Dynamical Dark Energy: Insights from DESI and Quintessence

Invisibles25

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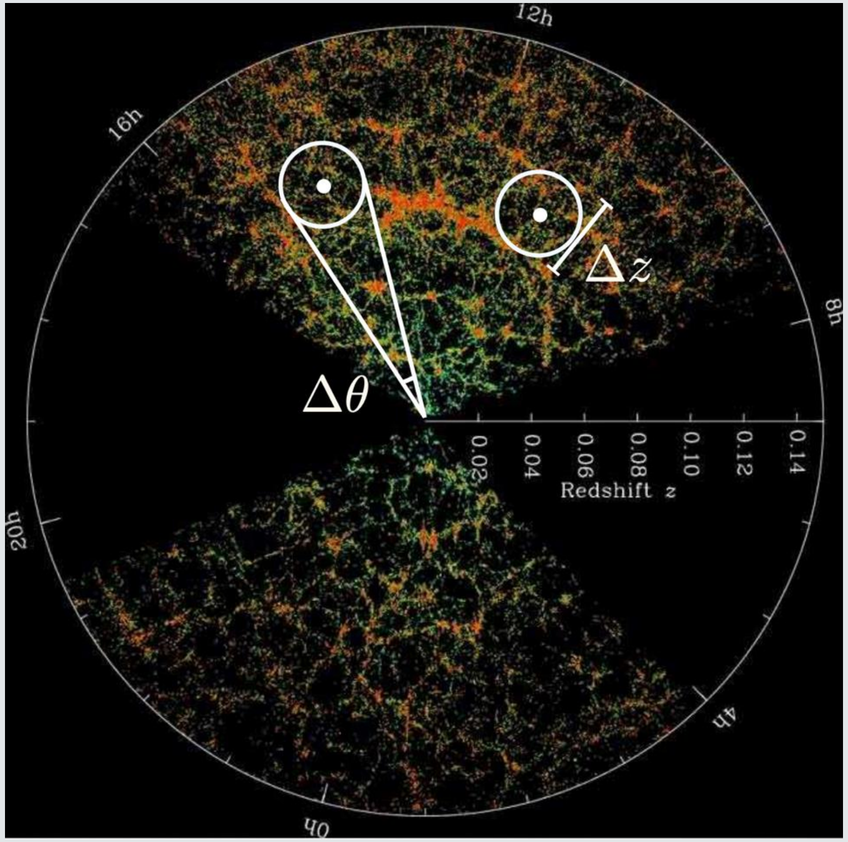
Structure

1. A brief introduction to the DESI results
2. Evidence for dynamical dark energy
3. Quintessence as a possible candidate
4. The dangers of CPL

Baryon acoustic oscillations

- Pre-recombination sound waves are propagating in the photon - baryon plasma
- At z~1000 (recombination) baryons decouple from photons, the universe becomes transparent, the sound speed decreases and the wave stalls

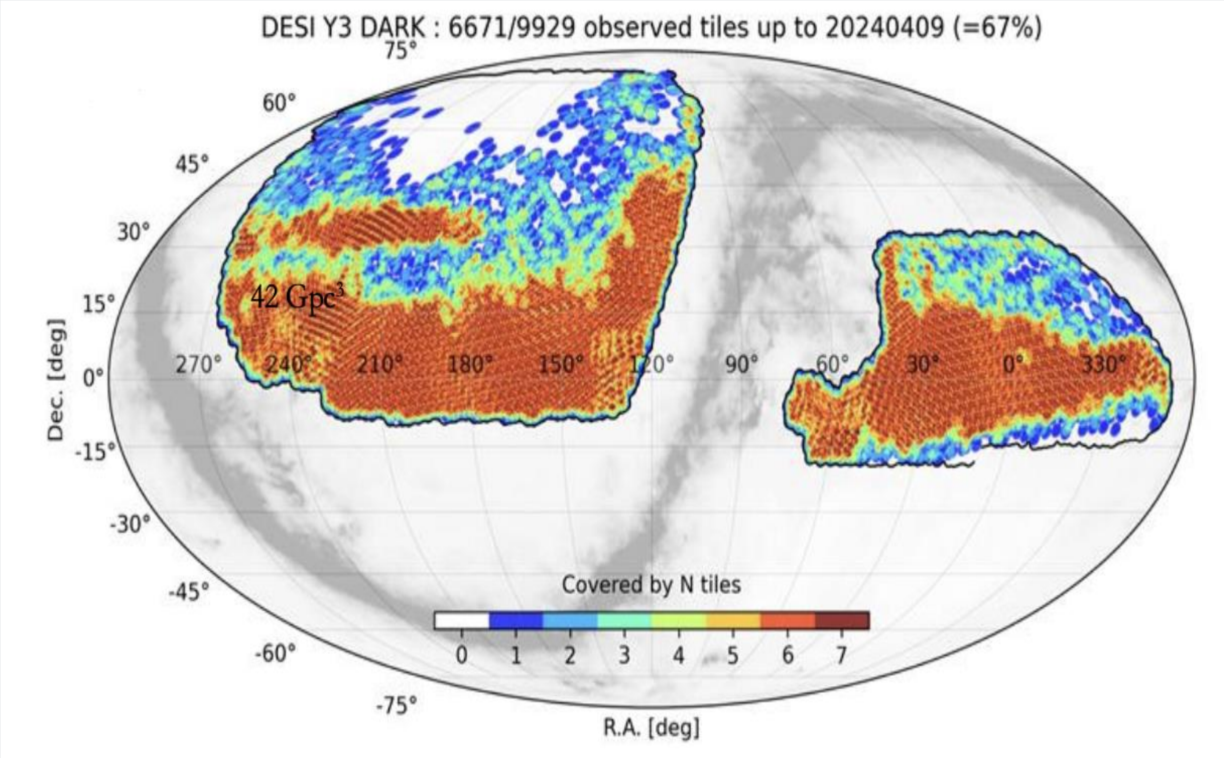


- There forms a spherical peak at the distance that the wave has travelled
- This defines the sound horizon scale (r_d) (~150Mpc), which is measured precisely by the CMB
- By measuring then the angular (Δθ) and redshift (Δz) separations we can infer the expansion rate of the Universe (H(z))

