RegPT: code description

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I. OVERVIEW

The code, RegPT, can be compiled with the fortran compilers, ifort or gfortran. It computes the power spectrum in flat wCDM class models based on the RegPT treatment when provided with either of transfer function or matter power spectrum. It then gives the multiple-redshift outputs for power spectrum, and optionally provides correlation function data. We have implemented two major options for power spectrum calculations:

- -fast: Applying the reconstruction method described in [1], this option quickly computes the power spectrum at two-loop level (typically a few seconds), using the pre-computed data set of PT kernels for fiducial cosmological models. We provide the data set for three fiducial models (wmap3, M001, and M023, see Table II of Ref. [1], and the code automatically finds an appropriate fiducial model to closely match the result of rigorous PT calculation with direct-mode.
- -direct: With this option, the code first applies the fast method, and then follows the regularized expression for power spectrum to directly evaluate the multi-dimensional integrals (it typically takes a few minutes). The output results are the power spectrum of direct calculation and difference of the results between fast and direct method. Further, the code gives the data set of PT diagrams necessary for power spectrum calculations, from which we can construct the power spectrum. We provide a supplemental code, read_stfile.f, with which the power spectrum and correlation function can be evaluated from the diagram data set in several PT methods, including the standard PT and Lagrangian resummation theory [2, 3] as well as RegPT treatment (see Sec. IV C).

In addition, the code supports the option, -direct1loop, to compute the power spectrum at one-loop order. Although this is based on the direct calculation with multi-dimensional integration, the one-loop expression involves two-dimensional integrals at most, and thus the computational cost is less expensive. It is potentially useful for the computation of high-z correlation function and power spectrum.

II. SETUP

A part of RegPT code uses the library for Monte Carlo integration, CUBA [4]. Before compiling the codes, users should download the library package cuba-1.5[1],

and correctly build the file, libcuba.a, compatible with the architecture of user's platform. This can be done in the directory /Cuba-1.5, and just type ./configure and make lib. After placing the library file libcuba.a at the directory /RegPT/src, users can use the Makefile to create the main executable file, RegPT.exe. Note that currently available compilers are intel fortran compiler, ifort, and GNU fortran compiler, gfortran.

III. RUNNING THE CODE

Provided with linear power spectrum or transfer function data, the code runs with a set of options, and computes power spectrum. Users can specify the options in the command line, or using the parameter file (suffix of file name should be .ini). Sample of parameter file is supplied in the code (see directory /RegPT/example).

For running the code with the command-line options, a simple example is (assuming the code is placed at the directory, /RegPT)

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[1] http://www.feynarts.de/cuba/

```
./RegPT.exe -spectrum -infile matterpower_wmap5.dat -nz 2 0.5 1.0
```

In the above example, the code first reads the input data file, `matterpower_wmap5.dat`, which is assumed to contain linear power spectrum data consisting of two columns, i.e., k and $P_0(k)$. By default setting, `fast` mode is chosen, and the output result of power spectrum is saved to `pk_RegPT.dat`. With the option `-nz 2 0.5 1.0`, the output file contains the power spectrum results at two redshifts, $z = 0.5$ and 1.0 (see Sec. IV A for output format). Note that by default, the code adopts specific values of cosmological parameters. Making use of options, users can change the value of cosmological parameters appropriately, consistently with input power spectrum (or transfer function) data.

Here we summarize the available options to run the code:

- Verbose level for output message

  `-verbose` n: This sets the verbose level for output information on the progress of numerical computation. The available level n is 1 or 2 (default: `-verbose 1`).

  `-noverbose`: This option suppresses the message while running the code.

- Input data file

  `-infile` [file]: Input file name of power spectrum or transfer function data is specified (default: `-infile matterpower.dat`).

  `-path` [path to input file]: This specifies the path to the input file (default: `-path ./`).

  `-spectrum`: With this option, the code assumes that the input file is power spectrum data. The data consists of two columns, i.e., wavenumber (in units of $h\,\mathrm{Mpc}^{-1}$) and matter power spectrum (in units of $h^{-3}\,\mathrm{Mpc}^3$) (default: `-spectrum`). The normalization of power spectrum amplitude can be made with the option `-sigma8`.

  `-transfer`: With this option, the code assumes that the input file is the transfer function data created by CAMB. The data should contain 7 columns, among which the code uses the first and seven columns (wavenumber in units of $h\,\mathrm{Mpc}^{-1}$ and matter transfer function). The normalization of power spectrum amplitude can be made with either of the option `-sigma8` or `-samp` and `-spivot`.

