

PAPER • OPEN ACCESS

Dark energy in light of the early JWST observations: case for a negative cosmological constant?

To cite this article: Shahnawaz A. Adil *et al* JCAP10(2023)072

View the [article online](#) for updates and enhancements.

Dark energy in light of the early JWST observations: case for a negative cosmological constant?

Shahnawaz A. Adil,^a Upala Mukhopadhyay,^b Anjan A. Sen^b
and Sunny Vagnozzi^{c,d}

^aDepartment of Physics, Jamia Millia Islamia,
Jamia Nagar, New Delhi-110025, India

^bCentre for Theoretical Physics, Jamia Millia Islamia,
Jamia Nagar, New Delhi-110025, India

^cDepartment of Physics, University of Trento,
Via Sommarive 14, 38122 Povo (TN), Italy

^dTrento Institute for Fundamental Physics and Applications (TIFPA)-INFN,
Via Sommarive 14, 38122 Povo (TN), Italy

E-mail: shahnawaz188483@st.jmi.ac.in, rs.umukhopadhyay@jmi.ac.in,
aasen@jmi.ac.in, sunny.vagnozzi@unitn.it

Received July 26, 2023

Revised September 18, 2023

Accepted September 27, 2023

Published October 27, 2023

Abstract. Early data from the James Webb Space Telescope (JWST) has uncovered the existence of a surprisingly abundant population of very massive galaxies at extremely high redshift, which are hard to accommodate within the standard Λ CDM cosmology. We explore whether the JWST observations may be pointing towards more complex dynamics in the dark energy (DE) sector. Motivated by the ubiquity of anti-de Sitter vacua in string theory, we consider a string-inspired scenario where the DE sector consists of a negative cosmological constant (nCC) and a evolving component with positive energy density on top, whose equation of state is allowed to cross the phantom divide. We show that such a scenario can drastically alter the growth of structure compared to Λ CDM, and accommodate the otherwise puzzling JWST observations if the dynamical component evolves from the quintessence-like regime in the past to the phantom regime today: in particular, we demonstrate that the presence of a nCC (which requires a higher density for the evolving component) plays a crucial role in enhancing the predicted cumulative comoving stellar mass density. Our work reinforces the enormous potential held by observations of the abundance of high- z galaxies in probing cosmological models and new fundamental physics, including string-inspired ingredients.

Keywords: dark energy experiments, dark energy theory, high redshift galaxies

ArXiv ePrint: [2307.12763](https://arxiv.org/abs/2307.12763)



Contents

1	Introduction	1
2	Dark energy models	3
3	High-redshift galaxy observables	7
3.1	Density perturbations and growth factor	7
3.2	Comoving number and mass densities	9
4	Comparison to the JWST observations	12
5	Conclusions	14

1 Introduction

It is now 25 years since the discovery of cosmic acceleration [1, 2], which led to what is perhaps one of the biggest paradigm shifts in cosmology. While the microphysics underlying cosmic acceleration remains as of yet unknown, the phenomenology thereof is better understood, and usually ascribed to a dark energy (DE) component with negative pressure but positive energy density [3]. In fact, observations are in good agreement with the concordance Λ CDM model where DE takes the form of a cosmological constant (CC) Λ , whose microphysical origin is to be sought in the zero-point vacuum energy density of quantum fields [4]. Nevertheless, there are good reasons to believe that a (positive) CC might not be the end of the story: from the theoretical perspective, the expected value of Λ is at odds — to use an euphemism — with the tiny value required to fit observations [5], whereas more recently from the data side, a number of tensions plaguing the Λ CDM model (e.g. tensions affecting the Hubble constant H_0 [6–15] and the amplitude of matter fluctuations S_8 [16–18]) might call for new physics in the DE sector. These and other considerations have motivated a wide range of beyond- Λ DE models, several of which based on the dynamics of scalar fields (with no claims as to completeness, see e.g. refs. [19–75]).

A feature common to most quintessence scalar field DE models is the positivity of the field potential’s ground state, corresponding to a stable or meta-stable de Sitter (dS) vacuum. Interestingly, constructing consistent dS vacua in string theory has proven to be a daunting task, to the point that it has been speculated that string theory may harbor no dS vacua at all [76], or at least no stable ones (as advocated by the swampland program, with important cosmological implications [77–86]). On the other hand anti-de Sitter (AdS) vacua, corresponding to a negative CC (nCC), are ubiquitous within string theory. There are various reasons why this is the case, one of them being the celebrated AdS/CFT correspondence [87], and more generally the enormous difficulties in formulating a consistent Quantum Field Theory in dS space [88], from the choice of vacuum state to the (non)-existence of a well-defined S-matrix. In more detail, string theory vacua should be solutions to supergravity theories, and these are typically unstable against quantum/stringy corrections unless they are supersymmetric vacua. There are no known supersymmetric dS vacua in string theory, as the Hamiltonian is a positive-definite operator in any supersymmetric algebra, and dS space does not possess a globally defined time-like Killing vector (along which the Hamiltonian

would generate translations) [89]. This is the reason why it is easy to construct Freund-Rubin $AdS_p \times S^q$ compactifications [90] in $p + q$ -dimensional (super)gravity theories with a q -form field strength [91]. These can be argued to preserve supersymmetry, and thus to be absolutely stable, explaining the ubiquity of AdS vacua in string theory. Constructing parametrically large, long-lived dS vacua has proven extremely difficult in string theory and, if the swampland program is correct, no stable dS vacua should exist.¹

The above considerations, along with the fact that negative scalar potentials (thus including AdS vacua) are among the best understood quantum gravity backgrounds by virtue of holography [87], provide strong motivations for testing the possible existence of a nCC in the DE sector from the cosmological perspective. Of course, a nCC on its own cannot explain cosmic acceleration, so we require an additional component on top, with positive energy density. One can think of such a scenario as describing a scalar field (quintessence) rolling along a potential whose minimum is an AdS vacuum. Here we shall be even more general and allow for an evolving/dynamical DE component (on top of the nCC) which can cross the phantom divide $w_x = -1$, where w_x is the DE equation of state (EoS).² Such a scenario has been studied earlier in light of various cosmological datasets [104–108],³ and our goal is to open a new window onto this class of models using observations of high- z galaxies.

Although most DE tests are carried out using low- z ($z \lesssim 2$), standard cosmological probes, it is worth studying whether other probes in different redshift ranges may help further shed light on this elusive component. A potentially interesting probe in this sense is the abundance of high- z massive galaxies: these populate high-mass dark matter (DM) haloes, whose mass function and redshift evolution thereof depend strongly on the underlying cosmology, in particular on the background expansion and growth rate, both of which can potentially be drastically altered *even at high redshift* within alternative DE models. The *predicted* abundance of massive DM haloes at a given redshift can be compared to the *observed* abundance of galaxies of given stellar mass in a conservative way bypassing complications introduced by complex galaxy formation physics. In fact, the stellar mass content M_\star of a galaxy is bounded above by the galaxy’s total baryonic matter, whose maximum is determined if the DM halo mass M and cosmic baryon fraction $f_b \equiv \Omega_b/\Omega_m$ are known: $M_\star \leq f_b M$.⁴ As galaxies cannot outnumber their DM haloes, the observed abundance of high- z galaxies of known stellar mass can be used to exclude cosmological models which do not allow for a sufficiently rapid growth of DM haloes, potentially including various DE models, as pointed out in ref. [119].

¹The KKLT [92] and Large Volume Compactification [93] constructions have been argued to provide a mechanism for uplifting AdS vacua into (meta)stable dS vacua, although there is significant debate as to whether the resulting vacua are stable enough.

²Very broadly speaking, one could also argue that such a scenario carries some string motivation. In fact, string compactifications typically predict the existence of a plethora of ultralight (pseudo)scalar particles, which arise from the Kaluza-Klein reduction of higher-dimensional form fields on the topological cycles of the compactification space, in number fixed by the topology of the compactification manifold but typically of order hundreds or more (as in the so-called “string axiverse” scenario) [94–98]. While a single standard, minimally coupled scalar field would have an EoS in the quintessence-like regime $w_x > -1$, multiple interacting scalar fields as well as modified gravity scenarios can lead to an *effective* phantom EoS $w_x < -1$ [99–103]. Broadly speaking, this motivates studying a scenario featuring an evolving DE component, which can potentially cross the phantom divide, on top of a nCC.

³See also ref. [109] for related results, as well as refs. [110–114] for recent works on cosmological implications of an AdS phase in the early Universe, specifically in the context of early dark energy [115].

⁴In general this relation is more properly written as $M_\star = \epsilon f_b M$, where ϵ is the efficiency of converting gas into stars, whose value is expected to be $\epsilon \lesssim 0.2$, with a moderate redshift dependence [116–118].

Such a comparison has become all the more urgent in light of early observations from the long-awaited, next-generation space telescope: the James Webb Space Telescope (JWST) [120], which has given us a first glimpse of high- z galaxy formation. Initial JWST imaging data from NIRC*am* observations of the Cosmic Evolution Early Release Science (CEERS) program have in fact uncovered the existence of a surprisingly abundant (cumulative stellar mass density $\rho_\star \gtrsim 10^6 M_\odot/\text{Mpc}^3$) population of massive galaxies ($M_\star \gtrsim 10^{10.5} M_\odot$) at very high redshift ($7 \lesssim z \lesssim 10$) [121–125]. While these results come with important caveats (e.g. the redshifts are photometric and only a handful have been spectroscopically confirmed [126, 127]), should they hold up to scrutiny, the challenge they would pose to the current concordance Λ CDM model would be huge [128], just as the results from JWST’s predecessor, the Hubble Space Telescope, challenged the then-current and eventually dethroned Einstein- dS model [129–131]: in fact, several works have already started exploring the intriguing possibility that the early JWST results may be calling for new fundamental physics, or more generally the potential of early JWST data to constrain fundamental physics, see e.g. refs. [132–157].⁵

In this paper we shall take a more conservative approach, and assess the potential of the JWST observations in discriminating between different DE models, and in particular in testing the possible existence of a nCC in the DE sector. In fact it was recently argued by ref. [163] that, if taken seriously, the early JWST observations rule out a major portion of the parameter space of dynamical DE models currently consistent with cosmological data. The implications of these conclusions can be very far-reaching. Here we show how these conclusions can be drastically altered if a nCC is introduced in the dark sector. Our results open a new window towards testing an important prediction of string theory using observations of massive, high- z galaxies, with minimal assumptions on galaxy formation.

The rest of this paper is then organized as follows. In section 2 we introduce the nCC and discuss the DE models we consider. In section 3 we discuss the methods used to compute the observables relevant for high- z galaxies. In section 4 we then compare our predicted cumulative stellar mass densities to the abundance of high- z galaxies inferred from JWST observations. Finally, we draw closing remarks in section 5.

2 Dark energy models

We now present the dark energy models considered, some of which include a nCC, while others do not, in order to provide a comparative assessment of the effect of a nCC on the observables studied. For what concerns the DE sector, we do not commit to any specific microphysical model for DE, but rather adopt a general parametrization for an evolving DE EoS $w_x(z)$. Specifically, we shall consider the widely used Chevallier-Polarski-Linder (CPL) parametrization for $w_x(z)$, given by [164, 165]:

$$w_x(z) = w_0 + w_a \frac{z}{1+z}, \quad (2.1)$$

where z denotes redshift, and w_0 and w_a are two constants, with w_0 corresponding to the present-time DE EoS. Clearly, eq. (2.1) corresponds to a Taylor series of the DE EoS in powers of the scale factor $a = (1+z)^{-1}$ around the present value $a_0 = 1$, truncated to first order. There are several reasons why the CPL parametrization is widely used. Firstly, its 2-dimensional nature makes it easy to manage from the computational point of view. Next, and

⁵Of course, the JWST results may also imply our need to rethink the physics of galaxy formation, see e.g. refs. [158–162] for works in this direction.

perhaps most importantly, it has a direct connection to several physical DE models, notably quintessence DE. In fact, after being tested against physical solutions of the Klein-Gordon equation, the CPL parametrization has been shown to be accurate to sub-percent level in recovering observables (e.g. expansion rate and distance measurements) for quintessence DE models for different choices of w_0 and w_a [165–170]. The only other parametrization which has been shown to possess these properties is the 4-parameter Copeland-Corasanti-Linder-Huterer parametrization [171, 172]. While a number of other EoS parametrizations for dynamical DE have been proposed in the literature,⁶ here we shall stick with the CPL parametrization given its appealing properties discussed above. Note that at asymptotically early times, i.e. for $z \rightarrow \infty$, the CPL EoS tends to $w_0 + w_a$. Therefore, even if the DE component is presently in the quintessence-like regime ($w_0 > -1$), if w_a is sufficiently negative the DE component will eventually become phantom in the past — similar considerations of course hold for a DE component which is phantom at present but can become quintessence-like in the past. For a dynamical DE model described by the CPL parametrization, the energy density $\rho_x(z)$ evolves as follows:

$$\rho_x(z) = \Omega_x \rho_{\text{crit}}^{(0)} (1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a \frac{z}{1+z}\right), \quad (2.2)$$

where $\rho_{\text{crit}}^{(0)}$ and $\rho_x^{(0)}$ are the current critical energy density and (positive) energy density of the CPL component respectively, and $\Omega_x \equiv \rho_x^{(0)}/\rho_{\text{crit}}^{(0)}$ is the CPL DE density parameter.

On top of the DE component described by eq. (2.1) we also consider the presence of a nCC in the dark sector, $\Lambda < 0$, with associated nCC density parameter $\Omega_\Lambda = \Lambda/3 < 0$. Considering also the presence of radiation and matter with density parameters Ω_r and Ω_m respectively, and assuming a spatially flat Universe, the first Friedmann equation governing the evolution of the Hubble rate can be expressed in the following form:

$$H^2(z) = H_0^2 \left[\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_x (1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a \frac{z}{1+z}\right) \right], \quad (2.3)$$

where H_0 is the Hubble constant. As we are assuming a spatially flat Universe, the density parameters are not independent, but obey the constraint:

$$\Omega_r + \Omega_m + \Omega_\Lambda + \Omega_x = 1. \quad (2.4)$$

Moreover, it is natural to identify the *combined* DE sector as comprising the CPL component with density parameter Ω_x , and the nCC component with density parameter Ω_Λ , and therefore we make the following identification:

$$\Omega_{\text{DE}} = \Omega_x + \Omega_\Lambda \simeq 1 - \Omega_m, \quad (2.5)$$

where the last equality is approximately true when neglecting the radiation component, completely subdominant today, whereas we can identify the total DE energy density as being:

$$\rho_{\text{DE}}(z) = \rho_x(z) + \rho_\Lambda = \Omega_x \rho_{\text{crit}}^{(0)} (1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a \frac{z}{1+z}\right) + \Omega_\Lambda \rho_{\text{crit}}^{(0)}. \quad (2.6)$$

⁶Most of these have been proposed with phenomenological motivations, see e.g. refs. [173–182] for examples in this sense (see also ref. [183] for a study on the theoretical viability conditions for these parametrizations, and ref. [184] for discussions on potential shortcomings of the CPL parametrization), although the community has been moving towards non-parametric reconstructions of the DE EoS and related quantities, see e.g. refs. [185–194].

