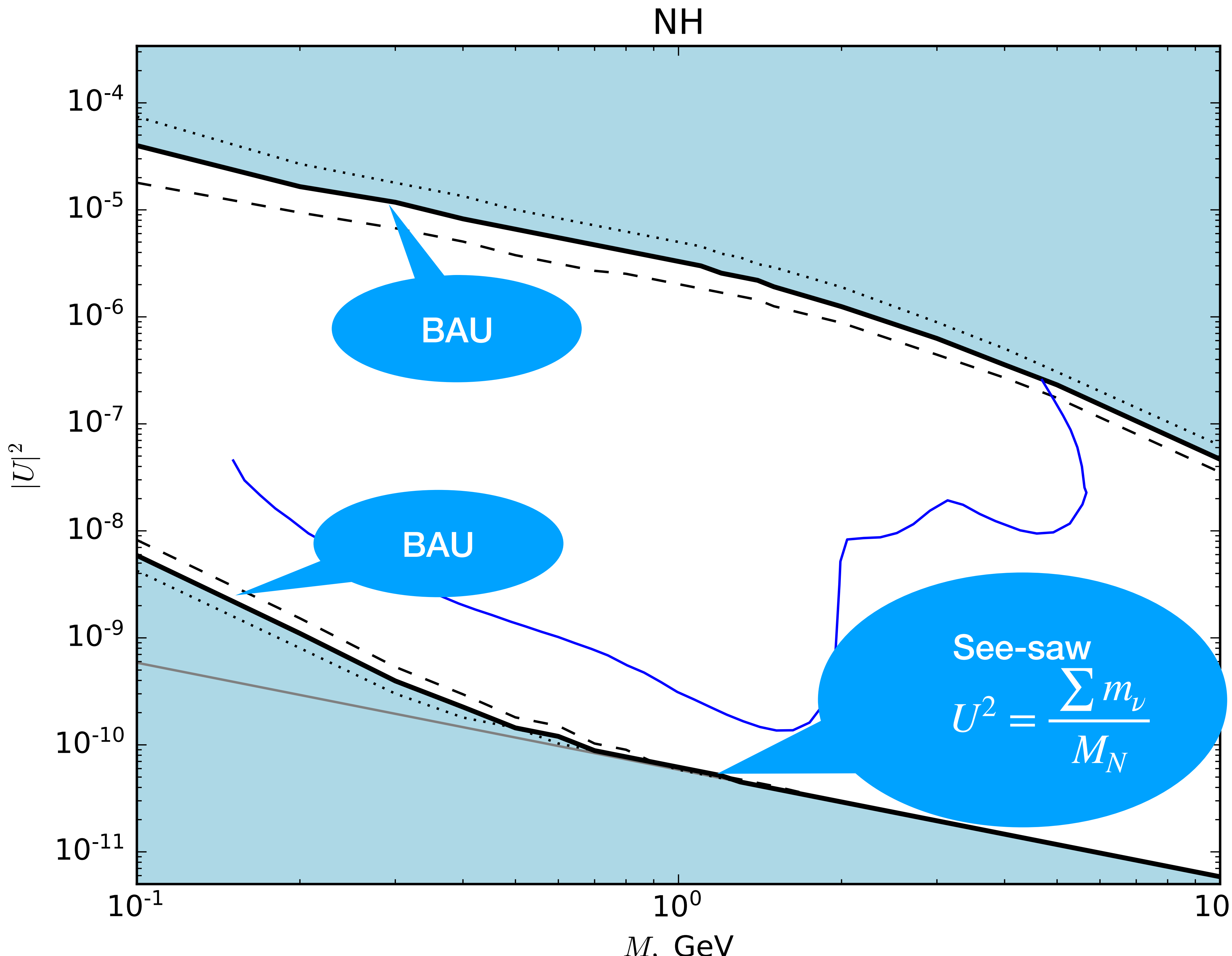
  - Gradual freeze-out of sphalerons

    1709.07834, 1711.08469

- Studies of the parameter space

