H0 Tension: New Physics vs Systematics

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Cosmic Acceleration

17-19 February 2020, IPMU, Tokyo, Japan

H0 Tension: New Physics vs Systematics

or maybe both?!

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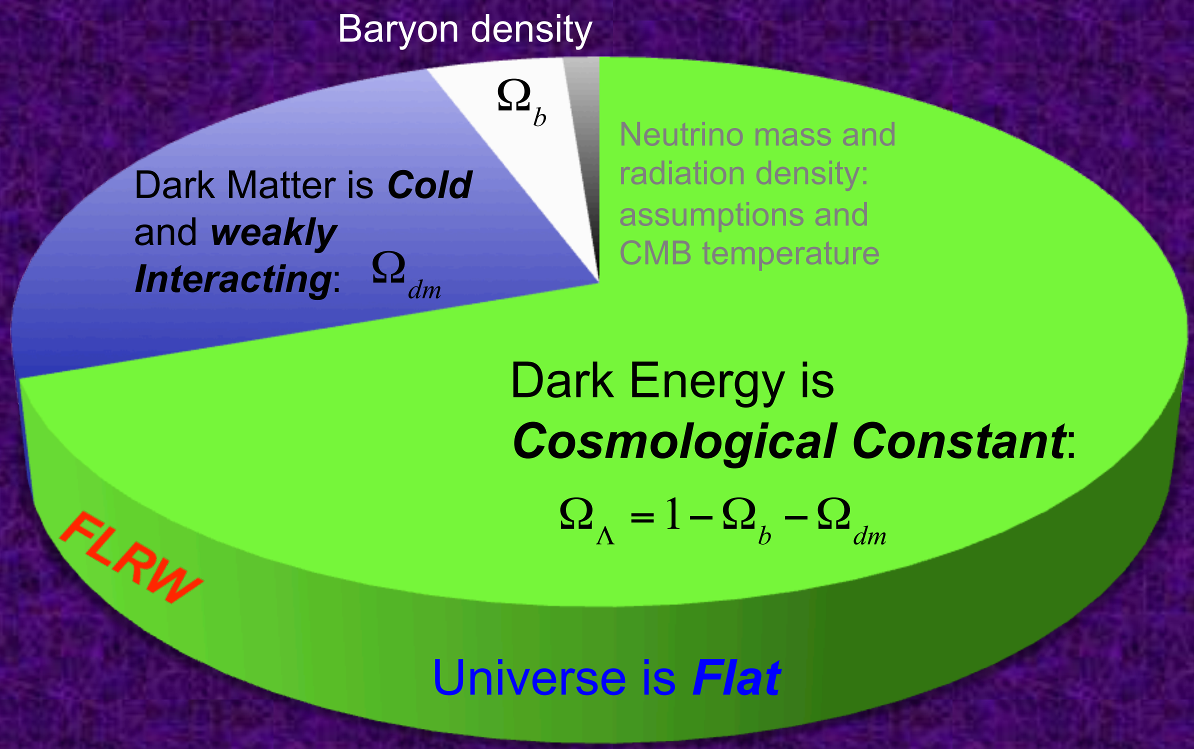
Standard Model of Cosmology

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



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

n_s, A_s

Epoch of reionization

τ

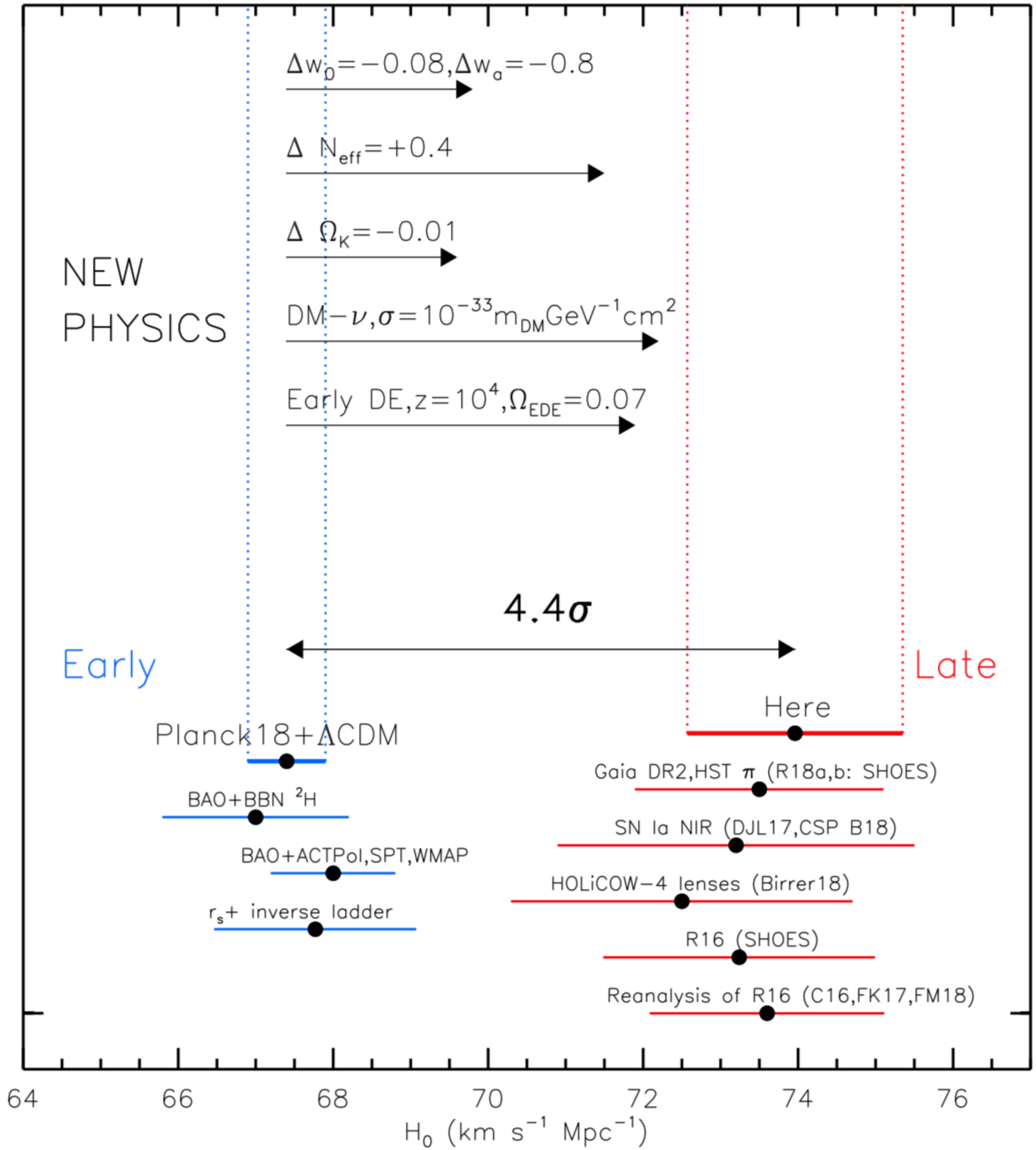
Hubble Parameter and the Rate of Expansion

H_0

Persistent Tensions in the Standard Model

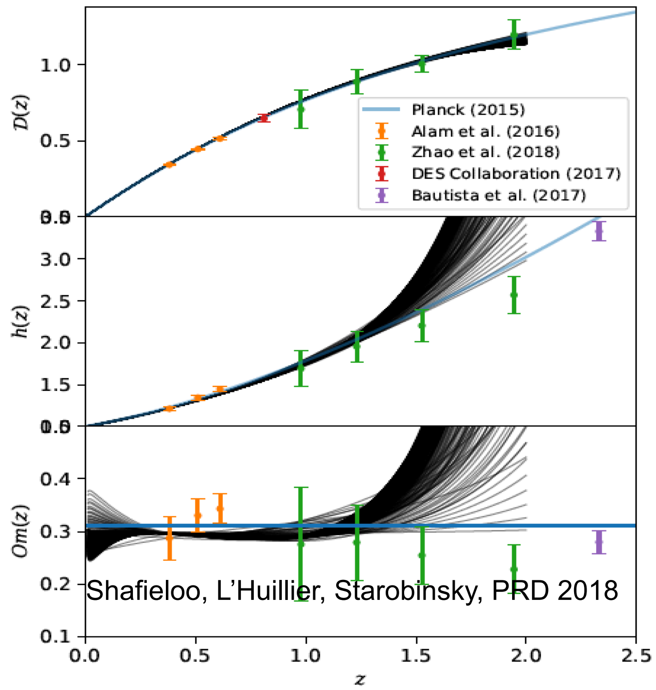
Local estimation of the Hubble constant seems to be substantially higher than the expected values fitting the standard LCDM model to CMB.

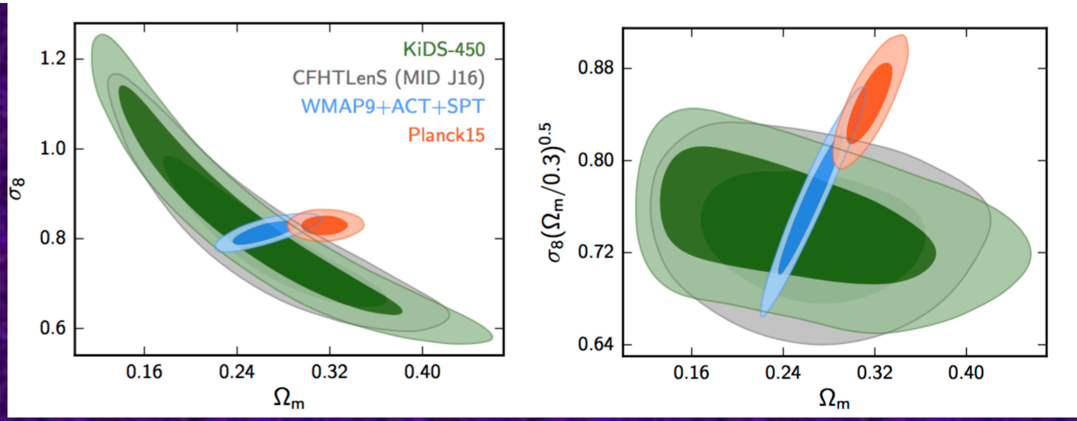
67 or 73?



