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Cosmology: theory

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The discovery of 126 GeV Higgs boson and observations of no signs of new physics at the LHC implies that the Standard Model of elementary particles is a self-consistent weakly-coupled effective field theory all the way up to the Planck scale without the addition of any new particles. I will discuss possible consequences of these findings for cosmology.

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1. Introduction

It is impossible to cover the wast field of cosmological theory in 30 minutes. So, a number of interesting topics, such as dark energy, quintessence, non-Gaussian inflationary perturbations, cosmological magnetic fields, primordial nucleosynthesis, string cosmology, quantum gravity, massive gravity, galileons, chameleons, radion cosmology, modified gravity, $f(R)$ gravity, Hořava-Lifshitz gravity, landscape and multiverse, holographic cosmology and a number of others, will not be addressed.

I will discuss here several cosmological issues that are related to a recent discovery of the 126 GeV Higgs boson at the LHC and to non-observation of signs of new physics at the LHC or elsewhere.

The paper is organised as follows. In Section 2 we discuss what the findings at the LHC may mean for cosmology in general, in Section 3 we consider cosmological inflation and the possibility that it may be associated with the Higgs boson of the Standard Model. In Section 4 we discuss baryon asymmetry of the Universe (BAU) and Dark Matter (DM) in the view of the LHC results. In Section 5 we overview cosmological constraints on neutrino masses and dark radiation. Section 6 is conclusions.

2. LHC, Higgs mass and Cosmology

After the discovery of the Higgs boson at the LHC by ATLAS [1] and CMS [2], the last missing particle of the Standard Model (SM) has been found. At present, the main LHC result can be formulated as follows: the SM is a self-consistent, weakly coupled effective field theory all the way up to the Planck scale. First, no significant deviations from the SM predictions are seen and no convincing signal in favour of existence of new physics beyond the SM is observed. Second, the mass of the Higgs boson M_H is smaller than $M_H^{\max} = 175$ GeV. If this were not the case, the Landau pole in the Higgs scalar self-coupling would be below the Planck quantum gravity scale $M_P = 2.44 \times 10^{18}$ GeV (see, e.g. [3]), calling for an extension of the SM at some energies between Fermi and Planck scales. Finally, the mass of the Higgs is sufficiently large, $M_H > 111$ GeV, meaning that our vacuum is stable or metastable with a lifetime greatly exceeding the Universe age [4]. The behaviour of the Higgs boson self-coupling λ as the function of energy and the life-time of the Universe as a function of the Higgs boson and top quark masses are shown in Fig. 1.

The mass of the Higgs boson, found experimentally, ($M_H = 125.5 \pm 0.2_{stat}\ {}^{+0.5}_{-0.6}{}_{syst}$ GeV, ATLAS [1] $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV, CMS [2]) is very close to the "critical Higgs mass" $M_{\rm crit}$, which appeared in the literature well before the Higgs discovery in different contexts. The value of $M_{\rm crit}$ is the stability bound on the Higgs mass $M_H > M_{\rm crit}$, see Fig. 2 (the "multiple point principle", put forward in [5], leads to prediction $M_H = M_{\rm crit}$), to the lower bound on the Higgs mass coming from requirement of the Higgs inflation [6, 7], and to the prediction of the Higgs mass coming from asymptotic safety scenario for the SM [8].

The computation of numerical value of $M_{\rm crit}$ was a subject of many papers, the most recent

