Parameter discordance in Planck and low-redshift measurements

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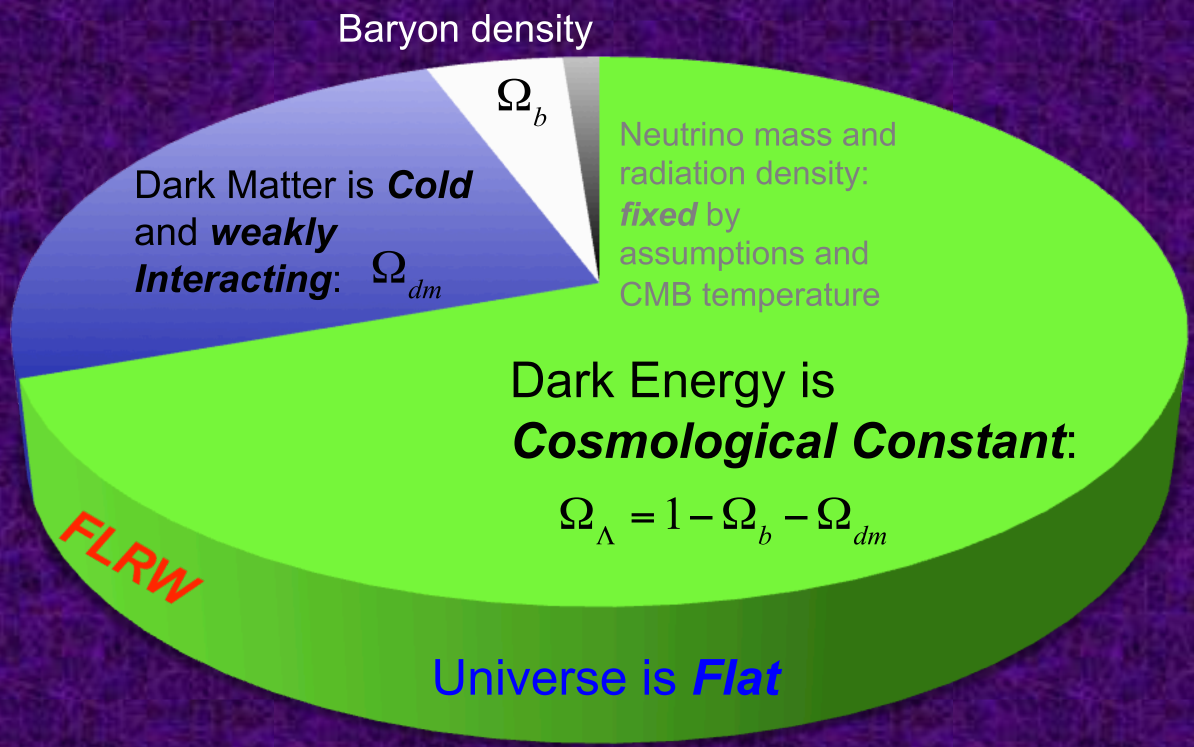
Standard Model of Cosmology

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

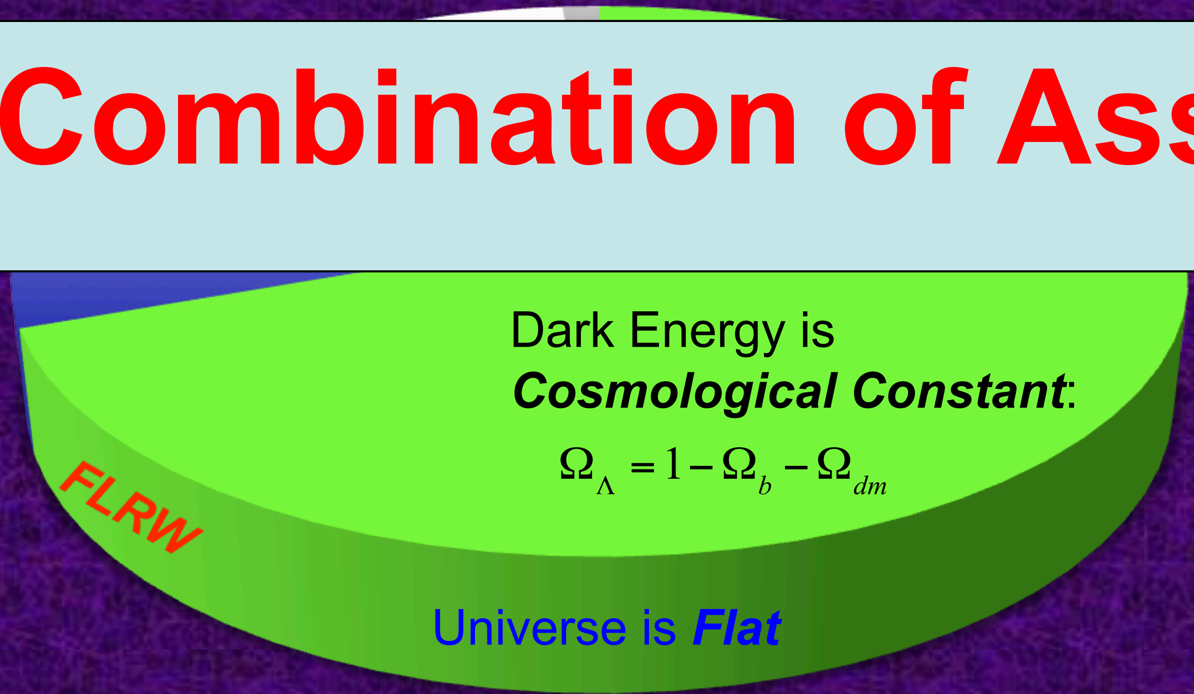
H_0

Standard Model of Cosmology

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

Combination of Assumptions

Baryon density



n_s, A_s

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τ

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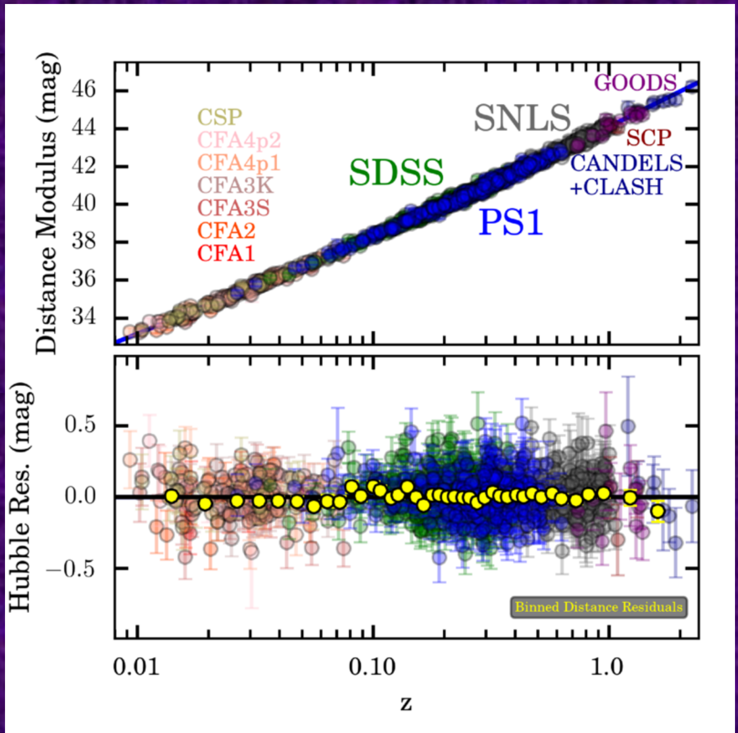
H_0

