Cosmology with Type Ia supernovae

Searching for systematics and model independent reconstructions

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For more detail, see

Koo et al. 2020, ApJ, 899, 9 (arXiv:2001.10887)
Kazantzidis et al. 2021, MNRAS, 501, 3421 (arXiv:2010.03491)
Koo et al. 2021, JCAP, 03, 034 (arXiv:2009.12045)

Introduction

- Type Ia supernovae (SNe Ia): Standardizable candles for distance measurement, one of important portion of modern cosmology

- The standardization is purely empirical and requires SN Ia light curve fitting model with a number of parameters and hyperparameters

- The light-curve hyperparameters are usually constrained based on assumption of cosmological model

Introduction

- To search for systematics in the SNe Ia data, model independent reconstruction is required
- Look for features in the data which can be a hint for systematics or new physics
- Also perform model selection and parameter estimation without comparing models

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

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

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

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

Light-curve hyperparameters

- The Joint Light-curve Analysis (JLA) compilation have light-curve parameters information based on SALT2 fitter
  Betoule et al. 2014
  Guy et al. 2007; Mosher et al. 2014

- $\mu = m_B^\star - (M_B - \alpha X_1 + \beta C)$
  Tripp.1998

- α, β and M_B^1, Δ_M are light-curve hyperparameters
  $M_B = M_B^1$ if $M_{\text{stellar}} < 10^{10} M_{\text{sun}}$ (M_{stellar}: Stellar mass of host galaxy)
  $M_B = M_B^1 + \Delta_M$ otherwise

- $m_B^\star$, X_1, C are provided light-curve parameters

Cosmological models

- ΛCDM: Lambda-cold dark matter model

  $w(z) = -1$ (w: equation-of-state parameter)

- CPL: Chevallier-Polarski-Linder parameterization

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

  Chevallier. Polarski. 2001; Linder. 2003

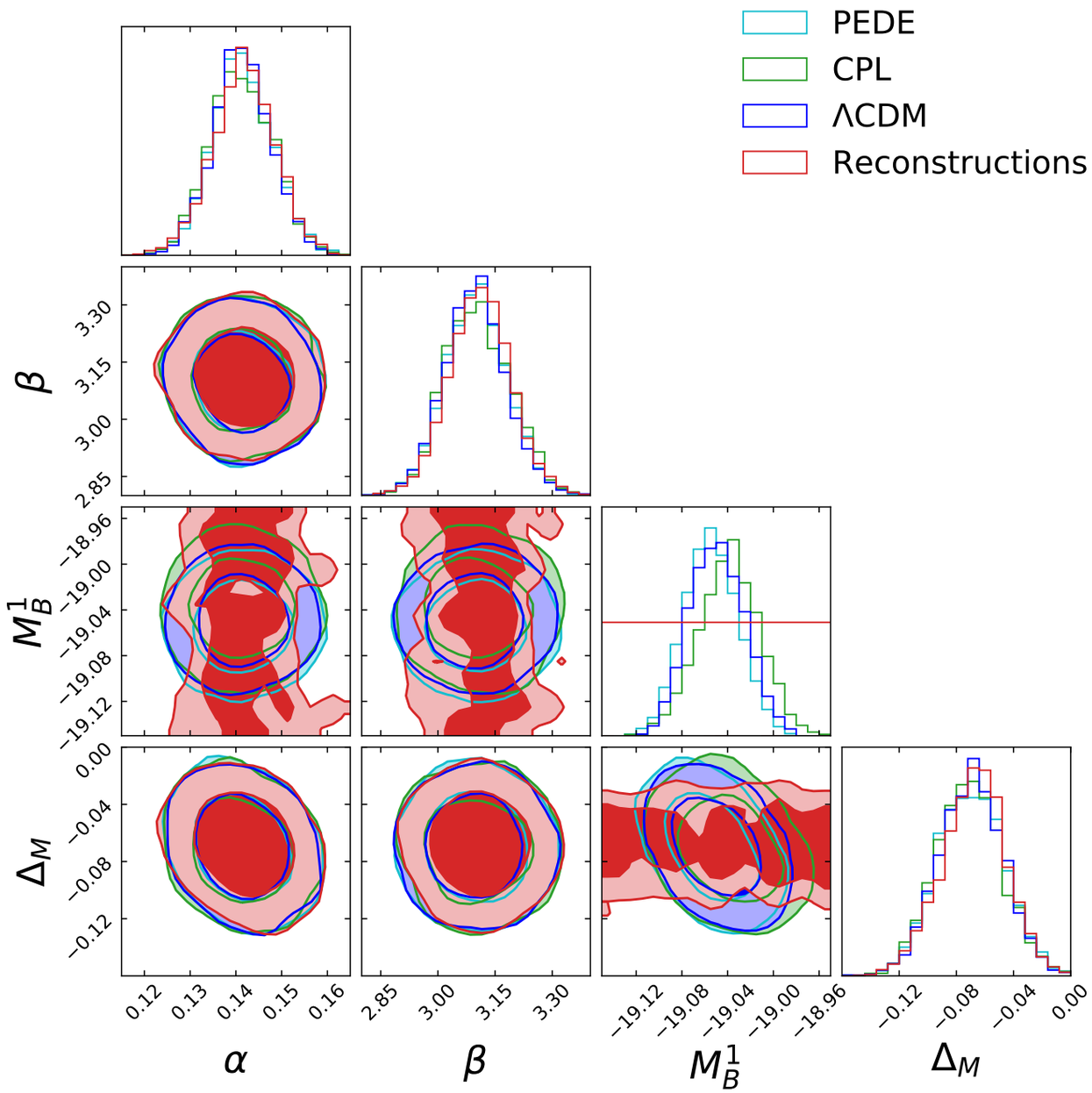
- PEDE: Phenomenologically Emergent Dark Energy model

