EPFL

When and how we are going to find the origin of the baryon asymmetry?

Mikhail Shaposhnikov

CP2023

Feb 12 – 17, 2023
École de Physique des Houches

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

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Some history

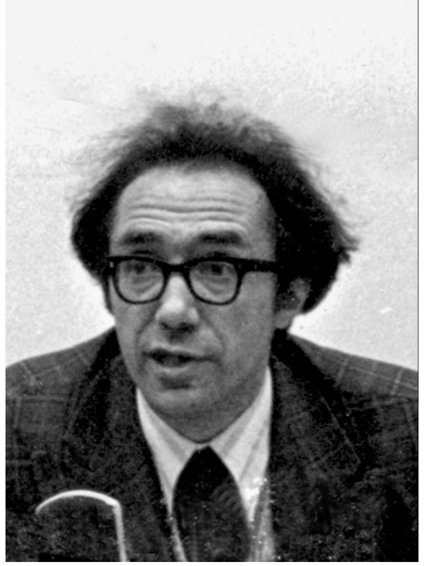
Sakharov proposal, 1967

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



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)

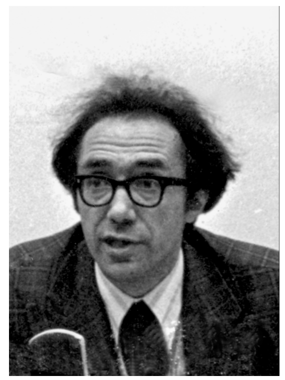
New insights:

- 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

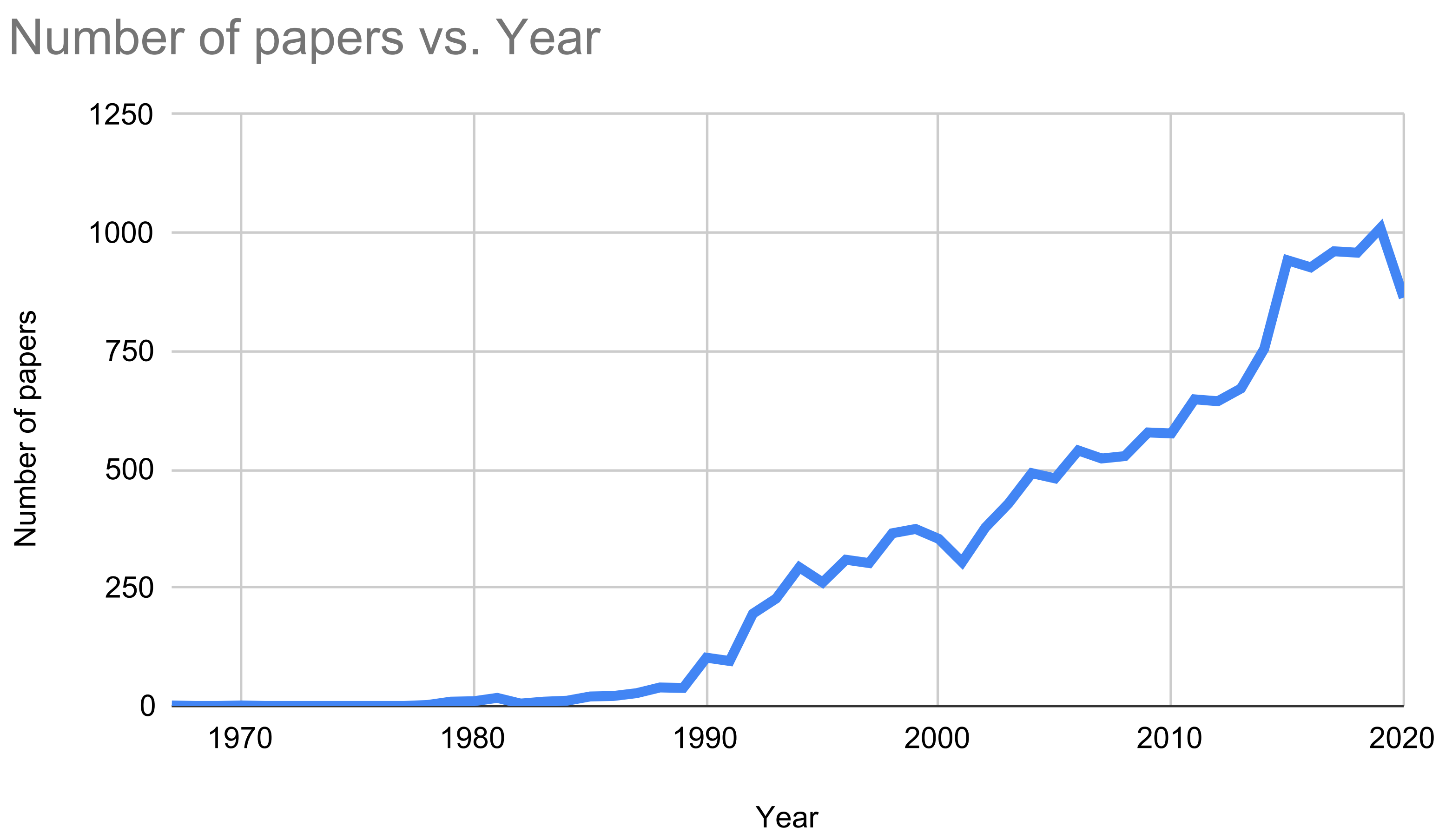
Unified Gauge Theories and the Baryon Number of the Universe

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!



Basic stats over all years	
Years:	1960-2020
Articles	16436
Authors	13452
Authors per article	2.9

Credit: Oleg Ruchayskiy
https://www.prophy.science

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?

