Can dark matter drive electroweak symmetry breaking?

Catarina M. Cosme

in collaboration with
João G. Rosa and Orfeu Bertolami

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Carleton UNIVERSITY

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

The model - Higgs portal scalar field dark matter

- **Idea**: oscillating scalar field accounting for dark matter, Φ, coupled to the Higgs, $\mathcal{H}$, driving a **non-thermal electroweak symmetry breaking** (EWSB):

$$-\mathcal{L}_{int} = g^2 |\Phi|^2 |\mathcal{H}|^2 + \lambda_\phi |\Phi|^4 + V(\mathcal{H}) - \xi R |\Phi|^2$$

$\boldsymbol{g}$ – Higgs-portal coupling; $\boldsymbol{\lambda_\phi}$ - dark scalar self-coupling, $\boldsymbol{\xi}$ – non-minimal coupling (NMC), $\boldsymbol{R}$ – Ricci Scalar; $\boldsymbol{\Phi} = \frac{\phi}{\sqrt{2}}$; $\boldsymbol{\mathcal{H}} = \frac{h}{\sqrt{2}}$

- Non-standard Cosmology: **late inflaton decay** $\Rightarrow$ **early matter era**.

Inflation

$$-\mathcal{L}_{int} = \frac{g^2}{4}\phi^2 h^2 + \frac{\lambda_\phi}{4}\phi^4 - \frac{\xi}{2} R\phi^2$$

$\text{R} \simeq 12\, H_{inf}^2$

- $\xi \gg g, \lambda_\phi \;\Rightarrow\; \boldsymbol{m_\phi \gtrsim H_{inf}}$ is given by the **NMC** to the curvature scalar $\Rightarrow$ **No** observable **isocurvature modes** in the CMB spectrum ;

- $\boldsymbol{\phi}$ acquires a **vev**, h does not:

$$\phi_{inf} = \sqrt{\frac{12\xi}{\lambda_\phi}}\, H_{inf}, \qquad h_{inf} = 0$$

$H_{inf} \simeq 2.5 \times 10^{13} \left(\frac{r}{0.01}\right)^{\frac{1}{2}} GeV,\; r < 0.10.$ [Planck Collaboration 2018]

$r \equiv \frac{\Delta_t^2}{\Delta_{\mathcal{R}}^2}$ (Tensor-to-scalar ratio)

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- **Higgs** is **massive** during inflation:

$$m_h = \frac{1}{\sqrt{2}} g\phi_{inf} = \frac{g}{\lambda_\phi{}^{1/2}}\sqrt{6\xi}\;\; H_{inf} \gtrsim H_{inf}$$

$H_{inf} \simeq 2.5 \times 10^{13} \left(\frac{r}{0.01}\right)^{\frac{1}{2}} GeV,\; r < 0.10.$ [Planck Collaboration 2018]

where $\frac{g}{\lambda_\phi^{1/2}} \simeq 6 \times 10^2 \left(\frac{T_R}{10\ \mathrm{GeV}}\right)^{-1/3} \left(\frac{r}{0.01}\right)^{-1/6} \xi^{-1/2} \left(\frac{H_{end}/H_{inf}}{0.2}\right)^{2/3};$

Large Higgs mass:

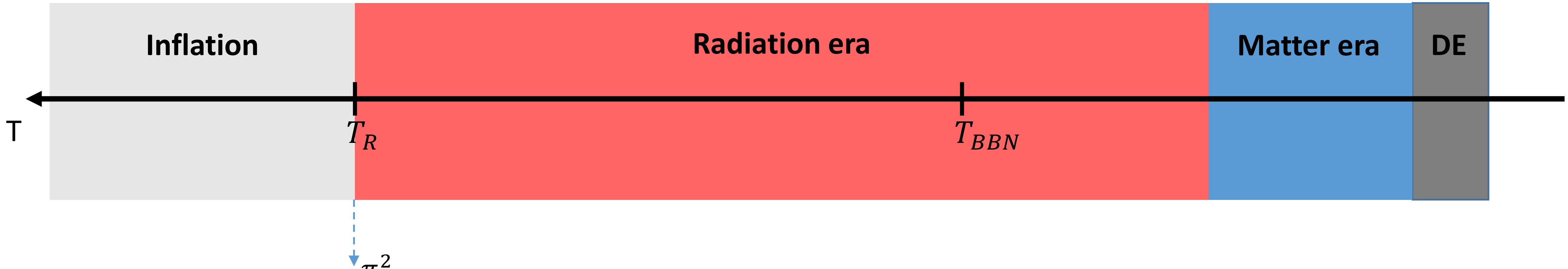
- Shifts value of h at which $\lambda_h < 0$ towards values larger than H_{inf} (above $\mathbf{10^{10} - 10^{12}}$ **GeV**);
- Quantum fluctuations are suppressed;

