CP-violating inflation

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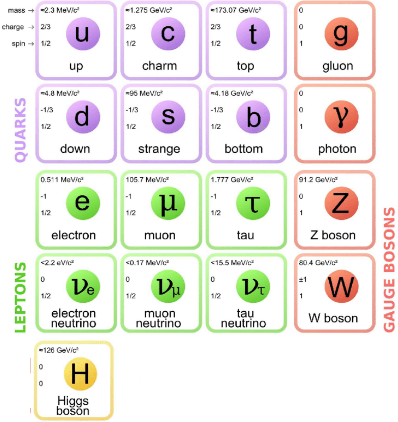
Based on arXiv:2102.07777 and work in progress

HPNP2021 March 25-27

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



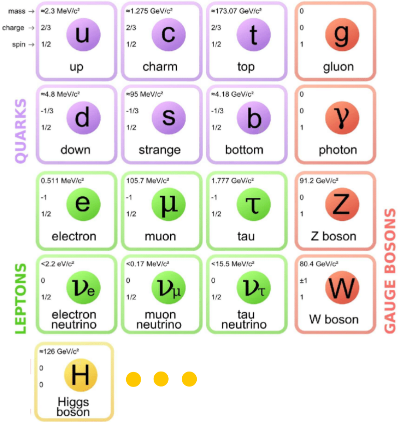
· · · and the need to go beyond

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**



3HDMs: the crown jewel of scalar extensions

SM + scalar singlets

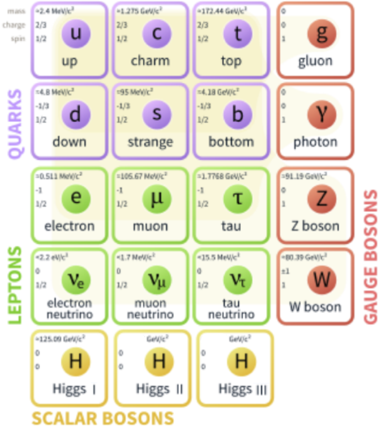
- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet

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

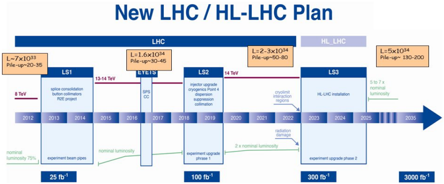
3HDM: SM + 2 doublets

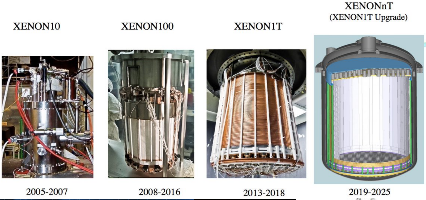
- Dark Matter many exotic possibilities
- CP-violation unbounded dark CPV
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation

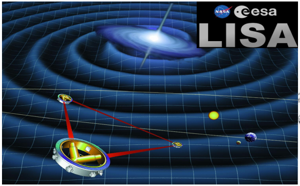


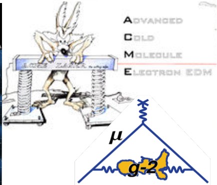
Upcoming experimental probes

- 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

Sakharov's conditions for any successful baryogenesis mechanism:

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

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

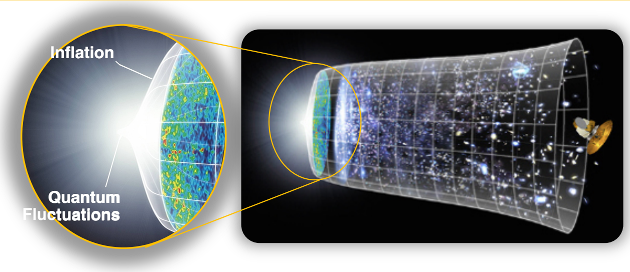
$\Rightarrow$ **New sources of CPV are needed** $\Leftarrow$

