Model-independent Constraints on Type Ia supernova Light-curve Hyperparameters and Reconstructions of the Expansion History of the Universe

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Koo et al. 2020, ApJ, 899, 9

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Introduction

- Type Ia supernovae (SN Ia) are used as standardizable candles for distance measurement and have become one of important portion of modern cosmology
- The standardization is purely empirical and requires SN Ia light curve fitting model with the number of parameters and hyperparameters
- The light-curve hyperparameters are usually constrained based on assumption of cosmological model

Joint Light-curve Analysis

- 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

- Provides observed B-band peak magnitude, stretching of the light curve, supernovae color at maximum brightness

Light-curve parameters

Tripp.1998
Betoule et al. 2014

- $\mu = m_B^\star - (M_B - \alpha X_1 + \beta C)$
- $m_B^\star$: Observed B-band peak magnitude
- X_1: Stretching of the light curve
- C: Supernovae color at maximum brightness
- Included in JLA

Light-curve hyperparameters

Tripp.1998
Betoule et al. 2014

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

- α, β: Proportional factors of X_1 and C

- M_B^1, Δ_M: Absolute B-band peak magnitude

  $M_B = M_B^1$ if $M_{\text{stellar}} < 10^{10} M_{\text{sun}}$ (M_{stellar}: Stellar mass of host galaxy)
  $M_B = M_B^1 + \Delta_M$ otherwise

- Need to be constrained

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)

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

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

Cosmological models to compare

- ΛCDM: Lambda-cold dark matter model

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

- CPL: Chevallier-Polarski-Linder parameterization

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

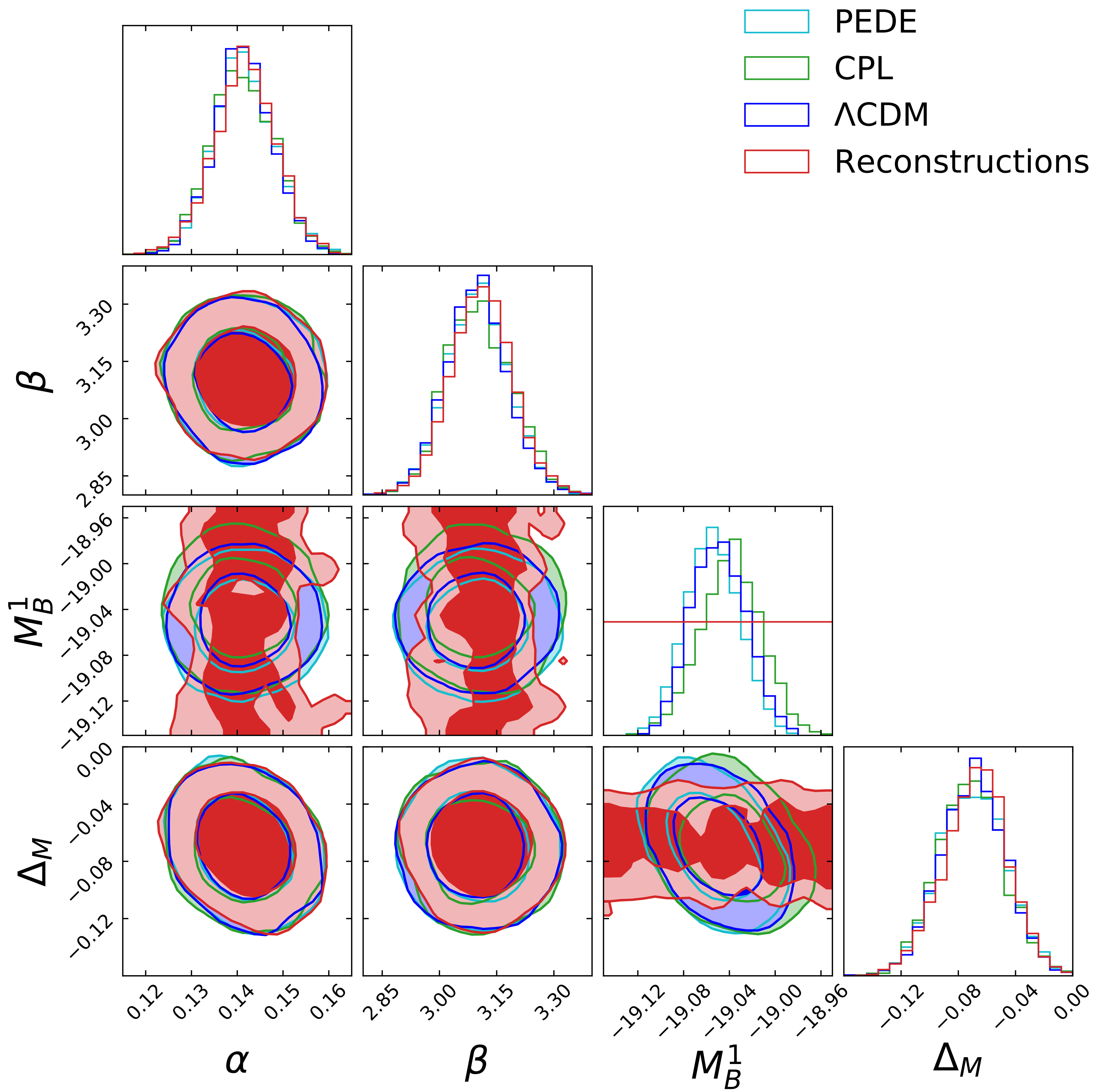
  Chevallier. Polarski. 2001; Linder. 2003

