Model-Independent Perspectives on Coupled Dark Energy and the Swampland

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(Dated: June 26, 2020)

We present a general model-independent approach to study the coupled dark energy and the string Swampland criteria. We show how the dark sector interaction is degenerated with the equation of state of dark energy in the context of the expansion of the Universe. With priors for either of them, the dynamics of dark energy and the dark sector interactions can be reconstructed together with the bounds of the Swampland criteria. Combining cosmic chronometers, baryon acoustic oscillation (BAO), and Type Ia supernovae our results suggest a mild 1σ significance of dark sector interactions at low redshift for the coupled quintessence. The Lyman-α BAO at \( z = 2.34 \) leads a 2σ signal of non-zero interactions at high redshift. The implications for coupled quintessence are discussed.

I. INTRODUCTION

The concordance cosmology—a cosmological constant \( \Lambda \) plus the cold dark matter (CDM), namely \( \Lambda \)CDM model, has proven to be remarkably successful at describing the Universe from a wide range of experiments including cosmic microwave background (CMB), baryon acoustic oscillations (BAO), Type Ia supernovae (SNe Ia), and large-scale structures (LSS) [1–3]. Despite the consistency with the observations, \( \Lambda \)CDM model still faces several problems [6]. In addition, tensions between different experiments when fitting the \( \Lambda \)CDM model have emerged in the last decade (see the Hubble tensions [4, 7–10] and cosmic shear discrepancies [11–13]). These discrepancies, if not induced by unknown systematics, challenge the standard cosmological model and hint at a fundamental problem or new physics. Many attempts, such as introducing dynamic dark energy (see reviews [14, 15]) or more fundamentally modify the general relativity (GR) [16–18], have been proposed on these issues. Among these extensions to the baseline \( \Lambda \)CDM model, the interaction between dark energy and dark matter have also been studied in the literature [19–24], which is aimed at solving the coincidence problem and may be an excellent solution to the \( H_0 \) and cosmic shear tensions [25].

Quintessence as a canonical scalar field is introduced to explain cosmological acceleration with a dynamical cosmological constant [15, 26]. It is also argued that unless there is a symmetry, a quintessence field should couple to other sectors [27]. Given the tight constraint of the couplings to the standard model particles, the scalar field is at least considered coupling to dark matter, namely the “coupled quintessence” [20, 21]. Coupled dark energy is closely related to modified theories of gravity, for example, there is a conformal equivalence between the \( f(R) \) gravity in the Jordan frame and the coupled dark energy model in the Einstein frame [19, 28]. These facts make the interactions between dark energy and dark matter a general consideration that cannot be excluded a priori.

Either the coupled phenomenological fluid or the quintessence of dark energy models have been constrained by various data sets in the literature [22–24, 29, 30]. Usually, a specific form of the dark energy model together with a coupling should be assumed to obtain the constraints from the model-fitting methodology (see [23] for exponential coupling and exponential potential of scalar field). A nonparametric and model-independent approach was proposed by Yang et al. [31] to reconstruct the interaction between the phenomenological fluid of dark energy and dark matter. In this paper, we investigate the coupled dark energy for both the phenomenological fluid and quintessence.

Recently, the string Swampland criteria on cosmology has been proposed [32–35]. A common viewpoint is that GR cannot be the ultimate theory of the universe. We can however assume that GR might be the low-energy limit of a well-motivated high-energy UV-complete theory such as the string theory. Thus effective field theory (EFT) describes this low-energy limits effectively captures the behavior of the inflaton field and dark energy phenomena. The landscape of string theory gives a vast range of choices for how our universe may fit in a consistent quantum theory of gravity. However it is surrounded by an even bigger swampland of consistent-looking semi-classical EFTs, which are actually inconsistent [34]. This could be an indicator that de Sitter vacua may reside in the Swampland.

One of the Swampland criteria comes from the de Sitter conjecture: Any scalar field potential from string theory obeys either \( M_{pl} \frac{V_{\phi}}{V} \equiv c \gtrsim \mathcal{O}(1) \) (C1) or \( M_{pl} \frac{V_{\phi}}{V} \equiv c \lesssim -\mathcal{O}(1) \) (C2) [35]. Here \( \phi \) is the scalar filed and \( V \) is the potential, which are usually built form quintessence model. Throughout this paper, we set the reduced Planck mass to be \( M_{pl} = 1 \). The Swampland criteria have sparked a lot of research recently on cosmology [36–41], especially on \( H_0 \) tensions [42–45]. It turns

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1 Another Swampland criterion is the distance conjecture which says, the range traversed by scalar fields in field space is bounded by \( \Delta \phi_{pl} \lesssim \mathcal{O}(1) \).
out that quintessence models exacerbate the Hubble tensions. Recently, Agrawal et al. [46] proposed an interacting quintessence model inspired from distance conjecture, which leads to a continually reducing dark matter mass as the scalar field rolls in the recent cosmological epoch, can reconcile the Hubble tension. However, the couplings emerge from $z \approx 15$ where the observations are rare.

