Testing $\Lambda$CDM with eBOSS

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Marcel Grossman 2021
Testing the Concordance Model

• $\Lambda$CDM + GR *

• $\Lambda$ - test via low-redshift distances *

• CDM - test via small scale structure

• GR - test via growth rate measurements *

• Inflation - CMB, LSS

• Testing FLRW (homogeneity + isotropy)
Inferences from the CMB predict $H(z=0) = 67.36 \pm 0.54 \text{ km/s/Mpc}$

Measuring $H_0$ directly gives $74.03 \pm 1.42 \text{ km/s/Mpc}$

Difference is now at 4.4-$\sigma$.

No obvious systematics

Potentially a challenge for LCDM

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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 $z\sim 0.1$ 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 $z\sim 0.01$ to 2.3

• Both datasets are unanchored and thus cannot tell which value of $H_0$ is correct

• Can only constrain a mutual scale $H_0 r_d$

• They can constrain the possible expansion histories that map between $z=0$ and $z=z^*$

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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 - $w(z) = w_0 + w_a \frac{z}{1 + z}$

- Chebyshev polynomials
  $$w(z) = - \sum_{i=1}^{4} c_i T_i(x), \quad x = \log(1 + z)/\log(1 + z_*)$$

- 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 $\sigma_f$ and $\ell$ 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”, $H_{mf}$, $\Rightarrow H_i(z) = \gamma_i(z)H_{mf}(z)$

- GP regression then involves training these samples based on how well they fit the data

$$P(H(z)|D) = \int d\sigma_f d\ell d\phi \mathcal{L}(D|H(z)(\sigma_f, \ell, \phi)) \frac{P(\sigma_f, \ell, \phi)}{P(D)}$$
Testing $\Lambda$CDM 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

Consistency with $\Lambda$CDM

- 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

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Model independent reconstruction of expansion history

\[ h(z) = \frac{H(z)}{H_0} \]

- 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 (in prep.)

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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

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Keeley et al (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