Detailed modeling of PopIII stars in cosmological 21-cm signal calculation

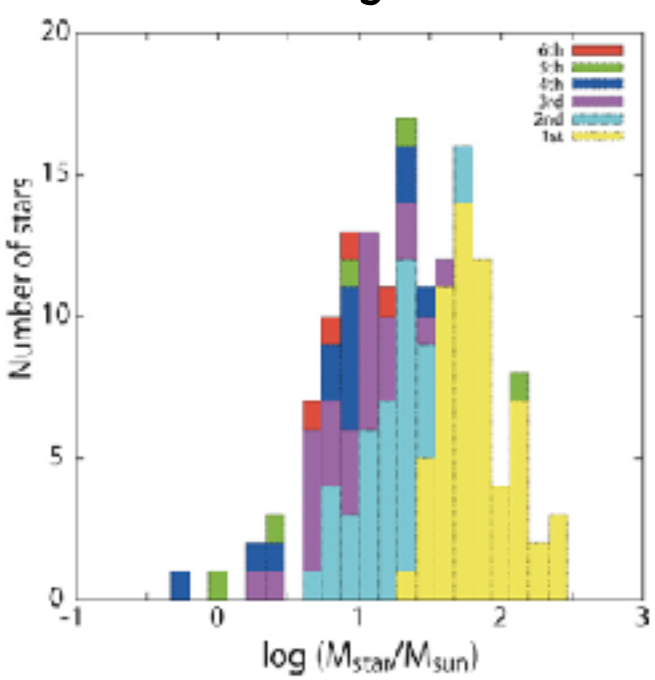
Toshiyuki Tanaka (Nagoya university)
Collaborator: Kenji Hasegawa

Population III star

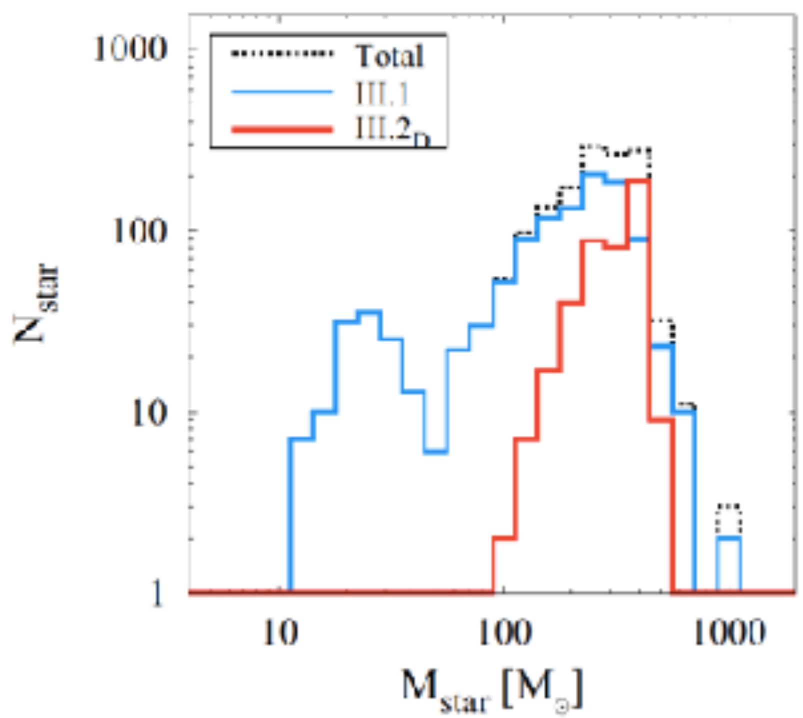
- Formed in mini-haloes (MHs) ~ $10^{5-8}\mathrm{M}_\odot$
- Zero-metal massive stars (10-1000 Msun)
- Have important roles in cosmic history (Reionization, SN, BH)
- Not observed yet
- **However, its properties NOT well understood**

