H0 Tension: New Physics or Systematics?

Arman Shafieloo

Korea Astronomy and Space Science Institute (KASI)

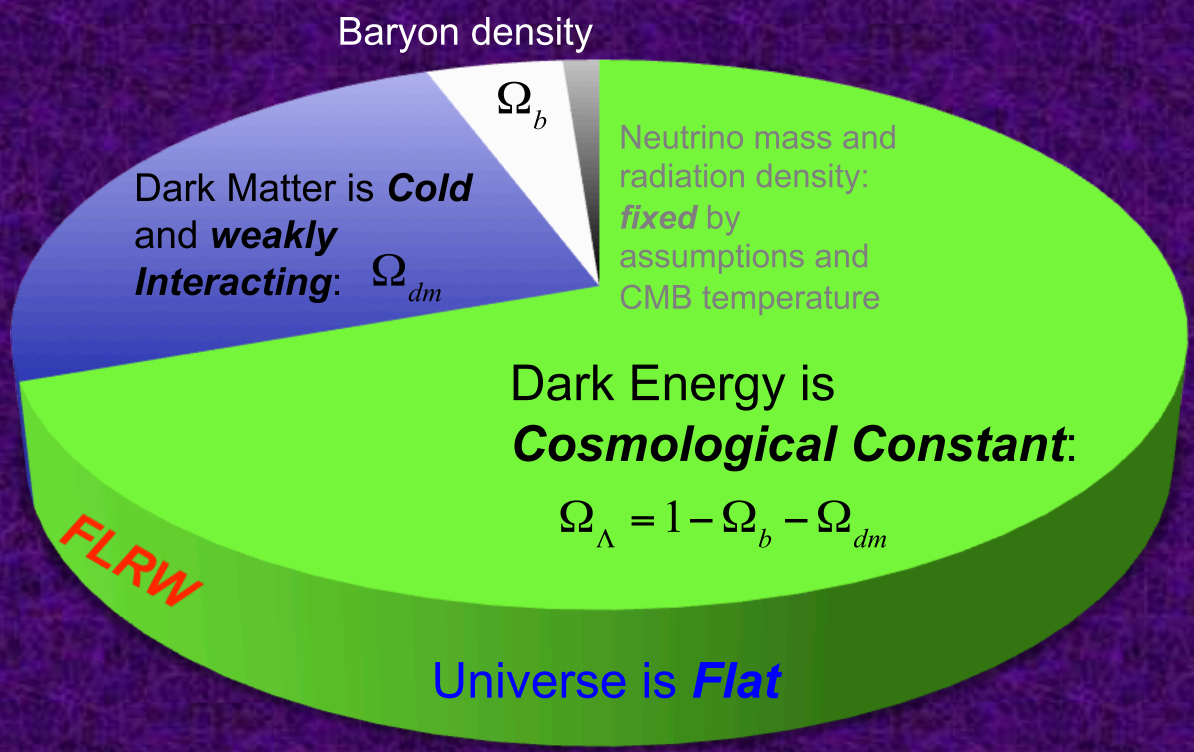
University of Science and Technology (UST)

15th Recontres du Vietnam, Qui Nhon, Vietnam

11-17 August 2019

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.



Initial Conditions:
Form of the Primordial Spectrum is ***Power-law***

n_s, A_s

Epoch of reionization

τ

Hubble Parameter and the Rate of Expansion

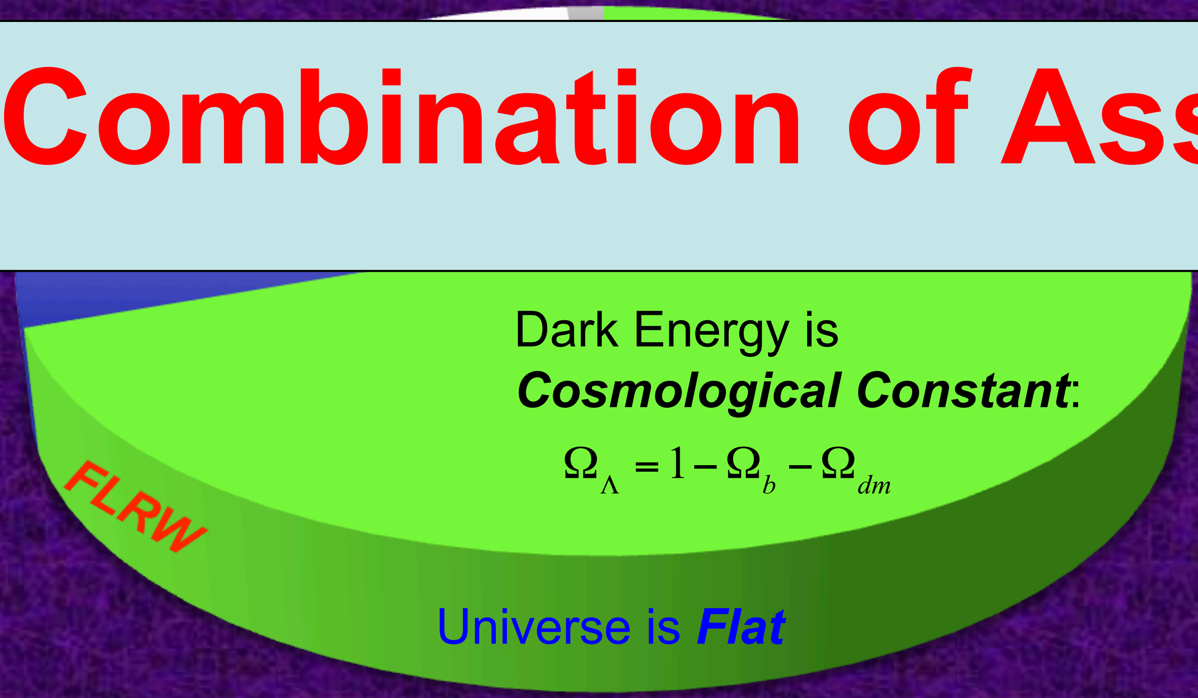
H_0

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.

Baryon density

Combination of Assumptions



Epoch of reionization

τ

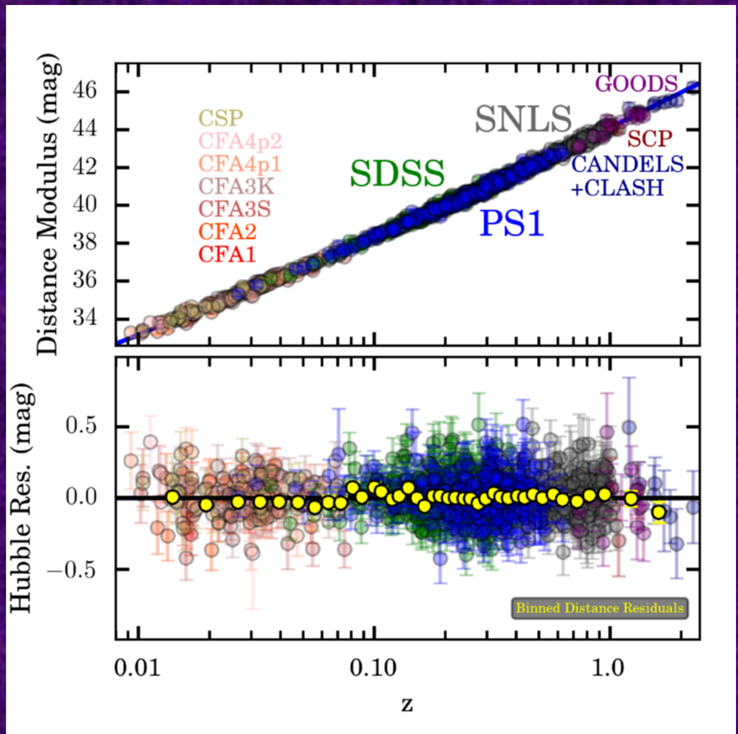
Hubble Parameter and the Rate of Expansion

H_0

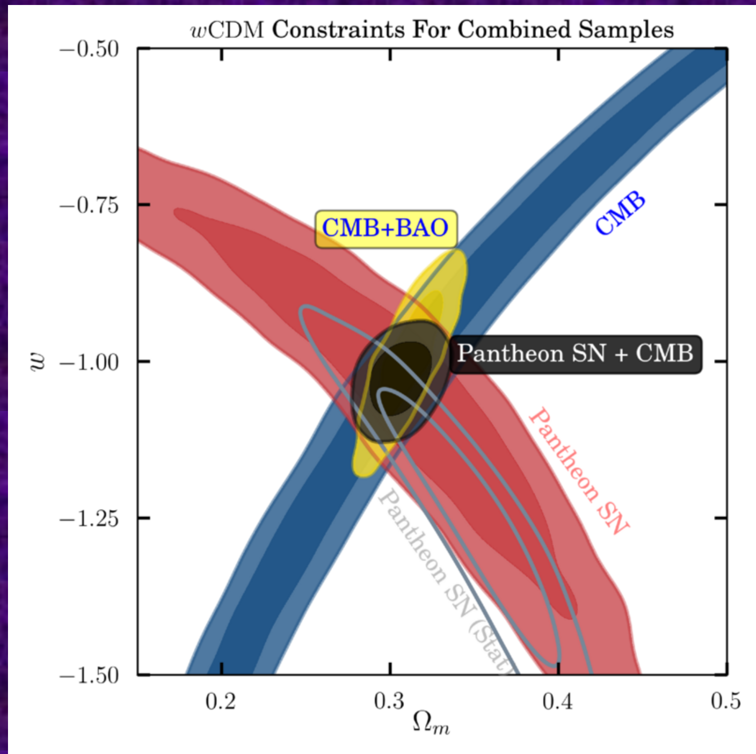
Standard Model in 2019 **SN**

20 years after discovery of the acceleration of the universe:

From 60 Supernovae Ia at cosmic distances, we now have ~1000 published distances, with better precision, better accuracy, out to z~2.0. ***Accelerating universe in proper concordance to the data.***



1048 spectroscopically confirmed SNIa



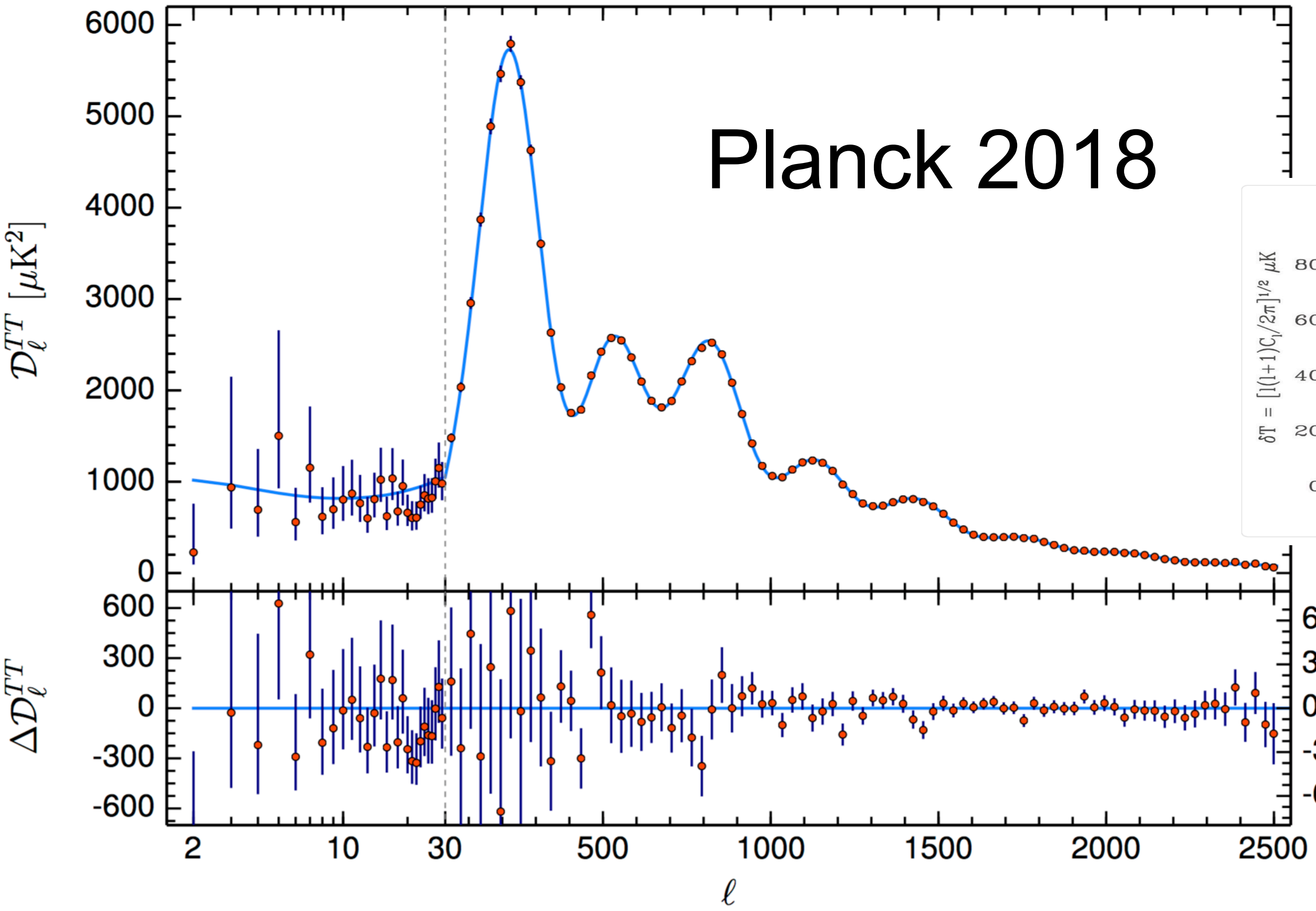
Pantheon Compilation
Scolnic et al. (2018)

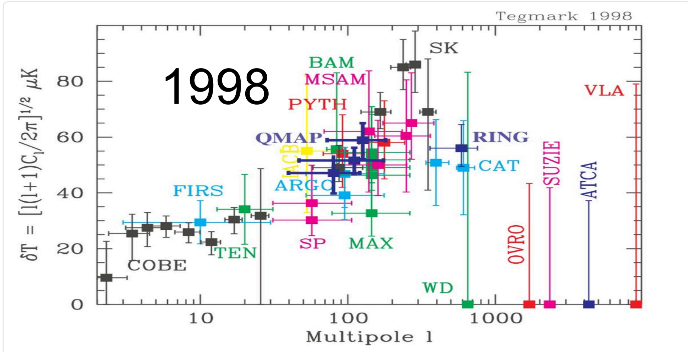
Standard Modelin 2019

CMB

Almost 20 years after discovery of the acceleration of the universe:

CMB directly points to acceleration. Didn't even have acoustic peak in 1998!



