The simulated 21 cm signal during the EoR : Ly-α and X-ray fluctuations

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Physics of the 21 cm Line

LICORICE for the 21 cm Transition

Simulations

X-ray effect on T_k

Future Work

Physics of the 21 cm Line

The Differential Brightness Temperature

$$\delta T_b \approx 28.1\,\mathrm{mK}\,x_{\mathrm{HI}}(1+\delta)\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\frac{T_S - T_{\mathrm{CMB}}}{T_S}\frac{H(z)/(1+z)}{dv_r/dr}$$

The usual assumption $T_s \approx T_k \gg T_{CMB}$

- No need for computing T_s or T_k
- No signal in absorption

Is $T_s \approx T_k \gg T_{CMB}$ always true?

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_c^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

1. $T_s \approx T_k$ is true either

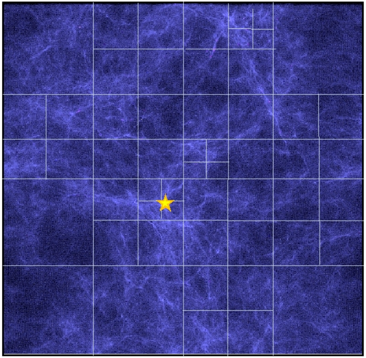
- $x_\alpha \gg 1$: sufficient Ly-α scattering (not in the early EoR)
- $x_c \gg 1$: sufficient collision (effective where $\delta\rho/\rho$)

2. $T_k \gg T_{CMB}$ is true

when neutral IGM in the voids is sufficiently pre-heated.

$\Longrightarrow$ In some cases(Early EoR), we need to compute $T_k(\vec{x}, z)$ and $T_s(\vec{x}, z)$ as well as $x_{HI}(\vec{x}, z)$ for an exact estimation of 21 cm transition.

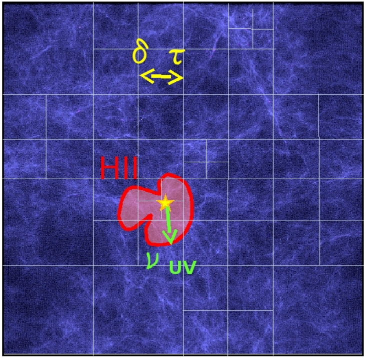
The code : LICORICE



General RT methods

- Monte Carlo ray-tracing
- Adaptive grid

The code : LICORICE



General RT methods

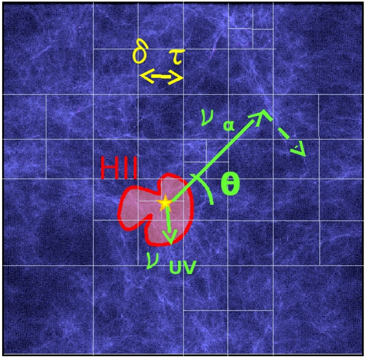
- Monte Carlo ray-tracing
- Adaptive grid

1. Compute $T_k(\vec{x}, z)$ and $x_{HI}(\vec{x}, z)$ in UV Continuum and now X-rays continuum

- Hydrogen and Helium
- Heating and Cooling process
- Adiabatic expansion
- Adaptive time step for ionization and cooling

+ ... shock heating(future work): need coupled hydro radiative simulation!

The code : LICORICE



2. Compute $T_s(\vec{x}, z)$ with Ly-α line transfer (Semelin et al. 2007)

- local x_α value from Ly-α line transfer
- Fully cosmological (redshifting photons, retarded time)
- Several acceleration schemes(a few tens of scatterings instead of 10^6)

General RT methods

- Monte Carlo ray-tracing
- Adaptive grid

The code : LICORICE

A typical run

2×256^3 particles, 130 snapshots from $z \sim 40$ to $z \sim 6$
Dynamics with GADGET (Y.Revaz)

Continuum RT

- $\sim$1000 CPU hours
- $\sim$10 Go shared memory(OpenMP)
- $\sim 10^8$ photon packets

Ly-α RT

- $\sim$1000 CPU hours
- $\sim$10 Go shared memory(OpenMP)
- $\sim 10^8$ to 10^9 photon

The next step

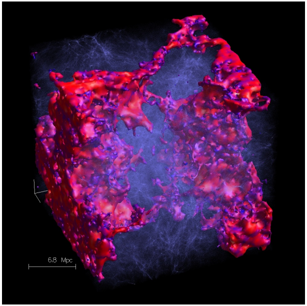
2×512^3 particles in a 100 Mpc/h box ($\sim 10^9 \mathrm{M}_\odot$ halos)
Dynamics : done
RT : Possible on Vargas(IDRIS). 256 Go on a single node.