Computation of baryon asymmetry

Qualitatively looks OK:

- B-nonconservation: OK, EW anomaly + sphalerons (Kuzmin, Rubakov, MS ‘1985)
- Non-equilibrium: OK, Universe expansion, electroweak phase transition?
- CP-violation: OK, complex phases in Higgs-fermion couplings, CKM matrix

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

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

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

Mechanisms for baryogenesis

- In 2004, I managed to count exactly 42 (cf. Douglas Adams) mechanisms for baryogenesis :

- 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

Now the number of different mechanisms is even larger.

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

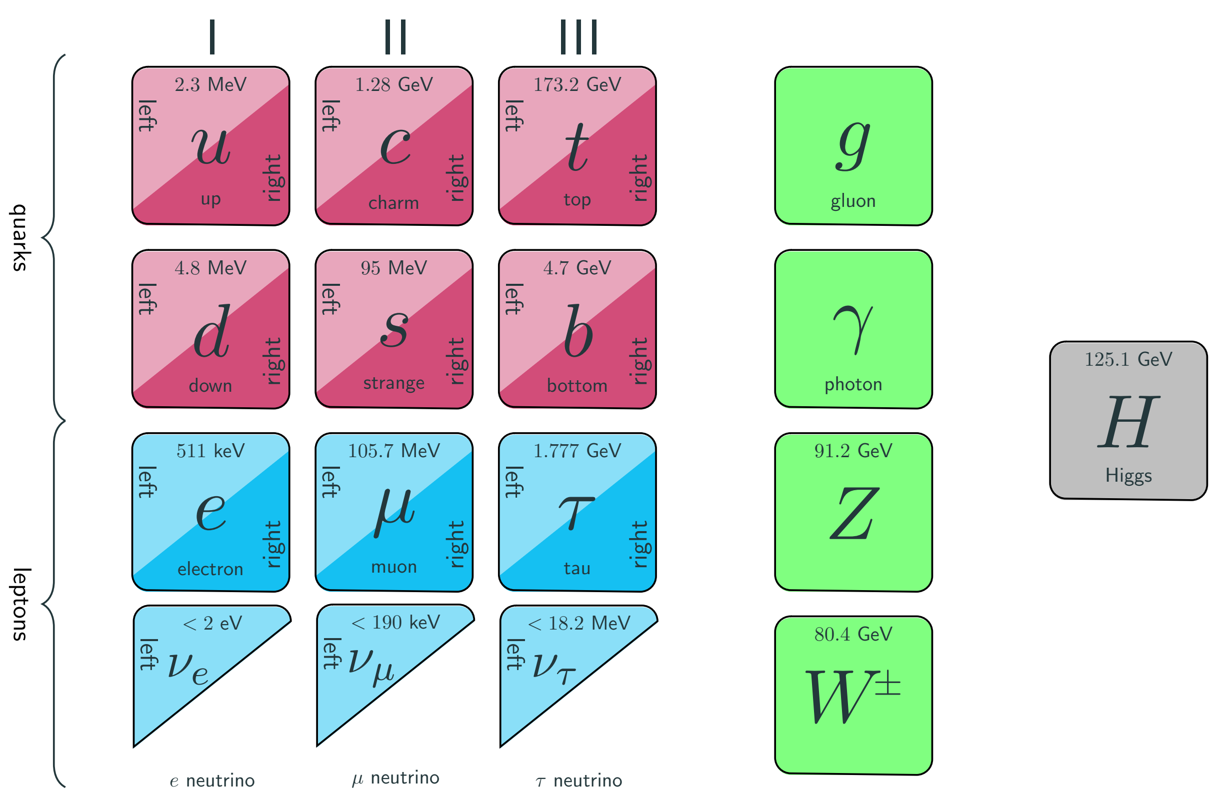
Analysis for two mechanisms only, other 40 possibilities are left as an exercise for homework.

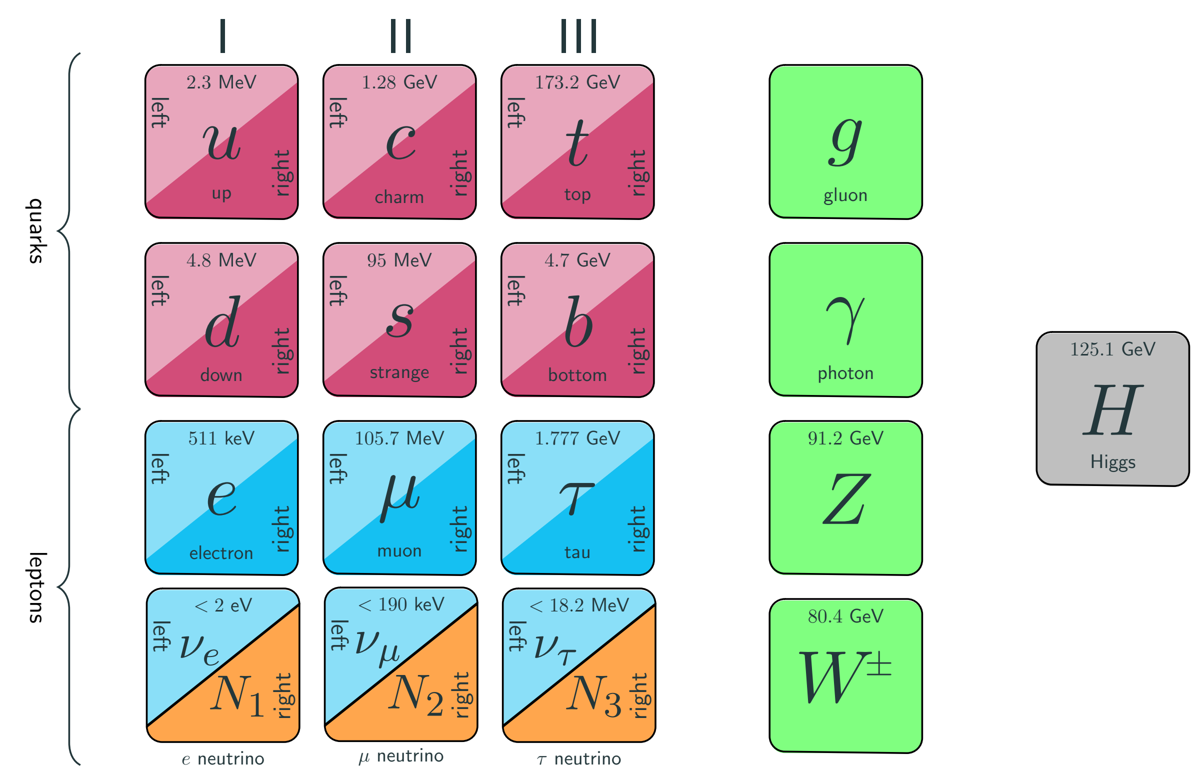
Lectures at this workshop: Julia Harz and Adam Falkowsky