Initial mass function

Susa, Hasegawa+2014

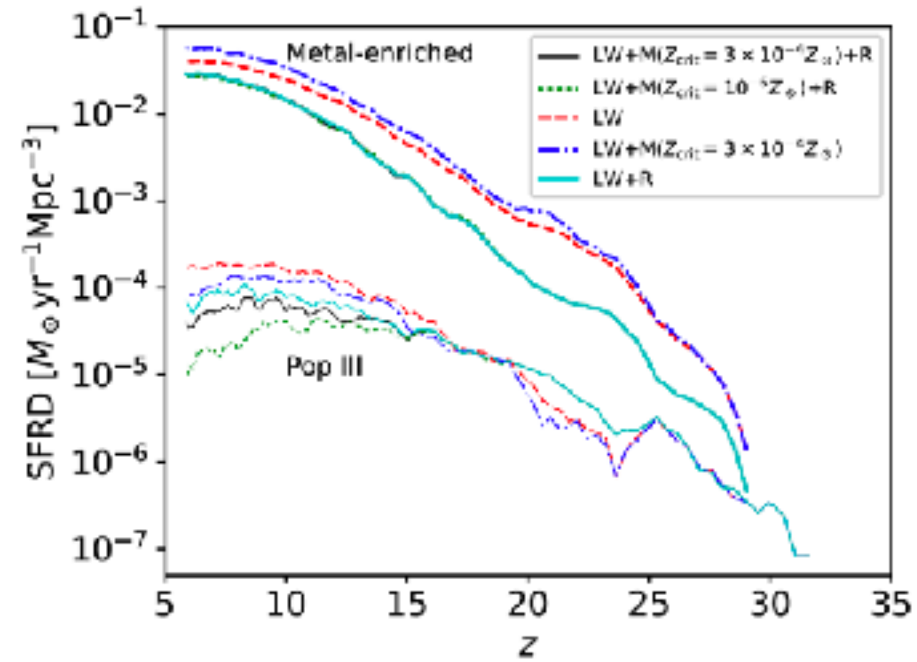


Hirano+ 2015

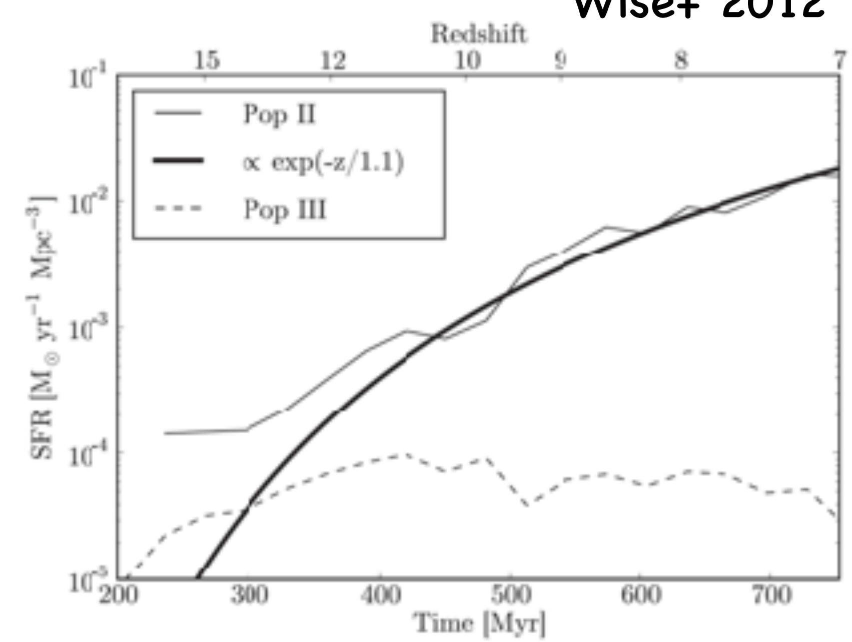


Star formation rate density

Visbal+ 2020

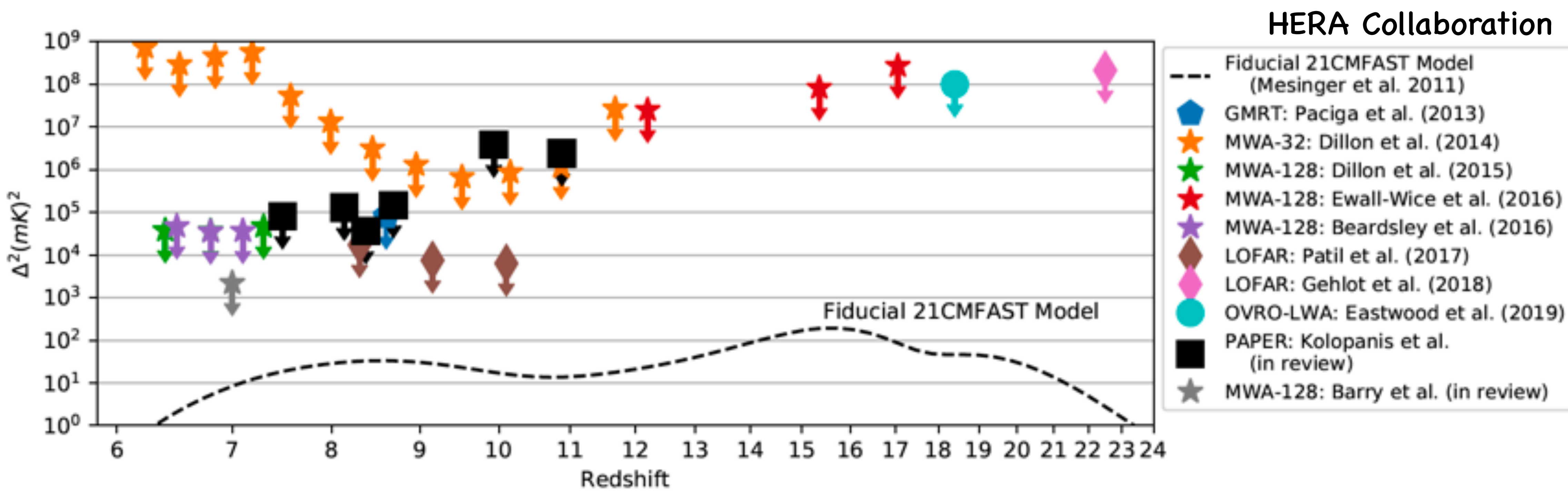


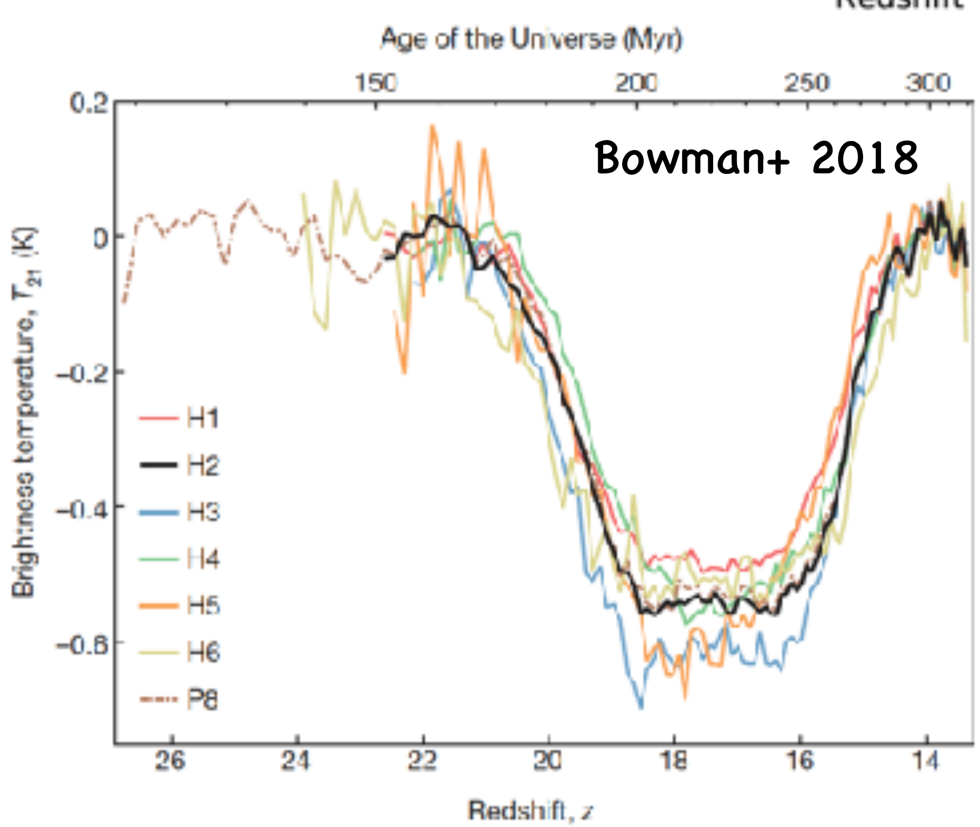
Wise+ 2012



21-cm observation

- Can see high-z universe tomographically
