CP-violating inflation

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In collaboration with Kimmo Tuominen

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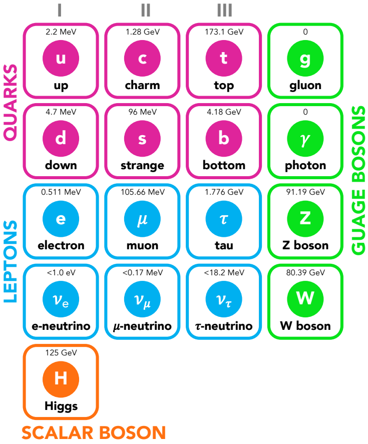
and work in progress

The Standard Model

Its current formulation was finalised in the 70's and predicted:

- the W & Z bosons
  discovered in 1983
- the top quark
  discovered in 1995
- the tau neutrino
  discovered in 2000
- the Brout-Englert-Higgs mechanism
  a scalar boson was discovered in 2012



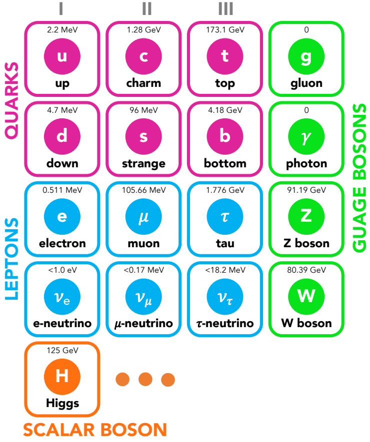
··· and the need to go beyond

What is missing:

- a suitable Dark Matter candidate
- a successful baryogenesis mechanism
  - strong first order phase transition
  - sufficient amount of CP-violation
- a natural inflation framework
- an explanation for the fermion mass hierarchy
- a stable electroweak vacuum

$\Rightarrow$ beyond the Standard Model

$\Rightarrow$ **scalar extensions of the SM**



Scalar extensions of the SM

SM + scalar singlets

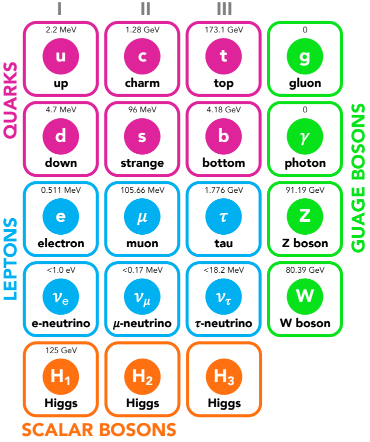
- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet

- Dark Matter constrained & CPV incompatible
- CP-violation severely constrained & DM incompatible
- Inflation CPV incompatible

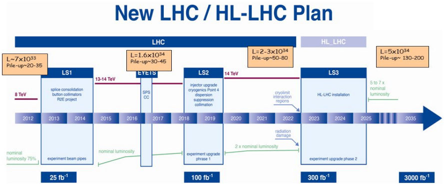
3HDM: SM + 2 doublets

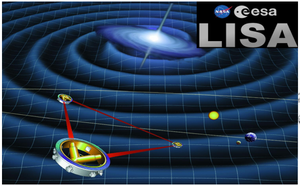
- Dark Matter many exotic possibilities
- CP-violation unbounded dark CP-violation
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation

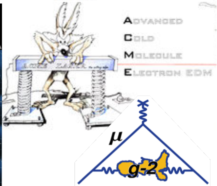


Upcoming experimental probes

- Collider experiments
  - 2021: LHC-RUN-III
  - 2026: HL-LHC
  - 2028: CEPC
- DM experiments
  - 2020: XENONnT
  - 2022: CTA
- GW experiments
  - 2027: DECIGO
  - 2034: LISA mission
- Precision experiments
  - 2020: $(g-2)_\mu$
  - 2020: Advanced ACME



