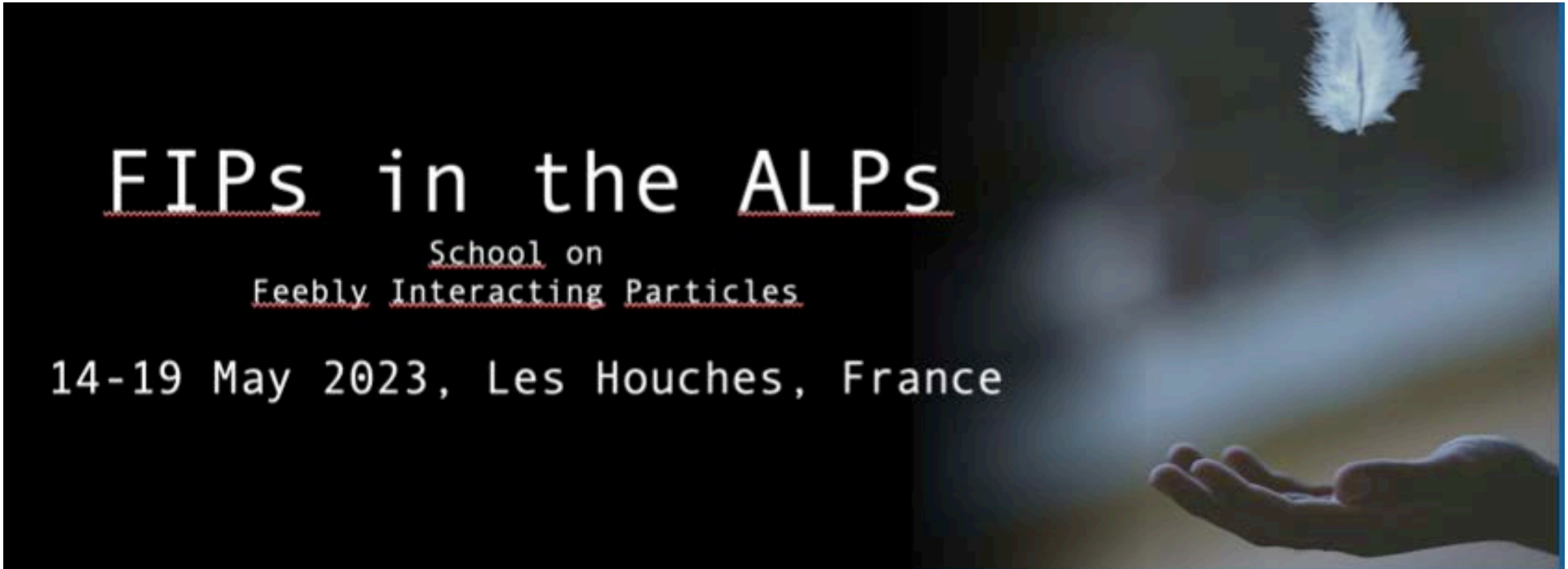
Heavy Neutral Leptons in particle physics and cosmology

Mikhail Shaposhnikov



Many overviews of the subject

- The Role of sterile neutrinos in cosmology and astrophysics, Ann. Rev. Nucl. Part. Sci. 59 (2009) , Boyarsky, Ruchayskiy, MS
- A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, Rept. Prog. Phys. 79 (2016) 12, Alekhin et al.
- Sterile neutrino Dark Matter, Prog. Part. Nucl. Phys. 104 (2019) 1, Boyarsky, Drewes et al
- The present and future status of heavy neutral leptons, J. Phys. G 50 (2023) 2, 020501, Abdullahi et al
- …

Outline

- (Very long) introduction with motivations: current situation in High Energy Physics, naturalness, problems of the Standard Model, simplicity
- νMSM as the minimal model of new physics
- HNLs in particle physics and cosmology
- Conclusions
- Continuation: Marco Drewes

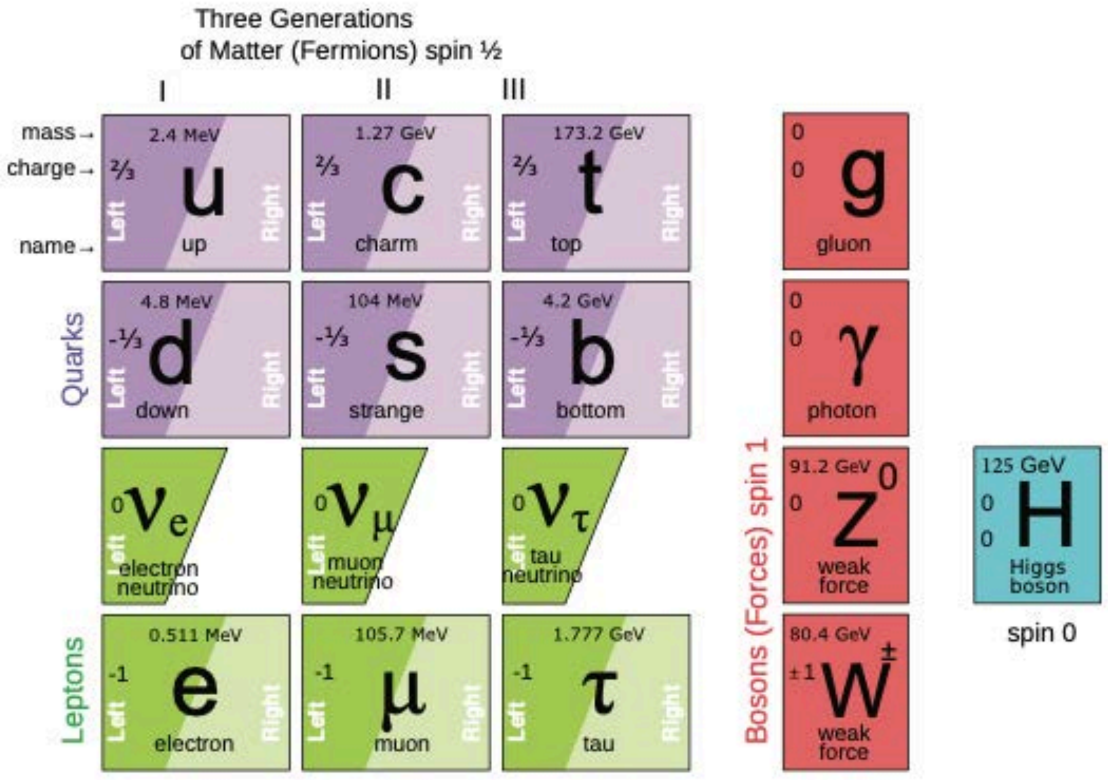
Current situation in High Energy Physics

The Standard Model (SM) of particle physics was invented in 1967 and completed with the discovery of the Higgs boson at the LHC 45 years later, in 2012.

- SM describes strong, weak and electromagnetic interactions of all known elementary particles

- it is consistent with almost all experiments in particle physics

- it is a self-consistent theory that allows to describe physics at very small and very large energies, possibly running all the way up to the Planck scale 10^{19} GeV (15 orders of magnitude larger than the LHC energy!).



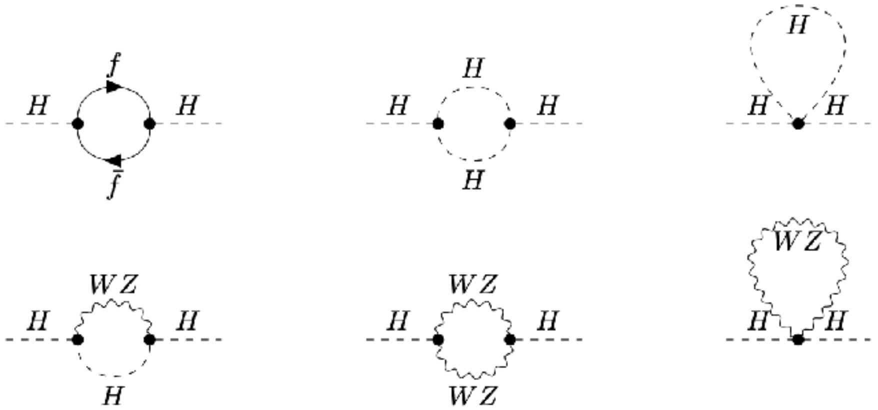
However, this is not a final story!

Naturalness as a guiding paradigm for new physics?

For about 30 years, many people thought that new physics beyond the SM is around the corner. This is because of the Higgs mass fine-tuning.

- The problem: take the Standard Model and consider radiative corrections to the Higgs mass. Quadratically divergent diagrams

$$\delta m_H^2 \propto f_t^2 \int \frac{d^4k}{k^2}$$



lead to the term $\delta m_H^2 \propto f_t^2 \Lambda^2$, f_t - top quark Yukawa coupling, Λ - the ultraviolet cutoff of the theory, i.e. the place where the Standard Model is substituted by the more fundamental theory of Nature. Since $m_H \ll \Lambda$, one has to fine-tune the tree Higgs mass M_{tree} to cancel the radiative correction(s). **The amount of fine-tuning:**

$$\epsilon_H = \frac{M_{\text{tree}}^2 - \delta m_H^2}{\Lambda^2} \sim \left(\frac{100 \text{ GeV}}{4\pi\Lambda}\right)^2 \ll 1$$

Cosmological constant fine-tuning

The similar logic can be applied to vacuum energy ϵ_{vac}:

$$\delta\epsilon_{\text{vac}} \propto \int d^4k$$

The radiative corrections are proportional to the fourth power of the cutoff scale, $\delta\epsilon_{\text{vac}} \propto \Lambda^4$, leading to **even higher degree of fine-tuning**

$$\epsilon_{\text{cc}} = \frac{\epsilon_{\text{vac}}^{\text{tree}} - \delta\epsilon_{\text{vac}}}{\Lambda^4} \sim \left(\frac{10^{-3}\ \text{eV}}{\Lambda}\right)^4 \ll \ll 1$$

Two problems

1. Why the physical values of the Higgs mass and of the cosmological constant are much smaller than the scale of new physics (cutoff Λ) ?

2. Why the tree values of these parameters are so fine-tuned to the radiative corrections?

Naturalness

- These fine tunings must be avoided at any price!

