Improvements in cosmological constraints from breaking growth degeneracy

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ABSTRACT

Context. The key probes of the growth of a large-scale structure are its rate \( f \) and amplitude \( \sigma_8 \). Redshift space distortions in the galaxy power spectrum allow us to measure only the combination \( f \sigma_8 \), which can be used to constrain the standard cosmological model or alternatives. By using measurements of the galaxy–galaxy lensing cross-correlation spectrum or of the galaxy bispectrum, it is possible to break the \( f \sigma_8 \) degeneracy and obtain separate estimates of \( f \) and \( \sigma_8 \) from the same galaxy sample. Currently there are very few such separate measurements, but even this allows for improved constraints on cosmological models.

Aims. We explore how having a larger and more precise sample of such measurements in the future could constrain further cosmological models.

Methods. We considered what can be achieved by a future nominal sample that delivers an \(~1\%) constraint on \( f \) and \( \sigma_8 \) separately, compared to the case with a similar precision on the combination \( f \sigma_8 \).

Results. For the six cosmological parameters of \( \Lambda \)CDM, we find improvements of \(~5-50\%\) on their constraints. For modified gravity models in the Horndeski class, the improvements on these standard parameters are \(~0-15\%). However, the precision on the sum of neutrino masses improves by \(~65\%\) and there is a significant increase in the precision on the background and perturbation Horndeski parameters.

Key words. dark energy – large-scale structure of Universe

1. Introduction

The growth of a large-scale structure is sensitive to the theory of gravity and its measurement is a powerful test of the standard and alternative models of cosmology. It is characterised at the most basic level by the rate of growth \( f = -d \ln D/d \ln (1+z) \), where \( D(z) \) is the growth function of the linear matter density contrast, \( \delta(z, k) = D(z) \delta(z, k) / D(z, 0) \), given an initial redshift \( z_0 \). This rate governs the evolution of peculiar velocities, whose impact on the observed galaxy power spectrum is to introduce a redshift space distortion (RSD). The measurement of this anisotropy at redshift \( z \) delivers an estimate of \( f(z) \sigma_8(z) \), where \( \sigma_8 \) fixes the amplitude of the matter density fluctuations. The degeneracy between \( f \) and \( \sigma_8 \) echoes the degeneracy between the linear galaxy bias and \( \sigma_8 \), and it cannot be broken via RSD power spectrum measurements alone.

The degeneracy can be broken by using an alternative observable in the galaxy sample that involves \( \sigma_8 \) or \( f \). For example, combining RSD power spectrum measurements with galaxy-galaxy lensing measurements has produced separate estimates of \( f \) and \( \sigma_8 \) (de la Torre et al. 2017; Shi et al. 2018; Jullo et al. 2019). There are currently only a handful of such estimates, but even with only three separated data pairs, constraints on cosmological models improve noticeably (Perenon et al. 2019). Another way to break the degeneracy is by combining RSD measurements in the power spectrum and bispectrum (Gil-Marín et al. 2017).

Breaking the growth degeneracy is expected to break degeneracies between certain cosmological and modified gravity parameters. Here we confirm this expectation by computing the improvement in precision when using future separated measurements of \( f \) and \( \sigma_8 \) compared to using the usual combined measurements \( f \sigma_8 \). We make forecasts for the standard \( \Lambda \) cold dark matter (CDM) model and for scalar-tensor theories in the Horndeski class (Horndeski 1974), using the effective field theory (EFT) of dark energy (DE; Gubitosi et al. 2013; Bloomfield et al. 2013), see Frusciante & Perenon (2020) for a recent review and Gleyzes et al. (2016), Alonso et al. (2017), Leung & Huang (2017), Abazajian et al. (2016), Reischke et al. (2019), Spurio Mancini et al. (2018), Frusciante et al. (2019), Ballardini et al. (2019) for more general Horndeski forecasts).

