CosmicFish Validation Notes V1.0

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These notes show and comment the examples that have been used to validate the CosmicFish code. We compare the results obtained with the code to several other results available in literature finding an overall good level of agreement. We will update this set of notes when relevant modifications to the CosmicFish code will be released or other validation examples are worked out.

The CosmicFish code and the package to produce all the validation results presented here are publicly available at \url{http://cosmicfish.github.io}. The present version is based on CosmicFish Jun16.

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\section{I. INTRODUCTION}

In \cite{1, 2} we introduced the CosmicFish code as a powerful tool to perform forecast on many different models with future cosmological experiments.

In this set of notes we show the validation pipeline that was used for the code. We compared the results obtained with the CosmicFish code to other results in literature. We find an overall good level of agreement.

Together with these notes we release a CosmicFish package that contains the relevant code to produce all the results presented here. This package is going to be updated as new validation results become available. The CosmicFish code and its validation package are publicly available at \url{http://cosmicfish.github.io}.
II. CMB FORECASTS

A. Planck Blue Book and CMBpol

The validation package contains forecasted results for the Planck mission, obtained using Planck Blue Book specifications \[3\], and for the proposed CMBpol satellite \[4\]. CosmicFish is used varying the standard 6 parameters \((\Omega_b h^2, \Omega_c h^2, \tau, n_s, \log(10^{10} A_s), h)\), from now on dubbed as S6, and the number of relativistic species \(N_{\text{eff}}\). The results are compared with what is obtained in Section III.C of \[5\]; even though these results were obtained with MCMC methods, CosmicFish bounds and degeneracies show a very good agreement (see Figure 1 and Table I).

FIG. 1: Contour plots between \(N_{\text{eff}}\) and standard parameters. Moving clockwise from top left panel, these can be compared with Figures 3, 4, 5 and 6 of \[5\]. Blue and red contours here correspond to blue and green contours on the paper.
TABLE I: 68% confidence level bounds on cosmological parameters obtained through Planck and CMBpol forecasts. This can be compared with Table IV of [5].

| Parameter | Fiducial | Planck 68% c.l. bound | CMBpol 68% c.l. bound |
|-----------|----------|------------------------|------------------------|
| $\Omega_b h^2$ | 0.0227 | 0.0002 | $5 \times 10^{-5}$ |
| $\Omega_c h^2$ | 0.11 | 0.003 | 0.0005 |
| $100 \theta_{MC}$ | 1.041 | 0.0005 | $9 \times 10^{-5}$ |
| $\tau$ | 0.09 | 0.004 | 0.003 |
| $n_s$ | 0.963 | 0.007 | 0.002 |
| $\log 10^{10} A_s$ | 3.18 | 0.01 | 0.005 |
| $N_{eff}$ | 3.0 | 0.2 | 0.04 |

B. Planck 2015

The CMB pipeline is also validated using Planck 2015 real performances specifications [6], which allow to produce bounds on the cosmological parameters mimicking the performances of the real experiment. Figure 2 and Table II show the results obtained varying the S6 parameters both using only temperature spectra and including also $EE$ and $TE$.

A comparison of the $TT$ results with [7] highlights good agreement with the Planck 2015 results, with the exception of the $\tau$ and $A_s$ parameters, due to the fact that in our analysis the low-$P$ Planck polarization at small multipoles is not included. More complicated is the comparison when the polarization spectra are considered; the Planck likelihood analysis relies on a modeling of foreground effects based on some nuisance parameters, which is not yet included in CosmicFish. In order to partially mimic the effect of these parameters on the constraining power brought by CMB polarization, we strongly reduce the sky fraction $f_{sky}$ observed for polarization to 0.01. The bound obtained this way are compatible with Planck 2015 results.

TABLE II: 68% confidence level bounds on cosmological parameters obtained using Planck 2015 $TT$ only and Planck 2015 $TT + TE + EE$ to be compared with the second and fifth column of Table 3 of [7].

| Parameter | Fiducial | $TT$ 68% c.l. bound | $TT + TE + EE$ 68% c.l. bound |
|-----------|----------|---------------------|-------------------------------|
| $\Omega_b h^2$ | 0.0222 | 0.0002 | 0.0001 |
| $\Omega_c h^2$ | 0.12 | 0.002 | 0.002 |
| $\theta$ | 1.0407 | 0.0004 | 0.0004 |
| $\tau$ | 0.08 | 0.03 | 0.02 |
| $\log (10^{10} A_s)$ | 3.09 | 0.05 | 0.04 |
| $n_s$ | 0.964 | 0.005 | 0.004 |
| $h$ | 0.673 | 0.009 | 0.008 |
| $\Omega_m$ | 0.32 | 0.01 | 0.01 |
| $\sigma_8$ | 0.83 | 0.02 | 0.01 |
III. REDSHIFT DRIFT FORECASTS

CosmicFish includes a Fisher matrix forecast module for redshift drift. This observable, considered alone, is not strongly constraining so we expect results to be biased by non-Gaussian features in the likelihood. We therefore validate this observables only in combination with CMB forecast.

As of redshift drift observations we consider E-ELT specifications as used in [8], while for CMB we use Planck Blue Book specifications. In this case CosmicFish is used with S6 parameters to which the possibility of a constant $w_0$ different from $-1$ is added. The results are then compared with Section V of [8], finding a good agreement with the MCMC results obtained there (see Figure 3 and Table III). Notice that bounds are slightly looser in our analysis; this is due to the inclusion of an HST prior in the analysis of [8].