BAO precision leaps forward

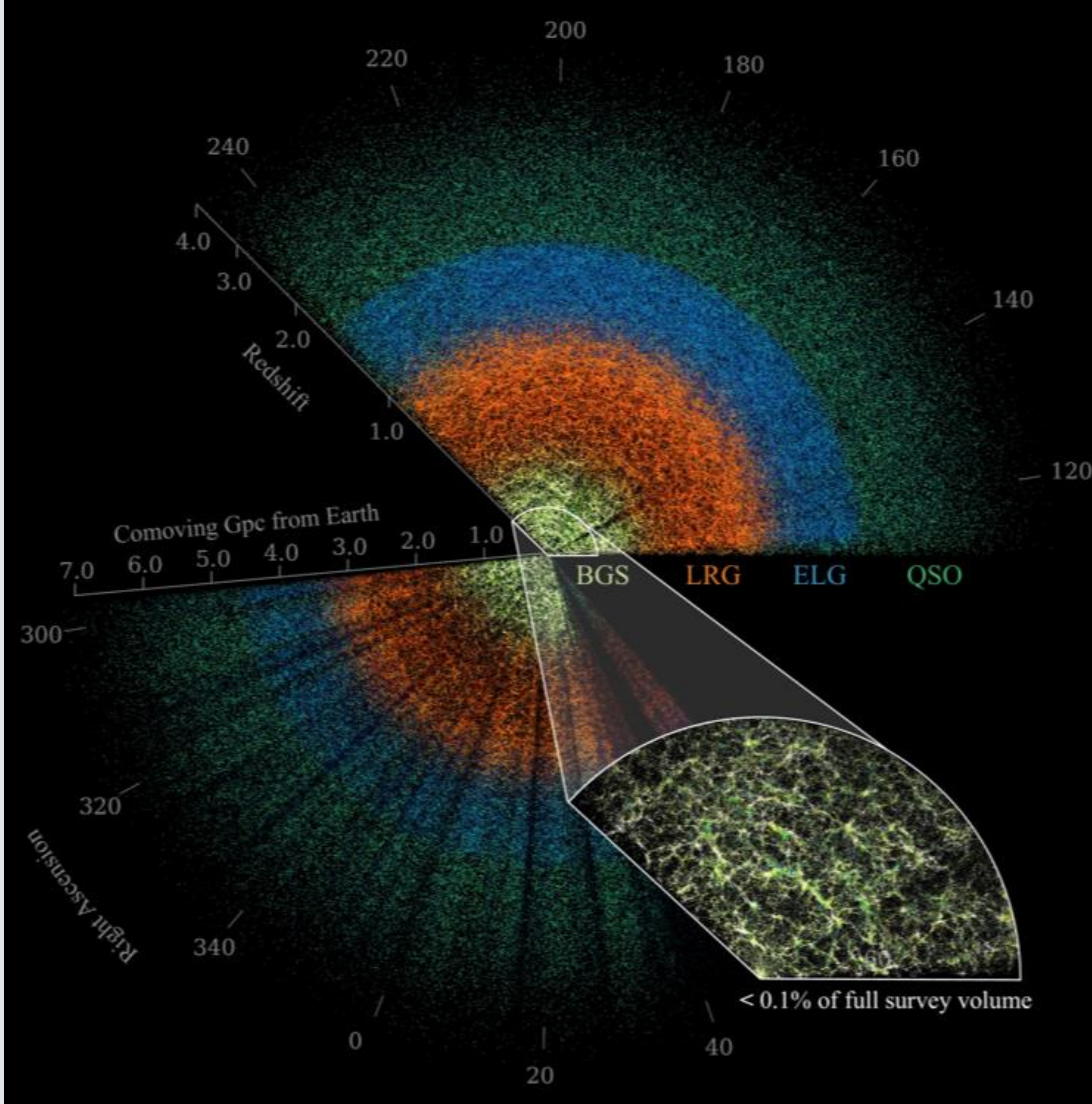
- DESI DR2 covers **>14 million galaxies and quasars** — doubling DR1's dataset of ~6 million objects

- It targets 40 million galaxies and quasars!



BAO precision leaps forward

- Improvement in precision from ~0.5% (DR1) to ~0.28%
- DESI data maps celestial objects from Earth (center) to billions of light years away.
- Among the objects are nearby **Bright Galaxies**, **Luminous Red Galaxies**, **Emission-Line Galaxies**, and **Quasars**.



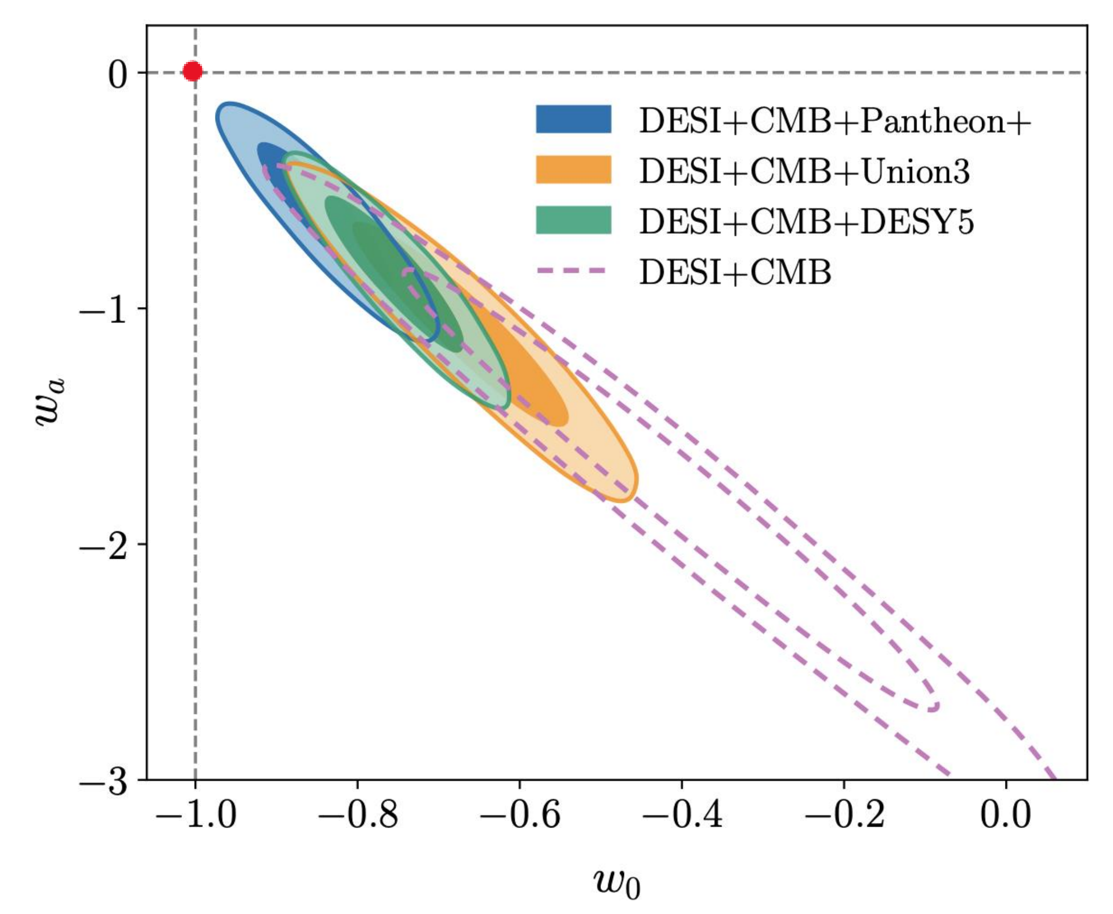
Tensions with ΛCDM – Dynamical DE

- DESI DR2 BAO distances are slightly **lower at z < 1** than expected under Planck-based ΛCDM
- When combined with CMB data, they reveal a 3.1σ preference for dynamical dark energy over ΛCDM, based on the CPL parametrization

