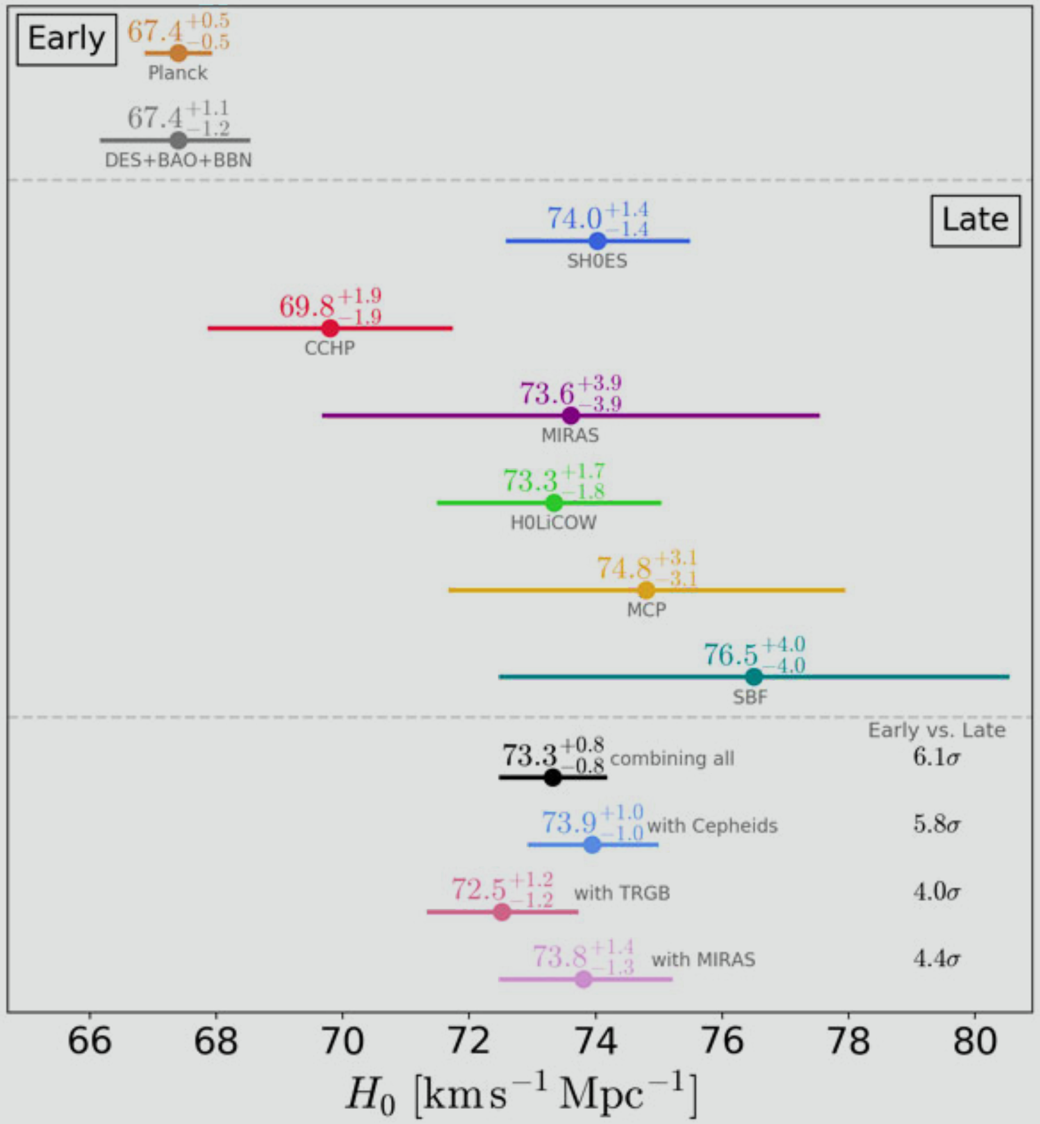
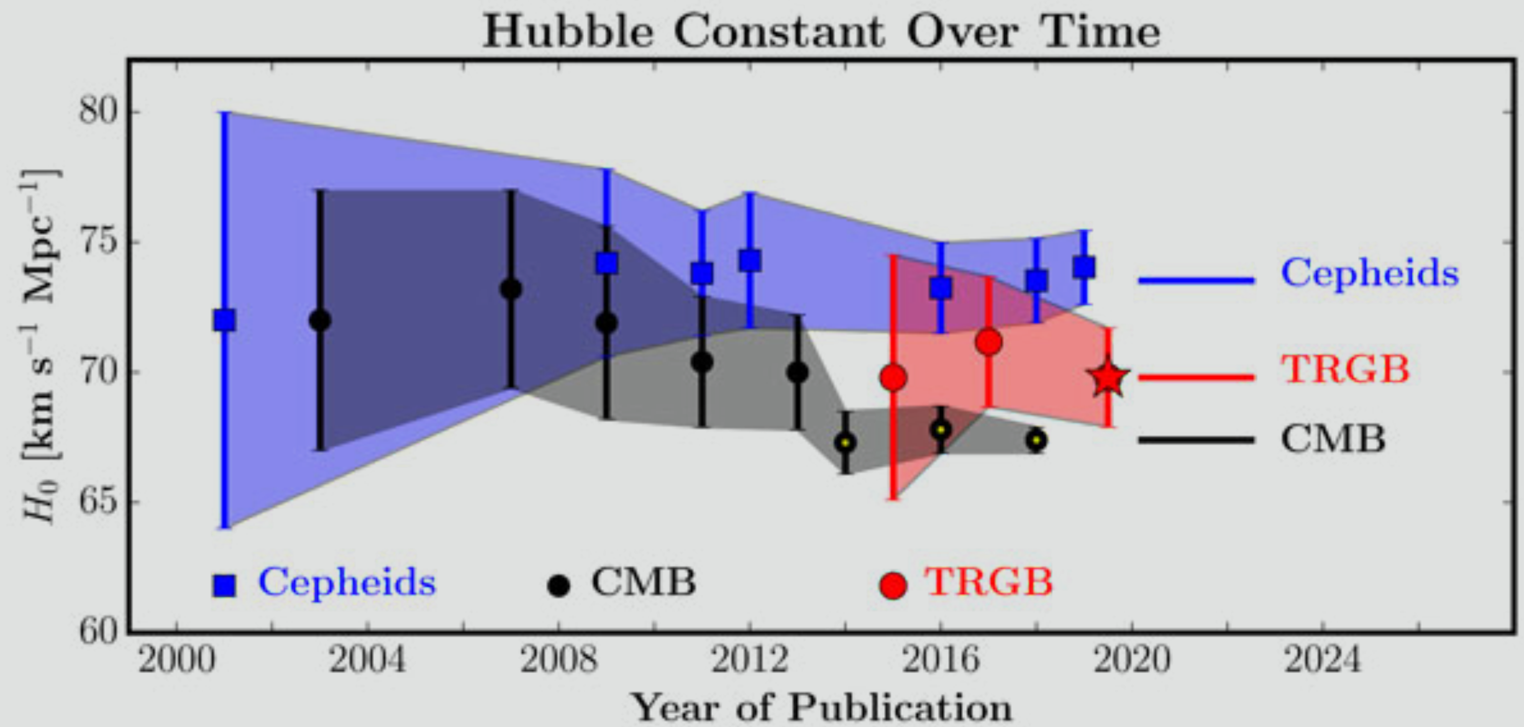