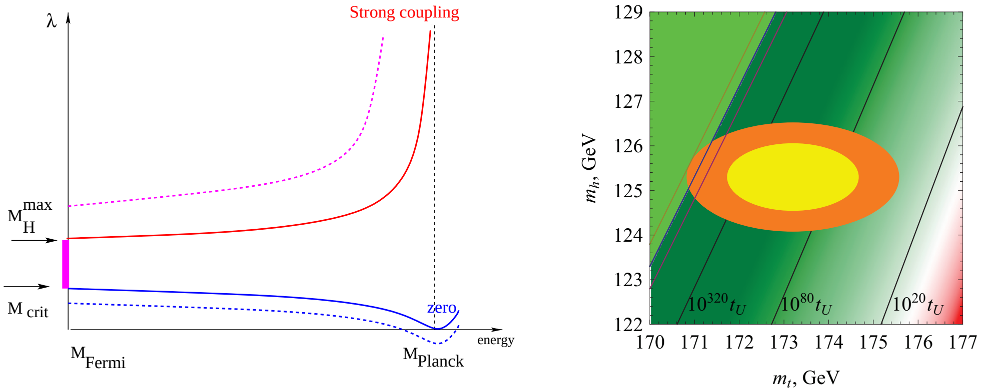

Figure 1: Left panel: Different patters of the behaviour of the Higgs self coupling with energy. For $M_H > M_H^{\max}$ the Landau pole appears at energies below the Planck scale. If $M_H < M_{\rm crit}$ the scalar constant becomes negative at energies below the Planck mass, and electroweak vacuum becomes metastable. Right panel (courtesy of F. Bezrukov): The lifetime of the electroweak vacuum as a function of top quark and Higgs boson masses. Ellipses correspond to 1 and 2 σ contours in M_H and m_t, t_U is the age of the Universe. Along the straight lines the lifetime of the vacuum is given by the number in the plot. The light green region in the upper left corner corresponds to the stable vacuum.

result is convenient to write in the form[1]

$$M_{\rm crit} = [129.3 + \frac{y_t(\mu_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5]\ \text{GeV}\ . \tag{2.1}$$

Here $y_t(\mu_t)$ is the top Yukawa coupling in $\overline{\rm MS}$ renormalisation scheme taken at $\mu_t = 173.2$ GeV, and $\alpha_s(M_Z)$ is the QCD coupling at the Z-boson mass. The computation consists of matching of $\overline{\rm MS}$ parameters of the SM to the physical parameters such as the masses of different particles and then renormalisation group running of coupling constants to high energy scale, supplemented by the computation of the effective potential for the Higgs field. All recent works [9, 10, 11] used 3-loop running of the coupling constants found in [12]-[17]; ref. [9] accounted for $\mathcal{O}(\alpha\alpha_s)$ corrections to the matching procedure, getting 129.4 GeV for the central value of $M_{\rm crit}$ with the theoretical error 1.0 GeV, ref. [10] got 129.6 GeV with smaller error 0.7 GeV, accounting for $\mathcal{O}(\alpha\alpha_s, y_t^2\alpha_s, \lambda^2, \lambda\alpha_s)$ terms in the matching, while the complete analysis of 2-loop corrections in [11] gives 129.3 GeV for the central value with very small theoretical error 0.07 GeV.

At present, *we do not know* whether our vacuum is stable or metastable. Fig. 3 shows the behaviour of the scalar self-coupling within experimental and theoretical uncertainties, together with confronting the value of $M_{\rm crit}$ from eq. (2.1) with the data. For making these plots, the pole top mass was taken from the Tevatron [18], $m_t = 173.2 \pm 0.51_{stat} \pm 0.71_{sys}$ GeV (the combined ATLAS and CMS value is $m_t = 173.4 \pm 0.4 \pm 0.9$ GeV [19]), and the value of $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ [20].

To determine the relation between $M_{\rm crit}$ and M_H, the precision measurements of m_H, y_t and α_s are needed. The main uncertainty is in the value of top Yukawa coupling, y_t. In general, an x GeV experimental error in m_t leads to $\simeq 2 \times x$ GeV error in $M_{\rm crit}$. The difficulties in extraction

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[1] Note that this form is different from the original works, as well as the uniform estimates of the theoretical errors, which are the sole responsibility of the present author.

