CLASS MANUAL

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Chapter 1

CLASS: Cosmic Linear Anisotropy Solving System

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with several major inputs from other people, especially Thomas Tram, as well as Benjamin Audren, Simon Prunet, Jesus Torrado, Miguel Zumalacarregui, etc.

For download and information, see http://class-code.net

Compiling CLASS and getting started

(the information below can also be found on the webpage, just below the download button)

After downloading the code, unpack the archive (tar -zxvf class_v*.tar.gz), go to the class directory (cd class_v*/) and compile (make clean; make class). If the first compilation attempt fails, you may need to open the Makefile and adapt the name of the compiler (default: gcc), of the optization flag (default: -O4) and of the OpenMP flag (default: -fopenmp; this flag is facultative, you are free to compile without OpenMP if you don't want parallel execution; note that you need the version 4.2 or higher of gcc to be able to compile with -fopenmp. Several details on the CLASS compilation are given on the wiki page

https://github.com/lesgourg/class_public/wiki/Installation

(in particular, for compiling on Mac 10.9 Mavericks).

To check that the code runs, type:

```
./class explanatory.ini
```

The explanatory.ini file is a reference input file, containing and explaining the use of all possible input parameters. We recommend to read it, to keep it unchanged (for future reference), and to create for your own purposes some shorter input files, containing only the input lines which are useful for you. Input files must have a *.ini extension.

If you want to play with the precision/speed of the code, you can use one of the provided precision files (e.g. cl_permille.pre) or modify one of them, and run with two input files, for instance:

```
./class test.ini cl_permille.pre
```

A simplified documentation can be found in the paper CLASS I: Overview <http://arxiv.org/abs/1104.2932>_. On top of that, if you wish to modify the code, you will find lots of comments directly into the files. Other CLASS papers dedicated to various aspects of the code are listed in the CLASS web page. Slides from CLASS-dedicated courses can be seen at

http://lesgourg.web.cern.ch/lesgourg/class-tour/class-tour.html

To use CLASS from python, or ipython notebooks, or from the Monte Python parameter extraction code, you need to compile not only the code, but also its python wrapper. This can be done by typing just 'make' instead of 'make class'. More details on the wrapper and its compilation are found on the wiki page

https://github.com/lesgourg/class_public/wiki

Plotting utility

Since version 2.3, the package includes an improved plotting script called CPU.py (Class Plotting Utility), written by Benjamin Audren and Jesus Torrado. It can plot the Cl's, the P(k) or any other CLASS output, for one or several models, as well as their ratio or percentage difference. The syntax and list of available options is obtained by typing 'pyhton CPU.py –help'. There is a similar script for MATLAB, written by Thomas Tram. To use it, once in MATLAB, type 'help plot_CLASS_output.m'

Developing the code

If you want to develop the code, we suggest that you download it from the github webpage

https://github.com/lesgourg/class_public

rather than from class-code.net. Then you will enjoy all the feature of git repositories. You can even develop your own branch and get it merged to the public distribution. For related instructions, check

https://github.com/lesgourg/class_public/wiki/Public-Contributing

Using the code

You can use CLASS freely, provided that in your publications, you cite at least the paper CLASS II↩ : Approximation schemes <http://arxiv.org/abs/1104.2933>_. Feel free to cite more C↩ LASS papers!

Support

To get support, please open a new issue on the

https://github.com/lesgourg/class_public

webpage!

Chapter 2

CLASS: Cosmic Linear Anisotropy Solving System

Author: Julien Lesgourgues

Overall architecture of `class`

The seven-module backbone

The purpose of `class` consists in computing some power spectra for a given set of cosmological parameters. This task can be decomposed in few steps or modules:

1. compute the evolution of cosmological background quantitites.
2. compute the evolution of thermodynamical quantitites (ionization fractions, etc.)
3. compute the evolution of source functions $S(k,\eta)$ (by integrating over all perturbations).
4. compute Bessel functions (in order to go from Fourier to harmonic space).
5. compute transfer functions $\Delta_l(k)$ (unless one needs only Fourier spectra $P(k)$'s and no harmonic spectra C_l's).
6. compute the primordial spectrum for scalars, tensors, etc. (straightforward if the input consists in spectral parameters A_s, n_s, r, ..., but this module will incorporate the option of integrating over inflationary perturbations).
7. compute power spectra C_l's and/or $P(k)$'s.

In `class`, each of these steps is associated with a structure:

1. `struct background` for cosmological background,
2. `struct thermo` for thermodynamics,
3. `struct perturbs` for source functions,
4. `struct bessels` for bessel functions,
5. `struct transfers` for transfer functions,
6. `struct primordial` for primordial spectra,
7. `struct spectra` for output spectra.

A given structure contains "everything concerning one step that the subsequent steps need to know" (for instance, everything about source functions that the transfer module needs to know). In particular, each structure contains one array of tabulated values (background quantitites as a function of time, thermodynamical quantitites as a function of redshift, sources as a function of (k, η), etc.). It also contains information about the size of this array and the value of the index of each physical quantity, so that the table can be easily read and interpolated. Finally, it contains any derived quantity that other modules might need to know. Hence, the comunication from one module A to another module B consists in passing a pointer to the structure filled by A, and nothing else.

Each structure is defined and filled in one of the following modules (and precisely in the order below):

1. `background.c`
2. `thermodynamics.c`
3. `perturbations.c`
4. `bessel.c`
5. `transfer.c`
6. `primordial.c`
7. `spectra.c`

Each of these modules contains at least three functions:

- *module*`_init(...)`
- *module*`_free()`
- *module*`_`∗something∗`_at_`∗somevalue∗`(...)`

The first function allocates and fills each structure. This can be done provided that the previous structures in the hierarchy have been already allocated and filled. In summary, calling one of *module*`_init(...)` amounts in solving entirely one of the steps 1 to 7.

The second function deallocates the fields of each structure. This can be done optionally at the end of the code (or, when the code is embedded in a sampler, this *must* be done between each execution of `class`, and especially before calling *module*`_init(...)` again with different input parameters).

The third function is able to interpolate the pre-computed tables. For instance, `background\_init()` fills a table of background quantitites for discrete values of conformal time η, but `background\_at\_eta(eta, \* values)` will return these values for any arbitrary η.

Note that functions of the type *module*`_`∗something∗`_at_`∗somevalue∗`(...)` are the only ones which are called from another module, while functions of the type *module*`_init(...)` and *module*`_free()` are the only one called by the main executable. All other functions are for internal use in each module.

Input

There are two types of input:

1. "precision parameters" (controlling the precision of the output and the execution time),
2. "input parameters" (cosmological parameters, flags telling to the code what it should compute, ...)

All "precision parameters" have been grouped in a single structure `struct precision`. The code contains *no other arbitrary numerical coefficient*. This structure is initialized in a simple module `precision.c` by the function `precision\_init()`. Nothing is allocated dynamically in this function, so there is no need for a `precision\_free()` function.

Each “input parameter” refers to one particular step in the computation: background, thermodynamics, perturbations, etc. Hence they are defined as part of the corresponding structure. Their values are assigned in a simple module input.c, by a function input_init(...) which has a pointer towards each structure in its list of arguments. Hence, when a given function *module*_init(...) is called, the corresponding structure already contains input parameters; the function fills the rest of this structure. The function input_init(...) does not allocate any field dynamically, so there is no need for an input_free() function.

Output

A simple module output.c writes the final results in files. The name of the files are considered as input parameters making part of a small structure struct output. Like for all other input parameters, these names are assigned inside the function input_init(...). Again this structure contains no dynamically allocated quantitites, so there is no need for an output_free() function.

Summary

We hope that after this short overview, it is clear for the reader that the main executable of class should consist only in the following lines (not including comments and error-management lines):

For a given purpose, somebody could only be interested in the intermediate steps (only background quantitites, only the thermodynamics, only the perturbations and sources, etc.) It is then straightforward to truncate the full hierarchy of modules 1, ... 7 at some arbitrary order. We provide several “reduced executables” test_*module* achieving precisely this.

Note also that if class is embedded in a parameter sampler and only “fast” parameters are varied (i.e., parameters related to the primordial spectra), then it is only necessary to repeat the following steps after output_↩ init(...):

‘spectra_free()

primordial_free()

input_init(&ba,&th,&pt,&bs,&tr,&pm,&sp,&op)

primordial_init(&pt,&pr,&pm)

spectra_init(&pt,&tr,&pm,&sp)

output_init(&pt,&tr,&sp,&op)

‘

General principles

Flexibility

Explain allocation of indices, ...

Control of precision

Explain precision structure, ...

Control of errors

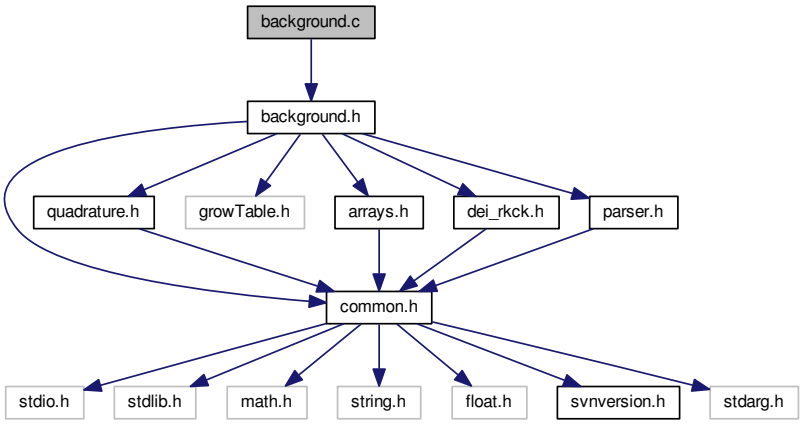
Chapter 3

File Documentation

3.1 background.c File Reference

```
#include "background.h"
```

Include dependency graph for background.c:



Functions

- int background_at_tau (struct background *pba, double tau, short return_format, short intermode, int *last↩ _index, double *pvecback)
- int background_tau_of_z (struct background *pba, double z, double *tau)
- int background_functions (struct background *pba, double *pvecback_B, short return_format, double *pvecback)
- int background_init (struct precision *ppr, struct background *pba)
- int background_free (struct background *pba)
- int background_free_input (struct background *pba)
- int background_indices (struct background *pba)
- int background_ncdm_distribution (void *pbadist, double q, double *f0)
- int background_ncdm_test_function (void *pbadist, double q, double *test)
- int background_ncdm_init (struct precision *ppr, struct background *pba)
- int background_ncdm_momenta (double *qvec, double *wvec, int qsize, double M, double factor, double z, double *n, double *rho, double *p, double *drho_dM, double *pseudo_p)

- int background_ncdm_M_from_Omega (struct precision *ppr, struct background *pba, int n_ncdm)
- int background_solve (struct precision *ppr, struct background *pba)
- int background_initial_conditions (struct precision *ppr, struct background *pba, double *pvecback, double *pvecback_integration)
- int background_output_titles (struct background *pba, char titles[_MAXTITLESTRINGLENGTH_])
- int background_output_data (struct background *pba, int number_of_titles, double *data)
- int background_derivs (double tau, double *y, double *dy, void *parameters_and_workspace, ErrorMsg error_message)
- double V_e_scf (struct background *pba, double phi)
- double V_p_scf (struct background *pba, double phi)
- double V_scf (struct background *pba, double phi)

3.1.1 Detailed Description

Documented background module

Julien Lesgourgues, 17.04.2011 routines related to ncdm written by T. Tram in 2011

Deals with the cosmological background evolution. This module has two purposes:

- at the beginning, to initialize the background, i.e. to integrate the background equations, and store all background quantities as a function of conformal time inside an interpolation table.
- to provide routines which allow other modules to evaluate any background quantity for a given value of the conformal time (by interpolating within the interpolation table), or to find the correspondence between redshift and conformal time.

The overall logic in this module is the following:

1. most background parameters that we will call {A} (e.g. rho_gamma, ..) can be expressed as simple analytical functions of a few variables that we will call {B} (in simplest models, of the scale factor 'a'; in extended cosmologies, of 'a' plus e.g. (phi, phidot) for quintessence, or some temperature for exotic particles, etc...).
2. in turn, quantities {B} can be found as a function of conformal time by integrating the background equations.
3. some other quantities that we will call {C} (like e.g. the sound horizon or proper time) also require an integration with respect to time, that cannot be inferred analytically from parameters {B}.

So, we define the following routines:

- background_functions() returns all background quantities {A} as a function of quantities {B}.
- background_solve() integrates the quantities {B} and {C} with respect to conformal time; this integration requires many calls to background_functions().
- the result is stored in the form of a big table in the background structure. There is one column for conformal time 'tau'; one or more for quantities {B}; then several columns for quantities {A} and {C}.

Later in the code, if we know the variables {B} and need some quantity {A}, the quickest and most precise way is to call directly background_functions() (for instance, in simple models, if we want H at a given value of the scale factor). If we know 'tau' and want any other quantity, we can call background_at_tau(), which interpolates in the table and returns all values. Finally it can be useful to get 'tau' for a given redshift 'z': this can be done with background_tau_of_z(). So if we are somewhere in the code, knowing z and willing to get background quantities, we should call first background_tau_of_z() and then background_at_tau().

In order to save time, background_at_tau() can be called in three modes: short_info, normal_info, long_info (returning only essential quantities, or useful quantities, or rarely useful quantities). Each line in the interpolation table is a vector which first few elements correspond to the short_info format; a larger fraction contribute to the normal format;

and the full vector corresponds to the long format. The guideline is that short_info returns only geometric quantities like a, H, H'; normal format returns quantities strictly needed at each step in the integration of perturbations; long_info returns quantities needed only occasionally.

In summary, the following functions can be called from other modules:

1. background_init() at the beginning
2. background_at_tau(), background_tau_of_z() at any later time
3. background_free() at the end, when no more calls to the previous functions are needed

3.1.2 Function Documentation

3.1.2.1 int background_at_tau (struct background * *pba*, double *tau*, short *return_format*, short *intermode*, int * *last_index*, double * *pvecback*)

Background quantities at given conformal time tau.

Evaluates all background quantities at a given value of conformal time by reading the pre-computed table ant interpolating.

Parameters

pba	Input: pointer to background structure (containing pre-computed table)
tau	Input: value of conformal time
return_format	Input: format of output vector (short, normal, long)
intermode	Input: interpolation mode (normal or closeby)
last_index	Input/Output: index of the previous/current point in the interpolation array (input only for closeby mode, output for both)
pvecback	Output: vector (assumed to be already allocated)

Returns

the error status

Summary:

- define local variables
- check that tau is in the pre-computed range
- deduce length of returned vector from format mode
- interpolate from pre-computed table with array_interpolate() or array_interpolate_growing_closeby() (depending on interpolation mode)

3.1.2.2 int background_tau_of_z (struct background * *pba*, double *z*, double * *tau*)

Conformal time at given redshift.

Returns tau(z) by interpolation from pre-computed table.

Parameters

pba	Input: pointer to background structure

z	Input: redshift
tau	Output: conformal time

Returns

the error status

Summary:

- define local variables
- check that z is in the pre-computed range
- interpolate from pre-computed table with array_interpolate()

3.1.2.3 int background_functions (struct **background** * *pba,* double * *pvecback_B,* short *return_format,* double * *pvecback*)

Background quantities at given a.

Function evaluating all background quantities which can be computed analytically as a function of {B} parameters such as the scale factor 'a' (see discussion at the beginning of this file). In extended cosmological models, the pvecback_B vector contains other input parameters than just 'a', e.g. (phi, phidot) for quintessence, some temperature of exotic relics, etc...

Parameters

pba	Input: pointer to background structure
pvecback_B	Input: vector containing all {B} type quantities (scale factor, ...)
return_format	Input: format of output vector
pvecback	Output: vector of background quantities (assumed to be already allocated)

Returns

the error status

Summary:

- define local variables
- initialize local variables
- pass value of a to output
- compute each component's density and pressure
- compute expansion rate H from Friedmann equation: this is the unique place where the Friedmann equation is assumed. Remember that densities are all expressed in units of $[3c^2/8\pi G]$, ie rho_class = $[8\pi G$ rho_$\hookleftarrow$ physical $/3c^2]$
- compute derivative of H with respect to conformal time
- compute relativistic density to total density ratio
- compute other quantities in the exhaustive, redundant format:
- compute critical density
- compute Omega_m

3.1.2.4 int background_init (struct **precision** * *ppr,* struct **background** * *pba*)

Initialize the background structure, and in particular the background interpolation table.

Parameters

ppr	Input : pointer to precision structure
pba	Input/Output : pointer to initialized background structure

Returns

the error status

Summary:

- local variables :
- in verbose mode, provide some information
- assign values to all indices in vectors of background quantities with background_indices()
- control that cosmological parameter values make sense
- this function integrates the background over time, allocates and fills the background table

3.1.2.5 int background_free (struct background * *pba*)

Free all memory space allocated by background_init().

Parameters

pba	Input : pointer to background structure (to be freed)

Returns

the error status

3.1.2.6 int background_free_input (struct background * *pba*)

Free pointers inside background structure which were allocated in input_read_parameters()

Parameters

pba	Input : pointer to background structure

Returns

the error status

3.1.2.7 int background_indices (struct background * *pba*)

Assign value to each relevant index in vectors of background quantities.

Parameters

pba	Input : pointer to background structure

Returns

the error status

Summary:

- define local variables
- initialize all flags: which species are present?
- initialization of all indices

3.1.2.8 int background_ncdm_distribution (void * *pbadist*, double *q*, double * *f0*)

This is the routine where the distribution function f0(q) of each ncdm species is specified (it is the only place to modify if you need a partlar f0(q))

Parameters

pbadist	Input: structure containing all parameters defining f0(q)
q	Input: momentum
f0	Output: phase-space distribution

Variables corresponding to entries in param:

- extract from the input structure pbadist all the relevant information
- shall we interpolate in file, or shall we use analytical formula below?

-> deal first with the case of interpolating in files

-> deal now with case of reading analytical function

Enter here your analytic expression(s) for the p.s.d.'s. If you need different p.s.d.'s for different species, put each p.s.d inside a condition, like for instance: if (n_ncdm==2) {*f0=...}. Remember that n_ncdm = 0 refers to the first species.

This form is only appropriate for approximate studies, since in reality the chemical potential are associated with flavor eigenstates, not mass eigenstates. It is easy to take this into account by introducing the mixing angles. In the later part (not read by the code) we illustrate how to do this

3.1.2.9 int background_ncdm_test_function (void * *pbadist*, double *q*, double * *test*)

This function is only used for the purpose of finding optimal quadrature weights. The logic is: if we can convolve accurately f0(q) with this function, then we can convolve it accurately with any other relevant function.

Parameters

pbadist	Input: structure containing all background parameters
q	Input: momentum
test	Output: value of the test function test(q)

Using a + bq creates problems for otherwise acceptable distributions which diverges as $1/r$ or $1/r^2$ for $r \to 0$

3.1.2.10 int background_ncdm_init (struct precision * *ppr*, struct background * *pba*)

This function finds optimal quadrature weights for each ncdm species

Parameters

ppr	Input: precision structure
pba	Input/Output: background structure

- in verbose mode, inform user of number of sampled momenta for background quantities

3.1.2.11 int background_ncdm_momenta (double * *qvec*, double * *wvec*, int *qsize*, double *M*, double *factor*, double *z*, double * *n*, double * *rho*, double * *p*, double * *drho_dM*, double * *pseudo_p*)

For a given ncdm species: given the quadrature weights, the mass and the redshift, find background quantities by a quick weighted sum over. Input parameters passed as NULL pointers are not evaluated for speed-up

Parameters

qvec	Input: sampled momenta
wvec	Input: quadrature weights
qsize	Input: number of momenta/weights
M	Input: mass
factor	Input: normalization factor for the p.s.d.
z	Input: redshift
n	Output: number density
rho	Output: energy density
p	Output: pressure
drho_dM	Output: derivative used in next function
pseudo_p	Output: pseudo-pressure used in perturbation module for fluid approx

- rescale normalization at given redshift
- initialize quantities
- loop over momenta
- adjust normalization

3.1.2.12 int background_ncdm_M_from_Omega (struct precision * *ppr*, struct background * *pba*, int *n_ncdm*)

When the user passed in input the density fraction Omeha_ncdm or omega_ncdm but not the mass, infer the mass with Newton iteration method.

Parameters

ppr	Input: precision structure
pba	Input/Output: background structure
n_ncdm	Input: index of ncdm species

3.1.2.13 int background_solve (struct precision * *ppr*, struct background * *pba*)

This function integrates the background over time, allocates and fills the background table

Parameters

ppr	Input: precision structure
pba	Input/Output: background structure

Summary:

- define local variables
- allocate vector of quantities to be integrated
- initialize generic integrator with initialize_generic_integrator()
- impose initial conditions with background_initial_conditions()
- create a growTable with gt_init()
- loop over integration steps : call background_functions(), find step size, save data in growTable with gt_add(), perform one step with generic_integrator(), store new value of tau
- save last data in growTable with gt_add()
- clean up generic integrator with cleanup_generic_integrator()
- retrieve data stored in the growTable with gt_getPtr()
- interpolate to get quantities precisely today with array_interpolate()
- deduce age of the Universe
- allocate background tables
- In a loop over lines, fill background table using the result of the integration plus background_functions()
- free the growTable with gt_free()
- fill tables of second derivatives (in view of spline interpolation)
- compute remaining "related parameters"

-> so-called "effective neutrino number", computed at earliest time in interpolation table. This should be seen as a definition: Neff is the equivalent number of instantaneously-decoupled neutrinos accounting for the radiation density, beyond photons

- done

3.1.2.14 int background_initial_conditions (struct precision * *ppr*, struct background * *pba*, double * *pvecback*, double * *pvecback_integration*)

Assign initial values to background integrated variables.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pvecback	Input : vector of background quantities used as workspace
pvecback_integration	Output : vector of background quantities to be integrated, returned with proper initial values

Returns

the error status

Summary:

- define local variables
- fix initial value of a

If we have ncdm species, perhaps we need to start earlier than the standard value for the species to be relativistic. This could happen for some WDM models.

We must add the relativistic contribution from NCDM species:

f is the critical density fraction of DR. The exact solution is

f = -Omega_rad+pow(pow(Omega_rad,3./2.)+0.5∗pow(a/pba->a_today,6)∗pvecback_integration[pba->index_bi↩ _rho_dcdm]∗pba->Gamma_dcdm/pow(pba->H0,3),2./3.); but it is not numerically stable for very small f which is always the case. Instead we use the Taylor expansion of this equation, which is equivalent to ignoring f(a) in the Hubble rate.

This is reserved for a future case where dr is not sourced by dcdm

- fix initial value of ϕ, ϕ' set directly in the radiation attractor => fixes the units in terms of rho_ur

TODO:

- There seems to be some small oscillation when it starts.
- Check equations and signs. Sign of phi_prime?
- is rho_ur all there is early on?

if there is no attractor solution for scf_lambda, assign some value. Otherwise would give a nan

If no attractor initial conditions are assigned, gets the provided ones

- compute initial proper time, assuming radiation-dominated universe since Big Bang and therefore $t = 1/(2H)$ (good approximation for most purposes)
- compute initial conformal time, assuming radiation-dominated universe since Big Bang and therefore $\tau = 1/(aH)$ (good approximation for most purposes)
- compute initial sound horizon, assuming $c_s = 1/\sqrt{3}$ initially
- compute initial value of the integral over $d\tau/(aH^2)$, assumed to be proportional to a^4 during RD, but with arbitrary normalization

3.1.2.15 int background_output_titles (struct background ∗ *pba,* char *titles[_MAXTITLESTRINGLENGTH_]*)

Subroutine for formatting background output Length of the column title should be less than *OUTPUTPRECISION*+6 to be indented correctly, but it can be as long as .

3.1.2.16 int background_output_data (struct background ∗ *pba,* int *number_of_titles,* double ∗ *data*)

Store quantities:

3.1.2.17 int background_derivs (double *tau*, double * *y*, double * *dy*, void * *parameters_and_workspace*, ErrorMsg *error_message*)

Subroutine evaluating the derivative with respect to conformal time of quantities which are integrated (a, t, etc).

This is one of the few functions in the code which are passed to the generic_integrator() routine. Since generic_integrator() should work with functions passed from various modules, the format of the arguments is a bit special:

- fixed input parameters and workspaces are passed through a generic pointer. Here, this is just a pointer to the background structure and to a background vector, but generic_integrator() doesn't know its fine structure.
- the error management is a bit special: errors are not written as usual to pba->error_message, but to a generic error_message passed in the list of arguments.

Parameters

tau	Input : conformal time
y	Input : vector of variable
dy	Output : its derivative (already allocated)
parameters_and_workspace	Input: pointer to fixed parameters (e.g. indices)
error_message	Output : error message

Summary:

- define local variables
- Calculates functions of a with background_functions()
- calculate $a' = a^2 H$
- calculate $t' = a$
- calculate $rs' = c_s$

calculate growth' $= 1/(aH^2)$

compute dcdm density $\rho' = -3aH\rho - a\Gamma\rho$

compute dcdm density $\rho' = -3aH\rho - a\Gamma\rho$

Compute dr density $\rho' = -4aH\rho - a\Gamma\rho$

- Scalar field equation: $\phi'' + 2aH\phi' + a^2 dV = 0$ (note H wrt cosmic time)

3.1.2.18 double V_e_scf (struct **background** * *pba*, double *phi*)

Scalar field potential and its derivatives with respect to the field _scf For Albrecht & Skordis model: 9908085 $V = V_{p_{scf}} * V_{e_{scf}}$ $V_e = \exp(-\lambda\phi)$ (exponential) $V_p = (\phi - B)^\alpha + A$ (polynomial bump)

TODO:

- Add some functionality to include different models/potentials (tuning would be difficult, though)
- Generalize to Kessence/Horndeski/PPF and/or couplings
- A default module to numerically compute the derivatives when no analytic functions are given should be added. Numerical derivatives may further serve as a consistency check. The units of phi, tau in the derivatives and the potential V are the following:
- phi is given in units of the reduced Planck mass $m_{pl} = (8\pi G)^{(-1/2)}$

- tau in the derivative is given in units of Mpc.

- the potential $V(\phi)$ is given in units of m_{pl}^2/Mpc^2. With this convention, we have $\rho^{class} = (8\pi G)/3\rho^{physical} = 1/(3m_{pl}^2)\rho^{physical} = 1/3 * [1/(2a^2)(\phi')^2 + V(\phi)]$ and ρ^{class} has the proper dimension Mpc^-2.

3.1.2.19 double V_p_scf (struct background * *pba*, double *phi*)

parameters and functions for the polynomial coefficient $V_p = (\phi - B)^\alpha + A$(polynomial bump)

double scf_alpha = 2;

double scf_B = 34.8;

double scf_A = 0.01; (values for their Figure 2)

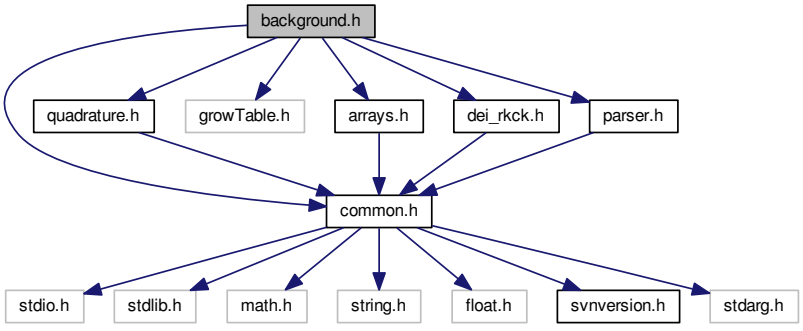
3.1.2.20 double V_scf (struct background * *pba*, double *phi*)

now the overall potential $V = V_p * V_e$

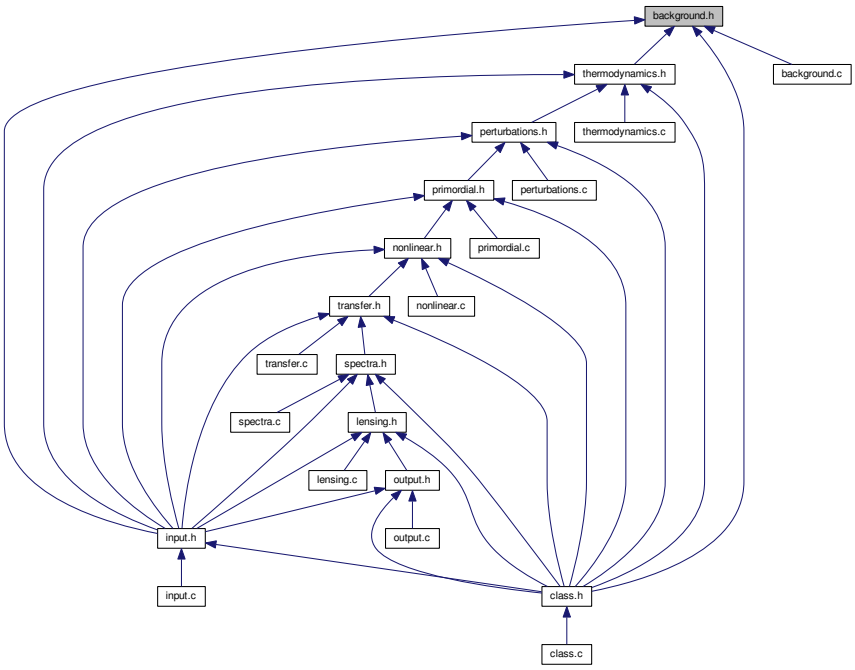
3.2 background.h File Reference

```
#include "common.h"
#include "quadrature.h"
#include "growTable.h"
#include "arrays.h"
#include "dei_rkck.h"
#include "parser.h"
```

Include dependency graph for background.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct background
- struct background_parameters_and_workspace
- struct background_parameters_for_distributions

3.2.1 Detailed Description

Documented includes for background module

3.2.2 Data Structure Documentation

3.2.2.1 struct background

All background parameters and evolution that other modules need to know.

Once initialized by the backgound_init(), contains all necessary information on the background evolution (excepted thermodynamics), and in particular, a table of all background quantities as a function of time and scale factor, used for interpolation in other modules.

Data Fields

double	H0	H_0 : Hubble parameter (in fact, [H_0/c]) in Mpc^{-1}
double	Omega0_g	$\Omega_{0\gamma}$: photons
double	T_cmb	T_{cmb} : current CMB temperature in Kelvins

double	Omega0_b	Ω_{0b} : baryons
double	Omega0_cdm	Ω_{0cdm} : cold dark matter
double	Omega0_↩ lambda	Ω_{0_Λ} : cosmological constant
double	Omega0_fld	Ω_{0de} : fluid with constant w and c_s^2
double	w0_fld	$w0_{DE}$: current fluid equation of state parameter
double	wa_fld	wa_{DE} : fluid equation of state parameter derivative
double	cs2_fld	$c_{s\ DE}^2$: sound speed of the fluid in the frame comoving with the fluid (so, this is not [delta p/delta rho] in the synchronous or newtonian gauge!!!)
double	Omega0_ur	$\Omega_{0\nu r}$: ultra-relativistic neutrinos
double	Omega0_↩ dcdmdr	$\Omega_{0dcdm} + \Omega_{0dr}$: dcdm decaying to dr
double	Gamma_dcdm	Γ_{dcdm} : decay constant for decaying cold dark matter
double	Omega0_scf	Ω_{0scf} : scalar field
short	attractor_ic_scf	whether the scalar field has attractor initial conditions
double	phi_ini_scf	$\phi(t_0)$: scalar field initial value
double	phi_prime_ini_↩ scf	$d\phi(t_0)/d\tau$: scalar field initial derivative wrt conformal time
double *	scf_parameters	list of parameters describing the scalar field potential
int	scf_↩ parameters_size	size of scf_parameters
int	scf_tuning_index	index in scf_parameters used for tuning
double	Omega0_k	Ω_{0_k} : curvature contribution
int	N_ncdm	Number of distinguishable ncdm species
double *	M_ncdm	vector of masses of non-cold relic: dimensionless ratios m_ncdm/T_↩ ncdm
double *	Omega0_ncdm	
double	Omega0_↩ ncdm_tot	Omega0_ncdm for each species and for the total Omega0_ncdm
double *	deg_ncdm	
double	deg_ncdm_↩ default	vector of degeneracy parameters in factor of p-s-d: 1 for one family of neutrinos (= one neutrino plus its anti-neutrino, total g$*$=1+1=2, so deg = 0.5 g$*$); and its default value
double *	T_ncdm	
double	T_ncdm_default	list of 1st parameters in p-s-d of non-cold relics: relative temperature T_ncdm1/T_gamma; and its default value
double *	ksi_ncdm	
double	ksi_ncdm_↩ default	list of 2nd parameters in p-s-d of non-cold relics: relative chemical potential ksi_ncdm1/T_ncdm1; and its default value
double *	ncdm_psd_↩ parameters	list of parameters for specifying/modifying ncdm p.s.d.'s, to be customized for given model (could be e.g. mixing angles)
int *	got_files	list of flags for each species, set to true if p-s-d is passed through file
char *	ncdm_psd_files	list of filenames for tabulated p-s-d
double	Omega_ini_↩ dcdm	$$$ definition missing $$$
double	h	reduced Hubble parameter
double	age	age in Gyears
double	conformal_age	conformal age in Mpc
double	K	K : Curvature parameter $K = -\Omega 0_k * a_{today}^2 * H_0^2$;
int	sgnK	K/|K|: -1, 0 or 1

double *	m_ncdm_in_eV	list of ncdm masses in eV (inferred from M_ncdm and other parameters above)
double	Neff	so-called "effective neutrino number", computed at earliest time in interpolation table
double	Omega0_dcdm	Ω_{0dcdm} : decaying cold dark matter
double	Omega0_dr	Ω_{0dr} : decay radiation
double	a_today	scale factor today (arbitrary and irrelevant for most purposes)
int	index_bg_a	scale factor
int	index_bg_H	Hubble parameter in Mpc^{-1}
int	index_bg_H_↩ prime	its derivative w.r.t. conformal time
int	index_bg_rho_g	photon density
int	index_bg_rho_b	baryon density
int	index_bg_rho_↩ cdm	cdm density
int	index_bg_rho_↩ lambda	cosmological constant density
int	index_bg_rho_↩ fld	fluid with constant w density
int	index_bg_rho_ur	relativistic neutrinos/relics density
int	index_bg_rho_↩ dcdm	dcdm density
int	index_bg_rho_dr	dr density
int	index_bg_phi_↩ scf	scalar field value
int	index_bg_phi_↩ prime_scf	scalar field derivative wrt conformal time
int	index_bg_V_scf	scalar field potential V
int	index_bg_dV_↩ scf	scalar field potential derivative V'
int	index_bg_ddV↩ _scf	scalar field potential second derivative V''
int	index_bg_rho_↩ scf	scalar field energy density
int	index_bg_p_scf	scalar field pressure
int	index_bg_rho_↩ ncdm1	density of first ncdm species (others contiguous)
int	index_bg_p_↩ ncdm1	pressure of first ncdm species (others contiguous)
int	index_bg_↩ pseudo_p_↩ ncdm1	another statistical momentum useful in ncdma approximation
int	index_bg_↩ Omega_r	relativistic density fraction ($\Omega_\gamma + \Omega_{\nu r}$)
int	index_bg_rho_↩ crit	critical density
int	index_bg_↩ Omega_m	non-relativistic density fraction ($\Omega_b + \Omega_c dm + \Omega_{\nu nr}$)
int	index_bg_conf↩ _distance	conformal distance (from us) in Mpc
int	index_bg_ang↩ _distance	angular diameter distance in Mpc

int	index_bg_lum↩ _distance	luminosity distance in Mpc
int	index_bg_time	proper (cosmological) time in Mpc
int	index_bg_rs	comoving sound horizon in Mpc
int	index_bg_D	density growth factor in dust universe, $D = H \int [da/(aH)^3]$ (arbitrary normalization)
int	index_bg_f	velocity growth factor in dust universe, [dlnD]/[dln a]
int	bg_size_short	size of background vector in the "short format"
int	bg_size_normal	size of background vector in the "normal format"
int	bg_size	size of background vector in the "long format"
int	bt_size	number of lines (i.e. time-steps) in the array
double *	tau_table	vector tau_table[index_tau] with values of τ (conformal time)
double *	z_table	vector z_table[index_tau] with values of z (redshift)
double *	background_↩ table	table background_table[index_tau*pba->bg_size+pba->index_bg] with all other quantities (array of size bg_size*bt_size)
double *	d2tau_dz2_table	vector d2tau_dz2_table[index_tau] with values of $d^2\tau/dz^2$ (conformal time)
double *	d2background↩ _dtau2_table	table d2background_dtau2_table[index_tau*pba->bg_size+pba->index_bg] with values of $d^2b_i/d\tau^2$ (conformal time)
int	index_bi_a	{B} scale factor
int	index_bi_rho_↩ dcdm	{B} dcdm density
int	index_bi_rho_dr	{B} dr density
int	index_bi_phi_scf	{B} scalar field value
int	index_bi_phi_↩ prime_scf	{B} scalar field derivative wrt conformal time
int	index_bi_time	{C} proper (cosmological) time in Mpc
int	index_bi_rs	{C} sound horizon
int	index_bi_tau	{C} conformal time in Mpc
int	index_bi_growth	{C} integral over $[da/(aH)^3] = [d\tau/(aH^2)]$, useful for growth factor
int	bi_B_size	Number of {B} parameters
int	bi_size	Number of {B}+{C} parameters
short	has_cdm	presence of cold dark matter?
short	has_dcdm	presence of decaying cold dark matter?
short	has_dr	presence of relativistic decay radiation?
short	has_scf	presence of a scalar field?
short	has_ncdm	presence of non-cold dark matter?
short	has_lambda	presence of cosmological constant?
short	has_fld	presence of fluid with constant w and cs2?
short	has_ur	presence of ultra-relativistic neutrinos/relics?
short	has_curvature	presence of global spatial curvature?
double **	q_ncdm_bg	Pointers to vectors of background sampling in q
double **	w_ncdm_bg	Pointers to vectors of corresponding quadrature weights w
double **	q_ncdm	Pointers to vectors of perturbation sampling in q
double **	w_ncdm	Pointers to vectors of corresponding quadrature weights w
double **	dlnf0_dlnq_↩ ncdm	Pointers to vectors of logarithmic derivatives of p-s-d
int *	q_size_ncdm_bg	Size of the q_ncdm_bg arrays
int *	q_size_ncdm	Size of the q_ncdm arrays

double *	factor_ncdm	List of normalization factors for calculating energy density etc.
short	short_info	flag for calling background_at_eta and return little information
short	normal_info	flag for calling background_at_eta and return medium information
short	long_info	flag for calling background_at_eta and return all information
short	inter_normal	flag for calling background_at_eta and find position in interpolation table normally
short	inter_closeby	flag for calling background_at_eta and find position in interpolation table starting from previous position in previous call
short	background_↩ verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.2.2.2 struct background_parameters_and_workspace

temporary parameters and workspace passed to the background_derivs function

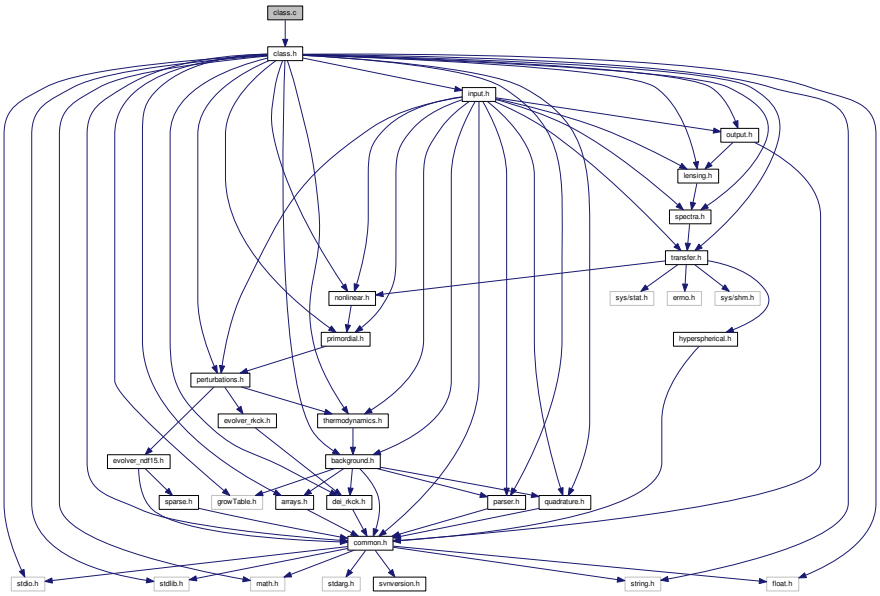
3.2.2.3 struct background_parameters_for_distributions

temporary parameters and workspace passed to phase space distribution function

3.3 class.c File Reference

```
#include "class.h"
```

Include dependency graph for class.c:



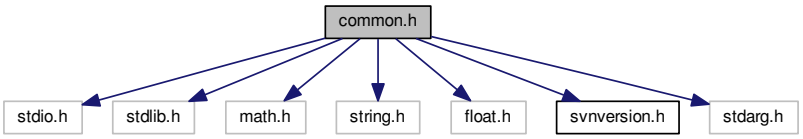
3.3.1 Detailed Description

Julien Lesgourgues, 17.04.2011

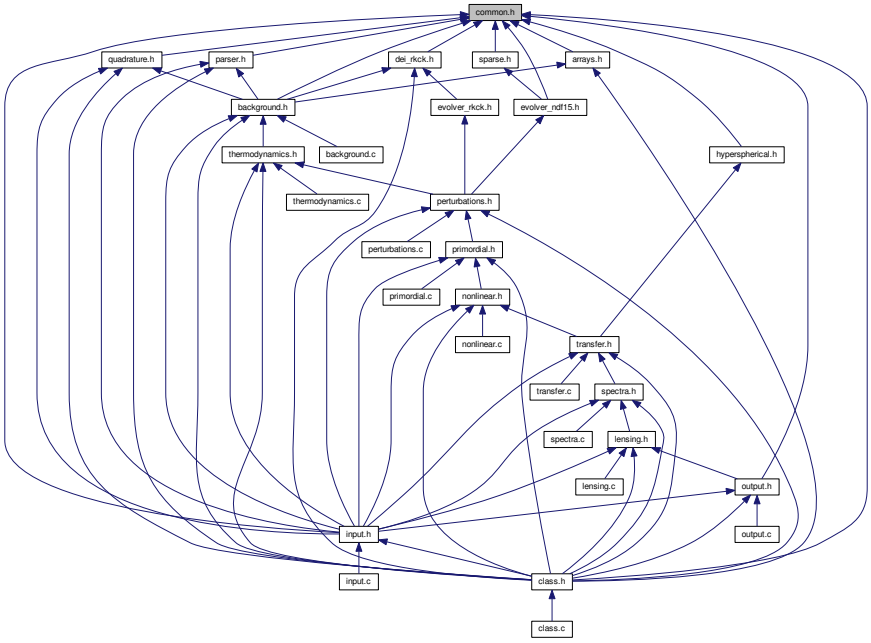
3.4 common.h File Reference

```
#include "stdio.h"
#include "stdlib.h"
#include "math.h"
#include "string.h"
#include "float.h"
#include "svnversion.h"
#include <stdarg.h>
```

Include dependency graph for common.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct precision

Enumerations

- enum evolver_type
- enum pk_def { delta_m_squared, delta_tot_squared, delta_bc_squared, delta_tot_from_poisson_squared }
- enum file_format

3.4.1 Detailed Description

Generic libraries, parameters and functions used in the whole code.

