21cm観測で探る
宇宙初期の構造形成と再電離

講演版からスライドを多少削除してあります

SKA-JP
Square Kilometre Array
Japanese Consortium

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初代星・初代銀河研究会 2018@茨城大学

はじめに

SKAを用いたCosmic Dawn/ Epoch of Reionizationのサイエンスについてまとめたもの

- **SKA science books (https://www.skatelescope.org/books/)**
- **SKA-JAPAN science book (日本語, SKA-JP 科学検討班著 http://ska-jp.org/science.html)**
- **Japanese Cosmic Dawn/Epoch of Reionization Science with the Square Kilometre Array (Hasegawa et al. 2016, arxiv:1603.01961 to be revised)**

今日は触れなかった話題にも興味があればこちらを

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CONTENTS

What can we learn from the high-redshift HI-21cm line?

21cm observation, cosmology => (Yoshiura-kun's Talk)

First Stars

- Initial Mass Function (IMF)
- Multiplicity
- SFR

Cosmic Reionization

- When did reionization start and end?
- How did reionization proceed spatially?
- What ionized the Universe?

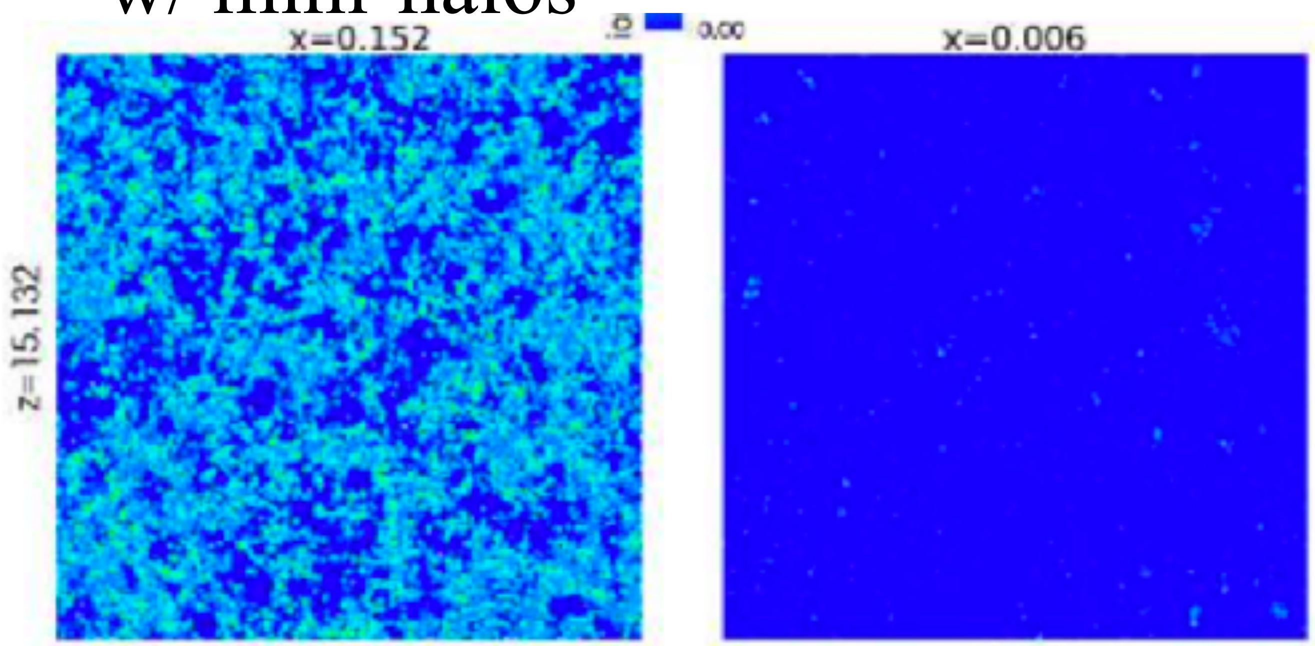
Impact of the First Stars on Cosmic Reionization

Planck 2018 (arXiv:1807.06209) indicates $\tau_{\rm e} = 0.054 \pm 0.007$

$$\tau_{\rm e} = c\sigma_{\rm t} \int_{z_r}^{0} n_{\rm e}(z) \frac{dt}{dz} dz$$

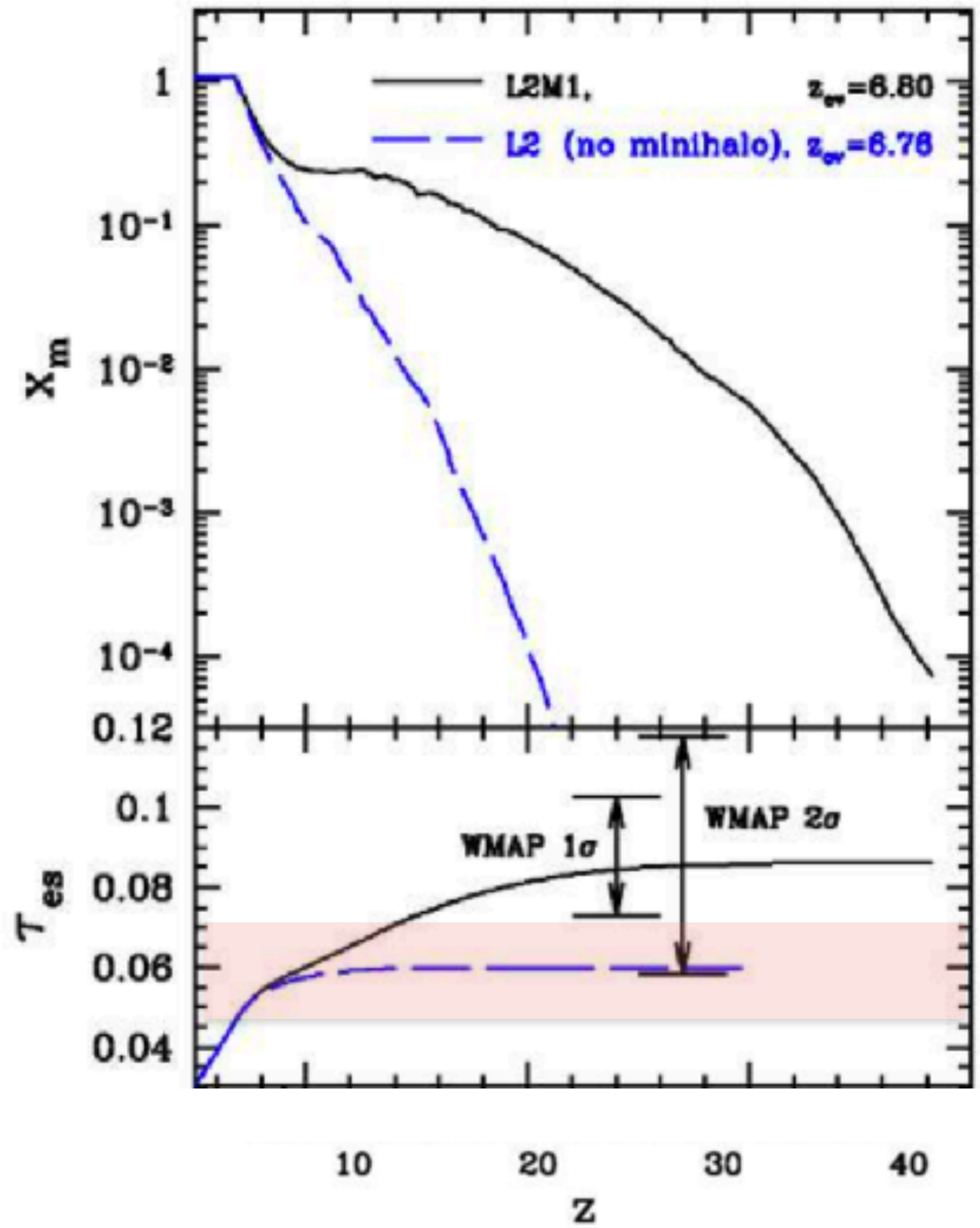
Ionized fraction at z~15

w/ mini-halos w/o mini-halos



100 Mpc

Ahn et al. (2012)



The impact must be small?

Basics of High-redshift HI 21-cm

21cm (1.42GHz): corresponding to the energy for hyperfine transition

$T_* = 0.068\mathrm{K}$

T_S: Spin Temperature

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_*}{T_s}\right)$$

Eq. of Radiative Transfer
(Rayleigh-Jeans Limit)

$$\delta T_b = \frac{T_S - T_{CMB}}{1+z}(1 - e^{-\tau})$$

Differential brightness temperature

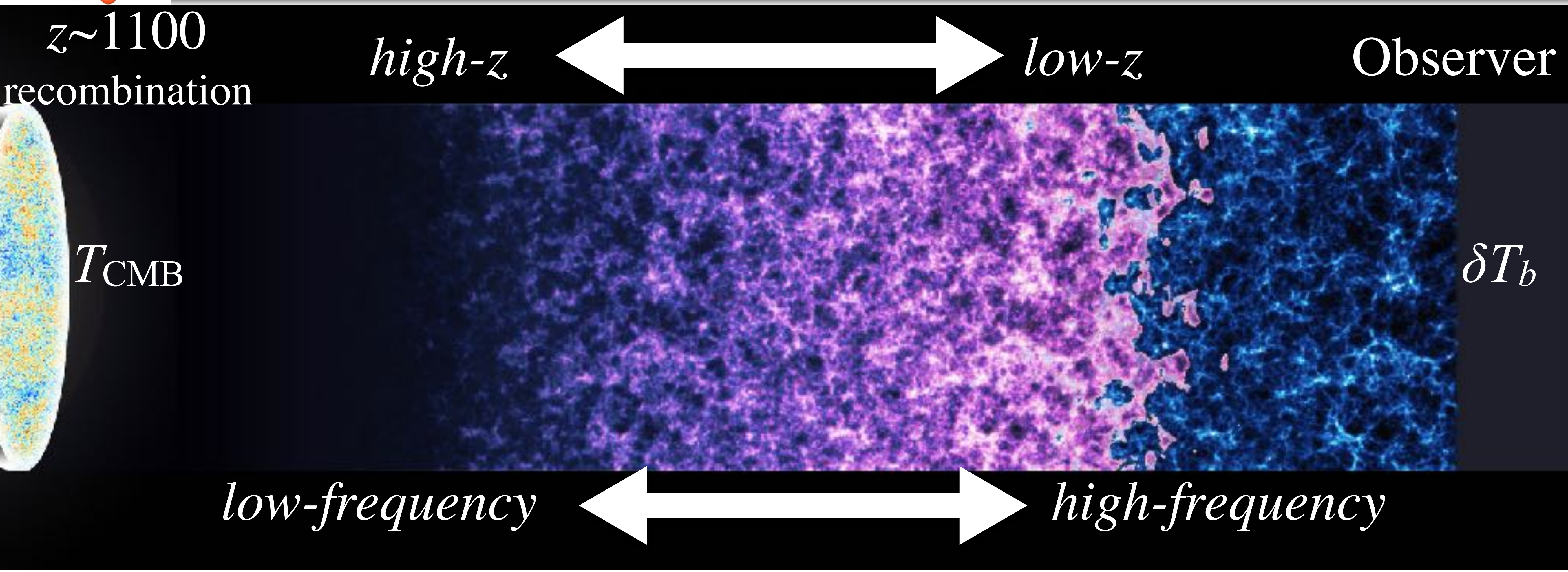
Opt. thin limit + follows Hubble expansion

$$\approx 27 x_{HI}(1+\delta)\left(1 - \frac{T_{CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2} [\mathrm{mK}]$$