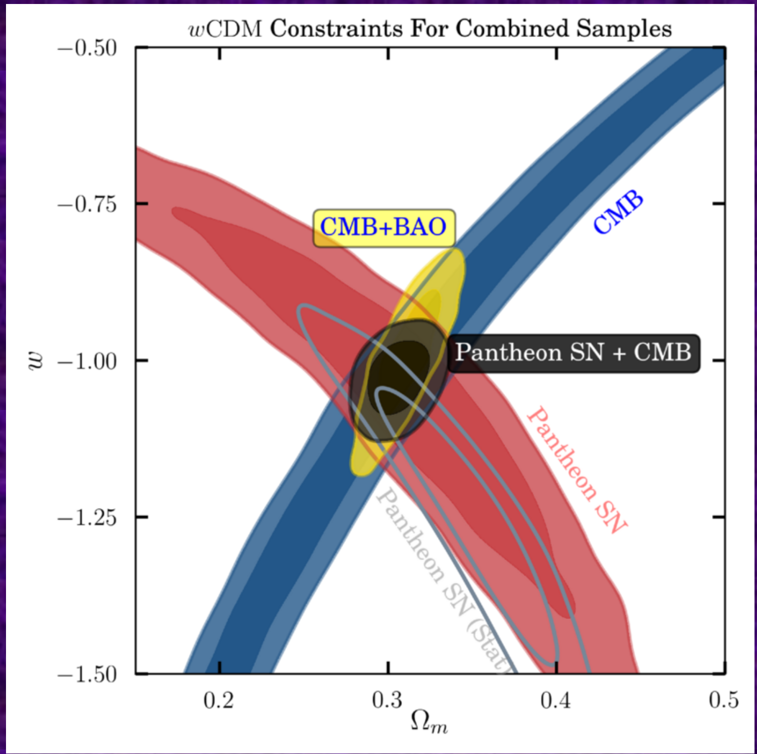
Standard Model in 2018 SN

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



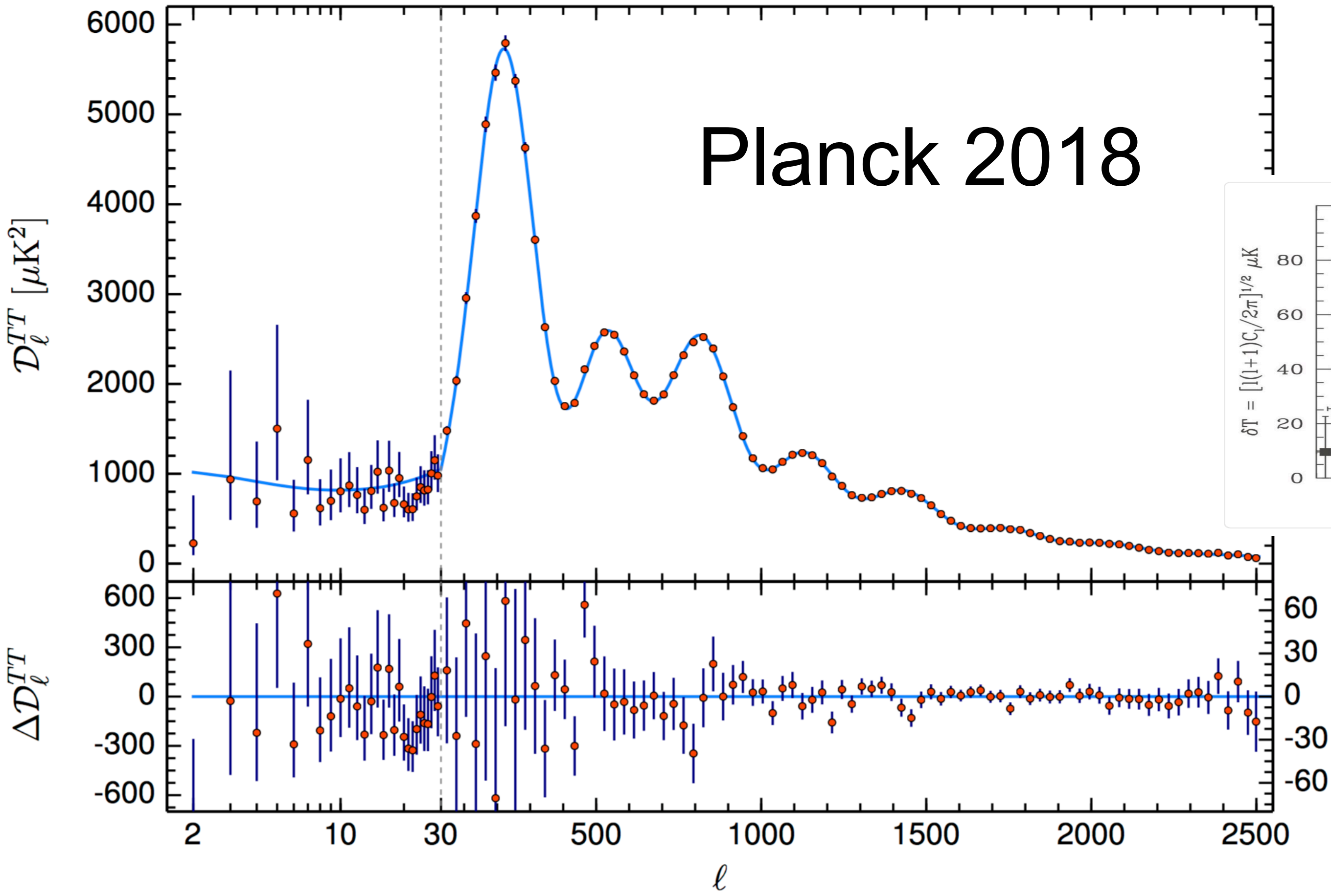
Pantheon Compilation
Scolnic et al. (2018)

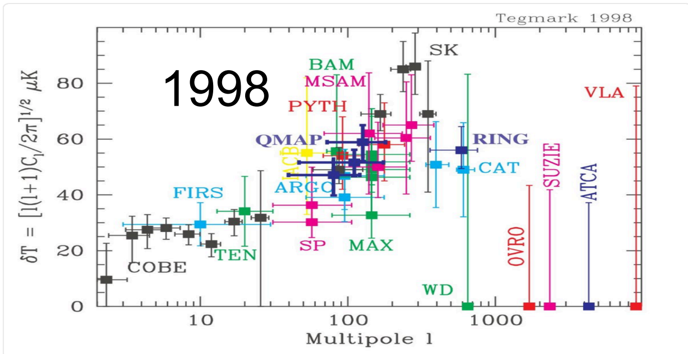
Standard Modelin 2018

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!