3.4.2 Data Structure Documentation

3.4.2.1 struct precision

All precision parameters.

Includes integrations steps, flags telling how the computation is to be performed, etc.

Data Fields

double	a_ini_over_a_today_default	default initial value of scale factor in background integration, in units of scale factor today
double	back_integration_stepsize	default step d tau in background integration, in units of conformal Hubble time ($d\tau$ = back_integration_stepsize / aH)
double	tol_background_integration	parameter controlling precision of background integration
double	tol_initial_Omega_r	parameter controlling how deep inside radiation domination must the initial time be chosen
double	tol_M_ncdm	parameter controlling relative precision of ncdm mass for given ncdm current density
double	tol_ncdm	parameter controlling relative precision of integrals over ncdm phase-space distribution during perturbation calculation
double	tol_ncdm_newtonian	$$$ definition missing $$$
double	tol_ncdm_synchronous	$$$ definition missing $$$
double	tol_ncdm_bg	parameter controlling relative precision of integrals over ncdm phase-space distribution during background evolution
double	tol_ncdm_initial_w	parameter controlling how relativistic must non-cold relics be at initial time
double	safe_phi_scf	parameter controlling the initial scalar field in background functions
double	recfast_z_initial	initial redshift in recfast
int	recfast_Nz0	number of integration steps
double	tol_thermo_integration	precision of each integration step
int	recfast_Heswitch	recfast 1.4 parameter
double	recfast_fudge_He	recfast 1.4 parameter
int	recfast_Hswitch	recfast 1.5 switching parameter
double	recfast_fudge_H	H fudge factor when recfast_Hswitch set to false (v1.4 fudging)
double	recfast_delta_fudge_H	correction to H fudge factor in v1.5
double	recfast_AGauss1	Amplitude of 1st Gaussian
double	recfast_AGauss2	Amplitude of 2nd Gaussian

double	recfast_zGauss1	ln(1+z) of 1st Gaussian
double	recfast_zGauss2	ln(1+z) of 2nd Gaussian
double	recfast_w↩ Gauss1	Width of 1st Gaussian
double	recfast_w↩ Gauss2	Width of 2nd Gaussian
double	recfast_z_He_1	down to which redshift Helium fully ionized
double	recfast_delta_↩ z_He_1	z range over which transition is smoothed
double	recfast_z_He_2	down to which redshift first Helium recombination not complete
double	recfast_delta_↩ z_He_2	z range over which transition is smoothed
double	recfast_z_He_3	down to which redshift Helium singly ionized
double	recfast_delta_↩ z_He_3	z range over which transition is smoothed
double	recfast_x_He0↩ _trigger	value below which recfast uses the full equation for Helium
double	recfast_x_He0↩ _trigger2	a second threshold used in derivative routine
double	recfast_x_He0↩ _trigger_delta	x_He range over which transition is smoothed
double	recfast_x_H0_↩ trigger	value below which recfast uses the full equation for Hydrogen
double	recfast_x_H0_↩ trigger2	a second threshold used in derivative routine
double	recfast_x_H0_↩ trigger_delta	x_H range over which transition is smoothed
double	recfast_H_frac	governs time at which full equation of evolution for Tmat is used
double	reionization_z↩ _start_max	maximum redshift at which reionization should start. If not, return an error.
double	reionization_↩ sampling	control stepsize in z during reionization
double	reionization_↩ optical_depth_tol	fractional error on optical_depth
double	reionization_↩ start_factor	parameter for CAMB-like parametrization
int	thermo_rate↩ _smoothing_↩ radius	plays a minor (almost aesthetic) role in the definition of the variation rate of thermodynamical quantities
enum evolver_type	evolver	which type of evolver for integrating perturbations (Runge-Kutta? Stiff?...)
double	k_min_tau0	number defining k_min for the computation of Cl's and P(k)'s (dimensionless): (k_min tau_0), usually chosen much smaller than one
double	k_max_tau0_↩ over_l_max	number defining k_max for the computation of Cl's (dimensionless): (k↩ _max tau_0)/l_max, usually chosen around two
double	k_step_sub	step in k space, in units of one period of acoustic oscillation at decoupling, for scales inside sound horizon at decoupling
double	k_step_super	step in k space, in units of one period of acoustic oscillation at decoupling, for scales above sound horizon at decoupling
double	k_step_transition	dimensionless number regulating the transition from 'sub' steps to 'super' steps. Decrease for more precision.

double	k_step_super_↩ reduction	the step k_step_super is reduced by this amount in the k–>0 limit (below scale of Hubble and/or curvature radius)
double	k_per_decade↩ _for_pk	if values needed between kmax inferred from k_oscillations and k_↩ kmax_for_pk, this gives the number of k per decade outside the BAO region
double	k_per_decade↩ _for_bao	if values needed between kmax inferred from k_oscillations and k_↩ kmax_for_pk, this gives the number of k per decade inside the BA↩ O region (for finer sampling)
double	k_bao_center	in ln(k) space, the central value of the BAO region where sampling is finer is defined as k_rec times this number (recommended: 3, i.e. finest sampling near 3rd BAO peak)
double	k_bao_width	in ln(k) space, width of the BAO region where sampling is finer: this number gives roughly the number of BAO oscillations well resolved on both sides of the central value (recommended: 4, i.e. finest sampling from before first up to 3+4=7th peak)
double	start_small_k_↩ at_tau_c_over↩ _tau_h	largest wavelengths start being sampled when universe is sufficiently opaque. This is quantified in terms of the ratio of thermo to hubble time scales, τ_c/τ_H. Start when start_largek_at_tau_c_over_tau_h equals this ratio. Decrease this value to start integrating the wavenumbers earlier in time.
double	start_large_k_↩ at_tau_h_over↩ _tau_k	largest wavelengths start being sampled when mode is sufficiently outside Hubble scale. This is quantified in terms of the ratio of hubble time scale to wavenumber time scale, τ_h/τ_k which is roughly equal to (k∗tau). Start when this ratio equals start_large_k_at_tau_k_over_tau↩ _h. Decrease this value to start integrating the wavenumbers earlier in time.
double	tight_coupling↩ _trigger_tau_c↩ _over_tau_h	when to switch off tight-coupling approximation: first condition: $\tau_c/\tau_H >$ tight_coupling_trigger_tau_c_over_tau_h. Decrease this value to switch off earlier in time. If this number is larger than start_sources_at_tau_c↩ _over_tau_h, the code returns an error, because the source computation requires tight-coupling to be switched off.
double	tight_coupling↩ _trigger_tau_c↩ _over_tau_k	when to switch off tight-coupling approximation: second condition↩ : $\tau_c/\tau_k \equiv k\tau_c <$ tight_coupling_trigger_tau_c_over_tau_k. Decrease this value to switch off earlier in time.
double	start_sources↩ _at_tau_c_↩ over_tau_h	sources start being sampled when universe is sufficiently opaque. This is quantified in terms of the ratio of thermo to hubble time scales, τ_c/τ_H. Start when start_sources_at_tau_c_over_tau_h equals this ratio. Decrease this value to start sampling the sources earlier in time.
int	tight_coupling↩ _approximation	$$$ definition missing $$$
int	l_max_g	number of momenta in Boltzmann hierarchy for photon temperature (scalar), at least 4
int	l_max_pol_g	number of momenta in Boltzmann hierarchy for photon polarization (scalar), at least 4
int	l_max_dr	number of momenta in Boltzmann hierarchy for decay radiation, at least 4
int	l_max_ur	number of momenta in Boltzmann hierarchy for relativistic neutrino/relics (scalar), at least 4
int	l_max_ncdm	number of momenta in Boltzmann hierarchy for relativistic neutrino/relics (scalar), at least 4
int	l_max_g_ten	number of momenta in Boltzmann hierarchy for photon temperature (tensor), at least 4

int	l_max_pol_g_↩ ten	number of momenta in Boltzmann hierarchy for photon polarization (tensor), at least 4
double	curvature_ini	initial condition for curvature for adiabatic
double	entropy_ini	initial condition for entropy perturbation for isocurvature
double	gw_ini	initial condition for tensor metric perturbation h
double	perturb_↩ integration_↩ stepsize	default step $d\tau$ in perturbation integration, in units of the timescale involved in the equations (usually, the min of $1/k$, $1/aH$, $1/\dot{\kappa}$)
double	perturb_↩ sampling_↩ stepsize	default step $d\tau$ for sampling the source function, in units of the timescale involved in the sources: $(\dot{\kappa} - \ddot{\kappa}/\dot{\kappa})^{-1}$
double	tol_perturb_↩ integration	control parameter for the precision of the perturbation integration
double	tol_tau_approx	precision with which the code should determine (by bisection) the times at which sources start being sampled, and at which approximations must be switched on/off (units of Mpc)
int	radiation_↩ streaming_↩ approximation	method for switching off photon perturbations
double	radiation_↩ streaming_↩ trigger_tau_↩ over_tau_k	when to switch off photon perturbations, ie when to switch on photon free-streaming approximation (keep density and thtau, set shear and higher momenta to zero): first condition: $k\tau >$ radiation_streaming_trigger_↩ tau_h_over_tau_k
double	radiation_↩ streaming_↩ trigger_tau_c_↩ over_tau	when to switch off photon perturbations, ie when to switch on photon free-streaming approximation (keep density and theta, set shear and higher momenta to zero): second condition:
int	ur_fluid_↩ approximation	$$$ definition missing $$$
double	ur_fluid_↩ trigger_tau_↩ over_tau_k	when to switch off ur (massless neutrinos / ultra-relativistic relics) fluid approximation
int	ncdm_fluid_↩ approximation	$$$ definition missing $$$
double	ncdm_fluid_↩ trigger_tau_↩ over_tau_k	when to switch off ncdm (massive neutrinos / non-cold relics) fluid approximation
double	neglect_CM↩ B_sources_↩ below_visibility	$$$ definition missing $$$
double	k_per_decade↩ _primordial	logarithmic sampling for primordial spectra (number of points per decade in k space)
double	primordial_↩ inflation_ratio_↩ min	$$$ definition missing $$$
double	primordial_↩ inflation_ratio_↩ max	$$$ definition missing $$$
int	primordial_↩ inflation_phi_↩ ini_maxit	$$$ definition missing $$$

double	primordial_↩ inflation_pt_↩ stepsize	$$$ definition missing $$$
double	primordial_↩ inflation_bg_↩ stepsize	$$$ definition missing $$$
double	primordial_↩ inflation_tol_↩ integration	$$$ definition missing $$$
double	primordial↩ _inflation_↩ attractor_↩ precision_pivot	$$$ definition missing $$$
double	primordial↩ _inflation_↩ attractor_↩ precision_initial	$$$ definition missing $$$
int	primordial↩ _inflation_↩ attractor_maxit	$$$ definition missing $$$
double	primordial_↩ inflation_jump↩ _initial	$$$ definition missing $$$
double	primordial_↩ inflation_tol_↩ curvature	$$$ definition missing $$$
double	primordial_↩ inflation_aH_↩ ini_target	$$$ definition missing $$$
double	primordial_↩ inflation_end_↩ dphi	$$$ definition missing $$$
double	primordial_↩ inflation_end_↩ logstep	$$$ definition missing $$$
double	primordial_↩ inflation_small↩ _epsilon	$$$ definition missing $$$
double	primordial_↩ inflation_small↩ _epsilon_tol	$$$ definition missing $$$
double	primordial_↩ inflation_extra↩ _efolds	$$$ definition missing $$$
int	l_linstep	factor for logarithmic spacing of values of l over which bessel and transfer functions are sampled
double	l_logstep	maximum spacing of values of l over which Bessel and transfer functions are sampled (so, spacing becomes linear instead of logarithmic at some point)
double	hyper_x_min	$$$ definition missing $$$
double	hyper_↩ sampling_flat	$$$ definition missing $$$

double	hyper_↩ sampling_↩ curved_low_nu	$$$ definition missing $$$
double	hyper_↩ sampling_↩ curved_high_nu	$$$ definition missing $$$
double	hyper_nu_↩ sampling_step	$$$ definition missing $$$
double	hyper_phi_min↩ _abs	$$$ definition missing $$$
double	hyper_x_tol	$$$ definition missing $$$
double	hyper_flat_↩ approximation↩ _nu	$$$ definition missing $$$
double	q_linstep	asymptotic linear sampling step in q space, in units of $2\pi/r_a(\tau_rec)$ (comoving angular diameter distance to recombination)
double	q_logstep_spline	initial logarithmic sampling step in q space, in units of $2\pi/r_a(\tau_{rec})$ (comoving angular diameter distance to recombination)
double	q_logstep_open	in open models, the value of q_logstep_spline must be decreased according to curvature. Increasing this number will make the calculation more accurate for large positive Omega_k
double	q_logstep_↩ trapzd	initial logarithmic sampling step in q space, in units of $2\pi/r_a(\tau_{rec})$ (comoving angular diameter distance to recombination), in the case of small q's in the closed case, for which one must used trapezoidal integration instead of spline (the number of q's for which this is the case decreases with curvature and vanishes in the flat limit)
double	q_numstep_↩ transition	number of steps for the transition from q_logstep_trapzd steps to q_↩ logstep_spline steps (transition must be smooth for spline)
double	transfer_↩ neglect_delta_↩ k_S_t0	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_S_t1	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_S_t2	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_S_e	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_V_t1	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_V_t2	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_V_e	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_V_b	$$$ definition missing $$$

double	transfer_↩ neglect_delta_↩ k_T_t2	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_T_e	$$$ definition missing $$$
double	transfer_↩ neglect_delta_↩ k_T_b	$$$ definition missing $$$
double	transfer_↩ neglect_late_↩ source	$$$ definition missing $$$
double	l_switch_limber	when to use the Limber approximation for project gravitational potential cl's
double	l_switch_↩ limber_for_cl_↩ density_over_z	when to use the Limber approximation for density cl's (relative to central redshift of each bin)
double	selection_cut_↩ at_sigma	in sigma units, where to cut gaussian selection functions
double	selection_↩ sampling	controls sampling of integral over time when selection functions vary quicker than Bessel functions. Increase for better sampling.
double	selection_↩ sampling_bessel	controls sampling of integral over time when selection functions vary slower than Bessel functions. Increase for better sampling
double	selection_↩ tophat_edge	controls how smooth are the edge of top-hat window function ($<<$1 for very sharp, 0.1 for sharp)
double	halofit_dz	parameters relevant for HALOFIT computation spacing in redshift space defining values of z at which HALOFIT will be used. Intermediate values will be obtained by interpolation. Decrease for more precise interpolations, at the expense of increasing time spent in nonlinear_init()
double	halofit_min_k_↩ nonlinear	value of k in 1/Mpc above which non-linear corrections will be computed
double	halofit_sigma_↩ precision	a smaller value will lead to a more precise halofit result at the highest requested redshift, at the expense of requiring a larger k_max
double	halofit_min_k_↩ max	when halofit is used, k_max must be at least equal to this value (otherwise halofit could not find the scale of non-linearity)
int	accurate_lensing	switch between Gauss-Legendre quadrature integration and simple quadrature on a subdomain of angles
int	num_mu_↩ minus_lmax	difference between num_mu and l_max, increase for more precision
int	delta_l_max	difference between l_max in unlensed and lensed spectra
double	tol_gauss_↩ legendre	tolerance with which quadrature points are found: must be very small for an accurate integration (if not entered manually, set automatically to match machine precision)
double	smallest_↩ allowed_↩ variation	machine-dependent, assigned automatically by the code
ErrorMsg	error_message	zone for writing error messages

3.4.3 Enumeration Type Documentation

3.4.3.1 enum evolver_type

parameters related to the precision of the code and to the method of calculation list of evolver types for integrating perturbations over time

3.4.3.2 enum pk_def

List of ways in which matter power spectrum P(k) can be defined. The standard definition is the first one (delta_↩ m_squared) but alternative definitions can be useful in some projects.

Enumerator

delta_m_squared normal definition (delta_m includes all non-relativistic species at late times)

delta_tot_squared delta_tot includes all species contributions to (delta rho), and only non-relativistic contributions to rho

delta_bc_squared delta_bc includes contribution of baryons and cdm only to (delta rho) and to rho

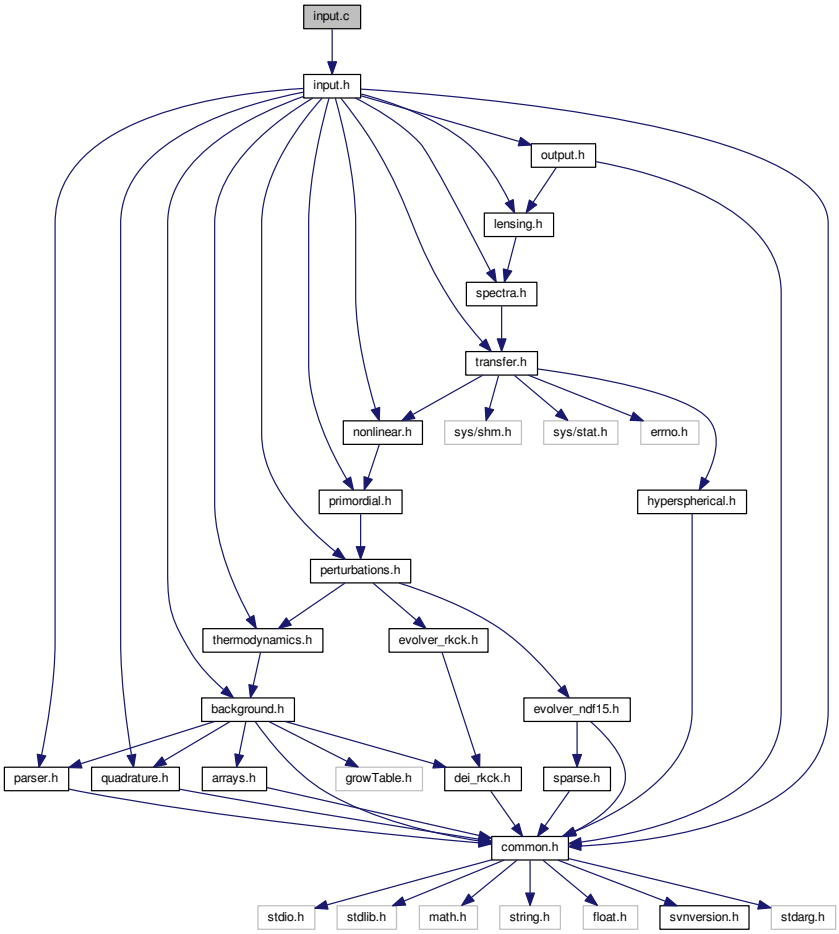
delta_tot_from_poisson_squared use delta_tot inferred from gravitational potential through Poisson equation

3.4.3.3 enum file_format

Different ways to present output files

3.5 input.c File Reference

`#include "input.h"`
Include dependency graph for input.c:



Functions

- int input_init_from_arguments (int argc, char **argv, struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple, struct output *pop, ErrorMsg errmsg)
- int input_init (struct file_content *pfc, struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple, struct output *pop, ErrorMsg errmsg)
- int input_read_parameters (struct file_content *pfc, struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple, struct output *pop, ErrorMsg errmsg)
- int input_default_params (struct background *pba, struct thermo *pth, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple, struct output *pop)
- int input_default_precision (struct precision *ppr)
- int get_machine_precision (double *smallest_allowed_variation)
- int class_fzero_ridder (int(*func)(double x, void *param, double *y, ErrorMsg error_message), double x1, double x2, double xtol, void *param, double *Fx1, double *Fx2, double *xzero, int *fevals, ErrorMsg error_message)
- int input_try_unknown_parameters (double *unknown_parameter, int unknown_parameters_size, void *voidpfzw, double *output, ErrorMsg errmsg)
- int input_get_guess (double *xguess, double *dxdy, struct fzerofun_workspace *pfzw, ErrorMsg errmsg)
- int input_auxillary_target_conditions (struct file_content *pfc, enum target_names target_name, double target_value, int *aux_flag, ErrorMsg errmsg)

3.5.1 Detailed Description

Documented input module.

Julien Lesgourgues, 27.08.2010

3.5.2 Function Documentation

3.5.2.1 int input_init_from_arguments (int *argc*, char ** *argv*, struct **precision** * *ppr*, struct **background** * *pba*, struct **thermo** * *pth*, struct **perturbs** * *ppt*, struct **transfers** * *ptr*, struct **primordial** * *ppm*, struct **spectra** * *psp*, struct **nonlinear** * *pnl*, struct **lensing** * *ple*, struct **output** * *pop*, ErrorMsg *errmsg*)

Use this routine to extract initial parameters from files 'xxx.ini' and/or 'xxx.pre'. They can be the arguments of the main() routine.

If class is embedded into another code, you will probably prefer to call directly input_init() in order to pass input parameters through a 'file_content' structure. Summary:

- define local variables

1. the final structure with all parameters
2. a temporary structure with all input parameters
3. a temporary structure with all precision parameters
4. a temporary structure with only the root name
5. sum of fc_inoput and fc_root
6. a pointer to either fc_root or fc_inputroot

- Initialize the two file_content structures (for input parameters and precision parameters) to some null content. If no arguments are passed, they will remain null and inform init_params() that all parameters take default values.

If some arguments are passed, identify eventually some 'xxx.ini' and 'xxx.pre' files, and store their name.

- if there is an 'xxx.ini' file, read it and store its content.
- check whether a root name has been set
- if root has not been set, use root=output/inputfilennameN_
- if there is an 'xxx.pre' file, read it and store its content.
- if one or two files were read, merge their contents in a single 'file_content' structure.
- now, initialize all parameters given the input 'file_content' structure. If its size is null, all parameters take their default values.

3.5.2.2 int input_init (struct file_content * *pfc,* struct **precision** * *ppr,* struct **background** * *pba,* struct **thermo** * *pth,* struct **perturbs** * *ppt,* struct **transfers** * *ptr,* struct **primordial** * *ppm,* struct **spectra** * *psp,* struct **nonlinear** * *pnl,* struct **lensing** * *ple,* struct **output** * *pop,* ErrorMsg *errmsg*)

Initialize each parameter, first to its default values, and then from what can be interpreted from the values passed in the input 'file_content' structure. If its size is null, all parameters keep their default values. These two arrays must contain the strings of names to be searched for and the corresponding new parameter

input_auxillary_target_conditions() takes care of the case where for instance Omega_dcdmdr is set to 0.0.

Here is our guess:

Do linear hunt for boundaries:

root has been bracketed

Find root using Ridders method. (Exchange for bisection if you are old-school.)

Read all parameters from tuned pfc:

Free arrays allocated

eventually write all the read parameters in a file, unread parameters in another file, and warnings about unread parameters

3.5.2.3 int input_read_parameters (struct file_content * *pfc,* struct **precision** * *ppr,* struct **background** * *pba,* struct **thermo** * *pth,* struct **perturbs** * *ppt,* struct **transfers** * *ptr,* struct **primordial** * *ppm,* struct **spectra** * *psp,* struct **nonlinear** * *pnl,* struct **lensing** * *ple,* struct **output** * *pop,* ErrorMsg *errmsg*)

Summary:

- define local variables
- set all parameters (input and precision) to default values
- if entries passed in file_content structure, carefully read and interpret each of them, and tune accordingly the relevant input parameters

Knowing the gauge from the very beginning is useful (even if this could be a run not requiring perturbations at all: even in that case, knowing the gauge is important e.g. for fixing the sampling in momentum space for non-cold dark matter)

(a) background parameters

Read Omega_ini_dcdm or omega_ini_dcdm

(flag3 == *FALSE*) || (param3 >= 0.) explained: it means that either we have not read Omega_scf so we are ignoring it (unlike lambda and fld!) OR we have read it, but it had a positive value and should not be used for filling.

We now proceed in two steps: 1) set each Omega0 and add to the total for each specified component. 2) go through the components in order {lambda, fld, scf} and fill using first unspecified component.

Step 1

Step 2

Test that the user have not specified Omega_scf = -1 but left either Omega_lambda or Omega_fld unspecified:

Read parameters describing scalar field potential

Assign shooting parameter

(b) assign values to thermodynamics cosmological parameters

(c) define which perturbations and sources should be computed, and down to which scale

(d) define the primordial spectrum

only polynomial coded so far: no need to interpret string1

Tests moved from primordial module:

(e) parameters for final spectra

(f) parameter related to the non-linear spectra computation

(g) amount of information sent to standard output (none if all set to zero)

(h) all precision parameters

h.1. parameters related to the background

h.2. parameters related to the thermodynamics

h.3. parameters related to the perturbations

Include ur and ncdm shear in tensor computation?

derivatives of baryon sound speed only computed if some non-minimal tight-coupling schemes is requested

h.5. parameter related to the primordial spectra

h.6. parameter related to the transfer functions

h.7. parameters related to nonlinear calculations

h.8. parameter related to lensing

(i.1) shall we write background quantities in a file?

(i.2) shall we write thermodynamics quantities in a file?

(i.3) shall we write perturbation quantities in files?

Sort the k_array using qsort

(i.4) shall we write primordial spectra in a file?

3.5.2.4 int input_default_params (struct background * pba, struct thermo * pth, struct perturbs * ppt, struct transfers * ptr, struct primordial * ppm, struct spectra * psp, struct nonlinear * pnl, struct lensing * ple, struct output * pop)

All default parameter values (for input parameters)

Parameters

pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure

ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfer structure
ppm	Input : pointer to primordial structure
psp	Input : pointer to spectra structure
pnl	Input : pointer to nonlinear structure
ple	Input : pointer to lensing structure
pop	Input : pointer to output structure

Returns

the error status

< Stefan-Boltzmann constant in $W/m^2/K^4 = Kg/K^4/s^3$

- background structure
- thermodynamics structure
- perturbation structure
- primordial structure
- transfer structure
- output structure
- spectra structure
- nonlinear structure
- lensing structure
- nonlinear structure
- all verbose parameters

3.5.2.5 int input_default_precision (struct precision * *ppr*)

Initialize the precision parameter structure.

All precision parameters used in the other modules are listed here and assigned here a default value.

Parameters

ppr	Input/Output: a precision_params structure pointer

Returns

the error status

Summary:

- parameters related to the background
- parameters related to the thermodynamics
- parameters related to the perturbations
- parameter related to the primordial spectra
- parameter related to the transfer functions

- parameters related to spectra module
- parameters related to nonlinear module
- parameter related to lensing
- automatic estimate of machine precision

3.5.2.6 int get_machine_precision (double * *smallest_allowed_variation*)

Computes automatically the machine precision.

Parameters

smallest_allowed_variation	a pointer to the smallest allowed variation

Returns the smallest allowed variation (minimum epsilon * *TOLVAR*)

3.5.2.7 int class_fzero_ridder (int(*)(double x, void *param, double *y, ErrorMsg error_message) *func,* double *x1,* double *x2,* double *xtol,* void * *param,* double * *Fx1,* double * *Fx2,* double * *xzero,* int * *fevals,* ErrorMsg *error_message*)

Using Ridders' method, return the root of a function func known to lie between x1 and x2. The root, returned as zriddr, will be found to an approximate accuracy xtol.

3.5.2.8 int input_try_unknown_parameters (double * *unknown_parameter,* int *unknown_parameters_size,* void * *voidpfzw,* double * *output,* ErrorMsg *errmsg*)

Do computations

In case scalar field is used to fill, pba->Omega0_scf is not equal to pfzw->target_value[i].

Free structures

3.5.2.9 int input_get_guess (double * *xguess,* double * *dxdy,* struct fzerofun_workspace * *pfzw,* ErrorMsg *errmsg*)

Here we should right reasonable guesses for the unknown parameters. Also estimate dxdy, i.e. how the unknown parameter responds to the known. This can simply be estimated as the derivative of the guess formula.

Update pb to reflect guess

```
This guess is arbitrary, something nice using WKB should be implemented.
```

Version 2: use a fit: xguess[index_guess] = 1.77835*pow(ba.Omega0_scf,-2./7.); dxdy[index_guess] = -0.↩
5081*pow(ba.Omega0_scf,-9./7.); Version 3: use attractor solution:

This works since correspondence is Omega_ini_dcdm -> Omega_dcdmdr and omega_ini_dcdm -> omega_↩
dcdmdr

Deallocate everything allocated by input_read_parameters

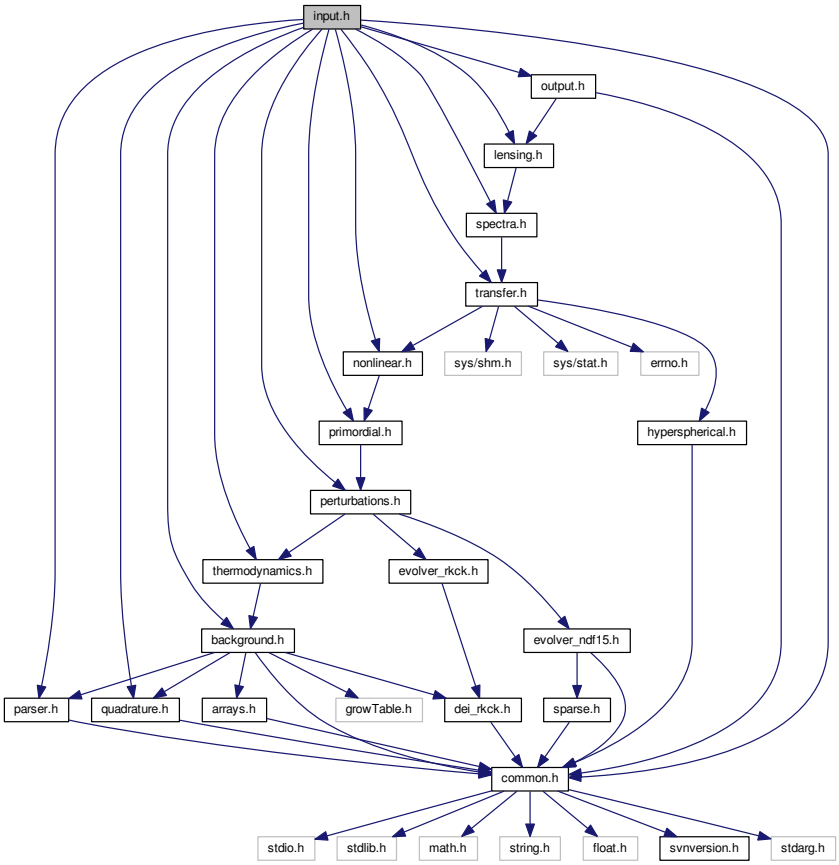
3.5.2.10 int input_auxillary_target_conditions (struct file_content * *pfc,* enum **target_names** *target_name,* double *target_value,* int * *aux_flag,* ErrorMsg *errmsg*)

double param1; int int1, flag1; int input_verbose = 0; class_read_int("input_verbose",input_verbose);

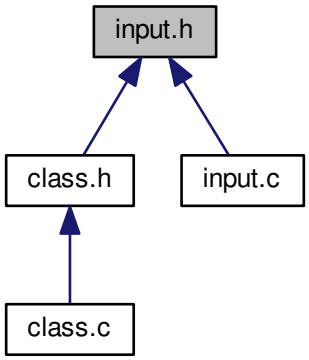
3.6 input.h File Reference

```
#include "common.h"
#include "parser.h"
#include "quadrature.h"
#include "background.h"
#include "thermodynamics.h"
#include "perturbations.h"
#include "transfer.h"
#include "primordial.h"
#include "spectra.h"
#include "nonlinear.h"
#include "lensing.h"
#include "output.h"
```

Include dependency graph for input.h:



This graph shows which files directly or indirectly include this file:



Enumerations

- enum target_names

3.6.1 Detailed Description

Documented includes for input module

3.6.2 Enumeration Type Documentation

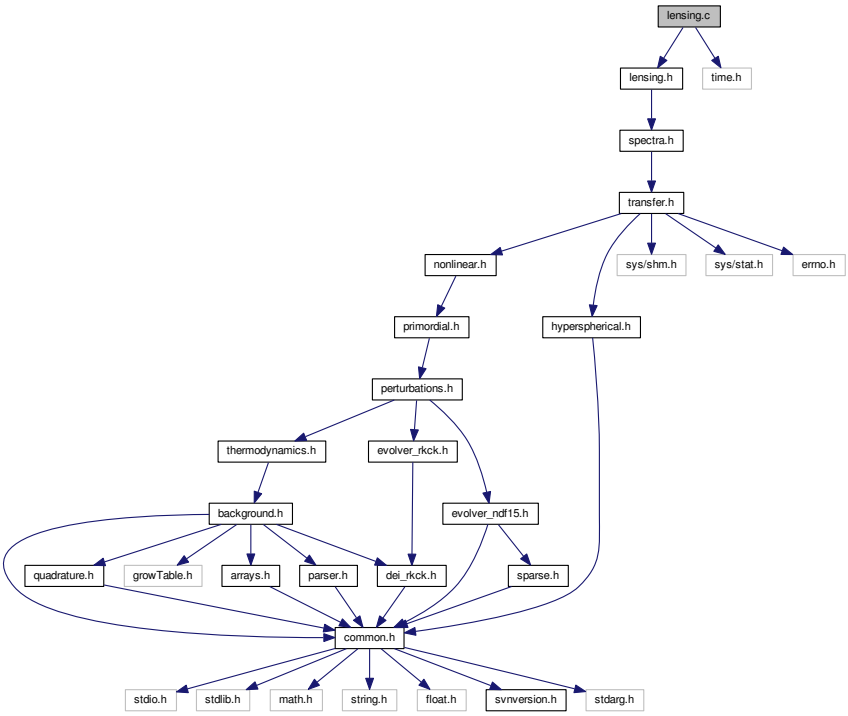
3.6.2.1 enum target_names

temporary parameters for background fzero function

3.7 lensing.c File Reference

```
#include "lensing.h"
#include <time.h>
```

Include dependency graph for lensing.c:



Functions

- int lensing_cl_at_l (struct lensing *ple, int l, double *cl_lensed)
- int lensing_init (struct precision *ppr, struct perturbs *ppt, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple)
- int lensing_free (struct lensing *ple)
- int lensing_indices (struct precision *ppr, struct spectra *psp, struct lensing *ple)
- int lensing_lensed_cl_tt (double *ksi, double **d00, double *w8, int nmu, struct lensing *ple)
- int lensing_addback_cl_tt (struct lensing *ple, double *cl_tt)
- int lensing_lensed_cl_te (double *ksiX, double **d20, double *w8, int nmu, struct lensing *ple)
- int lensing_addback_cl_te (struct lensing *ple, double *cl_te)
- int lensing_lensed_cl_ee_bb (double *ksip, double *ksim, double **d22, double **d2m2, double *w8, int nmu, struct lensing *ple)
- int lensing_addback_cl_ee_bb (struct lensing *ple, double *cl_ee, double *cl_bb)
- int lensing_d00 (double *mu, int num_mu, int lmax, double **d00)
- int lensing_d11 (double *mu, int num_mu, int lmax, double **d11)
- int lensing_d1m1 (double *mu, int num_mu, int lmax, double **d1m1)
- int lensing_d2m2 (double *mu, int num_mu, int lmax, double **d2m2)
- int lensing_d22 (double *mu, int num_mu, int lmax, double **d22)
- int lensing_d20 (double *mu, int num_mu, int lmax, double **d20)
- int lensing_d31 (double *mu, int num_mu, int lmax, double **d31)
- int lensing_d3m1 (double *mu, int num_mu, int lmax, double **d3m1)
- int lensing_d3m3 (double *mu, int num_mu, int lmax, double **d3m3)
- int lensing_d40 (double *mu, int num_mu, int lmax, double **d40)
- int lensing_d4m2 (double *mu, int num_mu, int lmax, double **d4m2)
- int lensing_d4m4 (double *mu, int num_mu, int lmax, double **d4m4)

3.7.1 Detailed Description

Documented lensing module

Simon Prunet and Julien Lesgourgues, 6.12.2010

This module computes the lensed temperature and polarization anisotropy power spectra $C_l^X, P(k), ...$'s given the unlensed temperature, polarization and lensing potential spectra.

Follows Challinor and Lewis full-sky method, astro-ph/0502425

The following functions can be called from other modules:

1. lensing_init() at the beginning (but after spectra_init())
2. lensing_cl_at_l() at any time for computing Cl_lensed at any l
3. lensing_free() at the end

3.7.2 Function Documentation

3.7.2.1 int lensing_cl_at_l (struct lensing * ple, int l, double * cl_lensed)

Anisotropy power spectra C_l's for all types, modes and initial conditions. SO FAR: ONLY SCALAR

This routine evaluates all the lensed C_l's at a given value of l by picking it in the pre-computed table. When relevant, it also sums over all initial conditions for each mode, and over all modes.

This function can be called from whatever module at whatever time, provided that lensing_init() has been called before, and lensing_free() has not been called yet.

Parameters

ple	Input : pointer to lensing structure
l	Input : multipole number
cl_lensed	Output: lensed C_l's for all types (TT, TE, EE, etc..)

Returns

the error status

3.7.2.2 int lensing_init (struct precision * ppr, struct perturbs * ppt, struct spectra * psp, struct nonlinear * pnl, struct lensing * ple)

This routine initializes the lensing structure (in particular, computes table of lensed anisotropy spectra C_l^X)

Parameters

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure (just in case, not used in current version...)
psp	Input : pointer to spectra structure
pnl	Input : pointer to nonlinear structure
ple	Output: pointer to initialized lensing structure

Returns

the error status

local variables

Summary:

- check that we really want to compute at least one spectrum
- initialize indices and allocate some of the arrays in the lensing structure

put here all precision variables; will be stored later in precision structure

Last element in mu will be for mu=1, needed for sigma2 The rest will be chosen as roots of a Gauss-Legendre quadrature

- allocate array of mu values, as well as quadrature weights
- compute $d^l_{mm'}(\mu)$

Allocate main contiguous buffer

- compute $Cgl(\mu)$, $Cgl2(\mu)$ and sigma2(μ)

Locally store unlensed temperature cl_tt and potential cl_pp spectra

Compute sigma2(mu) and Cgl2(mu)

- compute ksi, ksi+, ksi-, ksiX

ksi is for TT

ksiX is for TE

ksip, ksim for EE, BB

- compute lensed Cls by integration
- spline computed Cls in view of interpolation

Free lots of stuff

Exits

3.7.2.3 int lensing_free (struct lensing * *ple*)

This routine frees all the memory space allocated by lensing_init().

