Modeling 21cm signal from protocluster regions at the epoch of reionization

天体形成研究会

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Contents

Introduction

- "Big Bang"→recobination ($z \simeq 1300$)

→photon decoupling($z \simeq 1100$)

- As the universe expands and cools ,
  steller objects are formed .

- The universe becomes ionized again.

Question

How did the Reionization occour ?
(What did reionize the universe ?)

How can we probe ?

Cosmic age

0.3Myr

1.0Gyr

13.8Gyr

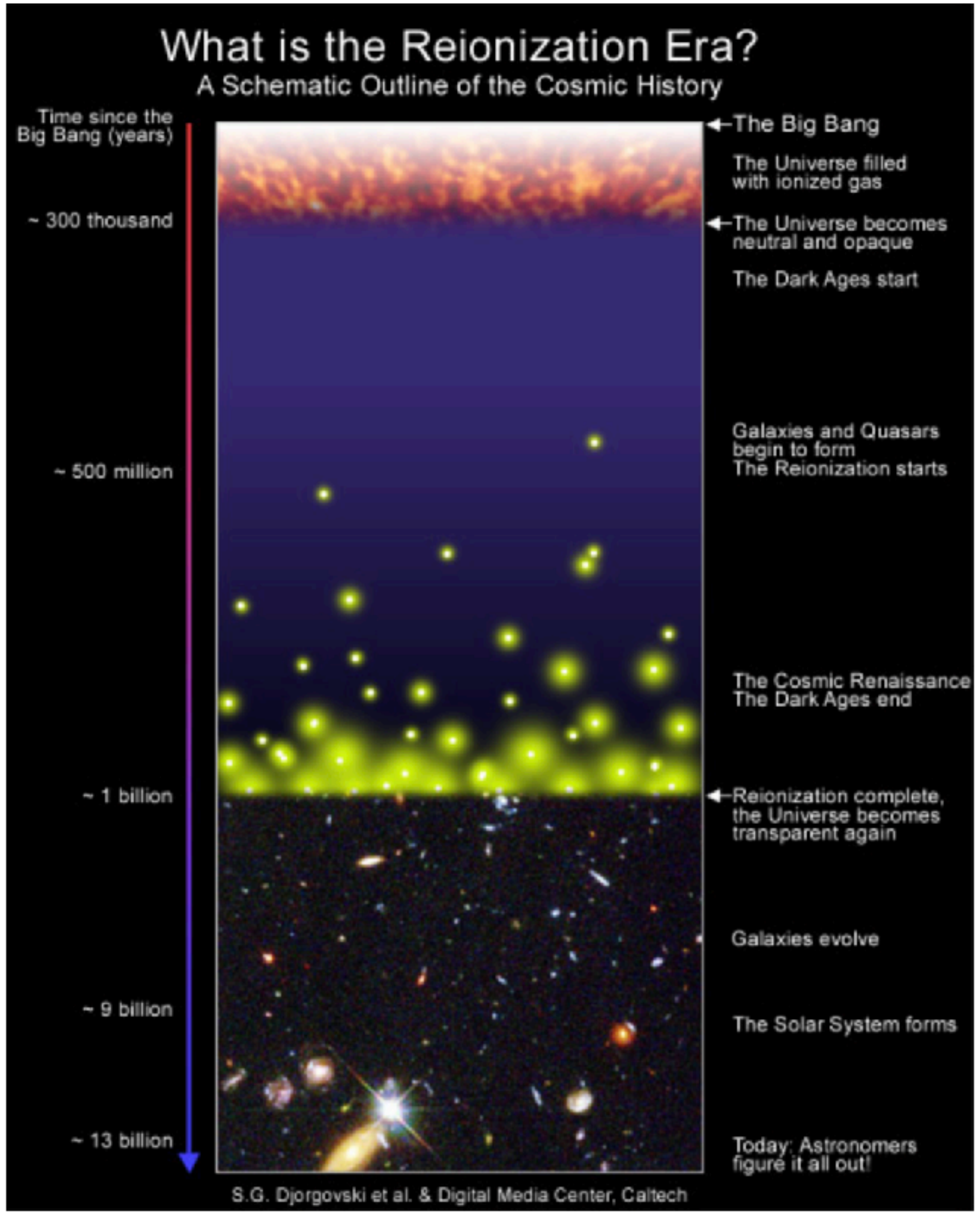
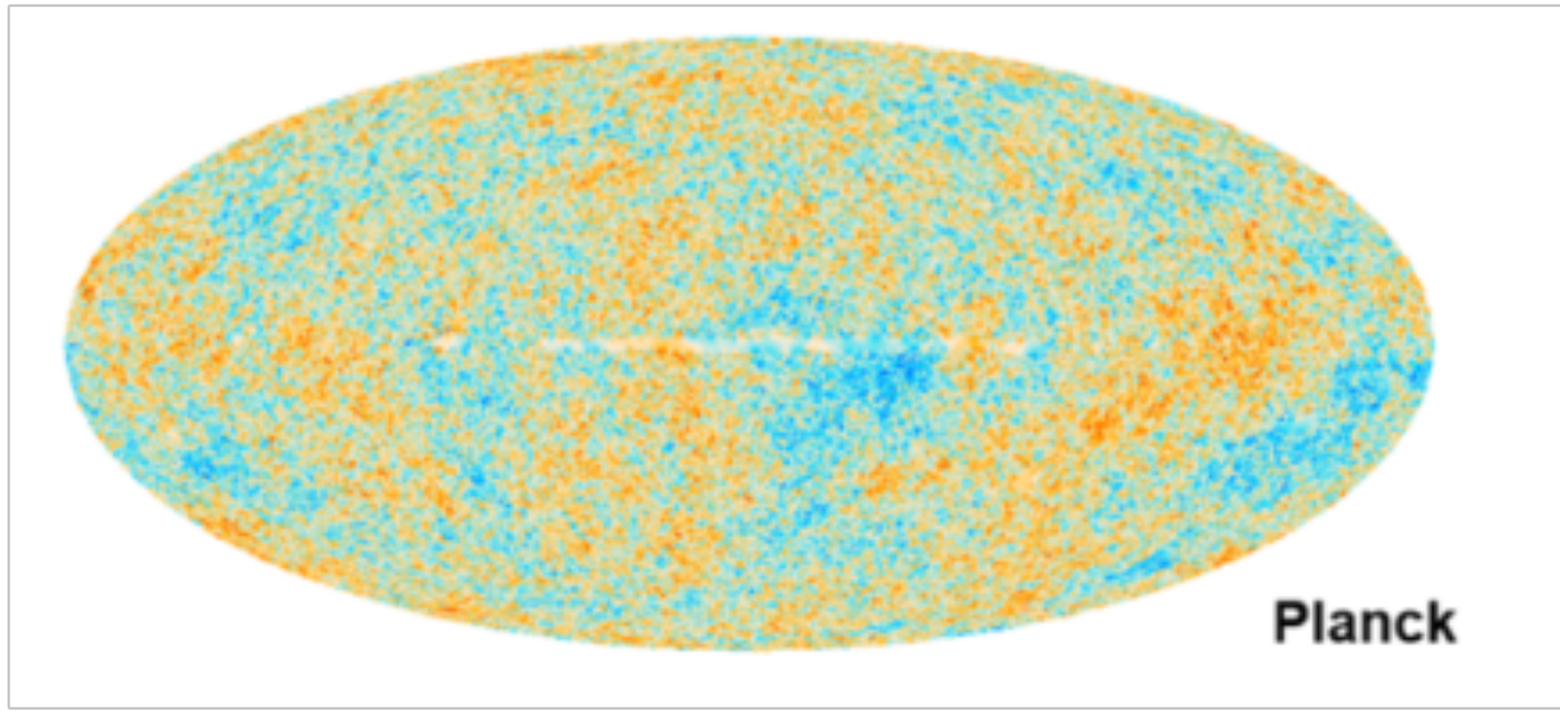


Image: Graphical representation of the history of the universe, by Djorgovski et al.

Introduction



Two major constrains on the epoch of reionization

・Spectra of 19 quasars observerd by SDSS show lack of Gun-Peterson trough at z~6

➡ <u>Imply that reionization ends at z~6</u>

・CMB photons were scattered by free electrons in IGM.

➡ <u>Suggests that reionization mostly starts at z~10</u>

(Fan et al.,2006)