The scalar sector (experimentally least constrained sector) - if extended - can accommodate:

- new sources of CP-violation
- a well-motivated & experimentally accessible baryogenesis mechanism:

Electroweak baryogenesis

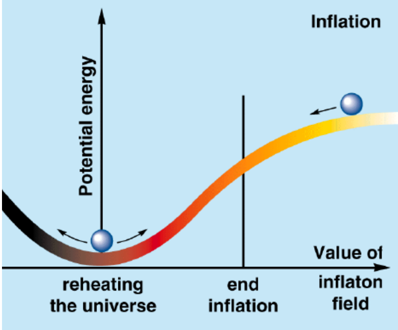
Inflation: an exponential expansion in the early universe



Slow roll inflation:

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

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



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

3HDMs: 3-Higgs doublet models

two scalar doublets + the SM Higgs doublet

$$\phi_1, \phi_2 \qquad\qquad \phi_3$$

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

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 $(-, -, +)$:

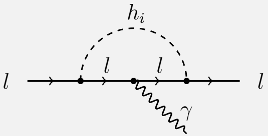
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \qquad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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, [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:

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

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

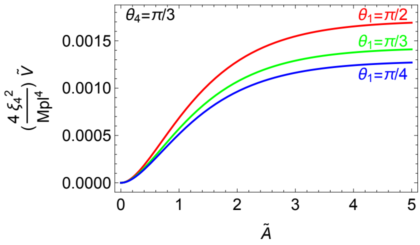
The inflationary potential $\tilde{V}$

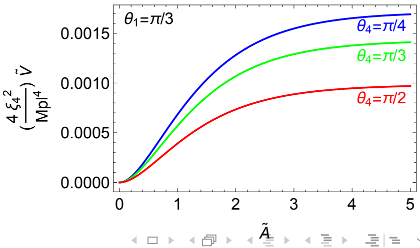
To simplify the analysis: $\eta_1 = \beta_1 h_1$ and $h_2 = \beta_2 h_1$

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

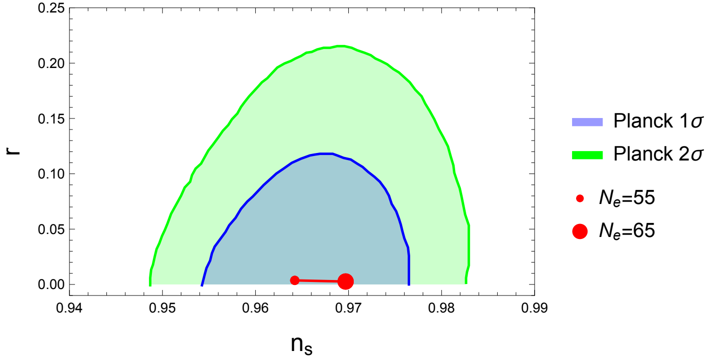
Another standard reparametrisation: $h_1^2 = \frac{M_{pl}^2}{2|\xi_4|\,\beta_2(c_{\theta_4}+\beta_1 s_{\theta_4})}\left(e^{\tilde{A}}-1\right)$

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





Inflationary predictions for the CMB spectrum parameters



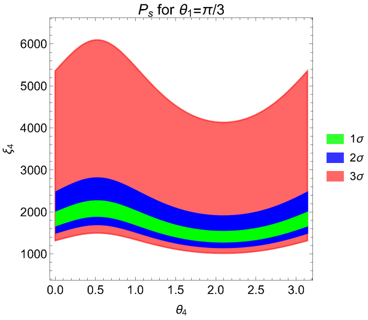
the 1σ and 2σ regions for n_s and r from Planck observation

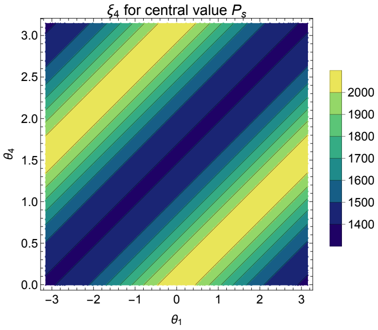
(N_e: number of e-folds, n_s: the spectral index, r: tensor to scalar ratio)

