Higgs field as the main character in the early Universe

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Barcelona University, 11.11.2011
Outline

1. Motivation: phenomena observed but unexplained within the SM

2. Top-down approach: starting from Higgs-inflation (no new fields!)
   - Chaotic inflation: preliminaries
   - Higgs field with nonminimal coupling to gravity: inflation and reheating
   - Strong coupling
   - Possible role of nonrenormalizable operators

3. Summary
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3. Summary
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Neutrino oscillations: masses and mixing angles

Solar $2 \times 2$ “subsector”

Atmospheric $2 \times 2$ “subsector”

$m_1 > 0.008 \text{ eV}$

MINOS, T2K, SNO, . . . , global fits: $\sin^2 2\theta_{13} \lesssim 0.3$

$m_2 > 0.05 \text{ eV}$

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Baryons and Dark Matter in Astrophysics

Rotation curves

Gravitational lensing

X-rays from clusters

“Bullet” cluster
Motivation: phenomena observed but unexplained within the SM

**Baryons and Dark Matter in Cosmology**

**Standard candles**

**Angular distance**

**BBN**

**Structures**

**BAO**

**CMB fluctuations**

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**Cosmological parameters:** $\Omega_{DM} = 0.22$, $\Omega_B = 0.046$

Motivation: phenomena observed but unexplained within the SM

![Diagram showing cosmological parameters](image-url)
Motivation: phenomena observed but unexplained within the SM

**Inflationary solution of Hot Big Bang problems**

Temperature fluctuations \( \delta T / T \sim 10^{-5} \)

Universe is uniform!

\( \delta \rho / \rho \sim 10^{-5} \)

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Motivation: phenomena observed but unexplained within the SM

True Extension of the Standard Model should

- Reproduce the correct neutrino oscillations
- Contain the viable DM candidate
- Be capable of explaining the baryon asymmetry of the Universe
- Have the inflationary mechanism operating at early times

Guiding principle:

use as little “new physics” as possible

Why?

No any hints observed so far!
- No FCNC
- No WIMPs
- No . . .
- . . . Nothing new at all
Standard Model: Success and Problems

Gauge fields (interactions): $\gamma, W^\pm, Z, g$
Three generations of matter: $L = (\nu_L, e_L), e_R; Q = (u_L, d_L), d_R, u_R$

- Describes
  - all experiments dealing with electroweak and strong interactions

- Does not describe
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage
  - Dark energy ($\Omega_\Lambda$)
  - Strong CP: boundary terms, new topology, . . .
  - Gauge hierarchy: No new fields at new scales!
  - Quantum gravity

Try to explain all above

Planck-scale physics saves the day
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3 Summary
Chaotic inflation: simple realization

\[ S = \int d^4x \sqrt{-g} \left( -\frac{M_P^2}{2} R + \frac{(\partial \mu X)^2}{2} - \beta X^4 \right) \]

\[ \dot{X} + 3H\dot{X} + V'(X) = 0 \]

\[ H^2 = \frac{1}{M_P^2} V(X), \quad a(t) \propto e^{Ht} \]

slow roll conditions get satisfied at

\[ X_e > M_{Pl} \]

\[ M_P^2 = M_{Pl}^2/(8\pi) \]

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of \( X \)

Gravity solves all problems — No scale, no problem

We have scalar in the SM! The Higgs field!

In a unitary gauge \( H^T = (0, (h + \nu)/\sqrt{2}) \) (and neglecting \( \nu = 246 \text{ GeV} \)) \( \lambda \sim 0.1 - 1 \)

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Higgs-driven inflation

\[ S = \int d^4x \sqrt{-g} \left( -\frac{M_P^2}{2} R - \frac{\xi}{2} H^\dagger H R + \mathcal{L}_{SM} \right) \]

In a unitary gauge \( H^T = (0, (h + \nu)/\sqrt{2}) \) (and neglecting \( \nu = 246 \text{ GeV} \))

\[ S = \int d^4x \sqrt{-g} \left( -\frac{M_P^2 + \xi h^2}{2} R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4} \right) \]

slow roll behavior due to modified kinetic term even for \( \lambda \sim 1 \)

