RockStar Baryogenesis:

Baryogenesis from primordial CP violation

Venus Keus

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Science Foundation Ireland — For what's next

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

Based on JHEP 07 (2025) 156 and ongoing work with Rocky Kolb

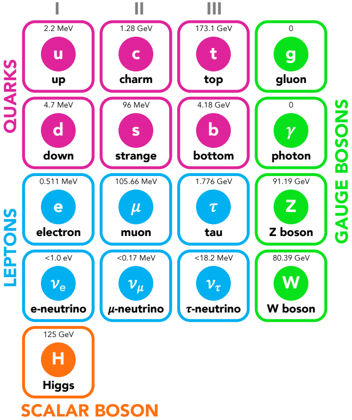
In solidarity with the people of Gaza, recognising our responsibility, as members of a global community, to stand against injustice and dehumanisation of others.

September 25, 2025

The Standard Model (SM) of particle physics

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

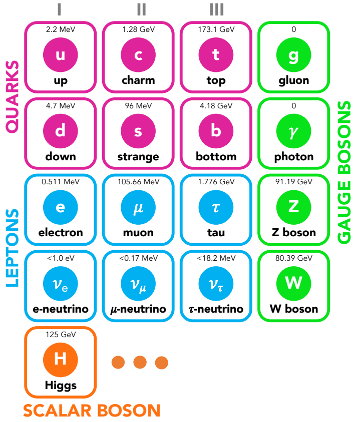
SM and the need to go beyond

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

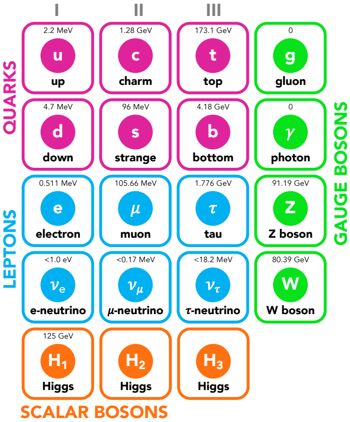
- Dark Matter severely constrained
- CP violation not possible

2HDM: SM + a doublet link

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

3HDM: SM + 2 doublets link

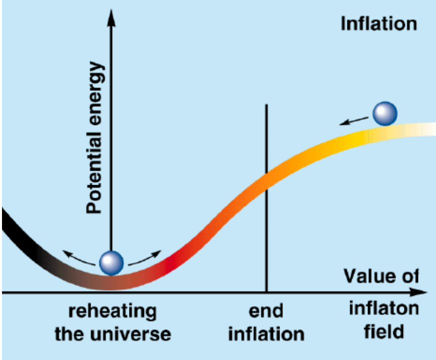
- Dark Matter many exotic possibilities
- CP violation unbounded dark CP violation
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation
- Bonus: EW vacuum stability



Simplest and best in agreement with observation

Slow roll inflation:

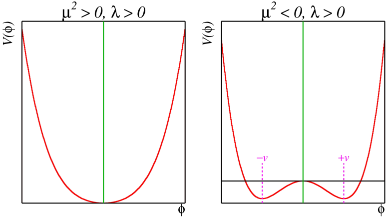
driven by a scalar field (inflaton) slowly rolling down its smooth potential



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

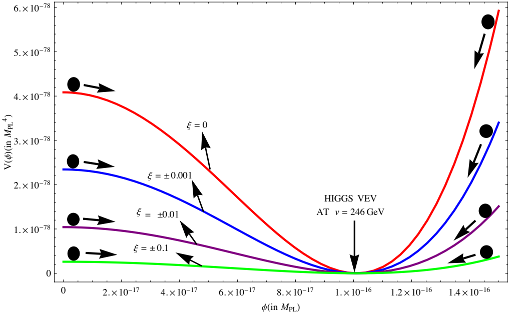
The Higgs inflation model

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:

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



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

3HDMs: 3-Higgs doublet models (*non c'è due senza tre*)

two scalar doublets + the SM Higgs doublet

$$\phi_1, \phi_2 \qquad\qquad \phi_3 \equiv \phi_{\rm SM}$$

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

Ivanov, VK, Vdovin, [J. Phys. A 45, 215201 (2012)], Ivanov, Vdovin, [Phys. Rev. D 86, 095030 (2012)]

Z_2-symmetric 3HDM with dark CPV

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

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

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

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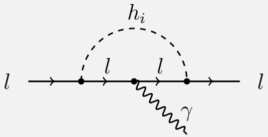
Only ϕ_{SM} can couple to fermions: $\phi_u = \phi_d = \phi_e = \phi_{\text{SM}}$

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



No contributions to electric dipole moments (EDMs)

VK, King, Moretti, Sokolowska, 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),

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

which is CP violating (complex parameters).

