Testing Late-Time Cosmic Acceleration with uncorrelated Baryon Acoustic Oscillations dataset

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Based on David Benisty, D.S.,
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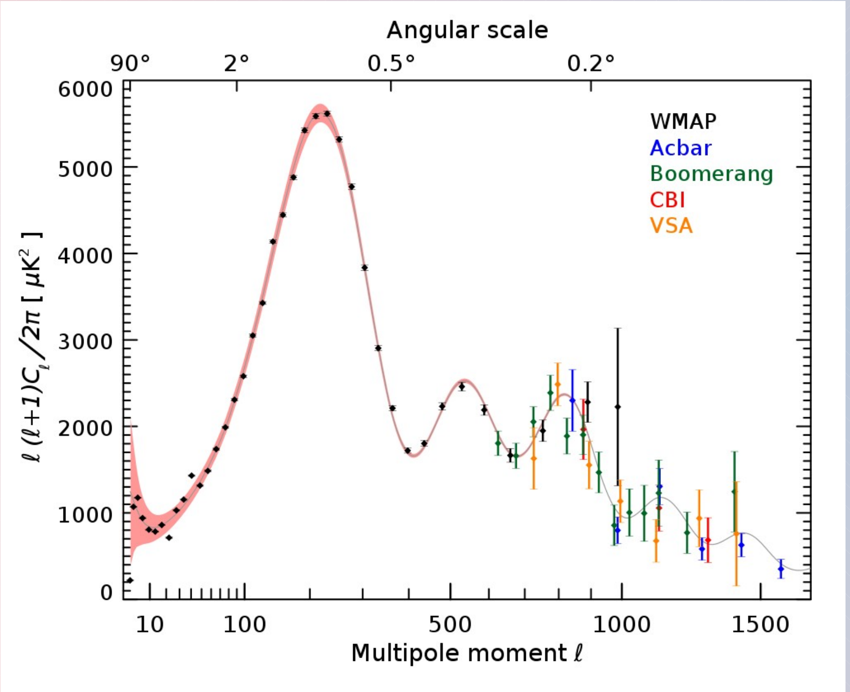
ИЯИЯЕ
INRNE

БЪЛГАРСКА
АКАДЕМИЯ
на НАУКИТЕ
1869

BAO – „standard ruler“ in cosmology



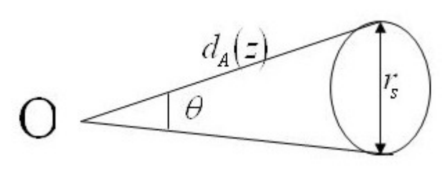
- Baryonic acoustic oscilations are regular, periodic fluctuations in the density of the visible baryonic matter of the universe.
- Created by the intrerplay of gravity, radiation pressure and the expansion of the universe acting on its different components
- The distance at which plasma waves induced by radiation pressure froze at recombination the sound horizon, r_d
- Measured by looking at the large scale structure of matter

Planck 2018:
r_d=147.5 Mpc,
z_d=1059, z_*=1100.

Credit: Chris Blake and Sam Moorfield

Connecting the dots...

Observational:



$$D_A = \frac{r_s}{\theta}$$

where

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$c_s(z) = \frac{c}{\sqrt{3\left(1 + \frac{3\Omega_b}{4\Omega_\gamma} \frac{1}{1+z}\right)}}$$

Theoretical:

$$D_M = \frac{c}{H_0} S_k\left(\int_0^z \frac{dz'}{E(z')}\right)$$

$$D_V(z) = \left(\frac{cz(1+z)^2 D_A^2}{H}\right)^{1/3}$$

$$D_A = D_M/(1+z)$$

with

$$S_k(x) = \begin{cases} \frac{1}{\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k} x\right) & \text{if} \quad \Omega_k > 0 \\ x & \text{if} \quad \Omega_k = 0 \\ \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k} x\right) & \text{if} \quad \Omega_k < 0 \end{cases}$$

