Lecture II: The Background

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Homogeneous cosmology

- treated by the module `background.c`. So this lecture will refer mainly to the content of `input/background.h`, `source/background.c`, and to the structure referred as `ba`:

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with fields `ba.blabla`, or through the pointer `pba`:

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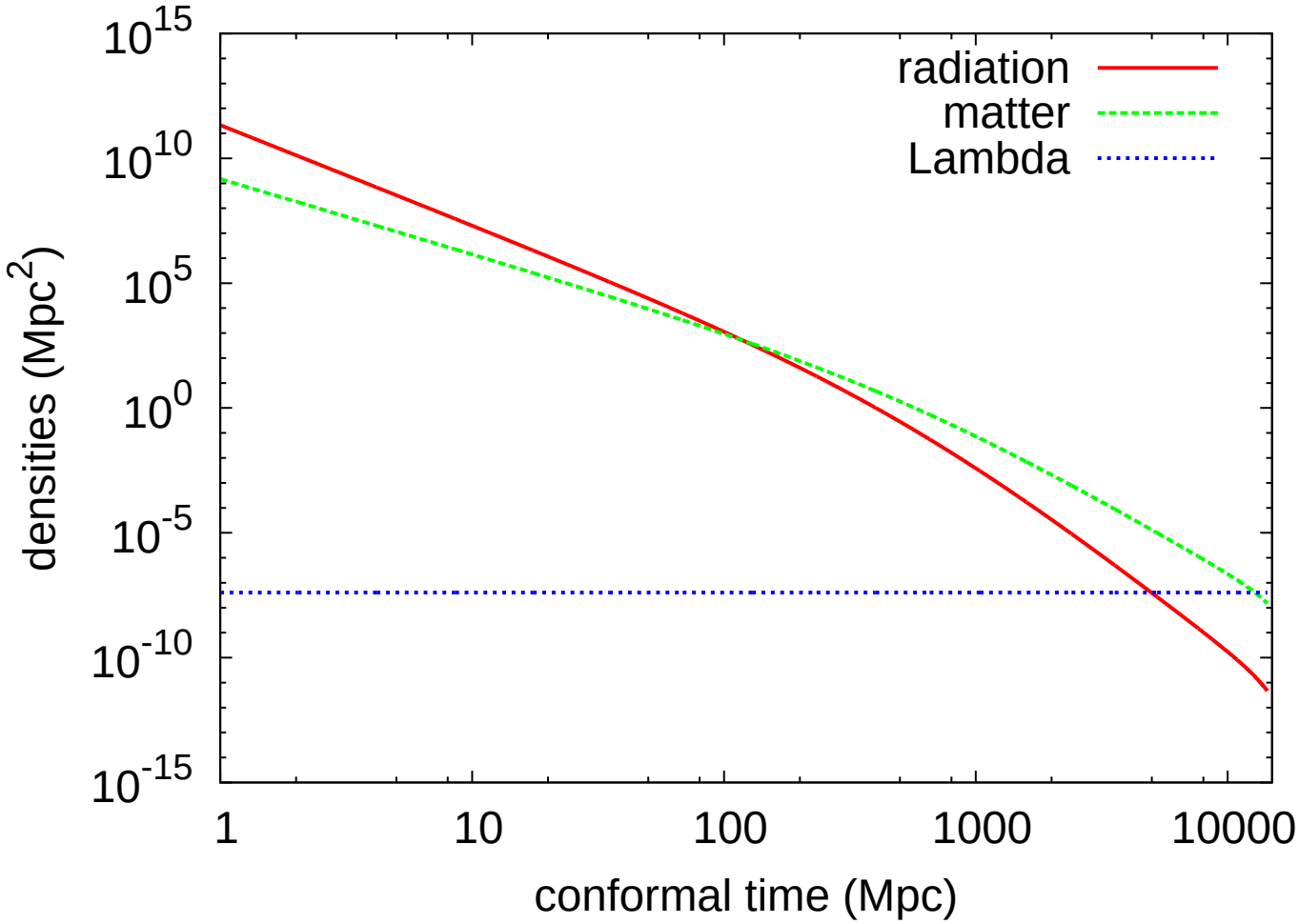
- the goal of this module is to solve the background evolution and store the results in a table. It should provide a function able to interpolate within this table at any value of time.
- other modules should be able to know all background quantities (densities, pressures, Hubble rate, angular/luminosity distances, etc.) at any given time or redshift.