- PEDE: Phenomenologically Emergent Dark Energy model

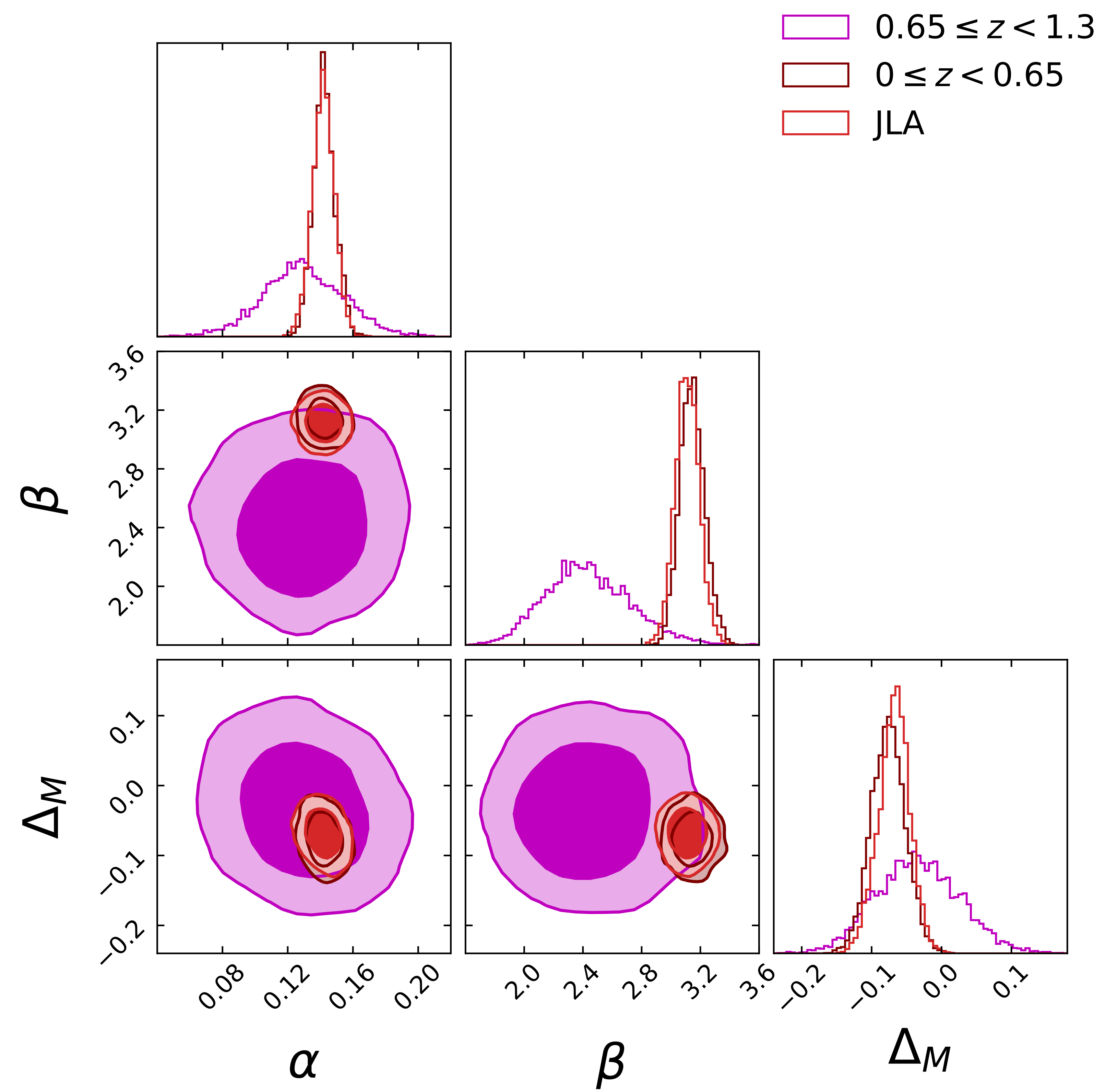
  $$w(z) = -\frac{1}{3 \ln 10}(1 + \tanh[\log_{10}(1+z)]) - 1$$

