Nils Schöneberg Monday 05.06.2023 **nils.science@gmail.com**

European Research Council

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Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020–2023

The CLASS code

Layout of the Tutorial

- Lecture separated into three parts:
  - What is CLASS and how do I get it?

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  - The layout of CLASS – internal and external

- What we probably won't cover:
  - Nitty-gritty details of the C code → ask me!

Part One

What is class ?

How do I get it?

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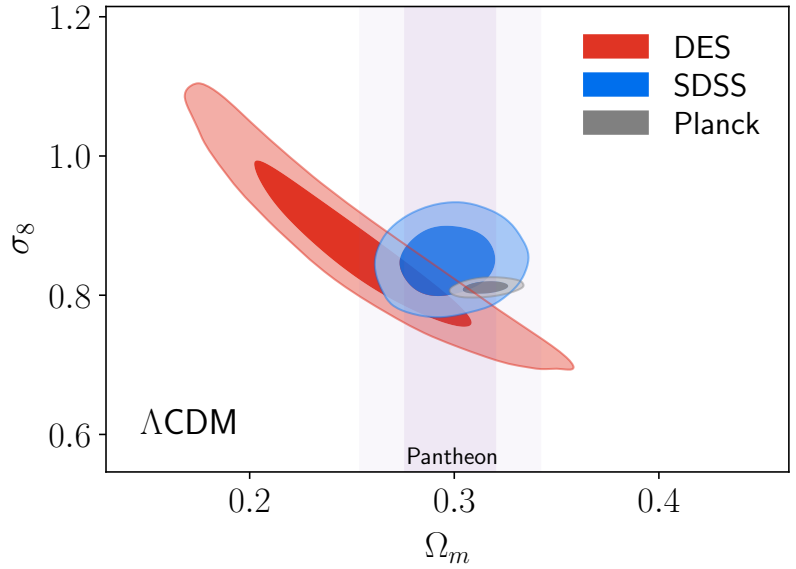
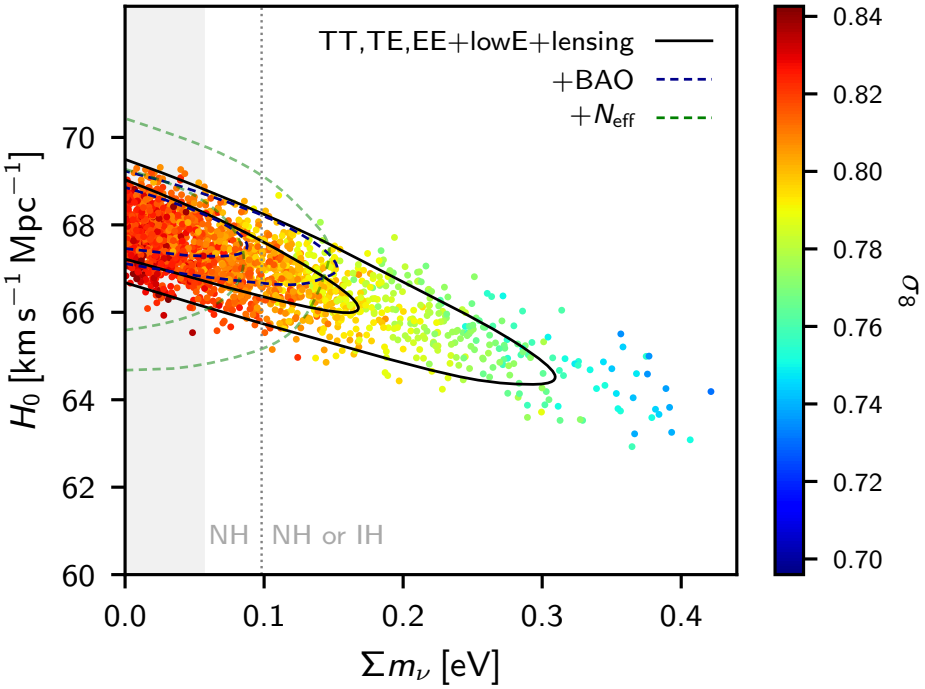
Einstein-Boltzmann solver (EBS)



Asgari+2020 | Astron.Astrophys. 645 (2021) A104, arXiv:2007.15633



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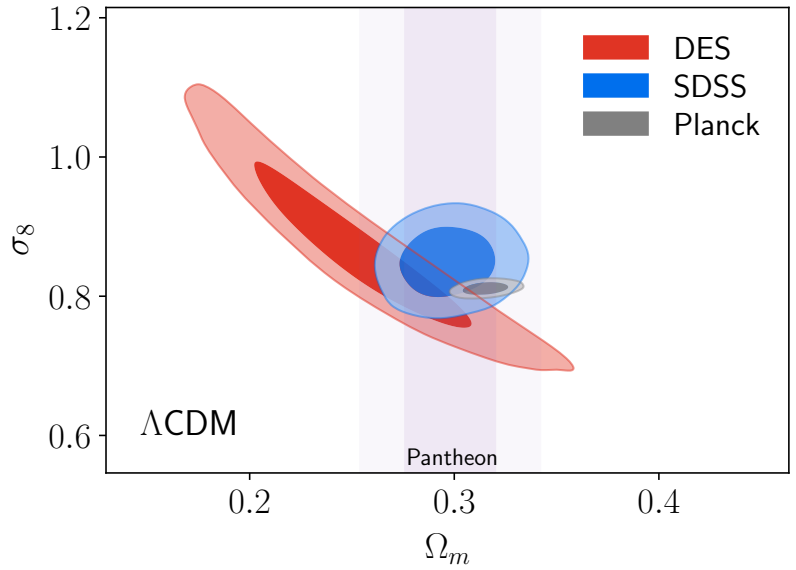
- **linear perturbations** = basis of modern cosmology



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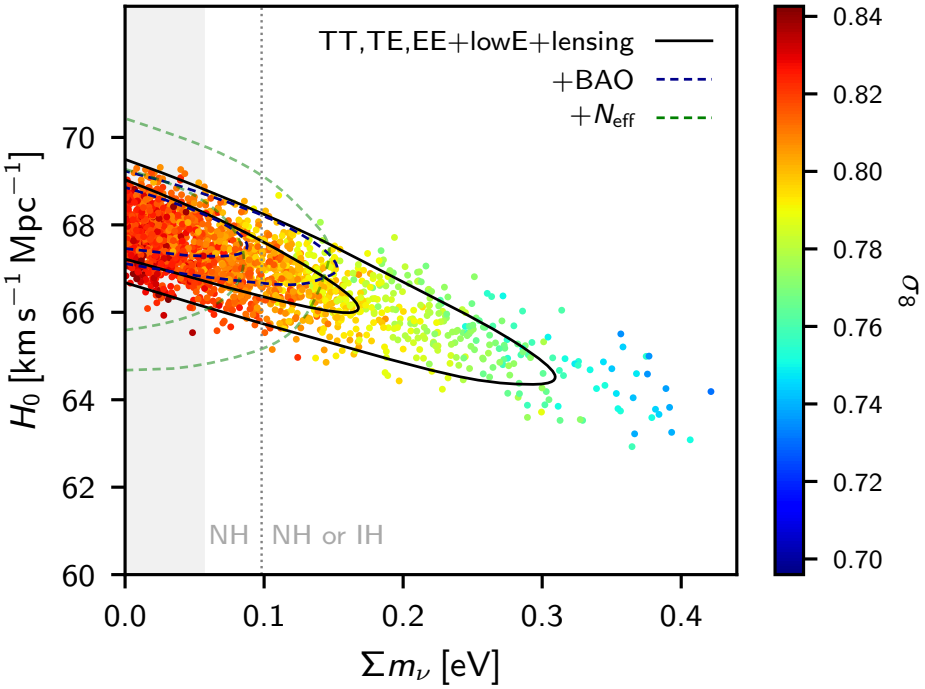

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    - Cosmic shear : $\xi^{\pm}(r,\vartheta)$
    - Linear galaxy counts : C_L^{dd}, $P_{lin}(k,z)$
  - Input for other codes:
    - Initial conditions for simulations (N-body, 21cm, Lyman-α forest, ...)

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Einstein **Boltzmann**

$$k^2(\phi + \mathcal{H}\psi) = 4\pi G a^2(\rho + P)\theta \qquad \delta_b' + \theta_b = 3\phi'$$

History of EBS

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  $\rightarrow$ Strong CLASS-CAMB competition leading to 0.1% agreement

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Why class?

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There is also a helpful community:

- Development continuous
- **Suggestions are welcome!**

Documentation example

```
/** - --> (a) fix current approximation scheme. */

ptw->ptdw->ap_current = index_interval;

/** - --> (b) define the vector of quantities to be integrated
    over. If the current interval starts from the
    initial time zinitial, fill the vector with initial
    conditions. If it starts from an approximation
    switching point, redistribute correctly the values
    from the previous to the new vector. For both
    RECFAST and HYREC, the vector consists of Tmat, x_H,
    x_He, + others for exotic models */

class_call(thermodynamics_vector_init(ppr,
                                      pba,
                                      pth,
                                      interval_limit[index_interval],
                                      ptw),
           pth->error_message,
           pth->error_message);

/* find the value of last_index_back at z = - interval_limit[index_interval], in order to speed up
   subsequent interpolations in thermodynamics_derivs */
class_call(background_at_z(pba,
...
```

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

Notebook (Installation)

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  (input python dictionary vs `.ini` file)

  (output python functions vs `.dat` files)

Usage (Command Line)

- Simple and easy file

  → `./class default.ini`

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  - or write your own from scratch with only needed input lines.

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`parameter_name = value`

```
omega_b = 0.022
```

Usage (Command Line)

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`parameter_name = value` `omega_b = 0.022`

`option = yes / no` `lensing = yes`

Usage (Command Line)

- Input .ini files

```
parameter_name = value
option = yes / no
selection = list, of, things
```

```
omega_b = 0.022
lensing = yes
output = tCl, pCl, lCl
```

Usage (Command Line)

- Input .ini files

```
parameter_name = value
option = yes / no
selection = list, of, things
# comment
```

```
omega_b = 0.022
lensing = yes
output = tCl, pCl, lCl
# To be or not to be?
```

Usage (Command Line)

- Files written to

  `<root>_xxx.dat`

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- With `<root>` = `output/<filename>`, except when `root` is explicitly passed as input
- Command line file outputs: `write_background`/`write_thermodynamics`/ `write_primordial`
- Other outputs: same as what we will discuss later

Usage (Python)

```
→ import classy
→ cosmo = classy.Class()
```

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→ cosmo = classy.Class()
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→ cosmo.set(input_dictionary)
→ cosmo.compute()
→ cosmo.lensed_cl()
→ cosmo.get_pk_all(k,z)
→ cosmo.get_background()
→ cosmo.Hubble(z)
→ ...
```

Part Two

Inputs and outputs

How to work with class?

Input Parameters

- If nothing given:
  - Planck 2013 with $m_\nu=0$

Input Parameters

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  `cl_ref.pre` → close to 'optimal' precision

Input Parameters

- If nothing given:
  - Planck 2013 with m_ν=0
- Parameters overwritten by `cosmo.set` or `xxx.ini`
- precision parameter file:

  `cl_ref.pre` → close to 'optimal' precision
- Can also be included in `.ini`

Input Parameters

- **Which output to generate:**

  `output =`

  `tCl`

  C_L^{TT}

Input Parameters

- **Which output to generate:**

```
output =
tCl , pCl
```

C_L^{TT} C_L^{EE}

C_L^{TE}

Input Parameters

- **Which output to generate:**

```
output =
tCl , pCl , lCl
```

C_L^{TT} C_L^{EE} $C_L^{\phi\phi}$

C_L^{TE}

$C_L^{E\phi}$ $C_L^{T\phi}$

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Input Parameters

- **Which output to generate:**

```
output =
tCl , pCl , lCl , mPk
```

C_L^{TT} C_L^{EE} $C_L^{\phi\phi}$ $P(k,z)$

C_L^{TE}

$C_L^{E\phi}$ $C_L^{T\phi}$

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Input Parameters

- **Which output to generate:**

```
output =
tCl , pCl , lCl , mPk , mTk , vTk
```

C_L^{TT} C_L^{EE} $C_L^{\phi\phi}$ $P(k,z)$ $\delta_x(k,z^*)$ $\theta_x(k,z^*)$

C_L^{TE}

$C_L^{E\phi}$ $C_L^{T\phi}$

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Input Parameters

- **Which output to generate:**

```
output =
tCl , pCl , lCl , mPk , mTk , vTk, nCl , sCl
```

C_L^{TT} C_L^{EE} $C_L^{\phi\phi}$ $P(k,z)$ $\delta_x(k,z^*)$ $\theta_x(k,z^*)$ $C_L^{\delta\delta}$ $C_L^{\Upsilon\Upsilon}$

C_L^{TE}

$C_L^{E\phi}$ $C_L^{T\phi}$

Input Parameters

- **Specifying output ranges:**

```
l_max_scalars = 5000
```

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```
l_max_scalars = 5000
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Input Parameters

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```
l_max_scalars = 5000
P_k_max_1/Mpc = 10
z_pk = 0, 1, 5, …        ← Command line
z_max_pk = 10            ← Python interface
```

Input Parameters

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```
l_max_scalars = 5000
P_k_max_1/Mpc = 10
z_pk = 0, 1, 5, …        ← Command line
z_max_pk = 10            ← Python interface
```

- **Useful things:**

```
format = class/CAMB      ← ! for N-body ICs
write_warnings =yes      ← ! for command line
```

Input Parameters

- **Verbosity (useful for debugging):**

```
input_verbose = 1
background_verbose = 1
thermodynamics_verbose = 1
perturbations_verbose = 1
transfer_verbose = 1
primordial_verbose = 1
harmonic_verbose = 1
fourier_verbose = 1
lensing_verbose = 1
distortions_verbose = 1
output_verbose = 1
```

Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_{\rm m}, \Omega_b h^2, \tau_{\rm reio}\}$
  - Hubble constant (basis of Hubble law)
  - `h = 0.67`
  - `H0 = 67`

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  - Hubble constant (basis of Hubble law)
  - `h = 0.67`
  - `H0 = 67`
  - `100*theta_s = 1.042`

$$\theta_s = \frac{r_s}{r_A} = \frac{H_0 r_s}{\int_0^{z_{\rm rec}} H_0/H(z) dz}$$

Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_{\rm m}, \Omega_b h^2, \tau_{\rm reio}\}$
  - Primordial amplitude of nearly scale-invariant power spectrum at pivot scale
  - `A_s = 2.01e-9`
  - `ln10^{10}A_s = 3.0` $\ln(10^{10} A_s)$
  - `ln_A_s_1e10 = 3.0`

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  - `ln_A_s_1e10 = 3.0`
  - `sigma8` = **Notebook!**

$$\sigma_8(z) = \int \frac{k^3 P(k,z)}{2\pi^2} T^2(kR_8) d\ln k$$

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  - `ln_A_s_1e10 = 3.0`
  - `sigma8 = 0.825`

$$\sigma_8(z) = \int \frac{k^3 P(k,z)}{2\pi^2} T^2(kR_8) d\ln k$$

Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_{\rm m}, \Omega_b h^2, \tau_{\rm reio}\}$
  - Primordial tilt of nearly scale-invariant power spectrum at pivot scale
  - `n_s = 0.96`

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Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_\mathrm{m}, \Omega_b h^2, \tau_\mathrm{reio}\}$
  - Matter abundance as fraction of current-day energy density
  - `Omega_m = 0.3` Ω_m
  - `omega_m = 0.15` $\Omega_m h^2$
  - `Omega_cdm = 0.25` Ω_cdm
  - `omega_cdm = 0.125` $\Omega_\mathrm{cdm} h^2$

Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_{\rm m}, \Omega_b h^2, \tau_{\rm reio}\}$
  - Baryon abundance as fraction of current-day energy density
  - `Omega_b = 0.05` Ω_b
  - `omega_b = 0.025` $\Omega_b h^2$

Model Inputs

- **Usual ΛCDM model:** $\{H_0, A_s, n_s, \Omega_{\rm m}, \Omega_b h^2, \tau_{\rm reio}\}$
  - Reionization as optical depth/redshift
  - `tau_reio = 0.05`
  - `z_reio = 7`

$$\tau(z) = \int \kappa' d\eta = \int \sigma n_H(z) x_e(z) d\eta$$

Further Parameters

- **One-parameter extensions:**

