Light-cone anisotropy in 21 cm fluctuations simulated with the LICORICE code

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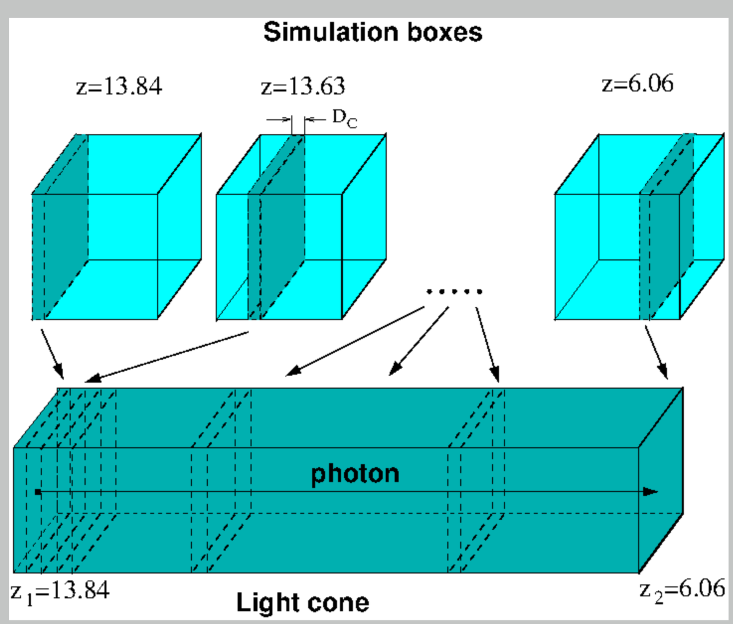
Introduction

One of the possible sources of an anisotropy in the power spectrum of 21 cm brightness fluctuations from the epoch of reionization (EoR) is the delay in light traveltime along the line-of-sight (LOS). We examine the anisotropy between the parallel and transverse directions with respect to the LOS with the LICORICE code. Based on Barkana & Loeb (2006) approach we study the time-delay effect in the realistic numerical simulations of the EoR.

Method

LICORICE is a 3D Monte-Carlo radiative transfer code coupled to the dynamics via an adaptative Tree-SPH code. The code includes continuum and Lyα radiative transfer. Dynamics simulations are made with the Gadget-2 code.



- Calculation of the comoving distance D_c traveled by photons between the redshifts of two consecutive snapshots determines the thickness of the slide which form the light-cone.

$$D_C = \frac{c}{H_0}\int_{z_A}^{z_B} \frac{dz}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

- The light cone has a length of 2 Gpc, 1 cell corresponds to 2.2 Mpc

The simulation with LICORICE uses the following set of parameters: $\mathbf{400h^{-1}}$ Mpc, grid $= \mathbf{512^3}$ for ionization, grid $= \mathbf{256^3}$ for $\delta \mathbf{T_b}$, $\mathbf{h}$=0.704, $\mathbf{\Omega_\Lambda} = 0.728$, $\mathbf{\Omega_M} = 0.272$, $\mathbf{\Omega_b} = 0.0455$. IGM is heated by PopII, Salpeter IMF with cut off at 120 $\mathbf{M_{Sun}}$

