Holographic Dark Energy: Possibility of negative dark energy at $z \gtrsim 2$

Trends in Astroparticle and Particle Physics
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UV/IR see-saw to Holographic Dark Energy

Holographic Dark Energy density

$$\rho_\Lambda = 3C^2 M_{\rm P}^2 L^{-2}. \tag{1}$$

Friedmann – Lemaître – Robertson – Walker metric,

$$ds^2 = c^2 dt^2 - a^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right). \tag{2}$$

Friedmann Equations

$$H^2 = \frac{8\pi G}{3}\rho, \tag{3}$$

$$\dot{H} + H^2 = \frac{-4\pi G}{3}\left(\rho + 3p\right), \tag{4}$$

$$\dot{\rho} = -3H\left(\rho + p\right). \tag{5}$$

Granda – Oliveros IR Cut-off

Granda – Oliveros IR Cut-off

$$L_{\mathrm{GO}} = \left(\alpha H^2 + \beta \dot{H}\right)^{-1/2} . \tag{6}$$

Granda – Oliveros HDE

$$\rho_\Lambda = 3M_\mathrm{P}^2 \left(\alpha H^2 + \beta \dot{H}\right) . \tag{7}$$

The Hubble parameter

$$H^2 = \frac{8\pi G}{3}\left[\rho_m + \rho_r - \frac{k}{a^2} + 3M_\mathrm{P}^2\left(\alpha H^2 + \beta \dot{H}\right)\right] . \tag{8}$$

The Hubble parameter $h = H/H_0$

$$h^2 = \frac{\Omega_r e^{-4x}}{-\alpha + 2\beta + 1} + \frac{2\Omega_m e^{-3x}}{-2\alpha + 3\beta + 2} + \frac{\Omega_k e^{-2x}}{-\alpha + \beta + 1} + C_1 e^{-\frac{2(\alpha-1)x}{\beta}}, \tag{9}$$

The Integration constant

$$C_1 = \frac{\alpha + \Omega_k}{\alpha - \beta - 1} - \frac{2\Omega_m}{-2\alpha + 3\beta + 2} + \frac{\Omega_r}{\alpha - 2\beta - 1} + \frac{\beta}{-\alpha + \beta + 1} + \frac{1}{-\alpha + \beta + 1}. \tag{10}$$

Granda – Oliveros HDE density parameter

$$\Omega_\Lambda(x) = e^{-4x}\left\{e^{\frac{2x(-\alpha+2\beta+1)}{\beta}}\left[\frac{(\alpha-\beta)(\Omega_k+1)-1}{\alpha-\beta-1}\right.\right.$$
$$\left.+\frac{\Omega_m}{\alpha-\frac{3}{2}\beta-1}+\frac{\Omega_r}{\alpha-2\beta-1}\right]+e^{2x}\Omega_k\left(\frac{1}{-\alpha+\beta+1}-1\right)$$
$$\left.+e^{x}\Omega_m\left(\frac{2}{-2\alpha+3\beta+2}-1\right)+\Omega_r\left(\frac{1}{-\alpha+2\beta+1}-1\right)\right\}. \quad (11)$$

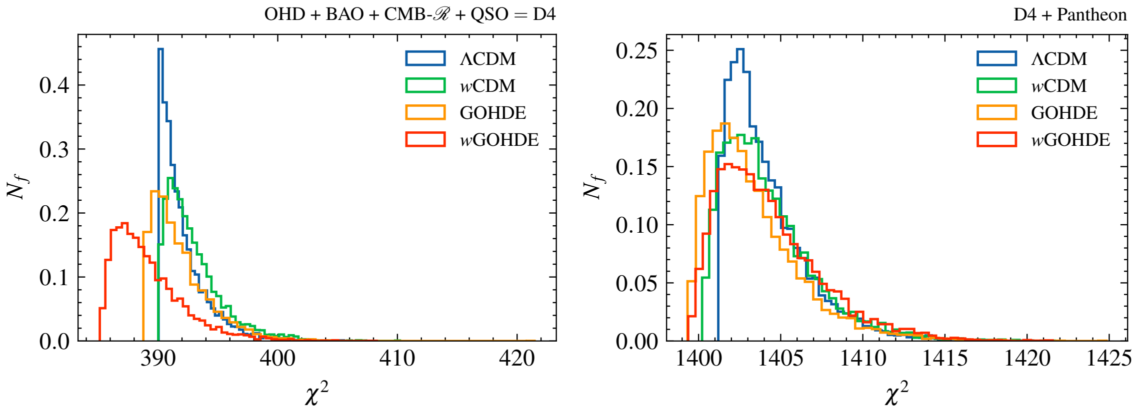
Dark Energy Equation of State parameter

$$w(z) = -1+\left(\frac{1+z}{3}\right)\partial_z \ln\Omega_\Lambda(z). \quad (12)$$