Tensions in the Standard Model

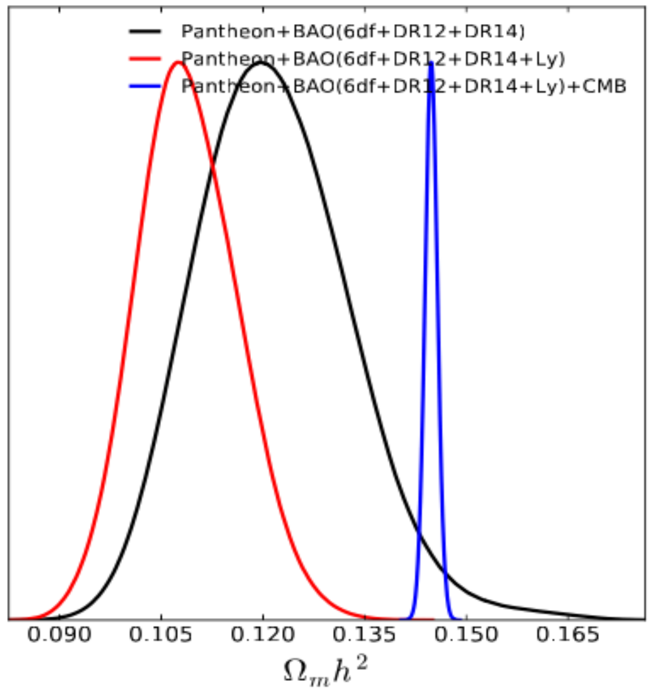
Riess et al, arXiv:1903.07603

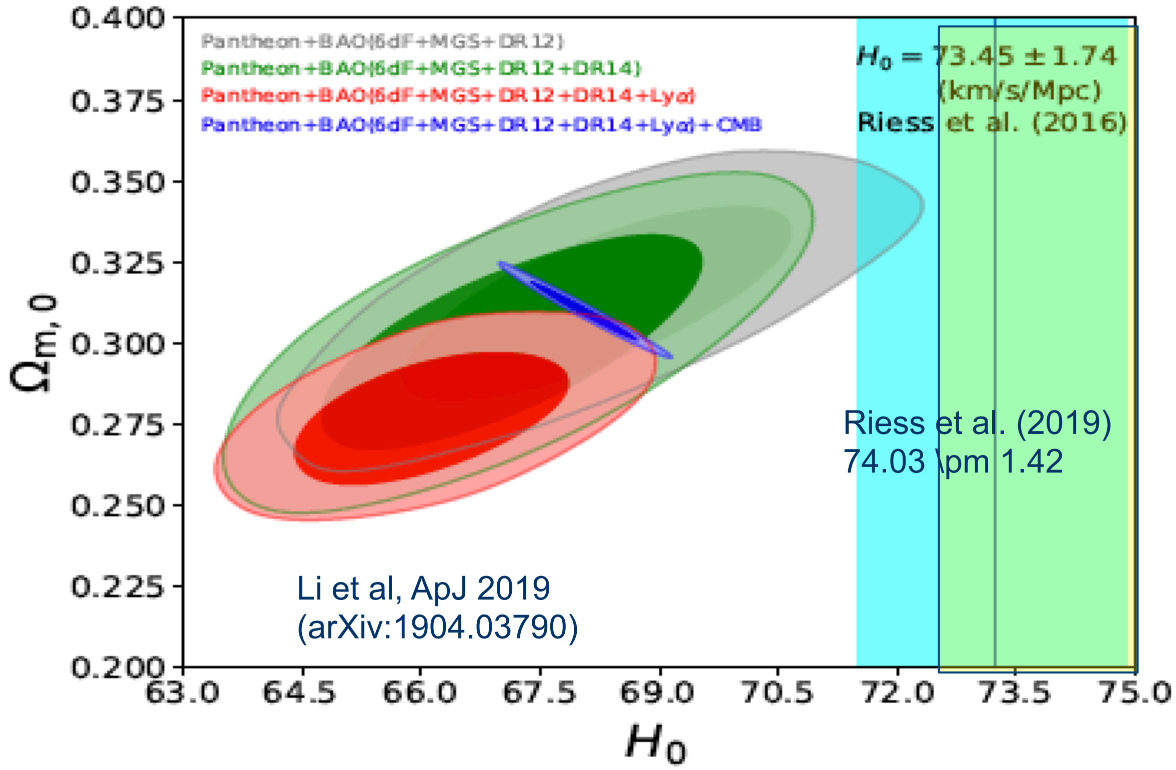




Hildebrandt et al, MNRAS 2017

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





Omh2

Important discovery if no systematic in the SDSS Quasar BAO data

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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

Only for Flat LCDM

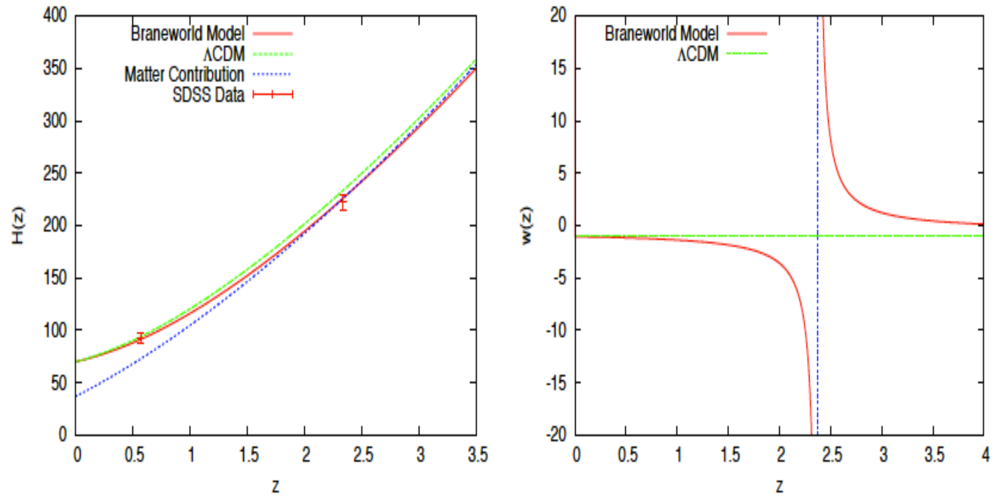
Sahni, Shafieloo, Starobinsky, ApJ Lett 2014

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

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

2020 Omh2

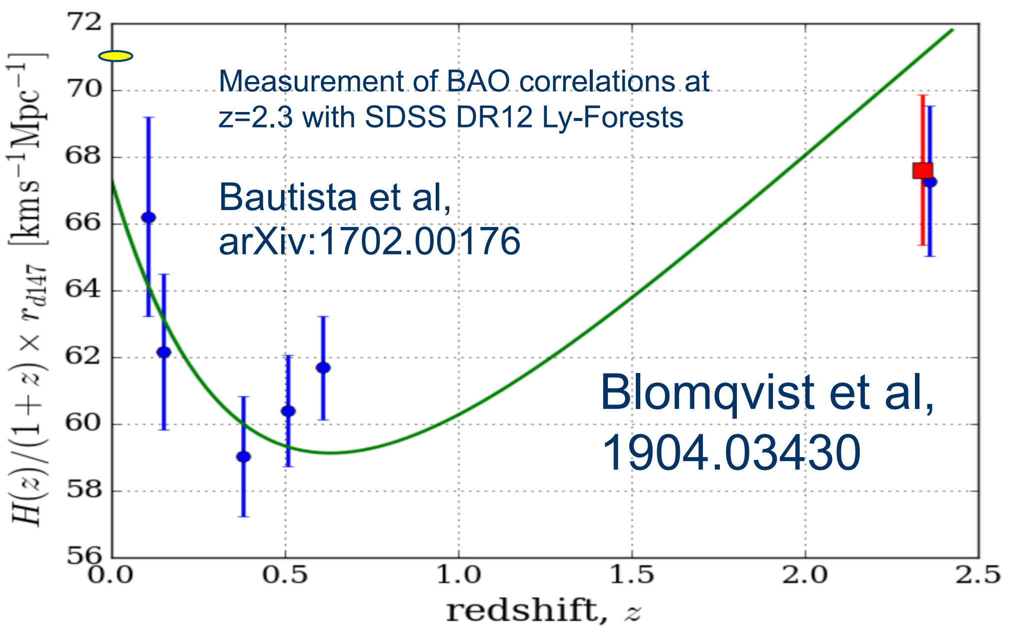
No systematic yet found,

Model Independent Evidence for Dark Energy Evolution from Baryon Acoustic Oscillation

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

Only for LCDM

Sahni, Shafieloo, Starobinsky, ApJ Lett 2014



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Multiple Suspects!

