

Falsifying the concordance model with the large-scale structure

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

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

L'Huillier, Hazra, Shafieloo, Smoot, Starobinsky MNRAS 477, 2503 (2018)

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Benjamin L'HUILLIER

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CosKASI III: The Correlated Universe

2019-04-23



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 Λ CDM 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?
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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
$100\theta_s$	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

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Background expansion in an FLRW universe

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

$$h^2(z) = \Omega_m(1+z)^3 + \Omega_k(1+z)^2 \\ + (1 - \Omega_k - \Omega_m) \exp \left(3 \int_0^z \frac{1+w(x)}{1+x} dx \right), \\ \mathcal{D}(z) = \frac{1}{\sqrt{-\Omega_k}} \sin \left(\sqrt{-\Omega_k} \int_0^z \frac{dx}{h(x)} \right)$$

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

$$r_d = \frac{c}{H_0 \sqrt{3}} \int_0^{1/(1+z_{\text{drag}})} \frac{da}{a^2 h(a) \sqrt{1 + \frac{3\Omega_b}{4\Omega_r} a}}$$

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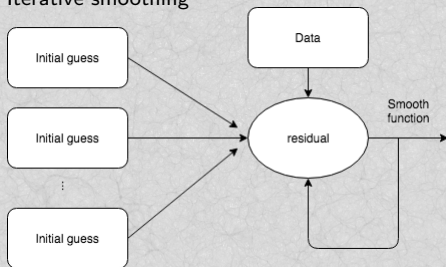
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Direct Reconstruction of the Expansion History

Iterative smoothing



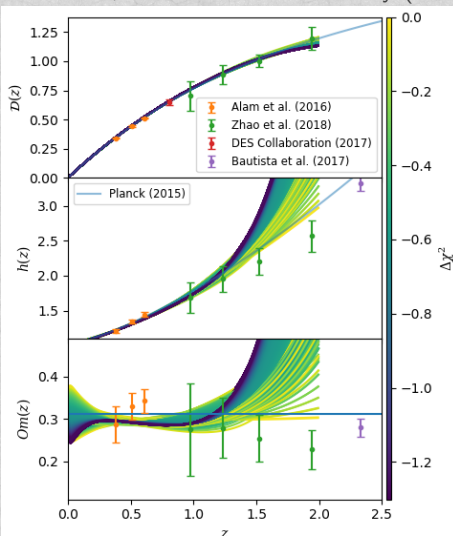
$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\delta\mu_n^T(z)\mathbf{C}^{-1}\mathbf{W}(z)}{(1, \dots, 1)\mathbf{C}^{-1}\mathbf{W}(z)};$$
$$\mathbf{W}_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right)$$

- 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 $\chi^2 < \chi^2_{\Lambda\text{CDM}}$: *Non-exhaustive sample* of plausible expansion histories
- New matrix formulation for correlated data (Shafieloo, L'Huillier & Starobinsky 2018): Covariance matrix $\mathbf{C}$

Testing Flat- Λ CDM

Consistency SNIa/BAO/CMB

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



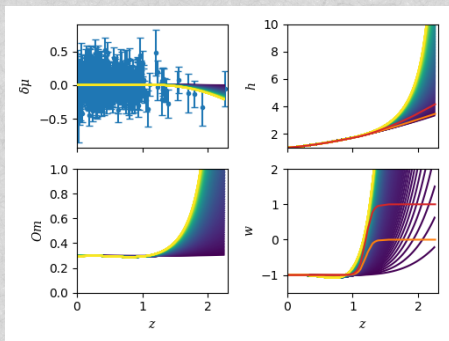
- Model-independent reconstruction of expansion from SNIa (iterative smoothing)
- Lines: Reconstructed $h(z)$ from SNIa
- Data points: BAO (Boss DR12, eBOSS DR 14Q, DES) + Planck 2015 $H_0 r_d$
- Ω_m diagnostics (Sahni et al. 2008):

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

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

High- z SNIa: cosmology or systematics?