2. Models

We consider two models to assess the constraining power of the different growth of structure quantities. The first is the standard cosmological model \( \Lambda \)CDM, whose free parameters are (Planck Collaboration V 2020)

\[
\{\Omega_\text{m}h^2, \Omega_\text{\Lambda}h^2, H_0, \tau, A_s, n_s, \Sigma m_\nu\},
\]

(1)
where the total neutrino mass $\sum m_\nu$ is equally shared by the three degenerate species. For the second, we chose the popular benchmark for studies of alternative gravitational models (Frusciante & Perenon 2020) that are Horndeski theories (Horndeski 1974). They are the most general covariant scalar-tensor theories with direct second-order equations of motion. We use in particular their description of linear perturbations provided by the $\alpha$-EFT basis Bellini & Sawicki (2014). Bellini & Sawicki (2014) provide complete details of the construction of the action.

Observations suggest that the speed of gravitational waves is equal to that of light (Abbott et al. 2017a,b). This reduces the number of redshift-dependent functions in the effective description that govern how modifications of gravity affect perturbations to three:

\[ \alpha_M(z) \] for the effective Planck mass;
\[ \alpha_B(z) \] for mixing between the metric and DE field;
\[ \alpha_K(z) \] for kinetic energy of scalar perturbations.

Although $\alpha_K$ has virtually no effect on constraints from current data (Bellini et al. 2016; Frusciante et al. 2019), it needs to be included as a free parameter, since it regulates the propagation speed of DE perturbations. Setting it arbitrarily to zero could restrict the space of stable models and thus bias the constraints (Kreisch & Komatsu 2018; Frusciante et al. 2019).

The functional forms of $\alpha_I(z), I = M, B, K$, are not given by the effective DE parametrisation (Piazza et al. 2014; Bellini & Sawicki 2014) common in the literature,

\[ \alpha_I(z) = \alpha_I \frac{\Omega_M(z)}{\Omega_M(0)}. \]  \hspace{1cm} (2)

We also allow for deviations from a $\Lambda$CDM background by using the Chevallier-Polarski-Linder (CPL; Chevallier & Polarski 2001; Linder 2003) parametrisation for the effective DE equation of state of the Horndeski models:

\[ w_s(z) = w_0 + w_a \frac{z}{1 + z}. \]  \hspace{1cm} (3)

In summary, the Horndeski model we consider contains five additional free parameters with respect to $\Lambda$CDM:

\[ \Omega_b h^2, \Omega_c h^2, H_0, \tau, A_s, n_s, \sum m_\nu, w_0, w_a, \alpha_M, \alpha_B, \alpha_K \]. \hspace{1cm} (4)

The $\Lambda$CDM model is recovered for $w_0 = -1$ and $w_a = \alpha_M = \alpha_B = \alpha_K = 0$.

3. Methodology

The cosmological evolution of the models was computed using the Boltzmann code1 CLASS (Blas et al. 2011), and its modified version2 $h$1$_{\text{class}}$ (Zumalacarregui et al. 2017; Bellini et al. 2020). The cosmological data – hereafter referred to as the “baseline” – contain the SDSS-II/SNLS3 Joint Light-curve Analysis (JLA) sample of type Ia supernova (SNIa; Betoule et al. 2014), the Baryon Oscillation Spectroscopic Survey (BOSS) baryon acoustic oscillation (BAO) measurements (Beutler et al. 2011; Anderson et al. 2014; Ross et al. 2015), and the low- and high-multipole temperature and polarisation of Planck 2018 cosmic microwave background (CMB) data (Planck Collaboration 2020). We chose not to include CMB lensing data to avoid inconsistencies related to potential $\Lambda$CDM-dependent assumptions made during the lensing reconstruction.

Our aim was to focus on the gain from breaking growth degeneracy, rather than making realistic mocks and forecasts. In order to compare the constraining power of separated measurements of $f$ and $\sigma_8$ with the combined measurements $f\sigma_8$, we simulated data for a nominal future galaxy sample that delivered a one percent precision for $f, \sigma_8,$ and $f\sigma_8$. We assumed a redshift range containing ten measurements at $z = 0.1, 0.2, \ldots, 1$. The effects of extending the redshift range are studied in Sect. 4.3. We anticipate that a Stage IV experiment conducting a spectroscopic galaxy count survey together with a weak lensing survey, such as Euclid (Amendola et al. 2018), should be able to achieve close to 1% precision on $f\sigma_8, f$, and $\sigma_8$, using Planck priors on standard cosmological parameters.

