Nu mass and the origin of baryons

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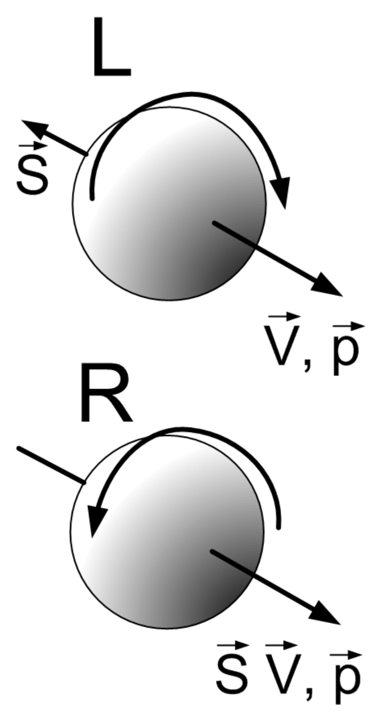
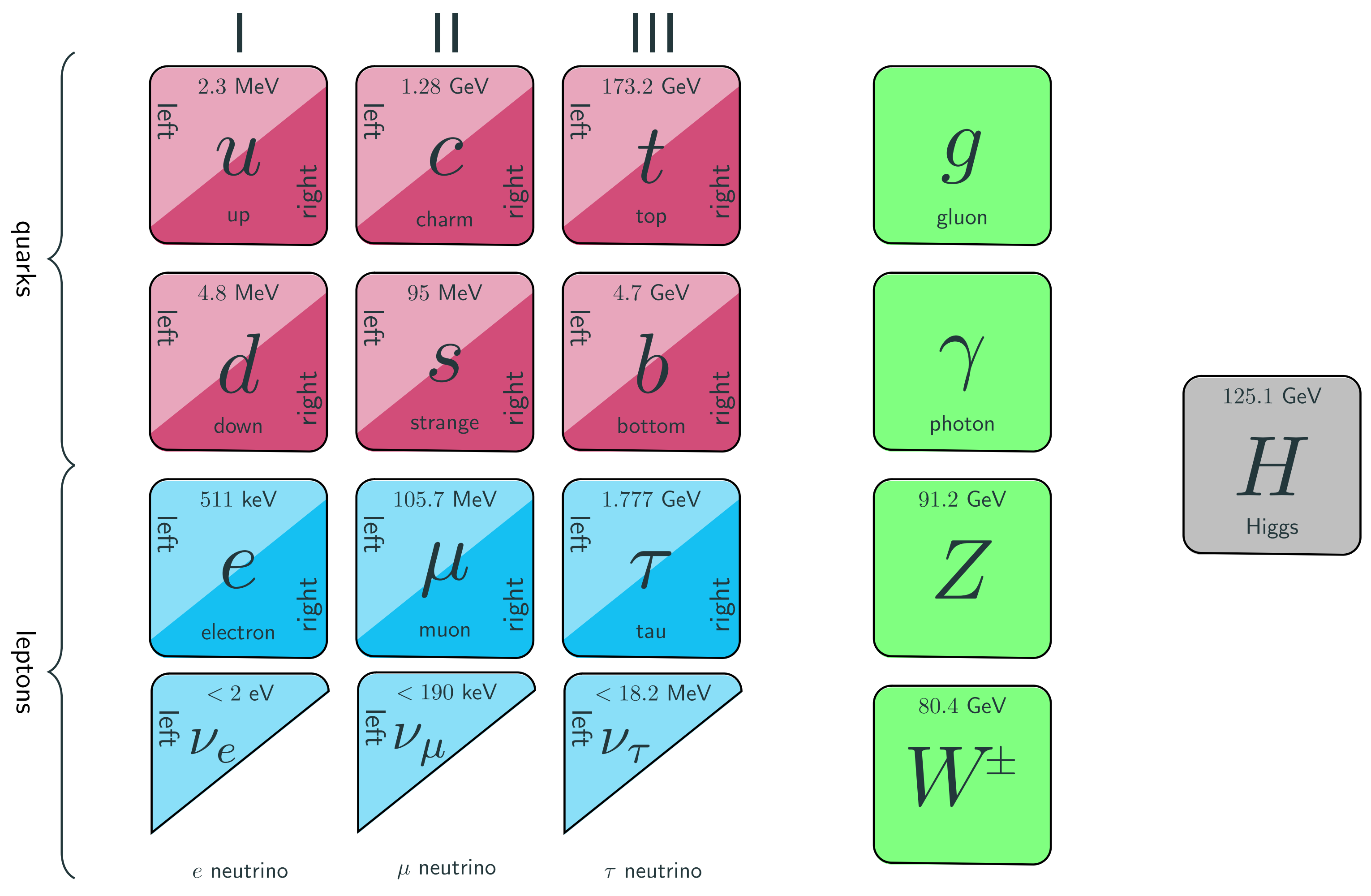
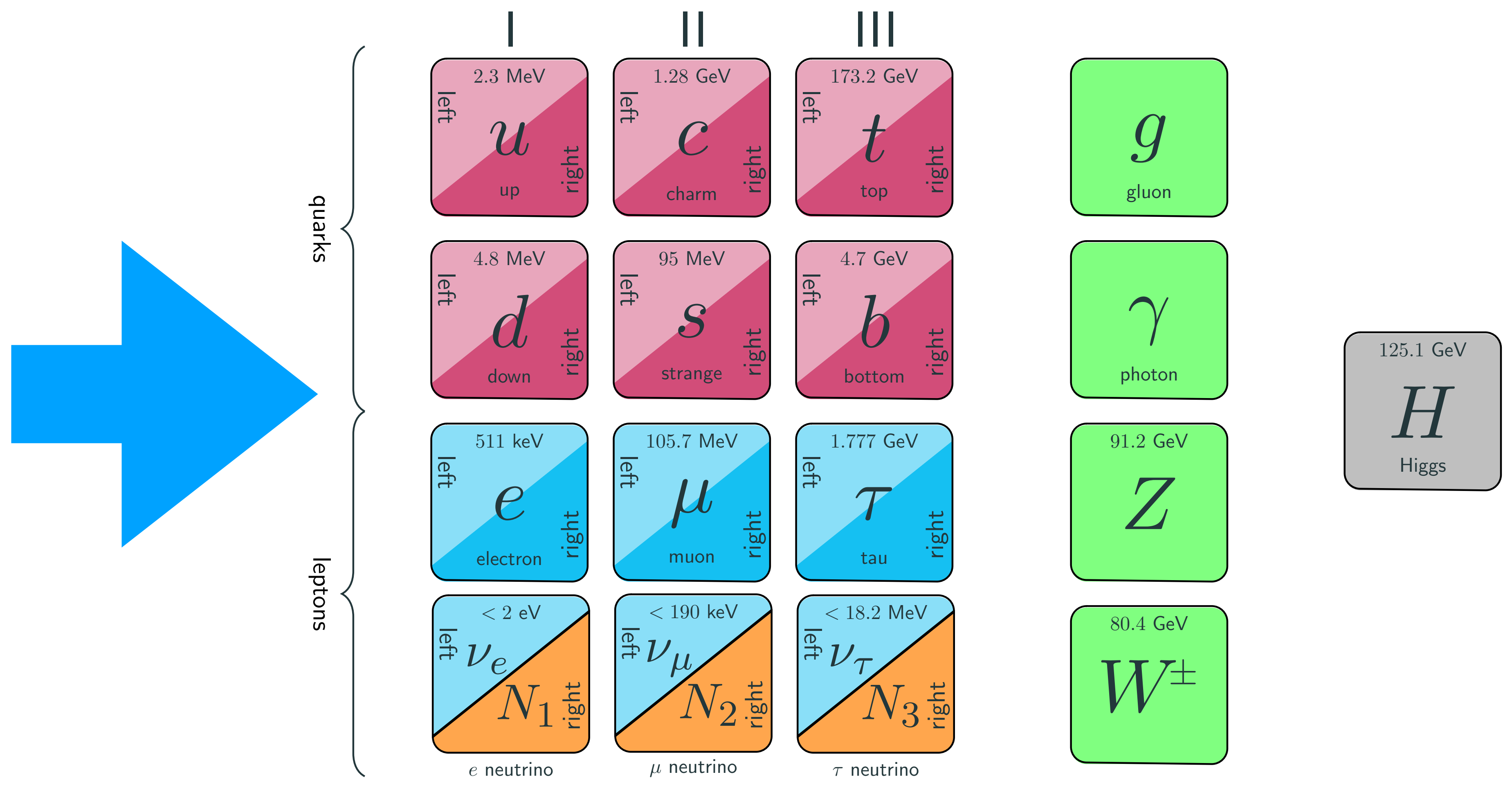
Neutrinos and new physics

- Neutrinos have masses and oscillate. This is not included in the canonical Standard Model
- The simplest and most economic renormalisable extension of the SM allowing to describe these phenomena is that with two Right-Handed (RH) neutrinos.
- Two RH neutrinos can explain two observed mass differences, solar and atmospheric.
- The theory with three RH neutrinos looks even more attractive, as we have three generations of fermions.





The Standard Model



The νMSM,
or minimal type I see-saw model

Neutrinos and new physics

There are two options to be in accordance with neutrino physics:

- Only lepton-number conserving Dirac masses due to interaction with the Higgs boson

- Lepton-number conserving Dirac masses due to interaction with the Higgs boson and Majorana RH neutrino masses, allowed by the gauge symmetries of the SM. “Type I” see-saw formula is valid.
  Extra benefits, not possible with Dirac neutrino masses:

  - explanation of the Baryon Asymmetry of the Universe: origin of baryons

  - explanation of the Dark Matter in the Universe

Revealing the origin of baryons

Step 1: define the theory

Standard Model

Higgs field

HNL Majorana mass

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

HNL kinetic term

HNL Yukawa couplings,
leading to Dirac mass

New states: right-handed neutrinos, sterile neutrinos, Majorana fermions, heavy neutral leptons - HNLs.

Revealing the origin of baryons

The minimal choice: 2 HNLs - all neutrino physics is explained

One extra HNL can be “reserved” for the explanation of Dark Matter in the Universe. It has very small Yukawa couplings (for stability at the cosmological times) and effectively decouples from ordinary neutrinos. Prediction of the scale of active neutrino masses - one of them is nearly massless.

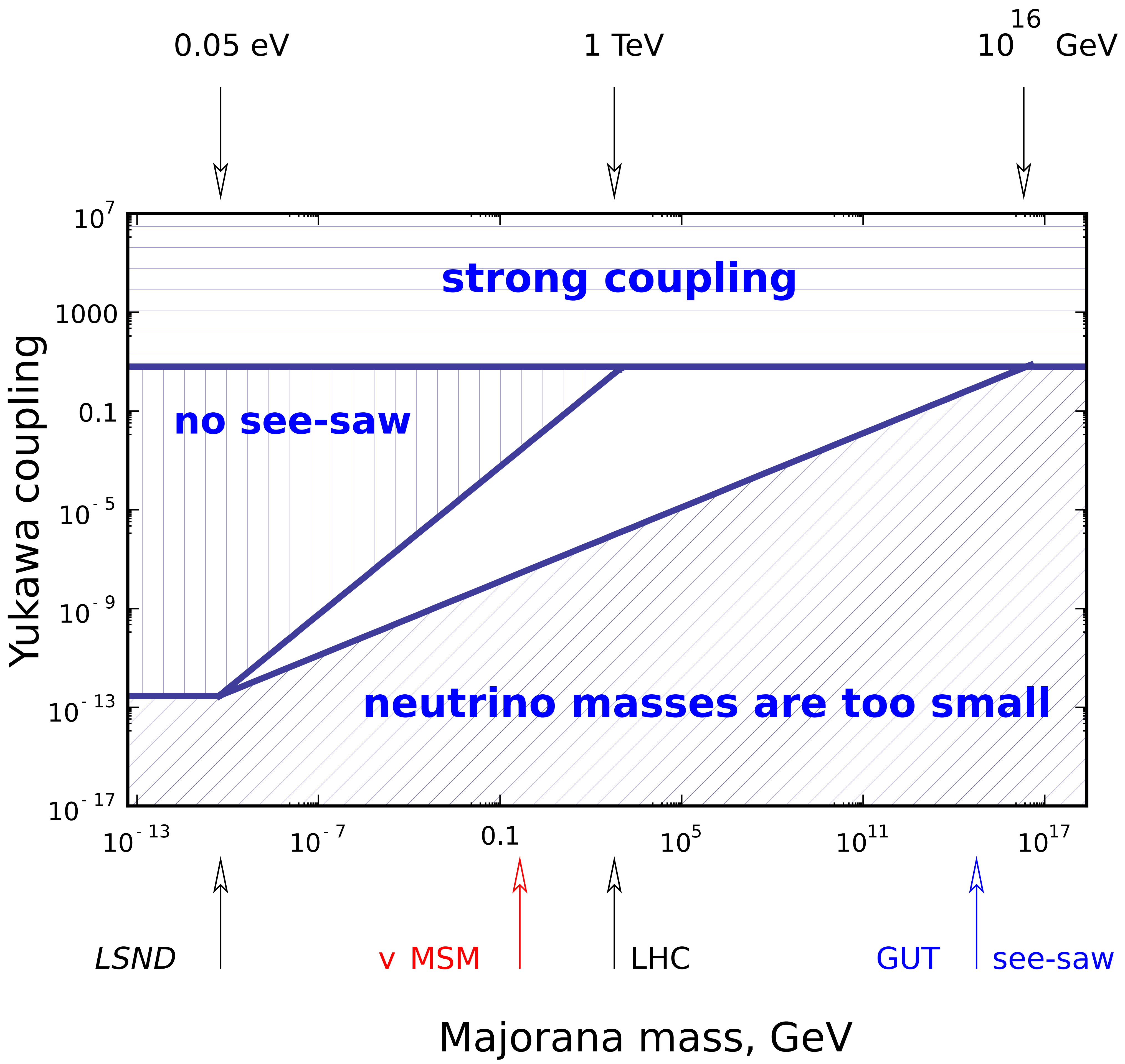
Step 2: count the parameters

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.