Z_2-symmetric 3HDM with dark CPV

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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 $V \equiv \widetilde{V}$

Fields affecting inflation: $\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h_1 + i\eta_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h_2 + i\eta_2 \end{pmatrix}$

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Some algebraic gymnastics

$\downarrow$

Potential in the Jordan frame: $V(h_1, \eta_1, h_2) \to V(h_1) = \frac{1}{4}\widetilde{\lambda}\, h_1{}^4$

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Some algebraic gymnastics

↓

Potential in the Jordan frame: $V(h_1, \eta_1, h_2) \to V(h_1) = \frac{1}{4}\widetilde{\lambda}\, {h_1}^4$

Conformal transformation: $h_1 \to \widetilde{A} = \sqrt{6}\ \ln\sqrt{1 + \widetilde{r}\ \widetilde{h}_1^2/M_{\rm Pl}^2}$

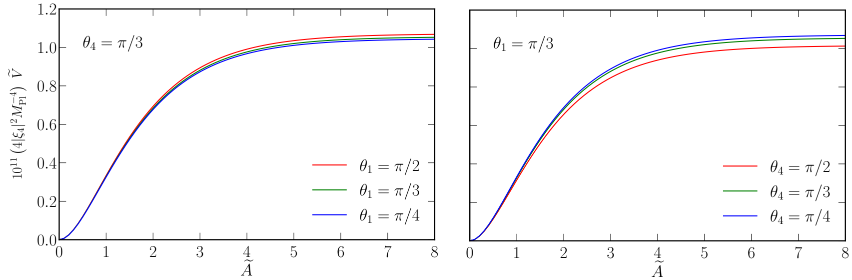
↓

Potential in the Einstein frame: $\widetilde{V}(\widetilde{A}) = \frac{\widetilde{\lambda}}{4}\frac{M_{\rm Pl}^4}{\widetilde{\xi}^2}\left(1 - e^{-2\widetilde{A}/\sqrt{6}}\right)^2$

details

The slow-roll parameters

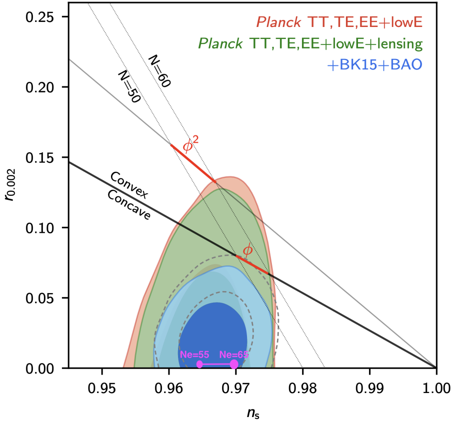
The inflationary potential:



The slow-roll parameters: $\epsilon = \frac{1}{2} M_{\rm Pl}^2 \left(\frac{1}{\widetilde{V}} \frac{d\widetilde{V}}{d\widetilde{A}} \right)^2$ and $\eta = M_{\rm Pl}^2 \frac{1}{\widetilde{V}} \frac{d^2\widetilde{V}}{d\widetilde{A}^2}$

The spectral index: $A_s = \frac{1}{24\pi^2} \frac{1}{\epsilon_V} \frac{\widetilde{V}}{M_{\rm Pl}^4}$