Reionization history

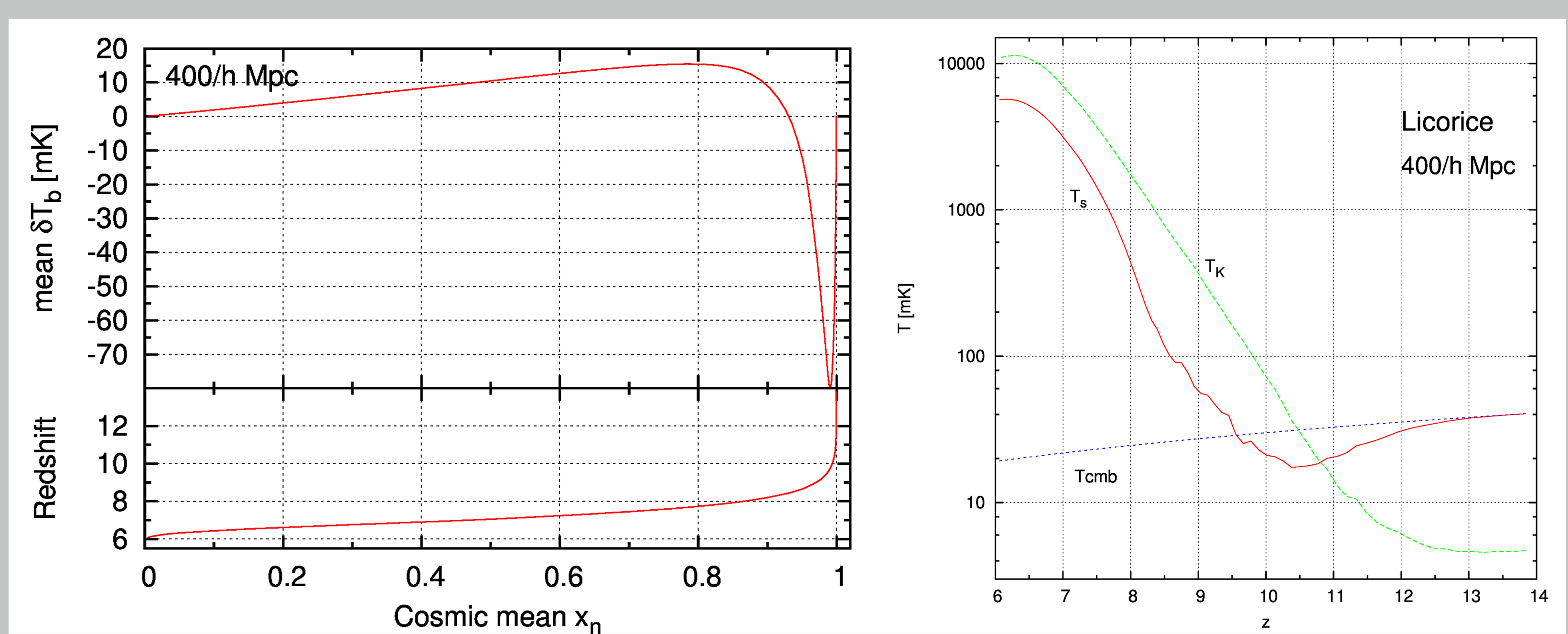
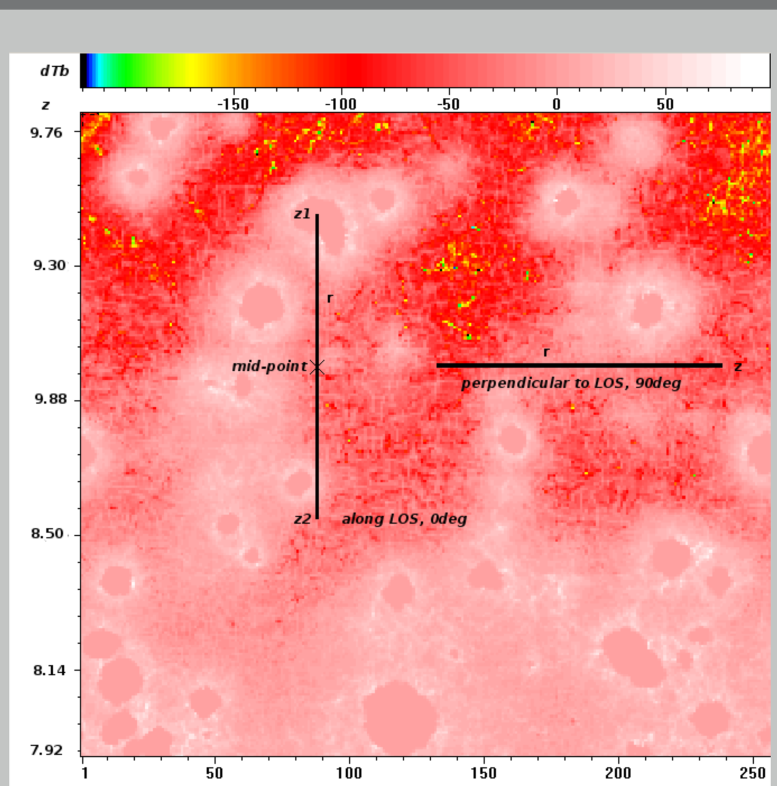