Like the dark sector interaction, traditional constraints of the Swampland criteria confronting the cosmological data sets were performed by the model-fitting methodology [36, 47]. In particular, Wang [48] fitted the cosmological model with a large parameter space including the coupling to various data sets. Recently, a model-independent approach was proposed by [49] to reconstruct C1 but they assumed no interaction in the dark sector, which is not general in the literature.

In this paper, without assuming any cosmological models, we investigate a model-independent approach to reconstruct the coupled dark energy and the bounds of the Swampland criteria in the context of the expansion of the Universe.

II. METHOD SET-UP

We consider a quintessence scalar field $\phi$ coupled to the non-relativistic dark matter. In the presence of this dark-sector interaction, the dark matter density no longer scales as $a^{-3}$ but $\rho_c \sim f/a^3$. Here $f$ is an arbitrary function of $\phi$ to denote the coupling [21]. To be consistent with the equivalence principle and solar-system tests of gravity [50, 51], we do not couple $\phi$ to baryons. Without loss of generality, we assume at present time $f_0 = 1$. In the flat Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime, the Friedmann and continuity equations for every species are

$$3H^2 = \rho_\phi + \rho_c + \rho_b,$$  \hspace{1cm} (1)

$$\dot{\rho}_c + 3H \rho_c = 3H^2 \Omega_c \frac{f}{a^2},$$  \hspace{1cm} (2)

$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = -3H^2 \Omega_c \frac{\dot{f}}{a^2},$$  \hspace{1cm} (3)

$$\dot{\rho}_b + 3H \rho_b = 0.$$  \hspace{1cm} (4)

Here $a$ is the scale factor, $H = \dot{a}/a$ is the Hubble parameter and dots denote time derivatives. The energy density and pressure of the scalar field are $\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V$ and $P_\phi = \frac{1}{2} \dot{\phi}^2 - V$, with the field potential $V$ and equation of state $w_\phi = P_\phi/\rho_\phi$. $\Omega_X = \rho_X/3H_0^2$ denotes the present values of the density parameters. Since we focus on the late-time Universe, the radiation contributions are ignored.

After some algebra, we can get the equations for the kinetic term and potential of the scalar field,

$$\dot{\phi}^2 = -2H - 3H_0^2 \frac{\Omega_c f + \Omega_b}{a^3},$$  \hspace{1cm} (5)

$$V = \dot{H} + 3H^2 - 3H_0^2 \frac{\Omega_c f + \Omega_b}{a^3},$$  \hspace{1cm} (6)

$$\dot{V} = \ddot{H} + 6H \dot{H} - 3H_0^2 \frac{\Omega_c f - 3H(\Omega_c f + \Omega_b)}{a^3}.$$  \hspace{1cm} (7)

The above equations make it possible to relate the Swampland criteria to the expansion data sets of the Universe and the coupling between dark energy and dark matter. For the uncoupled case $f = 1$, we recover the formulae in [49].

To relate the coupling and the equation of state of the scalar field, $w_\phi = (-2H - 3H^2)/(3H^2 - 3H_0^2 \Omega_c f/\Omega_b)$. We have

$$f = \frac{a^3}{3H_0^2 \Omega_c} \left( \frac{2\dot{H} + 3H^2(1+w_\phi)}{w_\phi} - \frac{\Omega_b}{\Omega_c} \right),$$  \hspace{1cm} (8)

$$\dot{f} = \frac{a^3}{3H_0^2 \Omega_c} \left( 9H^3 + 6\dot{H} \right) \left( 12H^2 + 2\dot{H} + 9H^3 \right) \frac{\Omega_b}{w_\phi} - \left( \frac{2\dot{H} + 3H^2}{w_\phi} \right) \dot{w}_\phi.$$  \hspace{1cm} (9)

Eqs. (8) and (9) are also valid for the phenomenological dark energy with a general equation of state $w$. The equation of state of dark energy is degenerated with the dark sector interactions in the context of the background expansion observations (e.g. Hubble parameter, distance). That is, for a fixed background expansion, $w_\phi$ (or a general $w$) and $f$ can be reconstructed only if either of them is given. In other words, the dynamics of the dark energy and dark sector interactions counterbalance each other to give the expansion of the Universe measured from the observations. Note that in order to reconstruct the functions from the data sets, we should convert the time derivatives to redshift derivatives in all equations through the relation $\frac{\dot{a}}{a} = -H(1+z)\frac{d}{dz}$.