```
Omega_k = 0
N_ur = 3.046
T_cmb = 2.7255
A_L = 1.0
alpha_s = 0
```

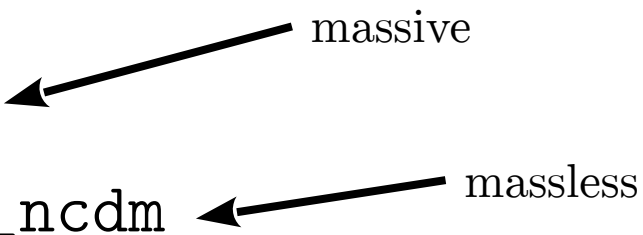
Dark Energy Models

- Cosmological constant `Omega_Lambda`
- fluid dark energy `Omega_fld`
  - `CPL` parameterization (`w0_fld`, `wa_fld`)
  - `EDE` is not the usual axion EDE → ***https://github.com/PoulinV/AxiCLASS*** and ***https://github.com/flo1984/TriggerCLASS*** still to be merged
- Quintessence `Omega_scf`

Neutrino parameters

- Ordinary free-streaming neutrinos:

```
N_ncdm = 1/2/3
m_ncdm = 0.02, 0.03, 0.05
N_ur = 3.046 - 1.0132 * N_ncdm
```



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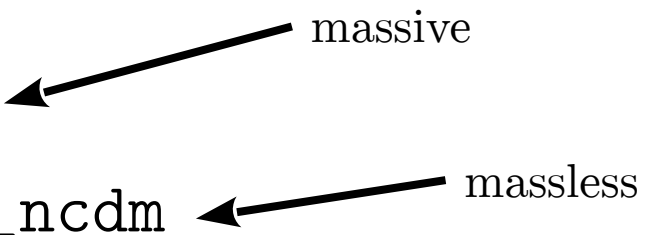
N_ncdm = 1/2/3
m_ncdm = 0.02, 0.03, 0.05
N_ur = 3.046 - 1.0132 * N_ncdm

deg_ncdm = 1, 2
```



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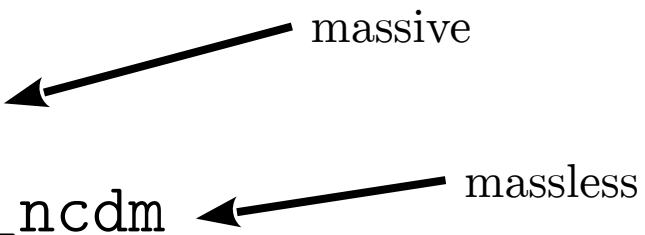


```
deg_ncdm = 1, 2

omega_ncdm = omega_cdm * f_wdm
T_ncdm = 0.71611 * (omega_ncdm*94.13/m_ncdm)^(1/3)
```

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Neutrino parameters

- Ordinary free-streaming neutrinos:

```
N_ncdm = 1/2/3
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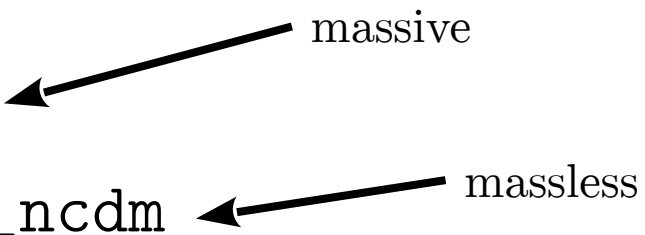

Also: non-trivial phase-space, neutrino flavor mixing, neutrino chemical potential

Dark Matter/Radiation Models

- Dark radiation extensions:
  - fluid/self-interacting dark radiation (`idr`)
  - Viscous dark radiation (`ceff2_ur`, `cvis_ur`)
  - `https://github.com/PoulinV/class_interacting_neutrinos`

Dark Matter/Radiation Models

- Dark radiation extensions:
  - fluid/self-interacting dark radiation (`idr`)
  - Viscous dark radiation (`ceff2_ur`, `cvis_ur`)
  - `https://github.com/PoulinV/class_interacting_neutrinos`
- Dark matter extensions:
  - Thermal WDM (see before)
  - Decaying dark matter (`dcdm`)
  - Interactions with photons, baryons, neutrinos (`idm`)

Inflation and ICs

A_s = 2.1e-9 / ln10^{10}A_s = 3.044 / sigma8 = 0.82

n_s = 0.966

alpha_s = 0

Inflation and ICs

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A_s = 2.1e-9 / ln10^{10}A_s = 3.044 / sigma8 = 0.82
n_s = 0.966
alpha_s = 0
```

```
f_bi = 0
```
b isocurvature fraction

```
c_ad_bi = 0
```
b isocurvature correlation

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Inflation and ICs

```
A_s = 2.1e-9 / ln10^{10}A_s = 3.044 / sigma8 = 0.82
n_s = 0.966
alpha_s = 0
```

```
f_bi = 0
```
b isocurvature fraction

```
c_ad_bi = 0
```
b isocurvature correlation

```
r = 1
```
tensor-scalar ratio

```
n_t = scc
```
tensor tilt (self-consistency single-field inflation)

Precision Parameters

- **Precision parameters (`include/precisions.h`):**

```
P_k_max_h/Mpc = 1.
```

Precision Parameters

- **Precision parameters (`include/precisions.h`):**

  `P_k_max_h/Mpc = 1.`

  `k_per_decade_for_pk = 10`

Precision Parameters

- **Precision parameters (`include/precisions.h`):**

```
P_k_max_h/Mpc = 1.
k_per_decade_for_pk = 10
k_max_tau0_over_lmax = 2.4
```

Precision Parameters

- **Precision parameters (include/precisions.h):**

```
P_k_max_h/Mpc = 1.
k_per_decade_for_pk = 10
k_max_tau0_over_lmax = 2.4
k_min_tau0 = 0.1
tight_coupling_approximation /
radiation_streaming_approximation /
ur_fluid_approximation / ncdm_fluid_approximation
```

Precision Parameters

- **Precision parameters (include/precisions.h):**

```
P_k_max_h/Mpc = 1.

k_per_decade_for_pk = 10

k_max_tau0_over_lmax = 2.4

k_min_tau0 = 0.1

tight_coupling_approximation /
radiation_streaming_approximation /
ur_fluid_approximation / ncdm_fluid_approximation

accurate_lensing = 1
```

Precision Parameters

- **Precision parameters (`include/precisions.h`):**

  `background_Nloga = 3000`

  `tol_background_integration = 1e-10`

Precision Parameters

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  `background_Nloga = 3000`

  `tol_background_integration = 1e-10`

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Precision Parameters

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  `background_Nloga = 3000`

  `tol_background_integration = 1e-10`

  `tol_ncdm = 1e-3 / tol_ncdm_synchronous = 1e-3 / tol_ncdm_bg = 1e-5`

  `tol_shooting_deltax = 1e-4 / tol_shooting_deltaF = 1e-6 /`
  `tol_shooting_deltax_rel = 1e-5 (1D)`

Precision Parameters

- **Precision parameters (`include/precisions.h`):**

  `background_Nloga = 3000`

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  `tol_shooting_deltax = 1e-4 / tol_shooting_deltaF = 1e-6 /`
  `tol_shooting_deltax_rel = 1e-5 (1D)`

  `thermo_z_initial = 5e6 / thermo_Nz_lin = 20000 / thermo_Nz_log = 5000`

  `tol_thermo_integration = 1e-6`

Precision Parameters

- **Precision parameters (include/precisions.h):**

  background_Nloga = 3000

  tol_background_integration = 1e-10

  tol_ncdm = 1e-3 / tol_ncdm_synchronous = 1e-3 / tol_ncdm_bg = 1e-5

  tol_shooting_deltax = 1e-4 / tol_shooting_deltaF = 1e-6 /
  tol_shooting_deltax_rel = 1e-5 (1D)

  thermo_z_initial = 5e6 / thermo_Nz_lin = 20000 / thermo_Nz_log = 5000

  tol_thermo_integration = 1e-6

  perturbations_sampling_stepsize = 0.1

  tol_perturbations_integration = 1e-5

Quick moment to catch your breath!

$\rightarrow$ On to outputs

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Output functions (classy)

`raw_cl(lmax=-1)`	$C_\ell^{\rm unlensed}$
`lensed_cl(lmax=-1)`	$C_\ell^{\rm lensed}$
`density_cl(lmax=-1)`	$C_\ell^{\rm galaxy}$

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Output functions (classy)

`raw_cl(lmax=-1)`	$C_\ell^{\rm unlensed}$
`lensed_cl(lmax=-1)`	$C_\ell^{\rm lensed}$
`density_cl(lmax=-1)`	$C_\ell^{\rm galaxy}$

`get_pk_all(k,z, nonlinear=True, cdmbar=False)` $P(k,z)$

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Output functions (classy)

`raw_cl(lmax=-1)`	$C_\ell^{\rm unlensed}$
`lensed_cl(lmax=-1)`	$C_\ell^{\rm lensed}$
`density_cl(lmax=-1)`	$C_\ell^{\rm galaxy}$

`get_pk_all(k,z, nonlinear=True, cdmbar=False)`	$P(k,z)$
`get_pk_and_k_and_z(nonlinear=True, only_clustering_species=False, h_units=False)`	
`get_transfer_and_k_and_z(output_format='class', h_units=False)`	$\delta(k,z), \theta(k,z)$

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Output functions (classy)

`raw_cl(lmax=-1)` $C_\ell^{\rm unlensed}$

`lensed_cl(lmax=-1)` $C_\ell^{\rm lensed}$

`density_cl(lmax=-1)` $C_\ell^{\rm galaxy}$

`get_pk_all(k,z, nonlinear=True, cdmbar=False)` $P(k,z)$

`get_pk_and_k_and_z(nonlinear=True, only_clustering_species=False, h_units=False)`

`get_transfer_and_k_and_z(output_format='class', h_units=False)` $\delta(k,z), \theta(k,z)$

`get_background()`, `get_thermodynamics()`, `get_primordial()`, `get_perturbations()`, `get_transfer(z)`

Output functions (classy)

```
sigma8()
h(), n_s(), theta_s_100()
tau_reio(), z_reio()
Omega_m()
Omega_r(), Omega_Lambda(), Omega_g(), Omega_b()
Neff()
keq(), age(), rs_drag()
```

Output functions (classy)

```
sigma8()
h(), n_s(), theta_s_100()
tau_reio(), z_reio()
Omega_m()
Omega_r(), Omega_Lambda(), Omega_g(), Omega_b()
Neff()
keq(), age(), rs_drag()

get_current_derived_parameters(names) → classy.pyx
```

Output functions (classy)

- `z_of_r(z)` → `conf_distance(z)`, `H(z)` [1/Mpc]
- `luminosity_distance(z)`, `angular_distance(z)`, `angular_distance_from_to(z1,z2)`, `comoving_distance(z)`

Output functions (classy)

- `z_of_r(z)` → `conf_distance(z)`, `H(z)` [1/Mpc]
- **`luminosity_distance(z)`, `angular_distance(z)`, `angular_distance_from_to(z1,z2)`, `comoving_distance(z)`**
- **`scale_independent_growth_factor(z)`** → `D(z)`
- `scale_independent_growth_factor_f(z)` → `f(z) = dlnD/dlna`

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Output functions (classy)

- z_of_r(z) → conf_distance(z), H(z) [1/Mpc]
- **luminosity_distance(z), angular_distance(z), angular_distance_from_to(z1,z2), comoving_distance(z)**
- **scale_independent_growth_factor(z)** → D(z)
- scale_independent_growth_factor_f(z) → f(z) = dlnD/dlna

- **sigma(R,z,hunits=False)** / sigma8() → sigma(8,0,hunits=True)
- scale_independent_f_sigma8()
- effective_f_sigma8() → dsigma8/dlna

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Output functions (classy)

- z_of_r(z) → conf_distance(z), H(z) [1/Mpc]
- **luminosity_distance(z), angular_distance(z), angular_distance_from_to(z1,z2), comoving_distance(z)**
- **scale_independent_growth_factor(z)** → D(z)
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- **sigma(R,z,hunits=False)** / sigma8() → sigma(8,0,hunits=True)
- scale_independent_f_sigma8()
- effective_f_sigma8() → dsigma8/dlna

- z_of_tau(tau)
- **Hubble(z)**
- Om_m(z) /Om_b(z), Om_cdm(z), Om_ncdm(z)

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Output functions (classy)

- z_of_r(z) → conf_distance(z), H(z) [1/Mpc]
- **luminosity_distance(z), angular_distance(z), angular_distance_from_to(z1,z2), comoving_distance(z)**
- **scale_independent_growth_factor(z)** → D(z)
- scale_independent_growth_factor_f(z) → f(z) = dlnD/dlna

- **sigma(R,z,hunits=False)** / sigma8() → sigma(8,0,hunits=True)
- scale_independent_f_sigma8()
- effective_f_sigma8() → dsigma8/dlna

- z_of_tau(tau)
- **Hubble(z)**
- Om_m(z) /Om_b(z), Om_cdm(z), Om_ncdm(z)

- pk_tilt(k,z)

- ionization_function(z) / baryon_temperature(z)

Short notebook break!

Part Three

The layout of class (internal and external)

Layout of CLASS

- Goal: Computing *summary statistics*

Layout of CLASS

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- For this, we require *perturbations*

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Layout of CLASS

- Goal: Computing *summary statistics*
- For this, we require *perturbations*
- For this, we require *initial conditions* (inflation) and *interaction rates* (thermodynamics) and *background quantities* (like Hubble, densities)

  $\rightarrow$ This suggests a causal code layout

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Layout of CLASS

Background

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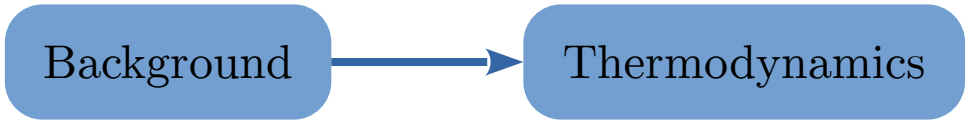
Layout of CLASS



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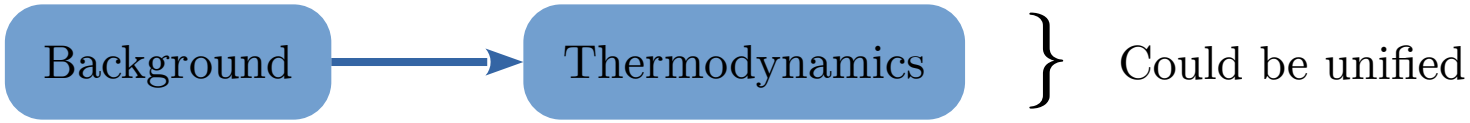

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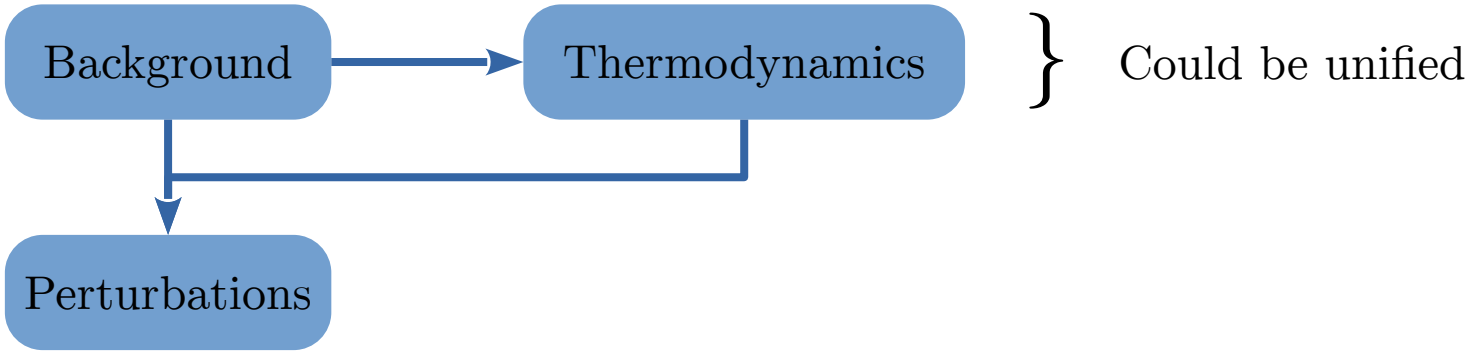