Figure: Left: The mean differential brightness temperature $\delta \mathbf{T_b}$ of the 21 cm signal (up) and the redshift $\mathbf{z}$ (down) during the process of cosmic reionization. Right: The spin, kinetic and CMB temperatures as a function of the redshift.

Two-point correlation function ξ of 21 cm brightness temperature offset δT_b



Any two points at a distance $\mathbf{r}$ observed along LOS are seen at different redshifts. The time-varying distribution of the HII regions influences the correlation function which is averaged over all such points. We follow an approximate model of correlation function ξ formulated by Barkana & Loeb (2006) to examine the time-delay anisotropy.

$$\xi(\delta T_b, \mu, r, z) = \left\langle \left[\delta T_{b,1} - \delta \bar{T}_b(z_1)\right] \times \left[\delta T_{b,2} - \delta \bar{T}_b(z_2)\right] \right\rangle$$

- ξ is a function of the comoving distance $\mathbf{r}$ between two points and two redshifts
- ξ is parametrized as a function of $\mathbf{r}$ and $\mu = \cos\Theta$, where $\Theta = 0°$ - along LOS and $\Theta = 90°$ - perpendicular to LOS
- redshift $\mathbf{z}$ is taken at the mid-point (in terms of comoving distance) of the two points
- the average value $\delta\bar{T}_b$ at the given redshift is subtracted from δT_b at each cell.

