Is H_0 a constant (in ΛCDM)?

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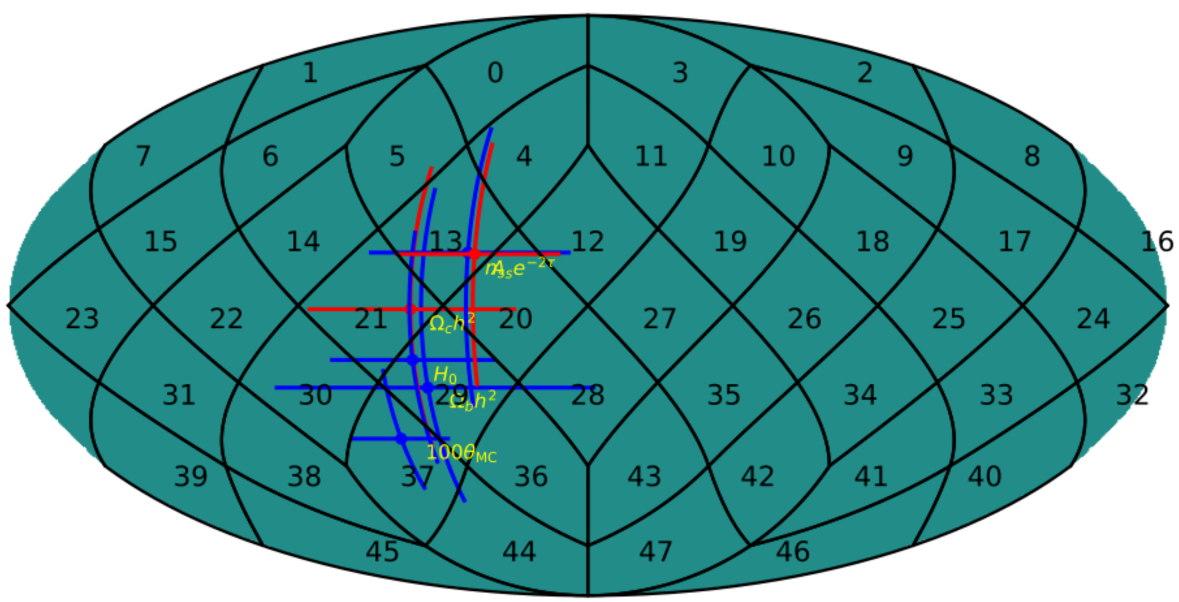
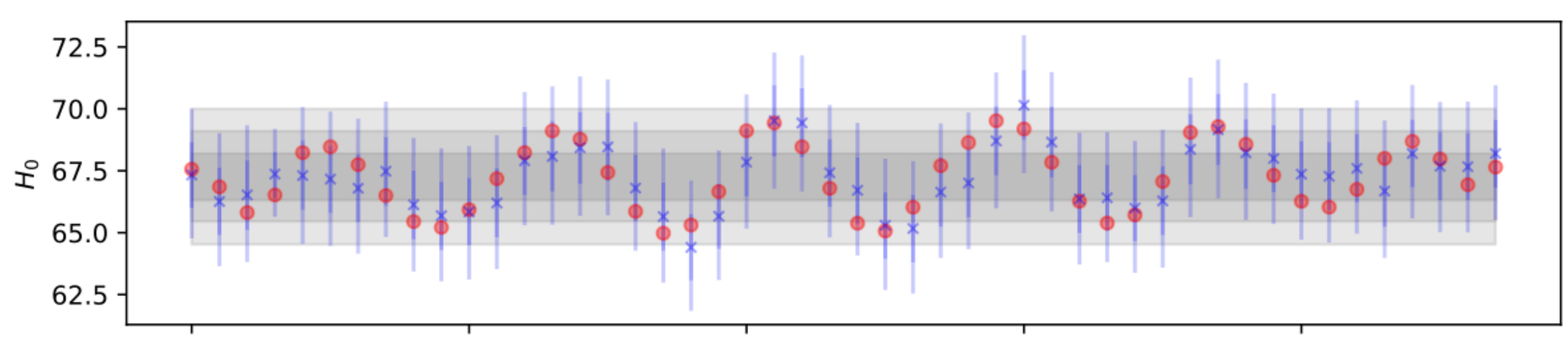
There are two ways that H_0 can vary observationally:

- With redshift (subject of this talk)
- With direction on the sky (a different kettle of fish)



Yeung & Chu (2201.03799)

also Fosalba & Gaztanaga (2011.00910)



FLRW Math

$$H \equiv \frac{\dot{a}}{a}$$

$$H^2 = \frac{1}{3}\rho \qquad c = M_{\rm pl} = 1$$

$$\dot{H} = -\frac{1}{2}(p+\rho) = -\frac{1}{2}(1+w_{\rm eff})\rho$$

$$H(z) = H_0 \exp\left(\frac{3}{2}\int_0^z \frac{1+w_{\rm eff}(z')}{1+z'}\,{\rm d}z'\right)$$

Mathematically, H_0 (also Ω_m) is an integration constant.
Integration constant = model parameter “defined today”.

Observationally, constants need not be constants.

ΛCDM Tension Debate

Systematics versus New/Missing Physics =

Systematics versus Redshift Evolution of integration constants in the ΛCDM cosmology

Good Physical Models

Planck-ΛCDM is a good model - it is predictive. It may be a bad physical model - predictions may be off.

In contrast, radioactive decay is a good physical model.

$$A(t) = A_0 e^{-\lambda t}$$

Without time separated data one cannot judge dynamical models.

