# Status of the Concordance Model of Cosmology

Arman Shafieloo,

Korea Astronomy and Space Science Institute (KASI)

University of Science and Technology (UST)

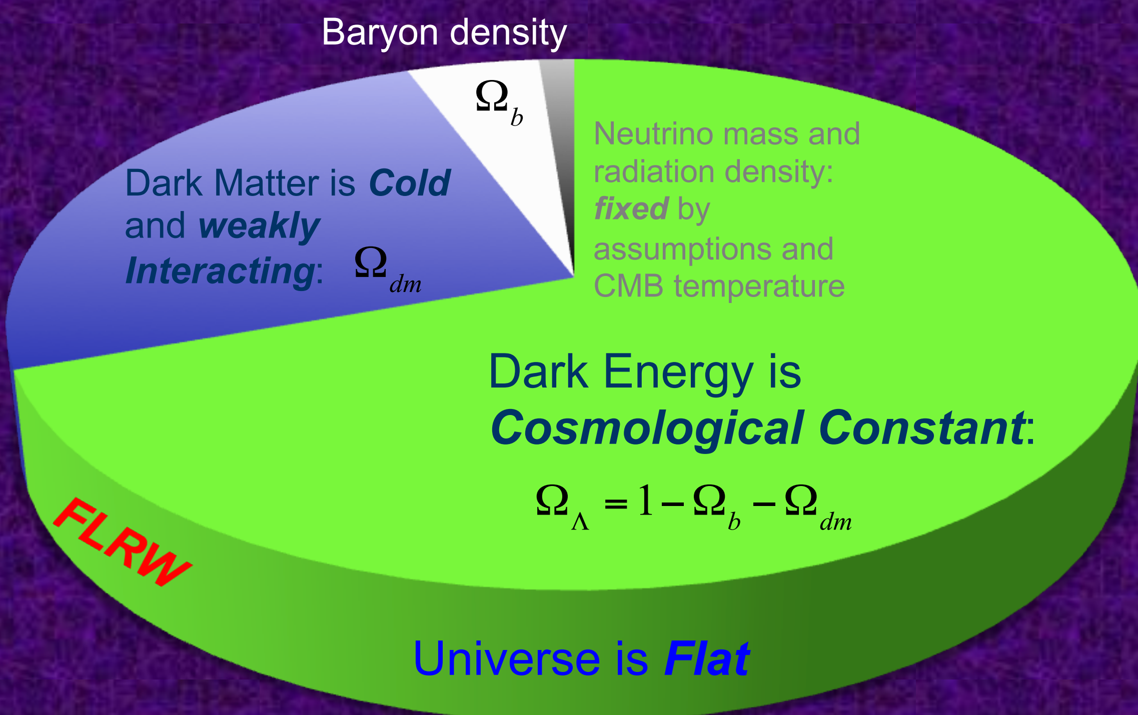
**SubirFest2023**

**A celebration of Subir Sarkar's contributions to astroparticle physics**

**11-13 September 2023, Oxford**

# 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

$\tau$

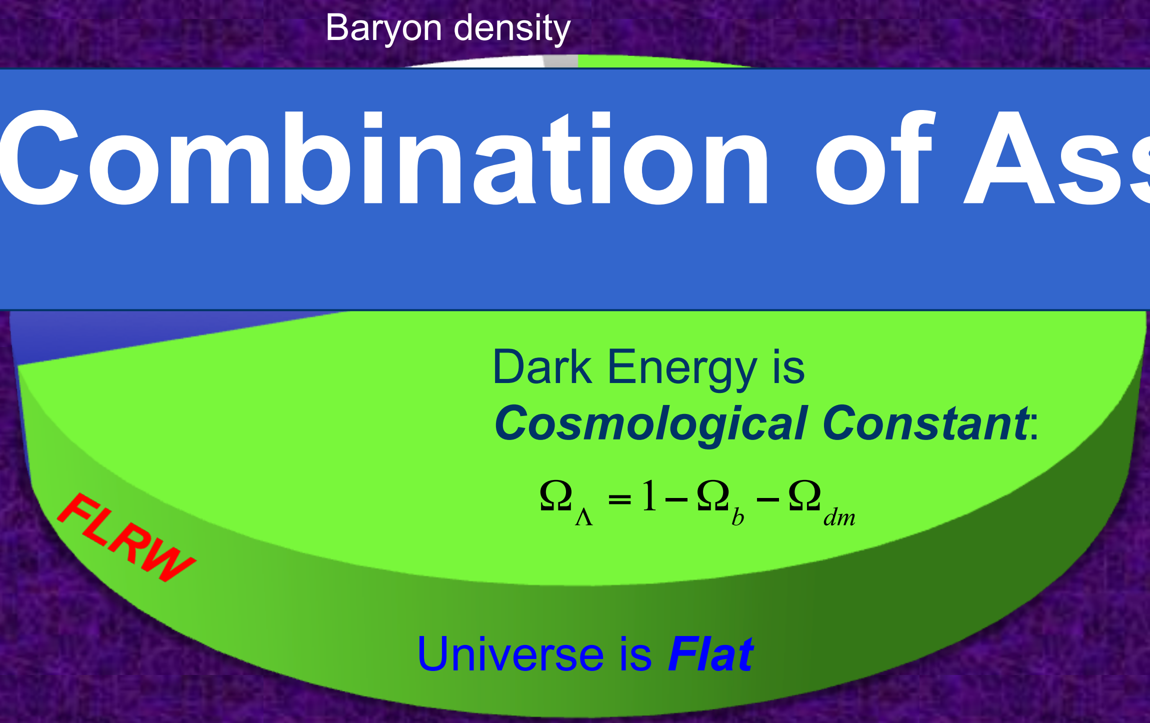
Hubble Parameter and the Rate of Expansion

$H_0$

# Standard Model of Cosmology

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

## Combination of Assumptions




Epoch of reionization

$\tau$

Hubble Parameter and the Rate of Expansion

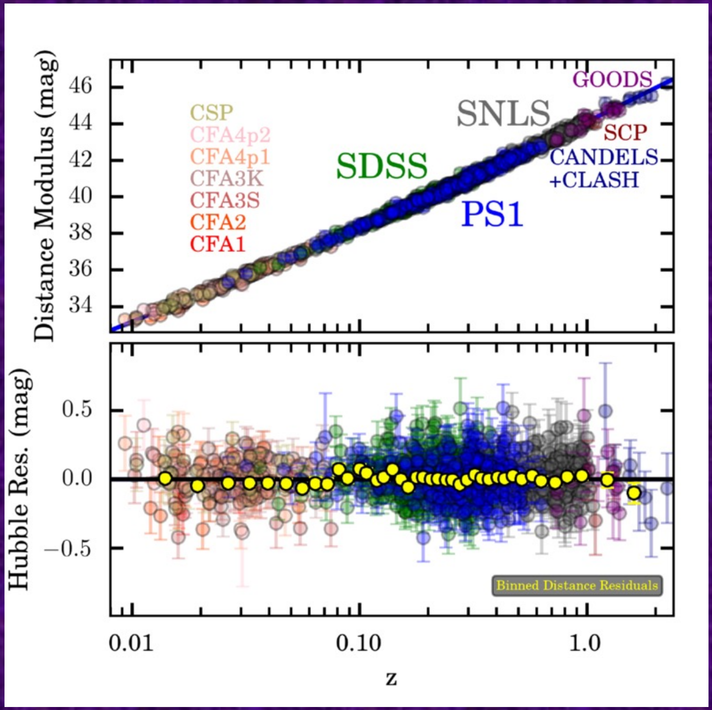
$H_0$

# Standard Model in 2023

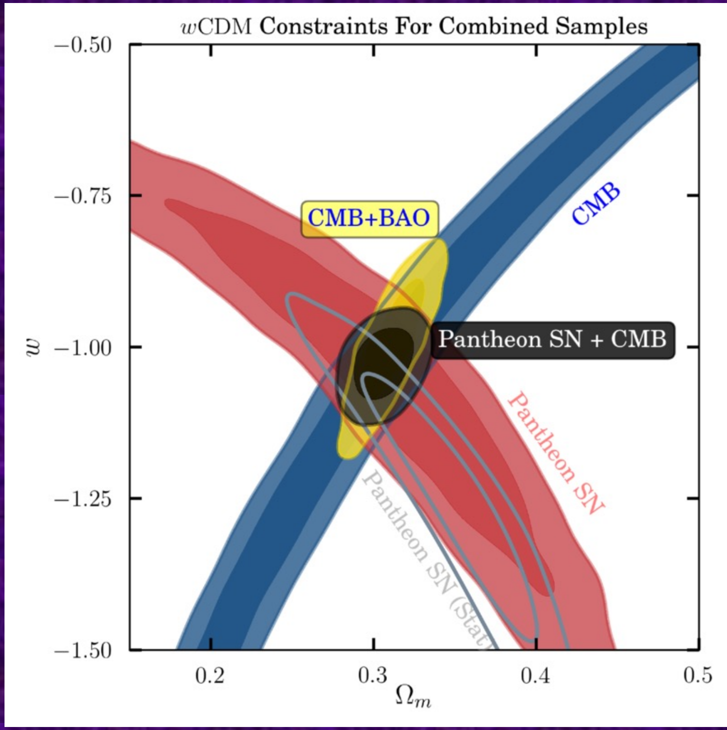
**SN Ia**

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

From 60 Supernovae Ia at cosmic distances, we now have ~1500 published distances, with better precision, better accuracy, out to z~2.0. ***Accelerating universe in proper concordance to the data.***




~1500 spectroscopically confirmed SNIa



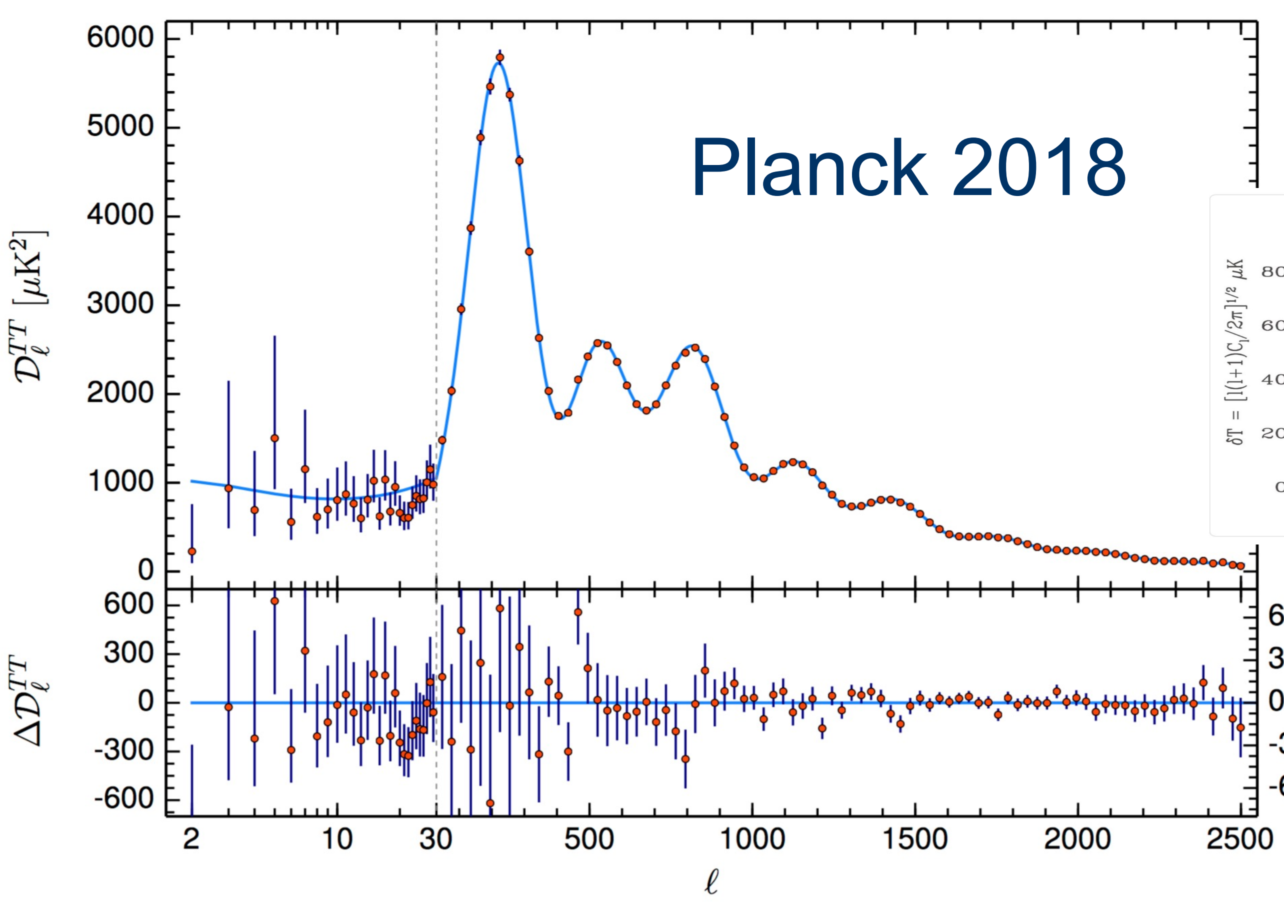

Pantheon+ Compilation
Scolnic et al. (2021)

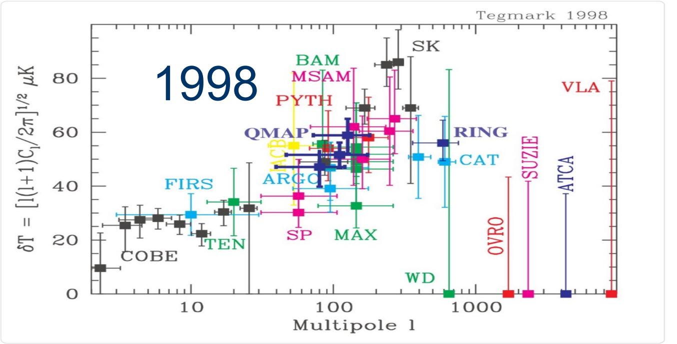
# Standard Model in 2023

**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 2023

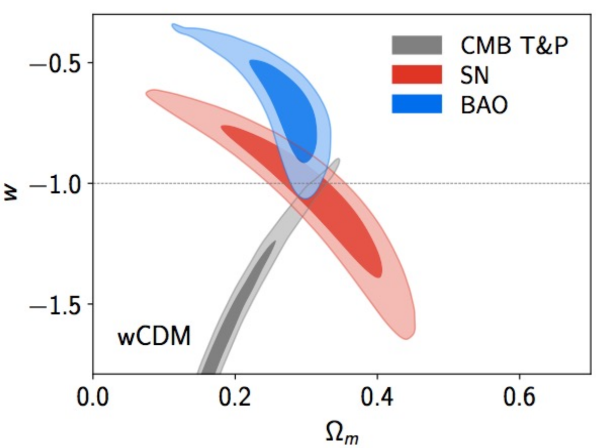
**LSS**

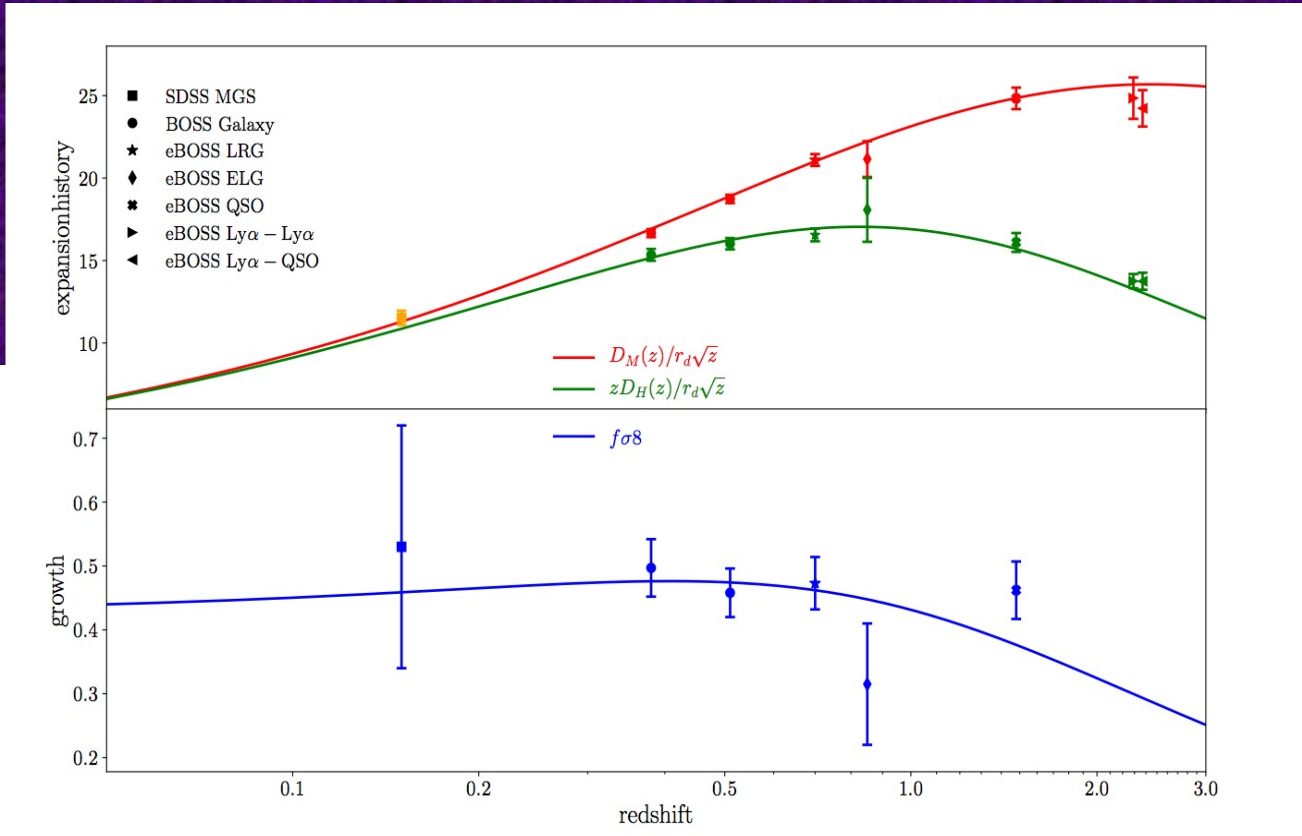
***20 years after discovery of the acceleration of the universe:***

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

SDSS IV - eBOSS Final Cosmology Results

Alam et al, PRD 2021 [arXiv:2007.08991]



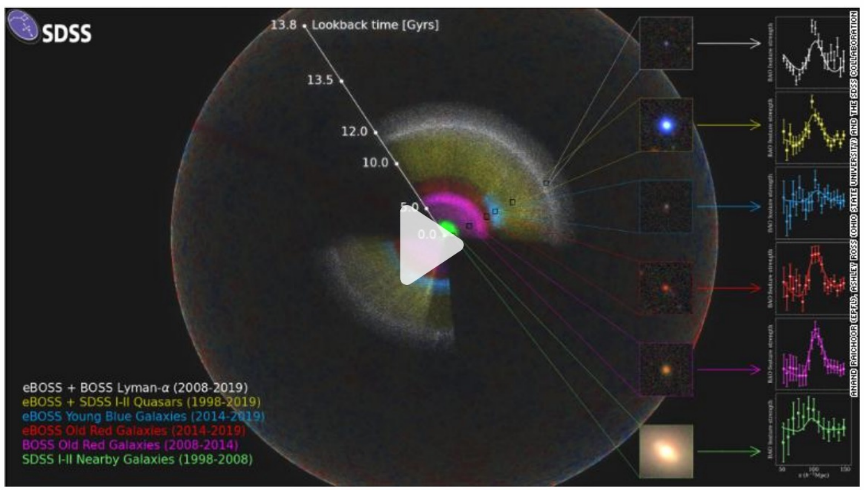



# SDSS IV: Largest 3D Map of the Universe Ever Created



## 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.

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

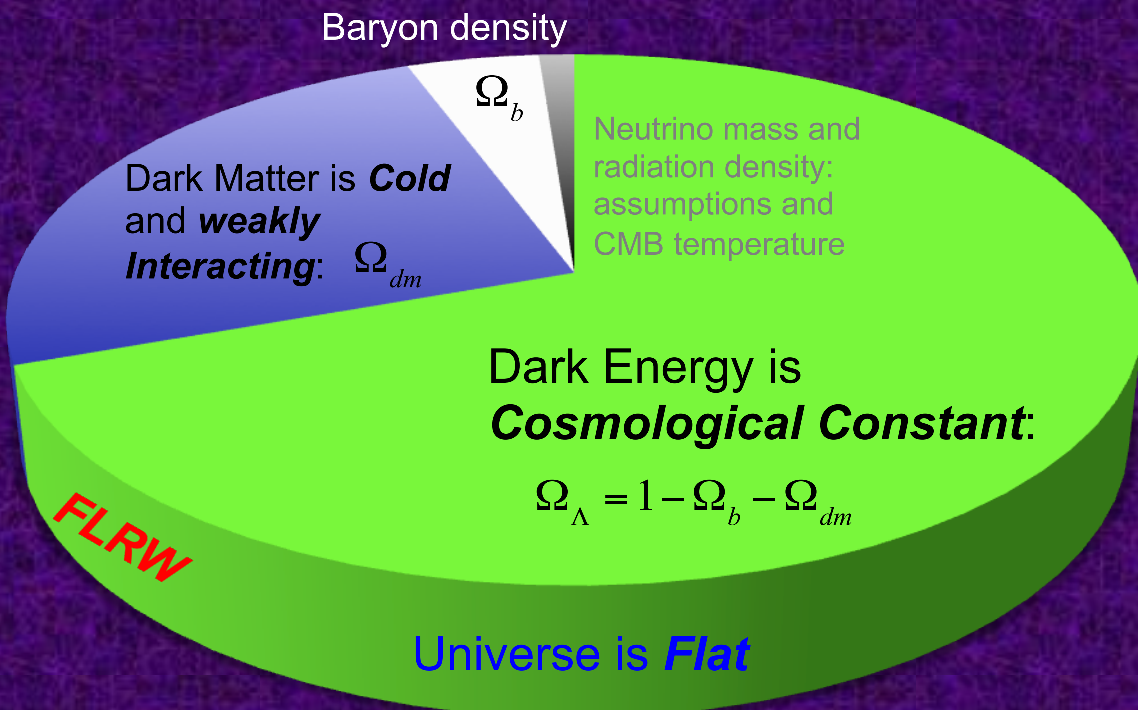
World Africa Americas Asia Australia China Europe India Middle East United Kingdom Edition

