Andreas Ringwald (DESY)

From the Vacuum to the Universe
Kitzbühel, Austria
26 June – 1 July 2016

The Quest for a Minimal Model of Particle Cosmology

Discovery of Higgs boson marks completion of SM particle content
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- Discovery of Higgs boson marks completion of SM particle content
- Observations in particle physics, astrophysics and cosmology point to existence of BSM particles

1. Inflation
2. Baryon asymmetry
3. Dark matter
4. Neutrino flavour oscillations
5. Non-observation of strong CP violation

[wikipedia]
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- Minimal SM extension by light right-handed singlet neutrinos [Asaka, Shaposhnikov `05]

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\mathcal{L} \supset - \left[ F_{ij} L_i \epsilon H N_j + \frac{1}{2} M_{ij} N_i N_j + h.c. \right]
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  1. Inflation
  2. Baryon asymmetry
  3. Dark matter
  4. Neutrino flavour oscillations
  5. Non-observation of strong CP violation
- Problems 1.-4. solved in $\nu$MSM:
  - Minimal SM extension by light right-handed singlet neutrinos [Asaka, Shaposhnikov `05]
  - Allowing for large, $\xi_H \sim 10^5 \sqrt{\lambda_H}$, non-minimally coupling of Higgs to Ricci scalar [Bezrukov, Shaposhnikov `08]

\[ S \supset - \int d^4 x \sqrt{-g} \xi_H H^\dagger H R \]
The Quest for a Minimal Model of Particle Cosmology

> Success of inflation in $\nu$MSM threatened:

- For $\xi_H \sim 10^4$, perturbative unitarity breaks down during inflation or, at the very least, during reheating, rendering predictions unreliable

[Barbon, Espinosa 09; Burgess et al. 09; Kehagias et al. 14]
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  [Degrassi et al. 12;..; Bezrukov et al. 12; Bednyakov et al. 15]

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Can be avoided by introducing Hidden complex Scalar (HS) charged under new global U(1) symmetry that is spontaneously broken

$$V(H, \sigma) = \lambda_H \left(H^\dagger H - \frac{\nu^2}{2}\right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{\nu_\sigma^2}{2}\right)^2 + 2\lambda_H\sigma \left(H^\dagger H - \frac{\nu^2}{2}\right) \left(|\sigma|^2 - \frac{\nu_\sigma^2}{2}\right)$$

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

> Role of the inflaton can now be played by modulus \(|\sigma| = \rho/\sqrt{2}\) of HS or a mixture of latter with the modulus of the Higgs

- Required non-minimal coupling \(\xi_\sigma \sim 10^5 \sqrt{\lambda_\sigma}\) to fit amplitude of CMB temperature fluctuations can be of order unity, for \(\lambda_\sigma \sim 10^{-10}\), raising scale of unitarity violation to \(M_P\)
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- Hidden scalar stabilizes scalar potential through Higgs portal coupling

  - Gives extra positive contribution to beta function of Higgs quartic

    [Gonderinger et al. 10]

  - Generates tree-level threshold effect on Higgs quartic coupling that can make potential absolutely stable if \( v_\sigma < \sqrt{\lambda_H/\lambda_{H\sigma}} \Lambda_I \)

    [Lebedev 12; Elias-Miro et al. 12]
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- Angular scalar excitation:
  - NG boson J

\[ N_1, N_2, N_3, N_{1/2} \]

<table>
<thead>
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<td>H</td>
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The Quest for a Minimal Model of Particle Cosmology

Add vector-like quark with chiral charge assignment under hidden U(1), rendering latter to a Peccei-Quinn (PQ) symmetry as in KSVZ axion model.

\[ \mathcal{L} \supset - \left[ Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + y \tilde{Q} \sigma Q + y_{Q,d} \sigma Q d_i + h.c. \right], \]

<table>
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<th></th>
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<th>u</th>
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> VEV \( v_\sigma \sim 10^{11} \) GeV:
  - gives also mass to Q

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<th>q</th>
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three generations of matter (fermions) spin 1/2

- mass
  - I: 2.4 MeV
  - II: 1.27 GeV
  - III: 173.2 GeV

- charge
  - I: 2/3
  - II: 2/3
  - III: 2/3

- name
  - up
  - charm
  - top

- quarks
  - down
  - charm
  - top

leptons
- electron
- muon
- tau

bosons (forces) spin 1
- weak force
- Higgs boson

bosons (forces) spin 0
- weak force
- Higgs boson
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- VEV \( v_\sigma \sim 10^{11} \text{ GeV} \):
  - gives also mass to Q