- Several observations now running (MWA, LOFAR, EDGES etc.) and forthcoming (SKA)





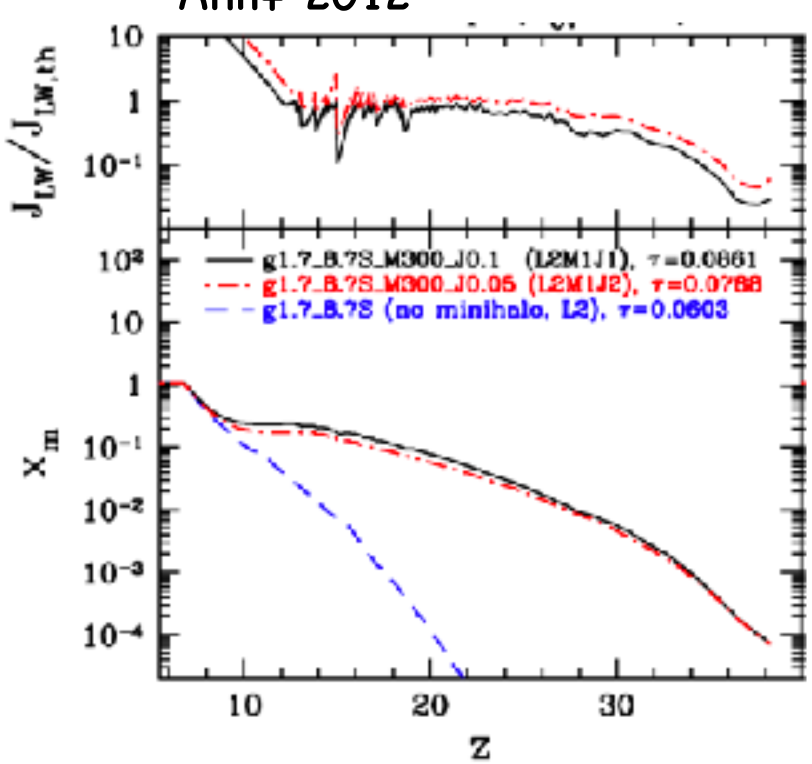
- To understand the PopIII stars from the observations, we **need to construct accurate theoretical model**.

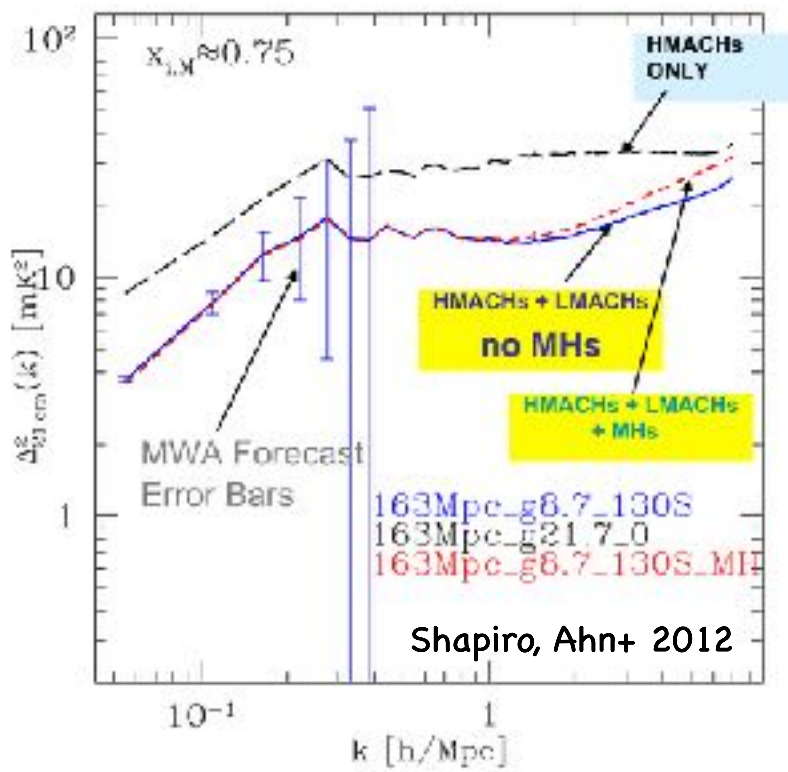
Cosmological 21-cm signal calculations including MH