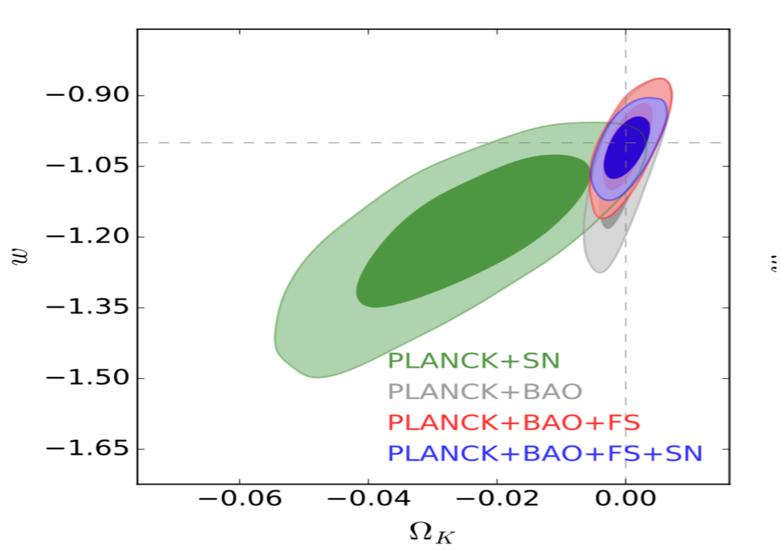


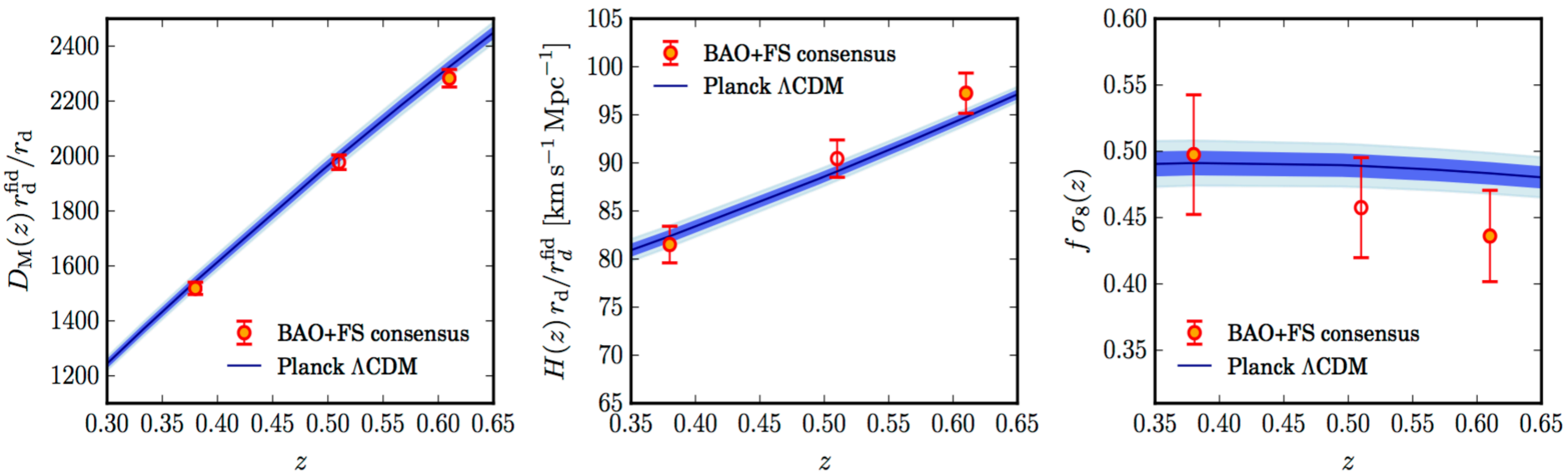
Dark Energy in 2018

LSS

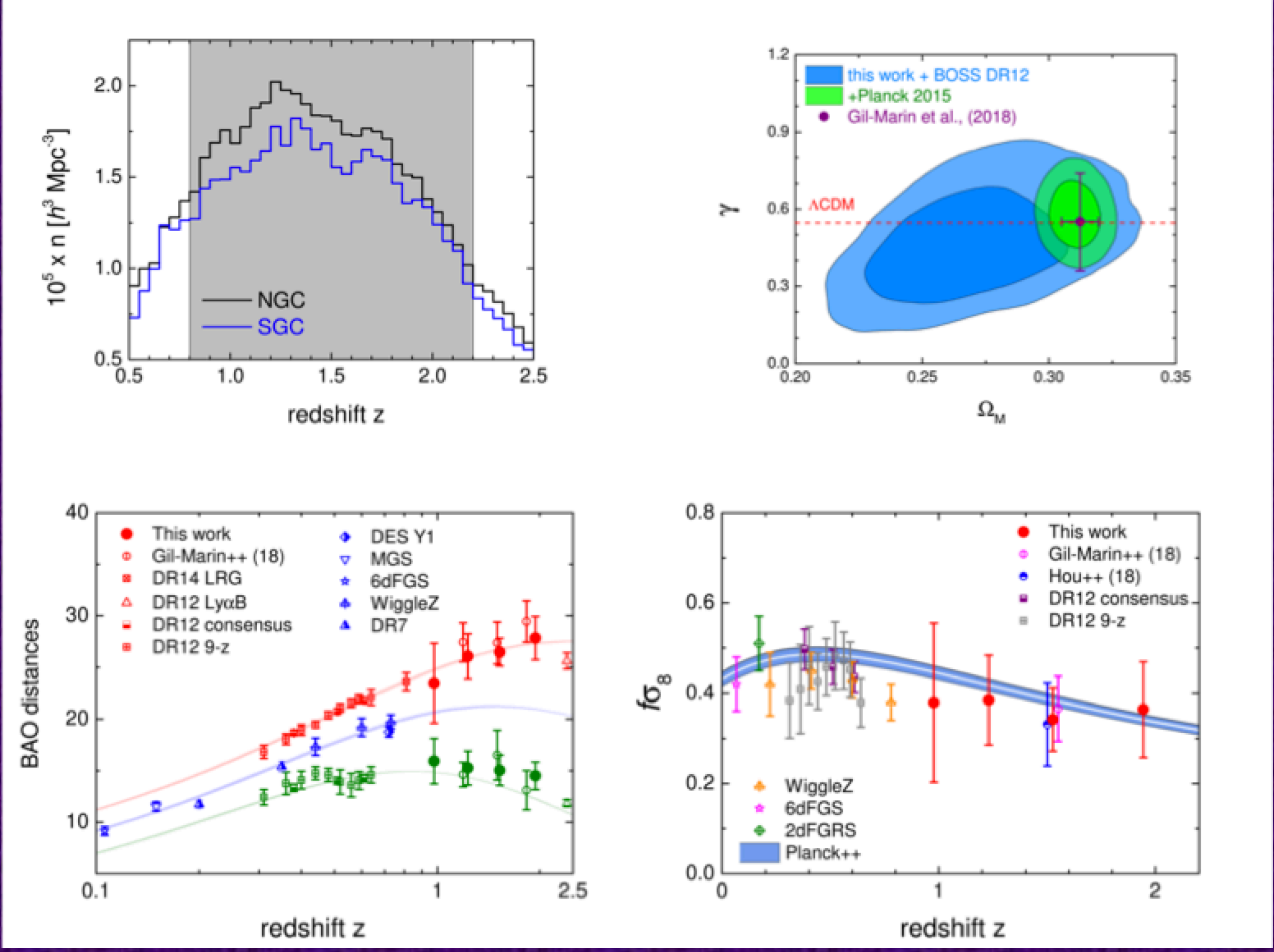
Almost 20 years after discovery of the acceleration of the universe:

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





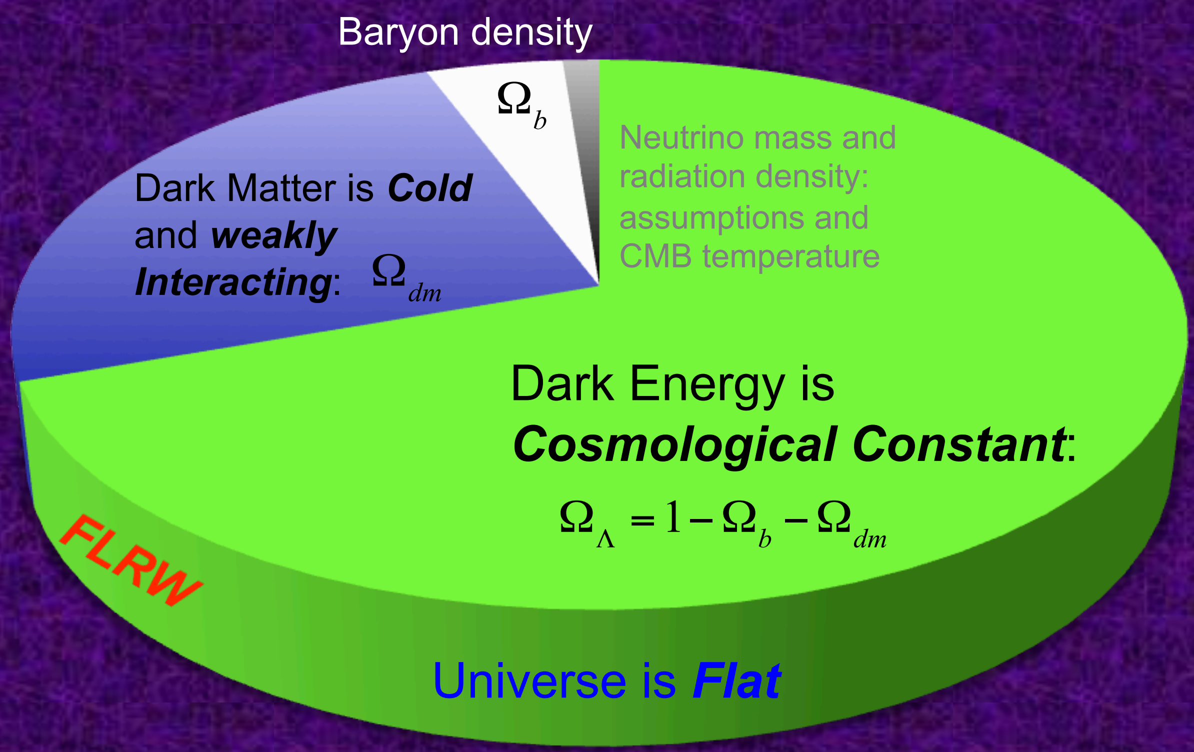
BOSS DR14Q



eBOSS collaboration: Zhao et al. MNRAS 2018

Standard Model of Cosmology

combination of *reasonable* assumptions, but.....



Initial Conditions:
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Beyond the Standard Model of Cosmology

- The universe might be more complicated than its current standard model (Vanilla Model).
- There might be some extensions to the standard model in defining the cosmological quantities.
- This needs proper investigation, using advanced statistical methods, high performance computational facilities and high quality observational data.

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!

2014 Omh2

SDSS Quasar BAO data at z=2.34

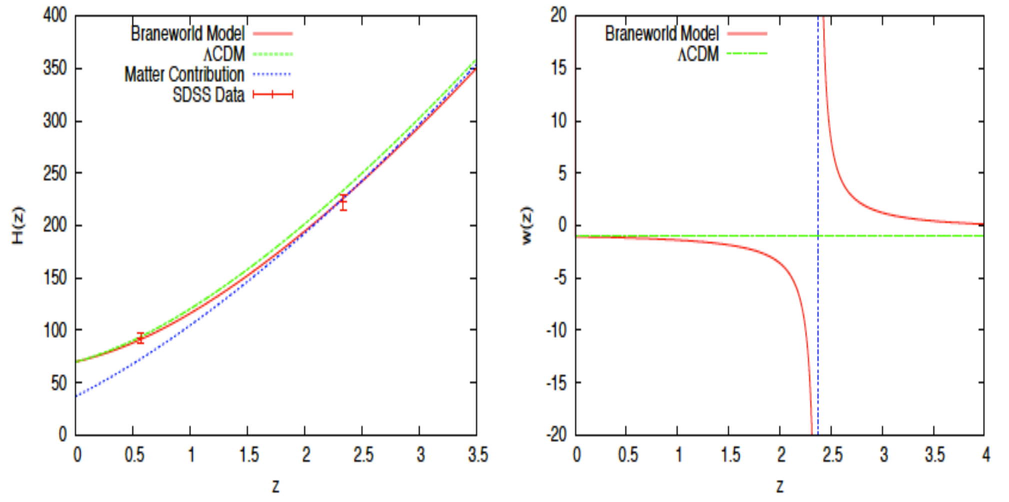
Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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

Only for LCDM

Sahni, Shafieloo, Starobinsky, ApJ Lett 2014

Introducing litmus tests of Lambda: Comparing direct observables assuming a model.



