Advances in theoretical cosmology in the light of data
21/07/2017, Nordita
A minimal extension of the standard model (SM) with a single new mass scale and providing a complete and consistent picture of particle physics and cosmology up to the Planck scale is presented. We add to the SM three right-handed SM-singlet neutrinos, a new vectorlike color triplet fermion, and a complex SM-singlet scalar $\sigma$ that stabilizes the Higgs potential and whose vacuum expectation value at $\sim 10^{11}$ GeV breaks lepton number and a Peccei-Quinn symmetry simultaneously. Primordial inflation is produced by a combination of $\sigma$ (nonminimally coupled to the scalar curvature) and the SM Higgs boson. Baryogenesis proceeds via thermal leptogenesis. At low energies, the model reduces to the SM, augmented by seesaw-generated neutrino masses, plus the axion, which solves the strong $CP$ problem and accounts for the dark matter in the Universe. The model predicts a minimum value of the tensor-to-scalar ratio $r \approx 0.004$, running of the scalar spectral index $\alpha \approx -7 \times 10^{-4}$, the axion mass $m_A \sim 100 \mu eV$, and cosmic axion background radiation corresponding to an increase of the effective number of relativistic neutrinos of $\sim 0.03$. It can be probed decisively by the next generation of cosmic microwave background and axion dark matter experiments.

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1. Who is the dark matter?

2. Who is the inflaton?

3. Matter/anti-matter asymmetry

\[
\frac{n_b - n\bar{b}}{n_\gamma} \approx 10^{-9} \quad \text{(CMB)}
\]

\[
n_p/n_{\bar{p}} \sim 10^4 \quad \text{(Galactic cosmic rays)}
\]

4. Smallness of the neutrino masses

\[
\sum m_\nu \lesssim 0.2 \text{ eV}
\]

5. Strong CP problem

\[
\mathcal{L}_{\text{QCD}} \in -\frac{\theta_0}{32\pi^2} \ G\tilde{G}
\]

\[
\theta \equiv \theta_0 - \arg(\det M) \lesssim 10^{-10}
\quad \text{(neutron e.d.m.)}
\]
Small neutrino masses $\rightarrow$ Matter/anti-matter asymmetry

Strong CP problem $\rightarrow$ Dark matter

Inflation

$\cdots$
Standard Model
Axion
See-saw
Higgs [portal inflation]
SMASH = SM +

★ Three singlet neutrinos: $N_i$

★ A complex scalar: $\sigma$

★ Two Weyl fermions: $Q$ and $\tilde{Q}$ in the $\mathbf{3}$ and $\mathbf{\bar{3}}$ of $SU(3)_c$

Dias, Machado, Nishi, Ringwald and Vaudrevange 2014

★ New $U(1)$ symmetry: PQ and lepton number

<table>
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<th>$u$</th>
<th>$d$</th>
<th>$L$</th>
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</table>
Strong CP problem

\[ Q, \tilde{Q} \]
complex scalar, \( \sigma \)

Axion \( \rightarrow \)

Dark Matter

Axion phase

Baryogenesis

Stabilizes the Higgs potential

Gives mass to RH neutrinos \( N_i \)

Drives Inflation (together with the Higgs)

and reheats the Universe

Small neutrino masses

Baryogenesis (via thermal leptogenesis)

see-saw mechanism
We will comment on the other alternative in Section identical phenomenology. In the rest of this work we will focus exclusively on the choice These hypercharge assignments

2 The SMASH model and reheating as long as temperature can be derived. We show that the Peccei-Quinn symmetry is e

Importantly, unlike in many other models of inflation, here the inflaton's couplings (in parameter space. In Section

a generic property of the model. We develop a semi-analytic understanding of the stability region

Inflation (that originates from the breakdown of perturbative unitarity). In Section

Importantly, we demonstrate that Hidden Scalar Inflation is possible for a non-minimal coupling of

SM active neutrinos by the hierarchy between

This realises the seesaw mechanism [9] or consult our Letter [7]