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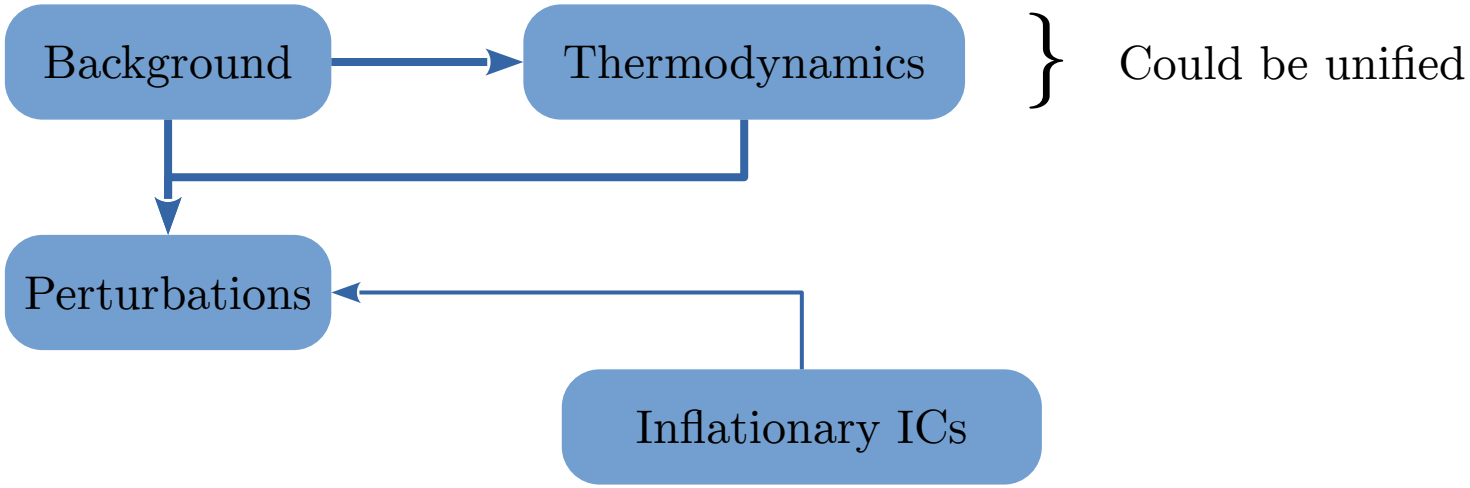

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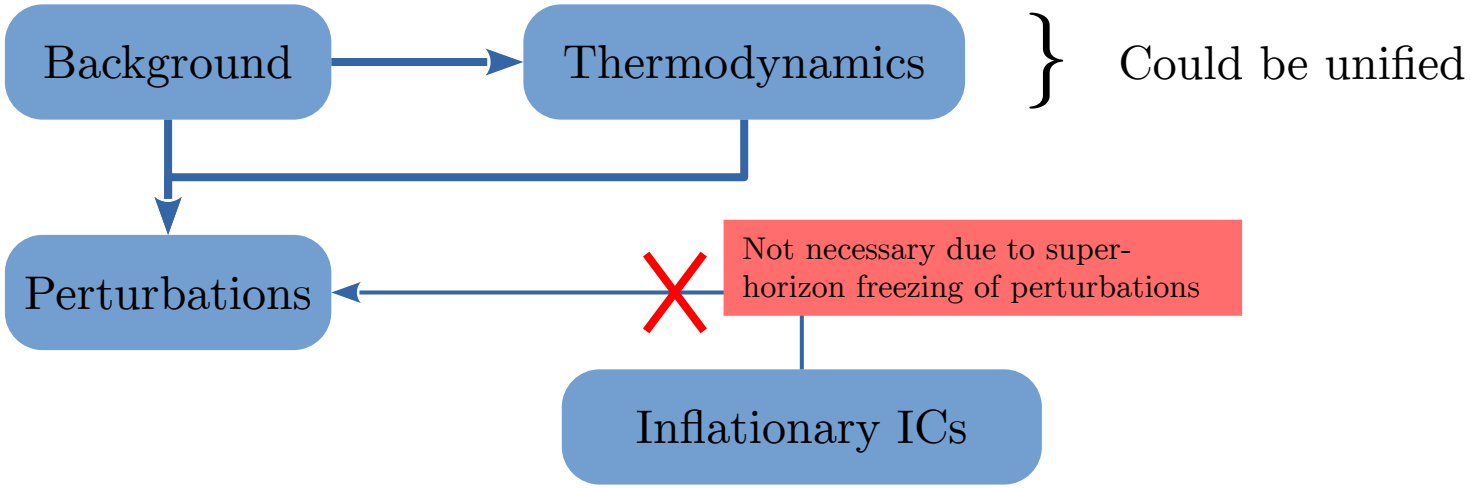

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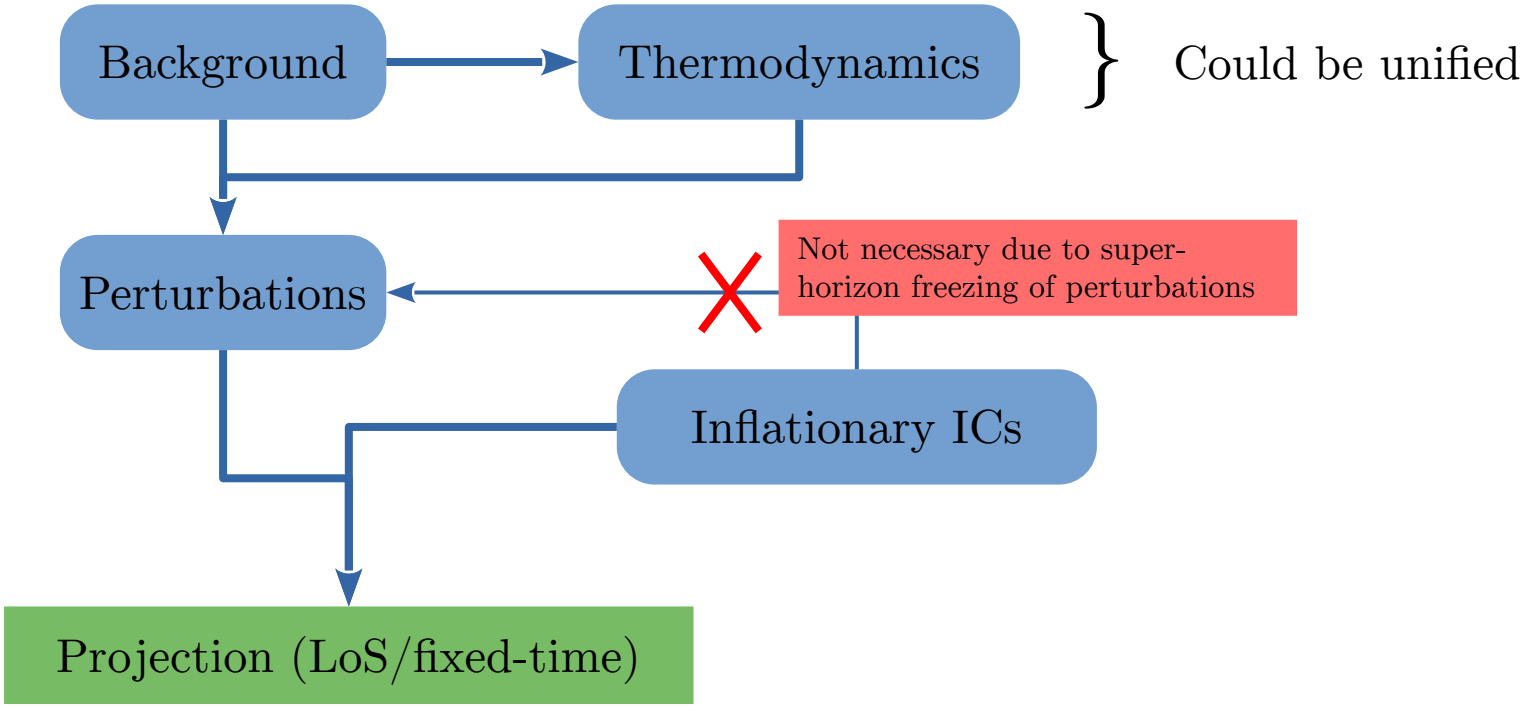

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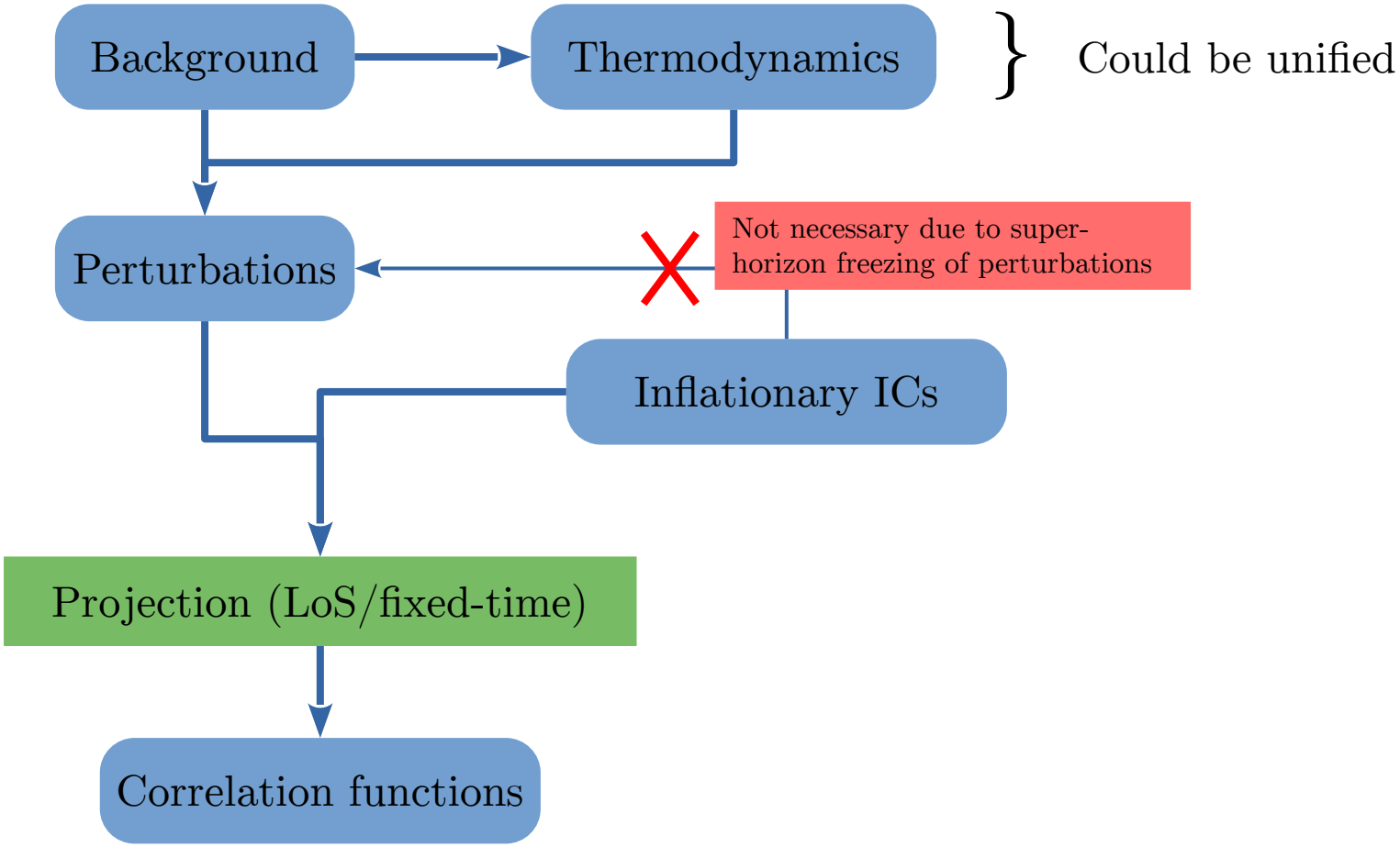

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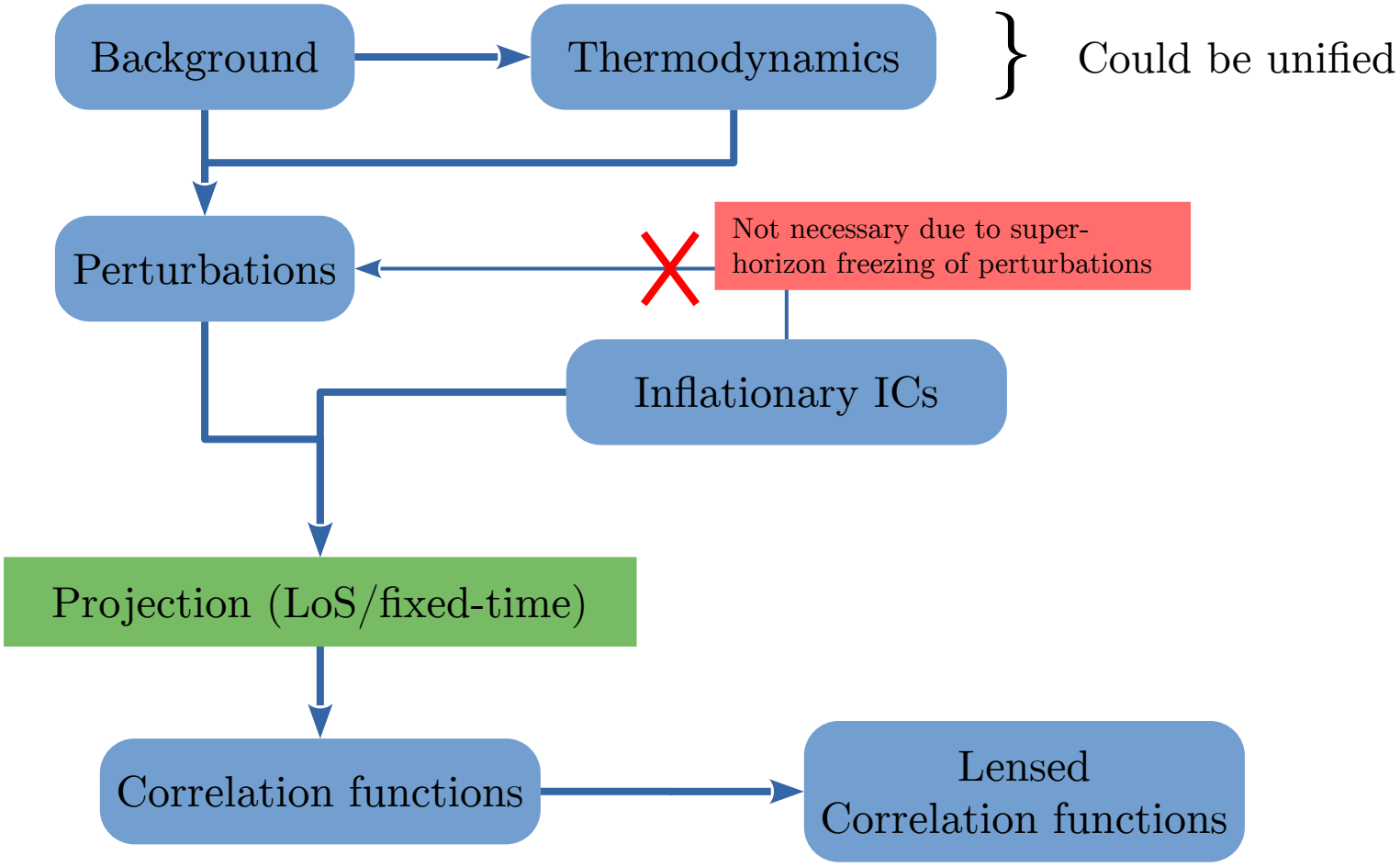

