H0 tension & breakdown of FLRW cosmology

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This story concerns background cosmology.

Most of the cosmology community have moved or are moving to large scale structure, i. e. perturbations.

However, H0 tension has thrown a spanner in the works.

At face value, there is a 10% discrepancy in the scale of the Hubble parameter.

Is 10% “precision cosmology”?

What about the sum of the neutrino masses?

At Sogang, some of us have made a bet on a resolution to H0 tension outside of FLRW.

Interestingly, a handful of other scientists inhabit this space, but motivation is a little unclear.

Some (Subir Sarkar) appear to be motivated by falsifying dark energy (this could be good for string theory).

An FLRW resolution to H0 tension seems unlikely, but cosmologists continue to explore this possibility.

If it does not work out, mainstream cosmology will have to come our direction.

Outline

1) Explain implications of FLRW resolution to H0 tension.

2) Explain why I think H0 tension is taking us outside FLRW.

Consider the FLRW metric (no curvature).

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \left(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2\right)$$

Next, recall the Friedmann equations:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

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

The Universe is expanding (light is obviously redshifted).

$$a(t) = \frac{1}{1+z}$$

Can solve H(z) once one assumes w(z):

$$(1+z)\frac{H'}{H} = \frac{3}{2}[1+w(z)]$$

$$H(z) = H_0 \exp\left(\frac{3}{2}\int_0^z \frac{1+w(z')}{1+z'}\mathrm{d}z'\right)$$

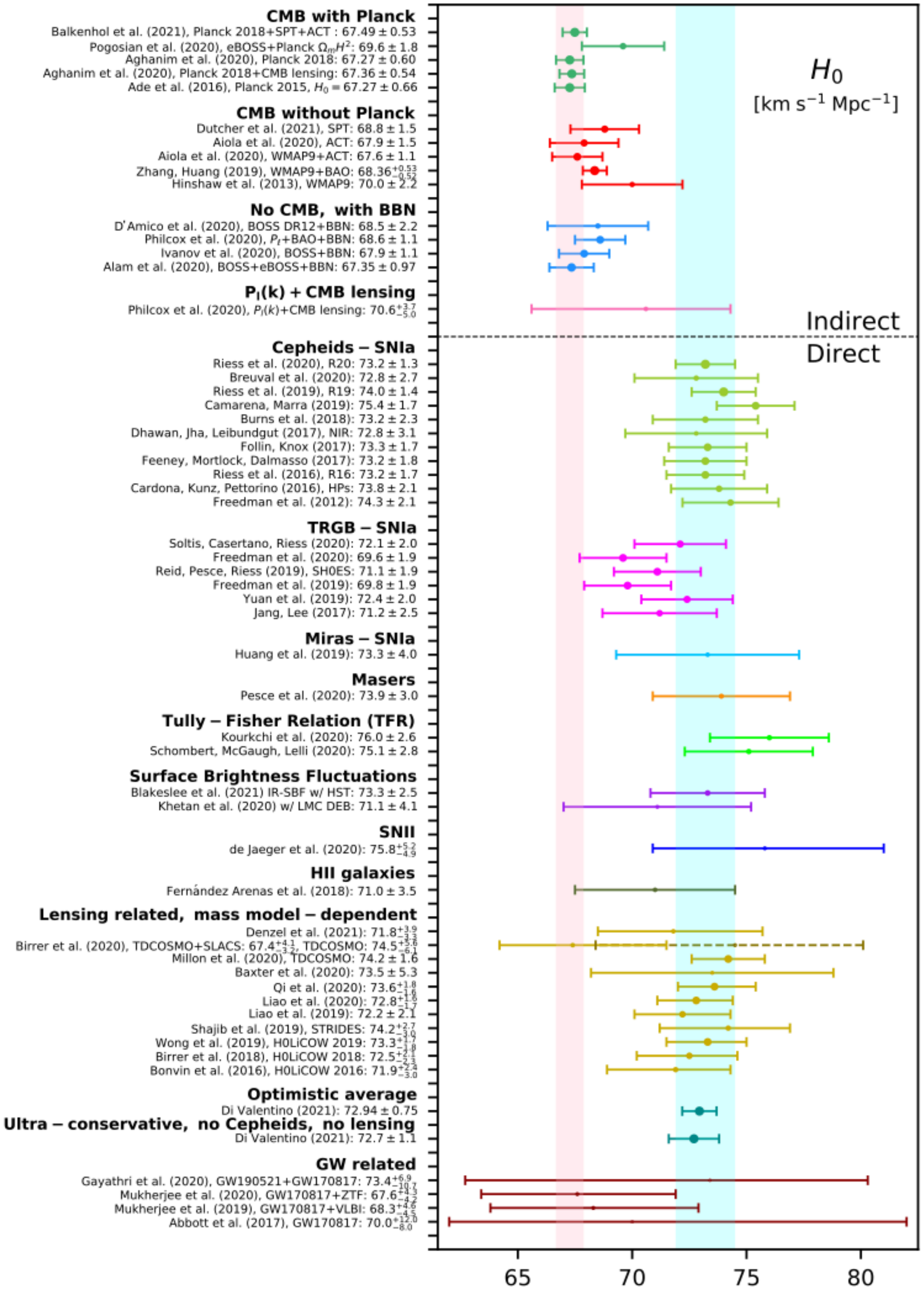
General solution for H(z). H0 is an integration constant.

Cosmology proceeds by assumption.

Contradictions are inevitable.

Systematics or contradiction?

Di Valentino et al. (2103.01183)



Q: what would a resolution to H0 tension look like in an FLRW cosmology?

A: H0 needs to run (evolve) with redshift within ΛCDM.

$$H_0 = H(z) \exp\left(-\frac{3}{2}\int_0^z \frac{1+w(z')}{1+z'} \mathrm{d}z'\right)$$

H0 is only a constant from the perspective of math.

w(z) is a guess on a model, but H(z) can be determined observationally.

If the model fits the data, then H0 is a constant, otherwise it is not.

Can determine H(z) directly - cosmic chronometers.

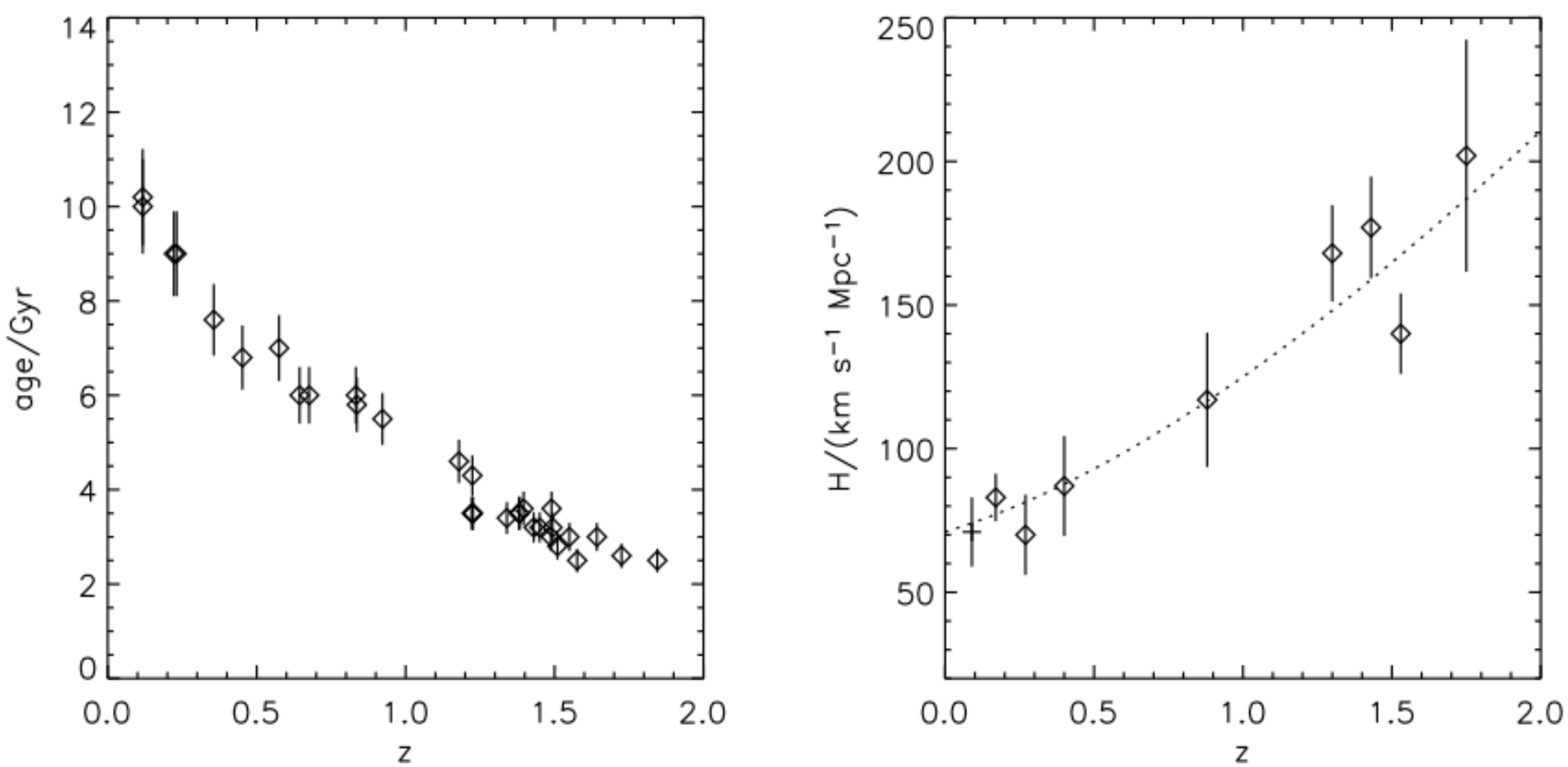
$$H(z) = -\frac{1}{1+z}\frac{\Delta z}{\Delta t}$$