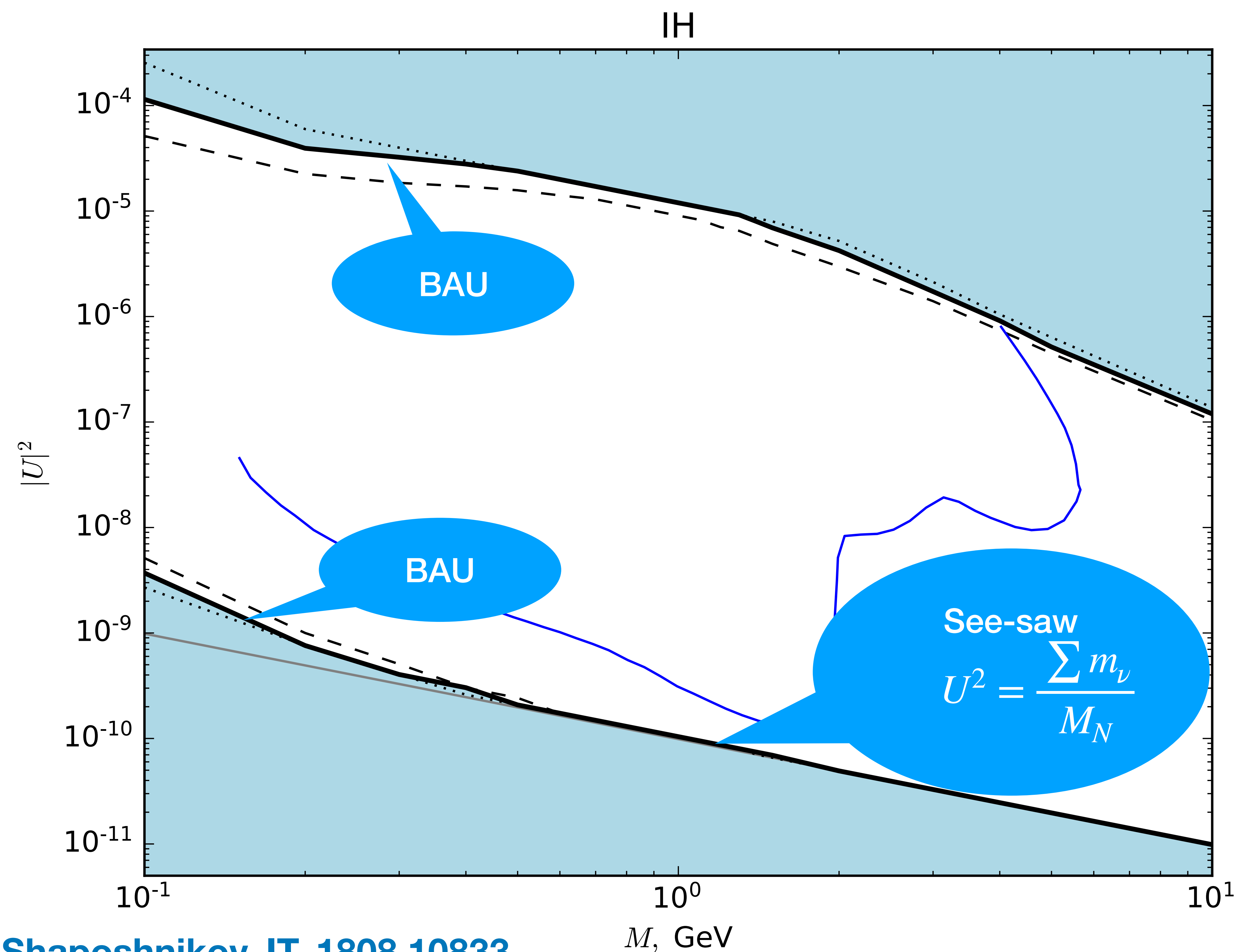
  1208.4607, 1606.06690,1606.06719, 1609.09069, 1710.03744

HNLs in the νMSM (BAU requirements)



