ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

SWISS NATIONAL SCIENCE FOUNDATION

European Research Council
Established by the European Commission

Neutrinos and 125 GeV Higgs -

what are they telling us about the Universe?

Mikhail Shaposhnikov

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

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

No low energy SUSY, no large extra dimensions, no new strong interactions.

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

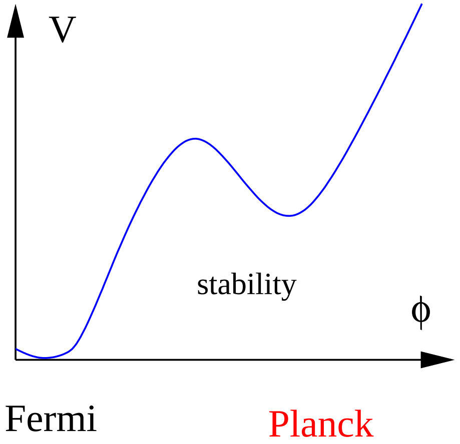
No low energy SUSY, no large extra dimensions, no new strong interactions.

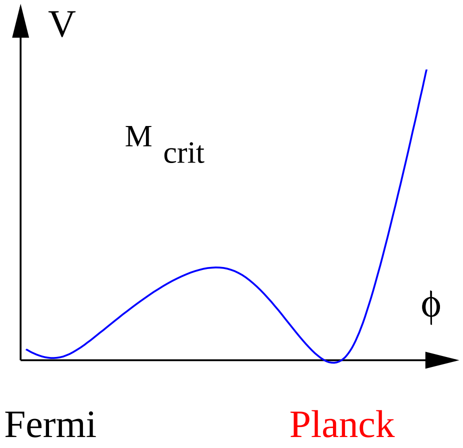
For $\mathbf{125}$ GeV Higgs mass the Standard Model is a self-consistent weakly coupled effective field theory for all energies up to the quantum gravity scale $M_P \sim 10^{19}$ GeV

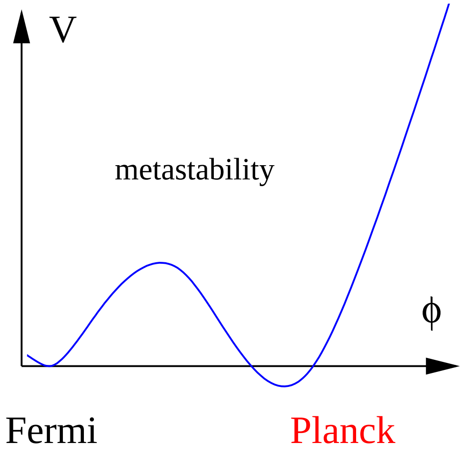
The LHC results must be reconciled with experimental evidence for new physics beyond the Standard Model:

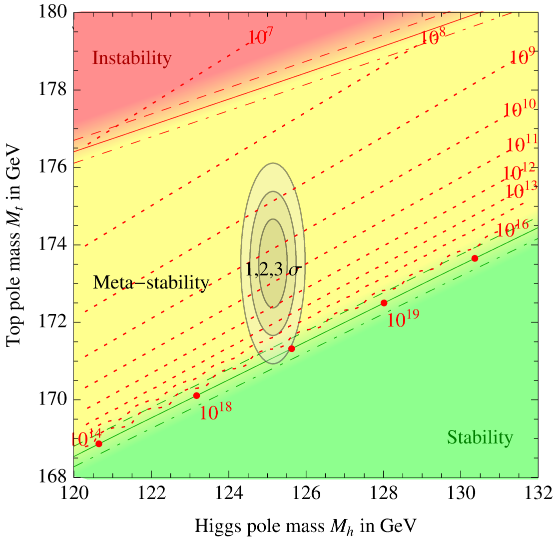
- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be “explained” by a cosmological constant.

- 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



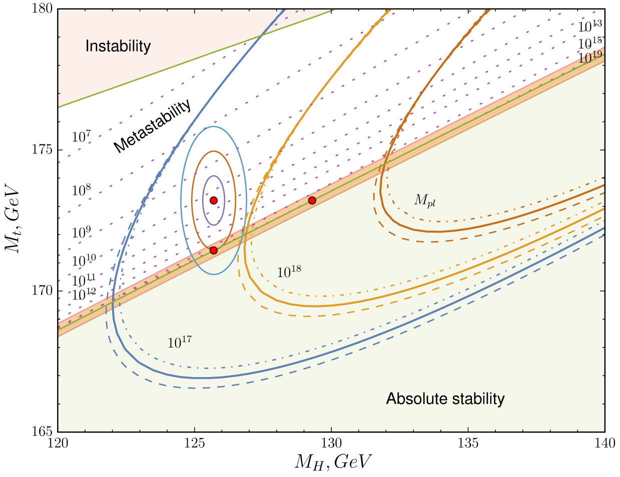






Buttazzo et al, ’13, ’14:

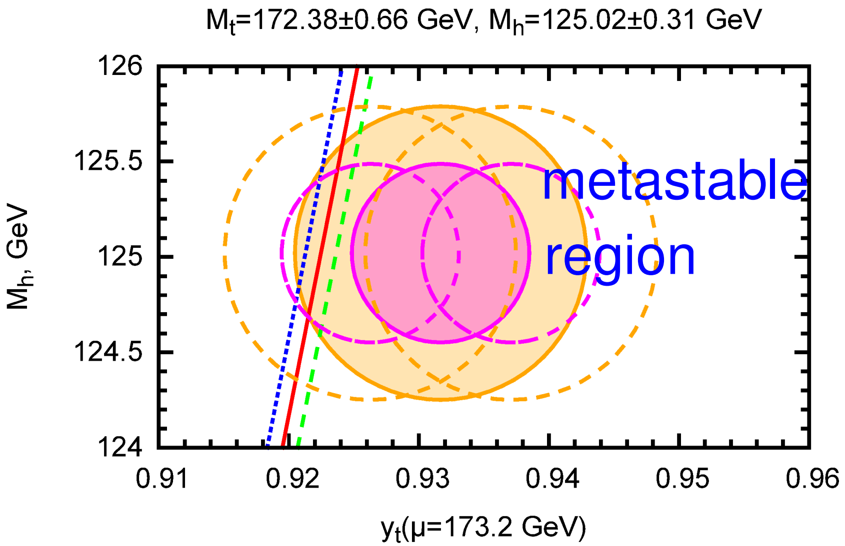
vacuum is unstable at 2.8σ



Bednyakov et al, ’15:

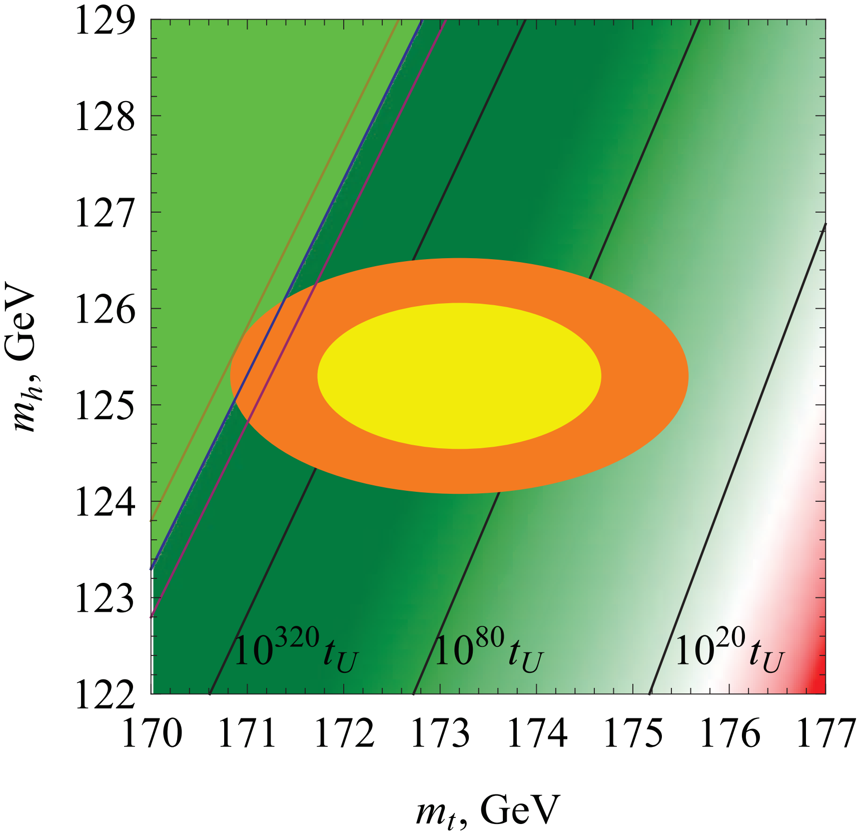
vacuum is unstable at 1.3σ

Bezrukov, MS updated



Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for ± 1 GeV in M_{top}. Alekhin et al, Frixione et al.

