ÉCOLE POLYTECHNIQUE
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The Standard Model and Particle Physics

Mikhail Shaposhnikov

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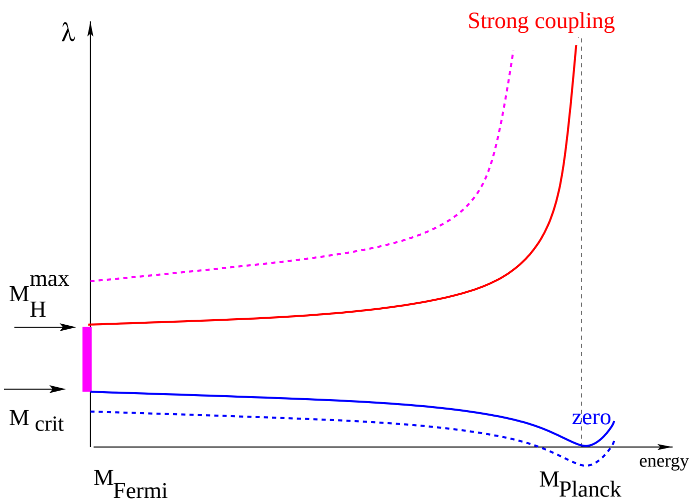
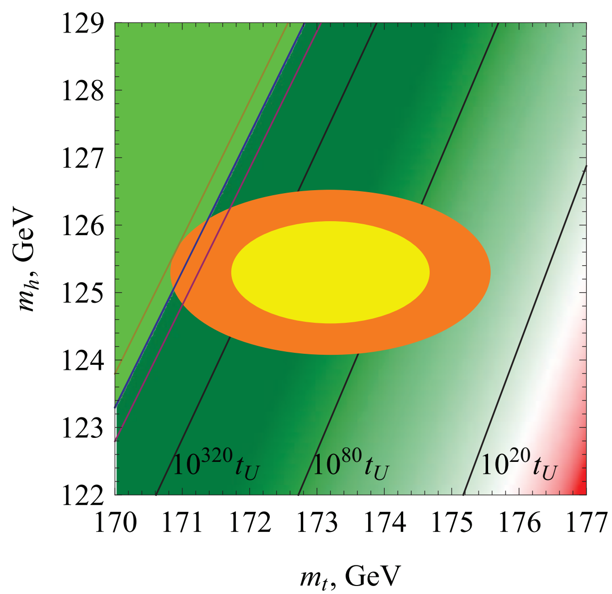
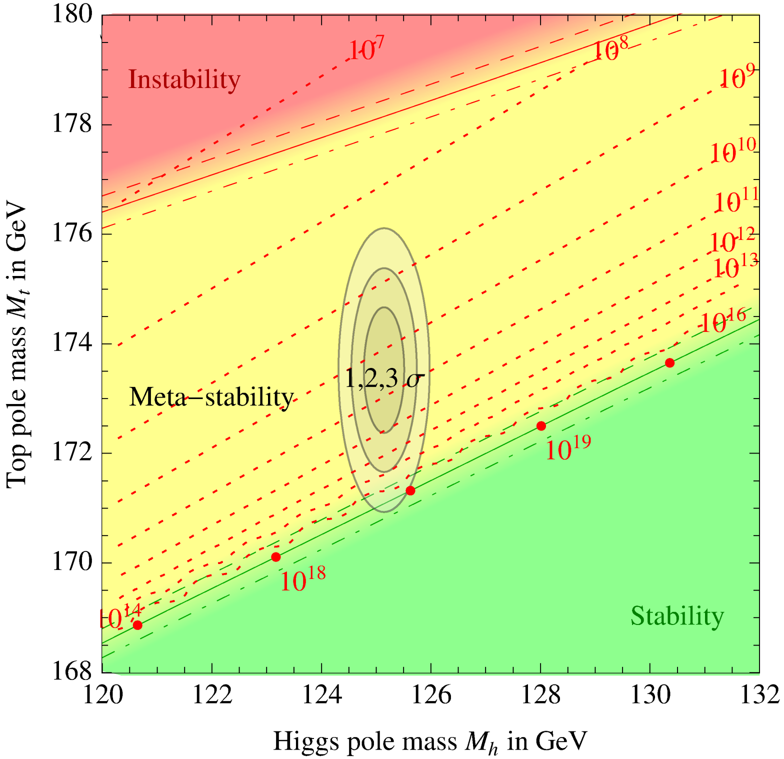
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age.