**(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.

## Wait for DESI Y1 Cosmology Results→ 2024

# 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

$\tau$

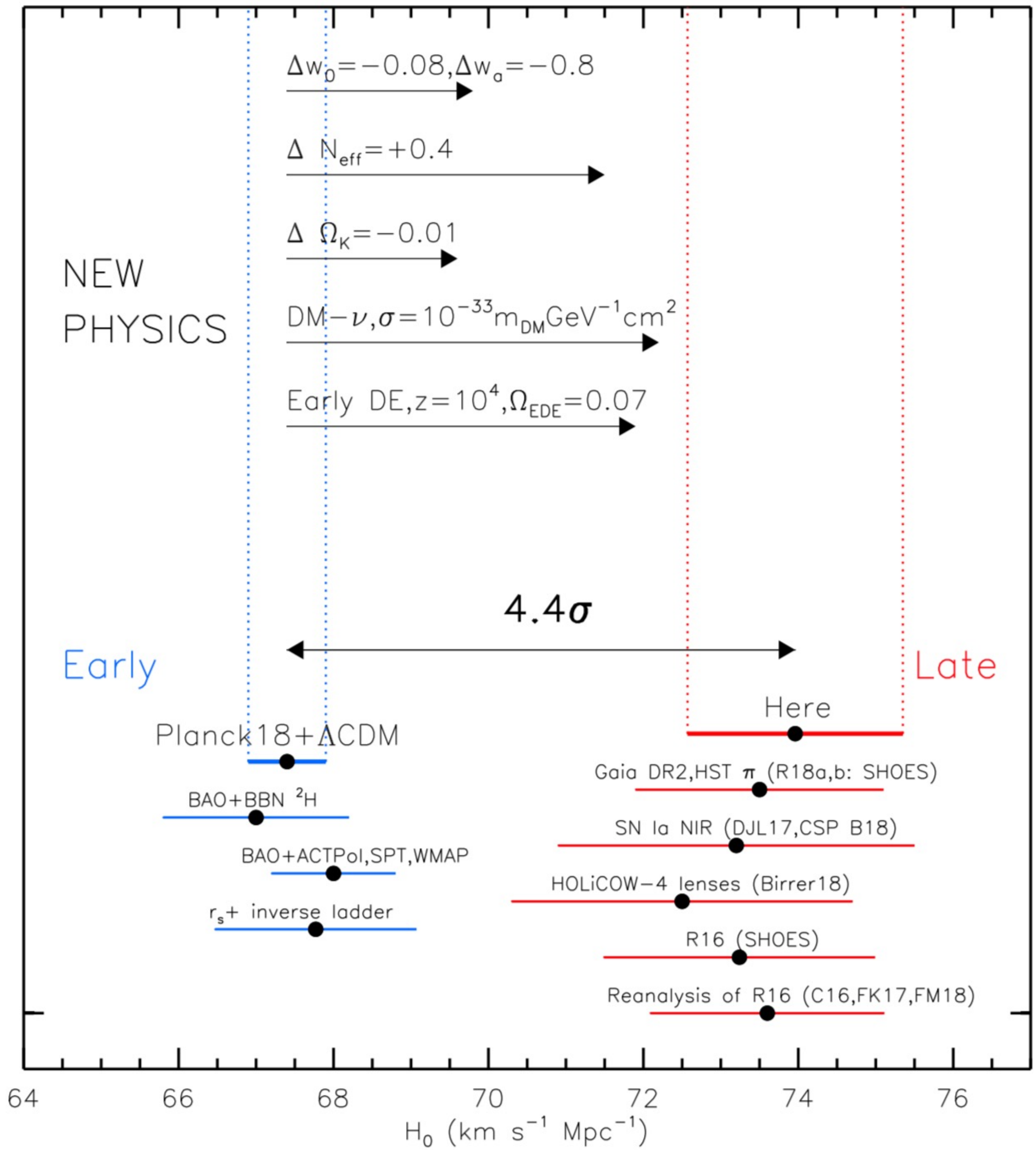
Hubble Parameter and the Rate of Expansion

$H_0$

# Persistent Tensions in the Standard Model

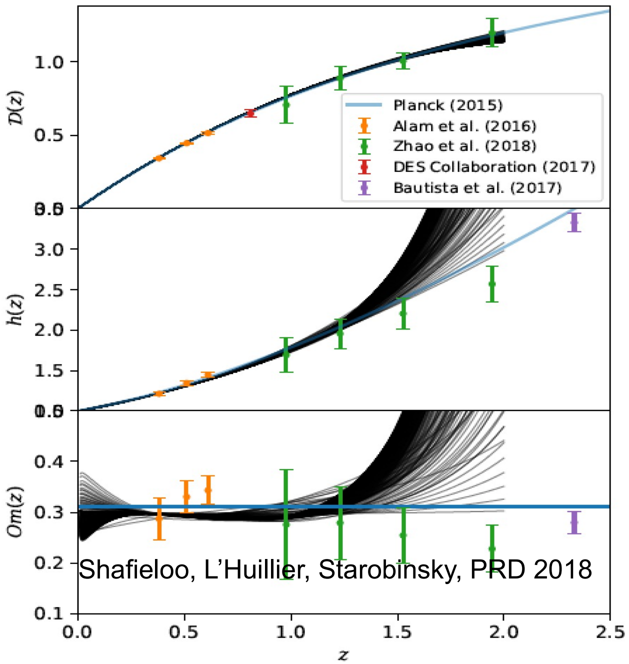
***Local estimation of the Hubble constant seems to be substantially higher than the expected values fitting the standard LCDM model to CMB or LSS.***

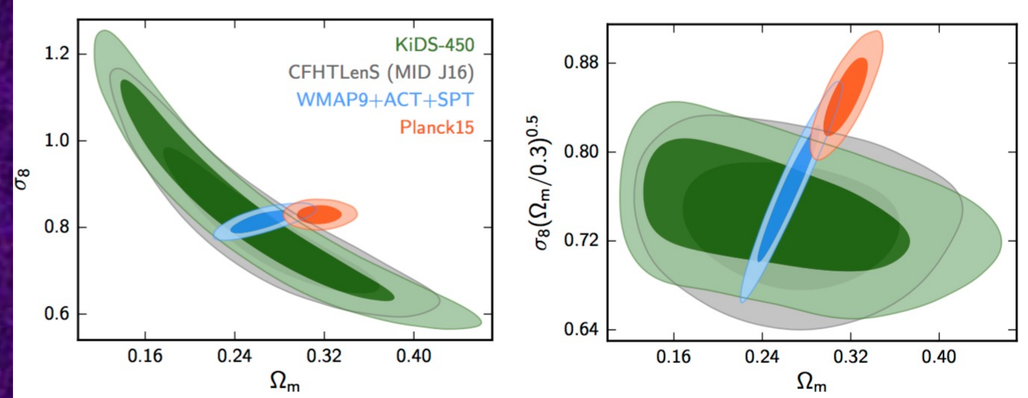
***67 or 74?***




# Tensions in the Standard Model

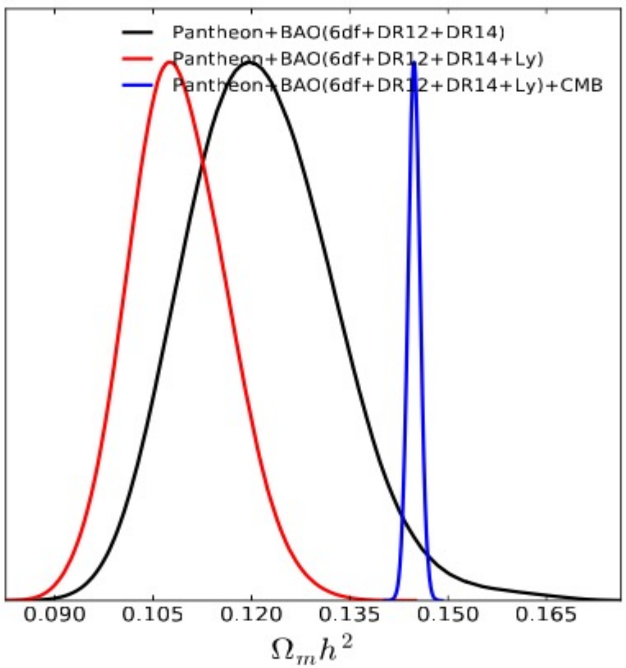
Riess et al, ApJ 2019
[arXiv:1903.07603]

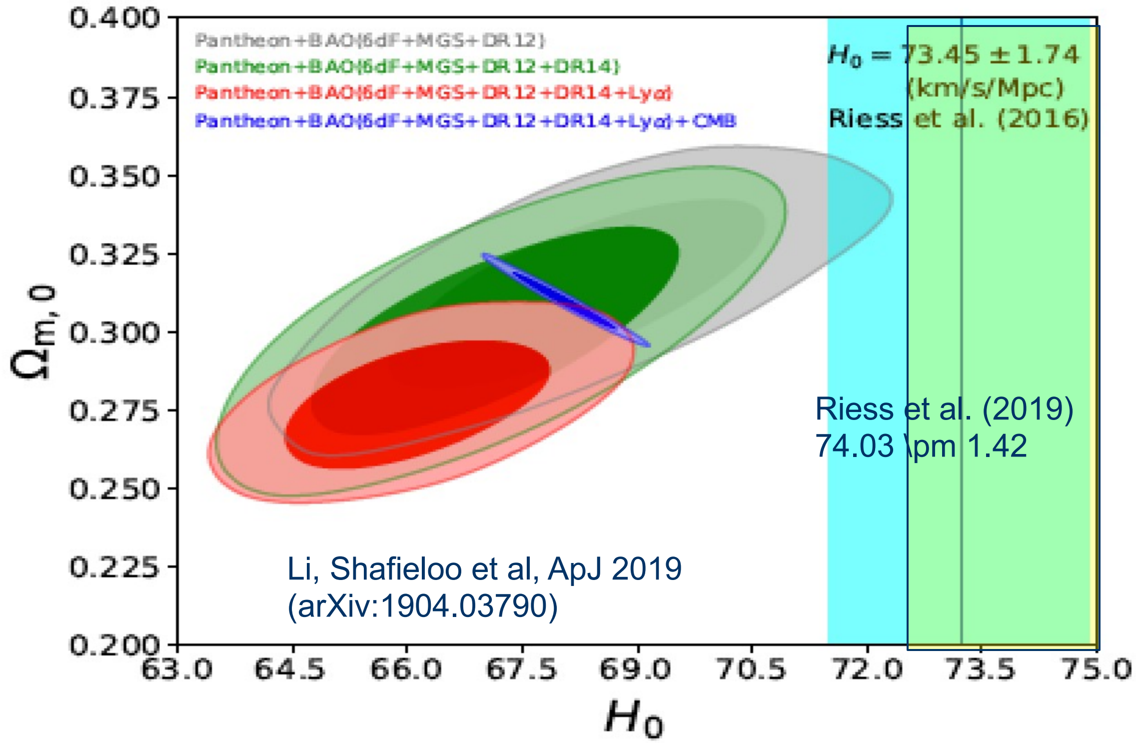


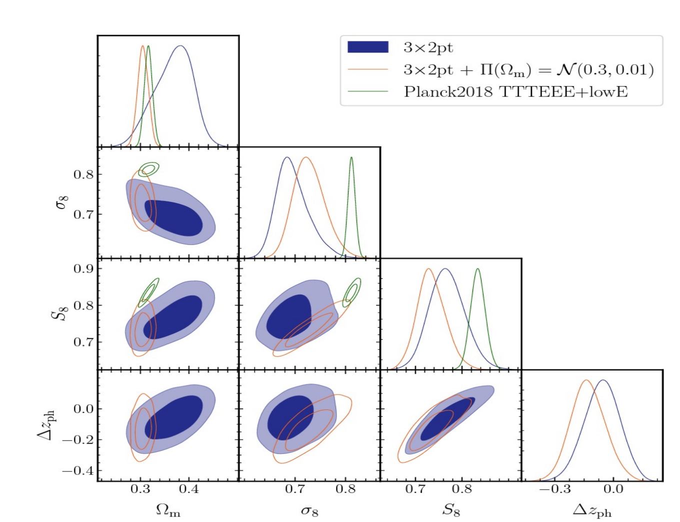




Hildebrandt et al, MNRAS 2017

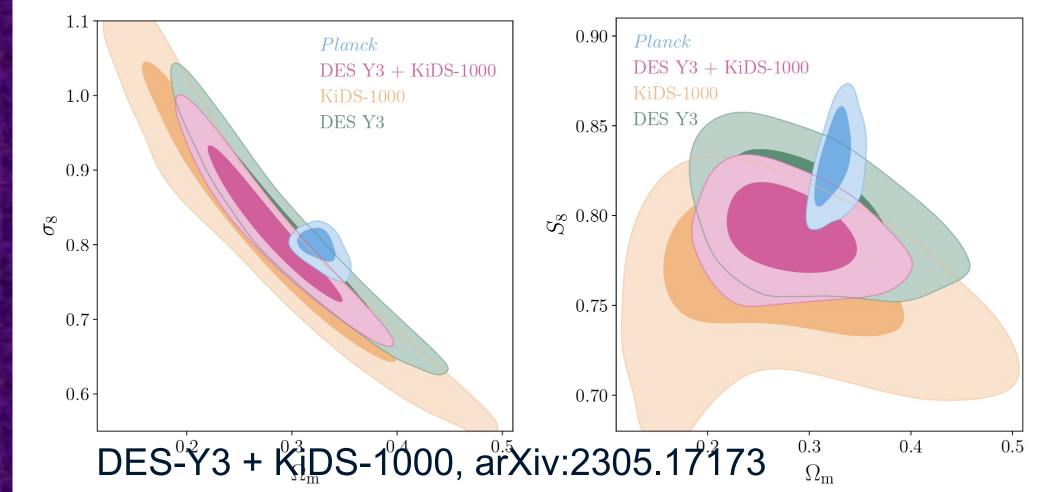
***It is not only about H0 and CMB***. Low H(z)r_d is suggested by BAO and low matter density by WL.



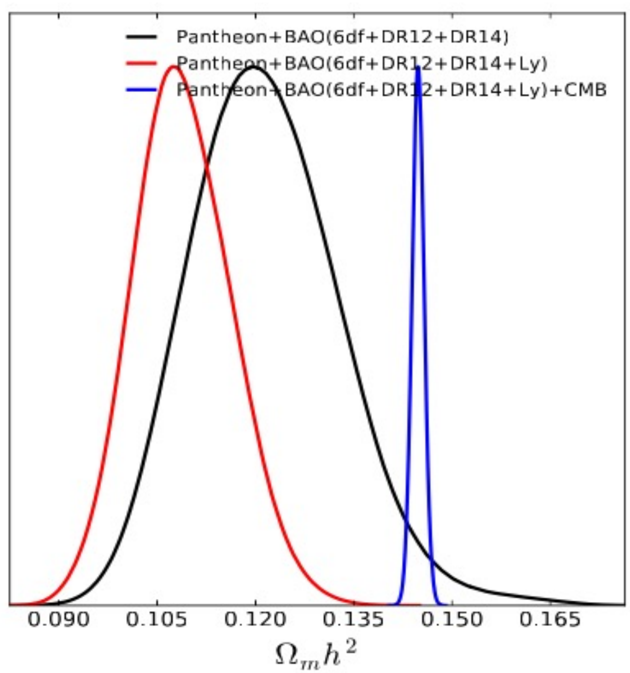


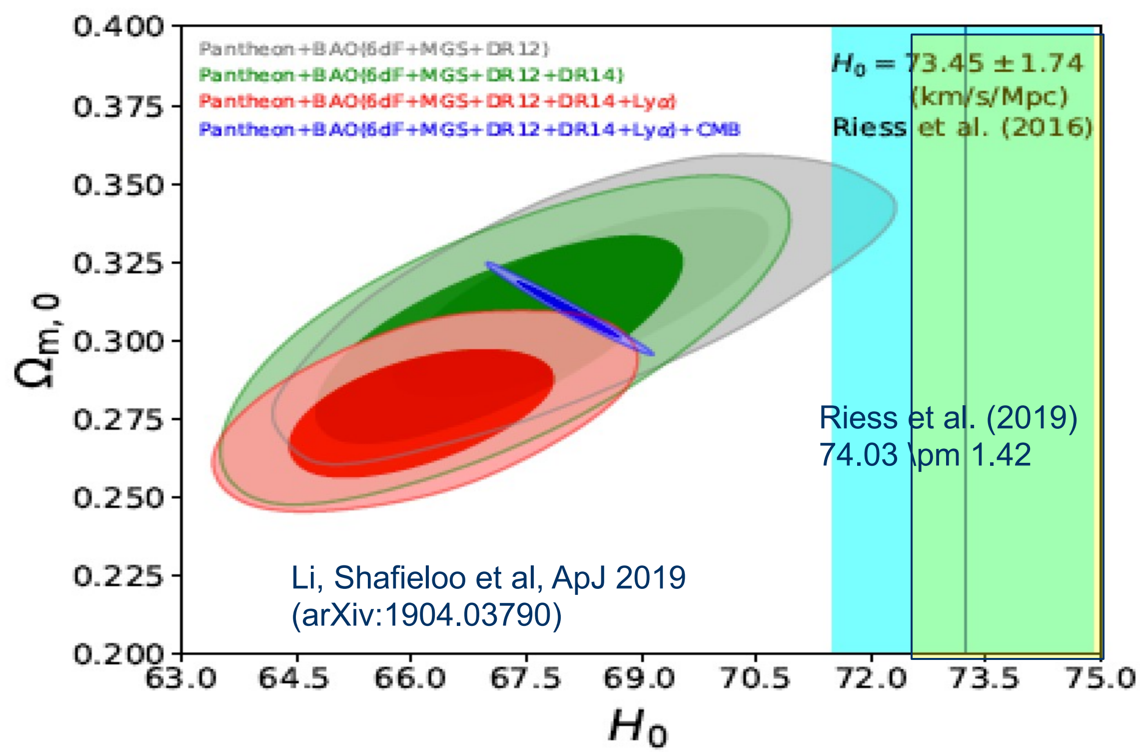

HSC-Y3, arXiv:2304.00704




DES-Y3 + KiDS-1000, arXiv:2305.17173

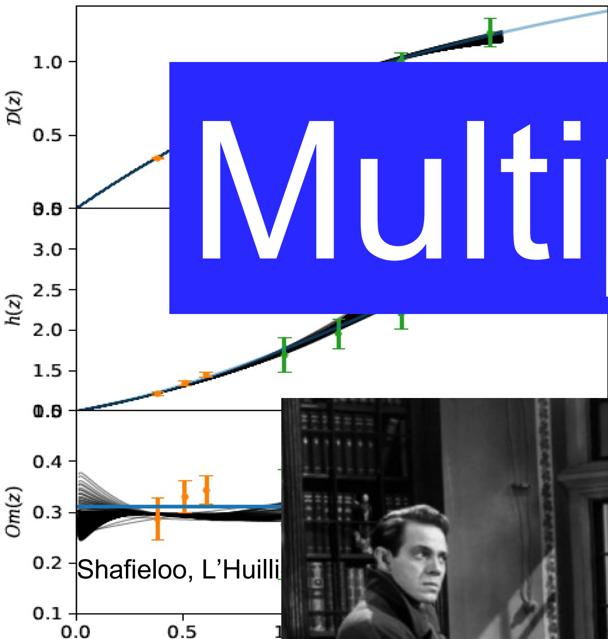
***It is not only about H0 and CMB***. Low S8 and low matter density by WL.

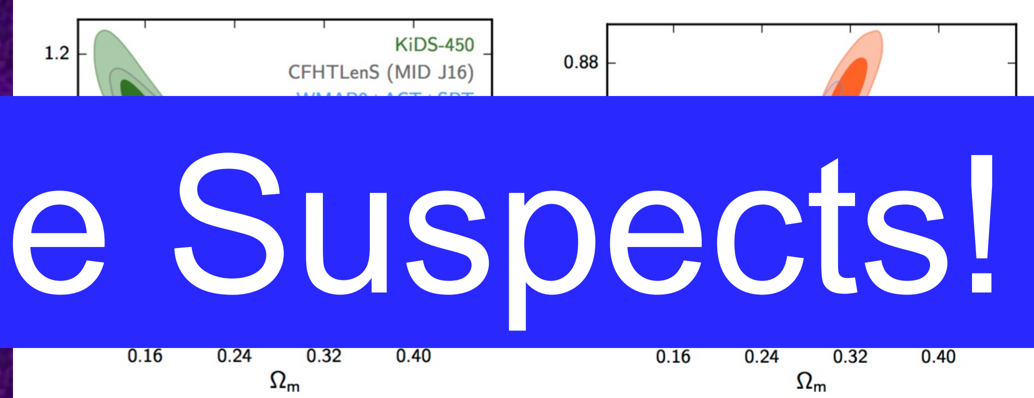


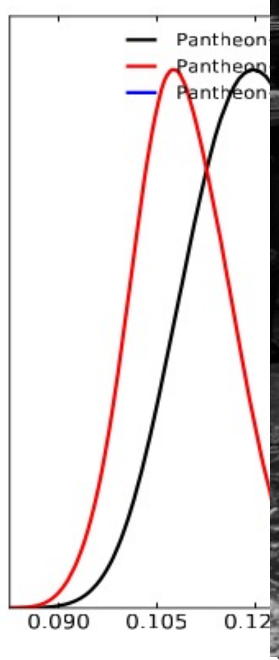

Li, Shafieloo et al, ApJ 2019 (arXiv:1904.03790)

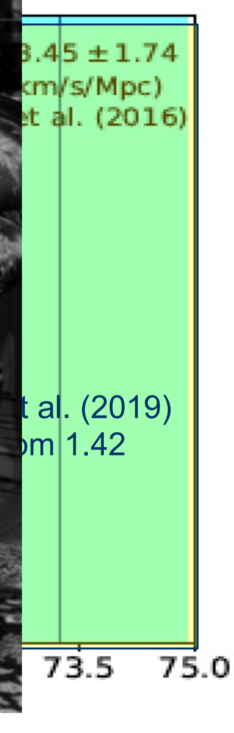
# Multiple Suspects!




…w H(z)r_d is
… by WL.




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, Keely & Shafieloo, PRL 2023)

- 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*

Does LCDM need modification? Which part?