Vacuum lifetime

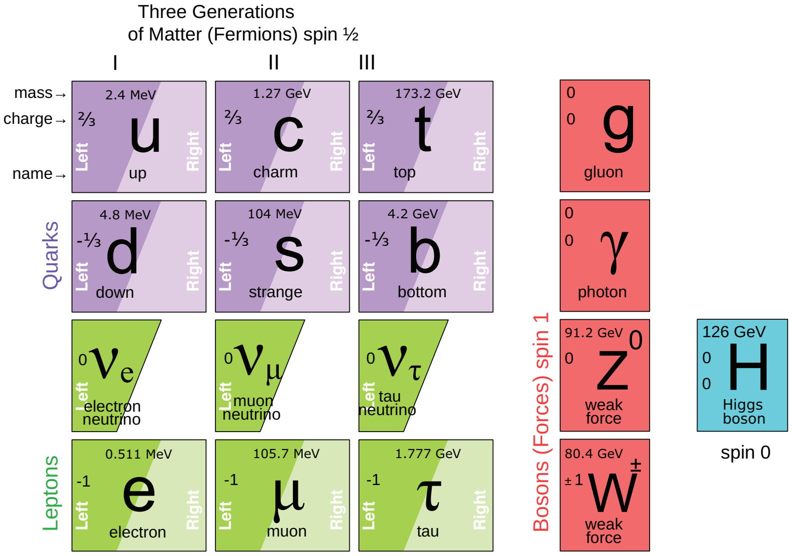


Where is new physics?

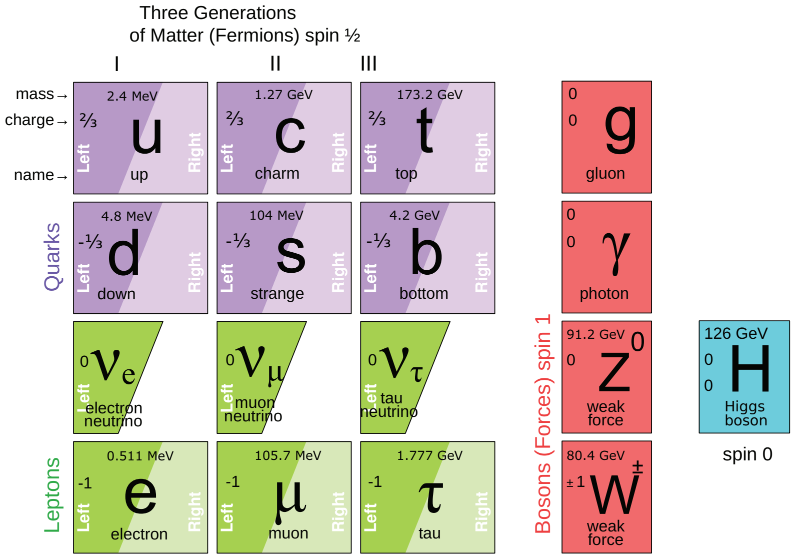
Energy scale of new physics:

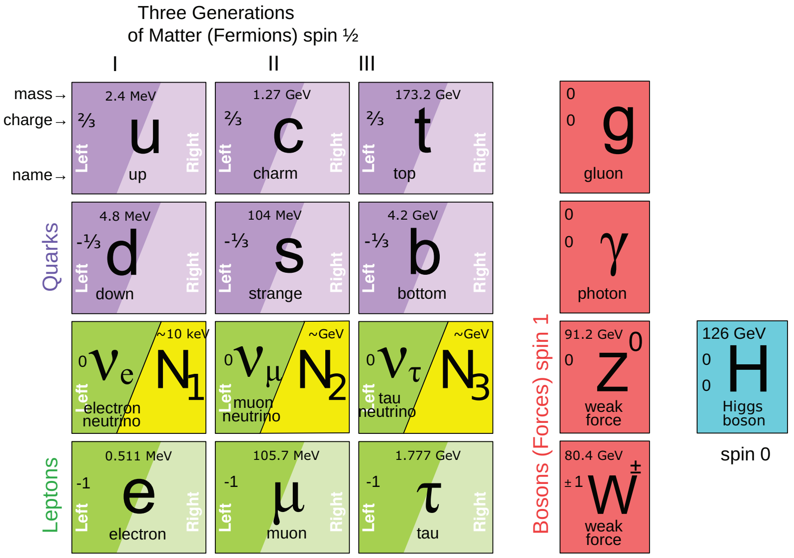
- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV
- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ 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 $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV
- Higgs mass hierarchy : models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale , whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

The missing piece of the SM



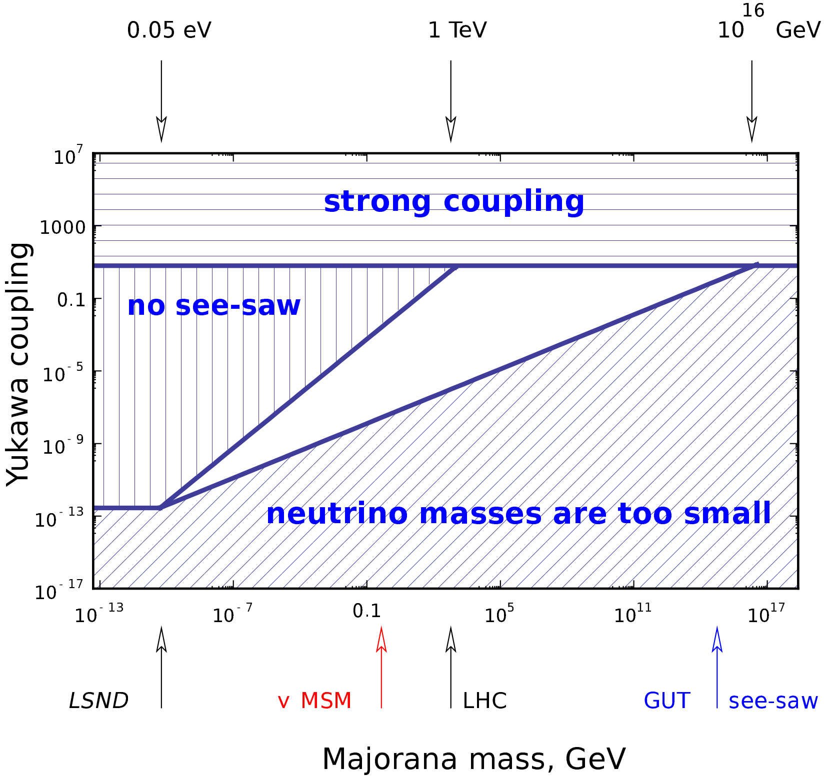
The missing piece of the SM



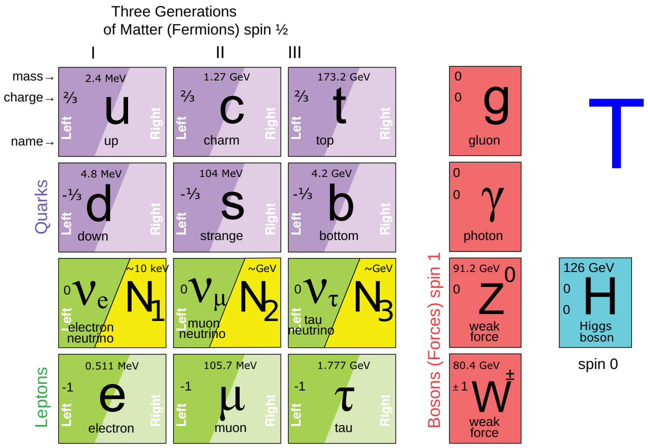


New mass scale and Yukawas

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



New physics below the Fermi scale



The νMSM = particles of the SM

+ graviton +

3 Majorana leptons

Lagrangian:

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_G + \left(\bar{N}_I i\gamma^\mu \partial_\mu N_I - h_{\alpha I}\,\bar{L}_\alpha N_I \tilde{\varphi} - M_I \bar{N_I}^c N_I + \mathrm{h.c.}\right)$$

Gravity part

$$\mathcal{L}_G = -\left(M_P^2 + 2\xi_h \varphi^\dagger \varphi\right)\frac{R}{2}\,,$$

Roles of the Higgs boson:

- Provide inflation
- Give masses to fermions and vector bosons of the SM
- Provide CP-violating Yukawa couplings in the leptonic sector necessary for baryogenesis
- Provide Yukawa couplings in the leptonic sector necessary for DM production