DESI, arXiv:2503.14738

$$w(a) = w_0 + w_a(1 - a)$$

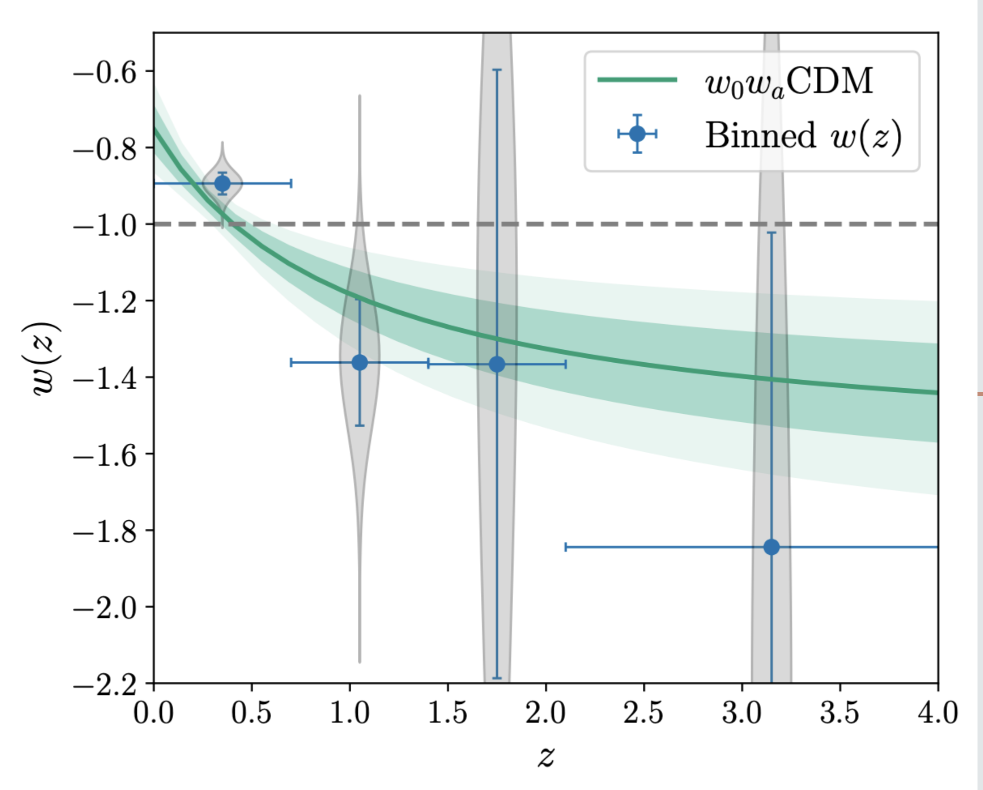
Datasets	$\Delta\chi^2_{\mathrm{MAP}}$	Significance	$\Delta(\mathrm{DIC})$
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_\mathrm{b}, \omega_\mathrm{bc})_\mathrm{CMB}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 (3×2pt)	-7.3	2.2σ	-2.8
DESI+DESY3 (3×2pt)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2



Tensions with ΛCDM – Dynamical DE

- Although the statistical significances from all data depend somewhat on the choice of SNe dataset included, even the weakest of them (the DESI+CMB+Pantheon⁺ combination) is still nearly 3σ, and the significance is 3.1σ even when excluding all SNe data altogether (DESI+CMB)

- In all cases, the favored w(z) shows a phase of $w > -1$ at low redshifts and a phantom crossing to $w < -1$ above redshifts $z \simeq 0.4$.



Comparison of the constraints on the equation of state of dark energy using the CPL parametrization and a binning reconstruction approach, using DESI+CMB+DESY5.

There seems to be an indication that a phantom crossing of the w(z) is needed in order to better fit the data.

DESI, arXiv:2503.14738

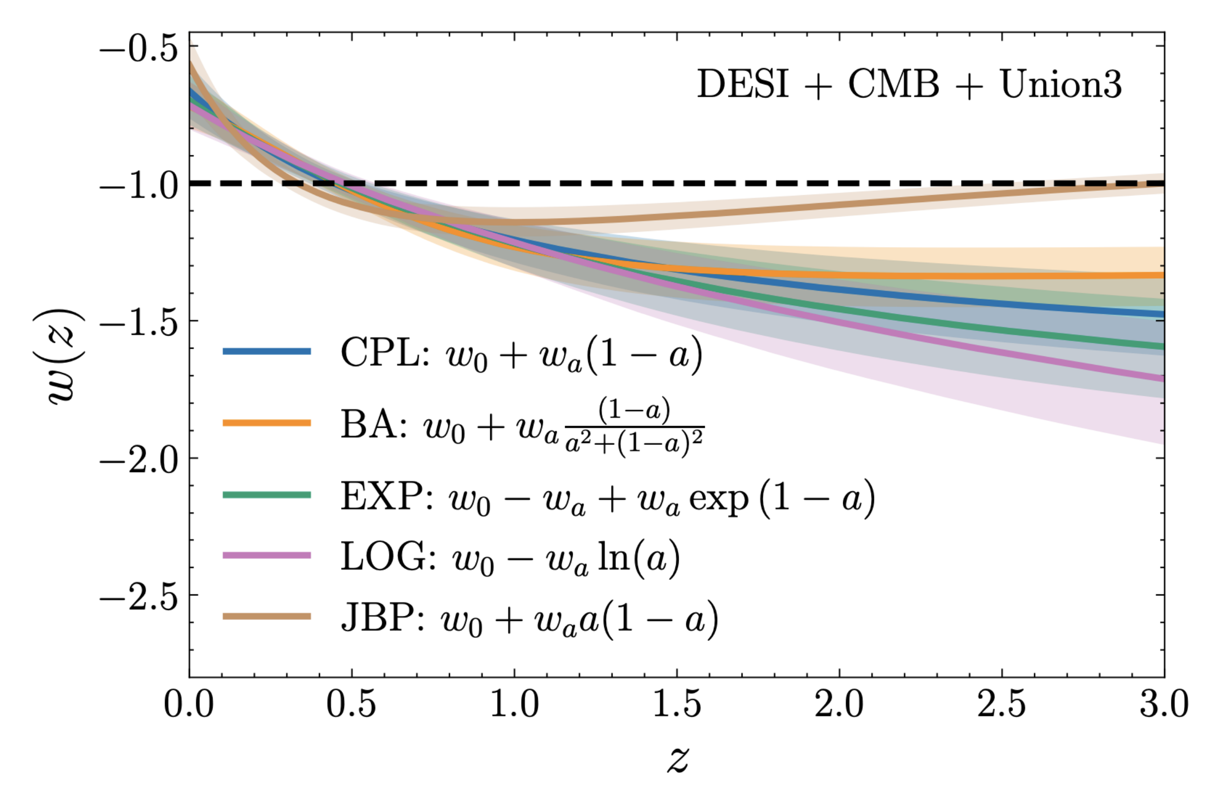
Alternative w(z) Parametrizations

- Some alternative w(z) parametrizations were considered, all of them provide statistically comparable fits to the data according to their $\Delta\chi^2$ with respect to ΛCDM.

- This suggests that current data lacks the sensitivity to distinguish between these parameterizations at $z > 2$, regardless of the different SNe Ia datasets used.

