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Late-Time Cosmic Acceleration from Coupled Higgs and Neutrino Mass Variation

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We explore a scalar-extended theory of gravity in which a non-minimally coupled scalar field accommodates a varying Higgs vacuum expectation value as well as a field-dependent neutrino mass within a single Lagrangian. We investigate whether this theory can account for the late-time acceleration of the Universe. The evolving Higgs sector induces a cosmological variation of fermion masses and consequently of the proton-to-electron mass ratio. We reconstruct the Hubble expansion history from the statefinder parameter and constrain the resulting cosmology using a Markov Chain Monte Carlo analysis. We use the reconstructed cosmological background to derive the scalar-field evolution and the neutrino mass profile, both in the absence and presence of varying Higgs vacuum expectation value. Constraining the Higgs-sector variation using Quasar Absorption Spectra, we find that a viable late-time accelerated expansion requires the neutrino mass variation to remain comparatively suppressed.

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I. INTRODUCTION

The transition of the Universe from a decelerated into a recent accelerated phase of expansion remains one of the central problems of modern cosmology [1–3]. This acceleration is commonly attributed to an effective cosmological component with a negative pressure, referred to as Dark Energy (DE). The primary candidate to serve as a model of dark energy is the cosmological constant Λ . It denotes a constant energy density correction and leads to the Λ CDM model. However, despite the model being remarkably popular, the physical origin of dark energy remains largely unknown [4, 7, 8, 112, 113]. Moreover, recent set of astrophysical observations increasingly points towards a requirement of dynamical DE [9–14]. It is of particular interest that the characteristic energy scale associated with DE is found to be intriguingly close to the mass scale of massive neutrinos. This can either be treated as a *coincidence* or it can be used to motivate a possibility that neutrino physics plays a nontrivial role in the late-time acceleration [15–20]. Indeed, massive neutrinos are known to become non-relativistic during the late-time cosmic expansion and has inspired a plethora of works in the context

of cosmic expansion. Considerations involving mass-varying neutrinos (MaVaNs), in which neutrino masses evolve through their coupling to a cosmological scalar field [21–27] are of particular interest to us. In these frameworks, a single scalar field governs the neutrino mass evolution as well as contributing to the DE sector. In general, such constructions are often associated with symmetries or broken symmetries inspired by the standard model. For instance, in a symmetron cosmology, a local Z_2 symmetry holds good in high-density regions but is spontaneously broken on cosmological scales as matter density drops below a critical value [28–31]. However, the standard symmetron model falls short due to local gravity constraints, which require that the scalar field mass be much greater compared to H_0 [32, 33]. As a result, a symmetron field can not undergo slow-roll to trigger a late-time acceleration. A notable alternative which employs symmetry breaking in low-density environments via radiative corrections is a Coleman-Weinberg model [34–42]. This framework further motivates the application of massive neutrinos in the construction of components that can bypass local constraints and avoid conflict with current limits on dark matter-dark energy interactions.

On the other hand, the idea of varying fundamental constants (such as mass of standard model particles or fundamental couplings) has a long history. Primary proposals involved an evolving gravitational constant G , which led to a series of theoretical and phenomenological investigations of the so-called Brans-Dicke theory and its

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generalizations [43–54]. More recently, considerable attention has been devoted to theories involving a varying fine-structure constant α , partly motivated by observational indications from low-redshift astrophysical measurements [55–60]. Variations in α can further instigate a cosmological evolution of gauge and Yukawa couplings [61, 62]. Variation in α can also lead to a variation in the QCD scale Λ_{QCD} [63, 64]. It further motivates the possibility that the Higgs vacuum expectation value (VEV), which determines quark masses through Yukawa interactions, can also undergo a mild cosmological evolution. Since quark and lepton masses depend directly on the Higgs VEV, any evolution of the VEV would induce corresponding variations in their masses. However, the proton mass is predominantly governed by the QCD confinement scale, with only a subdominant contribution arising from VEV. Thus, a variation of Higgs VEV leads to a variation in the proton-to-electron mass ratio μ [65, 66], usually written through the phenomenologically derived relation

$$\frac{\Delta\mu}{\mu} \sim \frac{\Delta\Lambda_{QCD}}{\Lambda_{QCD}} - \frac{\Delta v}{v} \sim R \frac{\Delta\alpha}{\alpha}. \quad (1)$$

The model dependent parameter R characterizes the relation between variations in μ and α [67]. Observational signature of this variation is found through molecular absorption spectra from distant quasars [68–77], which is often used as an important phenomenological benchmark of theories allowing cosmological evolution of fundamental constants.

We postulate that a single scalar field coupled to the Einstein-Hilbert action can enforce a mild cosmological variation of the Higgs VEV as well as control the evolution of the massive neutrino sector through its coupling profile. We investigate whether such a coupled scalar field can consistently reproduce the observed late-time acceleration of the Universe while remaining compatible with the spectroscopic constraints on the proton-to-electron mass ratio. We organize the article as follows. In Section II, we discuss the scalar field driven variation of VEV, Quark mass and the proton-to-electron mass ratio. In Section III, we introduce the unified lagrangian framework which for a field-dependent Neutrino mass variation. Section IV is devoted to the discussion of statefinder reconstruction of late-time cosmology, parameter estimations and the best-fit plots of cosmographic variables. In Section V, we show the corresponding solutions of the scalar field and Neutrino mass profiles and note our observations. We compare the results with a different cosmic expansion history, namely, the CPL in Section VI and conclude the article in Section VII.

II. QUARK MASS VARIATION AND THE PROTON-TO-ELECTRON MASS RATIO

Generalized versions of the Electroweak theory of interaction, in particular, frameworks with dynamical vacuum structure naturally allow the possibility that the Higgs VEV may undergo a mild cosmological evolution [56, 57, 78, 79]. Since fermion masses arise through Yukawa interactions with the Higgs field, any variation in the Higgs VEV directly induces a variation in the masses of elementary particles. In particular, the electron and quark masses can be written as

$$m_{e,q} = \lambda_{e,q} v, \quad (2)$$

where $\lambda_{e,q}$ denotes the corresponding Yukawa couplings and v is the Higgs vacuum expectation value. As a result, cosmological evolution of v leads to a varying proton-to-electron mass ratio μ . Unlike leptonic masses, the proton mass is governed predominantly by strong interaction dynamics and depends mainly on the QCD confinement scale Λ_{QCD} . This follows from the gauge-invariant decomposition of the QCD Hamiltonian, which allows one to express the proton mass as

$$m_p = a(\Lambda_{QCD}) + \sum_q b_q m_q. \quad (3)$$

The first term represents the dominant gluonic contribution associated with Λ_{QCD} , while the second term arises from explicit quark-mass contributions. Assuming that both Λ_{QCD} and the Yukawa couplings remain effectively constant over cosmological timescales, the fractional variations of the electron and proton masses can be written as

$$\frac{\Delta m_e}{m_e} = \frac{\Delta v}{v}, \quad (4)$$

$$\frac{\Delta m_p}{m_p} = \frac{\sum_q b_q m_q}{a(\Lambda_{QCD}) + \sum_q b_q m_q} \frac{\Delta v}{v} \sim \frac{9}{100} \frac{\Delta v}{v}. \quad (5)$$

Lattice QCD studies indicate that the explicit quark-mass contribution to the proton mass is relatively small [82, 83]. As a result, variations in the Higgs VEV affect the electron mass much more strongly than the proton mass, allowing the latter to remain nearly constant over cosmological epochs. Therefore, even a mild cosmological evolution of the Higgs VEV, potentially originating from residual scalar dynamics after electroweak symmetry breaking, can induce a measurable variation in the proton-to-electron mass ratio. Defining the fractional Higgs-VEV variation as $\frac{\Delta v}{v} = \frac{v_z - v_0}{v_0}$, one obtains from Eqs. (4) and (5)

$$\frac{\Delta\mu}{\mu} = \frac{\Delta m_p}{m_p} - \frac{\Delta m_e}{m_e} \sim -\frac{91}{100} \frac{\Delta v}{v}. \quad (6)$$