Note that it is Ω_{DE} , i.e. the sum of the dynamical DE and nCC components, which is required to be ≈ 0.7 in order to satisfy current observational constraints on the amount of DE. Therefore, observations approximately fix the sum $\Omega_x + \Omega_\Lambda$, but the two terms can in principle take any value (though Ω_Λ itself is subject to order unity constraints from cosmology). Moreover, it is this combined DE sector which has to be able to account for cosmic acceleration. From very general considerations, if Λ takes more negative values (i.e. $|\Omega_\Lambda|$ is increased), then more negative values of w_x , i.e. a dynamical DE component moving towards the phantom regime, are required in order for cosmic acceleration to occur today, in agreement with observations. In general, different combinations of Ω_x and Ω_Λ can lead to a rich phenomenology in the combined DE sector, including periods of transient acceleration potentially followed by a period of future deceleration [107].

Note, in addition, that we can define an effective EoS associated to the total DE sector, which is essentially given by a weighted average of the nCC (with EoS -1) and positive DE (with CPL EoS) components. By using the continuity equation, itself following from local energy conservation as dictated by the twice contracted Bianchi identity, the effective equation of state $w_{\text{eff}}(z)$ of the DE sector, with total energy density ρ_{DE} given by eq. (2.6), can be written as:

$$\begin{aligned}
 w_{\text{eff}}(z) &= \frac{1}{3} \frac{d \ln \rho_{\text{DE}}(z)}{d \ln(1+z)} - 1 = \frac{1+z}{3\rho_{\text{DE}}(z)} \frac{d\rho_{\text{DE}}(z)}{dz} - 1 \\
 &= \frac{\Omega_x(1+z)^{2+3w_0+3w_a} [w_0 + (w_0 + w_a)z] \exp\left(-3w_a \frac{z}{1+z}\right) - \Omega_\Lambda}{\Omega_x(1+z)^{3(1+w_0+w_a)} \exp\left(-3w_a \frac{z}{1+z}\right) + \Omega_\Lambda} \quad (2.7)
 \end{aligned}$$

which reduces to $(w_0\Omega_x - \Omega_\Lambda)/(\Omega_x + \Omega_\Lambda)$ as $z \rightarrow 0$, showing that the present-day effective EoS of the DE sector is $w_{\text{eff}}(z=0) \neq w_0$ unless $\Omega_\Lambda = 0$. It is easy to show that eq. (2.7) can also be obtained by taking the ratio between the total pressure of the DE sector and its total energy density, where the latter is given by eq. (2.6), and the nCC contributes with a positive pressure term $P_\Lambda = -\Omega_\Lambda \rho_{\text{crit}}^{(0)} > 0$.

In the following, our aim is to investigate the effect of a nCC on high- z galaxies, such as those observed by the JWST. In order to do so, we shall consider 9 different models, corresponding to 9 different choices of the CPL parameters w_0 and w_a , and the nCC parameter Ω_Λ , appearing in eq. (2.3). The 9 models we consider feature different combinations of phantom and quintessence-like DE components, with and without phantom crossing and/or a nCC component, and are given as follows:

- 1) Λ CDM model (positive CC): $w_0 = -1$, $w_a = 0$, $\Omega_\Lambda = 0$, $\Omega_x = 0.7$;
- 2) quintessence-like DE ($w_x > -1$) with constant DE EoS and no nCC: $w_0 = -0.95$, $w_a = 0$, $\Omega_\Lambda = 0$, $\Omega_x = 0.7$;
- 3) phantom DE ($w_x < -1$) with constant DE EoS and no nCC: $w_0 = -1.05$, $w_a = 0$, $\Omega_\Lambda = 0$, $\Omega_x = 0.7$;
- 4) dynamical DE which is quintessence-like today ($w_x > -1$), but was phantom in the past, with no nCC: $w_0 = -0.95$, $w_a = -1$, $\Omega_\Lambda = 0$, $\Omega_x = 0.7$;
- 5) dynamical DE which is phantom today ($w_x < -1$), but was quintessence-like in the past, with no nCC: $w_0 = -1.05$, $w_a = 1$, $\Omega_\Lambda = 0$, $\Omega_x = 0.7$;

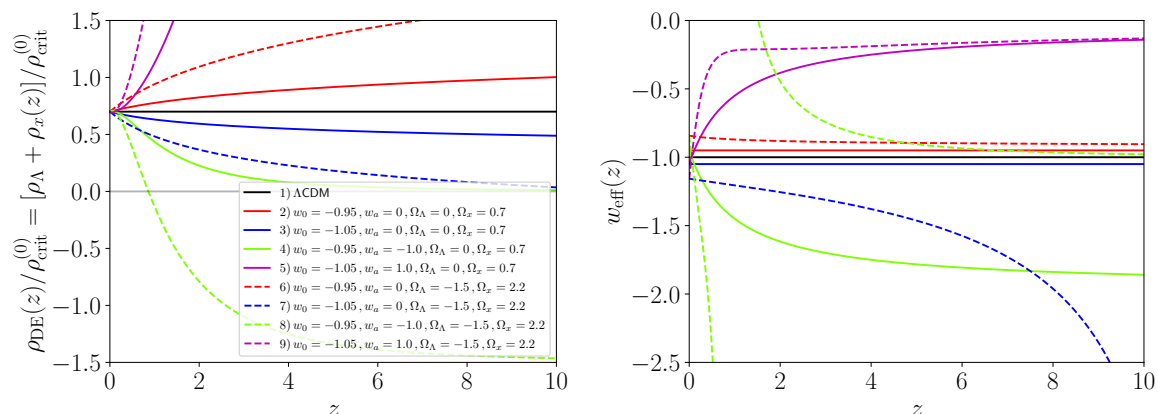


Figure 1. *Left panel:* evolution of the total dark density (negative cosmological constant plus evolving dark energy) as a function of redshift, given by eq. (2.6) and divided by the critical density, for the 9 different dark energy models summarized in section 2, as determined by the color coding. *Right panel:* evolution of the effective equation of state of the dark energy sector as a function of redshift, given by eq. (2.7), for the 9 different dark energy models summarized in section 2, and with the same color coding as in the left panel. The appearance of poles in the effective equation of state for models 7) and 8) is a direct consequence of the corresponding energy densities changing sign at a certain redshift, as is clear from the left panel (the horizontal grey line corresponds to $\rho_{\text{DE}} = 0$).

- 6) as in case 2), but with an additional nCC: $w_0 = -0.95, w_a = 0, \Omega_{\Lambda} = -1.5, \Omega_x = 2.2$;
- 7) as in case 3), but with an additional nCC: $w_0 = -1.05, w_a = 0, \Omega_{\Lambda} = -1.5, \Omega_x = 2.2$;
- 8) as in case 4), but with an additional nCC: $w_0 = -0.95, w_a = -1, \Omega_{\Lambda} = -1.5, \Omega_x = 2.2$;
- 9) as in case 5), but with an additional nCC: $w_0 = -1.05, w_a = 1, \Omega_{\Lambda} = -1.5, \Omega_x = 2.2$.

Note that in all cases, the total present-day density parameter of the DE sector [Ω_{DE} given in eq. (2.5)] is 0.7, resulting from a combination of a nCC and a positive evolving CPL DE density. Finally, we note that models such as 4), 5), 8), and 9), featuring crossing between the phantom and quintessence-like regimes (in either direction) have also been referred to as “quintom” models in the literature [195–204], see e.g. ref. [205] for a review.

In figure 1, we show the redshift evolution of the energy density and effective EoS of the total DE component, given by eq. (2.6) and eq. (2.7) respectively, for the 9 models described above. Note that for models 7) and 8), featuring a nCC and respectively a phantom DE component and a quintom DE component (phantom in the past), the total DE energy density changes sign at sufficiently high redshift. In particular, for the choice of parameters given above, the sign switch occurs at redshift $z_p \sim 0.86$ for model 7), and at $z_p \sim 11.85$ for model 8), although the latter is not visible in the figure. This sign change is reflected in the presence of a pole in the corresponding effective EoS (hence the subscript “ p ” in the pole redshift z_p), which diverges to negative infinity as $z \rightarrow z_p^-$, and to positive infinity as $z \rightarrow z_p^+$. This divergence does not signal a pathology, as the quantity which diverges is only the *effective* EoS of the total DE sector (nCC plus CPL DE component), which is an useful effective quantity but cannot otherwise be associated to a single fundamental microscopical degree of freedom. More importantly, the appearance of a pole in the effective EoS of a sign-switching perfect fluid component in a spatially uniform Universe has recently been rigorously demonstrated to

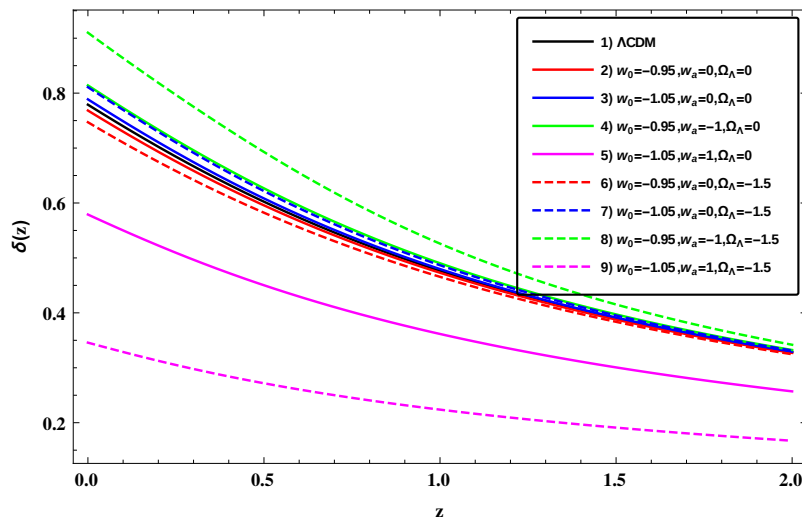


Figure 2. Evolution of the linear matter density contrast as a function of redshift, for the 9 different dark energy models summarized in section 2, with the same color coding as in figure 1.

be a consequence of local energy conservation, regardless of the underlying sources which are responsible for the sign switch [206]. As such, the appearance of poles in the green dotted and blue dotted curves (the latter not visible given the plotted redshift range) of figure 1 should not come as a surprise. Rather they show the importance, especially in the context of non-parametric reconstructions, of focusing on the total DE energy density rather than its effective EoS, as stressed in ref. [206].

3 High-redshift galaxy observables

We now discuss the methods used to compute the observables relevant for high- z galaxies, which include the structure growth rate, as well as comoving (cumulative) number or mass (stellar mass or DM halo mass) densities.

3.1 Density perturbations and growth factor

To account for the effects on high- z galaxies of the different DE models considered, described in section 2, the first step is to compute the evolution of the matter density contrast $\delta(a)$. On sub-horizon scales, i.e. those relevant for galaxy formation, and assuming that DE does not cluster, the evolution of δ is governed by the following growth equation:

$$\delta'' + \left(\frac{3}{a} + \frac{E'}{E} \right) \delta' - \frac{3}{2} \frac{\Omega_m}{a^5 E^2} \delta = 0, \quad (3.1)$$

where $'$ indicates a derivative with respect to the scale factor a , and $E(a) \equiv H(a)/H_0$ denotes the normalized expansion rate. Therefore, besides modifying the background expansion rate given by eq. (2.3), the different DE models we consider also affect the growth of structure by altering $E(a)$ in eq. (3.1).

We solve eq. (3.1) numerically for the 9 DE models presented in section 2, setting initial conditions $\delta(a_i) \sim a$ and $\delta'(a_i) \sim 1$ at some initial scale factor $a_i \ll 1$ deep in the matter-dominated era. The result is shown in figure 2, where we plot $\delta(z)$. From this figure,

taking as reference the black curve corresponding to Λ CDM, we notice a few interesting points.

- Whether a DE model leads to larger or smaller density contrasts relative to Λ CDM appears to be driven by whether the models are quintessence-like or phantom *in the past* rather than today. In fact, neglecting for the moment the nCC, we see that the two models which lead to larger density contrasts relative to Λ CDM are model 3) with constant phantom EoS (blue curve), and model 4) which was phantom in the past, but crossed the phantom divide and is quintessence-like today (green curve). In contrast, the two models which lead to smaller density contrasts relative to Λ CDM are model 2) with constant quintessence-like EoS (red curve), and model 5) which was quintessence-like in the past, but crossed the phantom divide and is phantom today (purple curve).
- Adding a nCC exacerbates all the previous effects: to see this, compare solid versus dashed curves for a fixed color. In other words, models which previously led to larger density contrasts relative to Λ CDM now see their enhancement effect amplified [3) \rightarrow 7) and 4) \rightarrow 8)], and conversely models which previously led to smaller density contrasts relative to Λ CDM see their suppression effect amplified [2) \rightarrow 6) and 5) \rightarrow 9)].

Overall, the inclusion of a nCC therefore amplifies in either direction the effects of dynamical DE on structure growth.

The previous findings can be understood as follows. When looking back in time, or equivalently going to higher redshift, and keeping all other parameters fixed, phantom models lead to a lower expansion rate relative to Λ CDM (or equivalently a stronger acceleration as one moves towards lower redshifts). This suppression in $E(z)$ results in an enhancement of the driving term $\propto 1/E^2$ appearing in eq. (3.1), explaining why the effect of phantom DE is to enhance the growth of structure, in agreement with previous findings. These effects are exacerbated by the inclusion of a nCC simply because, by virtue of eq. (2.5), including a nCC requires increasing Ω_x in order for $\Omega_{\text{DE}} \sim 0.7$ to hold: to put it differently, a nCC opposes cosmic acceleration, and therefore one requires a larger positive evolving DE density to counteract this effect and remain in agreement with observations. This therefore enhances the DE effects because the energy density of the evolving component, Ω_x , is increased. In some sense, the effect of the nCC on the growth of structure is therefore indirect, resulting from a parameter shift enforced by eq. (2.5) and, ultimately, by eq. (2.4).⁷

One further important quantity is the growth factor, which in linear perturbation theory is defined as:

$$D(z) \equiv \frac{\delta(z)}{\delta(0)}, \quad (3.2)$$

and can therefore be calculated from eq. (3.1). Once we have solved eq. (3.1), we therefore also calculate $D(z)$, with the results shown in figure 3 for the same models considered earlier, and in two different redshift ranges: low [$z \lesssim 2$, left panel (a)] and high [$7 \lesssim z \lesssim 12$, right panel (b)] redshift. Here we find a completely opposite trend relative to that seen in figure 2: in other words, models 3) and 4) which were phantom in the past and led to larger density

⁷It is worth mentioning that we have also calculated δ_c , the critical density contrast for a linear overdensity at the redshift of collapse, using eq. (3.1) and following refs. [207–209]. Specifically, we have first solved the full non-linear equation for the evolution of the density contrast and found the initial condition for which spherical collapse or divergence of δ occurs at $z \sim 7$. We have then solved the linear equation for the evolution of the density contrast, and used this to determine δ_c . We have found that for all DE models described in section 2, $\delta_c \simeq 1.686$ holds at high redshift.