LCDM:

$$H(z) = \dot{a}(z)/a(z)$$

$$H(z)/H_0 = E(z)$$

With EOS:

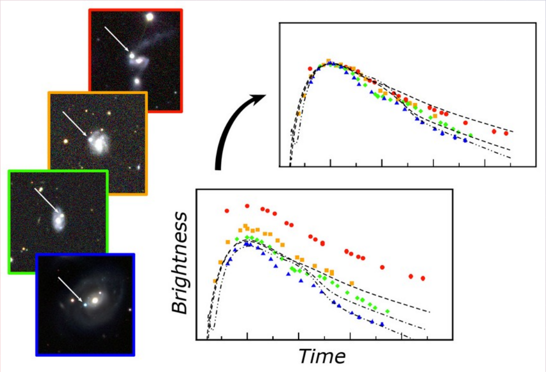
$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda$$

The datasets

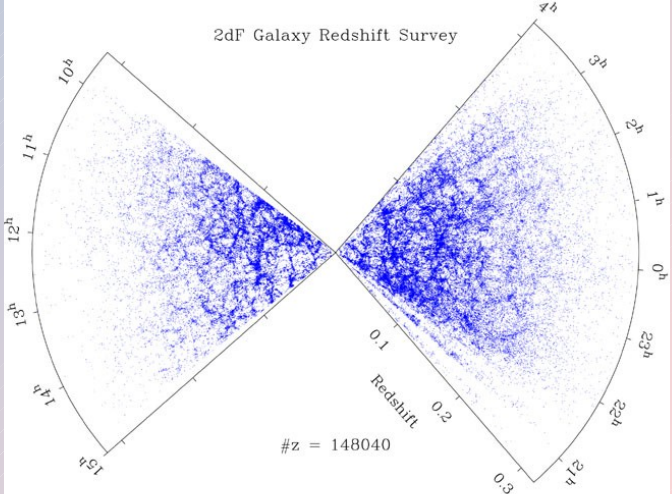
- BAO from eBoss, SDSS, DES, WiggleZ, 6dFGS
- Cosmic chronometers
- Standard candles:

-- Pantheon type Ia SNe

-- quasars and GRBs



- Collection of 333 data points from ~70 publications, in the period 2008 – 2020
- The SDSS's eBOSS uses low redshift galaxies (MGS), luminous red galaxies (LRG), emission line galaxies (ELG) and the Lyman-α forest of quasars.



Methodology

- Python + Polychord as a nested MCMC sampler + Getdist
- 5 parameters: $\mathbf{\Omega_m}$, $\mathbf{\Omega_\Lambda}$, $\mathbf{H_0}$, $\mathbf{r_d}$, $\mathbf{r_d/r_{dfid}}$, extended **with $\mathbf{\Omega_k}$** or **w**
- Additional H_0 prior using the Riess et al. (2019) measurement:

$$H_0 = 74.03 \pm 1.42 (km/s)/Mpc$$

- **LCDM priors** **Extended models priors**

$$\Omega_\Lambda \in [0.; 1 - \Omega_m],\ H_0 \in [50; 100] \text{ and } r_d \in [100; 200] Mpc$$
$$\Omega_m \in [0.; 1.], r_d/r_{d,fid} \in [0.9, 1.1]$$

$$\Omega_k \in [-0.1; 0.1]$$
$$w \in [-1.25; -0.75]$$

- Standard χ^2 function for uncorralated data:

$$\chi^2 = \left(\frac{y_i - y_{th}}{\sigma_i}\right)^2$$

Note $\mathbf{r_d}$, $\mathbf{r_d/r_{dfid}}$ are independent parameters!

Correlations:

- Covariance matrix
- Mock covariance
- Correlated χ^2:

$$\chi^2 = V^i C_{ij}^{-1} V^j$$

where

$$V^i = y_i - y_{th}$$

y_i are the observed values and y_{th} -- the theoretically predicted ones for this z and σ_i is the error

$$C_{ii} = \sigma_i^2 .$$
$$C_{ij} = 0.5\sigma_i\sigma_j$$

- **The results:**

Difference between 0% correlation and 30% correlation is ~10%.

