Falsifying the concordance model with the large-scale structure

L'Huillier & Shafieloo, JCAP 1, 15 (2017)
L'Huillier, Shafieloo & Kim MNRAS 476, 3263 (2018)
Shafieloo, L'Huillier & Starobinsky, PRD 98, 083526 (2018)
L'Huillier, Shafieloo, Linder, Kim 1812:03623

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Korea Astronomy & Space Science Institute

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The Concordance Model of Cosmology

Hypotheses

- Gravity described by General Relativity (GR)
- Isotropy and homogeneity
- Inflation in the early Universe, power-law primordial power spectrum

The concordance ΛCDM model

- Solution of the Einstein equations: FLRW metric
- Flat Universe
- Universe dominated by dark energy (Λ) and cold dark matter (CDM)
- Observationally supported by different datasets
- But what are dark energy and dark matter?
- Is gravity correctly described by GR?

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Planck 2018 cosmology

Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] – [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

- Precision cosmology
- *But this is model-dependent*
- Model-independent approaches: can go beyond the model
- Can see unexpected features
- But can be difficult to apply

Background expansion

Expansion for dark energy as a fluid with EOS $w(z)$:

$$h^2(z) = \Omega_\mathrm{m}(1+z)^3 + \Omega_k(1+z)^2 + (1-\Omega_k-\Omega_\mathrm{m})\exp\left(3\int_0^z \frac{1+w(x)}{1+x}\mathrm{d}x\right) \quad (1)$$

- Type Ia supernovae (SNIa): Pantheon (Scolnic et al. 2018): 1048 SNIa up to $z = 2.3$: $\mu(z) \propto \log_{10} d_\mathrm{L}(z) + \mathrm{cst}$.
- Baryon Acoustic Oscillations from BOSS DR12 (Alam et al. 2017) and eBOSS DR 14Q (Zhao et al. 2018): $H(z)r_\mathrm{d}, d_\mathrm{A}(z)/r_\mathrm{d}$.
  - r_d: Sound horizon at drag epoch

$$r_\mathrm{d} = \frac{c}{H_0\sqrt{3}}\int_0^{1/(1+z_\mathrm{drag})} \frac{\mathrm{d}a}{a^2 h(a)\sqrt{1+\frac{3\Omega_\mathrm{b}}{4\Omega_\mathrm{r}}a}} \quad (2)$$

Background expansion

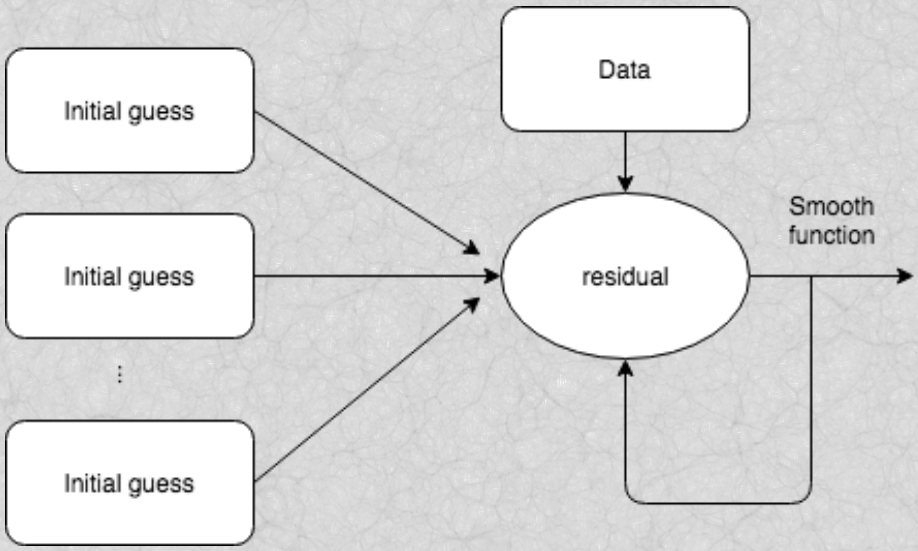
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Direct Reconstruction of the Expansion History



$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\delta\mu_n^{\mathrm{T}}(z)\mathbf{C}^{-1}\mathbf{W}(z)}{(1,\cdots,1)\mathbf{C}^{-1}\mathbf{W}(z)}; \tag{3}$$

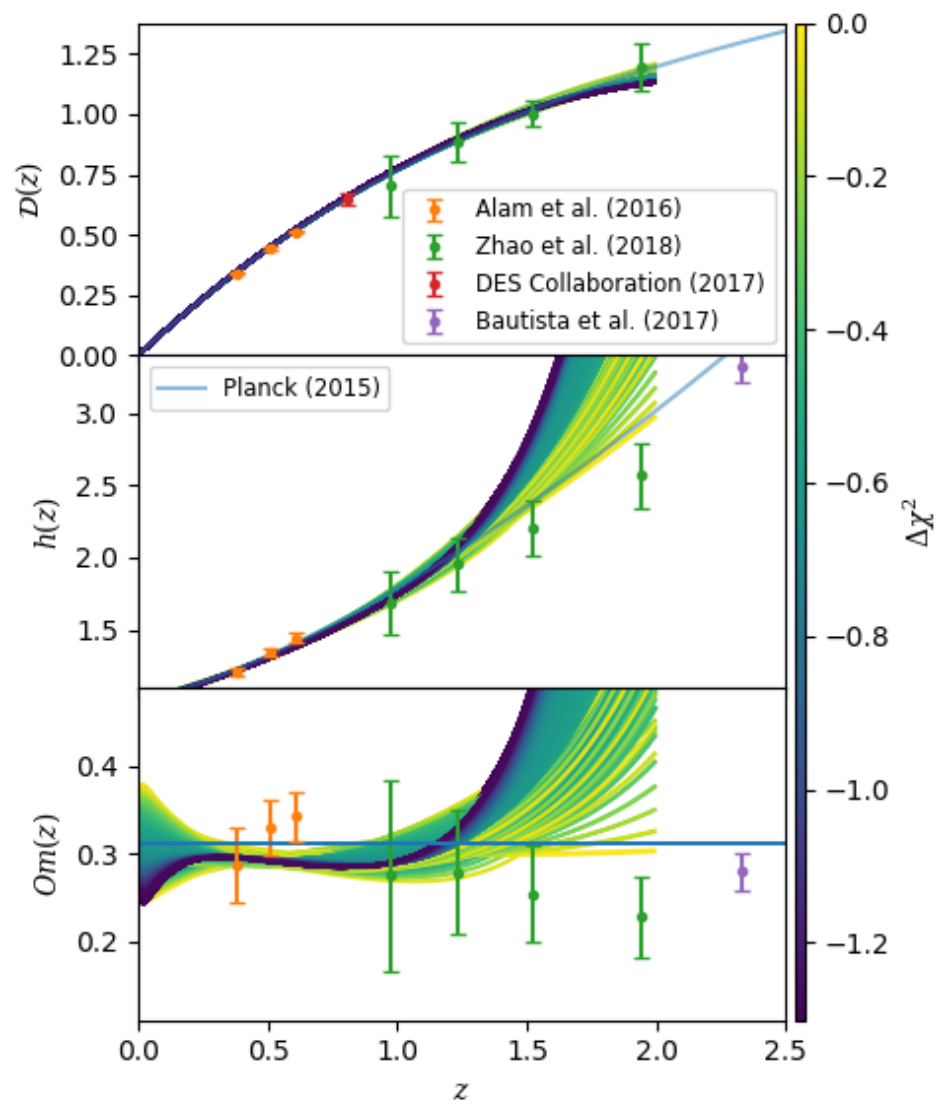
$$\mathbf{W}_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right) \tag{4}$$

- Iterative smoothing: Direct reconstruction from the data, no cosmological assumption Shafieloo et al. (2006), Shafieloo (2007),...
- Various initial guesses, iterations improve the χ^2
- Keep all reconstruction with $\chi^2 < \chi^2_{\Lambda\mathrm{CDM}}$: *Non-exhaustive sample* of plausible expansion histories
- New matrix formulation for correlated data (Shafieloo, L'Huillier & Starobinsky 2018): Covariance matrix $\mathbf{C}$

Testing Flat-ΛCDM

Consistency of SNIa and BAO

Shafieloo, L'Huillier & Starobinsky (2018), see also L'Huillier & Shafieloo (2017)



- Lines: Reconstructed $h(z)$ from SNIa
- Data points: BAO (Boss DR12, eBOSS DR 14Q, DES) + Planck 2015 $H_0 r_d$
- *Om* diagnostics (Sahni et al. 2008):

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1} \overset{\text{flat-}\Lambda\text{CDM}}{\equiv} \Omega_{\mathrm{m},0} \quad (5)$$

- $z \lesssim 1.5$: Consistent with flat-ΛCDM,
- $z \gtrsim 1.5$: Hints of tension (c.f. Sahni et al. (2014), Zhao et al. (2017))

Testing Λ

Zhao et al Nature Astron. 1, 627 (2017)

nature astronomy

LETTERS

DOI: 10.1038/s41550-017-0216-z

Dynamical dark energy in light of the latest observations

Gong-Bo Zhao[1,2*], Marco Raveri[3,4], Levon Pogosian[2,5], Yuting Wang[1,2], Robert G. Crittenden[2], Will J. Handley[6,7], Will J. Percival[2], Florian Beutler[2], Jonathan Brinkmann[8], Chia-Hsun Chuang[9,10], Antonio J. Cuesta[11,12], Daniel J. Eisenstein[13], Francisco-Shu Kitaura[14,15], Kazuya Koyama[2], Benjamin L'Huillier[16], Robert C. Nichol[2], Matthew M. Pieri[17], Sergio Rodriguez-Torres[9,18,19], Ashley J. Ross[2,20], Graziano Rossi[21], Ariel G. Sánchez[22], Arman Shafieloo[16,23], Jeremy L. Tinker[24], Rita Tojeiro[25], Jose A. Vazquez[26] and Hanyu Zhang[1]

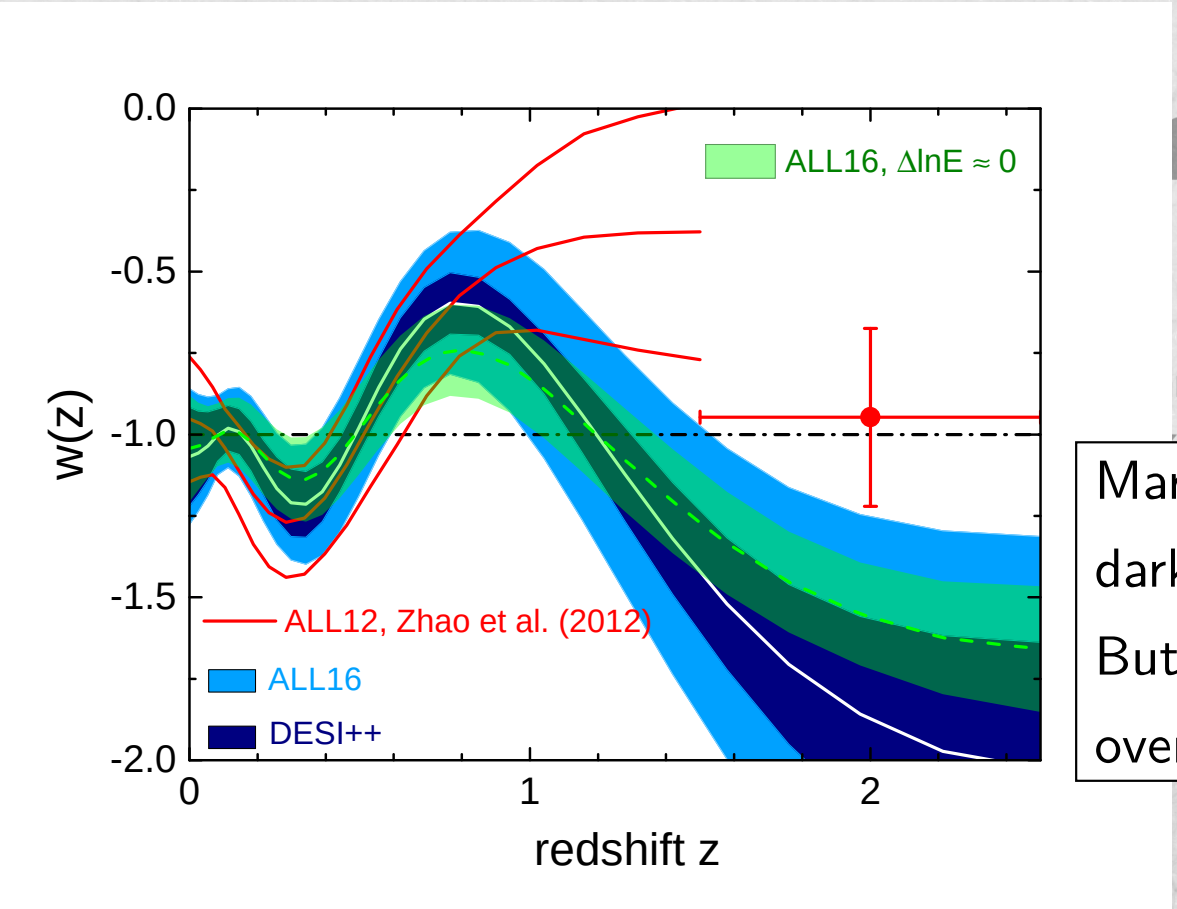
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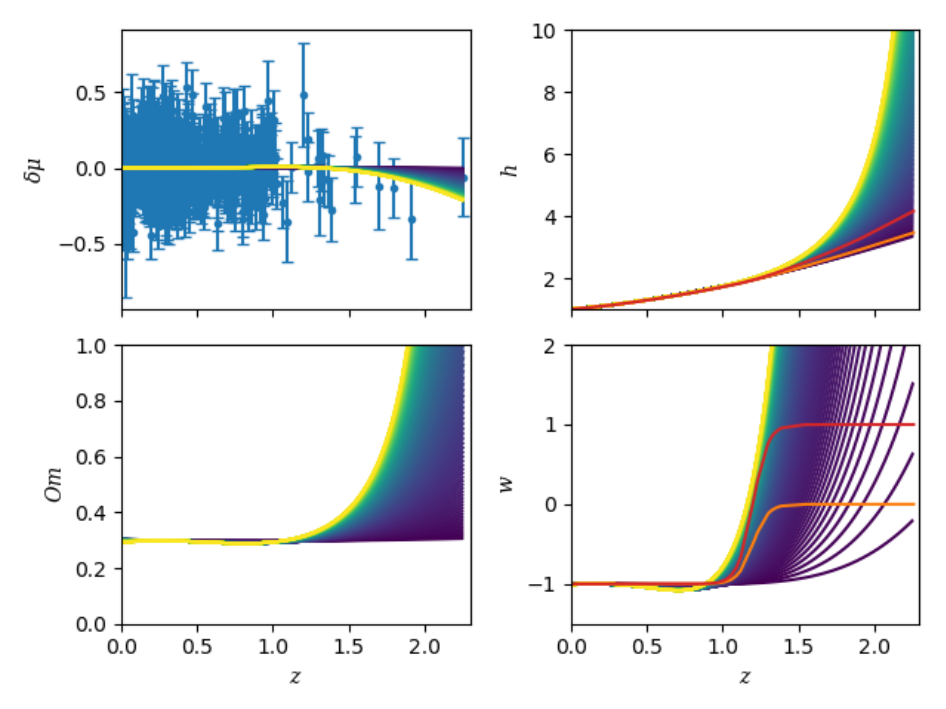


Marginal hints of dynamical dark energy

But not statistically favored over ΛCDM

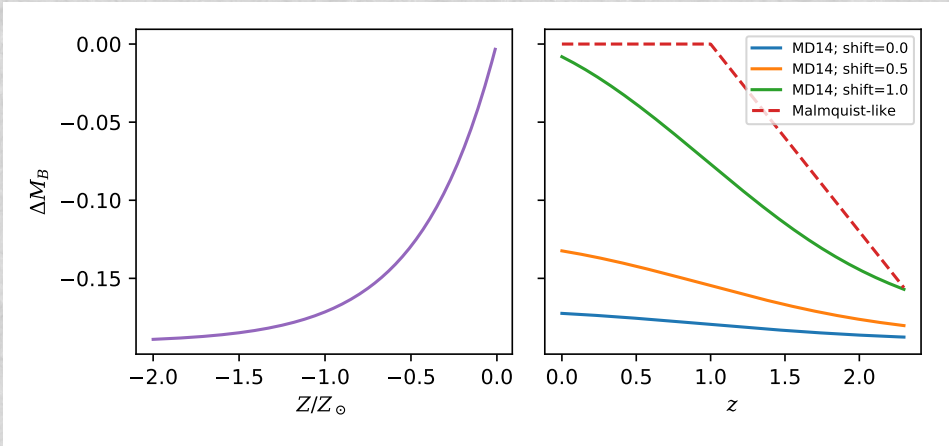
High-z: cosmology vs systematics

BL, Shafieloo, Linder, Kim 1812.03623



- Extreme $w(z)$ needed to reproduce the model-independent $h(z)$ behaviour:
- Matter ($w = 0$, orange) or stiff matter ($w = 1$, red) to DE ($w = -1$) not able to reproduce these

- Metallicity dependence? does not seem to explain

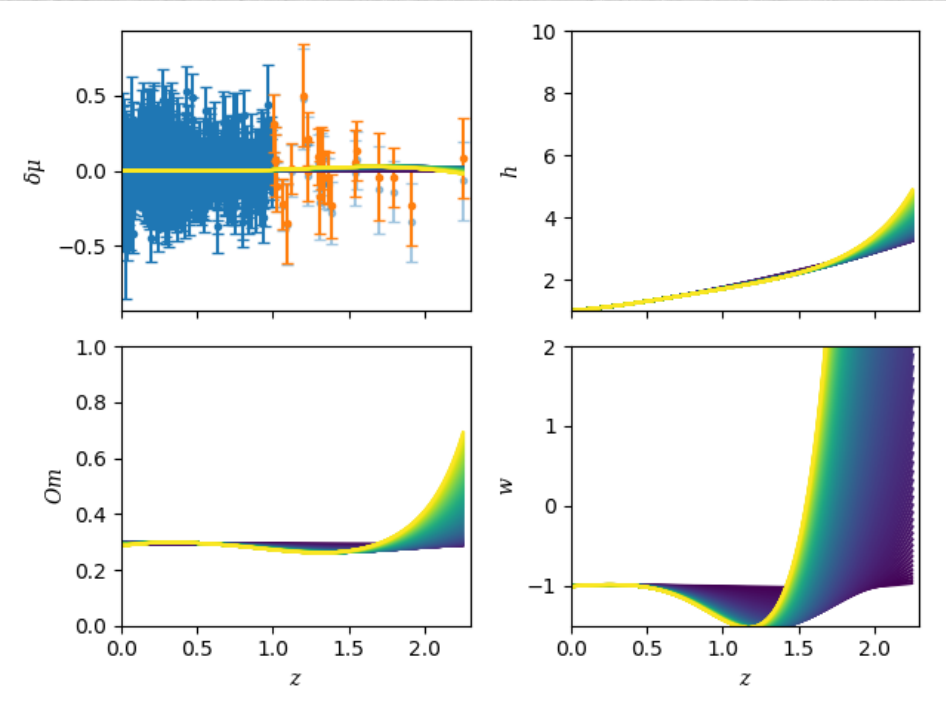


High-z: cosmology vs systematics

BL, Shafieloo, Linder, Kim 1812.03623

- Deviation seem to appear at $z \geq 1$, driven by the small number of data points
- High-z empirical Malmquist-like correction for $z > z_c = 1$:

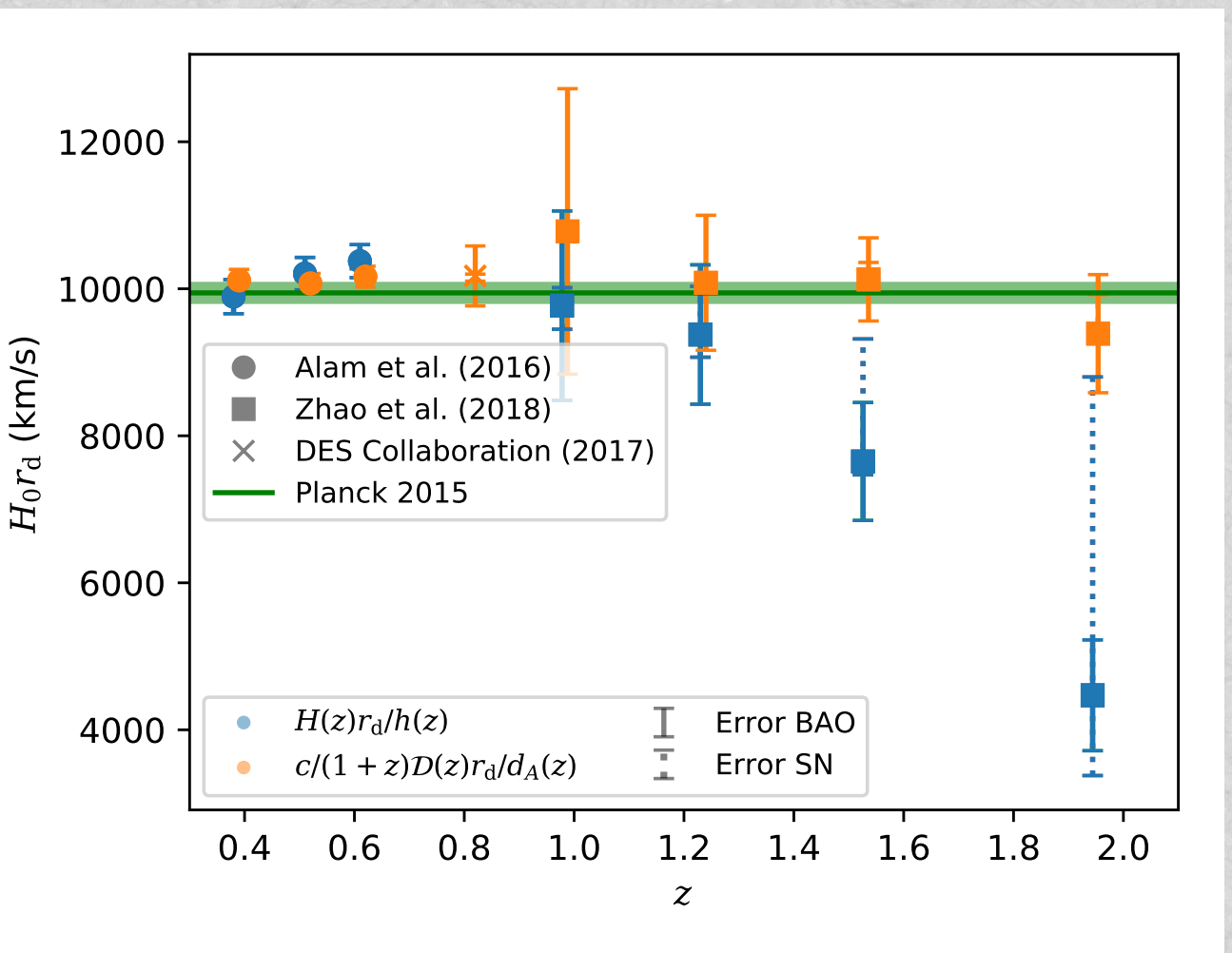
$$\delta\mu = A(z - z_c) \qquad (z > z_c) \tag{6}$$



- Strong reduction of the deviation from ΛCDM
- $\Delta\chi^2 = -0.9$: marginal improvement
- More and better high-z data needed

Model-independent measurement of $H_0 r_\mathrm{d}$

Shafieloo, L'Huillier & Starobinsky (2018), L'Huillier & Shafieloo (2017)



$$H_0 r_\mathrm{d} = \frac{H(z) r_\mathrm{d}}{h(z)} = \frac{c}{1+z} \frac{\mathcal{D}(z) r_\mathrm{d}}{d_\mathrm{A}(z)}$$

Consistent with Planck 2015: $H_0 r_\mathrm{d} = (9944.0 \pm 127.4)\,\mathrm{km\,s^{-1}}$

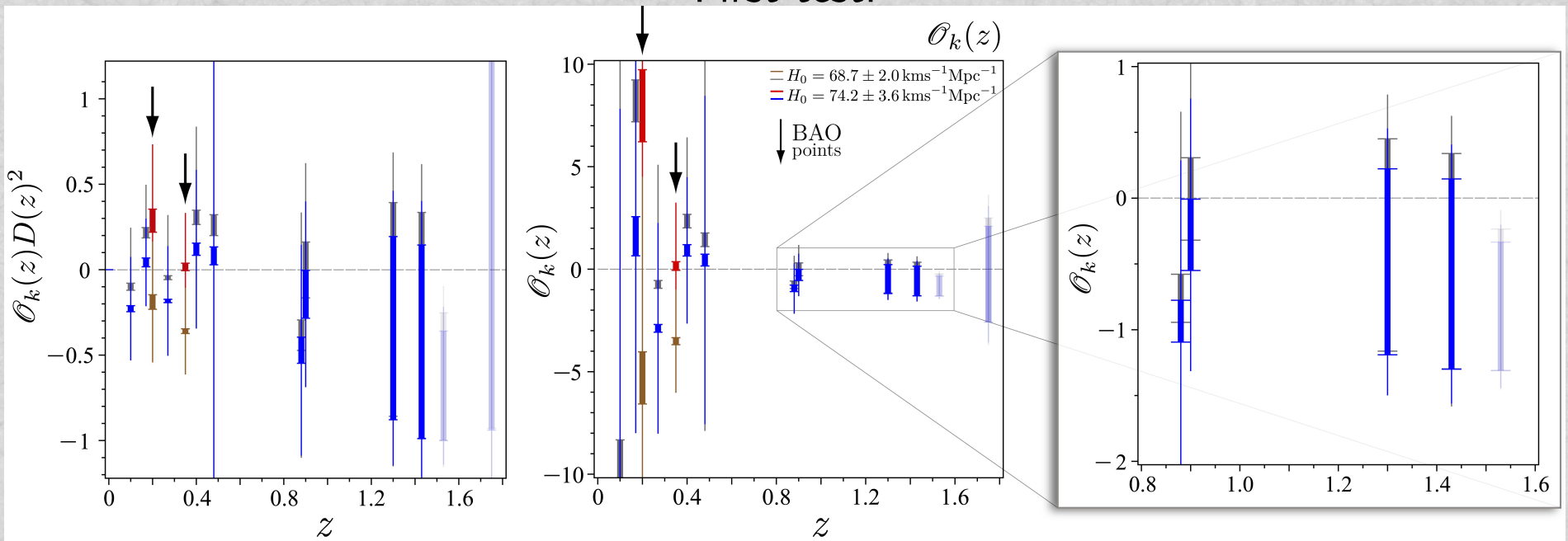
Model-independent test of the FLRW Metric and curvature

Clarkson et al. (2008):

$$\mathcal{D}(z) = \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{\mathrm{d}x}{h(x)}\right)$$

$$\mathcal{O}_k(z) = \frac{(h(z)\mathcal{D}'(z)^2 - 1)}{\mathcal{D}^2(z)} = \frac{\left(\frac{H(z)\mathcal{D}'(z)}{H_0}\right)^2 - 1}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k$$

First test:



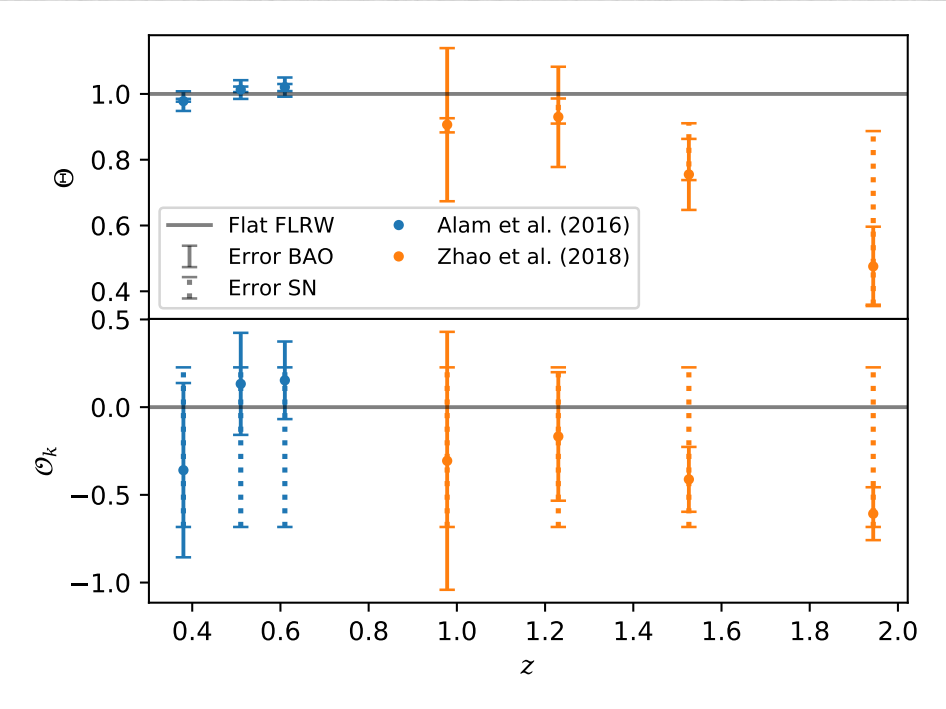
Shafieloo & Clarkson (2010)

Model-independent test of the FLRW Metric and curvature

L'Huillier & Shafieloo (2017), Shafieloo, L'Huillier, Starobinsky (2018)

$$\Theta(z) = h(z)\mathcal{D}'(z) = \frac{(1+z)}{c} H(z) r_\mathrm{d} \frac{d_\mathrm{A}(z)}{r_\mathrm{d}} \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} = F_\mathrm{AP}(z) \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} \overset{\text{flat-FLRW}}{\equiv} 1 \quad (7)$$

$$\mathcal{O}_k(z) = \frac{\Theta^2(z) - 1}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k \quad (8)$$



- L'Huillier & Shafieloo (2017): New formulation, independent of H_0, r_d!
- $H(z)r_\mathrm{d}, d_\mathrm{A}(z)/r_\mathrm{d}$ from BAO
- $\mathcal{D}(z), \mathcal{D}'(z)$ from supernovae
- **Consistent with a flat Universe!**

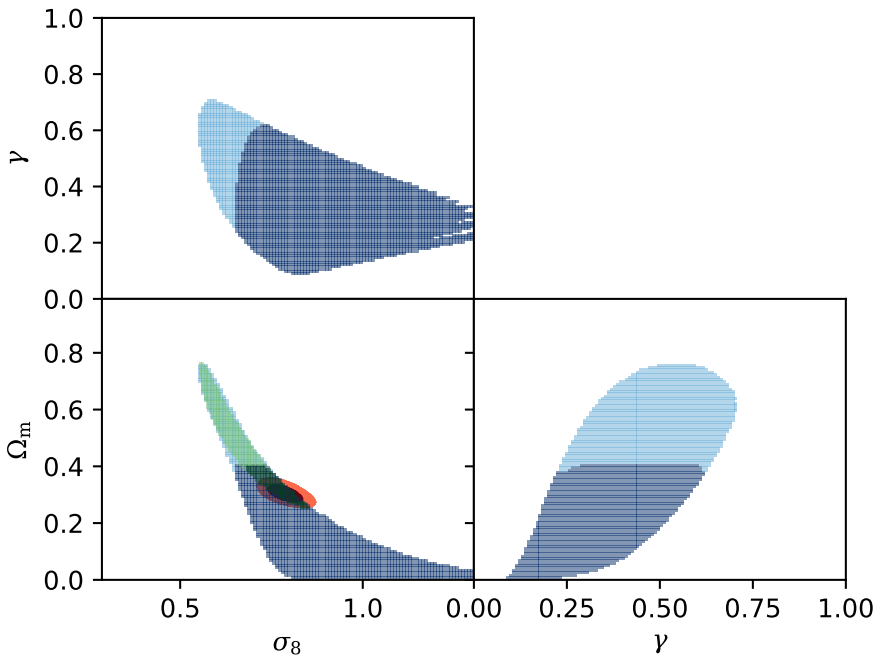
Shafieloo, L'Huillier & Starobinsky (2018)

Perturbation level: testing gravity

Shafieloo, L'Huillier & Starobinsky (2018), L'Huillier, Shafieloo & Kim (2018)

Redshift-space distortion provides

$$f\sigma_8(z) \simeq \sigma_8(0)\Omega_{\rm m}^{\gamma}(z)\exp\left(-\int_0^z \Omega_{\rm m}^{\gamma}(z')\frac{{\rm d}z'}{1+z'}\right), \quad \Omega_{\rm m}(z) = \frac{\Omega_{\rm m}(1+z)^3}{h^2(z)}. \tag{9}$$



ΛCDM (1σ,2σ)

Model-independent ($\chi^2 < \chi^2_{\rm min,\Lambda CDM}$)

Model-independent, $\gamma = 0.55$ (GR)

Dark Blue/Green:

$\Omega_{\rm DE}(z) = h^2(z) - \Omega_{\rm m}(1+z)^3 > 0.$

- Model-independent constraints: larger contours than ΛCDM
- Fully consistent with GR+ΛCDM background

Summary

- Model-independent tests: important in addition to model-fitting approaches
- Latest data: BOSS, eBOSS (BAO), Pantheon (SNIa), RSD
- Universe consistent with flat-ΛCDM with DE as Λ and gravity as GR
- Hints of tensions at $z \gtrsim 1.5$?
  - Low $Hr_{\rm d}$ from BAO
  - SNIa: Possible systematics at $z \geq 1$
  - Future data: DESI, LSST, Euclid, ...
- Perturbation level: GR+ΛCDM consistent with growth and expansion
- Non-linear level: N-body simulations
  - modified gravity,
  - features in the PPS: distinguish between models

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감사합니다!