Post-inflationary period

- The inflaton field, χ, does not decay immediately after inflation $\Rightarrow$ **evolves like non-relativistic matter** until reheating occurs.

Standard Cosmology:

Evolution of the Universe



$$\rho_\chi(a_R) = \frac{\pi^2}{30} g_{*R} T_R^4$$

Post-inflationary period

- The inflaton field, χ, does not decay immediately after inflation ⇒ **evolves like non-relativistic matter** until reheating occurs.

But…

Evolution of the Universe

$$\rho_\chi(a) = 3H_{end}^2\, M_{Pl}^2\, \left(\frac{a}{a_{end}}\right)^{-3}$$

Post-inflationary period

Constraints on the reheating temperature, $\boldsymbol{T_R}$:

$$\mathbf{10\ MeV} < \boldsymbol{T_R} < \mathbf{80\ GeV}$$

Big Bang nucleosynthesis constraint

No Electroweak symmetry restoration

Post-inflationary period – Early matter era

$$-\mathcal{L}_{int} = \frac{g^2}{4}\phi^2 h^2 + \frac{\lambda_\phi}{4}\phi^4 - \frac{\xi}{2}R\phi^2 + \frac{\lambda_h}{4}(h^2 - \mathrm{v}^2)^2$$

$\mathrm{R} \simeq 3H^2$

- Dark scalar **controls** the Higgs minimum:

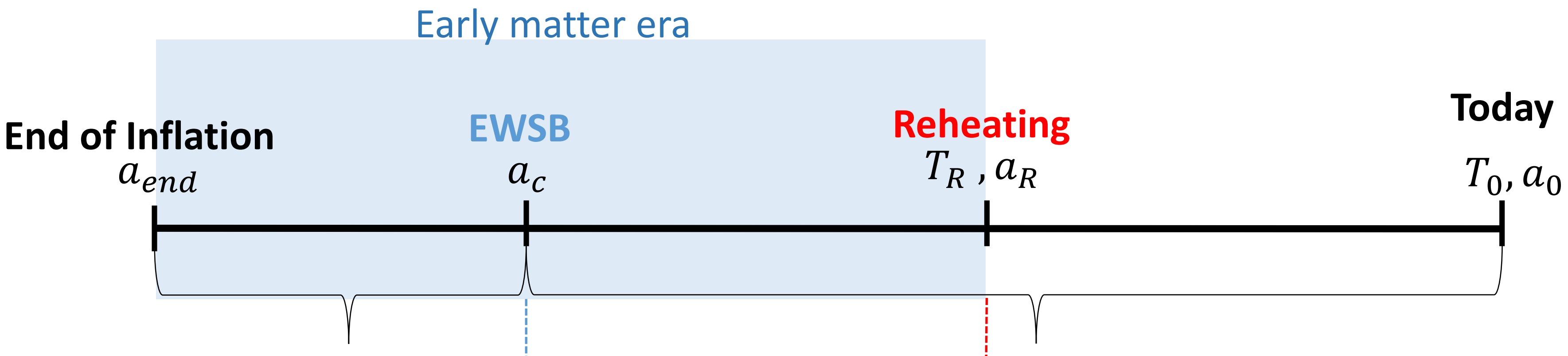
$$|h| = \sqrt{\mathrm{v}^2 - \frac{g^2\phi^2}{2\lambda_h}}$$

- At

$$\boldsymbol{\phi_c = \sqrt{2\lambda_h}\frac{\mathrm{v}}{g}}$$ ⇒ Electroweak symmetry breaking takes place;

- Two scenarios: reheating **after** or **before** electroweak symmetry breaking (EWSB);

Post-inflationary period - Reheating after EWSB



Dark scalar:

Dark Radiation (ϕ^4)

$$\rho_\phi \sim a^{-4}$$

$$\phi_{rad}(a) = \phi_{inf}\left(\frac{a}{a_{end}}\right)^{-1}$$

$$\phi_c = \sqrt{2\lambda_h}\,\frac{\mathrm{v}}{g}$$

Cold Dark Matter (ϕ^2)

$$\rho_\phi \sim a^{-3}$$

$$\phi_{DM}(a) = \phi_c\left(\frac{a}{a_c}\right)^{-3/2}$$

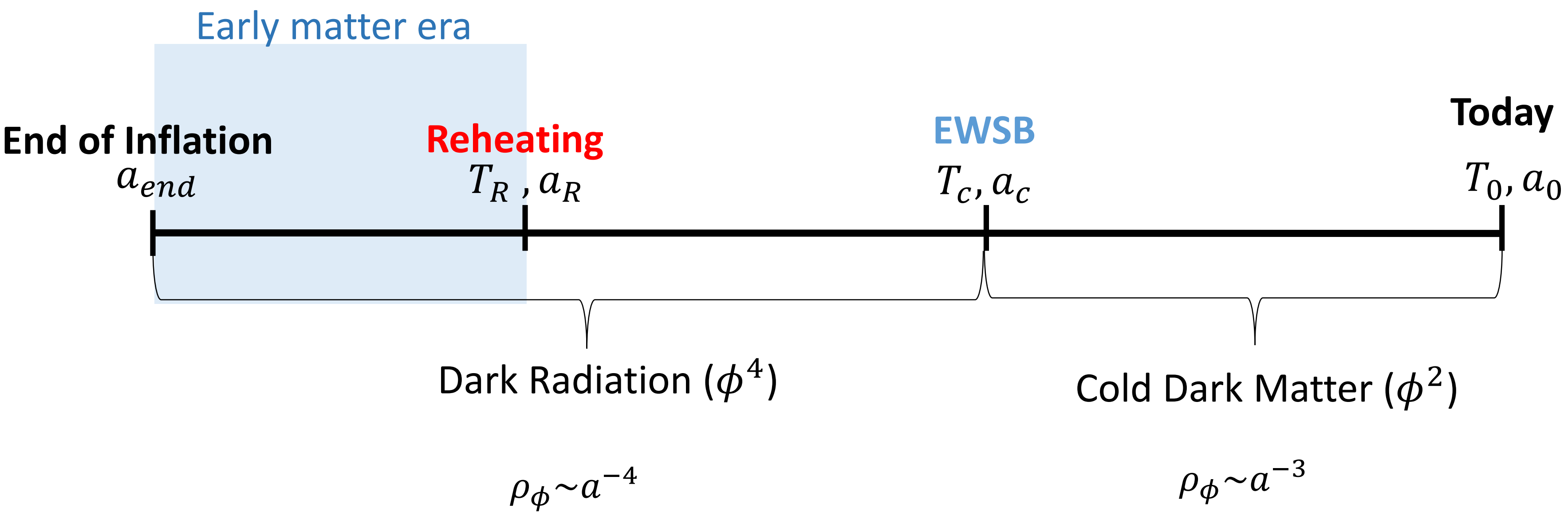
$$\phi_R = \phi_c\left(\frac{a_R}{a_c}\right)^{-3/2}$$

- At **EWSB**, $\frac{n_\phi}{s}$ constant ⇒ $\Omega_{\phi,0} = \frac{m_\phi}{6H_0^2 M_{Pl}^2}\phi_R^2 \frac{g_{*0}}{g_{*R}}\left(\frac{T_0}{T_R}\right)^3$ ⇒ $\frac{g}{\lambda_\phi^{1/2}} \simeq 6\times 10^2 \left(\frac{T_R}{10\ \mathrm{GeV}}\right)^{-1/3}\left(\frac{r}{0.01}\right)^{-1/6}\xi^{-1/2}\left(\frac{H_{end}/H_{inf}}{0.2}\right)^{2/3}$

$\boldsymbol{\Omega_{\phi,0} = 0.26}$

$\boldsymbol{m_\phi = \frac{g\mathrm{v}}{\sqrt{2}}}$

Post-inflationary period - Reheating before EWSB



Dark scalar:

- At **EWSB**, $\frac{n_\phi}{s}$ constant ➡ $\Omega_{\phi,0} = \frac{m_\phi}{6H_0^2 M_{Pl}^2} \phi_c^2 \frac{g_{*0}}{g_{*c}} \left(\frac{T_0}{T_c}\right)^3$ But, fixing $\boldsymbol{\Omega_{\phi,0} = 0.26}$:

$T_c \sim 7 \times 10^5$ GeV $\gg T_{EW}$ ➡ Not consistent with our starting assumption

Assumptions

- Dark scalar is **subdominant** during inflation:

$$V(\phi_{inf}) < 3H_{inf}^2 M_{Pl}^2 \;\Rightarrow\; \phi_{inf} < \frac{M_{Pl}}{\sqrt{\xi}}$$

- Field behaves like **CDM at EWSB**:

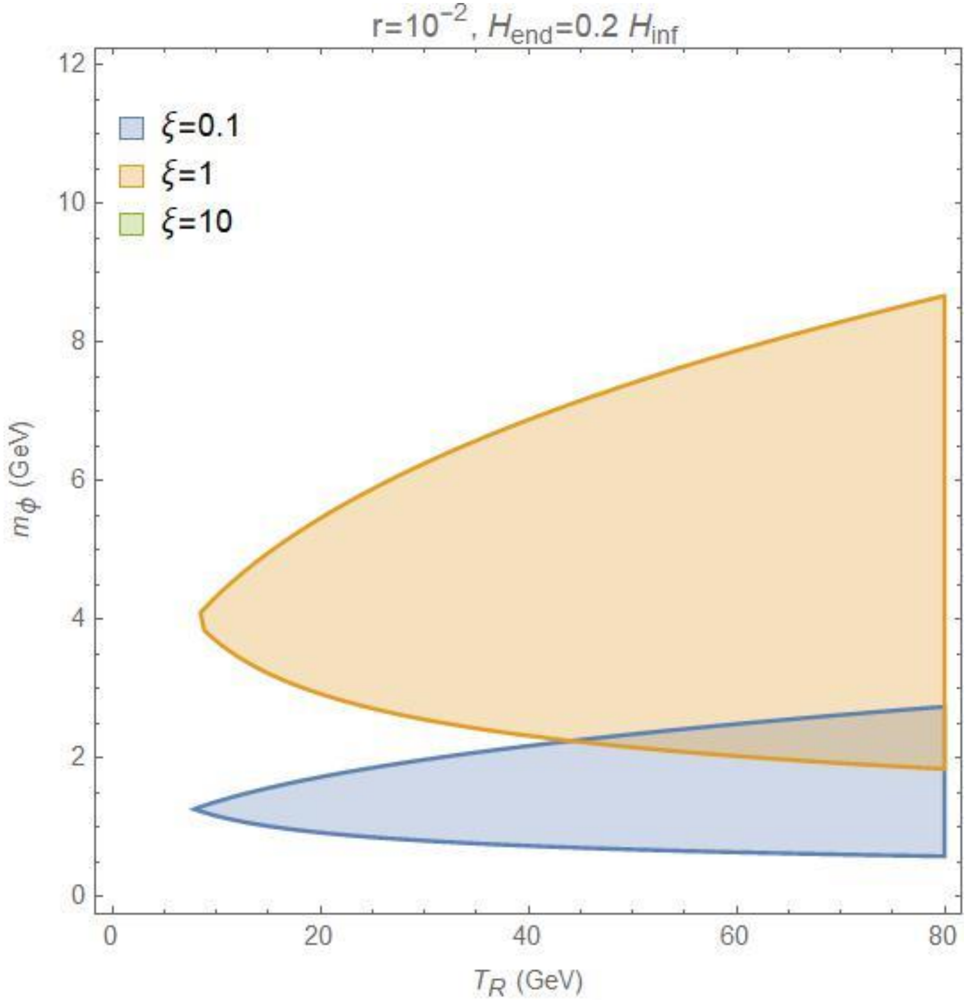
$$\frac{g^2 \mathrm{v}^2 \phi_c^2}{\lambda_\phi \;\phi_c^4} > 1 \Rightarrow g^4 > 2\,\lambda_h \lambda_\phi$$