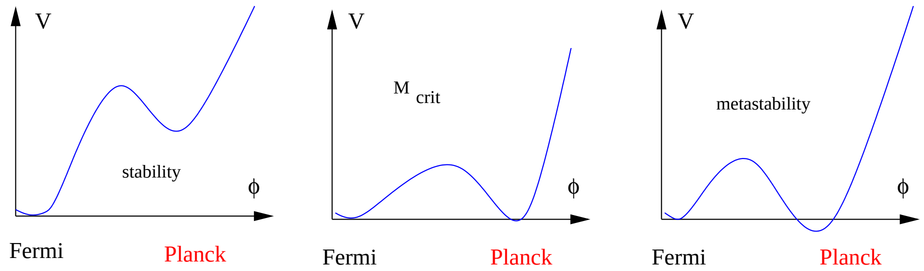

Figure 2: The form of the effective potential for the Higgs field ϕ which corresponds to the stable (left), critical (middle) and metastable (right) electroweak vacuum. The form of the effective potential is tightly related to the energy dependence of the Higgs self-coupling constant $\lambda(\mu)$: the potential is negative almost in the same domain where $\lambda(\phi) < 0$.

of y_t from experiments at the LHC or Tevatron are discussed in [21]. Here we just mention that the non-perturbative QCD effects, $\delta m_t \simeq \pm\Lambda_{QCD} \simeq \pm 300$ MeV lead to $\delta M_{\rm crit} \simeq \pm 0.6$ GeV. The similar in amplitude effect comes from (unknown) $\mathcal{O}(\alpha_s^4)$ corrections to the relation between the pole and $\overline{\rm MS}$ top quark masses. According to [22], this correction can be as large as $\delta y_t/y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, leading to $\delta M_{\rm crit} \simeq -0.5$ GeV.

What do the (meta) stability of our vacuum and the agreement of the Standard model with the LHC experiments mean for cosmology? We can consider two different possibilities.
(i) The Higgs mass is smaller than $M_{\rm crit}$, so that the scalar self coupling crosses zero at energy scale $M_\lambda \ll M_P$, where M_λ can be as "small" as 10^8 GeV, within the experimental and theoretical error-bars, see Fig. 3.
(ii) The Higgs mass is larger or equal to $M_{\rm crit}$, and the Higgs self coupling never crosses zero (or does so close to the Planck scale, where gravity effects must be taken into account), see Fig. 3.

If (i) is realised, there are two ways to deal with the metastability of our vacuum. The first one is cosmological: it is sufficient that the Universe after inflation finds itself in our vacuum with reheating temperature below M_λ. Then this guarantees that we will stay in it for a very long time. This happens, for example, in R^2 inflation [23]. The another possibility is related to possible existence of new physics at M_λ scale, which makes our vacuum unique (see, e.g. [24]).

If (ii) is realised, then no new physics is needed between the Fermi and Planck scales.

In the rest of this talk I will concentrate on the second, most conservative option and assume that there is no new physics between the Fermi and Planck scales. If it is realised, we have to address a number of questions anew: "What drives inflation?", "What is the origin of baryon asymmetry of the Universe?", "What is the dark matter particle?"

3. Inflation

It is well known that for inflation we better have some bosonic field, which drives it (for a review see, e.g. [25]). At last, the Higgs boson has been discovered. Can it make the Universe flat, homogeneous, and isotropic, and produce the necessary spectrum of fluctuations for structure formation? The answer to this question is affirmative [26].

