Cosmology with eBOSS

Ryan Keeley

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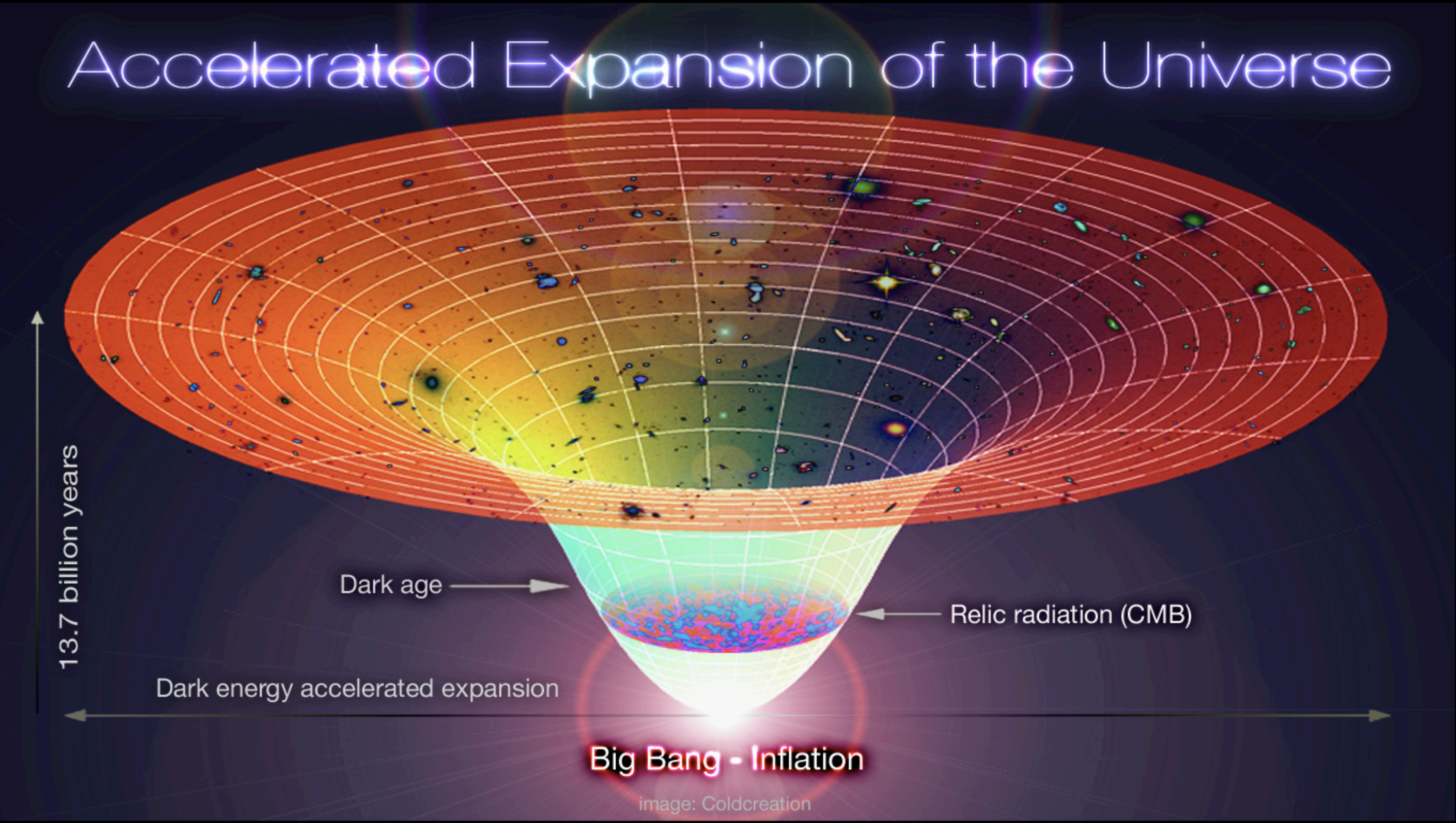
Cosmology Group at
Korea Astronomy and Space Science Institute