Loeb, Jimenez (astro-ph/0106145)

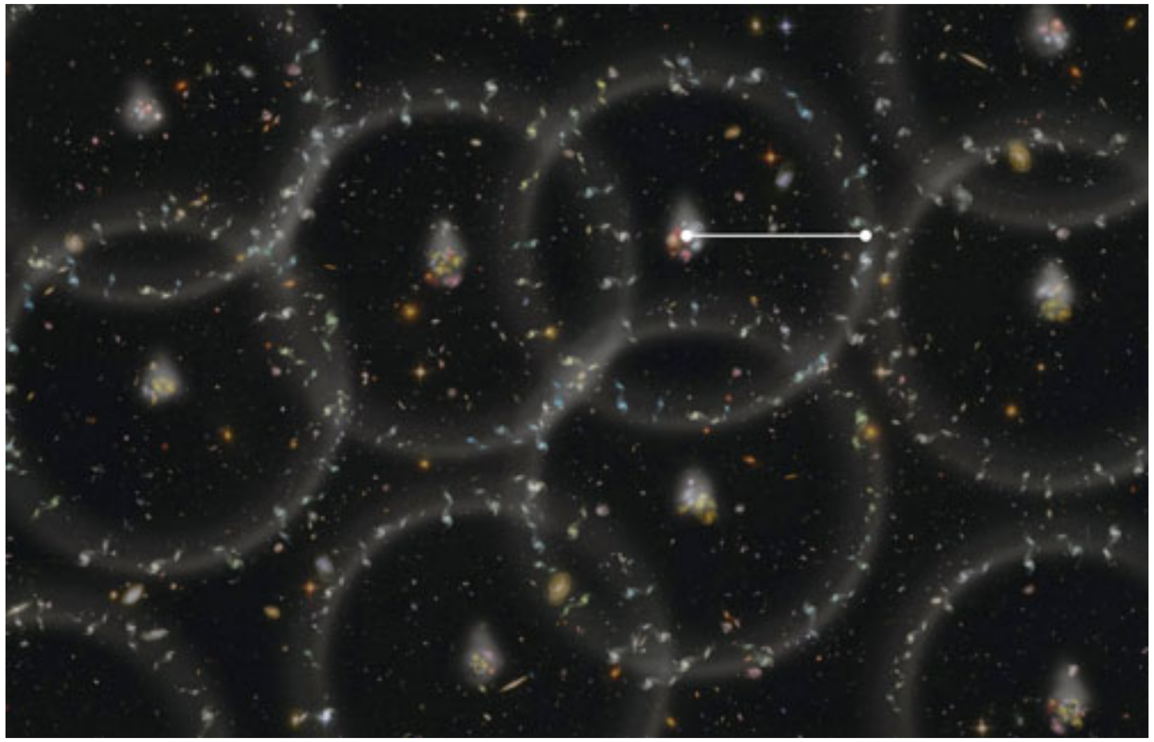
Cosmology independent, but modeling is elsewhere.

Simon, Verde, Jimenez (astro-ph/0412269)

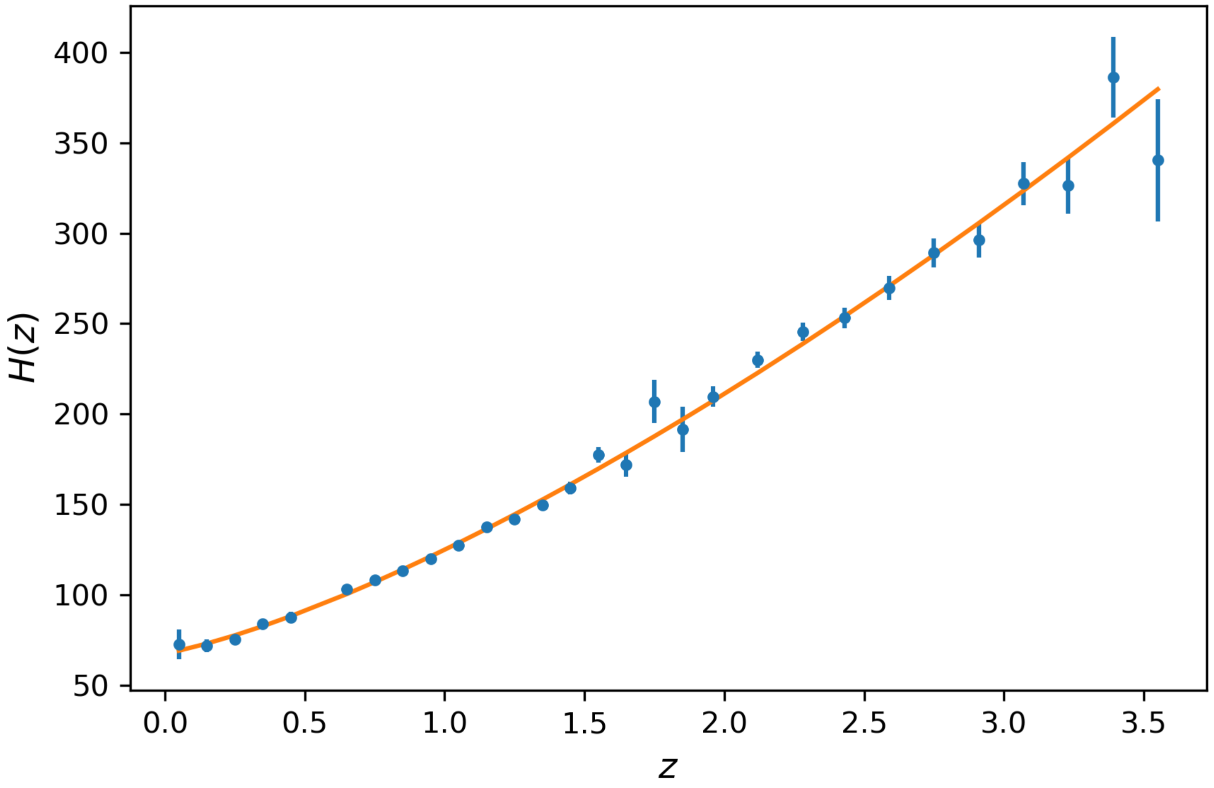
Kjerrgren, Morstell (2106.11317)

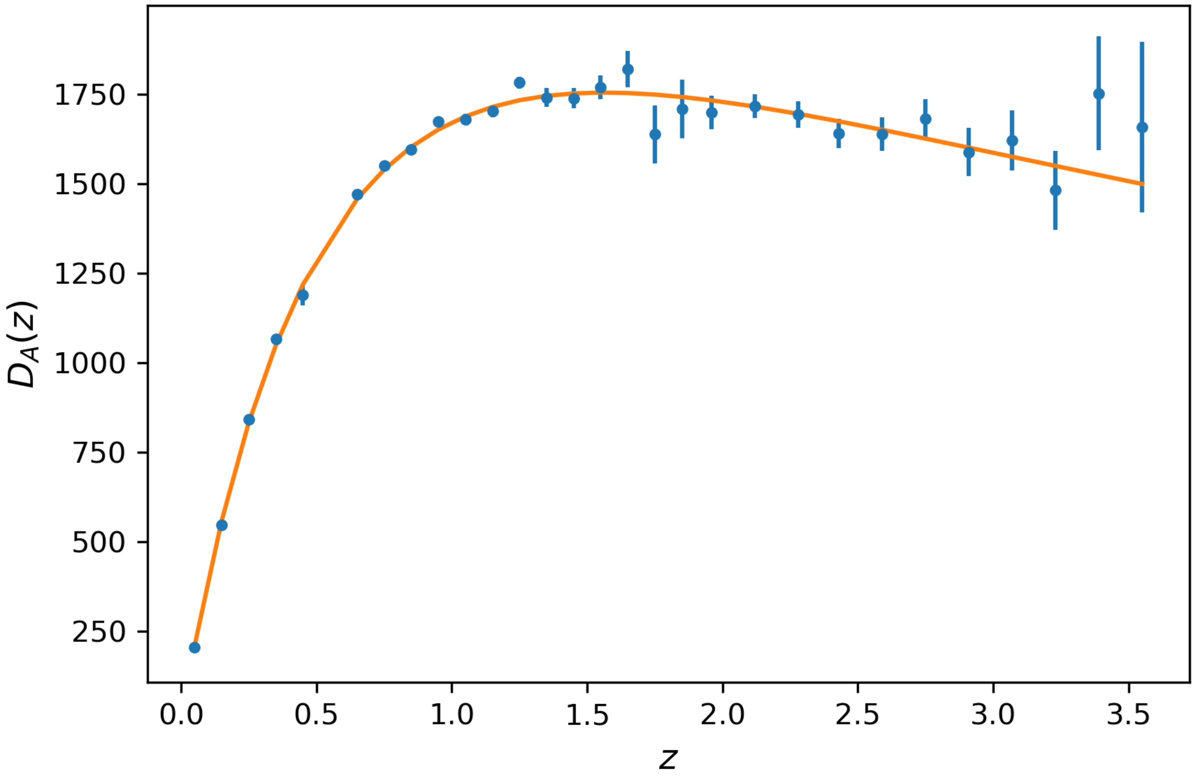


Baryon Acoustic Oscillations



In contrast to cosmic chronometers, BAO is much better quality.