Talks at this workshop: Michaël Sarrazin, Stéphane Lavignac, Rémi Faure, and Rukmani Mohant

Simplicity as a guiding principle

The simplest theory of new physics which can explain all experimental drawbacks of the Standard Model (neutrino masses and oscillations, dark matter, baryon asymmetry of the Universe, incorporating cosmological inflation leading to the observable universe) is at extension of the SM by 3 right-handed neutrinos (or heavy neutral leptons - HNLs) : the minimal see-saw model or νMSM.

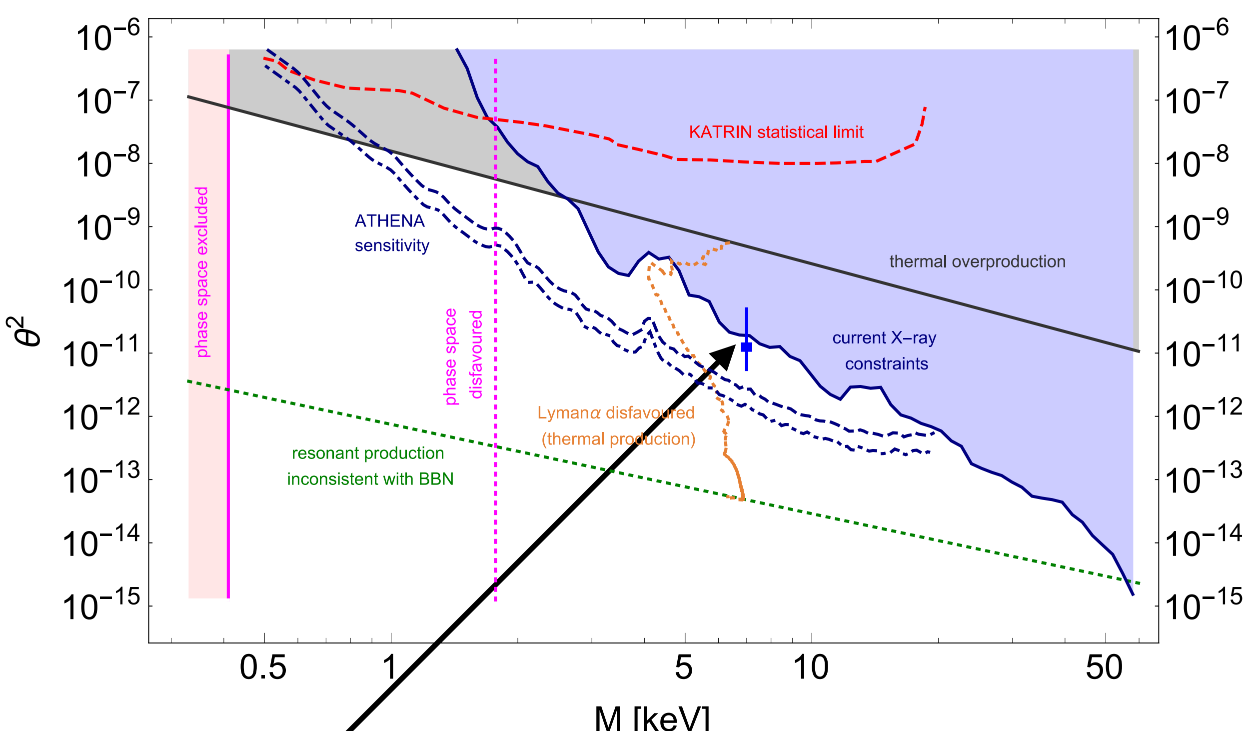




Dark Matter in the νMSM: N_1

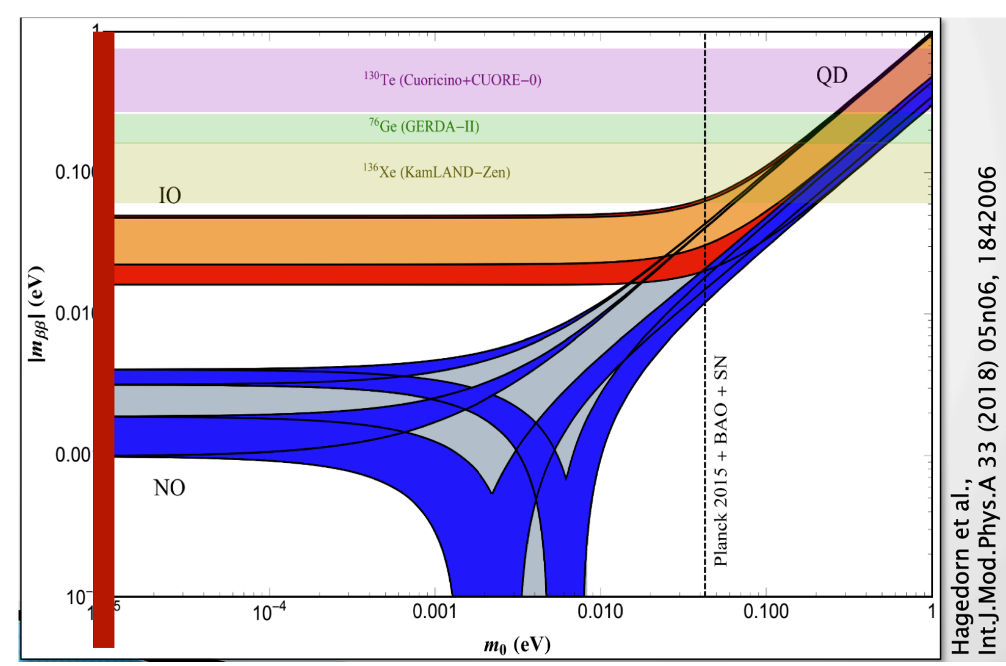
Dark matter sterile neutrino N_1: long-lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N_1 \to \gamma\nu$, what allows for experimental detection by X-ray telescopes in space.

Available parameter space, current situation



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

Future experimental searches:
Hitomi-like satellite XRISM (2023?),
Large ESA X-ray mission
Athena + (2028?)



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

Minimal see-saw model with 2 Majorana fermions (HNLs, or heavy neutral leptons) gives rise simultaneously to neutrino masses and baryon asymmetry of the Universe. The DM HNL decouples: its Yukawa couplings are very small!

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

Two generic cases:

(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.

Most general renormalisable see-saw Lagrangian with Majorana neutrinos:

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

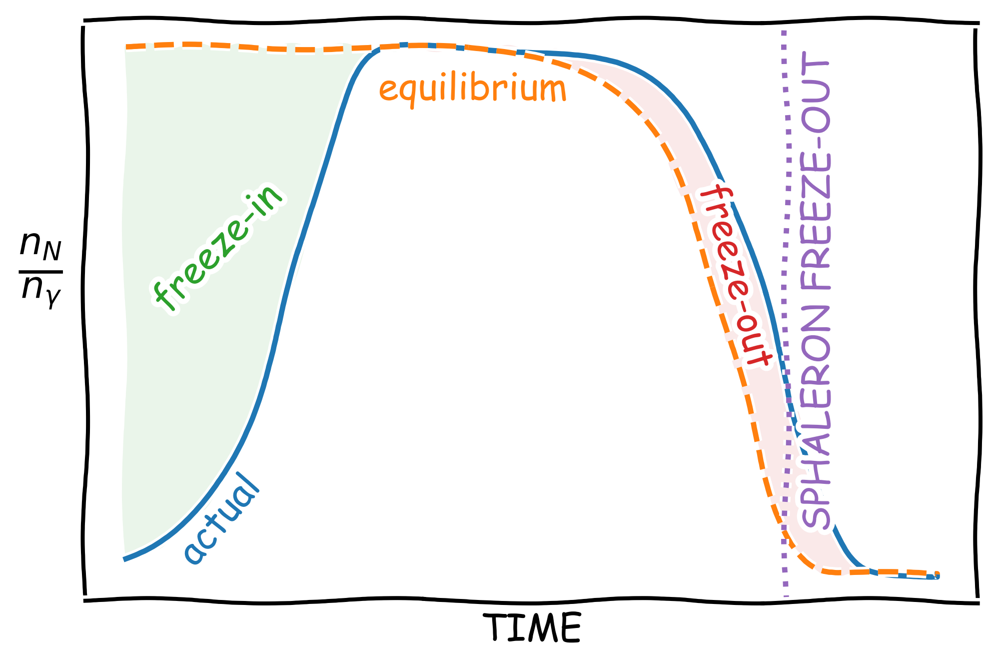
$$L_{\nu MSM} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.,$$

Counting “high energy” parameters, 2 HNLs:
2 Majorana masses of new neutral fermions, 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.

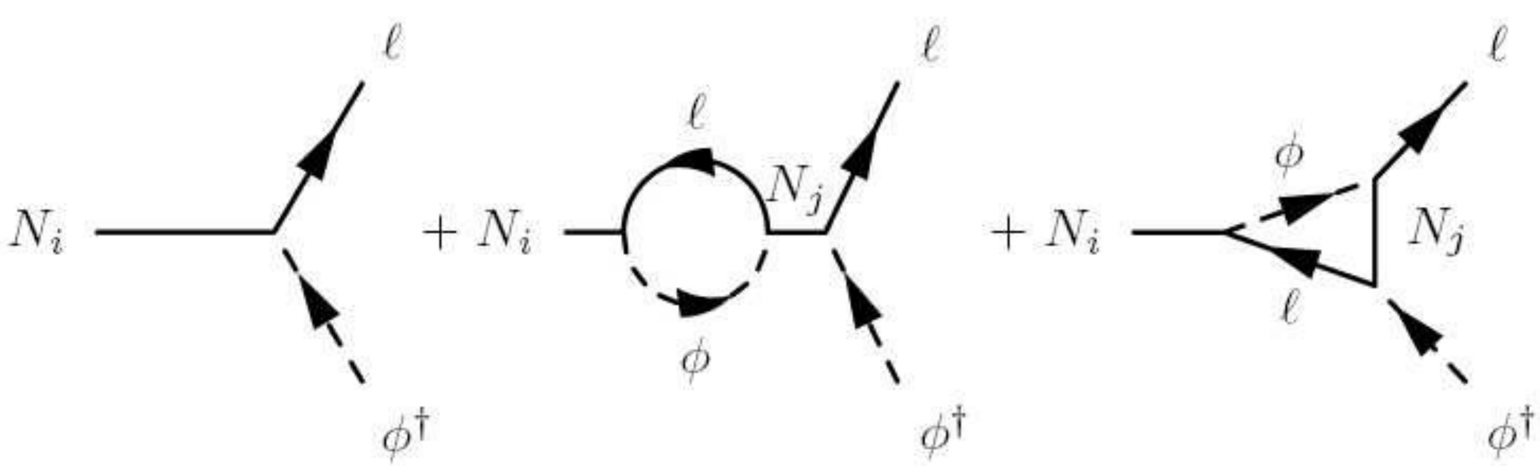
Counting “very low energy” parameters, 2 HNLs:

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

See-Saw leptogenesis



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.



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)

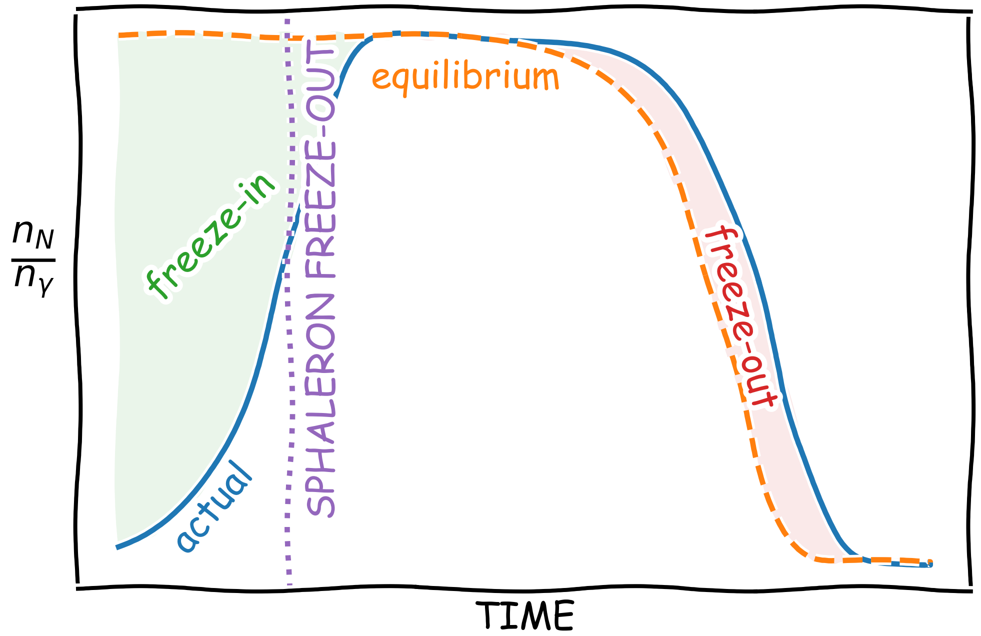
Question: Can we get baryon asymmetry if low energy CP phases are zero?

Answer: Yes, no problem!

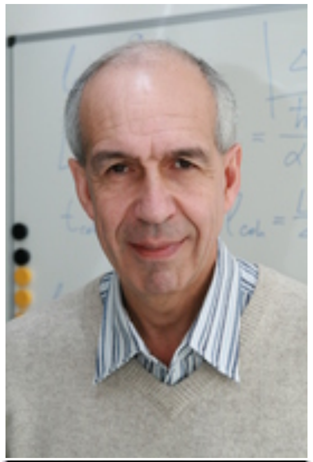
Conclusions for see-saw leptogenesis

It is impossible to find the sign and amplitude of BAU in high scale see-saw model, as we do not (and will not) have an access to essential information about these scales $M \sim 10^{10}$ GeV experimentally.

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.

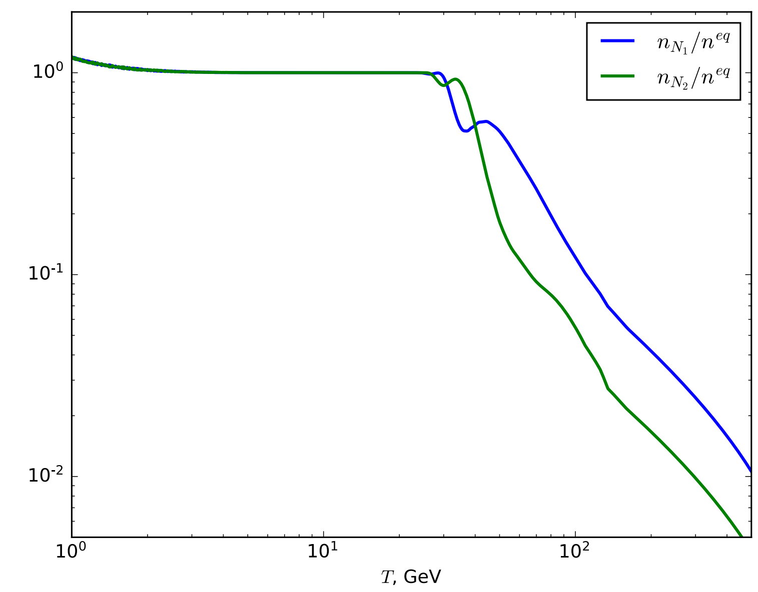
Initial idea: Akhmedov, Rubakov, Smirnov ‘98