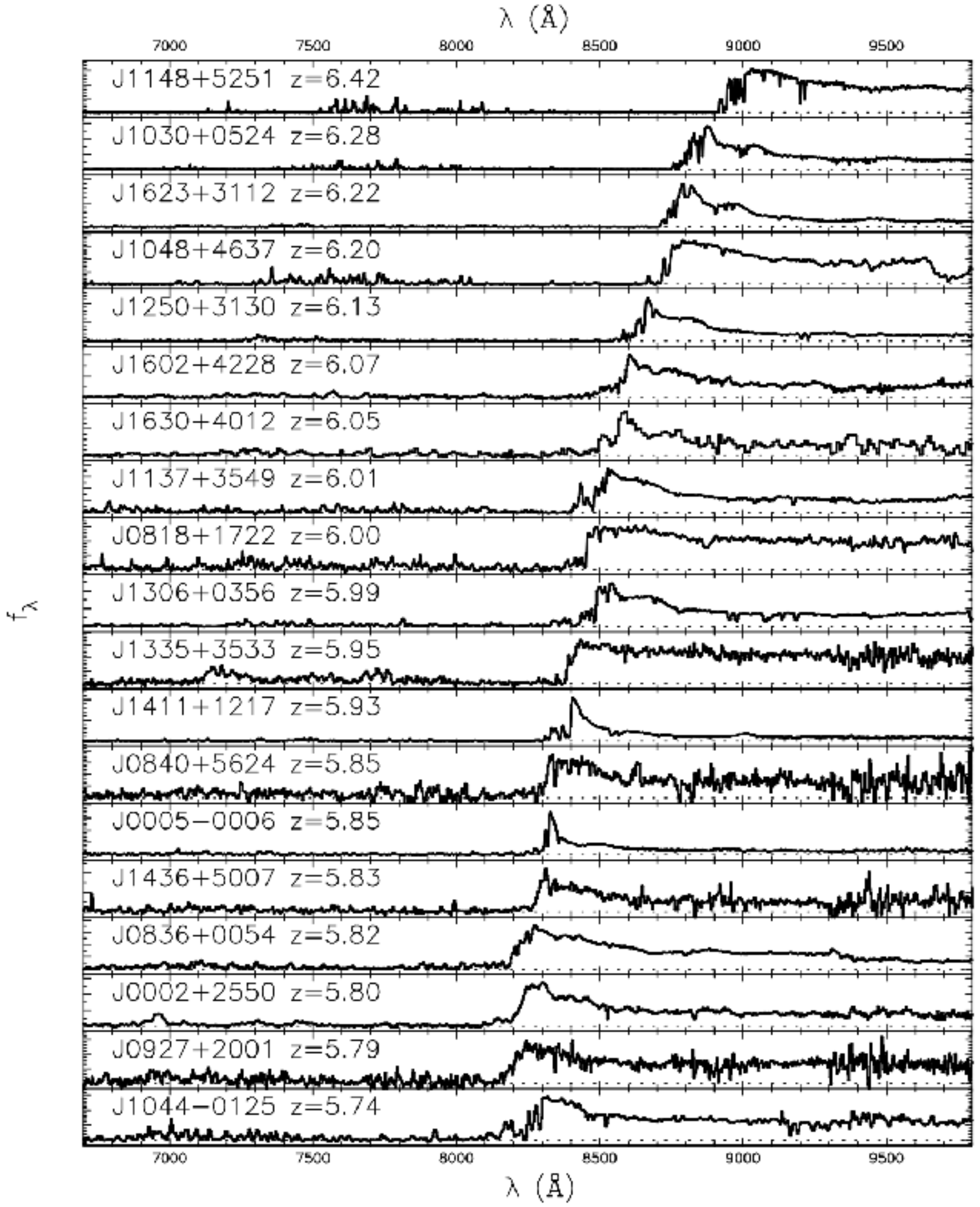
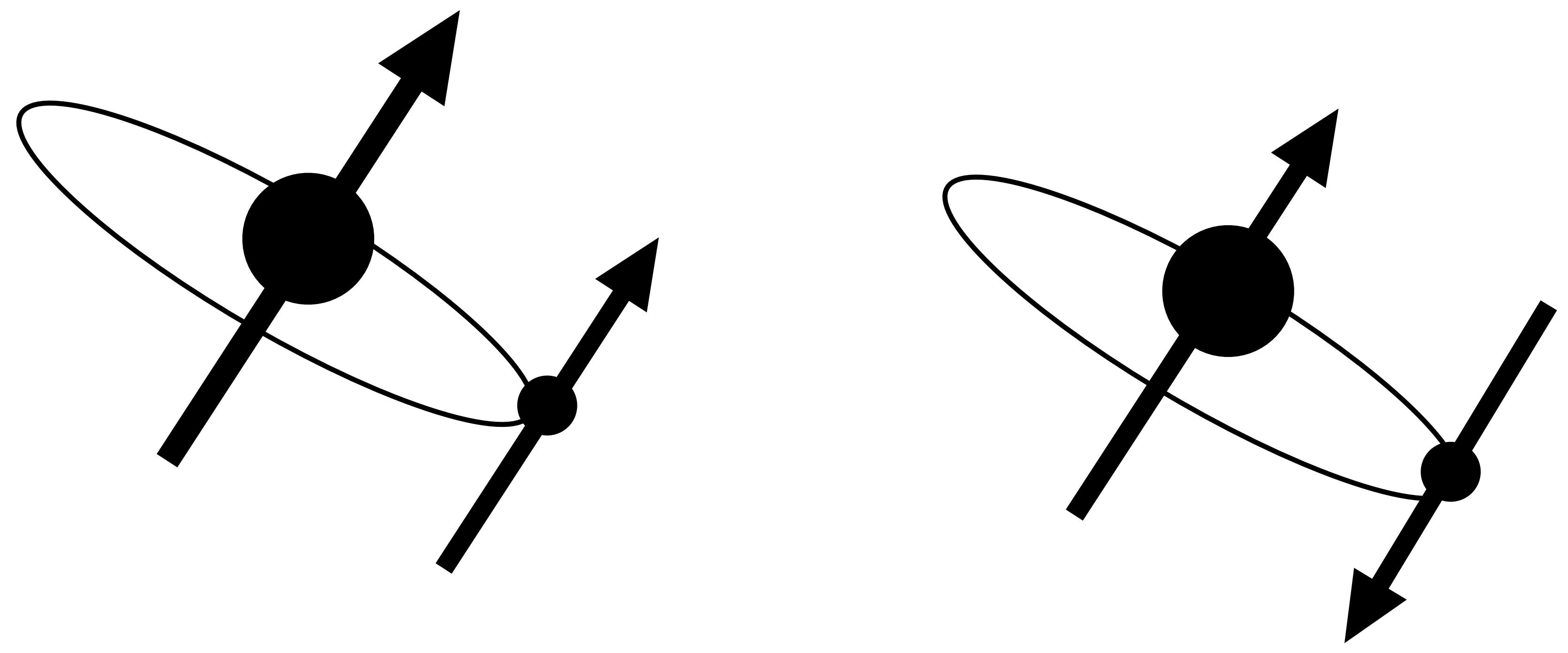


Fig. 1.— Spectra of our sample of nineteen SDSS quasars at $5.74 < z < 6.42$. Twelve of the spectra were taken with Keck/ESI, while the others were observed with the MMT/Red Channel and Kitt Peak 4-meter/MARS spectrographs. See Table 1 for detailed information.

Method

Neutral hydrogen spin flip



Parallel　　　Anti parallel

Energy difference corresponds

Wave length : $\lambda_{spinflip} = 21[\mathrm{cm}]$

Frequency : $\nu_{spinflip} = 1.4 \times 10^{9}[\mathrm{Hz}]$

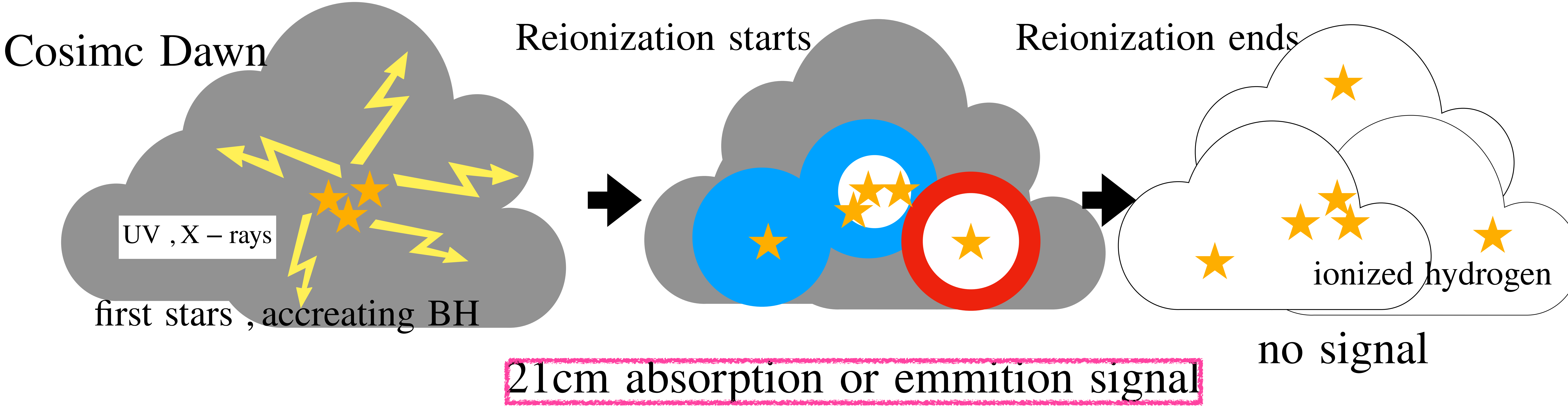
We can define spin tempareture T_s

$$\frac{n_1}{n_0} \equiv 3\exp(-\frac{h\nu_{spinflip}}{k_B T_s})$$

n_1, n_0 is number densiy of neutral hydrogen spin parallel , anitiparallel

Many neutral hydrogen in IGM during the epoch + Information about the signal's redshift →

Introduction



The signal is sensitive to following questions .

What is the source of reionization ?

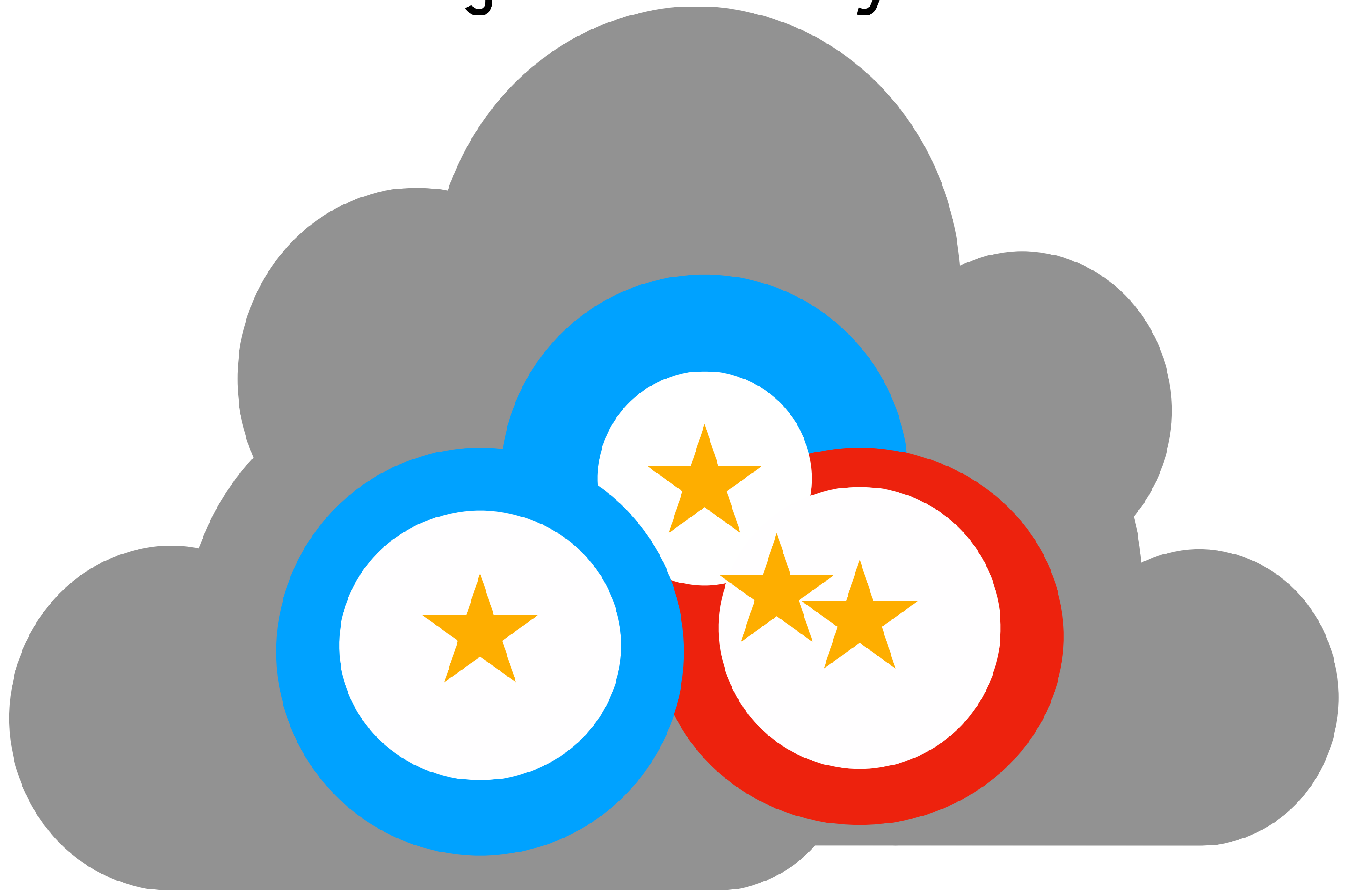
When was it made ?