Thus points are uncorrelated.

n	BAO	BAO + R19
$n = 0$	$\Omega_m = 0.257 \pm 0.02$ $\Omega_\Lambda = 0.735 \pm 0.021$	$\Omega_m = 0.255 \pm 0.03$ $\Omega_\Lambda = 0.736 \pm 0.021$ $r_d = 139.32 \pm 2.88\, Mpc$
$n = 3$	$\Omega_m = 0.268 \pm 0.023$ $\Omega_\Lambda = 0.725 \pm 0.019$	$\Omega_m = 0.267 \pm 0.021$ $\Omega_\Lambda = 0.725 \pm 0.018$ $r_d = 138.49 \pm 3.03\, Mpc$
$n = 6$	$\Omega_m = 0.275 \pm 0.021$ $\Omega_\Lambda = 0.719 \pm 0.016$	$\Omega_m = 0.274 \pm 0.020$ $\Omega_\Lambda = 0.720 \pm 0.012$ $r_d = 138.32 \pm 2.76\, Mpc$

Kazantzidis & Perivolaropoulos 2019, PRD 99, 063537

The LCDM model:

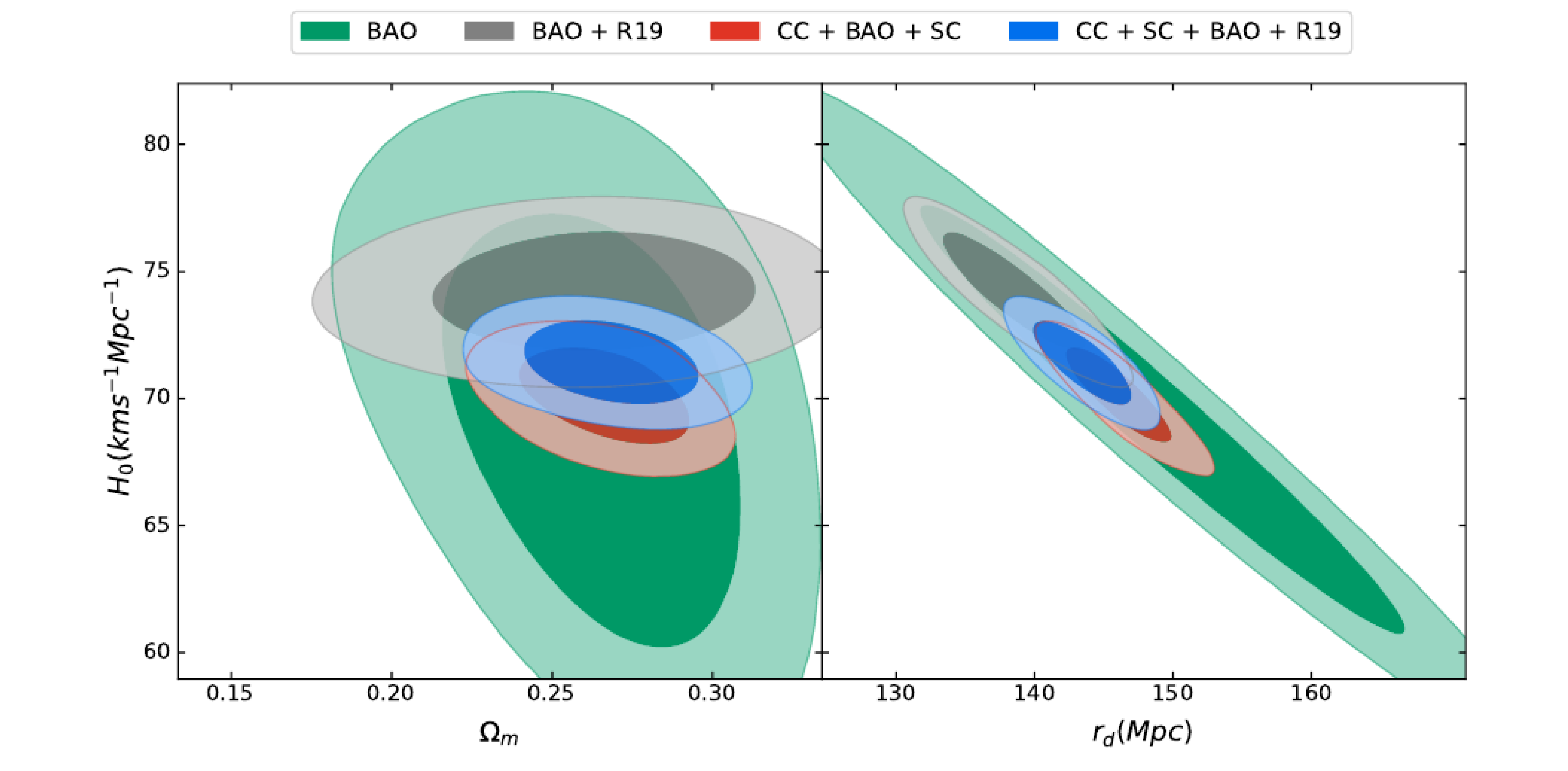
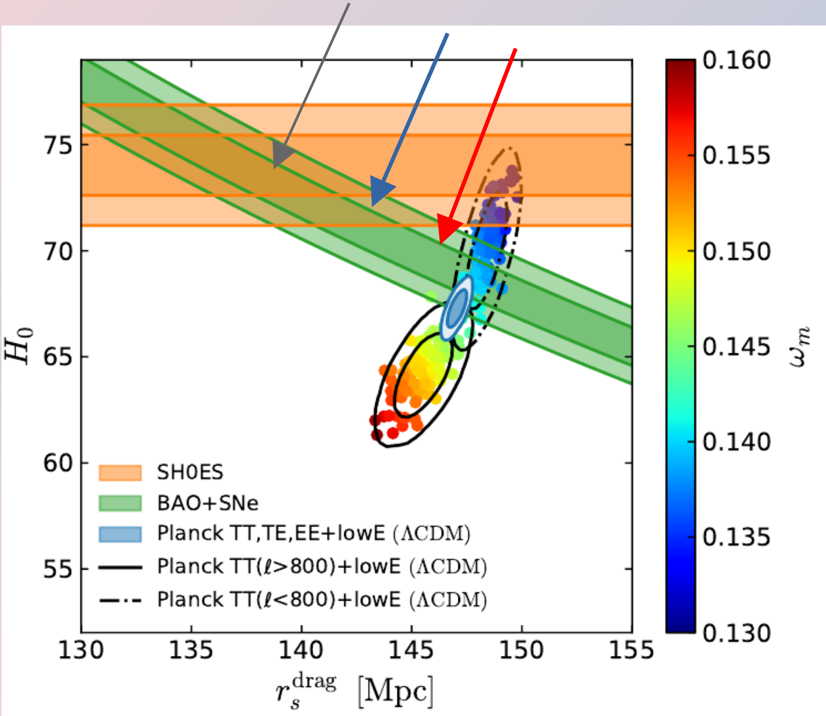
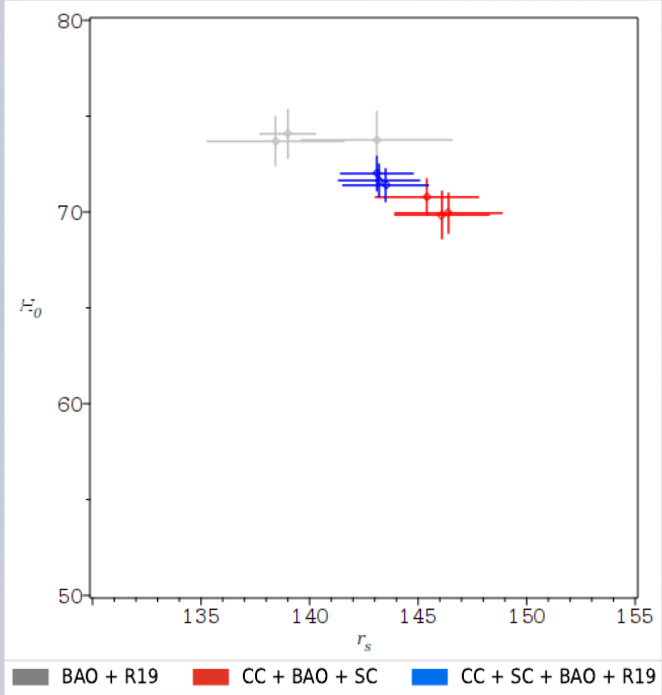