For the coupled quintessence, we can directly relate $\dot{\phi}^2$, $V$, $\dot{V}$ to the equation of state of the scalar field

$$\dot{\phi}^2 = -1 + \frac{1}{w_\phi} (2\dot{H} + 3H^2),$$  \hspace{1cm} (10)

$$V = \frac{(w_\phi - 1)(2\dot{H} + 3H^2)}{2w_\phi},$$  \hspace{1cm} (11)

$$\dot{V} = \frac{w_\phi(w_\phi - 1)(2\dot{H} + 6H\dot{H}) + \dot{w}_\phi(2\dot{H} + 3H^2)}{2w_\phi^2}.$$  \hspace{1cm} (12)

The derivations of $\dot{\phi}$ and $\dot{V}$ are straightforward. Having the prior of $w_\phi$, we can reconstruct the dark sector interactions ($f$, $f$) and the Swampland criteria $|V_\phi| = |V/\dot{\phi}|$ or $\frac{V_\phi}{V} = (\frac{\dot{V}}{\dot{\phi}^2} - \frac{\dot{\phi}^2}{\dot{\phi}^2})/V$ simultaneously.

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2 Actually, introducing a universal coupling between dark energy and the total non-relativistic matter including the subdominant baryons only slightly changes our results.
Equations (5-12) suggest that using the the expansion data sets of the Universe, we can reconstruct the dynamics of the dark energy, the kinetic term and potential of the scalar field, the dark sector interactions, and the final swampland criteria if we set a prior for either the coupling $f$ or the equation of state of dark energy $w$ (for quintessence, $w_\phi > -1$ should be hold).

Instead of the Hubble parameter, the distance can also be incorporated in the equations above using the relations $H(z)^{-1} \sim d(D_L/(1 + z))/dz \sim d(D_A/(1 + z))/dz$. Here $D_L$ is the luminosity distance and $D_A$ is the angular diameter distance. In this paper, we stick to using the Hubble observations.

We consider three data sets related to the expansion of the Universe:

- 31 $H(z)$ data from cosmic chronometers (CC) obtained using the differential-age technique. We use the compilation in Table 1 of Gómez-Valent and Amendola [52] (also see references therein);

- 18 $H(z)$ data from the homogenized model-independent BAO compiled in Table 2 of Magana et al. [53]. But we substitute the last three high redshift $z = 2.33, 2.34, 2.36$ Lyman-$\alpha$ (Ly$\alpha$) BAO [54-56] with the latest update at $z = 2.34$ from eBOSS DR14 [57, 58]. Note we adopt the Planck sound horizon around 147 Mpc at the drag epoch;

- 6 $E(z)$ data from Pantheon+MCT SNe Ia Measurements given by Riess et al. [59]. Here $E(z) = H(z)/H_0$ is the Hubble rate. For the $z = 1.5$ point we adopt the gaussian approximation by Gómez-Valent [60].

For the compatibility of the three data sets that we use for the reconstructions, we convert all the $H(z)$ data to $E(z)$ data by setting a fiducial value of $H_0$. Again, in the spirit of a model-independent approach, we set the fiducial value of $H_0$ estimated from the non-parametric reconstruction using CC+BAO $H(z)$ data. We get the mean $H_0 = 67.72$ km s$^{-1}$ Mpc$^{-1}$, which is consistent with Planck $^3$. We rewrite Eqs. (5-12) to substitute $H$ with $E$ by dividing $(H_0)^n$ on both sides of the equations. Here $n$ relates to the dimensions of the equations quantified by $H_0$. Then the dimensionless parameters we can reconstruct are actually $\frac{\phi^2}{Q^2}$, $\frac{\nabla^2 \phi}{\nabla^2}$, $\frac{\nabla \phi}{\nabla}$, $f$, $\frac{f}{\Phi}$, $w_\phi$ (or $w$), $c$, and $\dot{\epsilon}$, etc.

### III. Reconstructions

We use Gaussian process $^4$, a machine learning method which have been widely used in the data analysis of cosmology especially for the model-independent reconstructions of the cosmological parameters (see $[61, 62]$ and references therein), to reconstruct $E(z)$, $E'(z)$, $E''(z)$ and $E'''(z)$ from the three date sets combination. In this paper, we adopt the value $\Omega_c = 0.26$ and $\Omega_m = 0.05$ from Planck $^4$. From these $E''(z)$ reconstructions with their covariance, we first check the uncoupled case in Eqs. (5-7). For uncoupled quintessence, our reconstructed Swampland criteria $C1$ (see Fig. 1) is consistent with Elizalde and Khurshudyan $[49]$. Note that for quintessence as dark energy, we should stick to $w > -1$ (no phantom). From Eq. (10), this amounts to ensuring a positive value of the kinetic term $\dot{\phi}^2$. The equation of state of either the phenomenological dark energy or the quintessence is also shown in Fig. 1. The results show that the data sets are consistent with the $\Lambda$CDM model ($w = -1$ and $f = 0$). The upper bound of the Swampland criterion $C1$ at $z = 0$ is 1.23 at 95% significance $^5$.

