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

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Based on David Benisty, D.S.,
A&A 647, A38 2021

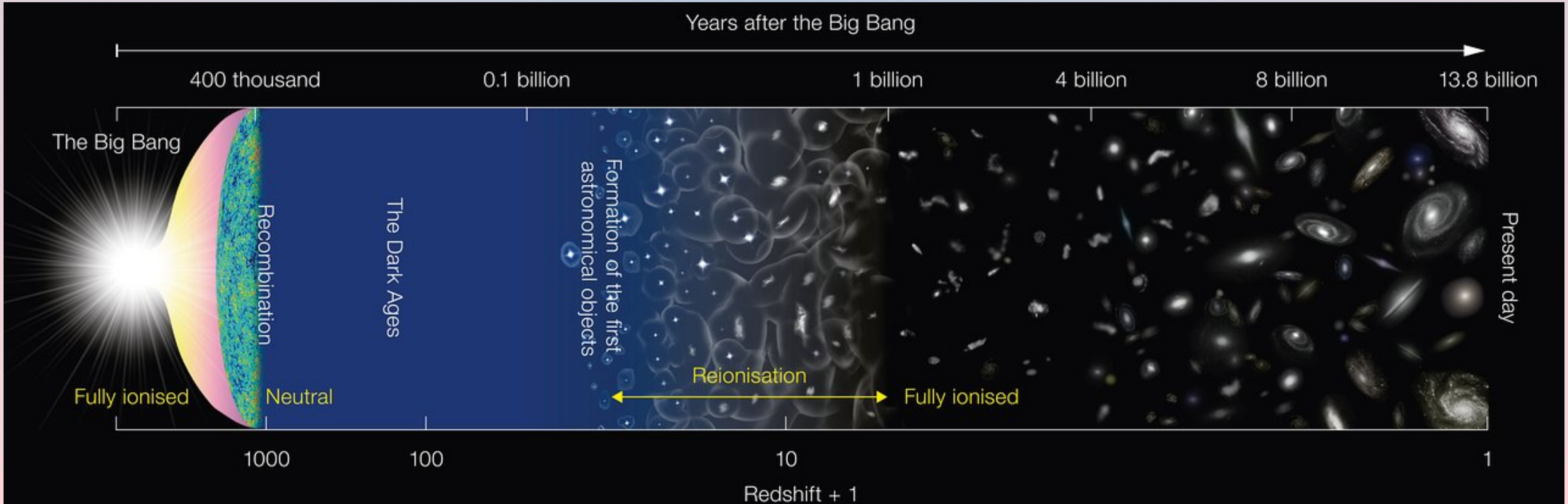
Seminar TMP-INRNE 04.03.2021

ИЯИЯЕ
INRNE

БЪЛГАРСКА
АКАДЕМИЯ
на НАУКИТЕ
1869

How it all began?

- Current paradigm – the Universe started 13.8 By ago with a hot Big Bang
- It keeps on expanding ever since and it`s even accelerating
- Current composition – DE (~73%), DM (~23%), baryons, neutrinos, photons (~4%)
- After inflation the Universe was hot, fully ionised, opaque soup. **Radiation rulez!**
- Neutrinos decouple about 1s after the Big Bang, so we mostly ignore them.



But different components evolve differently...

- Concordance model (LCDM) is given by the Friedmann equation.
- It connects the Hubble factor

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

- With the equation of state of the universe:

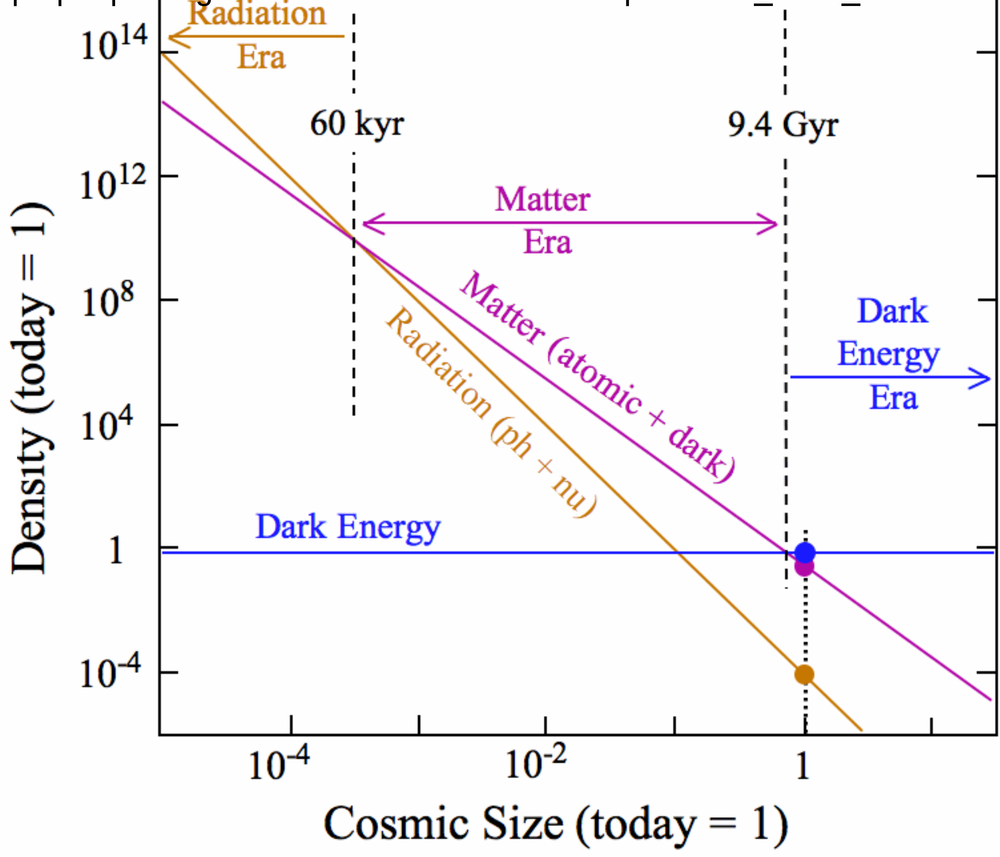
$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda,$$

- Trough

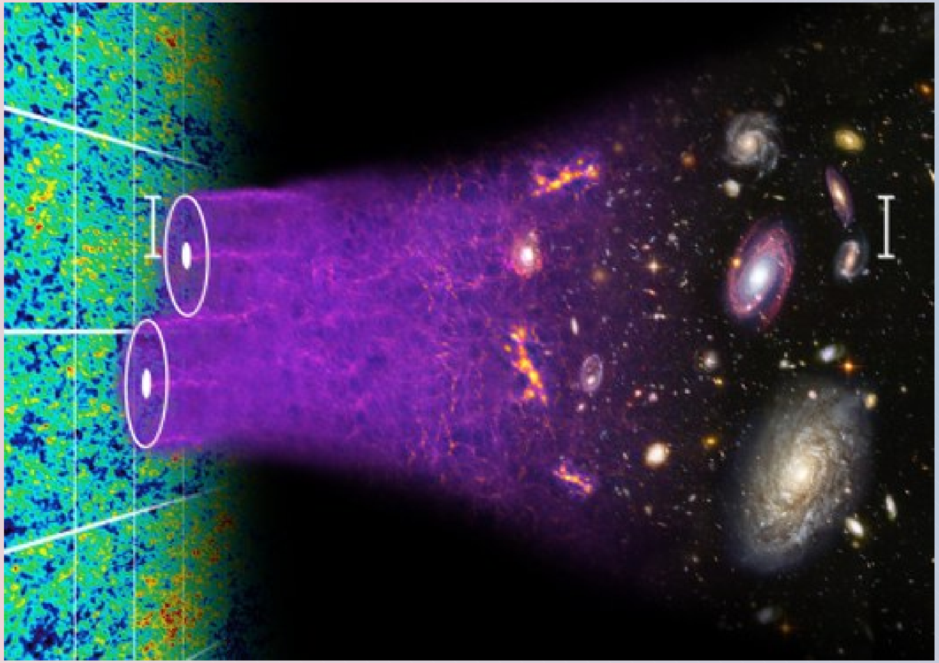
$$H(z)/H_0 = E(z)$$

- Different compontent evolve differently with the redshift (z) !

