CP-violating inflation

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Introduction

Google Maps

Kerman, Iran to Helsinki

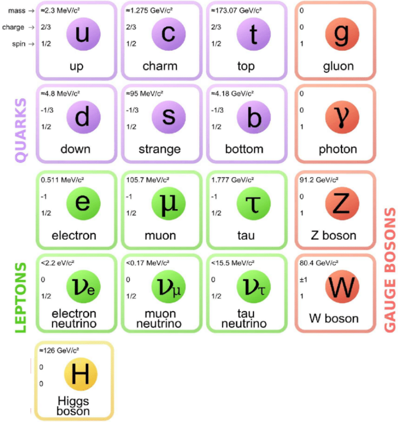
Drive 11,850 km, 125 h

Directions from primary school to postdoc university

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



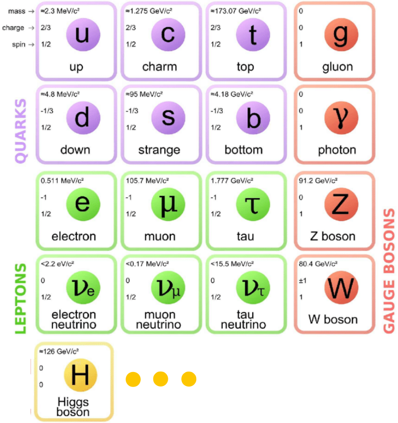
··· and the need to go beyond

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

⇒ beyond the Standard Model

⇒ scalar extensions of the SM



Scalar extensions of the SM

SM + scalar singlets

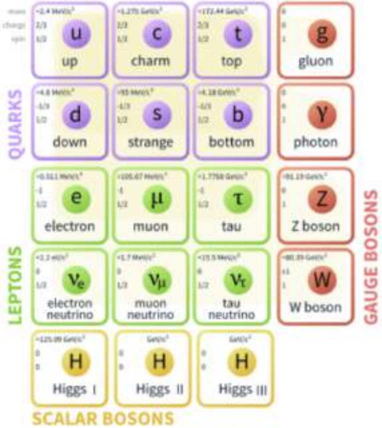
- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet

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

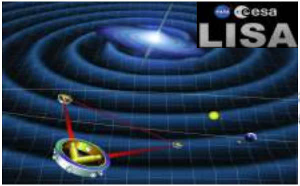
3HDM: SM + 2 doublets

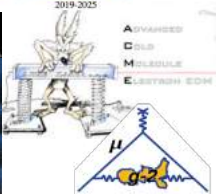
- Dark Matter many exotic possibilities
- CP-violation unbounded dark CP-violation
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation



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





Baryon asymmetry in the universe

Any successful baryogenesis mechanism must satisfy

Sakharov's conditions:

- B-violation
- C & CP violation
- Departure from thermal equilibrium

A well-motivated and **experimentally accessible** baryogenesis mechanism:

Electroweak baryogenesis (EWBG)

Sufficient amount of CP-violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ub} \neq V_{ub}^{*};\ V_{td} \neq V_{td}^{*} \Rightarrow \mathbf{CPV}$$

Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \gg 10^{-20}$ provided by the SM

$\Rightarrow$ New sources of CPV needed.

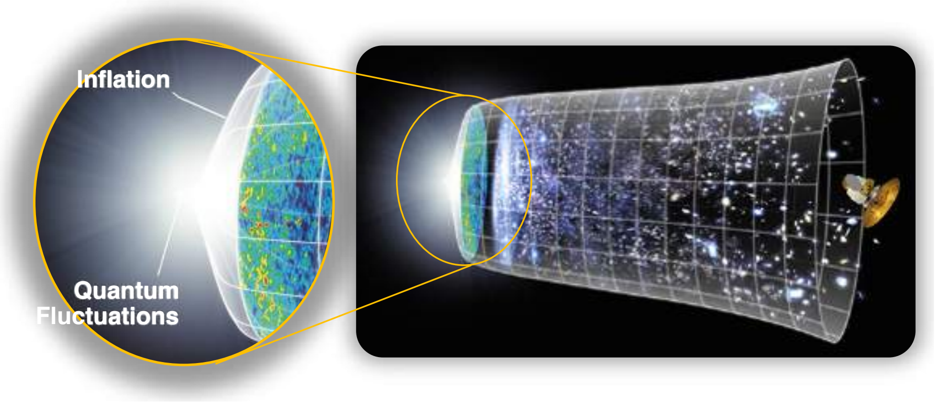
$\Rightarrow$ Scalar sector is the least experimentally constrained sector

