Simulations of the Epoch of Reionization with the LICORICE code

S. Baek, P. Di Matteo, B. Semelin, F. Combes, Y. Revaz
LERMA, Observatoire de Paris

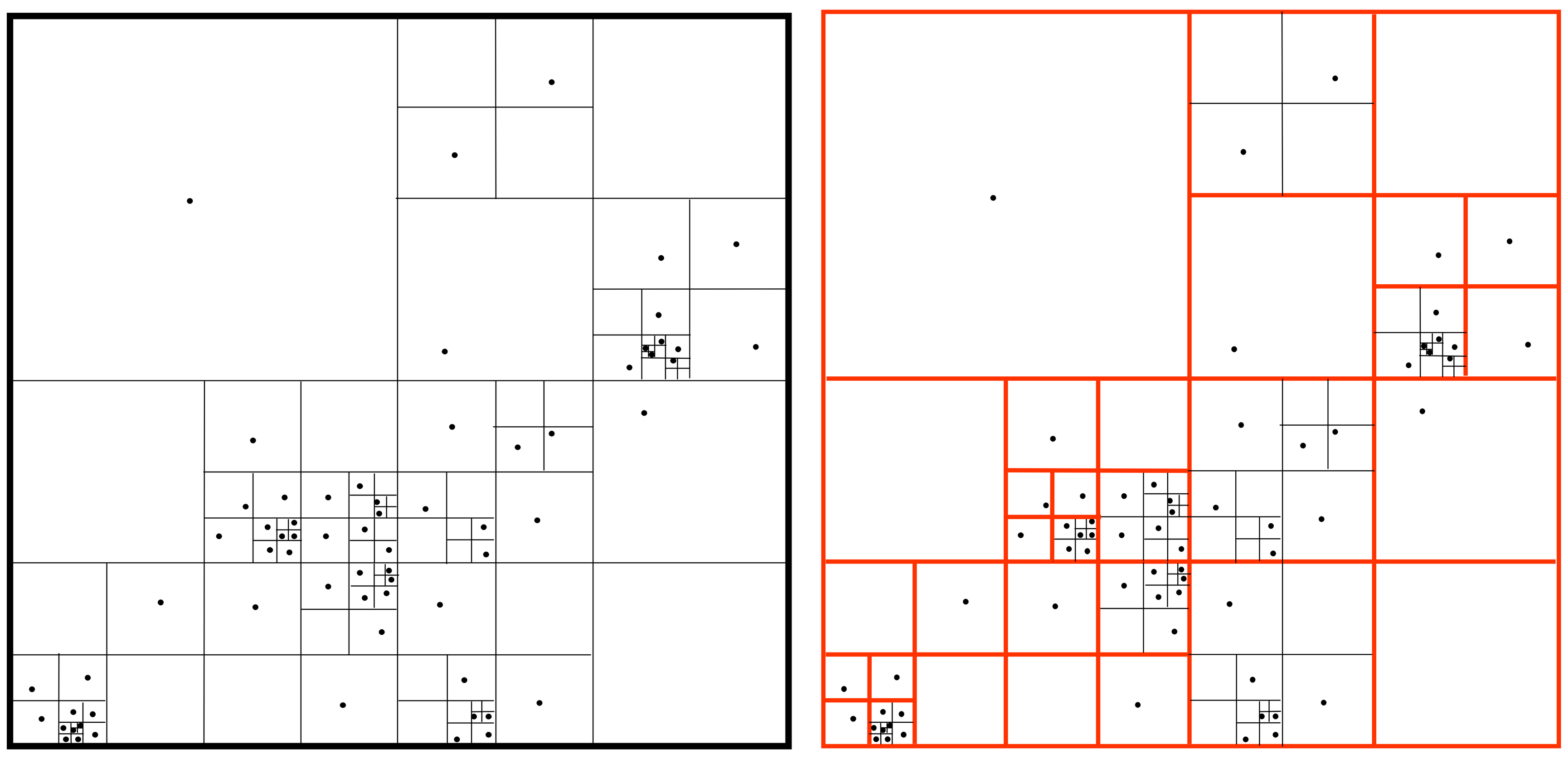
Abstract

We present our code, LICORICE, and results of cosmological simulations of the Epoch of Reionization. LICORICE is developed for computing radiative transfer of UV continuum and Ly-alpha line. Two simulations each with 256^3 dark matter particles and the same number of baryonic particles have been run in different box size : 20 h^{-1}Mpc(S20) and 100 h^{-1}Mpc(S100). In our simulations, full reionization occurs around the redshift 6 which is in good agreement with the quasar absoption observation of SDSS. Thompson optical depth are consistent with 1σ value from WMAP 3rd year results.

LICORICE Code

