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Steps beyond the Standard Model: searching for simplicity

Mikhail Shaposhnikov

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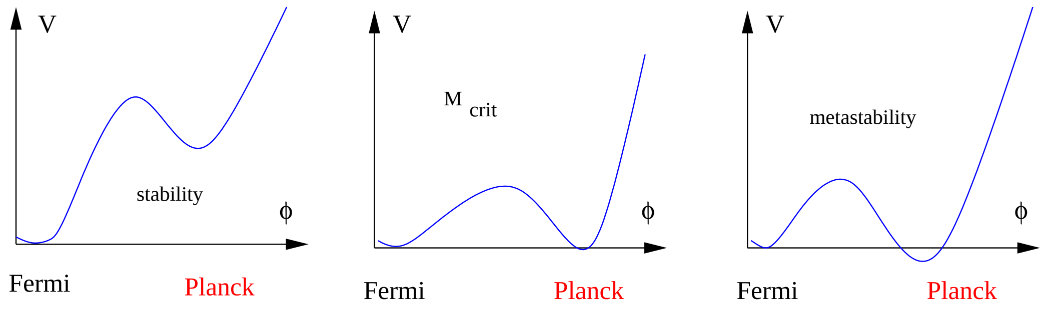
For 125 GeV Higgs mass the Standard Model is a self-consistent weakly coupled effective field theory for all energies up to the quantum gravity scale $M_P \sim 10^{19}$ GeV

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

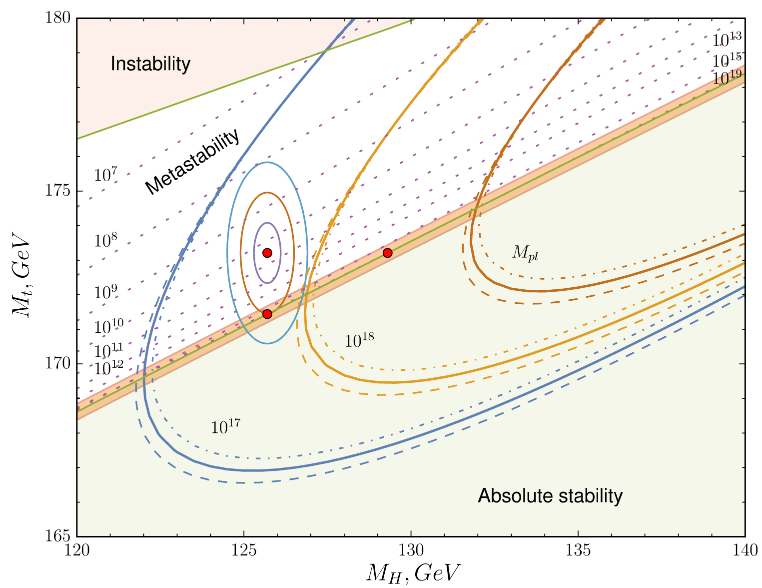
- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)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

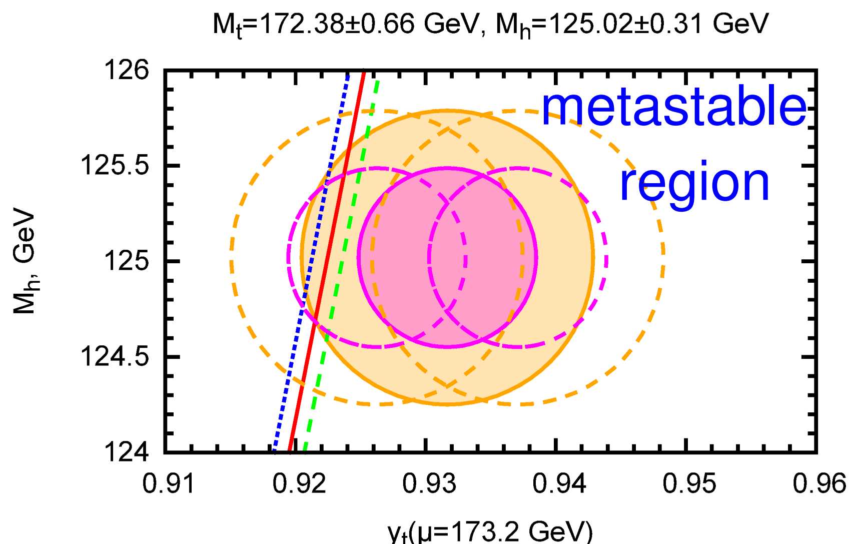
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling



Bednyakov et al, ’15

Vacuum is unstable at 1.3σ





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

Searching for simplicity:

New Physics without new energy scale

Quantum scale invariance and naturalness

Why scale invariance?

If the mass of the Higgs boson is put to zero in the SM, the Lagrangian has a wider symmetry: it is scale and conformally invariant:

Dilatations - global scale transformations ($\sigma = const$)

$$\Psi(x) \ \rightarrow \ \sigma^n \Psi(\sigma x) \ ,$$

$n = 1$ for scalars and vectors and $n = 3/2$ for fermions.

It is tempting to use this symmetry for solution of the hierarchy problem

Quantum scale invariance

Common lore: quantum scale invariance does not exist, divergence of dilatation current is not-zero due to quantum corrections:

$$\partial_\mu J^\mu \propto \beta(g) G^a_{\alpha\beta} G^{\alpha\beta\ a} \ ,$$

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The way out: scale independent subtraction of divergences

Toy model

Classically scale-invariant Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \chi)^2 - V(\varphi, \chi)$$

Potential (χ - “dilaton”, φ - “Higgs”):

$$V(\varphi, \chi) = \frac{\lambda}{4}\left(h^2 - \frac{\alpha}{\lambda}\chi^2\right)^2 + \beta\chi^4,$$

$\beta < 0$: vacuum is unstable

$\beta = 0$: flat direction, $h^2 = \frac{\alpha}{\lambda}\chi^2$. Choice of parameters:

$\alpha \sim \left(\frac{M_W}{M_P}\right)^2 \sim 10^{-32}$, to get the Higgs-Planck hierarchy correctly.