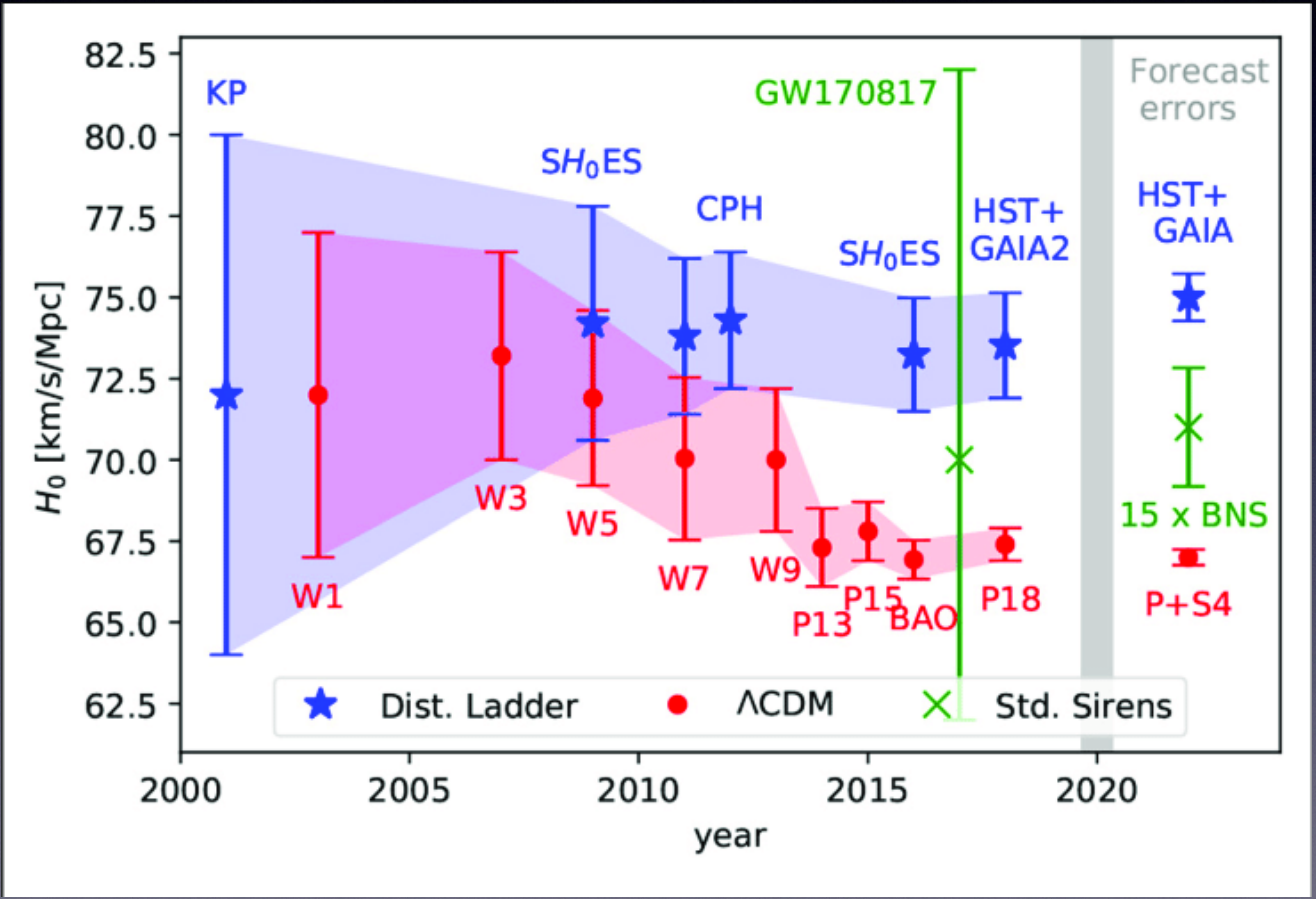
Testing the Concordance Model

- ΛCDM + GR *
- Λ - test via low-redshift distances *
- CDM - test via small scale structure
- GR - test via growth rate measurements *
- Inflation - CMB, LSS
- Testing FLRW (homogeneity + isotropy)



credit: Wikipedia Commons/Alex Mittelmann, Coldcreations

H0 Tension



- Inferences from the CMB predict H(z=0) = 67.36 +/- 0.54 km/s/Mpc
- Measuring H0 directly gives 74.03 +/- 1.42 km/s/Mpc
- Difference is now at 4.4-σ.
- No obvious systematics
- Potentially a challenge for LCDM