Fig. 2. *The posterior distribution for different measurements with the ΛCDM model with 1σ and 2σ. The BAO refers to the Baryon Acoustic Oscillations dataset from table 1. The CC dataset refers to Cosmic Chronometers and SC refers to the Hubble Diagram from Type Ia supernova, Quasars and Gamma Ray Bursts. R19 denotes the Riess 2019 measurement of the Hubble constant as a Gaussian prior.*

The r_d-H_0 tension



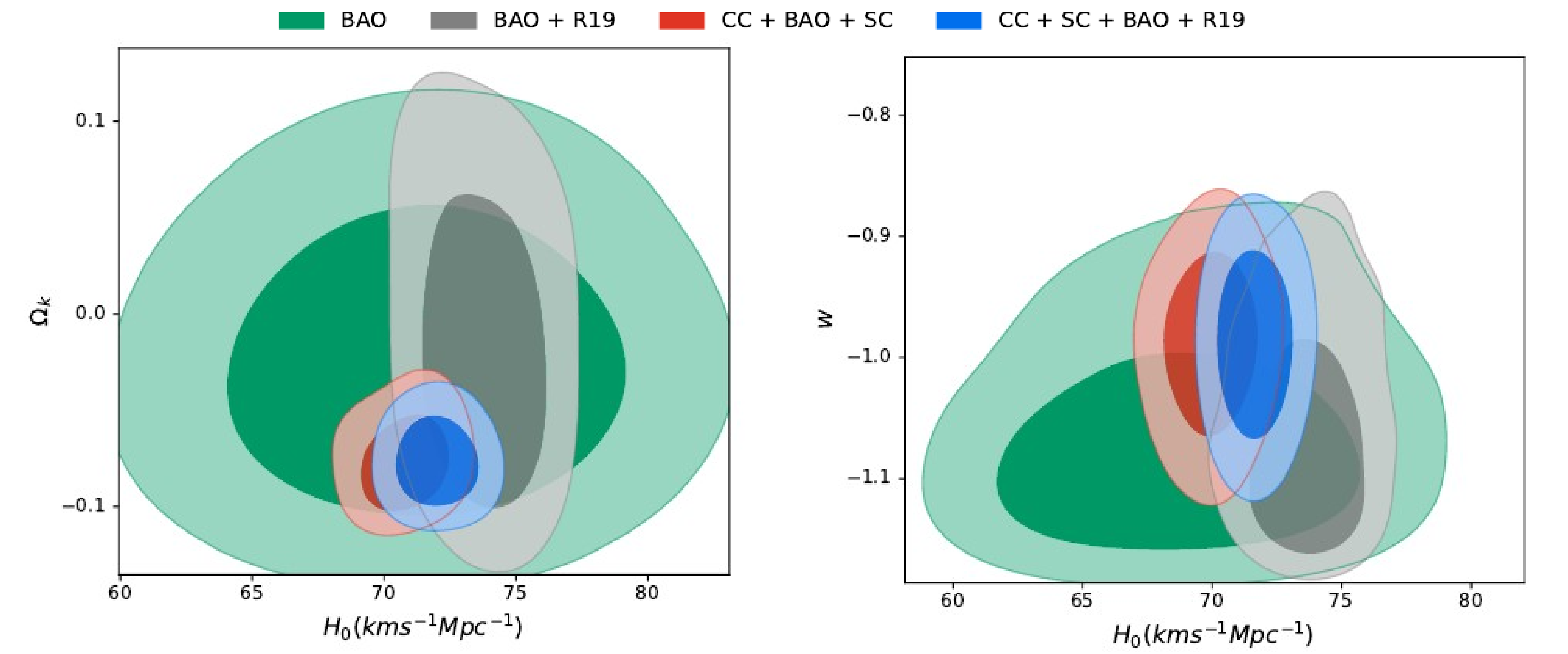