Aghamousa et al. (1611.00036)

So, can determine $H(z_i)$ observationally and eliminate it.

Krishnan, ÓC, Sheikh-Jabbari, Yang (2011.02858)

$$\frac{H_0^{(A)}}{H_0^{(B)}} \sim \exp\left(\frac{3}{2}\int_0^{z_i} \frac{\Delta w(z)}{1+z}\mathrm{d}z\right)$$

Model A and B only return same H0 if $\Delta w(z) = 0$ at all z, otherwise the ratio depends on redshift.

Now, H0 tension is a 10% discrepancy between Riess ($z \approx 0$) and Planck ($z \approx 1100$).

Riess is model independent, Planck assume ΛCDM.

Basically, we should find other H0 determinations at other redshifts if H0 tension has a resolution within FLRW.

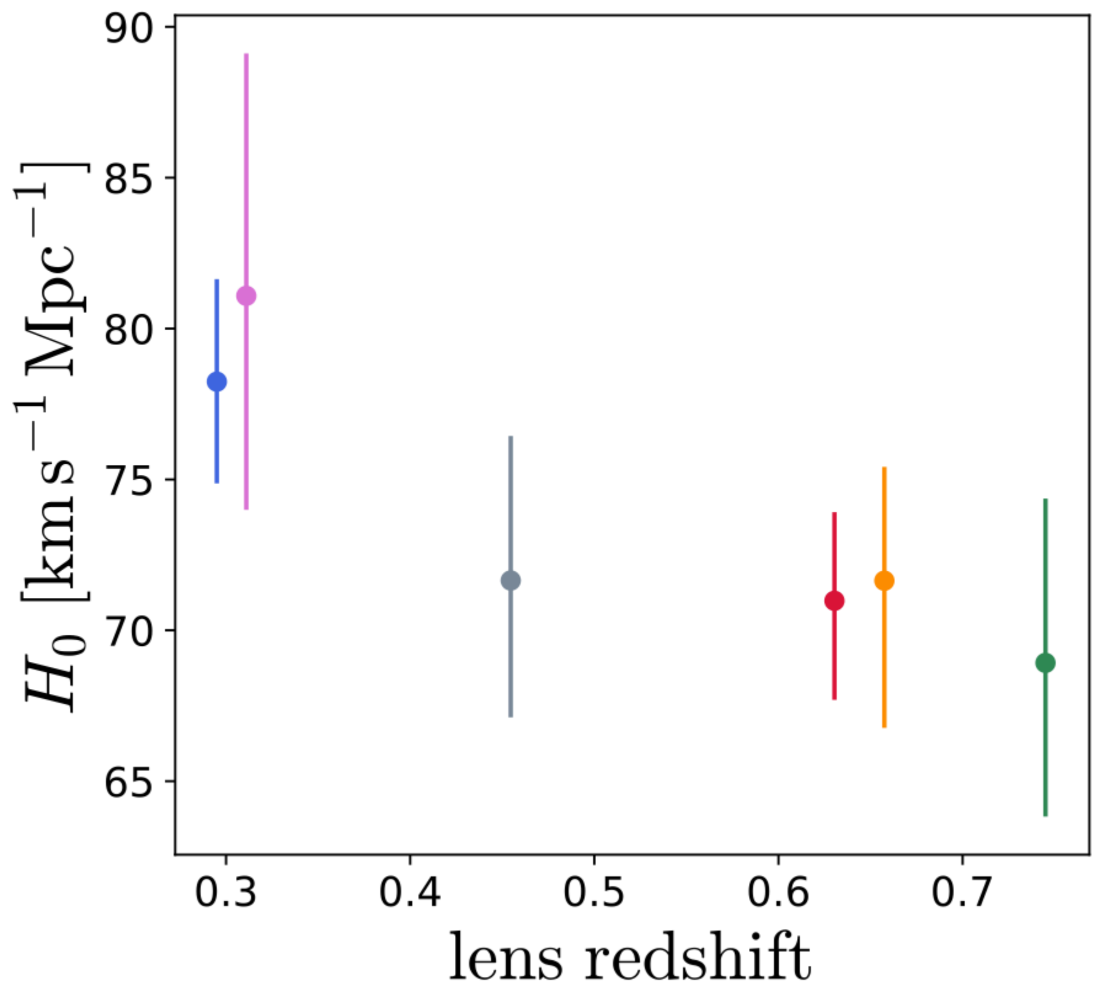
Of course, we may not have data where $\Delta w(z)$ changes.

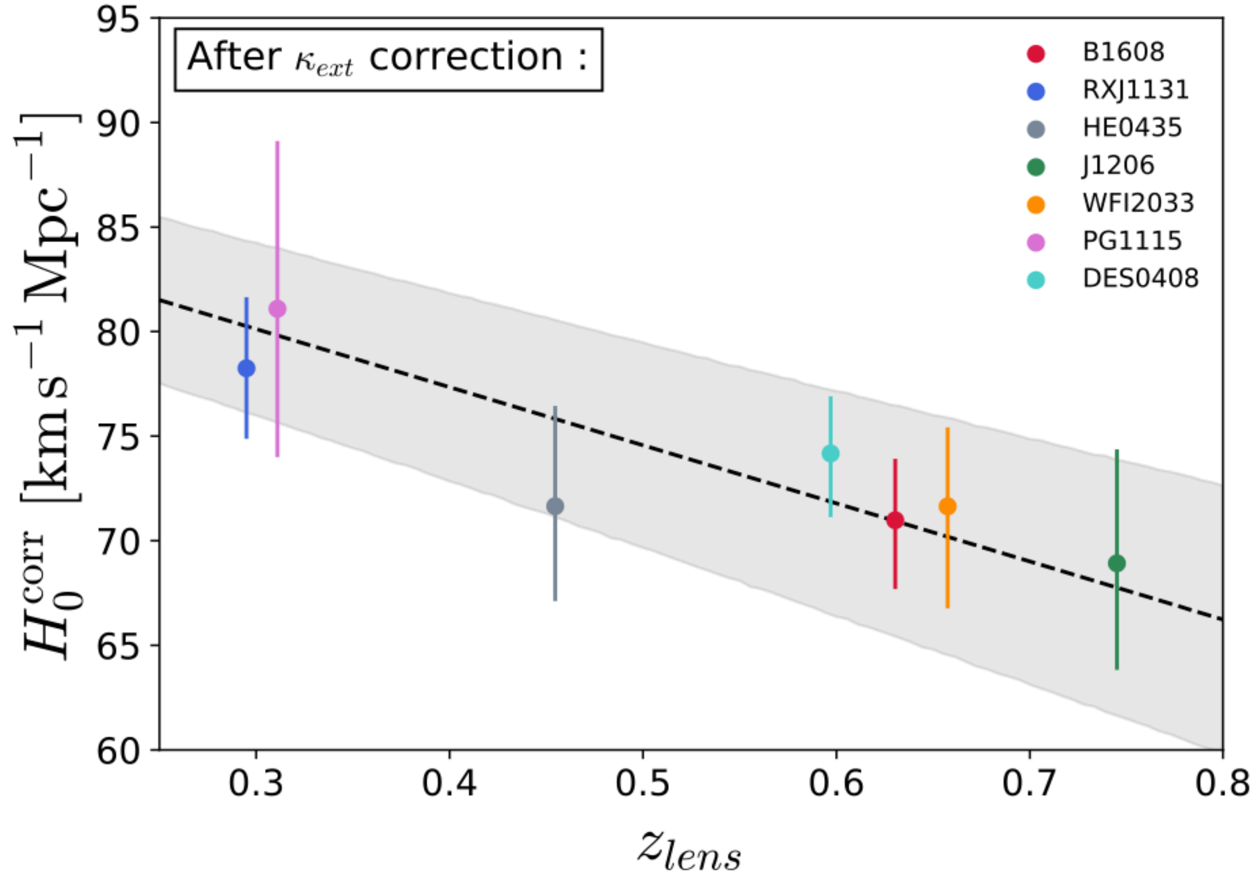
One of the leading ideas for resolutions to H0 tension makes use of new physics in the early Universe to change H0, while retaining ΛCDM in the late Universe, e. g. Early Dark Energy.

It's an interesting idea with many variants. As I will show later, it is the only way out beyond what we are proposing.

Poulin, Smith, Karwal, Kamionkowski (1811.04083)

One can find tentative evidence for such “running H0”.