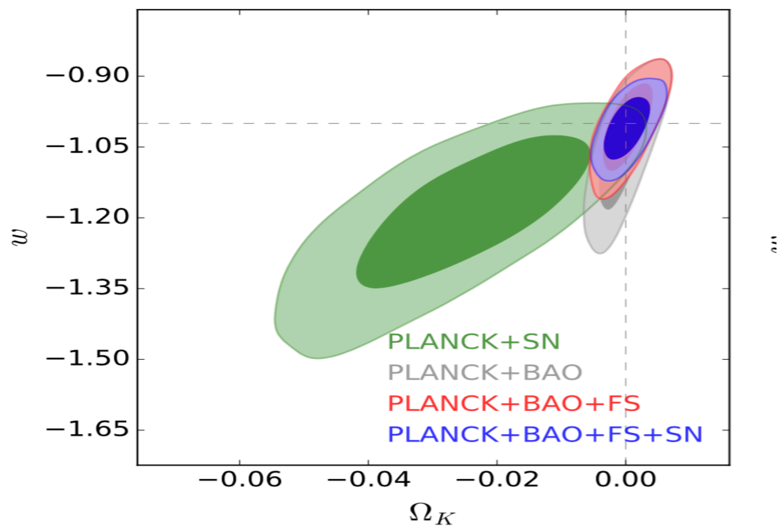


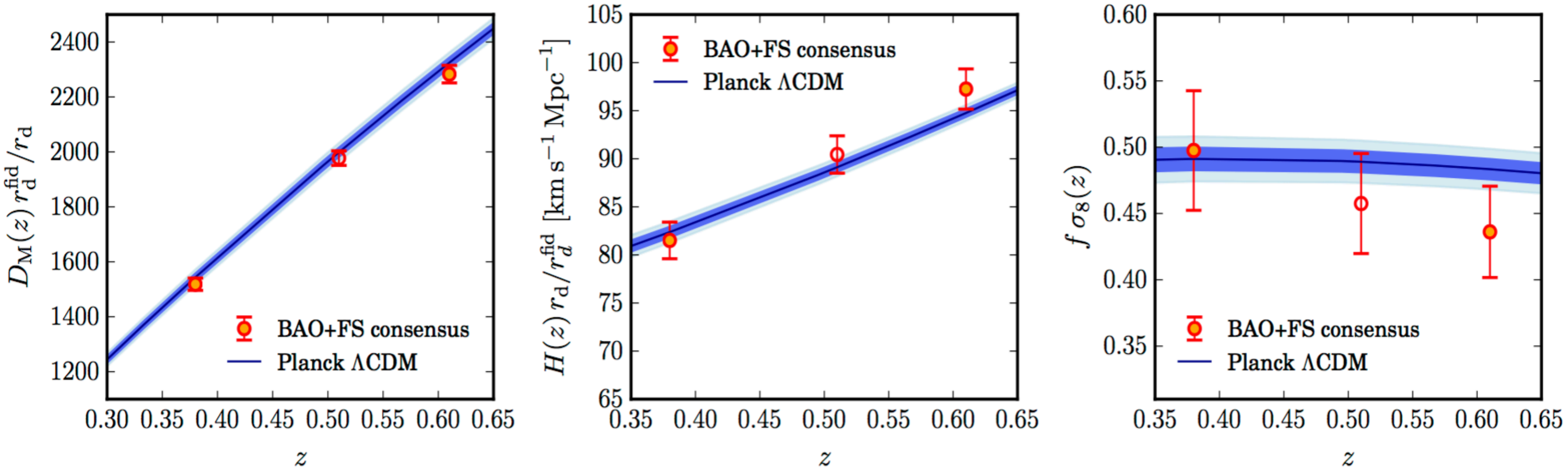
Dark Energy in 2019

LSS

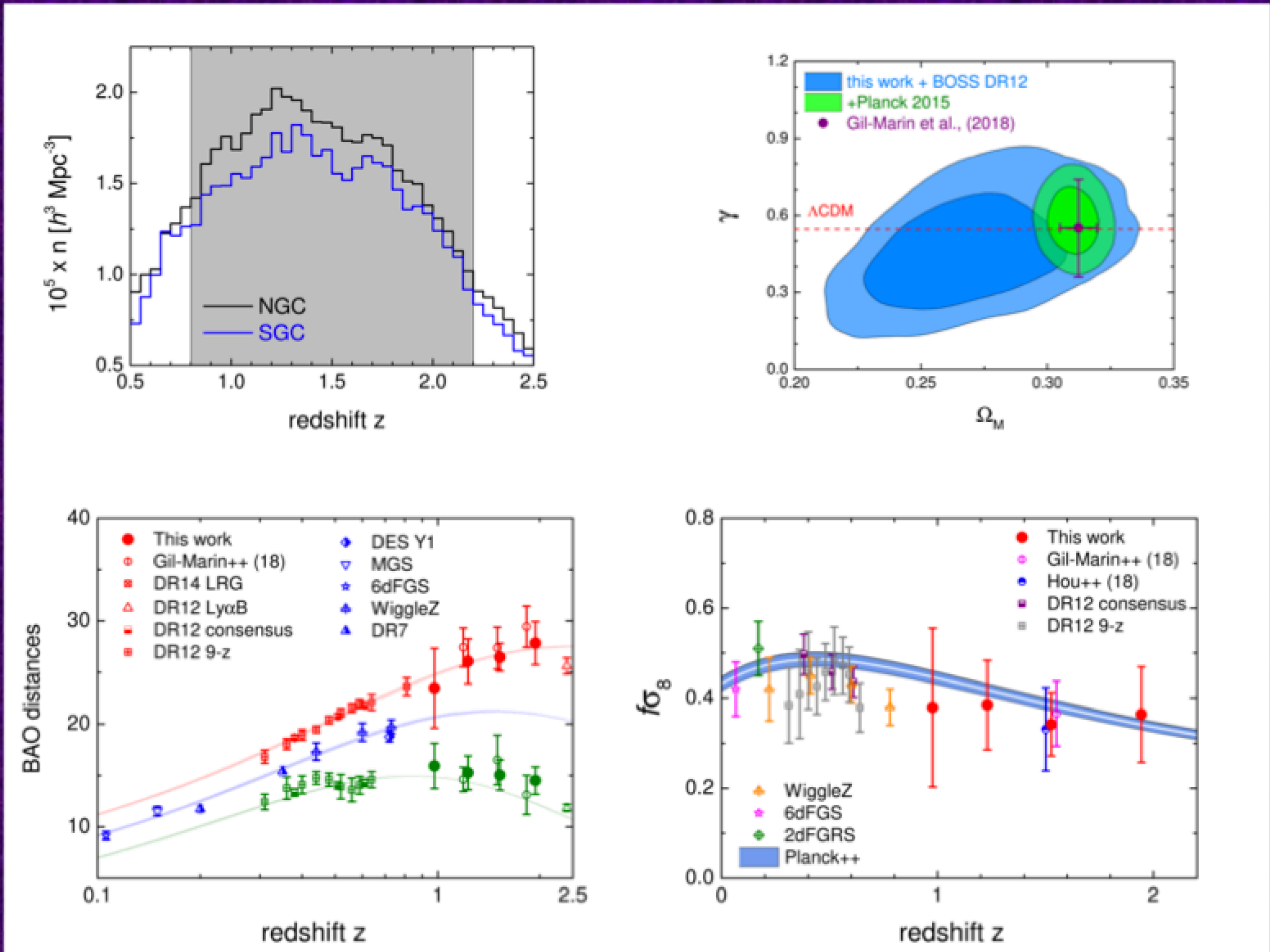
Almost 20 years after discovery of the acceleration of the universe:

BOSS collaboration DR12 (2016),
arXiv:Alam et al, MNRAS 2016





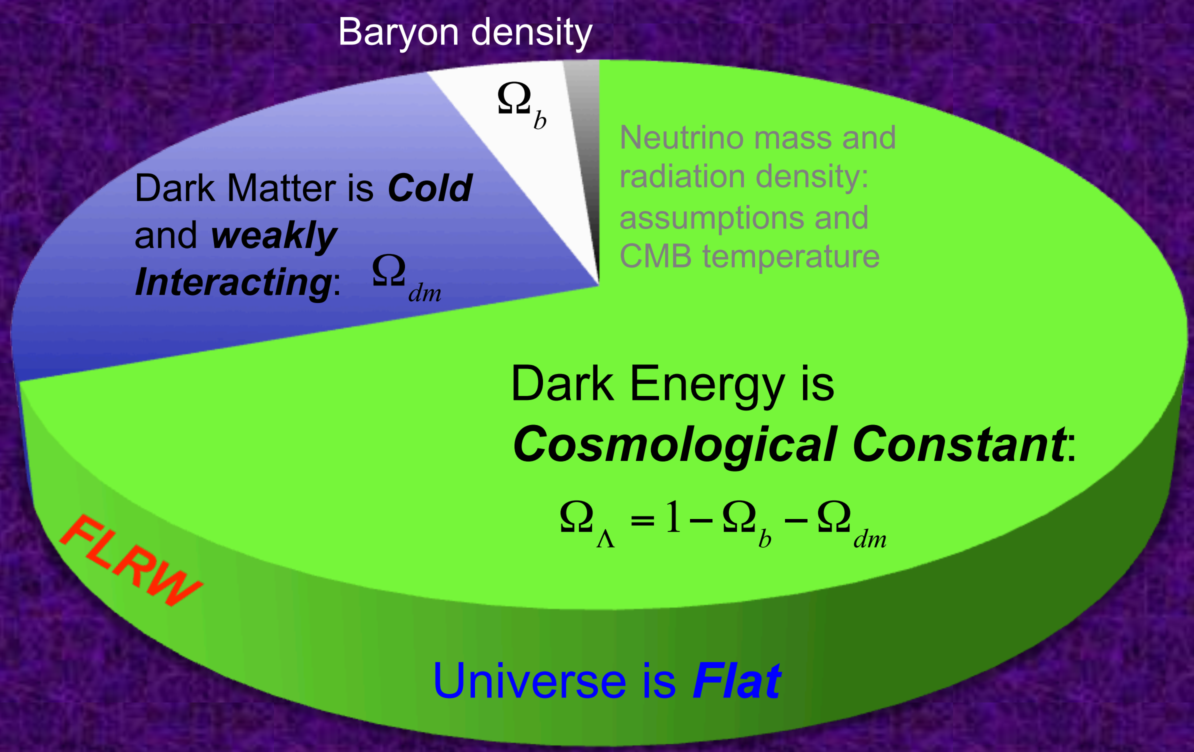
BOSS DR14Q



eBOSS collaboration: Zhao et al. MNRAS 2018

Standard Model of Cosmology

combination of *reasonable* assumptions, but…..



Initial Conditions:
Form of the Primordial Spectrum is ***Power-law***

n_s, A_s

Epoch of reionization

τ

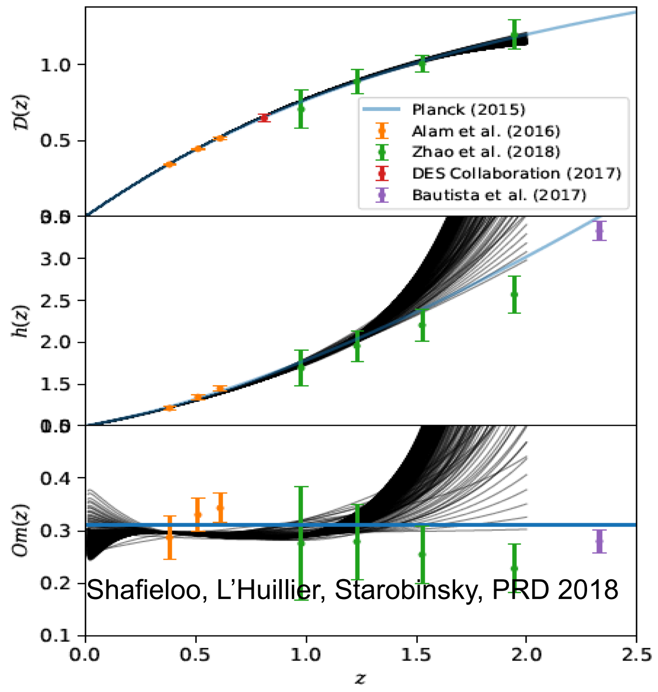
Hubble Parameter and the Rate of Expansion

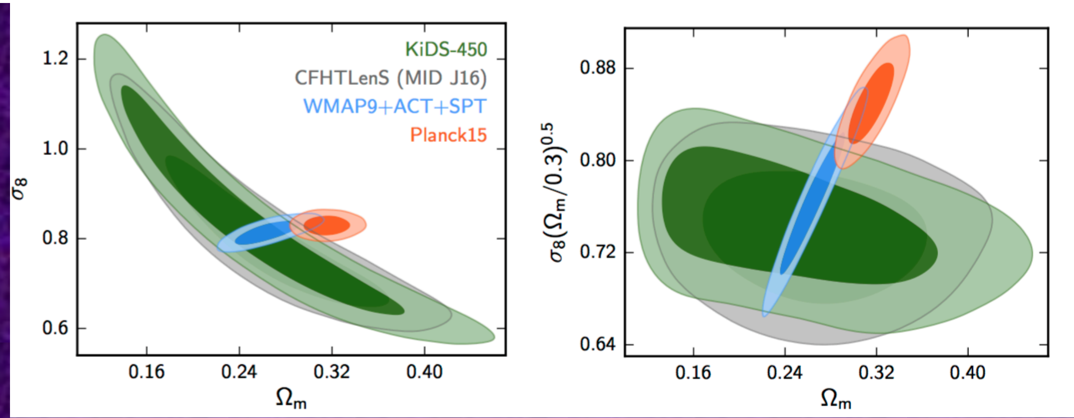
H_0

Persistent Tensions in the Standard Model

Local estimation of the Hubble constant seems to be substantially higher than the expected values fitting the standard LCDM model to CMB.

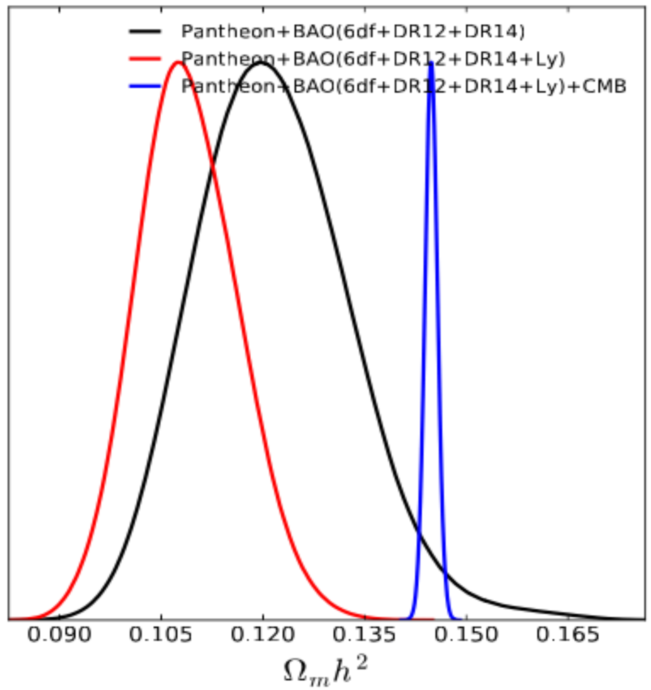
67 or 73?

