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Cosmology intertwined III: $f\sigma_8$ and S_8

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ABSTRACT

The standard Λ Cold Dark Matter cosmological model provides a wonderful fit to current cosmological data, but a few statistically significant tensions and anomalies were found in the latest data analyses. While these anomalies could be due to the presence of systematic errors in the experiments, they could also indicate the need for new physics beyond the standard model. In this Letter of Interest we focus on the tension between Planck data and weak lensing measurements and redshift surveys, in the value of the matter energy density Ω_m and the amplitude σ_8 (or the growth rate $f\sigma_8$) of cosmic structure. We list a few promising models for solving this tension, and discuss the importance of trying to fit multiple cosmological datasets with complete physical models, rather than fitting individual datasets with a few handpicked theoretical parameters.

1. The S_8 tension

The standard Λ Cold Dark Matter (ΛCDM) cosmological model provides an excellent fit to current cosmological data. However, some statistically-significant tensions in cosmological parameter estimates emerged between the Planck experiment, measuring the Cosmic Microwave Background (CMB) anisotropies, and other low-redshift cosmological probes. In addition to the long standing *Hubble constant* H_0 disagreement, a tension of the Planck data with weak lensing measurements and redshift surveys has been reported, in the value of the matter energy density Ω_m and the amplitude σ_8 (or the growth rate $f\sigma_8$) of cosmic structure. Although this tension could be due to systematic errors, it is worthwhile to investigate the possibility of new physics beyond the standard model. The tension can be readily visualized in the σ_8 vs. Ω_m plane (see Fig. 1) and is often quantified using the $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$ parameter, which is a combination of Ω_m and σ_8 that is well determined by weak lensing. This tension can be also related to $f\sigma_8(z=0)$, measured by galaxy redshift space distortions (RSD) [1,2], where $f=[\Omega_m(z)]^{0.55}$ approximates the growth rate.

The mismatch between the high S_8 value estimated by Planck assuming ΛCDM (grey contour in Fig. 1), $S_8 = 0.834 \pm 0.016$[1] and the lower value preferred by cosmic shear measurements, is known as the S_8 tension. This tension is above the 2σ level with KiDS-450 [4–7] ($S_8 = 0.745 \pm 0.039$), KiDS-450 + 2dFLenS [8] ($S_8 = 0.742 \pm 0.035$), with KiDS + VIKING-450 (KV450) [9] ($S_8 = 0.737^{+0.040}_{-0.036}$), with DES [10,11] ($S_8 = 0.783^{+0.021}_{-0.025}$), and with CFHTLenS [12–14]. Recently, KiDS-1000 [3] reported a $\sim 3\sigma$ tension ($S_8 = 0.766^{+0.020}_{-0.014}$, red contour in Fig. 1) with Planck. When cosmic shear is combined with galaxy clustering, the degeneracy between σ_8 and Ω_m is broken, but the tension remains. Therefore, the combined analysis helps in pointing out that the tension, at 3.1σ in this case, is driven by σ_8 rather than Ω_m. In addition, there is the Lyman-α result [15], a late time probe covering scales similar to weak lensing, completely in agreement with a lower S_8 value and in tension at $\sim 2.6\sigma$ with Planck. The tension becomes 3.2σ if we consider the combination of KV450 and DES-Y1 [16,17] or 3.4σ for BOSS + KV450 [18] ($S_8 = 0.728 \pm 0.026$, blue contour in Fig. 1). Preferring a higher value for the S_8 parameter is also the measurement from the first-year data of HSC SSP [19], for which $S_8 = 0.804^{+0.032}_{-0.029}$ (see Fig. 2), but also KiDS-450 + GAMA [20] finding $S_8 = 0.800^{+0.029}_{-0.027}$. Finally, the BOSS Galaxy Power Spectrum [21] measurement agrees with a lower value, $S_8 = 0.703 \pm 0.045$.

It has been pointed out in [22] that this tension could be related to the excess of lensing measured by Planck, pushing toward a larger S_8. However, ACT + WMAP [23] also find a large $S_8 = 0.840 \pm 0.030$ even though they do not find a large lensing amplitude, while SPTpol [24] and the Planck CMB lensing [25] measurements prefer a lower value of S_8. It is worth mentioning that, while weak lensing analyses are carried out with a blinding

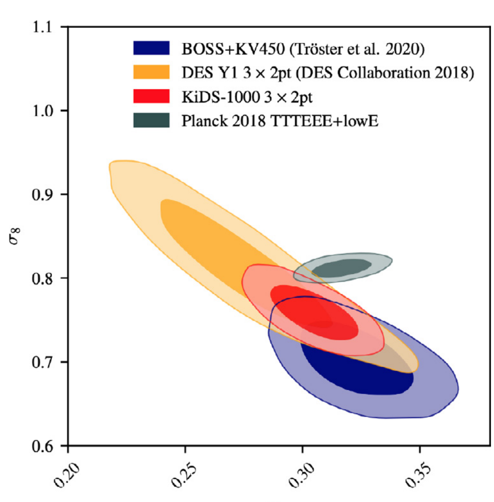

Fig. 1. 68% CL and 95% CL contour plots for σ_8 and Ω_m(from Ref. [3]).

