Large scale structure of the Universe becomes a leading source of precision cosmological information. We present two particular tools that can be used in cosmological analyses of the redshift space galaxy clustering data: a new open-source code CLASS-PT and the theoretical error approach. CLASS-PT computes one-loop power auto- and cross-power spectra for matter fields and biased tracers in real and redshift spaces. We show that the code meets the precision standards set by the upcoming high-precision large-scale structure surveys. The theoretical error likelihood approach allows one to analyze galaxy clustering data without having to measure the scale cut $k_{\text{max}}$. This approach takes into account that theoretical uncertainties affect parameter estimation gradually, which helps optimize data analysis and ensures that all available cosmological information is extracted.

1 Introduction

Large-scale structure (LSS) data becomes an increasingly important source of cosmological information. Very soon it will become competitive with the cosmic microwave background (CMB) data analysis. In contrast with the CMB, the LSS data analysis is complicated by non-linear clustering which is very hard to predict analytically. This problem is resolved in the effective field theory of large-scale structure, and its various extensions, such as time-sliced perturbation theory, which allow one to systematically model various short-scale phenomena on mildly nonlinear scales.

In the first part of this note we present a new code CLASS-PT that embodies an end-to-end calculation of one-loop power spectra for matter field and bias tracers using the state-of-the-art perturbation theory approach. Even though CLASS-PT is based on the well-known theoretical framework, it brings several novelties. First, it uses a new FFTLog method to efficiently compute convolution integrals. Second, another crucial advantage of CLASS-PT is an accurate and efficient description of the BAO wiggles using the infrared (IR) resummation of long-wavelength contributions. This is particularly important for data analysis, where the BAO encapsulate a significant portion of cosmological information.

In the second part, we introduce a novel data analysis technique based on the theoretical error covariance, which allows one to avoid uncertainties in the theoretical estimates of higher-order nonlinearities. We demonstrate that this approach yields unbiased constraints on all cosmological parameters. In addition, we also show that the theoretical error effectively optimizes the choice of $k_{\text{max}}$ in realistic data analyses.
2 CLASS–PT

Let us start with theoretical modeling of galaxy power spectrum in redshift space. The radial position of the galaxies in real surveys are distorted by the peculiar velocity field. It introduces so-called redshift-space distortions (RSD). We will work in the plane-parallel approximation, where the mapping between the redshift and real spaces is entirely parameterized by the cosine of the angle between the line-of-sight $\hat{z}$ and the wavevector of a given Fourier mode $k, \mu = (\hat{z} \cdot \mathbf{k})/k$. This setup allows one to express the one-loop redshift-space spectrum in the following simple form

$$
P_{gg, RSD}(z, k, \mu) = Z_1^2(k)P_{lin}(z, k) + 2 \int_q Z_2^2(q, k - q)P_{lin}(z, |k - q|)P_{lin}(z, q)$$

$$+ 6Z_1(k)P_{lin}(z, k) \int_q Z_3(q, -q, k)P_{lin}(z, q)$$

$$+ P_{ctr, RSD}(z, k, \mu) + P_{\epsilon, RSD}(z, k, \mu),$$

where the redshift-space kernels can be found in $^5$. $P_{ctr, RSD}(z, k, \mu)$ represents counterterm contributions in redshift space which in the leading order can be written as follows

$$P_{ctr, RSD}(z, k, \mu) = -2\epsilon_0(z)k^2P_{lin}(z, k) - 2\epsilon_2(z)f(z)\mu^2k^2P_{lin}(z, k)$$

$$- 2\epsilon_4(z)f^2(z)\mu^4k^2P_{lin}(z, k) - 2b_4(b_1 + f\mu^2)^2k^4P_{lin}(k),$$

$P_{\epsilon, RSD}(z, k, \mu)$ denotes the stochastic contribution which in the redshift space has the following structure

$$P_{\epsilon, RSD}(z, k, \mu) = P_{shot}(z) + a_0(z)k^2 + a_2(z)\mu^2k^2,$$

where $P_{shot}(z)$ describes a constant shot noise and the additional terms represent scale-dependent contributions to the monopole and the quadrupole moments of power spectrum.

The full angular dependence of the redshift-space power spectrum can be encoded in a number of multipoles using the following relation

$$P_{gg, RSD}(z, k, \mu) = \sum_{\ell = 0}^{\infty} L_{\ell}(\mu)P_{\ell}(z, k),$$

Explicit expressions for $P_{\ell}$ can be found in $^4$. Let us briefly discuss the accuracy of calculations in CLASS–PT. In Fig. 1 we show the residuals between evaluation of the one-loop correction to the matter power spectrum with the FFTLog method and its direct numerical calculation for two different precision settings. In the default regime we implement the FFTLog method for the grid with $N_{FFTLog} = 256$ harmonics. In the FAST mode we create a grid of lower dimension.