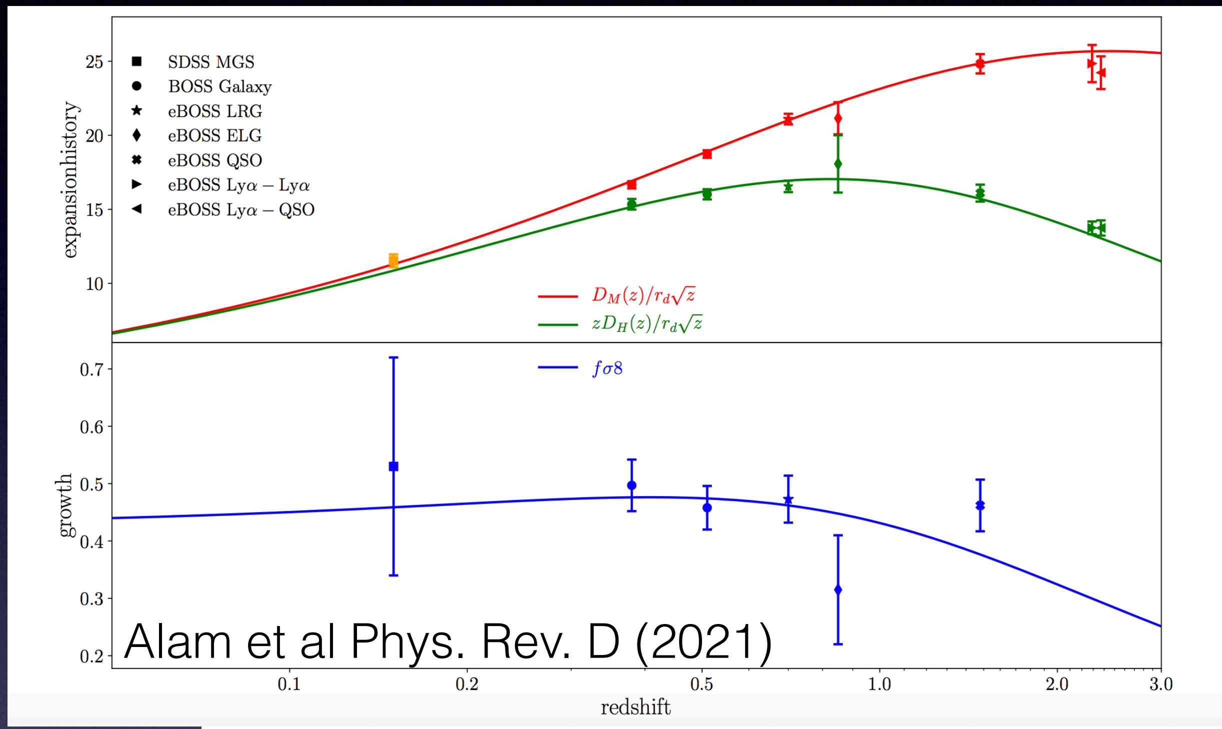
Ezquiaga et al. (2018) Arxiv:1807.09241

Case for low-z solutions

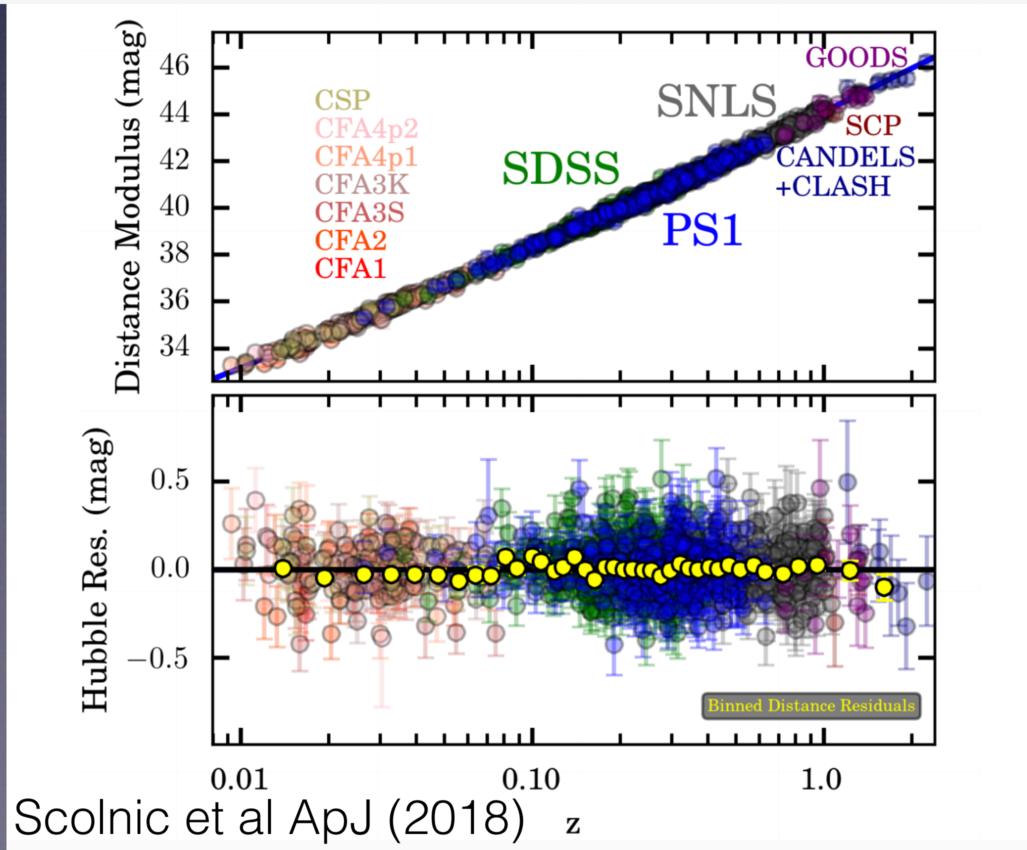
- The physics at the CMB is non-trivial
- Thus, it is natural to expect adding new physics between the CMB and today would solve the H0 tension
- Such solutions inherit the high-redshift successes of LCDM
- CMB does not measure H0 only predicts it
- The CMB only constrains H0 via the constraint on $\theta_s = r_s(z_*)/D_A(z_*)$
- Geometric degeneracy -> there exists w(z) such that the CMB is well fit and predicts any* value of H0

Guardrails

- BAO measure both DA(z) and H(z)
- 5 tracers in 7 redshift bins z~0.1 to 2.3
- The curves are predictions from just the Planck data (not fits to the eBOSS data)
- SN measure luminosity distances DL(z)
- 1048 SN from z~0.01 to 2.3
- Both datasets are unanchored and thus cannot tell which value of H0 is correct
- Can only constrain a mutual scale H0rd
- They can constrain the possible expansion histories that map between z=0 and z=z*



Alam et al Phys. Rev. D (2021)



Scolnic et al ApJ (2018)

Throwing everything at the wall

- The strategy is to throw whatever extensions to LCDM we can think of at the datasets and see if anything sticks
- Curved CPL - $w(z) = w_0 + w_a \frac{z}{1+z}$
- Chebyeshev polynomials