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)

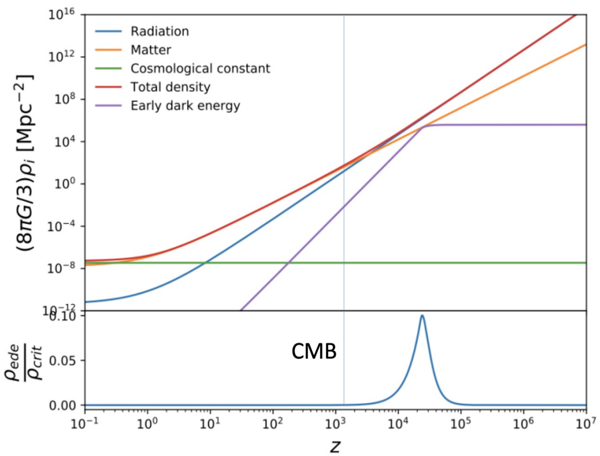
Power-Law primordial spectrum (n_s=const)

Dark Matter is cold

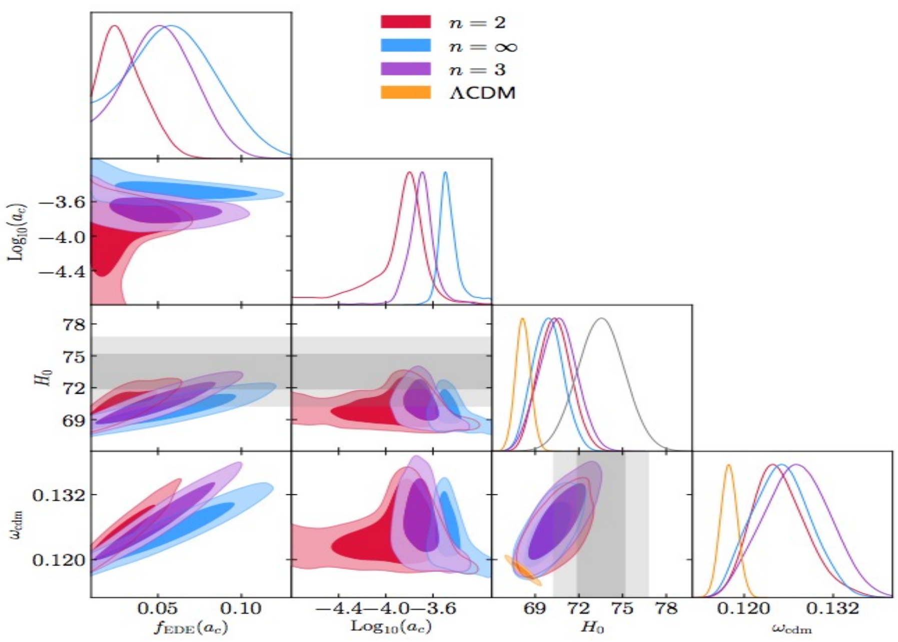
All within framework of FLRW

# Early Dark Energy

Example of an extended model:




Kamionkowski & Riess, arXiv:2211.04492




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

Decreasing r_d by having substantial early dark energy:

Allows having similar H0r_d with higher H0

[few extra dof]

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

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

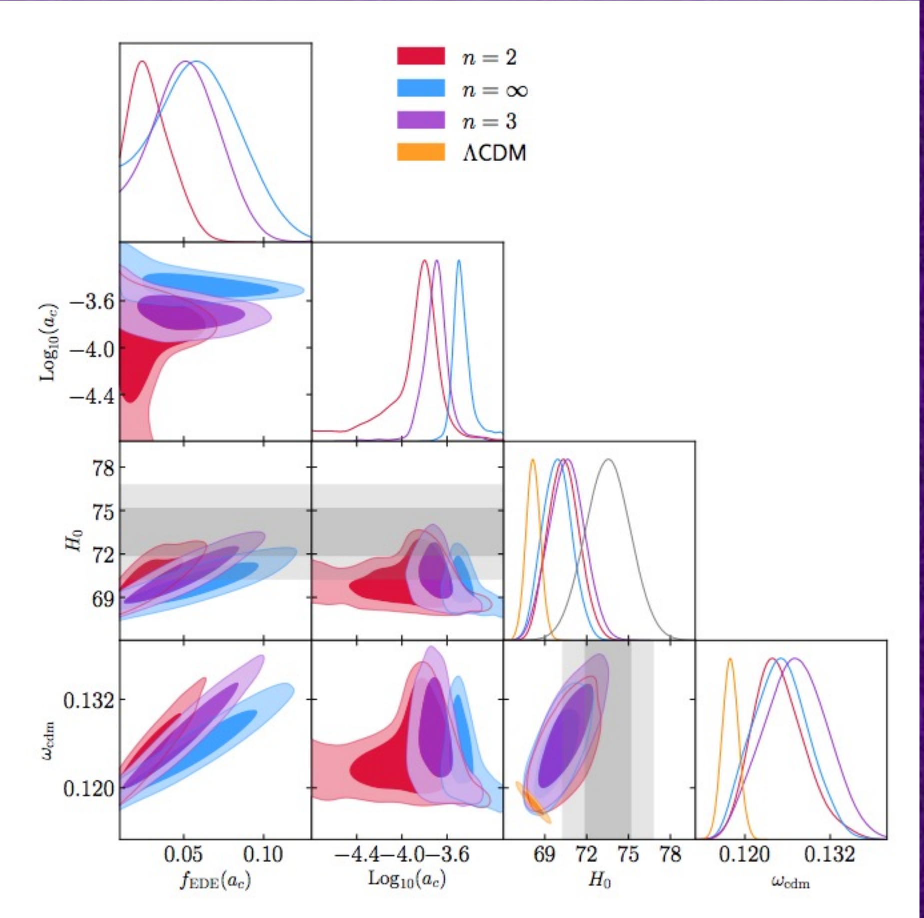
$$w_n = (n-1)/(n+1)$$

Poulin et al, Phys. Rev. Lett 2019

Example of an extended model:

# Early Dark Energy

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




Decreasing r_d by having substantial early dark energy:

Allows having similar H0r_d with higher H0
[few extra dof]

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

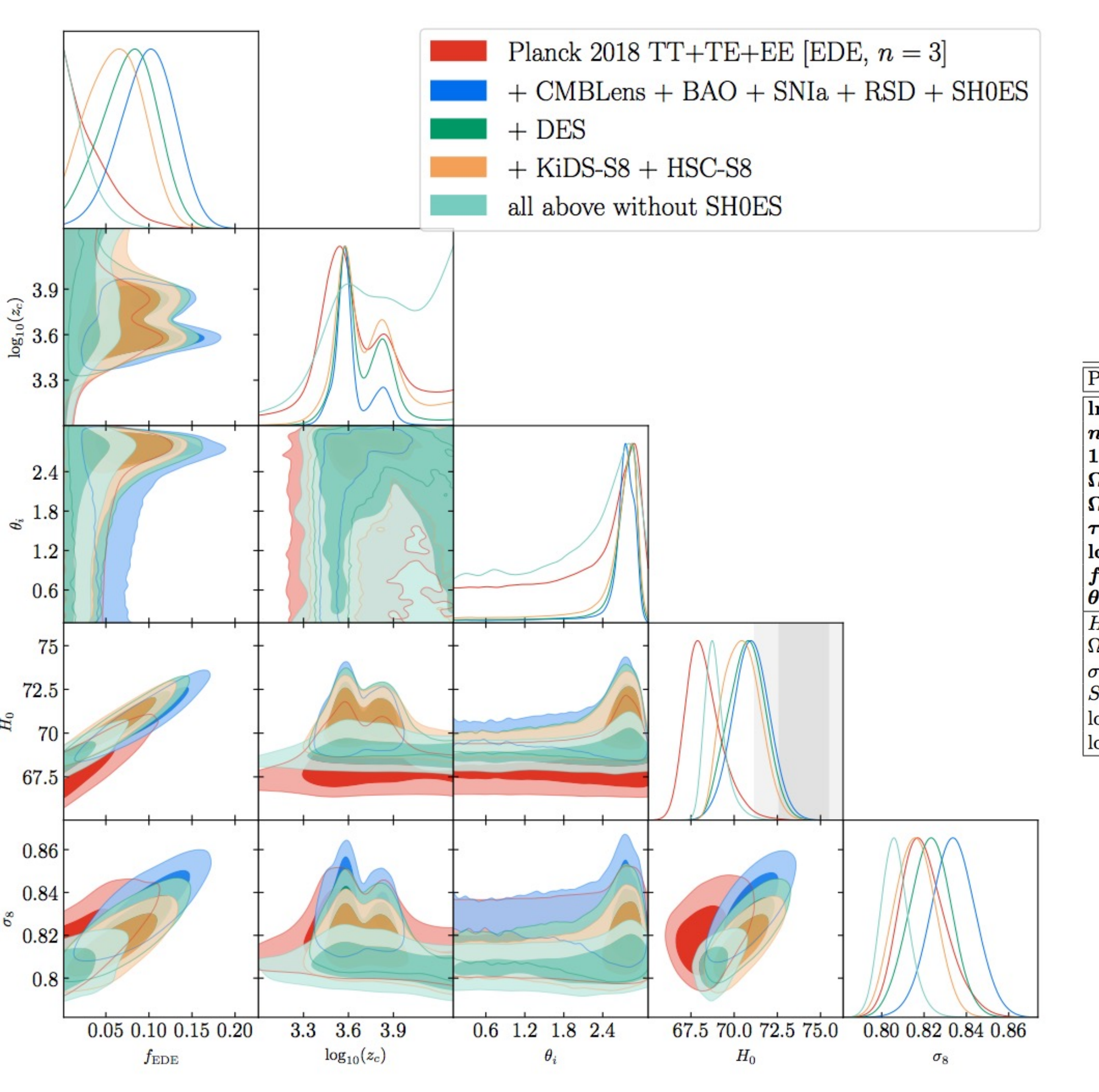
$$w_\varphi(z) = \frac{1 + w_n}{1 + (a_c/a)^{3(1+w_n)}} - 1.$$

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

Poulin et al, Phys. Rev. Lett 2019

Example of an extended model:

# Early Dark Energy



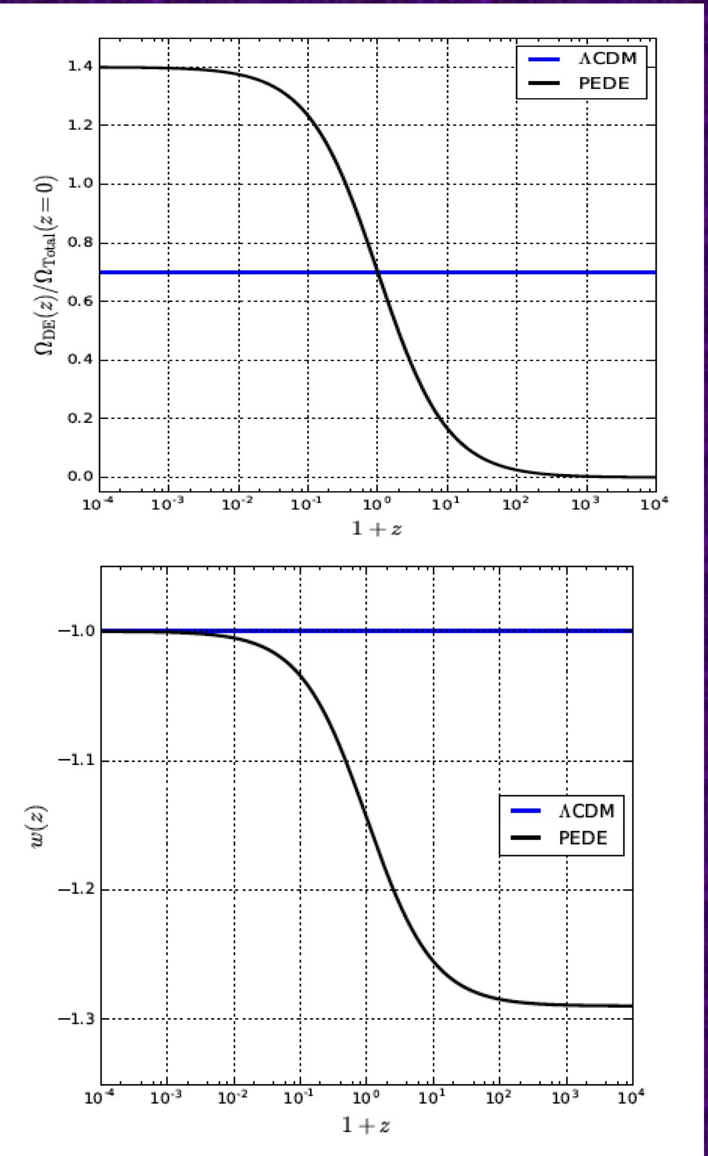

***Tension is not really resolved.***

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

| Parameter | ΛCDM | EDE ($n = 3$) |
|---|---|---|
| $\ln(10^{10} A_s)$ | 3.044 (3.055) ± 0.016 | 3.051 (3.056) ± 0.017 |
| $n_s$ | 0.9645 (0.9659) ± 0.0043 | 0.9702 (0.9769)$^{+0.0071}_{-0.0069}$ |
| $100\theta_s$ | 1.04185 (1.04200) ± 0.00029 | 1.04164 (1.04168) ± 0.00034 |
| $\Omega_b h^2$ | 0.02235 (0.02244) ± 0.00015 | 0.02250 (0.02250) ± 0.00020 |
| $\Omega_c h^2$ | 0.1202 (0.1201) ± 0.0013 | 0.1234 (0.1268)$^{+0.0031}_{-0.0030}$ |
| $\tau_{\rm reio}$ | 0.0541 (0.0587) ± 0.0076 | 0.0549 (0.0539) ± 0.0078 |
| $\log_{10}(z_c)$ | – | 3.66 (3.75)$^{+0.28}_{-0.24}$ |
| $f_{\rm EDE}$ | – | $< 0.087$ (0.068) |
| $\theta_i$ | – | $> 0.36$ (2.96) |
| $H_0$ [km/s/Mpc] | 67.29 (67.44) ± 0.59 | 68.29 (69.13)$^{+1.02}_{-1.00}$ |
| $\Omega_m$ | 0.3162 (0.3147) ± 0.0083 | 0.3145 (0.3138) ± 0.0086 |
| $\sigma_8$ | 0.8114 (0.8156) ± 0.0073 | 0.8198 (0.8280)$^{+0.0109}_{-0.0107}$ |
| $S_8$ | 0.8331 (0.8355) ± 0.0159 | 0.8393 (0.8468) ± 0.0173 |
| $\log_{10}(f/{\rm eV})$ | – | 26.57 (26.36)$^{+0.39}_{-0.36}$ |
| $\log_{10}(m/{\rm eV})$ | – | −26.94 (−26.90)$^{+0.58}_{-0.53}$ |

Hill et al, PRD 2020, arXiv:2003.07355

# Phenomenologically Emergent Dark Energy ( PEDE)




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

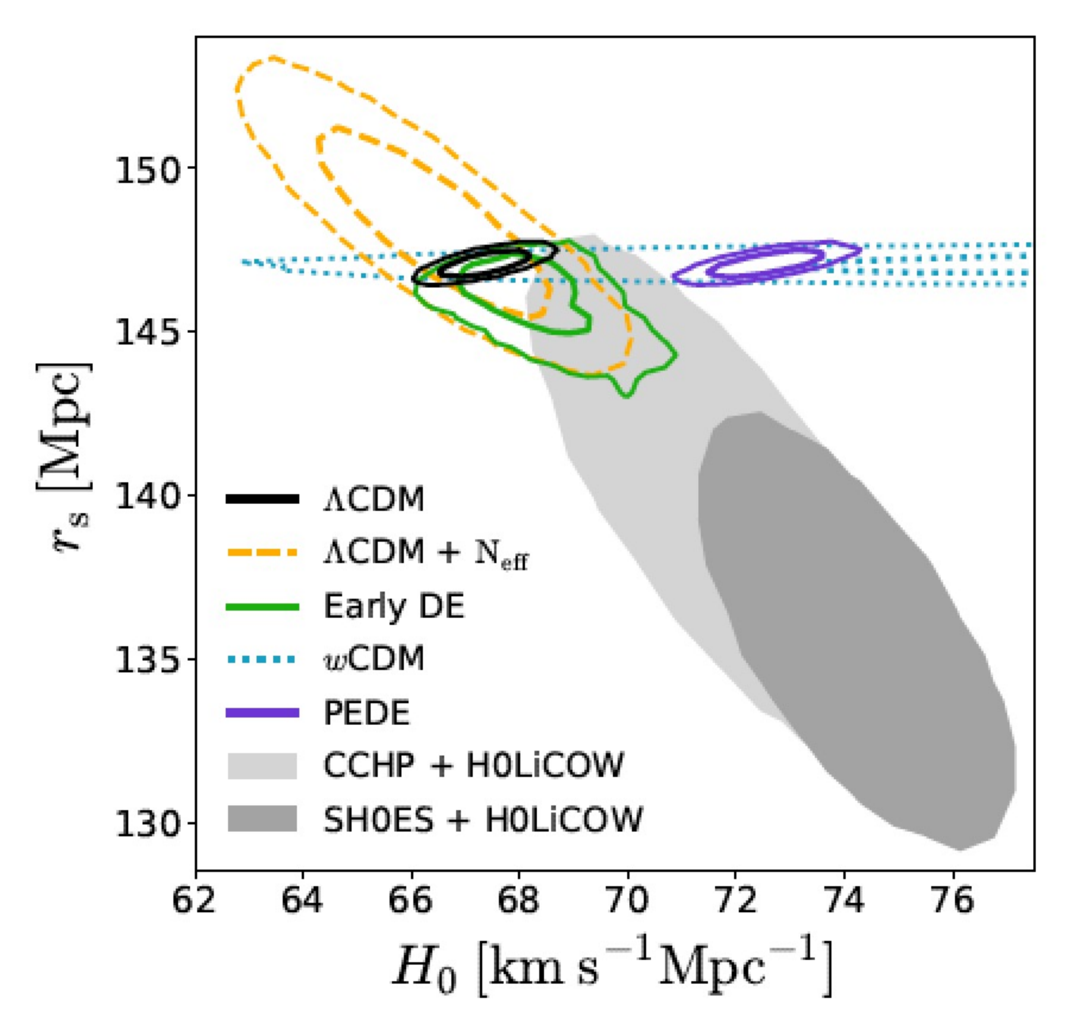
Allows lower rate of expansion in the past and higher rate of expansion at late times

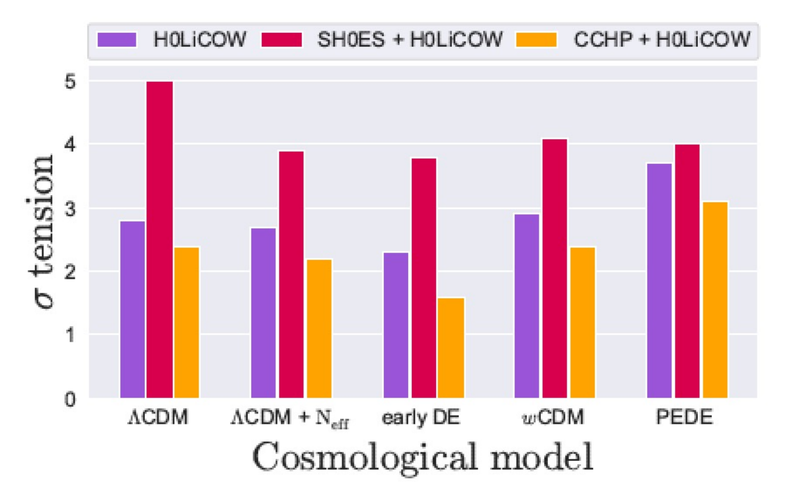
$$\Omega_{\rm DE}(z) = \Omega_{\rm DE,0} \times [1 - \tanh(\log_{10}(1+z))]$$

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

Li and Shafieloo, ApJ Lett 2019

# Comparing candidates




Arendse et al, A&A 2020
arXiv:1909.07986

H0LiCOW Collaboration

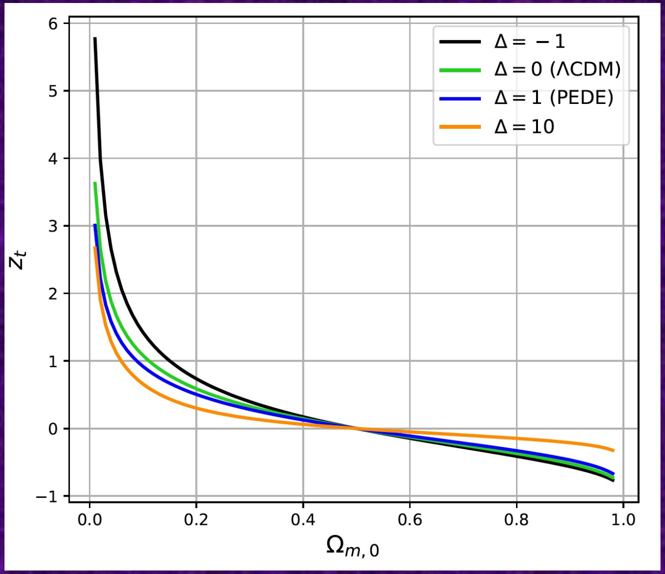
# Generalized Emergent Dark Energy (GEDE)

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

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

*-Has one degree of freedom for DE sector*

***-LCDM and PEDE are both included at special limits***




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

$\Delta = 0$ LCDM

$\Delta = 1$ PEDE

Li and Shafieloo, ApJ 2020 (arXiv:2001.05103)

# Generalized Emergent Dark Energy (GEDE)

| 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!

*True for any successful evolving DE model!*

W. Yang,et al, PRD 2021 [arXiv:2103.03815]

# Some side notes on conventional statistics:

- Be cautious about Jeffery's scale!

| Jeffreys scale $Z_i/Z_j$ | Kass-Rafferty scale $Z_i/Z_j$ | Interpretation |
|---|---|---|
| 1 to 3.2 | 1 to 3 | Not worth mentioning |
| 3.2 to 10 | 3 to 20 | Positive |
| 10 to 100 | 20 to 150 | Strong |
| > 100 | >150 | Very Strong |

Distribution of Bayes factors can greatly depend on the models and the data!