Roles of the HNLs

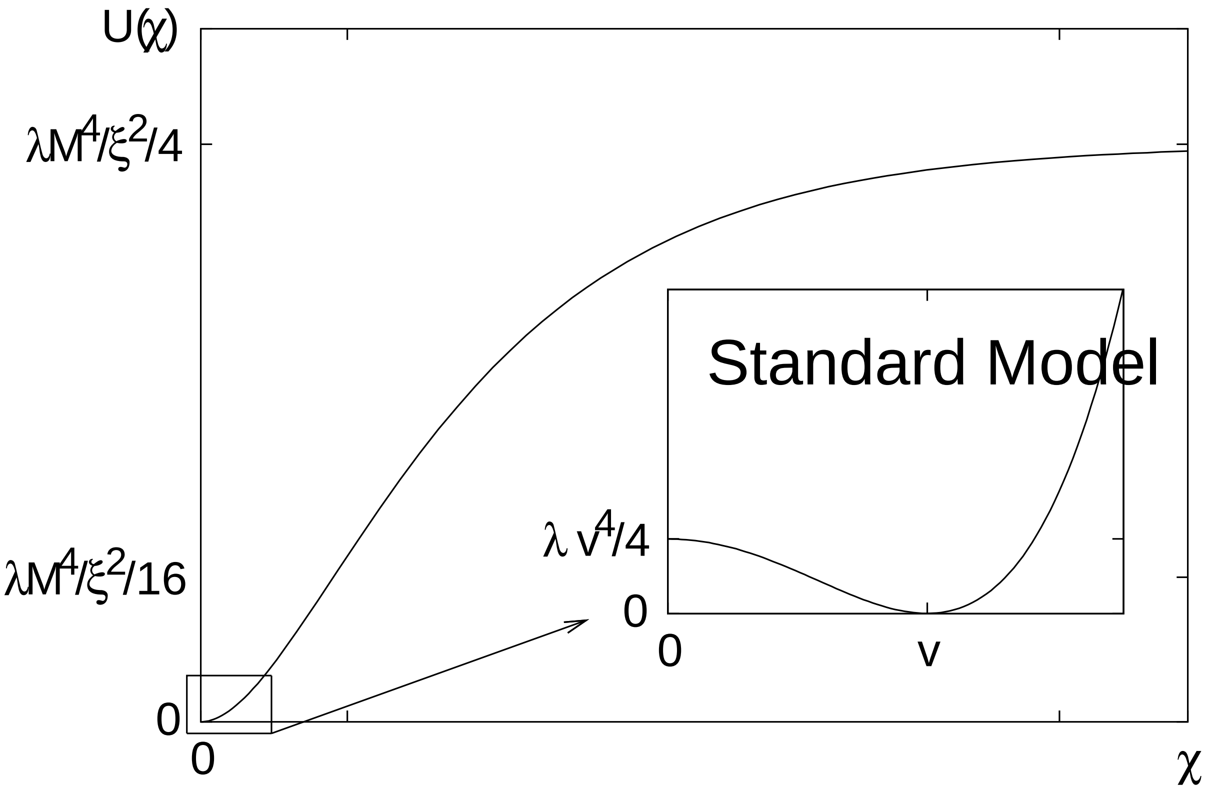
- N_1 with mass in keV region: dark matter
- $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Cosmology of a minimal model

Inflation: Higgs boson

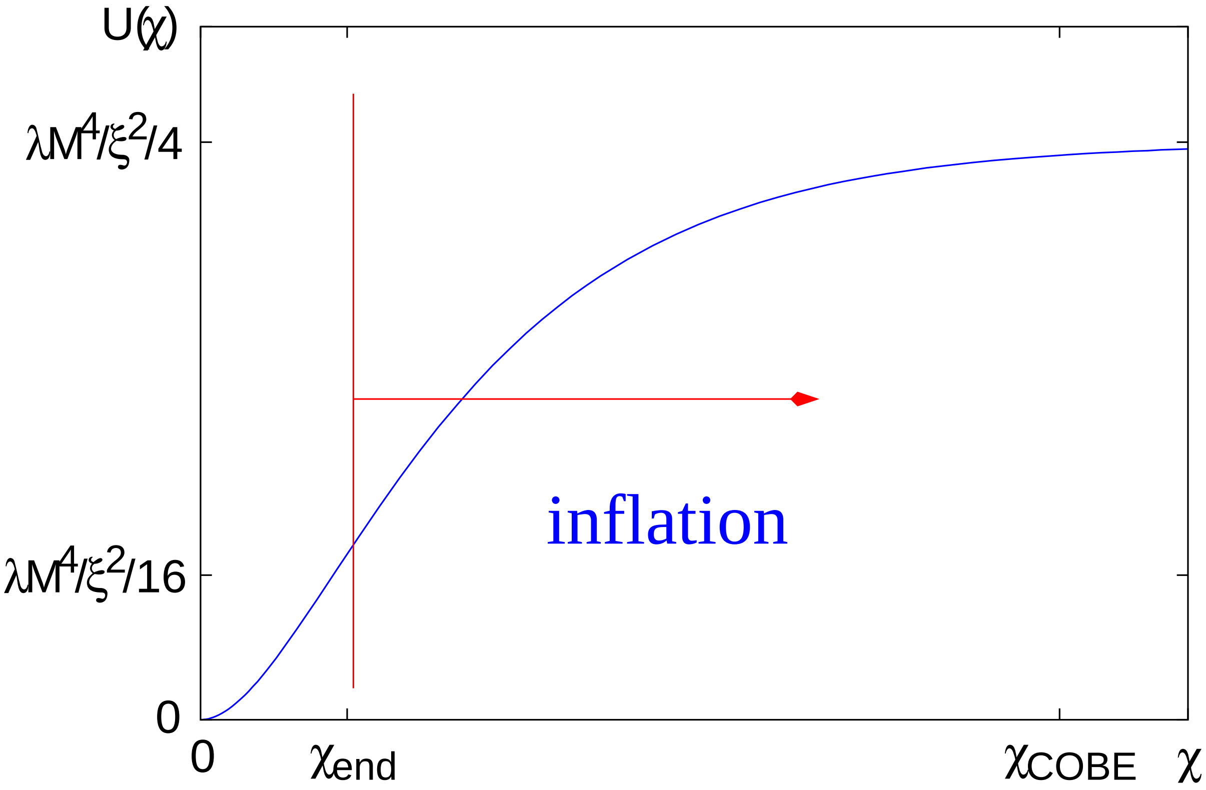
Potential in Einstein frame for non-minimally coupled Higgs, $\xi_h R h^2$.

Higgs field determines the strength of gravity, $G_N^{-1} = M_P^2 + \xi_h h^2$!



χ - canonically normalised scalar field in Einstein frame.

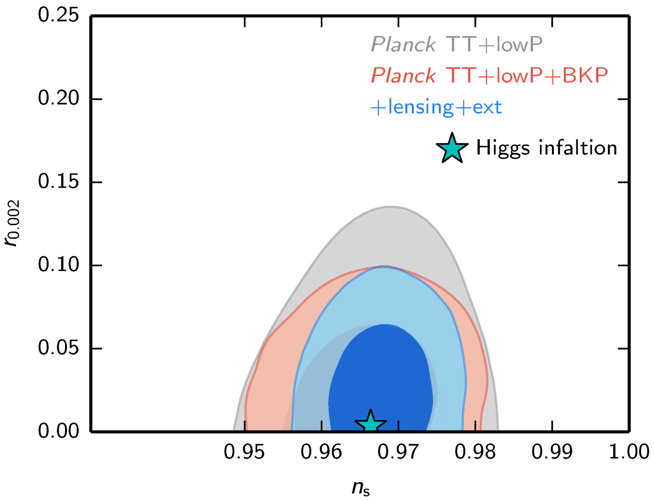
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

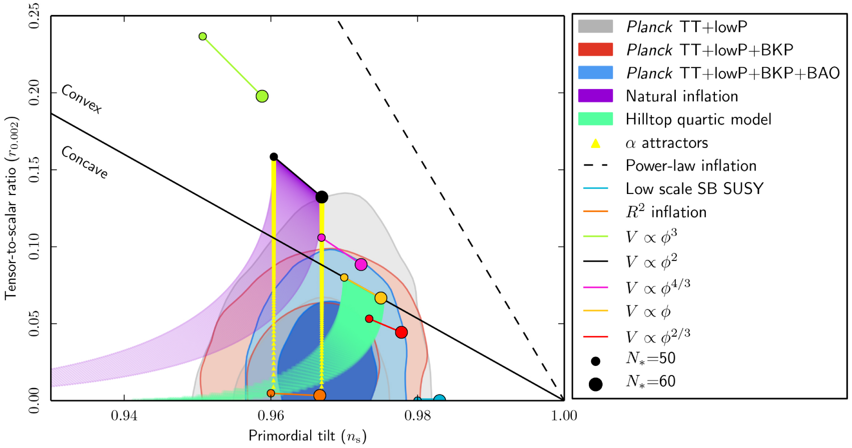


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

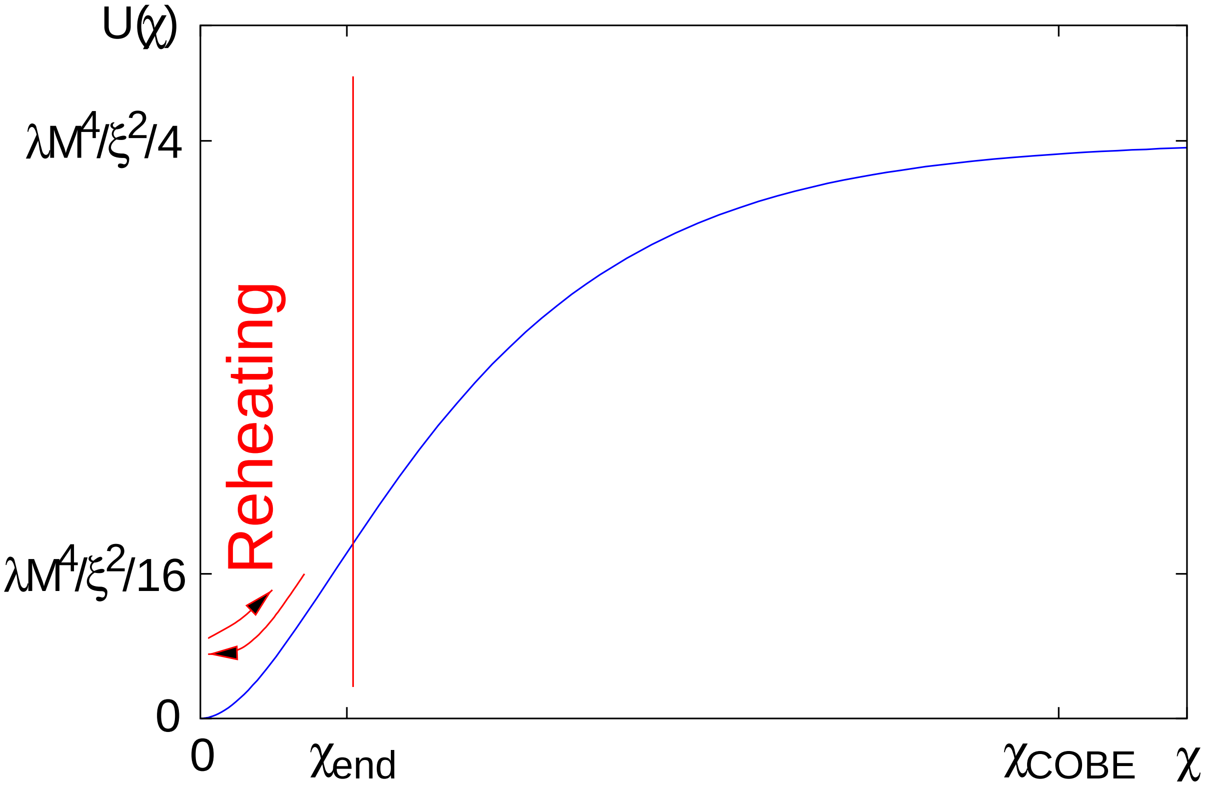
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