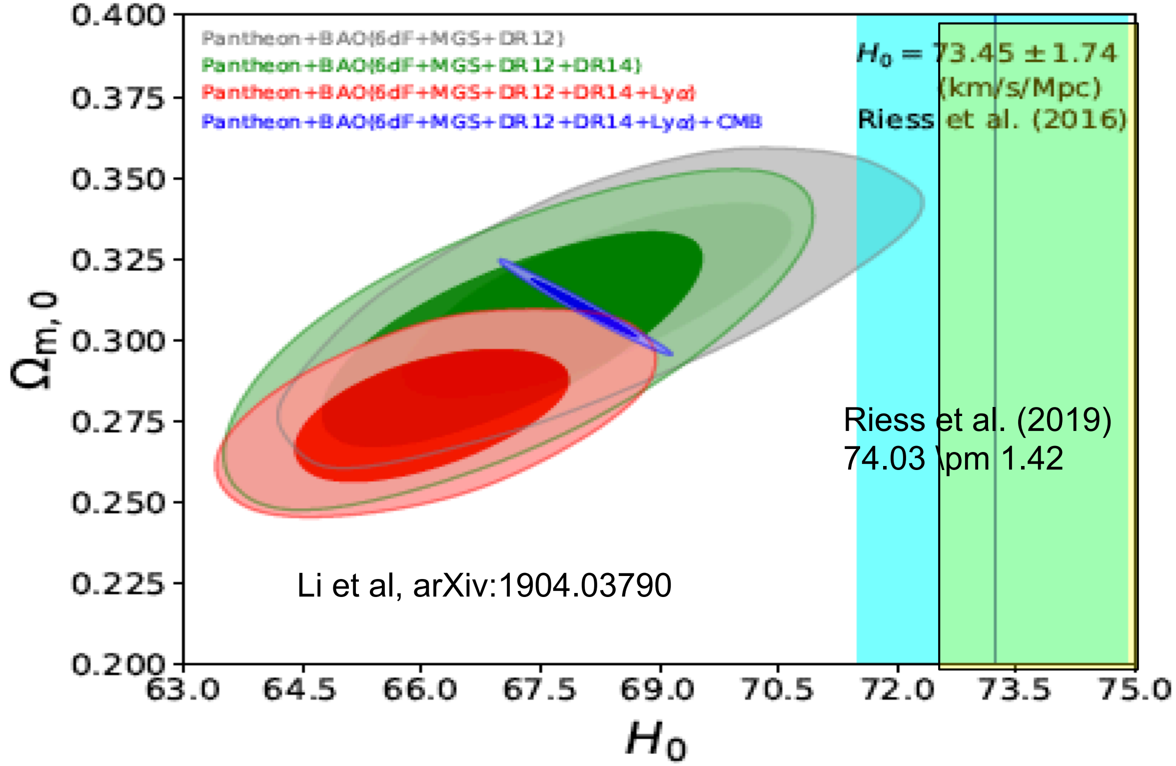


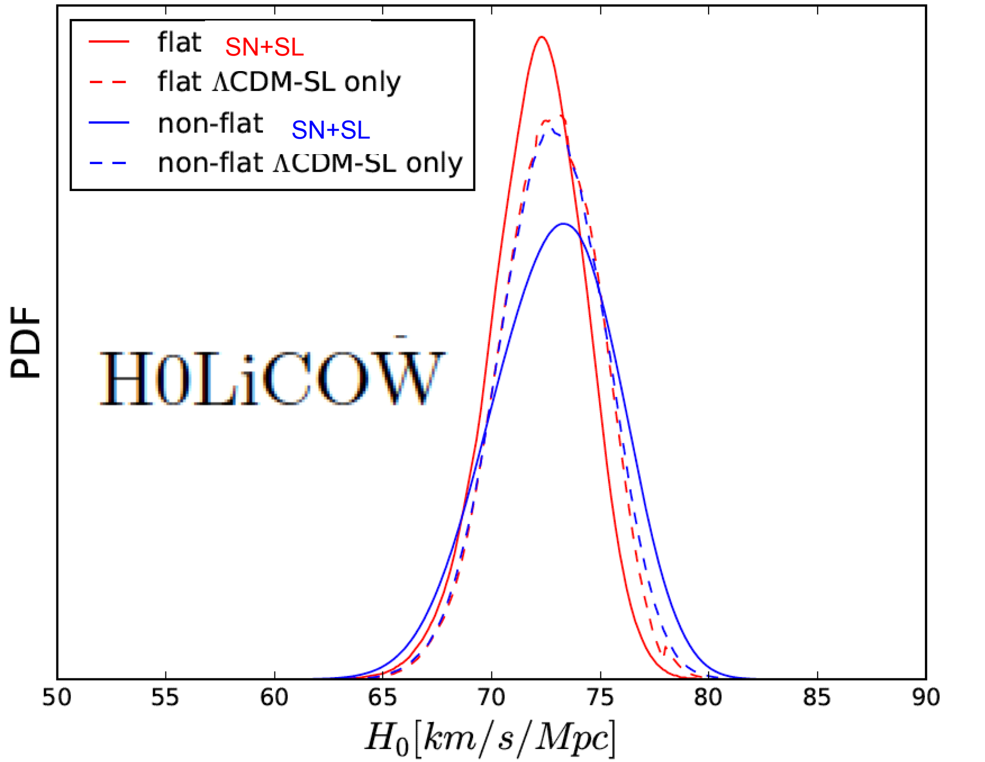


Hildebrandt et al, MNRAS 2017

It is not only about H0 and CMB. Low H(z)r_d is suggested by BAO and low matter density by WL.







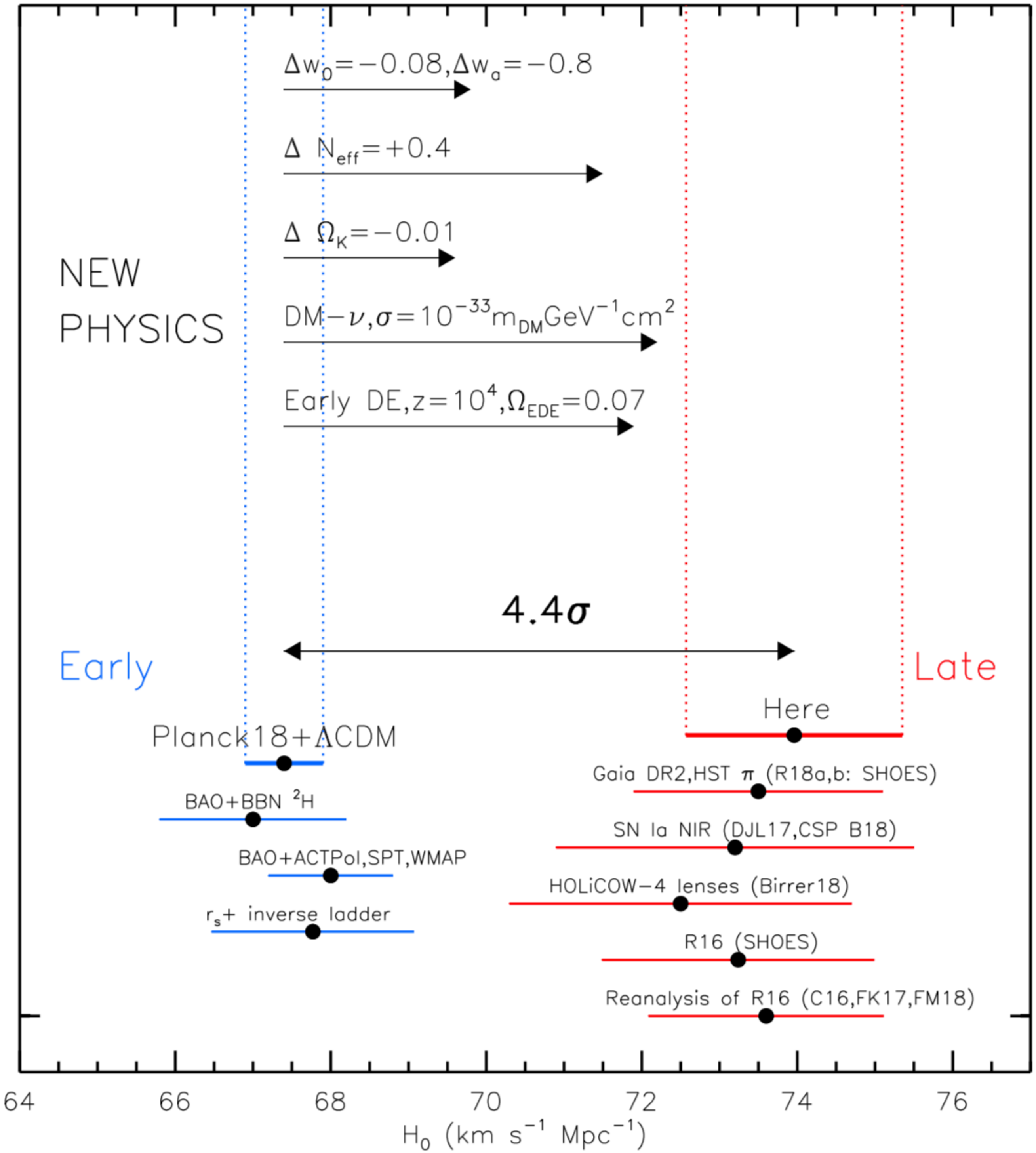
H0 from Strongly Lensed systems

Kai et. al, in preparation

H0LiCOW I. H0 Lenses in COSMOGRAIL's Wellspring

Suyu et al. MNRAS 2017

Order	Name	z_L	z_S
1	RXJ1131-1231	0.295	0.654
2	HE 0435-1223	0.4546	1.693
3	B1608+656	0.6304	1.394
4	SDSS 1206+4332	0.745	1.789



Tensions in the Standard Model

Riess et al, arXiv:1903.07603

How to go Beyond the Standard Model of Cosmology?

- Finding features/deviations in the data beyond the flexibility of the standard model using model-independent reconstructions.
- Falsifying the standard model using litmus tests.
- Introducing theoretical/phenomenological models that can explain the data better (statistically significant) than the standard model.
- Finding tension among different independent data assuming the standard model (making sure there is no systematic).

Implementing well cooked statistical approaches to get the most out of the data is essential!

Omh2

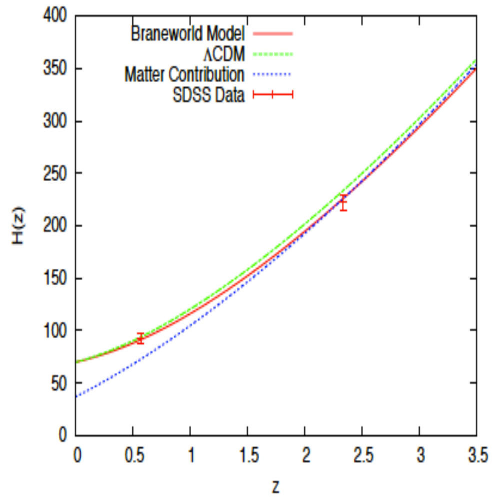
Important discovery if no systematic in the SDSS Quasar BAO data

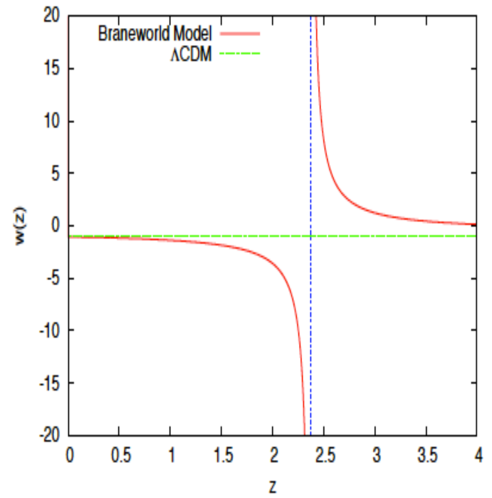
Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

$$Omh2(z_1, z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1+z_2)^3 - (1+z_1)^3} = \Omega_{0m} H_0^2$$

Only for LCDM

Sahni, Shafieloo, Starobinsky, ApJ Lett 2014





$$Omh^2 = 0.1426 \pm 0.0025$$

LCDM +Planck+WP

$$Omh^2(z_1; z_2) = 0.124 \pm 0.045$$
$$Omh^2(z_1; z_3) = 0.122 \pm 0.010$$
$$Omh^2(z_2; z_3) = 0.122 \pm 0.012$$

BAO+H0

H(z = 0.00) = 70.6 \pm 3.3 km/sec/Mpc
H(z = 0.57) = 92.4 \pm 4.5 km/sec/Mpc
H(z = 2.34) = 222.0 \pm 7.0 km/sec/Mpc

2019 Omh2

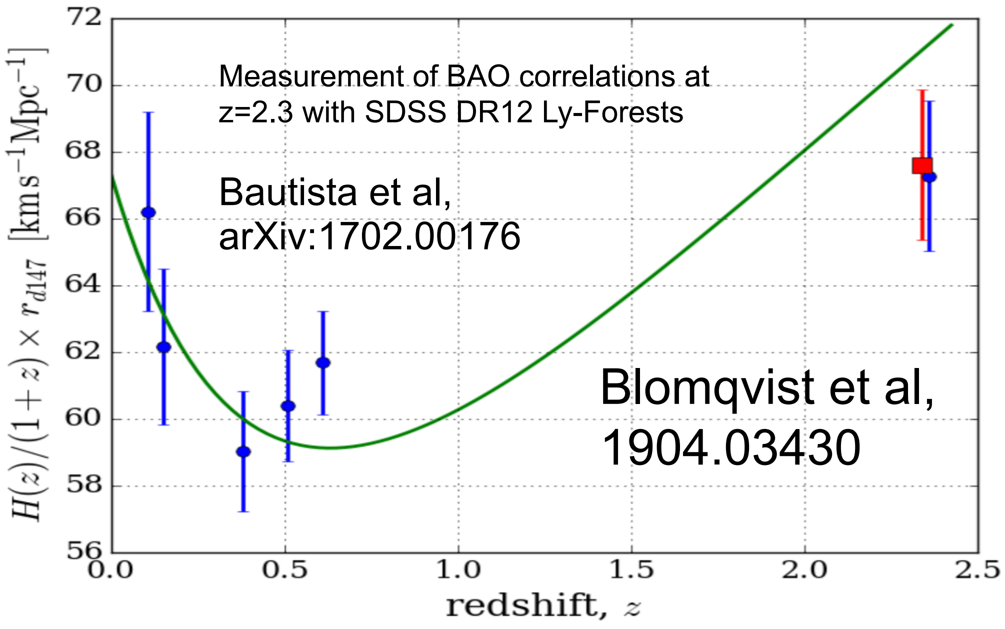
No systematic yet found,

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

$$Omh2(z_1,z_2) = \frac{H^2(z_2) - H^2(z_1)}{(1+z_2)^3 - (1+z_1)^3} = \Omega_{0m} H_0^2$$