To investigate cosmological scenarios involving a varying Higgs vacuum expectation value, we consider the

TABLE I: Variation of $\Delta\mu/\mu$ from Hydrogen Molecular Spectra of Quasars for all $z > 2$ and other molecular spectra for $z < 1$ in Hubble scale

Quasar	Redshift	$\Delta\mu/\mu$ [10^{-6}]
B0218+357	0.685	-0.35 ± 0.12
PKS1830-211	0.89	0.08 ± 0.47
HE0027-1836	2.40	-7.6 ± 10.2
Q0347-383	3.02	5.1 ± 4.5
Q0405-443	2.59	7.5 ± 5.3
Q0528-250	2.81	-0.5 ± 2.7
B0642-5038	2.66	10.3 ± 4.6
J1237+064	2.69	-5.4 ± 7.2
J1443+2724	4.22	-9.5 ± 7.5
J2123-005	2.05	7.6 ± 3.5

Higgs field with a classical cosmological component along with a local quantum fluctuation. The Standard Model Higgs field φ , governed by the Lagrangian

$$L = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{\lambda}{4}(\varphi^2 - v^2)^2, \quad (7)$$

is decomposed into a slowly evolving classical background field $\phi(t)$ and the quantum fluctuation corresponding to the physical Higgs boson h . One may therefore write

$$\varphi = v_0 + \phi(t) + h = v(t) + h. \quad (8)$$

We model the Higgs vacuum expectation value $v(t)$ as a cosmological quantity sourced by the background scalar field ϕ . We relate the observational probe of this variation with the measurement of proton-to-electron mass ratio μ , which is constrained with high precision using optical atomic clocks and molecular absorption spectra from distant quasars [74, 75]. Since atomic transition frequencies depend sensitively on the values of fundamental constants, even a very small cosmological evolution of the Higgs VEV or related couplings can induce measurable shifts in spectroscopic observations. Current laboratory constraints obtained from ultra-precise atomic clock measurements indicate $\frac{\Delta\mu}{\mu} = (-0.5 \pm 1.6) \times 10^{-16}, \text{year}^{-1}$, demonstrating that any late-time variation of μ must occur at a suppressed rate [84]. Using $H_0 \simeq 7 \times 10^{-11}, \text{year}^{-1}$, this corresponds to an approximate bound of order $\frac{\Delta v}{v} \sim 10^{-6} H_0$. The redshift evolution of $\Delta\mu/\mu$ measured using Hydrogen molecular absorption spectra is written in Table I [72, 73, 77, 85–87].

To model the cosmological evolution of the background field driven VEV, we consider a self-interacting potential of ϕ of the form

$$V(\phi) = V_0 + M(t)\phi^2 + \frac{\lambda}{4}\phi^4, \quad (9)$$

where V_0 is a constant vacuum contribution, $M(t)$ is a time-dependent coefficient with mass dimension two and λ is a dimensionless parameter. The vacuum expectation value of the scalar field is determined by the minimum of the potential,

$$\left. \frac{\partial V}{\partial \phi} \right|_v = 0, \quad (10)$$

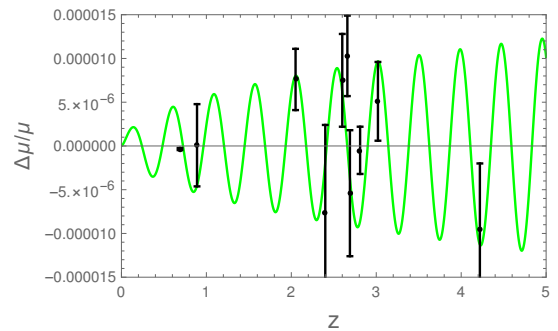


FIG. 1: Evolution of the conjectured $\Delta\mu/\mu$ as a function of redshift along with the fitted observational points from quasar absorption spectra, following Table I. The associated error bars are also shown in the graph below.

which yields

$$v(z) = \sqrt{\frac{-2M(z)}{\lambda}}. \quad (11)$$

The present-day value of the Higgs VEV must remain consistent with electroweak precision measurements, requiring $v(z \simeq 0) \simeq 246, \text{GeV}$ through the relation $M_W \propto v$. A cosmological evolution of $M(z)$ therefore induces a corresponding redshift dependence of the Higgs VEV and, through Eq. (6), a variation in the proton-to-electron mass ratio. Using the relation introduced previously, the fractional variation of μ can be written as

$$\frac{\Delta\mu}{\mu}(z) \simeq -\frac{91}{100} \frac{v(z) - v(z)|_{z \simeq 0}}{v(z)|_{z \simeq 0}}. \quad (12)$$

To connect the model with observations, we parameterize the time-dependent coefficient as $M(z) = M_0 u(z)$, where M_0 sets the overall mass scale and the dimensionless function $u(z)$ encodes the cosmological evolution of the Higgs sector. Since current observations do not uniquely determine the functional form of $u(z)$, we adopt a phenomenological ansatz motivated by the possibility of a slowly relaxing scalar field undergoing mild oscillatory departures from its equilibrium configuration,

$$u(z) = -u_1 + u_2(z + u_3)^{u_4} \sin(u_5 z). \quad (13)$$

The parameters u_i are positive constants. The oscillatory contribution may be interpreted as a residual relaxation mode of the scalar sector, while the power-law envelope allows the amplitude of the variation to evolve with cosmic time. Substituting Eq. (13) into Eq. (12), we compute the corresponding evolution of $\Delta\mu/\mu$ and compare it with observational measurements obtained from molecular absorption spectra of distant quasars. The resulting fit is shown in Fig. 1. A representative set of parameters providing good agreement with the available data is

$$(u_1, u_2, u_3, u_4, u_5) \approx (0.2, 2.5 \times 10^{-6}, 10^{-3}, 0.48, 13). \quad (14)$$

It should be emphasized that Eq. (13) is intended only as a phenomenological reconstruction and is not unique. Other functional forms may well be compatible with the current as well as advanced observational constraints, found from future spectroscopic observations or complementary probes emerging from gravitational-wave cosmology.

III. A FIELD-DEPENDENT NEUTRINO MASS

Having established that a slowly evolving scalar field can induce a cosmological variation of the Higgs vacuum expectation value, we now investigate the possibility that the same scalar degree of freedom also couples to the massive neutrino sector. Since neutrinos remain relativistic for a substantial part of the cosmological evolution, their influence on the scalar dynamics is expected to be negligible at early times. However, once neutrinos become non-relativistic, their energy density can interact more efficiently with the scalar field, potentially modifying the late-time cosmological evolution. We consider the action

$$S = \int d^4x \sqrt{g} \left[\frac{M_{pl}^2}{2} R - \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - V(\phi) \right] + \mathcal{S}_m + \mathcal{S}_r + S_\nu(\phi; \Psi). \quad (15)$$

The actions $\mathcal{S}_m$, $\mathcal{S}_r$ and S_ν describe the matter, radiation and massive neutrino sectors, respectively. A non-minimal interaction between the scalar field and neutrinos is introduced through a field-dependent neutrino mass [27], leading to the Lagrangian

$$\mathcal{L}_\nu = i\bar{\Psi}\gamma^\mu \partial_\mu \Psi - m_\nu(\phi)\bar{\Psi}\Psi. \quad (16)$$

