Status of the Standard Model of Cosmology

Arman Shafieloo

Korea Astronomy and Space Science Institute (KASI)

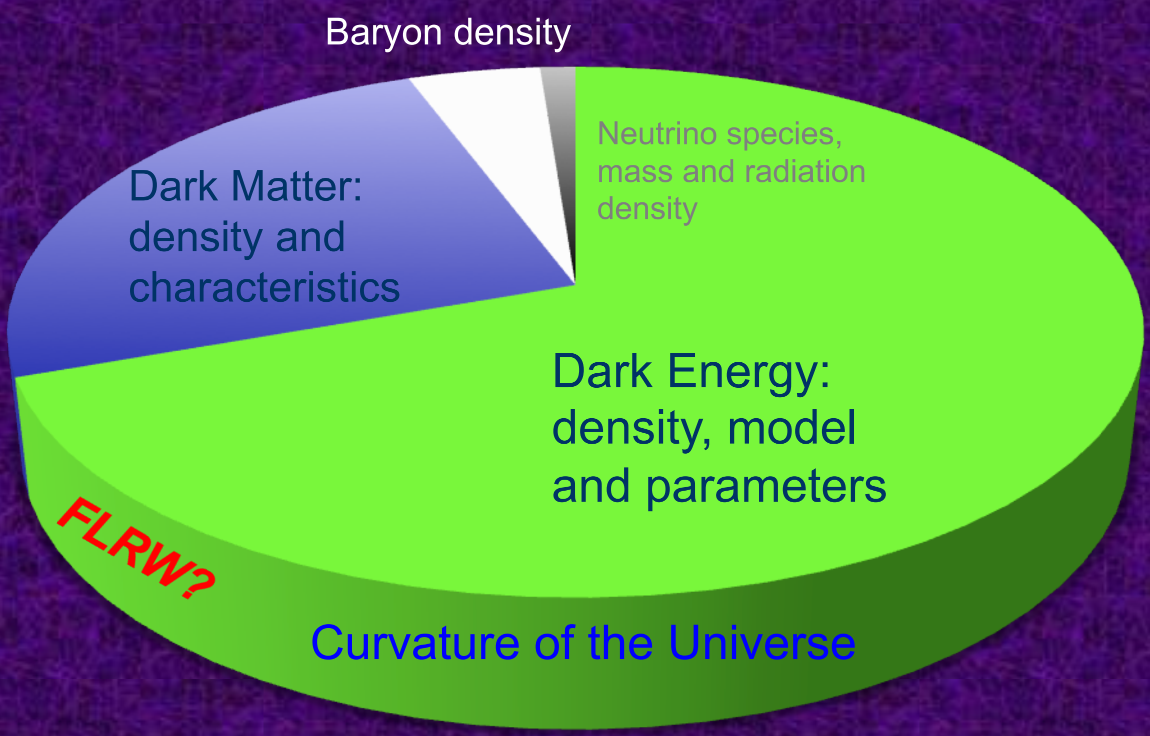
University of Science and Technology (UST)

2 – 5 February 2022

Second Chennai Symposium on Gravitation and Cosmology

Era of Precision Cosmology

Combining theoretical works with new measurements and using statistical techniques to place sharp constraints on cosmological models and their parameters.



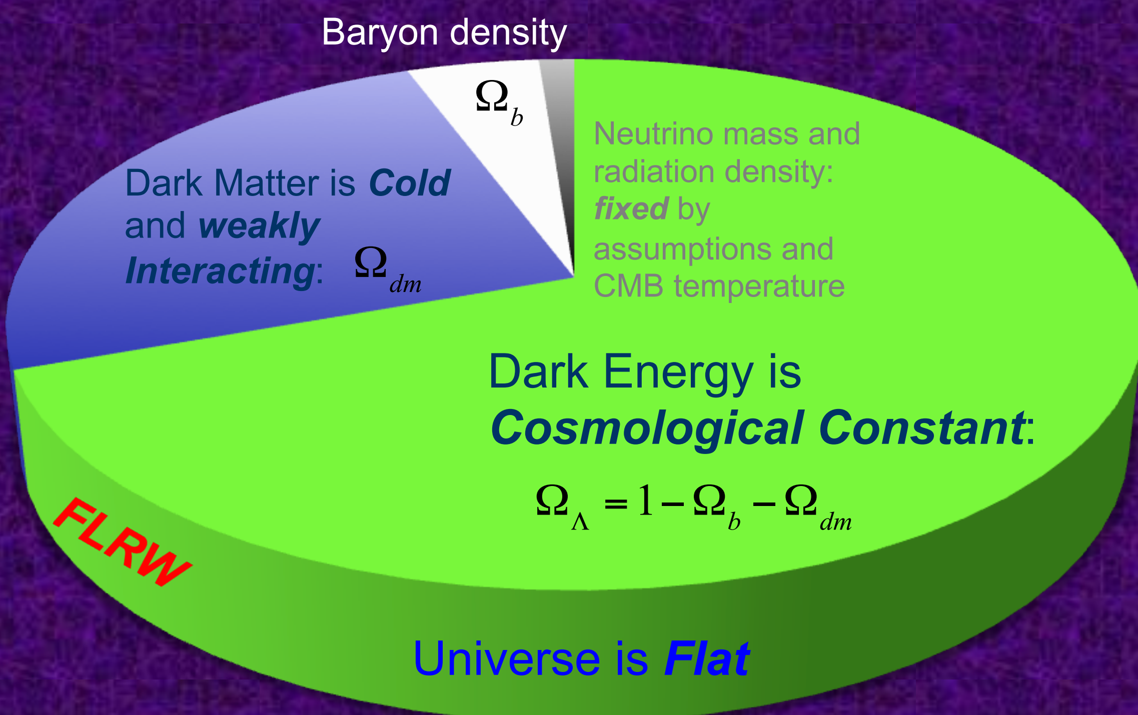
Initial Conditions:
Form of the Primordial Spectrum and Model of Inflation and its Parameters

Epoch of reionization

Hubble Parameter and the Rate of Expansion

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

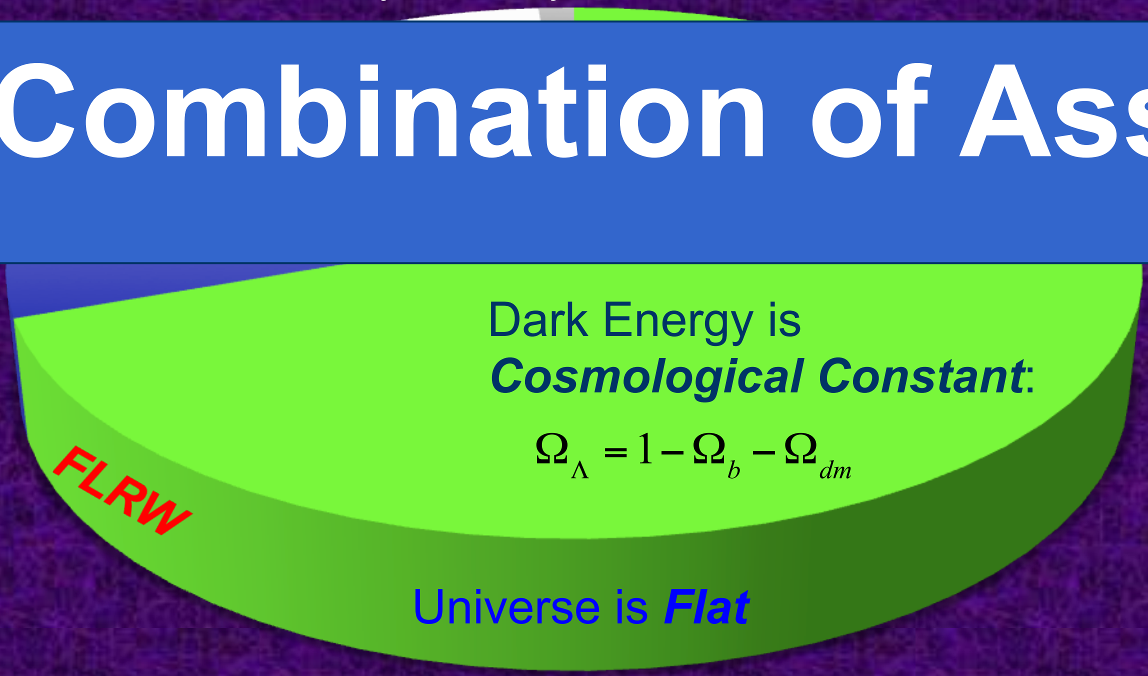
Hubble Parameter and the Rate of Expansion

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

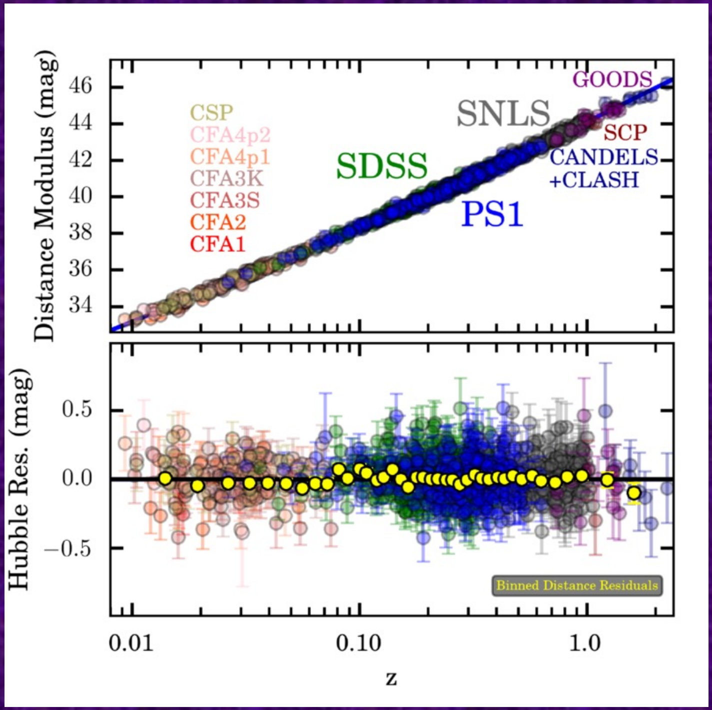
H_0

Standard Model in 2022

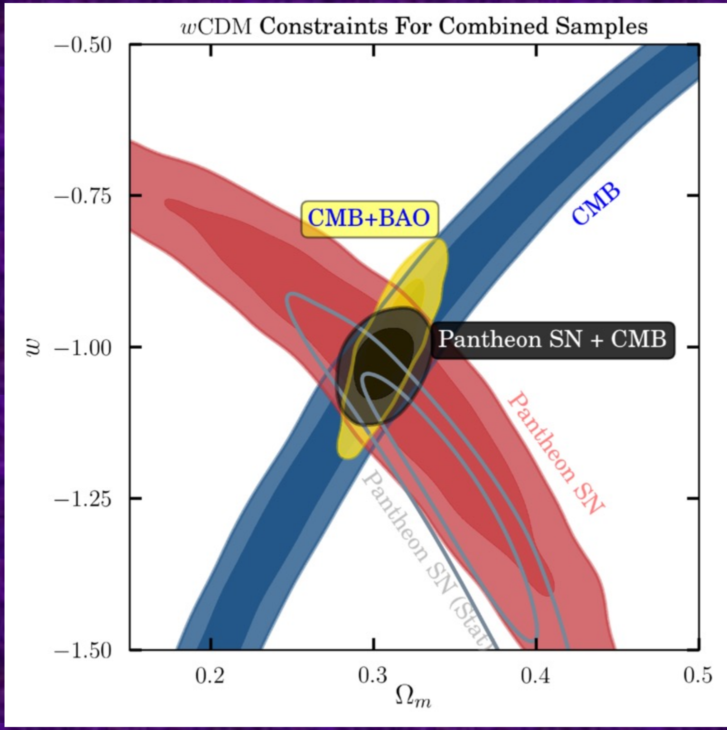
SN Ia

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



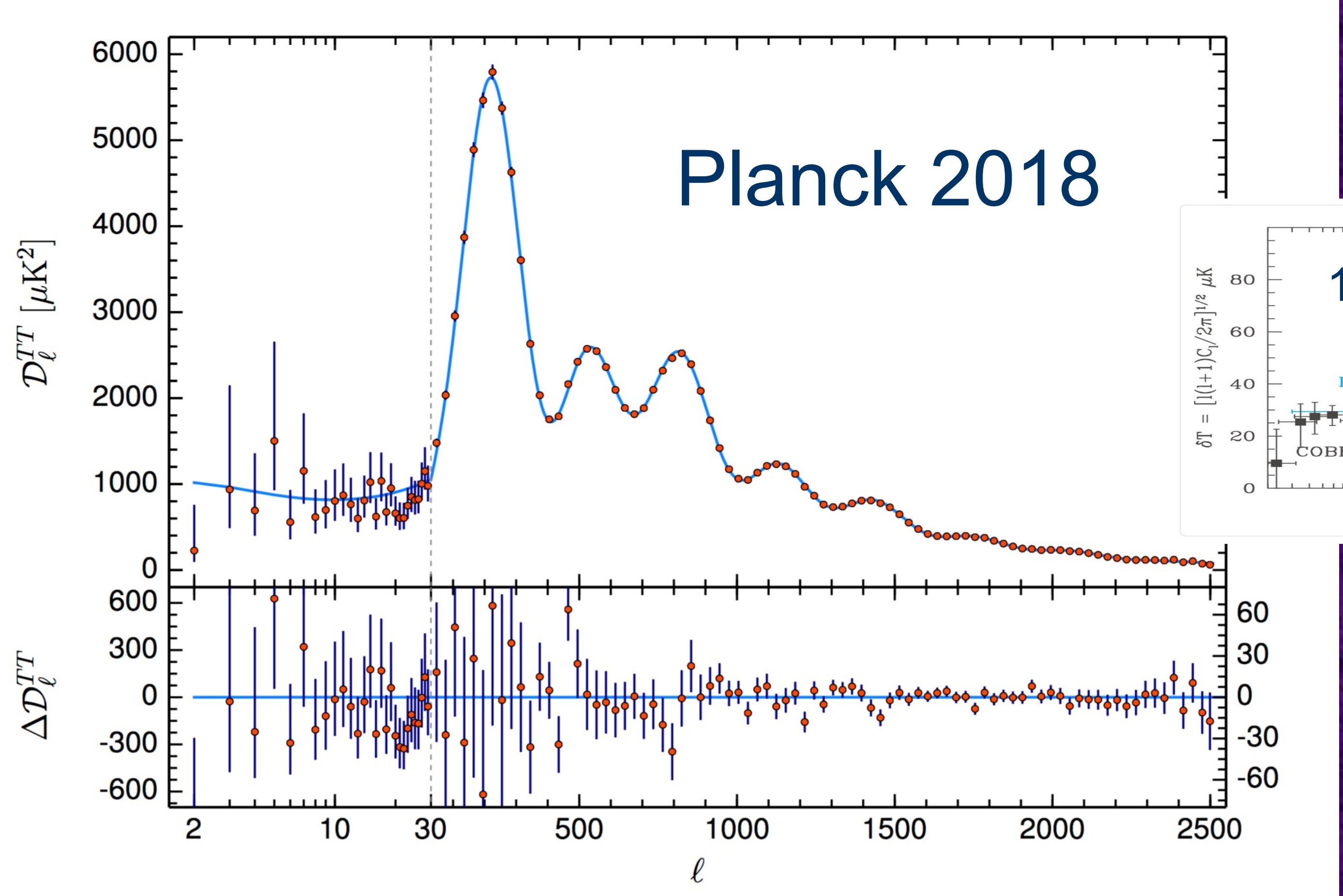
Pantheon Compilation
Scolnic et al. (2018)

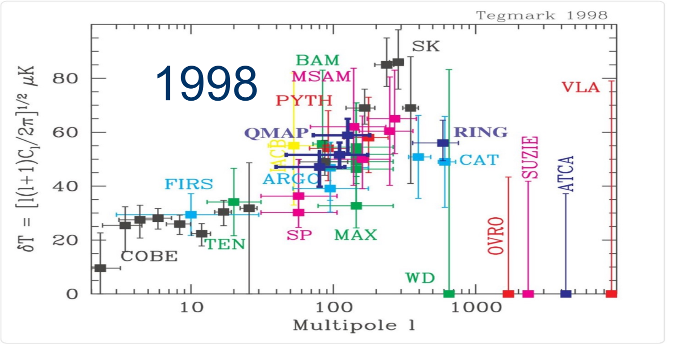
Standard Model in 2022

CMB

20 years after discovery of the acceleration of the universe:

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





Standard Model in 2022

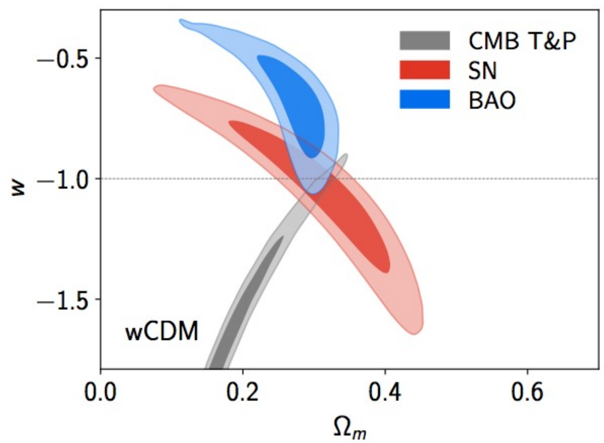
LSS

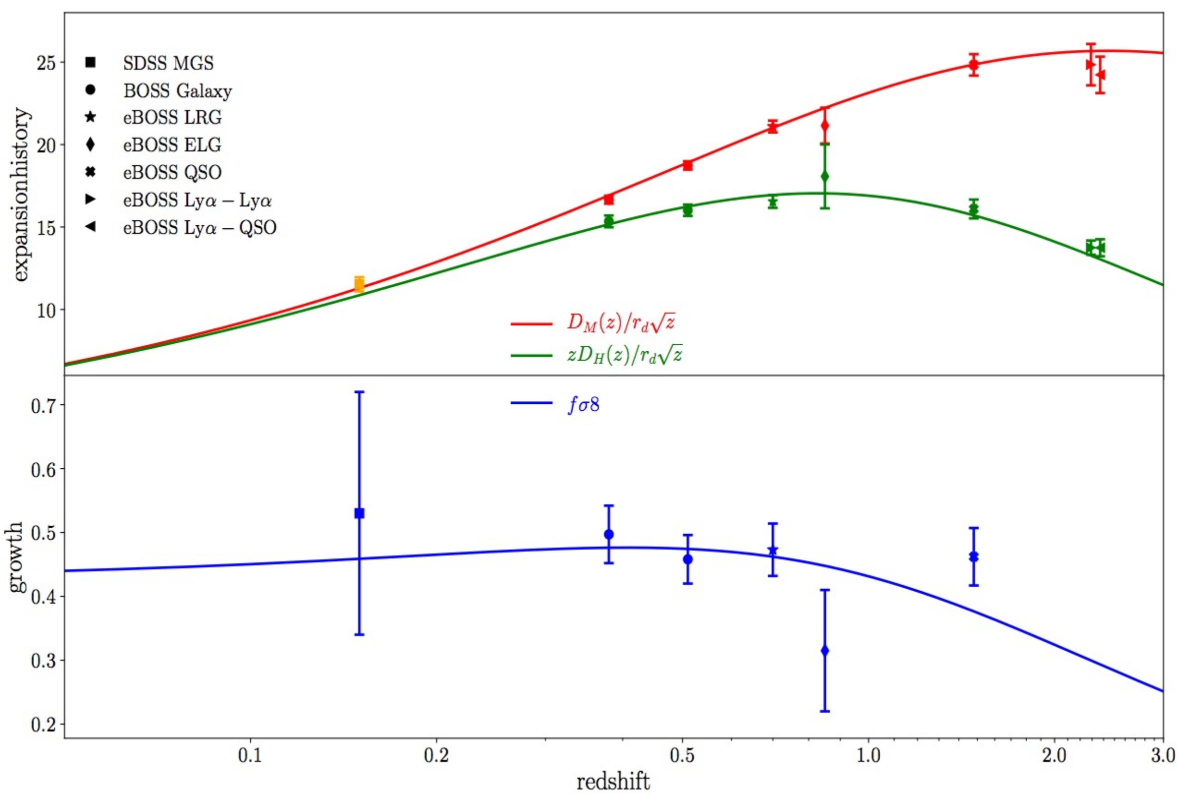
20 years after discovery of the acceleration of the universe:

Large Scale Structure data is consistent with the standard model including Lambda dark energy and GR.

SDSS IV - eBOSS Final Cosmology Results

arXiv:2007.08991

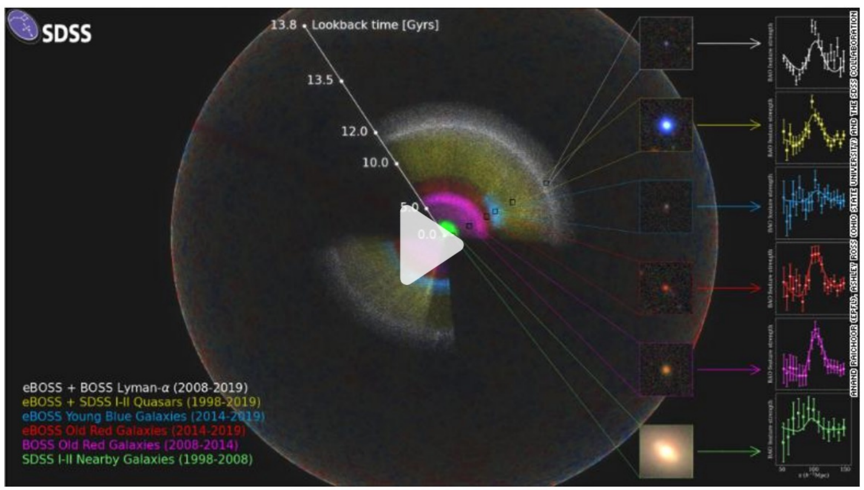




SDSS IV: Largest 3D Map of the Universe Ever Created

11 billion years of history in one map: Astrophysicists reveal largest 3D model of the universe ever created

By **Joshua Berlinger** and **Jessie Yeung**, CNN
Updated 1748 GMT (0148 HKT) July 22, 2020

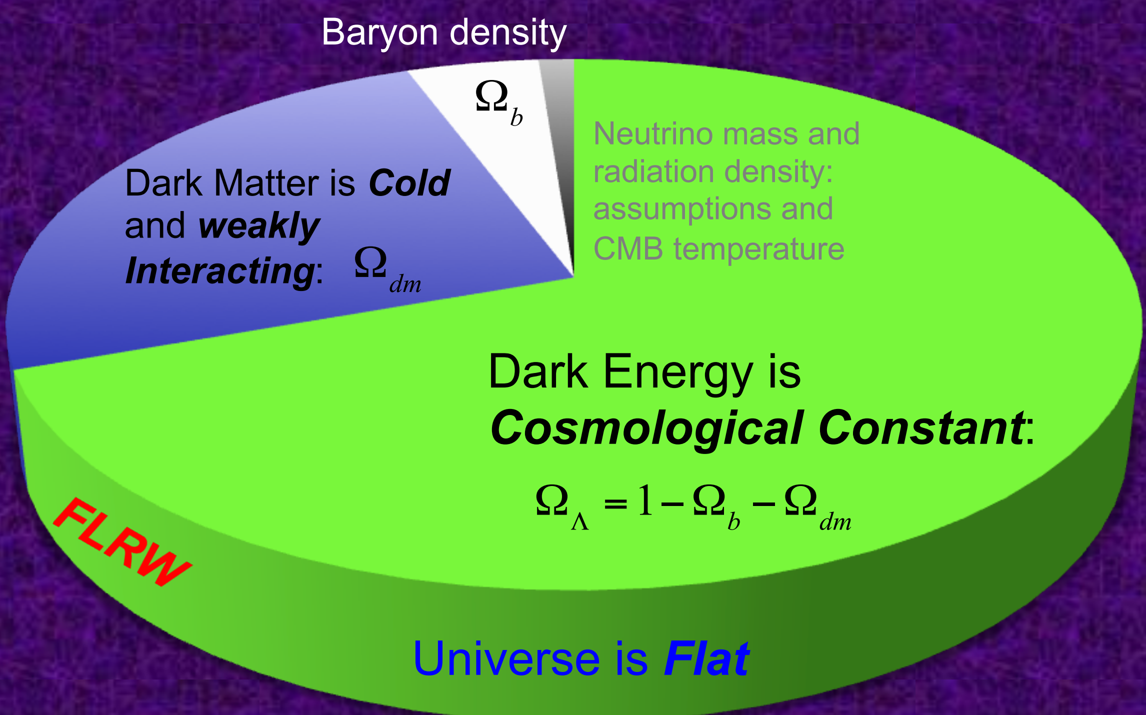


See a 3D model of the universe 01:17

(CNN) — A global consortium of astrophysicists have created the world's largest three-dimensional map of the universe, a project 20 years in the making that researchers say helps better explain the history of the cosmos.