Only for LCDM

Sahni, Shafieloo, Starobinsky, ApJ Lett 2014



$Omh^2 = 0.1426 \pm 0.0025$ LCDM +Planck+WP

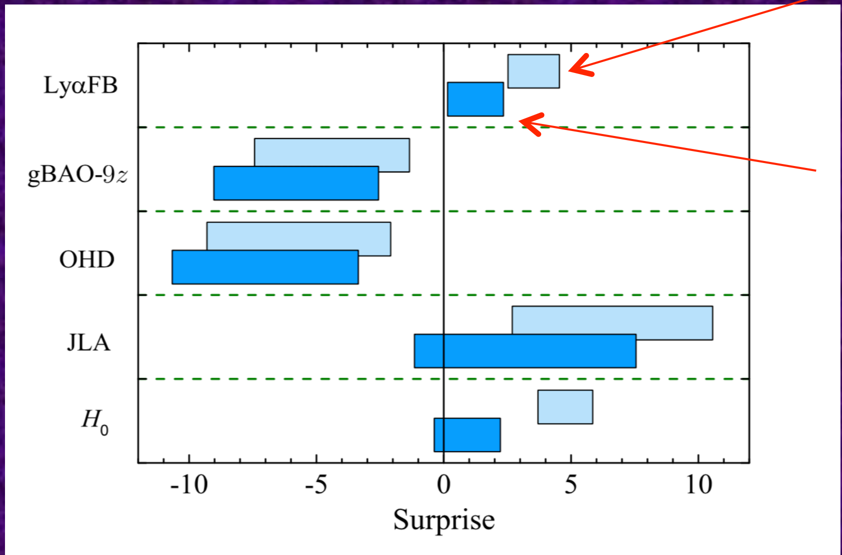
$Omh^2(z_1;z_2) = 0.124 \pm 0.045$
$Omh^2(z_1;z_3) = 0.122 \pm 0.010$
$Omh^2(z_2;z_3) = 0.122 \pm 0.012$
BAO+H0

H(z = 0.00) = 70.6 \pm 3.3 km/sec/Mpc
H(z = 0.57) = 92.4 \pm 4.5 km/sec/Mpc
H(z = 2.34) = 222.0 \pm 7.0 km/sec/Mpc

Comparing different data assuming a particular model

Zhao et al, Nature Astronomy, 2017

$$T \equiv \frac{S}{\Sigma} = \frac{(\theta_1 - \theta_2)^T \mathcal{C}_1^{-1}(\theta_1 - \theta_2) - \mathbf{Tr}\left(\mathcal{C}_2\,\mathcal{C}_1^{-1} + \mathbb{I}\right)}{\sqrt{\mathbf{Tr}\left(\mathcal{C}_2\,\mathcal{C}_1^{-1} + \mathbb{I}\right)^2}},$$



LCDM

w(z)CDM

Acronym	Meaning	References
P15	The *Planck* 2015 CMB power spectra	[6]
JLA	The JLA supernovae	[28]
6dF	The 6dFRS (6dF) BAO	[29]
MGS	The SDSS main galaxy sample BAO	[30]
$P(k)$	The WiggleZ galaxy power spectra	[31]
WL	The CFHTLenS weak lensing	[32]
H_0	The Hubble constant measurement	[10]
OHD	$H(z)$ from galaxy age measurements	[33]
gBAO-3z	3-bin BAO from BOSS DR12 galaxies	[34]
gBAO-9z	9-bin BAO from BOSS DR12 galaxies	[35, 36]
LyαFB	The Lyα forest BAO measurements	[2, 9]
B	P15 + JLA + 6dF + MGS	
ALL12	The combined dataset used in [27]	
ALL16-3z	B+$P(k)$+WL+H_0+OHD+gBAO-3z+LyαFB	
ALL16	B+$P(k)$+WL+H_0+OHD+gBAO-9z+LyαFB	
DESI++	P15 + mock DESI BAO [49] + mock SN [50]	

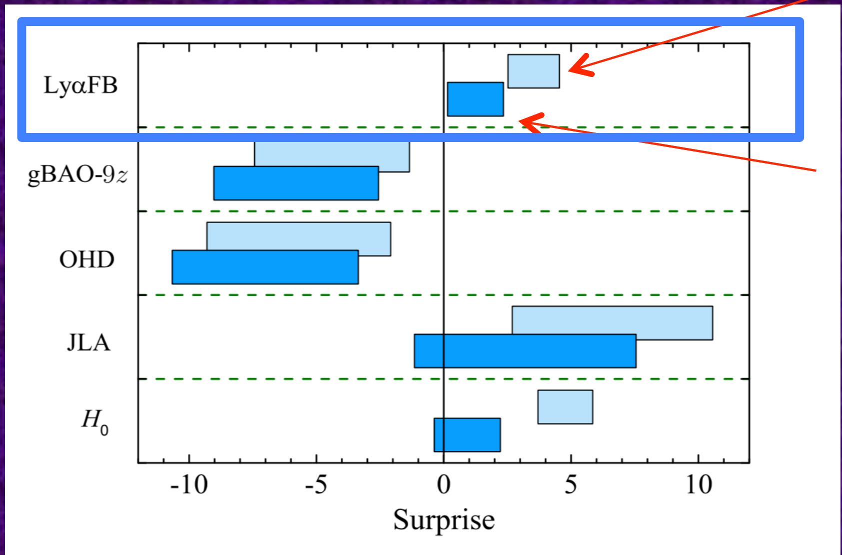
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

For LCDM; H0, LyFB and JLA measurements are in tension with the combined dataset, with tension values of T = 4.4, 3.5, 1.7.

Comparing different data assuming a particular model

Zhao et al, Nature Astronomy, 2017

$$T \equiv \frac{S}{\Sigma} = \frac{(\theta_1 - \theta_2)^T \mathcal{C}_1^{-1} (\theta_1 - \theta_2) - \mathbf{Tr}\left(\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I}\right)}{\sqrt{\mathbf{Tr}\left(\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I}\right)^2}} ,$$



Bautista et al, [1702.00176]
Blomqvist et al, [1904.03430]

Found no systematic/mistake in the previous measurement

gBAO-3z	3-bin BAO from BOSS DR12 galaxies	[34]
gBAO-9z	9-bin BAO from BOSS DR12 galaxies	[35, 36]
LyαFB	The Lyα forest BAO measurements	[2, 9]
B	P15 + JLA + 6dF + MGS	
ALL12	The combined dataset used in [27]	
ALL16-3z	B+$P(k)$+WL+H_0+OHD+gBAO-3z+LyαFB	
ALL16	B+$P(k)$+WL+H_0+OHD+gBAO-9z+LyαFB	
DESI++	P15 + mock DESI BAO [49] + mock SN [50]	

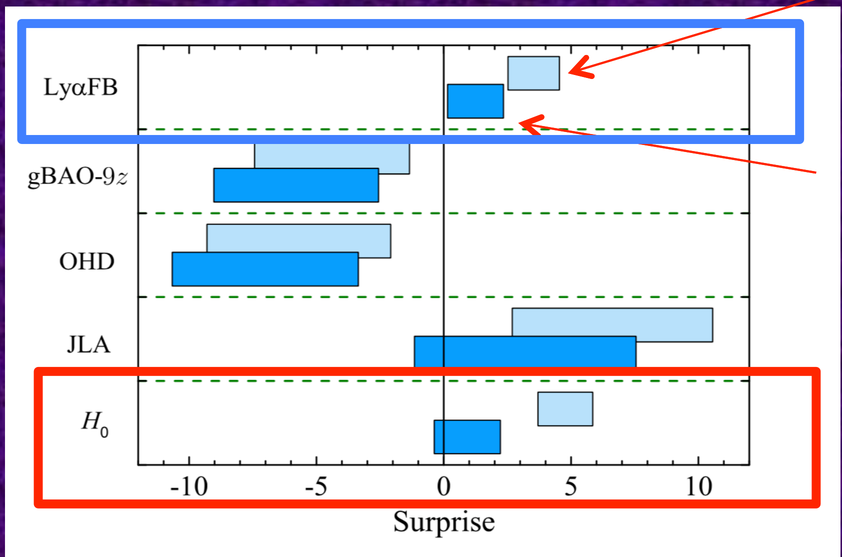
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

For LCDM; H0, LyFB and JLA measurements are in tension with the combined dataset, with tension values of T = 4.4, 3.5, 1.7.

Comparing different data assuming a particular model

Zhao et al, Nature Astronomy, 2017

$$T \equiv \frac{S}{\Sigma} = \frac{(\theta_1 - \theta_2)^T \mathcal{C}_1^{-1} (\theta_1 - \theta_2) - \mathbf{Tr}\left(\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I}\right)}{\sqrt{\mathbf{Tr}\left(\mathcal{C}_2 \mathcal{C}_1^{-1} + \mathbb{I}\right)^2}},$$



Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

Bautista et al, [1702.00176]
Blomqvist et al, [1904.03430]

Found no systematic/mistake in the previous measurement

Follin & Knox [1707.01175]
Zhang et al, [1706.07573]

Both agrees with Riess et al 2016 H0 measurement
New Ho measurement Riess et al 2019
(situation has become worse)

How to resolve the tensions?

- Tensions may disappear by themselves if they are due to statistical fluctuations ***(probably not anymore)***

- Extended Models and/or New Physics: such as proposing models with more degrees of freedom (having more parameters) and get larger confidence contours which looks like there are better consistencies (more overlap between larger contours). [OK to do that but better to avoid over-selling!]

- Finding systematics in different data [Sinful Adam? Not to be confused with primordial sin]

Touching any aspect of the concordance model, means going beyond the standard cosmology (which is great!) and its time to consider different possibilities:

➔ Current tensions seems to be persistent at the background level. So just touching GR (modified gravity models) cannot help.

➔ Evolving dark energy? Possible but not yet so easy to satisfy all observations.

➔ Neutrinos? As always they are a possibility (they may not be able to help much though)

➔ Early Universe and seeds of fluctuations.

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous

Dark Energy is Lambda (w=-1)

Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

Dark Energy Models

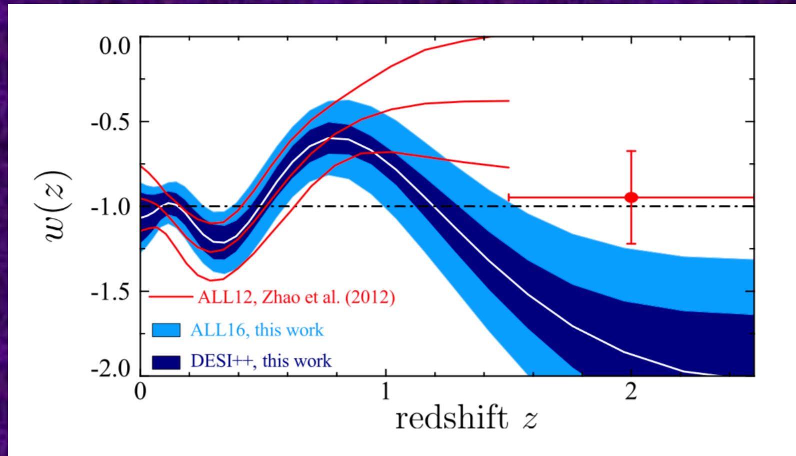
- Cosmological Constant
- Quintessence and k-essence (scalar fields)
- Exotic matter (Chaplygin gas, phantom, etc.)
- Braneworlds (higher-dimensional theories)
- Modified Gravity
- ……

But which one is really responsible for the acceleration of the expanding universe?!

Evolving Dark Energy?