CMB, BAO, SN agree on $\Omega_{\mathrm{m}} \sim 0.3$ to 5-10%.

In ΛCDM cosmology, redshift is time.

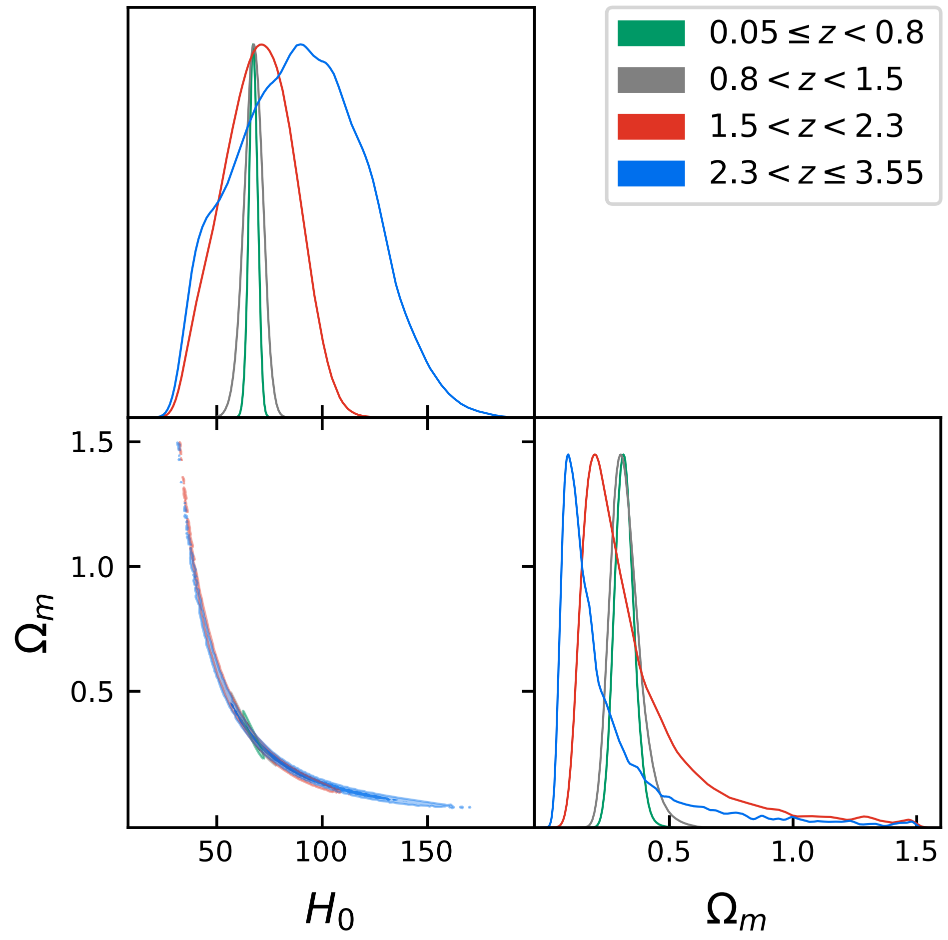
$$H(z) = H_0\sqrt{1-\Omega_m+\Omega_m(1+z)^3}$$

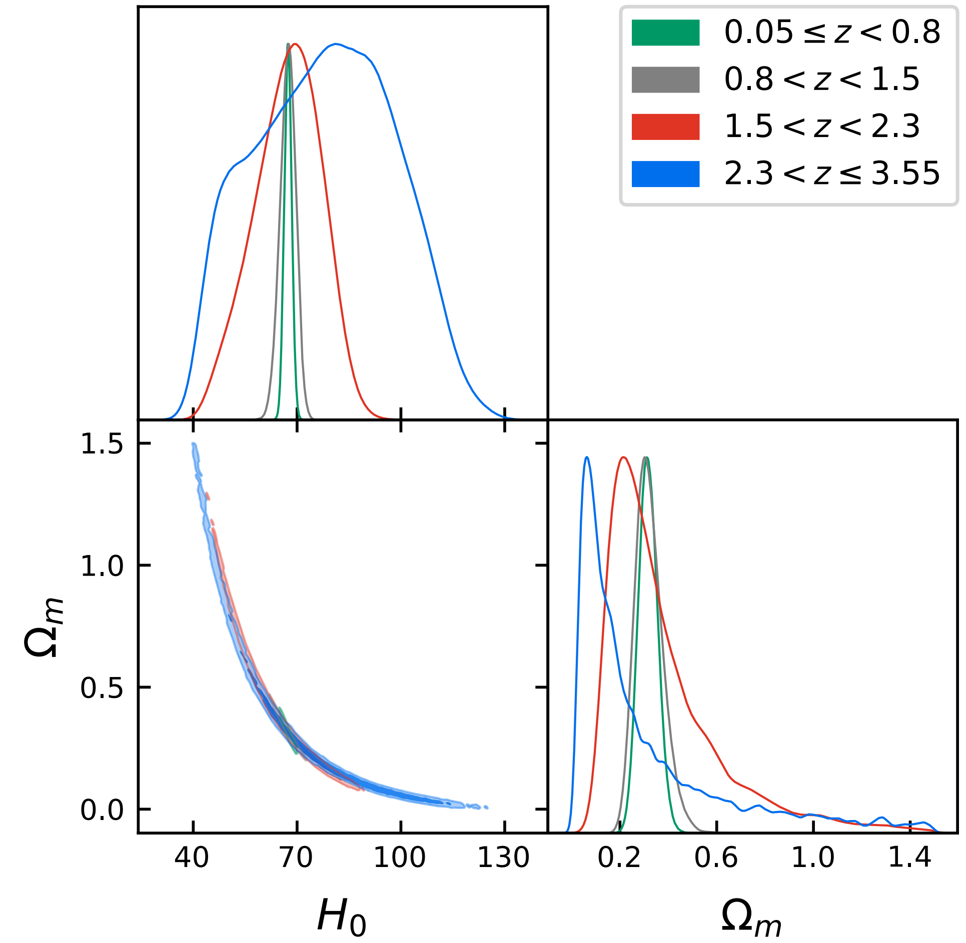
One encounters 13 gigayears of background evolution with effectively no free parameters (Ω_m~0.3).