http://people.virginia.edu/~dmw8f/astr5630/Topic16/t16_dens_evol.html

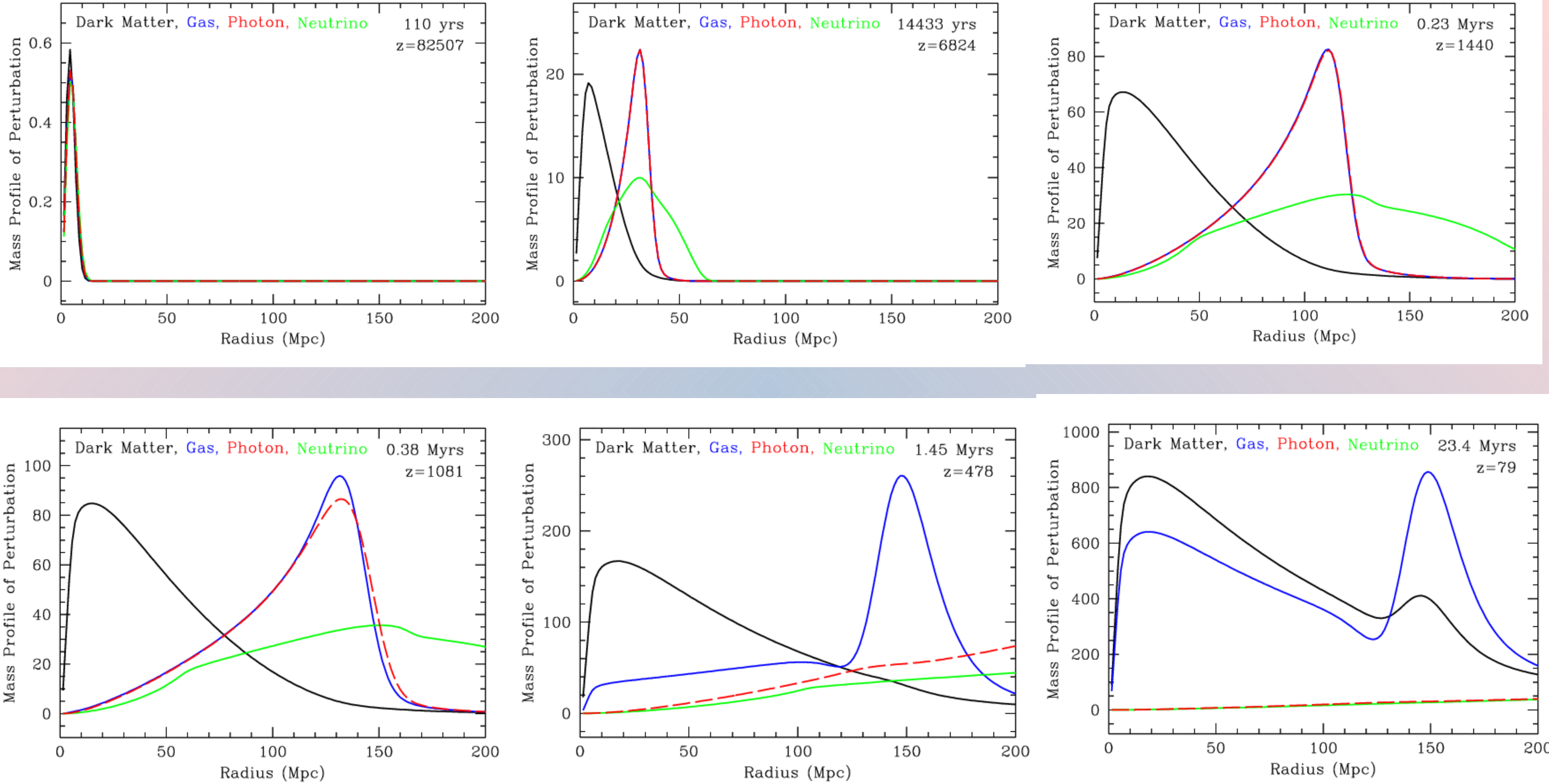


Baryonic Acoustic Oscilations

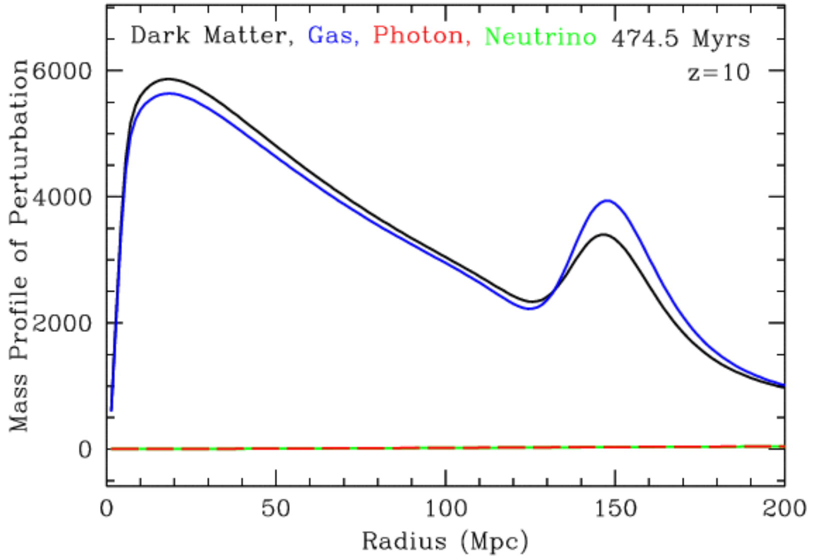


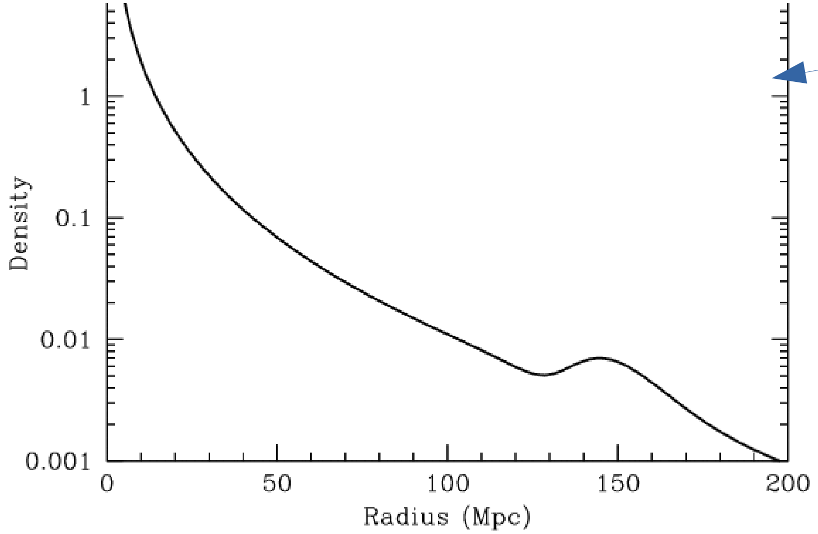
- Baryonic acoustic oscilations are regular, periodic fluctuations in the density of the visible baryonic matter of the universe.
- A product of the interaction between gravity, radiation pressure and the expansion of the universe acting on its different components
- BAO matter clustering provides a "standard ruler" for length scale in cosmology.
- They can be measured by looking at the large scale structure of matter using astronomical surveys.
- BAO measurements are a powerful tool for constraining cosmological parameters

Credit: Chris Blake and Sam Moorfield



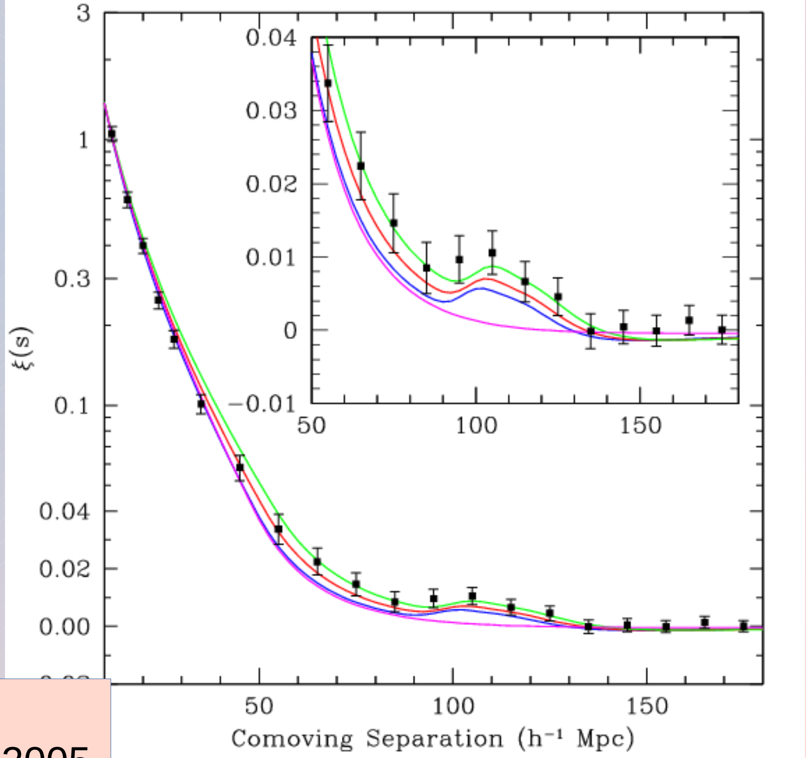
Credit: https://www.cfa.harvard.edu/~deisenst/acousticpeak/acoustic_physics.html





Theoretical Predictions:

Observationally, the correlation function looks like this:



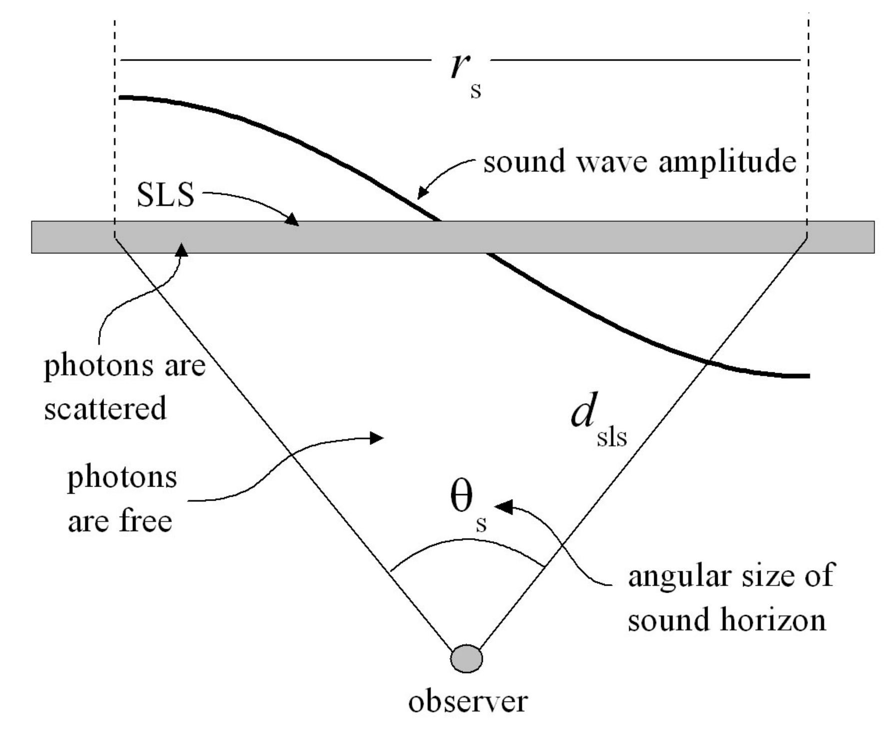
SDSS BAO, Eisenstein et al. 2005

The sound horizon

- The radius of the sound horizon, $r_{d.}$, the distance at which plasma waves induced by radiation pressure froze at recombination
- The photons "decouple" (stop noticing the baryons) before the baryons stop noticing the photons: $z_d < z_*$
- Corresponds to the peak in the correlation function or to oscilations in the power spectrum
- Characteristic BAO scale on the late-time matter clustering.
- Planck 2018: r_d=147.5 Mpc, z_d=1059, z_*=1100.

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

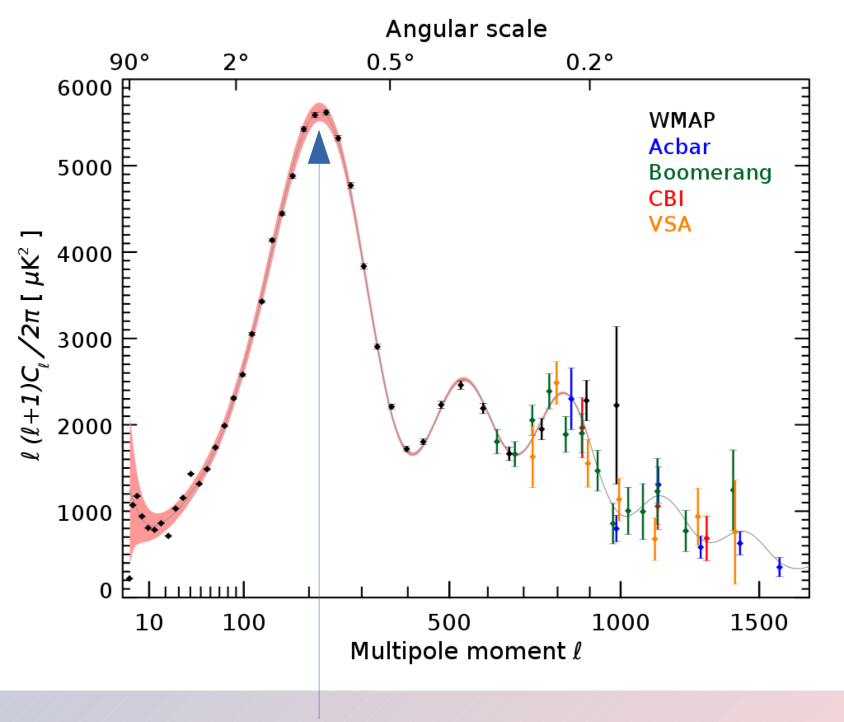
$$c_s(z) = \frac{c}{\sqrt{3\left(1 + \frac{3\Omega_b}{4\Omega_\gamma}\frac{1}{1+z}\right)}}$$



z_d -- redshifht of the drag epoch (when photons decouple from baryons)

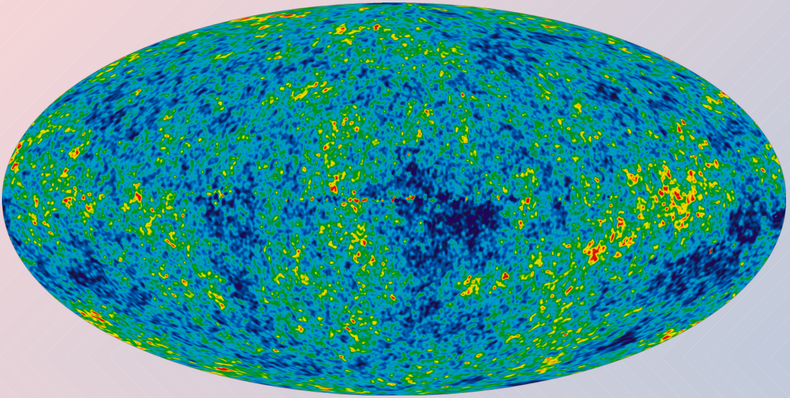
The power spectrum

- Fourrier transform of the two-point corelation function
- Measures the degree of clustering of galaxies
- The famous acoustic peaks
- First peak describe if the universe is closed, open or flat
- Second peak gives the baryonic content
- Third peak gives dark matter content

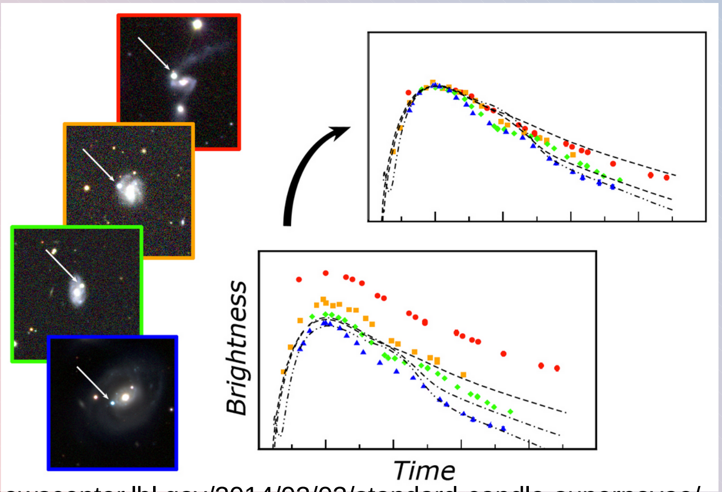


Sound horizon

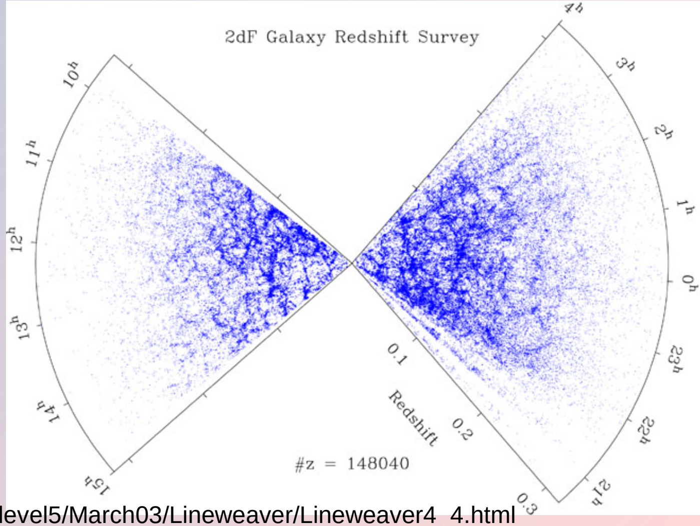
How do we know it?