NOT suitable for mini-halos

Peculiar velocity is neglected

Basics of High-redshift HI 21-cm



$$\delta T_{\rm b} \approx 27 x_{\rm HI}(1+\delta)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)\left(\frac{1+z}{10}\right)^{1/2} \ [{\rm mK}]$$

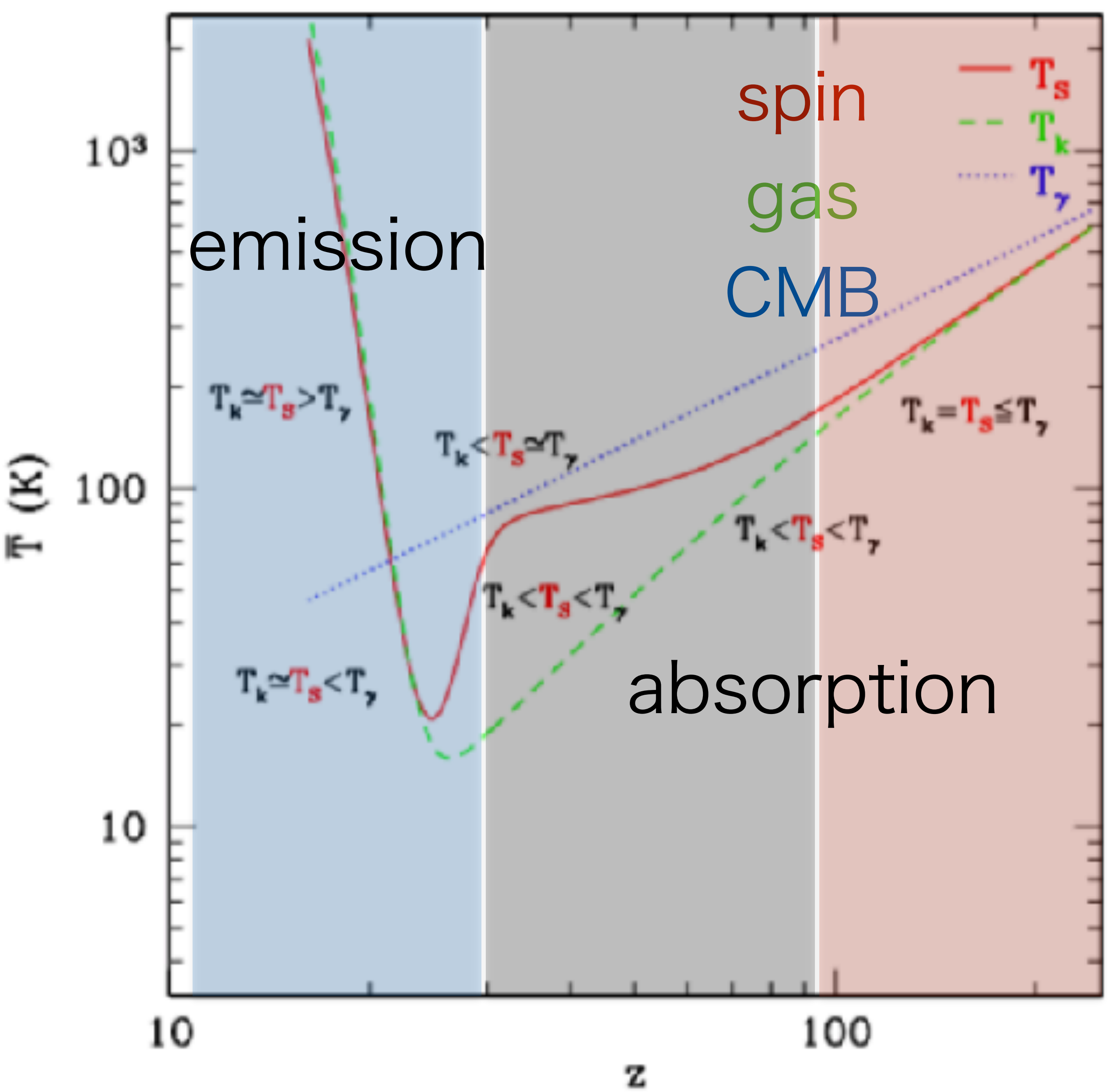
$T_{\rm s} > T_{\rm CMB}$: emission, $T_{\rm s} < T_{\rm CMB}$: absorption, $T_{\rm s}=T_{\rm CMB}$: no signal (CMB)

$\delta T_{\rm b}$ provides us with the information of
HI fraction ($x_{\rm HI}$), Overdensity ($1+\delta$), and Spin Temperature ($T_{\rm s}$)

Physics determining T_s

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

宇宙の平均温度進化



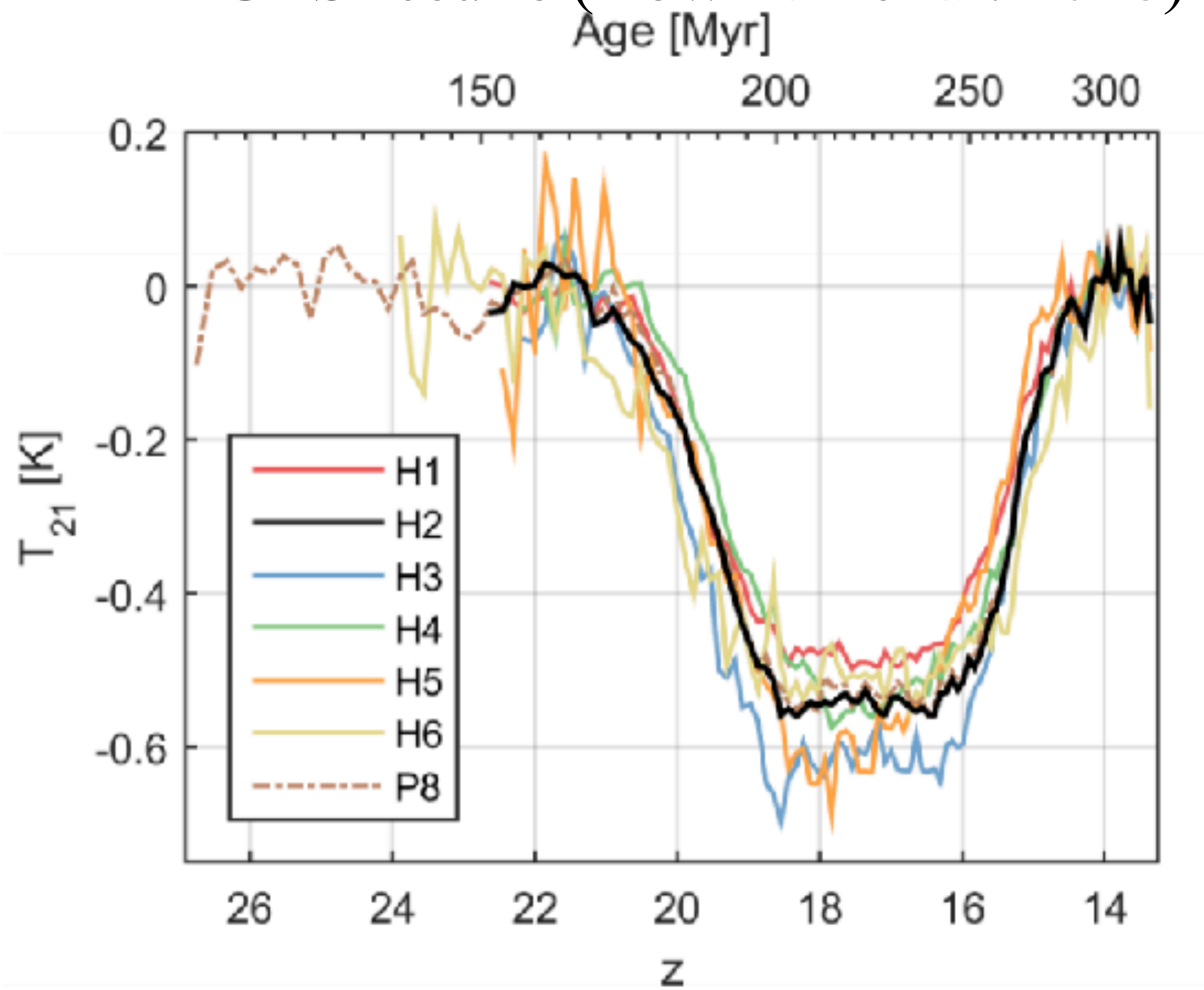
- Collisional interactions
  dominant if $n > 0.1$ cm^{-3} (high-z IGM, gas in halos)
  $T_S \rightarrow T_K$

- Interaction with the CMB
  $T_S \rightarrow T_{CMB}$

- Lyα pumping (Wouthuysen-Field effect)
  hyperfine transition during 1S→2P→1S transition
  $T_S \rightarrow T_\alpha$ (color temperature around Lyα frequency) = T_K **(if optically thick)**
  c.f $\tau_{\alpha,\,IGM} > 10^5$ @ $z>6$

We already detected a signature of the first stars?