The neutrino mass depends on the scalar field following $m_\nu(\phi) = A(\phi)m_{\nu 0}$, where $m_{\nu 0} \equiv m_\nu(\phi = 0)$ denotes the reference neutrino mass scale. This coupling allows the neutrino sector to backreact on the scalar dynamics once neutrinos become non-relativistic. For a spatially flat FLRW spacetime, the corresponding Friedmann equations are

$$3H^2 M_{pl}^2 = \rho_m + \rho_r + \rho_\nu + \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad (17)$$

$$(2\dot{H} + 3H^2) M_{pl}^2 = -\frac{1}{3}\rho_r - p_\nu - \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad (18)$$

where ρ_i and p_i denote the corresponding energy densities and pressures. Variation of the action with respect to the scalar field yields

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi} + \frac{A_{,\phi}}{A} T_\nu, \quad (19)$$

where T_ν is the trace of the neutrino energy-momentum tensor. The second term on the right-hand side explicitly captures the exchange of energy between the scalar and neutrino sectors. Owing to the non-minimal coupling,

the neutrino energy density obeys a modified conservation law as

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = \frac{A_{,\phi}}{A} \dot{\phi}(\rho_\nu - 3p_\nu). \quad (20)$$

An important feature of Eq. (20) is that the coupling is proportional to $(\rho_\nu - 3p_\nu)$ and therefore vanishes when neutrinos are relativistic, for which $p_\nu \simeq \rho_\nu/3$. The interaction consequently becomes significant only after neutrinos acquire a non-relativistic equation of state, naturally suppressing its impact on the early Universe. Defining $\hat{\rho}_\nu = A\rho_\nu$, where $\hat{\rho}_\nu$ is independent of ϕ , the continuity equation assumes its standard form in the non-relativistic regime and the scalar field equation reduces to

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi} - A_{,\phi}\hat{\rho}_\nu. \quad (21)$$

As discussed in the previous section, the scalar field is also responsible for the evolution of the Higgs VEV. We have already adopted a coupling that preserves the underlying Z_2 symmetry of the scalar sector

$$V(\phi) = V_0 + M(t)\phi^2 + \frac{\lambda}{4}\phi^4, \quad (22)$$

$$A(\phi) = 1 - \frac{\alpha\phi^2}{2M_{pl}^2}. \quad (23)$$

The parameter α characterizes the strength of the scalar-neutrino interaction and may be associated with an effective mass scale $M \equiv \alpha^{-1}M_{pl}$. Using Eq. (21), we find that the scalar-neutrino interaction leads to an effective potential,

$$V_{\text{eff}} = \left\{ M(t) - \frac{\alpha\hat{\rho}_\nu}{2M_{pl}^2} \right\} \phi^2 + \frac{\lambda}{4}\phi^4. \quad (24)$$

The effective mass of the scalar field is therefore modified by the neutrino energy density. As the neutrino background evolves with cosmic expansion, the position and curvature of the effective potential may also evolve, providing a mechanism through which the neutrino sector can influence the late-time scalar dynamics. In the framework considered here, this interaction simultaneously affects the cosmological evolution of the Higgs vacuum expectation value and the neutrino mass, establishing a direct dynamical link between varying fundamental constants and late-time cosmology.

IV. LATE-TIME ACCELERATION AND CONSTRAINTS ON THE SCALAR DYNAMICS

Having established a framework in which a single scalar field simultaneously governs the evolution of the Higgs vacuum expectation value and the neutrino mass, we now turn to its cosmological implications. In particular, we seek to determine whether such a scalar sector can support a viable late-time accelerated

expansion while remaining consistent with observational constraints on varying fundamental constants. If a variation of μ is indeed sourced by a dynamical scalar field, then the scalar equation of state and its coupling to gravity must evolve in a manner compatible with the observed expansion history of the Universe. Consequently, the cosmological viability of the model is closely tied to the dynamical behavior of the scalar sector at late times.

We adopt a reconstruction-based approach in which the expansion history is inferred directly from cosmological kinematics. Reconstruction techniques provide a useful bridge between observations and theory by allowing one to determine the evolution of cosmological quantities with minimal assumptions regarding the underlying dynamics. Broadly, such methods can be categorized into parametric and non-parametric approaches, and often rely on sophisticated statistical techniques such as principal component analysis and related methods to confront theoretical models with observational data [88–97]. In the present work, we employ a kinematic reconstruction based on the statefinder parameters, constructed from higher derivatives of the scale factor. These can provide a sensitive probe of departures from the standard Λ CDM cosmology and have been explored in literature [98–100]. Unlike quantities such as the Hubble parameter or deceleration parameter, which characterize only the first stages of the expansion history, statefinders contain additional information regarding the evolution of the cosmic acceleration and are therefore particularly useful in distinguishing between different dark-energy scenarios. An additional advantage is that they can be formulated independently of any specific gravitational theory, making them well suited for testing whether a given scalar-field framework can reproduce an observationally viable expansion history.

We assume that the statefinder remains approximately constant during the late-time evolution of the Universe and derive an analytical expression for the Hubble parameter as a function of redshift. The resulting Hubble function is subsequently confronted with observational data, allowing us to constrain the free parameters of the reconstruction. Since the procedure is based entirely on kinematic quantities, the reconstructed evolution remains independent of the underlying field equations and can therefore be used as a general benchmark against which scalar extensions of GR may be tested. The Hubble parameter and the deceleration parameter are defined as

$$H = \frac{\dot{a}}{a}, \quad (25)$$

$$q = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\dot{H}}{H^2} - 1, \quad (26)$$

where a denotes the cosmological scale factor and an overdot represents differentiation with respect to cosmic

time. The statefinder pair is introduced through the relations

$$r = \frac{\ddot{a}}{aH^3} = \frac{\ddot{H}}{H^3} + 3\frac{\dot{H}}{H^2} + 1, \quad (27)$$

$$s = \frac{r - 1}{3\left(q - \frac{1}{2}\right)}. \quad (28)$$

To facilitate comparison with observations, we rewrite these quantities in terms of the redshift. Defining $1+z = \frac{1}{a} \equiv x$, together with $H' = \frac{dH}{dx}$ and $a' = -a^2$, one obtains

$$\dot{H} = -H'H/a, \quad (29)$$

$$q(x) = \frac{H'}{H}x - 1, \quad (30)$$

$$r(x) = 1 - 2\frac{H'}{H}x + \left(\frac{H'^2}{H^2} + \frac{H''}{H}\right)x^2. \quad (31)$$

Substituting Eqs. (30) and (31) into Eq. (28), the statefinder parameter can be expressed as

$$s(x) = \frac{-2x\frac{H'}{H} + \left(\frac{H'^2}{H^2} + \frac{H''}{H}\right)x^2}{3\left(\frac{H'}{H}x - \frac{3}{2}\right)}. \quad (32)$$

This relation may be recast as a second-order differential equation for the Hubble parameter,

$$3s\frac{H'}{H}x - \frac{9s}{2} = -2\frac{H'}{H}x + \frac{H'^2}{H^2}x^2 + \frac{H''}{H}x^2. \quad (33)$$

In general, the statefinder parameter may itself be treated as a redshift-dependent quantity. We focus on the simpler and analytically tractable branch for which s remains approximately constant during the late-time transition. We parameterize the constant statefinder as $s = \delta - \frac{2}{3}$ and rewrite the differential equation as

$$\frac{H''}{H} + \frac{H'^2}{H^2} - \frac{3\delta}{x}\frac{H'}{H} + \frac{9}{2}\left(\delta - \frac{2}{3}\right)\frac{1}{x^2} = 0, \quad (34)$$

which admits the solution

$$H(x) = C_2 x^{\frac{1}{4}} \left[1 + 3\delta - \{1 + 6\delta + 9\delta^2 - 36(\delta - \frac{2}{3})\}^{1/2} \right] \left[C_1 + x \{1 + 6\delta + 9\delta^2 - 36(\delta - \frac{2}{3})\}^{1/2} \right]^{1/2}. \quad (35)$$

