Lecture 9: The Thermodynamics module

DAY IV : Thursday 30th October

09:30-10:15	CLASS	The thermodynamics module.	JL
10:15-11:00	MontePython	Internal structure of the code.	BA

Coffee

11:30-12:15	CLASS	The perturbation module.	JL

Lunch

13:30-14:15	CLASS	Playing with perturbations.	JL
14:15-15:00	General	Advanced ODE solvers. ndf15.	TT

Tea

15:45-16:30	Optional	Lecturers will answer questions	

Thermal history

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- solve recombination and reionisation, to compute the free electron fraction

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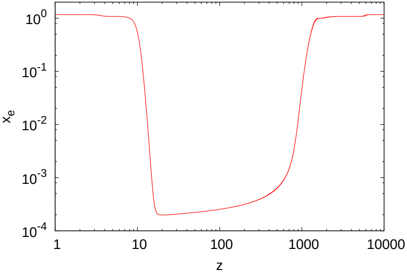

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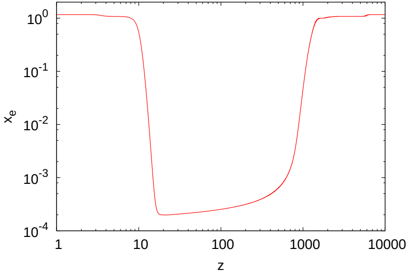

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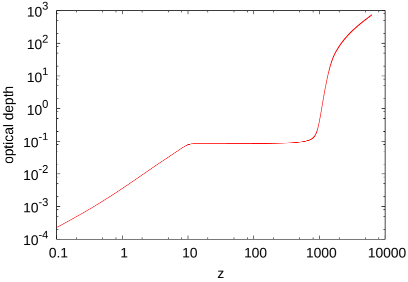
- Thomson scattering rate $\kappa' = \sigma_T a n_p x_e$: universe becomes transparent when $\kappa' < H$, i.e. at recombination

Thermal history

The module must:

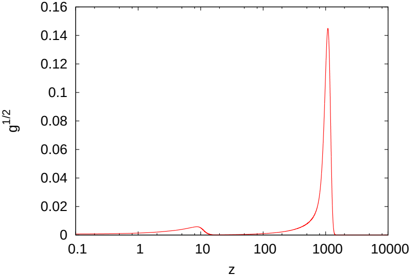
- integrate $\kappa' = \sigma_T a n_p x_e$ to get the optical depth of the cosmic fog, $\kappa(\tau) = \int_\tau^{\tau_0} \kappa' d\tau$



Thermal history

The module must:

- infer the visibility function $g(\tau) = \kappa' e^{-\kappa} =$ probability that last interaction took place at τ



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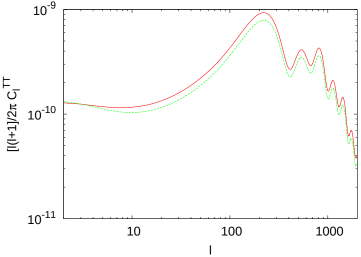
- In both cases, CLASS needs to keep in memory an interpolation table for just $\{x_e(z), T_b(z)\}$.

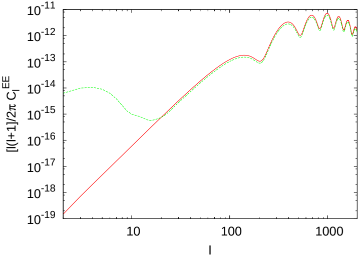
Recombination

- Recombination needs one more cosmological parameter: the primordial Helium fraction $Y_{\rm He}$.
- User can fix it to given value (e.g. `Y_He = 0.25`) or to `Y_He = BBN`. Then the value is infered from an interpolation table computed with a BBN code (Parthenope), for each given value of $N_{\rm eff}$, ω_b (assumes $\mu_{\nu_e} = 0$, easy to generalise).
- BBN interpolation table located in separate directory, in `bbn/bbn.dat`

Reionization

- reionisation very uncertain. Can be probed directly by looking at IGM (Lyman-α, ...) but with large uncertainties.
- CMB probes mainly an integrated quantity, $\tau_{\rm reio} = \int_{\tau_*}^{\tau_0} \kappa' d\tau$, close to 0.09. Gives suppression of C_l's at large l due to rescattering.
- small-l CMB (T and even better E) gives information on history (i.e. on $x_e(z)$, through $\kappa'(z)$).