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

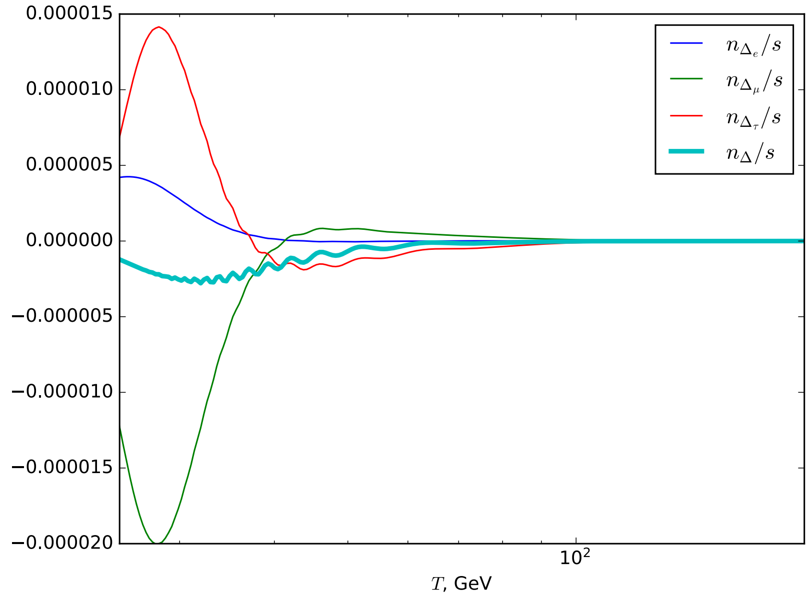
Analysis of baryon asymmetry generation in the NuMSM: Asaka, M.S., Canetti, Drewes, Frossard; Abada, Arcadia, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, Racker, J. Salvado; Drewes, Garbrech, Guetera, Klariç; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine,…