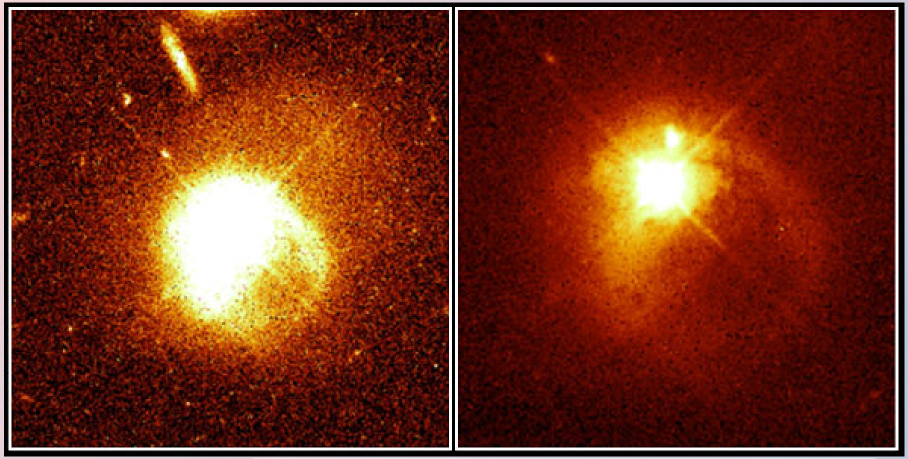
- CMB
- SNe Type Ia
- Large scale structures

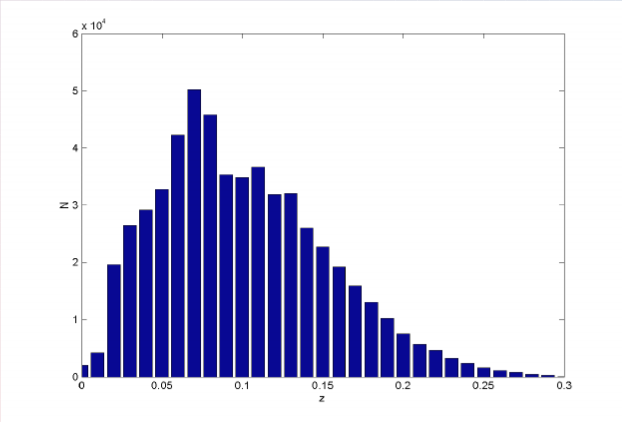


Credit: https://newscenter.lbl.gov/2014/03/03/standard-candle-supernovae/

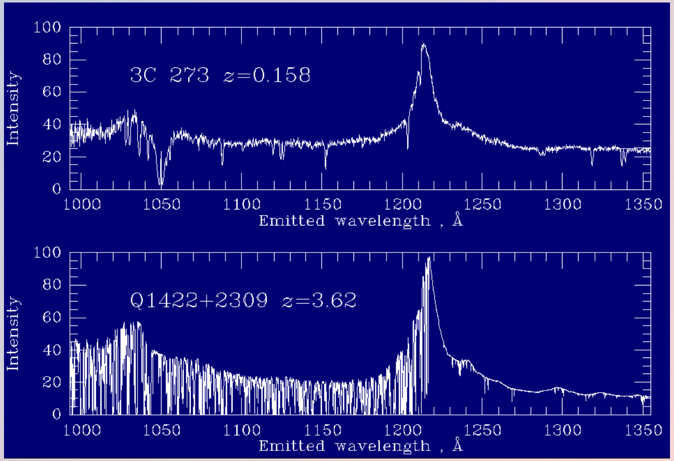


Credit: https://ned.ipac.caltech.edu/level5/March03/Lineweaver/Lineweaver4_4.html





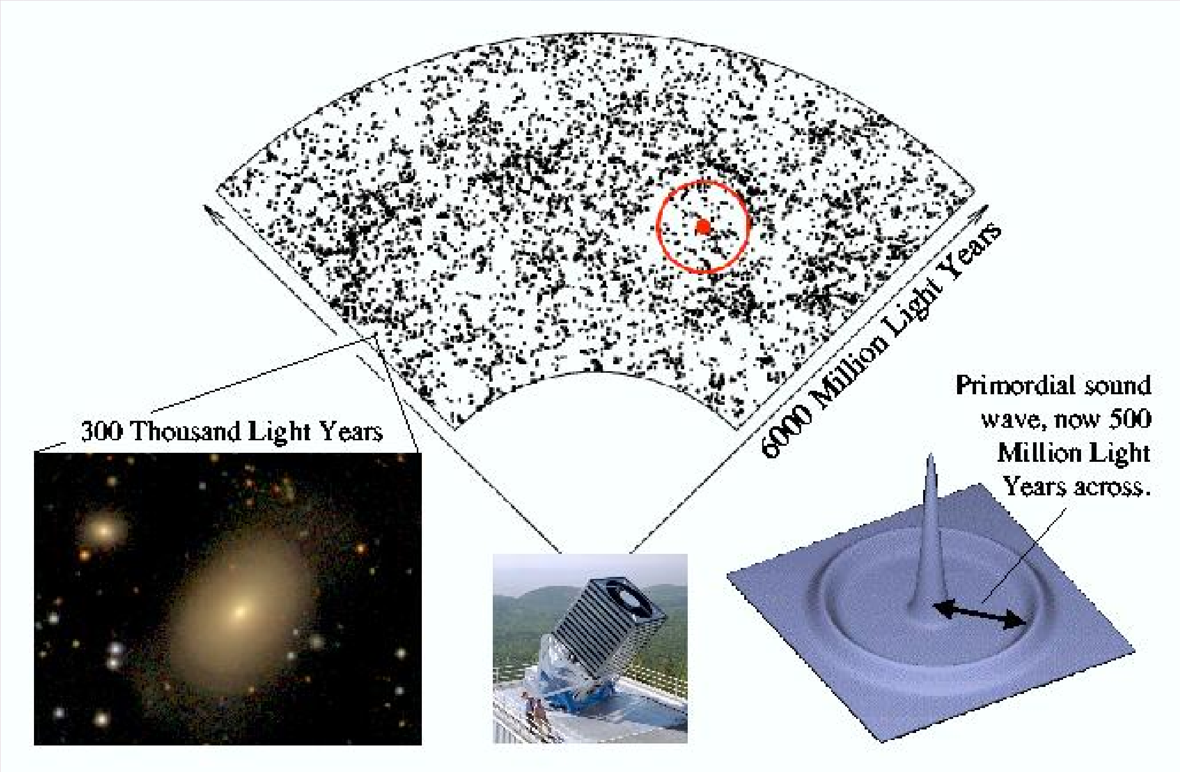
- Quasars
- Galaxies clustering
- Gravitational lensing
- LyAlpha lines



https://astronomy.stackexchange.com/questions/658/what-is-the-lyman-alpha-forest-used-for
https://www.britannica.com/science/quasar/Finding-quasars

https://arxiv.org/abs/1104.0884

The Sloan Digital Sky Survey



The SDSS has created the most detailed three-dimensional maps of the Universe, with deep multi-color images of one third of the sky, and spectra for **more than three million astronomical objects**.

Credit: Sloan Digital Sky Survey.

Distances in cosmology

- Hubble distance:
- Comoving distance
- Transverse comoving distance:
- Volume averaged distance:
- Angular diameter distance:

$$D_H = c/H(z)$$

$$D_C = \int_0^z \frac{dz'}{D_H(z')}$$

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

$$D_V(z) \equiv [z D_H(z) D_M^2(z)]^{1/3}$$

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

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

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

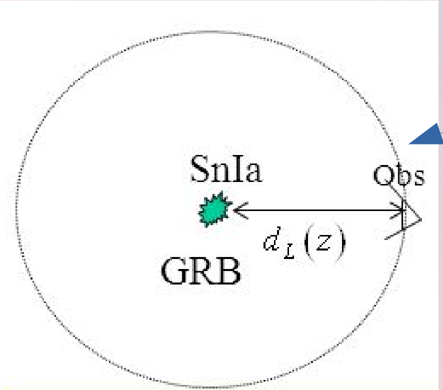
Observational distances

- Luminosity distance
- Angular distance
- Distance modulus

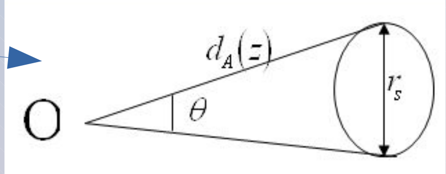
$$D_L = \sqrt{\frac{L}{4\pi S}}$$

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

$$\mu = m - M = 5log\left(\frac{D_L}{10pc}\right)$$



SNIa BAO



L – bolometric luminosity
S – bolometric flux
M – absolute magnitude
m – apparent magnitude
x – object physical size
θ – object angular size

$$D_L = (1+z)D_M = (1+z^2)D_A$$

The used datasets

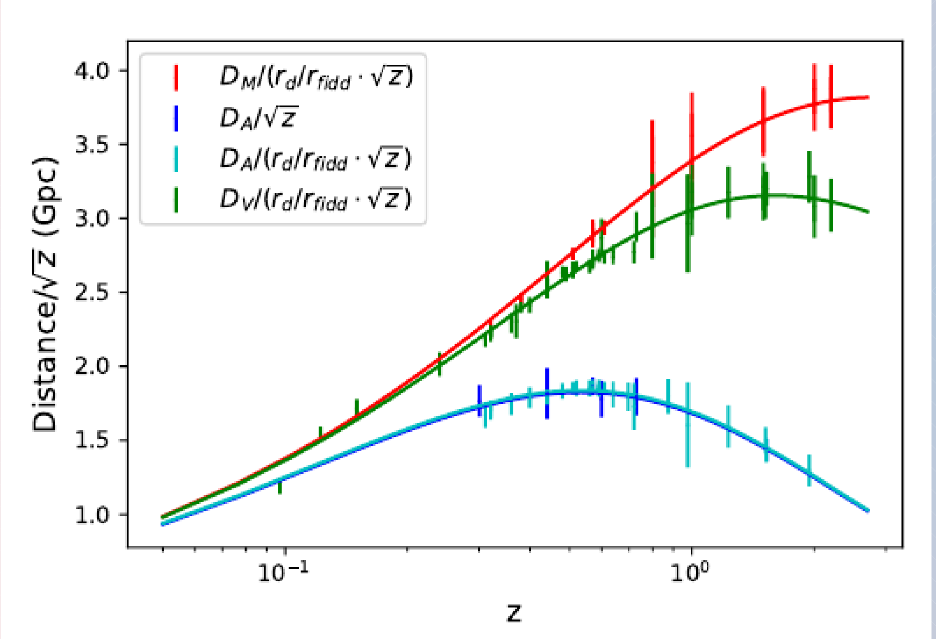
- BAO from eBoss, SDSS, DES, WiggleZ, 6dFGS
- Cosmic chronometers
- Standard candles:

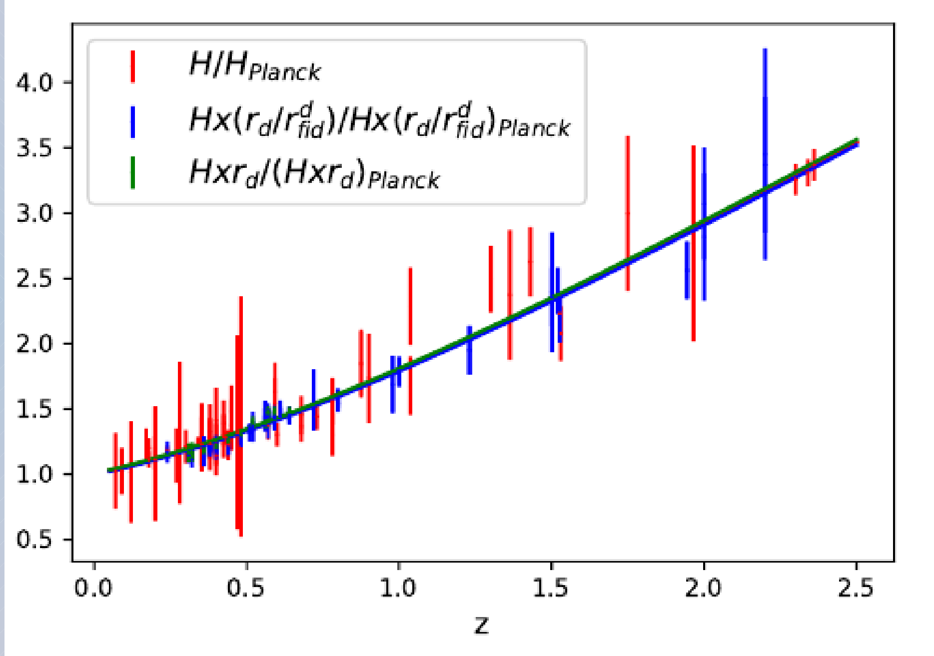
  -- Pantheon type Ia SNe

  -- quasars and GRBs

- 333 data points
- About 70 publications
- BAO measurements from 2008 – 2020
- The SDSS's eBOSS features measurements from both galaxy clustering -- low redshift galaxies (MGS), luminous red galaxies (LRG), emission line galaxies (ELG) and the Lyman-α forest of quasars.

Plotting the whole 333 poitns





A lot of points!

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.*

Methodology

- Python + Polychord – nested MCMC sampler
- Parameters: 5 (6), i.e. Ω_m, Ω_Λ, H_0, r_d, r_d/r_{dfid} (+ Ω_k or w)
- Riess et al. (2019):

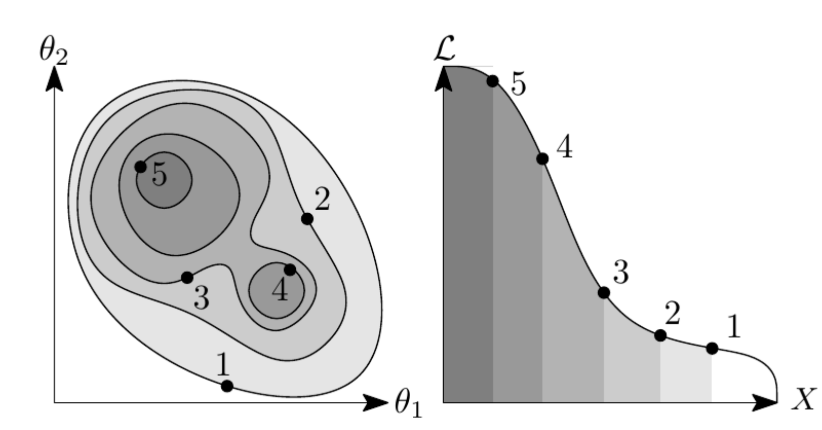
$$H_0 = 74.03 \pm 1.42 (km/s)/Mpc$$

- Priors:

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

- Chi2 function:

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



For more on PolyChord: arXiv:1506.00171

Correlated vs. Uncorrelated datapoints

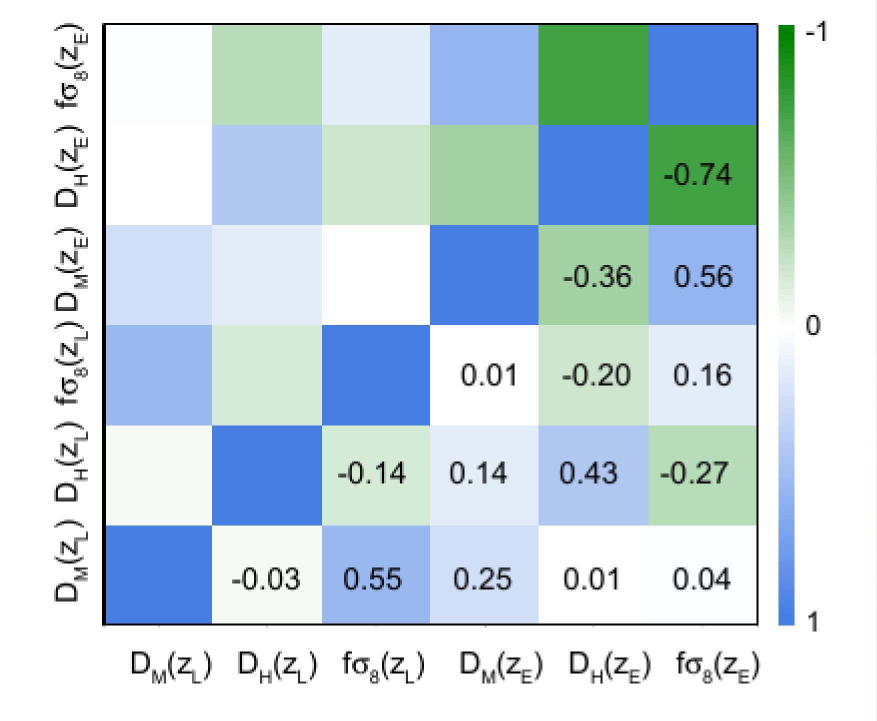
- Theoretical Covariance matrix:

$$C_{ij}^{\mathrm{BAO,total}} = \begin{pmatrix} \sigma_1^2 & 0 & 0 & \cdots \\ 0 & \sigma_2^2 & 0 & \cdots \\ 0 & 0 & \cdots & \sigma_N^2 \end{pmatrix}$$

- Often data from different measurements or dataruns is **correlated**
- Correlations could be due to systematic error or unknown correlations
- Usually one uses N-body mocks to find these correlations

Arxiv:2007.09011

- Real data:



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

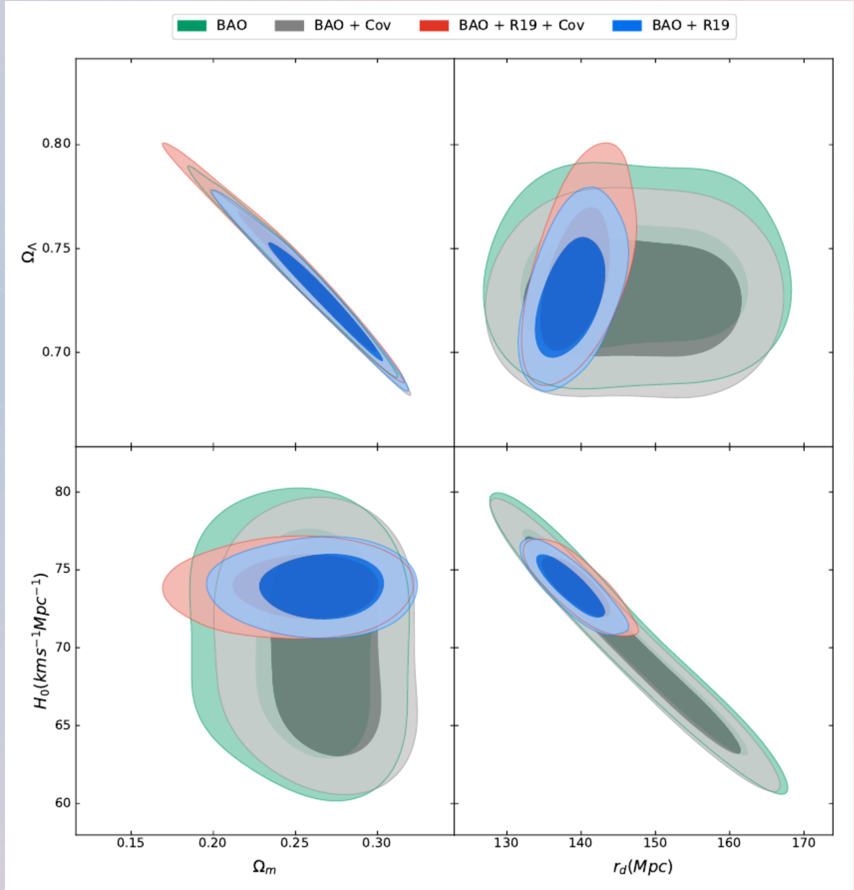
$$C_{ii} = \sigma_i^2 .$$

$$C_{ij} = 0.5\sigma_i\sigma_j$$

- Kazantzidis, L. & Perivolaropoulos, L. 2019, Phys. Rev., D99, 063537, arxiv: 1812.05356
- The results:

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

- We use this correlation mock up on the BAO subset and find the cosmological parameters in this case
- We see correlations to become significant when more than 30% of the points have non-diagonal elements
- We conclude that the points are not correlated and we can use them to constraint cosmological parameters



The LCDM model:

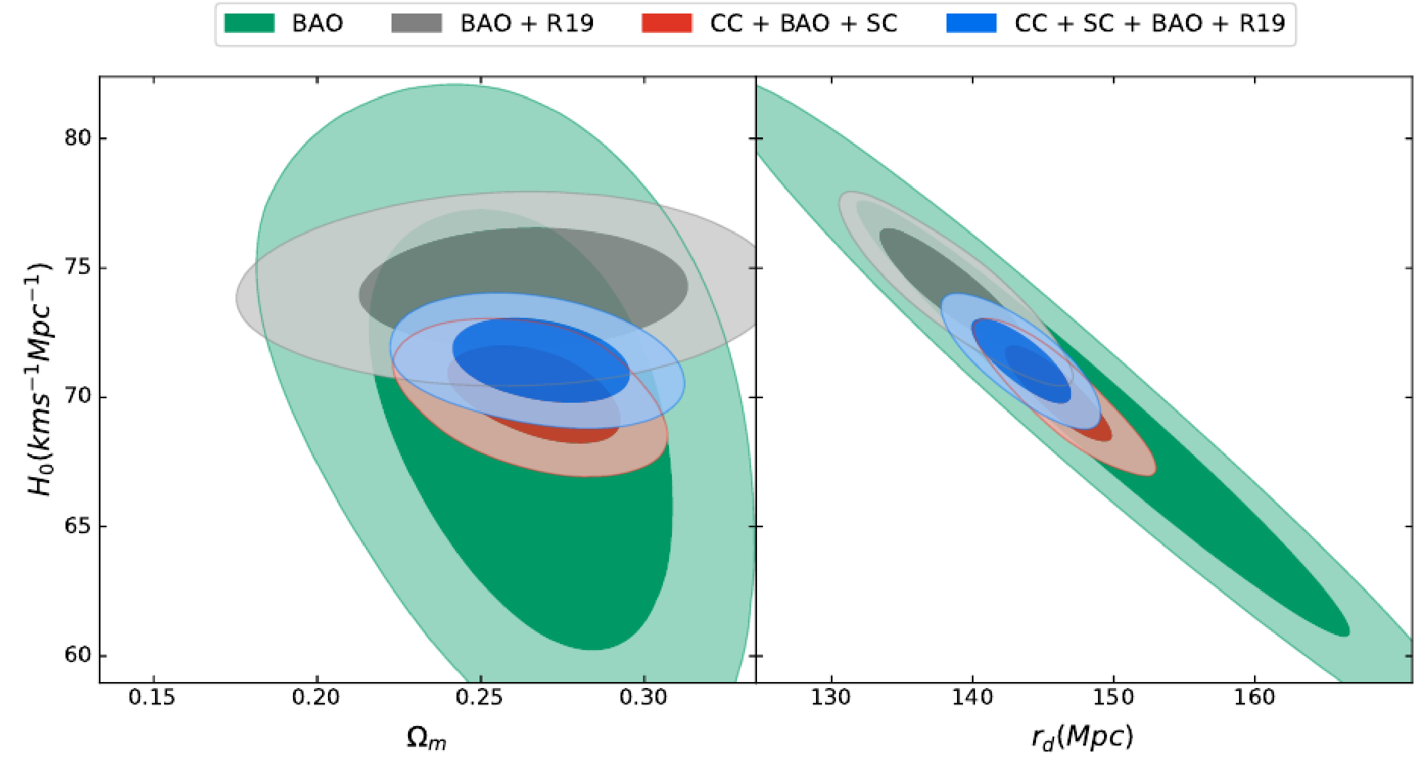
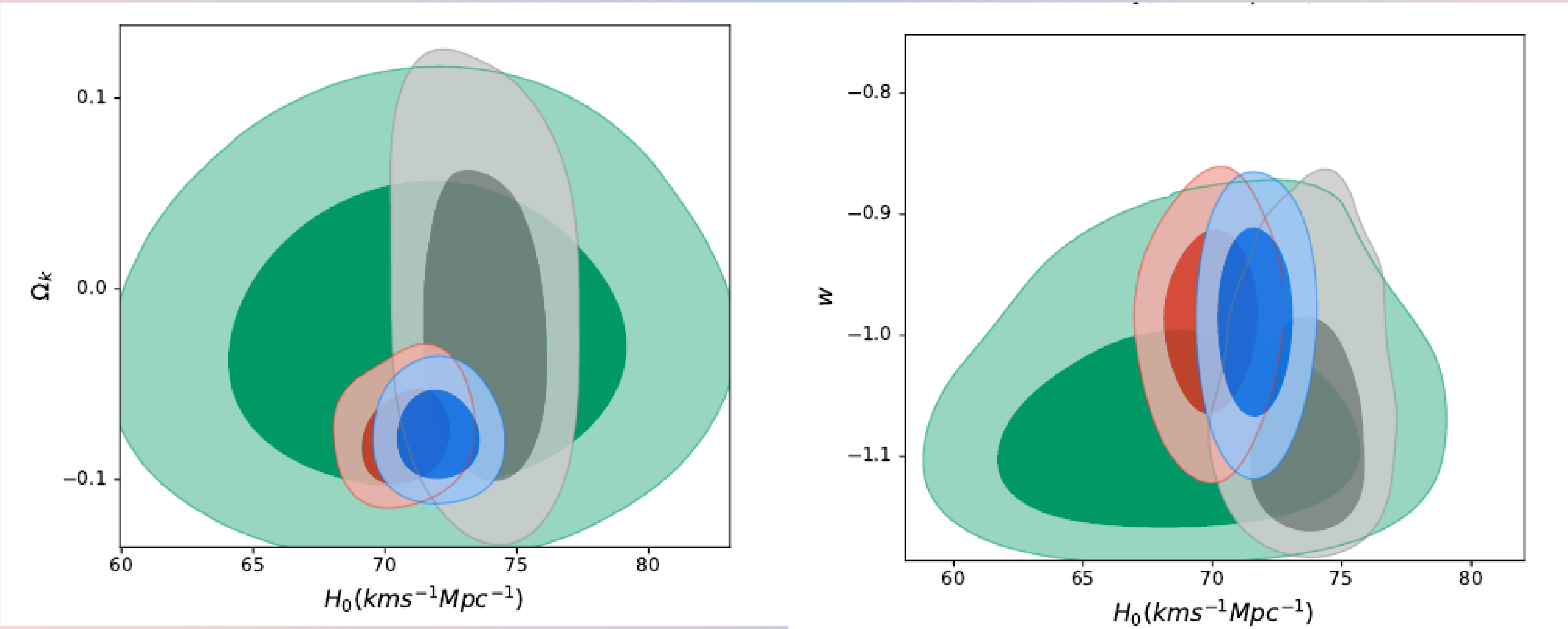


Fig. 2. *The posterior distribution for different measurements with the ΛCDM model with 1σ and 2σ. The BAO refers to the Baryon Acoustic Oscillations dataset from table 1. The CC dataset refers to Cosmic Chronometers and SC refers to the Hubble Diagram from Type Ia supernova, Quasars and Gamma Ray Bursts.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