For coupled dark energy, as we demonstrate in Sec. II, the priors of either the equation of state of dark energy or the dark sector interactions should be given to reconstruct the cosmological parameters. Since there are various forms for the small (generally speaking) couplings, setting priors on coupling is not rational. In this paper we use the priors of the equation of state of dark energy which has definite parameterizations (such as CPL) and has been constrained or reconstructed from different observations $[4, 18, 63, 64]$. We extract the constraints of CPL form $w(z) = w_0 + \frac{w_a}{1+z}$ from Planck $^4$ with the corresponding released covariance of $w_0$ and $w_a$ $^6$. The reconstructions of the dark sector interactions and Swampland criteria $C1$ are shown in Fig. 2. Our results suggest a 1$\sigma$ signal of non-zero dark sector interactions for the coupled quintessence at low redshift and a 2$\sigma$ signal at $z > 2$ for both the phenomenological dark energy and quintessence. In this paper we do not assume any cosmological model for either the dark energy or the couplings. Traditionally the interaction term is a parametric form of $Q$ in the literature, where $\dot{\rho}_c + 3H\rho_c = Q \sim \dot{f}$. Though we plot the interaction results for both $f$ and $\dot{f}$, $f$ is less meaningful since $f$ is only defined up to a constant that can be absorbed in $\Omega_c$. Note that whether $f$ is zero or not is independent of the values of the density parameters. The upper bound of the Swampland

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$^3$ The lower value of $H_0$ is caused by the Ly$\alpha$ BAO at high redshift. We find without Ly$\alpha$ the reconstructed $H_0$ is 69.03 km s$^{-1}$ Mpc$^{-1}$. However our approach is not sensitive to the value of $H_0$.

$^4$ In this paper we adopt the usual Matérn ($\nu = 9/2$) kernel function for the Gaussian process since we can reconstruct the third derivative of the function. However, we have checked the other kernel function such as the exponential form will lead only a slightly different result.

$^5$ We do not show the results of $C2$ in this paper because of the poor reconstructions using present data sets.

$^6$ [https://pla.esac.esa.int](https://pla.esac.esa.int)
criterion $C1$ at $z = 0$ is 4.44 at 95% significance.

IV. CONCLUSIONS AND DISCUSSIONS

In this paper, we investigated a model-independent approach to reconstruct the coupled dark energy and Swampland criteria in the context of the expansion of the Universe. We showed how the dynamics of dark energy and the dark sector interactions are degenerated and counterbalance each other in a fixed Universe expansion. Based on the expansion data from cosmic chronometers, BAO (including Lyα at $z = 2.34$) and SNe Ia, our results suggest a mild and significant non-zero dark sector interaction at low ($z < 0.3$) and high ($z > 2$) redshift respectively for the coupled quintessence. The Swampland criteria cannot be ruled out at present stage.

The mild deviations of non-zero $\dot{f}$ emerge at low redshift come from the compensation of the bias we stick to quintessence $w > -1$. This can be regarded as an indication of the preference of $\Lambda$CDM over quintessence. The inconsistency between Lyα and $\Lambda$CDM model at high redshift have been alleviated from 2.3σ to 1.7σ significance [4] with the latest update from eBOSS DR14 [57, 58]. In this paper we can interpret the inconsistency as a signal of dark sector interactions.

The flow of the dark sector interaction from dark matter to dark energy in the quintessence model at the low redshift is consistent with other model-fitting results [22, 25]. This is a result of the restriction for $w > -1$. While the flow from dark energy to dark matter induced by Lyα at high redshift contradicts the interacting quintessence proposed by Agrawal et al. [46] from string theory to alleviate the Hubble tension. All implications of our results cast a shadow over quintessence model.

Assuming no dark sector interaction, reconstructions of the dynamics of dark energy are consistent with the cosmological constant. While setting priors on the equation of state from Planck, which is consistent with $w = -1$, Lyα BAO at $z = 2.34$ give a 2σ deviation from null dark sector interaction at $z > 2$. This means the dark sector interaction is more sensitive to the data anomaly than the dynamics of dark energy in our approach. This can be seen from the Eq. (9), where the interactions rely on the second derivative of the Hubble parameter. This inspires that the evidence of the dynamics of the dark energy presented by Zhao et al. [63] can also be interpreted as a signal of null-zero dark sector interactions.