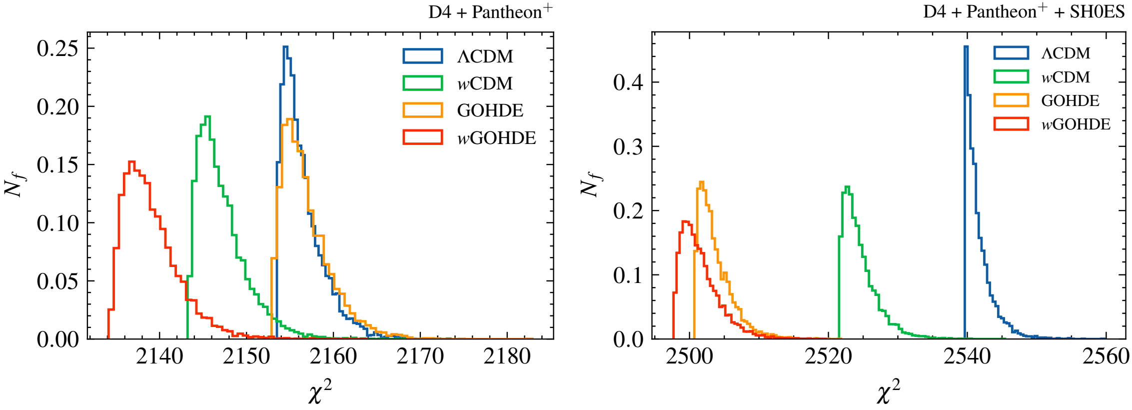
EoS at the present as the new free parameter

$$w_{z0} = \frac{-2\alpha(\Omega_k+1)}{3\beta(\Omega_m+\Omega_r-1)}+\frac{2\Omega_k+\Omega_r+3}{3(\Omega_m+\Omega_r-1)}-\frac{2}{3\beta}. \quad (13)$$