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

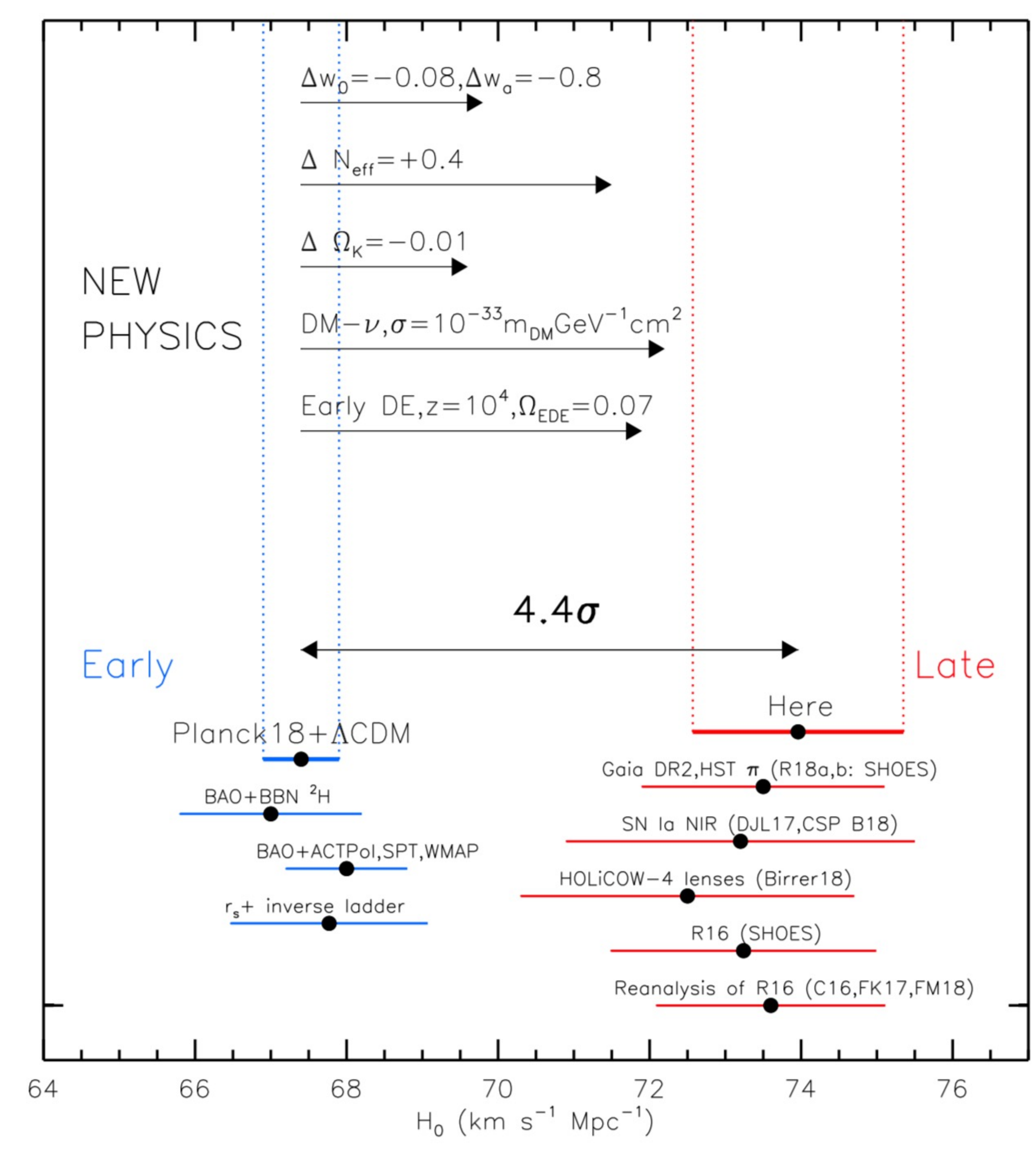
Hubble Parameter and the Rate of Expansion

H_0

Persistent Tensions in the Standard Model

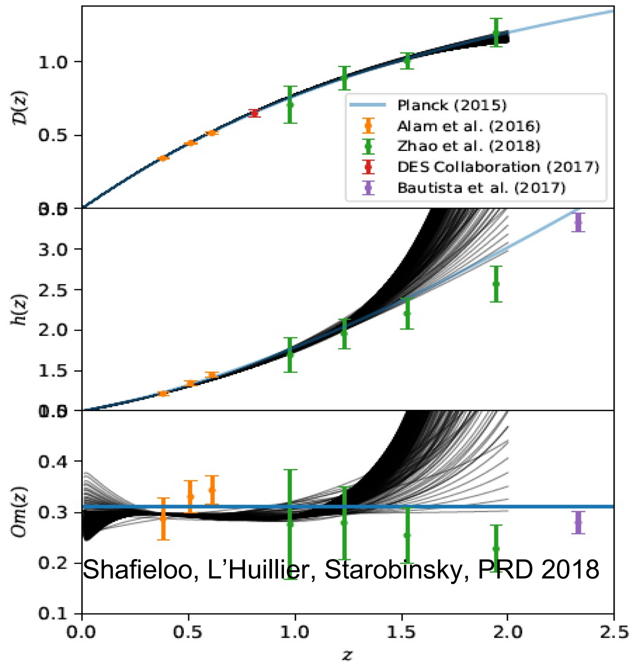
Local estimation of the Hubble constant seems to be substantially higher than the expected values fitting the standard LCDM model to CMB or LSS.

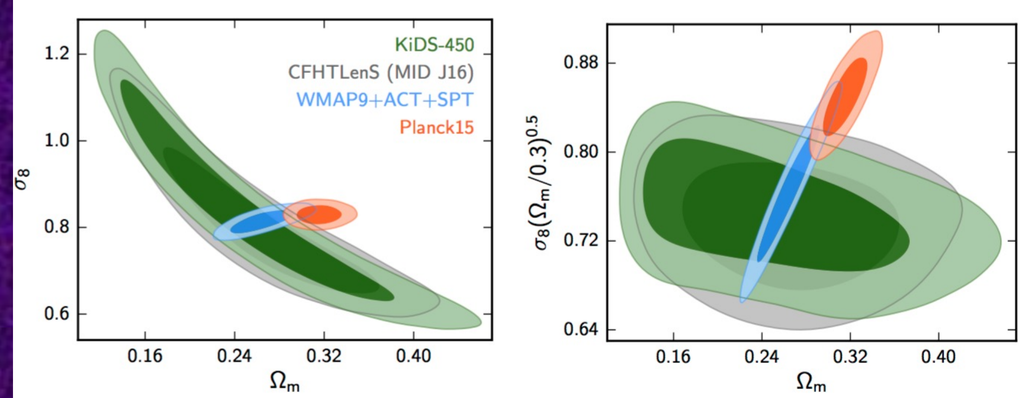
67 or 74?



Tensions in the Standard Model

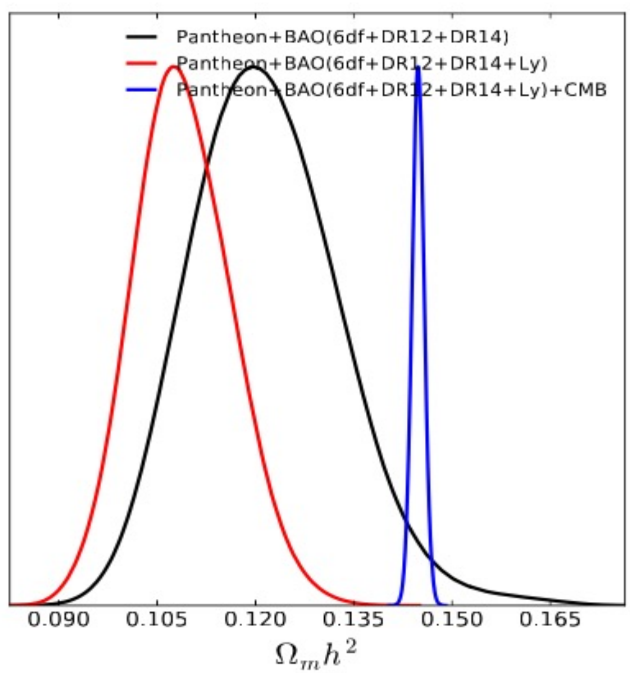
Riess et al, arXiv:1903.07603

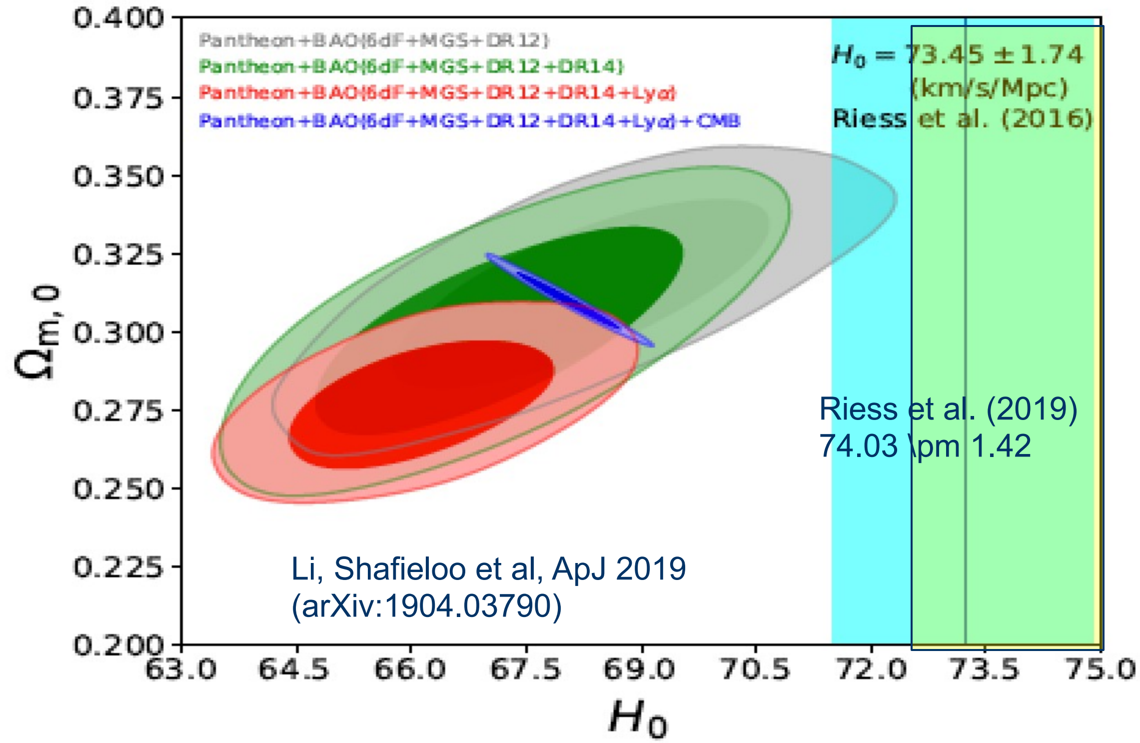




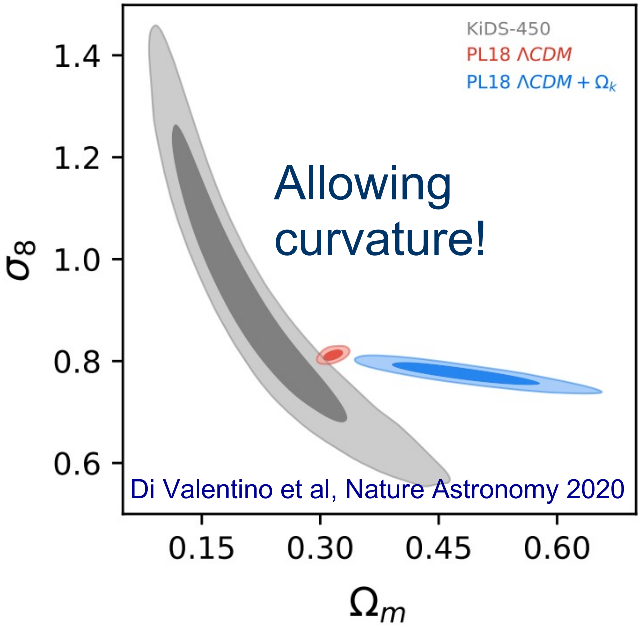
Hildebrandt et al, MNRAS 2017

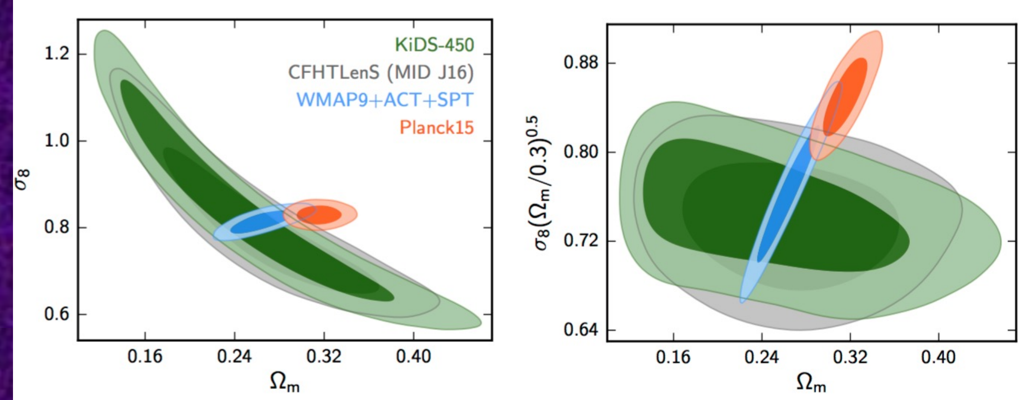
It is not only about H0 and CMB. Low H(z)r_d is suggested by BAO and low matter density by WL.





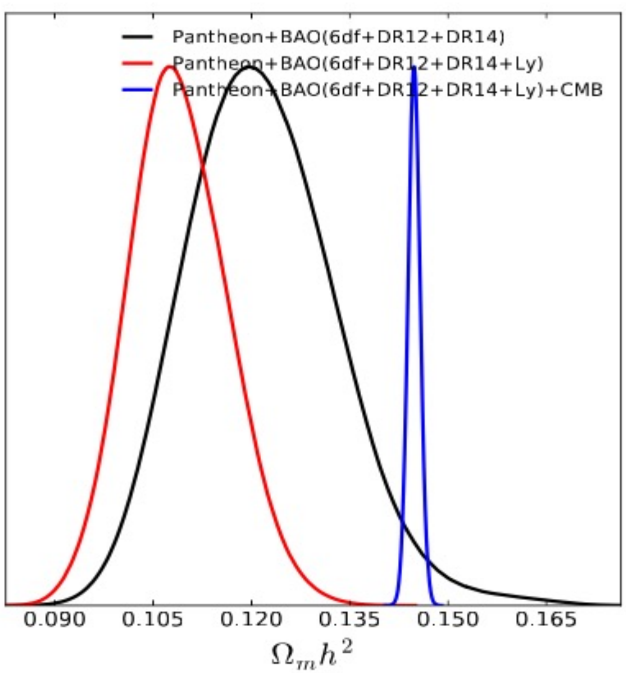
Li, Shafieloo et al, ApJ 2019 (arXiv:1904.03790)

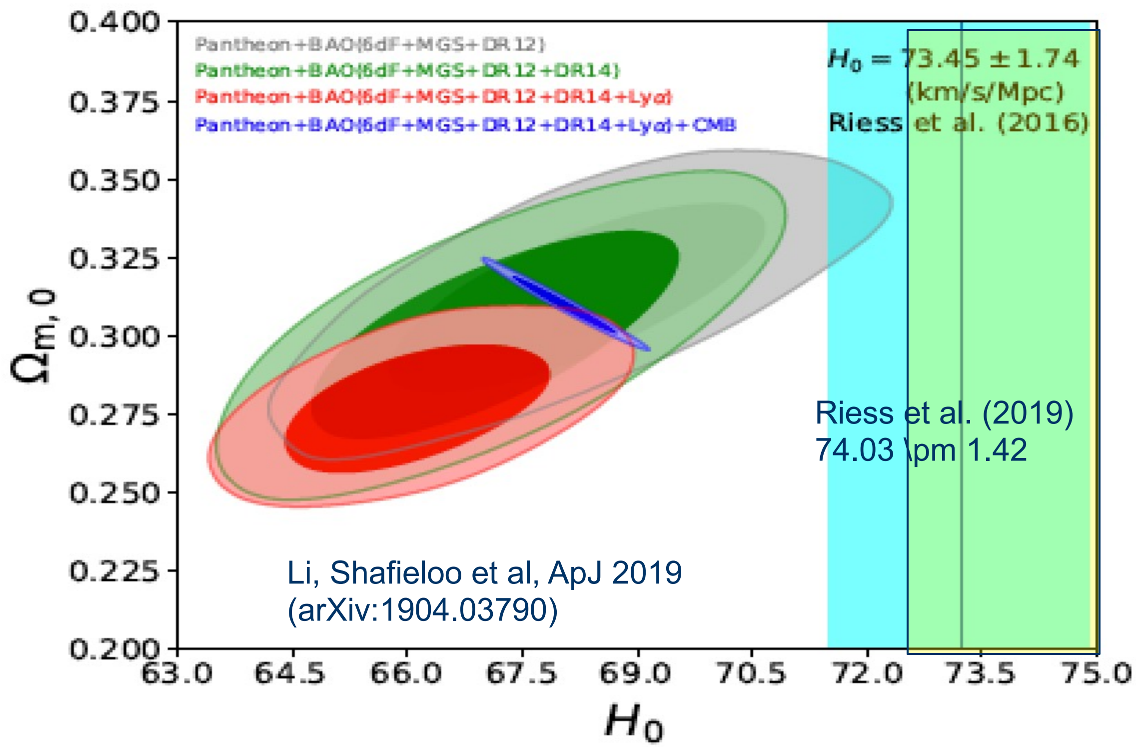




Hildebrandt et al, MNRAS 2017

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





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.
- Finding tension among different independent data assuming the standard model (making sure there is no systematic).
- Introducing theoretical/phenomenological models that can explain the data better *(statistically significant)* than the standard model.

2014

Omh2

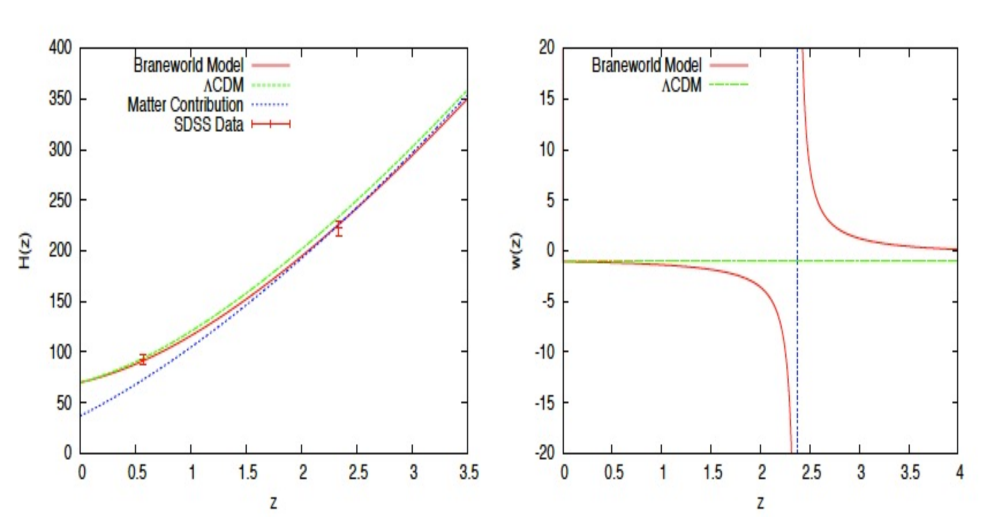
Important discovery if no systematic in the SDSS Quasar BAO data

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 Flat 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

2021 Omh2

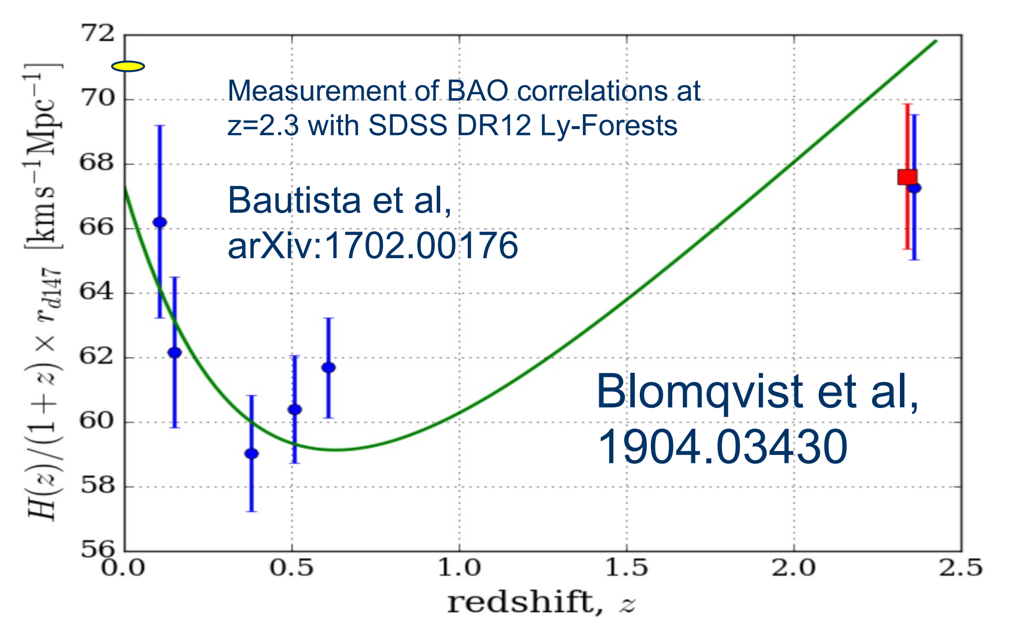
No systematic yet found,

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

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

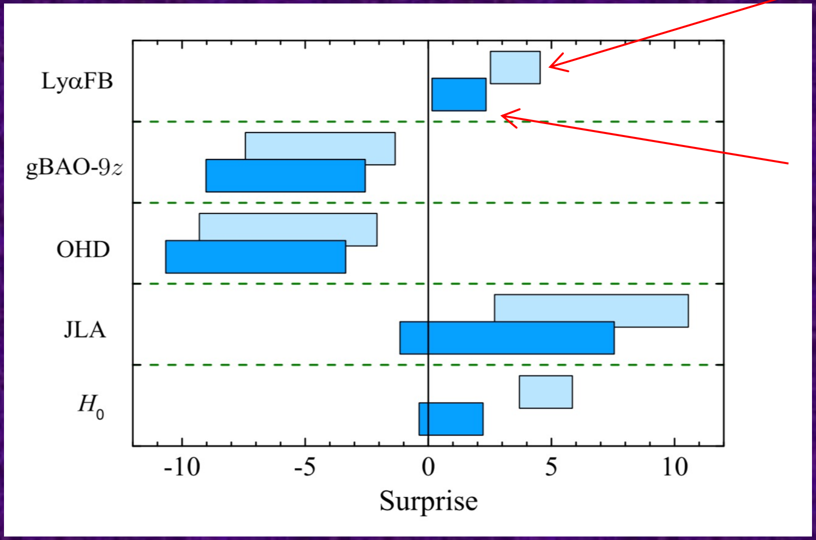
BAO+H0

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]	

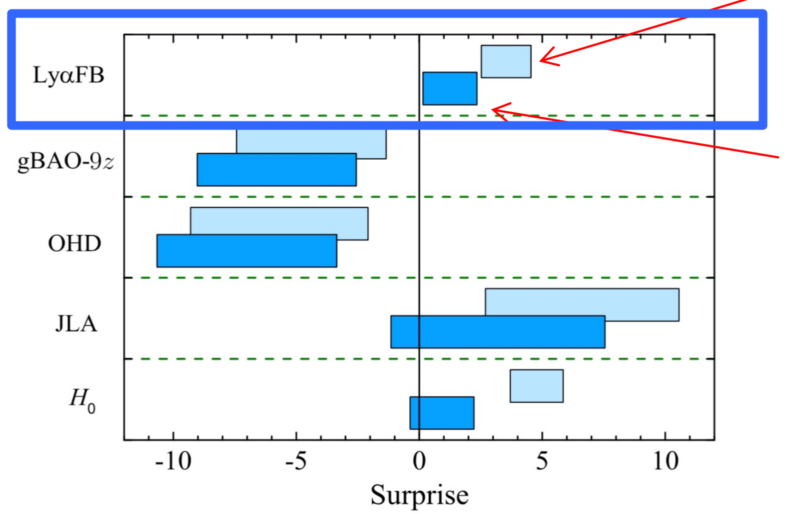
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

