Contribution Prospectives IN2P3 2020

Cosmological large-scale structures analysis in the context of LSST

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1. Scientific context

1.1. Cosmology with large-scale structure distribution

The distribution of galaxies in space and its time evolution brings a lot of information about the expansion of the Universe and the growth rate of structures. Therefore it is a key probe to test dark energy and modified gravity models. The signature of the various cosmological energy densities, as well as the underlying physics (in particular the gravitational interaction), is imprinted in the statistical characteristics of the matter distribution and its redshift evolution. The cosmological large-scale structures (LSS) are usually characterised by their power spectrum P(k) in the Fourier space, or equivalently of the 2-point correlation function in the real space. The measurement of the shape of these functions on all spatial scales and its redshift evolution can be compared with theoretical or simulated predictions to extract information on the cosmology. Also, they both exhibit a particular feature at a scale corresponding to the cosmic sound horizon, when protons and electrons combined to form neutral matter and stopped interacting with light. This particular scale translates in the galaxy distribution as the Baryonic Acoustic Oscillations (BAO) scale, a standard ruler since its size evolution with redshift traces directly the expansion of the universe.

Nowadays, the measurement of the BAO scale from spectroscopic surveys is one of the main tools to constrain the expansion of the universe from the analysis of the galaxy distribution in the universe [Dawson K.S., et al., 2016; Blanton M.R., et al., 2017]. It takes the form of the spatial 2-point correlation of the computation of the Fourier power spectrum of galaxies of certain types (Luminous Red Galaxies LRG, Emission Line Galaxies ELG, Quasi-Stellar Objects QSO), the correlation of the Lyman-alpha absorption lines (also called Lyman-alpha forests) in the QSO spectra, or the cross-correlation of QSOs with these spectral lines [Blomqvist et al., 2019]. This measurement can be performed at several redshifts z and maps the evolution of the angular diameter distance $D_A(z)$ (using the BAO-scale observation across the line of sight) and of the Hubble parameter H(z) (using the BAO-scale gradient along the line of sight). The Hubble parameter is a direct prediction of the cosmological models while the angular diameter distance is an integrated form of this parameter: H(z) measurements are nowadays the most precise data to constrain the cosmological expansion but needs plenty of galaxies with their spectroscopic redshifts.

These BAO analysis will be pushed to an extreme limit with the DESI survey, starting in 2020, and will come with their own sets of systematics. For instance the limitation of the spectroscopic capabilities to increase the galaxy sample ($3x10^7$ galaxies expected), the selection process to get their types, or the systematics inherent to each methodology. To complement and enhance the scientific impact of such galaxy survey, the combination with other types of surveys can help reduce the systematics.

1.2. LSS with LSST

The Large Synoptic Survey Telescope (LSST) is an automated ground-based 8.4m optical survey telescope, which should start observations in 2022. The aim of this new instrument is to conduct a ten year wide and deep imaging survey of 18,000 square degrees of the sky in six broad optical bands, with a deep stack reaching magnitude r~27.5. LSST will cover a large number of astrophysics domains, from Solar System physics (a catalog of 10^6 asteroids is expected), stellar and Milky Way physics 10^{10} observed stars), and cosmology (10^{10} galaxies and AGNs until redshift z~3, and 10^6 type Ia supernovae).

LSST will benefit from the large amount of observed galaxies to tackle the dark energy nature. First the galaxy number count can be used as a probe of the dark matter density, although it is a biased tracer of the dark matter field. The bias function b is introduced as $\boldsymbol{\delta n/n = b\ \delta\varrho/\varrho}$, where $\boldsymbol{\varrho}$ the dark matter field and $\boldsymbol{\delta}$ denoting the variation around the mean of the quantity. As the observed galaxies will cover half a sphere, the main analysis to constrain the cosmological parameters using the galaxy distributions will use the spherical harmonics formalism $C_l(z_1,z_2)$, instead of the traditional Fourier formalism that has been used so far [Campagne et al., 2017]. This formalism is more powerful to handle very wide surveys, to cross-correlate multiple cosmological probes, and to estimate their systematic uncertainties (see for instance [DES collaboration, 2018]). So, a tomographic analysis up to $z \sim 3$ with a single probe can efficiently study the bias function for instance as well as the cosmological parameters.

