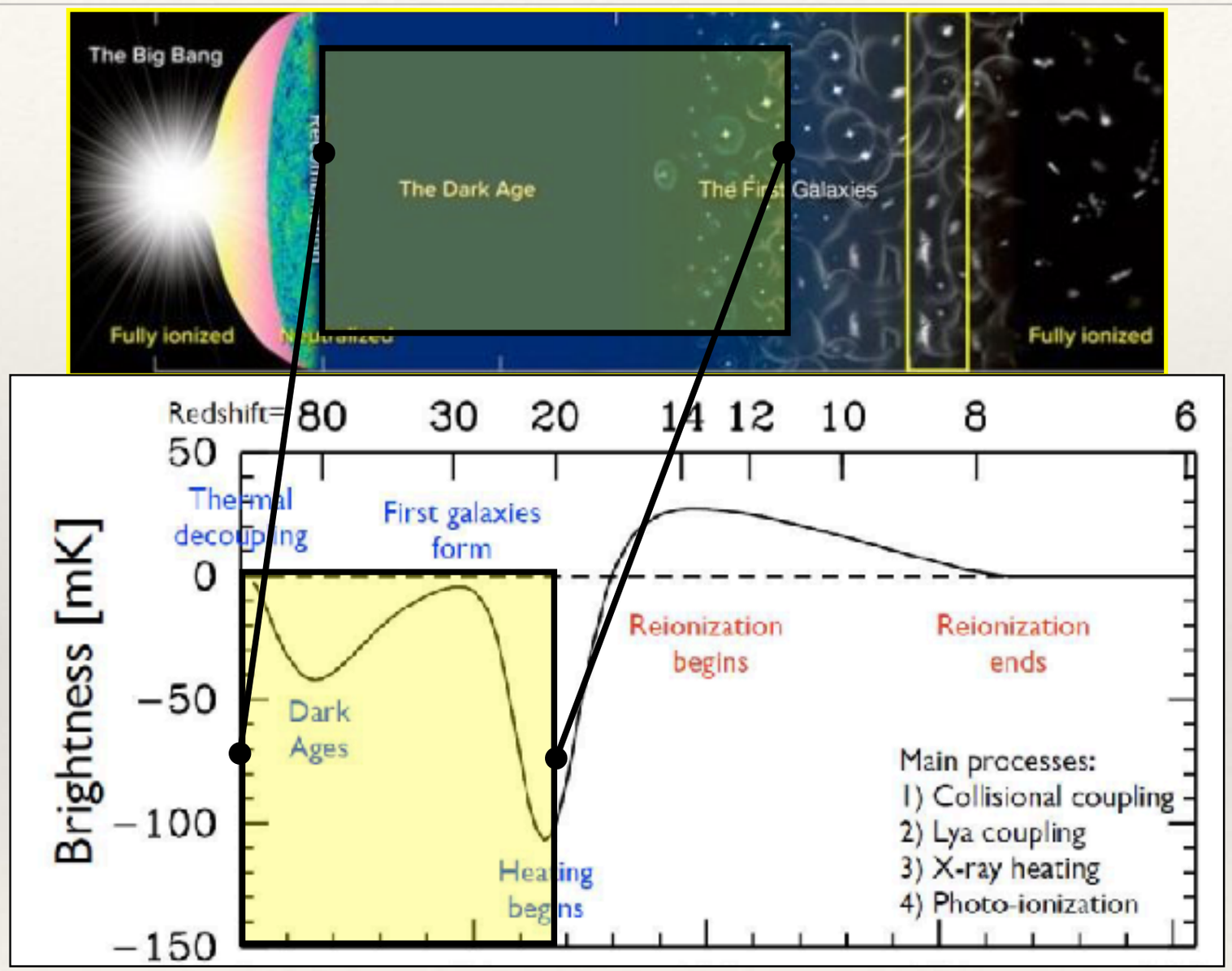
Hongo 21cm workshop (Oct 4)

Modeling the 21cm Signal from the Cosmic Dark Ages: Achieving Sub-Percent Accuracy

Hyunbae Park
(Tsukuba University)

Collaborators: Rennan Barkana, Naoki Yoshida and so on

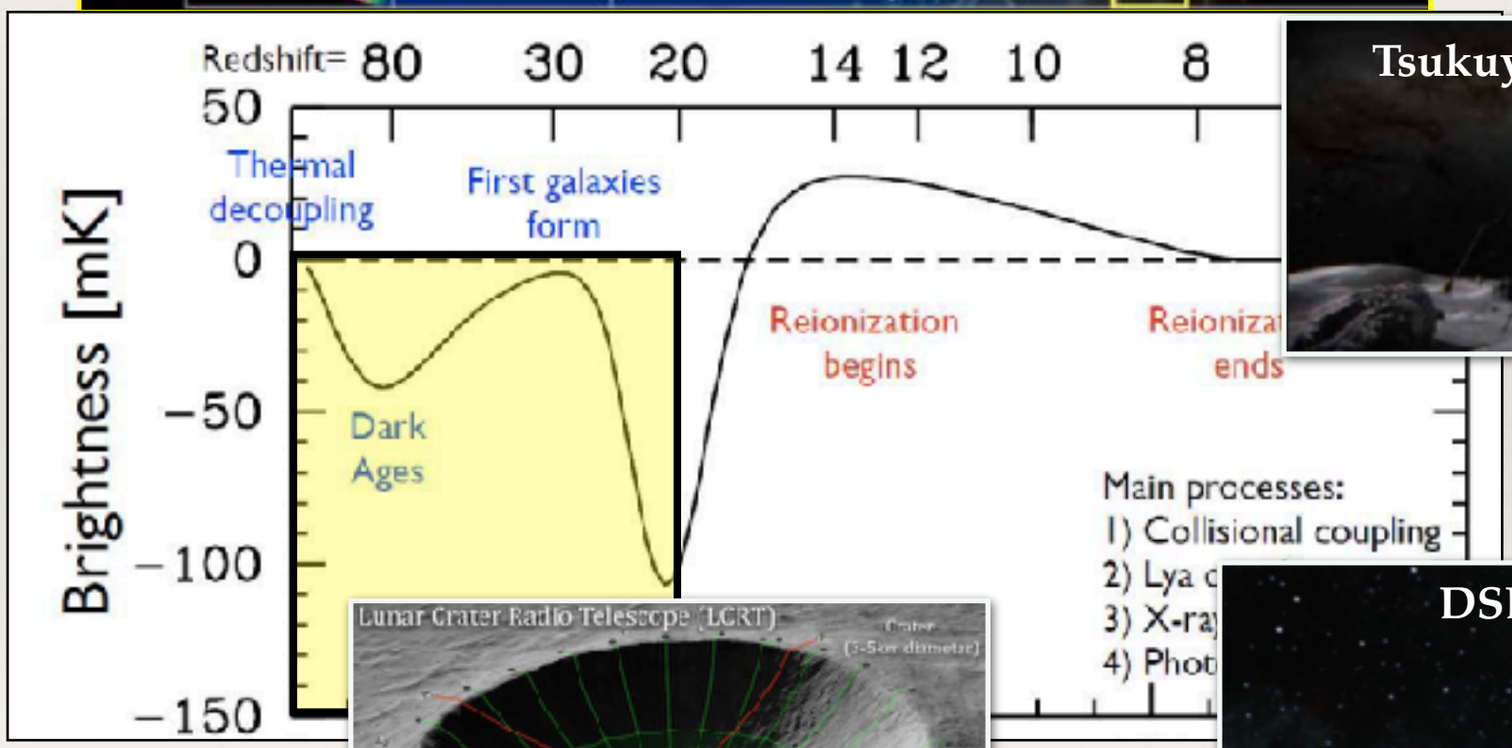
21cm Signal from $z > 20$

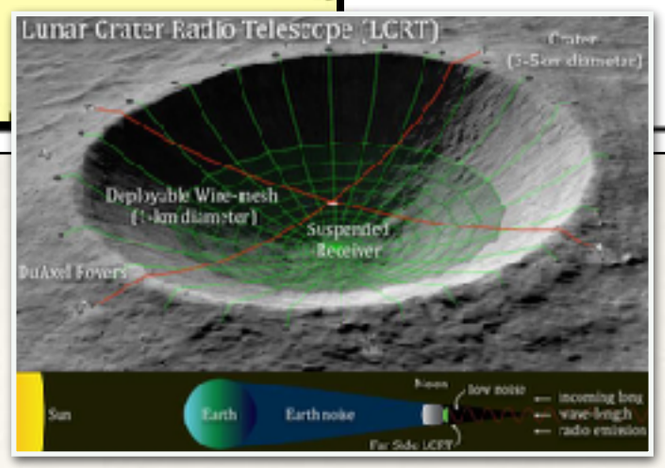


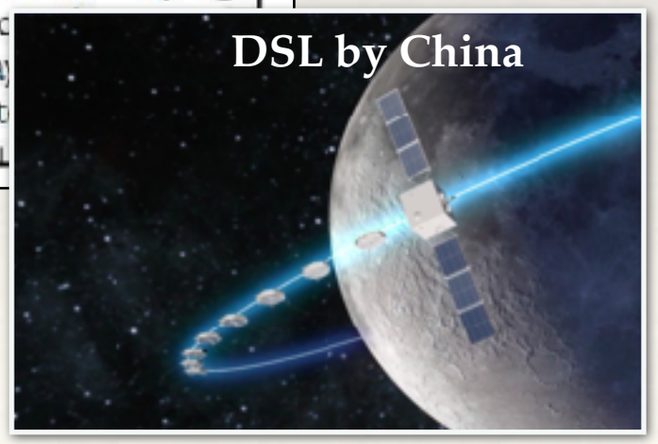
… comes from pristine gas before stars and galaxies ever formed and can constrain cosmology parameters without astrophysics uncertainties.

(Mondal & Barkana 2021)

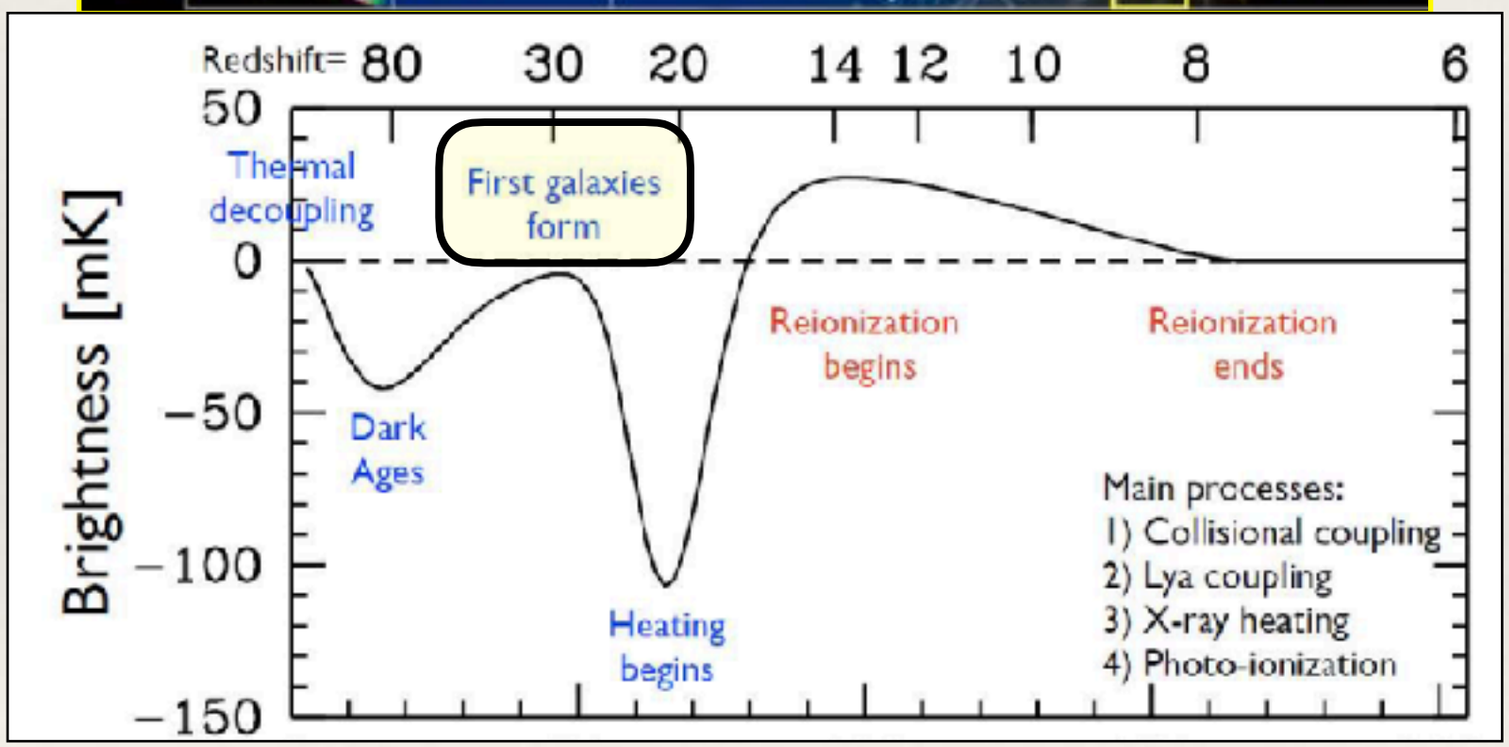
21cm Signal from $z > 20$







21cm Signal from $z > 20$



The signal is often calculated for the homogeneous Universe, but structures are forming at sub-Mpc scales. We need to model the impact on the signal.