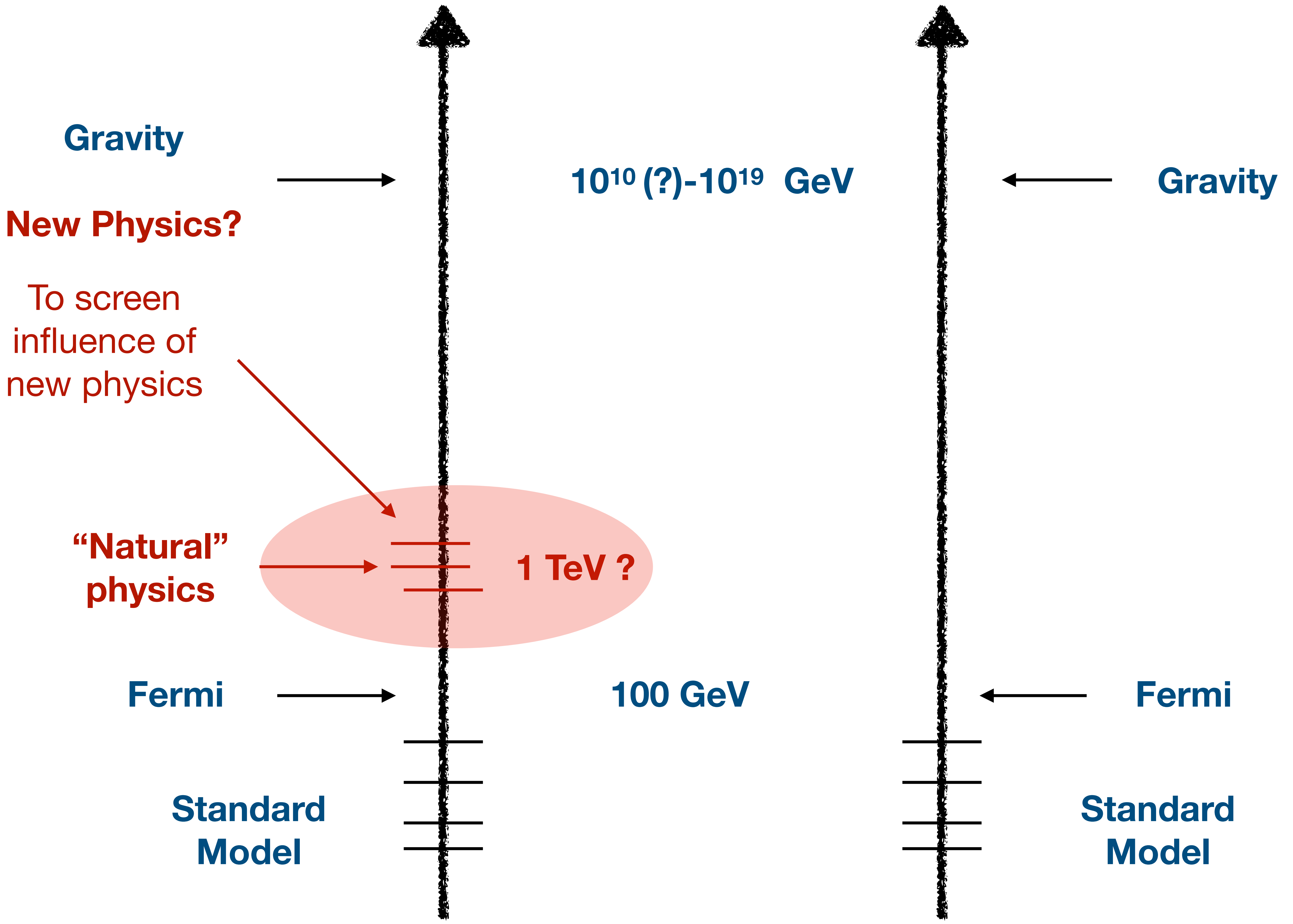
- The cutoff Λ must be of the order of the Fermi scale to screen the influence of high energy domain from low energy domain.

“Natural” theories

- SUSY: cancellation of quadratic divergences between bosons and fermions
- Composite Higgs boson: no fundamental scalars
- Large extra dimensions: fundamental constant of gravity - Planck scale - is of the order of electroweak scale
- Cosmological evolution leading to $m_H \ll \Lambda$?
- Environmental selection leading to $m_H \ll \Lambda$?

Generically, all these proposals lead to some kind of new physics right above the Fermi scale.

“Natural” spectrum versus “Unnatural” spectrum



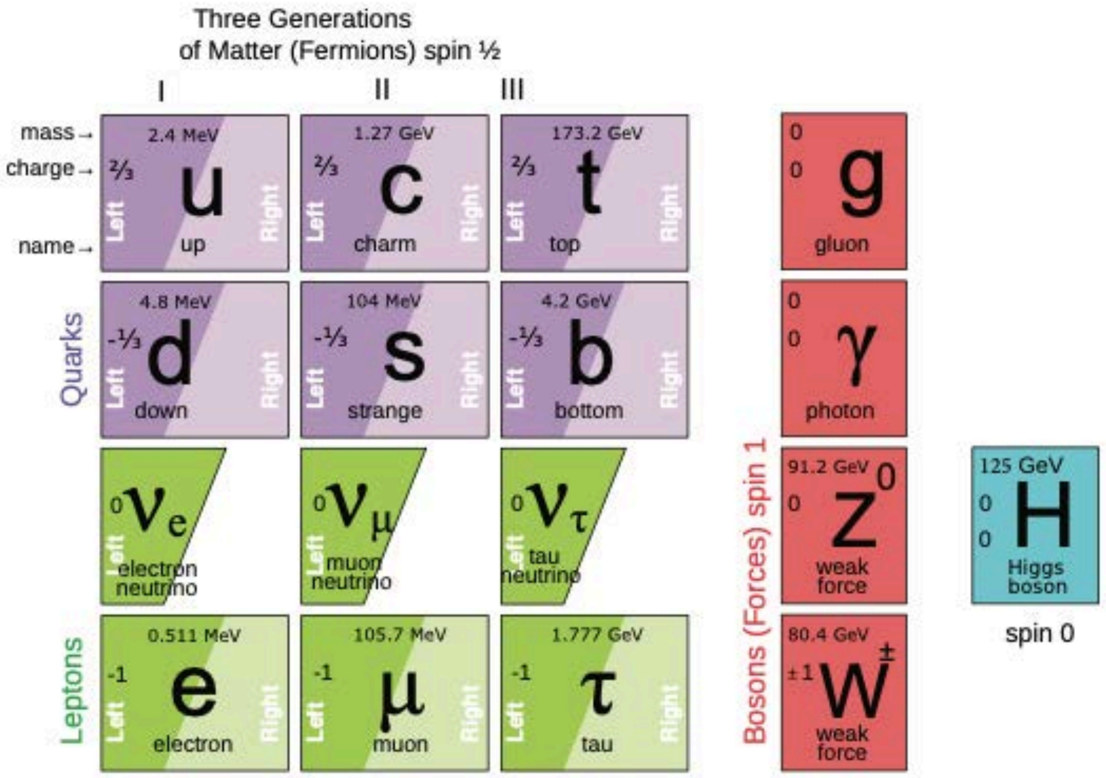
Experiment

LHC has discovered something quite unexpected: the Higgs boson and nothing else, confirming the Standard Model.

- SM correctly describes strong, weak and electromagnetic interactions of all known elementary particles

- it is consistent with almost all experiments in particle physics

- with 125 GeV Higgs boson, it is a self-consistent theory valid at very small and very large energies, possibly running all the way up to the Planck scale 10^{19} GeV (15 orders of magnitude larger than the LHC energy!).



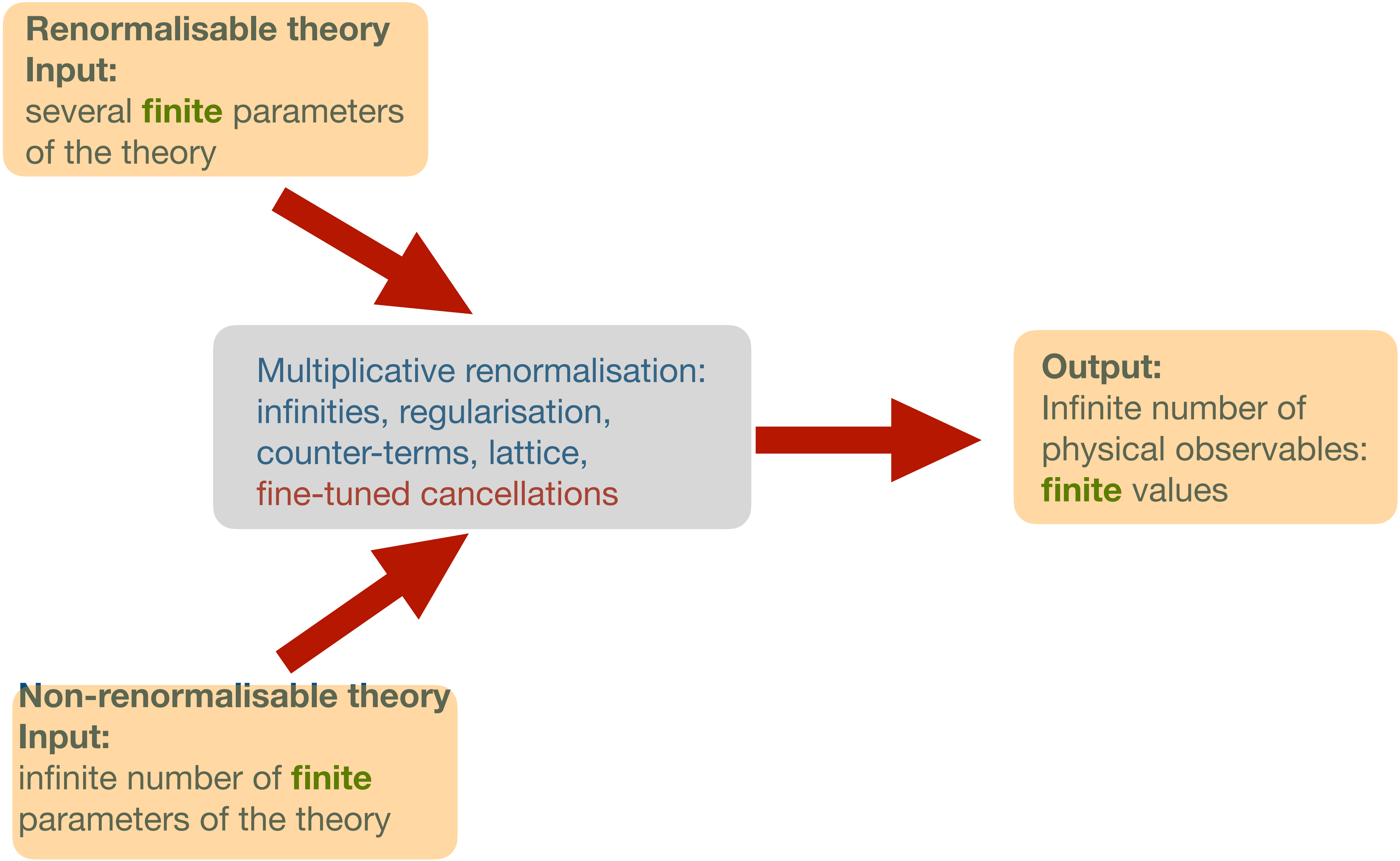
Naturalness failed experimentally.
Can we understand this theoretically?

Origin of the fine-tunings

The core of the problem: quadratic (or quartic, for the cosmological constant) divergences, inevitably appearing in Feynman diagrams with loops in theories with fundamental scalar fields

Renormalisation:

- Regularise UV divergent expressions (cutoff, Pauli-Villars, dimreg,…)
- Subtract divergences (this is exactly where fine-tunings show up)
- Get finite values for physical observables



Renormalisable theory
Input:
several **finite** parameters of the theory

Multiplicative renormalisation:
infinities, regularisation,
counter-terms, lattice,
fine-tuned cancellations

Output:
Infinite number of physical observables:
finite values

Non-renormalisable theory
Input:
infinite number of **finite** parameters of the theory

Finite formulation of QFT

Renormalisable theory
Input:
several **finite** parameters of the theory

Non-renormalisable theory
Input:
infinite number of **finite** parameters of the theory

Output:
Infinite number of physical observables: **finite** values

Is there hierarchy problem in finite formulations of QFT?