![Figure 1 - Residuals between the one-loop correction to the matter power spectrum and its direct numerical evaluation for the default settings (left panel) and in the FAST mode (right panel).]
N_{FFTLog} = 128 that significantly speeds up our calculations. We found that the default choice of $N_{FFTLog} = 256$ provides $\sim 0.1\%$ accuracy which is sufficient for future galaxy surveys. The FAST mode has somewhat worse accuracy of the one-loop calculation, around $\sim 1\%$. Still, it translates to the $\mathcal{O}(0.1\%)$ accuracy on the total power spectrum. Therefore, the FAST mode is sufficient for the analysis of current LSS data.

Let us discuss the performance of CLASS-PT. Tab. 1 summarizes the run times for various tests in two regimes (default and FAST). Our results show that the galaxy power spectra in redshift space can be calculated over 1.3 seconds for high precision settings. In the FAST mode the execution time reduces to 0.3 seconds.

Finally, we discuss the systematic uncertainties associated with the implementation of IR resummation in CLASS-PT. Detailed information about the implementation of IR resummation in CLASS-PT can be found in \cite{4}. In the left panel of Fig. 2 we show the contributions of all these effect to the total error budget along with the two-loop correction at $z = 0$. Once can see that the errors caused by inaccuracies in IR resummation are always smaller than the two-loop contributions missed in our model. It means that the CLASS-PT provides a stable calculation of one-loop power spectrum up to next-to-leading order corrections. These corrections can be systematically taken into account within time-sliced perturbation theory.

### Table 1: Performance of the code in the baseline and FAST precision modes. We show the execution time in [sec.] as follows: $t_{\text{full}}(t_{\text{FFTLog}})$, where $t_{\text{full}}$ is the full evaluation time taken by the non-linear module, and $t_{\text{FFTLog}}$ is the time elapsed during the matrix multiplication with FFTLog method.

| Run       | Real space | IR resum. | RSD   | IR+RSD | IR+RSD+AP |
|-----------|------------|-----------|-------|--------|-----------|
| Matter    | 0.036 (0.036) | 0.175 (0.036) | 0.375 (0.375) | 0.75 (0.62) | 0.76 (0.63) |
| Tracers   | 0.21 (0.21) | 0.35 (0.21) | 0.89 (0.89) | 1.27 (1.12) | 1.30 (1.14) |
| FAST mode | Matter     | 6.3 (6.1) $\times 10^{-3}$ | 0.14 (0.0061) | 0.063 (0.061) | 0.22 (0.09) |
|           | Tracers    | 0.033 (0.034) | 0.17 (0.034) | 0.14 (0.14) | 0.31 (0.18) |

Figure 2 – Left panel: Error budget of various systematic effects relative to the two-loop contribution (black line) at $z = 0$. Right panel: Residuals in measurements of cosmological parameters from the redshift space galaxy multipoles of N-body data.

3 Theoretical error approach

In this section we summarize the theoretical error approach \cite{9,10}. We show how the theoretical error covariance can be included in the realistic data analysis.

1. Choose some fiducial cosmological model.
2. Select the fiducial data cut $k_{\text{fid}}^\text{max}$. This data cut should be reasonably small to make theoretical error negligible.

3. Obtain the best-fit theoretical prediction $P_{\text{best-fit}}(k)$ by fitting the data at $k_{\text{fid}}^\text{max}$ and by varying only nuisance parameters.

4. Take this best-fit theoretical curve and construct the theoretical envelope as $P_i^{(\text{TE})} = P_i^\text{d} - P_{\text{best-fit}}(k_i)$. The statistical scatter in the data vector $P_i^\text{d}$ can be removed by fitting $P_i^{(\text{TE})}$ with a smooth polynomial.

5. Build up the TE likelihood using $P_i^{(\text{TE})}$

$$-2\ln L(P(\vec{\theta})) = (C + C^{(E)})^{-1} \left( P(\vec{\theta}) + P_i^{(\text{TE})} - P_i^\text{d} \right) \left( P(\vec{\theta}) + P_i^{(\text{TE})} - P_j^\text{d} \right),$$

where $C^{(E)}_{ij} = P_i^{(\text{TE})} P_j^{(\text{TE})} e^{-\frac{(k_i-k_j)^2}{2\Delta k^2}}$, with $\Delta k = 0.1 \, h/\text{Mpc}$. \hspace{1cm} (6)

We demonstrate the application of this approach using a suite of LasDamas Oriana simulations. Further details can be found in 9.

We run several analyses with different $k_{\text{max}}$ and compare these result with the TE approach. The marginalized constraints on cosmological parameters for the $k_{\text{max}}$ and TE (rightmost point) analyses are shown in the right panel of Fig. 2. We found that the TE analysis yields unbiased cosmological constraints with errorbars that match those coming from a carefully chosen $k_{\text{max}}$. Thus, the TE approach effectively optimizes the choice of the data cut.

4 Conclusion

In this work we presented a new module CLASS-PT that incorporates one-loop theory calculations. It contains all ingredients needed for direct application to real data. We also introduced a new approach based on the theoretical error covariance which allows one to avoid uncertainties in the theoretical estimates of higher-order nonlinearities. We showed that this approach yields unbiased estimates of cosmological parameters and effectively optimize the choice of $k_{\text{max}}$.

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