Where did it appear?

Introduction

In cosmological scale , very high density region (protocluster region)
could form steller objects earlier than the other regions.

These steller objects may start the reionization.



21cm signal feature depends on source spectra.

FOREVER22 cosmological hydrodanamics simulation's result (Yajima et al ., 2020)

+

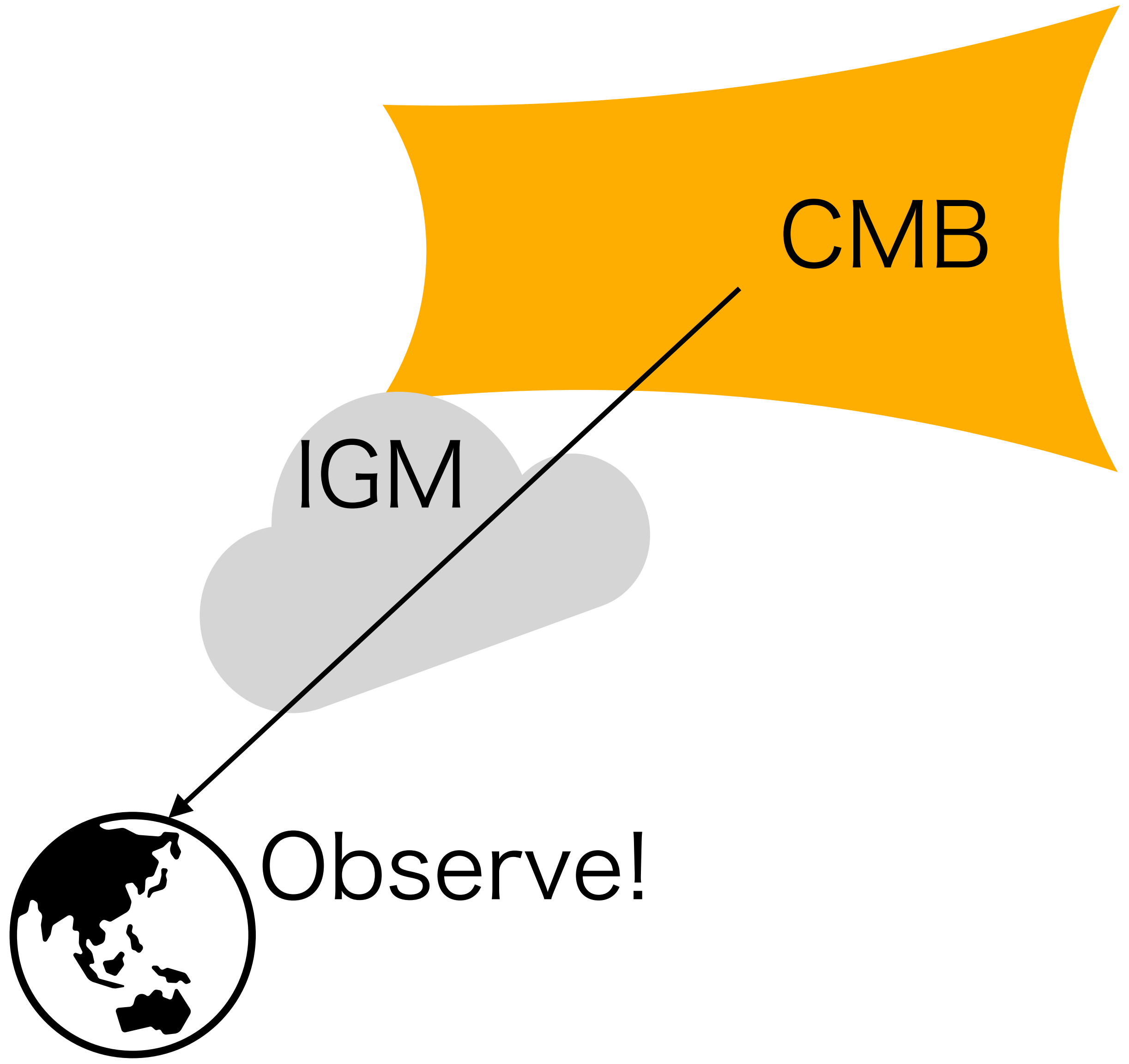
21cm signal calculation

→ What is the relation between 21cm signal and star formation activity ?

Method

$$\delta T_b = \frac{T_\nu - T_{CMB}}{1+z}$$

$$\approx 28.1(1 - x_{ion})(1+\delta)(1 - \frac{T_{CMB}}{T_s})\sqrt{\frac{1+z}{10}}[\mathrm{mK}]$$



Here δ , x_{ion} are overdensity and ionizing fraction .

$$T_\nu(\tau_\nu) = T_{CMB}e^{-\tau_\nu} + T_s(1 - e^{-\tau_\nu}) \, .$$

This formula comes from radiative transfer of 21cm line,

$$\frac{dI_\nu}{ds} = \frac{\phi(\nu)h\nu}{4\pi}[n_1A_{10} - (n_0B_{01} - n_1B_{10})I_\nu],$$

$\phi(\nu)$ is line profile .

(Furlanetto et al., 2006)

Method

T_s is determined in equiribrium by

$$n_1(C_{10}+P_{10}+A_{10}+B_{10}I_{CMB}) = n_0(C_{01}+P_{01}+B_{01}I_{CMB})\,.$$

n_1/n_0 is spin parallel/anti parallel state number density

C_{01} and P_{01} are collisional and Lyα scattering excitation rate

C_{10} and P_{10} are collisional and Lyα scattering de – excitation rate

$A_{10}, B_{10,01}$ are Einstein A, B coefficients

Using Rayleigh – Jeans approximation,

$$\boxed{T_s^{-1} = \frac{T_{CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_C + x_\alpha}}$$

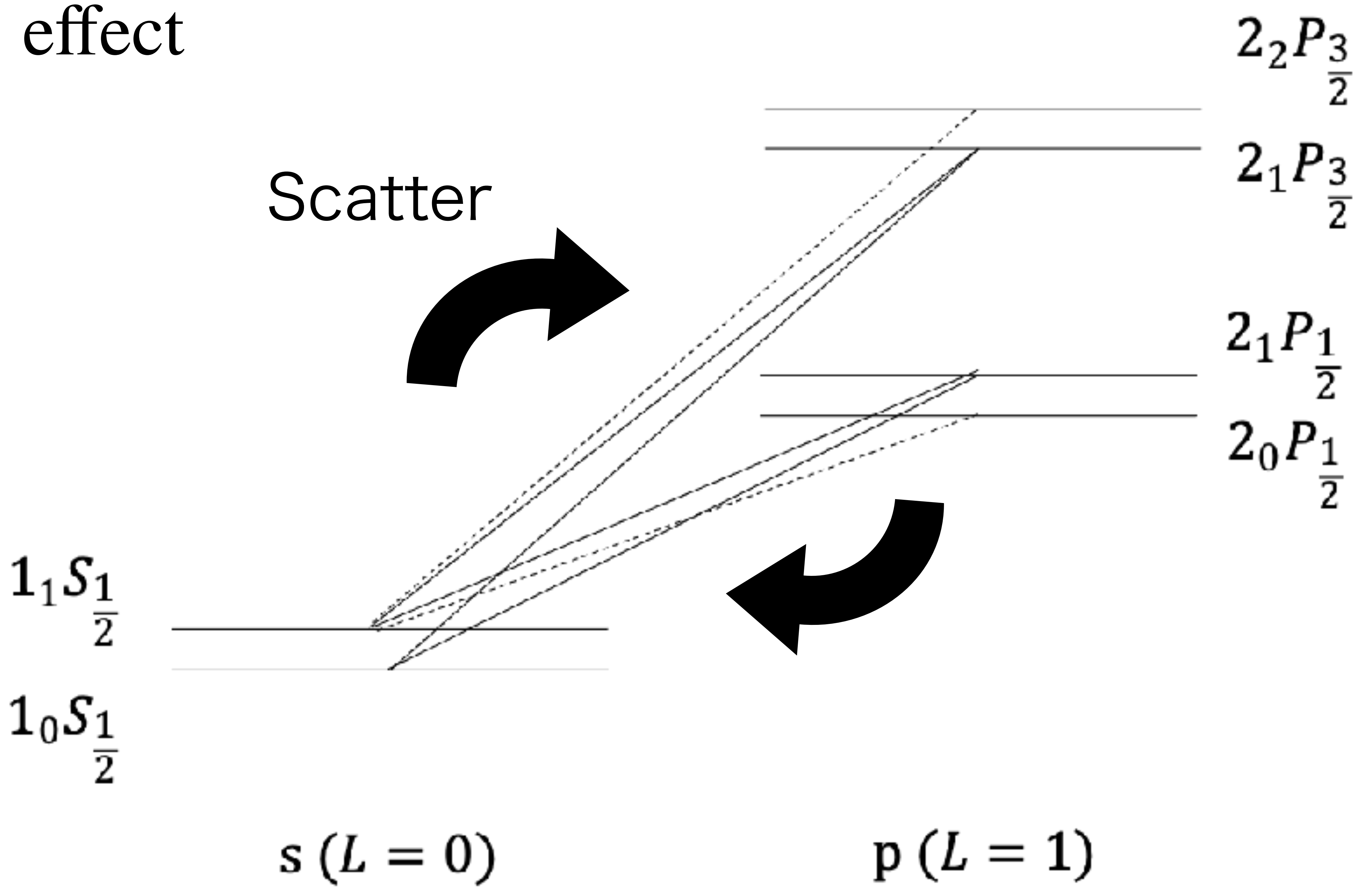
T_c is color temperature of Lyα
T_K is gas kinetic temperature

Each T corresponds $\frac{n_1}{n_0}$ in equiribrium of temperature T .