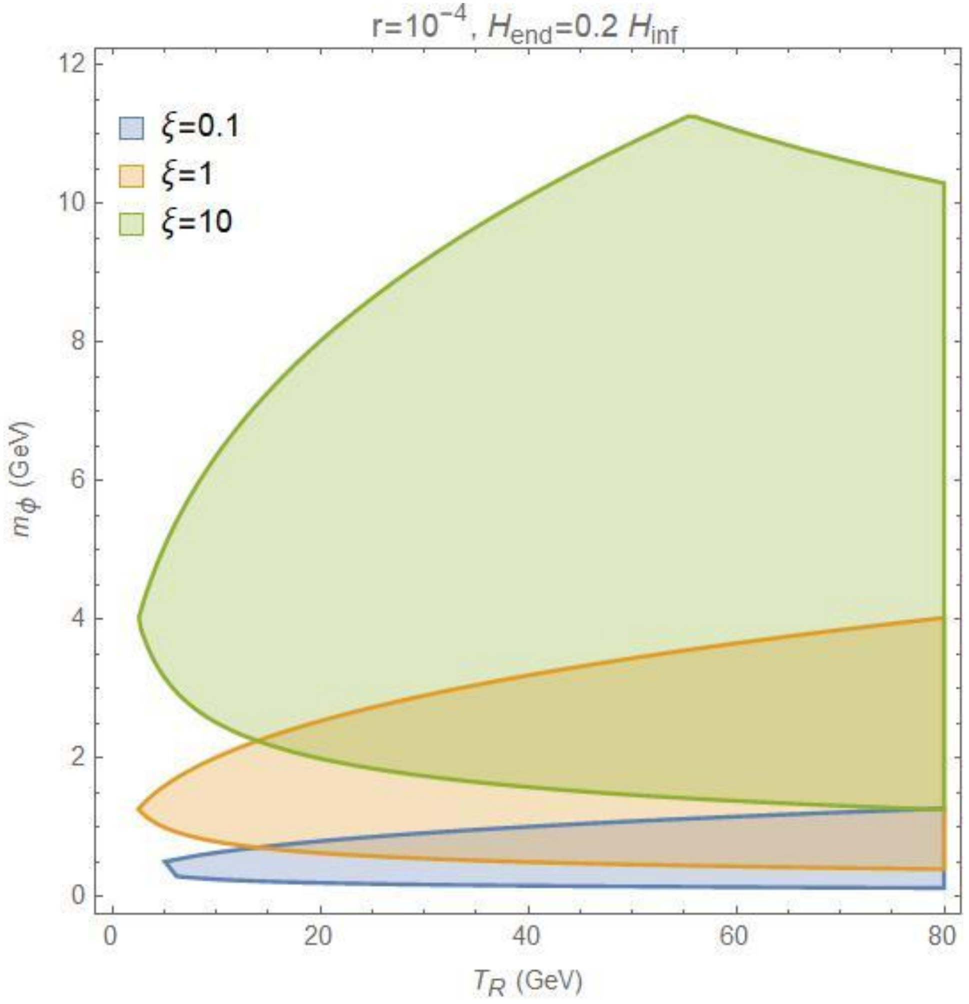
- **Small radiative corrections** from the Higgs-portal coupling (no fine tune): $\delta\lambda_\phi \sim \frac{g^4}{16\,\pi^2} < \lambda_\phi$;

- Upper bound on the **Higgs branching ratio** for invisibles (LHC): $Br(\Gamma_{h\to inv}) < 0.23 \;\Rightarrow\; g < 0.13$;

- Prevent the condensate's evaporation: $g < 0.2\,\left(\frac{T_R}{10\ \mathrm{GeV}}\right)^{-1/4}\left(\frac{r}{0.01}\right)^{-1/4}\,\xi^{-3/4}\left(\frac{H_{end}/H_{inf}}{0.2}\right)$.

Results





$$10\ \text{MeV} < T_R < 80\ \text{GeV}$$

Conclusions

- Yes, it can! - an **oscillating scalar field dark matter coupled to the Higgs** may **drive EWSB**;
- This can be **achieved** with a **late inflaton decay**;
- During the early-matter era, the **minimum of the Higgs potential is controlled** by the **dark scalar**;
- **EWSB** occurs when the **amplitude** of the dark scalar **falls below a critical value**;
- Larger Higgs-portal couplings – allows for Higgs invisible branching ratios $\lesssim 10^{-3}$ (current value: $Br(\Gamma_{h\rightarrow inv}) < 0.23$).