5 of these parameters (2 neutrino masses, 3 mixing angles) are already known from neutrino experiments. 1 Dirac phase and 1 Majorana phase in the PMNS matrix are not known yet.

HNL masses M and Yukawa couplings F from neutrino physics:

Scale F as x, and M as x^2, low energy neutrino physics is not changed!



Revealing the origin of baryons

Step 3: check Sakharov conditions for baryogenesis

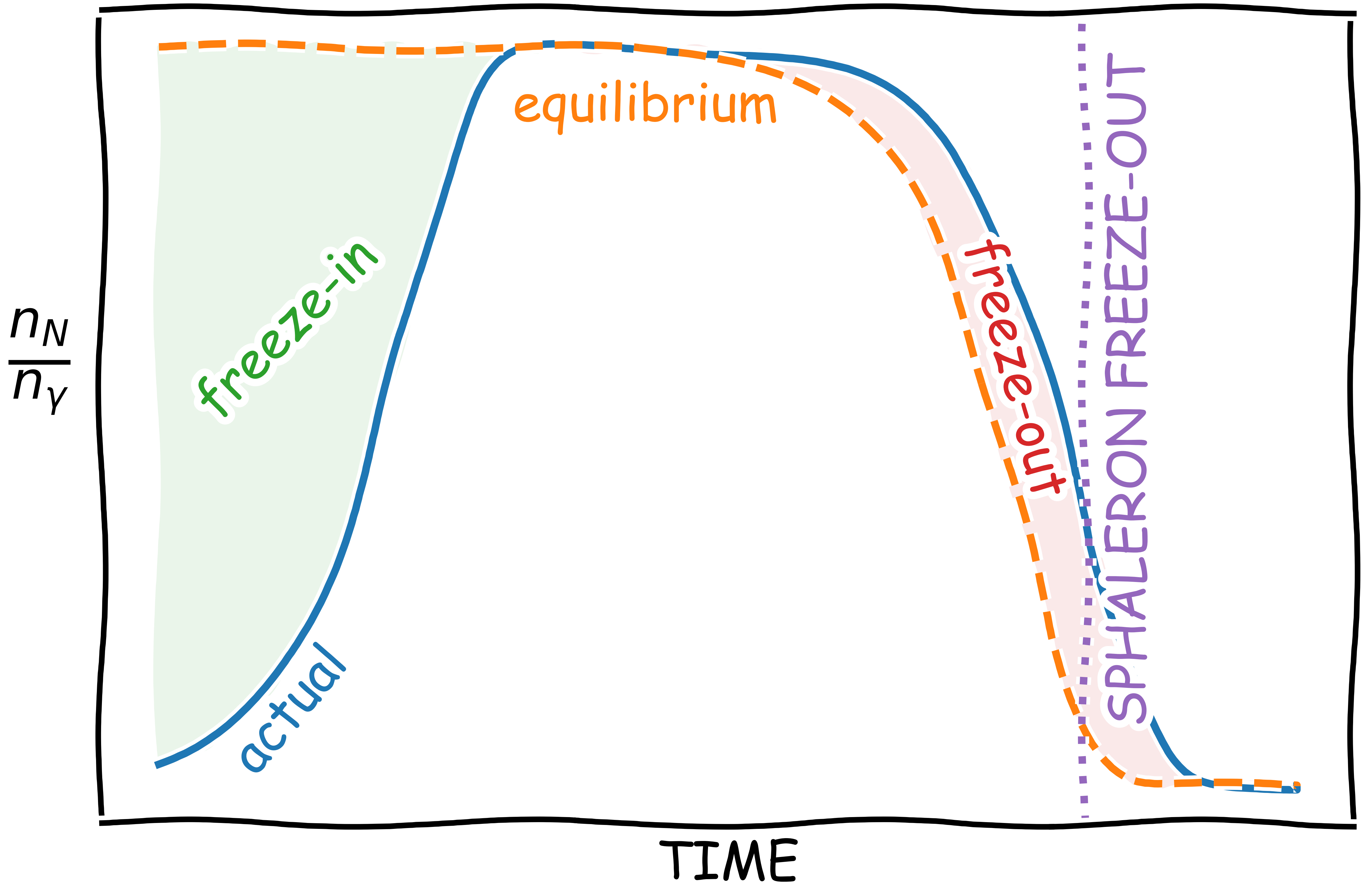
- Baryon number non-conservation - OK, due to anomalous fermion number non-conservation, already present in the SM. Sphalerons may convert lepton asymmetry into baryon asymmetry. In addition, lepton number is not conserved due to Majorana HNL masses.

- CP - violation - OK, we have 3 additional CP-violating phases leading to difference between matter and antimatter.

- Deviations from thermal equilibrium - OK, HNLs may freeze-in and freeze-out.

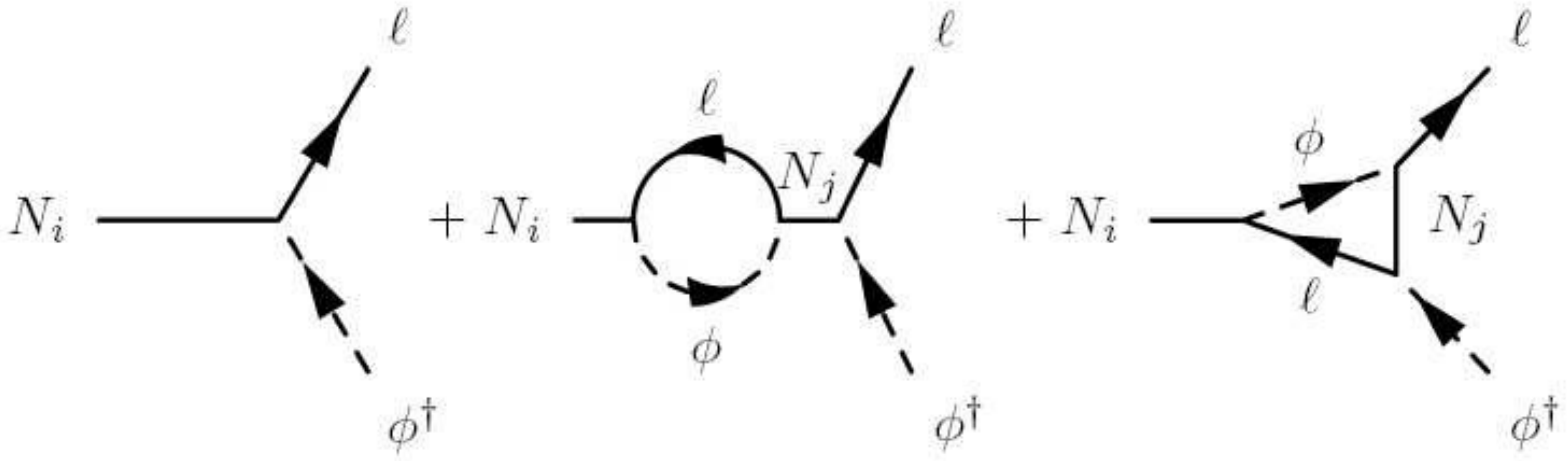
Step 4: make a computation of baryon asymmetry

See-Saw freeze-out leptogenesis



The mechanism: leptogenesis with superheavy Majorana neutrinos:

HNLs go out of thermal equilibrium, decay, and produce lepton asymmetry. 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.

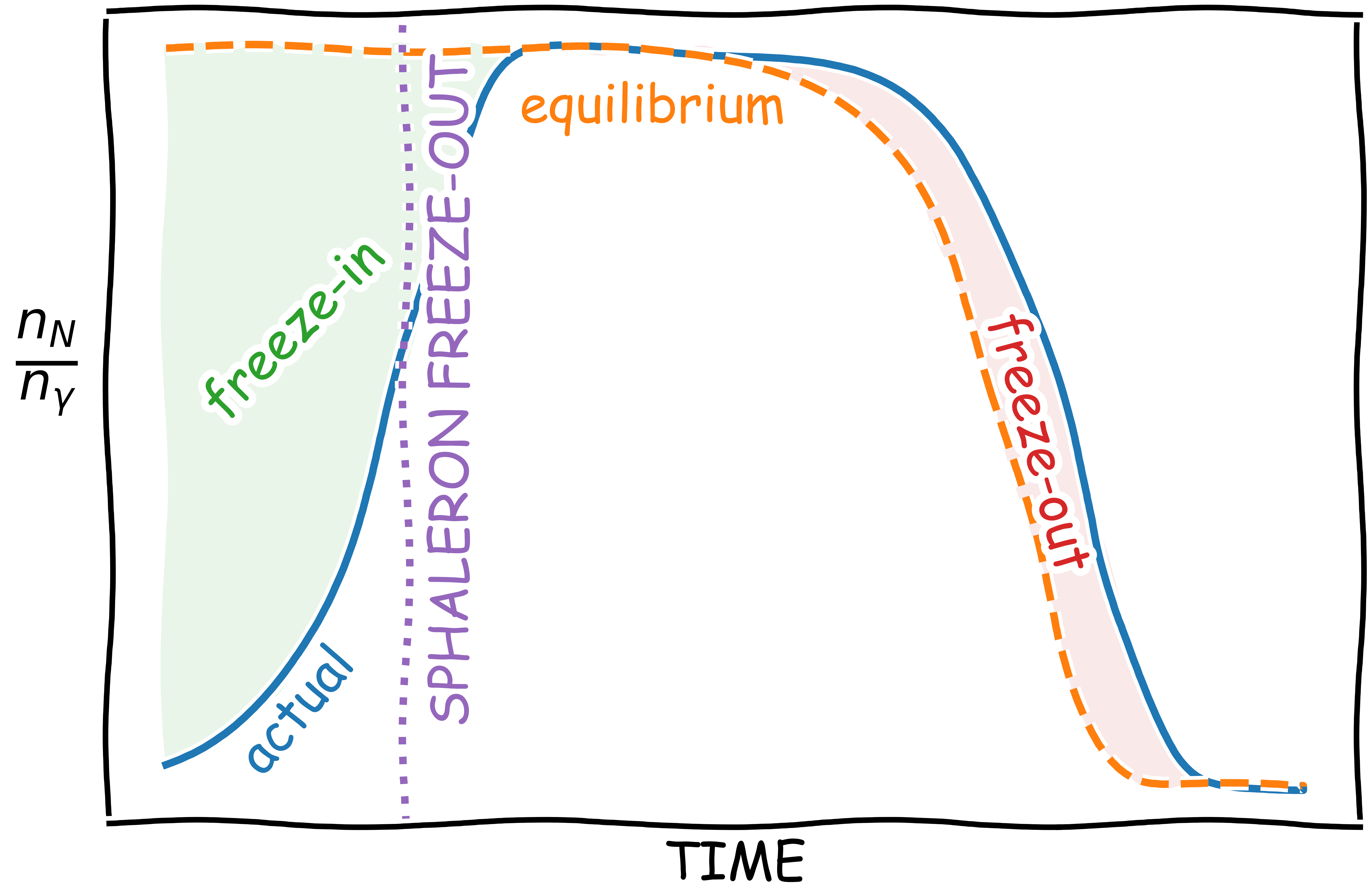


Initial idea: Fukugita, Yanagida, '86

Countless papers on different types of leptogenesis: thermal, non-thermal, Dirac, Resonant, Tri-resonant, flavoured, soft,…

Step 4: make a computation of baryon asymmetry

Low scale freeze-in leptogenesis



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 νMSM can explain simultaneously neutrino masses, dark matter, and baryon asymmetry of the Universe: Asaka, M.S. '05

Analysis of baryon asymmetry generation in the νMSM: 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; Granelli, Pascoli, Petcov, …

Step 4: make a computation of baryon asymmetry

Uniting Leptogeneses

Klaric, MS, Timiryasov 2020, Phys. Rev. Lett. 127 (2021) 11

Both mechanisms (freeze-in and freeze-out) are described by the same kinetic equations and allow for systematic study without any simplifying assumptions.