- J is the axion:
  - NG boson A/J has coupling
    \[ \mathcal{L}_A \ni - \frac{\alpha_s}{8\pi} \frac{A}{v_\sigma} G^c_{\mu \nu} \tilde{G}^{c, \mu \nu} \]
  - Strong CP problem solved!
  - A/J decay constant: \( f_A = v_\sigma \)
  - Mass \( m_A \sim f_\pi m_\pi / f_A \)
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- Axion cold DM plus sterile neutrino warm DM
The Quest for a Minimal Model of Particle Cosmology

Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges

\[ \mathcal{L} \supset - \left[ Y_{uij} q_i e H u_j + Y_{dij} q_i H^d d_j + G_{ij} L_i H^e E_j + F_{ij} L_i e H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \right. \\
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> VEV \( \nu_\sigma \sim 10^{11} \text{ GeV} \):

- Determines Majorana masses
- Explains smallness of active neutrino masses by see-saw relation

\[ m_\nu = 0.04 \text{ eV} \left( \frac{10^{11} \text{ GeV}}{\nu_\sigma} \right) \left( \frac{-F Y^{-1} F^T}{10^{-4}} \right) \]
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SM*A*S*H

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[Sm*Axion*See-saw*Hidden PQ scalar inflation]

[Diagrams and tables showing particle mass assignments and their respective charges and symmetries.]

Andreas Ringwald | SM*A*S*H*, From the Ve...
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\[\text{SM}^* \text{A}^* \text{S}^* \text{H}\]

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\[m_\nu = 0.04 \text{ eV} \left( \frac{10^{11} \text{ GeV}}{v_\sigma} \right) \left( \frac{-F Y^{-1} F^T}{10^{-4}} \right) \sim 10^{9} \text{ GeV} \]

> Thermal leptogenesis (out of equilibrium decay of RHN)

[Diass et al. `14]

[Ballesteros, Redondo, AR, Tamarit, arXiv:1607.????]

SM * Axion * See-saw * Hidden PQ scalar inflation
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- Axion cold DM

[Ballesteros,Redondo, AR,Tamarit, arXiv:1607.????]

Non-minimal couplings stretch scalar potential in Einstein frame; makes it convex and asymptotically flat at large field values

\[
\tilde{V}(h, \rho) = \frac{1}{\Omega^4(h, \rho)} \left[ \frac{\lambda_H}{4} (h^2 - v^2)^2 + \frac{\lambda_\sigma}{4} (\rho^2 - v_\sigma^2)^2 + \frac{\lambda_{H\sigma}}{2} (h^2 - v^2)(\rho^2 - v_\sigma^2) \right]
\]

\[
\tilde{g}_{\mu\nu} = \Omega^2(h, \rho) g_{\mu\nu} \quad \Omega^2 = 1 + \frac{\xi_H(h^2 - v^2) + \xi_\sigma(\rho^2 - v_\sigma^2)}{M_P^2}
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\]

\[
\Omega^2 = 1 + \frac{\xi_H(h^2 - v^2) + \xi_\sigma(\rho^2 - v_\sigma^2)}{M_P^2}
\]

Potential has valleys = attractors for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of \( \kappa_H \equiv \lambda_H\sigma\xi_H - \lambda_H\xi_\sigma \), \( \kappa_\sigma \equiv \lambda_H\sigma\xi_\sigma - \lambda_\sigma\xi_H \).
CMB observables

\[ A_s = (2.20 \pm 0.08) \times 10^{-9}, \]
\[ n_s = 0.967 \pm 0.004, \]
\[ r < 0.07 \]

can be fit for any \( \xi \gtrsim 10^{-3} \)

\[ \xi \equiv \begin{cases} 
\xi_H, & \text{for HI,} \\
\xi_\sigma, & \text{for HSI,} \\
\xi_\sigma, & \text{for HHSI} 
\end{cases} \]
Inflation: Confronting with Observations

\[
\lambda \equiv \begin{cases} 
\lambda_H, & \text{for HI,} \\
\lambda_\sigma, & \text{for HSI,} \\
\lambda_\sigma \left(1 - \frac{\lambda_H^2}{\lambda_\sigma \lambda_H}\right), & \text{for HHSI}
\end{cases}
\]

HI requires huge non-minimal coupling of the Higgs:

\[
\xi_H \sim 2 \times 10^5 \sqrt{\lambda_H (\sim M_P)} \sim 2 \times 10^4
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- Perturbative unitarity lost in HI

\[ \Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14} \text{ GeV} \sim H_I \ll \tilde{V}^{1/4}(h_I), h_I \]
Inflation: Confronting with Observations

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- Perturbative unitarity lost in HI
  \[ \Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14} \text{ GeV} \sim H_I \ll \tilde{V}^{1/4}(h_I, h_I) \]

