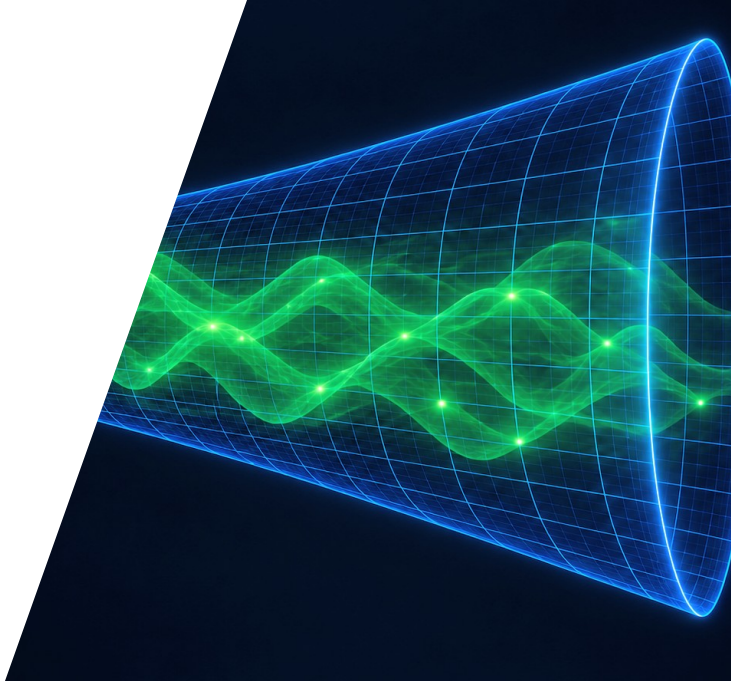


Unimodular Inflation with Higgs Seeds

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October 22, 2026

Inflation and the Inflaton in the Standard Cosmological Model

The standard cosmological model includes an early inflationary epoch. Inflation is driven by the **inflaton**, a hypothetical scalar field beyond the Standard Model (SM) of particle physics.

- **Generation of expansion:** With a suitable potential, the inflaton field can drive accelerated expansion of the early Universe and then lead to reheating. Technically, when the potential energy dominates and slow-roll conditions hold, the inflaton acts as an effective negative pressure, violating the strong energy condition and sourcing accelerated expansion.
- **Generation of primordial inhomogeneities:** Quantum fluctuations of the inflaton are stretched by cosmic expansion and become classical density perturbations, seeding the primordial inhomogeneities observed in the CMB and large-scale structure.

[1]

[1] No direct evidence for the actual existence of the inflaton field has been found so far.

Beyond the Inflaton: Alternative Inflationary Scenarios

The problem: no direct evidence for the inflaton field has been found to date.
This has motivated alternative models that do not rely on an inflaton:

- **Geometric inflation** (e.g. Starobinsky-type $f(R)$ and higher-curvature gravity)
- **Loop quantum cosmology and bouncing cosmologies**
- **Higgs inflation**

Our proposal

It is in this context that we find it interesting to propose another alternative inflationary model, based on **more standard ingredients** — such as the **Higgs boson** — together with **small modifications to General Relativity: Unimodular Gravity**.

Why do we modify GR? The recent **DESI DR2** results could, under some interpretations, be evidence of **unknown aspects of the gravitational interaction**.

Theory of Unimodular Gravity

A version of GR that imposes invariance under diffeomorphisms that preserve the four-volume

$$S[g_{\mu\nu}, \lambda, \phi] = \frac{M_P^2}{2} \int d^4x \sqrt{-g} \left[R - 2\lambda(x) \left(1 - \frac{\epsilon_0(x)}{\sqrt{-g}} \right) \right] + S_m[g_{\mu\nu}, \phi], \tag{1}$$

The term $\epsilon_0(x)$ is a non-dynamical 4-form that breaks the full diffeomorphism symmetry of GR, restricting it to those that preserve the volume element.