**On The Distribution of Bayesian Evidences**

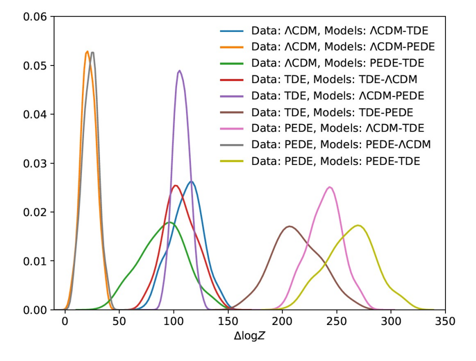
Ryan E. Keeley,[1,2]* Arman Shafieloo,[2,3]†
[1] Department of Physics, University of California Merced, 5200 North Lake Road, Merced, CA 95343, USA
[2] Korea Astronomy and Space Science Institute (KASI), 776 Daedeok-daero, Yuseong-gu, Daejeon 34055, Korea
[3] KASI Campus, University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Korea

Accepted XXX. Received YYY; in original form ZZZ

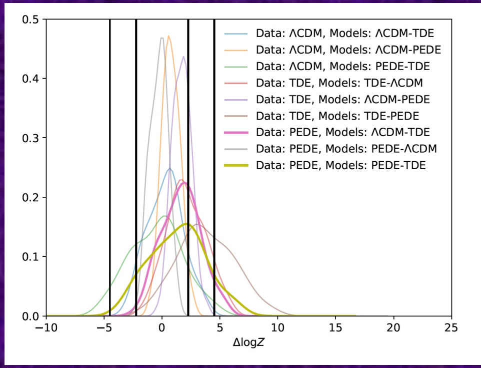
**ABSTRACT**
We look at the distribution of the Bayesian evidence for mock realizations of supernova and baryon acoustic oscillation data. The ratios of Bayesian evidences of different models are often used to perform model selection. The significance of these Bayes factors are then interpreted using scales such as the Jeffreys or Kass & Raftery scale. First, we demonstrate how to use the evidence itself to validate the model, that is to say how well a model fits the data, regardless of how well other models perform. The basic idea is that if, for some real dataset a model's evidence lies outside the distribution of evidences that result when the same fiducial model that generates the datasets is used for the analysis, then the model in question is robustly ruled out. Further, we show how to assess the significance of a hypothetically computed Bayes factor. We show that the range of the distribution of Bayes factors can greatly depend on the models in question and also the number of data points in the dataset. Thus, we have demonstrated that the significance of Bayes factors needs to be calculated for each unique dataset.

**Key words:** dark energy – cosmological parameters – methods: statistical

Keeley and Shafieloo, MNRAS 2022




Data with OK quality




Data with worse quality

Data with OK quality

# Some side notes on conventional statistics:

- Please throw away AIC and BIC in model selection!
- Bayesian evidence approach is solid but only can find the better model (or less wrong model/ranking models)

**Importance of Model Validation**

| $\Delta \log Z > 3$ | PEDE consistent | PEDE ruled-out |
|---|---|---|
| ΛCDM consistent | 6 | 994 |
| ΛCDM ruled-out | 0 | 0 |
| $\Delta \log Z > 5$ | PEDE consistent | PEDE ruled-out |
| ΛCDM consistent | 89 | 911 |
| ΛCDM ruled-out | 0 | 0 |

Conventional Bayesian Evidence Approach

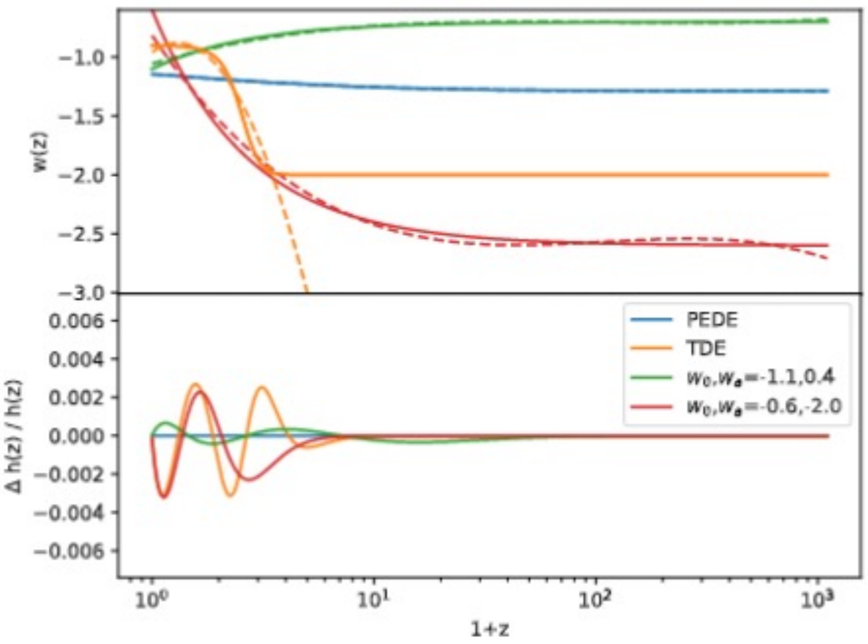
| 95% CL | PEDE consistent | PEDE ruled-out |
|---|---|---|
| ΛCDM consistent | 2 | 82 |
| ΛCDM ruled-out | 0 | 916 |
| 99% CL | PEDE consistent | PEDE ruled-out |
| ΛCDM consistent | 14 | 193 |
| ΛCDM ruled-out | 0 | 793 |

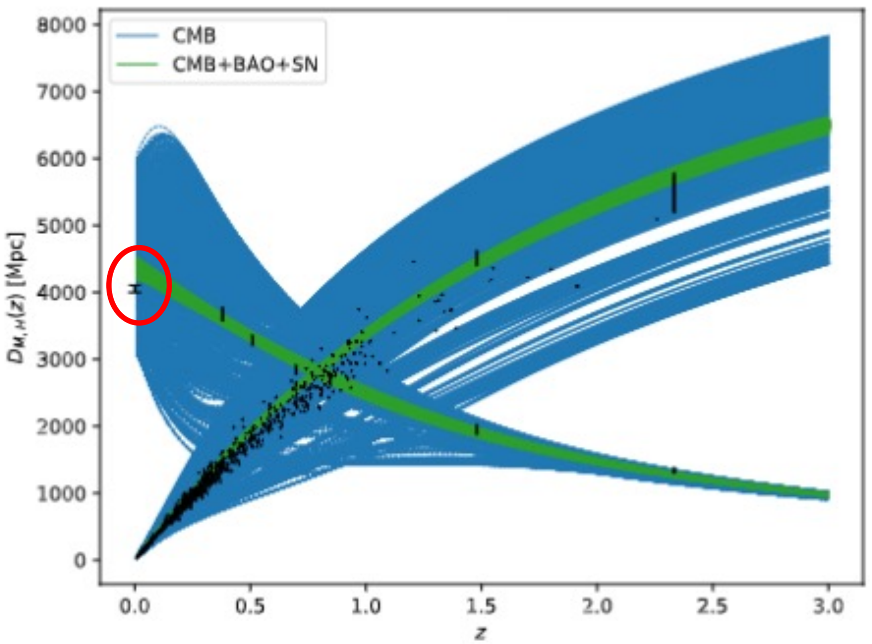
Iterative smoothing validation approach

Both models are wrong!

Koo, Keeley, Shafieloo, L'Huillier, JCAP 2022

# Ruling Out New Physics at Low Redshift as a solution to the H0 Tension

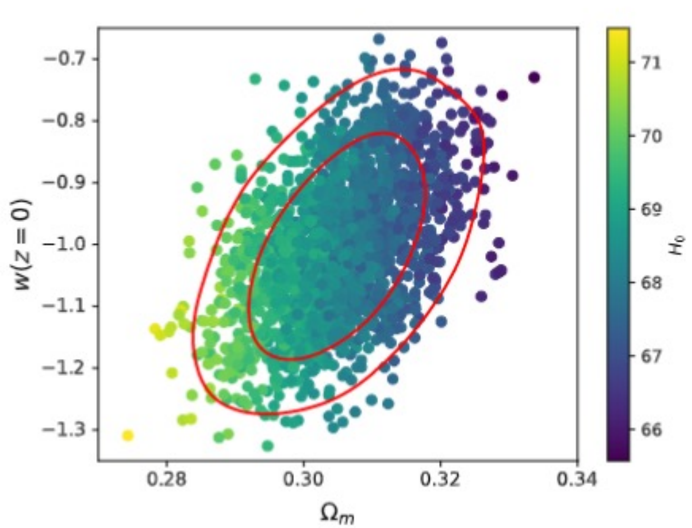


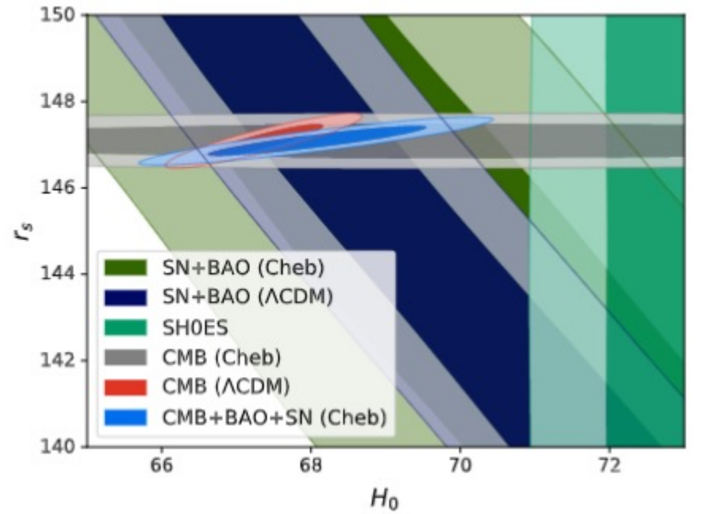



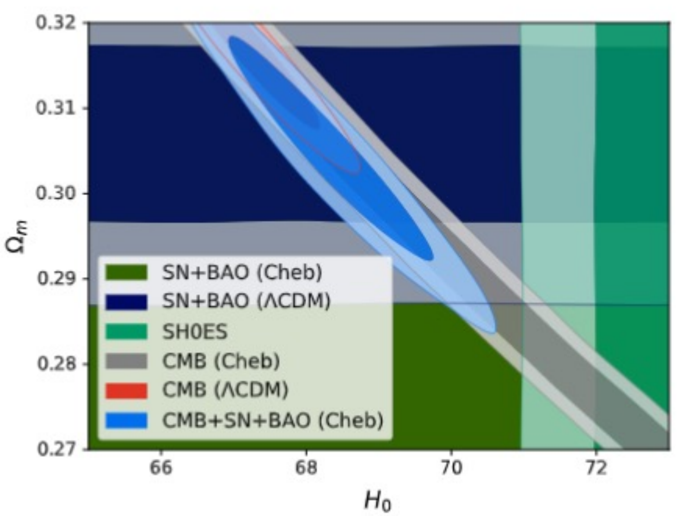

Exploring an **extensive** physical space with Crossing functions (Chebyshev polynomials)

Keeley and Shafieloo, Phys. Rev. Lett, 2023 (arXiv:2206.08440)

# Ruling Out New Physics at Low Redshift as a solution to the H0 Tension



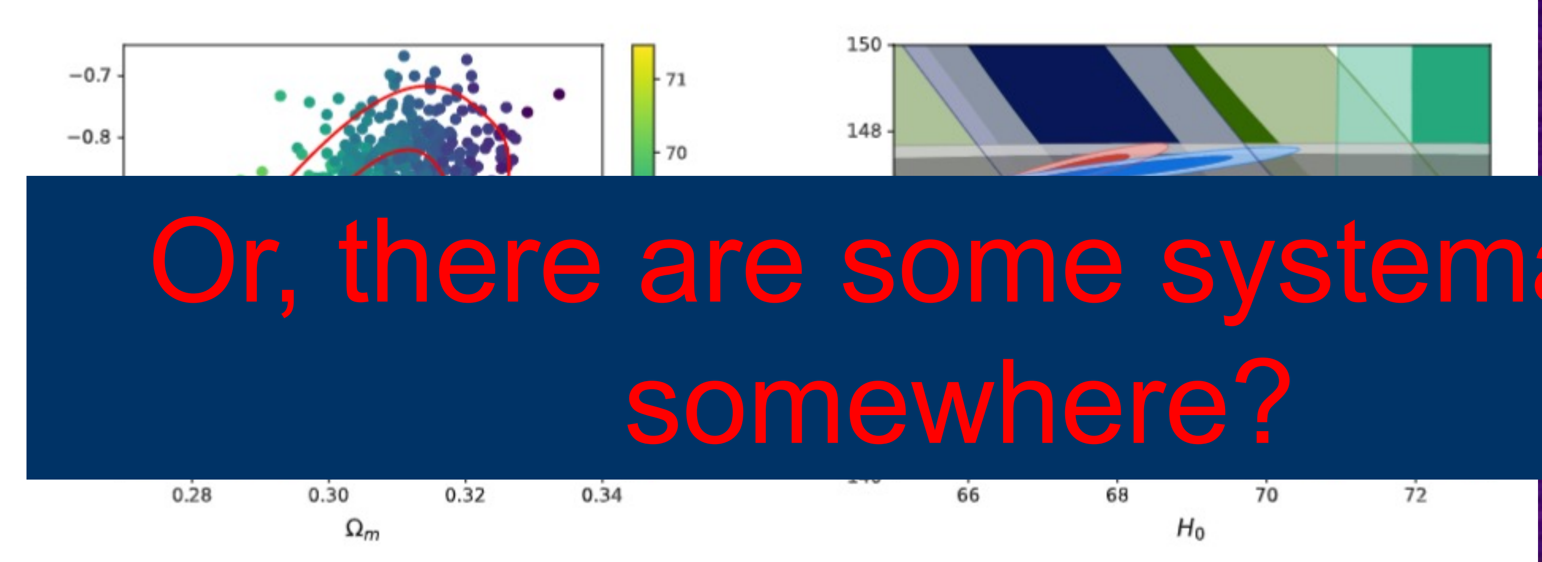




Even in such extensive physical space, inference on H0 is not consistent with SH0ES.

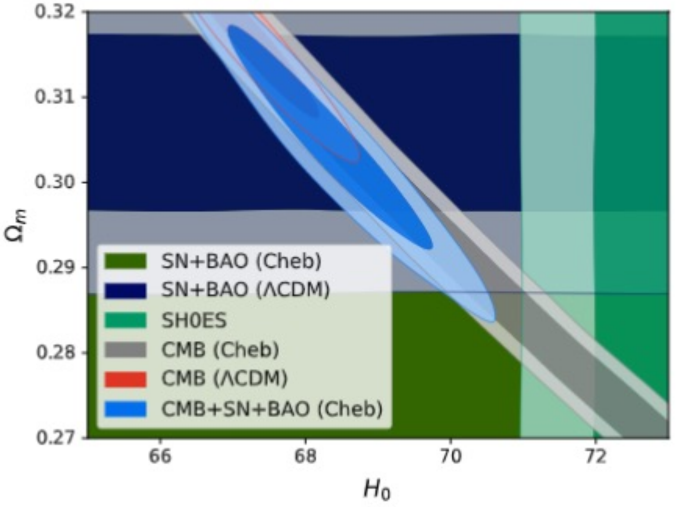
Results can be generalized for different class of models including evolving DE models, interacting DM-DE models and MG models

Keeley and Shafieloo,
Phys. Rev. Lett, 2023
(arXiv:2206.08440)

# Ruling Out New Physics at Low Redshift as a solution to the H0 Tension




## Or, there are some systematics somewhere?




Even in such extensive physical space, inference on H0 is not consistent with SH0ES.

Results can be generalized for different class of models including evolving DE models, interacting DM-DE models and MG models

Keeley and Shafieloo,
Phys. Rev. Lett, 2023
(arXiv:2206.08440)

(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 Reconstruction of Primordial Spectrum

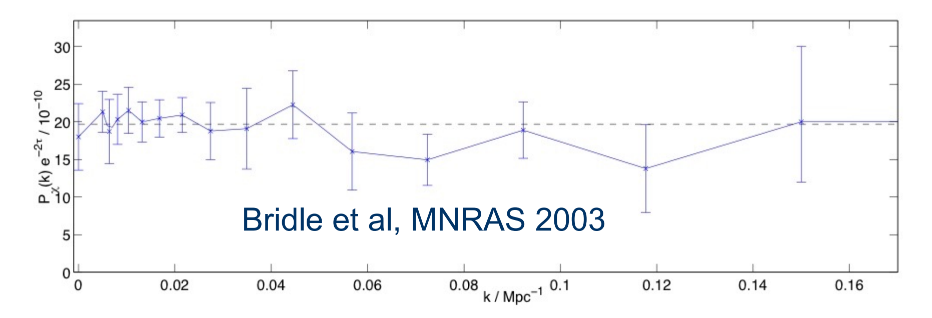
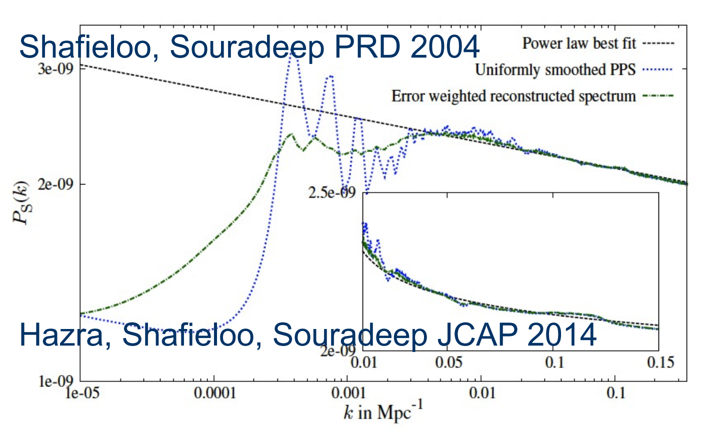
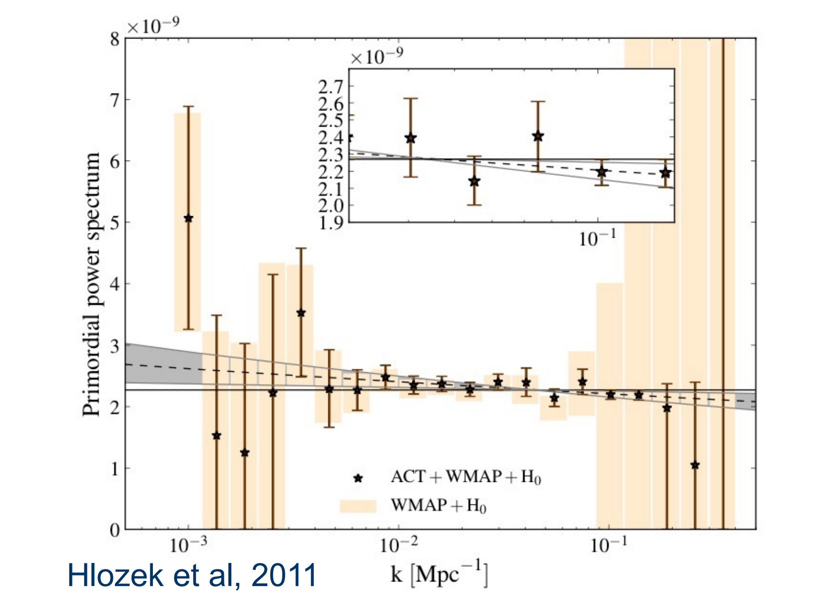
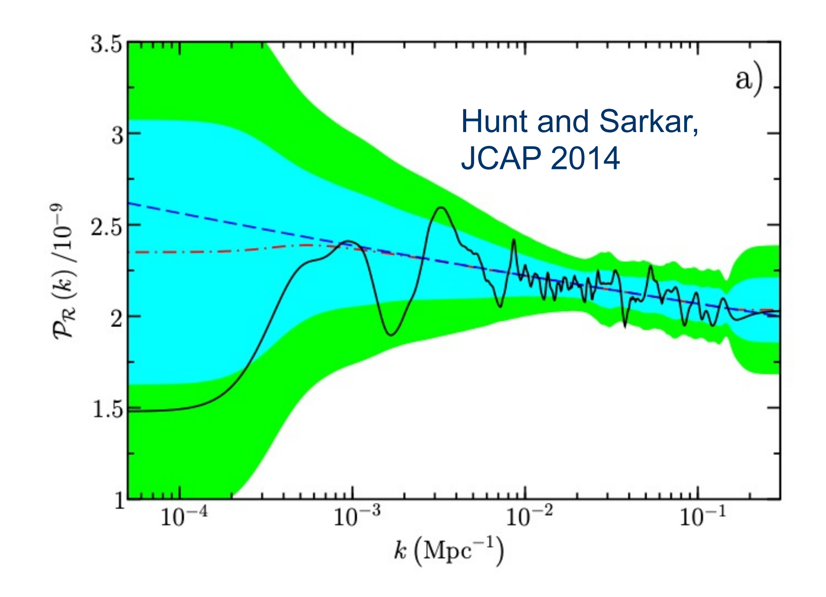


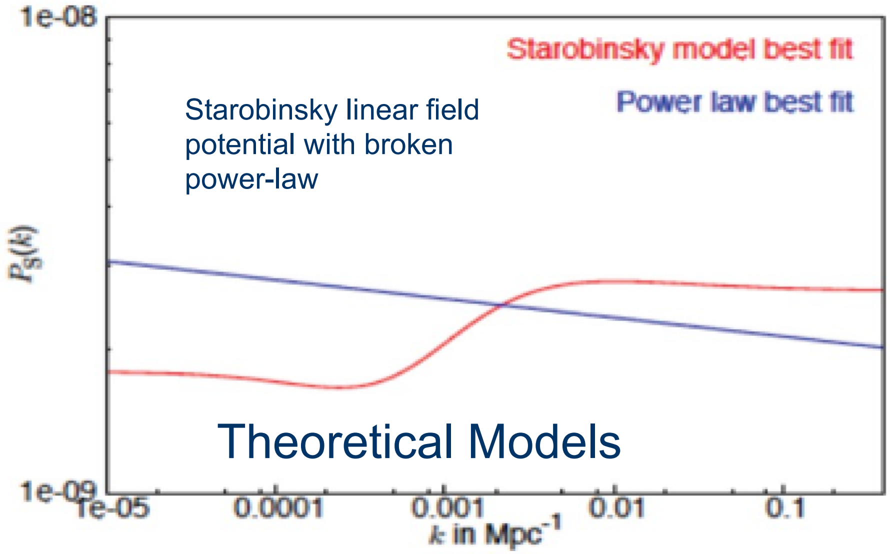

**Figure 4.** Reconstruction of the shape of the primordial power spectrum in 16 bands after marginalising over the Hubble constant, baryon and dark matter densities, and the redshift of reionization.

