EPFL

Baryon asymmetry of the Universe: a window to physics beyond the standard model

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PRISMA+

Outline

- The problem of baryon asymmetry of the Universe: a historical overview
- How to create baryons in the Universe
  - Thermal leptogenesis
  - Low scale leptogenesis
  - Uniting leptogeneses
- Conclusions

Baryon asymmetry in the present universe

Main questions:

- Why do the Earth, the Solar system and our galaxy consists of matter and not of antimatter?

- Why we do not see any traces of antimatter in the universe except of those where antiparticles are created in collisions of ordinary particles?

This looks really strange, as the properties of matter and antimatter are very similar.

Crucial historical steps

- Before 1930 : no antimatter - no problem. The only known elementary particles were protons, neutrons, electrons and photons

- 1933: Paul Dirac picture of the Universe (Nobel lecture): 50% of matter and 50% of antimatter. Parity P and charge conjugation C were believed to be exact symmetries of Nature

- 1956: Discovery of P and C breaking in weak interactions (Lee, Yang, Wu)

- 1957: Proposal of strict conservation of combined CP-symmetry (Landau)

Crucial historical steps

- 1964: Discovery of CP-violation in K^0 decays (Cronin, Fitch, Christenson, Turlay) showing that matter and antimatter are different ($\delta_{CP} \sim 10^{-3}$)

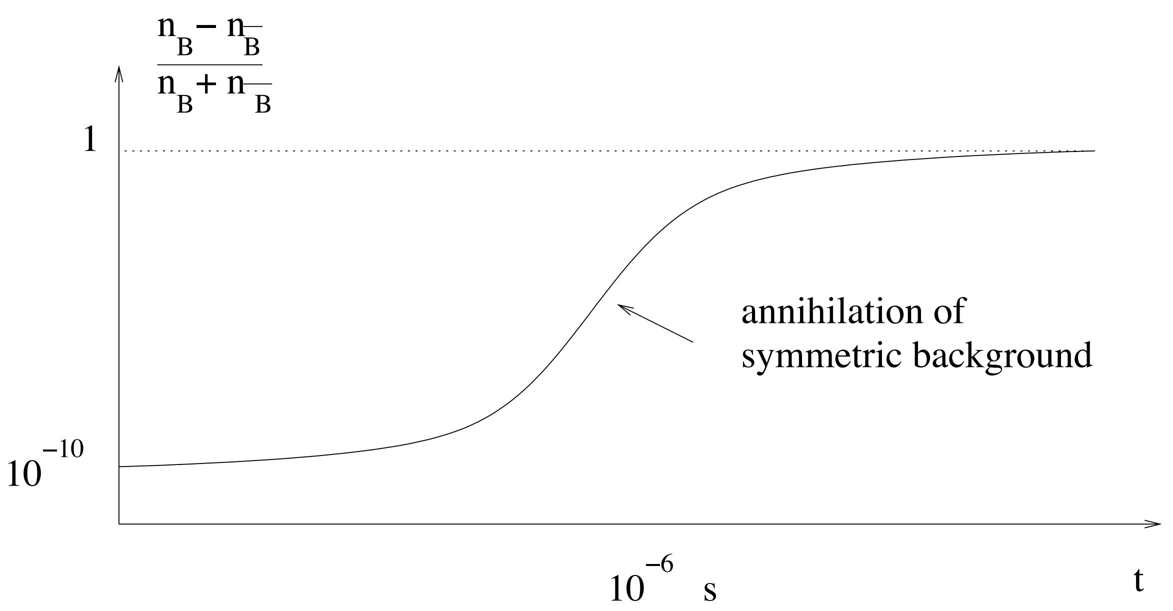
- Mounting cosmological evidence that the Universe contains no antimatter: no anti-nuclei in cosmic rays, no traces of matter-antimatter annihilation in the Universe, …

- 1965: discovery of the cosmic microwave background radiation (Penzias, Wilson): correct measure of baryon asymmetry of the Universe is

$$\Delta = \left.\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right|_{T\sim 1\ \mathrm{GeV}} \simeq \left.\frac{n_B}{n_\gamma}\right|_{\mathrm{now}} \simeq 10^{-10} \gg \delta_{CP} \text{ in kaons}$$

Big Bang and Baryon asymmetry

- At t ~ 10^{-6} s after the Big Bang for every 10^{10} quarks we have $(10^{10} - 1)$ antiquarks.
  Somewhat later the symmetric back- ground annihilates into photons and neutrinos while the asymmetric part survives and gives rise to galaxies, stars, planets.



Dependence of baryon asymmetry on time

Big Bang and Baryon asymmetry

Problems to solve:

- Why in the early universe the number of baryons is greater than the number of anti-baryons ?
- How to compute the primordial baryon asymmetry? (from observations $n_B/n_\gamma \simeq 10^{-10}$)

Sakharov proposal, 1967

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

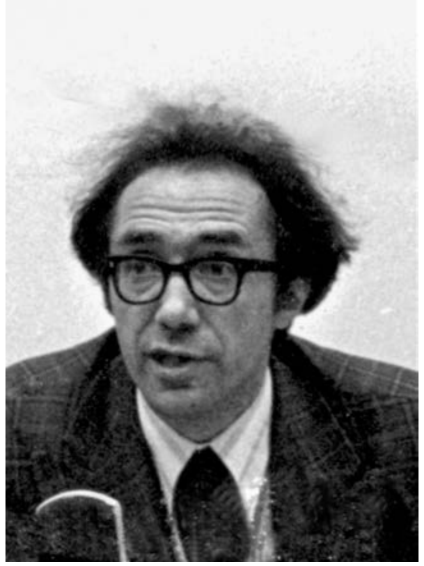
A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed

The source of baryon asymmetry:
decays of Markov's maximons with masses $\sim 10^{19}$ GeV

Sakharov conditions:

* **Baryon number non-conservation, to produce net baryon number**
* **C and CP-violation, to have difference between particles and antiparticles**
* **Departure from thermal equilibrium, "arrow of time", to kill static CPT prediction**



Kuzmin work, 1970

CP-NONINVARIANCE AND BARYON ASYMMETRY OF THE UNIVERSE

V.A. Kuz'min
P.N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 10 August 1970
ZhETF Pis. Red. 12, No. 6, 335 - 337 (20 September 1970)

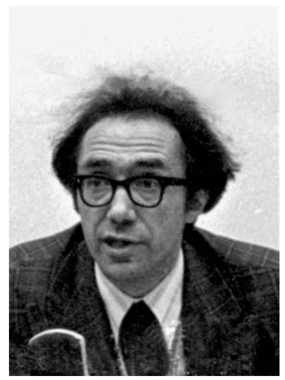
New insights:

- Source of asymmetry - decays of new Majorana fermion with mass M > 1 TeV (prototype of contemporary leptogenesis)
- Connection to CP-violation in K-decays
- Proposal of resonant baryogenesis
- Proposal to search for neutron-antineutron oscillations

It must be emphasized that, in light of the foregoing, searches for the process of baryon-number nonconservation are of great interest, especially searches for the oscillation process $n \rightleftarrows \tilde{n}$.

Sakharov and Kuzmin works were unnoticed until 1978 …






UNIVERSAL *CP*-NONINVARIANT SUPERWEAK INTERACTION AND BARYON ASYMMETRY OF THE UNIVERSE

A.Yu. IGNATIEV, N.V. KRASNIKOV, V.A. KUZMIN and A.N. TAVKHELIDZE
Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow, USSR

Received 4 April 1978

Unified Gauge Theories and the Baryon Number of the Universe

Motohiko Yoshimura
Department of Physics, Tohoku University, Sendai 980, Japan
(Received 27 April 1978)

Interesting : Yoshimura paper was doubly wrong:

- He got baryon asymmetry in thermal equilibrium
- He got baryon asymmetry in minimal SU(5) GUT (not enough CP violation)

These two works largely increased an interest to this problem: almost everybody wrote a paper discussion or mentioned this problem, as in gives a very non-trivial connection between particle physics and cosmology!

Mainz theory examples

Julia Harz: $n - \bar{n}$ oscillations and baryogenesis,
relationship to neutrinoless β decay,
lepton number violation at LHC and leptogenesis,…

Pedro Schwaller:
Little Higgs and baryogenesis,
density corrections to leptogenesis

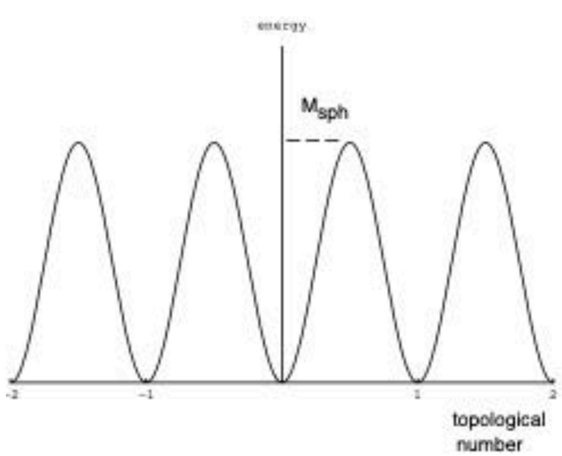
Matthias Neubert:
B-physics and CP-violation

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.

Standard Model?