χ^2 Analysis



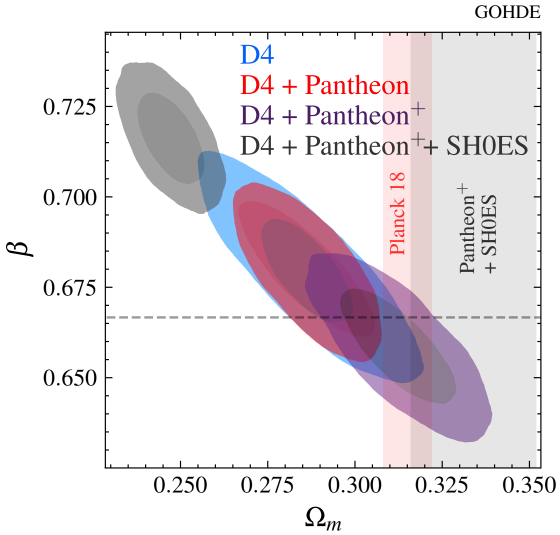
χ^2 Analysis

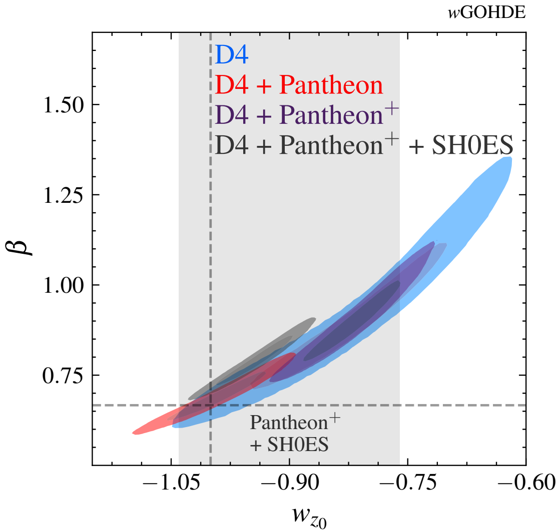


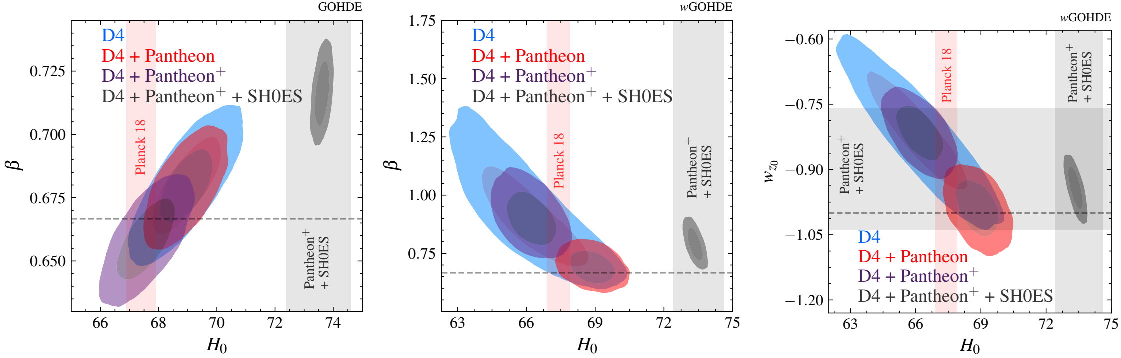
Best Fit Values

Model	Data Set	Ω_m $(\times 10^{-3})$	H_0	w_{z_0} for wGOHDE	β	M	$z_\dagger$	Age (Gyr)
GOHDE	D4	285^{+14}_{-13}	$68.94^{+0.88}_{-0.83}$	–	$0.680^{+0.013}_{-0.014}$	–	4.69	13.920
	D4 + Pantheon	$286.3^{+9.1}_{-9.3}$	$68.92^{+0.66}_{-0.62}$	–	$0.679^{+0.011}_{-0.010}$	$-19.390^{+0.018}_{-0.017}$	4.82	13.904
	D4 + Pantheon$^+$	312 ± 11	$67.56^{+0.71}_{-0.69}$	–	$0.658^{+0.012}_{-0.011}$	-19.433 ± 0.020	231.69	13.782
	" + SH0ES prior	$247.0^{+6.8}_{-6.7}$	$73.61^{+0.18}_{-0.16}$	–	$0.716^{+0.009}_{-0.010}$	–	2.98	13.673
wGOHDE	D4	293^{+14}_{-15}	$66.1^{+1.7}_{-1.6}$	$-0.819^{+0.098}_{-0.093}$	$0.87^{+0.17}_{-0.14}$	–	4.19	14.028
	D4 + Pantheon	285 ± 11	$68.87^{+0.67}_{-0.70}$	$-0.989^{+0.047}_{-0.044}$	$0.688^{+0.051}_{-0.047}$	$-19.390^{+0.017}_{-0.018}$	4.47	13.911
	D4 + Pantheon$^+$	291 ± 13	$66.17^{+0.77}_{-0.73}$	$-0.816^{+0.045}_{-0.044}$	$0.891^{+0.086}_{-0.076}$	-19.455 ± 0.020	3.75	14.064
	" + SH0ES prior	$238.3^{+8.6}_{-9.1}$	$73.34^{+0.24}_{-0.23}$	-0.941 ± 0.035	$0.786^{+0.052}_{-0.048}$	–	2.9	13.760

Table: Constraints (best-fit $\pm$ 1σ) on the free parameters of the models (GOHDE, and wGOHDE) using various combinations of data sets along with the best fit estimate of the negative energy transition redshift $z_\dagger$ and age.