DESI, arXiv:2503.14743

Param.	Functional Form	$\Delta\chi^2$
BA	$w_0 + w_a \frac{1-a}{a^2+(1-a)^2}$	−17.3
EXP	$(w_0 - w_a) + w_a \exp(1-a)$	−17.5
LOG	$w_0 - w_a \ln a$	−17.6
JBP	$w_0 + w_a\, a(1-a)$	−13.6
CPL	$w_0 + w_a(1-a)$	−17.4



- These are all effectively low-redshift parametrizations that behave almost exactly like the CPL parametrization at low redshifts

Could a physical model like Quintessence be a good fit?

Curvature-assisted Quintessence

The action for a canonical scalar field φ minimally coupled to gravity and in the presence of non-relativistic matter (composed of baryonic and cold dark matter) is given by

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{Pl}}^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) + \mathcal{L}_{\mathrm{m}}\right]$$

In the context of a FLRW metric the Friedmann equations are

$$3M_{\mathrm{Pl}}^2H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_{\mathrm{m}} - 3M_{\mathrm{Pl}}^2\frac{k}{a^2}\,,$$
$$2M_{\mathrm{Pl}}^2\dot{H} = -\dot{\phi}^2 - \rho_{\mathrm{m}} + 2M_{\mathrm{Pl}}^2\frac{k}{a^2}\,,$$

We define the following dimensionless variables

$$x \equiv \frac{\dot{\phi}}{\sqrt{6}M_{\mathrm{Pl}}H}\,, \quad y \equiv \frac{\sqrt{V(\phi)}}{\sqrt{3}M_{\mathrm{Pl}}H}\,, \quad z \equiv -\Omega_k \equiv \frac{k}{a^2H^2}$$

Curvature-assisted Quintessence

So, for an exponential potential $V(\phi) = V_0 e^{-\lambda\phi}$ the evolution of our dynamical system can be described by

$$\frac{\mathrm{d}x}{\mathrm{d}N} = \sqrt{\frac{3}{2}}\lambda y^2 - \frac{1}{2}x\left(-3x^2 + 3y^2 - z + 3\right) ,$$

$$\frac{\mathrm{d}y}{\mathrm{d}N} = \frac{1}{2}y\left(3x^2 - \sqrt{6}\lambda x - 3y^2 + z + 3\right) ,$$

$$\frac{\mathrm{d}z}{\mathrm{d}N} = z\left(3x^2 - 3y^2 + z + 1\right) ,$$

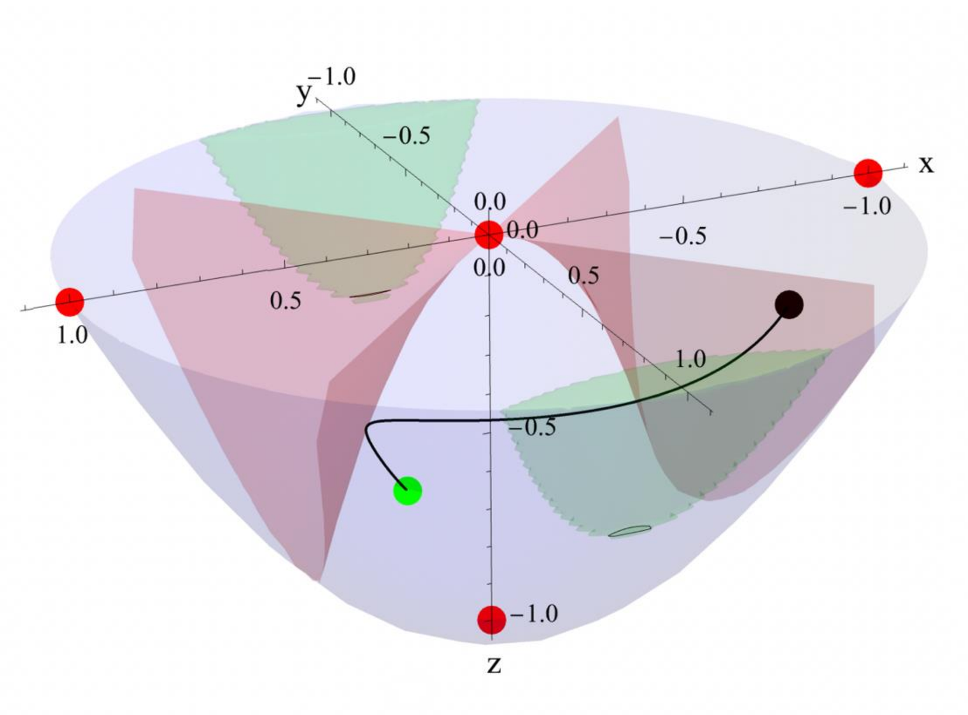
String theorists say it is possible.

Before proceeding to fit [illegible] the DESI data it is interesting to see whether the solution of this system produces viable cosm[illegible]tories with a long period of accelerated expansion for $\lambda > \sqrt{2}$ for $k = -1$

If true it is could allow us to embed a realistic cos[illegible]he asymptotic limit of moduli space, where string theory is under perturbative control.

Curvature-assisted Quintessence

The phase space of the dynamical system described for a hyperbolic (or open) universe (i.e., for $k = -1$). The paraboloid corresponds to the first Friedmann equation with $\Omega_m = 0$. Trajectories that pass through the **green areas** experience accelerating expansion with $w_{eff} \in [-1, -0.7]$, while the **red regions** correspond to $w_{eff} = 0$ (i.e., matter domination).



The **red** and **green** dots show the relevant fixed points of the system and correspond, respectively, to unstable and attractor solutions. For the example of $\lambda = 1.6$ the attractor point behaves like a node, as shown by the indicative trajectory (**black curve**), where the **black dot** shows the initial conditions.

Curvature-assisted Quintessence

We perform a **numerical grid analysis** of the phase space, to see whether we can have cosmologically viable trajectories with large values of λ and non-zero curvature. Their viability is determined by whether they satisfy the following 2 conditions,