&

can accommodate new sources of CPV if extended

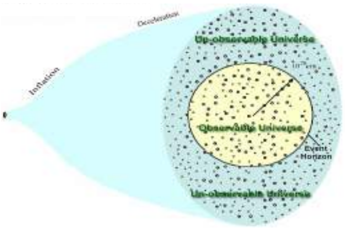
Cosmic inflation

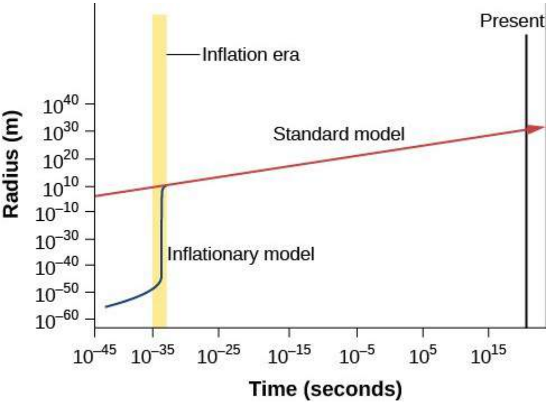
A period of exponential expansion in the early universe



which explains generation of primordial density fluctuations seeding structure formation

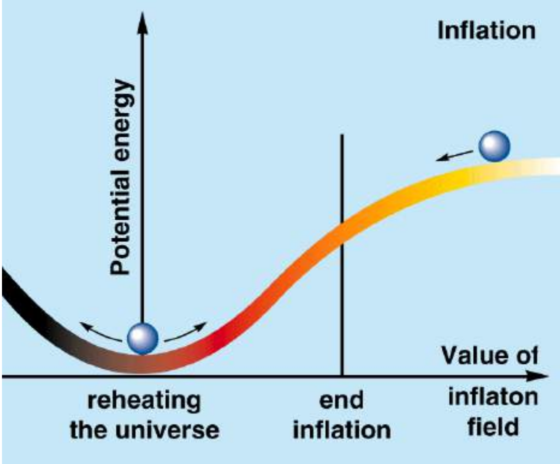
Cosmic inflation





also explains the flatness, homogeneity and isotropy of the universe

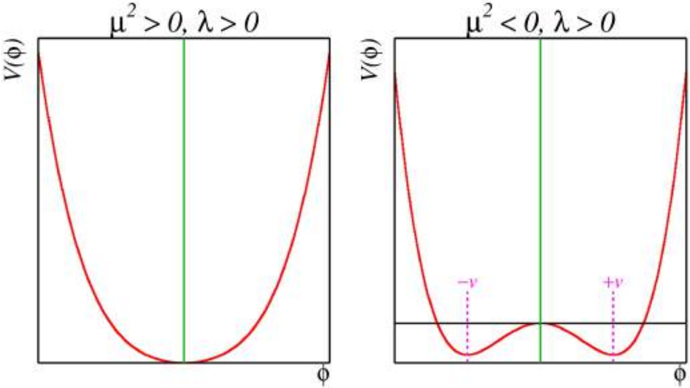
The slow roll inflation



driven by the scalar inflaton field slowly rolling down its smooth potential

The Higgs inflation model

The SM scalar Lagrangian: $\mathcal{L} = D_\mu \phi^\dagger D^\mu \phi - V(\phi)$