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)

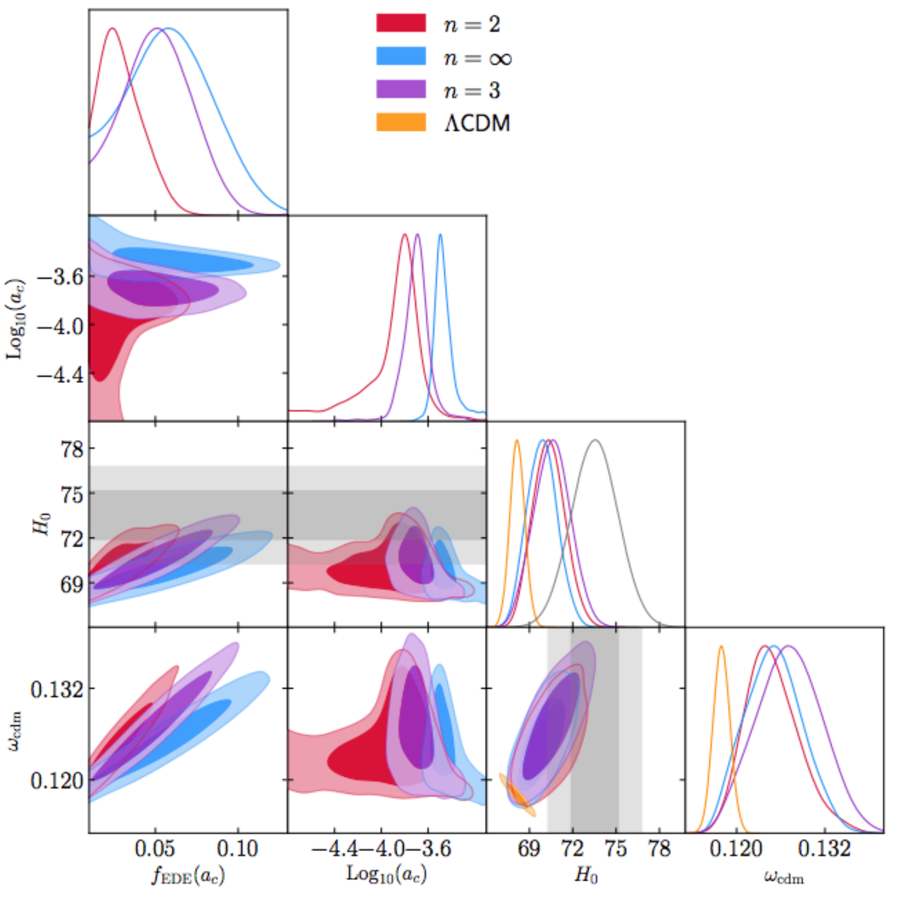
Dark Matter is cold

All within framework of FLRW

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]

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

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

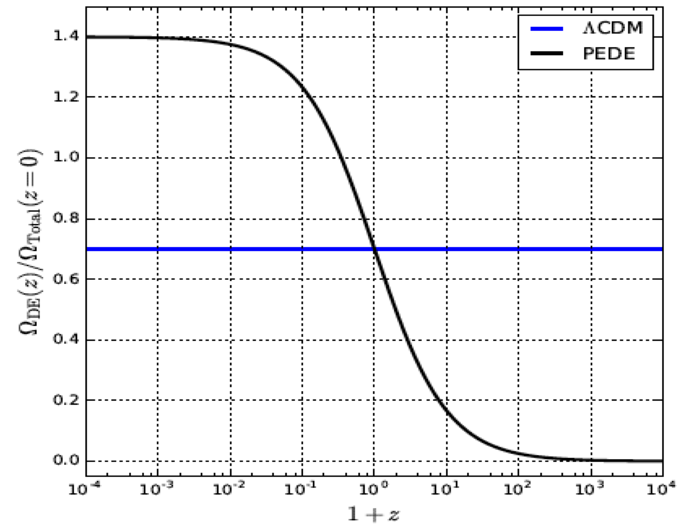
$$w_n = (n-1)/(n+1)$$

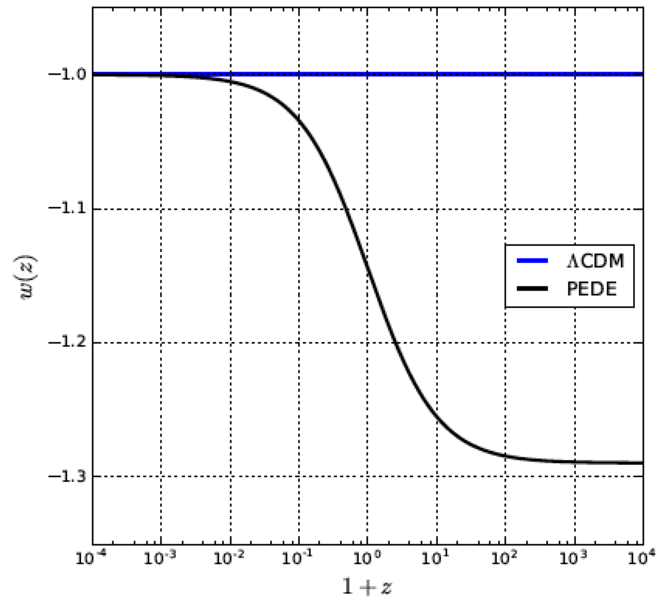
Poulin et al, Phys. Rev. Lett 2019

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

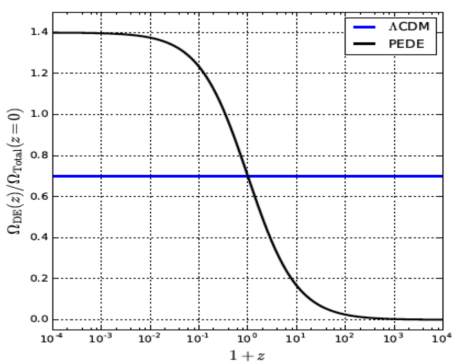
$$\Omega_{\rm DE}(z) = \Omega_{\rm DE,0} \times [1 - \tanh(\log_{10}(1+z))]$$

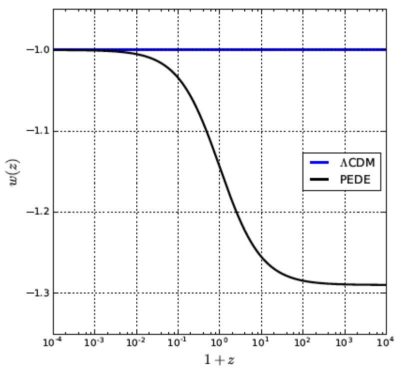
$$\begin{aligned} w(z) &= -\frac{1}{3\ln 10} \times \frac{1-\tanh^2[\log_{10}(1+z)]}{1-\tanh[\log_{10}(1+z)]} - 1 \\ &= -\frac{1}{3\ln 10} \times (1+\tanh[\log_{10}(1+z)]) - 1. \end{aligned}$$

Li and Shafieloo, ApJ Lett 2019

Phenomenologically Emergent Dark Energy (PEDE)

Model	Data Parameters	Pantheon+BAO			Pantheon+BAO+Lyα+CMB		
		No H_0 Prior	2σ H_0 Prior	1σ H_0 Prior	No H_0 Prior	2σ H_0 Prior	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

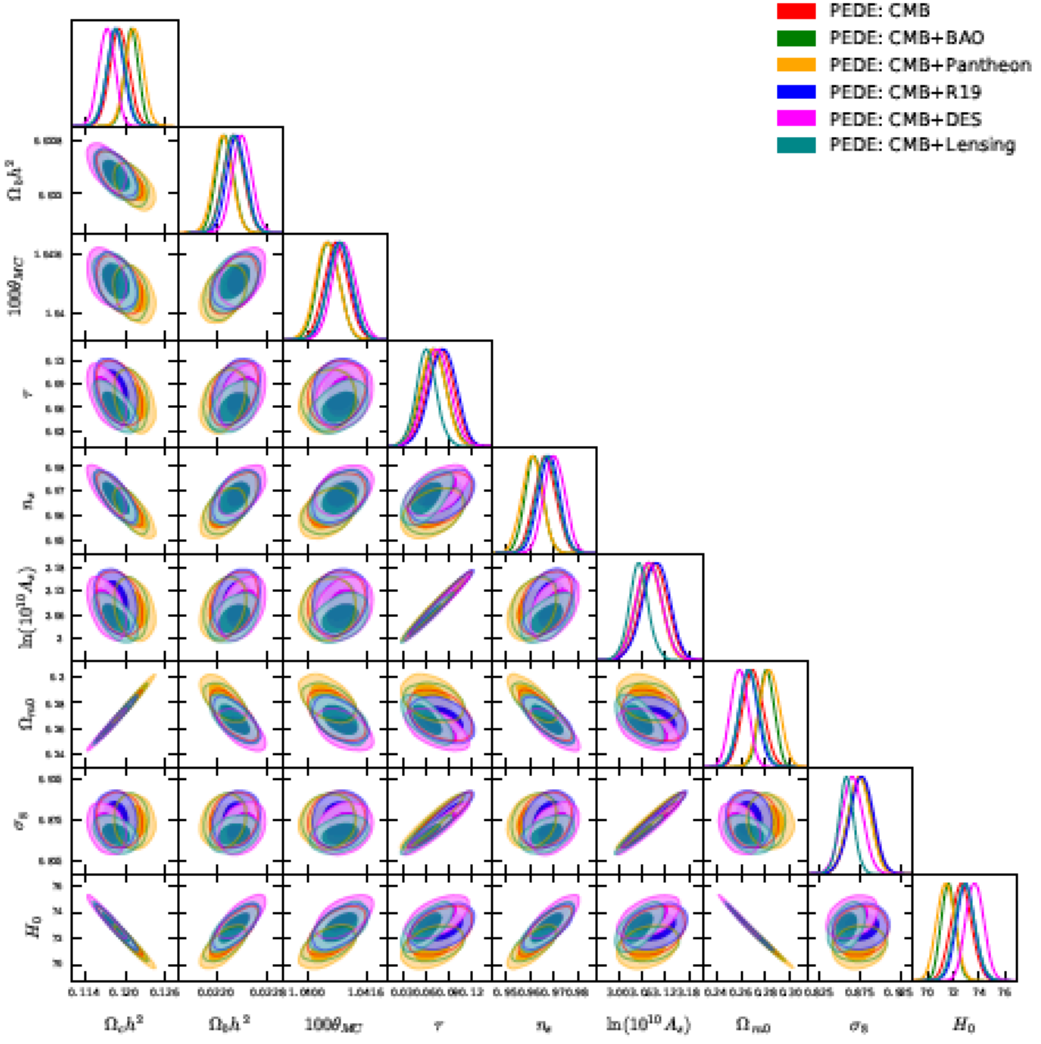
Near Future:
PEDE rules out Lambda

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

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

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

Phenomenologically Emergent Dark Energy (PEDE)