To be called at the end of each run, only when no further calls to lensing_cl_at_l() are needed.

Parameters

ple	Input: pointer to lensing structure (which fields must be freed)

Returns

the error status

3.7.2.4 int lensing_indices (struct precision * *ppr*, struct spectra * *psp*, struct lensing * *ple*)

This routine defines indices and allocates tables in the lensing structure

Parameters

ppr	Input : pointer to precision structure
psp	Input : pointer to spectra structure
ple	Input/output : pointer to lensing structure

Returns

the error status

3.7.2.5 int lensing_lensed_cl_tt (double * *ksi,* double ** *d00,* double * *w8,* int *nmu,* struct lensing * *ple*)

This routine computes the lensed power spectra by Gaussian quadrature

Parameters

ksi	Input : Lensed correlation function (ksi[index_mu])
d00	Input : Legendre polynomials (d^l_{00}[l][index_mu])
w8	Input : Legendre quadrature weights (w8[index_mu])
nmu	Input : Number of quadrature points (0<=index_mu<=nmu)
ple	Input/output: Pointer to the lensing structure

Returns

the error status

Integration by Gauss-Legendre quadrature

3.7.2.6 int lensing_addback_cl_tt (struct lensing * *ple,* double * *cl_tt*)

This routine adds back the unlensed cl_tt power spectrum Used in case of fast (and BB inaccurate) integration of correlation functions.

Parameters

ple	Input/output: Pointer to the lensing structure
cl_tt	Input : Array of unlensed power spectrum

Returns

the error status

3.7.2.7 int lensing_lensed_cl_te (double * *ksiX,* double ** *d20,* double * *w8,* int *nmu,* struct lensing * *ple*)

This routine computes the lensed power spectra by Gaussian quadrature

Parameters

ksiX	Input : Lensed correlation function (ksiX[index_mu])
d20	Input : Wigner d-function (d^l_{20}[l][index_mu])
w8	Input : Legendre quadrature weights (w8[index_mu])
nmu	Input : Number of quadrature points (0<=index_mu<=nmu)

ple	Input/output: Pointer to the lensing structure

Returns

the error status

Integration by Gauss-Legendre quadrature

3.7.2.8 int lensing_addback_cl_te (struct lensing * *ple*, double * *cl_te*)

This routine adds back the unlensed cl_te power spectrum Used in case of fast (and BB inaccurate) integration of correlation functions.

Parameters

ple	Input/output: Pointer to the lensing structure
cl_te	Input : Array of unlensed power spectrum

Returns

the error status

3.7.2.9 int lensing_lensed_cl_ee_bb (double * *ksip*, double * *ksim*, double ** *d22*, double ** *d2m2*, double * *w8*, int *nmu*, struct lensing * *ple*)

This routine computes the lensed power spectra by Gaussian quadrature

Parameters

ksip	Input : Lensed correlation function (ksi+[index_mu])
ksim	Input : Lensed correlation function (ksi-[index_mu])
d22	Input : Wigner d-function (d^l_{22}[l][index_mu])
d2m2	Input : Wigner d-function (d^l_{2-2}[l][index_mu])
w8	Input : Legendre quadrature weights (w8[index_mu])
nmu	Input : Number of quadrature points (0<=index_mu<=nmu)
ple	Input/output: Pointer to the lensing structure

Returns

the error status

Integration by Gauss-Legendre quadrature

3.7.2.10 int lensing_addback_cl_ee_bb (struct lensing * *ple*, double * *cl_ee*, double * *cl_bb*)

This routine adds back the unlensed cl_ee, cl_bb power spectra Used in case of fast (and BB inaccurate) integration of correlation functions.

Parameters

ple	Input/output: Pointer to the lensing structure
cl_ee	Input : Array of unlensed power spectrum

cl_bb	Input : Array of unlensed power spectrum

Returns

the error status

3.7.2.11 int lensing_d00 (double * *mu*, int *num_mu*, int *lmax*, double ** *d00*)

This routine computes the d00 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d00	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.12 int lensing_d11 (double * *mu*, int *num_mu*, int *lmax*, double ** *d11*)

This routine computes the d11 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d11	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.13 int lensing_d1m1 (double * *mu*, int *num_mu*, int *lmax*, double ** *d1m1*)

This routine computes the d1m1 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d1m1	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.14 int lensing_d2m2 (double * *mu*, int *num_mu*, int *lmax*, double ** *d2m2*)

This routine computes the d2m2 term

Parameters

mu	Input : Vector of cos(beta) values

num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d2m2	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.15 int lensing_d22 (double * *mu*, int *num_mu*, int *lmax*, double ** *d22*)

This routine computes the d22 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d22	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.16 int lensing_d20 (double * *mu*, int *num_mu*, int *lmax*, double ** *d20*)

This routine computes the d20 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d20	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.17 int lensing_d31 (double * *mu*, int *num_mu*, int *lmax*, double ** *d31*)

This routine computes the d31 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d31	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.18 int lensing_d3m1 (double * *mu*, int *num_mu*, int *lmax*, double ** *d3m1*)

This routine computes the d3m1 term

Parameters

mu	Input : Vector of cos(beta) values

num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d3m1	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.19 int lensing_d3m3 (double * *mu*, int *num_mu*, int *lmax*, double ** *d3m3*)

This routine computes the d3m3 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d3m3	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.20 int lensing_d40 (double * *mu*, int *num_mu*, int *lmax*, double ** *d40*)

This routine computes the d40 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d40	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.21 int lensing_d4m2 (double * *mu*, int *num_mu*, int *lmax*, double ** *d4m2*)

This routine computes the d4m2 term

Parameters

mu	Input : Vector of cos(beta) values
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d4m2	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

3.7.2.22 int lensing_d4m4 (double * *mu*, int *num_mu*, int *lmax*, double ** *d4m4*)

This routine computes the d4m4 term

Parameters

mu	Input : Vector of cos(beta) values

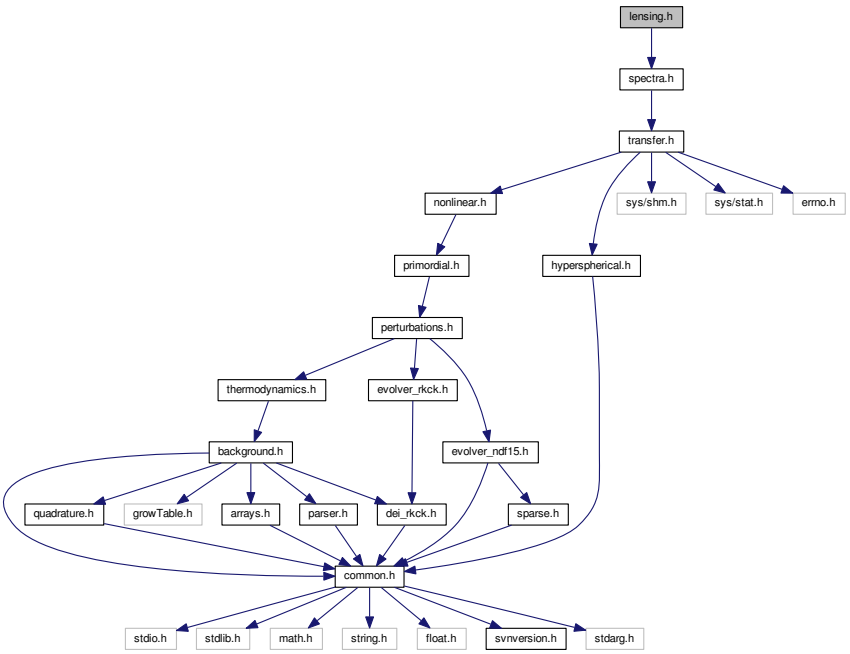
num_mu	Input : Number of cos(beta) values
lmax	Input : maximum multipole
d4m4	Input/output: Result is stored here

Wigner d-functions, computed by recurrence actual recurrence on $\sqrt{(2l+1)/2}d^l_{mm'}$ for stability Formulae from Kostelec & Rockmore 2003

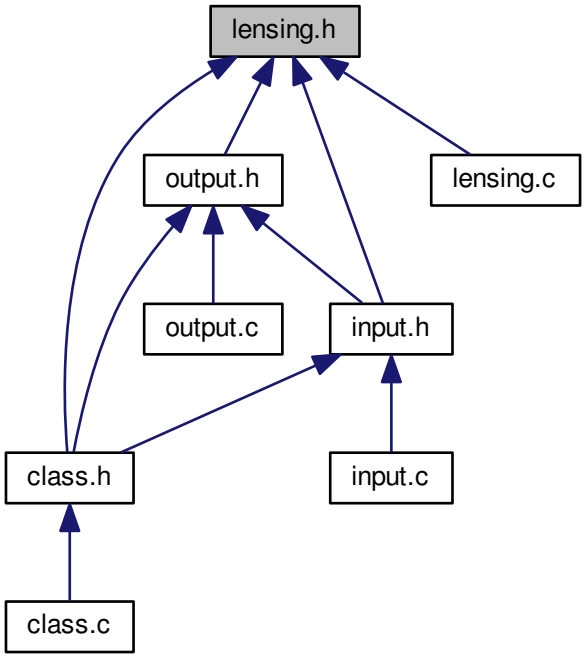
3.8 lensing.h File Reference

```
#include "spectra.h"
```

Include dependency graph for lensing.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct lensing

3.8.1 Detailed Description

Documented includes for spectra module

3.8.2 Data Structure Documentation

3.8.2.1 struct lensing

Structure containing everything about lensed spectra that other modules need to know.

Once initialized by lensing_init(), contains a table of all lensed C_l's for the all modes (scalar/tensor), all types (TT, TE...), and all pairs of initial conditions (adiabatic, isocurvatures...). FOR THE MOMENT, ASSUME ONLY SCALAR & ADIABATIC

Data Fields

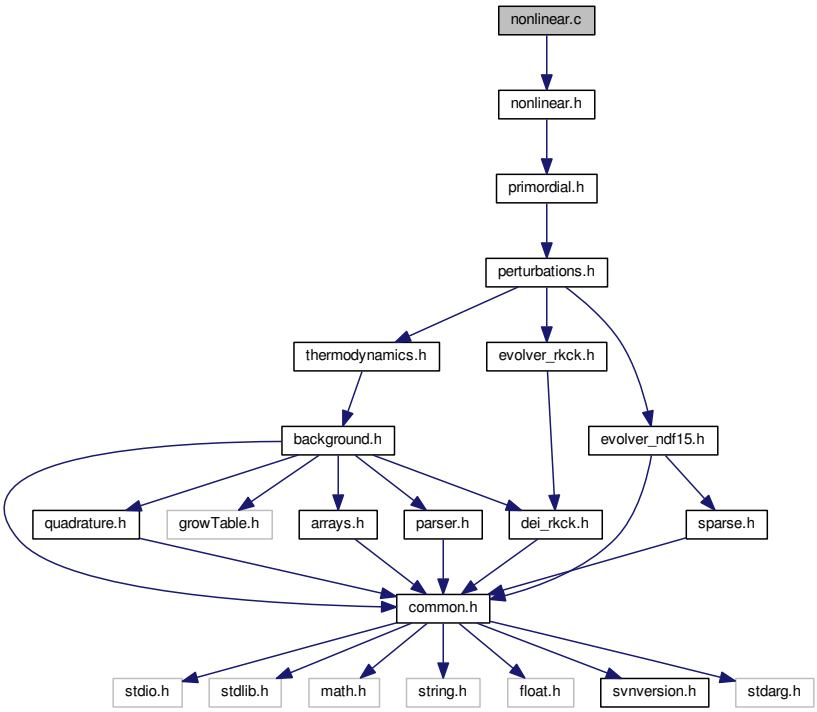
short	has_lensed_cls	do we need to compute lensed C_l's at all ?
int	has_tt	do we want lensed C_l^{TT}? (T = temperature)

int	has_ee	do we want lensed C_l^{EE}? (E = E-polarization)
int	has_te	do we want lensed C_l^{TE}?
int	has_bb	do we want C_l^{BB}? (B = B-polarization)
int	has_pp	do we want $C_l^{\phi\phi}$? (ϕ = CMB lensing potential)
int	has_tp	do we want $C_l^{T\phi}$?
int	has_dd	do we want C_l^{dd}? (d = matter density)
int	has_td	do we want C_l^{Td}?
int	has_ll	do we want C_l^{ll}? (l = lensing potential)
int	has_tl	do we want C_l^{Tl}?
int	index_lt_tt	index for type C_l^{TT}
int	index_lt_ee	index for type C_l^{EE}
int	index_lt_te	index for type C_l^{TE}
int	index_lt_bb	index for type C_l^{BB}
int	index_lt_pp	index for type $C_l^{\phi\phi}$
int	index_lt_tp	index for type $C_l^{T\phi}$
int	index_lt_dd	index for type C_l^{dd}
int	index_lt_td	index for type C_l^{Td}
int	index_lt_ll	index for type C_l^{dd}
int	index_lt_tl	index for type C_l^{Td}
int	lt_size	number of C_l types requested
int	l_unlensed_max	last multipole in all calculations (same as in spectra module)
int	l_lensed_max	last multipole at which lensed spectra are computed
int	l_size	number of l values
int $*$	l_max_lt	last multipole (given as an input) at which we want to output C_ls for a given mode and type
double $*$	l	table of multipole values l[index_l]
double $*$	cl_lens	table of anisotropy spectra for each multipole and types, cl[index_l $*$ ple->lt_size + index_lt]
double $*$	ddcl_lens	second derivatives for interpolation
short	lensing_verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.9 nonlinear.c File Reference

```
#include "nonlinear.h"
```

Include dependency graph for nonlinear.c:



Functions

- int nonlinear_init (struct precision ∗ppr, struct background ∗pba, struct thermo ∗pth, struct perturbs ∗ppt, struct primordial ∗ppm, struct nonlinear ∗pnl)
- int nonlinear_halofit (struct precision ∗ppr, struct background ∗pba, struct primordial ∗ppm, struct nonlinear ∗pnl, double tau, double ∗pk_l, double ∗pk_nl, double ∗k_nl)

3.9.1 Detailed Description

Documented nonlinear module

Julien Lesgourgues, 6.03.2014

New module replacing an older one present up to version 2.0 The new module is located in a better place in the main, allowing it to compute non-linear correction to Cl's and not just P(k). It will also be easier to generalize to new methods. The old implementation of one-loop calculations and TRG calculations has been dropped from this version, they can still be found in older versions.

3.9.2 Function Documentation

3.9.2.1 int nonlinear_init (struct precision ∗ *ppr,* struct background ∗ *pba,* struct thermo ∗ *pth,* struct perturbs ∗ *ppt,* struct primordial ∗ *ppm,* struct nonlinear ∗ *pnl*)

(a) if non non-linear corrections requested

(b) for HALOFIT non-linear spectrum

- copy list of (k,tau) from perturbation module

- loop over time

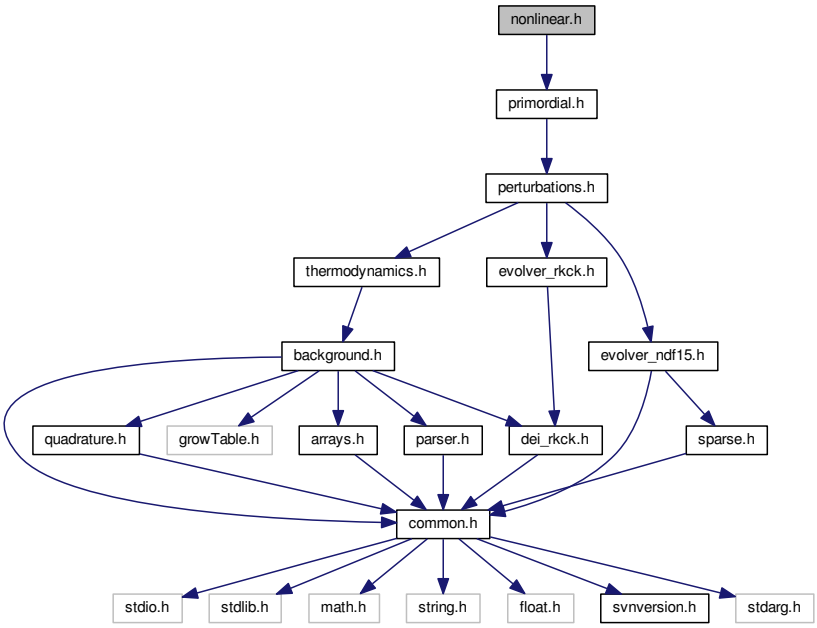
3.9.2.2 int nonlinear_halofit (struct precision * *ppr,* struct background * *pba,* struct primordial * *ppm,* struct nonlinear * *pnl,* double *tau,* double * *pk_l,* double * *pk_nl,* double * *k_nl*)

determine non linear ratios (from pk)

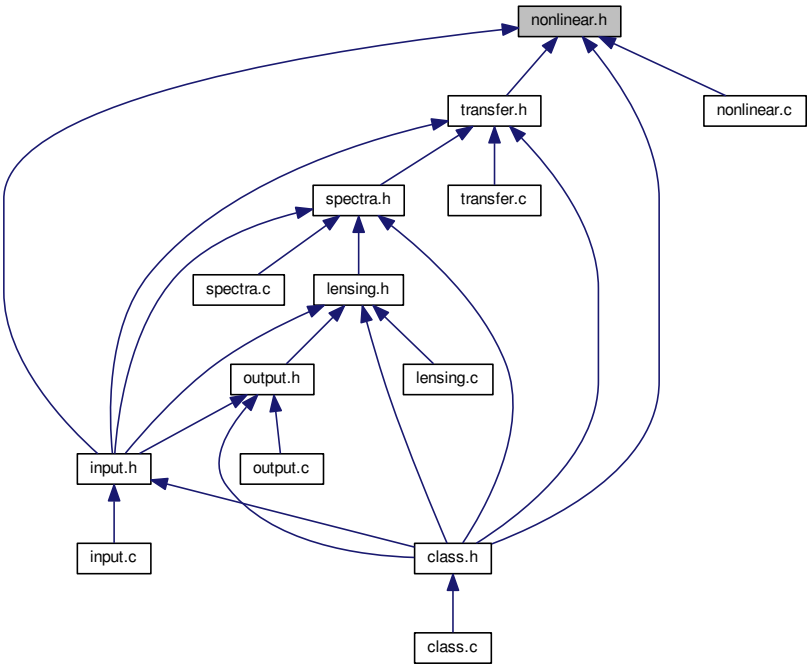
3.10 nonlinear.h File Reference

```
#include "primordial.h"
```

Include dependency graph for nonlinear.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct nonlinear

Macros

- #define _M_EV_TOO_BIG_FOR_HALOFIT_ 10.

3.10.1 Detailed Description

Documented includes for trg module

3.10.2 Data Structure Documentation

3.10.2.1 struct nonlinear

Structure containing all information on non-linear spectra.

Once initialized by nonlinear_init(), contains a table for all two points correlation functions and for all the ai,bj functions (containing the three points correlation functions), for each time and wave-number.

Data Fields

enum non_↩ linear_method	method	$$$ definition missing $$$
int	k_size	k_size = total number of k values
double *	k	k[index_k] = list of k values
int	tau_size	tau_size = number of values
double *	tau	tau[index_tau] = list of time values
double *	nl_corr_density	nl_corr_density[index_tau * ppt->k_size + index_k]
double *	k_nl	$$$ definition missing $$$
short	nonlinear_↩ verbose	amount of information written in standard output
ErrorMsg	error_message	zone for writing error messages

3.10.3 Macro Definition Documentation

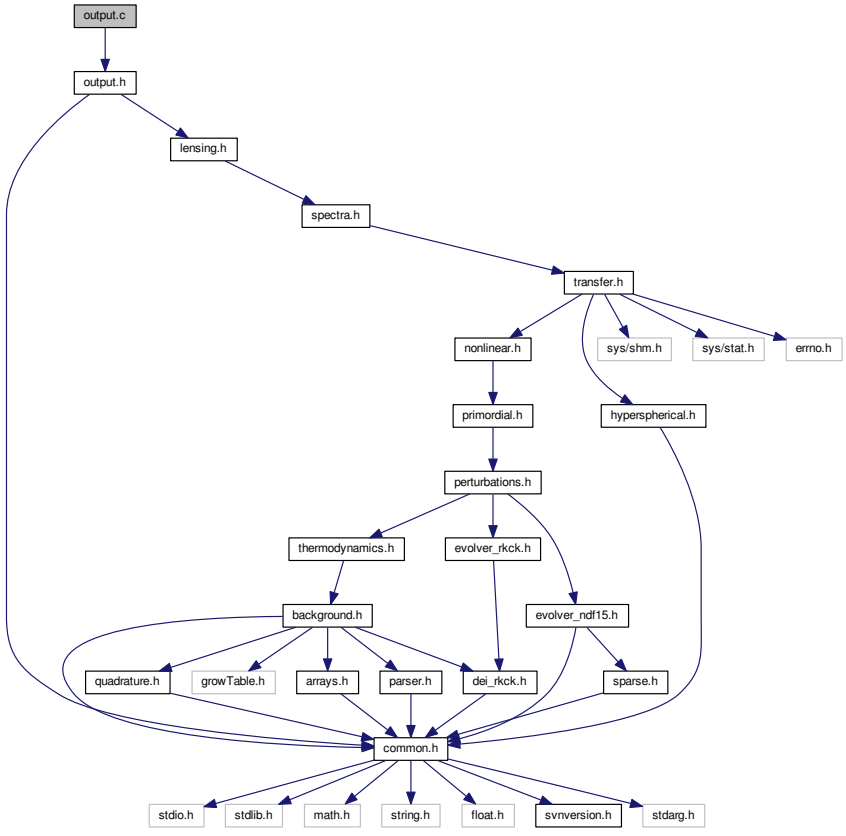
3.10.3.1 #define _M_EV_TOO_BIG_FOR_HALOFIT_ 10.

above which value of non-CDM mass (in eV) do we stop trusting halofit?

3.11 output.c File Reference

```
#include "output.h"
```

Include dependency graph for output.c:



Functions

- int output_init (struct background *pba, struct thermo *pth, struct perturbs *ppt, struct primordial *ppm, struct transfers *ptr, struct spectra *psp, struct nonlinear *pnl, struct lensing *ple, struct output *pop)
- int output_cl (struct background *pba, struct perturbs *ppt, struct spectra *psp, struct lensing *ple, struct output *pop)
- int output_pk (struct background *pba, struct perturbs *ppt, struct spectra *psp, struct output *pop)
- int output_pk_nl (struct background *pba, struct perturbs *ppt, struct spectra *psp, struct output *pop)
- int output_tk (struct background *pba, struct perturbs *ppt, struct spectra *psp, struct output *pop)
- int output_print_data (FILE *out, char titles[_MAXTITLESTRINGLENGTH_], double *dataptr, int size_dataptr)
- int output_open_cl_file (struct spectra *psp, struct output *pop, FILE **clfile, FileName filename, char *first_line, int lmax)
- int output_one_line_of_cl (struct background *pba, struct spectra *psp, struct output *pop, FILE *clfile, double l, double *cl, int ct_size)
- int output_open_pk_file (struct background *pba, struct spectra *psp, struct output *pop, FILE **pkfile, FileName filename, char *first_line, double z)
- int output_one_line_of_pk (FILE *pkfile, double one_k, double one_pk)

3.11.1 Detailed Description

Documented output module

Julien Lesgourgues, 26.08.2010

This module writes the output in files.

The following function can be called from other modules or from the main:

1. output_init() (must be called after spectra_init())
2. output_total_cl_at_l() (can be called even before output_init())

No memory needs to be deallocated after that, hence there is no output_free() routine like in other modules.

3.11.2 Function Documentation

3.11.2.1 int output_init (struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, struct primordial * *ppm*, struct transfers * *ptr*, struct spectra * *psp*, struct nonlinear * *pnl*, struct lensing * *ple*, struct output * *pop*)

This routine writes the output in files.

Parameters

pba	Input: pointer to background structure (needed for calling spectra_pk_at_z())
pth	Input : pointer to thermodynamics structure
ppt	Input : pointer perturbation structure
ppm	Input : pointer to primordial structure
ptr	Input : pointer to transfer structure
psp	Input : pointer to spectra structure
pnl	Input : pointer to nonlinear structure
ple	Input : pointer to lensing structure

pop	Input : pointer to output structure

Summary:

- check that we really want to output at least one file
- deal with all anisotropy power spectra C_l's
- deal with all Fourier matter power spectra P(k)'s
- deal with density and matter power spectra
- deal with background quantities
- deal with thermodynamics quantities
- deal with perturbation quantities
- deal with primordial spectra

3.11.2.2 int output_cl (struct background * *pba*, struct perturbs * *ppt*, struct spectra * *psp*, struct lensing * *ple*, struct output * *pop*)

This routines writes the output in files for anisotropy power spectra C_l's.

Parameters

pba	Input: pointer to background structure (needed for T_cmb)
ppt	Input : pointer perturbation structure
psp	Input : pointer to spectra structure
ple	Input : pointer to lensing structure
pop	Input : pointer to output structure

Summary:

- define local variables
- first, allocate all arrays of files and cls
- second, open only the relevant files, and write a heading in each of them
- third, perform loop over l. For each multipole, get all C_l's by calling spectra_cl_at_l() and distribute the results to relevant files
- finally, close files and free arrays of files and cls

3.11.2.3 int output_pk (struct background * *pba*, struct perturbs * *ppt*, struct spectra * *psp*, struct output * *pop*)

This routines writes the output in files for Fourier matter power spectra P(k)'s.

Parameters

pba	Input: pointer to background structure (needed for calling spectra_pk_at_z())
ppt	Input : pointer perturbation structure
psp	Input : pointer to spectra structure
pop	Input : pointer to output structure

Summary:

- define local variables
- first, check that requested redshift z_pk is consistent

- second, open only the relevant files, and write a heading in each of them
- third, compute P(k) for each k (if several ic's, compute it for each ic and compute also the total); if z_pk = 0, this is done by directly reading inside the pre-computed table; if not, this is done by interpolating the table at the correct value of tau.
- fourth, write in files
- fifth, free memory and close files

3.11.2.4 int output_pk_nl (struct background * *pba*, struct perturbs * *ppt*, struct spectra * *psp*, struct output * *pop*)

This routines writes the output in files for Fourier non-linear matter power spectra P(k)'s.

Parameters

pba	Input: pointer to background structure (needed for calling spectra_pk_at_z())
ppt	Input : pointer perturbation structure
psp	Input : pointer to spectra structure
pop	Input : pointer to output structure

Summary:

- define local variables
- first, check that requested redshift z_pk is consistent
- second, open only the relevant files, and write a heading in each of them
- third, compute P(k) for each k (if several ic's, compute it for each ic and compute also the total); if z_pk = 0, this is done by directly reading inside the pre-computed table; if not, this is done by interpolating the table at the correct value of tau.
- fourth, write in files
- fifth, free memory and close files

3.11.2.5 int output_tk (struct background * *pba*, struct perturbs * *ppt*, struct spectra * *psp*, struct output * *pop*)

This routines writes the output in files for matter transfer functions $T_i(k)$'s.

Parameters

pba	Input: pointer to background structure (needed for calling spectra_pk_at_z())
ppt	Input : pointer perturbation structure
psp	Input : pointer to spectra structure
pop	Input : pointer to output structure

Summary:

- define local variables
- first, check that requested redshift z_pk is consistent
- second, open only the relevant files, and write a heading in each of them

3.11.2.6 int output_print_data (FILE * *out*, char *titles[_MAXTITLESTRINGLENGTH_]*, double * *dataptr*, int *size_dataptr*)

Print titles

Print data:

3.11.2.7 int output_open_cl_file (struct spectra * psp, struct output * pop, FILE ** clfile, FileName filename, char * first_line, int lmax)

This routine opens one file where some C_l's will be written, and writes a heading with some general information concerning its content.

Parameters

psp	Input : pointer to spectra structure
pop	Input : pointer to output structure
clfile	Output: returned pointer to file pointer
filename	Input : name of the file
first_line	Input : text describing the content (mode, initial condition..)
lmax	Input : last multipole in the file (the first one is assumed to be 2)

Returns

the error status

Rest of the entries are independent of format type

3.11.2.8 int output_one_line_of_cl (struct background * *pba*, struct spectra * *psp*, struct output * *pop*, FILE * *clfile*, double *l*, double * *cl*, int *ct_size*)

This routine write one line with l and all C_l's for all types (TT, TE...)

Parameters

pba	Input: pointer to background structure (needed for T_cmb)
psp	Input : pointer to spectra structure
pop	Input : pointer to output structure
clfile	Input : file pointer
l	Input : multipole
cl	Input : C_l's for all types
ct_size	Input : number of types

Returns

the error status

Now print the remaining (if any) entries:

3.11.2.9 int output_open_pk_file (struct background * *pba*, struct spectra * *psp*, struct output * *pop*, FILE ** *pkfile*, FileName *filename*, char * *first_line*, double *z*)

This routine opens one file where some P(k)'s will be written, and writes a heading with some general information concerning its content.

Parameters

pba	Input: pointer to background structure (needed for h)
psp	Input : pointer to spectra structure
pop	Input : pointer to output structure
pkfile	Output: returned pointer to file pointer
filename	Input : name of the file
first_line	Input : text describing the content (initial conditions, ...)
z	Input : redshift of the output

Returns

the error status

3.11.2.10 int output_one_line_of_pk (FILE * *pkfile*, double *one_k*, double *one_pk*)

This routine writes one line with k and P(k)

Parameters

pkfile	Input : file pointer
one_k	Input : wavenumber
one_pk	Input : matter power spectrum

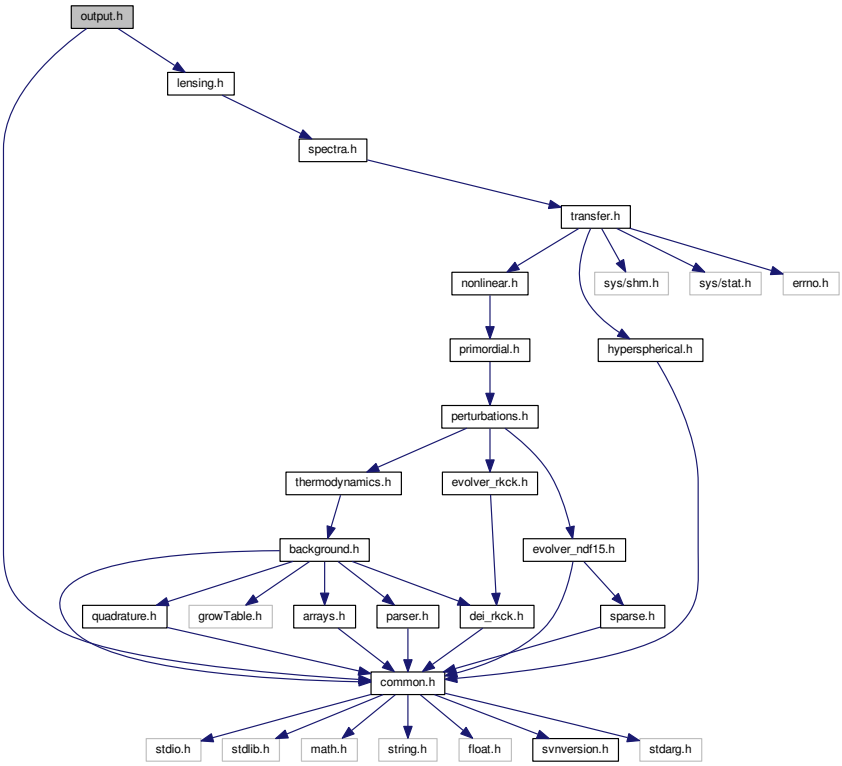
Returns

the error status

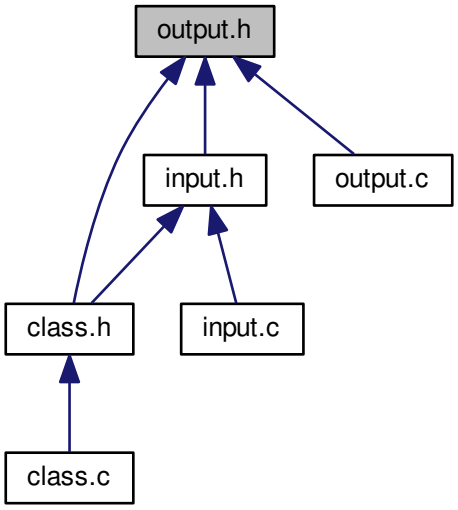
3.12 output.h File Reference

```
#include "common.h"
#include "lensing.h"
```

Include dependency graph for output.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct output

Macros

- #define _Z_PK_NUM_MAX_ 100

3.12.1 Detailed Description

Documented includes for output module

3.12.2 Data Structure Documentation

3.12.2.1 struct output

Structure containing various informations on the output format, all of them initialized by user in input module.

Data Fields

FileName	root	root for all file names
int	z_pk_num	number of redshift at which P(k,z) and T_i(k,z) should be written
double	z_pk[_Z_PK_↩ NUM_MAX_]	value(s) of redshift at which P(k,z) and T_i(k,z) should be written

short	write_header	$$$ definition missing $$$
enum file_format	output_format	$$$ definition missing $$$
short	write_↩ background	$$$ definition missing $$$
short	write_↩ thermodynamics	$$$ definition missing $$$
short	write_↩ perturbations	$$$ definition missing $$$
short	write_primordial	$$$ definition missing $$$
short	output_verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.12.3 Macro Definition Documentation

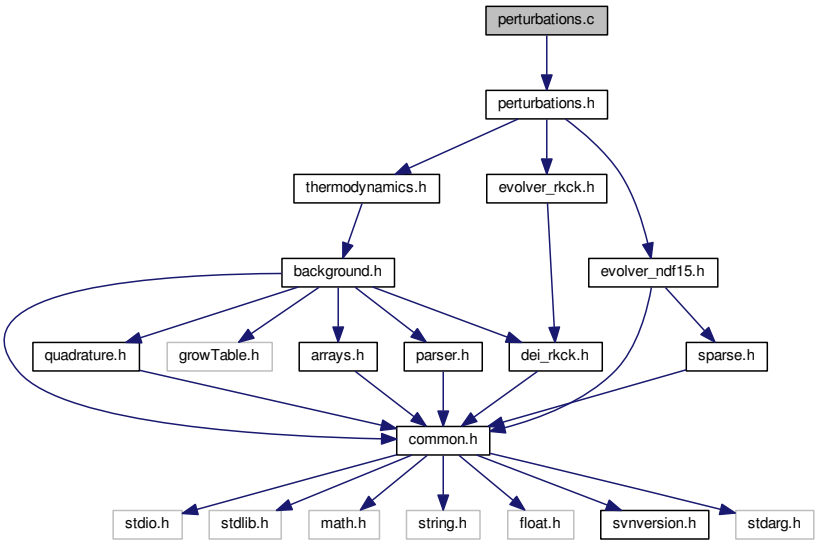
3.12.3.1 #define _Z_PK_NUM_MAX_ 100

Maximum number of values of redshift at which the spectra will be written in output files

3.13 perturbations.c File Reference

```
#include "perturbations.h"
```

Include dependency graph for perturbations.c:



Functions

- int perturb_sources_at_tau (struct perturbs ∗ppt, int index_md, int index_ic, int index_type, double tau, double ∗psource)
- int perturb_init (struct precision ∗ppr, struct background ∗pba, struct thermo ∗pth, struct perturbs ∗ppt)
- int perturb_free (struct perturbs ∗ppt)
- int perturb_indices_of_perturbs (struct precision ∗ppr, struct background ∗pba, struct thermo ∗pth, struct perturbs ∗ppt)

- int perturb_timesampling_for_sources (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt)
- int perturb_get_k_list (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt)
- int perturb_workspace_init (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, struct perturb_workspace *ppw)
- int perturb_workspace_free (struct perturbs *ppt, int index_md, struct perturb_workspace *ppw)
- int perturb_solve (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, int index_ic, int index_k, struct perturb_workspace *ppw)
- int perturb_prepare_output (struct background *pba, struct perturbs *ppt)
- int perturb_find_approximation_number (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, double k, struct perturb_workspace *ppw, double tau_ini, double tau_end, int *interval_number, int *interval_number_of)
- int perturb_find_approximation_switches (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, double k, struct perturb_workspace *ppw, double tau_ini, double tau_end, double precision, int interval_number, int *interval_number_of, double *interval_limit, int **interval_approx)
- int perturb_vector_init (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, int index_ic, double k, double tau, struct perturb_workspace *ppw, int *pa_old)
- int perturb_vector_free (struct perturb_vector *pv)
- int perturb_initial_conditions (struct precision *ppr, struct background *pba, struct perturbs *ppt, int index_md, int index_ic, double k, double tau, struct perturb_workspace *ppw)
- int perturb_approximations (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, double k, double tau, struct perturb_workspace *ppw)
- int perturb_timescale (double tau, void *parameters_and_workspace, double *timescale, ErrorMsg error_message)
- int perturb_einstein (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, double k, double tau, double *y, struct perturb_workspace *ppw)
- int perturb_total_stress_energy (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, int index_md, double k, double *y, struct perturb_workspace *ppw)
- int perturb_sources (double tau, double *y, double *dy, int index_tau, void *parameters_and_workspace, ErrorMsg error_message)
- int perturb_print_variables (double tau, double *y, double *dy, void *parameters_and_workspace, ErrorMsg error_message)
- int perturb_derivs (double tau, double *y, double *dy, void *parameters_and_workspace, ErrorMsg error_message)
- int perturb_tca_slip_and_shear (double *y, void *parameters_and_workspace, ErrorMsg error_message)
- int perturb_rsa_delta_and_theta (struct precision *ppr, struct background *pba, struct thermo *pth, struct perturbs *ppt, double k, double *y, double a_prime_over_a, double *pvecthermo, struct perturb_workspace *ppw)

3.13.1 Detailed Description

Documented perturbation module

Julien Lesgourgues, 23.09.2010

Deals with the perturbation evolution. This module has two purposes:

- at the beginning, to initialize the perturbations, i.e. to integrate the perturbation equations, and store temporarily the terms contributing to the source functions as a function of conformal time. Then, to perform a few manipulations of these terms in order to infer the actual source functions $S^X(k,\tau)$, and to store them as a function of conformal time inside an interpolation table.

- at any time in the code, to evaluate the source functions at a given conformal time (by interpolating within the interpolation table).

Hence the following functions can be called from other modules:

1. perturb_init() at the beginning (but after background_init() and thermodynamics_init())
2. perturb_sources_at_tau() at any later time
3. perturb_free() at the end, hen no more calls to perturb_sources_at_tau() are needed

3.13.2 Function Documentation

3.13.2.1 int perturb_sources_at_tau (struct perturbs * *ppt*, int *index_md*, int *index_ic*, int *index_type*, double *tau*, double * *psource*)

Source function $S^X(k,\tau)$ at a given conformal time tau.

Evaluate source functions at given conformal time tau by reading the pre-computed table and interpolating.

Parameters

ppt	Input : pointer to perturbation structure containing interpolation tables
index_md	Input : index of requested mode
index_ic	Input : index of requested initial condition
index_type	Input : index of requested source function type
tau	Input : any value of conformal time
psource	Output: vector (already allocated) of source function as a function of k

Returns

the error status

Summary:

- interpolate in pre-computed table contained in ppt

3.13.2.2 int perturb_init (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*)

Initialize the perturbs structure, and in particular the table of source functions.

Main steps:

- given the values of the flags describing which kind of perturbations should be considered (modes↩ : scalar/vector/tensor, initial conditions, type of source functions needed...), initialize indices and wavenumber list
- define the time sampling for the output source functions
- for each mode (scalar/vector/tensor): initialize the indices of relevant perturbations, integrate the differential system, compute and store the source functions.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure
ppt	Output: Initialized perturbation structure

Returns

the error status

Summary:

- define local variables
- preliminary checks
- initialize all indices and lists in perturbs structure using perturb_indices_of_perturbs()
- define the common time sampling for all sources using perturb_timesampling_for_sources()
- if we want to store perturbations, write titles and allocate storage
- create an array of workspaces in multi-thread case
- loop over modes (scalar, tensors, etc). For each mode:

create a workspace (one per thread in multi-thread case)

(a) initialize indices of vectors of perturbations with perturb_indices_of_current_vectors()

(c) loop over initial conditions and wavenumbers; for each of them, evolve perturbations and compute source functions with perturb_solve()

3.13.2.3 int perturb_free (struct perturbs * *ppt*)

Free all memory space allocated by perturb_init().

To be called at the end of each run, only when no further calls to perturb_sources_at_tau() are needed.