Vivien Bonvin / HOLiCOW Team



Freedman et al. *Astrophysical Journal*

Hubble Speed from First Principles

Alessandra Silvestri
Instituut Lorentz, Leiden U.

16th Marcel Grossmann Meeting **July 5, 2021**

Distances in Cosmology

Distances are set by the metric that describes our space-time; in a cosmological context, this implies that their scaling with time is related to the expansion rate of the Universe.

Comoving distance:

$$\chi(z) = \frac{1}{H_0}\int_0^z \frac{d\tilde{z}}{E(\tilde{z})}$$

where I will call cosmological model:

$$E^2(z) \equiv \frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_{\rm DE}X(z)$$

X represents all contributions to the expansion that are not matter or radiation, e.g. cosmological constant (X=1), DE, modified gravity, spatial curvature, etc..

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Distances in Cosmology

Comoving distance is not a direct observable. There are two types of distances measured in an expanding Universe:

Luminosity distance

standardizable candles/sirens

SNIe (GWs)

$$m_B = M_B + 5\log\left(\frac{d_L}{10\mathrm{pc}}\right) + 25$$

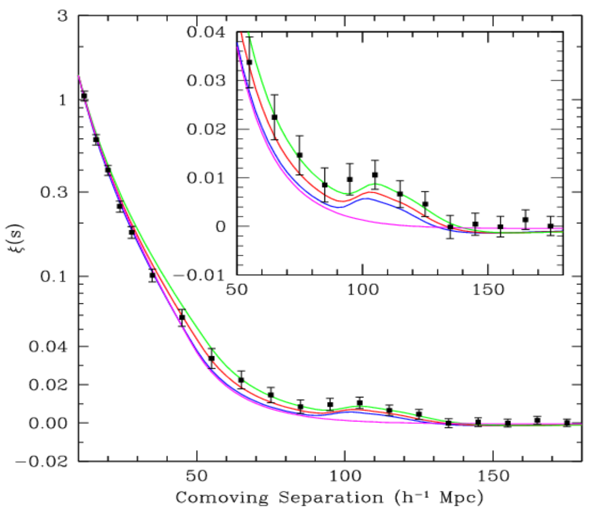
$$M_B = 5\log H_0 - 5a_B - 25$$

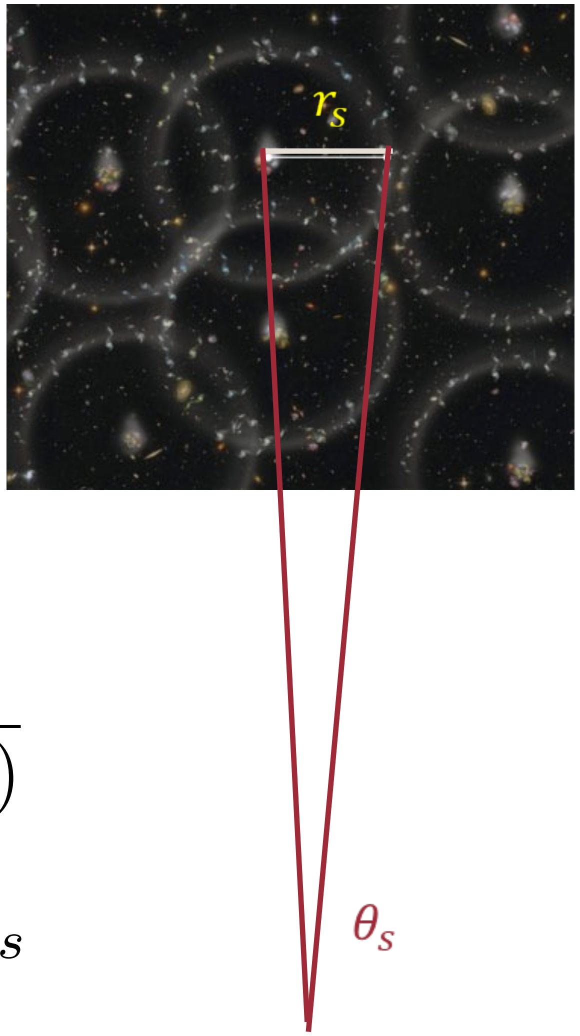
$$m_B = 5\log\left(\frac{H_0 d_L}{10\mathrm{pc}}\right) - 5a_B$$

Angular diameter distance

BAO standard rulers

(CMB peaks)





$$\theta_s(z) = \frac{r_s}{d_A(z)}$$

$$\Delta z = H(z) r_s$$

Distance Duality Relation

In any metric theory of gravity, if photons propagate along null geodesics and obey number conservation:

$$\eta(z) \equiv \frac{d_L(z)}{(1+z)^2 d_A(z)} = 1$$

Etherington Philos. Mag. 15, 761 (1933).

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Let us **set** $\eta = 1$ and rearrange the DDR as follows:

$$H_0 = \frac{1}{(1+z)^2} \frac{H_0 d_L(z)}{H(z) d_A(z)} H(z)$$

- H(z)d_A(z): from a combination of line-of-sight and transverse BAO measurements, without the need of an external anchor for the sound horizon at drag epoch `[7 data points from BOSS]`
- Cosmic chronometers (CC) measurements provide H(z) data that is free from calibration and does not depend on the underlying cosmological model `[a compilation of 30 measurements]`
- H_0d_L can be obtained from measurements of SNIa without the need of calibration `[Pantheon]`

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$$\eta(z) \equiv \frac{d_L(z)}{(1+z)^2 d}$$

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

Δz : measured spectroscopically

Δt : std clocks: passively evolving stellar population

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H_0 from Distance Duality Relation

Combining BAO and CC first, and then folding in SNIa, we can get a *calibration- and model-independent* estimate of the Hubble parameter:

Fabrizio Renzi (PD)

$$H_0 = \frac{1}{(1+z)^2} \frac{\left[H_0 d_L(z)\right]^{\rm SNIa}}{\left[d_A(z)\right]^{\rm BAO+CC}}$$

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Some technicalities:

- the three data set cover roughly same range, $0 \lesssim z \lesssim 2.5$, but data points are not exactly at same redshifts
- we choose the redshifts of BAO data points as reference ones, and perform **GP fit** to SNIa and CC data to get corresponding data points (including error bars), i.e. **PDFs**

H_0 from Distance Duality Relation

- at each of the 7 redshifts, we draw 10k realizations of $[H_0 d_L]^{\rm SNIe}$ and 10k realizations of $[d_A]^{\rm BAO+CC}$. We combine them together following the DDR equation to get realizations (PDFs) of H_0 at each redshift.