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

  Li. Shafieloo. 2019

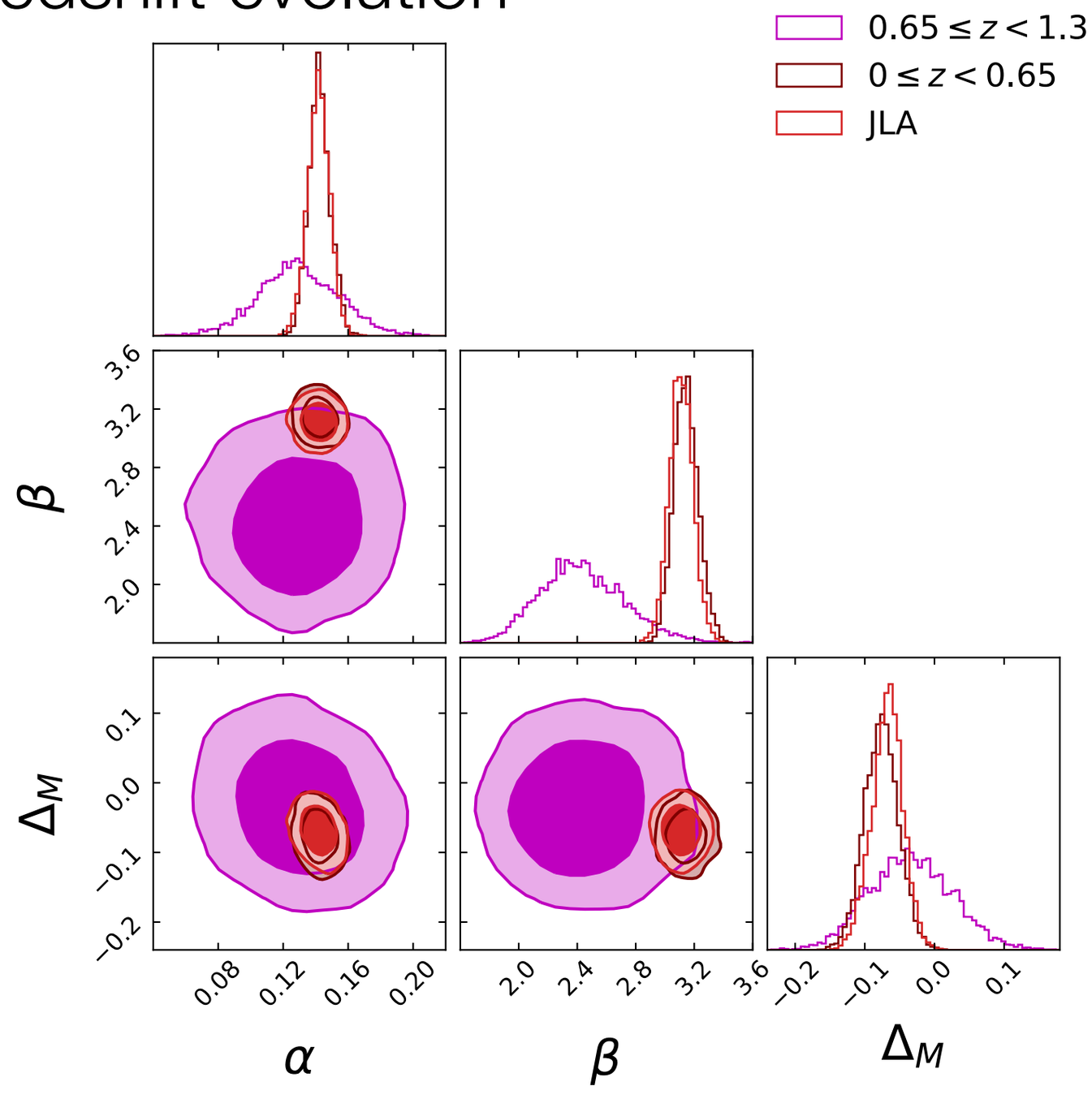
Constraints

- Contours are all consistent (No dependence on model)



Constraints (Reconstructions)