$$w(z) = -\sum_1^4 c_i T_i(x),\ x = \log(1+z)/\log(1+z_*)$$
- GP regression
- If these very broad cases cannot resolve the H0 tension, then we must conclude low-z physics as a whole cannot solve the H0 tension

GP

- Gaussian process - a distribution of functions characterized by a covariance function

$$\langle \gamma(s_1)\gamma(s_2)\rangle = \sigma_f^2\, e^{-(s_1-s_2)^2/(2\ell^2)}$$

- hyperparameters σ_f and ℓ control heights and lengths of the random fluctuations respectively.

GP

- An instance or a sample of a GP, $\gamma(z)$, is a hyperfunction that randomly varies around the "mean function", H_{mf} , => $H_i(z) = \gamma_i(z) H_{\mathrm{mf}}(z)$
- GP *regression* then involves training these samples based on how well they fit the data

$$P(H(z)\,|\,D) = \int d\sigma_f d\ell\, d\phi\;\; \mathscr{L}(D\,|\,H(z)(\sigma_f, \ell\,, \phi))\;\; P(\sigma_f, \ell\,, \phi)/P(D)$$

Testing LCDM via GP Hyperparameters

- These sort of tests can be performed because the hyperparameters of the GP regression encode information about whether the mean function is a good fit to the data

- i.e. how much information beyond the mean function is required to fit the data

- This test is performed by calculating the posterior of the hyperparameters to see if sigma_f, the parameter that describes the heights of the fluctuations in the GP, is consistent with 0 or not