Impact of Structure Formation

$$T_b = (1+z)^{-1}(T_{\rm S} - T_{\rm CMB})(1-e^{-\tau})$$

$$T_{\rm S}^{-1} = \frac{T_{\rm CMB}^{-1} + xT_{\rm gas}^{-1}}{1+x}$$

Coupling coefficient

$$x = x_\alpha + x_{\rm c}$$

$$x_{\rm c} \propto \kappa_{1-0}(T_{\rm gas}) n_{\rm H}$$

$$(1-e^{-\tau}) \approx \tau \text{ for small } \tau$$
$$\approx 1 \text{ for large } \tau$$

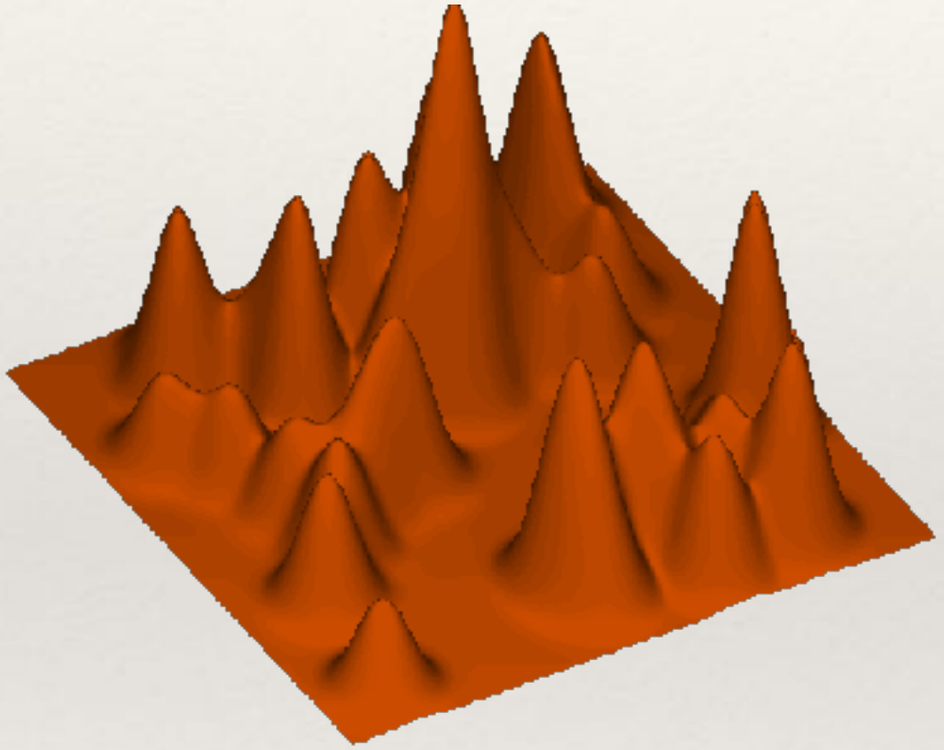
$$\tau(z) = \frac{3c\lambda_{21}h_{\rm p}A_{10}n_{\rm HI}}{32\pi k_{\rm B}T_{\rm S}(1+z)(dv_r/dr)} \propto \frac{n_{\rm HI}}{dv_r/dr}$$

$H(z)$ in the homogeneous Universe

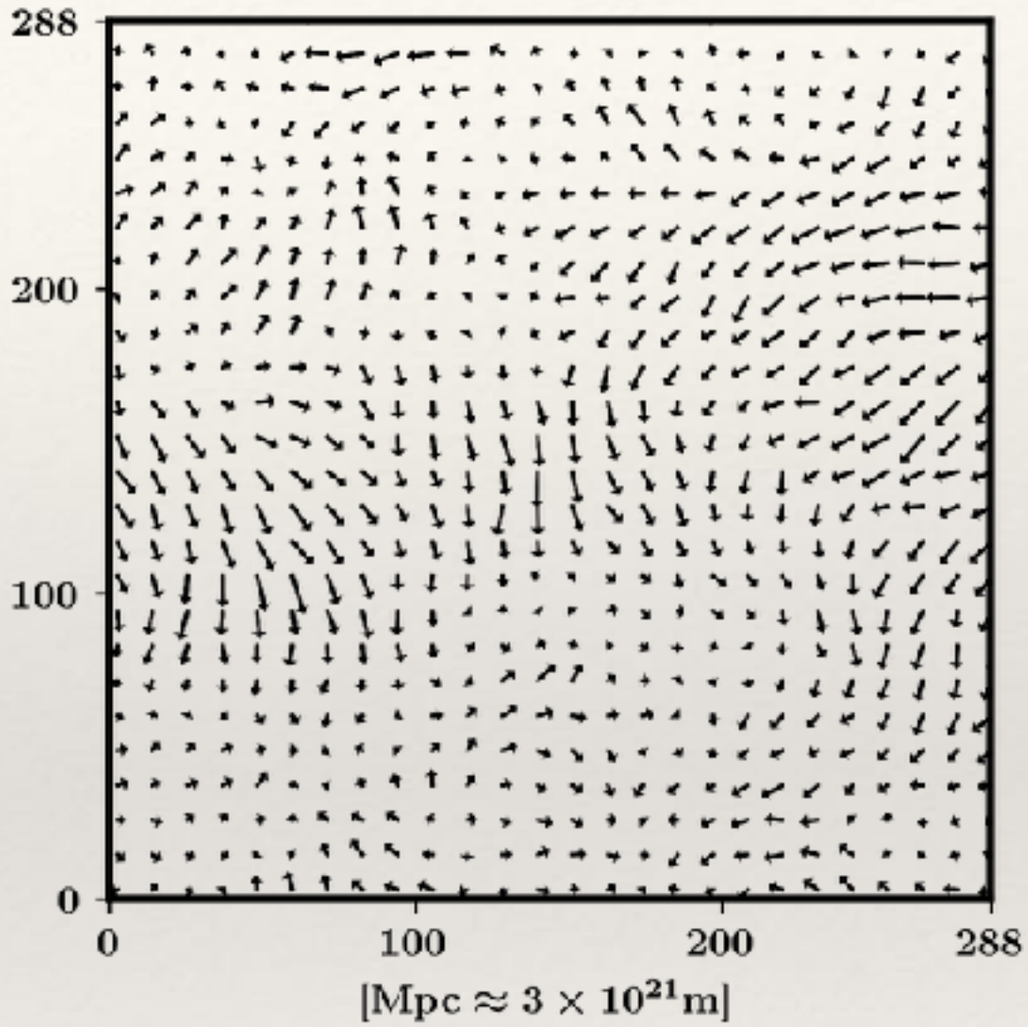
Structure formation introduces fluctuations in $T_{\rm gas}$ and $n_{\rm H}$, and v_r
How will that affect $T_{\rm b}$?

Baryon-DM Streaming

At $z > 1090$,

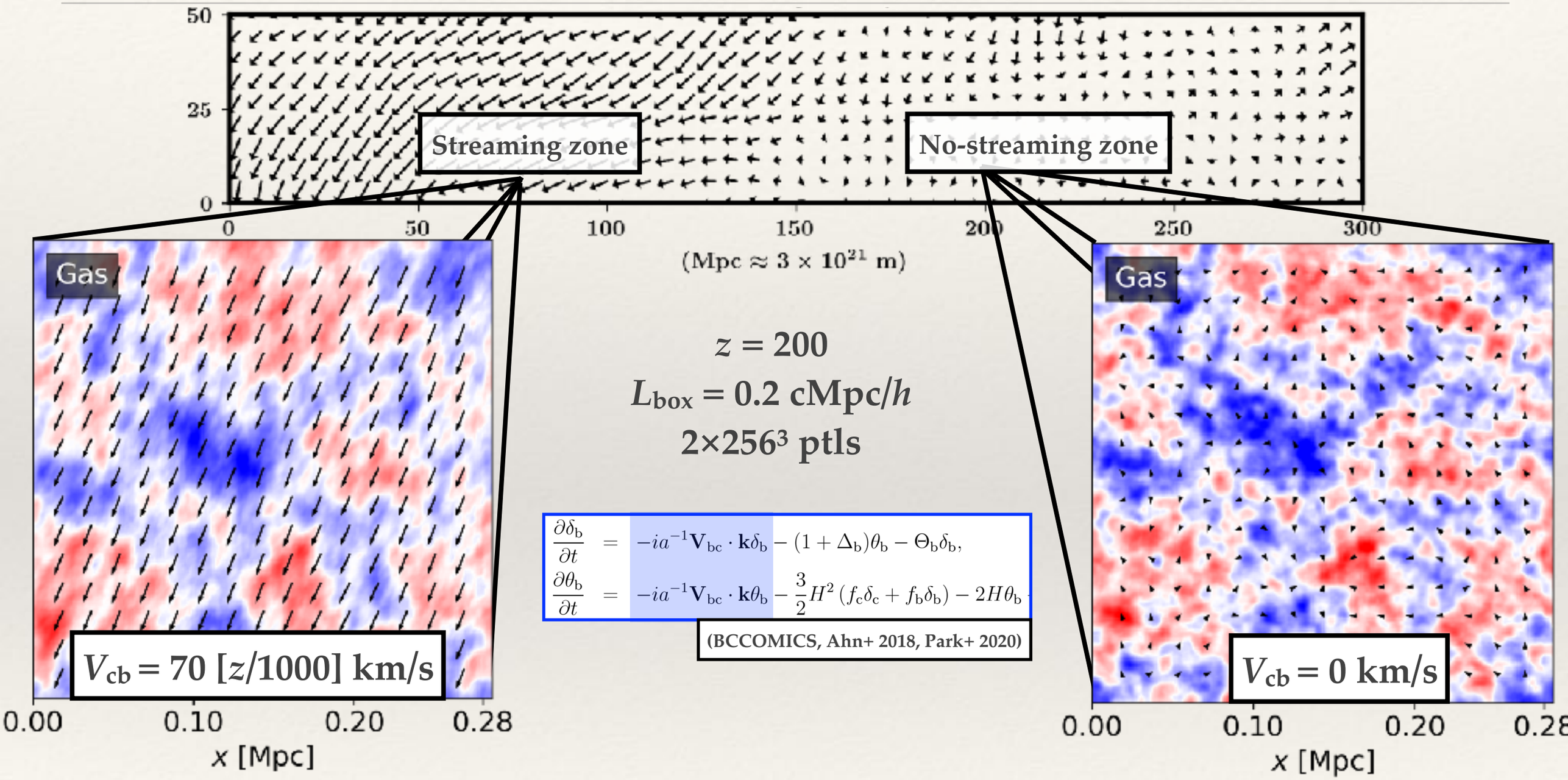


… pressure of photon-baryon fluid generates the Baryonic Acoustic Oscillations.
This sound wave became a *relative motion* between baryons and dark matter.



V_{cb} = 0 - 70 [z/1000] (km/s)
Not strong enough to affect SF at $z \sim 6$
But, strong enough disrupt some of small-scale gas structures

Initial Conditions with Streaming v



$z = 200$

$L_{box} = 0.2$ cMpc/h

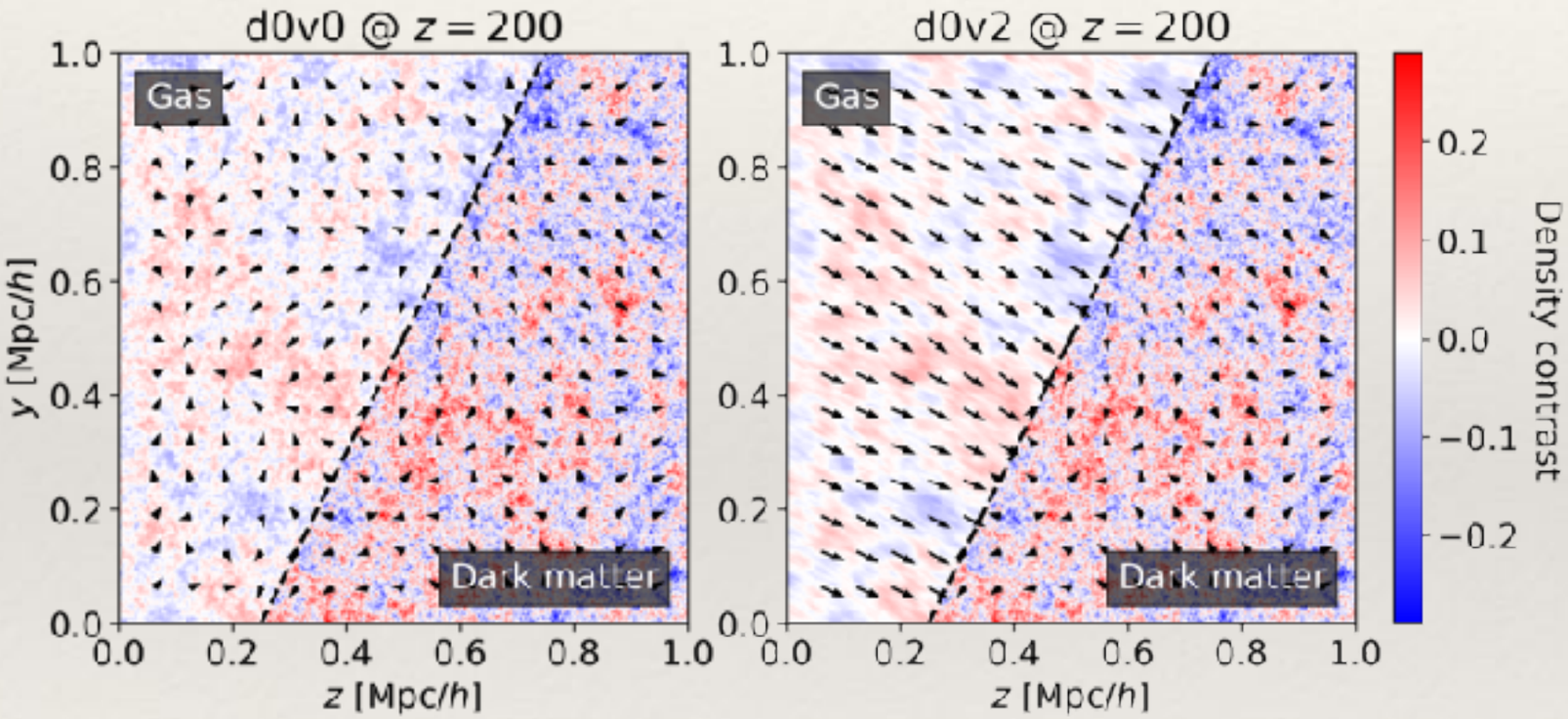
2×256^3 ptls

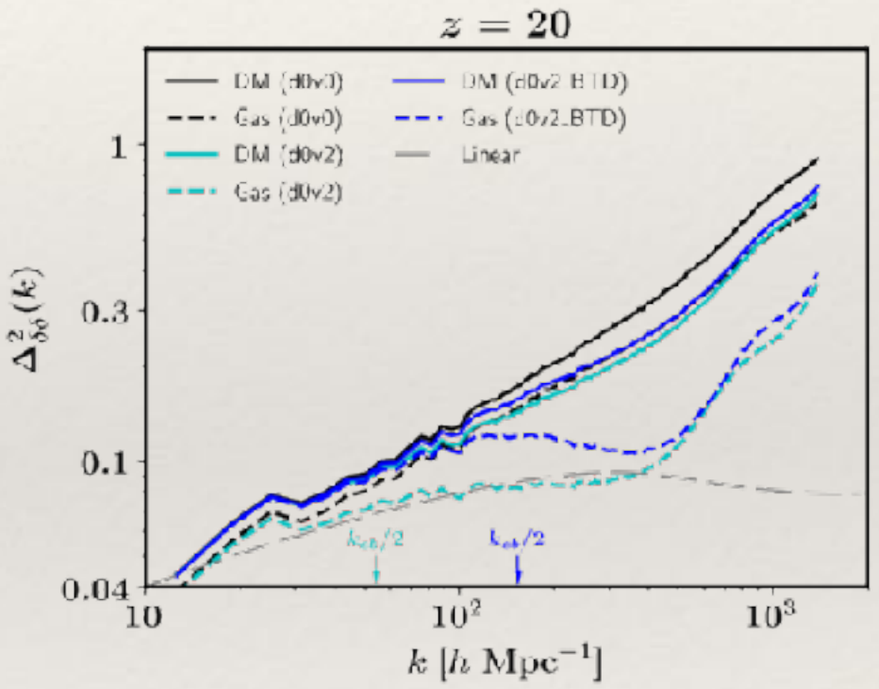
$$\frac{\partial \delta_b}{\partial t} = -ia^{-1}\mathbf{V}_{bc}\cdot\mathbf{k}\delta_b - (1+\Delta_b)\theta_b - \Theta_b\delta_b,$$
$$\frac{\partial \theta_b}{\partial t} = -ia^{-1}\mathbf{V}_{bc}\cdot\mathbf{k}\theta_b - \frac{3}{2}H^2\left(f_c\delta_c + f_b\delta_b\right) - 2H\theta_b$$

(BCCOMICS, Ahn+ 2018, Park+ 2020)

Streaming motion smoothes gas density.

