Litmus Tests of the Flat-ΛCDM model with stage IV surveys

★★★★★★★

BL, Mitra, Shafieloo, Keeley, Koo [2407.07847]

Benjamin L'Huillier (루일리예, 벤자민), Sejong University

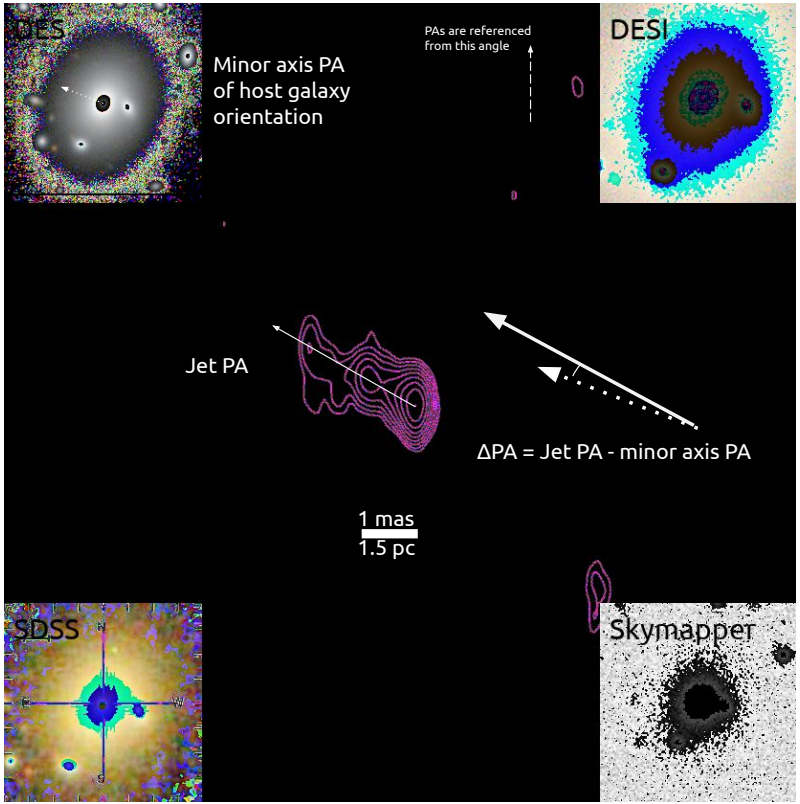
KIAS Workshop on Cosmology & Structure Formation

Gyeongju, 2024-11-01

NRF

CAMPUS FRANCE PHC STAR

Teaser: Alignments of Galaxy and VLBI Jet Position Angles





Fernandez Gil, Hodgson, BL, et al.
(Nature Astronomy in press)

- Is there a preferred orientation between the ***position angle*** of the ***optical galaxy*** and the ***direction*** of the ***VLBI jet***?
  - VLBI catalogue: Astrogeo
  - Optical shapes: DESI Legacy Survey (and others)
- Found ***weak but significant alignment***

The concordance model of cosmology

Isotropy & Homogeneity
FLRW metric

A theory of gravity
General relativity

Initial conditions
Inflation

- *Flat Universe dominated by dark energy & dark matter*
- *Concordance: CMB, BAO, SNIa*
- *But… tensions*

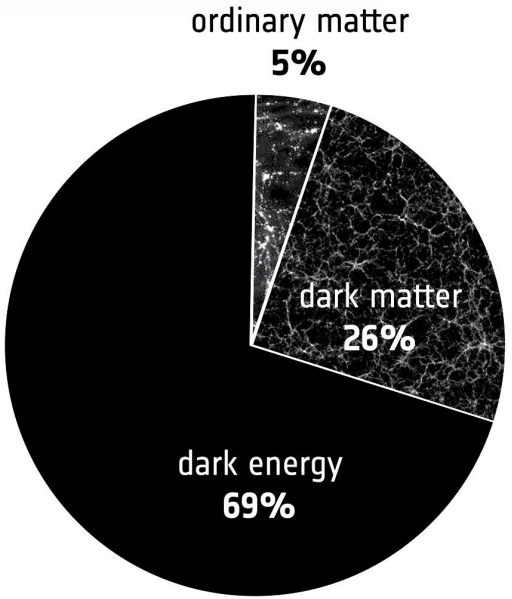


Image Credit:
Science/AAAS

The large scale structure hold valuable information

The concordance model of cosmology

Isotropy & Homogeneity
FLRW metric

A theory of gravity
General relativity

Initial conditions
Inflation

- ***Flat** Universe dominated by **dark energy** & dark matter*
- *Concordance: CMB, BAO, SNIa*
- *But… tensions*