We use a 3D Monte Carlo ray-tracing scheme for radiative transfer. The implemented numerical methods are similar to CRASH presented by Maselli et al.(2003). The radiation field is discretized into photon packets and the space is discretized into cells. The photon packets emitted from the sources propagate into these cells and deposit a fraction of their photon and energy content depending on the optical depth of the cell. Physical quantities of each particle are updated according to the number of photons or energy deposited in the cell during integration time step Δt_{RT}. We describe the main differences between our code and CRASH in the following.

Adaptative Grid

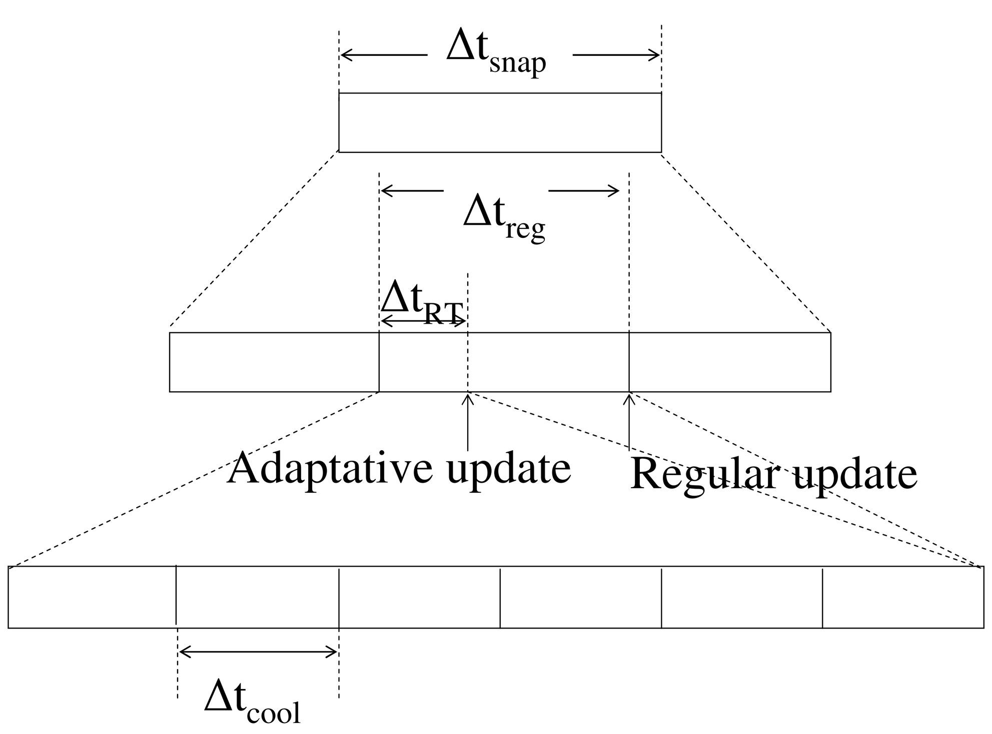


(a) Adaptative grid for TreeSPH dynamical part of LICORICE.

(b) Orange grid, called RT cells, are the adaptative grid for radiative transfer of UV continuum and Ly-α line. Each RT cells contains less than N_{max} particles, which is a tunable parameter. N_{max}=8 is used for this representation. So all RT cells contains less than 8 particles.