(Furlanetto et al., 2006)

Method

Wouthythen – Field effect



$$x_\alpha = \frac{4P_\alpha h\nu_{spinflip}}{27A_0T_{CMB}}$$

P_α is number of scatterings of Lyα per atom per second

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_C T_K^{-1} + \boxed{x_\alpha T_c^{-1}}}{1 + x_C + x_\alpha}$$

$(T_c \sim T_K)$

If x_α is large, $T_s \longrightarrow T_c$

Method

Lyα scattering number per atom is importnat .

- Including cascde Lyα photons (Hirata ., 2006)

- Taking into Lyα scattering effect by boost factor per Lyα photon (Beak et al ., 2018)

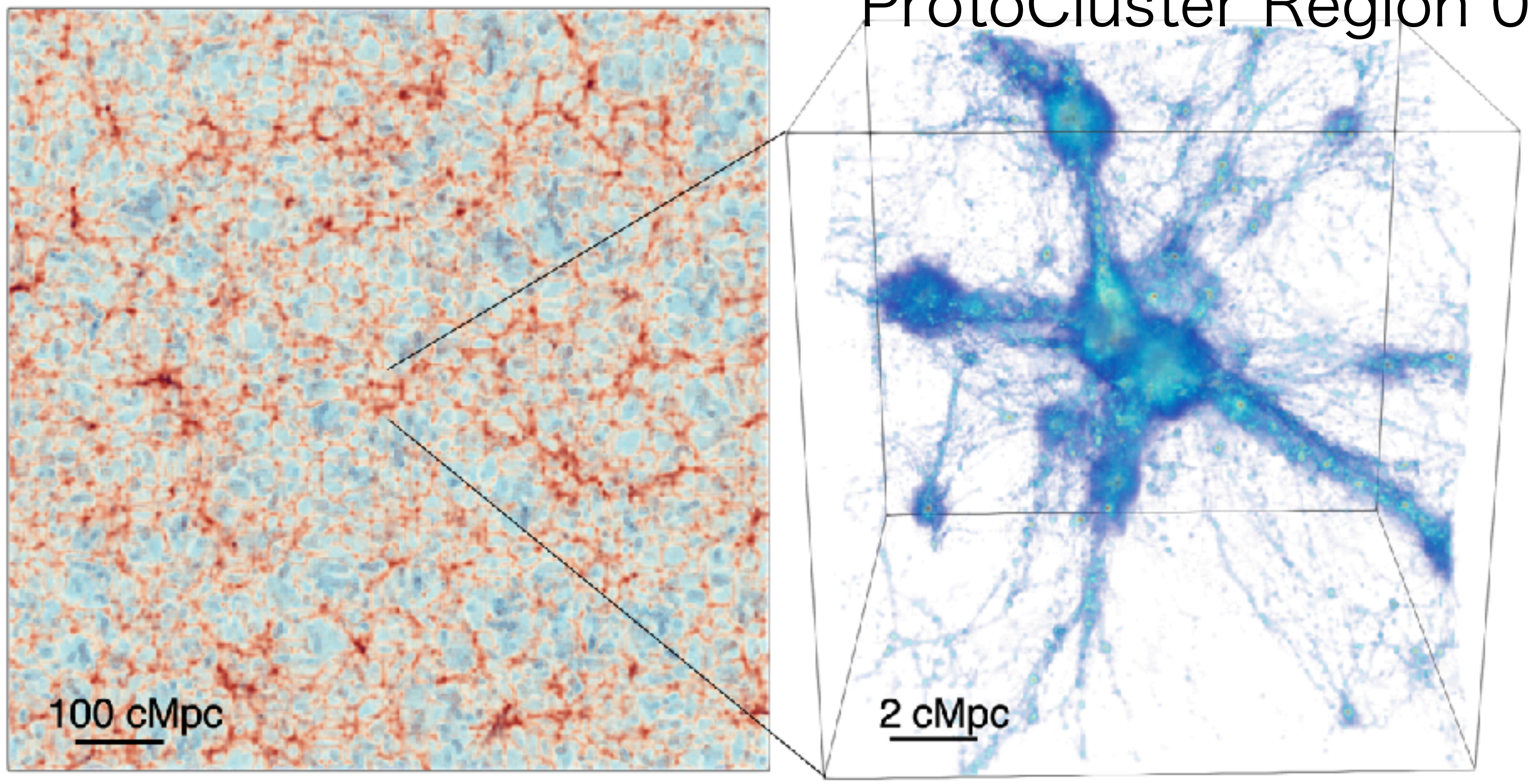
$$N_{scat} = 8 \times 10^5 \frac{H(z=10)}{H(z)}$$

- Optically thin approximation

Method

The most massive halo in the simulation box

ProtoCluster Region 0



(Yajima et al . , 2020)

$z = 3$

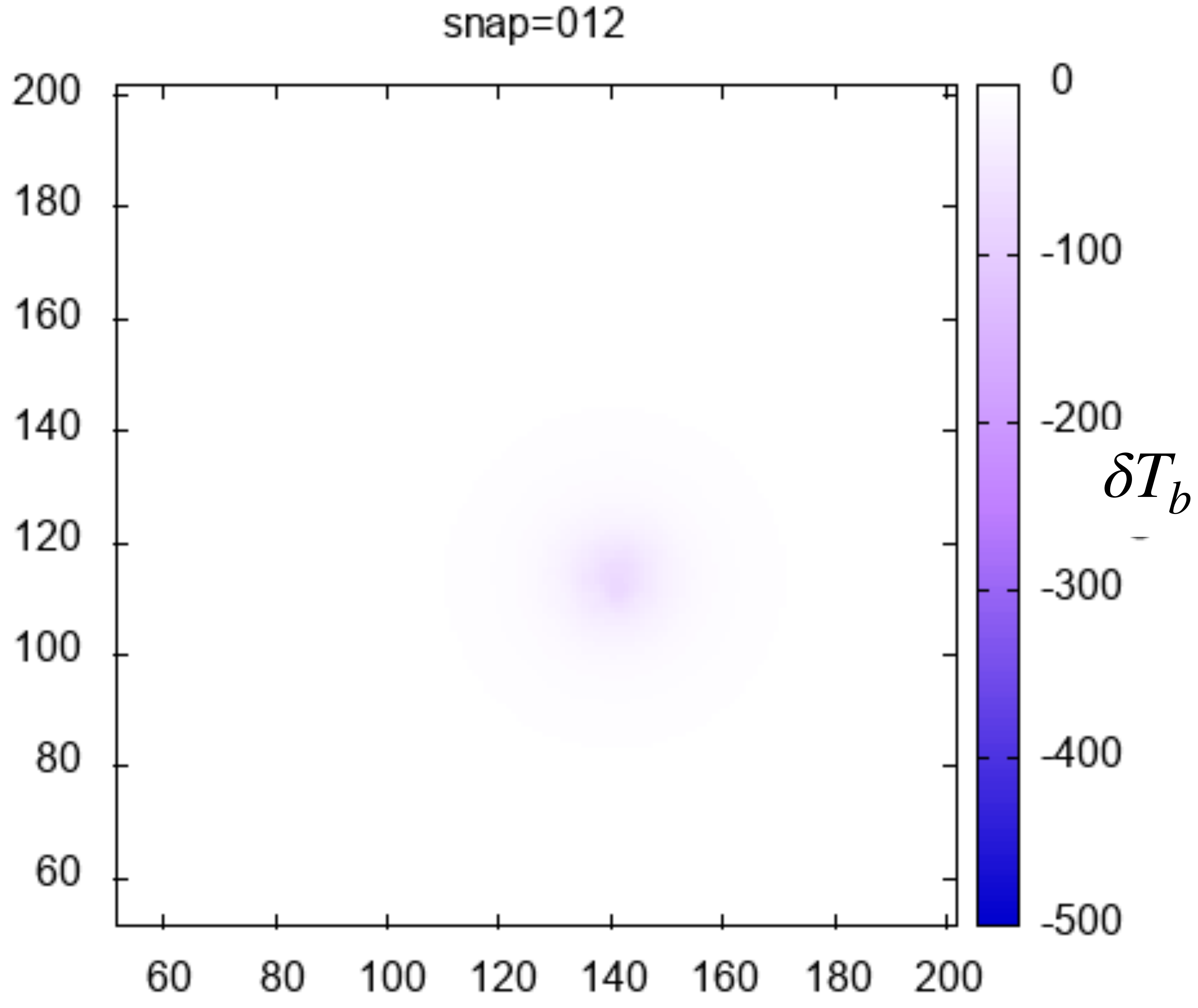
Assign SPH gas particles and Haloes to 256^3 meshes.

Set halo's UV radiation , $SFR(M_{sun}/yr) = 1.4 \times 10^{-28} L\nu(\mathrm{erg\ s^{-1} Hz^{-1}})$ (Kenicutt 1998)

Result

$z = 17.6,\ 16.7,\ 15.9,\ 15.2,\ 14.5,\ 14.0,\ 13.4$

17[cMpc]