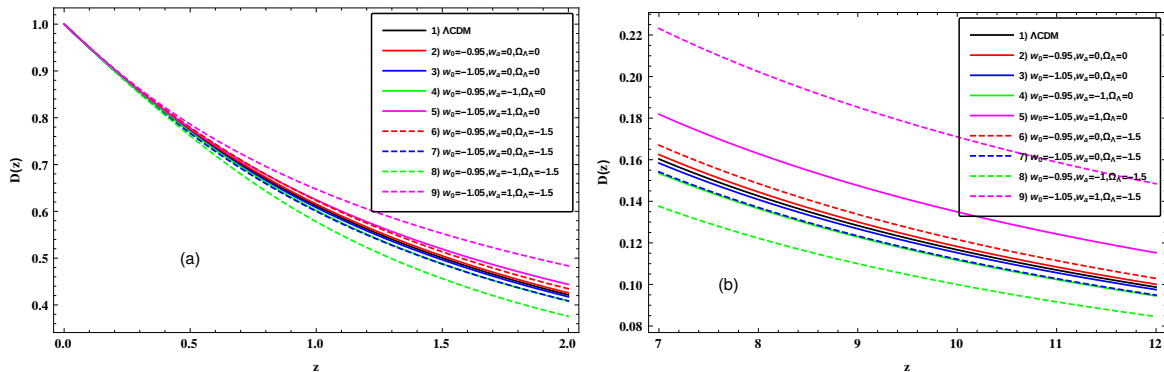


Figure 3. Evolution of the growth factor as a function of redshift, for the 9 different dark energy models summarized in section 2, with the same color coding as in figure 1. The evolution is shown for both low redshifts [$0 \leq z \leq 2$, left panel (a)] and high redshifts [$7 \leq z \leq 12$, right panel (b)].

contrasts relative to Λ CDM, in this case lead to a lower growth factor — conversely, models 2) and 5) which were quintessence-like in the past and led to smaller density contrasts relative to Λ CDM, in this case lead to a larger growth factor. Again, however, we see that adding a nCC exacerbates all these effects (once more, compare solid versus dashed curves for a fixed color). While perhaps somewhat counterintuitive, this effect can be understood from the fact that $\delta(0)$ appears in the denominator of eq. (3.2). The reason why a nCC exacerbates these effects remains the same as the one discussed earlier, and is therefore somewhat indirect, as a result of the required increase in Ω_x once a negative Ω_Λ is introduced.

By construction, all the growth factors are equal to each other at $z = 0$: $D(0) = 1$. In contrast, we see that the growth factors for the different DE models can deviate significantly from the Λ CDM evolution at high redshift, as the lower panel of figure 3 clearly shows for the redshift range $7 \lesssim z \lesssim 12$. Overall, the model which most strongly enhances the growth of structure at high redshift is therefore model 9), which features a nCC, was quintessence-like in the past, but crossed the phantom divide at some point and is therefore phantom today (dashed purple curves). Qualitatively, we can therefore already expect this model to lead to the strongest enhancement in the abundance of high- z galaxies, of interest for the JWST observations given the considerations made in section 1: this expectation will be confirmed quantitatively in section 4. To showcase these effects more clearly, in figure 4 we plot the (percent) relative deviation between the growth factors of the different dark energy models: $\Delta D/D \equiv (D(z)_{\text{DE}} - D(z)_{\Lambda\text{CDM}})/D(z)_{\Lambda\text{CDM}}$. Here we clearly see that the largest deviation is for the phantom-to-quintessence-like-crossing (as time goes on) model with a nCC, whose relative deviation with respect to Λ CDM increases with increasing redshift, before saturating at $\lesssim 50\%$ at redshift $z \sim 10$. We see that other models lead to a smaller relative growth (or suppression), and that in all cases the relative deviation with respect to Λ CDM saturates at sufficiently high redshift.

3.2 Comoving number and mass densities

We now proceed to compute comoving (cumulative) number or mass (stellar mass or DM halo mass) densities for the different models considered. To compute these quantities we adopt the Sheth-Tormen (ST) prescription [210], itself extending the Press-Schechter (PS) formalism [211], which we briefly review.

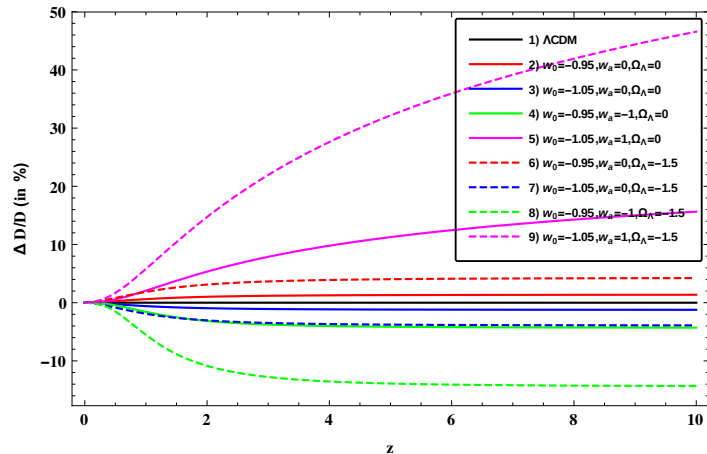


Figure 4. Percent relative deviation between the growth factors of the different dark energy models $[100 \times (D(z)_{\text{DE}} - D(z)_{\Lambda\text{CDM}})/D(z)_{\Lambda\text{CDM}}]$, for the 9 different dark energy models summarized in section 2, with the same color coding as in figure 1.

The DM halo mass function $dn(M, z)/dM$ quantifies the number of DM haloes of mass M per unit mass per unit co-moving volume at redshift z in the mass range $[M; M + dM]$, and is given by:

$$\frac{dn}{dM} = -\frac{\rho_m^{(0)}}{M} \frac{d \ln \sigma}{dM} f(\sigma), \quad (3.3)$$

where $\rho_m^{(0)}$ is the present-day matter energy density, σ is the variance of matter density fluctuations in a sphere of comoving radius R , and $f(\sigma)$ will be defined later. The mass M within the sphere of comoving radius R is given by $M = 4\pi R^3 \rho_m^{(0)}/3$, whereas σ , which is related to the power spectrum of matter density perturbations $P(k, z)$, is defined by:

$$\sigma^2(R, z) = \frac{1}{2\pi^2} \int_0^\infty dk k^2 P(k, z) W^2(kR). \quad (3.4)$$

In the above, we have implicitly moved to Fourier space, where k denotes the perturbation wavenumber, and $W(kR)$ is a window function used to smooth the density field on a certain scale. Here we consider a top-hat filter in real space, whose Fourier transform is given by $W(x) = 3(\sin x - x \cos x)/x^3$. Finally, in eq. (3.4), $P(k, z)$ denotes the power spectrum of matter density fluctuations, which is given by:

$$P(k, z) = P_0(k) T^2(k) D^2(z), \quad (3.5)$$

with $P_0(k)$ a normalization related to the present-day value of σ_8 , whereas $T(k)$ is the transfer function and $D(z)$ is the linear growth factor which we discussed earlier. We use the ST prescription [210], which extended the PS formalism to account for ellipsoidal (rather than spherical) collapse, and for which $f(\sigma)$ is given by:

$$f(\sigma) = A \sqrt{\frac{2a}{\pi}} \left[1 + \left(\frac{\sigma^2}{a\delta_c^2} \right)^p \right] \frac{\delta_c}{\sigma} \exp\left(-\frac{\delta_c^2 a}{2\sigma^2} \right), \quad (3.6)$$

where the three parameters are given by $A = 0.322$, $a = 0.707$, and $p = 0.3$ respectively, and the PS mass function is recovered in the limit $a \rightarrow 1$ and $p \rightarrow 0$.⁸

Finally, the quantity of interest to high-redshift galaxy observations is the cumulative comoving DM halo number density $n(> M_{\text{halo}}, z)$, which quantifies the number density of haloes above a given mass threshold M_{halo} , and is given by [128]:

$$n(> M_{\text{halo}}, z) = \int_{M_{\text{halo}}}^{\infty} dM \frac{dn(M, z)}{dM}. \quad (3.7)$$

A closely related quantity is the cumulative halo mass density $\rho(> M_{\text{halo}}, z)$, given by [128]:

$$\rho(> M_{\text{halo}}, z) = \int_{M_{\text{halo}}}^{\infty} dM M \frac{dn(M, z)}{dM}. \quad (3.8)$$

Finally, given values for the cosmic baryon fraction $f_b \equiv \Omega_b/\Omega_m$ and the efficiency of converting gas into stars $\epsilon \leq 1$, eqs. (3.7), (3.8) straightforwardly translate into the cumulative comoving number density of galaxies more massive than M_* [$n_{\text{gal}}(> M_*, z)$], the cumulative comoving mass density of stars contained in halos more massive than M_{halo} [$\rho_*(> M_{\text{halo}}, z)$], and finally the cumulative comoving mass density of stars contained in galaxies more massive than M_* : $\rho_*(> M_*, z)$, which is the quantity we will be most interested in for what concerns the comparison to JWST observations. To be explicit, $\rho_*(> M_*, z)$ is given by:

$$\rho_*(> M_*, z) = \epsilon f_b \rho(> M_{\text{halo}}, z) = \epsilon f_b \int_{M_{\text{halo}}}^{\infty} dM M \frac{dn(M, z)}{dM}, \quad (3.9)$$

which directly follows from the identification $M_* = \epsilon f_b M_{\text{halo}}$. Clearly, a measured/inferred value ρ_{obs} of the cumulative comoving stellar mass density at a certain z requires the underlying cosmology-dependent value of $\rho_*(> M_*, z)$ to be at least as large as ρ_{obs} when $\epsilon = 1$, i.e. in the most conservative and optimistic (but unrealistic) case [163].⁹ Finally, note that if one chooses to focus on a narrow redshift range $z \in [z_1; z_2]$ instead of a single (effective) redshift, eq. (3.9) should be modified as follows:

$$\rho_*(> M_*, z) = \epsilon f_b \int_{M_{\text{halo}}}^{\infty} dM M \frac{dn(M, z)}{dM} \frac{dV}{dz} \frac{dz}{V(z_1, z_2)}, \quad (3.10)$$

where V is the cosmic volume, such that $dV/dz = 4\pi d_L^2/[H(z)(1+z)^2]$, with d_L the luminosity distance, and $V(z_1, z_2)$ is the cosmic volume in the appropriate redshift range. For our purposes, we have checked that using eq. (3.10) with reasonable redshift limits in place of eq. (3.9) makes little to no difference. Therefore, for simplicity we stick to eq. (3.9) in what follows.

In what follows, we set our cosmological parameters (relevant to compute the expansion rate and matter power spectrum) to the following values: $H_0 = 67.32$ km/s/Mpc, $\Omega_m = 0.3158$,

⁸Although in principle high-resolution N-body simulations may provide better fitting functions compared to ST mass function [212, 213], here we have opted for using the ST mass function as we are only interested in providing a first assessment of the potential viability of DE models featuring a nCC in light of JWST data, leaving a more refined analysis to future work, should these models be found to be interesting in this context.

⁹In principle we would need to correct the observed densities ρ_{obs} by a ‘‘volume factor’’ to account for the fact that the densities derived in ref. [125] explicitly assumed a Λ CDM cosmology, and similarly we would need to correct the measured masses by a ‘‘luminosity distance factor’’ to account for the fact that ref. [125] also inferred the latter from measured luminosities assuming Λ CDM. In practice, we have checked that both corrections are small for the values of the parameters considered here. Therefore, in the interest of carrying out an exploratory study, to zeroth order we neglect both corrections, which are subdominant to the effects of evolving DE and a nCC.

$\Omega_b = 0.049$, $n_s = 0.96605$, and $\sigma_8 = 0.812$. For what concerns the parameters more of astrophysical interest, we set $f_b = 0.156$, $\epsilon = 0.32$, and $\delta_c = 1.686$, unless otherwise stated. We have explicitly checked that reasonable excursions around these values have very little effect on our conclusions.

4 Comparison to the JWST observations

Using $1 - 5 \mu\text{m}$ coverage data for galaxies identified by JWST NIRCcam observations of the CEERS program, ref. [125] recently searched for intrinsically red, extremely massive galaxies at $7.5 \lesssim z \lesssim 10$, finding six candidate galaxies with stellar masses $\gtrsim 10^{10} M_\odot$. If the fiducial masses of these galaxies are confirmed, and most importantly their redshifts verified spectroscopically, the inferred cumulative comoving stellar mass density is of order $\rho_\star(> 10^{10} M_\odot) \gtrsim 10^6 M_\odot/\text{Mpc}$ at $z \simeq 10$, significantly higher than anticipated from earlier studies based on rest-frame UV-selected samples [214]. Although issues related to calibration and the assumed initial mass function are still under debate [215], if confirmed, these early results are difficult if not impossible to realize within standard ΛCDM cosmologies. Our goal here is to examine whether an extended DE sector of the type discussed earlier, featuring a dynamical DE component in addition to a nCC, can potentially support the existence of this unexpectedly abundant population of extremely massive galaxies at very high redshift. We envisage this as being mostly an exploratory study, to work out whether such a possibility is even worth pursuing, and therefore shall limit ourselves to a zeroth order comparison between theory and observations, while leaving a significantly more detailed statistical analysis, whose goals would also include a stage of parameter inference, to follow-up work.

We compute the cumulative comoving stellar mass density within galaxies with stellar mass above M_\star , $\rho_\star(> M_\star)$, for the 9 different DE models discussed in section 2, and for 4 representative redshifts: $z = 2$, $z = 7.5$, $z = 9.1$, and $z = 10$. In particular, the latter three redshifts are representative of the redshift range probed by the analysis of JWST NIRCcam CEERS data in ref. [125]. In figure 5 we show the theoretical predictions for $\rho_\star(> M_\star)$ versus M_\star , alongside (for the three highest redshift bins) the cumulative stellar mass density inferred from the six most massive high- z galaxies studied in ref. [125], divided into three (effective) redshift bins.¹⁰ From these plots, which we remark once more have been obtained assuming an efficiency of converting gas into stars $\epsilon = 0.32$, high but not completely unrealistic, it is clear that these observations are in strong tension with the standard ΛCDM cosmology (given the assumed choice of cosmological parameters, in particular Ω_m , H_0 , and σ_8), whose predictions are represented by the solid black curve.

It is interesting to note that the differences between the different DE models considered, for what concerns the cumulative stellar mass density, are more noticeable at higher redshifts. In particular, as we will discuss in more detail shortly, for some of the DE models considered and in certain mass ranges, ρ_\star can be up to a couple of orders of magnitude larger compared to the ΛCDM prediction. This is in agreement with the earlier results shown in figure 3 and figure 4, in turn reflecting the fact that the growth factor $D(z)$, which is the quantity relevant for computing the linear power spectrum $P(k)$ and hence the halo mass function dn/dM , is

¹⁰It is worth clarifying once more that we have not included the volume factor and luminosity distance factor corrections. Had we chosen to include them, it would not have been possible to produce figure 5 in its current form, as each model would require a different correction factor, and therefore it would not have been possible to place all models on the same plot. However, we have checked that the effect of these corrections is small compared to the effects of evolving DE and the nCC.

