Is H_0 a constant (in ΛCDM)?

Ollscoil Teicneolaíochta an Atlantaigh
Atlantic Technological University

Eoin Ó Colgáin

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 $\Omega_{\rm m}$) is an integration constant.
Integration constant = model parameter "defined today".

Observationally, constants need not be constants.

There are two ways that H_0 can vary observationally:

- With redshift - signature of model breakdown
- With direction on the sky - signature of potential problem with FLRW

Surprisingly, the first idea is alien in cosmology because cosmological parameters are constant by assumption.

On FLRW, angles are simply thrown away in cosmology.

Good Physical Models

Planck-ΛCDM is a good (minimal) model - it is predictive.

Yet, 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 $\Omega_{\rm m} \sim 0.3$ 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 ($\Omega_m \sim 0.3$).

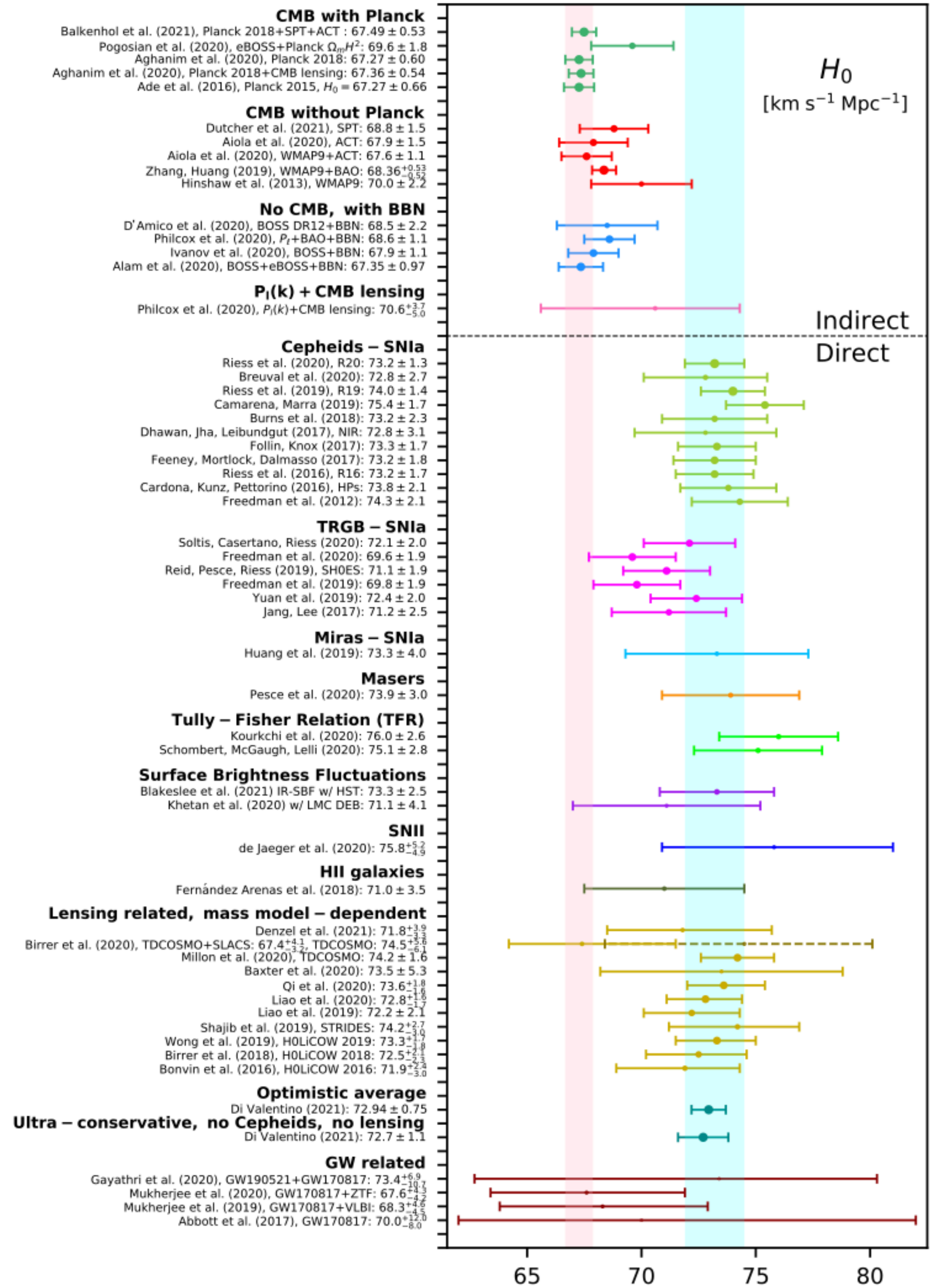
In any observable, H(z) or $D_A(z)$ or $D_L(z)$ constraints, one fixes (H_0, Ω_m) with data at $z \lesssim 1$.

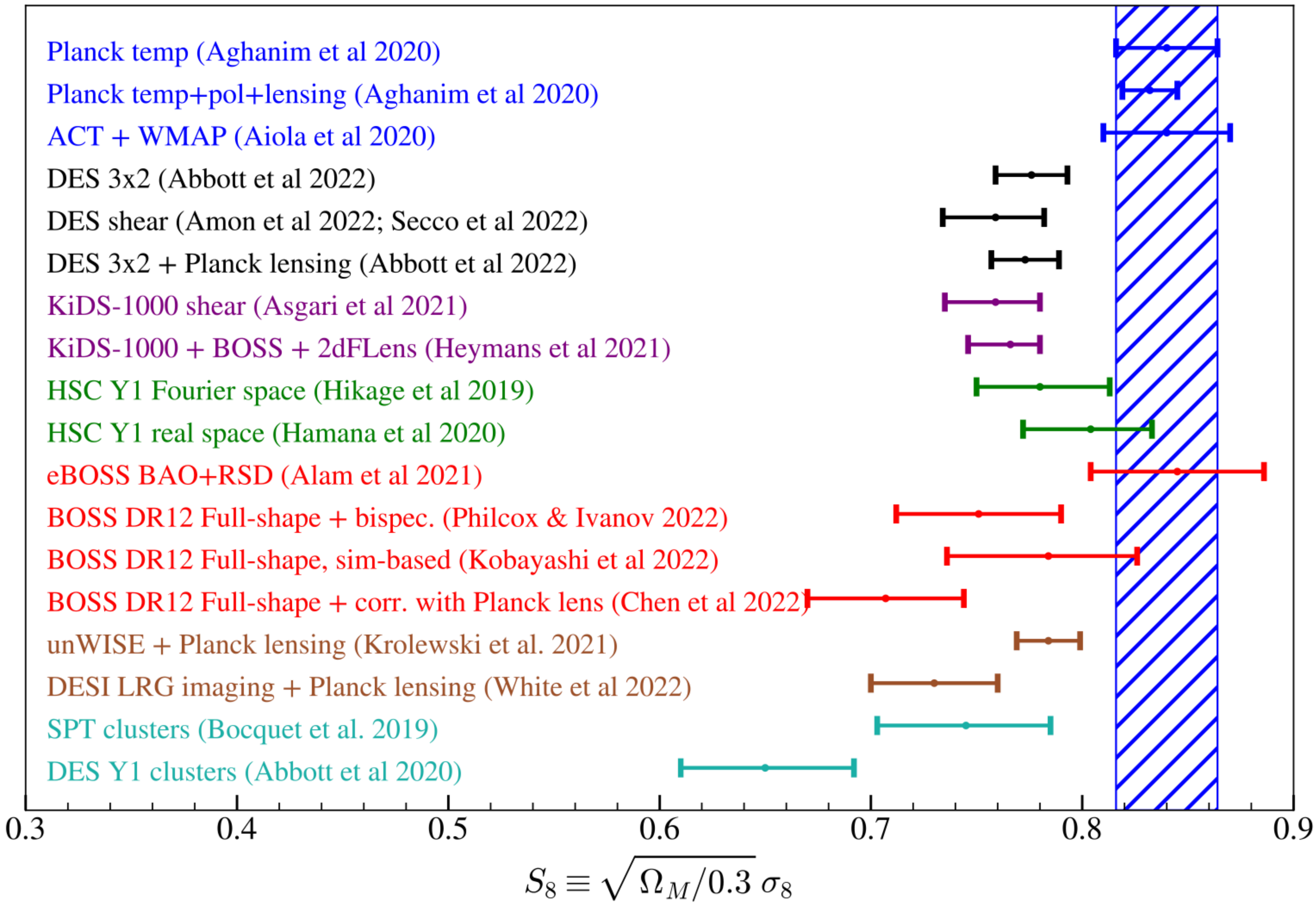
High redshift data is effectively reduced to a spectator.

Motivation

There are early (high z) versus late (low z) Universe tensions.

Di Valentino et al. (2103.01183)





Huterer (2212.05003)

ΛCDM Tension Debate

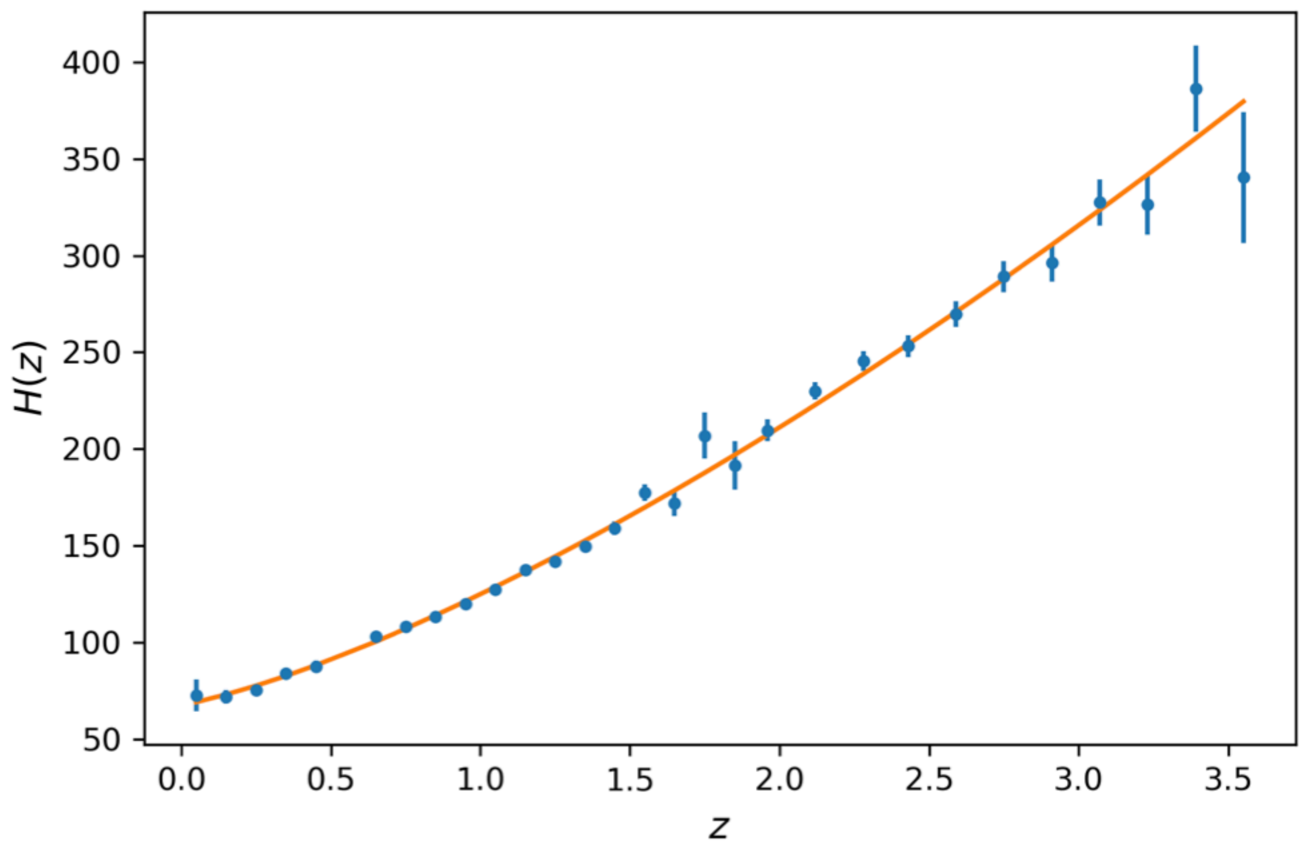
Systematics versus New/Missing Physics =