Rate of B-nonconservation

$T = 0$, t'Hooft; $T \neq 0$, Kuzmin, Rubakov, MS



$$\Gamma \sim \begin{cases} \exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}, & T = 0 \\ \exp\left(-\frac{M_{sph}}{T}\right), & T < T_c \\ (\alpha_W)^5 T^4, & T > T_c \end{cases}$$

These reactions are in thermal equilibrium for

$$100 \text{ GeV} \sim T_c < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} \text{ GeV}$$

BAU in the Standard Model

Potentially could be generated (Sakharov conditions are satisfied):

- Difference between matter and anti-matter: CP-violation present in the Standard Model (experimentally detected)

- Baryon number non-conservation in the Standard Model : rapid “sphaleron” transitions in the early Universe and very slow at normal conditions, may lead to creation of excess of baryons over anti-baryons

- Non-equilibrium: OK, Universe expansion, electroweak phase transition?

BAU in the Standard Model

In 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.

Measure of CP-Violation. Total baryon asymmetry is proportional to combination (MS'1986).

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

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 are too small, there is no electroweak phase transition for Higgs masses exceeding 73 GeV (Kajantie, Laine, Rummukainen, MS ' 96). This limit was superseded at LEP in 1997.

Recent failed resurrection attempt: Kharzeev, Shuryak, Zahed '2020
see Hong, Kamada, Yokoyama '2023

BAU tells that there is physics beyond the SM!

Baryogenesis: window to BSM physics!

But the window is wide open. There is just one number n_B/n_γ to explain, and therefore many possibilities.

Epistemology tells that the

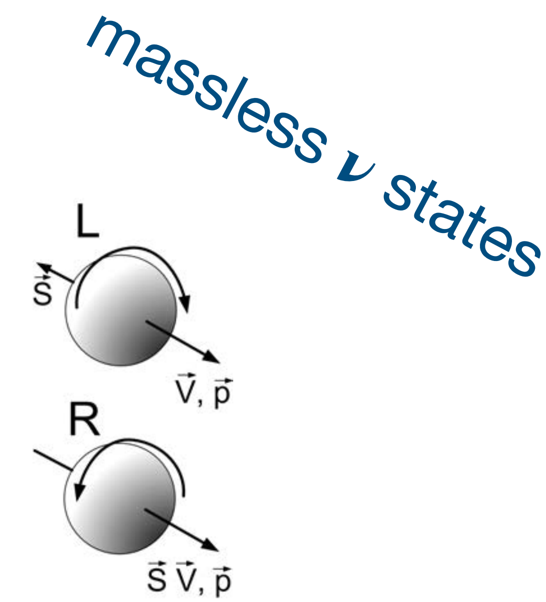
$$\#\ \text{of theories} \sim \text{const}/(\#\ \text{of data points})^{\alpha}, \alpha > 0$$

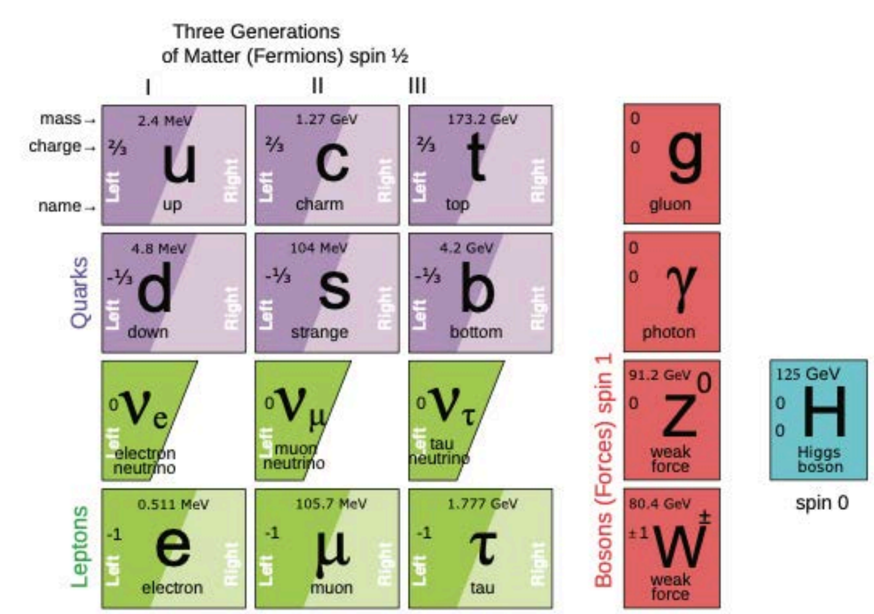
To narrow the search, we should look at other indications that the Standard model is not complete!

Problems of the Standard Model: neutrino masses and oscillations

In the SM neutrinos are exactly massless (every fermion comes in left and right handed states except neutrinos) and lepton numbers are conserved. Experimentally neutrinos have tiny, but non-zero masses. Atmospheric neutrino oscillations: 1998.

Extension of the Standard Model in neutrino sector is required!

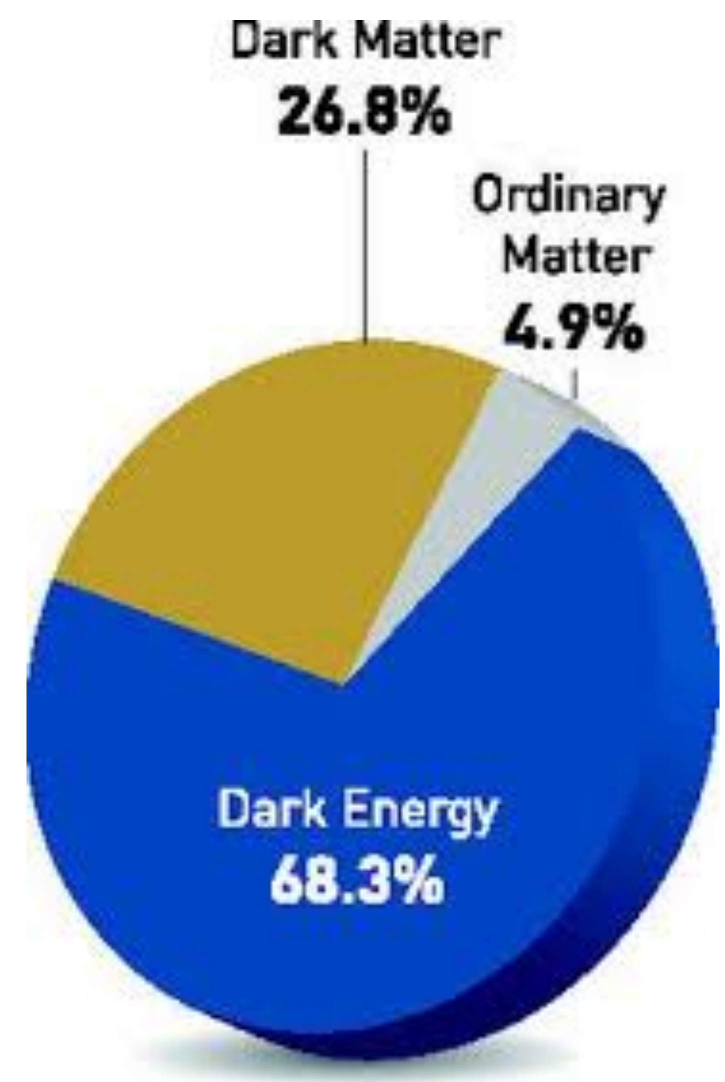




Problems of the Standard Model: missing mass in the Universe

Standard Model: no particle physics candidate for Dark Matter. The only neutral stable objects - atoms and neutrinos

- if atoms: contradiction with BBN - so many baryons are not admitted
- if neutrinos - hot DM: contradiction with structure formation - small scale inhomogeneities are erased



Dark energy: cosmological constant ?

Dark Matter: new particle(s) ?

Extension of the Standard Model is required!