Two-point correlation function ξ - results

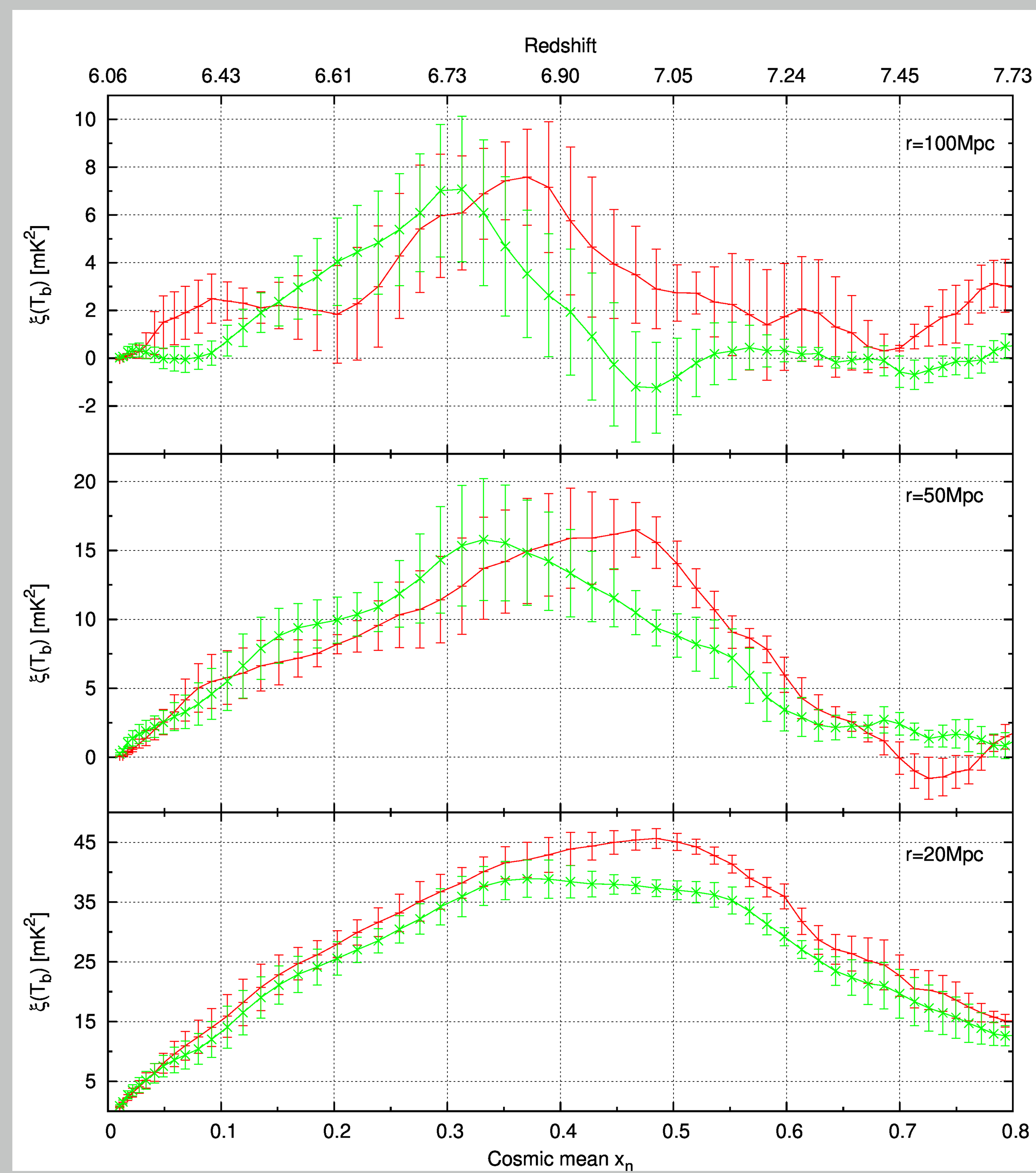


Figure: From top to bottom: Correlation function ξ of 21 cm $\delta \mathbf{T_b}$ at distance $\mathbf{r}$=100 Mpc, 50 Mpc, 20 Mpc, as a function of the neutral fraction. Red and green curves correspond to $\mathbf{0°}$ (2 points along LOS) and $\mathbf{90°}$ (transverse direction), respectively. The error bars depict the cosmic variance. ξ is in agreement with theoretical prediction. For 50 Mpc and 100 Mpc we observe a line-of-sight anisotropy caused by the rapid ionization fluctuations. The large error bars mean that the effect can be difficult to observe. For smaller values of $\mathbf{x_n}$ the correlation decreases since the dense ionized regions are almost point sources compared to the whole nearly neutral area.

