Snowmass2021 - Letter of Interest

Cosmology Intertwined III: $f\sigma_8$ and S_8

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The standard Λ Cold Dark Matter cosmological model provides a wonderful fit to current cosmological data, but a few tensions and anomalies became statistically significant with 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 of the Planck data with weak lensing measurements and redshift surveys, about the value of the matter energy density Ω_m, and the amplitude or rate of the growth of structure ($\sigma_8, f\sigma_8$). We list a few interesting models for solving this tension, and we discuss the importance of trying to fit with a single model a full array of data and not just one parameter at a time.

The S_8 tension – The standard Λ Cold Dark Matter (ΛCDM) cosmological model provides an amazing fit to current cosmological data. However, some statistically-significant tensions in cosmological parameter estimations 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, about the value of the matter energy density Ω_m, and the amplitude or rate of growth of structure ($\sigma_8, f\sigma_8$). 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 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, along the main degeneracy direction of weak lensing measurements. This 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, it is known as the S_8 tension. This tension is above the 2σ level with KiDS-450[4–7] ($S_8 = 0.745 \pm 0.039$) and 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. This is already obvious from cosmic shear alone[15], but when combined with galaxy clustering, the degeneracy breaking between σ_8 and Ω_m does not change the tension level. 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[16], a late time probe probing 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[17;18] or 3.4σ for BOSS+KV450[19] ($S_8 = 0.728 \pm 0.026$, blue contour in Fig. 1). Preferring a higher value for the S_8 parameter there is also the measurement from the first-year data of HSC SSP[20], for which $S_8 = 0.804^{+0.032}_{-0.029}$ (see Fig. 2), but also KiDS-450+GAMA[21] finding $S_8 = 0.800^{+0.029}_{-0.027}$. Finally, in agreement with a lower value $S_8 = 0.703 \pm 0.045$ there is an estimate from the BOSS Galaxy Power Spectrum[22].

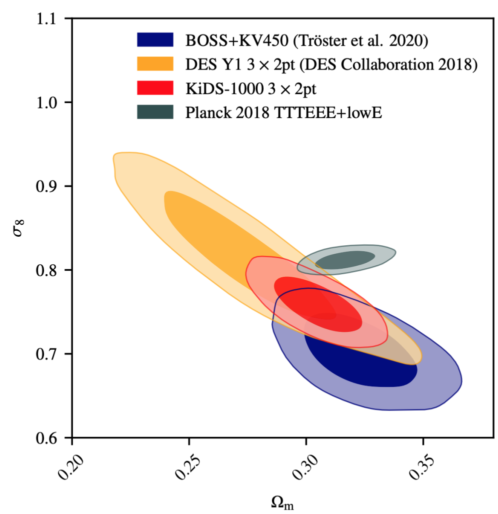

Figure 1: 68% CL and 95% CL contour plots for σ_8 and Ω_m(from Ref.[3]).

It has been pointed out in[23] that this tension could be related to the excess of lensing measured by Planck, mimicking a larger S_8. However, also ACT+WMAP[24] find a large $S_8 = 0.840 \pm 0.030$ even if it does not see a peculiar value for the lensing amplitude, while SPTpol[25] and the Planck CMB lensing [26] measurements prefer a lower value. Another possibility is the misuse of the units h^{-1}Mpc in observational cosmology in[27]. It might be worth mentioning that, while weak lensing analyses are carried out with a blinding procedure for KiDS, DES and HSC, the CMB analyses are either not blind or only partially blind.

Conjoined history problem – The H_0 disagreement is correlated to the σ_8 problem, indeed the solutions proposed to alleviate the first one, are exacerbating the CMB tension with the lower σ_8 values obtained from more direct measurements, such as galaxy clusters using the Sunyaev-Zel'dovich effect[28–30], i.e. measuring the number of clusters of a certain mass M over a range of redshift.

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

For example, late time transitions preferring a higher H_0 value, if they match the CMB data, prefer a lower Ω_m as well, to preserve the well measured value of $\Omega_m h^2$, known as geometric degeneracy. This effect produces a modification of distances to sources, the growth of structure, and of the sound horizon and CMB anisotropies[31], and usually results in higher σ_8 than for ΛCDM because of an extended era of matter domination. However, also early-time dark energy solutions of the H_0 tension increase σ_8 because they need a higher primordial curvature perturbation amplitude to offset the damping effect of the unclustered component. Therefore, because of the mutual effects and correlations, it is important to perform a conjoined analysis, fitting with a single model a full array of data[32–35], 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 redshift, by plotting $f\sigma_8(z)$ directly against $H(z)$, should be checked[36;37], because conjoint history can deviate significantly at intermediate scales. 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[38].

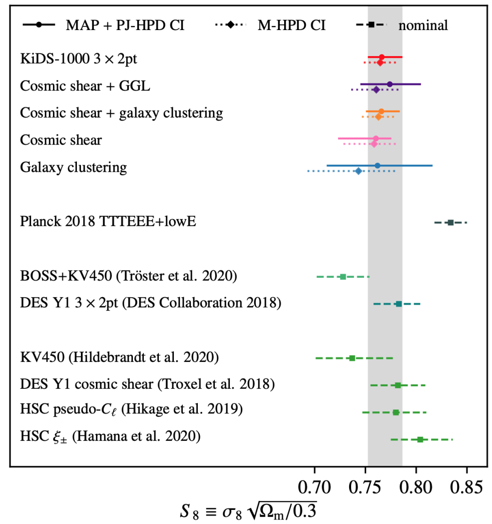

Figure 2: Whisker plot showing the 68% error bars on S_8 (from Ref.[3]).

Solutions – There are many papers investigating this tension[23;27;39–69], but the solutions proposed are not enough to put in agreement all the cosmological available data[70–72]. We can distinguish the following categories:

- Axion monodromy inflation[59].
- Extended parameter spaces[23;40;41;43;44] with $A_L > 1$[73], i.e. using the phenomenological lensing parameter as a consistency check and determining whether it is different from unity[74].
- Active and Sterile Neutrinos[57;58].
- Interacting dark energy models, where the energy flows from the dark matter to the dark energy[45;46].
- Decaying dark matter[65;66;75;76], or Cannibal dark matter[67].
- Minimally and non-minimally coupled scalar field models as possible alternatives for dark energy[53].
- Modified Gravity models[54;55;77;78].
- Running vacuum models in which $\Lambda = \Lambda(H)$ is an affine power-law function of the Hubble rate[47;48;79–84].
- Quartessence, a single dark component mimicking both dark matter and dark energy[50].

Future – In the near future, we expect percent measurements of the expansion and growth history over 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[85;86], considering RSD with DESI and 4MOST, or using voids[38]. An important role will be played by the SKA telescopes performing BAO surveys and measuring weak gravitational lensing using 21 cm intensity mapping[87–89]. Additional upcoming 21 cm neutral hydrogen experiments measuring the expansion history will be CHIME and HIRAX. Finally, line-intensity mapping of emission from star-forming galaxies can be used to measure the BAO reaching percent-level constraints[90;91] with the SPHEREx satellite or the ground-based COMAP instrument. All of these efforts will either reveal a systematic cause or harden the tension to strong statistical significance informing the theories mentioned above and guiding any extension/overhaul of the standard model.

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