Completing Einstein Gravity with a Single Scalar:

Cosmic History without Dark Matter or Dark Energy

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Abstract

We present a scalar–tensor completion of Einstein gravity, based on the MMA-DMF [1] in which a single light scalar field φ replaces both cold dark matter and dark energy at the level of cosmological phenomenology. The model is formulated as an effective field theory (EFT) valid below a cutoff scale Λ, with screened fifth forces on small scales [2] and a controlled modification of the background expansion and the growth of structure at late times. We show how a non-singular "reset" phase, an early-time bump in the expansion rate, a standard radiation and baryon dominated era, the present acceleration and a future turnaround can all be obtained from one scalar potential and its coupling to matter, without introducing additional dark fluids. We summarise the agreement with CMB [3], BAO, H_0 and large-scale structure observables obtained in previous phenomenological studies of this model.

1 Introduction

General Relativity (GR) [4] with a cosmological constant and cold dark matter (ΛCDM) gives an excellent description of most cosmological observables [5], but at the price of introducing two dark components whose microphysical origin remains unknown. In addition, there are well-known tensions between early- and late-time determinations of the Hubble constant H_0 [6] and the clustering amplitude S_8.

In this work we complete Einstein gravity with a single scalar field φ that couples to the trace of the energy–momentum tensor and drives both the early- and late-time departures from a pure GR background. The same field is responsible for an effective strengthening of gravity at cluster and galactic scales, reproducing the phenomenology usually attributed to cold dark matter, while remaining screened in the Solar System and in laboratory tests [2, 7]. Our goal here is not to repeat the detailed data analysis (typically performed using Boltzmann codes), but to present a compact and self-contained EFT description of the model, emphasising how the entire cosmic history—from a non-singular reset through the standard hot Big Bang era to a future turnaround—can be obtained from a single scalar degree of freedom.

2 Unified scalar–tensor action

We work with the Einstein-frame action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}R - \frac{1}{2}(\nabla\varphi)^2 - V(\varphi) + \beta_K\frac{\varphi^2}{M^2}K\right] + S_m[\tilde{g}_{\mu\nu}, \psi_m]\,, \tag{1}$$

where R is the Ricci scalar, K schematically denotes curvature invariants that become large in high-curvature regimes (bounce, black holes), M is a mass scale and S_m is the matter action with Jordan-frame metric

$$\tilde{g}_{\mu\nu} = A^2(\varphi) g_{\mu\nu}, \qquad A(\varphi) \simeq 1 + \frac{\beta\,\varphi}{M_{\text{Pl}}} + \dots \tag{2}$$

The function $A(\varphi)$ encodes the conformal coupling of the scalar to baryons and radiation, and is chosen such that local tests of gravity are satisfied thanks to a density- and curvature-dependent screening mechanism. This ensures compliance with stringent pulsar constraints [8] and gravitational wave speed limits [9].

The scalar equation of motion in the quasi-static limit reduces to

$$\left(\nabla^2 - m_{\text{eff}}^2(\rho, K)\right) \varphi = \frac{\beta(\varphi)}{M_{\text{Pl}}}\,\rho, \tag{3}$$

with

$$m_{\text{eff}}^2(\rho, K) = \frac{\rho}{M^2} - \mu^2 - \frac{\beta_K}{M^2} K, \tag{4}$$

where ρ is the local matter density and μ is a bare mass parameter. In dense or high-curvature environments m_{eff} becomes large and the scalar-mediated force is short-ranged, ensuring agreement with Solar System tests. Furthermore, couplings to fundamental particles are constrained by precision experiments such as neutron EDM measurements [10].

3 Background cosmology

On a spatially flat Friedmann–Robertson–Walker background with scale factor $a(t)$, the Hubble parameter $H = \dot{a}/a$ obeys

$$H^2(a) = H_0^2 \Big[\Omega_r a^{-4} + \Omega_b a^{-3} + \Omega_\varphi(a)\Big], \tag{5}$$

where Ω_r and Ω_b are the present-day radiation and baryon density fractions, and $\Omega_\varphi(a) \equiv \rho_\varphi(a)/\rho_{\text{crit},0}$ is the scalar contribution with

$$\rho_\varphi(a) = \rho_{\varphi,0} \exp\left[3 \int_a^1 \frac{1 + w_\varphi(a')}{a'}\, \mathrm{d}a'\right], \qquad w_\varphi(a) \equiv \frac{p_\varphi}{\rho_\varphi}. \tag{6}$$

In the detailed MMA-DMF implementation [1] the scalar background behaves effectively as three modules: an early-time bump ("Early-X") active near radiation–matter equality, a transient pre-CMB component that decays back into radiation before recombination, and a late-time component ("Late-X") responsible for the present acceleration. Here we simply model $w_\varphi(a)$ as a smooth function that interpolates between

$$w_\varphi(a) \simeq \begin{cases} +1, & a \ll a_{\text{eq}} \quad \text{(kinetic / reset phase)}, \\ 0, & a_{\text{eq}} \lesssim a \ll a_{\text{DE}} \quad \text{(effectively frozen)}, \\ w_0 \approx -1, & a \sim 1 \quad \text{(late-time acceleration)}, \\ w_\infty > -\frac{1}{3}, & a \gg 1 \quad \text{(future turnaround)}. \end{cases} \tag{7}$$

The early bump enhances $H(z)$ around equality without spoiling BBN or the CMB peaks, while the late-time behaviour with $w_0 \simeq -1$ reproduces the observed background expansion at $z \lesssim 2$.

