Tension between early and late Universe expansion measurements

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H_0 tension in ΛCDM

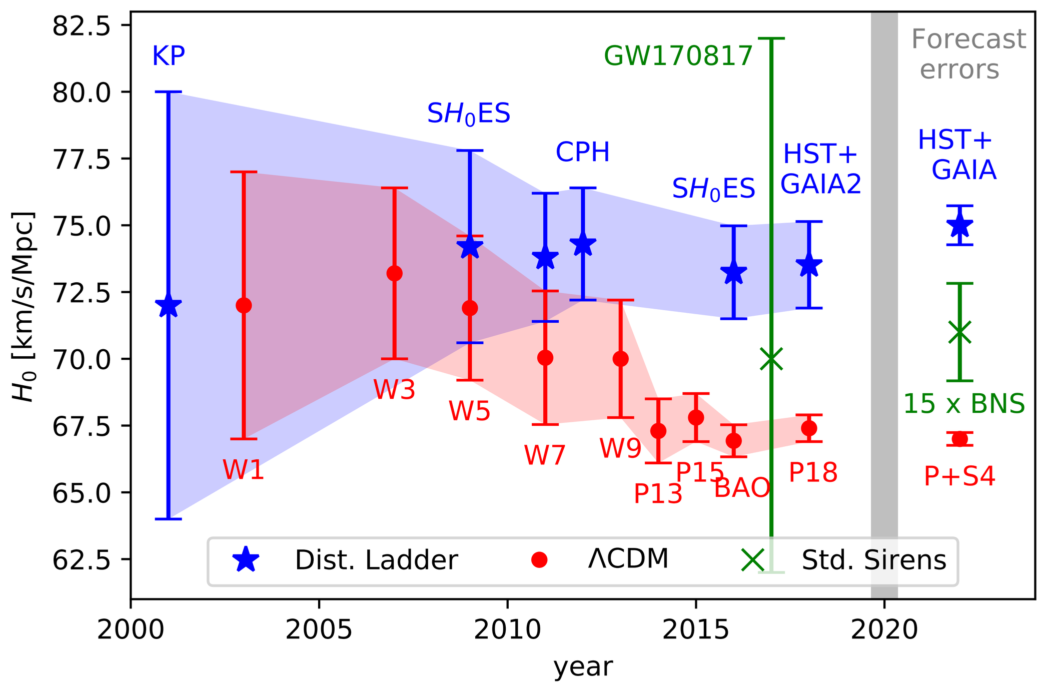


Figure 1: History of the Hubble parameter estimate with different probes: distance ladder calibrated supernovae estimates (SNe) are shown in blue, cosmic microwave background (CMB) and baryonic acoustic oscillations (BAO) in red, and gravitational waves in green [1]

Improved precision of cosmological probe measurements uncovered significant discordance between two distinguishable groups in the last decade. Nowadays estimate of the Hubble parameter for standard cosmological model (ΛCDM) obtained with constraints related to early universe perturbations of matter density (CMB, BAO) is in tension with measurements based on local calibrations with a statistical significance level of **5.3 σ** [2] and even higher [3].