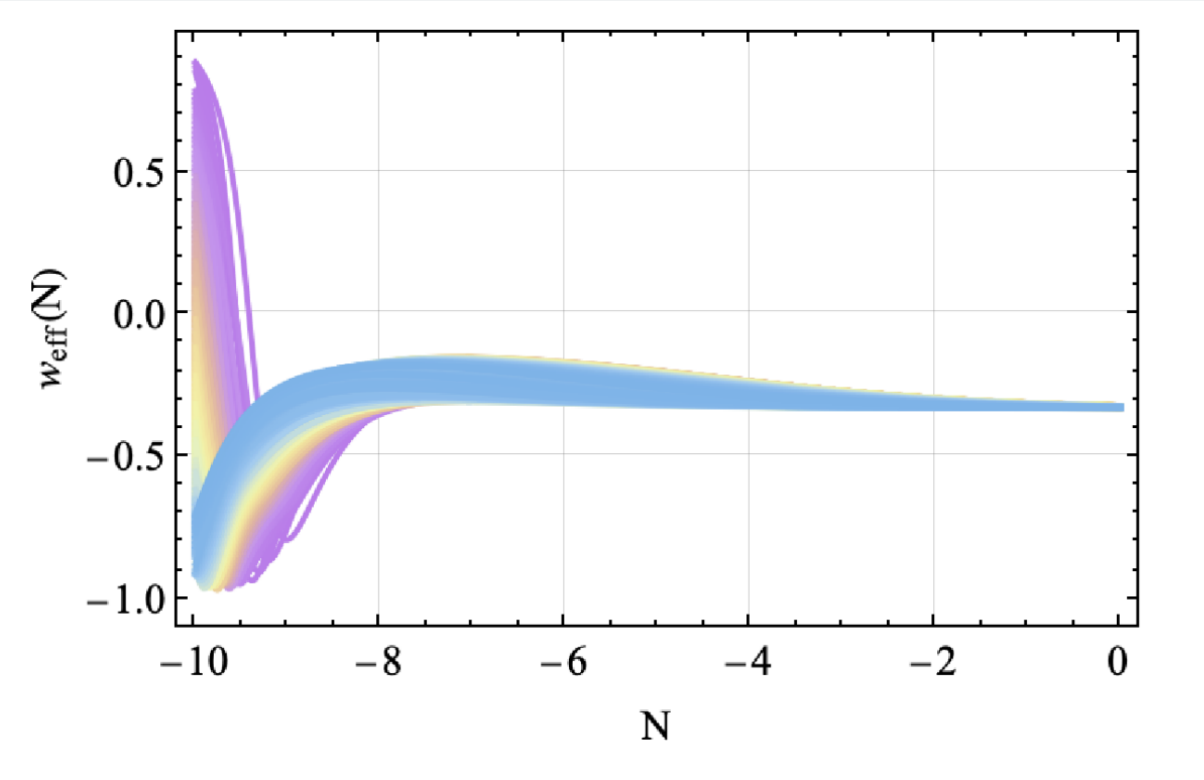
1. They should provide an extended matter domination phase before the onset of cosmic acceleration.
2. Yield an effective equation of state parameter, w_{eff}, that is ~ -0.7 at the present time, compatible with the ΛCDM model.

We solve the system of differential equations for different initial conditions, i.e., for different initial values of the three phase space variables $\{x, y, z\}$, and then study the behaviour of the cosmological background solution in each case.

To do this we perform a fine grid scan of the entire phase space contained within the **blue** paraboloid defined as $x^2 + y^2 - z \leq 1$. We compute all the trajectories for the different sets of initial conditions and keep only the ones that provide an epoch of $w_{eff} \leq -0.7$, i.e., solutions which go through the **green** regions.

Curvature-assisted Quintessence

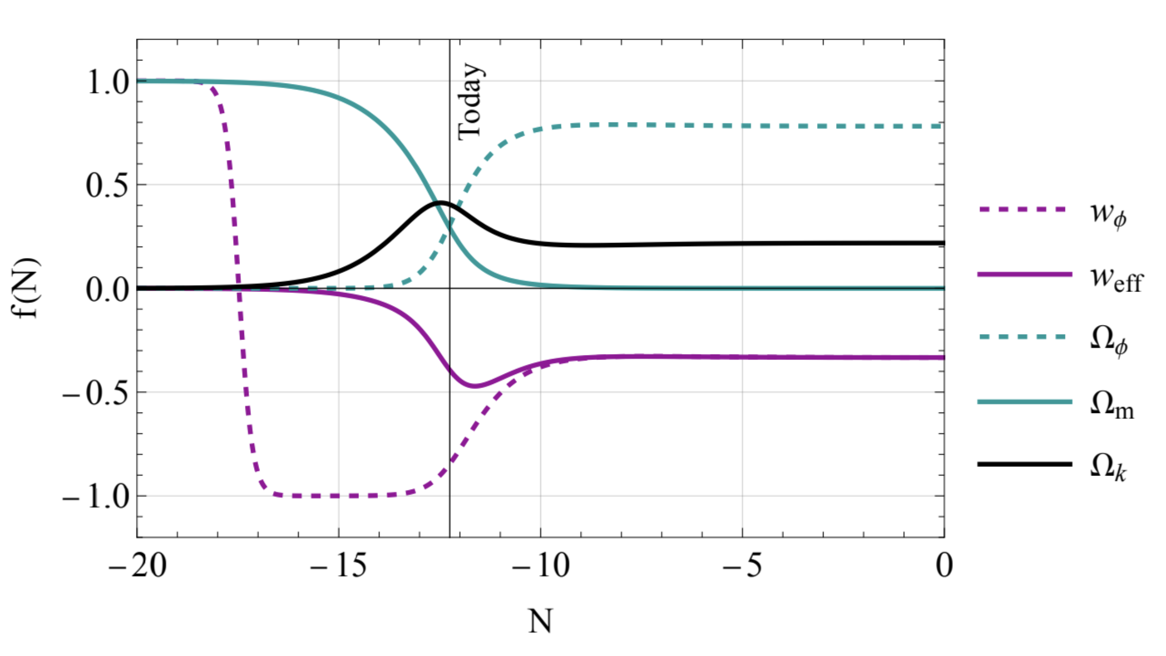
The evolution of w_{eff} as a function of the number of e-folds N for quintessence with λ = 1.6 and for trajectories that provide an epoch of $w_{eff} \leq -0.7$, these trajectories exhibit late-time accelerated expansion consistent with cosmological observations but do not contain a matter domination epoch.

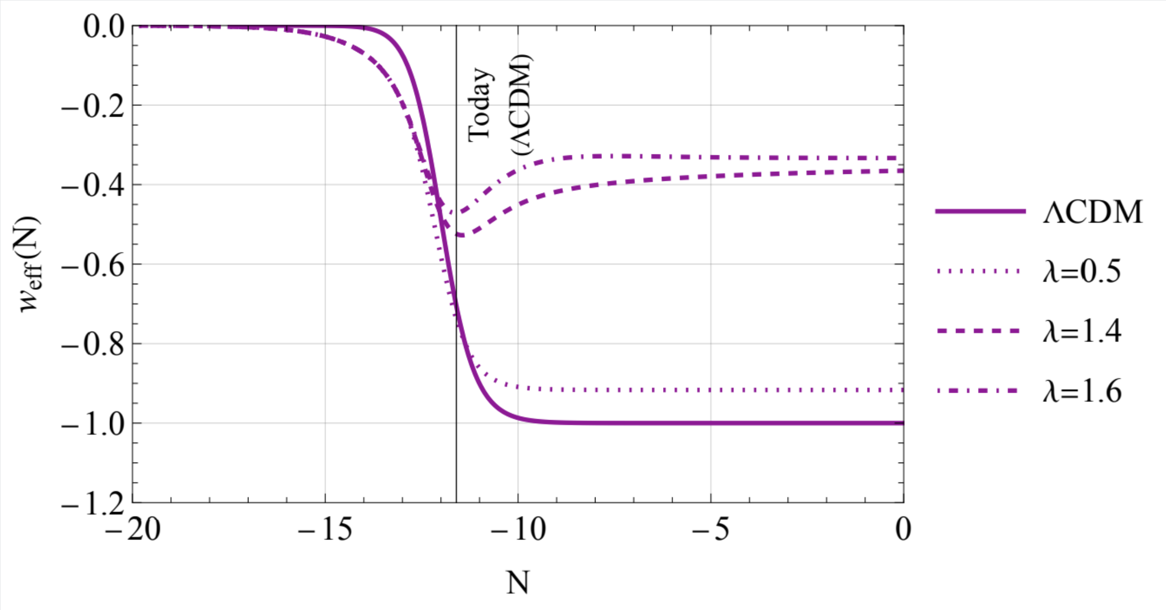


In other words, none of the solutions stay within the **red** regions for a sufficiently long time.