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]	

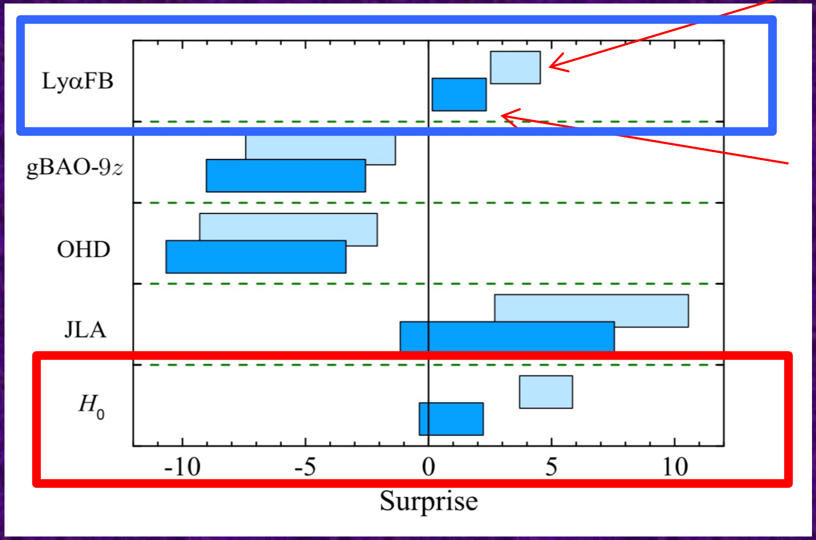
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

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

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



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

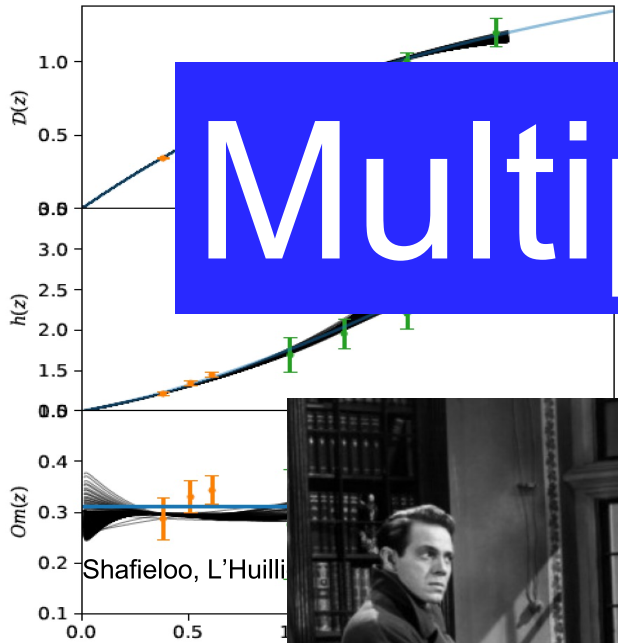
Found no systematic/mistake in the previous measurement

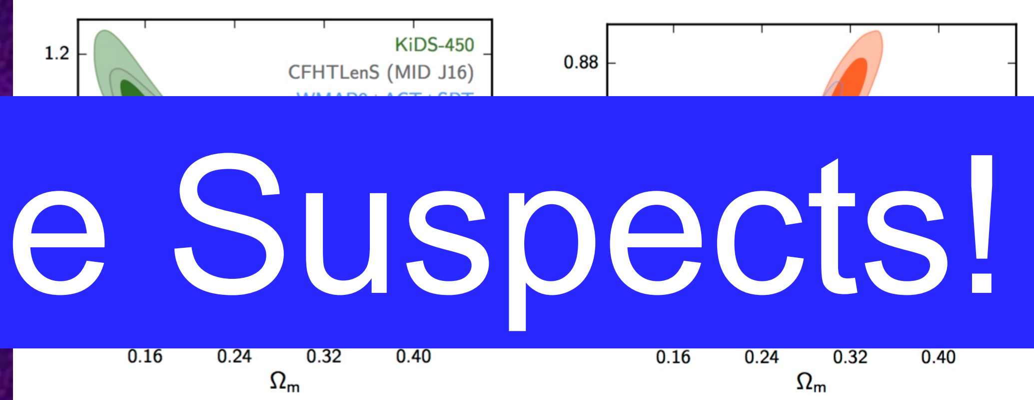
Follin & Knox [1707.01175]
Zhang et al, [1706.07573]

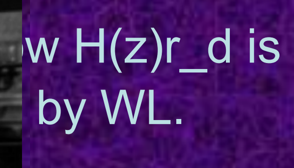
Both agrees with Riess et al 2016 H0 measurement
New Ho measurement Riess et al 2019 ***(situation has become worse)***

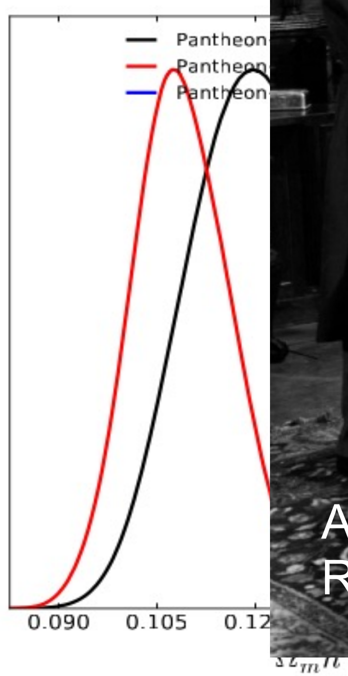
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

Multiple Suspects!









And Then There Were None (1945),
Rene Clair [Based on a novel by Agatha Christie]

How to resolve the tensions?

- Statistical fluctuations *(probably not anymore, some tensions are at high significance)*

- Systematic in one or some of the data? [Highly possible considering complications of the tensions that all cannot be resolved by minimal modifications.]

  (Li, Shafieloo, Sahni, Starobinsky, ApJ 2019)

- Extended models and/or new physics

  Caution: extended models with more degrees of freedom result to 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!] *If current observations are reliable, most of these models will be ruled out by future observations. Central values matter!*

(Present)

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

(Present)

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

Does LCDM need modification? Which part?

(Present)

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)

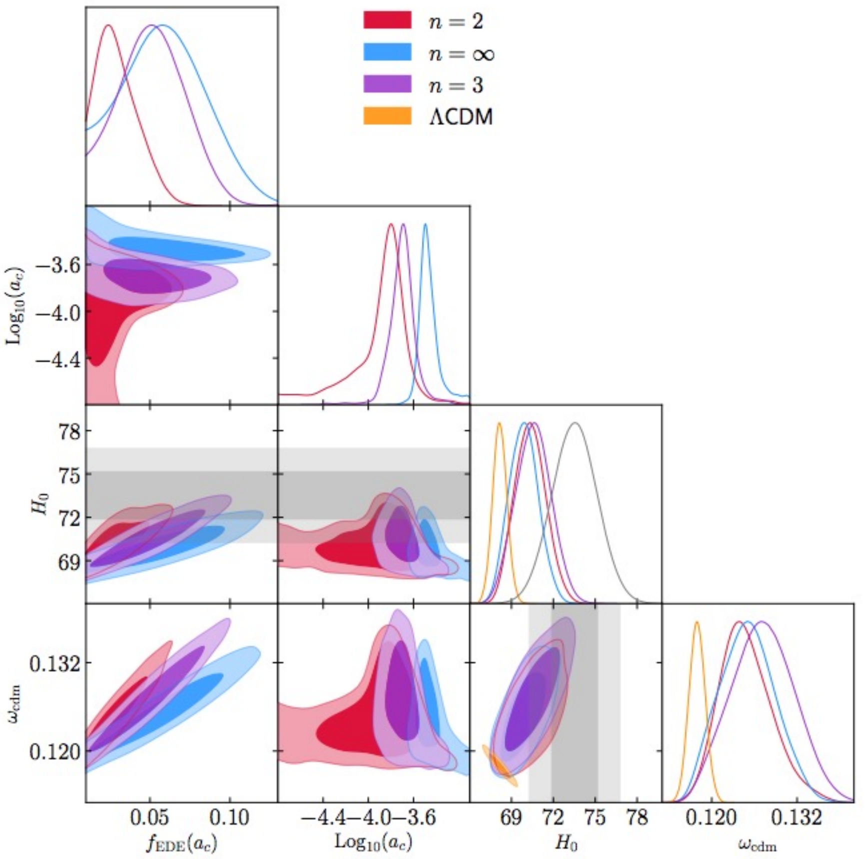
Dark Matter is cold

All within framework of FLRW

Example of an extended model:

Early Dark Energy

$$r_{\rm d} = \frac{c}{\sqrt{3}} \int_0^{1/(1+z_{\rm drag})} \frac{{\rm d}a}{a^2 H(a) \sqrt{1 + \frac{3\Omega_{\rm b}}{4\Omega_{\rm r}} a}}$$



Decreasing r_d by having substantial early dark energy:

Allows having similar H0r_d with higher H0

[few extra dof]

$$\Omega_\varphi(a) = \frac{2\Omega_\varphi(a_c)}{(a/a_c)^{3(w_n+1)} + 1},$$

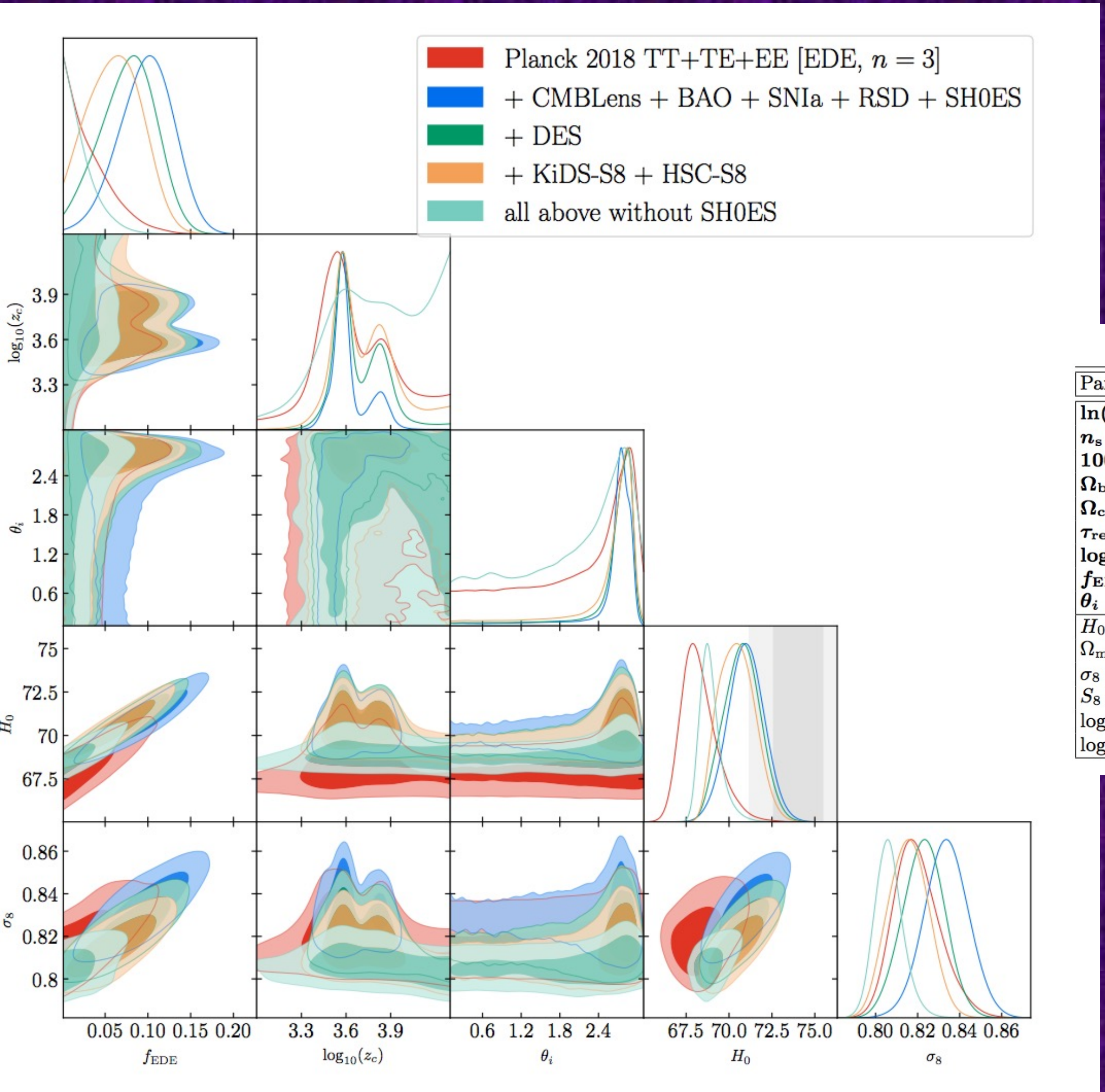
$$w_\varphi(z) = \frac{1 + w_n}{1 + (a_c/a)^{3(1+w_n)}} - 1.$$

$$w_n = (n-1)/(n+1)$$

Poulin et al, Phys. Rev. Lett 2019

Example of an extended model:

Early Dark Energy



Tension is not really resolved.

Constraints from *Planck* 2018 data only: TT+TE+EE

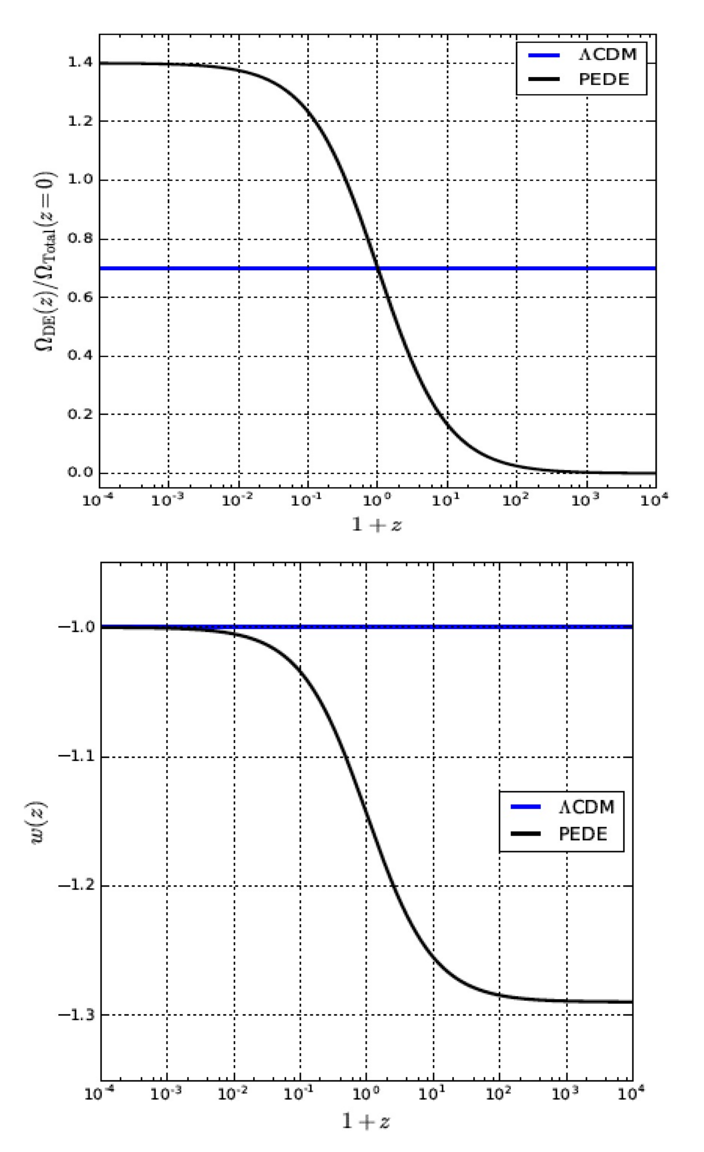
Parameter	ΛCDM	EDE $(n = 3)$
$\ln(10^{10} A_s)$	$3.044\,(3.055)\ \pm 0.016$	$3.051\,(3.056)\ \pm 0.017$
n_s	$0.9645\,(0.9659)\ \pm 0.0043$	$0.9702\,(0.9769)^{+0.0071}_{-0.0069}$
$100\theta_s$	$1.04185\,(1.04200)\ \pm 0.00029$	$1.04164\,(1.04168)\ \pm 0.00034$
$\Omega_b h^2$	$0.02235\,(0.02244)\ \pm 0.00015$	$0.02250\,(0.02250)\ \pm 0.00020$
$\Omega_c h^2$	$0.1202\,(0.1201)\ \pm 0.0013$	$0.1234\,(0.1268)^{+0.0031}_{-0.0030}$
τ_{reio}	$0.0541\,(0.0587)\ \pm 0.0076$	$0.0549\,(0.0539)\ \pm 0.0078$
$\log_{10}(z_c)$	–	$3.66\,(3.75)^{+0.28}_{-0.24}$
f_{EDE}	–	$< 0.087\,(0.068)$
θ_i	–	$> 0.36\,(2.96)$
H_0 [km/s/Mpc]	$67.29\,(67.44)\ \pm 0.59$	$68.29\,(69.13)^{+1.02}_{-1.00}$
Ω_m	$0.3162\,(0.3147)\ \pm 0.0083$	$0.3145\,(0.3138)\ \pm 0.0086$
σ_8	$0.8114\,(0.8156)\ \pm 0.0073$	$0.8198\,(0.8280)^{+0.0109}_{-0.0107}$
S_8	$0.8331\,(0.8355)\ \pm 0.0159$	$0.8393\,(0.8468)\ \pm 0.0173$
$\log_{10}(f/\text{eV})$	–	$26.57\,(26.36)^{+0.39}_{-0.36}$
$\log_{10}(m/\text{eV})$	–	$-26.94\,(-26.90)^{+0.58}_{-0.53}$

Hill et al, PRD 2020, arXiv:2003.07355

Strategy

- Its always fun to do something exciting in physical cosmology. Lets attempt to kill Lambda by introducing a challenger.
- One or some of the data might have systematics. Investing on a model to fully satisfy all current observations and resolving all tensions might not be the best strategy.
- Gambling is fun. I choose CMB and local H0 measurements as two completely independent data that are showing most significant tensions within the framework of the LCDM as the main observations. The new model has to satisfy these two simultaneously.
- I target the near future and not now. If current data is reliable, the proposed model should decisively rule out Lambda with near future data that would have higher precision. The model should satisfy CMB and prefer high H0 (and not just being consistent with current estimations).
- It should be simple phenomenological model, but better to have some hints for theory or theoretical implications.

Phenomenologically Emergent Dark Energy (PEDE)



No Dark Energy in the past and it acts as an emergent phenomena:

Allows lower rate of expansion in the past and higher rate of expansion at late times

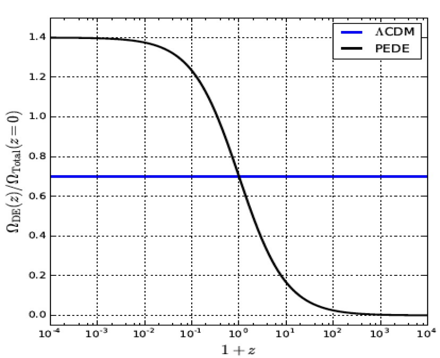
$$\Omega_{\rm DE}(z) = \Omega_{\rm DE,0} \times [1 - \tanh\left(\log_{10}(1+z)\right)]$$

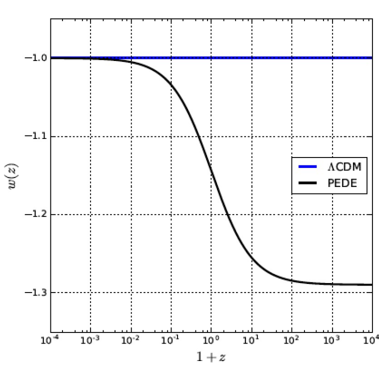
$$\begin{aligned} w(z) &= -\frac{1}{3\ln 10} \times \frac{1-\tanh^2\left[\log_{10}(1+z)\right]}{1-\tanh\left[\log_{10}(1+z)\right]} - 1 \\ &= -\frac{1}{3\ln 10} \times \left(1+\tanh\left[\log_{10}(1+z)\right]\right) - 1. \end{aligned}$$

Li and Shafieloo, ApJ Lett 2019

Phenomenologically Emergent Dark Energy (PEDE)

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	$0.675^{+0.547}_{-3.103}$	$-0.11^{+1.510}_{-3.192}$	$-0.46^{+1.830}_{-2.686}$	$-0.16^{+0.816}_{-1.109}$	$-0.20^{+0.986}_{-1.249}$	$-0.11^{+0.728}_{-1.321}$
	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**





Current:
LCDM is still better

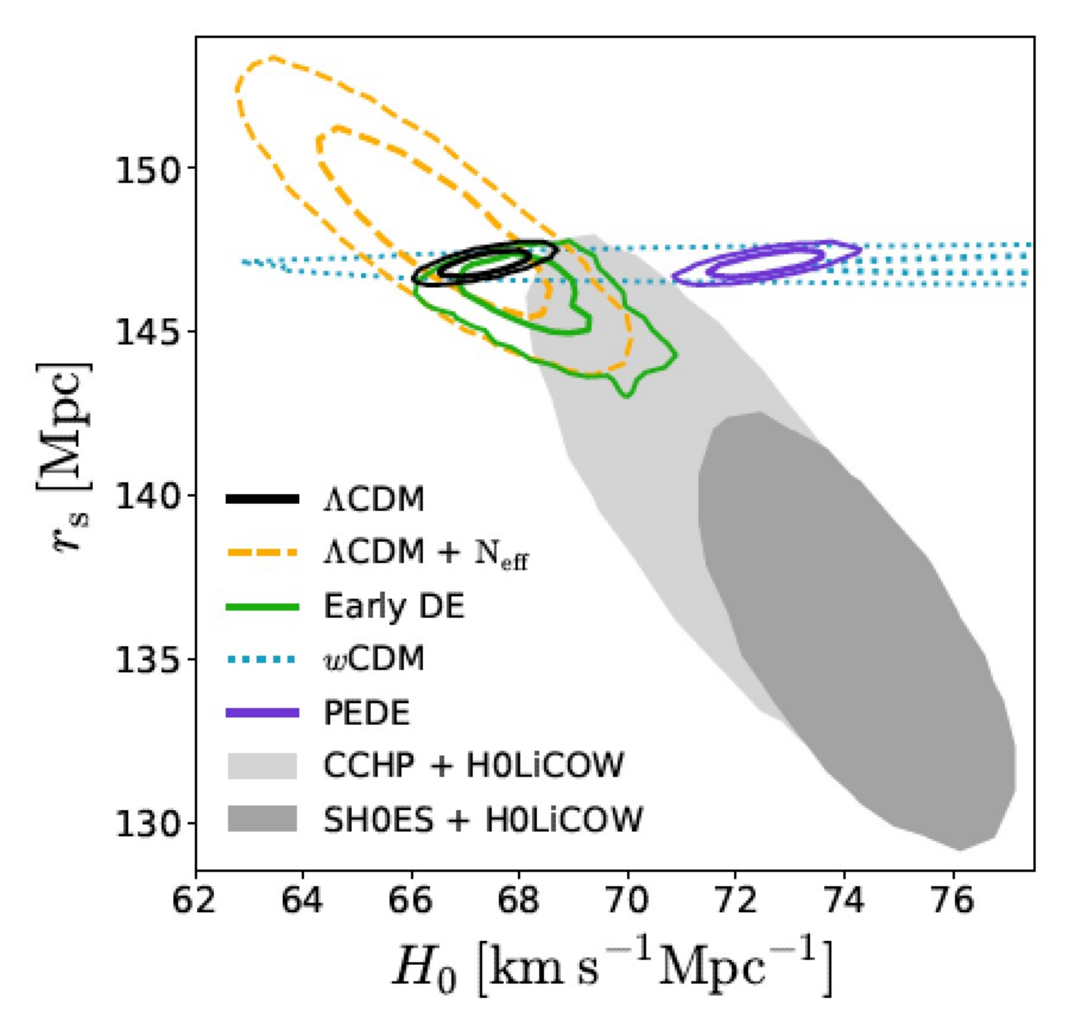
Near Future:
PEDE rules out Lambda

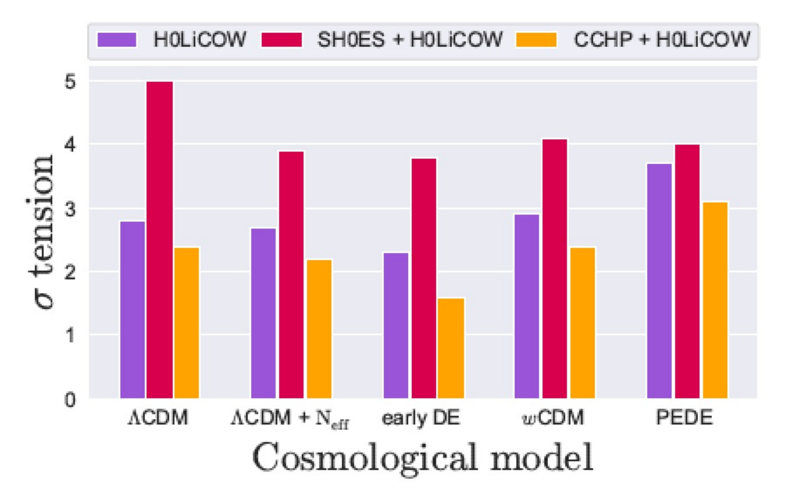
Li and Shafieloo, ApJ Lett 2019 (arXiv:1906.08275)