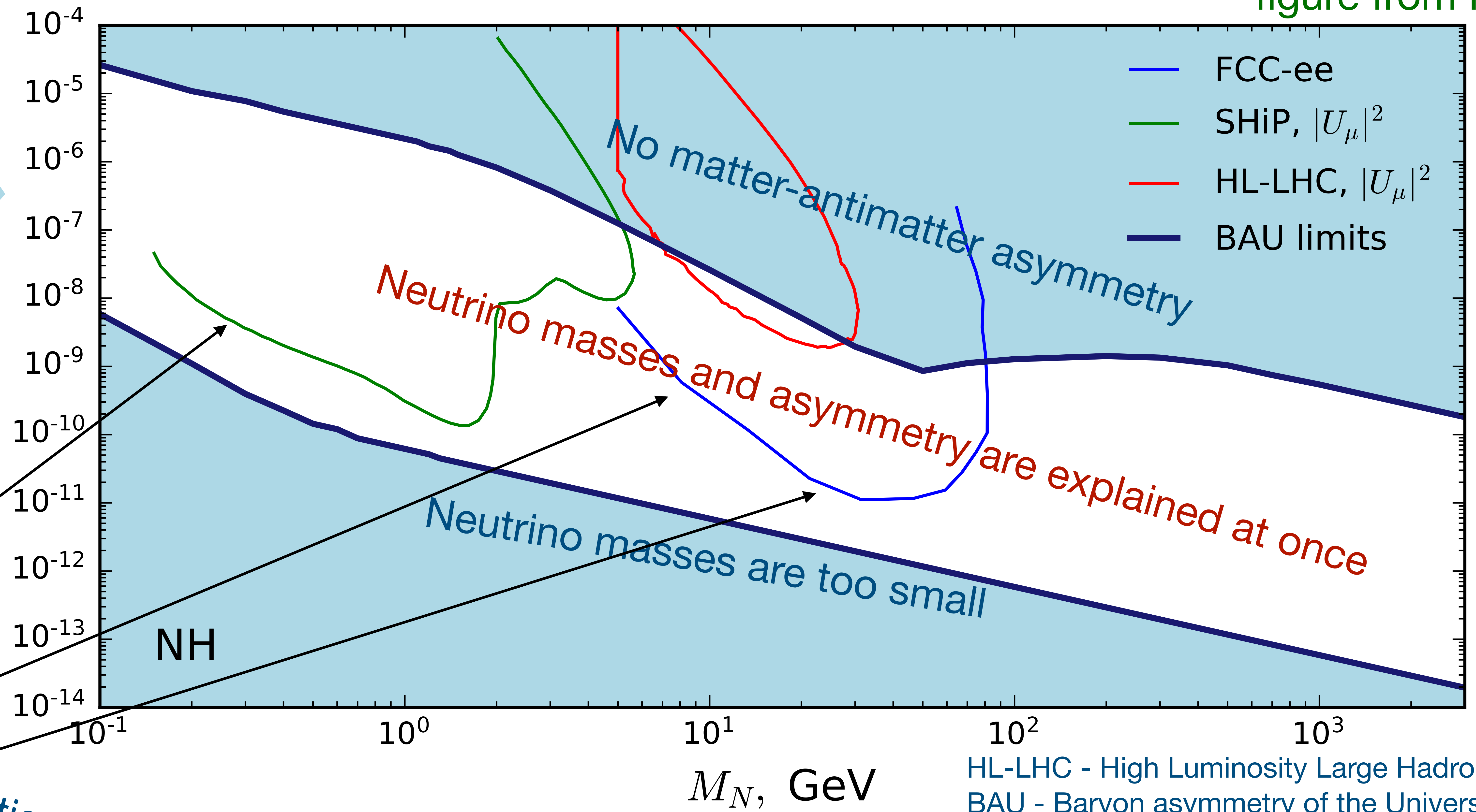
Main result: the freeze-in and freeze-out domains are actually connected, there is just one combined region where baryogenesis can happen.

Step 5: extract characteristics of HNLs relevant for their experimental search

Matter-antimatter asymmetry and neutrino masses in the νMSM: $N_{2,3}$

figure from Klaric, Timiryasov, MS

Strength in comparison with weak interaction interactions



Experimental sensitivities

HL-LHC - High Luminosity Large Hadron Collider
BAU - Baryon asymmetry of the Universe
NH - normal neutrino hierarchy

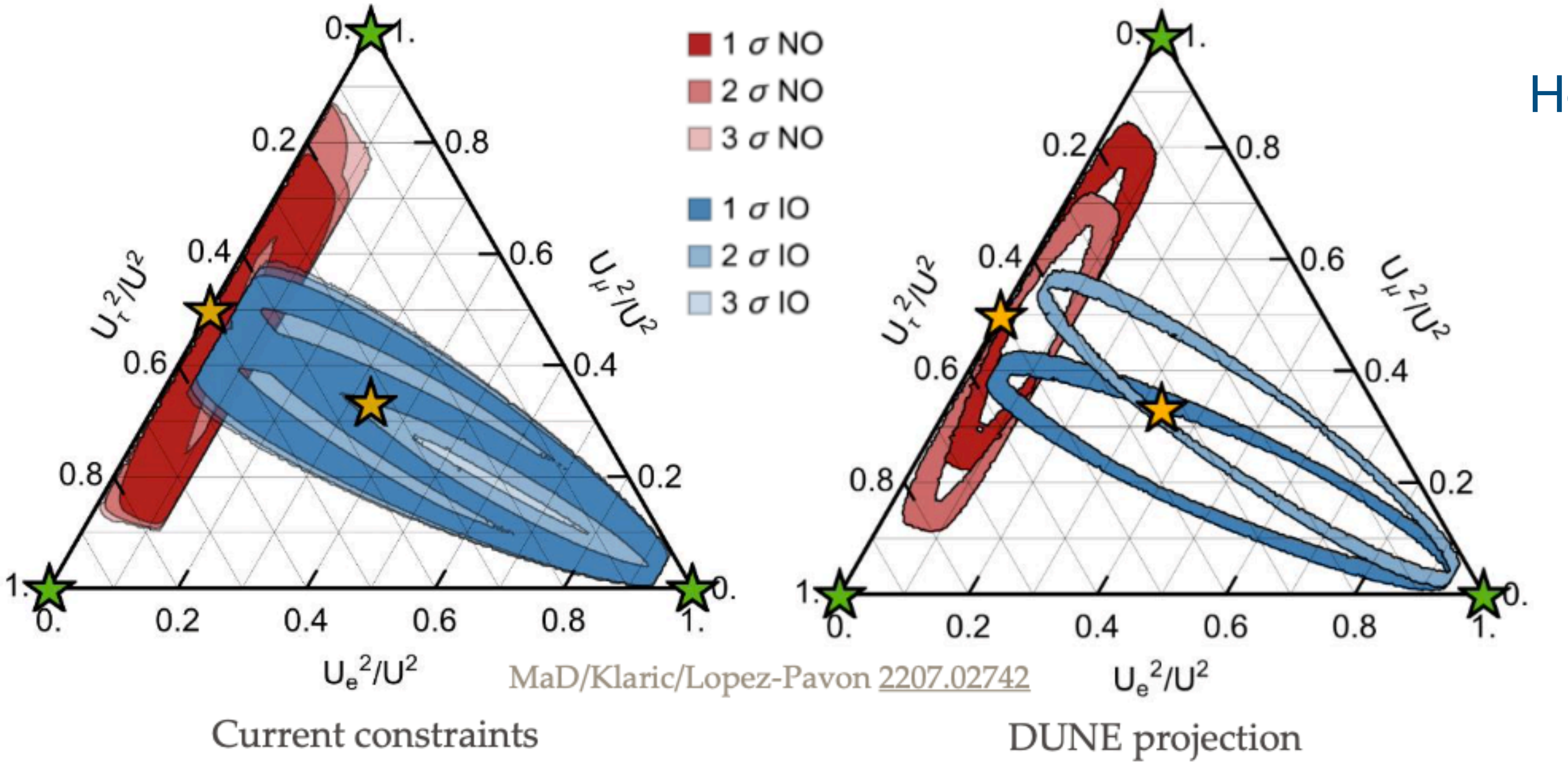
Consensus between computations of different groups

The mechanisms of neutrino mass and matter-antimatter asymmetry generation can be verified experimentally if HNL masses are below Z-mass

Testable model

Total number of parameters: 11, with 5 already known from neutrino experiments, 6 unknowns.
Number of future inputs (ν experiments, SHiP and FCC-ee) is at least 6:

- Dirac phase in PMNS matrix (1), neutrinoless double β-decay rate (1), HNL average mass $\bar{M} = (M_2 + M_3)/2$ (1), HNL mixings with e, μ and τ flavours (3)
- Very challenging measurements: HNL mass difference $\Delta M = M_2 - M_3$ is required to be small from baryogenesis, $\Delta M/\bar{M} \lesssim 0.01$ (1), CP-violation in HNL decays (1)



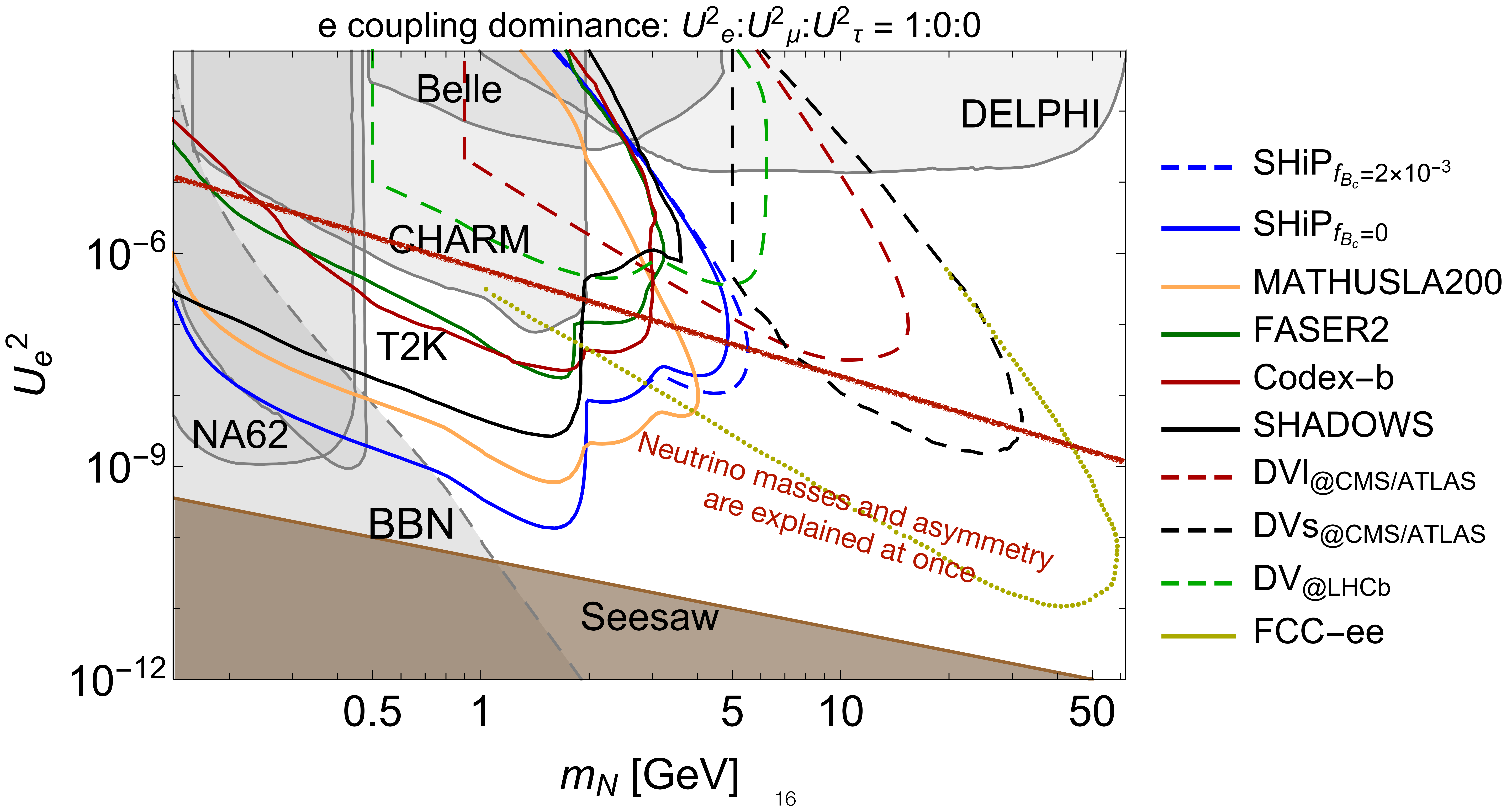
Hernández et al, 1606.06719

Experimental challenges of HNL searches:

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

- Mass below ~ 3 GeV - Intensity frontier, CERN SPS: SHiP
- Mass above ~ 3 GeV - FCC, CEPC in e+e– mode in Z-peak, LHC