Curvature-assisted Quintessence

We present three examples of w_{eff} evolution for the curvature-assisted quintessence model, i.e., for $\lambda = \{0.5, 1.4, 1.6\}$, and compare them with that of a flat ΛCDM model (i.e., with Ω_k set to zero) that provides a good fit to the data.





By increasing λ it becomes more and more difficult for the quintessence model to provide a cosmic history that is compatible with cosmological observations, as the current value of w_{eff} does not reach the observationally preferred value of ~ -0.7, as indicated by our ΛCDM example.

Curvature-assisted Quintessence

- When we find solutions that provide extended matter domination periods, **none** of them provides an effective equation of state parameter w_{eff} less than ~ -0.5 at the present time (i.e., when $\Omega_m \sim 0.3$).

- This means that we do not obtain sufficient acceleration in these cases where matter domination exists.

Has DESI detected exponential Quintessence?

We perform a full Bayesian statistical analysis of the quintessence model of cosmic acceleration with the exponential potential and provide updated constraints on its parameters.

We study the model both when spatial flatness is imposed and when the spatial curvature density parameter $\Omega_{k,0}$ is allowed to vary and test the model in terms of goodness-of-fit criteria when compared to the standard ΛCDM model.

The main goal is to see whether this model of dynamical DE is favored over ΛCDM, and if yes, at what confidence level?

Has DESI detected exponential Quintessence?

We use the **DESI DR2 BAO** data in combination with the Planck cosmic microwave background (**CMB**) distance priors and the Dark Energy Survey Year 5 (**DES Y5**) type Ia supernova data.

The 1σ (i.e., 68.3% confidence level) constraints on model parameters obtained through MCMC along with their corresponding minimum χ^2 and $\Delta \ln B$, where $\Delta \ln B_X = \ln B_X - \ln B_{\text{flat}\Lambda\text{CDM}}$ for a given model or parametrization X.

Parameter/Quantity	Flat ΛCDM	ΛCDM+Ω_K	Flat ϕCDM	ϕCDM+Ω_K	Flat CPL
$\Omega_{\rm m}$	0.305 ± 0.003	0.306 ± 0.003	0.315 ± 0.005	0.316 ± 0.006	0.320 ± 0.006
Ω_K	...	0.003 ± 0.001	...	0.003 ± 0.001	...
H_0	67.96 ± 0.23	68.48 ± 0.30	66.81 ± 0.56	67.29 ± 0.62	66.73 ± 0.57
λ	...	...	$0.698^{+0.173}_{-0.202}$	$0.722^{+0.182}_{-0.208}$	...
V_0	...	...	2.207 ± 0.389	2.299 ± 0.332	...
w_0	-1	-1	...	...	-0.751 ± 0.058
w_a	0	0	...	...	-0.877 ± 0.231
χ^2	1680.70	1672.08	1673.98	1664.11	1660.65
$\Delta \ln B$	0	-1.55	4.03	3.55	6.84

Has DESI detected exponential Quintessence?

- We notice that ΛCDM in the presence of free $\Omega_{k,0}$ is weakly disfavoured compared to flat ΛCDM, according to the Jeffreys' scale, even though it offers a lower minimum χ^2.

- Quintessence is moderately favoured over flat ΛCDM
  - → ΔlnB ~ 4, ~ 3.3σ significance (flat φCDM)
  - → ΔlnB ~ 3.5, ~ 3.2σ significance (φCDM+ $\Omega_{k,0}$)

- Quintessence is strongly favoured over ΛCDM + $\Omega_{k,0}$
  - → ΔlnB ~ 5.6, ~ 3.8σ significance (flat φCDM)
  - → ΔlnB ~ 5.1, ~ 3.6σ significance (φCDM+ $\Omega_{k,0}$)

However...

Flat CPL provides a better fit to the data → ΔlnB ~ 6.8, corresponding to ~ 4.1σ significance, compared to flat ΛCDM and with ΔlnB ~ 8.4, corresponding to ~ 4.5σ significance, compared to ΛCDM+ $\Omega_{k,0}$

Has DESI detected exponential Quintessence?

- To translate the Bayes factors into frequentist significance quantities we invert

$$B_{XY} \leq -\frac{1}{\mathrm{e}\,\wp\,\ln\wp}$$

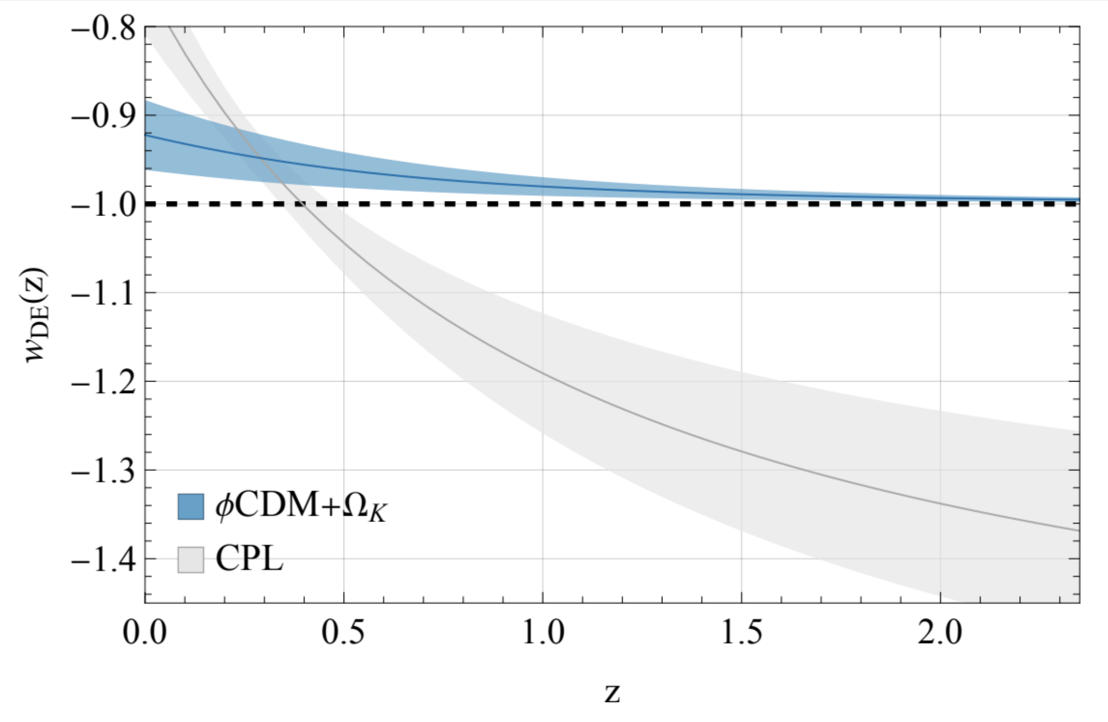
- We find the corresponding p-value in terms of the Lambert *W* function and then we translate it into the number of sigmas by assuming a normal distribution

$$\sigma = \sqrt{2}\;\mathrm{erf}^{-1}\left(1-\wp\right)$$

Has DESI detected exponential Quintessence?

