

On Dark Energy Reconstruction and Interpretation

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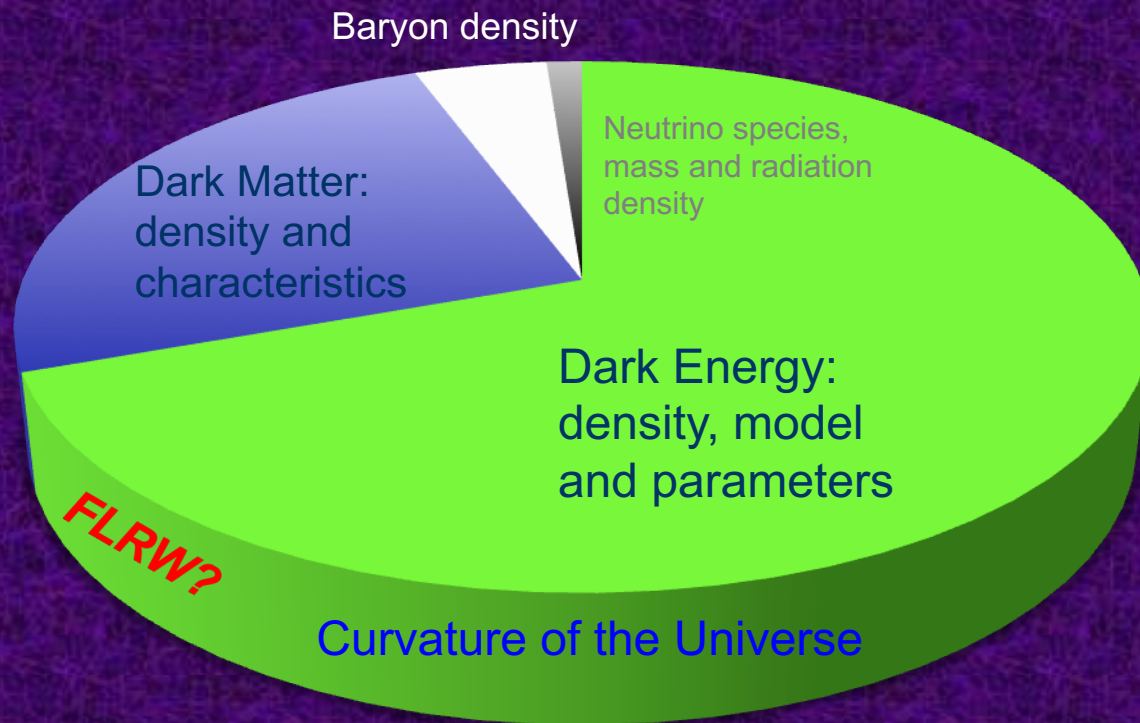
CosPA 2026 / ACGRG 13

International Symposium on Cosmology & Particle Astrophysics 2026;
13th Australasian Conference on General Relativity & Gravitation

05-09 July 2026, Christchurch, New Zealand

Era of Precision Cosmology

We try to **reconstruct and understand the dynamics of the universe** and **properties of its constituents** using various **measurements and statistical techniques**. **Phenomenological** and then **theoretical** works can follow to place **constraints on suggested models and their parameters**.



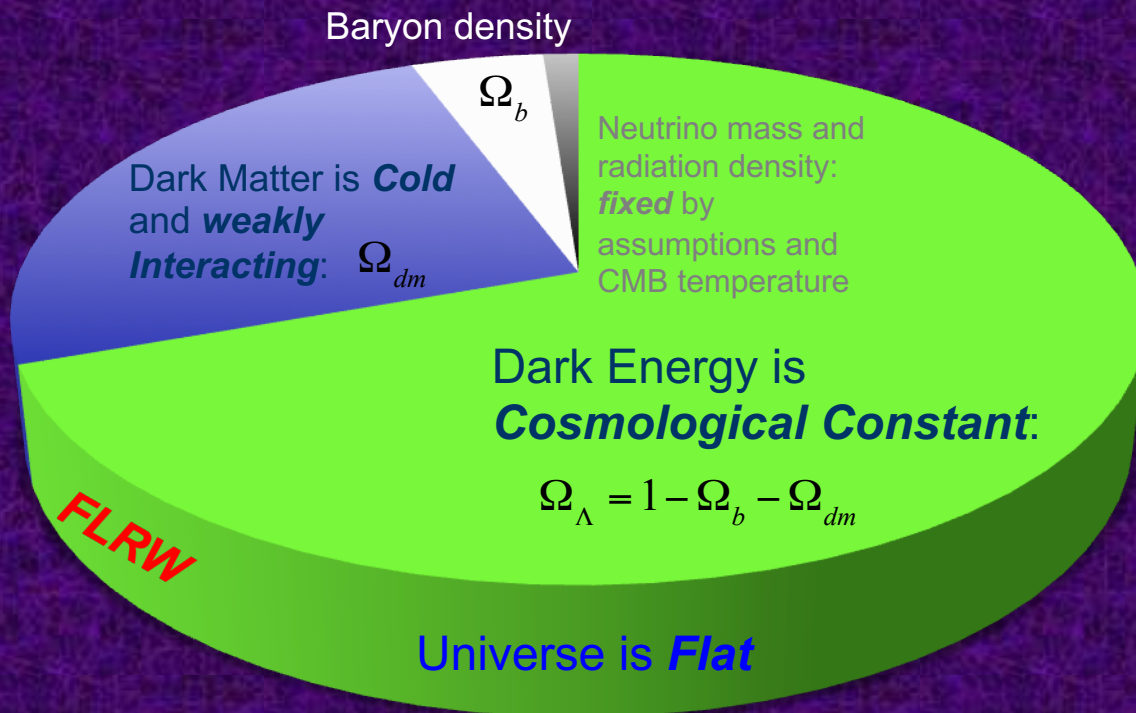
Initial Conditions:
Form of the Primordial
Spectrum and Model of
Inflation and its Parameters

Epoch of reionization

Hubble Parameter and
the Rate of Expansion

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.



Initial Conditions:
Form of the Primordial
Spectrum is **Power-law**

$$n_s, A_s$$

Epoch of reionization

$$\tau$$

Hubble Parameter and
the Rate of Expansion

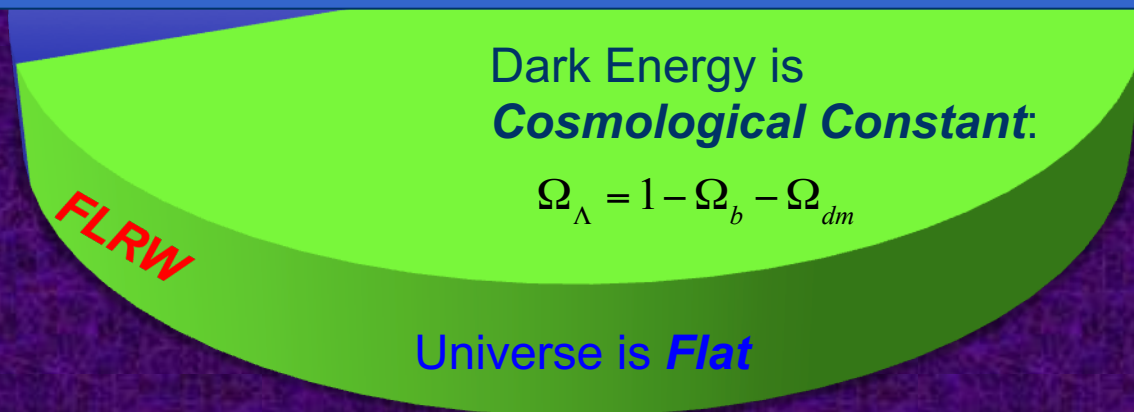
$$H_0$$

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

Baryon density

Combination of Assumptions



Epoch of reionization

τ

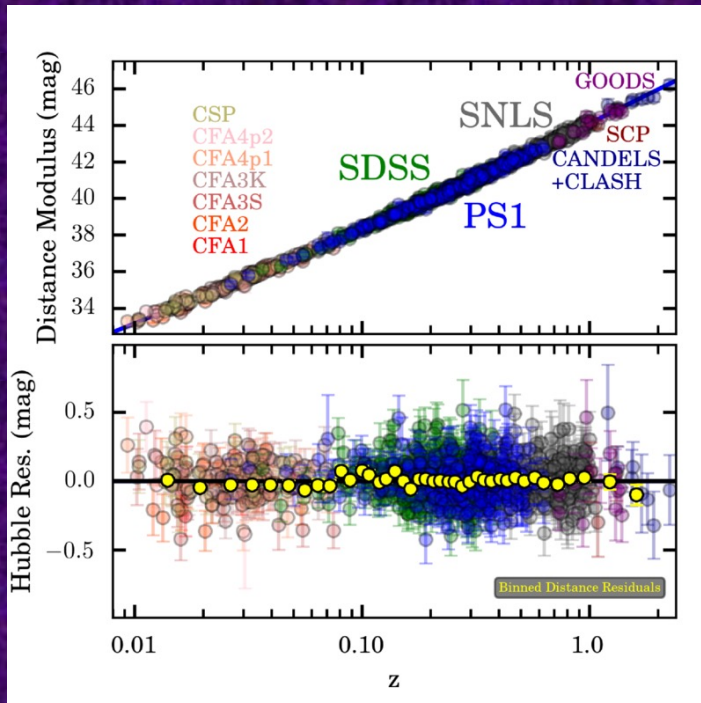
Hubble Parameter and the Rate of Expansion

H_0

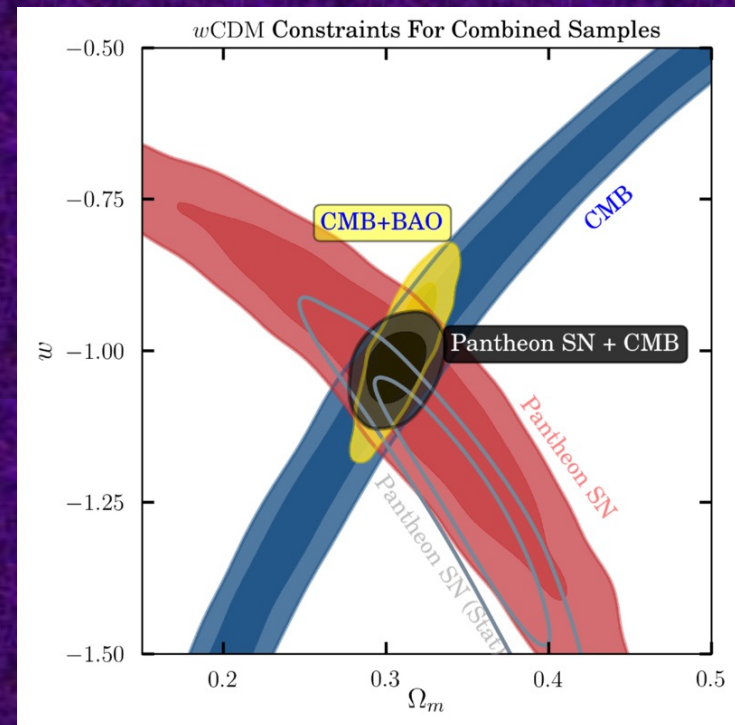
Standard Model in 2026 *SN Ia*

20 years after discovery of the acceleration of the universe:

From 60 Supernovae Ia at cosmic distances, we now have ~1500 published distances, with better precision, better accuracy, out to $z \sim 2.0$. **Accelerating universe in proper concordance to the data.**



~1500 spectroscopically confirmed SNIa



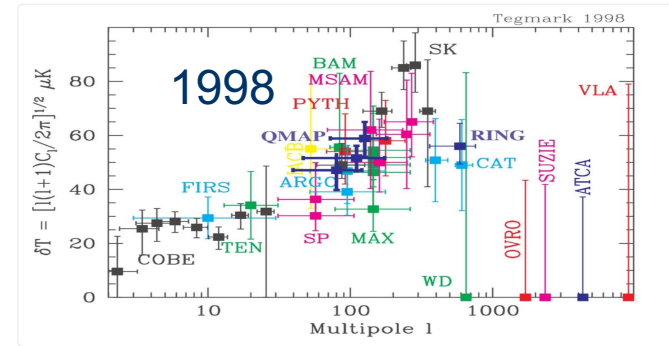
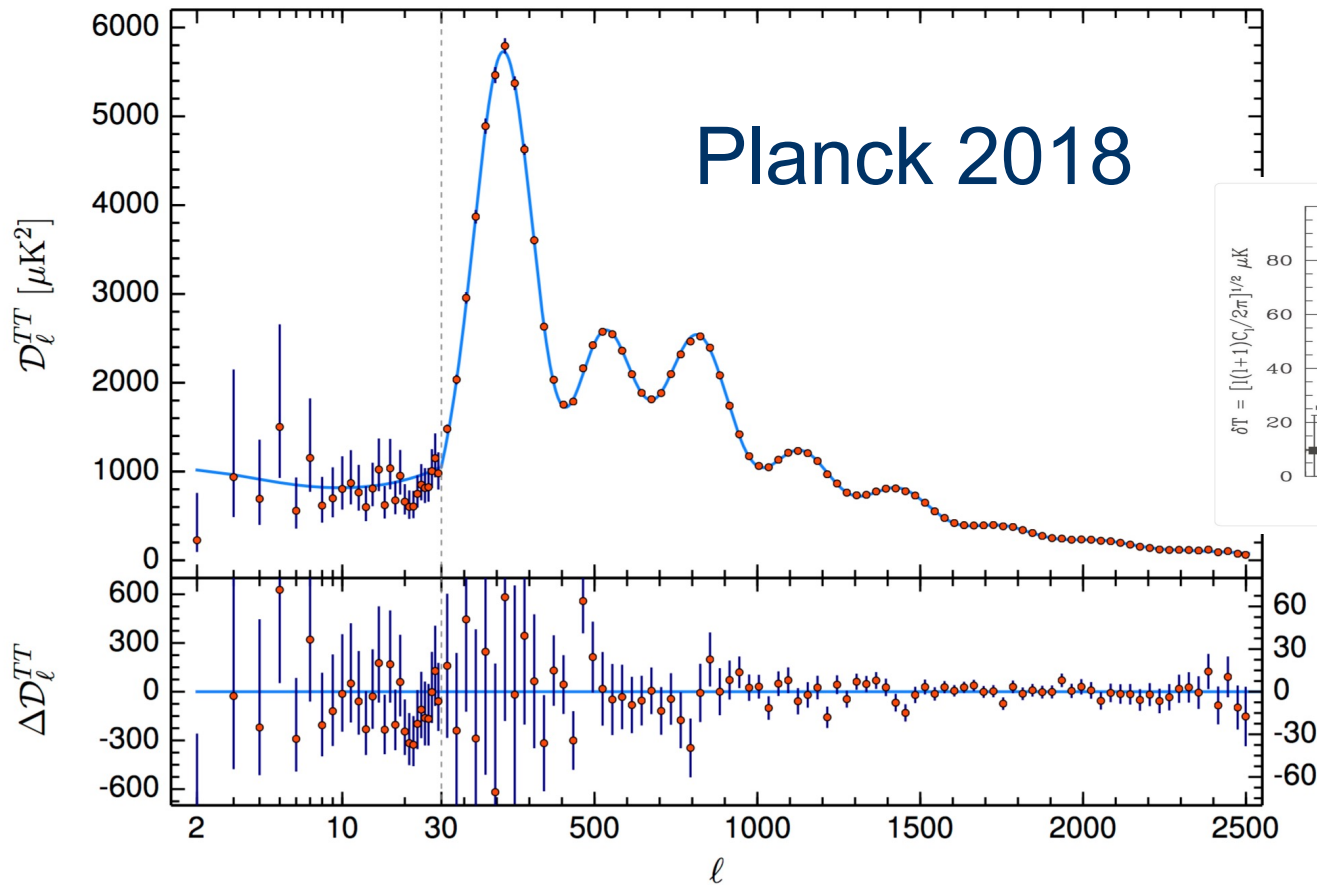
Pantheon+ Compilation
Scolnic et al. (2021)

Standard Model in 2026

CMB

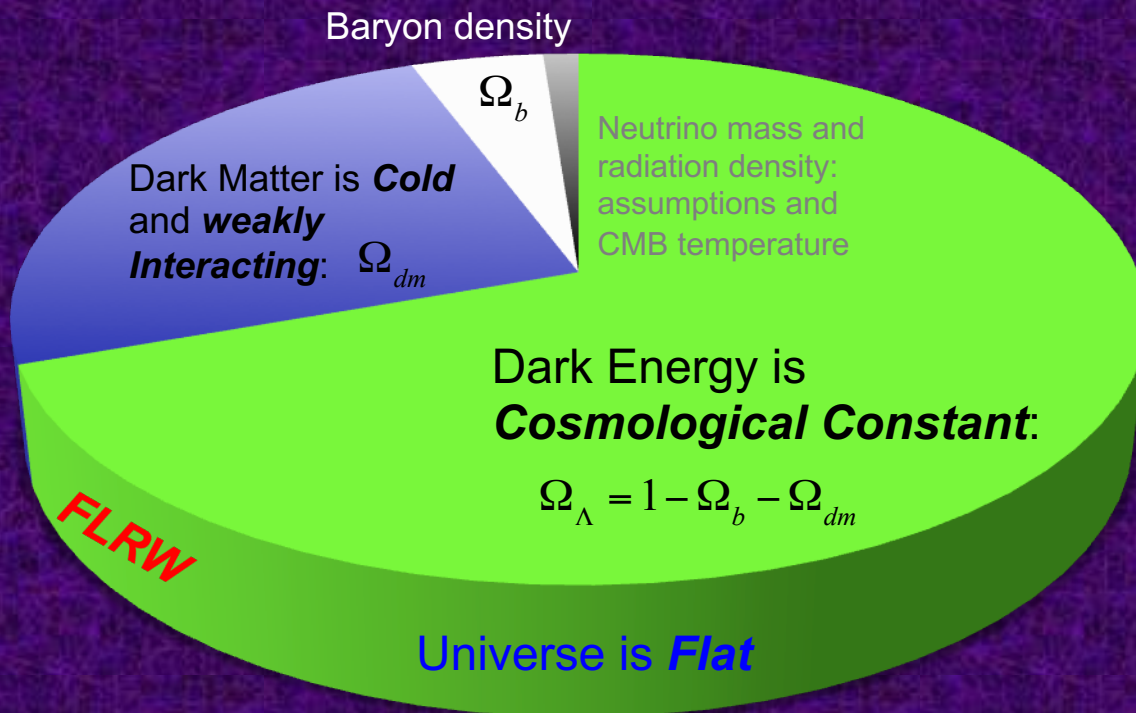
20 years after discovery of the acceleration of the universe:

CMB directly points to acceleration. Didn't even have acoustic peak in 1998!



Standard Model of Cosmology

combination of *reasonable* assumptions, but.....



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Epoch of reionization

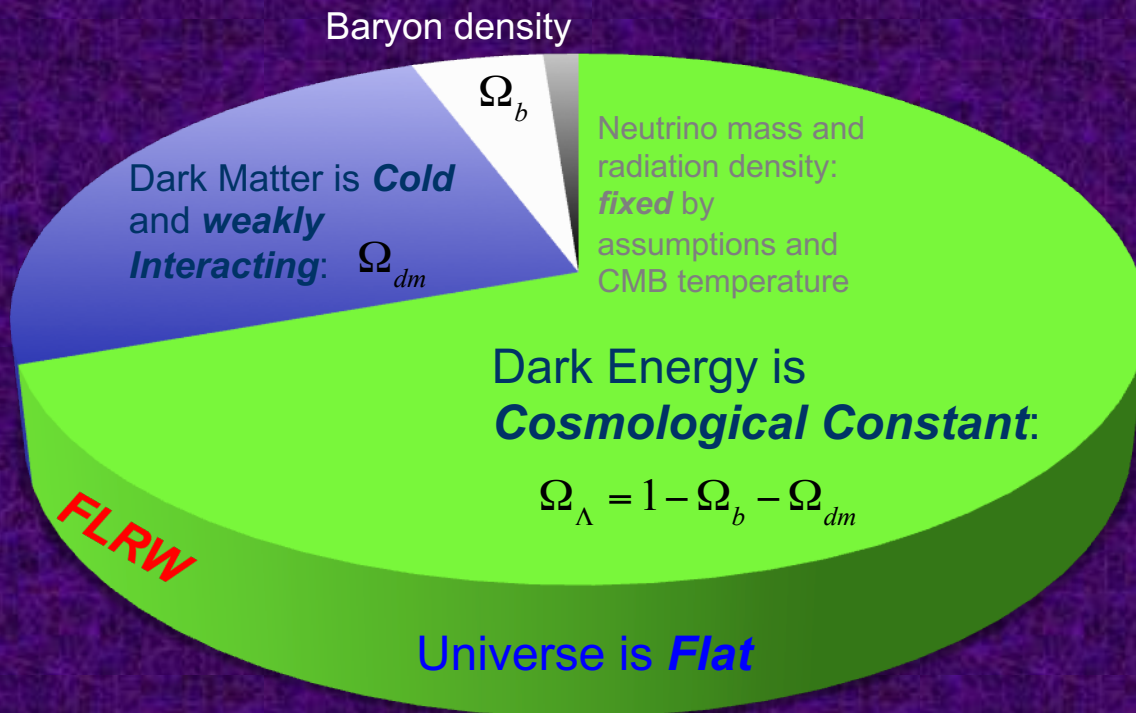
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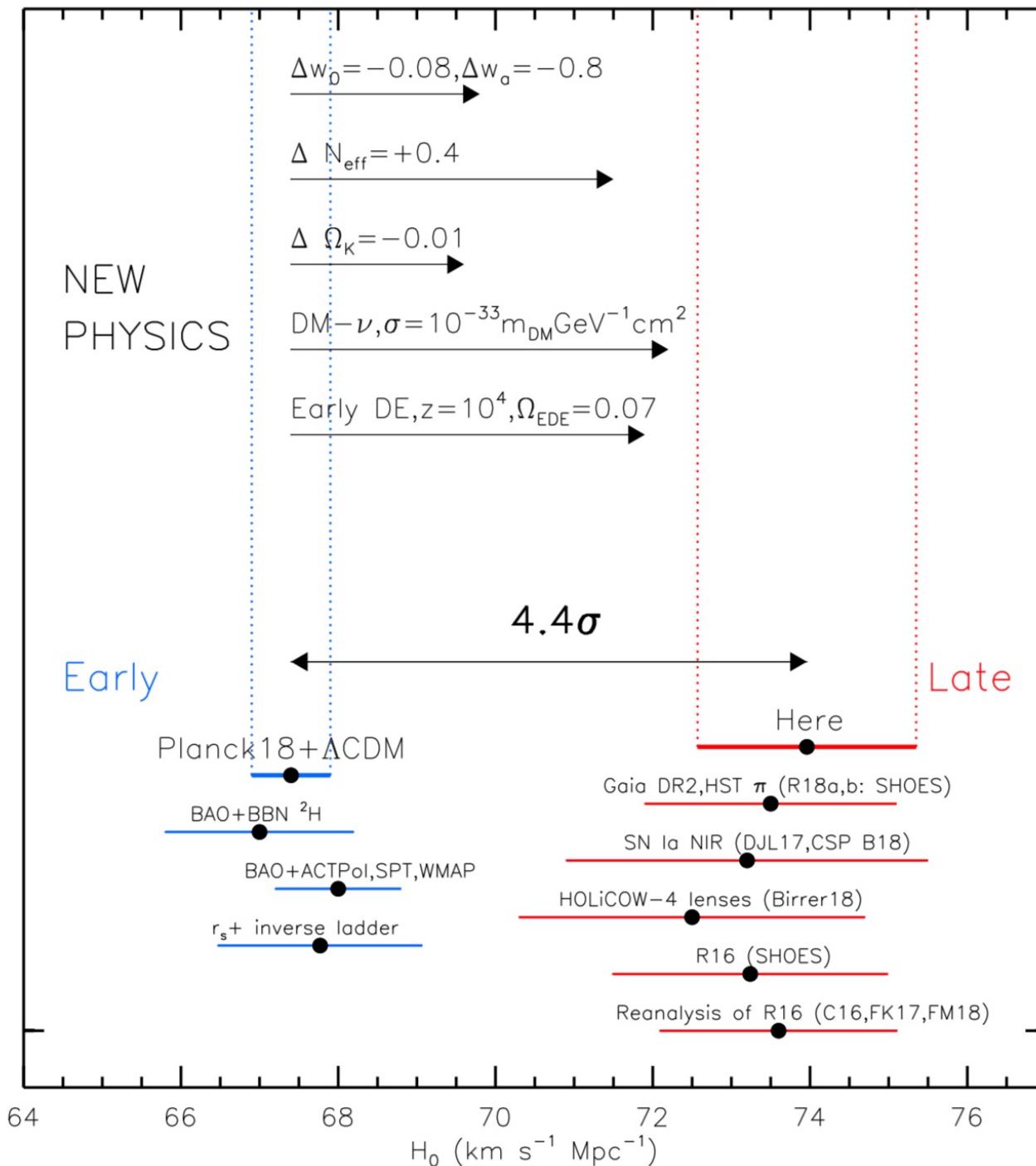
$$n_s, A_s$$

Epoch of reionization

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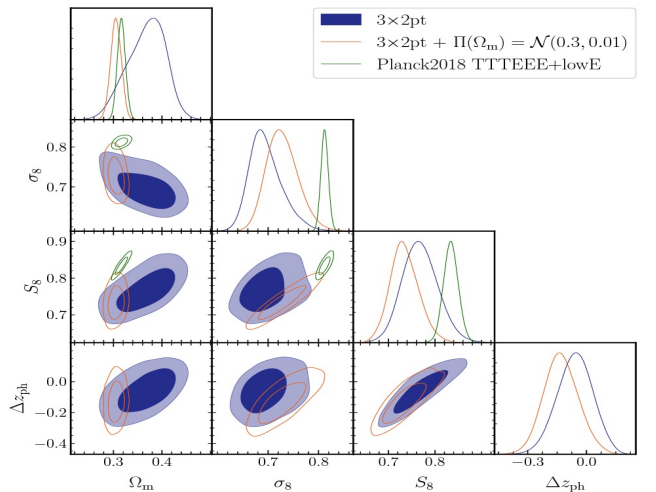
Hubble Parameter and
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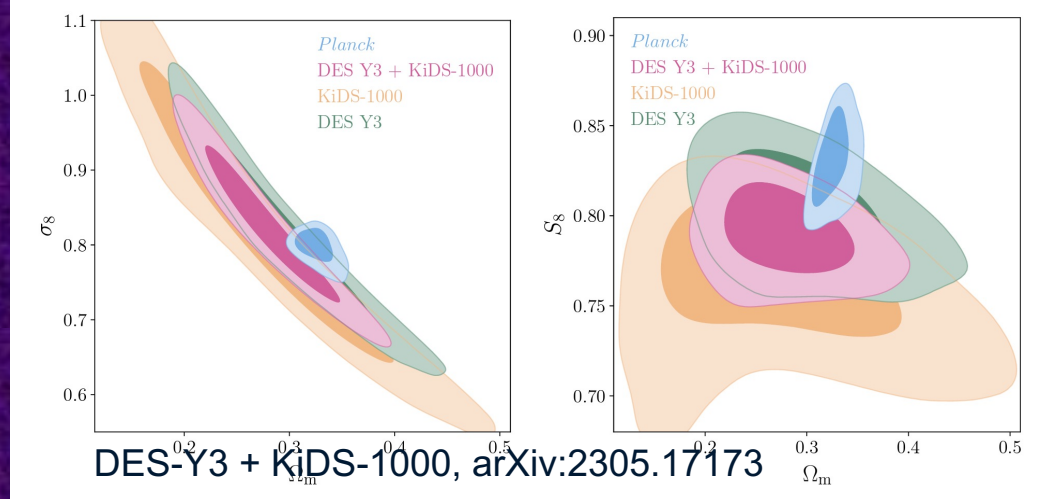


Tensions in the
Standard Model

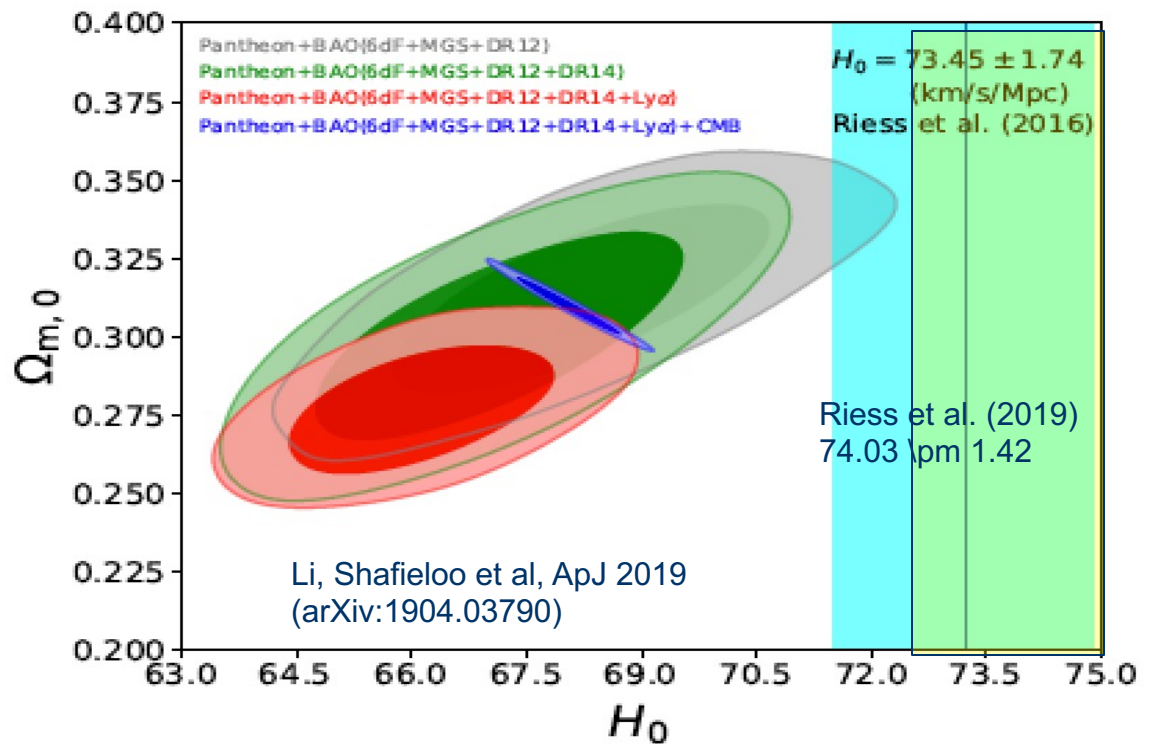
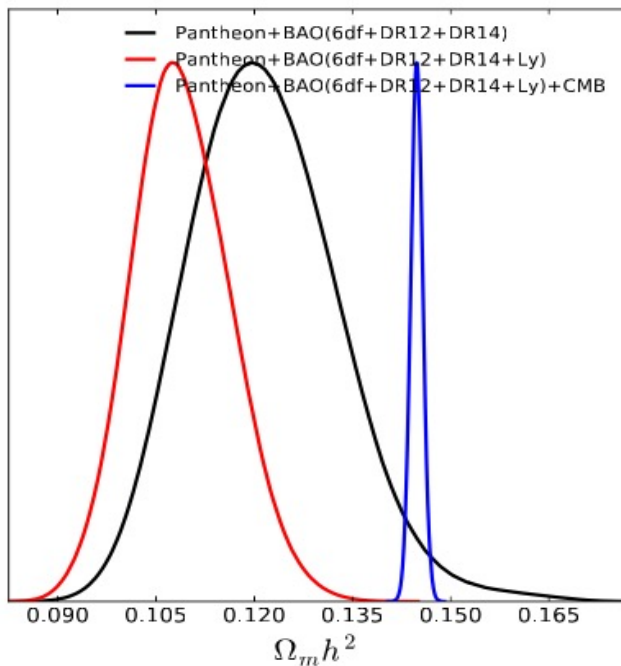
Riess et al, ApJ 2019
[arXiv:1903.07603]



HSC-Y3, arXiv:2304.00704

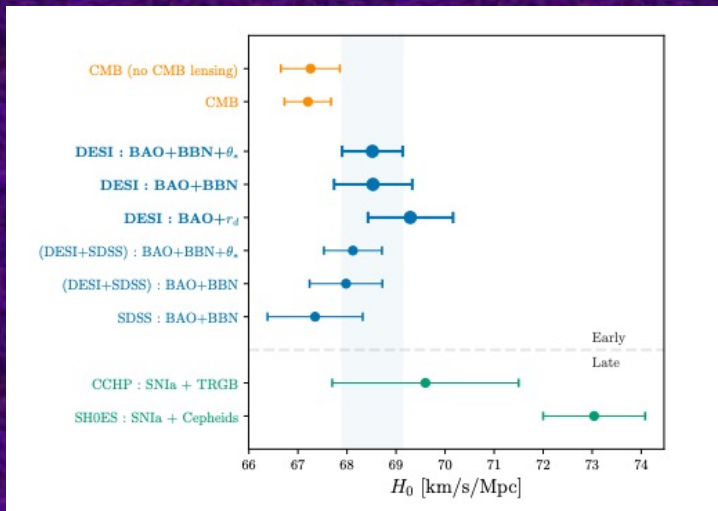


It is not only about H_0 and CMB. Low S_8 and low matter density by WL.

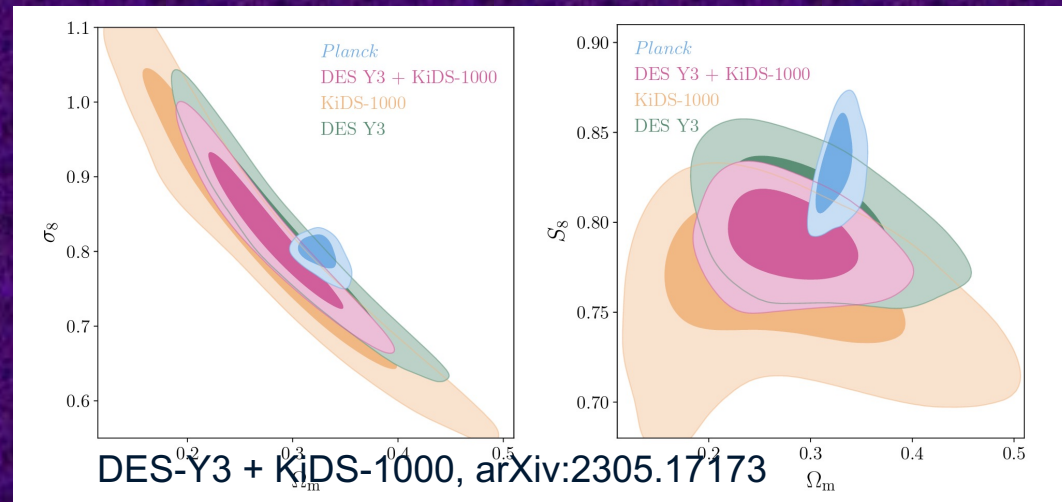


Tensions in the Standard Model

It is not only about H_0 and CMB

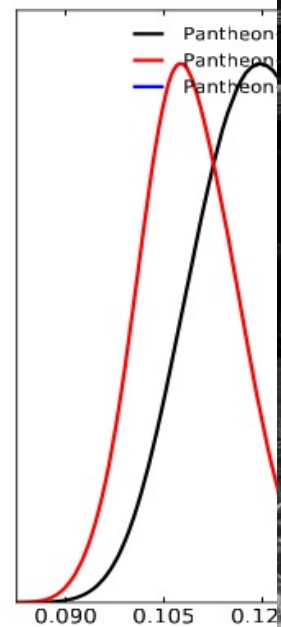
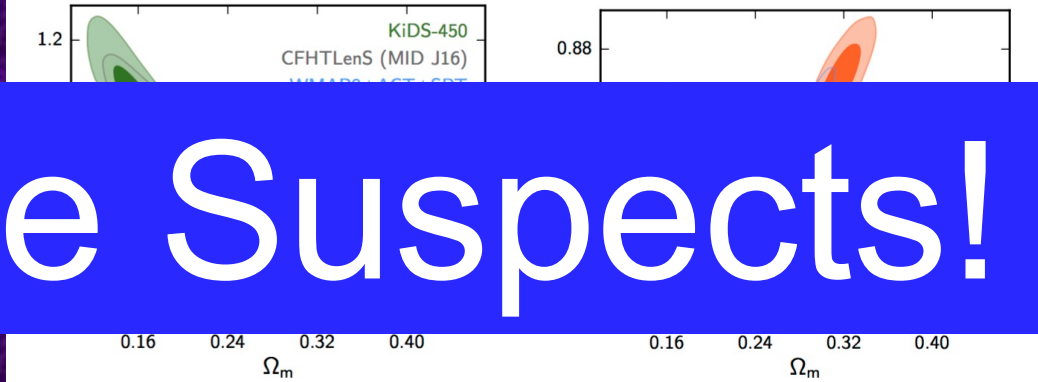
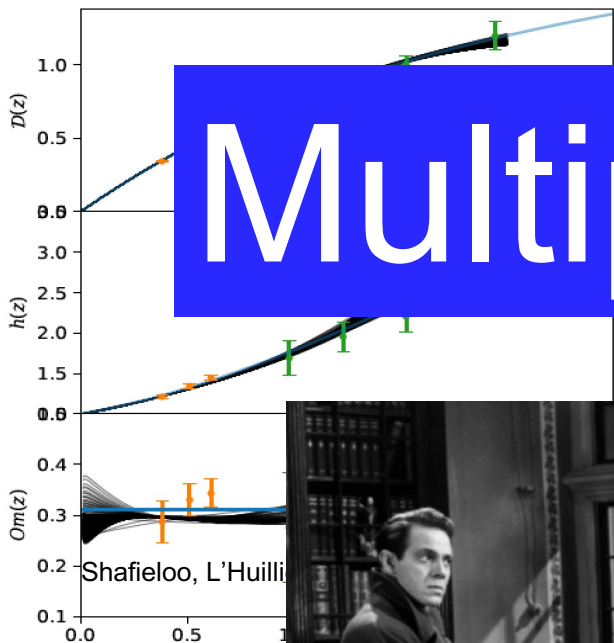


DESI-Y1 (2024),
arXiv:2404.03002



DES-Y3 + KiDS-1000, arXiv:2305.17173

Multiple Suspects!



And Then There Were None (1945),
Rene Clair [Based on a novel by Agatha Christie]

$H(z)r_d$ is
by WL.

3.45 ± 1.74
km/s/Mpc)
et al. (2016)

et al. (2019)
om 1.42

73.5 75.0

How to resolve the tensions?



- **Statistical fluctuations** (*probably not anymore, some tensions are at high significance*)
- **Systematic in one or some of the data?** [**Highly Possible** considering complications of the tensions that all cannot be resolved by minimal modifications.]

(Li, Shafieloo, Sahni, Starobinsky, ApJ 2019)

2025 Update: S8 tension is probably gone!

- **Extended models and/or new physics**

Caution: extended models with more degrees of freedom result to larger confidence contours which looks like there are better consistencies (more overlap between larger contours). [OK to do that but better to avoid over-selling!] *If current observations are reliable, most of these models will be ruled out by future observations. Central values matter!*

(Present)

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous

Dark Energy is Lambda ($w=-1$)

Power-Law primordial spectrum ($n_s=\text{const}$)

Dark Matter is cold

All within framework of FLRW

DE is directly relates to expansion history and growth of structure.

Many DE models have been proposed to alleviate tensions.

(Present)

*Take home 1: There might be an issue with some of the data.
Let's consider not to try solve all the problems together.*

Standard Model of Cosmology

Universe is Flat

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Dark Energy is Lambda ($w=-1$)

Power-Law primordial spectrum ($n_s=\text{const}$)

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All within framework of FLRW

DE is directly related to expansion history and growth of structure.

Many DE models have been proposed to alleviate tensions, early and late models. **None has been successful.**

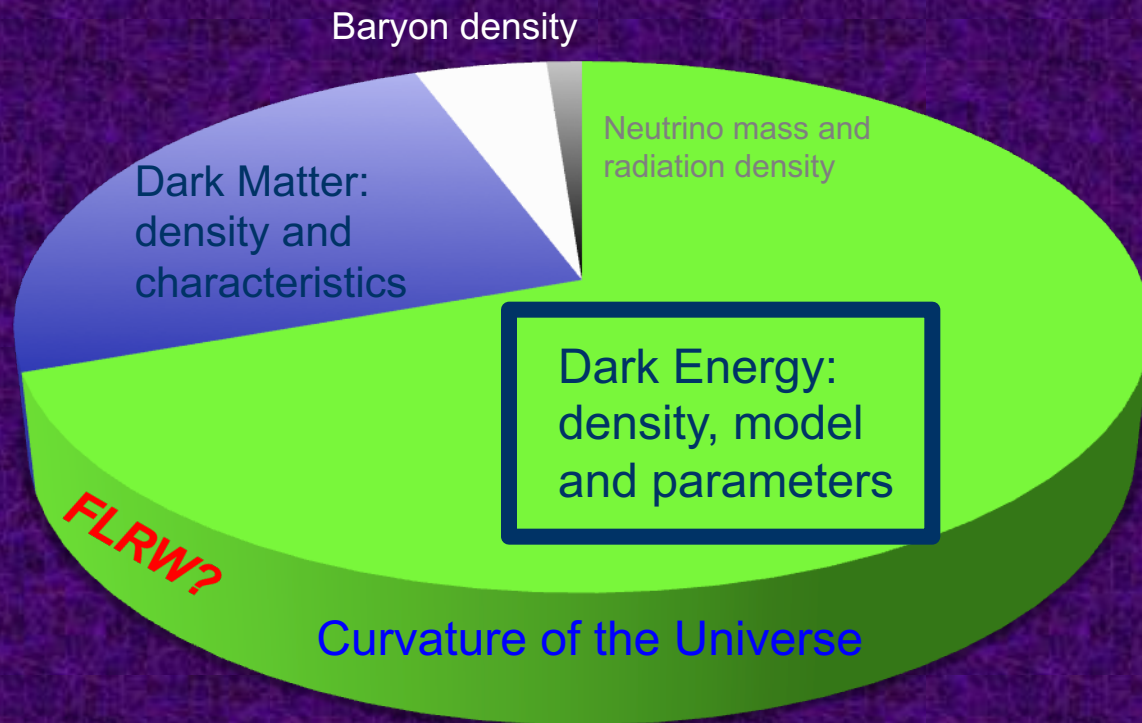
**However,
Understanding DE is important, with or without tensions.**

To move forward in understanding dark energy....

Reconstruction & **Falsification**

Reconstruction: Understanding the behavior

Falsification: Testing the consistency and validation of models



Initial Conditions:
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Reconstructing Dark Energy

To reconstruct cosmological quantities and key parameters there are two general approaches:

1. Parametric methods



Easy to confront with cosmological observations to put constraints on the parameters, but the results are highly **biased by the assumed** models and parametric forms.

2. Non Parametric methods

Difficult to apply on the raw data, but the results are **less biased and more reliable** and independent of theoretical models or parametric forms. Reconstructions can be used for **model validation**.

Reconstruction → Phenomenology → Theory

Dark Energy Parameterizations

$$F = \frac{L}{4\pi d_L^2}$$

Supernovae Ia as
Standardized Candles

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)}$$

BAO as standard ruler

$$d_L(z) = (1+z) \int_0^z \frac{dz'}{H(z')}$$

$$d_A(z) = (1+z)^{-1} \int_0^z \frac{dz'}{H(z')}$$

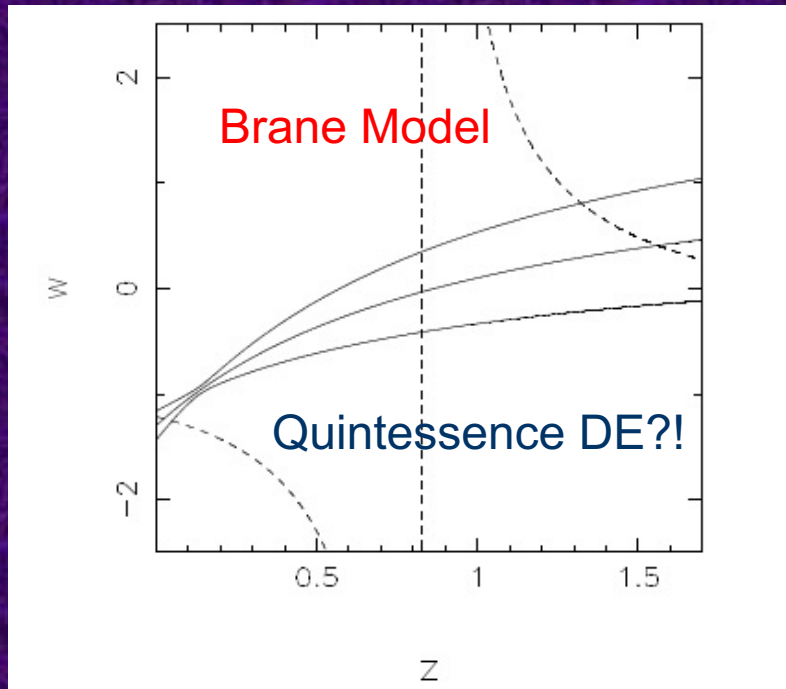
$$\frac{H^2(z)}{H_0^2} = \left[\Omega_{0M} (1+z)^3 + (1-\Omega_{0M}) X(z) \right]$$

1. Fitting functions for $d_L(z)$
2. Fitting functions for DE density
3. Fitting functions for EOS

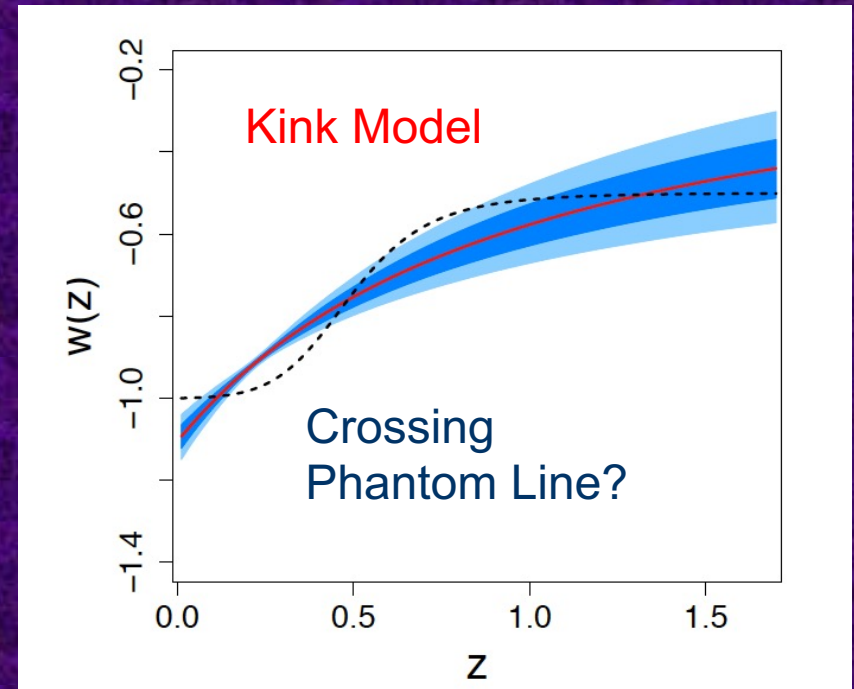
Most general form

$$\frac{H^2(z)}{H_0^2} = \left[\Omega_{0M} (1+z)^3 + (1-\Omega_{0M}) \exp \left[\int 3(1+w(z)) \frac{dz}{1+z} \right] \right]$$

Problems of Dark Energy Equation of State Parameterizations *[Why I don't like $w(z)$ fitting]*



Shafieloo, Alam, Sahni &
Starobinsky, MNRAS 2006

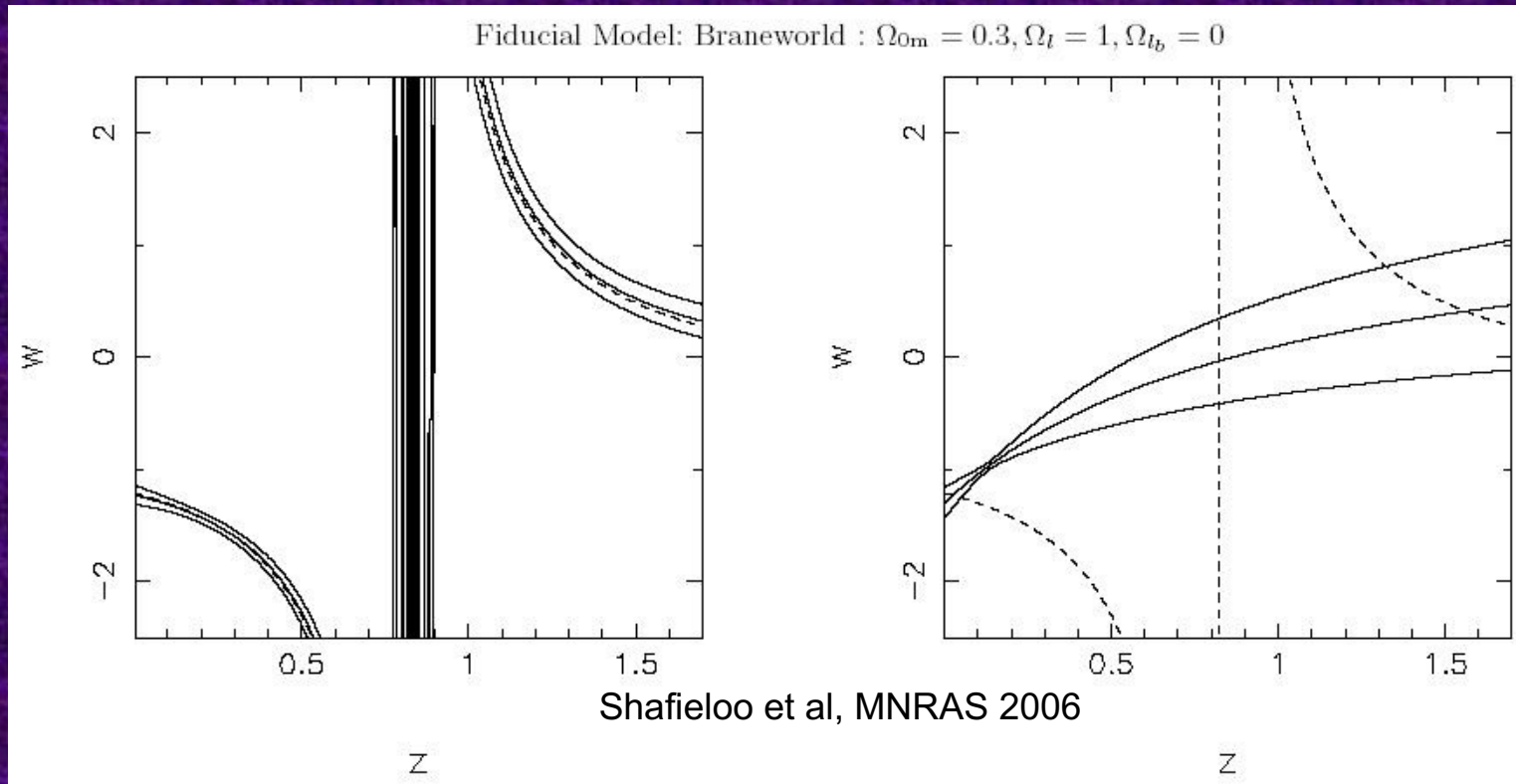


Holsclaw et al, PRD 2011

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

Chevallier-Polarski-Linder ansatz (CPL).

What should have been taken home 20 years ago (2): Fitting functions for $w(z)$ can be problematic



Reconstructed $w(z)$ by
Iterative smoothing method

Chevallier and Polarski (2001) and Linder (2003)

Reconstructed $w(z)$ by using
CPL fit.

$$w(z) = w_0 + \frac{w_1(z)}{1+z}$$

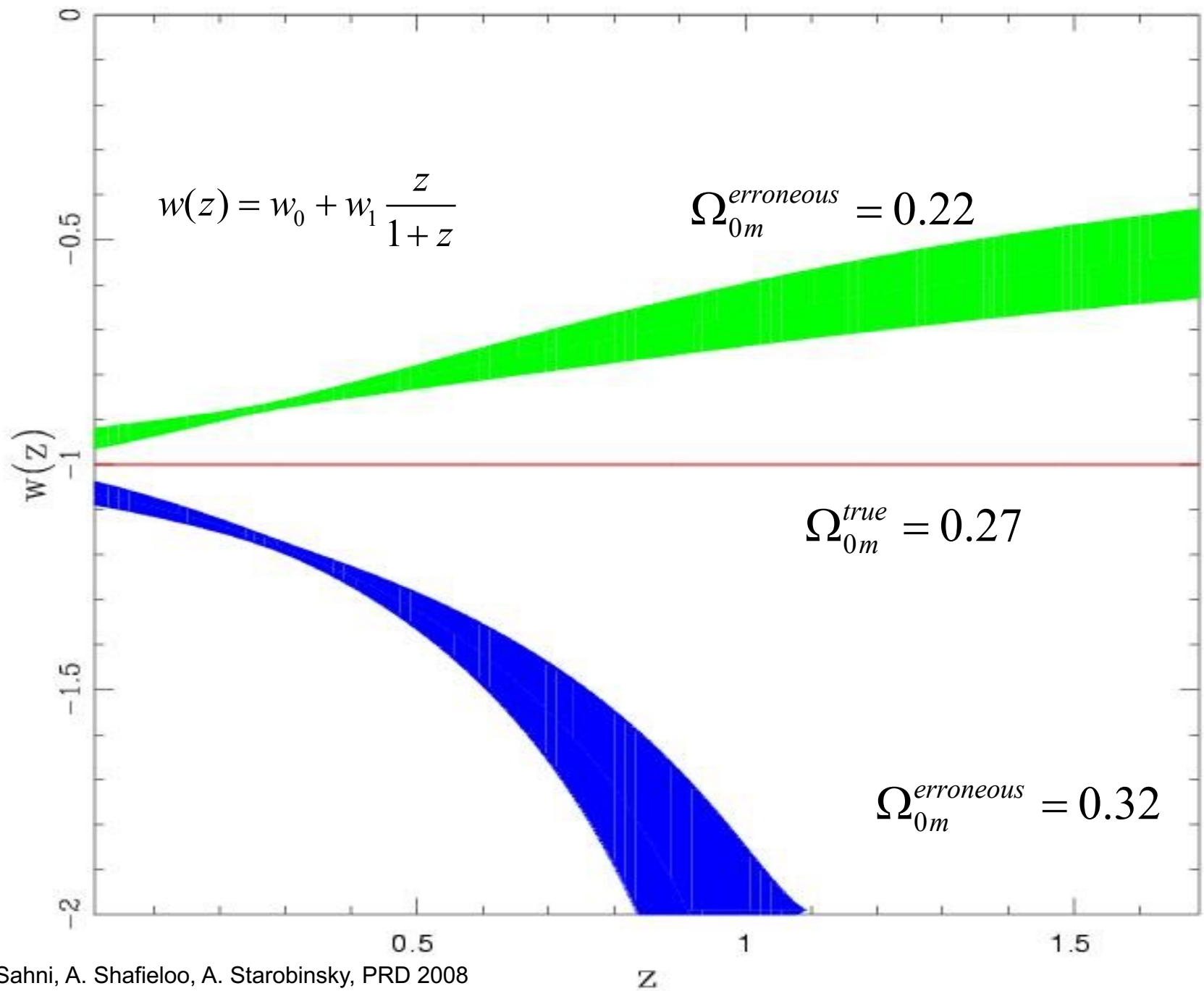
Dealing with $w(z)$ is difficult anyway!

Dealing with observational uncertainties in matter density

- Small uncertainties in the value of matter density may affect the reconstruction exercise quite dramatically.
- Hubble parameter is not affected to a very high degree by the value of matter density.
- Any uncertainties in matter density is bound to affect the reconstructed $w(z)$.

$$H(z) = \left[\frac{d}{dz} \left(\frac{d_L(z)}{1+z} \right) \right]^{-1}$$

$$\omega_{DE} = \frac{\left(\frac{2(1+z)}{3} \frac{H'}{H} \right) - 1}{1 - \left(\frac{H_0}{H} \right)^2 \Omega_{0M} (1+z)^3}$$

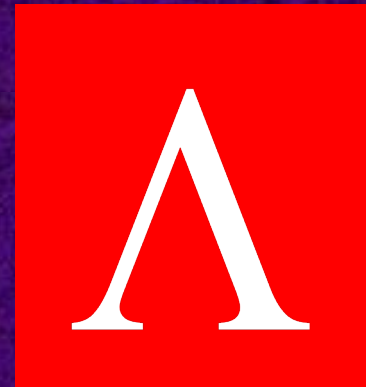


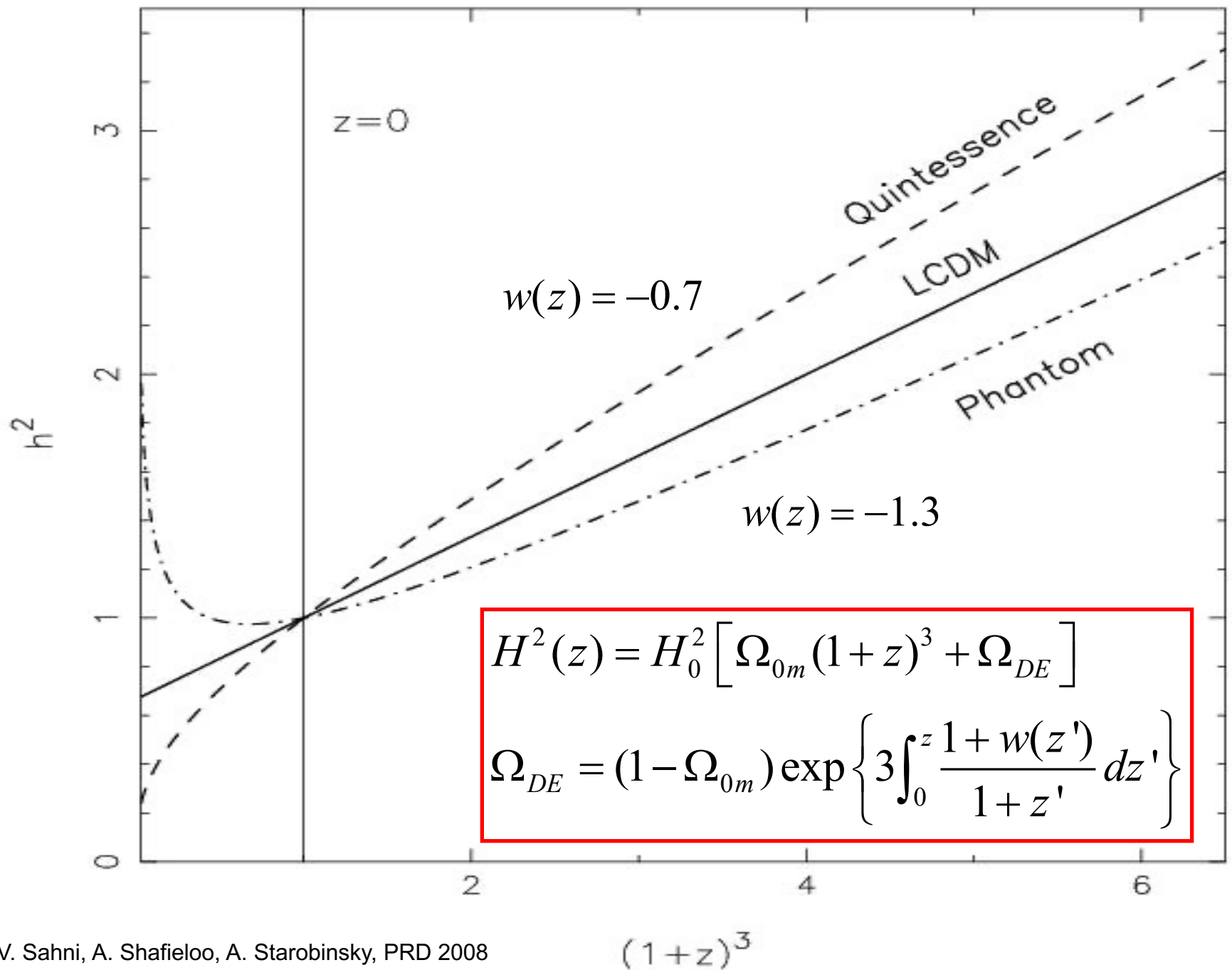
Falsification

- Instead of trying to find out $w(z)$ and exact properties of dark energy with current status of the data, we can concentrate on a more reasonable problem:



OR NOT





Om diagnostic

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1}$$

V. Sahni, A. Shafieloo, A. Starobinsky, PRD 2008

arXiv:0807.3548

$$Om(z) = \Omega_{0m} + (1 - \Omega_{0m}) \frac{x^{3(1+w)} - 1}{x^3 - 1}$$

Not sensitive to the value of matter density.

Can be directly derived from cosmological observables,

$$w = -1 \rightarrow Om(z) = \Omega_{0m}$$

$$w < -1 \rightarrow Om(z) < \Omega_{0m}$$

$$w > -1 \rightarrow Om(z) > \Omega_{0m}$$

LCDM

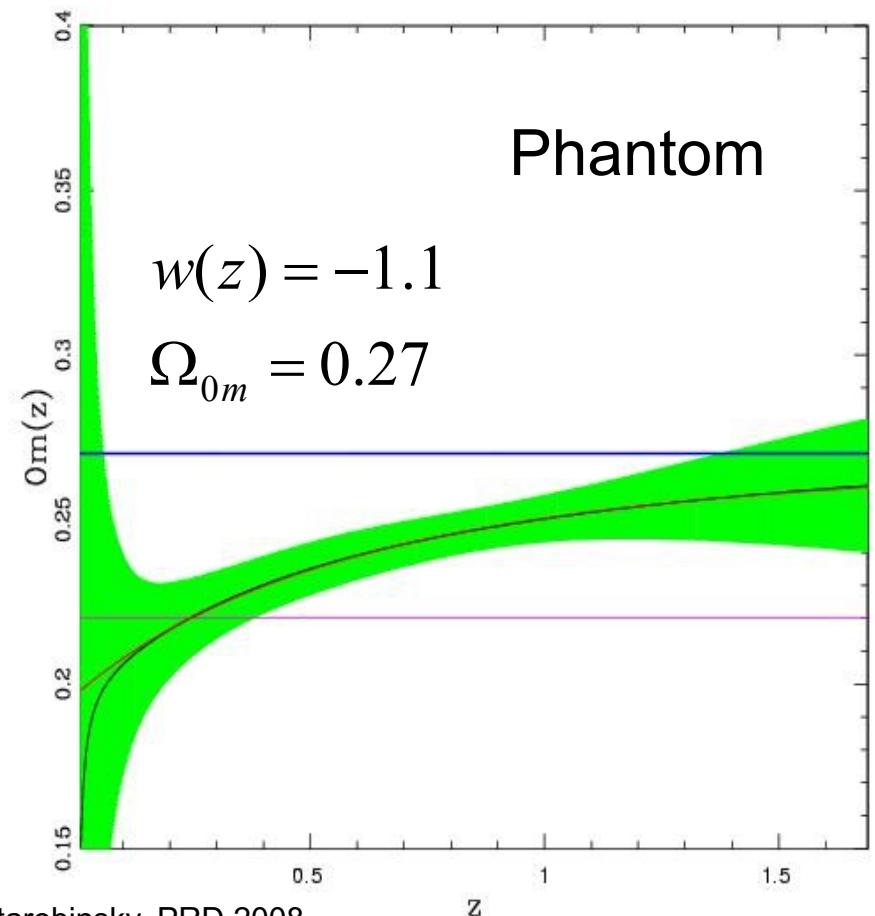
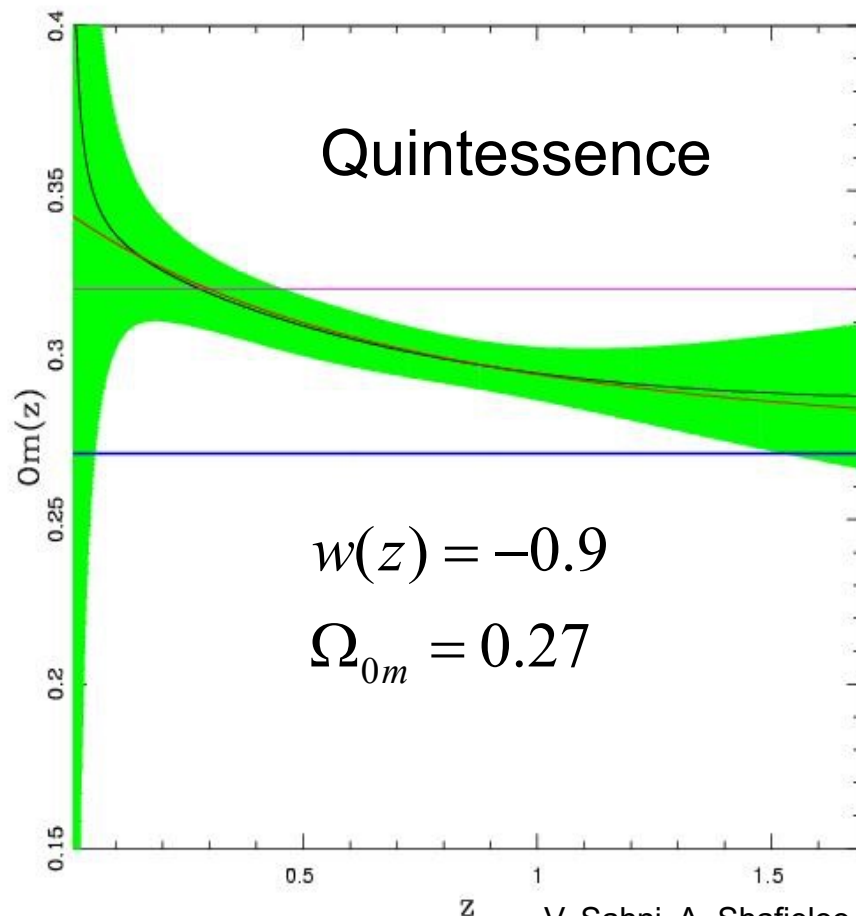
Phantom

Quintessence

Take home 3: Falsification is Important and probably the first step to kill a standard model

SNAP →
JDEM →
WFIRST →
Roman

Simulated results for 1000 realization of SNAP data, using Iterative Smoothing Method.



How about well motivated theoretical/phenomenological models?

Some models can fit the data better than some others and χ^2 values may look good. What if they are all wrong?

Importance of Model Validation

- Bayesian evidence approach is solid but only can find the better model among the candidates (or less wrong model/ranking models)
- When true model is unknown, finding a statistical anchor is not trivial. One can attempt using reliable non-parametric reconstructions

$\Delta \log Z > 3$	PEDE consistent	PEDE ruled-out
Λ CDM consistent	6	994
Λ CDM ruled-out	0	0
$\Delta \log Z > 5$	PEDE consistent	PEDE ruled-out
Λ CDM consistent	89	911
Λ CDM ruled-out	0	0

Conventional Bayesian
Evidence Approach

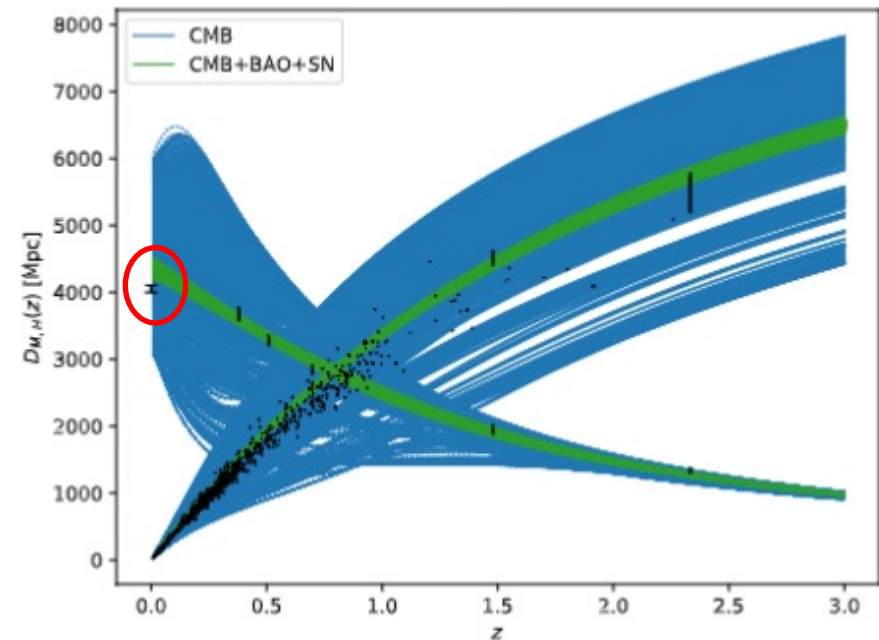
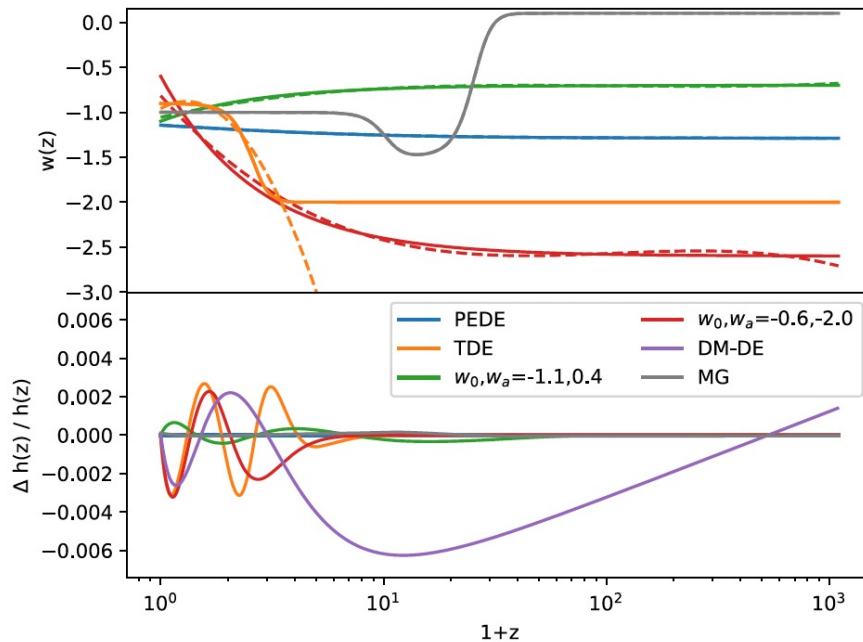
But both models are wrong.

95% CL	PEDE consistent	PEDE ruled-out
Λ CDM consistent	2	82
Λ CDM ruled-out	0	916
99% CL	PEDE consistent	PEDE ruled-out
Λ CDM consistent	14	193
Λ CDM ruled-out	0	793

Iterative smoothing
validation approach

Koo, Keeley, Shafieloo, L'Huillier, JCAP 2022
See also Amendola et al, PRD 2024

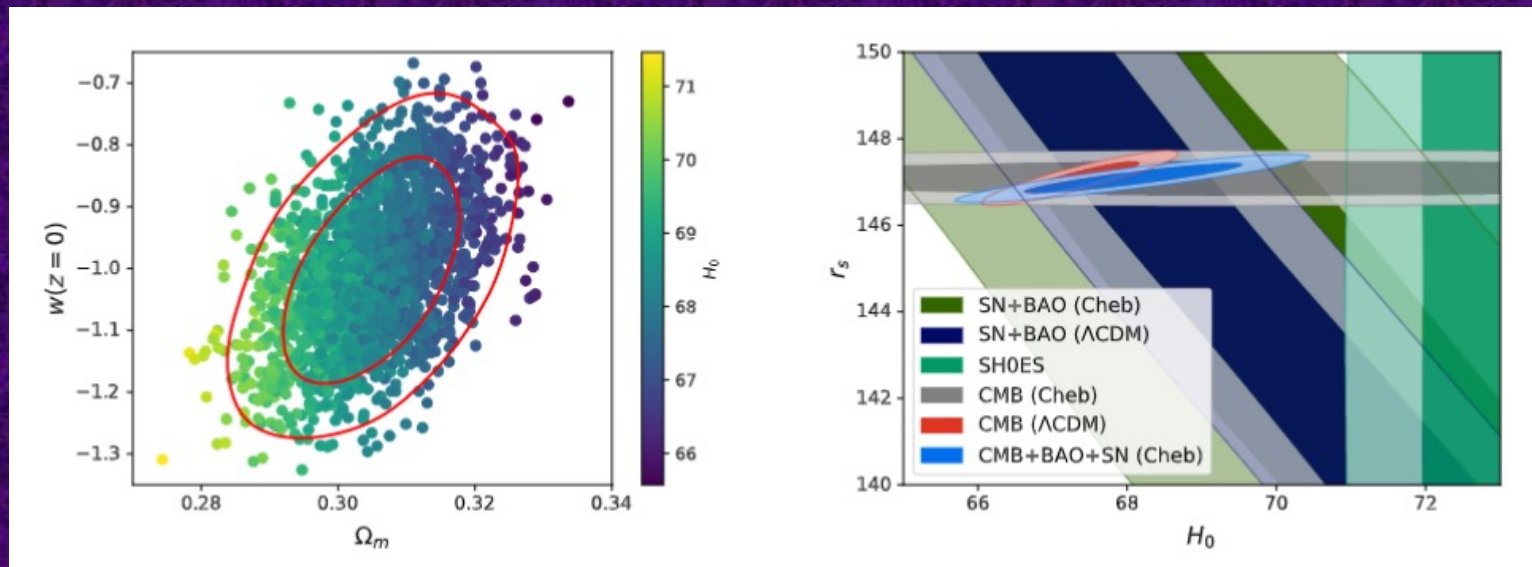
Ruling Out New Physics at Low Redshift as a solution to the H_0 Tension



Exploring an **extensive** physical space with Crossing functions for validation (Chebyshev polynomials)

Keeley and Shafieloo, Phys. Rev. Lett, 2023

Ruling Out New Physics at Low Redshift as a solution to the H_0 Tension



Exploring an **extensive** physical space with Crossing functions for validation (Chebyshev polynomials)

Keeley and Shafieloo, Phys. Rev. Lett, 2023
(**covered by Science**)

Take Home 4: Being better than Λ CDM doesn't make a model the actual model of the universe.

Non Parametric methods of Reconstruction

Usually involves binning and smoothing

$$F = \frac{L}{4\pi d_L^2}$$

$$d_L(z) = (1+z) \int_0^z \frac{dz'}{H(z')}$$

$$H(z) = \left[\frac{d}{dz} \left(\frac{d_L(z)}{1+z} \right) \right]^{-1}$$

$$\frac{H^2(z)}{H_0^2} = \left[\Omega_{0M} (1+z)^3 + (1 - \Omega_{0M}) \exp \left[\int 3(1+w(z)) \frac{dz}{1+z} \right] \right]$$

$$\omega_{DE} = \frac{\left(\frac{2(1+z)}{3} \frac{H'}{H} \right) - 1}{1 - \left(\frac{H_0}{H} \right)^2 \Omega_{0M} (1+z)^3}$$

Model-Independent Reconstruction (some of the works we have been doing)

Testing deviations from an assumed model (without comparing different models)

Gaussian Processes:

Modeling of the data around a mean function
searching for likely features by looking at the the
likelihood space of the hyperparameters.

Holsclaw et al, PRD 2011

Shafieloo, Kim, Linder, PRD 2012

:

Bayesian Interpretation of Crossing Statistic:

Comparing a model with its own possible
variations using a hyperfunction with orthogonal
basis.

Shafieloo, Clifton, Ferreira, JCAP 2010

Shafieloo, JCAP 2012a, JCAP 2012b

Gaussian Process

- Efficient in statistical modeling of stochastic variables
- Derivatives of Gaussian Processes are Gaussian Processes
- Provides us with all covariance matrices

Shafieloo, Kim & Linder, PRD 2012
Shafieloo, Kim & Linder, PRD 2013

Data

Mean Function

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix} \sim \mathcal{N} \left(\begin{bmatrix} \mathbf{m}(\mathbf{Z}) \\ \mathbf{m}(\mathbf{Z}_1) \\ \mathbf{m}'(\mathbf{Z}_1) \\ \mathbf{m}''(\mathbf{Z}_1) \end{bmatrix}, \begin{bmatrix} \Sigma_{00}(\mathbf{Z}, \mathbf{Z}) & \Sigma_{00}(\mathbf{Z}, \mathbf{Z}_1) & \Sigma_{01}(\mathbf{Z}, \mathbf{Z}_1) & \Sigma_{02}(\mathbf{Z}, \mathbf{Z}_1) \\ \Sigma_{00}(\mathbf{Z}_1, \mathbf{Z}) & \Sigma_{00}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{01}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{02}(\mathbf{Z}_1, \mathbf{Z}_1) \\ \Sigma_{10}(\mathbf{Z}_1, \mathbf{Z}) & \Sigma_{10}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{11}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{12}(\mathbf{Z}_1, \mathbf{Z}_1) \\ \Sigma_{20}(\mathbf{Z}_1, \mathbf{Z}) & \Sigma_{20}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{21}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{22}(\mathbf{Z}_1, \mathbf{Z}_1) \end{bmatrix} \right),$$

$$\Sigma_{\alpha\beta} = \frac{d^{(\alpha+\beta)} K}{dz_i^\alpha dz_j^\beta},$$

$$\begin{bmatrix} \bar{\mathbf{f}} \\ \bar{\mathbf{f}}' \\ \bar{\mathbf{f}}'' \end{bmatrix} = \begin{bmatrix} \mathbf{m}(\mathbf{Z}_1) \\ \mathbf{m}'(\mathbf{Z}_1) \\ \mathbf{m}''(\mathbf{Z}_1) \end{bmatrix} + \begin{bmatrix} \Sigma_{00}(\mathbf{Z}_1, \mathbf{Z}) \\ \Sigma_{10}(\mathbf{Z}_1, \mathbf{Z}) \\ \Sigma_{20}(\mathbf{Z}_1, \mathbf{Z}) \end{bmatrix} \Sigma_{00}^{-1}(\mathbf{Z}, \mathbf{Z}) \mathbf{y}$$

Kernel

$$k(z, z') = \sigma_f^2 \exp \left(-\frac{|z - z'|^2}{2l^2} \right),$$

GP Hyper-parameters

$$\text{Cov} \left(\begin{bmatrix} \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix} \right) = \begin{bmatrix} \Sigma_{00}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{01}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{02}(\mathbf{Z}_1, \mathbf{Z}_1) \\ \Sigma_{10}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{11}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{12}(\mathbf{Z}_1, \mathbf{Z}_1) \\ \Sigma_{20}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{21}(\mathbf{Z}_1, \mathbf{Z}_1) & \Sigma_{22}(\mathbf{Z}_1, \mathbf{Z}_1) \end{bmatrix} - \begin{bmatrix} \Sigma_{00}(\mathbf{Z}_1, \mathbf{Z}) \\ \Sigma_{10}(\mathbf{Z}_1, \mathbf{Z}) \\ \Sigma_{20}(\mathbf{Z}_1, \mathbf{Z}) \end{bmatrix} \Sigma_{00}^{-1}(\mathbf{Z}, \mathbf{Z}) [\Sigma_{00}(\mathbf{Z}, \mathbf{Z}_1), \Sigma_{01}(\mathbf{Z}, \mathbf{Z}_1), \Sigma_{02}(\mathbf{Z}, \mathbf{Z}_1)].$$

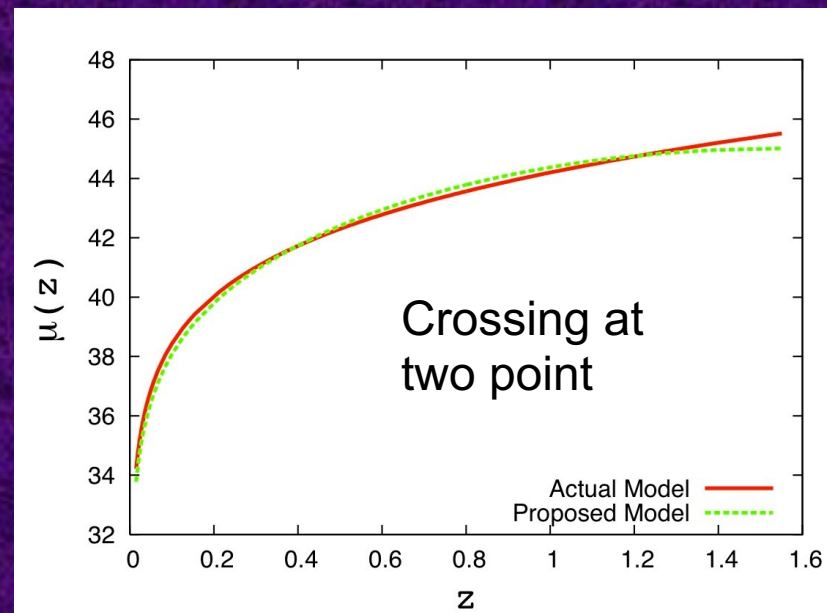
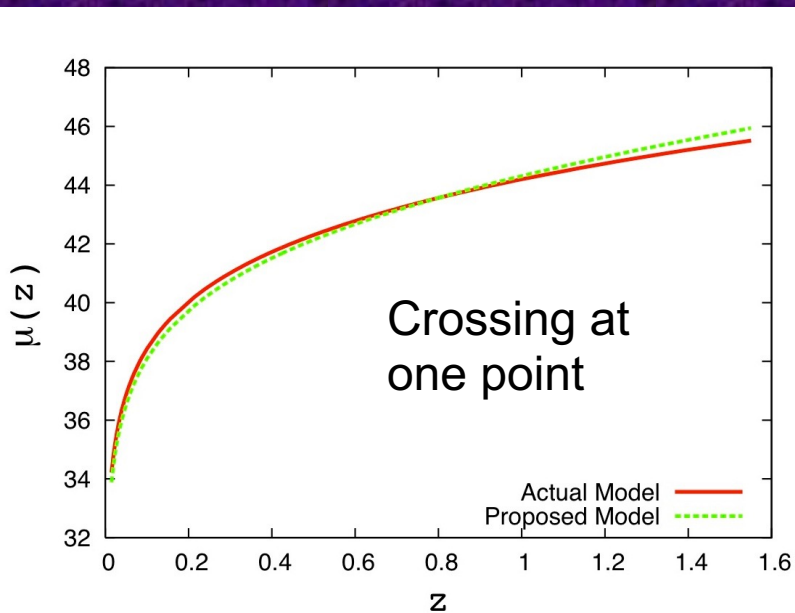
$$2 \ln p(\mathbf{y}|\mathbf{f}) = -\mathbf{y}^T \Sigma_{00}(\mathbf{Z}, \mathbf{Z})^{-1} \mathbf{y} - \ln \det \Sigma_{00}(\mathbf{Z}, \mathbf{Z}) - n \ln(2\pi),$$

GP Likelihood

Crossing Statistic

If a proposed model is different than the actual model, then they cross each other at none, one or two or three or ... N points.

A. Shafieloo, T. Clifton & P. Ferreira, JCAP 2010.



Important Features:

For N data points, **the last mode of Crossing Statistic** is $T(N-1)$ which **is identical to Chi Square Statistic**

$$T_{N-1} = \sum_i^N (q_i)^2 = \chi^2$$

The **zero mode** of Crossing Statistic is similar to **Median Statistic**

not only should the whole sample of residuals have a Gaussian distribution around the mean, but so should any continuous subsample.

$$T_0 = \left(\sum_i^N q_i \right)^2$$

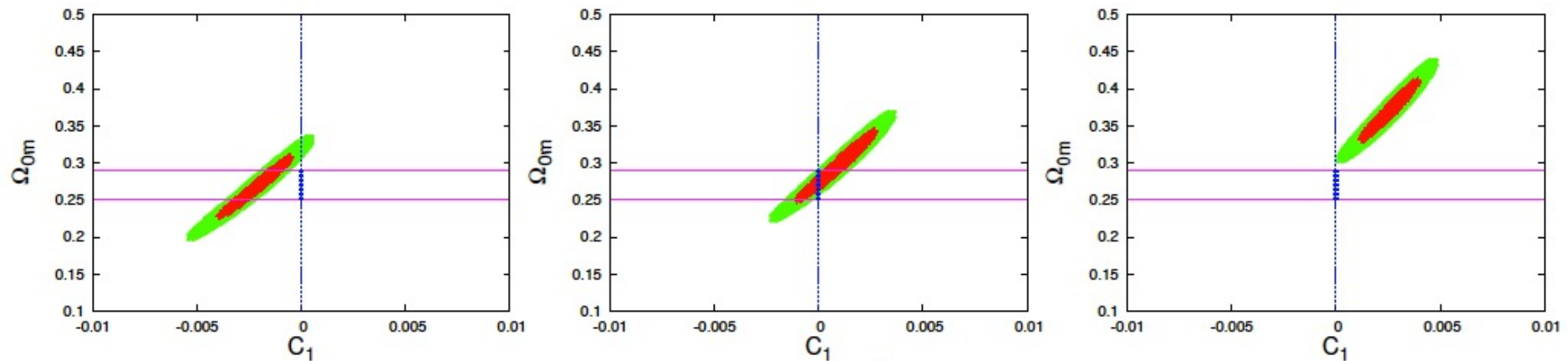
Extracting More Information

Crossing Statistic (Bayesian Interpretation)

Test model = Theoretical model $\times$ Crossing function

Is Crossing function consistent with 1 in the whole functional range?

Comparing a model with its own variations



$$T_I(C_1, z) = 1 + C_1 \left(\frac{z}{z_{max}} \right)$$

Chebyshev Polynomials
as Crossing Functions

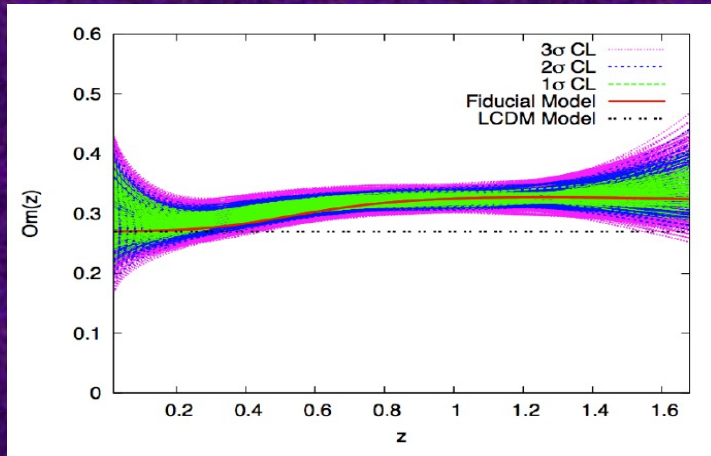
$$T_{II}(C_1, C_2, z) = 1 + C_1 \left(\frac{z}{z_{max}} \right) + C_2 \left[2 \left(\frac{z}{z_{max}} \right)^2 - 1 \right],$$

Shafieloo, JCAP 2012 (a)

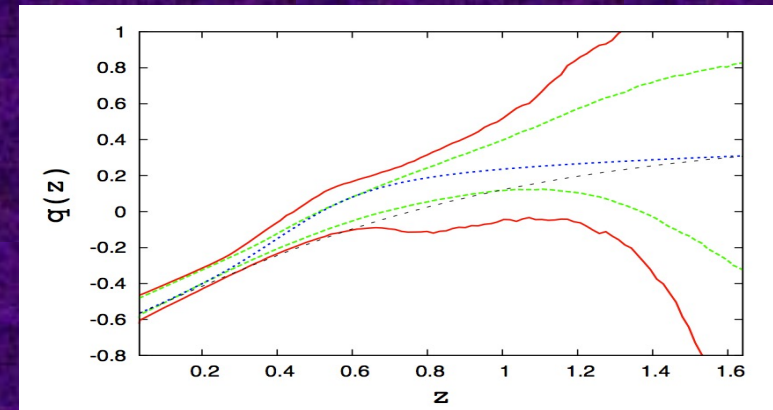
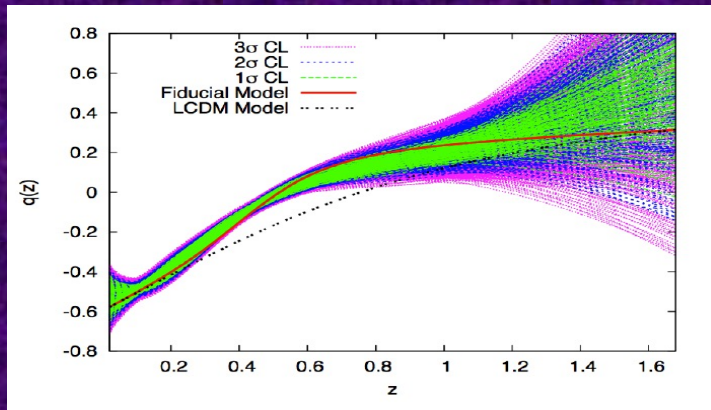
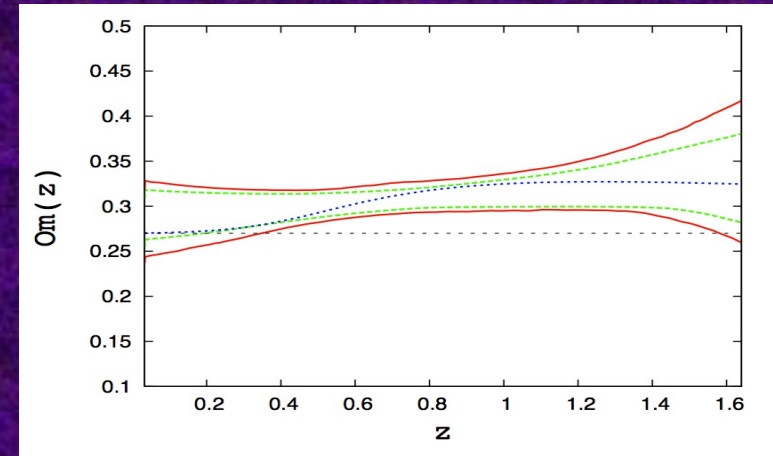
Shafieloo, JCAP 2012 (b)

Model independent reconstruction of the expansion history

Crossing Statistic + Smoothing



Gaussian Processes

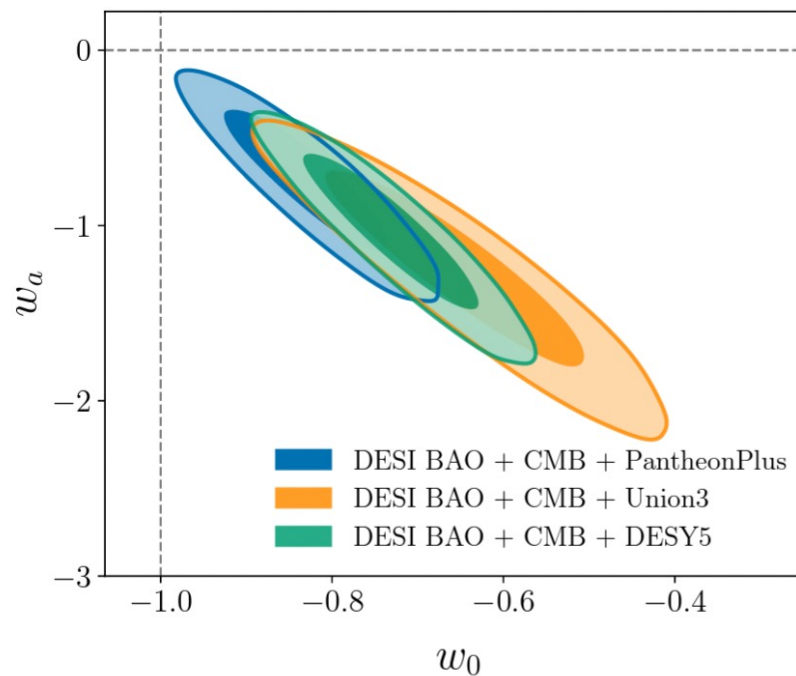
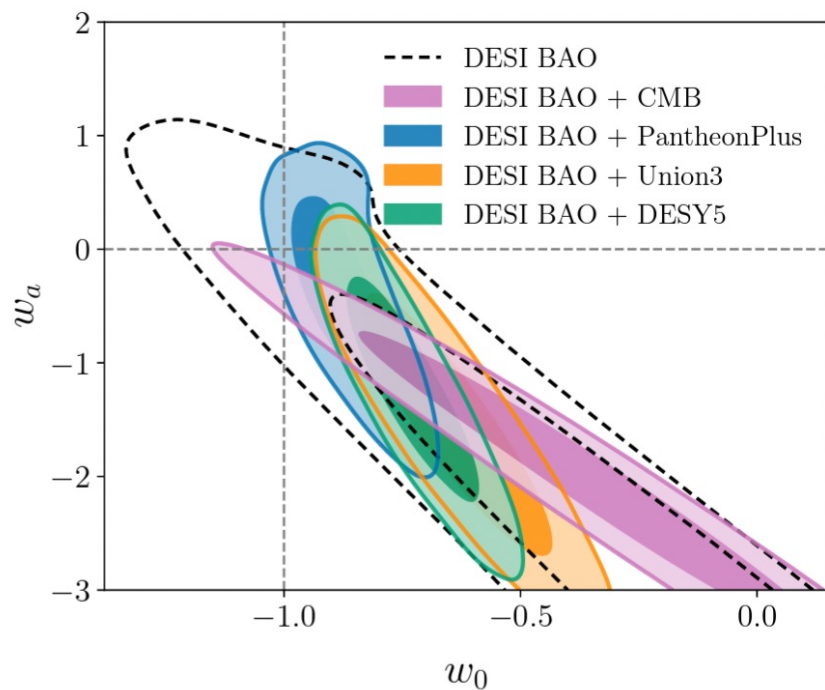


Shafieloo, JCAP (b) 2012

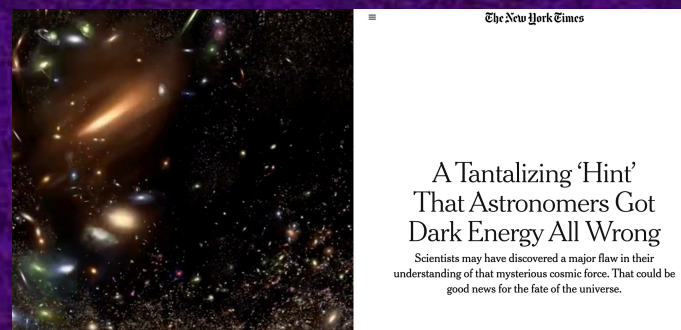
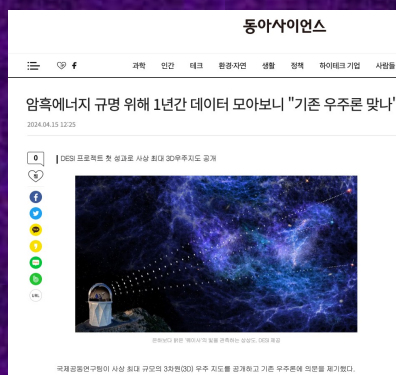
Shafieloo, Kim & Linder, PRD 2012

Take Home 5: Non-parametric reconstruction of dark energy is crucial for detecting features in the data beyond the flexibility of specific models.

DESI-2024



DESI-Y1 (2024),
arXiv:2404.03002

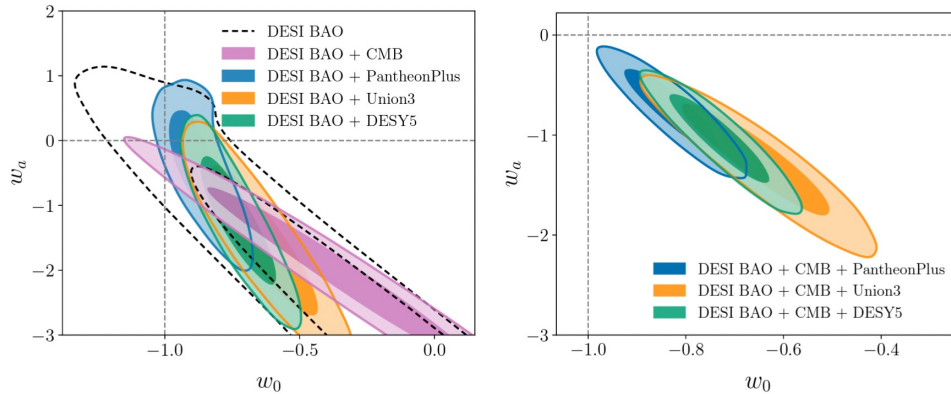


DESI-2024



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science



Dark energy reconstruction
and physics interpretation

KASI Led DESI Projects:



Rodrigo Calderon



Kushal Lodha

DESI-Y1 (2024), arXiv:2404.03002

arXiv > astro-ph > arXiv:2405.04216

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 7 May 2024]

DESI 2024: Reconstructing Dark Energy using Crossing Statistics with DESI DR1 BAO data

R. Calderon, K. Lodha, A. Shafieloo, E. Linder, W. Sohn, A. de Mattia, J. L. Cervantes-Cota, R. Crittenden, T. M. Davis, M. Ishak, A. G. Kim, W. Matthewson, G. Niz, S. Park, J. Aguilar, S. Ahlen, S. Allen, D. Brooks, T. Claybaugh, A. de la Macorra, A. Dey, B. Dey, P. Doel, J. E. Forero-Romero, E. Gaztañaga, S. Gontcho A Gontcho, K. Honscheid, C. Howlett, S. Juneau, A. Kremin, M. Landriau, L. Le Guillou, M. E. Levi, M. Manera, R. Miquel, J. Moustakas, J. A. Newman, N. Palanque-Delabrouille, W. J. Percival, C. Poppett, F. Prada, M. Rezaie, G. Rossi, V. Ruhlmann-Kleider, E. Sanchez, D. Schlegel, M. Schubnell, H. Seo, D. Sprayberry, G. Tarlé, P. Taylor, M. Vargas-Magaña, B. A. Weaver, P. Zarrouk, H. Zou

We implement Crossing Statistics to reconstruct in a model-agnostic manner the expansion history of the universe and properties of dark energy, using DESI Data Release 1 (DR1) BAO data in combination with one of three different supernova compilations (PantheonPlus, Union3, and DES-SNSR) and Planck CMB observations. Our results hint towards an evolving and emergent dark energy behaviour, with negligible presence of dark energy at $z \gtrsim 1$, at varying significance depending on data sets combined. In all these reconstructions, the cosmological constant lies outside the 95% confidence intervals for some redshift ranges. This dark energy behaviour, reconstructed using Crossing Statistics, is in agreement with results from the conventional $w_0 - w_a$ dark energy equation of state parametrization reported in the DESI Key cosmology paper. Our results add an extensive class of model-agnostic reconstructions with acceptable fits to the data, including models where cosmic acceleration slows down at low redshifts. We also report constraints on $\{Hord\}$ from our model-agnostic analysis, independent of the pre-recombination physics.

Comments: 24 pages, 10 figures

Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO)

Cite as: arXiv:2405.04216 [astro-ph.CO]

(or arXiv:2405.04216v1 [astro-ph.CO] for this version)

<https://doi.org/10.48550/arXiv.2405.04216>

arXiv > astro-ph > arXiv:2405.13588

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 22 May 2024 (v1), last revised 30 May 2024 (this version, v2)]

DESI 2024: Constraints on Physics-Focused Aspects of Dark Energy using DESI DR1 BAO Data

K. Lodha, A. Shafieloo, R. Calderon, E. Linder, W. Sohn, J. L. Cervantes-Cota, A. de Mattia, J. García-Bellido, M. Ishak, W. Matthewson, J. Aguilar, S. Ahlen, D. Brooks, T. Claybaugh, A. de la Macorra, A. Dey, B. Dey, P. Doel, J. E. Forero-Romero, E. Gaztañaga, S. Gontcho A Gontcho, C. Howlett, S. Juneau, S. Kent, T. Kisner, A. Kremin, A. Lambert, M. Landriau, L. Le Guillou, P. Martini, A. Meisner, R. Miquel, J. Moustakas, J. A. Newman, G. Niz, N. Palanque-Delabrouille, W. J. Percival, C. Poppett, F. Prada, G. Rossi, V. Ruhlmann-Kleider, E. Sanchez, E. F. Schlafly, D. Schlegel, M. Schubnell, H. Seo, D. Sprayberry, G. Tarlé, B. A. Weaver, H. Zou

Baryon acoustic oscillation data from the first year of the Dark Energy Spectroscopic Instrument (DESI) provide near percent-level precision of cosmic distances in seven bins over the redshift range $z = 0.1 - 4.2$. We use this data, together with other distance probes, to constrain the cosmic expansion history using some well-motivated physical classes of dark energy. In particular, we explore three physics-focused behaviors of dark energy from the equation of state and energy density perspectives: the thawing class (matching many simple quintessence potentials), emergent class (where dark energy comes into being recently, as in phase transition models), and mirage class (where phenomenologically the distance to CMB last scattering is close to that from a cosmological constant Λ despite dark energy dynamics). All three classes fit the data at least as well as Λ CDM, and indeed can improve on it by $\Delta\chi^2 \approx -5$ to -17 for the combination of DESI BAO with CMB and supernova data, while having one more parameter. The mirage class does essentially as well as w_0w_a CDM while having one less parameter. These classes of dynamical behaviors highlight worthwhile avenues for further exploration into the nature of dark energy.

Comments: 20 pages, 8 figures. Metadata updated, comments welcome

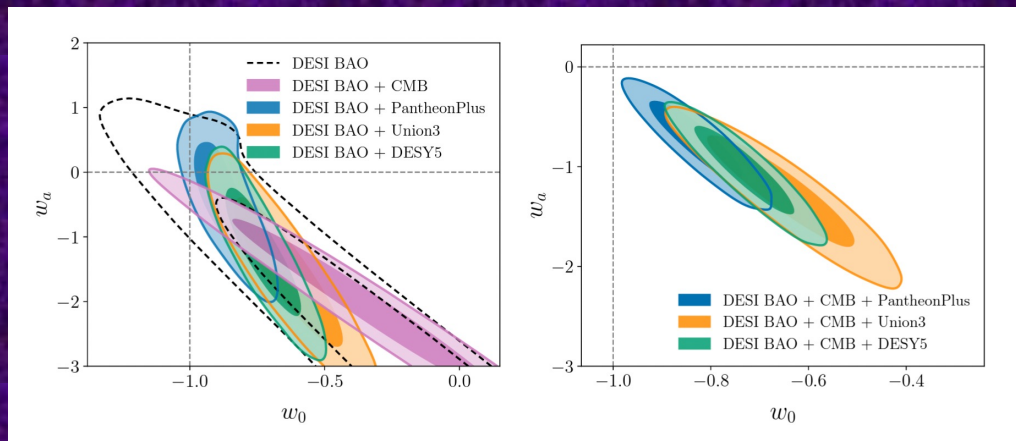
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO)

Cite as: arXiv:2405.13588 [astro-ph.CO]

(or arXiv:2405.13588v2 [astro-ph.CO] for this version)

<https://doi.org/10.48550/arXiv.2405.13588>

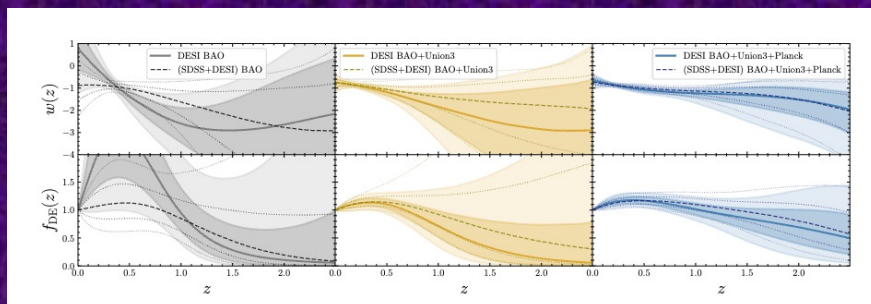
DESI-2024



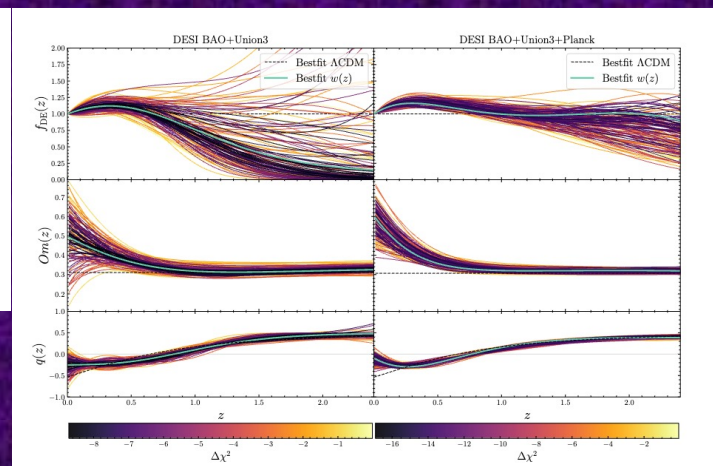
Model-Independent Reconstruction of Dark energy

(Blind Tests Conducted)

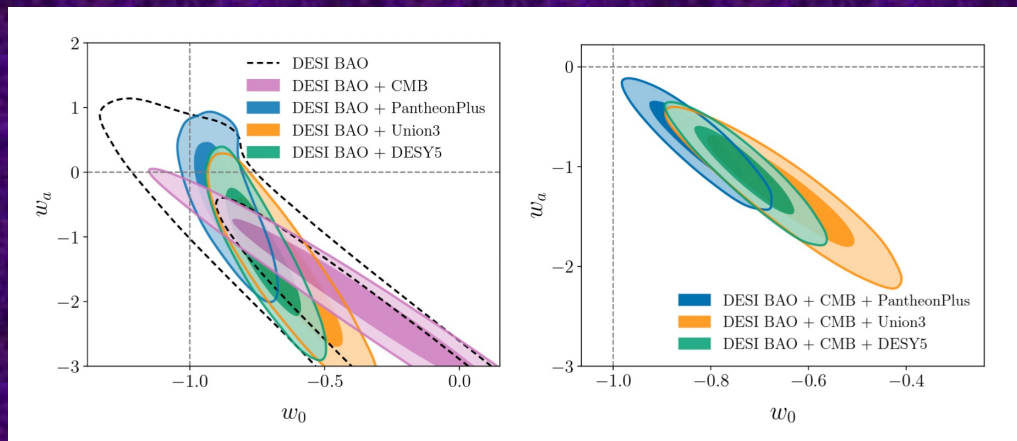
DESI-Y1 (2024),
arXiv:2404.03002



Reconstructing DE with Crossing Statistics
Calderon, Lodha, Shafieloo, Linder et al, JCAP 2024
(arXiv:2405.04216)



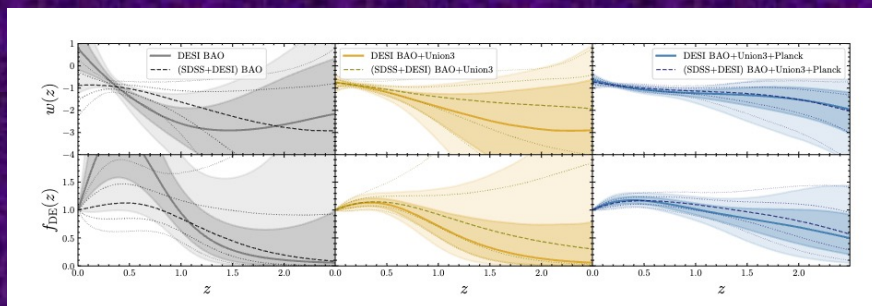
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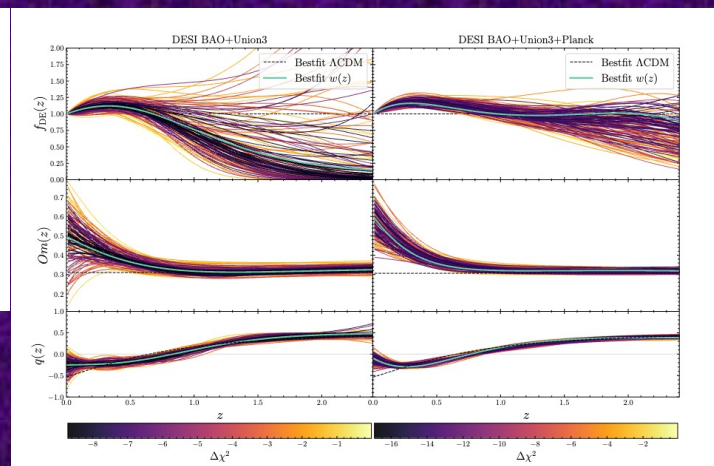
DESI-Y1 (2024),
arXiv:2404.03002

Model-Independent Reconstruction of Dark energy

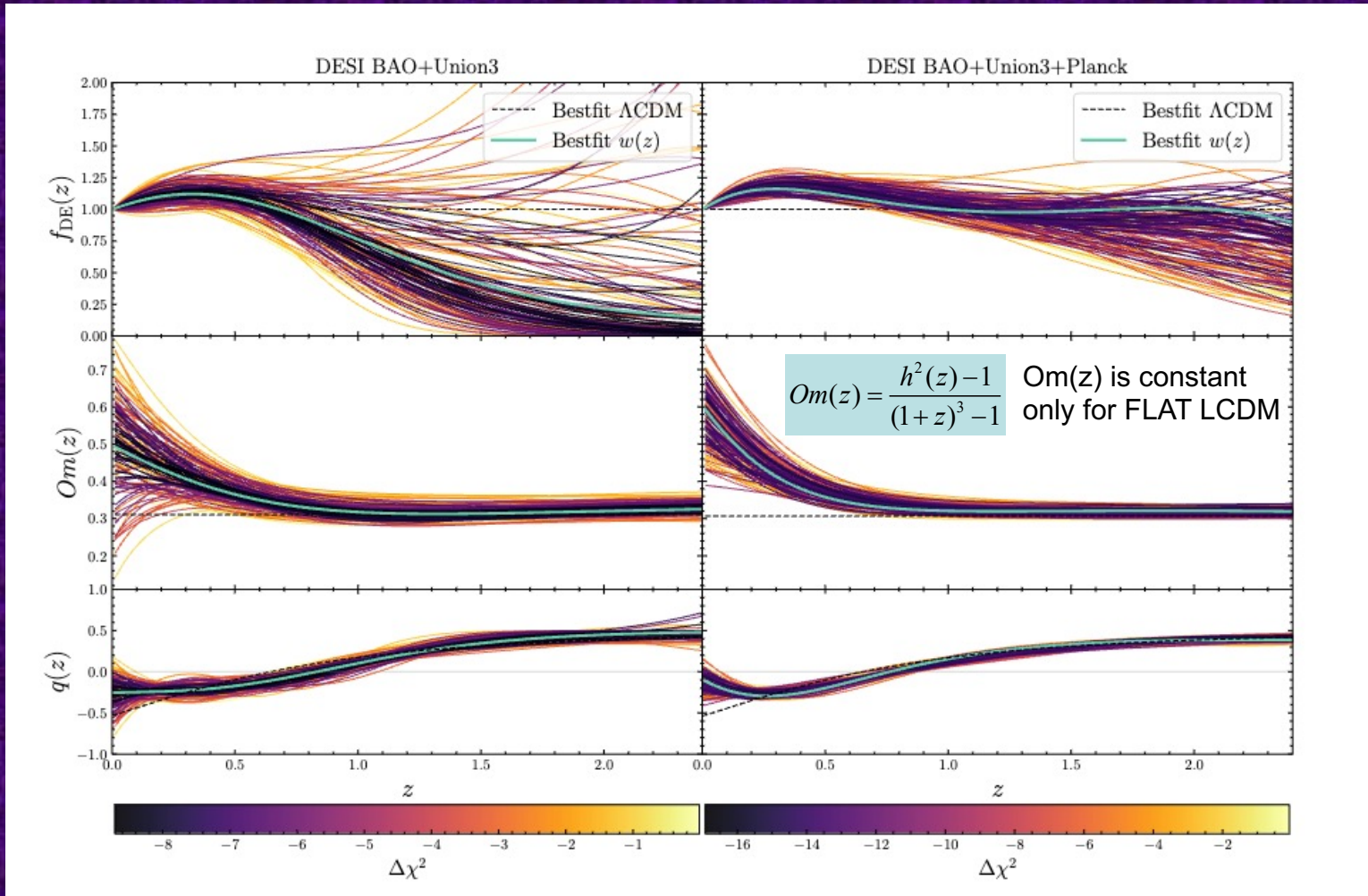
*Take Home 6: Importance of
pipeline validation and blind
analysis.*



Reconstructing DE with Crossing Statistics
Calderon, Lodha, Shafieloo, Linder et al, JCAP 2024
(arXiv:2405.04216)



DESI 2024: Reconstructing Dark Energy using Crossing Statistics with DESI DR1 BAO data

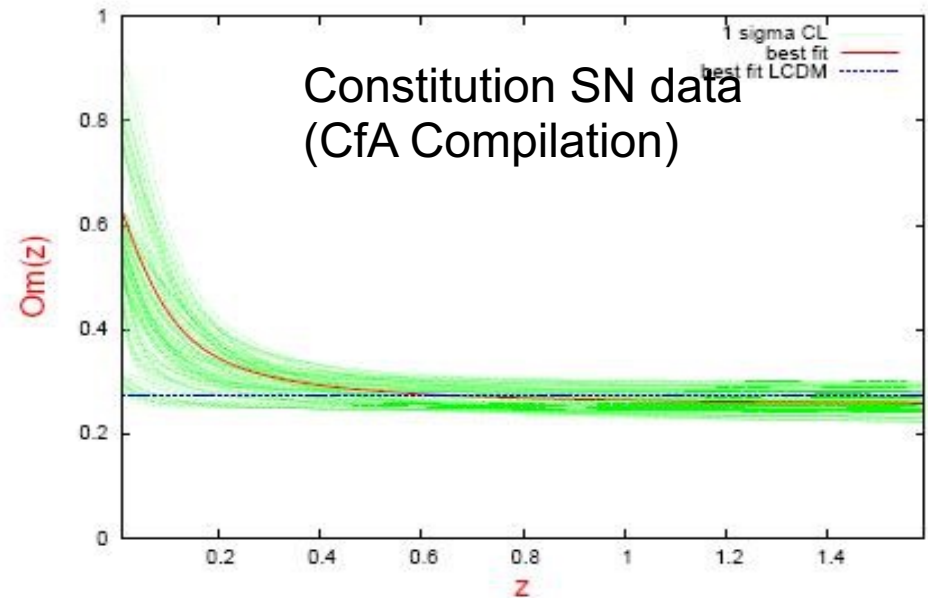
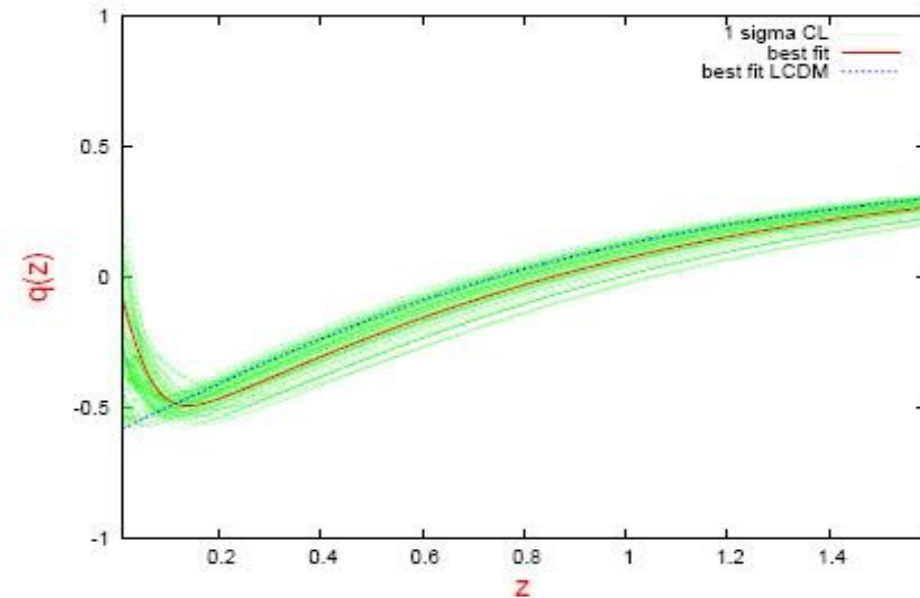


All
better
than
best fit
LCDM

Theoretical application of direct reconstruction

(2009)

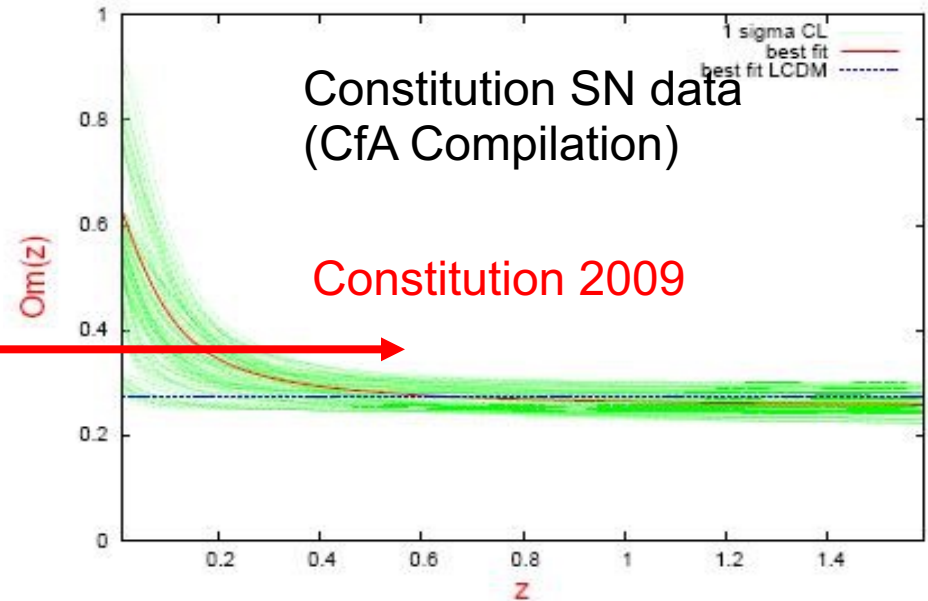
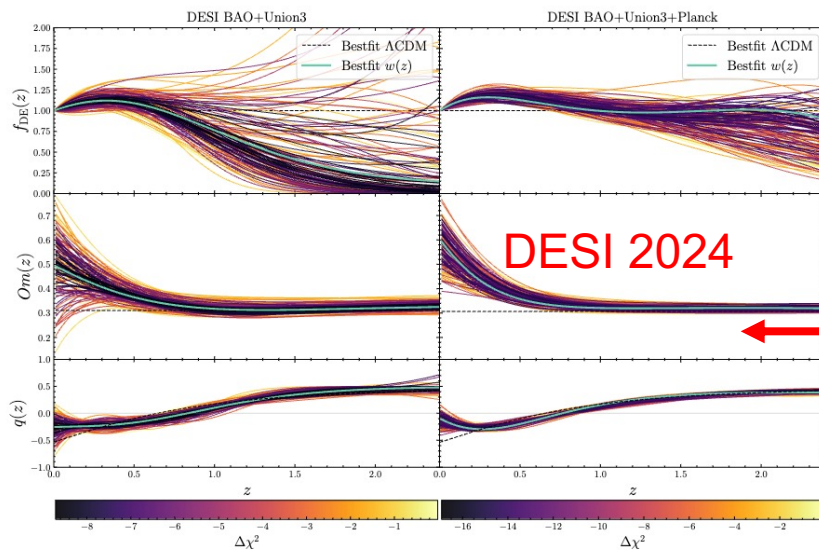
IS COSMIC ACCELERATION SLOWING DOWN?



$$w(z) = -\frac{1 + \tanh\left[\left(z - z_t\right)\Delta\right]}{2}$$

$$\Delta\chi^2 = -0.6 \text{ with respect to CPL}$$

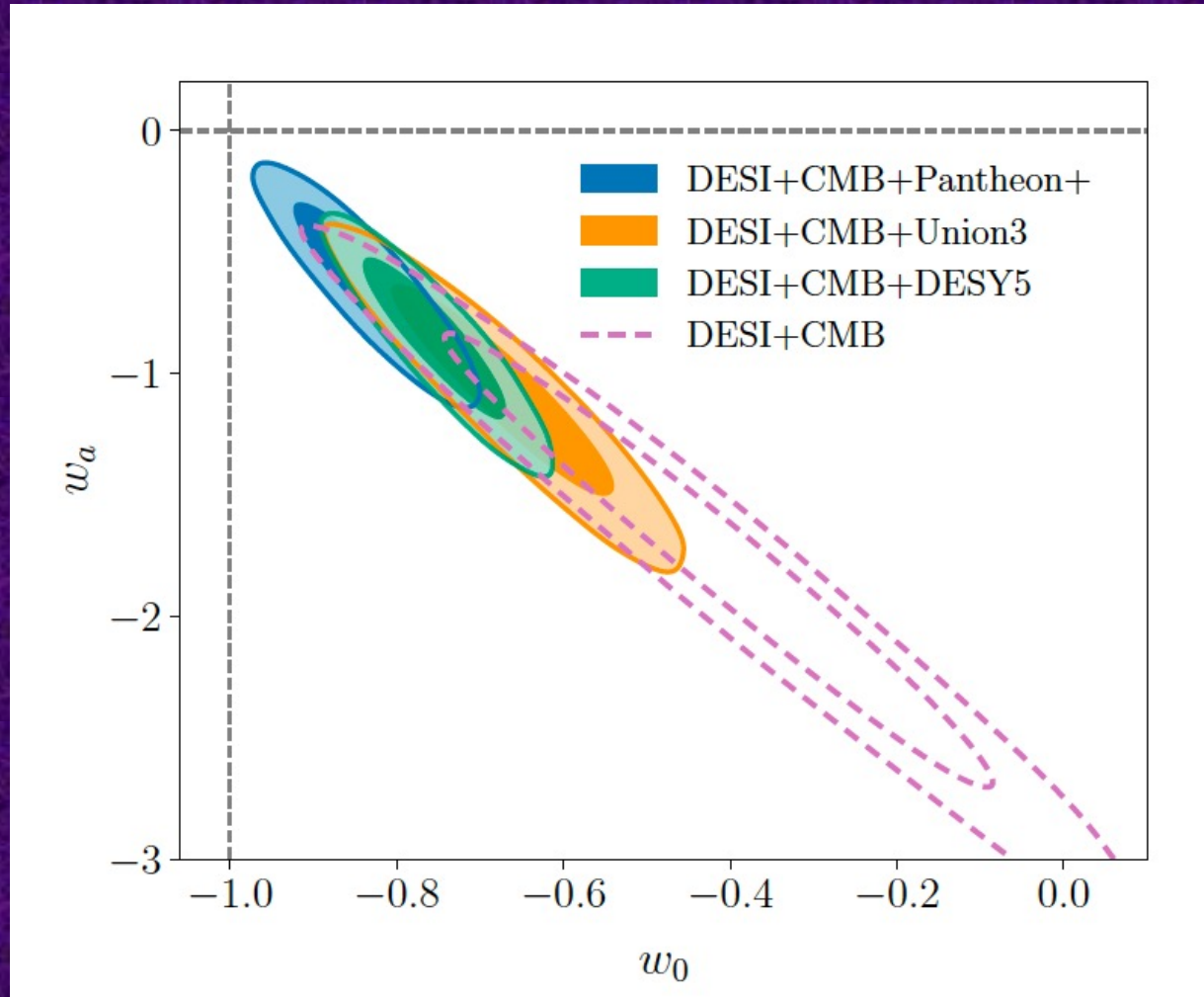
IS COSMIC ACCELERATION SLOWING DOWN Again?



$$w(z) = -\frac{1 + \tanh\left[\left(z - z_t\right)\Delta\right]}{2}$$

$$\Delta\chi^2 = -0.6 \text{ with respect to CPL}$$

DESI-2025 DR2



DESI-2025 DR2

DESI Supporting DE Paper



arXiv > astro-ph > arXiv:2503.14743

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 18 Mar 2025 (v1), last revised 3 Apr 2025 (this version, v2)]

Extended Dark Energy analysis using DESI DR2 BAO measurements

K. Lodha, R. Calderon, W. L. Matthewson, A. Shafieloo, M. Ishak, J. Pan, C. García-Quintero, D. Huterer, G. Valogiannis, L. A. Ureña-López, N. V. Kamble, D. Parkinson, A. G. Kim, G. B. Zhao, J. L. Cervantes-Cota, J. Rohlf, F. Lozano-Rodríguez, J. O. Román-Herrera, M. Abdul-Karim, J. Aguilar, S. Ahlen, O. Alves, U. Andrade, E. Armengaud, A. Aviles, S. BenZvi, D. Bianchi, A. Brodzeller, D. Brooks, E. Burtin, R. Canning, A. Carnero Rosell, L. Casas, F. J. Castander, M. Charles, E. Chaussidon, J. Chaves-Montero, D. Chebat, T. Claybaugh, S. Cole, A. Cuceu, K. S. Dawson, A. de la Macorra, A. de Mattia, N. Deiosso, R. Demina, Arjun Dey, Biprateep Dey, Z. Ding, P. Doel, D. J. Eisenstein, W. Elbers, S. Ferraro, A. Font-Ribera, J. E. Forero-Romero, Lehman H. Garrison, E. Gaztañaga, H. Gil-Marín, S. Gontcho A Gontcho, A. X. Gonzalez-Morales, G. Gutierrez, J. Guy, C. Hahn, M. Herbold, H. K. Herrera-Alcantar, K. Honscheid, C. Howlett, S. Juneau, R. Kehoe, D. Kirkby, T. Kisner, A. Kremin, O. Lahav, C. Lamman, M. Landriau, L. Le Guillou, A. Leauthaud, M. E. Levi, Q. Li, C. Magneville, M. Manera, P. Martini, A. Meisner, J. Mena-Fernández, R. Miquel, J. Moustakas, D. Muñoz Santos, A. Muñoz-Gutiérrez, A. D. Myers, S. Nadathur, G. Niz, H. E. Noriega, E. Paillas, N. Palanque-Delabrouille, W. J. Percival, Matthew M. Pieri, C. Poppett, F. Prada, A. Pérez-Fernández, I. Pérez-Ràfols, C. Ramírez-Pérez, M. Rashkovetskiy, C. Ravoux, A. J. Ross, G. Rossi, V. Ruhlmann-Kleider, L. Samushia, E. Sanchez, D. Schlegel, M. Schubnell, H. Seo, F. Sinigaglia, D. Sprayberry, T. Tan, G. Tarlé, P. Taylor, W. Turner, M. Vargas-Magaña, M. Walther, B. A. Weaver, M. Wolfson, C. Yèche, P. Zarrouk, R. Zhou, H. Zou (for the DESI Collaboration) (collapse list)

We conduct an extended analysis of dark energy constraints, in support of the findings of the DESI DR2 cosmology key paper, including DESI data, Planck CMB observations, and three different supernova compilations. Using a broad range of parametric and non-parametric methods, we explore the dark energy phenomenology and find consistent trends across all approaches, in good agreement with the w_0w_a CDM key paper results. Even with the additional flexibility introduced by non-parametric approaches, such as binning and Gaussian Processes, we find that extending Λ CDM to include a two-parameter $w(z)$ is sufficient to capture the trends present in the data. Finally, we examine three dark energy classes with distinct dynamics, including quintessence scenarios satisfying $w \geq -1$, to explore what underlying physics can explain such deviations. The current data indicate a clear preference for models that feature a phantom crossing; although alternatives lacking this feature are disfavored, they cannot yet be ruled out. Our analysis confirms that the evidence for dynamical dark energy, particularly at low redshift ($z \lesssim 0.3$), is robust and stable under different modeling choices.

Comments: 27 pages, 18 figures. This DESI Collaboration Publication is part of the Data Release 2 publication series (see [this https URL](https://arxiv.org/abs/2503.14743))

Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO)

Cite as: arXiv:2503.14743 [astro-ph.CO]

(or arXiv:2503.14743v2 [astro-ph.CO] for this version)

<https://doi.org/10.48550/arXiv.2503.14743>

Submission history

From: Kushal Lodha [[view email](mailto:kushal@desi.lbl.gov)]

[v1] Tue, 18 Mar 2025 21:14:17 UTC (5,193 KB)

[v2] Thu, 3 Apr 2025 13:50:59 UTC (5,195 KB)

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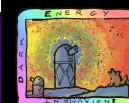
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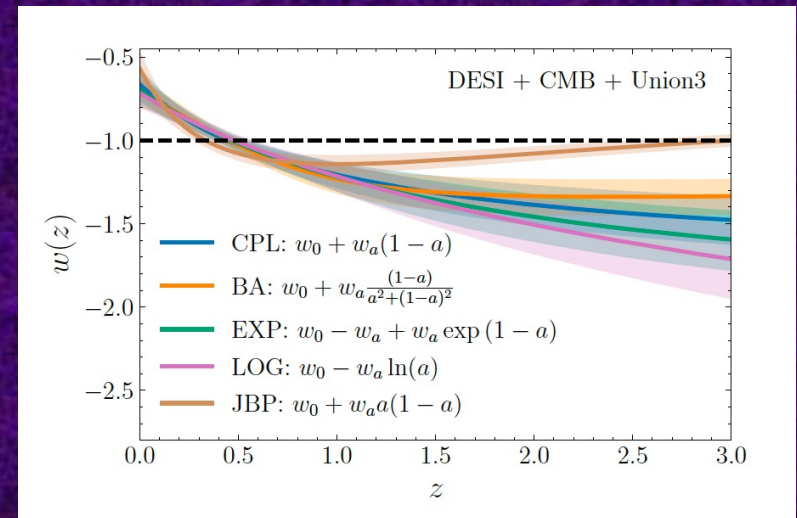
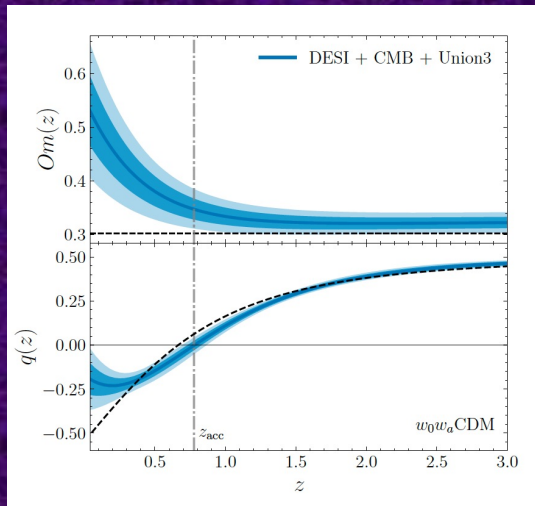
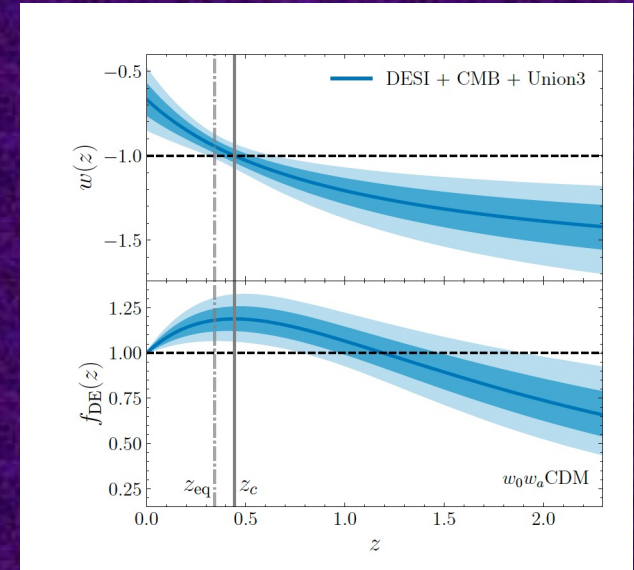
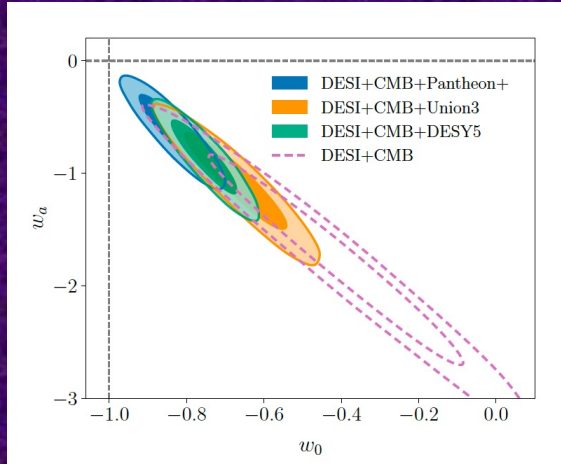
Extended Dark Energy Analysis, Lodha et al, arXiv:2503.14743 (PRD 2025)



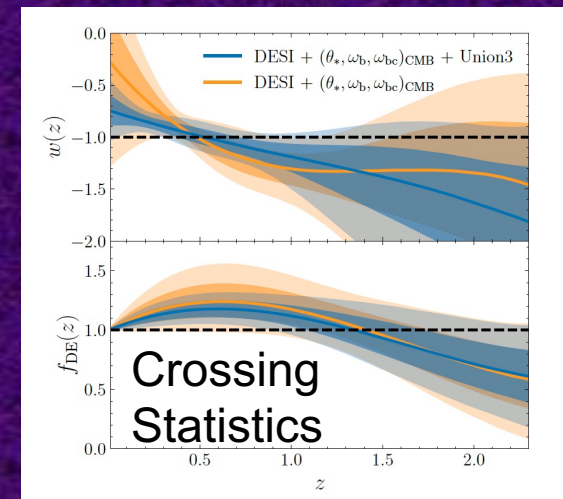
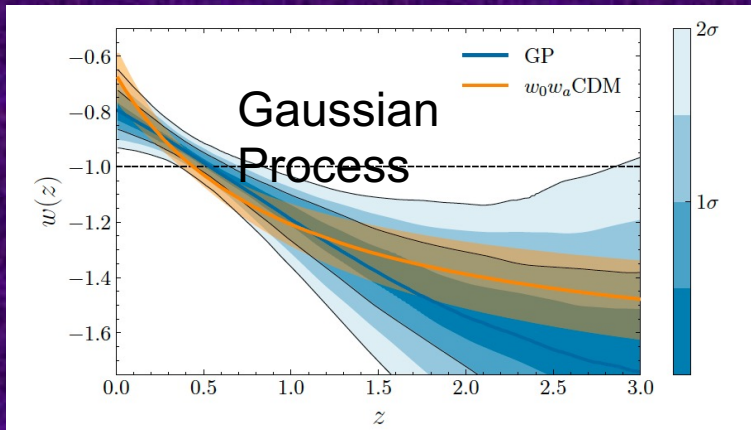
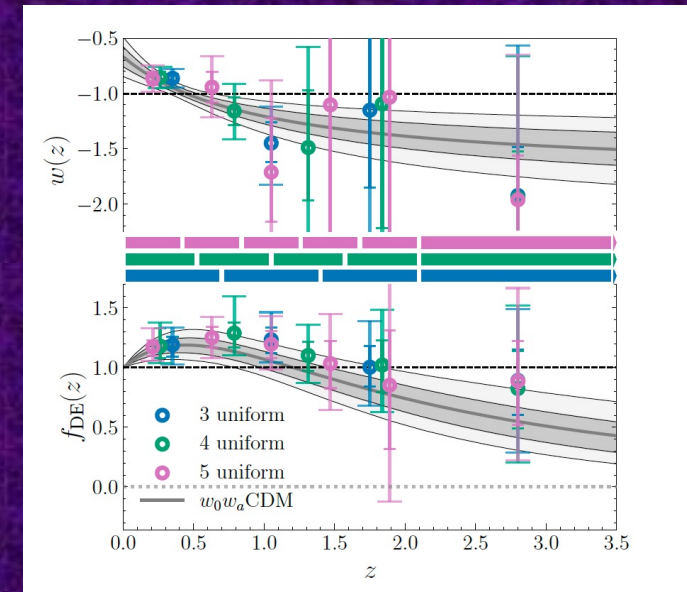
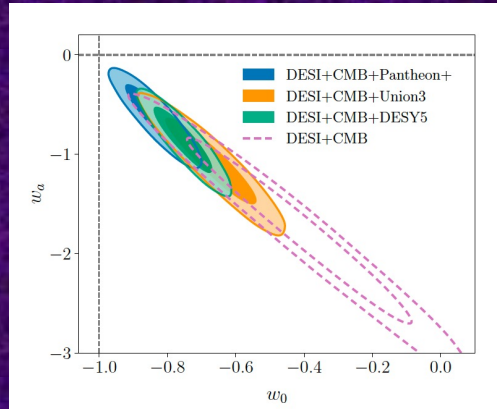
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DESI-2025 DR2



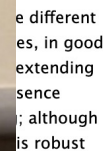
DESI-DR2 Extended DE Analysis: Non-Parametric



Extended Dark Energy Analysis, Lodha et al, (arXiv:2503.14743) PRD 2025
See also: Gu et al, (arXiv:2504.06118) Nature Astronomy 2025

A young man with brown hair tied back, wearing a dark green zip-up jacket with yellow trim and a small logo, looks up at a large, craggy rock formation under a bright sky. The jacket has the word "Kali" visible on the chest.

Ext

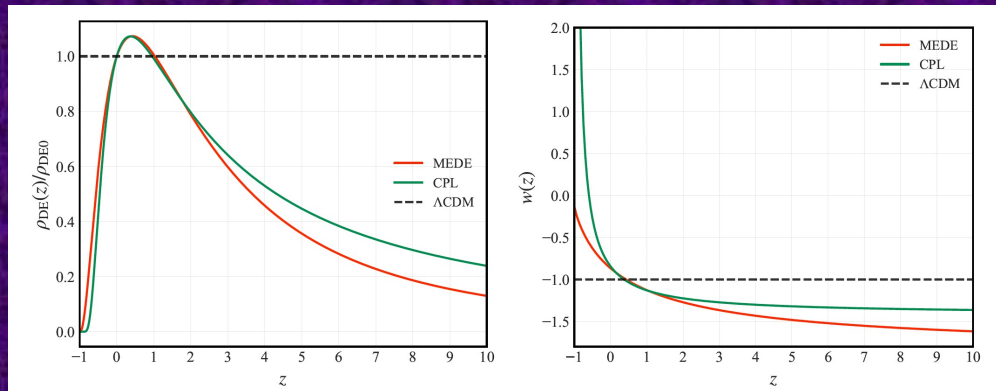


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Phenomenological/Theoretical Implications

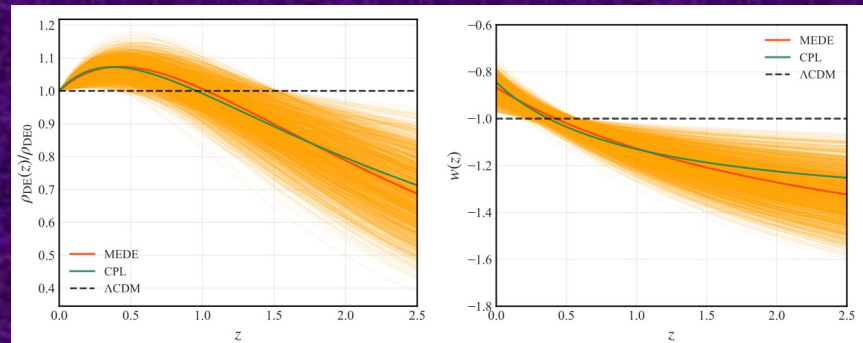
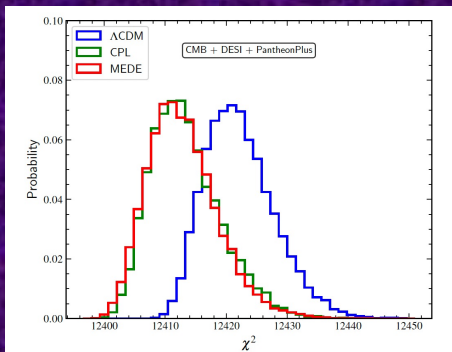


$$\rho_{\text{de}}(z) = \rho_{\text{de},0} \left[\frac{\cosh\left(\log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{\cosh\left(\log_{10}\left(\frac{1}{1+z_t}\right)\right)} \right]^{-3\Delta \ln 10}$$

$$w(z) = -1 - \Delta \tanh\left(\log_{10}\left(\frac{1+z}{1+z_t}\right)\right).$$

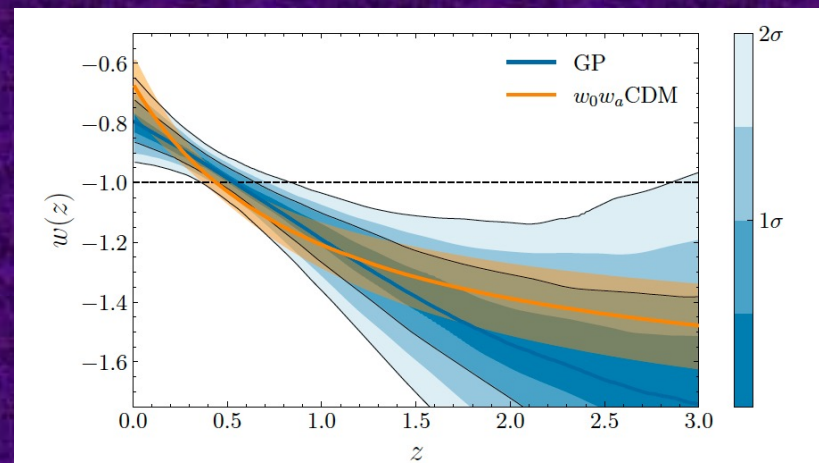
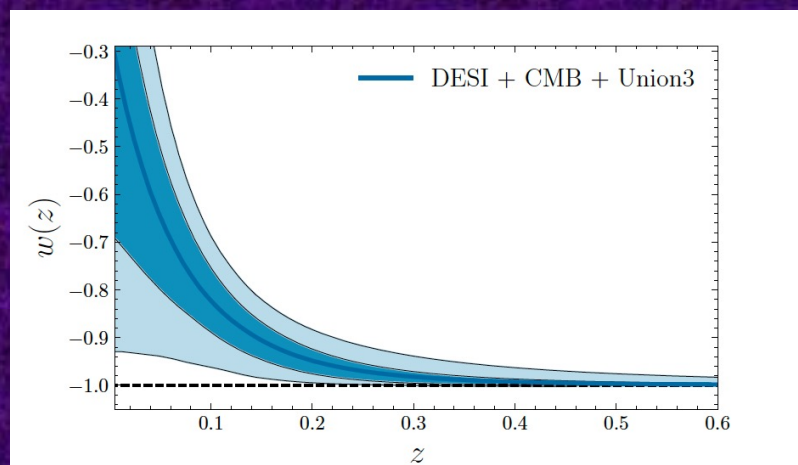
Metastability in Emergent Dark Energy

Li, Liu, Li, Du, Shafieloo, Biesiada,
ApJ Lett, 2026



See also Swagat Mishra et al, JCAP 11, 018, 2025 and many others!

Is Crossing PDL is Real?



$$1 + w(a) = (1 + w_0) a^p \left(\frac{1 + b}{1 + ba^{-3}} \right)^{1-p/3}$$

Crossing $w=-1$

A big key question!

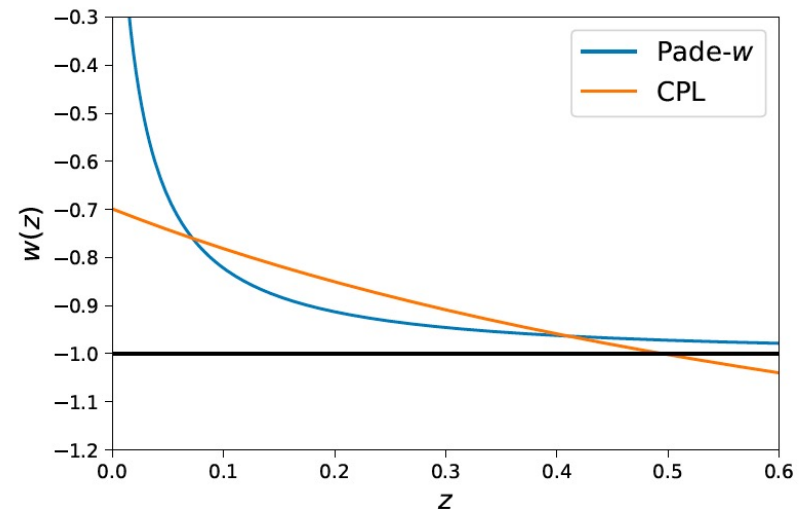
How to compare models that are not nested within one another?

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

CPL

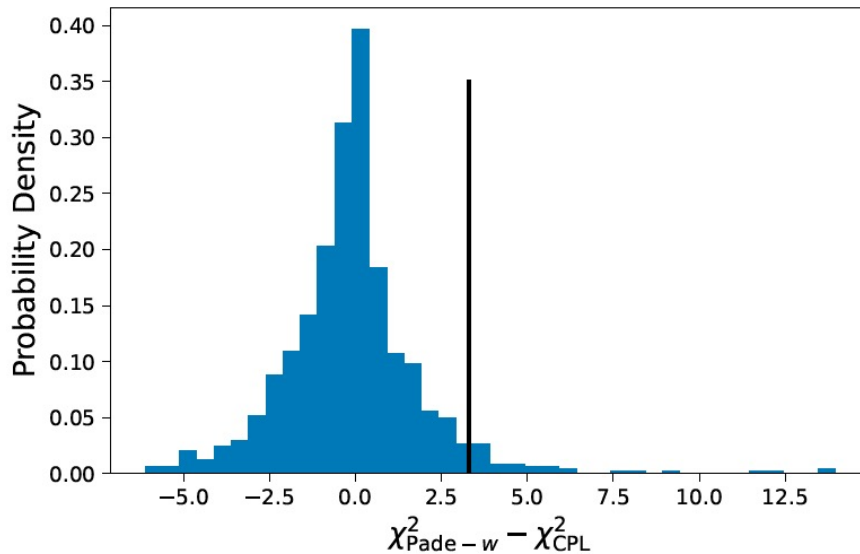
$$w(z) = \frac{2\epsilon_0}{3 + \eta_0(z^3 + 3z^2 + 3z)} - 1,$$

Algebraic Quintessence



- Best fit models to DESI DR2+Union3+Planck
- Same degrees of freedom
- Chi^2 relatively comparable

How to compare models that are not nested within one another?



Frequentist Approach

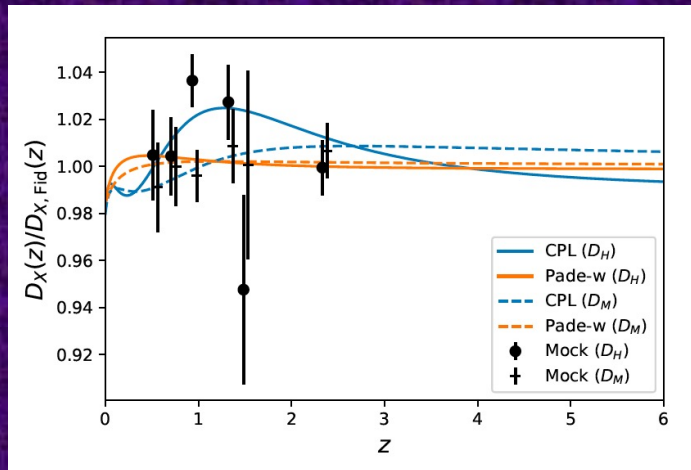
- 1000 realisations of the data based on best fit Pade-w
- **~36% cases CPL with phantom crossing has a better fit than true model (Pade-w) ==> Can be a potential generic behavior**

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

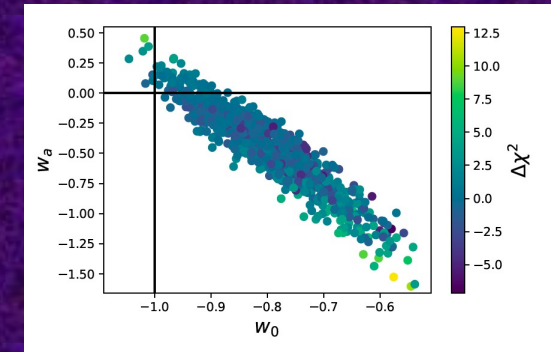
$$w(z) = \frac{2\epsilon_0}{3 + \eta_0(z^3 + 3z^2 + 3z)} - 1,$$

Simple Exercise to Demonstrate a Possibility

There exist scalar field models with no crossing of PDL that can be easily misinterpreted by current analysis

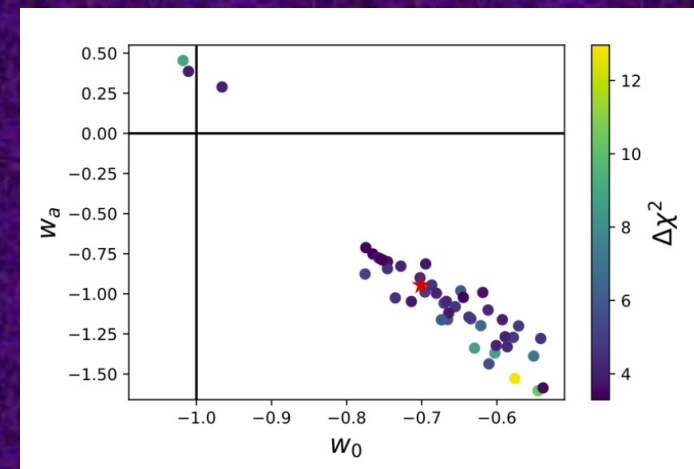


Take Home 7: Let's not rush and avoid over-interpretations.



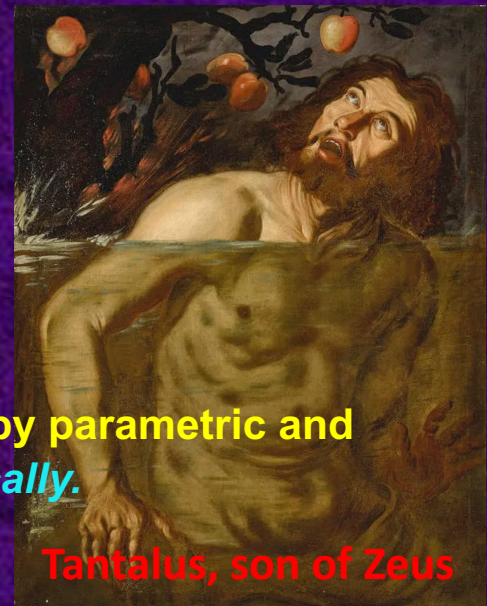
Keeley, Shafieloo, Matthewson, arXiv::2506.15091

- 1000 realisations of the data based on best fit Pade-w
- **~36% cases CPL with phantom crossing has a better fit than true model (Pade-w)**
- **~3.2% cases, the CPL yields a $\Delta\chi^2$ (wrt Pade-w) larger than that observed in the real data (sensitive to choice of the data/likelihood code).**



Current Status and Summary

- There are now **tantalizing** hints for Dark Energy Evolution.
- Data suggests crossing of the phantom divide line (supported by parametric and non-parametric approaches). *Uncomfortable situation theoretically.*
- Other viable solutions are not yet ruled out and actual significance for Phantom Crossing is not yet very high.



Tantalus, son of Zeus

Will they remain significant?

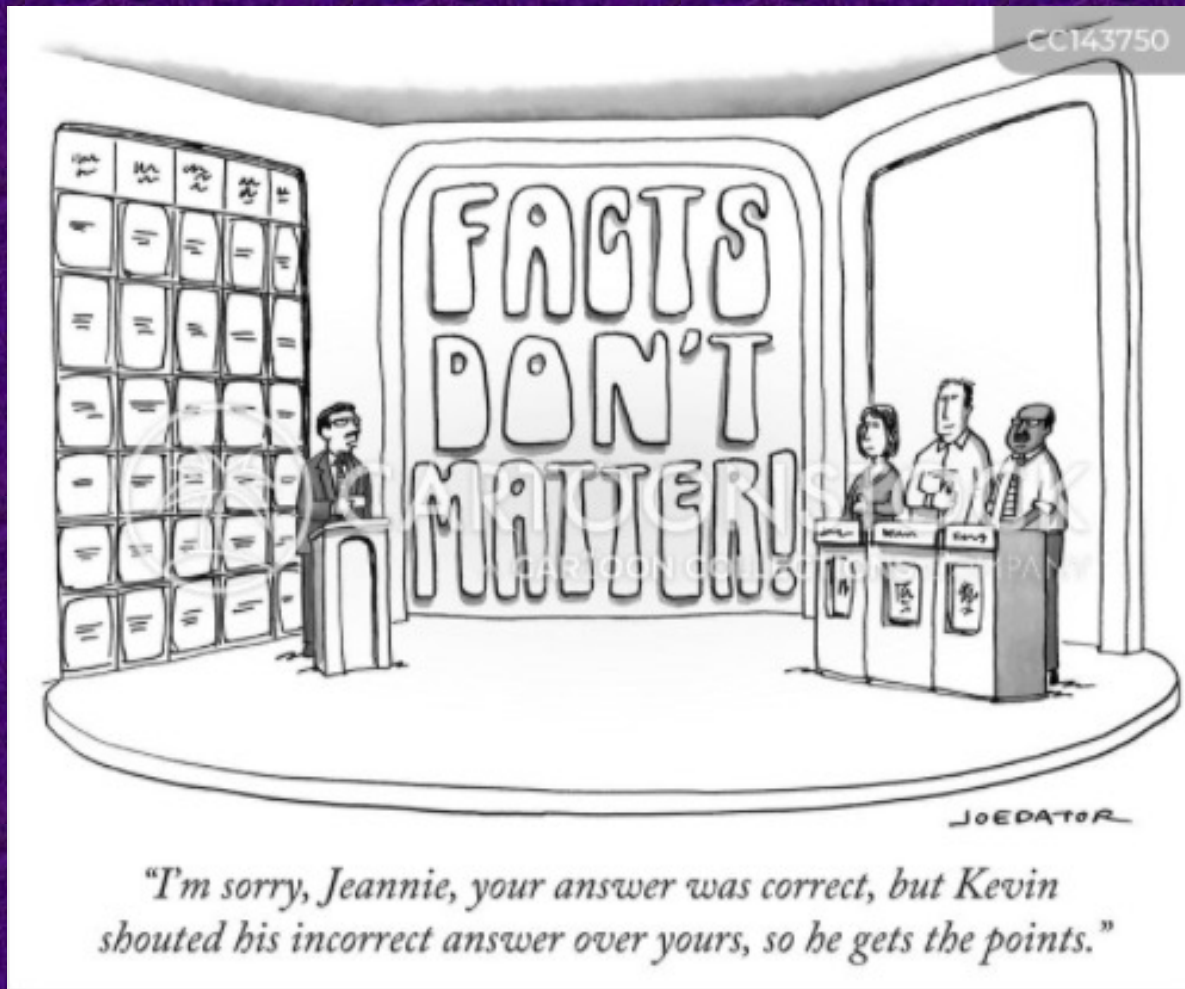
DESI DR2 Confirmed initial findings → Time will show (DESI DR3, Euclid, LSST, Roman).

- Never trust a data too much till you understand and verify it very very well!
- Hubble tension has remained a separate, but connected, issue.

*New probes and model independent consistency test between various data is essential to rule out **systematics**,....*

Big part of science these days....

Conclusion (Social Media)

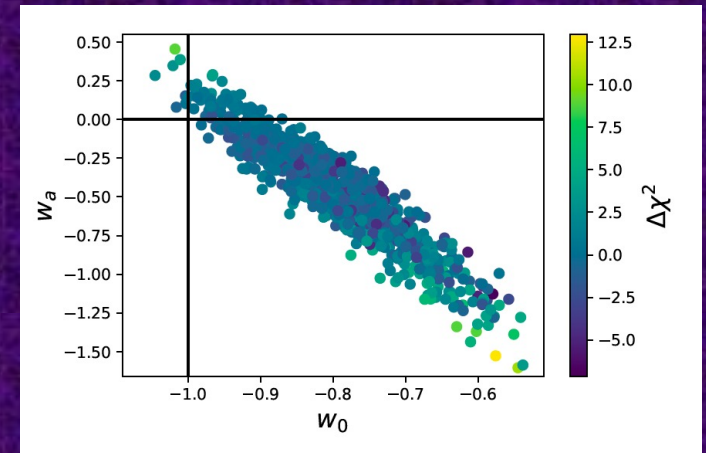
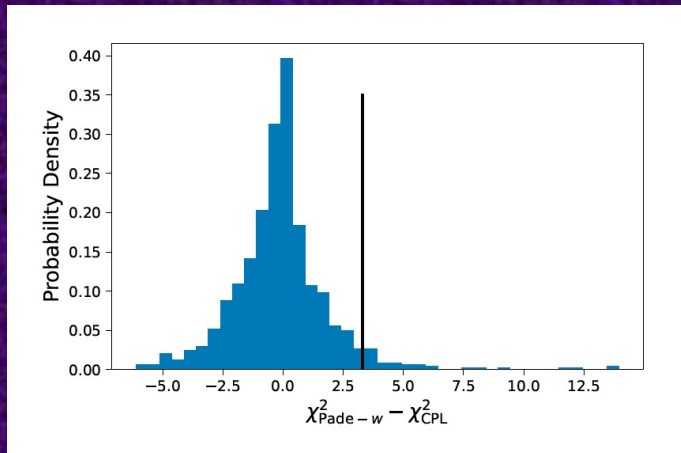


"I'm sorry, Jeannie, your answer was correct, but Kevin shouted his incorrect answer over yours, so he gets the points."

The New Yorker, 29 November 2016

But,....facts ultimately matter.

How to compare models that are not nested within one another?



Keeley, Shafieloo, Matthewson, arXiv::2506.15091

- 1000 realisations of the data based on best fit Pade-w
- **~36% cases CPL with phantom crossing has a better fit than true model (Pade-w)**
- **~3% cases, the CPL yields a $\Delta\chi^2$ (wrt Pade-w) larger than that observed in the real data.**