EDGES results (Bowman et al. 2018) sky-averaged brightness temperature

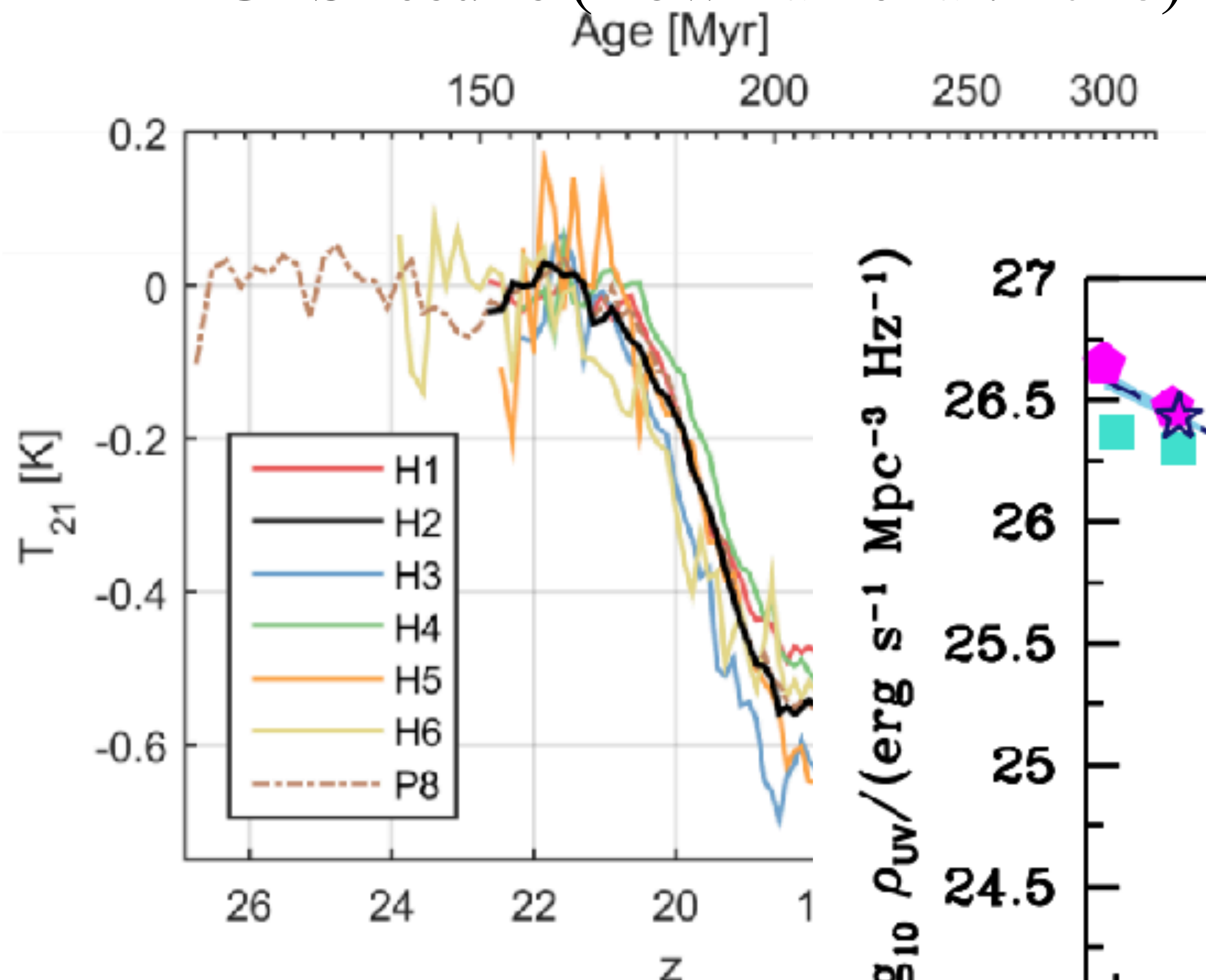


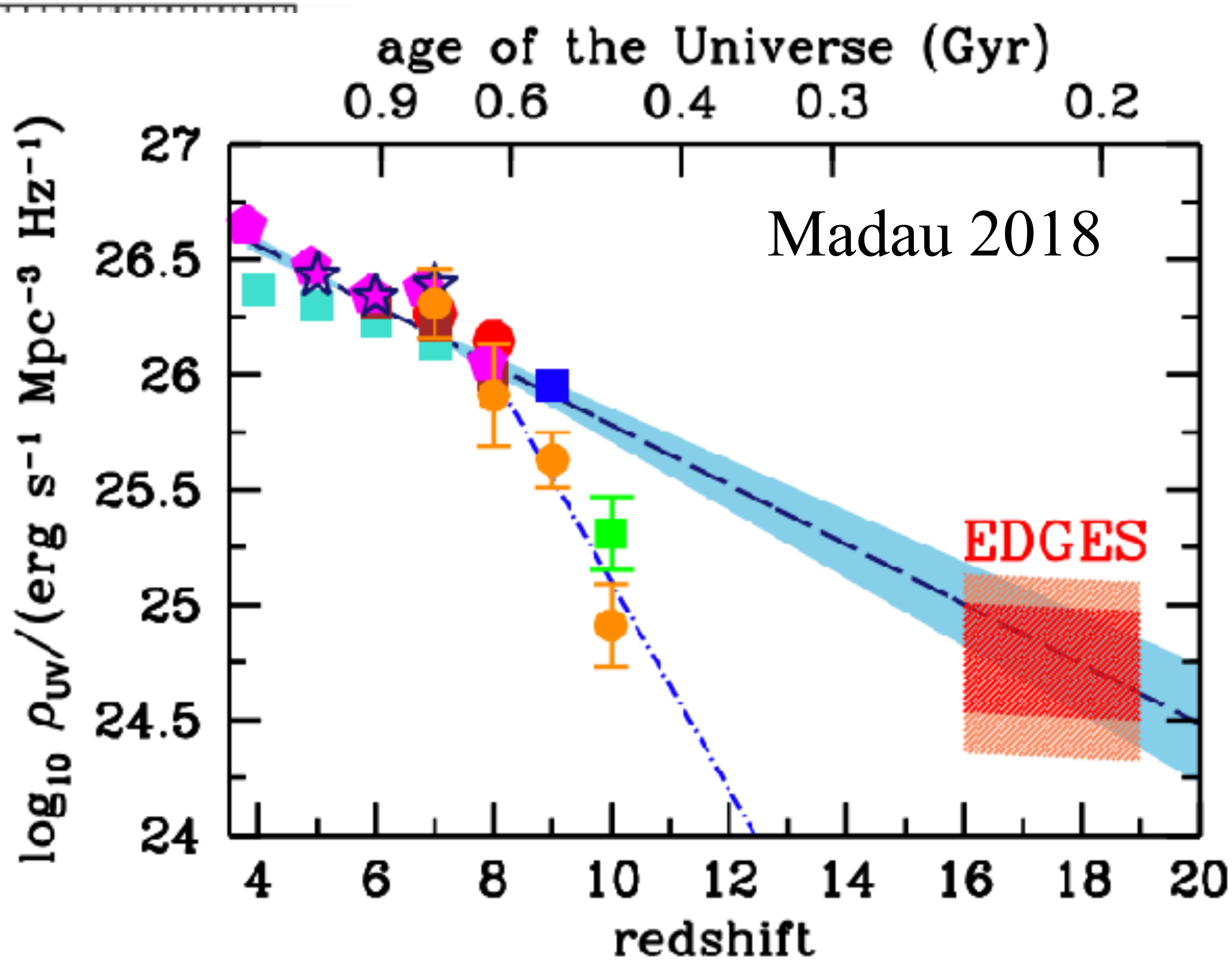
- Lyα photons suddenly increase at z<22.
- IGM gas cools down to a few K (two times lower than the expected value)
- Ionized fraction and/or gas temperature increases at z<16.

- Standard models usually fail to explain all of the properties, but some exotic DM models can (e.g., Fialkov et al. 2018).
- Background radiation is not the CMB but other radio sources.
- Assuming that the location of the absorption is true, SFRD is constrained. (e.g., Madau 2018)

We already detected a signature of the first stars?

EDGES results (Bowman et al. 2018)

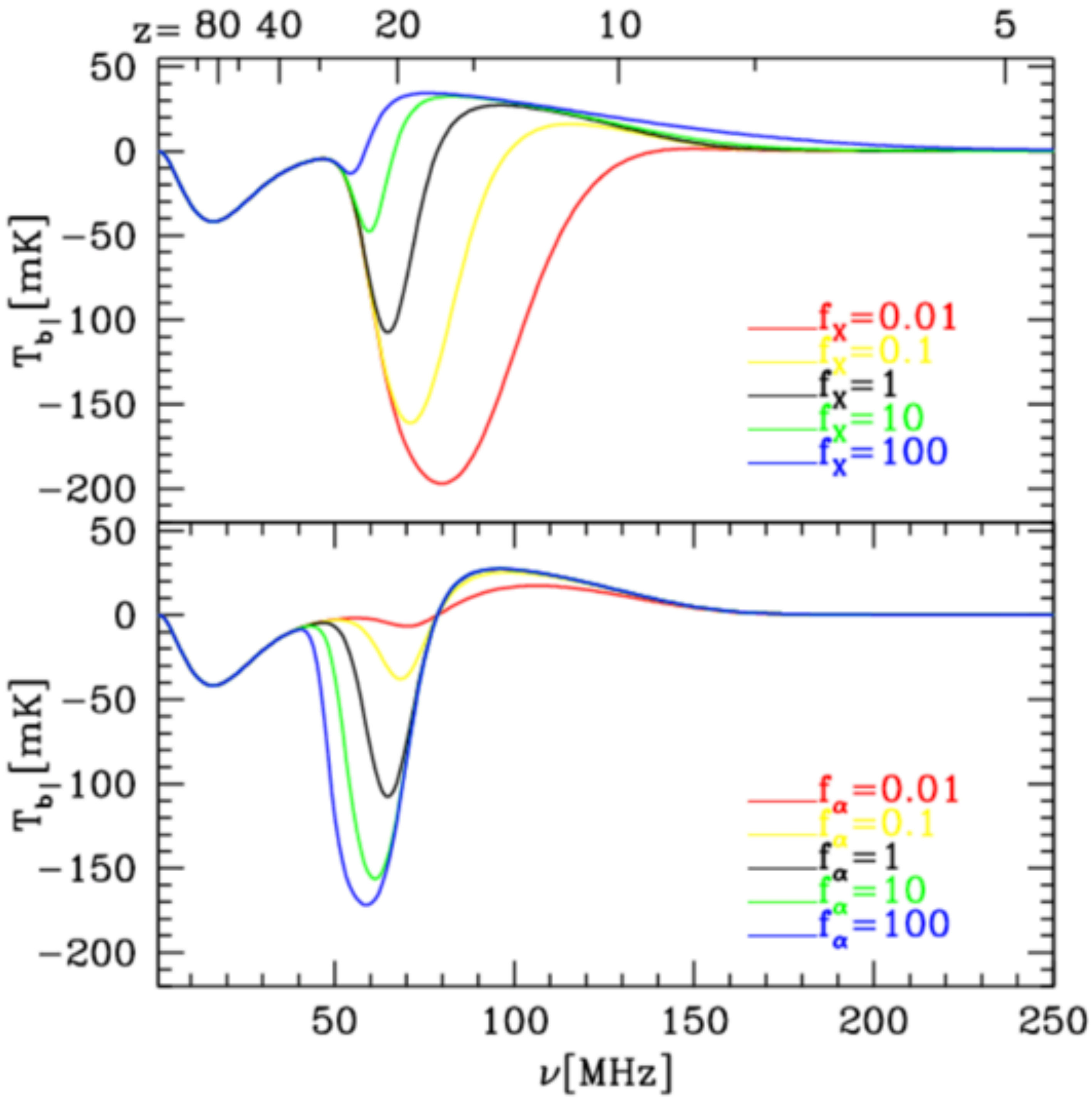




- Standard models usually fail
  models can (e.g., Fialkov et
- Background radiation is not the CMB but other astronomical objects.
- Assuming that only the location of the absorption is true, SFRD is constrained. (e.g., Madau 2018)

SKIP

Redshift Evolution of the Global Signal



Prichard & Loeb 2008

X-ray Heating Efficiency

The gas temperature increases with increasing f_x.

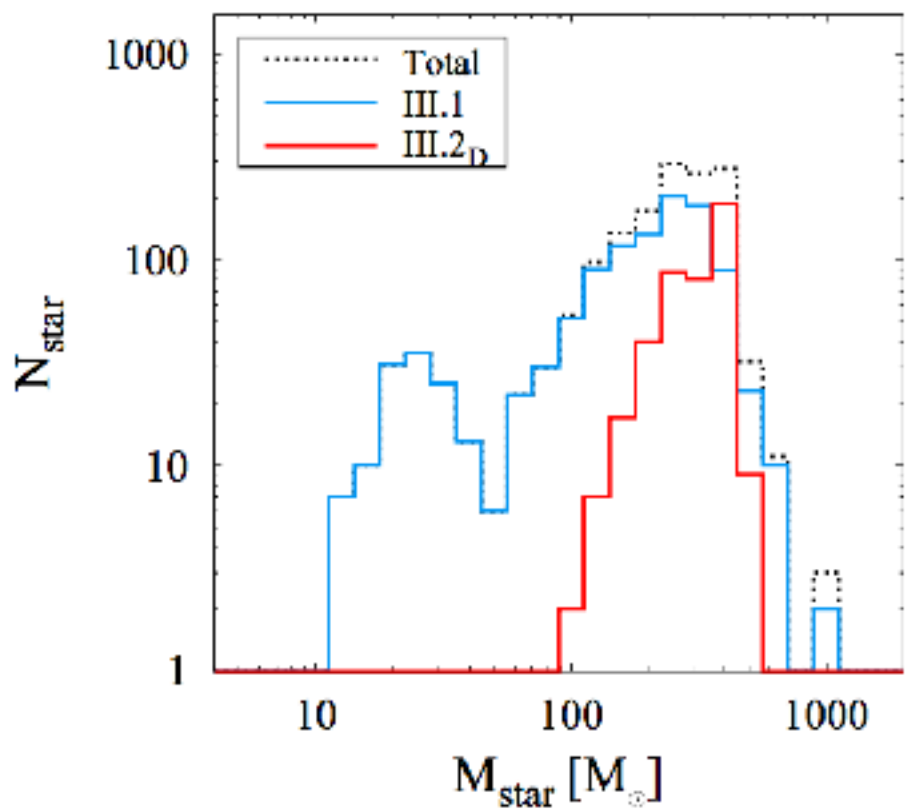
Lyα photon production rate

Increasing f_x. the spin temperature tends to be strongly coupled with the gas temperature.