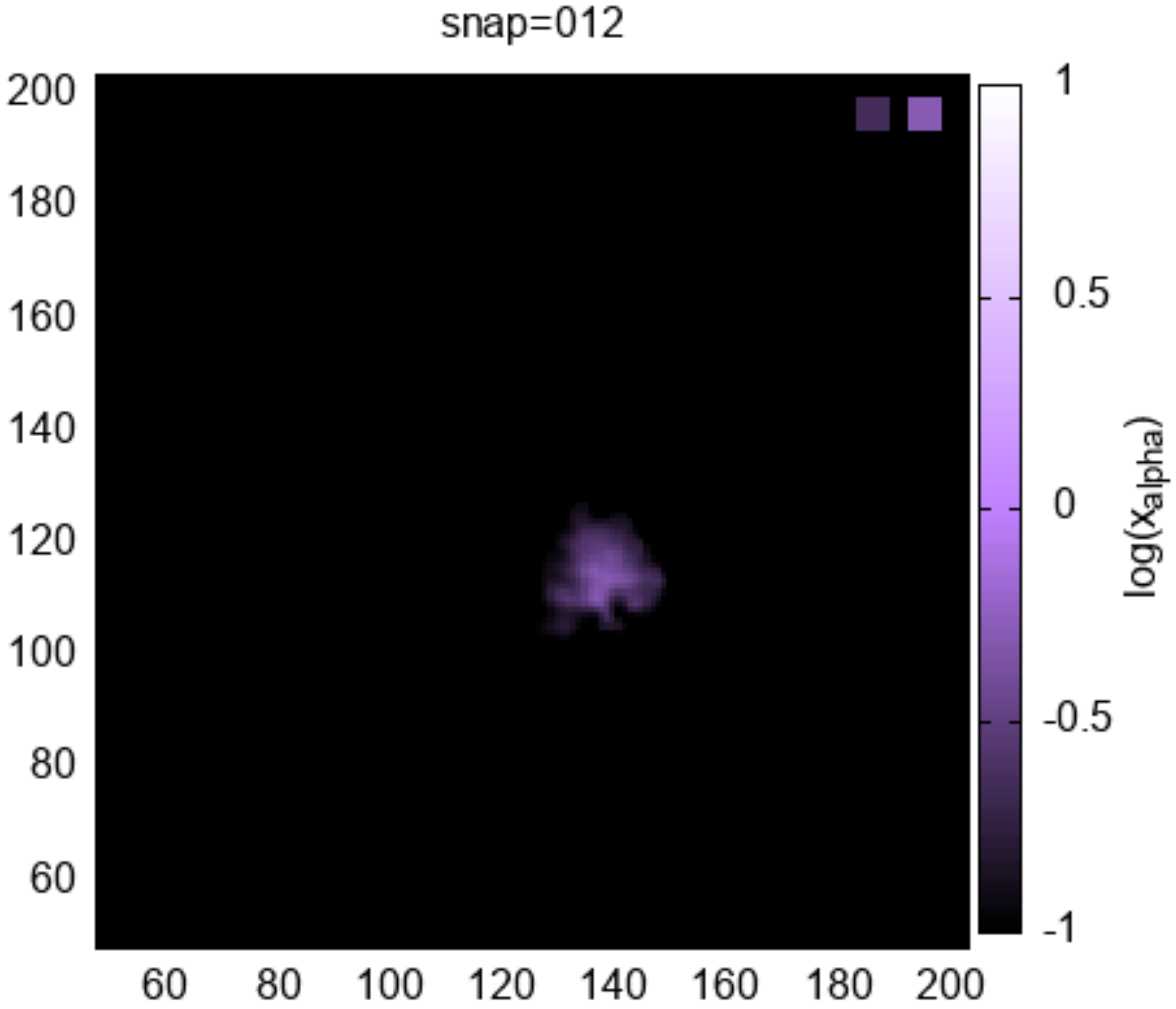


$$\delta T_b = 28.1(1+\delta)(1-\frac{T_{CMB}}{T_s})\sqrt{\frac{1+z}{10}}[\mathrm{mK}]$$

Result

z = 17.6, 16.7, 15.9, 15.2, 14.5, 14.0, 13.4

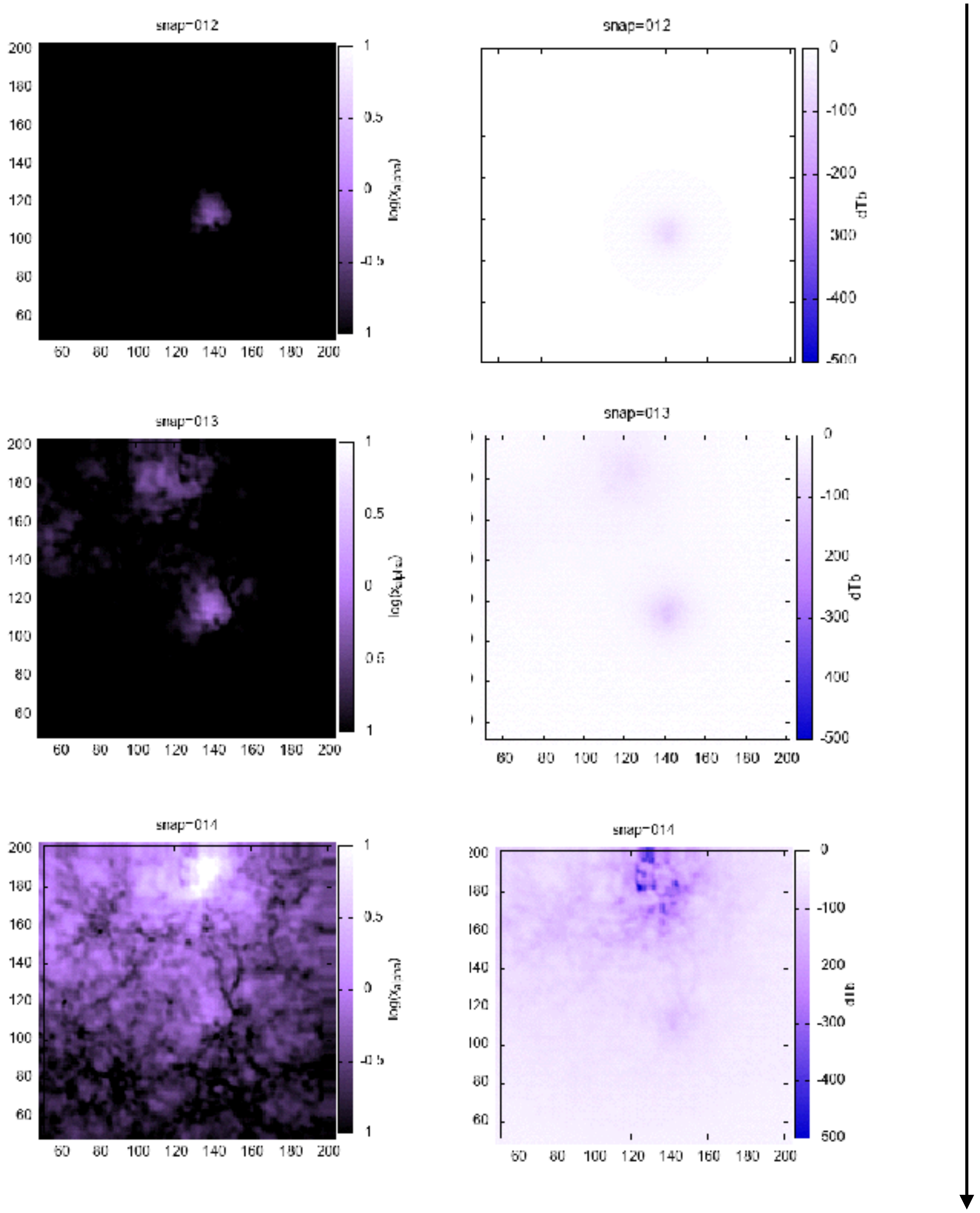
17[cMpc]