Physics behind neutrino 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 ,

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

Majorana neutrino mass: from five-dimensional Weinberg operator

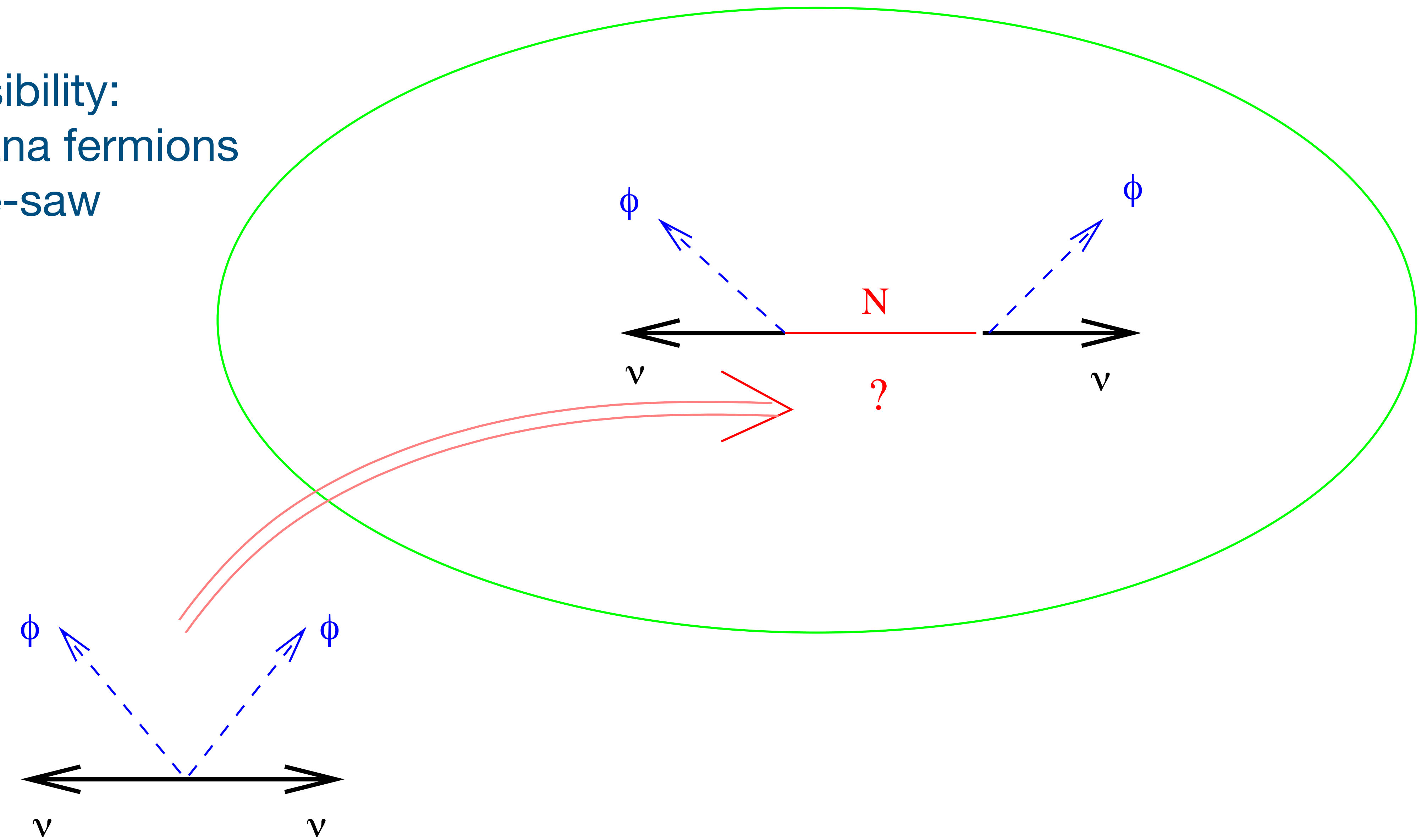
$$O_5 = A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi} \right) \left(\phi^\dagger L_\beta^c \right)$$

Neutrino mass matrix:

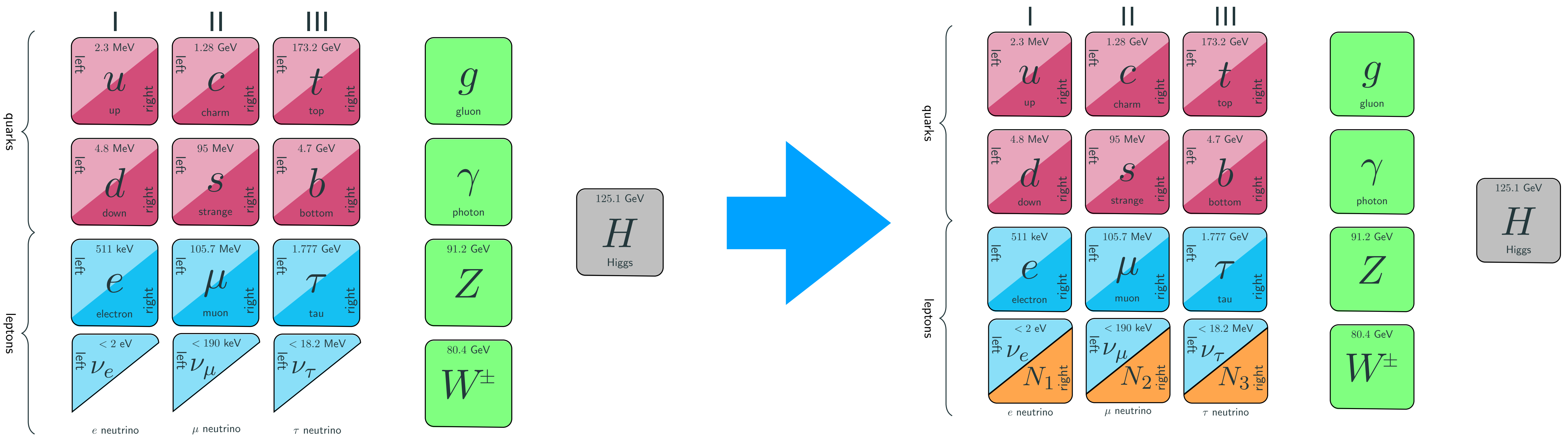
$$M_\nu \sim A_{\alpha\beta} \frac{v^2}{\Lambda}$$

Origin of the Weinberg operator

Simplest possibility:
singlet Majorana fermions
and type I see-saw



Minimal see-saw model or νMSM



This simplest theory of new physics can explain all experimental drawbacks of the Standard Model: neutrino masses and oscillations, dark matter, baryon asymmetry of the Universe, incorporating cosmological Higgs inflation leading to the observable universe.

Historical analogue

Historical development of the SM: gradual adaptation of electroweak theory to experimental data during the past 50 years.

- Bosonic sector of the electroweak model remains intact from 1967, with the discoveries of the W and Z bosons in 1983 and the Higgs boson in 2012.
- The fermionic sector evolved from one to two and finally to three generations, revealing the remarkable symmetry between quarks and leptons.
- It took about 20 years to find all the quarks and leptons of the third generation.

How much time it will take to discover HNLs, if they exist?

Most general renormalisable see-saw Lagrangian with Majorana neutrinos:

Standard Model

Higgs field

HNL Majorana mass

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

HNL kinetic term

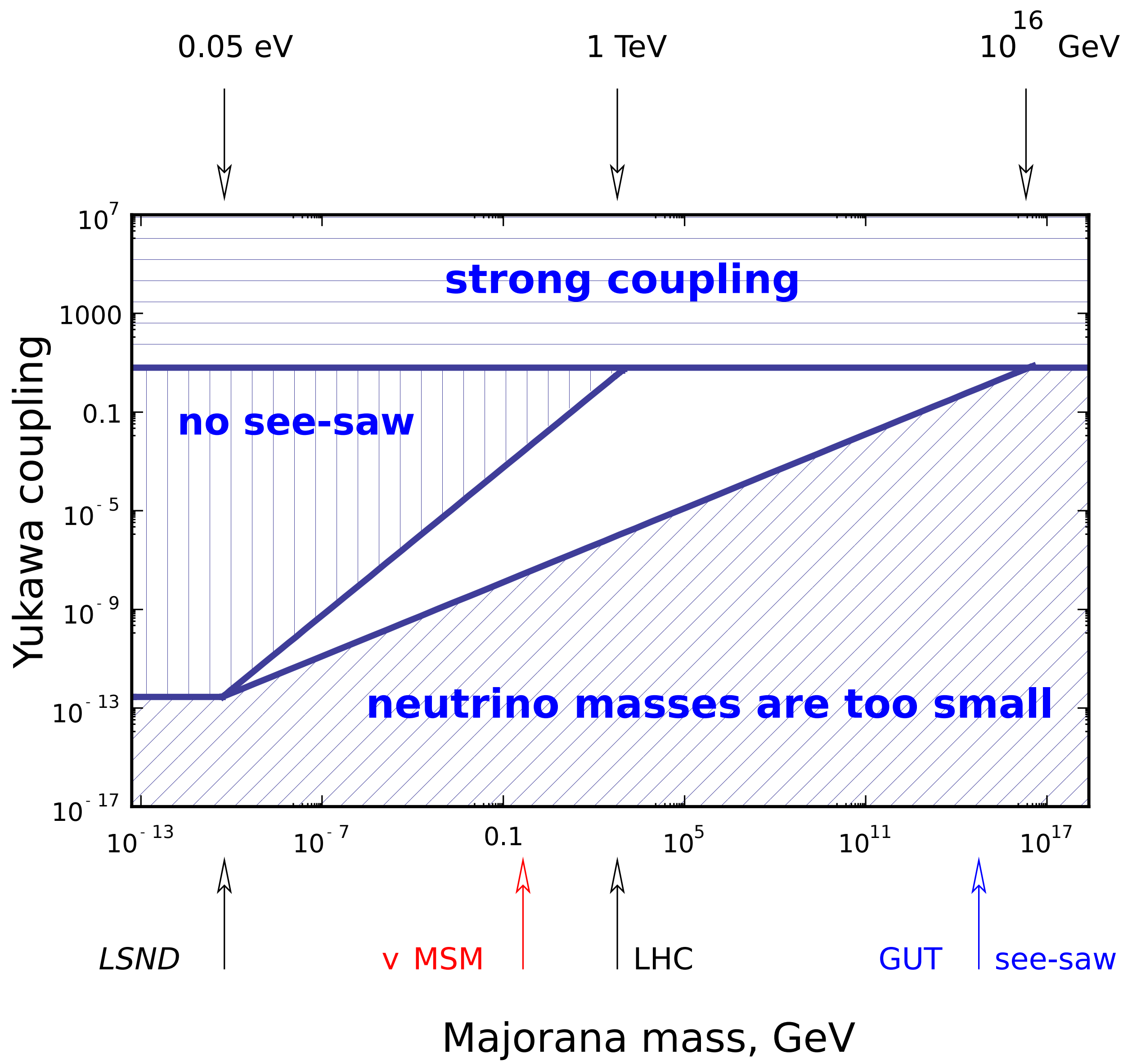
HNL Yukawa couplings, leading to Dirac mass