Here C_1 and C_2 are integration constants. To compare with observations, it is convenient to express all cosmological quantities in terms of the redshift as

$$(1+z) = \frac{a_0}{a(t)}, \quad (36)$$

where a_0 denotes the present value of the scale factor. Using the identification $x = 1+z$, the reconstructed Hubble parameter can be written as

$$H(z) = \frac{H_0}{(1+C_1)^{1/2}} (1+z)^{\frac{1}{4}} \left[1 + 3\delta - \{1 + 6\delta + 9\delta^2 - 36(\delta - \frac{2}{3})\}^{1/2} \right] \left[C_1 + (1+z) \{1 + 6\delta + 9\delta^2 - 36(\delta - \frac{2}{3})\}^{1/2} \right]^{1/2}, \quad (37)$$

which is simplified into

$$H(z) = \frac{H_0}{\sqrt{1+C_1}} \sqrt{C_1(1+z)^3 + (1+z)^{3\delta-2}}. \quad (38)$$

The parameter H_0 represents the present-day Hubble constant measured in $\text{kmMpc}^{-1}\text{s}^{-1}$. We find it convenient to work with the dimensionless reduced Hubble function defined as

$$h(z) = \frac{H(z)}{H_0} = \frac{H(z)}{100 \times h_0}. \quad (39)$$

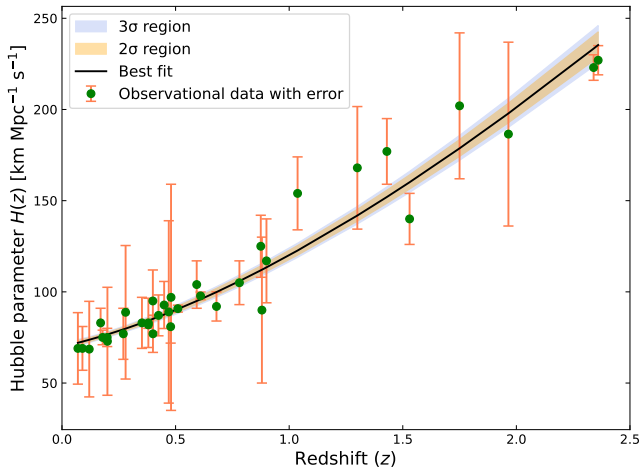


FIG. 2: Hubble parameter, $H(z)$ as a function of redshift (z) as reconstructed and compared with *OHD + BAO + JLA* data. The black line corresponds to the best-fitted value of $H(z)$. The blue and yellow colored regions correspond to 3σ and 2σ spread. The observational data is shown by green-colored dots with orange colored error bars.

To assess the observational viability of the reconstructed Hubble, we perform a comprehensive Bayesian parameter estimation using the Markov Chain Monte Carlo (MCMC) technique implemented through the *emcee* package [101]. The analysis is based on the likelihood function $\mathcal{L} \propto \exp(-\chi^2/2)$, where the total χ^2 is constructed from combinations of independent cosmological probes. In order to examine the robustness of the reconstruction and its sensitivity to different observational datasets, two complementary analyses are carried out. The first employs ‘Data-Set I’: a combination of Observational Hubble Data (OHD) [102–108], Baryon Acoustic Oscillation (BAO) measurements [109, 110] and the Joint Light-curve Analysis (JLA) supernova compilation [111]. The second set, dubbed ‘Data-Set II’ utilizes OHD, Cosmic Chronometer (CC) measurements [112, 113], the Pantheon+SH0ES supernova sample [114] and the latest DESI DR2 BAO observations [115]. The two independent datasets employed in the analysis probe complementary aspects of the cosmic expansion history. The OHD and CC datasets provide direct

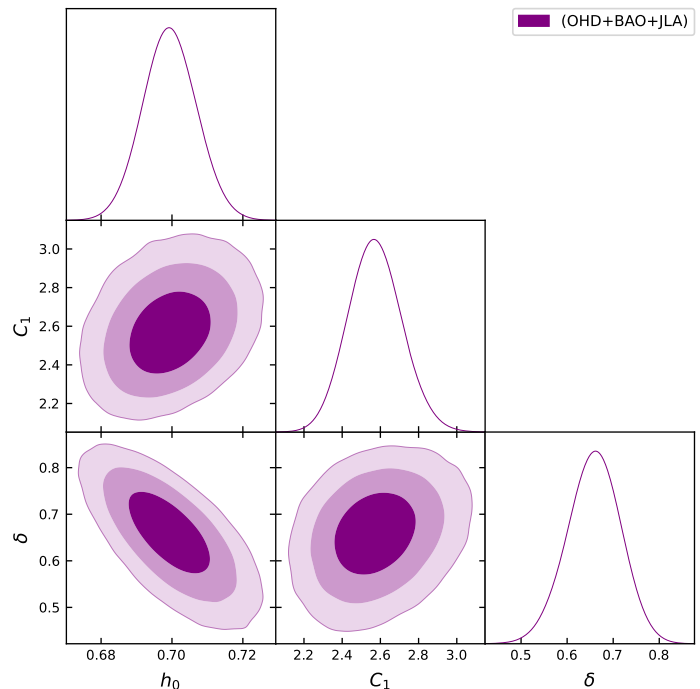


FIG. 3: The 1D and 2D posterior distribution of three input parameters (h_0 , C_1 , δ) along with the confidence contours (1σ , 2σ , and 3σ) using *OHD + BAO + JLA* data.

measurements of the Hubble parameter and therefore constrain the expansion rate in a relatively model-independent manner. Type Ia supernova observations from the JLA and Pantheon+ compilations furnish precise luminosity-distance measurements over a wide redshift range, thereby constraining the integrated expansion history of the Universe. The BAO and DESI DR2 measurements act as standard rulers and provide powerful geometric constraints on the late-time cosmological evolution. In particular, the inclusion of the recent DESI DR2 observations strengthens the constraints on deviations from the standard expansion scenario and also enables a test of the reconstructed Hubble function at intermediate redshifts.

The parameter estimation focuses on the dimensionless Hubble parameter $h_0 = H_0/(100\text{kmMpc}^{-1}\text{s}^{-1})$ together with the model parameters governing the reconstructed expansion history. The resulting best-fit values and their corresponding 1σ confidence intervals are summarized in Table II, while the associated one- and two-dimensional marginalized posterior distributions are displayed in Fig. 5 and Fig. 3. The dark, intermediate and light magenta regions correspond respectively to the 1σ , 2σ and 3σ confidence contours. The reconstructed Hubble evolution is shown in Fig. 2 and Fig. 4, where the best-fit trajectory is accompanied by the corresponding 2σ and 3σ confidence regions represented by the shaded bands.

The plots suggest a reliable validation of the Hubble function derived from a constant statefinder. The cosmological viability constitutes a necessary prerequisite for obtaining physically meaningful constraints on the mass-varying neutrino sector. The resulting constraints also indicate that the expansion history remains close to the standard Λ CDM scenario while allowing for small departures that may carry signatures of the underlying neutrino-dark-energy interaction.