GOHDE
D4
D4 + Pantheon
D4 + Pantheon+
D4 + Pantheon+ + SH0ES
Planck 18
Pantheon+
+ SH0ES
0.725
0.700
0.675
0.650
0.250
0.275
0.300
0.325
0.350
β
Ω_m


wGOHDE
D4
D4 + Pantheon
D4 + Pantheon+
D4 + Pantheon+ + SH0ES
Pantheon+
+ SH0ES
1.50
1.25
1.00
0.75
−1.05
−0.90
−0.75
−0.60
β
w_{z0}



GOHDE
D4
D4 + Pantheon
D4 + Pantheon+
D4 + Pantheon+ + SH0ES
Planck 18
Pantheon+ + SH0ES
0.725
0.700
0.675
0.650
β
66
68
70
72
74
H_0
wGOHDE
1.75
1.50
1.25
1.00
0.75
63
66
69
72
75
wGOHDE
−0.60
−0.75
−0.90
−1.05
−1.20
w_{z0}

Statistical quantifiers

Data Set	Model	DOF	AIC	BIC	B_{ij}
D4	ΛCDM	2.1549	142.49	148.91	1
	wCDM	2.1667	144.48	154.10	0.075
	GOHDE	2.1598	143.89	153.52	0.1
	wGOHDE	2.1516	144.17	157.01	0.017
D4 + Pantheon	ΛCDM	1.1410	165.42	180.77	1
	wCDM	1.1412	166.55	187.01	0.044
	GOHDE	1.1404	165.77	186.23	0.065
	wGOHDE	1.1414	167.81	193.39	0.002
D4 + Pantheon$^+$	ΛCDM	1.1449	257.89	274.51	1
	wCDM	1.1400	250.87	273.04	2.085
	GOHDE	1.1452	259.35	281.51	0.05
	wGOHDE	1.1358	244.87	272.57	2.64

Table: Statistical quantifiers (DOF, AIC, BIC and Bayes factor) of the models (ΛCDM, wCDM, GOHDE, and wGOHDE) using the complete data set without SH0ES prior.

Features of Dark Energy EoS

$$w_\Lambda = -1 + \frac{\left[\frac{(2\alpha-2)}{\beta}\left(\frac{1}{z+1}\right)^{\frac{2-2\alpha}{\beta}}\mathcal{G} + (z+1)\partial_z\mathcal{F}\right]}{3\left[\left(\frac{1}{z+1}\right)^{\frac{2-2\alpha}{\beta}}\mathcal{G} + \mathcal{F}\right]}, \tag{14}$$

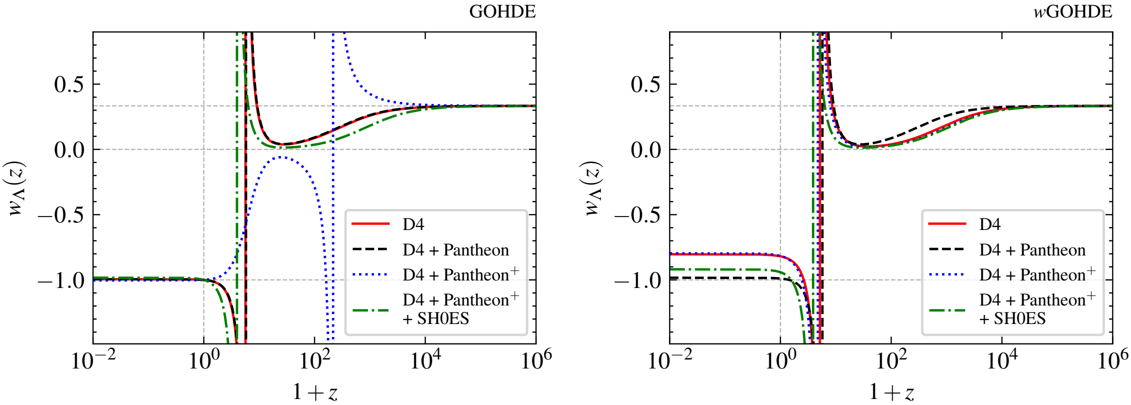
$$\mathcal{F} := \Omega_k\left[\frac{(z+1)^2}{-\alpha+\beta+1} - 1\right] + \Omega_m\left[\frac{2(z+1)^3}{-2\alpha+3\beta+2} - 1\right] + \Omega_r\left[\frac{(z+1)^4}{-\alpha+2\beta+1} - 1\right],$$

$$\mathcal{G} := \frac{(\alpha-\beta)(\Omega_k+1)-1}{\alpha-\beta-1} + \frac{\Omega_m}{\alpha-\frac{3}{2}\beta-1} + \frac{\Omega_r}{\alpha-2\beta-1}.$$