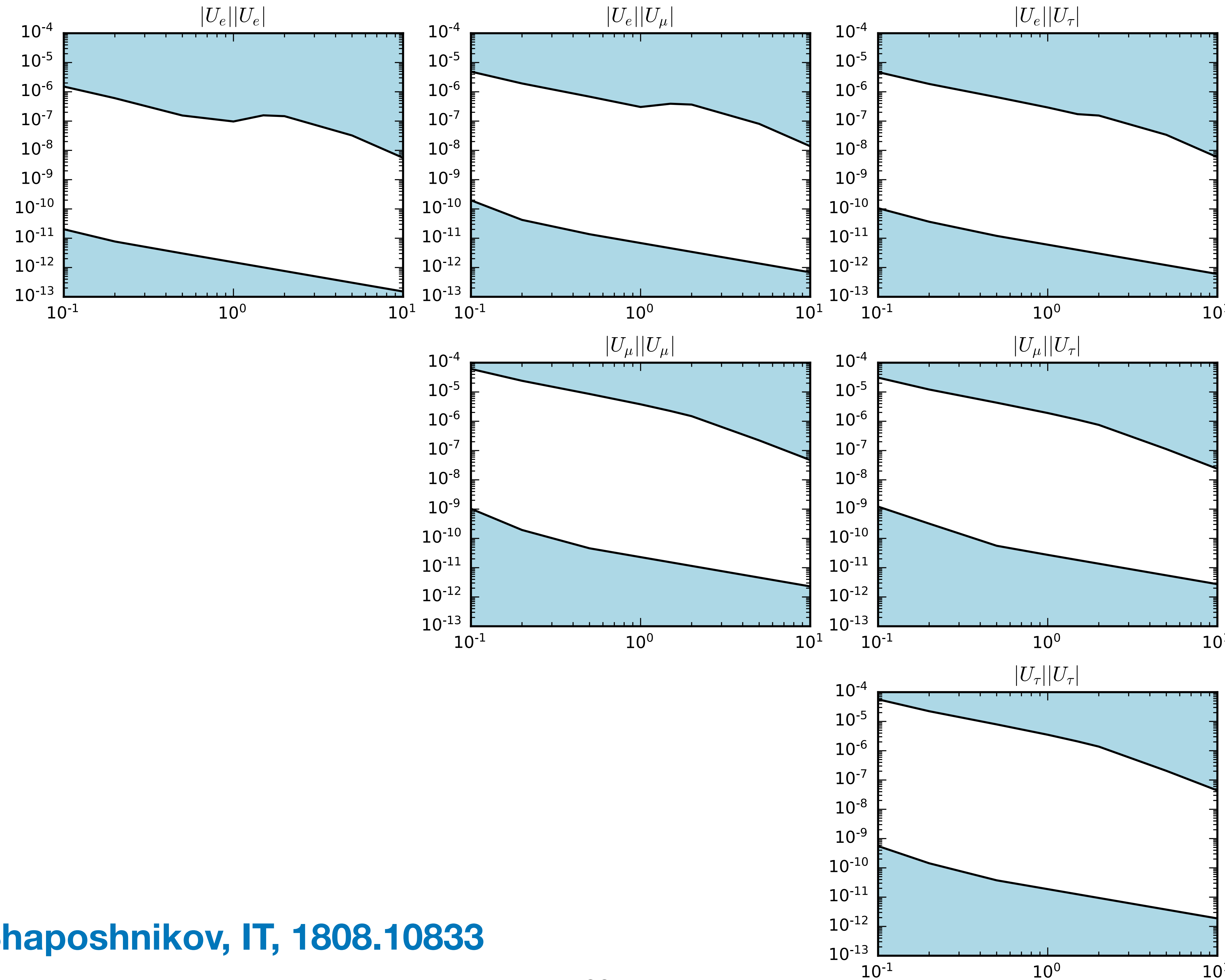
Eijima, Shaposhnikov, IT, 1808.10833

HNLs in the νMSM (BAU requirements)



Eijima, Shaposhnikov, IT, 1808.10833

HNLs in the νMSM (BAU requirements)