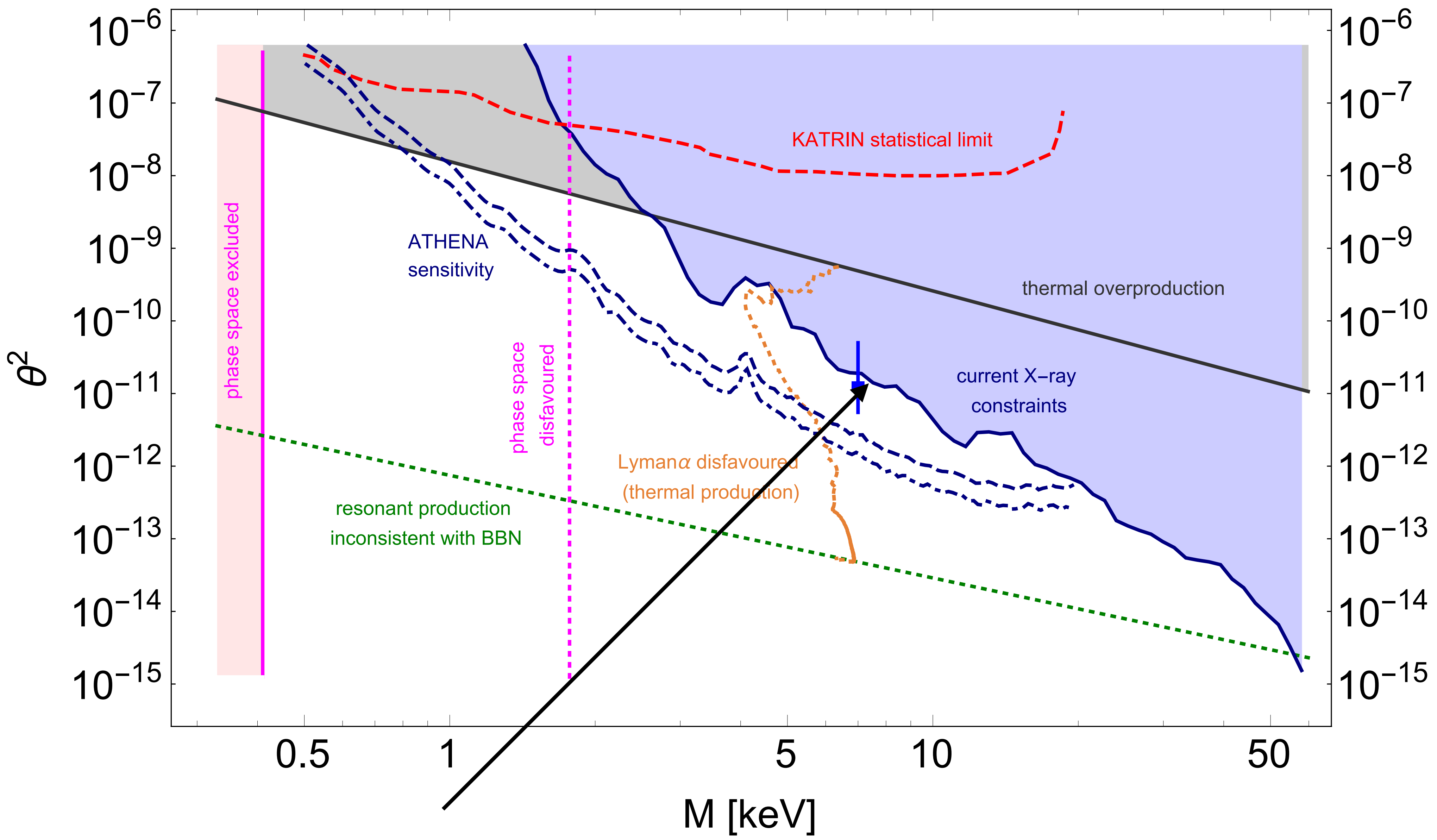
Projection of bounds on HNLs



Dark Matter in the νMSM: N_1

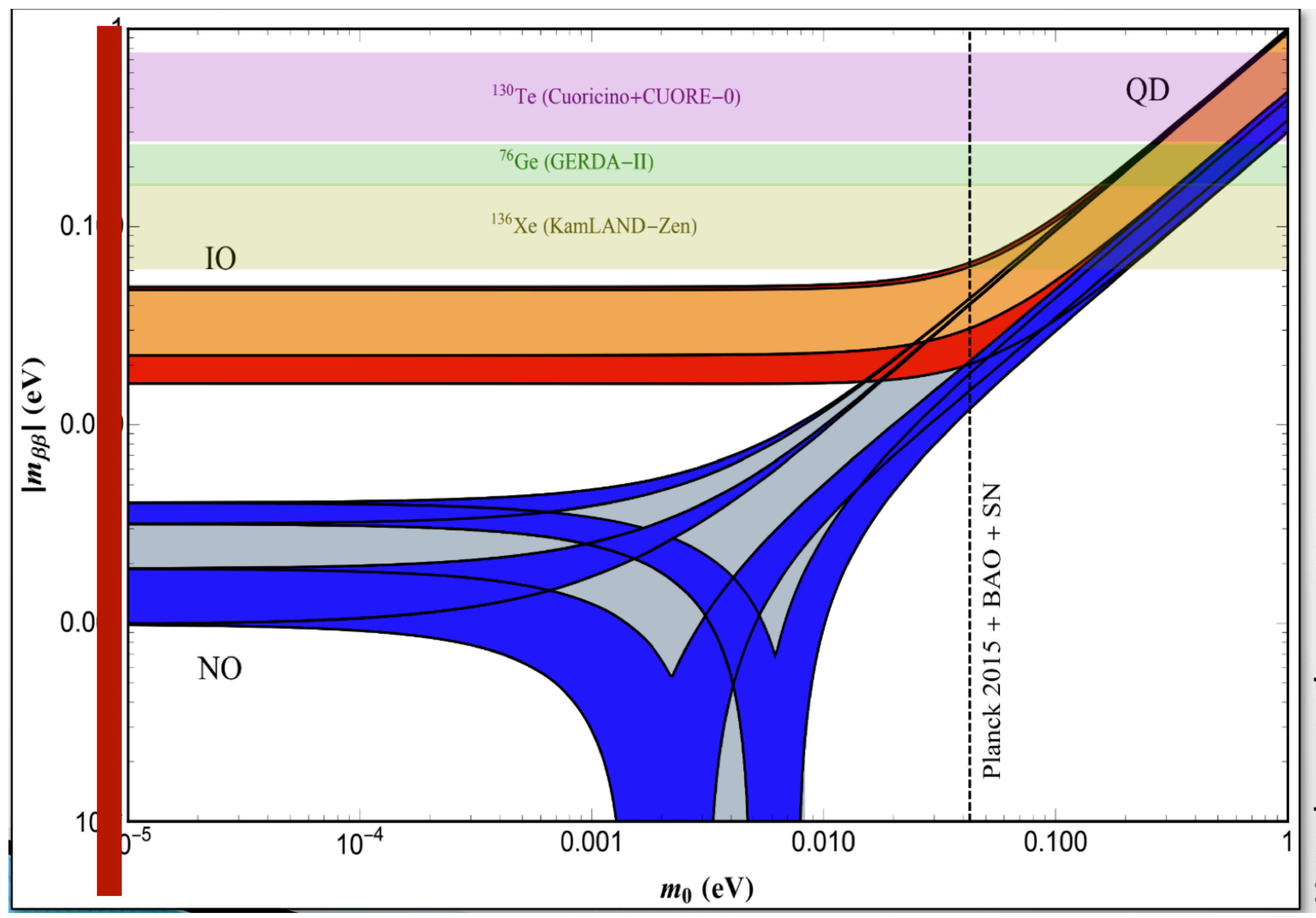
Dark matter sterile neutrino N_1: long-lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N_1 \to \gamma\nu$, what allows for experimental detection by X-ray telescopes in space. Future experimental searches: Hitomi-like satellite XRISM (2023), Large ESA X-ray mission, Athena + (2028?)

Available parameter space, current situation



Possible detection (?), controversial
Bulbul et al; Boyarsky et al

Prediction for neutrinoless double beta decay:



Hagedorn et al., Int.J.Mod.Phys.A 33 (2018) 05n06, 1842006

Prediction from Dark Matter:
minimal neutrino mass $< 10^{-5}$ eV

Important remarks

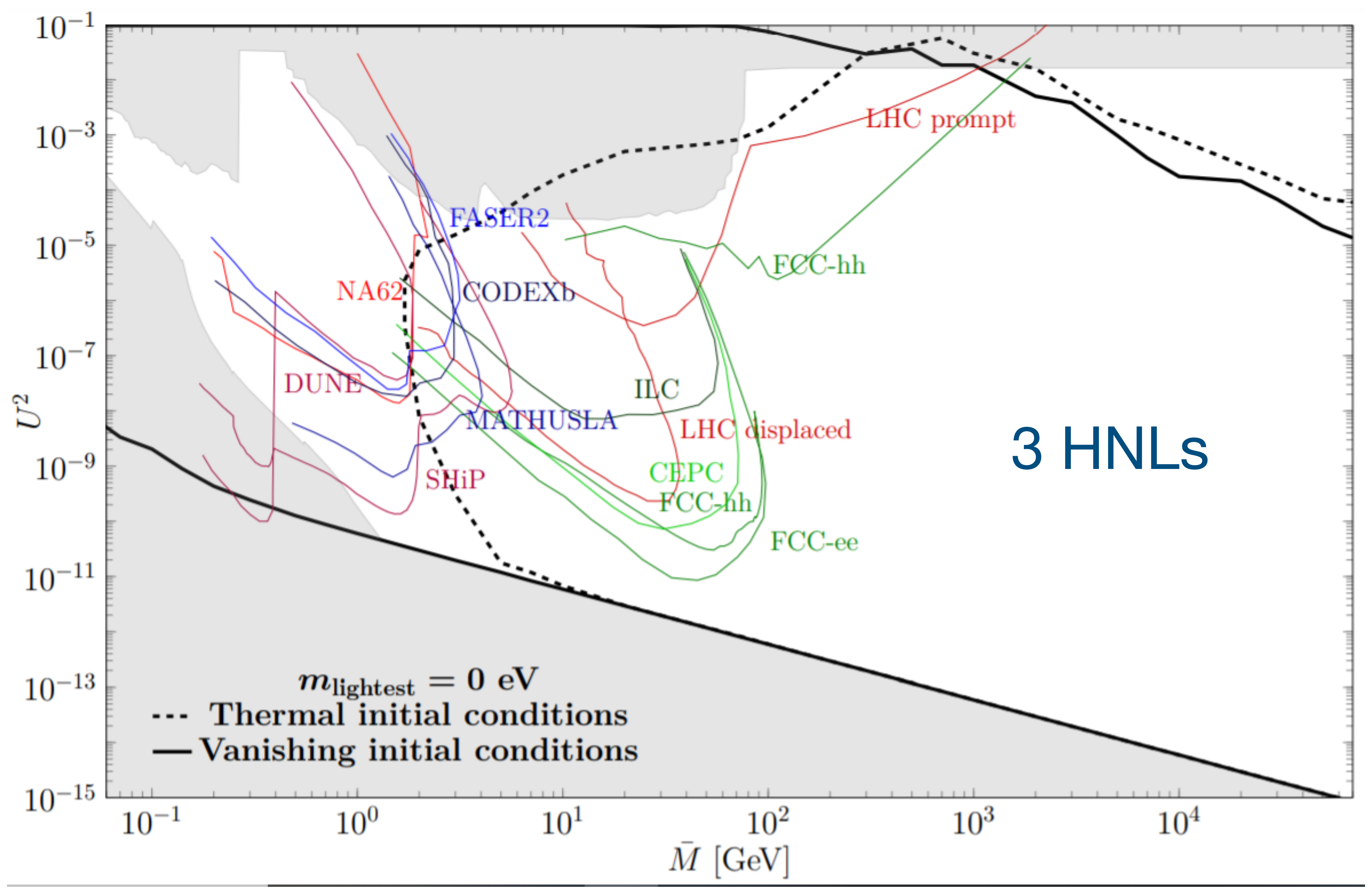
Many other extensions of the SM are possible and under intensive investigations:

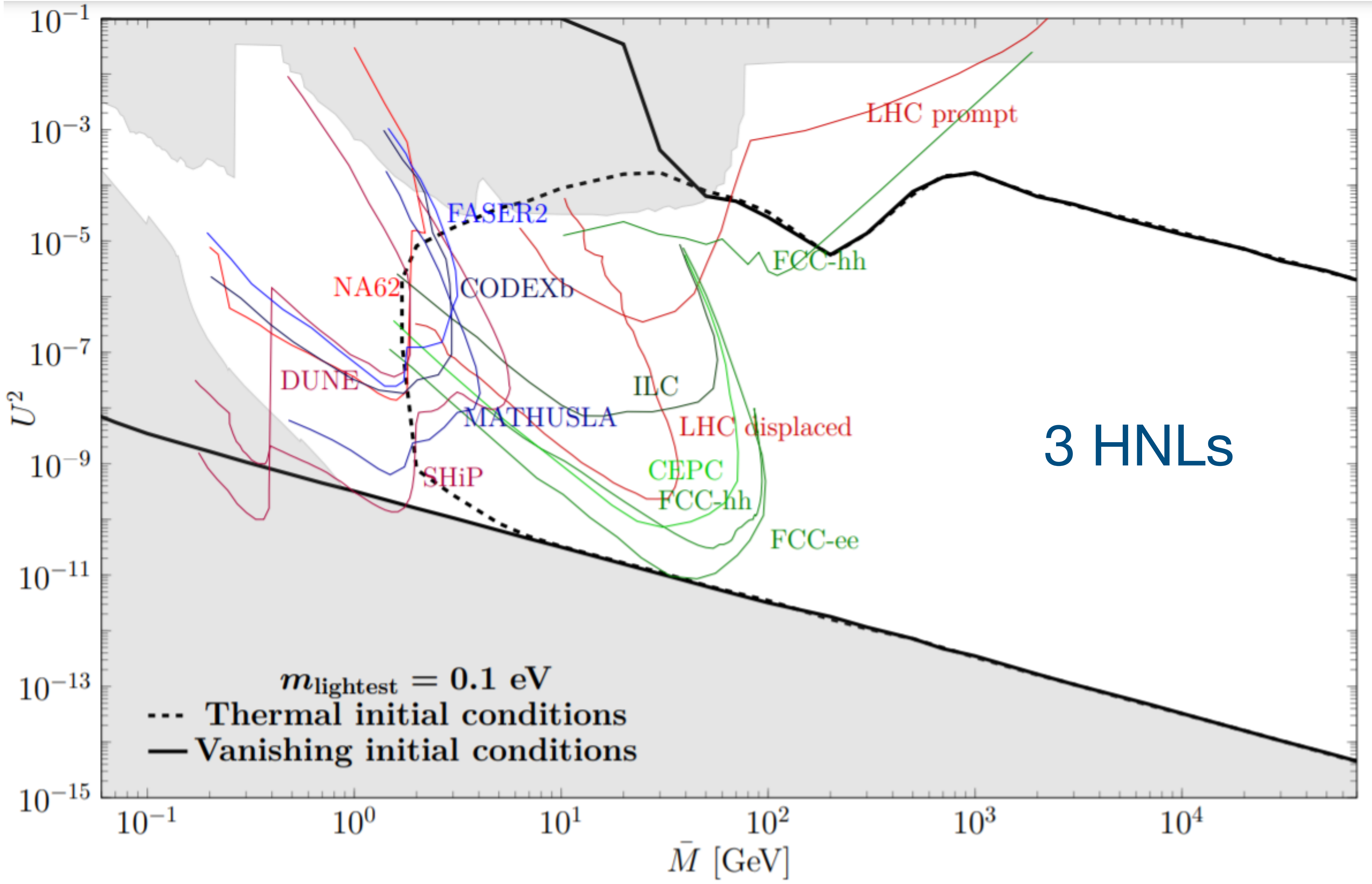
- All three HNLs participate in baryogenesis and neutrino mass generation, DM particle is something else
- Extensions of the SM in the Higgs sector, “type II” and “type III” see-saw
- Left-Right symmetric models
- Theories with spontaneous breaking of lepton number, Majorons
- Grand Unified theories

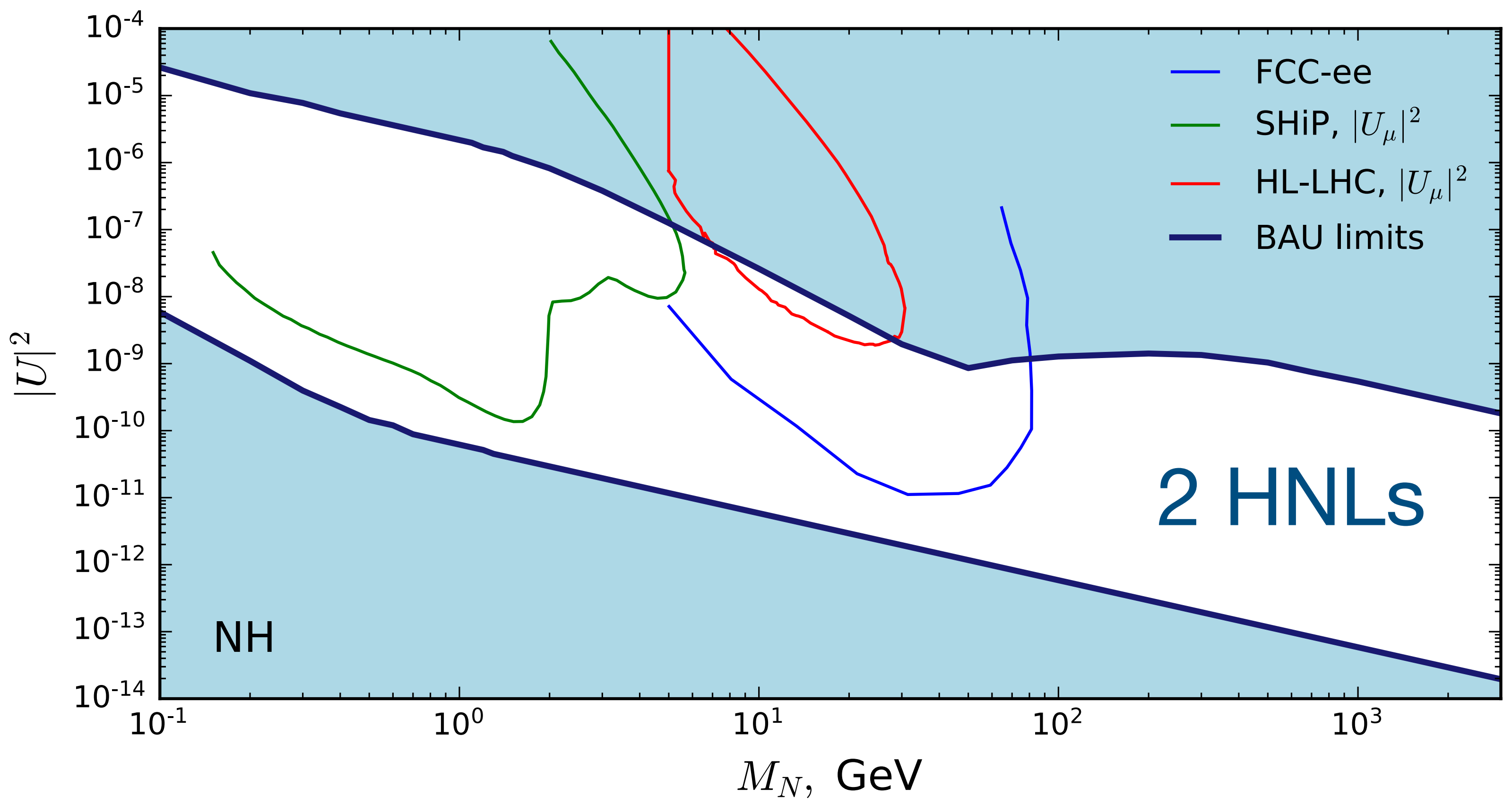
In most cases, they contain more parameters and are less predictive

Parameter space for 3 HNLs

Drewes, Georis, Klaric: much more space is available







Conclusions

Exciting future ahead:

- the neutrino experiments may pin down the Dirac phase and the hierarchy pattern of neutrino masses

- neutrinoless β decay may establish the nature of neutrino masses and provide indispensable information for underlying theory

Traditional goals of neutrino physics should be supplemented by the HNL searches

- masses below few GeV - SHiP, selected at CERN in March 2024, data taking in 2031
- masses above few GeV - FCC-ee or CEPC in the Z-resonance mode
- Dark matter sterile neutrino - X-ray telescopes in space

These cross-frontier efforts may lead to establishing a theory superseding the Standard Model and explaining all observed neutrino phenomena together with baryon asymmetry of the Universe and Dark Matter

Back up slides

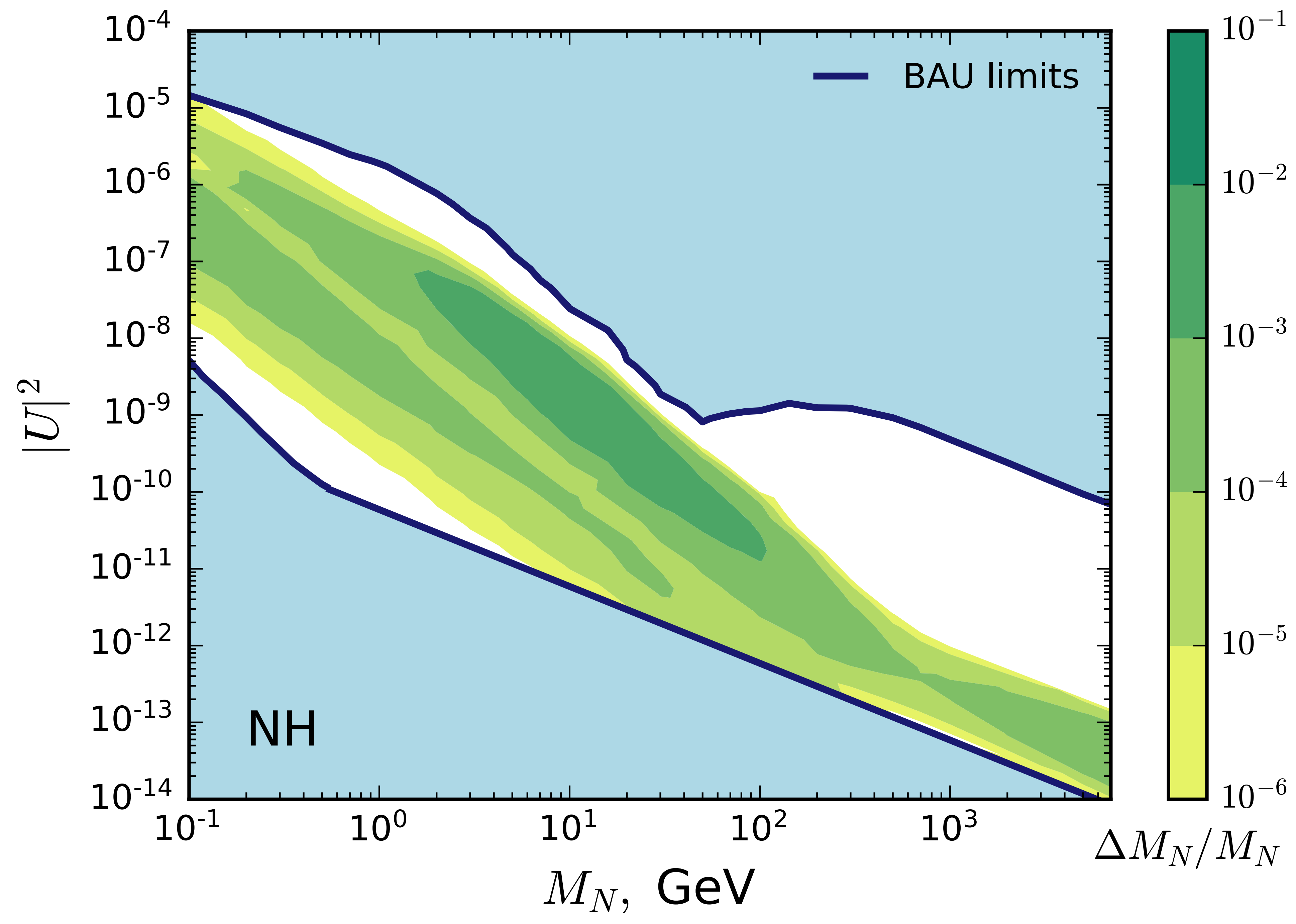
Counting parameters of low energy theory:

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

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. Minimal choice: all neutrino physics explained.

Number of parameters in effective theory is smaller than the number of parameters in complete theory - we should discover HNLs experimentally to understand completely BSM physics!

Uniting Leptogeneses



- "Freeze-in" leptogenesis: take zero initial conditions for HNL densities and neglect deviations from thermal equilibrium induced by the HNL mass
- "Freeze-out" leptogenesis: take equilibrium initial conditions for HNL densities