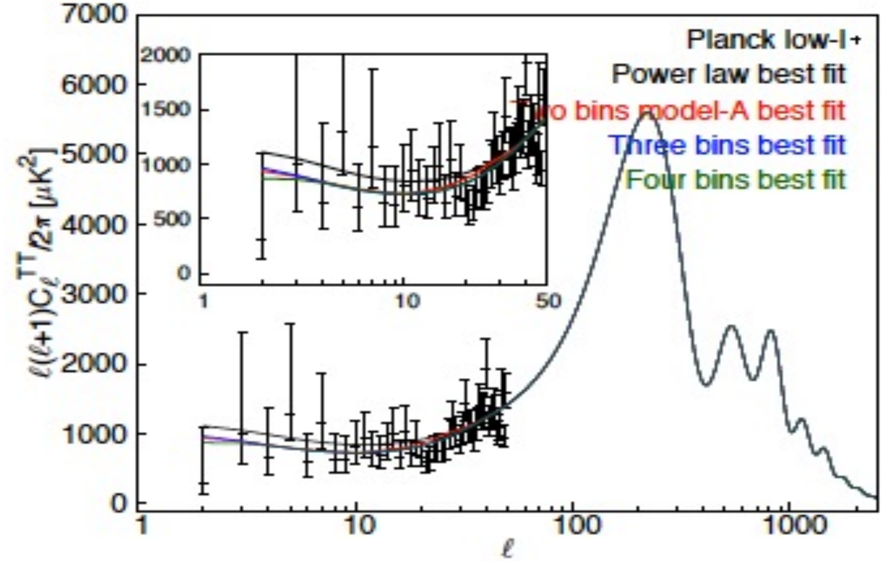


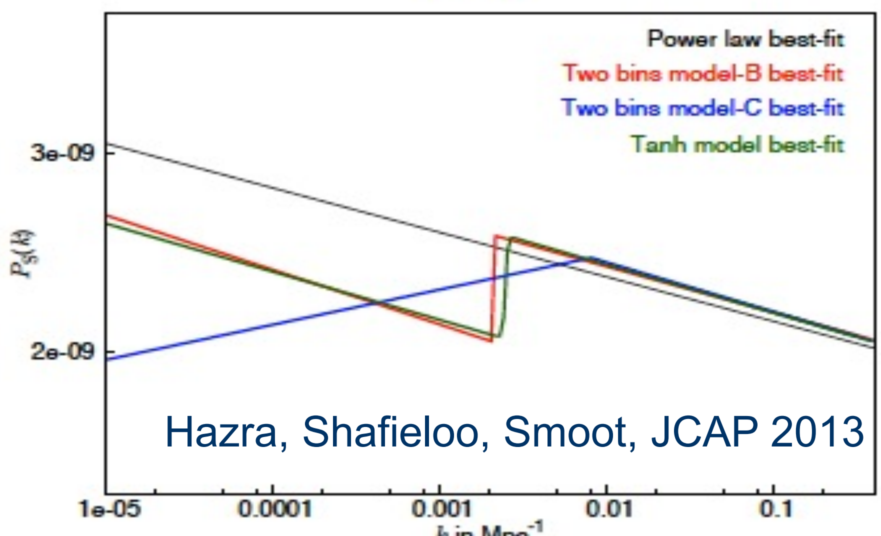



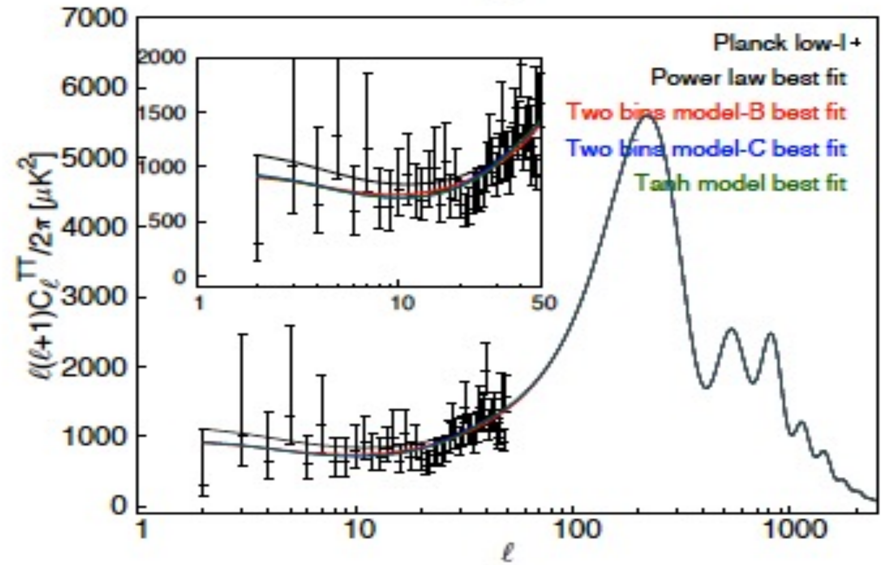



# Beyond Power-Law: there are some other models consistent to the data.



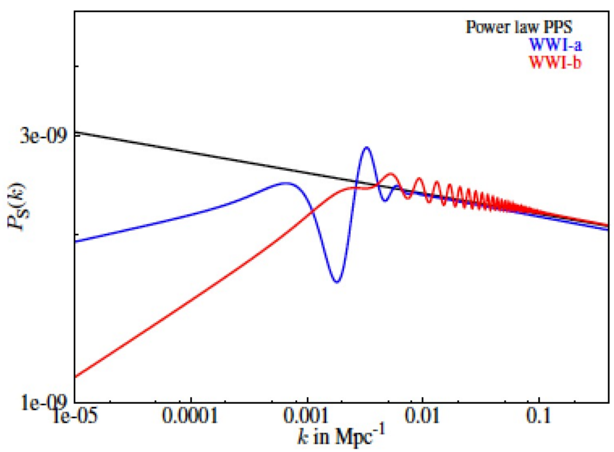



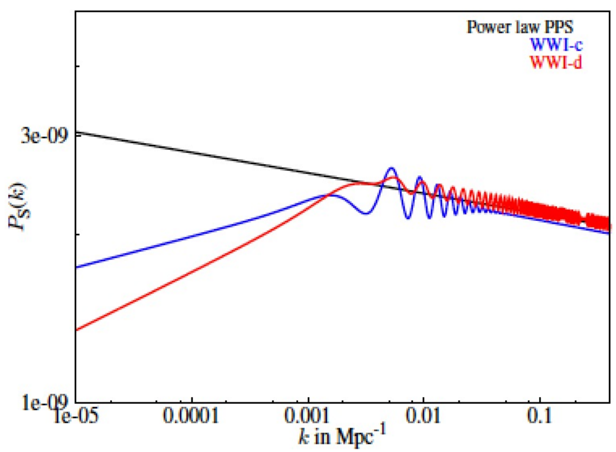
| *Individual likelihoods comparison* | | | | | | |
|---|---|---|---|---|---|---|
| Individual likelihood | Baseline | WWI-a $\Delta_{\rm DOF}=4$ | WWI-b $\Delta_{\rm DOF}=4$ | WWI-c $\Delta_{\rm DOF}=4$ | WWI-d $\Delta_{\rm DOF}=4$ | WWI′ $\Delta_{\rm DOF}=2$ |
| TT | 761.1 | 762 | 761.9 | 762.8 | 762.8 | 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) |

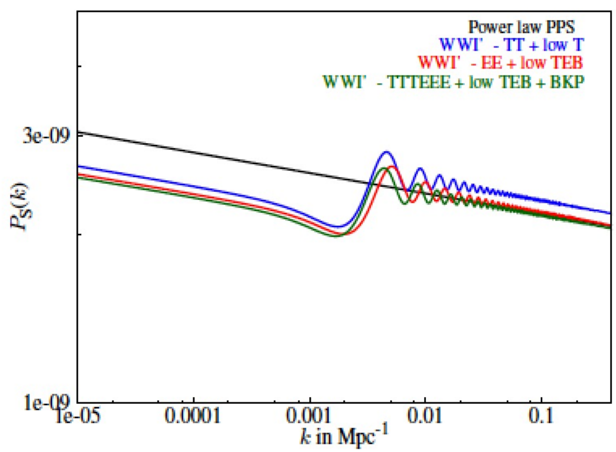
# Beyond Power-Law: ***there are some other models consistent to the data.***

## ***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.

$\Omega_b$

$\Omega_m$

$H_0$

$\tau$

1

2

G(l,k)

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

3

$$C_l^{obs}$$

2

$A_s$

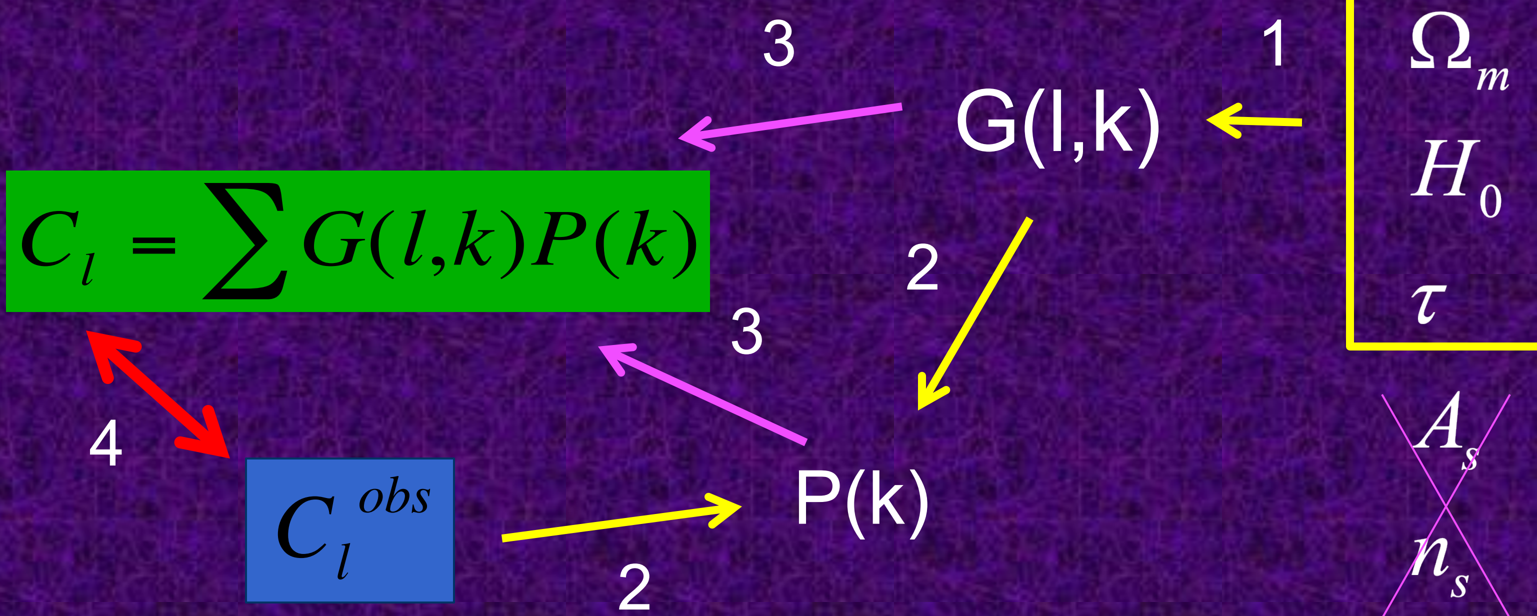
$n_s$

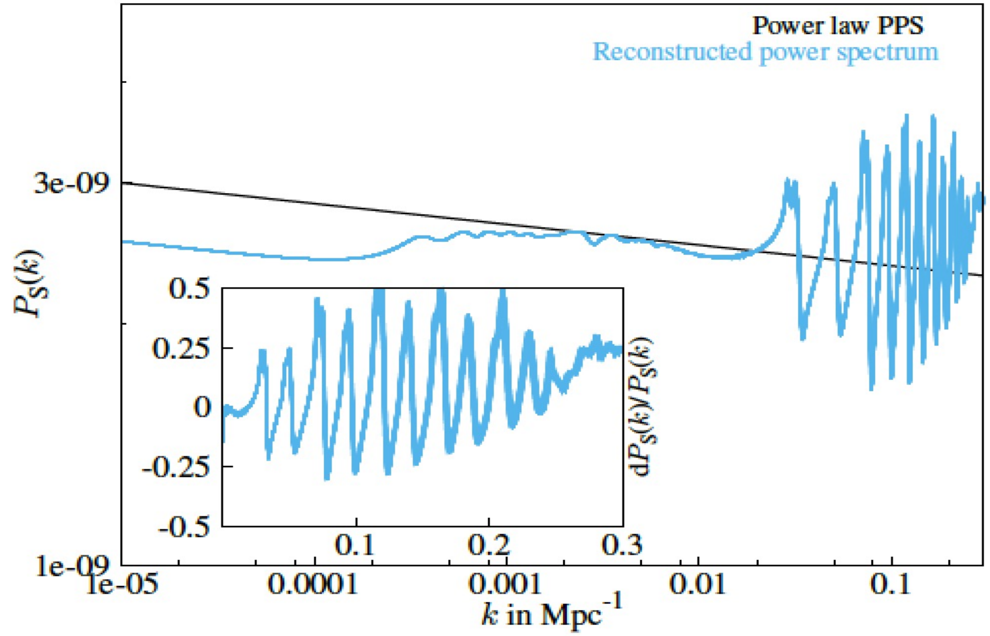
1

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

# *Forms of PPS and Effects on the Background Cosmology*

- Cosmological parameter estimation with free form primordial power spectrum

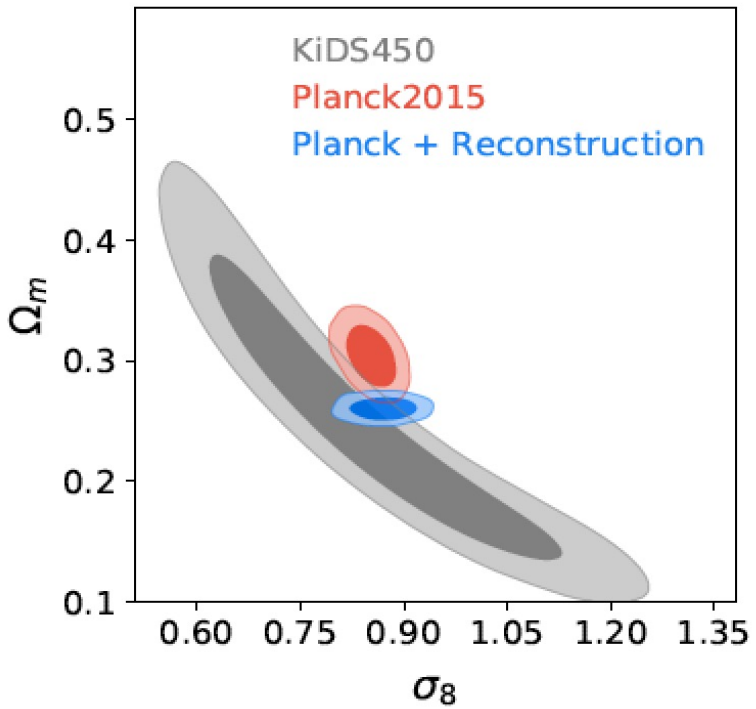


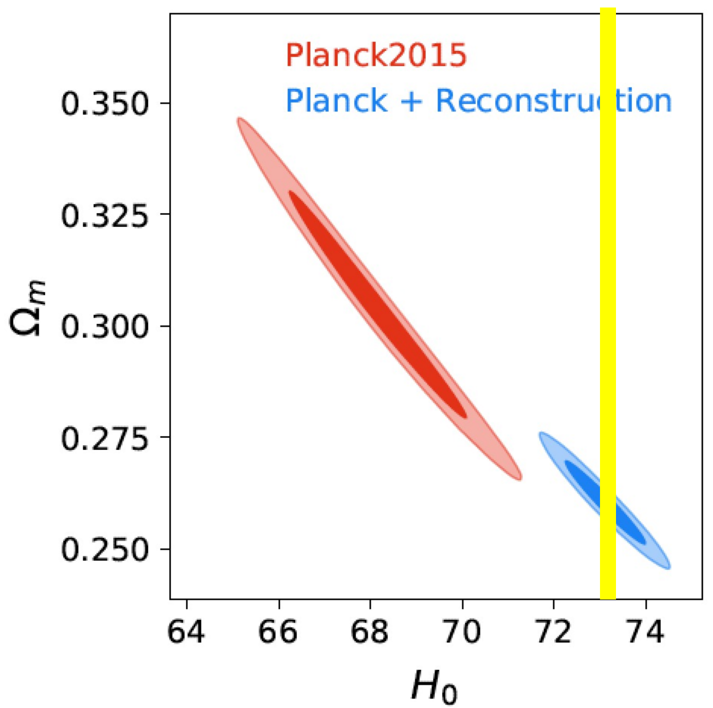


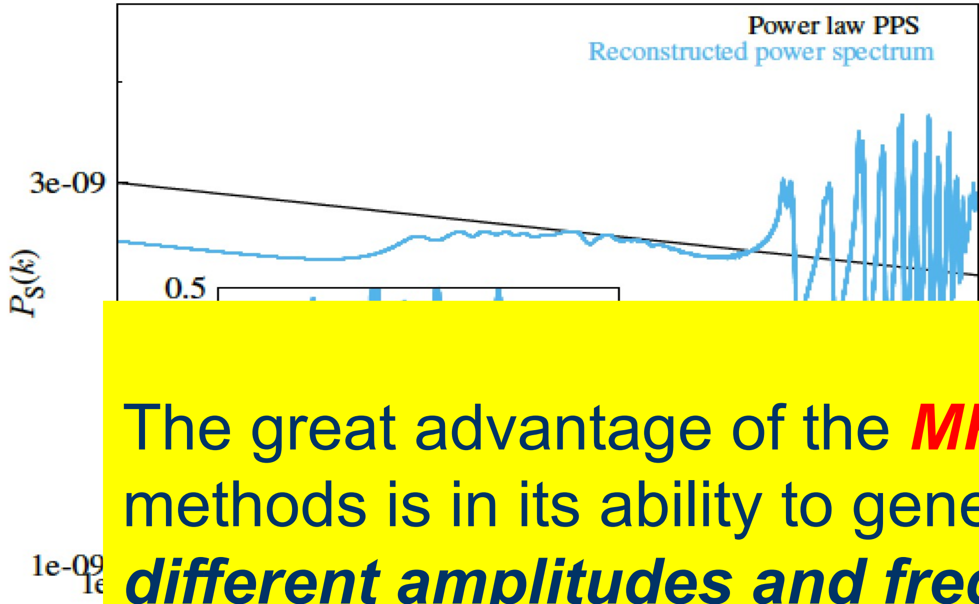

Hazra, Shafieloo, Souradeep, JCAP 2019

# ***Background Cosmological Parameters and PPS***

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



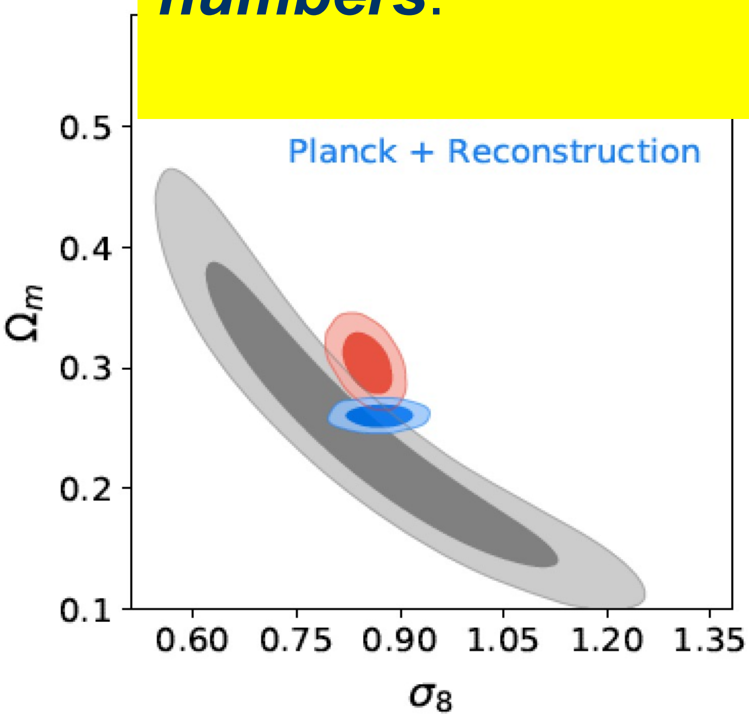





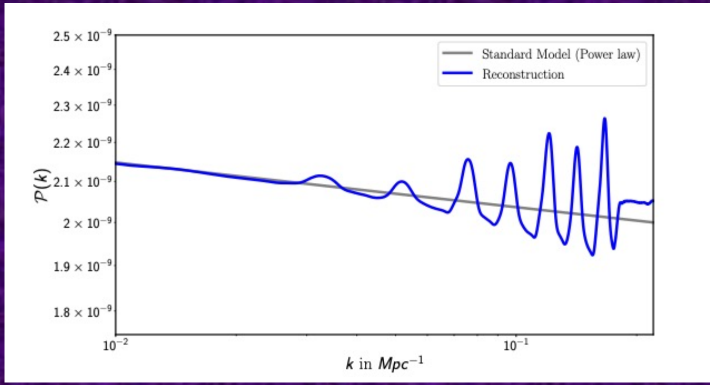

Hazra, Shafieloo, Souradeep, JCAP 2019

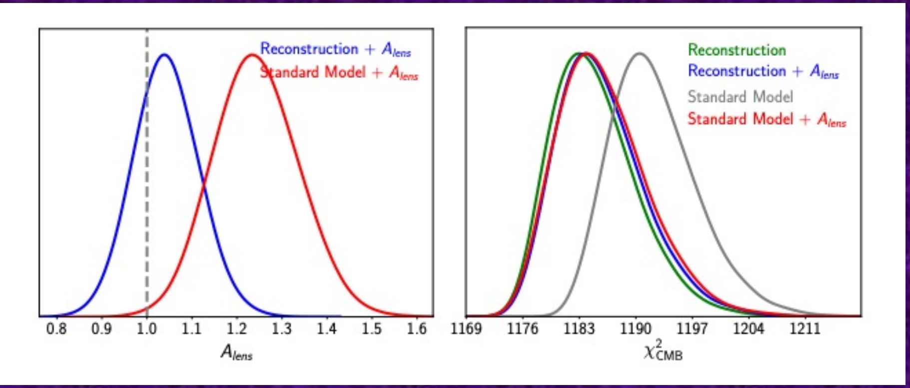
***Background Cosmological***

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***.