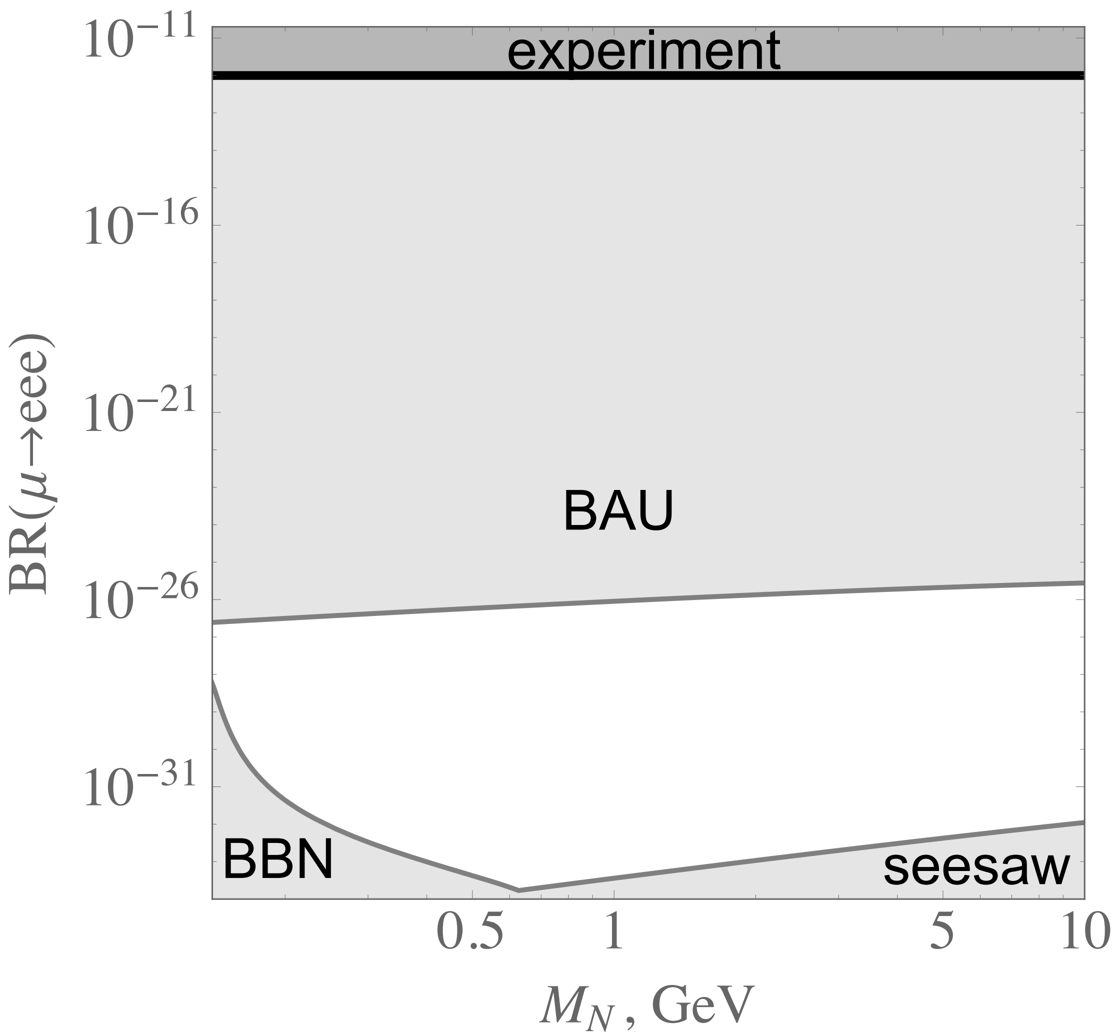


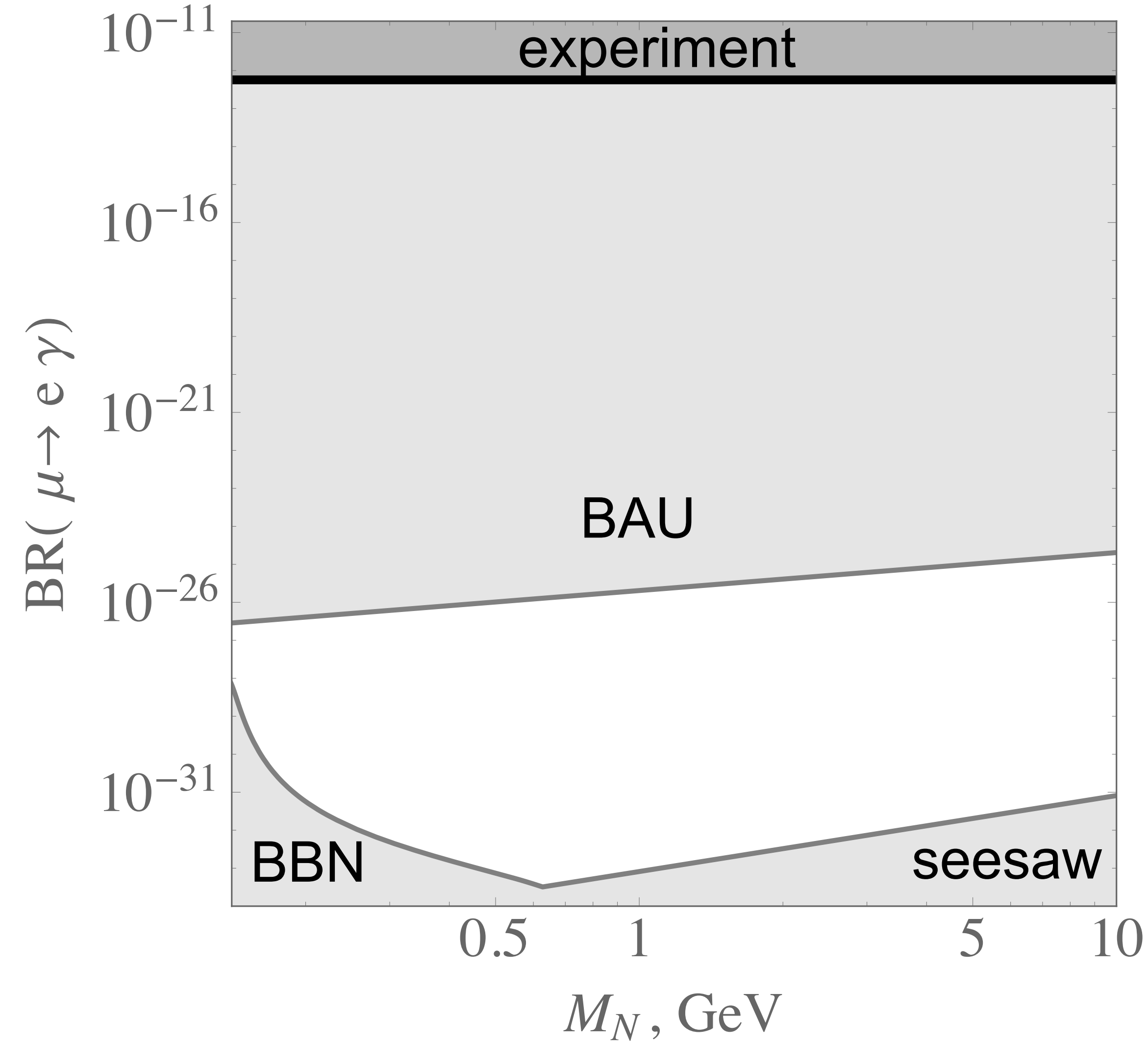
Eijima, Shaposhnikov, IT, 1808.10833

Indirect tests of the νMSM

In short: no way
(apart from, maybe, $0\nu\beta\beta$)