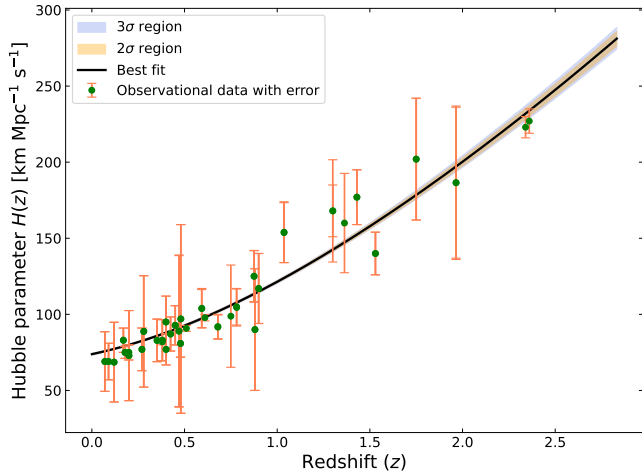


FIG. 4: Hubble parameter, $H(z)$ as a function of redshift (z) as reconstructed and compared from $OHD + CC + Pantheon + DESIDR2$ data. The black line corresponds to the best-fitted value of $H(z)$. The blue and yellow colored regions correspond to 3σ and 2σ spread. The observational data is shown by green-colored dots with orange colored error bars.

We should emphasize here that no CMB compressed prior has been imposed in the parameter estimation since the proposed Hubble ansatz is intended primarily as a phenomenological description of the late-time expansion history alone. The compressed CMB observables are derived under the standard assumptions related to an early-Universe cosmological framework. Incorporating such priors may therefore introduce model-dependent biases and obscure the genuine late-time behavior encoded in the reconstructed expansion history.

TABLE II: Parameter Estimation : best-fit value along with the 1σ uncertainty for two different data-sets. Data-set I corresponds to $OHD + JLA + BAO$. Data-set II corresponds to $OHD + CC + Pantheon + SH0ES + DESIDR2$.

Parameter	Data-set I	Data-set II
h_0	$0.705^{+0.007}_{-0.007}$	$0.737^{+0.003}_{-0.003}$
C_1	$2.932^{+0.303}_{-0.278}$	$2.968^{+0.079}_{-0.077}$
δ	$0.672^{+0.006}_{-0.006}$	$0.638^{+0.025}_{-0.026}$

The reconstructed Hubble parameter also allows us to

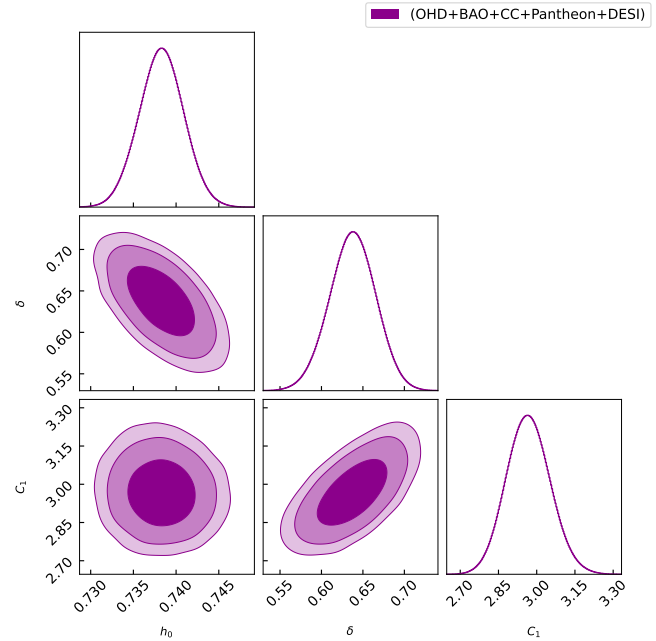


FIG. 5: The 1D and 2D posterior distribution of three input parameters (h_0 , C_1 , δ) along with the confidence contours (1σ , 2σ , and 3σ) using $OHD + CC + Pantheon + SH0ES + DESIDR2$ data.

examine the thermodynamic state of the Universe and determine whether the present cosmological evolution is compatible with an approach toward thermodynamic equilibrium. In cosmological thermodynamics, it is often assumed that the Universe can be treated as a thermodynamic system bounded by the Hubble horizon, with a total entropy given by $S = S_f + S_h$, where S_f denotes the entropy associated with the cosmic fluid and S_h represents the horizon entropy [116, 117]. Within this framework, the generalized second law of thermodynamics requires that the total entropy should never decrease, while thermodynamic stability further demands that the entropy approaches a maximum value asymptotically. These requirements are non-decreasing entropy: $\frac{dS}{dn} \geq 0$ and the second order stability criterion: $\frac{d^2S}{dn^2} < 0$, where $n = \ln a$ is the logarithm of the scale factor. For an FLRW spacetime bounded by the Hubble horizon, the entropy evolution can be expressed entirely in terms of the Hubble parameter and its derivatives. In particular, one obtains

$$S_{,n} \propto \frac{(H_{,n})^2}{H^4}, \quad (40)$$

$$S_{,nn} = 2S_{,n} \left(\frac{H_{,nn}}{H_{,n}} - \frac{2H_{,n}}{H} \right) = 2S_{,n} \Psi. \quad (41)$$

Since $S_{,n}$ is manifestly non-negative, the approach toward thermodynamic equilibrium is governed by the sign of the quantity $\Psi = \frac{H_{,nn}}{H_{,n}} - \frac{2H_{,n}}{H}$. The parameter Ψ therefore acts as a convenient thermodynamic diagnos-

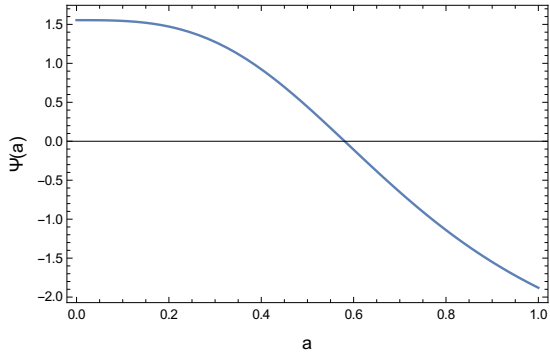


FIG. 6: Thermodynamic equilibrium of the system: Variation of Ψ with a for the best-fit parameter values.

tic of the cosmic expansion history. A negative value of Ψ implies $S_{,nn} < 0$, indicating that the total entropy evolves toward a maximum and the system approaches thermodynamic equilibrium. Conversely, $\Psi \geq 0$ corresponds to a departure from equilibrium or an unstable thermodynamic configuration. The evolution of Ψ as a function of the scale factor is shown in Fig. 6. The reconstructed cosmology exhibits a smooth evolution of the thermodynamic diagnostic with no pathological behavior or discontinuities throughout the considered range. More importantly, Ψ becomes negative during the late stages of cosmic evolution, indicating that the Universe evolves toward a thermodynamically stable state. This behavior is particularly noteworthy because the onset of accelerated expansion coincides with the approach to thermodynamic equilibrium, suggesting that the reconstructed late-time cosmology is not only observationally viable but also thermodynamically consistent.

V. PROFILE OF THE SCALAR FIELD AND NEUTRINO MASS VARIATION

Having reconstructed a Hubble expansion history that is consistent with the combined *JLA + BAO + OHD* datasets and exhibits a thermodynamic equilibrium at late times, we now investigate the effective matter sector capable of supporting such an evolution. In the present framework, the effective energy-momentum tensor consists of a cosmological scalar field coupled to both the Higgs and neutrino sectors. The scalar field induces a variation in the Higgs VEV through the quadratic coefficient of the Higgs-like potential, parameterized as $M(t) \equiv M_0 u(z)$. The model also contains a massive neutrino component whose conserved density evolves as $\hat{\rho}_\nu = \hat{\rho}_{\nu 0}(1+z)^3$. However, owing to the non-minimal scalar-neutrino coupling introduced in Eq. (16), the neutrino mass itself is field-dependent and is given by $m_\nu(\phi) = A(\phi)m_{\nu 0}$. As a result, both the Higgs-sector evolution and the neutrino mass variation are sourced by the same underlying scalar degree of freedom, leading to

a coupled system whose dynamics can be reconstructed from the observationally constrained Hubble expansion.