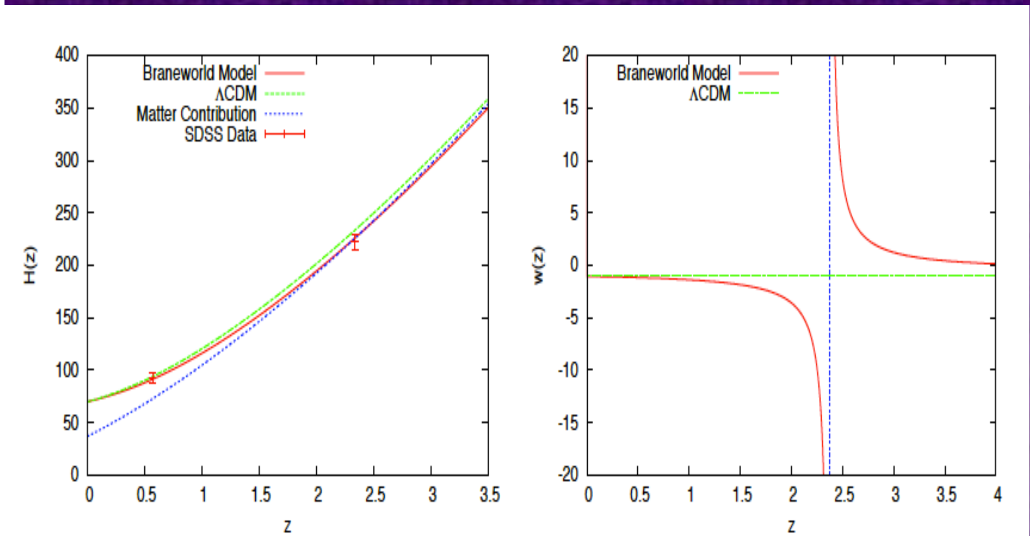
Zhao et al, Nature Astronomy, 2017

Not yet statistically significant



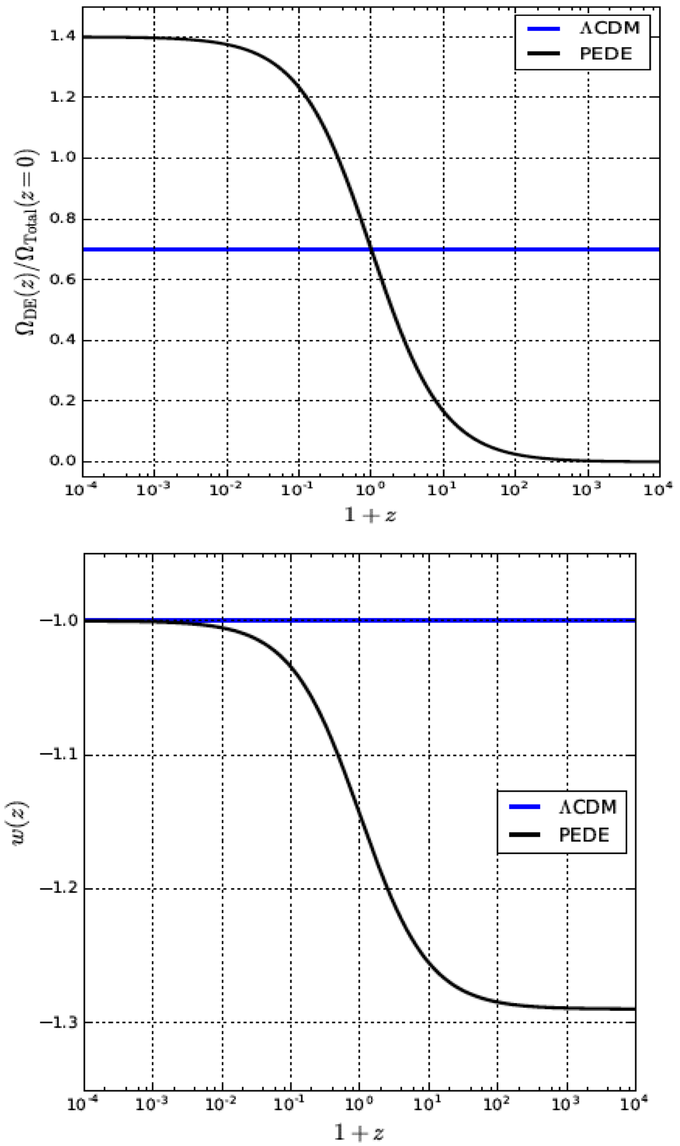
	P15	JLA	gBAO-9z	$P(k)$	WL	H_0	LyαFB	OHD
$\Delta\chi^2$	-0.7	-1.6	-2.8	$+1.1$	-0.1	-2.9	-3.7	-2.3

	ALL12	ALL16	DESI++
S/N	2.5σ	3.5σ	6.4σ
ΔAIC	-0.3	-4.3	-24.6
$\Delta\ln E$	-6.7 ± 0.3	-3.3 ± 0.3	11.3 ± 0.3



Sahni et al ApJ 2014

Phenomenologically Emergent Dark Energy (PEDE)



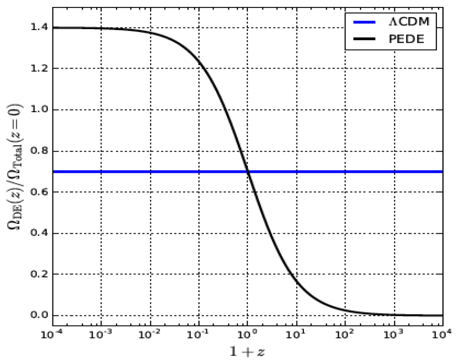
$$\Omega_{\rm DE}(z) \; = \; \Omega_{\rm DE,0} \times [1 - \tanh\left(\log_{10}(1+z)\right)]$$

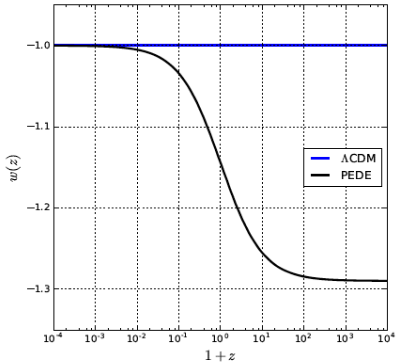
$$\begin{aligned} w(z) \; &= \; -\frac{1}{3\ln 10} \times \frac{1-\tanh^2\left[\log_{10}(1+z)\right]}{1-\tanh\left[\log_{10}\left(1+z\right)\right]} - 1 \\ &= -\frac{1}{3\ln 10} \times \left(1+\tanh\left[\log_{10}\left(1+z\right)\right]\right) - 1. \end{aligned}$$

Li and Shafieloo, arXiv:1906.08275

Phenomenologically Emergent Dark Energy

Model	Data Parameters	Pantheon+BAO No H_0 Prior	Pantheon+BAO 2σ H_0 Prior	Pantheon+BAO 1σ H_0 Prior	Pantheon+BAO+Lyα+CMB No H_0 Prior	Pantheon+BAO+Lyα+CMB 2σ H_0 Prior	Pantheon+BAO+Lyα+CMB 1σ H_0 Prior
ΛCDM	Ω_m	$0.299^{+0.047}_{-0.043}$	$0.335^{+0.040}_{-0.036}$	$0.347^{+0.041}_{-0.036}$	$0.311^{+0.016}_{-0.014}$	$0.271^{+0.002}_{-0.003}$	$0.256^{+0.002}_{-0.002}$
	H_0	$66.94^{+3.721}_{-3.256}$	$71.19^{+1.890}_{0.0}$	$72.61^{+1.617}_{-0.000}$	$67.91^{+1.074}_{-1.150}$	$71.19^{+0.271}_{-0.000}$	$72.61^{+0.200}_{-0.000}$
	χ^2_{bf}	1046.94	**1054.76**	**1060.25**	1056.12	**1112.28**	**1168.98**
	DIC	1051.00	**1058.88**	**1064.27**	1062.35	**1127.03**	**1195.07**
CPL	Ω_m	$0.285^{+0.113}_{-0.180}$	$0.332^{+0.071}_{-0.050}$	$0.350^{+0.050}_{-0.043}$	$0.307^{+0.026}_{-0.021}$	$0.286^{+0.007}_{-0.011}$	$0.274^{+0.006}_{-0.009}$
	H_0	$64.84^{+14.49}_{-16.12}$	$71.30^{+5.561}_{-0.117}$	$72.70^{+2.746}_{-0.091}$	$68.49^{+2.302}_{-2.680}$	$71.19^{+1.277}_{-0.002}$	$72.61^{+0.918}_{-0.004}$
	w_0	$-0.82^{+0.193}_{-0.541}$	$-1.08^{+0.422}_{-0.347}$	$-1.05^{+0.350}_{-0.347}$	$-0.98^{+0.267}_{-0.218}$	$-1.07^{+0.259}_{-0.240}$	$-1.13^{+0.274}_{-0.206}$
	w_a	$0.675^{+0.547}_{-3.103}$	$-0.11^{+1.510}_{-3.192}$	$-0.46^{+1.830}_{-2.686}$	$-0.16^{+0.816}_{-1.102}$	$-0.20^{+0.986}_{-1.249}$	$-0.11^{+0.728}_{-1.321}$
	χ^2_{bf}	1044.98	**1048.84**	**1049.66**	1055.52	**1066.85**	**1080.83**
	DIC	1052.59	**1054.46**	**1056.23**	1065.48	**1085.06**	**1128.50**
PEDE	Ω_m	$0.341^{+0.045}_{-0.041}$	$0.341^{+0.041}_{-0.037}$	$0.341^{+0.041}_{-0.030}$	$0.291^{+0.015}_{-0.016}$	$0.289^{+0.002}_{-0.014}$	$0.274^{+0.002}_{-0.006}$
	H_0	$72.84^{+3.814}_{-3.530}$	$73.01^{+3.371}_{-1.8231}$	$72.79^{+2.652}_{-0.186}$	$71.02^{+1.452}_{-1.368}$	$71.19^{+1.306}_{-0.001}$	$72.61^{+0.651}_{-0.000}$
	χ^2_{bf}	1050.04	**1050.04**	**1050.04**	1071.12	**1071.20**	**1080.40**
	DIC	1052.01	**1053.33**	**1052.98**	1091.15	**1091.65**	**1100.94**



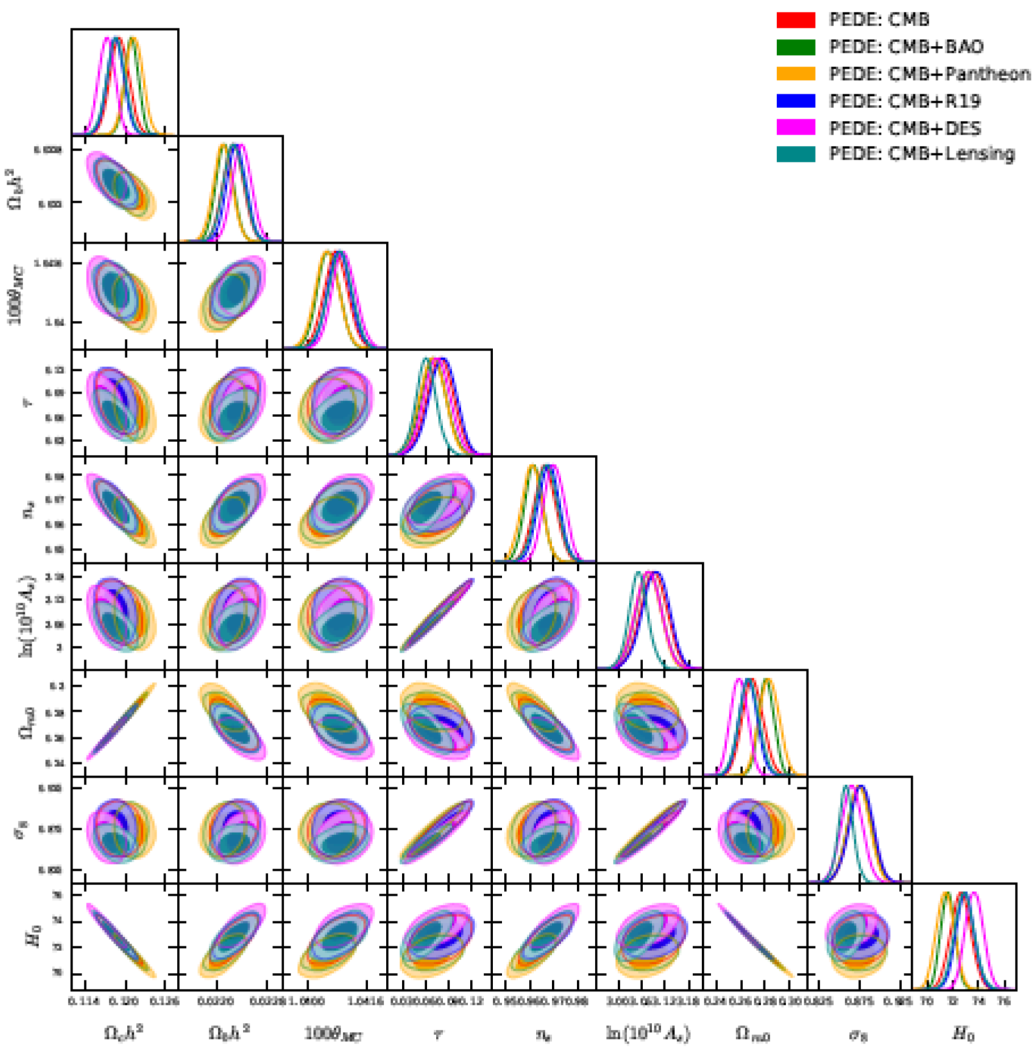


$$p_D = \overline{\chi^2(\theta)} - \chi^2(\bar{\theta}).$$

$$\mathrm{DIC} \equiv D(\bar{\theta}) + 2p_D = \overline{D(\theta)} + p_D,$$

Li and Shafieloo, arXiv:1906.08275

Phenomenologically Emergent Dark Energy (PEDE)



Reconciling H0 tension in a 6 parameter space?

Dataset	$\ln B_{ij}$	Strength of evidence
CMB	-0.2	Weak
CMB+BAO	-3.1	Strong
CMB+Pantheon	-5.8	Strong
CMB+R19	2.7	Definite/Positive
CMB+DES	-1.6	Definite/Positive
CMB+Lensing	-0.6	Weak

Pan, Yang, Di Valentino, Shafieloo and Chakraborty, arXiv: 1907.12551

(Present)t

Standard Model of Cosmology

Universe is Flat

Universe is Isotropic

Universe is Homogeneous

Dark Energy is Lambda (w=-1)

Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

All within framework of FLRW

Model Independent Estimation of Primordial Spectrum

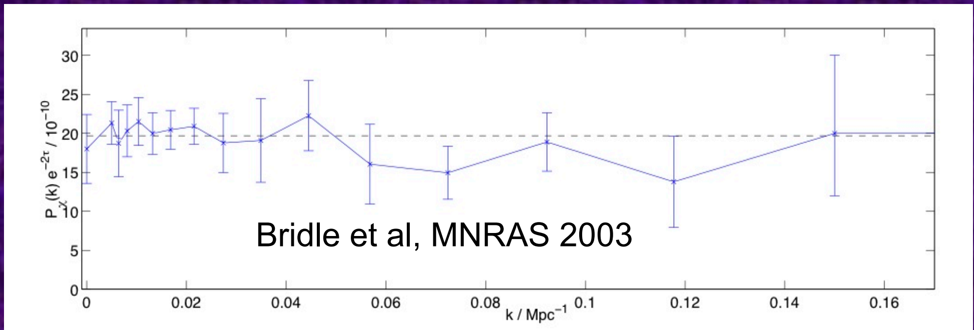
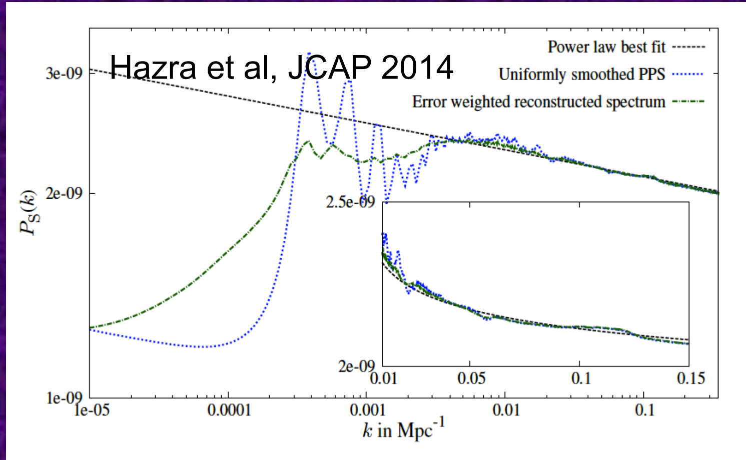
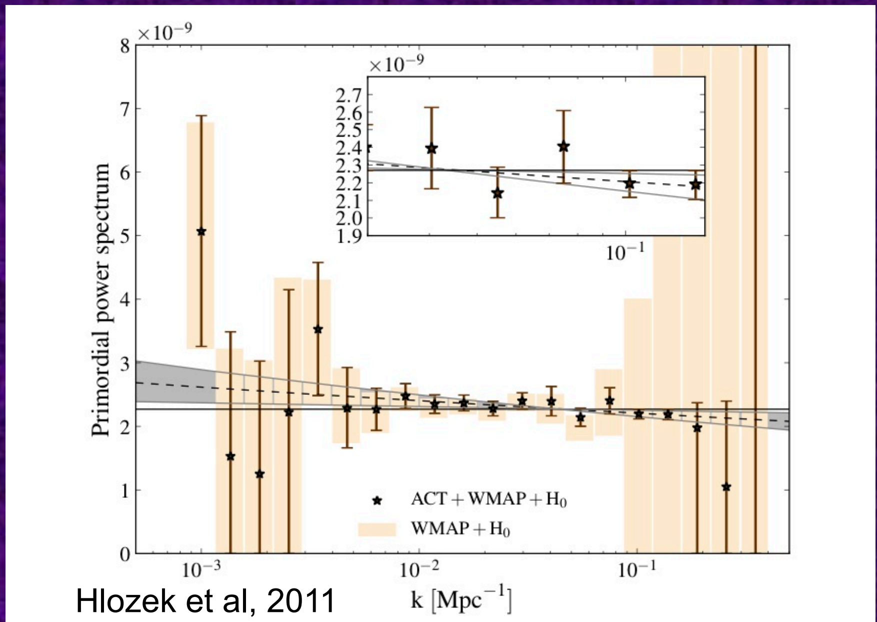
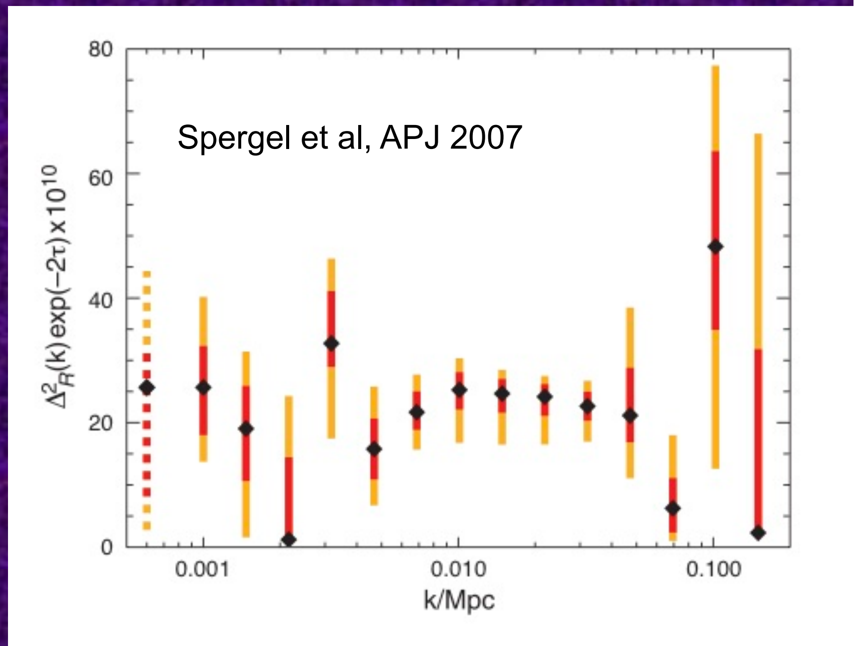


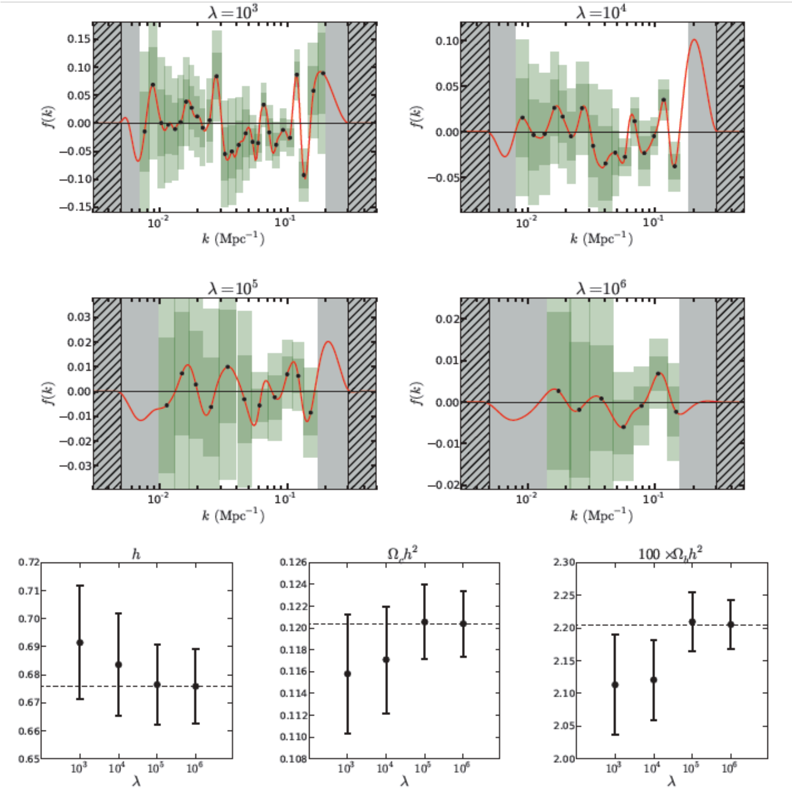
Figure 4. Reconstruction of the shape of the primordial power spectrum in 16 bands after marginalising over the Hubble constant, baryon and dark matter densities, and the redshift of reionization.



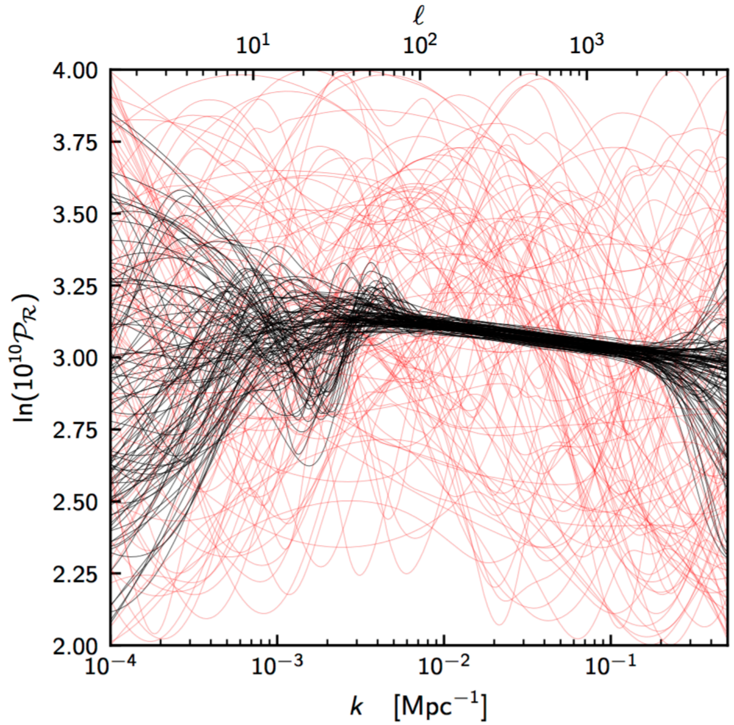




Planck 2013



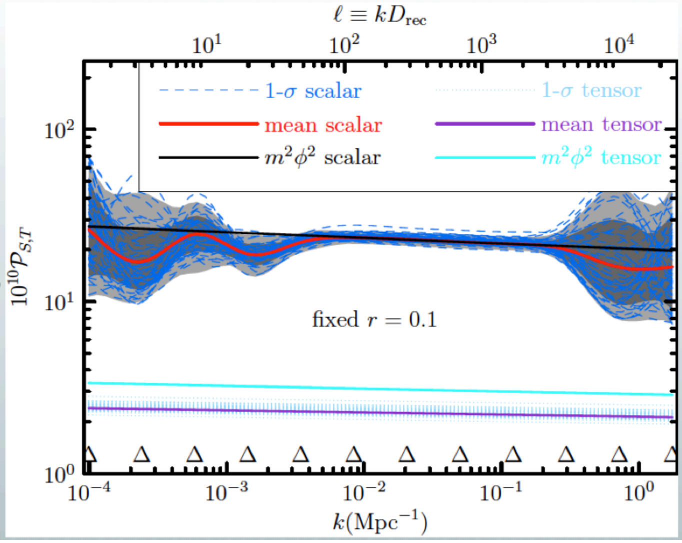
Planck 2018



Planck 2015

Power spectra reconstruction

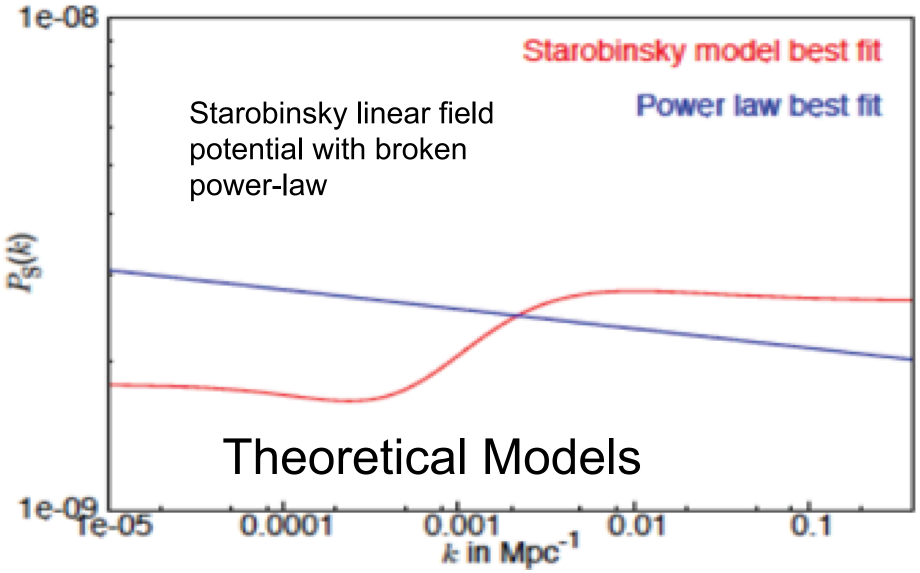
2015
TT+lowP
+BAO+JLA
+Hlow

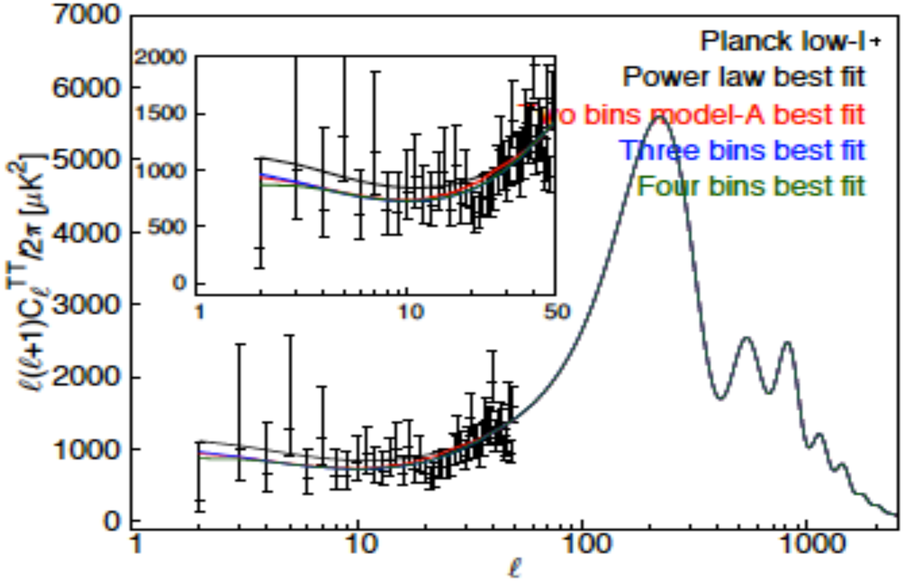


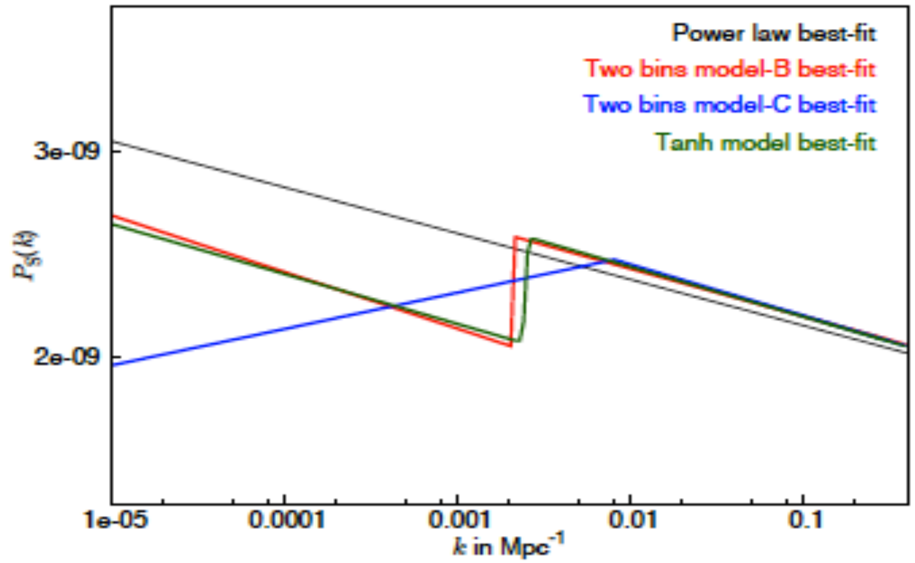
12-knots power spectra

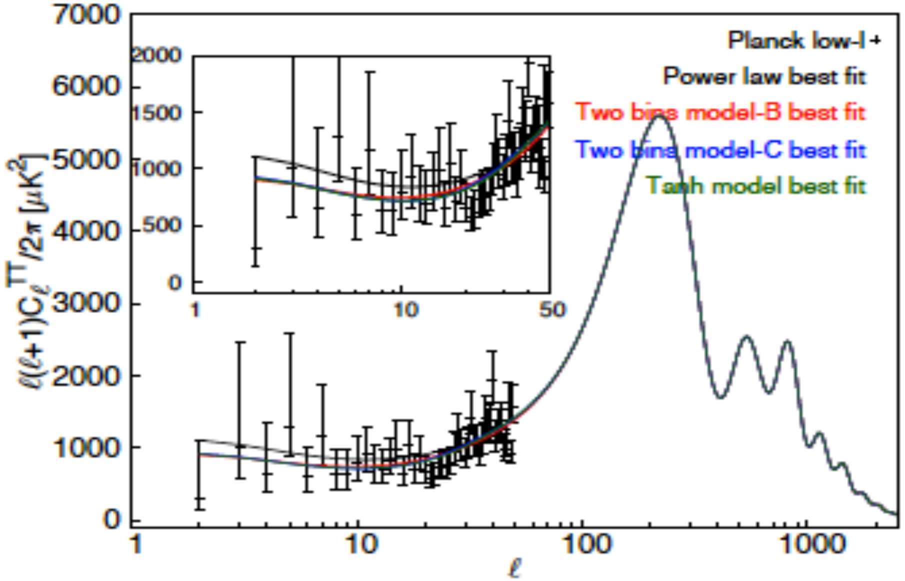
(actually used 3 different methods, all with similar results)

Beyond Power-Law: there are some other models consistent to the data.