To extract the cosmological signal from the observation of the galaxy distribution, several systematics must be considered. Astrophysical or observational effects can imprint their statistical structure on the observed galaxy statistical distribution and can alter, or worse, mimic the cosmological signal: the variations of the depth of the survey due to the observation strategy, the atmospheric conditions, the incompletude (masking) of the sky, the repartition of the galactic dust that reddens the galaxy light., etc. All these systematics must be studied carefully to extract the cosmological parameters and constitutes the main activities of cosmologist working on the LSS optical surveys.

In addition, the precision and the accuracy of the galaxy photometric redshifts are crucial to get unbiased and precise cosmological parameter values. One of the main difficulties for this task is the deblending of the galaxy colors in the images to get accurately their true colors and thus their redshift. Different types of methods are currently under investigation, some are based on Deep Learning networks but their systematics remains to be thoroughly studied [Pasquet et al., 2019], others on clustering redshifts [Ménard et al., 2013; Aragon-Calvo et al., 2015].

1.3. Other LSS cosmological surveys

The weakness of LSST compared with DESI is the lack of spectroscopic estimation of the redshift of galaxies. The redshift will be inferred from the colors coming from the six broadband filters only. This will degrade the precision of the BAO scale extraction despite the statistical power of such a large galaxy sample, and despite the fact that LSST will observe all types of galaxies while spectroscopic surveys have to concentrate on galaxies with specific bright spectral features (as Emission Line Galaxies ELG, Luminous Red Galaxies LRG or quasars QSO) [Ansari R., et al., 2019]. Thanks to the spectroscopy, spectroscopic surveys can measure directly H(z) and the so-called Redshift Space Distortions, which are not accessible with photometry-only instruments like LSST. However, LSST can perform a tomographic measurement of the galaxy distribution with the same tracer until redshifts around 3, giving a synoptic view on these objects very far in the past of the Universe.

In the landscape of the 2020 decade, the Euclid satellite will also conduct a galaxy survey, comparable with LSST, but from space. It loads a spectrophotometer and an imager to produce photometric redshifts as LSST but using infrared filters and spectroscopic redshift for a subsample of the survey.

	BOSS / eBOSS	**DES Y1**	**DESI**	**LSST**	**Euclid**
Years	2009 - 2019	2013 - 2018	2020 - 2025	2022 - 2032	2022 - 2028
Type of survey	Spectroscopic	Photometric	Spectroscopic	Photometric	Photometric and spectroscopic
Area [10^3 deg^2]	10	1	14	18	15
Depth [z]	3.5 / 2.2	0.9	3.5	3	2 & 6
# Galaxies	10^6 / 10^6	3x10^8	30x10^6	3x10^9	1.5x10^9 (photo) & 3e7 (spectro)
Colors	360-1000 nm	5 [grizy]	360-980 nm	6 [ugrizy]	4 [{riz}yjh] + 1-2um

Table 1. Main characteristics of previous and upcoming galaxy surveys: BOSS/eBOSS [Dawson K.S., et al., 2016], DES [Abbott T. et al., 2005], DESI [Levi et al., 2013, Aghamousa et al., 2016], LSST [Ivezic et al., 2008], Euclid [Laureijs et al., 2011].

Cosmological theory predicts the power spectrum for the dark matter field **ϱ** only: galaxies, depending on their type, are particular tracers of this field. The translation between the theory predicted dark matter distribution and the galaxy field needs the introduction of the so-called galaxy bias. The evaluation of the galaxy bias is difficult as it depends on the type of the galaxy, the spatial scale k and redshift z. To alleviate this difficulty, the cross-correlation with other probes as the weak lensing measurement is a powerful tool.