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

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

Comparing candidates





Arendse et al, arXiv:1909.07986

H0LiCOW Collaboration

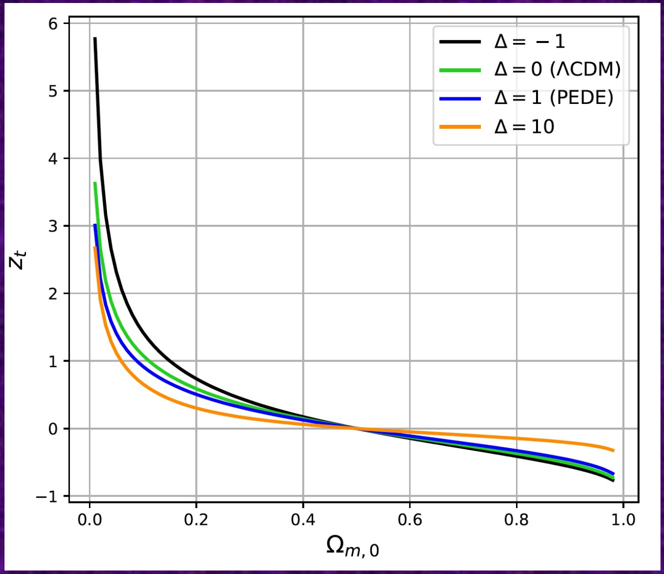
Generalized Emergent Dark Energy (GEDE)

$$\widetilde{\Omega}_{\mathrm{DE}}(z) = \Omega_{\mathrm{DE},0} \frac{1 - \tanh\left(\Delta \times \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{1 + \tanh\left(\Delta \times \log_{10}(1+z_t)\right)}$$

$$w(z) = -\frac{\Delta}{3\ln 10} \times \left(1 + \tanh\left(\Delta \times \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)\right) - 1.$$

-Has one degree of freedom for DE sector

-LCDM and PEDE are both included at special limits



$$\Omega_{\mathrm{DE}}(z_t) = \Omega_{m,0}(1+z_t)^3$$

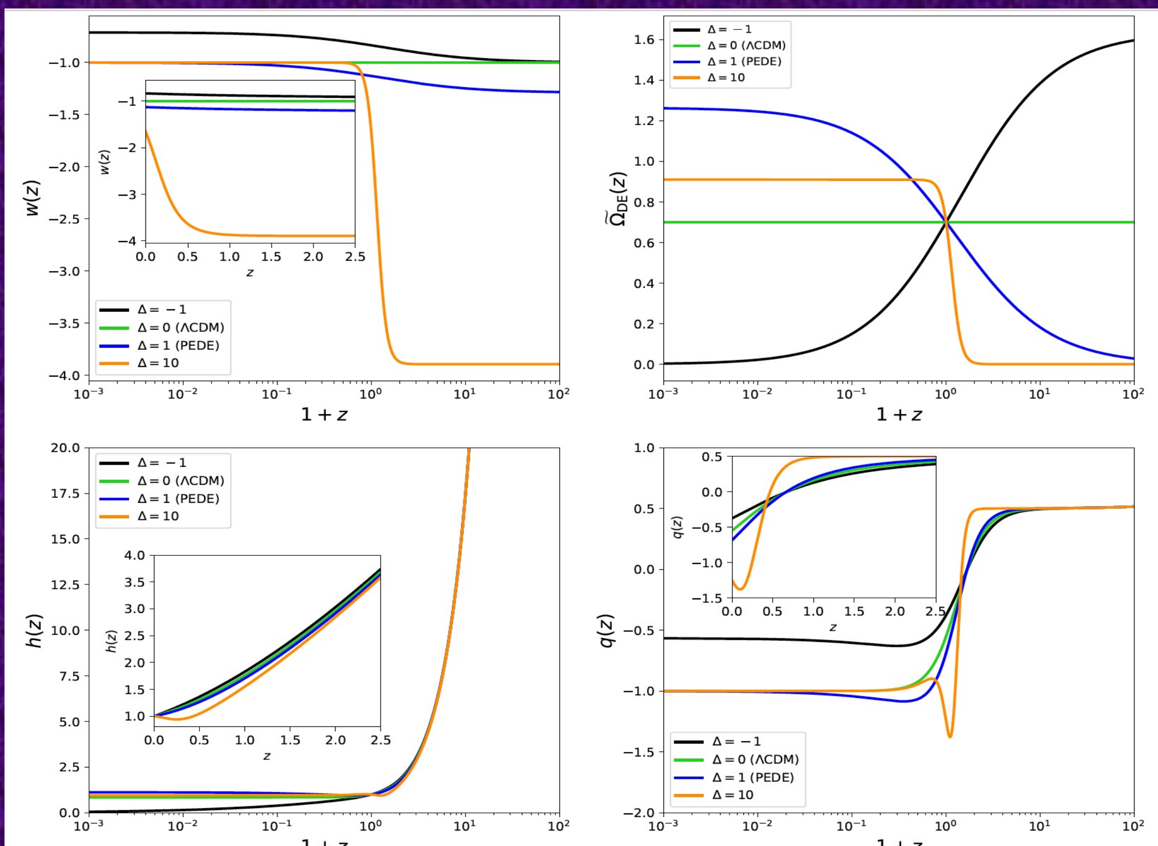
$\Delta = 0$ LCDM

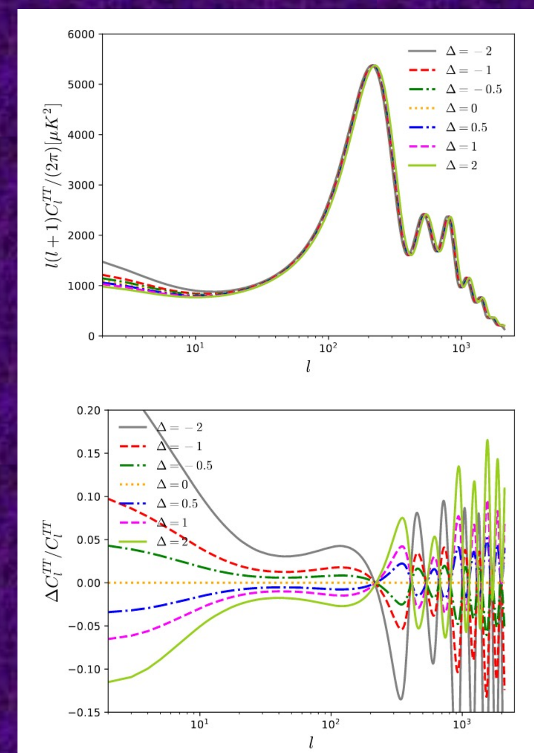
$\Delta = 1$ PEDE

Li and Shafieloo, ApJ 2020 (arXiv:2001.05103)

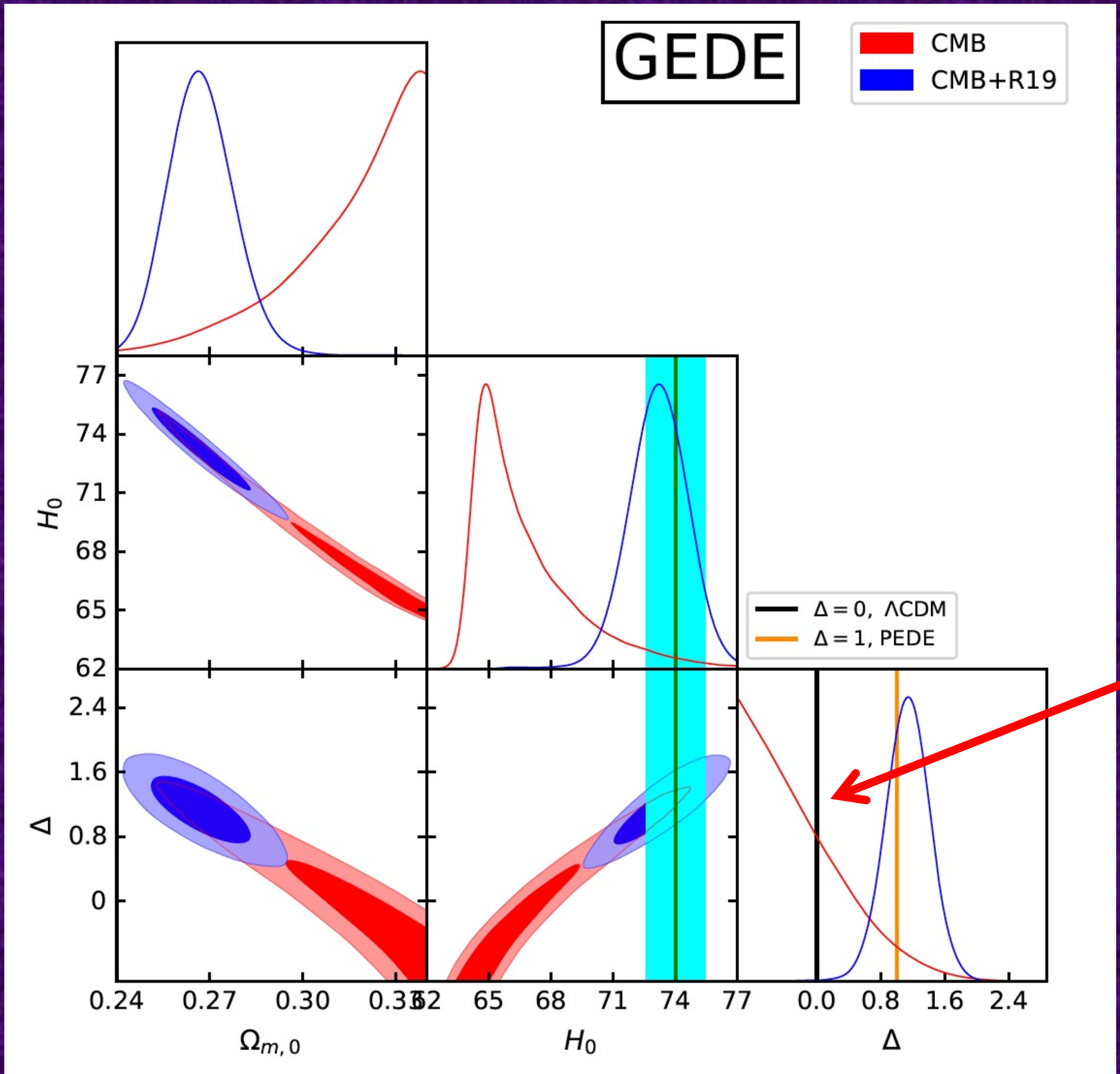
Generalized Emergent Dark Energy (GEDE)

Accommodates various forms and can be confronted with various data





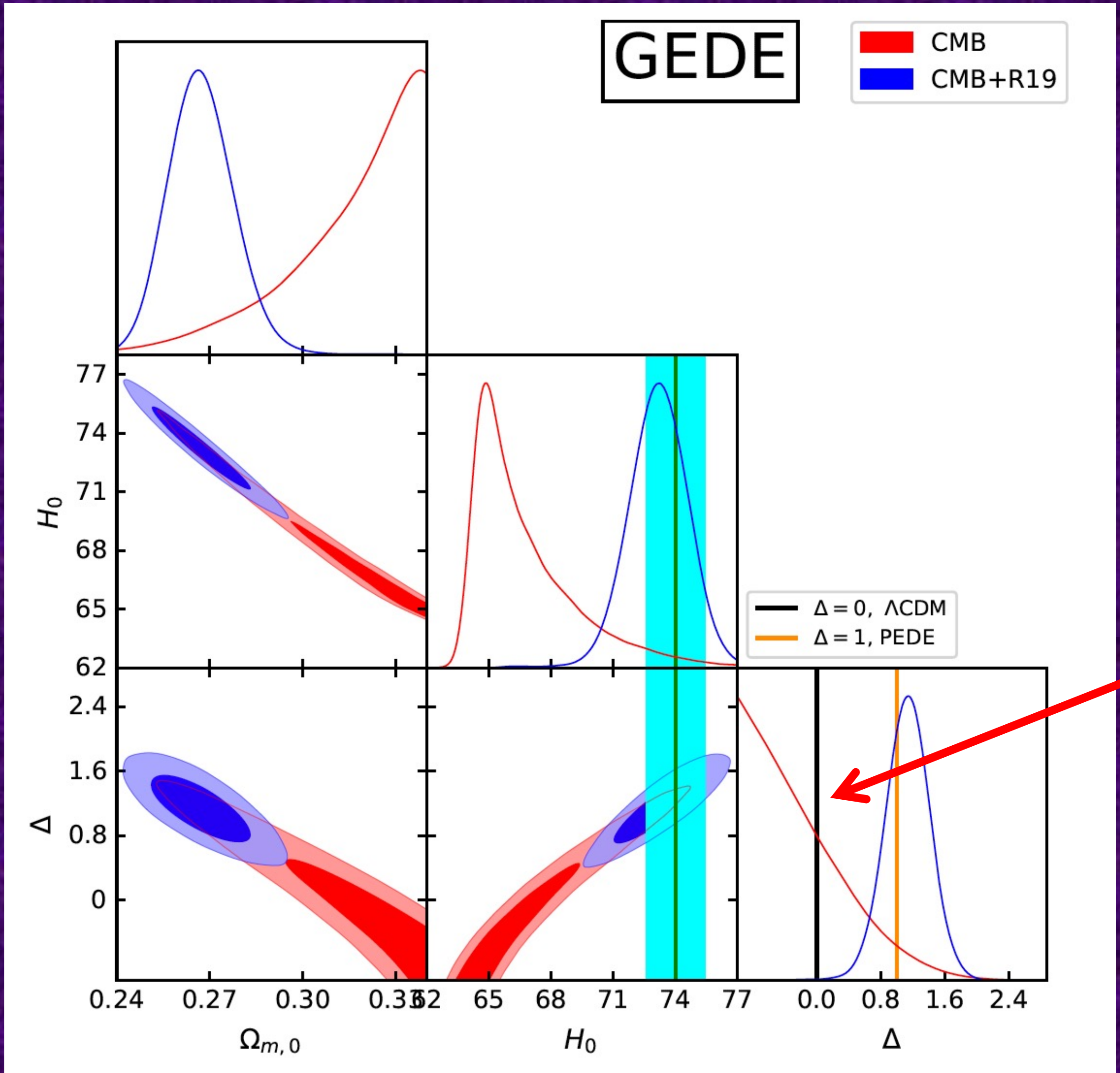
Generalized Emergent Dark Energy (GEDE)



Lambda outside the 4\sigma CL

Li and Shafieloo, ApJ 2020, arXiv:2001.05103

Generalized Emergent Dark Energy (GEDE)

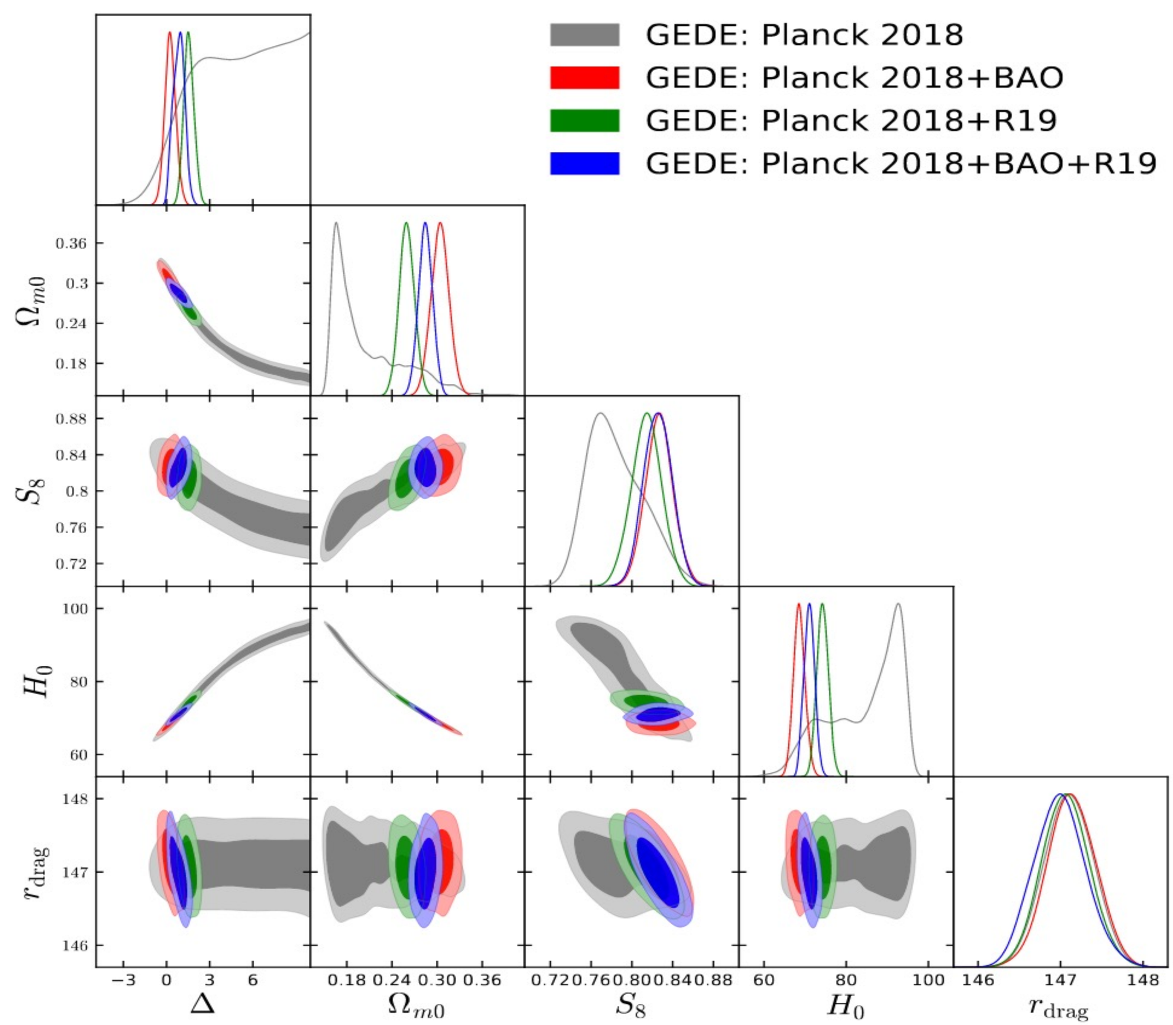


Time will show!

Lambda outside the 4\sigma CL

Li and Shafieloo, ApJ 2020, arXiv:2001.05103

Generalized Emergent Dark Energy (GEDE)



Full analysis using various combination of the data

W. Yang, E. Di Valentino, S. Pan, A. Shafieloo, X. Li, arXiv:2103.03815

Generalized Emergent Dark Energy (GEDE)

Full analysis using various combination of the data

Parameters	Planck 2018+JLA	Planck 2018+Pantheon	Planck 2018+BAO+JLA+R19	Planck 2018+BAO+Pantheon+R19
$\Omega_c h^2$	$0.1202^{+0.0013+0.0025}_{-0.0013-0.0026}$	$0.1203^{+0.0014+0.0027}_{-0.0014-0.0026}$	$0.1201^{+0.0012+0.0023}_{-0.0012-0.0024}$	$0.1199^{+0.0012+0.0023}_{-0.0012-0.0024}$
$\Omega_b h^2$	$0.02235^{+0.00015+0.00029}_{-0.00014-0.00029}$	$0.02236^{+0.00015+0.00030}_{-0.00015-0.00029}$	$0.02238^{+0.00014+0.00030}_{-0.00016-0.00028}$	$0.02240^{+0.00014+0.00029}_{-0.00015-0.00029}$
$100\theta_{MC}$	$1.04090^{+0.00031+0.00062}_{-0.00031-0.00062}$	$1.04092^{+0.00031+0.00061}_{-0.00031-0.00059}$	$1.04096^{+0.00031+0.00060}_{-0.00030-0.00060}$	$1.04095^{+0.00031+0.00058}_{-0.00031-0.00061}$
τ	$0.0544^{+0.0075+0.015}_{-0.0074-0.014}$	$0.0541^{+0.0074+0.015}_{-0.0075-0.015}$	$0.0543^{+0.0074+0.015}_{-0.0078-0.016}$	$0.0550^{+0.0076+0.016}_{-0.0077-0.015}$
n_s	$0.9647^{+0.0043+0.0085}_{-0.0047-0.0084}$	$0.9647^{+0.0047+0.0086}_{-0.0043-0.0089}$	$0.9649^{+0.0041+0.0081}_{-0.0041-0.0079}$	$0.9656^{+0.0041+0.0084}_{-0.0041-0.0080}$
$\ln(10^{10}A_s)$	$3.045^{+0.015+0.031}_{-0.016-0.029}$	$3.045^{+0.016+0.031}_{-0.016-0.031}$	$3.044^{+0.015+0.032}_{-0.016-0.031}$	$3.046^{+0.016+0.032}_{-0.016-0.030}$
Δ	$0.30^{+0.36+0.79}_{-0.40-0.73}$	$0.25^{+0.26+0.51}_{-0.26-0.52}$	$0.69^{+0.25+0.49}_{-0.25-0.48}$	$0.55^{+0.20+0.42}_{-0.21-0.43}$
Ω_{m0}	$0.305^{+0.015+0.029}_{-0.015-0.029}$	$0.307^{+0.011+0.021}_{-0.011-0.021}$	$0.289^{+0.0074+0.015}_{-0.0072-0.014}$	$0.293^{+0.0065+0.013}_{-0.0067-0.013}$
σ_8	$0.825^{+0.017+0.037}_{-0.019-0.034}$	$0.823^{+0.016+0.028}_{-0.013-0.028}$	$0.841^{+0.014+0.027}_{-0.014-0.027}$	$0.834^{+0.012+0.025}_{-0.012-0.025}$
H_0	$68.6^{+1.5+3.3}_{-1.8-3.0}$	$68.3^{+1.1+2.3}_{-1.1-2.1}$	$70.38^{+0.87+1.8}_{-0.89-1.7}$	$69.86^{+0.75+1.4}_{-0.74-1.4}$
S_8	$0.831^{+0.015+0.031}_{-0.015-0.030}$	$0.832^{+0.015+0.030}_{-0.015-0.029}$	$0.825^{+0.013+0.026}_{-0.013-0.025}$	$0.824^{+0.014+0.025}_{-0.013-0.025}$
$r_{\rm drag}$	$147.05^{+0.28+0.58}_{-0.31-0.55}$	$147.03^{+0.30+0.58}_{-0.30-0.57}$	$147.05^{+0.27+0.53}_{-0.28-0.54}$	$147.10^{+0.27+0.52}_{-0.27-0.54}$

W. Yang, E. Di Valentino, S. Pan, A. Shafieloo, X. Li, arXiv:2103.03815

Generalized Emergent Dark Energy (GEDE)

Data	$\ln B_{ij}$
Planck 2018	2.9
Planck 2018+BAO	0.8
Planck 2018+R19	12.1
Planck 2018+BAO+R19	7.9
Planck 2018+JLA	−0.2
Planck 2018+Pantheon	−0.9
Planck 2018+BAO+JLA+R19	6.1
Planck 2018+BAO+Pantheon+R19	5.8

Full analysis using various combination of the data

Model Comparison:
Bayesian evidence analysis in strong support of emergent dark energy

W. Yang,et al, arXiv:2103.03815

Generalized Emergent Dark Energy (GEDE)

Data	$\ln B_{ij}$
Planck 2018	2.9
Planck 2018+BAO	0.8
Planck 2018+R19	12.1
Planck 2018+BAO+R19	7.9
Planck 2018+JLA	−0.2
Planck 2018+Pantheon	−0.9
Planck 2018+BAO+JLA+R19	6.1
Planck 2018+BAO+Pantheon+R19	5.8

Full analysis using various combination of the data

Current tensions allow us to find models statistically better than LCDM but are all tensions resolved?