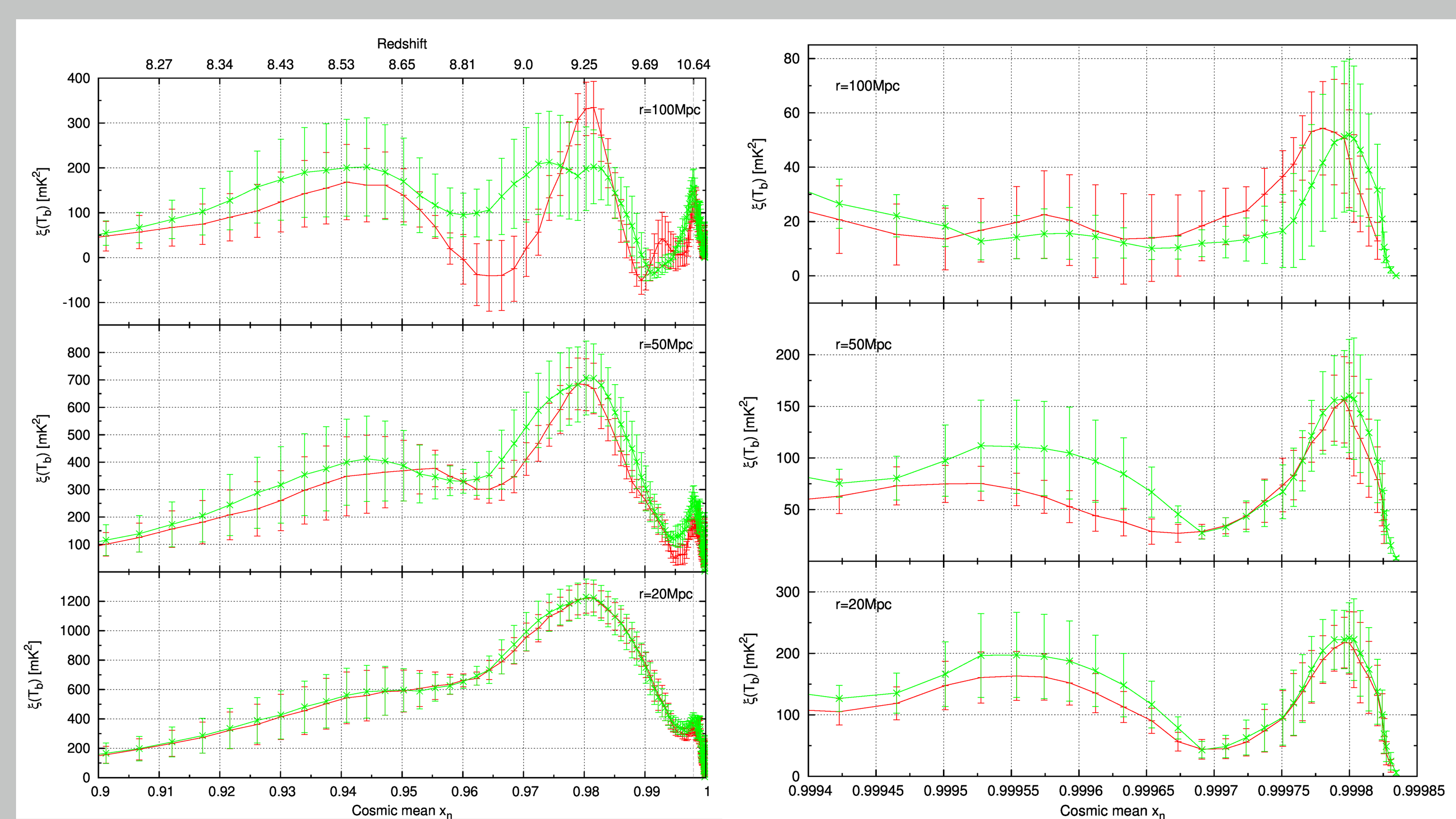


Figure: At the early stage of EoR ξ reaches maxima at $\mathbf{x_n = 0.94}$ ($\mathbf{z \sim 8.5}$) when mean $\delta \mathbf{T_b}$ becomes positive, at $\mathbf{x_n = 0.98}$ ($\mathbf{z \sim 9.25}$) just after mean $\mathbf{T_s}$ becomes larger than $\mathbf{T_{CMB}}$ and at $\mathbf{x_n = 0.998}$ ($\mathbf{z \sim 10.6}$) when $\mathbf{T_K}$ exceeds $\mathbf{T_s}$ and $\mathbf{T_{CMB}}$. We also see a clear peak around $\mathbf{x_n = 0.9998}$ at $z \sim \mathbf{12.9}$ when mean $\mathbf{T_s}$ decouples from $\mathbf{T_{CMB}}$ and $\delta\bar{\mathbf{T}}_\mathbf{b}$ starts to be negative.

Conclusions

- Light-cone anisotropy is significant on scales larger than 50 Mpc (comoving) at advanced stages of EoR when the ionization fluctuations become significant. The $\delta \mathbf{T_b}$ is around 5-10 mK at redshifts where the time-delay anisotropy is largest.
- At early stage of EoR we observe an increase in the amplitude of the correlation function at all examined distances when the neutral fraction is close to unity and the 21 cm power spectrum is dominated by fluctuations in density. Precise quantitative predictions require further study.
- There was no visible effect if box size $<$ 200 Mpc/h.

Bibliography

- LICORICE code description: Baek S. et al. *A&A*, **495**, 389 (2009)
- δT_b calculation are made by P.Vonlanthen similarly to Vonlanthen P. et al. *A&A*, **532**, A97 (2011)
- Barkana R., Loeb A., *MNRAS*, **378**, L43 (2006)

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