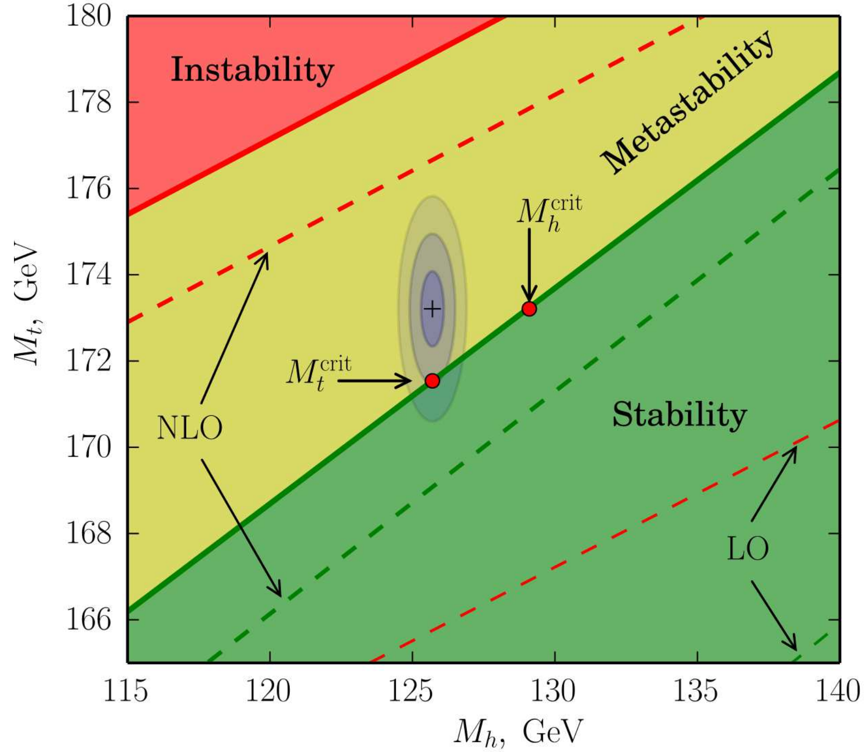




Buttazzo et al '14

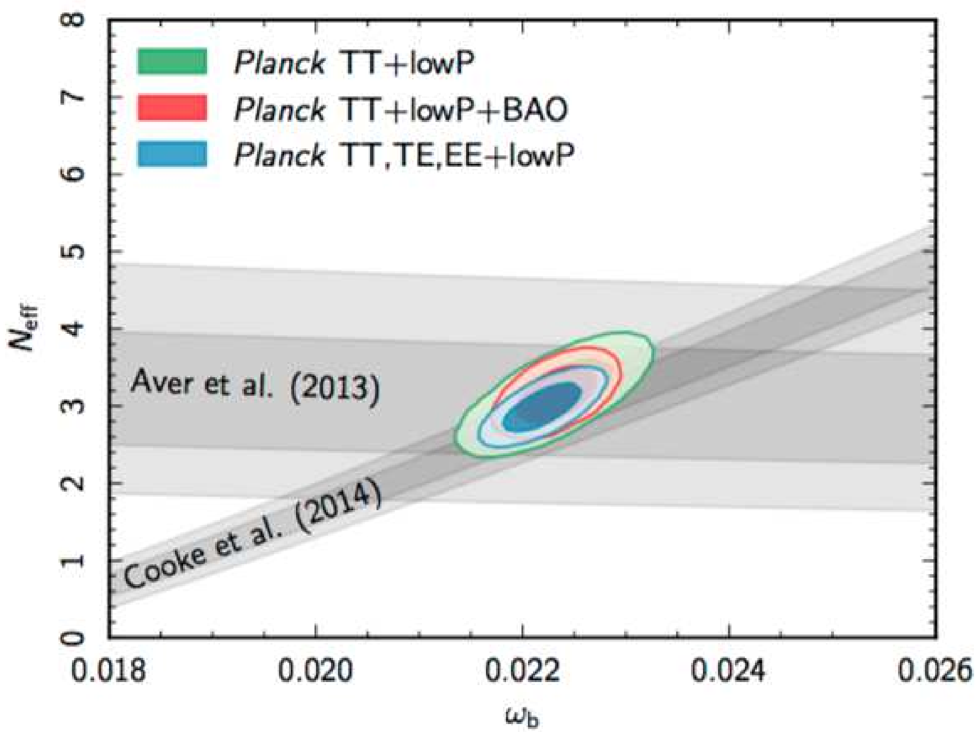


Bednyakov et al '15



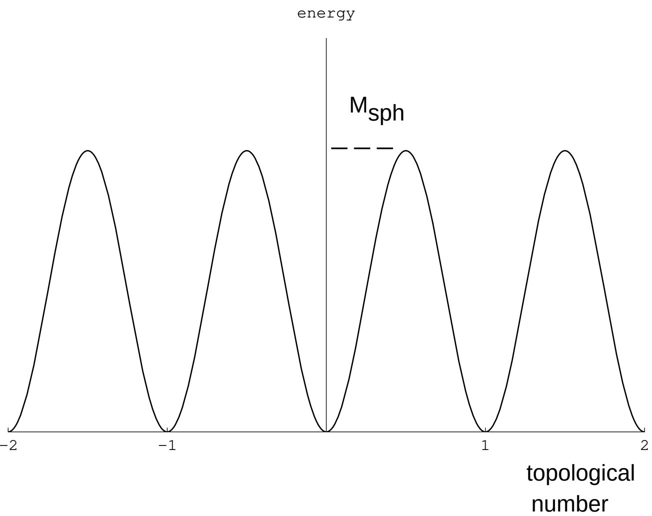
Great features of the SM in cosmology

- 3 light neutrino species: well consistent with Big Bang Nucleosynthesis, CMB and large scale structure of the Universe (Planck: $n_\nu = 3.15 \pm 0.23$).



Great features of the SM in cosmology

The rate of B non-conservation exactly as we would like it to have for baryogenesis!



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

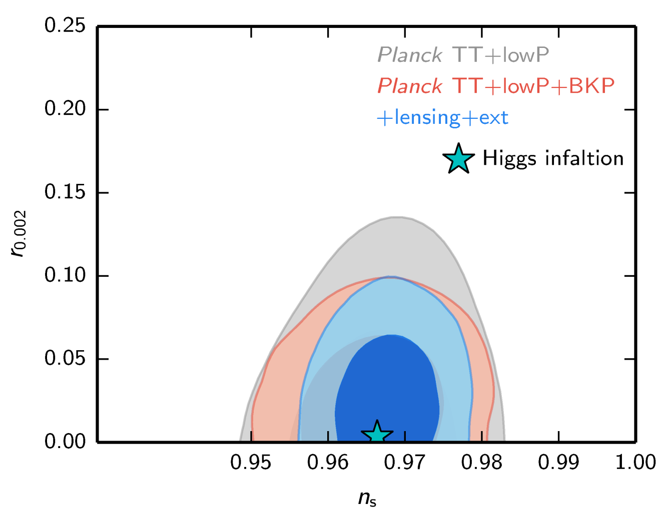
These reactions are in thermal equilibrium for

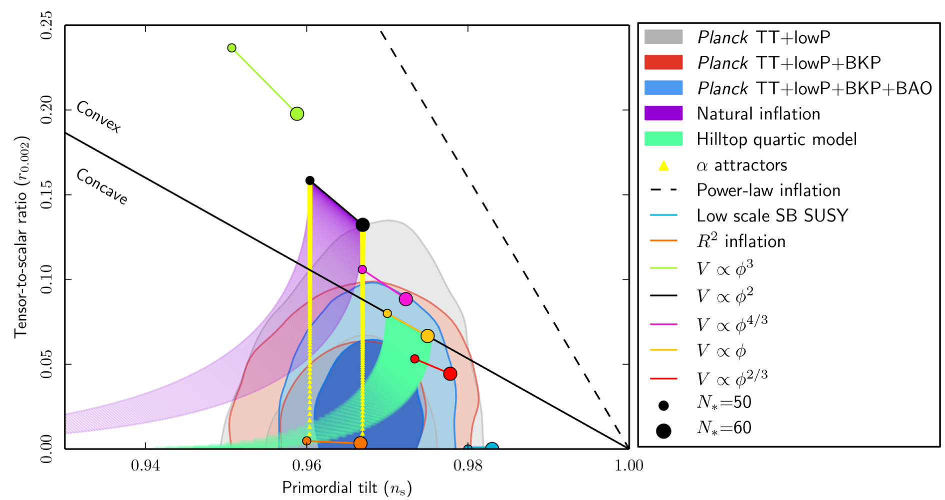
$$100 \text{ GeV} \sim T_c < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} \text{ GeV}$$

Great features of the SM in cosmology

- Presence of the fundamental scalar field – Higgs boson, which can play a role of the inflaton and make the Universe flat, homogeneous and isotropic and produce quantum fluctuations necessary for structure formation. Hot Big Bang due to Higgs field oscillations! Higgs-gravity coupling : $\xi H^2 R$.