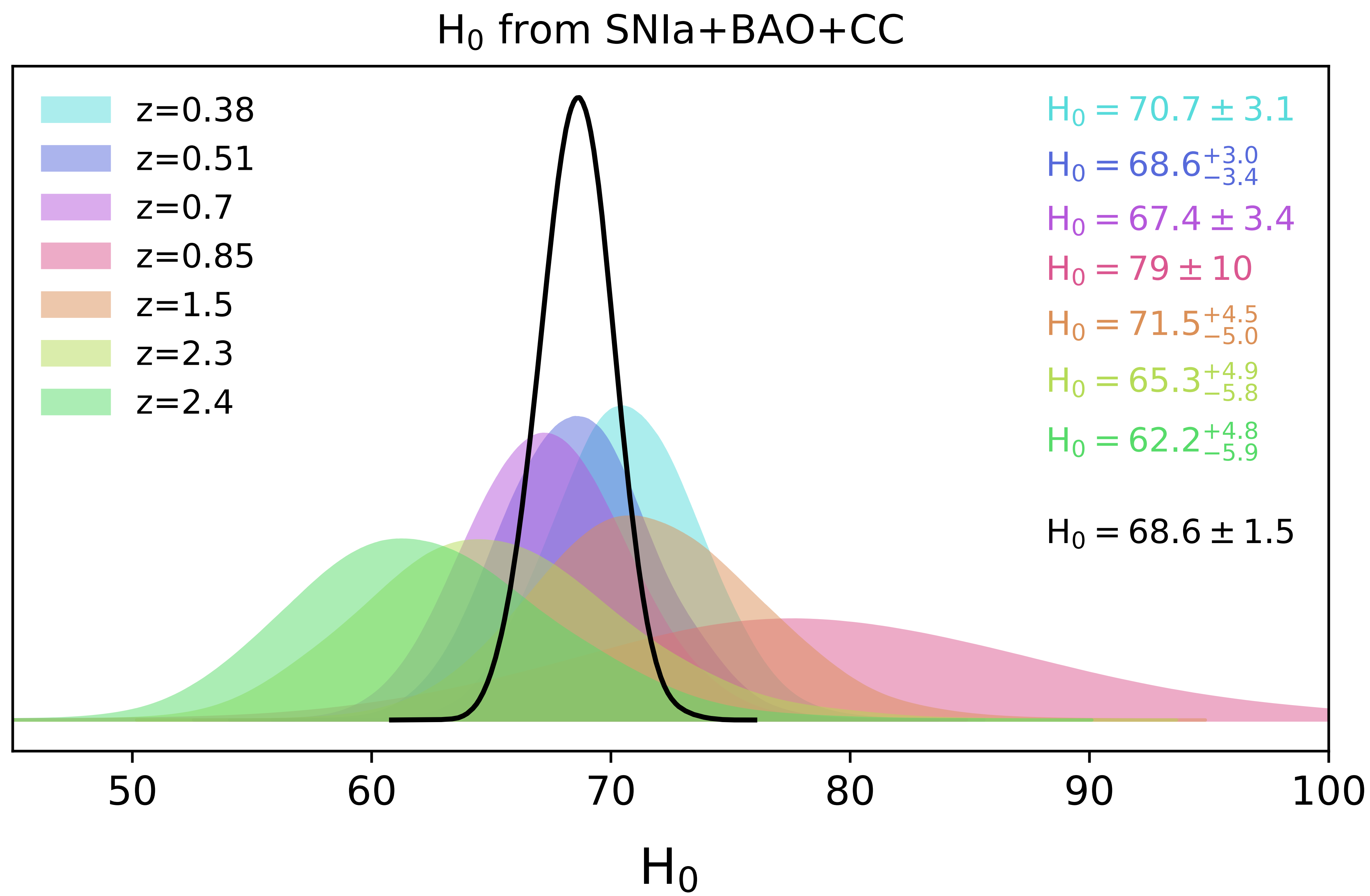
- resulting mean values are consistent within error bars, but they are different at each redshift, with two being notably lower…(next slide!)

- we finally multiply the 7 PDFs to get one PDF for H from which we can extract mean and variance using the inverse transform sampling.

- Overall the method is a combination of GP and MCMC, we refer to it as GPMC.

- It is important to highlight that we work strictly within the redshift range of the data, without performing any extrapolation.

