Cosmology with Type Ia Supernovae:

Searching for systematics and model independent reconstructions

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Introduction

We analyze the Joint Light-curve Analysis (JLA) Type Ia supernovae (SN Ia) compilation implementing the non-parametric iterative smoothing method. We explore the SN Ia light-curve hyperparameter space and find no dark energy model dependence nor redshift evolution of the hyperparameters. We also analyze the more recent Pantheon SN Ia compilation to search for possible deviations from the expectations of the concordance ΛCDM model. We demonstrate that the redshift binned best fit parameter values oscillate about their full dataset best fit values with considerably large amplitudes. At the redshifts below z≈0.5, we show that such oscillations can only occur in 4 to 5% of the simulations. This might be a hint for some behavior beyond the predictions of the concordance model or a possible additional systematic in the data. In addition, we develop a non-parametric approach using the distribution of likelihoods from the iterative smoothing method. It determines consistency of a model and the data without comparison with another model. Simulating future WFIRST-like data, we show how confidently we can distinguish different dark energy models using this approach.

Iterative smoothing method

- The non-parametric method to reconstruct the distance modulus and expansion history of the universe
- Starts from initial guess of distance modulus, but generates model independent reconstruction of distance modulus with lower χ^2 value after numerous iterations

$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\boldsymbol{\delta\mu_n}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{W}(z)}{\mathbf{1}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{W}(z)}, \quad \chi_n^2 = \boldsymbol{\delta\mu_n}^T \cdot \mathbf{C}^{-1} \cdot \boldsymbol{\delta\mu_n}$$

Where $\mathbf{1}^T = (1,\cdots,1), \quad W_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right), \quad \boldsymbol{\delta\mu_n}\big|_i = \mu_i - \hat{\mu}_n(z_i)$

($\mathbf{C}^{-1}$: inverse of the data covariance matrix, $\boldsymbol{W}$: Weight, $\Delta = 0.3$: Smoothing width, μ_i: Distance modulus data points)

SN Ia compilations

Joint Light-curve Analysis (JLA)

- To explore the SN Ia light-curve hyperparameter space

Betoule et al. 2014

Pantheon

- To search for possible deviations from the concordance model or additional systematic

Scolnic et al. 2018

Wide Field Infrared Survey Telescope (simulated)

- To check how confidently we can distinguish models using the new approach

Green et al. 2012; Spergel et al. 2015

Results

Koo et al. 2020, ApJ, 899, 9

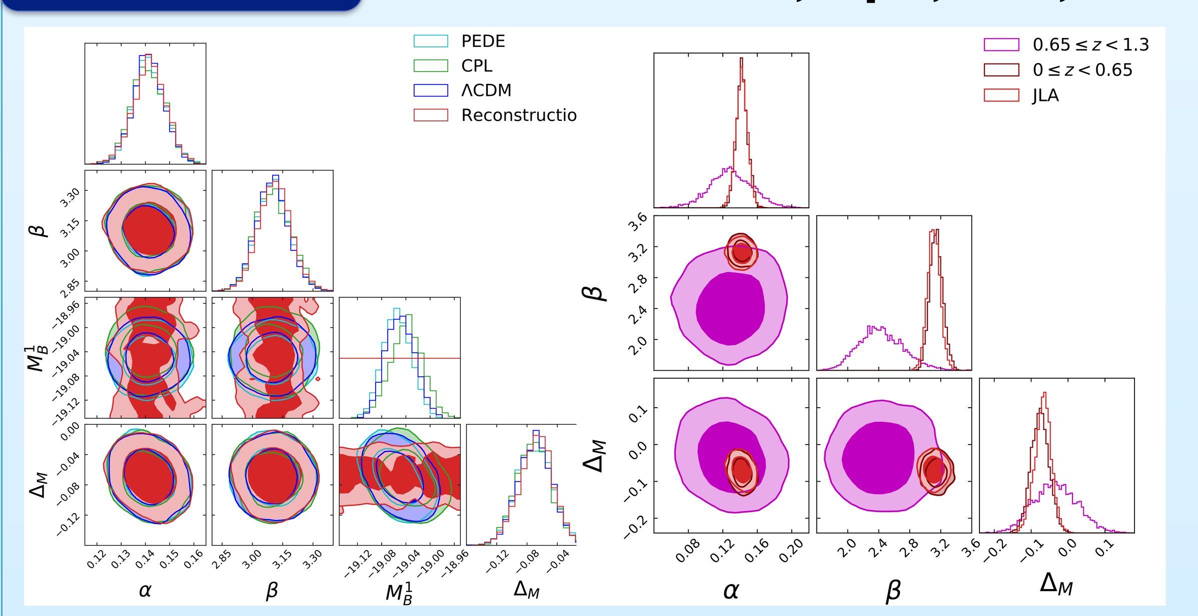


Fig. 1. Constrained light-curve hyperparameters from model-independent reconstructions (**left**) using JLA are in good agreement with conventional analysis with 3 assumed models (right) using redshift-binned JLA show no large enough statistical deviation.