No infinities (quartic, quadratic, log) in finite QFT - no fine-tunings?
If all expressions are finite, the computation of low energy observables should not require the knowledge of the UV domain of the theory.

No divergencies - no arguments in favour of SUSY or composite Higgs models (these theories proposed to take away quadratic divergencies).

The existence of such a formalism (without large cancellations) would challenge the “naturalness” paradigm.

If just one particular formalism of computations in QFT without necessity of fine-tunings exists, it will provide a strong argument that the problem of quantum stability of the electroweak scale against radiative corrections is formalism-dependent and thus unphysical.

Finite QFT formalisms

Details: Sander Mooij, MS (2021)

Replacement of Feynman diagram technique by the system of equations (similar to RG). The solution reproduces all the physics without any infinities and fine-tunings

Equations: similar to Callan-Symanzik (1970); t'Hooft (2004)

Other approaches: Bogolubov-Parasuk-Hepp-Zimmermann (1957); Lehmann, Symanzik and Zimmermann (1955); Nishijima (1960)

How to reconcile the different conclusions coming from "naturalness" and finite QFT? Infinities and fine-tunings in Feynman diagrams appear at intermediate steps of computations and occur between Lagrangian (rather than physical) parameters. Thus, they do not carry physical meaning.

“Naturalness” in effective field theories

“Prediction” of ρ-meson mass (also of the c-quark from K-physics): the mass difference between the charged and neutral pions is quadratically divergent

$$m_{\pi^+}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi} \cdot \Lambda^2, \quad \Lambda \simeq m_\rho (?)$$

- The low energy effective theory of pions is renormalisable - so prediction of the scale of “new physics” is impossible.
- The result of the naturalness paradigm for “new physics” is thus not generic and is rooted deeply into the structure of the underlying renormalisable field theory - QCD.

“Naturalness” in the SM?

New physics scales Λ from “naturalness”, for SM: $\Lambda \sim$ 1 TeV.

- for cosmological constant: $\Lambda \sim$ 0.01 eV.

- Nothing drastic happens at these energy scales! The SM is perfectly consistent for energies much exceeding the Planck scale without any new physics.

- The naturalness predictions would work if the SM extension were QCD- like, e.g. dynamically broken SUSY or composite Higgs boson.

- The failure of “naturalness” is telling us that the fundamental theory embracing the Standard Model is not QCD-like. Anyway, fundamental theory should include gravity, which has nothing to do with QCD.

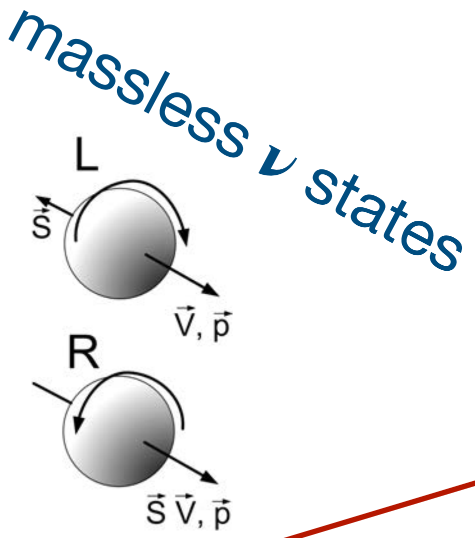
Steps beyond the Standard Model

Living without “naturalness” : how to construct the theory superseding the Standard Model? What is the scale of new physics?

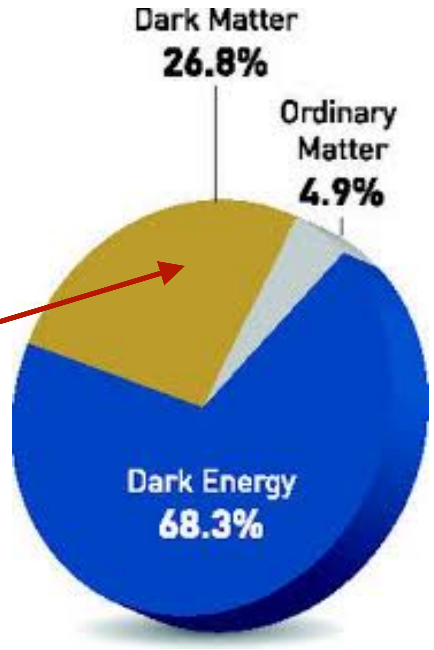
Use the observations indicating that the SM is not complete?

Problems of the Standard Model

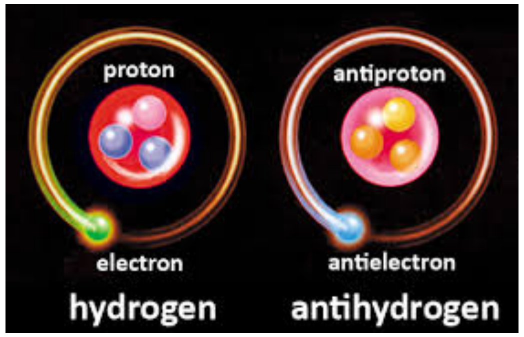
- In the SM neutrinos are exactly massless and lepton numbers are conserved. Experimentally neutrinos have tiny, but non-zero masses.



- Our Universe contains an unidentified substance: Dark Matter (DM), which the SM cannot explain.

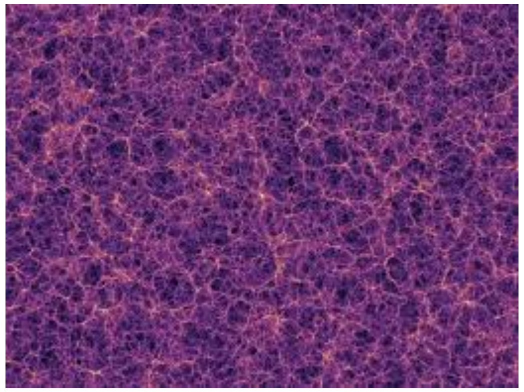


- Our Universe does not contain antimatter in amounts comparable with the matter. Why this asymmetry between particles and antiparticles?



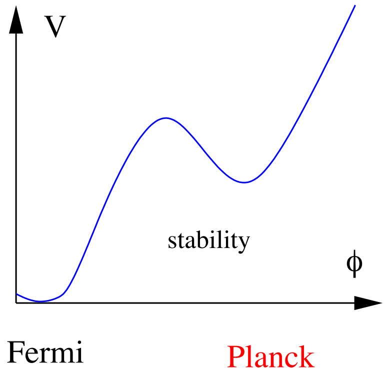
present absent

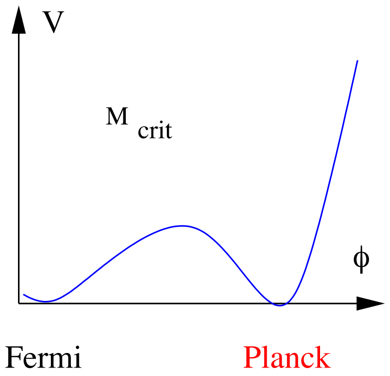
- Our Universe is flat, homogeneous and isotropic at very large scales, but contains structures - galaxies, clusters, at smaller scales. Why so?

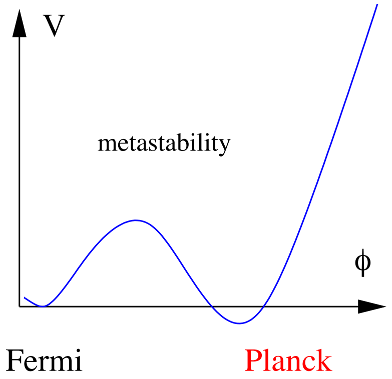


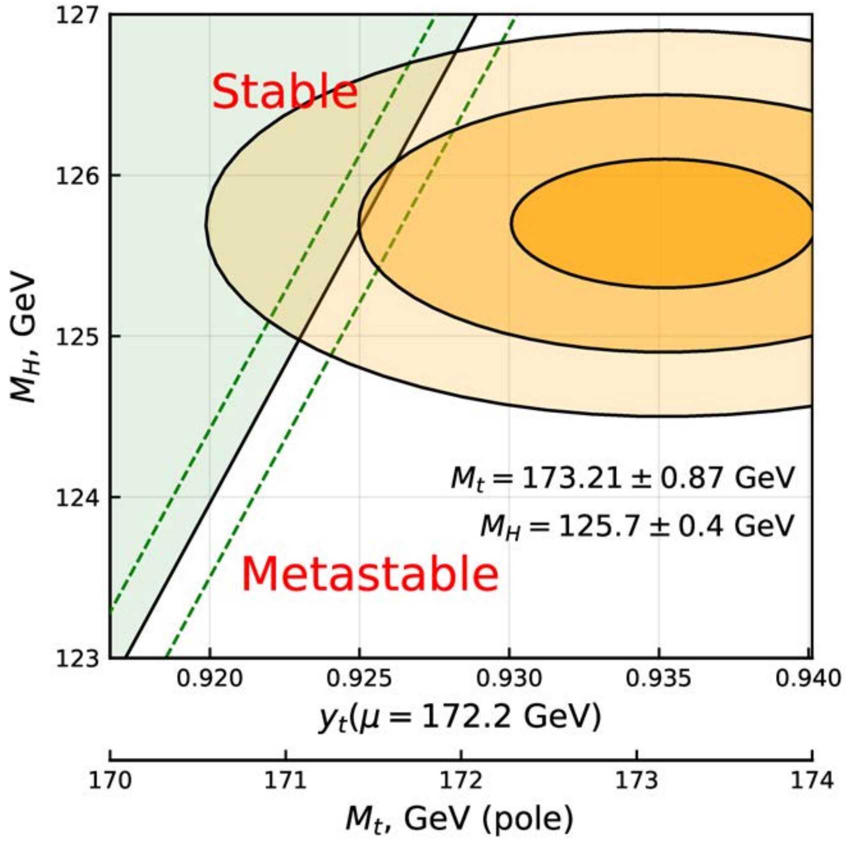
Matter distribution

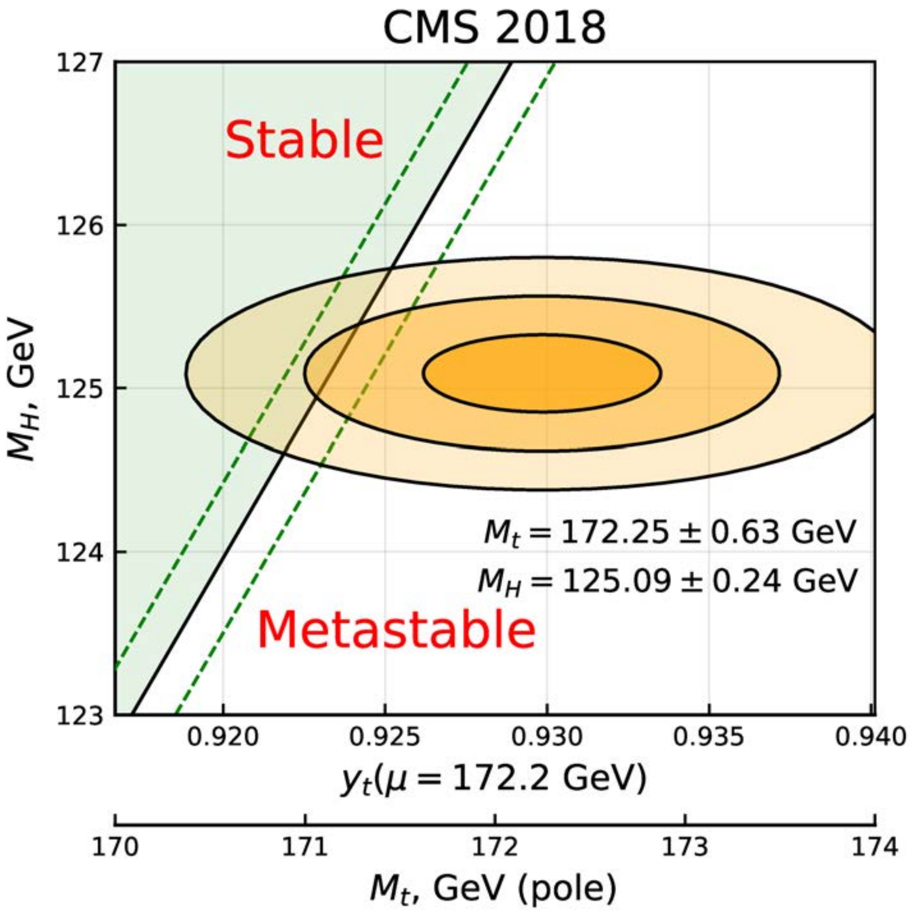
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling











Energy scale of new physics

The solid theory guidance which has led to the discovery of the Higgs boson is over (unitarity: either Higgs boson or new physics at the LHC): SM with 125 GeV Higgs is self-consistent up to the Planck scale!

Can we get the energy scale of new physics from experiment?

- Neutrino masses and oscillations:
  the masses of right-handed see-saw neutrinos can vary from 1 eV to 10^{15} GeV

- Dark matter, absent in the SM:
  the masses of DM particles can be as small as 10^{-22} eV (super-light scalar fields) or as large as 10^{20} GeV (wimpzillas, Q-balls)

- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as 10 MeV or as large as 10^{15} GeV

- Inflation: inflaton can be as light as few GeV or as heavy as 10^{10} GeV. Also, the Standard Model Higgs boson can drive inflation - no new particle is needed!

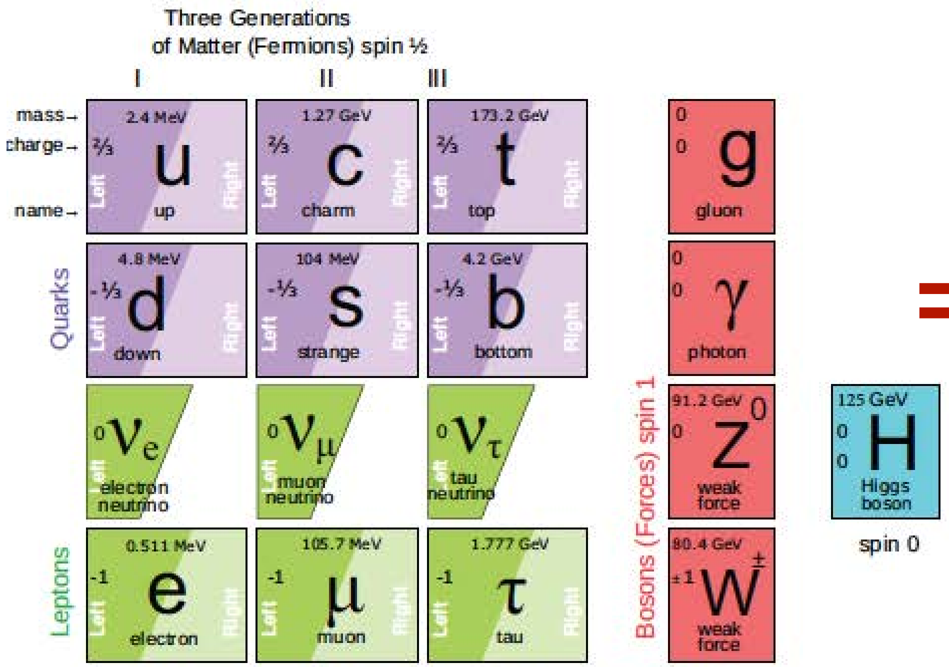
Simplicity as a guiding principle

“Simplicity” is the most conservative approach:

- no new symmetries in comparison with the Standard Model - SU(3)xSU(2)xU(1),
- the same family structure as in the SM

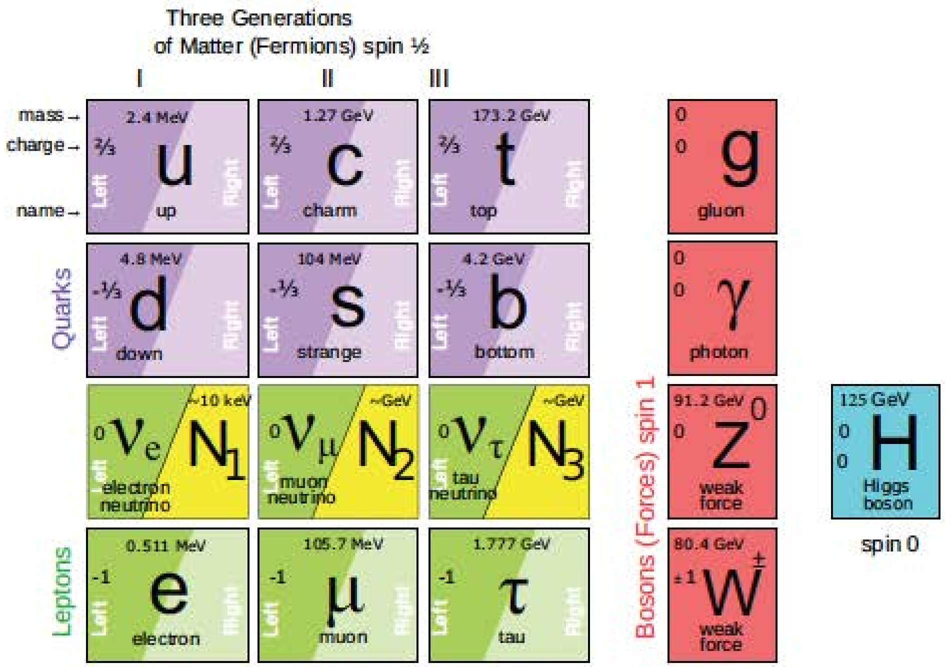
Simplicity: solving all SM problems with νMSM

massless ν



⇒

massive ν



- Role of Heavy Neutral leptons (HNLs) N_2, N_3 with masses above 100 MeV: "give" masses to neutrinos and produce baryon asymmetry of the Universe.
- Role of N_1 with mass in keV region: dark matter.
- Role of the Higgs boson: break the symmetry and inflate the Universe - Higgs inflation.

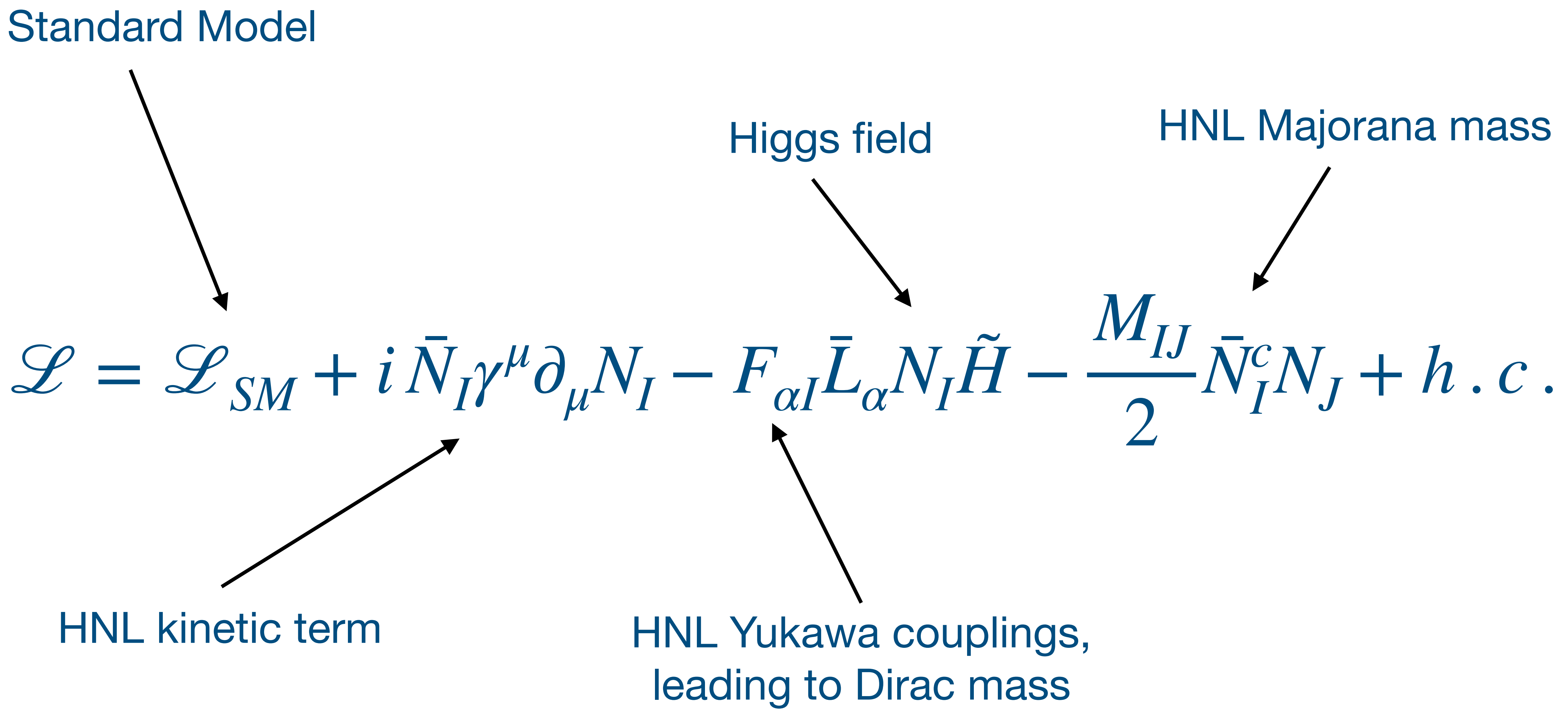
Historical analogue

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

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

HNL kinetic term

HNL Yukawa couplings,
leading to Dirac mass

Counting parameters:

1 HNL: does not work, only one neutrino is massive.

2 HNLs: 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. All neutrino physics explained. Baryon asymmetry is explained.

3 HNLs (motivation: we have 3 fermonic generations): 3 Majorana masses of new neutral fermions N, 15 new Yukawa couplings in the leptonic sector (3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases), 18 new parameters in total. All neutrino physics explained. Baryon asymmetry is explained. Dark matter is explained.