Prediction of Higgs inflation: $n_s = 0.97, \;\; r = 0.003$





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Spell Syllables

Synonyms Examples Word Origin

See more synonyms on Thesaurus.com

adjective

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This is unfair to "unnatural" SM as it describes the Nature better than "natural" theories...

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Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated, to remove sensitivity of m_H to physics at very high energy scale Λ (e.g. GUT).

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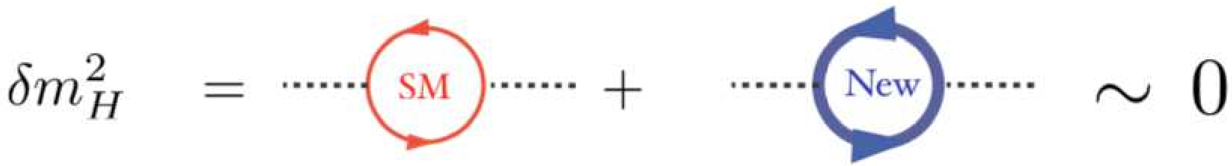


right above EW scale

The original source of the naturalness requirement: hierarchy problem in Grand Unified theories

PHYSICAL REVIEW D VOLUME 14, NUMBER 6 15 SEPTEMBER 1976

Gauge-symmetry hierarchies*

Eldad Gildener
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 June 1976)

It is shown that one cannot artifically establish a gauge hierarchy of any desired magnitude by arbitrarily adjusting the scalar-field parameters in the Lagrangian and using the tree approximation to the potential; radiative corrections will set an upper bound on such a hierarchy. If the gauge coupling constant is approximately equal to the electromagnetic coupling constant, the upper bound on the ratio of vector-meson masses is of the order of $\alpha^{-1/2}$, independent of the sclar-field masses and their self-couplings. In particular, the usual assumption that large scalar-field mass ratios in the Lagrangian can induce large vector-meson mass ratios is false. A thus far unsuccessful search for natural gauge hierarchies is briefly discussed. It is shown that if such a hierarchy occurred, it would have an upper bound of the order of $\alpha^{-1/2}$.

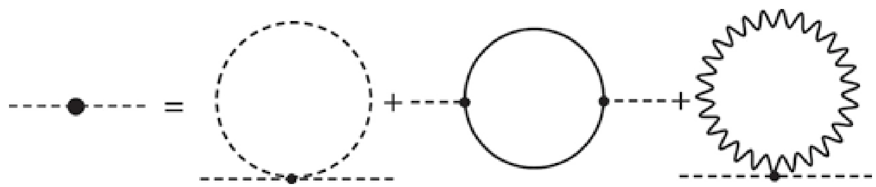
Extra GUT particles beyond the SM – leptoquarks (vector and scalar) must be very heavy, $M_X > 10^{15}$ GeV

- this is required by the gauge coupling unification
- this is needed for stability of matter, proton lifetime $\tau_p > 10^{34}$ years

Hierarchy: $(\frac{M_X}{M_W})^2 \simeq 10^{28}$

Two faces of hierarchy

- Ad hoc tuning between the parameters (masses and couplings of different multiplets) at the tree level with an accuracy of 26 orders of magnitude
- Stability of the Higgs mass against radiative corrections Gildener, '76



$$\delta m_H^2 \simeq \alpha_{GUT}^n M_X^2$$

Tuning is needed up to 14th order of perturbation theory!

Proposed solutions

Stability of EW scale – requirement of “naturalness”: absence of quadratic divergencies in the Higgs mass

- Low energy SUSY: compensation of bosonic loops by fermionic loops
- Composite Higgs boson - new strong interactions
- Large extra dimensions

All require new physics right above the Fermi scale, which was expected to show up at the LHC

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No new physics?

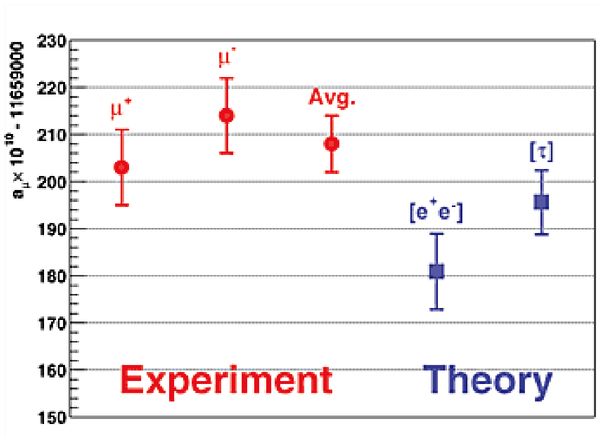
Last point cannot be true: neutrino physics and cosmology tell us that the SM is not the final theory

Solid experimental and observational evidence for new physics :

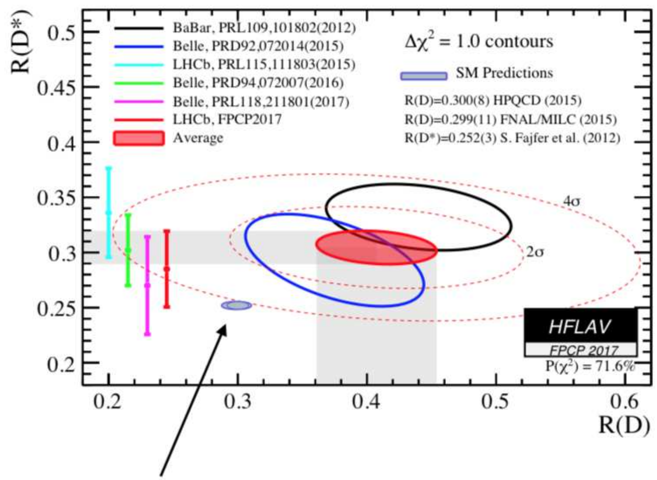
- Observations of neutrino oscillations (in the original SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM: CKM mixing is not enough, and there is no EW phase transition with experimental value of the Higgs mass – no large departures from thermal equilibrium)

Contradictions to high energy experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM.
  Will be checked by muon $g-2$ experiment at FNAL.