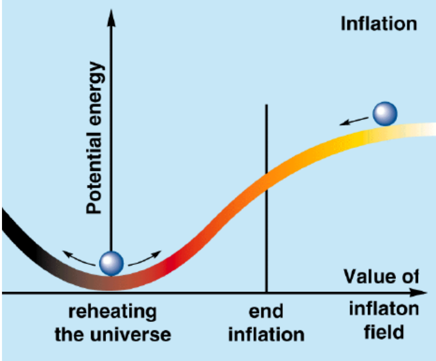




Simplest and best in agreement with observation:

Slow roll inflation:

driven by a scalar field (inflaton) slowly rolling down its smooth potential



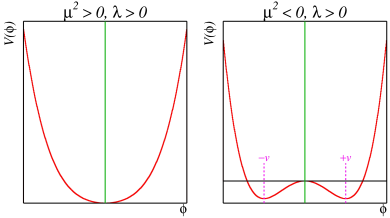
J. Garcia-Bellido, [arXiv:hep-ph/0303153 [hep-ph]]

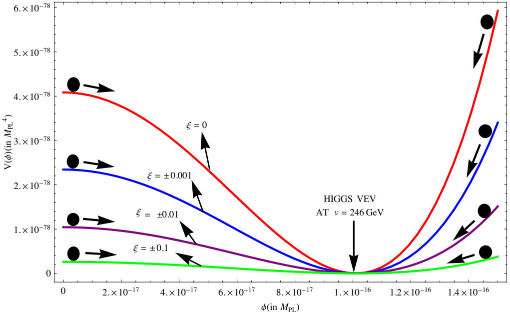
The Higgs inflation model

The SM Higgs potential:
$V(\phi) = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2$

Introducing a non-minimal coupling to gravity ξ:

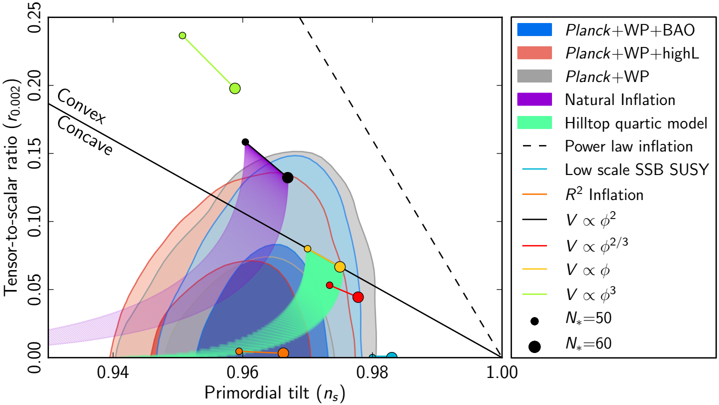
$$\mathcal{L}_J = \frac{\sqrt{-g_J}}{2} \Big[(\xi \phi^2 + M_{pl}^2) R + (\partial_\mu \phi)^2 - V(\phi) \Big]$$





S. Choudhury, T. Chakraborty, S. Pal, [Nucl. Phys. B 880, 155-174 (2014)]

Planck constraints on different inflationary models



Tensor to scalar ratio $r = 16\epsilon$ and the **spectral index** $n_s = 1 - 6\epsilon + 2\eta$

calculated from the slow-roll parameters $\epsilon = \frac{1}{2} M_{pl}^2 \left(\frac{1}{\tilde{V}} \frac{d\tilde{V}}{d\phi} \right)^2$ and $\eta = M_{pl}^2 \frac{1}{\tilde{V}} \frac{d^2\tilde{V}}{d\phi^2}$

P. A. R. Ade *et al.* [Planck], [Astron. Astrophys. 571, A22 (2014)]

3HDMs: 3-Higgs doublet models

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

$$\phi_1 = \begin{pmatrix} h_1^+ \\ \frac{h_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} h_2^+ \\ \frac{h_2+i\eta_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h_3+iG^0}{\sqrt{2}} \end{pmatrix}$$

I. P. Ivanov, V. Keus, E. Vdovin, [J. Phys. A 45, 215201 (2012)], I. P. Ivanov and E. Vdovin, [Phys. Rev. D 86, 095030 (2012)]

Z_2-symmetric 3HDM with dark CPV

Lagrangian invariant under a Z_2 symmetry $(-,-,+)$:

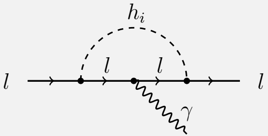
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \qquad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

and respected by the vacuum $(0,0,v)$:

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 + i\eta_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 + i\eta_2 \end{pmatrix}, \qquad \phi_3 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h + h_3 \end{pmatrix}$$

Only ϕ_3 can couple to fermions: $\phi_u = \phi_d = \phi_e = \phi_3$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.}$$



No contributions to electric dipole moments (EDMs)

VK, S. F. King, S. Moretti, D. Sokolowska, D. Rojas, [JHEP 12, 014 (2016)], VK, [Phys. Rev. D 101, 073007 (2020)]

Z_2-symmetric 3HDM with dark CPV

The scalar potential: $V = V_0 + V_{Z_2}$ with

$$V_0 = -\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2 + \lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i) \qquad (i = 1,2,3)$$

which is CP-conserving (real parameters),

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.$$

which is CP-violating (complex parameters).

The action of the model:

$$S_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}M_{pl}^2R - D_\mu\phi_i^\dagger D^\mu\phi_i - V - \left(\xi_i|\phi_i|^2 + \underbrace{\xi_4(\phi_1^\dagger\phi_2)}_{Z_2-\text{symmetric}} + h.c.\right)R\right]$$

The sources of CP-violation are $\lambda_1 = |\lambda_1|e^{i\theta_1}$ and $\xi_4 = |\xi_4|\,e^{i\theta_4}$.

The inflationary potential $\widetilde{V}$

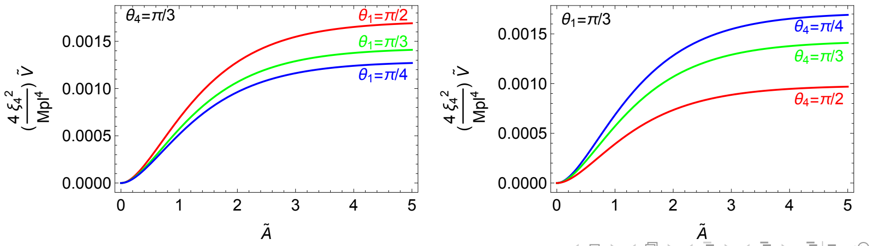
To simplify the analysis: $\eta_1 = \beta_1 h_1$ and $h_2 = \beta_2 h_1$

Finding the inflationary direction yields: $\beta_1(\theta_1, \theta_4)$, $\beta_2(\theta_1, \theta_4)$

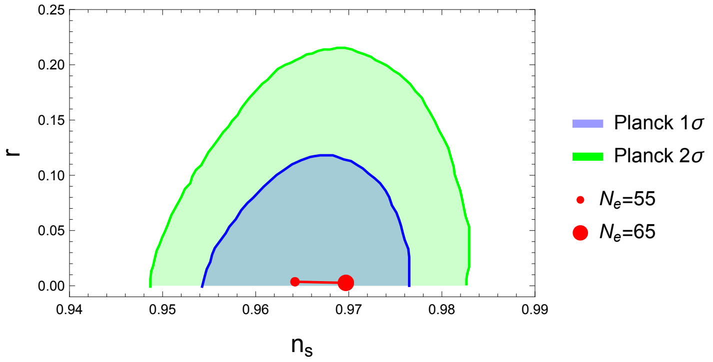
Another standard reparametrisation: $h_1^2 = \frac{M_{pl}^2}{2|\xi_4|\,\beta_2(c_{\theta_4} + \beta_1 s_{\theta_4})} \left(e^{\tilde{A}} - 1\right)$

(h_1: inflaton field; $\tilde{A}$: reparametrised inflaton field)

The potential is simplified to: $\widetilde{V} = \left(\frac{M_{pl}^2}{2|\xi_4|}\right)^2 \left(1 - e^{-\tilde{A}}\right)^2 \underbrace{X(\theta_1, \theta_4)}_{\text{new}}$