Modified field equations

Varying the action (1) with respect to the inverse metric $g^{\mu\nu}$, we obtain the field equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \lambda(x) g_{\mu\nu} = \mathcal{T}_{\mu\nu}, \tag{2}$$

where $\mathcal{T}_{\mu\nu} = T_{\mu\nu}/M_P^2$ and $T_{\mu\nu} = \frac{-2}{\sqrt{-g}} \delta S_m / \delta g^{\mu\nu}$

New conservation law

$$\nabla^{\mu}(T_{\mu\nu} - g_{\mu\nu}Q) = 0, \tag{3}$$

where $Q(x)$ is an arbitrary function, associated with the usually termed unimodular diffusion term, which, together with the traditional energy-momentum tensor, constitutes what could be interpreted as a Total energy-momentum tensor, which is conserved in the UG framework.

$$\lambda(x) = \Lambda_* + \frac{Q}{M_P^2}. \tag{4}$$

GU in a cosmological context

Now considering a homogeneous and isotropic universe described by the FLRW metric:

$$ds^2 = -dt^2 + a^2(t)(dx^2 + dy^2 + dz^2), \tag{5}$$

assuming the material content (perfect fluid + Higgs field), the Friedmann equations in UG take the form:

$$3H^2 = \frac{1}{M_P^2}(\rho_r + \rho_H + Q) + \Lambda_* \tag{6}$$

$$2\dot{H} + 3H^2 = \frac{1}{M_P^2}(-p_r - p_H + Q) + \Lambda_*, \tag{7}$$

where ρ_r and $p_r = \rho_r/3$ are the energy density and pressure of the radiation fluid, and ρ_H and p_H are the energy density and pressure of the Higgs field

Unimodular Inflation

in the regime where the diffusion term Q dominates over the other matter species, that is:

$$Q \gg \rho_r, \rho_H, \quad |p_r|, |p_H|, \tag{8}$$

the first Friedmann equation (6) reduces to:

$$H^2 = \frac{Q}{3M_P^2}. \tag{9}$$

This equation is fundamental, as it shows that the accelerated expansion of the universe during inflation is driven directly by the diffusion term Q.

Higgs Boson

Its action with non-minimal coupling to curvature, and considering the Higgs potential at high energies $V(\phi) = \frac{\lambda}{4}\phi^4$, is:

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\xi\phi^2 R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{\lambda}{4}\phi^4\right]. \tag{10}$$

Its evolution on a homogeneous, isotropic (FLRW) and spatially flat cosmological background.

whose perturbations are described by the following equation:

$$u_k'' + \left[k^2 - \frac{\nu^2 - 1/4}{\eta^2}\right] u_k = 0, \qquad \eta < 0 \tag{11}$$

with

$$u_k(\eta) \equiv a(\eta)\, \delta\phi_k(\eta). \tag{12}$$

$$\nu^2 \equiv \frac{1}{4} - \frac{(6\xi - 1)(2 - \epsilon) + 3\lambda\phi_*^2/H^2}{(1 - \epsilon)^2} \tag{13}$$

Primordial spectrum of Higgs perturbations

Finally, the primordial spectrum results in

$$\mathcal{P}_{\delta\phi}(k) = \frac{H_*^2}{2\pi^2} \frac{2^{2\nu-2}\Gamma(\nu)^2(1-\epsilon)^{2\nu-1}}{\pi} \left(\frac{k}{k_*}\right)^{3-2\nu} \tag{14}$$

It is interesting and can be shown that the index ν, initially obtained as 13, can be expressed as follows:

$$\nu \approx \frac{3}{2} + \epsilon - 4\xi - \delta, \tag{15}$$

with $\delta = \lambda\phi_*^2/H^2$. That is, the parameters ϵ, ξ and δ determine the small departures from the standard case $\nu = 3/2$.