- **Knox, L. & Millea, M. 2020, Physical Review D, 101, arXiv:1908.03663**

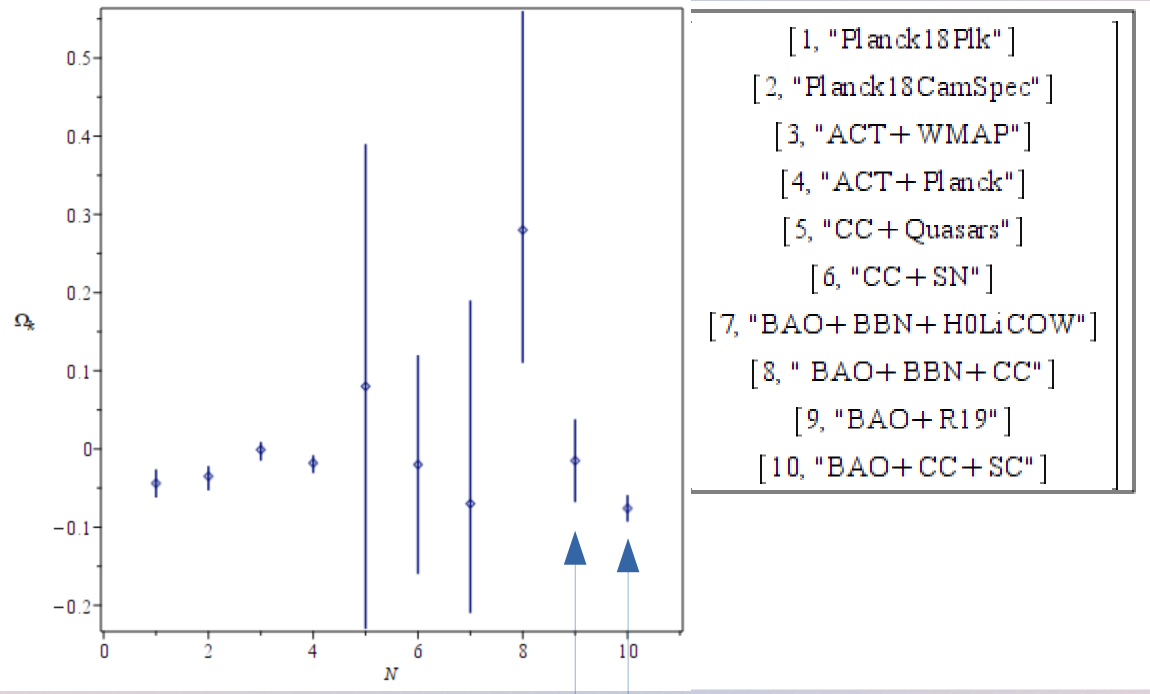
Our results fall on the BAO+SN line

Extensions

- Ω_kCDM $E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda,$
- wCDM $\Omega_\Lambda \rightarrow \Omega^0_{DE}(1+z)^{-3(1+w)}$



The spatial curvature



Our result

Di Valentino et al.
Astropart. Phys. 131, 102607 (2021), arXiv:2008.11286

Conclusions:

- BAO combined with other cosmological probes can be used to constrain cosmological parameters.
- LCDM is the best fit model
- The data shows preference for a closed universe (k=1) but with low statistical support
- The data has some support for wCDM with equation of state w≥-1
- BAO data cannot alleviate the H_0 tension entirely:

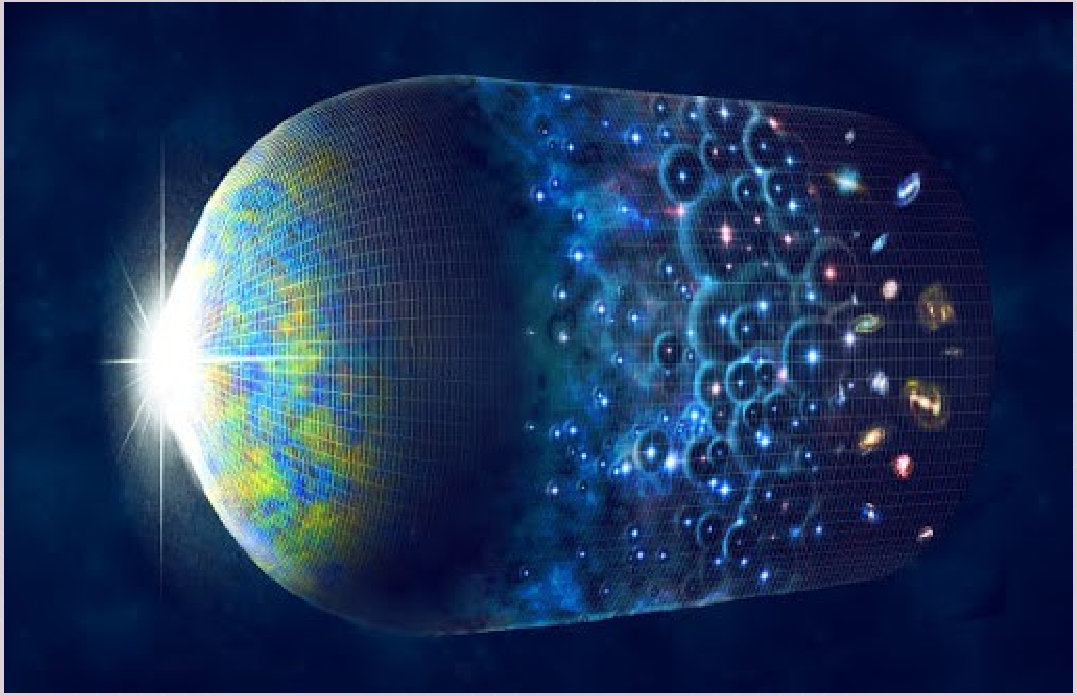
  LMC: H_0= 74.03 (km/s)/Mpc,

  CMB: H_0 = 67.4(km/s)/Mpc

  Our result: H_0=69.85 (km/s)/Mpc
- We see strong dependence of the final value of H_0 on the choice of r_d as expected.

A&A 2020
DOI: 10.1051/0004-6361/202039502
arXiv:2009.10701 [astro-ph.CO]

Thank you for your attention!



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In numbers:

Model	Parameters	BAO + R19	BAO + CC + SC	BAO + CC + SC + R19
	H_0[km/s/Mpc]	74.08 ± 1.31	69.85 ± 1.27	71.40 ± 0.89
	Ω_m	0.261 ± 0.028	0.271 ± 0.016	0.267 ± 0.017
ΛCDM	Ω_Λ	0.733 ± 0.021	0.722 ± 0.012	0.726 ± 0.012
	r_d [Mpc]	139.0 ± 3.1	146.1 ± 2.2	143.5 ± 2.0
	r_d/r_{fid}	0.97 ± 0.019	1.01 ± 0.021	0.98 ± 0.014
	H_0[km/s/Mpc]	73.76 ± 1.52	70.78 ± 0.99	72.01 ± 0.93
	Ω_m	0.181 ± 0.051	0.253 ± 0.011	0.252 ± 0.009
$\Omega_k\Lambda$CDM	Ω_Λ	0.806 ± 0.024	0.801 ± 0.009	0.802 ± 0.009
	r_d [Mpc]	143.1 ± 3.5	145.4 ± 2.4	143.1 ± 1.7
	Ω_k	-0.015 ± 0.053	-0.076 ± 0.017	-0.076 ± 0.012
	r_d/r_{fid}	0.962 ± 0.019	0.988 ± 0.019	0.969 ± 0.015
	H_0[km/s/Mpc]	73.69 ± 1.31	69.94 ± 1.08	71.65 ± 0.88
	Ω_m	0.243 ± 0.039	0.269 ± 0.023	0.266 ± 0.022
wCDM	Ω_Λ	0.746 ± 0.029	0.724 ± 0.019	0.727 ± 0.019
	r_d [Mpc]	138.43 ± 3.18	146.4 ± 2.5	143.2 ± 1.9
	w	-1.067 ± 0.065	-0.989 ± 0.049	-0.989 ± 0.049
	r_d/r_{fid}	0.935 ± 0.024	0.99 ± 0.0164	0.967 ± 0.015

Table 3. *Constraints at 95% CL errors on the cosmological parameters for the ΛCDM, $\Omega_k\Lambda$CDM model and the wCDM model. The datasets are: the BAO alone, the BAO + CC + SC combination and with with the Riess 2019 measurement as a Gaussian prior.*

The final dataset

z	Parameter	Value	Error	year	Survey	Ref.
0.106	r_d/D_V	0.336	0.015	2011	6dFGS	Beutler et al. (2011)
0.15	$D_V(r_{d,fidd}/r_d)$	664	25.0	2014	SDSS DR7	Ross et al. (2015)
0.275	r_d/D_V	0.1390	0.0037	2009	SDSS-DR7+2dFGRS	Percival et al. (2010)
0.32	$D_V(r_{d,fidd}/r_d)$	1264	25	2016	SDSS-DR11 LOWZ	Tojeiro et al. (2014)
0.44	r_d/D_V	0.0870	0.0042	2012	WiggleZ	Blake et al. (2012)
0.54	D_A/r_d	9.212	0.41	2012	SDSS-III DR8	Seo et al. (2012)
0.57	D_V/r_d	13.67	0.22	2012	SDSSIII/DR9	Anderson et al. (2013)
0.6	r_d/D_V	0.0672	0.0031	2012	WiggleZ	Blake et al. (2012)
0.697	$D_A(r_{d,fidd}/r_d)$	1499	77	2020	DECals DR8	Sridhar et al. (2020)
0.72	$D_V(r_{d,fidd}/r_d)$	2353	63	2017	SDSS-IV DR14	Bautista et al. (2018)
0.73	r_d/D_V	0.0593	0.0020	2012	WiggleZ	Blake et al. (2012)
0.81	D_A/r_d	10.75	0.43	2017	DES Year1	Abbott et al. (2019)
0.874	$D_A(r_{d,fidd}/r_d)$	1680	109	2020	DECals DR8	Sridhar et al. (2020)
1.48	$D_H \cdot r_d$	13.23	0.47	2020	eBoss DR16 BAO+RSD	Hou et al. (2020)
1.52	$D_V(r_{d,fidd}/r_d)$	3843	147.0	2017	SDSS-IV/DR14	Ata et al. (2018)
2.3	$H \cdot r_d$	34188	1188	2012	Boss Lya quasars DR9	Busca et al. (2013)
2.34	$D_H \cdot r_d$	8.86	0.29	2019	BOSS DR14 Lya in LyBeta	de Sainte Agathe et al. (2019)

Table 1. *The uncorrelated dataset that has been used is this paper. For each redshift, the table presents the parameter, the mean value and the corresponding error bar. The Ref. and the collaboration is also reported.*