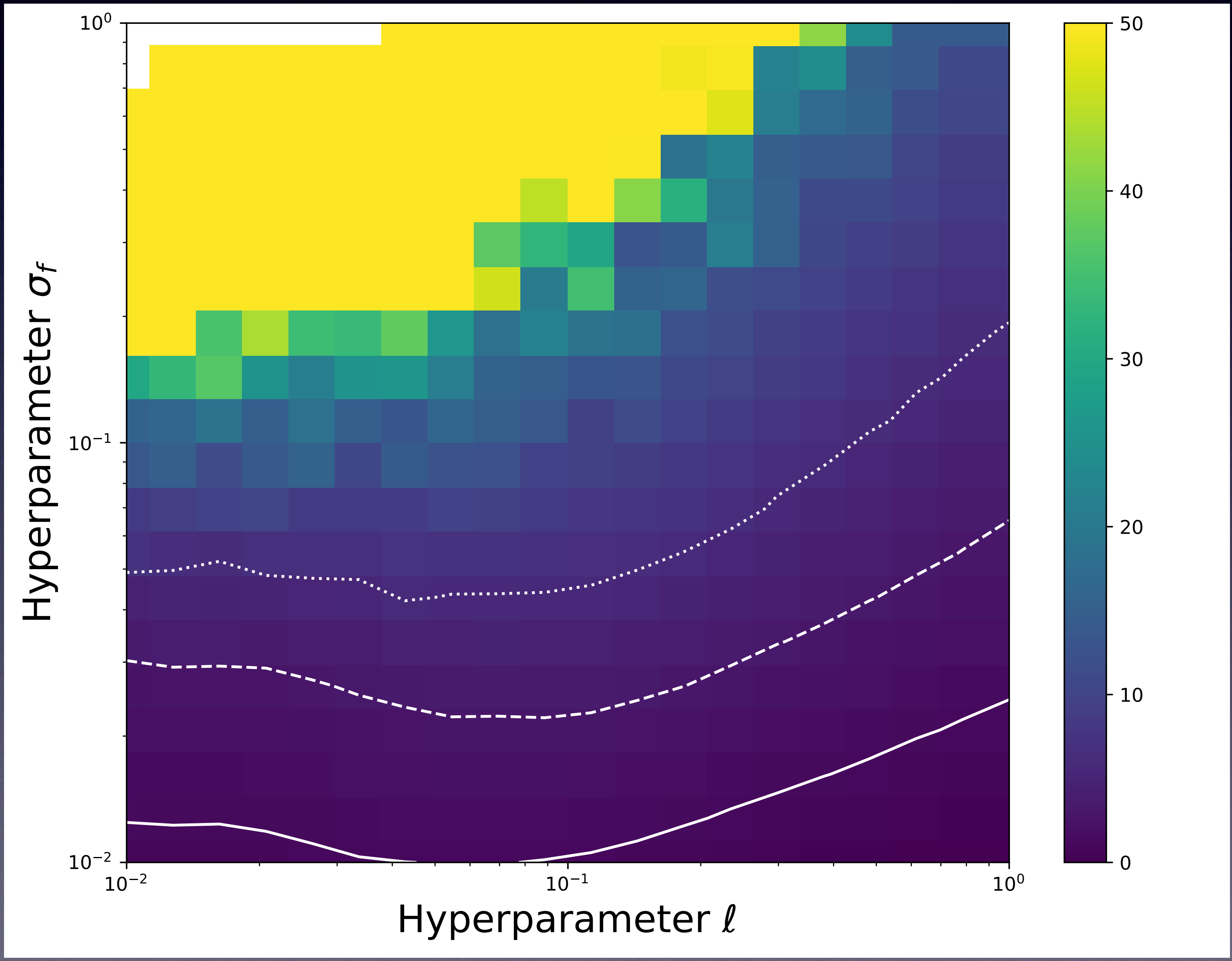
- If sigma_f > 0 then, data need more flexibility than the given mean function

- If mean function standard model, the GP can test if the standard model is sufficient

Shafieloo A., Kim A. G., Linder E. V., 2012, Phys. Rev. D
Keeley, Shafieloo, L'Huillier, Linder MNRAS (2020)

Consistency with LCDM

- Hyperparameters of GP reconstruction
- Data : Pantheon SN and SDSS BAO
- Mean function : best fit LCDM to both data sets
- sigma_f = 0 according to the data
- Therefore LCDM is consistent with the joint datasets