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

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 / 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

Omh2

Important discovery if no systematic in the SDSS Quasar BAO data

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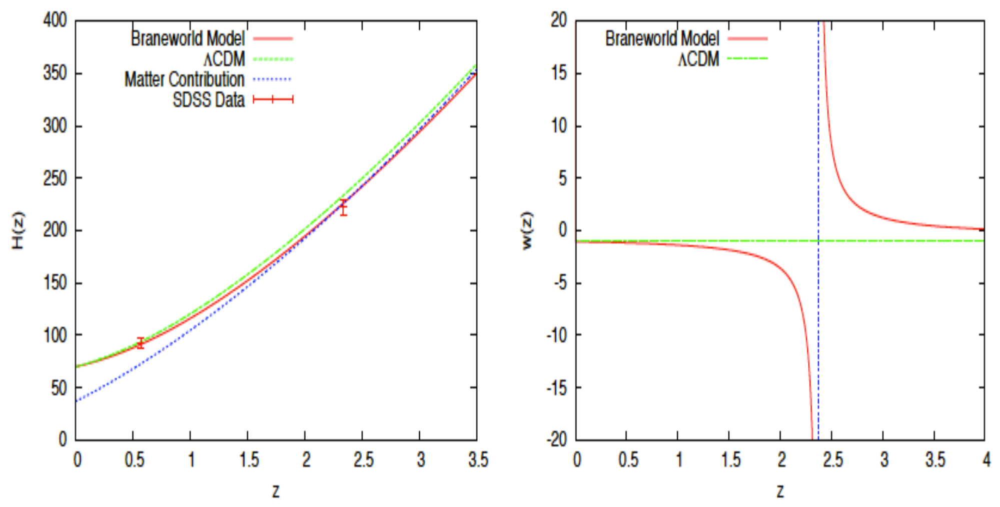

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2018 Omh2

No systematic yet found,

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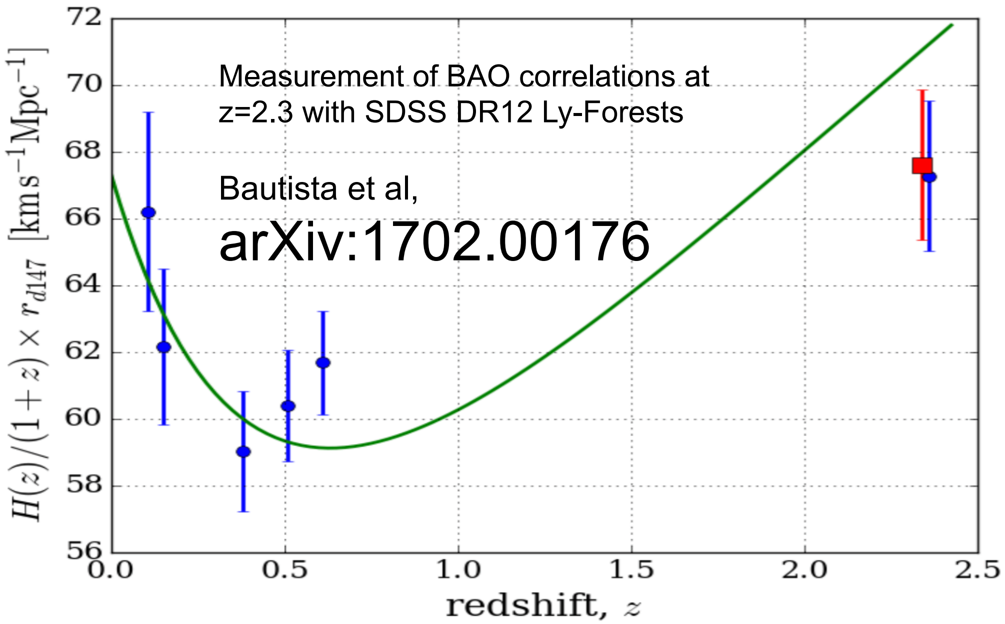

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2018 Omh2

No systematic yet found,
Results Persistent!

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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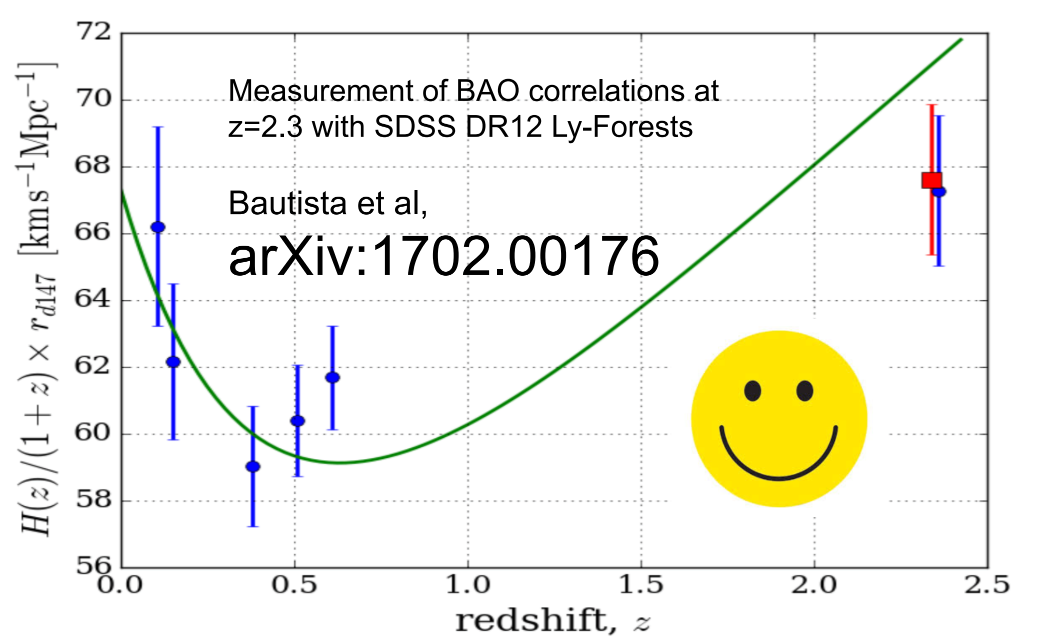

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What if we combine many different cosmology data?

Should we see evidence for deviation from Lambda?

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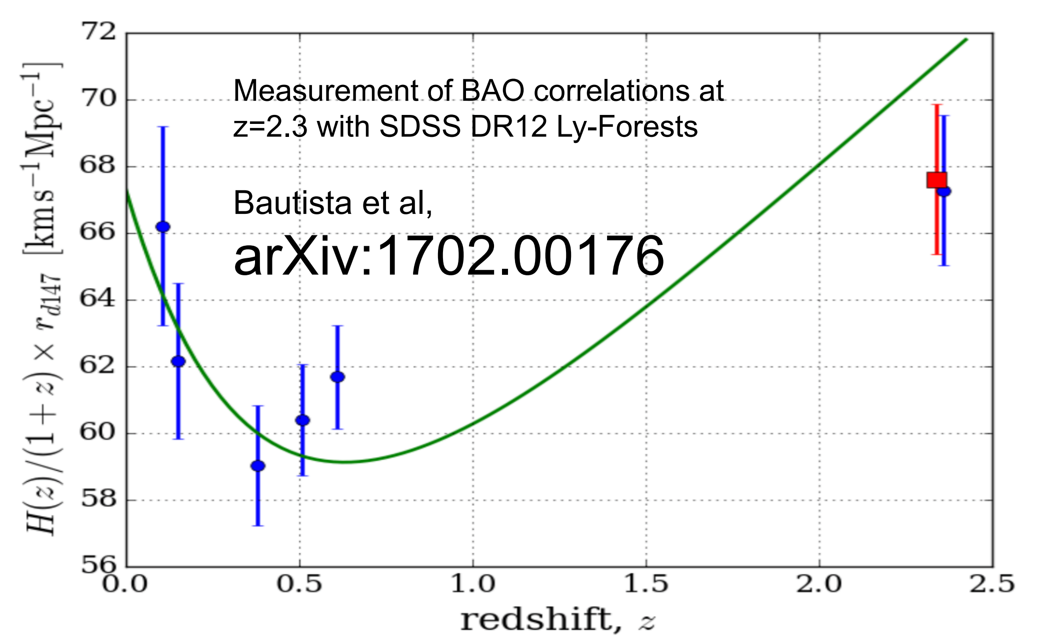