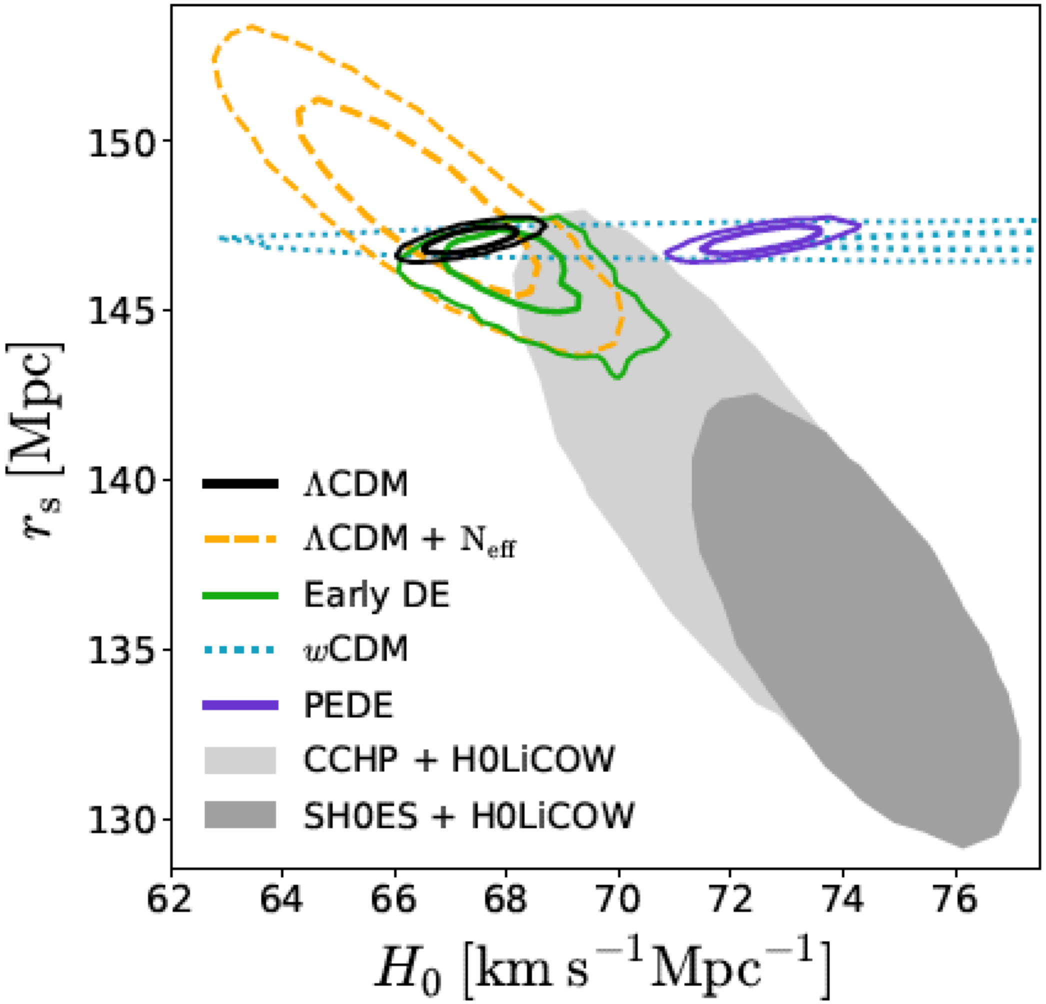


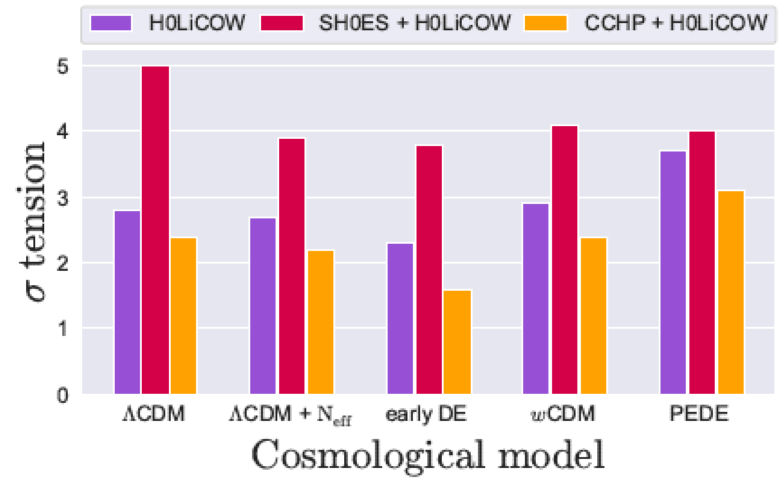
Reconciling H0 tension in a 6 parameter space?

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

Pan, Yang, Di Valentino,et al, arXiv: 1907.12551

Comparing candidates





Arendse et al, arXiv:1909.07986

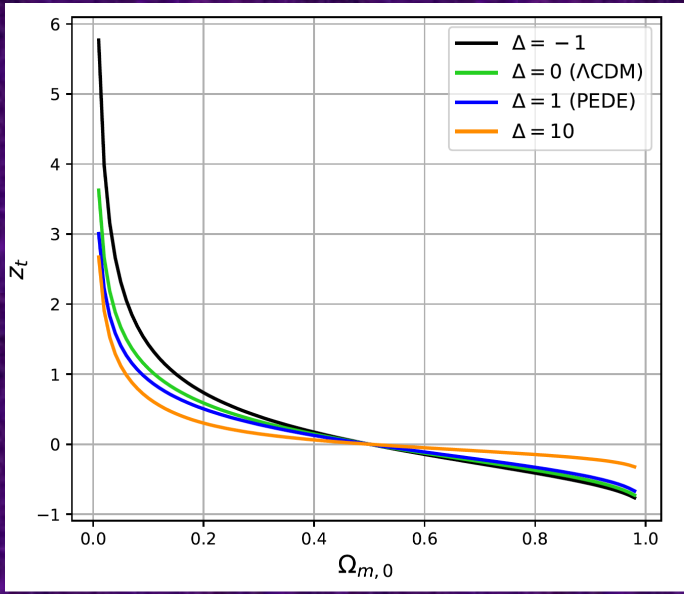
Generalized Emergent Dark Energy (GEDE)

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

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

-Has one degree of freedom for DE sector

-LCDM and PEDE are both included at special limits



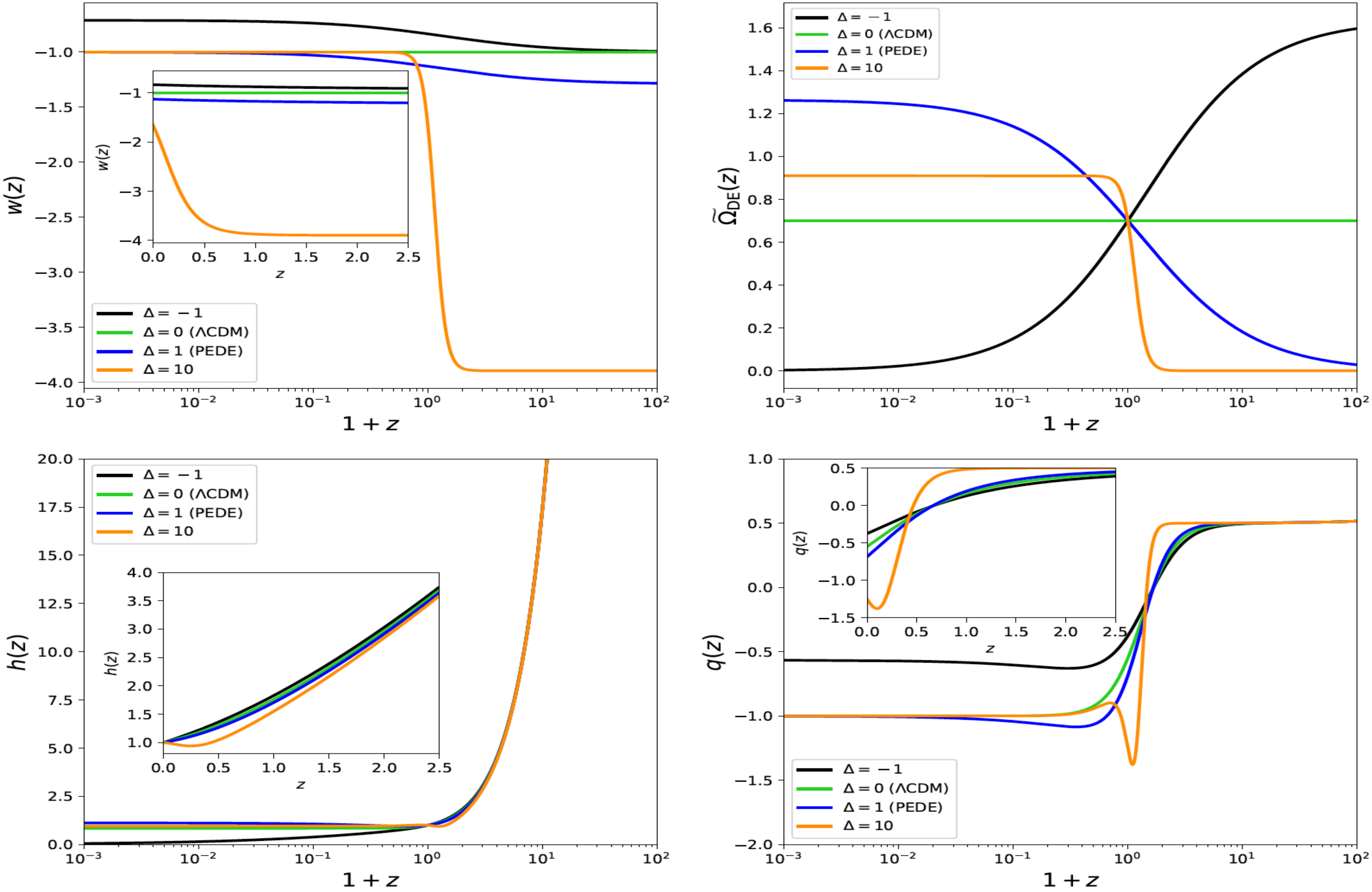
$$\Omega_{\rm DE}(z_t) = \Omega_{m,0}(1+z_t)^3$$