Go to the Einstein frame:

\[ (M_P^2 + \xi h^2) R \rightarrow M_P^2 \tilde{R} \]

\[ g_{\mu\nu} = \Omega^{-2} \tilde{g}_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2} \]

with canonically normalized \( \chi \):

\[ \frac{d\chi}{dh} = \frac{M_P \sqrt{M_P^2 + (6\xi + 1)\xi h^2}}{M_P^2 + \xi h^2}, \quad U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2 + \xi h^2(\chi))^2}. \]

we have a flat potential at large fields:

\[ U(\chi) \rightarrow \text{const} \quad @ \quad h \gg M_P/\sqrt{\xi} \]
Top-down approach: starting from Higgs-inflation (no new fields!)

Higgs field with nonminimal coupling to gravity: inflation and reheating

$\sqrt{6 \log(\sqrt{\xi h}/M_P)}$

$\frac{\sqrt{3}}{2} \frac{\xi h^2}{M_P^2}$

$h$

exact

$\log(h)$

Logarithmic scale!

$M_P\sqrt{\xi}$

$M_P$ is Planck mass.

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics: $h^2 \to \chi$

$\mathcal{L} = \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{\lambda}{6} \frac{M_P^2}{\xi^2} \chi^2$

Advantage: NO NEW interactions to reheat the Universe
inflaton couples to all SM fields!

Higgs field: the main character in Universe

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$$U(\chi) = \frac{\lambda M_P^4}{4 \xi^2} \left(1 - \exp \left(-\frac{\sqrt{2} \chi}{\sqrt{3} M_P}\right)\right)^2$$

coincides (apart of $T_{reh} \approx 10^{14} \text{ GeV}$) with $R^2$-model!

But NO NEW d.o.f.

$$n_s = 0.97 \ , \ r = 0.0034 \ , \ N = 59$$

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$
Top-down approach: starting from Higgs-inflation (no new fields!)

Higgs field with nonminimal coupling to gravity: inflation and reheating

\[ m^2_W(\chi) = \frac{g^2}{2\sqrt{6}} \frac{M_P |\chi(t)|}{\xi} \]

\[ m_t(\chi) = y_t \sqrt{\frac{M_P |\chi(t)|}{\sqrt{6} \xi}} \text{sign} \chi(t) \]

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reheating via \( W^+ W^- \), \( ZZ \) production at zero crossings
then nonrelativistic gauge bosons scatter to light fermions

\( W^+ W^- \rightarrow f \bar{f} \)

Hot stage starts almost from \( T = M_P / \xi \sim 10^{14} \text{ GeV} \):

\[ 3.4 \times 10^{13} \text{GeV} < T_r < 1.1 \times 10^{14} \left( \frac{\lambda}{0.25} \right)^{1/4} \text{GeV} \]
Fine theoretical descriptions both in

**UV:** $\chi \gg M_P$, $U = \text{const} + \mathcal{O}\left(\exp\left(-\sqrt{2} \chi / \sqrt{3} M_P\right)\right)$

and in

**IR:** $h \ll M_P / \xi$, $U = \frac{\lambda}{4} h^4$

Obvious problem with QFT-description of IR/UV matching at intermediate $\chi < \chi_{\text{end}}$ and $h < M_P / \sqrt{\xi}$

Hence no reliable prediction for the SM Higgs boson mass $m_h = \sqrt{2 \bar{\lambda} \nu}$ up to that from the absence of Landau pole and wrong minimum of Higgs potential (well) below $M_P / \xi$

$$130 \text{ GeV} \lesssim m_h \lesssim 190 \text{ GeV}$$

**exponentially flat potential!**

$@ h \gg M_P / \sqrt{\xi}$:

$$U(\chi) = \frac{\lambda M_P^4}{4 \xi^2} \left(1 - \exp\left(-\frac{\sqrt{2} \chi}{\sqrt{3} M_P}\right)\right)^2$$

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\[ 0812.3622 \]
Strong coupling in Higgs-inflation: scatterings

Jordan frame

Einstein frame

gravity-scalar sector:

$\Lambda_{g-s} (h) \sim \begin{cases} 
\frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\
\frac{\xi h^2}{M_P}, & \text{for } \frac{M_P}{\xi} \lesssim h \lesssim \frac{M_P}{\sqrt{\xi}}, \\
\sqrt{\xi} h, & \text{for } h \gtrsim \frac{M_P}{\sqrt{\xi}}.
\end{cases}$

gravitons: $\Lambda_{\text{Planck}}^2 \sim M_P^2 + \xi h^2$

gauge interactions:

$\Lambda_{\text{gauge}} (h) \sim \begin{cases} 
\frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\
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Top-down approach: starting from Higgs-inflation (no new fields!)

Strong coupling

Strong coupling at $M_P/\xi \ldots$

Can it change the initial conditions of the Hot Big Bang?

1. reheating temperature
2. baryon (lepton) asymmetry of the Universe
3. dark matter abundance

Let’s test these options adding all possible nonrenormalizable operators to the model
What can nonrenormalizable operators do?

\[ \delta \mathcal{L}_{NR} = - \frac{a_6}{\Lambda^2} (H^\dagger H)^3 + \cdots \]
\[ + \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L_\beta^c + \frac{\beta_B}{\Lambda^2} \mathcal{O}_{\text{baryon violating}} + \cdots + \text{h.c.} \]
\[ + \frac{\beta_N}{2\Lambda} H^\dagger H \tilde{N}^c N + \frac{b\lambda_\alpha}{\Lambda} \bar{L}_\alpha (\bar{\phi} N)^c \tilde{H} + \cdots , \]

\( L_\alpha \) are SM leptonic doublets, \( \alpha = 1,2,3 \), \( N \) stands for right handed sterile neutrinos potentially present in the model, \( \tilde{H}_a = \varepsilon_{ab} H_b^* \), \( a,b = 1,2 \);

and

\[ \Lambda = \Lambda(h) = \{ \Lambda_{g-s}(h) , \Lambda_{\text{gauge}}(h) , \Lambda_{\text{Planck}}(h) \} \]

couplings can differ significantly in different regions of \( h \):
today \( h < M_P/\xi \),
at preheating \( M_P/\sqrt{\xi} < h < M_P/\xi \).
Top-down approach: starting from Higgs-inflation (no new fields!)

Possible role of nonrenormalizable operators

**LFV, BV nonrenormalizable operators today**

Neutrino masses: easily

\[ \mathcal{L}_{\nu
\nu}^{(5)} = \frac{\beta_L v^2}{4\Lambda} \frac{F_{\alpha\beta}}{2} \bar{\nu}_{\alpha} \nu_{\beta}^c + \text{h.c.} \]

hence

\[ \Lambda \sim 3 \times 10^{14} \text{ GeV} \times \beta_L \times \left( \frac{3 \times 10^{-3} \text{ eV}^2}{\Delta m_{\text{atm}}^2} \right)^{1/2} \]

when

\[ \Lambda = \frac{M_P}{\xi} \sim 0.6 \times 10^{14} \text{ GeV} \]

can explain with

\[ \beta_L \sim 0.2 \]

Proton decay: probably

\[ \mathcal{L}^{(6)} \propto \frac{\beta_B}{\Lambda^2} QQL \]

then from experiments

\[ \Lambda \gtrsim \sqrt{\beta_B} \times 10^{16} \text{ GeV} \times \left( \frac{\tau_{p \rightarrow \pi^0 e^+}}{1.6 \times 10^{33} \text{ years}} \right)^{1/4} \]

with the same

\[ \Lambda = \frac{M_P}{\xi} \sim 0.6 \times 10^{14} \text{ GeV} \]

one needs

\[ \beta_B < 0.4 \times 10^{-4} \]

Either \( B \) and \( L_\alpha \) are significantly different

or we will observe proton decay in the next generation experiment
LFV, BV nonrenormalizable operators today