Extensions

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

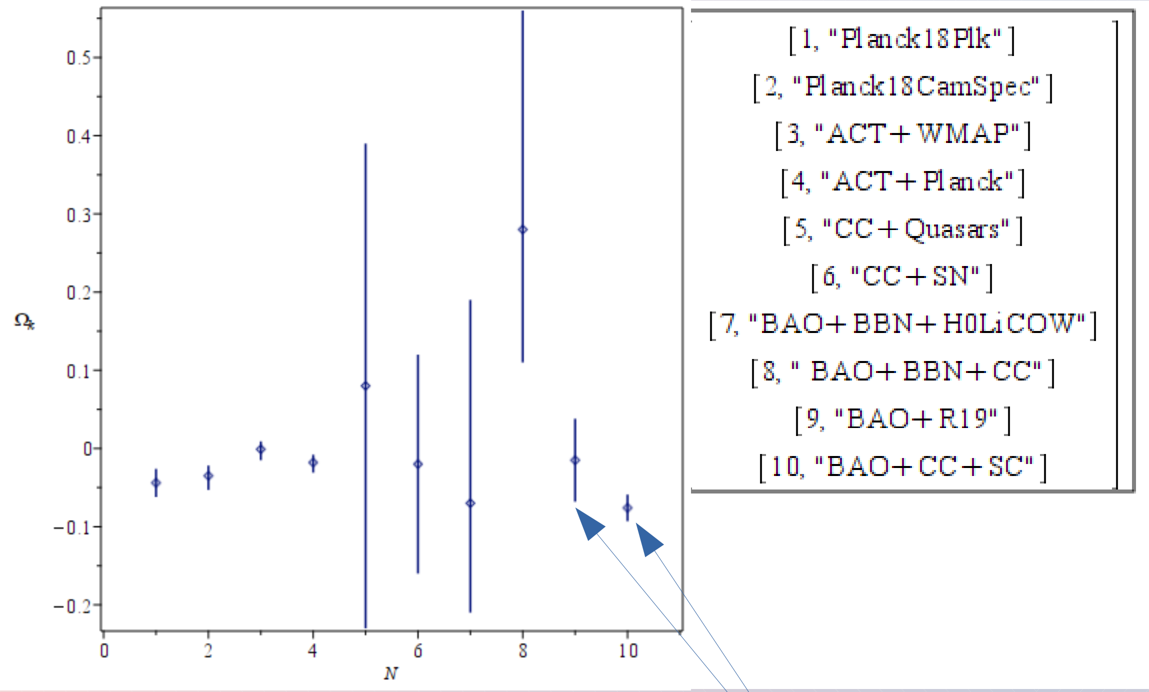


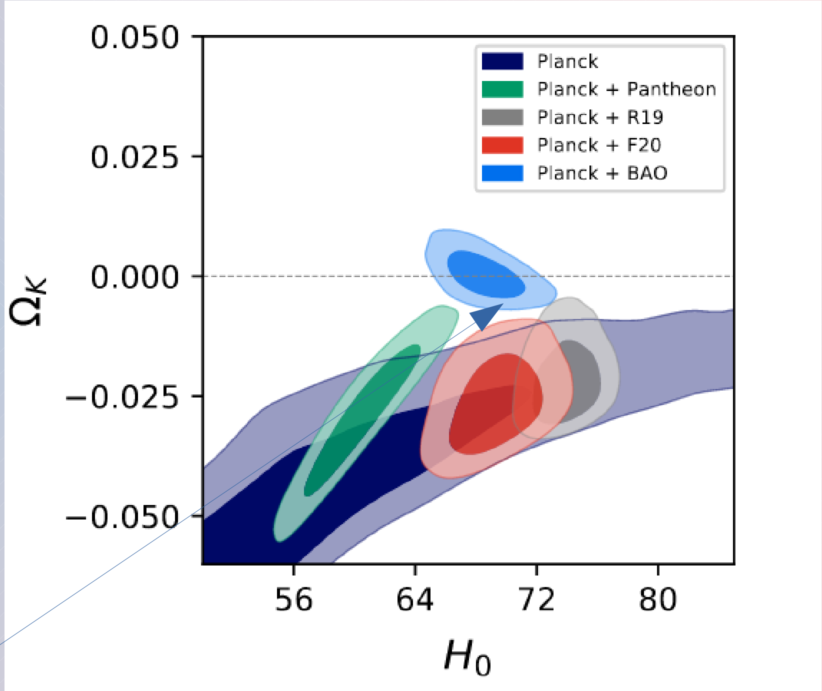
In numbers:

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 spacial curvature

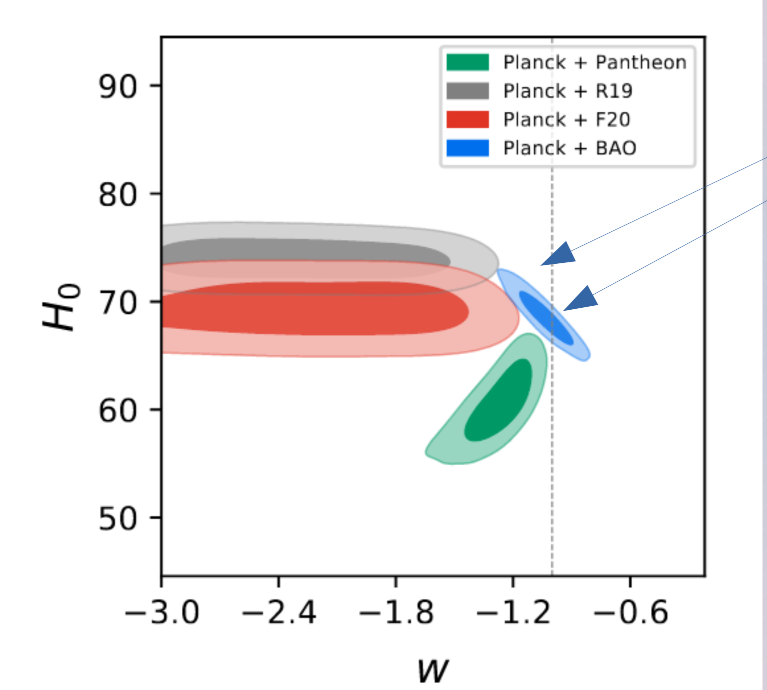




Our points

Di Valentino et al.
arXiv:2003.04935

The DE equation of state

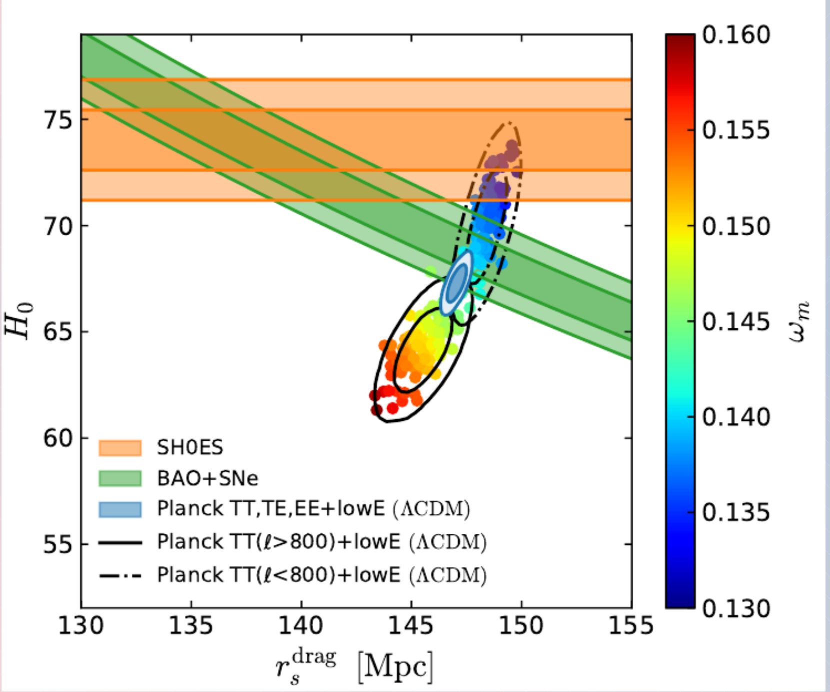


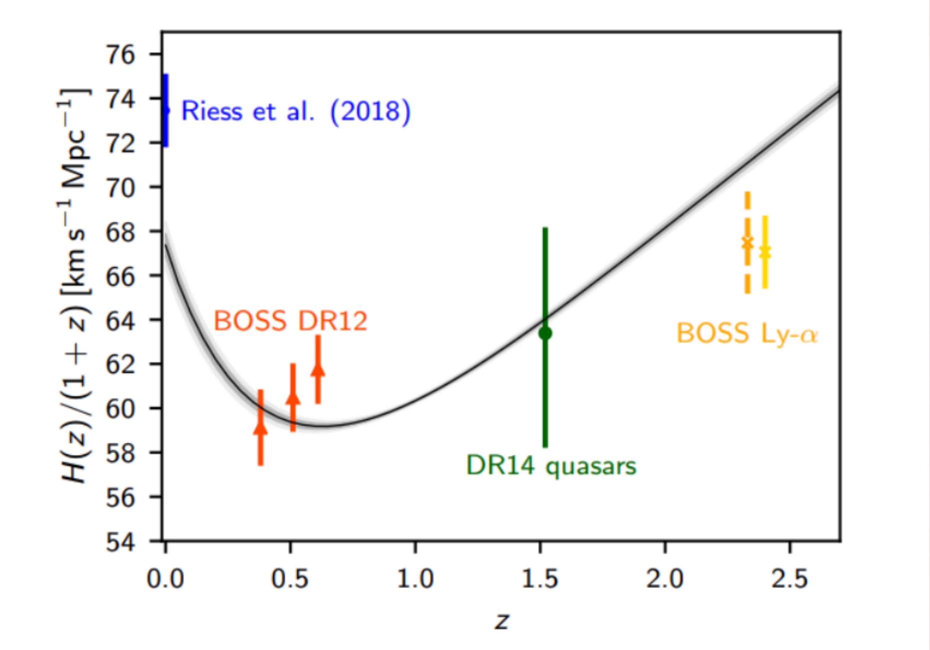
BAO+R19
w = -1.067
H_0=73.69

BAO+SC+CC+R19
w = - 0. 989
H_0=71.65

Di Valentino et al.
arXiv:2003.04935

The r_d-H_0 tension

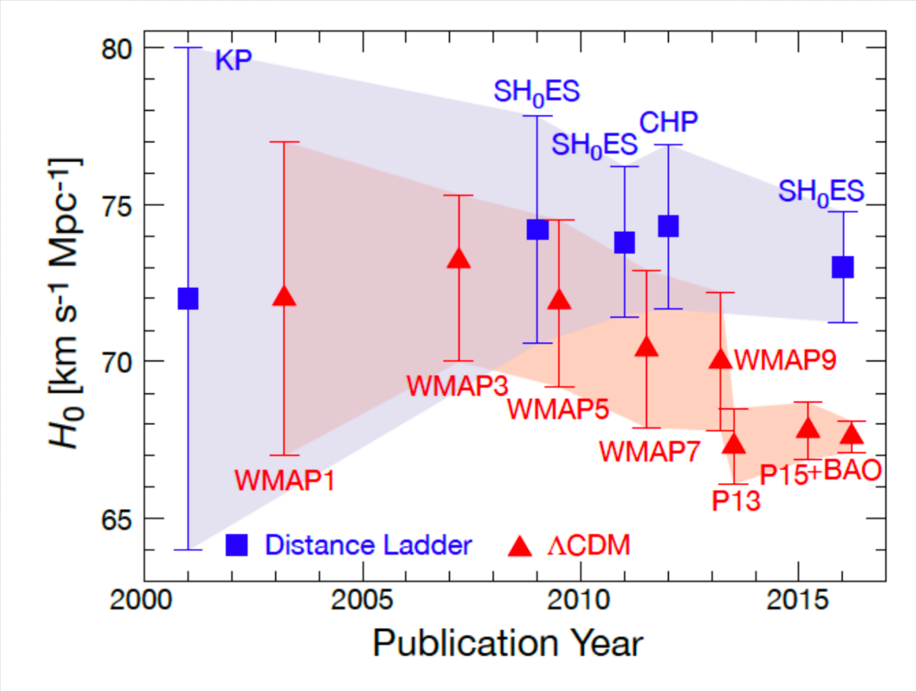




- Knox, L. & Millea, M. 2020, Physical Review D, 101, arXiv:1908.03663

Kazantzidis & Perivolaropoulos, arXiv:1907.03176 [astro-ph.CO]

In short the tension is here to stay:



Freedman W., Nature Astronomy, 1, 0169 (2017), arXiv:1706.02739 [astro-ph.CO]

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:

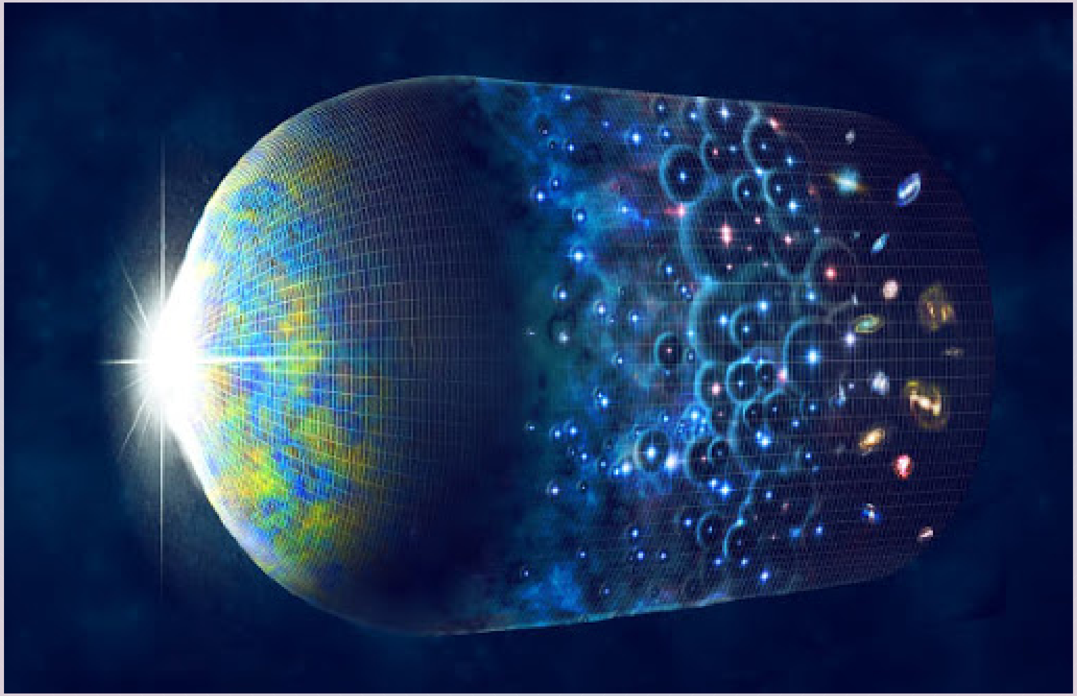
  LMC: H_0= 74.03 (km/s)/Mpc,

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

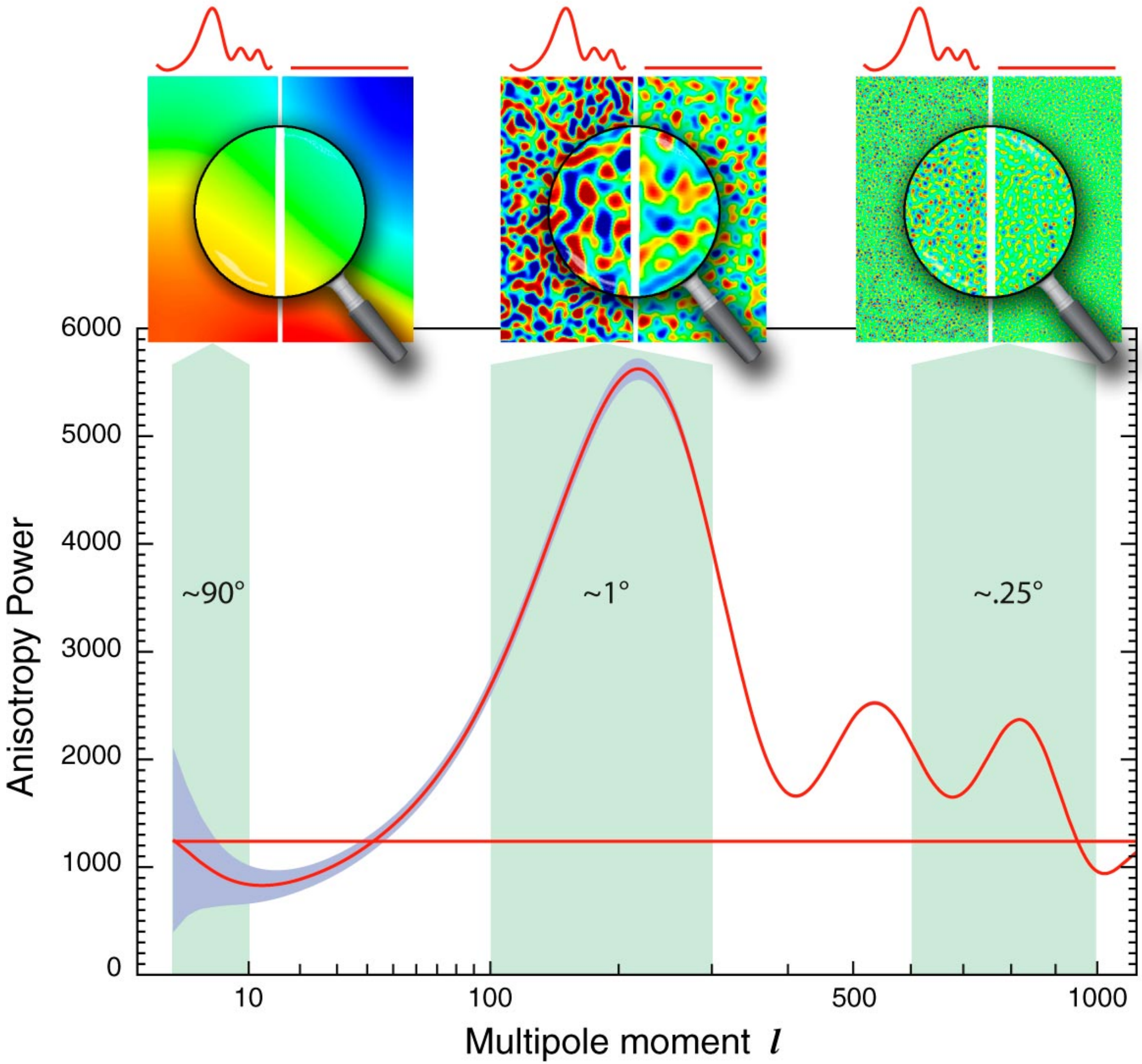
  Our result: H_0=69.85 (km/s)/Mpc
- We see strong dependence of the final value of H_0 on the choice of r_d as expected.

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

Thank you for your attention!



И честита Баба Марта!



6000
5000
4000
3000
2000
1000
0
Anisotropy Power
~90°
~1°
~.25°
10
100
500
1000
Multipole moment l