\footnote{\textsuperscript{1} notice these are not the most up to date specifications for E-ELT redshift drift measurements; they are used only for validation purposes.}
FIG. 3: Contour plots between $\Omega_m$ and $h$ (left panel) and between $\Omega_m$ and $w_0$. These plots can be compared respectively with the green contours of Figures 5 and 4 of [8].

| Parameter | Fiducial | Planck+E-ELT 68% c.l. bound |
|-----------|----------|-----------------------------|
| $\Omega_b h^2$ | 0.0226 | 0.0001 |
| $\Omega_c h^2$ | 0.1109 | 0.0009 |
| $100\theta_{MC}$ | 1.0397 | 0.0003 |
| $h$ | 0.71 | 0.01 |
| $\Omega_m$ | 0.27 | 0.01 |
| $w_0$ | -1.0 | 0.05 |

TABLE III: 68% confidence level bounds on cosmological parameters obtained through Planck+E-ELT forecasts. This can be compared with Table II of [8].

IV. SUPERNOVAE FORECASTS

The CosmicFish Supernovae pipeline is validated using as free parameters only the constant Dark Energy equation of state parameter $w_0$ and the baryon and cold dark matter densities $\Omega_b h^2$ and $\Omega_c h^2$. The bounds on $w_0$ and the derived parameter $\Omega_m$ are obtained combining the performances of the surveys used in [9] (low-z, SDSS, SNLS, HST) and the results are compared with the same paper.

What is shown in Figure 4 and Table IV is that the obtained bound on the parameters agree with the results of [9], although the contour plot of $\Omega_m$ and $w_0$ can't reproduce the non-Gaussian behavior of the actual posterior.

| Parameter | Fiducial 68% c.l. bound |
|-----------|-------------------------|
| $\Omega_m$ | 0.2 | 0.3 |
| $w_0$ | -0.9 | 0.1 |

TABLE IV: 68% confidence level bounds on cosmological parameters to be compared with the first row of Table 6 of [9].
FIG. 4: Contour plot between $\Omega_m$ and $w_0$ to be compared with Figure 4 of [9].

V. WEAK LENSING FORECASTS

The validation package also contains Weak Lensing forecasted bounds, obtained using the optimistic and pessimistic specifications for a ground based Dark Energy Task Force Stage IV (DETFIV) experiment [10]. Results are compared with what is obtained in the Weak Lensing section of the DETF document [10]. While the optimistic case is in good agreement with the DETF forecasts, the pessimistic case is less degraded in CosmicFish results; this is easily explained by the fact that we do not include the same systematic effects as in DETF pessimistic forecasts.

| Parameter | Fiducial | Pessimistic case | Optimistic case |
|-----------|----------|-----------------|-----------------|
| $\Omega_\Lambda$ | 0.73 | 0.006 | 0.005 |
| $w_0$ | −1.0 | 0.05 | 0.05 |
| $w_a$ | 0.0 | 0.2 | 0.2 |

TABLE V: 68% confidence level bounds on cosmological parameters Dark Energy parameters to be compared respectively with WL-IVLST-p and WL-IVLST-p entries of the Table at page 77 of [10].

VI. GALAXY CLUSTERING FORECASTS

The CosmicFish Galaxy Clustering pipeline is validated obtaining bounds on cosmological parameters using DES specifications found in [11]. As in this paper, the varying parameters are S6, the energy density of massive neutrinos $\Omega_\nu h^2$ and the Dark Energy equation of state parameters $w_0$ and $w_a$.

Results shown in Figure 5 and Table VI show a very good agreement with that is found in [11].

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FIG. 5: Contour plots for several parameter combinations, to be compared with the blue dashed contours of Figure 11 of [11]

| Parameter | Fiducial | Planck+DES 68% c.l. bound |
|-----------|----------|--------------------------|
| \(w_0\)   | \(-1.0\) | 0.3                      |
| \(w_a\)   | 0.0      | 0.8                      |
| \(\Sigma m_\nu\) | 0.32 | 0.08                     |

TABLE VI: 68% confidence level bounds on the sum of neutrino masses and on Dark Energy equation of states parameters. To be compared with the third row, fifth column of Table V and fourth row, second column of Table VII of [11].

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[1] M. Raveri, M. Martinelli, G. Zhao and Y. Wang, arXiv:1606.06273 [astro-ph.CO].
[2] M. Raveri, M. Martinelli, G. Zhao and Y. Wang, arXiv:1606.06268 [astro-ph.CO].
[3] Planck - The Scientific Programme [http://sci.esa.int/jump.cfm?oid=47331]
[4] J. Bock et al. (2009) arXiv:0906.1188
[5] S. Galli, M. Martinelli, A. Melchiorri, L. Pagano, B. D. Sherwin and D. N. Spergel, Phys. Rev. D 82 (2010) 123504 doi:10.1103/PhysRevD.82.123504 [arXiv:1005.3808 [astro-ph.CO]].
[6] R. Adam et al. [Planck Collaboration], arXiv:1502.01582 [astro-ph.CO].
[7] P. A. R. Ade et al. [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO].
[8] M. Martinelli, S. Pandolfi, C. J. A. P. Martins and P. E. Vielzeuf, Phys. Rev. D 86 (2012) 123001 doi:10.1103/PhysRevD.86.123001 [arXiv:1210.7166 [astro-ph.CO]].
[9] A. Conley et al. [SNLS Collaboration], Astrophys. J. Suppl. 192 (2011) 1 doi:10.1088/0067-0049/192/1/1 [arXiv:1104.1443 [astro-ph.CO]].
[10] A. Albrecht et al., astro-ph/0609591.
[11] A. Zablocki, arXiv:1411.7387 [astro-ph.CO].