CP violating inflation

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IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

Based on Phys. Rev. D 104 (2021) and work in progress
In collaboration with Kimmo Tuominen

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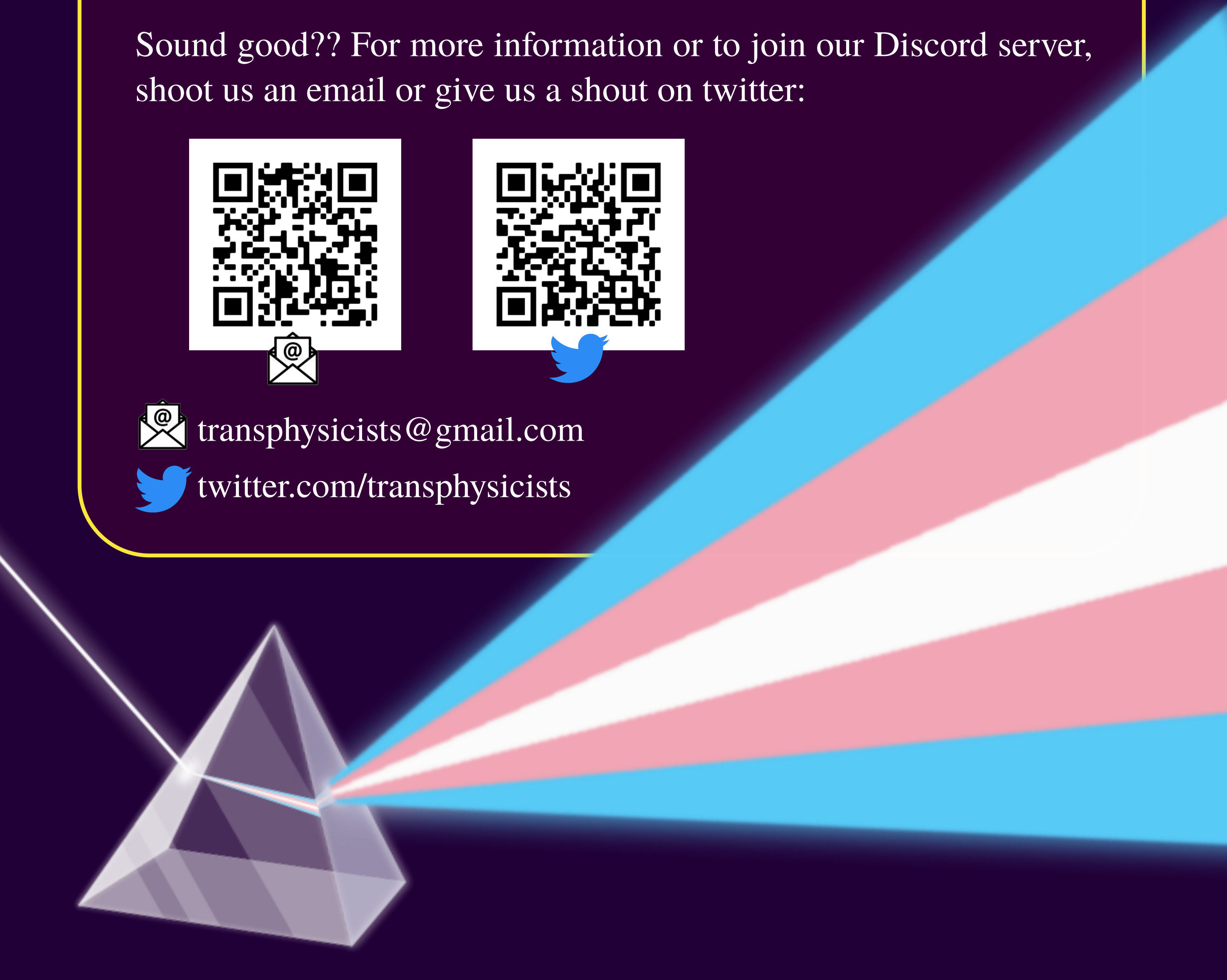
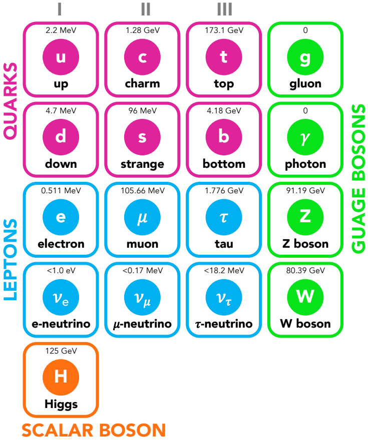


The Standard Model

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 discovered in 2012



VK experiment experiment
~~JFK~~: Ask not what your ~~country~~ can do for you - ask what you can do for your ~~country~~.

