



Observatório
Nacional

UNIDADE DE PESQUISA DO MCTI

Evidence for dynamical dark energy?

Jailson Alcaniz
Observatório Nacional

• Rio de Janeiro, September 18, 2026 – XXBSC/CBPF •

Overview of the talk

- Standard Cosmology (Λ CDM): some challenges
- A brief summary of DESI's results
- Phantom/thawing dark energy
- Assessment of the DE density evolution
- Conclusions

LETTERS TO NATURE (1990)

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

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THE cold dark matter (CDM) model¹⁻⁴ for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work⁵⁻⁸ suggests that there is more cosmological structure on very large scales ($l > 10 h^{-1} \text{ Mpc}$, where h is the Hubble constant H_0 in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

... observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

(1995)

The observational case for a low-density Universe with a non-zero cosmological constant

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OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determinations of the Hubble constant¹⁻³ (which quantifies the present expansion rate of the Universe) and measurements of the anisotropy of the cosmic microwave background^{4,5}. Although the limits imposed by these diverse observations have occasionally led to suggestions⁶ that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. The combined observations point to models in which the matter density of the Universe falls well below the critical energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive 'cosmological constant'), sufficient to recover the critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

TESTS OF COSMOLOGICAL MODELS CONSTRAINED BY INFLATION

P. J. E. PEEBLES

Joseph Henry Laboratories, Princeton University

Received 1984 February 6; accepted 1984 March 23

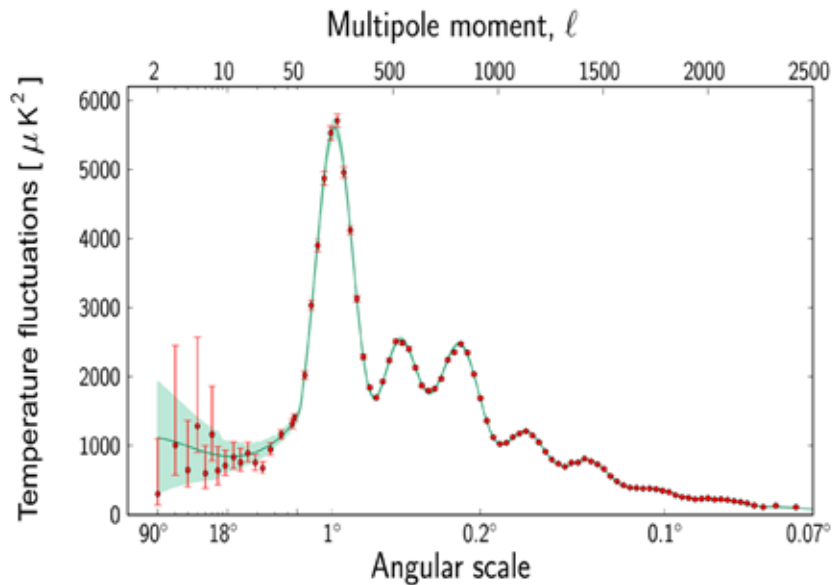
ABSTRACT

The inflationary scenario requires that the universe have negligible curvature along constant-density surfaces. In the Friedmann-Lemaître cosmology that leaves us with two free parameters, Hubble's constant H_0 and the density parameter Ω_0 (or, equivalently, the cosmological constant Λ). I discuss here tests of this set of models from local and high-redshift observations. The data agree reasonably well with $\Omega_0 \sim 0.2$.

Subject heading: cosmology

The standard Λ CDM model

- The Λ CDM model represents a great triumph of observational cosmology, as it provides an excellent fit to current observational data with just six parameters.



CMB data provide the most precise estimate of two contemporary quantities:

- $t_0 = 13.8 \pm 0.02$ Gyr and $H_0 = 67.44 \pm 0.50$ km/s/Mpc (Planck Collaboration).

The Standard Cosmological Model

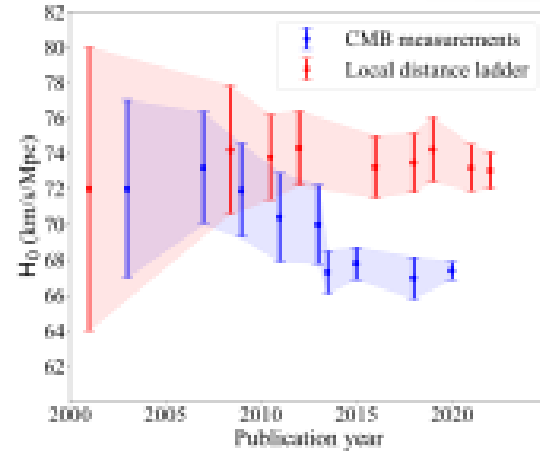
The Universe is homogeneous and isotropic at large scales, spatially flat and *accelerating*; composed of baryons, dark matter, and *dark energy*; underwent a hot, dense, early phase of expansion that produced the light elements via big bang nucleosynthesis and the CMB radiation; and experienced a much earlier epoch of accelerated expansion, known as inflation, which produced density perturbations from quantum fluctuations, leaving an imprint on the CMB anisotropy, and leading by gravitational instability to the formation of large-scale structure.

Observational challenges

- H_0 tension problem:** A persistent discrepancy between local determinations of H_0 and the value inferred from early-Universe observations assuming Λ CDM.

$H_0 = (73.17 \pm 0.86) \text{ km/s/Mpc}$ – SH0ES (2024)
 $H_0 = (67.44 \pm 0.50) \text{ km/s/Mpc}$ – Planck Coll. (2018)

$$D = \frac{|H_{0,\text{SH0ES}} - H_{0,\text{CMB}}|}{\sqrt{\sigma_{H_{0,\text{SH0ES}}}^2 + \sigma_{H_{0,\text{CMB}}}^2}} \approx 5.7\sigma$$



The Local Distance Network: a community consensus report on the measurement of the Hubble constant at $\sim 1\%$ precision

H0DN COLLABORATION

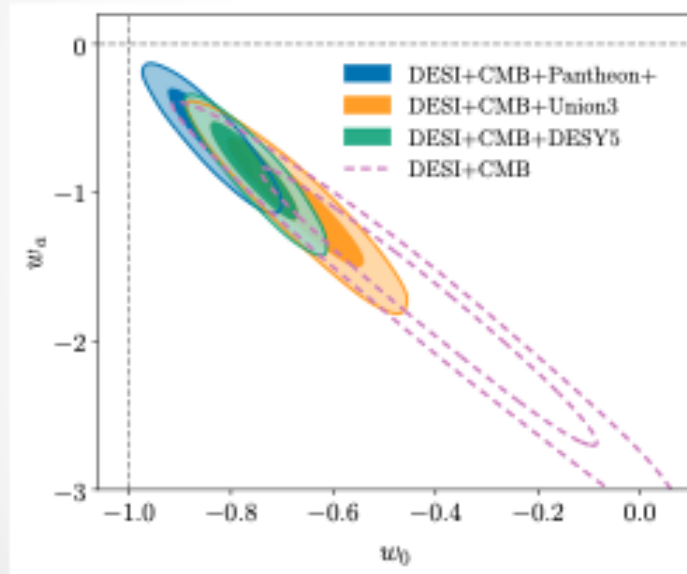
arXiv:2510.23823v1

The baseline result is $H_0 = 73.50 \pm 0.81 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Compared to early Universe+ Λ CDM results, our result differs by 7.1σ from the CMB anisotropies within flat Λ CDM, $67.24 \pm 0.35 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from Planck+SPT+ACT (Eq. (54) of [E. Camphuis et al. 2025](#)) and 5.0σ from BBN+BAO within flat Λ CDM from DESI DR2 ($68.51 \pm 0.58 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Tab. V of [M. Abdul Karim et al. 2025](#)). A net-

If not caused by an accounted-for systematic effects, this discrepancy may signal physics beyond the standard model.

Observational challenges

- **Evidence for a dynamical dark energy:** DESI BAO measurements, when combined with CMB and SNe data, seem to favor an evolving dark energy component (with a phantom-to-quintessence transition).



Λ CDM

$$\omega_0 = -1; \omega_a = 0$$

• Λ is an inert, non-dynamical component with constant energy density. •

The dark-energy question after DESI:

Λ CDM

$$\omega = -1$$

$$\rho_{\Lambda} = \text{constant}$$

**Is cosmic acceleration really
driven by a cosmological
constant?**

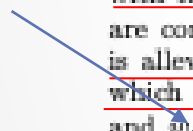
*DESI has made this question observationally
urgent again.*

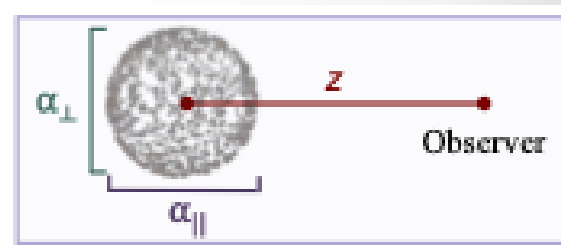
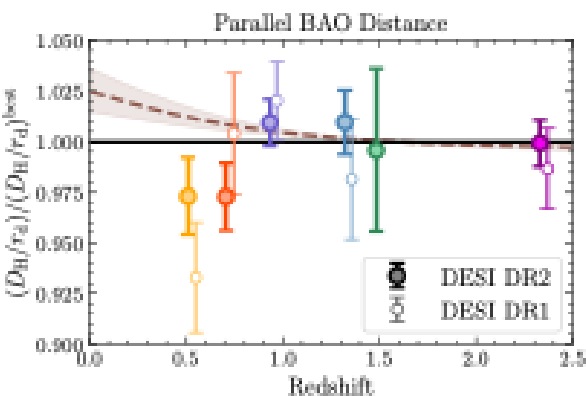
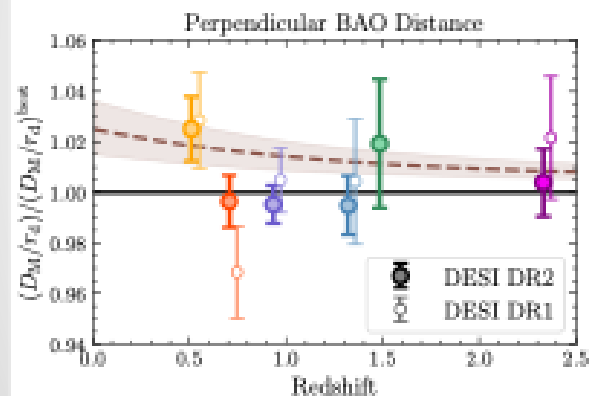
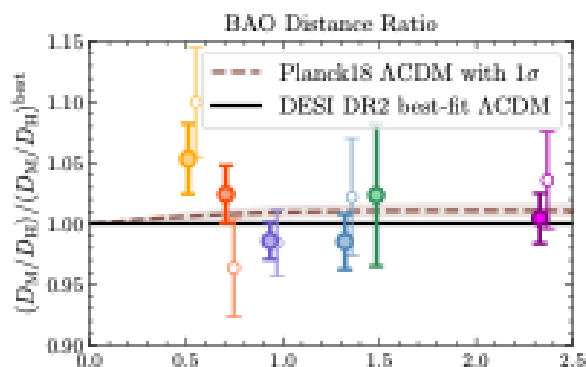
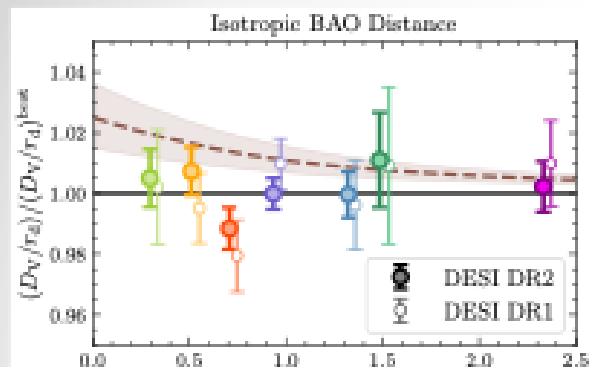
DESI DR2 Results

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

arXiv:2503.14738v2 [astro-ph.CO] 26 Mar 2025

We present baryon acoustic oscillation (BAO) measurements from more than 14 million galaxies and quasars drawn from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2), based on three years of operation. For cosmology inference, these galaxy measurements are combined with DESI Lyman- α forest BAO results presented in a companion paper. The DR2 BAO results are consistent with DESI DR1 and SDSS, and their distance-redshift relationship matches those from recent compilations of supernovae (SNe) over the same redshift range. The results are well described by a flat Λ CDM model, but the parameters preferred by BAO are in mild, 2.3σ tension with those determined from the cosmic microwave background (CMB), although the DESI results are consistent with the acoustic angular scale θ_* that is well-measured by Planck. This tension is alleviated by dark energy with a time-evolving equation of state parametrized by w_0 and w_a , which provides a better fit to the data, with a favored solution in the quadrant with $w_0 > -1$ and $w_a < 0$. This solution is preferred over Λ CDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SNe, the preference for a dynamical dark energy model over Λ CDM ranges from $2.8 - 4.2\sigma$ depending on which SNe sample is used. We present evidence from other data combinations which also favor the same behavior at high significance. From the combination of DESI and CMB we derive 95% upper limits on the sum of neutrino masses, finding $\sum m_\nu < 0.064$ eV assuming Λ CDM and $\sum m_\nu < 0.16$ eV in the w_0w_a model. Unless there is an unknown systematic error associated with one or more datasets, it is clear that Λ CDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution.

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


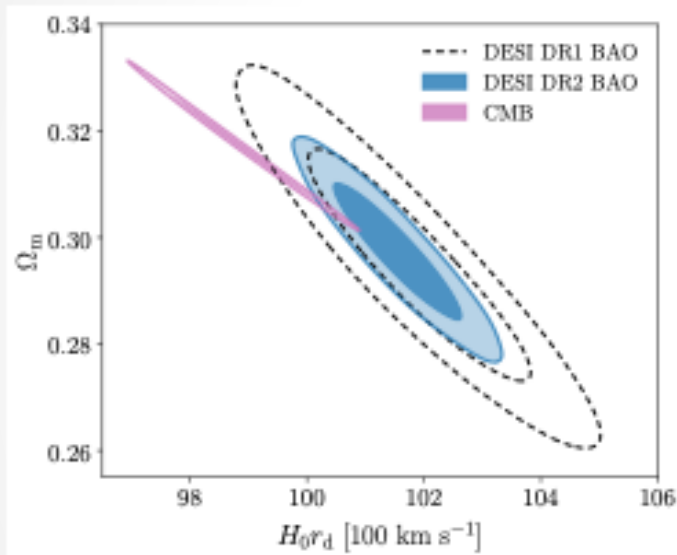


$$D_H(z) = \frac{c}{H(z)}.$$

$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{H(z')/H_0}$$

DESI DR2 BAO measurements compared to DR1 measurements. DR1 and DR2 results are shown with empty and filled circles, respectively. The distances are normalized by the DESI DR2 best-fit Λ CDM model predictions (black solid lines). The Planck Λ CDM predictions are shown with brown dashed lines with 68% confidence intervals in the brown shaded region.

Λ CDM results



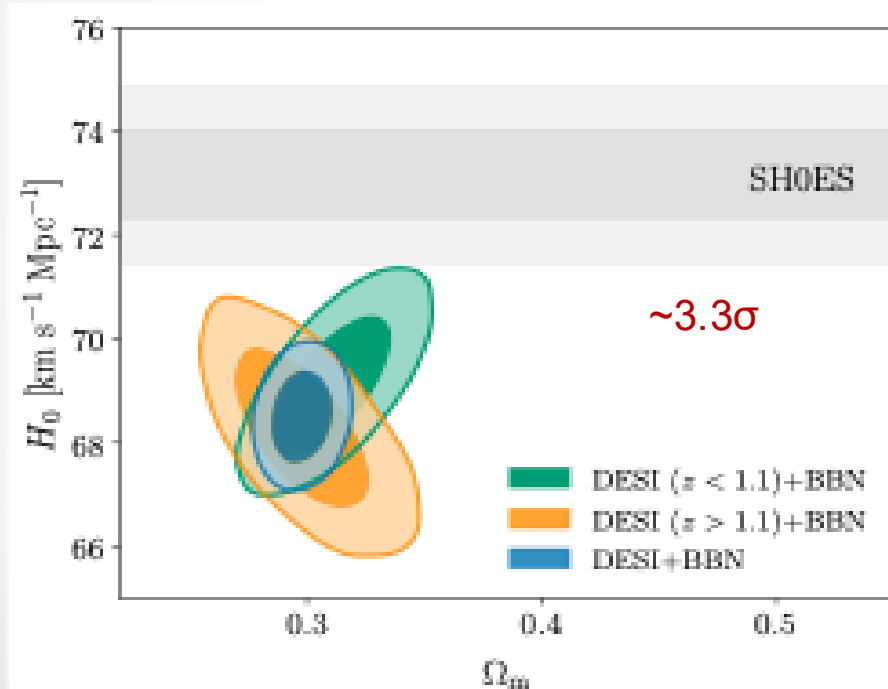
DESI BAO distances out to $z \sim 1$ are $\sim 2\%$ smaller than the Planck best-fit Λ CDM predictions, whereas DES-Dovekie SN distances at $z \sim 0.05$ are $\sim 2\%$ larger.

Although CMB, BAO, and SN data are individually well described by Λ CDM, their preferred values of the matter density differ, suggesting that a single Λ CDM cosmology may not simultaneously provide the best description of all three datasets.

Contours show the 68% and 95% regions. DESI DR2 is fully consistent with DR1 but as the statistical uncertainty has significantly decreased, the tension with the CMB has increased. Right panel: Comparison of DESI H_0 constraints with respect to SH0ES, assuming a Λ CDM model. Both subsets are individually in $> 3\sigma$ tension with SH0ES measurements.

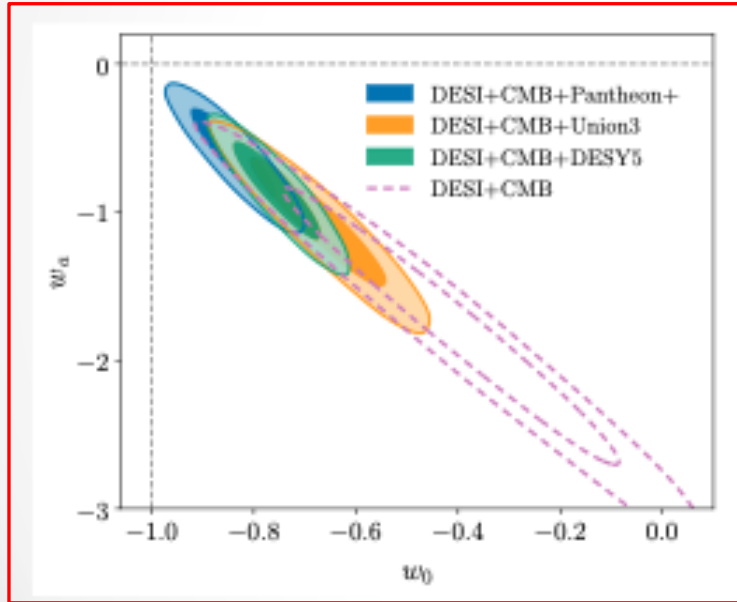
Λ CDM results

$$H_0 = 68.51 \pm 0.58 \text{ km/s/Mpc} - \text{DESI+BBN}$$



Comparison of DESI H_0 constraints with respect to SH0ES, assuming a Λ CDM model. Both subsets are individually in $> 3\sigma$ tension with SH0ES measurements.

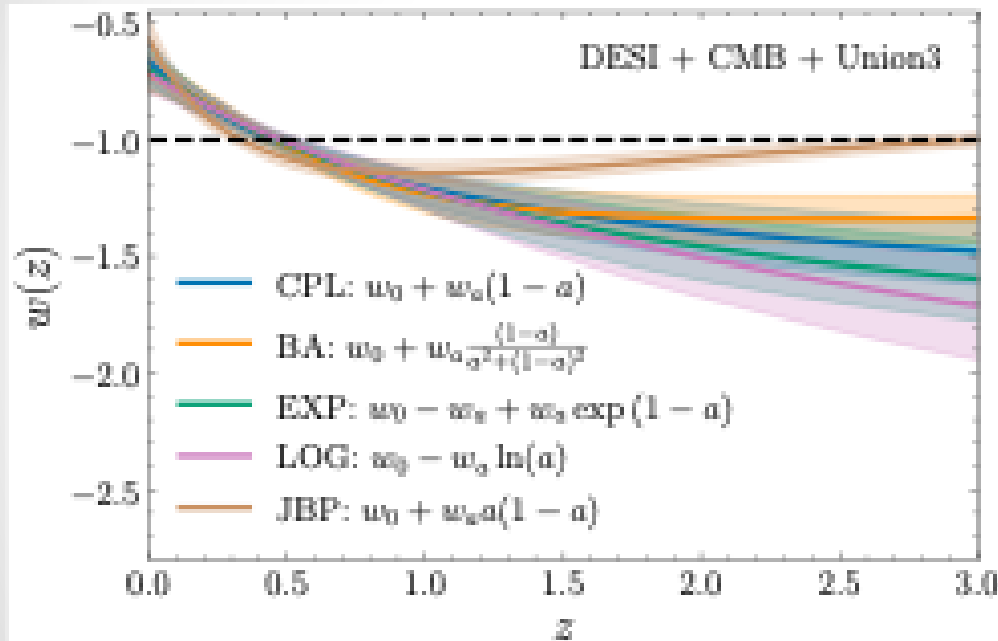
Dynamical dark energy



Results for w_0w_a CDM model to DESI in combination with CMB and three SNe datasets as labelled. The gray dashed lines indicate $w_0 = -1$ and $w_a = 0$ (Λ CDM).

The significance of rejection of Λ CDM is 2.8σ , 3.8σ and 3.2σ for combinations with the Pantheon+, Union3 and DES-Dovekie SNe samples, respectively, and 3.1σ for DESI+CMB without any SNe.

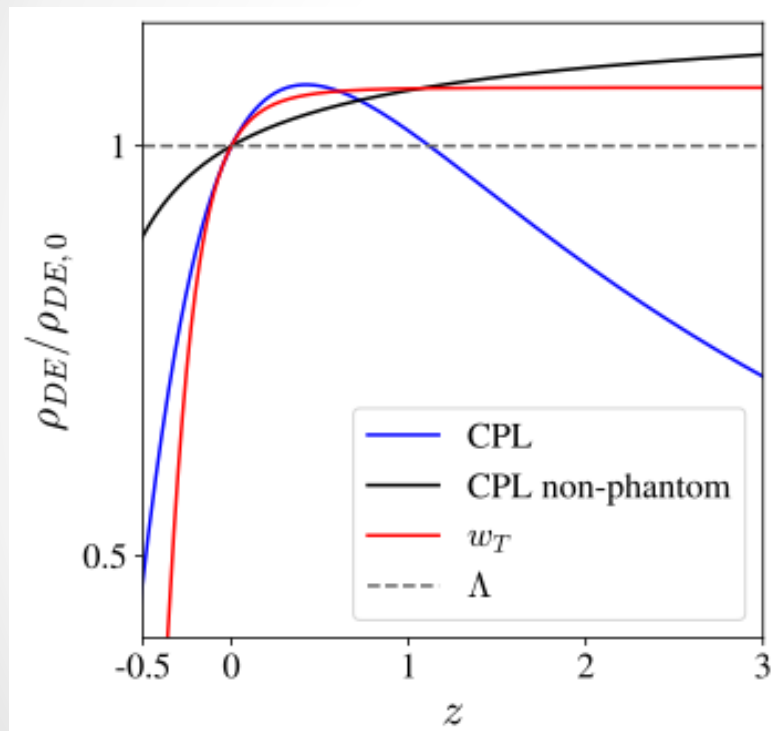
Phantom dark energy



The EoS parameter $w(z)$ for alternative $w_0 w_a$ parameterizations. The constraints integrate data from DESI, Union3 SNe, and CMB observations, with shaded regions representing 1σ uncertainty bands.

All parameterizations except JBP exhibit consistent phantom crossing near $z \sim 0.5$ and provide a similarly good fit to the data – a **“thawing”/phantom behavior**.

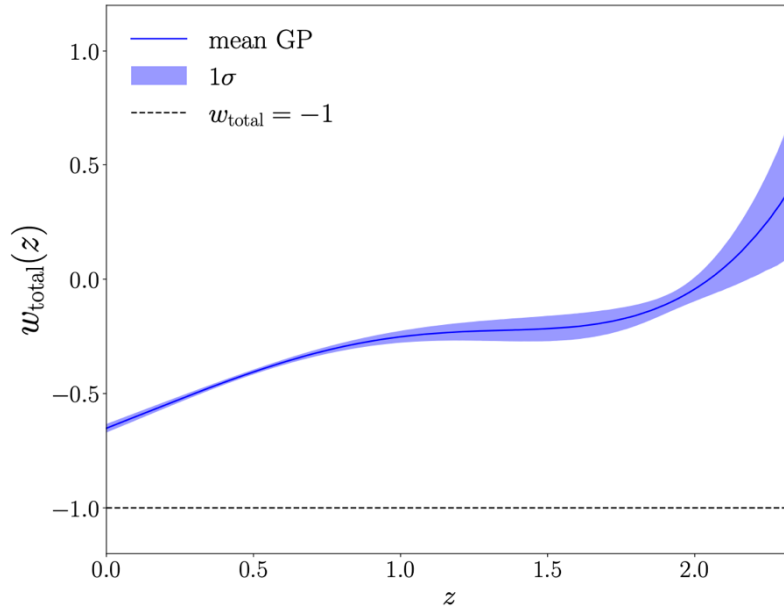
Phantom dark energy



Evolution of the dark energy density normalized to its current value. Unlike the other cases shown, the DESI DR2 BAO+CMB+Pantheon+ best-fit for the CPL parameterization predicts an increasing energy density as the Universe expands until a turnaround point at $z \approx 0.4$.

R. de Souza, G. Rodrigues & JSA, PRD, 2025

Phantom dark energy



Although phantom dark energy ($w < -1$) individually violates the null energy condition $\rho = p \geq 0$, **the total cosmic fluid** – including dark matter and baryons – **does not**, within the region favored by the data. The phantom dark energy is subdominant at higher z .

From Friedmann eqs.:

$$\omega_{\text{total}} = \frac{1}{2}(1+z) \frac{D'_M(z)}{D_M(z)}$$

R. de Souza, Sousa-Neto & JSA, PRD, 2026

DESI results show evidence for:

- Dynamical Dark Energy:

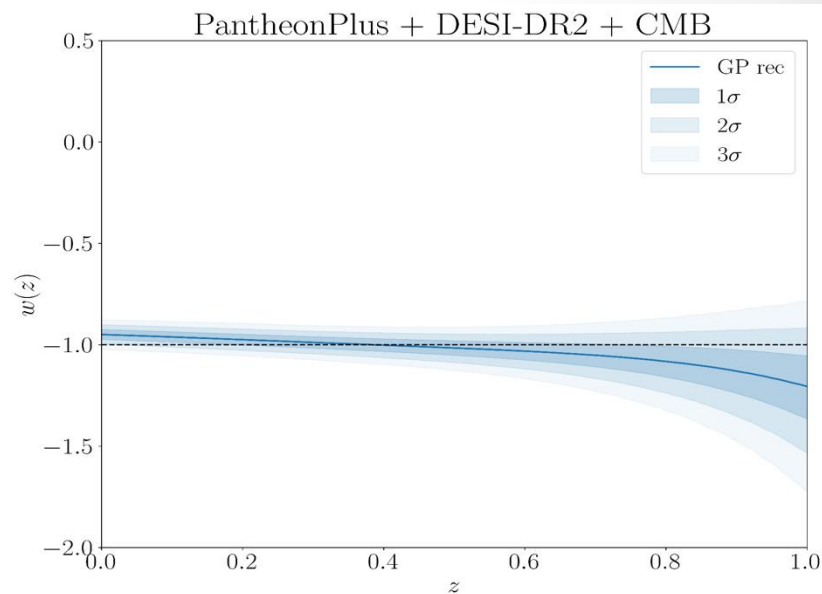
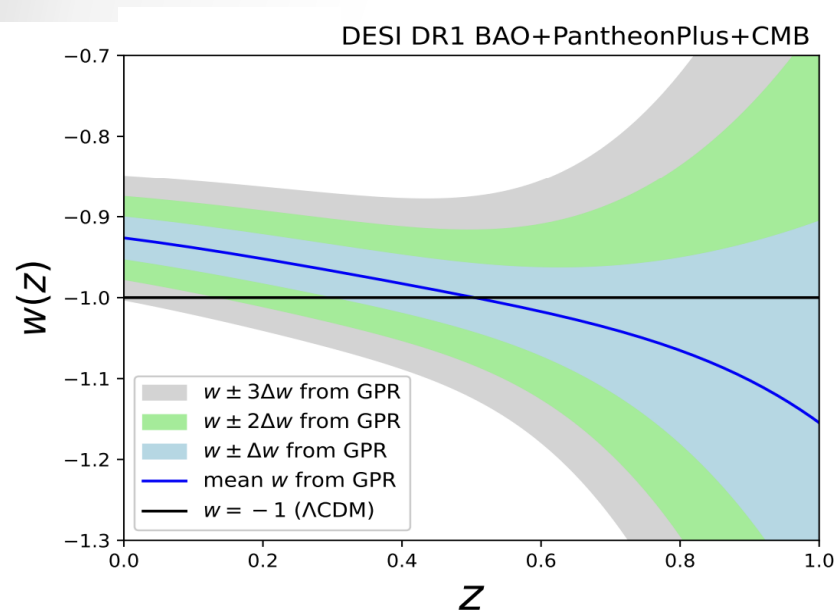
$$w(z)$$

- Phantom (“thawing”) dark energy:

$$w(z) < -1$$

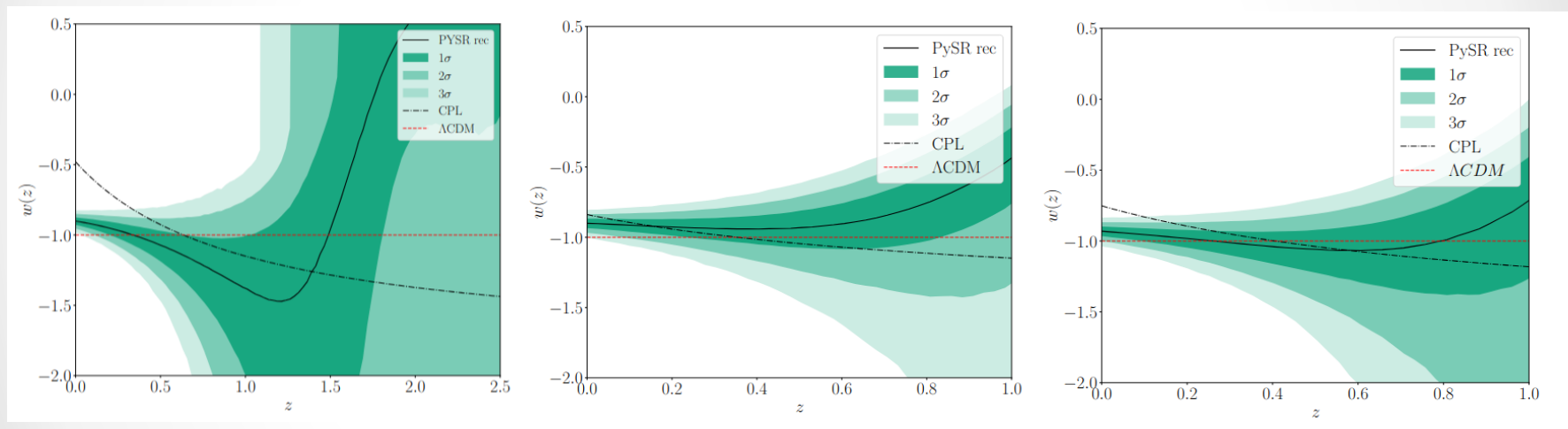
How much the evidence against the Λ CDM depends on assumptions about the DDE component?

- Model-independent approaches: Gaussian Processes



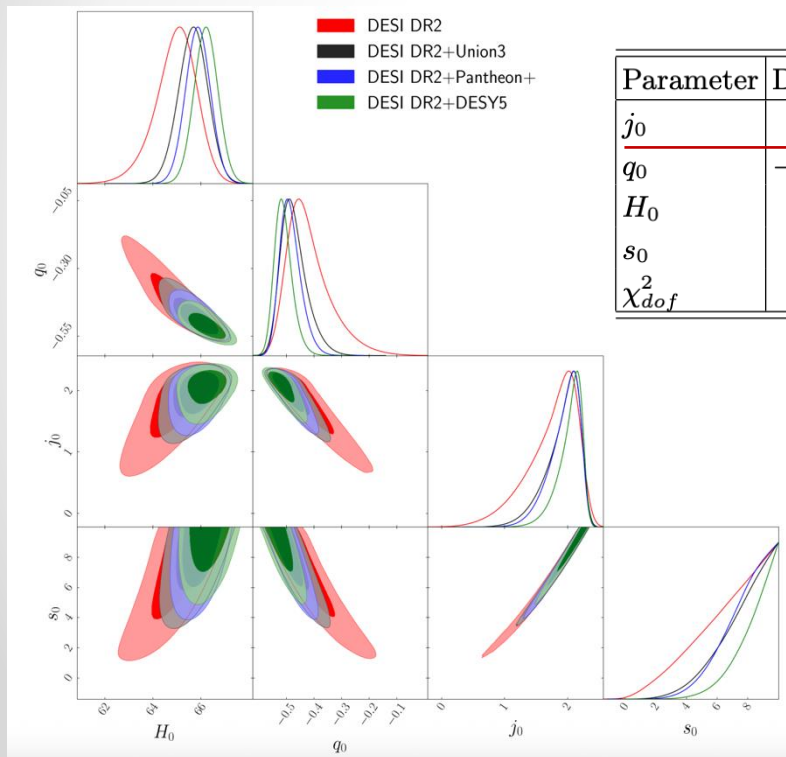
How much the evidence against the CDM depends on assumptions about the DDE component?

- Model-independent approaches: Symbolic Regression



How much the evidence against the CDM depends on assumptions about the DDE component?

- Model-independent approaches: Cosmography/Taylor-expansion of the scale factor



2 σ results				
Parameter	DESI DR2	DESI DR2 + Union3	DESI DR2 + Pantheon+	DESI DR2 + DESY5
j_0	$1.77^{+0.61}_{-0.86}$	$1.93^{+0.41}_{-0.58}$	$1.96^{+0.37}_{-0.50}$	$2.04^{+0.30}_{-0.42}$
q_0	$-0.42^{+0.17}_{-0.13}$	$-0.47^{+0.10}_{-0.086}$	$-0.48^{+0.079}_{-0.069}$	$-0.51^{+0.068}_{-0.060}$
H_0	$65^{+1.6}_{-1.8}$	$66^{+1.2}_{-1.2}$	$66^{+1.0}_{-1.0}$	$66^{+0.97}_{-0.97}$
s_0	> 2.63	> 4.57	> 5.01	> 5.93
χ^2_{dof}	1.94	1.42	1.04	1.01

When DESI is combined with the Union3, Pantheon+, and DESY5 SN data, the result obtained is discrepant with the Λ CDM model ($j_0 = 1$) at about 3.4σ , 4.1σ , and 5.4σ , respectively.

Underdetermination of dark energy

Different theories can generate nearly indistinguishable expansion histories.

Scalar-field potentials

Modified gravity

Interacting sectors

Effective fluids

Same background data

Similar $H(z)$ and distances

Different microphysics

Phantom dark energy

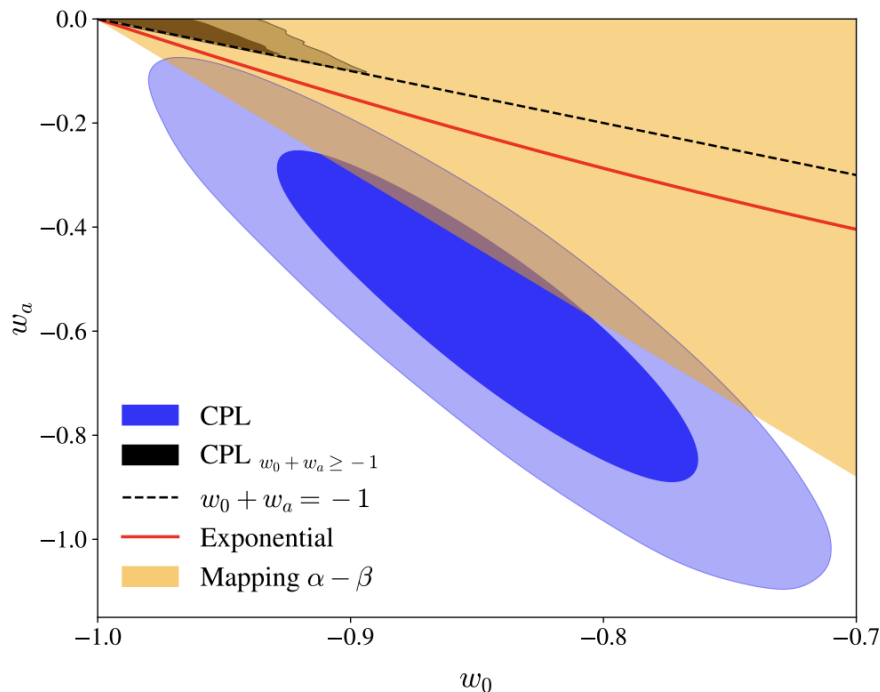
The region in the $w_0 - w_a$ plane of these EoS parameterizations that is preferred by data can be associated with the predictions of single-field scalar field models, due to a general mapping between their expansion rates that yields roughly the same background observables.

Wolf & Ferreira, arXiv:2310.07482;
Shlivko & Steinhardt, arXiv:2405.03933

A single scalar field minimally coupled to gravity with canonical kinetic term, never crosses to the phantom regime:

$$-1 \leq w(a) \leq -\frac{1}{3}$$

R. Souza, G. Rodrigues & JA, PRD, 2025



Example:

2) Is there an observationally viable, non-phantom, thawing model?

PRL **97**, 081301 (2006)

PHYSICAL REVIEW LETTERS

week ending
25 AUGUST 2006

Scalar-Field-Dominated Cosmology with a Transient Acceleration Phase

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(Received 12 May 2006; published 22 August 2006)

A new cosmological scenario driven by a slow rolling homogeneous scalar field whose exponential potential $V(\Phi)$ has a quadratic dependence on the field Φ in addition to the standard linear term is discussed. The derived equation of state for the field predicts a transient accelerating phase, in which the Universe was decelerated in the past, began to accelerate at redshift $z \sim 1$, is currently accelerated, but, finally, will return to a decelerating phase in the future. This overall dynamic behavior is profoundly different from the standard evolution of the cold dark matter model with a cosmological constant, and may alleviate some conflicts in reconciling the idea of a dark-energy-dominated universe with observables in String or M theory. Some theoretical predictions for the present scalar field plus dark matter dominated stage are confronted with cosmological observations in order to test the viability of the scenario.

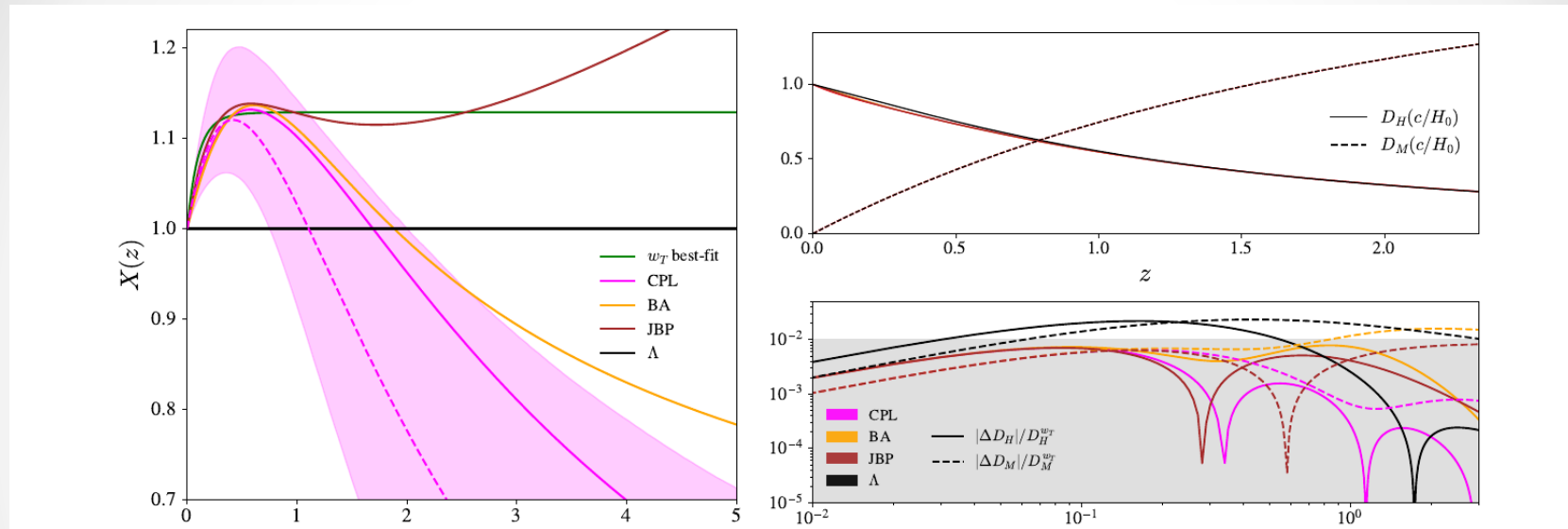
Scalar field potential:

$$V(\phi) = Y \exp \left[-3\alpha\sqrt{\sigma} \left(\phi + \frac{\beta\sqrt{\sigma}}{4} \phi^2 \right) \right] ,$$

EoS parameter:

$$w_T(a) = -1 + \alpha a^\beta$$

Different EoS, nearly identical distances



Large differences in $X(z)$ can hide behind sub-percent differences in distance.

Although models are degenerate at the level of expansion rate, they are not at the level of energy density.

Direct reconstruction of $X(z)$

- 1 DESI DR2 BAO plus one SNe compilation
- 2 Gaussian-process reconstruction of DM and D'M
- 3 Infer $X(z)$, **instead of $w(z)$** , and compare Λ , CPL, and thawing.

Pantheon+ Union3 DESY5

Dark energy evolution

The dark energy equation of state, $w_X(z)$, is related to $\rho_X(z)$ as follows:

$$w_X(z) = \frac{1}{3}(1+z) \frac{\rho'_X(z)}{\rho_X(z)} - 1,$$

so that

$$\frac{\rho_X(z)}{\rho_X(0)} = \exp \left\{ \int_0^z \frac{3[1+w_X(z)]}{1+z} dz \right\}.$$

One can see that it is easier to extract $\rho_X(z)$ from the data than to extract $w_X(z)$. To obtain the dark energy density directly, one needs only take a single derivative of the comoving distance, whereas to extract $w_X(z)$, one needs to take a second derivative as well - **smearing effect**.

$$\frac{H^2(z)}{H_0^2} \propto X(z) \quad \text{and} \quad D(z) \propto \int_0^z \frac{dz'}{H(z')}$$

Wang & Freese, arXiv:astro-ph/0402208

Dark energy evolution

The Hubble parameter in a flat FLRW spacetime is written as:

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + (1 - \Omega_m)X(z)$$

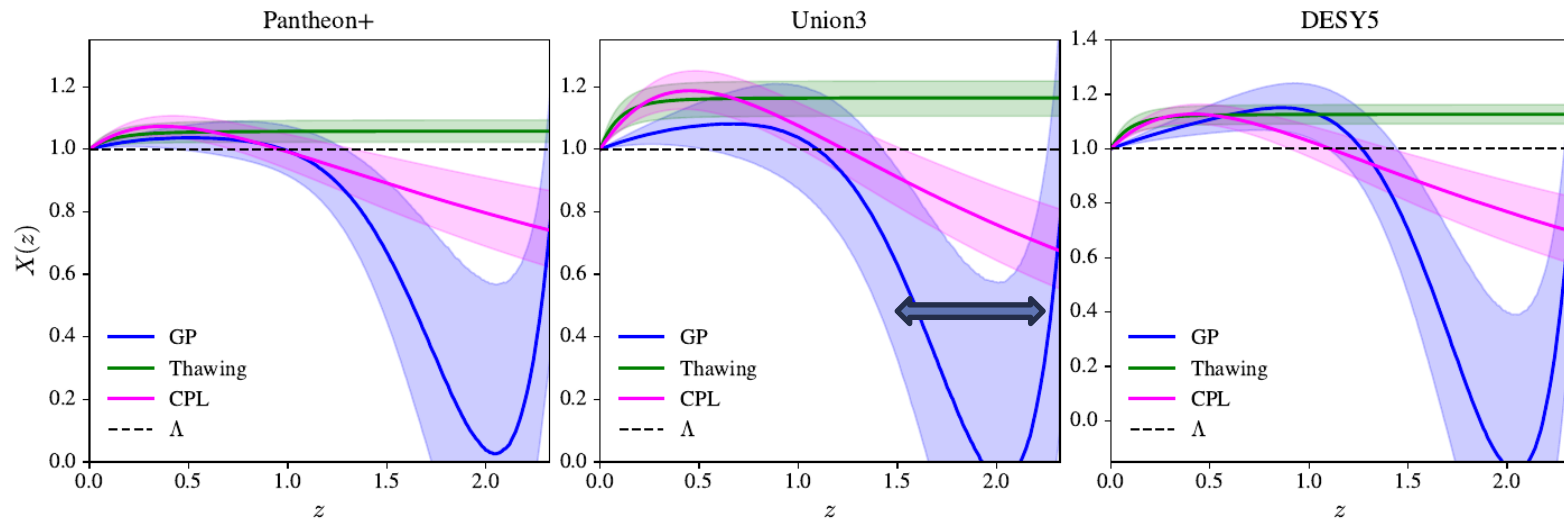
and

$$X(z) = \frac{[\tilde{D}'_{M,0}/\tilde{D}'_M(z)]^2 - \Omega_m(1+z)^3}{1 - \Omega_m}$$

where:

$$\tilde{D}_M(z) = \frac{c}{r_d} \int_0^z \frac{dz'}{H(z')} \quad \text{and} \quad \tilde{D}'_M(z) = \frac{c}{r_d H(z)}$$

The key result from the density reconstruction



Λ , CPL, and thawing all remain compatible with the GP reconstruction at 95% C.L.

Tracer	z_{eff}	D_H/r_d	D_M/r_d
LRG1	0.510	21.863 ± 0.425	13.588 ± 0.167
LRG2	0.706	19.455 ± 0.330	17.351 ± 0.177
LRG3+ELG1	0.934	17.641 ± 0.193	21.576 ± 0.152
ELG2	1.321	14.176 ± 0.221	27.601 ± 0.318
QSO	1.484	12.817 ± 0.516	30.512 ± 0.760
Ly α	2.330	8.632 ± 0.101	38.988 ± 0.531

Conclusions

- Cosmic acceleration remains the most pressing problem in contemporary cosmology, implying a new form of energy with exotic physical properties, or a breakdown of Einstein gravity on cosmological scales.
- The three pillars of Λ CDM - dark matter, dark energy and inflation - illustrate the deep connections between the very big (cosmology) and the very small (particle physics). **The Λ CDM is a simple model that represents a great triumph of observational cosmology, as it provides an excellent fit to current observational data.**
- **Besides the H_0 tension problem, analyses of the DESI DR2 data show evidence for a dynamical dark energy.** This possibility is preferred over Λ CDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SN, the preference for a phantom, dynamical dark energy model over Λ CDM ranges from $2.8 - 4.2\sigma$ depending on which SN sample is used.
- However, the level of discrepancy obtained in this manner significantly depends on the choice of the DDE modeling, ranging from well within $1-2\sigma$ to the $4-5\sigma$ threshold. The latter level of discrepancy is often obtained within the framework of generic w_0 , w_a parameterizations, which seem to provide a better fit to the data but have little to no physical motivation.
- **Are DESI results indicating a paradigm shift in our understanding of late time cosmology? Is Λ CDM dead?**
- **Background degeneracy.** Our analyses on the dark energy density evolution (and non-parametric $w(z)$ reconstruction) show that it may be premature to claim statistically significant evidence for evolving or phantom dark energy with current DESI and SN Ia measurements.

Obrigado!

Dark energy evolution

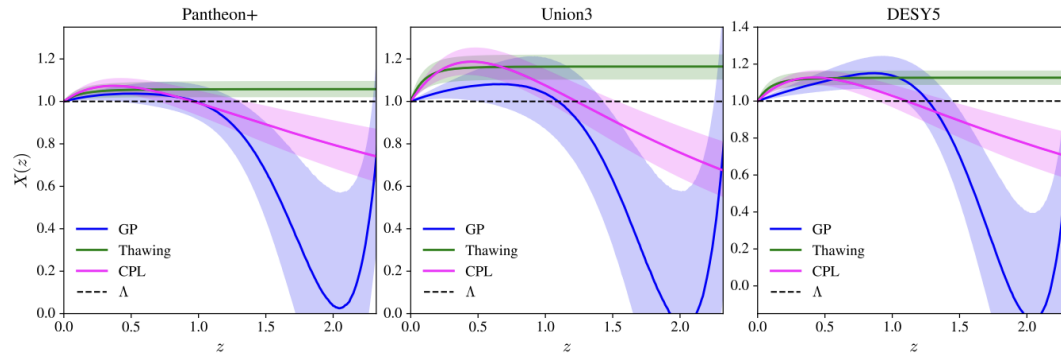


FIG. 4. GP dark energy density reconstruction and the statistical distribution of $X(z)$ for each parameterization. Each panel shows the results assuming the CMB+DESI DR2+SNe sample data combination. All shaded regions display the 68% C.L.

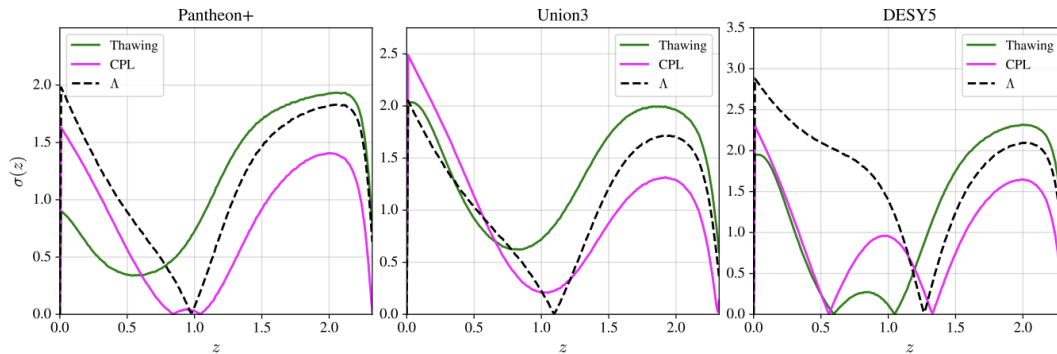
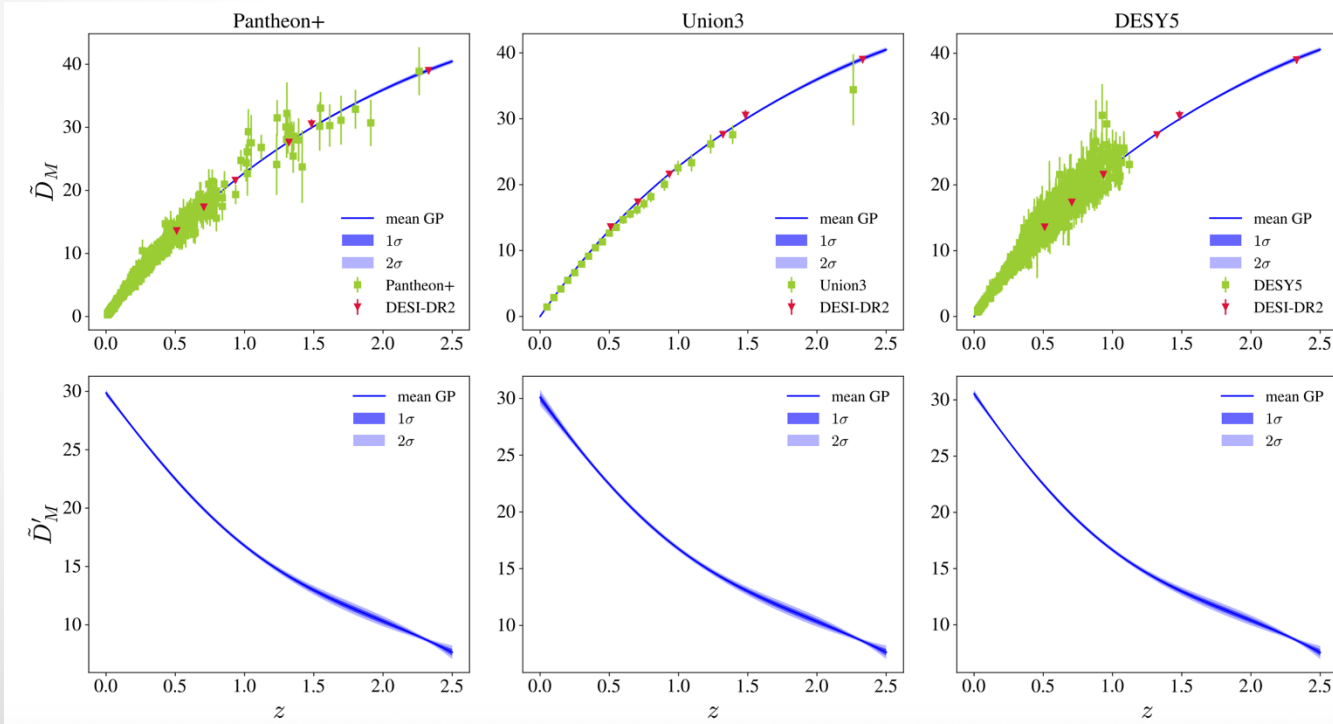


FIG. 5. Distribution of the standard deviation of each model relative to the GP reconstruction as a function of redshift, for each SNe sample used in the data combination.

Dark energy evolution

For SN data, we use: $\tilde{D}_M(z) = \frac{D_L(z)}{(1+z)r_d} = \frac{10^{\frac{m-M-25}{5}}}{(1+z)r_d}$

and assume $r_d = 147.09 \pm 0.26$ Mpc (Planck).



Theoretical Consequences

Why the DESI Results Should Not Be A Surprise

Robert Brandenberger^{1, *}

¹*Department of Physics, McGill University, Montréal, QC, H3A 2T8, Canada*

The recent DESI results provide increasing evidence that the density of dark energy is time-dependent. I will recall why, from the point of view of fundamental theory, this result should not be surprising.

arXiv:2503.17659

Trans-Planckian Problem

In a non-accelerating expanding cosmology the Hubble radius grows faster than the scale factor, and hence wavelengths which are trans-Planckian should never be able to exit the Hubble radius and become classical.



Transient Acceleration

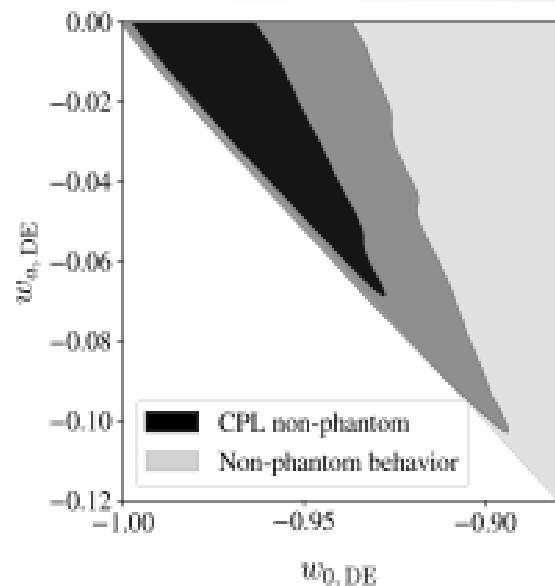
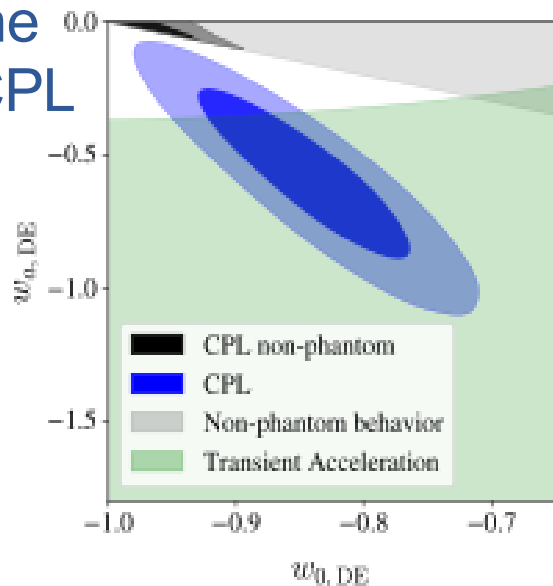
The CPL analysis from DESI data predicts a transient acceleration at the cost of a period of phantom behavior in the past.

- Two important questions:
- 1) How would the previous results be affected if the physical constraint $w(a) \geq -1$ were imposed in the DESI analysis for the CPL parameterization?
- 2) Is there an observationally viable, non-phantom model that leads to a transient acceleration?

Answers:

- 1) How would the previous results be affected if the physical constraint $w(a) \geq -1$ were imposed in the DESI analysis for the CPL parameterization?

$$w_0 = -0.954^{+0.017}_{-0.027} \quad w_a > -0.038 \text{ at } 1\sigma$$



R. Souza, G. Rodrigues & JSA,
in preparation

Answers:

PRL **97**, 081301 (2006)

PHYSICAL REVIEW LETTERS

week ending
25 AUGUST 2006

2) Is there an observationally viable, non-phantom model that leads to a transient acceleration?

Scalar-Field-Dominated Cosmology with a Transient Acceleration Phase

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A new cosmological scenario driven by a slow rolling homogeneous scalar field whose exponential potential $V(\Phi)$ has a quadratic dependence on the field Φ in addition to the standard linear term is discussed. The derived equation of state for the field predicts a transient accelerating phase, in which the Universe was decelerated in the past, began to accelerate at redshift $z \sim 1$, is currently accelerated, but, finally, will return to a decelerating phase in the future. This overall dynamic behavior is profoundly different from the standard evolution of the cold dark matter model with a cosmological constant, and may alleviate some conflicts in reconciling the idea of a dark-energy-dominated universe with observables in String or M theory. Some theoretical predictions for the present scalar field plus dark matter dominated stage are confronted with cosmological observations in order to test the viability of the scenario.

Scalar field potential:

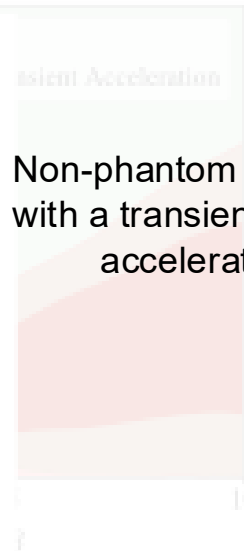
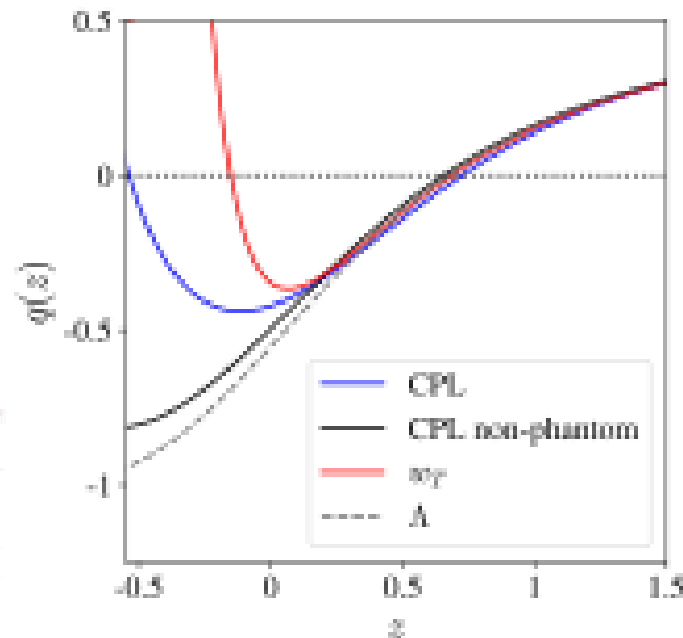
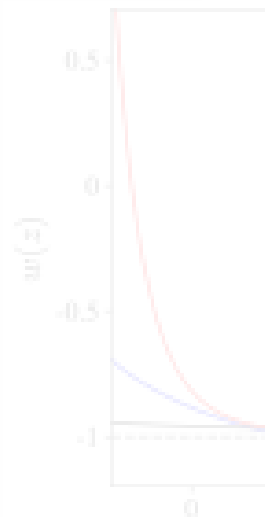
$$V(\phi) = Y \exp \left[-3\alpha\sqrt{\sigma} \left(\phi + \frac{\beta\sqrt{\sigma}}{4} \phi^2 \right) \right] ,$$

EoS parameter:

$$w_T(a) = -1 + \alpha a^\beta$$

Generalized exponential potential
for $\beta \neq 0$.

Results for w_t :

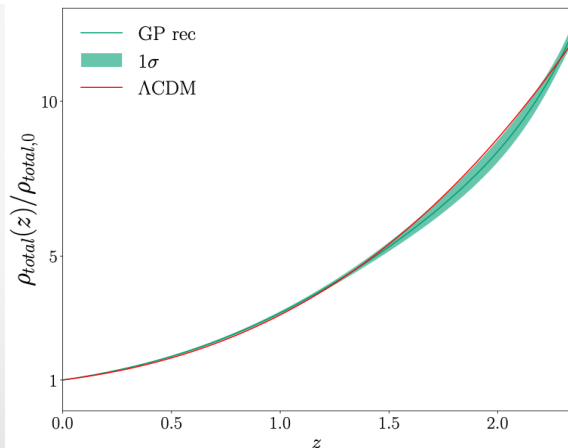
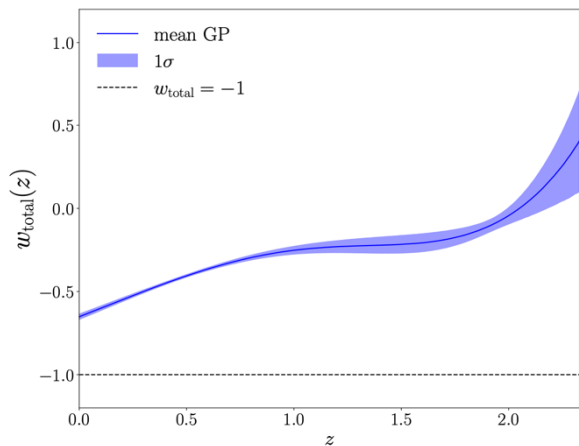


Non-phantom scenario
with a transient cosmic
acceleration

Model	Data								
CPL	DESI + CMB								
CPL	DESI + CMB + SN								
		Best-fit	0.306	0.680	0.048	-0.885	-0.444	—	—
CPL Non-Phantom	DESI + CMB	Mean (1σ)	$0.308^{+0.0049}_{-0.0041}$	$0.675^{+0.0044}_{-0.0047}$	$0.049^{+0.00062}_{-0.0010}$	$-0.957^{+0.011}_{-0.001}$	> -0.034	—	—
		Best-fit	0.303	0.681	0.048	-0.994	-0.001	—	—
CPL NP	DESI + CMB + SN	Mean (1σ)	$0.308^{+0.0046}_{-0.0032}$	$0.674^{+0.0054}_{-0.0043}$	$0.049^{+0.00064}_{-0.00054}$	$-0.954^{+0.017}_{-0.027}$	> -0.038	—	—
		Best-fit	0.308	0.675	0.049	-0.959	-0.034	—	—
Thawing	DESI + CMB + SN	Mean (1σ)	$0.309^{+0.0051}_{-0.0039}$	$0.674^{+0.0060}_{-0.0053}$	$0.049^{+0.00074}_{-0.00091}$	—	—	$0.129^{+0.063}_{-0.10}$	> 5.290
		Best-fit	0.309	0.670	0.050	—	—	0.183	6.729

Phantom dark energy and the NEC

DESI DR2 & Pantheon+



Null Energy Condition:

$$\rho + p \geq 0$$

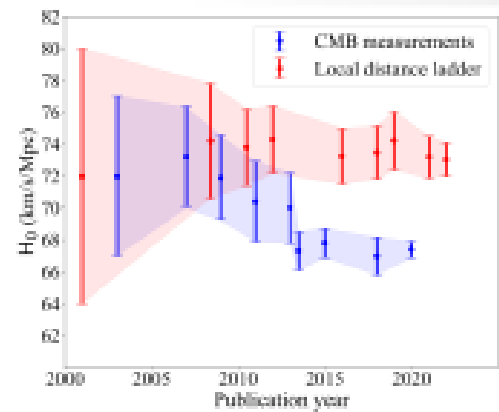
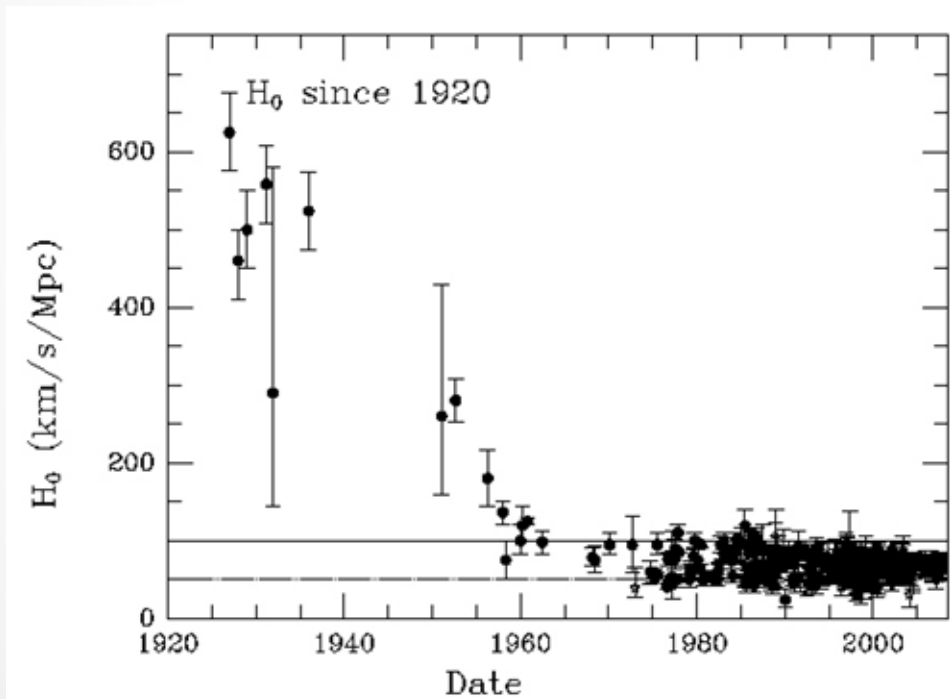
Violation of energy conditions

NEC implies the sum of the total energy density and pressure satisfies $\rho_{\text{tot}} + P_{\text{tot}} \geq 0$; the energy conditions do not apply separately to individual components of the cosmological fluid.

Caldwell & Linder, arXiv:2511.07526

H_0 measurements

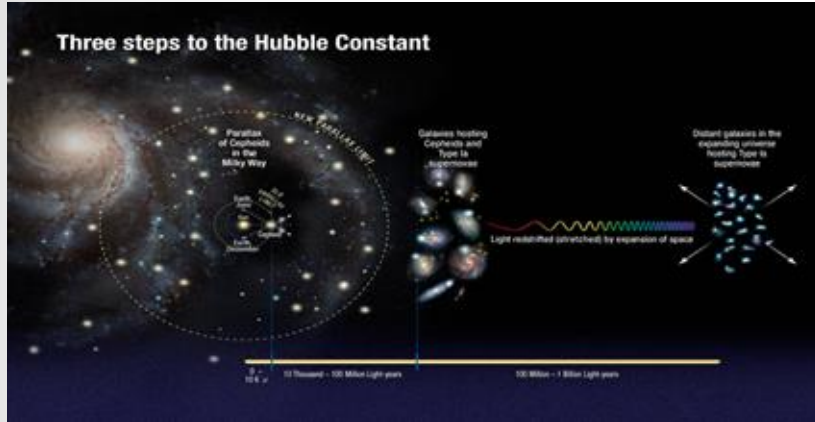
- The local or late Universe measurements of H_0 improved from 10% uncertainty twenty years ago to below 2% by today.



Perivolaropoulos and Skara 2023

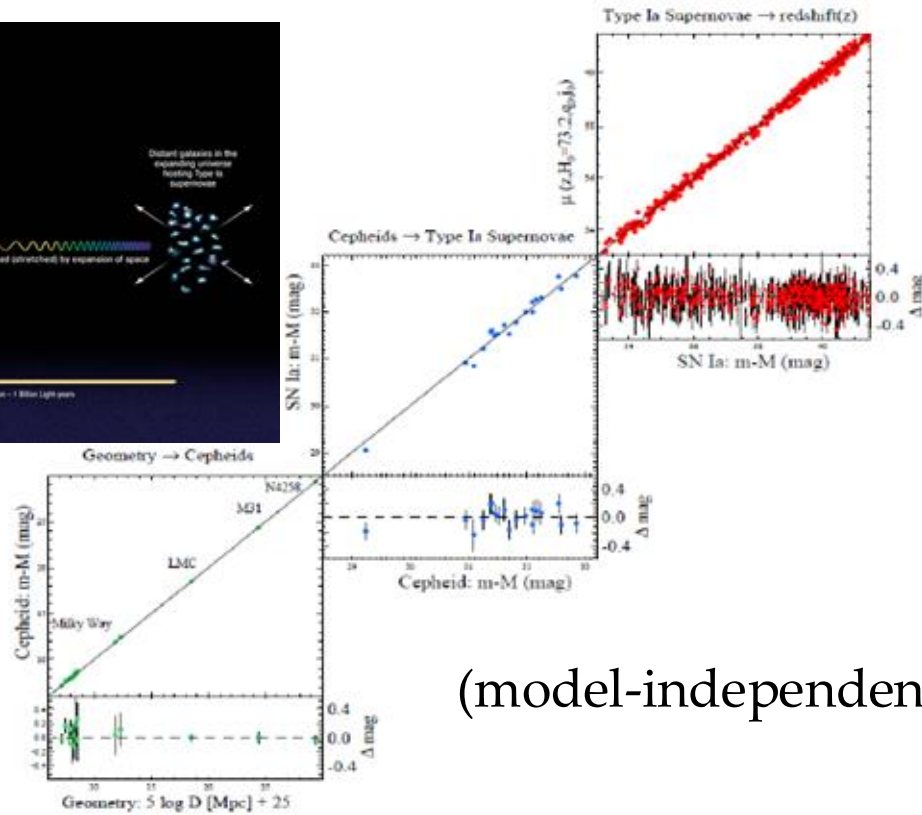
H_0 tension

- SH₀ES (Supernovae H_0 for the Equation of State)



$$H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc}$$

Riess et al. 2020



(model-independent approach)