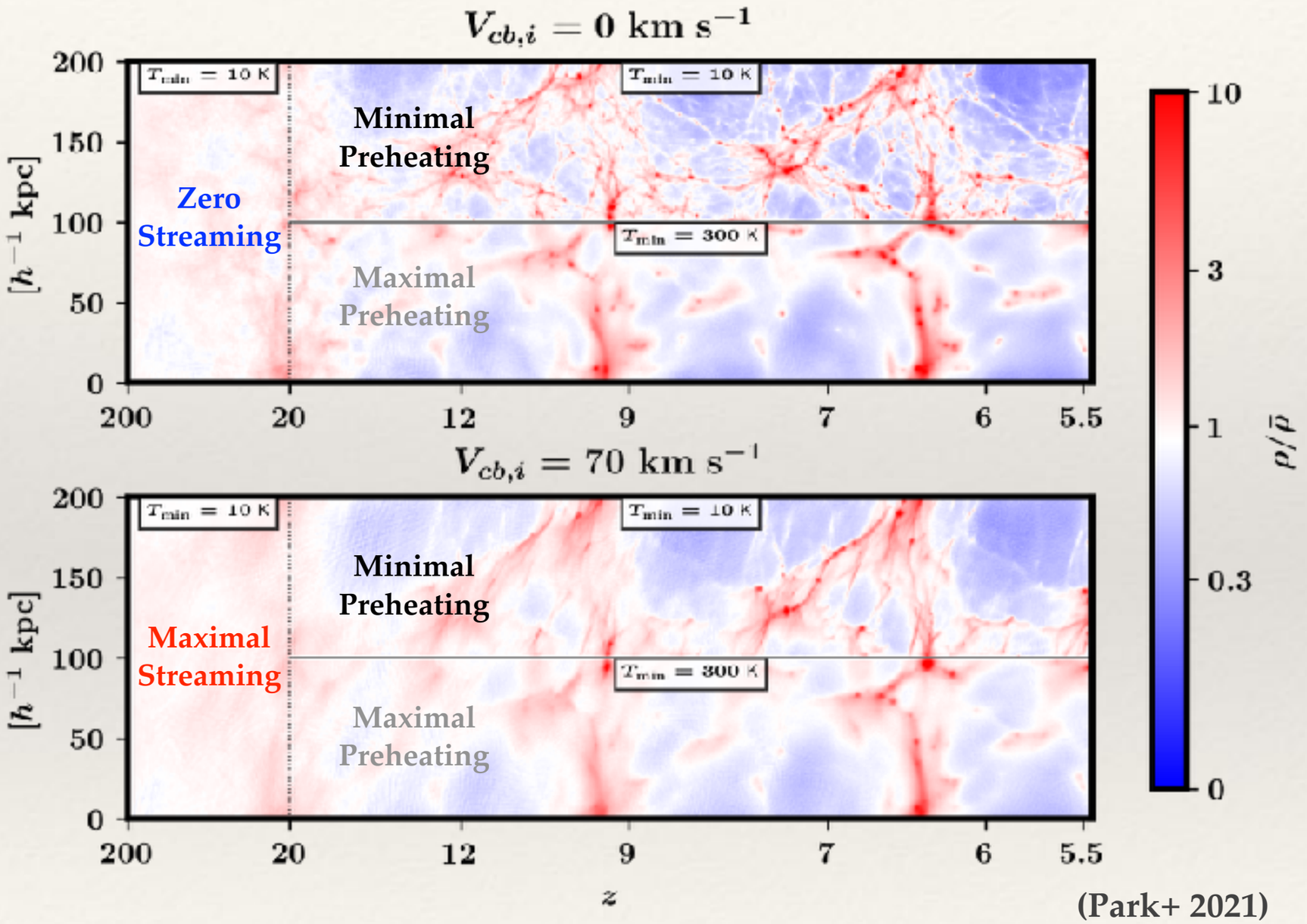
Baryon-dark Matter Streaming Velocity





(Park+ 2020)

Pre-reionization IGM with Streaming & Preheating



(Park+ 2021)

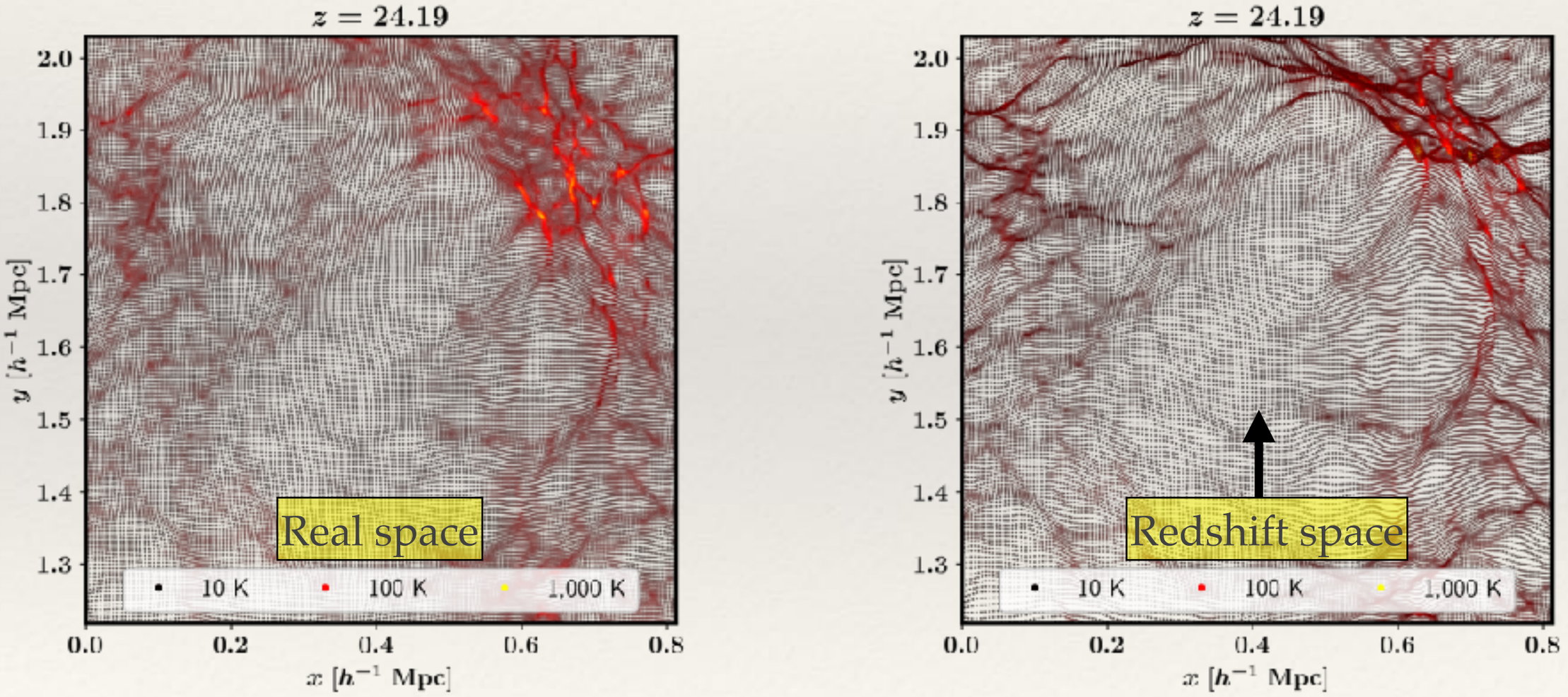
Streaming v & X-ray preheating erases small-scale gas structures.

Redshift Space Distortion

$$T_b = (1+z)^{-1}(T_{\rm S} - T_{\rm CMB})(1 - e^{-\tau})$$

$$\tau(z) = \frac{3c\lambda_{21}h_{\rm p}A_{10}n_{\rm HI}}{32\pi k_{\rm B}T_{\rm S}(1+z)(dv_r/dr)} \propto \frac{n_{\rm HI}}{dv_r/dr} = n_{\rm HI,RS}$$

$$(1 - e^{-\tau}) \approx \tau \text{ for small } \tau$$
$$\approx 1 \text{ for large } \tau$$

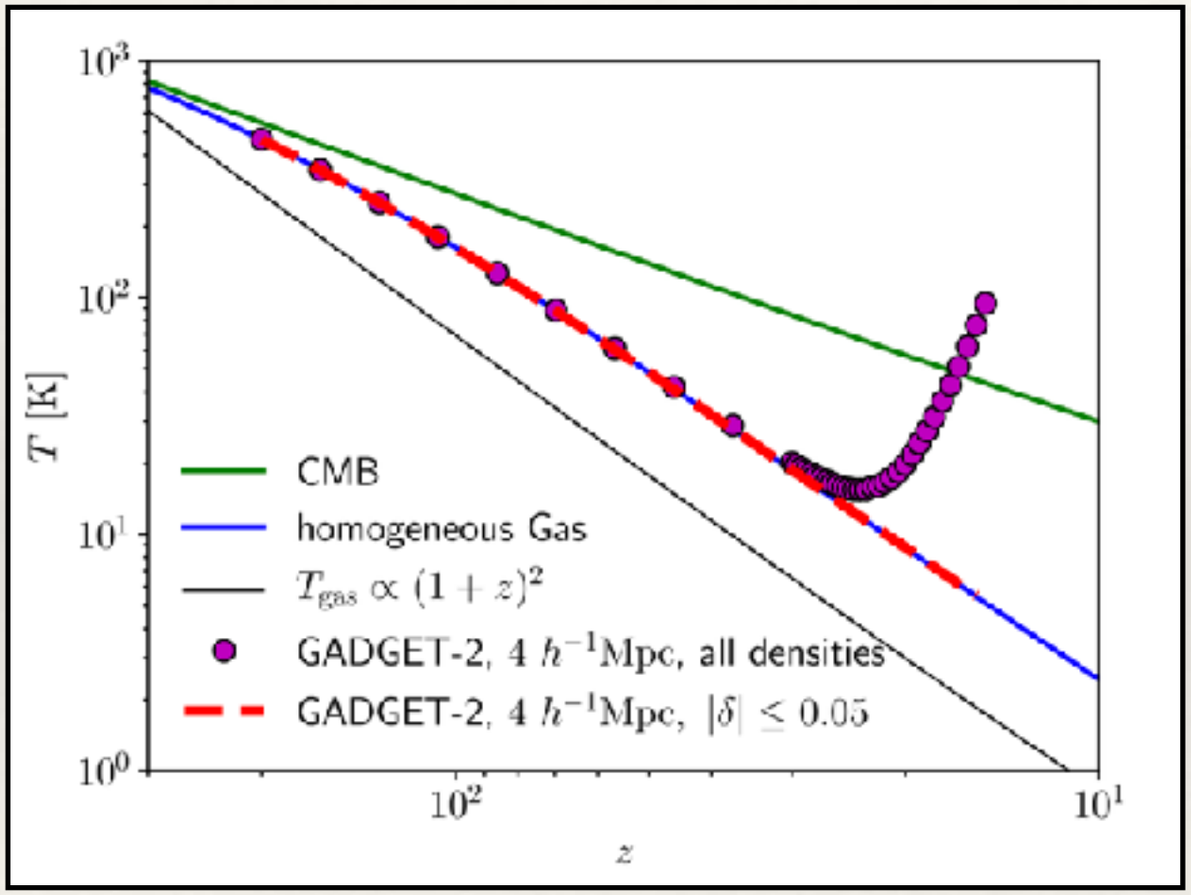


The RSD effect can reduces the signal from dense gas.

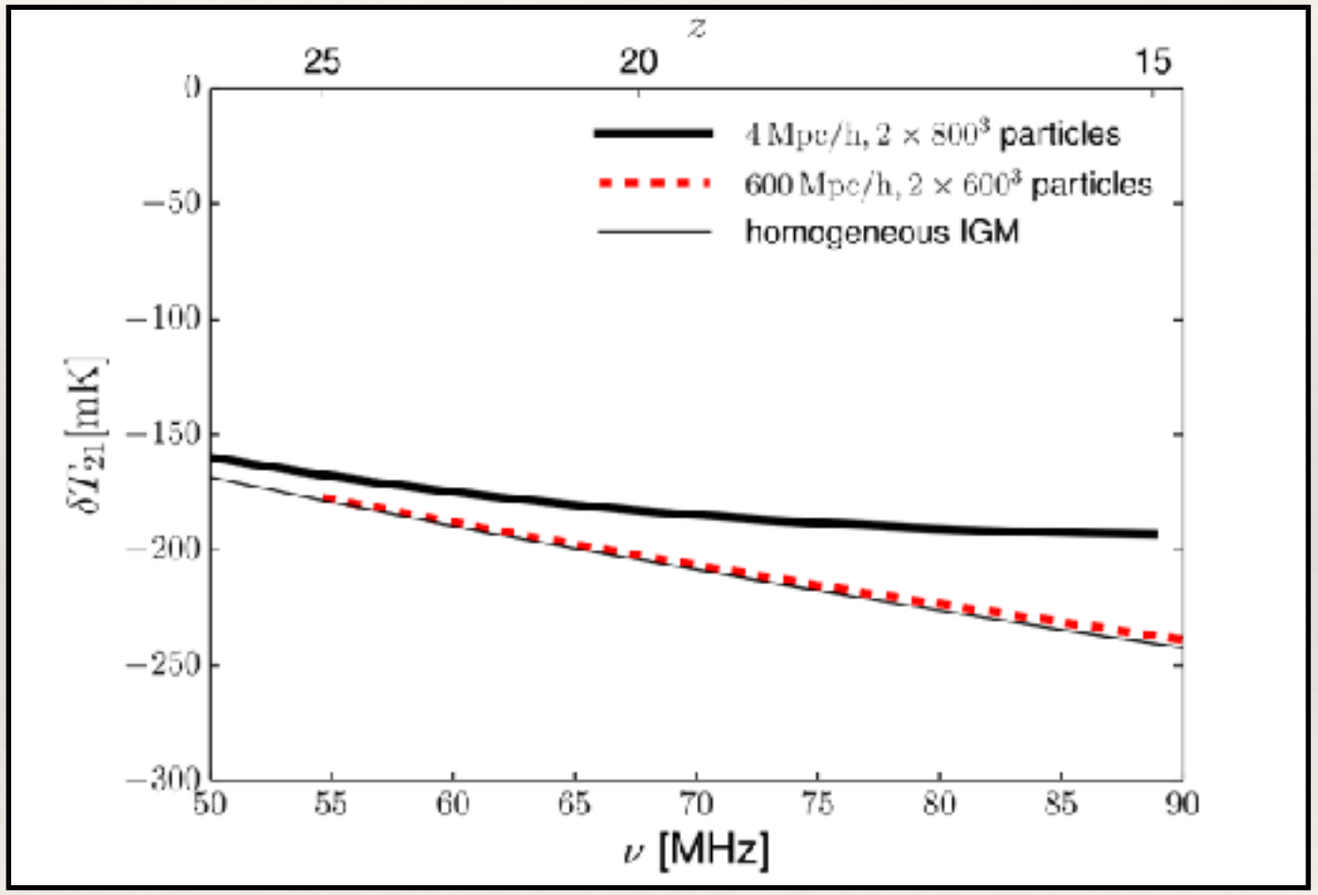
Impact on the Maximal 21 cm Signal at z=17

(Xu+ 2021)