Standard reasoning

Dimensional regularisation $d = 4 - 2\epsilon$, $\overline{MS}$ subtraction scheme:

mass dimension of the scalar fields: $1 - \epsilon$,

mass dimension of the coupling constant: 2ϵ

Counter-terms:

$$\lambda = \mu^{2\epsilon} \left[\lambda_R + \sum_{k=1}^{\infty} \frac{a_n}{\epsilon^n} \right] ,$$

μ is a dimensionful parameter!!

One-loop effective potential along the flat direction:

$$V_1(\chi) = \frac{m_H^4(\chi)}{64\pi^2} \left[\log \frac{m_H^2(\chi)}{\mu^2} - \frac{3}{2} \right] ,$$

Result: explicit breaking of the dilatation symmetry. Dilaton acquires a nonzero mass due to radiative corrections.

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Idea: Replace $\mu^{2\epsilon}$ by combinations of fields χ and h, which have the correct mass dimension:

$$\mu^{2\epsilon} \to \chi^{\frac{2\epsilon}{1-\epsilon}} F_\epsilon(x) \; ,$$

where $x = h/\chi$. $F_\epsilon(x)$ is a function depending on the parameter ϵ with the property $F_0(x) = 1$.

Englert, Truffin, Gastmans '76; Zenhäusern, M.S '09

two loop analysis: Ghilencea et al, '16

Almost trivial statement - by construction: Quantum effective action is scale invariant in all orders of perturbation theory.

Less trivial statement Gretsch, Monin '15: Quantum effective action is conformally invariant in all orders of perturbation theory.

The main problem with this construction: theory is not renormalisable, one needs to add infinite number of counter-terms.

However:

- For $\alpha \ll 1$ all counter-terms are suppressed by the dimensionful parameter $\langle\chi\rangle$
- We get an effective field theory valid up to the energy scale fixed by $\langle\chi\rangle$
- Gravity is non-renormalisable anyway, and making $\langle\chi\rangle \sim M_P$ does not make a theory worse

Hierarchy problem

For $\alpha = \beta = 0$ the classical Lagrangian has an extra symmetry : $\chi \to \chi + const$. Therefore, there are no large perturbative corrections to the Higgs mass: those proportional to χ contain necessarily α or β, those proportional to λ contain only logs of χ. This construction leads to "natural" hierarchy $\chi \gg h$. However, no explanation of why $\alpha \ll 1$.

$$V(\varphi, \chi) = \frac{\lambda}{4}\left(h^2 - \frac{\alpha}{\lambda}\chi^2\right)^2 + \beta\chi^4,$$

Important ingredient for naturalness: almost exact shift symmetry.

Requirement of the shift symmetry $\equiv$ requirement of absence of heavy particles with sufficiently strong interaction with the Higgs field and the dilaton, e.g.

$$\lambda_h h^2 \phi^2 + \lambda_\chi \chi^2 \phi^2$$

$\lambda_h \sim \lambda_\chi \sim 1$ spoils the argument!

Also: C. Tamarit

Conjecture: natural theory should not have heavy particles between the Fermi and Planck scales

Inclusion of gravity

Planck scale: through non-minimal coupling of the dilaton to the Ricci scalar.

Gravity part

$$\mathcal{L}_G = -\left(\xi_\chi \chi^2 + \xi_h h^2\right)\frac{R}{2} \,,$$

This term, for $\xi_\chi \sim 1$, does break the shift symmetry. However, this is a coefficient in front of graviton kinetic term. Since the graviton stays massless in any constant scalar background, the perturbative computations of gravitational corrections to the Higgs mass in scale-invariant regularisation are suppressed by M_P. There are no corrections proportional to M_P!

Consequences

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- Fifth force or Brans-Dicke constraints are not applicable to it

Problems

- What happens beyond perturbation theory?
- What leads to selection of parameter $\beta = 0 \equiv$ existence of flat direction $\equiv$ absence of the cosmological constant ?
- Unitarity and high-energy behaviour: What is the high-energy behaviour $(E > M_{Pl})$ of the scattering amplitudes? Is the theory unitary? Can it have a scale-invariant UV completion?

The minimal model - scale invariant νMSM

Requirements: no heavy particles with sufficiently strong interaction with the Higgs field and the dilaton + simplicity

Similar in spirit studies: SMASH by Ballesteros et al; V. Khoze et al

Particle content

Particles of the SM

+

graviton

+

dilaton

+

3 Majorana leptons

Scale-invariant Lagrangian

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM[M\to 0]}} + \mathcal{L}_G + \frac{1}{2}(\partial_\mu \chi)^2 - V(\varphi,\chi)$$
$$+ \left(\bar N_I i\gamma^\mu \partial_\mu N_I - h_{\alpha I}\, \bar L_\alpha N_I \tilde\varphi - f_I \bar N_I{}^c N_I \chi + \mathrm{h.c.}\right) ,$$

Potential (χ - dilaton, φ - Higgs, $\varphi^\dagger\varphi = 2h^2$):

$$V(\varphi,\chi) = \lambda\left(\varphi^\dagger\varphi - \frac{\alpha}{2\lambda}\chi^2\right)^2 + \beta\chi^4,$$

Gravity part

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

Roles of different particles

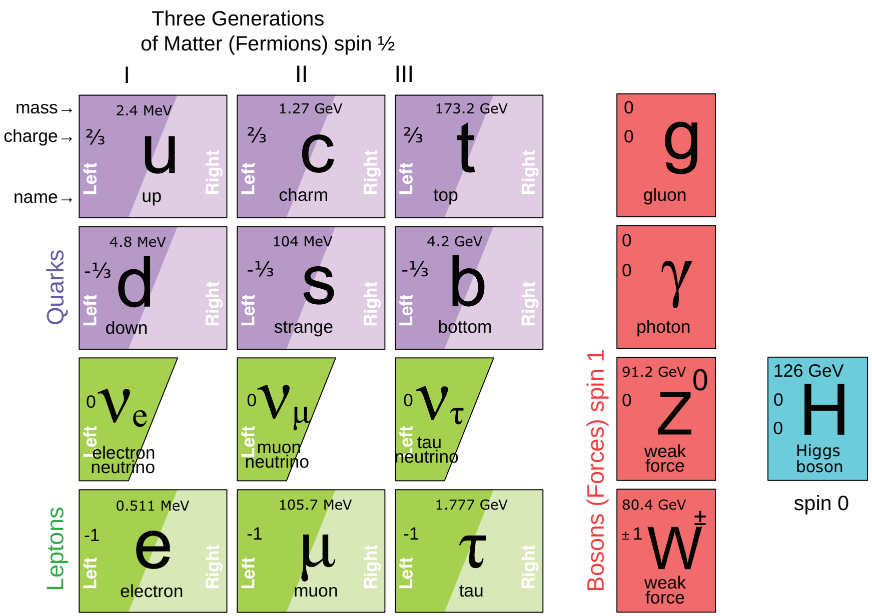
The roles of dilaton:

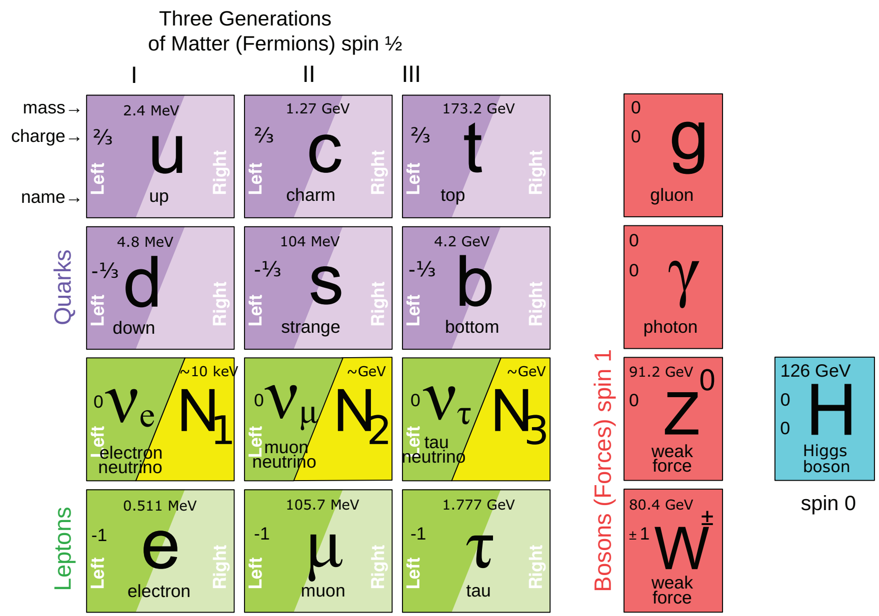
- determine the Planck mass
- give mass to the Higgs
- give masses to 3 Majorana leptons

Roles of the Higgs boson:

- give masses to fermions and vector bosons of the SM
- provide inflation

New physics below the Fermi scale: the νMSM





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.

The couplings of the νMSM

Particle physics part, accessible to low energy experiments: the νMSM. Mass scales of the νMSM:

$M_I < M_W$ (No see-saw)

Consequence: small Yukawa couplings,

$$F_{\alpha I} \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim (10^{-6} - 10^{-13}),$$

here $v \simeq 174$ GeV is the VEV of the Higgs field,

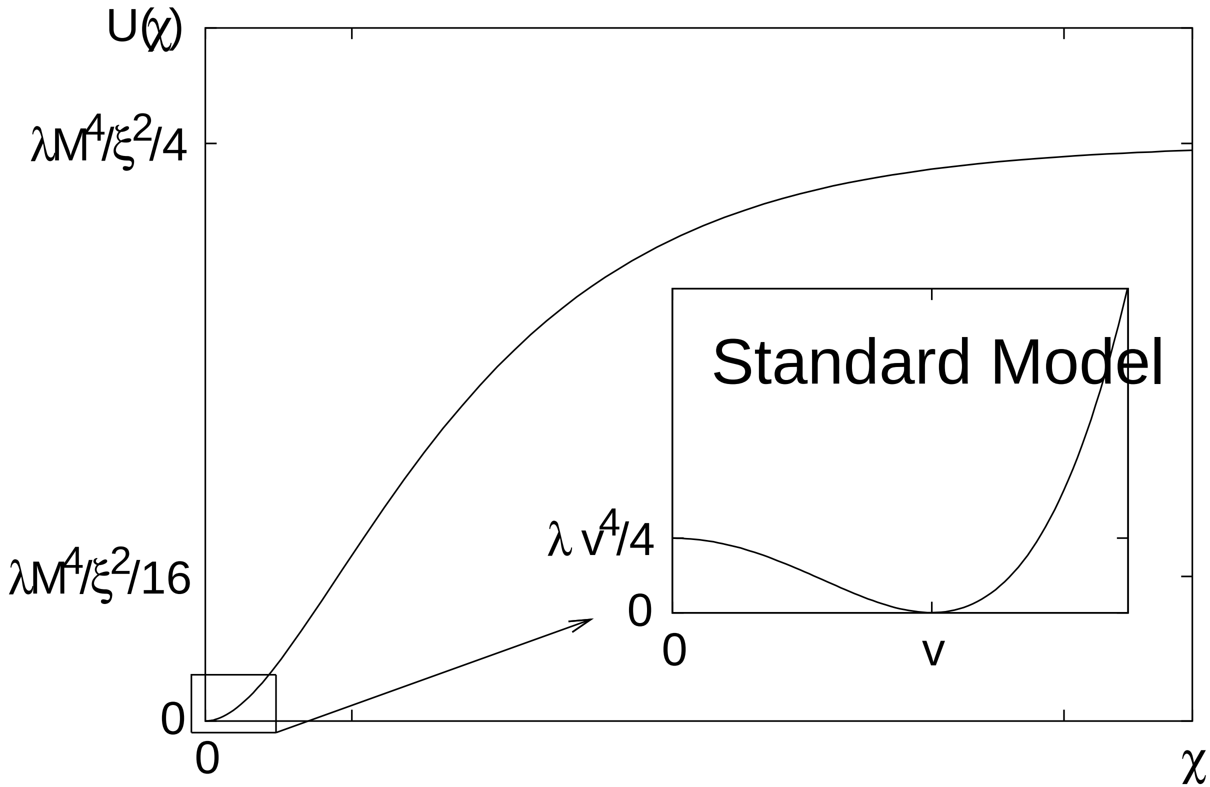
$m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference.

Small Yukawas are also necessary for stability of dark matter and baryogenesis (out of equilibrium at the EW temperature).