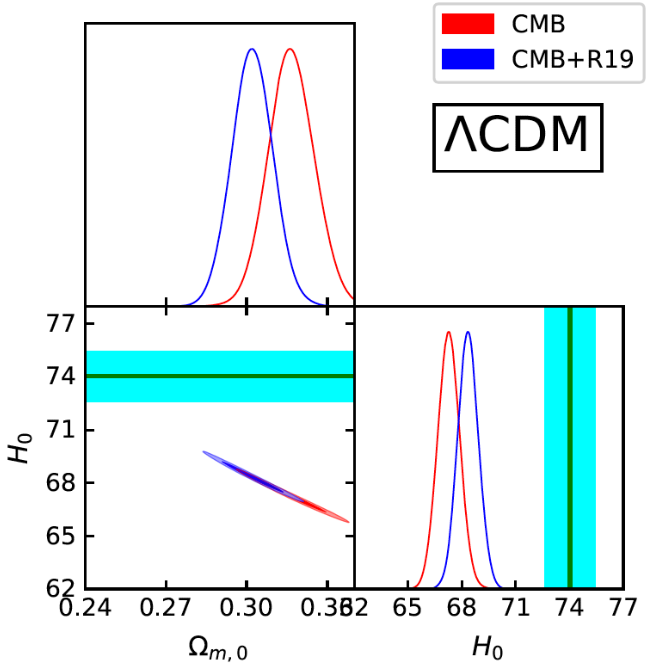
$\Delta = 0$ LCDM

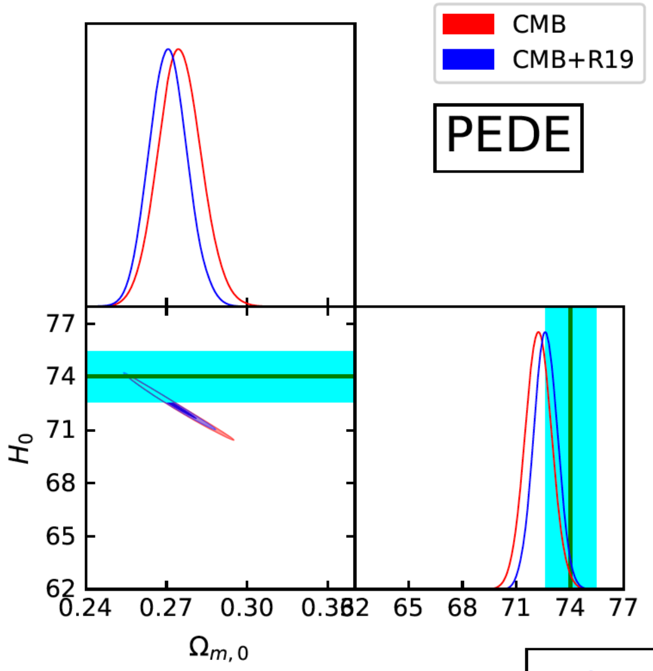
$\Delta = 1$ PEDE

Li and Shafieloo, arXiv:2001.05103

Generalized Emergent Dark Energy (GEDE)

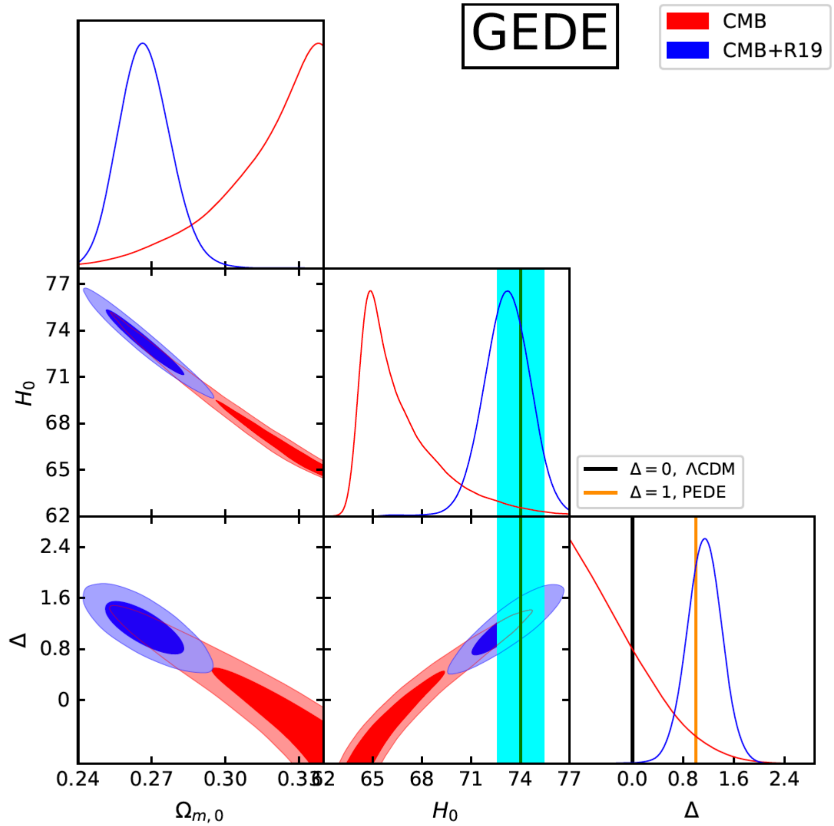




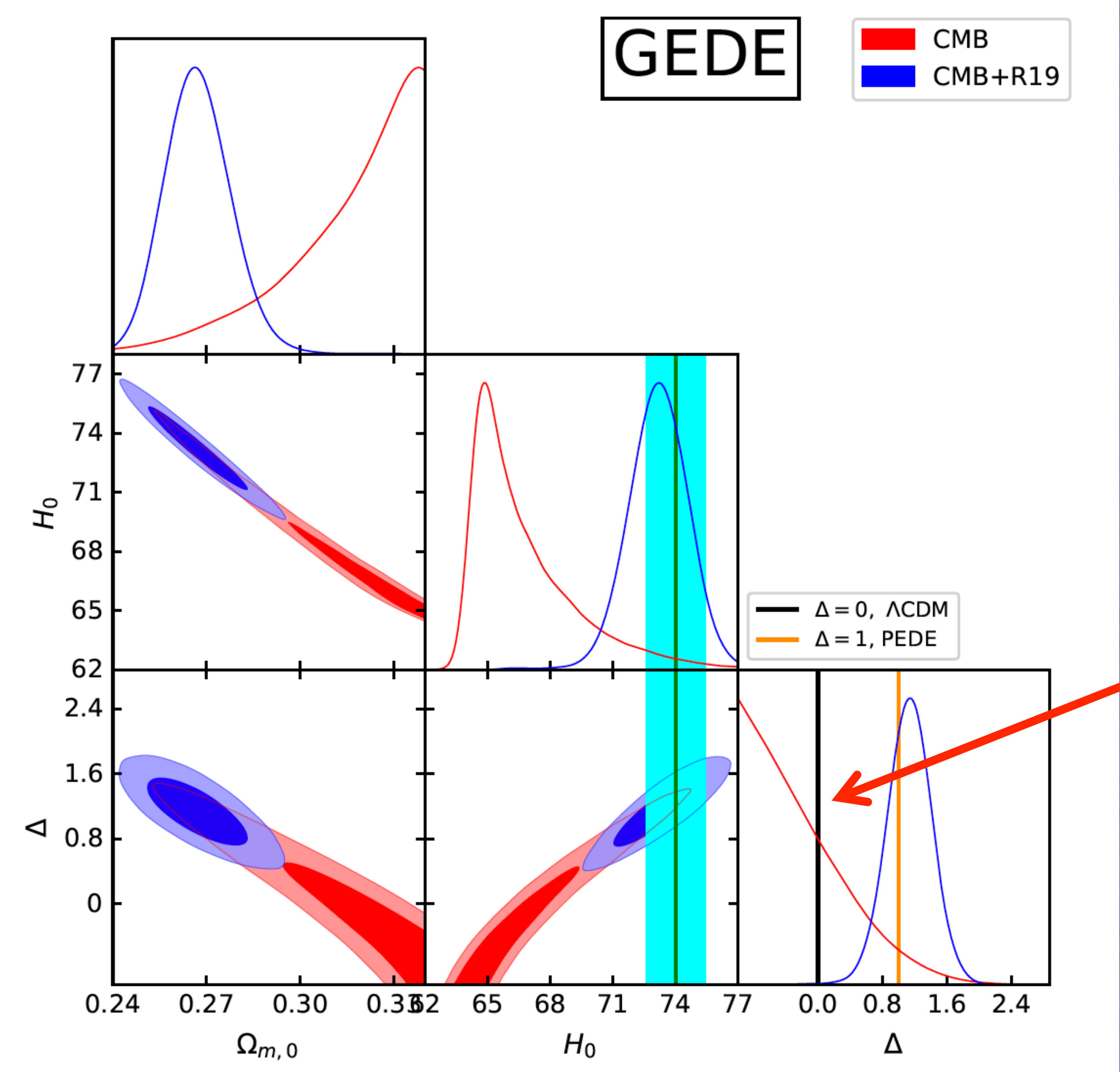


Generalized Emergent Dark Energy (GEDE)