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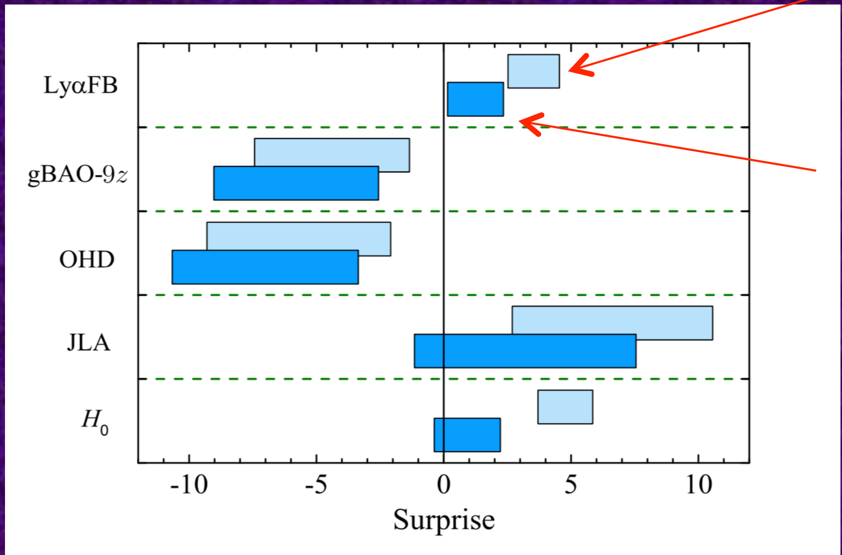
The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Examining the observational evidence for dynamical dark energy

Gong-Bo Zhao,[1,2,*] Marco Raveri,[3,4] Levon Pogosian,[5,2] Yuting Wang,[1,2] Robert G. Crittenden,[2] Will J. Handley,[6,7] Will J. Percival,[2] Jonathan Brinkmann,[8] Chia-Hsun Chuang,[9,10] Antonio J. Cuesta,[11] Daniel J. Eisenstein,[12] Francisco-Shu Kitaura,[13,14] Kazuya Koyama,[2] Benjamin L'Huillier,[15] Robert C. Nichol,[2] Matthew M. Pieri,[16] Sergio Rodriguez-Torres,[9,17,18] Ashley J. Ross,[19,2] Graziano Rossi,[20] Ariel G. Sánchez,[21] Arman Shafieloo,[15,22] Jeremy L. Tinker,[23] Rita Tojeiro,[24] Jose A. Vazquez,[25] and Hanyu Zhang[1]

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]	

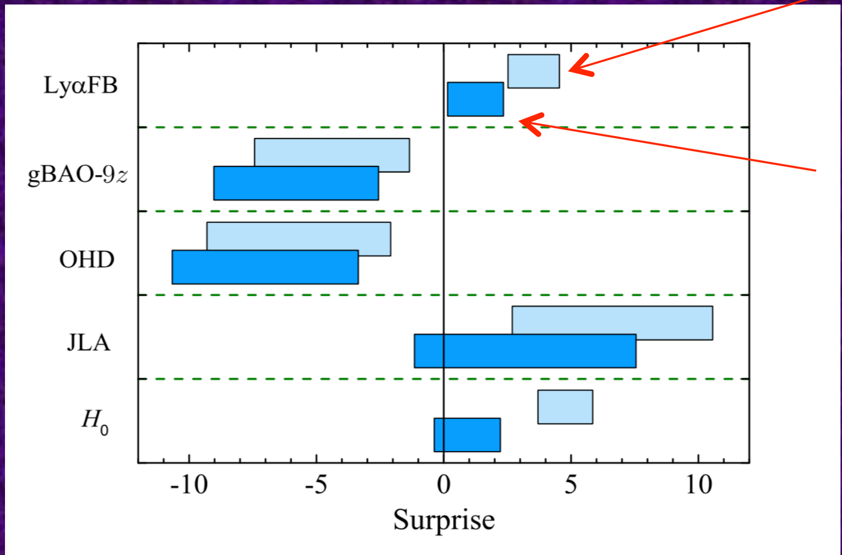
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

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.

Not Yet Statistically Significant to rule our Lambda

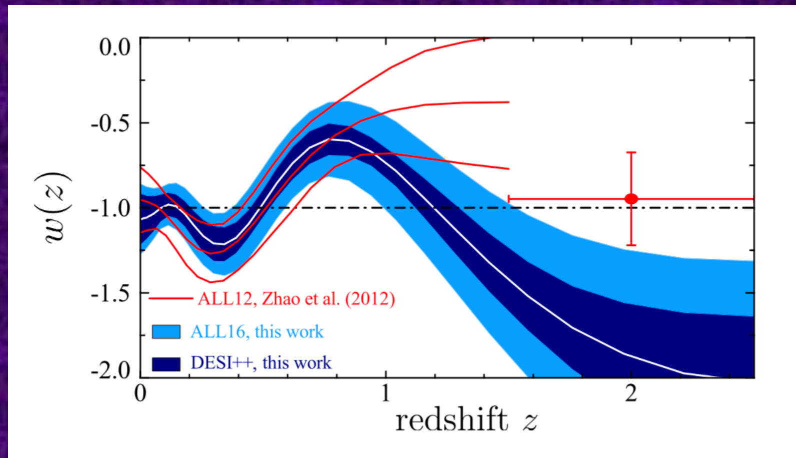
Zhao et al, Nature Astronomy, 2017

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



LCDM

w(z)CDM



	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

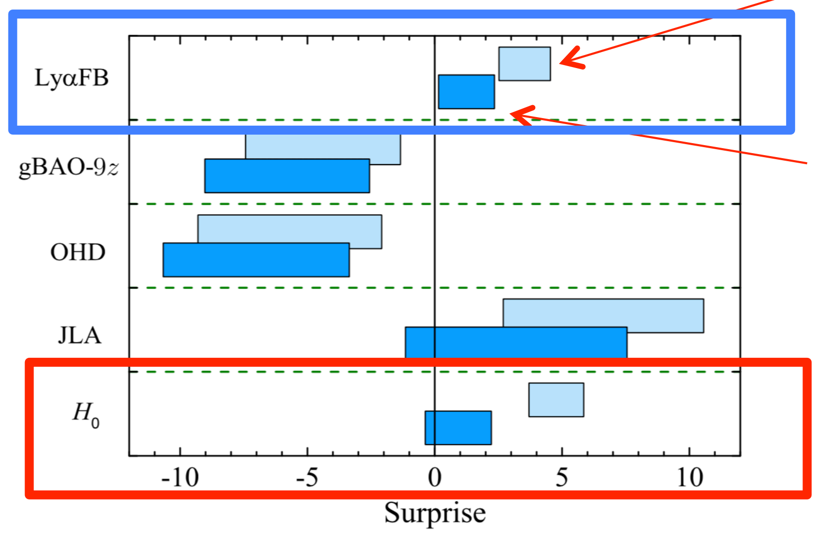
	ALL12	ALL16	DESI++
S/N	2.5σ	3.5σ	6.4σ
ΔAIC	-0.3	-4.3	-24.6
$\Delta\ln E$	-6.7 ± 0.3	-3.3 ± 0.3	11.3 ± 0.3

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.

Not Yet Statistically Significant to rule our Lambda, but data seems to be persistent.

Zhao et al, Nature Astronomy, 2017

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



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.

Bautista et al, [1702.00176]