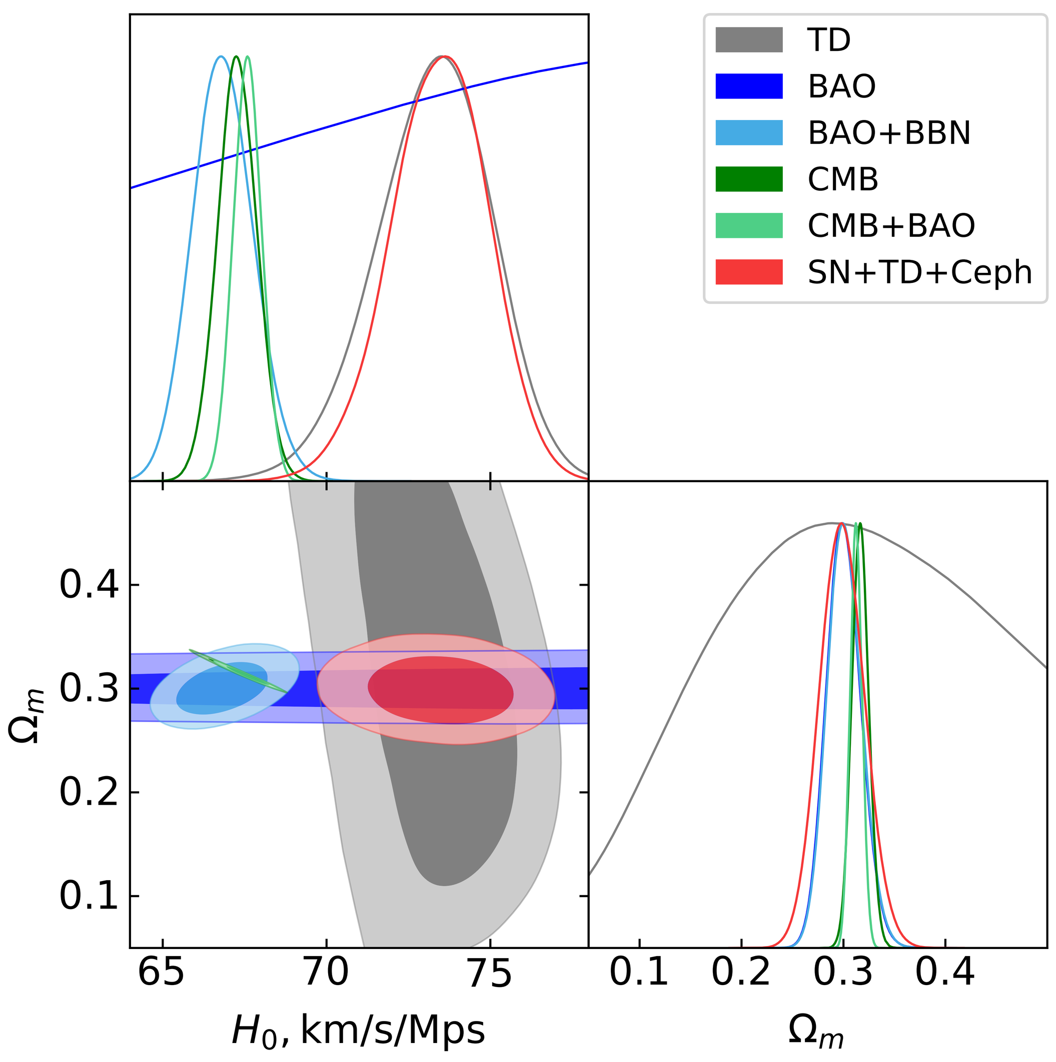


Figure 2: ΛCDM model parameter constraints obtained with TD, BAO, CMB, Big Bang Nucleosynthesis (BBN), and SNe calibrated with Cepheids

This tension is present only in the absolute expansion rate estimate and is not related to the shape of its evolution characterised only by the matter density parameter in the ΛCDM. Therefore, it can be a result of the **systematic errors in absolute distance calibration**:

- calibration of SNe brightness;
- calibration of sound horizon radius at recombination epoch;
- systematic errors in treatment of CMB foreground;
- local dynamic effects;
- the impact of fiducial cosmology.

On the other hand, it can be evidence for the new **physics beyond ΛCDM**. In this scenario, tension could be reduced by cosmological model extensions.