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Leptogenesis, $\Delta_B \approx \Delta_L/3$: can be successful

$$i \frac{d}{dt} \hat{Q}_L = [\hat{H}_{\text{int}}, \hat{Q}_L], \quad \Delta n_L \equiv n_L - n_{\bar{L}} = \langle Q_L \rangle$$

$$\mathcal{L}_Y = -Y_\alpha \bar{L}_\alpha H E_\alpha + \text{h.c.}, \quad \mathcal{L}^{(5)}_{VV} = \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L_\beta + \text{h.c.}$$

$$d\Delta n_L/dt \propto \text{Im} \left( \beta_L^4 \text{Tr} \left( FF^\dagger FYYF^\dagger YY \right) \right) \propto \beta_L^4 y_\tau^4 \cdot \text{Im} \left( F_{3\beta} F_{\alpha\beta}^* F_{\alpha3} F_{33}^* \right)$$

for the gauge cutoff $\Lambda = h$ one has

$$\beta_L^4 \left( \frac{y_\tau}{0.01} \right)^4 \left( \frac{0.25}{\lambda} \right)^{5/4} \times 10^{-10} < \Delta_L < \beta_L^4 \left( \frac{y_\tau}{0.01} \right)^4 \left( \frac{0.25}{\lambda} \right) \times 10^{-9},$$

for gravity-scalar cutoff $\Lambda = \xi h^2 / M_P$

$$\beta_L^4 \left( \frac{y_\tau}{0.01} \right)^4 \left( \frac{0.25}{\lambda} \right)^{13/4} \times 6.3 \times 10^{-13} < \Delta_L < \beta_L^4 \left( \frac{y_\tau}{0.01} \right)^4 \left( \frac{0.25}{\lambda} \right)^2 \times 2.4 \times 10^{-10}$$

In both cases the asymmetry can be (significantly) increased with operator

$$\delta \mathcal{L}^\tau = y_\tau L_\tau H E_\tau + \beta y L_\tau H E_\tau \frac{H^\dagger H}{\Lambda^2} + \cdots$$

one can fancy the hierarchy

$$1 \sim \beta y \gg y_\tau \sim 10^{-2}.$$
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$$d \Delta n_L / dt \propto \text{Im} \left( \beta_L^4 \text{Tr} \left( F F^\dagger F Y Y F^\dagger Y Y \right) \right) \propto \beta_L^4 y_\tau^4 \cdot \text{Im} \left( F_{3\beta} F_{\alpha\beta}^* F_{\alpha3} F_{33}^* \right)$$

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Possible role of nonrenormalizable operators

Dark matter: an example of sterile fermion

\[ \mathcal{L}_{\text{int}} = \beta_N \frac{H^\dagger H}{2\Lambda} \bar{N}^c N = \frac{\beta_N}{4} \frac{h^2}{\Lambda(h)} \bar{N}^c N \]

can be produced at preheating or at the hot stage

DM fermion has to be light! (WDM?)

Indeed, today

\[ f_\alpha \sim b_{L_\alpha} \frac{M_N}{\Lambda} \]

So, \( N \) is unstable with the \( \gamma\nu \) partial width of the order

\[ \Gamma_{N \rightarrow \gamma\nu} \sim \frac{9 b_{L_\alpha}^2 \alpha G_F^2 v^2 M_N^5}{512\pi^4 \Lambda^2} \]

EGRET gives \( \tau_{\gamma\nu} \gtrsim 10^{27} \text{ s} \), hence

\[ \text{for } \Lambda = M_P : \quad M_N \lesssim 200 \text{ MeV} , \quad \text{for } \Lambda = M_P/\xi : \quad M_N \lesssim 4 \text{ MeV} \]
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3 Summary
Summary on Higgs-inflation

- Guiding principle: use as little “new physics” as possible
- Predicted $n_s$, $r$ can be tested experimentally
- Can explain neutrino oscillations with nonrenormalizable operators
- Can explain BAU with nonrenormalizable operators
- Need a new field to be DM
- Fermion DM is light (?) and can be searched for in cosmic $X$- or $\gamma$-rays (?)
- Proton decays (???)

It can solve all the phenomenological problems we are aware of...

It would be great to describe IR/UV matching in $RH^\dagger H$
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The main character in the early Universe...?

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Backup slides