$$n_s = 0.97, \quad r = 0.003$$





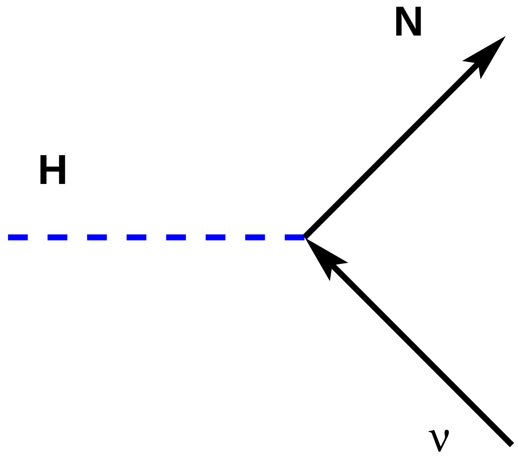
Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to $T \propto M_P/\xi \sim 10^{14}$ GeV

Dark Matter and baryon asymmetry

All comes due to the HNL interactions with the Higgs boson via Yukawa interactions - exactly in the same way other fermions do:



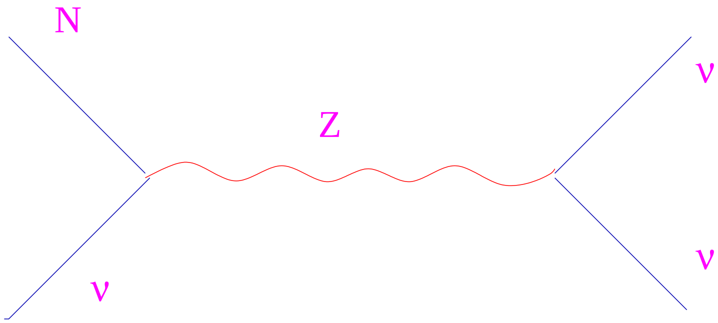
$F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{H}$

These interactions lead to

- active neutrino masses due to GeV scale see-saw
- to dark matter production at $T \sim 100$ MeV: Dodelson, Widrow; Shi, Fuller; + many recent works
- creation of matter-antimatter asymmetry at temperatures $T \sim 100$ GeV: Akhmedov, Rubakov, Smirnov; Asaka, MS; + many recent works

DM candidate: the lightest Majorana ν, N_1

Yukawa couplings are small → sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

For one flavour:

$$\tau_{N_1} = 5\times10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

$$\Theta = \frac{m_D}{M_I}$$

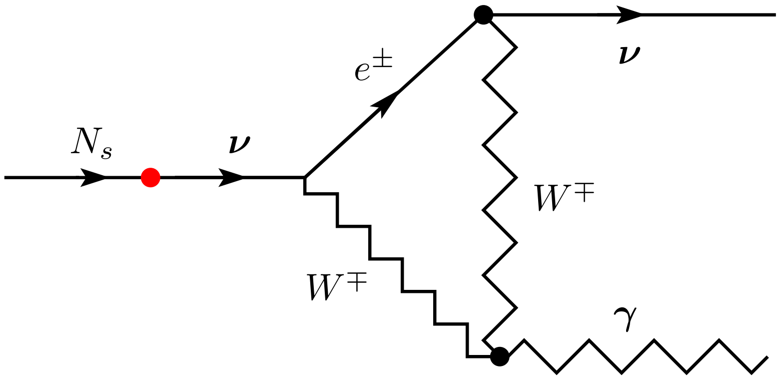
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$

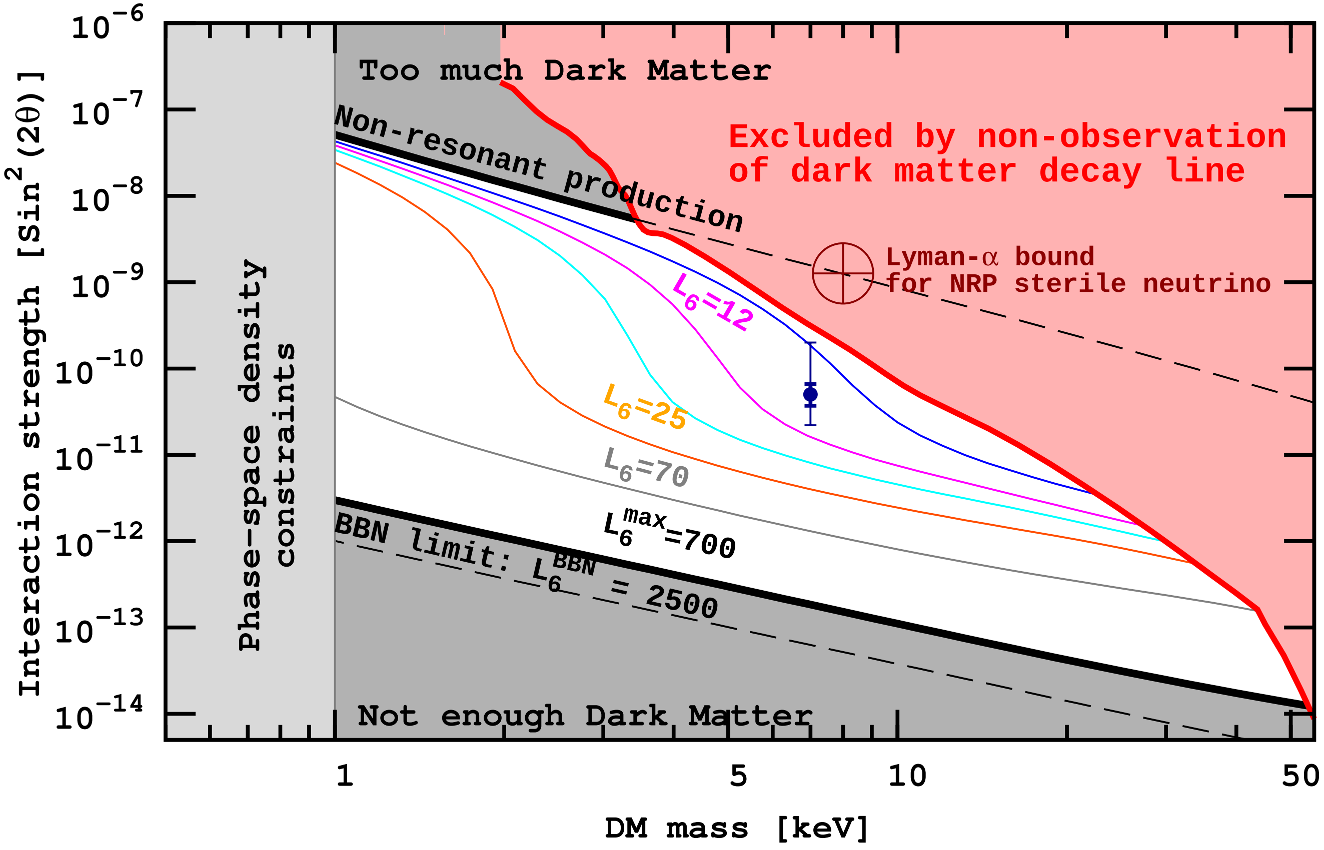


Radiative decay width:

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

Constraints on DM sterile neutrino N_1

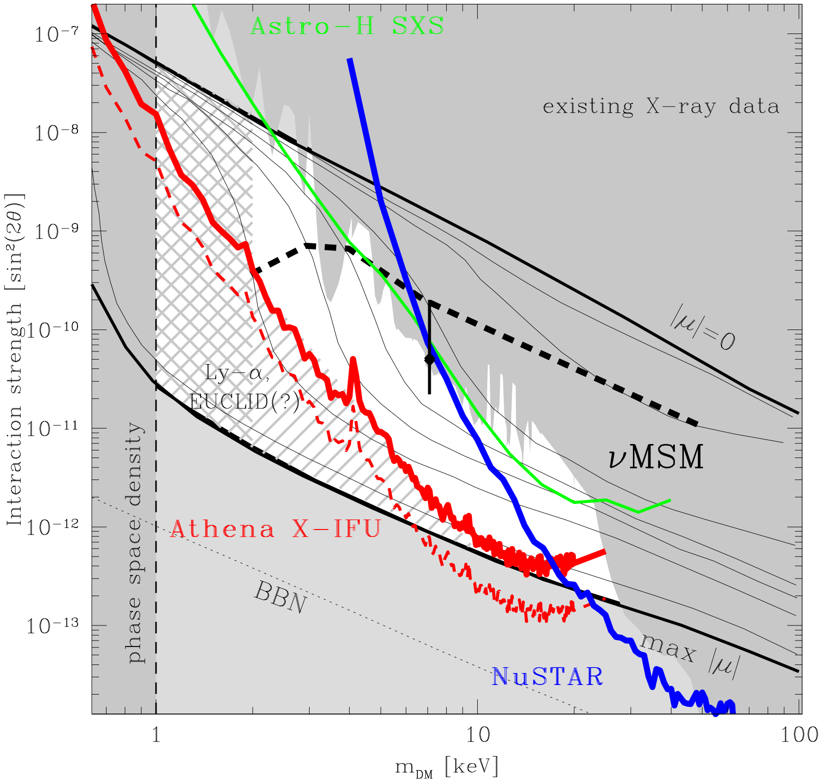
- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming 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
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

- HNL (***N_1***) dark matter searches in X-rays, future after Astro-H failure
  - New Hitomi,   2020?
  - Micro-calorimeter on sounding rocket (2017): instrument with large field-of-view and very high spectral resolution
  - Large ESA X-ray mission (2028) – Athena + , X-ray spectrometer (X-IFU) with unprecedented spectral resolution



Baryon asymmetry

Sakharov conditions:

- Baryon number violation - OK due co complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.

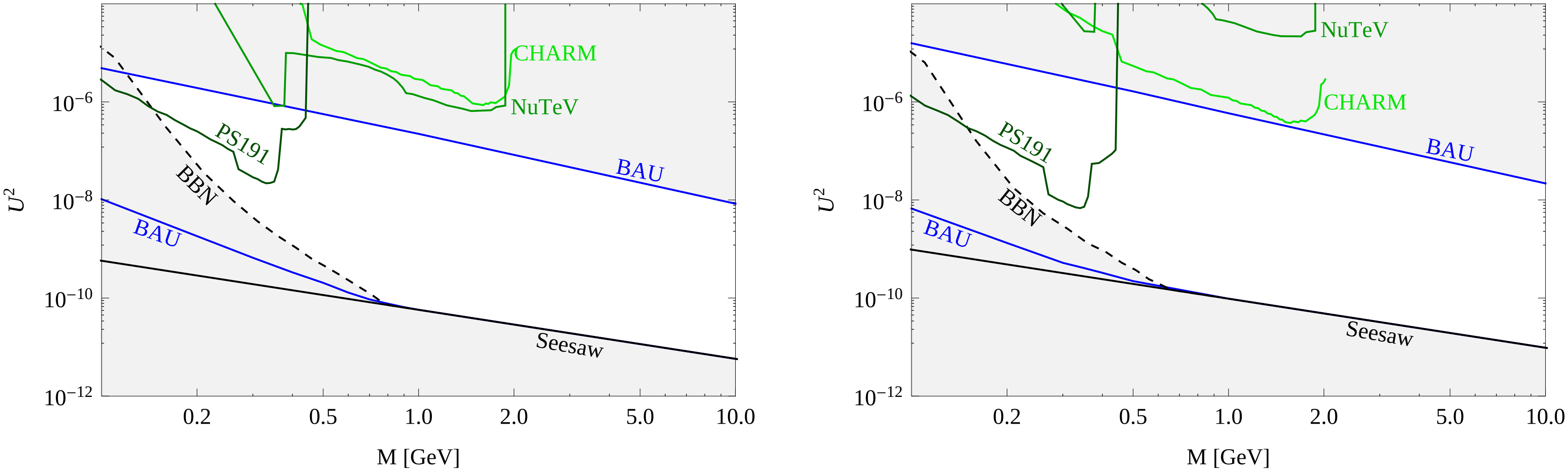
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen

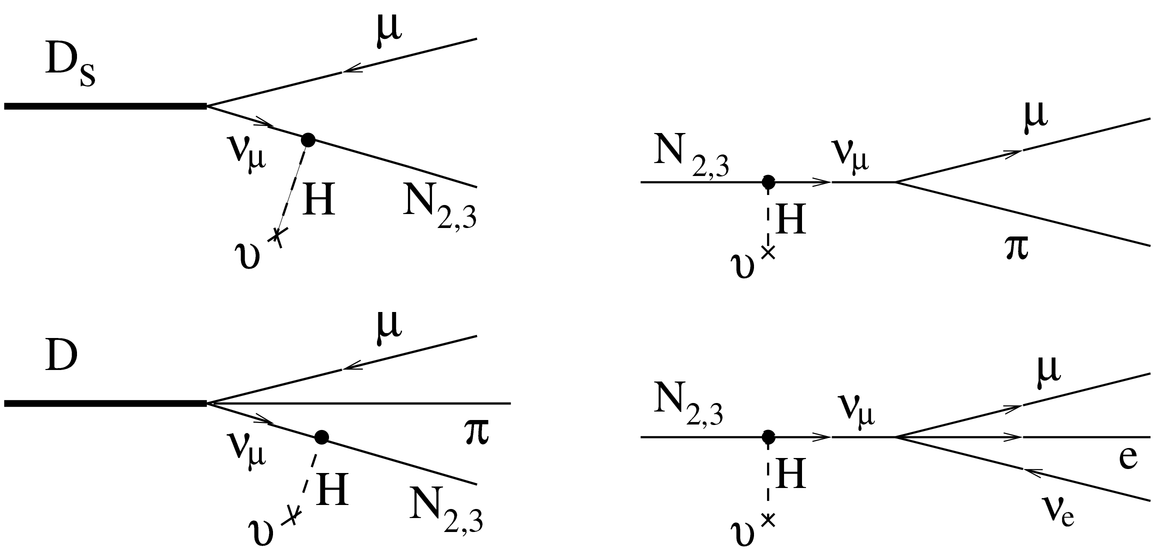


Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS). Other studies: Drewes et al., Hernandez et al

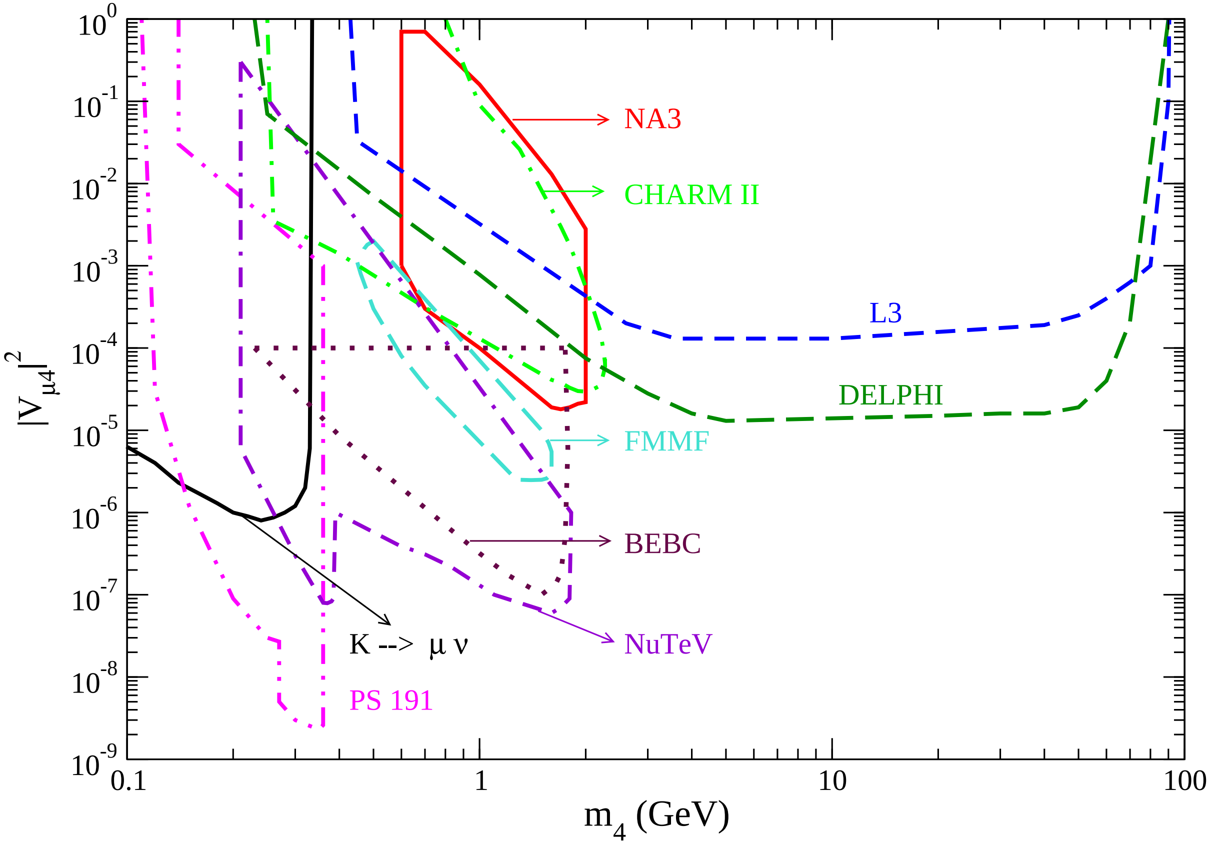
Experimental search for HNL

- Production
  - via intermediate (hadronic) state

    $\boldsymbol{p + \mathrm{target} \to \mathrm{mesons} + \ldots}$, and then hadron$\to$ $N + \ldots$.
  - via Z-boson decays: $e^+e^- \to Z \to \nu N$
- Detection
  - Subsequent decay of N to SM particles



Survey of constraints



Atre et al.