Maximal signal: $x_a = \infty \rightarrow T_S = T_{gas}$

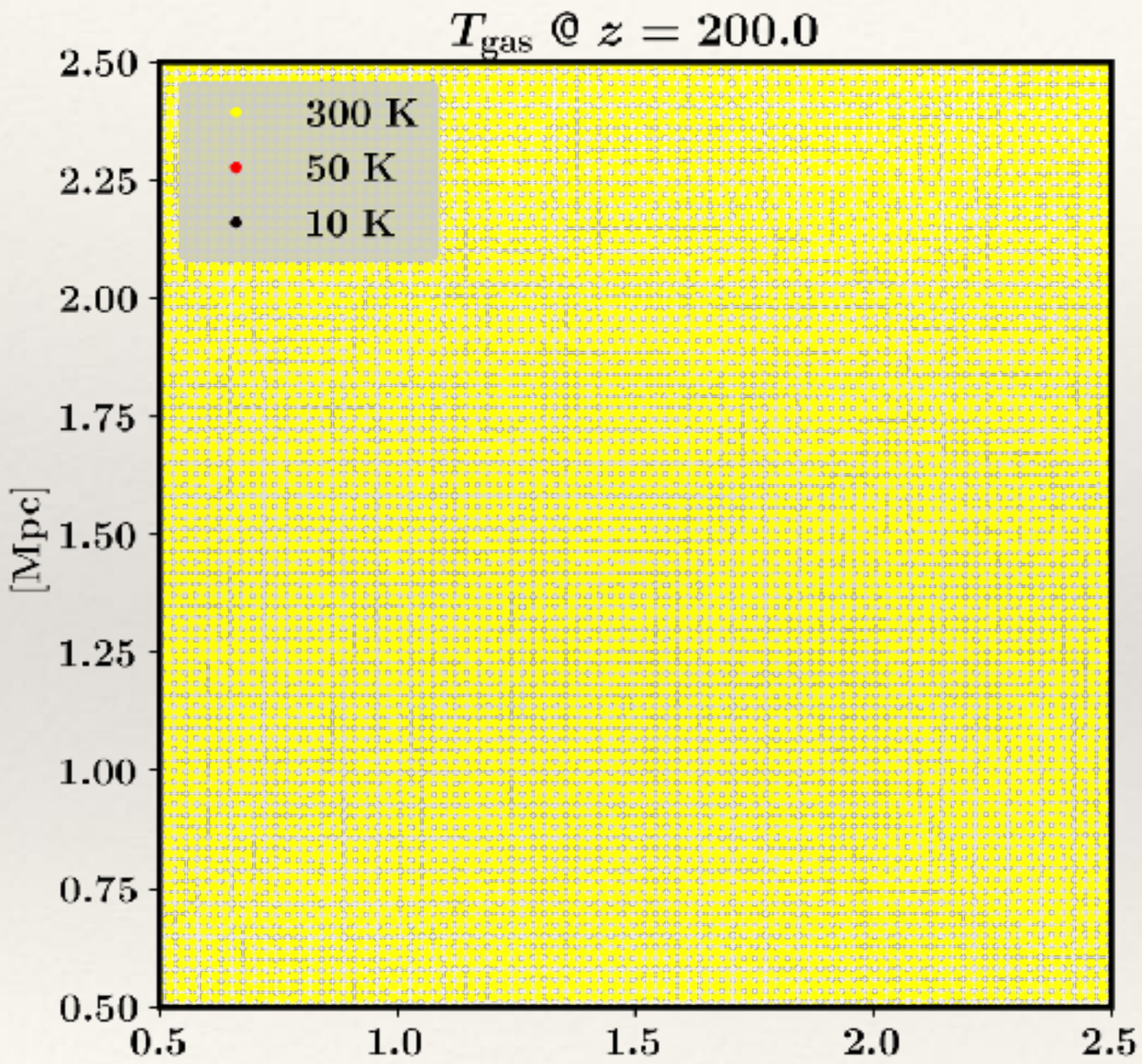


Gas heated by compression and shocks from structure formation



Weaker maximum absorption due to the heating

Simulation Setup & Gas Temperature



Code: GADGET-2

Box size: 3 Mpc

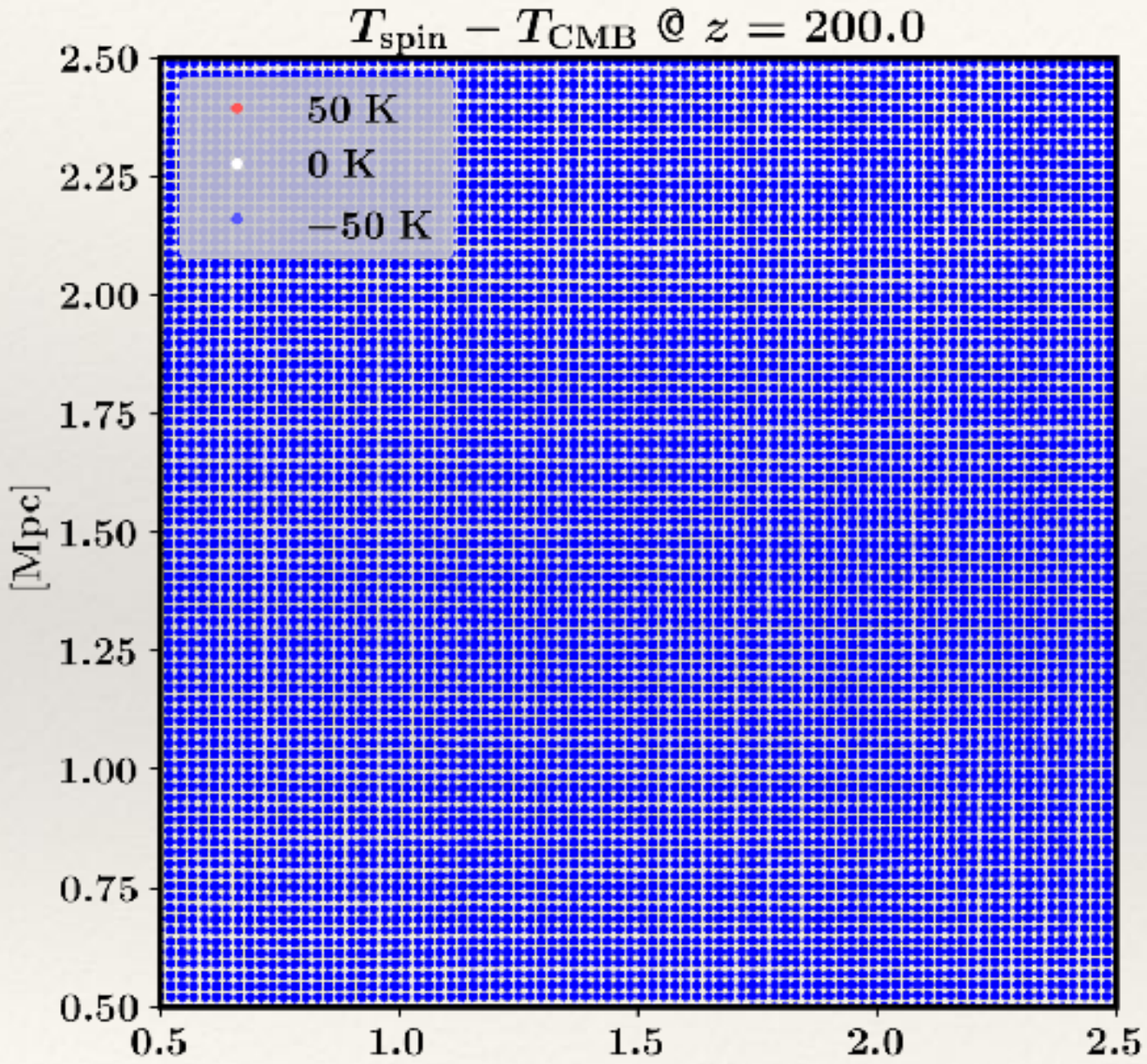
Resolution: 512^3 ptls

Chemical processes

- Compton heating
- $e + H^+ \rightarrow H$
- $e + He^+ \rightarrow He$
- Cooling by H and H_2 disabled
- No star formation

Our goal is to model the dark age signal from z > 20, assuming $x_a = 0$.

Spin Temperature



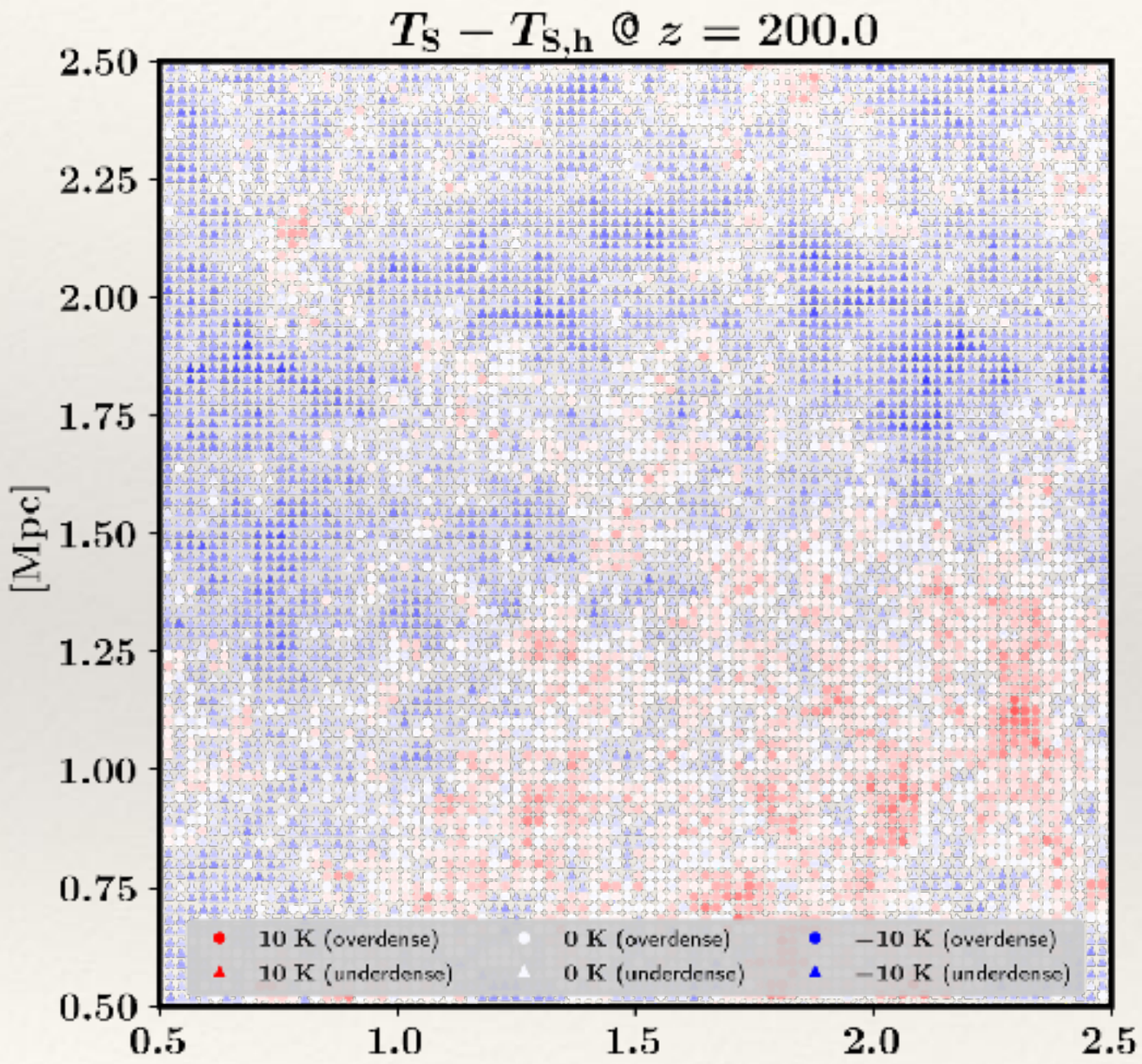
$$T_{\rm S}^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_{\rm gas}^{-1}}{1 + x_c}$$

where

$$x_c = \frac{\kappa_{1-0}(T_{\rm gas}) n_{\rm HI} T_*}{A_{10} T_{\rm CMB}}$$

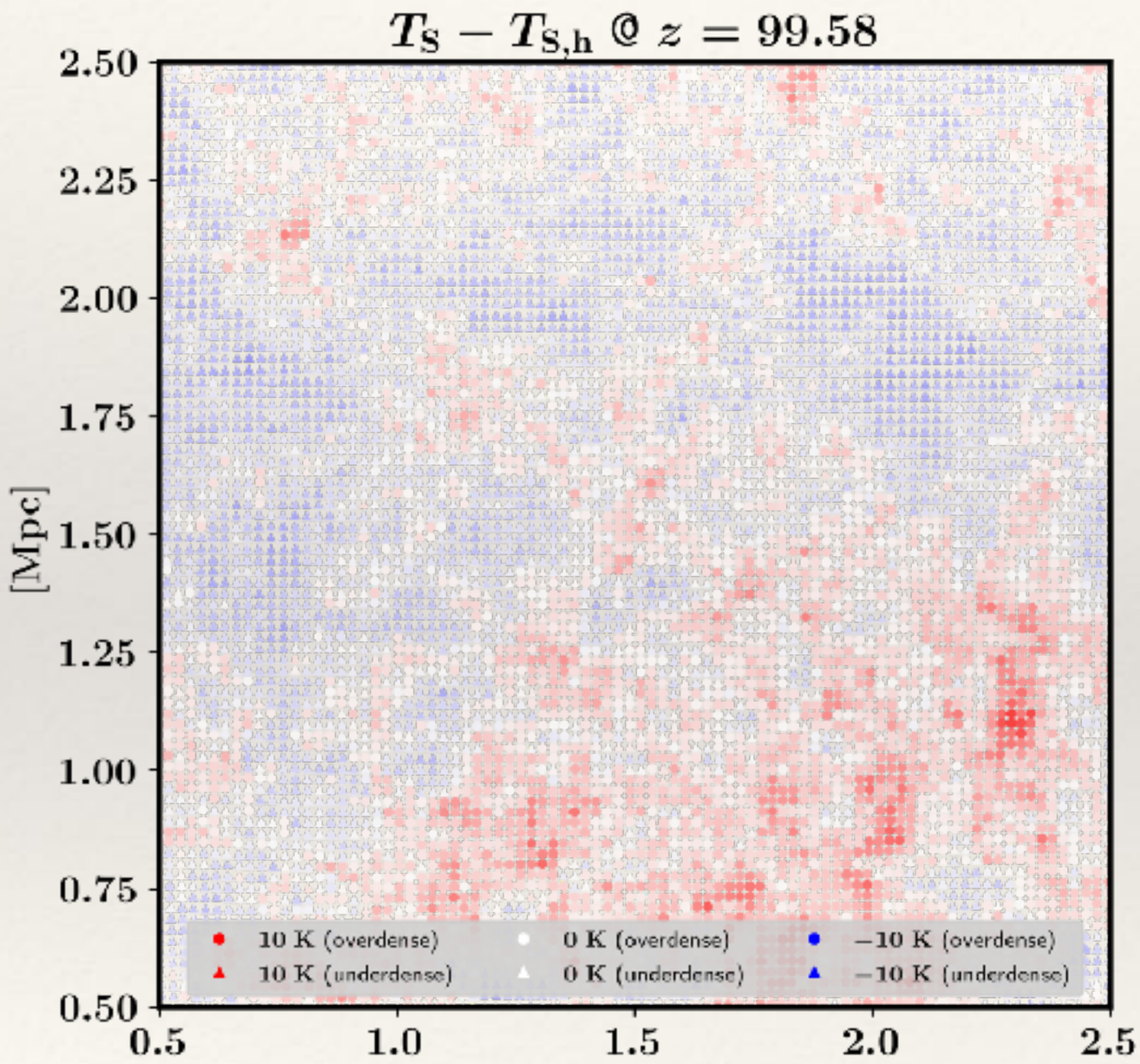
Strong coupling when $n_{\rm HI} > 0.1$ cm^{-3}
Weak coupling when $n_{\rm HI} < 0.1$ cm^{-3}