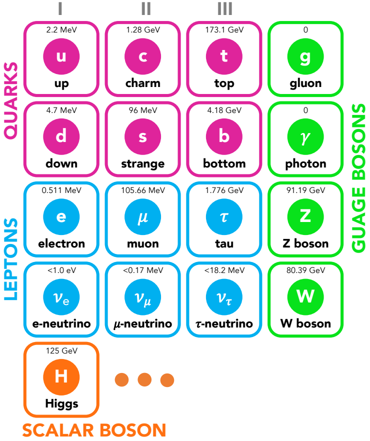
· · · and the need to go beyond

What is missing:

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

⇒ beyond the Standard Model

⇒ **scalar extensions of the SM**



Scalar extensions of the SM

SM + scalar singlets link

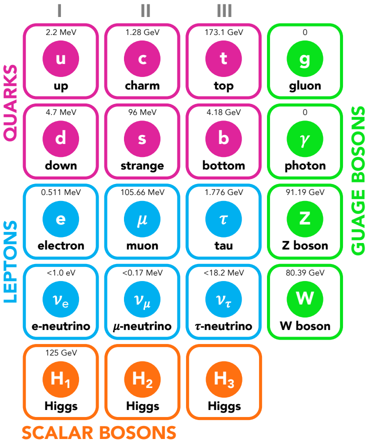
- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

2HDM: SM + a doublet link

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

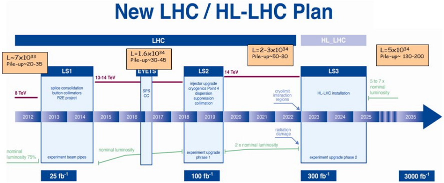
3HDM: SM + 2 doublets link

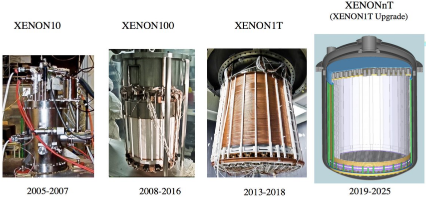
- Dark Matter many exotic possibilities
- CP-violation unbounded dark CP-violation
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation

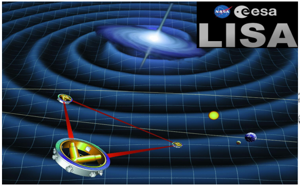


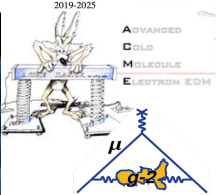
Upcoming experimental probes

- 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





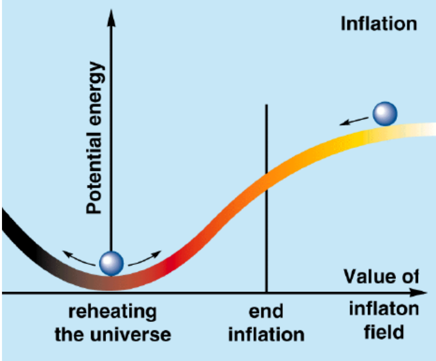




Simplest and best in agreement with observation

Slow roll inflation:

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



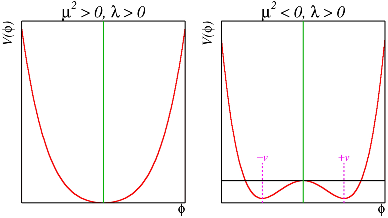
J. Garcia-Bellido, [arXiv:hep-ph/0303153 [hep-ph]]

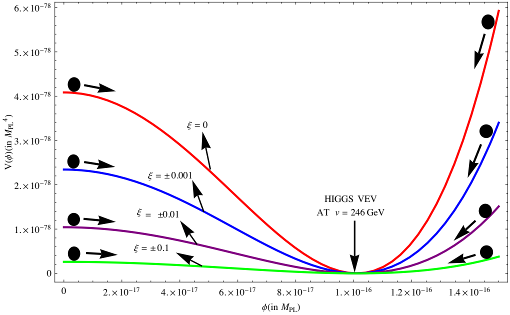
The Higgs inflation model

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:

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





S. Choudhury, T. Chakraborty, S. Pal, [Nucl. Phys. B 880, 155-174 (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 $(-,-,+)$:

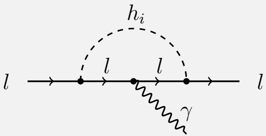
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \qquad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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: $\phi_u = \phi_d = \phi_e = \phi_3$

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



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:

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

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

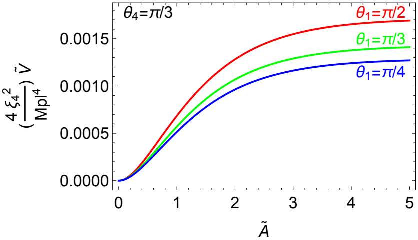
The inflationary potential $\widetilde{V}$

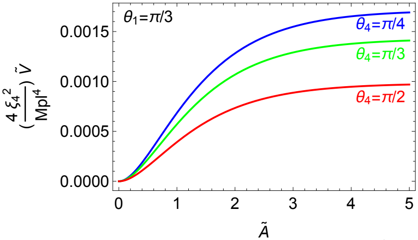
To simplify the analysis: $\eta_1 = \beta_1\, h_1$ and $h_2 = \beta_2\, h_1$

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

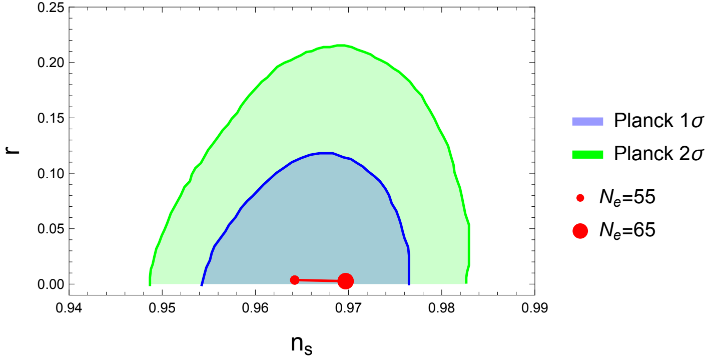
Another standard reparametrisation: $\underset{\substack{\uparrow\\ \text{inflaton field}}}{h_1^2} = \dfrac{M_{pl}^2}{2\,|\xi_4|\,\beta_2(c_{\theta_4}+\beta_1\, s_{\theta_4})}\left(e^{\tilde{A}}-1\right)$, with $\underset{\substack{\uparrow\\ \text{reparametrised inflaton field}}}{\tilde{A}}$

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





1σ and 2σ regions from Planck observation



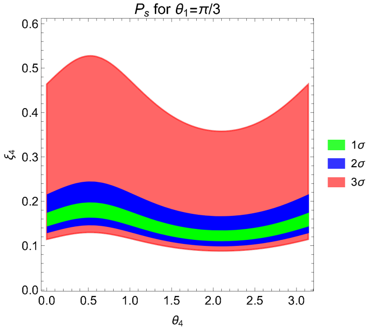
the

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

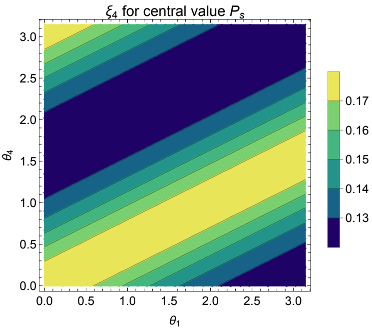
calculated from the slow-roll parameters $\epsilon = \frac{1}{2} M_{pl}^2 \left(\frac{1}{\tilde{V}} \frac{d\tilde{V}}{d\tilde{A}} \right)^2$ and $\eta = M_{pl}^2 \frac{1}{\tilde{V}} \frac{d^2\tilde{V}}{d\tilde{A}^2}$

WMAP7 constraints on the scalar power spectrum P_s

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



P_s for θ_1=π/3



ξ_4 for central value P_s

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

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

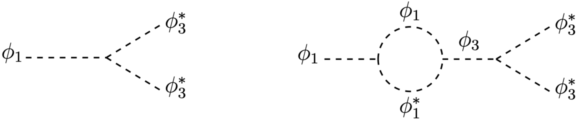
Reheating and scalar asymmetries

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



Interference between tree & loop diagrams ⇒ unequal ϕ_3 & ϕ_3^* numbers

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

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

SM-Higgs

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 $\xi_4 = |\xi_4|\, e^{i\theta_4}$

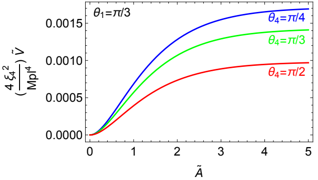
The action:

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

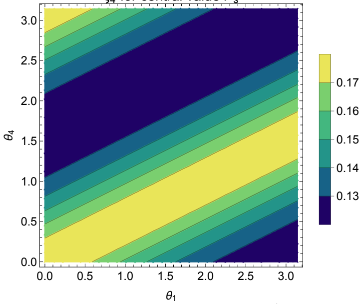
CP-violation inflation $\xrightarrow{?}$ Baryogenesis

The inflationary potential:

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



ξ_4 for central value P_s



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 DM incompatible

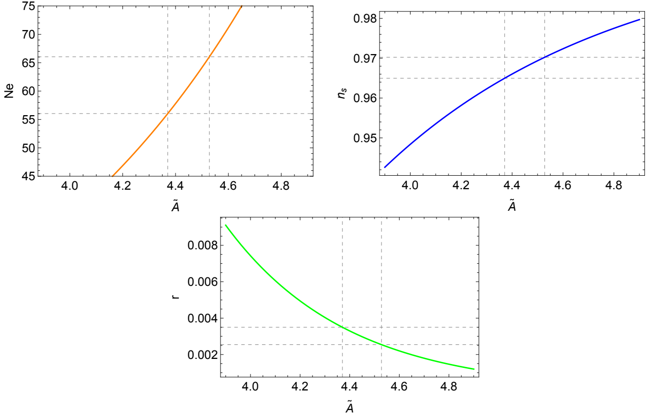
3HDM: SM + 2 doublets

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

BACKUP SLIDES

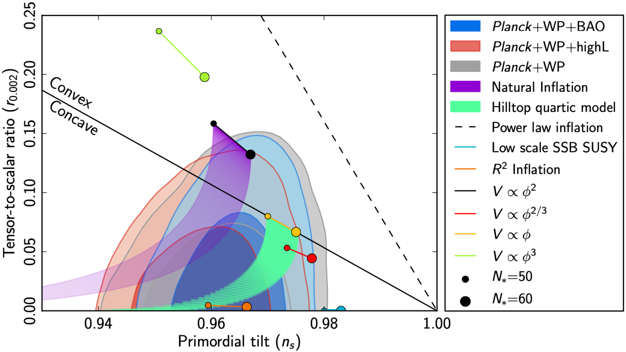
The slow roll parameters

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

Planck constraints on different inflationary models

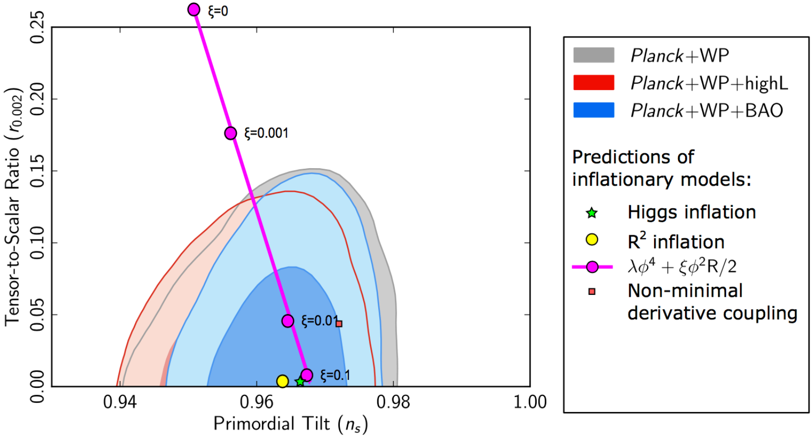


Tensor to scalar ratio $r = 16\epsilon$ and the **spectral index** $n_s = 1 - 6\epsilon + 2\eta$

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 $\eta = M_{pl}^2 \frac{1}{\tilde{V}} \frac{d^2\tilde{V}}{d\phi^2}$

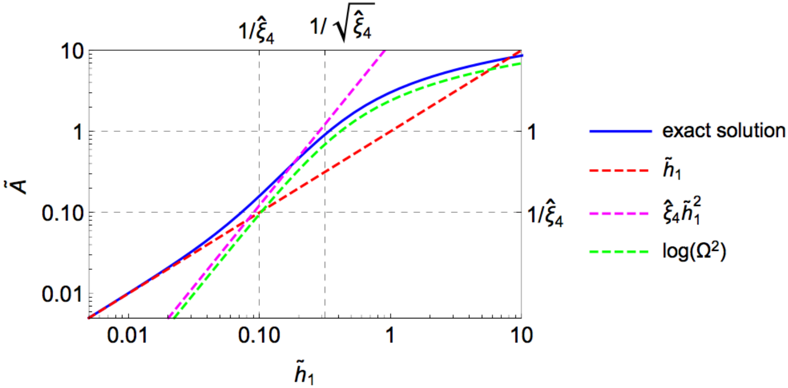
P. A. R. Ade *et al.* [Planck], [Astron. Astrophys. 571, A22 (2014)]