2. Combining with other probes and surveys to reduce the systematics

2.1. Weak lensing and 3x2pt analysis

Internally to LSST or with other surveys, the combined analysis of the spatial statistical correlation of the shear of galaxies due to the gravitational weak lensing with the galaxy statistical distribution has been proven to be a powerful tool to alleviate systematics from both probes [DES collaboration, 2018]. The gravitational weak lensing probes directly the gravitational field dominated by the dark matter field along the line of sight. The measurement can be done in 3D to perform a tomographic analysis of gravity in the Universe. However, the gravitational shear measurement can be mimicked by the intrinsic alignment of the galaxies in space due to their common evolution and shapes (see e.g. [Kirk et al., 2015]). The intrinsic alignment bias and the galaxy bias **b** are inherent systematics of each probe separately but the common analysis of both probes plus the cross-correlation between the shear signal and the galaxy counting signal can constrain these two systematics (see for instance [DES collaboration, 2018]). Once correctly constrained, the combination then gives an accurate access to the dark energy equation of state parameter w(z) (Figure 1 left and right).

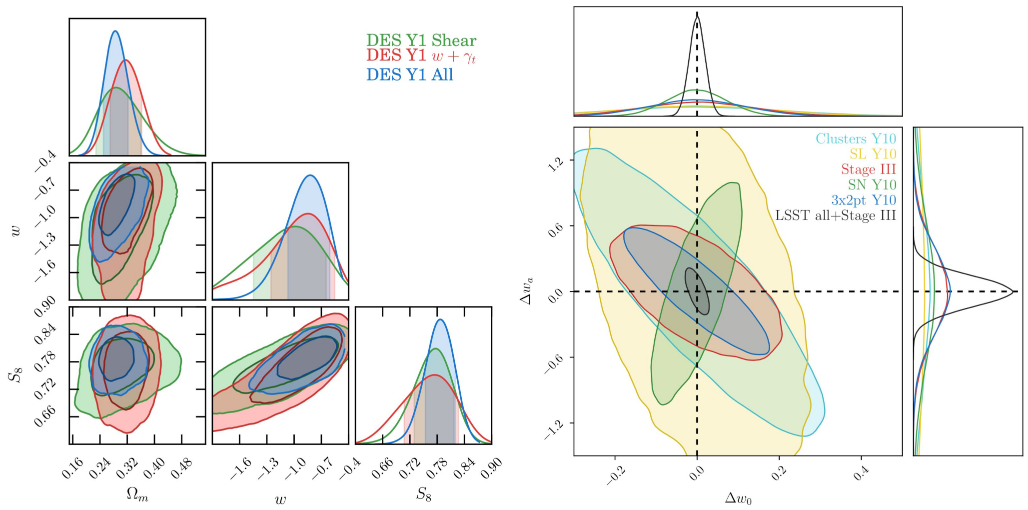

Figure 1. Left: Confidence contours from the DES survey combining galaxy counts $w(\theta)$ and galaxy weak lensing probe $\gamma_t(\theta)$ for the matter energy density Ω_m, the clustering of matter S_8 and the dark energy equation of state parameter w, after marginalisation over 20 nuisance parameters. Figure from [DES collaboration, 2018]. Right: Confidence contours combining all LSST cosmological probes after 10 years of observations, for a two-parameter model of the dark energy equation of state evolution with redshift. Figure from [The LSST Dark Energy Science Collaboration, 2018].

2.2. Euclid: colors, deblending, photometric redshifts

The Euclid satellite will observe galaxies from space. Thus, the optical response will be better, the galaxy images sharpest, and infrared bands accessible. Therefore, the combination of the colors from LSST and Euclid can possibly provide 9 colors per galaxy which can help determining the photometric redshifts considerably. Moreover, better images, and images taken with complementary filters gives additional lever arms to deblend the LSST and Euclid galaxy images (see the related white paper for Prospectives IN2P3 2020 Aubourg et al.).