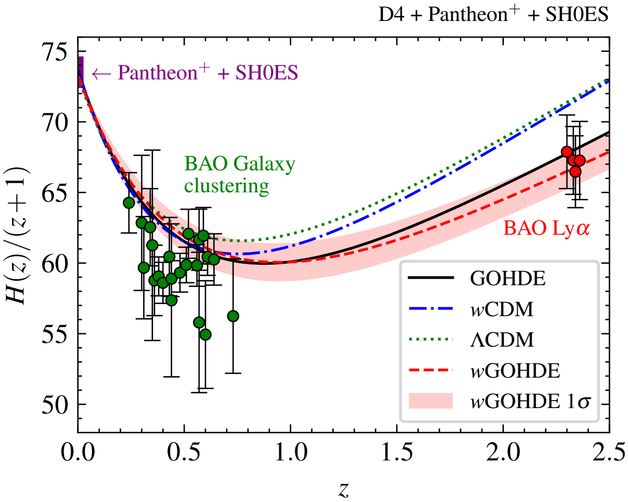
Condition for Cosmological Constant

$$\frac{(2\alpha-2)}{\beta}\left(\frac{1}{z+1}\right)^{\frac{2-2\alpha+\beta}{\beta}}\mathcal{G} = -\partial_z\mathcal{F}. \tag{15}$$

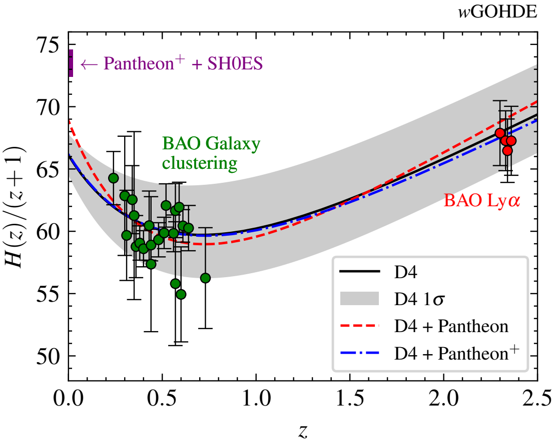
Dark Energy EoS

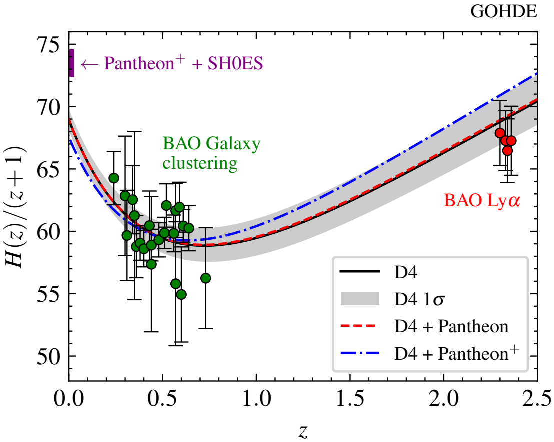


BAO Lyα Anomaly



BAO Lyα Anomaly





Summary

- The research centres on investigating Granda-Oliveros holographic dark energy (GOHDE) within a flat FLRW universe to provide observational constraints on model parameters and address the BAO Ly-α anomaly.
- The GOHDE density is defined, and the parameter α is re-parametrized as w_{z0}, representing the present value of the dark energy equation of state parameter.
- The study employs χ^2 minimization with the Markov Chain Monte Carlo (MCMC) method to estimate free parameters using various observational data sets. Both GOHDE and wGOHDE models are compared against the standard ΛCDM model, showing weak evidence against it.

Summary

- The research highlights the potential of the holographic dark energy (HDE) model to alleviate the BAO Ly-α anomaly. It emphasizes the importance of the transition from **early negative energy to positive energy** in resolving cosmological tensions, establishing upper and lower bounds for this transition region.
- The study demonstrates that HDE models mimic dominant energy forms unless free parameters are calibrated rigorously. It highlights the interdependence between a model's capability to explain late-time acceleration and the integration constant, which cannot be arbitrarily set to zero, providing insights into the origins of HDE and the Friedmann equations from the first law of horizon thermodynamics.

Thank you!