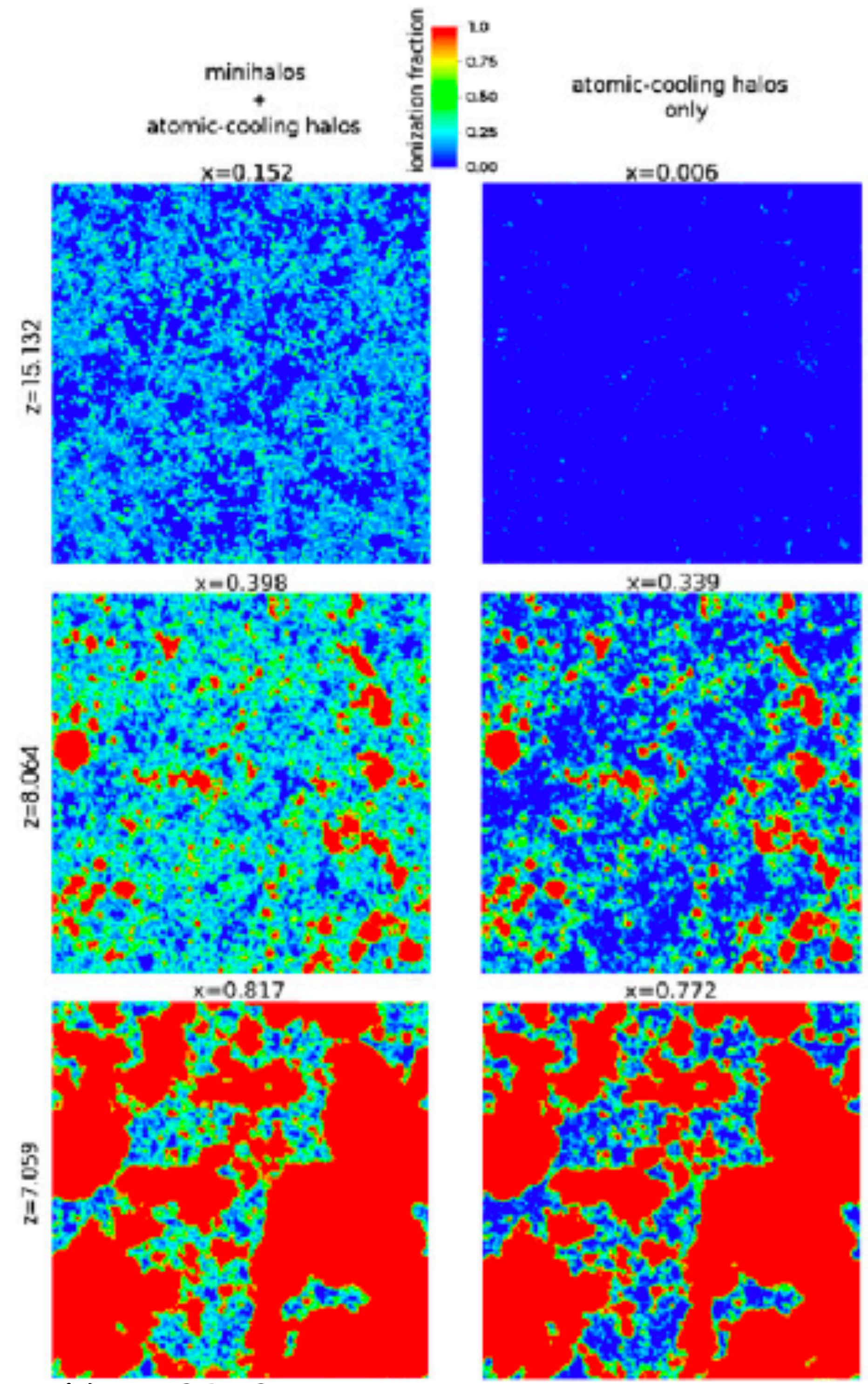
- Simulation with MH needs high computational resources. Thus, semi-analytic methods (e.g. Visbal+ 2020) or creative ideas like sub-grid models (e.g. Ahn+ 2012) are introduced.

- Ahn+ 2012 developed sub-grid model for number of mini-haloes in grids, and do RT simulation. LW feedback is included.

Ahn+ 2012







Ahn+ 2012

- **Model of PopIII in previous works are rather simple**: constant escape fraction of ionizing photons, and no gas heating effects.