How to improve the bounds or to discover light very weakly interacting HNL’s?

Dedicated experiments

Common features of all relatively light feebly interacting particles :

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

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62, BNL E949
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - 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

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

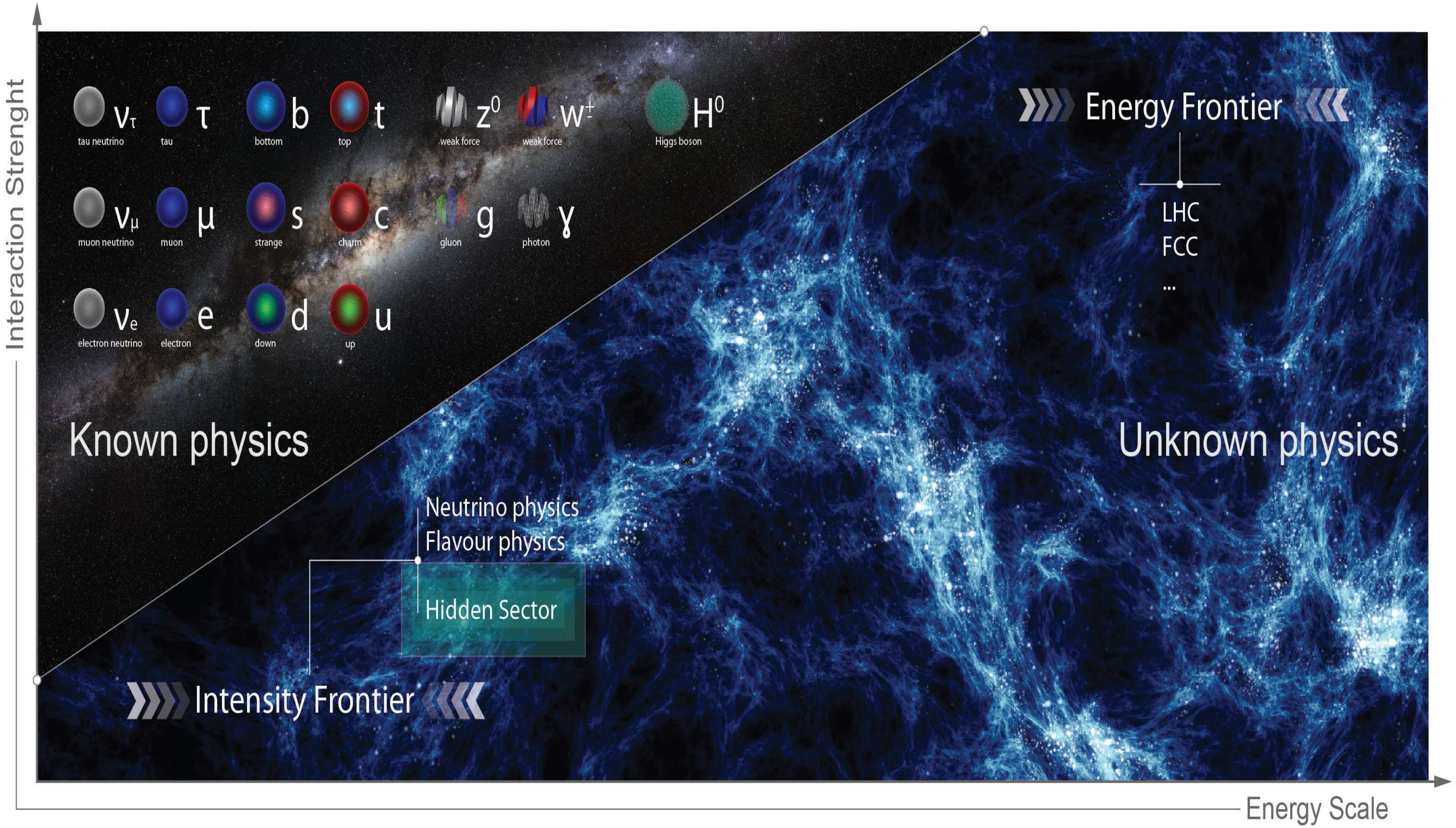
⇓

General beam dump facility: Search for Hidden Particles

SHiP

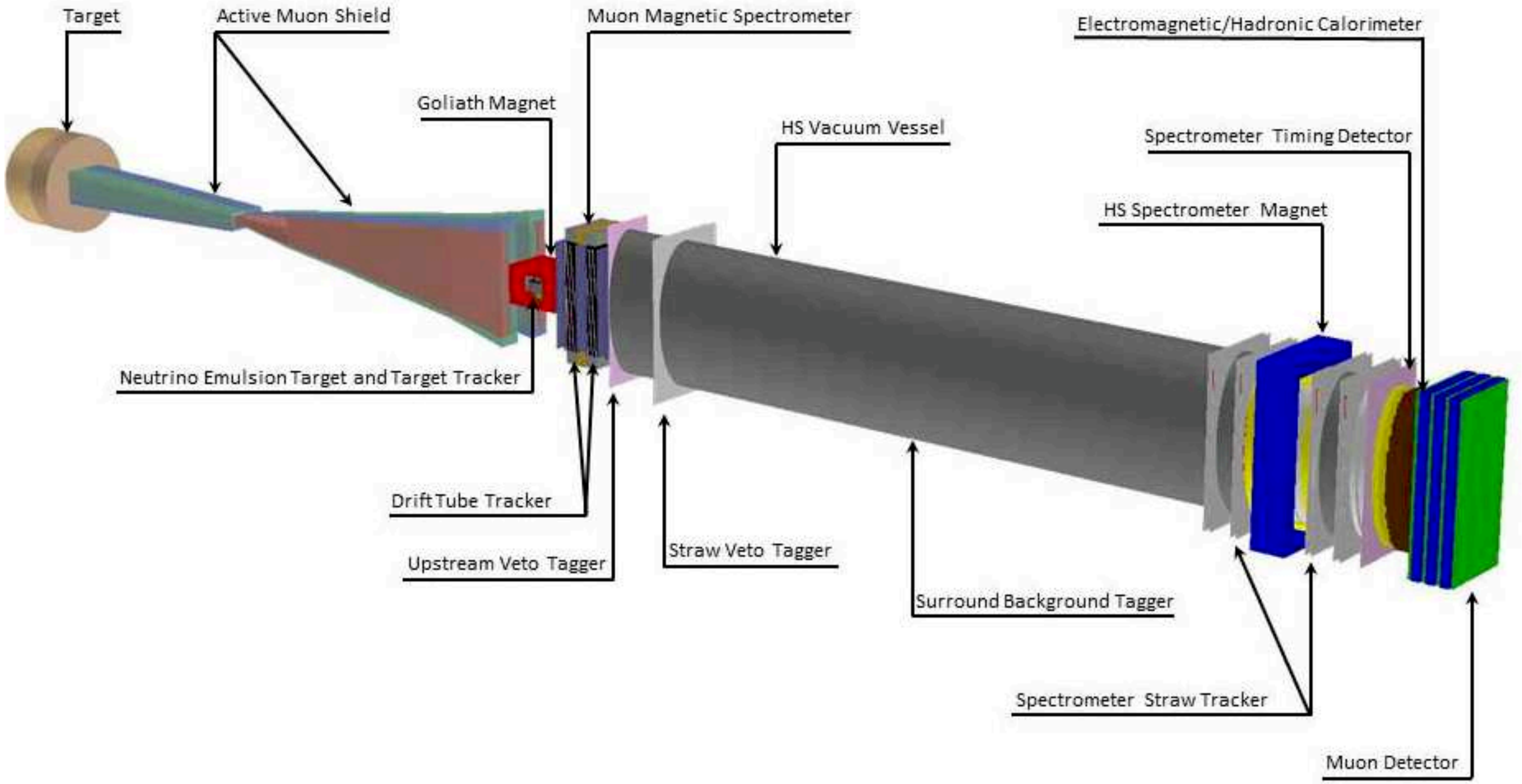
Search for Hidden Particles

Hidden sector: very weakly interacting relatively light particles: HNL, dark photon, scalars, ALPS, etc



SHiP is currently a collaboration of 46 institutes from 15 countries

web-site: http://ship.web.cern.ch/ship/



FCC-ee Z-factory, LHC

Processes: $Z \to N\nu, \quad N \to lq\bar{q}$ (lepton + meson, lepton + 2 quark jets),