Wong et al. (1907.04869)

Millon et al. (1912.08027)

(but this is probably not true)

One can also motivate “running H0” from the Universe’s age.

$$t_U = \frac{977.8}{H_0} \int_0^\infty \frac{\mathrm{d}z'}{(1+z')E(z')} \text{ Gyr}$$

Bernal, Verde, Jimenez, Kamionkowski et al. (2102.05066)

$$t_U = 13.5 \pm 0.27 \text{ Gyr}$$

Planck (1807.06209)

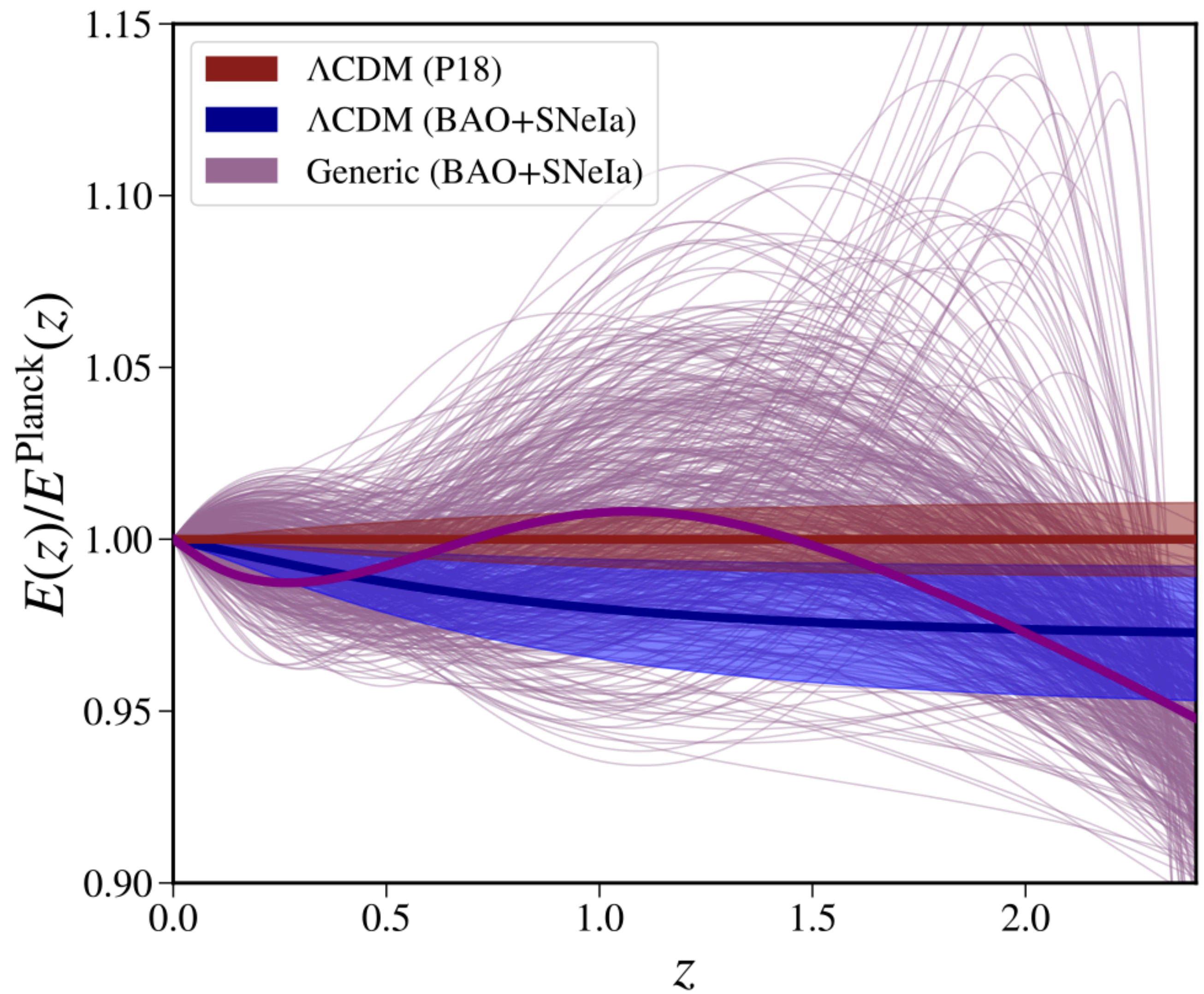
$$t_U = 13.80 \pm 0.02 \text{ Gyr}$$

Raising H0 requires compensation through E(z). This manifests itself in running.

But there is little evidence for this at late times.

Bernal, Verde, Jimenez, Kamionkowski et al. (2102.05066)

$$\frac{H_0^{(A)}}{H_0^{(B)}} \sim \frac{E(z)_B}{E(z)_A}$$

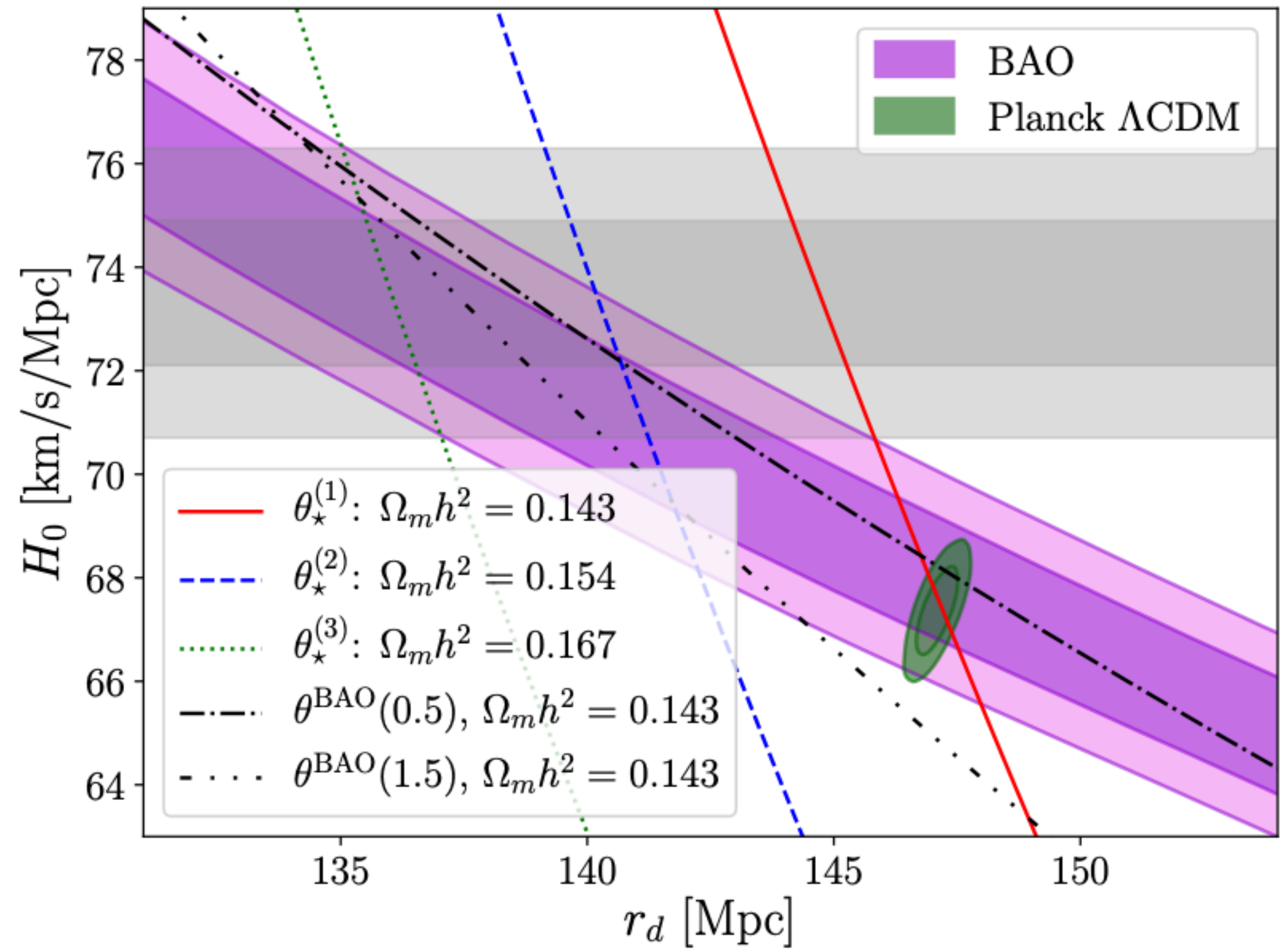


Note, EDE on its own is imperfect. One cannot just change H0 and have ΛCDM in the late Universe.

EDE (with variants) may be the best idea on the table.

But EDE runs into problems with LSS. Numerous works have demonstrated this.

E.g. BAO constrains H0 r_d



Jedamzik, Pogosian, Zhao (2010.04158)

EDE and its variants don't currently work. This is the current consensus.