Simulations(Baek et al. 2008)

- 256^3 DM + 256^3 Baryons(no He)
- 20 Mpc/h(S20) and 100 Mpc/h(S100) box size
- $8 \times 10^8 \mathrm{M}_\odot$ and $10^{11} \mathrm{M}_\odot$ resolved halos for S20 and S100 simulations

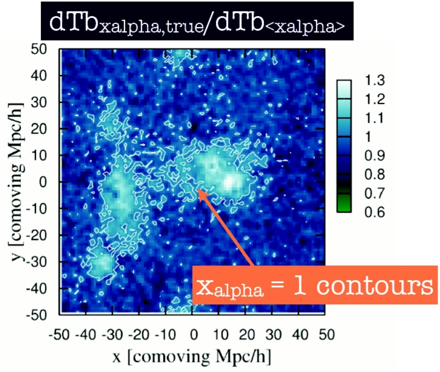
The simulation pipeline

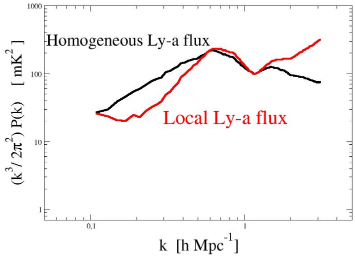
1. Dynamic (GADGET) $\Rightarrow$ Baryon overdensity, Star formation
2. UV continuum RT (LICORICE) $\Rightarrow$ $T_k(\vec{x}, z)$, $x_{HI}(\vec{x}, z)$
3. Ly-α RT (LICORICE) $\Rightarrow$ $T_s(\vec{x}, z)$



movie movie

Result 1. 3D Line transfer is necessary

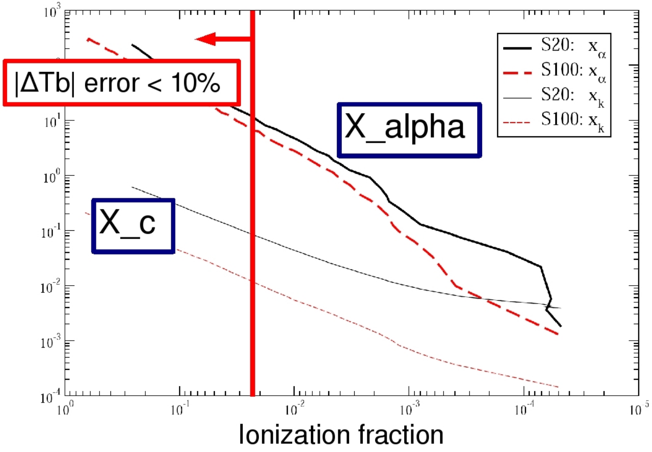




Local Ly-α flux $x_\alpha(\vec{x}, z)$ vs. homogeneous flux $x_\alpha(z)$ show up to 50% difference in δT_b locally

Visible effect in the 3D powerspectrum when $< x_\alpha >= 1$ (Directly observable by interferometers)

Result 2. x_α is not always $+\infty$



When $x_\alpha > 10$ ($< x_{HII} > \approx 0.04$), the error made on δT_b by assuming $x_\alpha = +\infty$ is smaller than $\sim 10\%$

Result 3. Signal in absorption

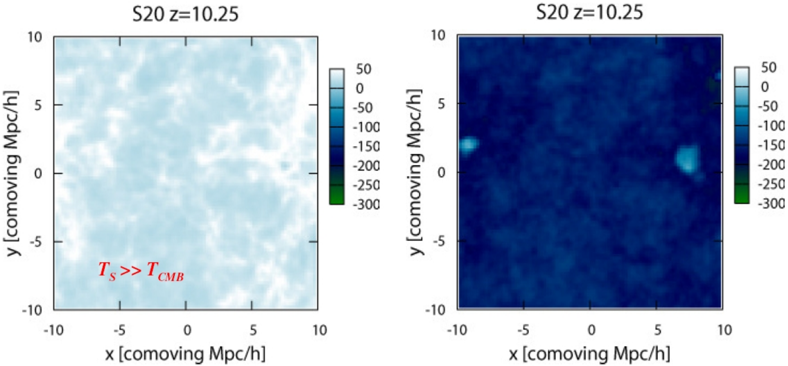


Figure: Early (moderate Ly-α)

Result 3. Signal in absorption

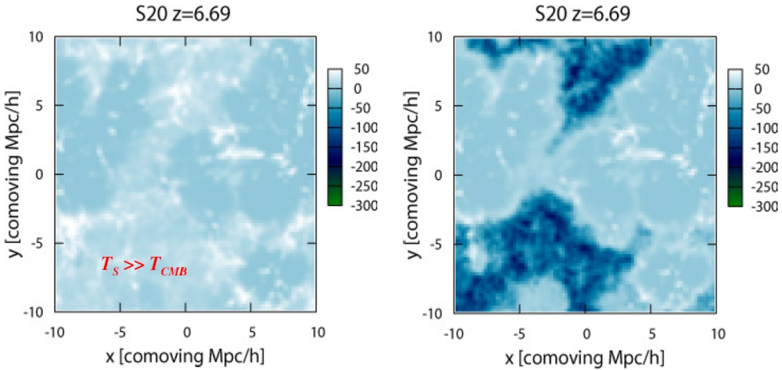
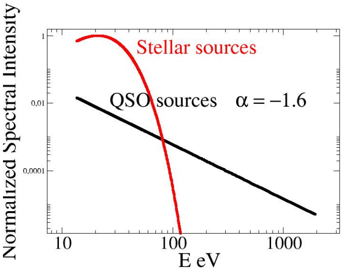


