Falsifying ΛCDM:

Model-independent tests of the concordance model

L'Huillier & Shafieloo, JCAP 1, 15 (2017)

L'Huillier, Shafieloo & Kim MNRAS 476, 3263 (2018)

Shafieloo, L'Huillier & Starobinsky, PRD 98, 083526 (2018)

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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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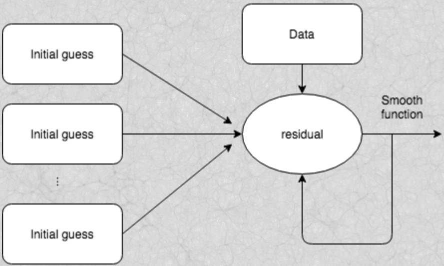
Background expansion

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

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

- 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

Direct Reconstruction of the Expansion History



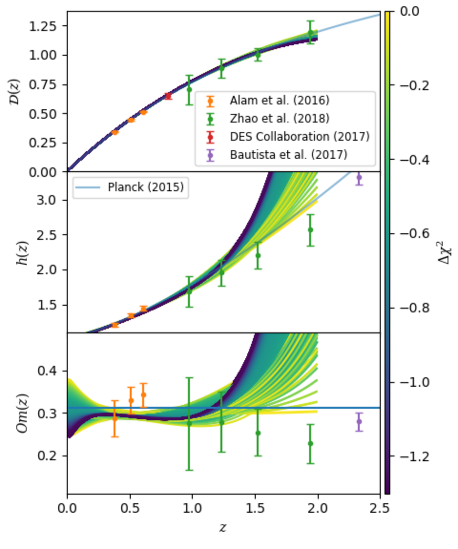
$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\delta\mu_n^{\mathrm{T}}(z)\mathbf{C}^{-1}\mathbf{W}(z)}{(1,\cdots,1)\mathbf{C}^{-1}\mathbf{W}(z)}; \quad (2)$$

$$\mathbf{W}_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right) \quad (3)$$

- Iterative smoothing: Direct reconstruction from the data, no cosmological assumption Shafieloo et al. (2006), Shafieloo (2007),...
- New matrix formulation for correlated data (Shafieloo, L'Huillier & Starobinsky 2018):

Testing Flat-ΛCDM

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



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

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1} \overset{\text{flat-}\Lambda\text{CDM}}{\equiv} \Omega_{\mathrm{m},0} \quad (4)$$

- $z \lesssim 1.5$: 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]

Testing Λ

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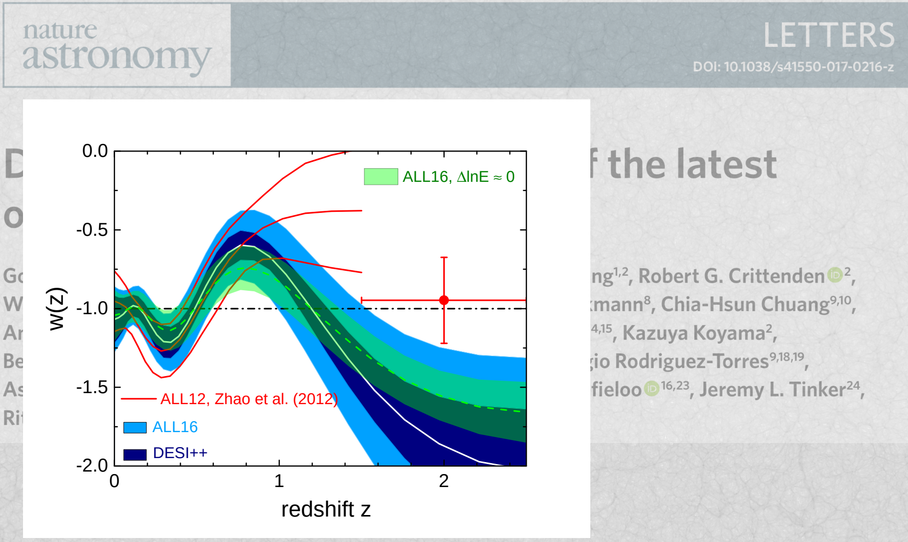
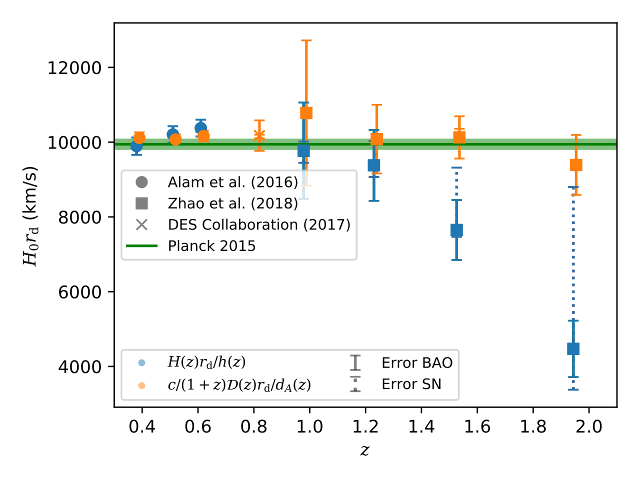