Parameters

ppt	Input: perturbation structure to be freed

Returns

the error status

Stuff related to perturbations output:

Free non-NULL pointers:

3.13.2.4 int perturb_indices_of_perturbs (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*)

Initialize all indices and allocate most arrays in perturbs structure.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure
ppt	Input/Output: Initialized perturbation structure

Returns

the error status

Summary:

- define local variables
- count modes (scalar, vector, tensor) and assign corresponding indices
- allocate array of number of types for each mode, ppt->tp_size[index_md]
- allocate array of number of initial conditions for each mode, ppt->ic_size[index_md]
- allocate array of arrays of source functions for each mode, ppt->source[index_md]

initialization all flags to false (will eventually be set to true later)

- source flags and indices, for sources that all modes have in common (temperature, polarization, ...). For temperature, the term t2 is always non-zero, while other terms are non-zero only for scalars and vectors. For polarization, the term e is always non-zero, while the term b is only for vectors and tensors.

define k values with perturb_get_k_list()

- loop over modes. Initialize flags and indices which are specific to each mode.

(a) scalars

- source flags and indices, for sources that are specific to scalars

– count scalar initial conditions (for scalars: ad, cdi, nid, niv; for tensors: only one) and assign corresponding indices

- source flags and indices, for sources that are specific to tensors

class_test(index_type == 0, ppt->error_message, "inconsistent input: you asked for vectors, so you should have at least one non-zero vector source type (temperature or polarization). Please adjust your input.");

– initial conditions for vectors

(b) tensors

- source flags and indices, for sources that are specific to tensors

class_test(index_type == 0, ppt->error_message, "inconsistent input: you asked for tensors, so you should have at least one non-zero tensor source type (temperature or polarization). Please adjust your input.");

– only one initial condition for tensors

(c) for each mode, allocate array of arrays of source functions for each initial conditions and wavenumber, (ppt->source[index_md])[index_ic][index_type]

3.13.2.5 int perturb_timesampling_for_sources (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*)

Define time sampling for source functions.

For each type, compute the list of values of tau at which sources will be sampled. Knowing the number of tau values, allocate all arrays of source functions.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure
ppt	Input/Output: Initialized perturbation structure

Returns

the error status

Summary:

- define local variables
- allocate background/thermodynamics vectors
- first, just count the number of sampling points in order to allocate the array containing all values:

(a) if CMB requested, first sampling point = when the universe stops being opaque; otherwise, start sampling gravitational potential at recombination [however, if perturbed recombination is requested, we also need to start the system before recombination. Otherwise, the initial conditions for gas temperature and ionization fraction perturbations (delta_T = 1/3 delta_b, delta_x_e) are not valid].

(b) next sampling point = previous + ppr->perturb_sampling_stepsize $*$ timescale_source, where:

- if CMB requested: timescale_source1 = $|g/\dot{g}| = |\dot{\kappa} - \ddot{\kappa}/\dot{\kappa}|^{-1}$; timescale_source2 = $|2\ddot{a}/a - (\dot{a}/a)^2|^{-1/2}$ (to sample correctly the late ISW effect; and timescale_source=1/(1/timescale_source1+1/timescale_source2); repeat till today.
- if CMB not requested: timescale_source = 1/aH; repeat till today.
- infer total number of time steps, ppt->tau_size
- allocate array of time steps, ppt->tau_sampling[index_tau]
- repeat the same steps, now filling the array with each tau value:

(a) first sampling point = when the universe stops being opaque

(b) next sampling point = previous + ppr->perturb_sampling_stepsize $*$ timescale_source, where timescale_source1 = $|g/\dot{g}| = |\dot{\kappa} - \ddot{\kappa}/\dot{\kappa}|^{-1}$; timescale_source2 = $|2\ddot{a}/a - (\dot{a}/a)^2|^{-1/2}$ (to sample correctly the late ISW effect; and timescale_source=1/(1/timescale_source1+1/timescale_source2); repeat till today

- if CMB not requested: timescale_source = 1/aH; repeat till today.
- last sampling point = exactly today
- loop over modes, initial conditions and types. For each of them, allocate array of source functions.

3.13.2.6 int perturb_get_k_list (struct precision $*$ *ppr,* struct background $*$ *pba,* struct thermo $*$ *pth,* struct perturbs $*$ *ppt*)

Define the number of comoving wavenumbers using the information passed in the precision structure.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure
ppt	Input : pointer to perturbation structure

Returns

the error status

- scalar modes
- find k_max (as well as k_max_cmb[ppt->index_md_scalars], k_max_cl[ppt->index_md_scalars])
- test that result for k_min, k_max make sense
- vector modes
- find k_max (as well as k_max_cmb[ppt->index_md_vectors], k_max_cl[ppt->index_md_vectors])
- test that result for k_min, k_max make sense
- tensor modes
- find k_max (as well as k_max_cmb[ppt->index_md_tensors], k_max_cl[ppt->index_md_tensors])
- test that result for k_min, k_max make sense

Find indices in ppt->k[index_md] corresponding to 'k_output_values'. We are assuming that ppt->k is sorted and growing, and we have made sure that ppt->k_output_values is also sorted and growing.

Decide if we should add k_output_value now. This has to be this complicated, since we can only compare the k-values when both indices are in range.

The two MIN statements is here because in a normal run, the cl and cmb arrays contain a single k value larger than their respective k_max. We are mimicking this behavior.

3.13.2.7 int perturb_workspace_init (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, struct perturb_workspace * *ppw*)

Initialize a perturb_workspace structure. All fields are allocated here, with the exception of the perturb_vector '->pv' field, which is allocated separately in perturb_vector_init. We allocate one such perturb_workspace structure per thread and per mode (scalar/../tensor). Then, for each thread, all initial conditions and wavenumbers will use the same workspace.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
ppw	Input/Output: pointer to perturb_workspace structure which fields are allocated or filled here

Returns

the error status

Summary:

- define local variables

Compute maximum l_max for any multipole

Allocate s_l[] array for freestreaming of multipoles (see arXiv:1305.3261) and initialize to 1.0 which is the K=0 value.

- define indices of metric perturbations obeying to constraint equations (this can be done once and for all, because the vector of metric perturbations is the same whatever the approximation scheme, unlike the vector of quantities to be integrated, which is allocated separately in perturb_vector_init)
- allocate some workspace in which we will store temporarily the values of background, thermodynamics, metric and source quantities at a given time
- count number of approximation, initialize their indices, and allocate their flags
- For definiteness, initialize approximation flags to arbitrary values (correct values are overwritten in pertub_↩ find_approximation_switches)
- allocate fields where some of the perturbations are stored

3.13.2.8 int perturb_workspace_free (struct perturbs * ppt, int index_md, struct perturb_workspace * ppw)

Free the perturb_workspace structure (with the exception of the perturb_vector '->pv' field, which is freed separately in perturb_vector_free).

Parameters

ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
ppw	Input: pointer to perturb_workspace structure to be freed

Returns

the error status

3.13.2.9 int perturb_solve (struct precision * ppr, struct background * pba, struct thermo * pth, struct perturbs * ppt, int index_md, int index_ic, int index_k, struct perturb_workspace * ppw)

Solve the perturbation evolution for a given mode, initial condition and wavenumber, and compute the corresponding source functions.

For a given mode, initial condition and wavenumber, this function finds the time ranges over witch the perturbations can be described within a given approximation. For each such range, it initializes (or redistribute) perturbations using perturb_vector_init(), and integrates over time. Whenever a "source sampling time" is passed, the source terms are computed and stored in the source table using perturb_sources().

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure
ppt	Input/Output: pointer to the perturbation structure (output source functions S(k,tau) written here)
index_md	Input: index of mode under consideration (scalar/.../tensor)
index_ic	Input: index of initial condition under consideration (ad, iso...)
index_k	Input: index of wavenumber

ppw	Input: pointer to perturb_workspace structure containing index values and workspaces

Returns

the error status

Summary:

- define local variables
- initialize indices relevant for back/thermo tables search
- get wavenumber value

If non-zero curvature, update array of free-streaming coefficients ppw->s_l

- maximum value of tau for which sources are calculated for this wavenumber
- using bisection, compute minimum value of tau for which this wavenumber is integrated
- find the number of intervals over which approximation scheme is constant
- fill the structure containing all fixed parameters, indices and workspaces needed by perturb_derivs
- check whether we need to print perturbations to a file for this wavenumber

class_call(perturb_prepare_output_file(pba,ppt,ppw,index_ikout,index_md), ppt->error_message, ppt->error_↩ message);

- loop over intervals over which approximation scheme is uniform. For each interval:

(a) fix the approximation scheme

(b) get the previous approximation scheme. If the current interval starts from the initial time tau_ini, the previous approximation is set to be a NULL pointer, so that the function perturb_vector_init() knows that perturbations must be initialized

(c) define the vector of perturbations to be integrated over. If the current interval starts from the initial time tau_ini, fill the vector with initial conditions for each mode. If it starts from an approximation switching point, redistribute correctly the perturbations from the previous to the new vector of perturbations.

(d) integrate the perturbations over the current interval.

- if perturbations were printed in a file, close the file

fill the source terms array with zeros for all times between then last integrated time tau_max and tau_today.

- free quantities allocated at the beginning of the routine

3.13.2.10 int perturb_prepare_output (struct background * *pba*, struct perturbs * *ppt*)

Write titles for all perturbations that we would like to print/store.

3.13.2.11 int perturb_find_approximation_number (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, double *k*, struct perturb_workspace * *ppw*, double *tau_ini*, double *tau_end*, int * *interval_number*, int * *interval_number_of*)

For a given mode and wavenumber, find the number of interval of times between tau_ini and tau_end such that the approximation scheme (and the number of perturbation equations) is uniform.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
k	Input: index of wavenumber
ppw	Input: pointer to perturb_workspace structure containing index values and workspaces
tau_ini	Input: initial time of the perturbation integration
tau_end	Input: final time of the perturbation integration
interval_number	Output: total number of intervals
interval_↩ number_of	Output: number of intervals with respect to each particular approximation

Returns

the error status

- fix default number of intervals to one (if no approximation switch)
- loop over each approximation and add the number of approximation switching times

3.13.2.12 int perturb_find_approximation_switches (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, double *k*, struct perturb_workspace * *ppw*, double *tau_ini*, double *tau_end*, double *precision*, int *interval_number*, int * *interval_number_of*, double * *interval_limit*, int ** *interval_approx*)

For a given mode and wavenumber, find the values of time at which the approximation changes.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
k	Input: index of wavenumber
ppw	Input: pointer to perturb_workspace structure containing index values and workspaces
tau_ini	Input: initial time of the perturbation integration
tau_end	Input: final time of the perturbation integration
precision	Input: tolerance on output values
interval_number	Input: total number of intervals
interval_↩ number_of	Input: number of intervals with respect to each particular approximation
interval_limit	Output: value of time at the boundary of the intervals: tau_ini, tau_switch1, ..., tau_end
interval_approx	Output: value of approximations in each interval

Returns

the error status

- write in output arrays the initial time and approximation
- if there are no approximation switches, just write final time and return
- if there are switches, consider approximations one after each other. Find switching time by bisection. Store all switches in arbitrary order in array unsorted_tau_switch[]

- now sort interval limits in correct order
- store each approximation in chronological order

3.13.2.13 int perturb_vector_init (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, int *index_ic*, double *k*, double *tau*, struct perturb_workspace * *ppw*, int * *pa_old*)

Initialize the field '->pv' of a perturb_workspace structure, which is a perturb_vector structure. This structure contains indices and values of all quantities which need to be integrated with respect to time (and only them: quantities fixed analytically or obeying a constraint equations are NOT included in this vector). This routine distinguishes between two cases:

-> the input pa_old is set to the NULL pointer:

This happens when we start integrating over a new wavenumber and we want to set initial conditions for the perturbations. Then, it is assumed that ppw->pv is not yet allocated. This routine allocates it, defines all indices, and then fill the vector ppw->pv->y with the initial conditions defined in perturb_initial_conditions.

-> the input pa_old is not set to the NULL pointer and describes some set of approximations:

This happens when we need to change of approximation scheme while integrating over a given wavenumber. The new approximation described by ppw->pa is then different from pa_old. Then, this routine allocates a new vector with a new size and new index values; it fills this vector with initial conditions taken from the previous vector passed as an input in ppw->pv, and eventually with some analytic approximations for the new variables appearing at this time; then the new vector comes in replacement of the old one, which is freed.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
index_ic	Input: index of initial condition under consideration (ad, iso...)
k	Input: wavenumber
tau	Input: conformal time
ppw	Input/Output: workspace containing input the approximation scheme, the background/thermodynamics/metric quantities, and eventually the previous vector y; and in output the new vector y.
pa_old	Input: NULL is we need to set y to initial conditions for a new wavenumber; points towards a perturb_approximations if we want to switch of approximation.

Returns

the error status

Summary:

- define local variables
- allocate a new perturb_vector structure to which ppw->pv will point at the end of the routine
- initialize pointers to NULL (they will be allocated later if needed), relevant for perturb_vector_free()
- defines all indices in this new vector (depends on approximation scheme, described by the input structure ppw->pa)

(b) metric perturbations V or h_v depending on gauge

(b) metric perturbation h is a propagating degree of freedom, so h and hdot are included in the vector of ordinary perturbations, no in that of metric perturbations

- allocate vectors for storing the values of all these quantities and their time-derivatives at a given time
- specify which perturbations are needed in the evaluation of source terms
- case of setting initial conditions for a new wavenumber

(a) check that current approximation scheme is consistent with initial conditions

(b) let ppw->pv points towards the perturb_vector structure that we just created

(c) fill the vector ppw->pv->y with appropriate initial conditions

- case of switching approximation while a wavenumber is being integrated

(a) for the scalar mode:

– check that the change of approximation scheme makes sense (note: before calling this routine there is already a check that we wish to change only one approximation flag at a time)

– some variables (b, cdm, fld, ...) are not affected by any approximation. They need to be reconducted whatever the approximation switching is. We treat them here. Below we will treat other variables case by case.

This is correct even when ncdmfa == off, since ppv->l_max_ncdm and ppv->q_size_ncdm is updated.

(b) for the vector mode

– check that the change of approximation scheme makes sense (note: before calling this routine there is already a check that we wish to change only one approximation flag at a time)

– some variables (gw, gwdot, ...) are not affected by any approximation. They need to be reconducted whatever the approximation switching is. We treat them here. Below we will treat other variables case by case.

(c) for the tensor mode

– check that the change of approximation scheme makes sense (note: before calling this routine there is already a check that we wish to change only one approximation flag at a time)

– some variables (gw, gwdot, ...) are not affected by any approximation. They need to be reconducted whatever the approximation switching is. We treat them here. Below we will treat other variables case by case.

For now, neutrinos go here.

(c) free the previous vector of perturbations

(d) let ppw->pv points towards the perturb_vector structure that we just created

3.13.2.14 int perturb_vector_free (struct perturb_vector * *pv*)

Free the perturb_vector structure.

Parameters

pv	Input: pointer to perturb_vector structure to be freed

Returns

the error status

3.13.2.15 int perturb_initial_conditions (struct precision * *ppr,* struct background * *pba,* struct perturbs * *ppt,* int *index_md,* int *index_ic,* double *k,* double *tau,* struct perturb_workspace * *ppw*)

For each mode, wavenumber and initial condition, this function initializes all values in the vector of perturbed variables (in a given gauge). It is assumed here that all values have been set previously to zero, only non-zero values are set here.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
index_ic	Input: index of initial condition under consideration (ad, iso...)
k	Input: wavenumber
tau	Input: conformal time
ppw	Input/Output: workspace containing input the approximation scheme, the background/thermodynamics/metric quantities, and eventually the previous vector y; and in output the new vector y.

Returns

the error status

Summary:

- declare local variables
- for scalars

(a) compute relevant background quantities: compute rho_r, rho_m, rho_nu (= all relativistic except photons), and their ratio.

(b) starts by setting everything in synchronous gauge. If another gauge is needed, we will perform a gauge transformation below.

(b.1) adiabatic

Canonical field (solving for the perturbations): initial perturbations set to zero, they should reach the attractor soon enough. TODO: Incorporate the attractor IC from 1004.5509 delta_phi $= -(a/k)^2/\phi'(\rho+p)\theta$ delta_phi_prime $= a^2/\phi'$ (delta_rho_phi + V'delta_phi) and assume theta, delta_rho as for perfect fluid with $c_s^2 = 1$ and w = 1/3 (ASSUMES radiation TRACKING)

a∗a/k/k/ppw->pvecback[pba->index_bg_phi_prime_scf]∗k∗ktau_three/4.∗1./(4.-6.∗(1./3.)+3.∗1.) ∗ (ppw->pvecback[pba->index_bg_rho_scf] + ppw->pvecback[pba->index_bg_p_scf])∗ ppr->curvature_ini ∗ s2_↩ squared;

delta_fld expression ∗ rho_scf with the w = 1/3, c_s = 1 a∗a/ppw->pvecback[pba->index_bg_phi_prime_↩ scf]∗(- ktau_two/4.∗(1.+1./3.)∗(4.-3.∗1.)/(4.-6.∗(1/3.)+3.∗1.)∗ppw->pvecback[pba->index_bg_rho_scf] - ppw->pvecback[pba->index_bg_dV_scf]∗ppw->pv->y[ppw->pv->index_pt_phi_scf])∗ ppr->curvature_ini ∗ s2_↩ squared;

(b.2) Cold dark matter Isocurvature

(b.3) Baryon Isocurvature

(b.4) Neutrino density Isocurvature

(b.5) Neutrino velocity Isocurvature

(c) If the needed gauge is really the synchronous gauge, we need to affect the previously computed value of eta to the actual variable eta

(d) If the needed gauge is the newtonian gauge, we must compute alpha and then perform a gauge transformation for each variable

- 2. ∗ a_prime_over_a ∗ alpha + eta
- 4.5 ∗ (a2/k2) ∗ ppw->rho_plus_p_shear;

(e) In any gauge, we should now implement the relativistic initial conditions in ur and ncdm variables

- for tensors

3.13.2.16 int perturb_approximations (struct precision * ppr, struct background * pba, struct thermo * pth, struct perturbs * ppt, int index_md, double k, double tau, struct perturb_workspace * ppw)

Evaluate background/thermodynamics at τ, infer useful flags / time scales for integrating perturbations.

Evaluate background quantities at τ, as well as thermodynamics for scalar mode; infer useful flags and time scales for integrating the perturbations:

- check whether tight-coupling approximation is needed.
- check whether radiation (photons, massless neutrinos...) perturbations are needed.
- choose step of integration: step = ppr->perturb_integration_stepsize * min_time_scale, where min_time_scale = smallest time scale involved in the equations. There are three time scales to compare:

1. that of recombination, $\tau_c = 1/\kappa'$
2. Hubble time scale, $\tau_h = a/a'$
3. Fourier mode, $\tau_k = 1/k$

So, in general, min_time_scale = $\min(\tau_c, \tau_b, \tau_h, \tau_k)$.

However, if $\tau_c \ll \tau_h$ and $\tau_c \ll \tau_k$, we can use the tight-coupling regime for photons and write equations in such way that the time scale τ_c becomes irrelevant (no effective mass term in $1/\tau_c$). Then, the smallest scale in the equations is only $\min(\tau_h, \tau_k)$. In practise, it is sufficient to use only the condition $\tau_c \ll \tau_h$.

Also, if $\rho_{matter} \gg \rho_{radiation}$ and $k \gg aH$, we can switch off radiation perturbations (i.e. switch on the free-streaming approximation) and then the smallest scale is simply τ_h.

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
k	Input: wavenumber
tau	Input: conformal time
ppw	Input/Output: in output contains the approximation to be used at this time

Returns

the error status

Summary:

- define local variables
- compute Fourier mode time scale = $\tau_k = 1/k$
- evaluate background quantities with background_at_tau() and Hubble time scale $\tau_h = a/a'$
- for scalars modes:

(a) evaluate thermodynamical quantities with thermodynamics_at_z()

(b.1) if $\kappa' = 0$, recombination is finished; tight-coupling approximation must be off

(b.2) if $\kappa' \neq 0$, recombination is not finished: check tight-coupling approximation

(b.2.a) compute recombination time scale for photons, $\tau_\gamma = 1/\kappa'$

(b.2.b) check whether tight-coupling approximation should be on

- for tensor modes:

(a) evaluate thermodynamical quantities with thermodynamics_at_z()

(b.1) if $\kappa' = 0$, recombination is finished; tight-coupling approximation must be off

(b.2) if $\kappa' \neq 0$, recombination is not finished: check tight-coupling approximation

(b.2.a) compute recombination time scale for photons, $\tau_\gamma = 1/\kappa'$

(b.2.b) check whether tight-coupling approximation should be on

3.13.2.17 int perturb_timescale (double *tau*, void * *parameters_and_workspace*, double * *timescale*, ErrorMsg *error_message*)

Compute typical timescale over which the perturbation equation vary. Some integrators (e.g. Runge-Kunta) benefit from calling this routine at each step in order to adapt the next step.

This is one of the few functions in the code which are passed to the generic_integrator() routine. Since generic_integrator() should work with functions passed from various modules, the format of the arguments is a bit special:

- fixed parameters and workspaces are passed through a generic pointer. generic_integrator() doesn't know the content of this pointer.
- the error management is a bit special: errors are not written as usual to pth->error_message, but to a generic error_message passed in the list of arguments.

Parameters

tau	Input : conformal time
parameters_and_workspace	Input : fixed parameters (e.g. indices), workspace, approximation used, etc.
timescale	Output: perturbation variation timescale (given the approximation used)
error_message	Output: error message

Summary:

- define local variables
- extract the fields of the parameter_and_workspace input structure
- compute Fourier mode time scale = $\tau_k = 1/k$
- evaluate background quantities with background_at_tau() and Hubble time scale $\tau_h = a/a'$
- for scalars modes:

(b.2.a) compute recombination time scale for photons, $\tau_\gamma = 1/\kappa'$

- for vector modes:

compute recombination time scale for photons, $\tau_\gamma = 1/\kappa'$

- for tensor modes:

compute recombination time scale for photons, $\tau_\gamma = 1/\kappa'$

3.13.2.18 int perturb_einstein (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, double *k*, double *tau*, double * *y*, struct perturb_workspace * *ppw*)

Compute metric perturbations (those not integrated over time) using Einstein equations

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to thermodynamics structure
ppt	Input: pointer to the perturbation structure
index_md	Input: index of mode under consideration (scalar/.../tensor)
k	Input: wavenumber
tau	Input: conformal time
y	Input: vector of perturbations (those integrated over time) (already allocated)
ppw	Input/Output: in output contains the updated metric perturbations

Returns

the error status

Summary:

- define local variables
- wavenumber and scale factor related quantities
- for scalar modes:

(c) infer metric perturbations from Einstein equations

3.13.2.19 int perturb_total_stress_energy (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, int *index_md*, double *k*, double * *y*, struct perturb_workspace * *ppw*)

Summary:

- define local variables
- wavenumber and scale factor related quantities

(a) deal with approximation schemes

(a.1) photons

(a.1.1) no approximation

(a.1.2) radiation streaming approximation

(a.1.3) tight coupling approximation

(a.2) ur

(b) compute the total density, velocity and shear perturbations

photon contribution to vector sources:

photon contribution to gravitational wave source:

ur contribution to gravitational wave source:

ncdm contribution to gravitational wave source:

3.13.2.20 int perturb_sources (double *tau*, double * *y*, double * *dy*, int *index_tau*, void * *parameters_and_workspace*, ErrorMsg *error_message*)

Compute the source functions (three terms for temperature, one for E or B modes, etc.)

This is one of the few functions in the code which are passed to the generic_integrator() routine. Since generic_↩ integrator() should work with functions passed from various modules, the format of the arguments is a bit special:

- fixed parameters and workspaces are passed through a generic pointer. generic_integrator() doesn't know the content of this pointer.
- the error management is a bit special: errors are not written as usual to pth->error_message, but to a generic error_message passed in the list of arguments.

Parameters

tau	Input: conformal time
y	Input: vector of perturbations
dy	Input: vector of time derivative of perturbations
index_tau	Input: index in the array tau_sampling
parameters_and_workspace	Input/Output: in input, all parameters needed by perturb_derivs, in output, source terms
error_message	Output: error message

Returns

the error status

Summary:

- define local variables
- rename structure fields (just to avoid heavy notations)
- get background/thermo quantities in this point
- compute metric perturbations
- compute quantities depending on approximation schemes

for each type, compute source terms

3.13.2.21 int perturb_print_variables (double *tau*, double * *y*, double * *dy*, void * *parameters_and_workspace*, ErrorMsg *error_message*)

When testing the code or a cosmological model, it can be useful to output perturbations at each step of integration (and not just the delta's at each source sampling point, which is achieved simply by asking for matter transfer functions). Then this function can be passed to the generic_evolver routine.

By default, instead of passing this function to generic_evolver, one passes a null pointer. Then this function is just not used.

Parameters

tau	Input: conformal time
y	Input: vector of perturbations
dy	Input: vector of its derivatives (already allocated)
parameters_and_workspace	Input: fixed parameters (e.g. indices)
error_message	Output : error message

ncdm sector begin

ncdm sector ends

- rename structure fields (just to avoid heavy notations)

perturbed recombination

Get delta, deltaP/rho, theta, shear and store in array

Do gauge transformation of delta, deltaP/rho (?) and theta using -= 3aH(1+w_ncdm) alpha for delta.

Handle (re-)allocation

Handle (re-)allocation

3.13.2.22 int perturb_derivs (double *tau*, double * *y*, double * *dy*, void * *parameters_and_workspace*, ErrorMsg *error_message*)

Compute derivative of all perturbations to be integrated

For each mode (scalar/vector/tensor) and each wavenumber k, this function computes the derivative of all values in the vector of perturbed variables to be integrated.

This is one of the few functions in the code which are passed to the generic_integrator() routine. Since generic_integrator() should work with functions passed from various modules, the format of the arguments is a bit special:

- fixed parameters and workspaces are passed through a generic pointer. generic_integrator() doesn't know what the content of this pointer is.
- errors are not written as usual in pth->error_message, but in a generic error_message passed in the list of arguments.

Parameters

tau	Input: conformal time
y	Input: vector of perturbations
dy	Output: vector of its derivatives (already allocated)
parameters_and_workspace	Input/Output: in input, fixed parameters (e.g. indices); in output, background and thermo quantities evaluated at tau.
error_message	Output : error message

Summary:

- define local variables
- rename the fields of the input structure (just to avoid heavy notations)
- get background/thermo quantities in this point

get metric perturbations with perturb_einstein()

- compute related background quantities

Compute 'generalised cotK function of argument sqrt(|K|)*tau, for closing hierarchy. (see equation 2.34 in arXiv:1305.3261):

- for scalar mode:

(a) define short-cut notations for the scalar perturbations

(b) perturbed recombination

(c) compute metric-related quantities (depending on gauge; additional gauges can be coded below)

Each continuity equation contains a term in (theta+metric_continuity) with metric_continuity = (h_prime/2) in synchronous gauge, (-3 phi_prime) in newtonian gauge

Each Euler equation contains a source term metric_euler with metric_euler = 0 in synchronous gauge, (k2 psi) in newtonian gauge

Each shear derivative equation contains a source term metric_shear equal to metric_shear = (h_prime+6eta_↩ prime)/2 in synchronous gauge, 0 in newtonian gauge

metric_shear_prime is the derivative of metric_shear

In the ufa_class approximation, the leading-order source term is (h_prime/2) in synchronous gauge, (-3 (phi_↩ prime+psi_prime)) in newtonian gauge: we approximate the later by (-6 phi_prime)

(d) if some approximation schemes are turned on, enforce a few y[] values computed in perturb_einstein

(e) BEGINNING OF ACTUAL SYSTEM OF EQUATIONS OF EVOLUTION:

-> photon temperature density

-> baryon density

-> baryon velocity (depends on tight-coupling approximation=tca)

perturbed recombination has an impact

perturbed recombination has an impact

-> photon temperature higher momenta and photon polarization (depend on tight-coupling approximation) :

—> if photon tight-coupling is off:

——> define $\Pi = G_{\gamma 0} + G_{\gamma 2} + F_{\gamma 2}$

——> photon temperature velocity

——> photon temperature shear

——> photon temperature l=3

——> photon temperature l>3

——> photon temperature lmax

——> photon polarization l=0

——> photon polarization l=1

——> photon polarization l=2

——> photon polarization l>2

——> photon polarization lmax_pol

—> if photon tight-coupling is on:

-—> in that case, only need photon velocity

perturbed recombination has an impact

-> cdm

—> newtonian gauge: cdm density and velocity

—> synchronous gauge: cdm density only (velocity set to zero by definition of the gauge)

-> dcdm and dr

-> dcdm

-> dr

——> dr F0

——> dr F1

——> exact dr F2

——> exact dr l=3

——> exact dr l>3

——> exact dr lmax_dr

-> fluid (fld)

—> factors w, w_prime, adiabatic sound speed ca2 (all three background-related), plus actual sound speed in the fluid rest frame cs2

—> fluid density

—> fluid velocity

-> scalar field (scf)

—> field value

—> Klein Gordon equation

-> ultra-relativistic neutrino/relics (ur)

—> if radiation streaming approximation is off

——> ur density

——> ur velocity

——> exact ur shear

——> exact ur l=3

——> exact ur l>3

——> exact ur lmax_ur

——> in fluid approximation (ufa): only ur shear needed

-> non-cold dark matter (ncdm): massive neutrinos, WDM, etc.

—> first case: use a fluid approximation (ncdmfa)

——> loop over species

——> define intermediate quantitites

——> exact continuity equation

——> exact euler equation

——> different ansatz for approximate shear derivative

——> jump to next species

—> second case: use exact equation (Boltzmann hierarchy on momentum grid)

——> loop over species

——> loop over momentum

——> define intermediate quantities

——> ncdm density for given momentum bin

——> ncdm velocity for given momentum bin

——> ncdm shear for given momentum bin

——> ncdm l>3 for given momentum bin

——> ncdm lmax for given momentum bin (truncation as in Ma and Bertschinger) but with curvature taken into account a la arXiv:1305.3261

——> jump to next momentum bin or species

-> metric

–> eta of synchronous gauge

- vector mode

-> baryon velocity

- tensor mode

-> non-cold dark matter (ncdm): massive neutrinos, WDM, etc.

——> loop over species

——> loop over momentum

——> define intermediate quantities

——> ncdm density for given momentum bin

——> ncdm l>0 for given momentum bin

——> ncdm lmax for given momentum bin (truncation as in Ma and Bertschinger) but with curvature taken into account a la arXiv:1305.3261

-——> jump to next momentum bin or species

3.13.2.23 int perturb_tca_slip_and_shear (double * *y,* void * *parameters_and_workspace,* ErrorMsg *error_message*)

Summary:

- define local variables
- rename the fields of the input structure (just to avoid heavy notations)
- compute related background quantities

(a) define short-cut notations for the scalar perturbations

(b) define short-cut notations used only in tight-coupling approximation

(d) compute metric-related quantities (depending on gauge; additional gauges can be coded below)

Each continuity equation contains a term in (theta+metric_continuity) with metric_continuity = (h_prime/2) in synchronous gauge, (-3 phi_prime) in newtonian gauge

Each Euler equation contains a source term metric_euler with metric_euler = 0 in synchronous gauge, (k2 psi) in newtonian gauge

Each shear derivative equation contains a source term metric_shear equal to metric_shear = (h_prime+6eta_↩ prime)/2 in synchronous gauge, 0 in newtonian gauge

metric_shear_prime is the derivative of metric_shear

In the ufa_class approximation, the leading-order source term is (h_prime/2) in synchronous gauge, (-3 (phi_↩ prime+psi_prime)) in newtonian gauge: we approximate the later by (-6 phi_prime)

(e) if some approximation schemes are turned on, enforce a few y[] values computed in perturb_einstein

——> like Ma & Bertschinger

——> relax assumption dkappa∼a^-2 (like in CAMB)

——> also relax assumption cb2∼a^-1

——> intermediate quantities for 2nd order tca: shear_g at first order in tight-coupling

——> intermediate quantities for 2nd order tca: zero order for theta_b' = theta_g'

perturbed recombination has an impact

——> intermediate quantities for 2nd order tca: shear_g_prime at first order in tight-coupling

——> 2nd order as in CRS

——> 2nd order like in CLASS paper

——> add only the most important 2nd order terms

—> store tight-coupling values of photon shear and its derivative

3.13.2.24 int perturb_rsa_delta_and_theta (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct perturbs * *ppt*, double *k*, double * *y*, double *a_prime_over_a*, double * *pvecthermo*, struct perturb_workspace * *ppw*)

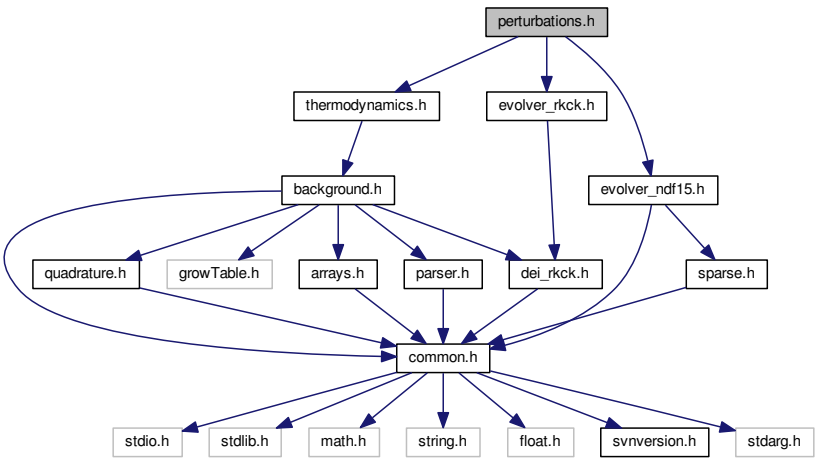
Summary:

- define local variables

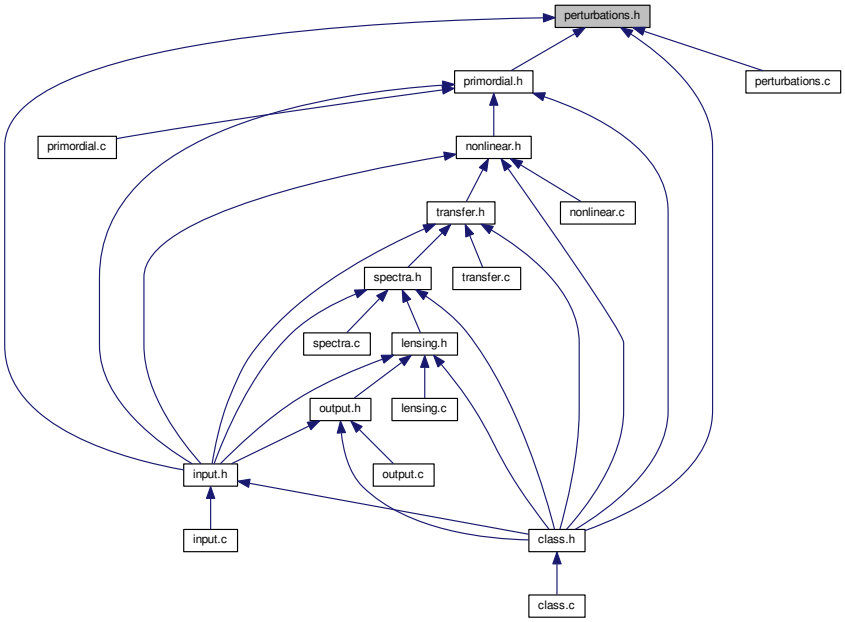
3.14 perturbations.h File Reference

```
#include "thermodynamics.h"
#include "evolver_ndf15.h"
#include "evolver_rkck.h"
```

Include dependency graph for perturbations.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct perturbs
- struct perturb_vector
- struct perturb_workspace
- struct perturb_parameters_and_workspace

Macros

- #define _MAX_NUMBER_OF_K_FILES_ 30

Enumerations

- enum tca_flags
- enum tca_method
- enum possible_gauges { newtonian, synchronous }
- #define _SELECTION_NUM_MAX_ 100

3.14.1 Detailed Description

Documented includes for perturbation module

3.14.2 Data Structure Documentation

3.14.2.1 struct perturbs

Structure containing everything about perturbations that other modules need to know, in particular tabled values of the source functions $S(k,\tau)$ for all requested modes (scalar/vector/tensor), initial conditions, types (temperature, E-polarization, B-polarization, lensing potential, etc), multipole l and wavenumber k.