The scalar perturbations of the metric are written as

$$
\begin{aligned}
g_{00} &= -a^2(1+2\phi), \\
g_{0i} &= a^2 \partial_i B, \\
g_{ij} &= a^2 \left[\delta_{ij}(1-2\psi) + \partial_{ij} 2E \right].
\end{aligned}
\tag{16}
$$

Perturbed Einstein equations

$$
\begin{aligned}
2\left[3\mathcal{H}(\mathcal{H}\Phi+\Psi')-\nabla^2(\Psi+\mathcal{H}\sigma)\right] &= 8\pi G\left[-\phi_0'\delta\phi'+\Phi\phi_0'^2-a^2V_{,\phi}\delta\phi-a^2\delta\rho_r-a^2\delta Q\right]\\
-2\,\partial_i(\mathcal{H}\Phi+\Psi') &= 8\pi G\left[-\phi_0'\,\partial_i\delta\phi+\frac{4}{3}a^2\rho_{r,0}\,\partial_i(v+B)\right]\\
2\Psi''+2\mathcal{H}(2\Psi'+\Phi')+2(2\mathcal{H}'+\mathcal{H}^2)\Phi &= 8\pi G\left[\phi_0'\delta\phi'-\Phi\phi_0'^2-a^2V_{,\phi}\delta\phi+\frac{a^2}{3}\delta\rho_r-a^2\delta Q\right].\\
\Psi-\Phi+\sigma'+2\mathcal{H}\sigma &= 0\\
\mathcal{H} &= a'/a\\
\sigma &= E'-B
\end{aligned}
\tag{17}
$$

Mukhanov-Sasaki equation

The modified Mukhanov-Sasaki equation of this particular cosmological model (Each Fourier mode satisfies):

$$v_k''(\eta) + \left(\frac{k^2}{3} - \frac{z''}{z}\right) v_k(\eta) = -\frac{z^3\gamma}{M_{Pl}^3\epsilon_1^2}\, Q_0(\eta)\, \delta\phi \tag{18}$$

where $v \equiv z\,\mathcal{R}$. with $z \equiv \sqrt{2\epsilon_1}\, a$

Solving the integral, the following solutions is obteined:

$$\mathcal{R}_k(\eta) = \frac{v_k}{z} = \frac{2\,s\,\gamma\,\delta\phi_k}{M_{Pl}\,\epsilon_1}\left(\ln\frac{1}{-\omega_k\eta} - \frac{23}{30}\right) \tag{19}$$

Finally, we obtain the primordial power spectrum of the comoving curvature perturbation:

$$\mathcal{P}_{\mathcal{R}}(k) \simeq \frac{\gamma^2 H_*^2}{\pi^2 M_{\rm Pl}^2 \epsilon_{1*}^2} \left(\frac{k}{k_*}\right)^{-2(\epsilon_1 - 4\xi - \delta)} \left(\ln \frac{1}{k|\eta_{\rm end}|} - \frac{23}{30}\right)^2 \tag{20}$$

with $\delta = \lambda\phi_*^2/H^2$. This is the most relevant result of the work, and it shows the prediction of this particular model for the primordial scalar power spectrum.

For the present approximate analysis, it is known that the most recent cosmic microwave background data (Planck, TT,TE,EE+lowE+lensing)2020AA...641A...6P indicate:

$$A_s = \mathcal{P}_{\mathcal{R}}(k_*) \simeq 2.10 \times 10^{-9}, \qquad n_s \simeq 0.9649 \pm 0.0042.$$

The amplitude A_s of the model scales as

$$A_s = \frac{\gamma^2 H_*^2}{\pi^2 M_{\rm Pl}^2 \epsilon_{1*}^2} L_*^2, \tag{21}$$

which, when set equal to the amplitude value fitted to CMB data $A_s = 2.10 \times 10^{-9}$, leads to

$$H_* \approx 6.38 \times 10^{12}\, \epsilon_{1*}\ \text{GeV}. \tag{22}$$

That is, a direct relation is obtained between the Hubble scale (the inflationary energy scale) and the slow-roll parameter ϵ_{1*}.