Found no systematic/mistake in the previous measurement

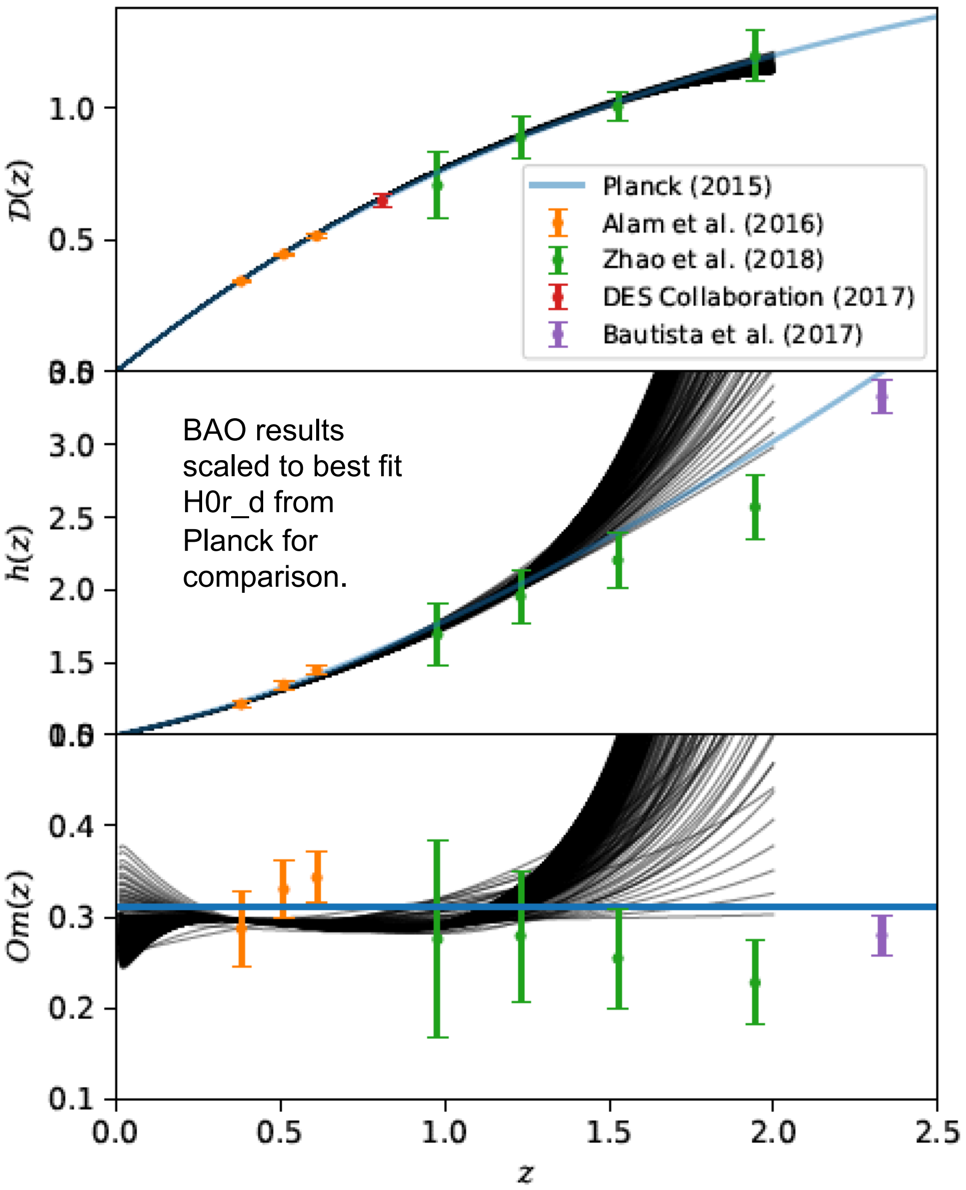
w(z)CDM

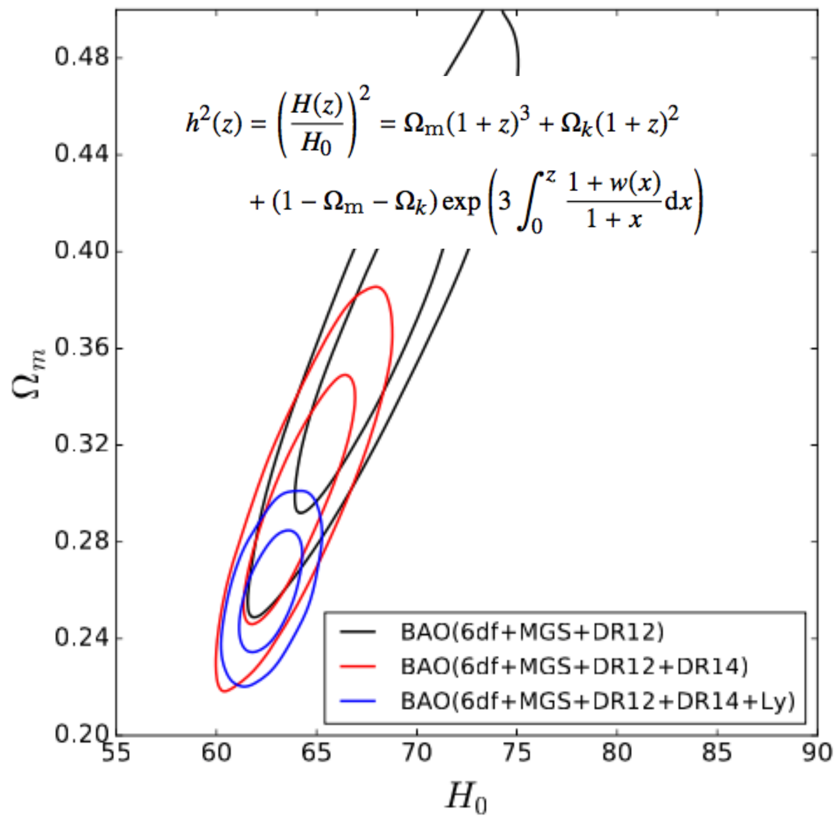
Follin & Knox [1707.01175]
Zhang et al, [1706.07573]

Both agrees with Riess et al 2016 H0 measurement

$\Delta \ln E$	-6.7 ± 0.3	-3.3 ± 0.3	11.3 ± 0.3

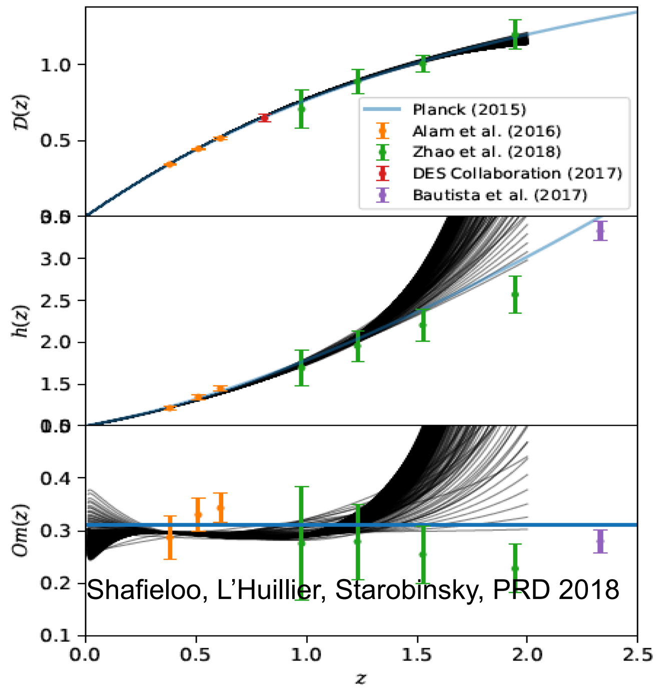
What is exactly going on?

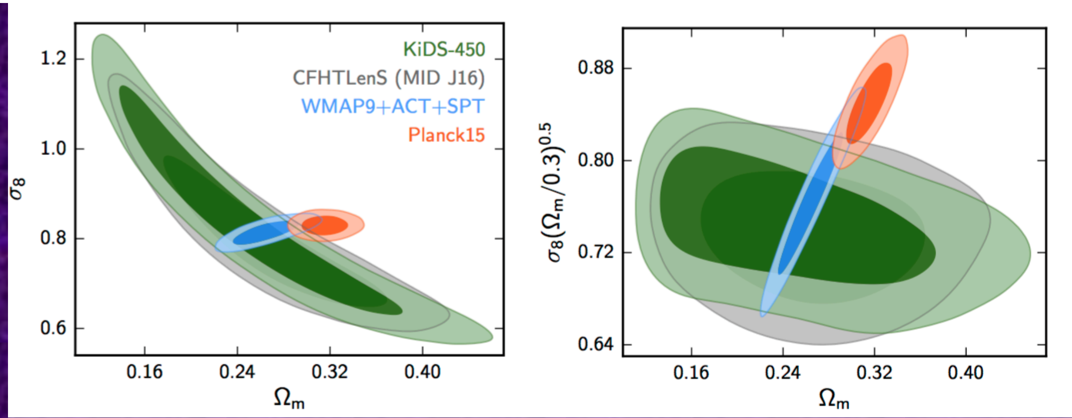




Shafieloo, L'Huillier, Starobinsky, PRD 2018

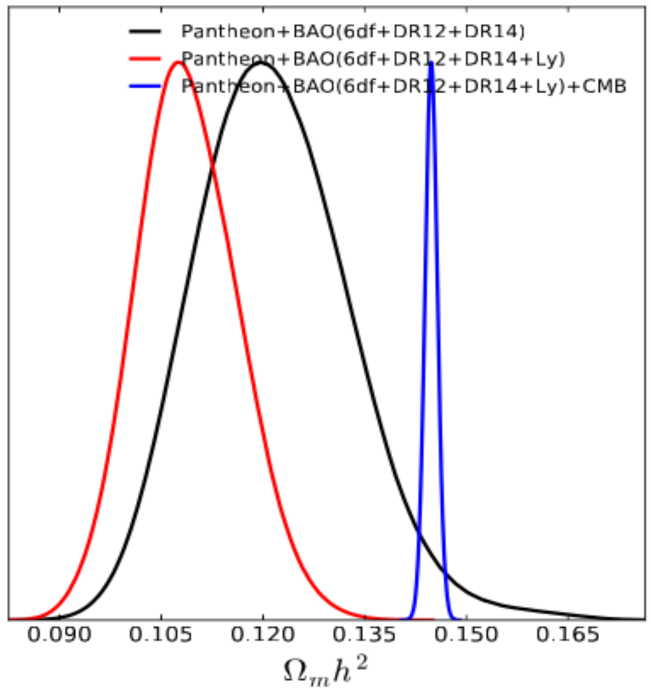
Li, Shafieloo, Sahni, Starobinsky, in prep