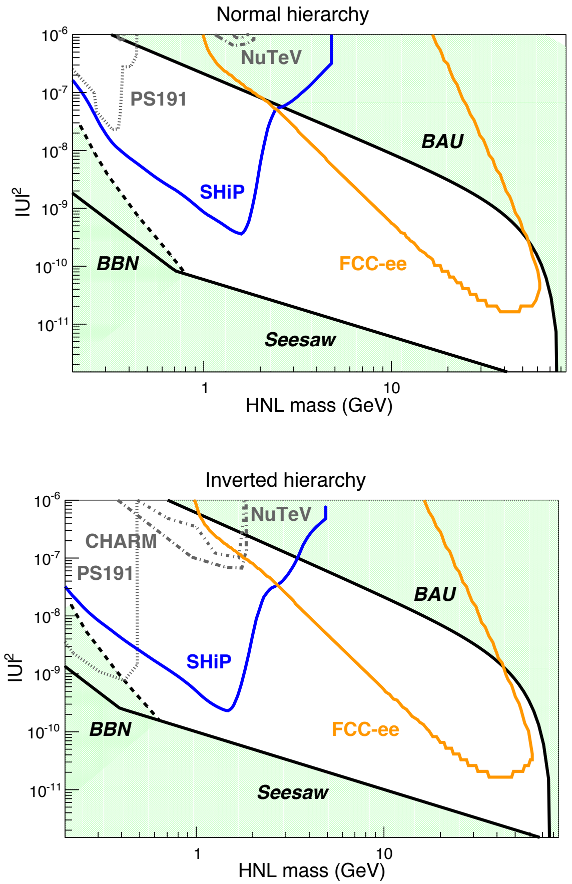
$$BR(Z \to \nu N) \simeq BR(Z \to \nu\nu)U^2, \qquad \Gamma_N \simeq \frac{G_F^2 M^5}{192\pi^3}U^2 A$$

Coefficient A counts the number of open channels, $A \sim 10$ for $M > 10$ GeV

Detector of size L:

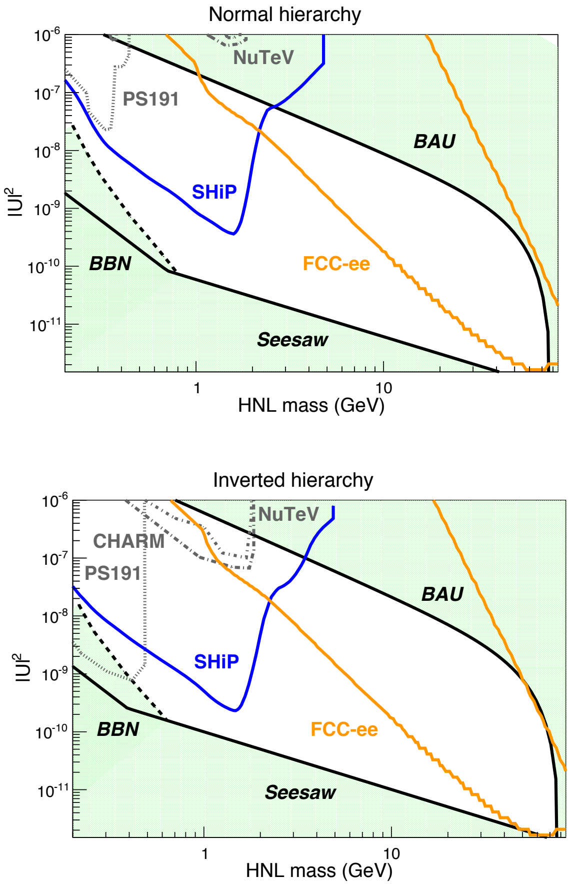
- “short lived” N: decay length < L $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 10^{-10}$ as the sensitivity will grow as the number of Z-decays! This works for $M \gtrsim 20$ GeV.
- “long lived” N: decay length exceeds the size of the detector $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 4 \times 10^{-8}$ as the sensitivity will grow as the square root of the number of Z-decays. This works for lighter HNL.

SHiP and FCC-ee sensitivity



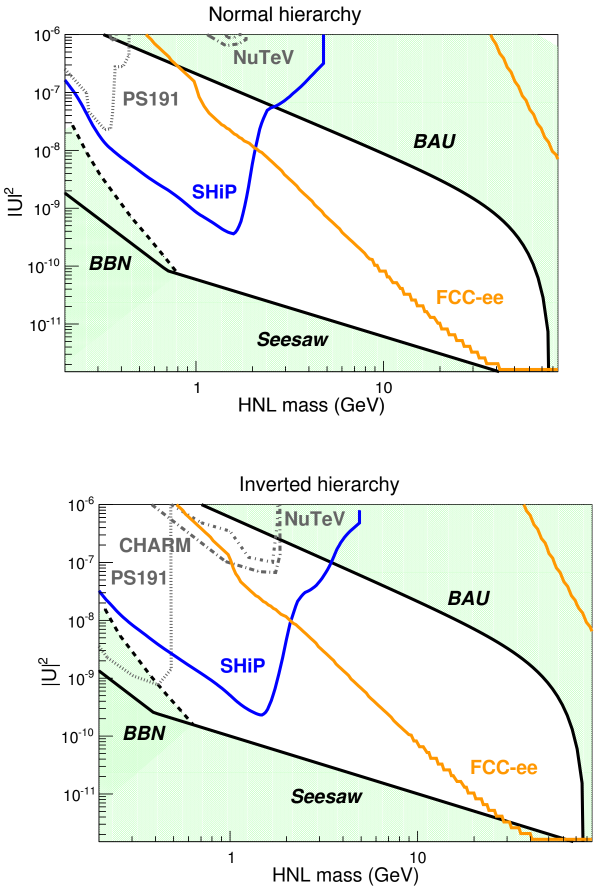
Decay length: 10-100 cm

$10^{12}\ Z^0$



10-100 cm

$10^{13}\ Z^0$



0.01-500 cm

$10^{13}\ Z^0$

Conclusions

- Perhaps, the 125 GeV Higgs and neutrinos are telling us that the fundamental interactions are relatively simple from the very small to the very high energy scale?

- Perhaps, the 125 GeV Higgs and neutrinos are telling us that the fundamental interactions are relatively simple from the very small to the very high energy scale?
- All observational drawbacks of the SM can be solved by the Higgs boson interactions in the νMSM = SM + 3 neutral leptons

- Perhaps, the 125 GeV Higgs and neutrinos are telling us that the fundamental interactions are relatively simple from the very small to the very high energy scale?
- All observational drawbacks of the SM can be solved by the Higgs boson interactions in the νMSM = SM + 3 neutral leptons
    - inflation - Higgs boson

- Perhaps, the 125 GeV Higgs and neutrinos are telling us that the fundamental interactions are relatively simple from the very small to the very high energy scale?
- All observational drawbacks of the SM can be solved by the Higgs boson interactions in the νMSM = SM + 3 neutral leptons
    - inflation - Higgs boson
    - neutrino masses, dark matter and baryogenesis - Higgs + 3 HNLs

Theoretical challenges, similar to the Standard Model:

- UV completion, unification with gravity
- Why the Higgs and HNL masses are so much smaller than the Planck scale?
- Why the cosmological constant (or dark energy) is so tiny?
- Why θ_{QCD} is so small?
- Origin and magnitude of Yukawa couplings
- ...

Experimental challenges:

- Cosmology
  - Inflationary parameters. The Higgs inflation predictions: Gaussian perturbations, $\boldsymbol{n_s = 0.967}$, $\boldsymbol{r = 0.003}$
  - X-ray searches of decaying DM
  - Properties of DM. In the νMSM, depending on parameters, the DM may contain the cold and warm components simultaneously.
  - The number of relativistic species. For the SM or the νMSM, this number (in terms of effective neutrino species) is $\boldsymbol{N_\nu = 3.046}$. Any deviation from it would signal the presence of BSM or BνMSM physics.

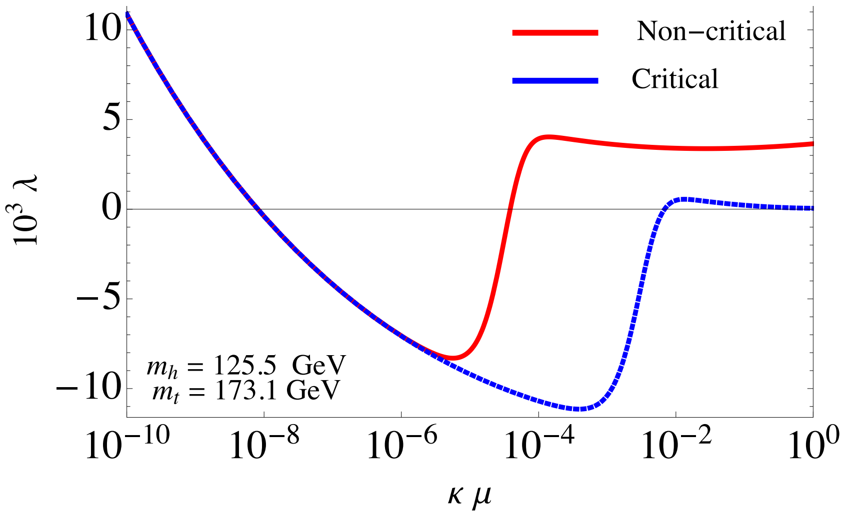
- Neutrino physics
  - Determine neutrino masses (or establish the best constraint on them). The νMSM prediction: one of the active neutrino masses is below 10^{-5} eV, meaning that $\sum m_\nu = 0.1$ eV or $= 0.06$ eV , depending on neutrino mass hierarchy (inverted or normal).
  - Prove the absence or presence of light sterile neutrinos ~ 1 eV
- Particle Physics
  - Top Yukawa coupling with accuracy 5×10^{-4} ($\delta M_t \simeq 100$ MeV) (LHC? future e^+e^- collider?)
  - HNL production and decays are highly suppressed – dedicated experiments are needed:
    - Mass below ~ 2 GeV - Intensity frontier, SHiP: CERN SPS.
    - Mass above ~ 2 GeV - FCC in e^+e^- mode in Z-peak, LHC