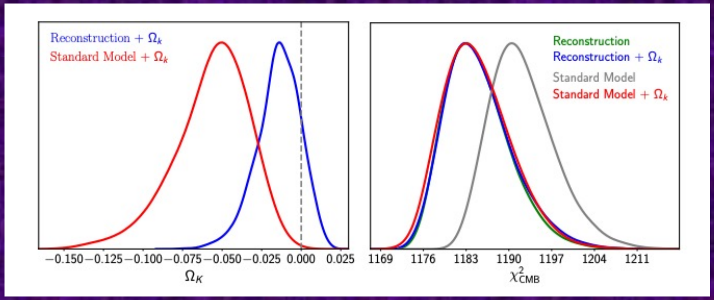


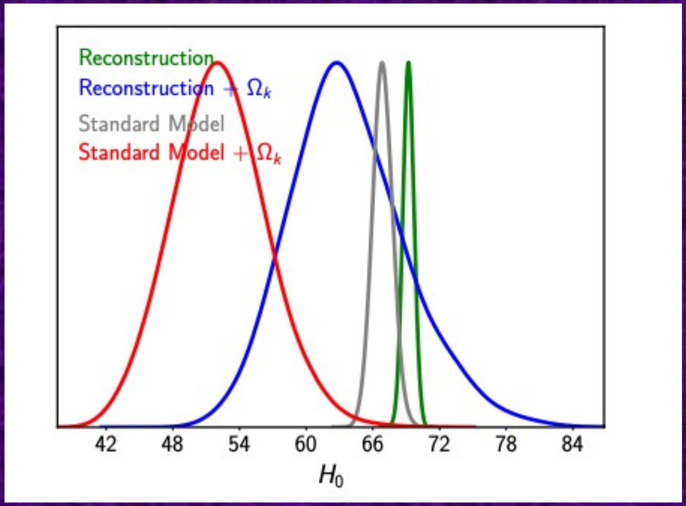
# One spectrum to cure them all: Signature from early Universe solves major anomalies and tensions in cosmology



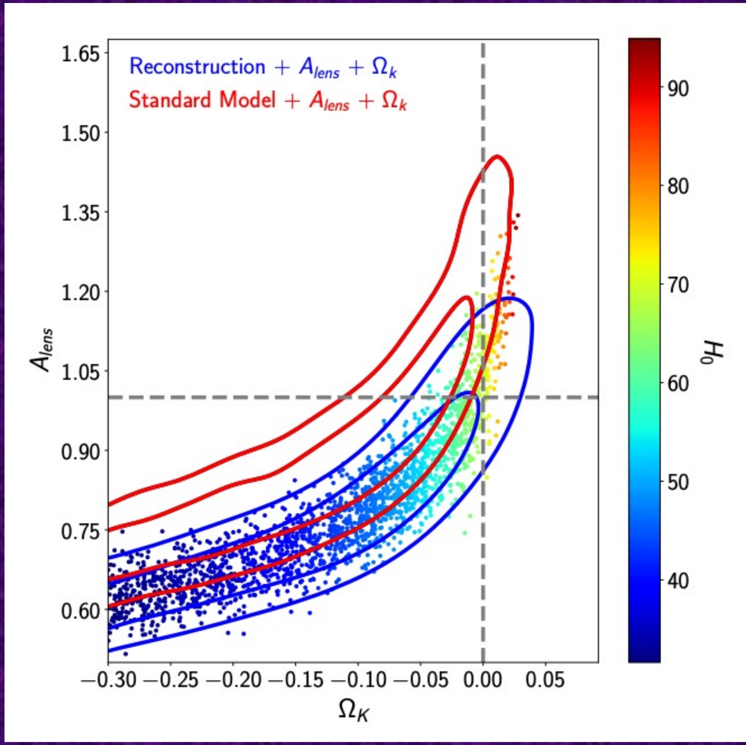

Curvature and A_lens anomalies

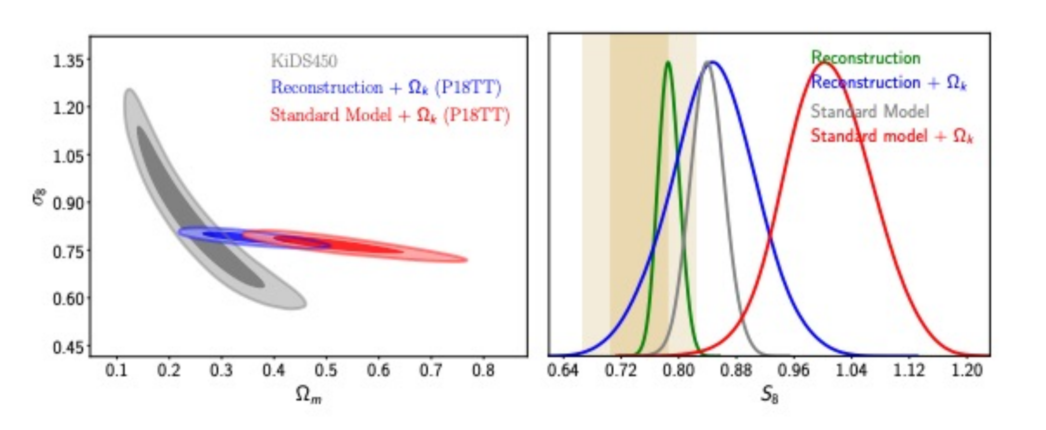



Hazra, Antony, Shafieloo : JCAP 2022

# One spectrum to cure them all: Signature from early Universe solves major anomalies and tensions in cosmology




Addressing Majour Anomalies and tensions

Hazra, Antony, Shafieloo :JCAP 2022 **(arXiv:2201.12000)**

**Reconstruction→ Phenomenology→Theory**

**See Antony, Finelli, Hazra, Shafieloo, Phys Rev Lett 2023 (arXiv:2202.14028), for theoretical implication**

# 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.***

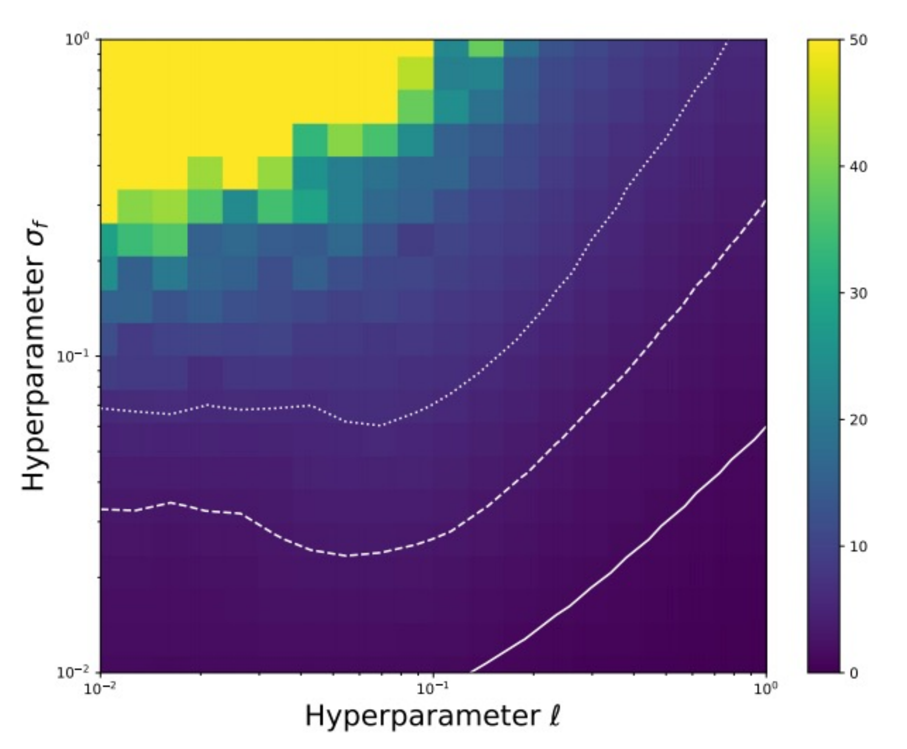
# Looking for systematics

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

GP for Falsification

Consistency of SDSS BAO and Pantheon SN Ia data
Keeley, Shafieloo, Zhao, et al MNRAS 2021 [arXiv:2010.03234] [SDSS IV paper]

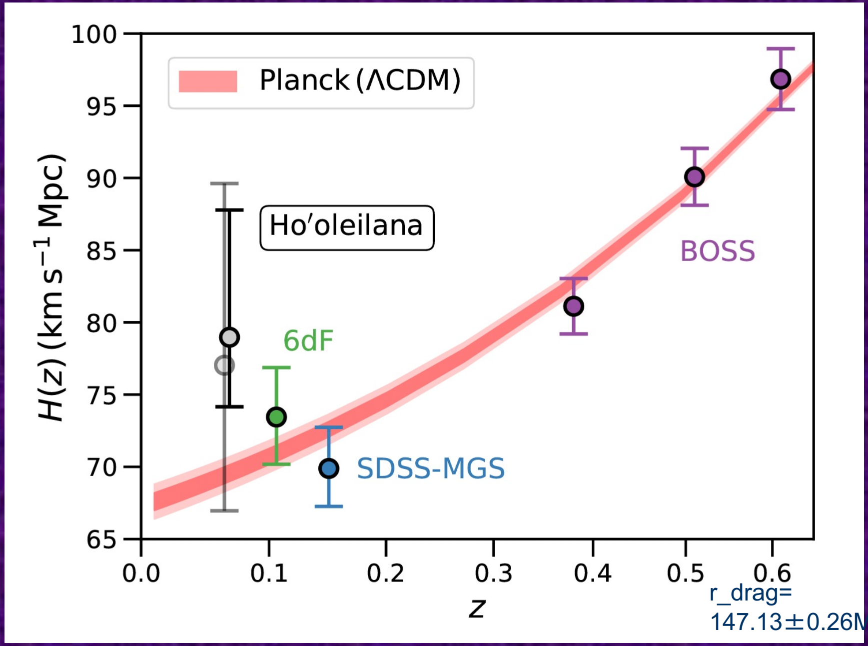
$H0rd$ = 10040 ± 140 km/s and
$\Omega k$ = 0.02 ± 0.20



# Looking for systematics

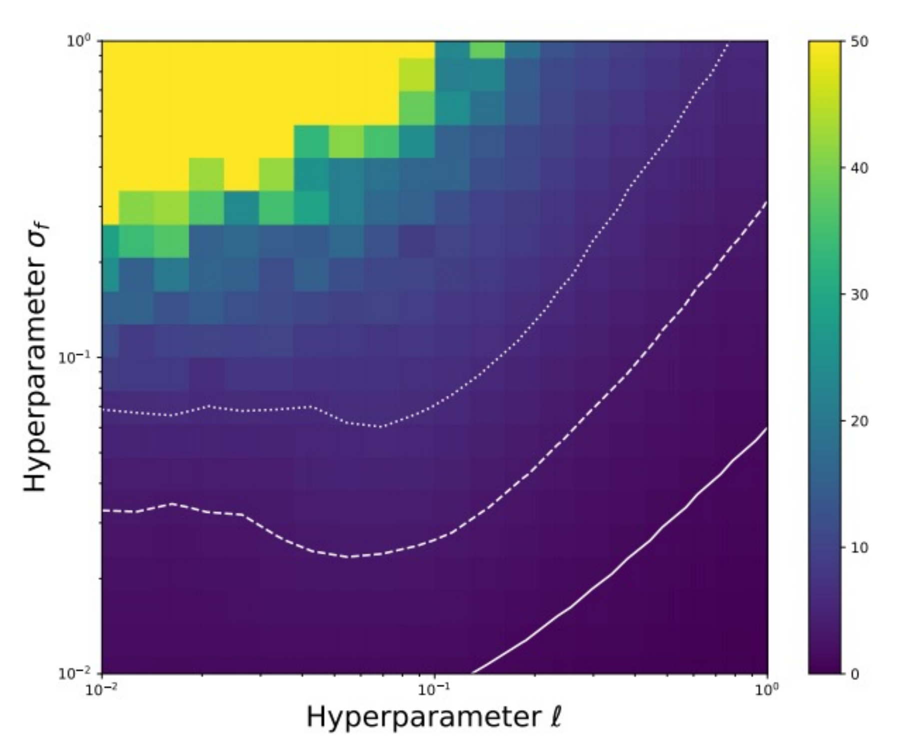
Model independent consistency test between various data is essential to rule out systematics.

GP for Falsification




r_drag=
147.13±0.26Mpc

Tully, Howlett, Pomarede, arXiv:2309.00677



# 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

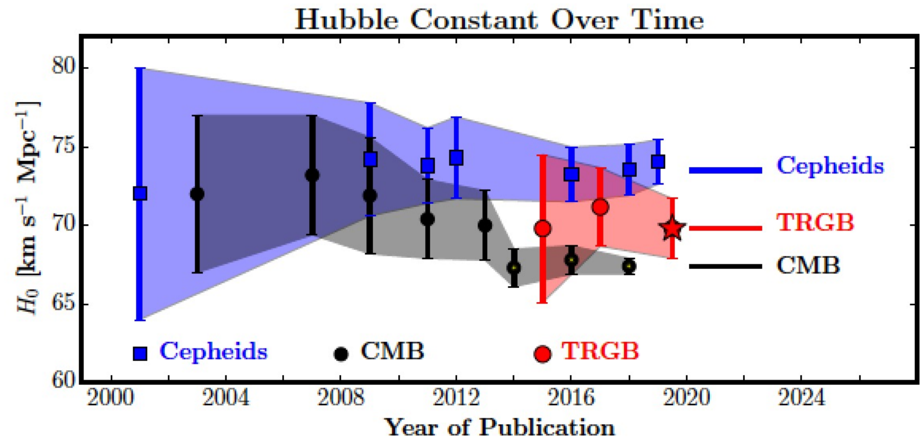
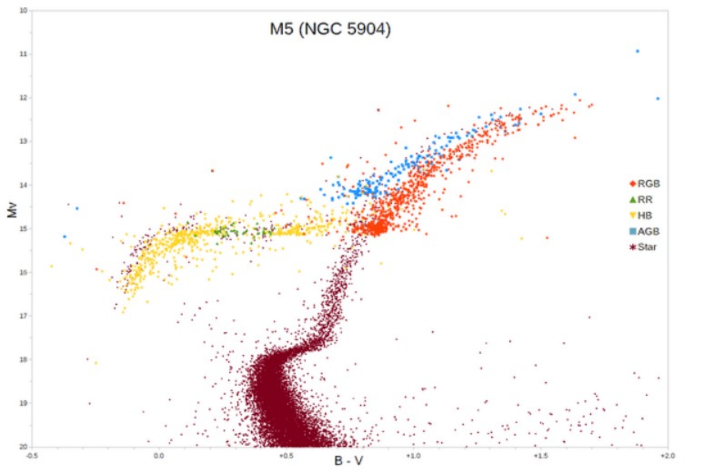



**Figure 17.** A plot of $H_0$ values as a function of time. The points and shaded region in black are those determined from measurements of the CMB; those in blue are Cepheid calibrations of the local value of $H_0$; and the red points are TRGB calibrations. The red star is the best-fit value obtained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

Freedman et al, arXiv:1907.05922



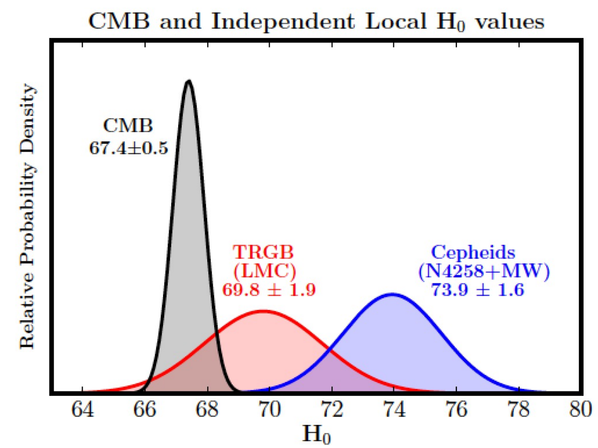
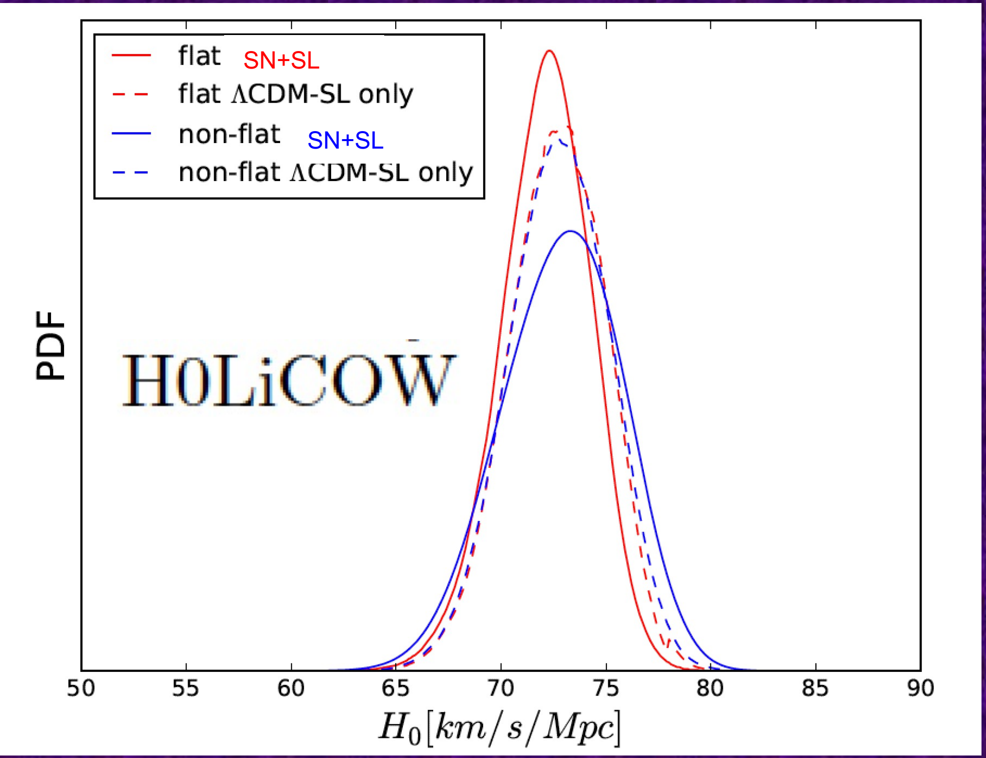




**Figure 18.** Completely independent calibrations of $H_0$. Shown in red is the probability density function based on our LMC CCHP TRGB calibration of CSP-I SNe Ia; in blue is the Cepheid calibration of $H_0$ (Riess et al. 2016), using the Milky Way parallaxes and the maser distance to NGC 4258 as anchors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

**Cosmology with Strong Lens Systems: Has become already competative!**




# H0 from Strongly Lensed systems

$$H_0 = 72.8^{+1.6}_{-1.7}\ \text{km/s/Mpc}$$

**2.3% model-independent measurment of Hubble constant**

Liao, Shafieloo, Keeley, Linder, ApJ Letters 2020

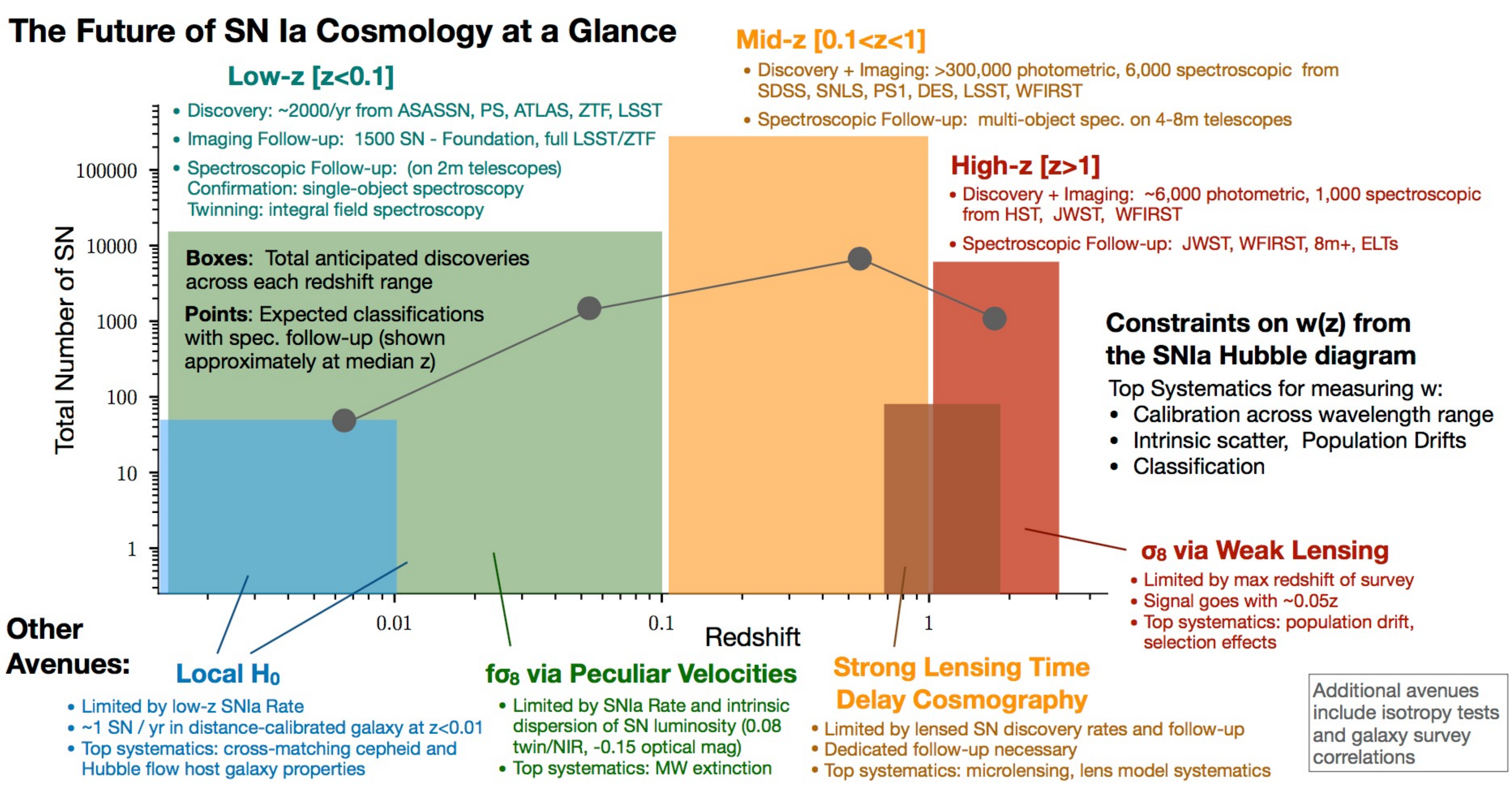
Liao, Shafieloo, Keeley, Linder, ApJ Letters 2019