Moving beyond FLRW

FLRW cosmologies have limitations

One can produce an upper bound on H0 for any FLRW cosmology subject to certain assumptions:

i) Gravity described by General Relativity

ii) Age of Universe from globular clusters

Bernal et al. (2102.05066)

iii) Planck have accurately determined $\Omega_m h^2$ (with low multipoles subtracted)

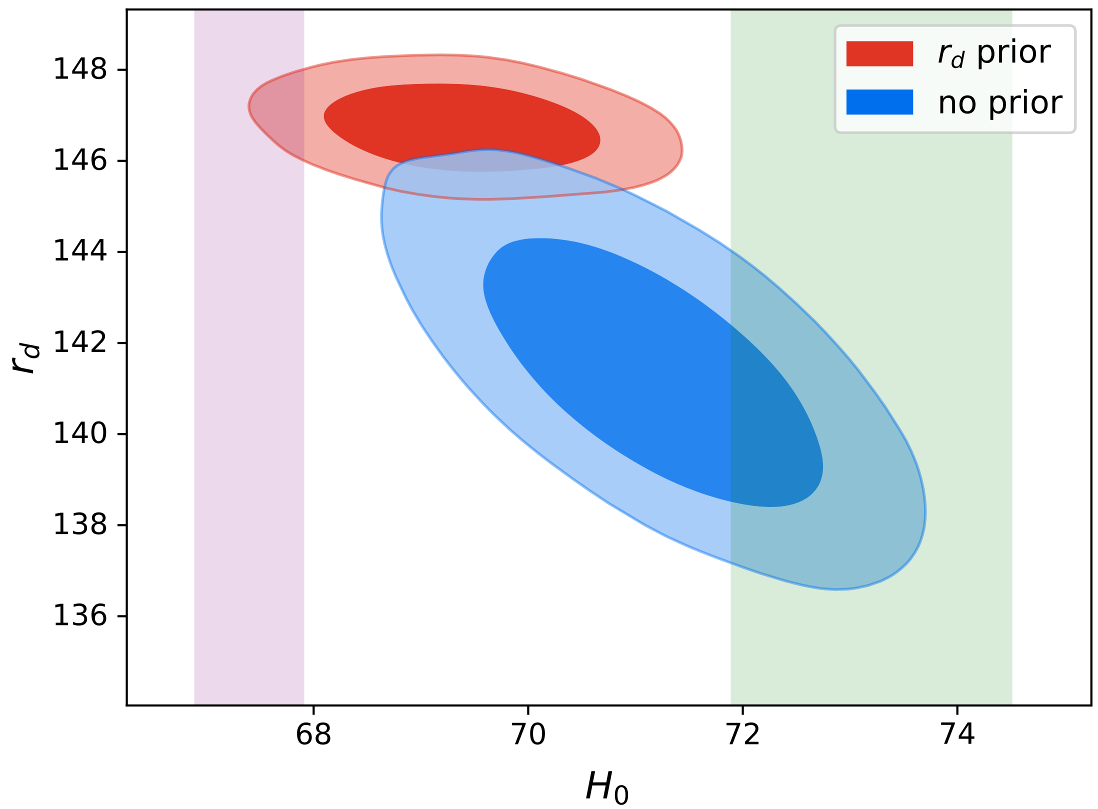
Vonlathen et al. (1003.0810)

iv) SHOES Prior on M_B

Efstathiou (2103.08723)

v) Matter + variable DE sector

vi) BAO, Type Ia supernovae, cosmic chronometers



Krishnan et al. (2105.09790)

$$H_0 \sim 71 \pm 1 \text{ km/s/Mpc}$$

Karwal, Raveri, Jain, Khoury, Trodden (2106.13290)

$$H_0 = 71.19 \pm 0.99 \text{ km/s/Mpc}$$

Values of H0 ~73 km/s/Mpc are clearly within 2 sigma.

But FLRW needs to find an early Universe resolution that works.

(can modify GR, but let's wait on evidence from GWs)

However, results stretching back decades make FLRW less clear cut. Prudent to confirm CMB dipole.

Siewert, Schmidt-Rubart, Schwarz (2010.08366)

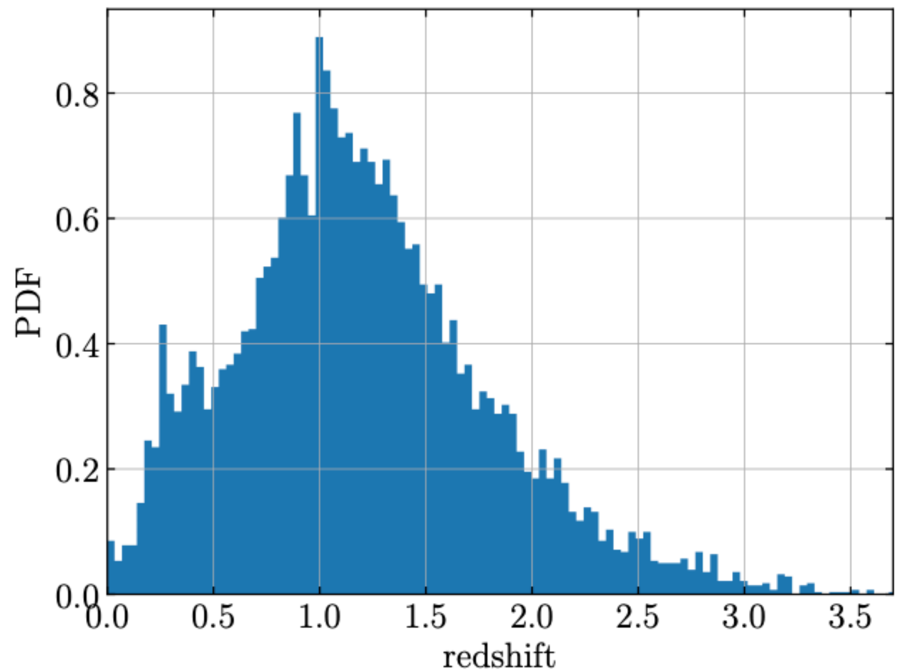
consistent with earlier results:

Blake & Wall (2002); Singal (2011); Rubart & Schwarz (2013); Tiwari & Nusser (2016); Bengaly et al. (2018)