Planck constraints in the n_s-r plane

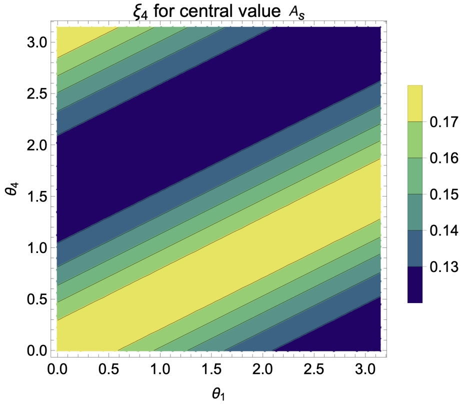


Tensor to scalar ratio $r = 16\epsilon$ and the **spectral index** $n_s = 1 - 6\epsilon + 2\eta$

Aghanim *et al.* [Planck], [Astron. Astrophys. **641**, A6 (2020)]

Planck constraints on the scalar power spectrum A_s

$$A_s = (3.044 \pm 0.014) \times 10^{-9}$$

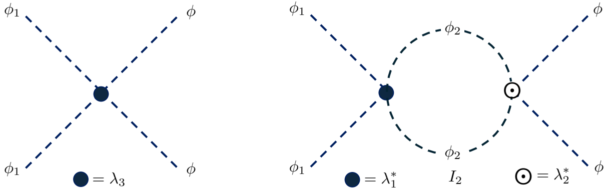


In Higgs inflation: $|\xi| \simeq 4.785 \times 10^4 \sqrt{\lambda_h} \quad \Rightarrow \quad |\xi| \sim 10^4$

In RockStar inflation: $|\xi_4| \simeq 4.785 \times 10^4 \sqrt{\widetilde{\lambda}} \quad \Rightarrow \quad |\xi_4| \sim \mathcal{O}(1)$

Reheating and scalar asymmetries

Instant reheating: the inflaton quickly decays to ϕ



$$\mathcal{M}^{\rm tree}_{\phi_1\phi_1\to\phi\phi} \propto \lambda_3 \quad \text{and} \quad \mathcal{M}^{\rm tree}_{\phi_1^*\phi_1^*\to\phi^*\phi^*} \propto \lambda_3^*$$

$$\mathcal{M}^{\rm loop}_{\phi_1\phi_1\to\phi\phi} \propto \lambda_1^* \, I_2 \, \lambda_2^* \quad \text{and} \quad \mathcal{M}^{\rm loop}_{\phi_1^*\phi_1^*\to\phi^*\phi^*} \propto \lambda_1 \, I_2 \, \lambda_2$$

Interference between tree & loop diagrams $\Rightarrow$ unequal ϕ & ϕ^* numbers

$$A^1_{CP} \propto \left|\mathcal{M}^{\rm tree}_{\phi_1\phi_1\to\phi\phi} + \mathcal{M}^{\rm loop}_{\phi_1\phi_1\to\phi\phi}\right|^2 - \left|\mathcal{M}^{\rm tree}_{\phi_1^*\phi_1^*\to\phi^*\phi^*} + \mathcal{M}^{\rm loop}_{\phi_1^*\phi_1^*\to\phi^*\phi^*}\right|^2$$

$$\propto \mathrm{Im}\left[\lambda_1\lambda_2\lambda_3\right] \mathrm{Im}[I_2] \propto -|\lambda_1|\,|\lambda_2|\,|\lambda_3| \sin(\theta_1+\theta_2+\theta_3)\,\mathrm{Im}[I_2]$$

Chemical potentials

The asymmetry in particle species i:

$$N_i \equiv n_i - n_{\bar{i}} = \frac{g_i T^2}{6} \mu_i \times \begin{cases} 2 & \text{for bosons} \\ 1 & \text{for fermions} \end{cases}$$

At temperatures after reheating - well before the EWSB

Primordial thermal bath:

$$\mu_{W^-} = \mu_W$$
$$\mu_{\phi^-} = \mu_-$$
$$\mu_{\phi^0} = \mu_0$$
$$\mu_{u_L},\ \mu_{d_L}$$
$$\mu_{e_L},\ \mu_{\nu_L}$$
$$\mu_{u_R},\ \mu_{d_R},\ \mu_{e_R}$$