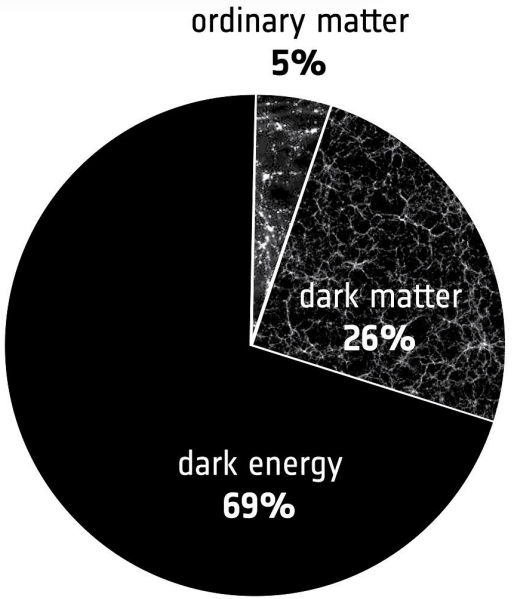


Image Credit:
Science/AAAS

The large scale structure hold valuable information

Advanced Statistical Methods

Model-dependent Methods

- *Widely used; more straightforward (model-fitting), "easier"*
- *More constraining power*
- ***Bias towards the (assumed) model***

MCMC, Nested sampling

VS.

Model-independent Methods

- *Less straightforward; overfitting problem*
- *Less constraining power*
- *More flexibility*
- ***No bias towards any model***
- ***Can detect unexpected features in the data***

Gaussian Process, Iterative Smoothing, Crossing Statistics, …

Both approaches *can* and *should* be used together

How to test the FLRW metric and the curvature?

Clarkson et al. (2008): in an FLRW universe:

$$\mathcal{O}_k(z) = \frac{\left(h(z)\mathcal{D}'(z)\right)^2 - 1}{\mathcal{D}^2(z)} \equiv \Omega_{k,0}$$

Independent of the form of dark energy!

Shafieloo & Clarkson (2008)
BL & Shafieloo (2017)
Shafieloo, BL, Starobinsky (2018)

Om diagnostics (Sahni et al. 2008) in a flat ΛCDM universe:

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1} \equiv \Omega_{\mathrm{m},0}$$

How to test the FLRW metric and the curvature?

$$\mathcal{O}_k(z) = \frac{\left(h(z)\mathscr{D}'(z)\right)^2 - 1}{\mathscr{D}^2(z)} \equiv \Omega_{k,0}$$

BAO: $\begin{cases} \dfrac{d_{\rm M}(z)}{r_{\rm d}} = \dfrac{c}{H_0 r_{\rm d}}\mathscr{D}(z) \\ \dfrac{d_{\rm H}(z)}{r_{\rm d}} = \dfrac{c}{H_0 r_{\rm d}}\dfrac{1}{h(z)} \end{cases}$

Dependent on $H_0 r_{\rm d}$

SNIa: $\mu(z) \Longrightarrow \begin{cases} \mathscr{D}(z) \\ \mathscr{D}'(z) = \dfrac{\sqrt{1+\Omega_{k0}\mathscr{D}^2(z)}}{h(z)} \end{cases}$

Independent of $H_0 r_{\rm d}$

Sound horizon at drag epoch $z_{\rm d}$:

$$\frac{H_0 r_{\rm d}}{c} = \frac{1}{\sqrt{3}} \int_0^{1/(1+z_d)} \frac{{\rm d}a}{h(a)\sqrt{1+\frac{3\Omega_b}{4\omega_\gamma}a}}$$