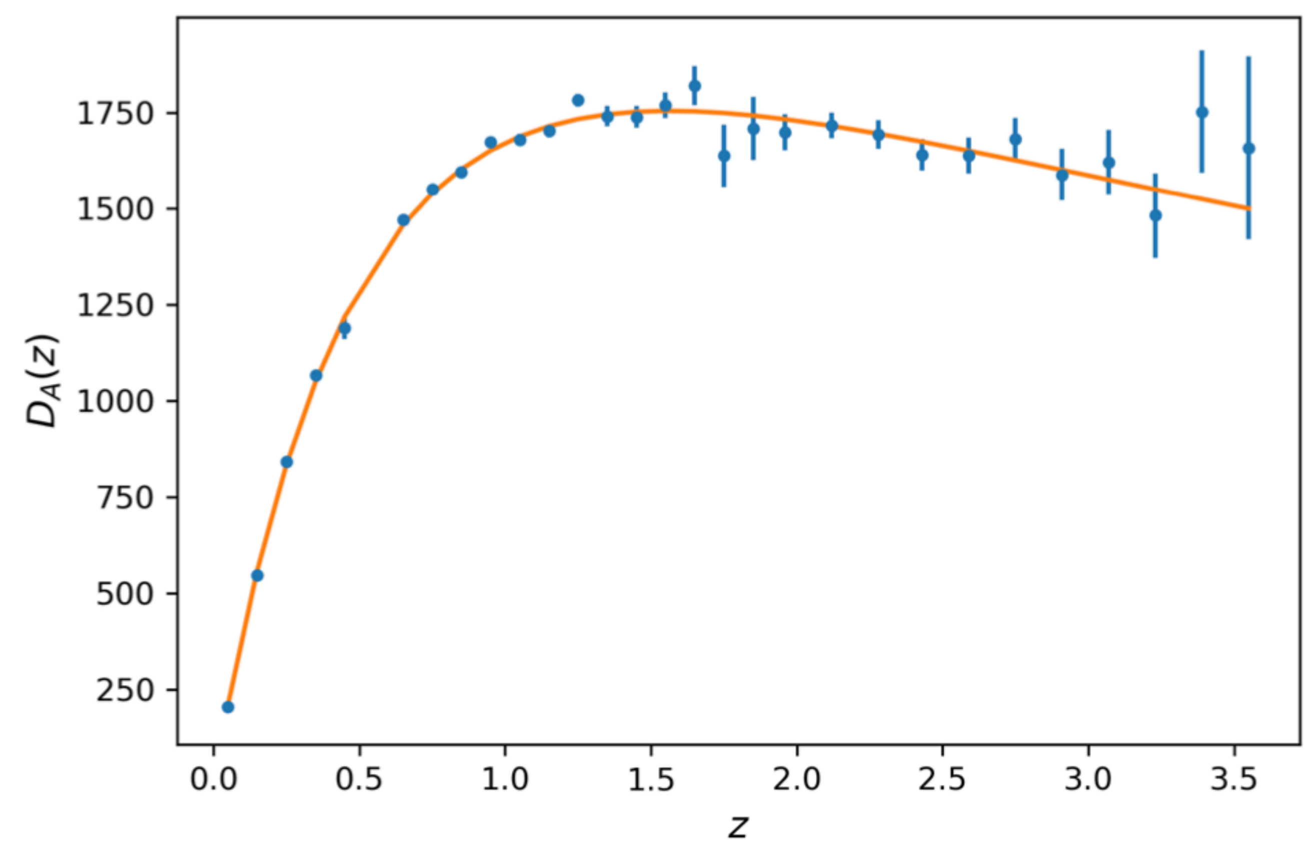
Systematics versus Redshift Evolution of integration constants in the ΛCDM cosmology

ΛCDM in redshift bins

(what to expect from mocks)

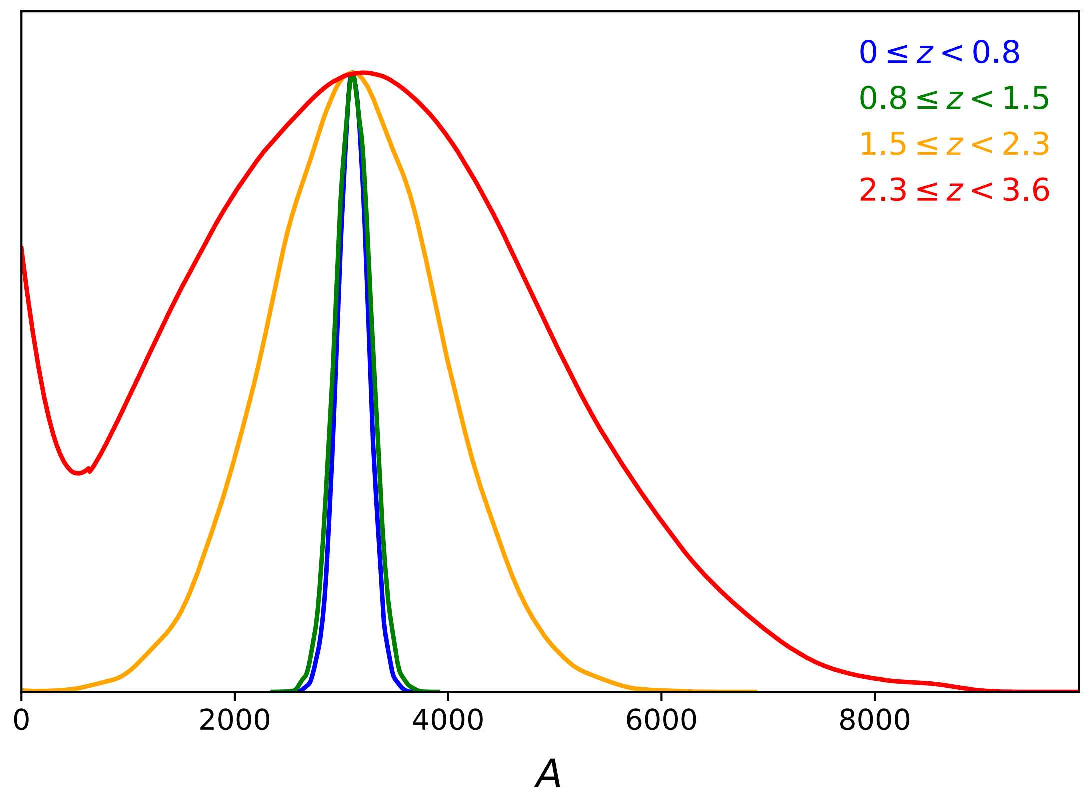
$$H(z) = H_0\sqrt{1 - \Omega_m + \Omega_m(1+z)^3}$$

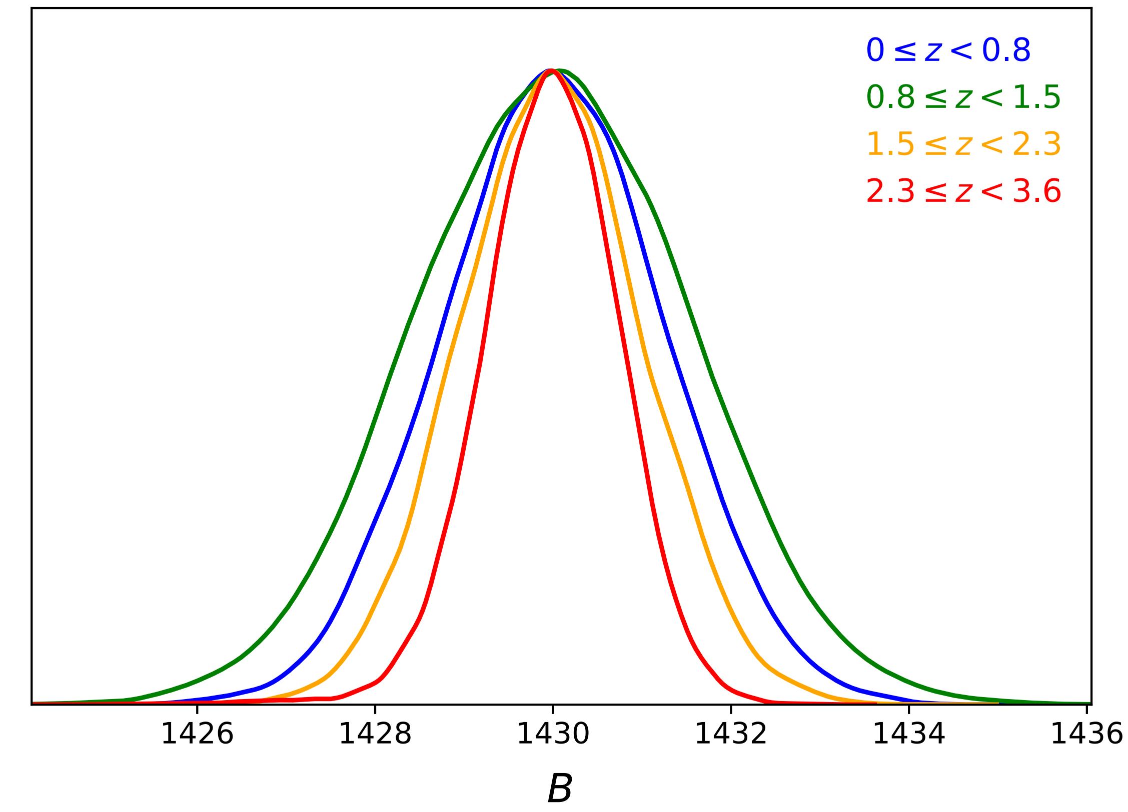




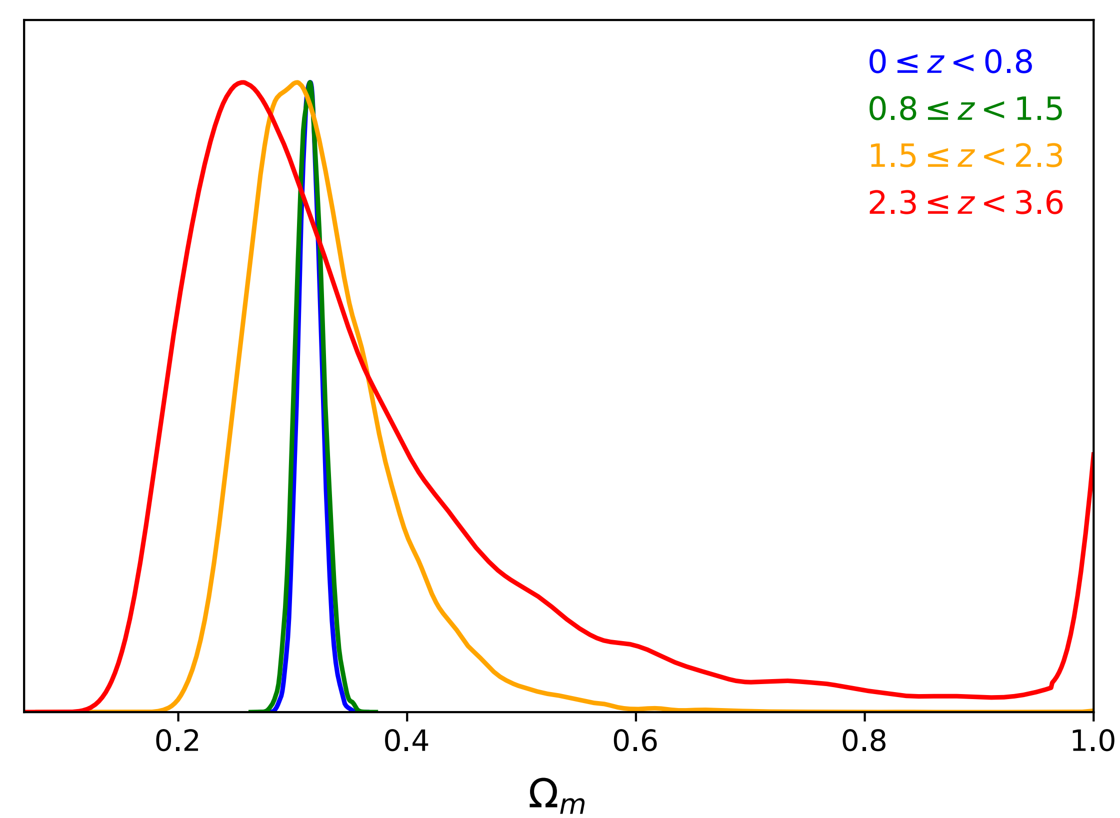
DESI (1611.00037)