- Specification of cosmological parameters

  `-sigma8` σ_8: This option sets the power spectrum normalization by σ_8 (default: `-sigma8 0.817`). For $\sigma_8 < 0$, the code will skip the σ_8 normalization.

  `-samp` A_s: This option sets the amplitude of power spectrum at pivot scale k_pivot (default: `-samp 2.1e-9`). This option is used for normalization of transfer function data, and is valid when the option `-transfer` is specified.

  `-spivot` k_pivot: This option sets the pivot scale of CMB normalization in units of Mpc^{-1} (default: `-spivot 0.05`). This option is used for normalization of transfer function data, and is valid when the option `-transfer` is specified.

  `-omegam` Ω_m: This option sets the mass density parameter (default: `-omegam 0.279`). This is used to estimate the linear growth factor and to compute the smooth reference spectrum, $P_\text{no-wiggle}(k)$.

  `-omegab` Ω_b: This option sets the baryon density parameter (default: `-omegab 0.165*omegam`). This is used to compute the smooth reference spectrum, $P_\text{no-wiggle}(k)$.

  `-ns` n_s: This option sets the scalar spectral index. This is used to compute the linear power spectrum from the transfer function data (option `-transfer` should be specified), and to compute the smooth reference spectrum, $P_\text{no-wiggle}(k)$.

  `-w` w: This option sets the equation of state for dark energy (default: `-w -1.0`). This is used to estimate the linear growth factor.

  `-h` h: This option sets the Hubble parameter (default: `-h 0.701`). This is used to compute the power spectrum from the transfer function data, and to compute the smooth reference spectrum, $P_\text{no-wiggle}(k)$.

  `-camb` [output parameter file of camb]: With this option, the code reads the CAMB output parameter file, and

specifies the cosmological parameters ($\Omega_{\rm m}$, $\Omega_{\rm b}$, w, h, $n_{\rm s}$, $A_{\rm s}$, $k_{\rm pivot}$).

- Calculation mode of `RegPT`

  `-fast`: This option adopts the fast method of power spectrum calculation to give `RegPT` results. This is default setting.

  `-direct`: This option first applies the fast method, and then follow the direct method for `RegPT` calculation.

  `-direct1loop`: With this option, the code adopts direct method to compute the power spectrum at one-loop order.

- Setup of fiducial models for fast- and direct-mode calculations

  `-datapath` [path to data directory]: This option specifies the path to the data files used for power spectrum calculation with fast and direct methods (default: `-datapath data/`). In the directory specified with this option, the data set of kernel functions given in Appendix B of Ref. [1] and un-perturbed part of power spectrum corrections, as well as the matter power spectrum should be stored for three fiducial cosmological models (`wmap3`, `M001`, `M023`).

  `-fiducial` [model]: This option sets the specific fiducial model among the three, `wmap3`, `M001`, and `M023` (in default setting, the code automatically selects an appropriate fiducial model).

- Output data file

  `-xicompute`: With this option, the code computes the correlation function after power spectrum calculations, and creates the output file.

  `-nz` n z_1 $\cdots$ z_n: This option specifies the output redshifts for power spectrum calculations. The integer n specifies the number of redshifts, and subsequent arguments specify the value of each redshift (default: `-nz 1 1.0`).

  `-pkfile` [file]: This option sets the output file name of power spectrum data (default: `pk_RegPT.dat`).

  `-xifile` [file]: This option sets the output file name of correlation function data (default: `xi_RegPT.dat`).

  `-stfile` [file]: This option sets the output file name of PT diagram data (default: `st_PT.dat`).

IV. OUTPUT FILE FORMAT

In what follows, wavenumber k and separation r are in units of $h\,{\rm Mpc}^{-1}$ and $h^{-1}\,{\rm Mpc}$, respectively. All the power spectrum data are assumed to be in units of $h^{-3}\,{\rm Mpc}^3$.