All Yukawa interactions are in equilibrium:

$$\begin{aligned}
W^- \, \phi^+ \phi^0 \quad &\Rightarrow \quad \mu_W - \mu_- - \mu_0 = 0 \\
W^- \, u_L \, \bar{d}_L \quad &\Rightarrow \quad \mu_W + \mu_{u_L} - \mu_{d_L} = 0 \\
W^- \, \nu_L \, \bar{e}_L \quad &\Rightarrow \quad \mu_W + \mu_{\nu_L} - \mu_{e_L} = 0 \\
\bar{Q}_L \cdot \phi \; d_R \quad &\Rightarrow \quad -\mu_{d_L} + \mu_0 + \mu_{d_R} = 0 \\
\epsilon^{ab} \, \bar{Q}_{La} \, \Phi_b^\dagger \; u_R \quad &\Rightarrow \quad -\mu_{u_L} - \mu_0 + \mu_{u_R} = 0 \\
\bar{\ell}_L \cdot \phi \, e_R \quad &\Rightarrow \quad -\mu_{e_L} + \mu_0 + \mu_{e_R} = 0
\end{aligned}$$

Scalar asymmetry yields baryon asymmetry

Above EWSB critical temperature $T > T_C$:

Conservation of 3^{rd} component of weak-isospin $\mathcal{T}^3$: $\mu_W = 0$

Charge density Q conservation: $\mu_{u_L} = -\frac{7}{12}\mu_0$

Sphalerons: $2\mu_{d_L} + \mu_{u_L} + \mu_{\nu_L} = 2\mu_W + 3\mu_{u_L} + \mu_{\nu_L} = 3\mu_{u_L} + \mu_{\nu_L} = 0$

The comoving baryon asymmetry

$$\mathcal{Y}_{\Delta B} = \frac{T^3}{2\,s}\left(4\frac{\mu_{u_L}}{T} + 2\frac{\mu_W}{T}\right) = -\frac{7}{6}\,\frac{T^3}{s}\,\frac{\mu_0}{T}$$

The lepton number comoving asymmetry

$$\mathcal{Y}_{\Delta L} = \frac{T^3}{2\,s}\left(3\frac{\mu_{\nu_L}}{T} + 2\frac{\mu_W}{T} - \frac{\mu_0}{T}\right) = \frac{51}{24}\,\frac{T^3}{s}\,\frac{\mu_0}{T}$$

The asymmetry in ϕ will convert to a baryon and a lepton asymmetry.

details

A 1-slide Summary

Three scalar doublets:

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

Inflaton (ϕ_1, ϕ_2) — SM-Higgs ($\phi_{_{SM}}$)

The potential:

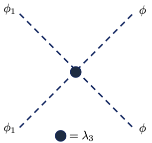
$$V_0 = -\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2 + \lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)$$

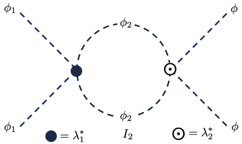
$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_{_{SM}})^2 + \lambda_3(\phi_{_{SM}}^\dagger\phi_1)^2 + h.c.$$

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:

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

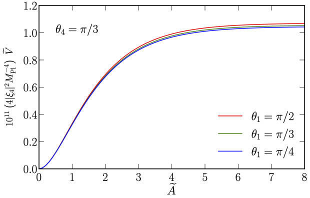


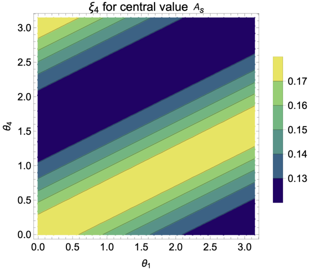


CP-violating inflation → Baryogenesis

The inflationary potential:

$$\widetilde{V}(\widetilde{A}) = \frac{\widetilde{\lambda}}{4}\frac{M_{\rm Pl}^4}{\widetilde{\xi}^2}\left(1 - e^{-2\widetilde{A}/\sqrt{6}}\right)^2$$





Take home message

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- CP violation not possible

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- Dark Matter constrained & CPV incompatible
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- Dark Matter many exotic possibilities
- CP violation unbounded dark CP violation
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation
- Bonus: EW vacuum stability

Backup slides

Backup slides

Image credit: **Andrew Long** (not Daniel Figueroa!)