The spectral index will be defined directly from expression 20 as:

$$n_s(k_*) \simeq 1 - 2(\epsilon_{1*} - 4\xi - \delta) \tag{23}$$

with $\delta = \lambda\phi_*^2/H^2$.

Three-loop running of the Higgs coupling

To estimate the value of $\lambda(\mu)$ at high energy scales, we use the analytical parametrization for the running of the Higgs coupling:

$$\lambda^{\text{3loop}}(\mu) = \lambda_0 + b \ln^2 \left[\frac{\mu}{q M_{\text{P}}} \right], \tag{24}$$

with

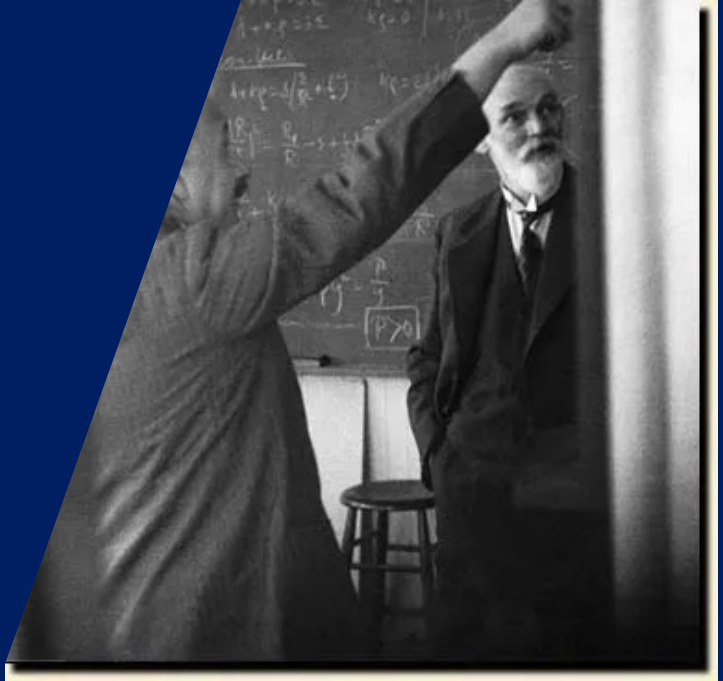
$$\begin{aligned} \lambda_0 &= 0.003297 \left((m_h - 126.13) - 2(m_t - 171.5) \right) \\ q &= 0.3 \exp \left[0.5(m_h - 126.13) - 0.03(m_t - 171.5) \right] \\ b &= 0.00002292 - 1.12524 \times 10^{-6} \left((m_h - 126.13) - 1.75912(m_t - 171.5) \right) \end{aligned}$$

where m_h and m_t are the masses of the Higgs boson and the top quark at the electroweak scale (in GeV) chosen within the constraints reported by CERN. [2]

[2] G. de Berredo-Peixoto, E. V. Gorbar, I. L. Shapiro, "On the renormalization group for the interacting massive scalar field theory in curved space", Class. Quantum Grav. 21 (2004) 2281, DOI:

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Results



Free input parameters		
Description	**Symbol**	**Value**
First slow-roll parameter	ϵ_1	1.800×10^{-2}
Higgs boson mass	m_h	125.6 GeV
Top quark mass	m_t	171.9 GeV
Non-minimal coupling constant	ξ	1.250×10^{-4}
Field at horizon crossing	ϕ_*	2.545×10^{5} GeV
Number of e-folds	$N_* \approx L_*$	5.500×10^{1}
Derived parameters		
Description	**Symbol**	**Value**
Hubble scale at crossing	H_*	1.147×10^{11} GeV
Quartic coupling constant	λ	1.516×10^{-3}
Renormalization scale	μ	1.147×10^{11} GeV
Delta parameter	δ	7.460×10^{-15}
Spectral index	n_s	0.965
Scalar amplitude	A_s	2.100×10^{-9}
Dominance of the gravitational sector		
Description	**Symbol**	**Value**
Diffusion energy density	$Q = 3H_*^2 M_{\mathrm{Pl}}^2$	2.341×10^{59} GeV^4
Higgs energy density	ρ_{Higgs}	6.394×10^{29} GeV^4