Data Fields

short	has_↩ perturbations	do we need to compute perturbations at all ?
short	has_cls	do we need any harmonic space spectrum C_l (and hence Bessel functions, transfer functions, ...)?
short	has_scalars	do we need scalars?
short	has_vectors	do we need vectors?
short	has_tensors	do we need tensors?
short	has_ad	do we need adiabatic mode?
short	has_bi	do we need isocurvature bi mode?
short	has_cdi	do we need isocurvature cdi mode?
short	has_nid	do we need isocurvature nid mode?
short	has_niv	do we need isocurvature niv mode?
short	has_perturbed↩ _recombination	Do we want to consider perturbed temperature and ionization fraction?
enum tensor_methods	tensor_method	Neutrino contribution to tensors way to treat neutrinos in tensor perturbations(neglect, approximate as massless, take exact equations)
short	evolve_tensor↩ _ur	will we evolve ur tensor perturbations (either because we have ur species, or we have ncdm species with massless approximation) ?
short	evolve_tensor↩ _ncdm	will we evolve ncdm tensor perturbations (if we have ncdm species and we use the exact method) ?
short	has_cl_cmb_↩ temperature	do we need Cl's for CMB temperature?
short	has_cl_cmb_↩ polarization	do we need Cl's for CMB polarization?
short	has_cl_cmb_↩ lensing_potential	do we need Cl's for CMB lensing potential?
short	has_cl_↩ lensing_potential	do we need Cl's for galaxy lensing potential?
short	has_cl_↩ number_count	do we need Cl's for density number count?
short	has_pk_matter	do we need matter Fourier spectrum?
short	has_density_↩ transfers	do we need to output individual matter density transfer functions?
short	has_velocity_↩ transfers	do we need to output individual matter velocity transfer functions?
short	has_nl_↩ corrections↩ _based_on_↩ delta_m	do we want to compute non-linear corrections with an algorithm relying on delta_m (like halofit)?

short	has_nc_density	in dCl, do we want density terms ?
short	has_nc_rsd	in dCl, do we want redshift space distortion terms ?
short	has_nc_lens	in dCl, do we want lensing terms ?
short	has_nc_gr	in dCl, do we want gravity terms ?
int	l_scalar_max	maximum l value for CMB scalars C_ls
int	l_vector_max	maximum l value for CMB vectors C_ls
int	l_tensor_max	maximum l value for CMB tensors C_ls
int	l_lss_max	maximum l value for LSS C_ls (density and lensing potential in bins)
double	k_max_for_pk	maximum value of k in 1/Mpc in P(k) (if C_ls also requested, overseeded by value kmax inferred from l_scalar_max if it is bigger)
int	selection_num	number of selection functions (i.e. bins) for matter density Cls
enum selection_type	selection	type of selection functions
double	selection_mean[_SELECTION_NUM_MAX_]	centers of selection functions
double	selection_width[_SELECTION_NUM_MAX_]	widths of selection functions
int	switch_sw	in temperature calculation, do we want to include the intrinsic temperature + Sachs Wolfe term?
int	switch_eisw	in temperature calculation, do we want to include the early integrated Sachs Wolfe term?
int	switch_lisw	in temperature calculation, do we want to include the late integrated Sachs Wolfe term?
int	switch_dop	in temperature calculation, do we want to include the Doppler term?
int	switch_pol	in temperature calculation, do we want to include the polarization-related term?
double	eisw_lisw_split_z	at which redshift do we define the cut between eisw and lisw ?
int	store_perturbations	Do we want to store perturbations?
int	k_output_values_num	Number of perturbation outputs (default=0)
double	k_output_values[_MAX_NUMBER_OF_K_FILES_]	List of k values where perturbation output is requested.
int *	index_k_output_values	List of indices corresponding to k-values close to k_output_values for each mode. [index_md*k_output_values_num+ik]
char	scalar_titles[_MAXTITLESTRINGLENGTH_]	*DELIMITER* separated string of titles for scalar perturbation output files.
char	vector_titles[_MAXTITLESTRINGLENGTH_]	*DELIMITER* separated string of titles for vector perturbation output files.

char	tensor_titles[_↩ MAXTITLEST↩ RINGLENGTH↩ _]	*DELIMITER* separated string of titles for tensor perturbation output files.
int	number_of_↩ scalar_titles	$$$ definition missing $$$
int	number_of_↩ vector_titles	$$$ definition missing $$$
int	number_of_↩ tensor_titles	$$$ definition missing $$$
double ∗	scalar_↩ perturbations_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of double pointers to perturbation output for scalars
double ∗	vector_↩ perturbations_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of double pointers to perturbation output for vectors
double ∗	tensor_↩ perturbations_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of double pointers to perturbation output for tensors
int	size_scalar_↩ perturbation_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of sizes of scalar double pointers
int	size_vector_↩ perturbation_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of sizes of vector double pointers
int	size_tensor_↩ perturbation_↩ data[_MAX_N↩ UMBER_OF_↩ K_FILES_]	Array of sizes of tensor double pointers
double	three_ceff2_ur	3 x effective squared sound speed for the ultrarelativistic perturbations
double	three_cvis2_ur	3 x effective viscosity parameter for the ultrarelativistic perturbations
short	has_cmb	do we need CMB-related sources (temperature, polarization) ?
short	has_lss	do we need LSS-related sources (lensing potential, ...) ?
enum possible_gauges	gauge	gauge in which to perform this calculation
int	index_md_↩ scalars	index value for scalars
int	index_md_↩ tensors	index value for tensors
int	index_md_↩ vectors	index value for vectors

int	md_size	number of modes included in computation
int	index_ic_ad	index value for adiabatic
int	index_ic_cdi	index value for CDM isocurvature
int	index_ic_bi	index value for baryon isocurvature
int	index_ic_nid	index value for neutrino density isocurvature
int	index_ic_niv	index value for neutrino velocity isocurvature
int	index_ic_ten	index value for unique possibility for tensors
int *	ic_size	for a given mode, ic_size[index_md] = number of initial conditions included in computation
short	has_source_t	do we need source for CMB temperature?
short	has_source_p	do we need source for CMB polarization?
short	has_source_↩ delta_m	do we need source for delta of total matter?
short	has_source_↩ delta_g	do we need source for delta of gammas?
short	has_source_↩ delta_b	do we need source for delta of baryons?
short	has_source_↩ delta_cdm	do we need source for delta of cold dark matter?
short	has_source_↩ delta_dcdm	do we need source for delta of DCDM?
short	has_source_↩ delta_fld	do we need source for delta of dark energy?
short	has_source_↩ delta_scf	do we need source for delta from scalar field?
short	has_source_↩ delta_dr	do we need source for delta of decay radiation?
short	has_source_↩ delta_ur	do we need source for delta of ultra-relativistic neutrinos/relics?
short	has_source_↩ delta_ncdm	do we need source for delta of all non-cold dark matter species (e.g. massive neutrinos)?
short	has_source_↩ theta_m	do we need source for theta of total matter?
short	has_source_↩ theta_g	do we need source for theta of gammas?
short	has_source_↩ theta_b	do we need source for theta of baryons?
short	has_source_↩ theta_cdm	do we need source for theta of cold dark matter?
short	has_source_↩ theta_dcdm	do we need source for theta of DCDM?
short	has_source_↩ theta_fld	do we need source for theta of dark energy?
short	has_source_↩ theta_scf	do we need source for theta of scalar field?
short	has_source_↩ theta_dr	do we need source for theta of ultra-relativistic neutrinos/relics?
short	has_source_↩ theta_ur	do we need source for theta of ultra-relativistic neutrinos/relics?
short	has_source_↩ theta_ncdm	do we need source for theta of all non-cold dark matter species (e.g. massive neutrinos)?

short	has_source_phi	do we need source for metric fluctuation phi?
short	has_source_↩ phi_prime	do we need source for metric fluctuation phi'?
short	has_source_↩ phi_plus_psi	do we need source for metric fluctuation (phi+psi)?
short	has_source_psi	do we need source for metric fluctuation psi?
int	index_tp_t0	index value for temperature (j=0 term)
int	index_tp_t1	index value for temperature (j=1 term)
int	index_tp_t2	index value for temperature (j=2 term)
int	index_tp_p	index value for polarization
int	index_tp_delta↩ _m	index value for delta tot
int	index_tp_delta↩ _g	index value for delta of gammas
int	index_tp_delta↩ _b	index value for delta of baryons
int	index_tp_delta↩ _cdm	index value for delta of cold dark matter
int	index_tp_delta↩ _dcdm	index value for delta of DCDM
int	index_tp_delta↩ _fld	index value for delta of dark energy
int	index_tp_delta↩ _scf	index value for delta of scalar field
int	index_tp_delta↩ _dr	index value for delta of decay radiation
int	index_tp_delta↩ _ur	index value for delta of ultra-relativistic neutrinos/relics
int	index_tp_delta↩ _ncdm1	index value for delta of first non-cold dark matter species (e.g. massive neutrinos)
int	index_tp_↩ perturbed_↩ recombination↩ _delta_temp	Gas temperature perturbation
int	index_tp_↩ perturbed_↩ recombination↩ _delta_chi	Inionization fraction perturbation
int	index_tp_theta↩ _m	index value for theta tot
int	index_tp_theta↩ _g	index value for theta of gammas
int	index_tp_theta↩ _b	index value for theta of baryons
int	index_tp_theta↩ _cdm	index value for theta of cold dark matter
int	index_tp_theta↩ _dcdm	index value for theta of DCDM
int	index_tp_theta↩ _fld	index value for theta of dark energy
int	index_tp_theta↩ _scf	index value for theta of scalar field

int	index_tp_theta↩ _ur	index value for theta of ultra-relativistic neutrinos/relics
int	index_tp_theta↩ _dr	index value for F1 of decay radiation
int	index_tp_theta↩ _ncdm1	index value for theta of first non-cold dark matter species (e.g. massive neutrinos)
int	index_tp_phi	index value for metric fluctuation phi
int	index_tp_phi_↩ prime	index value for metric fluctuation phi'
int	index_tp_phi_↩ plus_psi	index value for metric fluctuation phi+psi
int	index_tp_psi	index value for metric fluctuation psi
int *	tp_size	number of types tp_size[index_md] included in computation for each mode
int *	k_size_cmb	k_size_cmb[index_md] number of k values used for CMB calculations, requiring a fine sampling in k-space
int *	k_size_cl	k_size_cl[index_md] number of k values used for non-CMB Cl calculations, requiring a coarse sampling in k-space.
int *	k_size	k_size[index_md] = total number of k values, including those needed for P(k) but not for Cl's
double **	k	k[index_md][index_k] = list of values
double	k_min	minimum value (over all modes)
double	k_max	maximum value (over all modes)
int	tau_size	tau_size = number of values
double *	tau_sampling	tau_sampling[index_tau] = list of tau values
double	selection_min↩ _of_tau_min	used in presence of selection functions (for matter density, cosmic shear...)
double	selection_max↩ _of_tau_max	used in presence of selection functions (for matter density, cosmic shear...)
double	selection_↩ delta_tau	used in presence of selection functions (for matter density, cosmic shear...)
double *	selection_tau_↩ min	value of conformal time below which W(tau) is considered to vanish for each bin
double *	selection_tau_↩ max	value of conformal time above which W(tau) is considered to vanish for each bin
double *	selection_tau	value of conformal time at the center of each bin
double *	selection_↩ function	selection function W(tau), normalized to $\int W(tau)dtau = 1$, stored in selection_function[bin*ppt->tau_size+index_tau]
double ***	sources	Pointer towards the source interpolation table sources[index_md] [index_ic * ppt->tp_size[index_md] + index_type] [index_tau * ppt->k↩ _size + index_k]
short	perturbations_↩ verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.14.2.2 struct perturb_vector

Structure containing the indices and the values of the perturbation variables which are integrated over time (as well as their time-derivatives). For a given wavenumber, the size of these vectors changes when the approximation scheme changes.

Data Fields

int	index_pt_delta↩ _g	photon density
int	index_pt_theta↩ _g	photon velocity
int	index_pt_↩ shear_g	photon shear
int	index_pt_l3_g	photon l=3
int	l_max_g	max momentum in Boltzmann hierarchy (at least 3)
int	index_pt_pol0↩ _g	photon polarization, l=0
int	index_pt_pol1↩ _g	photon polarization, l=1
int	index_pt_pol2↩ _g	photon polarization, l=2
int	index_pt_pol3↩ _g	photon polarization, l=3
int	l_max_pol_g	max momentum in Boltzmann hierarchy (at least 3)
int	index_pt_delta↩ _b	baryon density
int	index_pt_theta↩ _b	baryon velocity
int	index_pt_delta↩ _cdm	cdm density
int	index_pt_theta↩ _cdm	cdm velocity
int	index_pt_delta↩ _dcdm	dcdm density
int	index_pt_theta↩ _dcdm	dcdm velocity
int	index_pt_delta↩ _fld	dark energy density
int	index_pt_theta↩ _fld	dark energy velocity
int	index_pt_phi_scf	scalar field density
int	index_pt_phi_↩ prime_scf	scalar field velocity
int	index_pt_delta↩ _ur	density of ultra-relativistic neutrinos/relics
int	index_pt_theta↩ _ur	velocity of ultra-relativistic neutrinos/relics
int	index_pt_↩ shear_ur	shear of ultra-relativistic neutrinos/relics
int	index_pt_l3_ur	l=3 of ultra-relativistic neutrinos/relics
int	l_max_ur	max momentum in Boltzmann hierarchy (at least 3)
int	index_pt_↩ perturbed_↩ recombination↩ _delta_temp	Gas temperature perturbation
int	index_pt_↩ perturbed_↩ recombination↩ _delta_chi	Inionization fraction perturbation

int	index_pt_F0_dr	The index to the first Legendre multipole of the DR expansion. Not that this is not exactly the usual delta, see Kaplinghat et al., astro-ph/9907388.
int	l_max_dr	max momentum in Boltzmann hierarchy for dr)
int	index_pt_psi0_↩ _ncdm1	$$$ definition missing $$$
int	N_ncdm	$$$ definition missing $$$
int *	l_max_ncdm	$$$ definition missing $$$
int *	q_size_ncdm	$$$ definition missing $$$
int	index_pt_eta	synchronous gauge metric perturbation eta
int	index_pt_phi	$$$ definition missing $$$
int	index_pt_hv_↩ prime	vector metric perturbation h_v' in synchronous gauge
int	index_pt_V	vector metric perturbation V in Newtonian gauge
int	index_pt_gw	tensor metric perturbation h (gravitational waves)
int	index_pt_gwdot	its time-derivative
int	pt_size	size of perturbation vector
double *	y	vector of perturbations to be integrated
double *	dy	time-derivative of the same vector
int *	used_in_sources	boolean array specifying which perturbations enter in the calculation of source functions

3.14.2.3 struct perturb_workspace

Workspace containing, among other things, the value at a given time of all background/perturbed quantities, as well as their indices.

There will be one such structure created for each mode (scalar/.../tensor) and each thread (in case of parallel computing)

Data Fields

int	index_mt_psi	psi in longitudinal gauge
int	index_mt_phi_↩ prime	(d phi/d conf.time) in longitudinal gauge
int	index_mt_h_↩ prime	h' (wrt conf. time) in synchronous gauge
int	index_mt_h_↩ prime_prime	h'' (wrt conf. time) in synchronous gauge
int	index_mt_eta_↩ prime	eta' (wrt conf. time) in synchronous gauge
int	index_mt_alpha	$\alpha = (h' + 6\eta')/(2k^2)$ in synchronous gauge
int	index_mt_↩ alpha_prime	α' wrt conf. time) in synchronous gauge
int	index_mt_gw_↩ prime_prime	second derivative wrt conformal time of gravitational wave field, often called h
int	index_mt_V_↩ prime	derivative of Newtonian gauge vector metric perturbation V
int	index_mt_hv_↩ prime_prime	Second derivative of Synchronous gauge vector metric perturbation h_v
int	mt_size	size of metric perturbation vector
double *	pvecback	background quantities

double *	pvecthermo	thermodynamics quantities
double *	pvecmetric	metric quantities
struct perturb_vector *	pv	pointer to vector of integrated perturbations and their time-derivatives
double	delta_rho	$$$ definition missing $$$
double	rho_plus_p_theta	$$$ definition missing $$$
double	rho_plus_p_shear	$$$ definition missing $$$
double	delta_p	$$$ definition missing $$$
double	gw_source	$$$ definition missing $$$
double	vector_source_pi	$$$ definition missing $$$
double	vector_source_v	$$$ definition missing $$$
double	tca_shear_g	photon shear in tight-coupling approximation
double	tca_slip	photon-baryon slip in tight-coupling approximation
double	rsa_delta_g	photon density in radiation streaming approximation
double	rsa_theta_g	photon velocity in radiation streaming approximation
double	rsa_delta_ur	photon density in radiation streaming approximation
double	rsa_theta_ur	photon velocity in radiation streaming approximation
double *	delta_ncdm	$$$ definition missing $$$
double *	theta_ncdm	$$$ definition missing $$$
double *	shear_ncdm	$$$ definition missing $$$
double	delta_m	$$$ definition missing $$$
double	theta_m	$$$ definition missing $$$
FILE *	perturb_output_file	filepointer to output file
int	index_ikout	index for output k value
short	inter_mode	$$$ definition missing $$$
int	last_index_back	the background interpolation function background_at_tau() keeps memory of the last point called through this index
int	last_index_thermo	the thermodynamics interpolation function thermodynamics_at_z() keeps memory of the last point called through this index
int	index_ap_tca	index for tight-coupling approximation
int	index_ap_rsa	index for radiation streaming approximation
int	index_ap_ufa	index for ur fluid approximation
int	index_ap_ncdmfa	index for ncdm fluid approximation
int	ap_size	number of relevant approximations for a given mode
int *	approx	array of approximation flags holding at a given time: approx[index_ap]
int	max_l_max	maximum l_max for any multipole
double *	s_l	array of freestreaming coefficients $s_l = \sqrt{1 - K * (l^2 - 1)/k^2}$

3.14.2.4 struct perturb_parameters_and_workspace

Structure pointing towards all what the function that perturb_derivs needs to know: fixed input parameters and indices contained in the various structures, workspace, etc.

Data Fields

struct precision *	ppr	pointer to the precision structure

struct background *	pba	pointer to the background structure
struct thermo *	pth	pointer to the thermodynamics structure
struct perturbs *	ppt	pointer to the precision structure
int	index_md	index of mode (scalar/.../vector/tensor)
int	index_ic	$$$ definition missing $$$
int	index_k	$$$ definition missing $$$
double	k	$$$ definition missing $$$
struct perturb_workspace *	ppw	workspace defined above

3.14.3 Macro Definition Documentation

3.14.3.1 #define _SELECTION_NUM_MAX_ 100

maximum number and types of selection function (for bins of matter density or cosmic shear)

3.14.3.2 #define _MAX_NUMBER_OF_K_FILES_ 30

maximum number of k-values for perturbation output

3.14.4 Enumeration Type Documentation

3.14.4.1 enum tca_flags

flags for various approximation schemes (tca = tight-coupling approximation, rsa = radiation streaming approximation, ufa = massless neutrinos / ultra-relativistic relics fluid approximation)

CAUTION: must be listed below in chronological order, and cannot be reversible. When integrating equations for a given mode, it is only possible to switch from left to right in the lists below.

3.14.4.2 enum tca_method

labels for the way in which each approximation scheme is implemented

3.14.4.3 enum possible_gauges

List of coded gauges. More gauges can in principle be defined.

Enumerator

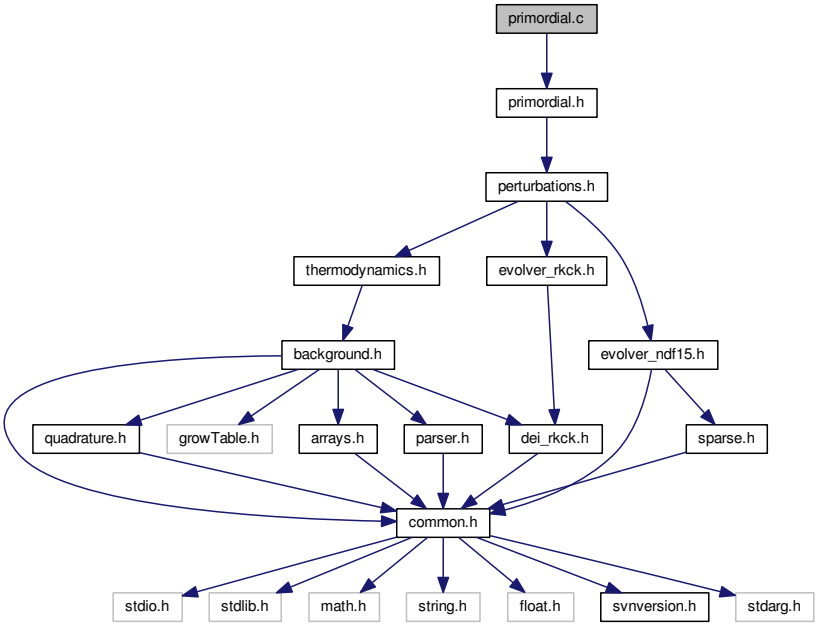
newtonian newtonian (or longitudinal) gauge

synchronous synchronous gauge with $\theta_{cdm} = 0$ by convention

3.15 primordial.c File Reference

```
#include "primordial.h"
```

Include dependency graph for primordial.c:



Functions

- int primordial_spectrum_at_k (struct primordial *ppm, int index_md, enum linear_or_logarithmic mode, double input, double *output)
- int primordial_init (struct precision *ppr, struct perturbs *ppt, struct primordial *ppm)
- int primordial_free (struct primordial *ppm)
- int primordial_indices (struct perturbs *ppt, struct primordial *ppm)
- int primordial_get_lnk_list (struct primordial *ppm, double kmin, double kmax, double k_per_decade)
- int primordial_analytic_spectrum_init (struct perturbs *ppt, struct primordial *ppm)
- int primordial_analytic_spectrum (struct primordial *ppm, int index_md, int index_ic1_ic2, double k, double *pk)
- int primordial_inflation_potential (struct primordial *ppm, double phi, double *V, double *dV, double *ddV)
- int primordial_inflation_hubble (struct primordial *ppm, double phi, double *H, double *dH, double *ddH, double *dddH)
- int primordial_inflation_indices (struct primordial *ppm)
- int primordial_inflation_solve_inflation (struct perturbs *ppt, struct primordial *ppm, struct precision *ppr)
- int primordial_inflation_spectra (struct perturbs *ppt, struct primordial *ppm, struct precision *ppr, double *y_ini, double *y, double *dy)
- int primordial_inflation_one_k (struct primordial *ppm, struct precision *ppr, double k, double *y, double *dy, double *curvature, double *tensor)
- int primordial_inflation_find_attractor (struct primordial *ppm, struct precision *ppr, double phi_0, double precision, double *y, double *dy, double *H_0, double *dphidt_0)
- int primordial_inflation_evolve_background (struct primordial *ppm, struct precision *ppr, double *y, double *dy, enum target_quantity target, double stop, short check_epsilon, enum integration_direction direction, enum time_definition time)

- int primordial_inflation_check_potential (struct primordial *ppm, double phi, double *V, double *dV, double *ddV)
- int primordial_inflation_check_hubble (struct primordial *ppm, double phi, double *H, double *dH, double *ddH, double *dddH)
- int primordial_inflation_get_epsilon (struct primordial *ppm, double phi, double *epsilon)
- int primordial_inflation_find_phi_pivot (struct primordial *ppm, struct precision *ppr, double *y, double *dy)
- int primordial_inflation_derivs (double tau, double *y, double *dy, void *parameters_and_workspace, Error↩ Msg error_message)
- int primordial_external_spectrum_init (struct perturbs *ppt, struct primordial *ppm)

3.15.1 Detailed Description

Documented primordial module.

Julien Lesgourgues, 24.08.2010

This module computes the primordial spectra. Can be used in different modes: simple parametric form, evolving inflaton perturbations, etc. So far only the mode corresponding to a simple analytic form in terms of amplitudes, tilts and runnings has been developed.

The following functions can be called from other modules:

1. primordial_init() at the beginning (anytime after perturb_init() and before spectra_init())
2. primordial_spectrum_at_k() at any time for computing P(k) at any k
3. p_primordial_free() at the end

3.15.2 Function Documentation

3.15.2.1 int primordial_spectrum_at_k (struct primordial * *ppm*, int *index_md*, enum linear_or_logarithmic *mode*, double *input*, double * *output*)

Primordial spectra for arbitrary argument and for all initial conditions.

This routine evaluates the primordial spectrum at a given value of k by interpolating in the pre-computed table.

When k is not in the pre-computed range but the spectrum can be found analytically, finds it. Otherwise returns an error.

Can be called in two modes: linear or logarithmic.

- linear: takes k, returns P(k)
- logarithmic: takes ln(k), return ln(P(k))

One little subtlety: in case of several correlated initial conditions, the cross-correlation spectrum can be negative. Then, in logarithmic mode, the non-diagonal elements contain the cross-correlation angle P_12/sqrt(P_11 P_22) (from -1 to 1) instead of ln(P_12)

This function can be called from whatever module at whatever time, provided that primordial_init() has been called before, and primordial_free() has not been called yet.

Parameters

ppm	Input: pointer to primordial structure containing tabulated primordial spectrum

index_md	Input: index of mode (scalar, tensor, ...)
mode	Input: linear or logarithmic
input	Input: wavenumber in 1/Mpc (linear mode) or its logarithm (logarithmic mode)
output	Output: for each pair of initial conditions, primordial spectra P(k) in Mpc∗∗3 (linear mode), or their logarithms and cross-correlation angles (logarithmic mode)

Returns

the error status

Summary:

- define local variables
- infer ln(k) from input. In linear mode, reject negative value of input k value.
- if ln(k) is not in the interpolation range, return an error, unless we are in the case of a analytic spectrum, for which a direct computation is possible
- otherwise, interpolate in the pre-computed table:

3.15.2.2 int primordial_init (struct precision ∗ *ppr,* struct perturbs ∗ *ppt,* struct primordial ∗ *ppm*)

This routine initializes the primordial structure (in particular, compute table of primordial spectrum values)

Parameters

ppr	Input : pointer to precision structure (defines method and precision for all computations)
ppt	Input : pointer to perturbation structure (useful for knowing k_min, k_max, etc.)
ppm	Output: pointer to initialized primordial structure

Returns

the error status

Summary:

- define local variables
- check that we really need to compute the primordial spectra
- get kmin and kmax from perturbation structure. Test that they make sense.
- allocate and fill values of lnk's
- define indices and allocate tables in primordial structure
- deal with case of analytic primordial spectra (with amplitudes, tilts, runnings etc.)
- deal with case of inflation with given V(phi) or H(phi)
- deal with the case of external calculation of Pk
- compute second derivative of each lnpk versus lnk with spline, in view of interpolation

derive spectral parameters from numerically computed spectra (not used by the rest of the code, but useful to keep in memory for several types of investigations)

expression for alpha_s comes from:

ns_2 = (lnpk_plus-lnpk_pivot)/(dlnk)+1. ns_1 = (lnpk_pivot-lnpk_minus)/(dlnk)+1. alpha_s = dns/dlnk = (ns_2-ns↩
_1)/dlnk = (lnpk_plus-lnpk_pivot-lnpk_pivot+lnpk_minus)/(dlnk)/(dlnk)

expression for beta_s:

ppm->beta_s = (alpha_plus-alpha_minus)/dlnk = (lnpk_plusplus-2.*lnpk_plus+lnpk_pivot - (lnpk_pivot-2.*lnpk_minus+lnpk_minusminus)/pow(dlnk,3);

This simplifies into:

3.15.2.3 int primordial_free (struct primordial * ppm)

This routine frees all the memory space allocated by primordial_init().

To be called at the end of each run.

Parameters

ppm	Input: pointer to primordial structure (which fields must be freed)

Returns

the error status

3.15.2.4 int primordial_indices (struct perturbs * ppt, struct primordial * ppm)

This routine defines indices and allocates tables in the primordial structure

Parameters

ppt	Input : pointer to perturbation structure
ppm	Input/output: pointer to primordial structure

Returns

the error status

3.15.2.5 int primordial_get_lnk_list (struct primordial * ppm, double kmin, double kmax, double k_per_decade)

This routine allocates and fills the list of wavenumbers k

Parameters

ppm	Input/output: pointer to primordial structure
kmin	Input : first value
kmax	Input : last value that we should encompass
k_per_decade	Input : number of k per decade

Returns

the error status

3.15.2.6 int primordial_analytic_spectrum_init (struct perturbs * ppt, struct primordial * ppm)

This routine interprets and stores in a condensed form the input parameters in the case of a simple analytic spectra with amplitudes, tilts, runnings, in such way that later on, the spectrum can be obtained by a quick call to the routine primordial_analytic_spectrum(()

Parameters

ppt	Input : pointer to perturbation structure
ppm	Input/output: pointer to primordial structure

Returns

the error status

3.15.2.7 int primordial_analytic_spectrum (struct primordial * ppm, int index_md, int index_ic1_ic2, double k, double * pk)

This routine returns the primordial spectrum in the simple analytic case with amplitudes, tilts, runnings, for each mode (scalar/tensor...), pair of initial conditions, and wavenumber.

Parameters

ppm	Input/output: pointer to primordial structure
index_md	Input: index of mode (scalar, tensor, ...)
index_ic1_ic2	Input: pair of initial conditions (ic1, ic2)
k	Input: wavenumber in same units as pivot scale, i.e. in 1/Mpc
pk	Output: primordial power spectrum A (k/k_pivot)^(n+...)

Returns

the error status

3.15.2.8 int primordial_inflation_potential (struct primordial * ppm, double phi, double * V, double * dV, double * ddV)

This routine encodes the inflaton scalar potential

Parameters

ppm	Input: pointer to primordial structure
phi	Input: background inflaton field value in units of Mp
V	Output: inflaton potential in units of MP^4
dV	Output: first derivative of inflaton potential wrt the field
ddV	Output: second derivative of inflaton potential wrt the field

Returns

the error status

3.15.2.9 int primordial_inflation_hubble (struct primordial * ppm, double phi, double * H, double * dH, double * ddH, double * dddH)

This routine encodes the function H(phi)

Parameters

ppm	Input: pointer to primordial structure
phi	Input: background inflaton field value in units of Mp

H	Output: Hubble parameters in units of Mp
dH	Output: dH / dphi
ddH	Output: d2H / dphi2
dddH	Output: d3H / dphi3

Returns

the error status

3.15.2.10 int primordial_inflation_indices (struct primordial * *ppm*)

This routine defines indices used by the inflation simulator

Parameters

ppm	Input/output: pointer to primordial structure

Returns

the error status

3.15.2.11 int primordial_inflation_solve_inflation (struct perturbs * *ppt*, struct primordial * *ppm*, struct precision * *ppr*)

Main routine of inflation simulator. Its goal is to check the background evolution before and after the pivot value phi=phi_pivot, and then, if this evolution is suitable, to call the routine primordial_inflation_spectra().

Parameters

ppt	Input: pointer to perturbation structure
ppm	Input/output: pointer to primordial structure
ppr	Input: pointer to precision structure

Returns

the error status

3.15.2.12 int primordial_inflation_spectra (struct perturbs * *ppt*, struct primordial * *ppm*, struct precision * *ppr*, double * *y_ini*, double * *y*, double * *dy*)

Routine coordinating the computation of the primordial spectrum. For each wavenumber it calls primordial_inflation_one_k() to integrate the perturbation equations, and then it stores the result for the scalar/tensor spectra.

Parameters

ppt	Input: pointer to perturbation structure
ppm	Input/output: pointer to primordial structure
ppr	Input: pointer to precision structure
y_ini	Input: initial conditions for the vector of background/perturbations, already allocated and filled
y	Input: running vector of background/perturbations, already allocated
dy	Input: running vector of background/perturbation derivatives, already allocated

Returns

the error status

3.15.2.13 int primordial_inflation_one_k (struct primordial * ppm, struct precision * ppr, double k, double * y, double * dy, double * curvature, double * tensor)

Routine integrating the background plus perturbation equations for or each wavenumber, and returning the scalar and tensor spectrum.

Parameters

ppm	Input: pointer to primordial structure
ppr	Input: pointer to precision structure
k	Input: Fourier wavenumber
y	Input: running vector of background/perturbations, already allocated and initialized
dy	Input: running vector of background/perturbation derivatives, already allocated
curvature	Output: curvature perturbation
tensor	Output: tensor perturbation

Returns

the error status

3.15.2.14 int primordial_inflation_find_attractor (struct primordial * *ppm,* struct precision * *ppr,* double *phi_0,* double *precision,* double * *y,* double * *dy,* double * *H_0,* double * *dphidt_0*)

Routine searching for the inflationary attractor solution at a given phi_0, by iterations, with a given tolerance. If no solution found within tolerance, returns error message. The principle is the following. The code starts integrating the background equations from various values of phi, corresponding to earlier and earlier value before phi_0, and separated by a small arbitrary step size, corresponding roughly to 1 e-fold of inflation. Each time, the integration starts with the initial condition phi=-V'/3H (slow-roll prediction). If the found value of phi' in phi_0 is stable (up to the parameter "precision"), the code considers that there is an attractor, and stops iterating. If this process does not converge, it returns an error message.

Parameters

ppm	Input: pointer to primordial structure
ppr	Input: pointer to precision structure
phi_0	Input: field value at which we wish to find the solution
precision	Input: tolerance on output values (if too large, an attractor will always considered to be found)
y	Input: running vector of background variables, already allocated and initialized
dy	Input: running vector of background derivatives, already allocated
H_0	Output: Hubble value at phi_0 for attractor solution
dphidt_0	Output: field derivative value at phi_0 for attractor solution

Returns

the error status

3.15.2.15 int primordial_inflation_evolve_background (struct primordial * *ppm,* struct precision * *ppr,* double * *y,* double * *dy,* enum target_quantity *target,* double *stop,* short *check_epsilon,* enum integration_direction *direction,* enum time_definition *time*)

Routine integrating background equations only, from initial values stored in y, to a final value (if target = *aH*, until aH = aH_stop; if target = *phi*, till phi = phi_stop; if target = *end_inflation*, until d^2a/dt^2 = 0 (here t = proper time)). In output, y contains the final background values. In addition, if check_epsilon is true, the routine controls at each step that the expansion is accelerated and that inflation hold (wepsilon>1), otherwise it returns an error. Thanks to the last argument, it is also possible to specify whether the integration should be carried forward or backward in time. For the inflation_H case, only a 1st order differential equation is involved, so the forward and backward case can be done exactly without problems. For the inflation_V case, the equation of motion is 2nd order. What the module will do in the backward case is to search for an approximate solution, corresponding to the (first-order) attractor inflationary solution. This approximate backward solution is used in order to estimate some initial times, but the approximation made here will never impact the final result: the module is written in such way that after using this approximation, the code always computes (and relies on) the exact forward solution.

Parameters

ppm	Input: pointer to primordial structure
ppr	Input: pointer to precision structure
y	Input/output: running vector of background variables, already allocated and initialized
dy	Input: running vector of background derivatives, already allocated
target	Input: whether the goal is to reach a given aH or phi
stop	Input: the target value of either aH or phi
check_epsilon	Input: whether we should impose inflation (epsilon>1) at each step
direction	Input: whether we should integrate forward or backward in time
time	Input: definition of time (proper or conformal)

Returns

the error status

3.15.2.16 int primordial_inflation_check_potential (struct primordial * ppm, double phi, double * V, double * dV, double * ddV)

Routine checking positivity and negative slope of potential. The negative slope is an arbitrary choice. Currently the code can only deal with monotonic variations of the inflaton during inflation. So the slope had to be always negative or always positive... we took the first option.

Parameters

ppm	Input: pointer to primordial structure
phi	Input: field value where to perform the check
V	Output: inflaton potential in units of MP^4
dV	Output: first derivative of inflaton potential wrt the field
ddV	Output: second derivative of inflaton potential wrt the field

Returns

the error status

3.15.2.17 int primordial_inflation_check_hubble (struct primordial * ppm, double phi, double * H, double * dH, double * ddH, double * dddH)

Routine checking positivity and negative slope of H(phi). The negative slope is an arbitrary choice. Currently the code can only deal with monotonic variations of the inflaton during inflation. And H can only decrease with time. So the slope dH/dphi has to be always negative or always positive... we took the first option: phi increases, H decreases.

Parameters

ppm	Input: pointer to primordial structure
phi	Input: field value where to perform the check
H	Output: Hubble parameters in units of Mp
dH	Output: dH / dphi
ddH	Output: d2H / dphi2
dddH	Output: d3H / dphi3

Returns

the error status

3.15.2.18 int primordial_inflation_get_epsilon (struct primordial * *ppm,* double *phi,* double * *epsilon*)

Routine computing the first slow-roll parameter epsilon

Parameters

ppm	Input: pointer to primordial structure
phi	Input: field value where to compute epsilon
epsilon	Output: result

Returns

the error status

3.15.2.19 int primordial_inflation_find_phi_pivot (struct primordial * ppm, struct precision * ppr, double * y, double * dy)

Routine searching phi_pivot when a given amount of inflation is requested.

Parameters

ppm	Input/output: pointer to primordial structure
ppr	Input: pointer to precision structure
y	Input: running vector of background variables, already allocated and initialized
dy	Input: running vector of background derivatives, already allocated

Returns

the error status

3.15.2.20 int primordial_inflation_derivs (double tau, double * y, double * dy, void * parameters_and_workspace, ErrorMsg error_message)

Routine returning derivative of system of background/perturbation variables. Like other routines used by the generic integrator (background_derivs, thermodynamics_derivs, perturb_derivs), this routine has a generic list of arguments, and a slightly different error management, with the error message returned directly in an ErrMsg field.

Parameters

tau	Input: time (not used explicitly inside the routine, but requested by the generic integrator)
y	Input/output: running vector of background variables, already allocated and initialized
dy	Input: running vector of background derivatives, already allocated
parameters_and_workspace	Input: all necessary input variables apart from y
error_message	Output : error message

Returns

the error status

3.15.2.21 int primordial_external_spectrum_init (struct perturbs * ppt, struct primordial * ppm)

This routine reads the primordial spectrum from an external command, and stores the tabulated values. The sampling of the k's given by the external command is preserved.

Author: Jesus Torrado (torradocacho@lorentz.leidenuniv.nl) Date: 2013-12-20

Parameters

ppt	Input/output: pointer to perturbs structure
ppm	Input/output: pointer to primordial structure

Returns

the error status

1. Initialization

2. Launch the command and retrieve the output

3. Store the read results into CLASS structures

Make room

Store them

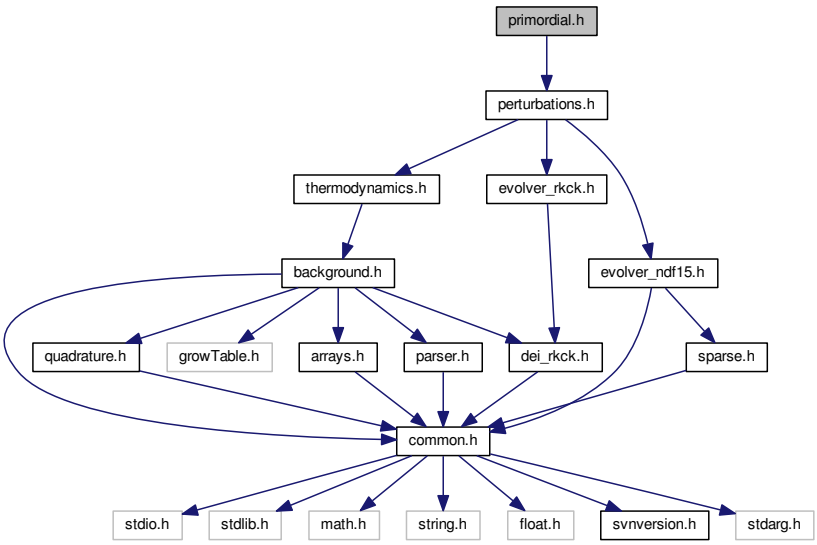
Release the memory used locally

Tell CLASS that the are scalar (and tensor) modes

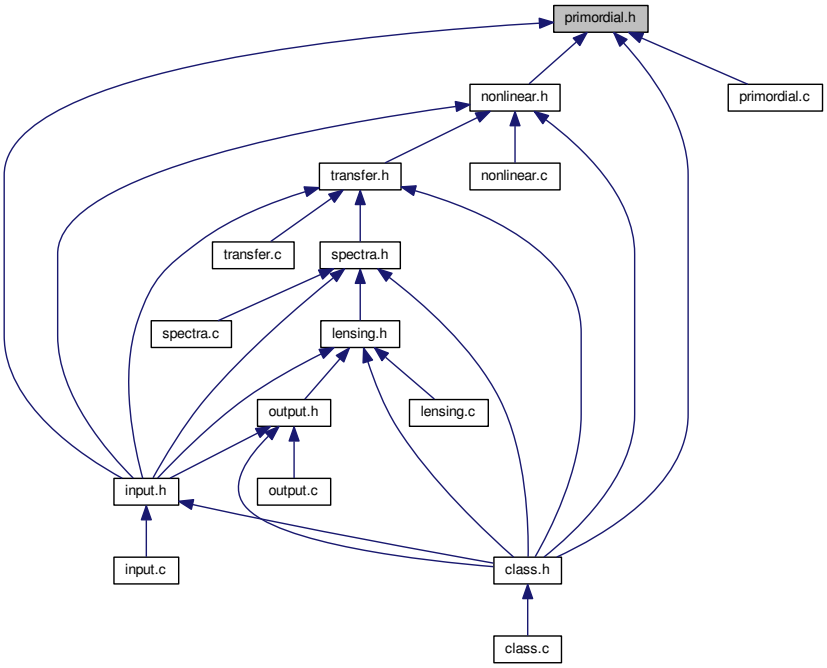
3.16 primordial.h File Reference

```
#include "perturbations.h"
```

Include dependency graph for primordial.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct primordial

Enumerations

- enum primordial_spectrum_type
- enum linear_or_logarithmic
- enum potential_shape
- enum target_quantity
- enum integration_direction
- enum time_definition
- enum phi_pivot_methods

3.16.1 Detailed Description

Documented includes for primordial module.

3.16.2 Data Structure Documentation

3.16.2.1 struct primordial

Structure containing everything about primordial spectra that other modules need to know.

Once initialized by primordial_init(), contains a table of all primordial spectra as a function of wavenumber, mode, and pair of initial conditions.