LICORICE uses an adaptative grid which is built using the oct-tree algorithm implemented in the dynamical part. However, the dynamical part is not used in this simulation. In the radiative transfer part, the photon packets emited from the source propagate through the cells, but these cells can cantain several particles.. Therefore we construct the RT grid so that the each RT cell contains less than the parameterized value N_{max}. It results in lower memory and CPU-time requirements than a regular grid.

Adaptative time integration

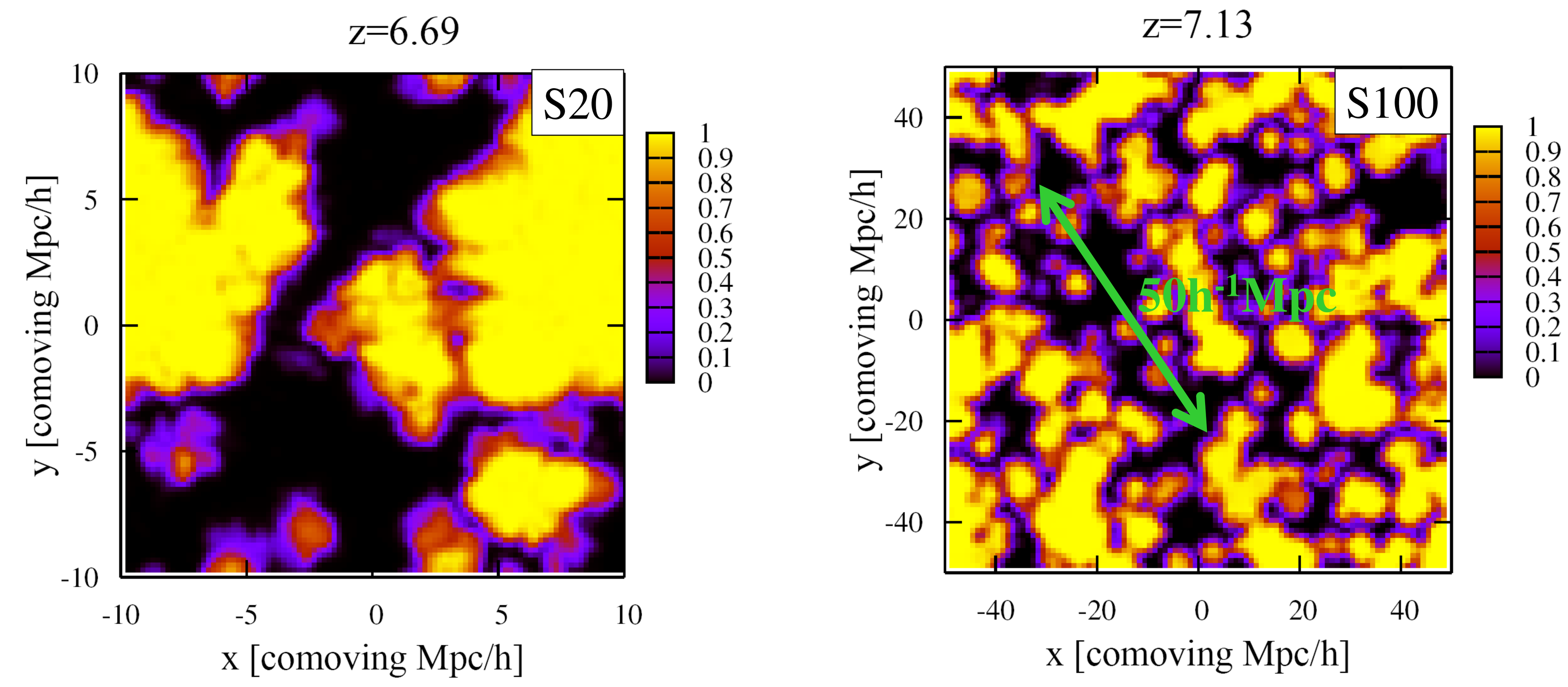


Δt_{snap} is the time interval between two snapshots of the dynamical simulation. The integration time step for updating the physical quantity, Δt_{RT}, is adaptative. We update automotically the physical quantities for all particles after the propagation of a given amount of photon packets within Δt_{reg}.