For numerical convenience, we rewrite all field equations in terms of the redshift variable z . Two distinct scenarios are explored. In the first, the Higgs effective mass parameter remains constant, corresponding to $u(z) = 1$ and hence $M(t) \equiv M_0$. This serves as a reference case in which the neutrino sector alone feeds the non-trivial scalar coupling. In the second scenario, the Higgs-sector parameter evolves according to the phenomenological profile introduced in Eq. (13), leading to a simultaneous variation of the Higgs VEV and the neutrino mass. In this case, the parameters governing $u(z)$ must be chosen such that the resulting evolution remains compatible with the observational bounds on the proton-to-electron mass ratio inferred from molecular absorption spectra.

$$H^2(1+z)^2 \frac{d^2\phi}{dz^2} - 2H^2(1+z) \frac{d\phi}{dz} + H(1+z)^2 \frac{d\phi}{dz} \frac{dH}{dz} + 2M_0\phi u + \lambda\phi^3 - \frac{\alpha\phi}{M_p^2} \tilde{\rho}_{\nu 0}(1+z)^3 = 0. \quad (42)$$

$$\omega_{de}(z) = \frac{\frac{(\frac{d\phi}{dz})^2 \times H^2(1+z)^2}{2} - V_0 - m_0 u \phi^2 - \frac{1}{4}\phi^4}{\frac{(\frac{d\phi}{dz})^2 \times H^2(1+z)^2}{2} + V_0 + m_0 u \phi^2 + \frac{1}{4}\phi^4},$$

$$\omega_{eff} = \frac{P_{tot}}{\rho_{tot}}. \quad (43)$$

For the case of a constant Higgs-sector parameter, $u(z) = 1$, the scalar field evolution is obtained numerically from Eq. (42). Once the scalar field profile is known, the corresponding dark energy equation of state, the effective equation of state of the combined cosmological fluid and the neutrino coupling function $A(\phi)$ can be reconstructed numerically. These quantities provide a useful characterization of the late-time dynamics, allowing us to examine both the dark-energy behavior and the evolution of the scalar-neutrino interaction. The resulting profiles are presented in Fig. 7. Throughout our analysis, we choose the initial condition $\left. \frac{d\phi}{dz} \right|_{z=0} < 0$, which corresponds to a scalar field whose amplitude increases as the Universe evolves toward the present epoch. Such a choice is consistent with the expectation that the scalar degree of freedom associated with late-time acceleration becomes dynamically more relevant at lower redshifts.

The reconstructed evolution shown in Fig. 7 exhibits several noteworthy features. The scalar field evolves smoothly throughout the considered redshift range and undergoes a sign change at intermediate redshifts. The corresponding dark energy equation of state evolves rapidly from negative values and approaches $\omega_{de} \simeq 1$ at low redshift, reflecting the increasingly dynamical role

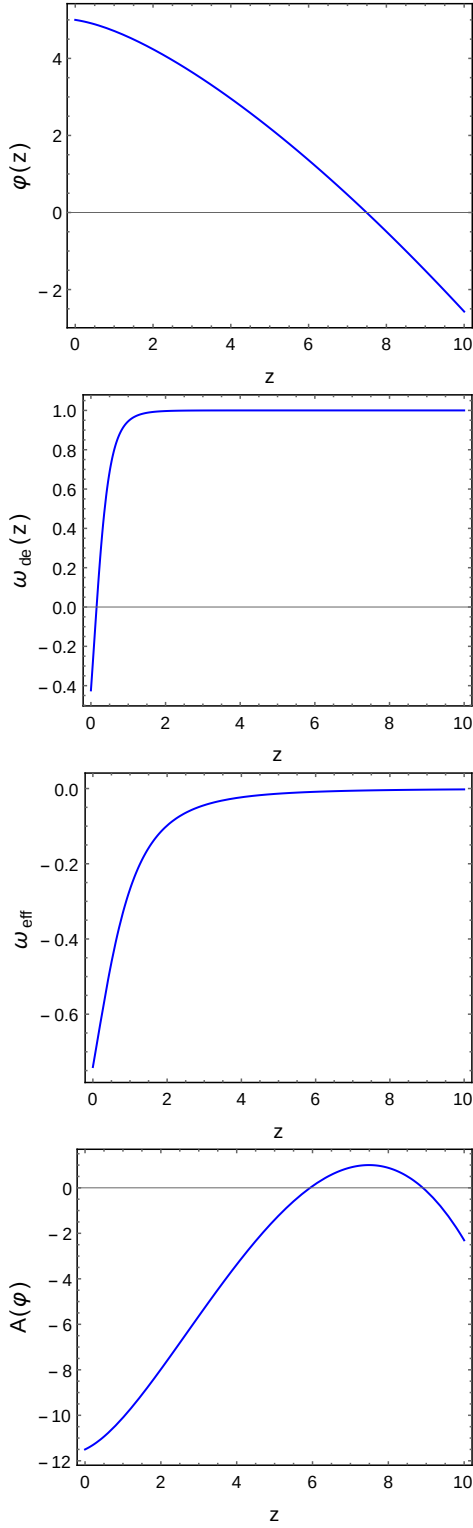


FIG. 7: Evolution of the scalar field, $\omega_{de}(z)$, $\omega_{eff}(z)$ and $A(\phi)$ as a function of redshift. The initial condition for numerical solution is $\phi_{z=0} > 0$ and $\frac{d\phi}{dz}|_{z=0} < 0$. No variation of the effective Higgs mass is considered ($u(z) = u_0$)

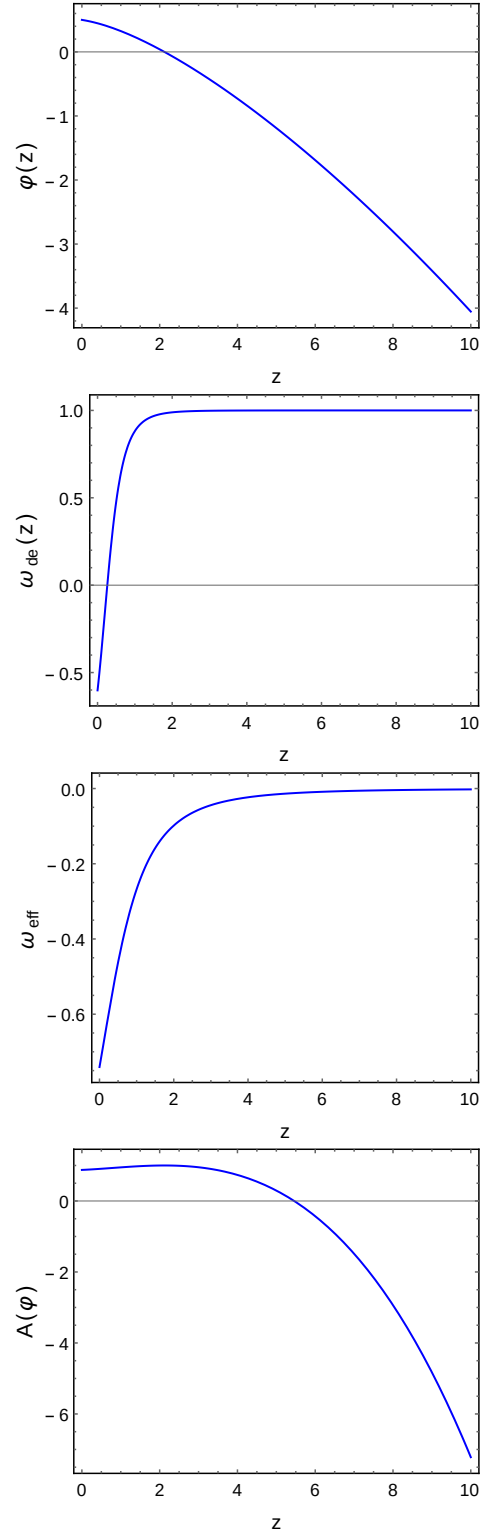


FIG. 8: Evolution of the scalar field, $\omega_{de}(z)$, $\omega_{eff}(z)$ and $A(\phi)$ as a function of redshift. The initial condition for numerical solution is $\phi_{z=0} > 0$ and $\frac{d\phi}{dz}|_{z=0} < 0$. Variation of the effective Higgs mass is considered ($u(z)$ varies according to Eq. (13))