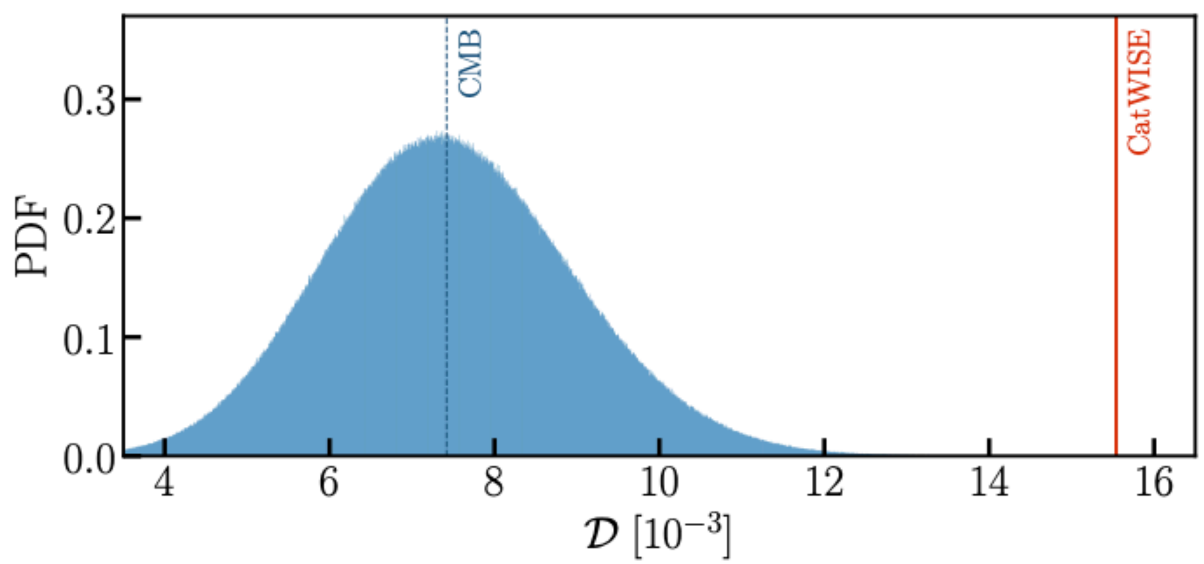
Survey	Mask	f_{sky}	S [mJy]	N	RA [deg]	DEC [deg]	$\Delta\theta$ [deg]	d ($\times 10^{-2}$)	χ^2/dof
TGSS	d	0.72	50	393 447	124.53 ± 4.13	25.66 ± 5.15	53.30 ± 4.02	6.6 ± 0.5	3.19
			100	244 881	135.61 ± 11.57	15.90 ± 11.24	39.33 ± 14.30	6.0 ± 0.8	2.91
			150	173 964	139.53 ± 11.33	12.88 ± 10.74	34.50 ± 13.86	5.9 ± 0.7	1.83
			200	133 547	141.99 ± 11.17	11.52 ± 10.21	31.74 ± 13.29	5.9 ± 0.7	1.65
	n	0.52	50	296 855	132.90 ± 4.57	15.68 ± 5.21	41.43 ± 4.17	6.2 ± 0.5	2.36
			100	179 951	137.25 ± 6.62	14.49 ± 5.39	37.23 ± 6.05	6.3 ± 0.6	1.94
			150	127 244	138.30 ± 6.25	14.96 ± 5.25	36.65 ± 5.63	6.5 ± 0.7	1.72
			200	97 355	138.86 ± 6.12	15.79 ± 5.51	36.69 ± 5.45	6.8 ± 0.8	1.54
WENSS	d	0.17	25	115 808	143.34 ± 19.48	−13.15 ± 4.58	24.99 ± 13.84	3.2 ± 1.0	1.91
			35	95 302	137.85 ± 24.47	−13.29 ± 4.98	30.27 ± 18.99	2.9 ± 0.9	1.77
			45	81 534	131.83 ± 27.76	−11.95 ± 6.28	35.94 ± 22.94	2.8 ± 0.9	1.68
			55	71 643	127.51 ± 29.27	−10.70 ± 6.59	40.10 ± 24.89	2.8 ± 0.9	1.57
	n	0.14	25	93 577	142.20 ± 23.25	−16.20 ± 5.77	26.83 ± 14.94	3.1 ± 0.9	1.88
			35	76 760	138.98 ± 27.58	−16.25 ± 6.16	29.81 ± 18.54	2.9 ± 0.9	1.75
			45	65 494	138.71 ± 34.24	−16.23 ± 7.66	30.06 ± 23.10	2.8 ± 1.0	1.67
			55	57 463	135.43 ± 35.16	−15.39 ± 7.60	32.95 ± 24.13	2.8 ± 1.0	1.56
SUMSS	d	0.16	18	99 835	106.67 ± 12.90	−9.50 ± 11.12	60.62 ± 12.49	3.8 ± 0.9	1.49
			25	75 642	106.18 ± 16.99	−5.11 ± 9.91	61.40 ± 16.79	3.5 ± 1.0	1.58
			35	55 973	108.05 ± 22.64	−4.12 ± 8.92	59.65 ± 20.85	3.4 ± 1.0	1.49
			45	44 403	105.33 ± 25.64	−4.08 ± 8.35	62.35 ± 23.73	3.3 ± 1.1	1.51
			55	36 646	106.72 ± 33.92	−4.92 ± 8.66	60.89 ± 27.50	3.2 ± 1.1	1.40
	n	0.16	18	96 816	106.67 ± 14.53	−9.50 ± 10.03	59.40 ± 14.36	3.8 ± 0.8	1.51
			25	73 356	106.18 ± 17.34	−5.11 ± 8.95	61.16 ± 17.28	3.5 ± 1.0	1.60
			35	54 336	108.05 ± 20.78	−4.12 ± 8.16	61.24 ± 20.09	3.4 ± 1.1	1.51
			45	43 121	105.33 ± 24.68	−4.08 ± 7.93	63.50 ± 23.62	3.3 ± 1.1	1.46
			55	35 574	106.72 ± 30.58	−4.92 ± 8.68	61.60 ± 25.75	3.2 ± 1.2	1.41
NVSS	d	0.66	15	328 207	138.90 ± 12.02	−2.74 ± 12.11	29.23 ± 11.07	1.6 ± 0.3	1.30
			25	209 034	140.02 ± 13.63	−5.14 ± 13.26	27.82 ± 12.17	1.8 ± 0.4	1.23
			35	151 702	140.51 ± 14.14	−8.32 ± 14.52	27.22 ± 12.61	1.8 ± 0.4	1.23
			45	117 617	140.67 ± 14.68	−13.01 ± 16.15	27.52 ± 12.65	2.0 ± 0.6	1.24
			55	95 129	143.86 ± 17.03	−16.45 ± 17.38	25.39 ± 12.76	2.1 ± 0.6	1.23
	n	0.53	15	266 839	156.33 ± 17.80	7.41 ± 17.63	18.44 ± 15.16	1.4 ± 0.4	1.18
			25	169 752	161.02 ± 17.37	2.69 ± 17.12	11.86 ± 13.94	1.6 ± 0.4	1.10
			35	123 037	165.14 ± 18.88	−1.84 ± 18.82	5.82 ± 13.65	1.6 ± 0.5	1.13
			45	95 291	169.15 ± 19.40	−5.99 ± 19.29	1.54 ± 13.05	1.8 ± 0.5	1.10
			55	77 081	173.60 ± 21.09	−9.18 ± 19.47	6.03 ± 13.47	2.0 ± 0.6	1.10

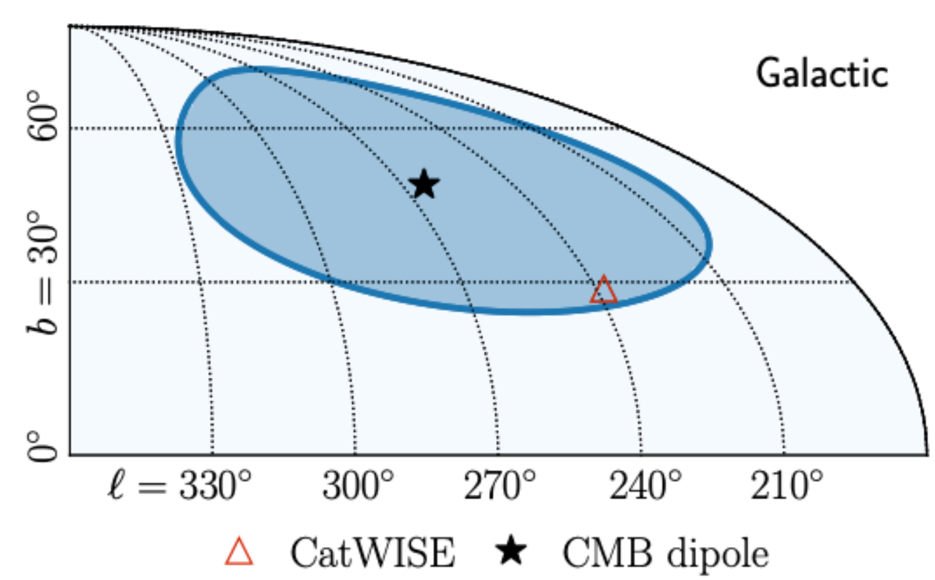
Dipoles agree with CMB direction but NOT magnitude.

Observation recently extended to QSOs (clearly a problem - systematics are different!). Authors are quoting 4.9 σ !!!