Data Fields

double	k_pivot	pivot scale in Mpc^{-1}
enum primordial_spectrum_type	primordial_spec_type	type of primordial spectrum (simple analytic from, integration of inflationary perturbations, etc.)
double	A_s	usual scalar amplitude = curvature power spectrum at pivot scale
double	n_s	usual scalar tilt = [curvature power spectrum tilt at pivot scale -1]
double	alpha_s	usual scalar running
double	beta_s	running of running
double	r	usual tensor to scalar ratio of power spectra, $r = A_T/A_S = P_h/P_R$
double	n_t	usual tensor tilt = [GW power spectrum tilt at pivot scale]
double	alpha_t	usual tensor running
double	f_bi	baryon isocurvature (BI) entropy-to-curvature ratio S_{bi}/R
double	n_bi	BI tilt
double	alpha_bi	BI running
double	f_cdi	CDM isocurvature (CDI) entropy-to-curvature ratio S_{cdi}/R
double	n_cdi	CDI tilt
double	alpha_cdi	CDI running
double	f_nid	neutrino density isocurvature (NID) entropy-to-curvature ratio S_{nid}/R
double	n_nid	NID tilt
double	alpha_nid	NID running
double	f_niv	neutrino velocity isocurvature (NIV) entropy-to-curvature ratio S_{niv}/R
double	n_niv	NIV tilt
double	alpha_niv	NIV running
double	c_ad_bi	ADxBI cross-correlation at pivot scale, from -1 to 1
double	n_ad_bi	ADxBI cross-correlation tilt
double	alpha_ad_bi	ADxBI cross-correlation running
double	c_ad_cdi	ADxCDI cross-correlation at pivot scale, from -1 to 1
double	n_ad_cdi	ADxCDI cross-correlation tilt
double	alpha_ad_cdi	ADxCDI cross-correlation running
double	c_ad_nid	ADxNID cross-correlation at pivot scale, from -1 to 1
double	n_ad_nid	ADxNID cross-correlation tilt
double	alpha_ad_nid	ADxNID cross-correlation running
double	c_ad_niv	ADxNIV cross-correlation at pivot scale, from -1 to 1
double	n_ad_niv	ADxNIV cross-correlation tilt
double	alpha_ad_niv	ADxNIV cross-correlation running
double	c_bi_cdi	BIxCDI cross-correlation at pivot scale, from -1 to 1
double	n_bi_cdi	BIxCDI cross-correlation tilt
double	alpha_bi_cdi	BIxCDI cross-correlation running
double	c_bi_nid	BIxNIV cross-correlation at pivot scale, from -1 to 1
double	n_bi_nid	BIxNIV cross-correlation tilt
double	alpha_bi_nid	BIxNIV cross-correlation running
double	c_bi_niv	BIxNIV cross-correlation at pivot scale, from -1 to 1
double	n_bi_niv	BIxNIV cross-correlation tilt

double	alpha_bi_niv	BIxNIV cross-correlation running
double	c_cdi_nid	CDIxNID cross-correlation at pivot scale, from -1 to 1
double	n_cdi_nid	CDIxNID cross-correlation tilt
double	alpha_cdi_nid	CDIxNID cross-correlation running
double	c_cdi_niv	CDIxNIV cross-correlation at pivot scale, from -1 to 1
double	n_cdi_niv	CDIxNIV cross-correlation tilt
double	alpha_cdi_niv	CDIxNIV cross-correlation running
double	c_nid_niv	NIDxNIV cross-correlation at pivot scale, from -1 to 1
double	n_nid_niv	NIDxNIV cross-correlation tilt
double	alpha_nid_niv	NIDxNIV cross-correlation running
enum potential_shape	potential	parameters describing the case primordial_spec_type = inflation_V
double	V0	$$$ definition missing $$$
double	V1	$$$ definition missing $$$
double	V2	$$$ definition missing $$$
double	V3	$$$ definition missing $$$
double	V4	$$$ definition missing $$$
double	H0	$$$ definition missing $$$
double	H1	$$$ definition missing $$$
double	H2	$$$ definition missing $$$
double	H3	$$$ definition missing $$$
double	H4	$$$ definition missing $$$
double	phi_end	$$$ definition missing $$$
enum phi_pivot_methods	phi_pivot_method	$$$ definition missing $$$
double	phi_pivot_target	$$$ definition missing $$$
char *	command	'external_Pk' mode: command generating the table of Pk and custom parameters to be passed to it
double	custom1	$$$ definition missing $$$
double	custom2	$$$ definition missing $$$
double	custom3	$$$ definition missing $$$
double	custom4	$$$ definition missing $$$
double	custom5	$$$ definition missing $$$
double	custom6	$$$ definition missing $$$
double	custom7	$$$ definition missing $$$
double	custom8	$$$ definition missing $$$
double	custom9	$$$ definition missing $$$
double	custom10	$$$ definition missing $$$
int	md_size	number of modes included in computation
int *	ic_size	for a given mode, ic_size[index_md] = number of initial conditions included in computation
int *	ic_ic_size	number of ordered pairs of (index_ic1, index_ic2); this number is just N(N+1)/2 where N = ic_size[index_md]
int	lnk_size	number of ln(k) values
double *	lnk	list of ln(k) values lnk[index_k]
double **	lnpk	depends on indices index_md, index_ic1, index_ic2, index_k as: lnpk[index_md][index_k*ppm->ic_ic_size[index_md]+index_ic1_ic2] where index_ic1_ic2 labels ordered pairs (index_ic1, index_ic2) (since the primordial spectrum is symmetric in (index_ic1, index_ic2)). • for diagonal elements (index_ic1 = index_ic2) this arrays contains ln[P(k)] where P(k) is positive by construction. • for non-diagonal elements this arrays contains the k-dependent cosine of the correlation angle, namely P(k)_(index_ic1, index_ic2)/sqrt[P(k)_index_ic1 P(k)_index_ic2] This choice is convenient since the sign of the non-diagonal cross-correlation is arbitrary. For fully correlated or anti-correlated initial conditions, this non - diagonal element is independent on k, and equal to +1 or -1.

double **	ddlnpk	second derivative of above array, for spline interpolation. So: • for index_ic1 = index_ic, we spline ln[P(k)] vs. ln(k), which is good since this function is usually smooth. • for non-diagonal coefficients, we spline P(k)_(index_ic1, index_ic2)/sqrt[P(k)_index_ic1 P(k)_index_ic2] vs. ln(k), which is fine since this quantity is often assumed to be constant (e.g for fully correlated/anticorrelated initial conditions) or nearly constant, and with arbitrary sign.
short **	is_non_zero	is_non_zero[index_md][index_ic1_ic2] set to false if pair (index_ic1, index_ic2) is uncorrelated (ensures more precision and saves time with respect to the option of simply setting P(k)_(index_ic1, index_ic2) to zero)
double **	amplitude	all amplitudes in matrix form: amplitude[index_md][index_ic1_ic2]
double **	tilt	all tilts in matrix form: tilt[index_md][index_ic1_ic2]
double **	running	all runnings in matrix form: running[index_md][index_ic1_ic2]
int	index_in_a	scale factor
int	index_in_phi	inflaton vev
int	index_in_dphi	its time derivative
int	index_in_ksi_re	Mukhanov variable (real part)
int	index_in_ksi_im	Mukhanov variable (imaginary part)
int	index_in_dksi_re	Mukhanov variable (real part, time derivative)
int	index_in_dksi_im	Mukhanov variable (imaginary part, time derivative)
int	index_in_ah_re	tensor perturbation (real part)
int	index_in_ah_im	tensor perturbation (imaginary part)
int	index_in_dah_re	tensor perturbation (real part, time derivative)
int	index_in_dah_im	tensor perturbation (imaginary part, time derivative)
int	in_bg_size	size of vector of background quantities only
int	in_size	full size of vector
double	phi_pivot	in inflationary module, value of phi_pivot (set to 0 for inflation_V, inflation_H; found by code for inflation_V_end)
double	phi_min	in inflationary module, value of phi when $k_{min} = aH$
double	phi_max	in inflationary module, value of phi when $k_{max} = aH$
double	phi_stop	in inflationary module, value of phi at the end of inflation
short	primordial_verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.16.3 Enumeration Type Documentation

3.16.3.1 enum primordial_spectrum_type

enum defining how the primordial spectrum should be computed

3.16.3.2 enum linear_or_logarithmic

enum defining whether the spectrum routine works with linear or logarithmic input/output

3.16.3.3 enum potential_shape

enum defining the type of inflation potential function V(phi)

3.16.3.4 enum target_quantity

enum defining which quantity plays the role of a target for evolving inflationary equations

3.16.3.5 enum integration_direction

enum specifying if we want to integrate equations forward or backward in time

3.16.3.6 enum time_definition

enum specifying if we want to evolve quantities with conformal or proper time

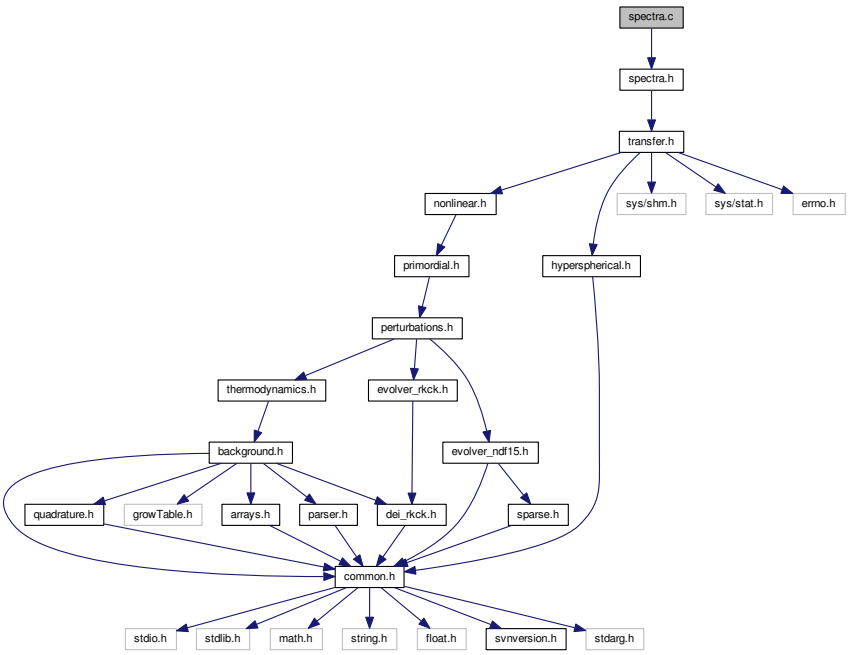
3.16.3.7 enum phi_pivot_methods

enum specifying how, in the inflation_V_end case, the value of phi_pivot should calculated

3.17 spectra.c File Reference

```
#include "spectra.h"
```

Include dependency graph for spectra.c:



Functions

- int spectra_cl_at_l (struct spectra *psp, double l, double *cl_tot, double **cl_md, double **cl_md_ic)
- int spectra_pk_at_z (struct background *pba, struct spectra *psp, enum linear_or_logarithmic mode, double z, double *output_tot, double *output_ic)
- int spectra_pk_at_k_and_z (struct background *pba, struct primordial *ppm, struct spectra *psp, double k, double z, double *pk_tot, double *pk_ic)

- int spectra_pk_nl_at_z (struct background *pba, struct spectra *psp, enum linear_or_logarithmic mode, double z, double *output_tot)
- int spectra_pk_nl_at_k_and_z (struct background *pba, struct primordial *ppm, struct spectra *psp, double k, double z, double *pk_tot)
- int spectra_tk_at_z (struct background *pba, struct spectra *psp, double z, double *output)
- int spectra_tk_at_k_and_z (struct background *pba, struct spectra *psp, double k, double z, double *output)
- int spectra_init (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct primordial *ppm, struct nonlinear *pnl, struct transfers *ptr, struct spectra *psp)
- int spectra_free (struct spectra *psp)
- int spectra_indices (struct background *pba, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp)
- int spectra_cls (struct background *pba, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp)
- int spectra_compute_cl (struct background *pba, struct perturbs *ppt, struct transfers *ptr, struct primordial *ppm, struct spectra *psp, int index_md, int index_ic1, int index_ic2, int index_l, int cl_integrand_num_columns, double *cl_integrand, double *primordial_pk, double *transfer_ic1, double *transfer_ic2)
- int spectra_k_and_tau (struct background *pba, struct perturbs *ppt, struct spectra *psp)
- int spectra_pk (struct background *pba, struct perturbs *ppt, struct primordial *ppm, struct nonlinear *pnl, struct spectra *psp)
- int spectra_sigma (struct background *pba, struct primordial *ppm, struct spectra *psp, double R, double z, double *sigma)
- int spectra_matter_transfers (struct background *pba, struct perturbs *ppt, struct spectra *psp)
- int spectra_output_tk_data (struct background *pba, struct perturbs *ppt, struct spectra *psp, enum file_format output_format, double z, int number_of_titles, double *data)

3.17.1 Detailed Description

Documented spectra module

Julien Lesgourgues, 25.08.2010

This module computes the anisotropy and Fourier power spectra $C_l^X, P(k), ...$'s given the transfer and Bessel functions (for anisotropy spectra), the source functions (for Fourier spectra) and the primordial spectra.

The following functions can be called from other modules:

1. spectra_init() at the beginning (but after transfer_init())
2. spectra_cl_at_l() at any time for computing C at any l
3. spectra_spectrum_at_z() at any time for computing P(k) at any z
4. spectra_spectrum_at_k_and z() at any time for computing P at any k and z
5. spectra_free() at the end

3.17.2 Function Documentation

3.17.2.1 int spectra_cl_at_l (struct spectra * *psp*, double *l*, double * *cl_tot*, double ** *cl_md*, double ** *cl_md_ic*)

Anisotropy power spectra C_l's for all types, modes and initial conditions.

This routine evaluates all the C_l's at a given value of l by interpolating in the pre-computed table. When relevant, it also sums over all initial conditions for each mode, and over all modes.

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

psp	Input: pointer to spectra structure (containing pre-computed table)
l	Input: multipole number
cl_tot	Output: total C_l's for all types (TT, TE, EE, etc..)
cl_md	Output: C_l's for all types (TT, TE, EE, etc..) decomposed mode by mode (scalar, tensor, ...) when relevant
cl_md_ic	Output: C_l's for all types (TT, TE, EE, etc..) decomposed by pairs of initial conditions (adiabatic, isocurvatures) for each mode (usually, only for the scalar mode) when relevant

Returns

the error status

Summary:

- define local variables

A) treat case in which there is only one mode and one initial condition. Then, only cl_tot needs to be filled.

B) treat case in which there is only one mode with several initial condition. Fill cl_md_ic[index_md=0] and sum it to get cl_tot.

C) loop over modes

C.1) treat case in which the mode under consideration has only one initial condition. Fill cl_md[index_md].

C.2) treat case in which the mode under consideration has several initial conditions. Fill cl_md_ic[index_md] and sum it to get cl_md[index_md]

C.3) add contribution of cl_md[index_md] to cl_tot

3.17.2.2 int spectra_pk_at_z (struct background * *pba*, struct spectra * *psp*, enum linear_or_logarithmic *mode*, double *z*, double * *output_tot*, double * *output_ic*)

Matter power spectrum for arbitrary redshift and for all initial conditions.

This routine evaluates the matter power spectrum at a given value of z by interpolating in the pre-computed table (if several values of z have been stored) or by directly reading it (if it only contains values at z=0 and we want P(k,z=0))

Can be called in two modes: linear or logarithmic.

- linear: returns P(k) (units: Mpc^3)
- logarithmic: returns ln(P(k))

One little subtlety: in case of several correlated initial conditions, the cross-correlation spectrum can be negative. Then, in logarithmic mode, the non-diagonal elements contain the cross-correlation angle P_12/sqrt(P_11 P_22) (from -1 to 1) instead of ln(P_12)

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
psp	Input: pointer to spectra structure (containing pre-computed table)

mode	Input: linear or logarithmic
z	Input: redshift
output_tot	Output: total matter power spectrum P(k) in Mpc^3 (linear mode), or its logarithms (logarithmic mode)
output_ic	Output: for each pair of initial conditions, matter power spectra P(k) in Mpc^3 (linear mode), or their logarithms and cross-correlation angles (logarithmic mode)

Returns

the error status

Summary:

- define local variables
- first step: convert z into ln(tau)
- second step: for both modes (linear or logarithmic), store the spectrum in logarithmic format in the output array(s)

(a.) if only values at tau=tau_today are stored and we want P(k,z=0), no need to interpolate

(b.) if several values of tau have been stored, use interpolation routine to get spectra at correct redshift

- third step: if there are several initial conditions, compute the total P(k) and set back all uncorrelated coefficients to exactly zero. Check positivity of total P(k).
- fourth step: depending on requested mode (linear or logarithmic), apply necessary transformation to the output arrays

(a.) linear mode: if only one initial condition, convert output_pk to linear format; if several initial conditions, convert output_ic to linear format, output_tot is already in this format

(b.) logarithmic mode: if only one initial condition, nothing to be done; if several initial conditions, convert output_tot to logarithmic format, output_ic is already in this format

3.17.2.3 int spectra_pk_at_k_and_z (struct background * *pba*, struct primordial * *ppm*, struct spectra * *psp*, double *k*, double *z*, double * *pk_tot*, double * *pk_ic*)

Matter power spectrum for arbitrary wavenumber, redshift and initial condition.

This routine evaluates the matter power spectrum at a given value of k and z by interpolating in a table of all P(k)'s computed at this z by spectra_pk_at_z() (when kmin <= k <= kmax), or eventually by using directly the primordial spectrum (when 0 <= k < kmin): the latter case is an approximation, valid when kmin << comoving Hubble scale today. Returns zero when k=0. Returns an error when k<0 or k > kmax.

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
ppm	Input: pointer to primordial structure (used only in the case 0 < k < kmin)
psp	Input: pointer to spectra structure (containing pre-computed table)
k	Input: wavenumber in 1/Mpc

z	Input: redshift
pk_tot	Output: total matter power spectrum P(k) in Mpc^3
pk_ic	Output: for each pair of initial conditions, matter power spectra P(k) in Mpc^3

Returns

the error status

Summary:

- define local variables
- first step: check that k is in valid range [0:kmax] (the test for z will be done when calling spectra_pk_at_z())
- deal with case 0 <= k < kmin

(a.) subcase k=0: then P(k)=0

(b.) subcase 0<k<kmin: in this case we know that on super-Hubble scales: P(k) = [some number] * k * P_↩ primordial(k) so P(k) = P(kmin) * (k P_primordial(k)) / (kmin P_primordial(kmin)) (note that the result is accurate only if kmin is such that [a0 kmin] << H0)

- deal with case kmin <= k <= kmax
- last step: if more than one condition, sum over pk_ic to get pk_tot, and set back coefficients of non-correlated pairs to exactly zero.

3.17.2.4 int spectra_pk_nl_at_z (struct background * *pba*, struct spectra * *psp*, enum linear_or_logarithmic *mode*, double *z*, double * *output_tot*)

Non-linear total matter power spectrum for arbitrary redshift.

This routine evaluates the non-linear matter power spectrum at a given value of z by interpolating in the pre-computed table (if several values of z have been stored) or by directly reading it (if it only contains values at z=0 and we want P(k,z=0))

Can be called in two modes: linear or logarithmic.

- linear: returns P(k) (units: Mpc^3)
- logarithmic: returns ln(P(k))

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
psp	Input: pointer to spectra structure (containing pre-computed table)
mode	Input: linear or logarithmic
z	Input: redshift
output_tot	Output: total matter power spectrum P(k) in Mpc^3 (linear mode), or its logarithms (logarithmic mode)

Returns

the error status

Summary:

- define local variables
- first step: convert z into ln(tau)
- second step: for both modes (linear or logarithmic), store the spectrum in logarithmic format in the output array(s)

(a.) if only values at tau=tau_today are stored and we want P(k,z=0), no need to interpolate

(b.) if several values of tau have been stored, use interpolation routine to get spectra at correct redshift

- fourth step: eventually convert to linear format

3.17.2.5 int spectra_pk_nl_at_k_and_z (struct background * *pba*, struct primordial * *ppm*, struct spectra * *psp*, double *k*, double *z*, double * *pk_tot*)

Non-linear total matter power spectrum for arbitrary wavenumber and redshift.

This routine evaluates the matter power spectrum at a given value of k and z by interpolating in a table of all P(k)'s computed at this z by spectra_pk_nl_at_z() (when kmin <= k <= kmax), or eventually by using directly the primordial spectrum (when 0 <= k < kmin): the latter case is an approximation, valid when kmin << comoving Hubble scale today. Returns zero when k=0. Returns an error when k<0 or k > kmax.

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
ppm	Input: pointer to primordial structure (used only in the case 0 < k < kmin)
psp	Input: pointer to spectra structure (containing pre-computed table)
k	Input: wavenumber in 1/Mpc
z	Input: redshift
pk_tot	Output: total matter power spectrum P(k) in Mpc^3

Returns

the error status

Summary:

- define local variables
- first step: check that k is in valid range [0:kmax] (the test for z will be done when calling spectra_pk_at_z())

3.17.2.6 int spectra_tk_at_z (struct background * *pba*, struct spectra * *psp*, double *z*, double * *output*)

Matter transfer functions T_i(k) for arbitrary redshift and for all initial conditions.

This routine evaluates the matter transfer functions at a given value of z by interpolating in the pre-computed table (if several values of z have been stored) or by directly reading it (if it only contains values at z=0 and we want T_i(k,z=0))

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
psp	Input: pointer to spectra structure (containing pre-computed table)
z	Input: redshift
output	Output: matter transfer functions

Returns

the error status

Summary:

- define local variables
- first step: convert z into ln(tau)
- second step: store the matter transfer functions in the output array

(a.) if only values at tau=tau_today are stored and we want T_i(k,z=0), no need to interpolate

(b.) if several values of tau have been stored, use interpolation routine to get spectra at correct redshift

3.17.2.7 int spectra_tk_at_k_and_z (struct background * *pba*, struct spectra * *psp*, double *k*, double *z*, double * *output*)

Matter transfer functions T_i(k) for arbitrary wavenumber, redshift and initial condition.

This routine evaluates the matter transfer functions at a given value of k and z by interpolating in a table of all T_i(k,z)'s computed at this z by spectra_tk_at_z() (when kmin <= k <= kmax). Returns an error when k<kmin or k > kmax.

This function can be called from whatever module at whatever time, provided that spectra_init() has been called before, and spectra_free() has not been called yet.

Parameters

pba	Input: pointer to background structure (used for converting z into tau)
psp	Input: pointer to spectra structure (containing pre-computed table)
k	Input: wavenumber in 1/Mpc
z	Input: redshift
output	Output: matter transfer functions

Returns

the error status

Summary:

- define local variables
- first step: check that k is in valid range [0:kmax] (the test for z will be done when calling spectra_tk_at_z())

3.17.2.8 int spectra_init (struct precision * *ppr*, struct background * *pba*, struct perturbs * *ppt*, struct primordial * *ppm*, struct nonlinear * *pnl*, struct transfers * *ptr*, struct spectra * *psp*)

This routine initializes the spectra structure (in particular, computes table of anisotropy and Fourier spectra $C_l^X, P(k), ...$)

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure (will provide H, Omega_m at redshift of interest)
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfer structure
ppm	Input : pointer to primordial structure
pnl	Input : pointer to nonlinear structure
psp	Output: pointer to initialized spectra structure

Returns

the error status

Summary:

- check that we really want to compute at least one spectrum
- initialize indices and allocate some of the arrays in the spectra structure
- deal with C_l's, if any
- deal with P(k,tau) and T_i(k,tau)

3.17.2.9 int spectra_free (struct **spectra** * *psp*)

This routine frees all the memory space allocated by spectra_init().

To be called at the end of each run, only when no further calls to spectra_cls_at_l(), spectra_pk_at_z(), spectra_pk_at_k_and_z() are needed.

Parameters

psp	Input: pointer to spectra structure (which fields must be freed)

Returns

the error status

3.17.2.10 int spectra_indices (struct **background** * *pba*, struct **perturbs** * *ppt*, struct **transfers** * *ptr*, struct **primordial** * *ppm*, struct **spectra** * *psp*)

This routine defines indices and allocates tables in the spectra structure

Parameters

pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
ppm	Input : pointer to primordial structure
psp	Input/output: pointer to spectra structure

Returns

the error status

3.17.2.11 int spectra_cls (struct **background** * *pba*, struct **perturbs** * *ppt*, struct **transfers** * *ptr*, struct **primordial** * *ppm*, struct **spectra** * *psp*)

This routine computes a table of values for all harmonic spectra C_l's, given the transfer functions and primordial spectra.

Parameters

pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
ppm	Input : pointer to primordial structure
psp	Input/Output: pointer to spectra structure

Returns

the error status

Summary:

- define local variables
- allocate pointers to arrays where results will be stored
- store values of l
- loop over modes (scalar, tensors, etc). For each mode:
- a) store number of l values for this mode
- b) allocate arrays where results will be stored

d) loop over initial conditions

- loop over l values defined in the transfer module. For each l, compute the C_l's for all types (TT, TE, ...) by convolving primordial spectra with transfer functions. This elementary task is assigned to spectra_compute↩ _cl()
- e) now that for a given mode, all possible C_l's have been computed, compute second derivative of the array in which they are stored, in view of spline interpolation.

3.17.2.12 int spectra_compute_cl (struct background * *pba*, struct perturbs * *ppt*, struct transfers * *ptr*, struct primordial * *ppm*, struct spectra * *psp*, int *index_md*, int *index_ic1*, int *index_ic2*, int *index_l*, int *cl_integrand_num_columns*, double * *cl_integrand*, double * *primordial_pk*, double * *transfer_ic1*, double * *transfer_ic2*)

This routine computes the C_l's for a given mode, pair of initial conditions and multipole, but for all types (TT, TE...), by convolving the transfer functions with the primordial spectra.

Parameters

pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
ppm	Input : pointer to primordial structure
psp	Input/Output: pointer to spectra structure (result stored here)
index_md	Input : index of mode under consideration
index_ic1	Input : index of first initial condition in the correlator
index_ic2	Input : index of second initial condition in the correlator

index_l	Input : index of multipole under consideration
cl_integrand_num_columns	Input : number of columns in cl_integrand
cl_integrand	Input : an allocated workspace
primordial_pk	Input : table of primordial spectrum values
transfer_ic1	Input : table of transfer function values for first initial condition
transfer_ic2	Input : table of transfer function values for second initial condition

Returns

the error status

3.17.2.13 int spectra_k_and_tau (struct **background** * *pba*, struct **perturbs** * *ppt*, struct **spectra** * *psp*)

This routine computes the values of k and tau at which the matter power spectra P(k,tau) and the matter transfer functions T_i(k,tau) will be stored.

Parameters

pba	Input : pointer to background structure (for z to tau conversion)
ppt	Input : pointer to perturbation structure (contain source functions)
psp	Input/Output: pointer to spectra structure

Returns

the error status

Summary:

- define local variables
- check the presence of scalar modes
- check the maximum redshift z_max_pk at which P(k,z) and T_i(k,z) should be computable by interpolation. If it is equal to zero, only P(k,z=0) needs to be computed. If it is higher, we will store in a table various P(k,tau) at several values of tau generously encompassing the range 0<z<z_max_pk
- allocate and fill table of tau values at which P(k,tau) and T_i(k,tau) are stored
- allocate and fill table of k values at which P(k,tau) is stored

3.17.2.14 int spectra_pk (struct **background** * *pba*, struct **perturbs** * *ppt*, struct **primordial** * *ppm*, struct **nonlinear** * *pnl*, struct **spectra** * *psp*)

This routine computes a table of values for all matter power spectra P(k), given the source functions and primordial spectra.

Parameters

pba	Input : pointer to background structure (will provide H, Omega_m at redshift of interest)
ppt	Input : pointer to perturbation structure (contain source functions)
ppm	Input : pointer to primordial structure
pnl	Input : pointer to nonlinear structure

psp	Input/Output: pointer to spectra structure

Returns

the error status

Summary:

- define local variables
- check the presence of scalar modes
- allocate temporary vectors where the primordial spectrum and the background quantities will be stored
- allocate and fill array of P(k,tau) values
- if interpolation of P(k,tau) will be needed (as a function of tau), compute array of second derivatives in view of spline interpolation
- if interpolation of P_NL(k,tau) will be needed (as a function of tau), compute array of second derivatives in view of spline interpolation

3.17.2.15 int spectra_sigma (struct background * *pba*, struct primordial * *ppm*, struct spectra * *psp*, double *R*, double *z*, double * *sigma*)

This routine computes sigma(R) given P(k) (does not check that k_max is large enough)

Parameters

pba	Input: pointer to background structure
ppm	Input: pointer to primordial structure
psp	Input: pointer to spectra structure
z	Input: redshift
R	Input: radius in Mpc
sigma	Output: variance in a sphere of radius R (dimensionless)

3.17.2.16 int spectra_matter_transfers (struct background * *pba*, struct perturbs * *ppt*, struct spectra * *psp*)

This routine computes a table of values for all matter power spectra P(k), given the source functions and primordial spectra.

Parameters

pba	Input : pointer to background structure (will provide density of each species)
ppt	Input : pointer to perturbation structure (contain source functions)
psp	Input/Output: pointer to spectra structure

Returns

the error status

Summary:

- define local variables
- check the presence of scalar modes
- allocate and fill array of T_i(k,tau) values

- allocate temporary vectors where the background quantities will be stored

- if interpolation of P(k,tau) will be needed (as a function of tau), compute array of second derivatives in view of spline interpolation

3.17.2.17 int spectra_output_tk_data (struct background * *pba,* struct perturbs * *ppt,* struct spectra * *psp,* enum file_format *output_format,* double *z,* int *number_of_titles,* double * *data*)

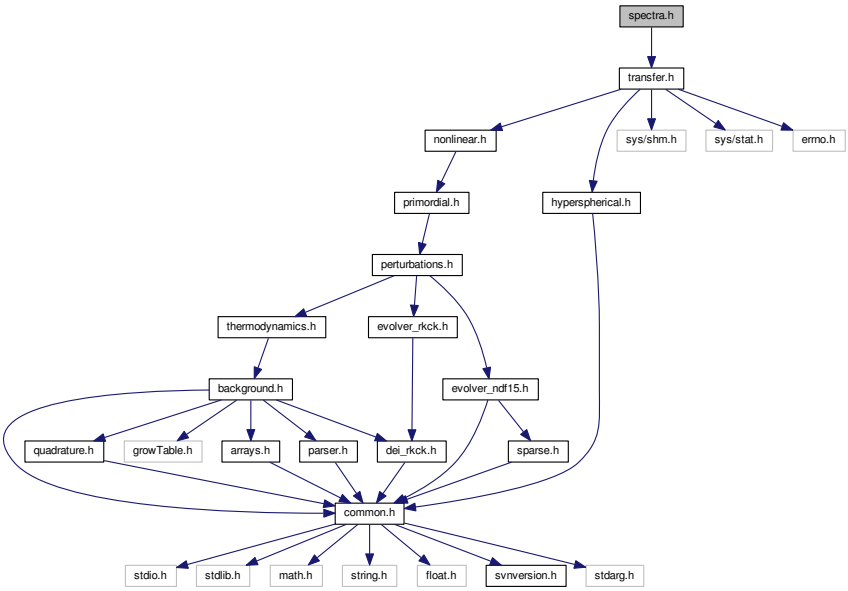
- compute T_i(k) for each k (if several ic's, compute it for each ic; if z_pk = 0, this is done by directly reading inside the pre-computed table; if not, this is done by interpolating the table at the correct value of tau.

- store data

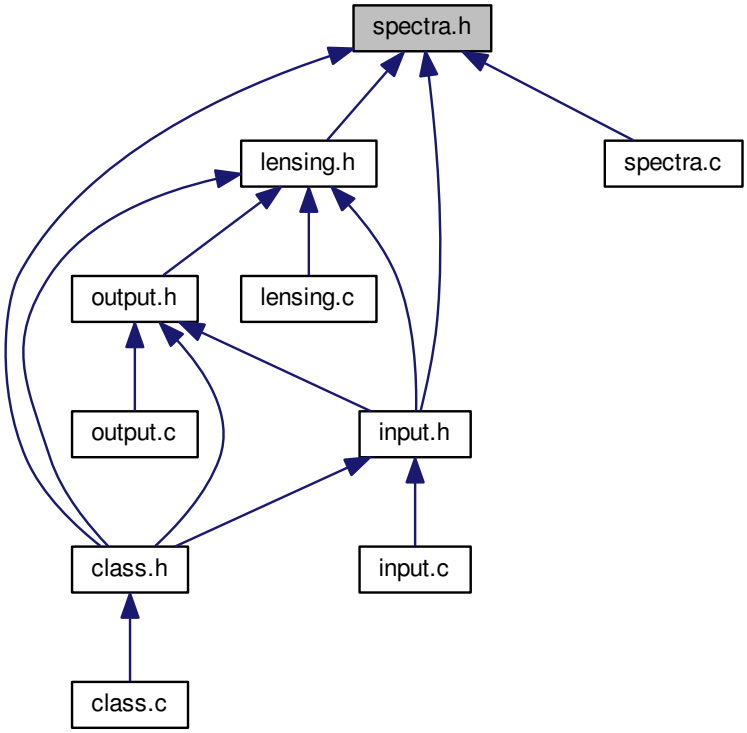
3.18 spectra.h File Reference

```
#include "transfer.h"
```

Include dependency graph for spectra.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct spectra

3.18.1 Detailed Description

Documented includes for spectra module

3.18.2 Data Structure Documentation

3.18.2.1 struct spectra

Structure containing everything about anisotropy and Fourier power spectra that other modules need to know.

Once initialized by spectra_init(), contains a table of all C_l's and P(k) as a function of multipole/wavenumber, mode (scalar/tensor...), type (for C_l's: TT, TE...), and pairs of initial conditions (adiabatic, isocurvatures...).

Data Fields

double	z_max_pk	maximum value of z at which matter spectrum P(k,z) will be evaluated; keep fixed to zero if P(k) only needed today

int	non_diag	sets the number of cross-correlation spectra that you want to calculate: 0 means only auto-correlation, 1 means only adjacent bins, and number of bins minus one means all correlations
int	md_size	number of modes (scalar, tensor, ...) included in computation
int	index_md_↩ scalars	index for scalar modes
int *	ic_size	for a given mode, ic_size[index_md] = number of initial conditions included in computation
int *	ic_ic_size	for a given mode, ic_ic_size[index_md] = number of pairs of (index_↩ ic1, index_ic2) with index_ic2 >= index_ic1; this number is just N(N+1)/2 where N = ic_size[index_md]
short **	is_non_zero	for a given mode, is_non_zero[index_md][index_ic1_ic2] is set to true if the pair of initial conditions (index_ic1, index_ic2) are statistically correlated, or to false if they are uncorrelated
int	has_tt	do we want C_l^{TT}? (T = temperature)
int	has_ee	do we want C_l^{EE}? (E = E-polarization)
int	has_te	do we want C_l^{TE}?
int	has_bb	do we want C_l^{BB}? (B = B-polarization)
int	has_pp	do we want $C_l^{\phi\phi}$? (ϕ = CMB lensing potential)
int	has_tp	do we want $C_l^{T\phi}$?
int	has_ep	do we want $C_l^{E\phi}$?
int	has_dd	do we want C_l^{dd}? (d = density)
int	has_td	do we want C_l^{Td}?
int	has_pd	do we want $C_l^{\phi d}$?
int	has_ll	do we want C_l^{ll}? (l = galaxy lensing potential)
int	has_tl	do we want C_l^{Tl}?
int	has_dl	do we want C_l^{dl}?
int	index_ct_tt	index for type C_l^{TT}
int	index_ct_ee	index for type C_l^{EE}
int	index_ct_te	index for type C_l^{TE}
int	index_ct_bb	index for type C_l^{BB}
int	index_ct_pp	index for type $C_l^{\phi\phi}$
int	index_ct_tp	index for type $C_l^{T\phi}$
int	index_ct_ep	index for type $C_l^{E\phi}$
int	index_ct_dd	first index for type C_l^{dd}((d_size*d_size-(d_size-non_diag)*(d_size-non↩ _diag-1)/2) values)
int	index_ct_td	first index for type C_l^{Td}(d_size values)
int	index_ct_pd	first index for type C_l^{pd}(d_size values)
int	index_ct_ll	first index for type C_l^{ll}((d_size*d_size-(d_size-non_diag)*(d_size-non↩ _diag-1)/2) values)
int	index_ct_tl	first index for type C_l^{Tl}(d_size values)
int	index_ct_dl	first index for type C_l^{dl}(d_size values)
int	d_size	$$$ definition missing $$$
int	ct_size	number of C_l types requested
int *	l_size	number of multipole values for each requested mode, l_size[index_md]
int	l_size_max	greatest of all l_size[index_md]
double *	l	list of multipole values l[index_l]
int **	l_max_ct	last multipole (given as an input) at which we want to output C_l's for a given mode and type; l[index_md][l_size[index_md]-1] can be larger than l_max[index_md], in order to ensure a better interpolation with no boundary effects

int *	l_max	last multipole (given as an input) at which we want to output C_l's for a given mode (maximized over types); l[index_md][l_size[index_md]-1] can be larger than l_max[index_md], in order to ensure a better interpolation with no boundary effects
int	l_max_tot	last multipole (given as an input) at which we want to output C_l's (maximized over modes and types); l[index_md][l_size[index_md]-1] can be larger than l_max[index_md], in order to ensure a better interpolation with no boundary effects
double **	cl	table of anisotropy spectra for each mode, multipole, pair of initial conditions and types, cl[index_md][(index_l * psp->ic_ic_size[index_md] + index_ic1_ic2) * psp->ct_size + index_ct]
double **	ddcl	second derivatives of previous table with respect to l, in view of spline interpolation
double	alpha_II_2_20	$$$ definition missing $$$
double	alpha_RI_2_20	$$$ definition missing $$$
double	alpha_RR_2_20	$$$ definition missing $$$
double	alpha_II_21_200	$$$ definition missing $$$
double	alpha_RI_21_↩ 200	$$$ definition missing $$$
double	alpha_RR_21↩ _200	$$$ definition missing $$$
double	alpha_II_201_↩ 2500	$$$ definition missing $$$
double	alpha_RI_201↩ _2500	$$$ definition missing $$$
double	alpha_RR_↩ 201_2500	$$$ definition missing $$$
double	alpha_II_2_2500	$$$ definition missing $$$
double	alpha_RI_2_↩ 2500	$$$ definition missing $$$
double	alpha_RR_2_↩ 2500	$$$ definition missing $$$
double	alpha_kp	$$$ definition missing $$$
double	alpha_k1	$$$ definition missing $$$
double	alpha_k2	$$$ definition missing $$$
int	ln_k_size	number ln(k) values
double *	ln_k	list of ln(k) values ln_k[index_k]
int	ln_tau_size	number ln(tau) values (only one if z_max_pk = 0)
double *	ln_tau	list of ln(tau) values ln_tau[index_tau]
double *	ln_pk	Matter power spectrum. depends on indices index_md, index_ic1, index_ic2, index_k, index_tau as: ln_pk[(index_tau * psp->k_size + index_k)* psp->ic_ic_size[index_md] + index_ic1_ic2] where index_↩ ic1_ic2 labels ordered pairs (index_ic1, index_ic2) (since the primordial spectrum is symmetric in (index_ic1, index_ic2)). • for diagonal elements (index_ic1 = index_ic2) this arrays contains ln[P(k)] where P(k) is positive by construction. • for non-diagonal elements this arrays contains the k-dependent cosine of the correlation angle, namely P(k)_(index_ic1, index_↩ ic2)/sqrt[P(k)_index_ic1 P(k)_index_ic2] This choice is convenient since the sign of the non-diagonal cross-correlation is arbitrary. For fully correlated or anti-correlated initial conditions, this non-diagonal element is independent on k, and equal to +1 or -1.