Interestingly, from the model-independent reconstruction the anomalous Lyα BAO at $z = 2.34$ gives a lower value of $H_0 = 67.72$ km s$^{-1}$ Mpc$^{-1}$ which is very consistent with Planck. While in the case without Lyα, $H_0 = 69.03$ km s$^{-1}$ Mpc$^{-1}$ is consistent with the local SNe Ia calibrated by Tip of the Red Giant Branch (TRGB) [65, 66]. However, our approach is insensitive to the value of $H_0$ which is cancelled in the reconstructions of $f, c$ or $\tilde{c}$. As for $\dot{f}/H_0$, the rescaling will not influence the statistics of the deviations from 0.

Our methodology in this paper is very general in the context of the model-independent approach. In principle, any machine-learning techniques applied on the regression or reconstruction of functions from the large data sets are suitable for our approach. The Deep Learning [67, 68] and Artificial Neural Networks [69] developed recently provide rich alternatives of applications in cosmology.

We have mentioned that distance data can also be incorporated in the formulae. Actually from Gaussian process, the Hubble parameter, which is inversely proportional to the derivative of distance, can be combined with the luminosity distance and angular diameter distance data sets to jointly reconstruct cosmological parameters. This gives a possibility of using standard candles such as quasars [70] and gamma ray bursts [71] at high redshift. In addition, future cosmic probes such as Euclid [72].
FIG. 2. Reconstructions of the dark sector interactions (left) and Swampland criterion $C1$ (right) for the coupled dark energy. We only show 68% confidence level for the dark sector interactions. The red dashed line denotes a null interaction. The priors of $w(z) = w_0 + w_a \frac{z}{1+z}$ are extracted from Planck.

DESI [73] and gravitational wave standard sirens [74–76] can play very import role in the test of $\Lambda$CDM model at very high redshift.

V. ACKNOWLEDGEMENTS

TY thanks Jia-Jun Zhang, Yun-Long Zhang and Eoin Ó Colgáin for helpful discussions. This work is supported by an appointment to the YST Program at the APCTP through the Science and Technology Promotion Fund and Lottery Fund of the Korean Government, and the Korean Local Governments - Gyeongsangbuk-do Province and Pohang City.

[1] A. G. Riess et al. (Supernova Search Team), Observational evidence from supernovae for an accelerating universe and a cosmological constant, Astron. J. 116, 1009 (1998), arXiv:astro-ph/9805201 [astro-ph].
[2] S. Perlmutter et al. (Supernova Cosmology Project), Measurements of $\Omega$ and $\Lambda$ from 42 high redshift supernovae, Astrophys. J. 517, 565 (1999), arXiv:astro-ph/9812133 [astro-ph].
[3] G. Hinshaw et al. (WMAP), Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results, Astrophys. J. Suppl. 208, 19 (2013), arXiv:1212.5226 [astro-ph.CO].
[4] N. Aghanim et al. (Planck), Planck 2018 results. VI. Cosmological parameters, (2018), arXiv:1807.06209 [astro-ph.CO].
[5] S. Alam et al. (BOSS), The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample, Mon. Not. Roy. Astron. Soc. 470, 2617 (2017), arXiv:1607.03155 [astro-ph.CO].
[6] S. Weinberg, The Cosmological constant problems, in Sources and detection of dark matter and dark energy in the universe, Proceedings, 4th International Symposium, DM 2000, Marina del Rey, USA, February 23-25, 2000 (2000) pp. 18–26, arXiv:astro-ph/0005265 [astro-ph].
[7] W. L. Freedman, Cosmology at a Crossroads, Nat. Astron. 1, 0121 (2017), arXiv:1706.02739 [astro-ph.CO].
[8] L. Verde, T. Treu, and A. G. Riess, Tensions between the Early and the Late Universe, in Nature Astronomy 2019 (2019) arXiv:1907.10625 [astro-ph.CO].
[9] K. C. Wong et al., H0LiCOW XIII. A 2.4% measurement of $H_0$ from lensed quasars: 5.3σ tension between early and late-Universe probes 10.1093/mnras/stz3094 (2019), arXiv:1907.04869 [astro-ph.CO].
[10] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond $\Lambda$CDM, Astrophys. J. 876, 85 (2019), arXiv:1903.07603 [astro-ph.CO].
[11] I. G. McCarthy, S. Bird, J. Schaye, J. Harnois-Deraps, A. S. Font, and L. Van Waerbeke, The BAHAMAS project: the CMB–large-scale structure tension and the roles of massive neutrinos and galaxy formation, Mon. Not. Roy. Astron. Soc. 476, 2990 (2018), arXiv:1712.02411 [astro-ph.CO].
[12] H. Hildebrandt et al., KiDS+VIKING-450: Cosmic shear tomography with optical and infrared data, Astron. Astrophys. 633, A69 (2020), arXiv:1812.06076 [astro-ph.CO].
[13] M. Asgari et al., KiDS+VIKING-450 and DES-Y1 combined: Mitigating baryon feedback uncertainty with COSEBIs, Astron. Astrophys. 634, A127 (2020), arXiv:1910.05336 [astro-ph.CO].
[14] E. J. Copeland, M. Sami, and S. Tsujikawa, Dynamics of dark energy, Int. J. Mod. Phys. D15, 1753 (2006), arXiv:hep-th/0603057 [hep-th].