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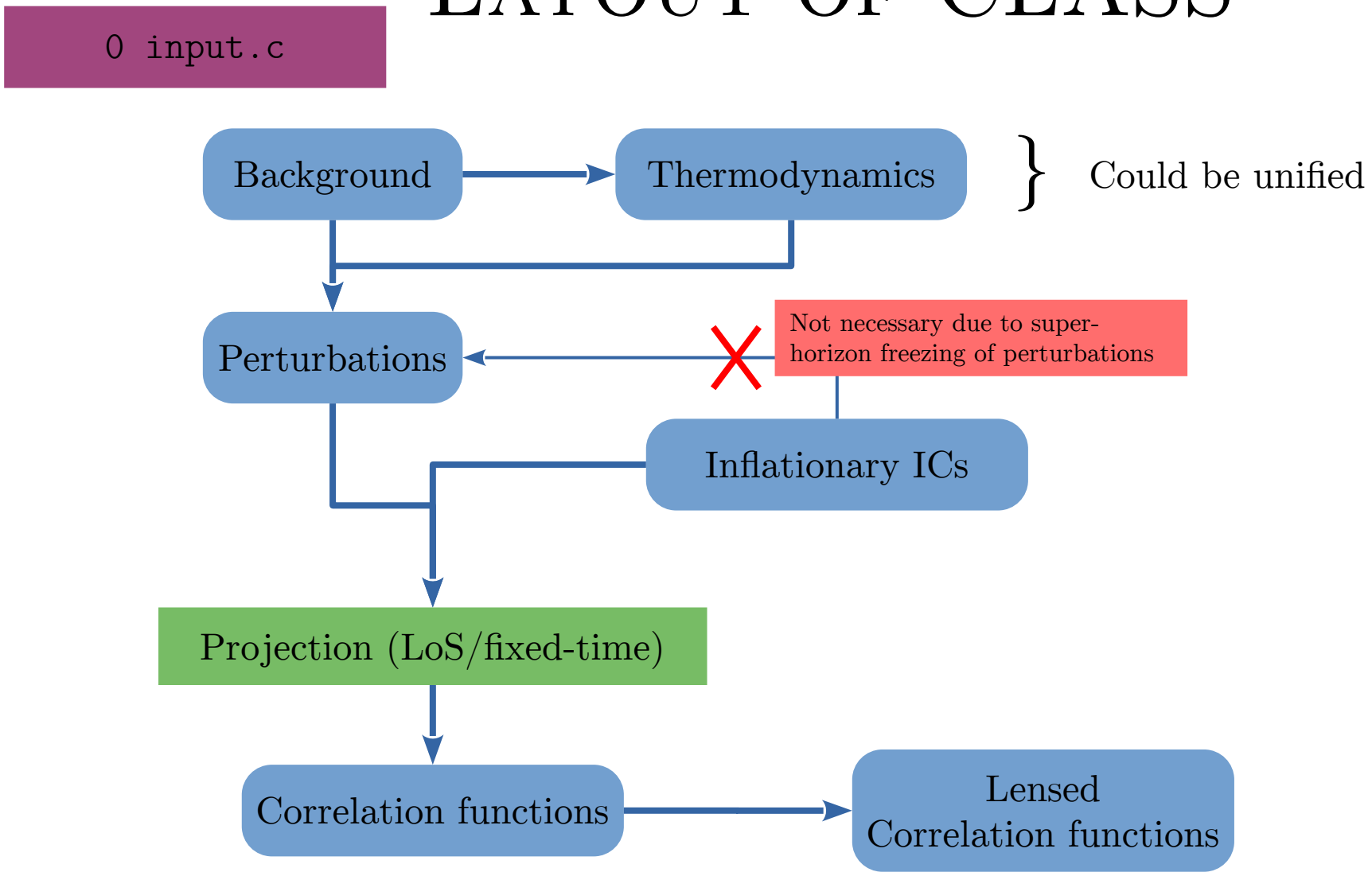

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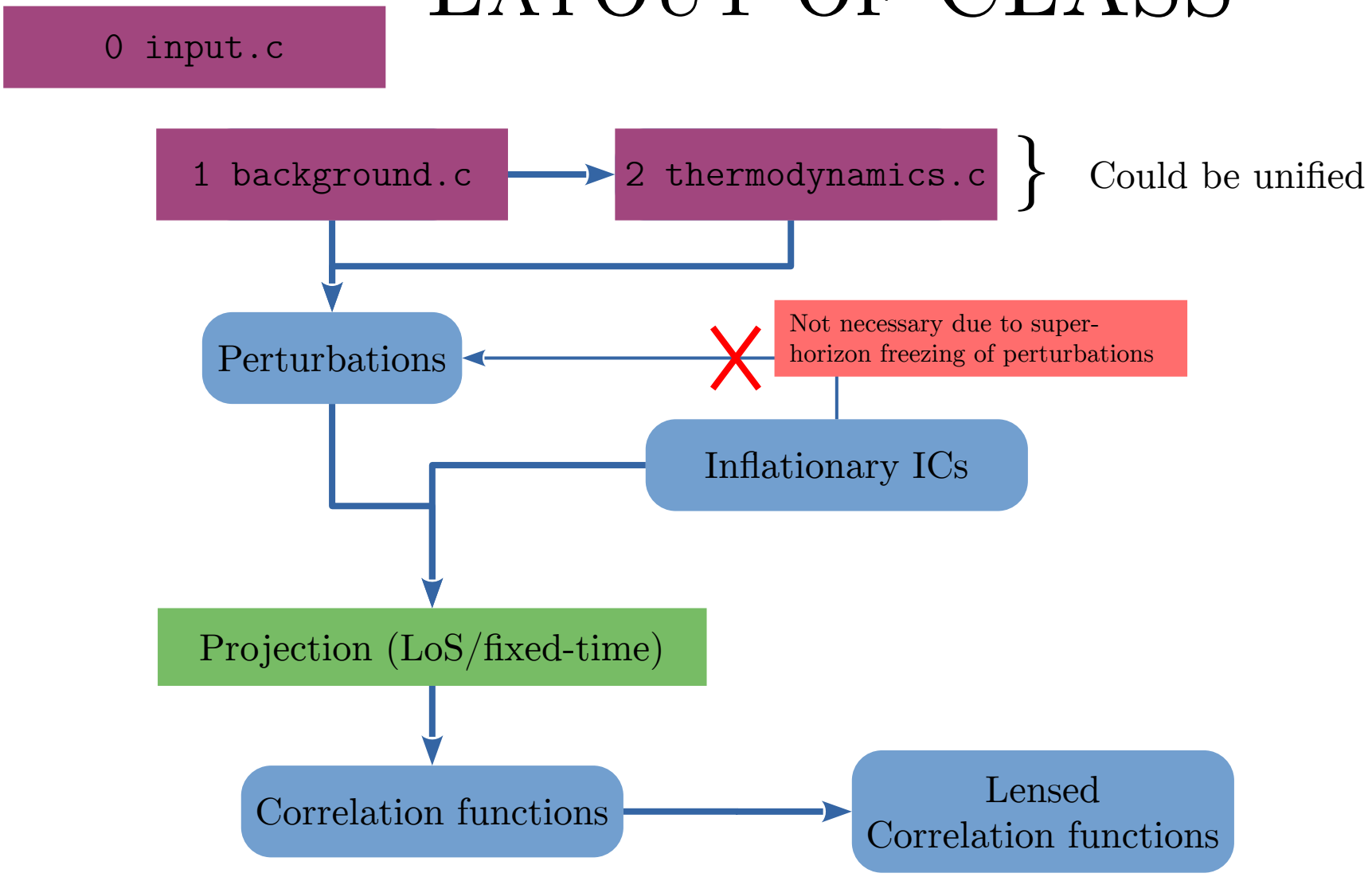

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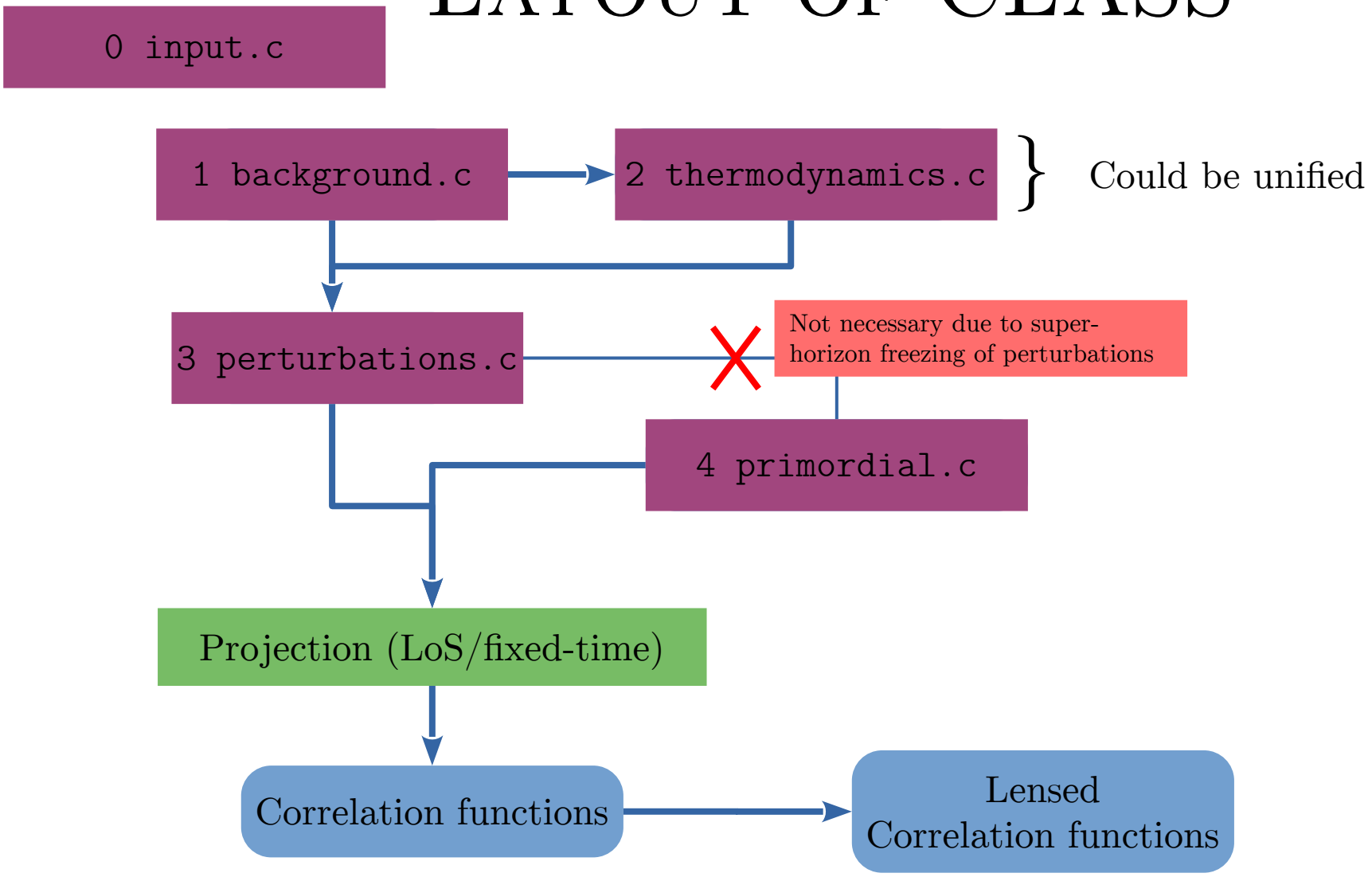

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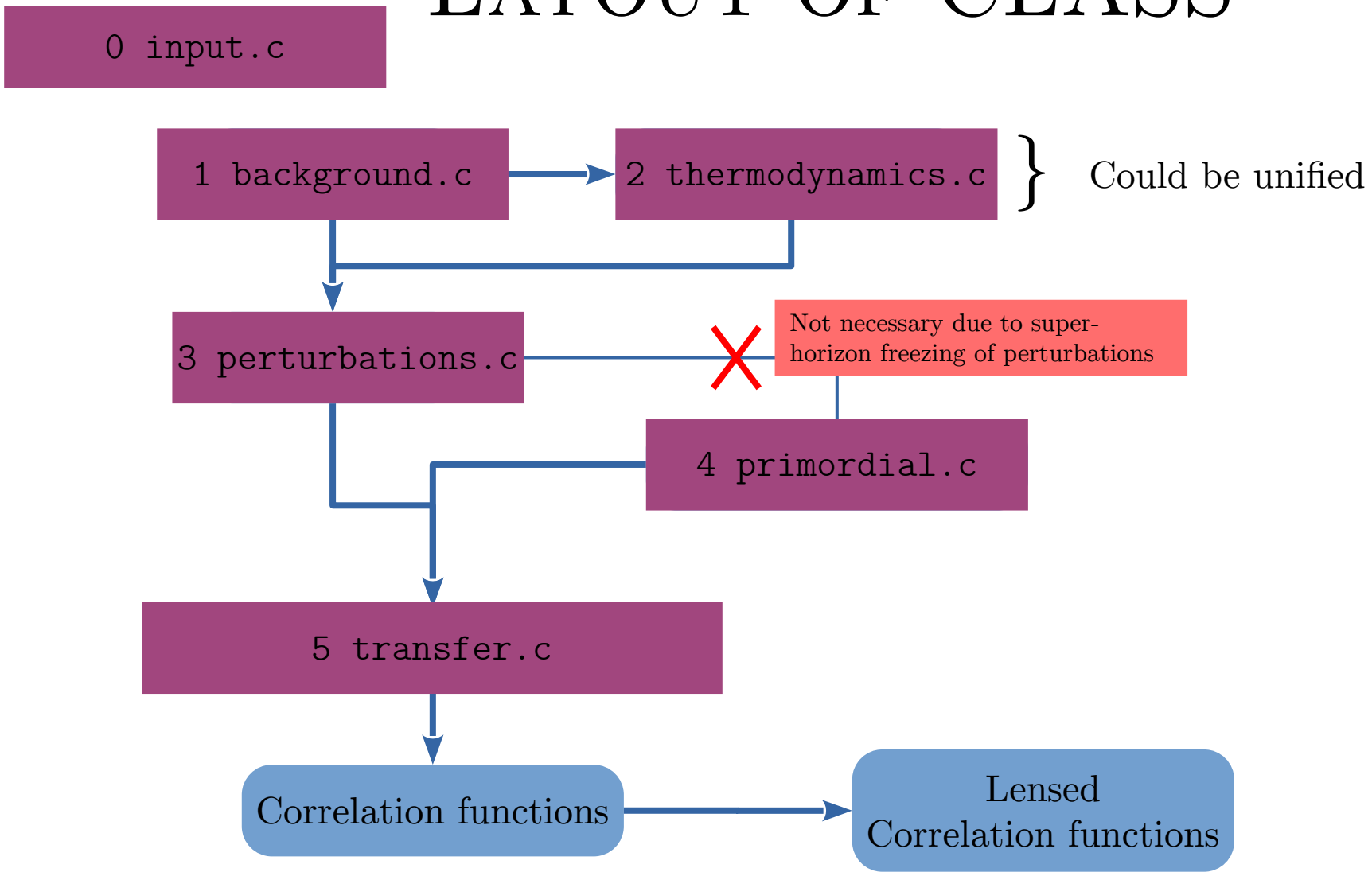

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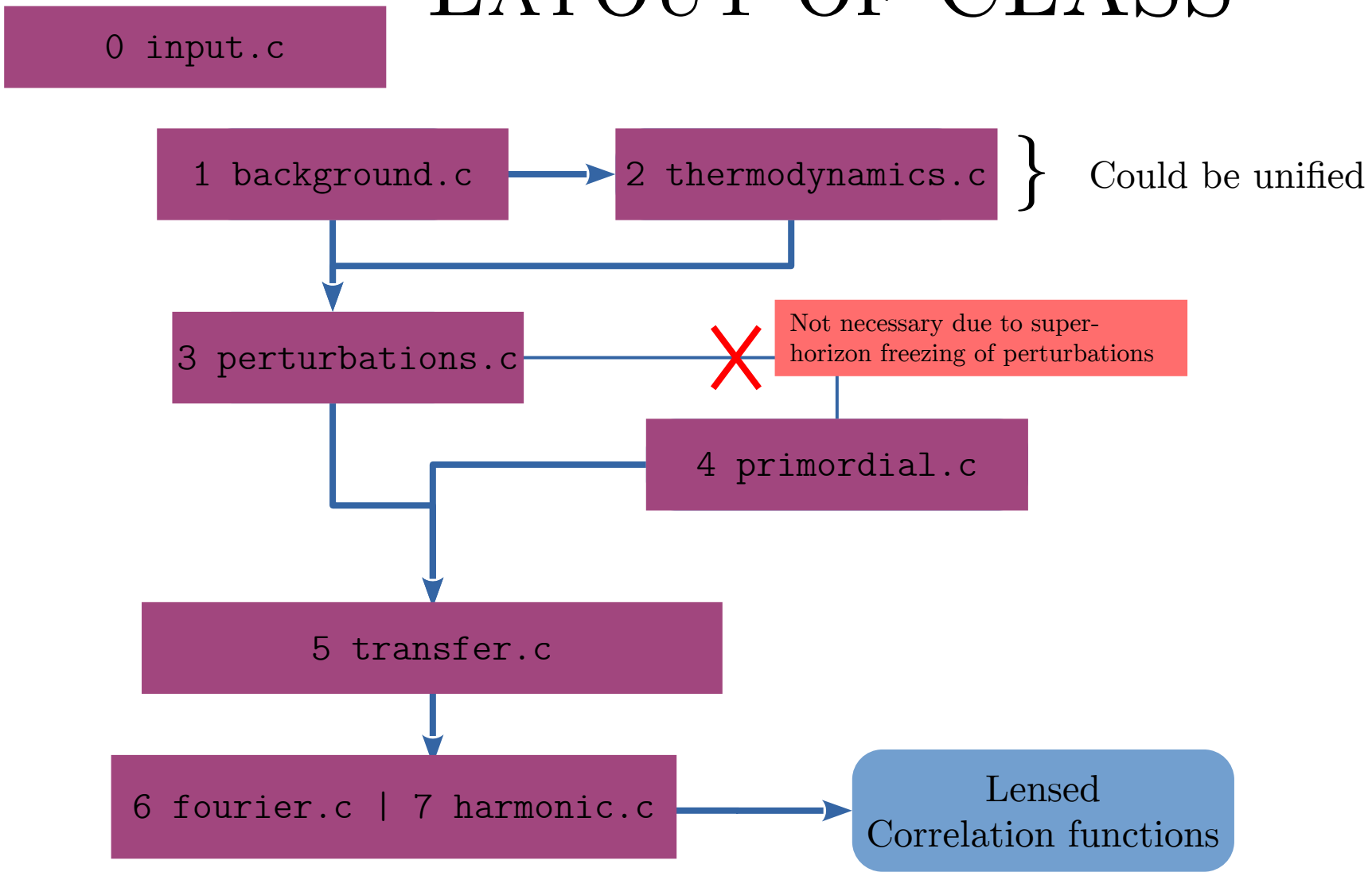