Low energy theory

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

When the Dirac mass $m_D \sim F\langle H\rangle \ll M$ Majorana mass, the HNLs can be “integrated out”. The resulting theory is the SM + 5-dimensional Weinberg operator

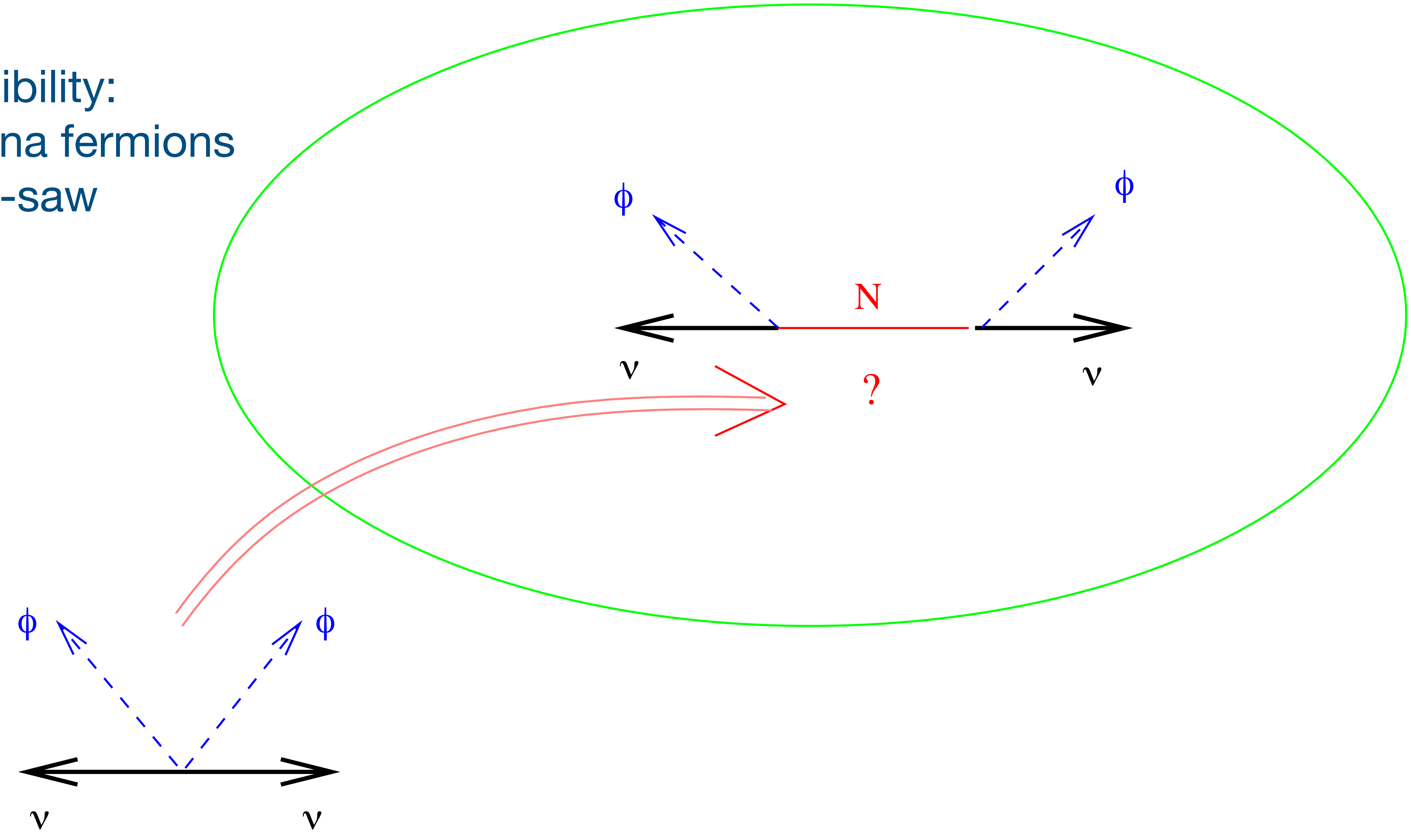
$$\mathscr{L} = \mathscr{L}_{SM} + A_{\alpha\beta}\left(\bar{L}_\alpha\tilde{H}\right)\left(H^\dagger L_\beta^c\right) \longleftarrow$$

Weinberg 5-dimension operator
See-saw formula for neutrino masses

with $A = -FM^{-1}F^T$ in matrix notations

Origin of the Weinberg operator

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



Counting parameters of low energy theory:

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!

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

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!

HNL properties in the νMSM

N_1- Dark Matter particle, $N_{2,3}$ - responsible for neutrino masses and baryogenesis

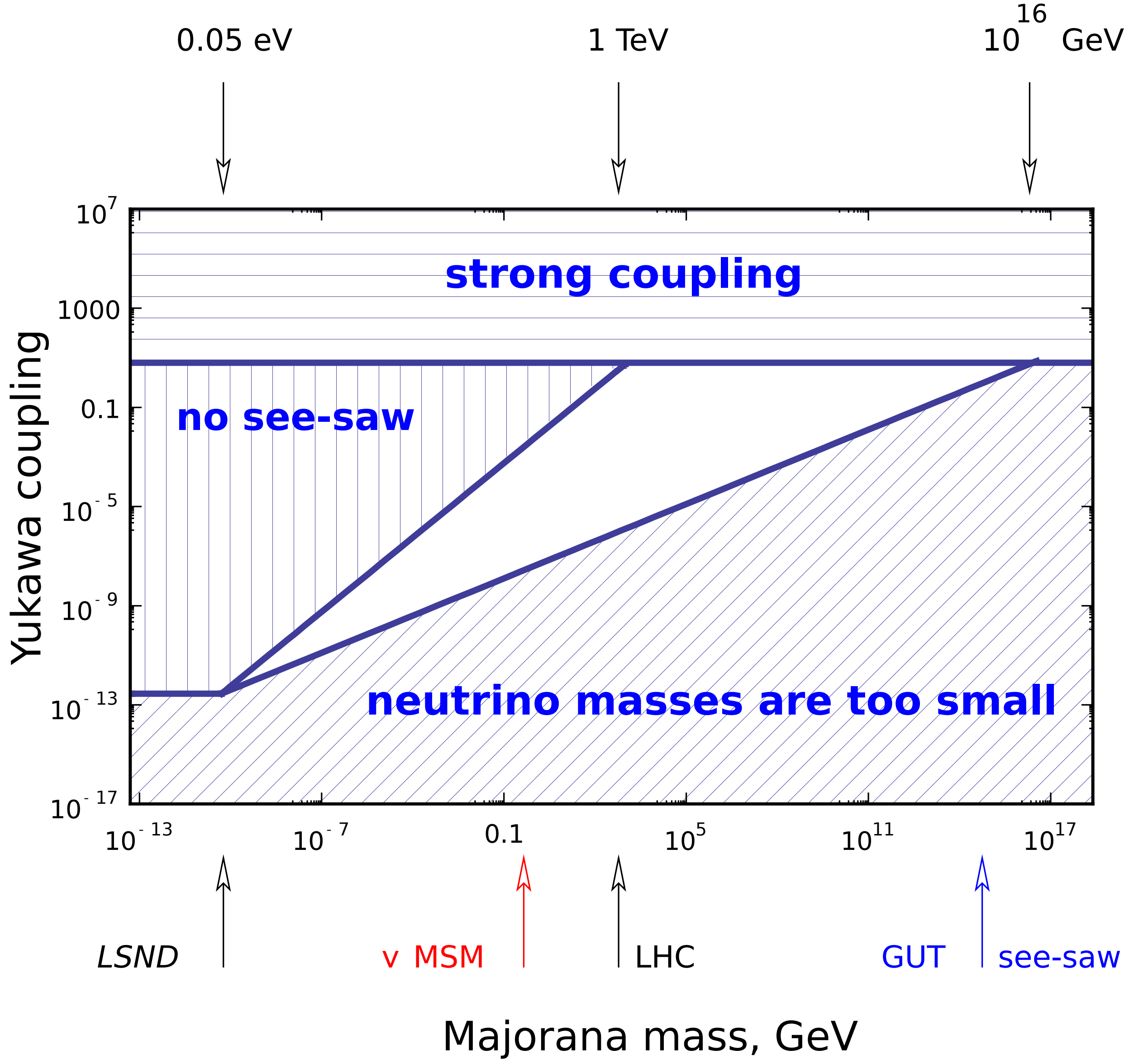
- From neutrino physics
- From cosmology: dark matter and baryon asymmetry of the Universe
- Applications to experiments: HNL searches, lepton flavour number violation, neutrino-less double beta decays,…

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!

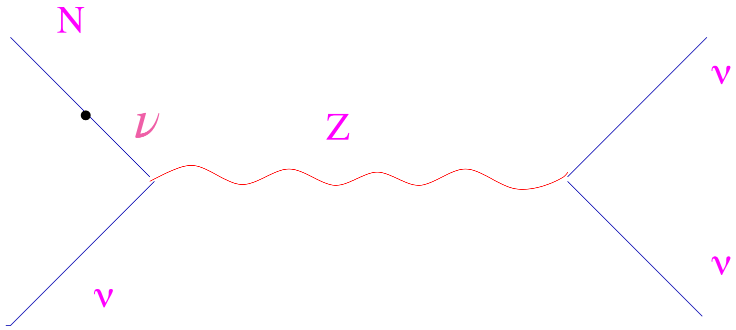
$$m_\nu \propto \frac{F^2 v^2}{M}$$



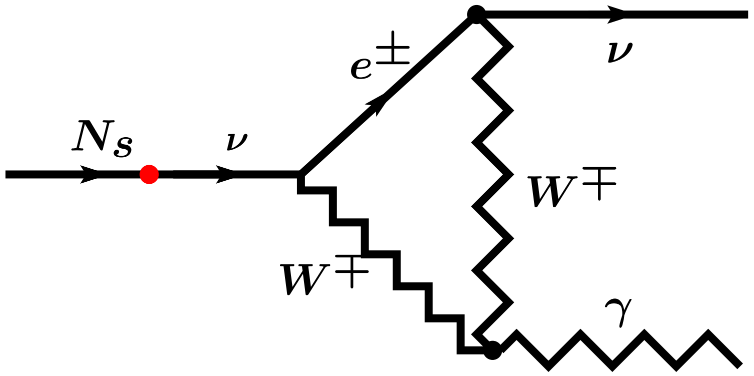
Constraints on DM sterile neutrino N₁

$$\theta = m_D/M_M$$

- **Stability.** N₁ must have a lifetime larger than that of the Universe. Main decay mode $N_1 \to 3\nu$ is not observable.



- **X-rays.** N₁ decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line $E_\gamma = M_1/2$ which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).