Cosmology and phenomenology of a minimal model

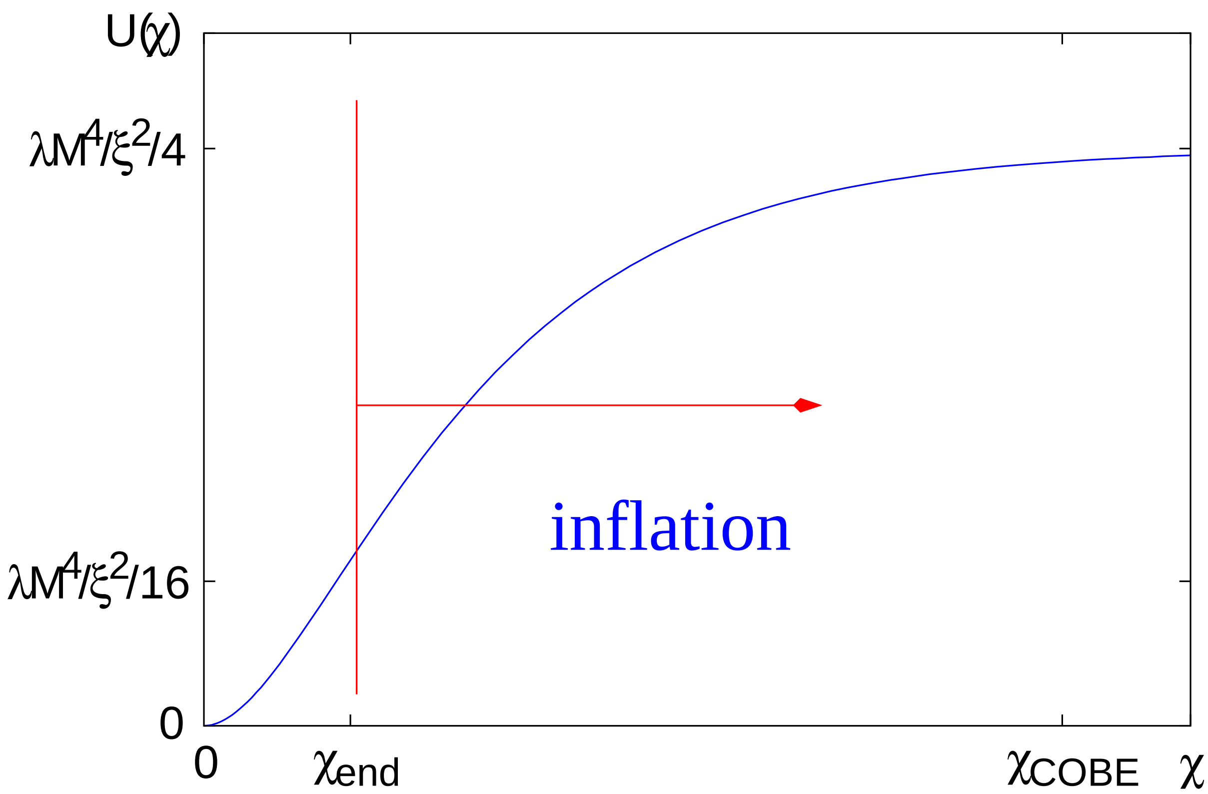
Inflation: Higgs boson

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



χ - canonically normalised scalar field in Einstein frame.

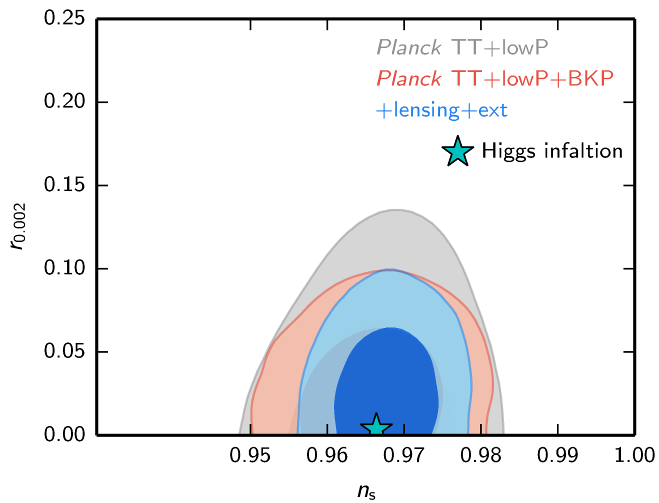
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