3.1 Non-singular reset

In the high-curvature regime preceding the hot Big Bang, the term $\beta_K \varphi^2 K/M^2$ makes the scalar effectively heavy and can trigger a non-singular "reset" or bounce, satisfying

$$H = 0, \qquad \dot{H} > 0, \qquad \rho_{\text{tot}} + 3p_{\text{tot}} < 0, \tag{8}$$

without introducing ghost instabilities. The details depend on the precise form of K and $V(\varphi)$ and are discussed elsewhere; for the purposes of this paper we simply assume that such a reset occurs and that the post-reset initial conditions correspond to a hot radiation bath plus a scalar field with the effective equation of state given above.

3.2 Future turnaround

At late times the scalar rolls away from the $w \approx -1$ plateau towards a regime with $w_\infty > -1/3$. As a result, the scalar energy density redshifts faster than a cosmological constant, and the Hubble rate $H(a)$ eventually vanishes at a scale factor $a_{\text{turn}} \gg 1$ determined by

$$H^2(a_{\text{turn}}) = 0 \quad \Rightarrow \quad \Omega_r a_{\text{turn}}^{-4} + \Omega_b a_{\text{turn}}^{-3} + \Omega_\varphi(a_{\text{turn}}) = 0. \tag{9}$$

Beyond a_{turn} the Universe enters a contracting phase. For the parameter choices consistent with current data, a_{turn} lies many orders of magnitude in the future and has no impact on present observations.

4 Linear perturbations and growth

In Newtonian gauge, the scalar perturbations of the metric are written as

$$\mathrm{d}s^2 = -(1 + 2\Psi)\mathrm{d}t^2 + a^2(t)(1 - 2\Phi)\mathrm{d}\boldsymbol{x}^2. \tag{10}$$

On sub-horizon scales and in the quasi-static approximation, the modified Poisson equation for the Newtonian potential Ψ can be written as

$$k^2\Psi = -4\pi G a^2 \mu(a,k) \rho_b \delta_b, \tag{11}$$

where ρ_b is the baryon density, δ_b its contrast and $\mu(a,k)$ parametrises the enhancement of gravity due to the scalar. The lensing potential depends on the combination $\Phi + \Psi$; in the no-slip implementation used here we impose

$$\Sigma(a,k) = 1, \qquad \eta(a,k) \equiv \frac{\Phi}{\Psi} = 1, \tag{12}$$

so that light deflection is unchanged with respect to GR for a given mass distribution, while the growth of structure is modified through $\mu(a,k)$.

The linear growth factor $D(a)$ obeys

$$D''(a) + \left[2 + \frac{\mathrm{d}\ln H}{\mathrm{d}\ln a}\right] D'(a) - \frac{3}{2}\,\Omega_b(a)\,\mu(a,k)\,D(a) = 0, \tag{13}$$

where primes denote derivatives with respect to $\ln a$ and $\Omega_b(a)$ is the baryon fraction at scale factor a. The growth rate is defined as $f(a) = \mathrm{d}\ln D/\mathrm{d}\ln a$, and the observable combination

$$f\sigma_8(z) = f(z)\,\sigma_8(z), \qquad \sigma_8(z) = \sigma_{8,0}\,\frac{D(z)}{D(0)}. \tag{14}$$

For comparison with weak-lensing surveys we also define

$$S_8^{\rm eff} \equiv \sigma_8(0) \left(\frac{\Omega_m^{\rm eff}}{0.3} \right)^{1/2}, \tag{15}$$

where $\Omega_m^{\rm eff}$ is the effective clustering density generated by the enhanced gravitational coupling. In the MMA-DMF fits one typically finds $S_8^{\rm eff} \simeq 0.80$, compatible with KiDS, DES and HSC and relieving the S_8 tension of ΛCDM, while maintaining a high value of H_0 inferred from early-time data.

5 Summary and outlook

We have presented a compact effective-field-theory description of a scalar completion of Einstein gravity in which a single scalar field φ replaces the dark sector at the level of cosmological phenomenology. The model realises a non-singular reset, an early-time enhancement of the expansion rate, a standard hot Big Bang era, late-time acceleration and a future turnaround within one coherent scalar–tensor framework, while remaining consistent with CMB, BAO, H_0, large-scale structure and local tests of gravity.

Future work will refine the confrontation with high-precision data from Euclid, LSST, DESI and CMB-S4, and explore in more detail the microphysical origin of the scalar sector, including its possible role in baryogenesis and the resolution of the strong CP problem.

Appendix: Example parameter values

Table 1 lists an illustrative set of parameters for which the model reproduces the main cosmological observables while remaining dark-sector free.

Parameter	Value	Comment
H_0	$72\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$	CMB/BAO calibrated
$\Omega_b h^2$	0.0224	BBN prior
$f_{\rm peak}$	0.36	Early bump amplitude
w_0	-1.01	Present-day scalar EoS
w_∞	-0.8	Future asymptotic EoS
$S_8^{\rm eff}$	0.80	Linear clustering amplitude

Table 1: Illustrative parameter set for the scalar-completed Einstein gravity model.

References

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