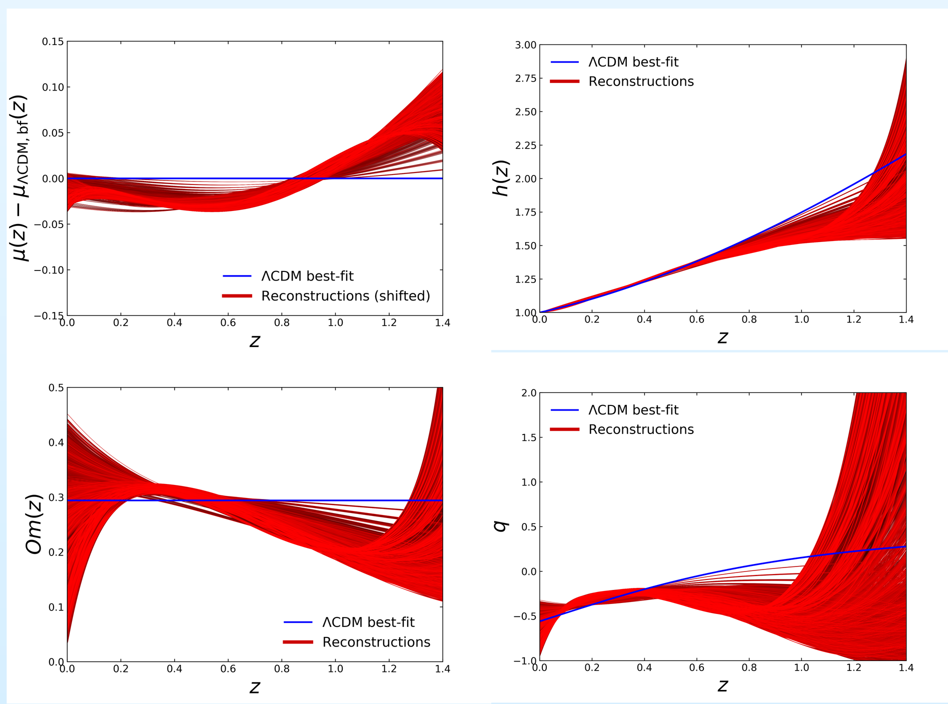


Fig. 2. (**top-left**) Relative deviation of reconstructed distance moduli from the best-fit ΛCDM model with a constant shift. Others are reconstructions of the (top-right) expansion history of the universe, (bottom-left) Om parameter and (bottom-right) deceleration parameter.

- Luminosity distance: $d_L(z) = 10^{\hat{\mu}_n/5-5}$

Expansion history: $h(z) = \frac{c}{H_0}\left[\frac{\mathrm{d}}{\mathrm{d}z}\frac{d_L(z)}{(1+z)}\right]^{-1}$

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

Sahni. Shafieloo. Starobinsky. 2008

(Equals to $\Omega_{m,0}$ when the background model is the ΛCDM model)

Deceleration parameter: $q(z) = (1+z)\frac{\frac{\mathrm{d}h}{\mathrm{d}z}}{h} - 1$

- 20 reconstructions from each of 4 different initial guesses and each of 100 random light-curve hyperparameter values (Total: 8000)
- Reconstructions are consistent with prediction of ΛCDM allowing some additional flexibility

Kazantzidis. Koo. Nesseris. Shafieloo. Perivolaropoulos. 2020, arXiv:2010.03491

Bin	z Range	$\mathcal{M} \pm 1\sigma$ error	$\Delta\sigma_{\mathcal{M}}$	$\Omega_{0m} \pm 1\sigma$ error	$\Delta\sigma_{\Omega_{0m}}$
Full Data	$0.01 < z < 2.26$	23.81 ± 0.01	-	0.29 ± 0.02	-
1st	$0.01 < z < 0.13$	23.78 ± 0.03	1.14	0.07 ± 0.17	1.35
2nd	$0.13 < z < 0.25$	23.89 ± 0.06	1.48	0.56 ± 0.19	1.34
3rd	$0.25 < z < 0.42$	23.75 ± 0.06	0.99	0.18 ± 0.11	1.05
4th	$0.42 < z < 2.26$	23.85 ± 0.06	0.69	0.33 ± 0.06	0.50

Tab. 1. The first three bins show large σ deviation of the redshift binned best-fit $\Omega_{m,0}$ and $\mathscr{M}$ (effective absolute magnitude) values from their full dataset best-fit values.