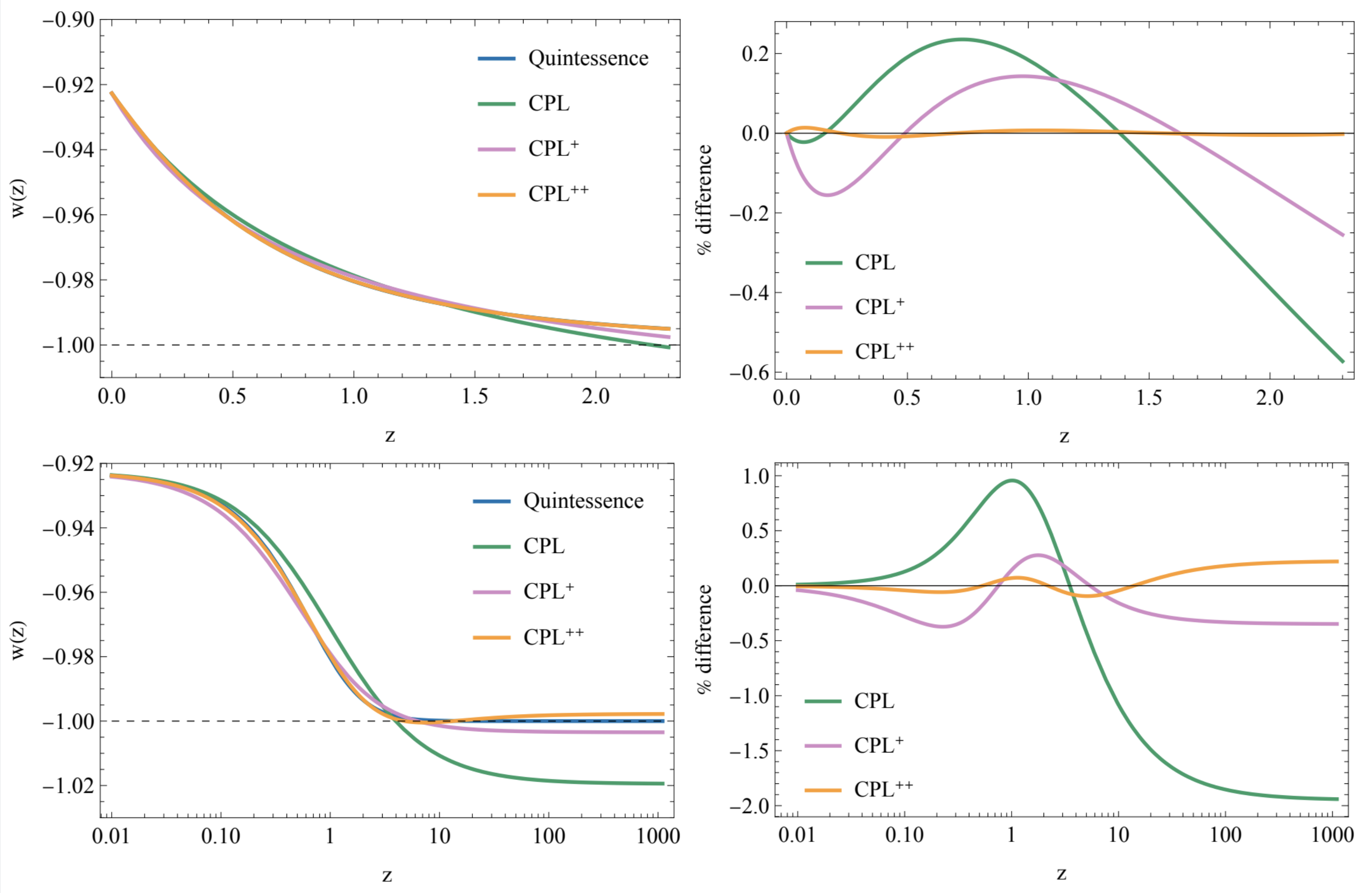
The redshift evolution of the DE equation-of-state parameter corresponding to the Bayesian mean quintessence model when $\Omega_{k,0}$ is allowed to vary as a free parameter (blue solid curve).

The best-fit CPL parametrization with $\Omega_{k,0} = 0$ is included for comparison (gray solid curve).



- DESI data **may not require** phantom crossing.
- Even though it is slightly less favoured statistically than CPL, quintessence is physically motivated.
- **CPL is a phenomenological fit**, not a physical theory.

Has DESI detected exponential Quintessence?

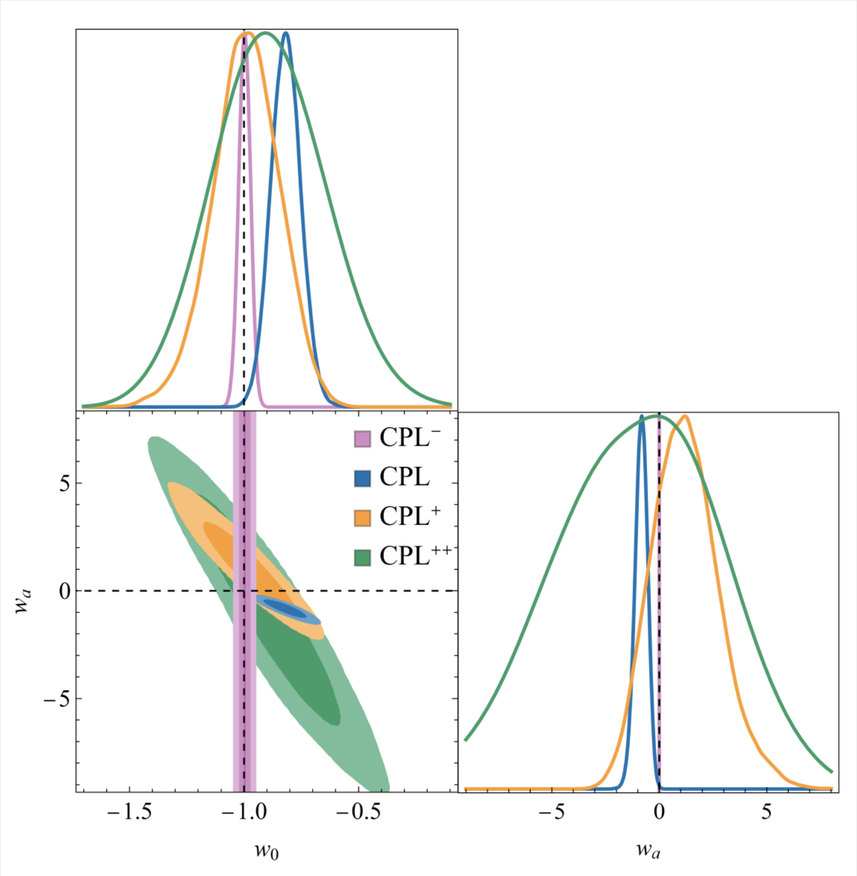


$$w_{\rm DE}(a) = w_0 + w_a(1-a) + w_b(1-a)^2 + w_c(1-a)^3$$

- CPL is able to provide a ≲ 2% fit to quintessence at all redshifts, all the way to the redshift of recombination
- Even though the best-fit $w_{CPL}(z)$ goes slightly below −1 at high redshifts, which is forbidden by quintessence.