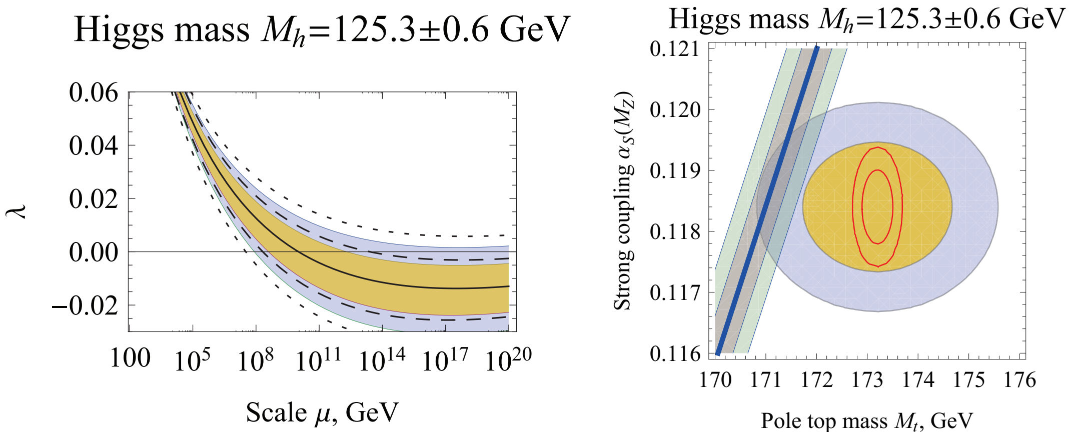

Figure 3: Both panels: The shaded regions account for 1 and 2 σ experimental uncertainties in α_s and the pole top quark mass m_t, and theoretical errors in extraction of y_t from experiment. Left panel: Running of the scalar self coupling constant with energy. Dashed and dotted lines correspond to varying in addition the mass of the Higgs boson within 1 and 2 σ experimental errors. Right panel: The blue line gives the relation between α_s and the pole top mass following from eq. (2.1) if M_H is identified with $M_{\rm crit}$. The shaded regions around it correspond to 1 and 2 σ experimental errors in the Higgs mass. Red ellipses correspond to the accuracy achievable at e^+e^- collider [21].

The main idea of Higgs inflation is related to a non-minimal coupling of the Higgs field to gravity, described by the action

$$S_G = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R - \frac{\xi|\phi|^2}{2}R\right\}. \tag{3.1}$$

Here R is the scalar curvature, the first term is the standard Hilbert-Einstein action, ϕ is the Higgs field, and ξ is a new coupling constant, fixing the strength of "non-minimal" interaction. This constant cannot be fixed by a theoretical computation, but its presence is actually required for consistency of the SM in curved space-time (see, e.g. [27]).

Consider now large Higgs fields, typical for chaotic inflation [28]. Then the gravity strength, given by the effective Planck mass in the Higgs background, is changed as $M_P^{\rm eff} = \sqrt{M_P^2 + \xi|\phi|^2} \propto |\phi|$. In addition, all particle masses are also proportional to the Higgs field. This means that for $|\phi| \gg \frac{M_P}{\sqrt{\xi}}$ the physics does not depend on the value of the Higgs field, as all dimensionless ratios are $|\phi|$ independent. This leads to an existence of the flat direction for a canonically normalized scalar field χ, related to the Higgs field by conformal transformation. After inflation with $N \simeq 58$ e-foldings the energy of the Higgs field is transferred to other particles of the SM, reheating the Universe up to the temperature $T_{reh} \sim 10^{13-14}$ GeV [29, 30].

For the Higgs inflation to work, the scalar self-coupling constant λ must be positive up to the scale of inflation $\mu_{infl} = M_P/\sqrt{\xi}$. Numerically, this leads to the constraint $M_H > M_{\rm crit}$ with extra theoretical uncertainty of $\delta M_H \sim 1$ GeV [31]. Though the theory in the electroweak vacuum enters into strong coupling regime at energies smaller than the Planck scale by a factor ξ [32, 33], the analysis of higher dimensional operators and radiative corrections at large Higgs background, necessary for inflation, shows that the Higgs inflation occurs in the weak coupling regime and is self-consistent [31].