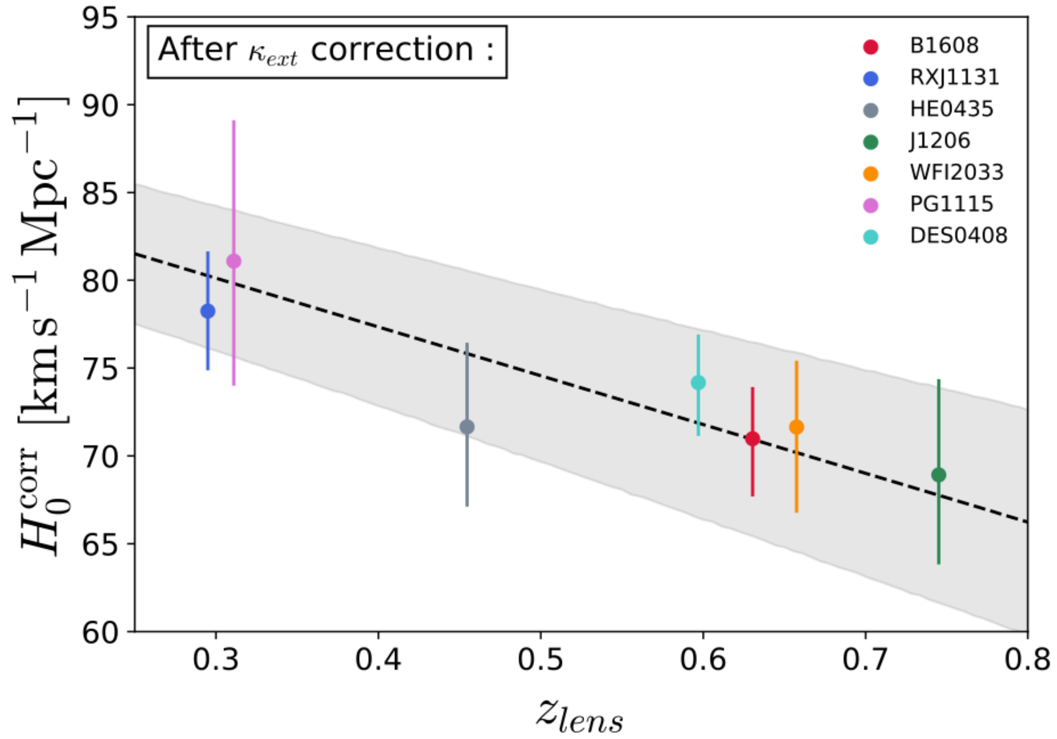


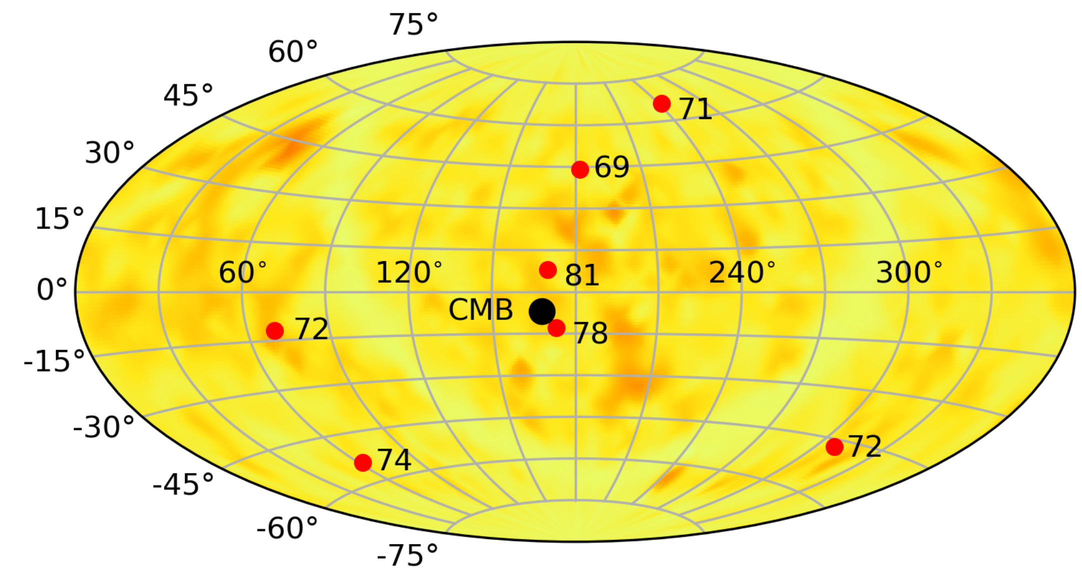
Secrest, Sarkar, Mohayaee et al. (2009.14826)





But dipoles may be less accessible.





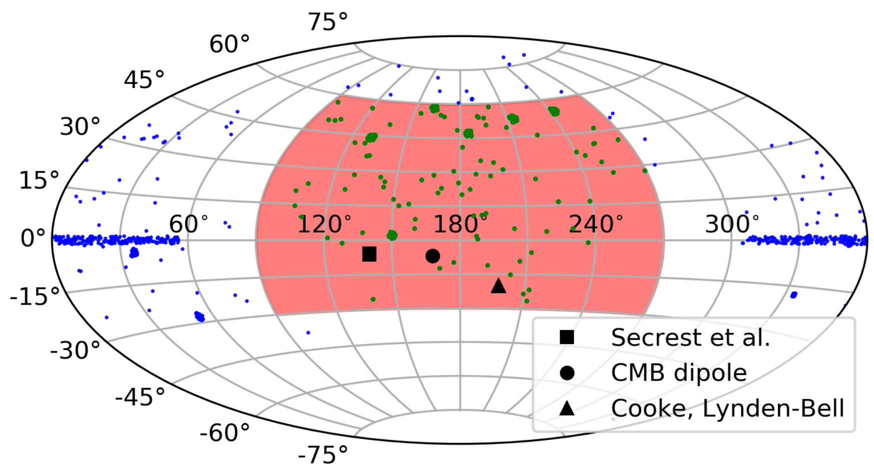
Millon et al. (1912.08027)

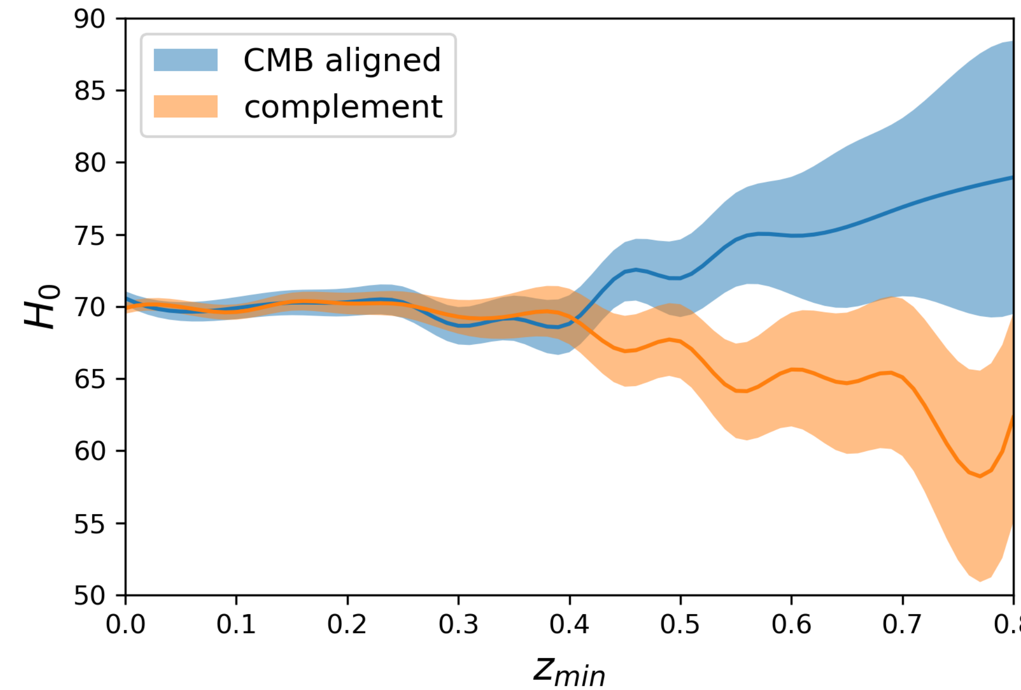
Krishnan et al. (2105.09790)

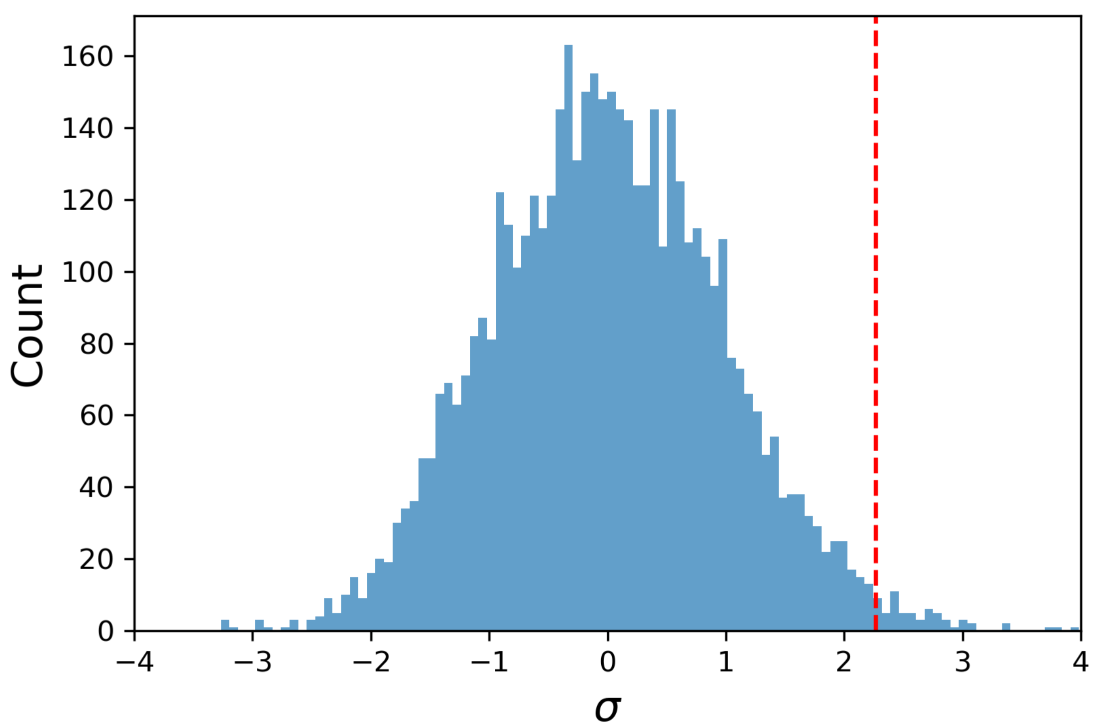
Strongly lensed QSOs have higher H0 values aligned with CMB dipole.