Impact of Structure Formation on Spin Temperature



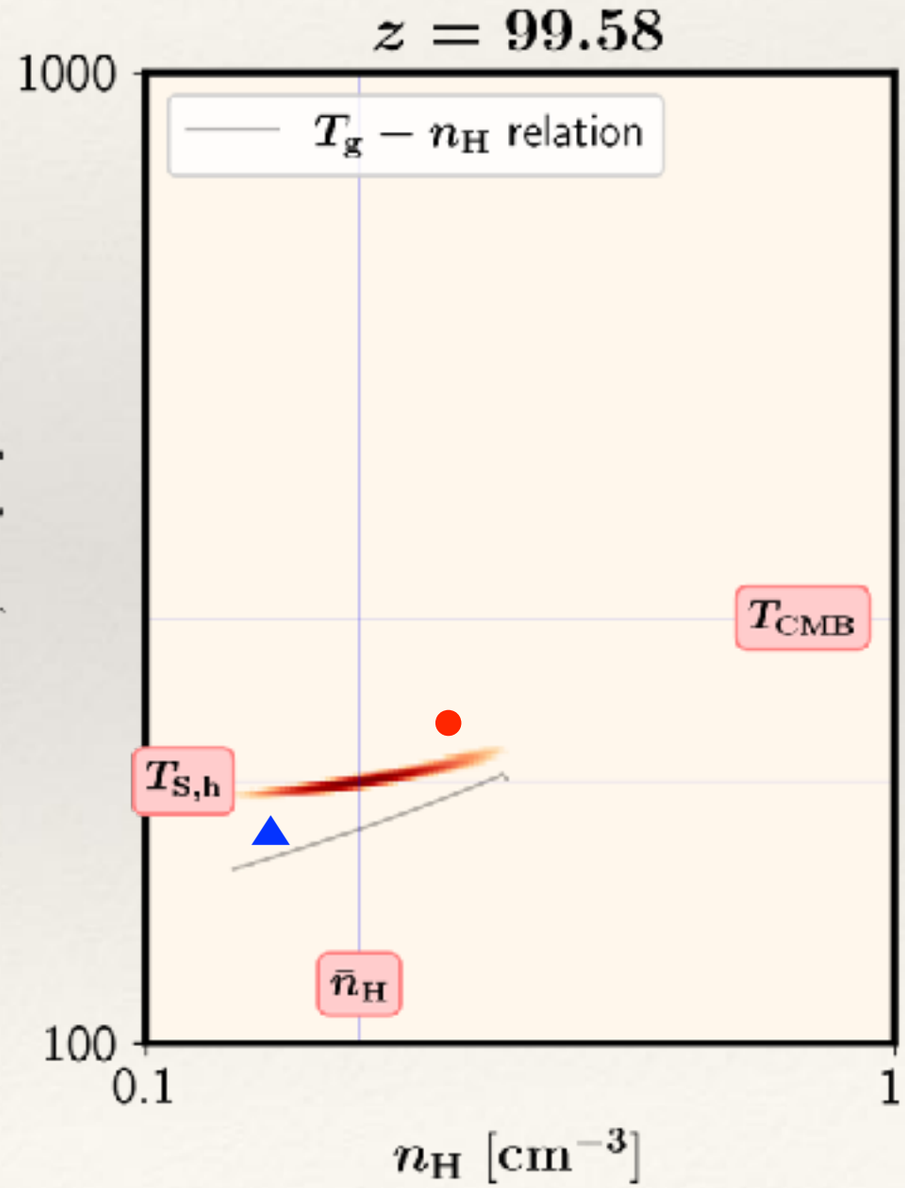
- Positive relation btw ΔT_S and δ at $z > 70$ (▲&●)
- Negative relation btw ΔT_S and δ at $z < 60$ (▲&●)
- $\Delta T_S = 0$ in underdense regions (△) &
  $\Delta T_S < 0$ or $\Delta T_S > 0$ in overdense regions at $z < 30$ (●&●)

ΔT_S due to Structure Formation ($z > 70$)

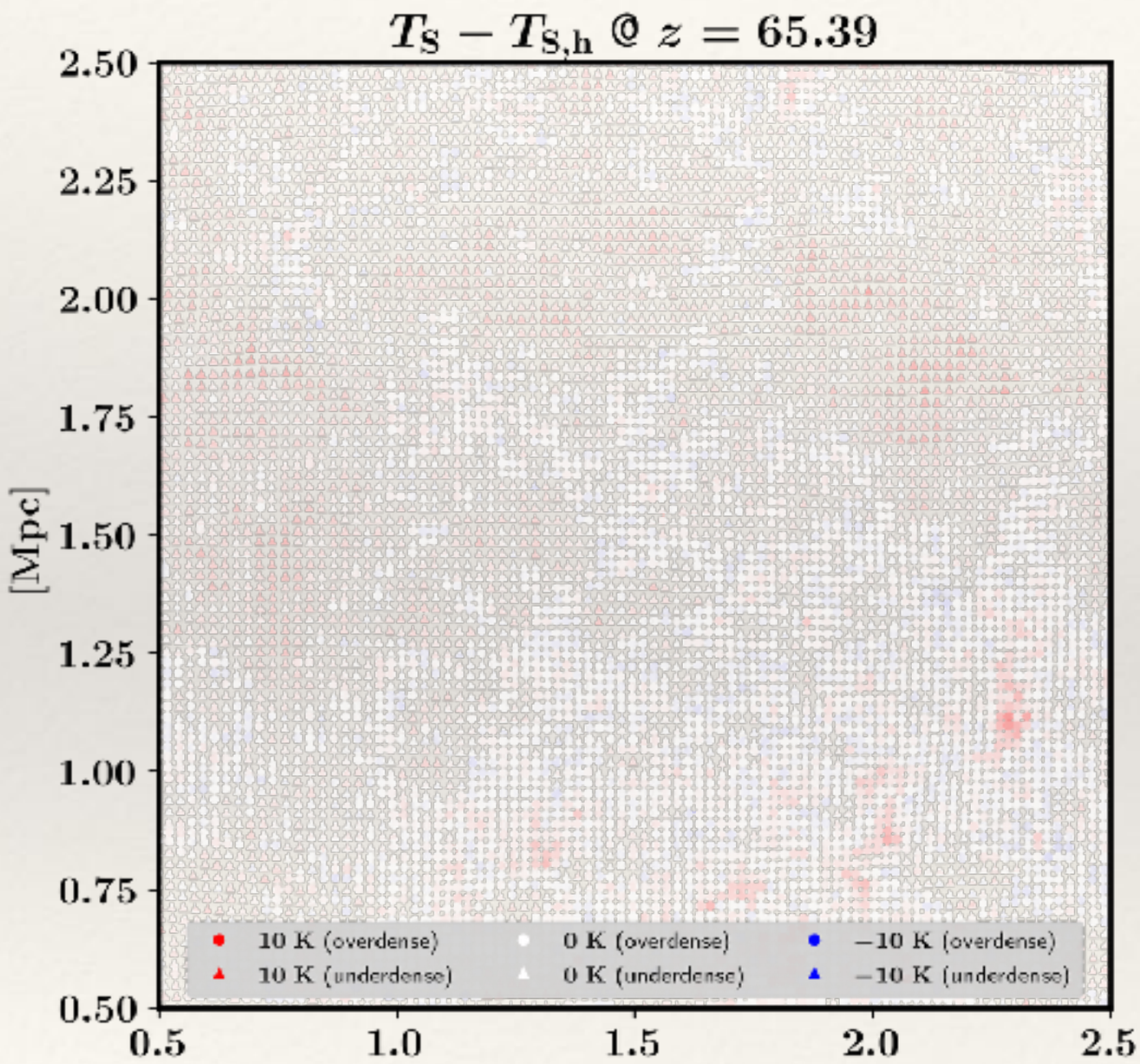


Positive relation btw ΔT_S and δ at $z > 70$

as T_S is tightly coupled to T_{gas} (▲&●)

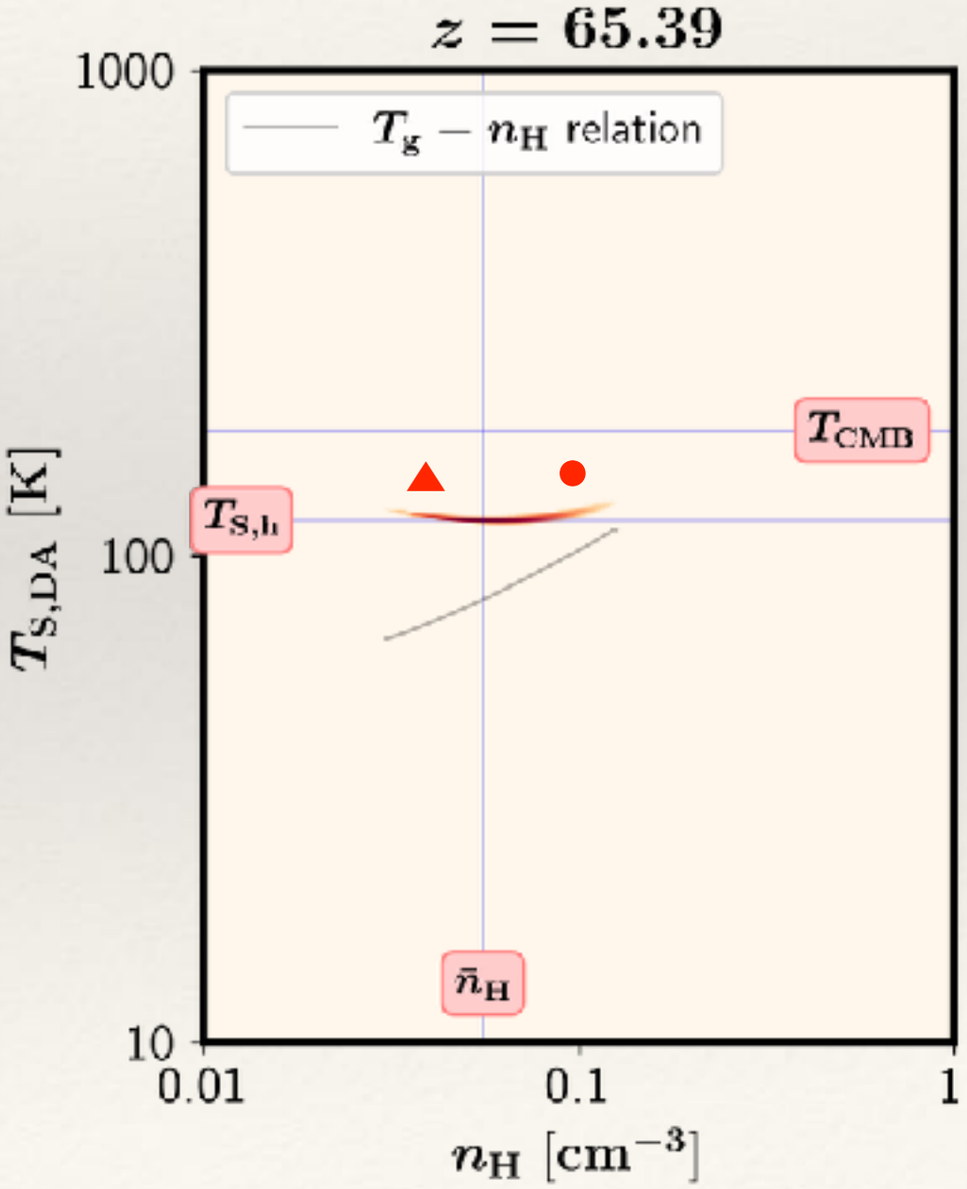


ΔT_S due to Structure Formation ($z = 65$)