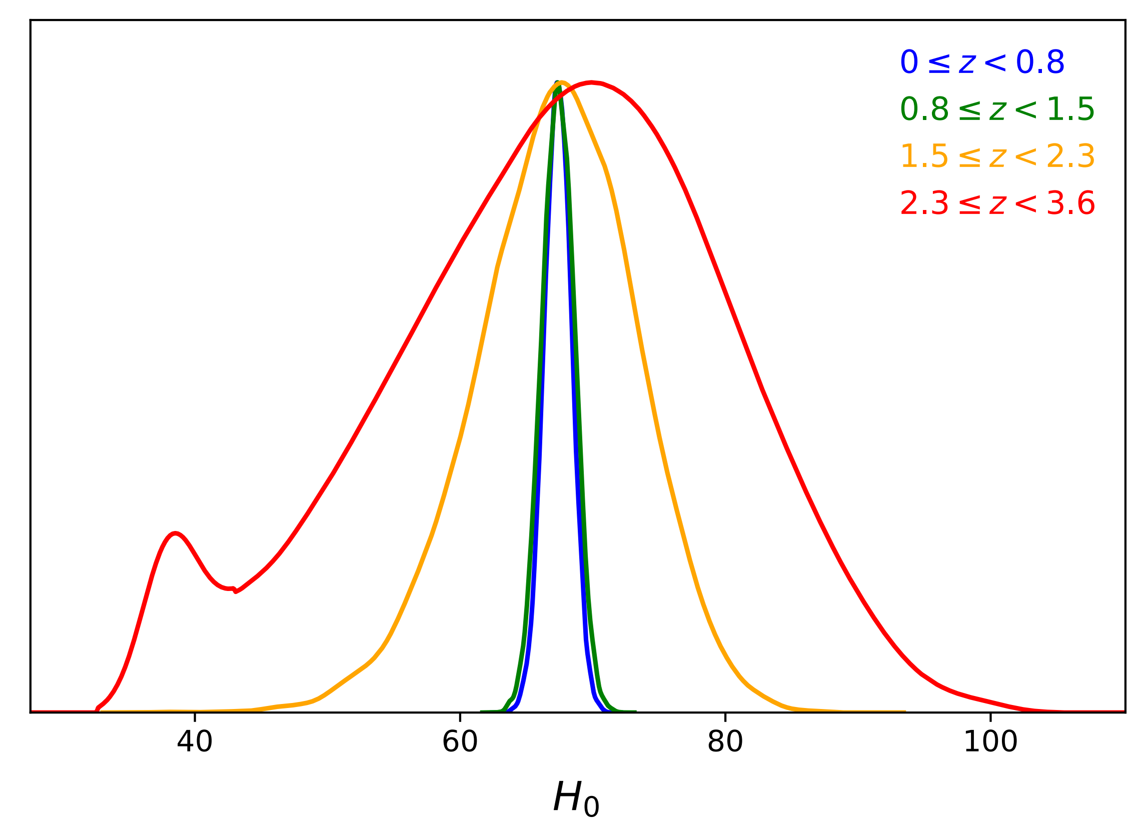
At higher redshifts, we expect $H(z) \sim H_0\sqrt{\Omega_m}(1+z)^{\frac{3}{2}}$





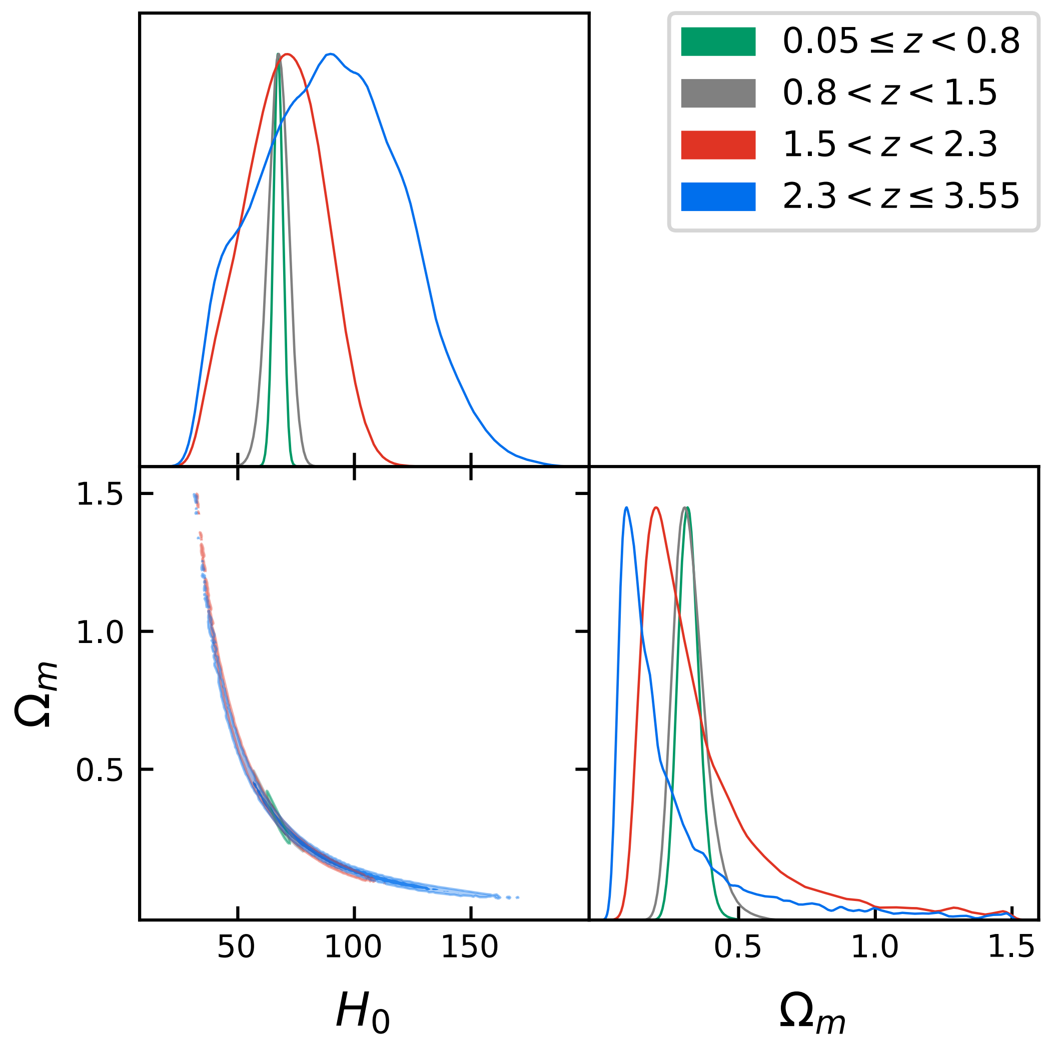
$A = (H_0)^2\,(1-\Omega_m)$ $B = (H_0)^2\,\Omega_m$