Can we obtain more detailed information regarding the first stars?

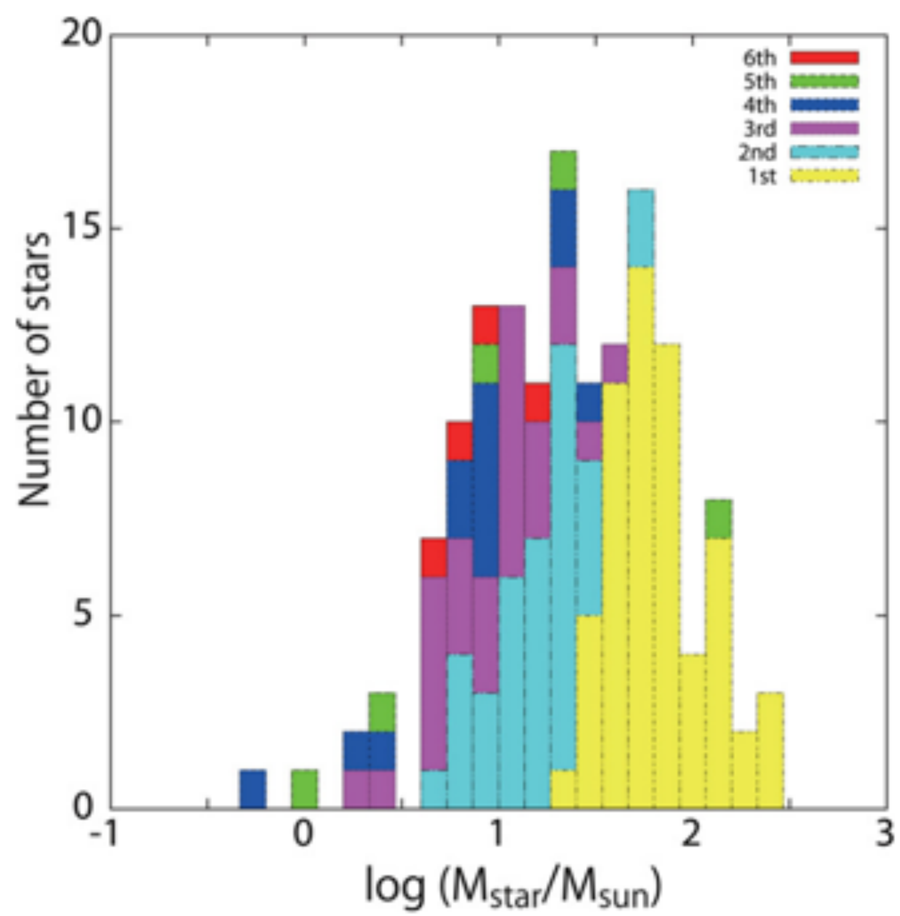
The First Stars: what we want to know

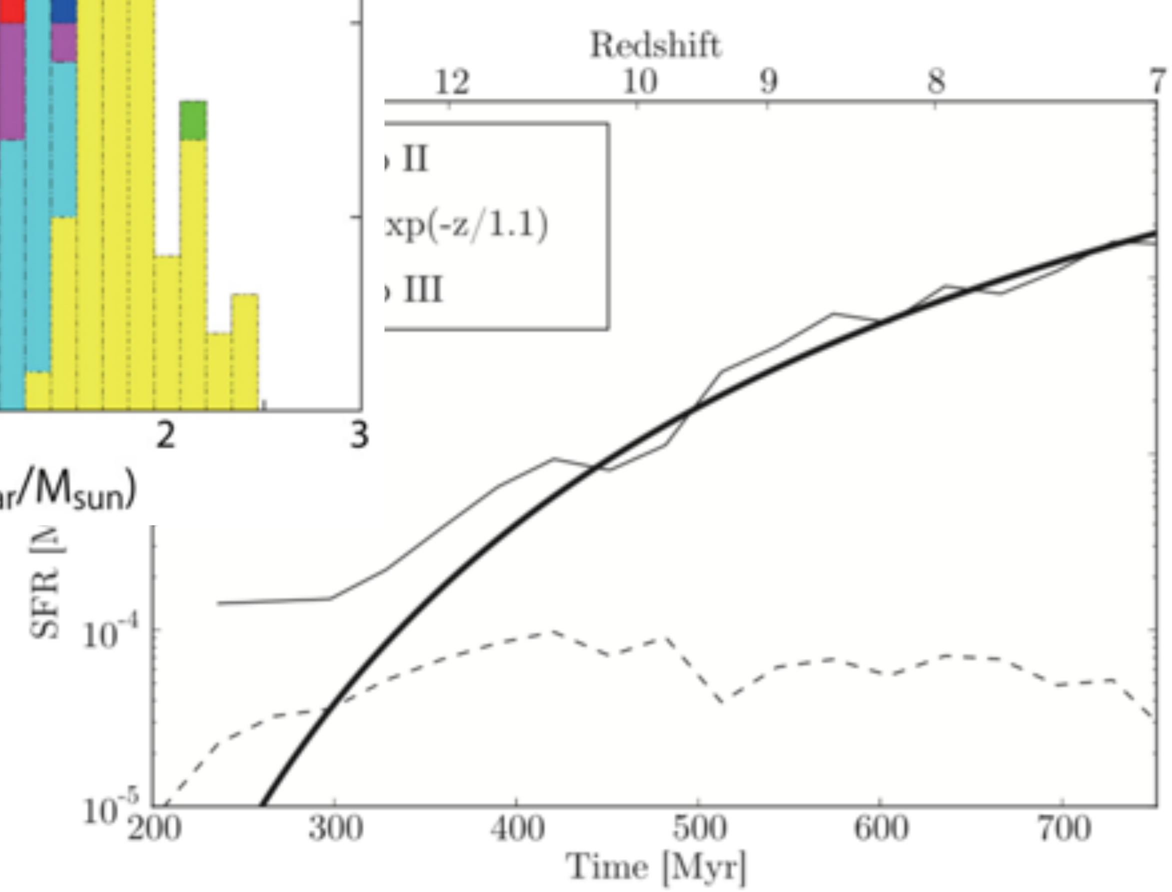
Initial Mass Function, Cosmic Star Formation Rate



Hirano et al. (2014, 2015)

Susa, KH, Tominaga (2014)





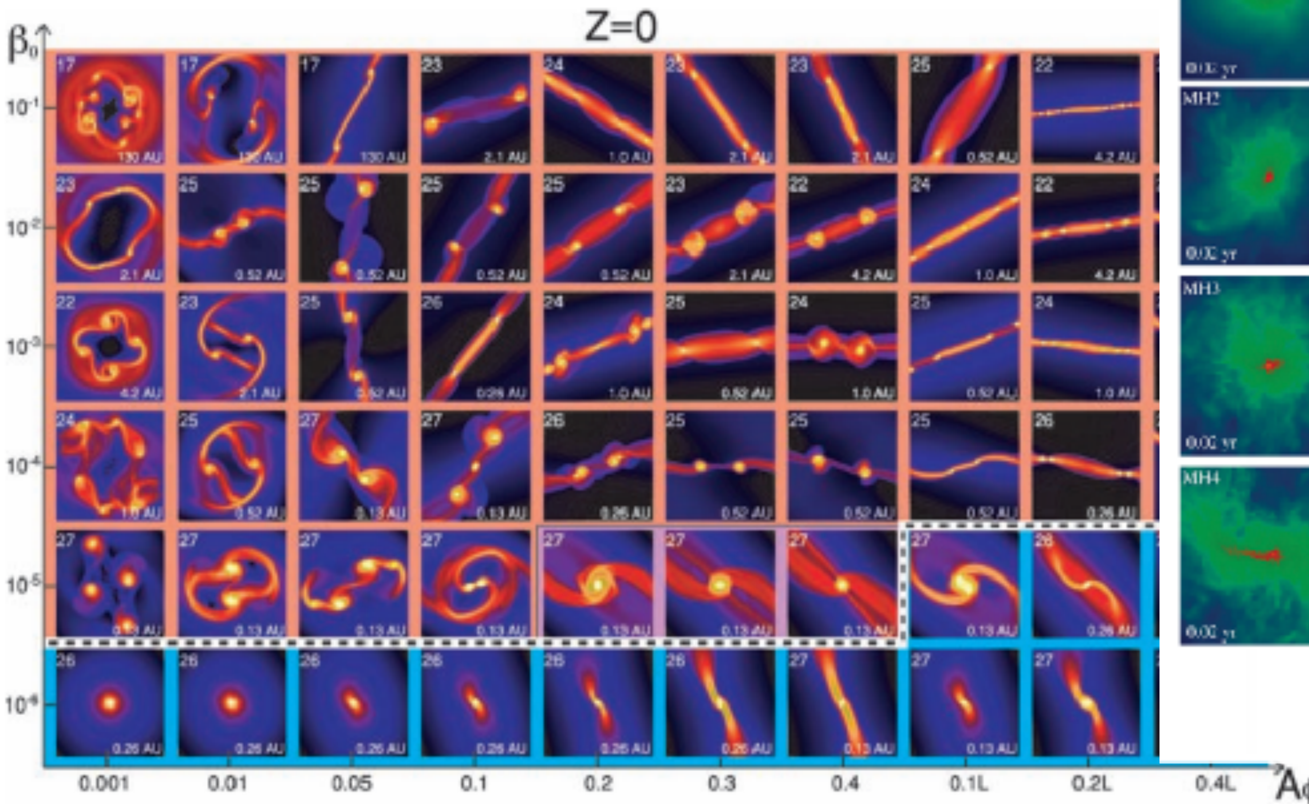
Wise et al. (2012)