Thank you for your attention!

Backup slides

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- Dark scalar **can control EWSB** if the reheating temperature, $\boldsymbol{T_R}$, is lower than usual $\Rightarrow$ **late inflaton decay** $\Rightarrow$ **early matter era**.

- At **reheating**: inflaton **decays** into Standard Model particles $\Rightarrow$ Reheats the Universe and forms a thermal bath $\Rightarrow$ Universe enters the usual **radiation** era;

Higgs vacuum stability

- Higgs **vacuum** is **stable** if $\lambda_h > 0$ for any scale μ where the minimum of its potential is a global minimum;
- $m_h = 125$ GeV, $\boldsymbol{\lambda_h < 0}$ for energy scales $\boldsymbol{\mu \sim 10^{10} - 10^{12}}$ **GeV** (below GUT, Planck scales);
- **Massive Higgs**:
  - **Additional quadratic** term in its potential ⇒ **shifts** the **field value** at which the **potential** becomes **unbounded** towards values above $\boldsymbol{10^{10} - 10^{12}}$ **GeV**;
  - **Suppresses Higgs** de Sitter **quantum fluctuations:**

$$\langle h^2 \rangle \simeq \left(\frac{H_{inf}}{2\pi}\right)^2 \frac{H_{inf}}{m_h} \simeq \left(\frac{H_{inf}}{2\pi}\right)^2 \frac{{\lambda_\phi}^{1/2}}{g\sqrt{6\xi}} \quad \Rightarrow \quad \sqrt{\langle h^2 \rangle} \lesssim 10^{11} \text{ GeV for } r \lesssim 10^{-2}$$

Post-inflationary period

- Evolution of the **inflaton energy density**:

$$\rho_\chi(a) = 3H_{end}^2\, M_{Pl}^2\, \left(\frac{a}{a_{end}}\right)^{-3}$$

- Here, $H_{end} \simeq \left(\frac{\sqrt{n}}{2}\frac{1}{\sqrt{N_e}}\right)^{n/2} H_{inf}$, but this is model dependent ($N_e = 60$, $N_e = \ln\left(\frac{a_e}{a_i}\right)$);

- At **reheating**:

$$\rho_\chi(a_R) = \frac{\pi^2}{30} g_{*R} T_R^4$$

- Number of **e-folds** from **inflation** until **reheating**:

$$N_R = \ln\left(\frac{a_R}{a_{inf}}\right) = -\frac{1}{3}\log\left(\frac{\pi^2}{90} g_{*R}\frac{T_R^4}{H_{end}^2\, M_{Pl}^2}\right)$$

Model constraints – Condensate Evaporation

Initial conditions that prevent the modulus of the field from oscillating significantly

- Idea: make the field **oscillate** in the **complex plane** ⇒ its modulus does not oscillate;
- How? Introducing terms in the potential that depend **on the phase of the dark scalar field**:

$$V(\phi) = -\xi R(\phi^2 + h.c.) + \frac{1}{M_{Pl}^n}(c\,\phi^{n+4} + h.c.) + g^2\,|\Phi|^2|\mathcal{H}|^2 + \lambda_\phi|\Phi|^4$$

- **Ricci** value **during inflation** ≠ **end of inflation** ⇒ ϕ **phase** is different **during/after inflation** ⇒ dark scalar **oscillates** in the **complex plane** ⇒ $|\phi|$ **does not oscillate** significantly ⇒ **no Higgs** production.

Model constraints – Condensate Evaporation

Perturbative production of ϕ-particles by the oscillating background condensate

- Field can be decomposed into **background** + particle fluctuations $\boldsymbol{\delta\phi}$;
- Production rate: $\Gamma_{\phi\to\delta\phi\delta\phi} \simeq 4\times 10^{-2}\,\lambda_\phi^{3/2}\phi_c$
- Condition:

$$\frac{\Gamma_{\phi\to\delta\phi\delta\phi}}{H_c} < 1$$

$$g < 0.2\,\left(\frac{T_R}{10\text{ GeV}}\right)^{-1/4}\left(\frac{r}{0.01}\right)^{-1/4}\,\xi^{-3/4}\left(\frac{H_{end}/H_{inf}}{0.2}\right)$$