1σ and 2σ regions from Planck observation



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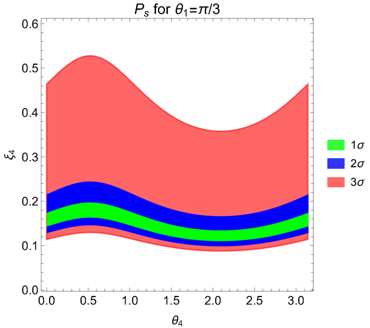
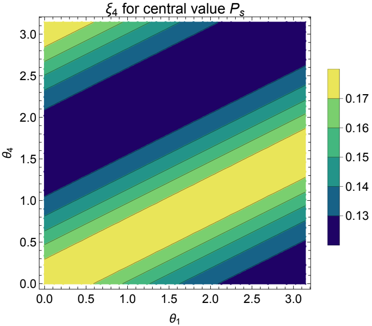
Tensor to scalar ratio $r = 16\epsilon$ and the **spectral index** $n_s = 1 - 6\epsilon + 2\eta$

calculated from the slow-roll parameters $\epsilon = \frac{1}{2} M_{pl}^2 \left(\frac{1}{\tilde{V}} \frac{d\tilde{V}}{d\tilde{A}} \right)^2$ and $\eta = M_{pl}^2 \frac{1}{\tilde{V}} \frac{d^2\tilde{V}}{d\tilde{A}^2}$

WMAP7 constraints on the scalar power spectrum P_s

$$P_s = \frac{1}{12\,\pi^2 M_{pl}^6}\frac{(\tilde{V})^3}{(\tilde{V}\,')^2} = (2.430 \pm 0.091) \times 10^{-9}$$





In Higgs inflation: $|\xi| \simeq 4.785 \times 10^4 \sqrt{\lambda_h} \quad \Rightarrow \quad |\xi| \sim 10^3$

In our model: $|\xi_4| \simeq 4.785 \times 10^4 \sqrt{\lambda_i}\sqrt{X(\theta_1, \theta_4)} \quad \Rightarrow \quad |\xi_4| \sim 1/6$

Reheating and scalar asymmetries

At the exit from inflation: doublets acquire an initial expectation value

$$\begin{cases} \phi_1 \to \phi_1 - a_1 e^{i\alpha} \\ \phi_1^\dagger \to \phi_1^* - a_1 e^{-i\alpha} \end{cases} \qquad \begin{cases} \phi_2 \to \phi_2 - a_2 \\ \phi_2^\dagger \to \phi_2^* - a_2 \end{cases} \qquad \begin{cases} \phi_3 \to \phi_3 - a_3 \\ \phi_3^\dagger \to \phi_3^* - a_3 \end{cases}$$

where the phase $\alpha = \alpha(\theta_1, \theta_4)$.

Instant reheating: the inflaton quickly decays to ϕ_3

$$\mathcal{M}_{(\phi_1 \to \phi_3^* \phi_3^*)} \propto 2a_1\lambda_3\, e^{i(\alpha+\theta_3)}$$

$$\mathcal{M}_{(\phi_1 \to \phi_3 \to \phi_3^* \phi_3^*)} \propto 4a_1 a_3^2 \lambda_{11}\lambda_{33}(\lambda_{31} + \lambda'_{31}) e^{-i\alpha}$$

resulting in unequal number of ϕ_3 and ϕ_3^* states with asymmetries

$$A_{CP}^1 = \Gamma^{\text{tree+loop}}_{(\phi_1 \to \phi_3^* \phi_3^*)} - \Gamma^{\text{tree+loop}}_{(\phi_1^* \to \phi_3 \phi_3)} \propto \sin(2\alpha + \theta_3)$$

Such asymmetries are then transferred to the fermion sector through the couplings of the Higgs/W/Z with the fermions.