Extensions of the standard model

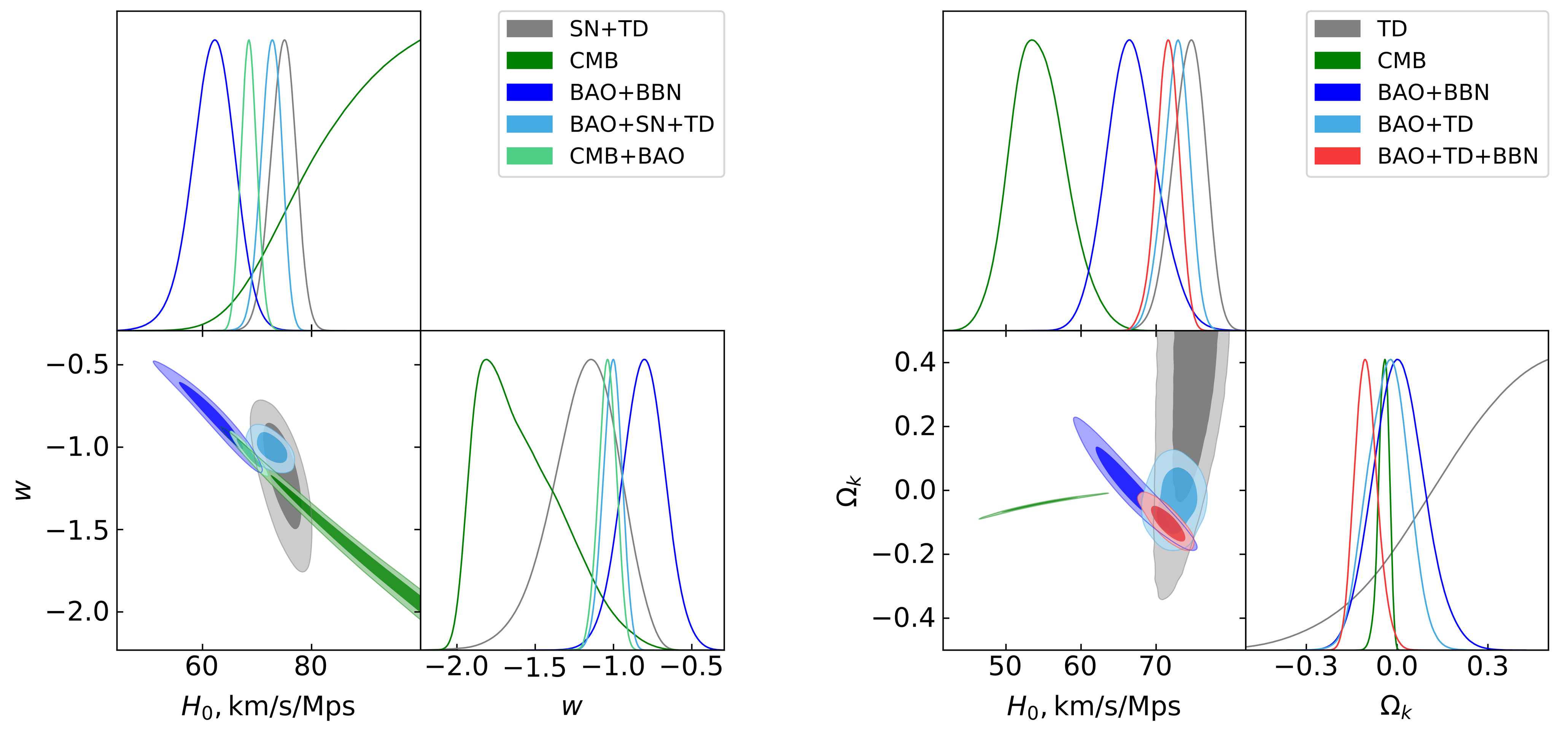


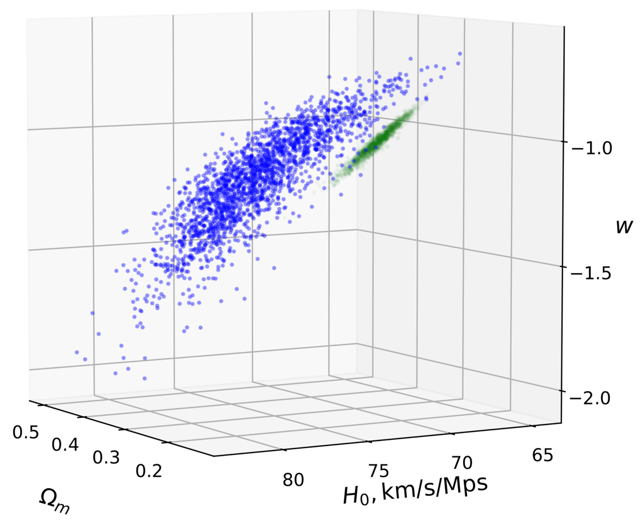
Figure 3: Two-dimensional marginalised cosmological parameter constrains on wCDM (left) and kΛCDM (right) models obtained with different probes and their combinations

Although the posterior distribution of parameter estimates in the case of extended models feature strong degeneracy and therefore weaker constraints on parameters, the discordance between cosmological probes is still present.

***w*CDM** model considers dark energy with a constant equation of state but different from vacuum energy. In this scenario, early universe probe degeneracy is defined by a constant scale of a sound horizon radius at recombination epoch which is completely degenerate in $w - H_0$ parameter projection. However, the line of sight component of the BAO probe breaks this degeneracy. Due to the difference between time-delay and luminosity distance degeneracies, TD and SN probes also complement each other. Discordance between these two combinations of probes is at level of **2.8σ** statistical significance and can be increased by the inclusion of Cepheid calibration of SNe.

kΛCDM model allows the presence of spacial curvature in the universe. For this model, CMB shows evidence of universe with positive curvature with 2-3σ statistical significance (depends on foreground cleaning procedures) while all other probes separately show no evidence for spatial curvature. This model is excluded because it shows **4σ** tension between two Early universe probes. This result was a reason for the recent discussion about present systematics in the CMB probe.