Model-independent measurement of $H_0 r_\mathrm{d}$

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

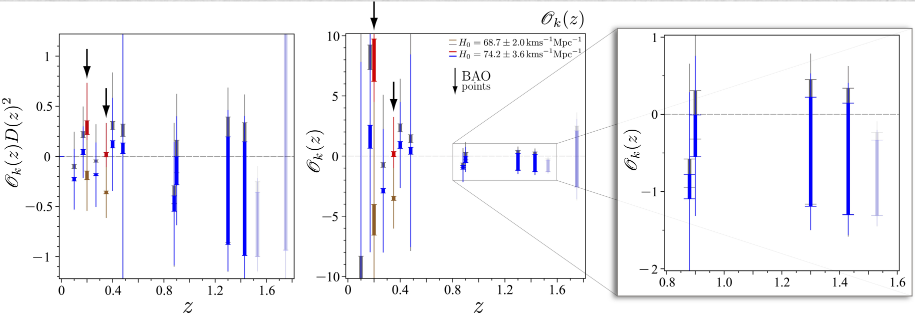
Model-independent test of the FLRW Metric and curvature

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:



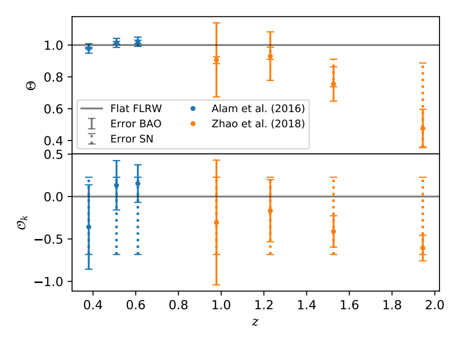
Shafieloo & Clarkson (2010)

Model-independent test of the FLRW Metric and curvature

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

$$\Theta(z) = h(z)\mathcal{D}'(z) = \frac{(1+z)}{c} H(z) r_\mathrm{d} \frac{d_\mathrm{A}(z)}{r_\mathrm{d}} \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} = F_\mathrm{AP}(z) \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} \overset{\text{flat-FLRW}}{\equiv} 1 \quad (5)$$

$$\mathcal{O}_k(z) = \frac{\Theta^2(z) - 1}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k \quad (6)$$



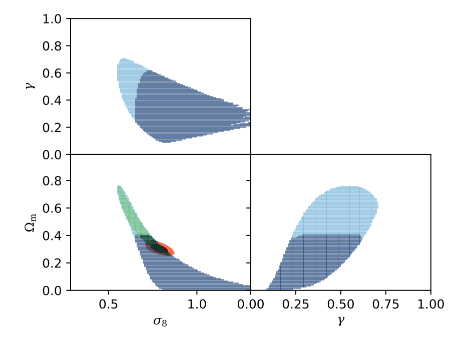
- L'Huillier & Shafieloo (2017): New formulation, independent of H_0, r_d!
- $H(z)r_\mathrm{d}, d_\mathrm{A}(z)/r_\mathrm{d}$ from BAO
- $\mathcal{D}(z), \mathcal{D}'(z)$ from supernovae
- **Consistent with a flat Universe!**

Shafieloo, L'Huillier & Starobinsky (2018)

Perturbation level: testing gravity

Shafieloo, L'Huillier & Starobinsky (2018), L'Huillier et al. (2018)

$$f\sigma_8(z) \simeq \sigma_8(0)\Omega_{\rm m}^{\gamma}(z)\exp\left(-\int_0^z \Omega_{\rm m}^{\gamma}(z')\frac{{\rm d}z'}{1+z'}\right), \quad \Omega_{\rm m}(z) = \frac{\Omega_{\rm m}(1+z)^3}{h^2(z)}. \tag{7}$$



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_d from BAO
- Future data: DESI, LSST, Euclid, ...

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감사합니다!