Neutrino masses and Yukawa couplings from Neutrino physics

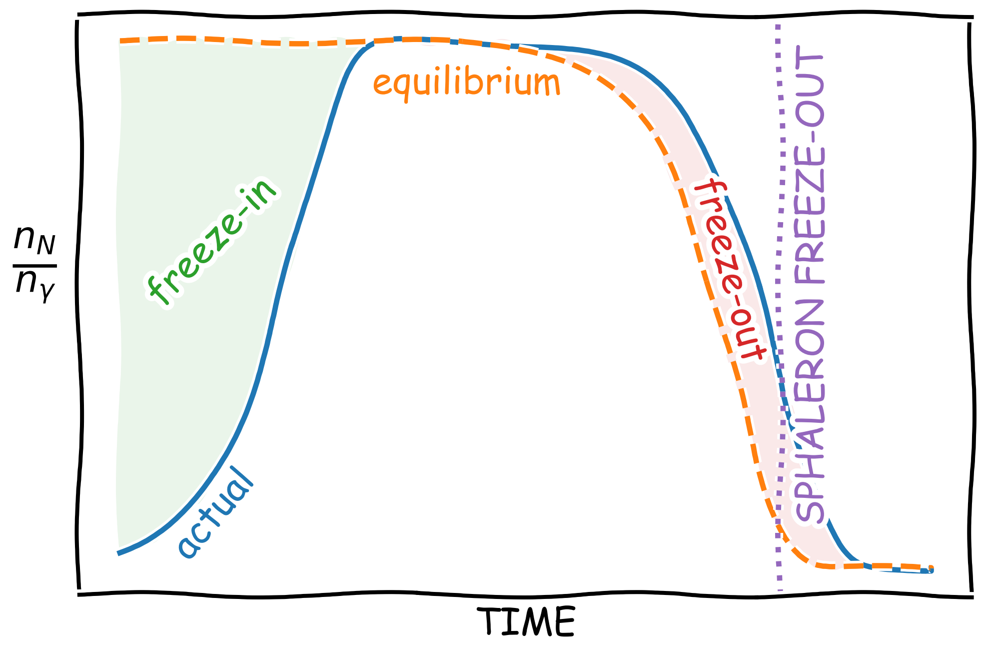
$$Y^2 = Trace[F^\dagger F]$$

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

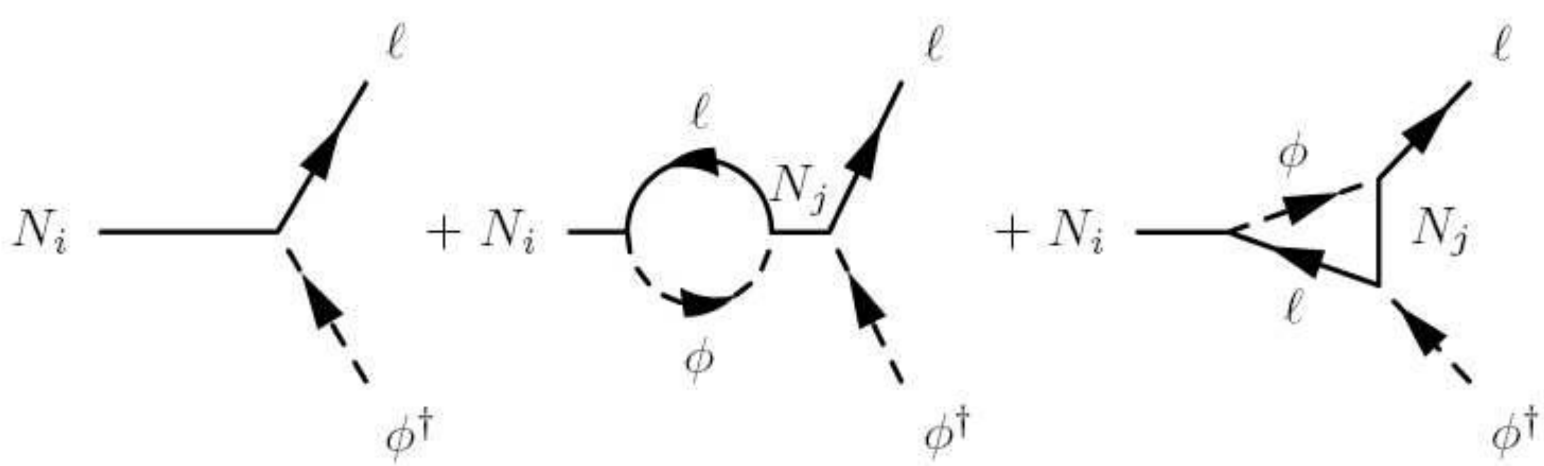
$$m_\nu \propto \frac{F^2 v^2}{M}$$



See-Saw leptogenesis



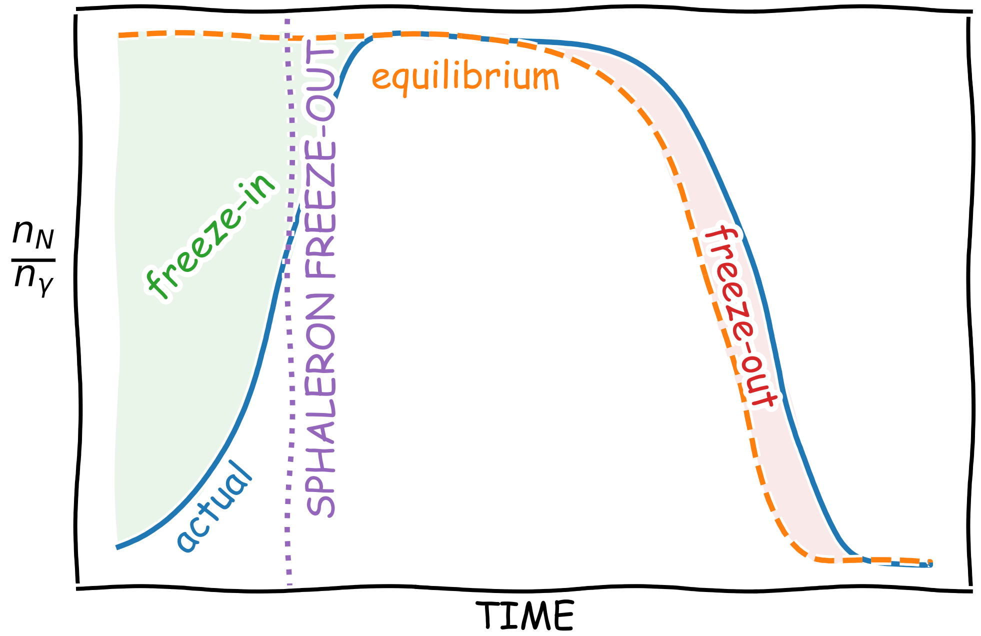
The mechanism: leptogenesis with superheavy Majorana neutrinos: HNLs go out of thermal equilibrium, decay, and produce lepton asymmetry. Then the lepton number is converted into baryon asymmetry by sphalerons which are active until $T \simeq 130\ GeV$. The resulting baryon asymmetry is just a numerical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



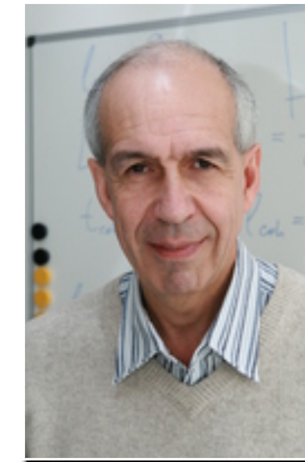
Initial idea: Fukugita, Yanagida, ’86

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

Low scale 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.

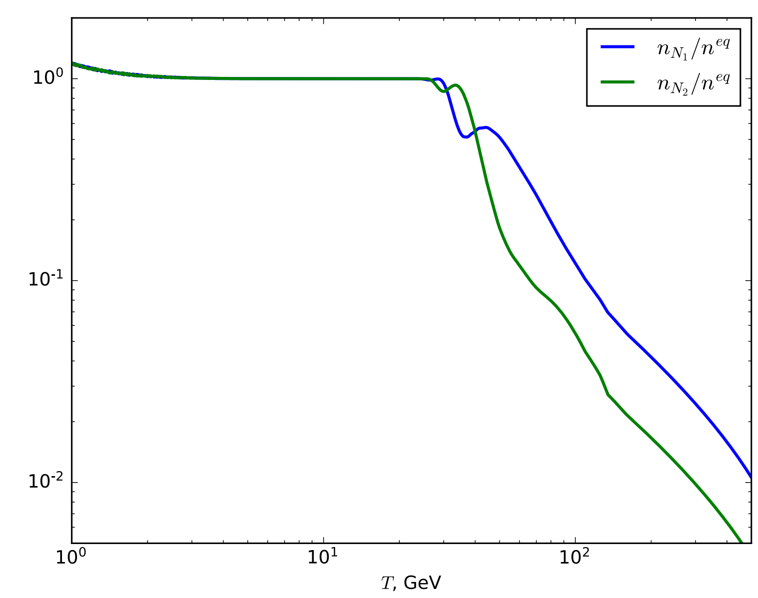
Initial idea: Akhmedov, Rubakov, Smirnov ‘98