In any observable, H(z) or D_A(z) or D_L(z) constraints, one fixes (H_0, Ω_m) with data at $z \lesssim 1$.

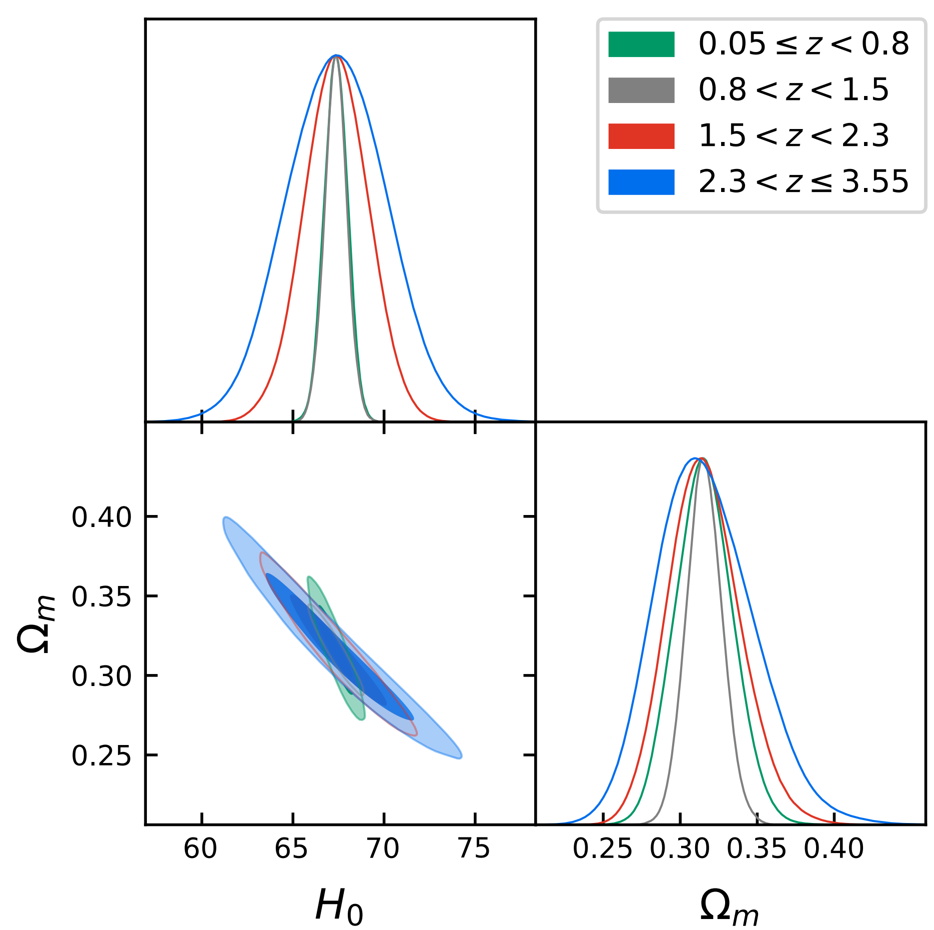
Problem: high redshift data is reduced to a spectator.

This need not be the case.