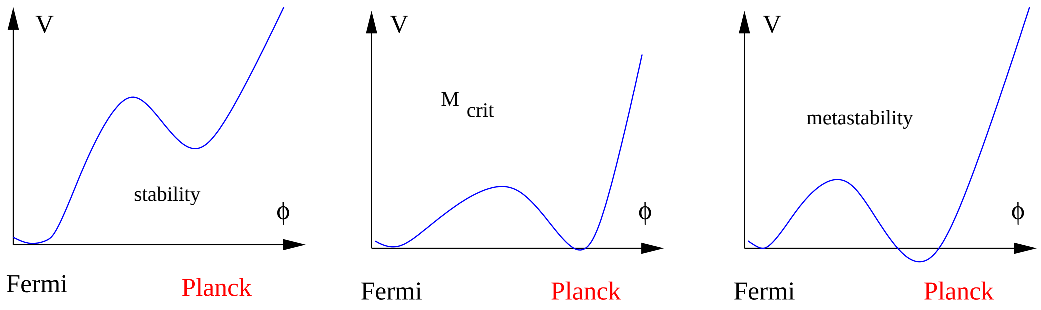


- Violation of lepton flavour universality
  Will be checked by future flavour experiments



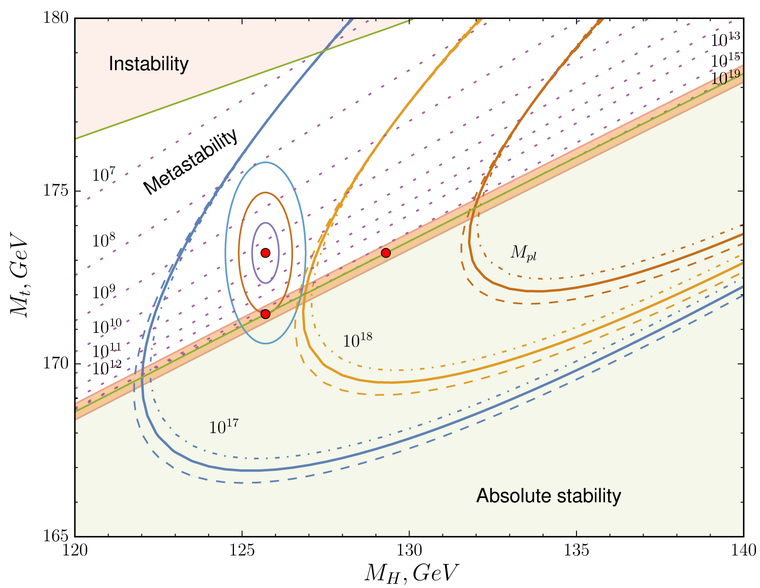
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

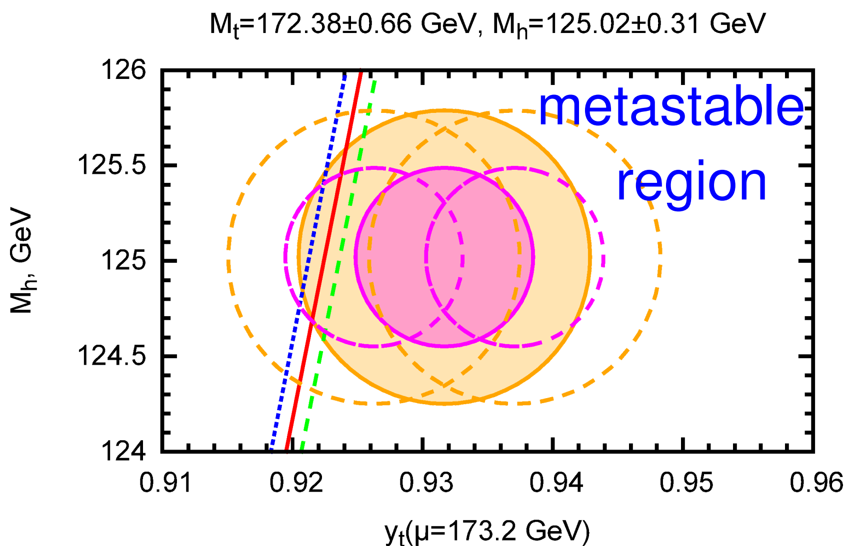
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling



Bednyakov et al, '15

Vacuum is unstable at 1.3σ





Theoretical prejudice for new physics beyond the Standard Model: WHY questions

- SM contains 19 free parameters, none of them is theoretically predicted, they are all taken from experiment. Why do they have the values we observe? Why $m_e \ll m_t$? ...
- Cosmological constant problem: Why $\epsilon_{vac}/M_{Pl}^4 \lll 1$?
- Hierarchy problem: Why $M_W/M_{Pl} \ll 1$?
- Strong CP-problem: Why $\theta_{QCD} \ll 1$?
- ...

Where is new physics?

Only at the Planck scale?

Does not work: neutrino masses from five-dimensional operator

$$\frac{1}{M_P} A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi} \right) \left(\phi^\dagger L^c_\beta \right)$$

suppressed by the Planck scale are too small, $m_\nu < 10^{-5}$ eV.

Below the Planck scale, but where?

- 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

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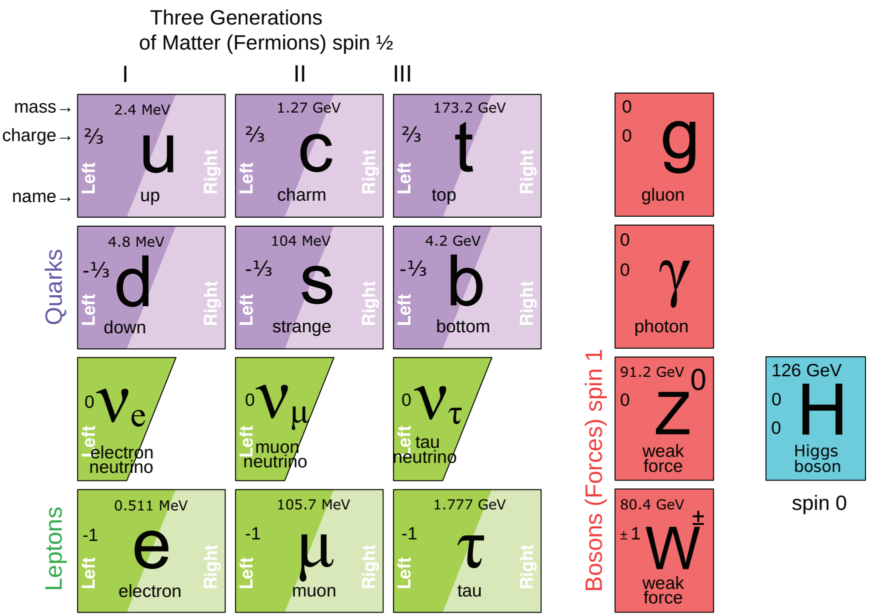
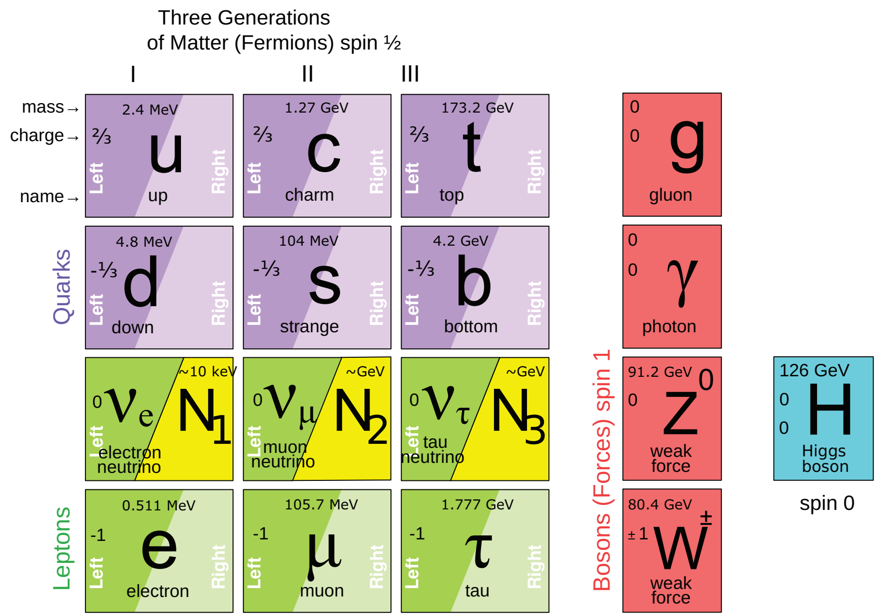
Challenge: all the experimental BSM problems should be explained by light particles!