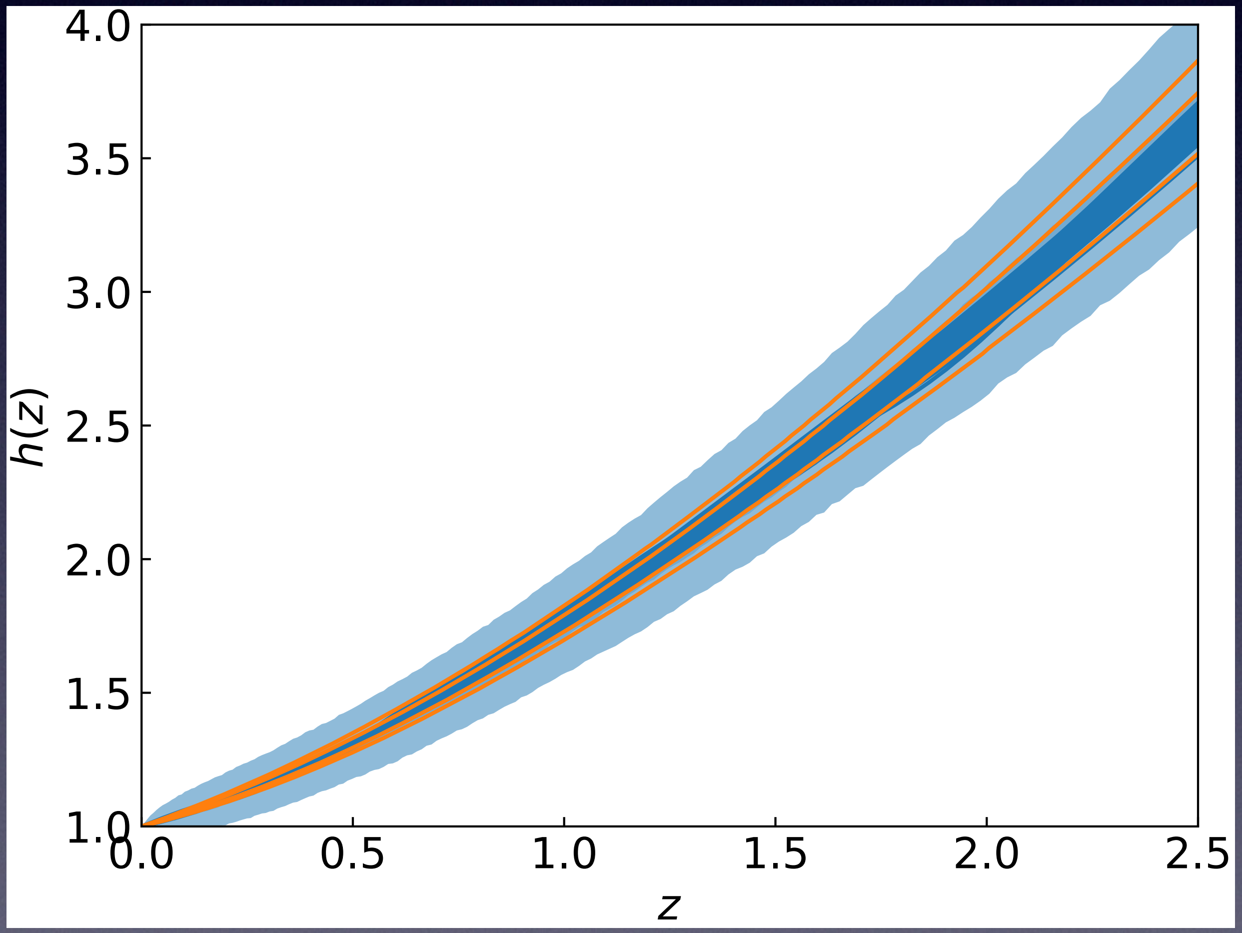
Keeley, Shafieloo, Zhao et al AJ 2021, arxiv:2010.03234