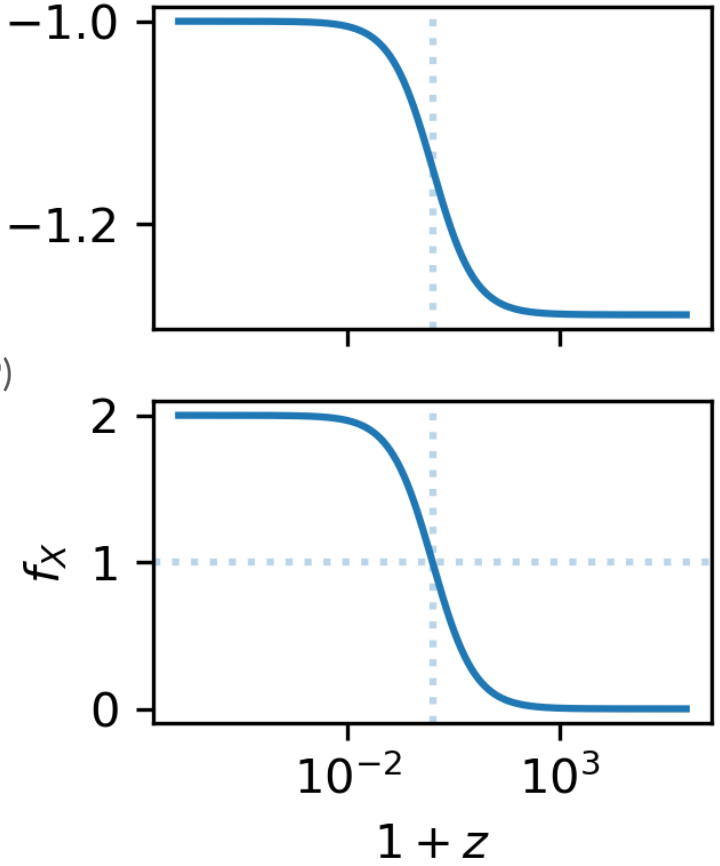
Forecast: LSST SNIa + DESI 5Y BAO

Fiducial Cosmology	$\Omega_{k,0}$	w
ΛCDM	0	-1
k-ΛCDM	0.1	-1
PEDE	0	$\frac{1}{3\ln(10)}\left[1-\tanh\left(\log_{10}(1+z)\right)\right]$
k-PEDE	0.1	

Li & Shafieloo (2019)

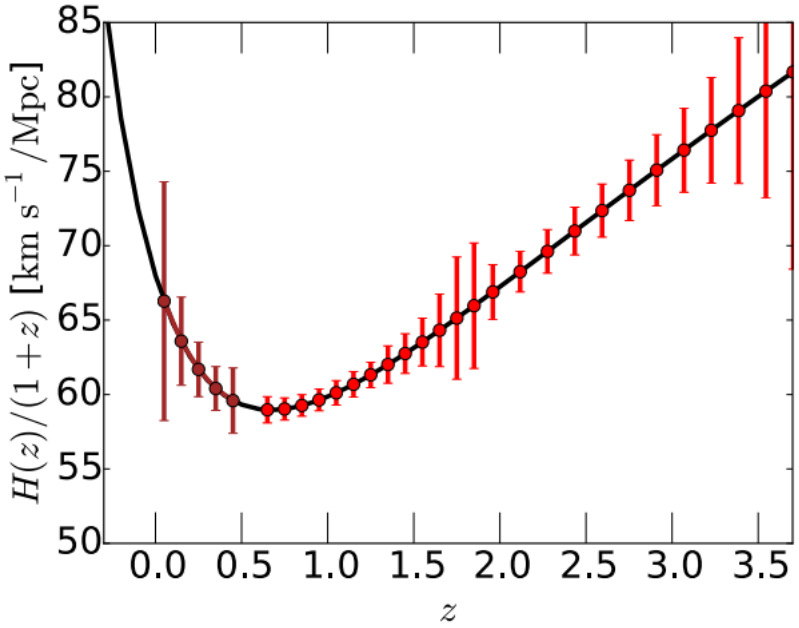
$$h^2(z) = \Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{k,0}(1+z)^2 + (1-\Omega_{\mathrm{m},0}-\Omega_{k,0})f_X(z)$$

$$f_X(z) = \exp\left(3\int_0^z \frac{1+w(z)}{1+z}\mathrm{d}z\right)$$

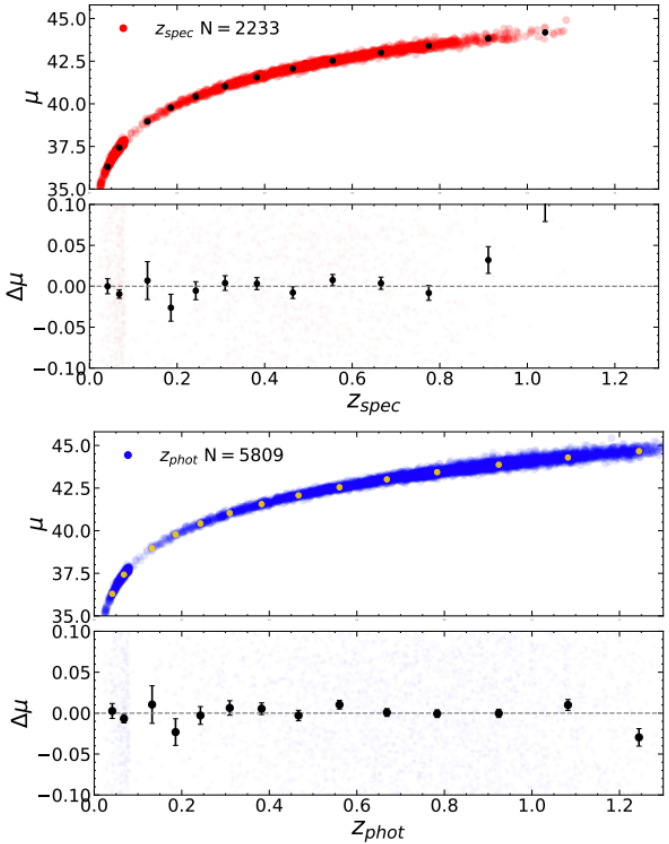


BL+ [2407.07847]

Forecast: LSST SNIa + DESI 5Y BAO

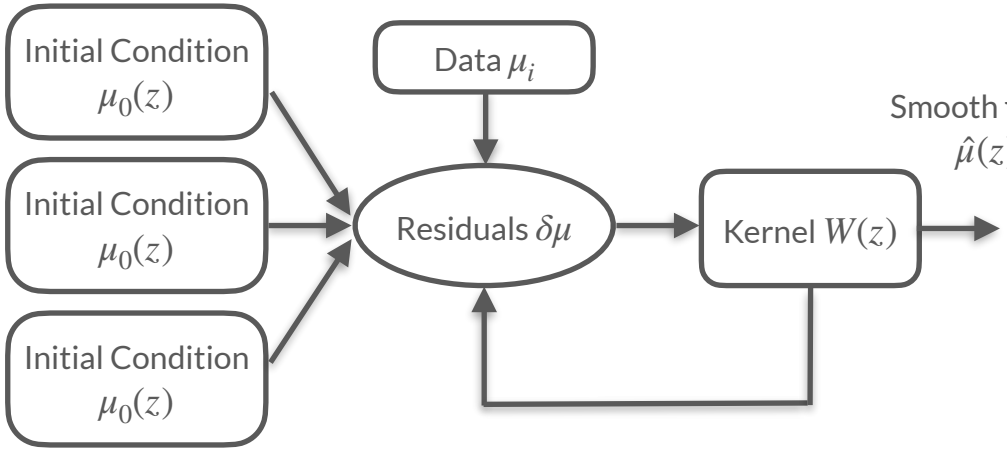


BAO: DESI 5-Year forecast [1611.00036]



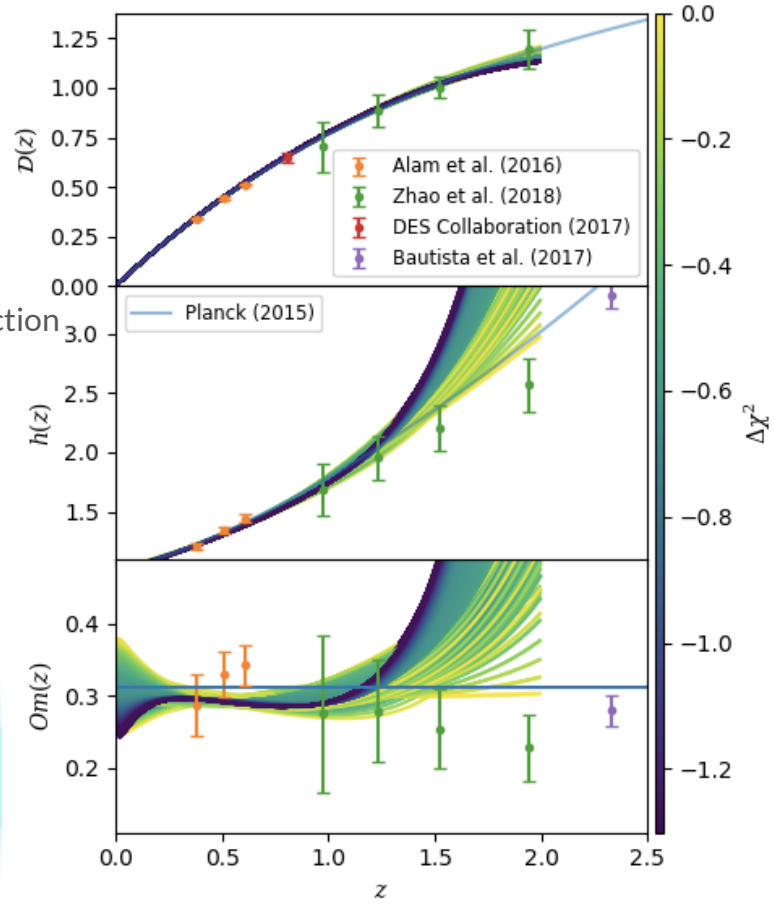
SNIa: LSST forecast Mitra et al. 2024

Direct reconstruction of the Expansion History: Iterative Smoothing



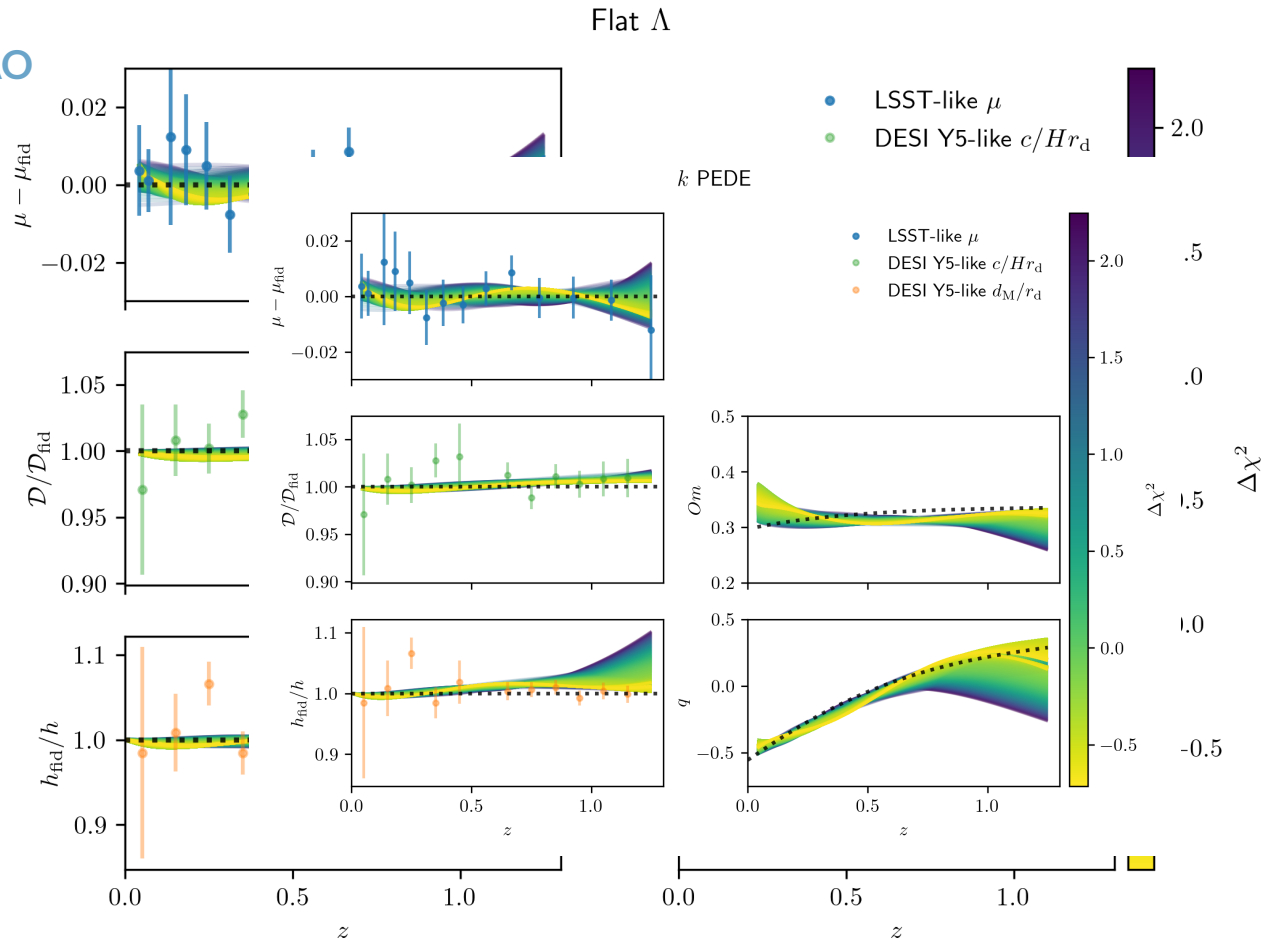
Independent of the initial guess!

Shafieloo et al. (2006), Shafieloo (2007)
BL & Shafieloo (2017)



Shafieloo, BL, Starobinsky (2018)

Forecast: LSST SNIa + DESI 5Y BAO



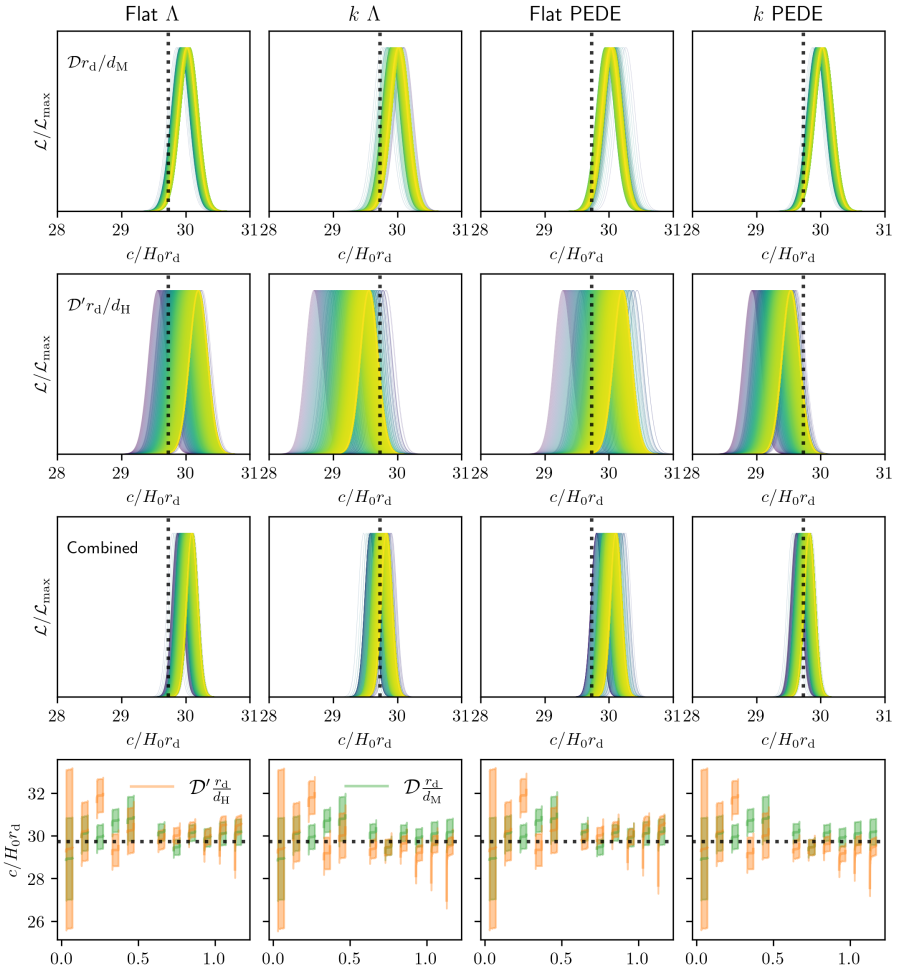
BL+ [2407.07847]

Forecast: LSST SNIa + DESI 5Y BAO

Flat universe:
$\mathscr{D}' = 1/h$

$$\frac{H_0 r_\mathrm{d}}{c} = \frac{\mathscr{D}(z)}{d_M(z)} = \frac{\mathscr{D}'(z)}{d_H(z)}$$

All three methods can recover the fiducial values of $c/H_0 r_d$



BL+ [2407.07847]

Forecast: LSST SNIa + DESI 5Y BAO

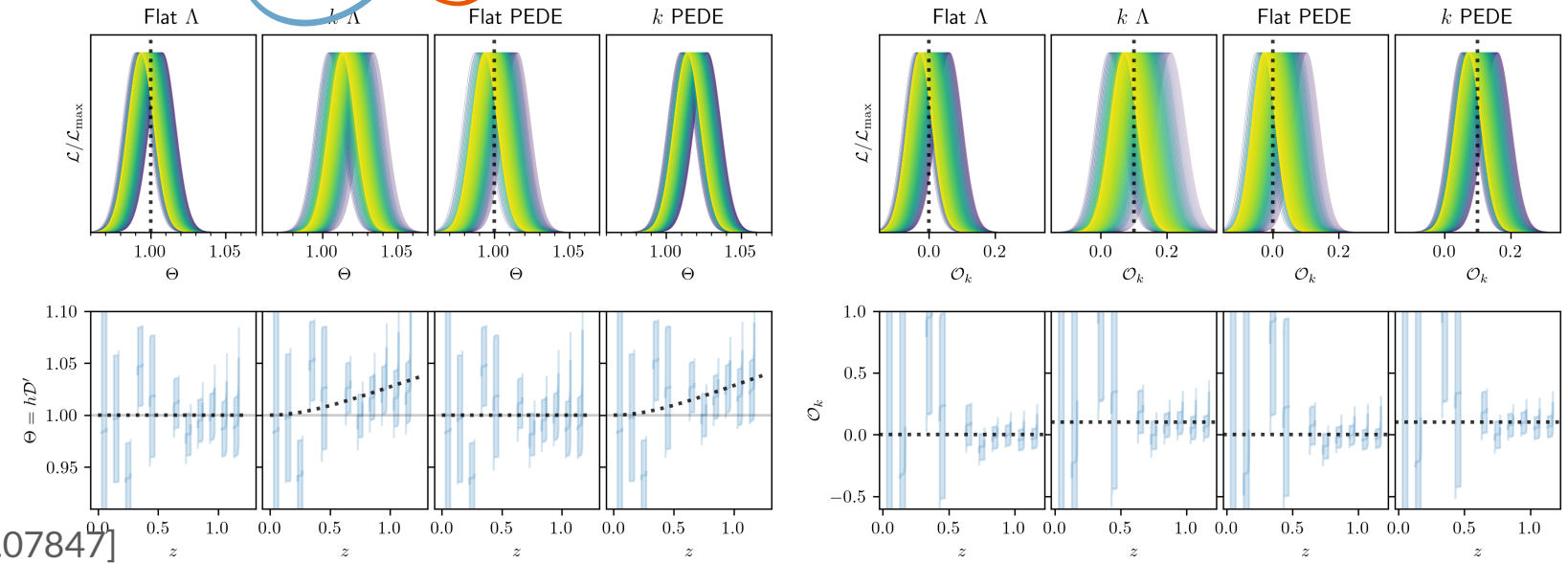
Recover the fiducial values of Θ and $\Omega_{k,0}$

BAO

SNIa

$$\Theta(z) = h(z)\mathscr{D}'(z) = \frac{d_M(z)/r_d}{d_H(z)/r_d}\frac{\mathscr{D}'(z)}{\mathscr{D}(z)} = \sqrt{1+\Omega_{k,0}\mathscr{D}^2(z)}$$

$$\mathscr{O}_k(z) = \frac{\Theta^2(z)-1}{\mathscr{D}^2(z)}$$



BL+ [2407.07847]

Summary

- LSST SNIa:
  - Allow for accurate reconstruction of the expansion history regardless of DE
- Combination with DESI Y5 BAO: DE-independent
  - measurement of $H_0 r_{\mathrm{d}}$
  - Test of the FLRW metric
  - Measurement of the curvature parameter Ω_{k0}

감사합니다