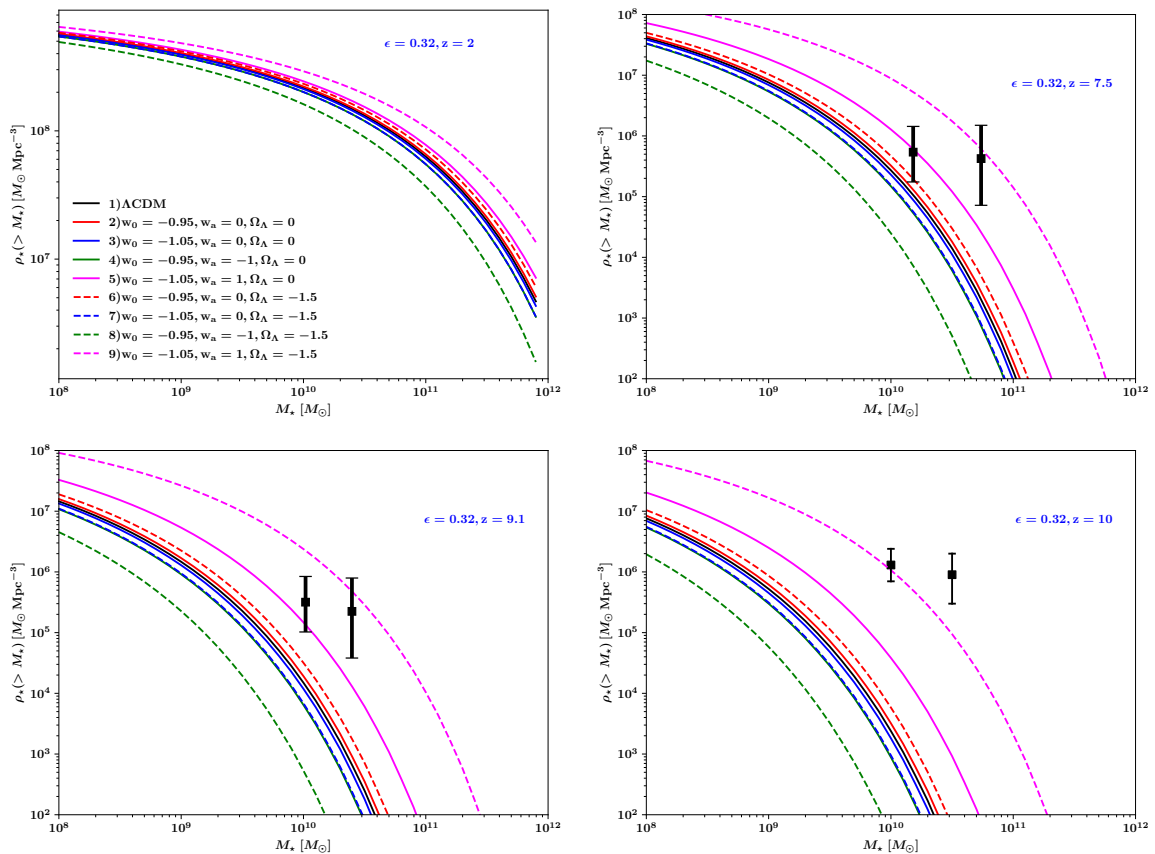


Figure 5. Cumulative comoving stellar mass density as a function of stellar mass, $\rho_*(> M_*, z)$, for the 9 different dark energy models summarized in section 2, with the same color coding as in figure 1. The mass densities have been evaluated assuming a value of the efficiency of converting gas into stars $\epsilon = 0.32$, and at redshifts $z = 2$ (upper left panel), $z = 7.5$ (upper right panel), $z = 9.1$ (lower left panel), and $z = 10$ (lower right panel). The datapoints within the three highest redshift bins are indicative of the cumulative stellar mass density inferred from the six most massive high- z galaxies studied in refs. [125, 132].

normalized to $\delta(z = 0)$. Our results therefore confirm that observations of massive, high- z galaxies (such as those detected by JWST) can potentially shed light on the dynamics of DE, an intrinsically late-time phenomenon, through its indirect imprint on the growth of structure at much higher redshift.

In agreement with the earlier results shown in figure 3 and figure 4 and discussed in section 3.1, we find that the model leading to the most significant departures from Λ CDM is model 9), represented by the dashed magenta curve, where besides a nCC the DE sector consists of a dynamical DE component which is phantom today but was quintessence-like in the past, and hence crossed the phantom divide at some point during its evolution. For the particular choice of parameters made in this work, which we stress once more is made purely for exploratory purposes, the phantom divide is crossed when the scale factor of the Universe is $a_p = (w_0 + w_a + 1)/w_a = 0.95$, or equivalently at redshift $z_p = 1/a_p - 1 = -(w_0 + 1)/(w_0 + w_a + 1) \approx 0.05$.

As we see from the panels corresponding to the highest redshift bins in figure 5, at the masses relevant for the JWST observations the theoretical predictions for the cumulative stellar mass density in these dynamical DE+nCC cosmologies can be up to four orders of magnitude larger compared to Λ CDM, and are in good agreement with the JWST observations, with the only datapoint which is more than 1σ off being that corresponding to the highest mass bin at $z = 10$ (rightmost datapoint in the lower right panel). Moreover, as is clear from the same panels (compare the dashed versus solid magenta curves), the inclusion of the nCC is crucial in order to increase the theoretical predictions for the cumulative stellar mass density, thereby improving agreement with the JWST results. As discussed earlier, the reason is that including a nCC (and hence a larger, more negative Ω_Λ) requires increasing the positive energy density of the dynamical DE component Ω_x in order for $\Omega_{\text{DE}} \approx 0.7$ to hold, in agreement with cosmological observations.

The final interesting point to note is that the combination of phantom DE and a nCC has been shown to possess interesting features in light of the Hubble tension [105, 106, 108]. In fact, due to the well-known negative correlation between w and H_0 , phantom DE and/or effective phantom components (e.g. arising from modified gravity) can help raise H_0 and therefore partially alleviate the Hubble tension, as investigated in a large number of works, see e.g. refs. [216–245].¹¹ These features can be further enhanced in the presence of a nCC, as shown for instance in refs. [251, 252] in the context of DE models for which phantom crossing and negative DE energy densities are allowed, particularly for models where the phantom divide is crossed going from quintessence-like DE at early times to phantom DE today. This makes the combination of phantom DE and a nCC an interesting one in light of the Hubble tension, at least from the phenomenological point of view. An important clarification is however in order. It is known that phantom DE, and more generally late-time new physics, can never fully solve the Hubble tension *alone* while remaining in agreement with Baryon Acoustic Oscillations and Hubble flow Type Ia Supernovae data [253–262]. Therefore, even though the phantom+nCC model is interesting in this regard, we know that it cannot be the end of the story, at least if we take these late-time datasets seriously. Nevertheless, we remark that a DE model displaying phantom nature at late times and quintessence-like nature at early times (with phantom crossing in between), supplemented with a nCC in the dark sector [e.g. our model 9) with $w_0 = -1.05$, $w_a = 1$, $\Omega_\Lambda = -1.5$, and $\Omega_x = 2.2$], remains a phenomenologically very interesting one, given its ability to simultaneously alleviate the Hubble tension (in part) and explain the puzzling JWST observations of high- z galaxies. We thus believe that this class of models is worthy of further studies.

5 Conclusions

The first glimpse of high- z galaxy formation from the James Webb Space Telescope (JWST) has delivered extremely surprising results which, if confirmed spectroscopically and by other means, have the potential to revolutionize our understanding of the Universe. In particular the surprising abundance of massive, high- z galaxies observed by JWST appears to pose a serious challenge for the Λ CDM model and, in turn, can be used to test alternative cosmological models which allow for a faster growth of structure at early times. Our work falls within the

¹¹Conversely, it is known that the simplest quintessence models based on a single scalar field with canonical kinetic term, minimally coupled to gravity, and in the absence of higher derivative operators, are marginally disfavored observationally, as they worsen the Hubble tension [246–250].

promising and fruitful direction of testing new fundamental physics using high- z galaxies:¹² in particular, we have further strengthened the case for the use of the abundance of high- z galaxies inferred from JWST data to test dark energy (DE) models, complementing standard tests of DE which are typically based on probes at very low redshift.

We have considered a DE sector featuring a negative cosmological constant (nCC) and a time-varying DE component with positive energy density, modelled following the CPL parametrization, and allowed to cross the phantom divide $w_x = -1$. Such a scenario carries strong motivation from string theory, where AdS vacua appear ubiquitously, while the construction of stable dS vacua has so far proven extremely hard [76]. We have shown that the combination of phantom-crossing DE (with equation of state $w_x > -1$ in the past and $w_x < -1$ today) and a nCC can enhance structure growth at early times, potentially bringing the predicted cumulative comoving stellar mass density in agreement with the JWST observations, an agreement which cannot be achieved within the standard cosmological model even if star formation is maximally efficient ($\epsilon = 1$). It is worth noting that such a model also has the ability to alleviate (while not fully solving) the Hubble tension [106, 108, 251]. We believe this combination of ingredients is therefore interesting from all three the observational, phenomenological, and theoretical (string-inspired) perspective.

While our work should be intended as an exploratory analysis, it reinforces the enormous potential held by observations of the abundance of high- z galaxies in probing new fundamental physics, including string theory-inspired ingredients. These considerations alone are reason enough to keep exploring this promising direction from multiple related perspectives, one of which could be a first-principles implementation of well-motivated string scenarios, going beyond the phenomenological parametrization we have adopted, as done for example in refs. [60, 268]. Another interesting direction to pursue would be that of performing a complete statistical/parameter inference analysis in light of JWST observations (which would require a more careful treatment of the volume and luminosity distance factor corrections), as well as a more detailed study of the complementarity between the latter and standard cosmological probes [269, 270]. In particular, such an analysis would allow us to constrain the DE parameters w_0 , w_a , and Ω_Λ from a joint analysis of JWST data and standard cosmological data, allowing us to assess the degree to which the nCC scenario we have studied is preferred (if any) over Λ CDM. All of these directions are potentially extremely fruitful, and we plan to report on these and related results in future work.

Acknowledgments

We are grateful to Chethan Krishnan, Nicola Menci, Eoin Ó Colgáin, Ruchika, and Shahin Sheikh-Jabbari for useful discussions. A.A.S. and U.M. acknowledge support from the Science and Engineering Research Board (SERB) of the Government of India through research grant no. CRG/2020/004347. S.A.A., U.M., and A.A.S. acknowledge the use of the High Performance Computing facility Pegasus at IUCAA, Pune, India. S.V. acknowledges support from the Istituto Nazionale di Fisica Nucleare (INFN) through the Iniziativa Specifica “FieLds And Gravity” (FLAG). This publication is based upon work from COST Action CA21136 — “Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)”, supported by COST (European Cooperation in Science and Technology).

¹²See also refs. [263–267] for related works in this direction.

References

- [1] SUPERNOVA SEARCH TEAM collaboration, *Observational evidence from supernovae for an accelerating universe and a cosmological constant*, *Astron. J.* **116** (1998) 1009 [[astro-ph/9805201](#)] [[INSPIRE](#)].
- [2] SUPERNOVA COSMOLOGY PROJECT collaboration, *Measurements of Ω and Λ from 42 high redshift supernovae*, *Astrophys. J.* **517** (1999) 565 [[astro-ph/9812133](#)] [[INSPIRE](#)].
- [3] D. Huterer and D.L. Shafer, *Dark energy two decades after: Observables, probes, consistency tests*, *Rept. Prog. Phys.* **81** (2018) 016901 [[arXiv:1709.01091](#)] [[INSPIRE](#)].
- [4] S.M. Carroll, *The Cosmological constant*, *Living Rev. Rel.* **4** (2001) 1 [[astro-ph/0004075](#)] [[INSPIRE](#)].
- [5] S. Weinberg, *The Cosmological Constant Problem*, *Rev. Mod. Phys.* **61** (1989) 1 [[INSPIRE](#)].
- [6] L. Verde, T. Treu and A.G. Riess, *Tensions between the Early and the Late Universe*, *Nature Astron.* **3** (2019) 891 [[arXiv:1907.10625](#)] [[INSPIRE](#)].
- [7] A.G. Riess, *The Expansion of the Universe is Faster than Expected*, *Nature Rev. Phys.* **2** (2019) 10 [[arXiv:2001.03624](#)] [[INSPIRE](#)].
- [8] E. Di Valentino et al., *Snowmass2021 — Letter of interest cosmology intertwined II: The hubble constant tension*, *Astropart. Phys.* **131** (2021) 102605 [[arXiv:2008.11284](#)] [[INSPIRE](#)].
- [9] E. Di Valentino et al., *In the realm of the Hubble tension — a review of solutions*, *Class. Quant. Grav.* **38** (2021) 153001 [[arXiv:2103.01183](#)] [[INSPIRE](#)].
- [10] L. Perivolaropoulos and F. Skara, *Challenges for Λ CDM: An update*, *New Astron. Rev.* **95** (2022) 101659 [[arXiv:2105.05208](#)] [[INSPIRE](#)].
- [11] N. Schöneberg et al., *The H_0 Olympics: A fair ranking of proposed models*, *Phys. Rept.* **984** (2022) 1 [[arXiv:2107.10291](#)] [[INSPIRE](#)].
- [12] P. Shah, P. Lemos and O. Lahav, *A buyer’s guide to the Hubble constant*, *Astron. Astrophys. Rev.* **29** (2021) 9 [[arXiv:2109.01161](#)] [[INSPIRE](#)].
- [13] E. Abdalla et al., *Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies*, *JHEAp* **34** (2022) 49 [[arXiv:2203.06142](#)] [[INSPIRE](#)].
- [14] E. Di Valentino, *Challenges of the Standard Cosmological Model*, *Universe* **8** (2022) 399 [[INSPIRE](#)].
- [15] J.-P. Hu and F.-Y. Wang, *Hubble Tension: The Evidence of New Physics*, *Universe* **9** (2023) 94 [[arXiv:2302.05709](#)] [[INSPIRE](#)].
- [16] E. Di Valentino and S. Bridle, *Exploring the Tension between Current Cosmic Microwave Background and Cosmic Shear Data*, *Symmetry* **10** (2018) 585 [[INSPIRE](#)].
- [17] E. Di Valentino et al., *Cosmology Intertwined III: $f\sigma_8$ and S_8* , *Astropart. Phys.* **131** (2021) 102604 [[arXiv:2008.11285](#)] [[INSPIRE](#)].
- [18] R.C. Nunes and S. Vagnozzi, *Arbitrating the S_8 discrepancy with growth rate measurements from redshift-space distortions*, *Mon. Not. Roy. Astron. Soc.* **505** (2021) 5427 [[arXiv:2106.01208](#)] [[INSPIRE](#)].
- [19] C. Wetterich, *Cosmology and the Fate of Dilatation Symmetry*, *Nucl. Phys. B* **302** (1988) 668 [[arXiv:1711.03844](#)] [[INSPIRE](#)].
- [20] B. Ratra and P.J.E. Peebles, *Cosmological Consequences of a Rolling Homogeneous Scalar Field*, *Phys. Rev. D* **37** (1988) 3406 [[INSPIRE](#)].

