Unifying inflation with the axion, dark matter, baryogenesis and the seesaw mechanism

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The aim:

Introduce a theory, “SMASH”, that builds upon the νMSM and addresses several problems in particle physics and cosmology, providing a consistent picture of the evolution of the universe, while remaining falsifiable.

The plan:

Discussion of the problems

Definition of the model

Overview of the cosmological evolution and the way problems are addressed.
The particle physics and cosmology paradigm

The **Standard Model** plus **neutrino masses** plus **dark matter**, together with a **cosmological constant** and an early period of **inflation**, is able to explain the overwhelming majority of experiments in Earth and in space.

**Open questions** relevant for this talk:

- Mechanism of inflation
- BEH stability
- Origin of neutrino masses
- Strong CP problem
- Origin of dark matter
- Origin of the baryon asymmetry
cosmological constant
Abridged problem dictionary

**Inflation.** Period of accelerated expansion needed to explain the isotropy and homogeneity of the Universe.

A slowly-rolling scalar field with positive potential energy can drive accelerated expansion. Could it be the BEH boson [Bezrukov, Shaposhnikov]??

H inflation problem: Lack of predictivity! [Barbon, Espinosa, Burgess, Lee, Trott]

\[ S_{HI} = \int d^4x \sqrt{-g} \left[ \mathcal{L}_{SM} - \frac{M^2}{2} R - \xi H^\daggerHR \right] \]

CMB fluctuations require \( \xi \sim 10^5 \sqrt{\lambda_H} \sim 10^4 \)

Theory has cutoff below field scales probed during inflation!

\[ \Lambda = \frac{M}{\xi} \sim \frac{M_P}{\xi} > h_{inf} \sim \frac{M_P}{\sqrt{\xi}} \]
**Neutrino mass problem.** Neutrino oscillation data imply that neutrinos are massive, while in the SM they remain massless.

\[ \sum_i m_{\nu,i} < 0.23 \text{ eV} \quad \text{[PLANCK 2015]}, \quad |\Delta m^2_{ij}| < 3 \times 10^{-3} \text{ eV}^2 \quad \text{[NuFIT 2016]} \]
Abridged problem dictionary

**CP problem.** Absence of CP violation in strong interactions

\[ \mathcal{L}_{QCD} \supset \frac{g^2 \theta}{16 \pi^2} \text{Tr} \bar{G}_{\mu \nu} G^{\mu \nu}, \quad \theta_{\text{phys}} = \theta - \arg \det M_q, \quad |\theta_{\text{phys}}| < 10^{-11} \quad [\text{Kim 09}] \]

**Dark matter.** Galactic rotation curves and the CMB power spectrum imply the existence of non-baryonic matter in the Universe, which SM particles cannot account for.

\[ \Omega_B = 0.05, \quad \Omega_{DM} = 0.26 \quad [\text{Planck 2015}] \]

**Baryogenesis.** The known Universe is overwhelmingly made of matter rather than antimatter, although physical laws don’t establish a fundamental distinction.

\[ \eta = \frac{n_B}{n_\gamma} = \frac{n_b - \bar{n}_b}{n_\gamma} = 6.1 \times 10^{-10} \quad [\text{Cyburt et al, 2015 Planck data}] \]
### All those problems... all those solutions

<table>
<thead>
<tr>
<th>Zero $T$</th>
<th>Finite $T$</th>
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<tbody>
<tr>
<td><strong>Inflation</strong></td>
<td><strong>Baryogenesis</strong></td>
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<tr>
<td><strong>Scalar inflaton</strong></td>
<td><strong>Electroweak baryogenesis, leptogenesis, Affleck-Dine...</strong></td>
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<tr>
<td><strong>Higgs stability</strong></td>
<td><strong>WIMP, sterile neutrinos, axion</strong></td>
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<td><strong>Scalar interactions</strong></td>
<td><strong>Axion, Nelson-Barr</strong></td>
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<td><strong>Seesaw models, radiative mass generation</strong></td>
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<td><strong>CP problem</strong></td>
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<td><strong>Axion, Nelson-Barr</strong></td>
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**Neutrino masses**
## Relating solutions