A. Power spectrum data

By default, `RegPT` code creates the output file for the power spectrum data (default file name is `pk_RegPT.dat`). The columns of this file include

$$k,\ [\text{data for } z_1],\ [\text{data for } z_2],\ \cdots, [\text{data for } z_n]$$

The first column is the wavenumber, while the bracket [data for z_i] represents a set of power spectra at given redshift z_i and wavenumber k. Number of the data set is specified with the option `-nz`, and each data contains

$$P_{\text{no-wiggle}}(k,z_i),\ P_{\rm lin}(k,z_i),\ P_{\rm RegPT}(k,z_i),\ {\rm Err}(k)$$

Here, the spectrum $P_{\text{no-wiggle}}$ is the smooth reference spectrum calculated from the no-wiggle formula of linear transfer function in Ref. [5], $P_{\rm lin}$ is the linearly extrapolated spectrum, and $P_{\rm RegPT}(k,z_i)$ represents the power spectrum based on the RegPT calculations with fast and/or direct method (depending on the choice of options, `-fast`, `-direct` or `-direct1loop`). The last column, Err, usually sets to zero, but with the option `-direct`, it gives the difference of the power spectra between fast and direct methods.

B. Correlation function data

With the option `-xicompute`, the code also provides the output file for correlation function data (default file name is `xi_RegPT.dat`). Similar to the power spectrum data, the structure of the data is

$$r,\ [\text{data for } z_1],\ [\text{data for } z_2],\ \cdots, [\text{data for } z_n]$$

The first column is the separation, while the bracket [data for z_i] represents a set of correlation functions given at redshift z_i and separation r, containing two columns:

$$\xi_{\rm lin}(r, z_i),\ \xi_{\rm RegPT}(r, z_i)$$

These are simply obtained from the output results of power spectrum based on the expression:

$$\xi(r) = \int \frac{dk\, k^2}{2\pi^2}\, P(k)\, \frac{\sin(kr)}{kr}.$$

Note that the range of wavenumber for output power spectrum is restricted to the wavenumber coverage of input linear spectrum (or transfer function). To get a convergent result of correlation functions, users may have to supply the input data file with a sufficiently wide range of wavenumber (e.g., $10^{-3} \le k \le 10\, h\,{\rm Mpc}^{-1}$).

C. Diagram data

When users specifies the `-direct` option, the code additionally provides a set of PT diagram data necessary for power spectrum computation, from which we can construct the power spectrum at one- and two-loop order. The output file (default file name is `st_PT.dat`) includes the following columns:

$$k,\ P_{\text{no-wiggle}}(k),\ P_{\rm lin}(k),\ \overline{\Gamma}^{(1)}_{\text{1-loop}}(k),\ \overline{\Gamma}^{(1)}_{\text{2-loop}}(k),\ P^{(2)\text{tree-tree}}_{\rm corr}(k),\ P^{(2)\text{tree-1loop}}_{\rm corr}(k),\ P^{(2)1\text{loop-1loop}}_{\rm corr}(k),\ P^{(3)\text{tree-tree}}_{\rm corr}(k)$$

Here, the power spectra $P_{\text{no-wiggle}}$ and $P_{\rm lin}$ are basically the same data as contained in the power spectrum file, but these are the extrapolated data at $z = 0$ (that is, $P_{\rm lin}$ corresponds to P_0). The function $\overline{\Gamma}^{(1)}_{n\text{-loop}}$ is the two-point propagator of the standard PT expansion (see Ref. [1] for definition). The functions in the remaining four columns, $P^{(2)\text{tree-tree}}_{\rm corr}$, $P^{(2)\text{tree-1loop}}_{\rm corr}$, $P^{(2)1\text{loop-1loop}}_{\rm corr}$, and $P^{(3)\text{tree-tree}}_{\rm corr}$, are defined by

$$P^{(2)\text{tree-tree}}_{\rm corr}(k) = 2\int \frac{d^3\boldsymbol{q}}{(2\pi)^3} F^{(2)}_{\rm sym}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) F^{(2)}_{\rm sym}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) P_0(q) P_0(|\boldsymbol{k}-\boldsymbol{q}|), \tag{4.1}$$

$$P^{(2)\text{tree-1loop}}_{\rm corr}(k) = 4\int \frac{d^3\boldsymbol{q}}{(2\pi)^3} F^{(2)}_{\rm sym}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) \overline{\Gamma}^{(2)}_{\text{1-loop}}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) P_0(q) P_0(|\boldsymbol{k}-\boldsymbol{q}|), \tag{4.2}$$

$$P^{(2)1\text{loop-1loop}}_{\rm corr}(k) = 2\int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \overline{\Gamma}^{(2)}_{\text{1-loop}}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) \overline{\Gamma}^{(2)}_{\text{1-loop}}(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) P_0(q) P_0(|\boldsymbol{k}-\boldsymbol{q}|), \tag{4.3}$$

$$P^{(3)\text{tree-tree}}_{\rm corr}(k) = 6\int \frac{d^3\boldsymbol{p}\, d^3\boldsymbol{q}}{(2\pi)^6} F^{(3)}_{\rm sym}(\boldsymbol{p}, \boldsymbol{q}, \boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q}) F^{(3)}_{\rm sym}(\boldsymbol{p}, \boldsymbol{q}, \boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q}) P_0(p) P_0(q) P_0(|\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q}|). \tag{4.4}$$