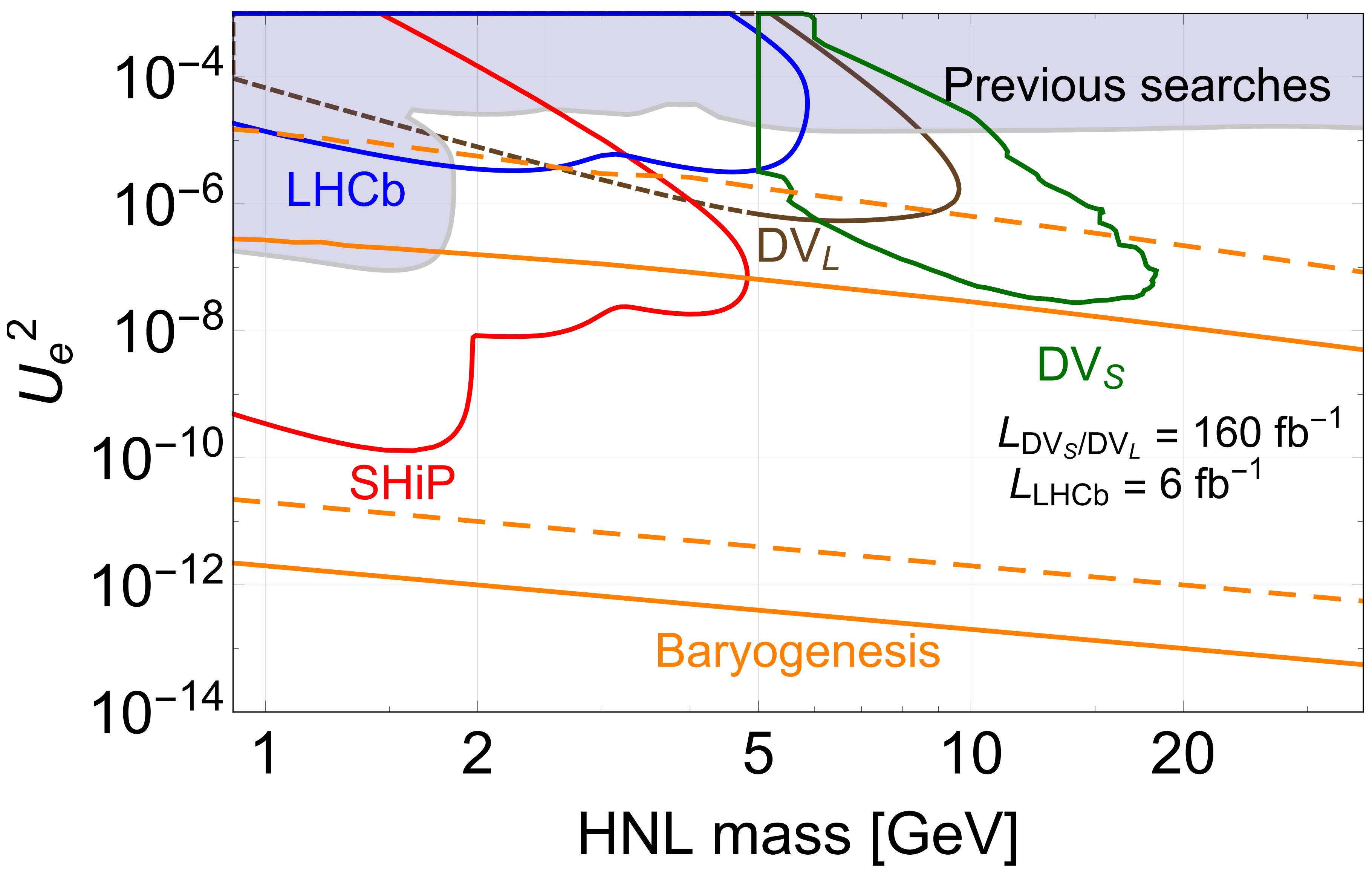
Gorbunov, IT, 1412.7751





High intensity experiments and LHC: Synergy

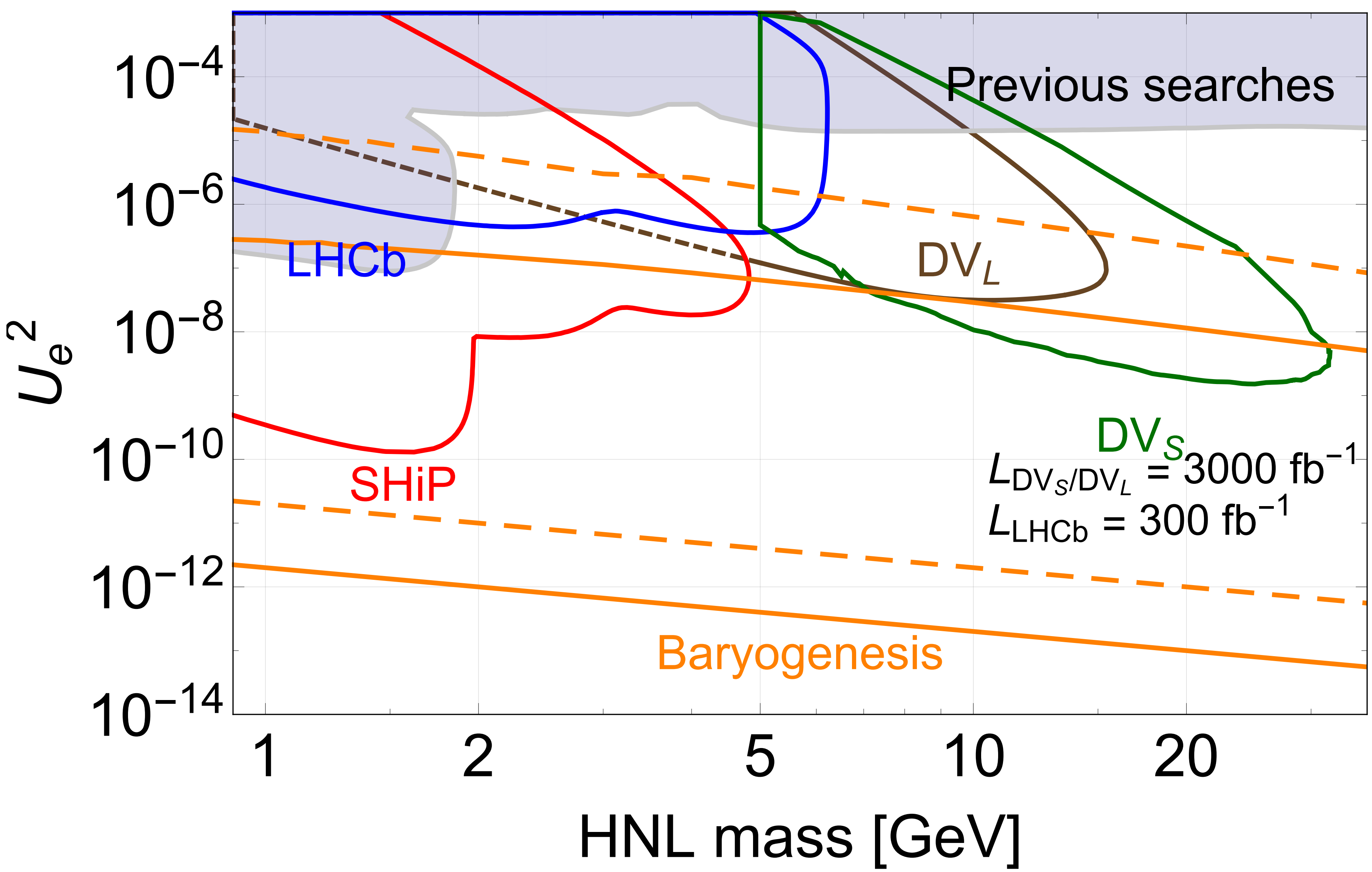
1902.04535



Current luminosity

High intensity experiments and LHC: Synergy

1902.04535



HL LHC

Useful links

- HNL production and decay formulas: 1805.08567
- An open source package to calculate HNL decays: https://github.com/f-thiele/cHNLdecay
- An example of a search at fixed target experiments: 1811.00930
- Most recent BAU limits, mixings compatible with see-saw: 1808.10833
- Helicity effects in beam-dump experiments: 1905.00284 and Tastet&IT (coming soon)

Conclusions

- HNLs appear in many models
- High-intensity frontier accelerator experiments are ideal for HNL searches
- The freedom in mixings is limited if one wants to explain active neutrino data with two HNLs
- It is limited further if one wants to explain BAU


Thank you!