[15] S. Tsujikawa, Quintessence: A Review, Class. Quant. Grav. 30, 214003 (2013), arXiv:1304.1961 [gr-qc].

[16] M. Kunz and D. Sapone, Dark Energy versus Modified Gravity, Phys. Rev. Lett. 98, 121301 (2007), arXiv:astro-ph/0612452 [astro-ph].

[17] S. Tsujikawa, Modified gravity models of dark energy, Lect. Notes Phys. 800, 99 (2010), arXiv:1101.0191 [gr-qc].

[18] P. A. R. Ade et al. (Planck), Planck 2015 results. XIV. Dark energy and modified gravity, Astron. Astrophys. 594, A14 (2016), arXiv:1502.01500 [astro-ph.CO].

[19] 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, 096901 (2016), arXiv:1603.08299 [astro-ph.CO].

[20] L. Amendola, Coupled quintessence, Phys. Rev. D62, 043511 (2000), arXiv:astro-ph/9908023 [astro-ph].

[21] S. Das, P. S. Corasaniti, and J. Khoury, Super-acceleration as signature of dark sector interaction, Phys. Rev. D75, 083509 (2006), arXiv:astro-ph/0510628 [astro-ph].

[22] A. A. Costa, X.-D. Xu, B. Wang, and E. Abdalla, Constraints on interacting dark energy models from Planck 2015 and redshift-space distortion data, JCAP 1701, 028, arXiv:1605.04138 [astro-ph.CO].

[23] C. Van De Bruck and J. Mifsud, Searching for dark matter - dark energy interactions: going beyond the conformal case, Phys. Rev. D97, 023506 (2018), arXiv:1709.04882 [astro-ph.CO].

[24] J. Zhang, R. An, W. Luo, Z. Li, S. Liao, and B. Wang, The First Constraint from SDSS Galaxy–Galaxy Weak Lensing Measurements on Interacting Dark Energy Models, Astrophys. J. Lett. 875, L11 (2019), arXiv:1807.05252 [astro-ph.CO].

[25] E. Di Valentinio, A. Melchiorri, O. Mena, and S. Vagnozzi, Interacting dark energy after the latest Planck, DES, and H0 measurements: an excellent solution to the H0 and cosmic shear tensions, (2019), arXiv:1908.04281 [astro-ph.CO].

[26] E. V. Linder, The Dynamics of Quintessence, The Quintessence of Dynamics, Gen. Rel. Grav. 40, 329 (2008), arXiv:0704.2064 [astro-ph].

[27] S. M. Carroll, Quintessence and the rest of the world, Phys. Rev. Lett. 81, 3067 (1998), arXiv:astro-ph/9806099 [astro-ph].

[28] A. De Felice and S. Tsujikawa, f(R) theories, Living Rev. Rel. 13, 3 (2010), arXiv:1002.4928 [gr-qc].

[29] R. An, A. A. Costa, L. Xiao, J. Zhang, and B. Wang, Testing a quintessence model with Yukawa interaction from cosmological observations and N-body simulations, Mon. Not. Roy. Astron. Soc. 489, 297 (2019), arXiv:1809.03224 [astro-ph.CO].

[30] J. Mifsud and C. Van De Bruck, Probing the imprints of generalized interacting dark energy on the growth of perturbations, JCAP 1711, 001, arXiv:1707.07667 [astro-ph.CO].

[31] T. Yang, Z.-K. Guo, and R.-G. Cai, Reconstructing the interaction between dark energy and dark matter using Gaussian Processes, Phys. Rev. D91, 123533 (2015), arXiv:1505.04443 [astro-ph.CO].

[32] P. Agrawal, G. Obied, P. J. Steinhardt, and C. Vafa, On the Cosmological Implications of the String Swampland, Phys. Lett. B784, 271 (2018), arXiv:1806.09718 [hep-th].

[33] G. Obied, H. Ooguri, L. Spodyneiko, and C. Vafa, De Sitter Space and the Swampland, (2018), arXiv:1806.08362 [hep-th].

[34] C. Vafa, The String landscape and the swampland, (2005), arXiv:hep-th/0509212 [hep-th].