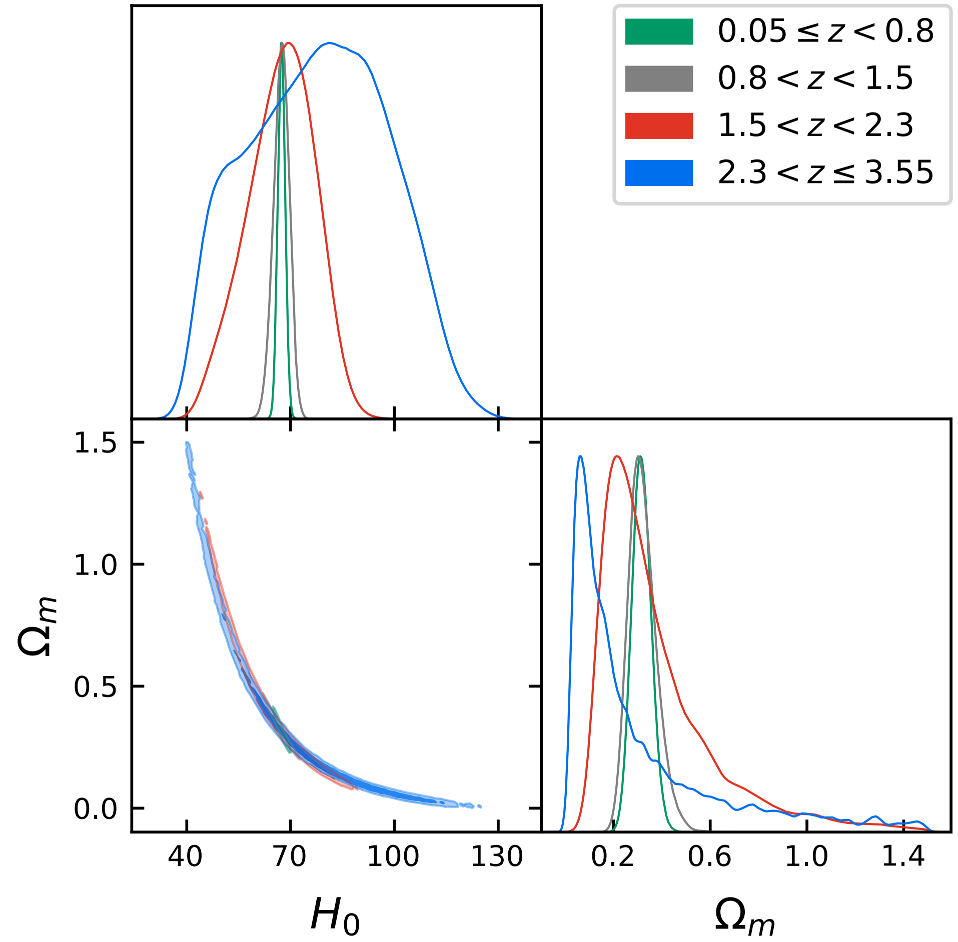


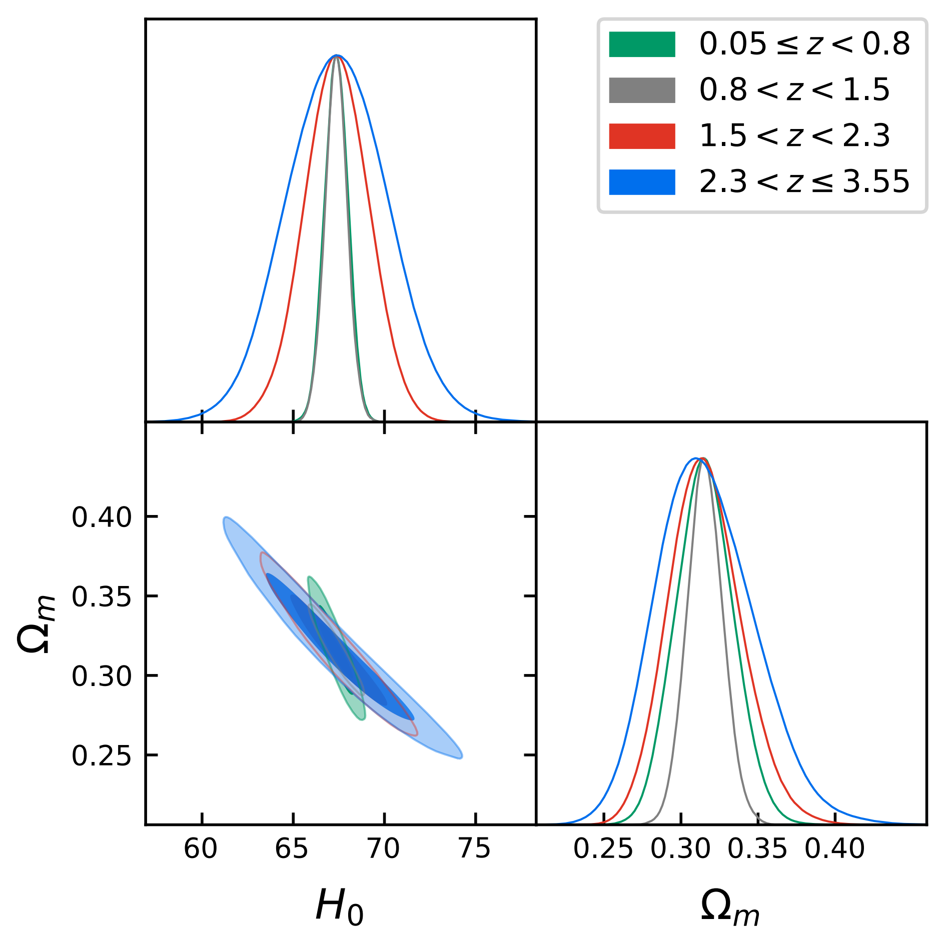


ÓC, Sheikh-Jabbari, Solomon, Dainotti, Stojkovic (2206.11447)

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







ÓC, Sheikh-Jabbari, Solomon
(2211.02129)

Degeneracies place one on a curve/banana in the (H_0, Ω_m) plane.

This banana/curve stretches with effective redshift. This largely explains the non-Gaussian tails.

Projection effects lead to decreasing Ω_m/increasing H_0 peaks of the PDFs at higher redshifts.

Even if one injects peak at $\Omega_m \sim 0.3$, peak moves to lower values with increasing effective redshift.

The PDF ultimately becomes a uniform or flat distribution at very large (or infinitely large) redshifts.

Hypothesis

In ΛCDM, we have a decreasing H_0/increasing Ω_m trend with effective redshift in observed data.

Since $S_8 \propto \sigma_8 \sqrt{\Omega_m}$, S_8 also increases with effective redshift.

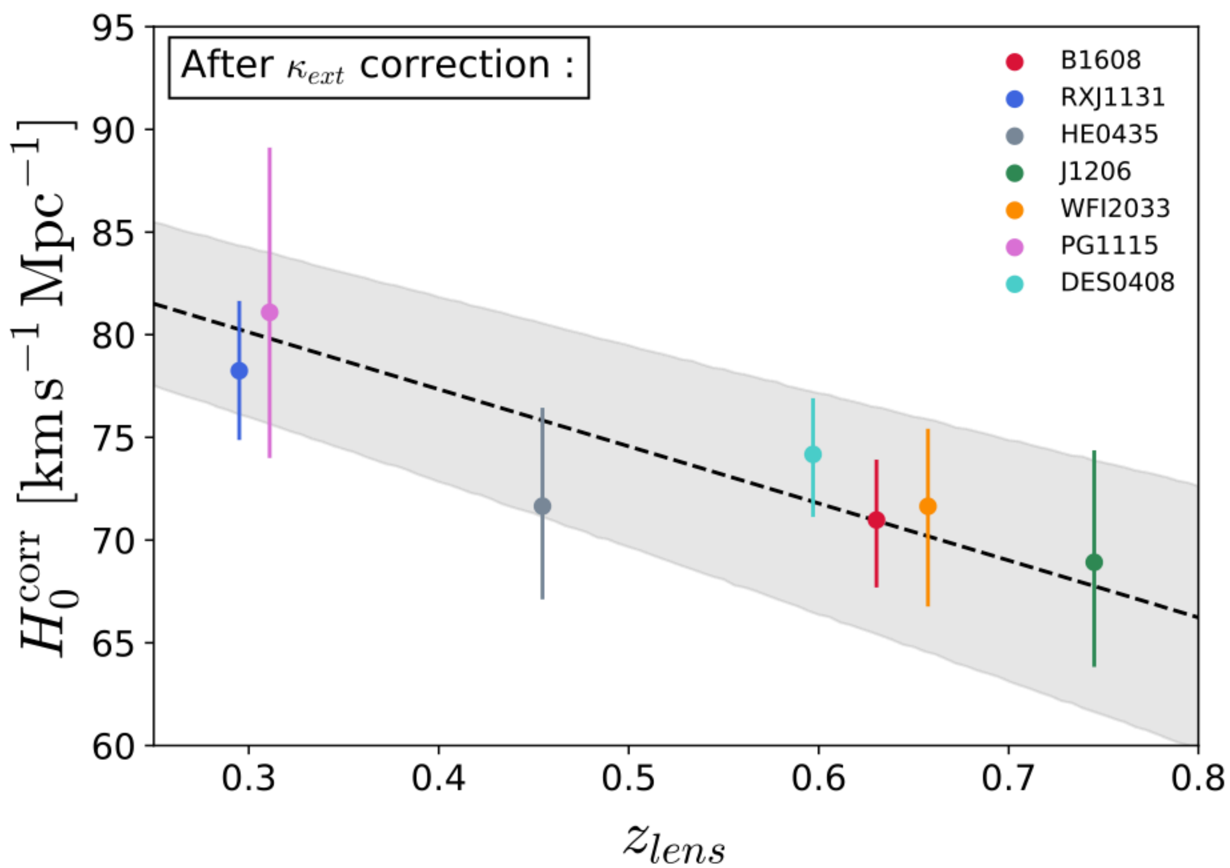
Note, claim consistent with existing tensions.

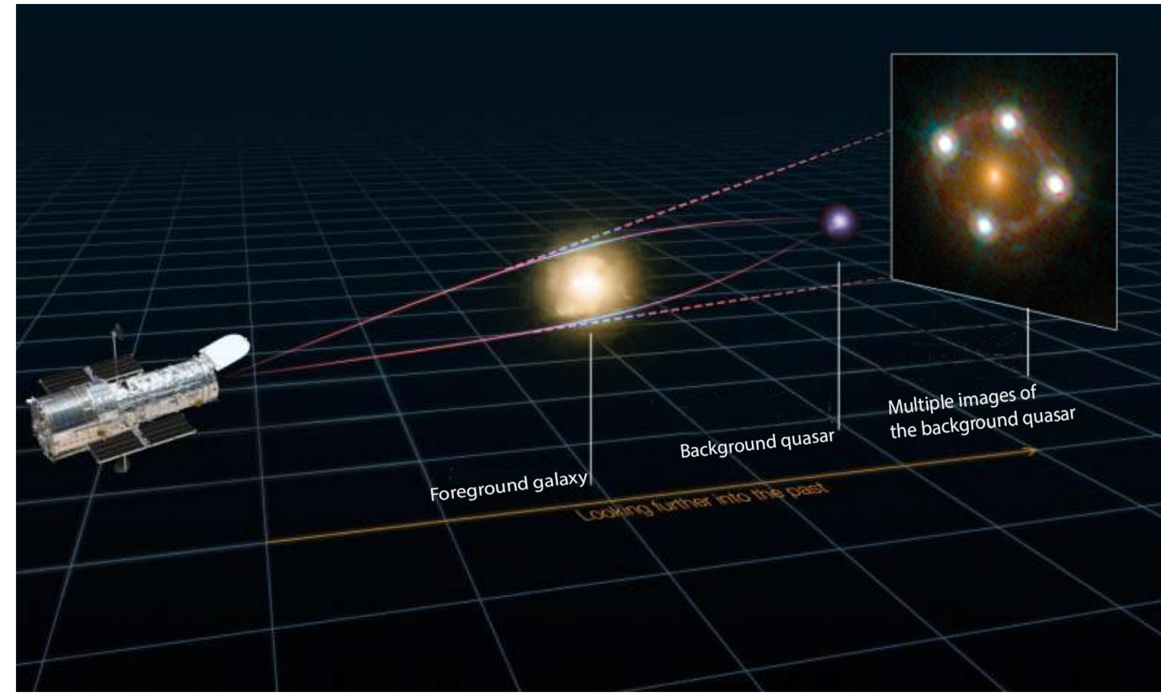
If true, H_0 and S_8 tensions are not independent.

Obviously, the ΛCDM model has broken down.

Can strong lensing time delay or GWs determine H_0?

NOT CLEAR.





TDCOSMO recently revisited RXJ1131 with stellar kinematics finding consistent results.

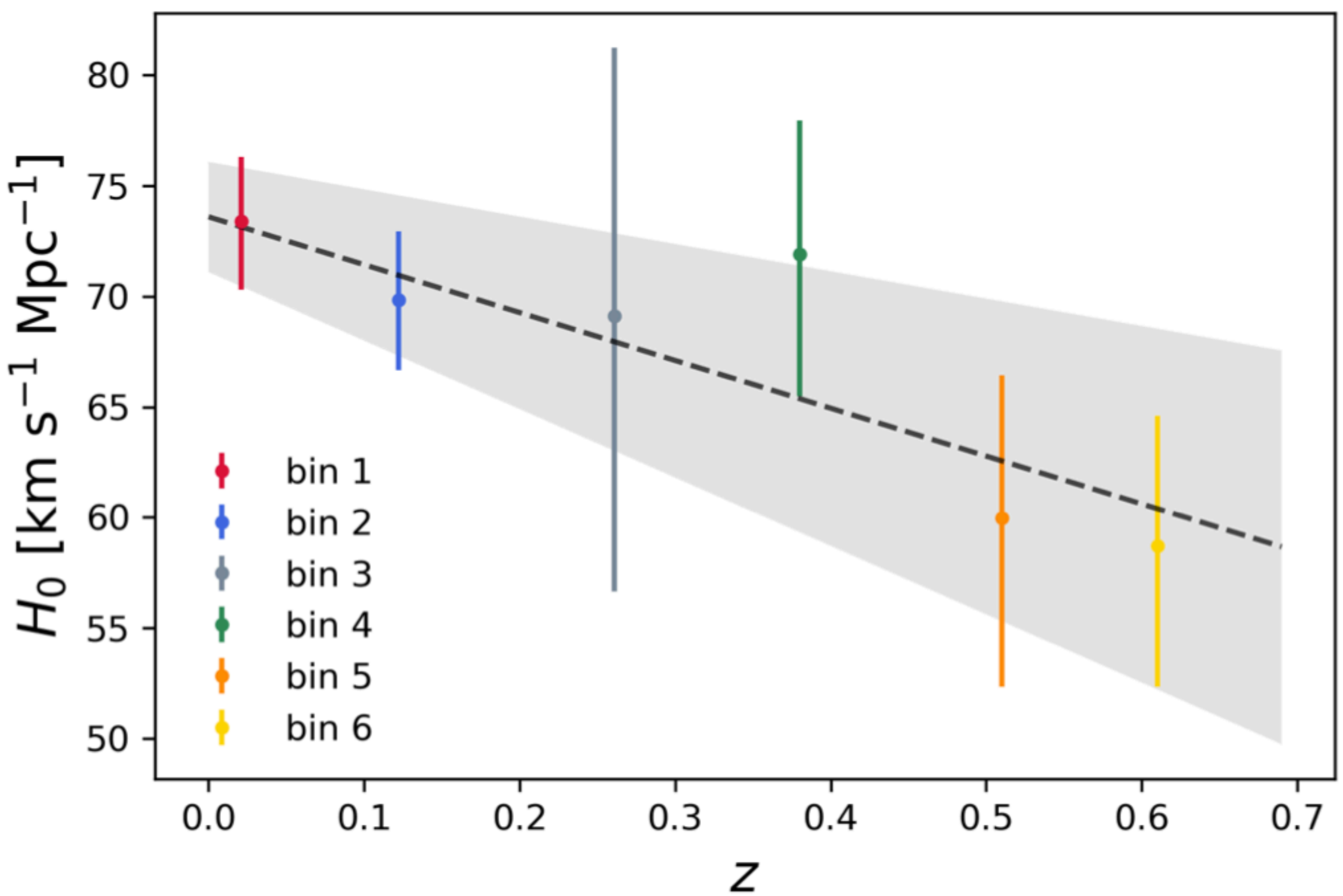
Wong et al. (1907.04869); Millon et al. (1912.08027)