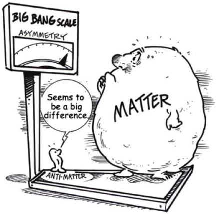
Baryon asymmetry in the universe

Sakharov's conditions for a successful baryogenesis mechanism:

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

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

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



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

$\Rightarrow$ New sources of CPV needed.

back

Dark Matter

We know it exists because of:

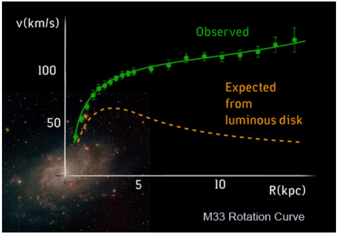
- galactic rotation curves
- the CMB pattern
- ...

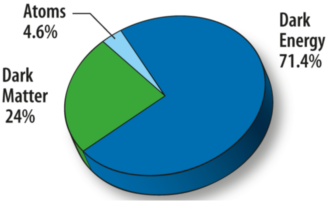
None of the SM particles are suitable DM candidates.

$\Rightarrow$ Beyond the SM

Weakly Interacting Massive Particles (WIMPs)

$$\underbrace{\text{DM DM} \to \text{SM SM}}_{\text{pair annihilation}}, \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$





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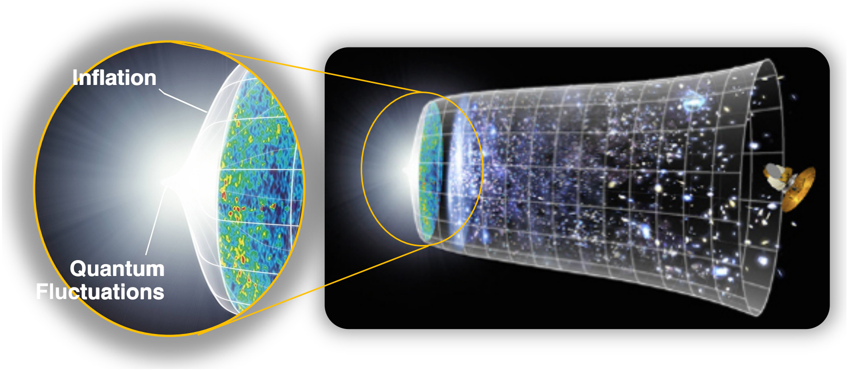
Inflation: an exponential expansion in the early universe



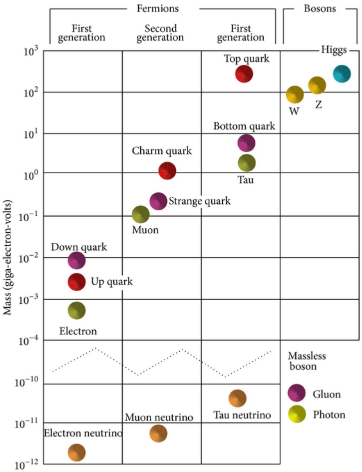
Explains: generation of primordial density fluctuations seeding structure formation, the flatness, homogeneity and isotropy of the universe

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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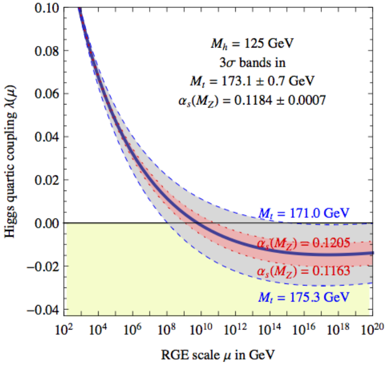
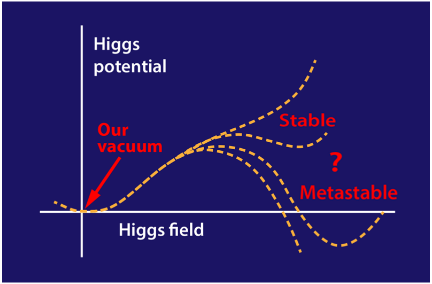
The SM electroweak vacuum is not stable





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

⇒ Scalar extensions can stabilise the EW vacuum.

back

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, 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

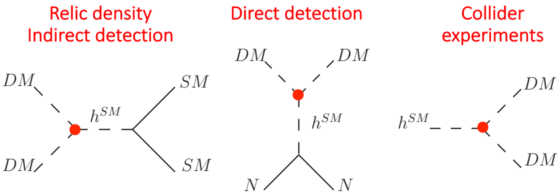
SM + scalar singlet — DM ✓, CPV ×

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: $\langle\phi\rangle = v$, $\langle S \rangle = 0$