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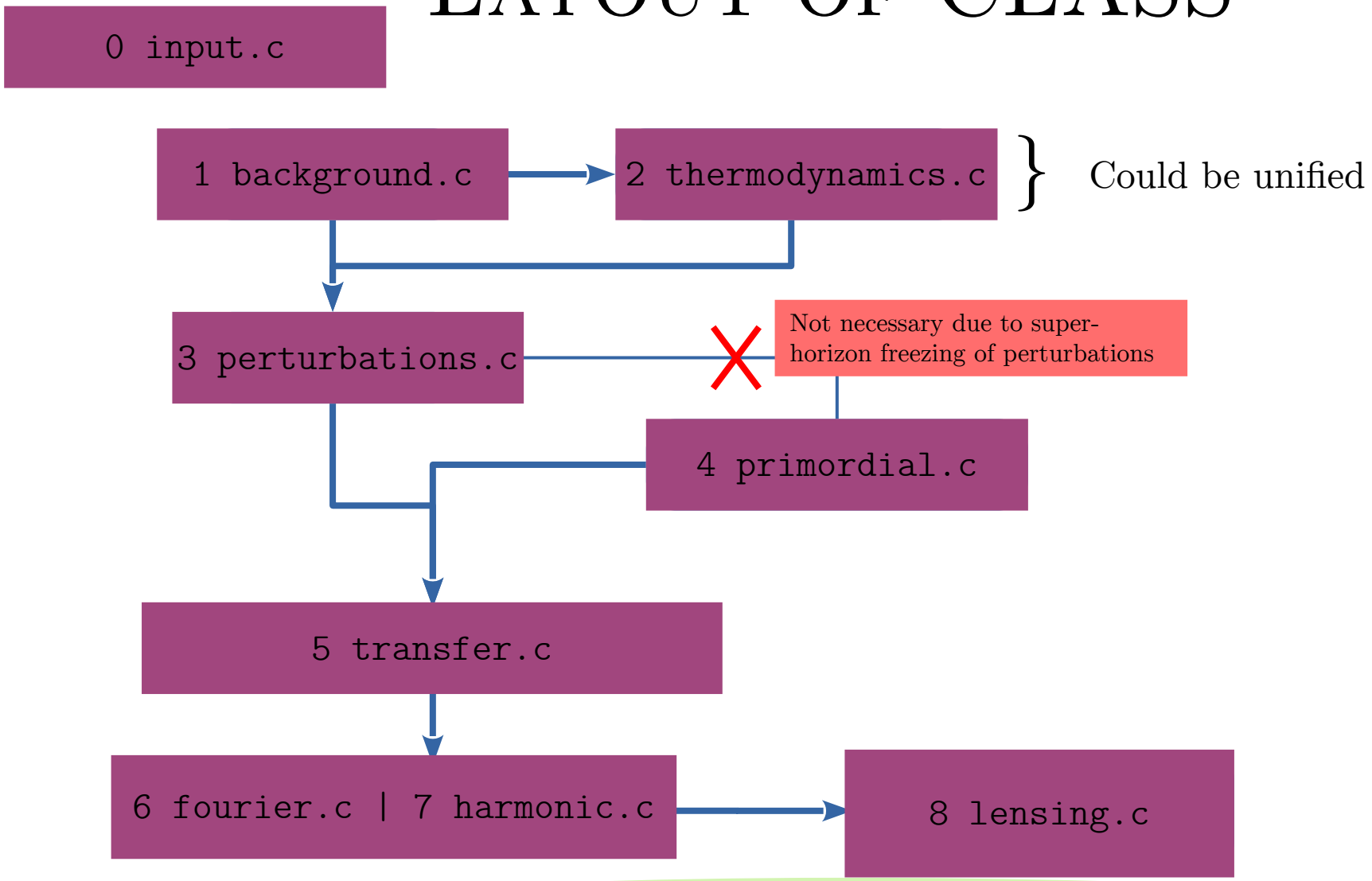

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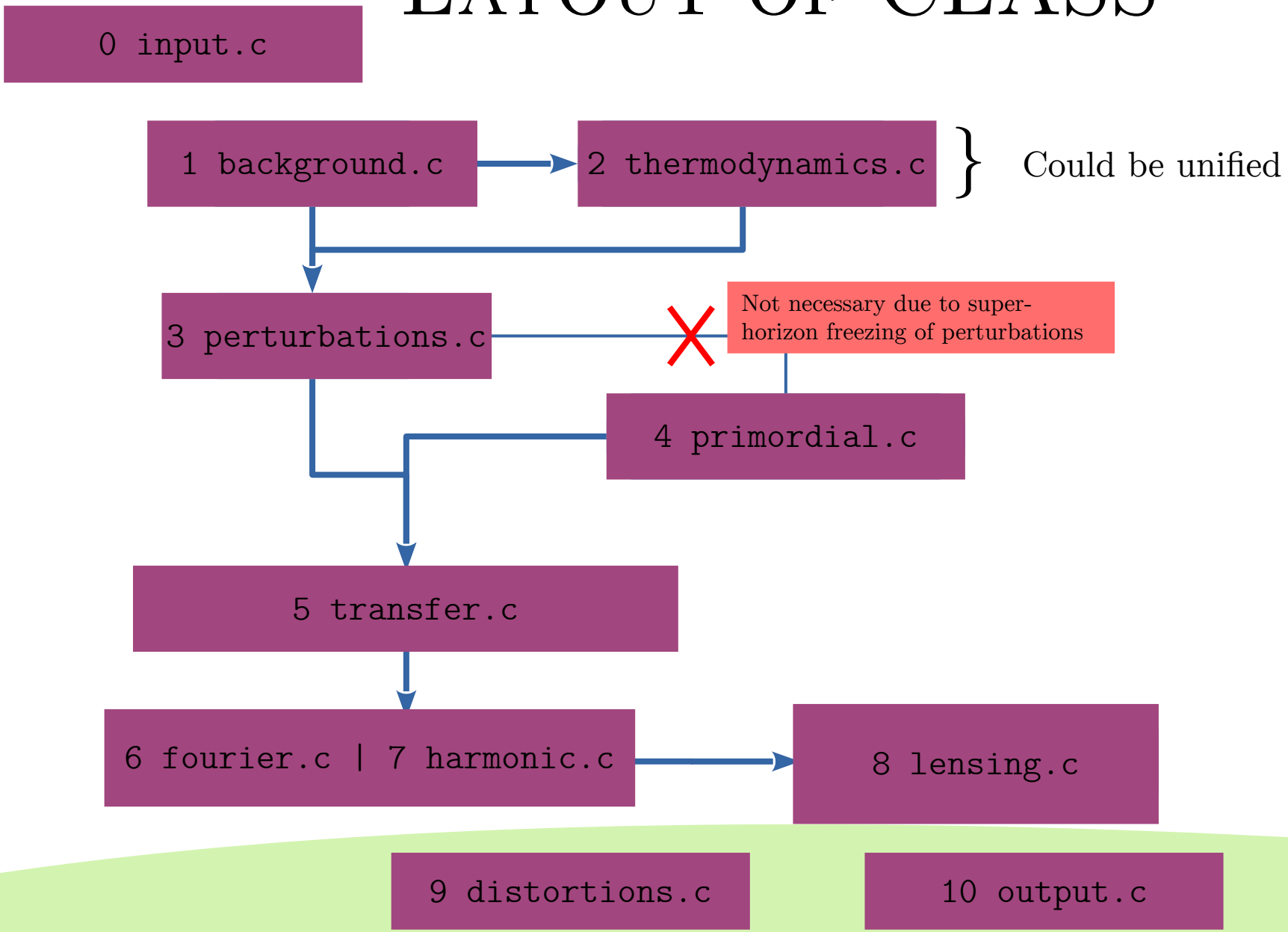

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Input Layout of CLASS

python script **command line**

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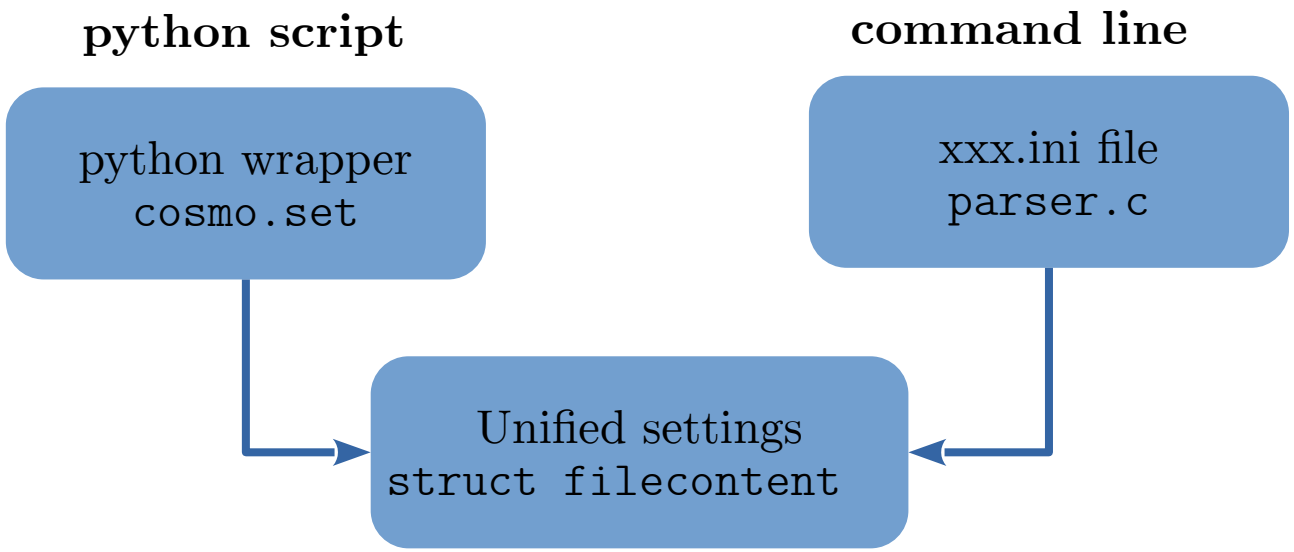
Input Layout of CLASS



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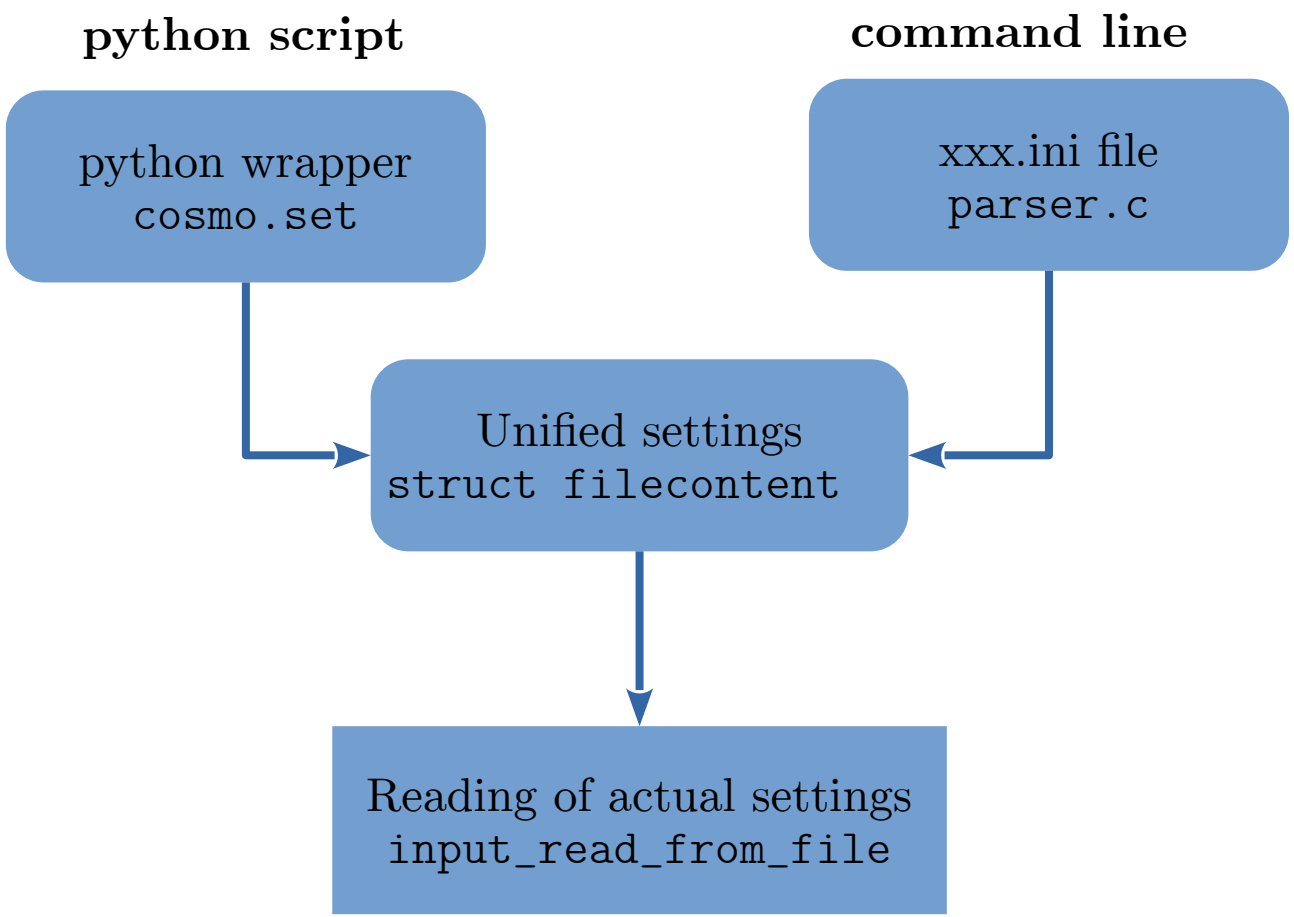

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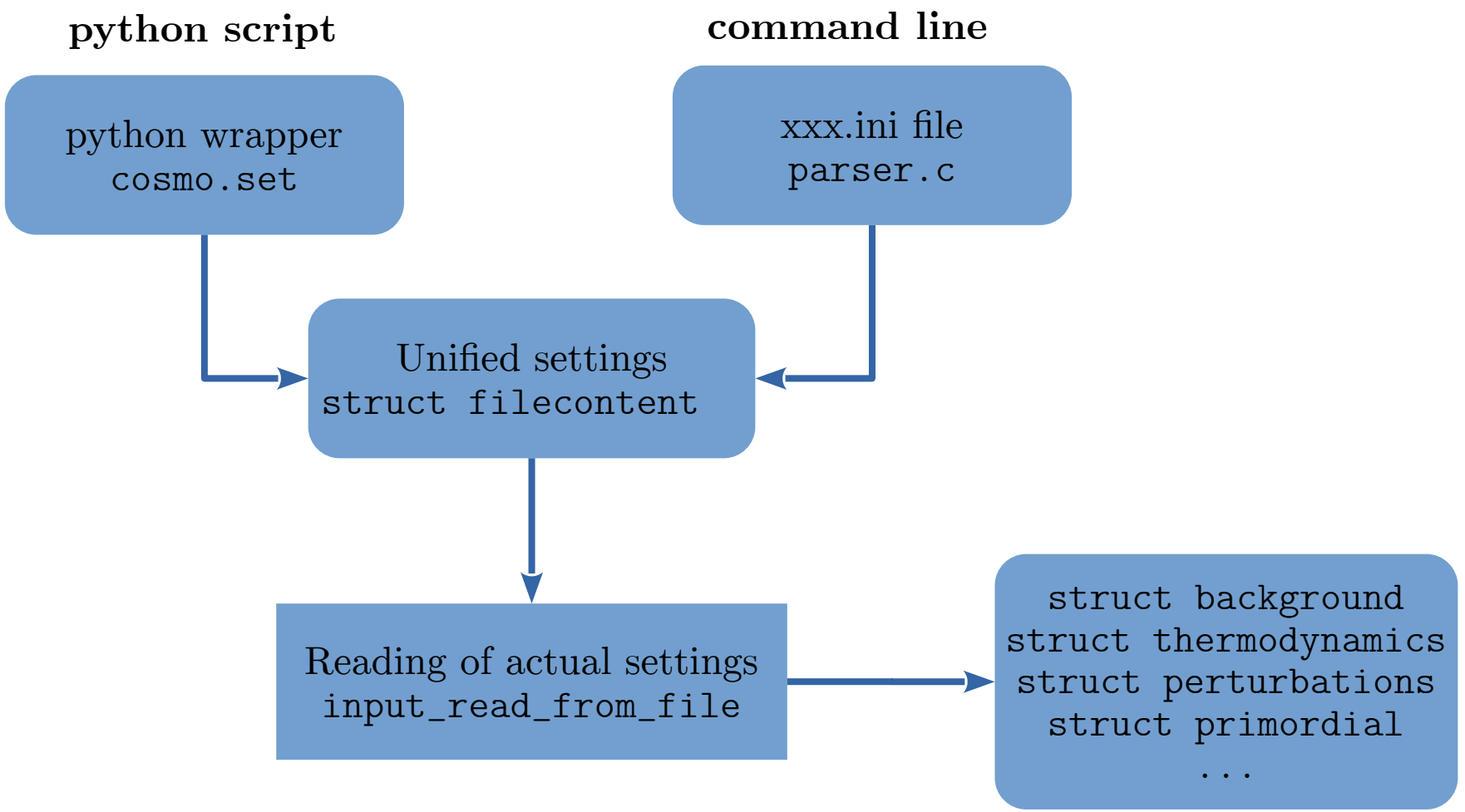