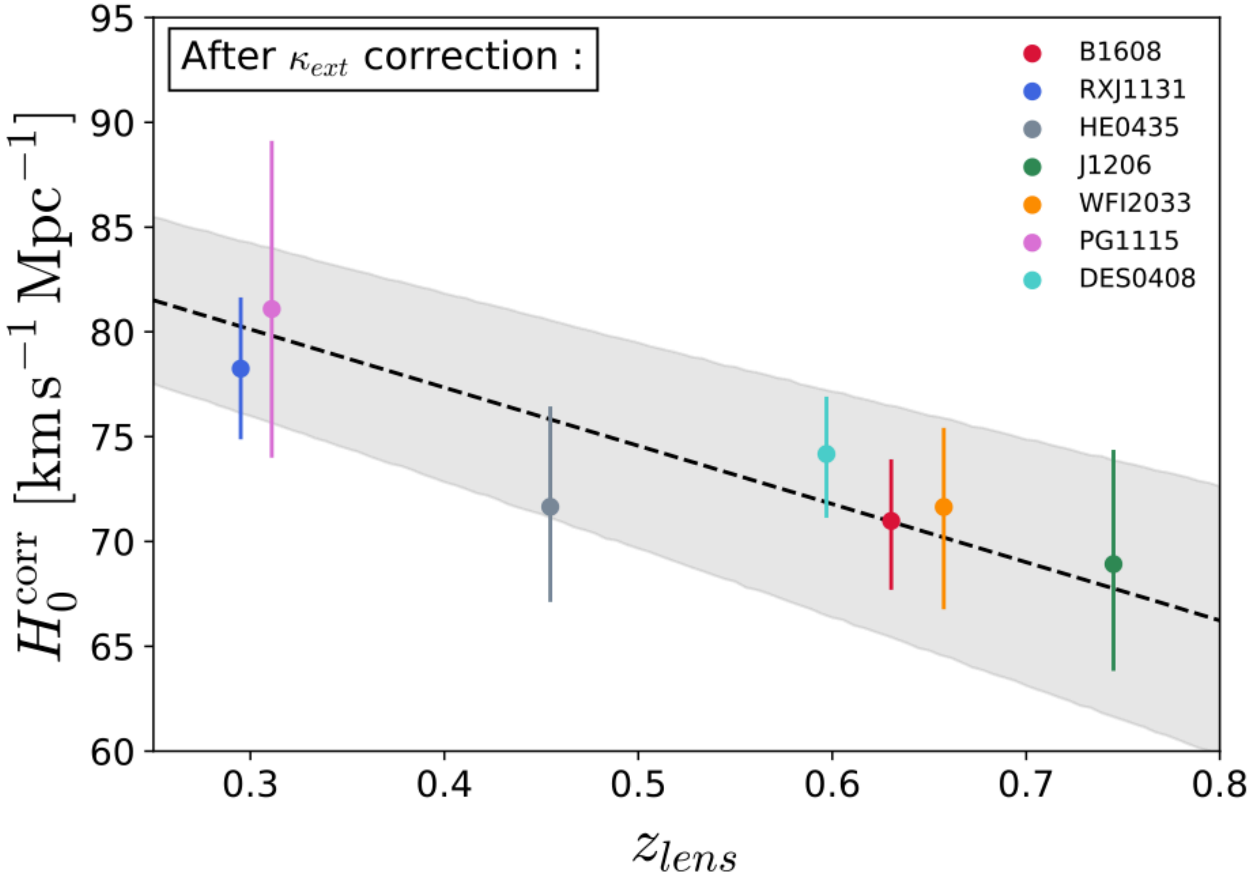
$$D_A(z) = \frac{c}{(1+z)} \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

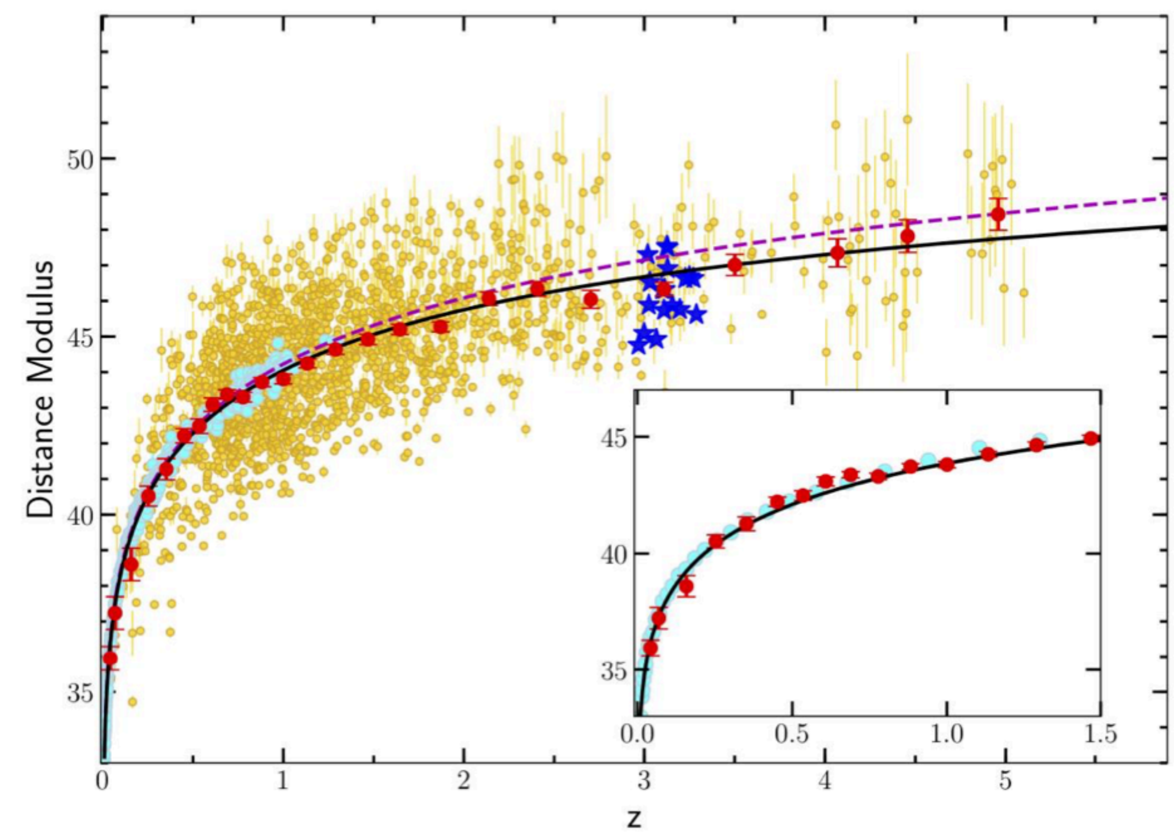


ÓC, Sheikh-Jabbari, Solomon
(2211.02129)

Motivation

Naively, H_0 tension tells us that H_0 is smaller in the early Universe (higher redshifts).