However, if the number of accumulated photons in a cell during this integration time Δt_{reg}, is greater than pre-set limit(e.g. 10% of the total number of neutral hydrogen atoms in the cell), we update them with a time step Δt_{RT} ($<\Delta t_{reg}$) corresponding to the time elapsed since the last update in this cell. Time step for recombination and cooling, Δt_{cool} is 100 times smaller than Δt_{RT}.

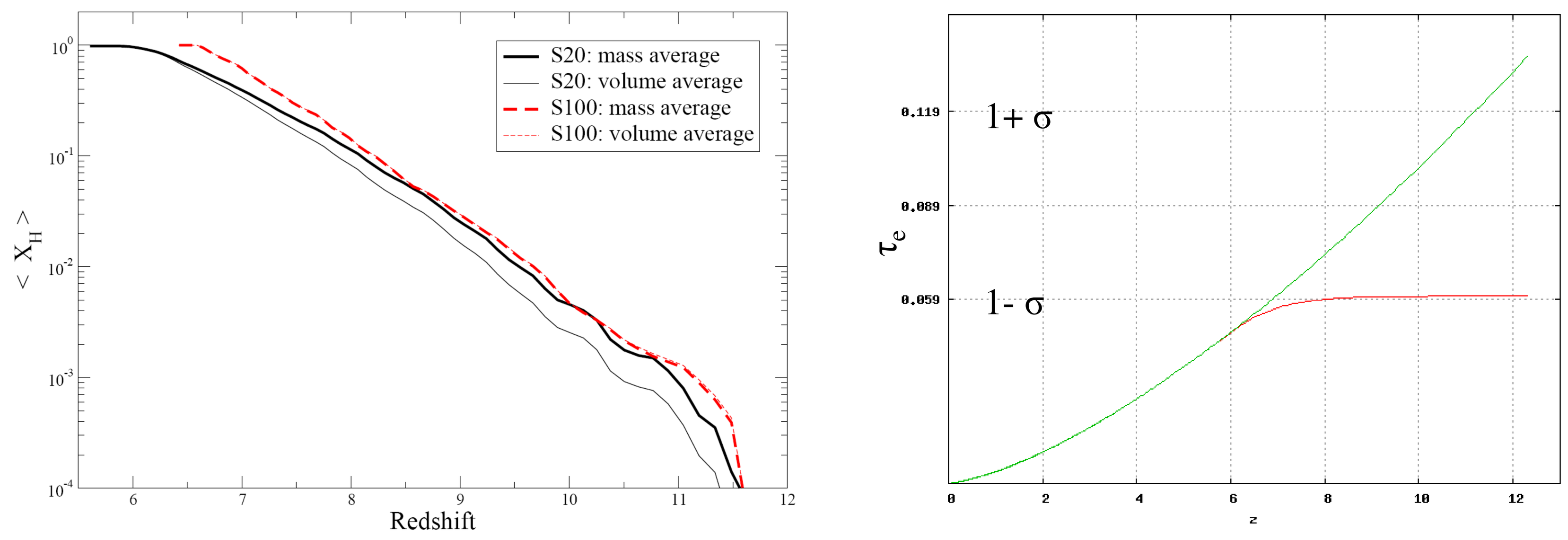
Results

Ionization map



We present maps of the ionization fraction of hydrogen for both box sizes at a redshift when $\langle x_H \rangle$ =0.5. The slice thickness is 2 h^{-1}Mpc. The 100 h^{-1}Mpc simulation shows coherent structures on scales up to 50 h^{-1}Mpc which cannot exist in the 20 h^{-1}Mpc maps.