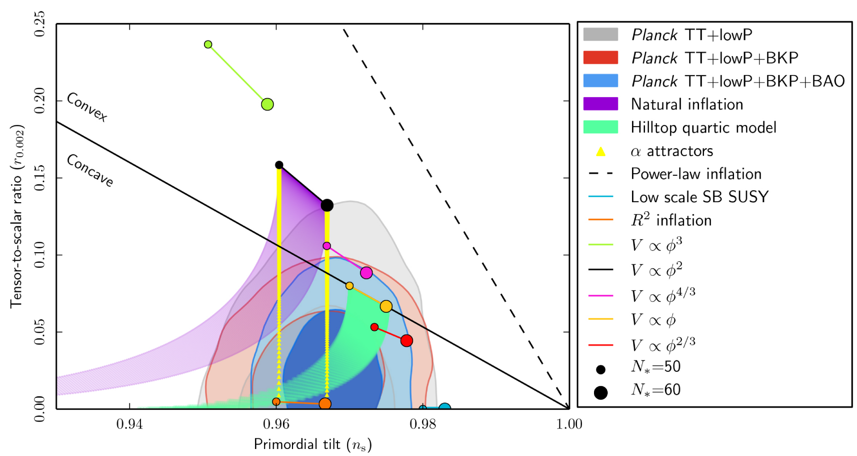


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

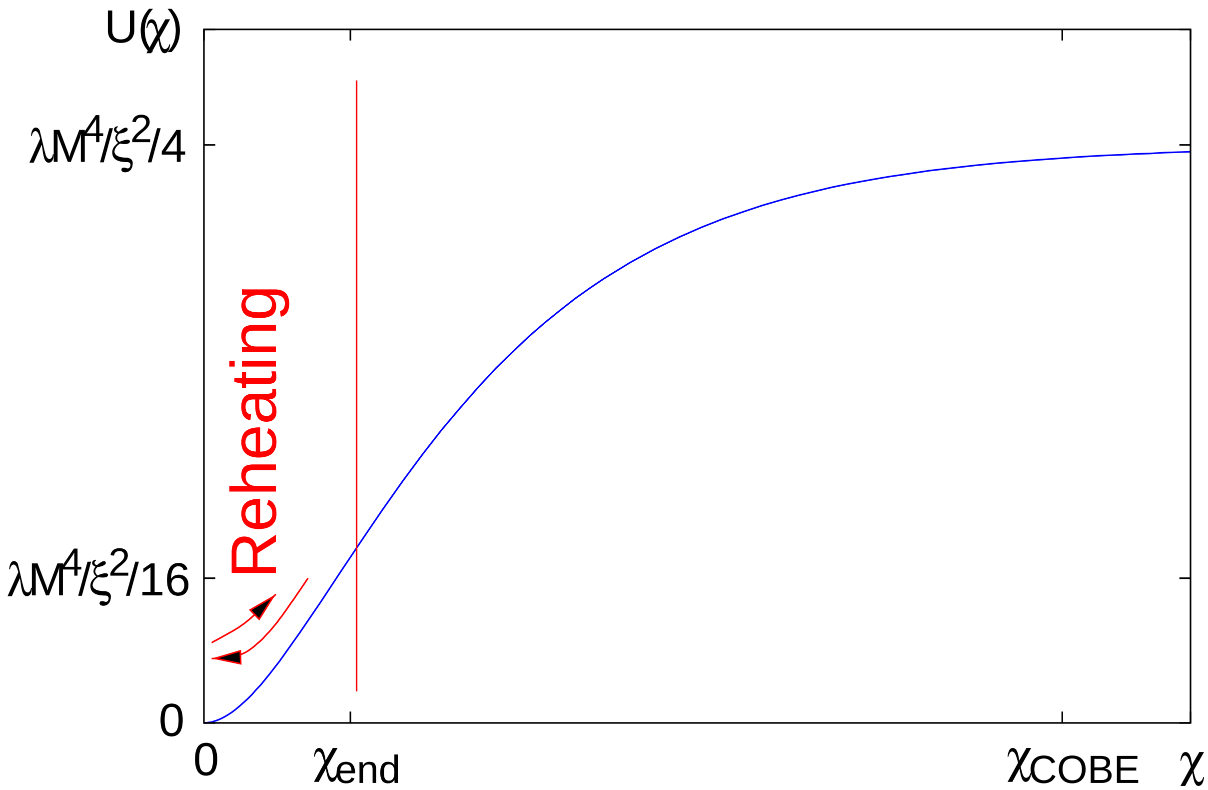
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

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



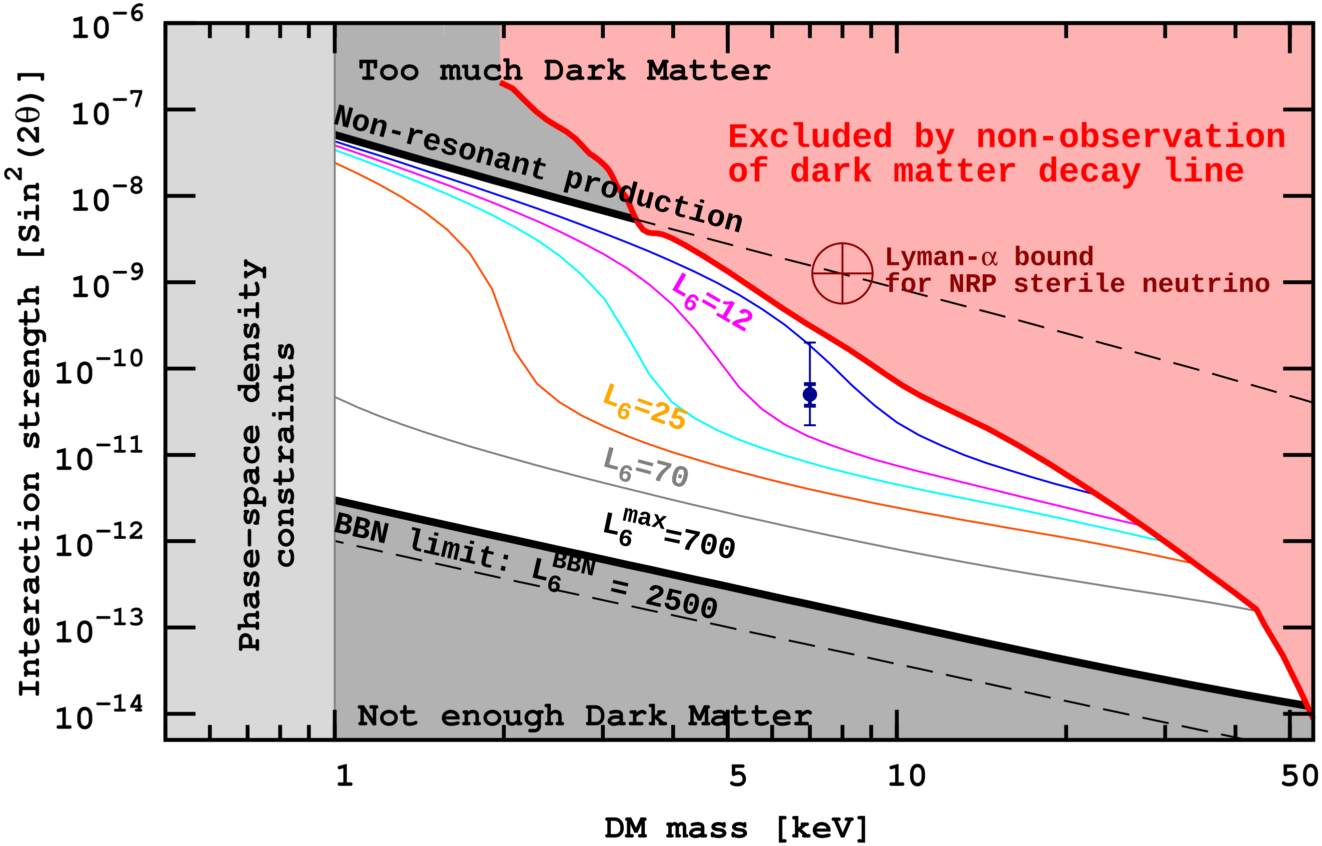


Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- 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