The scalar power spectrum P_s

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: $|\xi_4| \simeq 47000\,\sqrt{\lambda_i}\,\sqrt{X(\theta_1,\theta_4)}$

In Higgs inflation: $\xi \simeq 47000\,\sqrt{\lambda_h}$

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 α is related to θ_1 and θ_4:

$$h_1(\theta_1, \theta_4) \rightsquigarrow a_1 \cos\alpha, \qquad \eta_1(\theta_1, \theta_4) = \beta_1 h_1 \rightsquigarrow a_1 \sin\alpha$$

Instant reheating: the inflaton quickly decay to ϕ_3

$$\begin{cases} \phi_1 \to \phi_3\phi_3 \;\propto\; 2a_1\lambda_3\, e^{i(\alpha+\theta_3)} \\ \phi_1^* \to \phi_3^*\phi_3^* \;\propto\; 2a_1\lambda_3\, e^{-i(\alpha+\theta_3)} \end{cases} \qquad \begin{cases} \phi_2 \to \phi_3\phi_3 \;\propto\; 2a_2\lambda_2\, e^{i\theta_2} \\ \phi_2^* \to \phi_3^*\phi_3^* \;\propto\; 2a_2\lambda_2\, e^{-i\theta_2} \end{cases}$$

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

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

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

Summary

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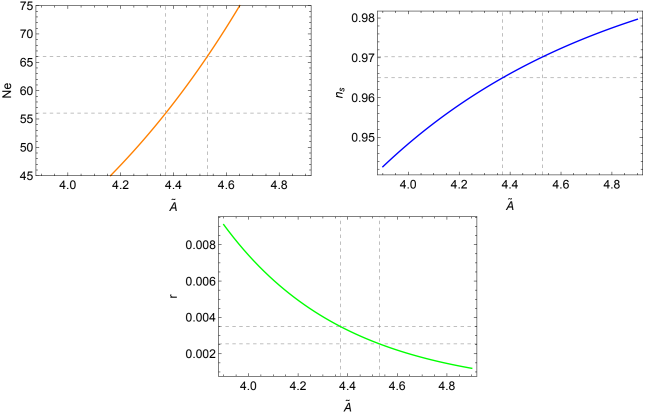
- CP-violation unbounded dark CP-violation
- Inflation CP-violating inflation
- Bonus: fermion mass hierarchy explanation

BACKUP SLIDES

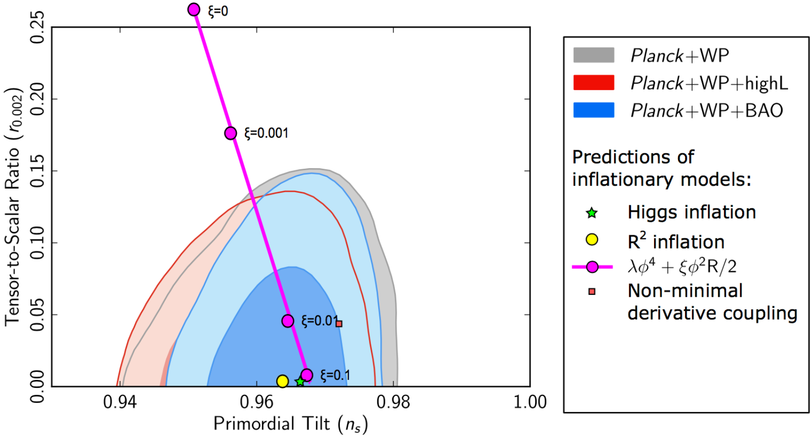
The slow roll parameters

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

Other inflationary models



F. Bezrukov, [Class. Quant. Grav. 30, 214001 (2013)]