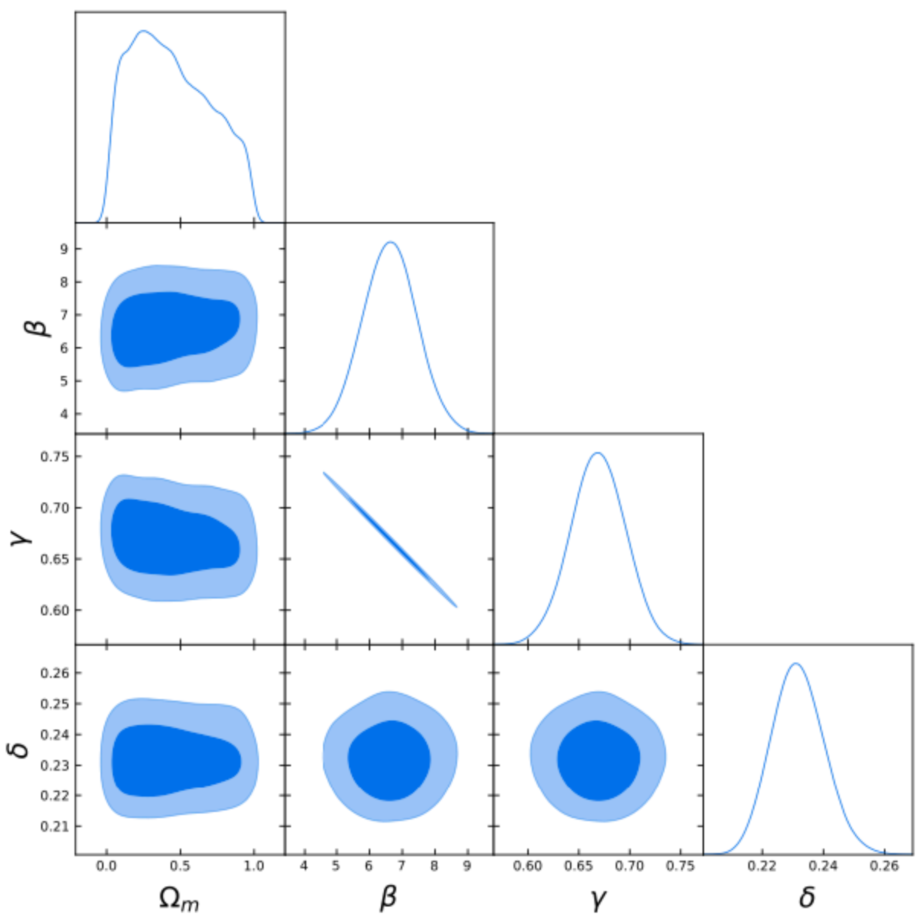




Wong et al. (1907.04869); Millon et al. (1912.08027)

Risaliti, Lusso (1811.02590)

Risaliti-Lusso QSOs actually show evolution of $\boldsymbol{\Omega}_m$ through the sample. But agree with SN at lower z.