Tension estimation and degeneracy



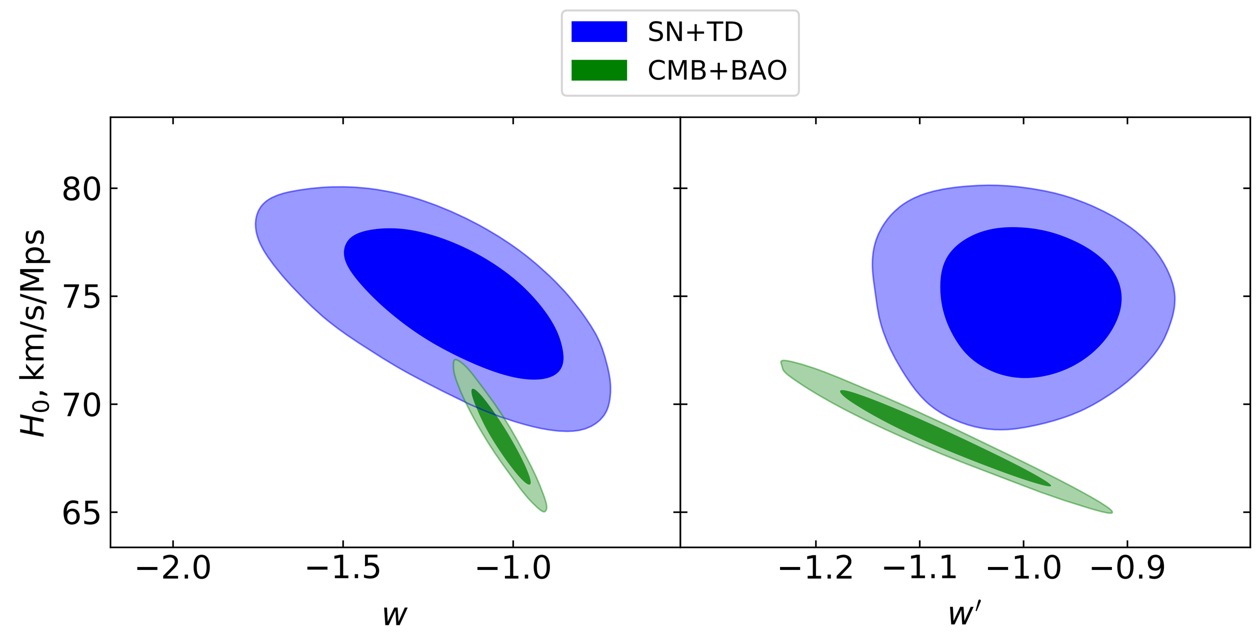


Figure 4: Non-trivial projection of wCDM parameter space that represents present degeneracy and tension between cosmological probes (scan QR-code for 3d view)

Figure 5: 2d-projection of parameter constraints on wCDM model in case of classical parametrization (left) and optimized for least degeneracy (right)

Even in such simple extensions analysis of parameter estimate discordance is complicated by present degeneracies. Currently used inconsistency estimators are correctly applicable only for Gaussian distributions [4]. This problem can be solved with different dimensionality reduction techniques. Here I show an example of a simple parameter change, that simplifies SN+TD degeneracy hypersurface to almost Gaussian 3-dimensional distribution. This change of parameter increases the estimate of tension between two probes to the level of **3.2σ**

Outlook

Currently, I am studying **1)** the impact of reddening and **2)** systematics in the Color-Period-Luminosity relation of Cepheids on the calibration of SNe absolute brightness and **3)** working on obtaining constraints for more extended models (e.g. early dark energy model). The next step of my research is to **4)** extend the reduction of the present observable degeneracies in more complicated models.

References

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[5] E. Di Valentino, A. Melchiorri, and J. Silk, Nature Astronomy, vol. 4,pp. 196–203, Feb. 2020

3D plots

Scan this QR-code for animated and interactive 3d-plots with parameter posterior distribution for wCDM and kΛCDM models