Li & Shafieloo, ApJ Lett 2019
Li & Shafieloo, arXiv:2001.05103



Generalized Emergent Dark Energy (GEDE)



Lambda outside the 4\sigma CL

Li and Shafieloo, arXiv:2001.05103

(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

Forms of PPS and Effects on the Background Cosmology

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

Ω_b

Ω_m

H_0

τ

1

2

G(l,k)

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

2

3

$$C_l^{obs}$$

1

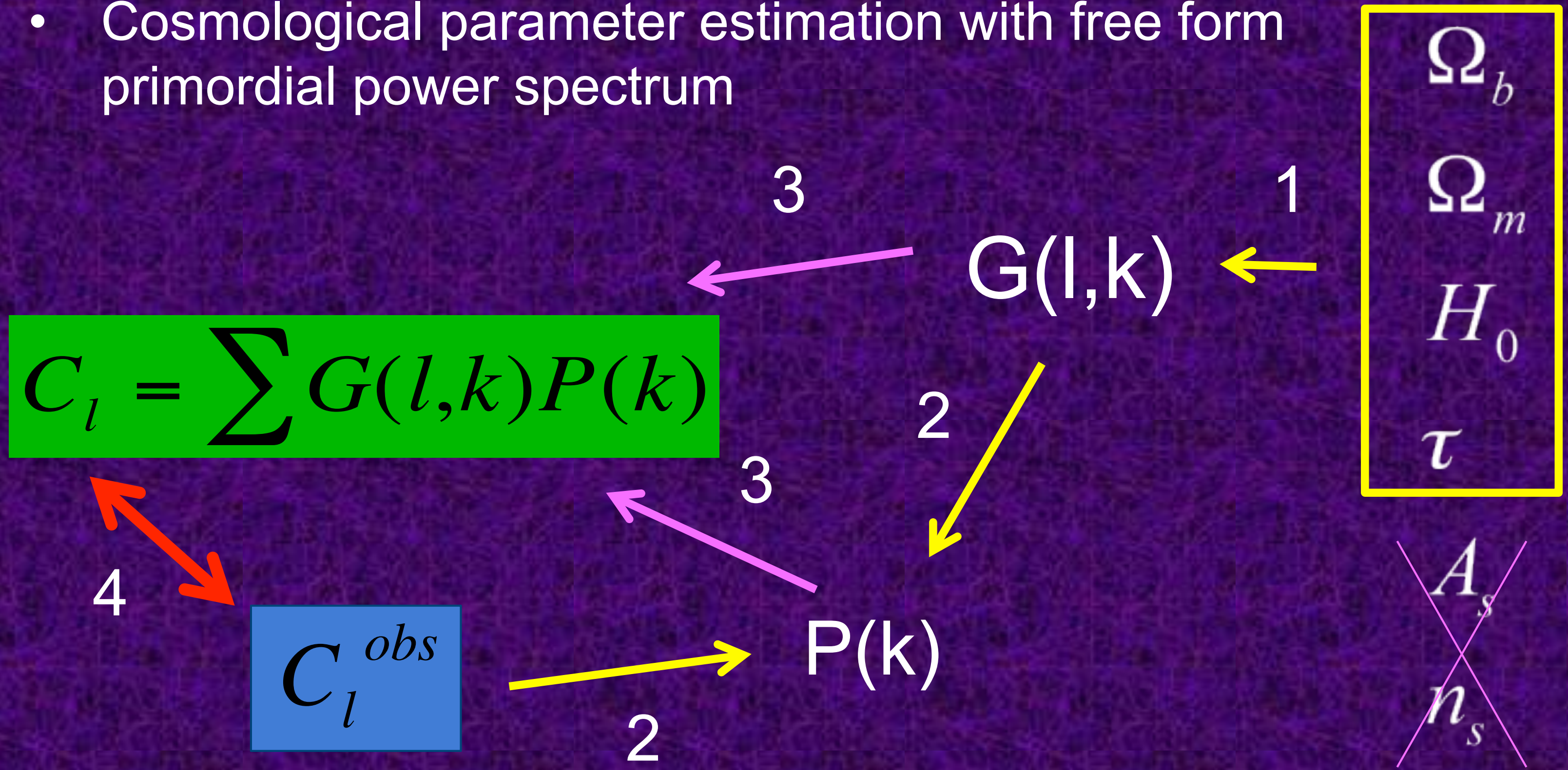
A_s

n_s

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

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]

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

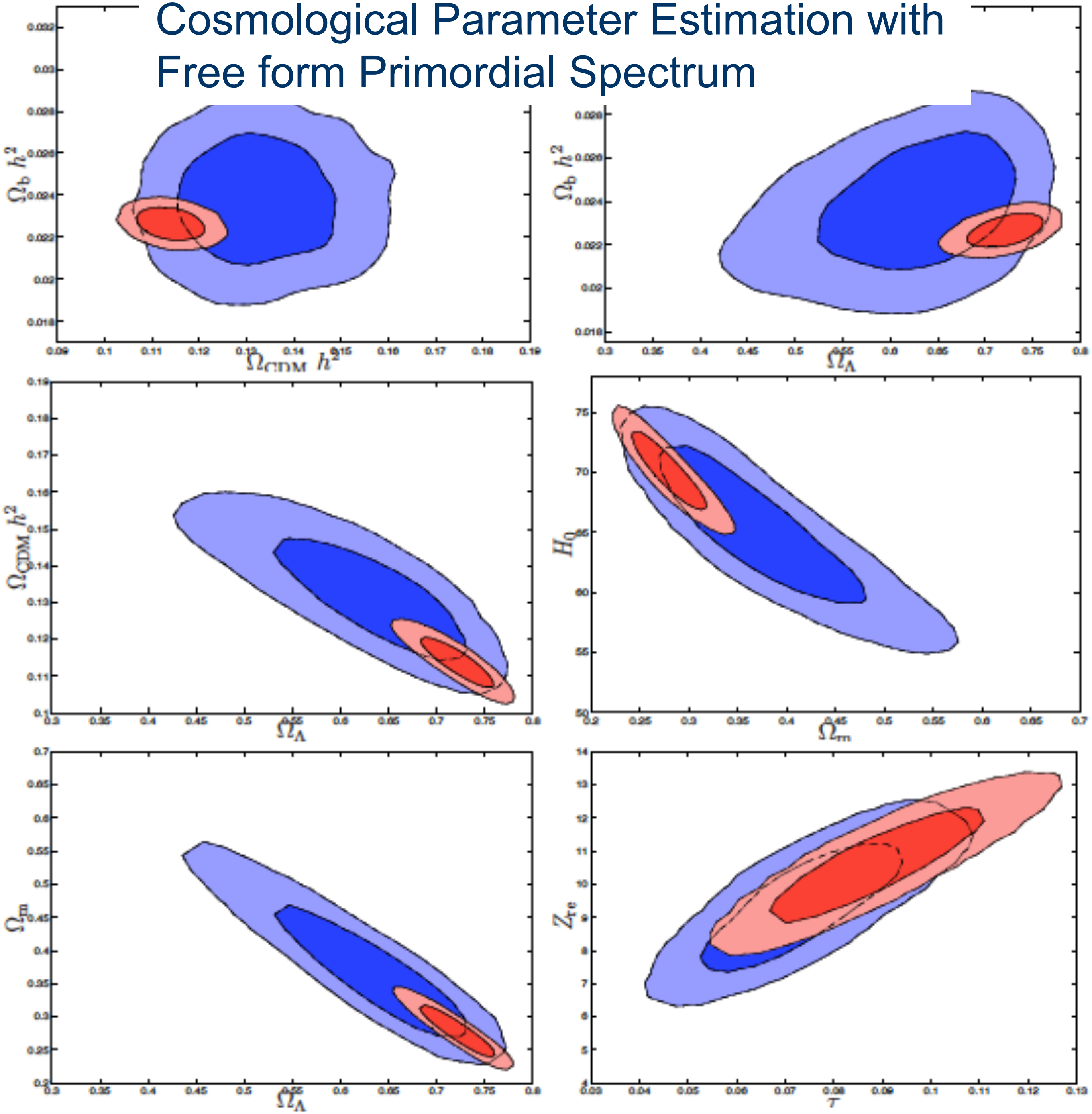
$$\begin{aligned} P_k^{(i+1)} - P_k^{(i)} &= P_k^{(i)} \times \left[\sum_{\ell=2}^{\ell=900} \tilde{G}_{\ell k}^{\rm un-binned} \left\{ \left(\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{C_\ell^{\rm T(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{\rm D} - C_\ell^{\rm T(i)}) \right] \right\}_{\rm un-binned}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