2.3. DESI: spectroscopic redshifts

The intersection of the observing area of LSST and DESI is rather small but some combinations can be made between both surveys to help LSST calibrating the photometric redshifts and brings DESI images of the galaxies. Moreover, it might be possible that in the next decade a new DESI survey is built to conduct a survey of the southern sky. In this case, the overlap between both surveys will be maximum and the training of the photometric redshift determination algorithm more optimized.

3. Combining with other probes and surveys

3.1. CMB, CMB lensing, 5x2pt analysis

The fact that neutrinos have a mass alters the shape of the matter power spectrum P(k): the amplitude decreases at small scales with the sum of neutrino masses. The combination with the cosmological microwave background (CMB) measurement of the power spectrum of temperature anisotropies is essential to correctly account for this change of shape. Moreover, the combination with the CMB gravitational lensing maps enable the constraint of the galaxy bias too (see Figure 2, [Doux et al. 2018, Nicola et al., 2016]).

The cross-correlation of the LSST galaxy survey with higher resolution CMB experiment maps like the lensing maps from the South Pole Telescope (SPT) is the future tool to fit the systematics of each probe and gain precision on the measurement of neutrino masses and the test of gravity. This type of analysis cross-correlating galaxy number count maps, galaxy lensing and CMB lensing has been called 5x2pt analysis, and has been tested recently by the SPT and Dark Energy Survey (DES) collaborations in [DES and SPT collaborations, 2019] (see Figure 3).

3.2. Hydrogen 21 cm surveys

The cross-correlation with maps from the 21cm surveys as SKA, maps of galaxies and maps of intensity mapping is also a tool to get better constraints on the cosmological parameters. For this subject, see the related white paper Prospectives IN2P3 2020 Ansari et al..

3.3. Gravitational waves and LSS to constrain the Hubble constant H_0

The measurement of the Hubble constant H_0 has been enabled by the first observation of a neutron star merger GW170817 [LIGO/VIRGO collaborations, 2017]. Until now, no more neutron star merger detections have been announced but tens of binary black hole mergers have been detected. Recently, [Soares-Santos, et al., 2019] proposes a new type of measurement of the local Hubble constant using the cross-correlation with the map of galaxy counts and the distribution of binary black hole (BBH) merger detected by gravitational wave observatories. The precision of the estimate of H_0 is still weak, but promises to be competitive in the next decade thanks to the large galaxy sample offered by LSST and the rapidly increasing number of BBH detections.

4. Summary and perspectives

The IN2P3 scientists implication during the next decade has to focus first on the preparation of the LSS analysis: estimating the systematics, building $C_l(z_1,z_2)$ maps of galaxy counts, training the photometric redshift and deblending algorithms. For the two latter points, sharing the data between LSST and Euclid can enhance the scientific capabilities of both instruments, for the LSS analysis but also for galaxy cluster analysis (see the related white paper Prospectives IN2P3 2020 Adam et al.).

The study of the large-scale structure distribution using the galaxy catalog that LSST will provide is a key science case for the IN2P3 scientists. This probe is the keystone to constrain the nature of dark energy but also to measure the sum of the neutrino masses when combined with other probes (weak lensing, CMB lensing) and other surveys (SPT, Planck, SKA, DESI). The unprecedented volume of the LSST galaxy catalog, in number, completeness, width and depth, will be a milestone for decades.