Model Comparison:
Bayesian evidence analysis in strong support of emergent dark energy

No!

W. Yang,et al, arXiv:2103.03815

(Present)

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

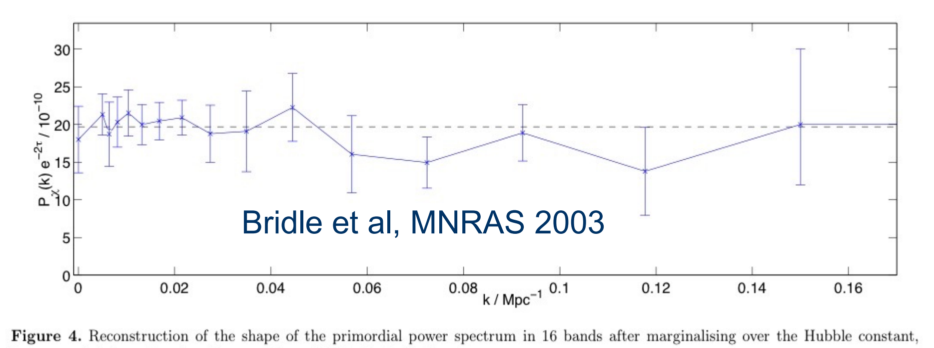
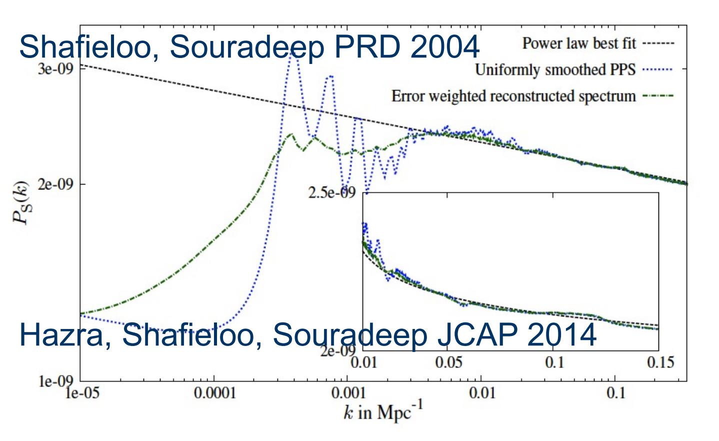
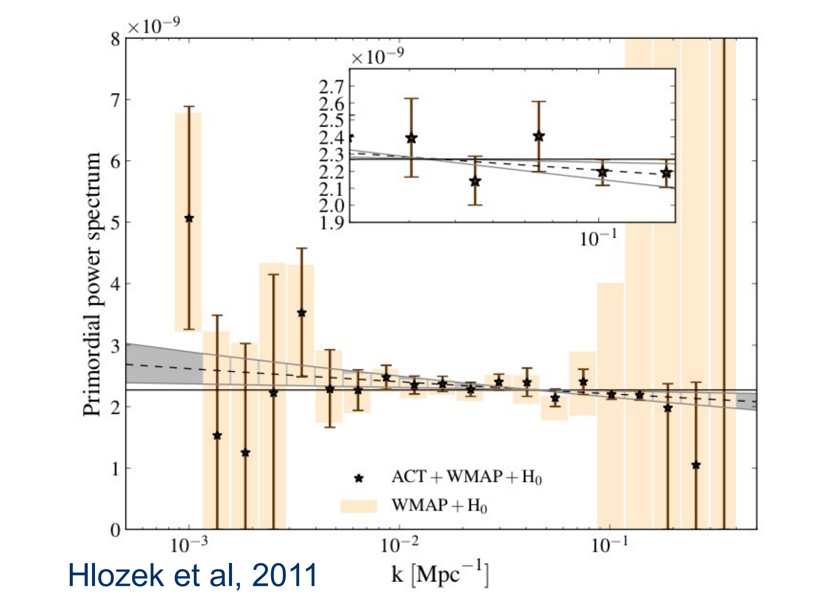
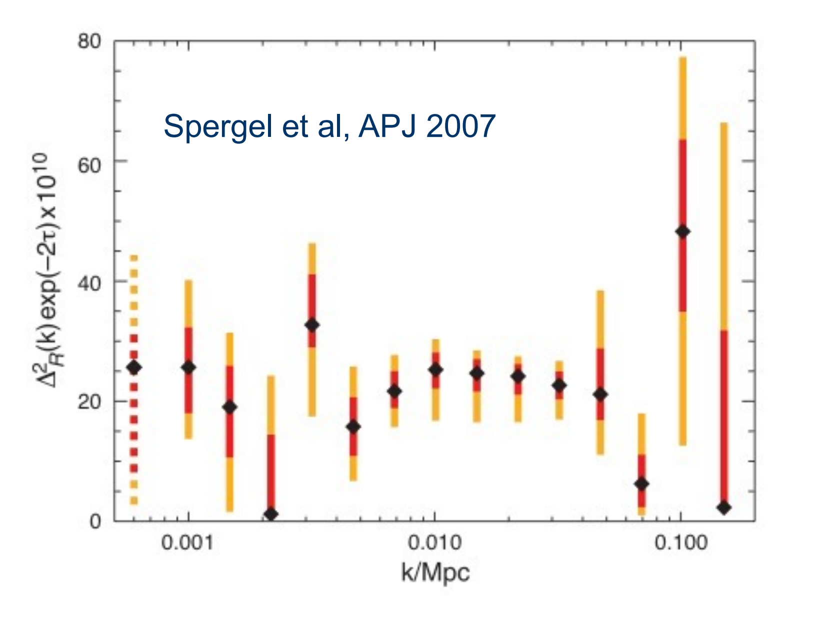
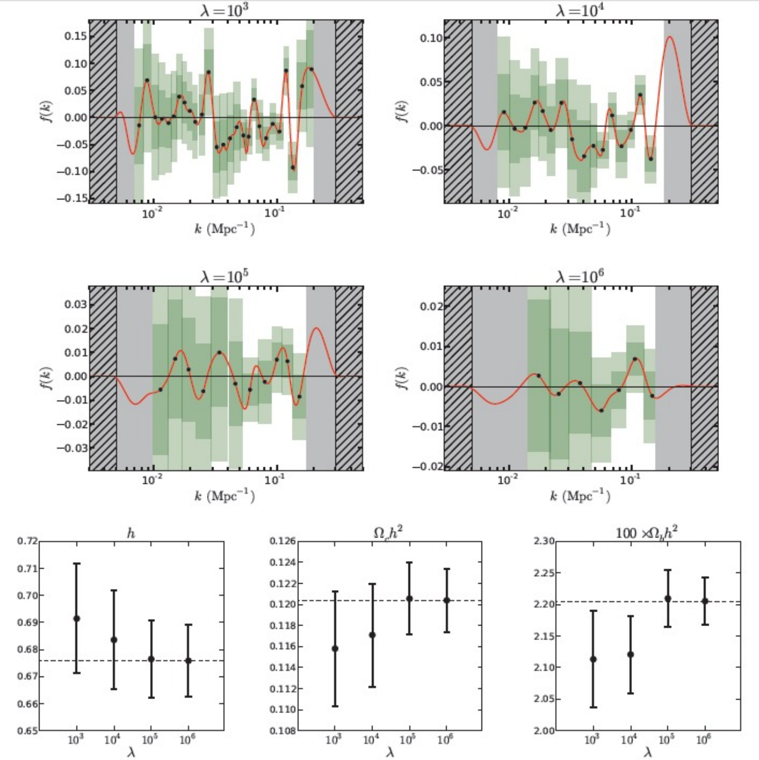


Figure 4. Reconstruction of the shape of the primordial power spectrum in 16 bands after marginalising over the Hubble constant, baryon and dark matter densities, and the redshift of reionization.

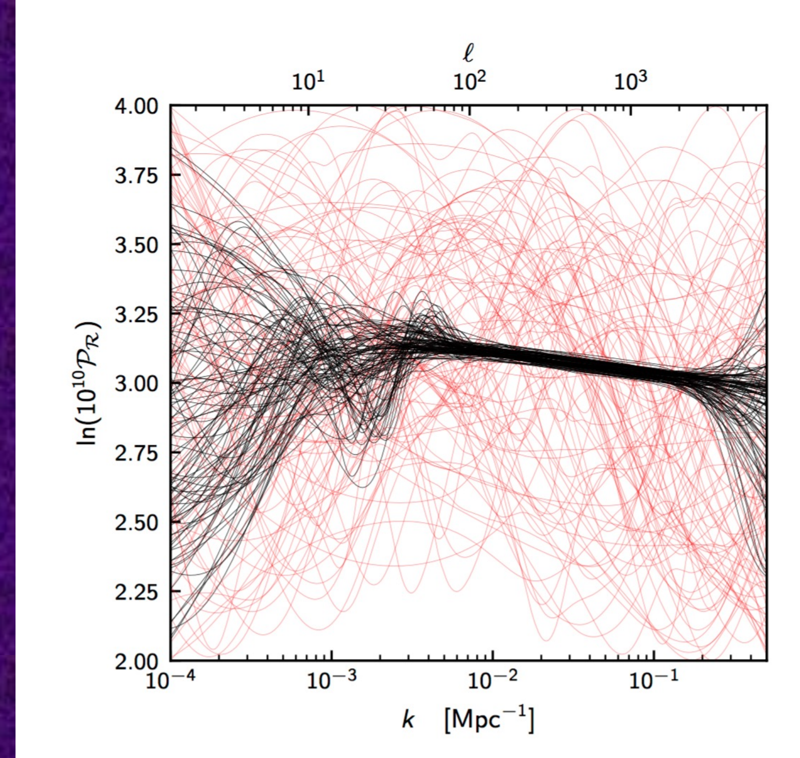






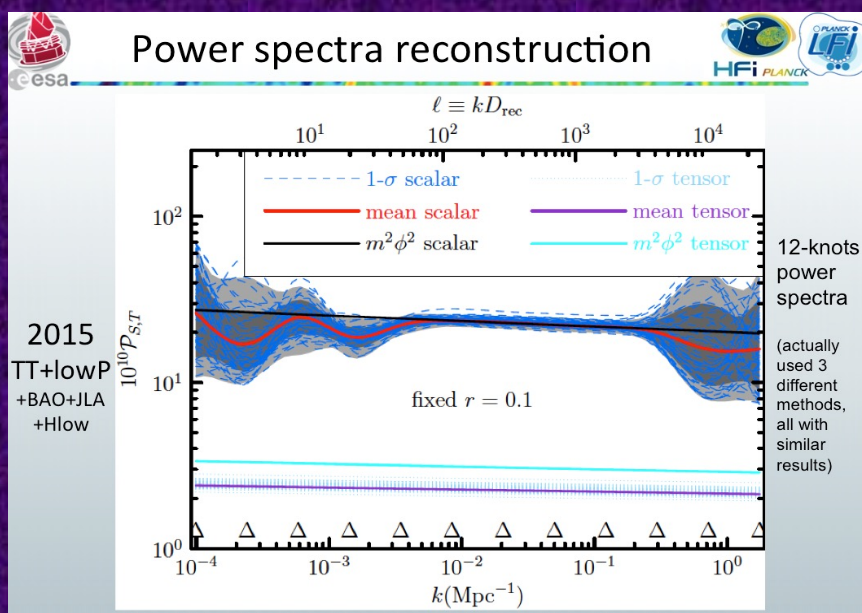


Planck 2013

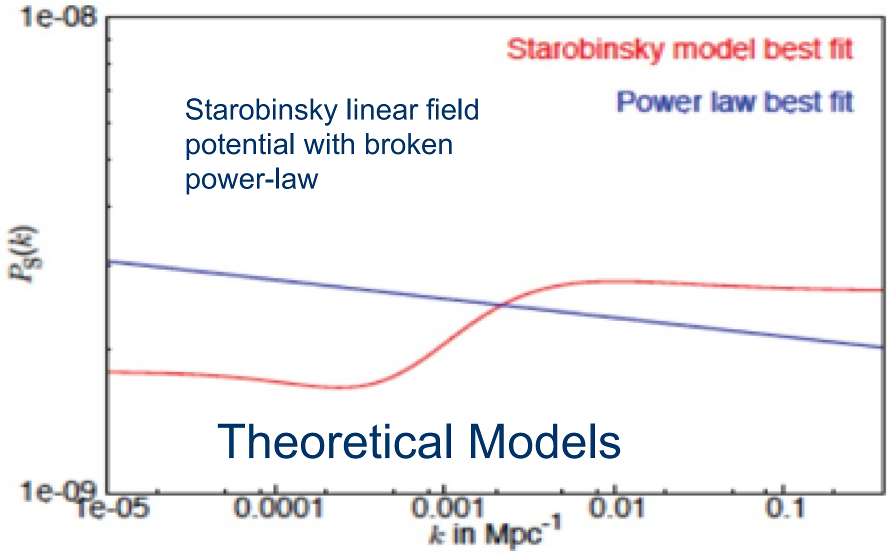


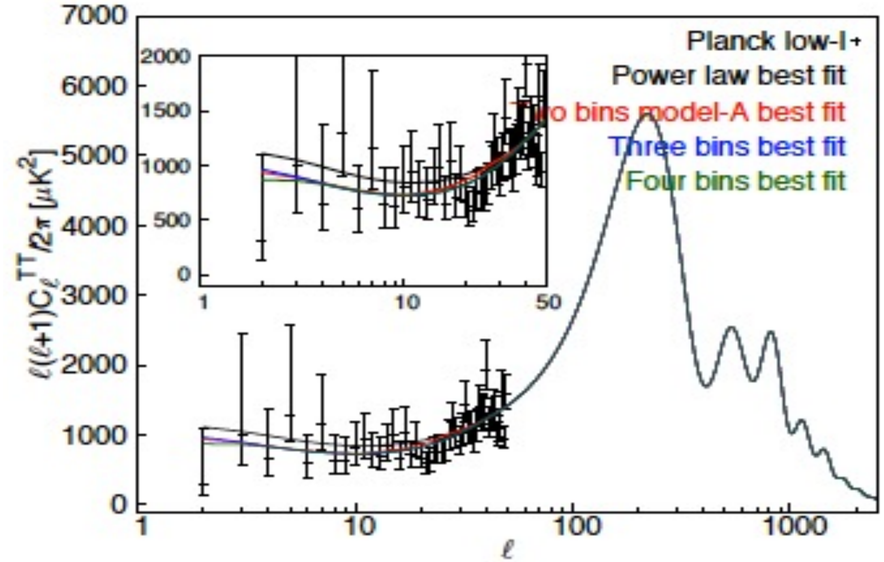
Planck 2018

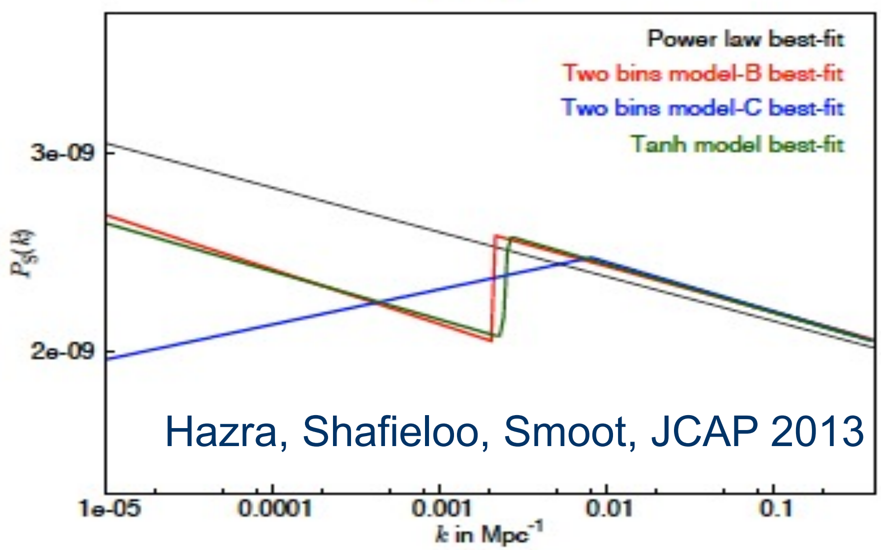
Planck 2015

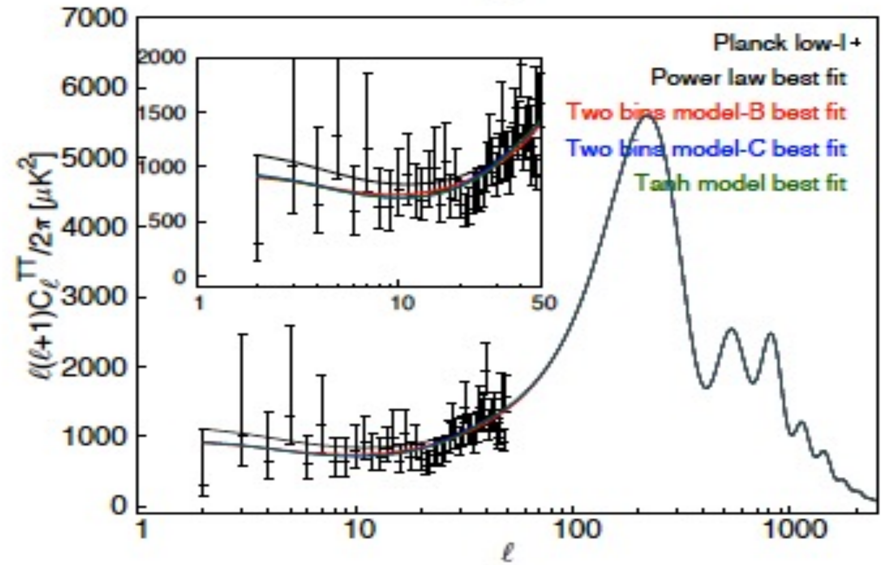


Beyond Power-Law: there are some other models consistent to the data.







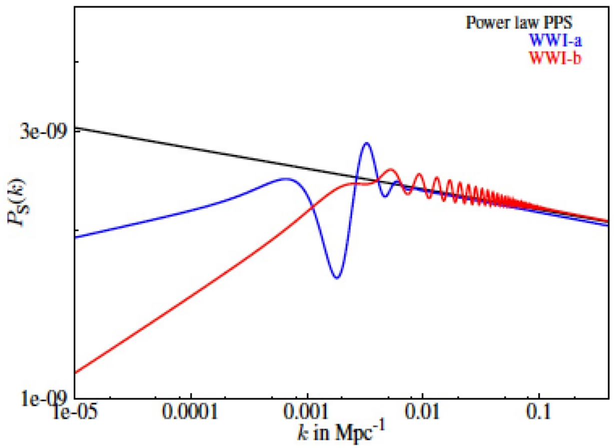


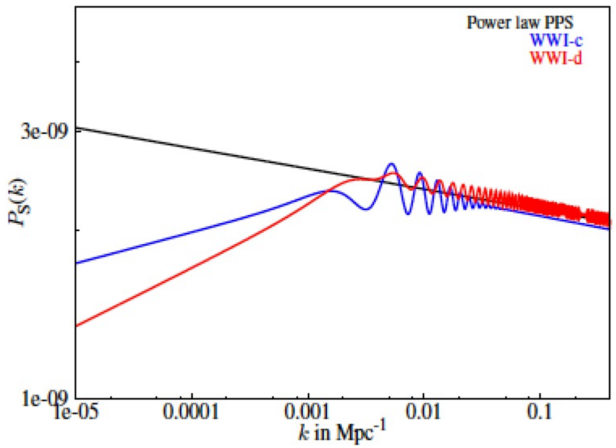
Individual likelihoods comparison						
Individual likelihood	Baseline	WWI-a $\Delta_{DOF}=4$	WWI-b $\Delta_{DOF}=4$	WWI-c $\Delta_{DOF}=4$	WWI-d $\Delta_{DOF}=4$	WWI′ $\Delta_{DOF}=2$
TT	761.1	762	761.9	762.8	762.8	762.4
lowT	15.4	8.2	13.4	12.1	13	10.2
Total	778.1	772.1 (-6)	777 (-1.1)	777 (-1.1)	778.4 (0.3)	775 (-3.1)
EE	751.2	748.8	747.2	748.6	750.2	746.8
lowTEB	10493.6	10490	10495.6	10492.4	10495.7	10492.2
Total	11248.8	11241.8 (-7)	11246.2 (-2.6)	11244.5 (-4.3)	11249.3 (0.5)	11242.3 (-6.5)
TTTEEE	2431.7	2432.7	2422.6	2427.8	2421.7	2426.5
lowTEB	10497	10490.8	10495.1	10493.4	10495.3	10492.7
Total	12935.6	12929.5 (-6.1)	12924.2 (-11.4)	12927.6 (-8)	12923.4 (-12.2)	12925.2 (-10.4)
TT	764.5	763.6	762.2	764.4	762.9	762.8
EE	753.9	754.8	750.5	750.8	750.8	751
TE	932	933.4	928.7	929.2	927	928.8
lowTEB	10498.4	10490.4	10495.8	10493.7	10495.6	10492.4
BKP	41.6	42	42	42.6	41.8	42.9
Total	12997	12991 (-6)	12985.9 (-11.1)	12987.2 (-9.8)	12985 (-12)	12985.1 (-11.9)
TTTEEE	2431.7	2432.8	2421.4	2426.7	2421	2425.7
lowTEB	10498.5	10490.5	10495.5	10493.6	10495.8	10492.6
BKP	41.6	42	42.7	42	41.9	42.5
Total	12978.3	12971.3 (-7)	12967.3 (-11)	12968.6 (-9.7)	12965 (-13.3)	12968.6 (-9.7)
TT (bin1)	8402.1	8404.1	8403.9	8405.2	8402.1	8401.9
lowT	15.4	8.3	13.3	11.9	13.2	10.3
Total	8419.6	8414.7 (-4.9)	8419.5 (-0.1)	8419.8 (0.2)	8418.1 (-1.5)	8414.4 (-5.2)
TTTEEE (bin1)	24158.2	24158.6	24149	24155	24148.4	24151.5
lowTEB	10497.6	10490.3	10493.4	10493.6	10495.3	10492.7
Total	34661.9	34655.3 (-6.6)	34650.5 (-11.4)	34654.4 (-7.5)	34649.5 (-12.4)	34650.6 (-11.3)

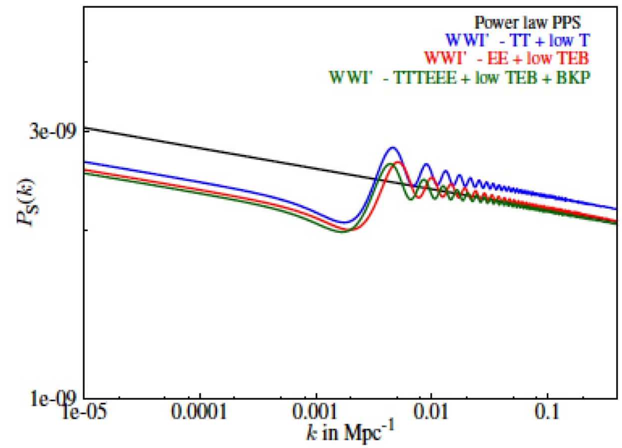
Beyond Power-Law: ***there are some other models consistent to the data.***

Whipped Inflation

Hazra, Shafieloo, Smoot, JCAP 2013
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B
Hazra, Shafieloo, Smoot, Starobinsky, Phys. Rev. Lett 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016
Hazra et al, JCAP 2018
Debono, Hazra, Shafieloo, Smoot, Starobinsky, MNRAS 2020
Hazra, Paoletti, Debono, Shafieloo, Smoot, Starobinsky, JCAP 2021