Model independent reconstruction of expansion history

$$h(z) = H(z)/H_0$$

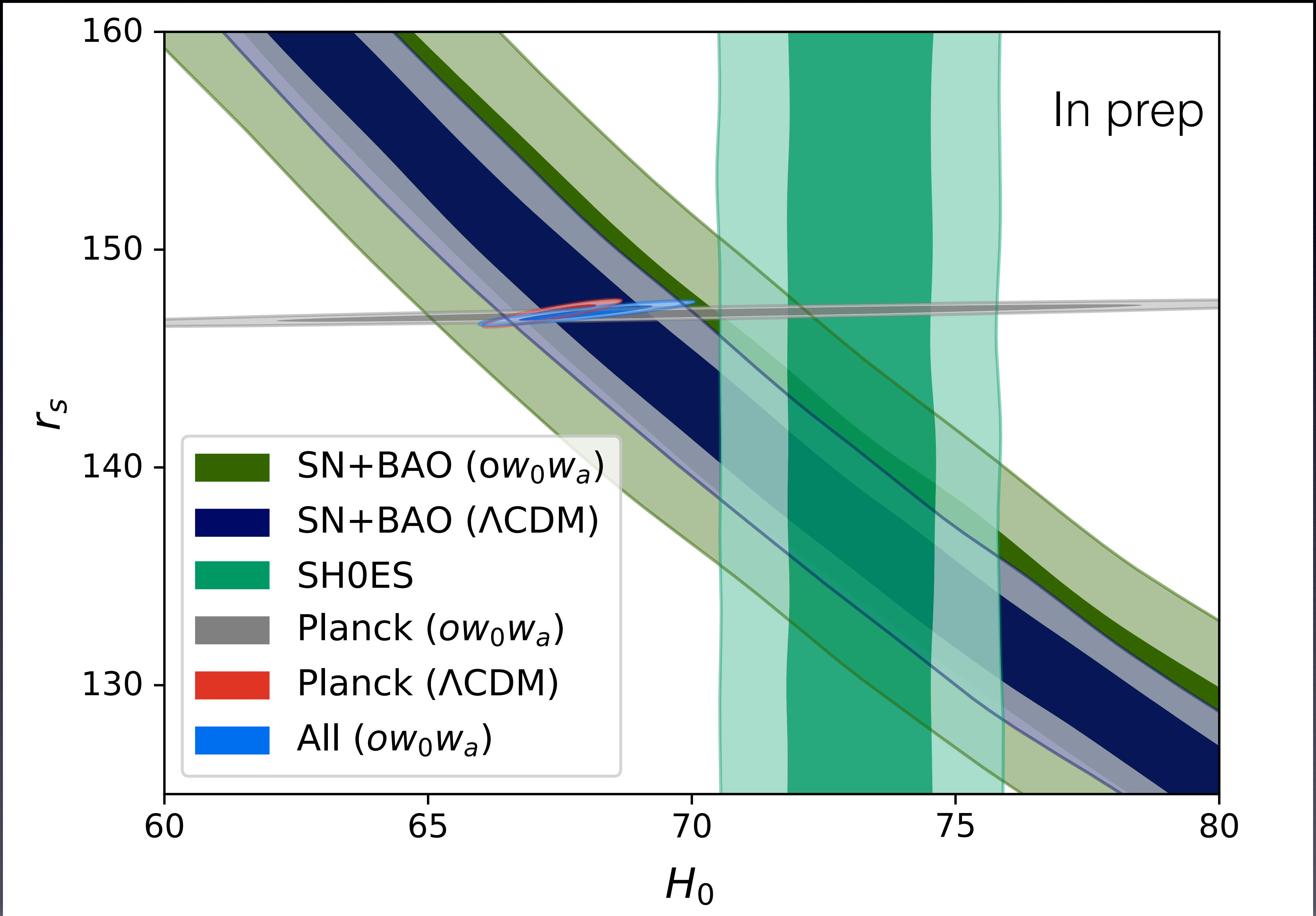
- Orange - 68% and 95% CLs for LCDM

- Blue - Bands - 68% and 95% CLs; Lines - example GP reconstruction samples that have a better chi^2 than the best-fit LCDM