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

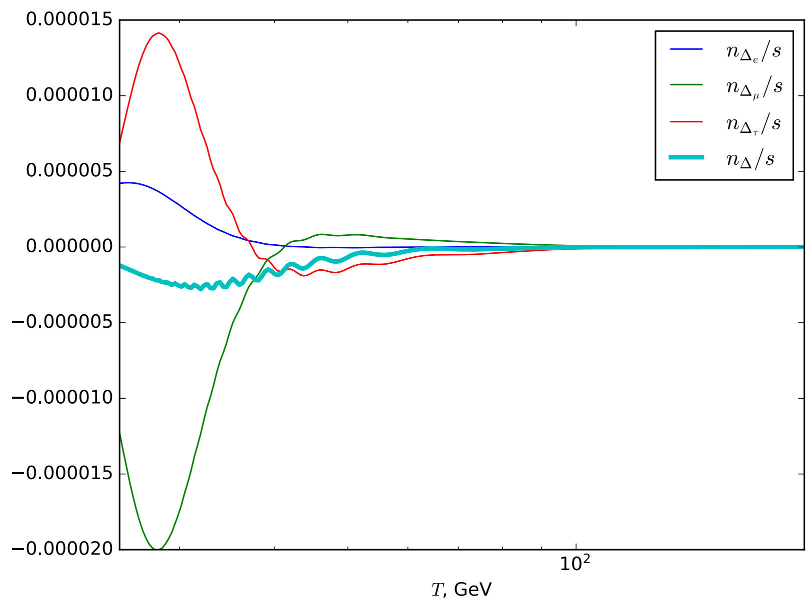
Analysis of baryon asymmetry generation in the NuMSM: Asaka, M.S., Canetti, Drewes, Frossard; Abada, Arcadia, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, Racker, J. Salvado; Drewes, Garbrech, Guetera, Klariç; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine,…

Time evolution

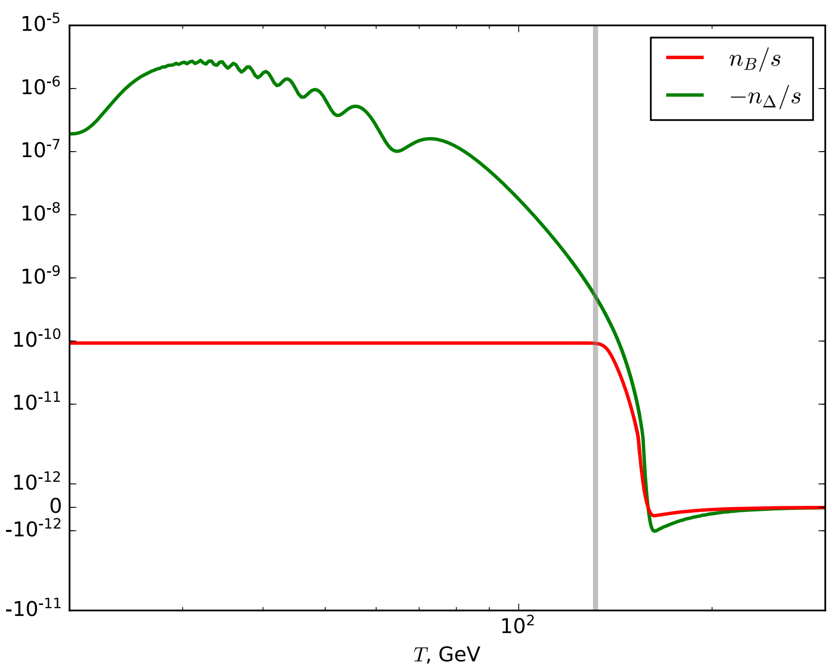
HNL densities



Lepton asymmetries



Baryon asymmetry

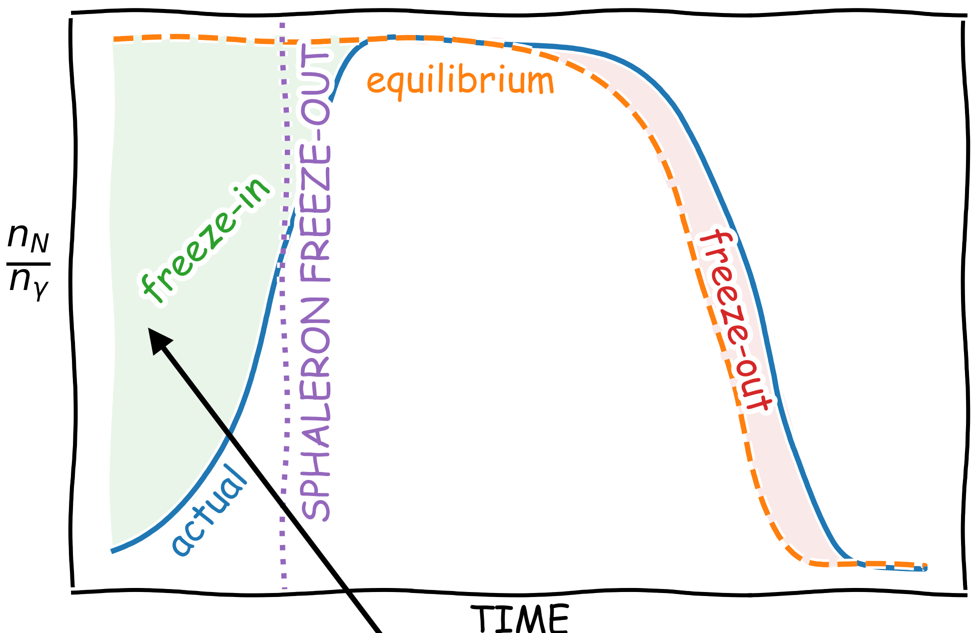


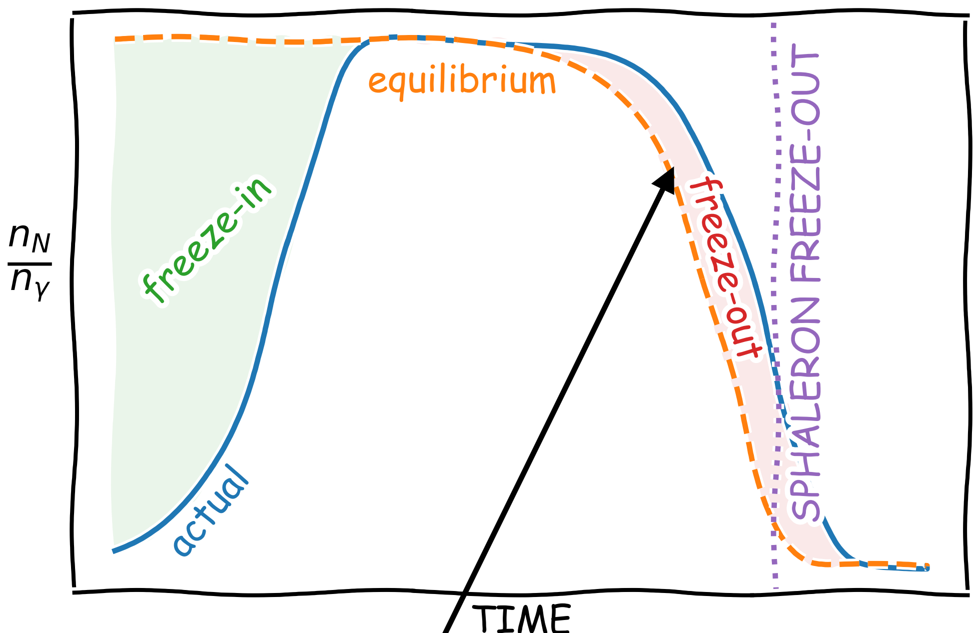
Uniting Leptogeneses

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 window for new physics.