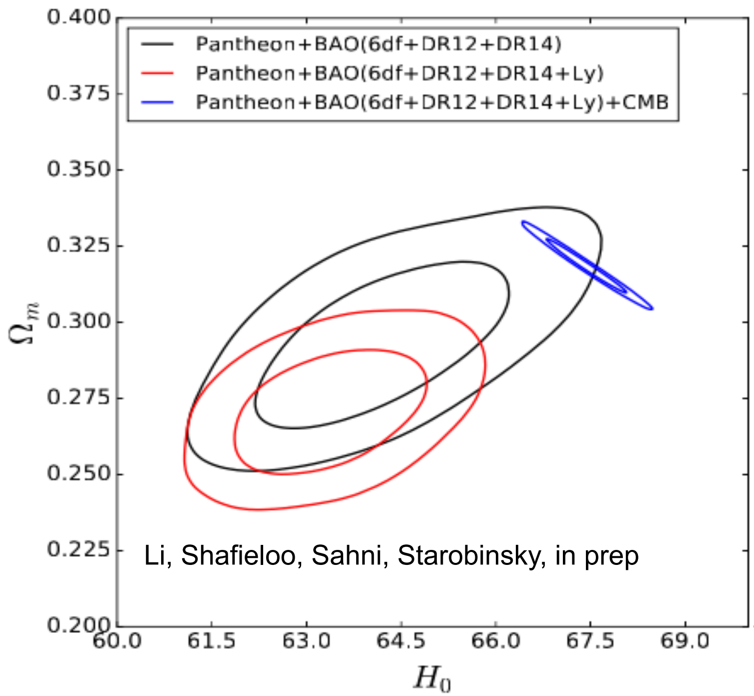


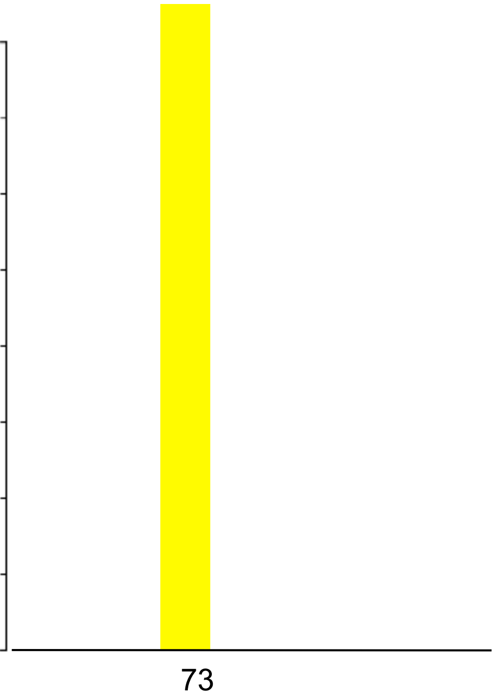


Hildebrandt et al, MNRAS 2017

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







Local H0 constraints

How to resolve the tensions?

Tensions may disappear by themselves if they are due to statistical fluctuations

- With popular pseudo-solutions: 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 stop 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? ***We can try!***

Lets play!

- Lets keep omega_CDM and omega_b equal to their best fit flat LCDM values from Planck : $\omega_{\rm CDM} = \Omega_{\rm CDM} h^2$ $\omega_{\rm b} = \Omega_{\rm b} h^2$

Why?: Height and dept of the CMB angular power spectrum acoustic peaks will remain the same and hence minimal changes at large CMB scales

- Lets assume H0=73.48 and consequently Omega_m=0.259.

Why?: This automatically satisfies local H0 observations and weak lensing constraints by having large H0 and low matter density. It may help BAO as well.

- Task is now to find a form of Primordial Power Spectrum that by having a kernel with above background parameters can result to exactly the same form of the angular power spectrum as given by the best fit Flat LCDM Planck model (No data involved).

Why?: To explore the possibility, looking for possible systematics, theoretical implications .

How?: We use the MRL deconvolution algorithm we developed over the years for the purpose of reconstruction.

Modified Richardson-Lucy Deconvolution

$$C_\ell = \sum_i G_{\ell k_i} P_{k_i}$$

- ➔ Iterative algorithm.
- ➔ Not sensitive to the initial guess.
- ➔ Enforce positivity of P(k).

[$G(l,k)$ is positive definite and C_l is positive]

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_{\ell=2}^{\ell=900} \tilde{G}_{\ell k}^{\mathrm{un-binned}} \left\{ \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}) \right] \right\}_{\mathrm{un-binned}} + \sum_{\ell_{\mathrm{binned}} > 900} \tilde{G}_{\ell k}^{\mathrm{binned}} \left\{ \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \tanh^2 \left[\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{\sigma_\ell^{\mathrm{D}}} \right]^2 \right\}_{\mathrm{binned}} \right], \quad (1)$$

$$Q_\ell = \sum_{\ell'} (C_{\ell'}^{\mathrm{D}} - C_{\ell'}^{\mathrm{T}(i)}) COV^{-1}(\ell, \ell'),$$

Shafieloo & Souradeep PRD 2004 ;
Shafieloo et al, PRD 2007;
Shafieloo & Souradeep, PRD 2008;
Nicholson & Contaldi JCAP 2009
Hamann, Shafieloo & Souradeep JCAP 2010
Hazra, Shafieloo & Souradeep PRD 2013
Hazra, Shafieloo & Souradeep JCAP 2013
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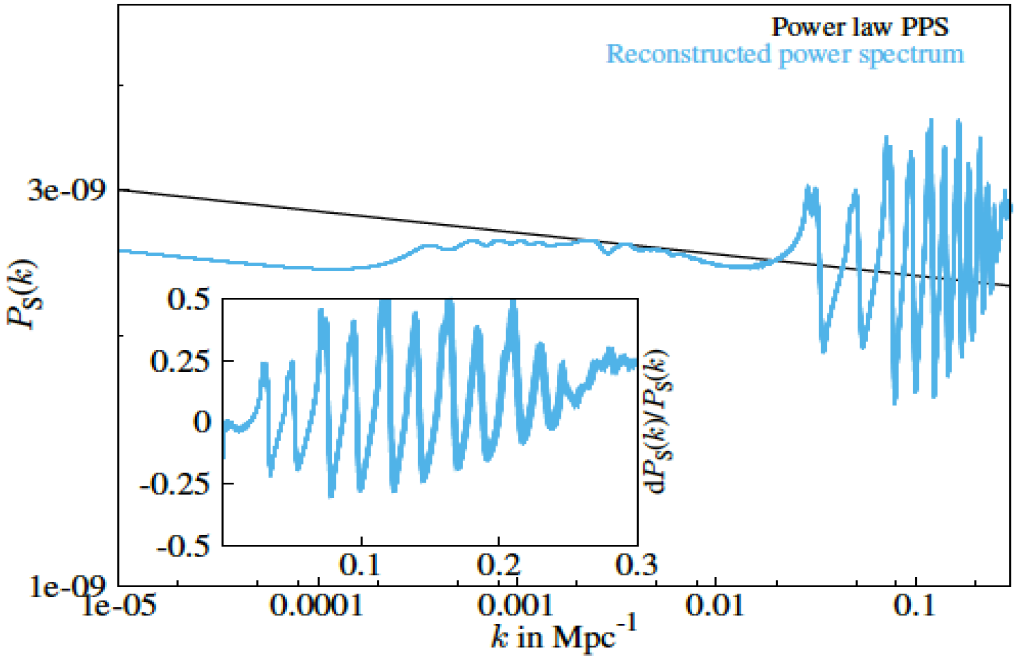
Hazra, Shafieloo & Souradeep JCAP 2015

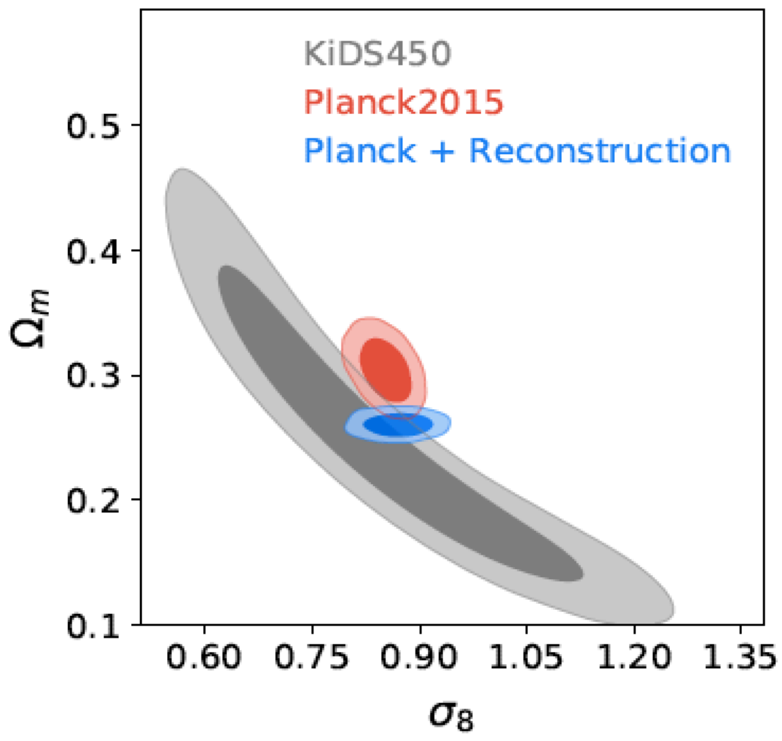
Hazra, Shafieloo, Souradeep, arXiv:1810.08110