<table>
<thead>
<tr>
<th>Concept</th>
<th>Authors</th>
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<tbody>
<tr>
<td>CP problem plus dark matter</td>
<td>Abbot et al, Dine et al, Preskill et al, ...</td>
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<tr>
<td>Neutrino masses plus axion</td>
<td>Dias et al, Kim, Mohapatra et al, Berezhiani, Shafi et al, Langacker et al, Shin, He et al, Celis et al, Bertolini et al, Ng et al, Carvajal et al, Clarke et al, Ahn et al, ...</td>
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<td>Neutrino masses plus inflation</td>
<td>Boucenna et al, Budhi et al, ...</td>
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<tr>
<td>Inflation plus dark matter</td>
<td>Lerner, McDonald, Kahlhofer, ...</td>
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<tr>
<td>Inflation plus dark matter plus CP problem</td>
<td>Fairbairn &amp; Marsh, ...</td>
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Non-minimal list of minimal models of the Universe

vMSM  [Asaka, Blanchet, Shaposhnikov]

SM+ RH neutrinos

(Inflaton=Higgs, DM=RH neut, baryogenesis: RH neut. oscillations)

nMSM  [Davoudiasl, Kitano, Li, Murayama]

SM+two real scalars+RH neutrinos

(Inflaton, DM: scalars, baryogenesis: Decays of RH neut)

Salvio  [Salvio]

SM+KSVZ axion+ RH neutrinos

(Inflaton=Higgs, DM=axion, baryogenesis: Decays of RH neut)
### Non-minimal list of minimal models of the Universe

<table>
<thead>
<tr>
<th></th>
<th>vMSM</th>
<th>nMSM</th>
<th>Salvio</th>
<th>SMASH</th>
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<tbody>
<tr>
<td><strong>Zero T</strong></td>
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<td>v masses</td>
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<td>Baryogenesis</td>
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<td><strong>New scales</strong></td>
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<tr>
<td></td>
<td>$M_a$</td>
<td>$M_a, m^2_S, m^2_\phi$</td>
<td>$M_a, f_A$</td>
<td>$f_A$</td>
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A minimal model providing a consistent, predictive picture of:

Particle physics from the electroweak to the Planck scale

Cosmology from inflation to today

Highlights:

A single new scale, playing a role in dark matter, the CP problem and baryogenesis

Predictive inflation free from unitarity concerns

Detailed understanding of parameter space yielding stability

Detailed understanding of reheating

Accurate predictions for ns, r, axion mass, $N_{\text{eff}}$ in the reach of future experiments
Building up SMASH

\[ \text{S} \quad \text{M} \quad \text{H} \]

\[
\begin{array}{cccc}
\text{u} & \text{d} & \text{e} & \nu_1 \\
\text{c} & \text{s} & \mu & \nu_2 \\
\text{t} & \text{b} & \tau & \nu_3 \\
\text{g} & \text{W} & \text{Z} & \text{Y}
\end{array}
\]
Building up SMASH

\[ S M \]

\[ H \]

\[ u d e \]
\[ c s \]
\[ t b \]
\[ g \]

\[ v_1 \]
\[ v_2 \]
\[ v_3 \]

\[ N_1 \]
\[ N_2 \]
\[ N_3 \]

SEESAW LEPTOGENESIS
Building up SMASH

\[
\begin{pmatrix}
S & M
\end{pmatrix}
\begin{pmatrix}
* & S* & H
\end{pmatrix}
\]

\[
\begin{array}
| u & d & e & \nu_1 \\
| c & s & \mu & \nu_2 \\
| t & b & \tau & \nu_3 \\
| g & W & Z & Y \\
\end{array}
\begin{array}
| N_1 \\
| N_2 \\
| N_3 \\
\end{array}
\]

\[
\begin{array}
| A & P \\
\end{array}
\]

SEESAW
LEPTOGENESIS
INFLATION
STABILITY
Building up SMASH

\[
\begin{align*}
SMASH &= H \\
A &= Q \\
S &= N_1 \\
H &= N_2 \\
M &= N_3 \\
\end{align*}
\]

\[
\begin{align*}
u &\quad d &\quad e &\quad v_1 \\
c &\quad s &\quad \mu &\quad v_2 \\
t &\quad b &\quad \tau &\quad v_3 \\
g &\quad W &\quad Z &\quad Y \\
\end{align*}
\]
SMASH recap

\[ \mathcal{L} = \mathcal{L}_{\text{kin}}^{SM} + \mathcal{L}_{\text{yuk}}^{SM} \]