- No clear redshift evolution

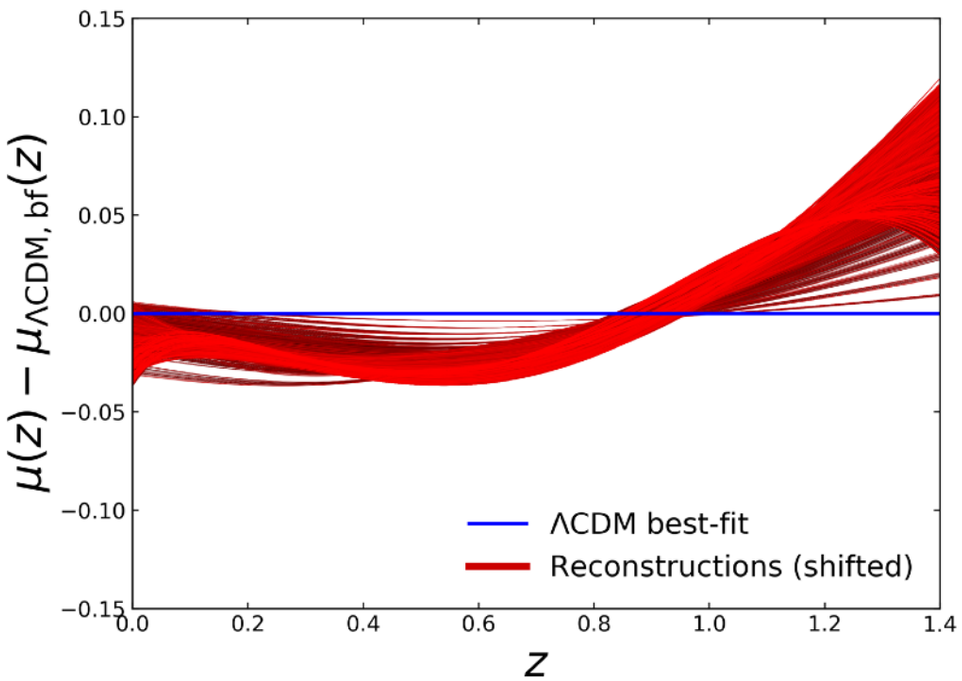


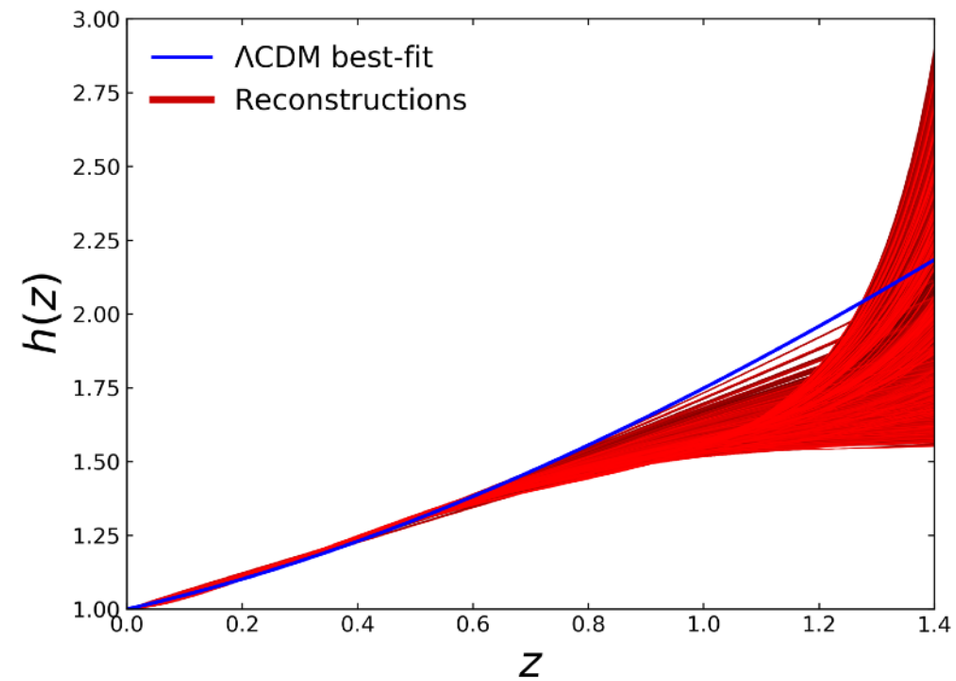
Reconstructions

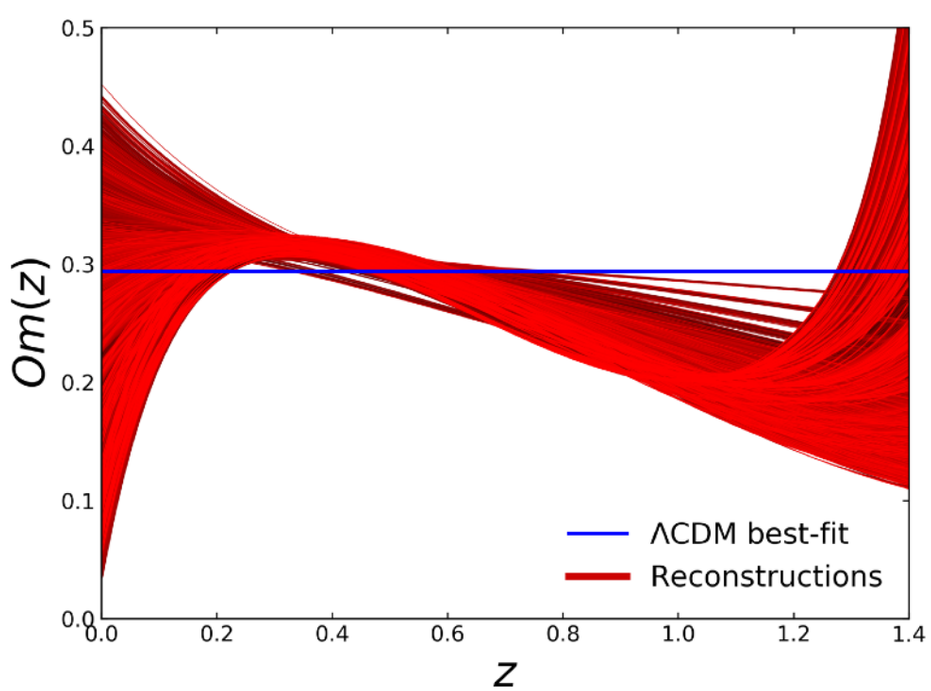
- Luminosity distance: $d_L(z) = 10^{\hat{\mu}_n/5-5}$
- Expansion history: $h(z) = \frac{c}{H_0}\left[\frac{\mathrm{d}}{\mathrm{d}z}\frac{d_L(z)}{(1+z)}\right]^{-1}$
- Om parameter: $Om(z) = \frac{h(z)^2 - 1}{(1+z)^3 - 1}$