Freeze-in and freeze out

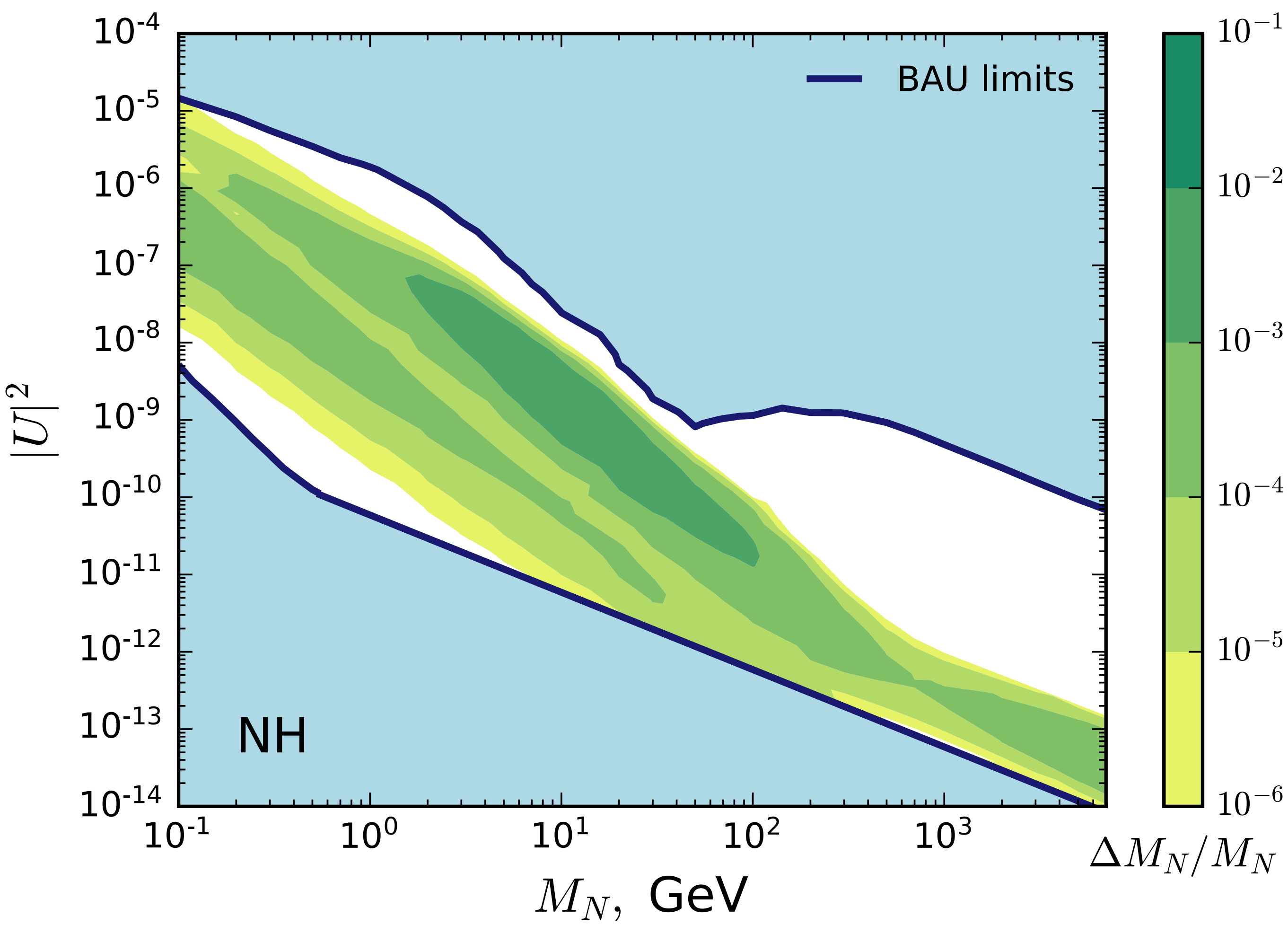




Lepton number generation
in freeze-in

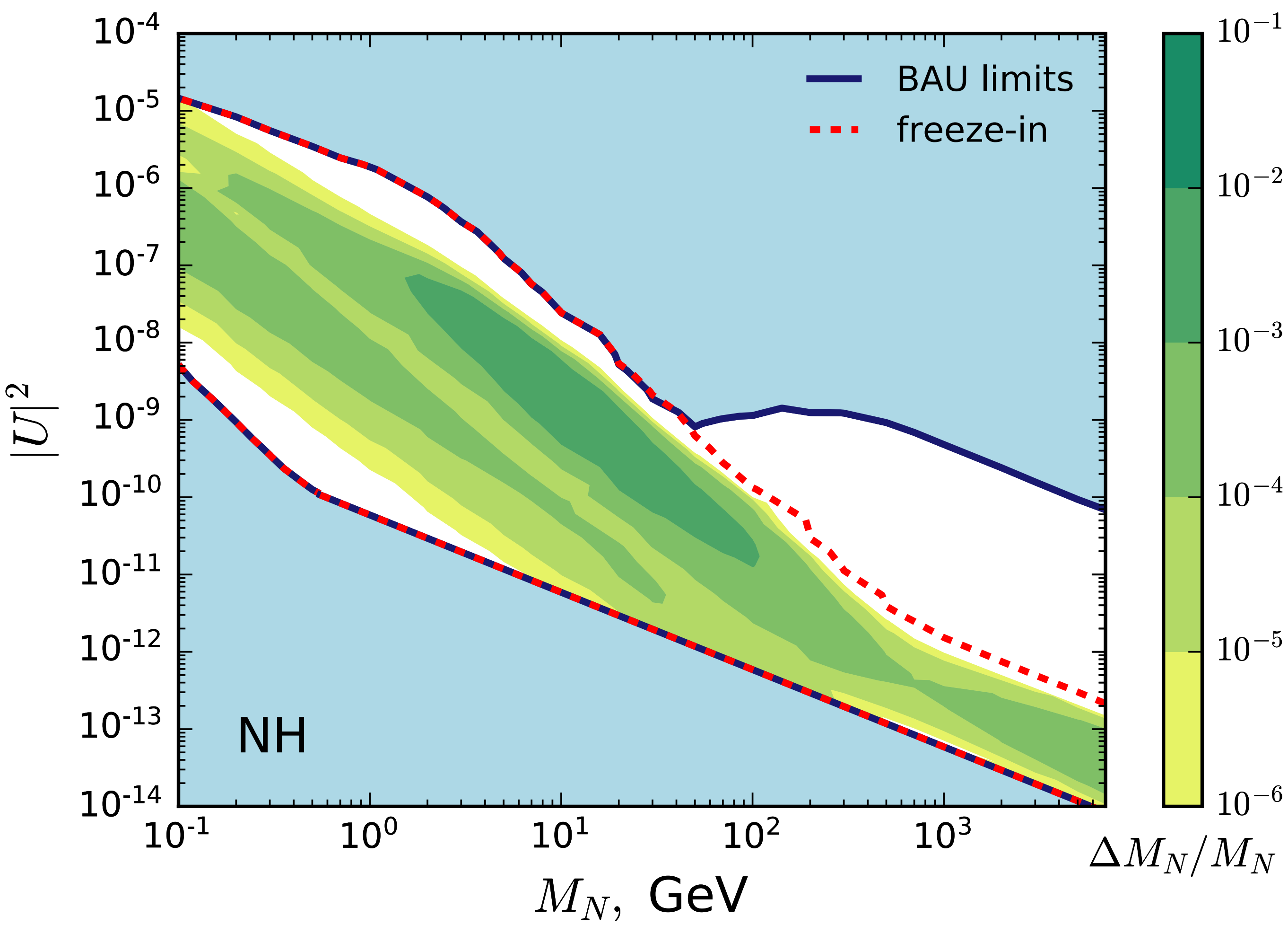
Lepton number generation
in freeze-out

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

Uniting Leptogeneses



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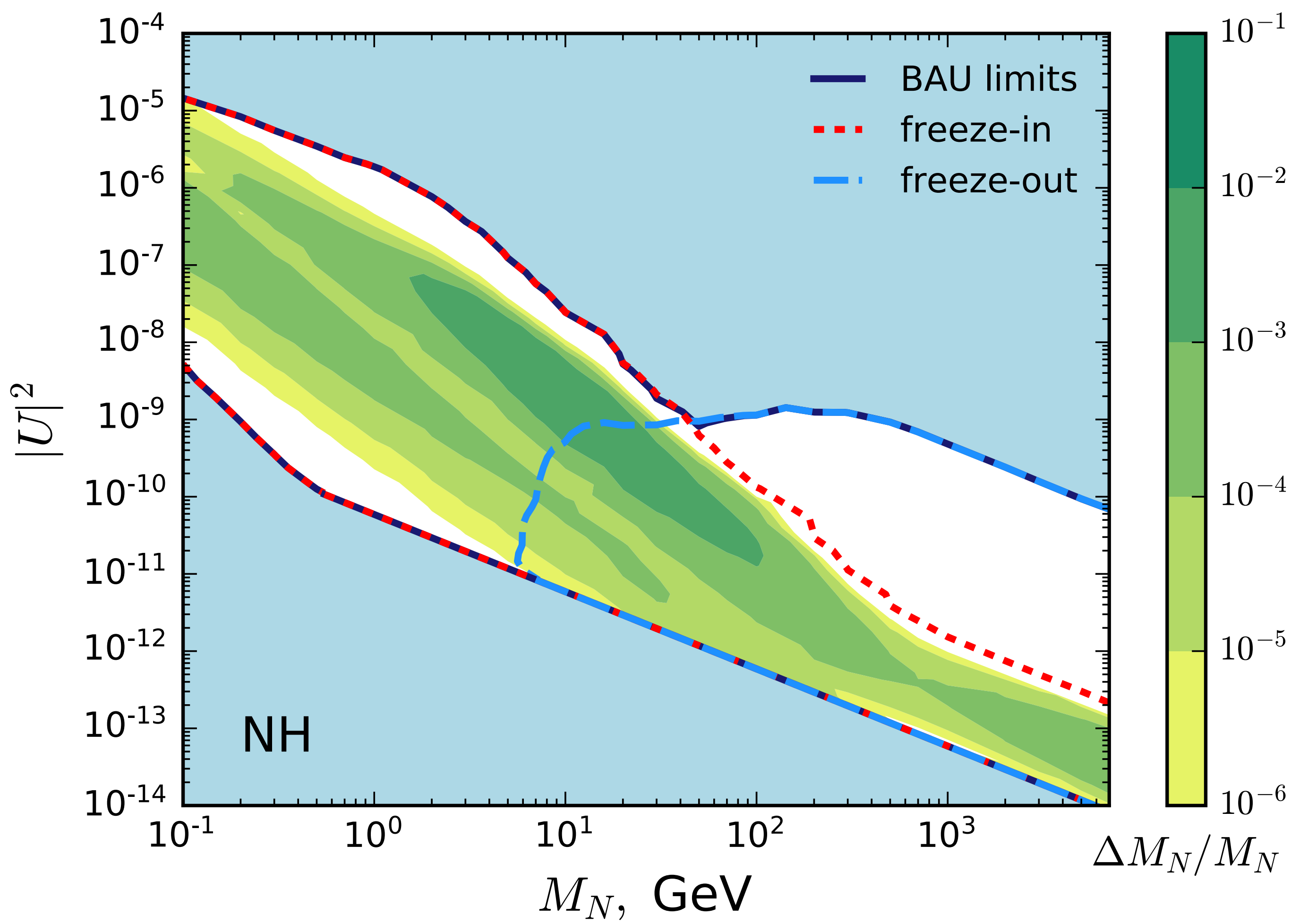