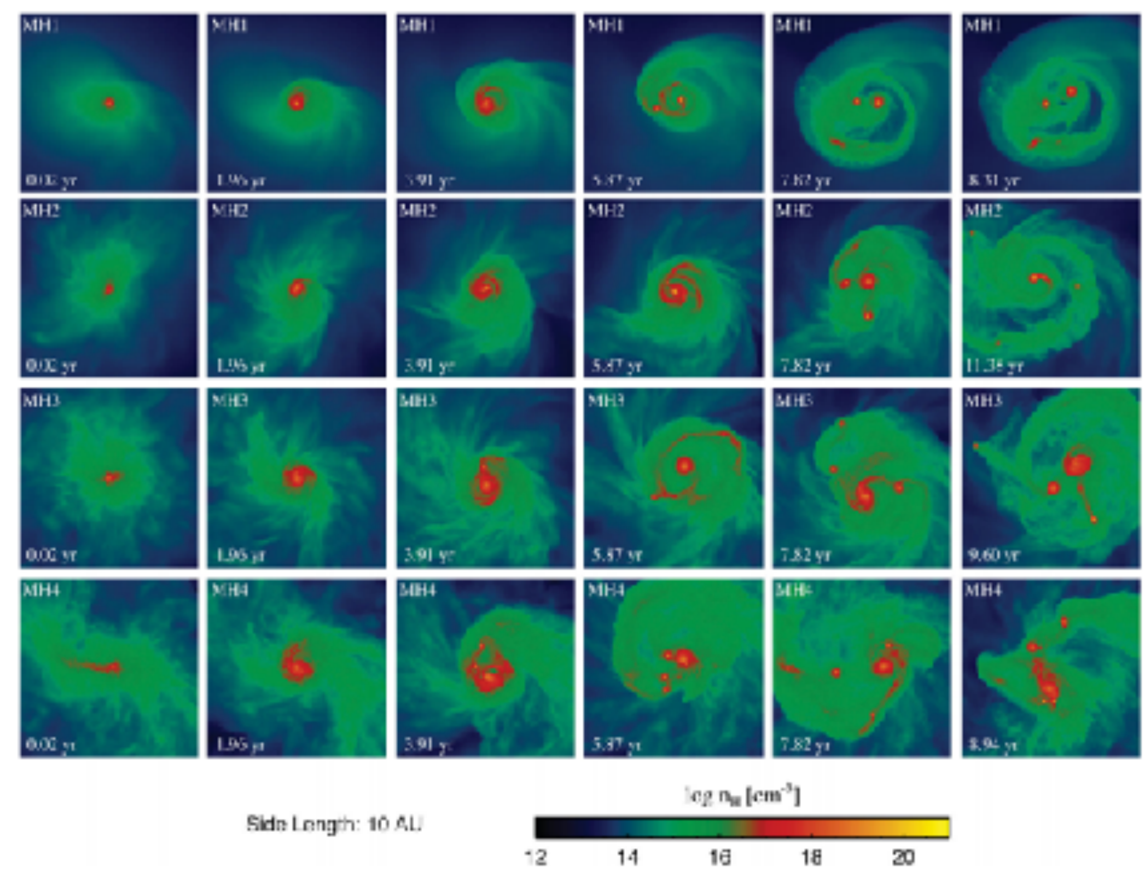
The First Stars: what we want to know

Initial Mass Function, Cosmic Star Formation Rate

Multiplicity (closely related to X-ray sources, Gravitational Waves)

Machida et al. (2009)



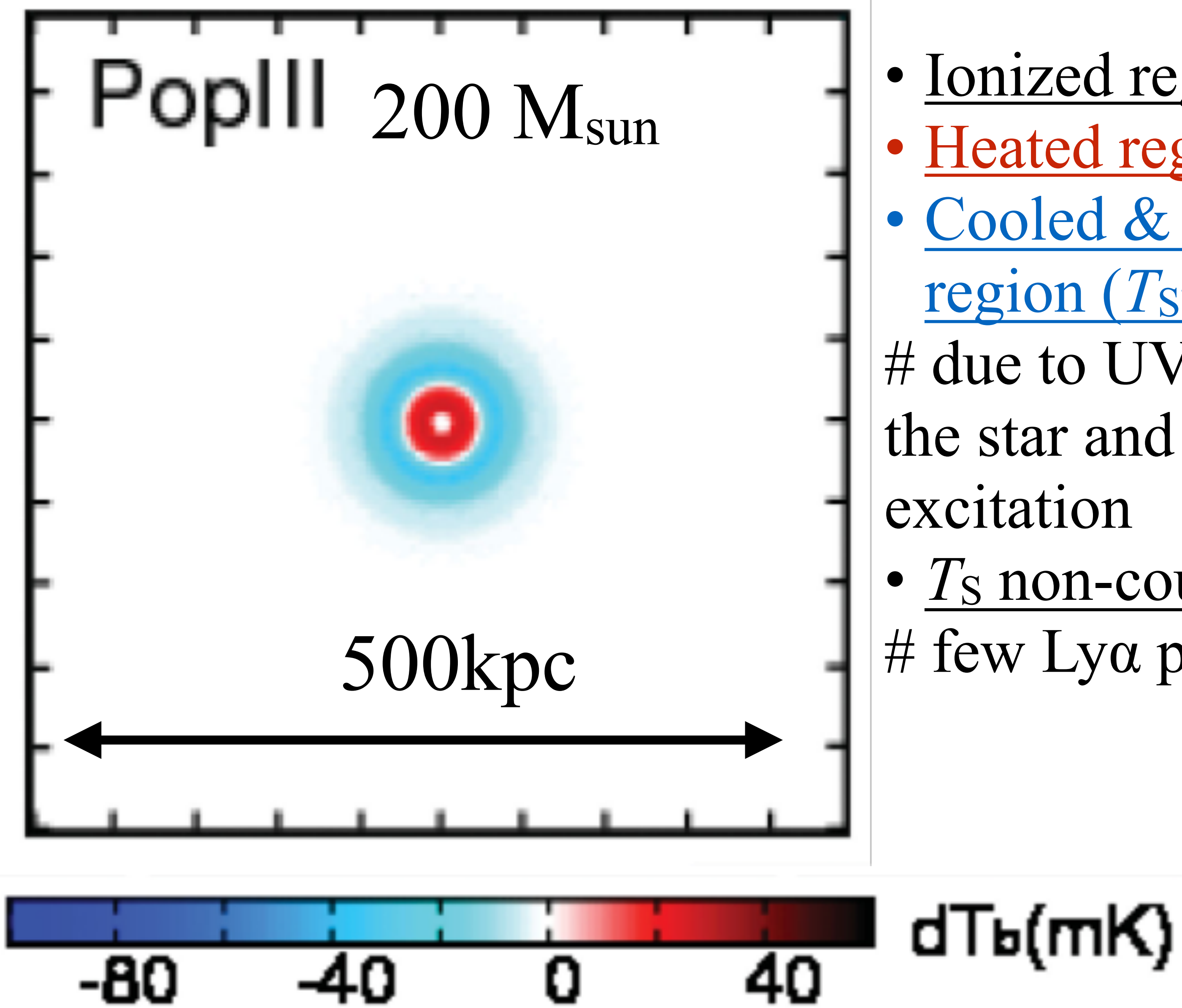


Greif et al. (2013)

21cm Imaging in the vicinity a Mini-halo

- The SED of a source is imprinted on the surrounding medium.

  - Yajima & Li (2014) : LyC and Lyα Radiation Transfer



Blackbody

- Ionized region
- Heated region ($T_S > T_{CMB}$)
- Cooled & T_S coupling region ($T_S < T_{CMB}$)

due to UV continuum form the star and secondary excitation

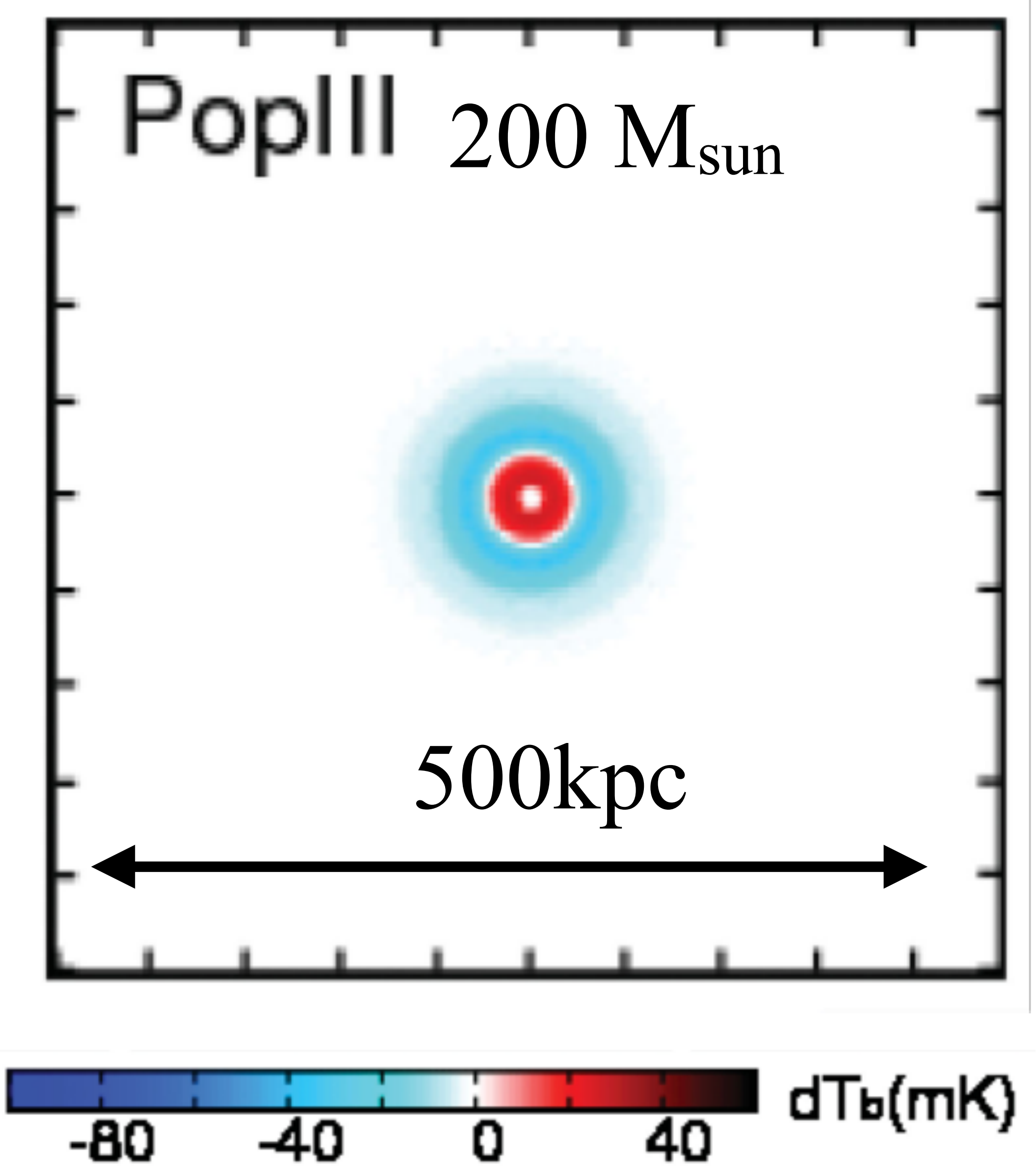
- T_S non-coupling region

few Lyα photons

21cm Imaging in the vicinity a Mini-halo

- Information of luminosity and SED of a source is imprinted on the surrounding medium.