Whenever needed, the growth quantities are computed with CLASS or $h$1$_{\text{class}}$. In order to compare the constraints on the same footing and avoiding non-linear model dependencies, we computed the growth quantities with the linear power spectrum only. The values of $\sigma_8$ were obtained via the usual weighted integral of the linear power spectrum and $f$ was computed as the log derivative $f = -(1 + 2\ln \sigma_8/d\ln z)$ for simplicity.

As fiducial parameters we used the best-fit values obtained from the baseline constraints for the $\Lambda$CDM and Horndeski models. Then we created three sets of mocks for both models (for $f, \sigma_8$, and $f\sigma_8$), each exactly centred on their fiducial, meaning no random variance added to the data. The $\Lambda$CDM model has been shown to lie in a corner of the parameter space of stable Horndeski models (Piazza et al. 2014), which are ghost- and gradient-free models. When performing forecasts using Markov chain Monte Carlo (MCMC) methods, the stability priors can lead to a disfavouring of models lying close to the corner, purely due to volume effects and independently of their actual likelihood. Such considerations may have a significant effect on our results. This is hinted at for example by the highly irregular posteriors in the baseline case in Fig. 3 (grey contours) and the mismatch between their maximum and the best-fit model (dotted lines), characteristic of non-negligible prior effects. We can however expect those effects to be mitigated when additional data is added to the analysis, due to the fact that our Horndeski fiducial model (derived from the baseline best fit and used to produce our mocks) lies noticeably away from the “$\Lambda$CDM corner”. Even if our MCMC explorations were impacted by such priors, this should not affect our conclusions since we always make statements regarding relative improvements.

4. Constraints

The sampling of all the considered likelihoods, as well as the computation of best-fit parameters, are performed using the publicly available3 suite of codes ECLAIR (Ilč et al. 2020). It uses as its main sampling algorithm the affine-invariant ensemble method of Foreman-Mackey et al. (2013) and contains a novel and robust maximiser with reliable convergence towards the global maximum of the posterior.

4.1. $\Lambda$CDM

Marginalised posterior distributions are shown in Fig. 1. The corresponding means and 68% confidence intervals are given in Table 1, while Table 2 shows the gain in precision relative to the
baseline (first two columns) and for the separated growth measurements \( f + \sigma_f \) relative to the standard \( f \sigma_f \) measurements (last column). We define the precision as the inverse width of the 68% marginalised confidence interval rather than using relative errors, since the latter can become misleading when the mean values are close to zero (e.g., in the case of \( \Sigma m_i \)). In addition, comparing relative errors would also be biased when the mean values shift, as happens for the Horndeski models (see below).

Next-generation surveys are forecast to deliver improved constraints from high-precision RSD \( f \sigma_f \) data (see e.g. Amendola et al. 2018; Bacon et al. 2020). The triangle plots and the tables confirm this. Table 2 (first column) shows that the gain in precision ranges from \( \sim 10\% \) for \( \Omega_b h^2 \) up to more than \( \sim 50\% \) for \( \Omega_c h^2, H_0 \) and \( \Sigma m_i \), when considering the addition of the mock data on \( f \sigma_f \), with 1% relative error combined to current cosmological data sets.

As expected the constraints improve further with the split mock data on \( f \) and \( \sigma_f \), each with a 1% relative error. This combination performs from 6% to almost 50% better. In particular, the precision on \( \Omega_c h^2 \) and \( H_0 \) is more than doubled relative to the baseline data alone.