Provided the data set above, the power spectrum can be constructed with

$$P^{\rm RegPT}_{\text{1-loop}}(k;\eta) = e^{2\eta}\, e^{-2\alpha_k} \left[\left\{ 1 + \alpha_k + e^{2\eta}\, \overline{\Gamma}^{(1)}_{\text{1-loop}}(k) \right\}^2 P_0(k) + e^{2\eta}\, P^{(2)\text{tree-tree}}_{\rm corr}(k) \right], \tag{4.5}$$

$$\begin{aligned} P^{\rm RegPT}_{\text{2-loop}}(k;\eta) = e^{2\eta}\, e^{-2\alpha_k} \Bigg[& \left\{ 1 + \alpha_k + \frac{\alpha_k^2}{2} + e^{2\eta}\, \overline{\Gamma}^{(1)}_{\text{1-loop}}(k)\, (1+\alpha_k) + e^{4\eta}\, \overline{\Gamma}^{(1)}_{\text{2-loop}}(k) \right\}^2 P_0(k) \\ & + e^{2\eta} \left\{ (1+\alpha_k)^2 P^{(2)\text{tree-tree}}_{\rm corr}(k) + e^{2\eta}(1+\alpha_k) P^{(2)\text{tree-1loop}}_{\rm corr}(k) + e^{4\eta}\, P^{(2)1\text{loop-1loop}}_{\rm corr}(k) \right\} + e^{4\eta}\, P^{(3)1\text{loop-1loop}}_{\rm corr}(k) \Bigg], \end{aligned} \tag{4.6}$$

for the RegPT calculation at one- and two-loop order, respectively. Here, α_k is given by $\alpha_k = k^2\sigma_{\rm d}^2 e^{2\eta}/2$ with $\sigma_{\rm d}$ being the dispersion of displacement field (see Ref. [1] for definition). Note that the diagram data set can be also used to compute the power spectrum in the standard PT calculations:

$$P^{\rm SPT}_{\text{1-loop}}(k;\eta) = e^{2\eta}\,P_0(k) + e^{4\eta}\left[2\,P_0(k)\,\overline{\Gamma}^{(1)}_{\text{1-loop}}(k) + P^{(2)\text{tree-tree}}_{\rm corr}(k)\right], \tag{4.7}$$

$$P^{\rm SPT}_{\text{2-loop}}(k;\eta) = P^{\rm SPT}_{\text{1-loop}}(k;\eta) + e^{6\eta}\left[\,P_0(k)\,\{\overline{\Gamma}^{(1)}_{\text{1-loop}}(k)\}^2 + P^{(3)\text{tree-tree}}_{\rm corr}(k) + P^{(2)\text{tree-1loop}}_{\rm corr}(k) + 2P_0(k)\,\overline{\Gamma}^{(1)}_{\text{2-loop}}(k)\right]. \tag{4.8}$$

With the supplemental code, `read_stfile.f`, users can easily compute the power spectrum in both RegPT and standard PT treatments. The code also provides the power spectrum result for Lagrangian resummation theory [2, 3]. A brief instruction on how to run the code and the output format of data is described in the header of the code.

V. LIMITATION

Since the RegPT code is the PT-based calculation code valid at weakly non-linear scales, the applicability of the output results is restriced to a certain range of wavenumber in power spectrum. We provide an empirical estimate of critical wavenumber $k_{\rm crit}$, below which the RegPT results are reliable and their accuracy can reach a percent level. This is based on the expression

$$\frac{k^2_{\rm crit}}{6\pi^2}\int_0^{k_{\rm crit}} dq\,P_{\rm lin}(q;z) = C, \tag{5.1}$$

with constant value $C = 0.7\,(0.3)$ for two-loop (one-loop) [1]. With the option `-verbose 2`, the code displays the critical wavenumbers at output redshifts. Note that the value $k_{\rm crit}$ given here is just a crude estimate, and the actual domain of applicability may be somewhat wider or narrower. Users should use the output results with a great care.

VI. NOTES

The RegPT code is free software: you can redistribute it and/or modify it at your own risk. This program is distributed in the hope that it will be useful in scientific research, but without any warranty.

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