Shooting

Allows us to use parameters like $100_{\,s}$ or σ_8 even though they are technically outputs not inputs

Shooting

Try out a *reasonable* value (with a pre-programmed guess)

Then iterate in *correct* direction

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1D :	More robust Ridder's method
2D or higher:	Less robust but faster Newton's method

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- Example: Dark Energy with equation of state `Omega_Lambda=0.2` (`Omega_scf=0`)

Background Module

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Background Module

Einstein Boltzmann Solver:

Einstein Equation:

$$H^2 = \frac{8\pi G}{3} \sum_{\text{species } i} \rho_i$$

Boltzmann Equations:

$$\frac{d\rho_i}{d\ln a} + 3(\rho_i + P_i) = 0$$

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Background Module

Computation of the background quantities like $\rho(z)$, $H(z)$

AND derivation of **other useful quantities** for cosmology like

$$D_A(z) \ , \ r_s \ , \ t_{\text{age}} \ \ldots$$

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Quantities that have to be evolved:

$$\frac{dt}{d\ln 1+z} = -\frac{1}{H(z)} \qquad \frac{d\ln \rho_{\rm fld}(z)}{d\ln 1+z} = 3(1+w_{\rm fld}(z))$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

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Thermodynamics module

Integration of the thermodynamic variables like temperature, ionization rate, and derivation of interaction rates

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This is actually complicated, and there ∃ some codes to solve this

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$$T \approx \frac{13.6\text{eV}}{39.9} \approx 0.34\text{eV} \rightarrow z \approx 1400$$

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- Slow processes:
- 2p → 1s with subsequent redshifting of photon

  or 2s → 1s with two-photon decay

Thermodynamical choices

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  - `Camb`
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- Spectral distortions (y, μ, PCA)
- Helium abundance: `YHe=0.25/BBN` `external/bbn/sBBN_2017.dat`

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Perturbation Module

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Einstein Boltzmann Solver:

Einstein Equations:

$$k^2\phi + 3\mathcal{H}(\phi' + \mathcal{H}\psi) = -4\pi G a^2 \delta\rho$$

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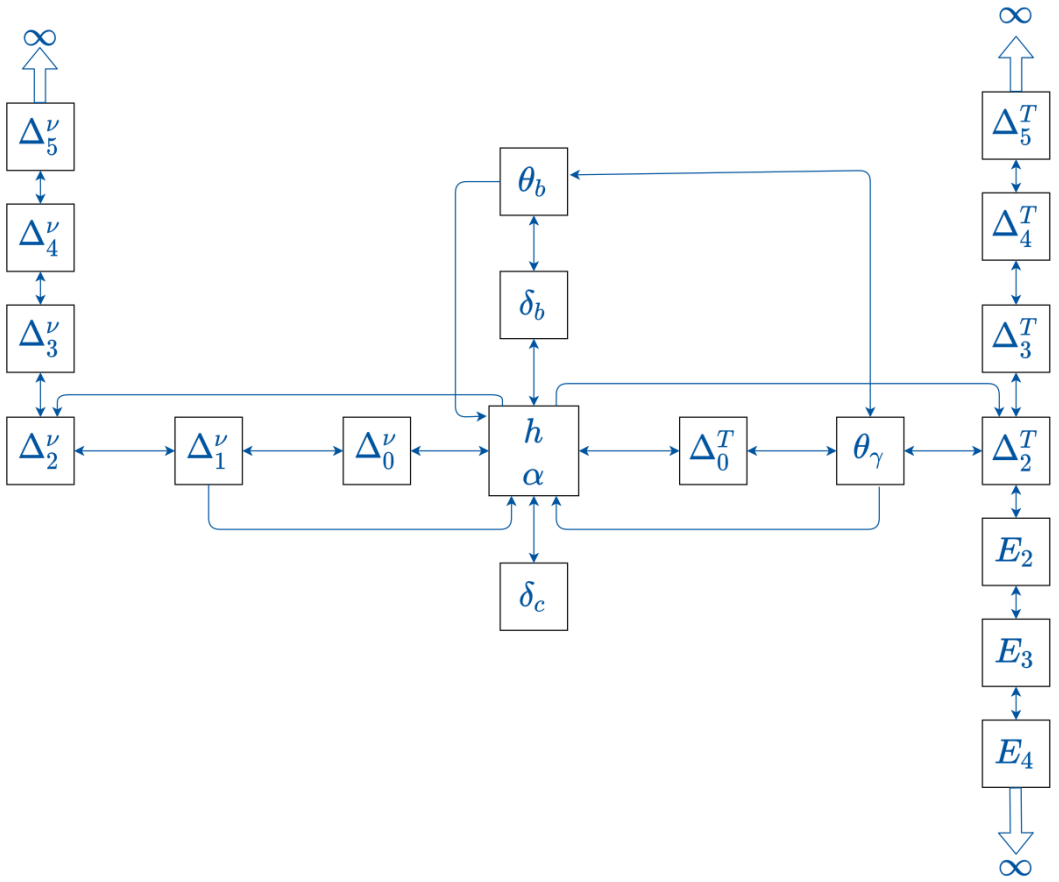

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Alternative:
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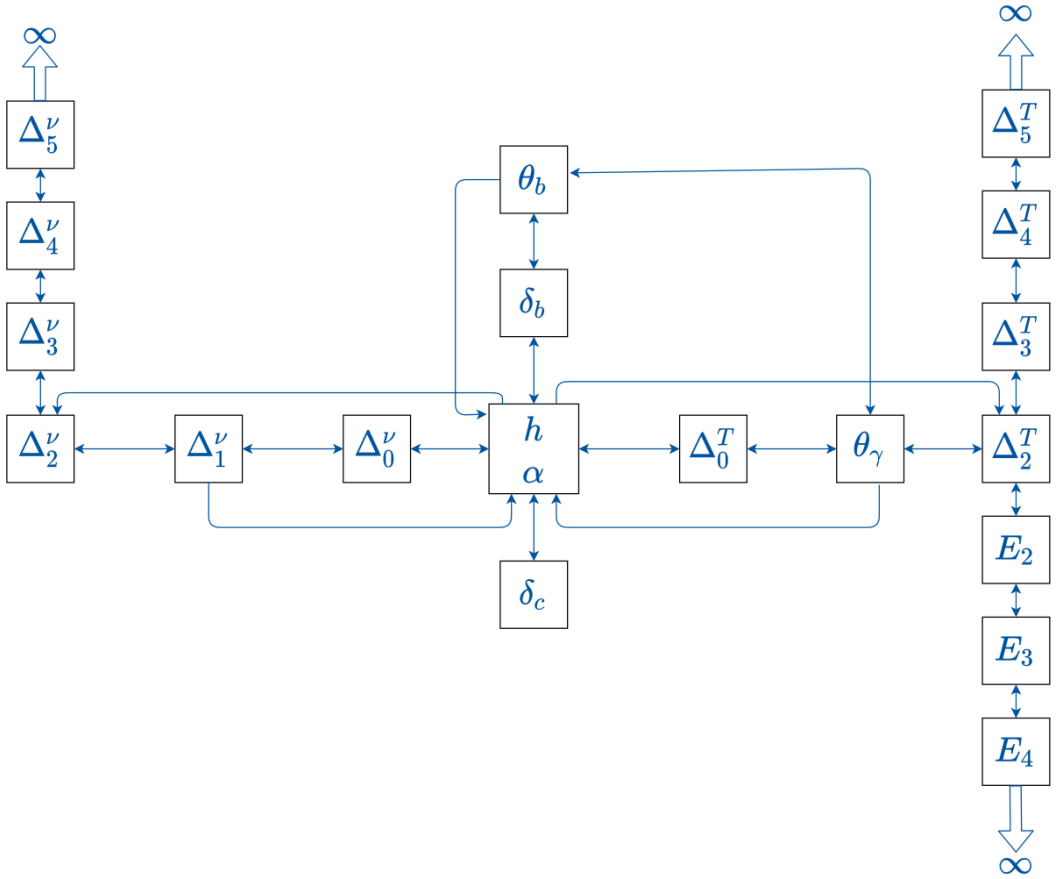

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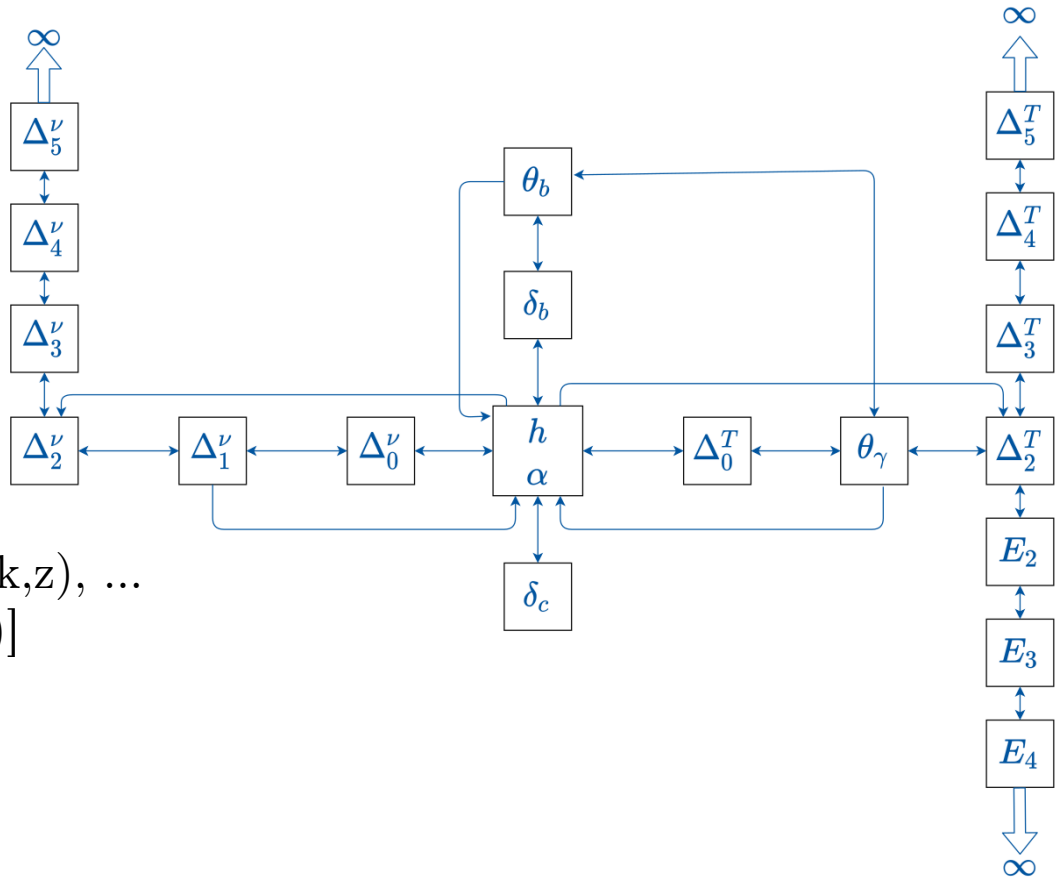

Solve the hierarchy of perturbations
→ Get source functions of CMB, P(k,z), ...
[Non-trivial combinations of δ, , g(z)]

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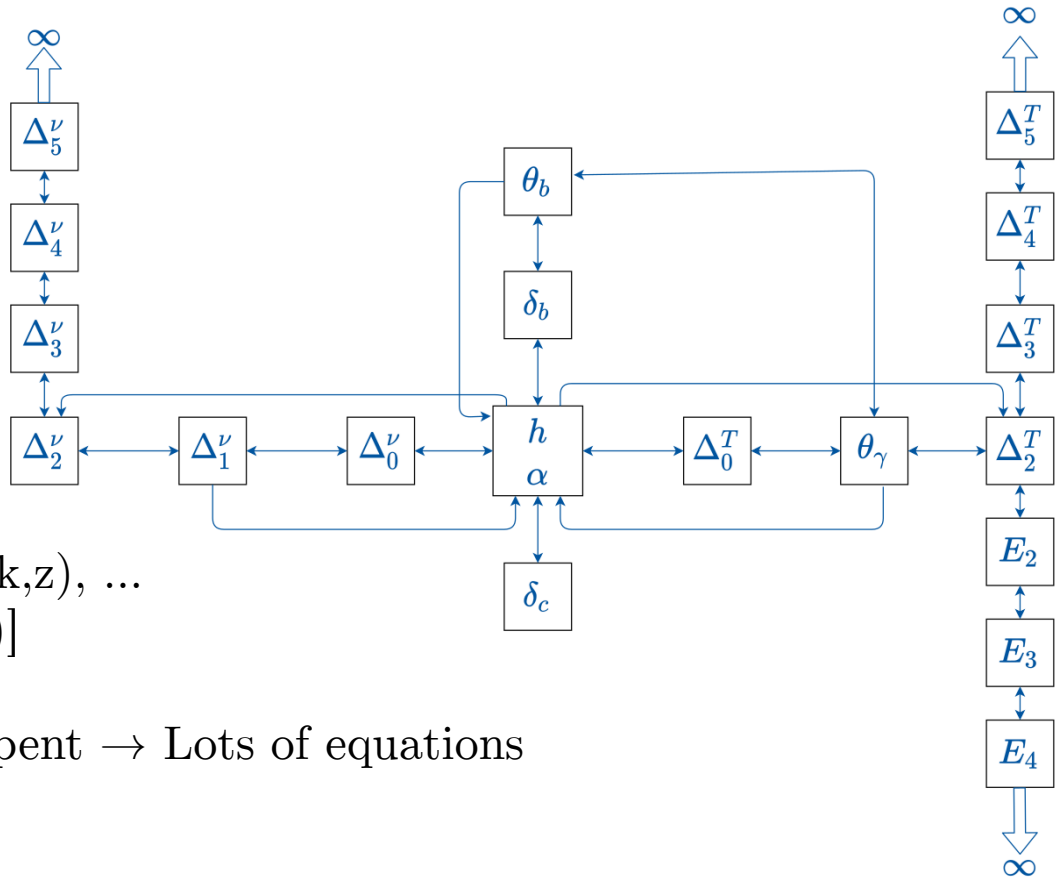