[35] H. Ooguri, E. Palti, G. Shiu, and C. Vafa, Distance and de Sitter Conjectures on the Swampland, Phys. Lett. B788, 180 (2019), arXiv:1810.05506 [hep-th].

[36] L. Heisenberg, M. Bartelmann, R. Brandenberger, and A. Refregier, Dark Energy in the Swampland, Phys. Rev. D98, 123502 (2018), arXiv:1808.02877 [astro-ph.CO].

[37] M. Raveri, W. Hu, and S. Sethi, Swampland Conjectures and Late-Time Cosmology, Phys. Rev. D99, 083518 (2019), arXiv:1812.10448 [hep-th].

[38] R.-G. Cai, S. Khimphun, B.-H. Lee, S. Sun, G. Tumurtsaah, and Y.-L. Zhang, Emergent Dark Universe and the Swampland Criteria, Phys. Dark Univ. 26, 100387 (2019), arXiv:1812.11105 [hep-th].

[39] S. Brahma and M. W. Hossain, Dark energy beyond quintessence: Constraints from the swampland, JHEP 06, 070, arXiv:1902.11014 [hep-th].

[40] D. O. C. Thomas, Dark Energy, the Swampland and the Equivalence Principle, Phys. Rev. D100, 023515 (2019), arXiv:1904.07082 [hep-th].

[41] L. Heisenberg, M. Bartelmann, R. Brandenberger, and A. Refregier, Model Independent Analysis of Supernova Data, Dark Energy, Trans-Planckian Censorship and the Swampland, (2020), arXiv:2003.13283 [hep-th].

[42] E. Ó Colgáin, M. H. P. M. van Putten, and H. Yavartanoo, de Sitter Swampland, H0 tension & observation, Phys. Lett. B793, 126 (2019), arXiv:1807.07451 [hep-th].

[43] E. Ó Colgáin and H. Yavartanoo, Testing the Swampland: H0 tension, Phys. Lett. B797, 134907 (2019), arXiv:1905.02555 [astro-ph.CO].

[44] L. A. Anchordoqui, I. Antoniadis, D. Lüst, J. F. Soriano, and T. R. Taylor, H0 tension and the String Swampland, Phys. Rev. D101, 083532 (2020), arXiv:1912.00242 [hep-th].

[45] A. Banerjee, H. Cai, L. Heisenberg, E. Ó Colgáin, M. M. Sheikh-Jabbari, and T. Yang, Hubble Sinks In The Low-Redshift Swampland, (2020), arXiv:2006.00244 [astro-ph.CO].

[46] P. Agrawal, G. Obied, and C. Vafa, H0 Tension, Swampland Conjectures and the Epoch of Fading Dark Matter, (2019), arXiv:1906.08261 [astro-ph.CO].

[47] Y. Akrami, R. Kallosh, A. Linde, and V. vardanyan, The Landscape, the Swampland and the Era of Precision Cosmology, Fortschr. Phys. 67, 1800075 (2019), arXiv:1808.09440 [hep-th].

[48] D. Wang, Multi-feature universe: large parameter space cosmology and the swampland, Phys. Dark Univ. 28, 100545 (2020), arXiv:1809.04854 [astro-ph.CO].

[49] E. Elizalde and M. Khurshudyan, Swampland Conjectures and the Dark Energy Dominated Universe ensuing from Gaussian processes and H(z) data analysis, Phys. Rev. D99, 103533 (2019), arXiv:1811.03861 [astro-ph.CO].