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



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

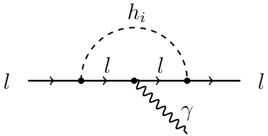
CP-violating 2HDM   DM ×, CPV ✓

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

VK, King, Moretti, Yagyu, [JHEP 04, 048 (2016)] VK, Koivunen, Tuominen, [JHEP 09, 059 (2018)]

3-Higgs doublet models (3HDMs)

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

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

back

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

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

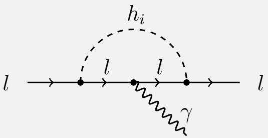
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

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 $h_i = h$

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



No contributions to electric dipole moments (EDMs)

back VK, [Phys. Rev. D 101, 073007 (2020)]

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

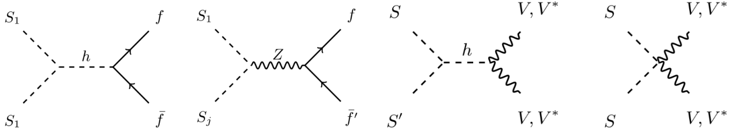
DM is protected by a Z_2 symmetry $(-,-,+)$:

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

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 $H_{1,2}, A_{1,2}$)



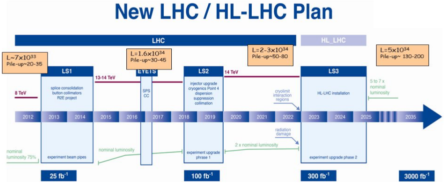
Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

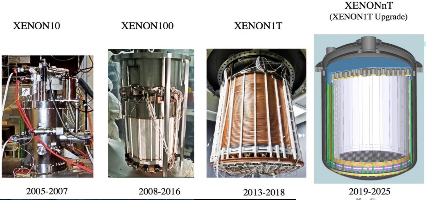
back

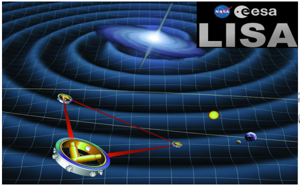
VK, King, Moretti, Sokolowska, et al., [JHEP 12, 014 (2016)]

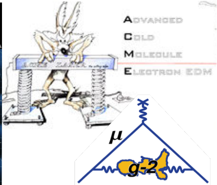
Current & upcoming experimental probes

- 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









The inflationary potential V

Charged fields do not affect the inflationary dynamics

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

The part of the potential relevant for inflation

$$\begin{aligned} V \;=\; & -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) + \lambda_{11}(\phi_1^\dagger\phi_1)^2 + \lambda_{22}(\phi_2^\dagger\phi_2)^2 \\ & +\lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda'_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) - \mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + h.c. \end{aligned}$$

The phase freedom allows: $\eta_2 \to 0$

Consider a proportional solution: $\eta_1 = \beta_1 h_1$ and $h_2 = \beta_2 h_1$
with $\beta_1(\theta_1, \theta_4)$, $\beta_2(\theta_1, \theta_4)$.

In this limit: $V(h_1, \eta_1, h_2) \to V(h_1) = \frac{1}{4} \widetilde{\lambda}\, h_1{}^4$
with $\widetilde{\lambda}(\theta_1, \theta_4, \beta_1, \beta_2)$.

back

The inflationary potential $\widetilde{V}$

The action in the Jordan frame:

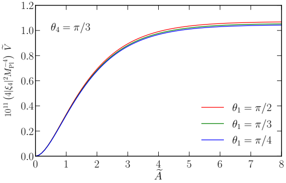
$$S_J = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R\left(1+\widetilde{r}\frac{\widetilde{h}_1^2}{M_{\rm Pl}^2}\right) - \frac{1}{2}g^{\mu\nu}\partial_\mu\widetilde{h}_1\partial_\nu\widetilde{h}_1 - \overbrace{\frac{\widetilde{\lambda}}{4}\frac{\widetilde{h}_1^4}{\widetilde{\zeta}^2}}^{V(h_1)}\right]$$