A one-slide summary

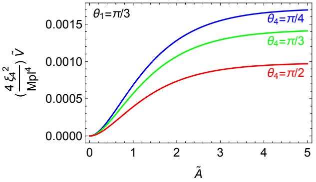
Three scalar doublets:

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 + i\eta_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 + i\eta_2 \end{pmatrix}, \qquad \phi_3 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h + h_3 \end{pmatrix}$$

Inflaton (ϕ_1, ϕ_2) SM-Higgs (ϕ_3)

The inflationary potential:

$$\tilde{V} = \left(\frac{M_{pl}^2}{2|\xi_4|}\right)^2 \left(1 - e^{-\tilde{A}}\right)^2 \underbrace{X(\theta_1, \theta_4)}_{\text{new}}$$

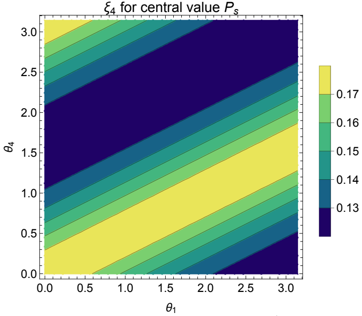


The potential:

$$V_0 = -\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2 + \lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)$$

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.$$

The sources of CP-violation are $\lambda_1 = |\lambda_1|e^{i\theta_1}$ and $\xi_4 = |\xi_4|\, e^{i\theta_4}$



The action:

$$S_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}M_{pl}^2 R - D_\mu\phi_i^\dagger D^\mu\phi_i - V - \left(\xi_i|\phi_i|^2 + \underbrace{\xi_4(\phi_1^\dagger\phi_2)}_{Z_2-\text{symmetric}} + h.c.\right)R\right]$$

CP-violation inflation $\xrightarrow{?}$ Baryogenesis

In memory of

BACKUP SLIDES

Summary

SM + scalar singlets

- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet

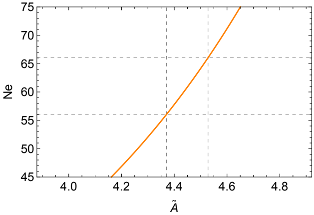
- Dark Matter constrained & CPV incompatible
- CP-violation severely constrained & DM incompatible
- Inflation CPV incompatible

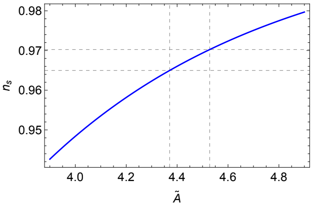
3HDM: SM + 2 doublets

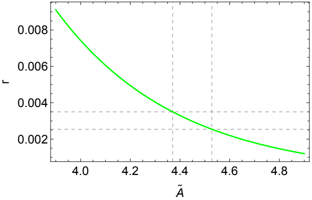
- Dark Matter **CP-violating DM**
- CP-violation **unbounded dark CP-violation**
- Inflation **CP-violating inflation**
- Bonus: fermion mass hierarchy explanation

The slow roll parameters

number of e-folds N_e, the spectral index n_s, tensor to scalar ratio r

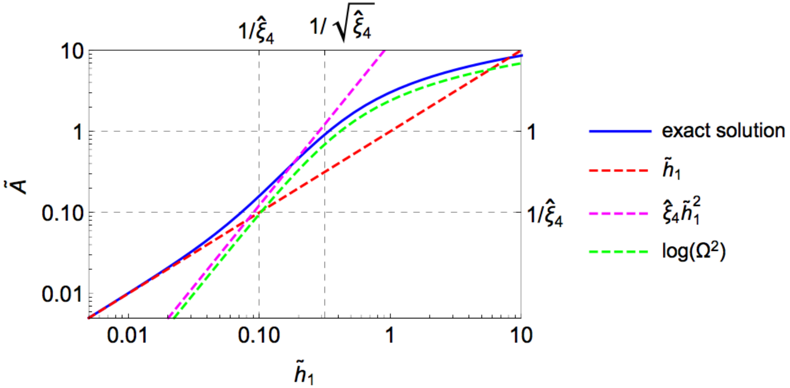






as a function of $\tilde{A}$ with the $55 < N_e < 65$ grid-lines

Reheating



1/$\hat{\xi}_4$
1/$\sqrt{\hat{\xi}_4}$
10
1
0.10
0.01
$\tilde{A}$
1
1/$\hat{\xi}_4$
0.01
0.10
1
10
$\tilde{h}_1$
exact solution
$\tilde{h}_1$
$\hat{\xi}_4 \tilde{h}_1^2$
log(Ω^2)