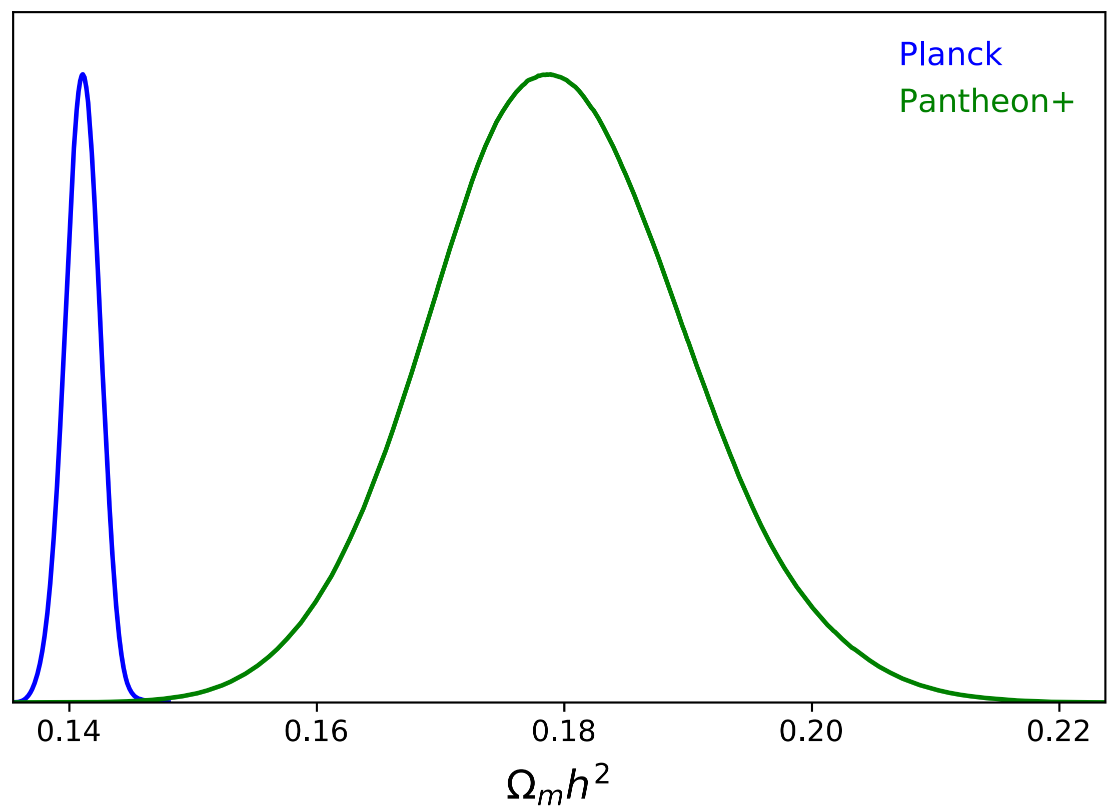


$z_{\max}$	Ω_m	β	γ
0.7 (398 QSOs)	0.266 $0.411^{+0.342}_{-0.259}$	6.601 $6.620^{+0.814}_{-0.841}$	0.670 $0.669^{+0.027}_{-0.027}$
0.8 (543 QSOs)	0.418 $0.511^{+0.305}_{-0.275}$	7.162 $7.162^{+0.715}_{-0.712}$	0.652 $0.651^{+0.023}_{-0.023}$
0.9 (678 QSOs)	0.592 $0.601^{+0.248}_{-0.250}$	7.736 $7.709^{+0.662}_{-0.679}$	0.633 $0.633^{+0.022}_{-0.021}$
1 (826 QSOs)	0.953 $0.717^{+0.184}_{-0.231}$	7.921 $7.792^{+0.571}_{-0.571}$	0.626 $0.631^{+0.019}_{-0.019}$

ÓC, Sheikh-Jabbari, Solomon, Bargiacchi, Capozziello, Dainotti, Stojkovic (2203.10558)

Type Ia SN are arguably the closest observable to a controlled lab environment.

ALL OBSERVABLES HAVE SYSTEMATICS.



Malekjani, Mc Conville, ÓC, Pourojaghi, Sheikh-Jabbari (2301.12725)

ÓC, Sheikh-Jabbari, Solomon, Dainotti, Stojkovic (2206.11447)

Splits of the Pantheon+ sample with 77 SN in Cepheid hosts decoupled.

Restoring covariance matrix does not remove features.

$z_{\rm split}$	# SN		H_0 (km/s/Mpc)		Ω_m		$\Delta\chi^2$	
	$\leq z_{\rm split}$	$> z_{\rm split}$	$\leq z_{\rm split}$	$> z_{\rm split}$	$\leq z_{\rm split}$	$> z_{\rm split}$	$\leq z_{\rm split}$	$> z_{\rm split}$
0.1	664	960	73.19	73.41	0.359	0.334	−0.4	0
0.2	871	753	73.19	73.27	0.388	0.341	−0.7	−0.1
0.3	1130	494	73.24	72.09	0.374	0.384	−1.3	−2.3
0.4	1316	308	73.37	72.64	0.337	0.365	0	−0.3
0.5	1414	210	73.38	76.84	0.333	0.252	−0.1	−3.0
0.6	1495	129	73.30	76.98	0.348	0.249	−0.5	−1.0
0.7	1549	75	73.30	80.29	0.348	0.190	−0.5	−2.4
0.8	1594	30	73.27	74.20	0.353	0.266	−1.1	−1.7
0.9	1597	27	73.26	60.86	0.354	0.604	−1.4	−3.2
1	1599	25	73.28	34.37	0.351	3.391	−1.0	−6.2
1.1	1604	20	73.35	34.19	0.342	3.478	−0.3	−3.3
1.2	1605	19	73.37	34.08	0.340	3.508	−0.1	−2.5

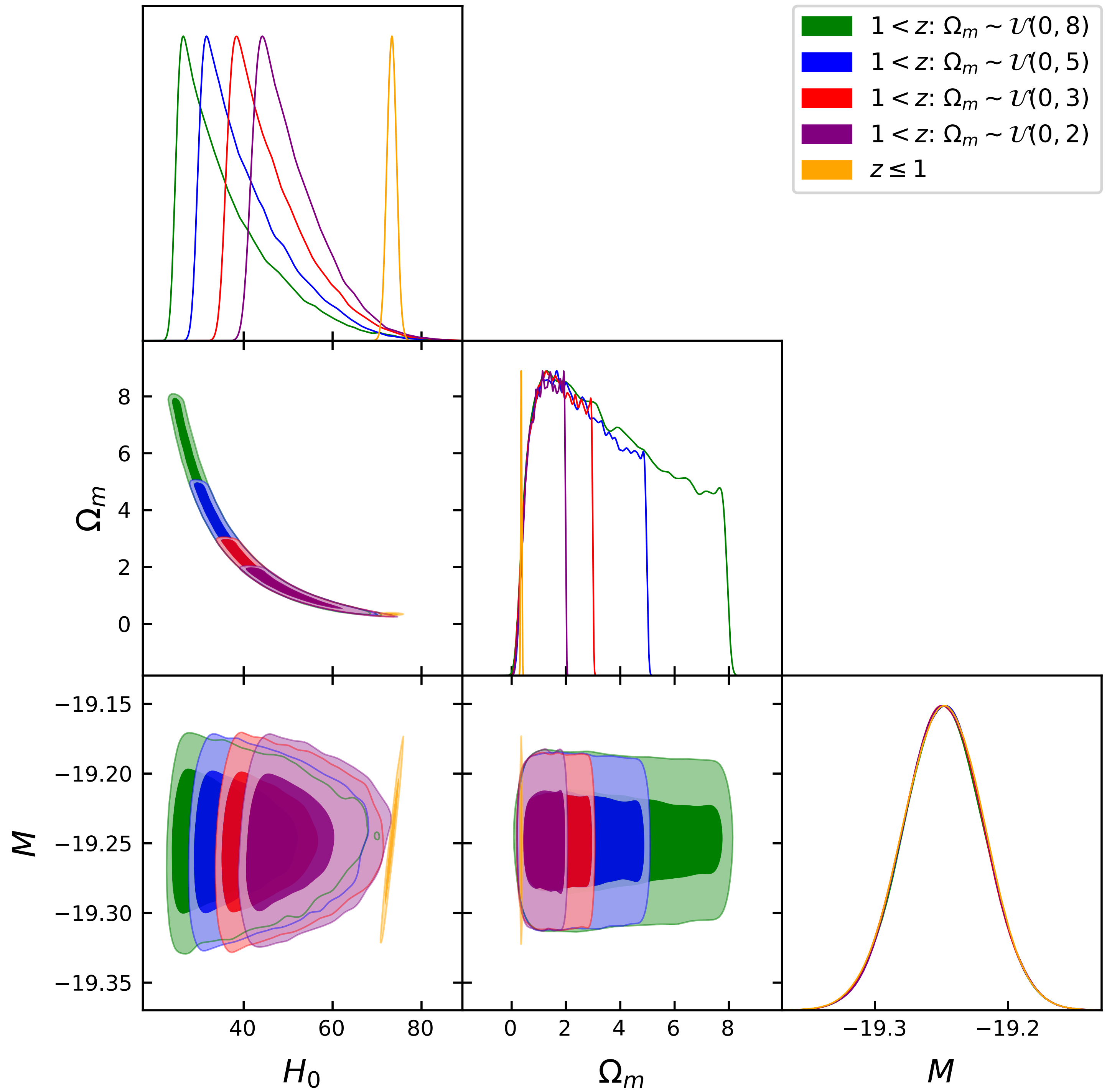
$$\chi^2 = \chi^2_{\rm Cepheid} + \chi^2_{\rm SN}$$