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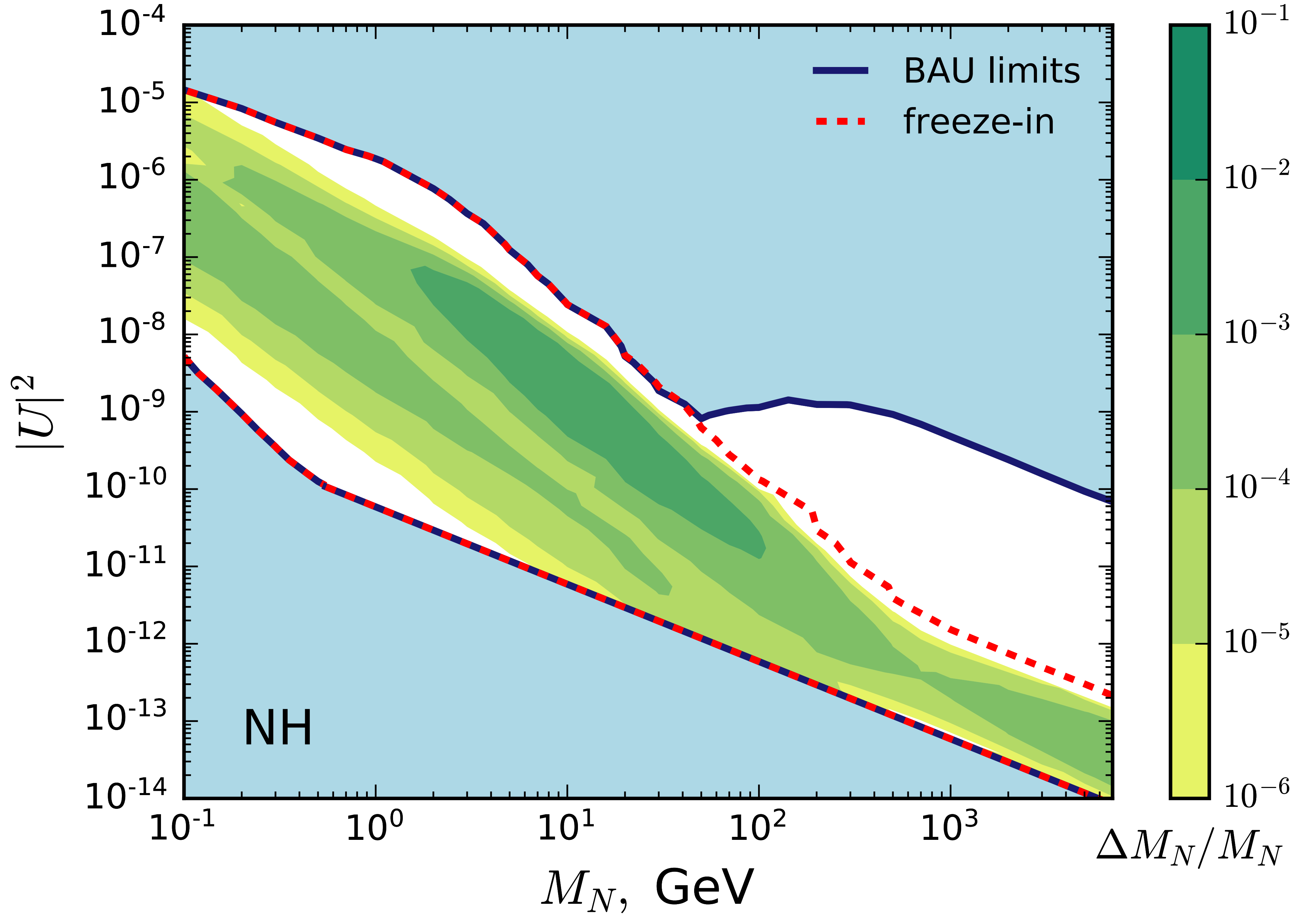

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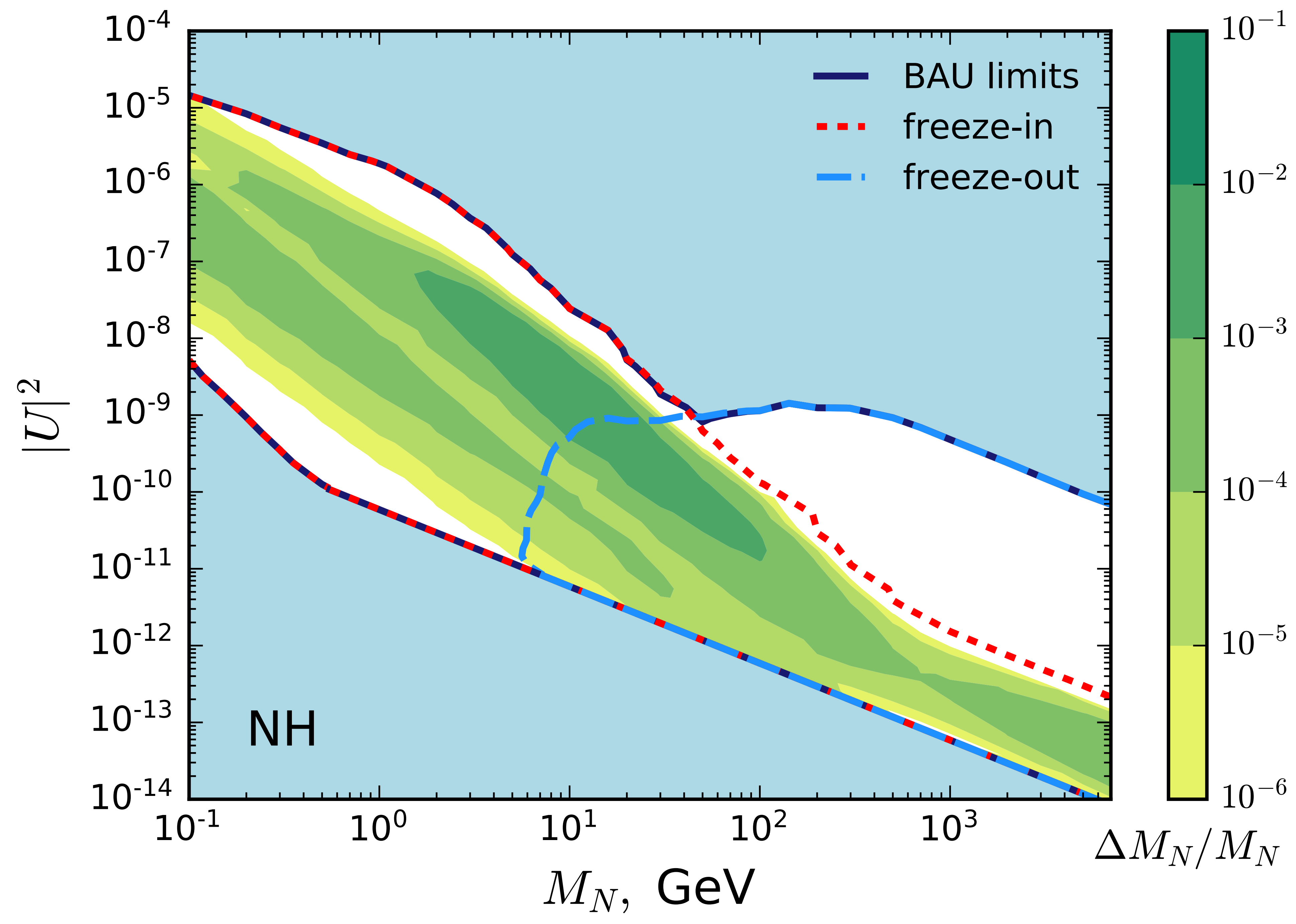

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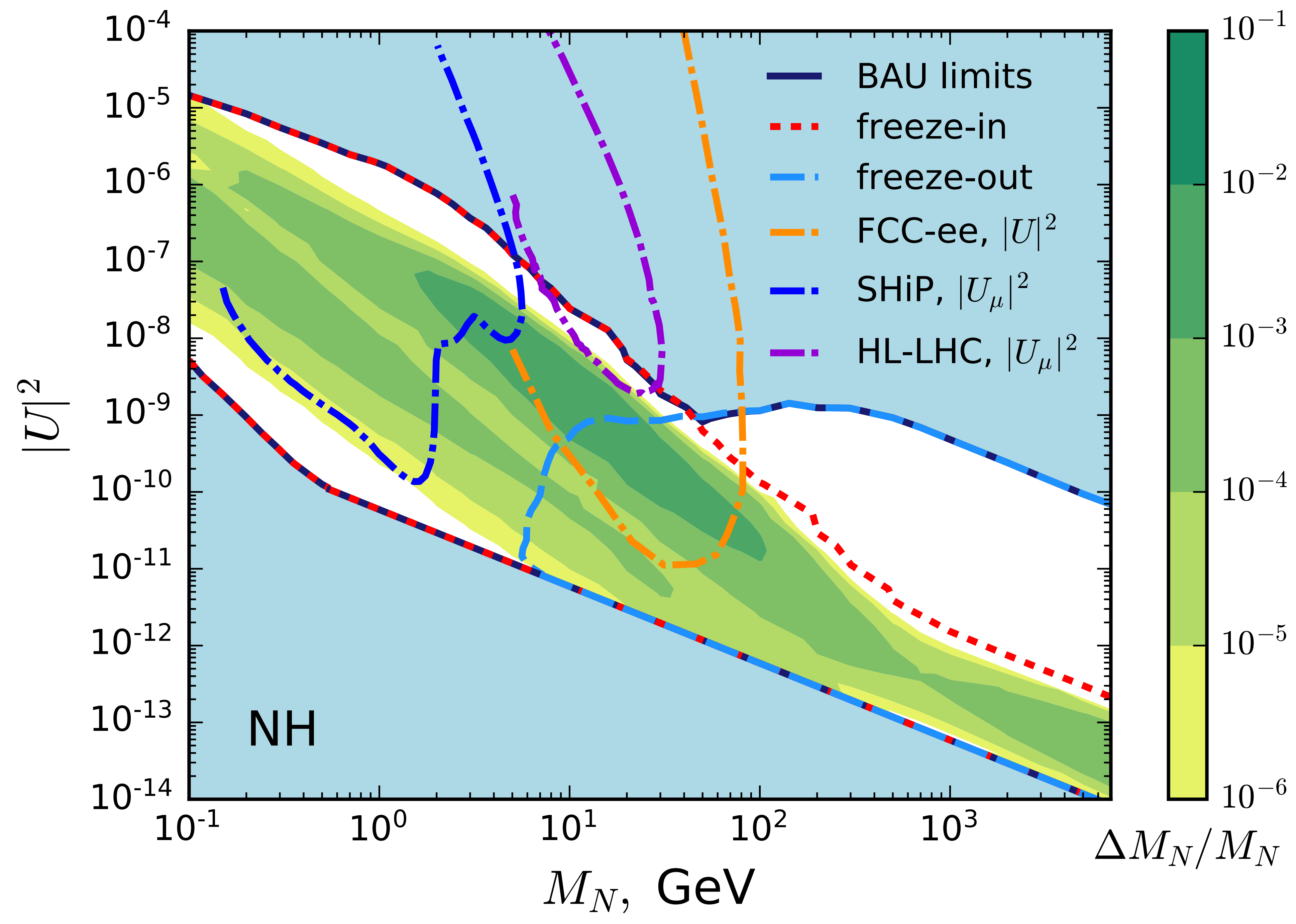

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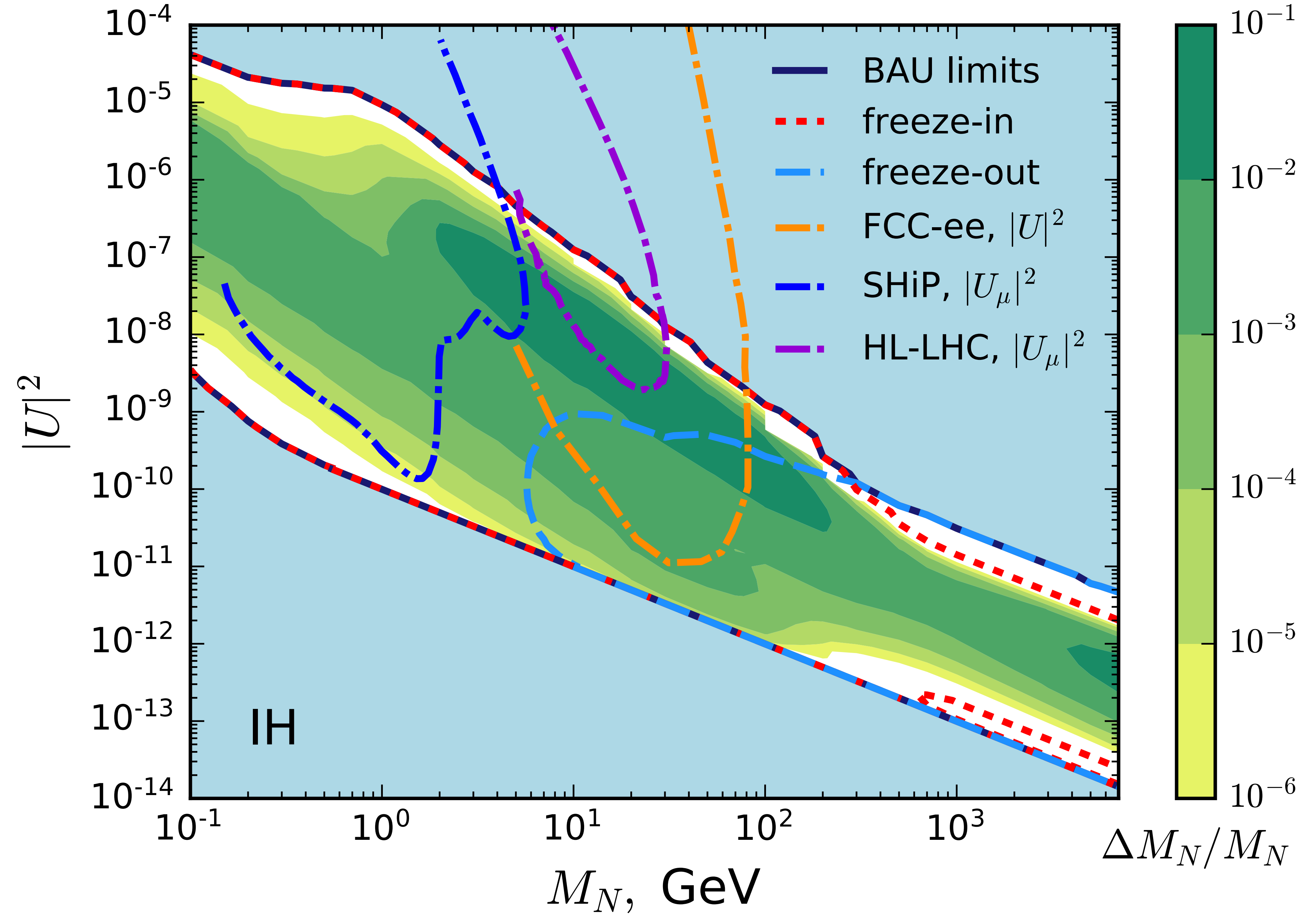