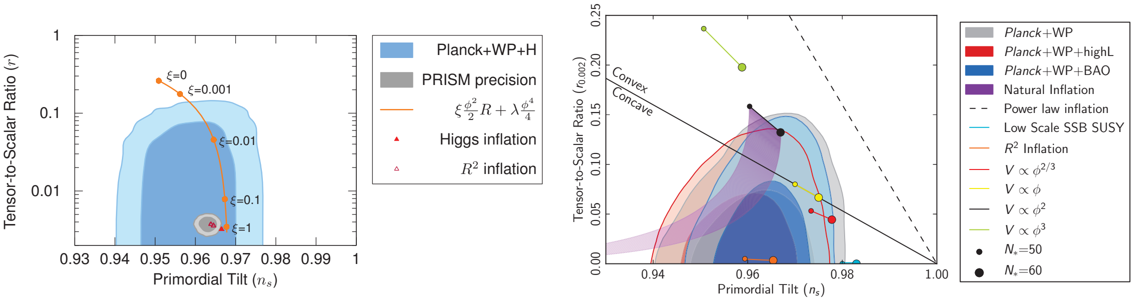

Figure 4: Left panel (courtesy of F. Bezrukov): The predictions of different inflationary models, closely related to the Higgs inflation, versus observations. The red line corresponds to a theory with light inflaton and small non-minimal coupling to gravity [35]. The predictions of R^2 inflation [36, 37] can be distinguished from the Higgs inflation with PRISM mission. Right panel: Predictions of different inflationary models contrasted with the Planck results (from ref. [34]).

The cosmological predictions of the Higgs inflation can be compared with observations performed by the Planck satellite. The Higgs-inflaton potential depends on one unknown parameter, ξ. It can be fixed by the amplitude of the CMB temperature fluctuations $\delta T/T$ at the WMAP normalization scale ~ 500 Mpc, with the use of precise knowledge of the top quark and Higgs masses, and α_s. In general, $\xi > 600$ [6]. Since the Higgs mass lies near $M_{\rm crit}$, the actual value of ξ may be close to the lower bound.

Also, the value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T}\frac{\delta T(y)}{T}\right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s-1} \tag{3.2}$$

and the amplitude of tensor perturbations $r = \frac{\delta\rho_s}{\delta\rho_t}$ can be determined. The predictions, together with the Planck results, are presented in Fig. 4, and are well inside the 1 sigma experimental contour. Moreover, as for any single field inflationary model, the perturbations are Gaussian, in complete agreement with Planck [34] (for discussion of Planck results see Rosset talk at the parallel Session).

There is a number of inflationary models which give predictions for n_s and r similar to those of the Higgs inflation. This is true, in particular, for the modification of the theory in the gravitational sector by adding the R^2 term [36, 37]. The R^2 theory contains an additional degree of freedom – scalaron, with the mass $M_S \simeq 3\times 10^{13}$ GeV^2. It has somewhat smaller reheating temperature $\sim 3\times 10^9$ GeV and smaller number of e-foldings, $N \simeq 54$ [38, 39]. The generalisations of the Higgs and R^2 inflation to the case of supergravity were discussed in [40]-[46]. For more extended discussion of inflationary model see talk by Bezrukov at the parallel Session.

4. Baryon asymmetry of the Universe, dark matter and the LHC

One of the most popular mechanisms for for creation of the cosmological baryon excess is electroweak baryogenesis. In short, its idea is as follows [47]. At high temperatures the Universe

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[2] This particle creates an extra fine-tuning problem, as its loops shift the Higgs mass by $\delta M_H^2 \sim \frac{1}{16\pi^2}\frac{M_S^4}{M_P^2} \sim 10^{14}$ GeV$^2 \gg M_H^2$.