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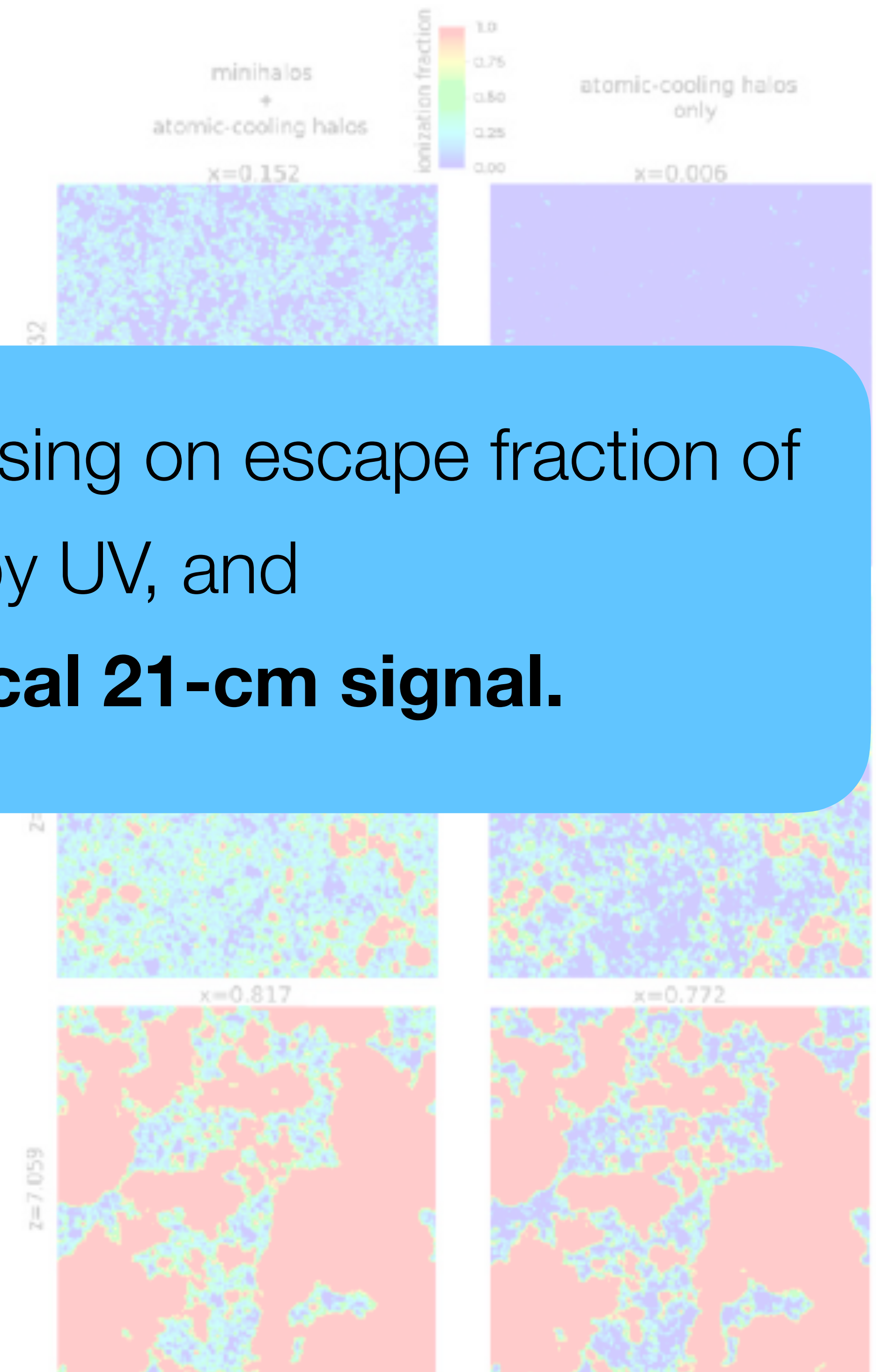
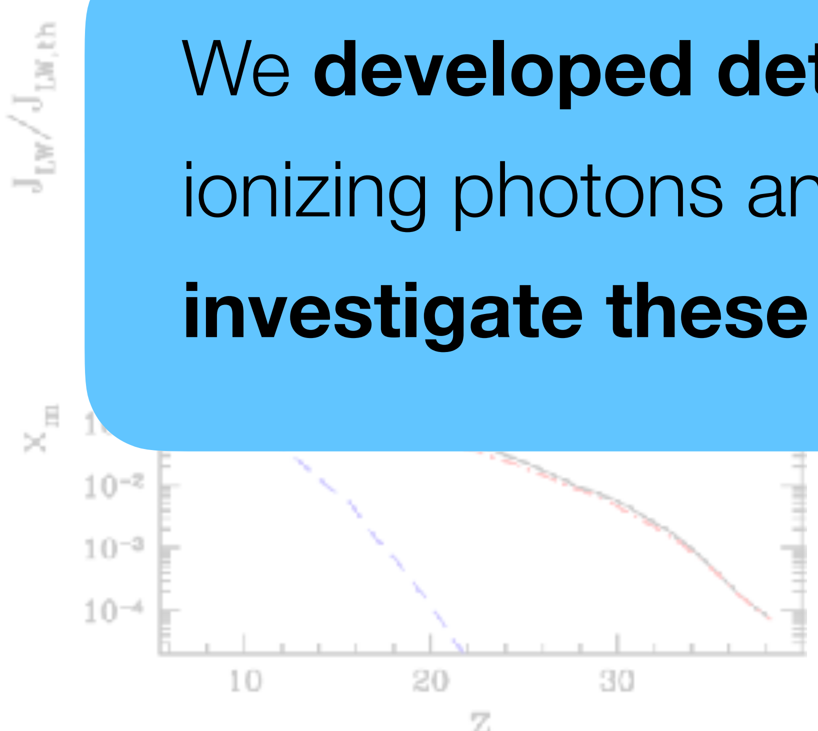
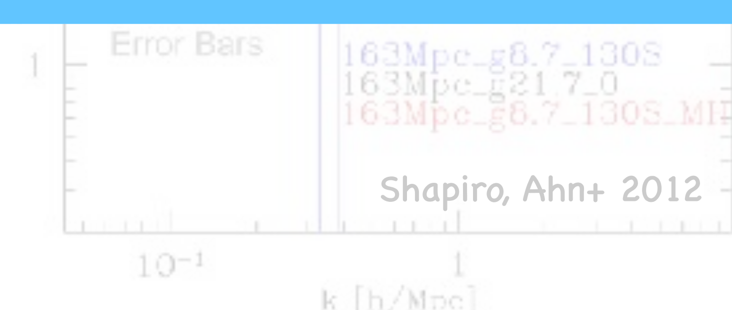


We **developed detailed PopIII model** focusing on escape fraction of ionizing photons and heating effect on IGM by UV, and **investigate these impacts on cosmological 21-cm signal.**