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This is usually where most time is spent → Lots of equations
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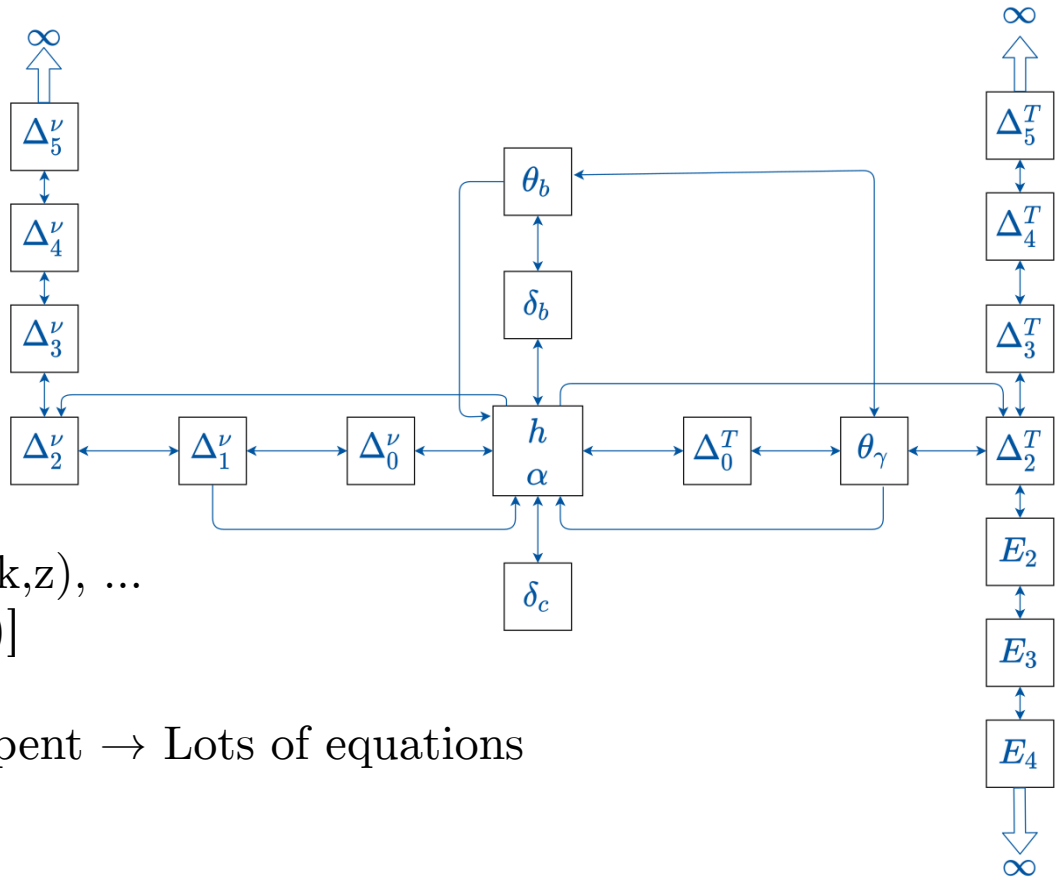

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Equations relative to $\mathcal{R} = 1$ initial condition

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Stiff ODE solver (ndf15)
Implicit using Newton method, Jacobian recycling
On-the-fly adaptive stepsize

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Primordial module

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- Either: Analytical power spectrum $P_{\mathcal{R}}(k)$

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Primordial stuff

- CLASS uses an inflation solver
- Taylor expansion in V(ϕ) / H(ϕ)
- Automatic determination of observable window
- Impose inflation duration

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- Impose inflation duration
- `Pk_ini_type = analytic_Pk`

$$P_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_{\rm piv}}\right)^{n_s - 1 + \alpha_s \ln k/k_{\rm piv}}$$

- `inflation_V, inflation_H, inflationV_end, two_scales`

  → `V_0…V_4 , R_0…R_4, PSR_0…PSR_4, H_0…H_4`

- Read spectrum from file (`external_Pk`)

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Fourier Module

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- Compute linear power spectrum of matter, cb

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  - HMcode2016
  - HMcode2020
  - (soon) perturbation theory

Model Inputs

Example: HMcode

$$\Delta^2_{\rm NL}(k,z) = \Big(\Delta^2_{\rm 1-halo}{}^{\alpha} + \Delta^2_{\rm 2-halo}{}^{\alpha}\Big)^{1/\alpha}$$

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$$P_{2-{\rm halo}} = P_{\rm dewiggle}\left[1 - f_{\rm damp}\frac{\left(\frac{k}{k_{\rm dam}}\right)^{\alpha_{\rm damp}}}{1+\left(\frac{k}{k_{\rm dam}}\right)^{\alpha_{\rm damp}}}\right]$$

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- $e^{i\vec{k}\cdot\vec{r}} = \sum (2\ell+1) i^{\ell} j_{\ell}(kr) P_{\ell}(\cos(\vartheta))$

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details: astro-ph/0502425

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- $\boxed{\vec{\alpha} = \nabla\psi} \rightarrow \int \frac{d^2\vec{l}}{2\pi}(i\vec{l})\psi_{\vec{l}}e^{i\vec{l}\vec{n}}$

$$\langle \alpha_i(\vec{n})\alpha_j(\vec{n}')\rangle = \int \frac{d^2\vec{l}}{(2\pi)^2} l_i l_j C_\ell^\psi e^{i\vec{l}(\vec{n}-\vec{n}')}$$

$$C_\ell^{xy,\text{lensed}} = 2\pi\int_{-1}^{1}\xi^{xy}(\mu)d_{00}^\ell(\mu)d\mu \quad \xi^{xy}(\mu) \sim \int C_\ell^{xy}\sum_i\left(C_\ell^{GLa_n}J_{2n}(\ell r)\right) \quad C^{GL}(r) = \int\frac{dll^3}{2\pi}C_\ell^{\Psi\Psi}J_0(lr)$$

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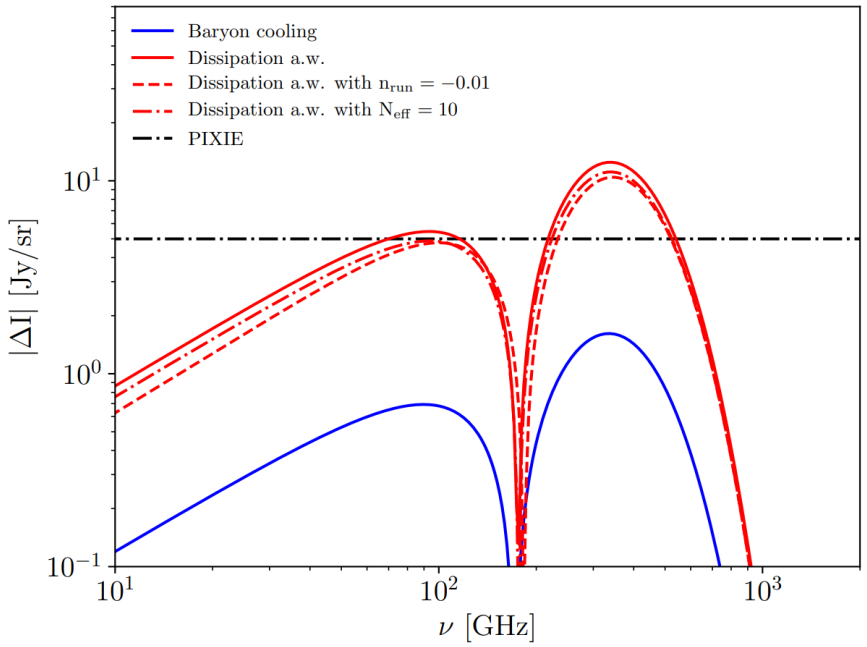
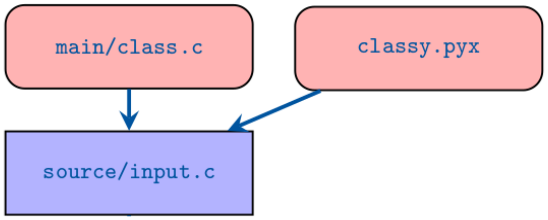
Distortions Module

- Computes injected energy into photons
- Computes distortions y μ that could be measured in the CMB in the future



The complete structure



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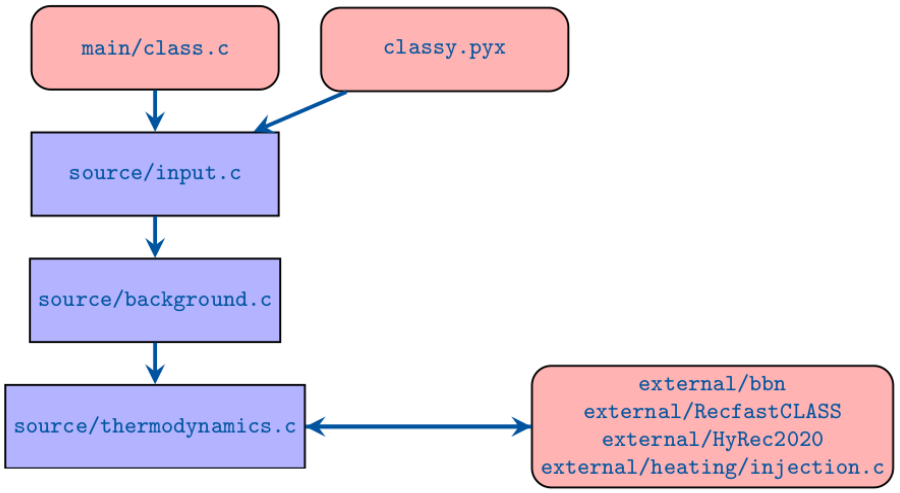

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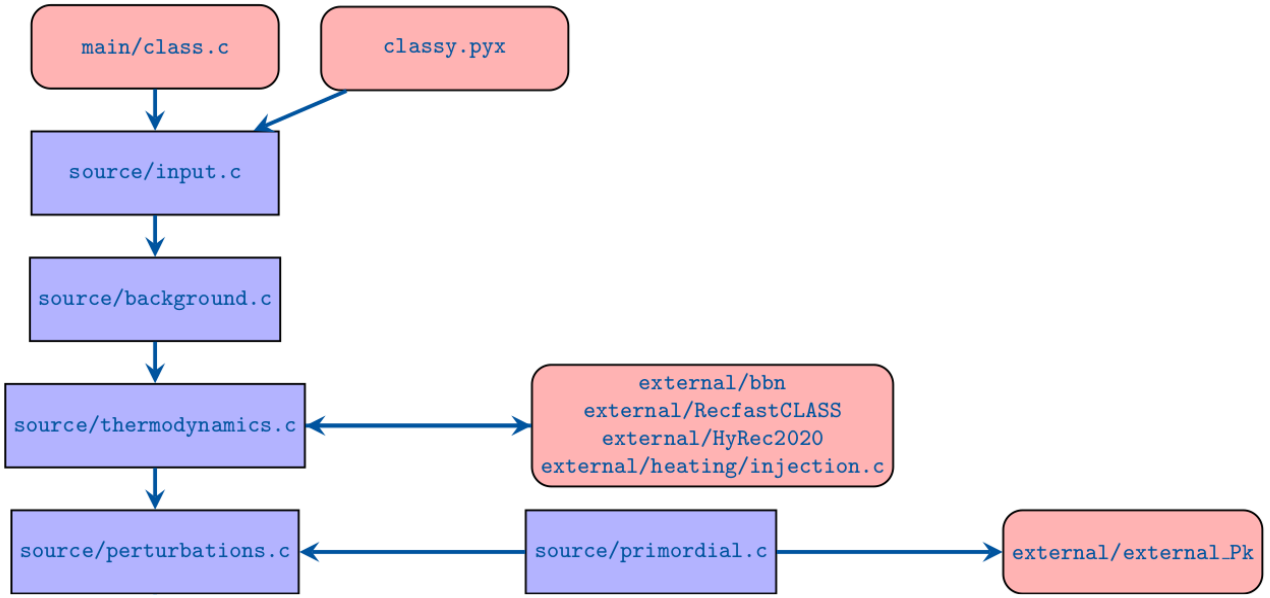

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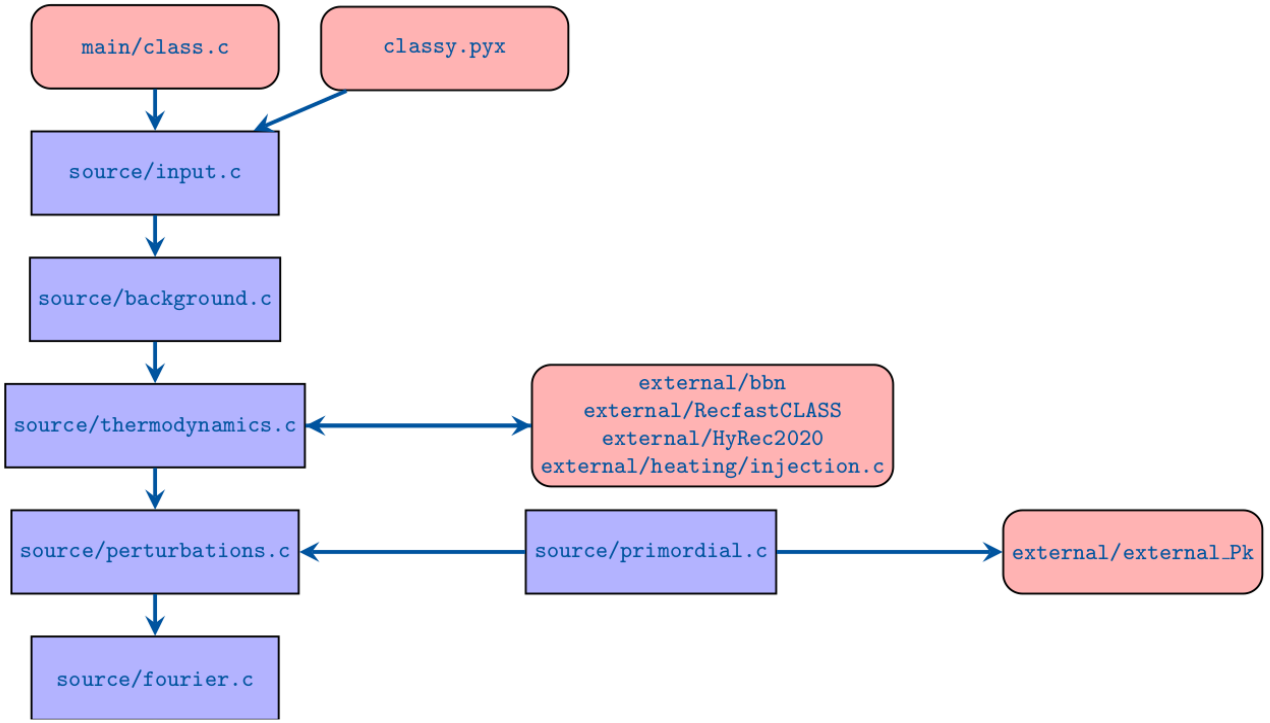

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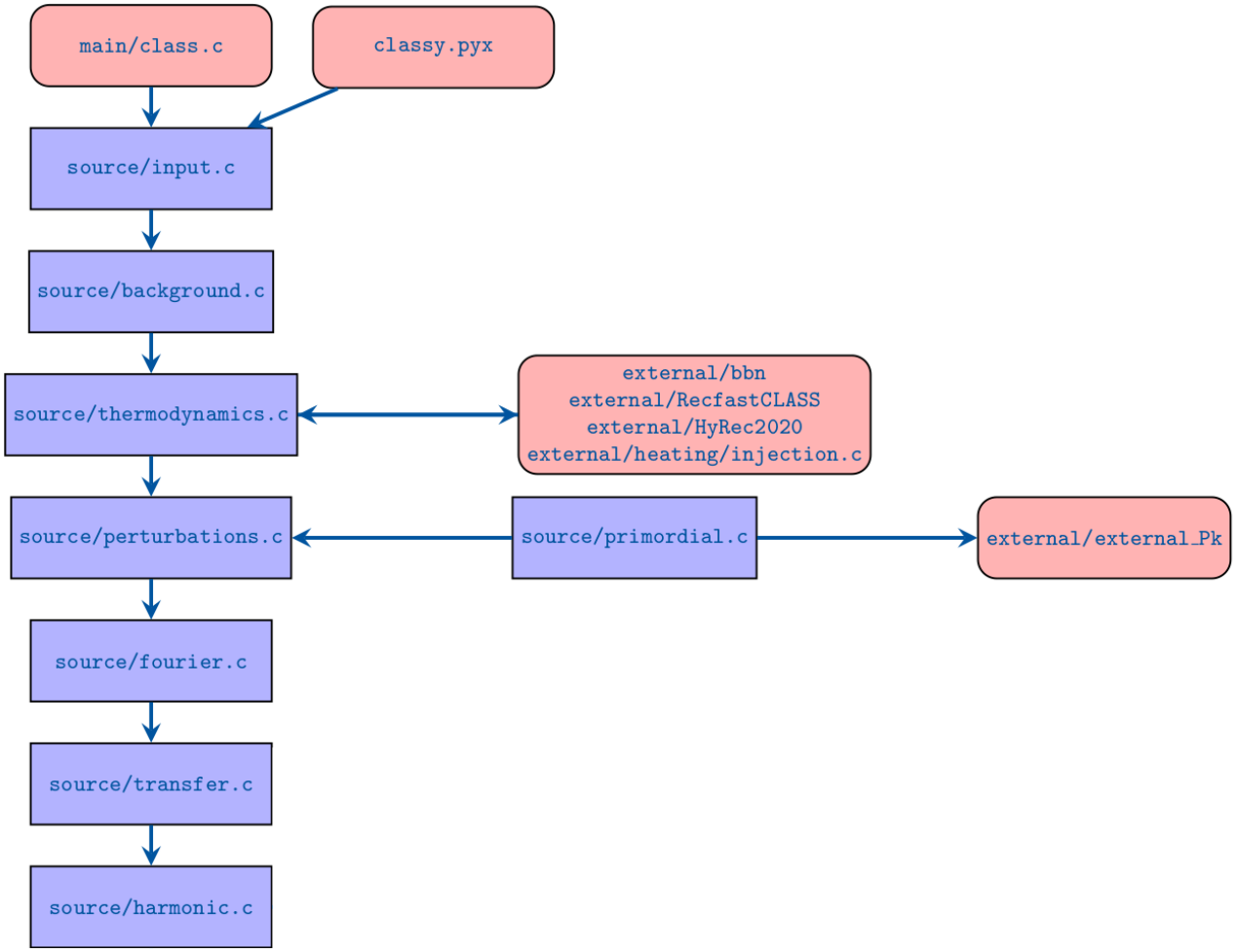