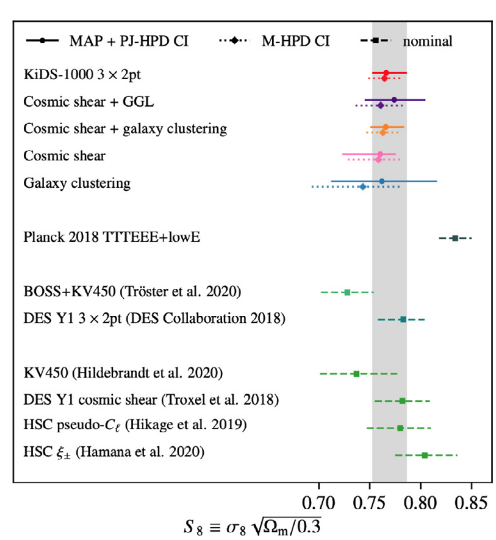

Fig. 2. Whisker plot showing the 68% error bars on S_8 (from Ref. [3]).

[1] All the bounds are reported at 68% confidence level in the text.

procedure implemented in KiDS, DES and HSC, the CMB analyses are either not blind or only partially blind.

2. Conjoined history problem

The H_0 disagreement is correlated with the σ_8 problem. Indeed the solutions proposed to alleviate the former, are exacerbating the S_8 problem and, consequently, the σ_8 tension between the CMB and the more direct measurements, such as galaxy clusters using the Sunyaev-Zel'dovich effect [26–28], i.e. measuring the number of clusters of a certain mass M over a range of redshift. For example, late time transitions that predict a higher H_0 value, if they match the CMB data, also prefer a lower Ω_m, to preserve the well measured value of $\Omega_m h^2$. Such models produce a modification of distances to sources, the growth of structure, and of the sound horizon and CMB anisotropies [29], and usually result in a higher σ_8 than in ΛCDM because of an extended era of matter domination. However, early-time dark energy solutions of the H_0 tension also increase σ_8 because they need a higher primordial curvature perturbation amplitude to offset the damping effect of the unclustered component. Therefore, because of these mutual correlations, it is important to perform a joint analysis, fitting with a single model a full array of data [30–33], and not just one parameter alone. At the same time, if a model solves the S_8 tension (the $z = 0$ value), the growth history at different redshifts, by plotting $f\sigma_8(z)$ directly against $H(z)$, should be checked [34,35]. Hence, any solution to the S_8 tension should pass other cosmological tests, i.e. it should simultaneously fit the expansion and growth histories probed by Baryon Acoustic Oscillations (BAO), RSD-lensing cross correlations, galaxy power spectrum shape and void measurements [36].

3. Solutions

There are many papers investigating the S_8 tension [22,37–68], but the solutions proposed are not enough to make all the cosmological data mutually consistent [69–71]. We can distinguish the following categories of solutions:

- Axion monodromy inflation [57].
- Extended parameter spaces [22,38,39,41,42] with $A_L > 1$ [72], i.e. using the phenomenological lensing parameter as a consistency check and determining whether it is different from unity [73].
- Active and sterile neutrinos [55,56].
- Interacting dark energy models, where the energy flows from the dark matter to the dark energy [43,44].
- Decaying dark matter [63,64,74,75], or cannibal dark matter [65].
- Minimally and non-minimally coupled scalar field models as possible alternatives for dark energy [51].
- Modified Gravity models [52,53,76,77].
- Running vacuum models in which $\Lambda = \Lambda(H)$ is an affine power-law function of the Hubble rate [45,46,78–83].
- Quartessence, a single dark component mimicking both dark matter and dark energy [48].

4. Future

In the near future, we expect percent-level measurements of the expansion and growth history from a large range of experiments, i.e. using maps of the Universe obtained by the Euclid satellite, measuring the peculiar motions of galaxies using Type Ia supernovae from LSST [84,85], mapping out RSD with DESI and 4MOST, or using voids [36]. An important role will be played by the SKA telescopes performing BAO surveys and measuring weak gravitational lensing using 21 cm intensity mapping [86–88]. Additional upcoming 21 cm neutral hydrogen experiments measuring the expansion history will be CHIME and HIRAX. Finally, line-intensity mapping from star-forming galaxies can be used to measure the BAO, reaching percent-level constraints [89,90] with the SPHEREx satellite or the ground-based COMAP instrument. All of these efforts will either reveal a systematic-error cause or sharpen the tension to strong statistical significance informing the theories mentioned above and guiding any extension/overhaul of the standard model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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