H_0 from Distance Duality Relation



$$H_0 = 69.5 \pm 1.7 \mathrm{km/s/Mpc}$$

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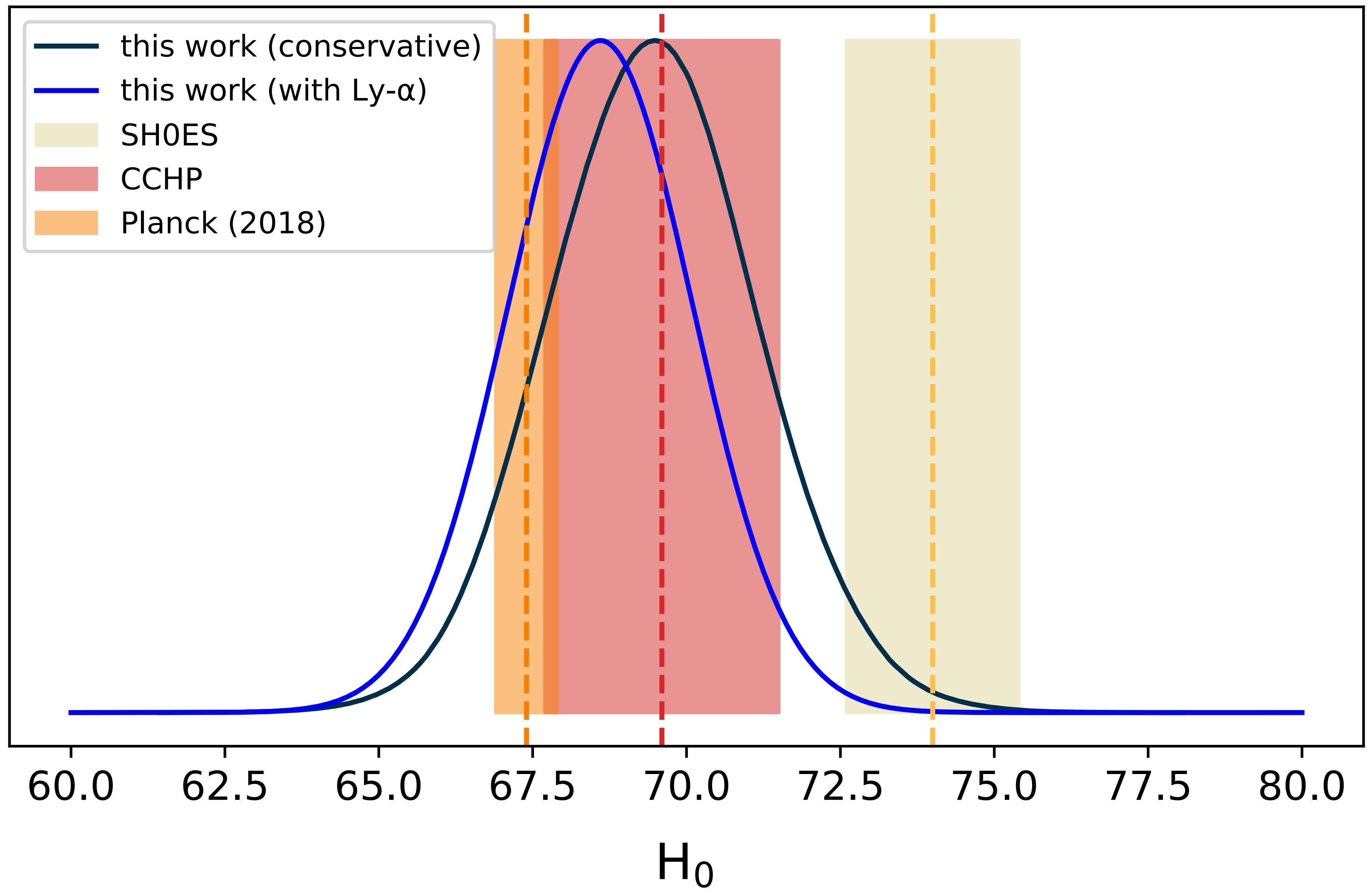