Least squares fitting is robust. No false minima.
For 77+25 SN, we find:

(H_0, Ω_m)	H_0 (km/s/Mpc)	Ω_m	χ^2
(ϵ, ϵ)	34.366	3.3914	68.496048154
$(\epsilon, 5-\epsilon)$	34.365	3.3916	68.496048156
$(150-\epsilon, \epsilon)$	34.365	3.3917	68.496048156
$(150-\epsilon, 5-\epsilon)$	34.365	3.3916	68.496048156

But estimating errors is difficult at high redshifts.

Fisher matrix assumes Gaussian errors. MCMC prone to degeneracies, projection effects, etc.



Projection effects are evident in MCMC.

Resort to AIC:

$$\mathrm{AIC} = \chi^2_{\mathrm{min}} + 2d$$

Data marginally prefers a 5-parameter model with a split over 2-parameter ΛCDM.

$$\{H_0^{(1)}, \Omega_m^{(1)}, H_0^{(2)}, \Omega_m^{(2)}, z_{\mathrm{split}}\}$$

This new model is contradictory, since both H_0 and Ω_m are integration constants.

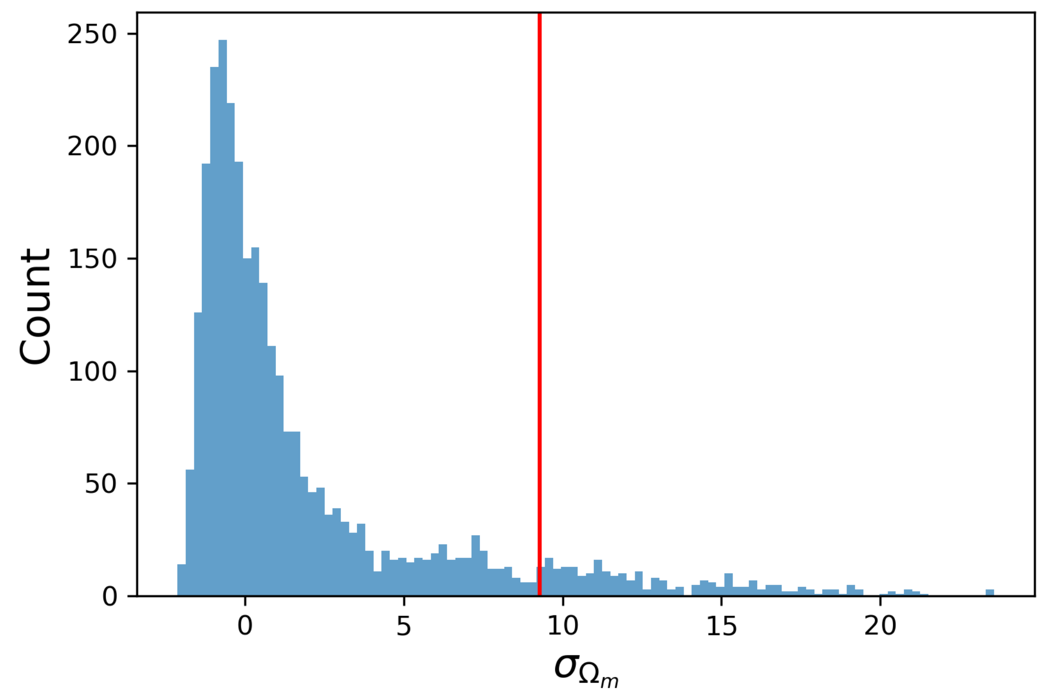
They cannot vary, yet data prefers a split.