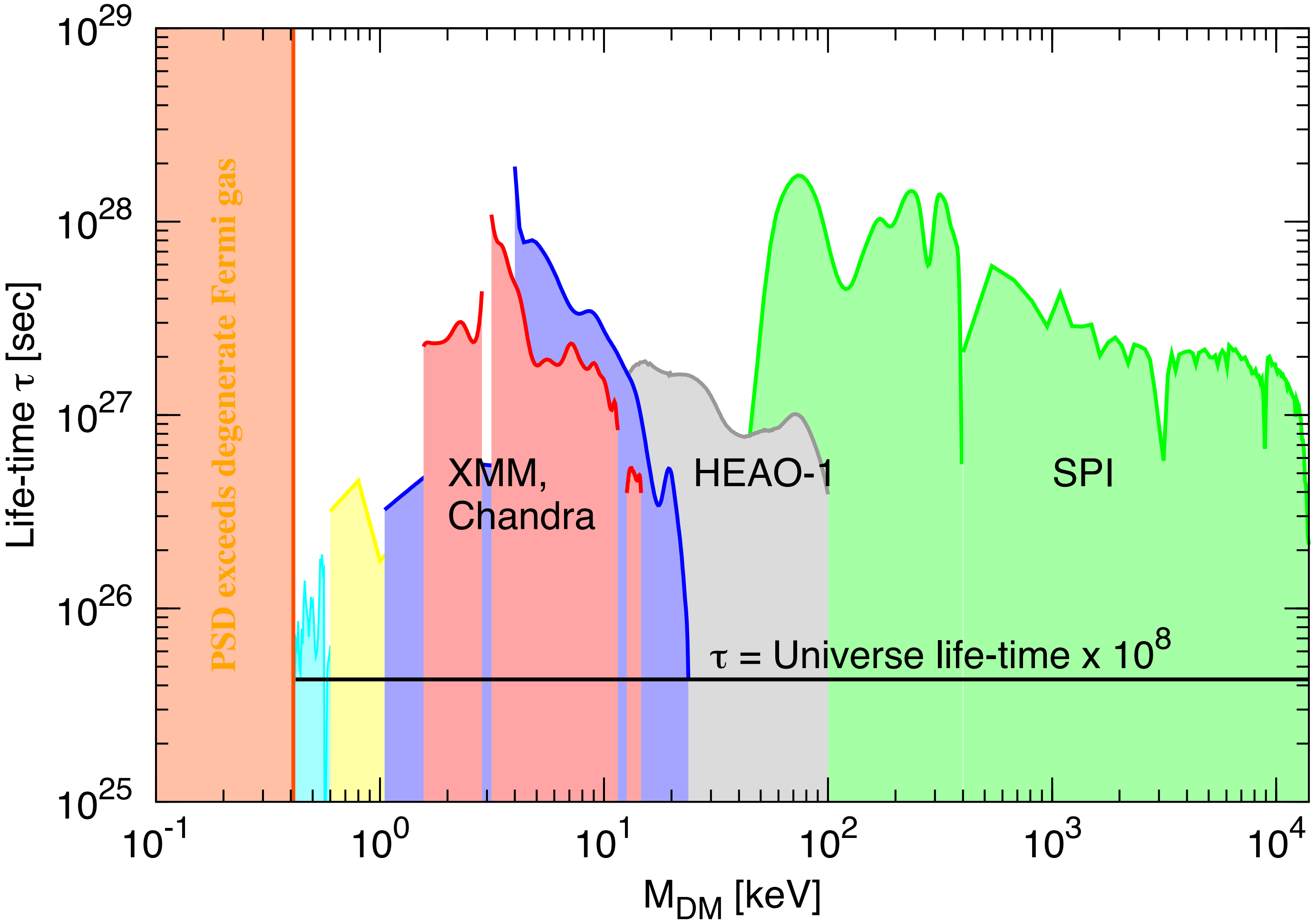


$$\Gamma_{\rm rad} = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) M_s^5$$

Lifetime constraints

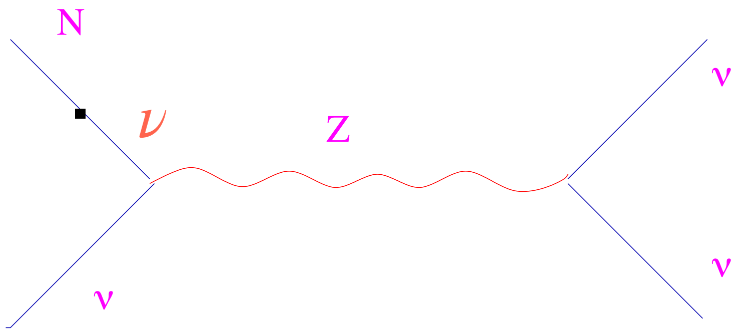
Available X-ray satellites:

Suzaku, XMM-Newton, Chandra, INTEGRAL, NuStar



Constraints on DM sterile neutrino N_1

- **Production.** N_1 are created in the early Universe in SM reactions via νN_1 mixing, $l\bar{l} \to \nu N_1$, $q\bar{q} \to \nu N_1$ etc, or beyond the νMSM processes. We should get correct DM abundance.

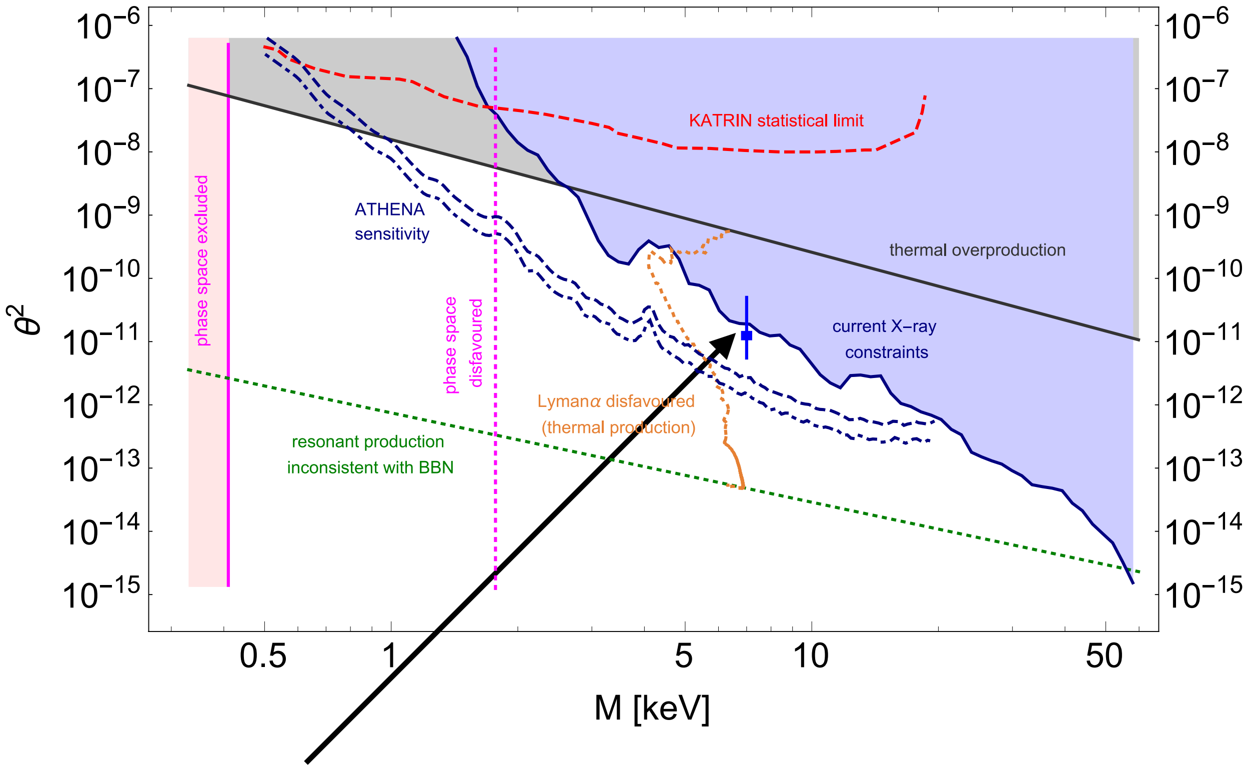


- **Structure formation.** If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies

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

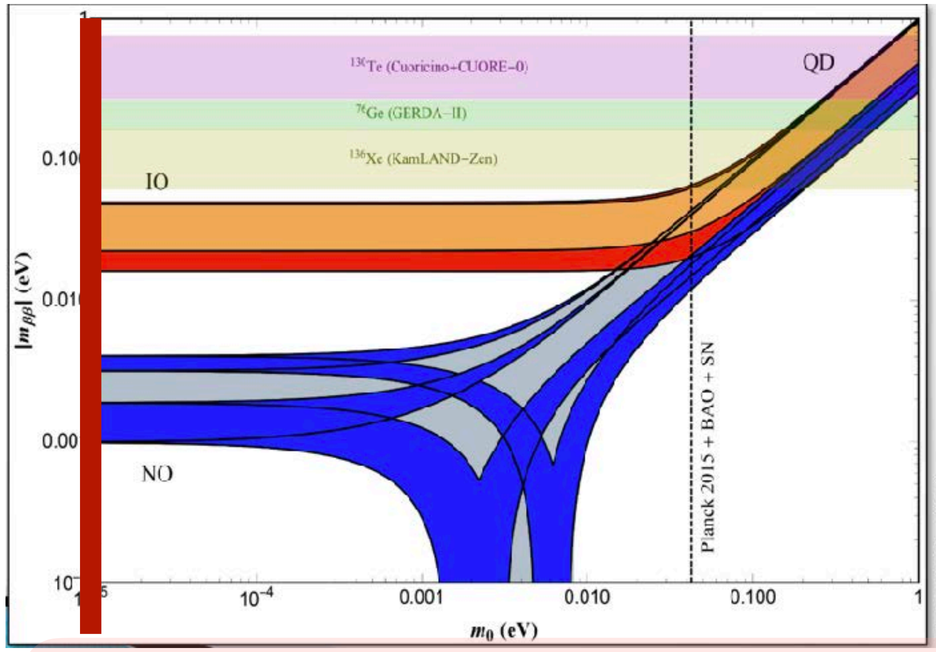
Bulbul et al; Boyarsky et al

Future experimental searches:

Hitomi-like satellite XRISM (2023?),

Large ESA X-ray mission

Athena + (2028?)