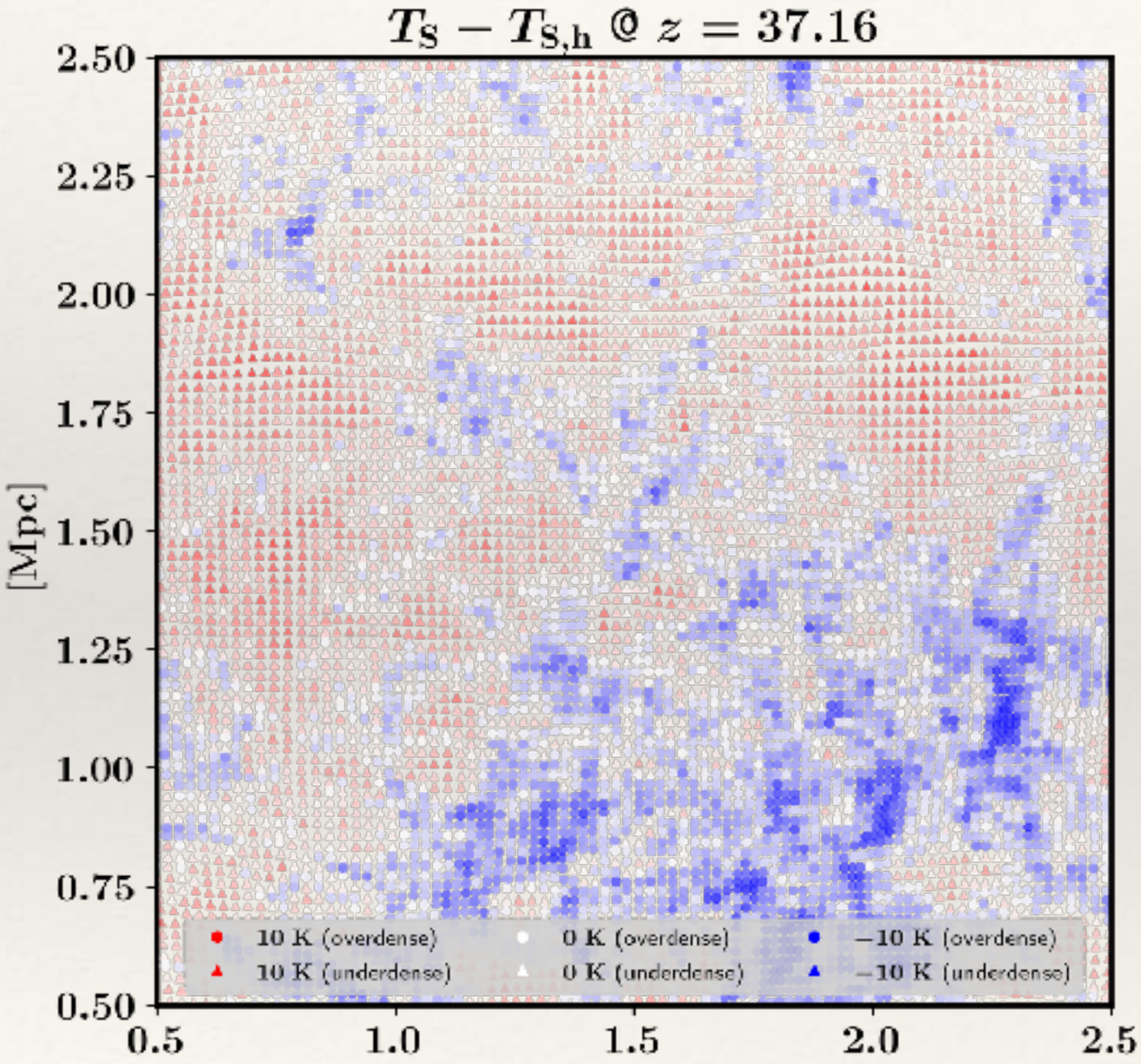


T_S starts to decouple from T_{gas} from δ<0

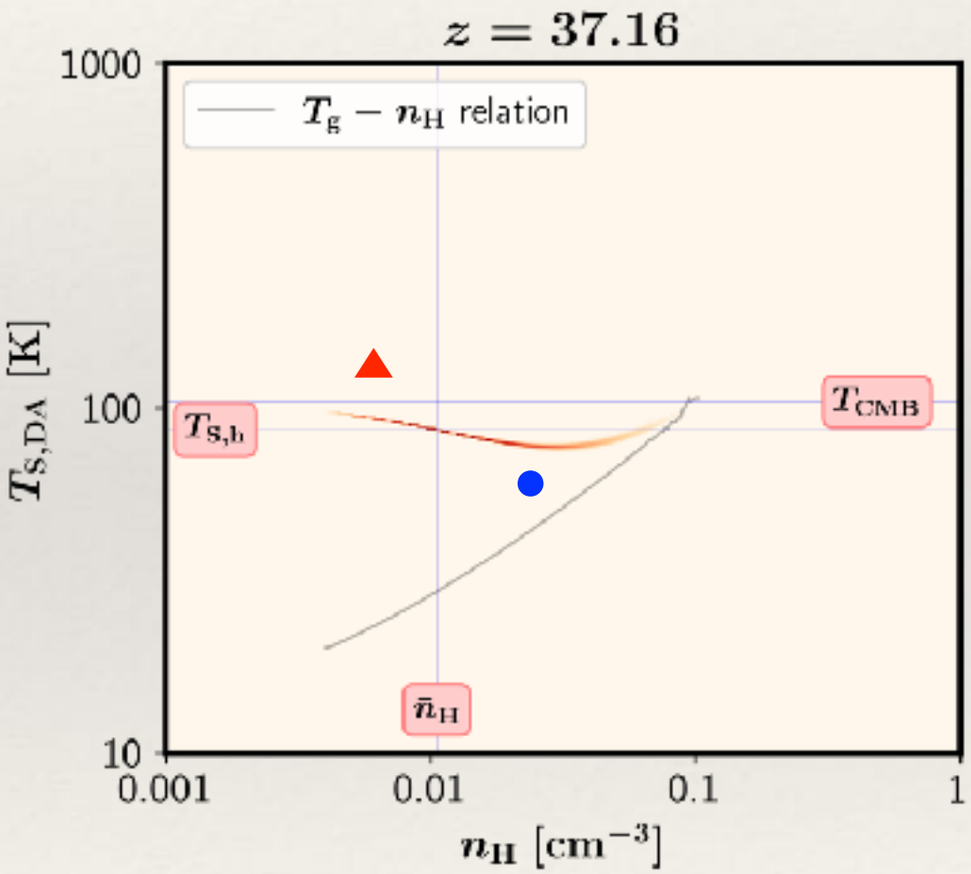
→ Positive ΔT_S from both δ<0 and δ>0 (▲&●)



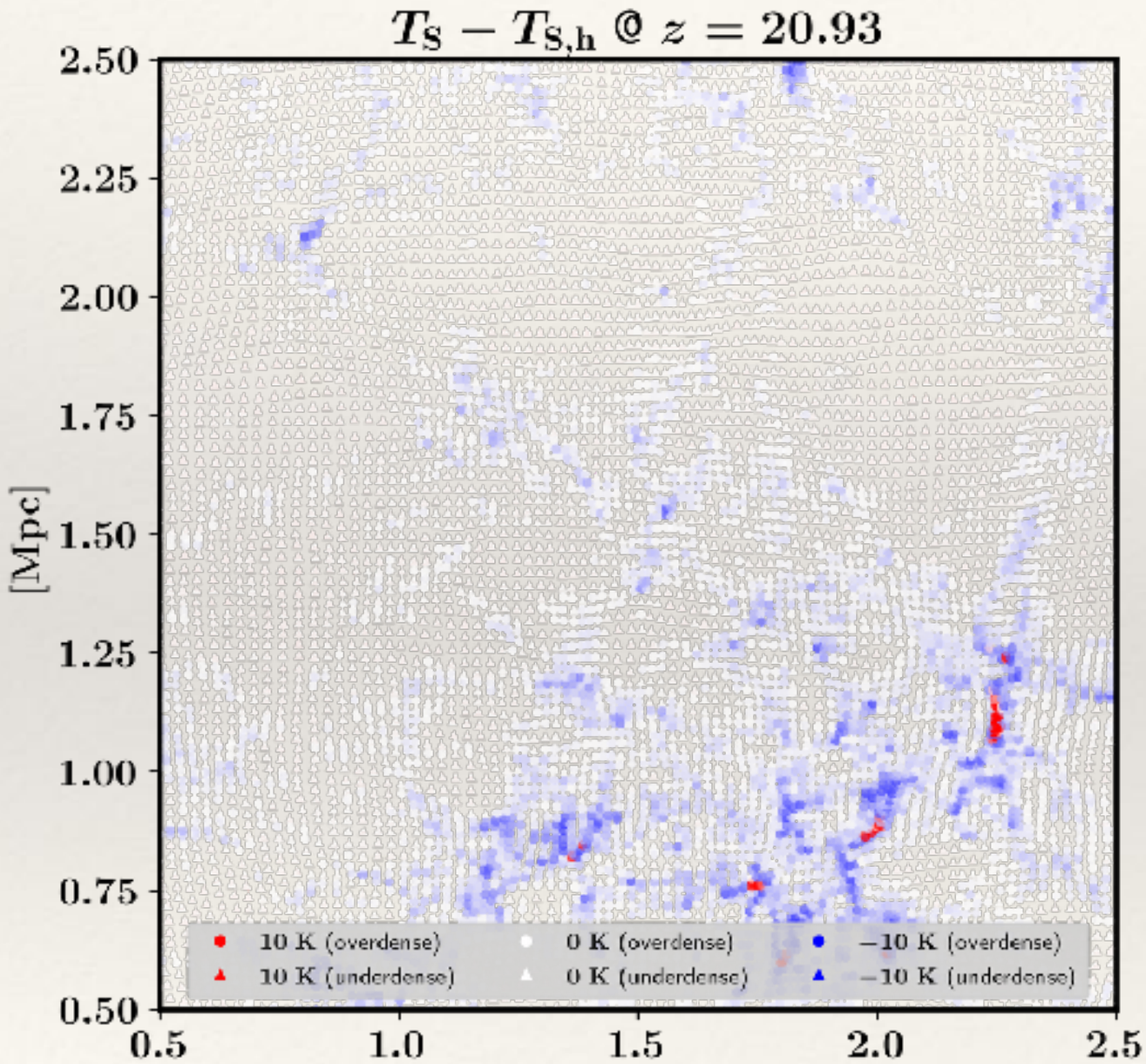
ΔT_S due to Structure Formation ($z < 60$)



Negative relation btw ΔT_S and δ at $z < 60$
as T_S driven by decoupling from T_{CMB} (▲&●)

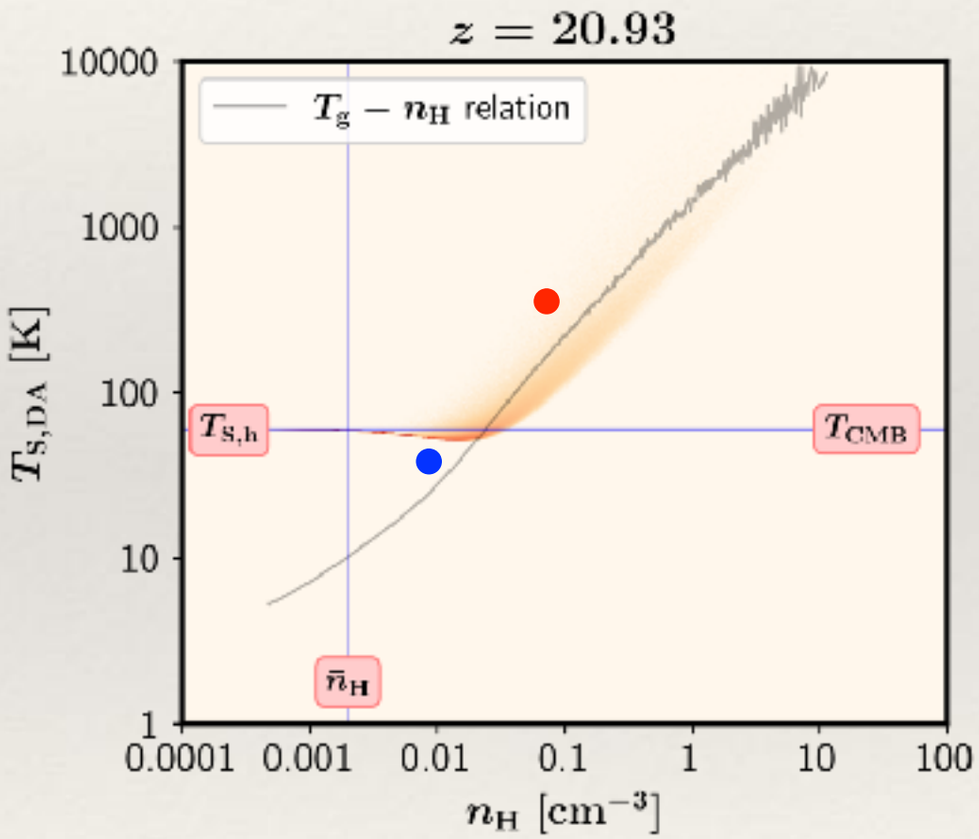


ΔT_S due to Structure Formation ($z < 30$)

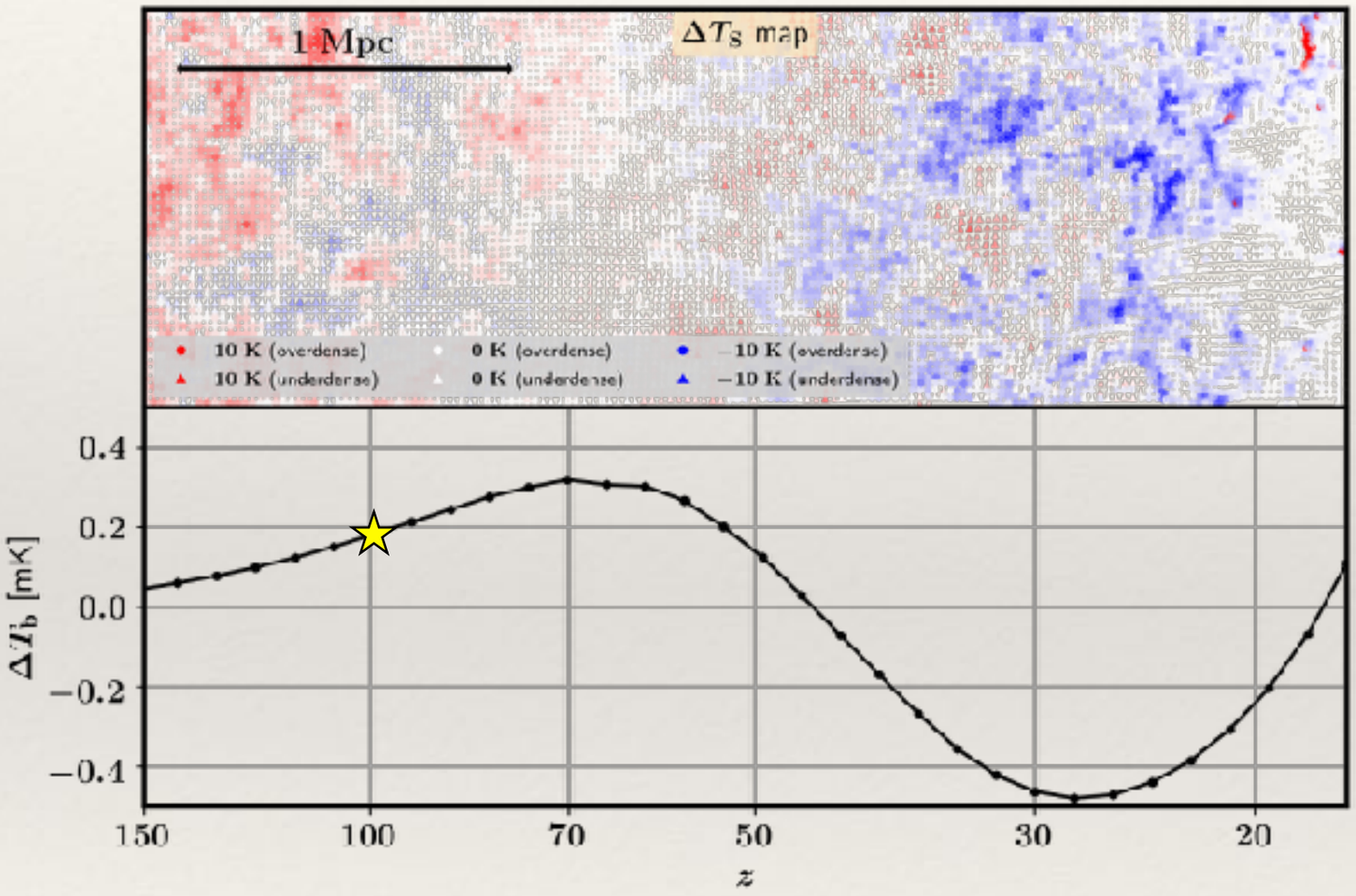


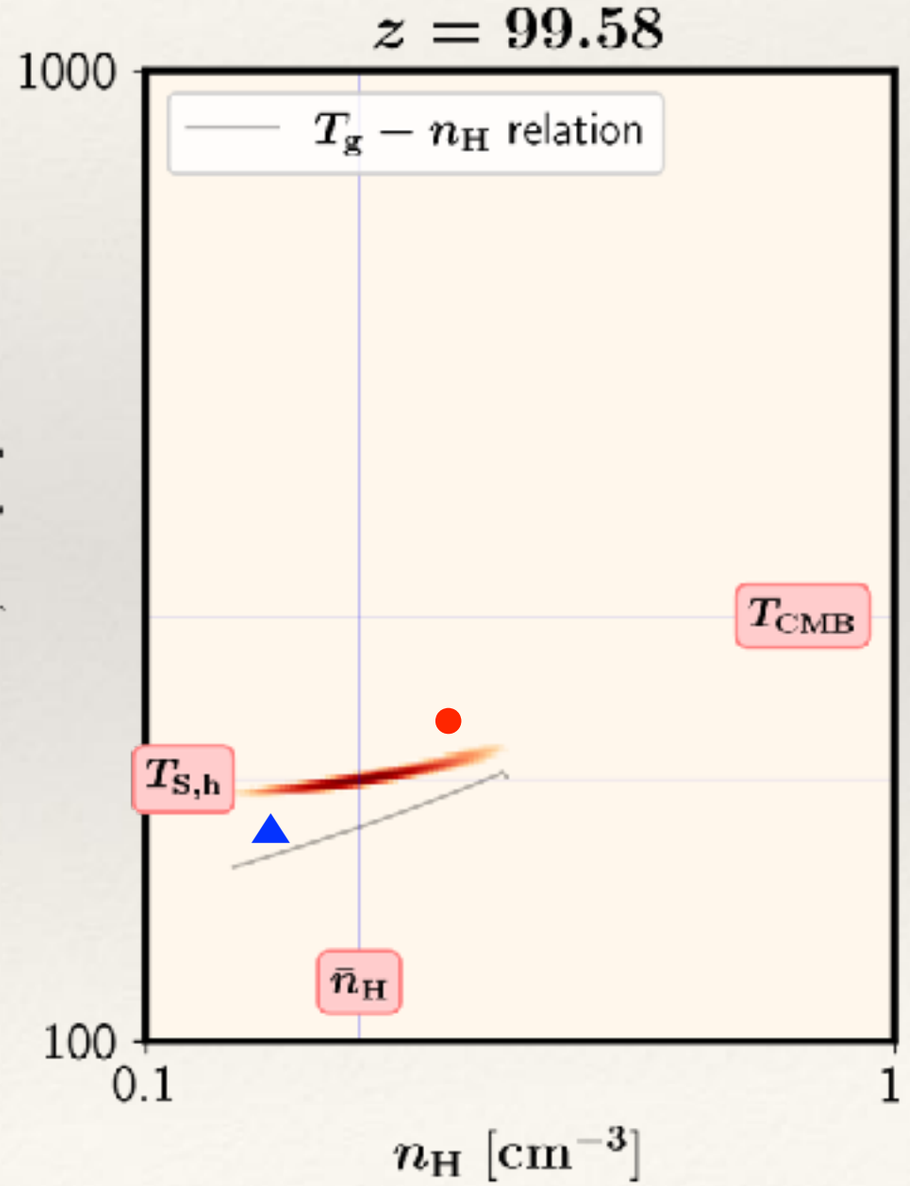
$\Delta T_S < 0$ from $0 < \delta \lesssim 10$ (●) due to $T_{gas} < T_{CMB}$