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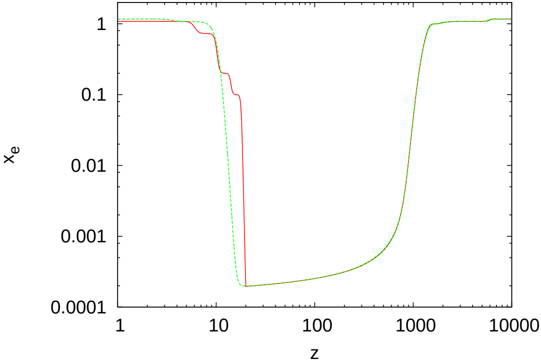
- Module in charge of
  1. applying the function chosen by the user (`reio_parametrization =`, and extra parameters ...)
  2. ensuring automatically a smooth transition at some $z \sim 40$ between the solution for $x_e(z)$ computed by the recombination code, and the requested reionisation function.

Reionization

- if `reio_parametrization = reio_camb`, $x_e(z)$ has a $tanh$-shaped step, centered on $z_{\rm reio}$, and matched to the correct value corresponding to freeze-out after recombination. User free to pass either `z_reio = ...` or `tau_reio = ...`. Codes find the missing one automatically, stores it in `pth` (and indicates it in output if `thermodynamics_verbose` > 0).

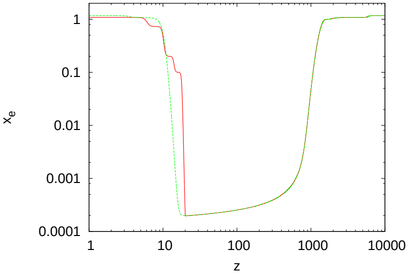


Reionization models

- instead, if `reio_parametrization = reio_bins_tanh`, code assumes a binned reionisation history, with smooth $tanh$ steps between bin centers. User passes e.g.

```
binned_reio_num = 3
binned_reio_z = 8,12,16
binned_reio_xe = 0.7,0.2,0.1
binned_reio_step_sharpness = 0.3
```

- then `tau_reio` cannot be passed in input, but calculated, stored and given in output.



Quantities stored in thermodynamics_table

The table `pth->thermodynamics_table[index_z*pth->th_size+pba->index_th]` has indices:

`index_th_xe`	ionization fraction	x_e
`index_th_dkappa`	Thomson scattering rate	κ' (units Mpc^{-1})
`index_th_tau_d`	Baryon drag optical depth	$\int_\tau^{\tau_0} \frac{4\rho_\gamma}{3\rho_b}\kappa' d\tau$
`index_th_exp_m_kappa`	exp. of (photon) optical depth	$e^{-\kappa}$ with $\kappa = \int_\tau^{\tau_0} \kappa' d\tau$
`index_th_g`	visibility function	$g = \kappa' e^{-\kappa}$
`index_th_Tb`	baryon temperature	T_b given by RECFAST
`index_th_cb2`	squared baryon sound speed	$c_b^2 = \frac{k_B}{\mu} T_b \left(1 - \frac{1}{3}\frac{d\ln T_b}{d\ln a}\right)$
`index_th_rate`	max. variation rate	(for sampling the sources)

(plus extra indices for other derivatives: κ'', κ''', g', g'', $(c_b^2)'$, $(c_b^2)''$).

Look in `include/thermodynamics.h`

External functions in thermodynamics.c

- thermodynamics_at_z(pba,pth,z,...,pvecthermo): interpolates in thermodynamics table (stored in pth) at a given z, returns a vector pvecthermo.

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- it stores the related quantities pth->z_d, pth->tau_d, pth->ds_d, pth->rs_d (the latter gives the phase of the BAOs in large scale structure).

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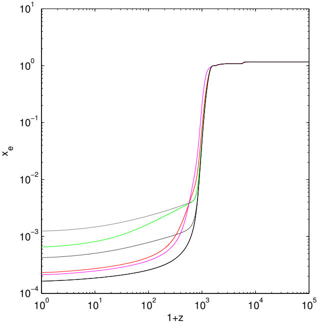
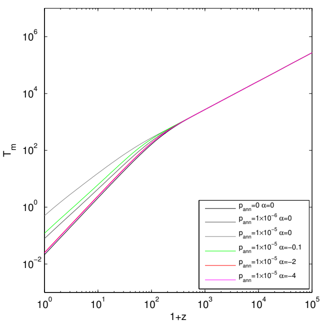
- RECFAST solution slightly smoothed around points where solution is not derivable. Just useful for testing the limit of high accuracy / small stepsize in RECFAST.
- several input parameters allow to play with a DM annihilation effect, as described in Giesen et al. 2012. Effect on x_e and T_b, with signatures on CMB.





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2. use python, classy, and `thermo = cosmo.get_thermodynamics()`