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

Prediction from Dark Matter:

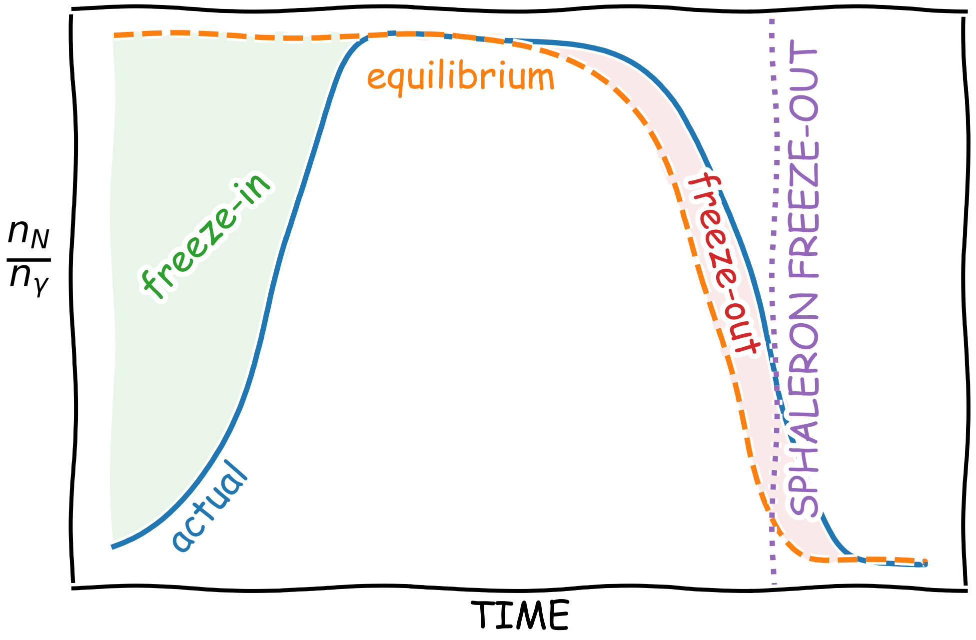
minimal neutrino mass $< 10^{-5}$ eV

Baryon asymmetry of the universe

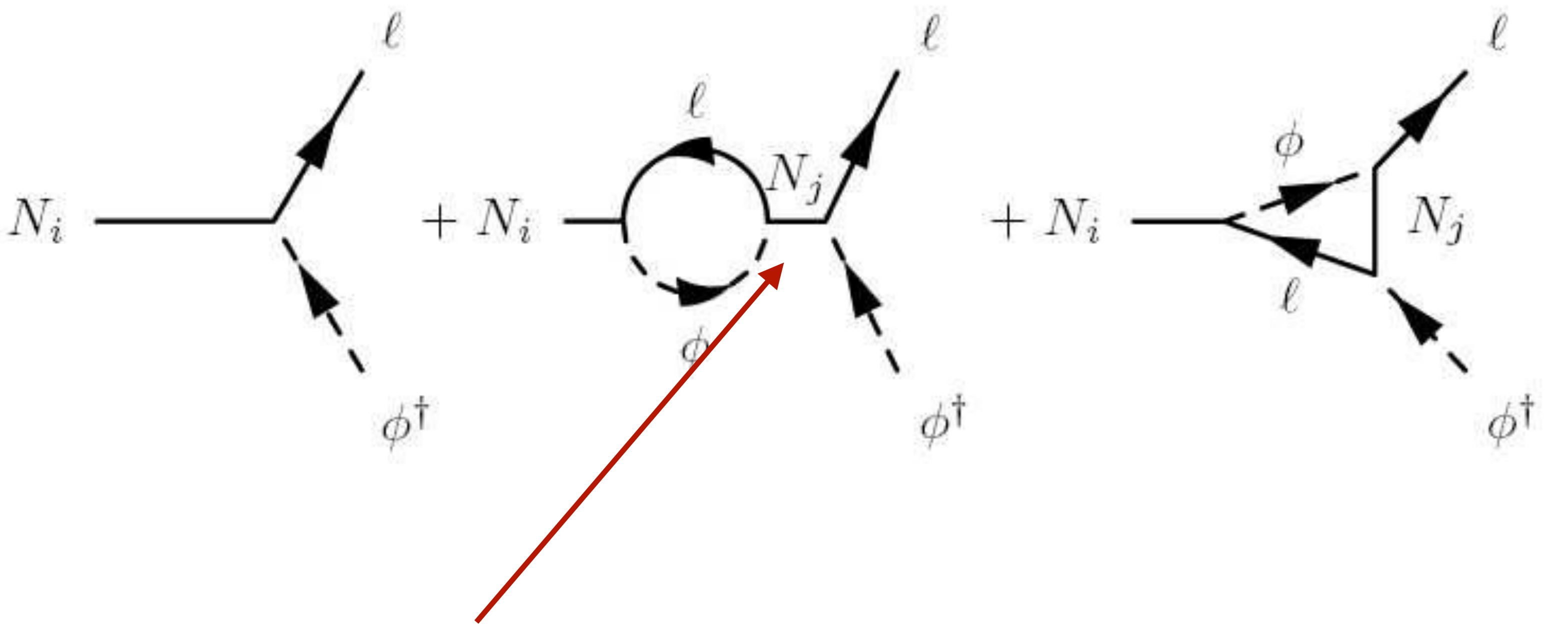
Sakharov conditions

- CP-violation - OK due to new complex phases in Yukawa couplings
- Lepton number violation - OK due to HNL Yukawa couplings and due to Majorana masses
- Baryon number violation: OK due to electroweak anomaly and sphalerons, rate $\sim \exp[-M_W(T)/(\alpha_W T)]$
- Deviations from thermal equilibrium: OK as HNL are out of thermal equilibrium for T > O(100) GeV

See-Saw leptogenesis

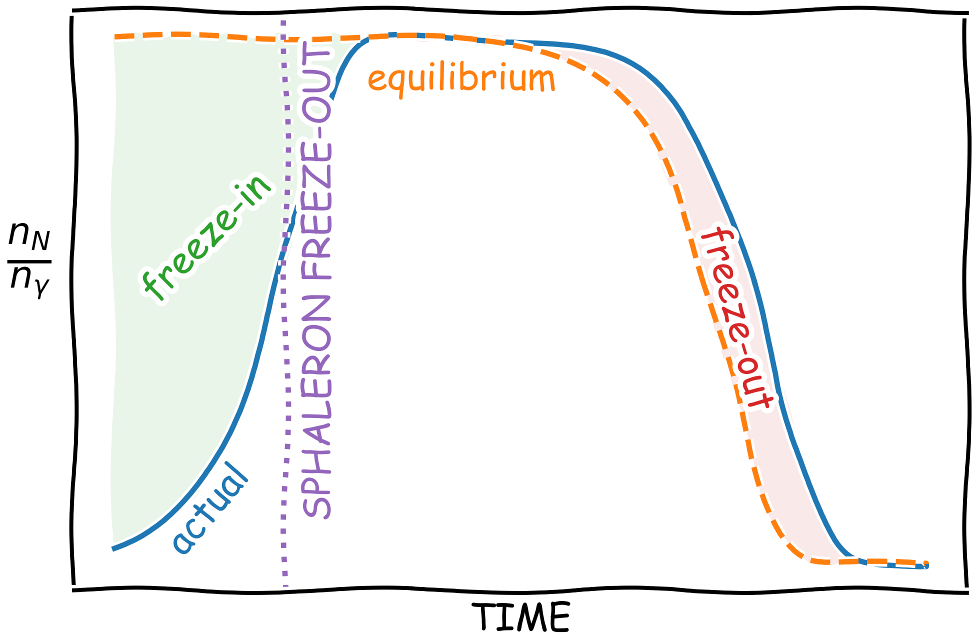


The mechanism: leptogenesis with superheavy Majorana neutrinos (Fukugita, Yanagida) : HNLs go out of thermal equilibrium, decay, and produce lepton asymmetry at temperatures. Then the lepton number is converted into baryon asymmetry by sphalerons which are active until $T \simeq 130\ GeV$. The resulting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



Resonant leptogenesis: may work for $M \sim M_W$

Low scale leptogenesis



Leptogenesis with GeV HNLs $N_{2,3}$

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.

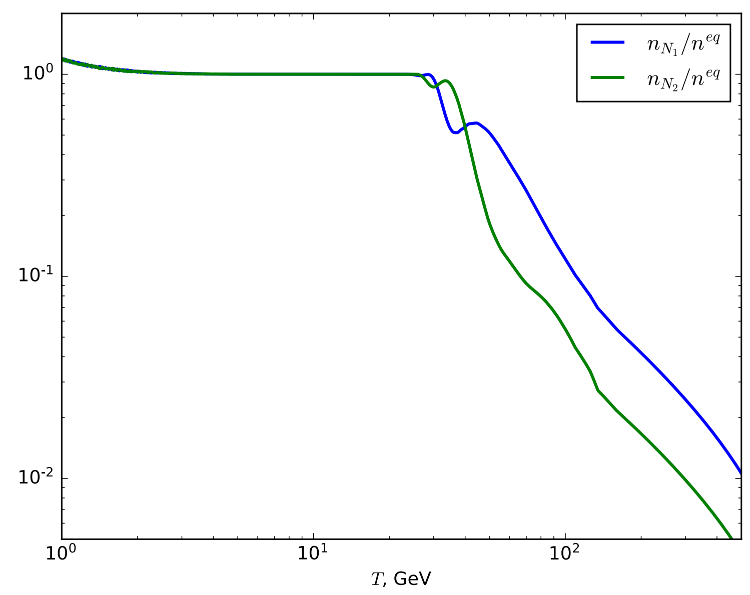
Initial idea: Akhmedov, Rubakov, Smirnov ‘98

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

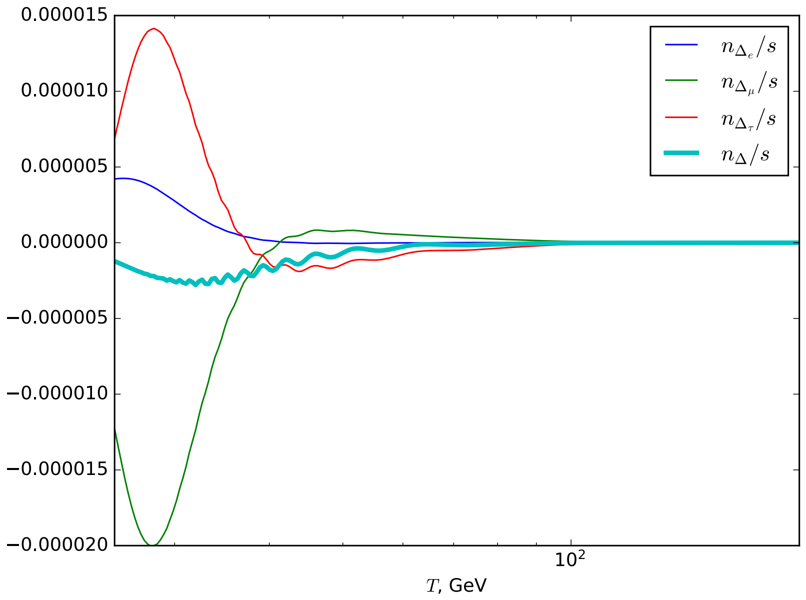
Analysis of baryon asymmetry generation in the NuMSM: Asaka, M.S., Canetti, Drewes, Frossard; Abada, Arcadia, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, Racker, J. Salvado; Drewes, Garbrech, Guetera, Klariç; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine,…