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

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

Cosmological Parameter Estimation with Free form Primordial Spectrum



WMAP9 Data

Red Contours:
Power Law PPS

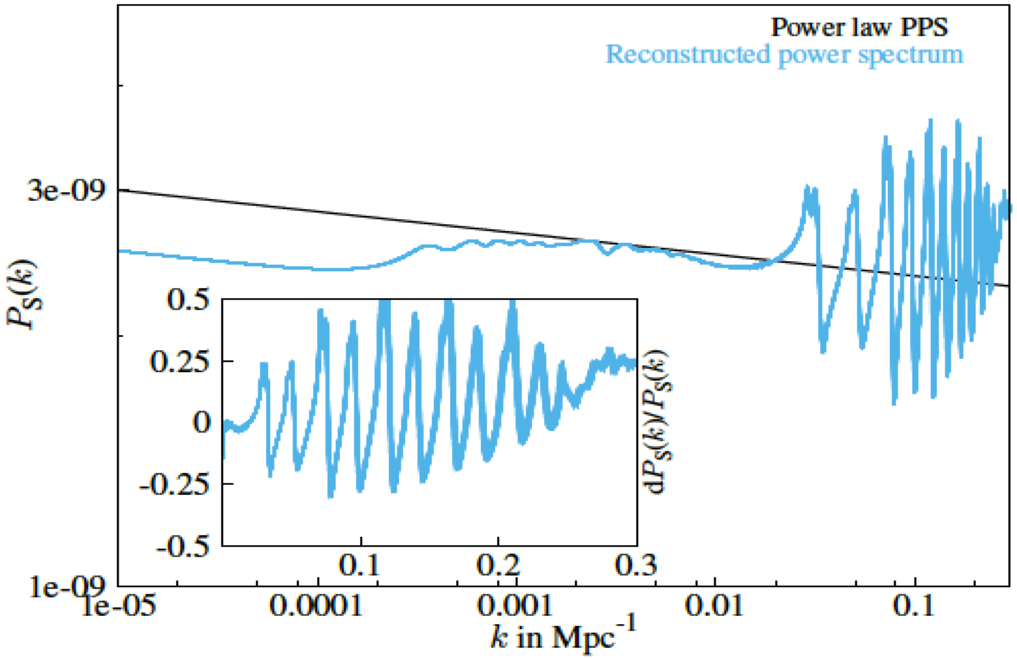
Blue Contours:
Free Form PPS

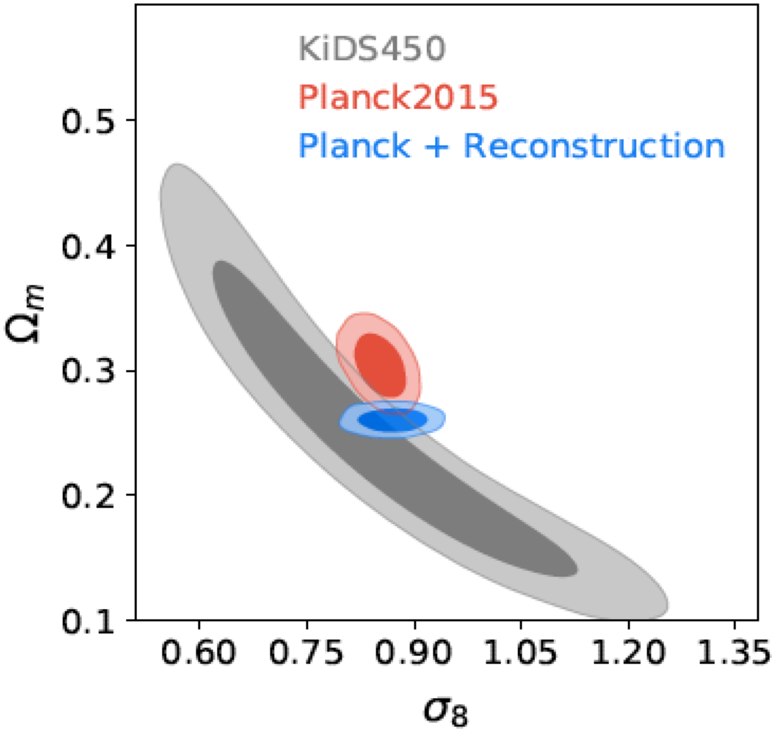
Hazra, et al, PRD 2013

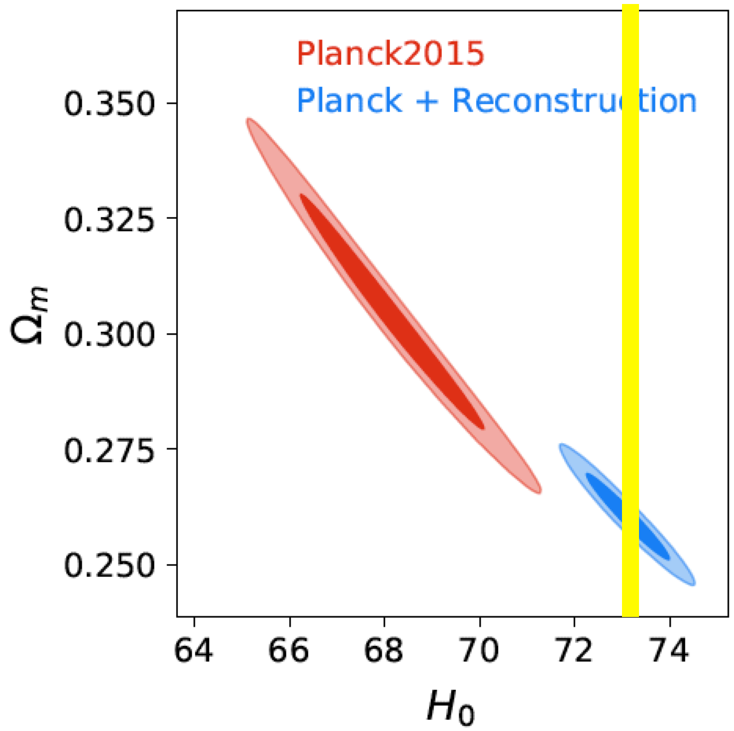
Hazra, Shafieloo, Souradeep, JCAP 2019

Background Cosmological Parameters and PPS

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

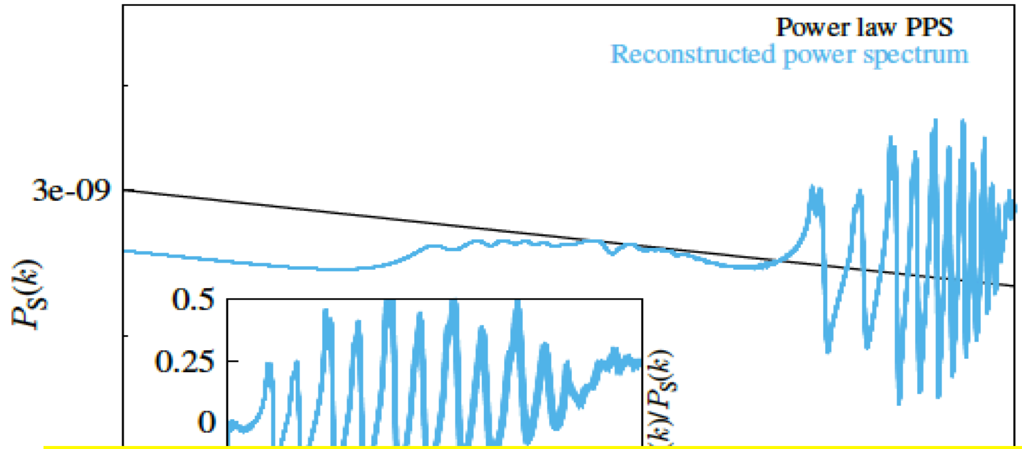






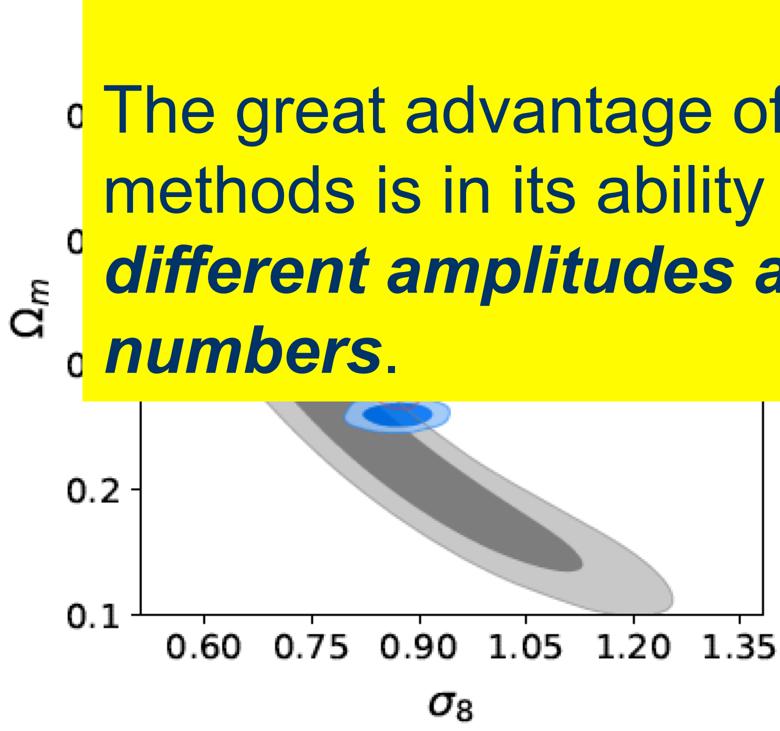
Hazra, Shafieloo, Souradeep, JCAP 2019

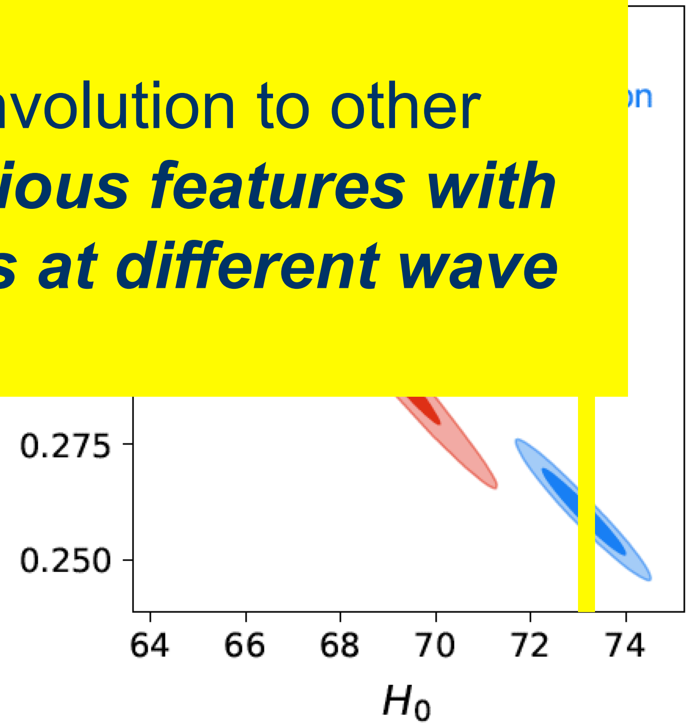
Background Cosmological Parameters and PPS