The improvement obtained from the split \( f \) and \( \sigma_f \) data over \( f \sigma_f \) (as quantified by the third column of Table 2) does not lead to an equal increase in precision on all the parameters that were

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**Table 1.** Mean and 68% confidence interval for ΛCDM parameters.

| Parameter | \( f \sigma_f \) | \( f + \sigma_f \) |
|-----------|----------------|------------------|
| \( \Omega_b h^2 \) | 0.02244 ± 0.00013 | 0.02245 ± 0.00012 |
| \( \Omega_c h^2 \) | 0.11918 ± 0.00062 | 0.11904 ± 0.00048 |
| \( H_0 \) | 68.10 ± 0.16 | 68.17 ± 0.16 |
| \( \tau \) | 0.0581 ± 0.0058 | 0.0589 ± 0.0044 |
| \( \ln(10^{10} A_s) \) | 3.0509 ± 0.0106 | 3.0524 ± 0.0075 |
| \( n_s \) | 0.9671 ± 0.0034 | 0.9673 ± 0.0031 |
| \( \Sigma m_i \) | 0.0263 ± 0.0026 | 0.0248 ± 0.0028 |

**Notes.** The constraints are obtained by combining the baseline with the \( f \sigma_f \) mock (middle column) and \( f \) and \( \sigma_f \) mocks (right column).

**Table 2.** Precision ratios for ΛCDM parameters.

| Parameter | Baseline | Baseline | Baseline |
|-----------|----------|----------|----------|
| | \( + f \sigma_f \) | \( + f + \sigma_f \) | \( + f + \sigma_f \) |
| \( \Omega_b h^2 \) | 1.08 | 1.15 | 1.06 |
| \( \Omega_c h^2 \) | 1.66 | 2.16 | 1.30 |
| \( H_0 \) | 1.55 | 2.26 | 1.46 |
| \( \tau \) | 1.25 | 1.54 | 1.22 |
| \( \ln(10^{10} A_s) \) | 1.40 | 1.77 | 1.26 |
| \( n_s \) | 1.16 | 1.27 | 1.09 |
| \( \Sigma m_i \) | 1.48 | 1.57 | 1.13 |

**Notes.** Section 4.1 gives details.
already well constrained with \( f\sigma_8 \) RSD data. As an example, we can compare \( \Sigma m_\nu \) and \( H_0 \). Adding \( f\sigma_8 \) data yields almost a 50% gain on \( \Sigma m_\nu \), while the split \( f + \sigma_8 \) data further increases the precision by 13%. By contrast, \( H_0 \) precision first increases by 55% followed by another 46% with the splitting.

The growth probes \( f \), \( \sigma_8 \), and \( f\sigma_8 \) have different sensitivities to each cosmological parameter, which explains the range of changes in precision. One way to examine those sensitivities is to start with the baseline-only constraints. Figure 2 shows the posterior distributions of \( f \), \( \sigma_8 \), and \( f\sigma_8 \) at redshift \( z = 0.1 \) as derived parameters versus the cosmological parameters\(^4\). Each posterior thus illustrates how a change in a given cosmological parameter impacts the values of the derived growth quantities, taking into account (i.e. marginalising over) the remaining cosmological parameters and how their values need to change to keep a decent fit to the data.

On the other hand, adding constraints on the growth quantities amounts to convolving their posteriors with a Gaussian distribution (with a width equal to 1% of the central value). This in turn may reduce the width of the posterior on cosmological parameters, depending on the amount of correlation between the two. It is thus expected that cosmological parameters that are highly correlated (i.e. thin tilted ellipses) with a given growth quantity in the baseline case, will show the best improvements after including measurements of that growth quantity.

From Fig. 2 we find that \( \Omega_b \), \( \Omega_c \), \( H_0 \), and \( n_s \) are better constrained by adding the mock (green) to the baseline, while \( \tau \), \( A\), and \( \Sigma m_\nu \) are better constrained by adding the \( \sigma_8 \) mock (purple). This may appear counter to the common expectation that \( \sigma_8 \) is more sensitive to parameters affecting the power spectrum amplitude, while \( f \) is more sensitive to parameters affecting its shape. It is the correlations induced by the baseline constraints that are the decisive factor.