Time evolution

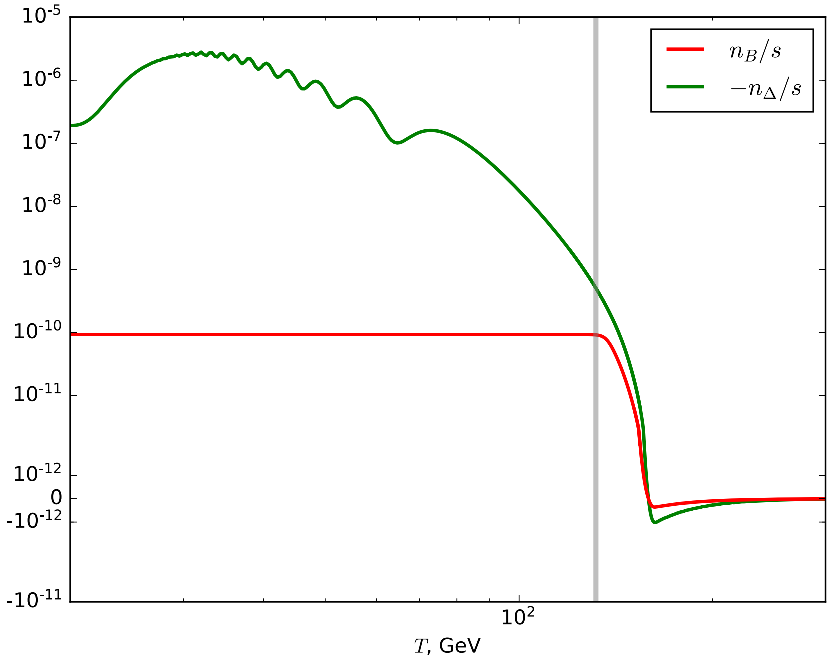
HNL densities



Lepton asymmetries



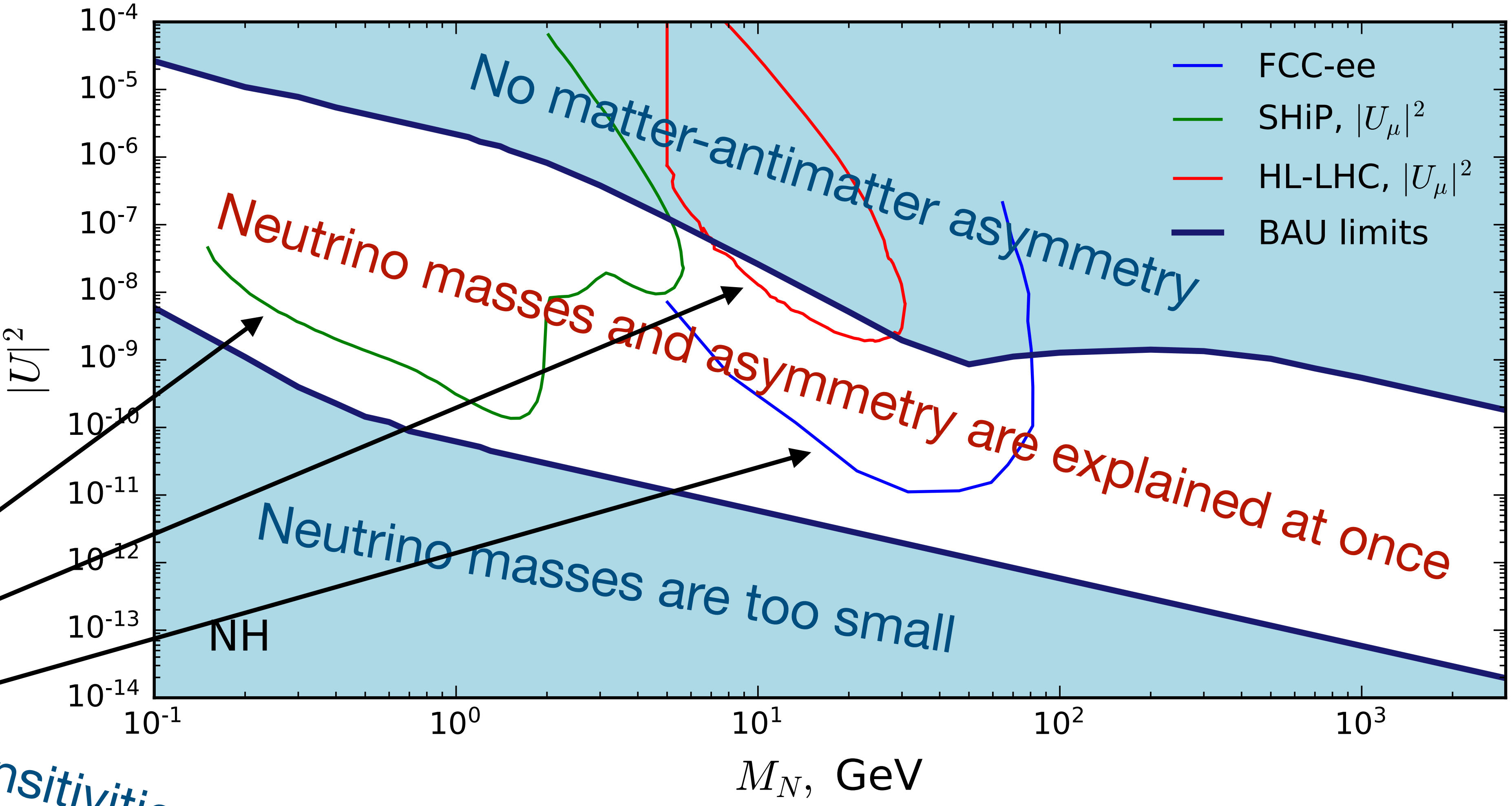
Baryon asymmetry



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

Strength in comparison with weak interaction

figure from Klaric, Timiryasov, MS



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!

How to search for HNLs?

HNLs are belongs to the class of “feebly interacting particles” - FIPs: weaker that weak interactions

Common features of feebly interacting hidden particles

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

Other extensions of the SM offer extra feebly interacting particles: hidden photon, dark scalar, axion-like particles, etc…

Experimental challenges of the hidden particle searches

Hidden particle production and decays are highly suppressed => dedicated experiments are needed.

- New generic purpose experiments to search for all sorts of relatively light dark sector particles (heavy neutral leptons, dark photons, hidden scalars, etc).
- Use the existing experiments for the quest of hidden sector particles.

Generic requirements: fixed target and collider experiments

- Have as many protons on target (pot) as you can, with the energy enough to produce charmed (or beauty) mesons or W and Z. Or, tune e^+e^- energy to Z-resonance.

- Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)

- Have the detector as large as possible to increase the probability of hidden particle decay inside the detector

- Have the detector as empty as possible to decrease neutrino and other backgrounds

Searches for dark sectors

NA62 P326

SHiP
Search for Hidden Particles

DARKLIGHT

Belle II

CMS

T2K

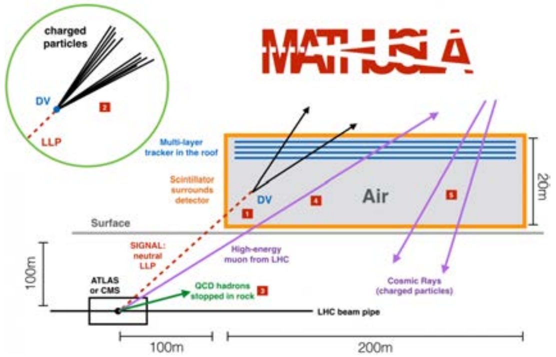
LHCb

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

ATLAS EXPERIMENT

NA64 Search for dark sectors in missing energy events

MATHUSLA

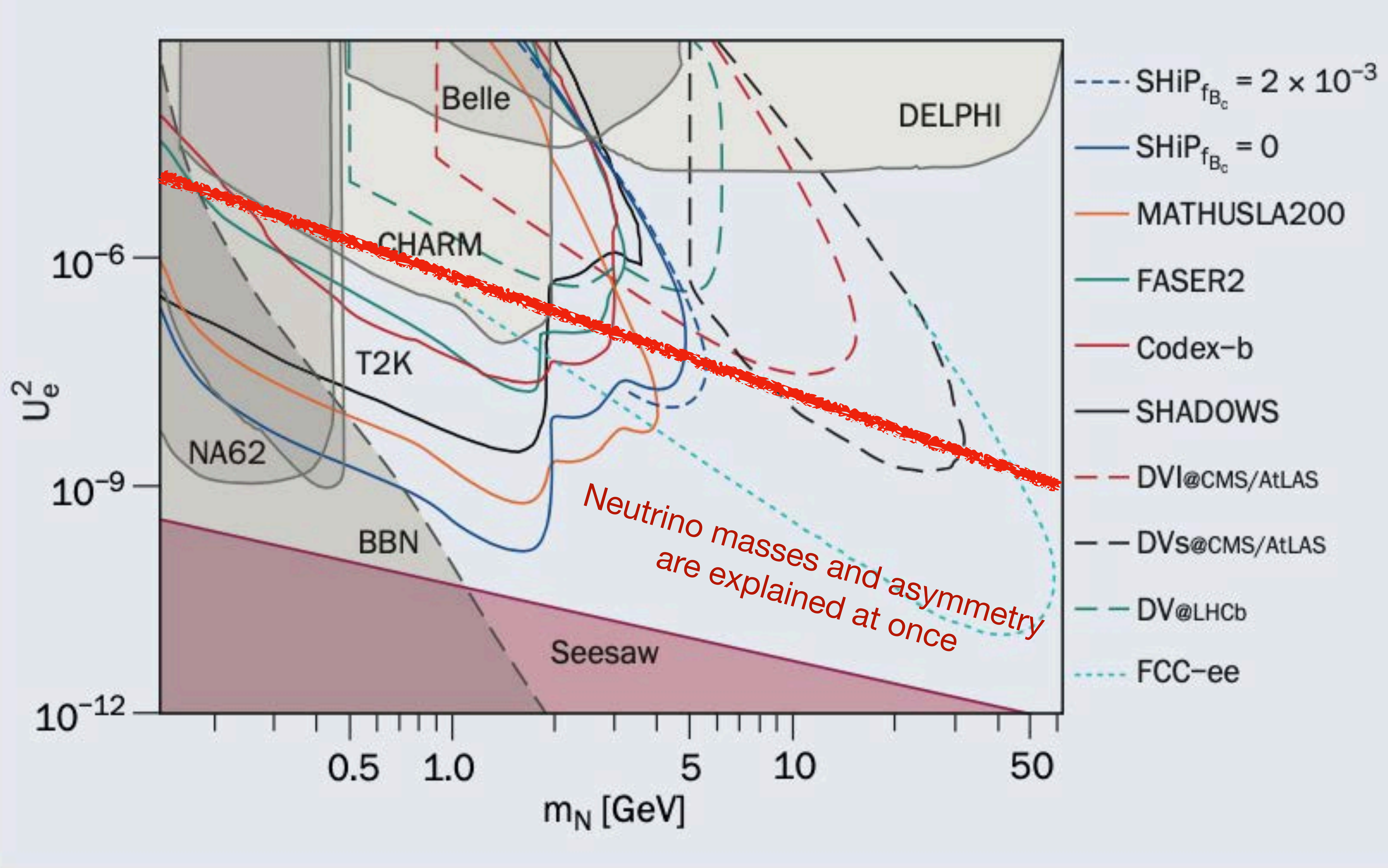


FCC
hh ee he

FASER

SHADOWS
Search for Hidden And Dark Objects With the SPS

Projection of bounds on HNLs



Neutrino masses and asymmetry are explained at once

Conclusions

- Heavy neutral leptons can be a key to all experimental Standard Model problems:
- neutrino masses and oscillations
- dark matter
- baryon asymmetry of the universe

We are at an exciting point in history: the planned future experiments have chances to uncover soon (?) the origin of neutrino masses and baryon asymmetry of the Universe.

νMSM under experimental attacks

- Anomalous muon magnetic dipole moment, 4.2σ deviation from the SM and νMSM, 2021, FNAL.
  - With lattice analysis of BMW experimental results are consistent with the SM within 1.5σ.
  - Recent (2023) CMD-3 measurements of $e^+e^- \to$ hadrons move results from g-2 experiment closer to the SM prediction
- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012.
  - Disfavoured by the results from IceCube neutrino observatory, 2016 and by the global neutrino fits.
- The 750 GeV digamma excess, 2015.
  - Disappeared in 2016.
- Lepton flavour non-universality in B-decays, 2014-2021.
  - Disappeared in December 2022.