[50] B. Bertotti, L. iess, and P. Tortora, A test of general relativity using radio links with the Cassini spacecraft, Nature 425, 374 (2003).
[51] C. M. Will, Was Einstein Right? A Centenary Assessment, (2014), arXiv:1409.7871 [gr-qc].
[52] A. Gómez-Valent and L. Amendola, $H_0$ from cosmic chronometers and Type Ia supernovae, with Gaussian Processes and the novel Weighted Polynomial Regression method, JCAP 1804, 051, arXiv:1802.01505 [astro-ph.CO].
[53] J. Magana, M. H. Amante, M. A. Garcia-Aspeitia, and C. M. Will, Was Einstein Right? A Centenary Assessment, Mon. Not. Roy. Astron. Soc. 476, 1036 (2018), arXiv:1706.09848 [astro-ph.CO].
[54] A. Font-Ribera et al. (BOSS), Quasar-Lyman $\alpha$ Forest Cross-Correlation from BOSS DR11: Baryon Acoustic Oscillations, JCAP 05, 027, arXiv:1311.1767 [astro-ph.CO].
[55] T. Delubac et al. (BOSS), Baryon acoustic oscillations in the Ly$\alpha$ forest of BOSS DR11 quasars, Astron. Astrophys. 574, A59 (2015), arXiv:1404.1801 [astro-ph.CO].
[56] J. E. Bautista et al., Measurement of baryon acoustic oscillation correlations at $z = 2.3$ with SDSS DR12 Ly$\alpha$-Forests, Astron. Astrophys. 603, A12 (2017), arXiv:1702.00176 [astro-ph.CO].
[57] V. de Sainte Agathe et al., Baryon acoustic oscillations at $z = 2.34$ from the correlations of Ly$\alpha$ absorption in eBOSS DR14, Astron. Astrophys. 629, A85 (2019), arXiv:1904.03400 [astro-ph.CO].
[58] M. Blomqvist et al., Baryon acoustic oscillations from the cross-correlation of Ly$\alpha$ absorption and quasars in eBOSS DR14, Astron. Astrophys. 629, A86 (2019), arXiv:1904.03430 [astro-ph.CO].
[59] A. G. Riess et al., Type Ia Supernova Distances at Redshift $>1.5$ from the Hubble Space Telescope Multicycle Treasury Programs: The Early Expansion Rate, Astrophys. J. 853, 126 (2018), arXiv:1710.00844 [astro-ph.CO].
[60] A. Gómez-Valent, Quantifying the evidence for the current speed-up of the Universe with low and intermediate-redshift data, A more model-independent approach, JCAP 1905, 026, arXiv:1810.02278 [astro-ph.CO].
[61] A. Shafieloo, A. G. Kim, and E. V. Linder, Gaussian Process Cosmography, Phys. Rev. D85, 123530 (2012), arXiv:1204.2272 [astro-ph.CO].
[62] M. Seikel, C. Clarkson, and M. Smith, Reconstruction of dark energy and expansion dynamics using Gaussian processes, JCAP 1206, 036, arXiv:1204.2832 [astro-ph.CO].
[63] G.-B. Zhao et al., Dynamical dark energy in light of the latest observations, Nature Astron. 1, 627 (2017), arXiv:1701.08165 [astro-ph.CO].
[64] V. Sahni, A. Shafieloo, and A. A. Starobinsky, Model independent evidence for dark energy evolution from Baryon Acoustic Oscillations, Astrophys. J. Lett. 793, L40 (2014), arXiv:1406.2209 [astro-ph.CO].
[65] W. L. Freedman et al., The Carnegie-Chicago Hubble Program. VIII. An Independent Determination of the Hubble Constant Based on the Tip of the Red Giant Branch 10.3847/1538-4357/ab2f73 (2019), arXiv:1907.05922 [astro-ph.CO].
[66] W. L. Freedman, B. F. Madore, T. Hoyt, I. S. Jang, R. Beaton, M. G. Lee, A. Monson, J. Neeley, and J. Rich, Calibration of the Tip of the Red Giant Branch (TRGB) 10.3847/1538-4357/ab7339 (2020), arXiv:2002.01550 [astro-ph.GA].
[67] D. George and E. A. Huerta, Deep Learning for Real-time Gravitational Wave Detection and Parameter Estimation: Results with Advanced LIGO Data, Phys. Lett. B778, 64 (2018), arXiv:1711.03121 [gr-qc].
[68] C. Escamilla-Rivera, Bayesian deep learning for dark energy 10.5772/intechopen.91466 (2020), arXiv:2005.06412 [astro-ph.CO].
[69] G.-J. Wang, X.-J. Ma, S.-Y. Li, and J.-Q. Xia, Reconstructing Functions and Estimating Parameters with Artificial Neural Networks: A Test with a Hubble Parameter and SNe Ia, Astrophys. J. Suppl. 246, 13 (2020), arXiv:1910.03636 [astro-ph.CO].
[70] G. Risaliti and E. Lusso, Cosmological constraints from the Hubble diagram of quasars at high redshifts, Nat. Astron. 3, 272 (2019), arXiv:1811.02590 [astro-ph.CO].
[71] M. Demianski, E. Piedipalumbo, D. Sawant, and L. Amati, Cosmology with gamma-ray bursts: I. The Hubble diagram through the calibrated $E_{\text{P},i} - E_{\text{iso}}$ correlation, Astron. Astrophys. 598, A12 (2017), arXiv:1610.00854 [astro-ph.CO].
[72] L. Amendola et al., Cosmology and fundamental physics with the Euclid satellite, Living Rev. Rel. 21, 2 (2018), arXiv:1606.00180 [astro-ph.CO].
[73] M. E. Levi et al. (DESI), The Dark Energy Spectroscopic Instrument (DESI), (2019), arXiv:1907.10688 [astro-ph.IM].
[74] B. P. Abbott et al. (LIGO Scientific, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER), A gravitational-wave standard siren measurement of the Hubble constant, Nature 551, 85 (2017), arXiv:1710.05835 [astro-ph.CO].