of the scalar sector. At the same time, the effective

equation of state of the combined cosmological fluid remains negative throughout the present epoch and approaches zero at higher redshifts, ensuring compatibility with a viable late-time expansion history. The evolution of the neutrino coupling function $A(\phi)$ is particularly interesting. Although $A(\phi)$ remains negative over most of the redshift interval considered, its magnitude decreases significantly toward lower redshifts, indicating a weakening of the effective scalar-induced neutrino mass modulation near the present epoch. In the constant- $u(z)$ scenario, the scalar field therefore plays a dual role: it supports the reconstructed expansion history while simultaneously generating a nontrivial but gradually softened coupling to the massive neutrino sector.

$$H^2(1+z)^2 \frac{d^2\phi}{dz^2} - 2H^2(1+z) \frac{d\phi}{dz} + H(1+z)^2 \frac{d\phi}{dz} \frac{dH}{dz} + M_0\phi^2 \frac{du}{dz} \frac{d\phi}{dz} + 2M_0\phi u(z) + \lambda\phi^3 - \frac{\alpha\phi}{M_p^2} \tilde{\rho}_{\nu_0}(1+z)^3 = 0.$$

We now turn to the more general scenario in which the Higgs-effective mass parameter evolves with redshift according to the phenomenological ansatz $u(z) = -u_1 + u_2(z+u_3)^{u_4} \sin(u_5 z)$. Unlike the constant- $u(z)$ case, this choice allows for a mild cosmological evolution of the VEV remaining consistent with observational bounds on the proton-to-electron mass ratio. The scalar field evolution is obtained numerically from Eq. (44), after which the corresponding dark energy equation of state, effective equation of state and neutrino coupling function $A(\phi)$ are reconstructed. The resulting evolution profiles are shown in Fig. 8. Comparing Fig. 8 with the constant- $u(z)$ case shown in Fig. 7, one immediately notices that the overall qualitative features of the reconstructed cosmology remain unchanged. The scalar field continues to evolve smoothly with redshift, the dark energy equation of state rapidly approaches $\omega_{de} \simeq 1$ at low redshifts, while the effective equation of state remains negative throughout the present epoch. This suggests that the introduction of a mild Higgs-sector evolution does not significantly alter the background expansion history reconstructed from observational data. The only notable difference appears in the neutrino coupling function. In the varying- $u(z)$ scenario, the scalar field remains confined to a narrower range of values compared to the constant- $u(z)$ case, indicating that part of the cosmological evolution is now absorbed by the Higgs-sector variation itself. This behavior is in fact reflected in the evolution of the coupling $A(\phi)$, whose magnitude remains substantially smaller throughout the redshift range considered. While $A(\phi)$ becomes strongly negative in the constant- $u(z)$ case, the inclusion of a varying Higgs-sector parameter softens this behavior and keeps the neutrino-mass modulation closer to its uncoupled limit. The result suggests that once a mild variation of the Higgs vacuum expectation value is allowed, the scalar field requires a comparatively weaker coupling to the neutrino sector in order to support the same recon-

structed cosmological evolution. In this sense, the Higgs and neutrino sectors appear to share the burden of the late-time scalar dynamics, leading to a reduced deformation of the effective neutrino coupling near the present epoch.

VI. CPL RECONSTRUCTION AND THE EVOLUTION OF THE NEUTRINO COUPLING

The constant-statefinder reconstruction discussed in the previous section provides a convenient kinematic description of the late-time expansion history. It allows one to investigate the coupled evolution of the Higgs and neutrino sectors. However, the assumption of a constant statefinder represents only one possible realization of the late-time epoch and in fact, there can be numerous such examples. It is therefore realistic to cross-examine whether the qualitative features derived thus far can persist within a more widely used phenomenological description of dark energy. To this end, we repeat the reconstruction procedure using the Chevallier-Polarski-Linder (CPL) parametrization [13, 119–121] of the dark energy equation of state. The CPL parametrization provides a convenient phenomenological framework for describing a slowly evolving dark energy sector which captures the leading deviations from a cosmological constant while retaining analytical simplicity and a direct connection to observations. We derive the behavior of the scalar field and the neutrino coupling function $A(\phi)$ that is required to support a CPL expansion. We find that a CPL reconstruction leads to a significantly weaker deformation of the neutrino coupling $A(\phi)$ compared to the constant- M Higgs scenario discussed earlier. This behavior suggests that an observational viable model of phantom divide crossing in the dark energy equation of state can suppress neutrino mass variation.

Within the CPL framework, the dark energy equation of state is parameterized as

$$w(z) = w_0 + w_a \frac{z}{1+z}. \quad (44)$$

This form allows for a smooth evolution of the dark energy equation of state from its present value w_0 while introducing a single additional parameter w_a that quantifies its redshift dependence. The parametrization reduces to the cosmological constant case when $w_0 = -1$ and $w_a = 0$, making it particularly useful for exploring departures from the standard Λ CDM scenario. The evolution of the dark energy density follows from the conservation equation,

$$\frac{d\rho_{de}}{dz} = \frac{3}{1+z} \left[1 + w_0 + w_a \frac{z}{1+z} \right] \rho_{de}. \quad (45)$$

Integrating from the present epoch ($z = 0$) to an arbitrary redshift z , one obtains

$$\rho_{de}(z) = \rho_{de0}(1+z)^{3(1+w_0+w_a)} e^{-3w_a z/(1+z)}. \quad (46)$$

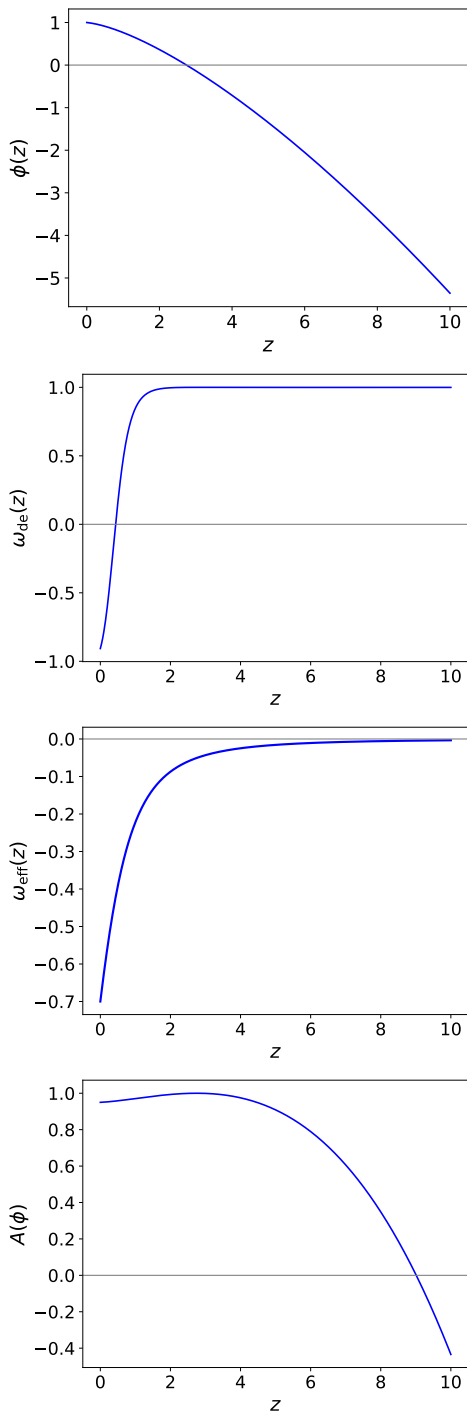


FIG. 9: Evolution of the scalar field, $\omega_{de}(z)$, $\omega_{eff}(z)$ and $A(\phi)$ as a function of redshift for a CPL parametrized Hubble. The initial condition for numerical solution is $\phi_{z=0} > 0$ and $\frac{d\phi}{dz}|_{z=0} < 0$.

