Recombination exercises

1 Warmups

a) Run Recfast++ (with/without correction function) and CosmoRec for $\Omega_c = 0.216$, $\Omega_b = 0.044$, $\Omega_k = 0$, $T_0 = 2.726\,\mathrm{K}$, $h = 0.7$, $Y_p = 0.24$ and $N_{\rm eff} = 3.046$ (default run-mode settings otherwise). Plot the resulting free electron fraction, X_e, and their relative difference, $\Delta X_e/X_e$, (CosmoRec & Recfast++ with correction function relative to Recfast++ without correction function) as a function of redshift for $z = [0, 3000]$. [*Hint: make sure to interpolate the solutions to a common grid if you compute relative differences between datasets*]

b) Repeat a) but set $\Omega_b = 0.02$. Are the differences between Recfast++ and CosmoRec relevant? Any idea what the main cause for the difference is?

c) Repeat a) but set $Y_p = 0.1$. Are the differences between Recfast++ and CosmoRec relevant? Any idea what the main cause for the difference is?

2 Exploring some standard CosmoRec options

a) Run CosmoRec for the cosmology given in 1a) and change the effective number of shells that is included for the hydrogen atom. Plot the free electron fraction, X_e, for $n_{\rm eff} = \{20, 100, 500\}$ and briefly explain the physical reason for the differences in the freeze-out tail.

b) Plot the relative difference in the free electron fraction when including (i) stimulated 2s-1s transitions, (ii) the 1s-2s feedback effect and (iii) both effects. Do you understand the physics behind the differences?

c) Plot the free electron faction around helium recombination ($z = [1500, 3000]$) fpr (i) default case, (ii) the spin-forbidden lines off, (iii) feedback among the helium lines included and (iv) feedback among the helium lines included but without HI absorption between lines.

3 Exploring some non-standard CosmoRec features

a) The heart of the CosmoRec radiative transfer module for hydrogen resides in the directory `./PDE_Problem/` with the driver `./PDE_Problem/Solve_PDEs.cpp`. Can you plot the high frequency distortion at a few redshifts ($x^3\Delta n$ as a function of x is fine)? Does the figure make sense to you? Can you change the number of outputs in redshift and the frequency resolution?

b) What about the 2s-1s two-photon profile? Do you know how to access it? Also, how about the 5d-1s two-photon profile and the 4s-1s Raman profile? [*Hint: have a closer look at* `./PDE_Problem/Solve_PDEs.cpp` *and be clever with uncommenting things. Also, make sure you included enough hydrogen shells*]

c) The main setup for the hydrogen and helium atom models can be found in `./Modules/HI_routines.cpp` and `./Modules/He_routines.cpp`, respectively. If you were interested in atomic transitions rates and recombination rates for certain levels, this would be a good place to start. Can you setup a 30-shell hydrogen atom (make it 100 if you are brave) and compute the vacuum dipole transition rate for $(27, 5) \rightarrow (22, 4)$? How about the recombination rates for $T_e = 3500\,$K in a blackbody radiation field at $T_\gamma = 3000\,$K to each of these levels? Why does T_γ enter the problem? [*Hint: if you want to know how to access those rates check the* `./Development/Hydrogenic/Atom.h` *header-file. The recombination rate setup also has to be activated*]

4 Dark matter annihilation and decay with CosmoRec

a) Run CosmoRec switching the annihilation efficiency to $f_{\rm ann} = 10^{-23}\,{\rm eV\,s^{-1}}$. Illustrate the effect on the free electron faction. What happens when you set a high annihilation rate $f_{\rm ann} = 10^{-22}\,{\rm eV\,s^{-1}}$? Any idea how to solve the problem?

b) Repeat a) but using Recfast++ and compare the results. How large are the effects for $f_{\rm ann} = 10^{-22}\,{\rm eV\,s^{-1}}$?

c) The dark matter annihilation terms are defined in the file `./Modules/DM_annihilation.cpp`. Can you modify the code to include decaying particles instead? Argue why the effective heating rate for decaying particles can be parametrized as $\mathrm{d}E/\mathrm{d}t = f_X \Gamma_X N_H(z)\, e^{-\Gamma_X t}$, where $\Gamma_X = 1/t(z_X)$ sets the lifetime of the particle and f_X the energy-release efficiency. Plot the free electron fraction for some reasonable values of f_X (estimate the best values or try a bit starting really small) and $z_X = 900$. [*Hint: you will need the function* `cosmos.t(z)` *from the Cosmology-object to obtain the cosmological time as a function of redshift*]

d) Plot the final shape of the high frequency distortion for the decaying particle model of 4c) and dark matter annihilation with $f_{\rm ann} = 5 \times 10^{-23}\,{\rm eV\,s^{-1}}$. Do you understand the differences?