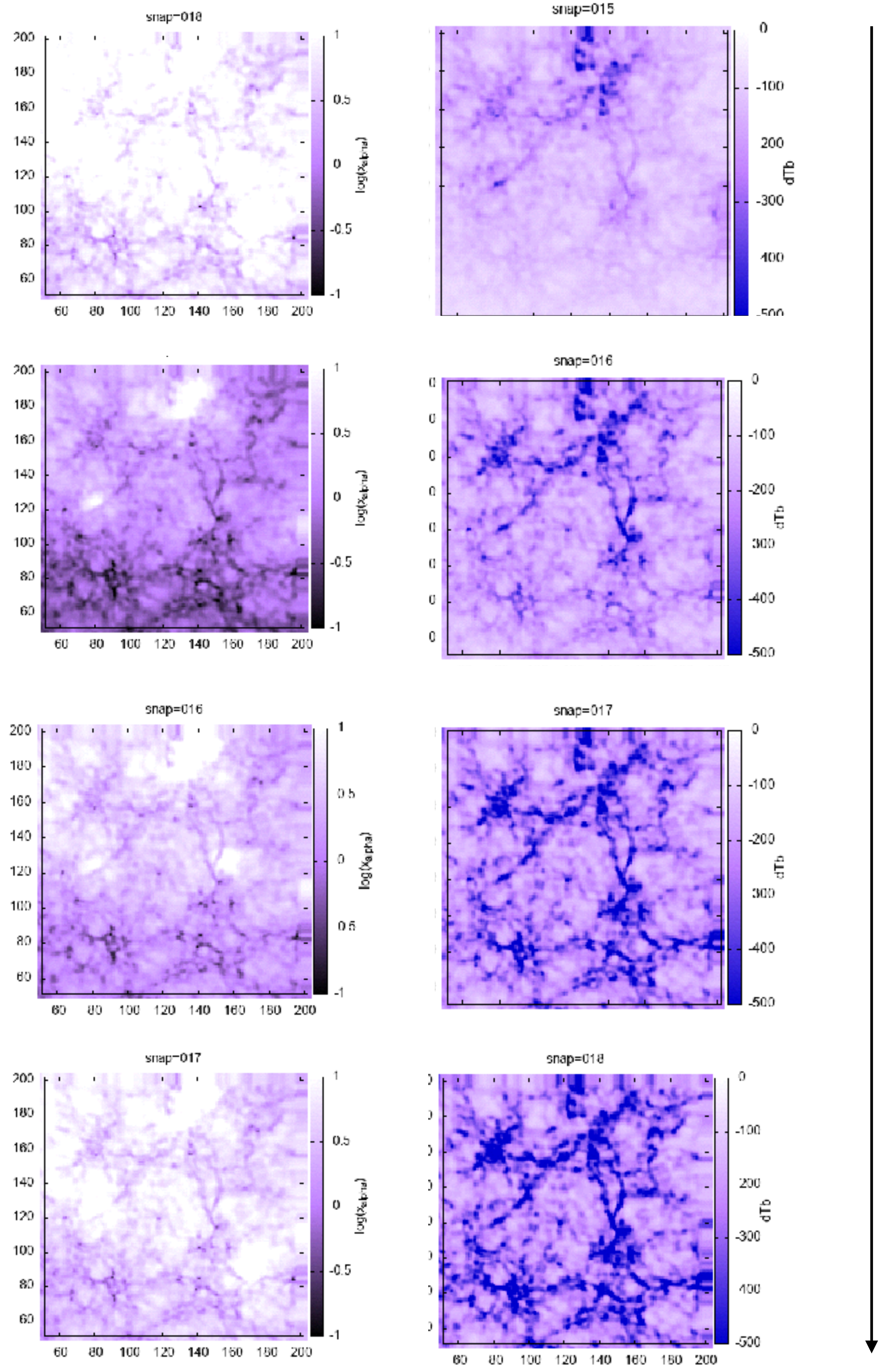


$$x_\alpha = \frac{4P_\alpha h\nu_{spinflip}}{27A_0 T_{CMB}}$$

Result

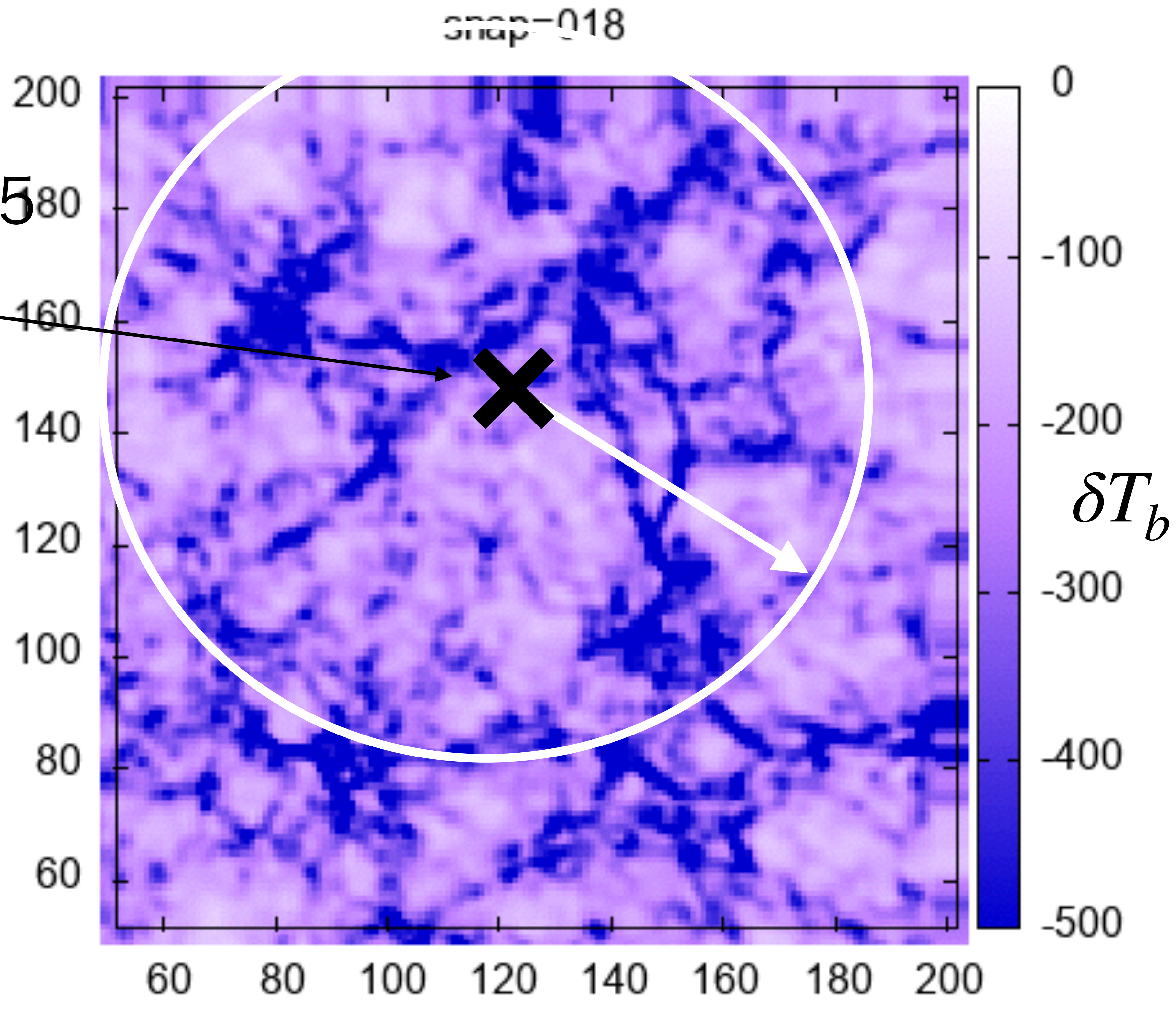
$\log x_\alpha$ δT_b





Discussion

Center of haloes in map at z=13.5



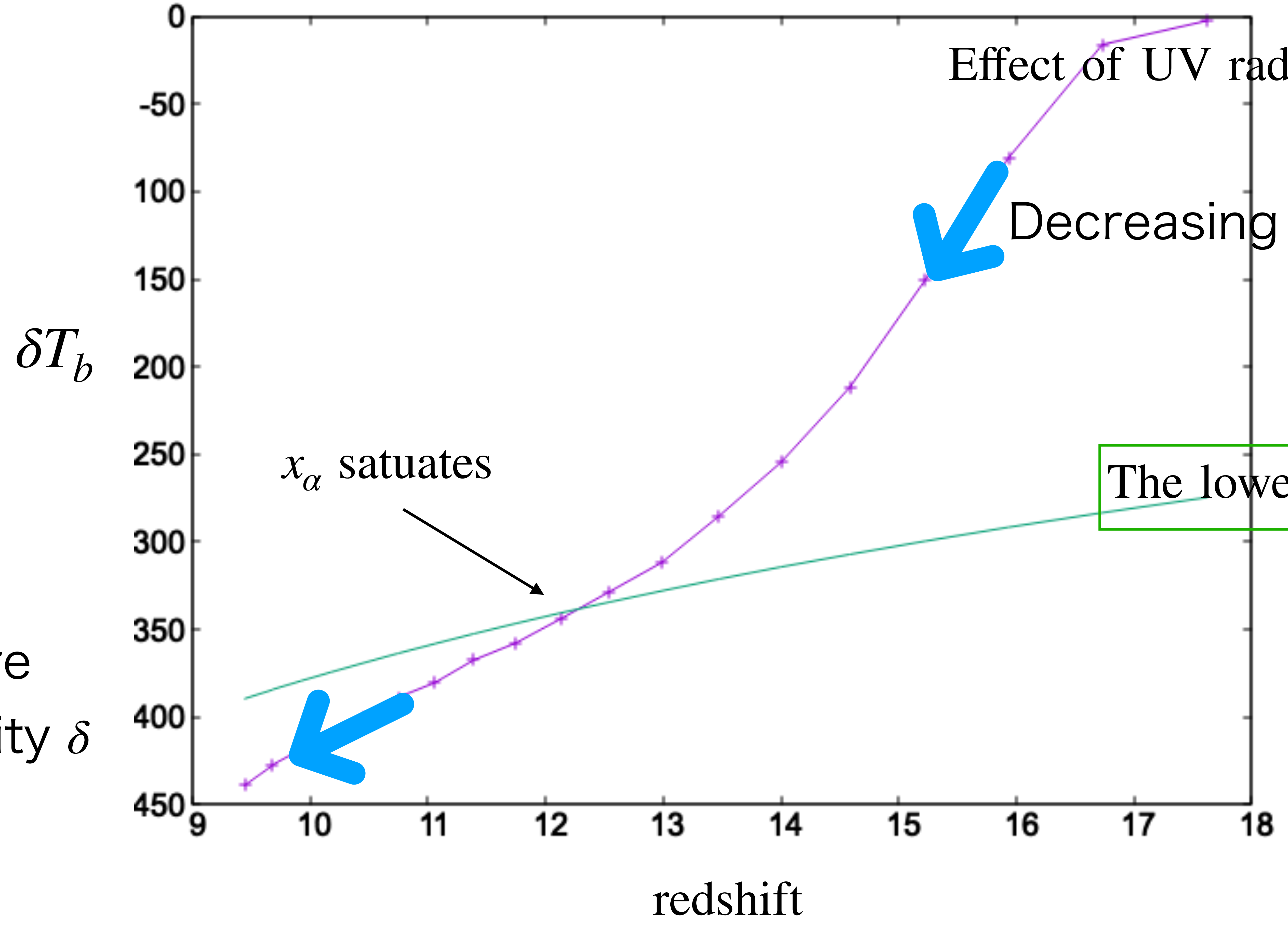
$$R = \frac{10}{(1+z)}\mathrm{Mpc}$$

Consider radius R circle area's average value

Discussion

Effect of UV radiation from starforming haloes

T_s begins to couples to T_α