  Li. Shafieloo. 2019

Constraints



Constraints (Reconstructions)



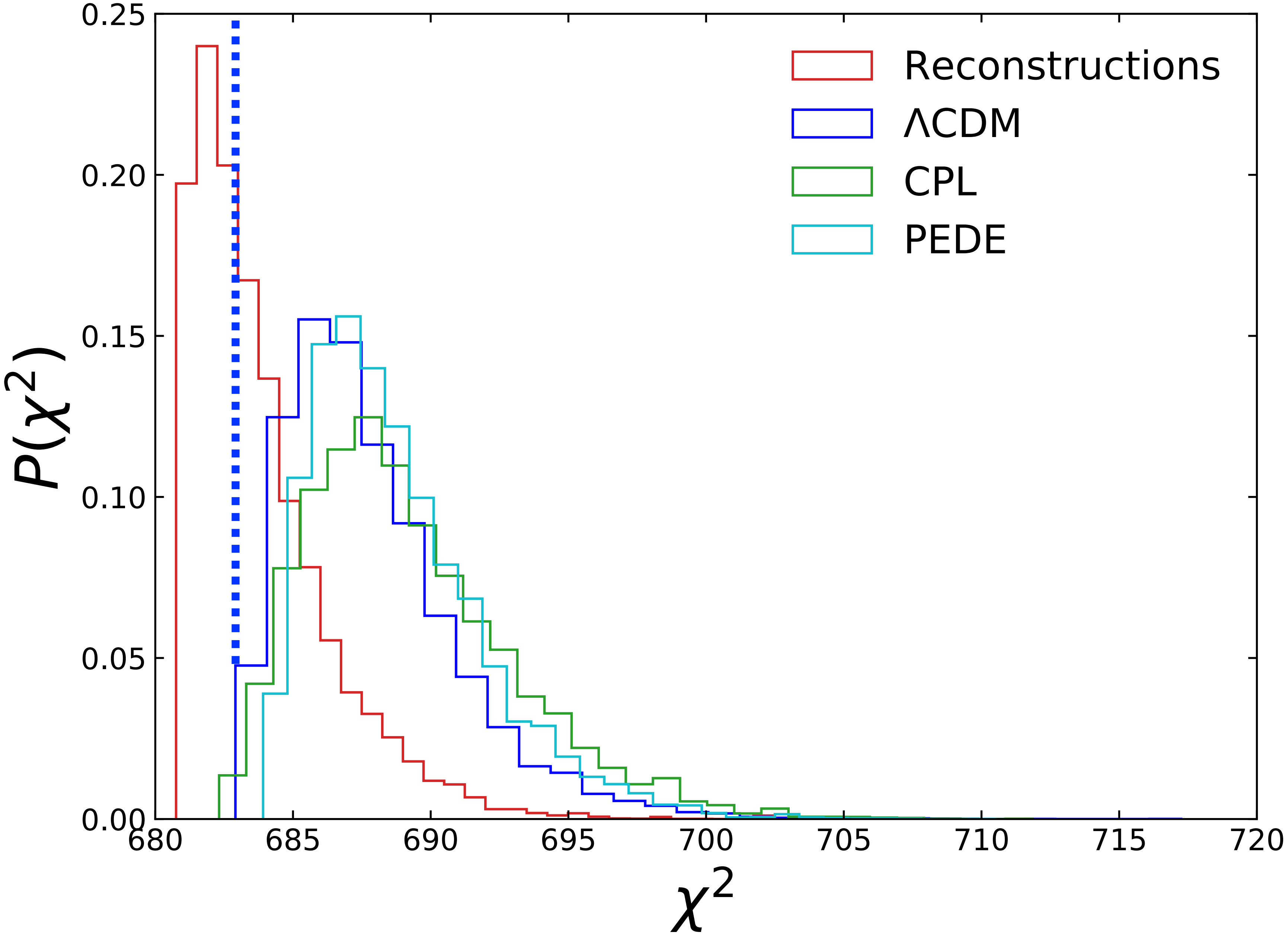
Constraints

- Constraints from reconstructions and predictions of 3 different models are consistent with each other
- Distance moduli constructed from the JLA data are mostly independent of cosmological model
- The light-curve hyperparameters are constrained mainly by the data included in the low redshift bin

Reconstructions

- Explore possibilities of the expansion history of the universe with higher likelihood than that of ΛCDM
- Reconstruct the expansion history of the universe on parametric space of light-curve hyperparameters explored by MCMC analysis
- Reconstruct the parameters which describe the dark energy properties and compare them with predictions of ΛCDM, CPL, PEDE