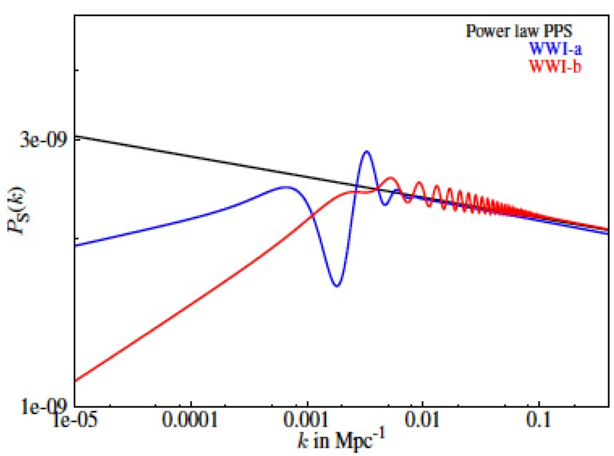
Individual likelihoods comparison						
Individual likelihood	Baseline	WWI-a $\Delta_{\rm DOF}=4$	WWI-b $\Delta_{\rm DOF}=4$	WWI-c $\Delta_{\rm DOF}=4$	WWI-d $\Delta_{\rm DOF}=4$	WWI′ $\Delta_{\rm DOF}=2$
TT	761.1	762	761.9	762.8	762.8	762.4
lowT	15.4	8.2	13.4	12.1	13	10.2
Total	778.1	772.1 (-6)	777 (-1.1)	777 (-1.1)	778.4 (0.3)	775 (-3.1)
EE	751.2	748.8	747.2	748.6	750.2	746.8
lowTEB	10493.6	10490	10495.6	10492.4	10495.7	10492.2
Total	11248.8	11241.8 (-7)	11246.2 (-2.6)	11244.5 (-4.3)	11249.3 (0.5)	11242.3 (-6.5)
TTTEEE	2431.7	2432.7	2422.6	2427.8	2421.7	2426.5
lowTEB	10497	10490.8	10495.1	10493.4	10495.3	10492.7
Total	12935.6	12929.5 (-6.1)	12924.2 (-11.4)	12927.6 (-8)	12923.4 (-12.2)	12925.2 (-10.4)
TT	764.5	763.6	762.2	764.4	762.9	762.8
EE	753.9	754.8	750.5	750.8	750.8	751
TE	932	933.4	928.7	929.2	927	928.8
lowTEB	10498.4	10490.4	10495.8	10493.7	10495.6	10492.4
BKP	41.6	42	42	42.6	41.8	42.9
Total	12997	12991 (-6)	12985.9 (-11.1)	12987.2 (-9.8)	12985 (-12)	12985.1 (-11.9)
TTTEEE	2431.7	2432.8	2421.4	2426.7	2421	2425.7
lowTEB	10498.5	10490.5	10495.5	10493.6	10495.8	10492.6
BKP	41.6	42	42.7	42	41.9	42.5
Total	12978.3	12971.3 (-7)	12967.3 (-11)	12968.6 (-9.7)	12965 (-13.3)	12968.6 (-9.7)
TT (bin1)	8402.1	8404.1	8403.9	8405.2	8402.1	8401.9
lowT	15.4	8.3	13.3	11.9	13.2	10.3
Total	8419.6	8414.7 (-4.9)	8419.5 (-0.1)	8419.8 (0.2)	8418.1 (-1.5)	8414.4 (-5.2)
TTTEEE (bin1)	24158.2	24158.6	24149	24155	24148.4	24151.5
lowTEB	10497.6	10490.3	10493.4	10493.6	10495.3	10492.7
Total	34661.9	34655.3 (-6.6)	34650.5 (-11.4)	34654.4 (-7.5)	34649.5 (-12.4)	34650.6 (-11.3)

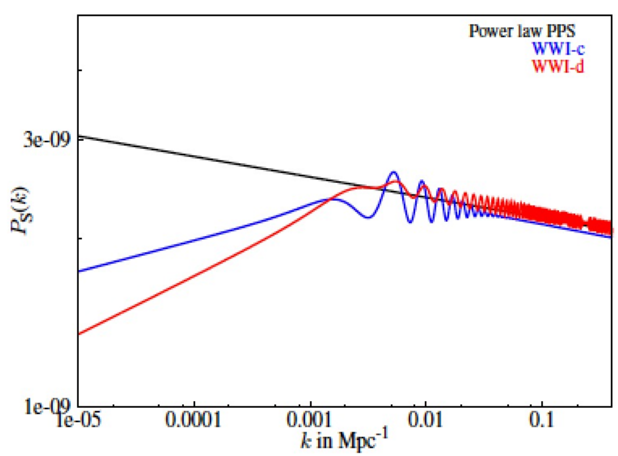
Beyond Power-Law:

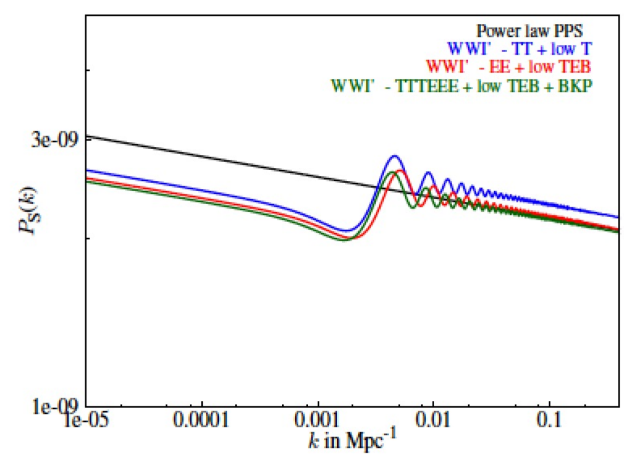
there are some other models consistent to the data.

Whipped Inflation

Hazra, Shafieloo, Smoot, JCAP 2013
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B
Hazra, Shafieloo, Smoot, Starobinsky, Phys. Rev. Lett 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016
Hazra et al, JCAP 2018
Debono, Hazra, Shafieloo, Smoot, Starobinsky, MNRAS 2020
Hazra, Paoletti, Debono, Shafieloo, Smoot, Starobinsky, JCAP 2021







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

A_s

n_s

1

G(l,k)

2

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

3

C_l^{obs}

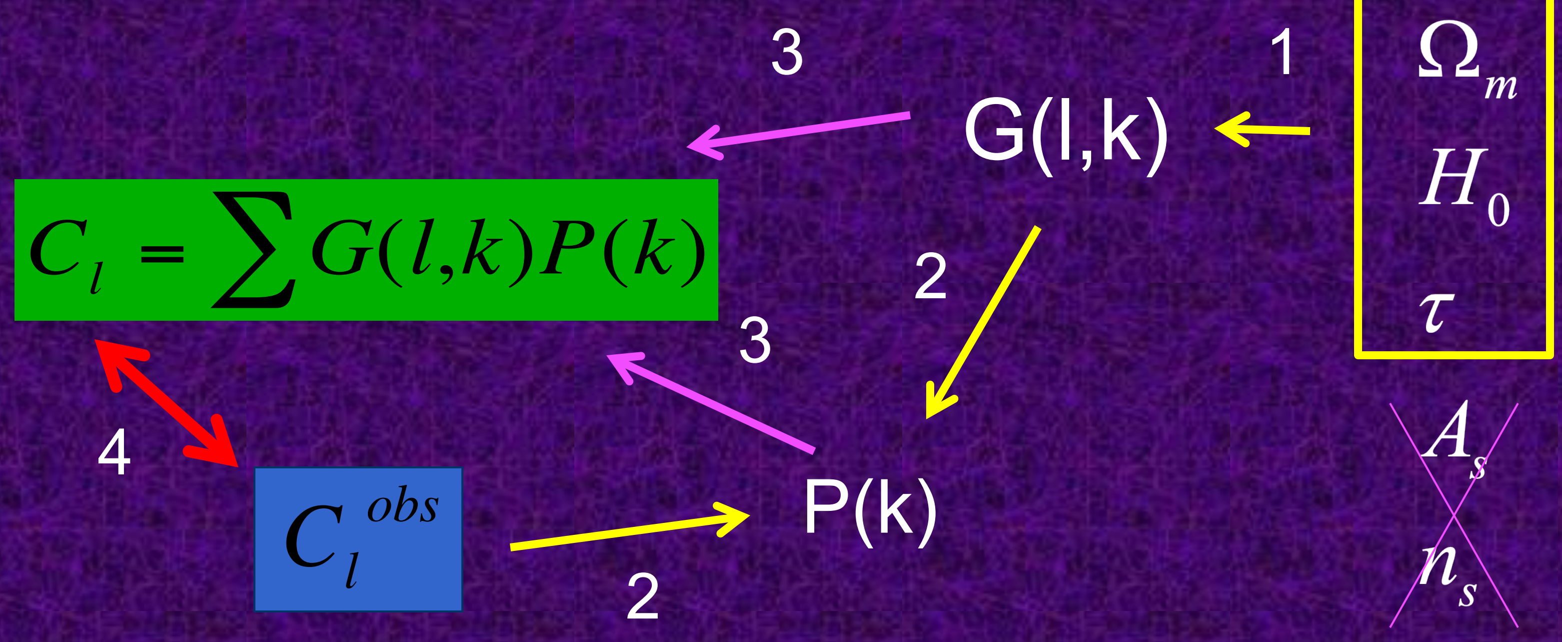
2

1

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

Forms of PPS and Effects on the Background Cosmology

- Cosmological parameter estimation with free form primordial power spectrum



Modified Richardson-Lucy Deconvolution

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

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

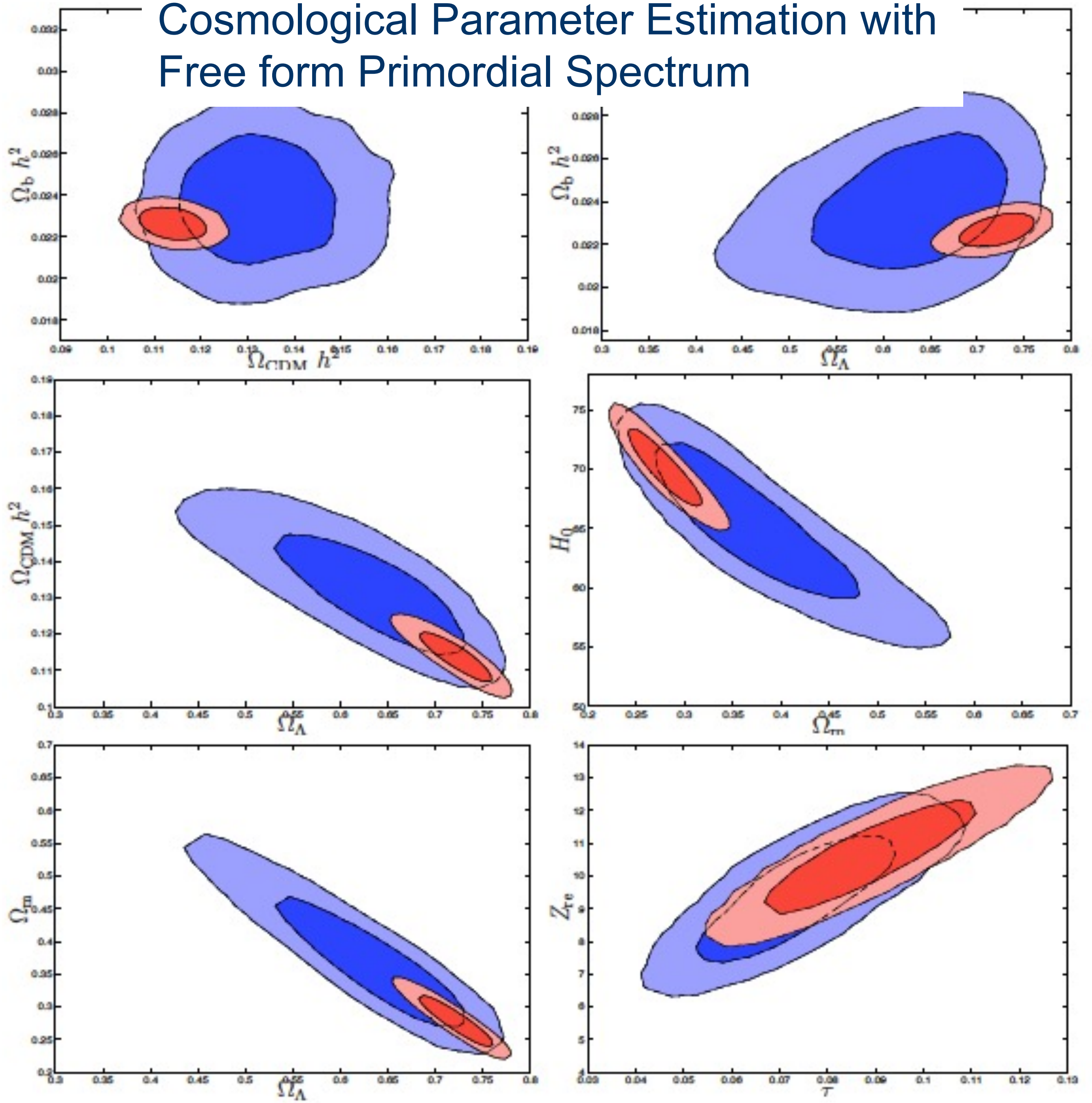
$$C_\ell = \sum_i G_{\ell k_i} P_{k_i}$$

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

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

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
Hazra, Shafieloo & Souradeep JCAP 2014
Hazra, Shafieloo & Souradeep JCAP 2015
Hazra, Shafieloo, Souradeep, JCAP 2019
Keeley, Shafieloo, Hazra, Souradeep, JCAP 2020
Hazra, Antony, Shafieloo, arXiv:2201.12000

Cosmological Parameter Estimation with Free form Primordial Spectrum



WMAP9 Data

Red Contours: Power Law PPS

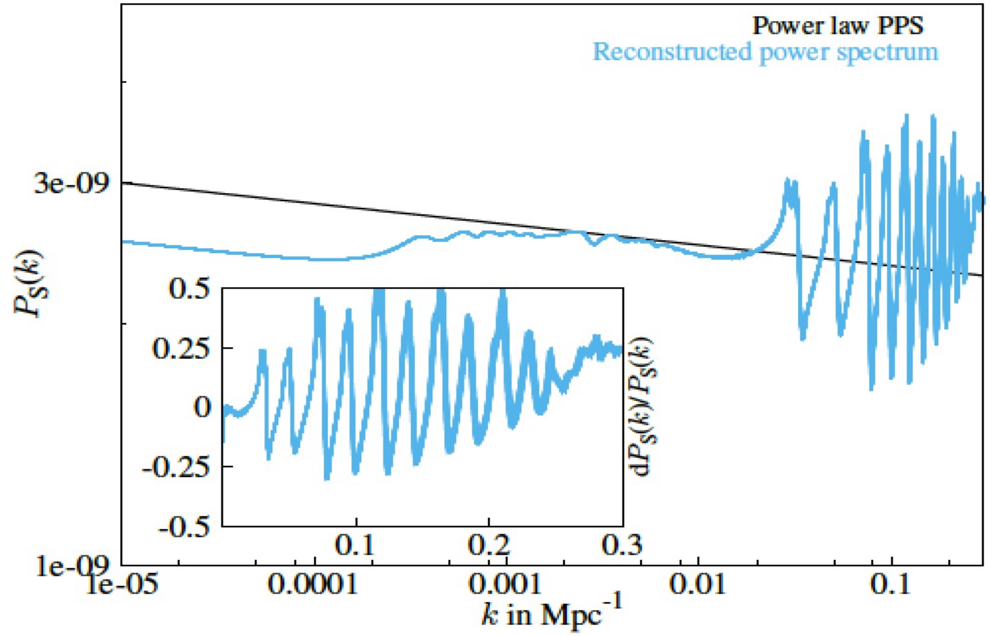
Blue Contours: Free Form PPS

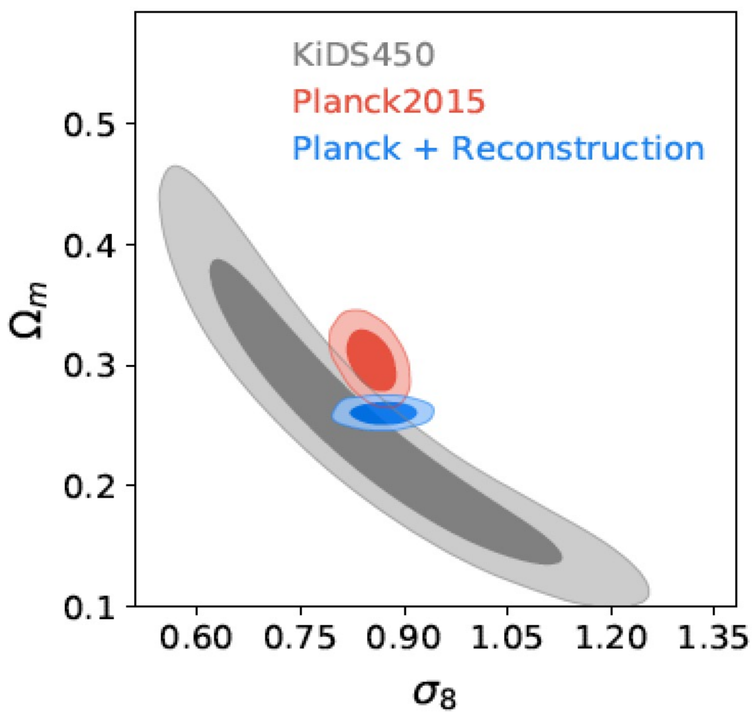
Hazra, Shafieloo, Souradeep, PRD 2013

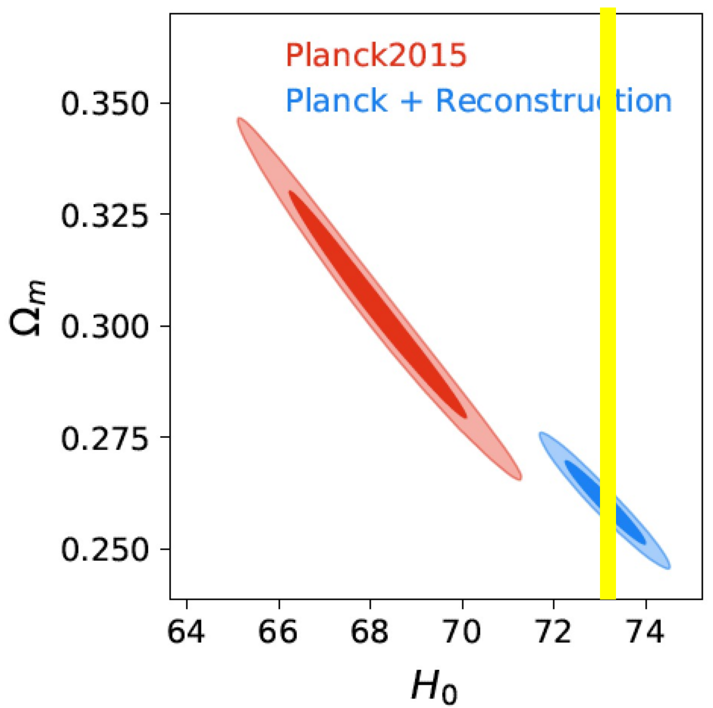
Hazra, Shafieloo, Souradeep, JCAP 2019

Background Cosmological Parameters and PPS

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

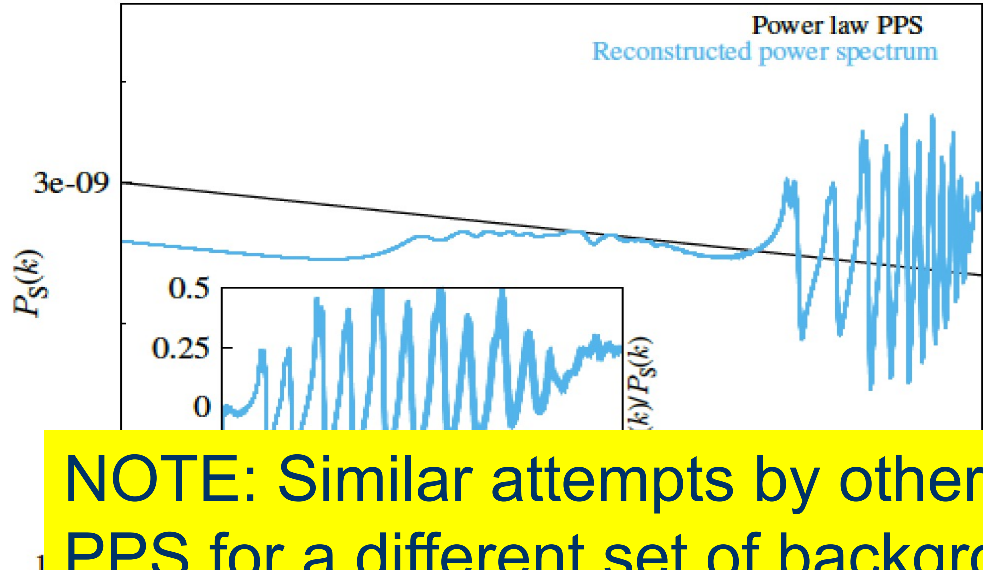






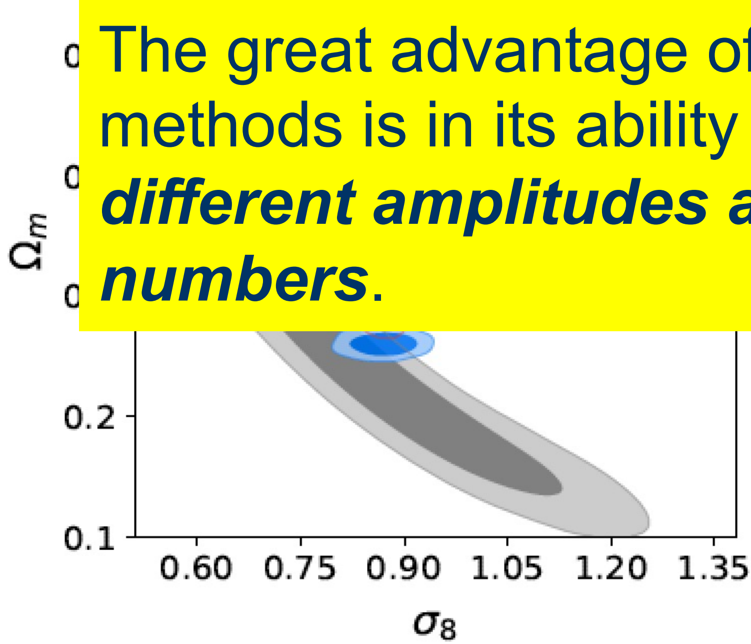
Hazra, Shafieloo, Souradeep, JCAP 2019

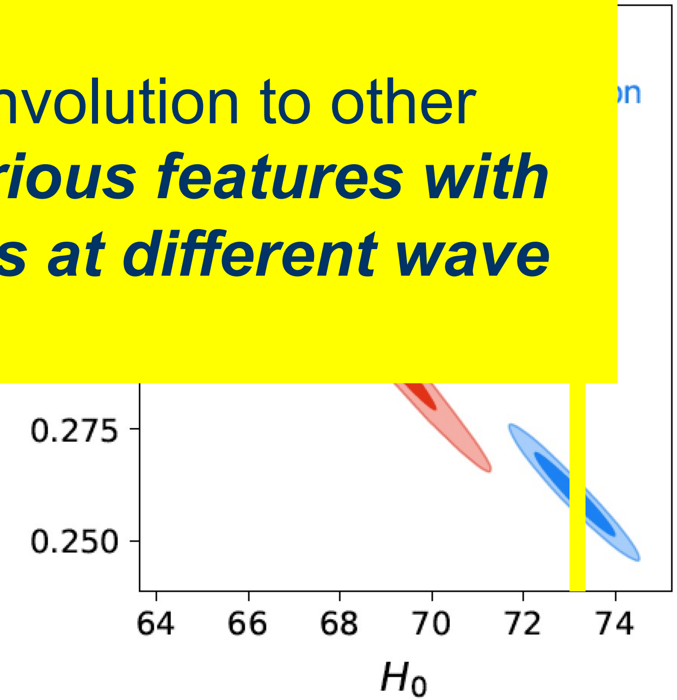
Background Cosmological Parameters and PPS

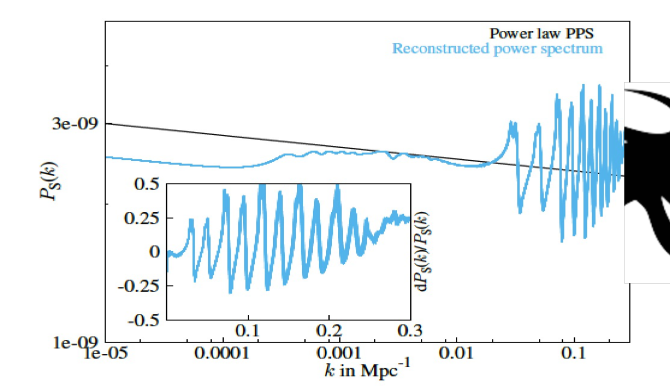


NOTE: Similar attempts by other groups to find a form of PPS for a different set of background parameters (to resolve Hubble tension) has failed so far.