Has DESI detected exponential Quintessence?

DESI+CMB+Pantheon⁺



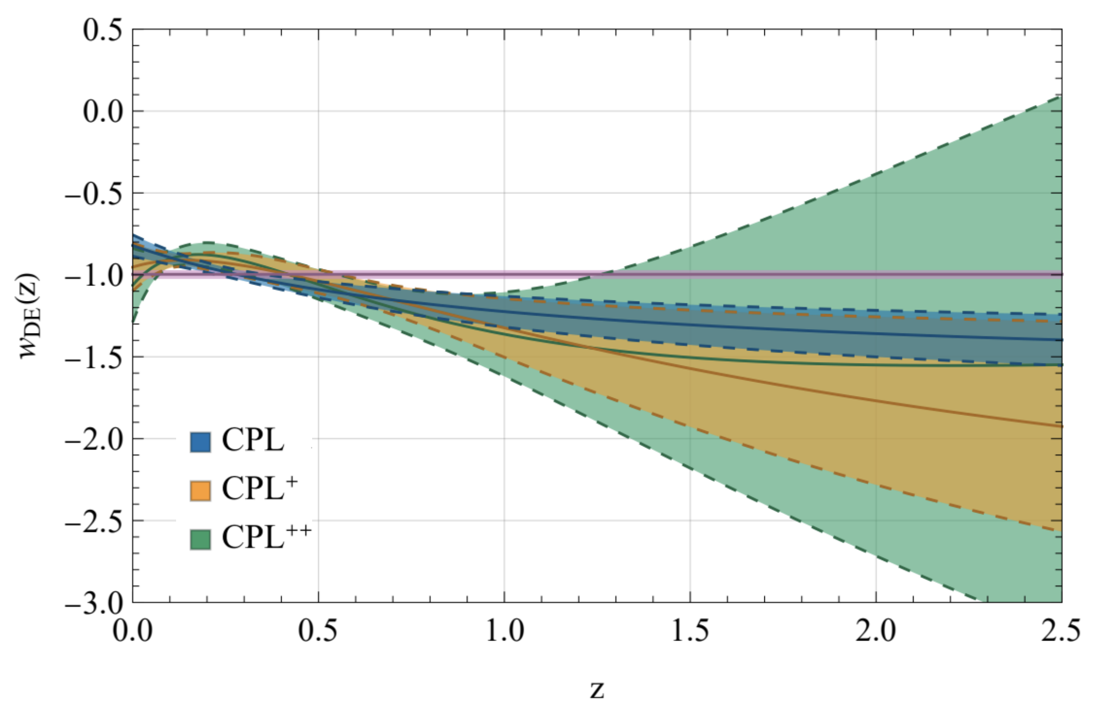
- By projecting the data into a two-dimensional, phenomenological parameter space CPL injects a priori information into the data not necessarily consistent with the observations.

$$\frac{\mathrm{d}^p}{\mathrm{d}a^p} w_{\mathrm{CPL}}(a) = 0,\ \forall p \in \mathbb{Z}^{\geq 2}$$

- So what happens if we include more terms in the Taylor expansion?

Nesseris et.al. arXiv:2503.22529

Has DESI detected exponential Quintessence?



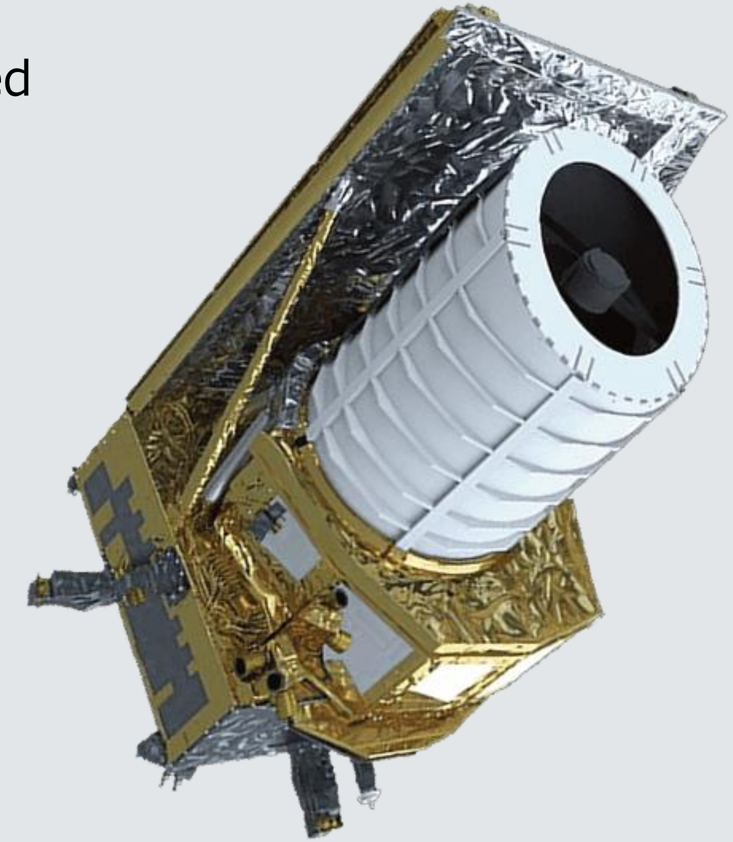
- If one allows even one additional term in the Taylor series (the CPL^+ parametrization), then the preferred value of w_{DE} today is consistent with -1
- If one marginalizes over the coefficient w_b instead of setting it to 0, then the evidence against $(w_0, w_a) = (-1, 0)$ falls below 2σ
- If one allows two additional terms (CPL^{++}) and marginalizes over w_b and w_c, the evidence falls below 1σ

Nesseris et.al. arXiv:2503.22529

Has DESI detected exponential Quintessence?

Maybe…

EUCLID



- It is a space-based telescope that is equipped with a visible imager (VIS) and a near-infrared slitless spectrometer combined with a multiband photometer (NISP)

- The survey started on 14th February 2024 and the first cosmologicaly relevant results are expected in 2026

- It will measure the shapes of 1.5 billion galaxies for cosmic shear analysis and the 3-dimensional positions of 35 million galaxies for galaxy clustering analysis.

- Its main goal is to determine the evolution of dark energy. Considering CPL Euclid is going to determine w_0 and w_a sto precisely that the figure-of-merit defined by

$$\mathrm{FOM} = \frac{1}{\sqrt{\mathrm{detCov}(w_0, w_a)}}$$

  reaches at least 400.

- It will also constrain the sum of the neutrino masses to 0.03 eV

Conclusions

- DESI is the largest BAO survey
- It points to dynamical dark energy with a possible phantom crossing
- Quintessence could be a good fit to the data, without the phantom crossing
- The CPL parametrization should be taken with a pinch of salt

Thank you!!