Homogeneous cosmology

- at the end of this lecture, we also see who to plot the background evolution.



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So the Friedmann equation reads

$$H = \left(\sum_i \rho_i - \frac{K}{a^2}\right)^{1/2}$$

with the curvature K also in Mpc^{-2}.

The function background_functions()

Most quantities can be immediately inferred from a given value of a without integrating any differential equations:

- $\rho_i = \Omega_i^0 H_0^2 \left(\frac{a}{a_0}\right)^{-3(1+w_i)}$
- $p_i = w_i \rho_i$
- $H = \left(\sum_i \rho_i - \frac{K}{a^2}\right)^{1/2}$
- $H' = \left(-\frac{3}{2}\sum_i (\rho_i + p_i) + \frac{K}{a^2}\right) a$
- $\rho_{\rm crit} = H^2$
- $\Omega_i = \rho_i / \rho_{\rm crit}$

These quantities are all returned by a function `background_functions(pba,a,...)`

What shall we integrate?

But to get them as a function of time we need to integrate one differential equation:

$$a' = a^2 H$$

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- comoving sound horizon: $r_s' = c_s$, since $r_s = \int_{\tau_{\rm ini}}^{\tau_0} c_s d\tau$, with a squared sound speed in the photon+baryon+electron fluid

$$c_s^2 = \frac{\delta p_\gamma}{\delta \rho_\gamma + \delta \rho_b} = \frac{1}{3(1 + [3\rho_b/4\rho_\gamma])}.$$

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- linear growth factor of density perturbations in minimal ΛCDM model (filled with dust), $D' = 1/(aH^2)$ (such that $\delta_m \propto D$).

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Exemple of extended cosmology with quintessence ϕ (see Thomas's lecture):

- $\{A\} = \{\rho_i, p_i, H, ..., V_\phi, \rho_\phi, p_\phi\}$
- $\{B\} = \{a, \phi, \phi'\}$

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Exemple of decaying dark matter with non-trivial differential equation giving $\rho_{dm}(t)$:

- $\{A\} = \{\rho_i, p_i, H, ...\}$
- $\{B\} = \{a, \rho_{dm}\}$

How can we classify background variables?

Reflected by arguments of

```
background_functions(pba, pvecback_B, format,  pvecback)
```

Input background parameters

In the `*.ini` file, the user may pass:

- Hubble: `h` or `H0`
- Photons: `T_cmb` or `Omega_g` or `omega_g`
- Ultra-relativvistic relics: `N_ur` or `Omega_ur` or `omega_ur`
- CDM: `Omega_cdm` or `omega_cdm`
- Non-cold DM: `ncdm` : lots of possible input, see dedicated lectures
- Decaying CDM plus its relat. decay product: `Omega_dcdmdr` or `omega_dcdmdr`
- Curvature: `Omega_k`
- Cosmological constant: `Omega_Lambda`
- Fluid: `Omega_fld, w0_fld, wa_fld, cs2_fld` (assuming CLP: $w = w_0 + w_a(1 - a/a_0)$ and $\delta p = c_s^2 \delta\rho$)

Input background parameters

Just one convention to remember !!!!

One of `Omega_Lambda` or `Omega_fld` must be left unspecified, to let the code match with H_0:

$$H_0^2 = \sum_i \rho_i^0 - K/a_0^2$$

If the two are passed, there is an error message.

All details on the syntax and on these rules are explicitly written in the comments of `explanatory.ini`

Remark on the component called "fluid"

Remark on the fluid:

- $\rho_i = \Omega_i^0 H_0^2 \left(\frac{a}{a_0}\right)^{-3(1+w_i)}$ is only valid when $w_i = \text{constant}$.
- for $w = w_0 + w_a(1 - a/a_0)$, an analytic integration of the energy conservation equation gives

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Finally there is a parameter `background_verbose=...` (one verbose parameter for each module). 0 gives no output at all, 1 the standard output that you see by default, etc.