DM: sterile neutrino N_1



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

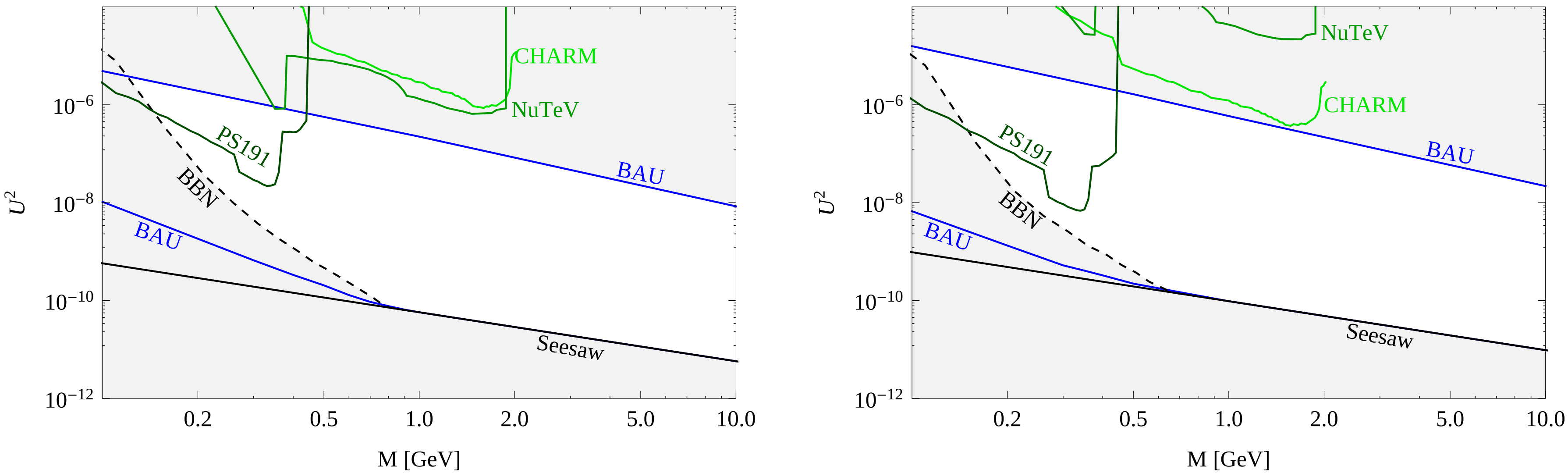
Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

$N_{2,3}$ HNL dynamics 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 and back.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

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



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). Other studies: Drewes et al., Hernandez et al

Summary of predictions, 2005-2009

Prediction	assumptions	status
No deviations from SM at LHC	structure of νMSM	OK
SM Higgs boson with $M_H > 127 \pm 2$ GeV	Higgs inflation	OK within 2σ
SM Higgs boson with $M_H = 127 \pm 2$ GeV	asymptotic safety	OK within 2σ
No WIMPS	structure of νMSM	OK
DM is a keV scale HNL , $N \to \nu\gamma$	structure of νMSM	3.5 keV X-ray line?
New particles - HNL	structure of νMSM	constraints only
Unitarity of PMNS matrix	structure of νMSM	OK
no light sterile ν	structure of νMSM	OK
neutrino mass $m_1 \lesssim 10^{-5}$ eV	dark matter	constraints only
No visible $\mu \to e\gamma,\ \mu \to 3e, etc$	BAU	OK
$N_\nu = 3$	structure of νMSM	OK, Planck
spectral index $n_s = 0.967$	Higgs inflation	OK, Planck
small tensor to scalar ratio $r = 0.003$	Higgs inflation	Planck, constraints only
no non-Gaussianities	Higgs inflation	Planck, constraints only

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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:

- HNL production and decays are highly suppressed – dedicated experiments or analyses are needed:
  - Mass below $\sim \mathbf{2}$ GeV - Intensity frontier, CERN SPS.
  - Mass above $\sim \mathbf{2}$ GeV - FCC in e^+e^- mode in Z-peak, LHC
  - HNL's in beauty and charm decays: Belle, LHCb