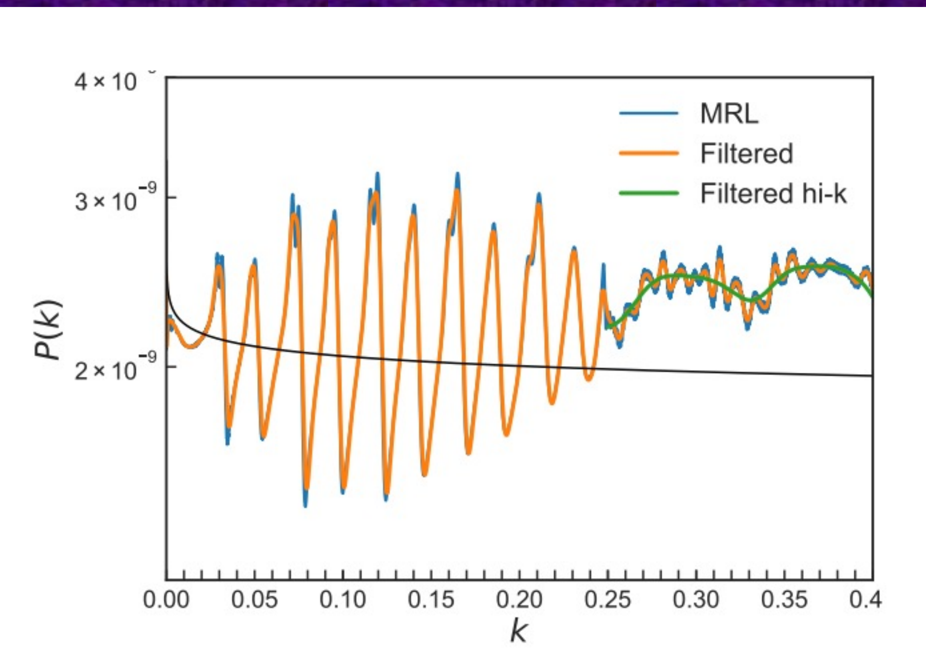
The great advantage of the MRL deconvolution to other methods is in its ability to generate ***various features with different amplitudes and frequencies at different wave numbers***.



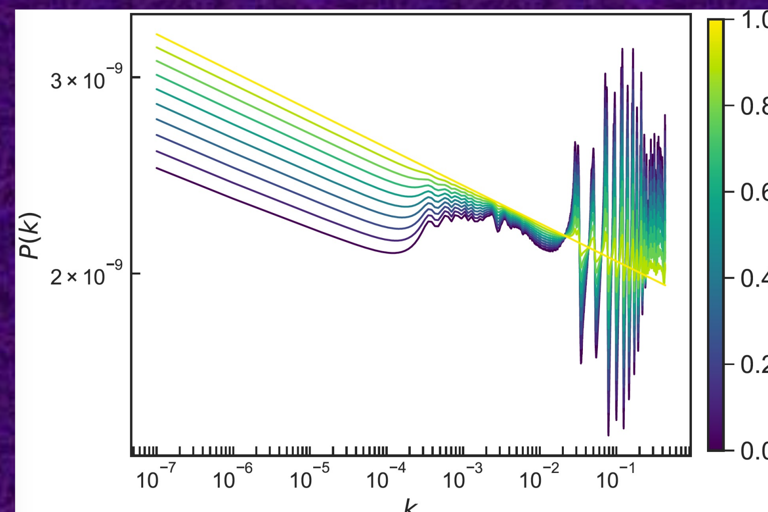




Do we need the high-k features?



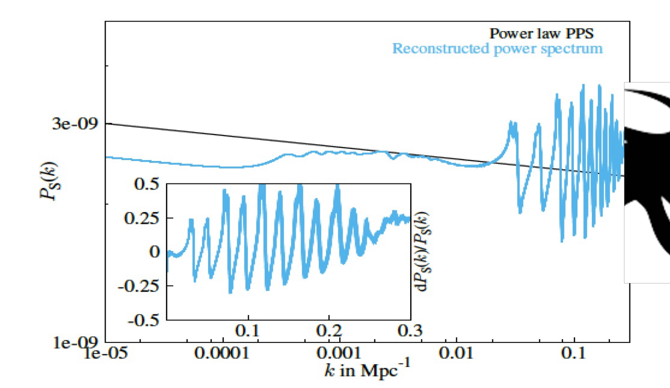
No, a featured decorated HZ should be fine ;)



H0 = 71.8 ± 0.9 km/s/Mpc.
Bayes factor of log K = 5.7 in favor of the deformation model.

$$P(k, f) = P_{\rm MRL}(k) + f(P_{\rm PL}(k) - P_{\rm MRL}(k)).$$

Keeley, Shafieloo, Hazra, Souradeep, JCAP 2020 (arXiv:2006.12710)



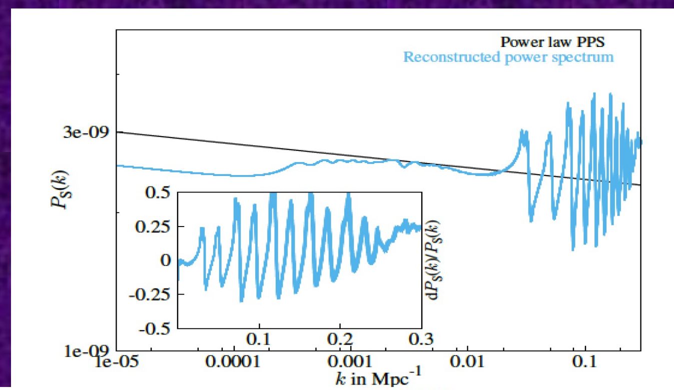
Issues:

1. Is it natural to generate a 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. We are currently searching for such scenarios!
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 and A_Lens issue!

Issues:

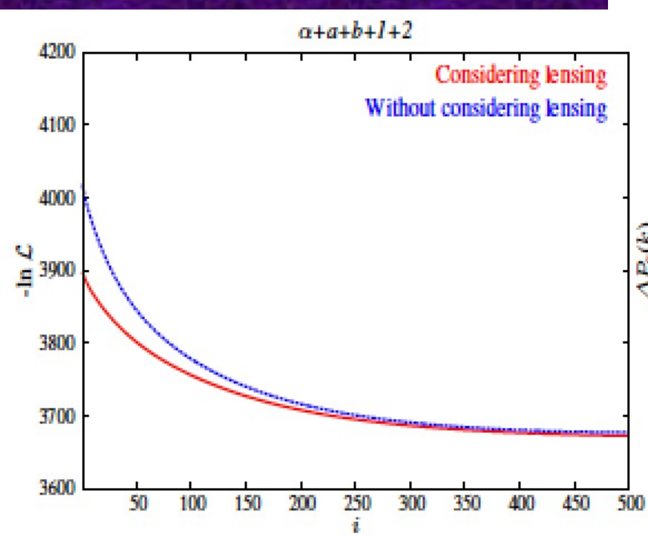
5. The features at high k values are very similar to the features we reconstructed previously when we did not consider CMB lensing (trying to project the effect on the form of the PPS). Can CMB lensing and A_Lens problem play a key role?

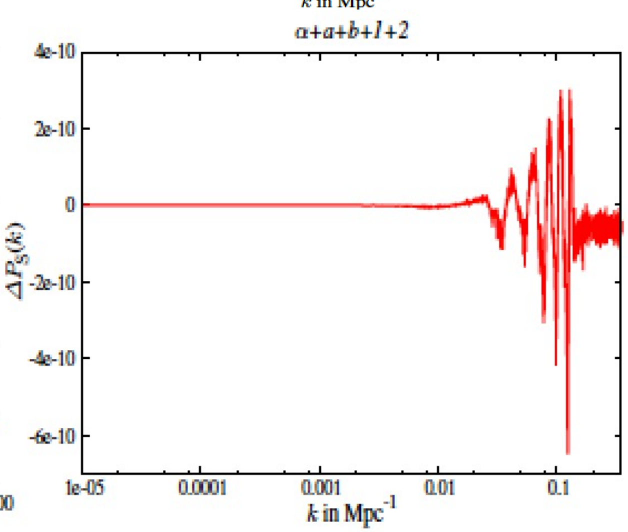
Also see: Kable, Addison, Bennett, arXiv:1809.03983

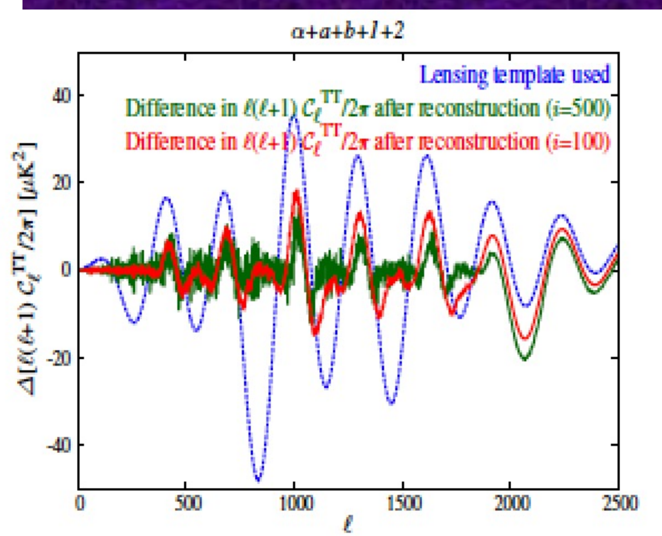


Hazra, Shafieloo, Souradeep, JCAP 2019

Hazra, Shafieloo, Souradeep, JCAP 2014







Issues:

Features in the primordial spectrum, CMB lensing, Hubble tension, can there be any connection?

See talk by Akhil in the afternoon!

5. The fea ... cted
previou ... ect
on the f ... y
role?

Also see: Kable, ...
arXiv:1809.03983 ...

... AP 2019

... AP 2014

Current Status

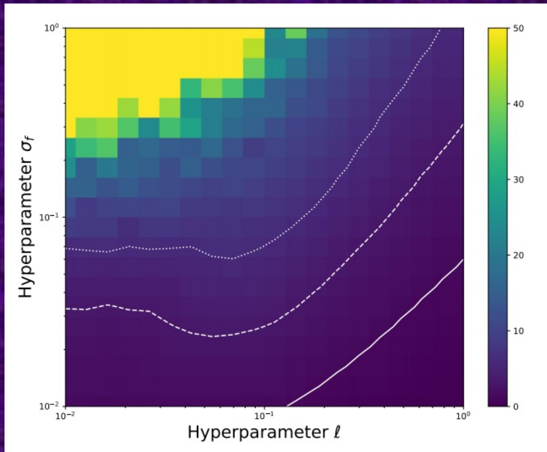
Open problem. Many tensions and hints for various systematics

Many theoretical/phenomenological models are proposed to ease the tensions. None is convincing so far.

Not possible to resolve all problems with minimal modification of the standard model. This has helped the standard model to survive so far.

Model independent consistency test between various data is essential to rule out systematics.

Consistency of SDSS BAO and Pantheon SN Ia data
Keeley, Shafieloo, Zhao et al, arXiv:2010.03234 [SDSS IV paper]



Future Perspective

High possibilities for systematics in different data

Need for independent measurements

Two key questions:

Power-Law Primordial Power Spectrum?
Lambda Dark Energy?

Tip of the Red Giant Branch

Future Perspective

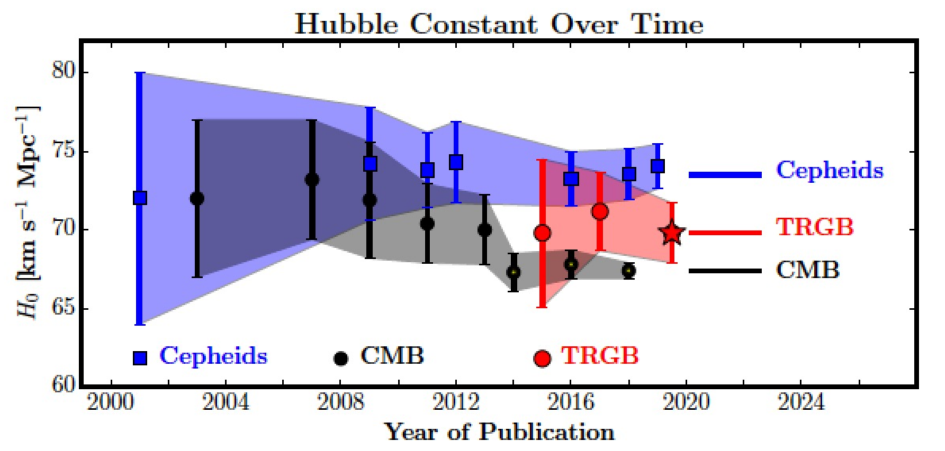
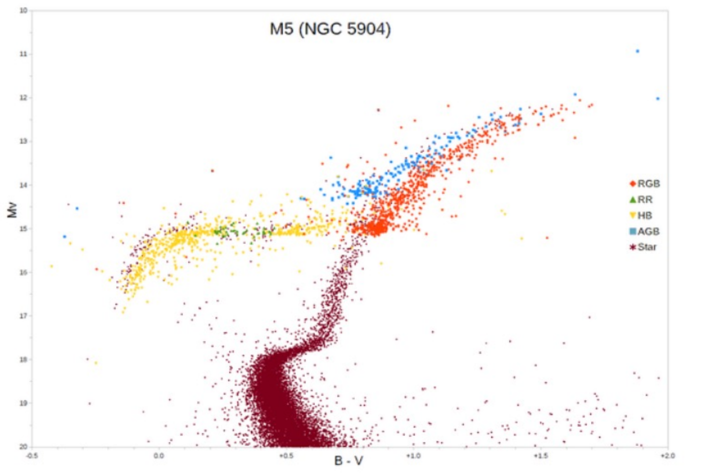


Figure 17. A plot of H_0 values as a function of time. The points and shaded region in black are those determined from measurements of the CMB; those in blue are Cepheid calibrations of the local value of H_0; and the red points are TRGB calibrations. The red star is the best-fit value obtained in this paper. Error bars are 1σ.

Freedman et al, arXiv:1907.05922



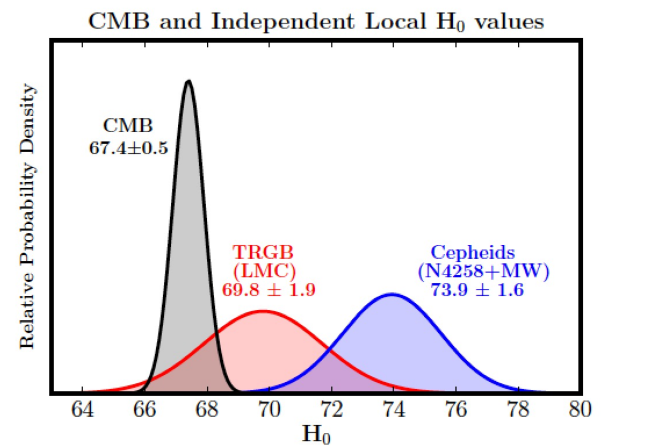
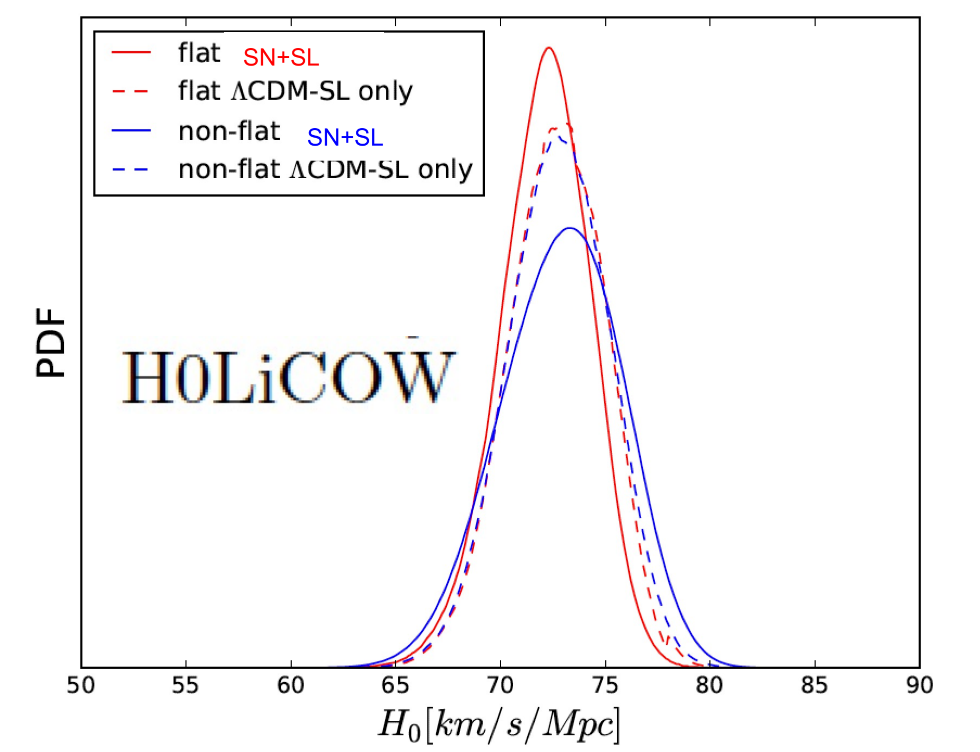


Figure 18. Completely independent calibrations of H_0. Shown in red is the probability density function based on our LMC CCHP TRGB calibration of CSP-I SNe Ia; in blue is the Cepheid calibration of H_0 (Riess et al. 2016), using the Milky Way parallaxes and the maser distance to NGC 4258 as anchors (excluding the LMC). The Planck value of H_0 is shown in black.

Future Perspective

H0 from Strongly Lensed systems



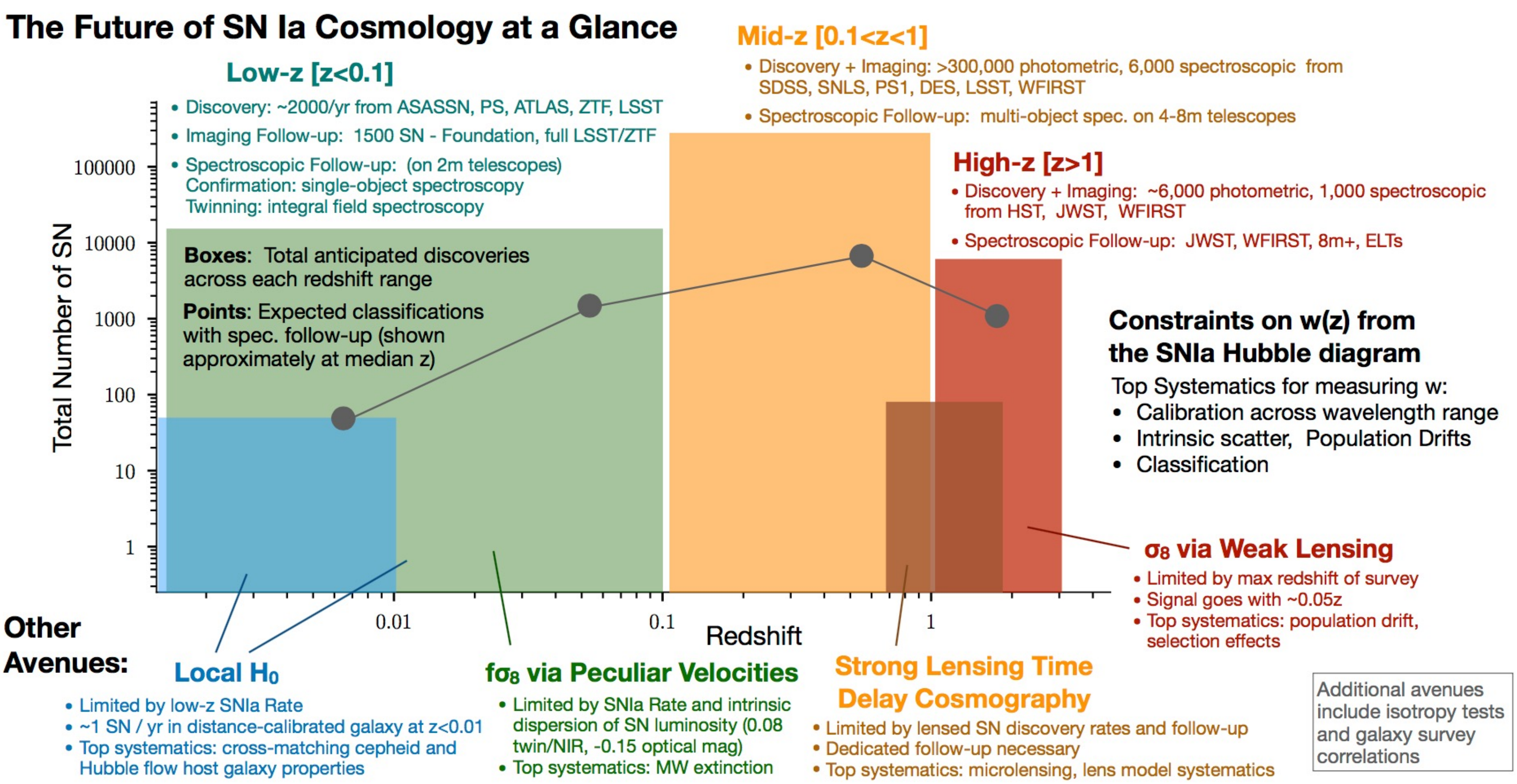
Kai, Shafieloo, Keeley, Linder, ApJ Letters 2019
Kai, Shafieloo, Keeley, Linder, ApJ Letters 2020
Bag, Kim, Linder, Shafieloo, ApJ 2021

H0LiCOW I. H0 Lenses in COSMOGRAIL's Wellspring

Suyu et al. MNRAS 2017

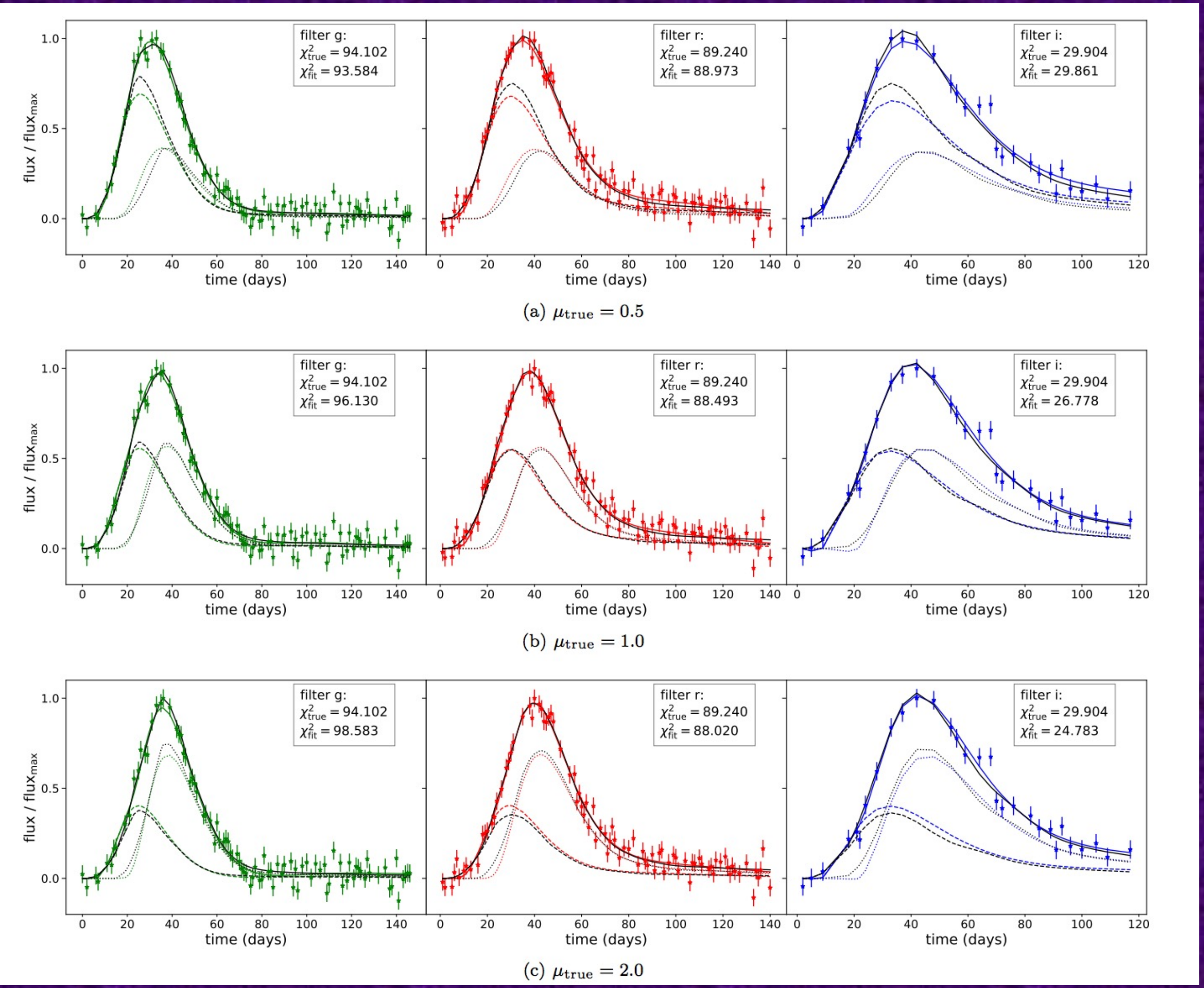
Order	Name	z_L	z_S
1	RXJ1131-1231	0.295	0.654
2	HE 0435-1223	0.4546	1.693
3	B1608+656	0.6304	1.394
4	SDSS 1206+4332	0.745	1.789