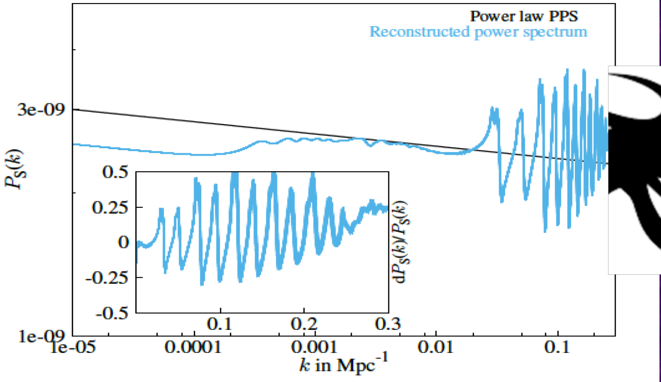


NOTE: Similar attempts by other groups to find a form of PPS for a different set of background parameters (to resolve Hubble tension) has failed so far.

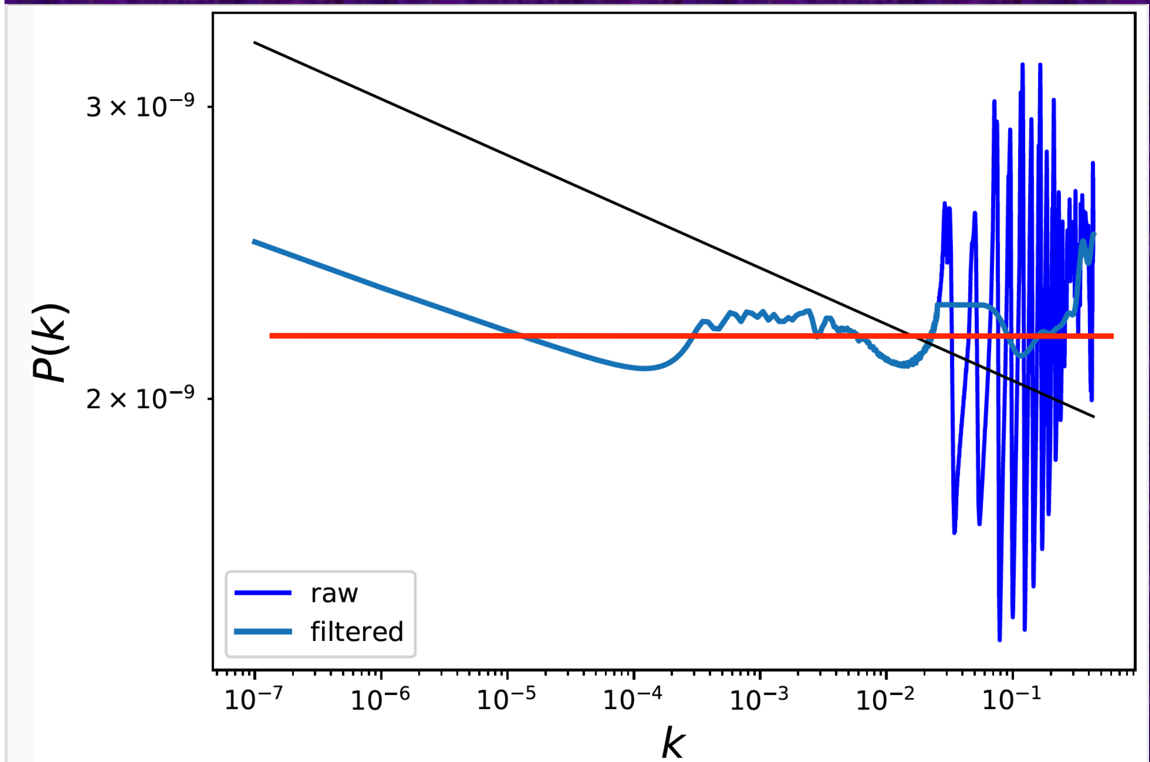
The great advantage of the MRL deconvolution to other methods is in its ability to generate ***various features with different amplitudes and frequencies at different wave numbers***.





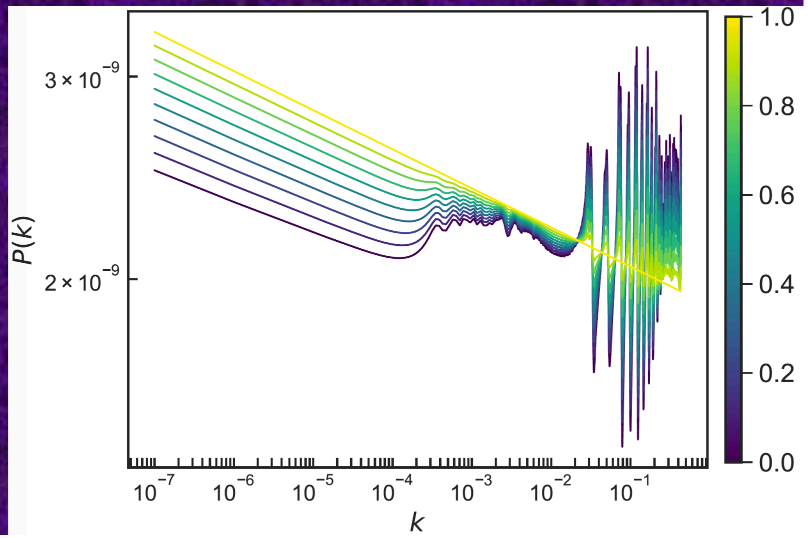


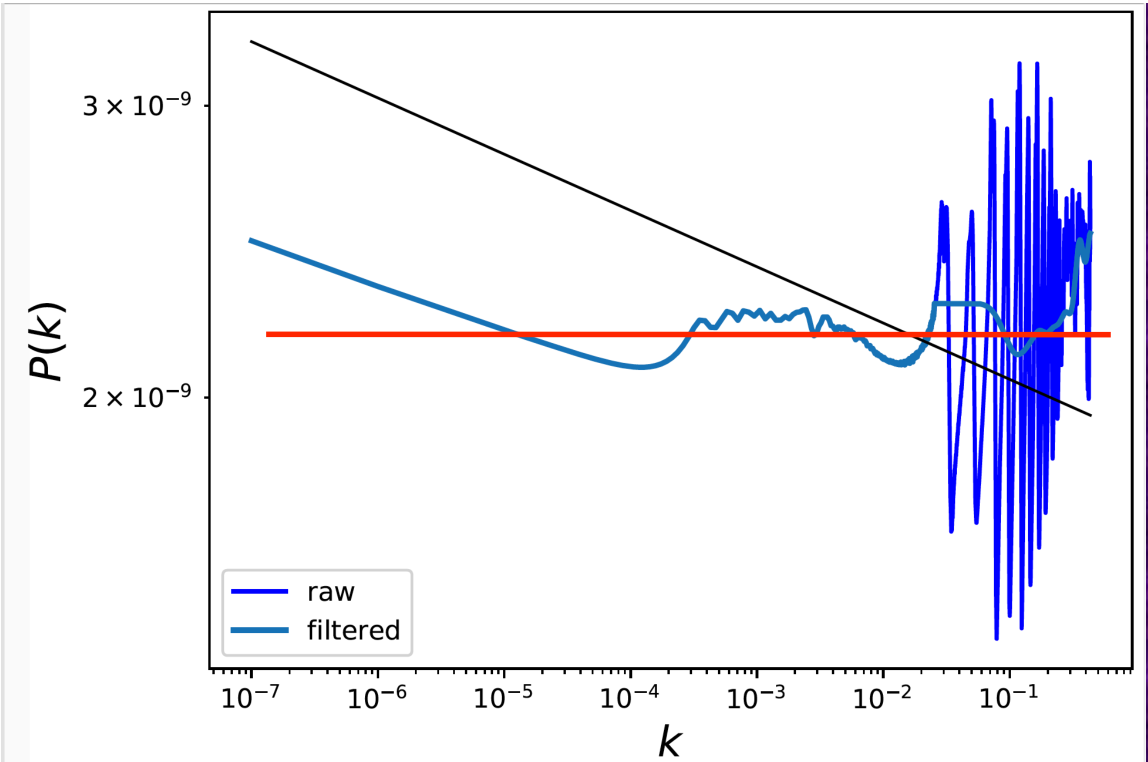
Do we need the high-k features?



No, a featured decorated HZ should be fine ;)

Keeley, Shafieloo, … in prepration





Issues:

1. it appears to be unnatural to generate the complex form of the reconstructed PPS within an inflationary scenario without extreme fine tuning. However, we do not provide any conclusive reason to close the possibility of a physical early Universe explanation.

2. Using polarization data it should be possible to validate further the possibility of the reconstructed form of the PPS. Likewise, using polarization data we might be able to look for a more optimized form of the PPS to remove tensions from different observations.

3. A wider exploration of the underlying parameter space of the cosmological model would be essential to reveal potential routes to ameliorate the disagreements in cosmological parameters inferred.

Conclusion

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

- 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/cosmological observations, (DESI, Euclid, LSST, WFIRST, SKA(?), etc) will make it clear about the status of the concordance model in 2020s.