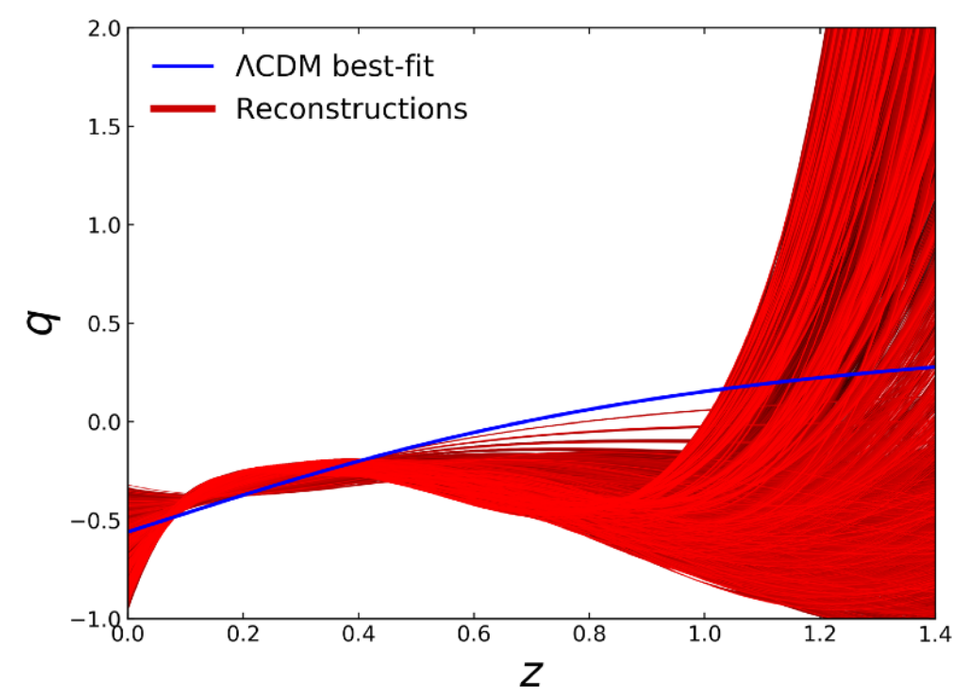
  Sahni. Shafieloo. Starobinsky. 2008
- Deceleration parameter: $q(z) = (1+z)\frac{\frac{\mathrm{d}h}{\mathrm{d}z}}{h} - 1$

Reconstructions









Looking for features in SNe Ia data

- Pantheon: Based on SALT2 fitter, more recent than JLA, includes more SNe Ia, considers more uncertainties
  Scolnic et al. 2018

- Oscillating features in the Pantheon data at $z<0.5$ around the best-fit ΛCDM model

- How generic such behavior is found at many Monte Carlo realizations of the data (using full covariance matrix of the Pantheon data)

Looking for features in SNe Ia data

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

Kazantzidis. Koo. Nesseris. Shafieloo. Perivolaropoulos. 2021

- Large σ deviation of the redshift binned best-fit parameter values from their full dataset best-fit values
- Occur in 4-5% of Pantheon-like simulations
- Might be a hint to possible systematic or new physics

Direct model testing

- Model testing using Bayesian analysis depends on comparing models
- We try to test consistency of a model and the data without comparing different models
- Estimate likelihood distribution of $\Delta\chi^2$ using iterative smoothing method for model selection and parameter estimation

Cosmological models

- ΛCDM, PEDE model

- ‘kink’ model

$$w(z) = w_0 + (w_\infty - w_0)\frac{1+\exp(\frac{a_c}{d_m})}{1+\exp(-\frac{a-a_c}{d_m})}\frac{1-\exp(-\frac{a-1}{d_m})}{1-\exp(\frac{1}{d_m})}$$