Other inflationary models



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

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
$\tilde{h}_1$
$\hat{\xi}_4\tilde{h}_1^2$
$\log(\Omega^2)$

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

Baryon asymmetry in the universe

Sakharov's conditions for a successful baryogenesis mechanism:

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

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

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

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

$\Rightarrow$ New sources of CPV needed.

Dark Matter

We know it exists because of:

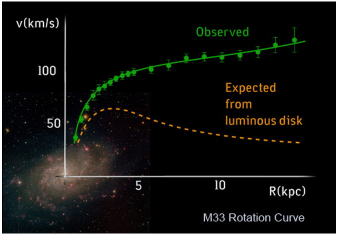
- galactic rotation curves
- the CMB pattern
- ...

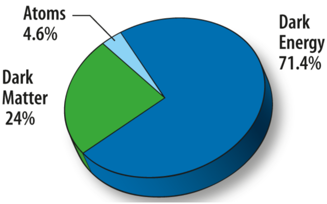
None of the SM particles are suitable DM candidates.

$\Rightarrow$ Beyond the SM

Weakly Interacting Massive Particles (WIMPs)

$$\underbrace{\text{DM DM} \rightarrow \text{SM SM},}_{\text{pair annihilation}} \quad \underbrace{\text{DM} \not\rightarrow \text{SM}, \dots}_{\text{stable}}$$





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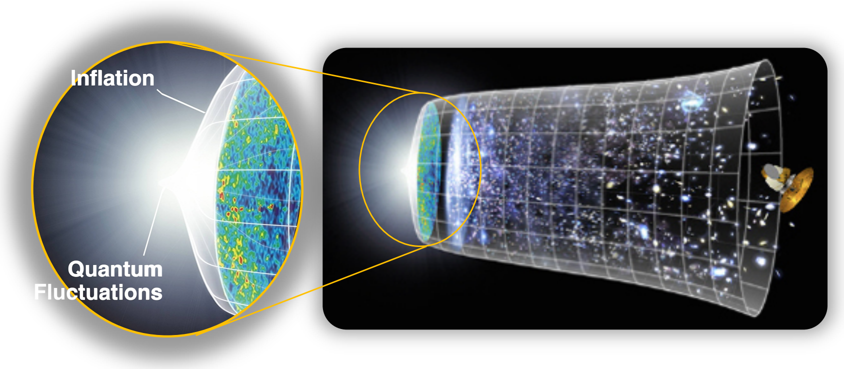
Inflation: an exponential expansion in the early universe



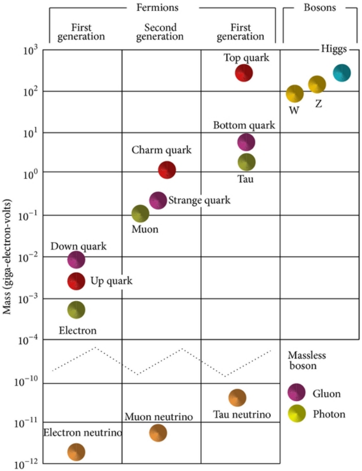
Explains: generation of primordial density fluctuations seeding structure formation, the flatness, homogeneity and isotropy of the universe

back

Fermion mass hierarchy in the SM

No explanation for

- $m_t/m_e \approx 10^6$
- $m_t/m_\nu \approx 10^{11}$



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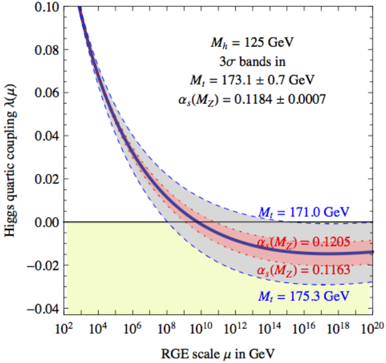
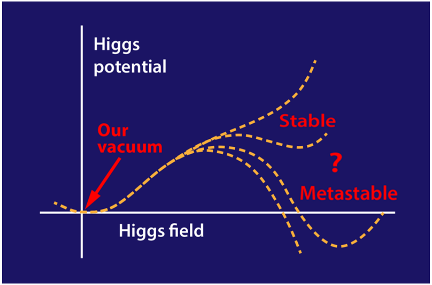
The SM electroweak vacuum is not stable





$$V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

⇒ Scalar extensions can stabilise the EW vacuum.