\[ - \left[ \frac{M^2}{2} + \xi_H H^\dagger H + \xi_\sigma |\sigma|^2 \right] R \]

\[ -\lambda_H \left( H^\dagger H - \frac{v^2}{2} \right)^2 \quad - 2\lambda_{H\sigma} \left( H^\dagger H - \frac{v^2}{2} \right) \left( |\sigma|^2 - \frac{v_\sigma^2}{2} \right) \quad \text{STABILITY} \]

\[ -\lambda_\sigma \left( |\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 \quad - [y_\sigma \bar{Q} Q + y_{Q_d_i} \sigma Q_d_i + c.c.] \quad \text{CP PROBLEM} \]

\[ -[F_{ij} L_i e H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.] \quad \text{DARK MATTER} \]

\[ \text{SEESAW AND LEPTOGENESIS} \]

Most general, renormalizable Lagrangian compatible with the following global Peccei-Quinn (PQ) symmetry:

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SMASHY history of the Universe

- Inflation
- Radiation
- Matter
- Reheating
- PQ transition
- Leptogenesis
- Axion DM
- Recombination
H stabilized by portal coupling
H stabilized by portal coupling

Radiation domination after inflation
σ fluctuations take over
H stabilized by portal coupling

Radiation domination after inflation
σ fluctuations take over
PQ symmetry restored

Pure σ inflation ruled out by \( \Delta N_{\text{eff}} \sim 1 \)
Mixed σ-H inflation \( T_R \sim 10^{10} \text{ GeV} \)
SM plasma dominates energy from $T \sim 10^{10}$ GeV but reaches higher $T$.

At $T = T_c \sim 10^8$ GeV the PQ symmetry breaks in second order phase transition.

$$\langle \sigma \rangle = \frac{f_A}{\sqrt{2}}$$

**RH neutrinos acquire masses**

$$M_i = Y_{ii} \langle \sigma \rangle$$

Stability in $\sigma$ direction requires $M_i \lesssim 10^7$ GeV $< T_c$ so RH neutrinos can keep a thermal abundance: thermal leptogenesis from decays of $Ni$ at $T \lesssim 10^7$ GeV.

At the EW phase transition, SM neutrinos acquire see-saw masses

$$m_\nu = -\frac{FY^{-1}F^T}{\sqrt{2}} \frac{\nu^2}{f_A} = 0.04 \text{ eV} \left( \frac{10^{11} \text{ GeV}}{f_A} \right) \left( \frac{-FY^{-1}F^T}{10^{-4}} \right).$$
Relativistic axions:

Sourced early on by SM-axion interactions in equilibrium for $T \gtrsim 10^9 \text{GeV}$. After freezeout they end up giving

$$\Delta N_{\text{eff}} \sim 0.02 - 0.03$$

Non-relativistic axions:

Axions couple to the SU(3) anomaly like the $\theta$ term: dynamical $\theta_{\text{eff}}$

After the QCD phase transition, $\theta_{\text{eff}}$ acquires a mass, solving the CP problem.

Axion field starts oscillating, behaving as dark matter. Additional nonrelativistic axions are radiated by decaying strings.

Relic abundance and lattice results for $m_A$ [Borsanyi et al] enforce

$$\Omega_A h^2 \approx 0.12 \Rightarrow 3 \times 10^{10} \text{ GeV} \lesssim f_A \lesssim 1.2 \times 10^{11} \text{ GeV} \ ; \ 50 \mu\text{eV} \lesssim m_A \lesssim 200 \mu\text{eV}$$
Summary: predictions of the model

Axion mass and coupling to photons in reach of upcoming experiments (MADMAX, CULTASK)

\[50 \mu eV \lesssim m_A \lesssim 200 \mu eV, |C_{A\gamma}| = 1.25(4)\]

Precise predictions for cosmological observables \(n_s, r, \alpha \leq 10^{-3}, \Delta N_{\text{eff}} = 0.02-0.03\) can be probed by experiments (LiteBird, CORE, 21cm measurements)

QCD axion window could be probed by microlensing data (EROS, Subaru) [Fairbairn et al]

\[f_A[\text{GeV}]\]

\[\frac{C_{A\gamma}}{10^2} \quad 10^{11} \quad 10^{12} \quad 10^{13}\]

\[\frac{m_A[\text{eV}]}{10^{-6}} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3}\]

Possible CORE \(n_s\) resolution