- [21] C. Wetterich, *The Cosmon model for an asymptotically vanishing time dependent cosmological ‘constant’*, *Astron. Astrophys.* **301** (1995) 321 [[hep-th/9408025](#)] [[INSPIRE](#)].
- [22] R.R. Caldwell, R. Dave and P.J. Steinhardt, *Cosmological imprint of an energy component with general equation of state*, *Phys. Rev. Lett.* **80** (1998) 1582 [[astro-ph/9708069](#)] [[INSPIRE](#)].
- [23] L. Amendola, *Coupled quintessence*, *Phys. Rev. D* **62** (2000) 043511 [[astro-ph/9908023](#)] [[INSPIRE](#)].
- [24] A.Y. Kamenshchik, U. Moschella and V. Pasquier, *An Alternative to quintessence*, *Phys. Lett. B* **511** (2001) 265 [[gr-qc/0103004](#)] [[INSPIRE](#)].
- [25] S. Capozziello, *Curvature quintessence*, *Int. J. Mod. Phys. D* **11** (2002) 483 [[gr-qc/0201033](#)] [[INSPIRE](#)].
- [26] M.C. Bento, O. Bertolami and A.A. Sen, *Generalized Chaplygin gas, accelerated expansion and dark energy matter unification*, *Phys. Rev. D* **66** (2002) 043507 [[gr-qc/0202064](#)] [[INSPIRE](#)].
- [27] G. Mangano, G. Miele and V. Pettorino, *Coupled quintessence and the coincidence problem*, *Mod. Phys. Lett. A* **18** (2003) 831 [[astro-ph/0212518](#)] [[INSPIRE](#)].
- [28] G.R. Farrar and P.J.E. Peebles, *Interacting dark matter and dark energy*, *Astrophys. J.* **604** (2004) 1 [[astro-ph/0307316](#)] [[INSPIRE](#)].
- [29] J. Khoury and A. Weltman, *Chameleon fields: Awaiting surprises for tests of gravity in space*, *Phys. Rev. Lett.* **93** (2004) 171104 [[astro-ph/0309300](#)] [[INSPIRE](#)].
- [30] M. Li, *A Model of holographic dark energy*, *Phys. Lett. B* **603** (2004) 1 [[hep-th/0403127](#)] [[INSPIRE](#)].
- [31] L. Amendola, R. Gannouji, D. Polarski and S. Tsujikawa, *Conditions for the cosmological viability of $f(R)$ dark energy models*, *Phys. Rev. D* **75** (2007) 083504 [[gr-qc/0612180](#)] [[INSPIRE](#)].
- [32] W. Hu and I. Sawicki, *Models of $f(R)$ Cosmic Acceleration that Evade Solar-System Tests*, *Phys. Rev. D* **76** (2007) 064004 [[arXiv:0705.1158](#)] [[INSPIRE](#)].
- [33] G. Cognola et al., *A Class of viable modified $f(R)$ gravities describing inflation and the onset of accelerated expansion*, *Phys. Rev. D* **77** (2008) 046009 [[arXiv:0712.4017](#)] [[INSPIRE](#)].
- [34] M. Rinaldi, *Higgs Dark Energy*, *Class. Quant. Grav.* **32** (2015) 045002 [[arXiv:1404.0532](#)] [[INSPIRE](#)].
- [35] O. Luongo and H. Quevedo, *A Unified Dark Energy Model from a Vanishing Speed of Sound with Emergent Cosmological Constant*, *Int. J. Mod. Phys. D* **23** (2014) 1450012 [[INSPIRE](#)].
- [36] R. Myrzakulov, L. Sebastiani and S. Vagnozzi, *Inflation in $f(R, \phi)$ -theories and mimetic gravity scenario*, *Eur. Phys. J. C* **75** (2015) 444 [[arXiv:1504.07984](#)] [[INSPIRE](#)].
- [37] M. Rinaldi, *Dark energy as a fixed point of the Einstein Yang-Mills Higgs Equations*, *JCAP* **10** (2015) 023 [[arXiv:1508.04576](#)] [[INSPIRE](#)].
- [38] B. Wang, E. Abdalla, F. Atrio-Barandela and D. Pavon, *Dark Matter and Dark Energy Interactions: Theoretical Challenges, Cosmological Implications and Observational Signatures*, *Rept. Prog. Phys.* **79** (2016) 096901 [[arXiv:1603.08299](#)] [[INSPIRE](#)].
- [39] T. Josset, A. Perez and D. Sudarsky, *Dark Energy from Violation of Energy Conservation*, *Phys. Rev. Lett.* **118** (2017) 021102 [[arXiv:1604.04183](#)] [[INSPIRE](#)].
- [40] C. Burrage and J. Sakstein, *A Compendium of Chameleon Constraints*, *JCAP* **11** (2016) 045 [[arXiv:1609.01192](#)] [[INSPIRE](#)].
- [41] L. Sebastiani, S. Vagnozzi and R. Myrzakulov, *Mimetic gravity: a review of recent developments and applications to cosmology and astrophysics*, *Adv. High Energy Phys.* **2017** (2017) 3156915 [[arXiv:1612.08661](#)] [[INSPIRE](#)].

- [42] S. Nojiri, S.D. Odintsov and V.K. Oikonomou, *Modified Gravity Theories on a Nutshell: Inflation, Bounce and Late-time Evolution*, *Phys. Rept.* **692** (2017) 1 [[arXiv:1705.11098](#)] [[INSPIRE](#)].
- [43] C. Burrage and J. Sakstein, *Tests of Chameleon Gravity*, *Living Rev. Rel.* **21** (2018) 1 [[arXiv:1709.09071](#)] [[INSPIRE](#)].
- [44] S. Capozziello, R. D’Agostino and O. Luongo, *Cosmic acceleration from a single fluid description*, *Phys. Dark Univ.* **20** (2018) 1 [[arXiv:1712.04317](#)] [[INSPIRE](#)].
- [45] D. Benisty and E.I. Guendelman, *Unified dark energy and dark matter from dynamical spacetime*, *Phys. Rev. D* **98** (2018) 023506 [[arXiv:1802.07981](#)] [[INSPIRE](#)].
- [46] A. Casalino, M. Rinaldi, L. Sebastiani and S. Vagnozzi, *Mimicking dark matter and dark energy in a mimetic model compatible with GW170817*, *Phys. Dark Univ.* **22** (2018) 108 [[arXiv:1803.02620](#)] [[INSPIRE](#)].
- [47] W. Yang et al., *Tale of stable interacting dark energy, observational signatures, and the H_0 tension*, *JCAP* **09** (2018) 019 [[arXiv:1805.08252](#)] [[INSPIRE](#)].
- [48] E.N. Saridakis, K. Bamba, R. Myrzakulov and F.K. Anagnostopoulos, *Holographic dark energy through Tsallis entropy*, *JCAP* **12** (2018) 012 [[arXiv:1806.01301](#)] [[INSPIRE](#)].
- [49] D. Langlois, *Dark energy and modified gravity in degenerate higher-order scalar-tensor (DHOST) theories: A review*, *Int. J. Mod. Phys. D* **28** (2019) 1942006 [[arXiv:1811.06271](#)] [[INSPIRE](#)].
- [50] D. Benisty, E. Guendelman and Z. Haba, *Unification of dark energy and dark matter from diffusive cosmology*, *Phys. Rev. D* **99** (2019) 123521 [Erratum *ibid.* **101** (2020) 049901] [[arXiv:1812.06151](#)] [[INSPIRE](#)].
- [51] K. Boshkayev, R. D’Agostino and O. Luongo, *Extended logotropic fluids as unified dark energy models*, *Eur. Phys. J. C* **79** (2019) 332 [[arXiv:1901.01031](#)] [[INSPIRE](#)].
- [52] J.J. Heckman et al., *Pixelated Dark Energy*, *Fortsch. Phys.* **67** (2019) 1900071 [[arXiv:1901.10489](#)] [[INSPIRE](#)].
- [53] R. D’Agostino, *Holographic dark energy from nonadditive entropy: cosmological perturbations and observational constraints*, *Phys. Rev. D* **99** (2019) 103524 [[arXiv:1903.03836](#)] [[INSPIRE](#)].
- [54] U. Mukhopadhyay, D. Majumdar and D. Adak, *Evolution of Dark Energy Perturbations for Slotheon Field and Power Spectrum*, *Eur. Phys. J. C* **80** (2020) 593 [[arXiv:1903.08650](#)] [[INSPIRE](#)].
- [55] U. Mukhopadhyay and D. Majumdar, *Swampland criteria in the slotheon field dark energy*, *Phys. Rev. D* **100** (2019) 024006 [[arXiv:1904.01455](#)] [[INSPIRE](#)].
- [56] U. Mukhopadhyay, A. Paul and D. Majumdar, *Addressing the high- f problem in pseudo-Nambu-Goldstone boson dark energy models with dark matter-dark energy interaction*, *Eur. Phys. J. C* **80** (2020) 904 [[arXiv:1909.03925](#)] [[INSPIRE](#)].
- [57] S. Vagnozzi, L. Visinelli, O. Mena and D.F. Mota, *Do we have any hope of detecting scattering between dark energy and baryons through cosmology?*, *Mon. Not. Roy. Astron. Soc.* **493** (2020) 1139 [[arXiv:1911.12374](#)] [[INSPIRE](#)].
- [58] Ö. Akarsu, J.D. Barrow, L.A. Escamilla and J.A. Vazquez, *Graduated dark energy: Observational hints of a spontaneous sign switch in the cosmological constant*, *Phys. Rev. D* **101** (2020) 063528 [[arXiv:1912.08751](#)] [[INSPIRE](#)].
- [59] E.N. Saridakis, *Barrow holographic dark energy*, *Phys. Rev. D* **102** (2020) 123525 [[arXiv:2005.04115](#)] [[INSPIRE](#)].
- [60] Ruchika et al., *Observational constraints on axion(s) dark energy with a cosmological constant*, *Phys. Dark Univ.* **40** (2023) 101199 [[arXiv:2005.08813](#)] [[INSPIRE](#)].

- [61] S.D. Odintsov, V.K. Oikonomou and T. Paul, *From a Bounce to the Dark Energy Era with $F(R)$ Gravity*, *Class. Quant. Grav.* **37** (2020) 235005 [[arXiv:2009.09947](#)] [[INSPIRE](#)].
- [62] S.D. Odintsov, V.K. Oikonomou, F.P. Fronimos and K.V. Fasoulakos, *Unification of a Bounce with a Viable Dark Energy Era in Gauss-Bonnet Gravity*, *Phys. Rev. D* **102** (2020) 104042 [[arXiv:2010.13580](#)] [[INSPIRE](#)].
- [63] V.K. Oikonomou, *Unifying inflation with early and late dark energy epochs in axion $F(R)$ gravity*, *Phys. Rev. D* **103** (2021) 044036 [[arXiv:2012.00586](#)] [[INSPIRE](#)].
- [64] V.K. Oikonomou, *Rescaled Einstein-Hilbert Gravity from $f(R)$ Gravity: Inflation, Dark Energy and the Swampland Criteria*, *Phys. Rev. D* **103** (2021) 124028 [[arXiv:2012.01312](#)] [[INSPIRE](#)].
- [65] S. Vagnozzi et al., *Direct detection of dark energy: The XENON1T excess and future prospects*, *Phys. Rev. D* **104** (2021) 063023 [[arXiv:2103.15834](#)] [[INSPIRE](#)].
- [66] R. Solanki, S.K.J. Pacif, A. Parida and P.K. Sahoo, *Cosmic acceleration with bulk viscosity in modified $f(Q)$ gravity*, *Phys. Dark Univ.* **32** (2021) 100820 [[arXiv:2105.00876](#)] [[INSPIRE](#)].
- [67] S. Arora, S.K.J. Pacif, A. Parida and P.K. Sahoo, *Bulk viscous matter and the cosmic acceleration of the universe in $f(Q, T)$ gravity*, *JHEAp* **33** (2022) 1 [[arXiv:2106.00491](#)] [[INSPIRE](#)].
- [68] S.A. Narawade, L. Pati, B. Mishra and S.K. Tripathy, *Dynamical system analysis for accelerating models in non-metricity $f(Q)$ gravity*, *Phys. Dark Univ.* **36** (2022) 101020 [[arXiv:2203.14121](#)] [[INSPIRE](#)].
- [69] R. D’Agostino, O. Luongo and M. Muccino, *Healing the cosmological constant problem during inflation through a unified quasi-quintessence matter field*, *Class. Quant. Grav.* **39** (2022) 195014 [[arXiv:2204.02190](#)] [[INSPIRE](#)].
- [70] V.K. Oikonomou and I. Giannakoudi, *A panorama of viable $F(R)$ gravity dark energy models*, *Int. J. Mod. Phys. D* **31** (2022) 2250075 [[arXiv:2205.08599](#)] [[INSPIRE](#)].
- [71] A. Belfiglio, R. Giambò and O. Luongo, *Alleviating the cosmological constant problem from particle production*, *Class. Quant. Grav.* **40** (2023) 105004 [[arXiv:2206.14158](#)] [[INSPIRE](#)].
- [72] S.A. Kadam, J. Levi Said and B. Mishra, *Accelerating cosmological models in $f(T, B)$ gravitational theory*, *Int. J. Geom. Meth. Mod. Phys.* **20** (2023) 2350083 [[arXiv:2210.17075](#)] [[INSPIRE](#)].
- [73] Y.C. Ong, *An Effective Sign Switching Dark Energy: Lotka-Volterra Model of Two Interacting Fluids*, [arXiv:2212.04429](#) [[INSPIRE](#)].
- [74] A. Belfiglio, Y. Carloni and O. Luongo, *Particle production from non-minimal coupling in a symmetry breaking potential transporting vacuum energy*, [arXiv:2307.04739](#) [[INSPIRE](#)].
- [75] O. Akarsu et al., *Λ_s CDM model: A promising scenario for alleviation of cosmological tensions*, [arXiv:2307.10899](#) [[INSPIRE](#)].
- [76] U.H. Danielsson and T. Van Riet, *What if string theory has no de Sitter vacua?*, *Int. J. Mod. Phys. D* **27** (2018) 1830007 [[arXiv:1804.01120](#)] [[INSPIRE](#)].
- [77] C. Vafa, *The String landscape and the swampland*, [hep-th/0509212](#) [[INSPIRE](#)].
- [78] G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, *De Sitter Space and the Swampland*, [arXiv:1806.08362](#) [[INSPIRE](#)].
- [79] P. Agrawal, G. Obied, P.J. Steinhardt and C. Vafa, *On the Cosmological Implications of the String Swampland*, *Phys. Lett. B* **784** (2018) 271 [[arXiv:1806.09718](#)] [[INSPIRE](#)].
- [80] A. Achúcarro and G.A. Palma, *The string swampland constraints require multi-field inflation*, *JCAP* **02** (2019) 041 [[arXiv:1807.04390](#)] [[INSPIRE](#)].