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Annexes

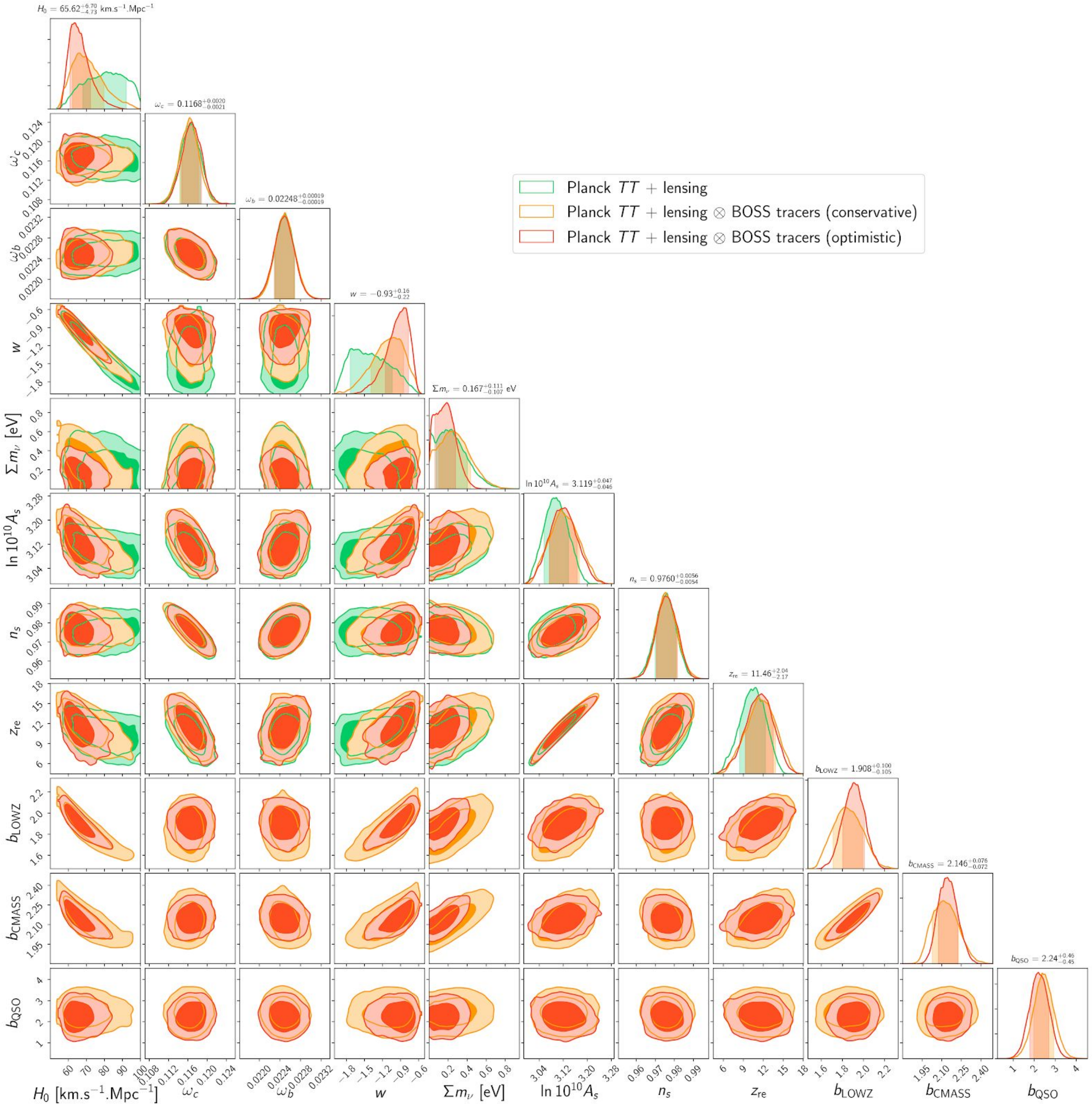

Figure 2. Confidence contours for a subset of the parameters of the LCDM model with a free equation of state parameter w for dark energy and a free parameter for the sum of neutrino masses Σm_υ obtained with the combination of Planck maps of temperature anisotropies, Planck map of gravitational lensing and galaxy and quasar samples from BOSS. The tracer bias for the three samples b_{LOWZ}, b_{CMASS} and b_{QSO} are fitted jointly to the cosmological parameters thanks to the combination with the lensing map. Figure from [Doux et al., 2018].