Shajib et al. (2301.02656)

Observation of similar trend in combination of local (megamasers) and cosmological (SN, BAO, CC) data.

Driven largely by lowest bin (local H_0), so perhaps cute, but admittedly less compelling.

However, evolution disfavors early Universe modifications.

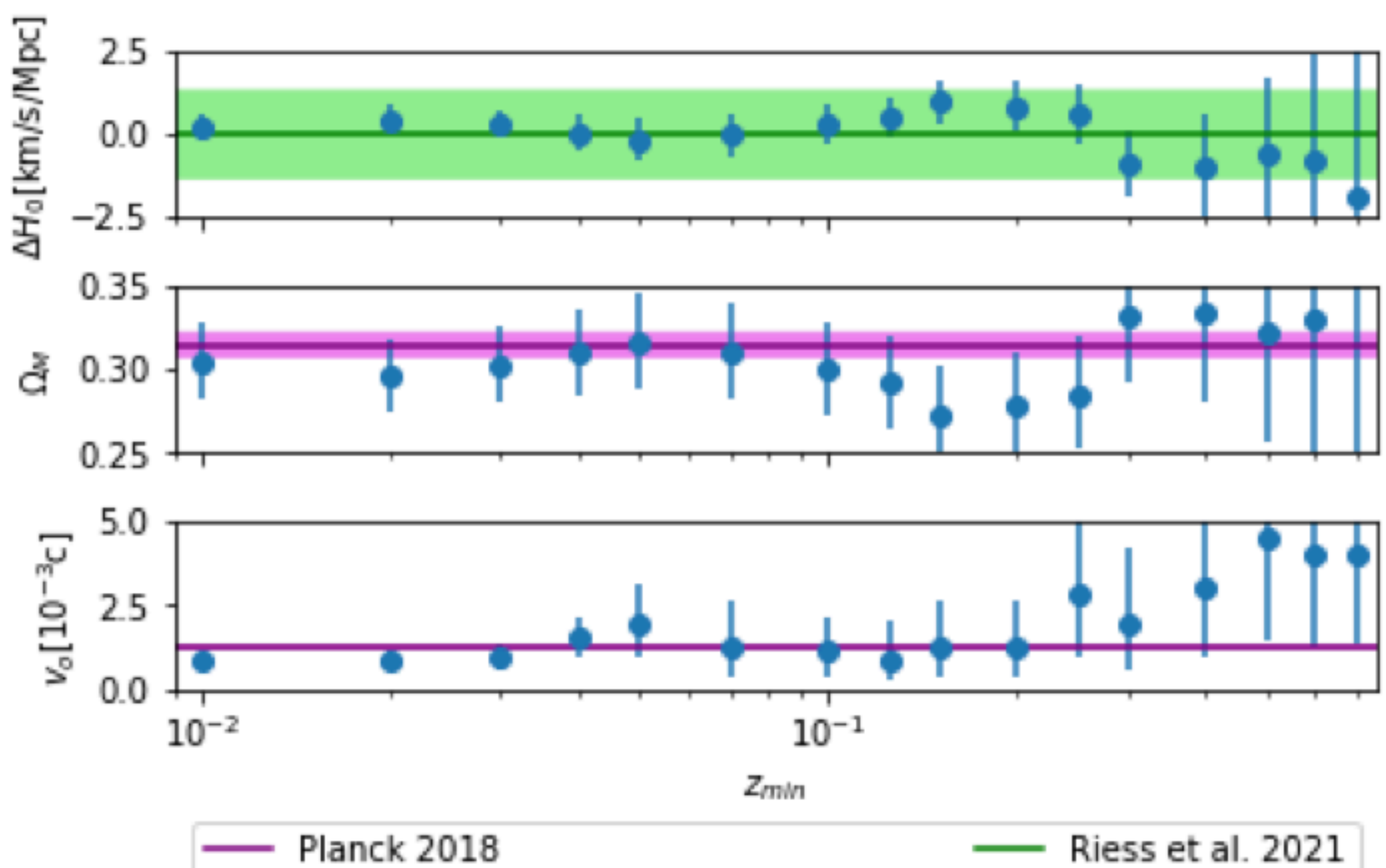


Krishnan, ÓC, Ruchika, Sen, Sheikh-Jabbari, Yang (2002.06044)

These claims resurfaced in Dainotti et al. (2021) within the Pantheon SN sample.

Dainotti et al. (2103.02117, 2201.09848)

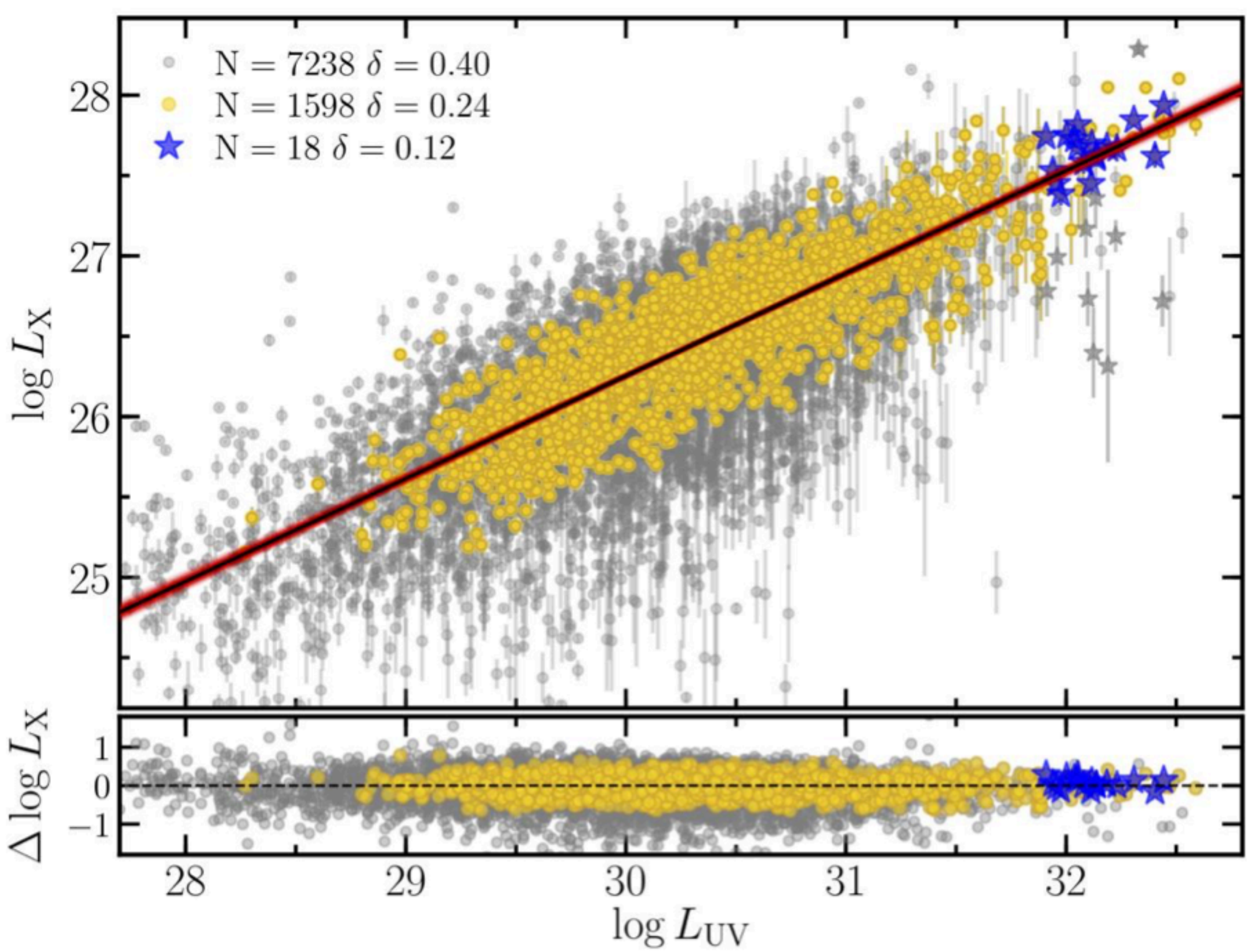
$$H_0(z) = \frac{\tilde{H}_0}{(1+z)^{\alpha}}$$