- Yajima & Li (2014) : LyC and Lyα Radiation Transfer



Blackbody

- Ionized region
- Heated region ($T_S > T_{CMB}$)
- Cooled & T_S coupling region ($T_S < T_{CMB}$)

due to UV continuum form the star and excitation by secondary electrons

- T_S non-coupling region

few Lyα photons

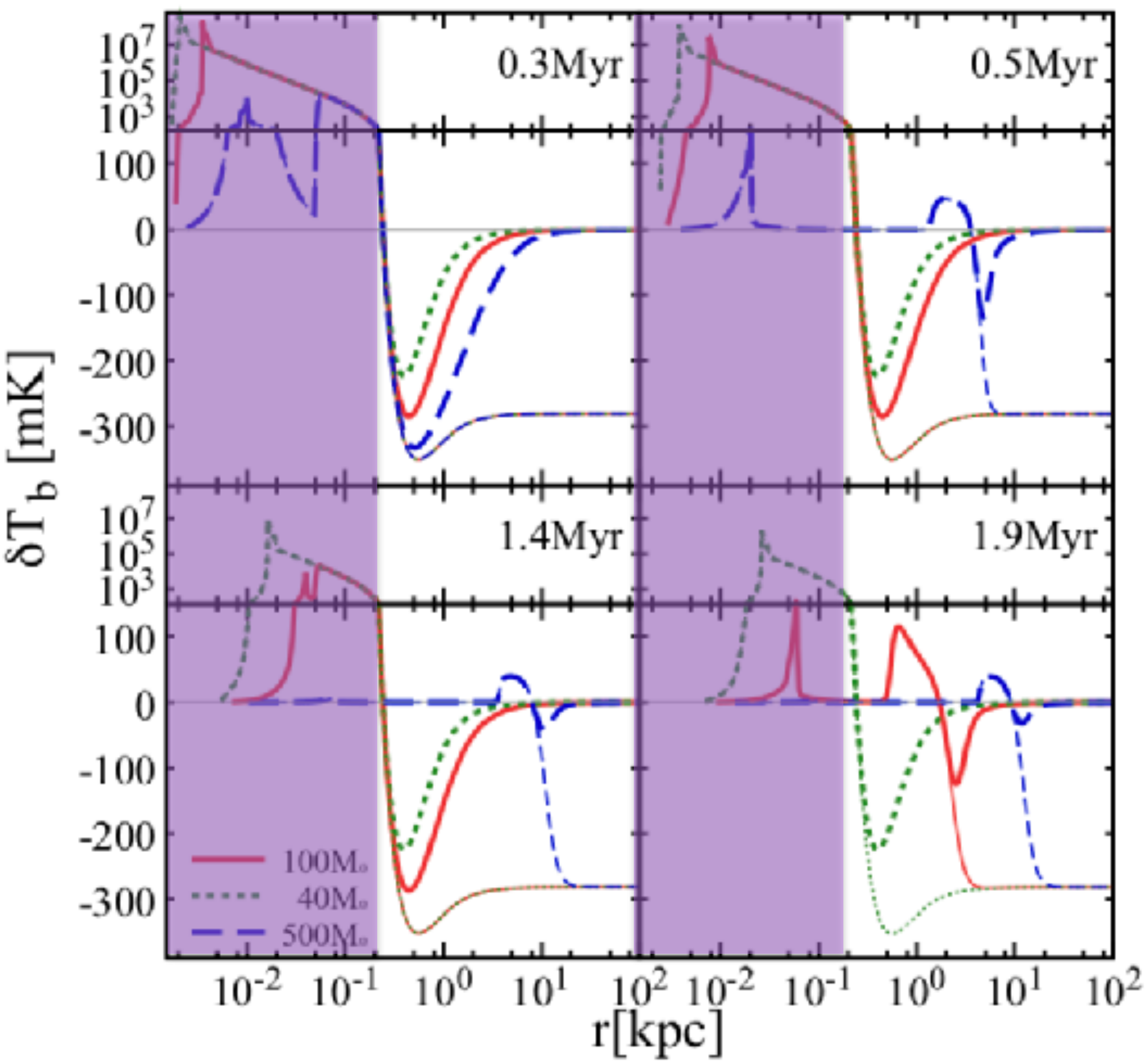
X-ray source

- Ionized region
- Broad Heated region ($T_S > T_{CMB}$)
- Narrow and weak absorption region ($T_S < T_{CMB}$)
- T_S non-coupling region

- **The signal reflects the spectral type of a source.**
- **Detecting the signal of individual Pop III star is difficult. (cf 1arcmin)**

21cm Imaging in the vicinity a Mini-halo

- Tanaka, KH, Yajima+ (2018): RHD resolving mini-halo enables us to consider a stellar mass dependent escape fraction (e.g., Kitayama et al. 2004) and the expansion of HII region.



- The expansion of HII region hardly affect the detectability.
- The distribution of HI signal strongly depends on the mass of the first star.
  - Less Massive Star ($40M_{sun}$) : A strong absorption feature lasts during the lifetime (IGM is not ionized and heated)
  - Massive Star : Basically same as Yajima & Li 2014
- **This mass-dependence is imprinted on the global signal.**

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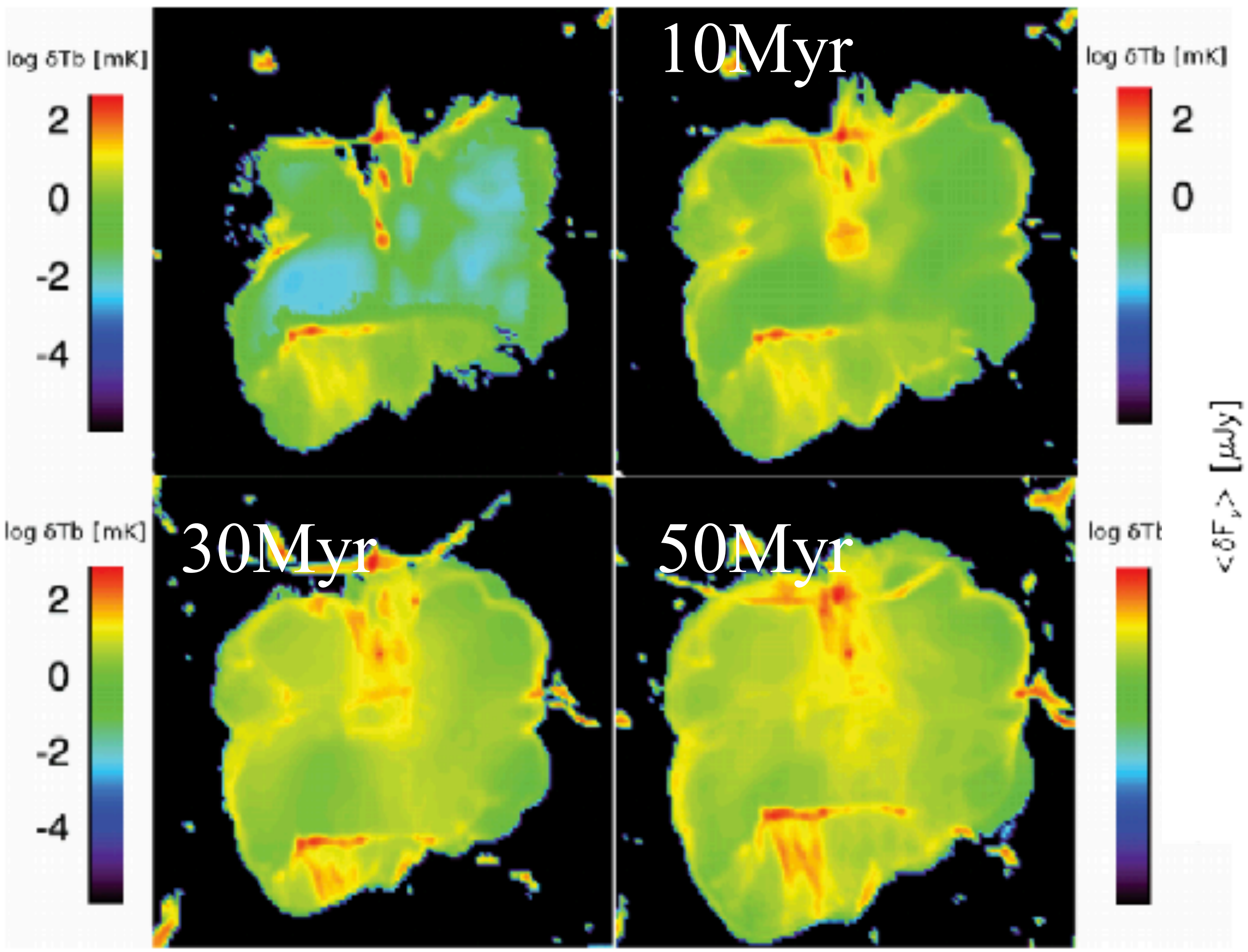
21cm signature after the death of the first star

Emission from fossil HII regions (e.g., Tokutani et al. 2009, Greif et al. 2009)

Tokutani et al. 2009



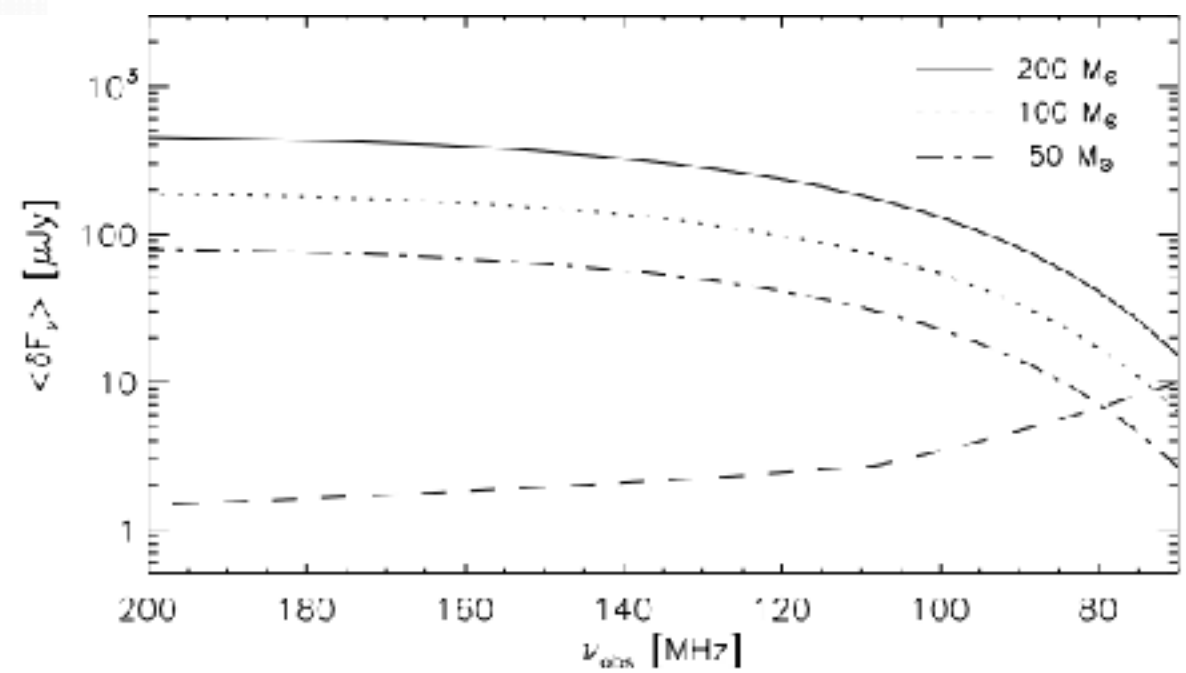
100kpc

~10-100mK during ~50Myr

(~recombination time >> stellar lifetime)

Greif et al .2009

21cm (+ Bremsstrahlung)



Individual signal cannot be resolved, but the emission contribute to the global signal

Summary : The First Stars

- HI 21cm signal around an individual source well reflects the properties of the source.
- But, it is difficult to detect it even with the SKA.
  => we need to understand the properties of the first stars form observations of the global signal and the power spectrum.