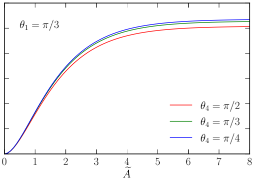
Conformal transformation and a reparametrised inflaton field:

$$\Omega^2 = 1+\widetilde{r}\,\widetilde{h}_1^2/M_{\rm Pl}^2 \quad\rightarrow\quad \widetilde{A} = \sqrt{6}\,\ln\sqrt{1+\widetilde{r}\,\widetilde{h}_1^2/M_{\rm Pl}^2}$$

The action in the Einstein frame:

$$S_E = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}M_{\rm Pl}^2\,\partial_\mu\widetilde{A}\,\partial_\nu\widetilde{A} - \overbrace{\frac{\widetilde{\lambda}}{4}\frac{M_{\rm Pl}^4}{\widetilde{\xi}^2}\left(1-e^{-2\widetilde{A}/\sqrt{6}}\right)^2}^{\widetilde{V}(\widetilde{A})}\right]$$





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Baryon and lepton number asymmetry details

The comoving baryon asymmetry

$$\mathcal{Y}_{\Delta B} \equiv \frac{n_B}{s} = \frac{T^2}{6\,s} N_g \left(N_{u_L} + N_{u_R} + N_{d_L} + N_{d_R}\right) ,$$

$$\mathcal{Y}_{\Delta B} = \frac{T^2}{2\,s} \left(\mu_{u_L} + \mu_{u_R} + \mu_{d_L} + \mu_{d_R}\right) ,$$

$$\mathcal{Y}_{\Delta B} = \frac{T^3}{2\,s} \left(4\frac{\mu_{u_L}}{T} + 2\frac{\mu_W}{T}\right)$$

The lepton number comoving asymmetry

$$\mathcal{Y}_{\Delta L} \equiv \frac{n_L}{s} = \frac{T^2}{6\,s} N_g \left(N_{e_L} + N_{e_R} + N_{\nu_L}\right) ,$$

$$\mathcal{Y}_{\Delta L} = \frac{T^2}{2\,s} \left(\mu_{e_L} + \mu_{e_R} + \mu_{\nu_L}\right) ,$$

$$\mathcal{Y}_{\Delta L} = \frac{T^3}{2\,s} \left(3\frac{\mu_{\nu_L}}{T} + 2\frac{\mu_W}{T} - \frac{\mu_0}{T}\right)$$

back

Baryon and lepton number asymmetry details

Charge density

$$\begin{aligned} Q &= N_g \left(Q_e N_{e_R} + Q_e N_{e_L} + 3Q_u N_{u_L} + 3Q_u N_{u_R} + 3Q_d N_{d_L} + 3Q_d N_{d_R}\right) \\ &\quad + Q_{\phi^-} N_{\phi^-} + Q_{W^-} N_{W^-} \,, \\ Q &\propto -3\mu_{e_R} - 3\mu_{e_L} + 6\mu_{u_L} + 6\mu_{u_R} - 3\mu_{d_L} - 3\mu_{d_R} - 2\mu_- - 4\mu_W \,, \\ &\propto 6\mu_{u_L} - 6\mu_{\nu_L} - 18\mu_W + 14\mu_0 \end{aligned}$$

Density of the third component of isospin

$$\begin{aligned} \mathcal{T}^3 &= N_g \left(\mathcal{T}^3_{e_L} N_{e_L} + \mathcal{T}^3_{\nu_L} N_{\nu_L} + 3\mathcal{T}^3_{u_L} N_{u_L} + 3\mathcal{T}^3_{d_L} N_{d_L}\right) + \mathcal{T}^3_{\phi^0} N_{\phi^0} + \mathcal{T}^3_{\phi^-} N_{\phi^-} + \mathcal{T}^3_{W^-} N_{W^-} \,, \\ \mathcal{T}^3 &\propto -\frac{3}{2}\mu_{e_L} + \frac{3}{2}\mu_{\nu_L} + \frac{9}{2}\mu_{u_L} - \frac{9}{2}\mu_{d_L} - \mu_0 - \mu_- - 4\mu_W \,, \\ &\propto -11\mu_W 0 \end{aligned}$$

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