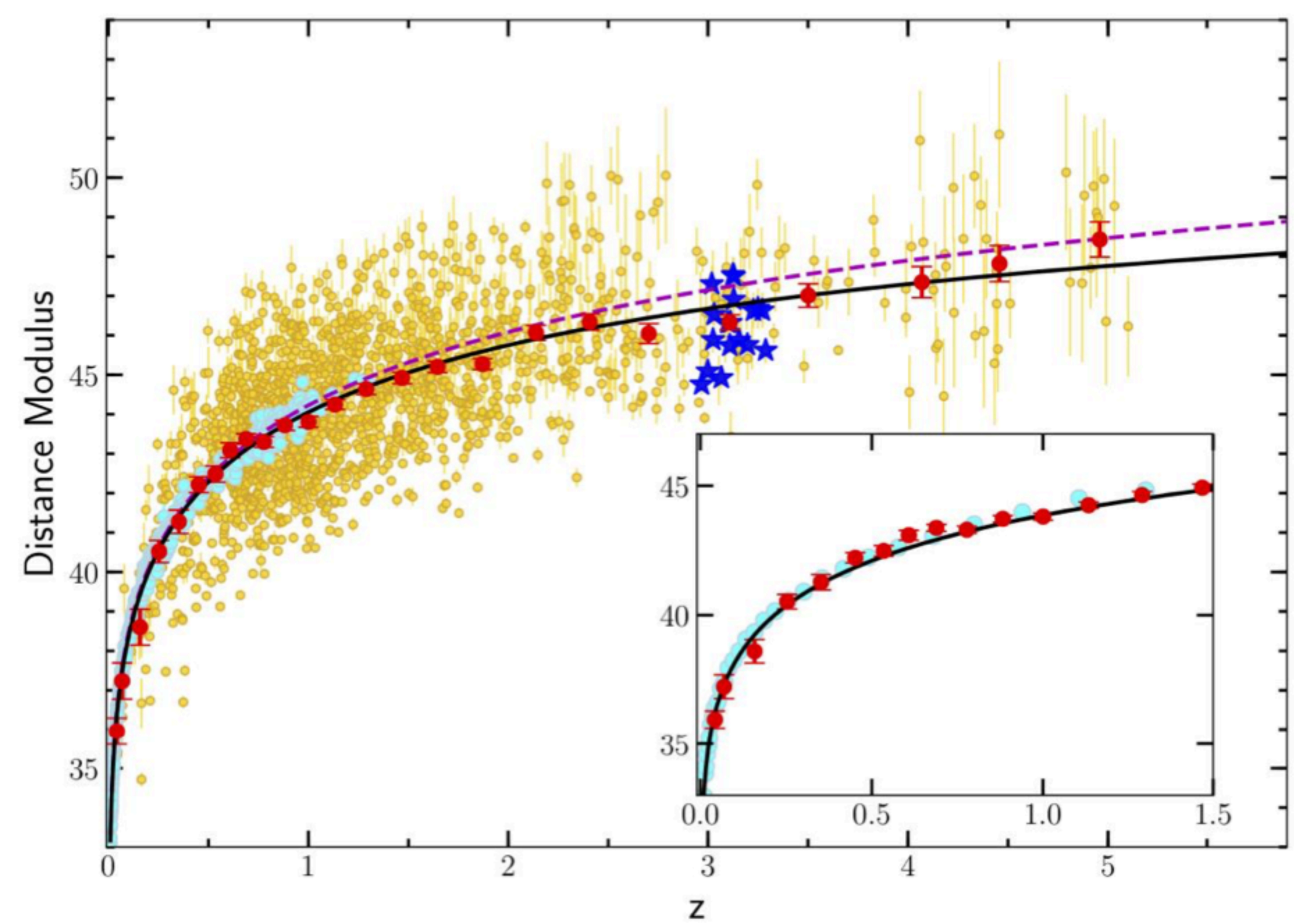


Horstmann, Pietschke, Schwarz (2111.03055)

QSOs as standardisable candles are deeply challenging.

Note, $\Omega_{\rm m} \gtrsim 1$ is possible in (flat) ΛCDM.





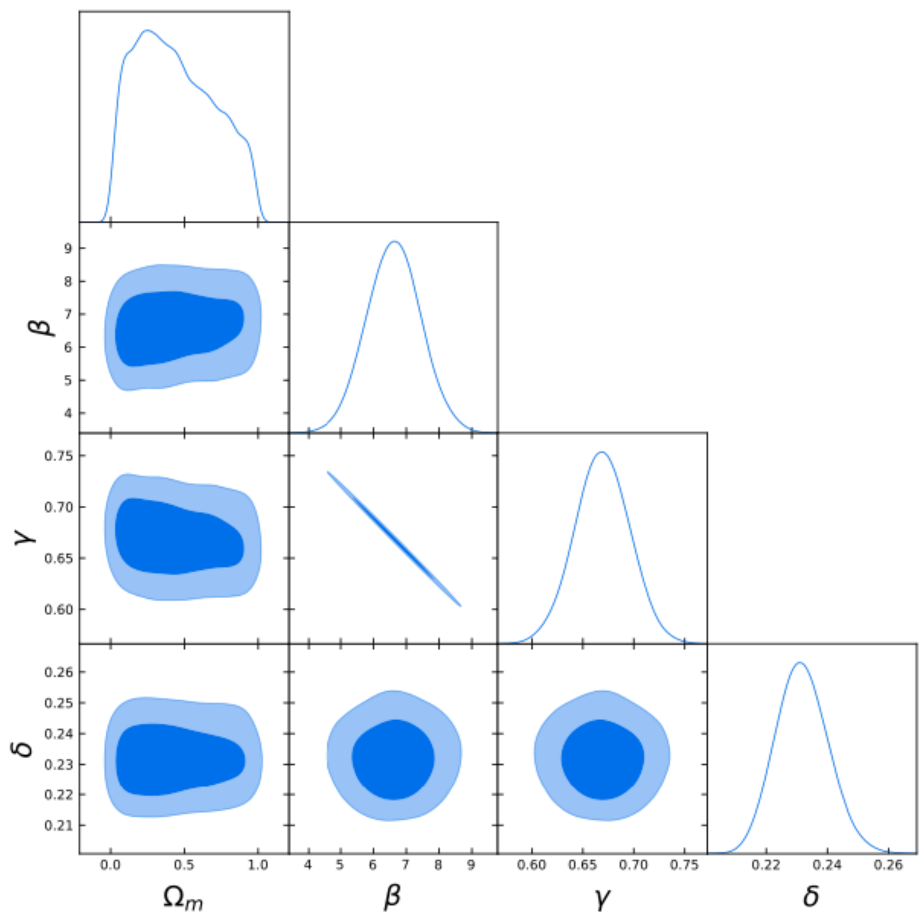
$$\log_{10} L_X = \beta + \gamma \log_{10} L_{UV}$$

Risaliti, Lusso (1811.02590)

Lusso, Risaliti, Nardini, Bargiacchi, Benetti et al. (2008.08586)

RL QSOs actually show evolution of Ω_m through the sample. However, agree with SN at lower z (with caveat).

Do we see deviations from Planck in SN at high z?

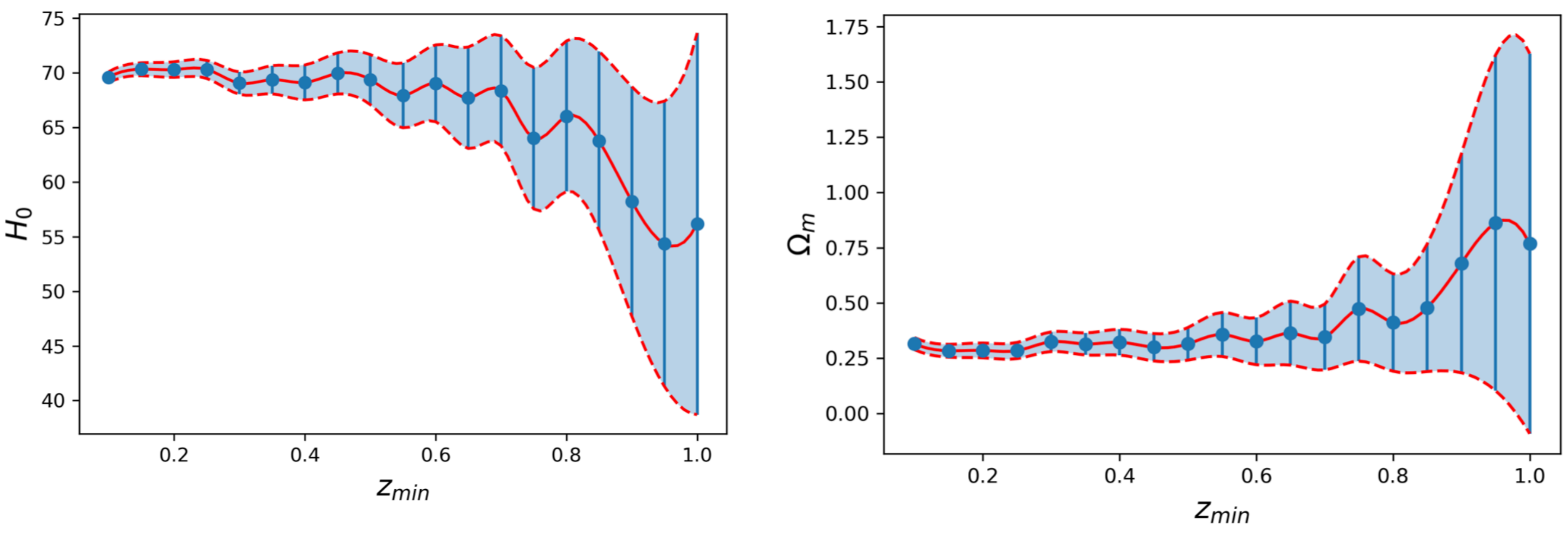


z_{max}	Ω_m	β	γ
0.7 (398 QSOs)	0.266	6.601	0.670
	$0.411^{+0.342}_{-0.259}$	$6.620^{+0.814}_{-0.841}$	$0.669^{+0.027}_{-0.027}$
0.8 (543 QSOs)	0.418	7.162	0.652
	$0.511^{+0.305}_{-0.275}$	$7.162^{+0.715}_{-0.712}$	$0.651^{+0.023}_{-0.023}$
0.9 (678 QSOs)	0.592	7.736	0.633
	$0.601^{+0.248}_{-0.250}$	$7.709^{+0.662}_{-0.679}$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

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

Evolution in central values in Pantheon Type Ia SN sample.

SN are uncalibrated (M errors not propagated).



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

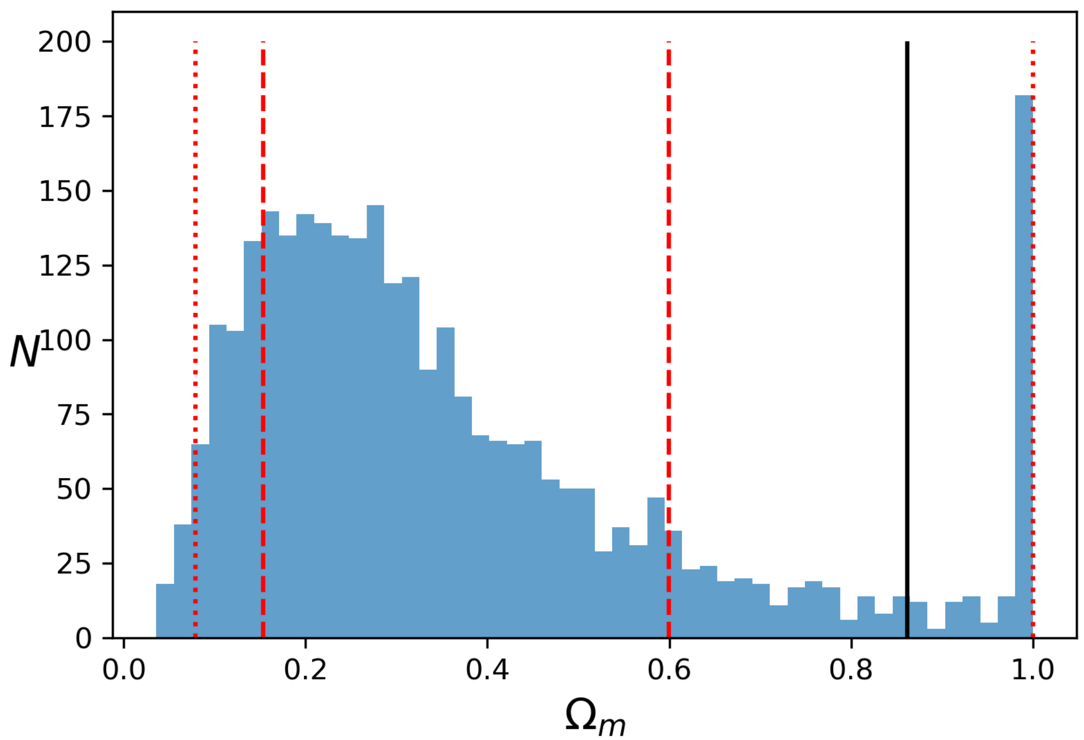
Evolution in OHD, Type Ia SN and QSOs with a Planck prior on $\Omega_m h^2$