Let us consider an illustrative example from Fig. 2: the 2D posterior of \( (f(0.1), H_0) \) exhibits a high correlation (thin tilted ellipse), while that of \( (\sigma_8(0.1), H_0) \) is relatively irregular and close to an uncorrelated case. As a result, the addition of the mock improves the \( H_0 \) constraint significantly more relative to the baseline (see the 1D posterior of \( H_0 \) in the top row of Fig. 2).

These correlations can even lead to improved constraints on parameters that \( f \) and \( \sigma_8 \) should not depend on. An example is the tight constraint on the reionisation parameter \( \tau \) produced by the mock on \( \sigma_8 \), which originates in the tight constraint on \( A_\) from \( \sigma_8 \), combined with the underlying high correlation between \( A \) and \( \tau \), as shown in Fig. 1. A tight constraint on \( \tau \) is obtained even though it does not play a role in the value of \( \sigma_8 \).

### 4.2. Horndeski

The Horndeski parameter space is extended to include modifications in the background \((w_0, w_a)\) and in the perturbations \((\alpha_M, \alpha_K, \alpha_B)\). Marginalised posterior distributions with the baseline and mock data sets are displayed in Fig. 3, with the corresponding means and 68% confidence intervals in Table 3. We observe that the maximum of the posterior distribution for the extension parameters shifts significantly towards the best-fit model (dotted lines), while the contours assume a much more regular, ellipsoidal shape compared to the baseline case. This is expected in a transition from a regime where priors still play a significant role (as discussed at the end of Sect. 3), to a situation where data dominate the posterior. Interestingly, these results also show that if the true underlying cosmology is indeed close to the Horndeski best-fit fiducial, then growth data with 1% relative precision (over the redshift range considered) could lead to the detection of this deviation from \( \Lambda \)CDM with strong significance (more than 5\( \sigma \)).

Table 4 shows the gain in precision relative to the baseline (first two columns) and for the separated growth measurements \( f + \sigma_8 \) relative to the standard \( f\sigma_8 \) measurements (last column). As pointed out earlier, the kineticity coupling \( \alpha_K \) is not constrained by the data and is therefore not included in the figure and tables, but \( \alpha_K \) is included as a free parameter in the analysis. The accuracy that was gained on the cosmological parameters in \( \Lambda \)CDM is largely lost. Adding the mock on \( f\sigma_8 \) only delivers a precision gain of up to \( \sim 20\% \) (see Table 4). This can
The constraints are obtained by combining the baseline with the parameters when using the baseline data only. Fig. 3 shows how and degenerate final parameters via correlations, as both sets may have similar be attributed to the addition of new, poorly constrained degrees of freedom, which naturally leads to larger errors on all the original parameters via correlations, as both sets may have similar degenerate effects on the growth of structure. For example, Fig. 3 shows how and are relatively degenerate with other parameters when using the baseline data only.

However, there is significant improvement for the extension parameters: adding future fits yields a 230% improvement for the running of the effective Planck mass and a remarkable ~50% gain for . Even though is a probe of the perturbations, adding its mock to the baseline achieves a surprising ~30% and ~60% gain in precision for and respectively.

The additional gain from disentangling and measurements is also subject to the effects of opening up the parameter space. The standard parameters see little improvement (<15%) over the case. By contrast, , and precision jumps by a further ~20%, ~65%, and ~80% respectively.

The underlying reason why growth data provide such an enhancement in precision for the Horndeski parameters is rooted in the modification of gravitational dynamics (e.g. the Poisson equation) by . As discussed in Perenon et al. (2019), these modifications produce two opposing contributions:

- a fifth force, enhancing growth;
- a higher effective Planck mass, suppressing growth.

The effective Planck mass is controlled solely by and also . Table 4 shows that the splitting of into and is very effective to further constrain , thereby disentangling the fifth force and effective Planck mass contributions. This feature was seen even with current split data in Perenon et al. (2019).

The modified background parameters and also contribute to the growth of structure through Hubble friction. Their effects on growth are therefore degenerate with those of . We see in Fig. 4 that, and display some degeneracies in their 2D marginalised posteriors.