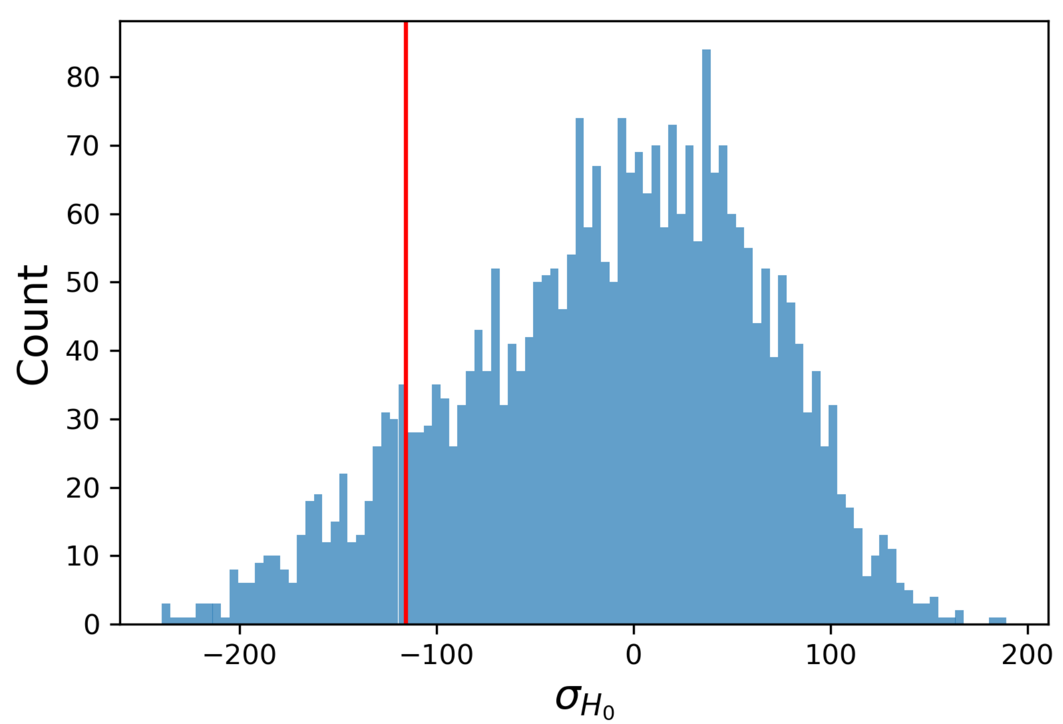
Resort to mocks:

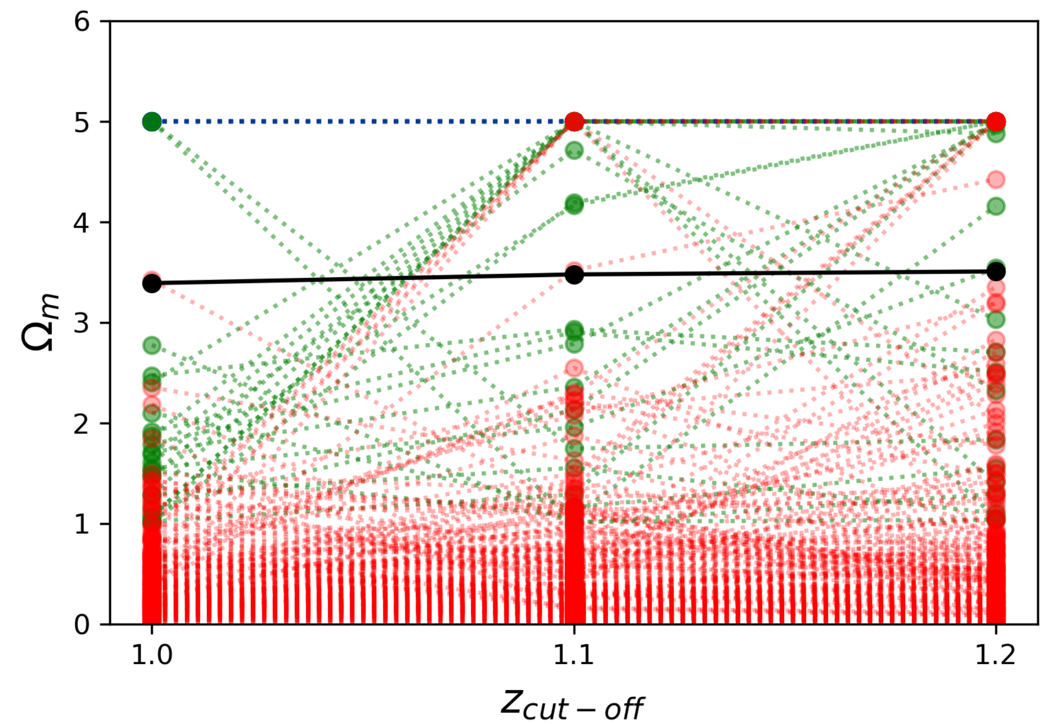
H_0 (km/s/Mpc)	Ω_m	M
73.41 ± 1.04	0.333 ± 0.018	-19.249 ± 0.030

$$\sigma_{H_0} = \sum_{z_{\text{cut-off}}} (H_0 - 73.41)$$

$$\sigma_{\Omega_m} = \sum_{z_{\text{cut-off}}} (\Omega_m - 0.333)$$







Summary

HST Pantheon+ SN (also QSOs and OHD) at high z return unexpected (H_0, Ω_m) best fits. Do we remove data?

High z SN double the redshift range of Pantheon+. Note, QSOs are plentiful.

The AIC marginally supports a split model with a transition in integration constants over ΛCDM.

From mocks, we estimated the unlikeliness of best fits at $p = 0.1$ ($\Omega_m > 1$), $p = 0.08$ (sums) and $p = 0.026$ ($\Omega_m \gtrsim 3$).

Must test for (H_0, Ω_m) evolution in all observables.