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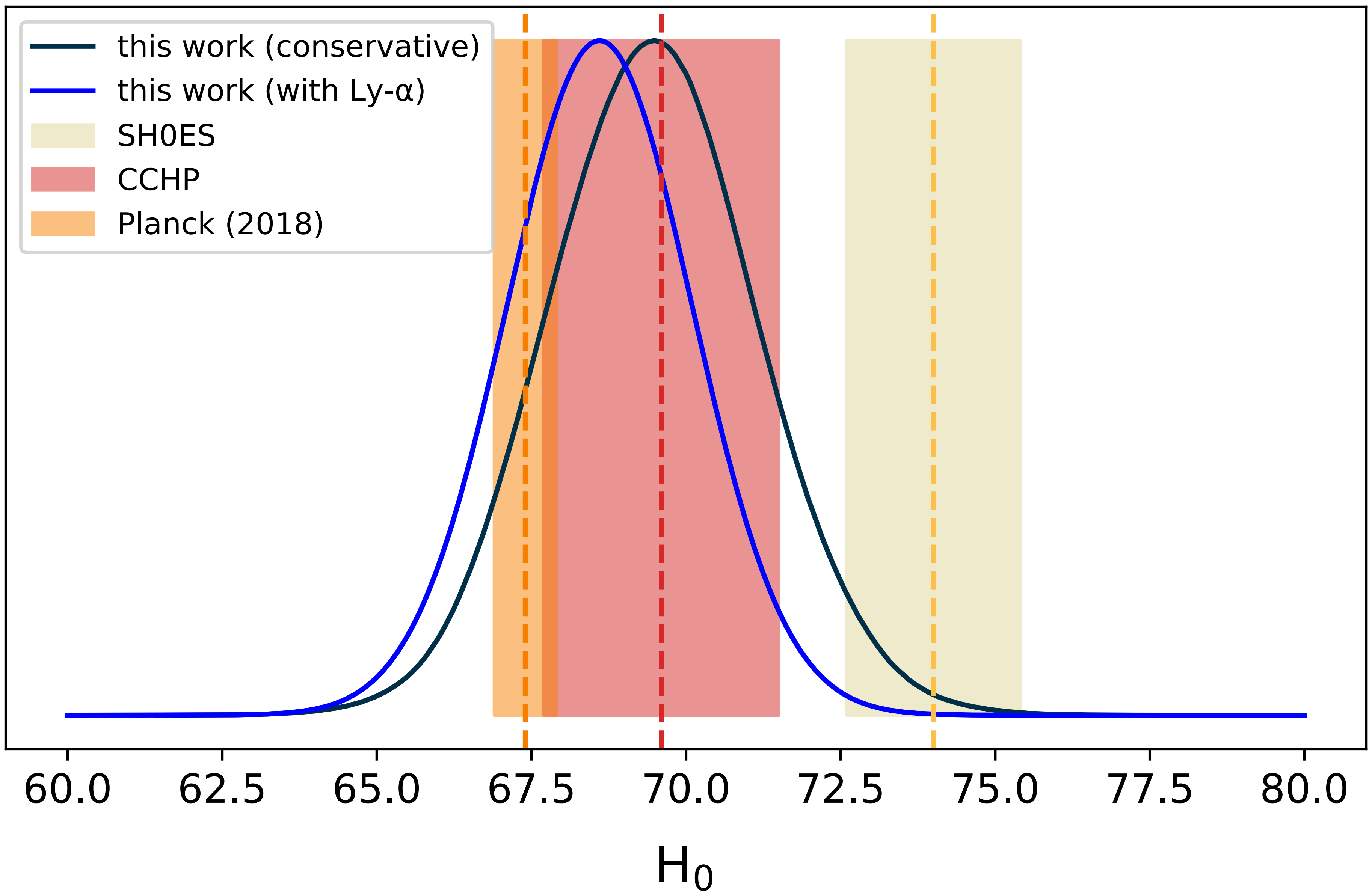
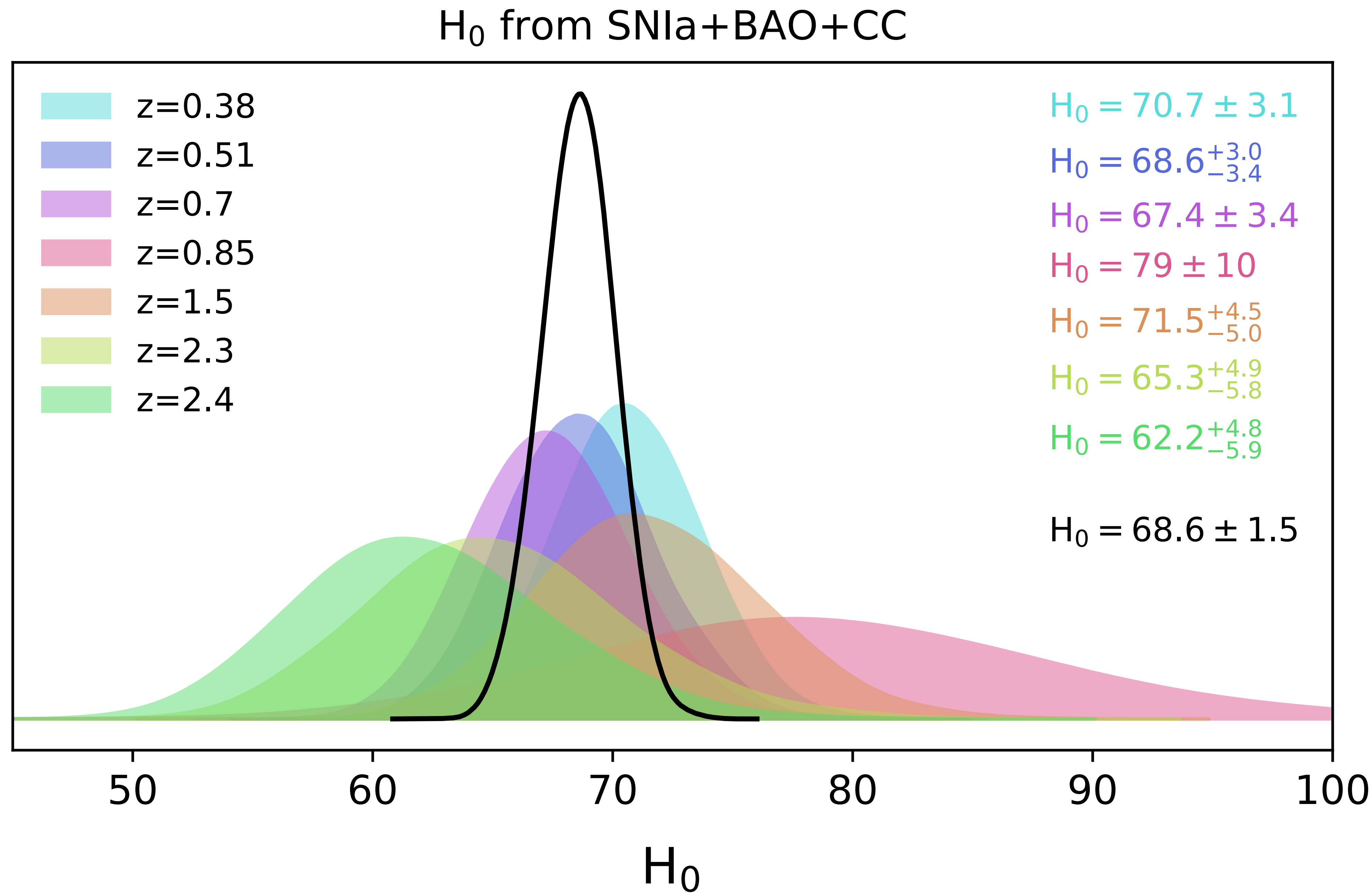