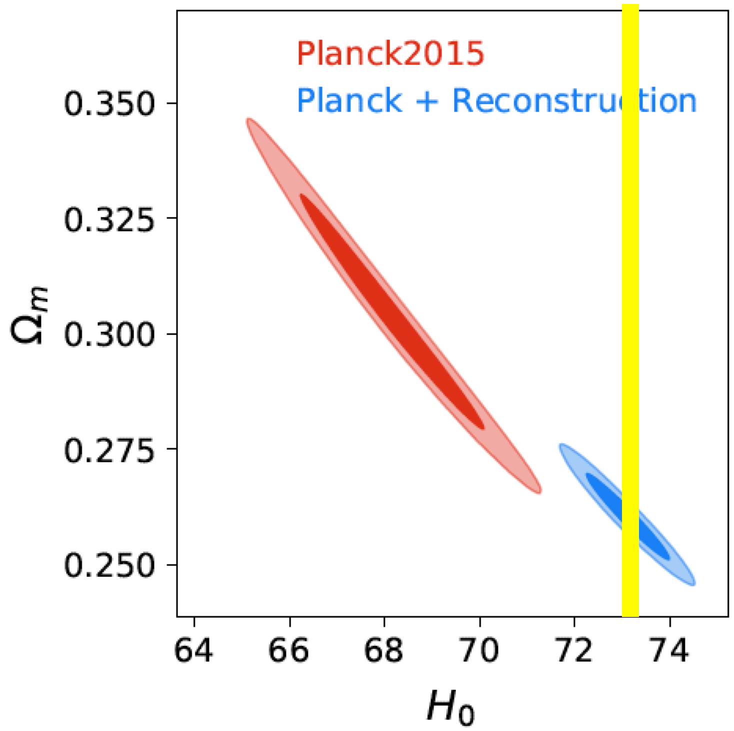


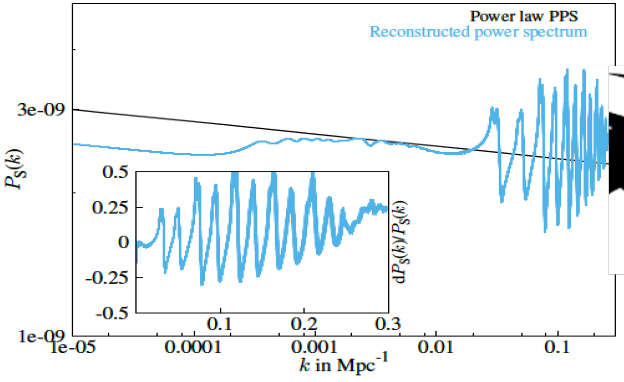
Hazra, Shafieloo, Souradeep, arXiv:1810.08110

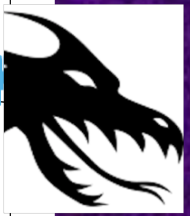
It Is POSSIBLE!

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









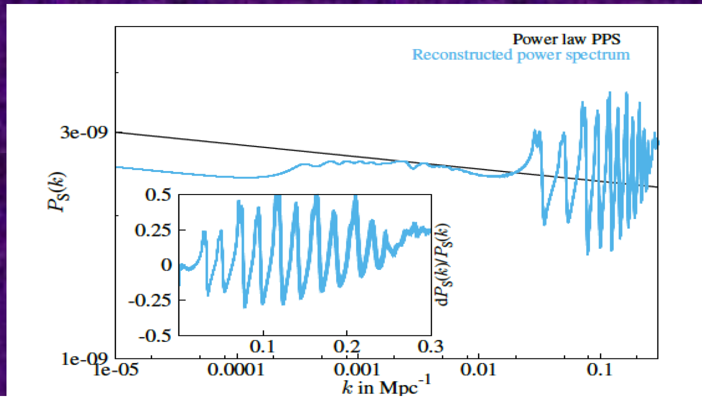
Issues:

1. it appears to be unnatural to generate the complex form of the reconstructed PPS within an inflationary scenario without extreme fine tuning. However, we do not provide any conclusive reason to close the possibility of a physical early Universe explanation.
2. Using polarization data it should be possible to validate further the possibility of the reconstructed form of the PPS. Likewise, using polarization data we might be able to look for a more optimized form of the PPS to remove tensions from different observations.
3. A wider exploration of the underlying parameter space of the cosmological model would be essential to reveal potential routes to ameliorate the disagreements in cosmological parameters inferred.
4. Need for a comprehensive iterative approach to derive observational constraints and confront vs theoretical/phenomenological models.
5. Lensing templates! Are they reliable?

Issues:

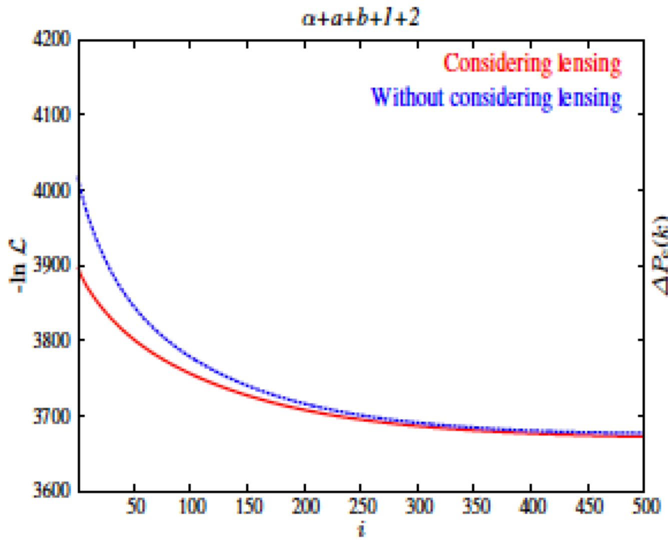
5. The features at high k values are very similar to the features we reconstructed previously when we did not consider CMB lensing (trying to project the effect on the form of the PPS). Can lensing templates play a key role?

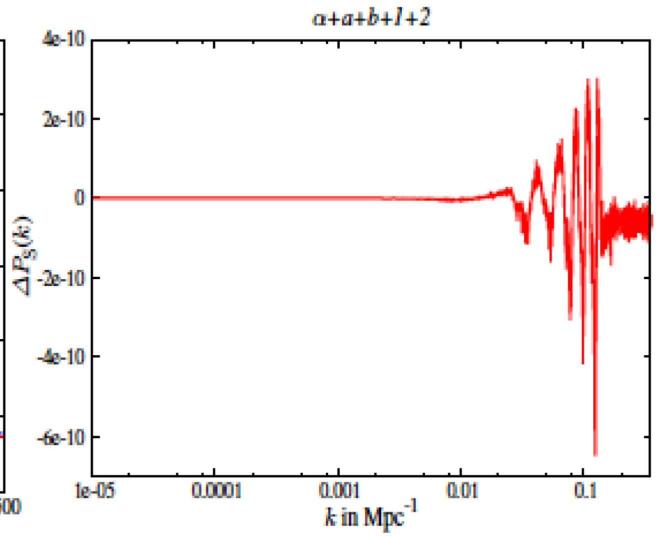
Also see: Kable, Addison, Bennett, arXiv:1809.03983

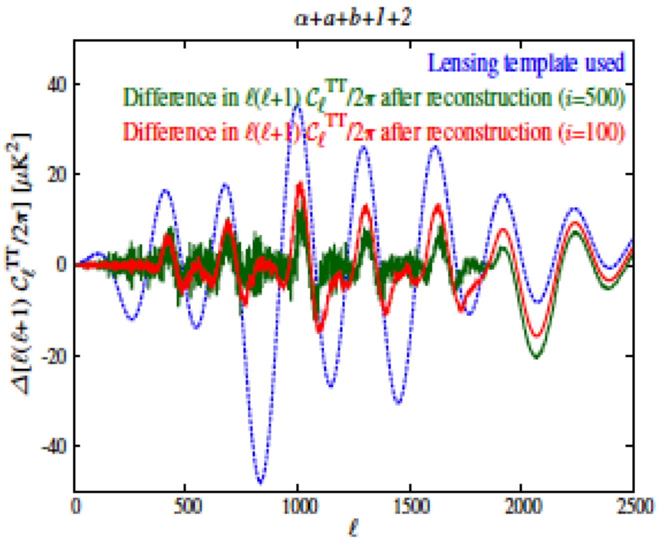


Hazra, Shafieloo, Souradeep, arXiv:1810.08110

Hazra, Shafieloo, Souradeep, JCAP 2014







Conclusion

- The current standard model of cosmology seems to work fine but this does not mean all the other models are wrong.
- ***Combination of different cosmological data hints towards some tension with LCDM model. If future data continues the current trend, we may have some exciting times ahead!***
- ***It is possible to put all the blame on PPS but we need suitable EU scenario to explain reconstructed features.***
- ***High multiple CMB lensing: Suspicious (no strong claim though, yet!)***
- 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, SKA, LSST, WFIRST etc) will make it clear about the status of the concordance model.