back

D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio, A. Strumia [JHEP 1312, 089 (2013)]

Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

$$\phi = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad S = \left(\frac{s}{\sqrt{2}} \right)$$

$$\underbrace{S\, S \to \mathrm{SM\ SM},}_{\text{pair annihilation}} \qquad \underbrace{S \not\to \mathrm{SM\ SM}}_{\text{stable}}$$

back

SM + scalar singlet DM ✓, CPV ×

DM protected by a Z_2 symmetry $(+, -)$ from decaying to SM particles.

$$\text{SM fields} \to \text{SM fields}, \quad \phi \to \phi, \quad S \to -S$$

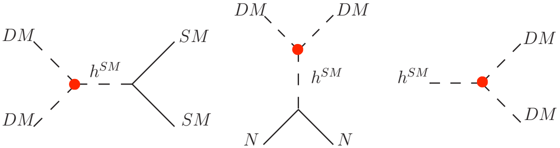
The Lagrangian and the vacuum are Z_2 symmetric: $\langle \phi \rangle = v$, $\langle S \rangle = 0$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - m_s^2 S^2 - \lambda_s S^4 - \lambda_{hs}\phi^2 S^2$$

Relic density
Indirect detection

Direct detection

Collider
experiments



Tension: all relevant interactions are governed by the same coupling!

back

2-Higgs doublet models (2HDMs)

the SM Higgs doublet + a scalar doublet

ϕ_1 ϕ_2

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

back

Z_2-symmetric 2HDM DM ✓, CPV ×

DM is protected by a Z_2 symmetry $(+,-)$ from decaying to SM particles:

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

Z_2 symmetry: only ϕ_1 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_1$

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

Z_2 symmetry respected by the vacuum: $\phi_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$

DM candidate: the lightest neutral particle from the dark doublet

$$HH \to h \to \text{SM}, \quad HA \to Z \to \text{SM}, \quad HH^\pm \to W^\pm \to \text{SM}$$

Tension: all scalar interactions are governed by the same coupling!
Gauge couplings are fixed!

back

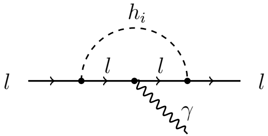
CP-violating 2HDM DM ×, CPV ✓

Break the Z_2 symmetry and let the two doublets mix

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix}$$

No Dark Matter candidate!

Mixing doublets means h_i (mixtures of $h^0_{1,2}$, $a^0_{1,2}$) are CP-mixed states



contributing to electric dipole moments (EDMs).

CP-violation is very constrained!

back

V. Keus, S. F. King, S. Moretti, K. Yagyu, [JHEP 04, 048 (2016)] V. Keus, N. Koivunen, K. Tuominen, [JHEP 09, 059 (2018)]

3-Higgs doublet models (3HDMs)

two scalar doublets + the SM Higgs doublet

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

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix}$$

back

Z_2-symmetric 3HDM with dark CPV DM ✓, CPV ✓

DM is protected by a Z_2 symmetry $(-,-,+)$:

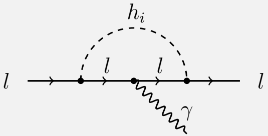
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

Z_2 symmetry respected by the vacuum $(0,0,v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

Only ϕ_3 can couple to fermions $\phi_u = \phi_d = \phi_e = \phi_3$ and $h_i = h$

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



No contributions to electric dipole moments (EDMs)

back

V. Keus, [Phys. Rev. D 101, 073007 (2020)]

Z_2-symmetric 3HDM with dark CPV DM ✓, CPV ✓

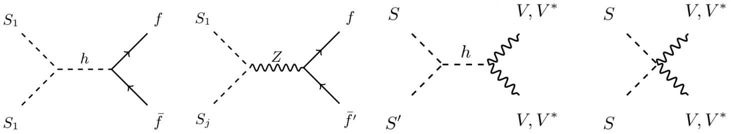
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

Z_2 symmetry respected by the vacuum $(0,0,v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

DM candidate: the lightest CP-mixed state $S_{1,2,3,4}$ (mixtures of $H_{1,2}, A_{1,2}$)



Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

back

V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]