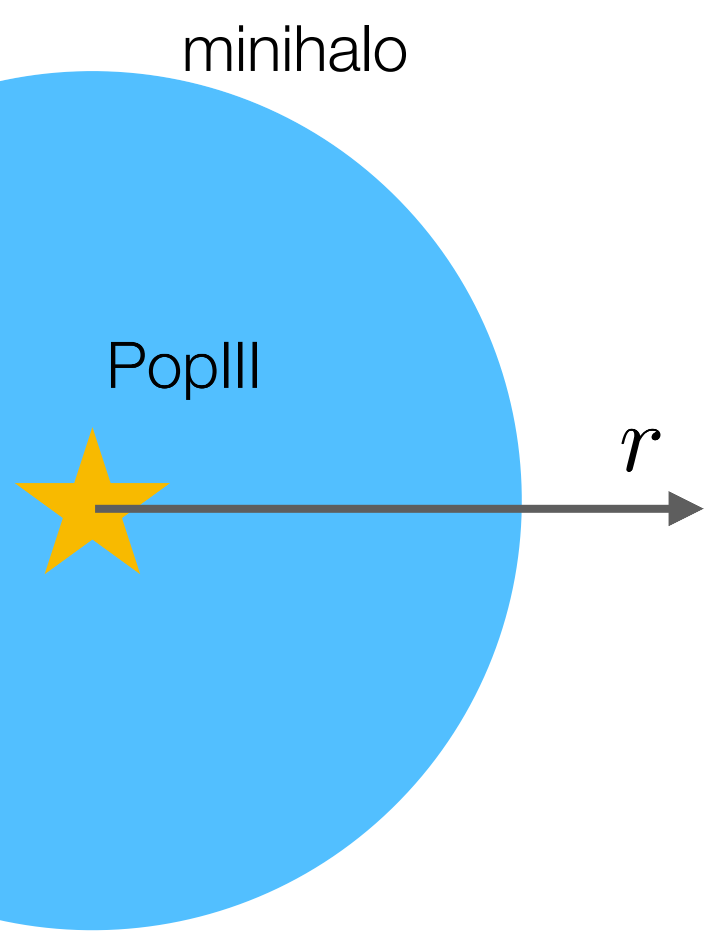
- **Model of MH in Previous works are rather simple**: constant escape fraction of ionizing photons, no other effects on 21-cm brightness temperature.

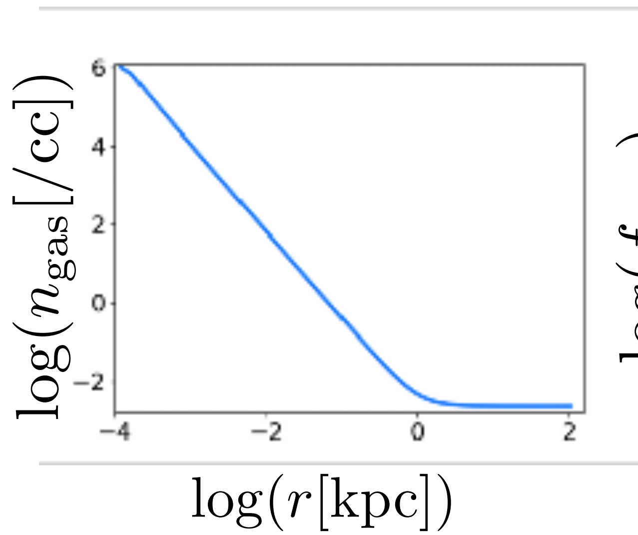
Ahn+ 2012

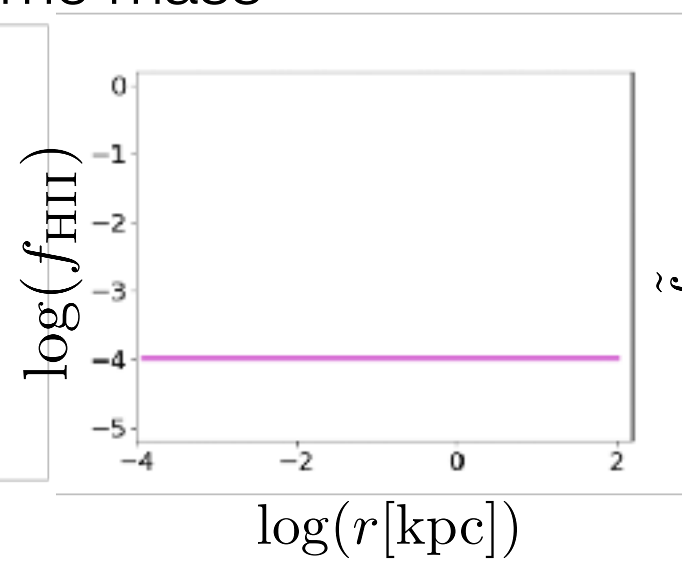
Modeling Escape fraction

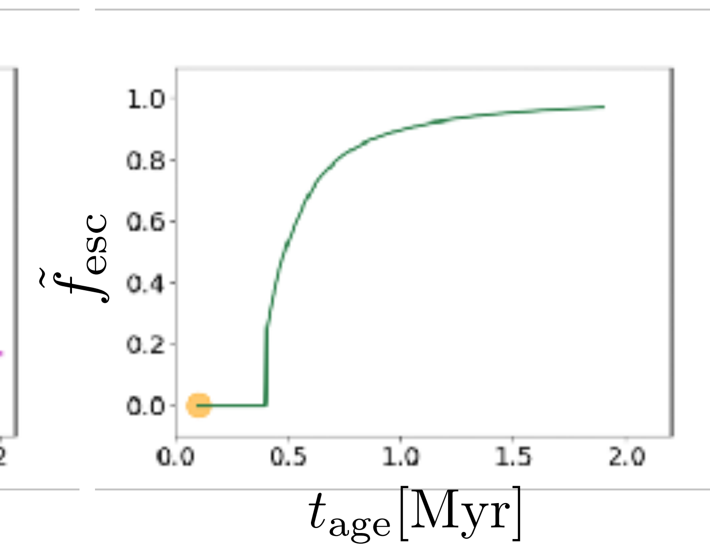
- Basic idea: taking average of fesc weighted by halo mass function
- Assume 1star/halo and all stars have the same mass