External function in the background module

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- `background_at_tau(pba, tau,...)` interpolates inside this table and returns $\{A(\tau)\}$, $\{B(\tau)\}$, $\{C(\tau)\}$.
- `background_tau_of_z(pba, z, &tau)` returns $\tau(z)$, can be useful just before calling `background_at_tau(pba, tau,...)`

Internal function in the background module

- `background_indices(...)` allocates dynamically all indices (see next slides)
- `background_functions(pba, pvecback_B,...)` gets $\{B\}$ and returns $\{A\}$.
- `background_solve(...)` integrates the differential system for $\{B\}$, $\{C\}$ variables
- `background_initial_conditions(...)` assigns initial conditions $\{B_{\rm ini}\}$, $\{C_{\rm ini}\}$ to this system, e.g. $a(\tau_{\rm ini})$ assuming pure radiation domination since Big Bang
- `background_derivs(z,...)` contains the differential eqns. `dy[i] = f(y[j])`

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These functions call auxiliary functions in `tools/`:

- for array interpolation, `tools/array.c` (contains functions with all operations on arrays: interpolation, extrapolation, integration, derivation, smoothing, ...)
- for the integration of Ordinary Differential Equations, `generic_integrator()`, which can be set either to `rkck` or `ndf15` (see dedicated lecture). We will find this feature anytime we need to integrate ODE (also in `thermodynamics` and in `perturbations`).

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- Then we declare all possible indices `index_bg_<blabla>` in `common/background.h` (more precisely, inside the structure background, because these indices are necessary for manipulating the background table).

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- Then we declare all possible indices `index_bg_<blabla>` in `common/background.h` (more precisely, inside the structure background, because these indices are necessary for manipulating the background table).
- We also declare flags saying whether these indices need to be defined or not.

Dynamical indexing

In include/background.h:

```
struct background {
    /** input parameters with assigned in the input module*
        */
    double Omega0_cdm;
    ...
    /** flags and indices **/
    int has_cdm;     // can take values _TRUE_ or _FALSE_
    ....

    int index_bg_rho_cdm;
    ...

    int bg_size;

    /** interpolation table **/
    double * background_table;
}
```

Dynamical indexing

In source/background.c, the function background_indices() called at the beginning of background_init() assigns numerical value to indices, that the user will never need to know (quantities always written symbolically as y[pba->index_bg_rho_cdm])

```
int background_indices(pba,...) {
    /* initialize all flags */
    if (pba->Omega0_cdm != 0.)
       pba->has_cdm = _TRUE_;
    ...
    /* initialize all indices */
    index_bg=0;
    class_define_index(pba->index_bg_rho_cdm,
                       pba->has_cdm,
                       index_bg,
                       1);
    class_define_index(pba->index_bg_rho_fld,
                       pba->has_fld,
                       index_bg,
                       1);
    ...
    pba->bg_size = index_bg;
}
```

Getting background quantities from outside

Calling background quantitites from another module is then very simple: e.g., in the perturbation module:

```
double * pvecback;
class_alloc(pvecback,
            pba->bg_size*sizeof(double),
            ppt->error_message);
...
class_call(background_at_tau(pba,tau,...,...,...,pvecback),
                             pba->error_message,
                             ppt->error_message);

/* We want here to compute the total background density*/
if (pba->has_cdm == _TRUE_) {
   rho_tot += pvecback[pba->index_bg_rho_cdm];
}
if (pba->has_fld == _TRUE_) {
   rho_tot += pvecback[pba->index_bg_rho_fld];
   p_tot += pvecback[pba->index_bg_p_fld];
}
...
```