- [81] S.K. Garg and C. Krishnan, *Bounds on Slow Roll and the de Sitter Swampland*, *JHEP* **11** (2019) 075 [[arXiv:1807.05193](#)] [[INSPIRE](#)].
- [82] A. Kehagias and A. Riotto, *A note on Inflation and the Swampland*, *Fortsch. Phys.* **66** (2018) 1800052 [[arXiv:1807.05445](#)] [[INSPIRE](#)].
- [83] W.H. Kinney, S. Vagnozzi and L. Visinelli, *The zoo plot meets the swampland: mutual (in)consistency of single-field inflation, string conjectures, and cosmological data*, *Class. Quant. Grav.* **36** (2019) 117001 [[arXiv:1808.06424](#)] [[INSPIRE](#)].
- [84] H. Ooguri, E. Palti, G. Shiu and C. Vafa, *Distance and de Sitter Conjectures on the Swampland*, *Phys. Lett. B* **788** (2019) 180 [[arXiv:1810.05506](#)] [[INSPIRE](#)].
- [85] E. Palti, *The Swampland: Introduction and Review*, *Fortsch. Phys.* **67** (2019) 1900037 [[arXiv:1903.06239](#)] [[INSPIRE](#)].
- [86] M. Graña and A. Herráez, *The Swampland Conjectures: A Bridge from Quantum Gravity to Particle Physics*, *Universe* **7** (2021) 273 [[arXiv:2107.00087](#)] [[INSPIRE](#)].
- [87] J.M. Maldacena, *The Large N limit of superconformal field theories and supergravity*, *Adv. Theor. Math. Phys.* **2** (1998) 231 [[hep-th/9711200](#)] [[INSPIRE](#)].
- [88] N. Goheer, M. Kleban and L. Susskind, *The Trouble with de Sitter space*, *JHEP* **07** (2003) 056 [[hep-th/0212209](#)] [[INSPIRE](#)].
- [89] E. Witten, *Quantum gravity in de Sitter space*, in the proceedings of the *Strings 2001: International Conference*, (2001) [[hep-th/0106109](#)] [[INSPIRE](#)].
- [90] P.G.O. Freund and M.A. Rubin, *Dynamics of Dimensional Reduction*, *Phys. Lett. B* **97** (1980) 233 [[INSPIRE](#)].
- [91] O. DeWolfe et al., *Stability of $AdS(p) \times M(q)$ compactifications without supersymmetry*, *Phys. Rev. D* **65** (2002) 064033 [[hep-th/0105047](#)] [[INSPIRE](#)].
- [92] S. Kachru, R. Kallosh, A.D. Linde and S.P. Trivedi, *De Sitter vacua in string theory*, *Phys. Rev. D* **68** (2003) 046005 [[hep-th/0301240](#)] [[INSPIRE](#)].
- [93] V. Balasubramanian, P. Berglund, J.P. Conlon and F. Quevedo, *Systematics of moduli stabilisation in Calabi-Yau flux compactifications*, *JHEP* **03** (2005) 007 [[hep-th/0502058](#)] [[INSPIRE](#)].
- [94] P. Svrcek and E. Witten, *Axions In String Theory*, *JHEP* **06** (2006) 051 [[hep-th/0605206](#)] [[INSPIRE](#)].
- [95] A. Arvanitaki et al., *String Axiverse*, *Phys. Rev. D* **81** (2010) 123530 [[arXiv:0905.4720](#)] [[INSPIRE](#)].
- [96] M. Cicoli, M. Goodsell and A. Ringwald, *The type IIB string axiverse and its low-energy phenomenology*, *JHEP* **10** (2012) 146 [[arXiv:1206.0819](#)] [[INSPIRE](#)].
- [97] L. Visinelli and S. Vagnozzi, *Cosmological window onto the string axiverse and the supersymmetry breaking scale*, *Phys. Rev. D* **99** (2019) 063517 [[arXiv:1809.06382](#)] [[INSPIRE](#)].
- [98] M. Cicoli et al., *String Cosmology: from the Early Universe to Today*, [arXiv:2303.04819](#) [[INSPIRE](#)].
- [99] S.M. Carroll, M. Hoffman and M. Trodden, *Can the dark energy equation-of-state parameter w be less than -1 ?*, *Phys. Rev. D* **68** (2003) 023509 [[astro-ph/0301273](#)] [[INSPIRE](#)].
- [100] A. Vikman, *Can dark energy evolve to the phantom?*, *Phys. Rev. D* **71** (2005) 023515 [[astro-ph/0407107](#)] [[INSPIRE](#)].
- [101] S.M. Carroll, A. De Felice and M. Trodden, *Can we be tricked into thinking that w is less than -1 ?*, *Phys. Rev. D* **71** (2005) 023525 [[astro-ph/0408081](#)] [[INSPIRE](#)].

- [102] C. Deffayet, O. Pujolas, I. Sawicki and A. Vikman, *Imperfect Dark Energy from Kinetic Gravity Braiding*, *JCAP* **10** (2010) 026 [[arXiv:1008.0048](#)] [[INSPIRE](#)].
- [103] I. Sawicki and A. Vikman, *Hidden Negative Energies in Strongly Accelerated Universes*, *Phys. Rev. D* **87** (2013) 067301 [[arXiv:1209.2961](#)] [[INSPIRE](#)].
- [104] R. Cardenas et al., *A model of the universe including dark energy accounted for by both a quintessence field and a (negative) cosmological constant*, *Phys. Rev. D* **67** (2003) 083501 [[astro-ph/0206315](#)] [[INSPIRE](#)].
- [105] K. Dutta et al., *Beyond Λ CDM with low and high redshift data: implications for dark energy*, *Gen. Rel. Grav.* **52** (2020) 15 [[arXiv:1808.06623](#)] [[INSPIRE](#)].
- [106] L. Visinelli, S. Vagnozzi and U. Danielsson, *Revisiting a negative cosmological constant from low-redshift data*, *Symmetry* **11** (2019) 1035 [[arXiv:1907.07953](#)] [[INSPIRE](#)].
- [107] R. Calderón, R. Gannouji, B. L’Huillier and D. Polarski, *Negative cosmological constant in the dark sector?*, *Phys. Rev. D* **103** (2021) 023526 [[arXiv:2008.10237](#)] [[INSPIRE](#)].
- [108] A.A. Sen, S.A. Adil and S. Sen, *Do cosmological observations allow a negative Λ ?*, *Mon. Not. Roy. Astron. Soc.* **518** (2022) 1098 [[arXiv:2112.10641](#)] [[INSPIRE](#)].
- [109] M. Malekjani et al., *Negative Dark Energy Density from High Redshift Pantheon+ Supernovae*, [arXiv:2301.12725](#) [[INSPIRE](#)].
- [110] G. Ye and Y.-S. Piao, *Is the Hubble tension a hint of AdS phase around recombination?*, *Phys. Rev. D* **101** (2020) 083507 [[arXiv:2001.02451](#)] [[INSPIRE](#)].
- [111] G. Ye and Y.-S. Piao, *T_0 censorship of early dark energy and AdS vacua*, *Phys. Rev. D* **102** (2020) 083523 [[arXiv:2008.10832](#)] [[INSPIRE](#)].
- [112] G. Ye, B. Hu and Y.-S. Piao, *Implication of the Hubble tension for the primordial Universe in light of recent cosmological data*, *Phys. Rev. D* **104** (2021) 063510 [[arXiv:2103.09729](#)] [[INSPIRE](#)].
- [113] J.-Q. Jiang and Y.-S. Piao, *Testing AdS early dark energy with Planck, SPTpol, and LSS data*, *Phys. Rev. D* **104** (2021) 103524 [[arXiv:2107.07128](#)] [[INSPIRE](#)].
- [114] G. Ye, J. Zhang and Y.-S. Piao, *Alleviating both H_0 and S_8 tensions: Early dark energy lifts the CMB-lockdown on ultralight axion*, *Phys. Lett. B* **839** (2023) 137770 [[arXiv:2107.13391](#)] [[INSPIRE](#)].
- [115] V. Poulin, T.L. Smith and T. Karwal, *The Ups and Downs of Early Dark Energy solutions to the Hubble tension: a review of models, hints and constraints circa 2023*, [arXiv:2302.09032](#) [[INSPIRE](#)].
- [116] A.K. Leroy et al., *The Star Formation Efficiency in Nearby Galaxies: Measuring Where Gas Forms Stars Effectively*, *Astron. J.* **136** (2008) 2782 [[arXiv:0810.2556](#)] [[INSPIRE](#)].
- [117] F. Combes et al., *Galaxy Evolution and Star Formation Efficiency at $0.2 < z < 0.6$* , *Astron. Astrophys.* **528** (2011) A124 [[arXiv:1009.2040](#)] [[INSPIRE](#)].
- [118] S. Tacchella et al., *A Redshift-independent Efficiency Model: Star Formation and Stellar Masses in Dark Matter Halos at $z \gtrsim 4$* , *Astrophys. J.* **868** (2018) 92 [[arXiv:1806.03299](#)] [[INSPIRE](#)].
- [119] N. Menci et al., *Constraints on Dynamical Dark Energy Models from the Abundance of Massive Galaxies at High Redshifts*, *Astrophys. J.* **900** (2020) 108 [[arXiv:2007.12453](#)] [[INSPIRE](#)].
- [120] J.P. Gardner et al., *The James Webb Space Telescope*, *Space Sci. Rev.* **123** (2006) 485 [[astro-ph/0606175](#)] [[INSPIRE](#)].
- [121] R.P. Naidu et al., *Two Remarkably Luminous Galaxy Candidates at $z \approx 10$ –12 Revealed by JWST*, *Astrophys. J. Lett.* **940** (2022) L14 [[arXiv:2207.09434](#)].

- [122] M. Castellano et al., *Early Results from GLASS-JWST. III. Galaxy Candidates at $z \sim 9$ –15*, *Astrophys. J. Lett.* **938** (2022) L15 [[arXiv:2207.09436](#)].
- [123] N.J. Adams et al., *Discovery and properties of ultra-high redshift galaxies ($9 < z < 12$) in the JWST ERO SMACS 0723 Field*, *Mon. Not. Roy. Astron. Soc.* **518** (2022) 4755 [[arXiv:2207.11217](#)].
- [124] H. Atek et al., *Revealing galaxy candidates out to $z \sim 16$ with JWST observations of the lensing cluster SMACS0723*, *Mon. Not. Roy. Astron. Soc.* **519** (2022) 1201 [[arXiv:2207.12338](#)].
- [125] I. Labbé et al., *A population of red candidate massive galaxies ~ 600 Myr after the Big Bang*, *Nature* **616** (2023) 266 [[arXiv:2207.12446](#)].
- [126] R. Bouwens et al., *UV luminosity density results at $z > 8$ from the first JWST/NIRCam fields: limitations of early data sets and the need for spectroscopy*, *Mon. Not. Roy. Astron. Soc.* **523** (2023) 1009 [[arXiv:2212.06683](#)] [[INSPIRE](#)].
- [127] M. Xiao et al., *Massive Optically Dark Galaxies Unveiled by JWST Challenge Galaxy Formation Models*, [arXiv:2309.02492](#) [[DOI:10.48550/ARXIV.2309.02492](#)].
- [128] M. Boylan-Kolchin, *Stress testing Λ CDM with high-redshift galaxy candidates*, *Nature Astron.* **7** (2023) 731 [[arXiv:2208.01611](#)] [[INSPIRE](#)].
- [129] M. Bolte and C.J. Hogan, *Conflict over the age of the Universe*, *Nature* **376** (1995) 399.
- [130] L.M. Krauss and M.S. Turner, *The Cosmological constant is back*, *Gen. Rel. Grav.* **27** (1995) 1137 [[astro-ph/9504003](#)] [[INSPIRE](#)].
- [131] J.P. Ostriker and P.J. Steinhardt, *The Observational case for a low density universe with a nonzero cosmological constant*, *Nature* **377** (1995) 600 [[INSPIRE](#)].
- [132] M. Biagetti, G. Franciolini and A. Riotto, *High-redshift JWST Observations and Primordial Non-Gaussianity*, *Astrophys. J.* **944** (2023) 113 [[arXiv:2210.04812](#)] [[INSPIRE](#)].
- [133] M. Haslbauer, P. Kroupa, A.H. Zonoozi and H. Haghi, *Has JWST Already Falsified Dark-matter-driven Galaxy Formation?*, *Astrophys. J. Lett.* **939** (2022) L31 [[arXiv:2210.14915](#)] [[INSPIRE](#)].
- [134] G. Hütsi et al., *Did JWST observe imprints of axion miniclusters or primordial black holes?*, *Phys. Rev. D* **107** (2023) 043502 [[arXiv:2211.02651](#)] [[INSPIRE](#)].
- [135] G. Gandolfi, A. Lapi, T. Ronconi and L. Danese, *Astroparticle Constraints from the Cosmic Star Formation Rate Density at High Redshift: Current Status and Forecasts for JWST*, *Universe* **8** (2022) 589 [[arXiv:2211.02840](#)] [[INSPIRE](#)].
- [136] U. Maio and M. Viel, *JWST high-redshift galaxy constraints on warm and cold dark matter models*, *Astron. Astrophys.* **672** (2023) A71 [[arXiv:2211.03620](#)] [[INSPIRE](#)].
- [137] N. Lovyagin, A. Raikov, V. Yershov and Y. Lovyagin, *Cosmological Model Tests with JWST*, *Galaxies* **10** (2022) 108 [[arXiv:2212.06575](#)] [[INSPIRE](#)].
- [138] D. Wang and Y. Liu, *JWST high redshift galaxy observations have a strong tension with Planck CMB measurements*, [arXiv:2301.00347](#) [[INSPIRE](#)].
- [139] G.-W. Yuan et al., *Rapidly growing primordial black holes as seeds of the massive high-redshift JWST Galaxies*, [arXiv:2303.09391](#) [[INSPIRE](#)].
- [140] P. Dayal and S.K. Giri, *Warm dark matter constraints from the JWST*, [arXiv:2303.14239](#) [[INSPIRE](#)].
- [141] C. Ilie, J. Paulin and K. Freese, *Supermassive Dark Star candidates seen by JWST*, *Proc. Nat. Acad. Sci.* **120** (2023) e2305762120 [[arXiv:2304.01173](#)] [[INSPIRE](#)].