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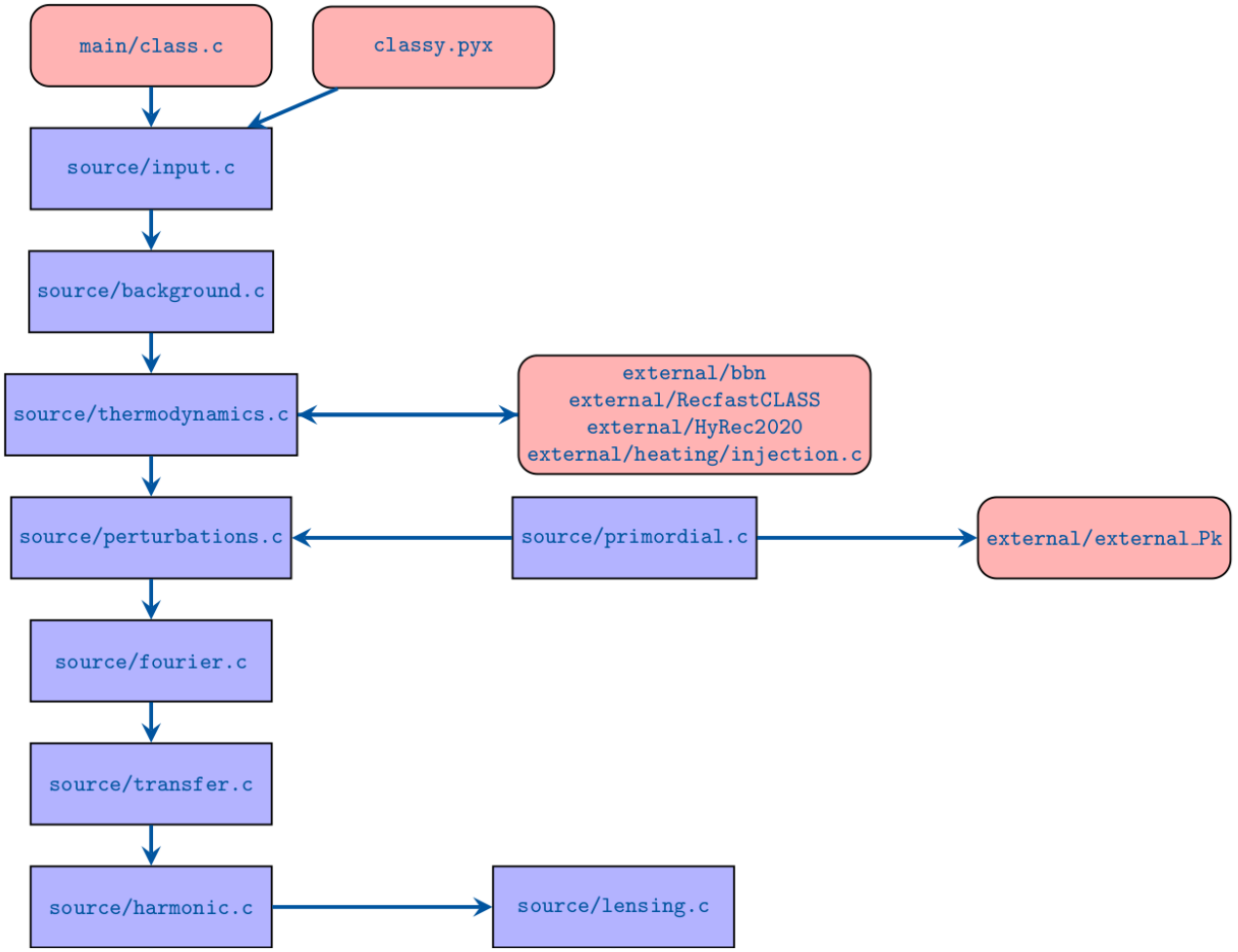

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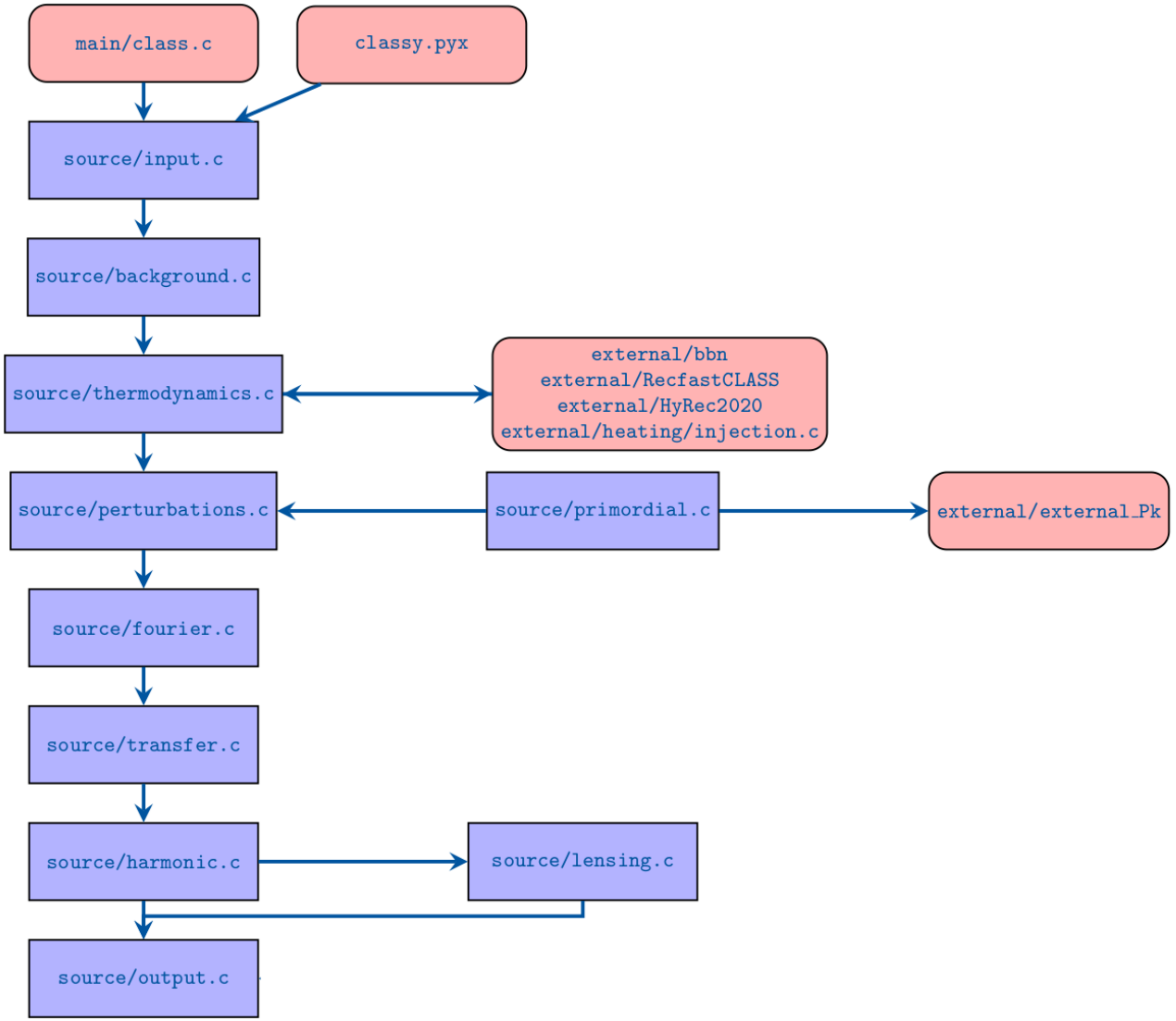

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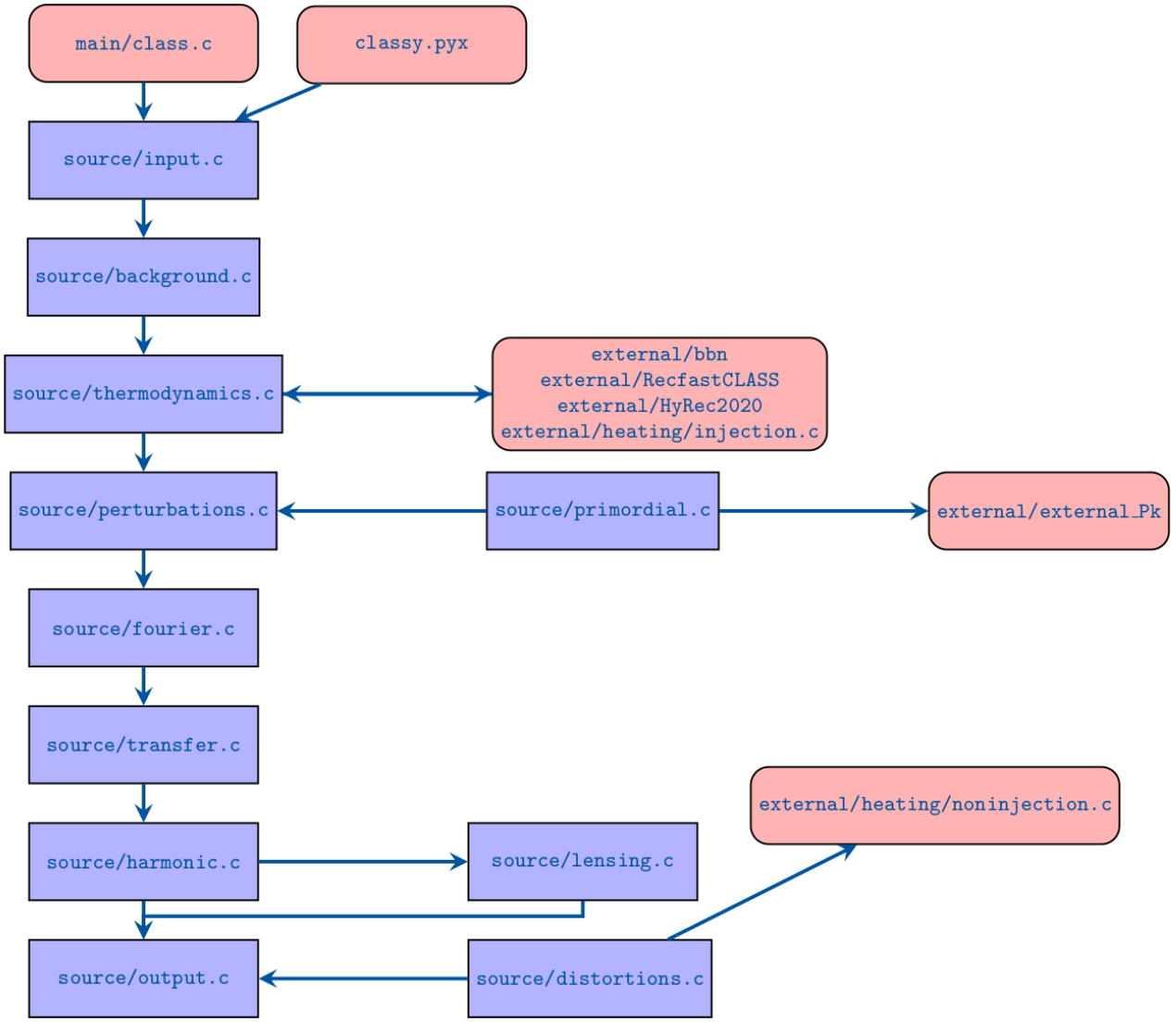

Careful

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- Density units are even weirder:

$$\rho_i^{\mathrm{CLASS}} = \frac{8\pi G}{3}\rho_i^{\mathrm{physical}}$$

$$H^2 = \sum_{\mathrm{species}\, i} \rho_i^{\mathrm{CLASS}}$$

Implementing new models

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- General guidelines:
  - Follow existing code conventions
  - Copy existing models and modify them
  - Main modifications likely to be in
    - `input.c`, `background.c`, `thermodynamics.c`, `perturbations.c`

Any Questions?

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Nitty Gritty Coding Stuff

Structure	Pointer	Description
input.c	--	Convert input strings into C variables, shooting
background.c	pba	Homogeneous background evolution
thermodynamics.c	pth	Recombination, reionization, energy injection
Perturbations.c	ppt	Linear perturbation theory (EBS)
Primoridal.c	ppm	Inflation, primordial P(k)
fourier.c	pfo	Power spectrum, nonlinear treatment
transfer.c	ptr	Line-of-sight integral
Harmonic.c	pha	Two-point correlation functions
Lensing.c	ple	CMB lensing
Distortions.c	psd	Spectral distortions
Output.c	pop	Output formatting/files

Nitty Gritty Coding Stuff

- Input management
- `parser_read`: Name → value, flag (manual assignment)
- `class_read`: Name → value

Type	parser	class_read
double	parser_read_double	class_read_double
int	parser_read_int	class_read_int
boolean	---	class_read_flag
string	parser_read_string	class_read_string
double list	parser_read_list_of_doubles	class_read_list_of_doubles_or_default
int list	parser_read_list_of_integers	class_read_list_of_integers_or_default
string list	parser_read_list_of_strings	---

Nitty Gritty Coding Stuff

```
class_call(parser_read_double(pfc,"monkey",&param1,&flag1,errmsg),
           errmsg,
           Errmsg);

if (flag1 == _TRUE_){
  pba->monkey = param1;
}
```

→ Much simpler:

```
class_read_double("monkey",pba→monkey);
```

Nitty Gritty Coding Stuff

```
class_call(parser_read_double(pfc,"H0",&param1,&flag1,errmsg),
           errmsg,
           errmsg);
class_call(parser_read_double(pfc,"h",&param2,&flag2,errmsg),
           errmsg,
           errmsg);
/* Test */
class_test((flag1 == _TRUE_) && (flag2 == _TRUE_),
           errmsg,
           "You can only enter one of 'h' or 'H0'.");
/* Complete set of parameters */
if (flag1 == _TRUE_){
  pba->H0 = param1*1.e3/_c_;
  pba->h = param1/100.;
}
if (flag2 == _TRUE_){
  pba->H0 = param2*1.e5/_c_;
  pba->h = param2;
}
```

Indexing rules

- Always written as
  - `index_name_type`
  - `index_bg_rho`
  - `index_pt_delta_cdm`
  - `index_ct_tt`
- Here `name` is the shortcut for the specific table/array that is referenced to, and `type` is the specific entry column in the table

Indexing rules

```
/* 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;
```

Features

- Always use:

```
if (has_feature == _TRUE_)  {
    …
}
```

Error Management

- Always use:

```
class_call(function, from, to);
```

- Example:

```
class_call(background_at_z(pba,z),
                   pba→error_message,
                   ppt→error_message);
```

- Always `return _SUCCESS_;` at the end

Error Management

- Use `class_test` and `class_stop`:

```
class_test(xsize < 2, errmsg,
  “Something went wrong with the size!”)
```

```
class_stop(errmsg,
  “How did I get here?!”)
```

Error Management

- ```
  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.e-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
  ```
  ```

Module layout

- Each module contains:

  One function `xxx_init(...)` filling the structure `xx`

  One function `xxx_free(...)` freeing all the memory allocated to this structure

  Some functions `xxx_external_1(...)`, ..., `xxx_external_n(...)` that can be called from other modules (e.g. to read correctly or interpolate the content of the structure `xxx`)

  Some functions `xxx_internal_1(...)`, ..., `xxx_internal_m(...)` that are called only inside the module, within `xxx_init(...)`

- Following order in `xxx.c`:

  ```
  xxx_external_1(...)
  ...
  xxx_external_n(...)
  xxx_init(...)
  xxx_free(...)
  xxx_internal_1(...)
  ...
  xxx_internal_m(...)
  ```

Memory allocation

- Unsafe allocation:

```
ptr = malloc(number*sizeof(type));
```

- Safe allocation:

```
class_alloc(ptr, number*sizeof(type),
            errmsg);
```

- Error management (e.g. if `number==0`)

Wrapper Additions

- classy.pxd:

```
class background:
    double new_thing
```

- classy.pyx

```
def newfunction():
    return bg.new_thing
```

cosmo.newfunction() → new_thing