Forms of PPS and Effects on the Background Cosmology

- Flat Lambda Cold Dark Matter Universe (LCDM) with power–law form of the primordial spectrum
- It has 6 main parameters.

Ω_b, Ω_m, H_0, τ → 1 → G(l,k) → 2

A_s, n_s → 1 → $P(k)$ → 2

$$C_l = \sum G(l,k)P(k)$$

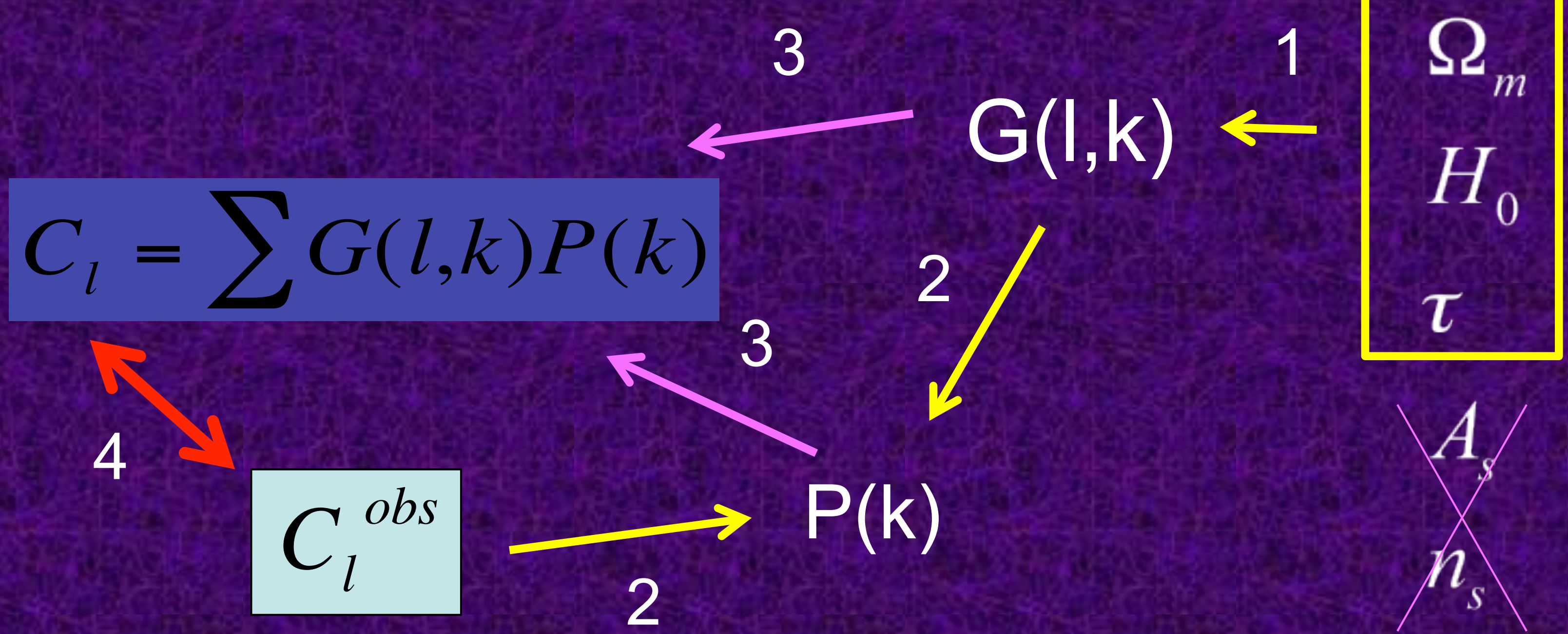
3 ↕

$$C_l^{obs}$$

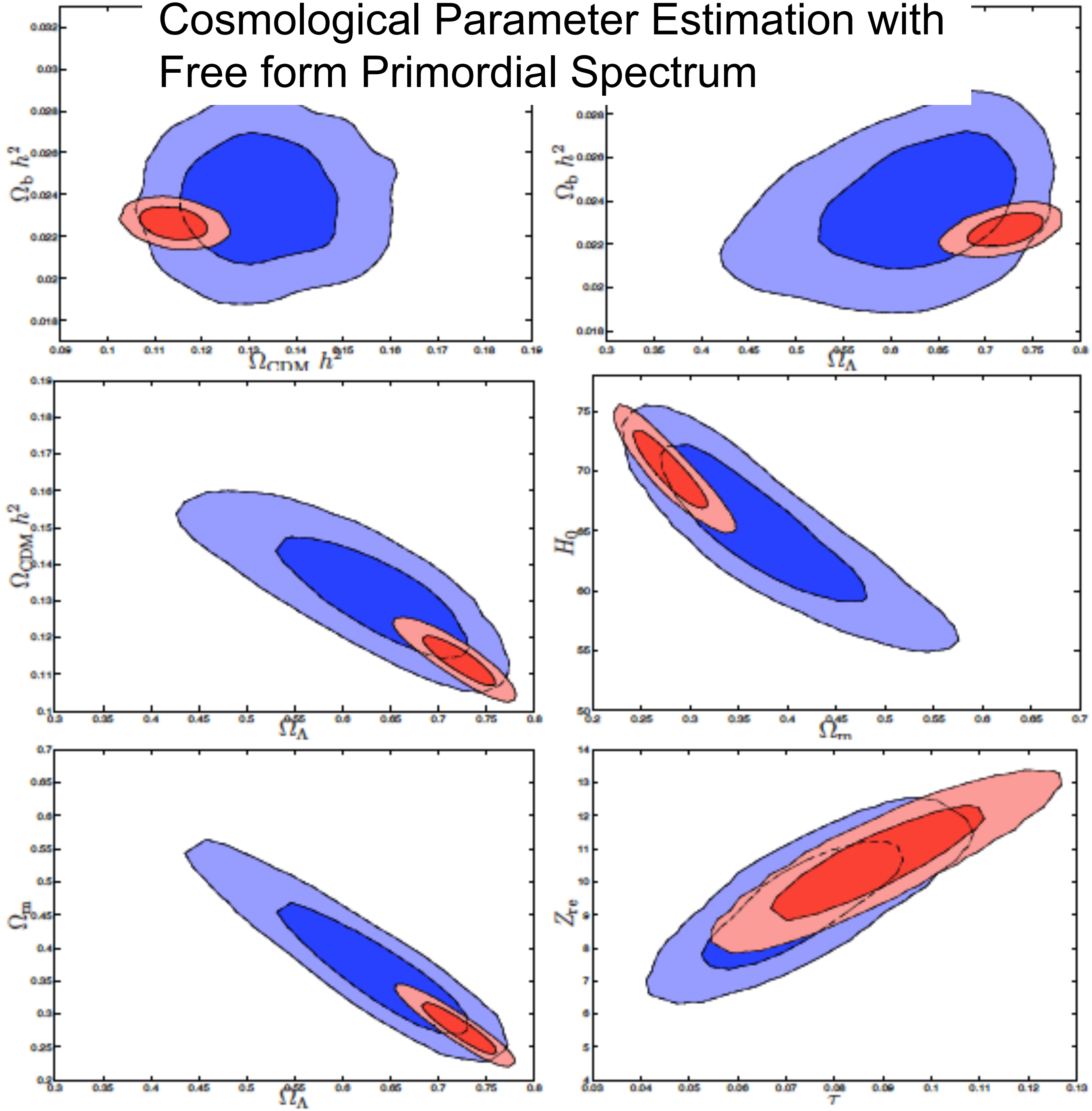
$$P(k) = A_s[\frac{k}{k_*}]^{n_s - 1}$$

Forms of PPS and Effects on the Background Cosmology

- Cosmological parameter estimation with free form primordial power spectrum



Cosmological Parameter Estimation with Free form Primordial Spectrum

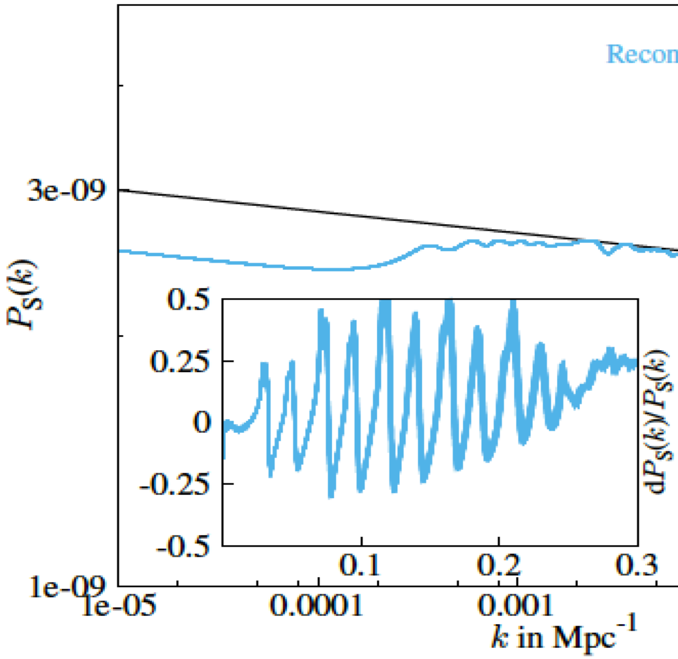


WMAP9 Data

Red Contours:
Power Law PPS

Blue Contours:
Free Form PPS

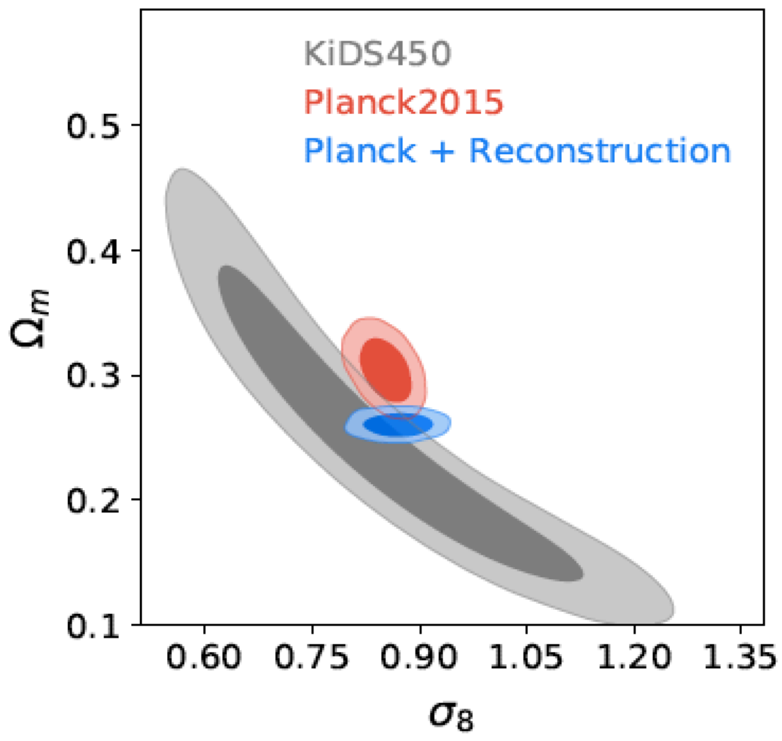
Hazra, et al, PRD 2013

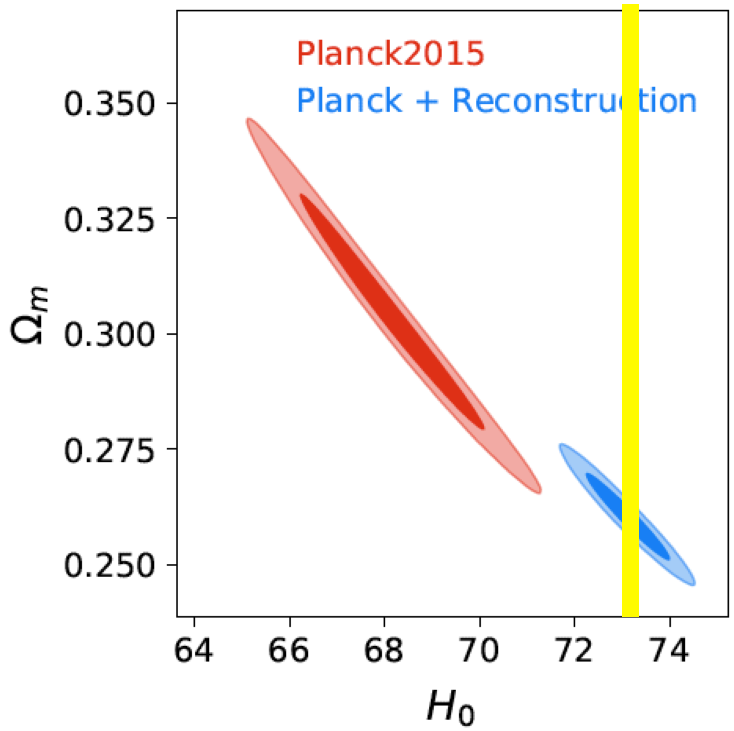


Hazra, Shafieloo, Souradeep, JCAP 2019

Background Cosmological Parameters and PPS

We use the reconstructed PPS for parameter estimation, similar to what we do with PL.





Systematics and Cosmology

High possibilities for systematics in different data

Need for independent measurements

Two key questions:

Power-law PPS?
Lambda DE?

Future Perspective

Full picture

Complete reconstruction analysis with polarization data

$$C_\ell^{TT} = \int \frac{dk}{k} P(k) \quad G_\ell^{TT}(k)$$

$$C_\ell^{EE} = \int \frac{dk}{k} P(k) \quad G_\ell^{EE}(k)$$

$$C_\ell^{BB} = \int \frac{dk}{k} P_t(k) \quad G_\ell^{BB}(k)$$

$$C_\ell^{TE} = \int \frac{dk}{k} P(k) \quad G_\ell^{TE}(k)$$

Searching for correlations!