Keeley, Shafieloo, Zhao et al AJ 2021, arxiv:2010.03234

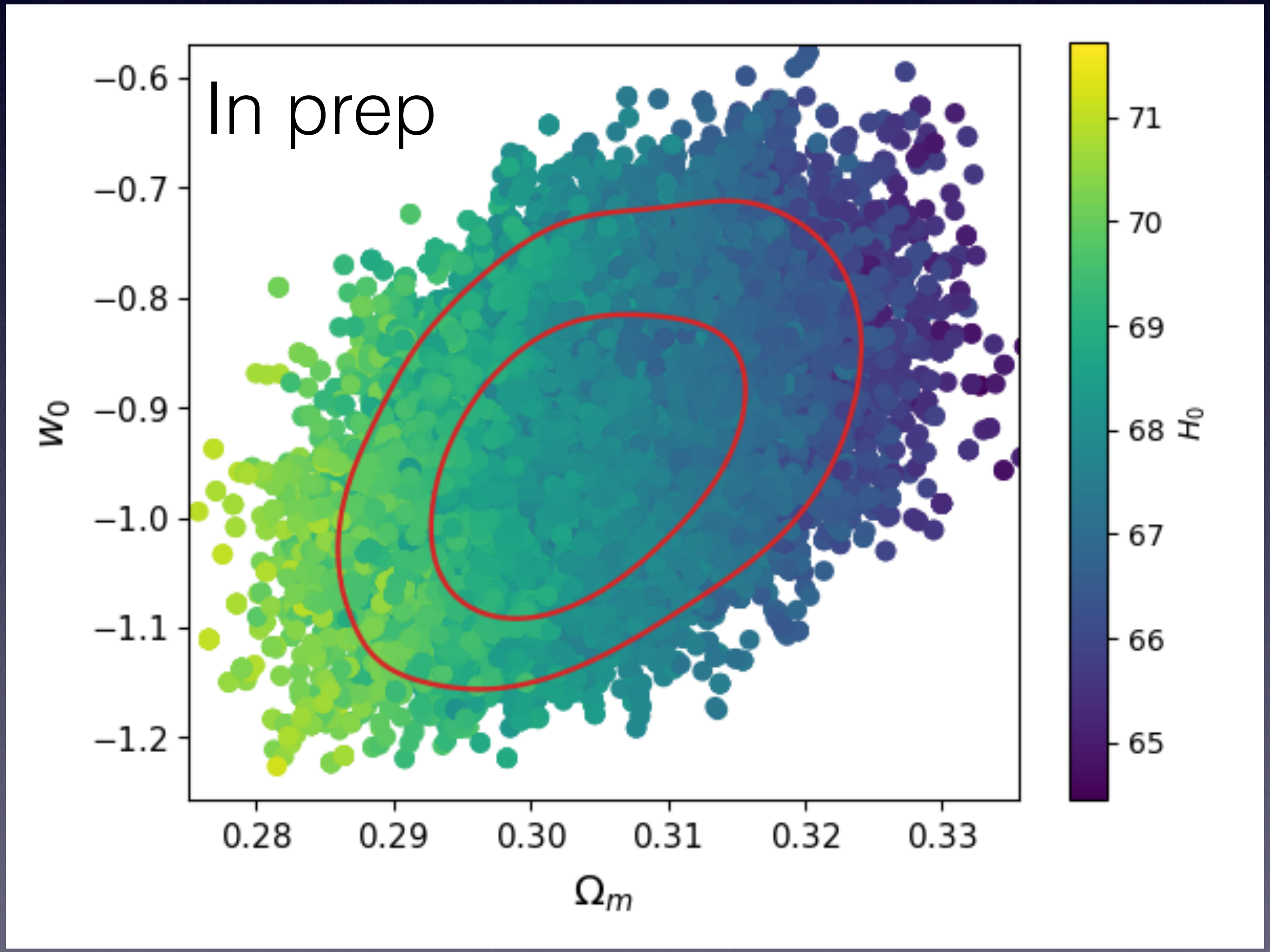
Tension Triangles



Keeley et al PRL 2021 in prep.

Correlations

- Data: CMB+BAO+SN
- Colorbar: H0
- Correlation between H0 and Om is simple primarily from Omh^2
- Correlation between w0 and H0 comes from theta_s



Keeley et al PRL 2021 in prep.

Conclusions

- SN+BAO alone have large degeneracies in extended parameter spaces
- CMB alone has large degeneracies in extended parameter spaces
- BAO and SN are completely consistent with each other (in extended parameter spaces) and with LCDM
- BAO+SN are broadly consistent with Planck, even in extended parameter spaces
- No preference for curvature / evolving DE, but large swaths of parameter space are still allowed
- BAO+SN+CMB are in stark tension with SH0ES H0, even in extended parameter spaces
- Taken all together, new low-redshift physics cannot solve the H0 tension