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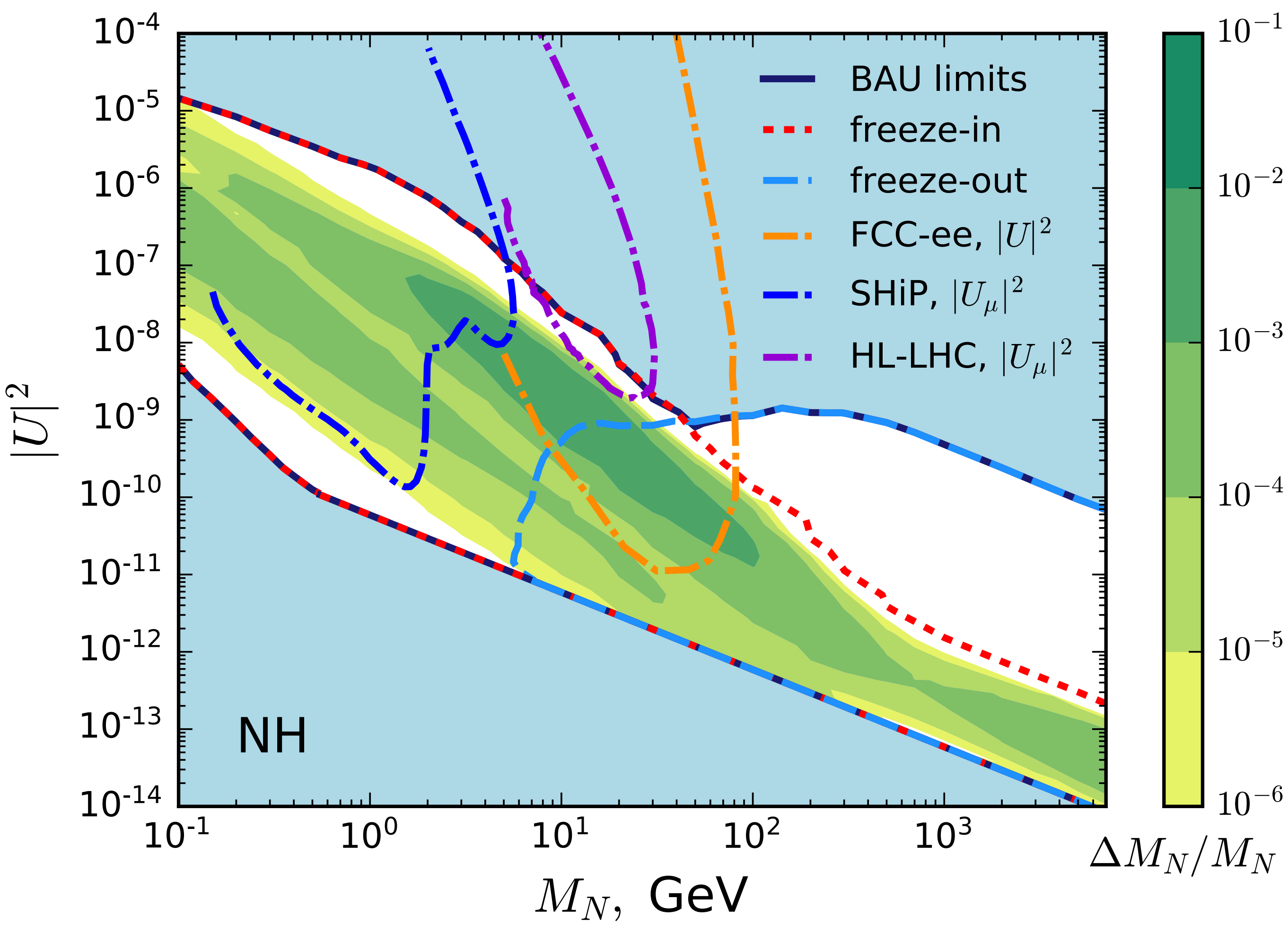

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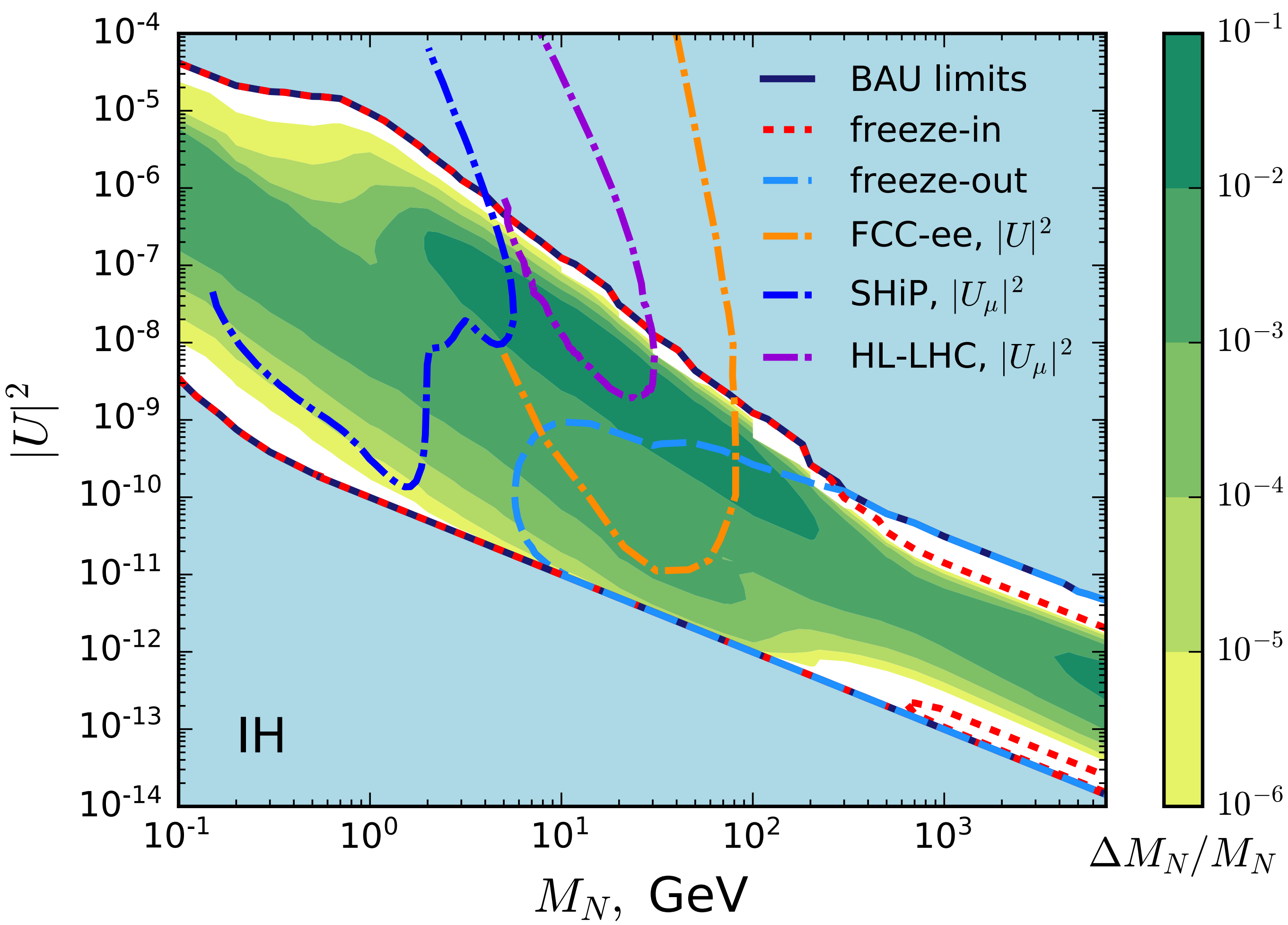
Uniting Leptogeneses