- Can be of order one for HSI or HHSI; e.g. \( \xi_\sigma = 1 \) requires
  \[ \lambda_\sigma, \tilde{\lambda}_\sigma = (4.1^{+3.0}_{-2.1}) \times 10^{-10} \]

- No unitarity problem in HSI/HHSI!
Stability

- Effective scalar potential in SMASH can be positive up to the Planck scale
- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos
Stability

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- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos
- Stability in Higgs direction enforces maximum on Higgs portal coupling
Stability

- Effective scalar potential in SMASH can be positive up to the Planck scale.
- Stability in HS direction enforces a maximum on Yukawas of RH neutrinos.
- Stability in Higgs direction enforces maximum on Higgs portal coupling and a maximum on $f_A$. 

\[ \delta(m_\rho) = f_A \left[ \text{GeV} \right] \]
Reheating

> Mechanism of reheating in SMASH well defined: proceeds via the Higgs portal

> Fundamental questions:

  - Is PQ symmetry restored after inflation?
  - Is reheating temperature large enough for successful thermal leptogenesis?

> Reheating proceeds in two steps:

  - Preheating: Fluctuations of hidden scalar grow fast due to parametric resonance while HS-inflaton oscillates in its quartic potential. PQ symmetry effectively restored for \( f_A \lesssim 10^{16} \text{ GeV} \)
  - Perturbative reheating: HS fluctuations thermalize quickly and dump their energy into SM particles once their decay rate goes above the Hubble rate. In stabilised parameter region, \( 10^{11} \text{ GeV} \sim T_R \gg T_c \sim 2\chi^{1/4} f_A \sim 10^9 \text{ GeV} \)

> PQ thermally restored phase continues for a few e-folds and then PQ symmetry is spontaneously broken

> Leptogenesis proceeds by out of equilibrium decays of RHNs
Axion Dark Matter

- In postinflationary PQ SB scenario: one-to-one relation between axion mass and relic abundance

- Mechanisms of production:
  - Vacuum realignment

\[ m_a < 3H \]

axion is frozen

\[ m_a \approx 3H \]

axion starts rolling, turns into pressureless matter.

[Wantz, Shollard 09]
Axion Dark Matter

- In postinflationary PQ SB scenario: one-to-one relation between axion mass and relic abundance

- Mechanisms of production:
  - Vacuum realignment
  - Decay of topological defects (domain walls and strings)

\[
\Omega_{A,\text{tot}} h^2 = \Omega_{A,\text{real}} h^2 + \Omega_{A,\text{string}} h^2 + \Omega_{A,\text{wall}} h^2
\]

[Hiramatsu et al. 12]
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- Key quantity entering prediction: Temperature dependence of axion mass, \( m_A(T) f_A = \sqrt{\chi(T)} \)
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- Key quantity entering prediction: Temperature dependence of axion mass, \( m_A(T) f_A = \sqrt{\chi(T)} \)

- For a 100%/50%/1% contribution from misalignment; remainder from topological defects:

\[ m_A = 28(2)/50/1500 \mu eV \]

[Borsanyi et al. `16]
Presently operating (ADMX) and planned next generation experiments based on RF cavities (G2, G3) not able to cover whole mass range

More promising: Experiments exploiting dielectric mirrors or antenna dishes

$P_{\text{out}} \sim g^2 |B_0|^2 \rho_{\text{DM}} V Q / m_a$

$P_{\text{center}} \approx \langle |E_{a}|^2 \rangle_{\text{dish}} \sim \chi^2 \rho_{\text{CDM}} A_{\text{dish}}$

$\sim 10^{-26} \left( \frac{B C_0}{5T^2} \right)^2 \frac{A}{\text{m}^2} \text{Watt}$

[Adiabatic resonance]

[50-1500 µeV]

[ADMX06]

[DFSZ]

[ADMX]

[G2]

[KSVZ]

[DFSZ]

[CAST]

[IAXO]

[Used with permission from Borsanyi et al. `16]

[Used with permission from Horns et al. `13]
Summary

Remarkably simple extension of the SM provides solution of five fundamental problems of particle physics and cosmology

1. Inflation
2. Baryon asymmetry
3. Dark matter
4. Neutrino flavour oscillations
5. Non-observation of strong CP violation

SM*A*S*H

Conclusions

> SMASHy history of the universe:
Summary

- Crucial prediction: Dark matter comprised of axions with mass in range
  \[ m_A = (50 \div 1500) \mu\text{eV} \]

- Can be tested experimentally in next decade by new direct detection experiments, such as the MADMAX haloscope.