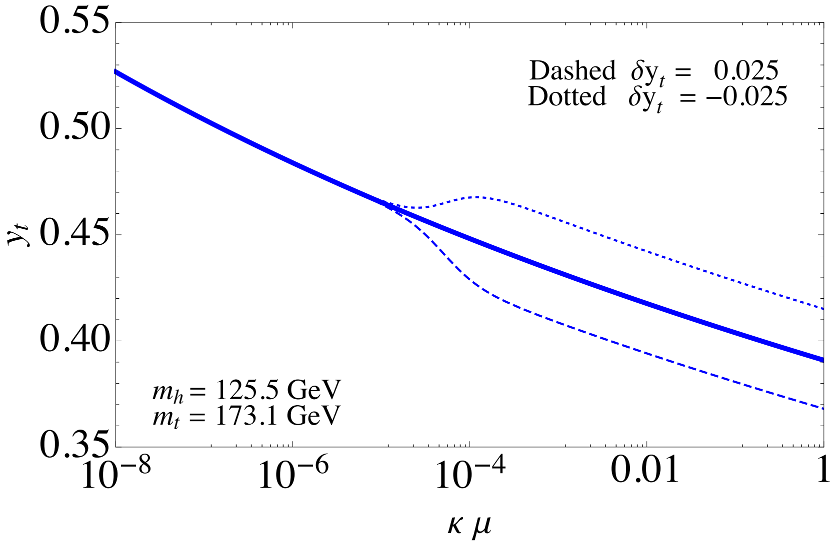
Backup slides

Higgs inflation with metastable vacuum

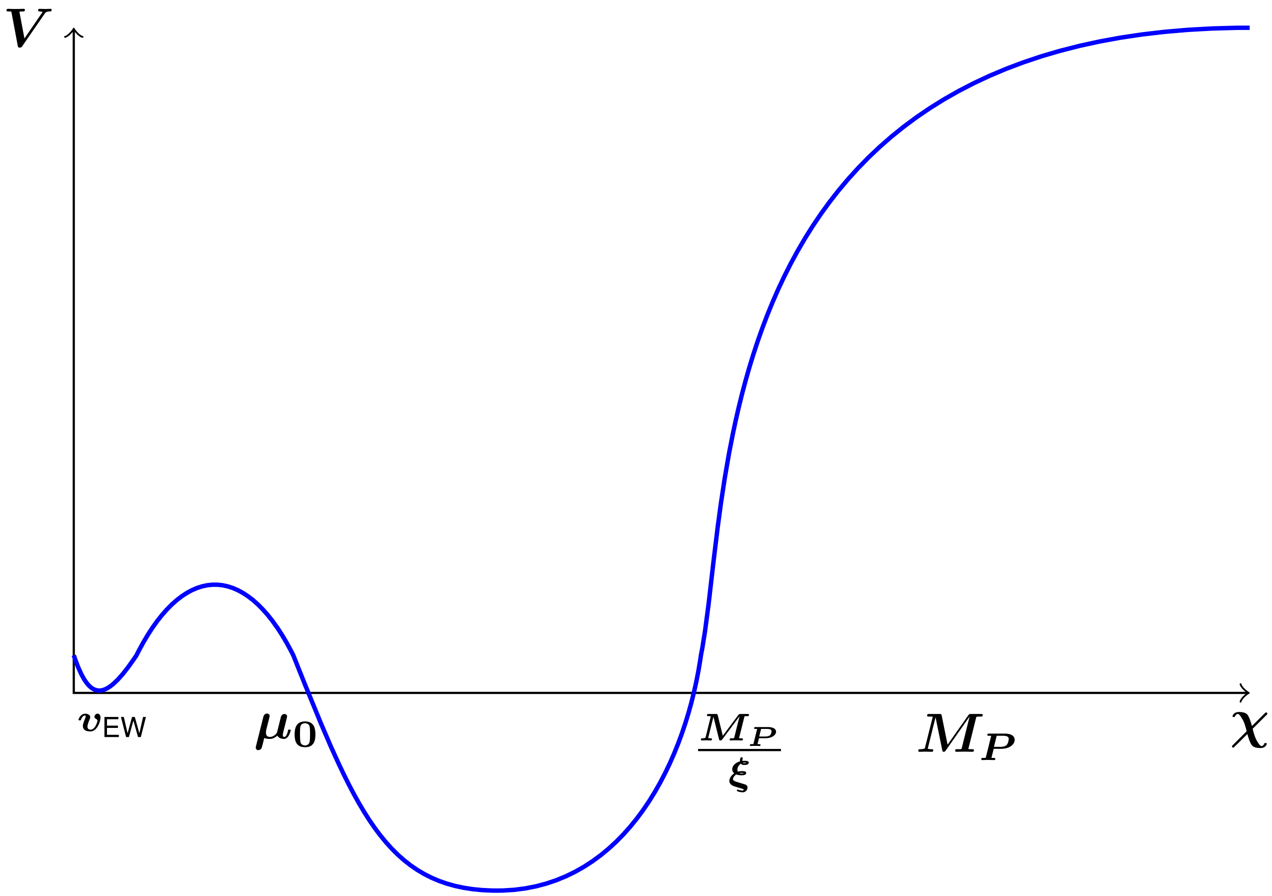
The scale M_P/ξ is the boundary between low energy and high energy behaviours. Here the “jumps” of the coupling constants occur.

$\lambda(M_P/\xi)$ is small due to cancellations between fermionic and bosonic loops: $\delta\lambda$ can be of the order of λ

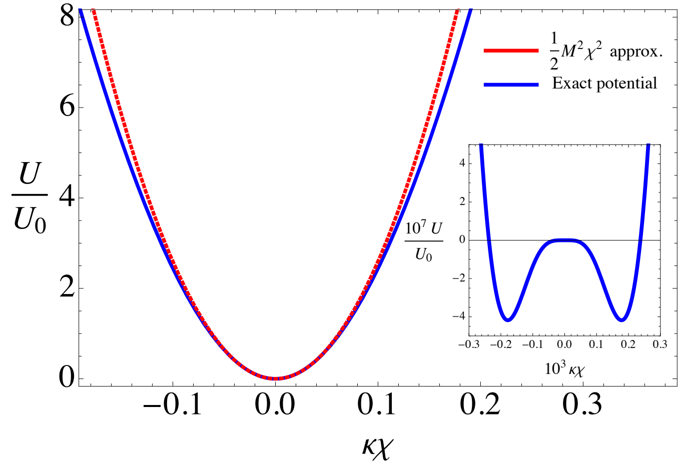


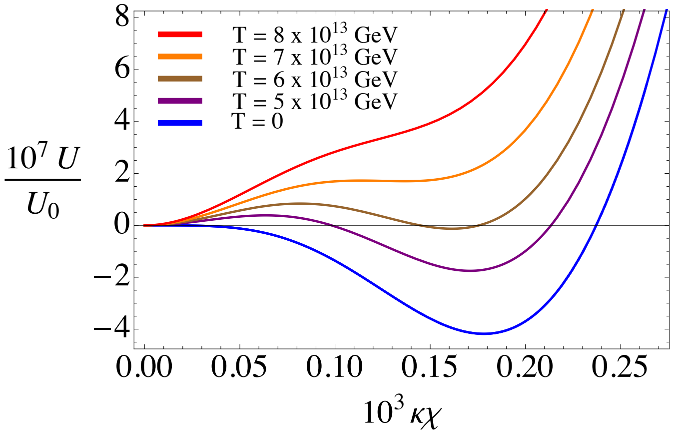


Higgs potential



Symmetry restoration





Reheating temperature $T_R \simeq 2 \times 10^{14}$ GeV $> T_+ \simeq 7 \times 10^{13}$ GeV,

$T_c = 6 \times 10^{13}$ GeV

System is trapped at the vacuum with zero Higgs field and does not go to the false vacuum!

Predictions for critical indexes n_s and r are the same:

$$n_s = 0.97, \quad r = 0.003$$

Effective field theory and neutrino masses

Neutrinos have non-zero masses - how to incorporate this into the Standard Model? Effective field theory approach: low energy Lagrangian can contain all sorts of higher-dimensional SU(3)×SU(2)×U(1) invariant operators, suppressed by some unknown scale Λ:

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

Majorana neutrino mass: from five-dimensional operator

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

Neutrino mass matrix:

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

Crucial questions:

- What is the physics behind non-renormalizable terms?
- What is the value of Λ ?

Common lore: origin of neutrino masses - existence of new unseen particles; complete theory is renormalisable

Common lore: origin of neutrino masses - existence of new unseen particles; complete theory is renormalisable

- Higgs triplet with hypercharge 2 - direct contribution to neutrino mass
- Singlet Majorana fermions - effective contribution to neutrino mass

Common lore: origin of neutrino masses - existence of new unseen particles; complete theory is renormalisable

- Higgs triplet with hypercharge 2 - direct contribution to neutrino mass
- Singlet Majorana fermions - effective contribution to neutrino mass