Table 1:

Three SM-singlet neutrinos, respectively. Apart from an executive summary, Section

•

This symmetry may be an accidental symmetry of the low energy e

of spontaneous breaking of global lepton number [8]. Apart from being the lightest of the new particles, the

The reader that is avid for knowing our main results and conclusions may now move directly to

section 6...
VEV of new scalar and axion decay constant

\[ f_A = \nu_\sigma \sim \text{SM instability scale } \Lambda_I \]

Its value ensures axions account for all DM
Axion mass: \( m_A = (57.2 \pm 0.7) \left( \frac{10^{11}\text{GeV}}{f_A} \right) \mu\text{eV} \)

*Borsanyi et al. 2016* from lattice QCD

\[
\frac{M_{N_i}}{Y} \sim \frac{m_Q}{y} \sim \frac{m_\rho}{\sqrt{\lambda_\sigma}} \sim v_\sigma + \mathcal{O}(v) \sim 10^{11}\text{GeV}
\]

Upper limit on Yukawas \( Y, y \) for stability

Typically: \( 10^{-13} \lesssim \frac{\lambda_\sigma}{5} \lesssim 10^{-10} \) from inflation
The strong CP problem

\[ \mathcal{L}_{QCD} \propto -\frac{\theta_0}{32\pi^2} G\tilde{G} \] breaks CP

\[ \theta \equiv \theta_0 - \arg(\det M) \]

\[ \theta \lesssim 10^{-10} \]

Invariant under chiral transformations
Quark mass matrix

Solution?

\[ \delta S \propto \int G\tilde{G} \]

E.g. another transformation under which making \( \theta \) unphysical.

Global sym. that is anomalous under \( SU(3)c \)
(but there is no such symmetry in the SM)
The axion

\[ \mathcal{L} \equiv \frac{1}{2} \partial_\mu A \partial^\mu A + i \frac{A}{32\pi^2} G\tilde{G} + V(A) \]

The axion potential is generated by non-perturbative QCD physics
KSVZ-like axion

\[ \mathcal{L} = \frac{1}{2} \partial_\mu A \partial^\mu A + i \frac{A}{32\pi^2} G\tilde{G} + V(A) \]

The coupling of the axion to QCD is a dim. 5 operator.

\[ \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma^* + \lambda_\sigma \left( |\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 + y \tilde{Q} \sigma Q + \text{h.c.} \]

\[ \sigma \rightarrow e^{i\alpha} \sigma, \quad Q \rightarrow e^{-i\frac{\alpha}{2} \gamma_5} Q, \quad \alpha = A/v_\sigma \]

and integrate out \( Q \) and \( |\sigma| \) below \( v_\sigma = f_A \)
Combining in quadrature the theoretical uncertainty with the experimental errors on Planck scale is significant reduction of the theoretical error on function. As a result of this improved determination of the Yukawa sector and can be considered the first complete NNLO evaluation of.

Figure 1:}
Inflation and the SM instability

\[ V(h) \sim \frac{\lambda H(h)}{4} h^4 \]

\[ \Lambda_I \sim 10^{11} \text{GeV} \]

Fluctuations during inflaton:

\[ \sqrt{\langle h^2 \rangle} \sim \mathcal{H} \sim 10^{-5} M_P \sim 10^{14} \text{GeV} \gg \Lambda_I \]
Threshold stabilization

\[ V(H, \sigma) = \lambda_H \left( H^\dagger H - \frac{v^2}{2} \right)^2 + \lambda_\sigma \left( |\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 + 2\lambda_{H\sigma} \left( H^\dagger H - \frac{v^2}{2} \right) \left( |\sigma|^2 - \frac{v_\sigma^2}{2} \right) \]

At low energies, below the mass of \(|\sigma|\)

\[ \lambda_{H}^{(SM)} = \lambda_H - \delta \]

\[ \delta \equiv \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} \sim 10^{-2} \]
Inflation from the Higgs?