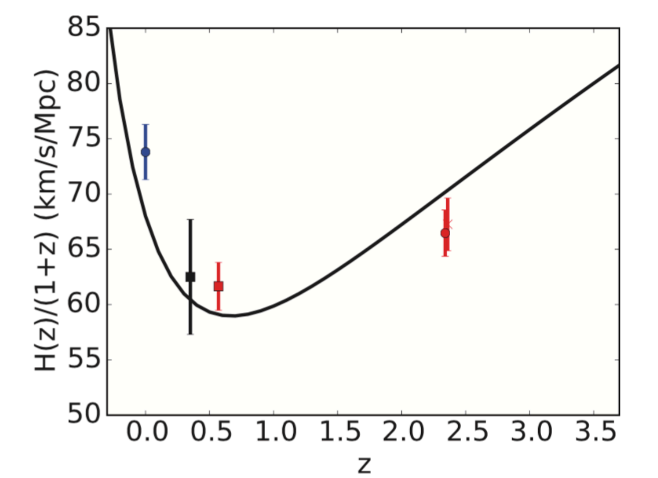
$$P_S(k), P_T(k), P_{iso}(k)$$

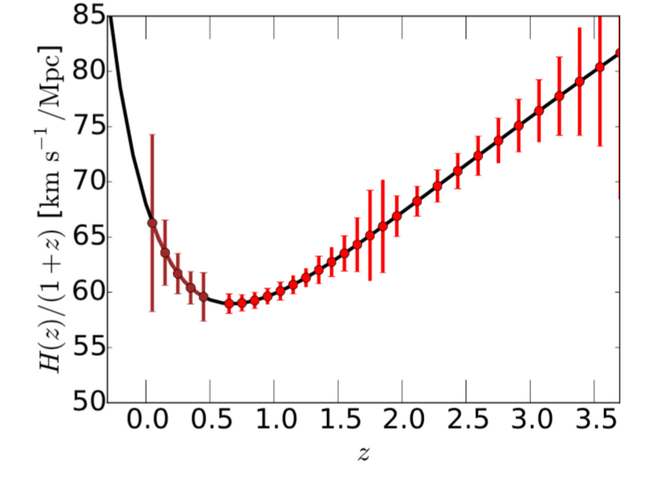
Primordial power spectra from Early universe

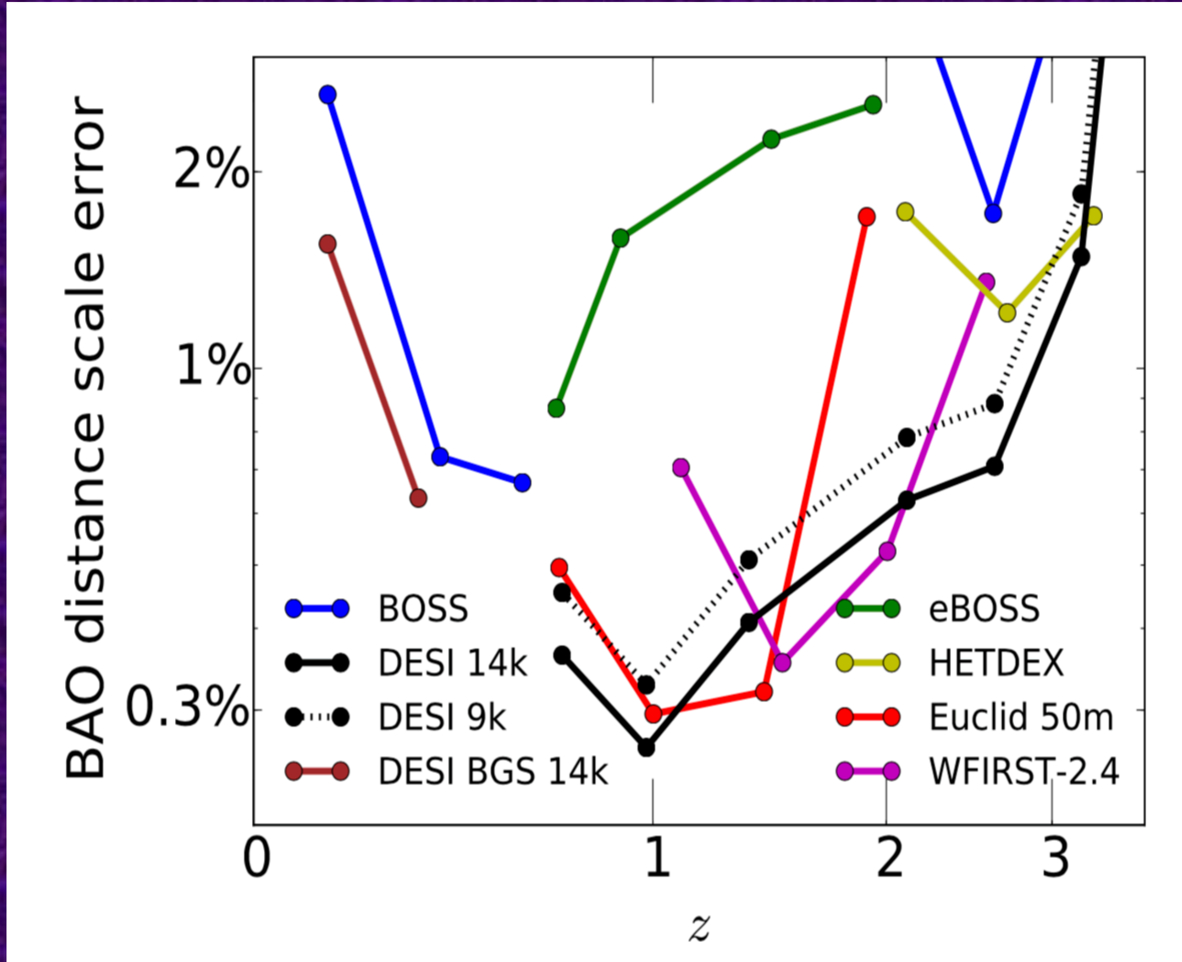
$$G_\ell^{TT}(k), G_\ell^{EE}(k), G_\ell^{BB}(k), G_\ell^{TE}(k)$$

Post recombination Radiative transport kernels in a given cosmology

Future perspective (late universe)

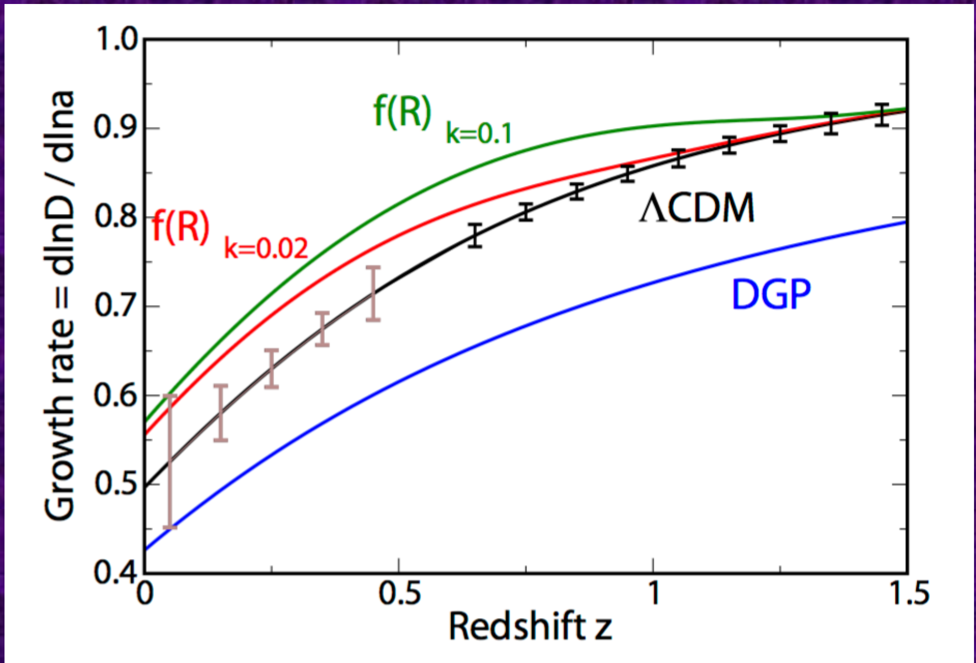


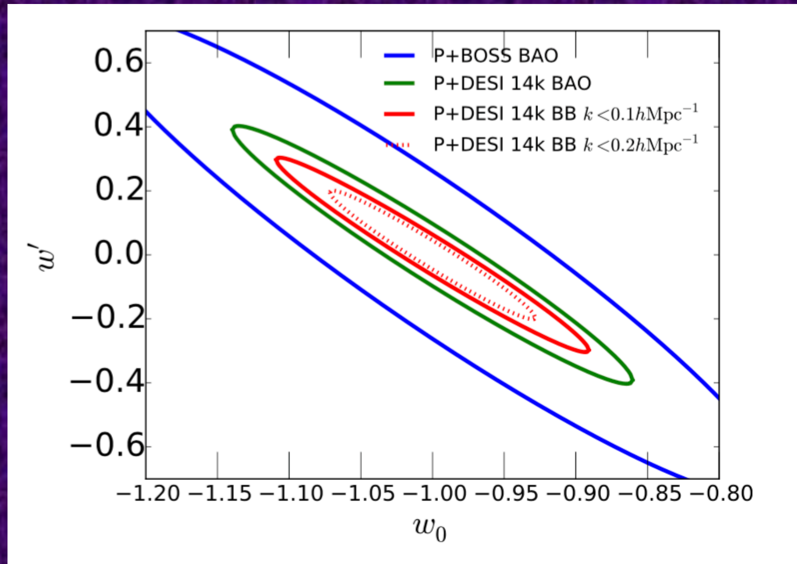




Aghamousa et al, [arXiv:1611.00036] DESI Collaboration

Future perspective (late universe)

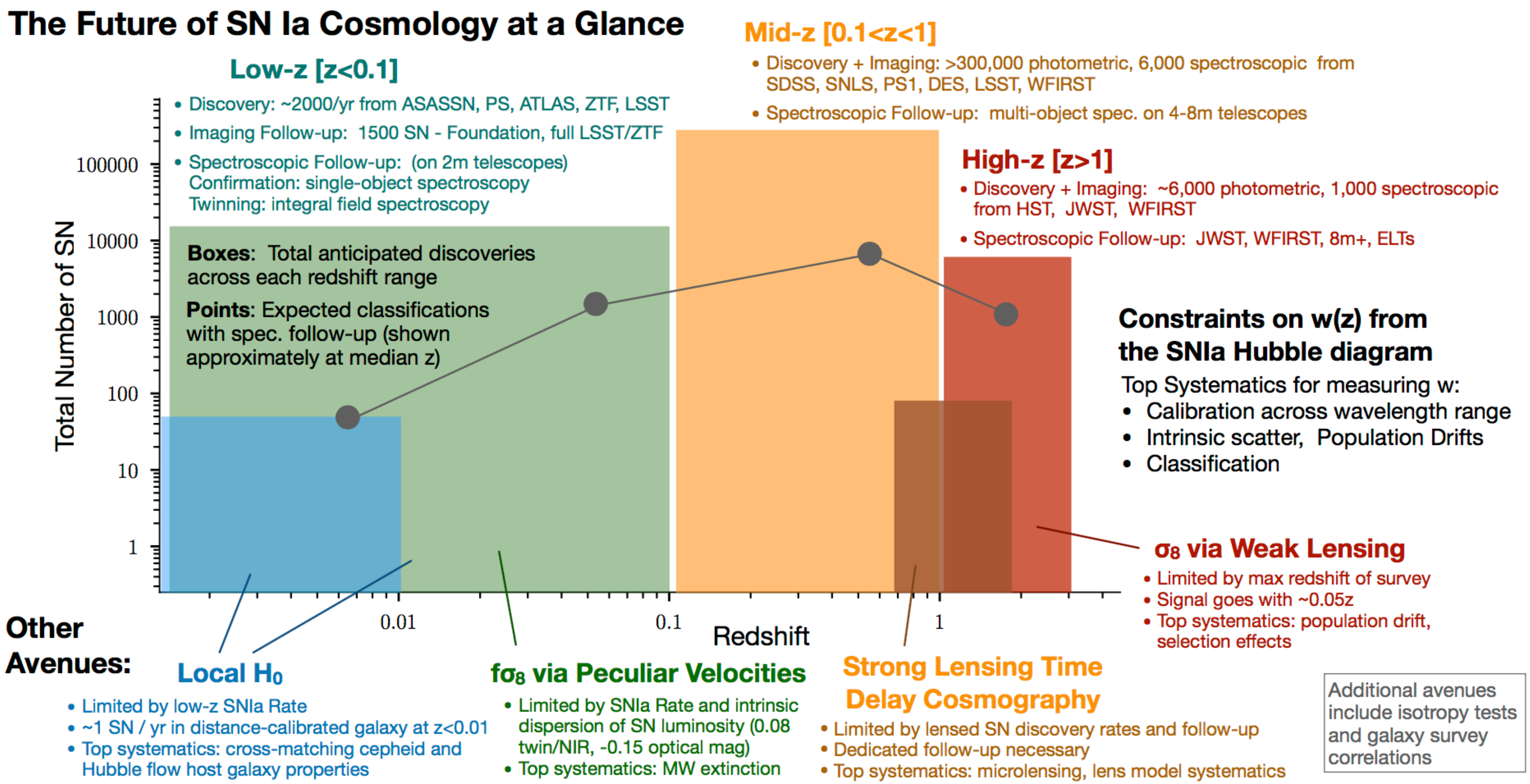




Aghamousa et al, [arXiv:1611.00036] DESI Collaboration

Future perspective

Astro2020



Scolnic,et al,
arXiv:1903.05128

Cosmology vs Systematics vs Assumptions

- With higher quality of the data the role of systematics will become more and more prominent.
- Higher precision may cost us uncontrollable bias if we make wrong assumptions.

Conclusion

- The current standard model of cosmology seems to work fine but this does not mean all the other models are wrong.
- H0 tension seems remaining persistent in the context of the LCDM model. This can open ways for competitive alternatives ***(PEDE?)***.
- First target can be testing different aspects of the standard 'Vanilla' model. If it is not '*Lambda*' dark energy or power-law primordial spectrum then we can look further. It is possible to focus the power of the data for the purpose of the falsification. Next generation of astronomical/ cosmological observations, (DESI, Euclid, LSST, WFIRST, SKA(?), etc) will make it clear about the status of the concordance model in 2020s.
- ***Combination of different cosmological data also hints towards some tension with LCDM model. If future data continues the current trend, we may have some exciting times ahead!***