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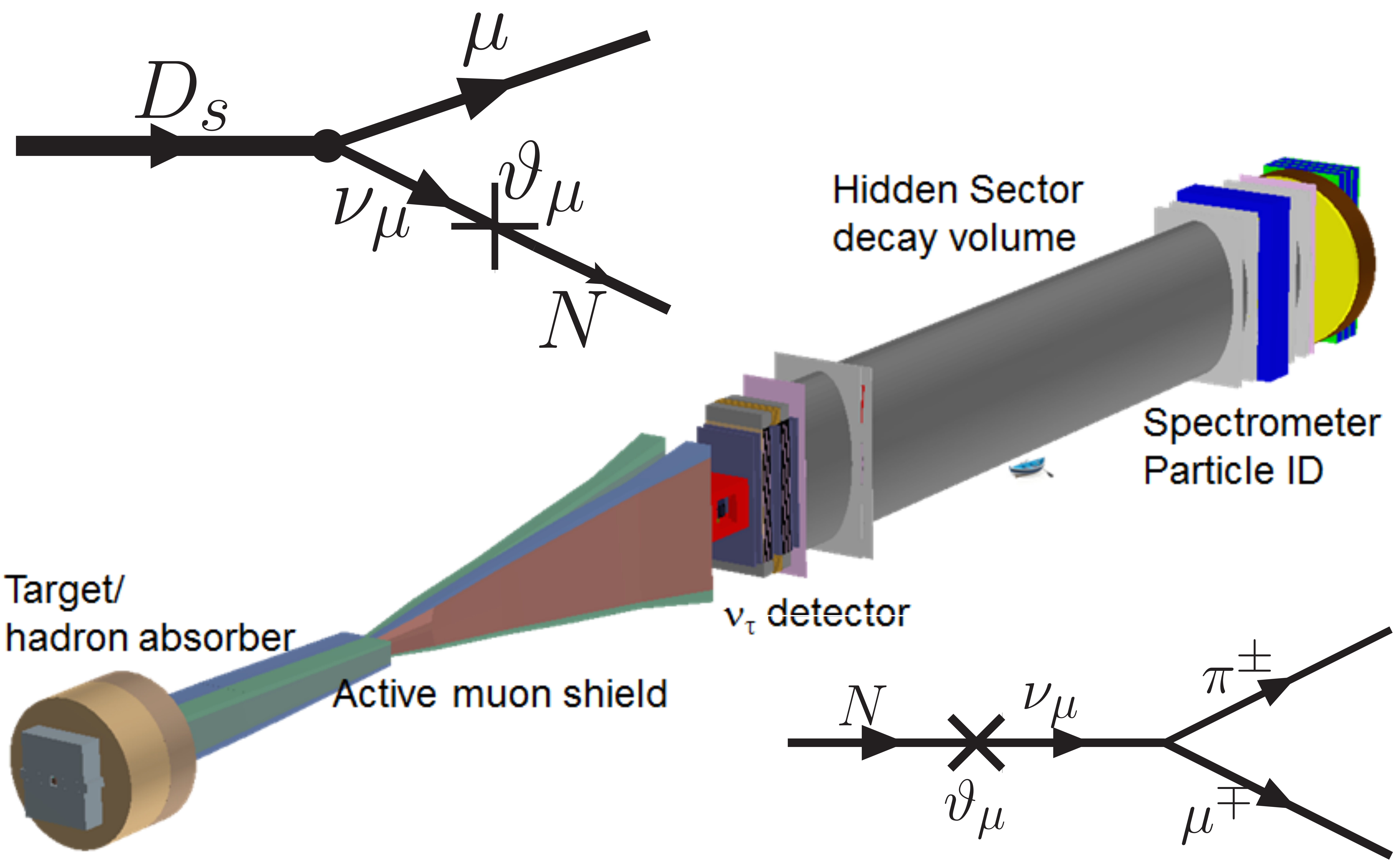
SHiP experiment



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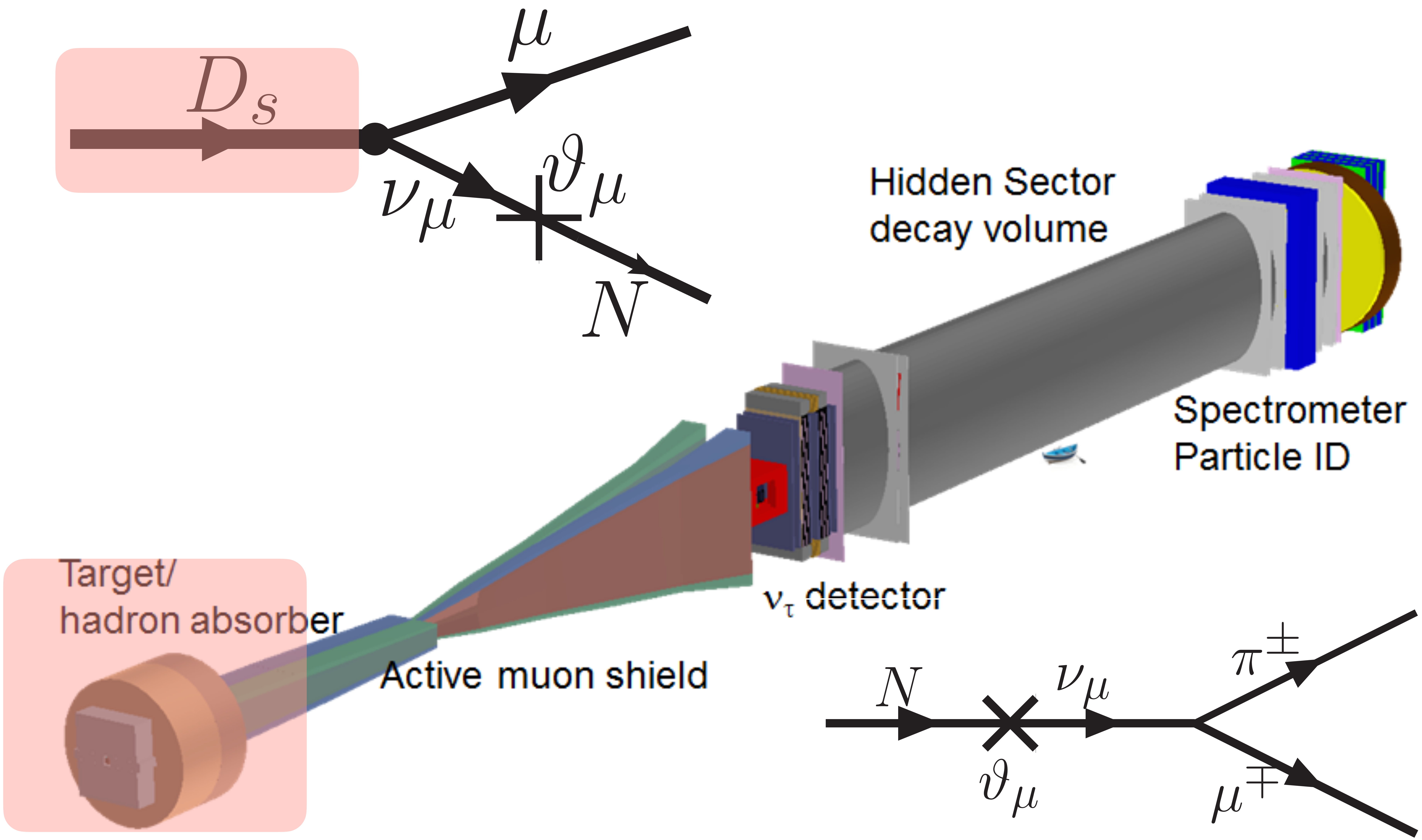

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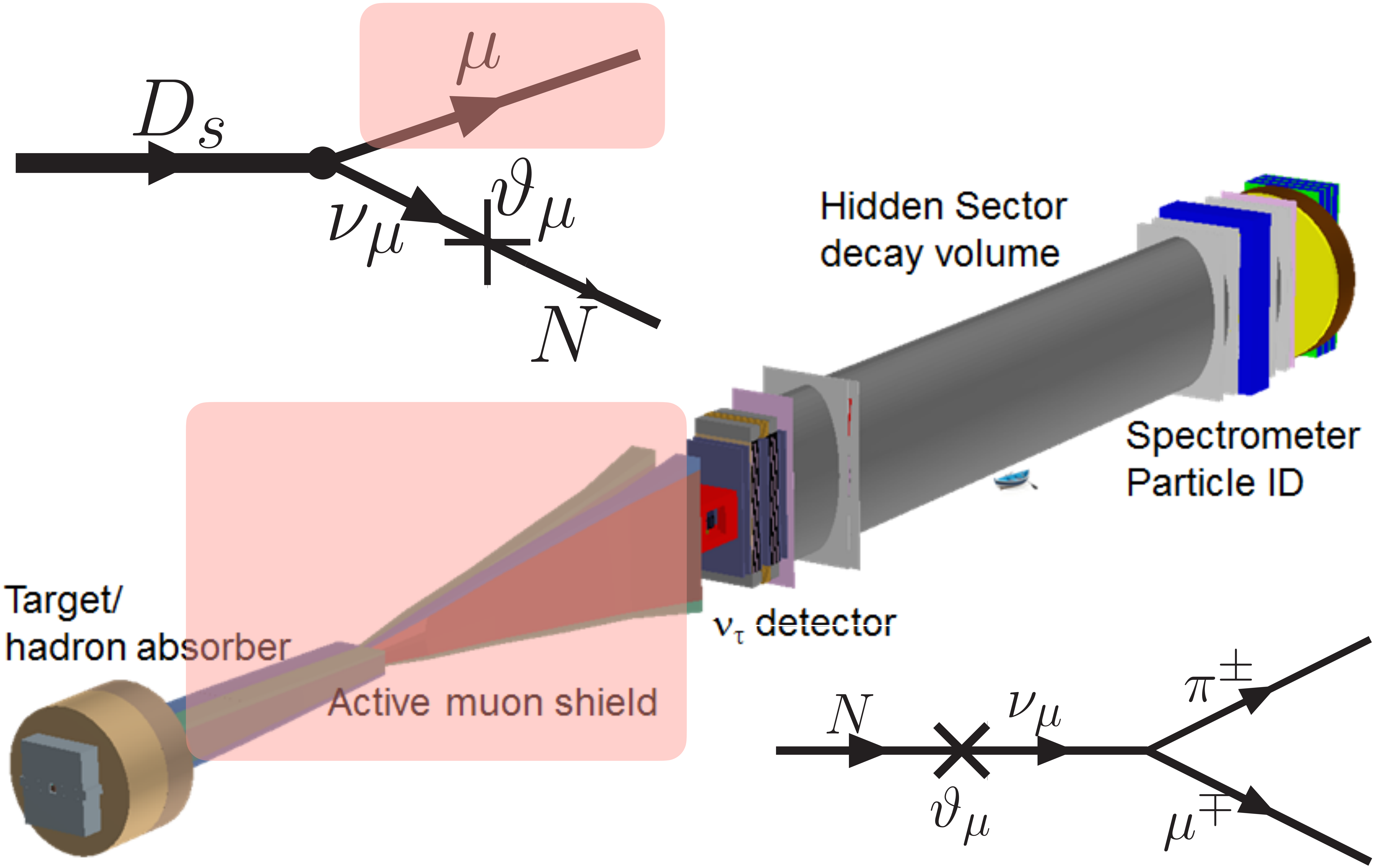