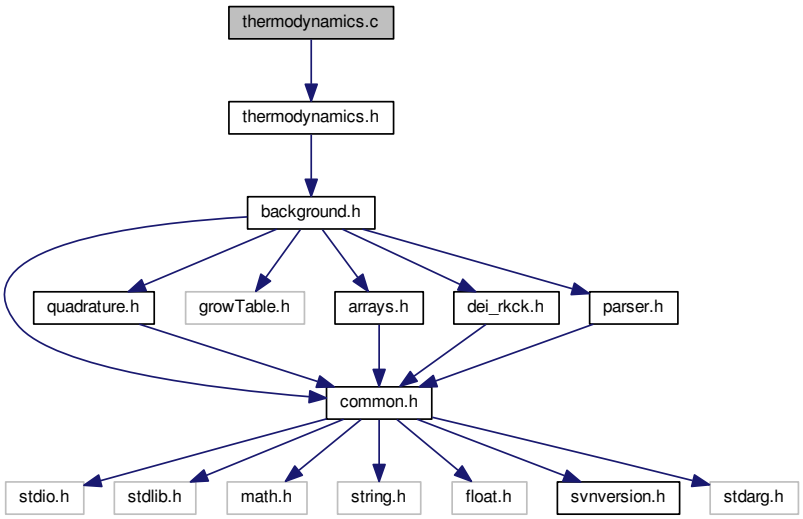
double *	ddln_pk	second derivative of above array with respect to log(tau), for spline interpolation. So: • for index_ic1 = index_ic, we spline ln[P(k)] vs. ln(k), which is good since this function is usually smooth. • for non-diagonal coefficients, we spline P(k)_(index_ic1, index_ic2)/sqrt[P(k)_index_ic1 P(k)_index_ic2] vs. ln(k), which is fine since this quantity is often assumed to be constant (e.g for fully correlated/anticorrelated initial conditions) or nearly constant, and with arbitrary sign.
double	sigma8	sigma8 parameter
double *	ln_pk_nl	Non-linear matter power spectrum. depends on indices index_k, index_tau as: ln_pk_nl[index_tau * psp->k_size + index_k]
double *	ddln_pk_nl	second derivative of above array with respect to log(tau), for spline interpolation.
int	index_tr_delta_g	index of gamma density transfer function
int	index_tr_delta_b	index of baryon density transfer function
int	index_tr_delta_cdm	index of cold dark matter density transfer function
int	index_tr_delta_dcdm	index of decaying cold dark matter density transfer function
int	index_tr_delta_scf	index of scalar field phi transfer function
int	index_tr_delta_fld	index of dark energy fluid density transfer function
int	index_tr_delta_ur	index of ultra-relativistic neutrinos/relics density transfer function
int	index_tr_delta_dr	index of decay radiation density transfer function
int	index_tr_delta_ncdm1	index of first species of non-cold dark matter (massive neutrinos, ...) density transfer function
int	index_tr_delta_tot	index of total matter density transfer function
int	index_tr_theta_g	index of gamma velocity transfer function
int	index_tr_theta_b	index of baryon velocity transfer function
int	index_tr_theta_cdm	index of cold dark matter velocity transfer function
int	index_tr_theta_dcdm	index of decaying cold dark matter velocity transfer function
int	index_tr_theta_scf	index of derivative of scalar field phi transfer function
int	index_tr_theta_fld	index of dark energy fluid velocity transfer function
int	index_tr_theta_ur	index of ultra-relativistic neutrinos/relics velocity transfer function
int	index_tr_theta_dr	index of decay radiation velocity transfer function

int	index_tr_theta↩ _ncdm1	index of first species of non-cold dark matter (massive neutrinos, ...) velocity transfer function
int	index_tr_theta↩ _tot	index of total matter velocity transfer function
int	tr_size	total number of species in transfer functions
double *	matter_transfer	Matter transfer functions. Depends on indices index_md,index↩ _tau,index_ic,index_k, index_tr as: matter_transfer[((index_tau*psp->ln_k_size + index_k) * psp->ic_size[index_md] + index_ic) * psp->tr↩ _size + index_tr]
double *	ddmatter_↩ transfer	second derivative of above array with respect to log(tau), for spline interpolation.
short	spectra_verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.19 thermodynamics.c File Reference

```
#include "thermodynamics.h"
```

Include dependency graph for thermodynamics.c:



Functions

- int thermodynamics_at_z (struct background *pba, struct thermo *pth, double z, short inter_mode, int *last↩ _index, double *pvecback, double *pvecthermo)
- int thermodynamics_init (struct precision *ppr, struct background *pba, struct thermo *pth)
- int thermodynamics_free (struct thermo *pth)
- int thermodynamics_indices (struct thermo *pth, struct recombination *preco, struct reionization *preio)
- int thermodynamics_helium_from_bbn (struct precision *ppr, struct background *pba, struct thermo *pth)
- int thermodynamics_onthespot_energy_injection (struct precision *ppr, struct background *pba, struct recombination *preco, double z, double *energy_rate, ErrorMsg error_message)
- int thermodynamics_energy_injection (struct precision *ppr, struct background *pba, struct recombination *preco, double z, double *energy_rate, ErrorMsg error_message)

- int thermodynamics_reionization_function (double z, struct thermo *pth, struct reionization *preio, double *xe)
- int thermodynamics_get_xe_before_reionization (struct precision *ppr, struct thermo *pth, struct recombination *preco, double z, double *xe)
- int thermodynamics_reionization (struct precision *ppr, struct background *pba, struct thermo *pth, struct recombination *preco, struct reionization *preio, double *pvecback)
- int thermodynamics_reionization_sample (struct precision *ppr, struct background *pba, struct thermo *pth, struct recombination *preco, struct reionization *preio, double *pvecback)
- int thermodynamics_recombination (struct precision *ppr, struct background *pba, struct thermo *pth, struct recombination *preco, double *pvecback)
- int thermodynamics_recombination_with_hyrec (struct precision *ppr, struct background *pba, struct thermo *pth, struct recombination *preco, double *pvecback)
- int thermodynamics_recombination_with_recfast (struct precision *ppr, struct background *pba, struct thermo *pth, struct recombination *preco, double *pvecback)
- int thermodynamics_derivs_with_recfast (double z, double *y, double *dy, void *parameters_and_workspace, ErrorMsg error_message)
- int thermodynamics_merge_reco_and_reio (struct precision *ppr, struct thermo *pth, struct recombination *preco, struct reionization *preio)
- int thermodynamics_output_titles (struct background *pba, struct thermo *pth, char titles[_MAXTITLESTR↩INGLENGTH_])
- int thermodynamics_output_data (struct background *pba, struct thermo *pth, int number_of_titles, double *data)

3.19.1 Detailed Description

Documented thermodynamics module

Julien Lesgourgues, 6.09.2010

Deals with the thermodynamical evolution. This module has two purposes:

- at the beginning, to initialize the thermodynamics, i.e. to integrate the thermodynamical equations, and store all thermodynamical quantities as a function of redshift inside an interpolation table. The current version of recombination is based on RECFAST v1.5. The current version of reionization is based on exactly the same reionization function as in CAMB, in order to make allow for comparison. It should be easy to generalize the module to more complicated reionization histories.
- to provide a routine which allow other modules to evaluate any thermodynamical quantities at a given redshift value (by interpolating within the interpolation table).

The logic is the following:

- in a first step, the code assumes that there is no reionization, and computes the ionization fraction, Thomson scattering rate, baryon temperature, etc., using RECFAST. The result is stored in a temporary table 'recombination_table' (within a temporary structure of type 'recombination') for each redshift in a range 0 $<$ z $<$ z_initial. The sampling in z space is done with a simple linear step size.
- in a second step, the code adds the reionization history, starting from a redshift z_reio_start. The ionization fraction at this redshift is read in the previous recombination table in order to ensure a perfect matching. The code computes the ionization fraction, Thomson scattering rate, baryon temperature, etc., using a given parametrization of the reionization history. The result is stored in a temporary table 'reionization_table' (within a temporary structure of type 'reionization') for each redshift in the range 0 $<$ z $<$ z_reio_start. The sampling in z space is found automatically, given the precision parameter 'reionization_sampling'.
- in a third step, the code merges the two tables 'recombination_table' and 'reionization_table' inside the table 'thermodynamics_table', and the temporary structures 'recombination' and 'reionization' are freed. In 'thermodynamics_table', the sampling in z space is the one defined in the recombination algorithm for z_↩reio_start $<$ z $<$ z_initial, and the one defined in the reionization algorithm for 0 $<$ z $<$ z_reio_start.

- at this stage, only a few columns in the table 'thermodynamics_table' have been filled. In a fourth step, the remaining columns are filled, using some numerical integration/derivation routines from the 'array.c' tools module.
- small detail: one of the columns contains the maximum variation rate of a few relevant thermodynamical quantities. This rate will be used for defining automatically the sampling step size in the perturbation module. Hence, the exact value of this rate is unimportant, but its order of magnitude at a given z defines the sampling precision of the perturbation module. Hence, it is harmless to use a smoothing routine in order to make this rate look nicer, although this will not affect the final result significantly. The last step in the thermodynamics↩ _init module is to perform this smoothing.

In summary, the following functions can be called from other modules:

1. thermodynamics_init() at the beginning (but after background_init())
2. thermodynamics_at_z() at any later time
3. thermodynamics_free() at the end, when no more calls to thermodynamics_at_z() are needed

3.19.2 Function Documentation

3.19.2.1 int thermodynamics_at_z (struct background * *pba*, struct thermo * *pth*, double *z*, short *inter_mode*, int * *last_index*, double * *pvecback*, double * *pvecthermo*)

Thermodynamics quantities at given redshift z.

Evaluates all thermodynamics quantities at a given value of the redshift by reading the pre-computed table and interpolating.

Parameters

pba	Input: pointer to background structure
pth	Input: pointer to the thermodynamics structure (containing pre-computed table)
z	Input: redshift
inter_mode	Input: interpolation mode (normal or growing_closeby)
last_index	Input/Output: index of the previous/current point in the interpolation array (input only for closeby mode, output for both)
pvecback	Input: vector of background quantities (used only in case z>z_initial for getting ddkappa and dddkappa; in that case, should be already allocated and filled, with format short_info or larger; in other cases, will be ignored)
pvecthermo	Output: vector of thermodynamics quantities (assumed to be already allocated)

Returns

the error status

Summary:

- define local variables
- interpolate in table with array_interpolate_spline() (normal mode) or array_interpolate_spline_growing_↩ closeby() (closeby mode)

3.19.2.2 int thermodynamics_init (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*)

Initialize the thermo structure, and in particular the thermodynamics interpolation table.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input/Output : pointer to initialized thermo structure

Returns

the error status

Summary:

- define local variables
- initialize pointers, allocate background vector
- compute and check primordial Helium fraction
- check energy injection parameters
- assign values to all indices in the structures with thermodynamics_indices()
- solve recombination and store values of $z, x_e, d\kappa/d\tau, T_b, c_b^2$ with thermodynamics_recombination()
- if there is reionization, solve reionization and store values of $z, x_e, d\kappa/d\tau, T_b, c_b^2$ with thermodynamics_reionization()
- merge tables in recombination and reionization structures into a single table in thermo structure
- compute table of corresponding conformal times
- store initial value of conformal time in the structure
- fill missing columns (quantities not computed previously but related)

-> baryon drag interaction rate time minus one, -[R $*$ kappa'], stored temporarily in column ddkappa

-> second derivative of this rate, -[R $*$ kappa']", stored temporarily in column dddkappa

-> compute tau_d = [int_{tau_today}^{tau} dtau -dkappa_d/dtau]

-> second derivative with respect to tau of dkappa (in view of spline interpolation)

-> first derivative with respect to tau of dkappa (using spline interpolation)

-> compute -kappa = [int_{tau_today}^{tau} dtau dkappa/dtau], store temporarily in column "g"

-> derivatives of baryon sound speed (only computed if some non-minimal tight-coupling schemes is requested)

-> second derivative with respect to tau of cb2

-> first derivative with respect to tau of cb2 (using spline interpolation)

-> compute visibility : $g = (d\kappa/d\tau)e^{-\kappa}$

-> compute g

-> compute exp(-kappa)

-> compute g' (the plus sign of the second term is correct, see def of -kappa in thermodynamics module!)

-> compute g"

-> store g

-> compute variation rate

-> smooth the rate (details of smoothing unimportant: only the order of magnitude of the rate matters)

- fill tables of second derivatives with respect to z (in view of spline interpolation)

- find maximum of g
- find conformal recombination time using background_tau_of_z()
- find time (always after recombination) at which tau_c/tau falls below some threshold, defining tau_free_↩ streaming
- find baryon drag time (when tau_d crosses one, using linear interpolation) and sound horizon at that time
- find time above which visibility falls below a given fraction of its maximum
- if verbose flag set to next-to-minimum value, print the main results

3.19.2.3 int thermodynamics_free (struct thermo * pth)

Free all memory space allocated by thermodynamics_init().

Parameters

pth	Input/Output : pointer to thermo structure (to be freed)

Returns

the error status

3.19.2.4 int thermodynamics_indices (struct thermo * pth, struct recombination * preco, struct reionization * preio)

Assign value to each relevant index in vectors of thermodynamical quantities, as well as in vector containing reionization parameters.

Parameters

pth	Input/Output: pointer to thermo structure
preco	Input/Output: pointer to recombination structure
preio	Input/Output: pointer to reionization structure

Returns

the error status

Summary:

- define local variables
- initialization of all indices and flags in thermo structure
- initialization of all indices and flags in recombination structure
- initialization of all indices and flags in reionization structure

add two values: beginning and end of reio

3.19.2.5 int thermodynamics_helium_from_bbn (struct precision * ppr, struct background * pba, struct thermo * pth)

Infer the primordial helium fraction from standard BBN, as a function of the baryon density and expansion rate during BBN.

This module is simpler then the one used in arXiv:0712.2826 because it neglects the impact of a possible significant chemical potentials for electron neutrinos. The full code with xi_nu_e could be introduced here later.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input/Output : pointer to initialized thermo structure

Returns

the error status

Infer effective number of neutrinos at the time of BBN

8.6173e-11 converts from Kelvin to MeV. We randomly choose 0.1 MeV to be the temperature of BBN

3.19.2.6 int thermodynamics_onthespot_energy_injection (struct precision * *ppr,* struct background * *pba,* struct recombination * *preco,* double *z,* double * *energy_rate,* ErrorMsg *error_message*)

In case of non-minimal cosmology, this function determines the energy rate injected in the IGM at a given redshift z (= on-the-spot annihilation). This energy injection may come e.g. from dark matter annihilation or decay.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
preco	Input : pointer to recombination structure
z	Input : redshift
energy_rate	Output : energy density injection rate
error_message	Output: error message

Returns

the error status

3.19.2.7 int thermodynamics_energy_injection (struct precision * *ppr,* struct background * *pba,* struct recombination * *preco,* double *z,* double * *energy_rate,* ErrorMsg *error_message*)

In case of non-minimal cosmology, this function determines the effective energy rate absorbed by the IGM at a given redshift (beyond the on-the-spot annihilation). This energy injection may come e.g. from dark matter annihilation or decay.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
preco	Input : pointer to recombination structure
z	Input : redshift
energy_rate	Output : energy density injection rate
error_message	Output: error message

Returns

the error status

3.19.2.8 int thermodynamics_reionization_function (double *z,* struct thermo * *pth,* struct reionization * *preio,* double * *xe*)

This subroutine contains the reionization function $X_e(z)$ (one for each scheme; so far, only the function corresponding to the reio_camb scheme is coded)

Parameters

z	Input : redshift
pth	Input : pointer to thermo structure, to know which scheme is used
preio	Input : pointer to reionization structure, containing the parameters of the function $X_e(z)$
xe	Output: $X_e(z)$

Summary:

- define local variables
- implementation of ionization function similar to the one in CAMB

-> case z $>$ z_reio_start

-> case z $<$ z_reio_start: hydrogen contribution (tanh of complicated argument)

-> case z $<$ z_reio_start: helium contribution (tanh of simpler argument)

- implementation of binned ionization function similar to astro-ph/0606552

-> case z $>$ z_reio_start

3.19.2.9 int thermodynamics_get_xe_before_reionization (struct precision * *ppr*, struct thermo * *pth*, struct recombination * *preco*, double *z*, double * *xe*)

This subroutine reads $X_e(z)$ in the recombination table at the time at which reionization starts. Hence it provides correct initial conditions for the reionization function.

Parameters

ppr	Input : pointer to precision structure
pth	Input : pointer to thermo structure
preco	Input : pointer to recombination structure
z	Input : redshift z_reio_start
xe	Output: $X_e(z)$ at z

3.19.2.10 int thermodynamics_reionization (struct precision * *ppr*, struct background * *pba*, struct thermo * *pth*, struct recombination * *preco*, struct reionization * *preio*, double * *pvecback*)

This routine computes the reionization history. In the reio_camb scheme, this is straightforward if the input parameter is the reionization redshift. If the input is the optical depth, need to find z_reio by dichotomy (trying several z_reio until the correct tau_reio is approached).

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermo structure
preco	Input : pointer to filled recombination structure
preio	Input/Output: pointer to reionization structure (to be filled)
pvecback	Input: vector of background quantities (used as workspace: must be already allocated, with format short_info or larger, but does not need to be filled)

Returns

the error status

Summary:

- define local variables
- allocate the vector of parameters defining the function $X_e(z)$

(a) if reionization implemented like in CAMB

- set values of these parameters, excepted those depending on the reionization redshift
- if reionization redshift given as an input, initialize the remaining values and fill reionization table
- if reionization optical depth given as an input, find reionization redshift by dichotomy and initialize the remaining values

3.19.2.11 int thermodynamics_reionization_sample (struct precision * ppr, struct background * pba, struct thermo * pth, struct recombination * preco, struct reionization * preio, double * pvecback)

For fixed input reionization parameters, this routine computes the reionization history and fills the reionization table.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermo structure
preco	Input : pointer to filled recombination structure
preio	Input/Output: pointer to reionization structure (to be filled)
pvecback	Input: vector of background quantities (used as workspace: must be already allocated, with format short_info or larger, but does not need to be filled)

Returns

the error status

Summary:

- define local variables

(a) allocate vector of values related to reionization

(b) create a growTable with gt_init()

(c) first line is taken from thermodynamics table, just before reionization starts

- look where to start in current thermodynamics table
- get redshift
- get X_e
- get $dkappa/dz = (dkappa/dtau) * (dtau/dz) = -(dkappa/dtau)/H$
- get baryon temperature
- after recombination, Tb scales like (1+z)**2. Compute constant factor Tb/(1+z)**2.
- get baryon sound speed
- store these values in growing table

(d) set the maximum step value (equal to the step in thermodynamics table)

(e) loop over redshift values in order to find values of z, x_e, kappa' (Tb and cb2 found later by integration). The sampling in z space is found here.

- initial step

(f) allocate reionization_table with correct size

(g) retrieve data stored in the growTable with gt_getPtr()

(h) copy growTable to reionization_temporary_table (invert order of lines, so that redshift is growing, like in recombination table)

(i) free the growTable with gt_free() , free vector of reionization variables

(j) another loop on z, to integrate equation for Tb and to compute cb2

- derivative of baryon temperature
- increment baryon temperature
- get baryon sound speed
- spline $dtau/dz$ with respect to z in view of integrating for optical depth
- integrate for optical depth

3.19.2.12 int thermodynamics_recombination (struct precision * *ppr,* struct background * *pba,* struct thermo * *pth,* struct recombination * *preco,* double * *pvecback*)

Integrate thermodynamics with your favorite recombination code.

3.19.2.13 int thermodynamics_recombination_with_hyrec (struct precision * *ppr,* struct background * *pba,* struct thermo * *pth,* struct recombination * *preco,* double * *pvecback*)

Integrate thermodynamics with HyRec.

Integrate thermodynamics with HyRec, allocate and fill the part of the thermodynamics interpolation table (the rest is filled in thermodynamics_init()). Called once by thermodynamics_recombination(), from thermodynamics_init().

```
        HYREC: Hydrogen and Helium Recombination Code                         *
Written by Yacine Ali-Haimoud and Chris Hirata (Caltech)                      *
```

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to thermodynamics structure
preco	Output: pointer to recombination structure
pvecback	Input: pointer to an allocated (but empty) vector of background variables

3.19.2.14 int thermodynamics_recombination_with_recfast (struct precision * *ppr,* struct background * *pba,* struct thermo * *pth,* struct recombination * *preco,* double * *pvecback*)

Integrate thermodynamics with RECFAST.

Integrate thermodynamics with RECFAST, allocate and fill the part of the thermodynamics interpolation table (the rest is filled in thermodynamics_init()). Called once by thermodynamics_recombination, from thermodynamics_init().

RECFAST is an integrator for Cosmic Recombination of Hydrogen and Helium, * developed by Douglas Scott (dscott@astro.ubc.ca) * based on calculations in the paper Seager, Sasselov & Scott * (ApJ, 523, L1, 1999). * and "fudge" updates in Wong, Moss & Scott (2008). *

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Version 1.5: includes extra fitting function from Rubino-Martin et al. arXiv:0910.4383v1 [astro-ph.CO]

Parameters

ppr	Input: pointer to precision structure
pba	Input: pointer to background structure
pth	Input: pointer to thermodynamics structure
preco	Output: pointer to recombination structure
pvecback	Input: pointer to an allocated (but empty) vector of background variables

Returns

the error status

Summary:

- define local variables
- allocate memory for thermodynamics interpolation tables (size known in advance)
- initialize generic integrator with initialize_generic_integrator()
- read a few precision/cosmological parameters
- define the fields of the 'thermodynamics parameter and workspace' structure
- impose initial conditions at early times
- loop over redshift steps Nz; integrate over each step with generic_integrator(), store the results in the table using thermodynamics_derivs_with_recfast()

-> first approximation: H and Helium fully ionized

-> second approximation: first Helium recombination (analytic approximation)

-> third approximation: first Helium recombination completed

-> fourth approximation: second Helium recombination starts (analytic approximation)

-> fifth approximation: second Helium recombination (full evolution for Helium), H recombination starts (analytic approximation)

-> last case: full evolution for H and Helium

-> store the results in the table

- cleanup generic integrator with cleanup_generic_integrator()

3.19.2.15 int thermodynamics_derivs_with_recfast (double *z*, double * *y*, double * *dy*, void * *parameters_and_workspace*, ErrorMsg *error_message*)

Subroutine evaluating the derivative with respect to redshift of thermodynamical quantities (from RECFAST version 1.4).

Computes derivatives of the three variables to integrate: $dx_H/dz, dx_{He}/dz, dT_{mat}/dz$.

This is one of the few functions in the code which are passed to the generic_integrator() routine. Since generic_integrator() should work with functions passed from various modules, the format of the arguments is a bit special:

- fixed parameters and workspaces are passed through a generic pointer. Here, this pointer contains the precision, background and recombination structures, plus a background vector, but generic_integrator() doesn't know its fine structure.
- the error management is a bit special: errors are not written as usual to pth->error_message, but to a generic error_message passed in the list of arguments.

Parameters

z	Input : redshift
y	Input : vector of variable to integrate
dy	Output: its derivative (already allocated)
parameters_and_workspace	Input : pointer to fixed parameters (e.g. indices) and workspace (already allocated)
error_message	Output: error message

Summary:

- define local variables

3.19.2.16 int thermodynamics_merge_reco_and_reio (struct **precision** * *ppr*, struct **thermo** * *pth*, struct **recombination** * *preco*, struct **reionization** * *preio*)

This routine merges the two tables 'recombination_table' and 'reionization_table' inside the table 'thermodynamics_table', and frees the temporary structures 'recombination' and 'reionization'.

Parameters

ppr	Input : pointer to precision structure
pth	Input/Output : pointer to thermo structure
preco	Input : pointer to filled recombination structure
preio	Input : pointer to reionization structure

Returns

the error status

Summary:

- define local variables
- first, a little check that the two tables match each other and can be merged
- find number of redshift in full table = number in reco + number in reio - overlap
- allocate arrays in thermo structure
- fill these arrays
- free the temporary structures

3.19.2.17 int thermodynamics_output_titles (struct background * *pba*, struct thermo * *pth*, char *titles[_MAXTITLESTRINGLENGTH_]*)

Subroutine for formatting thermodynamics output

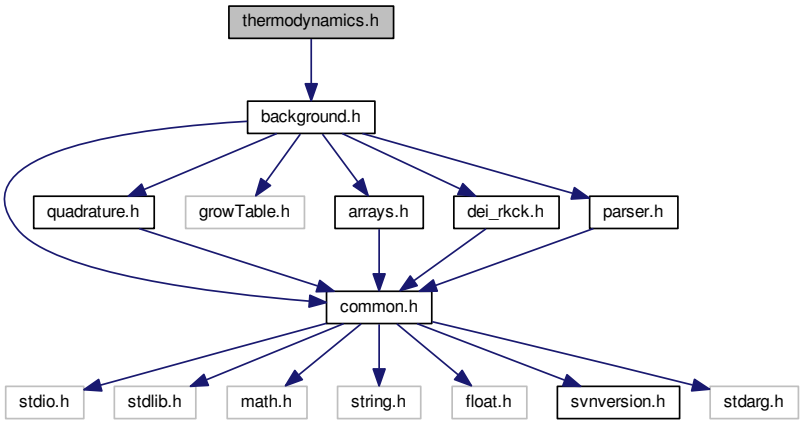
3.19.2.18 int thermodynamics_output_data (struct background * *pba*, struct thermo * *pth*, int *number_of_titles*, double * *data*)

Store quantities:

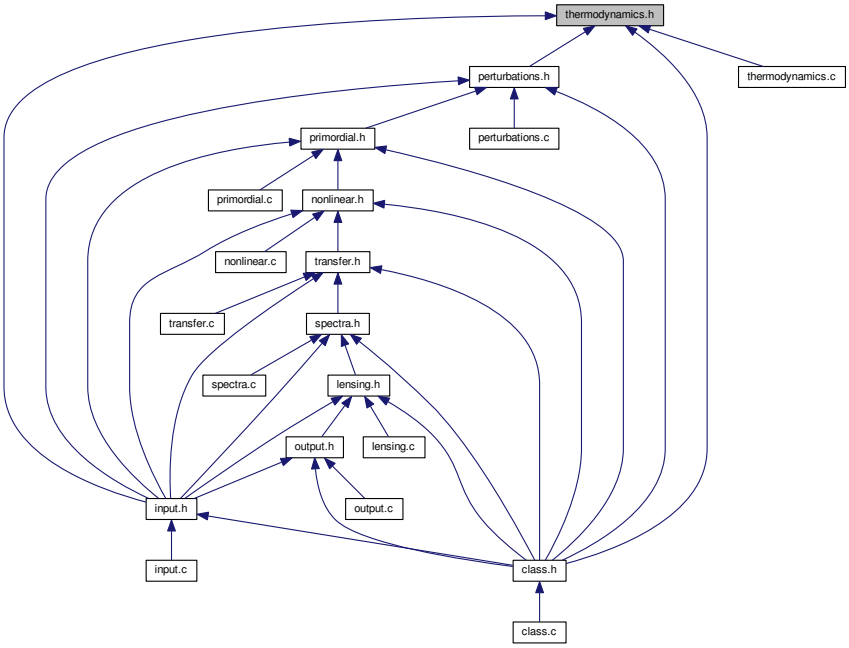
3.20 thermodynamics.h File Reference

```
#include "background.h"
```

Include dependency graph for thermodynamics.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct thermo
- struct recombination
- struct reionization
- struct thermodynamics_parameters_and_workspace

Macros

- #define f1(x) (-0.75∗x∗(x∗x/3.-1.)+0.5)
- #define f2(x) (x∗x∗(0.5-x/3.)∗6.)

- #define _YHE_BIG_ 0.5
- #define _YHE_SMALL_ 0.01

Enumerations

- enum recombination_algorithm
- enum reionization_parametrization { reio_none, reio_camb, reio_bins_tanh, reio_half_tanh }
- enum reionization_z_or_tau { reio_z, reio_tau }

3.20.1 Detailed Description

Documented includes for thermodynamics module

3.20.2 Data Structure Documentation

3.20.2.1 struct thermo

All thermodynamics parameters and evolution that other modules need to know.

Once initialized by thermodynamics_init(), contains all the necessary information on the thermodynamics, and in particular, a table of thermodynamical quantities as a function of the redshift, used for interpolation in other modules.

Data Fields

double	YHe	Y_{He} : primordial helium fraction
enum recombination_algorithm	recombination	recombination code
enum reionization_parametrization	reio_parametrization	reionization scheme
enum reionization_z_or_tau	reio_z_or_tau	is the input parameter the reionization redshift or optical depth?
double	tau_reio	if above set to tau, input value of reionization optical depth
double	z_reio	if above set to z, input value of reionization redshift
short	compute_cb2_derivatives	do we want to include in computation derivatives of baryon sound speed?
double	reionization_width	parameters for reio_camb width of H reionization
double	reionization_exponent	shape of H reionization
double	helium_fullreio_redshift	redshift for of helium reionization
double	helium_fullreio_width	width of helium reionization
int	binned_reio_num	parameters for reio_bins_tanh with how many bins de we want to describe reionization?
double *	binned_reio_z	central z value for each bin
double *	binned_reio_xe	imposed x_e(z) value at center of each bin
double	binned_reio_step_sharpness	sharpness of tanh() step interpolating between binned values
double	annihilation	parameters for energy injection
short	has_on_the_spot	parameter describing CDM annihilation (f <sigma*v> / m_cdm, see e.g. 0905.0003)
double	decay	flag to specify if we want to use the on-the-spot approximation
double	annihilation_variation	parameter describing CDM decay (f/tau, see e.g. 1109.6322)
double	annihilation_z	if this parameter is non-zero, the function F(z)=(f <sigma*v> / m_cdm)(z) will be a parabola in log-log scale between zmin and zmax, with a curvature given by annihlation_variation (must be negative), and with a maximum in zmax; it will be constant outside this range
double	annihilation_zmax	if annihilation_variation is non-zero, this is the value of z at which the parameter annihilation is defined, i.e. F(annihilation_z)=annihilation
double	annihilation_zmin	if annihilation_variation is non-zero, redshift above which annihilation rate is maximal

double	annihilation_f_↩ halo	if annihilation_variation is non-zero, redshift below which annihilation rate is constant
double	annihilation_z↩ _halo	takes the contribution of DM annihilation in halos into account
int	index_th_xe	ionization fraction x_e
int	index_th_dkappa	Thomson scattering rate $d\kappa/d\tau$ (units 1/Mpc)
int	index_th_tau_d	Baryon drag optical depth
int	index_th_↩ ddkappa	scattering rate derivative $d^2\kappa/d\tau^2$
int	index_th_↩ dddkappa	scattering rate second derivative $d^3\kappa/d\tau^3$
int	index_th_exp_↩ m_kappa	$exp^{-\kappa}$
int	index_th_g	visibility function $g = (d\kappa/d\tau) * exp^{-\kappa}$
int	index_th_dg	visibility function derivative $(dg/d\tau)$
int	index_th_ddg	visibility function second derivative $(d^2g/d\tau^2)$
int	index_th_Tb	baryon temperature T_b
int	index_th_cb2	squared baryon sound speed c_b^2
int	index_th_dcb2	derivative wrt conformal time of squared baryon sound speed $d[c_b^2]/d\tau$ (only computed if some non-minimal tight-coupling schemes is requested)
int	index_th_ddcb2	second derivative wrt conformal time of squared baryon sound speed $d^2[c_b^2]/d\tau^2$ (only computed if some non0-minimal tight-coupling schemes is requested)
int	index_th_rate	maximum variation rate of $exp^{-\kappa}$, g and $(dg/d\tau)$, used for computing integration step in perturbation module
int	th_size	size of thermodynamics vector
int	tt_size	number of lines (redshift steps) in the tables
double *	z_table	vector z_table[index_z] with values of redshift (vector of size tt_size)
double *	thermodynamics↩ _table	table thermodynamics_table[index_z*pth->tt_size+pba->index_th] with all other quantities (array of size th_size*tt_size)
double *	d2thermodynamics↩ _dz2_table	table d2thermodynamics_dz2_table[index_z*pth->tt_size+pba->index_th] with values of d^2t_i/dz^2 (array of size th_size*tt_size)
double	z_rec	z at which the visibility reaches its maximum (= recombination redshift)
double	tau_rec	conformal time at which the visibility reaches its maximum (= recombination time)
double	rs_rec	comoving sound horizon at recombination
double	ds_rec	physical sound horizon at recombination
double	ra_rec	conformal angular diameter distance to recombination
double	da_rec	physical angular diameter distance to recombination
double	z_d	baryon drag redshift
double	tau_d	baryon drag time
double	ds_d	physical sound horizon at baryon drag
double	rs_d	comoving sound horizon at baryon drag
double	tau_cut	at at which the visibility goes below a fixed fraction of the maximum visibility, used for an approximation in perturbation module
double	angular_↩ rescaling	[ratio ra_rec / (tau0-tau_rec)]: gives CMB rescaling in angular space relative to flat model (=1 for curvature K=0)
double	tau_free_↩ streaming	minimum value of tau at which sfree-streaming approximation can be switched on

double	tau_ini	initial conformal time at which thermodynamical variables have been be integrated
double	n_e	total number density of electrons today (free or not)
short	inter_normal	flag for calling thermodynamics_at_z and find position in interpolation table normally
short	inter_closeby	flag for calling thermodynamics_at_z and find position in interpolation table starting from previous position in previous call
short	thermodynamics↩ _verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.20.2.2 struct recombination

Temporary structure where all the recombination history is defined and stored.

This structure is used internally by the thermodynamics module, but never passed to other modules.

Data Fields

int	index_re_z	redshift z
int	index_re_xe	ionization fraction x_e
int	index_re_Tb	baryon temperature T_b
int	index_re_cb2	squared baryon sound speed c_b^2
int	index_re_↩ dkappadtau	Thomson scattering rate $d\kappa/d\tau$ (units 1/Mpc)
int	re_size	size of this vector
int	rt_size	number of lines (redshift steps) in the table
double ∗	recombination↩ _table	table recombination_table[index_z∗preco->re_size+index_re] with all other quantities (array of size preco->rt_size∗preco->re_size)
double	CDB	$$$ definition missing $$$
double	CR	$$$ definition missing $$$
double	CK	$$$ definition missing $$$
double	CL	$$$ definition missing $$$
double	CT	$$$ definition missing $$$
double	fHe	$$$ definition missing $$$
double	CDB_He	$$$ definition missing $$$
double	CK_He	$$$ definition missing $$$
double	CL_He	$$$ definition missing $$$
double	fu	$$$ definition missing $$$
double	H_frac	$$$ definition missing $$$
double	Tnow	$$$ definition missing $$$
double	Nnow	$$$ definition missing $$$
double	Bfact	$$$ definition missing $$$
double	CB1	$$$ definition missing $$$
double	CB1_He1	$$$ definition missing $$$
double	CB1_He2	$$$ definition missing $$$
double	H0	$$$ definition missing $$$
double	YHe	$$$ definition missing $$$
double	annihilation	parameter describing CDM annihilation (f <sigma∗v> / m_cdm, see e.g. 0905.0003)

short	has_on_the_↩ spot	flag to specify if we want to use the on-the-spot approximation
double	decay	parameter describing CDM decay (f/tau, see e.g. 1109.6322)
double	annihilation_↩ variation	if this parameter is non-zero, the function F(z)=(f <sigma∗v> / m_↩ cdm)(z) will be a parabola in log-log scale between zmin and zmax, with a curvature given by annihlation_variation (must be negative), and with a maximum in zmax; it will be constant outside this range
double	annihilation_z	if annihilation_variation is non-zero, this is the value of z at which the parameter annihilation is defined, i.e. F(annihilation_z)=annihilation
double	annihilation_↩ zmax	if annihilation_variation is non-zero, redshift above which annihilation rate is maximal
double	annihilation_↩ zmin	if annihilation_variation is non-zero, redshift below which annihilation rate is constant
double	annihilation_f_↩ halo	takes the contribution of DM annihilation in halos into account
double	annihilation_z↩ _halo	characteristic redshift for DM annihilation in halos

3.20.2.3 struct reionization

Temporary structure where all the reionization history is defined and stored.

This structure is used internally by the thermodynamics module, but never passed to other modules.

Data Fields

int	index_re_z	redshift z
int	index_re_xe	ionization fraction x_e
int	index_re_Tb	baryon temperature T_b
int	index_re_cb2	squared baryon sound speed c_b^2
int	index_re_↩ dkappadtau	Thomson scattering rate $d\kappa/d\tau$ (units 1/Mpc)
int	index_re_↩ dkappadz	Thomson scattering rate with respect to redshift $d\kappa/dz$ (units 1/Mpc)
int	index_re_↩ d3kappadz3	second derivative of previous quantity with respect to redshift
int	re_size	size of this vector
int	rt_size	number of lines (redshift steps) in the table
double ∗	reionization_↩ table	table reionization_table[index_z∗preio->re_size+index_re] with all other quantities (array of size preio->rt_size∗preio->re_size)
double	reionization_↩ optical_depth	reionization optical depth inferred from reionization history
int	index_reio_↩ redshift	hydrogen reionization redshift
int	index_reio_↩ exponent	an exponent used in the function x_e(z) in the reio_camb scheme
int	index_reio_width	a width defining the duration of hydrogen reionization in the reio_camb scheme
int	index_reio_xe↩ _before	ionization fraction at redshift 'reio_start'
int	index_reio_xe↩ _after	ionization fraction after full reionization

int	index_helium_↩ fullreio_fraction	helium full reionization fraction inferred from primordial helium fraction
int	index_helium_↩ fullreio_redshift	helium full reionization redshift
int	index_helium_↩ fullreio_width	a width defining the duration of helium full reionization in the reio_camb scheme
int	reio_num_z	$$$ definition missing $$$
int	index_reio_↩ first_z	$$$ definition missing $$$
int	index_reio_↩ first_xe	$$$ definition missing $$$
int	index_reio_↩ step_sharpness	$$$ definition missing $$$
int	index_reio_start	redshift above which hydrogen reionization neglected
double *	reionization_↩ parameters	$$$ definition missing $$$
int	reio_num_↩ params	$$$ definition missing $$$
int	index_reco_↩ when_reio_start	index of line in recombination table corresponding to first line of reionization table

3.20.2.4 struct thermodynamics_parameters_and_workspace

temporary parameters and workspace passed to the thermodynamics_derivs function

3.20.3 Macro Definition Documentation

3.20.3.1 #define f1(*x*) (-0.75∗x∗(x∗x/3.-1.)+0.5)

Two useful smooth step functions, for smoothing transitions in recfast. goes from 0 to 1 when x goes from -1 to 1

3.20.3.2 #define f2(*x*) (x∗x∗(0.5-x/3.)∗6.)

goes from 0 to 1 when x goes from 0 to 1

3.20.3.3 #define _YHE_BIG_ 0.5

maximal Y_{He}

3.20.3.4 #define _YHE_SMALL_ 0.01

minimal Y_{He}

3.20.4 Enumeration Type Documentation

3.20.4.1 enum recombination_algorithm

List of possible recombination algorithms.

3.20.4.2 enum reionization_parametrization

List of possible reionization schemes.

Enumerator

reio_none no reionization

reio_camb reionization parameterized like in CAMB

reio_bins_tanh binned reionization history with tanh interpolation between bins

reio_half_tanh half a tanh, instead of the full tanh

3.20.4.3 enum reionization_z_or_tau

Is the input parameter the reionization redshift or optical depth?

Enumerator

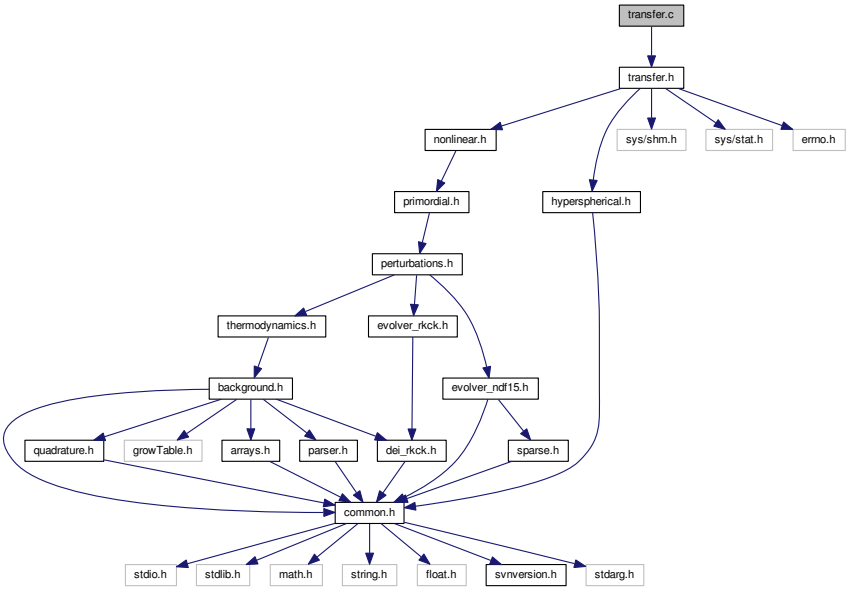
reio_z input = redshift

reio_tau input = tau

3.21 transfer.c File Reference

```
#include "transfer.h"
```

Include dependency graph for transfer.c:



Functions

- int transfer_functions_at_q (struct transfers ∗ptr, int index_md, int index_ic, int index_tt, int index_l, double q, double ∗transfer_function)
- int transfer_init (struct precision ∗ppr, struct background ∗pba, struct thermo ∗pth, struct perturbs ∗ppt, struct nonlinear ∗pnl, struct transfers ∗ptr)

- int transfer_free (struct transfers *ptr)
- int transfer_indices_of_transfers (struct precision *ppr, struct perturbs *ppt, struct transfers *ptr, double q_↩ period, double K, int sgnK)
- int transfer_get_l_list (struct precision *ppr, struct perturbs *ppt, struct transfers *ptr)
- int transfer_get_q_list (struct precision *ppr, struct perturbs *ppt, struct transfers *ptr, double q_period, double K, int sgnK)
- int transfer_get_k_list (struct perturbs *ppt, struct transfers *ptr, double K)
- int transfer_get_source_correspondence (struct perturbs *ppt, struct transfers *ptr, int **tp_of_tt)
- int transfer_source_tau_size (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, double tau_rec, double tau0, int index_md, int index_tt, int *tau_size)
- int transfer_compute_for_each_q (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, int **tp_of_tt, int index_q, int tau_size_max, double tau_rec, double ***pert_sources, double ***pert_sources_spline, struct transfer_workspace *ptw)
- int transfer_interpolate_sources (struct perturbs *ppt, struct transfers *ptr, int index_q, int index_md, int index_ic, int index_type, double *pert_source, double *pert_source_spline, double *interpolated_sources)
- int transfer_sources (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, double *interpolated_sources, double tau_rec, int index_q, int index_md, int index_tt, double *sources, double *tau0_minus_tau, double *w_trapz, int *tau_size_out)
- int transfer_selection_function (struct precision *ppr, struct perturbs *ppt, struct transfers *ptr, int bin, double z, double *selection)
- int transfer_dNdz_analytic (struct transfers *ptr, double z, double *dNdz, double *dln_dNdz_dz)
- int transfer_selection_sampling (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, int bin, double *tau0_minus_tau, int tau_size)
- int transfer_lensing_sampling (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, int bin, double tau0, double *tau0_minus_tau, int tau_size)
- int transfer_source_resample (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, int bin, double *tau0_minus_tau, int tau_size, int index_md, double tau0, double *interpolated_↩ sources, double *sources)
- int transfer_selection_times (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, int bin, double *tau_min, double *tau_mean, double *tau_max)
- int transfer_selection_compute (struct precision *ppr, struct background *pba, struct perturbs *ppt, struct transfers *ptr, double *selection, double *tau0_minus_tau, double *w_trapz, int tau_size, double *pvecback, double tau0, int bin)
- int transfer_compute_for_each_l (struct transfer_workspace *ptw, struct precision *ppr, struct perturbs *ppt, struct transfers *ptr, int index_q, int index_md, int index_ic, int index_tt, int index_l, double l, double q_max↩ _bessel, radial_function_type radial_type)
- int transfer_integrate (struct perturbs *ppt, struct transfers *ptr, struct transfer_workspace *ptw, int index_q, int index_md, int index_tt, double l, int index_l, double k, radial_function_type radial_type, double *trsf)
- int transfer_limber (struct transfers *ptr, struct transfer_workspace *ptw, int index_md, int index_q, double l, double q, radial_function_type radial_type, double *trsf)
- int transfer_limber_interpolate (struct transfers *ptr, double *tau0_minus_tau, double *sources, int tau_size, double tau0_minus_tau_limber, double *S)
- int transfer_limber2 (int tau_size, struct transfers *ptr, int index_md, int index_k, double l, double k, double *tau0_minus_tau, double *sources, radial_function_type radial_type, double *trsf)
- int transfer_update_HIS (struct precision *ppr, struct transfers *ptr, struct transfer_workspace *ptw, int index_q, double tau0)
- int transfer_get_lmax (int(*get_xmin_generic)(int sgnK, int l, double nu, double xtol, double phiminabs, double *x_nonzero, int *fevals), int sgnK, double nu, int *lvec, int lsize, double phiminabs, double xmax, double xtol, int *index_l_left, int *index_l_right, ErrorMsg error_message)

3.21.1 Detailed Description

Documented transfer module.