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if (pba->has_cdm == _TRUE_) {
   rho_tot += pvecback[pba->index_bg_rho_cdm];
}
if (pba->has_fld == _TRUE_) {
   rho_tot += pvecback[pba->index_bg_rho_fld];
   p_tot += pvecback[pba->index_bg_p_fld];
}
...
```

5th argument can be: `pba->long_info`, `pba->normal_info` or `pba->short_info`

Full list of coded background quantities

Currently, the list of all available background quantities is:

short_info	index_bg_a	a
"	index_bg_H	H
"	index_bg_H_prime	H'
normal_info	index_bg_rho_<i>	ρ for _b, _g,_cdm,_ur,_fld,_lambda
"	variables for ncdm	see dedicated lecture
"	index_bg_Omega_r	$\Omega_{\rm radiation}$
long_info	index_bg_rho_crit	$\rho_{\rm crit}$
"	index_bg_Omega_m	$\Omega_{\rm matter}$
"	index_bg_conf_distance	$\tau_0 - \tau = \chi$
"	index_bg_ang_distance	$d_A = a\,r$
"	index_bg_lum_distance	$d_L = (1+z)^2 d_A$
"	index_bg_time	proper time t
"	index_bg_rs	conformal sound horizon r_s
"	index_bg_D	density growth factor of ΛCDM
"	index_bg_f	velocity growth factor of ΛCDM

(with $r = \chi$, or $\sin(\sqrt{K}\chi)/\sqrt{K}$, or $\sinh(\sqrt{-K}\chi)/\sqrt{-K}$)

To conclude on dynamical indexing in CLASS

These rules for flags and indices are followed everywhere in the code, with maybe 50 different lists of indices `index_ab_blabla`. In the background module, two such lists:

- for all variables in the table ($\{A\}$, $\{B\}$, $\{C\}$),

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int index_bg_a;
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int index_bg_a;
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  declared in `include/background.h` inside the background structure, to be used in other modules.

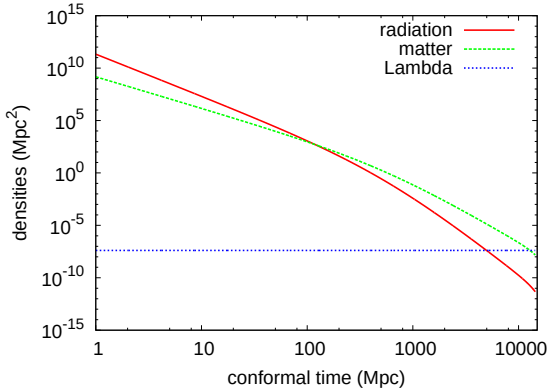
- for the ODE `dy[i] = f(y[j])`, i.e. for variables $\{B\}$, $\{C\}$,

```
int index_bi_a;
int index_bi_time;
int index_bi_rs;
int index_bi_growth;
int bi_size;
```

  declared in `include/background.h` outside the background structure, and erased/forgotten after the execution of `background_init()`.

Printing the background evolution

Two ways to produce such a plot with the quantitates of your choice (maybe customised to your own model):



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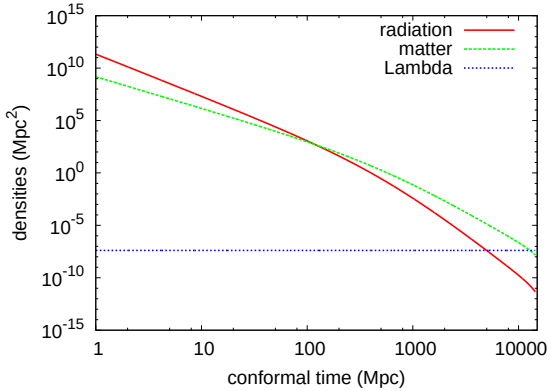

1. easiest: execute e.g. `./class myinput.ini` including in the input file:

```
write background = yes
root = output/toto_
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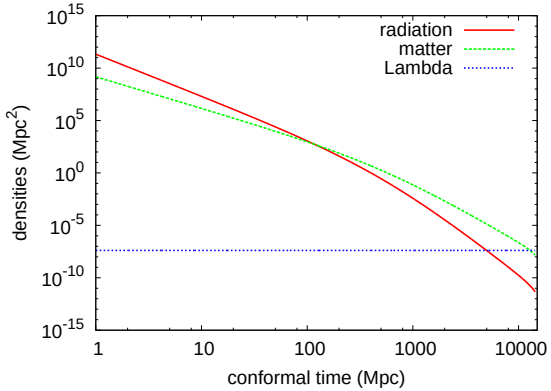