The corresponding Hubble expansion rate is then obtained by substituting the matter, radiation and dark

energy densities into the Friedmann equation,

$$H^2(z) = H_0^2 \left[\Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 + \Omega_{de0}(1+z)^{3(1+w_0+w_a)} e^{-3w_a z/(1+z)} \right]. \quad (47)$$

In contrast to the constant-statefinder reconstruction discussed previously, the CPL parametrization incorporates a redshift-dependent dark energy sector directly into the Hubble function, thereby providing an independent observationally motivated description of the late-time expansion history. Defining the dimensionless Hubble function through $E^2(z) \equiv H^2(z)/H_0^2$, we substitute the CPL background evolution into the scalar-field equation and express the latter entirely in terms of redshift. The resulting equation governing the scalar dynamics is

$$H^2(1+z)^2 \frac{d^2\phi}{dz^2} - 2H^2(1+z) \frac{d\phi}{dz} + H(1+z)^2 \frac{dH}{dz} \frac{d\phi}{dz} + 2M_0 u(z)\phi + \lambda\phi^3 - \frac{\alpha}{M_{Pl}^2} \rho_{\nu 0}(1+z)^3 \phi = 0.$$

As before, the function $u(z)$ determines the evolution of the Higgs-sector mass scale, while the final term represents the effective coupling between the scalar field and the non-relativistic neutrino background. We solve this equation numerically and reconstruct the scalar field evolution, the associated equations of state and the neutrino coupling function within the CPL cosmological background and plot them in Fig. 9.

The reconstructed profile for the CPL background exhibits some notable differences compared to the statefinder-based constant- $u(z)$ and varying- $u(z)$ reconstructions. The scalar field evolves smoothly and monotonically throughout the redshift range considered. The dark energy equation of state rapidly approaches $\omega_{de} \simeq 1$ at low redshifts, indicating that the scalar sector becomes increasingly kinetic-energy dominated near the present epoch. The effective equation of state starts from negative values at low redshift, ω_{eff} briefly enters the positive regime before gradually approaching values close to zero at higher redshifts. The most significant result, however, emerges from the evolution of the neutrino coupling function $A(\phi)$. Unlike the constant- $u(z)$ case, where $A(\phi)$ remains strongly negative over most of the redshift interval, and the varying- $u(z)$ scenario, where the magnitude of the negative coupling is partially reduced, the CPL reconstruction keeps $A(\phi)$ close to unity throughout a substantial portion of the evolution. Even at larger redshifts, the deviation from the uncoupled value is small. This indicates that the scalar field requires a considerably weaker deformation of the neutrino sector in order to reproduce the reconstructed CPL expansion history. Taken together with the previous results, a clear hierarchy emerges: the magnitude of the effective neutrino-mass modulation decreases as the cosmological reconstruction becomes increasingly aligned with observationally viable late-time dynamics. The CPL reconstruction

therefore suggests that realistic expansion histories can be supported with only a mild departure from the standard neutrino sector, while the Higgs-sector evolution absorbs a larger share of the scalar dynamics.

VII. CONCLUSION

In this work, we investigated a unified framework which allows a single cosmological scalar field to simultaneously drive a mild evolution of Higgs VEV and neutrino mass. The evolving Higgs sector induced a cosmological variation of proton-to-electron mass ratio, which is constrained by data from Quasar absorption spectra. To explore the viability of this setup, we reconstructed the late-time cosmic expansion history using a kinematic reconstruction, based on a constant statefinder. We constrained the reconstructed Hubble function using a combined analysis of two different data-sets : Dataset I corresponding to *JLA + BAO + OHD* and Dataset II corresponding to *OHD + CC + Pantheon + SH0ES + DESIDR2*. The best-fit model gave a present-day Hubble parameter of $H_0 \simeq 70.5 \text{ km Mpc}^{-1} \text{ s}^{-1}$ for the first data set and $73.7 \text{ km Mpc}^{-1} \text{ s}^{-1}$ for the second data set. The statefinder parameter was constrained to the interval $0.011 \geq s \geq -0.001$ at the 1σ level, indicating a cosmological evolution very close to that of the standard Λ CDM model. Using the reconstructed expansion history as cosmological background, we derived the scalar-field profiles for constant as well as evolving Higgs-sector parameters. In both of the cases, the scalar field admits physically consistent solutions. Using the scalar field we derived the evolutions of the dark energy equation of state, the effective equation of state and the field-dependent neutrino mass. The resulting cosmologies remained compatible with late-time acceleration while simultaneously accommodating small variations in the Higgs sector.

A particularly noteworthy feature was the behavior of the neutrino coupling function $A(\phi)$. In the constant Higgs-sector scenario, the reconstructed cosmology allowed a comparatively stronger variation of the neutrino mass in low redshift regime. Allowing a viable variation of the Higgs VEV successfully constrained this variation. The CPL reconstruction suppressed it even further. One can therefore note that the neutrino coupling function approaches values increasingly closer to its uncoupled limit as the reconstructed cosmology becomes more tightly aligned with observationally viable expansion histories.

The result is interesting in the context of recent studies on the emerging cosmological neutrino-mass tension. Recent analyses combining DESI BAO and CMB data have suggested that the preference for unphysical negative effective neutrino masses may be signaling missing late-time structure in the cosmological expansion his-

tory, in particular, referring to a redshift-dependent modification of $H(z)$ capable of suppressing the expansion rate over an intermediate redshift range while remaining consistent with low-redshift distance measurements. In that context, sign-switching dark-energy scenarios and other models admitting non-trivial late-time evolution have been shown to alleviate the tension by reshaping the background expansion history rather than invoking exotic neutrino physics [122]. The scalar-field framework developed in the present work is conceptually related to this broader direction. Although our primary motivation is the simultaneous evolution of the Higgs sector and neutrino masses, the reconstructed cosmologies naturally generate departures from a pure Λ CDM expansion history, through the scalar field and its couplings. The fact that the CPL reconstruction yields a weaker neutrino-mass modulation than the constant- M and varying $M(z)$ scenarios is particularly noteworthy, since it suggests that observationally preferred expansion histories may require progressively smaller deviations in the neutrino sector. While a dedicated analysis using DESI and CMB lensing data would be required to establish a direct connection with the neutrino-mass tension, our results indicate that a simultaneous, scalar-mediated, Higgs and neutrino mass evolution can provide a physically motivated mechanism for generating the type of late-time cosmological modifications that have recently attracted considerable attention in this context. While the Higgs-sector evolution considered here remains phenomenological, future high-precision measurements of the proton-to-electron mass ratio, together with improved cosmological observations, may provide increasingly stringent tests of such coupled scalar cosmologies and their connection to varying fundamental constants.

Conflict of Interest

The authors declare no conflict of interest.

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Data Availability Statement

The Markov Chain Monte Carlo code alongwith other software-based numerical analysis is open-source and can be found on ZENODO [123].

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