\[ S \supset - \int d^4x \sqrt{-g} \left[ \frac{M^2}{2} + \xi_H H^\dagger H + \ldots \right] R \]

\[ \tilde{V} \sim \frac{\lambda_H}{\xi_H^2} M_P^4 \]

CMB temperature fluctuations \[ \xi_H \sim 10^5 \sqrt{\lambda_H} \sim 10^4 \]

Breaking of perturbative unitarity:

\[ \Lambda_U = \frac{M_P}{\xi_H} \sim 10^{14} \text{ GeV} \ll \frac{M_P}{\sqrt{\xi_H}} \sim 10^{16} \text{ GeV} \]
Inflation with the new singlet

\[ S \supset - \int d^4 x \sqrt{-g} \left[ \frac{M^2}{2} + \xi_H H^\dagger H + \xi_\sigma \sigma^* \sigma \right] R, \]

\[ \tilde{V} \sim \frac{\lambda}{\xi_\sigma} M_P^4, \quad \xi_\sigma \lesssim 1 \quad \text{and also} \quad \xi_H \lesssim 1 \]

\[ \lambda_{H \sigma} > 0 \quad \text{inflaton} = |\sigma|, \quad \lambda = \lambda_\sigma \]

\[ \lambda_{H \sigma} < 0 \quad \text{inflaton} = |\sigma| + \text{small Higgs component}, \]

\[ \lambda = \lambda_\sigma - \lambda_{H \sigma}^2 / \lambda_H \]
Reheating after inflation

A small Higgs component in the inflaton of SMASH guarantees successful reheating

\[ N_{\nu}^{\text{eff}} = 3.04 \pm 0.18 \]
from CMB and BAO data

\[ \lambda_{H\sigma} > 0 \, , \, T_R \sim 10^7 \, \text{GeV} \]
Axions remain decoupled from thermal bath

\[ \Delta N_{\text{eff}} \sim 1 \]
Too much axion radiation

\[ \lambda_{H\sigma} < 0 \, , \, T_R \sim 10^{10} \, \text{GeV} \]

\[ \Delta N_{\text{eff}} \sim 0.03 \]
CMB S4, Simons O. ...
Primordial spectrum

CMB + unitarity: \(0.004 \lesssim r \lesssim 0.07\)

\((CORE, LiteBird, Pixie, CMB S4)\)

\[5 \times 10^{-13} \lesssim \lambda \lesssim 5 \times 10^{-10}\]

Small non-Gaussianities and isocurvature

\[0.962 \lesssim n_s \lesssim 0.966\]

Spectral index running: \(\alpha \simeq -7 \times 10^{-4}\)

\((21 \text{ cm line of neutral Hydrogen})\)
Axion dark matter

\[ \lambda_{H\sigma} < 0 \quad : \text{SSB of PQ symmetry after inflation} \]

**Vacuum misalignment:**

\[ \ddot{A} + 3\mathcal{H}\dot{A} + m_A^2 A = 0 \]

and decay of Peccei-Quinn strings

\[ 3 \times 10^{10} \text{ GeV} \lesssim \nu_\sigma \lesssim 1.2 \times 10^{11} \text{ GeV}, \]

\[ 50 \mu\text{eV} \lesssim m_A \lesssim 200 \mu\text{eV} \]
Axions restrict the symmetry breaking scale to the range of SMASH. Requiring that all the DM is made of the realignment mechanism \[43–45\] constitute the dark population of axions that together with those arising from thermal temperature thermal after inflation and then spontaneously broken in the phase transition, which happens at a critical temperature. This small value of the relativistic neutrino species is just above, in this case there is no dark radiation problem; out to be \(2\) relativistic degrees of freedom at the thermal and non-thermal sources, and accounting for the energy loss of the background, we can estimate the reheating temperature by finding the time at which the energy density of the background is equal. The reheating temperature turns out to be \(\text{ca.} 10^{10}\) GeV for the benchmark values \(4\) of SMASH there is a low reheating temperature \(37\), leading to a significant reheating and remain decoupled in the case of such scenarios.