- [142] H. Jiao, R. Brandenberger and A. Refregier, *Early structure formation from cosmic string loops in light of early JWST observations*, *Phys. Rev. D* **108** (2023) 043510 [[arXiv:2304.06429](#)] [[INSPIRE](#)].
- [143] P. Parashari and R. Laha, *Primordial power spectrum in light of JWST observations of high redshift galaxies*, *Mon. Not. Roy. Astron. Soc.* **526** (2023) L63 [[arXiv:2305.00999](#)] [[INSPIRE](#)].
- [144] S. Hassan et al., *JWST constraints on the UV luminosity density at cosmic dawn: implications for 21-cm cosmology*, [arXiv:2305.02703](#) [[INSPIRE](#)].
- [145] L. Lei et al., *Black holes as the source of dark energy: a stringent test with high-redshift JWST AGNs*, [arXiv:2305.03408](#) [[INSPIRE](#)].
- [146] S. Yoshiura, T. Minoda and T. Takahashi, *EDGES and JWST with 21cm global signal emulator*, [arXiv:2305.11441](#) [[INSPIRE](#)].
- [147] M.V. John and K.B. Joseph, *Cosmological significance of the early bright galaxies observed with JWST*, [arXiv:2306.04577](#) [[INSPIRE](#)].
- [148] H. Padmanabhan and A. Loeb, *Alleviating the need for exponential evolution of JWST galaxies in $10^{10}M_{\odot}$ haloes at $z > 10$ by a modified Λ CDM power spectrum*, *Astrophys. J. Lett.* **953** (2023) L4 [[arXiv:2306.04684](#)] [[INSPIRE](#)].
- [149] H. Lin, Y. Gong, B. Yue and X. Chen, *Implications of the Stellar Mass Density of High- z Massive Galaxies from JWST on Warm Dark Matter*, [arXiv:2306.05648](#) [[INSPIRE](#)].
- [150] B.-Y. Su, N. Li and L. Feng, *An inflation model for massive primordial black holes to interpret the JWST observations*, [arXiv:2306.05364](#) [[INSPIRE](#)].
- [151] M. Forconi et al., *Do the Early Galaxies observed by JWST disagree with Planck's CMB polarization measurements?*, [arXiv:2306.07781](#) [[INSPIRE](#)].
- [152] Y. Gouttenoire, S. Trifinopoulos, G. Valogiannis and M. Vanvlasselaer, *Scrutinizing the Primordial Black Holes Interpretation of PTA Gravitational Waves and JWST Early Galaxies*, [arXiv:2307.01457](#) [[INSPIRE](#)].
- [153] S.-Y. Guo et al., *Footprints of Axion-Like Particle in Pulsar Timing Array Data and JWST Observations*, [arXiv:2306.17022](#) [[INSPIRE](#)].
- [154] H.-L. Huang et al., *Supermassive primordial black holes in multiverse: for nano-Hertz gravitational wave and high-redshift JWST galaxies*, [arXiv:2306.17577](#) [[INSPIRE](#)].
- [155] S. Bird, C.-F. Chang, Y. Cui and D. Yang, *Enhanced Early Galaxy Formation in JWST from Axion Dark Matter?*, [arXiv:2307.10302](#) [[INSPIRE](#)].
- [156] P. Wang et al., *Exploring the Dark Energy Equation of State with JWST*, [arXiv:2307.11374](#) [[INSPIRE](#)].
- [157] R.P. Gupta, *JWST early Universe observations and Λ CDM cosmology*, *Mon. Not. Roy. Astron. Soc.* **524** (2023) 3385 [[arXiv:2309.13100](#)] [[INSPIRE](#)].
- [158] A. Ferrara, A. Pallottini and P. Dayal, *On the stunning abundance of super-early, luminous galaxies revealed by JWST*, *Mon. Not. Roy. Astron. Soc.* **522** (2023) 3986 [[arXiv:2208.00720](#)] [[INSPIRE](#)].
- [159] Y. Qin, S. Balu and J.S.B. Wyithe, *Implications of $z \gtrsim 12$ JWST galaxies for galaxy formation at high redshift*, [arXiv:2305.17959](#) [[INSPIRE](#)].
- [160] A. Pallottini and A. Ferrara, *Stochastic star formation in early galaxies: JWST implications*, *Astron. Astrophys.* **677** (2023) L4 [[arXiv:2307.03219](#)] [[INSPIRE](#)].
- [161] Y.-Y. Wang, L. Lei, G.-W. Yuan and Y.-Z. Fan, *Modeling the JWST High-redshift Galaxies with a General Formation Scenario and the Consistency with the Λ CDM Model*, *Astrophys. J. Lett.* **954** (2023) L48 [[arXiv:2307.12487](#)] [[INSPIRE](#)].

- [162] F. Pacucci et al., *JWST CEERS & JADES Active Galaxies at $z = 4-7$ Violate the Local $M_{\bullet} - M_{\star}$ Relation at $> 3\sigma$: Implications for Low-Mass Black Holes and Seeding Models*, [arXiv:2308.12331](#) [INSPIRE].
- [163] N. Menci et al., *High-redshift Galaxies from Early JWST Observations: Constraints on Dark Energy Models*, *Astrophys. J. Lett.* **938** (2022) L5 [[arXiv:2208.11471](#)] [INSPIRE].
- [164] M. Chevallier and D. Polarski, *Accelerating universes with scaling dark matter*, *Int. J. Mod. Phys. D* **10** (2001) 213 [[gr-qc/0009008](#)] [INSPIRE].
- [165] E.V. Linder, *Exploring the expansion history of the universe*, *Phys. Rev. Lett.* **90** (2003) 091301 [[astro-ph/0208512](#)] [INSPIRE].
- [166] E.V. Linder, *Probing dark energy with SNAP*, in the proceedings of the *4th International Workshop on the Identification of Dark Matter*, (2002), p. 52–57 [[astro-ph/0210217](#)] [INSPIRE].
- [167] E.V. Linder, *The paths of quintessence*, *Phys. Rev. D* **73** (2006) 063010 [[astro-ph/0601052](#)] [INSPIRE].
- [168] E.V. Linder, *The Dynamics of Quintessence, The Quintessence of Dynamics*, *Gen. Rel. Grav.* **40** (2008) 329 [[arXiv:0704.2064](#)] [INSPIRE].
- [169] E.V. Linder, *Mapping the Cosmological Expansion*, *Rept. Prog. Phys.* **71** (2008) 056901 [[arXiv:0801.2968](#)] [INSPIRE].
- [170] R.J. Scherrer, *Mapping the Chevallier-Polarski-Linder parametrization onto Physical Dark Energy Models*, *Phys. Rev. D* **92** (2015) 043001 [[arXiv:1505.05781](#)] [INSPIRE].
- [171] P.S. Corasaniti and E.J. Copeland, *A Model independent approach to the dark energy equation of state*, *Phys. Rev. D* **67** (2003) 063521 [[astro-ph/0205544](#)] [INSPIRE].
- [172] E.V. Linder and D. Huterer, *How many dark energy parameters?*, *Phys. Rev. D* **72** (2005) 043509 [[astro-ph/0505330](#)] [INSPIRE].
- [173] G. Efstathiou, *Constraining the equation of state of the universe from distant type Ia supernovae and cosmic microwave background anisotropies*, *Mon. Not. Roy. Astron. Soc.* **310** (1999) 842 [[astro-ph/9904356](#)] [INSPIRE].
- [174] H.K. Jassal, J.S. Bagla and T. Padmanabhan, *WMAP constraints on low redshift evolution of dark energy*, *Mon. Not. Roy. Astron. Soc.* **356** (2005) L11 [[astro-ph/0404378](#)] [INSPIRE].
- [175] Y.-G. Gong and Y.-Z. Zhang, *Probing the curvature and dark energy*, *Phys. Rev. D* **72** (2005) 043518 [[astro-ph/0502262](#)] [INSPIRE].
- [176] E.M. Barboza Jr. and J.S. Alcaniz, *A parametric model for dark energy*, *Phys. Lett. B* **666** (2008) 415 [[arXiv:0805.1713](#)] [INSPIRE].
- [177] J.-Z. Ma and X. Zhang, *Probing the dynamics of dark energy with novel parametrizations*, *Phys. Lett. B* **699** (2011) 233 [[arXiv:1102.2671](#)] [INSPIRE].
- [178] G. Pantazis, S. Nesseris and L. Perivolaropoulos, *Comparison of thawing and freezing dark energy parametrizations*, *Phys. Rev. D* **93** (2016) 103503 [[arXiv:1603.02164](#)] [INSPIRE].
- [179] W. Yang, S. Pan and A. Paliathanasis, *Latest astronomical constraints on some non-linear parametric dark energy models*, *Mon. Not. Roy. Astron. Soc.* **475** (2018) 2605 [[arXiv:1708.01717](#)] [INSPIRE].
- [180] S. Pan, E.N. Saridakis and W. Yang, *Observational Constraints on Oscillating Dark-Energy Parametrizations*, *Phys. Rev. D* **98** (2018) 063510 [[arXiv:1712.05746](#)] [INSPIRE].
- [181] W. Yang et al., *Observational constraints on one-parameter dynamical dark-energy parametrizations and the H_0 tension*, *Phys. Rev. D* **99** (2019) 043543 [[arXiv:1810.05141](#)] [INSPIRE].

- [182] J.K. Singh, P. Singh, E.N. Saridakis and S. Myrzakul, *New parametrization of the dark-energy equation of state with a single parameter*, [arXiv:2304.03783](#) [INSPIRE].
- [183] D. Perkovic and H. Stefancic, *Barotropic fluid compatible parametrizations of dark energy*, *Eur. Phys. J. C* **80** (2020) 629 [[arXiv:2004.05342](#)] [INSPIRE].
- [184] E.Ó. Colgáin, M.M. Sheikh-Jabbari and L. Yin, *Can dark energy be dynamical?*, *Phys. Rev. D* **104** (2021) 023510 [[arXiv:2104.01930](#)] [INSPIRE].
- [185] M. Seikel, C. Clarkson and M. Smith, *Reconstruction of dark energy and expansion dynamics using Gaussian processes*, *JCAP* **06** (2012) 036 [[arXiv:1204.2832](#)] [INSPIRE].
- [186] S. Hee et al., *Constraining the dark energy equation of state using Bayes theorem and the Kullback-Leibler divergence*, *Mon. Not. Roy. Astron. Soc.* **466** (2017) 369 [[arXiv:1607.00270](#)] [INSPIRE].
- [187] A. Shafieloo, B. L’Huillier and A.A. Starobinsky, *Falsifying Λ CDM: Model-independent tests of the concordance model with eBOSS DR14Q and Pantheon*, *Phys. Rev. D* **98** (2018) 083526 [[arXiv:1804.04320](#)] [INSPIRE].
- [188] Y. Wang, L. Pogosian, G.-B. Zhao and A. Zucca, *Evolution of dark energy reconstructed from the latest observations*, *Astrophys. J. Lett.* **869** (2018) L8 [[arXiv:1807.03772](#)] [INSPIRE].
- [189] F. Gerardi, M. Martinelli and A. Silvestri, *Reconstruction of the Dark Energy equation of state from latest data: the impact of theoretical priors*, *JCAP* **07** (2019) 042 [[arXiv:1902.09423](#)] [INSPIRE].
- [190] A. Diaz Rivero, V. Miranda and C. Dvorkin, *Observable Predictions for Massive-Neutrino Cosmologies with Model-Independent Dark Energy*, *Phys. Rev. D* **100** (2019) 063504 [[arXiv:1903.03125](#)] [INSPIRE].
- [191] A. Bonilla, S. Kumar and R.C. Nunes, *Measurements of H_0 and reconstruction of the dark energy properties from a model-independent joint analysis*, *Eur. Phys. J. C* **81** (2021) 127 [[arXiv:2011.07140](#)] [INSPIRE].
- [192] S. Dhawan, J. Alsing and S. Vagnozzi, *Non-parametric spatial curvature inference using late-Universe cosmological probes*, *Mon. Not. Roy. Astron. Soc.* **506** (2021) L1 [[arXiv:2104.02485](#)] [INSPIRE].
- [193] K. Dialektopoulos et al., *Neural network reconstruction of late-time cosmology and null tests*, *JCAP* **02** (2022) 023 [[arXiv:2111.11462](#)] [INSPIRE].
- [194] R.C. Bernardo, D. Grandón, J. Levi Said and V.H. Cárdenas, *Dark energy by natural evolution: Constraining dark energy using Approximate Bayesian Computation*, *Phys. Dark Univ.* **40** (2023) 101213 [[arXiv:2211.05482](#)] [INSPIRE].
- [195] B. Feng, M. Li, Y.-S. Piao and X. Zhang, *Oscillating quintom and the recurrent universe*, *Phys. Lett. B* **634** (2006) 101 [[astro-ph/0407432](#)] [INSPIRE].
- [196] Z.-K. Guo, Y.-S. Piao, X.-M. Zhang and Y.-Z. Zhang, *Cosmological evolution of a quintom model of dark energy*, *Phys. Lett. B* **608** (2005) 177 [[astro-ph/0410654](#)] [INSPIRE].
- [197] Y.-F. Cai et al., *A String-Inspired Quintom Model Of Dark Energy*, *Phys. Lett. B* **651** (2007) 1 [[hep-th/0701016](#)] [INSPIRE].
- [198] Y.-F. Cai et al., *Bouncing universe with quintom matter*, *JHEP* **10** (2007) 071 [[arXiv:0704.1090](#)] [INSPIRE].
- [199] X. Zhang, *Holographic Ricci dark energy: Current observational constraints, quintom feature, and the reconstruction of scalar-field dark energy*, *Phys. Rev. D* **79** (2009) 103509 [[arXiv:0901.2262](#)] [INSPIRE].
- [200] E.N. Saridakis, *Quintom evolution in power-law potentials*, *Nucl. Phys. B* **830** (2010) 374 [[arXiv:0903.3840](#)] [INSPIRE].