1D spherically symmetric RHD simulation (TT+ 2018)







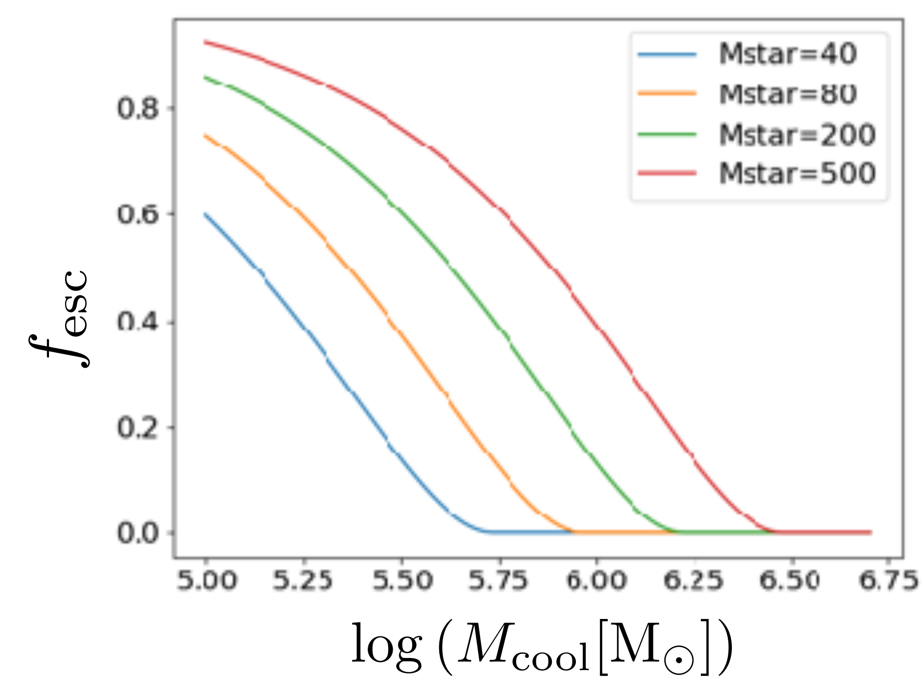


$$f_{\rm esc}(M_{\rm star}, M_{\rm min}) = \frac{\int_{M_{\rm min}}^{\infty} {\rm d}M \frac{{\rm d}n}{{\rm d}M} \overline{\tilde{f}}_{\rm esc}(M_{\rm halo}, M_{\rm star})}{\int_{M_{\rm min}}^{\infty} {\rm d}M \frac{{\rm d}n}{{\rm d}M}}$$