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The output module will also write a file `output/toto_background.dat` with header:

```
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# z, proper time [Gyr], conformal time * c [Mpc], H/c [1/Mpc] (etc.)
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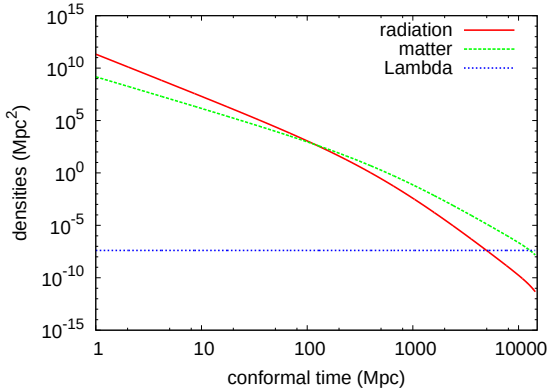

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(etc.)

Output easy to customise in `output.c`, by editing:
`output_one_line_of_background(...)` for the quantities to plot in each line
`output_open_background_file(...)` for the header (description of columns)

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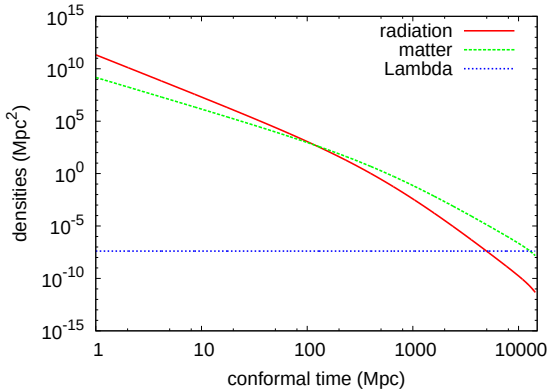

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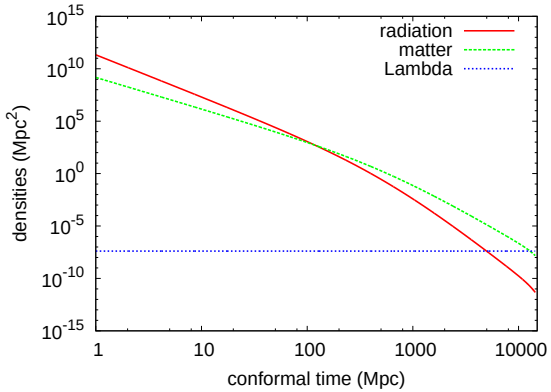


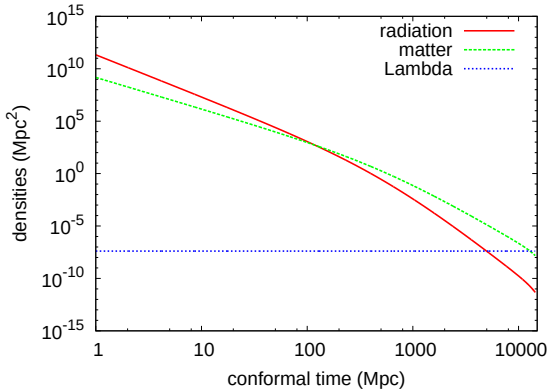
2. good to know: directory `test/` contains several test codes executing only part of the `main(...)` function.

For instance: `test/test_background.c` only executes `input_init(...)`, `background_init(...)`, and then outputs a table of all background quantities. Useful also for quick debugging!
Usage:

```
> make test_background
> ./test_background myinput.ini
```

Printing the background evolution

Two ways to produce such a plot with the quantitates of your choice (maybe customised to your own model):



2. good to know: directory `test/` contains several test codes executing only part of the `main(...)` function.

For instance: `test/test_background.c` only executes `input_init(...)`, `background_init(...)`, and then outputs a table of all background quantities. Useful also for quick debugging!
Usage:

```
> make test_background
> ./test_background myinput.ini
```

Same with `test_thermodynamics.c`, `test_perturbations.c`, `test_nonlinear.c`, `test_transfer.c`...

Background exercises (see exercise sheet for more details)

Exercise IIa

Reproduce this plot from the Dodelson book *Modern Cosmology*, using the plotting software of your choice.

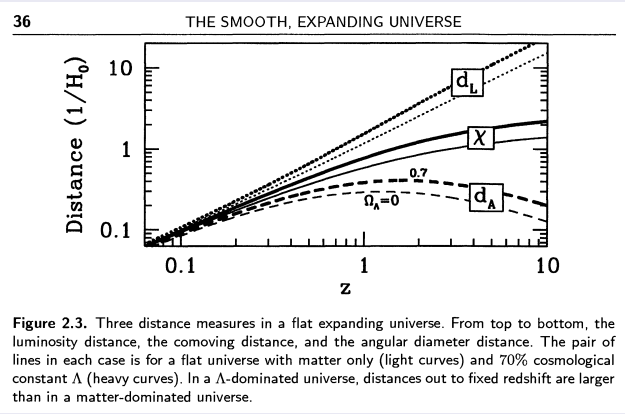


Figure 2.3. Three distance measures in a flat expanding universe. From top to bottom, the luminosity distance, the comoving distance, and the angular diameter distance. The pair of lines in each case is for a flat universe with matter only (light curves) and 70% cosmological constant Λ (heavy curves). In a Λ-dominated universe, distances out to fixed redshift are larger than in a matter-dominated universe.

Exercise IIb

Add a new matter species with an equation of state $p = w\rho$. Visualise its evolution with time. Provoke an error on purpose, to check the error format.

Error management in class

By following a few general rules, we get automatically some very informative error messages like:

```
Error in thermodynamics_init
=>thermodynamics_init(L:292) :error in
    thermodynamics_helium_from_bbn(ppr,pba,pth);
=>thermodynamics_helium_from_bbn(L:1031) :condition (omega_b
     > omegab[num_omegab-1]) is true; You have asked for an
    unrealistic high value omega_b = 7.350000e-02. The
    corrresponding value of the primordial helium fraction
    cannot be found in the interpolation table. If you
    really want this value, you should fix YHe to a given
    value rather than to BBN
```

We only wrote the piece starting with "`You have asked...`". All the rest was generated automatically by the code. This follows from following everywhere 5 rules.

Error management in class

Rule 1:

All functions are of type `int`, and return either `_SUCCESS_` or `_FAILURE_` (defined internally in `include/common.h`: `#define _SUCCESS_ 0` , `#define _FAILURE_ 1`)

```
int function(input, &output) {
    ...
    if (something goes wrong) return _FAILURE_;
    ...
    return _SUCCESS_;
}
```

Error management in class

Rule 2:

All functions are called with the macro `class_call(.,.,.)` (all macros `class_xxx(...)` are defined in `include/common.h`):

```
class_call(function(input, &output),
           error_message_from_function,
           error_message_output);
```

This is simply a short-cut for

```
if (function == _FAILURE_) {
    ErrorMsg Transmit_Error_Message;
    sprintf(Transmit_Error_Message,"%s(L:%d) : error in %s;\
        n=>%s",__func__,__LINE__,#function,
        error_message_from_function);
    sprintf(error_message_output,"%s",Transmit_Error_Message
        );
    return _FAILURE_;
}
```

Error management in class

Rule 3:

Each of the 9 main structures `xx` has a field called `error_message`. Any function in the module `xxx.c` is called `xxx_something()` and writes its error message in `xx.error_message` (if `pxx` is a pointer to `xx`, in `pxx->error_message`).

So if we are in `perturb_init()` and we call `perturb_indices()` we write:

```
class_call(perturb_indices(...,ppt),
           ppt->error_message,
           ppt->error_message);
```

But if we are in `perturb_init()` and we call `background_at_tau()` we write:

```
class_call(background_at_tau(...,pba),
           pba->error_message,
           ppt->error_message);
```

Error management in class

Rule 4:

Whenever an error could occur, we first write a test with the macro `class_test(.,.,.)`:

```
class_test(condition, error_message, "Some text");
```

or

```
class_test(condition, error_message, "Some text and numbers
    %d %e",n,x);
```

Example:

```
class_test(num_points == 0,
           ppt->error_message,
           "this might be caused by ...");
step = (max-min)/((double)num_points);
```

In the text, no need to say in which function we are, or to write that the number of points is zero, or to put a `\n`, all this is done automatically.

Error management in class

Rule 5:

Always allocate memory with the macros `class_alloc()`, `class_calloc()`, `class_realloc()`.

Instead of

```
malloc(parray, N*sizeof(double));
```

use

```
class_alloc(parray, N*sizeof(double), pxx->error_message);
```

If allocation fails (N too big, null or negative), the function will automatically return a `_FAILURE_` and the code will return an appropriate error message:

```
Error running background_init
=>background_init(L:537):error in background_solve(ppr,pba);
=>background_solve(L:1303):could not allocate pvecback with
    size -8
```

Error management in class

Final remark: in `main/class.c` there is no "higher level" so the 10 initialisation functions are called like e.g.:

```
int main(int argc, char **argv) {
    ....
    if (background_init(&pr,&ba) == _FAILURE_) {
    printf("\n\nError running background_init \n=>%s\n",ba.
        error_message);
    return _FAILURE_;
    }
    ...
```

But when CLASS is called as a function from another code (e.g. `Monte Python` or `test/test_loops.c`) we can use the standard way:

```
int class(....,ErrorMsg errmsg) {
    ....
    class_call(background_init(ppr,pba),
               pba->error_message,
               errmsg);
    ...
```

Then, CLASS never crashes (in principle...), it only returns `class(...)== _FAILURE_`