Following the arguments for , we can understand the separate improvements from and by analysing their posterior distributions versus cosmological parameters, shown in Fig. 4. We note that the stability requirements for the Horndeski models induce highly non-Gaussian posterior distributions, which makes the analysis more subtle. Figure 4 shows that correlates more strongly with and than , so that adding measurements results in a larger increase in precision for these parameters. Since these two parameters control the strength of the fifth force, this could be expected, given that is an integrated function of , which tends to wash out the effects of the fifth force. The fifth force is an effect occurring at low redshifts as opposed to the effect of Hubble friction or neutrinos. A chain of correlations – seen in the baseline constraints – shows that brings a larger gain in precision for and . This signals therefore a higher sensitivity of to modifications of gravity spanning longer periods.

It is in fact expected that the effect of neutrinos is partially degenerate with that of modified gravity (see e.g. Wright et al. 2019; Ballardini et al. 2020). Massive neutrinos suppress the growth of structure on small scales, which can either oppose or reinforce modified gravity, depending on whether the fifth force or the Planck mass running is favoured. Horndeski models compatible with current RSD fits constraints produce a suppression of growth at late times (Perenon et al. 2019).

The baseline constraints in Fig. 3 show that the 2D posteriors of , with and , have a fairly irregular shape, while those with and are more correlated. More surprisingly, as noted above, has almost a 50% gain with the addition of the fits mock data, as in the case of . The splitting improves constraints by a further 70% as opposed to 7% in . It is therefore clear that these growth mocks break the neutrino-modified gravity degeneracy by efficiently constraining and the extension parameters. Figure 4 tells us that this is rooted in the correlation of with in the baseline.

On the other hand, we also see that all the intrinsic degeneracies between the extension parameters and standard model parameters render the baseline constraints for the latter much less correlated than in the case of . This explains why the improvements from the splitting are not as great in the case of Horndeski for the other standard parameters. We note that when the background evolution is fixed to that of , displays a correlation with (Bellomo et al. 2017). Here, the freedom that arises from varying and lessens that correlation.

4.3. Extending the redshift range

Having understood better the influence of each mock data set on the constraints, we now assess the effect of extending the

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**Table 3.** Mean and 68% confidence interval for Horndeski parameters.

| Parameter | baseline | baseline + | baseline + |
|-----------|----------|------------|------------|
|          | $f\sigma_8$ | $f + \sigma_8$ | $f + \sigma_8$ |
| $\Omega_b h^2$ | 0.02259^{+0.0003+} \, {0.00015}^{-} | 0.02258^{-0.00015+} | 0.02258^{-0.00015+} |
| $\Omega_c h^2$ | 0.11801^{+0.00122+} \, {0.000122}^{-} | 0.11819^{-0.000122+} | 0.11819^{-0.000122+} |
| $H_0$ | 68.4^{+0.96} \, {0.96}^{-} | 68.69^{+0.85} \, {0.85}^{-} | 68.69^{+0.85} \, {0.85}^{-} |
| $\tau$ | 0.0508^{+0.0075} \, {0.0075}^{-} | 0.0526^{+0.0070} \, {0.0070}^{-} | 0.0526^{+0.0070} \, {0.0070}^{-} |
| ln($10^{10} A_s$) | 3.032^{+0.1575} \, {0.1575}^{-} | 3.036^{+0.140} \, {0.140}^{-} | 3.036^{+0.140} \, {0.140}^{-} |
| $n_s$ | 0.970^{+0.0042} \, {0.0042}^{-} | 0.9702^{+0.0042} \, {0.0042}^{-} | 0.9702^{+0.0042} \, {0.0042}^{-} |
| $\Sigma m_\nu$ | 0.0953^{+0.0201} \, {0.0201}^{-} | 0.0742^{+0.0206} \, {0.0206}^{-} | 0.0742^{+0.0206} \, {0.0206}^{-} |
| $w_0$ | $-0.963^{+0.0862} \, {0.0862}^{-}$ | $-0.977^{+0.0813} \, {0.0813}^{-}$ | $-0.977^{+0.0813} \, {0.0813}^{-}$ |
| $w_a$ | $-0.190^{+0.10} \, {0.2636}^{-}$ | $-0.154^{+0.10} \, {0.2984}^{-}$ | $-0.154^{+0.10} \, {0.2984}^{-}$ |
| $a_b$ | $1.94^{+0.2058} \, {0.2058}^{-}$ | $1.92^{+0.1791} \, {0.1791}^{-}$ | $1.92^{+0.1791} \, {0.1791}^{-}$ |
| $a_M$ | $3.34^{+0.4411} \, {0.3942}^{-}$ | $3.04^{+0.2630} \, {0.2379}^{-}$ | $3.04^{+0.2630} \, {0.2379}^{-}$ |