Time evolution

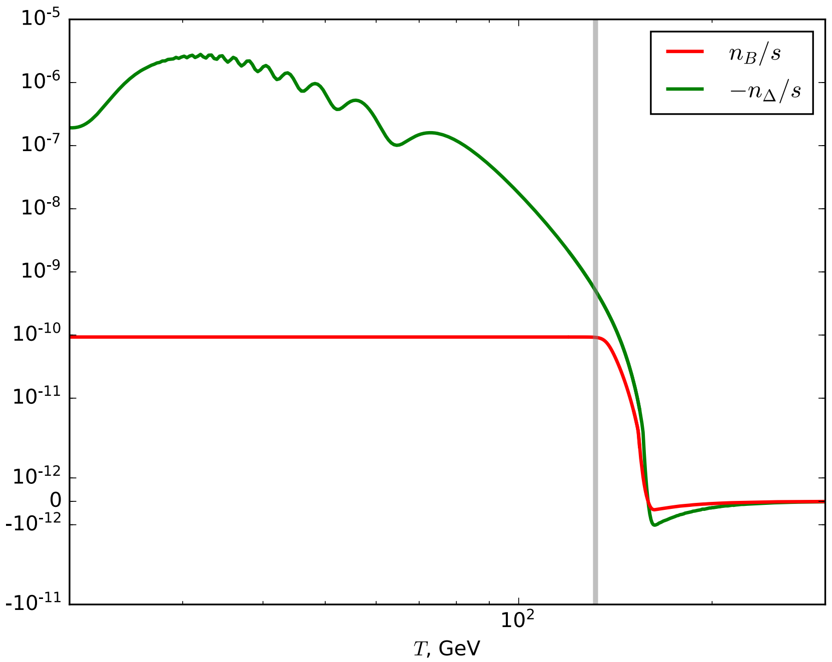
HNL densities



Lepton asymmetries



Baryon asymmetry

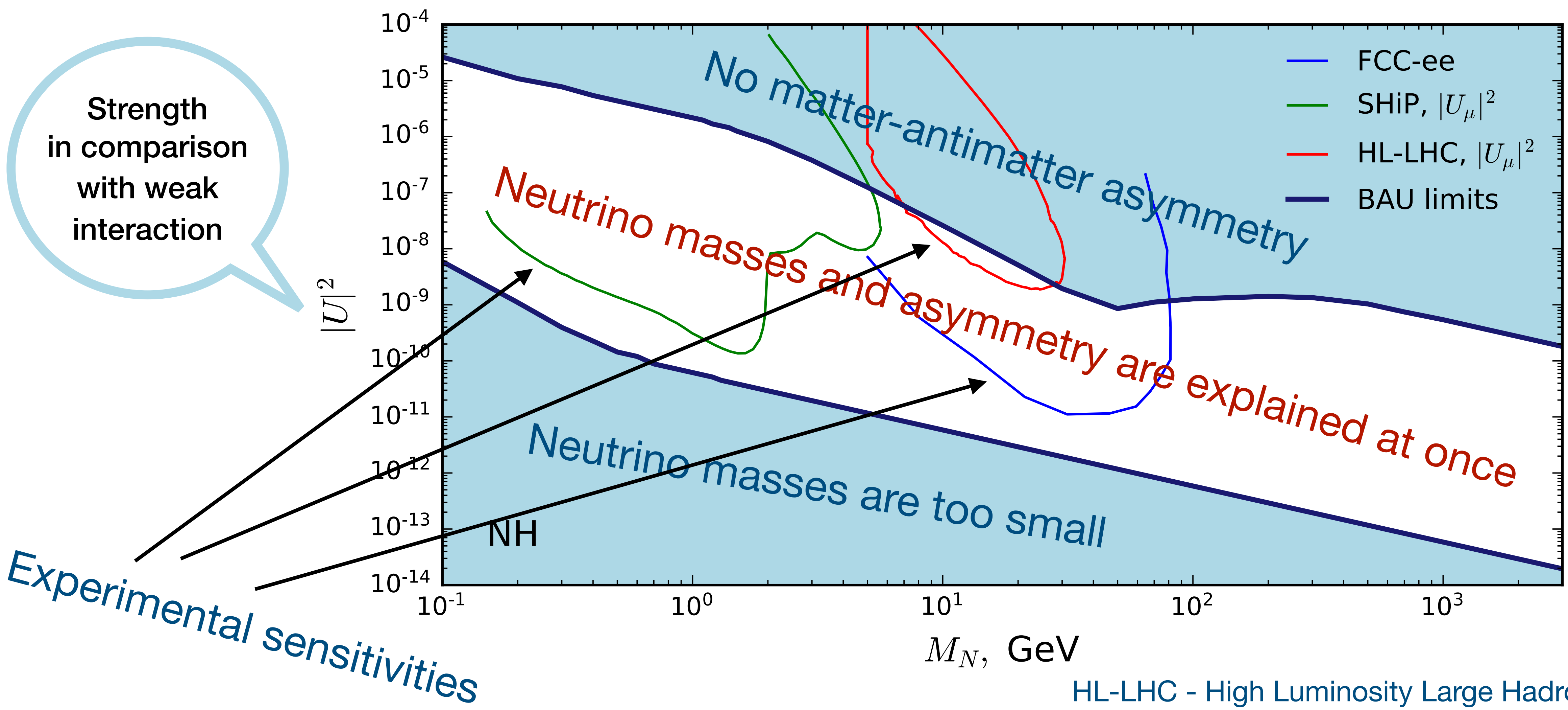


- **Very challenging dream but realistic scenario.** Both HNLs N_2 and N_3 are discovered, their masses and decay branching ratios to electron, muon and tau flavours are found, and CP-violation in their decays is observed. 3 phases must be determined (at least 1 in HNL decays, 2 others can come from "very low energy" neutrino data). This determines all νMSM 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.

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

figure from Klaric, Timiryasov, MS



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!

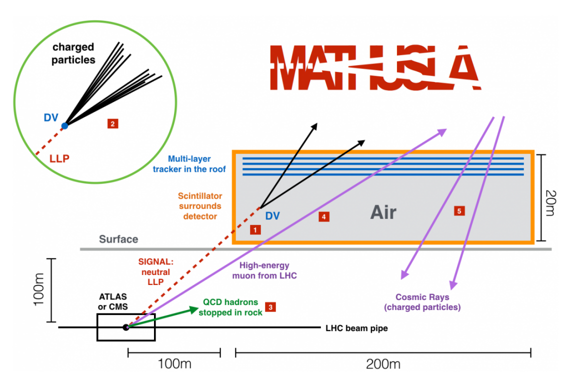
Experimental challenges of the HNL searches

HNLs are the particles belongs to the “Hidden or Dark sector” which commonly known now as FIPs (Feebly Interacting Particles). Feebly means weaker than the weak interactions.Their production and decays are highly suppressed => dedicated experiments are needed.

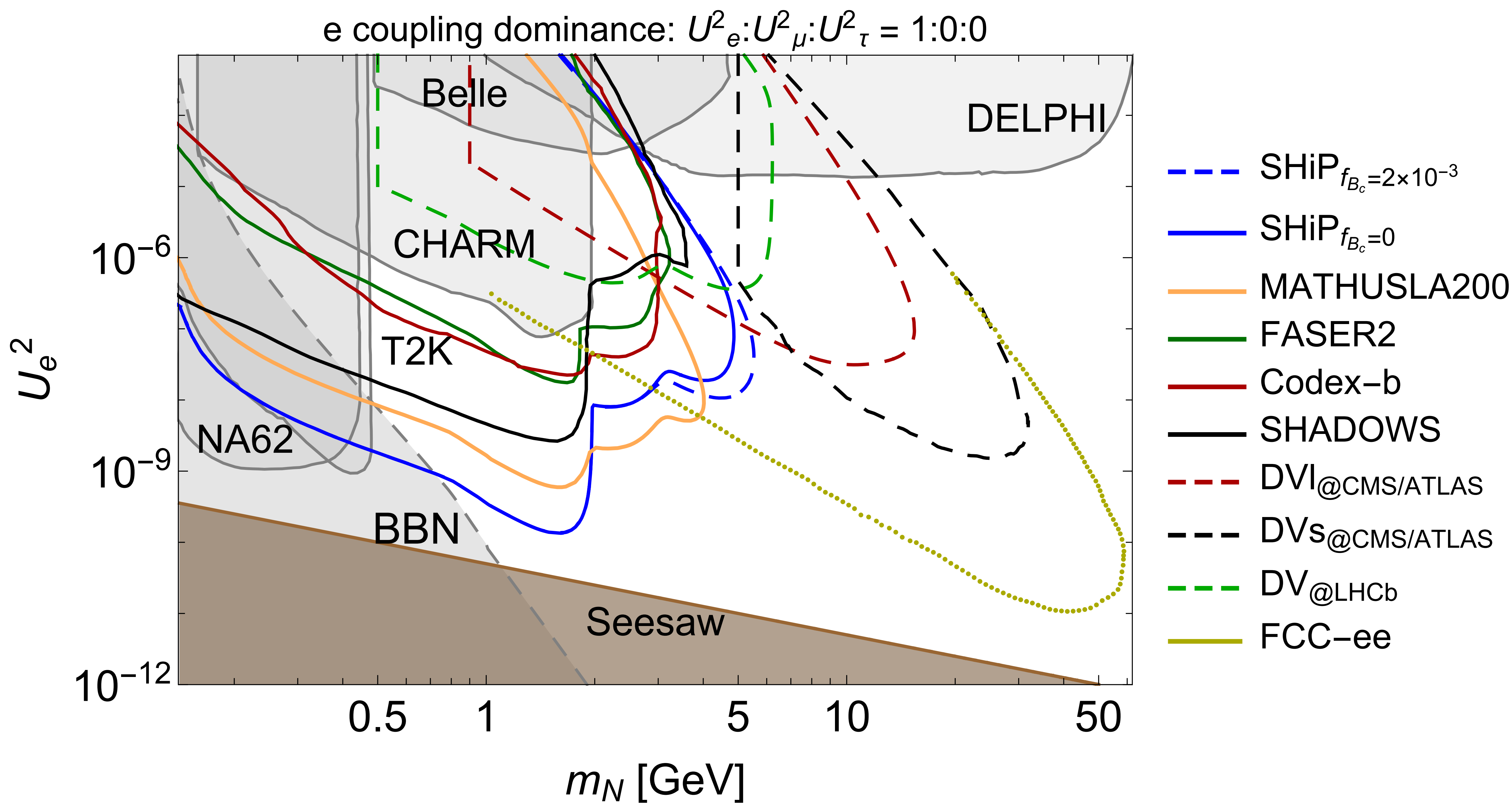
- HNLs can be produced in decays of different mesons (π, K, charm, beauty) , Z and W
- HNLs can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- HNLs can be long lived