Ionization Fraction and Thompson optical depth

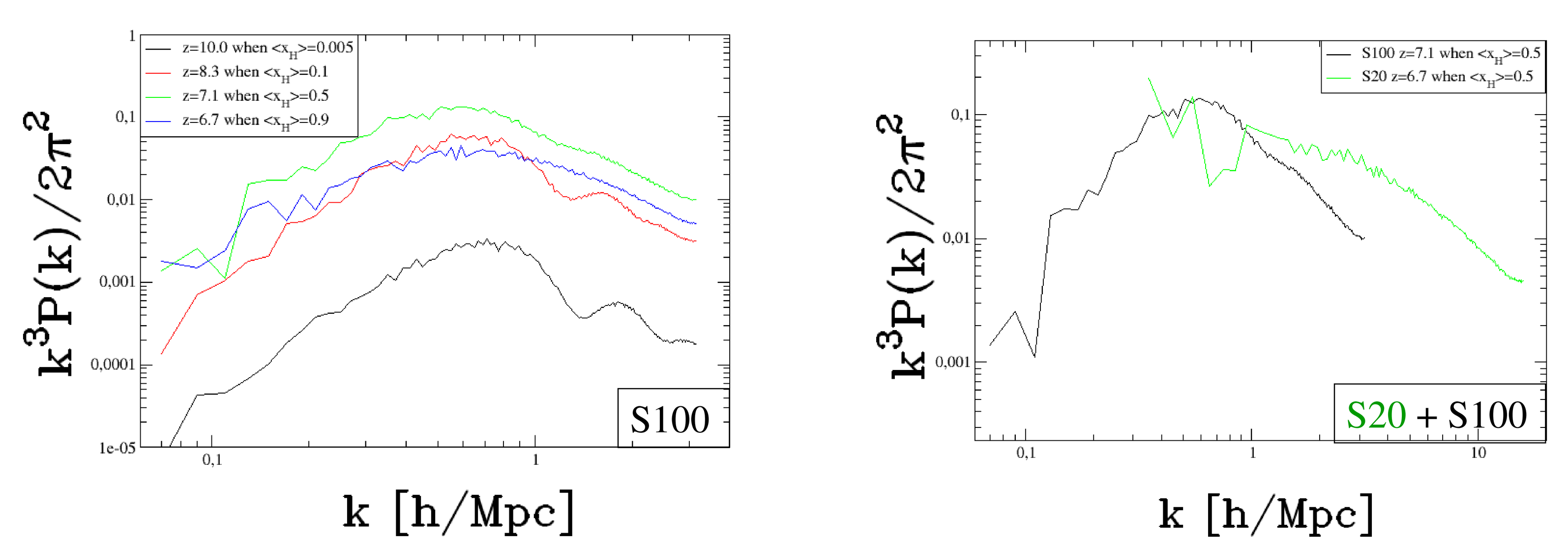


(a) Mass weighted and volume weighted averaged ionization fraction.

(b) The integrated Thomson optical depth from simulations(red). Green curve shows the optical depth produced assuming complete ionization out to corresponding redshift. Horizontal lines are the best-fit and 1σ uncertainties of the 3rd year WMAP results. (τ_e=0.089± 0.030; Spergel et al. 2007)

The star formation histories of the two simulations were calibrated to produce the same amount of ionizing photons. Indeed, the mass weighted ionization fractions shows similar evolution. We also compute the Thomson optical depth from the simulations ignoring the presence of helium. It seems that the relatively small value of τ_e=0.06 is due to the late star formation of our simulations.

Power Spectrum



Power spectra of ionization fraction, $\delta \equiv x_H$, for the two simulations are presented. 4 spectra in the left figure are from S100 simulation at different redshift. They increase until $\langle x_H \rangle$=0.5 where the ionization maps show structures on all scales then decrease. We superposed two spectra of the S100 and S20 simulations in the right figure. Two curves superpose around middle value of k but S20 miss power on large scales while S100 does on small scales on the contrary.