Free input parameters		
Description	**Symbol**	**Value**
First slow-roll parameter	ϵ_1	0.076
Higgs boson mass	m_h	125.480 GeV
Top quark mass	m_t	171.880 GeV
Non-minimal coupling constant	ξ	0.015
Field at horizon crossing	ϕ_*	4.849×10^4 GeV
Number of e-folds	$N_* \approx L_*$	50.0
Derived parameters and quantities		
Description	**Symbol**	**Value**
Hubble scale at crossing	H_*	5.328×10^{11} GeV
Quartic coupling constant (running)	$\lambda(\mu)$	-4.982×10^{-6}
Delta parameter	δ	-4.126×10^{-20}
Spectral index	n_s	0.965
Scalar amplitude	A_s	2.1×10^{-9}
Renormalization scale	μ	5.328×10^{11} GeV
Critical field value (background stability)	ϕ_c	1.000×10^{14} GeV
Barrier position	ϕ_b	5.064×10^{12} GeV
Minimum ξ for vacuum stability	ξ_{min}	1.052×10^{-2}
Validity criterion for ξ_{min} analysis	$V_{\text{quadratic}} > V_{\text{quartic}}$	$5.858 \times 10^{31} > 1.931 \times 10^{15}$
Dominance of the gravitational sector		
Diffusion energy density	$Q = 3H_*^2 M_{\text{Pl}}^2$	5.050×10^{60} GeV^4
Higgs energy density	ρ_{Higgs}	5.858×10^{31} GeV^4

Free input parameters		
Description	**Symbol**	**Value**
First slow-roll parameter	ϵ_1	1.750×10^{-2}
Higgs boson mass	m_h	125.1 GeV
Top quark mass	m_t	171.86 GeV
Non-minimal coupling constant	ξ	2.225×10^{-10}
Field at horizon crossing	ϕ_*	1.142×10^{8} GeV
Number of e-folds	$N_* \approx L_*$	55.0
Delta parameter	δ	1.1×10^{-10}
Particular extra free parameter of the model	γ	1.2
Derived parameters		
Description	**Symbol**	**Value**
Hubble scale at crossing	H_*	9.295×10^{10} GeV
Quartic coupling constant ($\gamma = 1.2$)	λ_γ	7.275×10^{-5}
Quartic coupling constant with $\gamma = 1$	λ	-6.520×10^{-5}
Renormalization scale	μ	9.295×10^{10} GeV
Spectral index	n_s	0.965
Scalar amplitude	A_s	2.1×10^{-9}
Minimum ξ for symmetry restoration	$\xi_{\min}$	7.547×10^{-20}
Dominance of the gravitational sector		
Description	**Symbol**	**Value**
Diffusion energy density	$Q = 3H_*^2 M_{\rm Pl}^2$	1.536×10^{59} GeV^4
Higgs energy density	$\rho_{\rm Higgs}$	1.537×10^{29} GeV^4

Summary and Conclusions:

- We see that for the three cases we obtain standard values for the model's predictions, specifically for the amplitude and the spectral index of the primordial spectrum, consistent with the CMB data
- The model is shown to be viable for positive values of the quartic Higgs coupling λ, and MAYBE it could also be viable for negative values; however, a rigorous stability analysis should be performed as future work.
- The model also proves to be viable for very small values of the no minimal coupling parameter, which is not possible in the Higgs inflation model, since the latter requires high values such that $\xi \approx 10^6$; this, together with higher values of the field, gives rise to the unitarity problem, which is avoided in this model.

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Thank you!





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