- [201] Y.-F. Cai, M. Li and X. Zhang, *Emergent Universe Scenario via Quintom Matter*, *Phys. Lett. B* **718** (2012) 248 [[arXiv:1209.3437](#)] [[INSPIRE](#)].
- [202] S. Bahamonde, M. Marciu and P. Rudra, *Generalised teleparallel quintom dark energy non-minimally coupled with the scalar torsion and a boundary term*, *JCAP* **04** (2018) 056 [[arXiv:1802.09155](#)] [[INSPIRE](#)].
- [203] G. Leon, A. Paliathanasis and J.L. Morales-Martínez, *The past and future dynamics of quintom dark energy models*, *Eur. Phys. J. C* **78** (2018) 753 [[arXiv:1808.05634](#)] [[INSPIRE](#)].
- [204] S. Panpanich, P. Burikham, S. Ponglertsakul and L. Tannukij, *Resolving Hubble Tension with Quintom Dark Energy Model*, *Chin. Phys. C* **45** (2021) 015108 [[arXiv:1908.03324](#)] [[INSPIRE](#)].
- [205] Y.-F. Cai, E.N. Saridakis, M.R. Setare and J.-Q. Xia, *Quintom Cosmology: Theoretical implications and observations*, *Phys. Rept.* **493** (2010) 1 [[arXiv:0909.2776](#)] [[INSPIRE](#)].
- [206] E. Ozulker, *Is the dark energy equation of state parameter singular?*, *Phys. Rev. D* **106** (2022) 063509 [[arXiv:2203.04167](#)] [[INSPIRE](#)].
- [207] F. Pace, J.-C. Waizmann and M. Bartelmann, *Spherical collapse model in dark energy cosmologies*, *Mon. Not. Roy. Astron. Soc.* **406** (2010) 1865 [[arXiv:1005.0233](#)] [[INSPIRE](#)].
- [208] L. Campanelli et al., *Galaxy cluster number count data constraints on cosmological parameters*, *Eur. Phys. J. C* **72** (2012) 2218 [[arXiv:1110.2310](#)] [[INSPIRE](#)].
- [209] D.F. Mota, *Probing Dark Energy at Galactic and Cluster Scales*, *JCAP* **09** (2008) 006 [[arXiv:0812.4493](#)] [[INSPIRE](#)].
- [210] R.K. Sheth and G. Tormen, *Large scale bias and the peak background split*, *Mon. Not. Roy. Astron. Soc.* **308** (1999) 119 [[astro-ph/9901122](#)] [[INSPIRE](#)].
- [211] W.H. Press and P. Schechter, *Formation of galaxies and clusters of galaxies by selfsimilar gravitational condensation*, *Astrophys. J.* **187** (1974) 425 [[INSPIRE](#)].
- [212] S. Basilakos, J.C. Bueno Sanchez and L. Perivolaropoulos, *The spherical collapse model and cluster formation beyond the Λ cosmology: Indications for a clustered dark energy?*, *Phys. Rev. D* **80** (2009) 043530 [[arXiv:0908.1333](#)] [[INSPIRE](#)].
- [213] S. Bhattacharya et al., *Mass Function Predictions Beyond LCDM*, *Astrophys. J.* **732** (2011) 122 [[arXiv:1005.2239](#)] [[INSPIRE](#)].
- [214] M. Stefanon et al., *Blue Rest-frame UV-optical Colors in $z \sim 8$ Galaxies from GREATS: Very Young Stellar Populations at ~ 650 Myr of Cosmic Time*, *Astrophys. J.* **927** (2022) 48 [[arXiv:2103.06279](#)].
- [215] C.C. Lovell et al., *Extreme value statistics of the halo and stellar mass distributions at high redshift: are JWST results in tension with Λ CDM?*, *Mon. Not. Roy. Astron. Soc.* **518** (2022) 2511 [[arXiv:2208.10479](#)] [[INSPIRE](#)].
- [216] E. Di Valentino, A. Melchiorri and J. Silk, *Reconciling Planck with the local value of H_0 in extended parameter space*, *Phys. Lett. B* **761** (2016) 242 [[arXiv:1606.00634](#)] [[INSPIRE](#)].
- [217] G.-B. Zhao et al., *Dynamical dark energy in light of the latest observations*, *Nature Astron.* **1** (2017) 627 [[arXiv:1701.08165](#)] [[INSPIRE](#)].
- [218] E. Mörtzell and S. Dhawan, *Does the Hubble constant tension call for new physics?*, *JCAP* **09** (2018) 025 [[arXiv:1801.07260](#)] [[INSPIRE](#)].
- [219] X. Li and A. Shafieloo, *A Simple Phenomenological Emergent Dark Energy Model can Resolve the Hubble Tension*, *Astrophys. J. Lett.* **883** (2019) L3 [[arXiv:1906.08275](#)] [[INSPIRE](#)].
- [220] S. Vagnozzi, *New physics in light of the H_0 tension: An alternative view*, *Phys. Rev. D* **102** (2020) 023518 [[arXiv:1907.07569](#)] [[INSPIRE](#)].

- [221] E. Di Valentino, A. Melchiorri, O. Mena and S. Vagnozzi, *Interacting dark energy in the early 2020s: A promising solution to the H_0 and cosmic shear tensions*, *Phys. Dark Univ.* **30** (2020) 100666 [[arXiv:1908.04281](#)] [[INSPIRE](#)].
- [222] K. Dutta et al., *Cosmology with low-redshift observations: No signal for new physics*, *Phys. Rev. D* **100** (2019) 103501 [[arXiv:1908.07267](#)] [[INSPIRE](#)].
- [223] E. Di Valentino, A. Melchiorri, O. Mena and S. Vagnozzi, *Nonminimal dark sector physics and cosmological tensions*, *Phys. Rev. D* **101** (2020) 063502 [[arXiv:1910.09853](#)] [[INSPIRE](#)].
- [224] M. Zumalacarregui, *Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions*, *Phys. Rev. D* **102** (2020) 023523 [[arXiv:2003.06396](#)] [[INSPIRE](#)].
- [225] G. Alestas, L. Kazantzidis and L. Perivolaropoulos, *H_0 tension, phantom dark energy, and cosmological parameter degeneracies*, *Phys. Rev. D* **101** (2020) 123516 [[arXiv:2004.08363](#)] [[INSPIRE](#)].
- [226] W. Yang, E. Di Valentino, S. Pan and O. Mena, *Emergent Dark Energy, neutrinos and cosmological tensions*, *Phys. Dark Univ.* **31** (2021) 100762 [[arXiv:2007.02927](#)] [[INSPIRE](#)].
- [227] G. Alestas, L. Kazantzidis and L. Perivolaropoulos, *$w - M$ phantom transition at $z_t < 0.1$ as a resolution of the Hubble tension*, *Phys. Rev. D* **103** (2021) 083517 [[arXiv:2012.13932](#)] [[INSPIRE](#)].
- [228] S. Kumar, *Remedy of some cosmological tensions via effective phantom-like behavior of interacting vacuum energy*, *Phys. Dark Univ.* **33** (2021) 100862 [[arXiv:2102.12902](#)] [[INSPIRE](#)].
- [229] Y.-P. Teng, W. Lee and K.-W. Ng, *Constraining the dark-energy equation of state with cosmological data*, *Phys. Rev. D* **104** (2021) 083519 [[arXiv:2105.02667](#)] [[INSPIRE](#)].
- [230] C. Krishnan et al., *Does Hubble tension signal a breakdown in FLRW cosmology?*, *Class. Quant. Grav.* **38** (2021) 184001 [[arXiv:2105.09790](#)] [[INSPIRE](#)].
- [231] S. Bag, V. Sahni, A. Shafieloo and Y. Shtanov, *Phantom Braneworld and the Hubble Tension*, *Astrophys. J.* **923** (2021) 212 [[arXiv:2107.03271](#)] [[INSPIRE](#)].
- [232] A. Theodoropoulos and L. Perivolaropoulos, *The Hubble Tension, the M Crisis of Late Time $H(z)$ Deformation Models and the Reconstruction of Quintessence Lagrangians*, *Universe* **7** (2021) 300 [[arXiv:2109.06256](#)] [[INSPIRE](#)].
- [233] G. Alestas et al., *Late-transition versus smooth $H(z)$ -deformation models for the resolution of the Hubble crisis*, *Phys. Rev. D* **105** (2022) 063538 [[arXiv:2110.04336](#)] [[INSPIRE](#)].
- [234] N. Roy, S. Goswami and S. Das, *Quintessence or phantom: Study of scalar field dark energy models through a general parametrization of the Hubble parameter*, *Phys. Dark Univ.* **36** (2022) 101037 [[arXiv:2201.09306](#)] [[INSPIRE](#)].
- [235] L. Heisenberg, H. Villarrubia-Rojo and J. Zosso, *Simultaneously solving the H_0 and σ_8 tensions with late dark energy*, *Phys. Dark Univ.* **39** (2023) 101163 [[arXiv:2201.11623](#)] [[INSPIRE](#)].
- [236] A. Chudaykin, D. Gorbunov and N. Nedelko, *Exploring Λ CDM extensions with SPT-3G and Planck data: 4σ evidence for neutrino masses and implications of extended dark energy models for cosmological tensions*, [arXiv:2203.03666](#) [[INSPIRE](#)].
- [237] O. Akarsu et al., *Relaxing cosmological tensions with a sign switching cosmological constant: Improved results with Planck, BAO, and Pantheon data*, *Phys. Rev. D* **108** (2023) 023513 [[arXiv:2211.05742](#)] [[INSPIRE](#)].
- [238] F.B.M. Santos, *Updating constraints on phantom crossing $f(T)$ gravity*, *JCAP* **06** (2023) 039 [[arXiv:2211.16370](#)] [[INSPIRE](#)].

- [239] T. Schiavone, G. Montani and F. Bombacigno, *f(R) gravity in the Jordan frame as a paradigm for the Hubble tension*, *Mon. Not. Roy. Astron. Soc.* **522** (2023) L72 [[arXiv:2211.16737](#)] [[INSPIRE](#)].
- [240] M. Ballardini, A.G. Ferrari and F. Finelli, *Phantom scalar-tensor models and cosmological tensions*, *JCAP* **04** (2023) 029 [[arXiv:2302.05291](#)] [[INSPIRE](#)].
- [241] Y. Zhai et al., *A consistent view of interacting dark energy from multiple CMB probes*, *JCAP* **07** (2023) 032 [[arXiv:2303.08201](#)] [[INSPIRE](#)].
- [242] G. Montani, M. De Angelis, F. Bombacigno and N. Carlevaro, *Metric f(R) gravity with dynamical dark energy as a paradigm for the Hubble Tension*, [arXiv:2306.11101](#) [[INSPIRE](#)].
- [243] L.A. Escamilla et al., *The state of the dark energy equation of state circa 2023*, [arXiv:2307.14802](#) [[INSPIRE](#)].
- [244] J.M. Cline, M. Puel, T. Toma and Q.S. Wang, *Phantom fluid cosmology: impact of a phantom hidden sector on cosmological observables*, [arXiv:2308.12989](#) [[INSPIRE](#)].
- [245] S. Vagnozzi, *Seven hints that early-time new physics alone is not sufficient to solve the Hubble tension*, *Universe* **9** (2023) 393 [[arXiv:2308.16628](#)] [[INSPIRE](#)].
- [246] S. Vagnozzi et al., *Constraints on the sum of the neutrino masses in dynamical dark energy models with $w(z) \geq -1$ are tighter than those obtained in Λ CDM*, *Phys. Rev. D* **98** (2018) 083501 [[arXiv:1801.08553](#)] [[INSPIRE](#)].
- [247] E. Ó Colgáin, M.H.P.M. van Putten and H. Yavartanoo, *de Sitter Swampland, H_0 tension & observation*, *Phys. Lett. B* **793** (2019) 126 [[arXiv:1807.07451](#)] [[INSPIRE](#)].
- [248] E.Ó. Colgáin and H. Yavartanoo, *Testing the Swampland: H_0 tension*, *Phys. Lett. B* **797** (2019) 134907 [[arXiv:1905.02555](#)] [[INSPIRE](#)].
- [249] A. Banerjee et al., *Hubble sinks in the low-redshift swampland*, *Phys. Rev. D* **103** (2021) L081305 [[arXiv:2006.00244](#)] [[INSPIRE](#)].
- [250] L. Heisenberg, H. Villarrubia-Rojo and J. Zosso, *Can late-time extensions solve the H_0 and σ_8 tensions?*, *Phys. Rev. D* **106** (2022) 043503 [[arXiv:2202.01202](#)] [[INSPIRE](#)].
- [251] E. Di Valentino, A. Mukherjee and A.A. Sen, *Dark Energy with Phantom Crossing and the H_0 Tension*, *Entropy* **23** (2021) 404 [[arXiv:2005.12587](#)] [[INSPIRE](#)].
- [252] S.A. Adil et al., *Omnipotent dark energy: A phenomenological answer to the Hubble tension*, [arXiv:2306.08046](#) [[INSPIRE](#)].
- [253] J.L. Bernal, L. Verde and A.G. Riess, *The trouble with H_0* , *JCAP* **10** (2016) 019 [[arXiv:1607.05617](#)] [[INSPIRE](#)].
- [254] G.E. Addison et al., *Elucidating Λ CDM: Impact of Baryon Acoustic Oscillation Measurements on the Hubble Constant Discrepancy*, *Astrophys. J.* **853** (2018) 119 [[arXiv:1707.06547](#)] [[INSPIRE](#)].
- [255] P. Lemos, E. Lee, G. Efstathiou and S. Gratton, *Model independent $H(z)$ reconstruction using the cosmic inverse distance ladder*, *Mon. Not. Roy. Astron. Soc.* **483** (2019) 4803 [[arXiv:1806.06781](#)] [[INSPIRE](#)].
- [256] K. Aylor et al., *Sounds Discordant: Classical Distance Ladder & Λ CDM -based Determinations of the Cosmological Sound Horizon*, *Astrophys. J.* **874** (2019) 4 [[arXiv:1811.00537](#)] [[INSPIRE](#)].
- [257] N. Schöneberg, J. Lesgourgues and D.C. Hooper, *The BAO+BBN take on the Hubble tension*, *JCAP* **10** (2019) 029 [[arXiv:1907.11594](#)] [[INSPIRE](#)].
- [258] L. Knox and M. Millea, *Hubble constant hunter's guide*, *Phys. Rev. D* **101** (2020) 043533 [[arXiv:1908.03663](#)] [[INSPIRE](#)].

- [259] N. Arendse et al., *Cosmic dissonance: are new physics or systematics behind a short sound horizon?*, *Astron. Astrophys.* **639** (2020) A57 [[arXiv:1909.07986](#)] [[INSPIRE](#)].
- [260] G. Efstathiou, *To H_0 or not to H_0 ?*, *Mon. Not. Roy. Astron. Soc.* **505** (2021) 3866 [[arXiv:2103.08723](#)] [[INSPIRE](#)].
- [261] R.-G. Cai et al., *No-go guide for the Hubble tension: Late-time solutions*, *Phys. Rev. D* **105** (2022) L021301 [[arXiv:2107.13286](#)] [[INSPIRE](#)].
- [262] R.E. Keeley and A. Shafieloo, *Ruling Out New Physics at Low Redshift as a Solution to the H_0 Tension*, *Phys. Rev. Lett.* **131** (2023) 111002 [[arXiv:2206.08440](#)] [[INSPIRE](#)].
- [263] R. Jimenez et al., *The local and distant Universe: stellar ages and H_0* , *JCAP* **03** (2019) 043 [[arXiv:1902.07081](#)] [[INSPIRE](#)].
- [264] S. Vagnozzi, F. Pacucci and A. Loeb, *Implications for the Hubble tension from the ages of the oldest astrophysical objects*, *JHEAp* **36** (2022) 27 [[arXiv:2105.10421](#)] [[INSPIRE](#)].
- [265] D. Valcin et al., *The age of the Universe with globular clusters: reducing systematic uncertainties*, *JCAP* **08** (2021) 017 [[arXiv:2102.04486](#)] [[INSPIRE](#)].
- [266] J.L. Bernal et al., *The trouble beyond H_0 and the new cosmic triangles*, *Phys. Rev. D* **103** (2021) 103533 [[arXiv:2102.05066](#)] [[INSPIRE](#)].
- [267] A. Cimatti and M. Moresco, *Revisiting the Oldest Stars as Cosmological Probes: New Constraints on the Hubble Constant*, *Astrophys. J.* **953** (2023) 149 [[arXiv:2302.07899](#)] [[INSPIRE](#)].
- [268] M. Cicoli et al., *De Sitter vs Quintessence in String Theory*, *Fortsch. Phys.* **67** (2019) 1800079 [[arXiv:1808.08967](#)] [[INSPIRE](#)].
- [269] SIMONS OBSERVATORY collaboration, *The Simons Observatory: Science goals and forecasts*, *JCAP* **02** (2019) 056 [[arXiv:1808.07445](#)] [[INSPIRE](#)].
- [270] SIMONS OBSERVATORY collaboration, *The Simons Observatory: Astro2020 Decadal Project Whitepaper*, *Bull. Am. Astron. Soc.* **51** (2019) 147 [[arXiv:1907.08284](#)] [[INSPIRE](#)].