$\Delta T_S > 0$ from $\delta > 10$ (●) due to $T_{gas} > T_{CMB}$

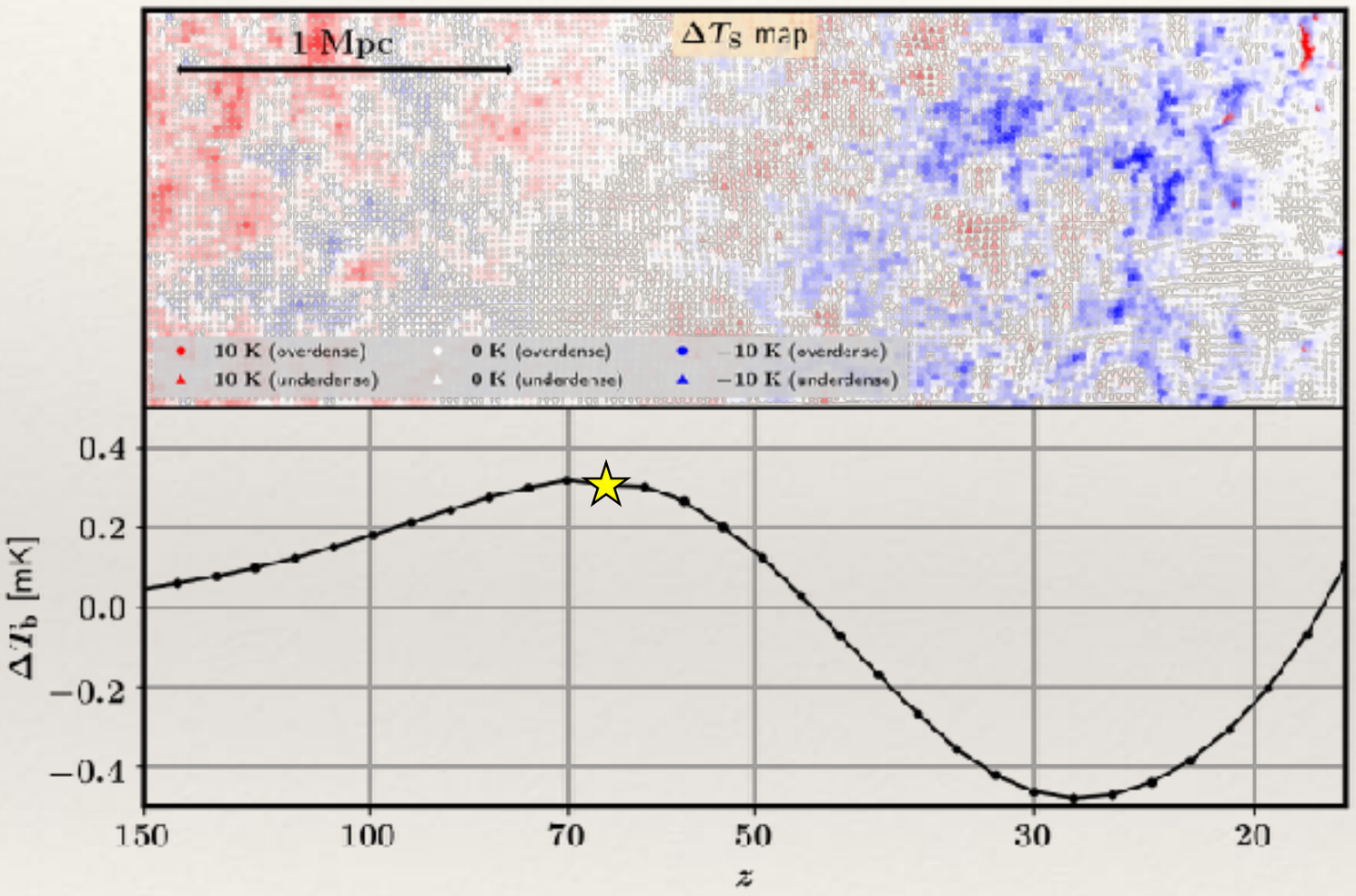


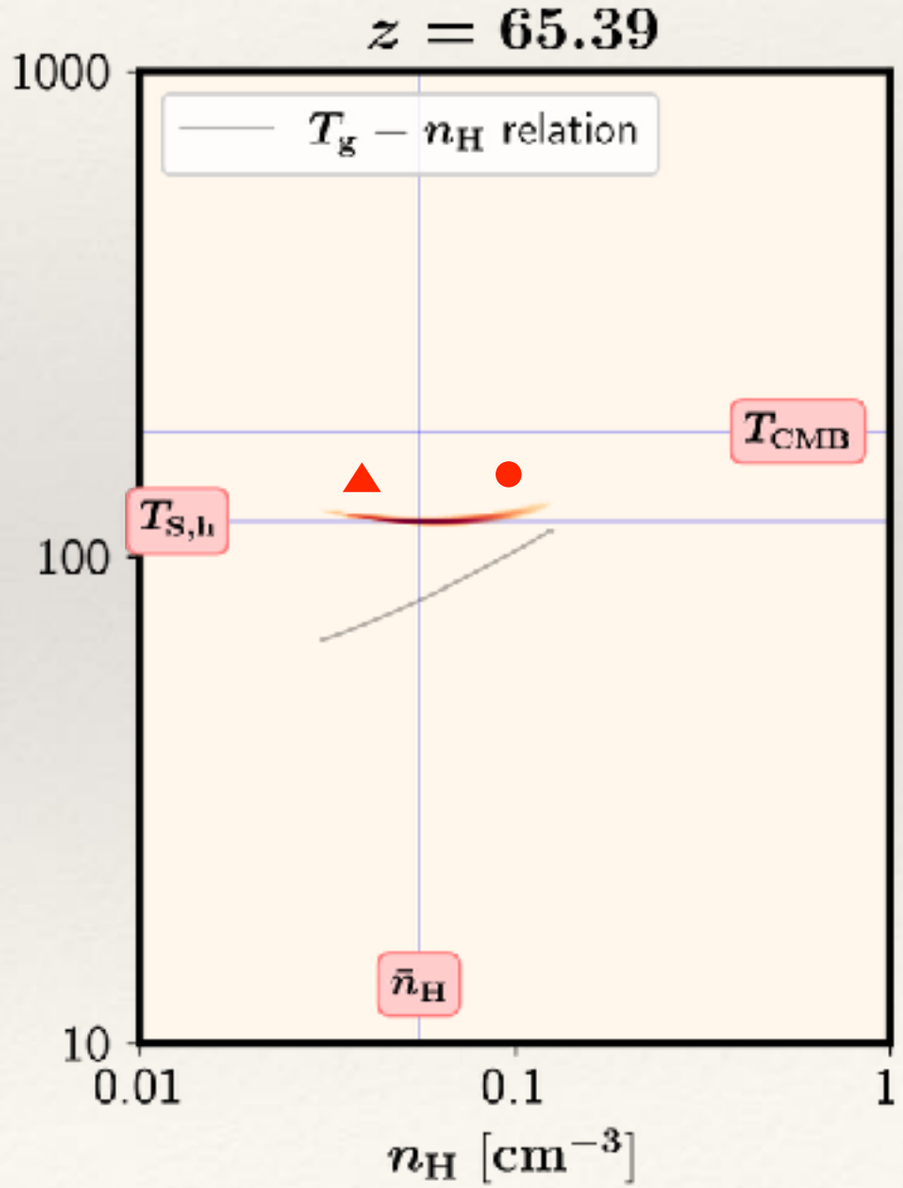
Impact on 21cm Brightness Temperature



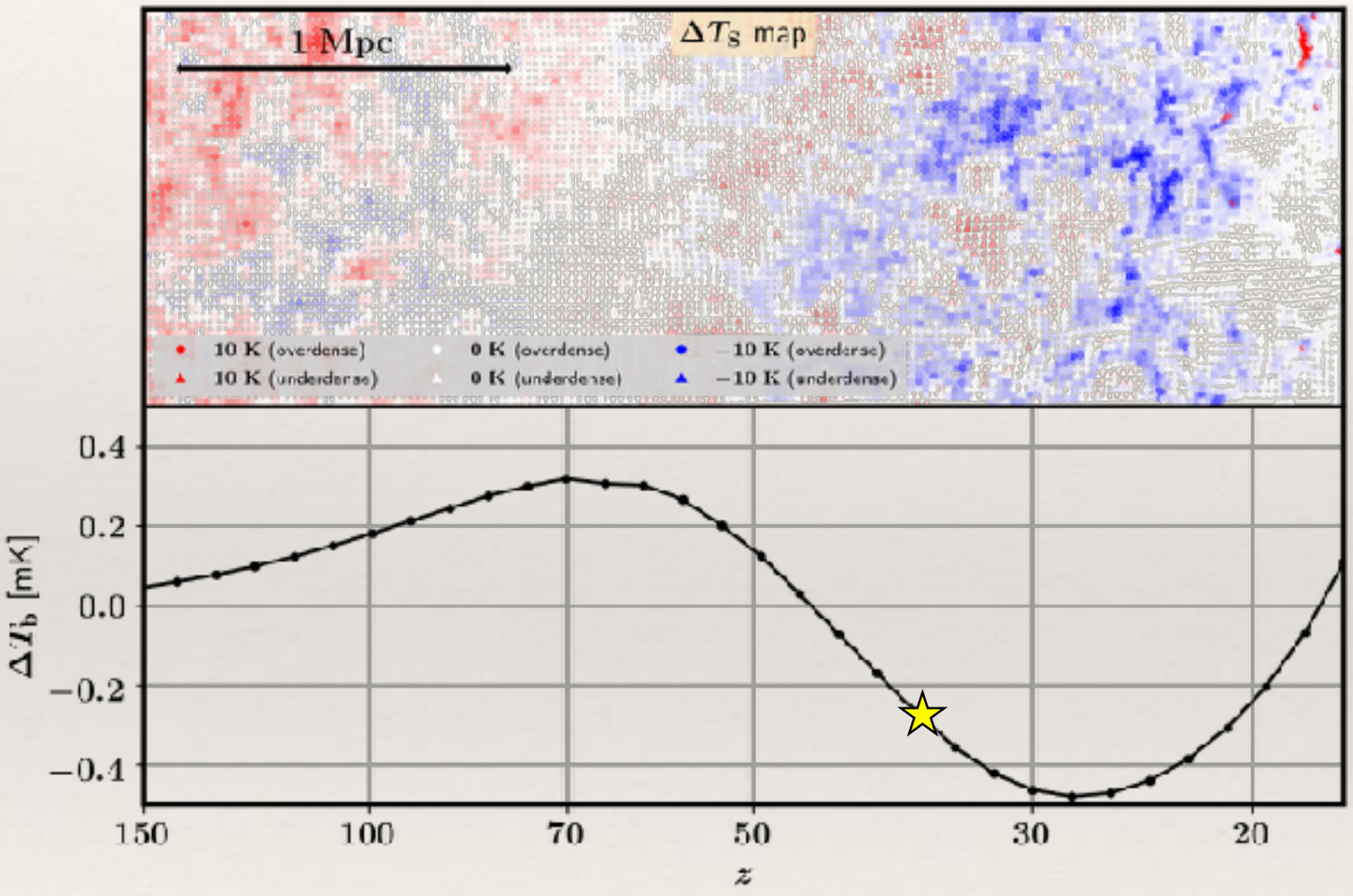


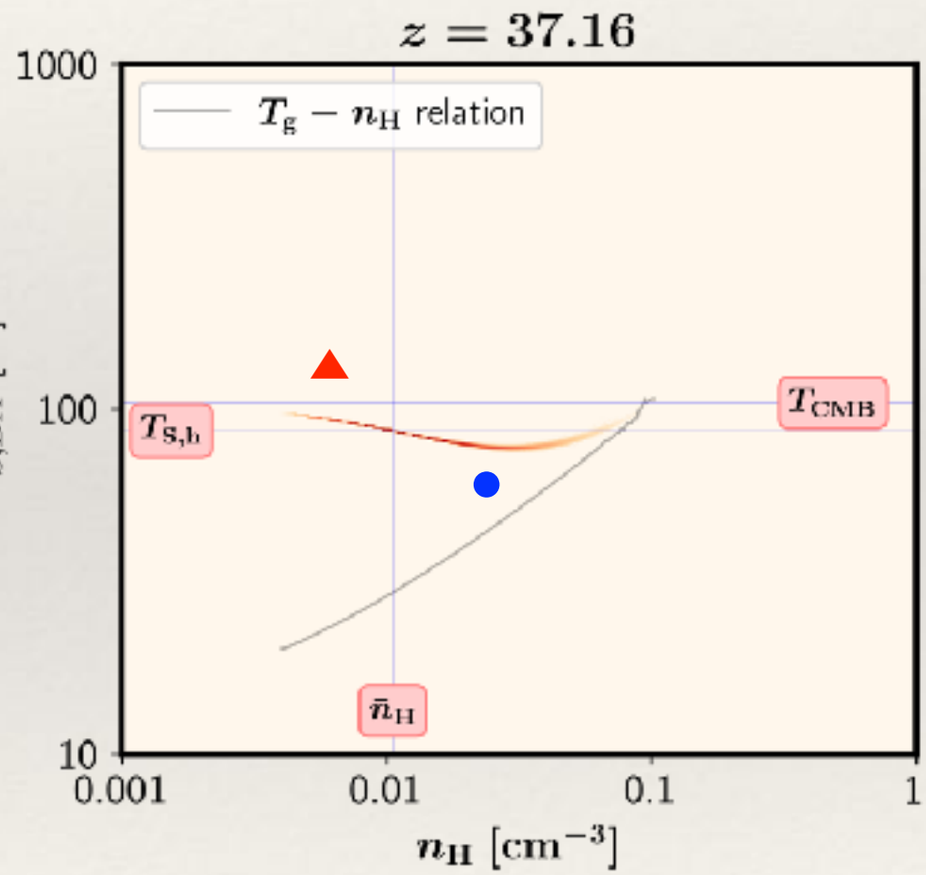
Impact on 21cm Brightness Temperature



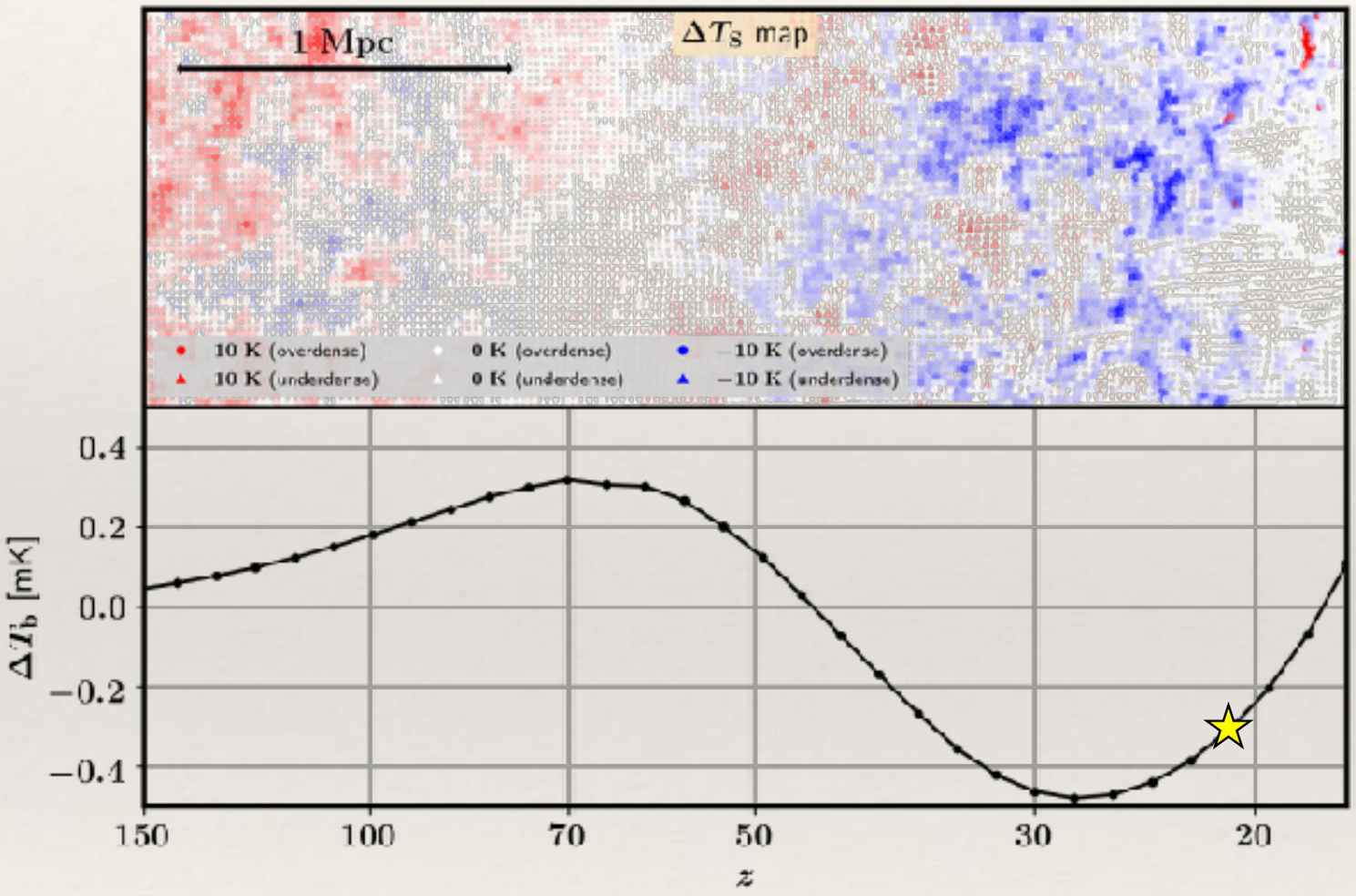


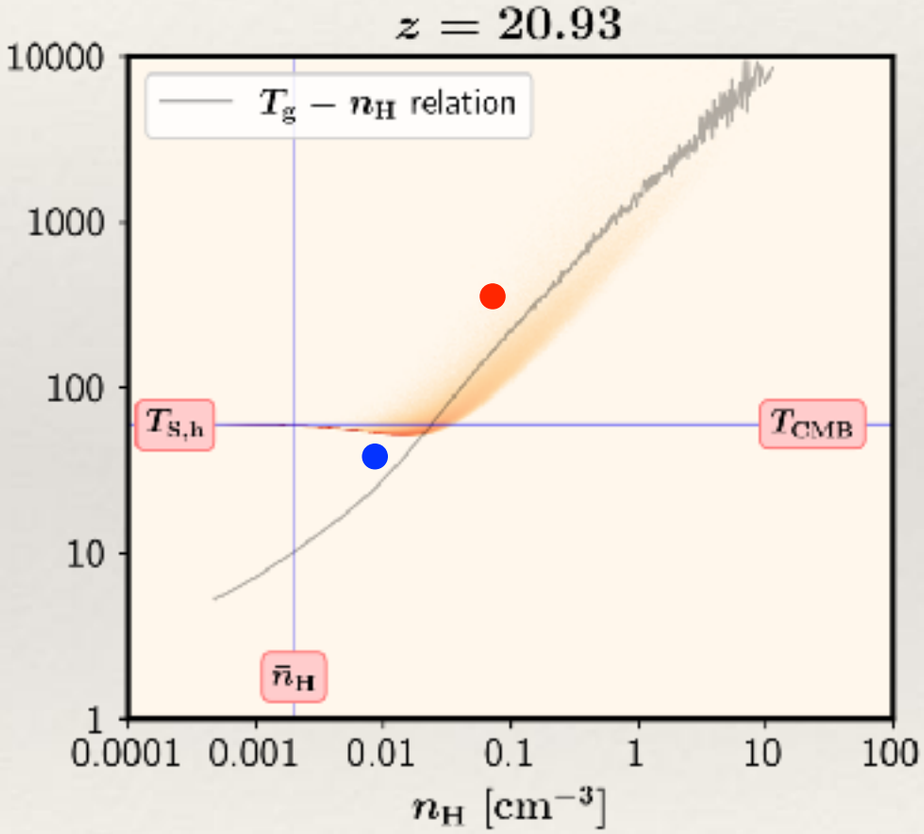
Impact on 21cm Brightness Temperature



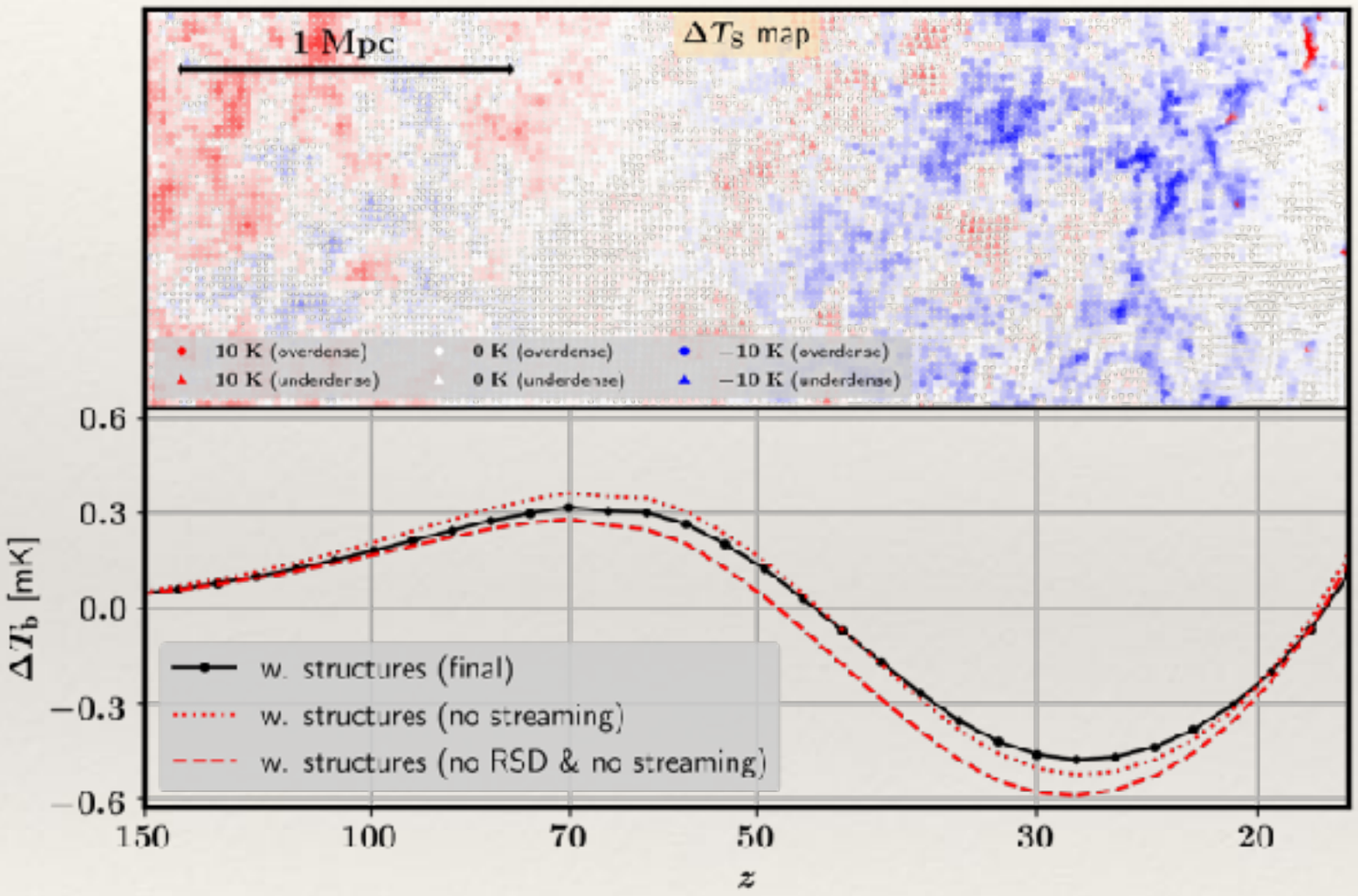


Impact on 21cm Brightness Temperature





Impact of Streaming and RSD



$z = 30$

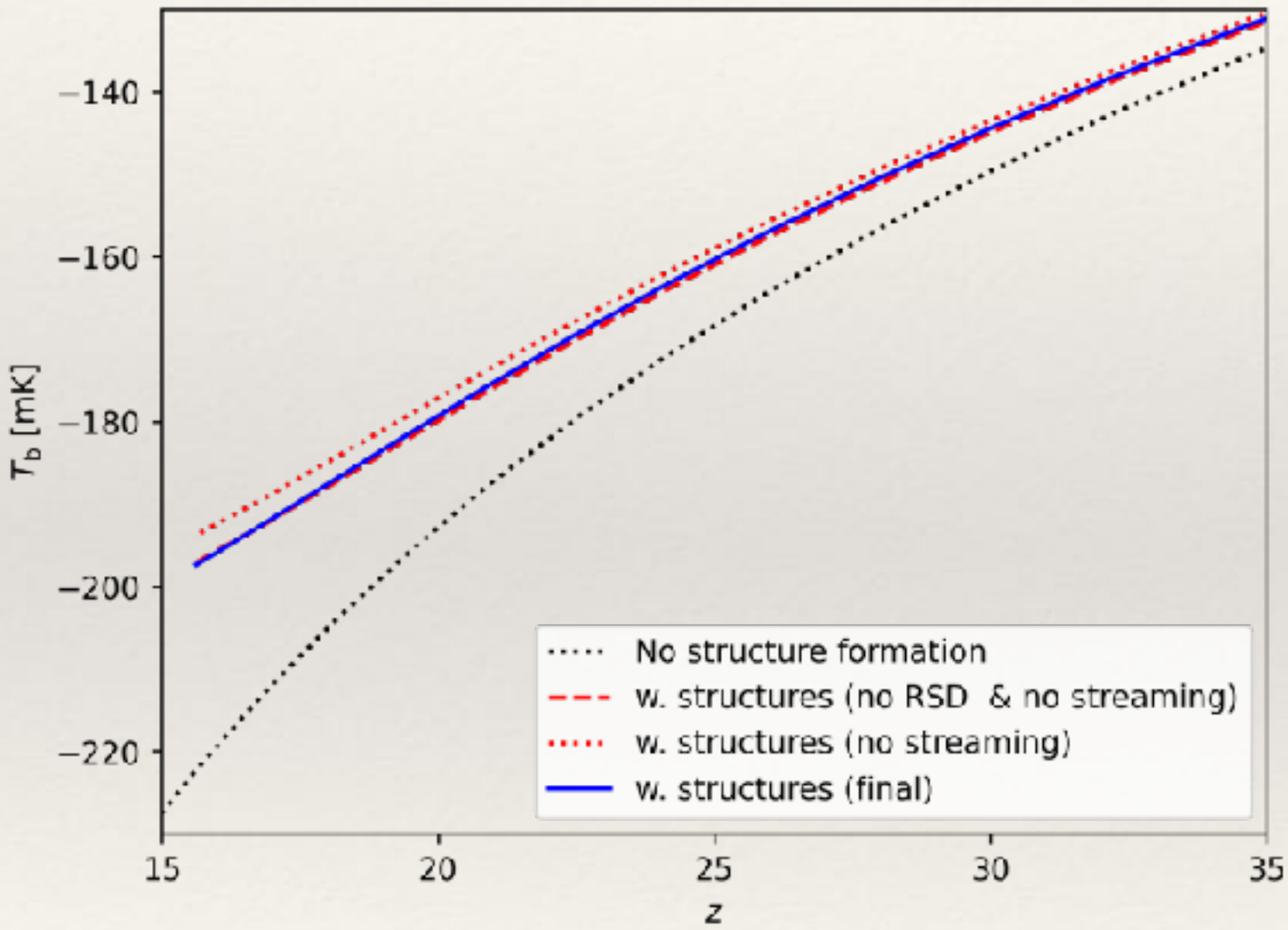
T_b = - 4.270 [mK],
structure formation (X)

T_b = - 4.270 - 0.583 = - 4.853 [mK]
structure formation (O)
RSD effect (X)
streaming velocity (X)

T_b = - 4.270 - 0.506 = - 4.777 [mK]
structure formation (O)
RSD effect (O)
streaming velocity (X)

T_b = - 4.270 - 0.463 = - 4.733 [mK]
structure formation (O)
RSD effect (O)
streaming velocity (O)

Maximal Lya Coupling Case



<u>z = 16.8</u>
T_b = - 213.22 [mK],
structure formation (X)

T_b = - 192.63 [mK]
structure formation (O)
RSD effect (X)
streaming velocity (X)

T_b = -189.45 [mK]
structure formation (O)
RSD effect (O)
streaming velocity (X)

T_b = -192.56 [mK]
structure formation (O)
RSD effect (O)
streaming velocity (O)

Did not fully understand the RSD effect yet…

Summary

- Calculated 21cm signal from the dark ages, accounting for structure formation, RSD effect, and baryon-dark matter streaming velocity.
- ~10% correction to the homogeneous Universe value at z~30
- Important correction for constraining cosmology parameter with the dark age signal