More detailed theoretical modeling for the global signal and Power spectrum would be important to understand the properties of the first stars.

Cosmic Reionization

Q: When did reionization start and end?
A: The The distribution of δT_b almost directly tells us it.

Q: How did reionization proceed spatially?
A: δT_b alone cannot distinguish inside-out/outside-in scenarios. But a cross-correlation between high-z galaxies and δT_b likely provides us with the information of the EoR topology.
(The cross-correlation also helps in decreasing the foreground contamination. => Yoshiura-kun's talk)

Q: What are the ionizing sources?

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Candidates for ionizing sources

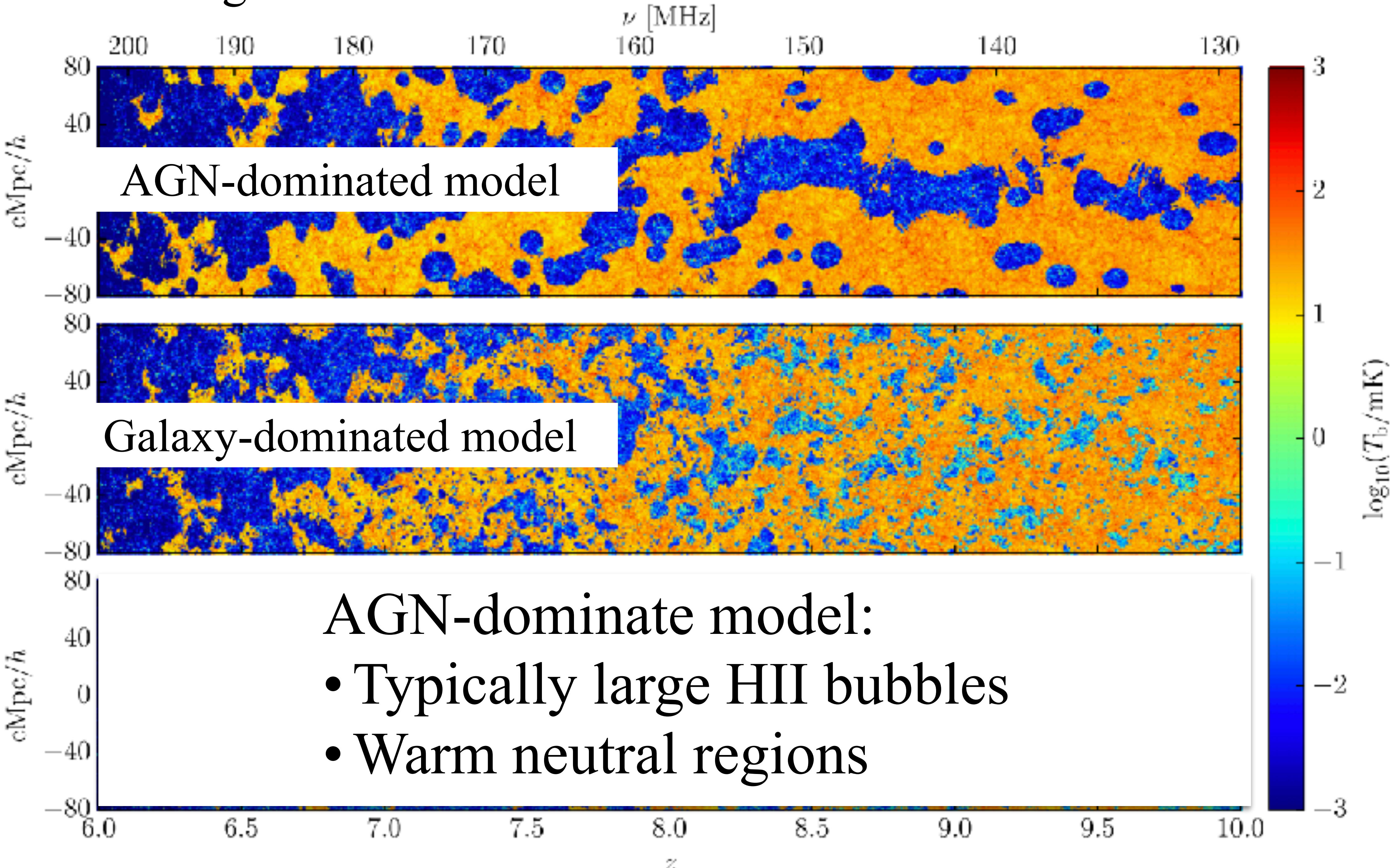
- **Star Forming Galaxies**
  - A number of high-z galaxies have been already discovered (e.g, recent obs. with HSC, SILVERRUSH; Ouchi et al. 2018)
  - Contribution form the high-z galaxies strongly depend on the escape fraction of ionizing photons, which is still highly uncertain)

- **(faint)AGNs?**
  - Giallongo et al. (2015) have indicated more abundant AGNs at $z>4$.
    - Several observations disclaim it(e.g, Onoue et al. 2017, Parsa et al. 2017)
  - Contribution from AGNs depend on the abundance of faint AGNs and the redshift evolution of AGNs' luminosity function.

Current constraints on the reionization history allows both of the galaxy-dominated and AGN-dominated scenarios (e.g., Madau & Haardt 2015, Yoshiura, KH+ 2016)

Imprints on Power Spectra

SPH + semi-numerical modeling for ionization state.
Assuming that massive halos host AGNs.



AGN-dominate model:
- Typically large HII bubbles
- Warm neutral regions

Not Radiative Transfer calculation. Redshifted photons are not appropriately considered.

Kulkarni et al. 2017

Imprints on Power Spectrum

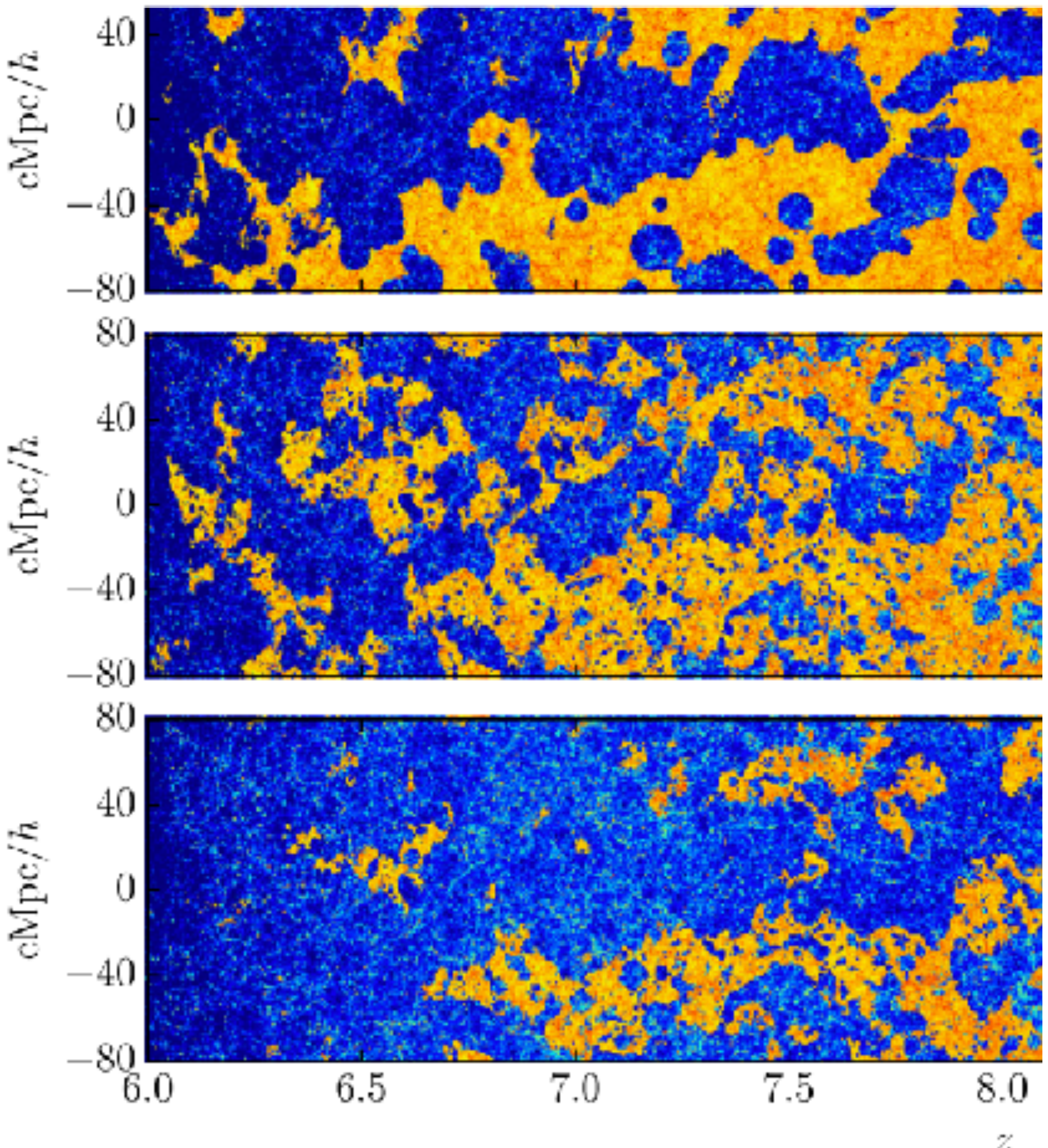
The Fourier transform of the brightness temperature