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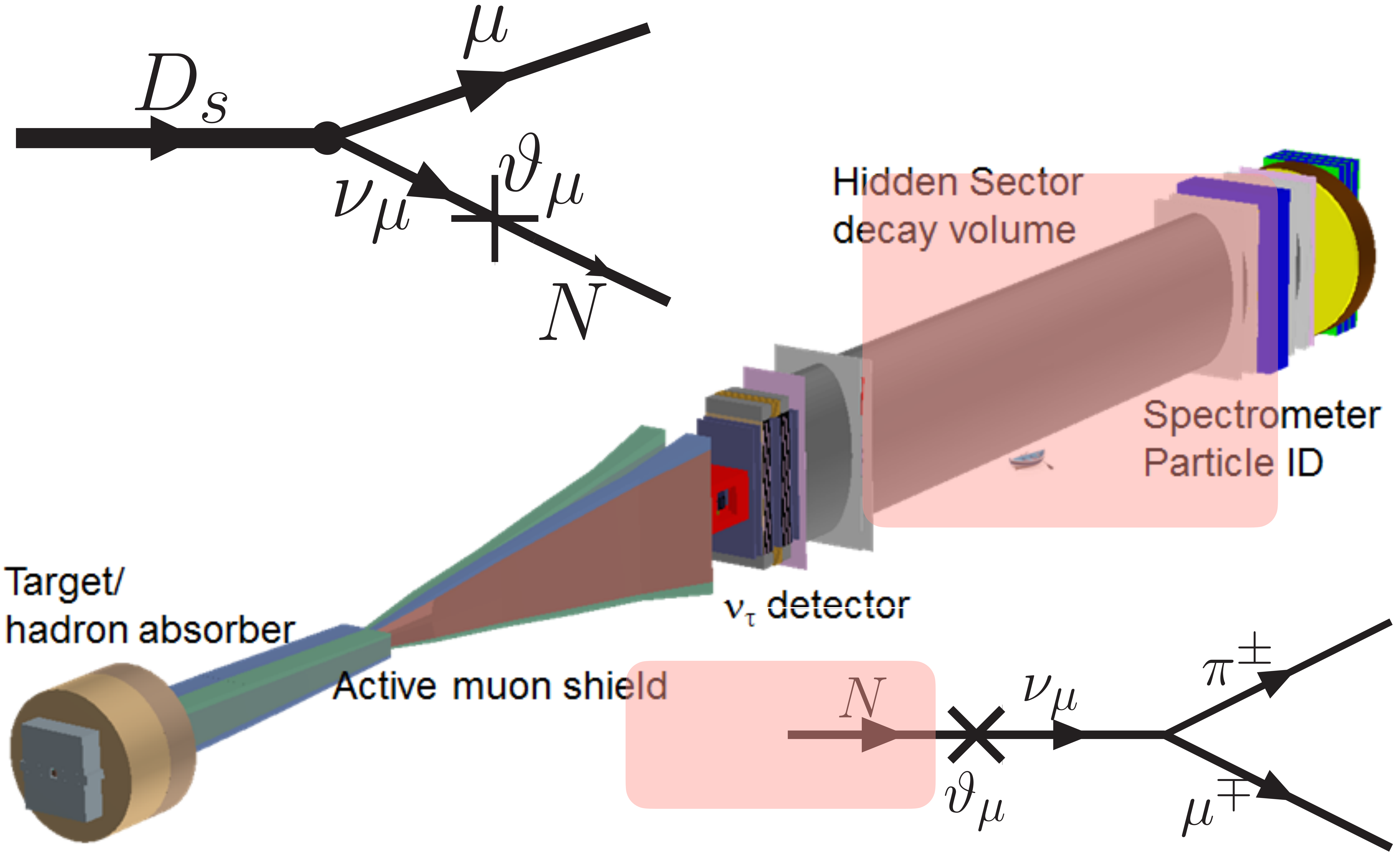

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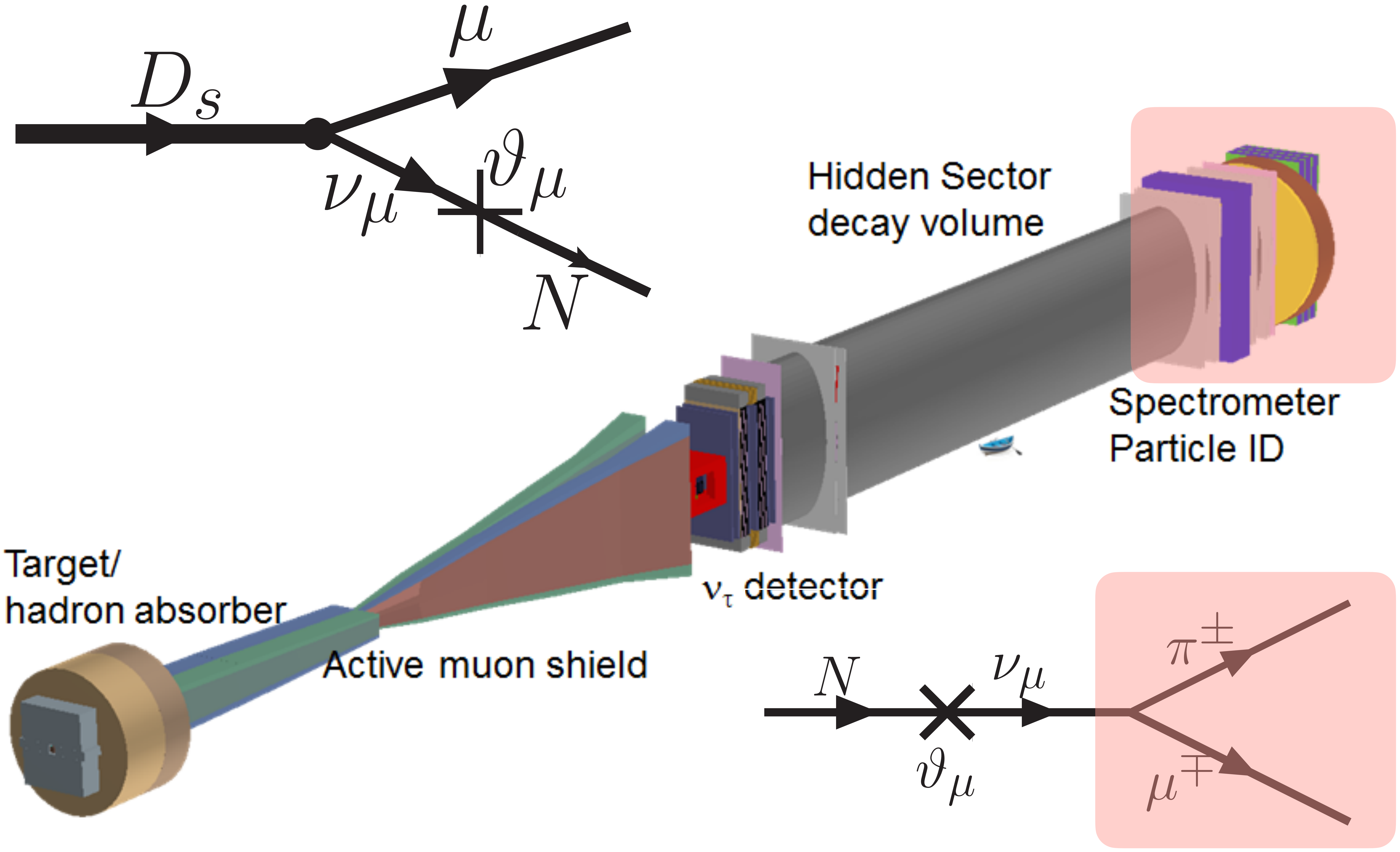
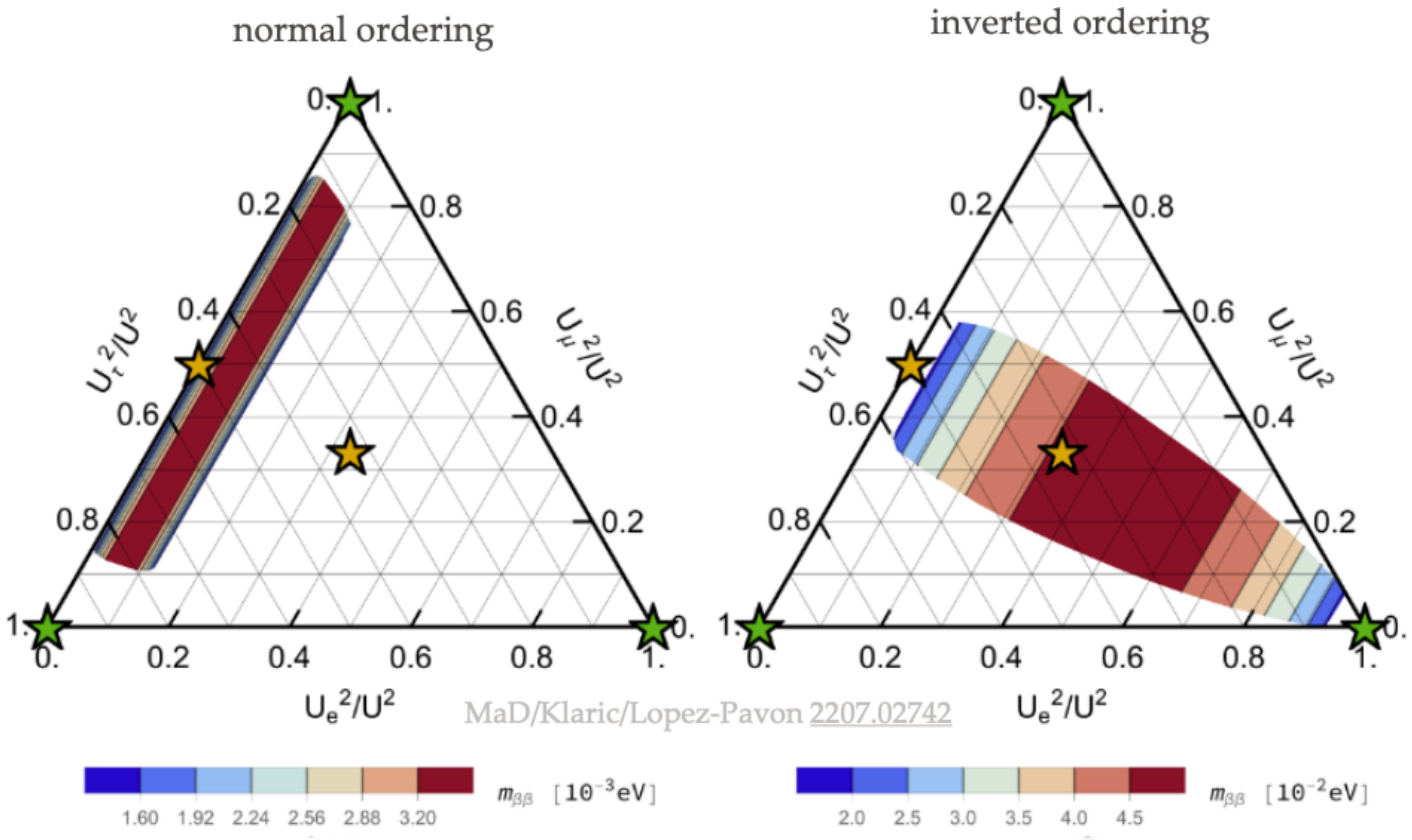


Slide by Marco Drewes



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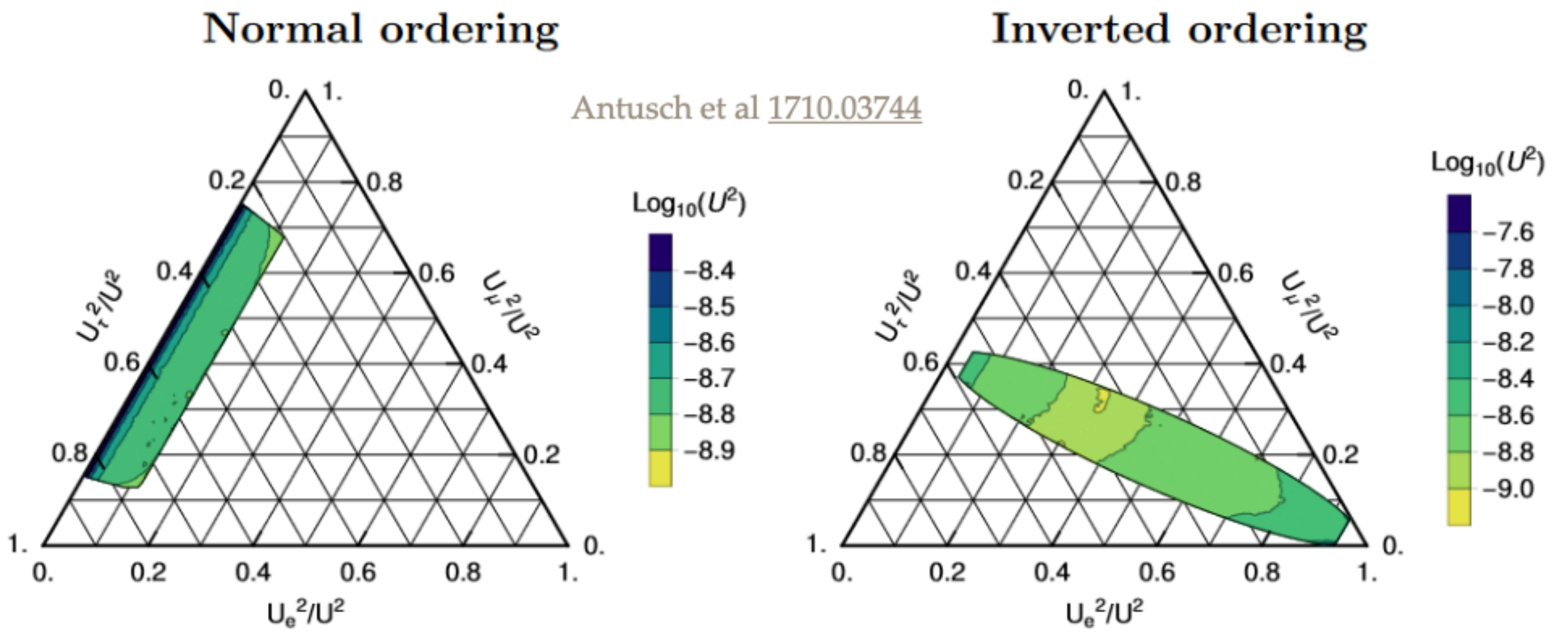

- Requirement for leptogenesis imposes additional constraints on branching ratios Antusch et al 1710.03744
- Recently confirmed and refined in Hernandez et al 2207.01651