Figure: Later($x_{HI} = 0.5$)

X-ray heating

The Source Model

- QSOs, X binaries, SNe
- Soft X-ray photon 100eV to 2keV (Prichard & Furlanetto 2007)
- Spectral power index $\alpha = -1.6$ (Telfer et al 2002)
- 0.1% of L_{tot} to L_{QSO} and 99.9% to $L_{stellar}$ (Glover & Brand 2003)



X-ray heating

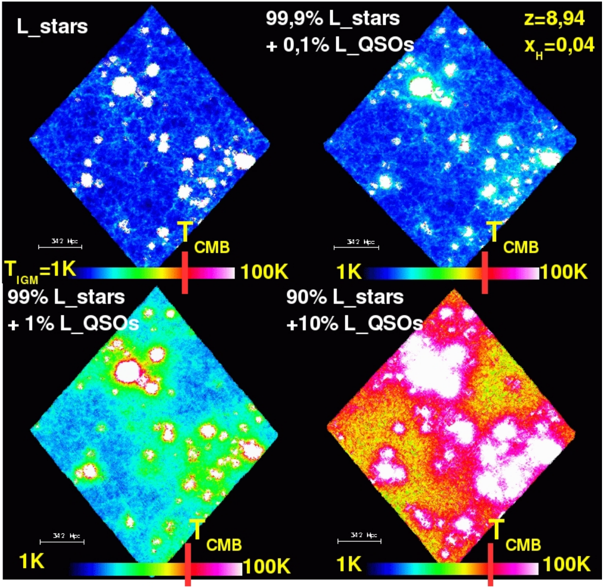
Method

- Ray-tracing of X-ray photons (homogeneous background X)
- Redshifting photon, retarded time

$$\lambda_X \approx 4.9 \left(\frac{E}{300eV}\right)^3 \mathrm{Mpc} \ \ \mathrm{(comoving)}$$

- Secondary ionization and heating by high energy electrons (Shull & van Steenberg 1985)

The evolution of T_k with X-ray heating



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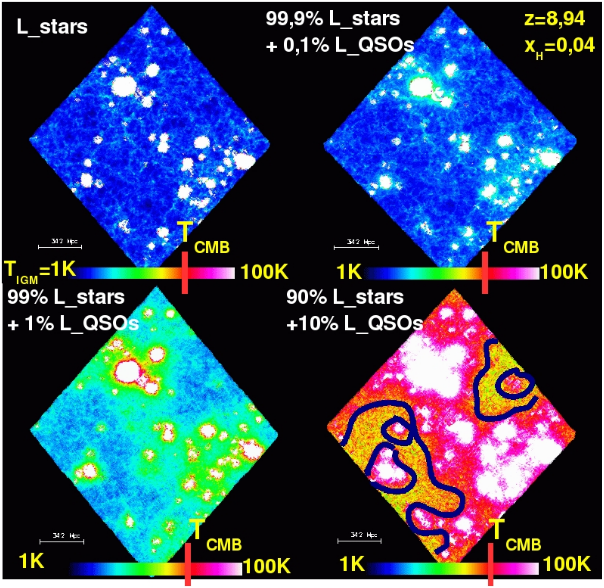

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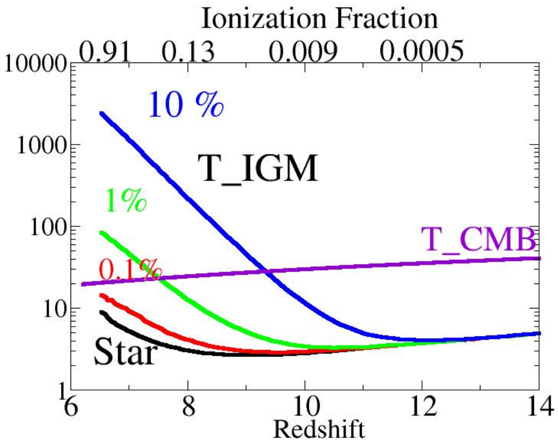

First conclusion

$\Rightarrow$ Preheating takes time!

Reference

S. Baek, P. Di Matteo, B. Semelin, F. Combes, Y. Revaz (A&A accepted) arXiv:0808.0925

Future Work

- 2×512^3 in 100 to 250 Mpc/h
- Helium + X-ray heating
- dv_r/dr effect
- Shock heating in coupled simulation