Reconstructions



- Reconstructions with $\chi^2 < \chi^2_{\Lambda\mathrm{CDM,bf}}$ have been selected

Reconstructions

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

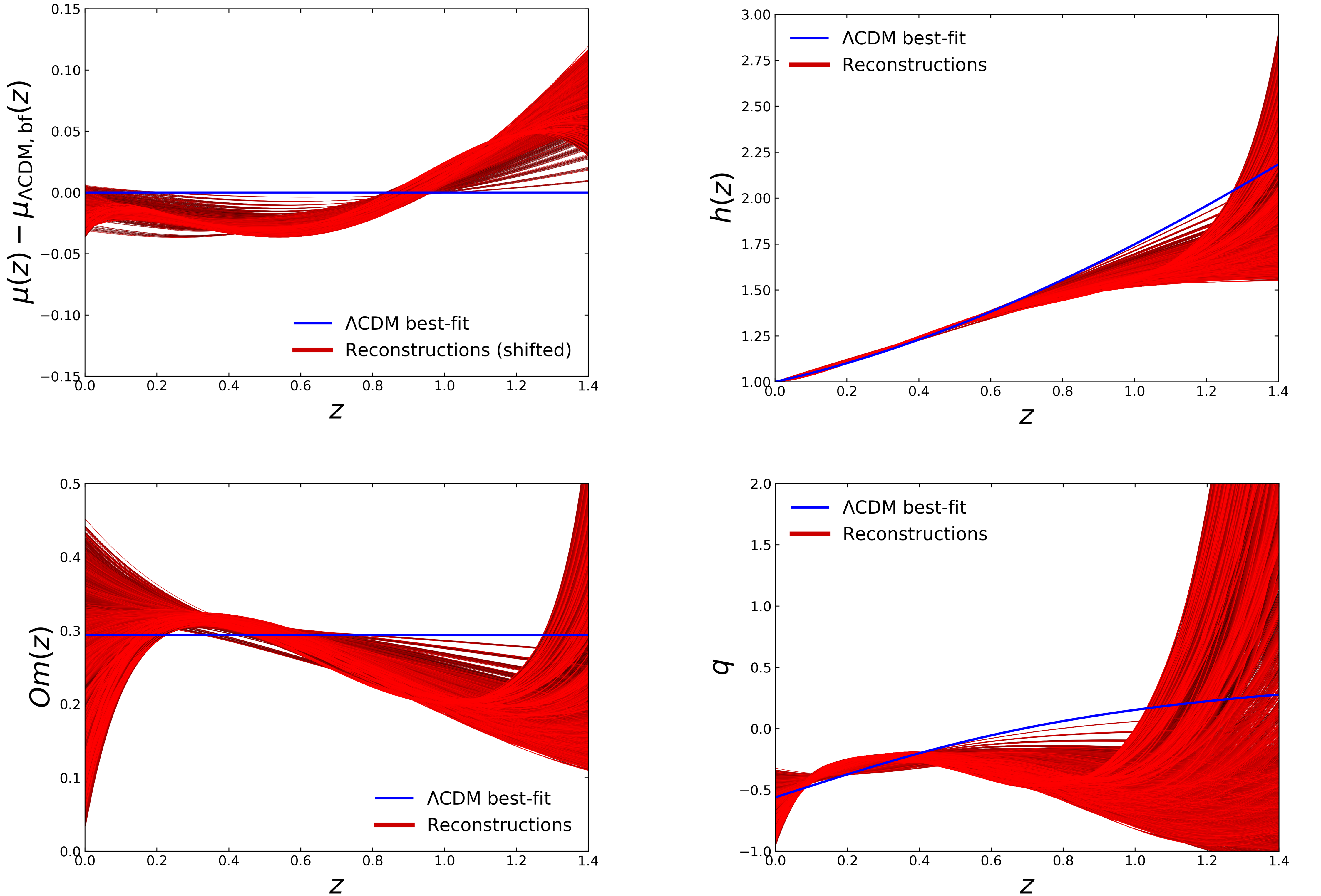
- Expansion history: $h(z) = \frac{c}{H_0}\left[\frac{\mathrm{d}}{\mathrm{d}z}\frac{d_L(z)}{(1+z)}\right]^{-1}$

- 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



Reconstructions

- Reconstructed expansion history of the universe and parameters which describe properties of dark energy are in good agreement with prediction of ΛCDM

- Reconstructions of expansion history of the universe and the other parameters show considerable flexibility

Summary

- Constraints from model-independent reconstructions are in good agreement with predictions of 3 different models
- Distance moduli constructed from the JLA data are mostly independent of cosmological model
- Reconstructed expansion history of the universe are consistent with prediction of the standard ΛCDM model with considerable flexibility