Example of “complete” theory: the νMSM





νMSM $\equiv$ Neutrino minimal Standard Model

$\equiv$ Minimal low scale see-saw model with 3 singlet fermions

Role of the Higgs boson: break the symmetry and inflate the Universe

Role of N_1 with mass in keV region: dark matter.

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe.

Parameter counting: the νMSM

Most general renormalizable Lagrangian

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

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

15 new Yukawa couplings in the leptonic sector

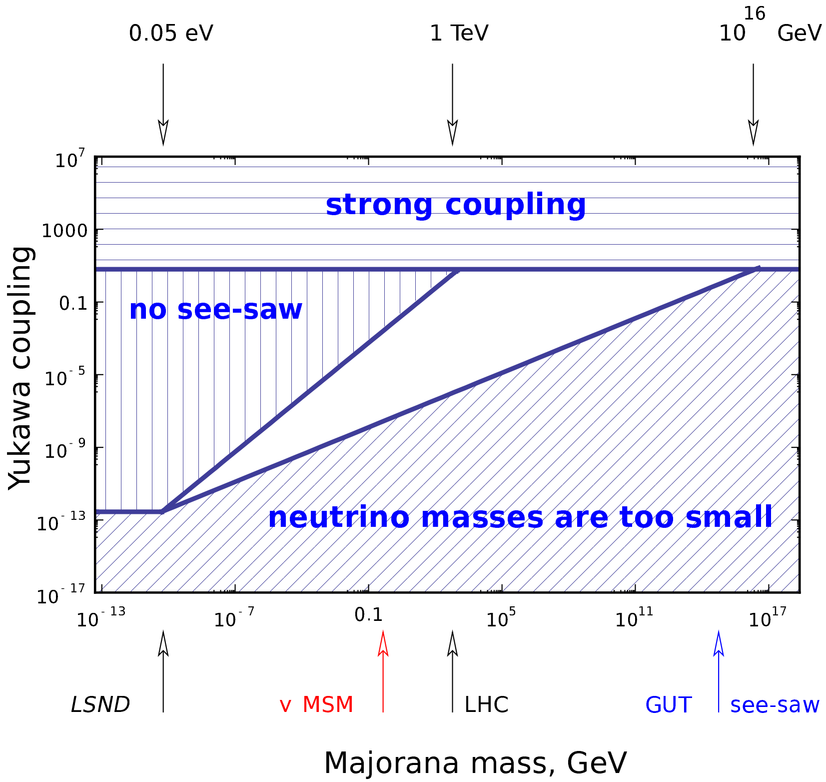
(3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases),

18 new parameters in total. The number of parameters is doubled in comparison with SM!

Cosmology and phenomenology of a minimal model

Neutrino masses and Yukawa couplings

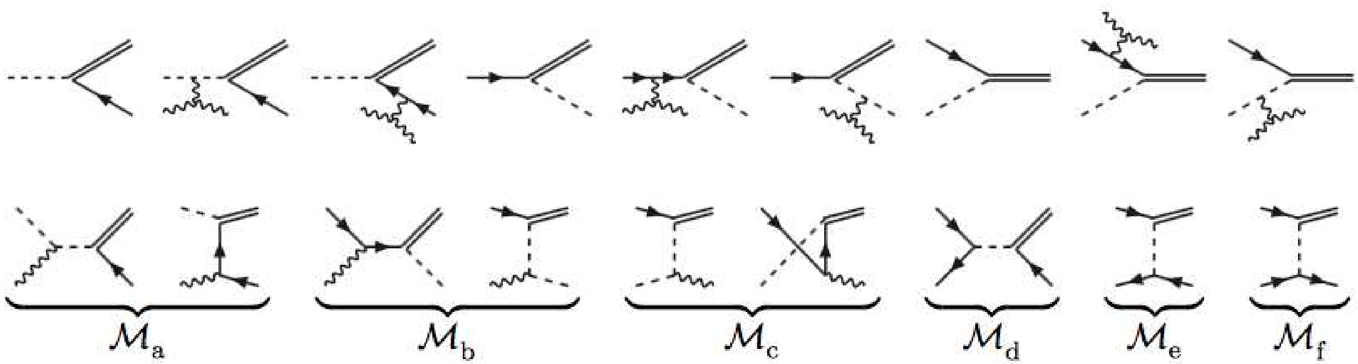
Yukawa couplings: $Y^2 = Trace[F^\dagger F]$