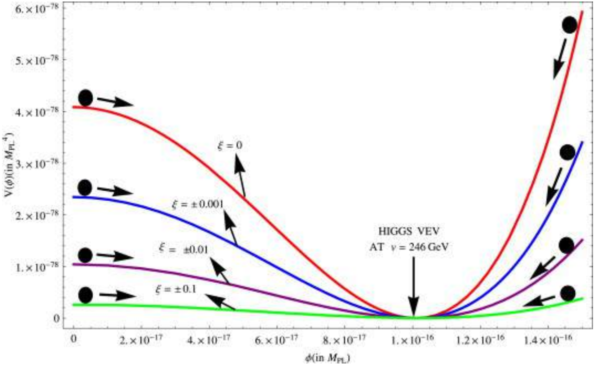


The SM scalar potential: $V(\phi) = \mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2$

The Higgs inflation model

The action S_J and the non-minimal coupling to gravity ξ:

$$S_J = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_{pl}^2 R - D_\mu \phi^\dagger D^\mu \phi - V(\phi) - \xi |\phi|^2 R \right]$$



3-Higgs doublet models (3HDMs)

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

Z_2-symmetric 3HDM

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

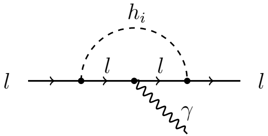
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2 \qquad \text{SM fields} \to \text{SM fields}, \qquad \phi_3 \to \phi_3$$

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)

Z_2-symmetric 3HDM

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:

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

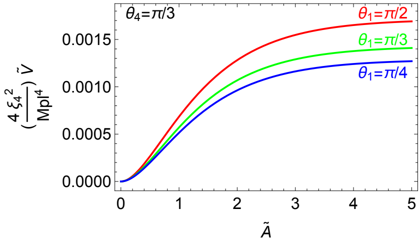
The sources of CP-violation are $\lambda_1 = |\lambda_1|e^{i\theta_1}$ and $\xi_4 = |\xi_4|\, e^{i\theta_4}$.

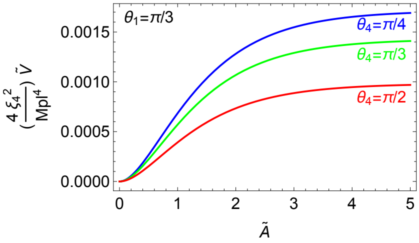
The inflationary potential $\tilde{V}$

To simplify the analysis: $\eta_1 = \beta_1\, h_1$ and $h_2 = \beta_2\, h_1$
(β_1, β_2 can be field dependent)

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

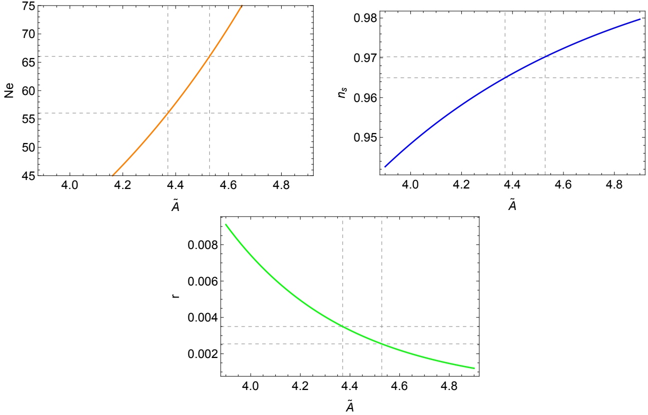
The potential is simplified to: $\tilde{V} = \left(\frac{M_{pl}^2}{2\,|\xi_4|}\right)^2 \left(1 - e^{-\tilde{A}}\right)^2 \underline{X(\theta_1, \theta_4)}$