correspondingly we infer the absolute magnitude to be $M_B = -19.355 \pm 0.054$
i.e a shift of $|\delta M_B| = 0.138 \pm 0.067$ wrt SH0ES value.

in agreement with $\mu_{\mathbf{Cepheid}} - \mu_{TRGB} = -0.139 \pm 0.024$ **mag** [Efstathiou, arXiv:2007.10716]

A redshift trend in H_0?

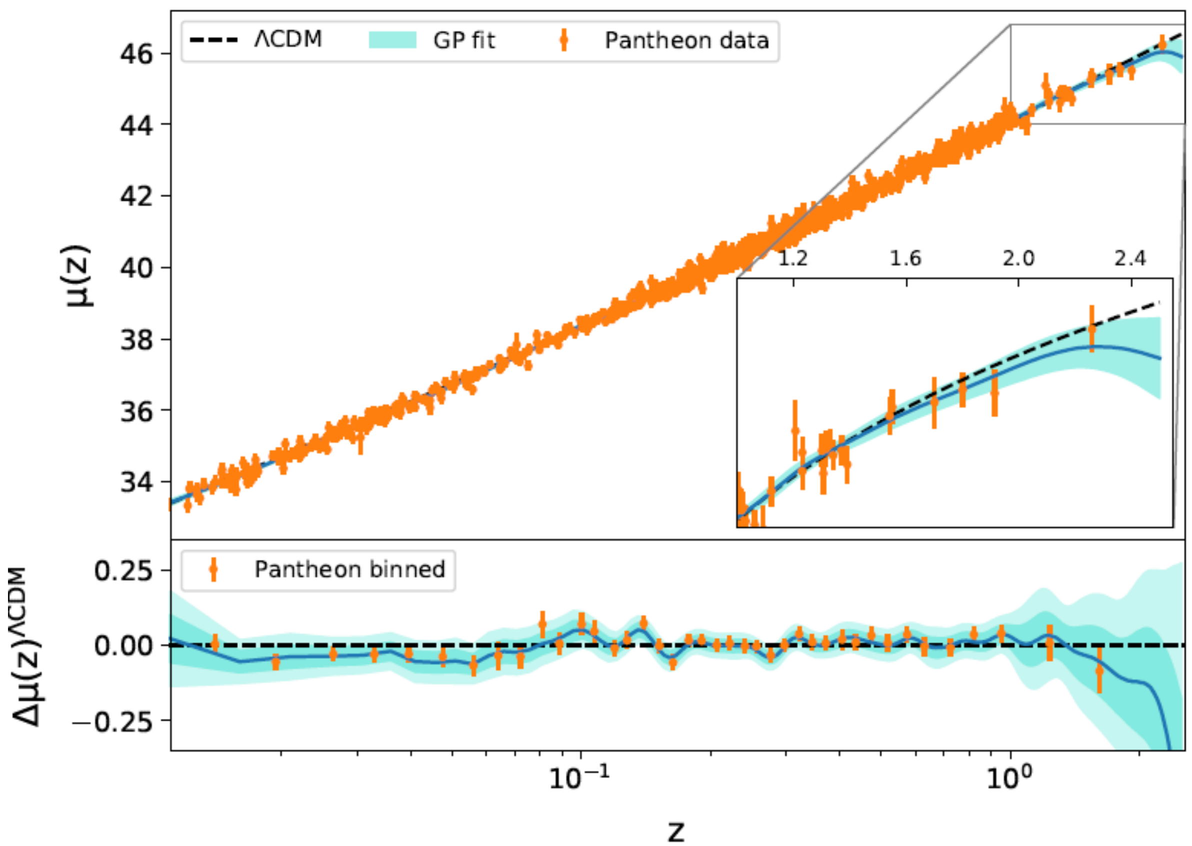


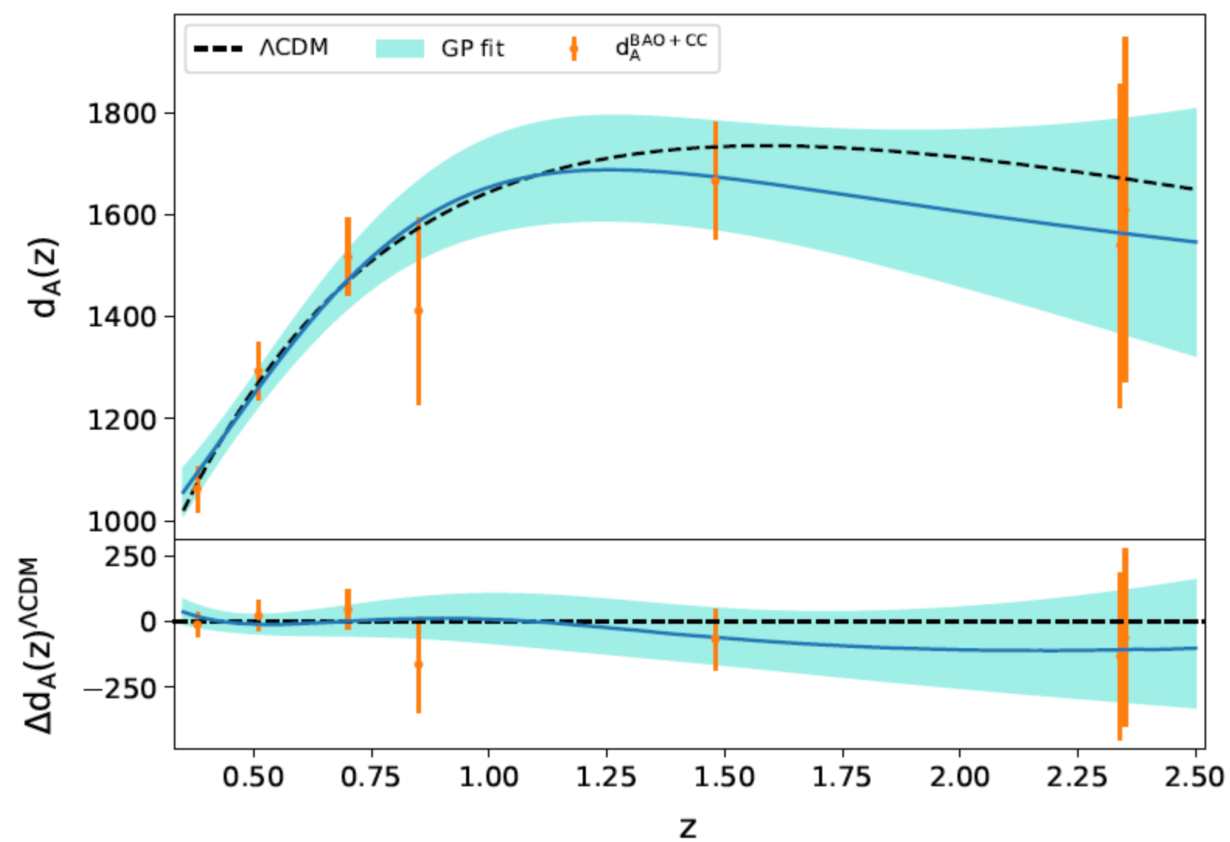
$$H_0 = 69.5 \pm 1.7 \mathrm{km/s/Mpc}$$

A redshift trend in H_0?

Assuming the validity of the DDR, is equivalent to assuming that ***the two probes are consistent tracers of cosmic expansion***.

If this was not the case, the H_0 inferred from the previous procedure would not be a constant, but it would rather show some, ***unphysical trend in redshift***.





perhaps a mild dynamical feature in H(z)