Reconstructing Dark Energy

Can we be fooled by Phantom Crossing?

Arman Shafieloo

Korea Astronomy and Space Science Institute (KASI)

University of Science and Technology (UST)

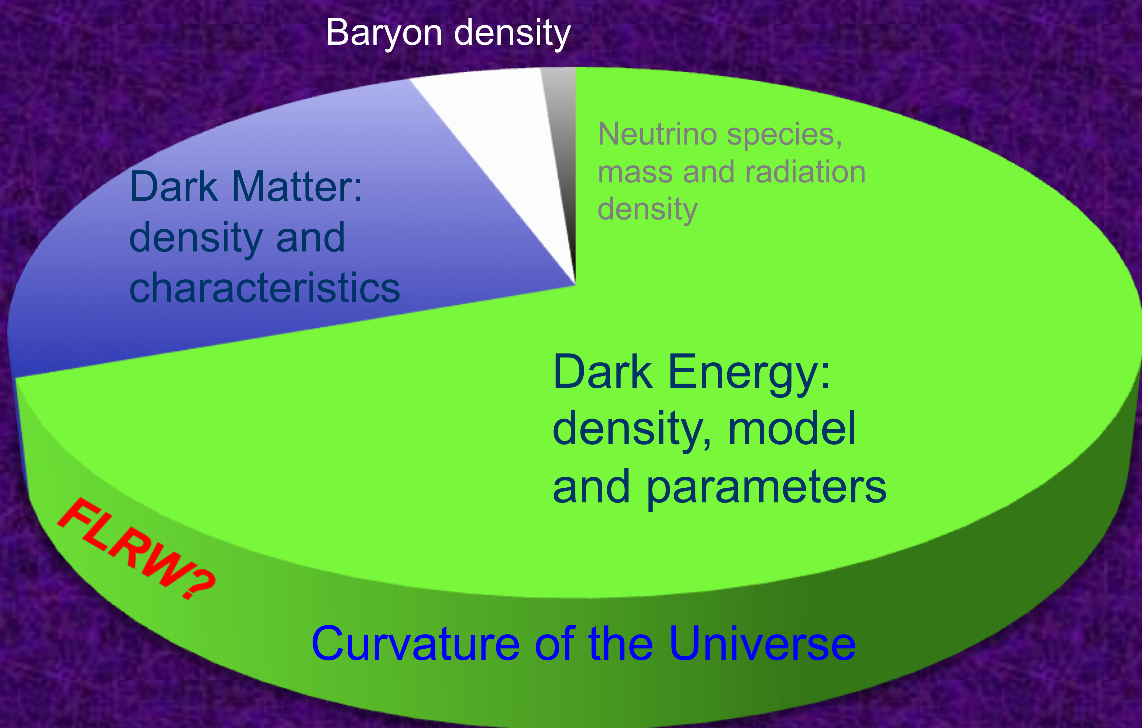
Division of the Elementary Particle Physics

Institute of Physics, Czech Academy of Science

Prague, 22nd January 2026

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.



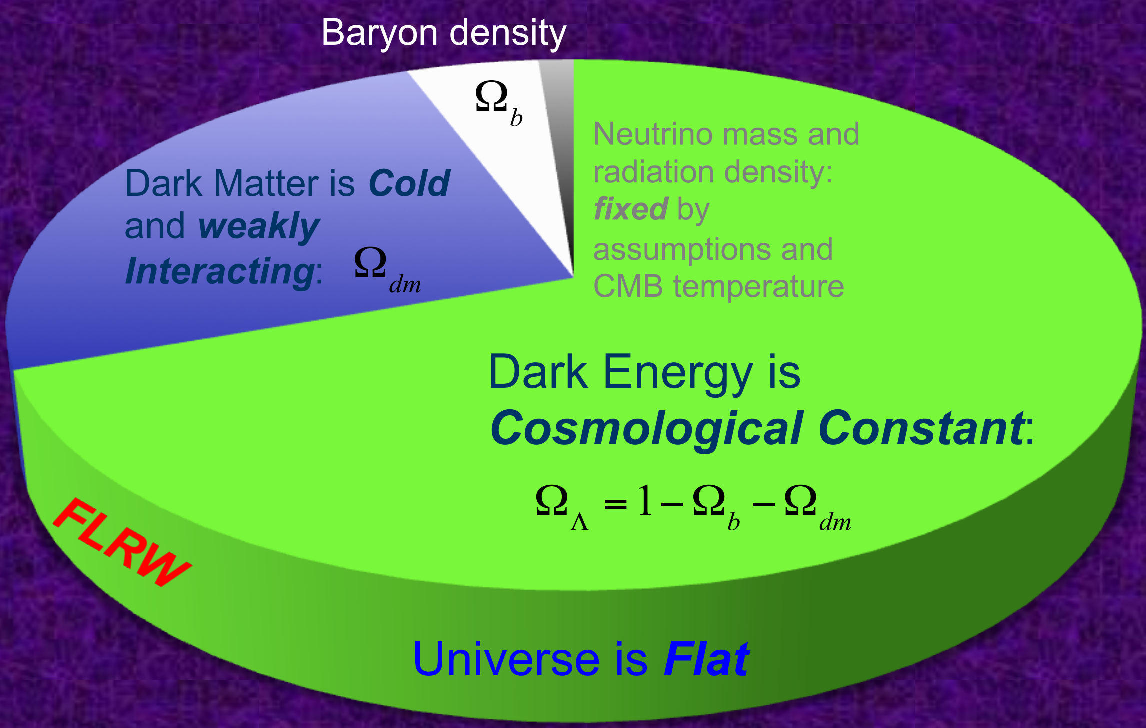
Initial Conditions: Form of the Primordial Spectrum and Model of Inflation and its Parameters

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

τ

Hubble Parameter and the Rate of Expansion

H_0

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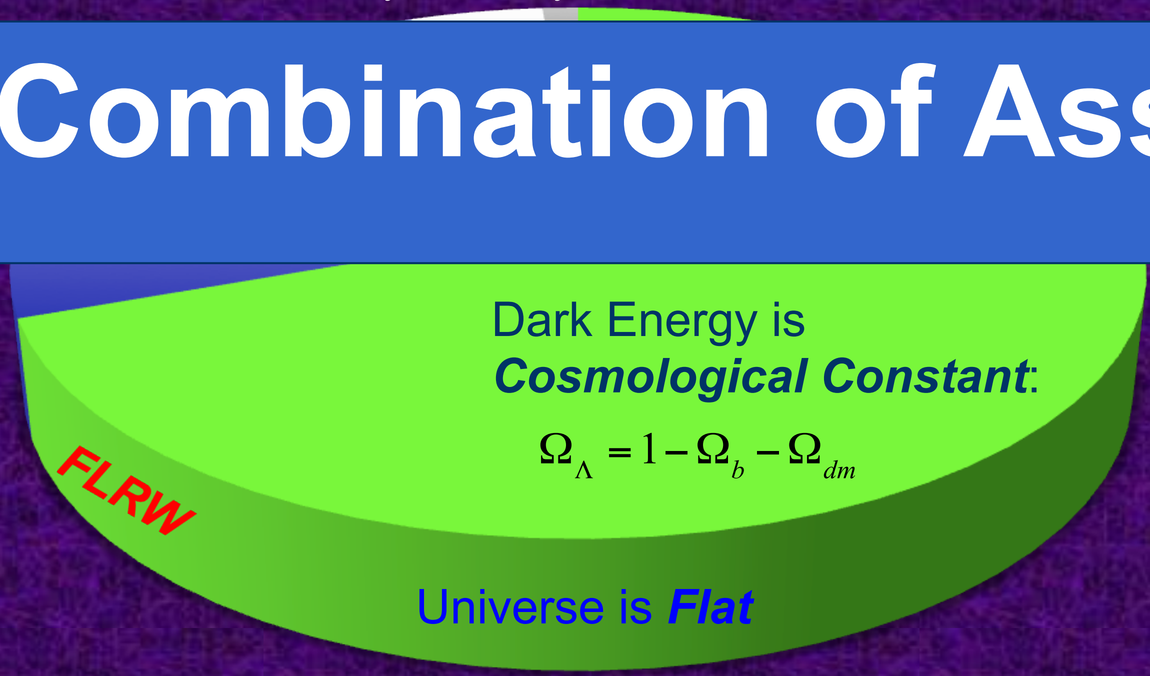
Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

Baryon density

Combination of Assumptions



n_s, A_s

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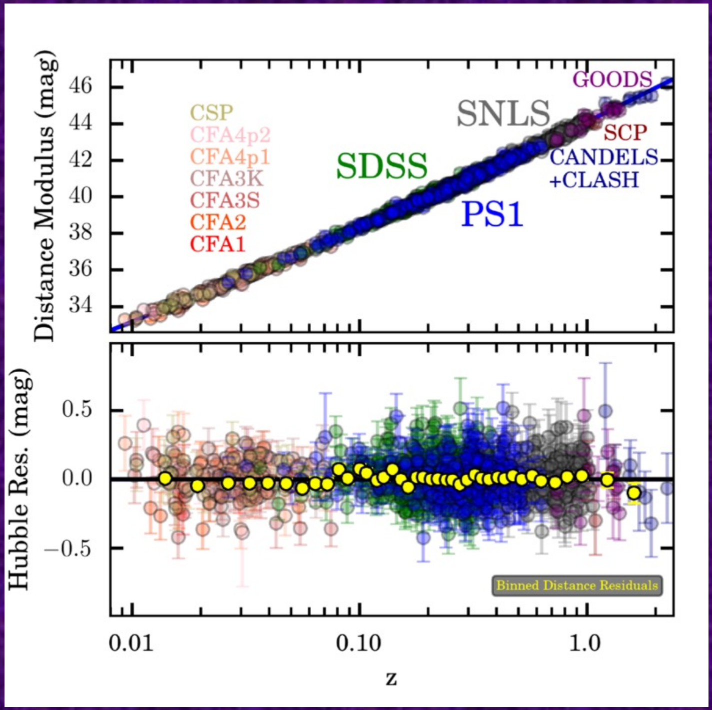
Standard Model in Jan 2026

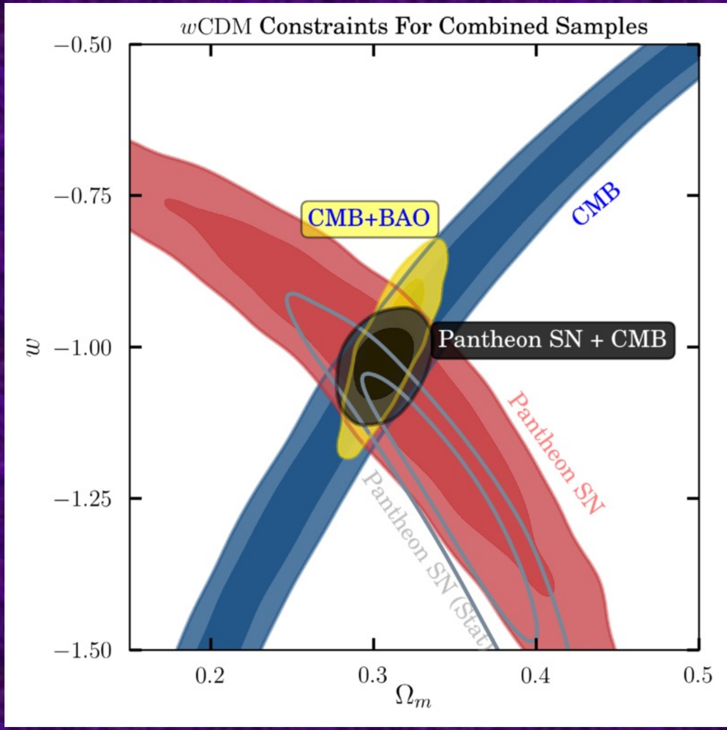
SN Ia

25 years after discovery of the acceleration of the universe:

From 60 Supernovae Ia at cosmic distances, we now have ~2000 published distances, with better precision, better accuracy, out to z~2.0. ***Accelerating universe in proper concordance to the data.***



1000+ spectroscopically confirmed SNIa



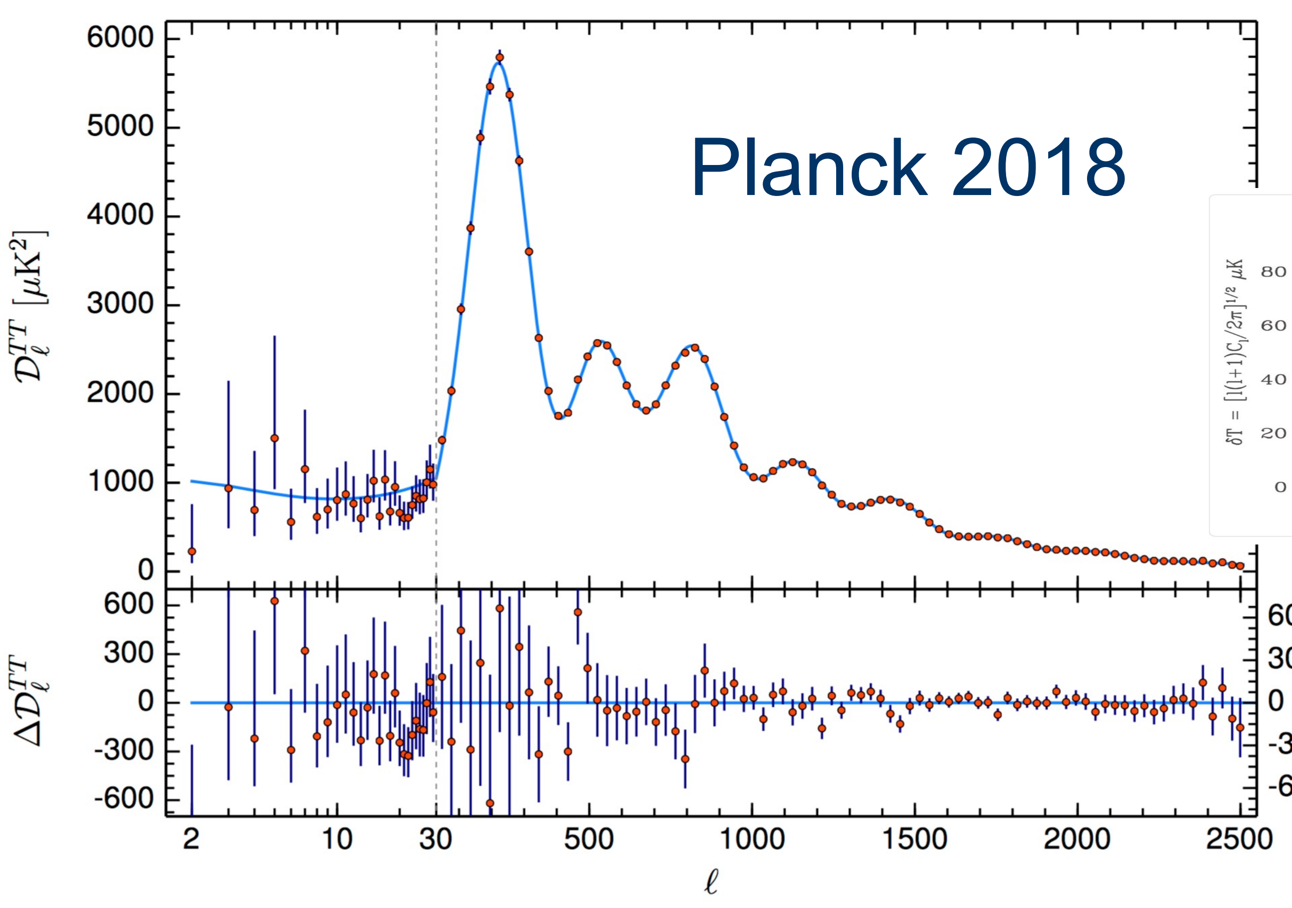
Pantheon Compilation
Scolnic et al. (2018)

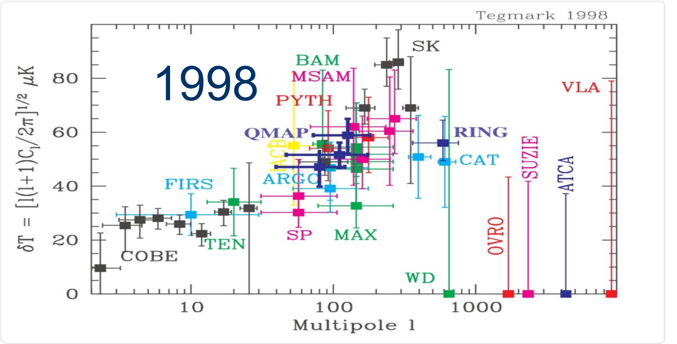
Standard Model in Jan 2026

CMB

25 years after discovery of the acceleration of the universe:

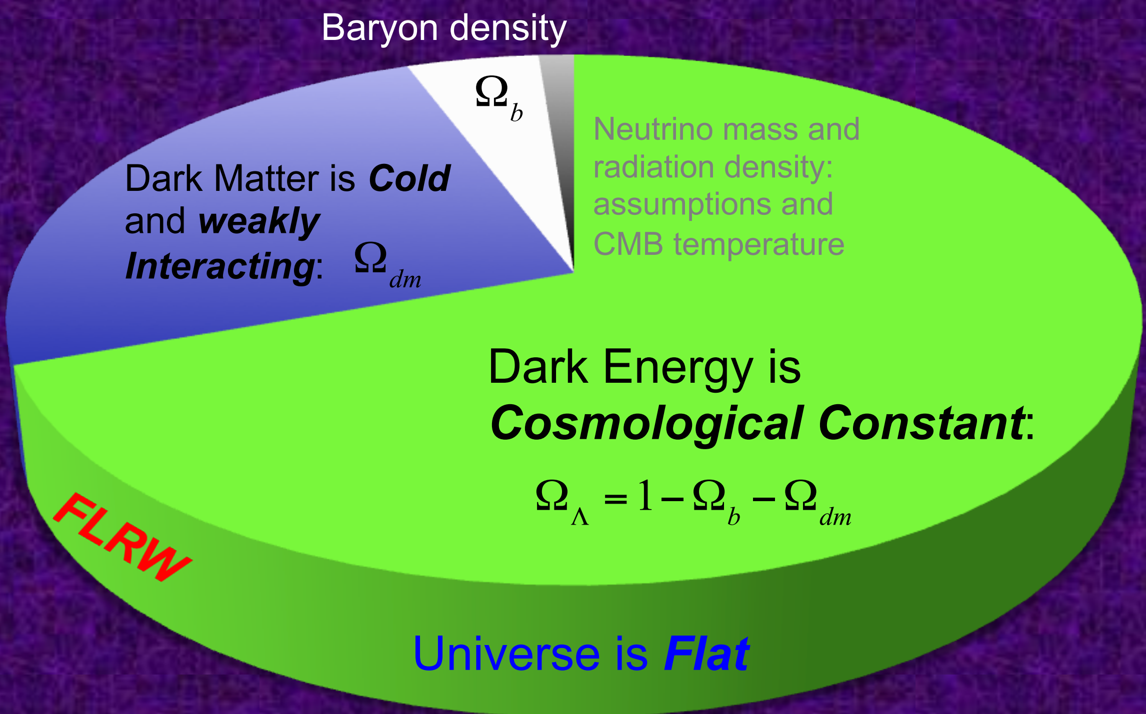
CMB directly points to acceleration. Didn't even have acoustic peak in 1998!





Standard Model of Cosmology

combination of *reasonable* assumptions, but…..



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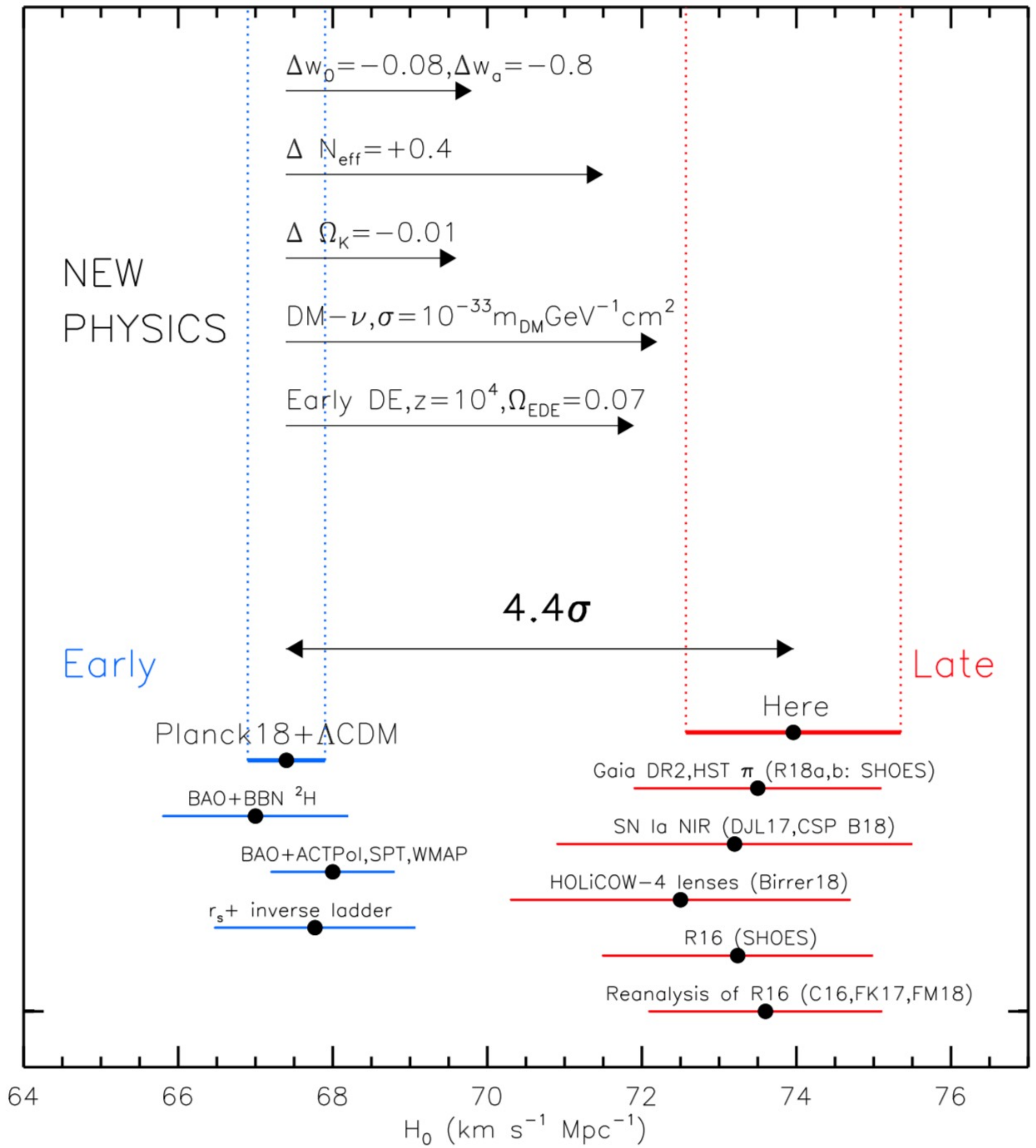
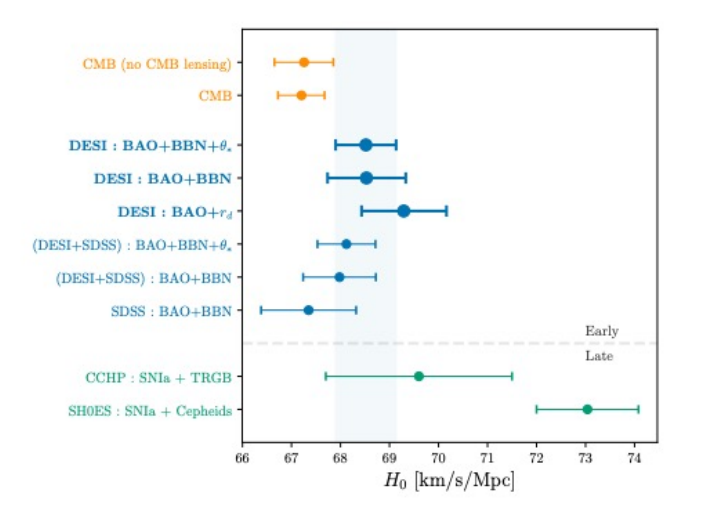


Tensions in the Standard Model

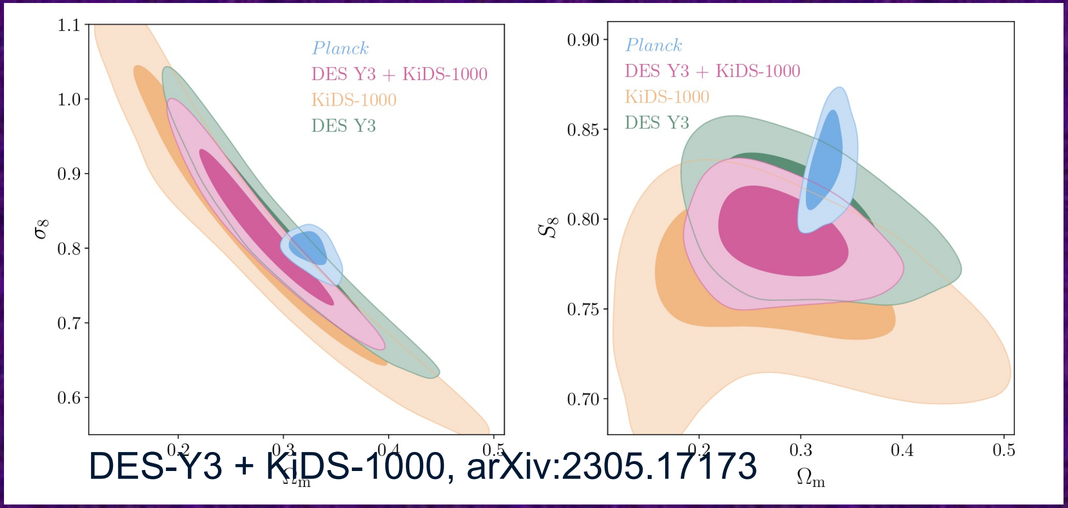
Riess et al, ApJ 2019 [arXiv:1903.07603]

Tensions in the Standard Model

It is not only about H0 and CMB

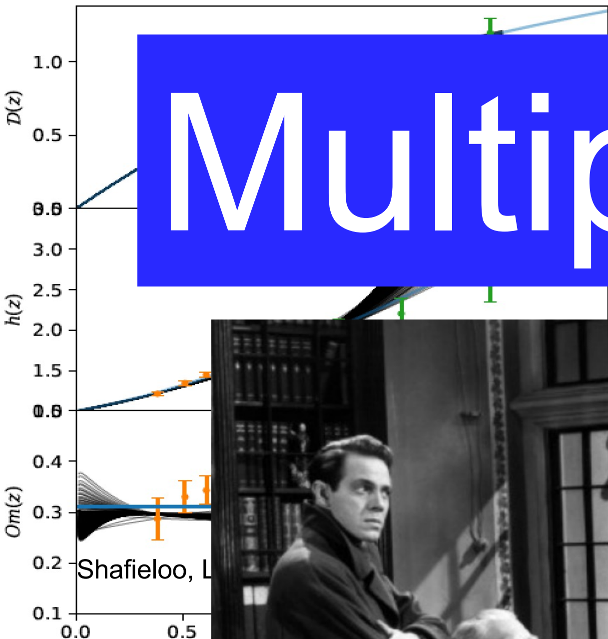


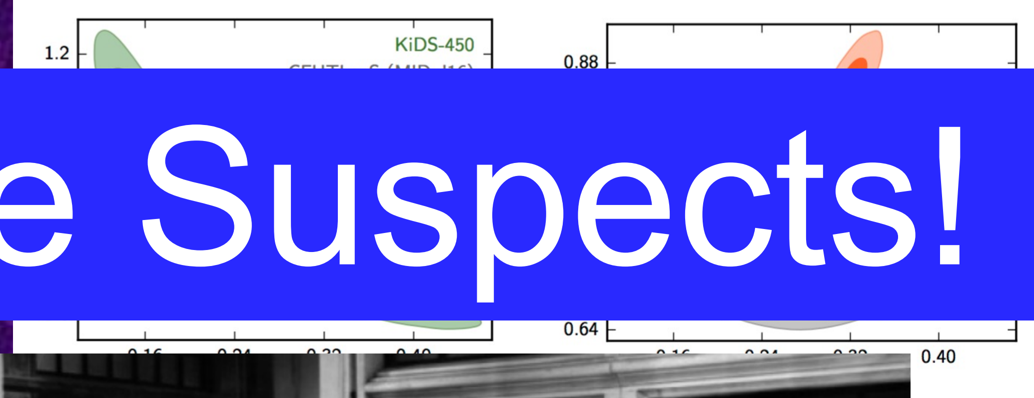
DESI-Y1 (2024), arXiv:2404.03002



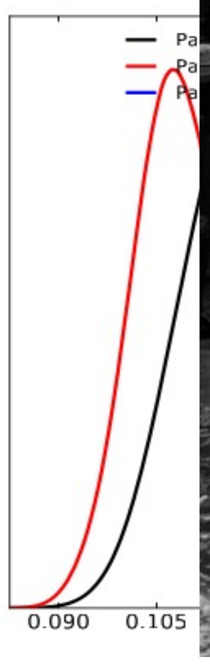
DES-Y3 + KiDS-1000, arXiv:2305.17173

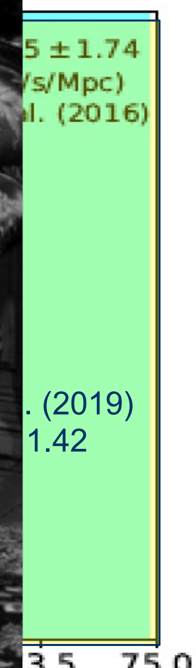
Multiple Suspects!





H(z)r_d is
y WL.






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

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=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.

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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, early and late models . None has been successful.

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

Why Dark Energy is Important?

- Drives the Universe's Accelerated Expansion
- Shapes the Universe's Fate
- Challenges Our Understanding of Physics
- Affects Cosmic Structure Formation
- Guides the Design of Future Experiments:

- Dark energy does not fit into the Standard Model of particle physics
- A de Sitter space, a spacetime with a positive cosmological constant does not fit within current formulations of string theory

Main Probes of Dark Energy

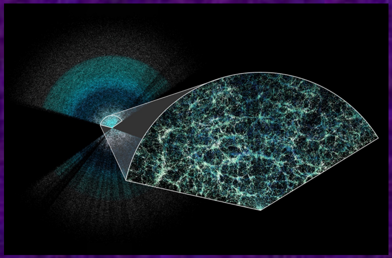
- ***Standard candles***:
  measure luminosity distance.

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

Supernovae Ia as
Standardized Candles

- ***Standard rulers***:
  measure angular diameter distance.

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



BAO as standard ruler

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{\rm eff}\rho\delta = 0,$$

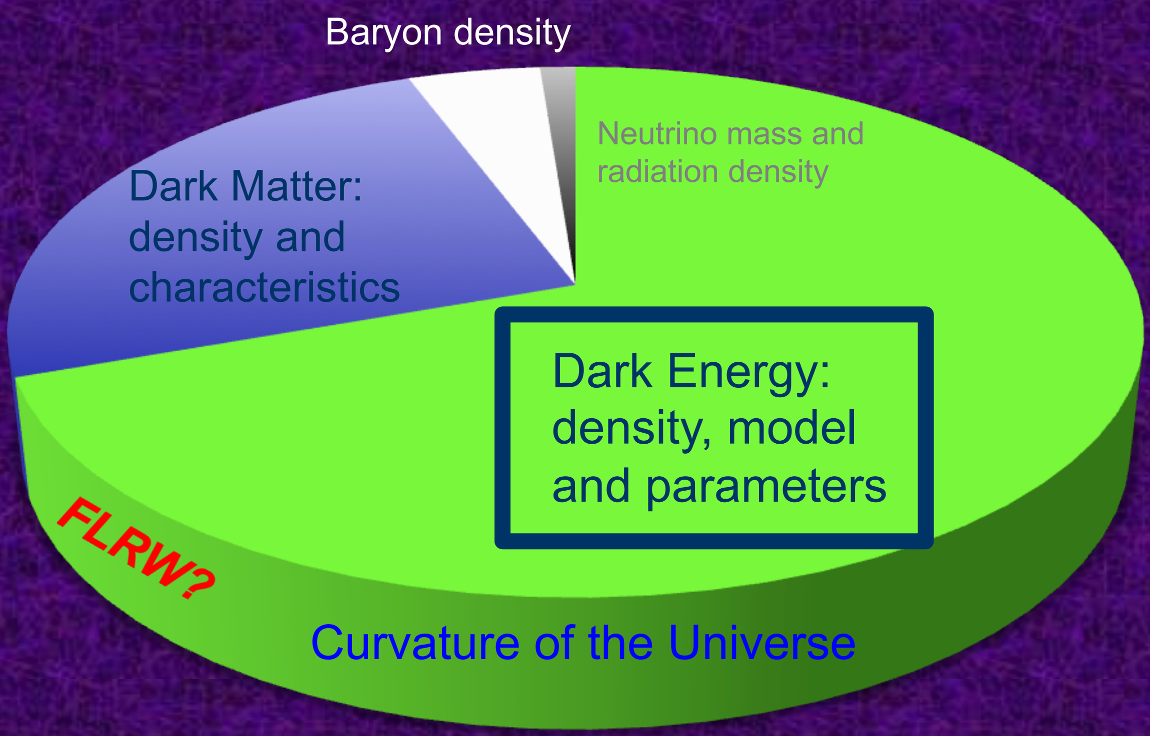
- ***Growth of fluctuations***:
  testing modified gravity models or to distinguish between physical and geometrical models of Dark Energy.

To move forward in understanding dark energy….

Reconstruction & *Falsification*

Reconstruction: Understanding the behavior

Falsification: Testing the consistency and validation of models



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Falsification / Validation

(going beyond precision)

Some models can fit the data better than some others and chi^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.

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

One can attempt using reliable non-parametric reconstruction approaches to construct a statistical anchor in likelihood analysis.

Example: Fitting two DE models (LCDM & PEDE) to a data set
Using conventional Bayesian Evidence Approach
But both models are wrong.

Iterative Smoothing Method

- The non-parametric method to reconstruct the distance modulus and expansion history of the universe
  Shafieloo et al. 2006, 2018; Shafieloo. 2007; Shafieloo & Clarkson 2010

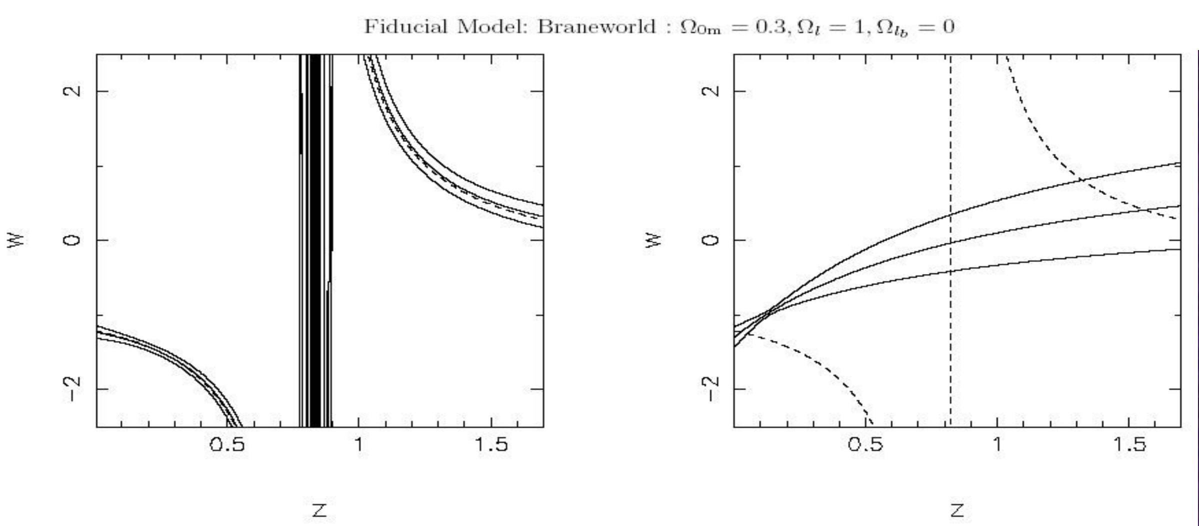
- Starts from initial guess of distance modulus, but generates model-independent reconstruction of distance modulus with lower χ^2 value after numerous iterations

$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\boldsymbol{\delta\mu_n}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{W}(z)}{\mathbf{1}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{W}(z)}$$ (**C**: Covariance matrix of the data)

$$\mathbf{1}^T = (1, \cdots, 1), \boldsymbol{W}_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right), \boldsymbol{\delta\mu_n}|_i = \mu_i - \hat{\mu}_n(z_i)$$ (**Δ**: Smoothing width)

$$\chi^2_n = \boldsymbol{\delta\mu_n}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{\delta\mu_n}$$

Reconstructed w(z) by iterative smoothing method
Shafieloo et al, MNRAS 2006



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$$\chi_n^2 = \boldsymbol{\delta\mu_n}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{\delta\mu_n}$$

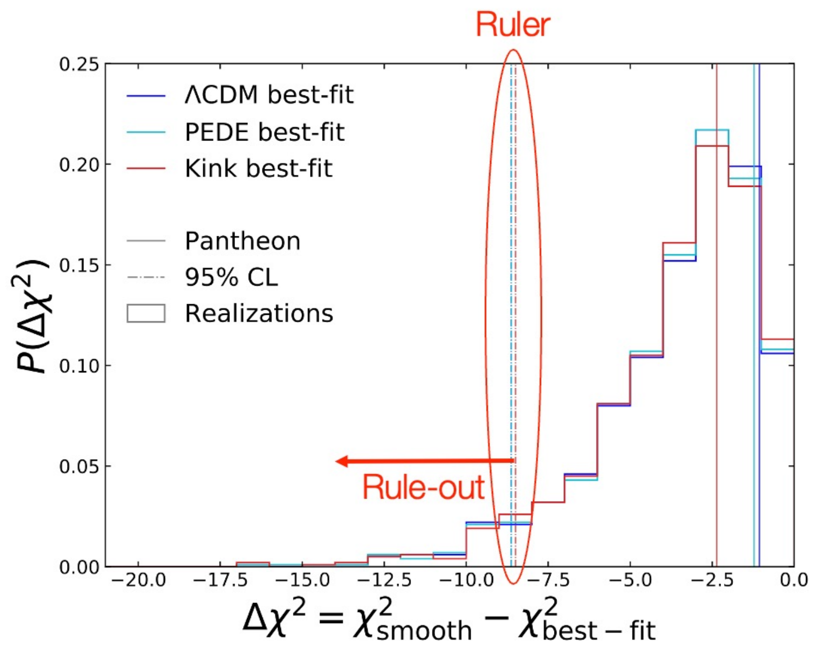
- Derive the **likelihood distribution** function $P(\Delta\chi^2)$ (for a large number of data realizations), where $\Delta\chi^2 = \chi^2_{\mathrm{smooth}} - \chi^2_{\mathrm{best-fit}}$, when the true model is assumed
  Koo et al. 2021, JCAP, 03, 034

- χ^2_{smooth}: χ^2 of the converged reconstruction using smoothing method

- $\chi^2_{\mathrm{best-fit}}$: Best-fit χ^2 of the correct model fits the data

Testing Models based on Likelihood Distribution

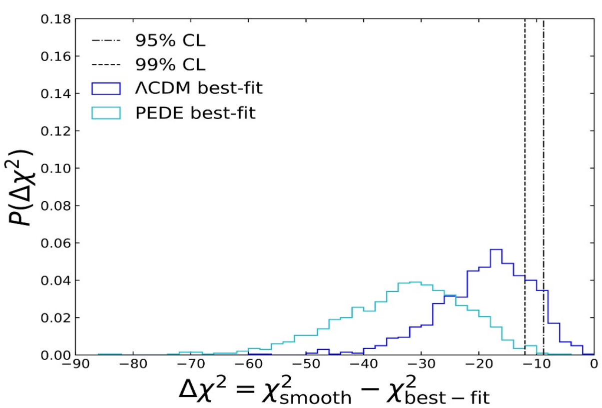
- $P(\Delta\chi^2)$ have no dependence on the true model and depends only on the covariance matrix of the data
  → One $\Delta\chi^2$ for given confidence (Ruler)
  Koo et al. 2021, JCAP, 03, 034



- Evaluating how much we can fit the data better by our non-parametric iterative smoothing method wrt the best fit of fiducial model.

Non-parametric way to measure likelihood of the data given a model (without model comparison).

- Likelihood distributions exclude both models



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ΛCDM ruled-out	0	916

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Non-parametric reconstruction and Model Validation

Falsification / Validation

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Conventional Bayesian Evidence Approach

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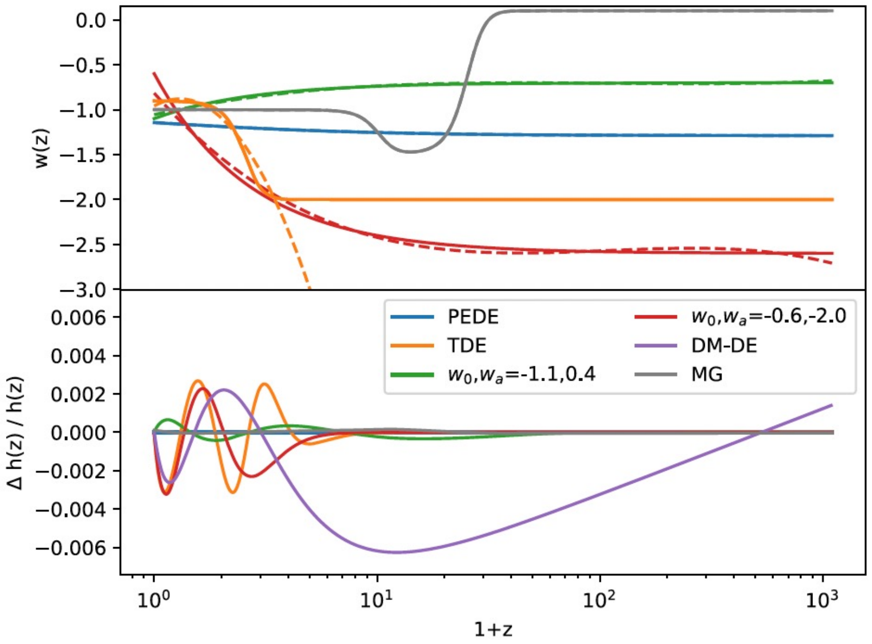
Iterative smoothing validation approach

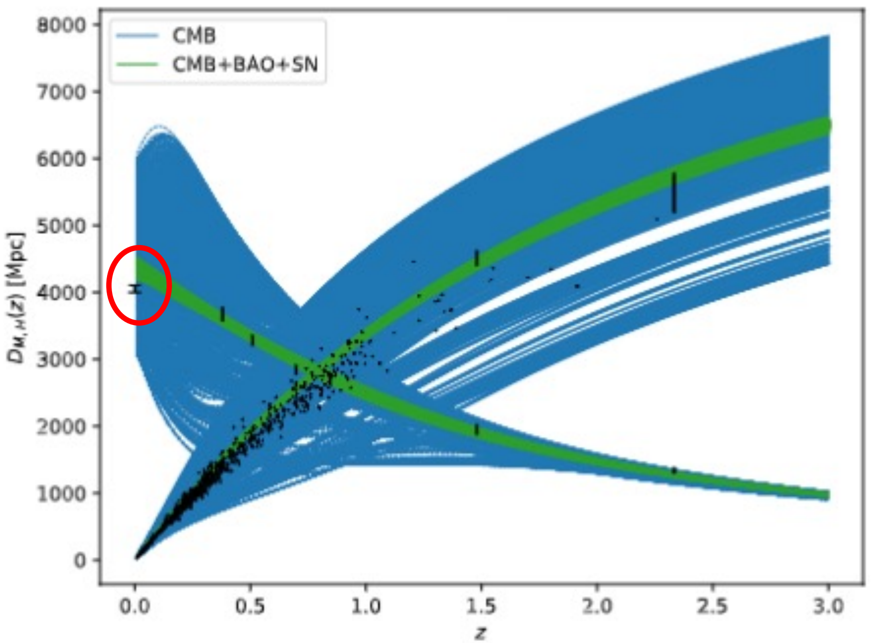
But both models are wrong.

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

Application of model validation

Ruling Out New Physics at Low Redshift as a solution to the H0 Tension





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

Keeley and Shafieloo, Phys. Rev. Lett, 2023

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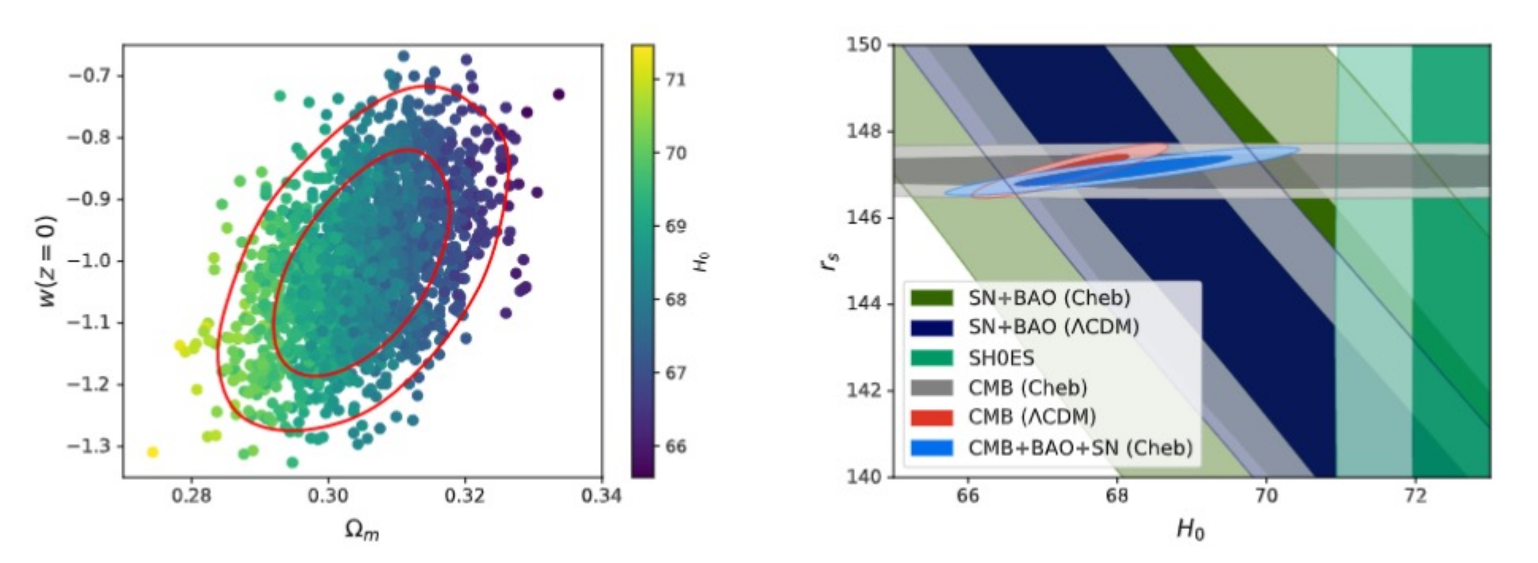

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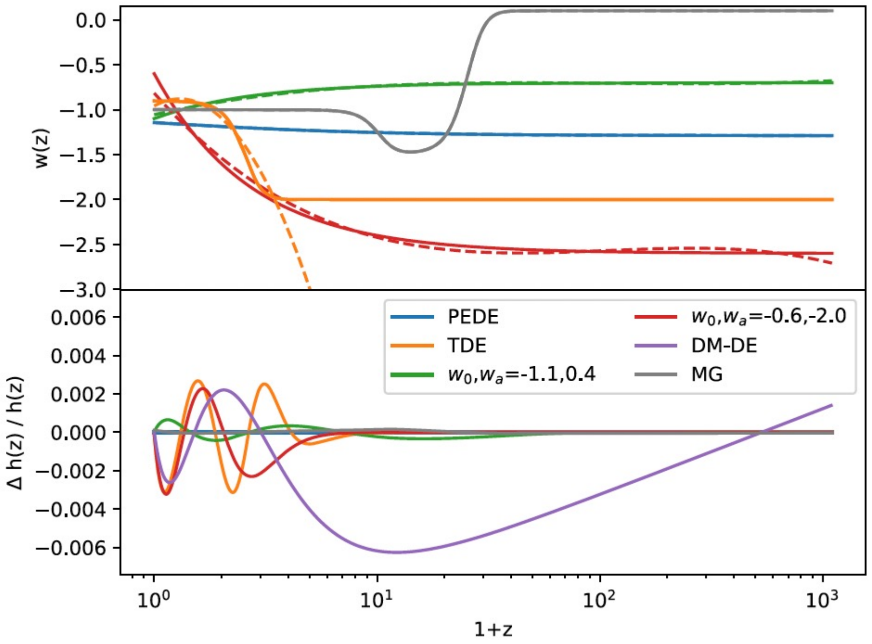
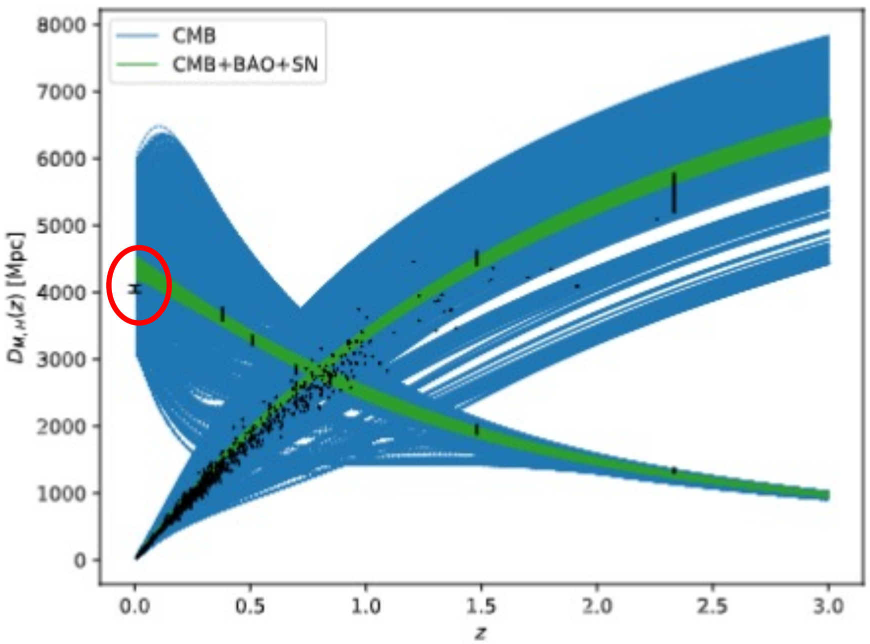
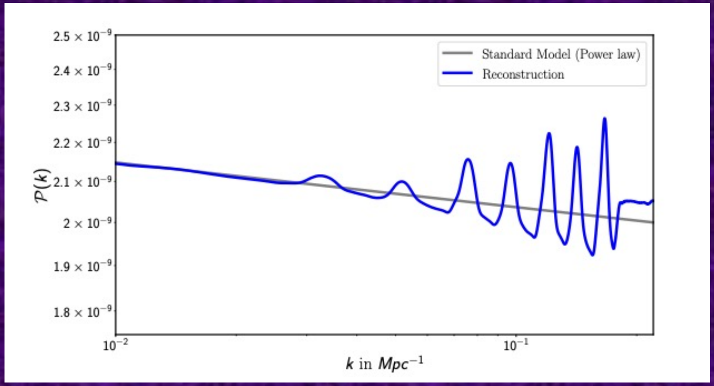


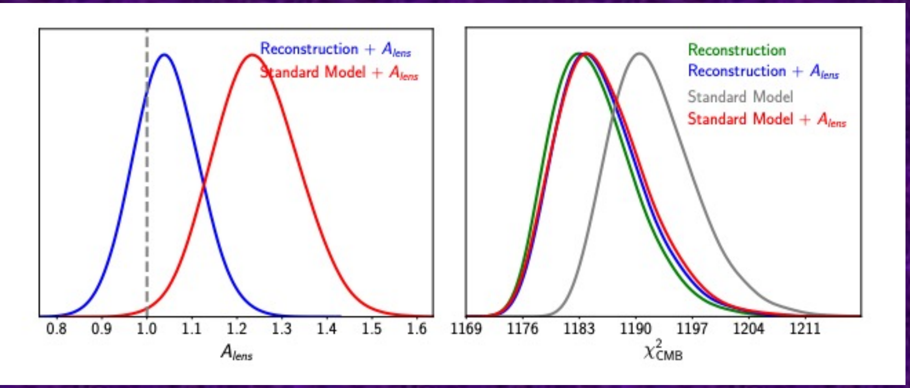


Keeley and Shafieloo, Phys. Rev. Lett, 2023

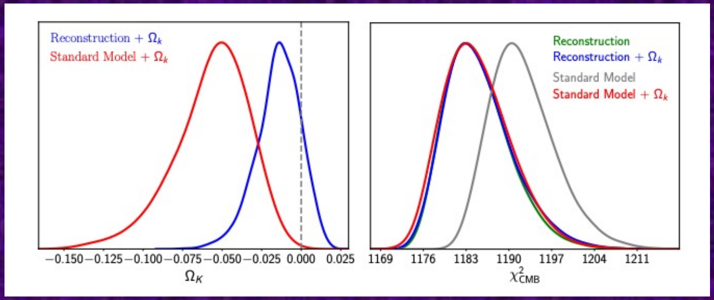
Theoretical implication: Connecting Early and Later Universe.
Looking for early universe solutions in the form of primordial spectrum!

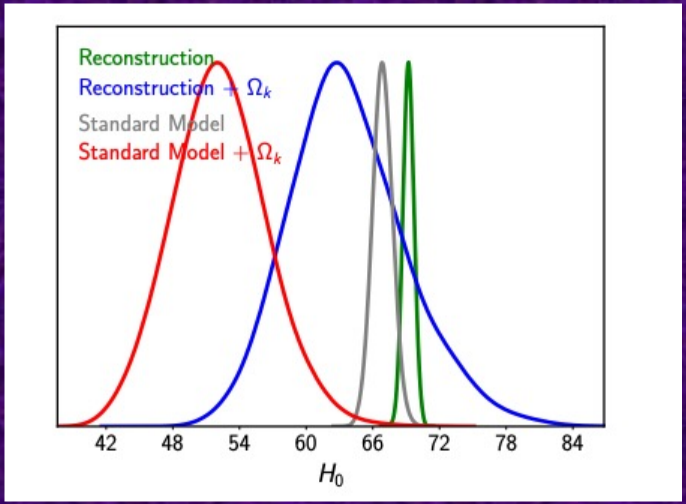
One spectrum to cure them all





Curvature and A_lens anomalies





Hazra, Antony, Shafieloo : JCAP 2022

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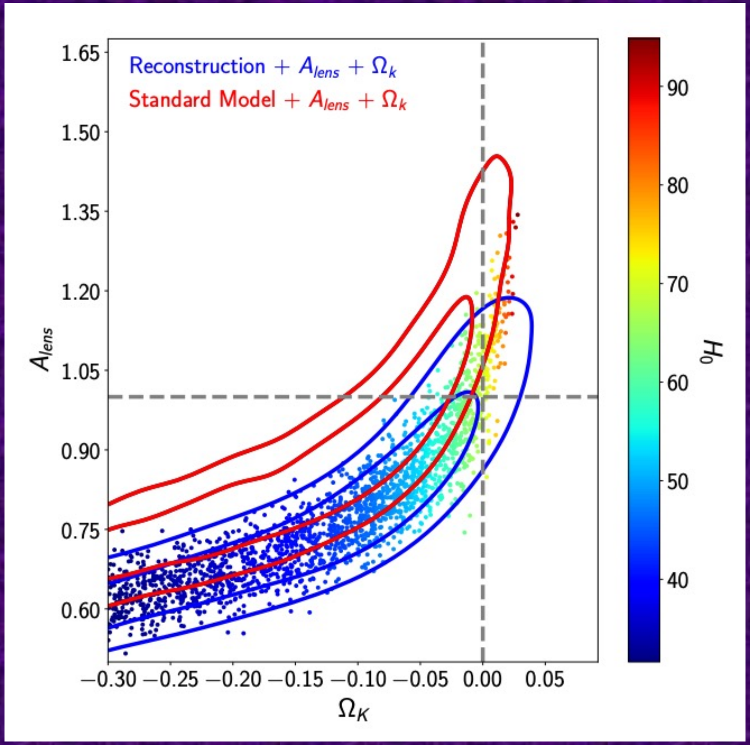
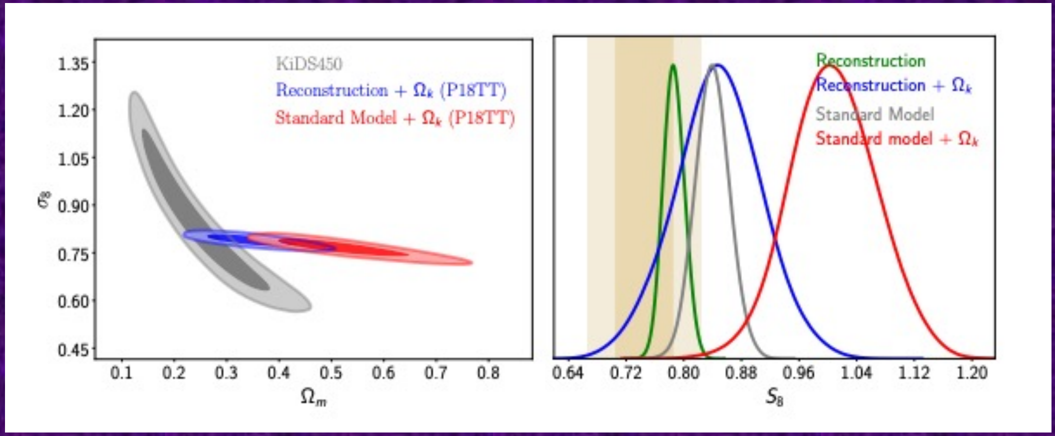




Addressing CMB anomalies and tensions

Constructed single field potential to generate features like what we need….

Hazra, Antony, Shafieloo :JCAP 2022

See Antony, Finelli, Hazra, Shafieloo, PRL 2023, for theoretical implication

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 constrains 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

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

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

$$\frac{H^2(z)}{H^2_0} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})X(z)\right]$$

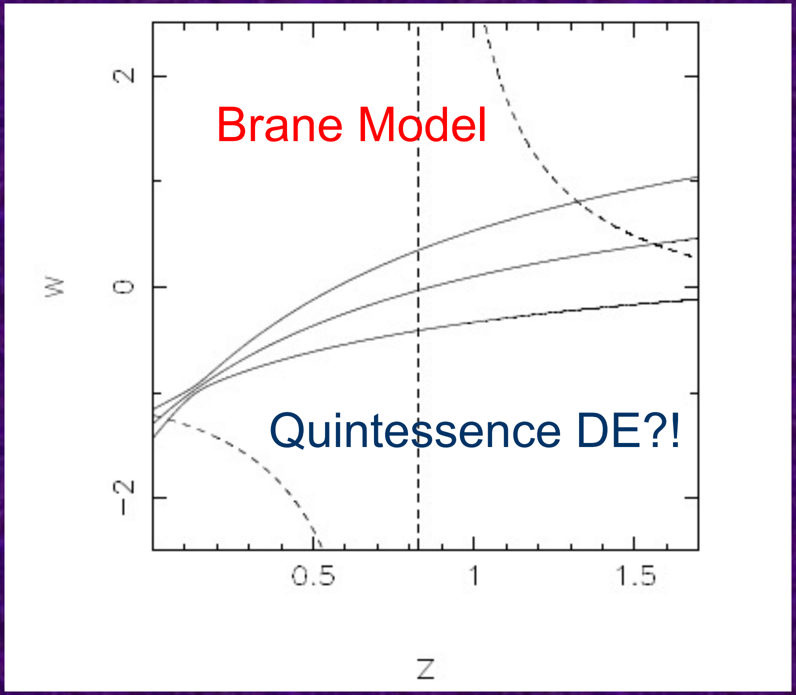
1. Fitting functions for d_l(z)
2. Fitting functions for DE density
3. Fitting functions for EOS

Most general form

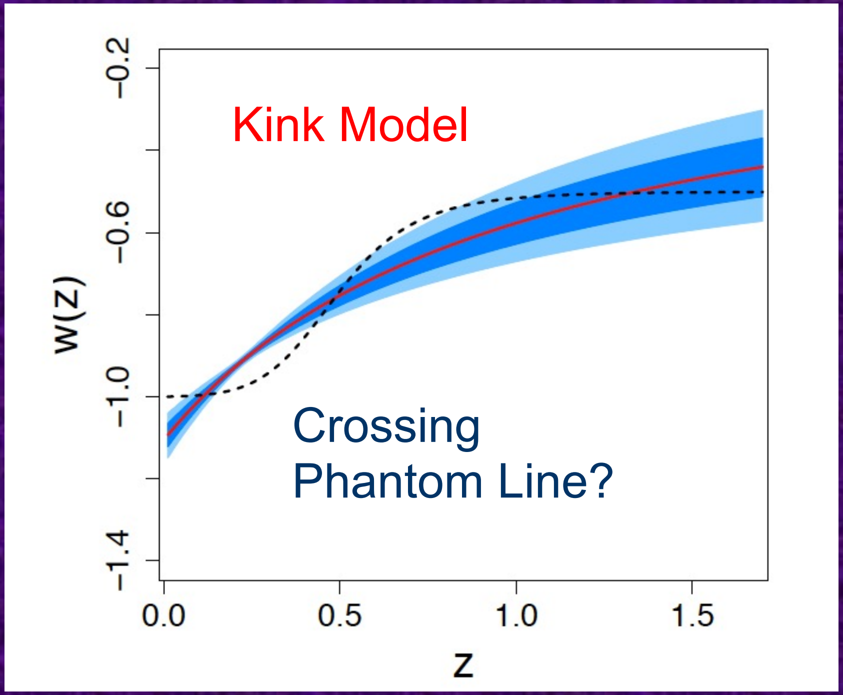
$$\frac{H^2(z)}{H^2_0} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})\exp[\int 3(1+w(z))\frac{dz}{1+z}]\right]$$

How I got to know Eric Linder and David Polarski ☺

Problems of Dark Energy Parameterizations (model 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).

Non Parametric methods of Reconstruction

Usually involves binning and smoothing

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

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

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

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

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

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

:

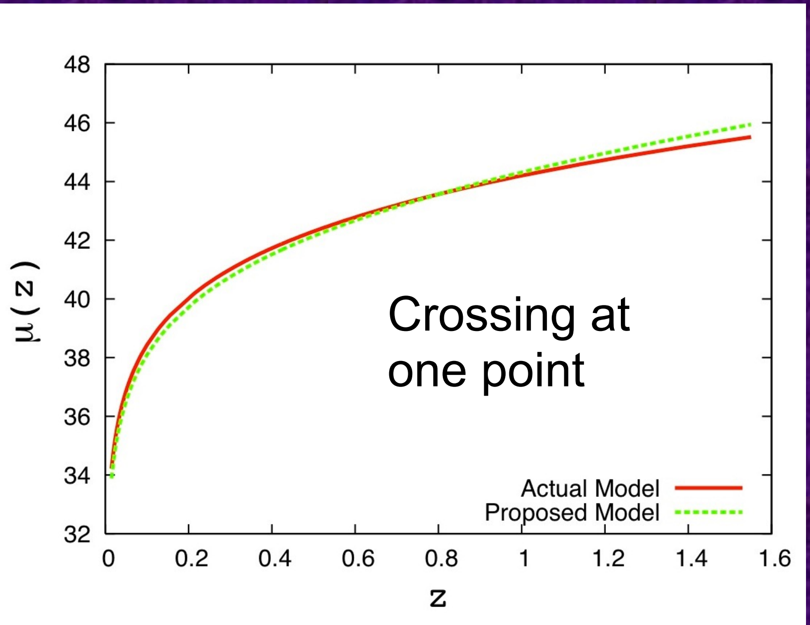
Bayesian Interpretation of Crossing Statistic:

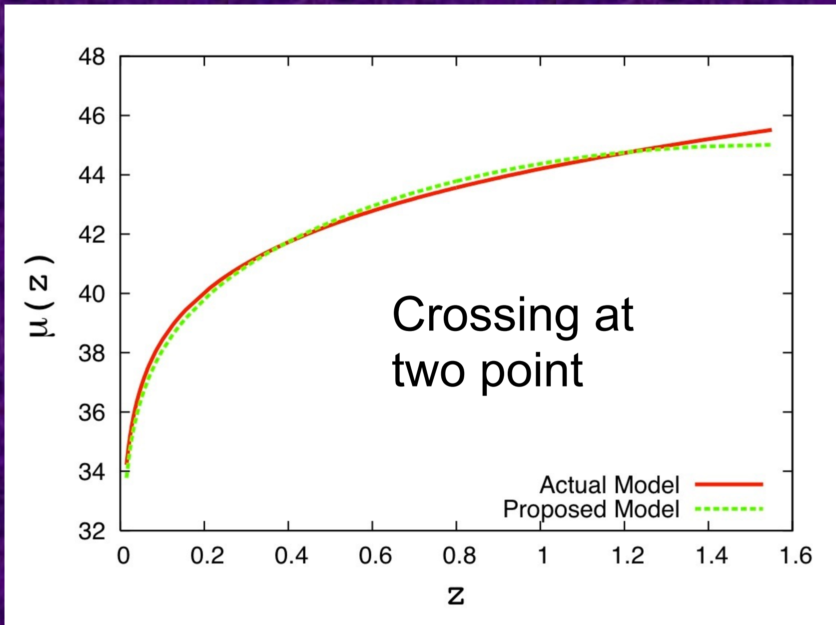
Comparing a model with its own possible variations using a hyperfunction with orthogonal basis.

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.

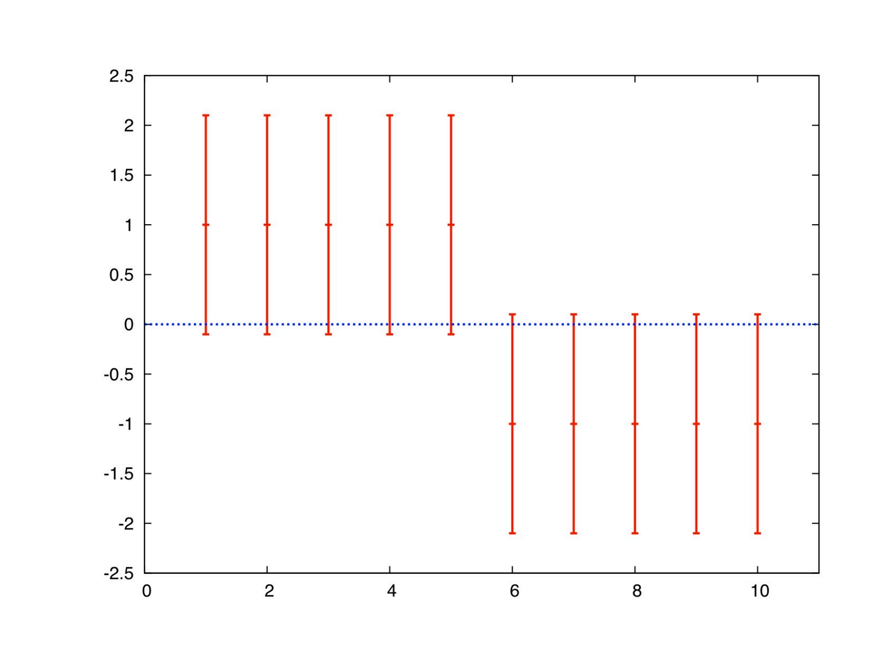
A. Shafieloo, T. Clifton & P. Ferreira, JCAP 2010.

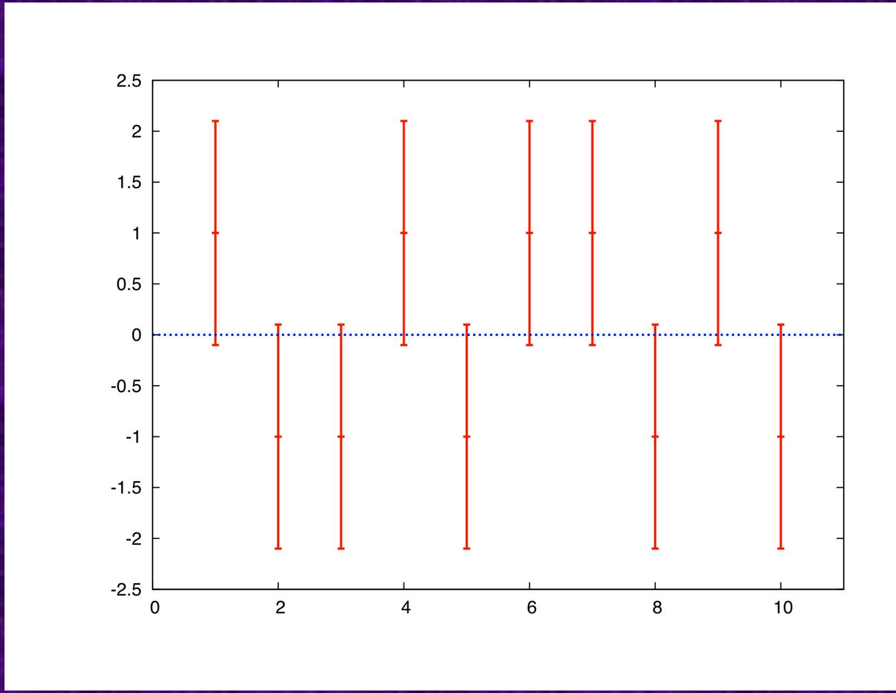




Equally probable?!

Going beyond chi^2….





Residuals

$$\chi^2 = \sum_i^N \frac{(\mu_i^t - \mu_i^e)^2}{\sigma_i^2},$$

Detecting correlated residuals

Simplified cookbook

One point Crossing: T1

1. Assume a model

$$q_i(z_i) = \frac{\mu_i(z_i) - \bar{\mu}(z_i)}{\sigma_i(z_i)}.$$

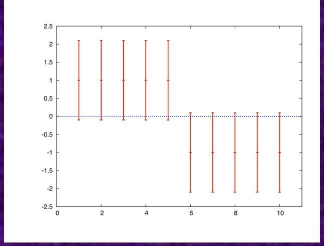
2. Construct the normalized residuals

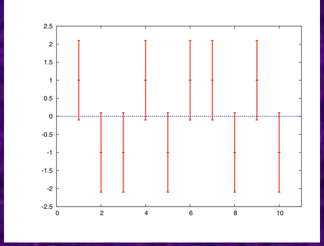
$$T(n_1) = Q_1(n_1)^2 + Q_2(n_1)^2,$$

3. Finding the crossing point and calculating T1 by maximizing T(n1):

$$Q_1(n_1) = \sum_{i=1}^{n_1} q_i(z_i)$$
$$Q_2(n_1) = \sum_{i=n_1+1}^{N} q_i(z_i),$$

4. Comparing the results with Monte Carlo simulations using the data error-matrix.





Comparing Two Statistics

	T1	Chi Square
Ruling out by 99% CL	1% (Correct Model) 28.5% (Incorrect Model)	1% (Correct Model) 1.9% (Incorrect Model)
Ruling out by 99% CL Assuming extra (0.05) intrinsic dispersion	0.5% (Correct Model) 26.4% (Incorrect Model)	0% (Correct Model) 0% (Incorrect Model)

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

$$\sigma_i^2 = \sigma_{i(data)}^2 + \sigma_{(sys)}^2$$

Correct Model: Flat LCDM with $\Omega_{0m}^{true} = 0.27$

Incorrect Model: Flat LCDM with $\Omega_{0m}^{erroneous} = 0.22$

Simulated SN Ia data similar to Constitution (2009) compilation

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.

$$T_0 = (\sum_{i}^{N} q_i)^2$$

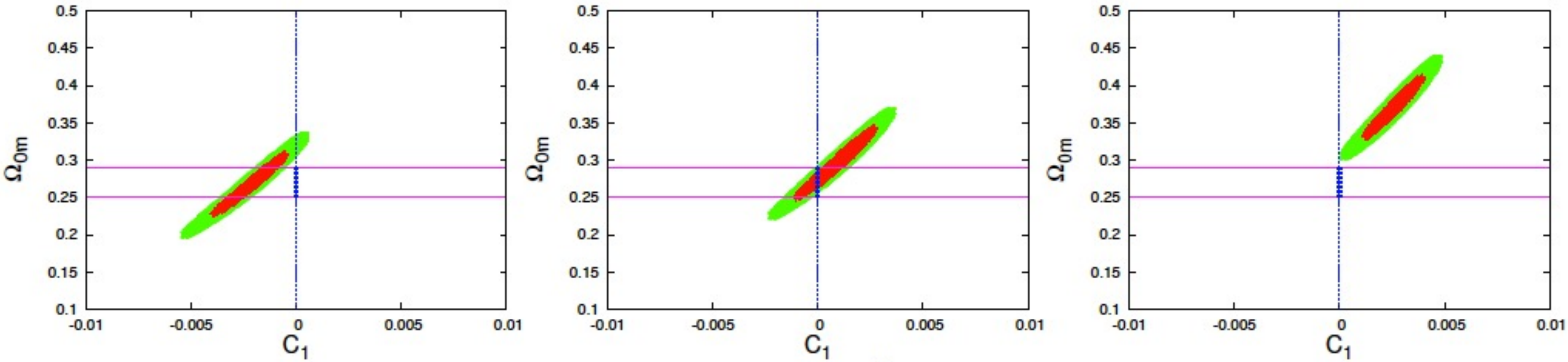
Extracting More Information

Crossing Statistic (Bayesian Interpretation)

Test model = Theoretical model x Crossing function

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

Comparing a model with its own variations



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

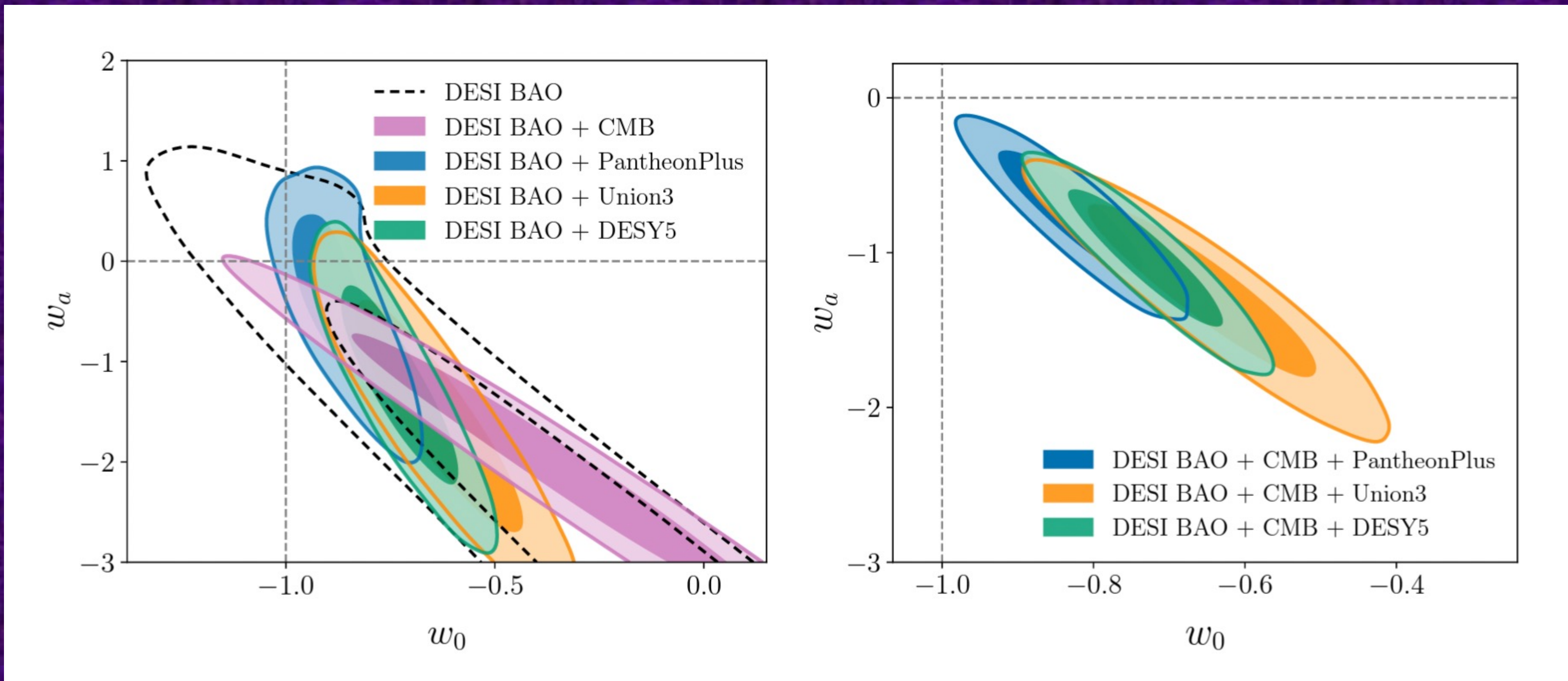
Chebishev Polynomials as Crossing Functions

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

Shafieloo. JCAP 2012 (a)

Shafieloo, JCAP 2012 (b)

DESI-2024



DESI-Y1 (2024), arXiv:2404.03002

동아사이언스

과학 인간 테크 환경·자연 생활 정책 하이테크 기업 사람들

암흑에너지 규명 위해 1년간 데이터 모아보니 "기존 우주론 맞나"

2024.04.15 12:25

DESI 프로젝트 첫 성과로 사상 최대 3D우주지도 공개

은하보다 밝은 '퀘이사'의 빛을 관측하는 상상도. DESI 제공

국제공동연구팀이 사상 최대 규모의 3차원(3D) 우주 지도를 공개하고 기존 우주론에 의문을 제기했다.

The New York Times

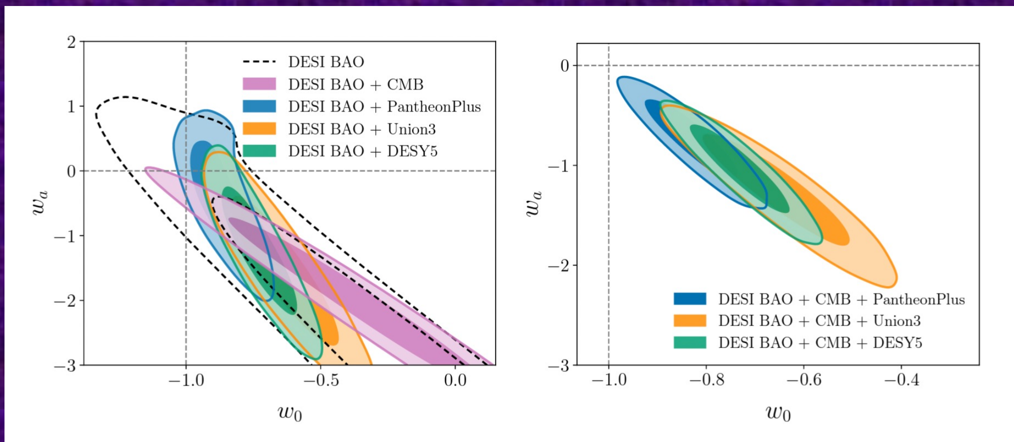
A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

DESI-2024

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



DESI-Y1 (2024), arXiv:2404.03002

Dark energy reconstruction and physics interpretation

KASI Led DESI Projects:

Rodrigo Calderon

Kushal Lodha

arXiv > astro-ph > arXiv:2405.04216

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-SN5YR) 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

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

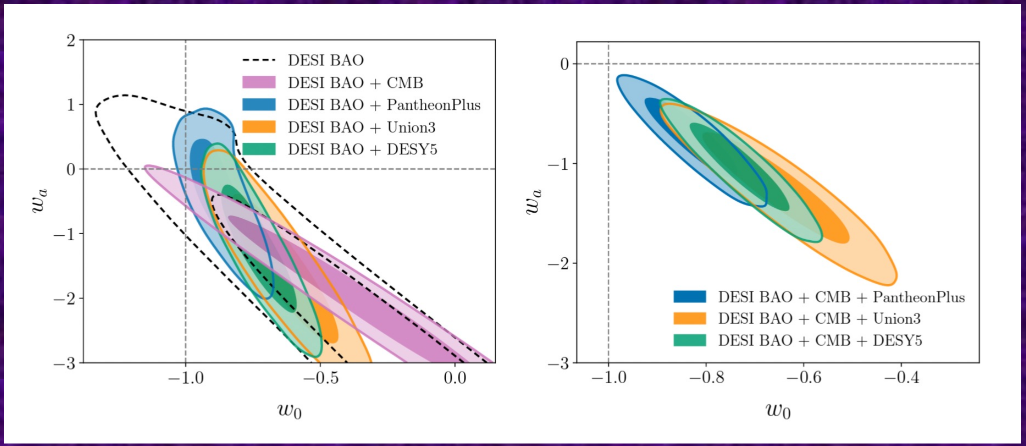
K. Lodha, A. Shafieloo, R. Calderon, E. Linder, W. Sohn, J. L. Cervantes-Cota, A. de Mattia, J. García-Bellido, M. Ishak, W. Matthewson, J. Aguilar, S. Ahlen, D. Brooks, T. Claybaugh, A. de la Macorra, A. Dey, B. Dey, P. Doel, J. E. Forero-Romero, E. Gaztañaga, S. Gontcho A Gontcho, C. Howlett, S. Juneau, 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 ΛCDM, 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_aCDM 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

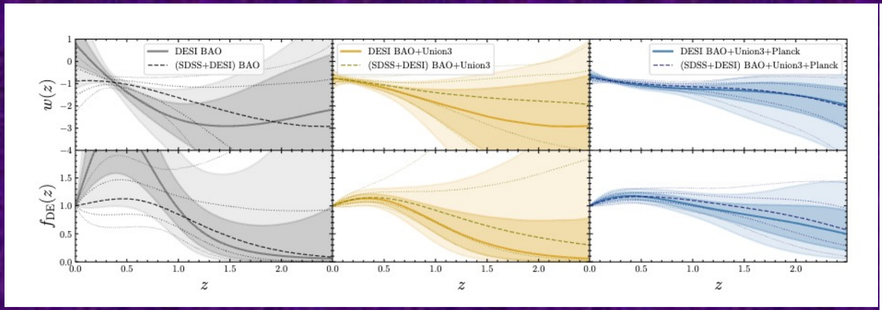
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

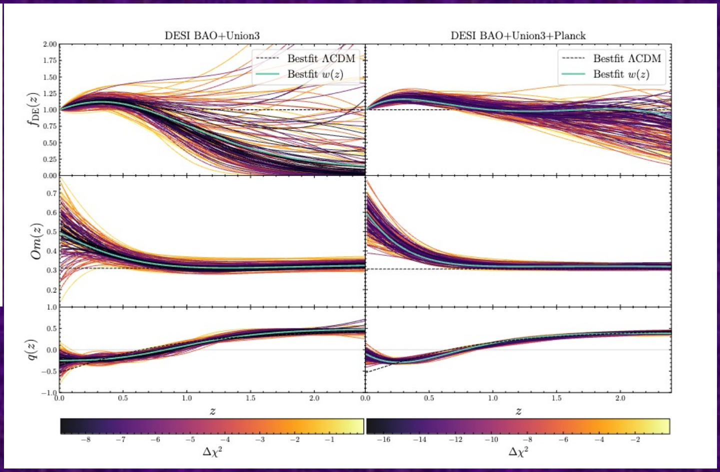


DESI-Y1 (2024),
arXiv:2404.03002

Model-Independent Reconstruction of Dark energy

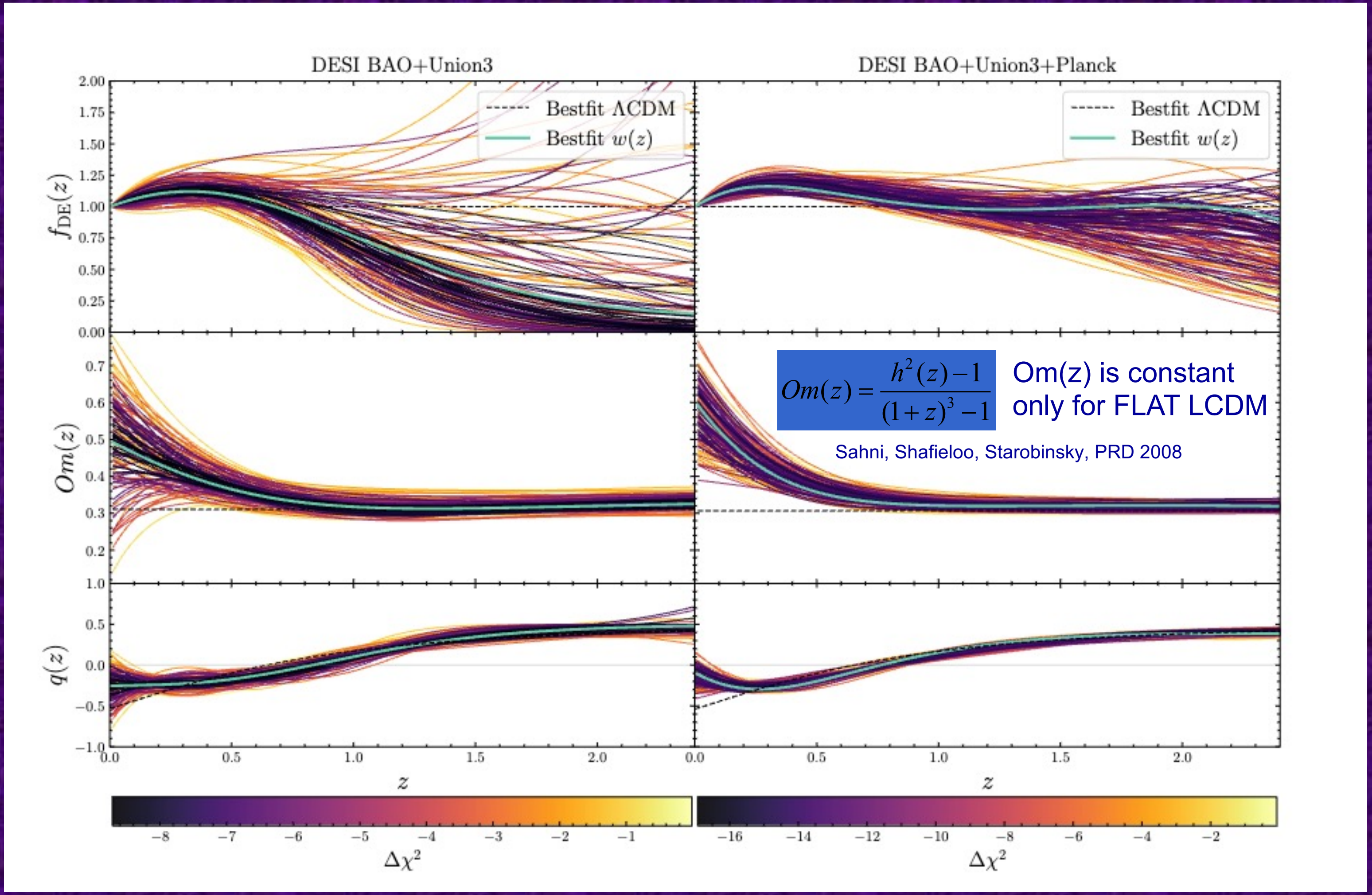
(Blind Tests Conducted)





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



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

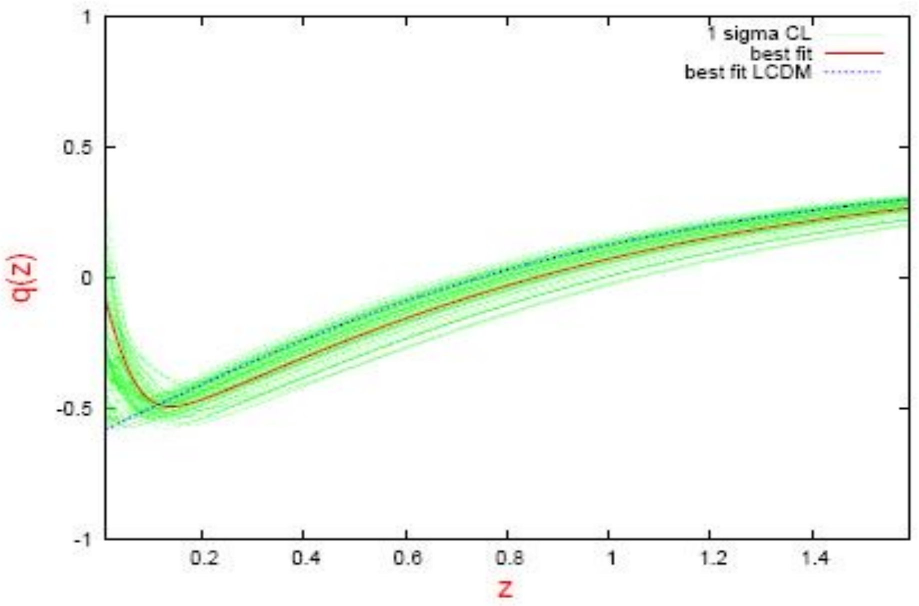
All better than best fit LCDM

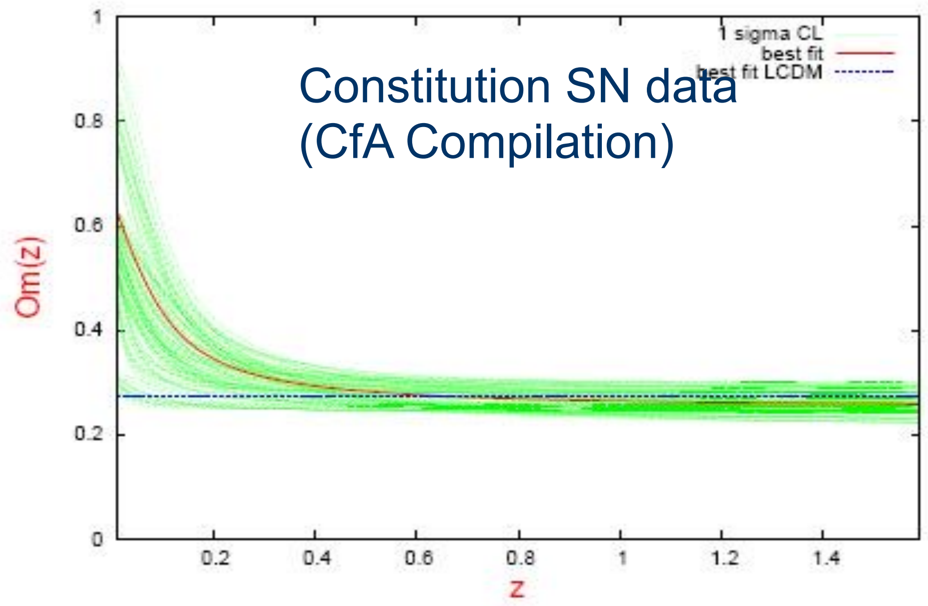
Calderon, Lodha, Shafieloo, Linder et al, JCAP 2024 (arXiv:2405.04216)

Theoretical application of direct reconstruction

(2009)

IS COSMIC ACCELERATION SLOWING DOWN?





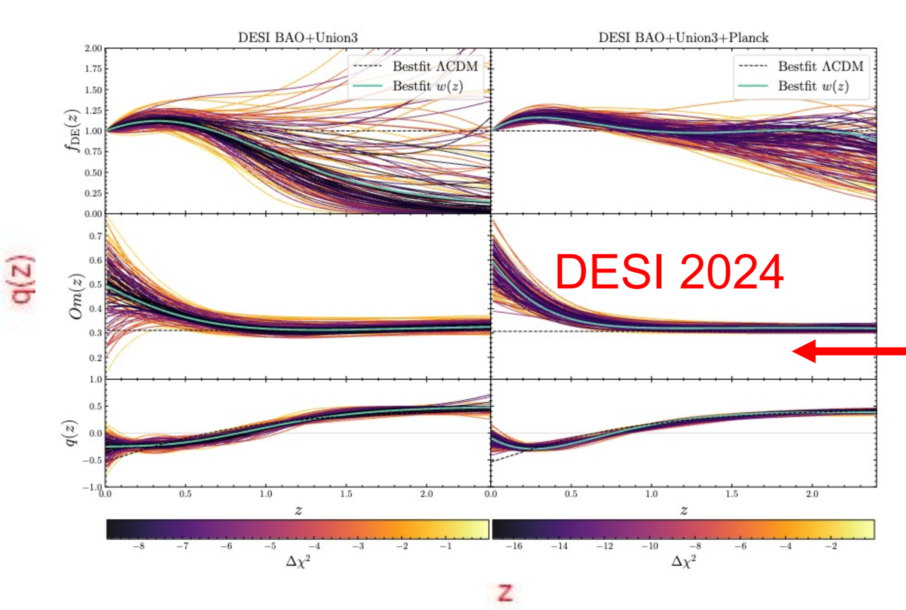
$$w(z) = -\frac{1 + \tanh\left[\left(z - z_t\right)\Delta\right]}{2}$$

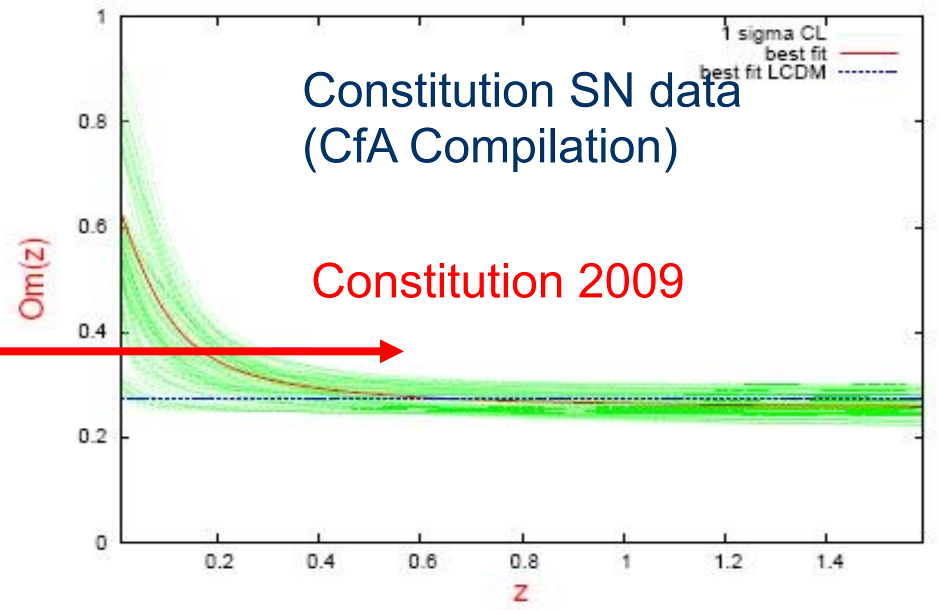
$\Delta\chi^2 = -0.6$ with respect to CPL

A. Shafieloo, V. Sahni, A. Starobinsky, Phys. Rev. D-RC 2009 [Reported in ***Nature*** and ***New Scientist***]

Theoretical application of direct reconstruction

IS COSMIC ACCELERATION SLOWING DOWN ***Again?***





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

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

A. Shafieloo, V. Sahni, A. Starobinsky, Phys. Rev. D-RC 2009 [Reported in Nature and New Scientist]

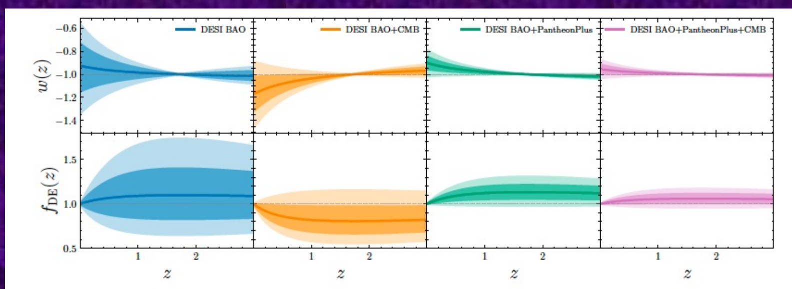
Theoretical application of direct reconstruction

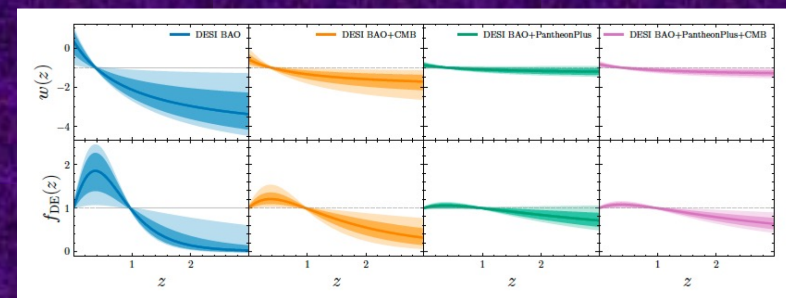
Thawing models, Emergent models and Mirage!

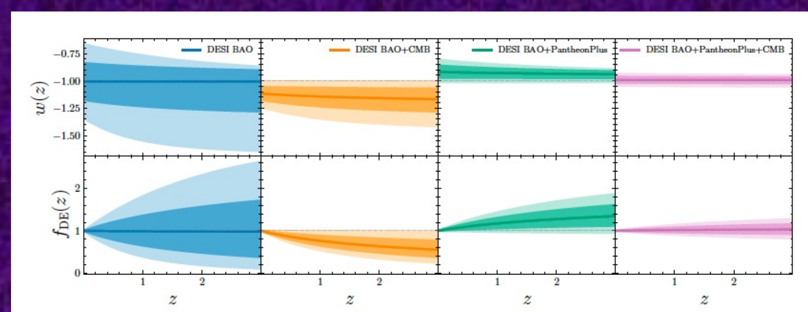
$$w_a \approx -1.58(1 + w_0)\ .$$

$$w(z) = -1 - \frac{\Delta}{3\ln(10)}\left[1 + \tanh\left(\Delta \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)\right]\ .$$

$$w_a = -3.66\,(1 + w_0)\ .$$



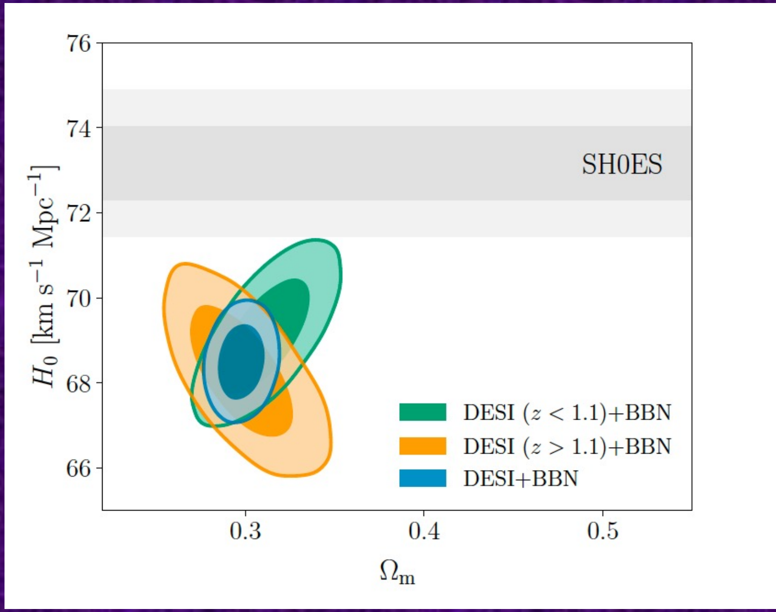


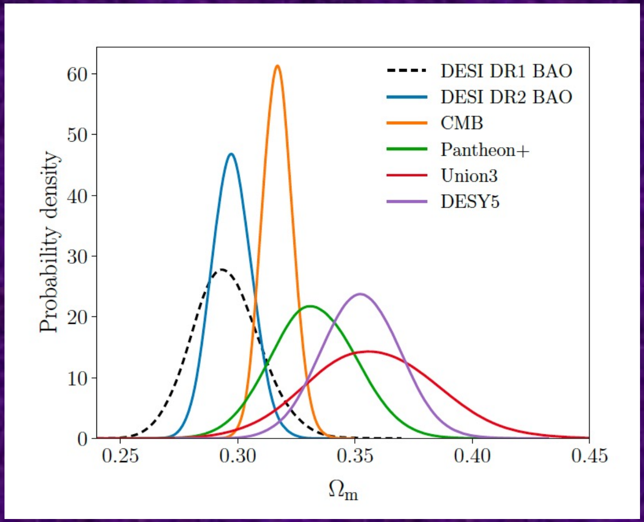


Lodha, Shafieloo, Calderon, Linder et al, PRD 2025 (arXiv:2405.13588)

In B21 = 2.8 (0.65), 4.2 (2.4), 6.4 (2.8) in favor of the mirage class over ΛCDM (w0waCDM) for the DESI+CMB with Pantheon+, Union3, and DES-SN5YR data combinations.

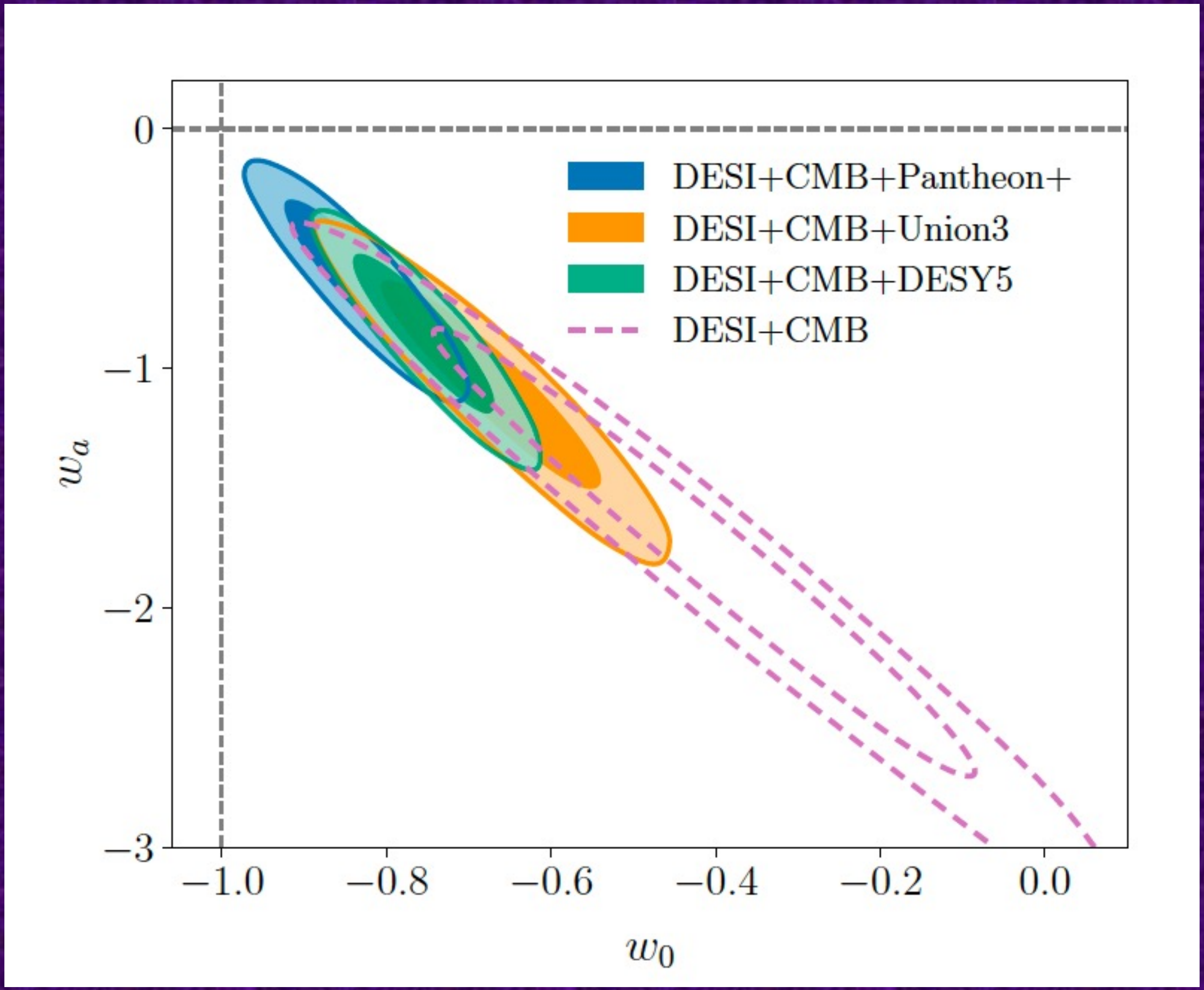
DESI-2025 DR2





Hubble Tension Persist
[Within LCDM model]

DESI-2025 DR2

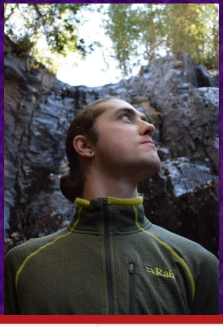


Dynamical Dark Energy, arXiv:2503.14738

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. Garcia-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. Rashkovetskyi, 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_aCDM key paper results. Even with the additional flexibility introduced by non-parametric approaches, such as binning and Gaussian Processes, we find that extending ΛCDM 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)
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]
[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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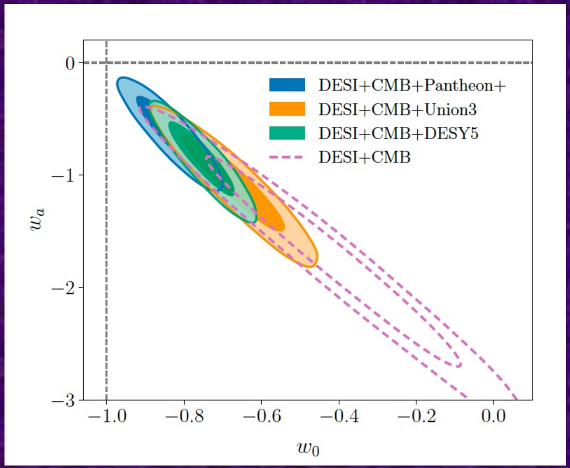
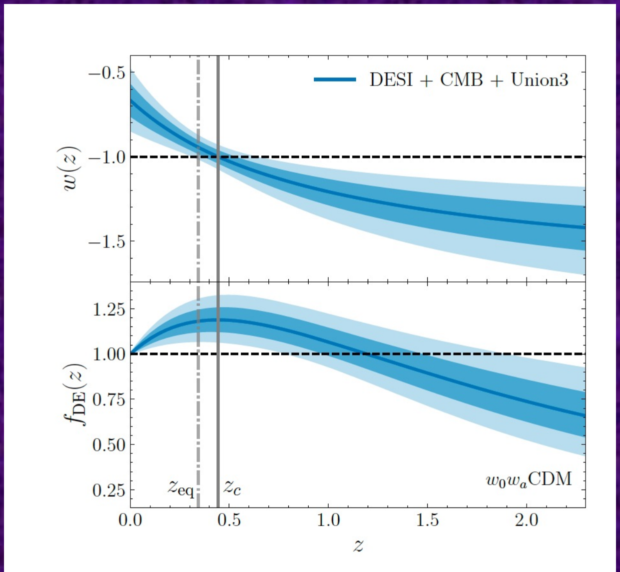
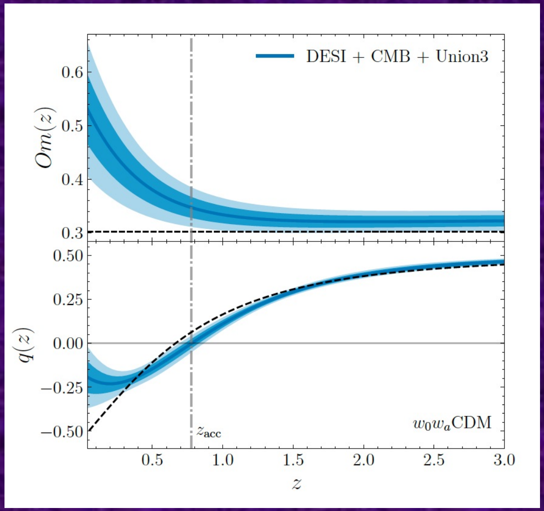
Extended Dark Energy Analysis, Lodha et al, arXiv:2503.14743 (PRD 2025)

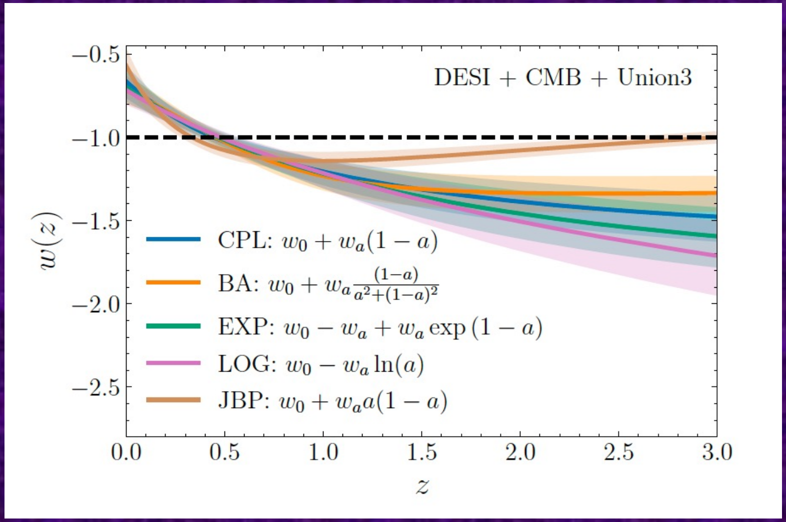
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI-2025 DR2



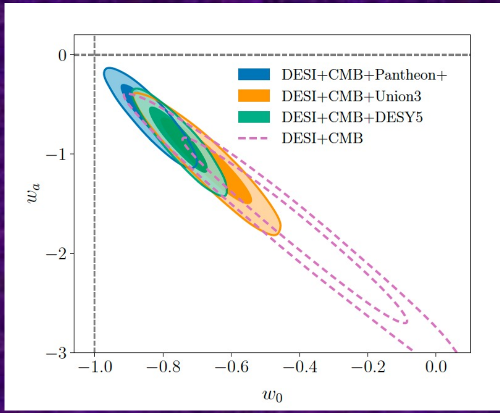


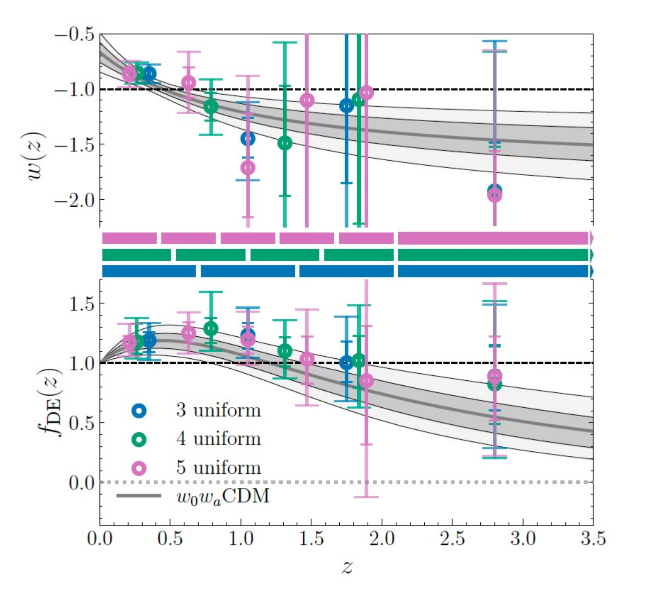


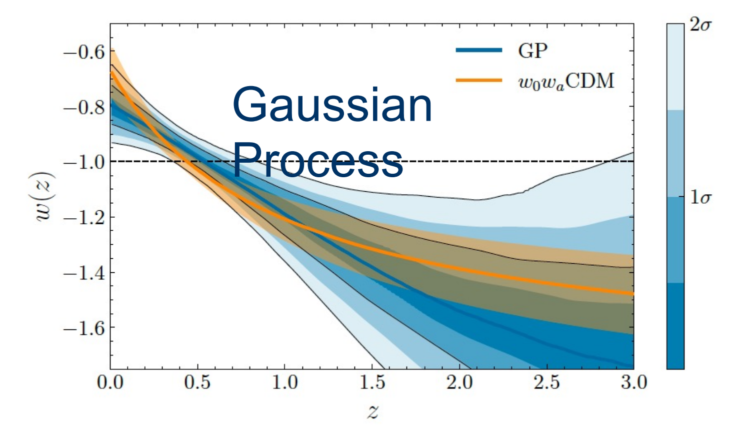


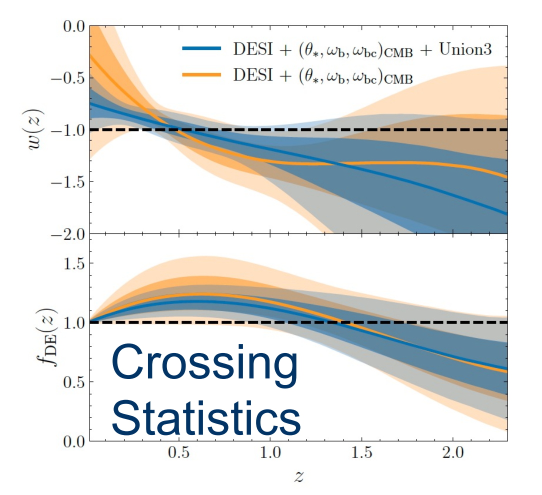
Extended Dark Energy Analysis, Lodha et al, arXiv:2503.14743 (PRD 2025)

DESI-DR2 Extended DE Analysis: Non-Parametric



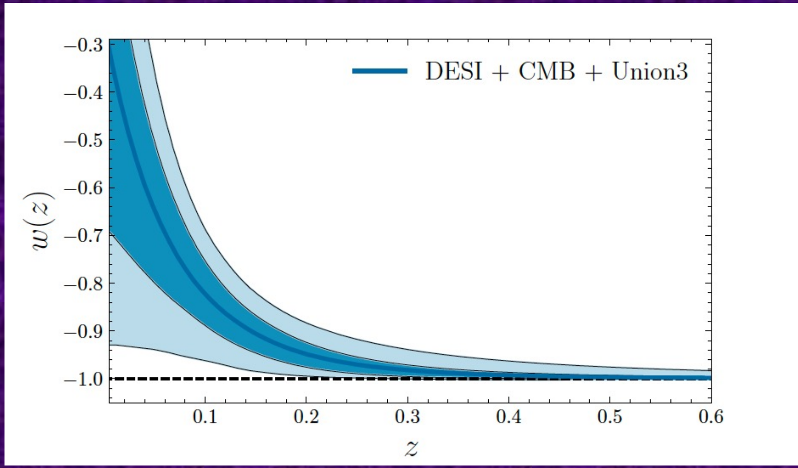


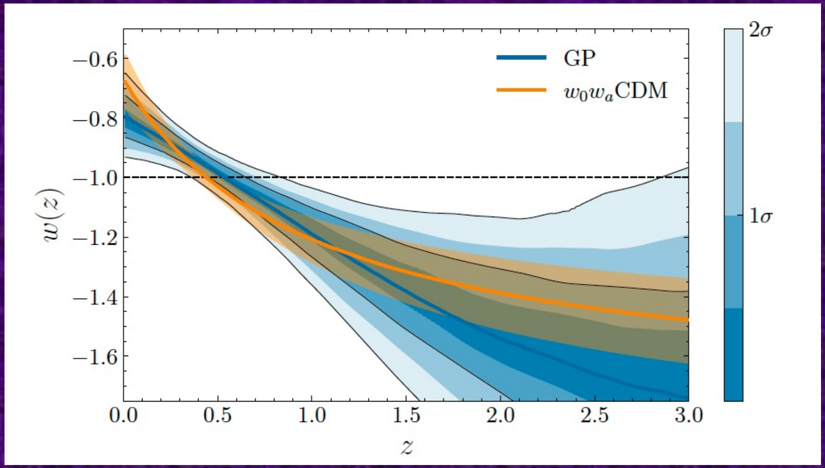




Extended Dark Energy Analysis, Lodha et al, (arXiv:2503.14743) PRD 2025
See also: Gu et al, (arXiv:2504.06118) Nature Astronomy 2025

Is Crossing PDL is Real?





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

Crossing w=-1

A big key question!

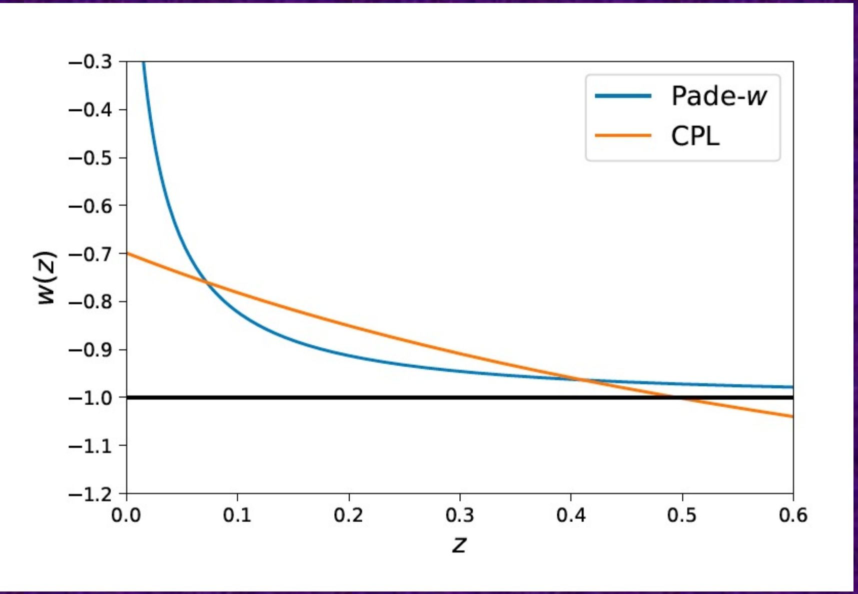
How to compare models that are not nested within one another?

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

CPL

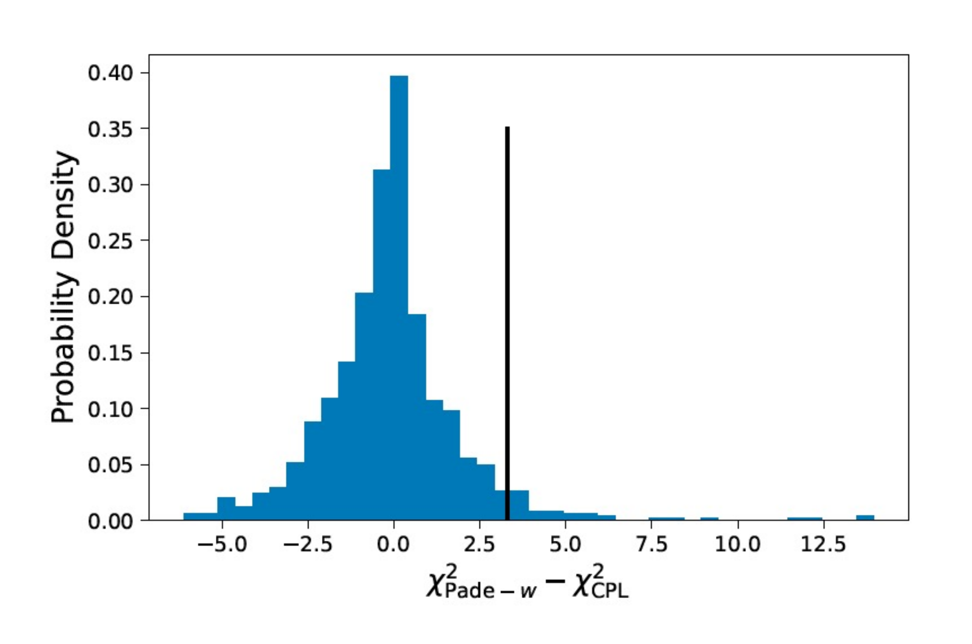
$$w(z) = \frac{2\epsilon_0}{3 + \eta_0(z^3 + 3z^2 + 3z)} - 1,$$

Algebraic Quintessence



-Best fit models to DESI DR2+Union3+Planck
-Same degrees of freedom
-Chi^2 difference of ~3.4

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



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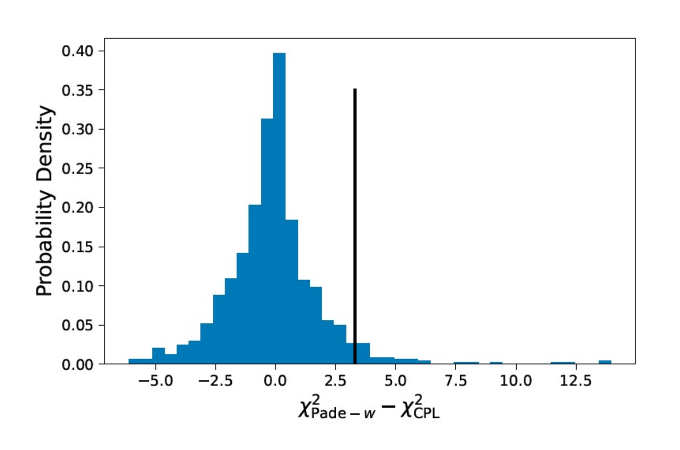
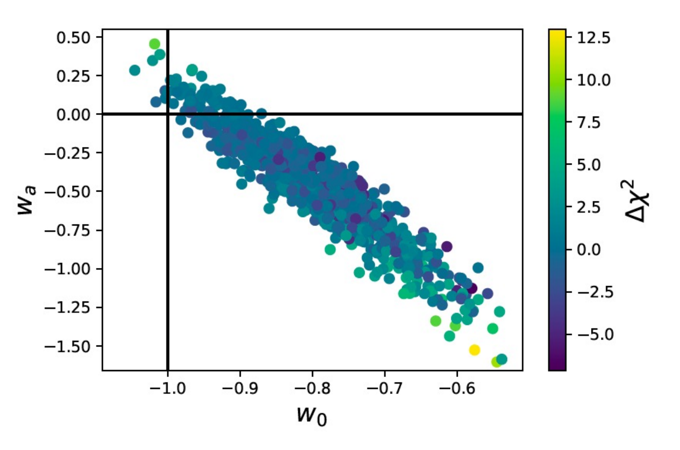
$$w(z) = \frac{2\epsilon_0}{3 + \eta_0(z^3 + 3z^2 + 3z)} - 1,$$

Frequentist Approach

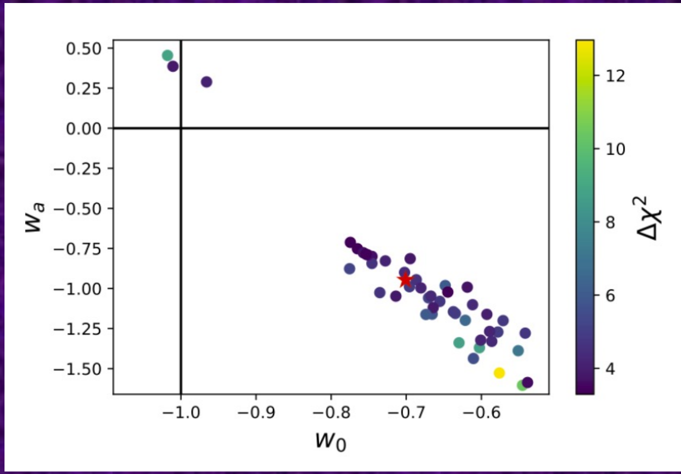
- 1000 realisations of the data based on best fit Pade-w
- ~36% cases CPL with phantom crossing has a better fit than true model (Pade-w)
- **~3.2% cases, the CPL yields a Δχ2 (wrt Pade-w) larger than that observed in the real data.**

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





Keeley, Shafieloo, Matthewson, arXiv::2506.15091



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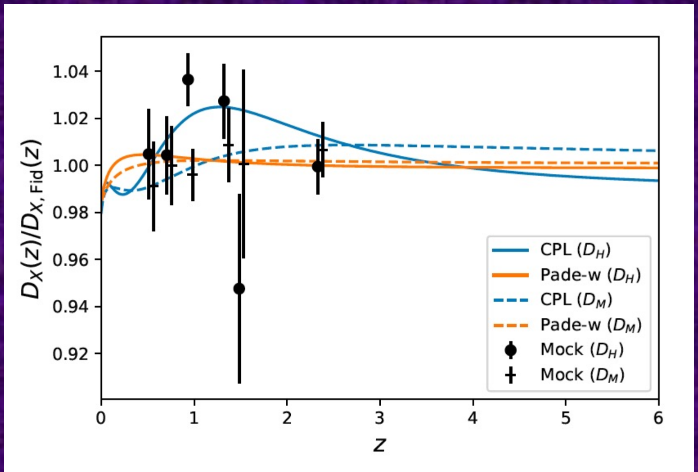

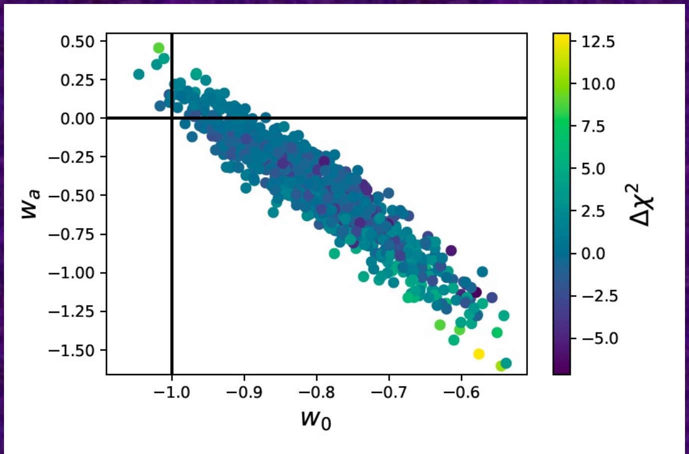

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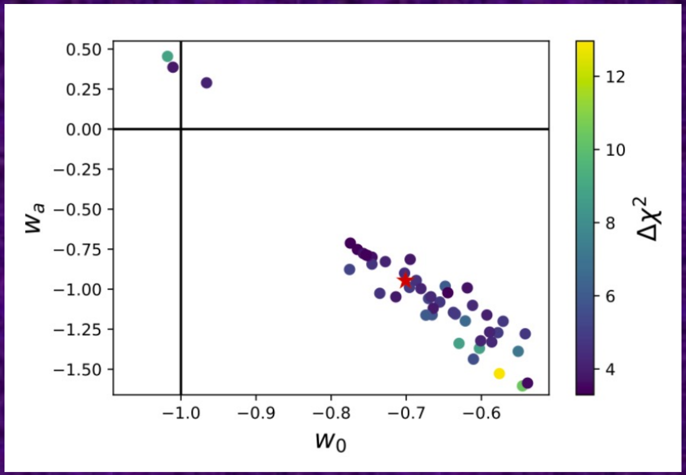

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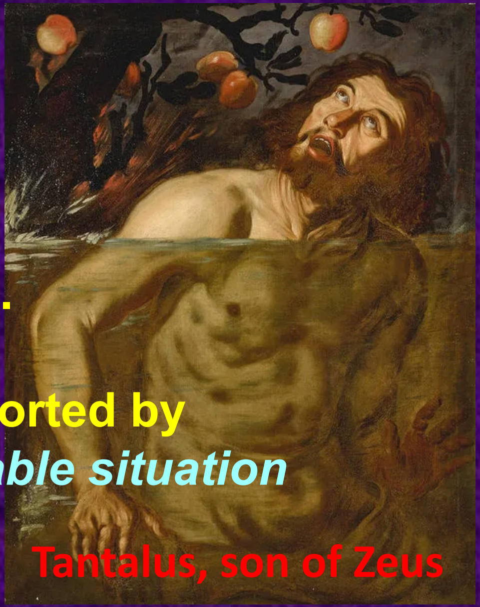
Current Status and Summary



- 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.

Will they remain significant?

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

- 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,….