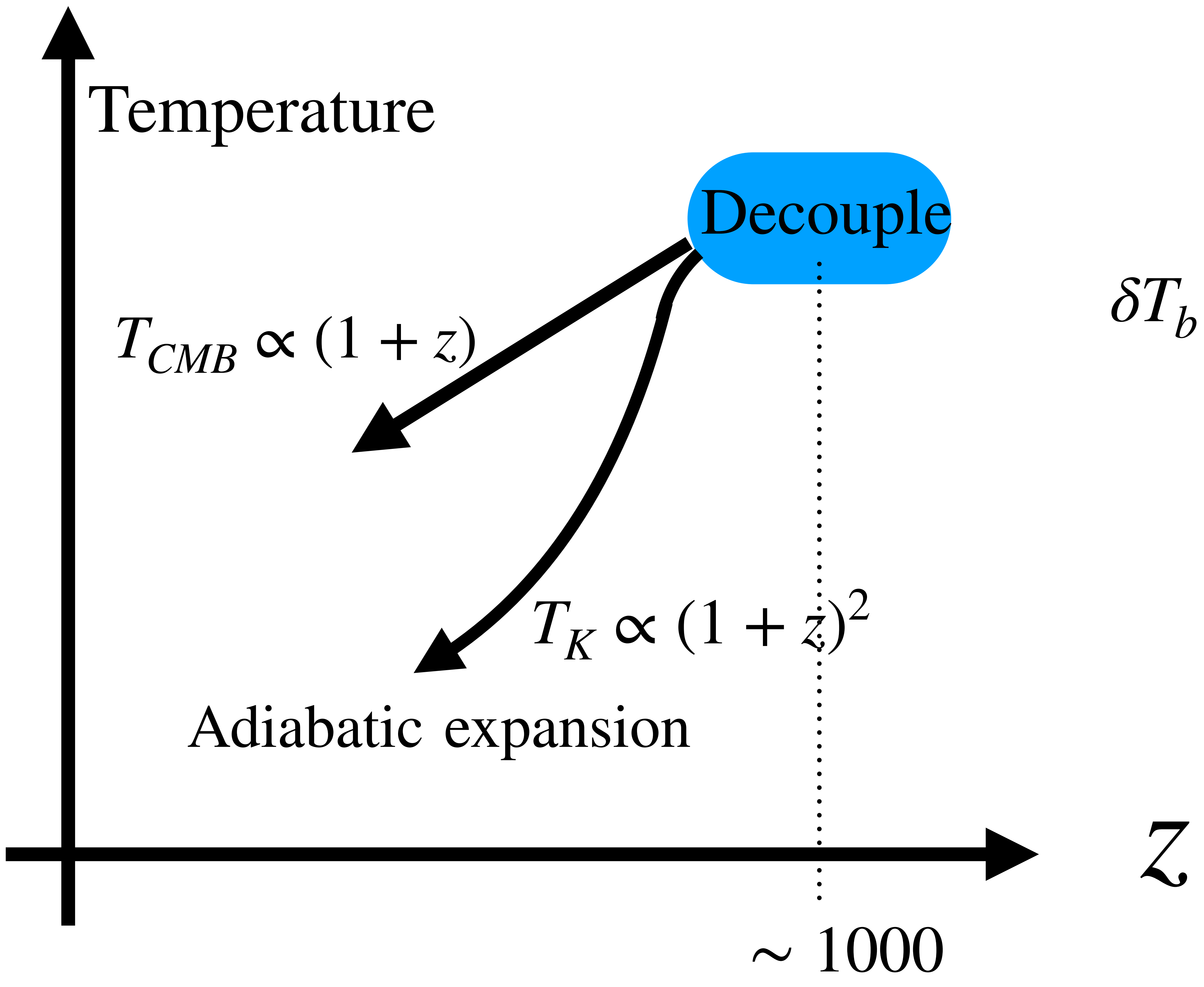
The lowest δT_b at cosmic mean density

Decreasing more

Effect of over density δ

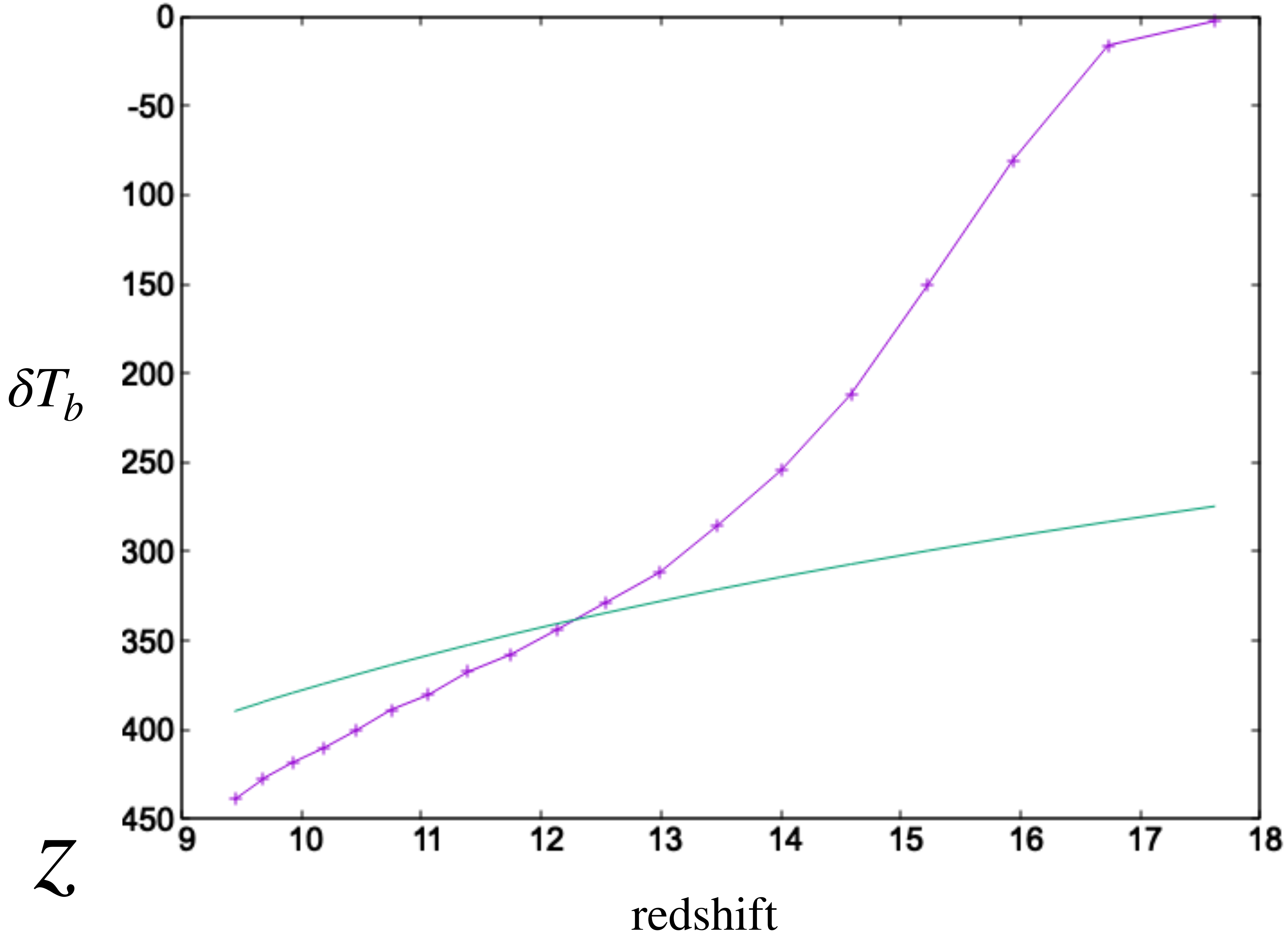
$$\delta T_b = 28.1(1+\delta)(1-\frac{T_{CMB}}{T_s})\sqrt{\frac{1+z}{10}}[\mathrm{mK}]$$

Discussion

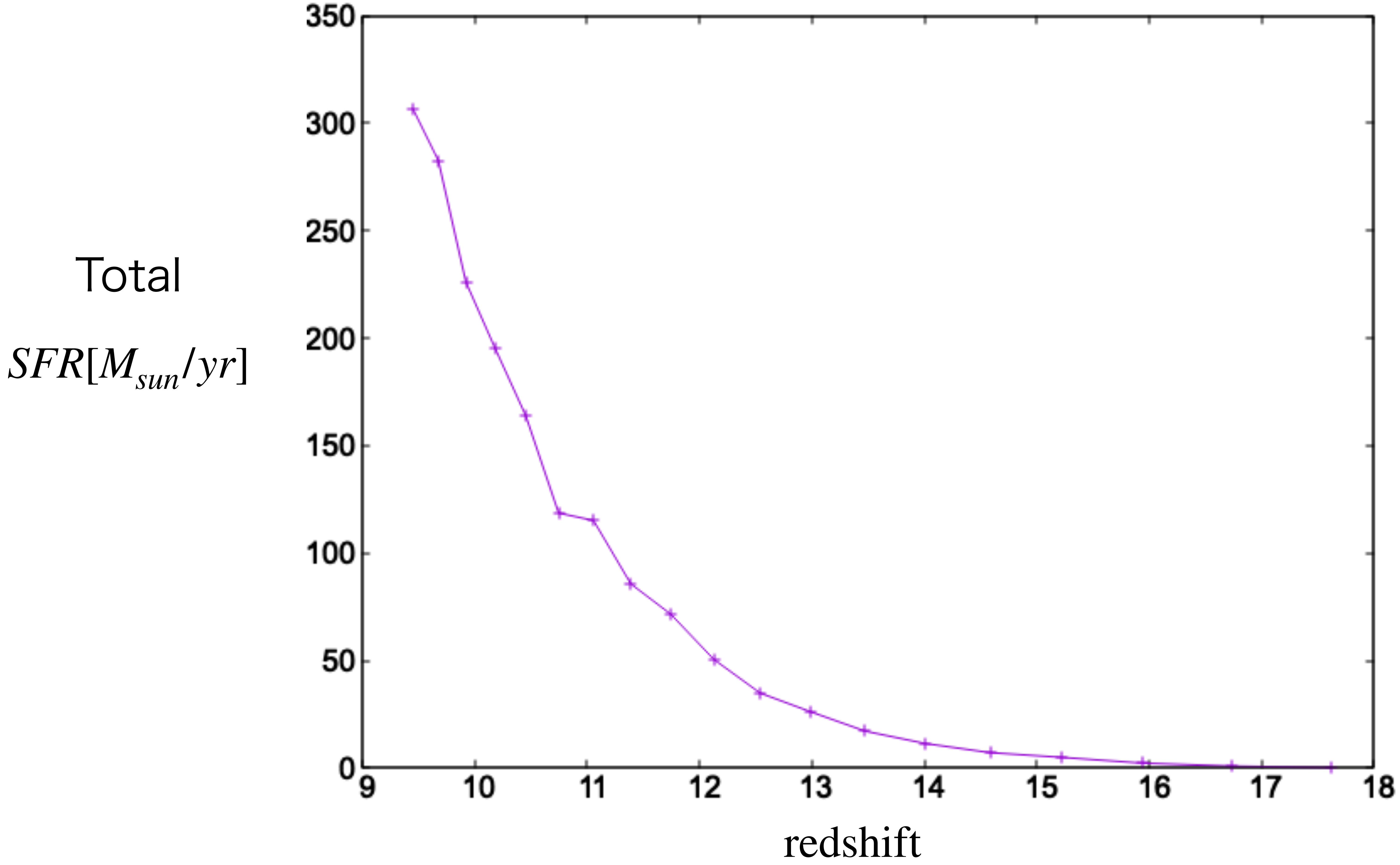


Thermal history of the universe

$$\delta T_b = 28.1(1+\delta)(1-\frac{T_{CMB}}{T_s})\sqrt{\frac{1+z}{10}}[\mathrm{mK}]$$