Julien Lesgourgues, 28.07.2013

This module has two purposes:

- at the beginning, to compute the transfer functions $\Delta_l^X(q)$, and store them in tables used for interpolation in other modules.
- at any time in the code, to evaluate the transfer functions (for a given mode, initial condition, type and multipole l) at any wavenumber q (by interpolating within the interpolation table).

Hence the following functions can be called from other modules:

1. transfer_init() at the beginning (but after perturb_init() and bessel_init())
2. transfer_functions_at_q() at any later time
3. transfer_free() at the end, when no more calls to transfer_functions_at_q() are needed

Note that in the standard implementation of CLASS, only the pre-computed values of the transfer functions are used, no interpolation is necessary; hence the routine transfer_functions_at_q() is actually never called.

3.21.2 Function Documentation

3.21.2.1 int transfer_functions_at_q (struct transfers * *ptr,* int *index_md,* int *index_ic,* int *index_tt,* int *index_l,* double *q,* double * *transfer_function*)

Transfer function $\Delta_l^X(q)$ at a given wavenumber q.

For a given mode (scalar, vector, tensor), initial condition, type (temperature, polarization, lensing, etc) and multipole, computes the transfer function for an arbitrary value of q by interpolating between pre-computed values of q. This function can be called from whatever module at whatever time, provided that transfer_init() has been called before, and transfer_free() has not been called yet.

Wavenumbers are called q in this module and k in the perturbation module. In flat universes k=q. In non-flat universes q and k differ through $q2 = k2 + K(1 + m)$, where m=0,1,2 for scalar, vector, tensor. q should be used throughout the transfer module, excepted when interpolating or manipulating the source functions S(k,tau) calculated in the perturbation module: for a given value of q, this should be done at the corresponding k(q).

Parameters

ptr	Input: pointer to transfer structure
index_md	Input: index of requested mode
index_ic	Input: index of requested initial condition
index_tt	Input: index of requested type
index_l	Input: index of requested multipole
q	Input: any wavenumber
transfer_function	Output: transfer function

Returns

the error status

Summary:

- interpolate in pre-computed table using array_interpolate_two()

3.21.2.2 int transfer_init (struct precision * *ppr,* struct background * *pba,* struct thermo * *pth,* struct perturbs * *ppt,* struct nonlinear * *pnl,* struct transfers * *ptr*)

This routine initializes the transfers structure, (in particular, computes table of transfer functions $\Delta_l^X(q)$)

Main steps:

- initialize all indices in the transfers structure and allocate all its arrays using transfer_indices_of_transfers().
- for each thread (in case of parallel run), initialize the fields of a memory zone called the transfer_workspace with transfer_workspace_init()
- loop over q values. For each q, compute the Bessel functions if needed with transfer_update_HIS(), and defer the calculation of all transfer functions to transfer_compute_for_each_q()
- for each thread, free the the workspace with transfer_workspace_free()

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
pth	Input : pointer to thermodynamics structure
ppt	Input : pointer to perturbation structure
pnl	Input : pointer to nonlinear structure
ptr	Output: pointer to initialized transfers structure

Returns

the error status

Summary:

- define local variables
- array with the correspondence between the index of sources in the perturbation module and in the transfer module, tp_of_tt[index_md][index_tt]

check whether any spectrum in harmonic space (i.e., any C_l's) is actually requested

get number of modes (scalars, tensors...)

- get conformal age / recombination time from background / thermodynamics structures (only place where these structures are used in this module)
- correspondence between k and l depend on angular diameter distance, i.e. on curvature.

order of magnitude of the oscillation period of transfer functions

- initialize all indices in the transfers structure and allocate all its arrays using transfer_indices_of_transfers()
- copy sources to a local array sources (in fact, only the pointers are copied, not the data), and eventually apply non-linear corrections to the sources
- spline all the sources passed by the perturbation module with respect to k (in order to interpolate later at a given value of k)
- allocate and fill array describing the correspondence between perturbation types and transfer types
- evaluate maximum number of sampled times in the transfer sources: needs to be known here, in order to allocate a large enough workspace
- compute flat spherical bessel functions
- eventually read the selection and evolution functions

(a.3.) workspace, allocated in a parallel zone since in openmp version there is one workspace per thread

- loop over all wavenumbers (parallelized). For each wavenumber:

3.21.2.3 int transfer_free (struct transfers * *ptr*)

This routine frees all the memory space allocated by transfer_init().

To be called at the end of each run, only when no further calls to transfer_functions_at_k() are needed.

Parameters

ptr	Input: pointer to transfers structure (which fields must be freed)

Returns

the error status

3.21.2.4 int transfer_indices_of_transfers (struct precision * *ppr*, struct perturbs * *ppt*, struct transfers * *ptr*, double *q_period*, double *K*, int *sgnK*)

This routine defines all indices and allocates all tables in the transfers structure

Compute list of (k, l) values, allocate and fill corresponding arrays in the transfers structure. Allocate the array of transfer function tables.

Parameters

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure
ptr	Input/Output: pointer to transfer structure
q_period	Input: order of magnitude of the oscillation period of transfer functions
K	Input : spatial curvature (in absolute value)
sgnK	Input : spatial curvature sign (open/closed/flat)

Returns

the error status

Summary:

- define local variables

define indices for transfer types

- type indices common to scalars and tensors
- type indices for scalars
- type indices for vectors
- type indices for tensors
- allocate arrays of (k, l) values and transfer functions

get q values using transfer_get_q_list()

get k values using transfer_get_k_list()

get l values using transfer_get_l_list()

- loop over modes (scalar, etc). For each mode:

allocate arrays of transfer functions, (ptr->transfer[index_md])[index_ic][index_tt][index_l][index_k]

3.21.2.5 int transfer_get_l_list (struct precision * *ppr*, struct perturbs * *ppt*, struct transfers * *ptr*)

This routine defines the number and values of multipoles l for all modes.

Parameters

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure
ptr	Input/Output : pointer to transfers structure containing l's

Returns

the error status

- start from l = 2 and increase with logarithmic step
- when the logarithmic step becomes larger than some linear step, stick to this linear step till l_max
- last value set to exactly l_max
- so far we just counted the number of values. Now repeat the whole thing but fill array with values.

3.21.2.6 int transfer_get_q_list (struct precision * *ppr*, struct perturbs * *ppt*, struct transfers * *ptr*, double *q_period*, double *K*, int *sgnK*)

This routine defines the number and values of wavenumbers q for each mode (goes smoothly from logarithmic step for small q's to linear step for large q's).

Parameters

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure
ptr	Input/Output : pointer to transfers structure containing q's
q_period	Input: order of magnitude of the oscillation period of transfer functions
K	Input : spatial curvature (in absolute value)
sgnK	Input : spatial curvature sign (open/closed/flat)

Returns

the error status

3.21.2.7 int transfer_get_k_list (struct perturbs * *ppt*, struct transfers * *ptr*, double *K*)

This routine infers from the q values a list of corresponding k values for each mode.

Parameters

ppt	Input : pointer to perturbation structure
ptr	Input/Output : pointer to transfers structure containing q's
K	Input : spatial curvature

Returns

the error status

If ptr->k[index_md][0] < ppt->k[index_md][0] at the level of rounding, adjust first value of k_list to avoid interpolation errors:

class_test(ptr->k[index_md][0] < ppt->k[index_md][0], ptr->error_message, "bug in k_list calculation: in perturbation module k_min=%e, in transfer module k_min[mode=%d]=%e, interpolation impossible", ppt->k[0][0], index_md, ptr->k[index_md][0]);

3.21.2.8 int transfer_get_source_correspondence (struct perturbs * *ppt*, struct transfers * *ptr*, int ** *tp_of_tt*)

This routine defines the correspondence between the sources in the perturbation and transfer module.

Parameters

ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure containing l's
tp_of_tt	: Input/Output: array with the correspondence (allocated before, filled here)

Returns

the error status

- which source are we considering? Define correspondence between transfer types and source types

3.21.2.9 int transfer_source_tau_size (struct precision * ppr, struct background * pba, struct perturbs * ppt, struct transfers * ptr, double tau_rec, double tau0, int index_md, int index_tt, int * tau_size)

the code makes a distinction between "perturbation sources" (e.g. gravitational potential) and "transfer sources" (e.g. total density fluctuations, obtained through the Poisson equation, and observed with a given selection function).

This routine computes the number of sampled time values for each type of transfer sources.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
tau_rec	Input : recombination time
tau0	Input : time today
index_md	Input : index of the mode (scalar, tensor)
index_tt	Input : index of transfer type
tau_size	Output: pointer to number of sampled times

Returns

the error status

3.21.2.10 int transfer_compute_for_each_q (struct precision * ppr, struct background * pba, struct perturbs * ppt, struct transfers * ptr, int ** tp_of_tt, int index_q, int tau_size_max, double tau_rec, double *** pert_sources, double *** pert_sources_spline, struct transfer_workspace * ptw)

Summary:

- define local variables
- for a given l, maximum value of k such that we can convolve the source with Bessel functions j_l(x) without reaching x_max

store the sources in the workspace and define all fields in this workspace

- loop over all modes. For each mode:
- loop over initial conditions. For each of them:
- loop over types. For each of them:

check if we must now deal with a new source with a new index ppt->index_type. If yes, interpolate it at the right values of k.

Select radial function type:

3.21.2.11 int transfer_interpolate_sources (struct perturbs * ppt, struct transfers * ptr, int index_q, int index_md, int index_ic, int index_type, double * pert_source, double * pert_source_spline, double * interpolated_sources)

This routine interpolates sources $S(k,\tau)$ for each mode, initial condition and type (of perturbation module), to get them at the right values of k, using the spline interpolation method.

Parameters

ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
index_q	Input : index of wavenumber
index_md	Input : index of mode
index_ic	Input : index of initial condition
index_type	Input : index of type of source (in perturbation module)
pert_source	Input : array of sources
pert_source_spline	Input : array of second derivative of sources
interpolated_sources	Output: array of interpolated sources (filled here but allocated in transfer_init() to avoid numerous reallocation)

Returns

the error status

Summary:

- define local variables
- interpolate at each k value using the usual spline interpolation algorithm.

3.21.2.12 int transfer_sources (struct precision * *ppr*, struct background * *pba*, struct perturbs * *ppt*, struct transfers * *ptr*, double * *interpolated_sources*, double *tau_rec*, int *index_q*, int *index_md*, int *index_tt*, double * *sources*, double * *tau0_minus_tau*, double * *w_trapz*, int * *tau_size_out*)

the code makes a distinction between "perturbation sources" (e.g. gravitational potential) and "transfer sources" (e.g. total density fluctuations, obtained through the Poisson equation, and observed with a given selection function).

This routine computes the transfer source given the interpolated perturbation source, and copies it in the workspace.

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
interpolated_sources	Input : interpolated perturbation source
tau_rec	Input : recombination time
index_q	Input : index of wavenumber
index_md	Input : index of mode
index_tt	Input : index of type of (transfer) source
sources	Output: transfer source
tau0_minus_tau	Output: values of (tau0-tau) at which source are sample
w_trapz	Output: trapezoidal weights for integration over tau
tau_size_out	Output: pointer to size of previous two arrays, converted to double

Returns

the error status

Summary:

- define local variables

3.21.2.13 int transfer_selection_function (struct precision * *ppr,* struct perturbs * *ppt,* struct transfers * *ptr,* int *bin,* double *z,* double * *selection*)

arbitrarily normalized selection function dN/dz(z,bin)

Parameters

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
bin	Input : redshift bin number
z	Input : one value of redshift
selection	Output: pointer to selection function

Returns

the error status

3.21.2.14 int transfer_dNdz_analytic (struct **transfers** * *ptr*, double *z*, double * *dNdz*, double * *dln_dNdz_dz*)

Analytic form for dNdz distribution, from arXiv:1004.4640

Parameters

ptr	Input: pointer to transfer structure
z	Input: redshift
dNdz	Output: density per redshift, dN/dZ
dln_dNdz_dz	Output: dln(dN/dz)/dz, used optionally for the source evolution

Returns

the error status

3.21.2.15 int transfer_selection_sampling (struct **precision** * *ppr*, struct **background** * *pba*, struct **perturbs** * *ppt*, struct **transfers** * *ptr*, int *bin*, double * *tau0_minus_tau*, int *tau_size*)

for sources that need to be multiplied by a selection function, redefine a finer time sampling in a small range

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
bin	Input : redshift bin number
tau0_minus_tau	Output: values of (tau0-tau) at which source are sample
tau_size	Output: pointer to size of previous array

Returns

the error status

3.21.2.16 int transfer_lensing_sampling (struct **precision** * *ppr*, struct **background** * *pba*, struct **perturbs** * *ppt*, struct **transfers** * *ptr*, int *bin*, double *tau0*, double * *tau0_minus_tau*, int *tau_size*)

for lensing sources that need to be convolved with a selection function, redefine the sampling within the range extending from the tau_min of the selection function up to tau0

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
bin	Input : redshift bin number
tau0	Input : time today
tau0_minus_tau	Output: values of (tau0-tau) at which source are sample
tau_size	Output: pointer to size of previous array

Returns

the error status

3.21.2.17 int transfer_source_resample (struct precision * *ppr*, struct background * *pba*, struct perturbs * *ppt*, struct transfers * *ptr*, int *bin*, double * *tau0_minus_tau*, int *tau_size*, int *index_md*, double *tau0*, double * *interpolated_sources*, double * *sources*)

for sources that need to be multiplied by a selection function, redefine a finer time sampling in a small range, and resample the perturbation sources at the new value by linear interpolation

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
bin	Input : redshift bin number
tau0_minus_tau	Output: values of (tau0-tau) at which source are sample
tau_size	Output: pointer to size of previous array
index_md	Input : index of mode
tau0	Input : time today
interpolated_sources	Input : interpolated perturbation source
sources	Output: resampled transfer source

Returns

the error status

3.21.2.18 int transfer_selection_times (struct precision * *ppr*, struct background * *pba*, struct perturbs * *ppt*, struct transfers * *ptr*, int *bin*, double * *tau_min*, double * *tau_mean*, double * *tau_max*)

for each selection function, compute the min, mean and max values of conformal time (associated to the min, mean and max values of redshift specified by the user)

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure

ptr	Input : pointer to transfers structure
bin	Input : redshift bin number
tau_min	Output: smallest time in the selection interval
tau_mean	Output: time corresponding to z_mean
tau_max	Output: largest time in the selection interval

Returns

the error status

3.21.2.19 int transfer_selection_compute (struct precision * *ppr*, struct background * *pba*, struct perturbs * *ppt*, struct transfers * *ptr*, double * *selection*, double * *tau0_minus_tau*, double * *w_trapz*, int *tau_size*, double * *pvecback*, double *tau0*, int *bin*)

compute and normalize selection function for a set of time values

Parameters

ppr	Input : pointer to precision structure
pba	Input : pointer to background structure
ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
selection	Output: normalized selection function
tau0_minus_tau	Input : values of (tau0-tau) at which source are sample
w_trapz	Input : trapezoidal weights for integration over tau
tau_size	Input : size of previous two arrays
pvecback	Input : allocated array of background values
tau0	Input : time today
bin	Input : redshift bin number

Returns

the error status

3.21.2.20 int transfer_compute_for_each_l (struct transfer_workspace * *ptw*, struct precision * *ppr*, struct perturbs * *ppt*, struct transfers * *ptr*, int *index_q*, int *index_md*, int *index_ic*, int *index_tt*, int *index_l*, double *l*, double *q_max_bessel*, radial_function_type *radial_type*)

This routine computes the transfer functions $\Delta_l^X(k))$ as a function of wavenumber k for a given mode, initial condition, type and multipole l passed in input.

For a given value of k, the transfer function is inferred from the source function (passed in input in the array interpolated_sources) and from Bessel functions (passed in input in the bessels structure), either by convolving them along tau, or by a Limber approximation. This elementary task is distributed either to transfer_integrate() or to transfer_limber(). The task of this routine is mainly to loop over k values, and to decide at which k_max the calculation can be stopped, according to some approximation scheme designed to find a compromise between execution time and precision. The approximation scheme is defined by parameters in the precision structure.

Parameters

ptw	Input : pointer to transfer_workspace structure (allocated in transfer_init() to avoid numerous reallocation)

ppr	Input : pointer to precision structure
ppt	Input : pointer to perturbation structure
ptr	Input/output : pointer to transfers structure (result stored there)
index_q	Input : index of wavenumber
index_md	Input : index of mode
index_ic	Input : index of initial condition
index_tt	Input : index of type of transfer
index_l	Input : index of multipole
l	Input : multipole
q_max_bessel	Input : maximum value of argument q at which Bessel functions are computed
radial_type	Input : type of radial (Bessel) functions to convolve with

Returns

the error status

Summary:

- define local variables

3.21.2.21 int transfer_integrate (struct perturbs * *ppt*, struct transfers * *ptr*, struct transfer_workspace * *ptw*, int *index_q*, int *index_md*, int *index_tt*, double *l*, int *index_l*, double *k*, radial_function_type *radial_type*, double * *trsf*)

This routine computes the transfer functions $\Delta_l^X(k)$) for each mode, initial condition, type, multipole l and wavenumber k, by convolving the source function (passed in input in the array interpolated_sources) with Bessel functions (passed in input in the bessels structure).

Parameters

ppt	Input : pointer to perturbation structure
ptr	Input : pointer to transfers structure
ptw	Input : pointer to transfer_workspace structure (allocated in transfer_init() to avoid numerous reallocation)
index_q	Input : index of wavenumber
index_md	Input : index of mode
index_tt	Input : index of type
l	Input : multipole
index_l	Input : index of multipole
k	Input : wavenumber
radial_type	Input : type of radial (Bessel) functions to convolve with
trsf	Output: transfer function $\Delta_l(k)$

Returns

the error status

Summary:

- define local variables
- find minimum value of (tau0-tau) at which $j_l(k[\tau_0 - \tau])$ is known, given that $j_l(x)$ is sampled above some finite value $x_{\rm min}$ (below which it can be approximated by zero)
- if there is no overlap between the region in which bessels and sources are non-zero, return zero
- if there is an overlap:

-> trivial case: the source is a Dirac function and is sampled in only one point

-> other cases

(a) find index in the source's tau list corresponding to the last point in the overlapping region. After this step, index_tau_max can be as small as zero, but not negative.

(b) the source function can vanish at large τ. Check if further points can be eliminated. After this step and if we did not return a null transfer function, index_tau_max can be as small as zero, but not negative.

Compute the radial function:

Now we do most of the convolution integral:

This integral is correct for the case where no truncation has occurred. If it has been truncated at some index_tau↩_max because f[index_tau_max+1]==0, it is still correct. The 'mistake' in using the wrong weight w_trapz[index↩_tau_max] is exactly compensated by the triangle we miss. However, for the Bessel cut off, we must subtract the wrong triangle and add the correct triangle

3.21.2.22 int transfer_limber (struct transfers * *ptr,* struct transfer_workspace * *ptw,* int *index_md,* int *index_q,* double *l,* double *q,* radial_function_type *radial_type,* double * *trsf*)

This routine computes the transfer functions $\Delta_l^X(k))$ for each mode, initial condition, type, multipole l and wavenumber k, by using the Limber approximation, i.e by evaluating the source function (passed in input in the array interpolated_sources) at a single value of tau (the Bessel function being approximated as a Dirac distribution)

Parameters

ptr	Input : pointer to transfers structure
ptw	Input : pointer to transfer workspace structure
index_md	Input : index of mode
index_q	Input : index of wavenumber
l	Input : multipole
q	Input : wavenumber
radial_type	Input : type of radial (Bessel) functions to convolve with
trsf	Output: transfer function $\Delta_l(k)$

Returns

the error status

Summary:

- define local variables
- get k, l and infer tau such that k(tau0-tau)=l+1/2; check that tau is in appropriate range
- get transfer = source * sqrt(pi/(2l+1))/q = source*[tau0-tau] * sqrt(pi/(2l+1))/(l+1/2)

3.21.2.23 int transfer_limber_interpolate (struct transfers * *ptr,* double * *tau0_minus_tau,* double * *sources,* int *tau_size,* double *tau0_minus_tau_limber,* double * *S*)

- find bracketing indices. index_tau must be at least 1 (so that index_tau-1 is at least 0) and at most tau_size-2 (so that index_tau+1 is at most tau_size-1).
- interpolate by fitting a polynomial of order two; get source and its first two derivatives. Note that we are not interpolating S, but the product S*(tau0-tau). Indeed this product is regular in tau=tau0, while S alone diverges for lensing.

3.21.2.24 int transfer_limber2 (int *tau_size,* struct **transfers** * *ptr,* int *index_md,* int *index_k,* double *l,* double *k,* double * *tau0_minus_tau,* double * *sources,* **radial_function_type** *radial_type,* double * *trsf*)

This routine computes the transfer functions $\Delta_l^X(k)$) for each mode, initial condition, type, multipole l and wavenumber k, by using the Limber approximation at order two, i.e as a function of the source function and its first two derivatives at a single value of tau

Parameters

tau_size	Input : size of conformal time array
ptr	Input : pointer to transfers structure
index_md	Input : index of mode
index_k	Input : index of wavenumber
l	Input : multipole
k	Input : wavenumber
tau0_minus_tau	Input : array of values of (tau_today - tau)
sources	Input : source functions
radial_type	Input : type of radial (Bessel) functions to convolve with
trsf	Output: transfer function $\Delta_l(k)$

Returns

the error status

Summary:

- define local variables
- get k, l and infer tau such that k(tau0-tau)=l+1/2; check that tau is in appropriate range
- find bracketing indices
- interpolate by fitting a polynomial of order two; get source and its first two derivatives
- get transfer from 2nd order Limber approx (inferred from 0809.5112 [astro-ph])

3.21.2.25 int transfer_update_HIS (struct **precision** * *ppr,* struct **transfers** * *ptr,* struct **transfer_workspace** * *ptw,* int *index_q,* double *tau0*)

First try to find lmax using fast approximation:

Now use WKB approximation to eventually modify borders:

3.21.2.26 int transfer_get_lmax (int(*)(int sgnK, int l, double nu, double xtol, double phiminabs, double *x_nonzero, int *fevals) *get_xmin_generic,* int *sgnK,* double *nu,* int * *lvec,* int *lsize,* double *phiminabs,* double *xmax,* double *xtol,* int * *index_l_left,* int * *index_l_right,* ErrorMsg *error_message*)

Hunt for left boundary:

If not found, hunt for right boundary:

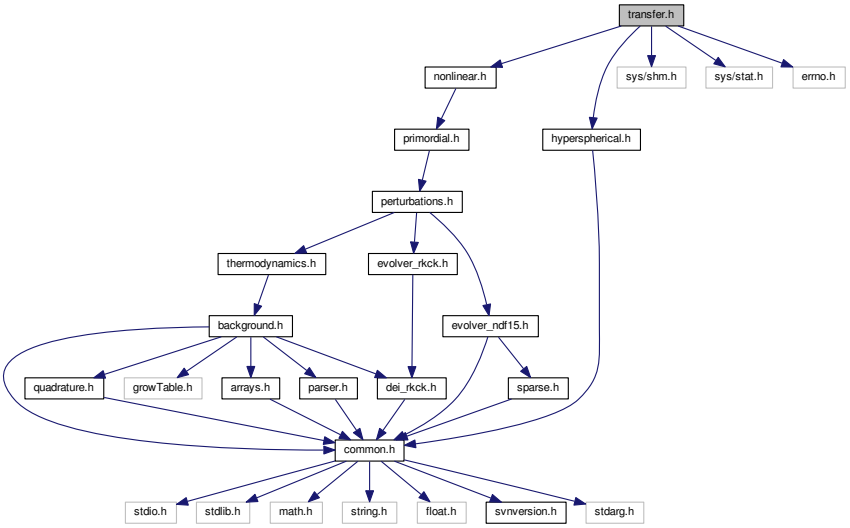
printf("Hunt left iter=%d, hunt right iter=%d (fevals: %d). For binary search: %d (fevals: %d)\n", hil,hir,fevalshunt,bini,fevals);

3.22 transfer.h File Reference

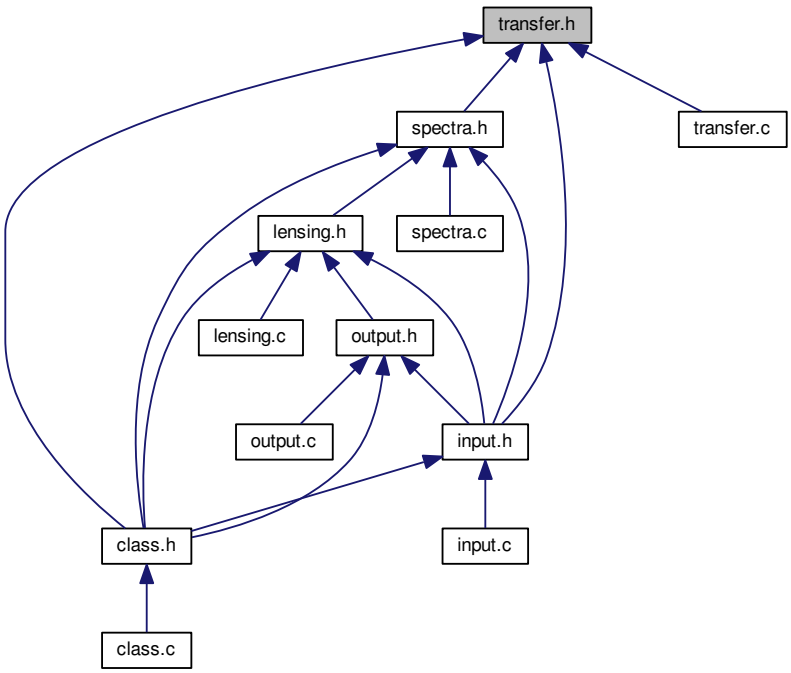
```
#include "nonlinear.h"
```

```
#include "hyperspherical.h"
#include <sys/shm.h>
#include <sys/stat.h>
#include "errno.h"
```

Include dependency graph for transfer.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct transfers
- struct transfer_workspace

Enumerations

- enum radial_function_type

3.22.1 Detailed Description

Documented includes for transfer module.

3.22.2 Data Structure Documentation

3.22.2.1 struct transfers

Structure containing everything about transfer functions in harmonic space $\Delta_l^X(q)$ that other modules need to know.

Once initialized by transfer_init(), contains all tables of transfer functions used for interpolation in other modules, for all requested modes (scalar/vector/tensor), initial conditions, types (temperature, polarization, etc), multipoles l, and wavenumbers q.

Wavenumbers are called q in this module and k in the perturbation module. In flat universes k=q. In non-flat universes q and k differ through q2 = k2 + K(1+m), where m=0,1,2 for scalar, vector, tensor. q should be used throughout the transfer module, except when interpolating or manipulating the source functions S(k,tau) calculated in the perturbation module: for a given value of q, this should be done at the corresponding k(q).

The content of this structure is entirely computed in this module, given the content of the 'precision', 'bessels', 'background', 'thermodynamics' and 'perturbation' structures.

Data Fields

double	lcmb_rescale	normally set to one, can be used exceptionally to rescale by hand the CMB lensing potential
double	lcmb_tilt	normally set to zero, can be used exceptionally to tilt by hand the CMB lensing potential
double	lcmb_pivot	if lcmb_tilt non-zero, corresponding pivot scale
double	selection_bias[_SELECTION_NUM_MAX_]	light-to-mass bias in the transfer function of density number count
double	selection_magnification_bias[_SELECTION_NUM_MAX_]	magnification bias in the transfer function of density number count
short	has_nz_file	Has dN/dz (selection function) input file?
short	has_nz_analytic	Use analytic form for dN/dz (selection function) distribution?
FileName	nz_file_name	dN/dz (selection function) input file name
int	nz_size	$$$ definition missing $$$
double *	nz_z	$$$ definition missing $$$

double *	nz_nz	$$$ definition missing $$$
double *	nz_ddnz	$$$ definition missing $$$
short	has_nz_evo_file	Has dN/dz (evolution function) input file?
short	has_nz_evo_↩ analytic	Use analytic form for dN/dz (evolution function) distribution?
FileName	nz_evo_file_↩ name	dN/dz (evolution function) input file name
int	nz_evo_size	$$$ definition missing $$$
double *	nz_evo_z	$$$ definition missing $$$
double *	nz_evo_nz	$$$ definition missing $$$
double *	nz_evo_dlog_nz	$$$ definition missing $$$
double *	nz_evo_dd_↩ dlog_nz	$$$ definition missing $$$
short	has_cls	copy of same flag in perturbation structure
int	md_size	number of modes included in computation
int	index_tt_t0	index for transfer type = temperature (j=0 term)
int	index_tt_t1	index for transfer type = temperature (j=1 term)
int	index_tt_t2	index for transfer type = temperature (j=2 term)
int	index_tt_e	index for transfer type = E-polarization
int	index_tt_b	index for transfer type = B-polarization
int	index_tt_lcmb	index for transfer type = CMB lensing
int	index_tt_density	index for first bin of transfer type = matter density
int	index_tt_lensing	index for first bin of transfer type = galaxy lensing
int	index_tt_rsd	index for first bin of transfer type = redshift space distortion of number count
int	index_tt_d0	index for first bin of transfer type = doppler effect for of number count (j=0 term)
int	index_tt_d1	index for first bin of transfer type = doppler effect for of number count (j=1 term)
int	index_tt_nc_lens	index for first bin of transfer type = lensing for of number count
int	index_tt_nc_g1	index for first bin of transfer type = gravity term G1 for of number count
int	index_tt_nc_g2	index for first bin of transfer type = gravity term G2 for of number count
int	index_tt_nc_g3	index for first bin of transfer type = gravity term G3 for of number count
int	index_tt_nc_g4	index for first bin of transfer type = gravity term G3 for of number count
int	index_tt_nc_g5	index for first bin of transfer type = gravity term G3 for of number count
int *	tt_size	number of requested transfer types tt_size[index_md] for each mode
int **	l_size_tt	number of multipole values for which we effectively compute the transfer function,l_size_tt[index_md][index_tt]
int *	l_size	number of multipole values for each requested mode, l_size[index_md]
int	l_size_max	greatest of all l_size[index_md]
int *	l	list of multipole values l[index_l]
double	angular_↩ rescaling	correction between l and k space due to curvature (= comoving angular diameter distance to recombination / comoving radius to recombination)
size_t	q_size	number of wavenumber values
double *	q	list of wavenumber values, q[index_q]
double **	k	list of wavenumber values for each requested mode, k[index_md][index↩ _q]. In flat universes k=q. In non-flat universes q and k differ through q2 = k2 + K(1+m), where m=0,1,2 for scalar, vector, tensor. q should be used throughout the transfer module, excepted when interpolating or manipulating the source functions S(k,tau): for a given value of q this should be done in k(q).

int	index_q_flat_approximation	index of the first q value using the flat rescaling approximation
double **	transfer	table of transfer functions for each mode, initial condition, type, multipole and wavenumber, with argument transfer[index_md][((index_ic * ptr->tt_size[index_md] + index_tt) * ptr->l_size[index_md] + index_l) * ptr->q_size + index_q]
short	initialise_HIS_cache	only true if we are using CLASS for setting up a cache of HIS structures
short	transfer_verbose	flag regulating the amount of information sent to standard output (none if set to zero)
ErrorMsg	error_message	zone for writing error messages

3.22.2.2 struct transfer_workspace

Structure containing all the quantities that each thread needs to know for computing transfer functions (but that can be forgotten once the transfer functions are known, otherwise they would be stored in the transfer module)

Data Fields

HyperInterpStruct	HIS	structure containing all hyperspherical bessel functions (flat case) or all hyperspherical bessel functions for a given value of beta=q/sqrt(|K|) (non-flat case). HIS = Hyperspherical Interpolation Structure.
int	HIS_allocated	flag specifying whether the previous structure has been allocated
HyperInterpStruct *	pBIS	$$$ definition missing $$$
int	l_size	number of l values
int	tau_size	number of discrete time values for a given type
int	tau_size_max	maximum number of discrete time values for all types
double *	interpolated_sources	interpolated_sources[index_tau] : sources interpolated from the perturbation module at the right value of k
double *	sources	sources[index_tau] : sources used in transfer module, possibly differing from those in the perturbation module by some resampling or rescaling
double *	tau0_minus_tau	tau0_minus_tau[index_tau] : values of (tau0 - tau)
double *	w_trapz	w_trapz[index_tau] : values of weights in trapezoidal integration (related to time steps)
double *	chi	chi[index_tau] : value of argument of bessel function: k(tau0-tau) (flat case) or sqrt(|K|)(tau0-tau) (non-flat case)
double *	cscKgen	cscKgen[index_tau] : useful trigonometric function
double *	cotKgen	cotKgen[index_tau] : useful trigonometric function
double	K	curvature parameter (see background module for details)
int	sgnK	0 (flat), 1 (positive curvature, spherical, closed), -1 (negative curvature, hyperbolic, open)
double	tau0_minus_tau_cut	$$$ definition missing $$$
short	neglect_late_source	$$$ definition missing $$$

3.22.3 Enumeration Type Documentation

3.22.3.1 enum radial_function_type

enumeration of possible source types. This looks redundant with respect to the definition of indices index_tt_... This definition is however convenient and time-saving: it allows to use a "case" statement in transfer_radial_function()

Chapter 4

The ‘external_Pk‘ mode

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- Date: 2013-12-20

Introduction

This mode allows for an arbitrary primordial spectrum `P(k)` to be calculated by an external command and passed to CLASS. That external command may be anything that can be run in the shell: a python script, some compiled C or Fortran code... This command is executed from within CLASS, and CLASS is able to pass it a number of parameters defining the spectrum (an amplitude, a tilt...). Those parameters can be used in a Markov chain search performed by MontePython.

This mode includes the simple case of a precomputed primordial spectrum stored in a text file. In that case, the `cat` shell command will do the trick (see below).

Currently, scalar and tensor spectra of perturbations of adiabatic modes are supported.

Use case #1: reading the spectrum from a table

In this case, say the file with the table is called `spectrum.txt`, located under `/path/to`, simply include in the `.ini` file

```
command = cat path/to/spectrum.txt
```

It is necessary that 1st 4 characters are exactly `cat`.

Use case #2: getting the spectrum from an external command

Here an external command is called to generate the spectrum; it may be some compiled C or Fortran code, a python script... This command may be passed up to 10 floating point arguments, named `custom1` to `custom10`, wich are assigned values inside the `.ini` file of CLASS. The `command` parameter would look like

```
command = /path/to/example.py
```

if it starts with `#/usr/bin/python`, otherwise

```
command = python /path/to/example.py
```

As an example of the 1st use case, one may use the included script `generate_Pk_example.py`, which implements a single-field slow-roll spectrum without running, and takes 3 arguments:

- `custom1` – the pivot scale (`k_0 = 0.05 1/Mpc` for Planck).

- `custom2` – the amplitude of the scalar power spectrum.
- `custom3` – the scalar spectral index.

In order to use it, the following lines must be present in the parameter file:

```
P_k_ini type = external_Pk
command = /path/to/CLASS/external_Pk/generate_Pk_example.py
custom1 = 0.05
custom2 = 2.2e-9
custom3 = 1.
```

Defined or not (in that case, 0-valued), parameters from `custom4` to `custom10` will be passed to the example script, which should ignore them. In this case, CLASS will run in the shell the command

```
/path/to/CLASS/external_Pk/generate_Pk_example.py 0.05 2.2e-9 1. 0 0 0 0 0 0 0
```

If CLASS fails to run the command, try to do it directly yourself by hand, using exactly the same string that was given in `command`.

Output of the command / format of the table

The command must generate an output separated into lines, each containing a tuple (`k`, `P(k)`). The following requirements must be fulfilled:

- Each line must contain 2 (3, if tensors) floating points numbers: `k` (in `1/Mpc` units) and `P_s(k)` (and `P_t(k)`, if tensors), separated by any number of spaces or tabs. The numbers can be in scientific notation, e.g. `1.4e-3`.
- The lines must be sorted in increasing values of `k`.
- There must be at least two points `(k, P(k))` before and after the interval of `k` requested by CLASS, in order not to introduce unnecessary interpolation error. Otherwise, and error will be raised. In most of the cases, generating the spectrum between `1e-6` and `1 1/Mpc` should be more than enough.

Precision

This implementation properly handles double-precision floating point numbers (i.e. about 17 significant figures), both for the input parameters of the command and for the output of the command (or the table).

The sampling of `k` given by the command (or table) is preserved to be used internally by CLASS. It must be fine enough a sampling to clearly show the features of the spectrum. The best way to test this is to plot the output/table and check it with the naked eye.

Another thing to have in mind arises at the time of convolving with the transfer funcions. Two precision parameters are implied: the sampling of `k` in the integral, given by `k_step_trans`, and the sampling of the transfer functions in `l`, given by `l_logstep` and `l_linstep`. In general, it will be enough to reduce the values of the first and the third parameters. A good start is to give them rather small values, say `k_step_trans=0.01` and `l_linstep=1`, and to increase them slowly until the point at which the effect of increasing them gets noticeable.

Parameter fit with MontePython

(MontePython)[http://montepython.net/] is able to interact with the `external_Pk` mode transparently, using the `custom` parameters in an MCMC fit. One must just add the appropriate lines to the input file of MontePython. For our example, if we wanted to fit the amplitude and spectral index of the primordial spectrum, it would be:

```
data.cosmo_arguments['P_k_ini type'] = 'external_Pk'
data.cosmo_arguments['command'] = '/path/to/CLASS/external_Pk/generate_Pk_example.py'
data.cosmo_arguments['custom1'] = 0.05                                  # k_pivot
data.parameters['custom2']      = [ 2.2,  0, -1,  0.055, 1.e-9, 'cosmo'] # A_s
data.parameters['custom3']      = [  1.,  0, -1, 0.0074,     1, 'cosmo'] # n_s
```

Notice that since in our case `custom1` represents the pivot scale, it is passed as a (non-varying) argument, instead of as a (varying) parameter.

In this case, one would not include the corresponding lines for the primordial parameters of CLASS: `k_pivot`, `A_s`, `n_s`, `alpha_s`, etc. They would simply be ignored.

Limitations

- So far, this mode cannot handle vectors perturbations, neither isocurvature initial conditions.
- The external script knows nothing about the rest of the CLASS parameters, so if it needs, e.g., `k_pivot`, it should be either hard coded, or its value passed as one of the `custom` parameters.

Chapter 5

Updating the manual

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This pdf manual and accompanying web version have been generated using the doxygen software (http://www.doxygen.org). This software directly reads the code and extracts the necessary comments to form the manual, meaning it is very easy to generate newer versions of the manual as desired.

To keep the manual up-to-date, a new version should be generated after any major upgrade to CLASS. To keep track of how updated the manual is, the title page also displays the last modification date.

To generate a new version of this manual, one should install the doxygen software. Once installed, doxygen uses a specific configuration file to know how to read the code. The configuration file for this project can be found in /class/doc/input/doxyconf. To run doxygen, navigate in terminal to the above-mentioned folder containing the configuration file and type

```
doxygen doxyconf
```

This will generate a new version of the html manual and the necessary files to make the pdf version. Note that any changes in the doxyconf file can dramatically impact the outcome, so the configuration file should only be modified with great care.

Currently doxygen does not offer the option to order the output chapters in the pdf version of the manual. Hence, before compiling the pdf one must check that the manual is ordered correctly. To do this, navigate to /class/doc/output/latex. From here, the refman.tex file can be easily modified to obtain the desired order. Once the 'refman.tex file is correct, the pdf can be created in the same directory by typing

```
make
```

in the terminal. This will result in the generation of the pdf manual. It is often useful to run make twice consecutively, to insure all the references and links have been generated correctly. The updated version of the manual should now be ready. For convenience, one can copy the final pdf to /class/doc/output.

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