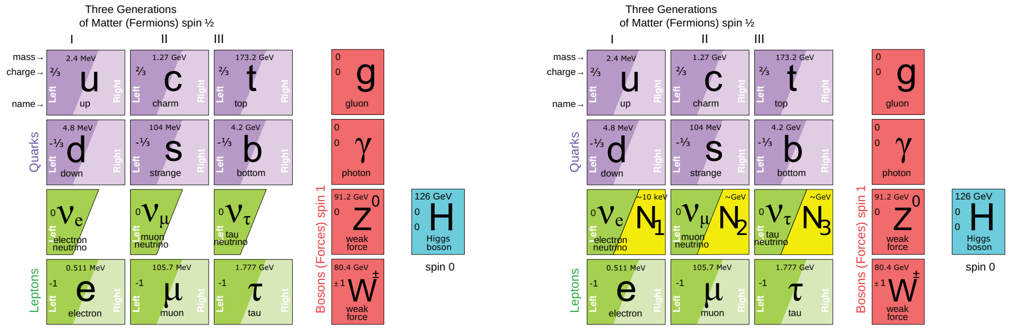

Figure 5: Particle content of the SM and its minimal extension in the neutrino sector. In the SM the right-handed partners of neutrinos are absent. In the νMSM all fermions have both left- and right-handed components and masses below the Fermi scale.

is in the symmetric phase of the SM. During the Universe cooling the first order phase transition converting the symmetric phase to the Higgs phase occurs. The phase transition goes through nucleation of bubbles of the Higgs phase. The scattering of different particles on the domain walls leads to the spacial separation of baryon number: an excess of baryons inside the bubbles survives till the present time, whereas the excess of antibaryons outside the bubbles is destroyed by sphalerons [48, 49].

This mechanism does not work in the SM. First, there is no phase transition for the Higgs boson with the mass above 75 GeV [50]. Second, the SM CP-violation is most probably too weak [51, 52, 53] (see however [54]). With the new LHC constraints on SUSY the electroweak baryogenesis is challenged, but still possible in the Minimal Supersymmetric Standard Model [55, 56, 57].

The another popular mechanism for baryogenesis is thermal leptogenesis [58]. Here the superheavy Majorana leptons with the mass $\sim 10^{10}$ GeV decay and produce lepton asymmetry, which is converted to baryon asymmetry by sphalerons. The necessity of having superheavy particles leads to the hierarchy problem [59]: their loops shift the Higgs mass towards the Grand Unified scale. This may be cured by low energy SUSY, but no signs of it were seen at LEP, Tevatron or LHC. A possible way out is the resonant leptogenesis with degenerate Majorana leptons and relatively small masses ~ 1 TeV [60]. In any event, the thermal leptogenesis cannot be disproved experimentally, but it is fine tuned without new physics at the Fermi scale.

So, if the next LHC runs will continue to confirm the SM, the popular mechanisms for baryogenesis will be disfavored.

Now, let us come to dark matter. The most popular DM candidate is the Weakly Interacting Massive Particle – WIMP, associated with new physics solving the hierarchy problem at the electroweak scale. If no new physics will be discovered at the LHC, this candidate will not be that attractive anymore.

Therefore, it is timely to readdress the problems of baryon asymmetry of the Universe and of dark matter in case there is no new physics between the Fermi and Planck scales.

A possible solution to these problem is given by the Neutrino Minimal Standard Model (νMSM) [61, 62] (for extensive discussion see Ruchayskiy talk at the Cosmology parallel Session, the review [63] and references therein). It adds to the SM three Majorana leptons N_I – right-handed partners of active neutrinos, see Fig. 5. The N_1 with the mass in keV region plays the role of dark matter particle, which can be searched for with the use of X-ray telescopes. The role of N_2, N_3 with masses in 100 MeV – GeV region is to "give" masses to neutrinos via electroweak scale see-saw mechanism and produce BAU. They can be searched for at fixed target experiments with the use of intensive proton beams, such as SPS at CERN [64].