\[f_A[\text{GeV}] = \nu_\sigma\]
Solves **the strong CP problem** with a *KSVZ-like axion*,

explains:

*the nature of dark matter* (with *the axion*),

*the smallness of neutrino masses* (*through the see-saw*),

*baryogenesis* (*via leptogenesis*)

and

gives a candidate for **primordial inflation**.
Neutrino masses, from see-saw

\[ F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \]

\( \sigma \) takes a large VEV \( \nu_\sigma \sim 10^{11} \text{GeV} \)

\[ M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & F_\nu \\ F_\nu^T \nu & Y \nu \nu_\sigma \end{pmatrix} \]

\[ m_\nu = -M_D M_M^{-1} M_D^T = -\frac{F Y^{-1} F^T}{\sqrt{2}} \frac{\nu^2}{\nu_\sigma} = 0.04 \text{eV} \left( \frac{10^{11} \text{GeV}}{\nu_\sigma} \right) \left( \frac{-F Y^{-1} F^T}{10^{-4}} \right) \]
$\lambda_{H\sigma} > 0, \quad \lambda_{H\sigma} < 0$

\[ \mu = m_\rho \text{ (solid)} \text{ and } \mu = 30M_P \text{ (dashed)} \]
Reheating with a quartic potential

\[ \ln \frac{H}{a} \]

Inflation

Present horizon scale

Radiation

Matter

Lambda

Reheating in SMASH

Liddle and Leach, 2003
Figure 15: 2D slice of our 3D simulations of the growth of perturbations of the inflaton during preheating at $\tau = 400$ showing patches of the Universe with different values of $\theta$. The length in the abscissa is given in comoving units $1/p_f(t)$. Hence for an oscillating $\omega^2 = \omega^2_0$, which induces oscillating masses, the decays or annihilations can only happen when $\omega$ crosses the origin and the induced masses approach zero. This is possible during preheating, i.e. $\tau \approx 100$, but not after because effective masses are actually proportional to $h|\theta|^2$ which soon tends to 0 and will decrease very slowly but without further crossing zero, see Fig. 14. This implies that the masses of the particles coupling directly to the inflaton set on values much above the frequency of oscillation $\omega$. This closes the particle production channels from the background condensate. The decays of the excitations themselves are also closed at this stage, as their typical momentum is of the order of $\omega$. Thus, reheating is quenched until our assumption of neglecting $f_A$ is not valid anymore. When the amplitudes become of the order of $f_A$, the PQ symmetry becomes broken. This happens when quadratic terms in the potential become relevant, and the fluctuations end up confined in potential wells around $|\theta| = f_A/p_2$. After the PQ symmetry breaking, the physics is described more easily using a massive modulus excitation $\theta$, with mass $m_{\theta} = p_2 f_A$ and a massless axion; see equations 46. PQ symmetry non-thermally restored after ~14 oscillations.

Preheating

Parametric resonance of fluctuations of $\sigma$

$\theta$

PQ symmetry non-thermally restored after ~14 oscillations
Matter/anti-matter asymmetry

Obtained from thermal leptogenesis:

\[ 3M_1 \lesssim M_3 \sim M_2 \]

(determined by the Yukawas in our case)

Vanilla leptogenesis:

Hierarchical RH neutrino mass spectrum

For a thermal distribution of the lightest RH neutrino and neglecting flavour effects, the observed baryon asymmetry is generated if

\[ M_1 \gtrsim 5 \times 10^8 \text{ GeV}; \quad \frac{(M_D M_D^T)_{11}}{M_1} \lesssim 10^{-3} \text{ eV} \]

Davidson and Ibarra, 2002

Buchmüller, di Bari and Plumacher 2002

For larger RH masses, resonant leptogenesis may occur

Pilaftsis and Underwood, 2003