**Notes.** The constraints are obtained by combining the baseline with the $f\sigma_8$ mocks (middle column) and $f$ and mocks (right column).

**Table 4.** Precision ratios for Horndeski parameters.

| Parameter | Baseline | Baseline | Baseline |
|-----------|----------|----------|----------|
|          | $f\sigma_8$ | $f + \sigma_8$ | $f + \sigma_8$ |
| $\Omega_b h^2$ | 1.11 | 1.10 | 0.99 |
| $\Omega_c h^2$ | 1.20 | 1.20 | 1.00 |
| $H_0$ | 1.19 | 1.35 | 1.12 |
| $\tau$ | 0.96 | 1.04 | 1.05 |
| ln($10^{10} A_s$) | 0.98 | 1.11 | 1.13 |
| $n_s$ | 1.10 | 1.10 | 1.00 |
| $\Sigma m_\nu$ | 1.49 | 1.91 | 1.65 |
| $w_0$ | 1.29 | 1.52 | 1.01 |
| $w_a$ | 1.65 | 1.59 | 1.18 |
| $a_b$ | 2.83 | 2.87 | 1.03 |
| $a_M$ | 3.30 | 5.32 | 1.77 |

**Notes.** Section 4.2 gives details.
Fig. 3. One-dimensional and two-dimensional marginalised posterior distributions for Horndeski parameters derived from the baseline only (grey), baseline with mock on $f\sigma_8$ (blue), and baseline with mocks on $f$ and $\sigma_8$ (red). The dotted lines indicate the parameter values for the fiducial model (corresponding to the baseline best fit) used when generating mocks.

redshift coverage of the mocks. More specifically, we examine the respective merits of adding $f\sigma_8$ or $f + \sigma_8$ measurements, when extending the maximum redshift of each mock. Table 5 shows that the combined data $f\sigma_8$ with $z_{\text{max}} = 2$ (first column) performs no better than $f + \sigma_8$ data with half the redshift range ($z_{\text{max}} = 1$, see Tables 1 and 3). We find that extending the redshift range further improves the precision up to 30% with respect to $z_{\text{max}} = 1$ in the case of the combined mock $f\sigma_8$ for $\Lambda$CDM and Horndeski models, and respectively 20% and 15% in the case of $f$ and $\sigma_8$ mocks.

5. Conclusion

Upcoming galaxy surveys such as Euclid (Amendola et al. 2018) and Square Kilometre Array (SKA; Bacon et al. 2020) with their unprecedented precision is a call to sharpen our tools for constraining gravity. One cosmological probe well suited for that task is the growth of structure. This toolbox is further complemented by the releases of measurements on $f$ and $\sigma_8$ (de la Torre et al. 2017; Shi et al. 2018; Jullo et al. 2019; Gil-Marín et al. 2017).

In this paper, we considered the performance that a future nominal galaxy sample can deliver with a $\sim 1\%$ relative error on $f$ and $\sigma_8$ separately and on the combination $f\sigma_8$. We compared the constraints from the separated data with those from the combination data. We assumed ten measurements per growth quantity equally spread over the redshift range $z = 0.1, 0.2, \ldots, 1.0$. For the case of $\Lambda$CDM, the improvements in precision range over $\sim 5\%$ to $\sim 50\%$. For modified gravity described by Horndeski models, the improvements on these standard model parameters reduce to $\sim 0\%$ to $\sim 15\%$.