5. Dark radiation, neutrino masses

There are other predictions of the Standard Model where it can be compared with cosmological observations. There are four very light or massless particles in the SM: 3 neutrinos and a photon. The Standard cosmology leads to prediction of the number of relativistic degrees of freedom (photon is not included) in terms of "effective number of neutrino species" $N_{eff} = 3.046$. The deviation of this number from 3 is due to non-instantaneous decoupling and finite temperature effects (for a review see, e.g. [65]). Also, the analysis of neutrino oscillations provides the lower bound on the sum of neutrino masses (see, e.g. [66]): $\sum m_\nu > 0.06$ eV, $\sum m_\nu > 0.1$ eV for normal and inverted hierarchies of neutrino masses respectively.

These predictions can be compared with cosmological observations by Planck [67]: $\sum m_\nu < 0.23$ eV, $N_{eff} = 3.30 \pm 0.27$[3]. This is consistent with the SM, but cannot rule out new physics, which can potentially change N_{eff}. The possible candidates that can lead to deviations from the SM prediction contain light ~ 1 eV sterile neutrinos (see, e.g. [68]), quintessence [69, 70], dilaton [71], relic gravitational waves [72], or new particle decays during Big Bang Nucleosynthesis [73].

6. Conclusions

During the last year a remarkable progress has been achieved both in the field of particle physics and cosmology. The LHC experiments have lead to the triumph of the Standard Model of particle physics, with discovery of 126 GeV Higgs boson. The data from the Planck satellite provided more arguments in favour of validity of the Standard ΛCDM cosmology.

Still, a number of fundamental questions remains unanswered, and I present below my personal wish-list for new experiments and precision measurements.

In the domain of particle physics, to understand whether our vacuum is stable or metastable and whether there is a necessity for any intermediate energy scale between the Fermi and Planck scales (together with the closely related issues of the Higgs inflation and asymptotic safety of the Standard Model) we should know the mass of the Higgs boson, the top Yukawa coupling and strong coupling constant with highest possible accuracy. This is one of the arguments if favour of the future e^+e^- collider - top quark factory, where a precision measurement of the top quark mass is possible.

The experiments that can shed light on the origin of baryon asymmetry of the Universe and the nature of Dark Matter are of great importance. Quite paradoxically, the largely unexplored up to now domain of energies where the new physics can be hidden is related to physics *below* the Fermi scale. It may be very well that the new particles giving rise to BAU and DM are light and very weakly interacting (as in the νMSM, briefly discussed here). Then the search for them

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[3] These numbers are based on the analysis of CMB with inclusion of Baryon Acoustic Oscillations (BAO). However, the results depend on the dataset used, such as WMAP polarisation, high resolution CMB from ACT and SPT.

is not possible at the LHC but would require new dedicated experiments [64] at the intensity and precision frontier of high energy physics.

There is a number cosmological and astrophysical experiments, which can elucidate the structure of the underlying theory. In particular, to test the Higgs inflation, and to distinguish it from other models, such as R^2, we need to have measurements of the spectral index n_s of scalar perturbations at the level of 10^{-3}. In addition, the determination of tensor-to-scalar ratio should be done down to values $r \simeq 0.003$ and that of the running of the spectral index $dn_s/dlogk$ down to 5×10^{-4}. These measurements are possible, presumably, at COrE [74], PRISM [75] and SKA [76].

To check the predictions of different dynamical Dark Energy models such as, for example, the Higgs-dilaton [77], the equation of state of dark energy (the pressure to energy density ratio) should be known with accuracy of 1%, achievable at the Euclid mission [78].

To test the infrared sector of the theory, associated with massless or very light particles, we should know neutrino masses from cosmology with accuracy $\sum m_\nu \simeq 0.05$ eV, to reach the lower bound coming from particle physics. The accuracy in determination of effective number of massless degrees of freedom below ~ 0.04, to check the SM prediction 3.046. According to [79, 80], this should be possible with the use of a combination of Planck and Euclid data.

The search for dark matter particles should not only be restrained to WIMPS or axions. The dark matter may have a different nature. An example includes the sterile neutrino with the mass in the keV region, the radiative decays of which can be observed with the help of high resolution X-ray telescopes (see, e.g. [81]).

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