Baryon asymmetry

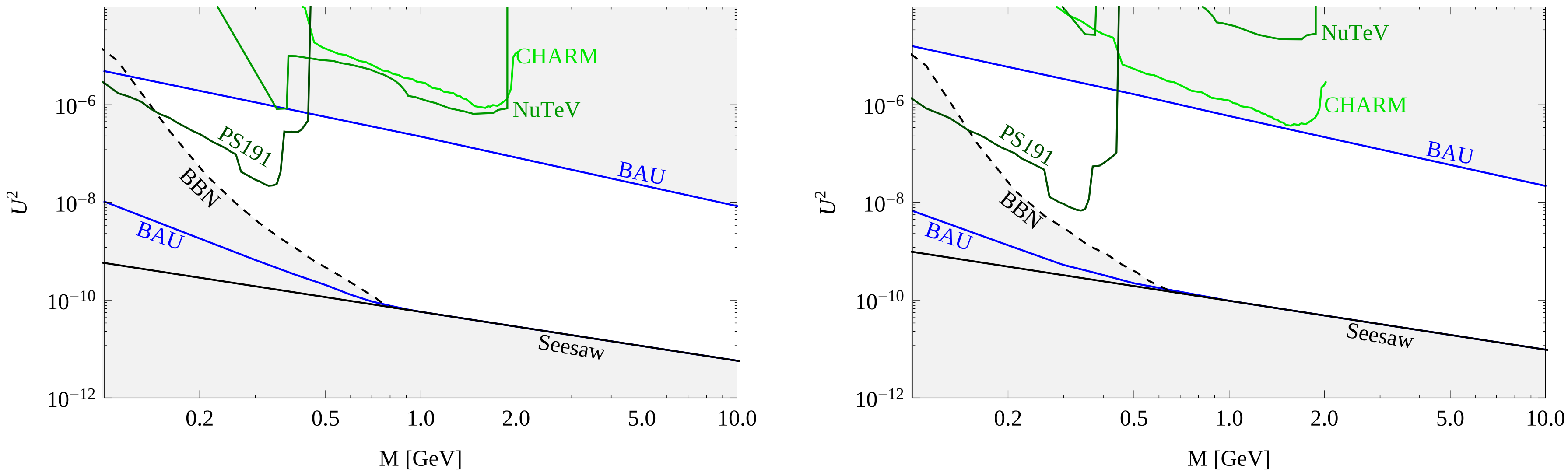
Creation of baryon asymmetry - a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation

Akhmedov, Rubakov, Smirnov; Asaka, MS



Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable.

Baryon asymmetry: HNLs $N_{2,3}$

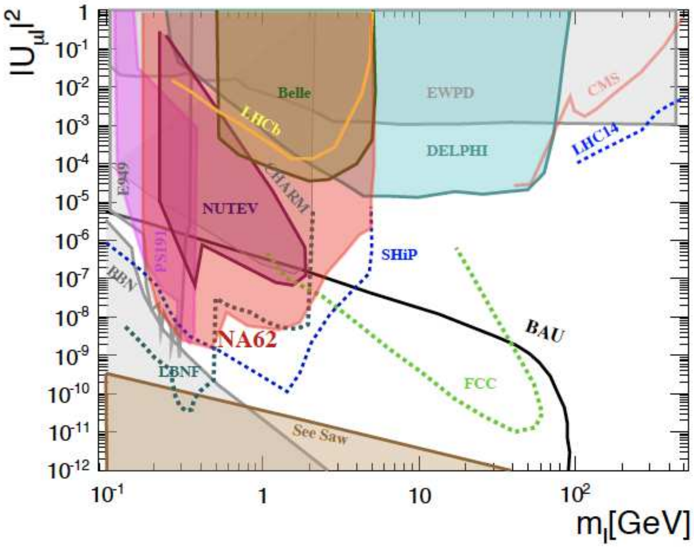


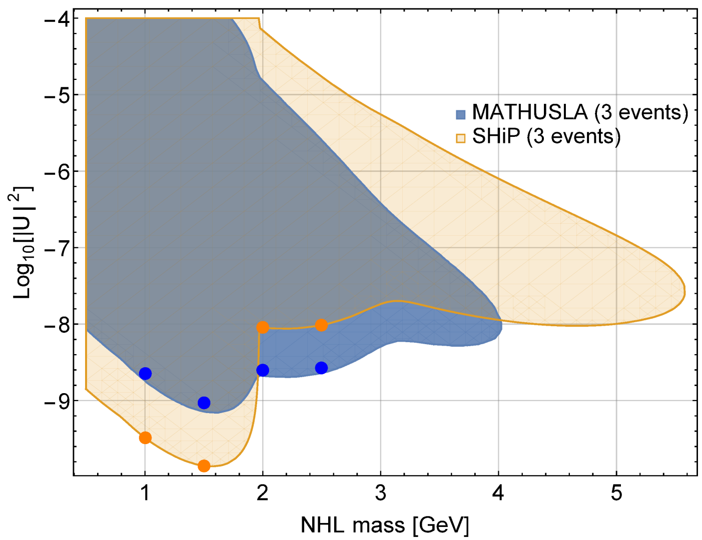
Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS '12). Similar results: recent works by Abada, Arcadia, Domcke, Lucente ' 15, Hernández, Kekic, J. López-Pavón, Racker, J. Salvado '16,Drewes, Garbrech, Guetera, Klarić '16, Hambye, Teresi '17

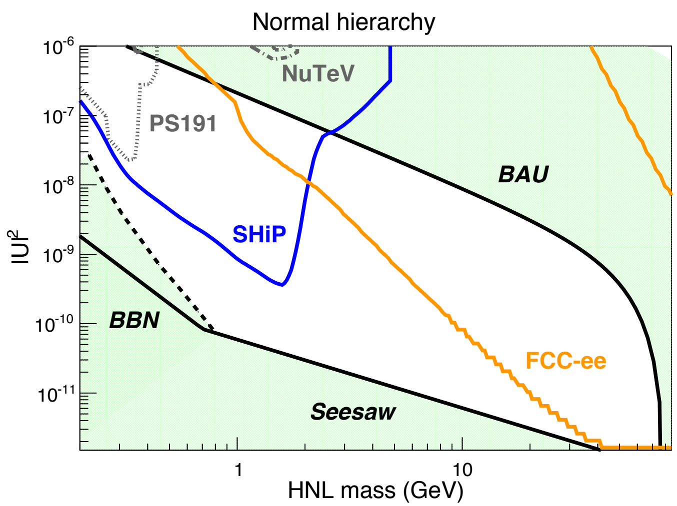
Experimental challenges:

- HNL production and decays are highly suppressed – dedicated experiments are needed:
  - Mass below ~ 5 GeV - Intensity frontier, CERN SPS: NA62 in beam dump mode, SHiP
  - Mass below ~ 5 GeV - Energy frontier, LHC: MATHUSLA
  - Mass above ~ 5 GeV - FCC in e^+e^- mode in Z-peak, LHC

Generic purpose experiments to search for all sorts of relatively light dark sector particles (dark photons, hidden scalars, etc).