H0LiCOW I. H0 Lenses in COSMOGRAIL's Wellspring

Suyu et al. MNRAS 2017

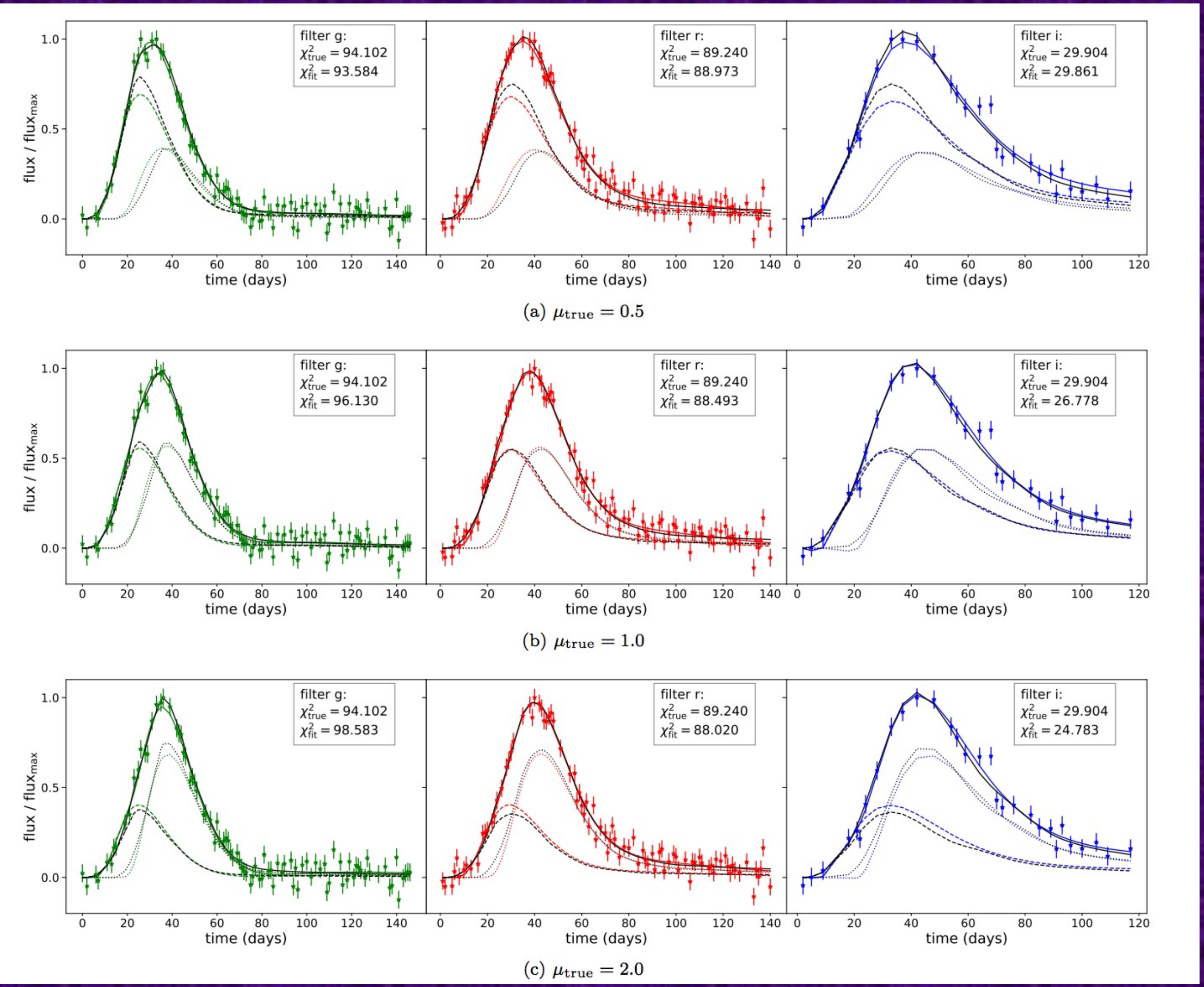
| Order | Name | $z_L$ | $z_S$ |
|---|---|---|---|
| 1 | RXJ1131-1231 | 0.295 | 0.654 |
| 2 | HE 0435-1223 | 0.4546 | 1.693 |
| 3 | B1608+656 | 0.6304 | 1.394 |
| 4 | SDSS 1206+4332 | 0.745 | 1.789 |

# Future perspective (late universe, SN Ia)




Scolnic,et al, arXiv:1903.05128

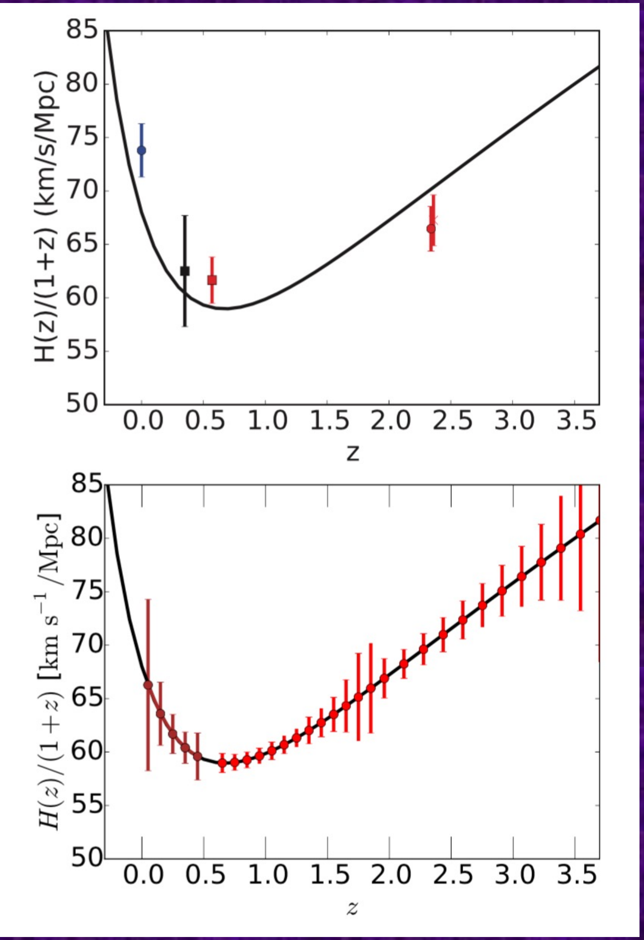
# Future Perspective (late universe, SN Ia, QSO SL)

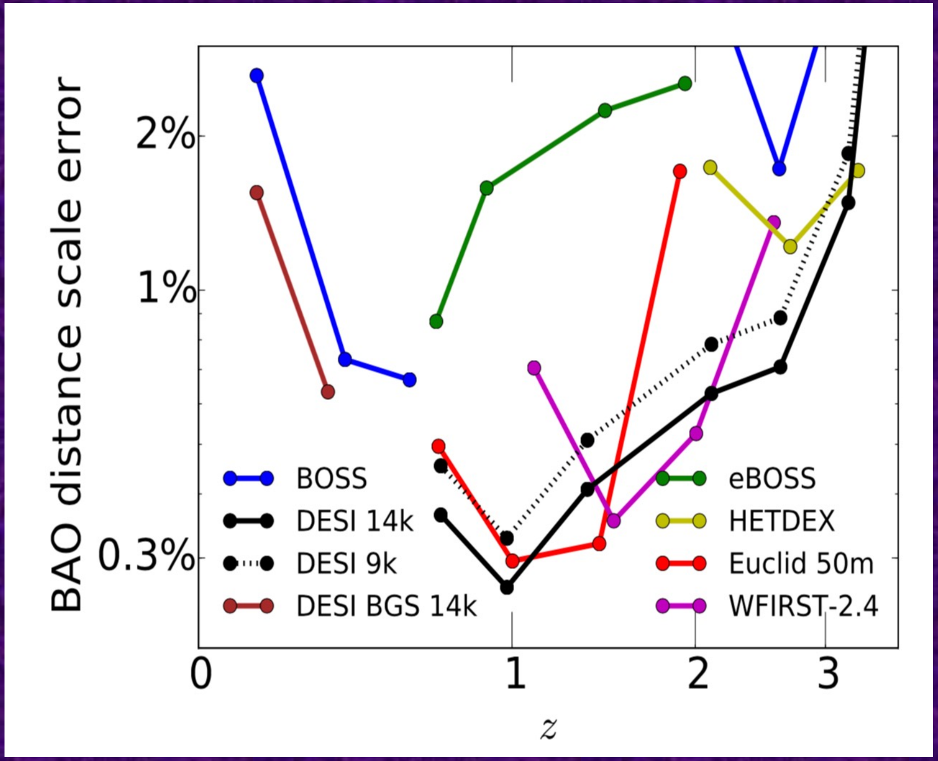



**Resolving Unresolved Lensed Systems!**

Bag, Kim, Linder & Shafieloo, ApJ 2021
Bag, Shafieloo, Liao, Treu, ApJ 2022

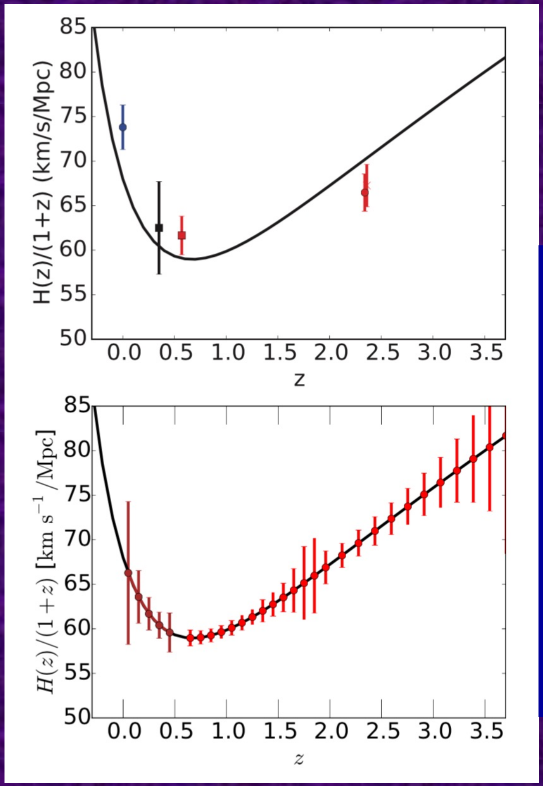
# Future perspective (late universe; BAO)




Aghamousa et al, [arXiv:1611.00036]
DESI Collaboration

# Future perspective (late universe; BAO)

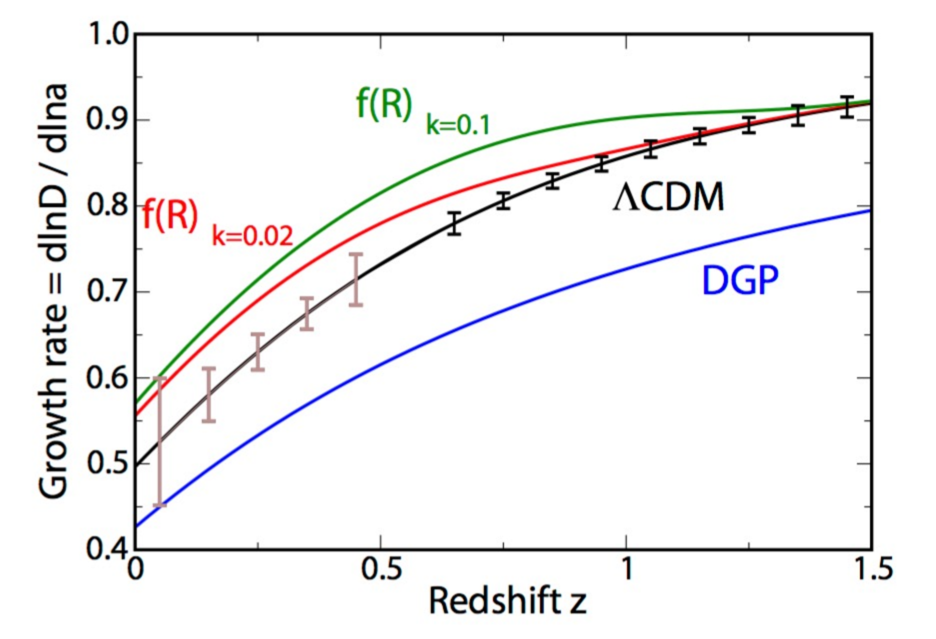


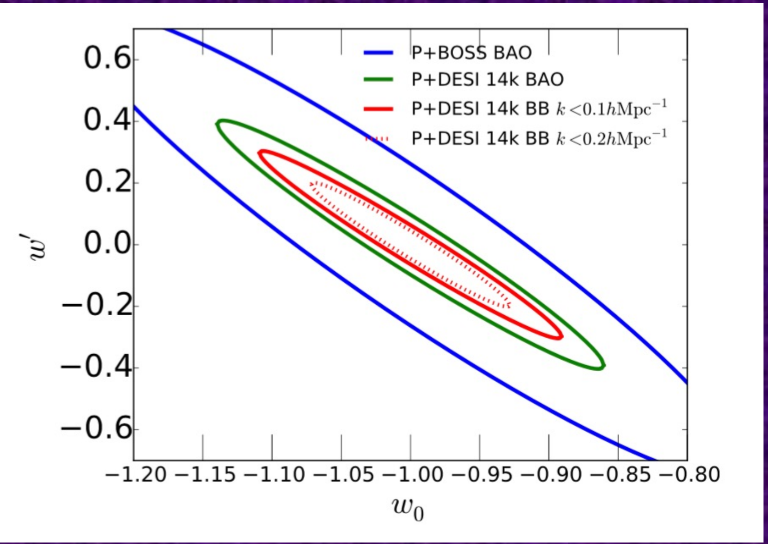

DESI Y1 data will be **better than all existing LSS data combined**

**arXiv:2306.06307** **DESI SV**
**arXiv:2306.06308** **DESI EDR**

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

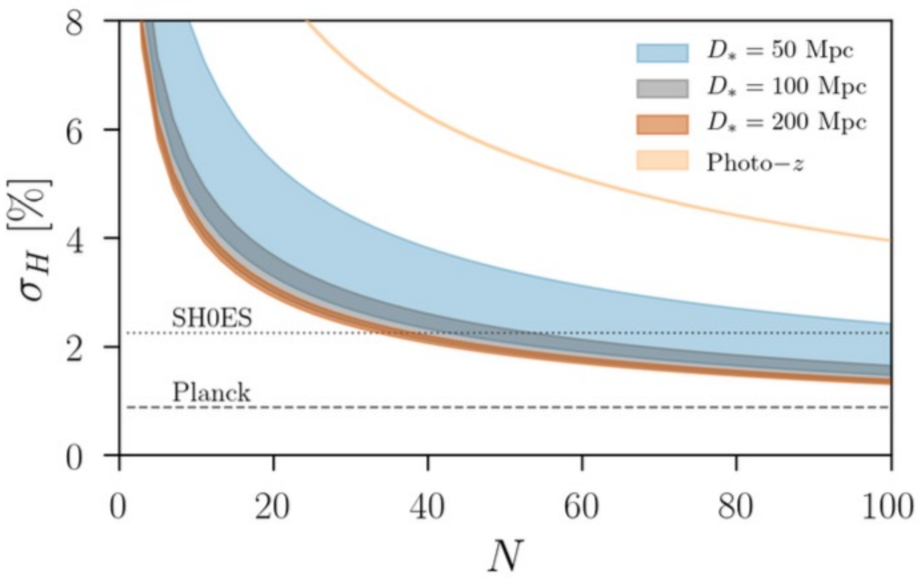



Figure 1: Hubble constant uncertainty ($1\sigma$) as a function of combined GW events with associated EM counterpart. The shaded regions show the impact of the peculiar velocity uncertainty between 100 and 400 $\mathrm{km\,s^{-1}}$ for different distance reaches $D_*$. The latest results from standard 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!*

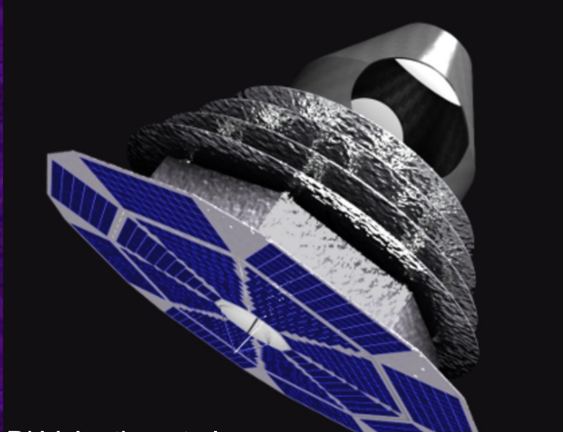
$$P_S(k), P_T(k), P_{iso}(k)$$

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

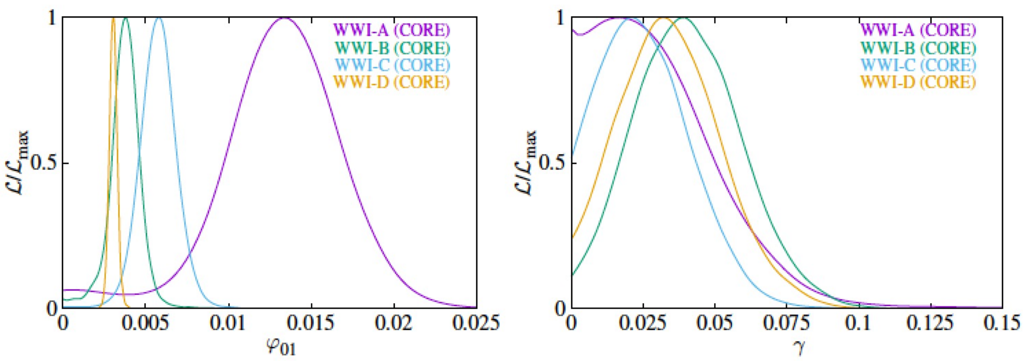
# Features with Future of CMB (S4)



Di Valentino et al,
arXiv:1612.00021

With Cosmic Origins Explorer (CORE)-like survey specification

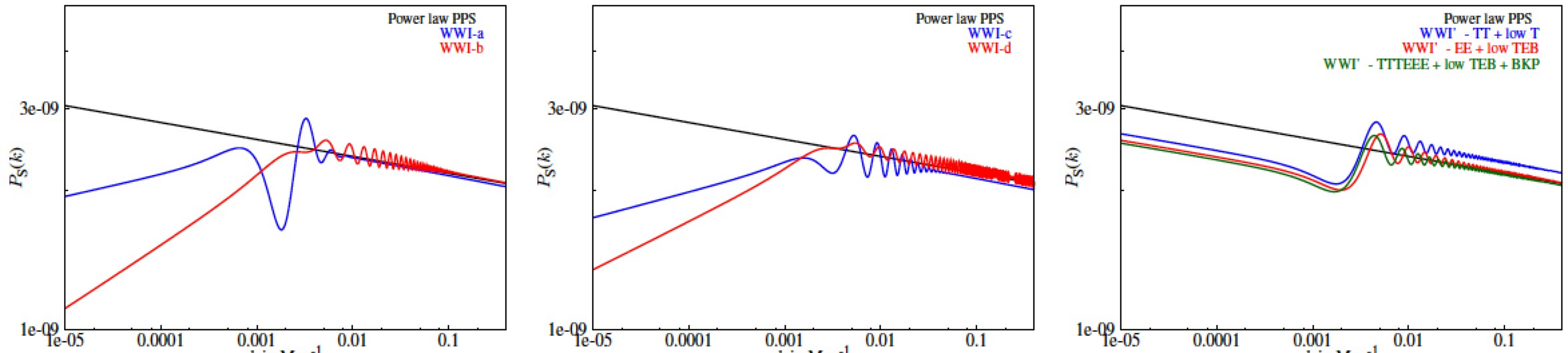
**Wiggles** **Suppression**




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

*Wiggly Whipped Inflation*

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



# 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

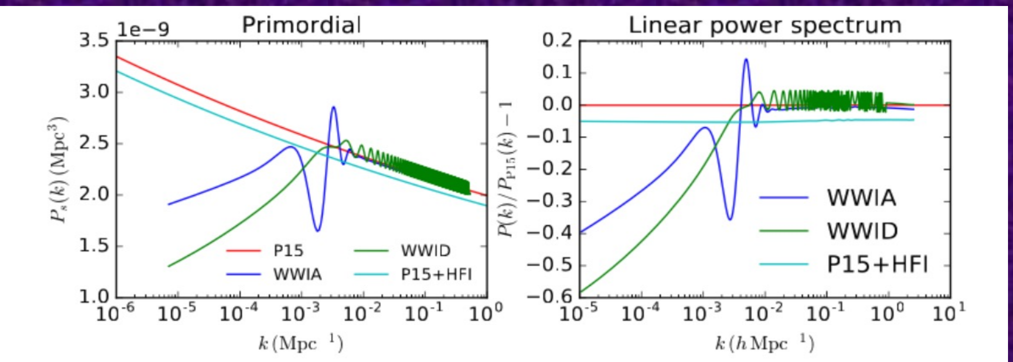
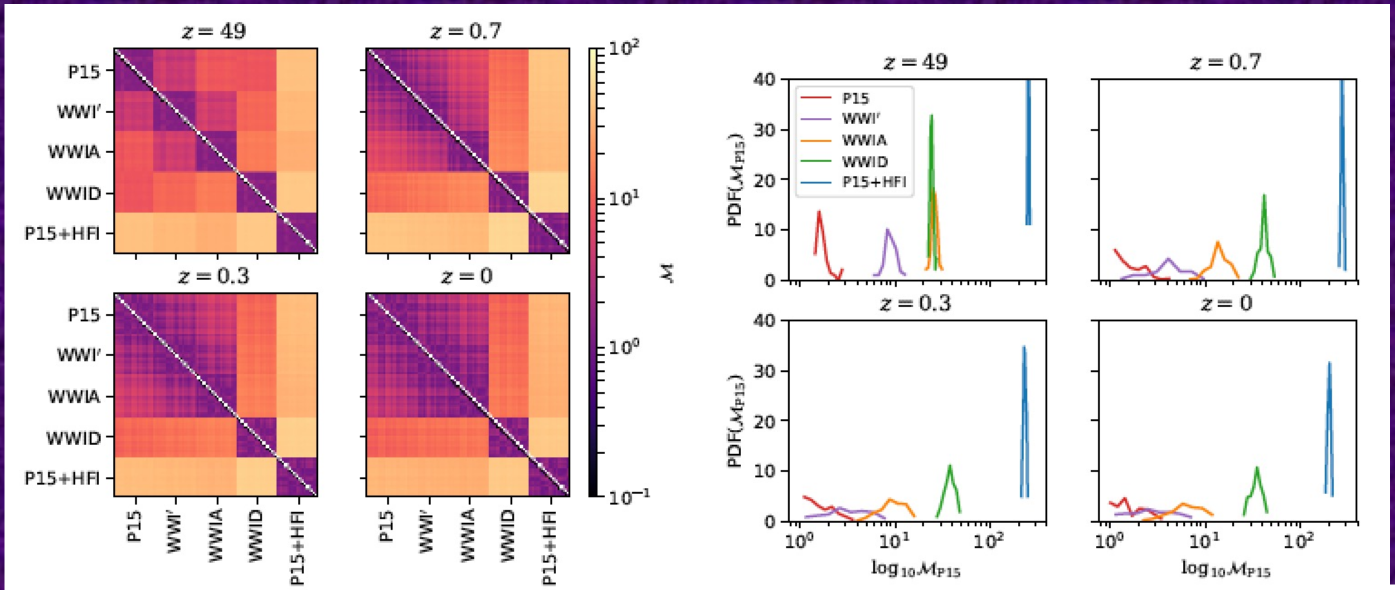