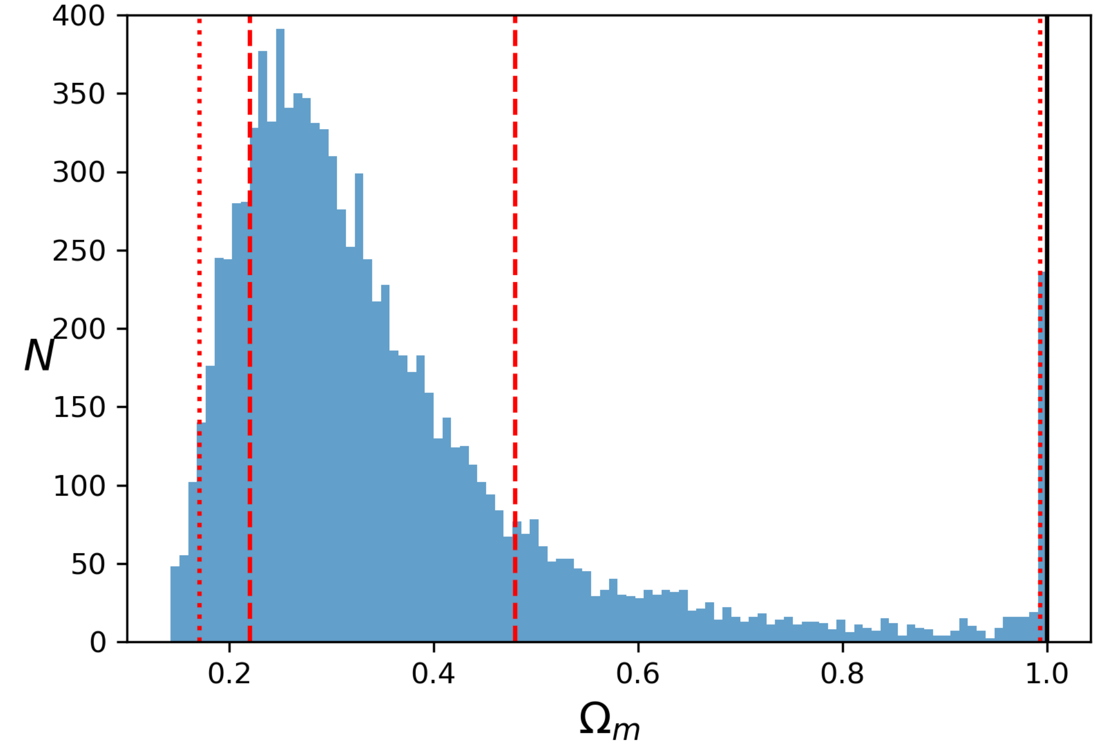
z	H_0 (km/s/Mpc)	Ω_m	Probability
$0 \leq z \leq 2.36$ (54)	69.11	0.299	–
$0.5 \leq z \leq 2.36$ (28)	69.68	0.294	0.646
$0.7 \leq z \leq 2.36$ (18)	65.67	0.331	0.326
$1 \leq z \leq 2.36$ (11)	61.27	0.380	0.258
$1.2 \leq z \leq 2.36$ (10)	53.91	0.491	0.120
$1.4 \leq z \leq 2.36$ (8)	41.55	0.828	0.037
$1.45 \leq z \leq 2.36$ (7)	37.80	1	0.021
$1.5 \leq z \leq 2.36$ (6)	37.80	1	0.069

z	H_0 (km/s/Mpc)	Ω_m	Probability
$0 < z \leq 2.26$ (1048)	69.26	0.298	–
$0.7 < z \leq 2.26$ (124)	64.37	0.345	0.381
$0.8 < z \leq 2.26$ (82)	58.99	0.411	0.258
$0.9 < z \leq 2.26$ (49)	45.88	0.679	0.117
$0.95 < z \leq 2.26$ (34)	40.73	0.862	0.081
$1 < z \leq 2.26$ (23)	43.16	0.768	0.170

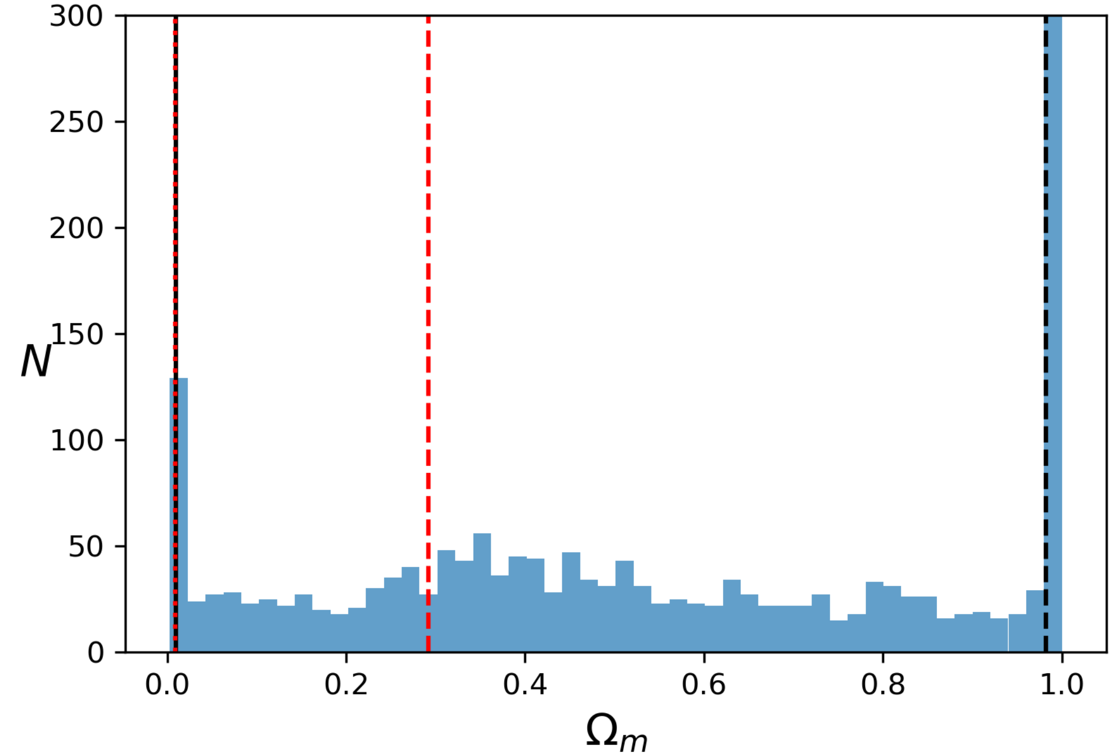
z	H_0 (km/s/Mpc)	Ω_m	Probability
$0 < z \leq 0.3$ (56)	406.41	0.009	0.073
$0 < z \leq 0.5$ (177)	353.47	0.011	0.028
$0 < z \leq 0.55$ (233)	433.91	0.008	0.019
$0 < z \leq 0.6$ (279)	381.50	0.010	0.020
$0 < z \leq 0.7$ (398)	73.40	0.265	0.096
$0 < z \leq 0.8$ (543)	58.48	0.418	0.117
$0 < z \leq 1$ (826)	40.69	0.864	0.400
$0 < z \leq 1.4$ (1326)	37.82	1.000	–

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





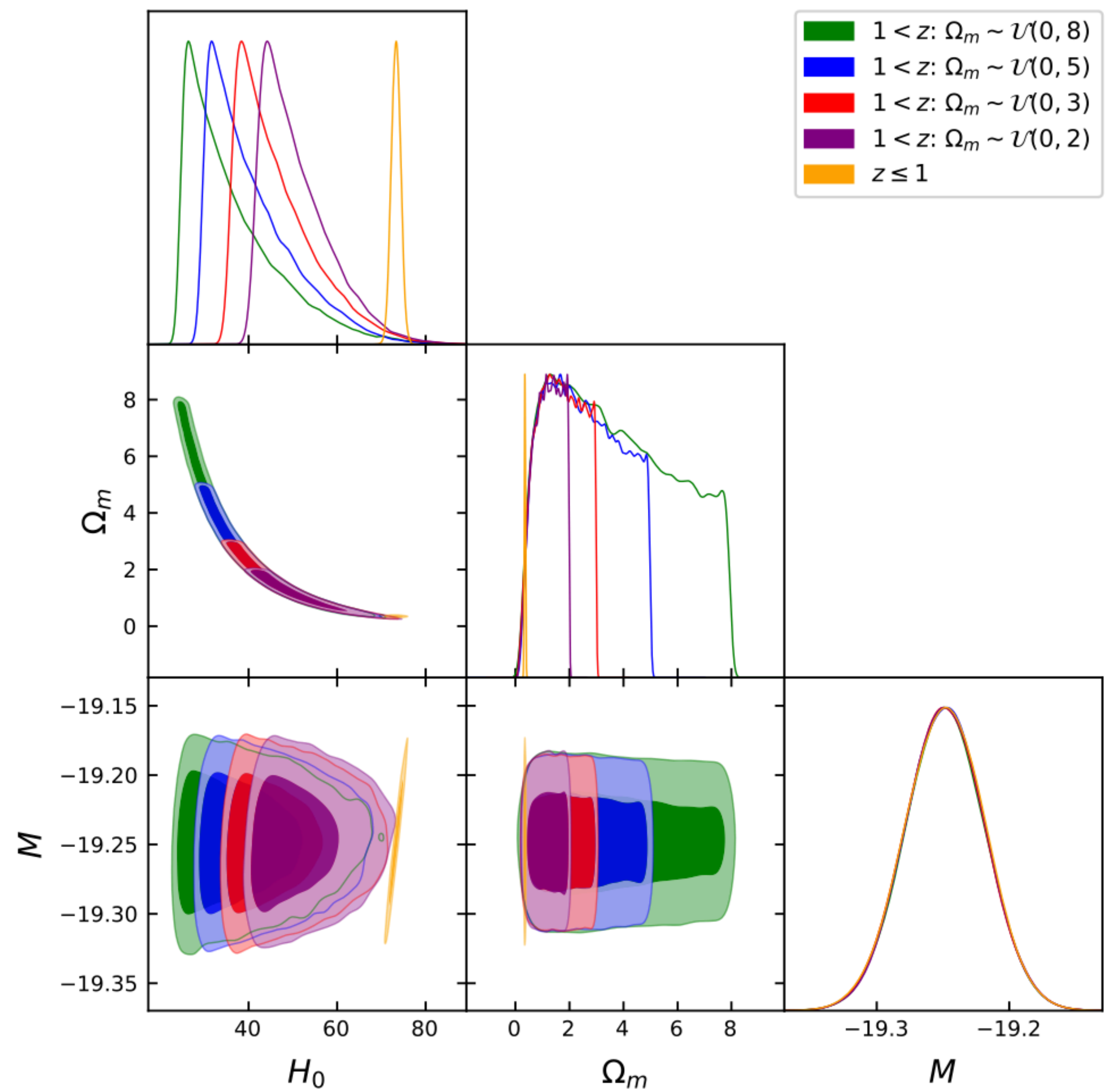
Evolution in the samples between low and high redshift up to ~3**σ** based on Fisher's method.



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

Upgrading to Pantheon+ sample one sees the same features (even negative DE density, cf. QSOs) with calibrated SN (M errors propagated).