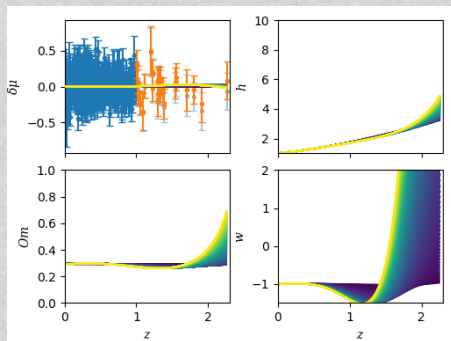
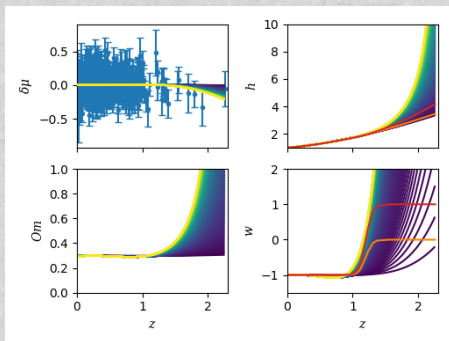
L'Huillier, Shafieloo, Linder & Kim MNRAS 485, 2783 (2019)



- Possible deviation from Λ CDM at $z \geq 1$. $Om(z) \neq \text{Constant}$: cosmology? Unlikely

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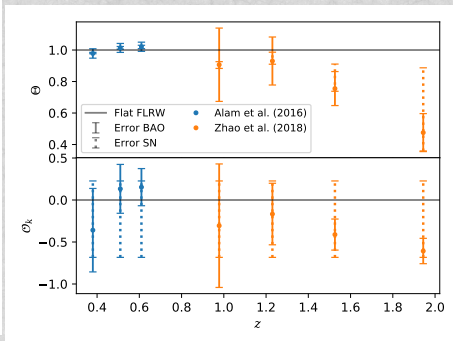
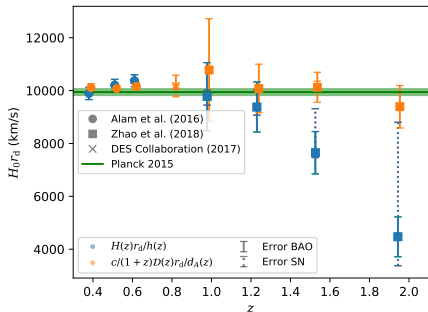
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- Possible deviation from Λ CDM at $z \geq 1$. $Om(z) \neq \text{Constant}$: cosmology? Unlikely
- Malmquist-like correction at $z > 1$: $\mu \rightarrow \mu + A(z - 1)$
- After correction: Om better behaved
- But not statistically significant

Model-independent measurement of $H_0 r_d$, curvature test

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



$$H_0 r_d = \frac{H(z) r_d}{h(z)} = \frac{c}{1+z} \frac{D(z) r_d}{d_A(z)}$$

$$\Theta(z) = \frac{(1+z)}{c} H(z) r_d \frac{d_A(z)}{r_d} \frac{D'(z)}{D(z)} \stackrel{\text{flat-FLRW}}{\equiv} 1$$

Consistent with Planck 2015:

$$H_0 r_d = (9944.0 \pm 127.4) \text{ km s}^{-1}$$

$$\Theta_k(z) = \frac{\Theta^2(z) - 1}{D^2(z)} \stackrel{\text{FLRW}}{\equiv} \Omega_k$$

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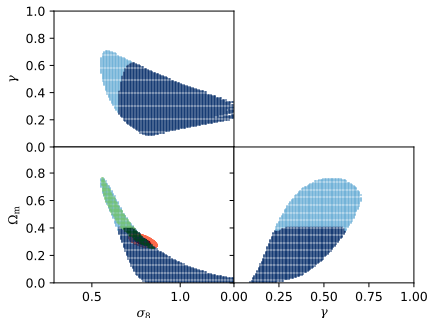
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Perturbation level: testing gravity

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

Redshift-space distortion provides

$$f\sigma_8(z) \simeq \sigma_8(0)\Omega_m^\gamma(z) \exp\left(-\int_0^z \Omega_m^\gamma(z') \frac{dz'}{1+z'}\right), \quad \Omega_m(z) = \frac{\Omega_m(1+z)^3}{h^2(z)}. \quad (2)$$



Λ CDM ($1\sigma, 2\sigma$)

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

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

Dark Blue/Green:

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

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

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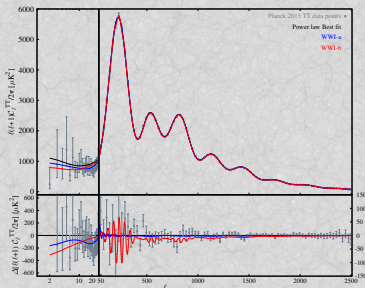
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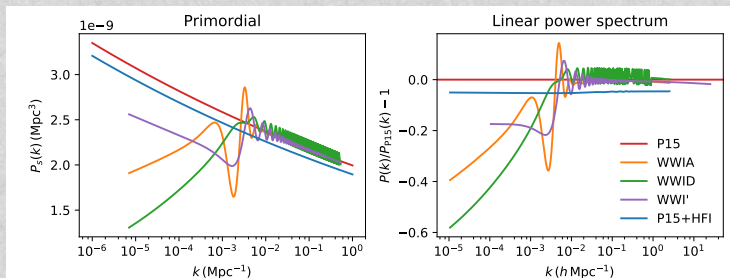
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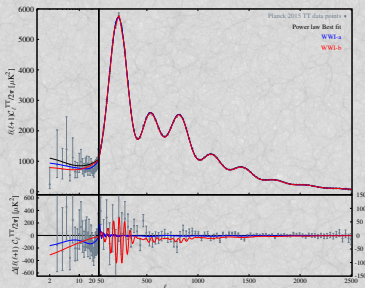
Features in the PPS



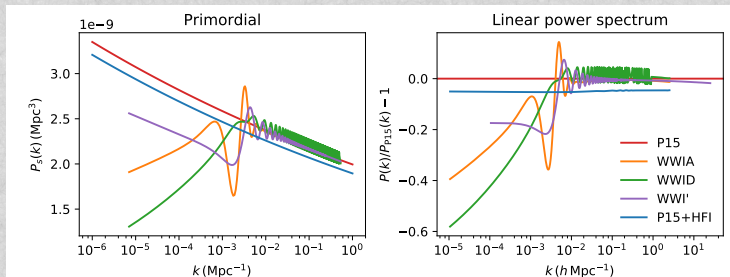
- Models with features in the PPS allowed by data (ex: WWI)
- CMB alone cannot distinguish the model
- 2D (CMB) $\rightarrow$ 3D (LSS)
- Can we use the LSS to distinguish these models? $\rightarrow$ N -body simulations



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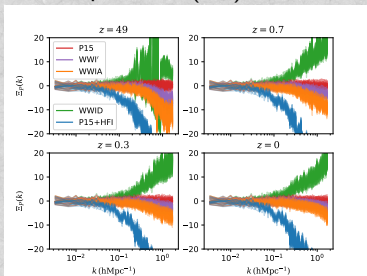
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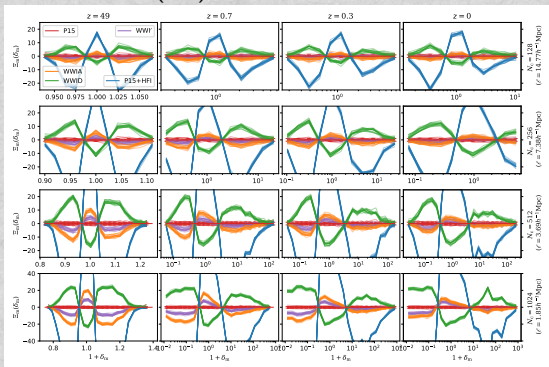
N-body simulations with non-power law PPS

L'Huillier, Shafieloo, Hazra, Smoot & Starobinsky (2018)

Power spectrum (1D)



Count-in-cell (3D)



Able to distinguish between the models

- Features vanish in the non-linear regime.
- WWID and P15+HFI can be distinguished, but not WWIA, WWID and P15

Summary

- Model-independent tests: important in addition to model-fitting approaches
- Latest data: BOSS, eBOSS (BAO), Pantheon (SNIa), RSD
- Universe consistent with flat- Λ CDM 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, ...
- N -body simulations to study haloes in modified gravity, features in the PPS: distinguish between models
- N -body simulations of modified gravity: effects of MG on haloes

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