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

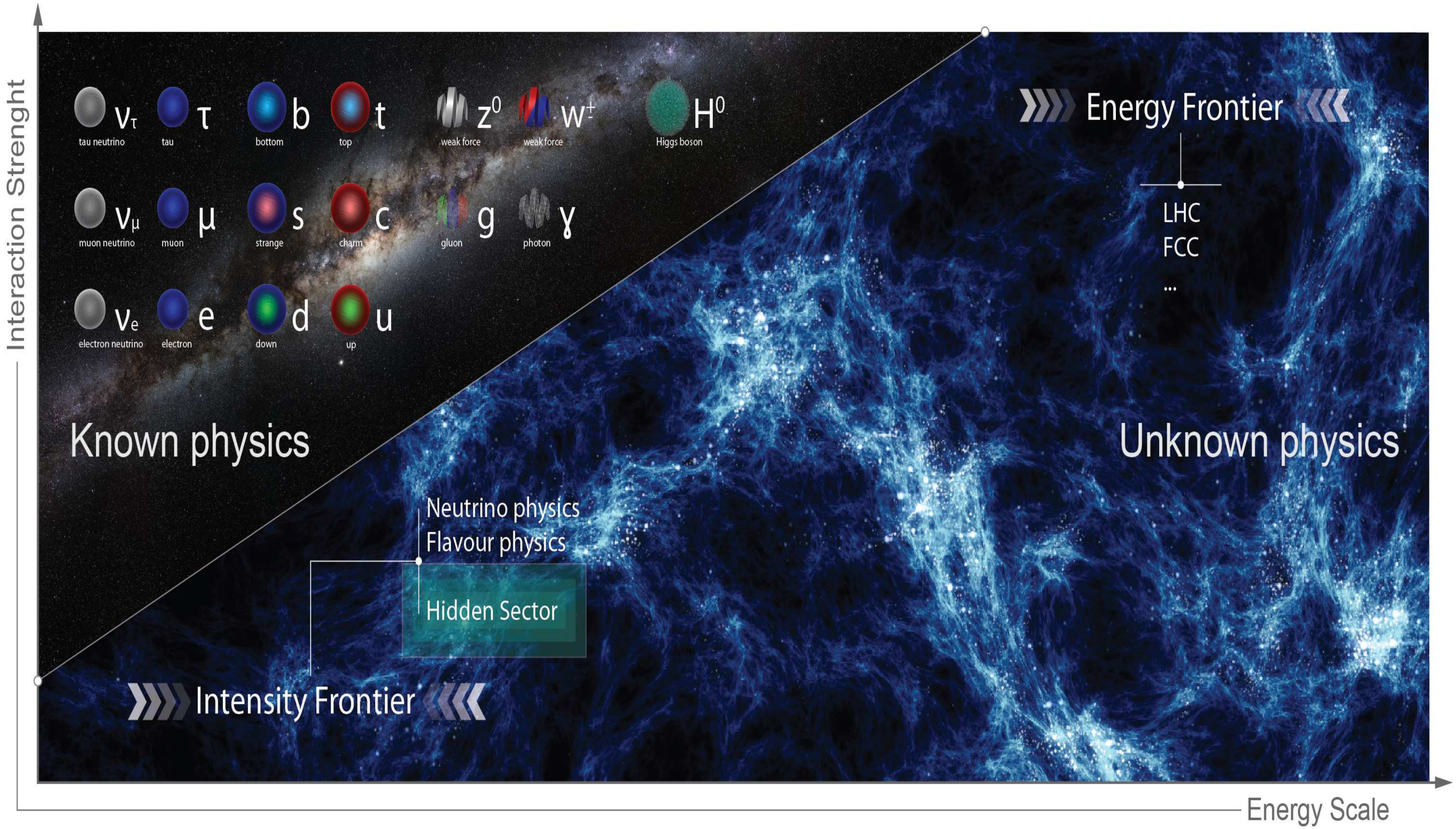
$\Downarrow$

General beam dump facility: Search for Hidden Particles

SHiP

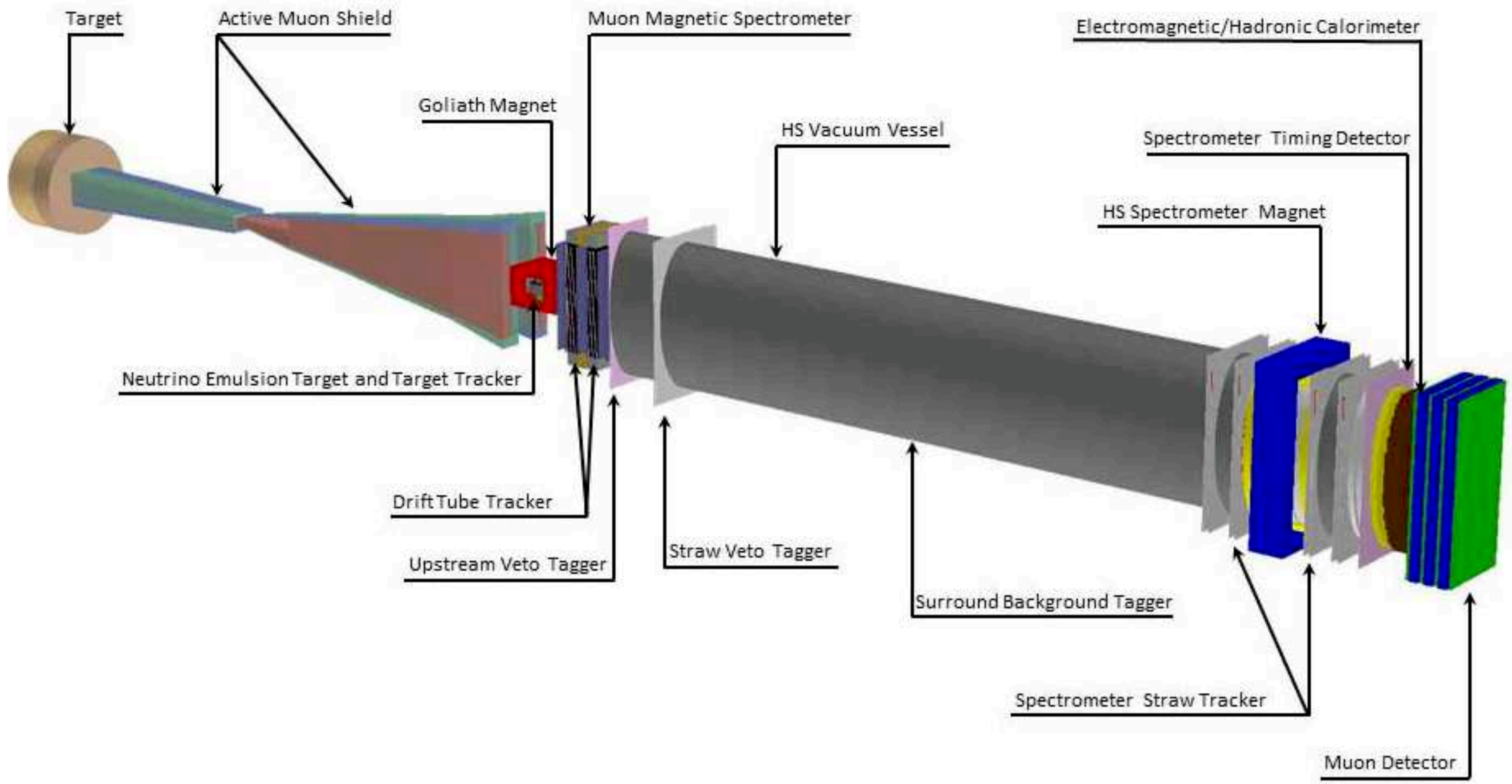
Search for Hidden Particles

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

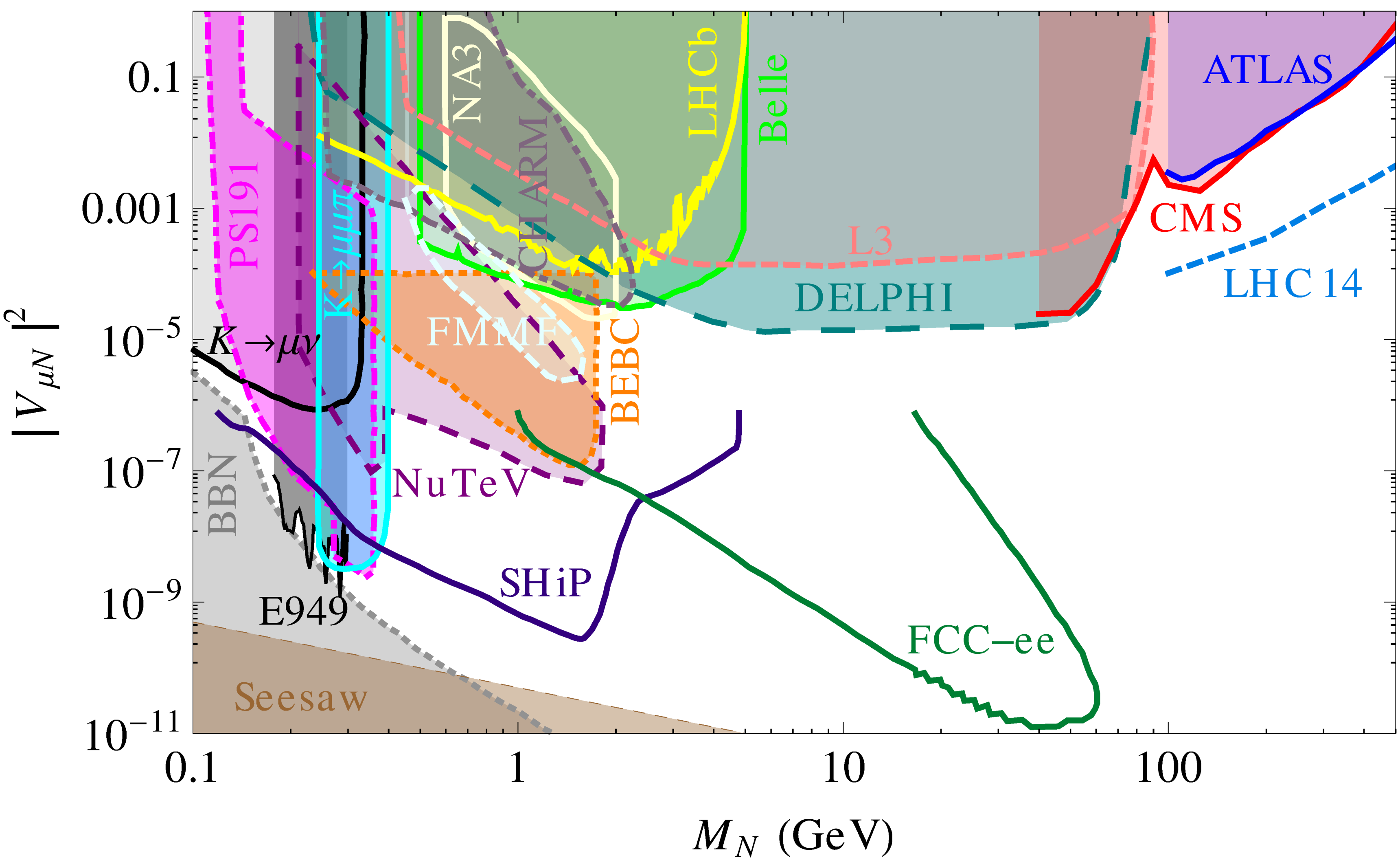


SHiP is currently a collaboration of 46 institutes from 15 countries

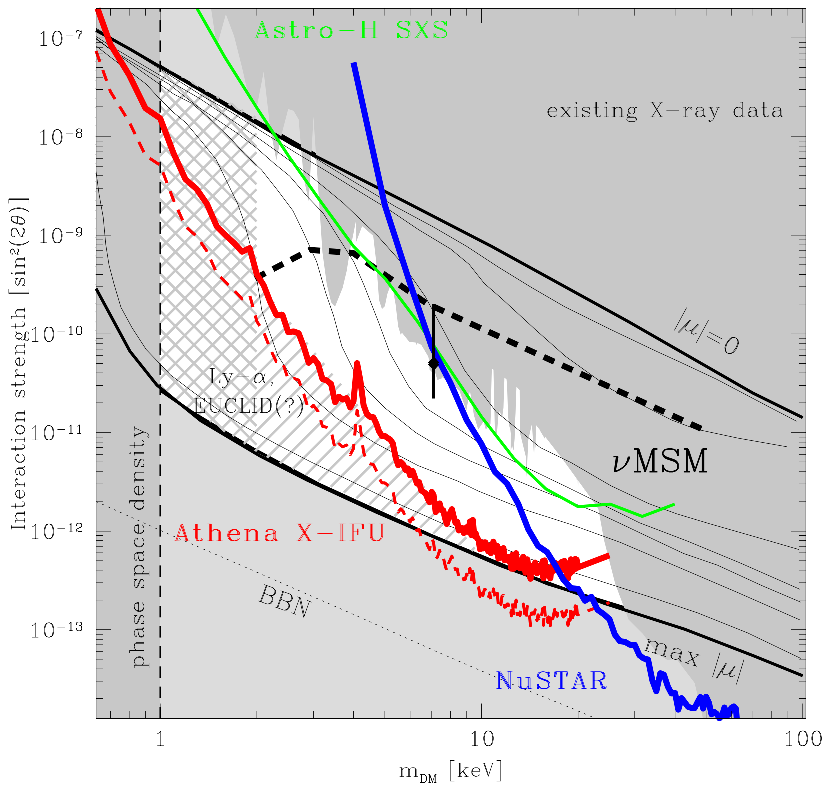
web-site: http://ship.web.cern.ch/ship/



Survey of constraints, $N_{2,3}$



- HNL (N_1) dark matter searches in X-rays, future after Astro-H failure
  - 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



Conclusions

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  - neutrino masses, dark matter and baryogenesis - 3 HNLs

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- High energy limit?

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- Find heavy neutral leptons $N_{2,3}$ - responsible for neutrino masses and baryogenesis: SHiP and FCC