Future perspective (late universe, SN Ia)



Scolnic,et al, arXiv:1903.05128

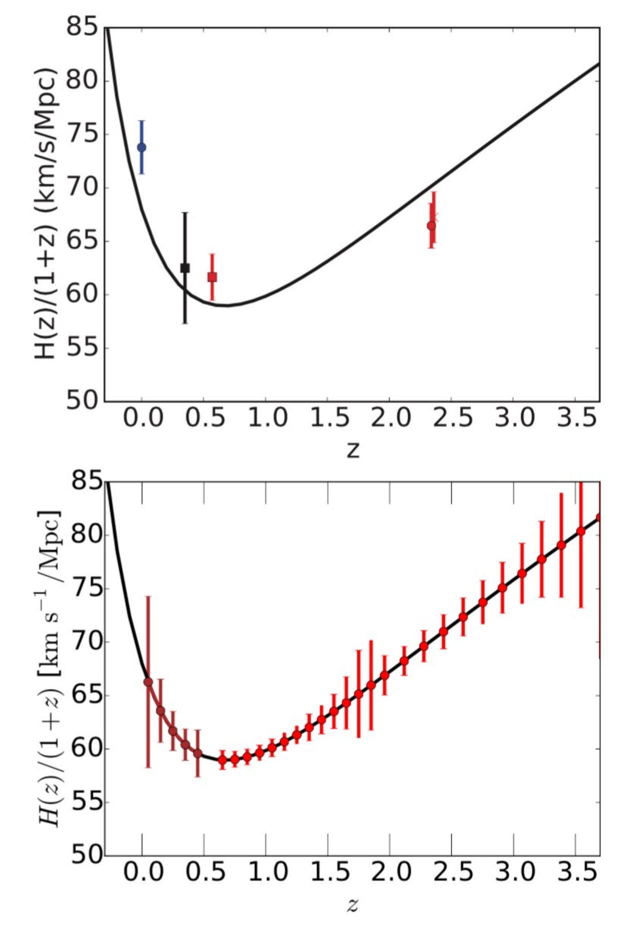
Future Perspective (late universe, SN Ia SL)

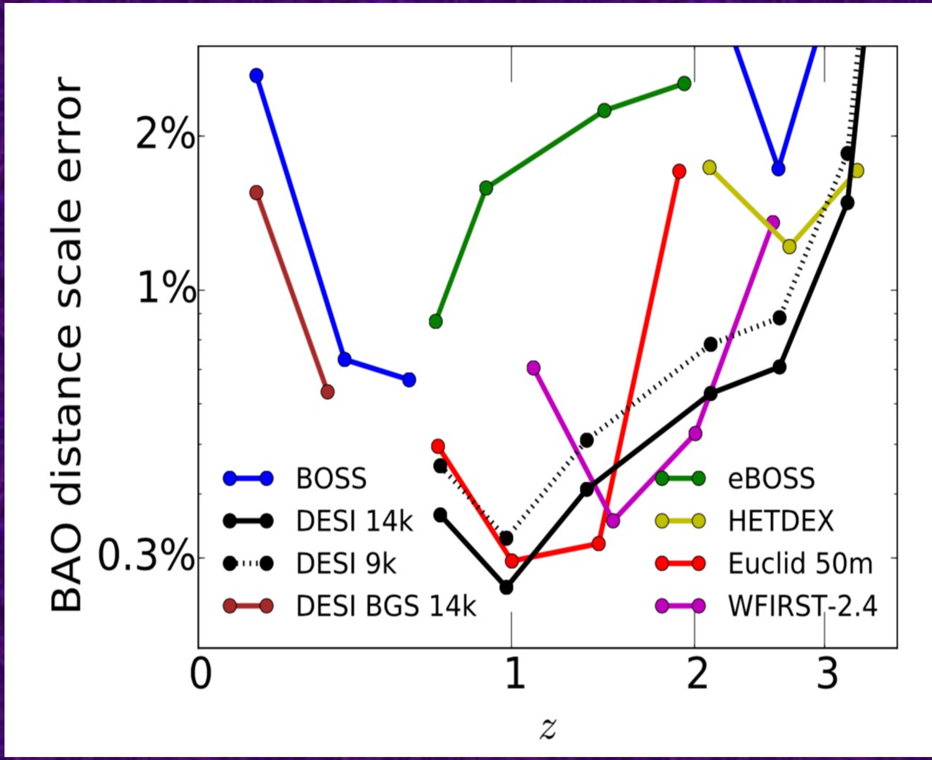


Resolving Unresolved Lensed Systems!

Bag, Kim, Linder & Shafieloo, ApJ 2021

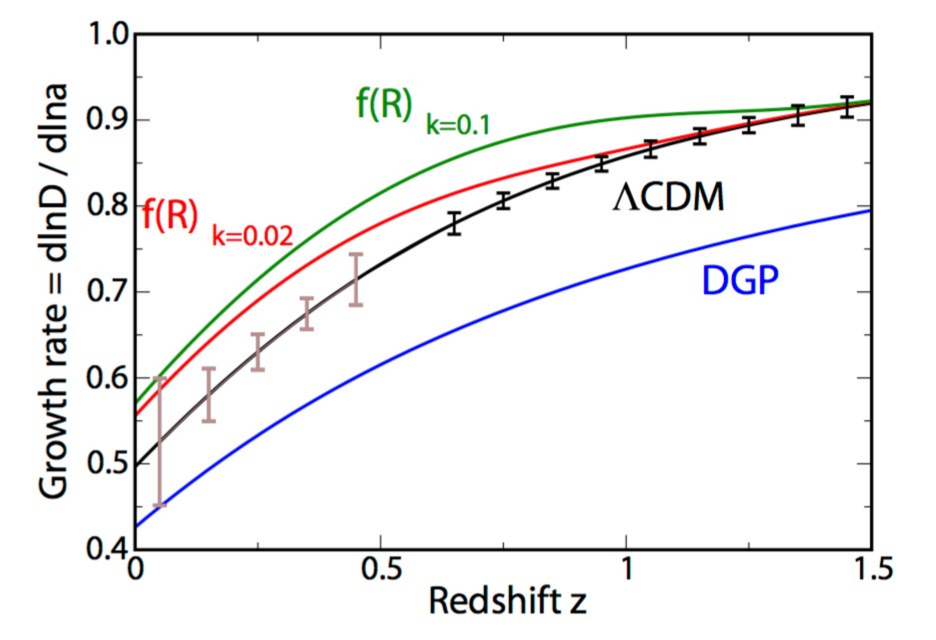
Future perspective (late universe; BAO)

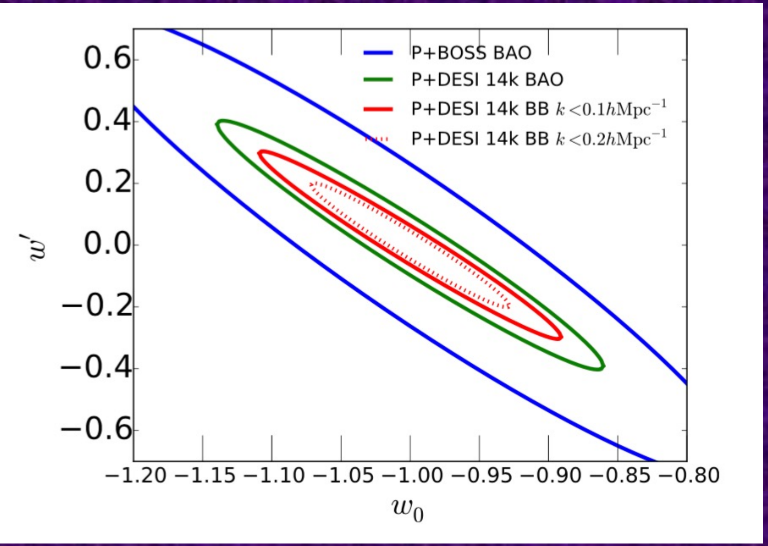




Aghamousa et al, [arXiv:1611.00036]
DESI Collaboration

Future perspective (late universe, RSD)





Aghamousa et al, [arXiv:1611.00036] DESI Collaboration

Future perspective [G-Waves and Standard Sirens]

Astro2020

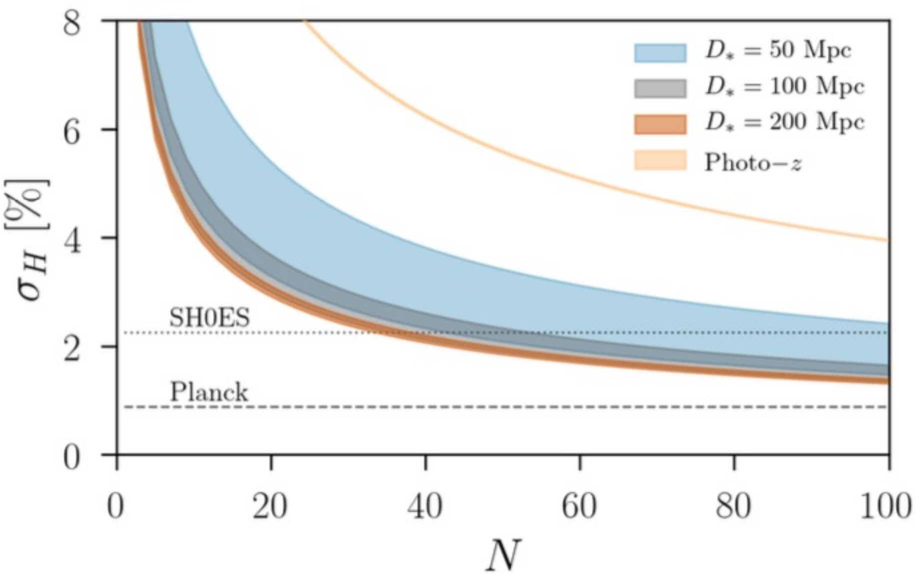


Figure 1: Hubble constant uncertainty (1σ) as a function of combined GW events with associated EM counterpart. The shaded regions show the impact of the peculiar velocity uncertainty between 100 and 400 km s^{-1} for different distance reaches D_*. The latest results from standard candles (SH0ES, [13]) and CMB (*Planck*, [14]) are also shown.

Palmese et al,
arXiv:1903.04730

Future Perspective (primordial)

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!

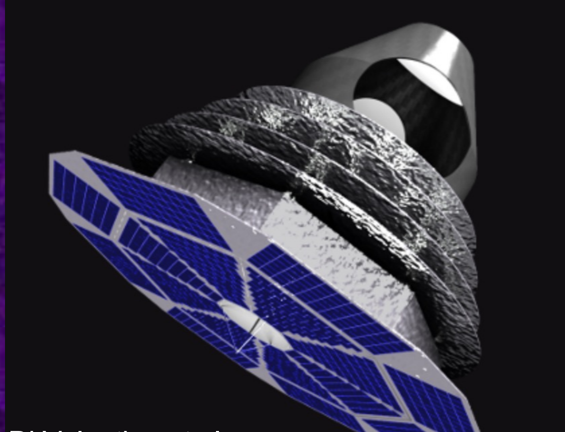
$$P_S(k), P_T(k), P_{iso}(k)$$

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

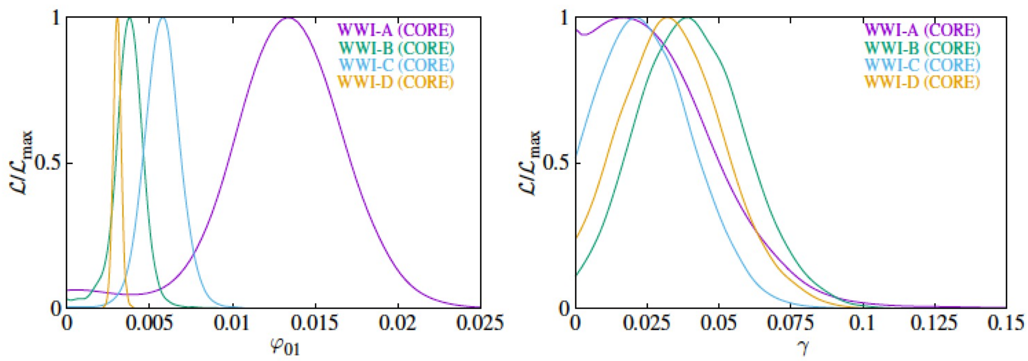
Features with Future of CMB (S4)



Di Valentino et al,
arXiv:1612.00021

With Cosmic Origins Explorer (CORE)-like survey specification

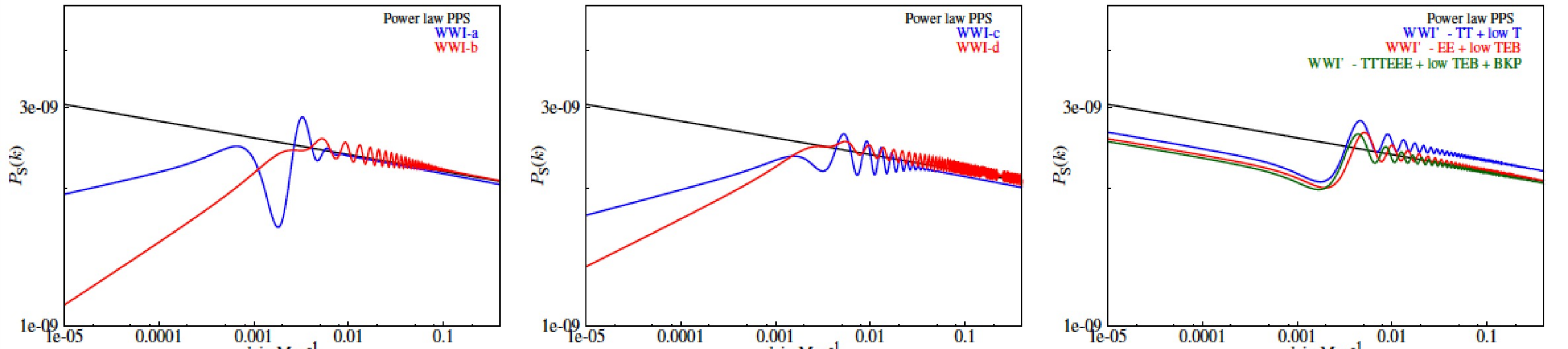
Wiggles **Suppression**



Wiggly Whipped Inflation

Hazra et al, JCAP 2018
Debono et al, MNRAS 2020

- Large scale suppressions can not be detected with high significance
- Some of the intermediate and small scale oscillations can be detected, if present



Future Perspective

From 2D to 3D

Using LSS data to test early universe scenarios

1. We need to estimate matter power spectrum but we observe galaxies. Hence we have to model linear clustering bias and estimate its parameters accurately and precisely to connect the observables to theory. Bias modeling would be different for different surveys and susceptible to systematics.

1. Does power spectrum (or bi-spectrum, etc) necessarily contains all the information in 3D data of LSS? Can't reducing dimensionality of the data wash out some information?

From 2D to 3D

N-Body Simulation (DESI/Euclid like)

L'Huillier, Shafieloo, Hazra, Starobinsky, MNRAS 2018

Hassani, L'Huillier, Shafieloo, Kunz, Adamek, JCAP 2020

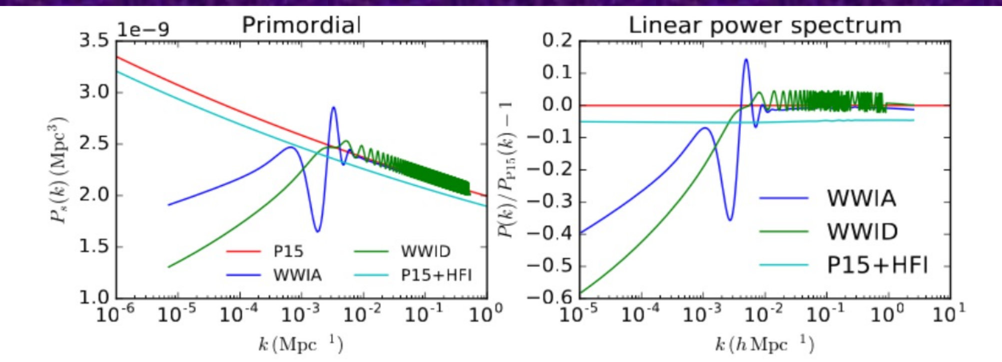
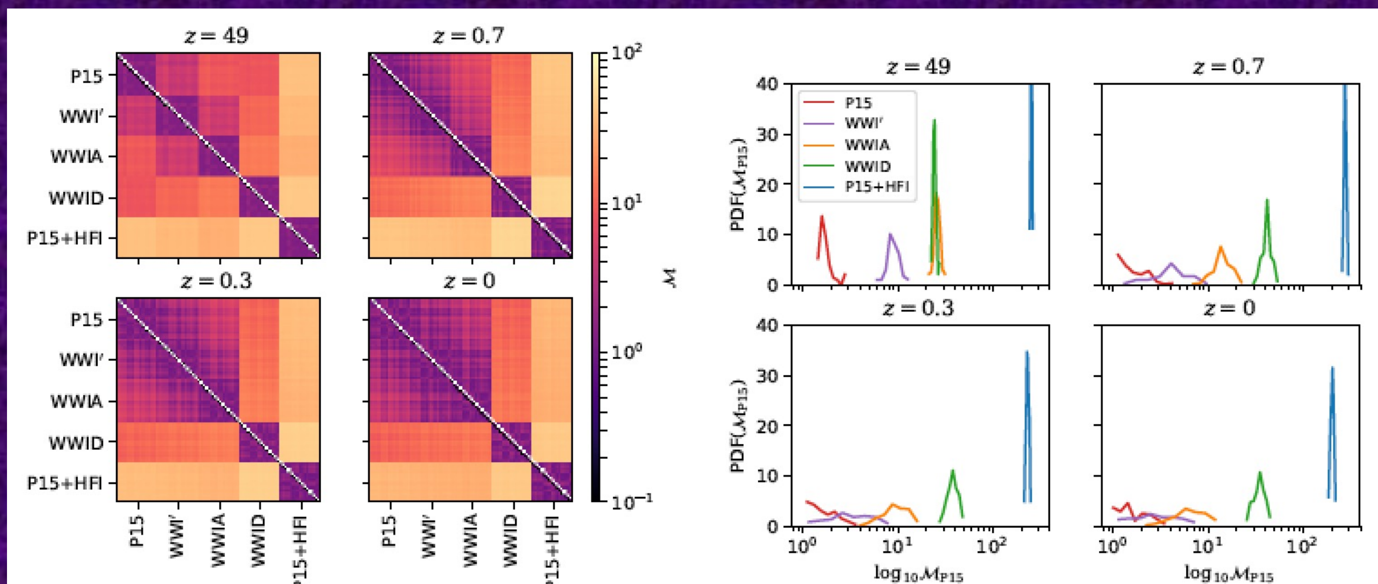


Table 2: Cosmological parameters of models

Model	Ω_m	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	σ_8	n_s
P15	0.319	66.93	0.8156	0.9625
WWIA	0.320	66.86	0.8340	NA
WWID	0.318	67.01	0.8419	NA
P15+HFI	0.319	66.93	0.8156	0.9619

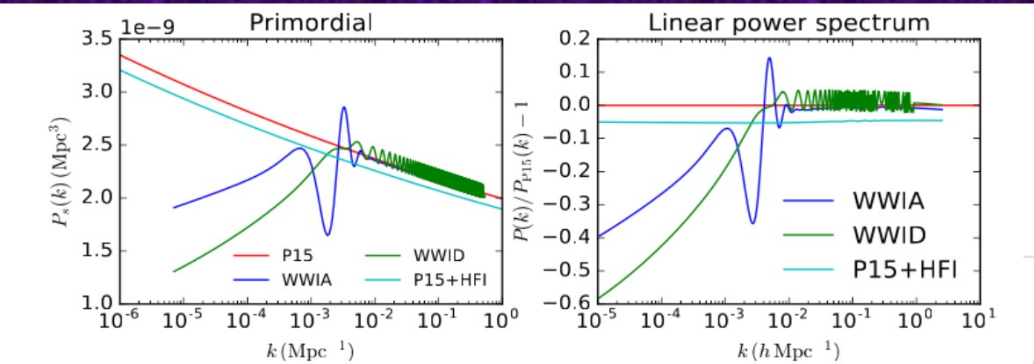
2 point correlation functions and power spectrum unable to distinguish between the models



$$\Xi_{P_i}(k) = \frac{P_i(k) - \langle P_{\mathrm{P15}}(k)\rangle}{\sigma_{P_{\mathrm{P15}}}(k)},$$

$$M_{\mathrm{mod}_i^m,\mathrm{mod}_j^n} = \sqrt{\frac{1}{N_k}\sum_k \left(\Xi_{P_{\mathrm{mod}_i^m}}(k) - \Xi_{P_{\mathrm{mod}_j^n}}(k)\right)^2},$$

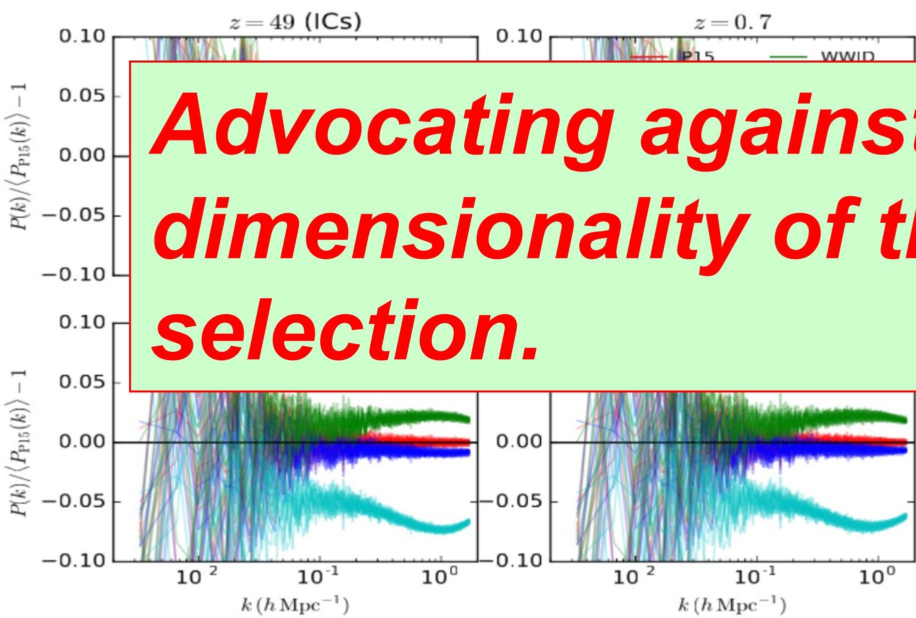
From 2D to 3D



N-Body Simulation (DESI like)

Table 2: Cosmological parameters of models

Model	Ω_m	H_0 ($km\,s^{-1}\,Mpc^{-1}$)	σ_8	n_s
P15	0.319	66.93	0.8156	0.9625
WWIA	0.320	66.86	0.8340	NA
WWID	0.318	67.01	0.8419	NA
P15+HFI	0.319	66.93	0.8156	0.9619



(c) $N_{Mesh} = 512$ ($R = 3.69\,h^{-1}$ Mpc)

(d) $N_{Mesh} = 1024$ ($R = 1.85\,h^{-1}$ Mpc)

Advocating against reducing the dimensionality of the data for model selection.

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.

What we Should be worried about!

Conclusion

- Standard Model of Cosmology fits different data pretty well ***individually*** but there are tensions fitting different combinations of the data.

- H0 tension (and some others) seems remaining persistent in the context of the LCDM model. This can open ways for competitive alternatives ***(GEDE?)***.

- ***Tensions are not resolved with minimal extensions of the standard model.*** It is highly possible that there are ***systematics*** in some of the data and we might need ***new physics*** too. ***It can be a combination of both!*** New independent measurements and observations can help to clear things up.

- ***First target*** can be testing different aspects of the standard 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 observations***, (DESI, Euclid, LSST, WFIRST, SKA(?), etc) will make it much more clear about the status of the concordance model in 2020s.