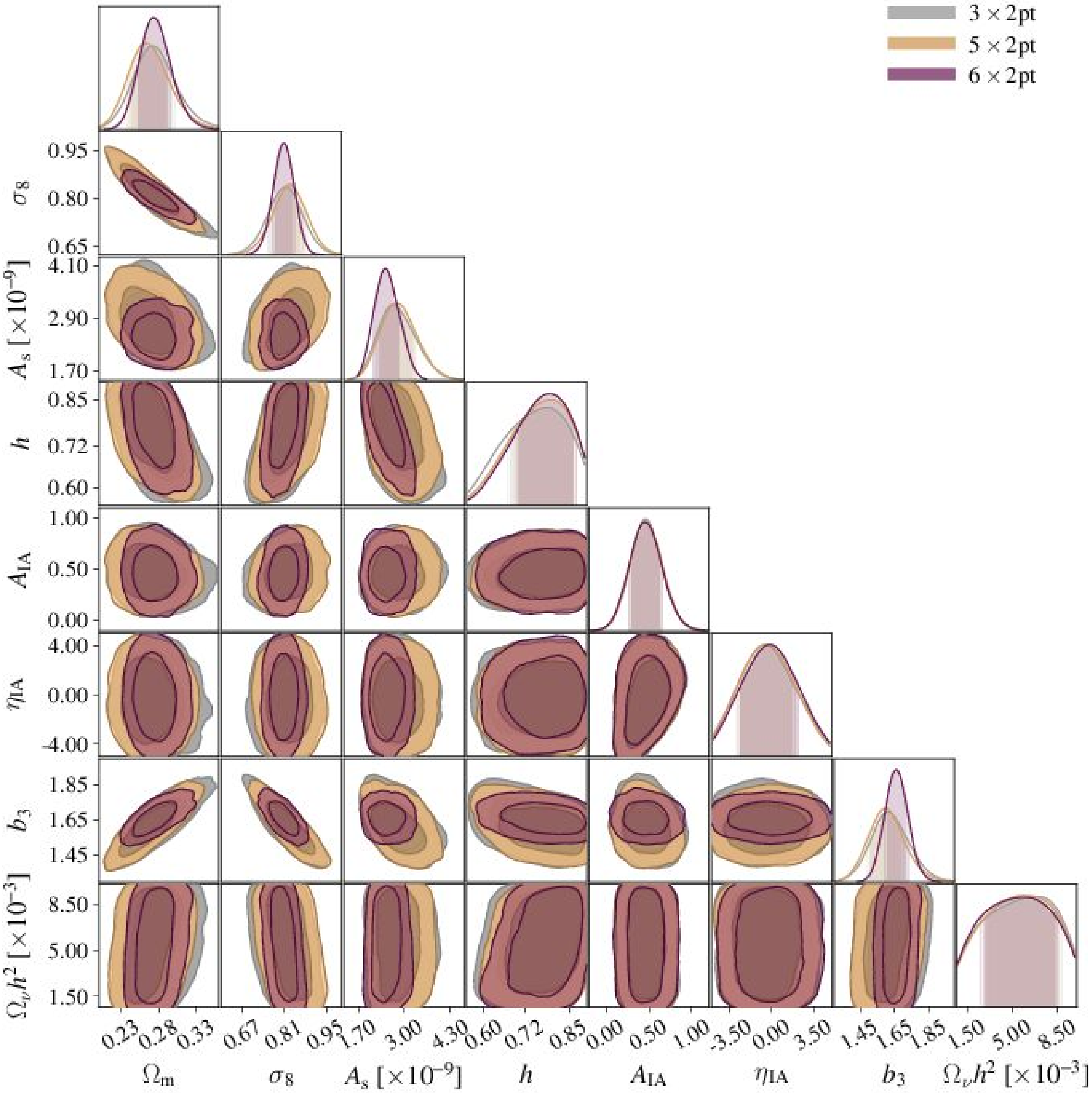

Figure 3. Confidence contours for some of the cosmological parameters and systematics parameters. The 3x2pt contours are the combination of the galaxy weak lensing and galaxy density maps, the 5x2pt cross-correlates the latter with the SPT lensing map and in the 6x2pt analysis the Planck CMB maps is added. The intrinsic alignment nuisance parameters A_{IA} and η_{IA} are fitted jointly with the galaxy bias parameter b3 and the density of neutrino $\Omega_\nu h^2$. Figure from [DES and SPT collaborations, 2019].