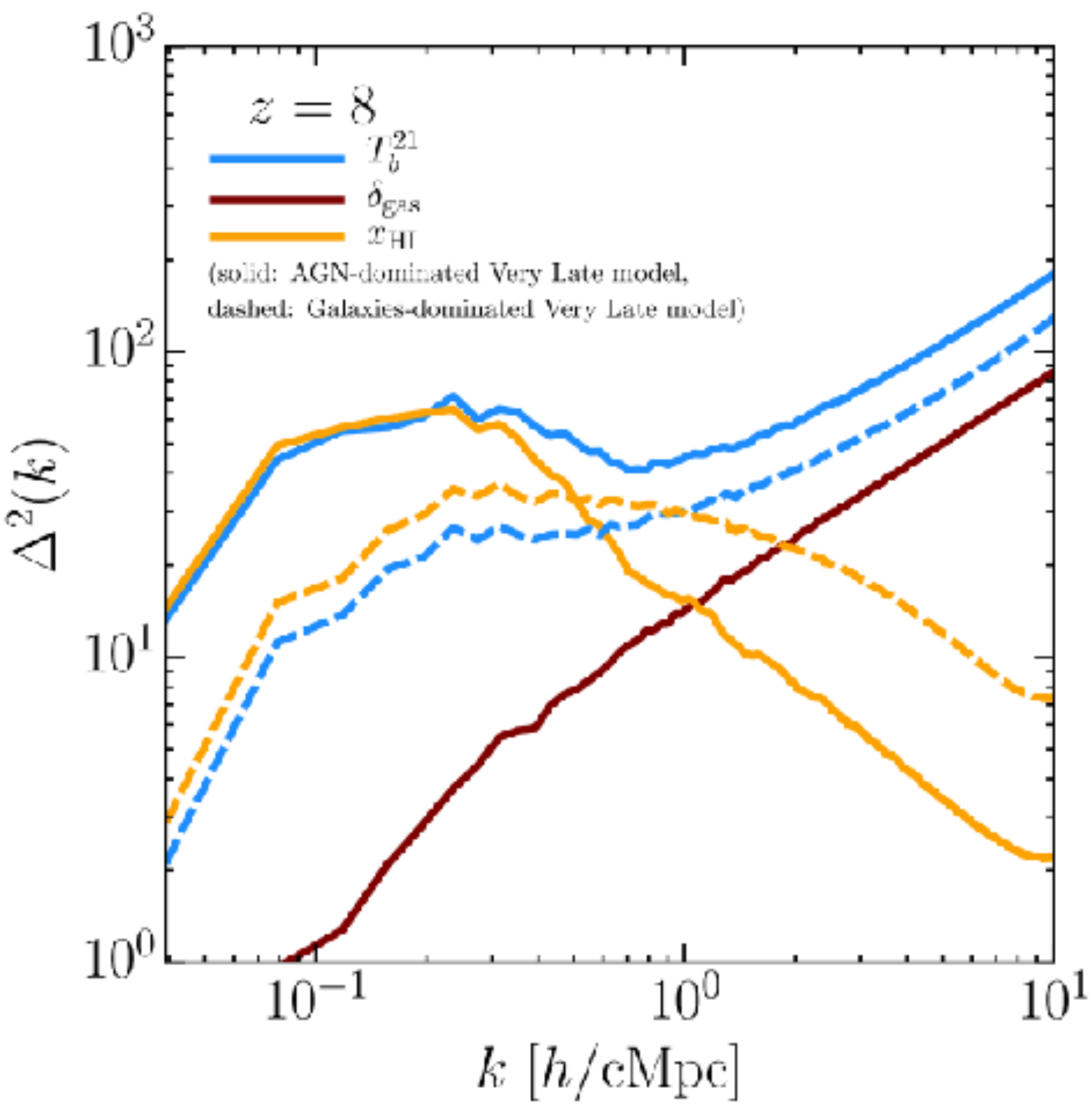
$$\Delta^2_{21}(k) = \frac{k^3}{2\pi^2} \cdot \frac{\langle \tilde{T_b}^2(k) \rangle}{V_{\rm box}},$$

Dimensionless power spectrum

$$\Delta^2_{21}(k) = b_\delta \Delta^2_\delta(k) + b_x \Delta^2_{x_{\rm HI}}(k) + \text{cross-correlations}$$

Decomposition





Kulkarni et al. 2017

Imprints on Power Spectrum

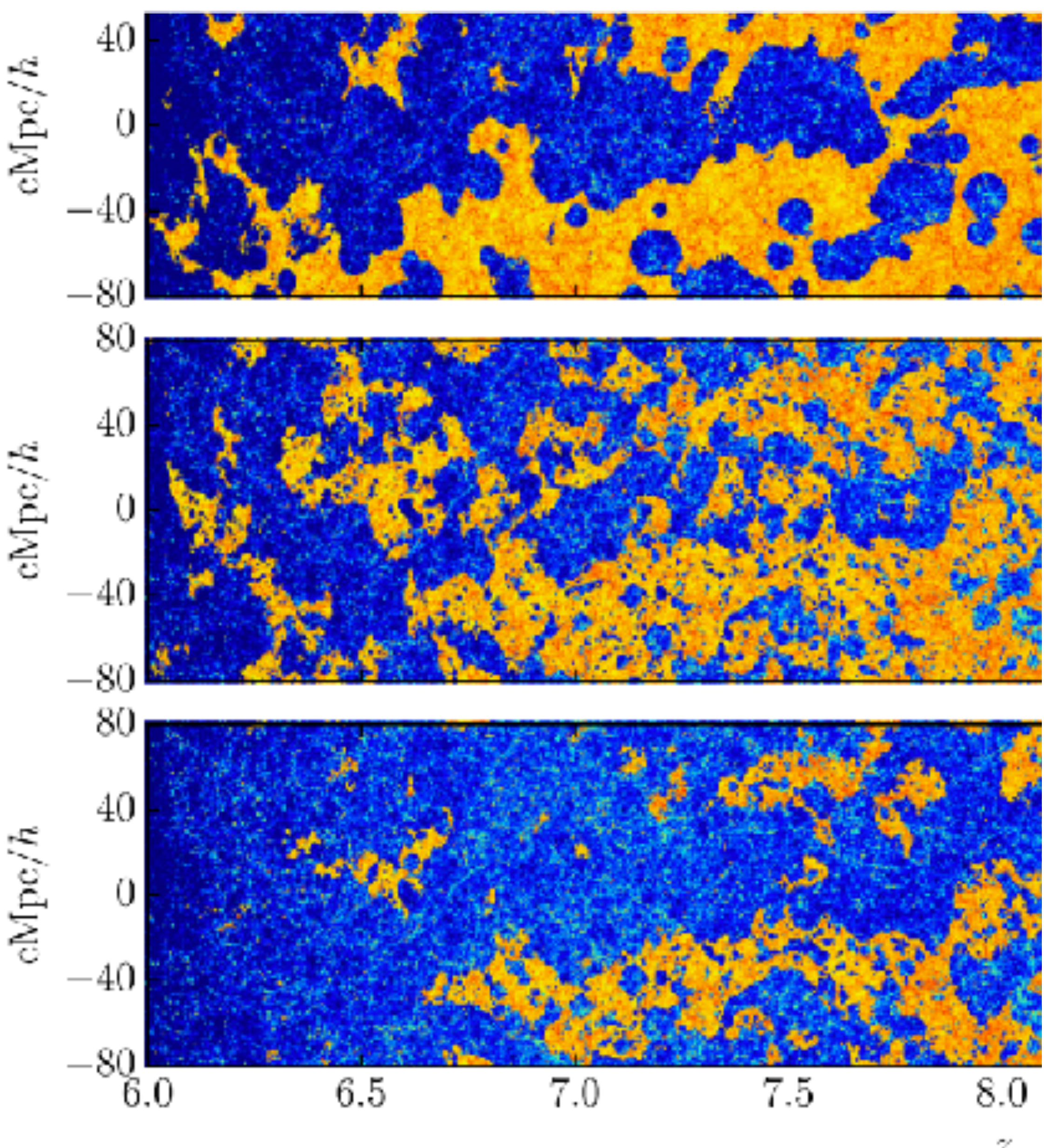
$$\Delta_{21}^2(k) = \frac{k^3}{2\pi^2} \cdot \frac{\langle \tilde{T}_b^{\,2}(k) \rangle}{V_{\mathrm{box}}},$$

← The Fourier transform of the brightness temperature

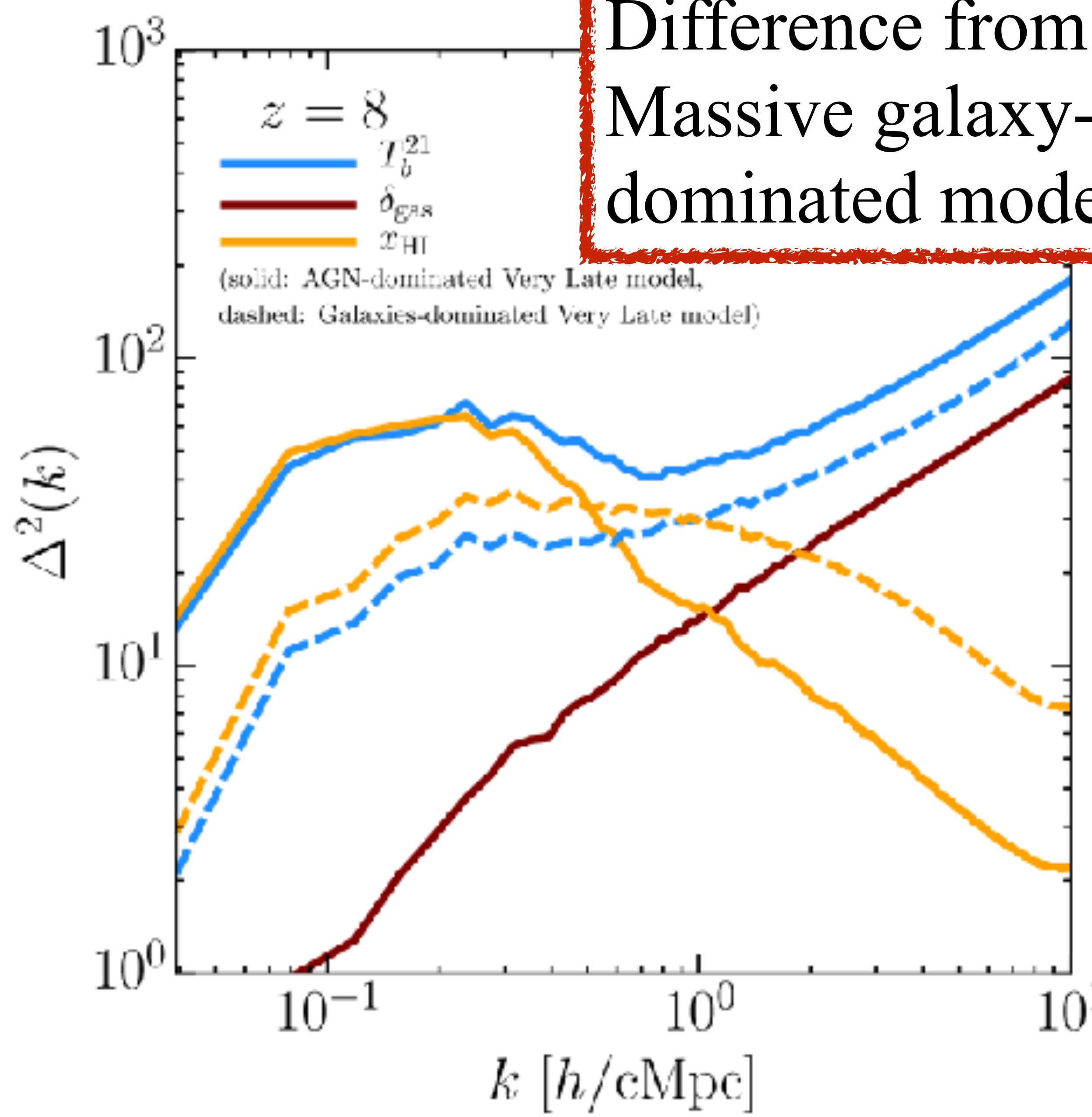
Dimensionless power spectrum

$$\Delta_{21}^2(k) = b_\delta \Delta_\delta^2(k) + b_x \Delta_{x_{\mathrm{HI}}}^2(k) + \text{cross-correlations}$$

Decomposition [3]



Kulkarni et al. 2017



Difference from Massive galaxy-dominated model?

Summary: Cosmic Reionization

- **If we can observe the HI 21cm signal during the EoR**, our understanding on the reionization history, the EoR topology, and the ionizing source would drastically progresses.

  ➡ **Yoshiura-kun will talk about the difficulties of the 21cm observation and the current progress.**

- If we observe δT_b around an individual ionizing source (e.g., galaxies) with sufficiently high resolution, we may measure the LyC escape fraction of the source.

- HII bubble size distributions and Power Spectra involve the information of ionizing source.