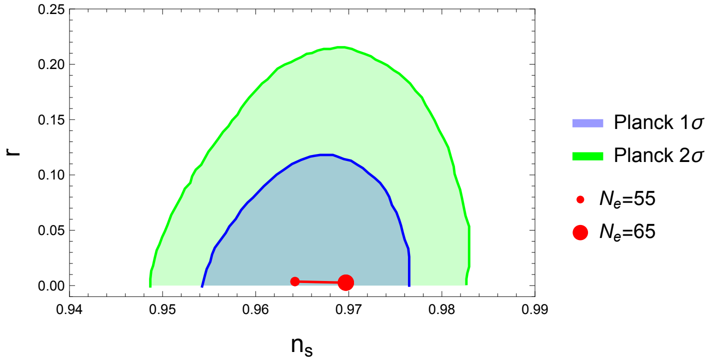
The slow roll parameters

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

The slow roll parameters and the Planck observation

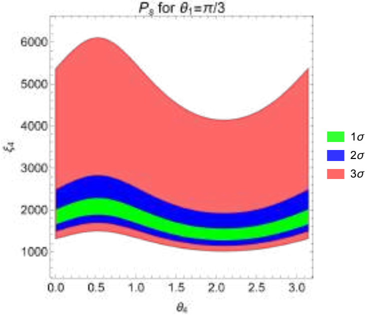


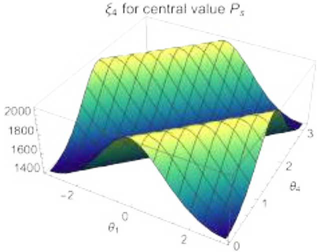
the 1σ and 2σ regions for n_s and r from Planck observation

The scalar power spectrum

Observations from WMAP7 constrain the scalar power spectrum

$$P_s = (2.430 \pm 0.091) \times 10^{-9} = 5.565 \times \frac{X(\theta_1, \theta_4)}{|\xi_4|^2}$$





Fixing P_s to have the central value: $|\xi_4| = 4.785 \times 10^4 \sqrt{X(\theta_1, \theta_4)}$

Reheating and scalar asymmetries

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

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

where the phase α is related to θ_1 and θ_4

Instant reheating: the inflaton quickly decay to ϕ_3

$$\phi_1 \to \phi_3\phi_3 \;\propto\; 2a_1\lambda_3\, e^{i(\alpha+\theta_3)} \quad \text{and} \quad \phi_1^* \to \phi_3^*\phi_3^* \;\propto\; 2a_1\lambda_3\, e^{-i(\alpha+\theta_3)}$$

$$\phi_2 \to \phi_3\phi_3 \;\propto\; 2a_2\lambda_2\, e^{i\theta_2} \quad \text{and} \quad \phi_2^* \to \phi_3^*\phi_3^* \;\propto\; 2a_2\lambda_2\, e^{-i\theta_2}$$

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

$$A^1_{CP} \;\sim\; 8\, a_1^2\, \lambda_3^2\, \sin 2(\alpha+\theta_3)\,, \qquad A^2_{CP} \;\sim\; 8\, a_2^2\, \lambda_2^2\, \sin 2\theta_2$$

This asymmetry is then transferred to the fermion sector through the couplings of the Higgs field with the fermions.

Summary

SM + scalar singlets

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

2HDM: SM + a doublet

- Dark Matter constrained & CPV incompatible
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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

BACKUP SLIDES

Roadmap

Scalar extensions with or without a Z_2 symmetry:

- SM + scalar singlet(s)
  - $\phi_{SM}, S \Rightarrow$ DM, ~~CPV~~
  - $\phi_{SM}, S_1, S_2 \Rightarrow$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - $\phi_1, \phi_2 \Rightarrow$ ~~DM~~, CPV
  - $\phi_1, \phi_2 \Rightarrow$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - $\phi_1, \phi_2, \phi_3 \Rightarrow$ ~~DM~~, CPV
  - $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV
  - $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV

Roadmap

- SM + scalar singlets
  - Dark Matter severely constrained
  - CP-violation not possible
  - Strong first order EWPT constrained & DM incompatible
- 2HDM: SM + a doublet
  - Dark Matter constrained & CPV incompatible
  - CP-violation severely constrained & DM incompatible
  - Strong first order EWPT severely constrained
- 3HDM: SM + 2 doublets
  - Dark Matter many exotic possibilities
  - CP-violation unbounded dark CP-violation
  - Strong first order EWPT easily achieved
  - Inflaton easily achieved + exotic possibilities