- Significance increases considering only statistical errors of the data
- Such oscillating features occur in 4-5% of Pantheon-like simulations

Koo et al. 2020, arXiv:2009.12045

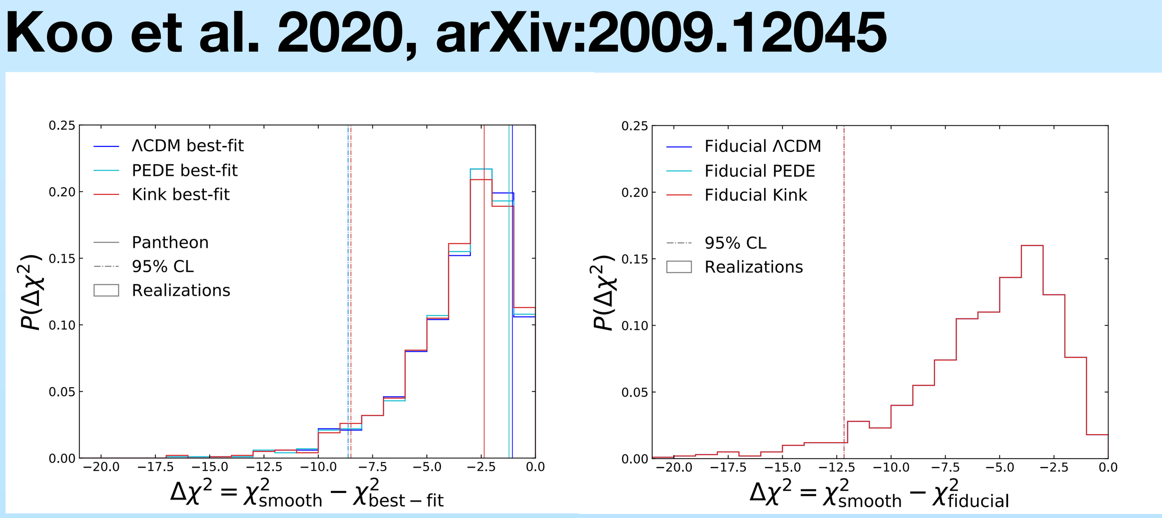


Fig. 3. Likelihood distributions of $\Delta\chi^2$ with initial guess of different (left) model best-fits (right) fiducial models.

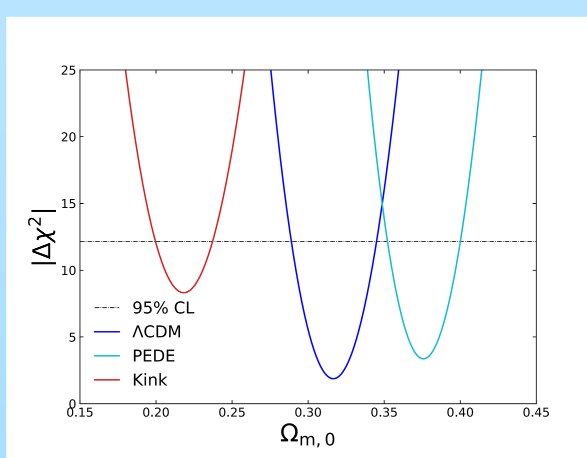
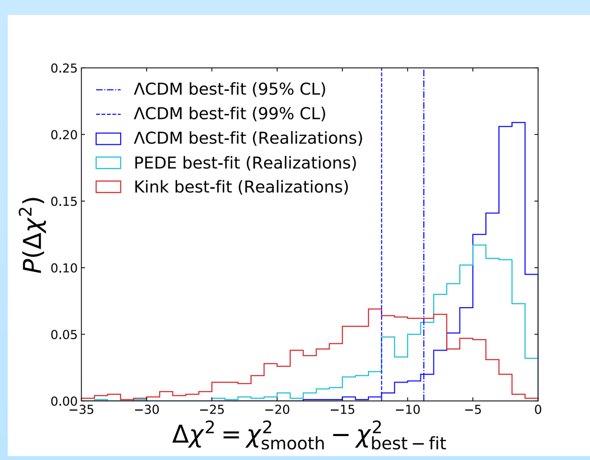


Fig. 4. Estimated parameter values based on 95% CL from the right panel of **Fig. 3.**



Type II	>95%	>99%
PEDE	24.7%	10.5%
Kink	70.1%	49.5%

Fig. 5. Likelihood distributions from the simulated WFIRST data based on the same fiducial model but with different model best-fits.

Tab. 2. The Type II errors for different models with 95%, 99% CLs (the probability that we can rule out the model) derived from **Fig. 5.** The values are highly distinguishable with each other.

Discussion

- No model dependence nor redshift evolution of light-curve hyperparameters are found
- Reconstructed expansion history of the universe are consistent with prediction of ΛCDM allowing some additional flexibility
- 4-5% of Pantheon-like simulations have similar oscillatory features with that in Pantheon data (systematic or new physics?)
- Model selection and parameter estimation using iterative smoothing method work well (confronting with Bayesian analysis)

Papers

Koo et al. 2020, ApJ, 899, 9
Kazantzidis et al. 2020, arXiv:2010.03491
Koo et al. 2020, arXiv:2009.12045