However, the splitting of $f$ and $\sigma_8$ stands out as very effective in breaking the neutrino – modified gravity degeneracy, with the sum of neutrino masses enjoying an improvement of 65% over
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![Image](image.png)

**Fig. 4.** One-dimensional marginalised posterior distributions (top row) for Horndeski parameters, from baseline only (grey), baseline + mock on f (green), and baseline + mock on $\sigma_8$ (purple). Rows below show 2D posteriors of cosmological parameters against derived parameters f, $\sigma_8$, and $f\sigma_8$ computed at $z = 0.1$.

Table 5. Mean and 68% confidence interval for $\Lambda$CDM (top) and Horndeski (bottom) parameters with the redshift of the mocks extended to $z = 0.1, 0.2, \ldots, 2.0$.

| Parameter | Mean (68% CI) | Mean (68% CI) |
|-----------|---------------|---------------|
| $\Omega_b h^2$ | 0.02245 (0.00012, 0.00012) | 0.02244 (0.00012, 0.00012) |
| $\Omega_c h^2$ | 0.11910 (0.00055, 0.00055) | 0.11907 (0.00046, 0.00046) |
| $H_0$ | 68.17 (0.25, 0.25) | 68.17 (0.21, 0.21) |
| $\tau$ | 0.0588 (0.0056, 0.0056) | 0.0587 (0.0048, 0.0048) |
| $\ln(10^{10} A_s)$ | 3.0524 (0.0075, 0.0075) | 3.0521 (0.0062, 0.0062) |
| $n_s$ | 0.9673 (0.0032, 0.0032) | 0.9673 (0.0031, 0.0031) |
| $\Sigma m_{\nu}$ | 0.0234 (0.0055, 0.0055) | 0.0234 (0.0055, 0.0055) |
| $\Omega_b h^2$ | 0.0225 (0.0015, 0.0015) | 0.0225 (0.0015, 0.0015) |
| $\Omega_c h^2$ | 0.1181 (0.00123, 0.00123) | 0.11824 (0.00117, 0.00117) |
| $H_0$ | 68.60 (0.88, 0.88) | 68.63 (0.82, 0.82) |
| $\tau$ | 0.0523 (0.0072, 0.0072) | 0.0524 (0.0071, 0.0071) |
| $\ln(10^{10} A_s)$ | 3.0357 (0.0144, 0.0144) | 3.0365 (0.0143, 0.0143) |
| $n_s$ | 0.9702 (0.0042, 0.0042) | 0.9701 (0.0041, 0.0041) |
| $\Sigma m_{\nu}$ | 0.0656 (0.0086, 0.0086) | 0.0693 (0.0088, 0.0088) |
| $w_0$ | -0.976 (0.0840, 0.0840) | -0.9764 (0.0705, 0.0705) |
| $w_a$ | -0.1328 (0.2831, 0.2831) | -0.1452 (0.2666, 0.2666) |
| $a_B$ | 1.949 (0.1701, 0.1701) | 1.9266 (0.1594, 0.1594) |
| $a_M$ | 3.1274 (0.3412, 0.3412) | 3.0552 (0.2409, 0.2409) |

Notes. The constraints are obtained by combining the baseline with the $f\sigma_8$ mock (middle column) and f and $\sigma_8$ mocks (right column).

Our results highlight that growth data, whether split or combined with 1% relative error could lead to the detection of deviations from $\Lambda$CDM with strong significance (more than 5σ), should the underlying cosmology be close to the current Horndeski best-fit fiducial. The splitting of growth data on $f\sigma_8$ into data on f and $\sigma_8$ with galaxy-galaxy lensing (de la Torre et al. 2017; Shi et al. 2018; Julio et al. 2019) or by combinations with the bispick (Gil-Marín et al. 2017) emerges clearly from this work as both a powerful complementary probe for the standard model and a stringent probe to detect departures from it. The latter could prove crucial in the era of future surveys, given the current tensions within the standard model and the emergence of alternative models of gravity favoured by Bayesian evidence (Peirone et al. 2019; Solá Peraudella et al. 2019).

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