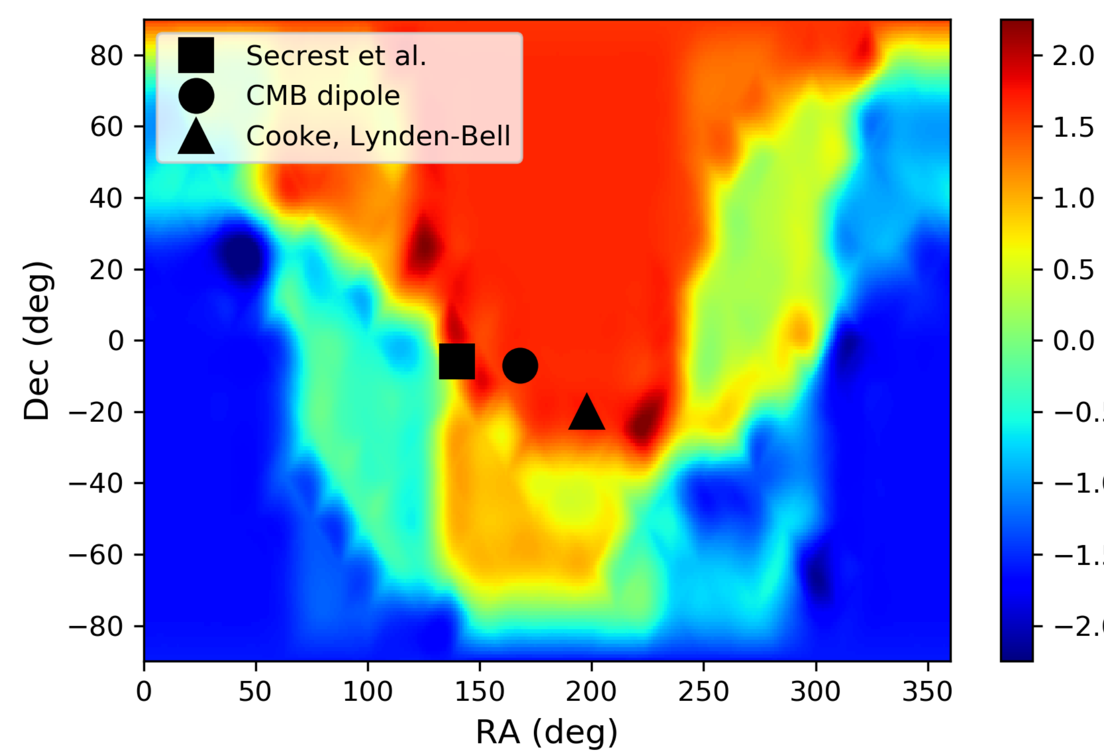
One can see a separation in H0 within SNE, i. e. a "standard candle", at higher z.

Krishnan et al. (2106.02532)





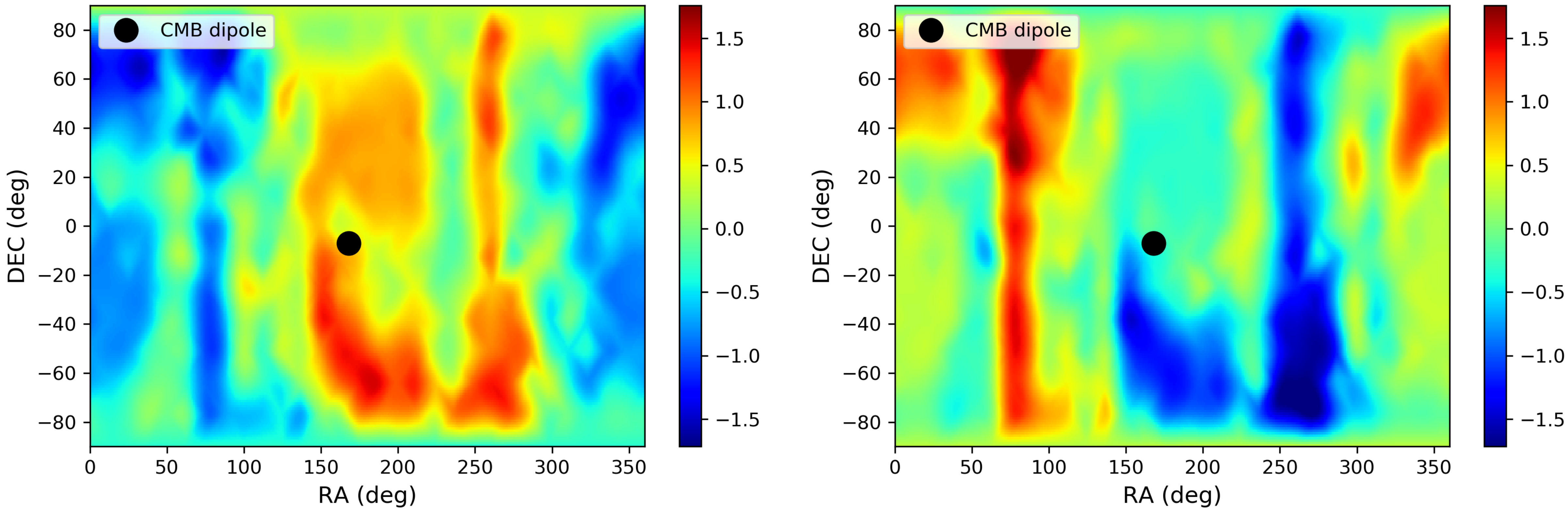




Cooke, Lynden-Bell (0909.3861)

One can find “evidence” at ALL redshifts in Pantheon.

Significance is low, but glaring. ÓC et al. (to appear)



Consistent with a large anisotropy, one so blatant that one does not need to be in heliocentric frame.

Singal (2106.11968)

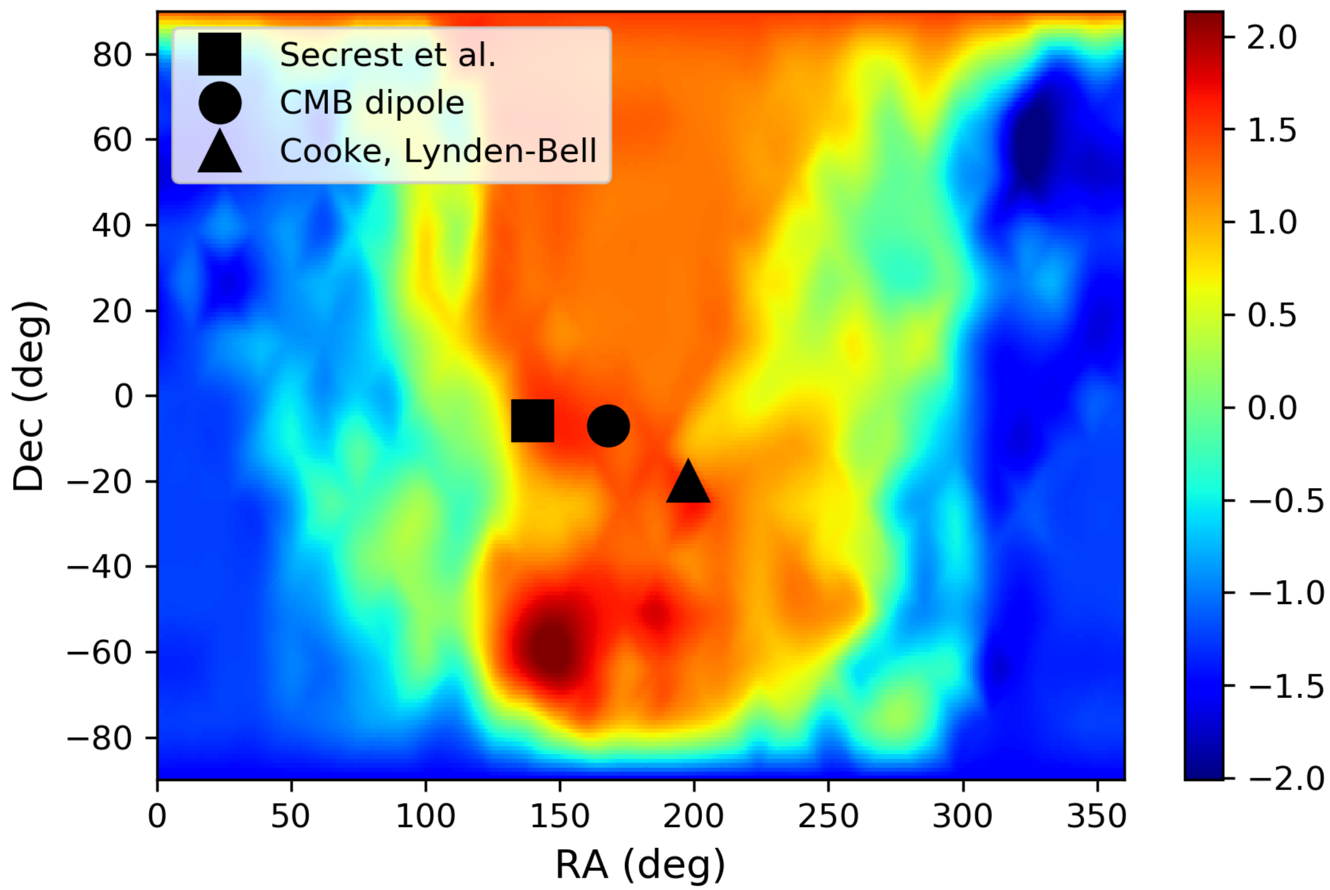
One can see the same thing in Risaliti & Lusso QSOs.

Risaliti, Lusso (1505.07118, 2008.08586)

$$\log_{10}(L_X) = \beta + \gamma \log_{10}(L_{UV}),$$
$$\log_{10}(F_X) = \beta + (\gamma - 1)\log_{10}(4\pi) + \gamma \log_{10}(F_{UV}) + 2(\gamma - 1)\log_{10}(D_L)$$

There appears to be a value of **β** so that $D_L(z)$ from QSOs agrees with SNE in range $0.7 \lessapprox z \lessapprox 1.7$ (~ 1000 QSOs)

Δ*β* is over 2 ***σ*** & can be checked by MCMC.



Take homes

The Planck-ΛCDM Universe based on FLRW is a thing of beauty. It's the pinnacle of "precision cosmology".

It's being seriously challenged by H0 tension.

Ultimately, nothing seems to work within FLRW.

But do supernovae, QSOs (& matter more generally) live in the Planck-ΛCDM Universe?

Why are H0 determinations separating in hemispheres?

Is H0 tension a well defined problem?