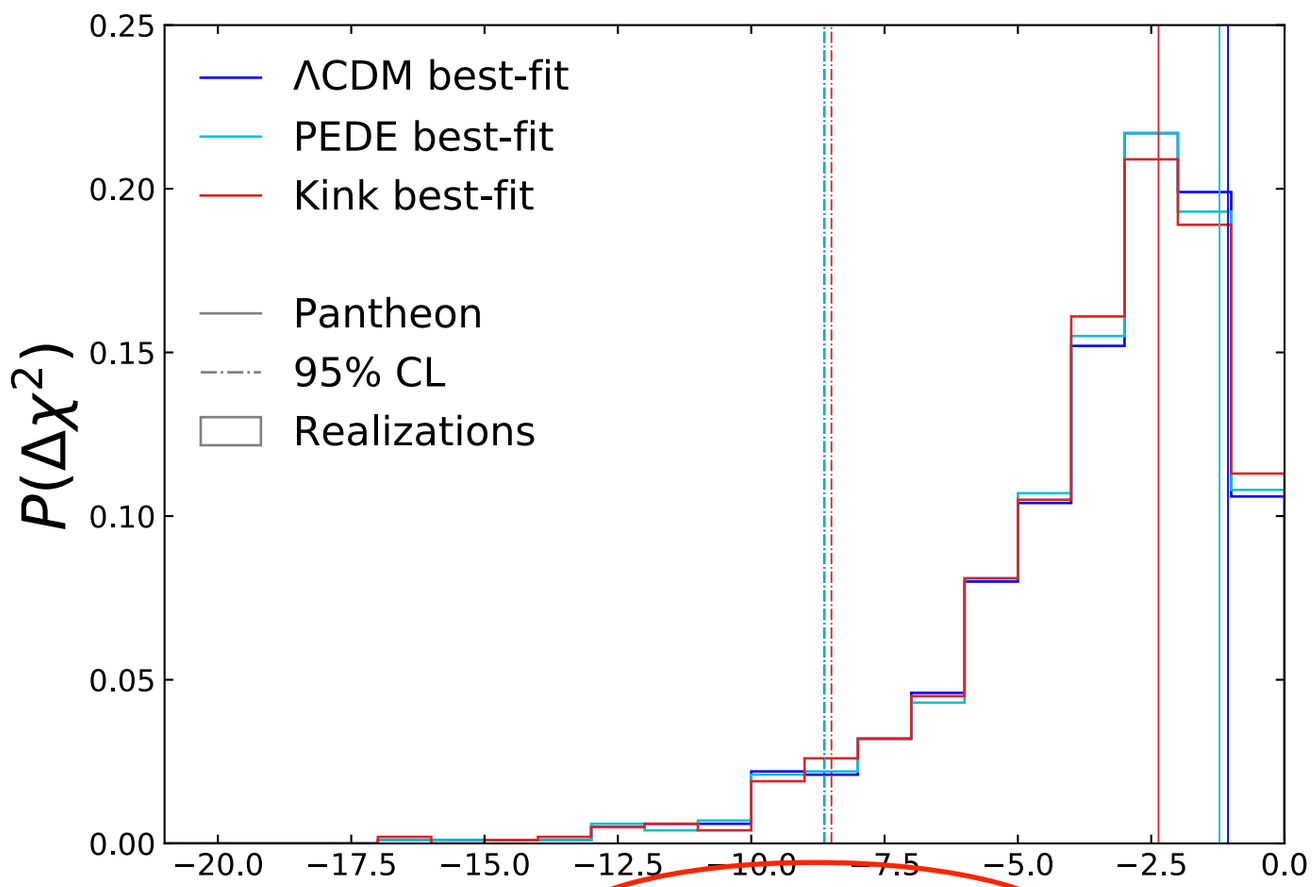
Corasaniti. Copeland. 2003

with $w_0 = -1$, $w_\infty = -0.5$, $a_c = \frac{2}{3}$, and $d_m = 1$

Holsclaw et al. 2010; Shafieloo et al. 2012

Model selection

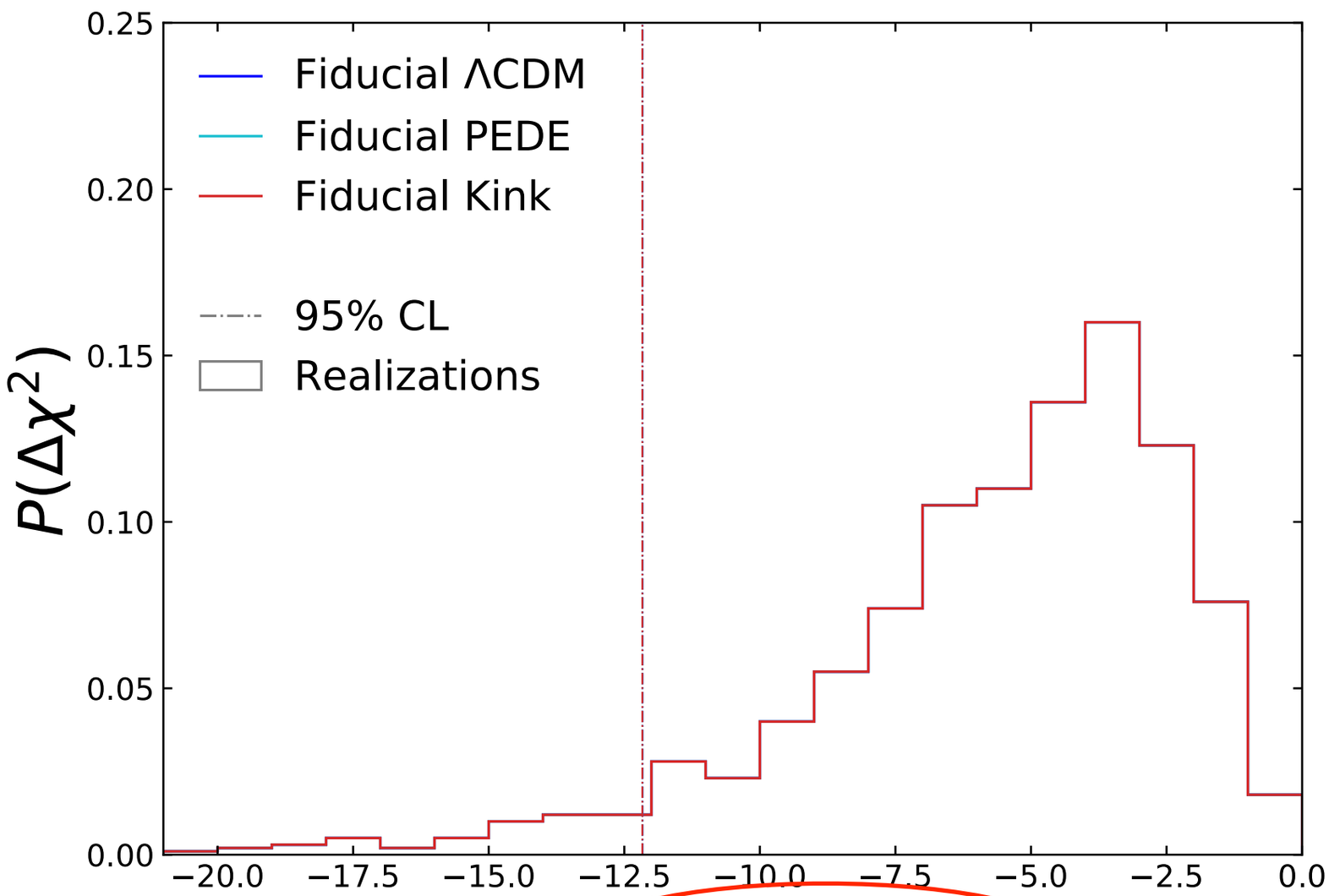
- 1000 Pantheon-like mock realizations
- No dependence on cosmological models that are used for simulation