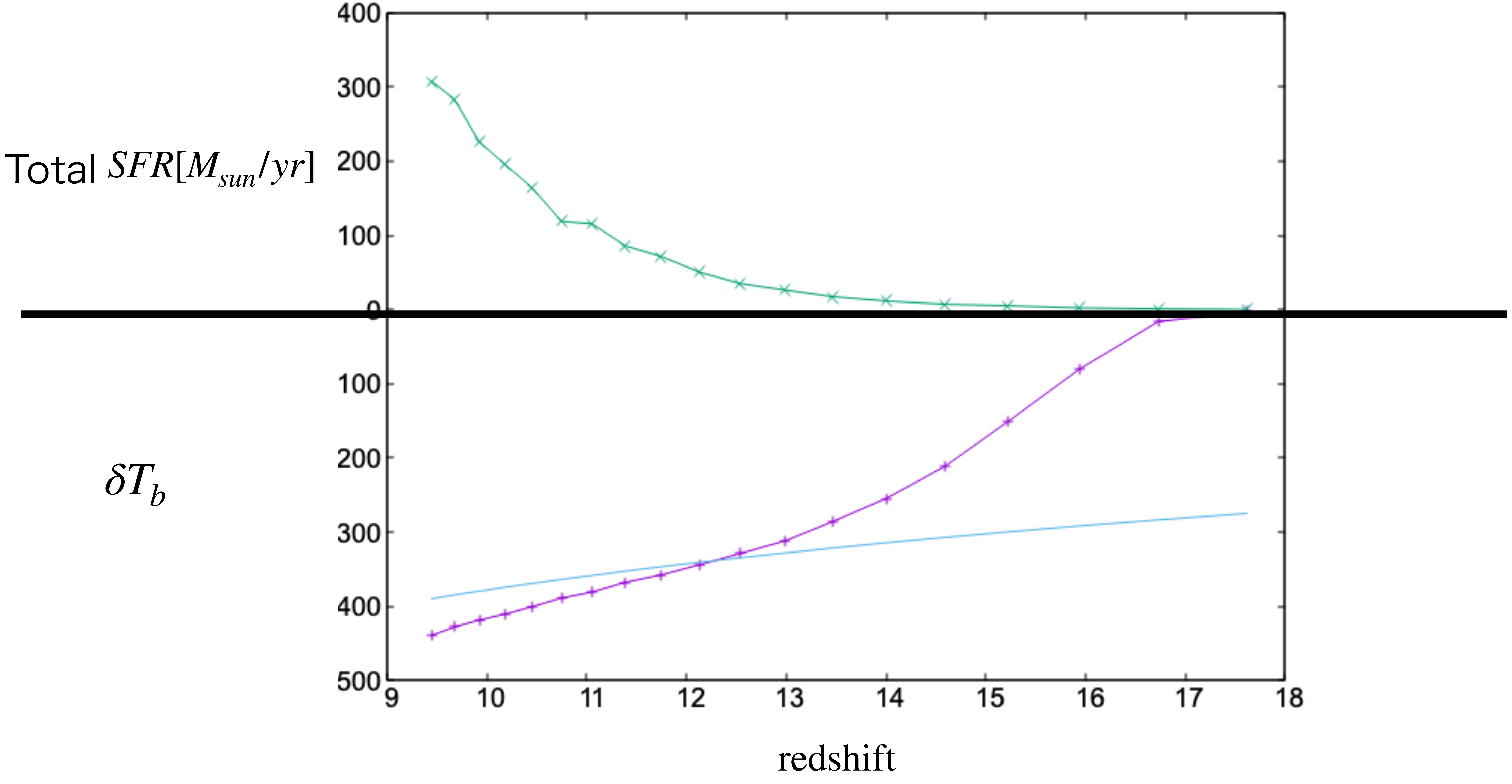


Discussion



Total
$SFR[M_{sun}/yr]$
350
300
250
200
150
100
50
0
9
10
11
12
13
14
15
16
17
18
redshift

Discussion



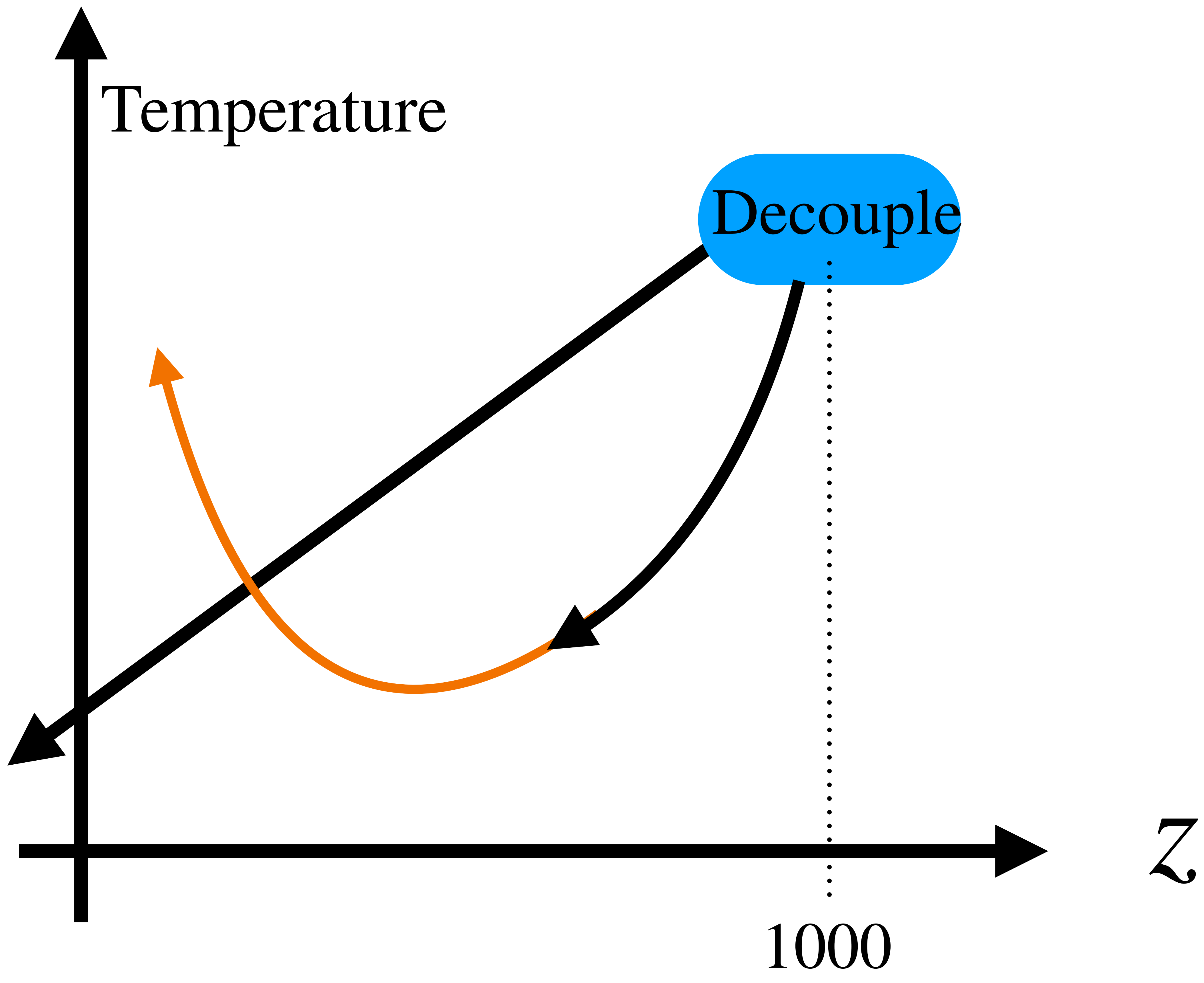
Total $SFR[M_{sun}/yr]$
δT_b
400
300
200
100
0
100
200
300
400
500
9
10
11
12
13
14
15
16
17
18
redshift

Future work1

Taking into ionization effect

Gas was heated by steller objects

How did T_s change ?

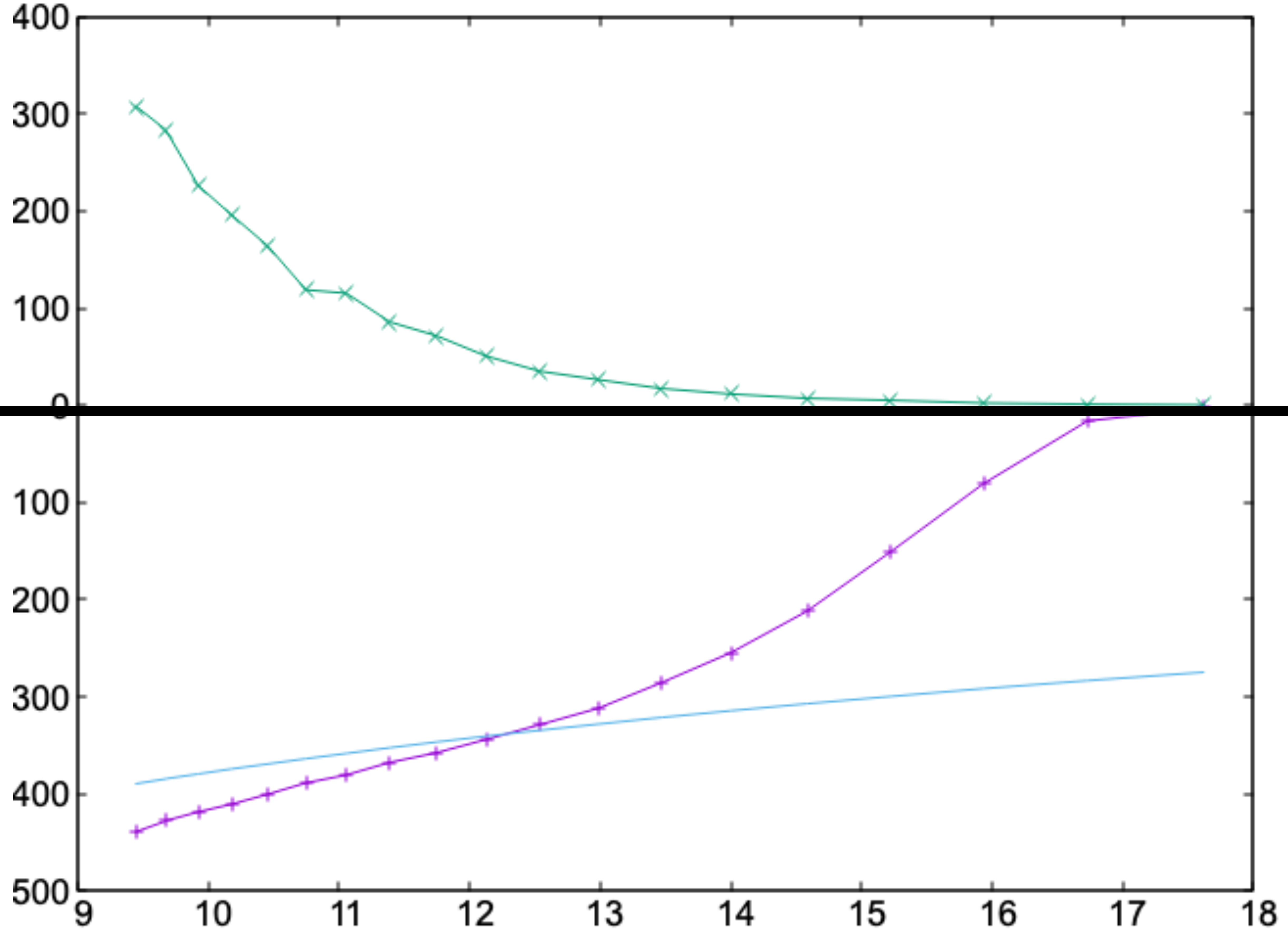


Thermal history of the universe

Future work2

Total $SFR[M_{sun}/yr]$

δT_b



Collect more samples

redshift

Future work

Future work 1

Future work 2

- To understand the relation between 21cm signal and star formation ,evolution precisely.

- To make some limitation for first star and galaxy formation.