Table 2: Cosmological parameters of models

| Model | $\Omega_m$ | $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | $\sigma_8$ | $n_s$ |
|---|---|---|---|---|
| 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***




$$\Xi_{P_i}(k) = \frac{P_i(k) - \langle P_{\mathrm{P15}}(k)\rangle}{\sigma_{P_{\mathrm{P15}}}(k)},\qquad M_{\mathrm{mod}_i^m,\mathrm{mod}_j^n} = \sqrt{\frac{1}{N_k}\sum_k \left(\Xi_{P_{\mathrm{mod}_i^m}}(k) - \Xi_{P_{\mathrm{mod}_j^n}}(k)\right)^2},$$

# From 2D to 3D

N-Body Simulation (DESI like)

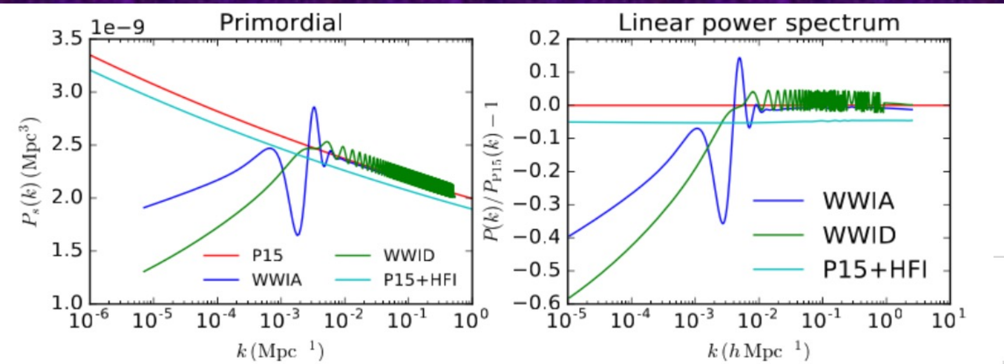
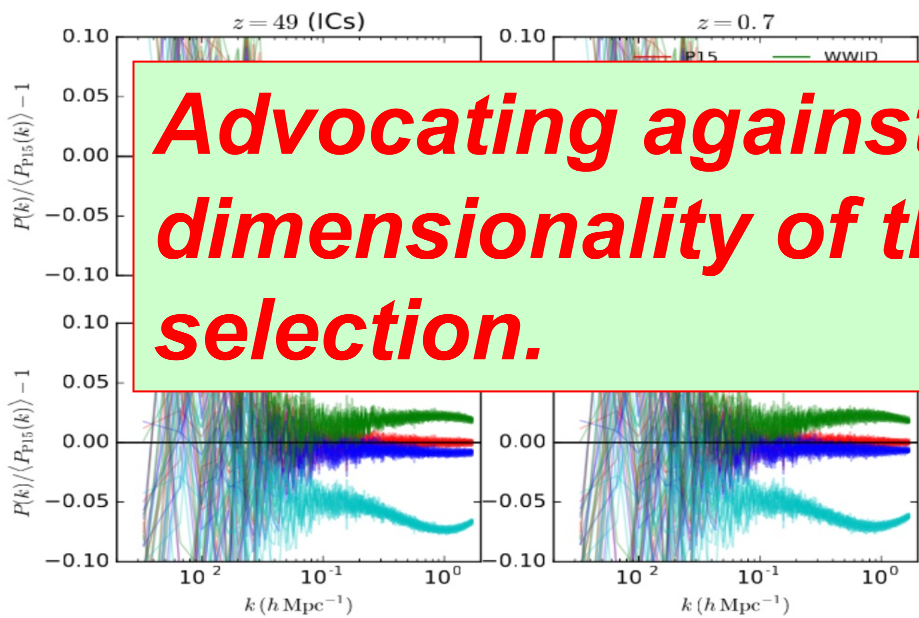



Table 2: Cosmological parameters of models

| Model | $\Omega_m$ | $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | $\sigma_8$ | $n_s$ |
|---|---|---|---|---|
| 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

- 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?, EDE, features in PPS?)***.

- ***Tensions are not resolved with minimal extensions of the standard model and there is no low redshift resolution.*** 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, Rubin, Roman, SKA(?), etc) will make it much more clear about the status of the concordance model in 2020s.

Big part of science these days….

# Conclusion (social media)


*"I'm sorry, Jeannie, your answer was correct, but Kevin shouted his incorrect answer over yours, so he gets the points."*

The New Yorker, 29 November 2016

***But in doing scince, facts eventually matter***

# 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**

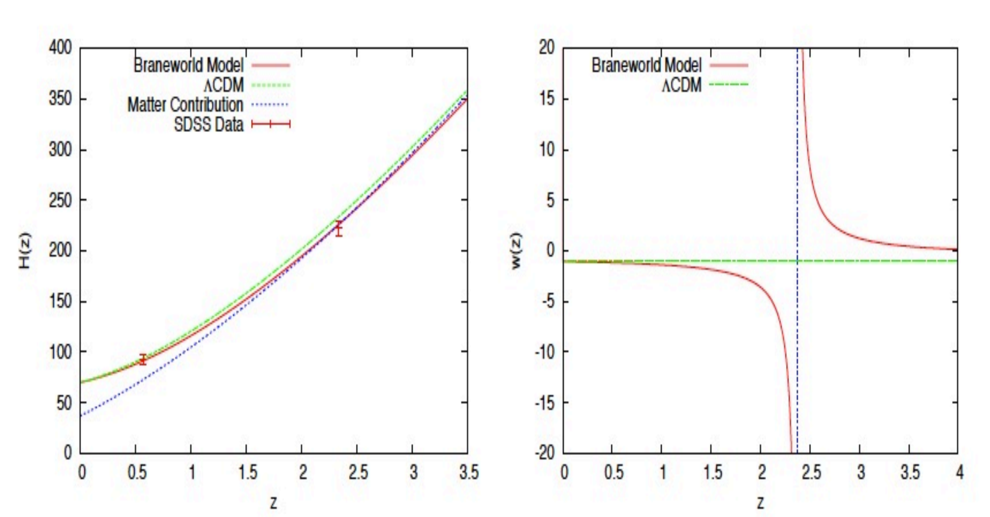
Sahni, Shafieloo, Starobinsky, ApJ Lett 2014

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

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

# 2022 Omh2

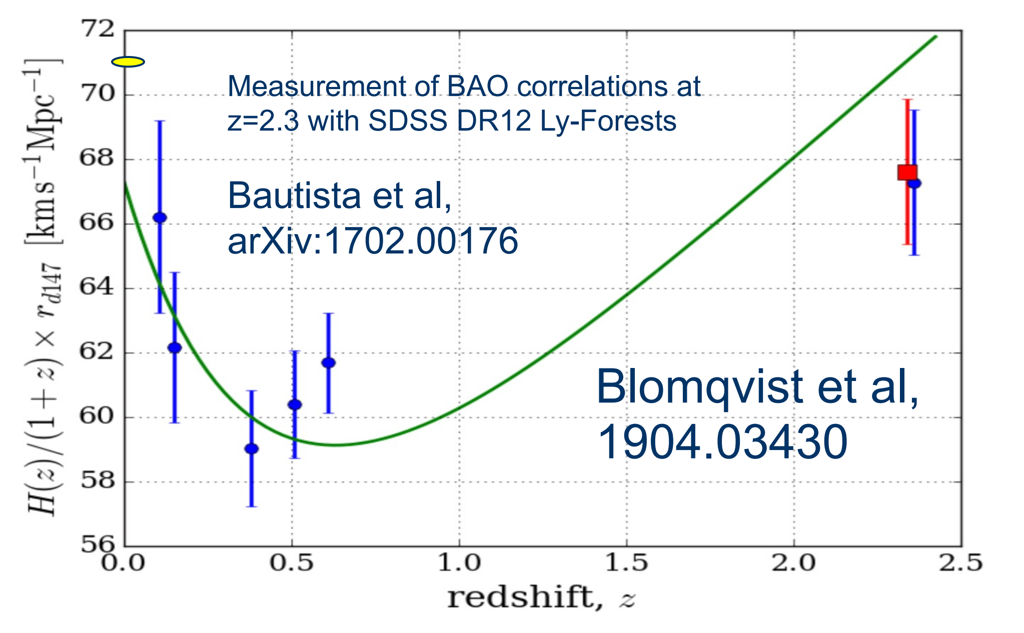
**No systematic yet found,**

*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

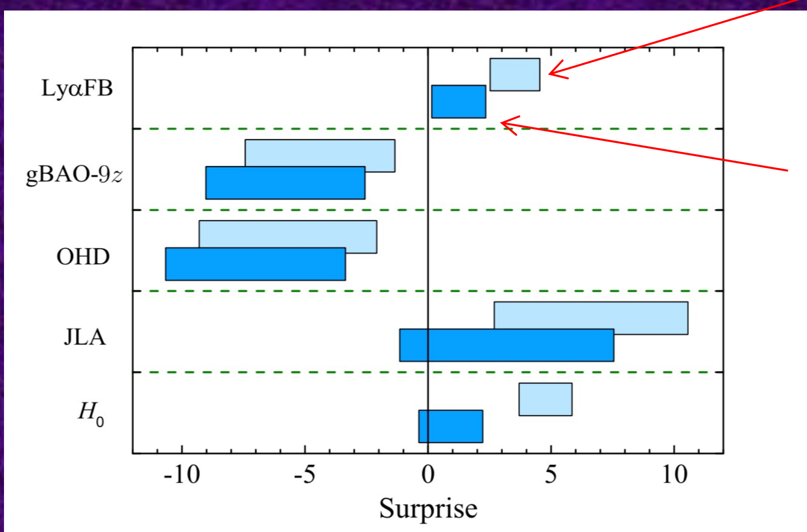
H(z = 0.00) = 70.6 \pm 3.3 km/sec/Mpc
H(z = 0.57) = 92.4 \pm 4.5 km/sec/Mpc
H(z = 2.34) = 222.0 \pm 7.0 km/sec/Mpc

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

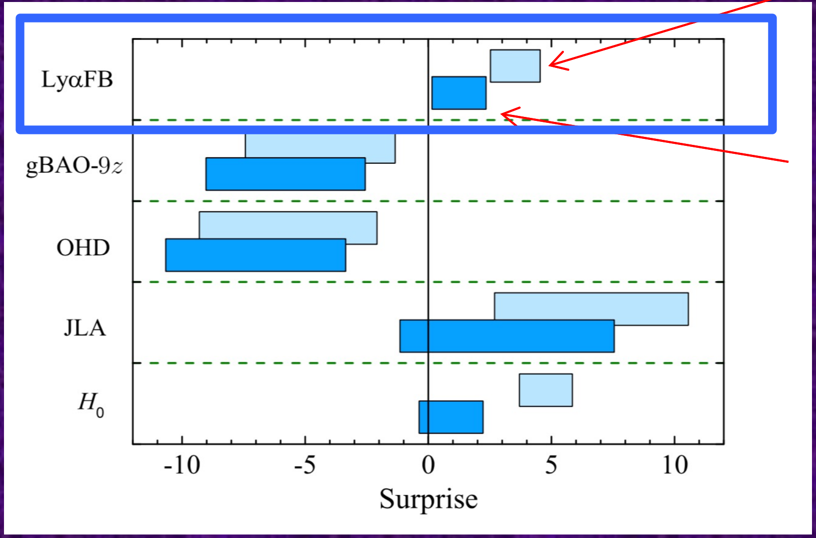
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

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

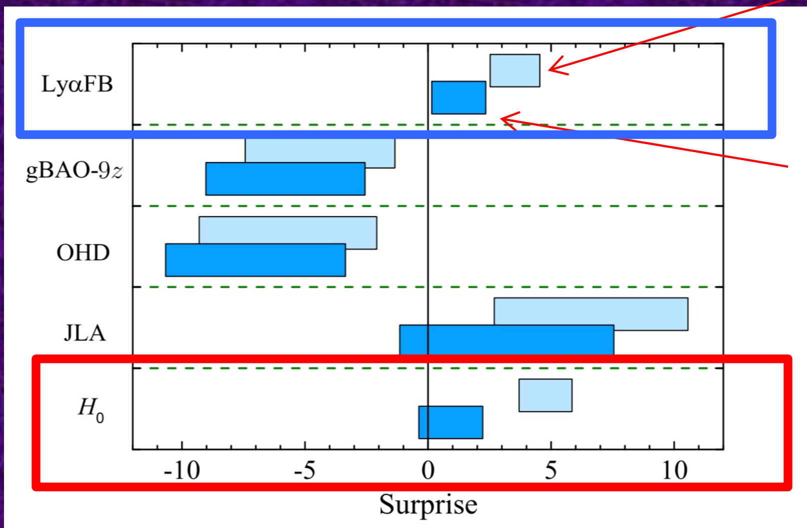
Kullback-Leibler (KL) divergence to quantify the degree of tension between different datasets assuming a model.

**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)***

# *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]

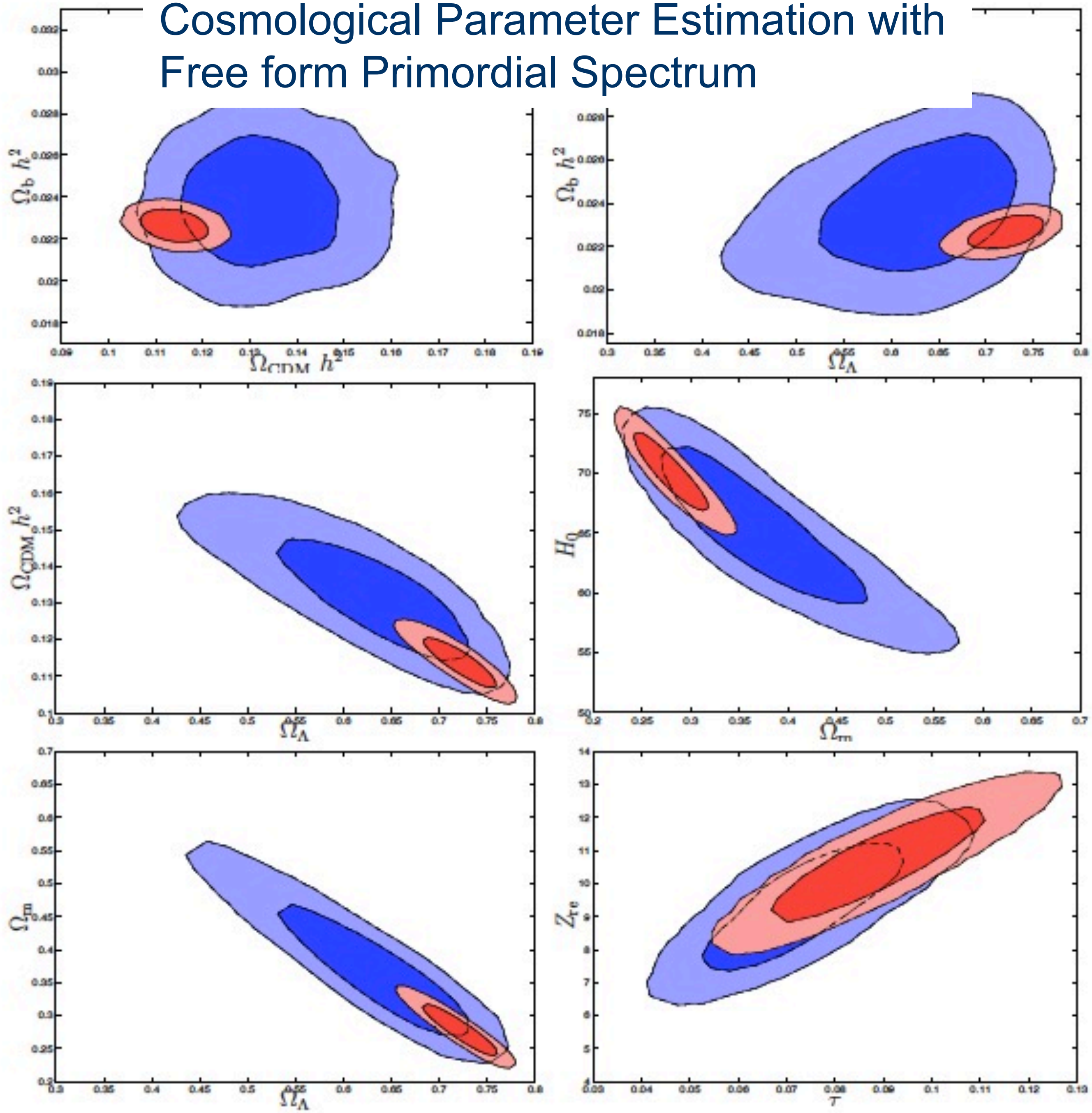
$$C_\ell = \sum_i G_{\ell k_i} P_{k_i}$$

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

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


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

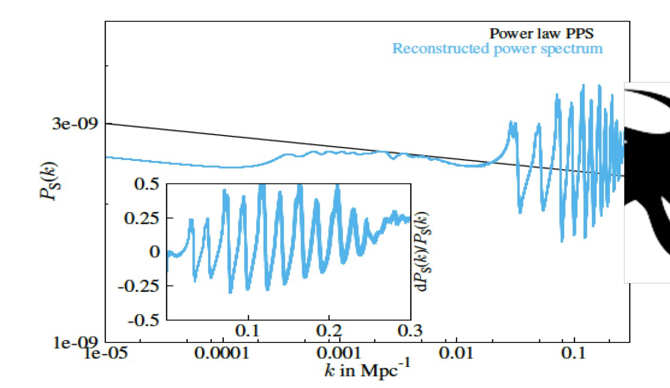


WMAP9 Data

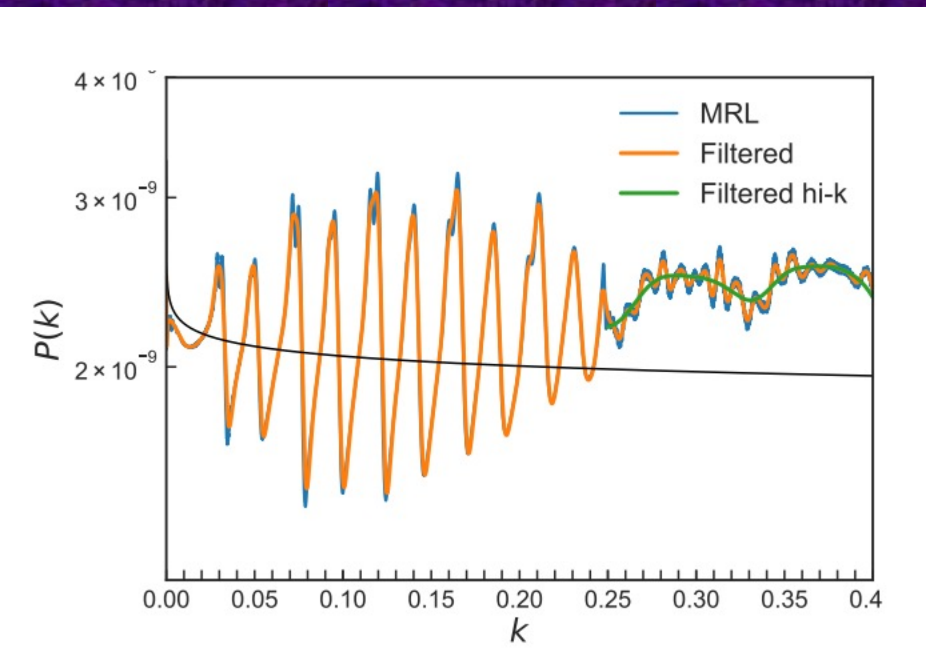
Red Contours:
Power Law PPS

Blue Contours:
Free Form PPS

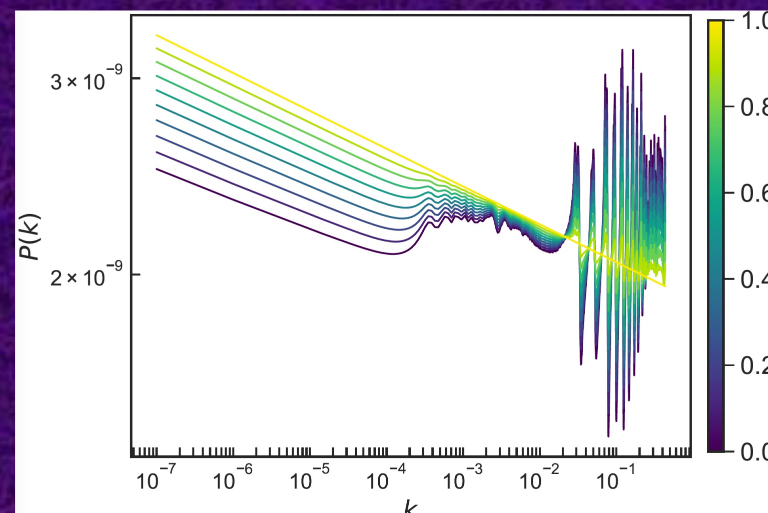
Hazra, Shafieloo, Souradeep, PRD 2013




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.

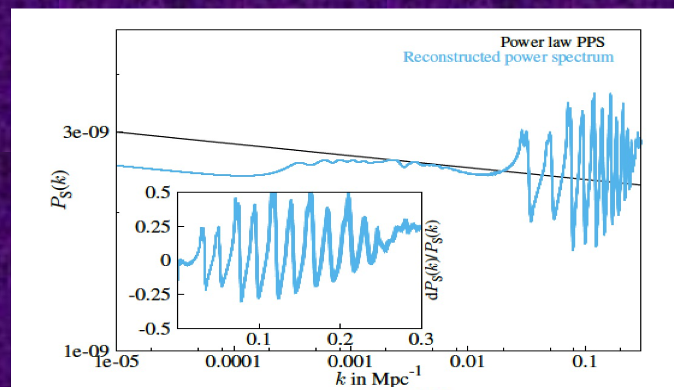
$$P(k,f) = P_{\mathrm{MRL}}(k) + f\left(P_{\mathrm{PL}}(k) - P_{\mathrm{MRL}}(k)\right).$$

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

# Observation:

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 A_Lens problem and other tensions/anomalies being connected?

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




Hazra, Shafieloo, Souradeep, JCAP 2019

Hazra, Shafieloo, Souradeep, JCAP 2014