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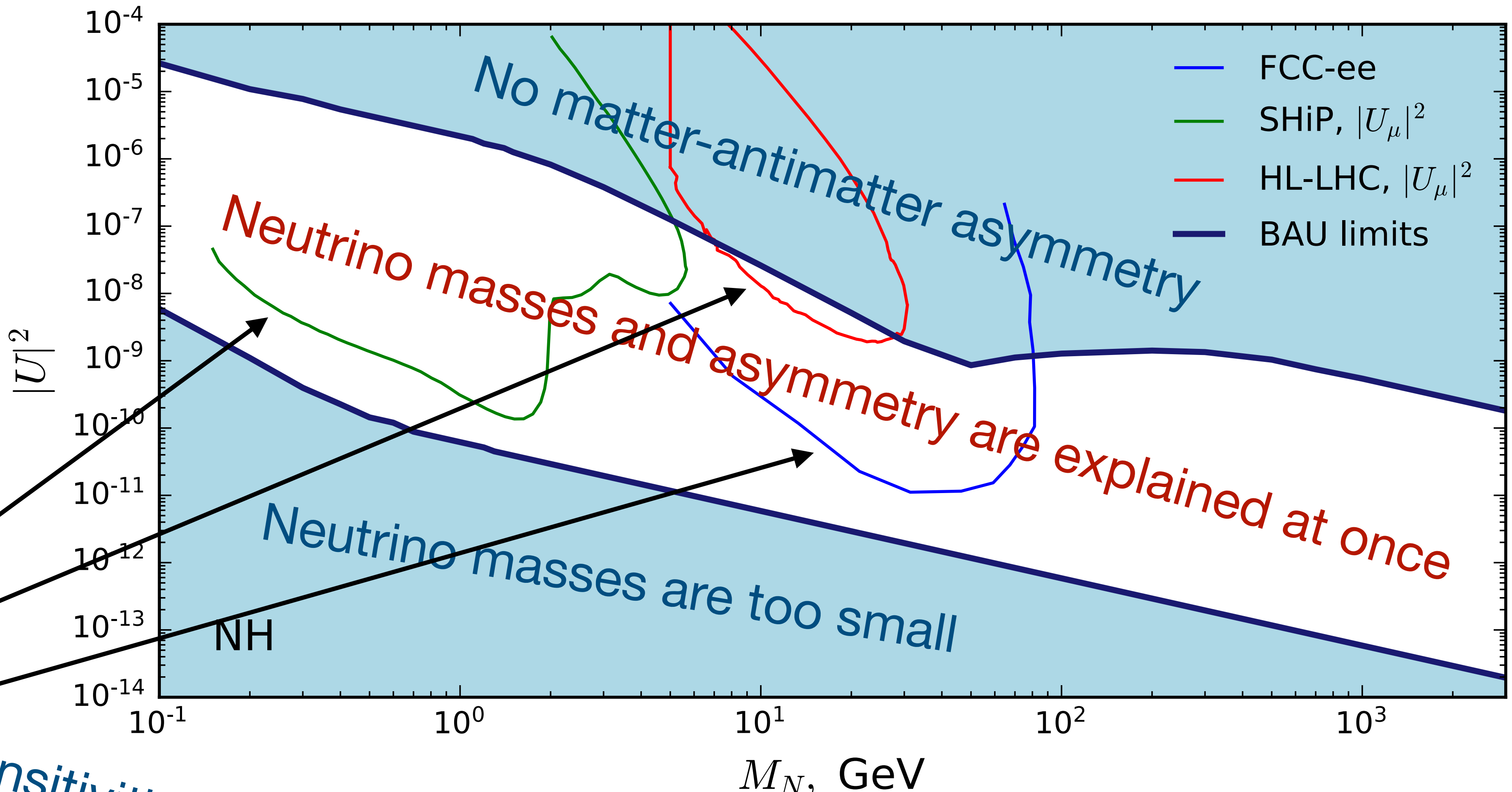
Matter-antimatter asymmetry and neutrino masses in the νMSM: $N_{2,3}$

figure from Klaric, Timiryasov, MS

Strength
in comparison
with weak
interaction



Experimental sensitivities

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

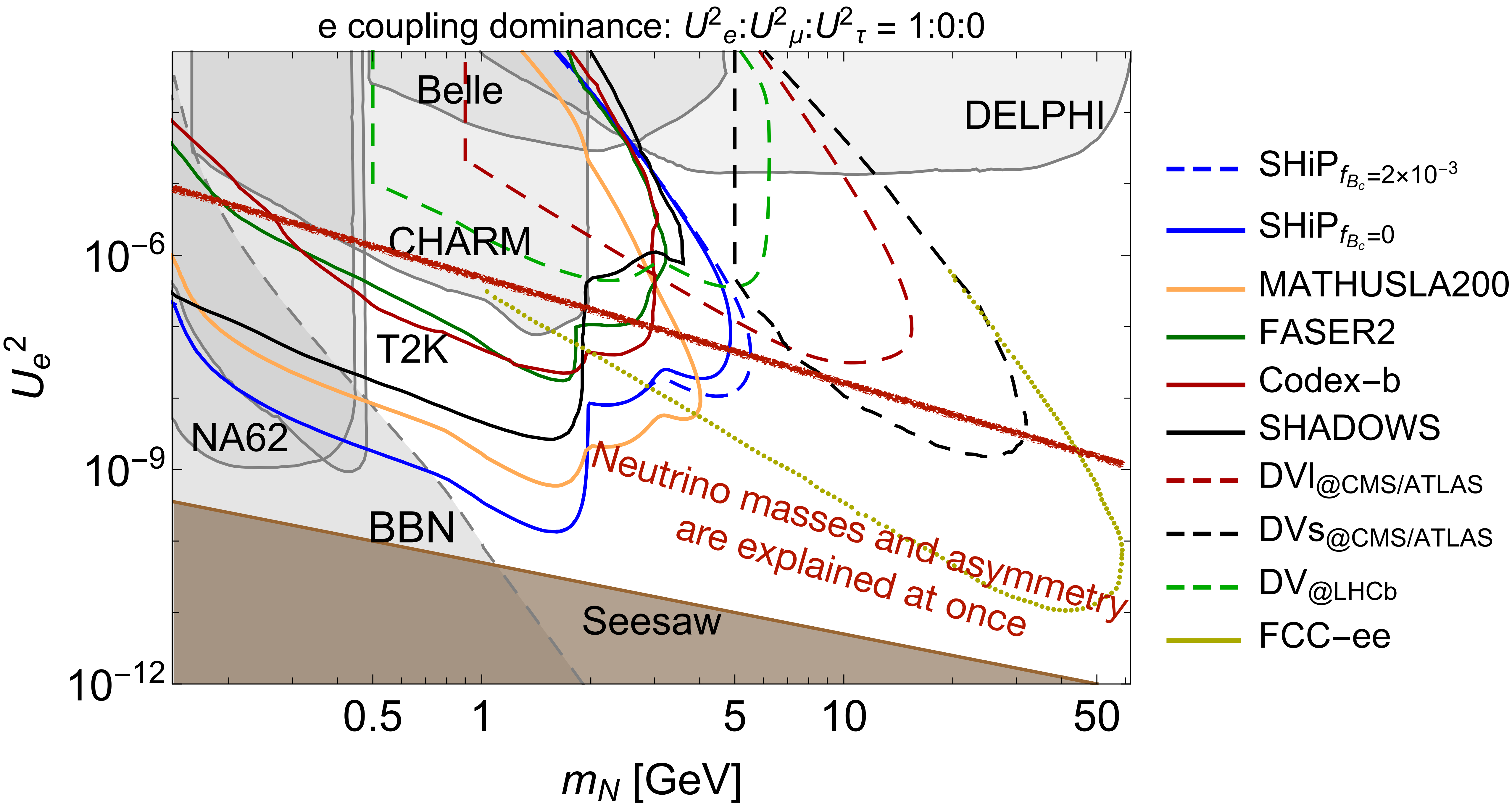
The mechanisms of neutrino mass and matter-antimatter asymmetry generation can be verified experimentally!

Experimental challenges of HNL searches:

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

- Mass below ~ 5 GeV - Intensity frontier, CERN SPS: SHiP, SHADOWS
- Mass above ~ 5 GeV - FCC in e+e– mode in Z-peak, LHC

Projection of bounds on HNLs



Conclusions

Window even to the simplest new physics from baryogenesis is wide open.

- 😀 Perhaps, this is good: baryon asymmetry and neutrino masses are the generic consequence of the theory

- ☹️ Perhaps, this is bad: we cannot tell to our experimental friends where exactly to search for HNLs: leptogenesis is a viable explanation of baryon asymmetry and active neutrino oscillations for all HNL masses above the O(1) MeV

In any event, we are at an exciting point in history: the planned future experiments such as SHiP and FCC-ee in the Z-resonance mode have chances to uncover soon (?) the origin of neutrino masses and baryon asymmetry of the Universe.

Remark: only one of the theories of baryogenesis was discussed, there are many others:

1. GUT baryogenesis 2. GUT baryogenesis after preheating
3. Baryogenesis from primordial black holes 4. String scale baryogenesis 5. Affleck-Dine (AD) baryogenesis 6. Hybridized AD baryogenesis 7. No-scale AD baryogenesis 8. Single field baryogenesis 9. Electroweak (EW) baryogenesis 10. Local EW baryogenesis 11. Non-local EW baryogenesis 12. EW baryogenesis at preheating 13. SUSY EW baryogenesis 14. String mediated EW baryogenesis 15. Baryogenesis via leptogenesis 16. Inflationary baryogenesis 17. Resonant baryogenesis 18. Spontaneous baryogenesis 19. Coherent baryogenesis 20. Gravitational baryogenesis 21. Defect mediated baryogenesis 22. Baryogenesis from long cosmic strings 23. Baryogenesis from short cosmic strings 24. Baryogenesis from collapsing loops 25. Baryogenesis through collapse of vortons 26. Baryogenesis through axion domain walls 27. Baryogenesis through QCD domain walls 28. Baryogenesis through unstable domain walls 29. Baryogenesis from classical force 30. Baryogenesis from electrogenesis 31. B-ball baryogenesis 32. Baryogenesis from CPT breaking 33. Baryogenesis through quantum gravity 34. Baryogenesis via neutrino oscillations 35. Monopole baryogenesis 36. Axino induced baryogenesis 37. Gravitino induced baryogenesis 38. Radion induced baryogenesis 39. Baryogenesis in large extra dimensions 40. Baryogenesis by brane collision 41. Baryogenesis via density fluctuations 42. Baryogenesis from hadronic jets …