$$\Delta\chi^2 = \chi^2_{\text{smooth}} - \chi^2_{\text{best-fit}}$$

Parameter estimation

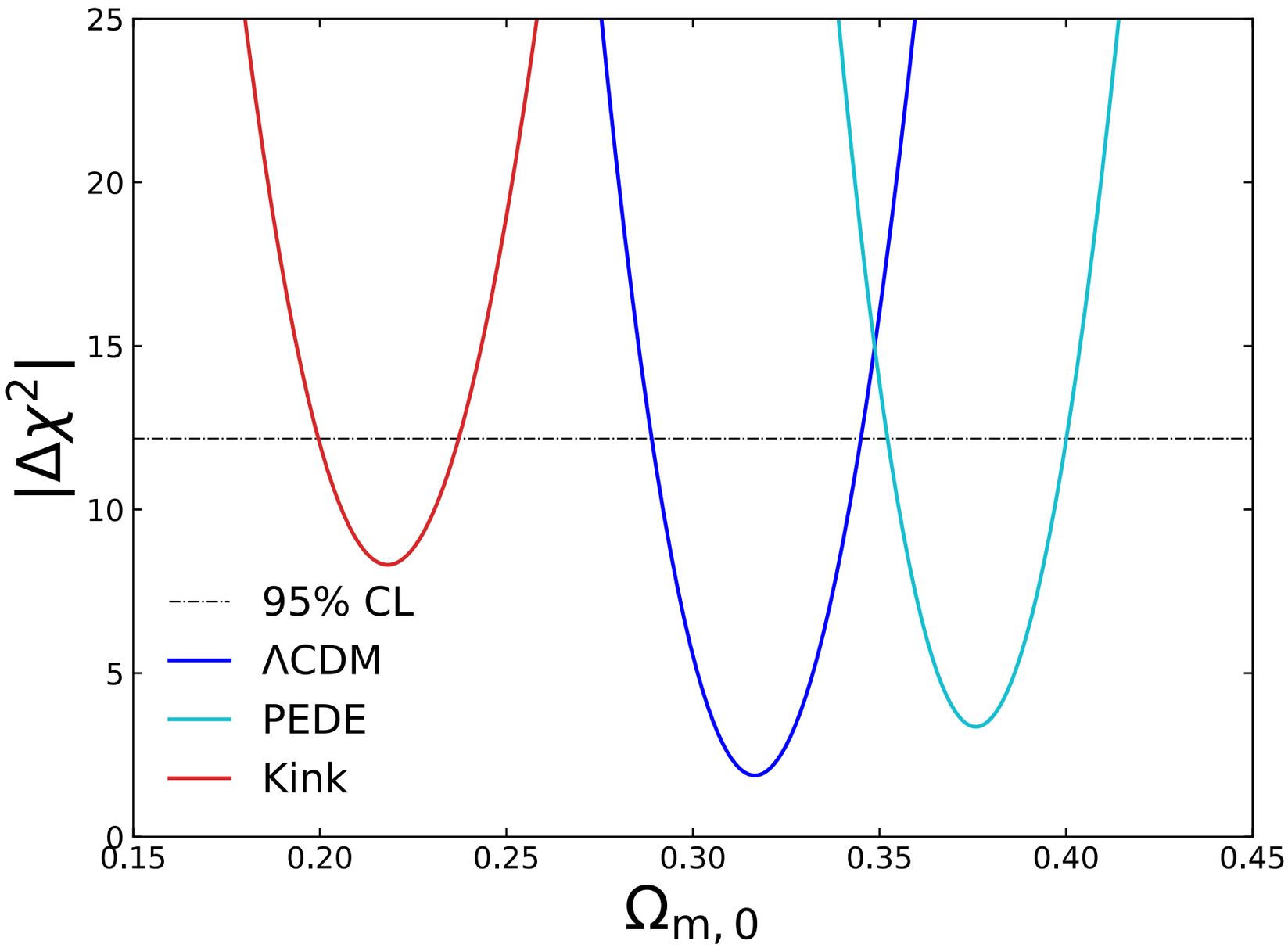
- 1000 Pantheon-like mock realizations



$$\Delta\chi^2 = \chi^2_{\text{smooth}} - \chi^2_{\text{fiducial}}$$