FCC at 10^{13} Z^0 and decay length 0.01-500 cm

Dark Matter candidate: N_1

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

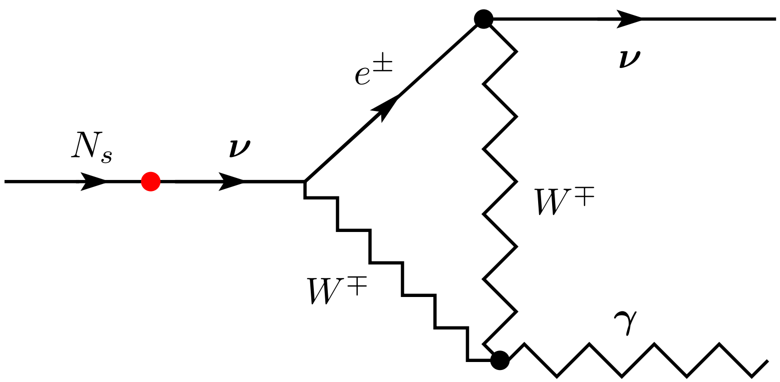
Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

Photon energy:

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

Radiative decay width:

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

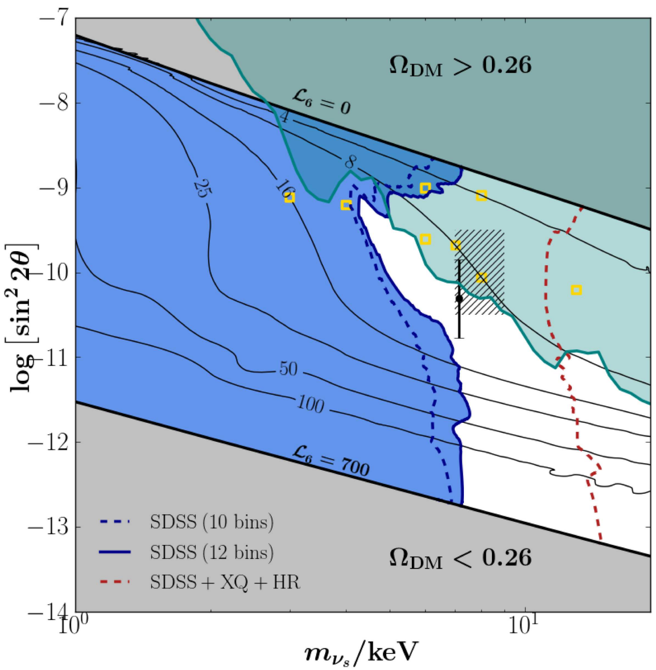


N_1 decays radiatively, $N_1 \rightarrow \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes!

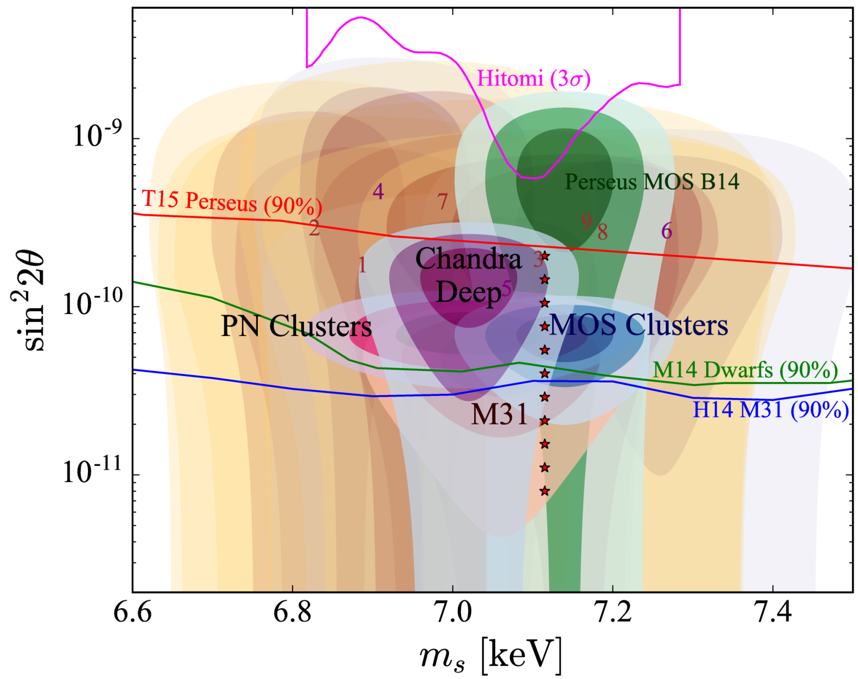
Status of sterile neutrino dark matter N_1

Decaying DM: $N_1 \to \gamma\nu$

3.5 keV line: E. Bulbul et al, Boyarsky et al



1706.03118, Baur et al.



1705.01837 Abazajian

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

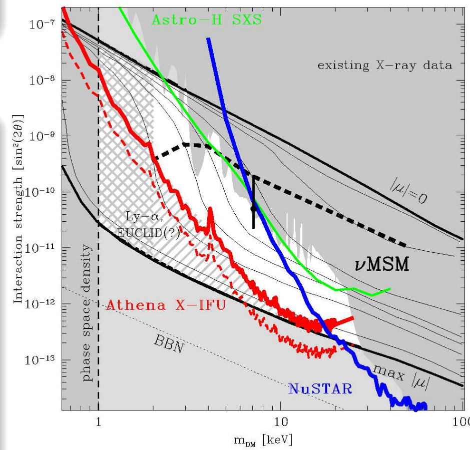
It is planned to send a replacement of the Hitomi satellite

Microcalorimeter on sounding rocket (2019)

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

Athena+ (around 2028)

- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution



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- find particles that lead to baryon asymmetry of the Universe
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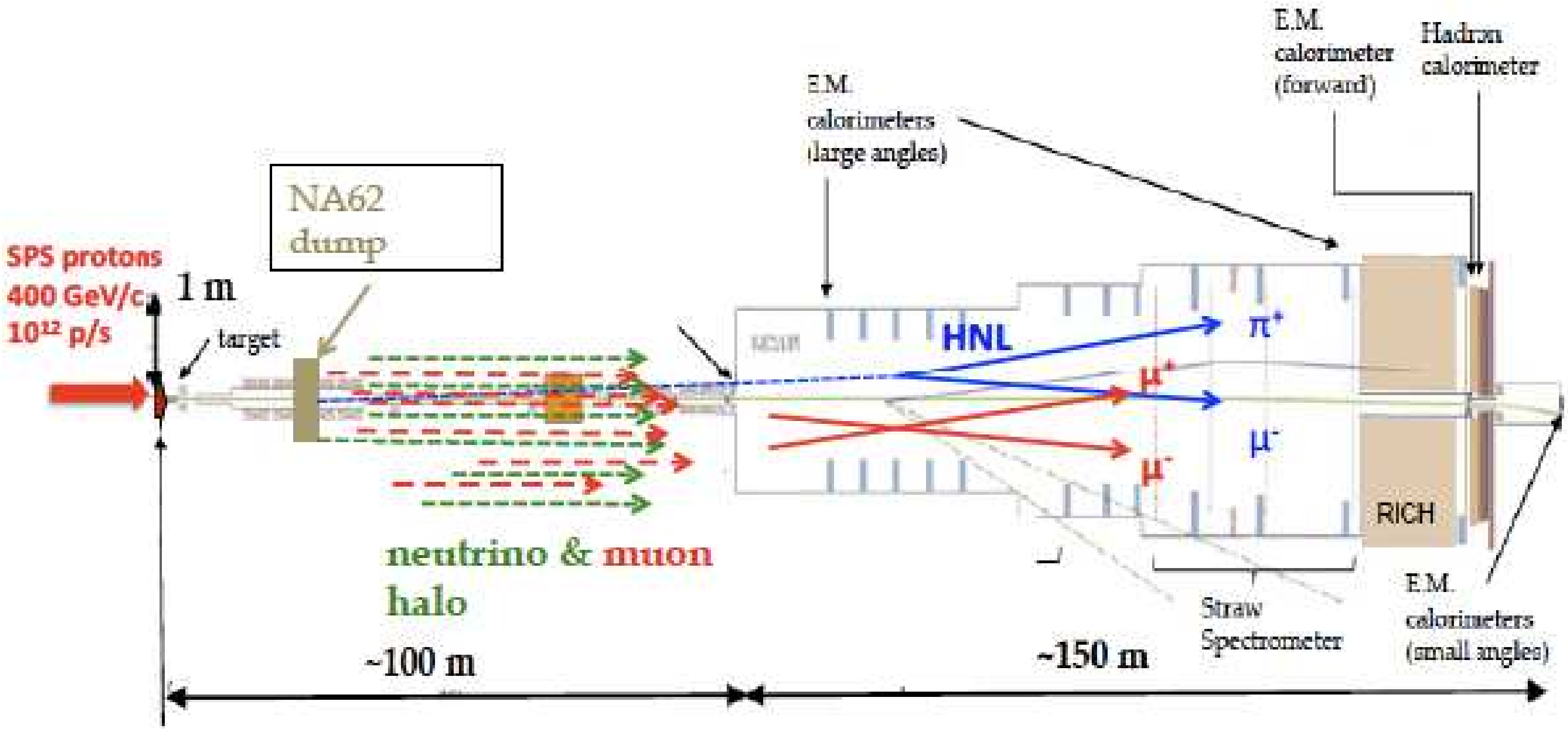
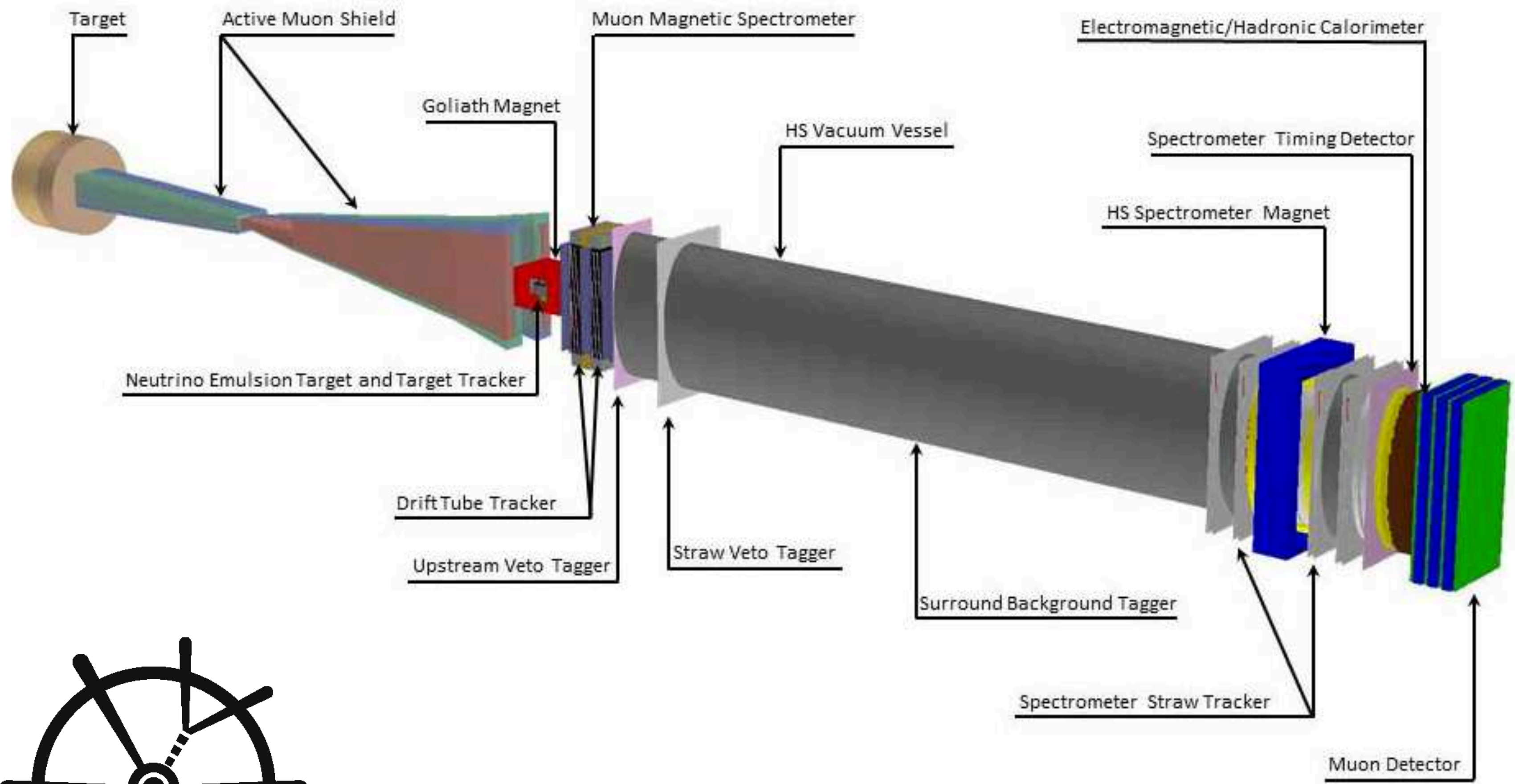
This opportunity should not be missed!

Backup slides

NA62



SPS protons
400 GeV/c
10^{12} p/s
1 m
target
NA62 dump
neutrino & muon halo
E.M. calorimeters (large angles)
E.M. calorimeter (forward)
Hadron calorimeter
HNL
π^+
μ^+
μ^-
μ^-
RICH
Straw Spectrometer
E.M. calorimeters (small angles)
~100 m
~150 m



SHiP
Search for Hidden Particles

MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles