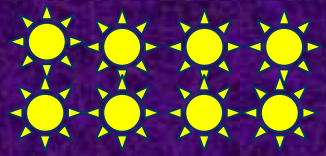
Reconstructing Dark Energy

Arman Shafieloo,

Korea Astronomy and Space Science Institute (KASI)

University of Science and Technology (UST)

11th KIAS Workshop on Cosmology and Structure Formation

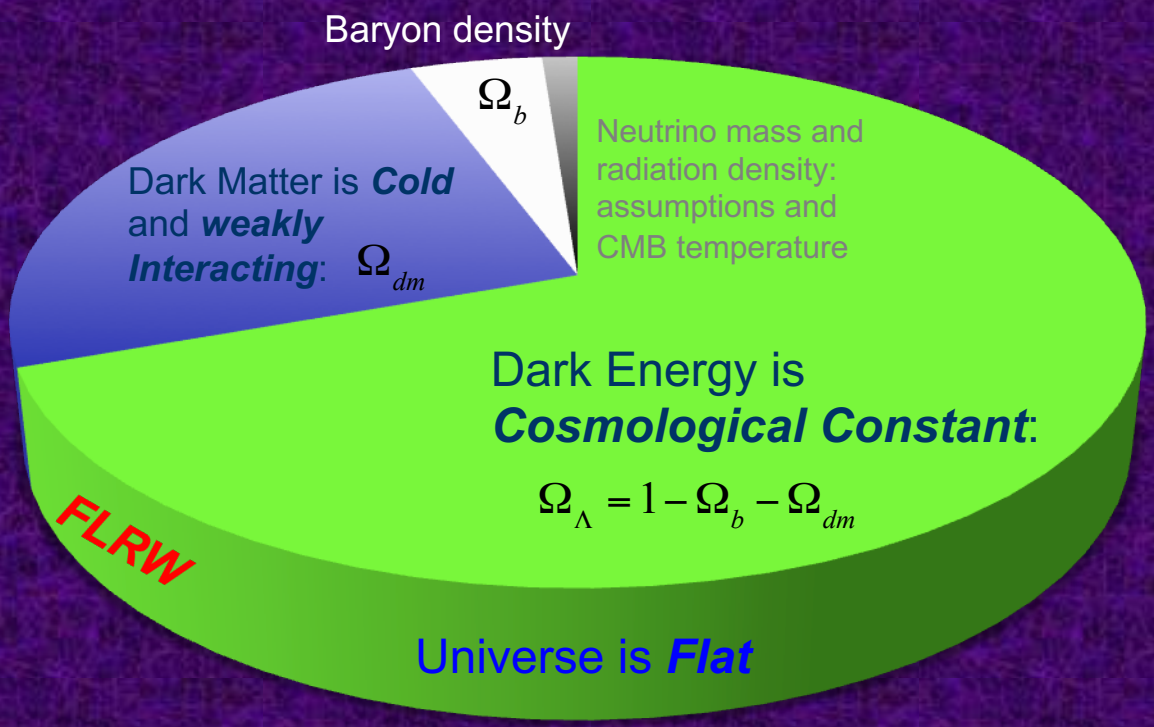


경주 (Kyeongju)

28-32 October 2024

Standard Model of Cosmology

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



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

n_s, A_s

Epoch of reionization

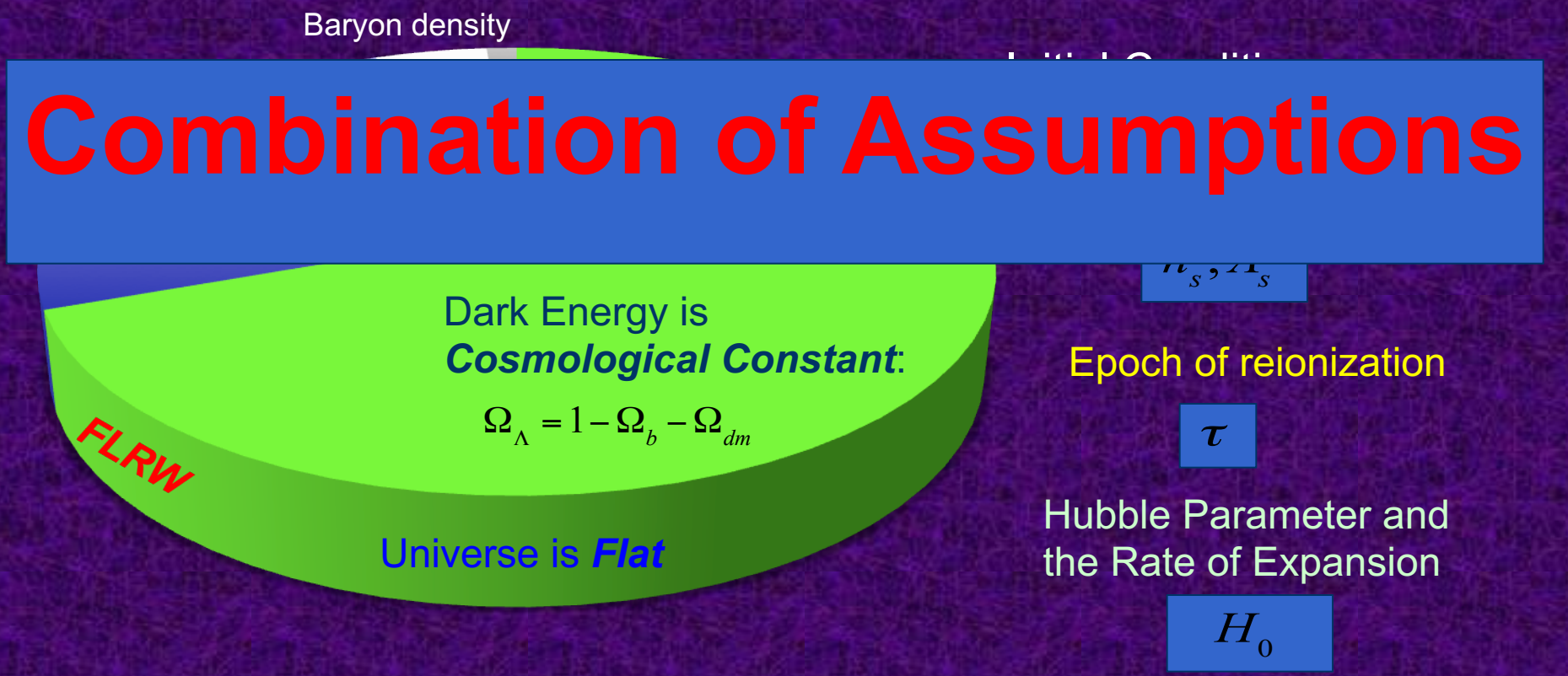
τ

Hubble Parameter and the Rate of Expansion

H_0

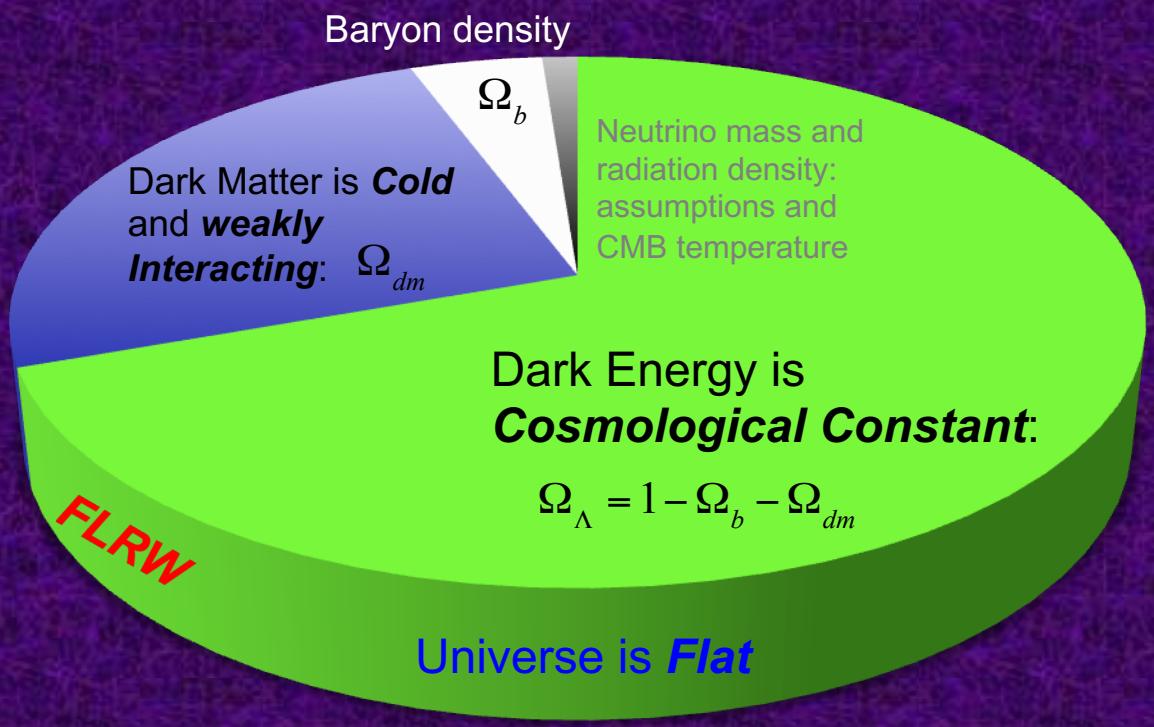
Standard Model of Cosmology

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



Standard Model of Cosmology

combination of *reasonable* assumptions, but…..



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

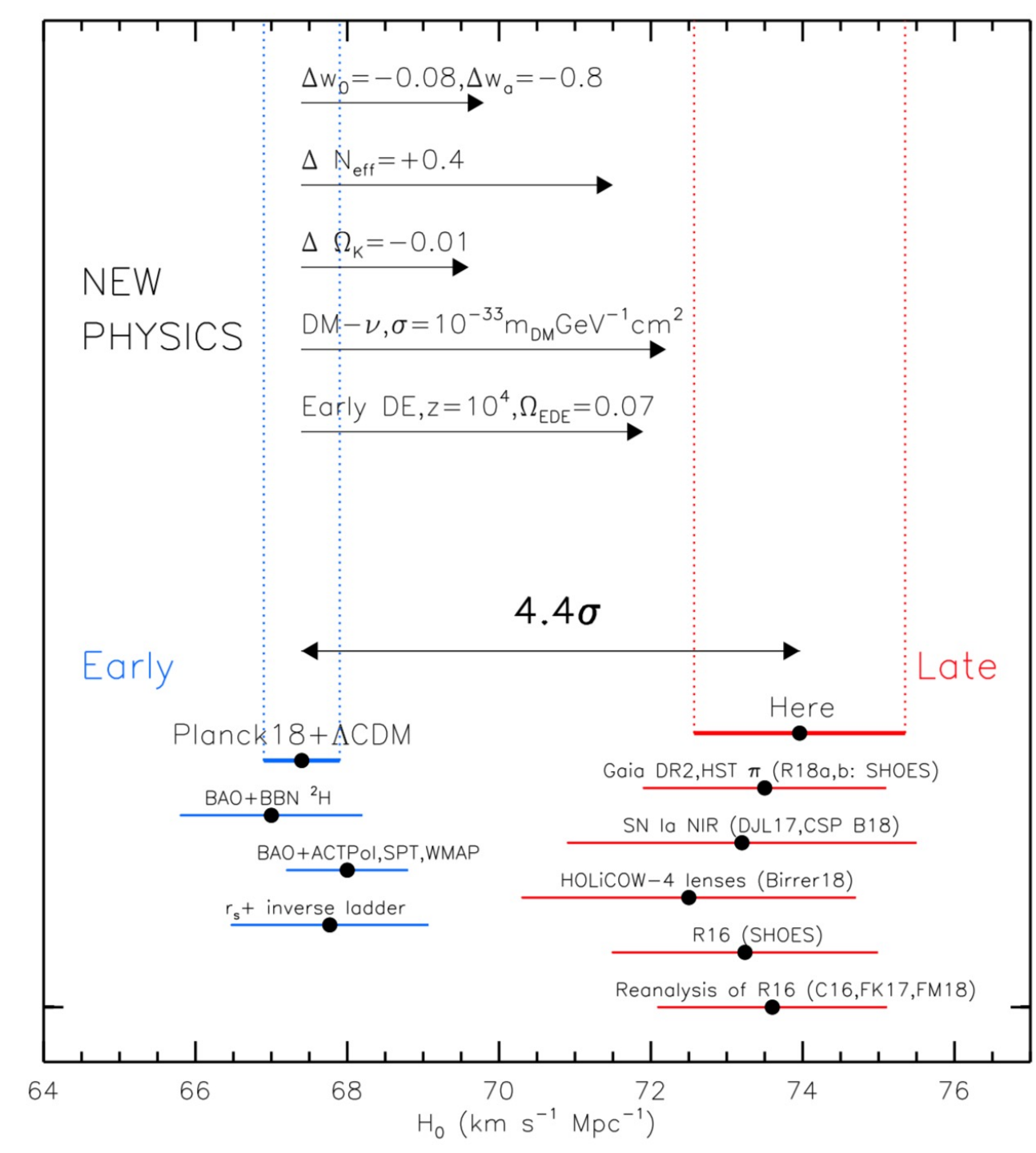
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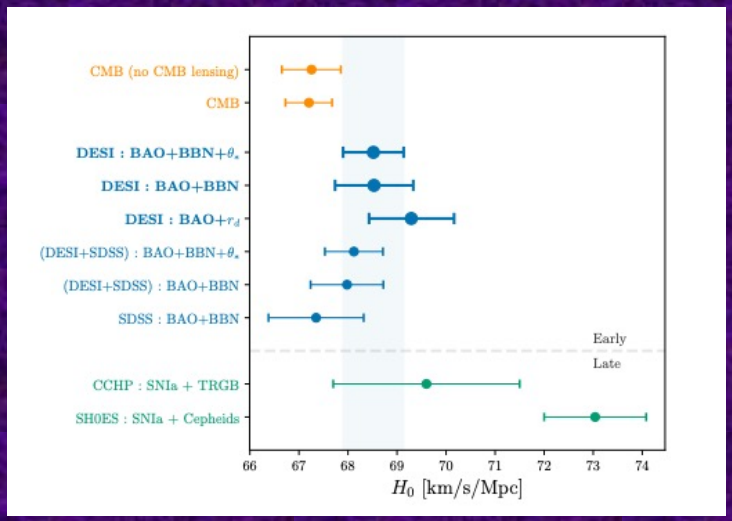
Tensions in the Standard Model

Riess et al, ApJ 2019 [arXiv:1903.07603]

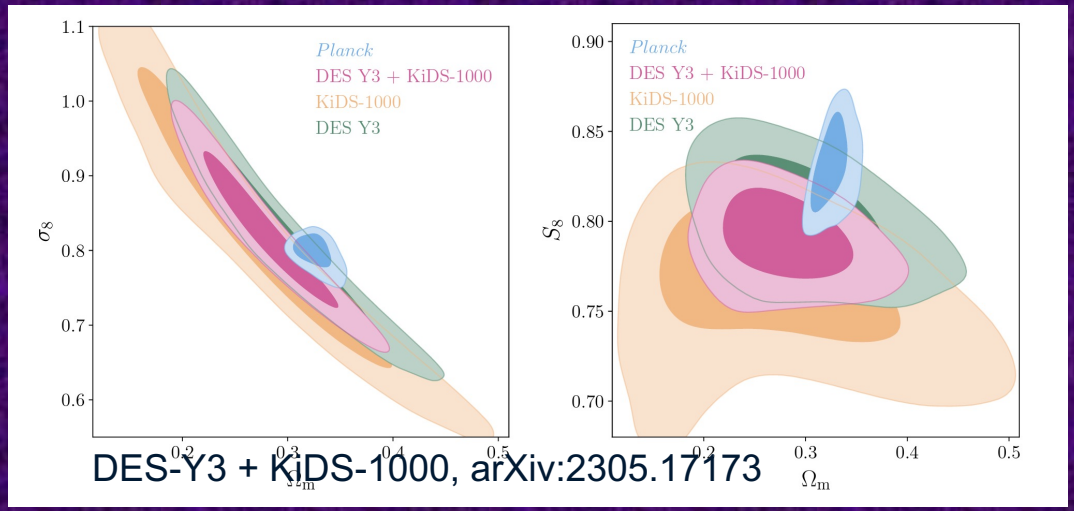
Tensions in the Standard Model

It is not only about H0 and CMB





DESI-Y1 (2024), arXiv:2404.03002



DES-Y3 + KiDS-1000, arXiv:2305.17173

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, Keely & Shafieloo, PRL 2023)

- 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

Does LCDM need modification? Which part?

(Present)

Standard Model of Cosmology

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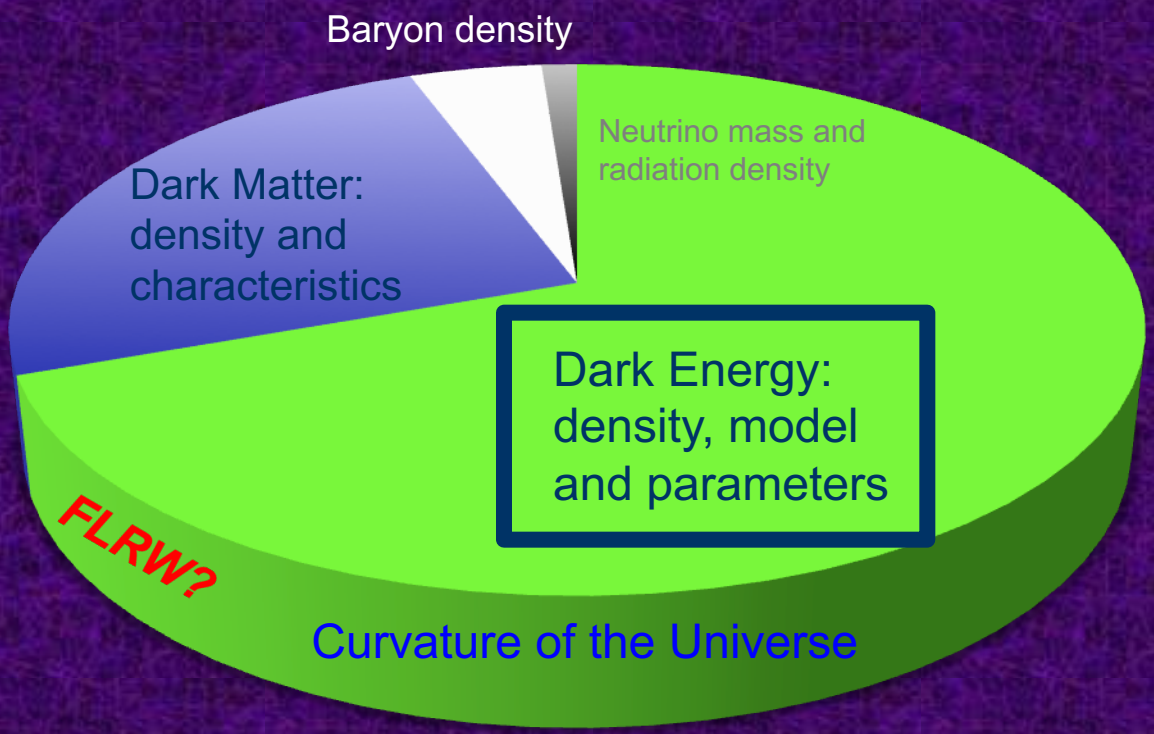
DE is directly relates to expansion history and growth of structure.

Understanding DE is important, with or without tensions.

Reconstruction & *Falsification*

Reconstruction: Understanding the behavior

Falsification: Testing the Consistency and Validation



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

Epoch of reionization

Hubble Parameter and the Rate of Expansion

Reconstructing Dark Energy

To find cosmological quantities and 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.

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Reconstructing Dark Energy

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Reconstruction → Phenomenology → 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

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

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

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

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

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

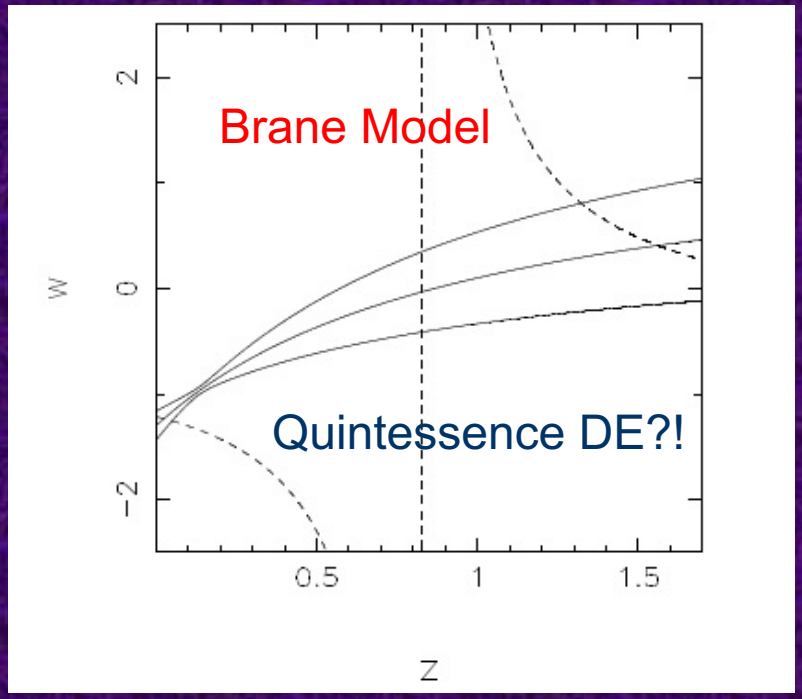
$$\frac{H^2(z)}{H_0^2} = \left[\Omega_{0M}(1+z)^3 + (1-\Omega_{0M})X(z)\right]$$

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

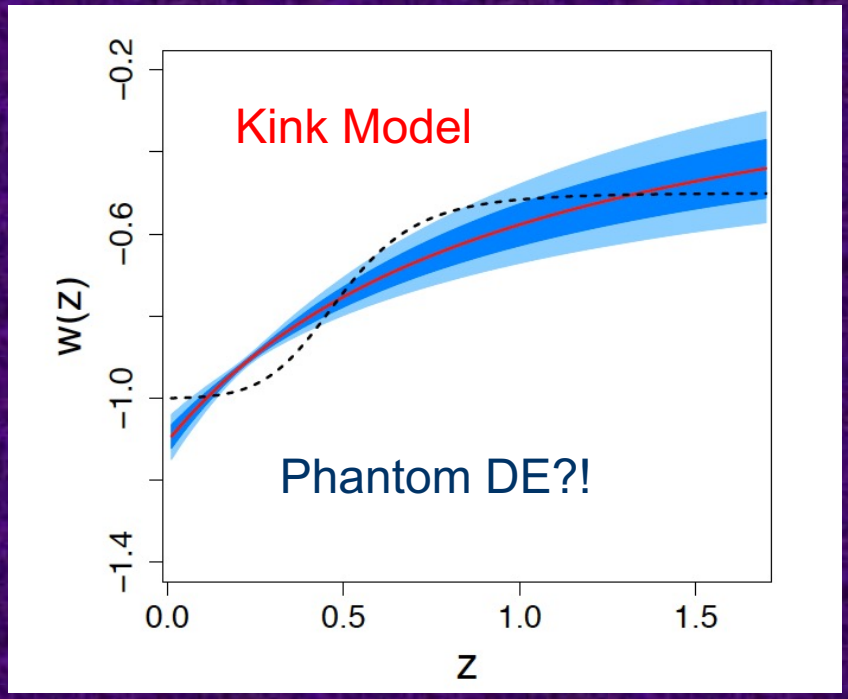
Most general form

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

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

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

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

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

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

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

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

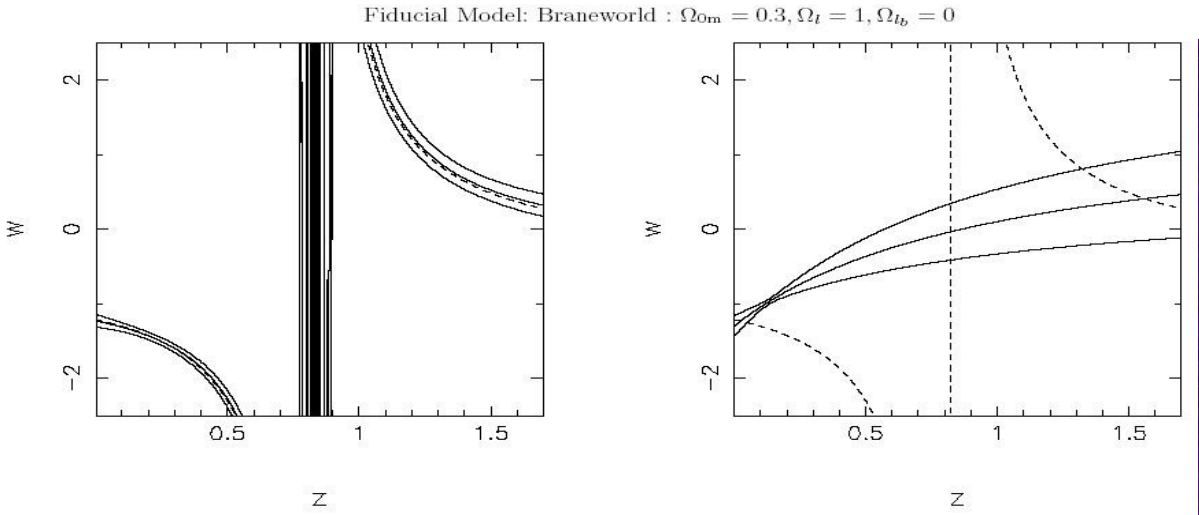
- Starts from initial guess of distance modulus, but generates model-independent reconstruction of distance modulus with lower χ^2 value after numerous iterations

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

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

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

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



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

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

For Model Validation!

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

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

Model Validation

Bayesian evidence approach is solid but only can find the better model among the candidates (or less wrong model/ranking models)

Importance of Model Validation

One can design robust statistical approaches for model validation using non-parametric methods

$\Delta \log Z > 3$	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

Conventional Bayesian Evidence Approach

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

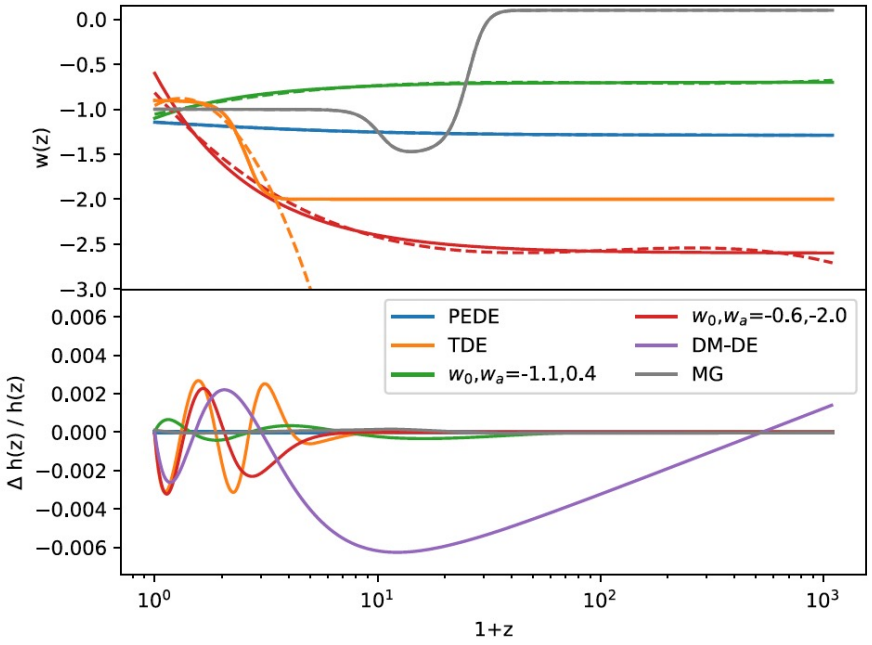
Iterative smoothing validation approach

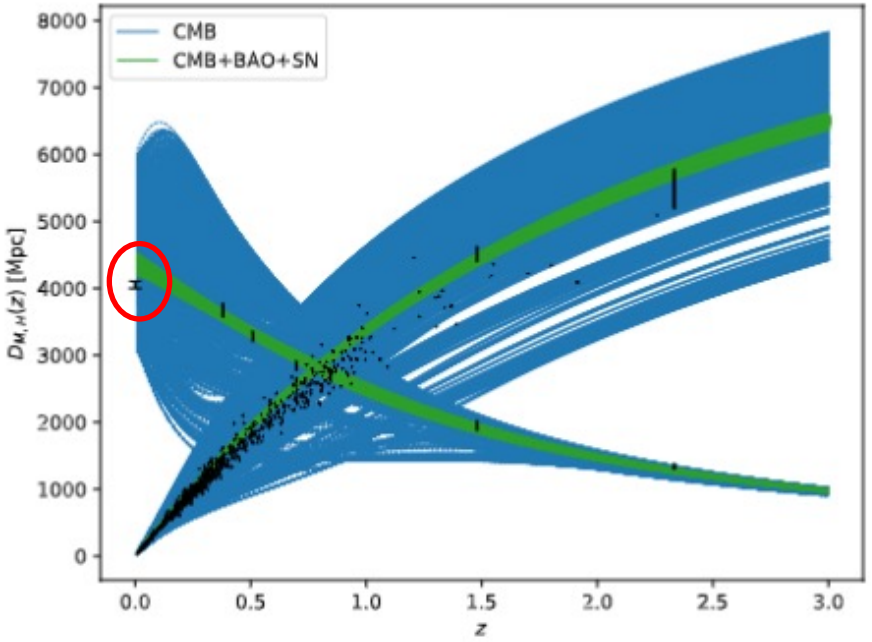
Both models are wrong!

Koo, Keeley, Shafieloo, L'Huillier, JCAP 2022

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

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.

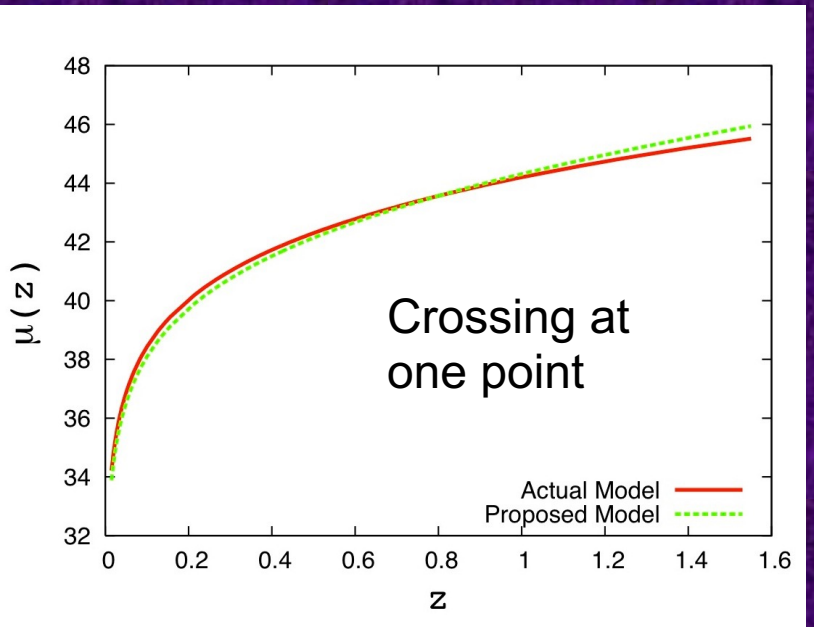
Bayesian Interpretation of Crossing Statistic:

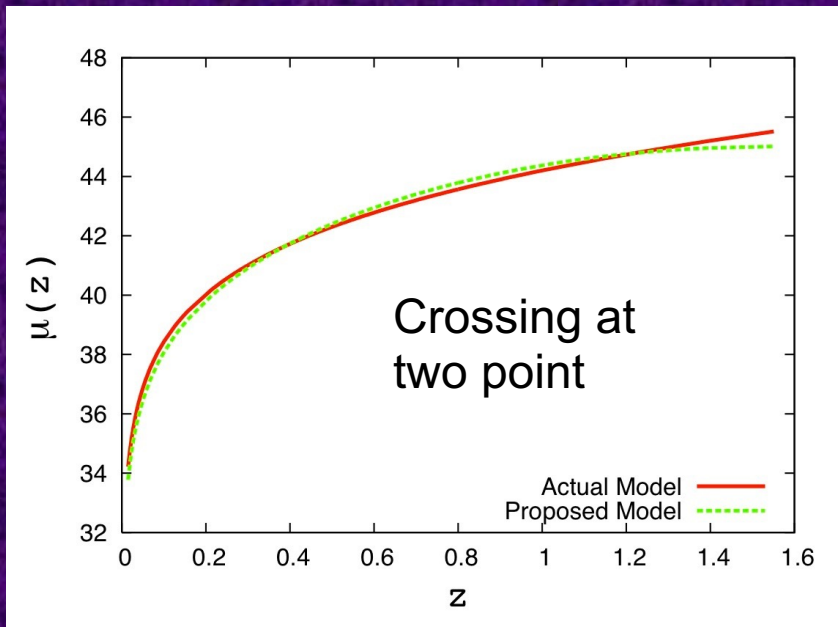
Comparing a model with its own possible variations using a hyperfunction with orthogonal basis.

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.

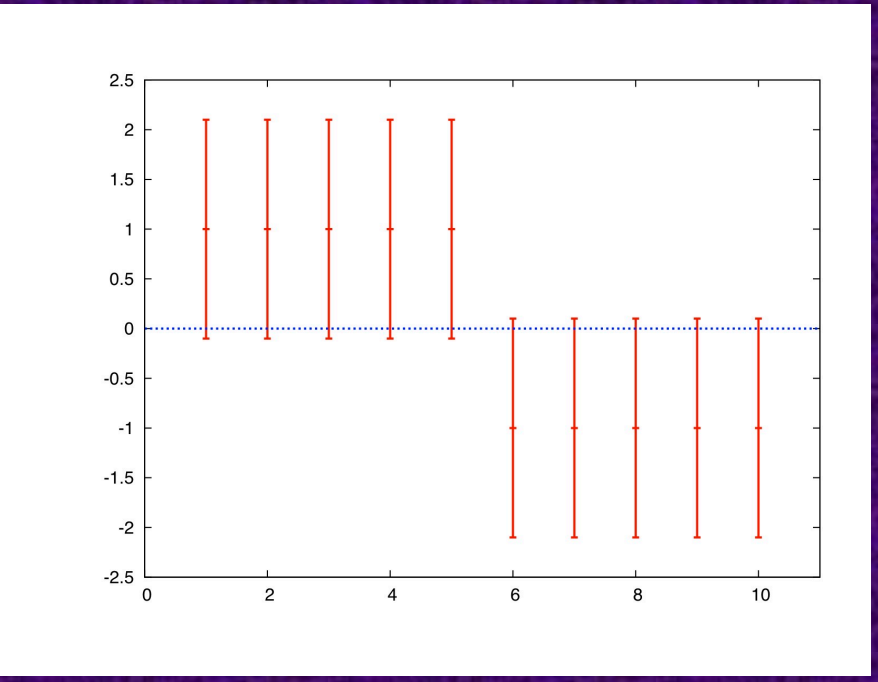
A. Shafieloo, T. Clifton & P. Ferreira, JCAP 2010.

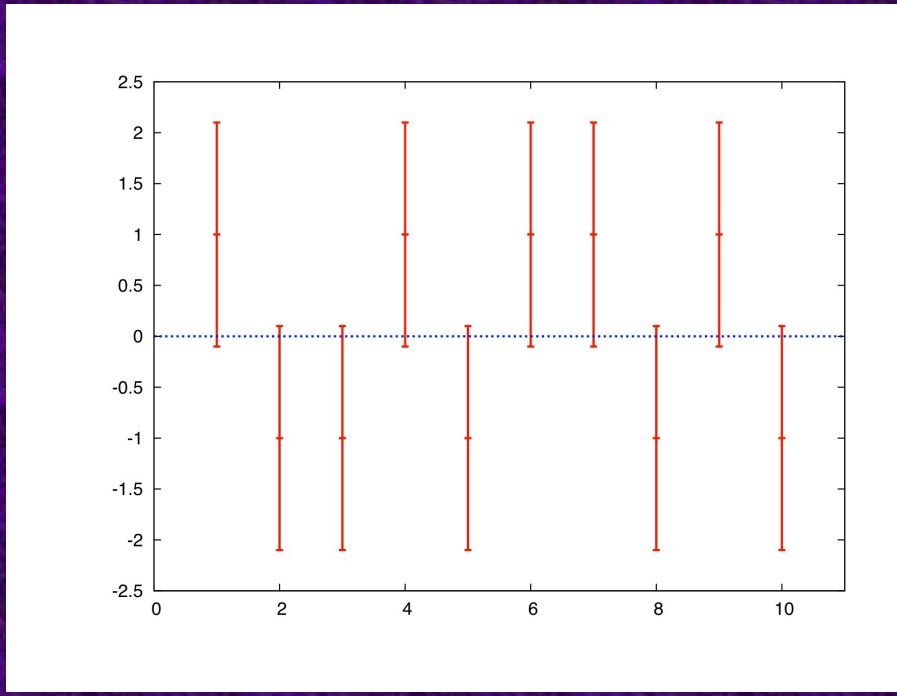




Equal in being probable?!

When chi^2 is not sensitive….





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

One point Crossing: T1

1. Assume a model

2. Construct the normalized residuals

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

4. Comparing the results with Monte Carlo simulations.

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

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

$$Q_1(n_1) = \sum_{i=1}^{n_1} q_i(z_i)$$

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

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

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

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

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 $\Omega_{0m}^{erroneous} = 0.22$

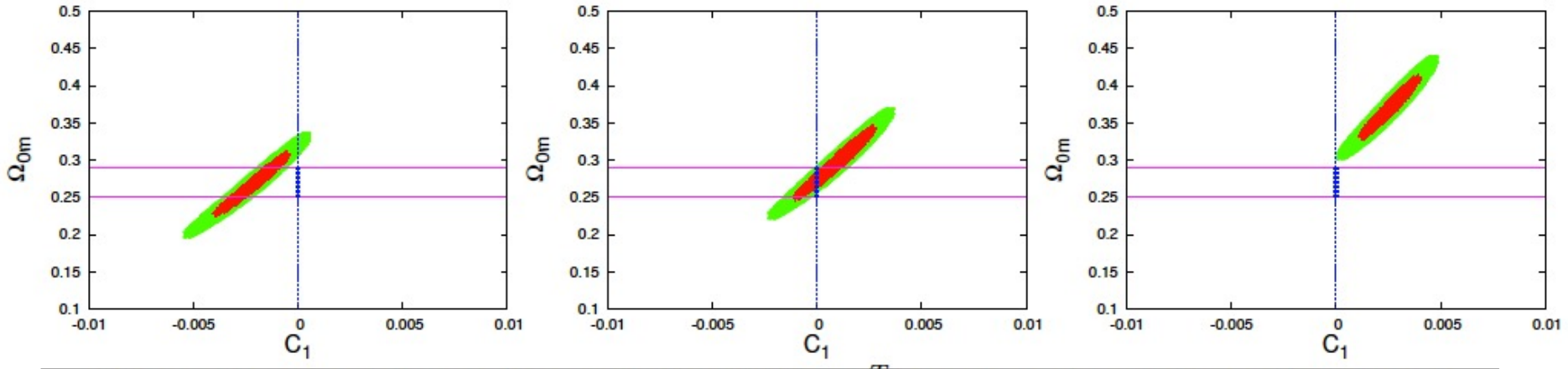
Simulated SN Ia data similar to Constitution compilation

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



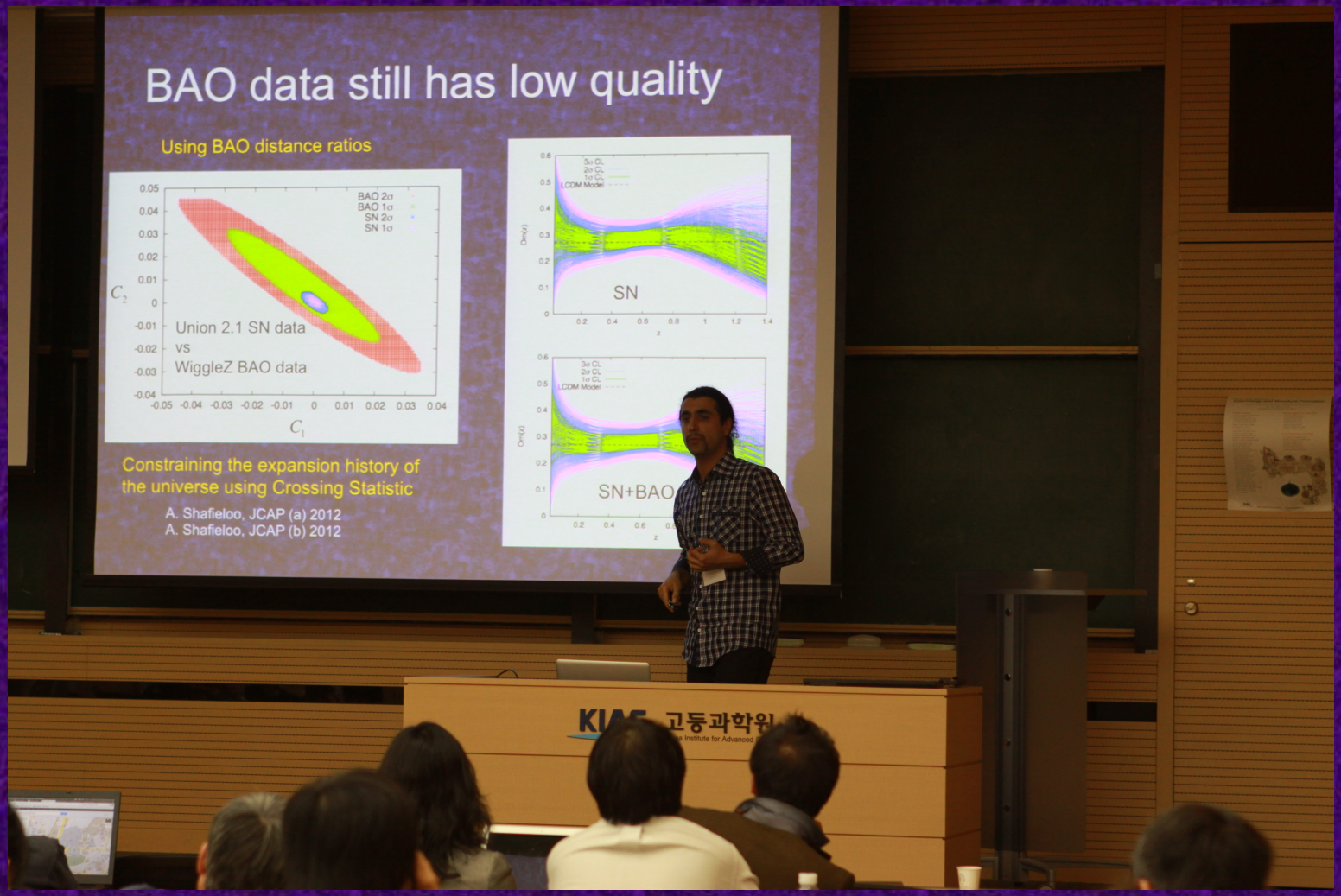
$$T_I(C_1, z) = 1 + C_1(\frac{z}{z_{max}})$$

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)

Some History….



5th KIAS Workshop on Cosmology and Structure Formation, October 2012

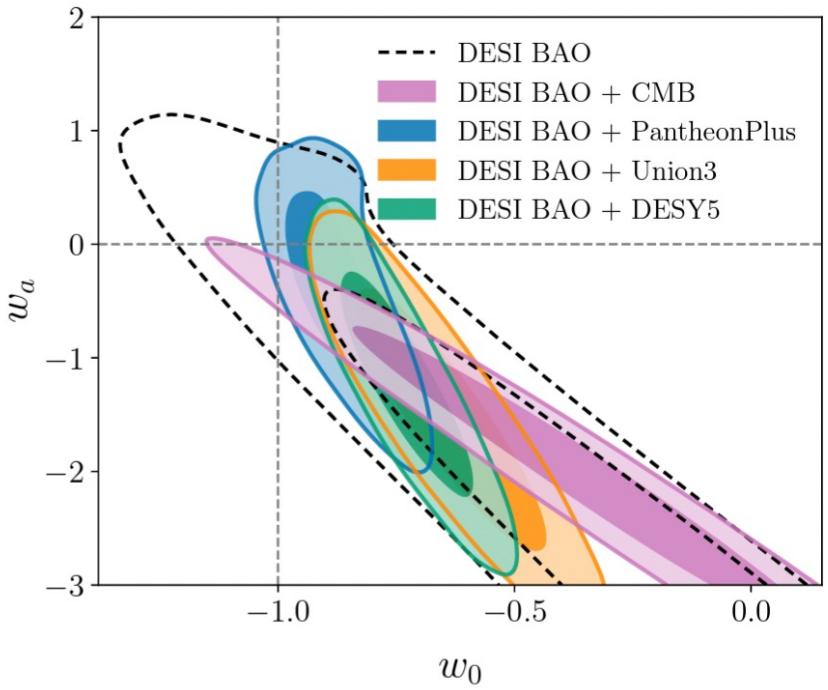
Find your younger self ☺

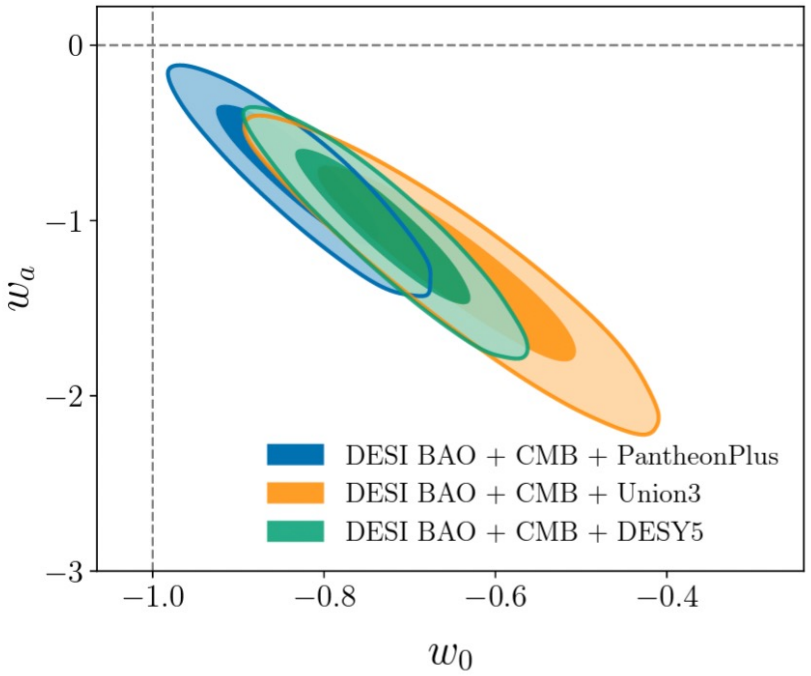


The 5th KIAS Workshop on

Cosmology and Structure Formation

DESI-2024





DESI-Y1 (2024),
arXiv:2404.03002


동아사이언스

암흑에너지 규명 위해 1년간 데이터 모아보니 "기존 우주론 맞나"



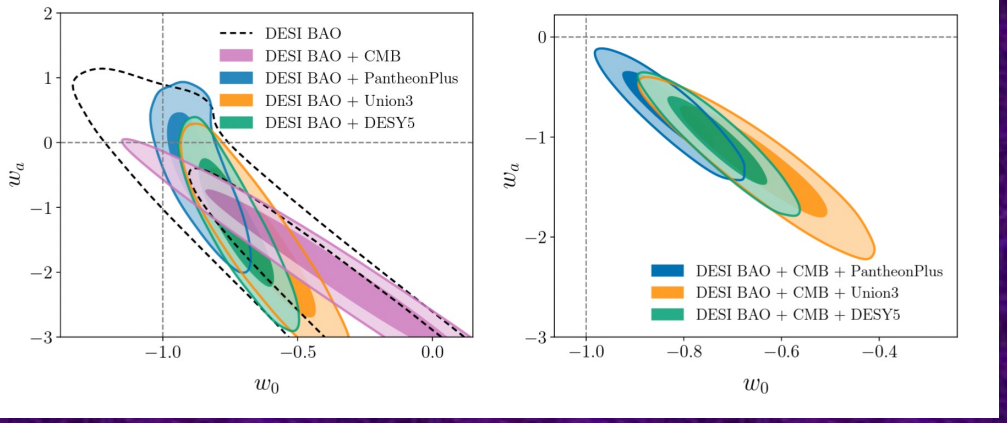

The New York Times

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 reconstruction and physics interpretation



DESI-Y1 (2024), arXiv:2404.03002

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)]

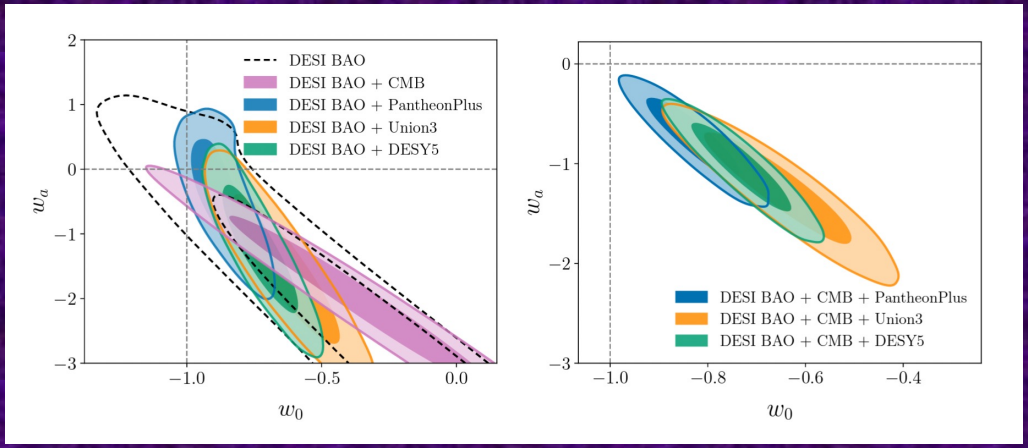
DESI 2024: Constraints on Physics-Focused Aspects of Dark Energy using DESI DR1 BAO Data

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.

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DESI-2024

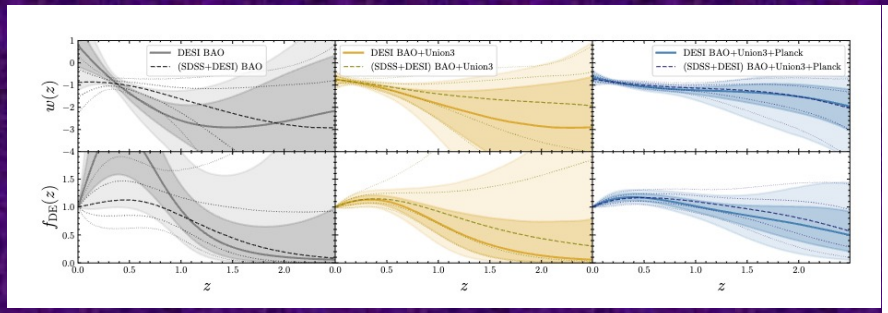


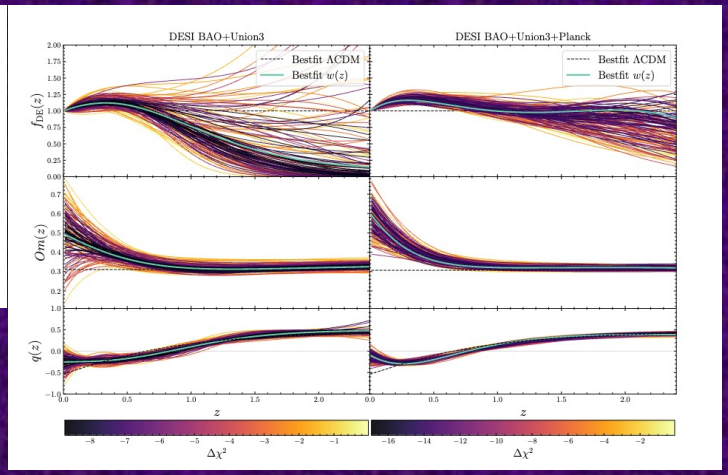
DESI-Y1 (2024),
arXiv:2404.03002

Model-Independent Reconstruction of Dark energy



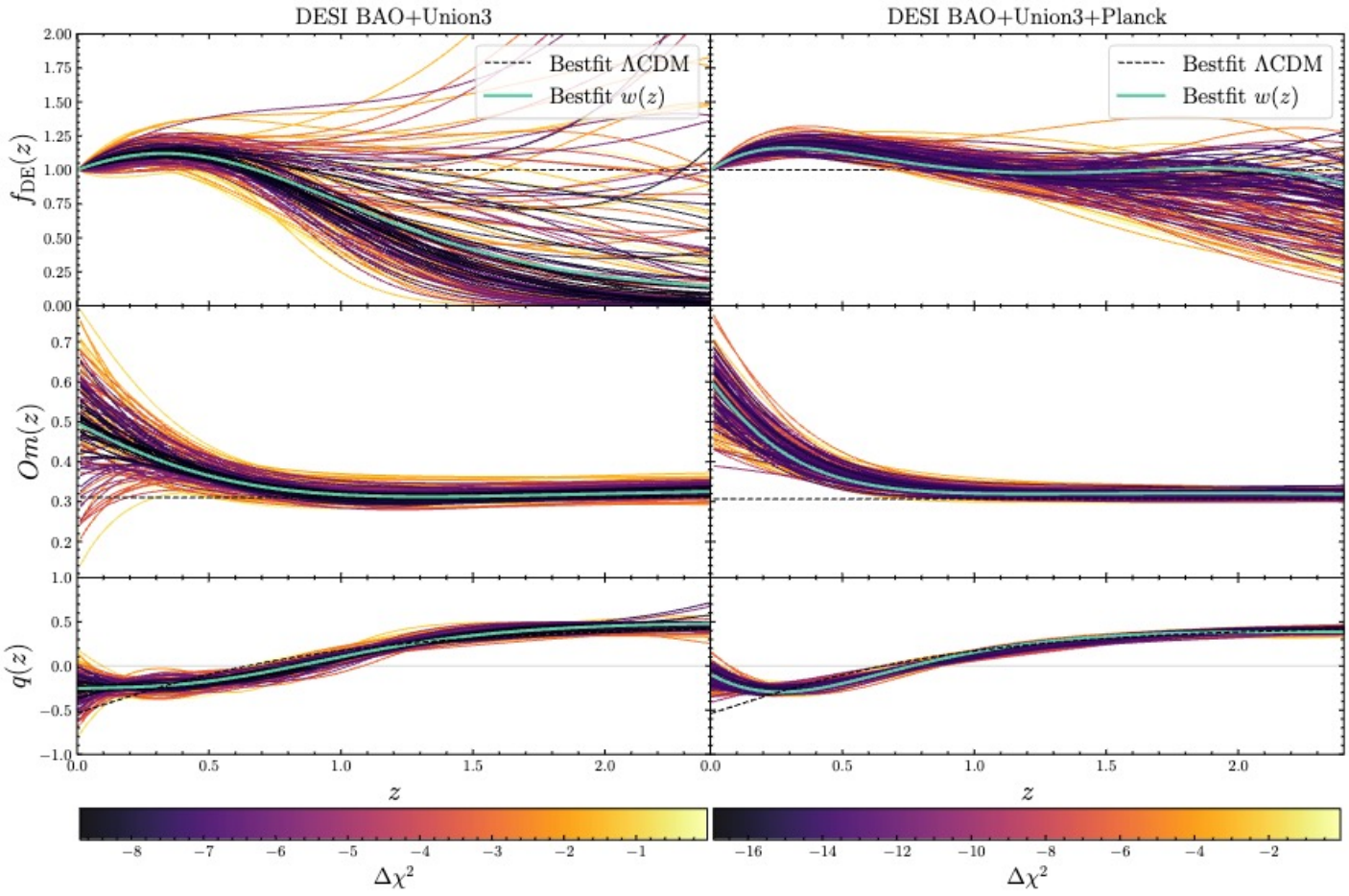






Reconstructing DE with Crossing Statistics
Calderon, Lodha, Shafieloo, Linder et al, JCAP 2024
(arXiv:2405.04216)

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

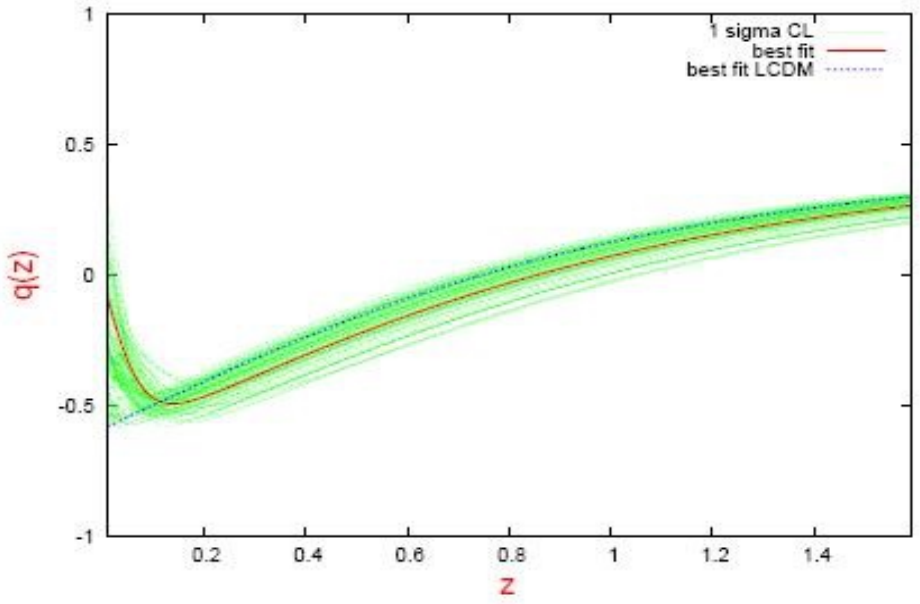


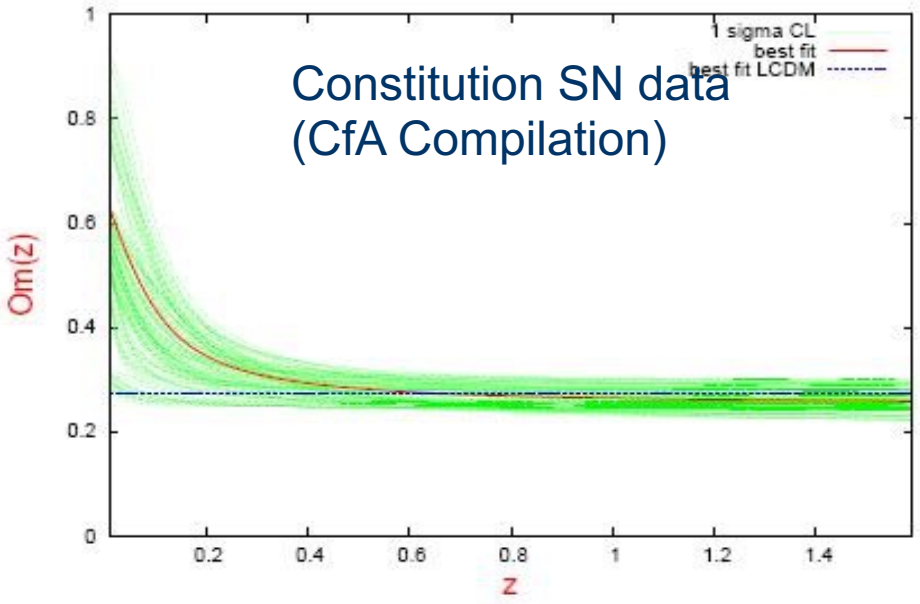
Calderon, Lodha, Shafieloo, Linder et al, JCAP 2024 (arXiv:2405.04216)

Theoretical application of direct reconstruction

(2009)

IS COSMIC ACCELERATION SLOWING DOWN?





Constitution SN data
(CfA Compilation)

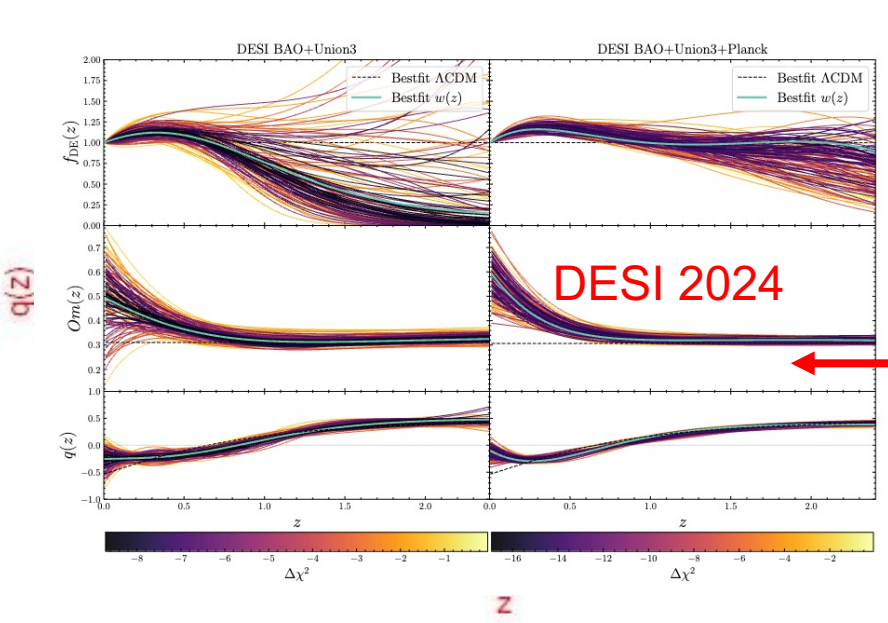
$$w(z) = -\frac{1+\tanh\left[\left(z-z_t\right)\Delta\right]}{2}$$

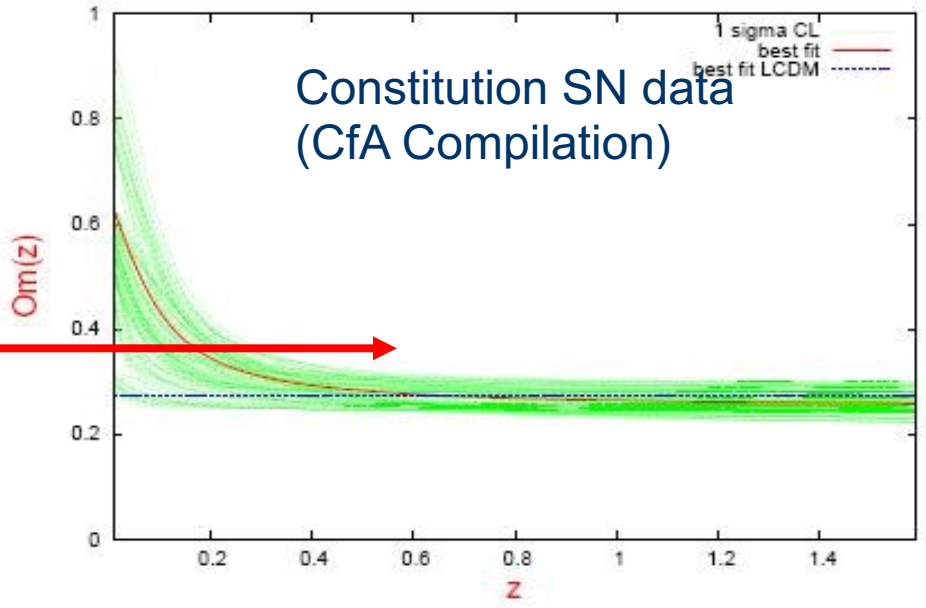
$\Delta\chi^2 = -0.6$ with respect to CPL

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 Rapid Communication 2009 [Reported in Nature and New Scientist]

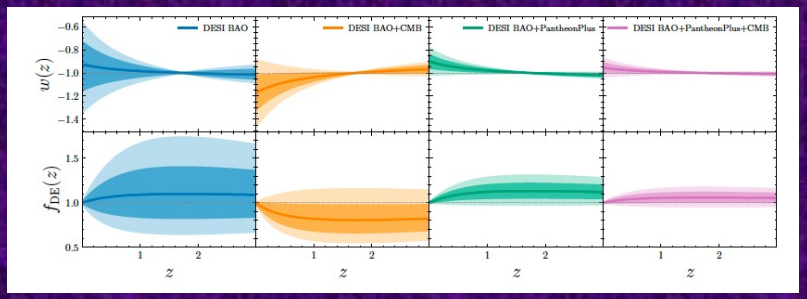
Theoretical application of direct reconstruction

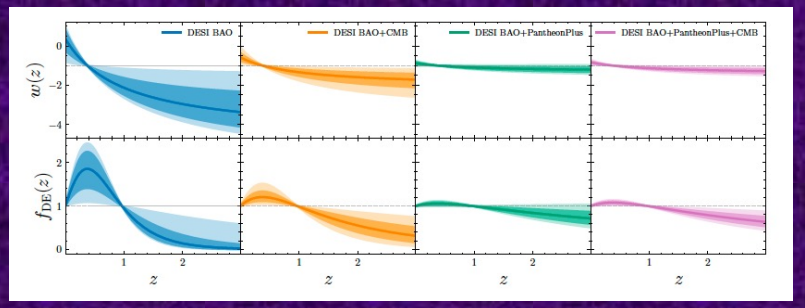
Thawing models, Emergent models and Mirage!

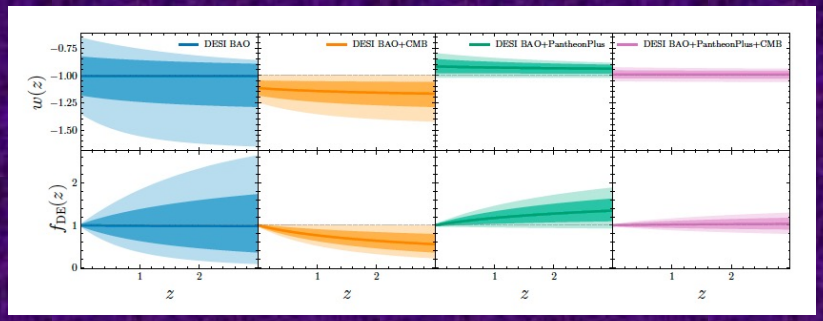
$$w_a \approx -1.58(1+w_0)\ .$$

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

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







Lodha, Shafieloo, Calderon, Linder et al, 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.

Current Status and Summary

There are now tantalizing hints for Dark Energy Evolution.

Will they remain significant?!
Time may show ➔ DESI RSD (very soon), DESI Y-3 (next summer)

Hubble tension has remained a separate, but connected, issue.

Many theoretical/phenomenological models of DE are proposed to ease the tensions. None is convincing so far (none can pass all validation tests).

Can systematics be responsible for all the anomalies and tensions?

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