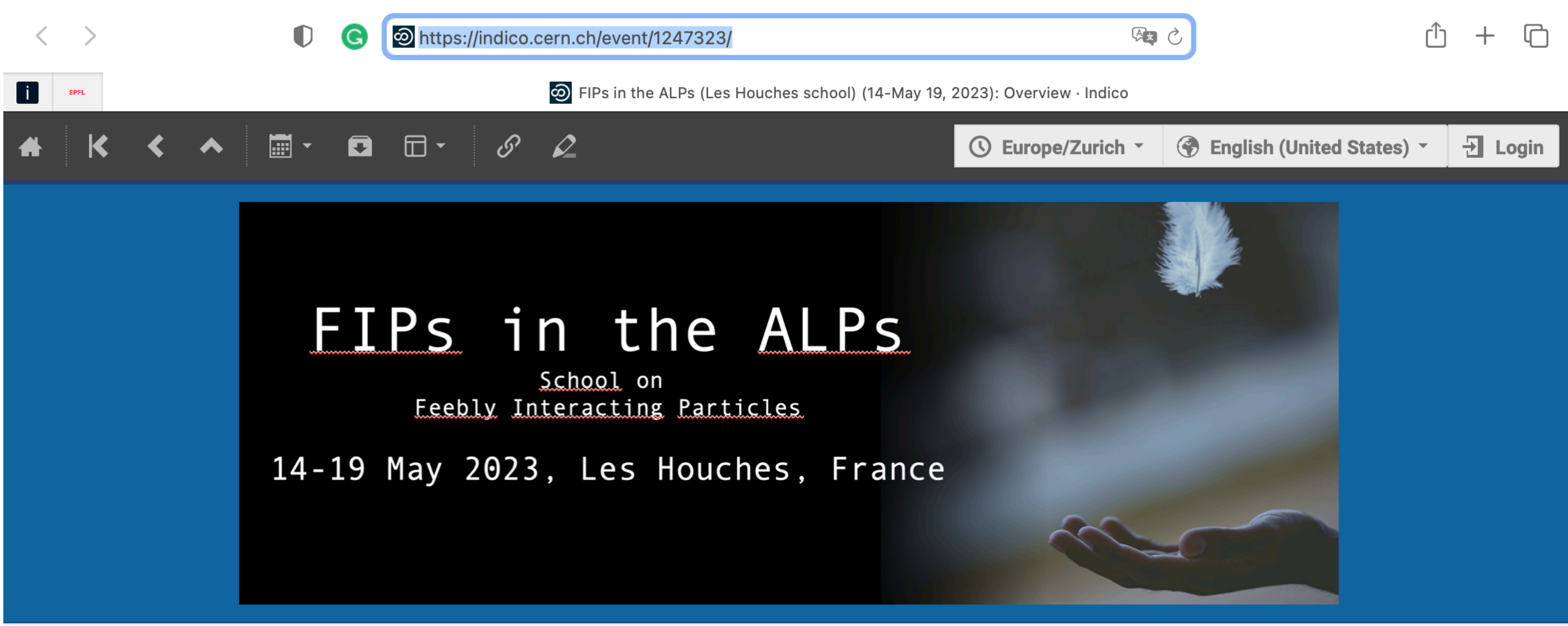
Searches for dark sectors

Search for dark sectors in missing energy events



Projection of bounds on HNLs




https://indico.cern.ch/event/1247323/
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FIPs in the ALPs
School on
Feebly Interacting Particles
14-19 May 2023, Les Houches, France

Conclusions

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

Yes, if we find relevant particles (e.g. HNLs) and find the theory which supersedes the Standard Model.

Search for HNLs

Search for CP-violation in neutrinos and their mass ordering

Search for neutrinoless double beta-decay

Search for New Physics

Search for CP violation in New Physics

When and how we are going to find the origin of the baryon asymmetry?

Nobel expectations for new physics at the LHC

2008

Carlo Rubbia: "Nature will tell"

I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

Our experience of the past has demonstrated that in the world of the infinitely small, it is extremely silly to make predictions as to where the next physics discovery will come from and what it will be.

In a variety of ways, this world will always surprise us all. The next breakthrough might come from beta decay, or from underground experiments, or from accelerators.

We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science.

See expectations of Gross, t'Hooft, Osheroff, Smoot, and Veltman at http://lhc2008.web.cern.ch/lhc2008/nobel/

Many thanks to organisers!

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