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

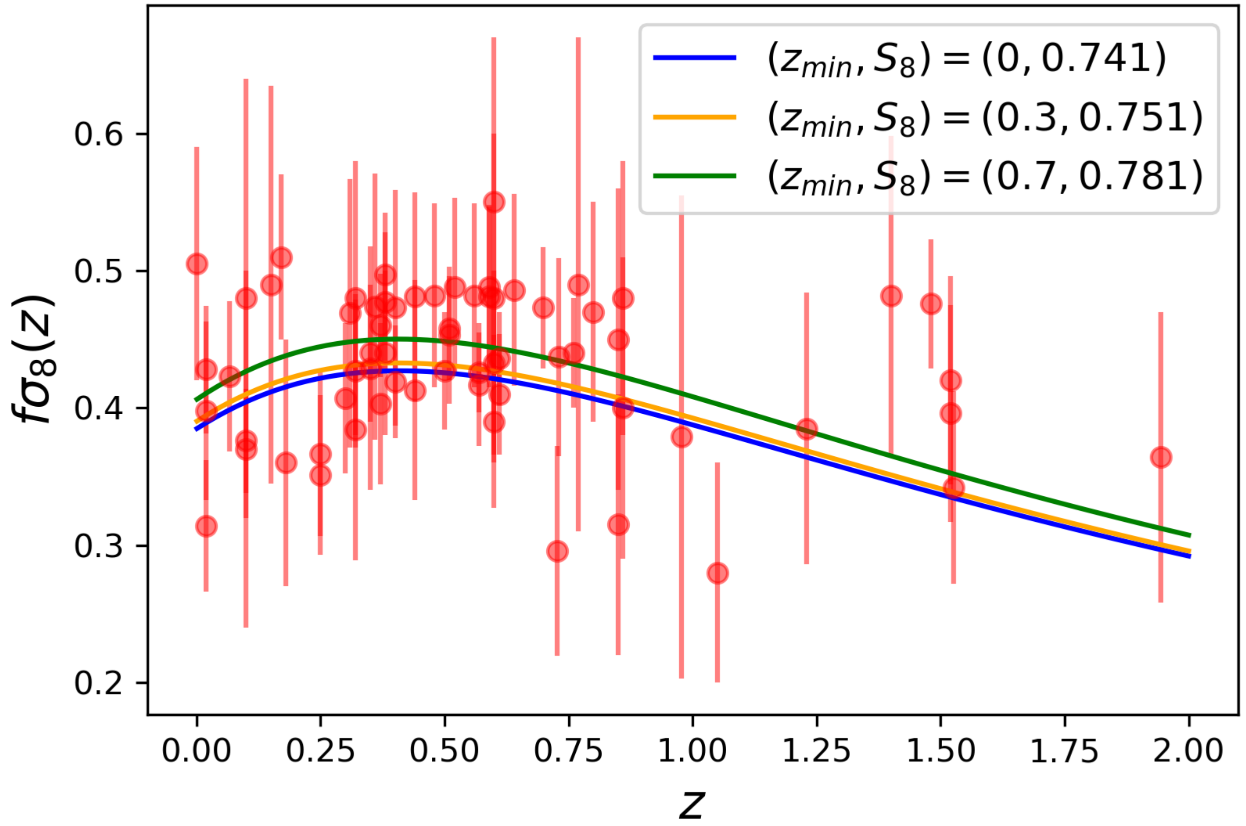


If evolution in (H_0, Ω_m) is real, then evolution in $S_8 \propto \sigma_8\sqrt{\Omega_m}$ difficult to rule out.

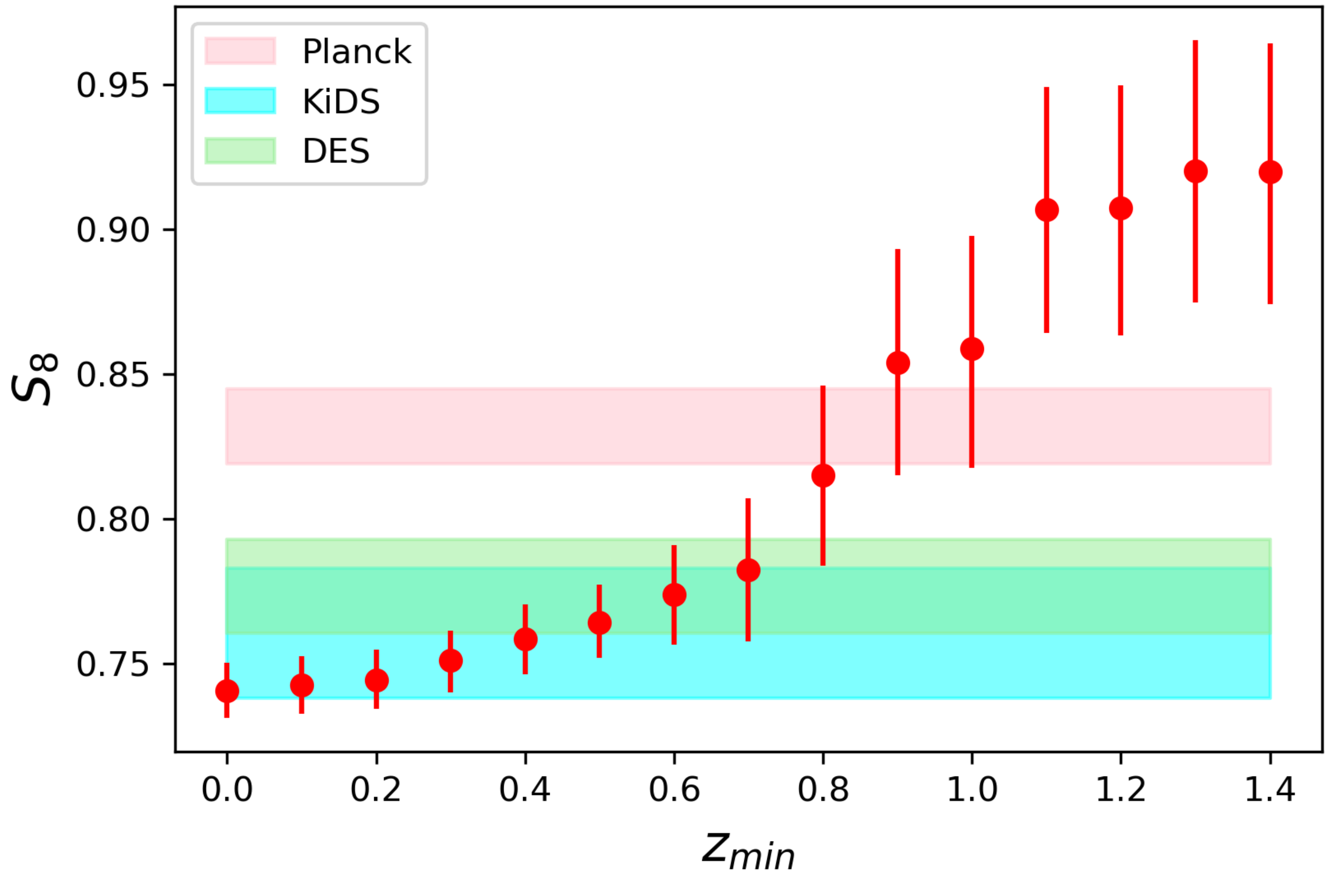
Adil, Akarsu, Malekjani, ÓC, Pourojaghi, Sen, Sheikh-Jabbari (2303.06928)

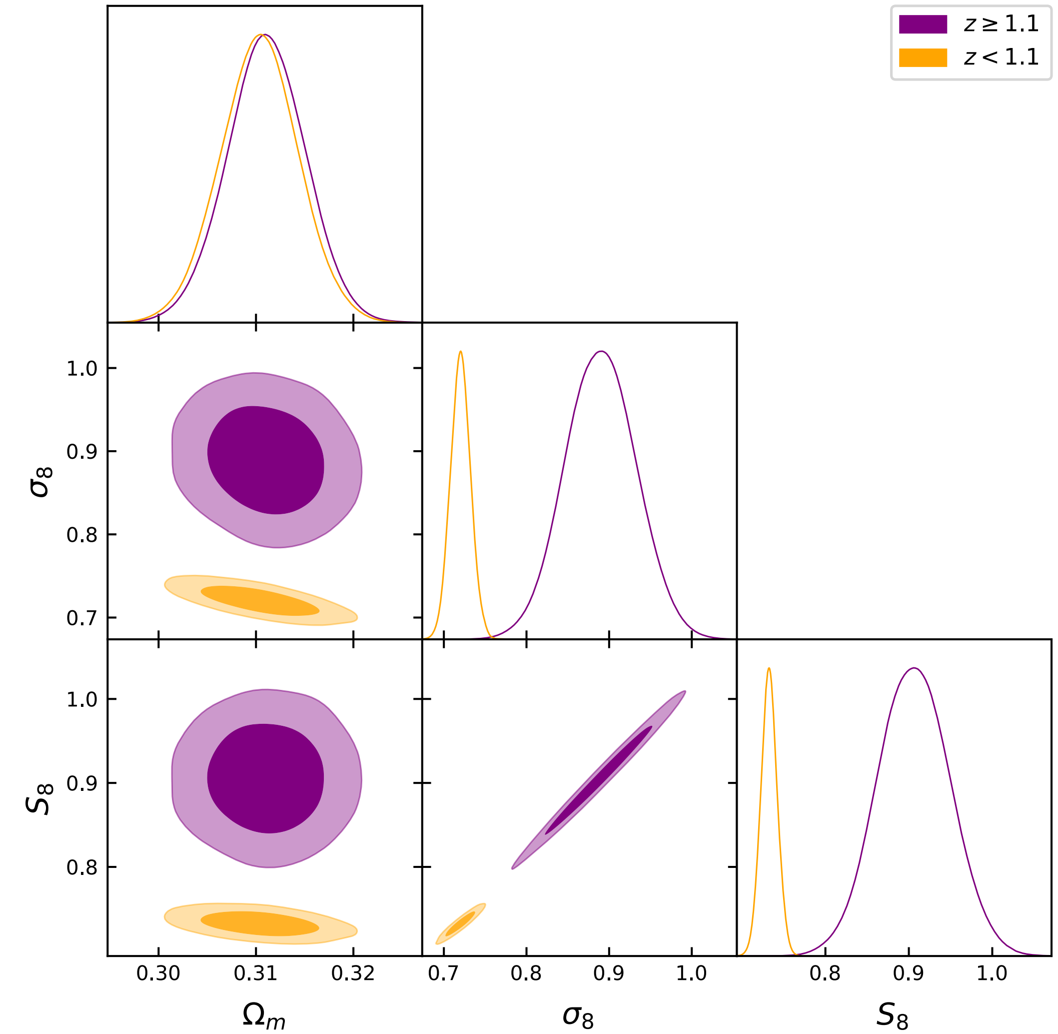
Consider growth rate data $f\sigma_8(z)$.

$$f\sigma_8(z) = \sigma_8 \Omega^{\frac{6}{11}}(z) \exp\left(- \int_0^z \frac{\Omega^{\frac{6}{11}}(z')}{1+z'} \mathrm{d}z' \right), \quad \Omega(z) = \frac{\Omega_m (1+z)^3}{1 - \Omega_m + \Omega_m (1+z)^3}$$



Data compiled by Kazantzidis, Perivolaropoulos (1803.01337)





Data points are not independent, so tension is overestimated, but redshift evolution is clear.

Similar evolution in $\boldsymbol{\sigma_8}$ between low z clusters and high z Lyman-$\boldsymbol{\alpha}$ at 3.3$\boldsymbol{\sigma}$. Systematics?

Esposito, Iršič, Costanzi, Borgani, Saro, Viel (2202.00974)

Related observation in recent ACT+DES paper - 2306.17268

"Intriguingly, constraints from CMB lensing ($z \sim 0.5 - 5$) from both Planck [18] and ACT [19, 20], reveal a S_8 value consistent with the one inferred using early Universe CMB data, possibly suggesting that tracers at higher redshift and probing larger scales prefer higher S_8."

19 = 2304.05203, 20 = 2304.05202

Summary

Persistent tensions disfavour systematics and favour model breakdown.

If so, redshift evolution of parameters is expected, i. e. assumed constant H_0, Ω_m, S_8, etc, are not constants.

It is important to test the ΛCDM model in a systematic way.

Evidence suggests evolution is happening in the late Universe across the same observable (same systematics).

If true, choice between i) DE = Λ ii) pressure-less matter.