Questions and Comments are welcome

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Read more at
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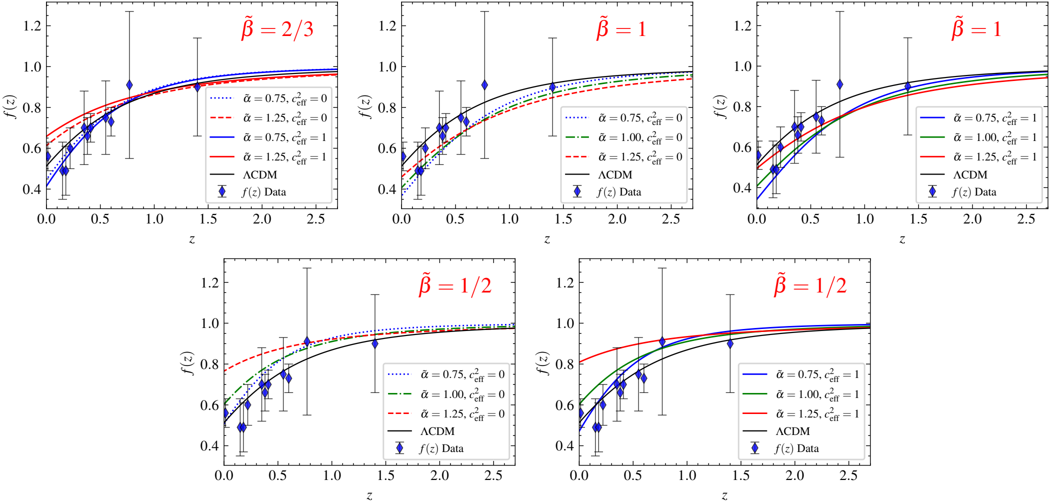
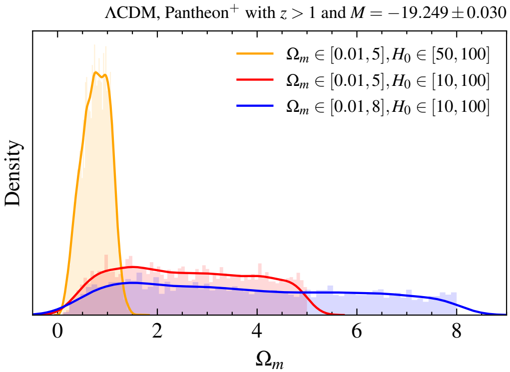
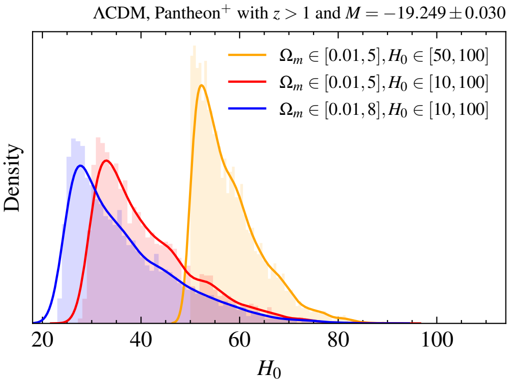
Back up slides

Linear perturbation and growth function

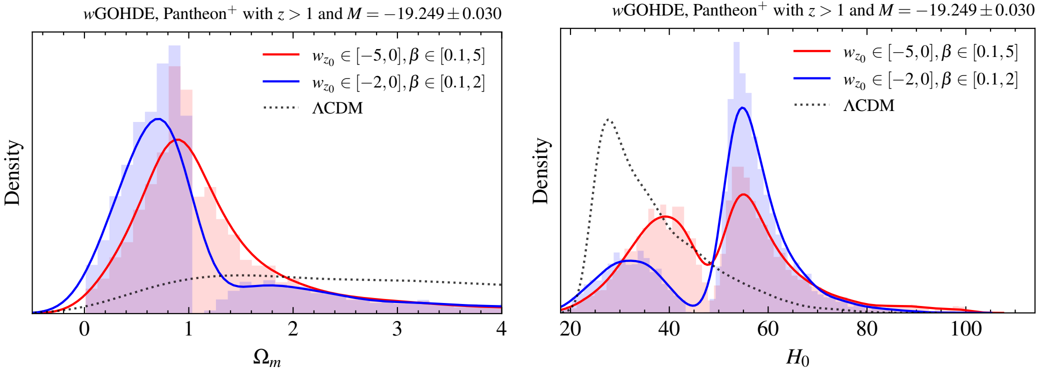


$z > 1$ Pantheon$^+$ Data for ΛCDM





$z > 1$ Pantheon$^+$ Data for (w)GOHDE



Cosmic Chronometers with CM