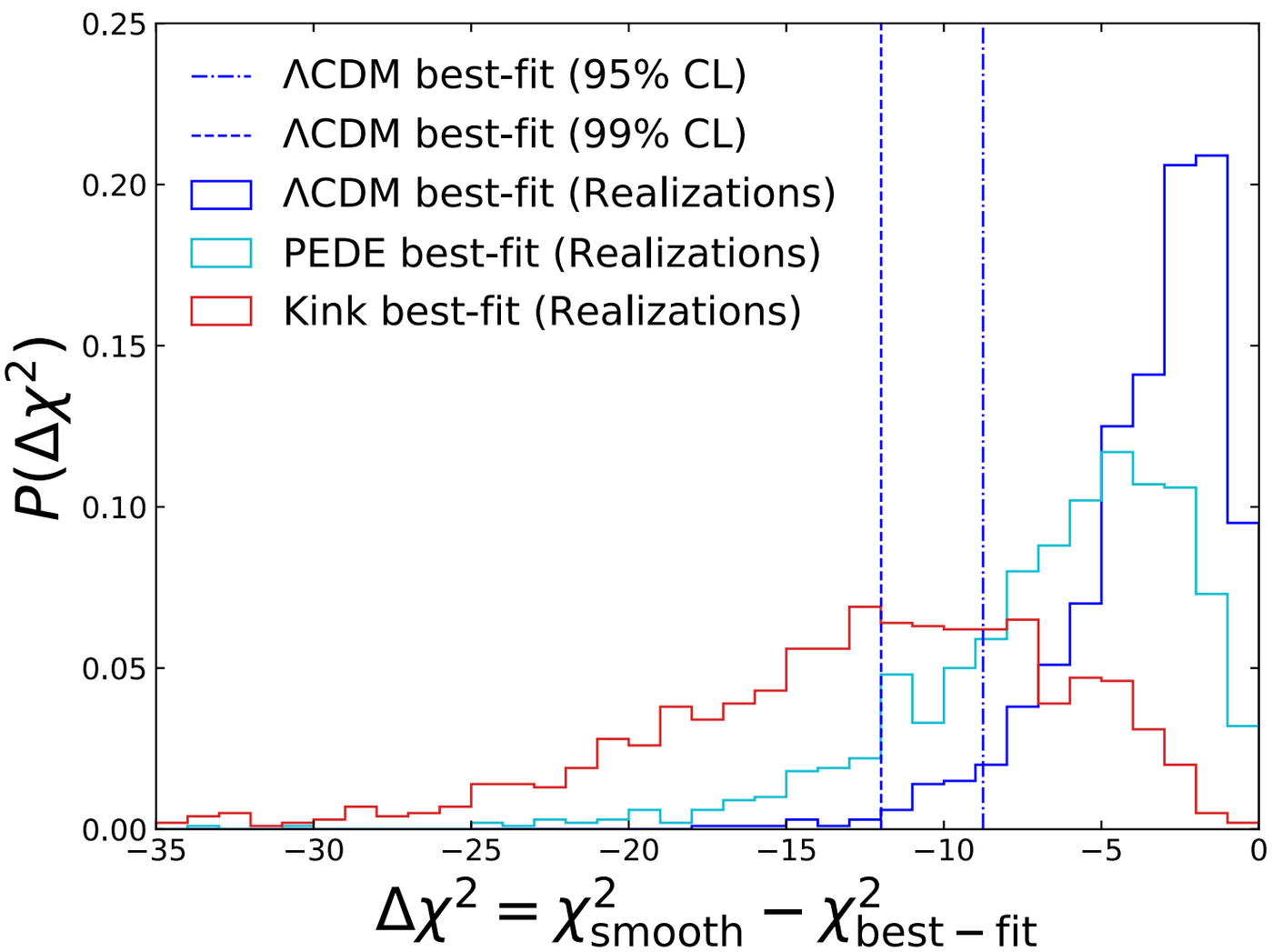
Parameter estimation

- Based on previous 95% CLs from Pantheon



Model selection with future data

- 1000 WFIRST mock realizations, ΛCDM fiducial model
- Estimated Type II successes:



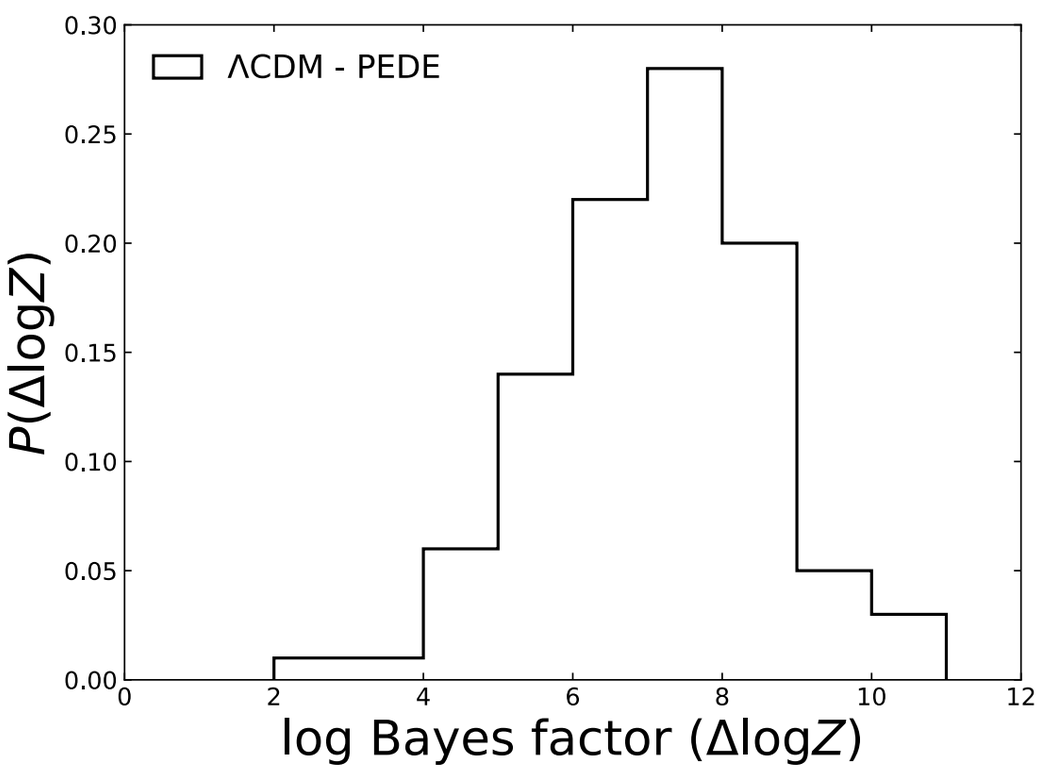
Type II	>95%	>99%
PEDE	24.7%	10.5%
Kink	70.1%	49.5%

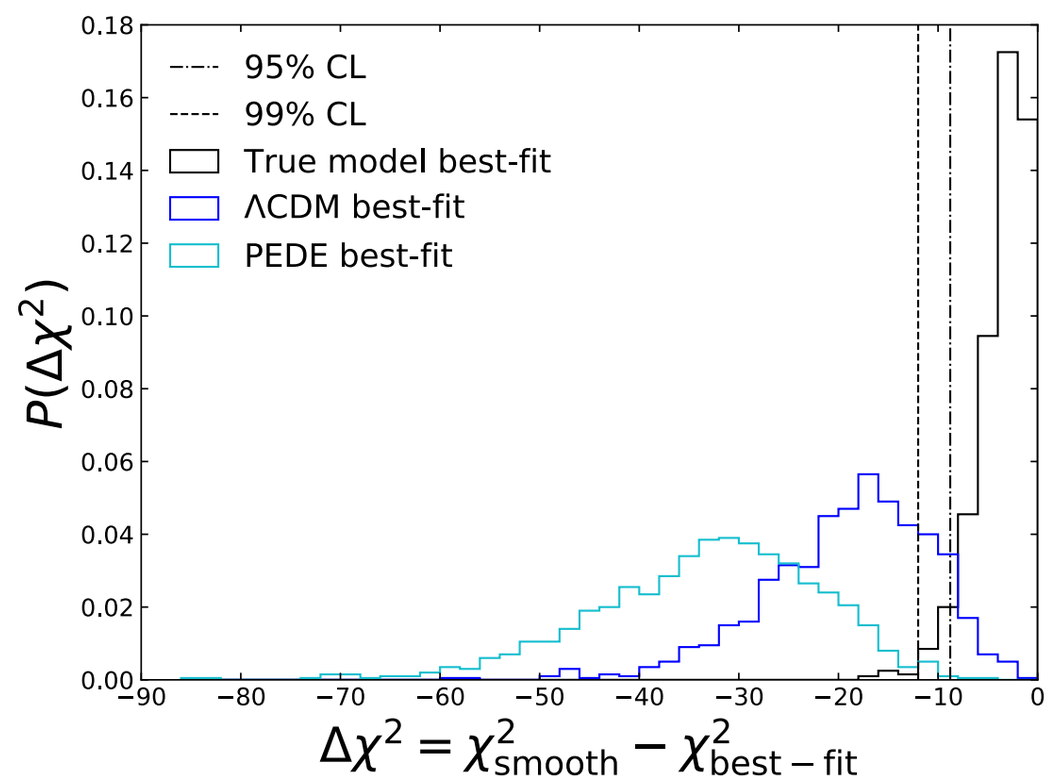
Summary

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

Next paper in preparation

- The true model is not ΛCDM nor PEDE
- Bayesian evidence distribution supports ΛCDM
- Likelihood distributions exclude both models





Thank You!

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