$$M_{\rm min} = M_{\rm cool}(\bar{J}_{\rm LW})$$

Halo mass function: $\frac{{\rm d}n}{{\rm d}M}$ **ishiyama+ 2016**

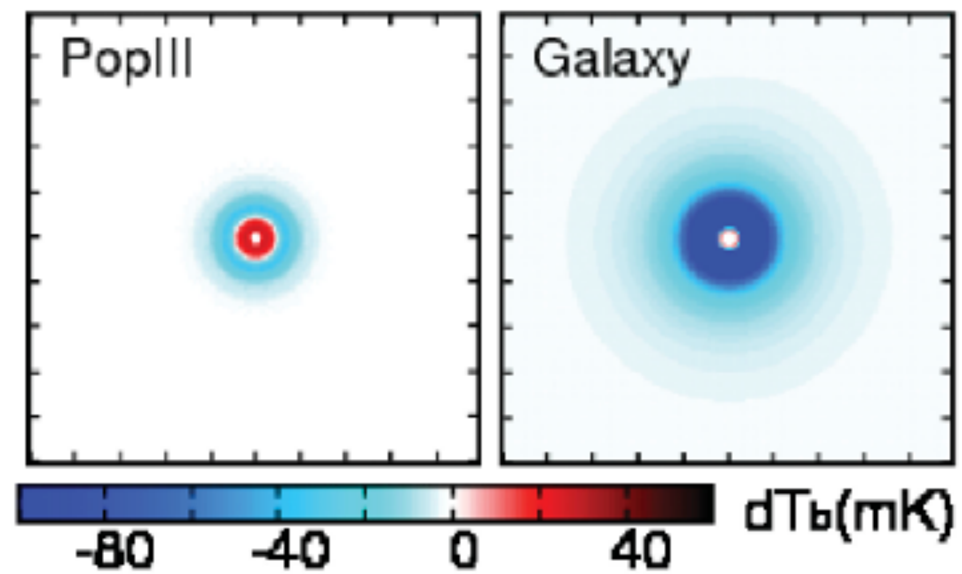
Mcool - J_LW relation: **Visbal+ 2014**



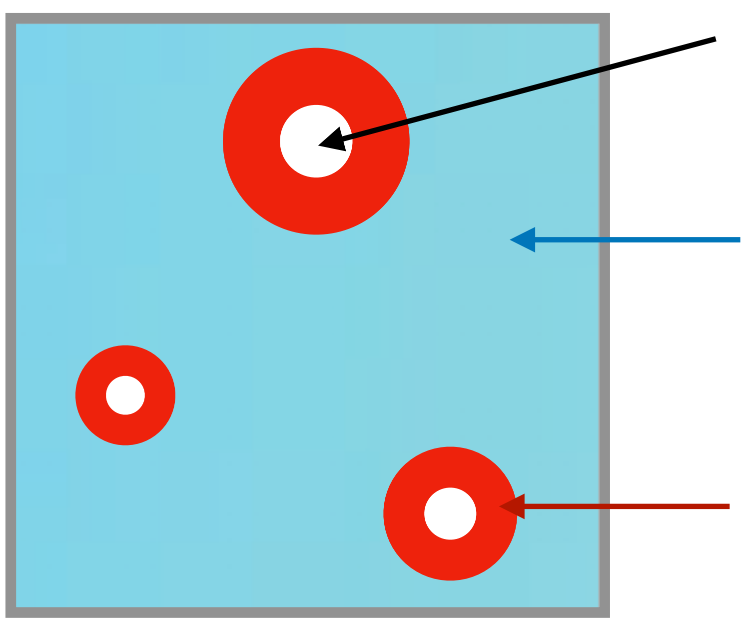
Modeling UV heating

- UV heating has been neglected, but not obvious wether UV heating is negligible or not for PopIII star because of high effective temperature.

Yajima & Li 2014



- Three fluid approximation method



Ionized region:

$$\delta T_{\rm b,ion} = 0\,[\rm mK]$$

Cold region (absorption region):

$$\delta T_{\rm b,cold} = 38.7(1+\delta)\left(\frac{1+z}{20}\right)^{1/2}\left(\frac{T_{\rm S}-T_{\rm CMB}}{T_{\rm S}}\right)\,[\rm mK]$$

Heated region (emission region):

$$\delta T_{\rm b,heat} = 38.7(1+\delta)\left(\frac{1+z}{20}\right)^{1/2}\,[\rm mK]$$

$$\delta T_{\rm b,grid} = \sum_j f_j\,\delta T_{\rm b,j}$$

f_j : Volume fraction of j region (j = ion, heat, cold)

$f_{\rm ion}$: ionization fraction $\quad f_{\rm cold} = 1-(f_{\rm ion}+f_{\rm heat})$

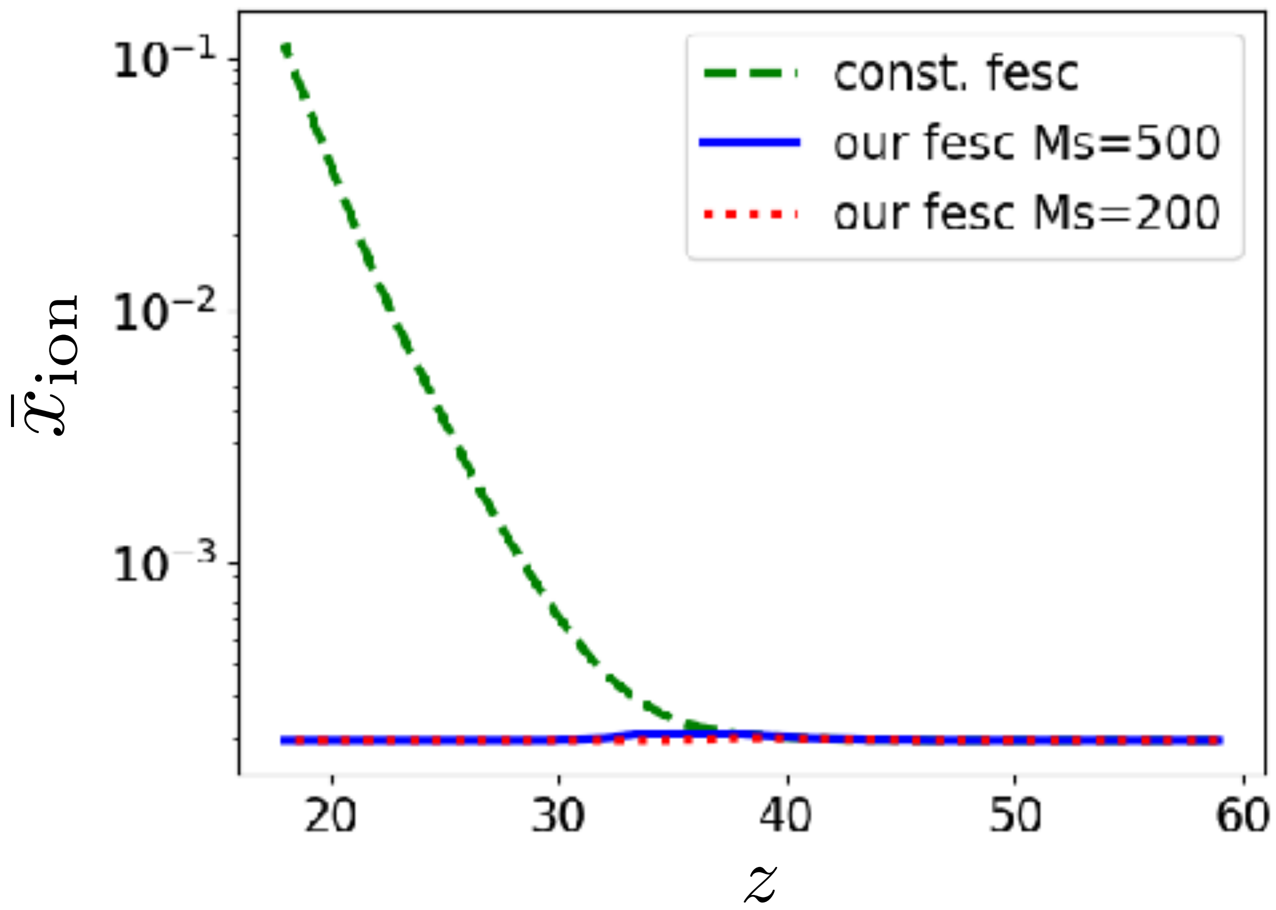
$f_{\rm heat}/f_{\rm ion}$: model with data from the 1D RHD simulation

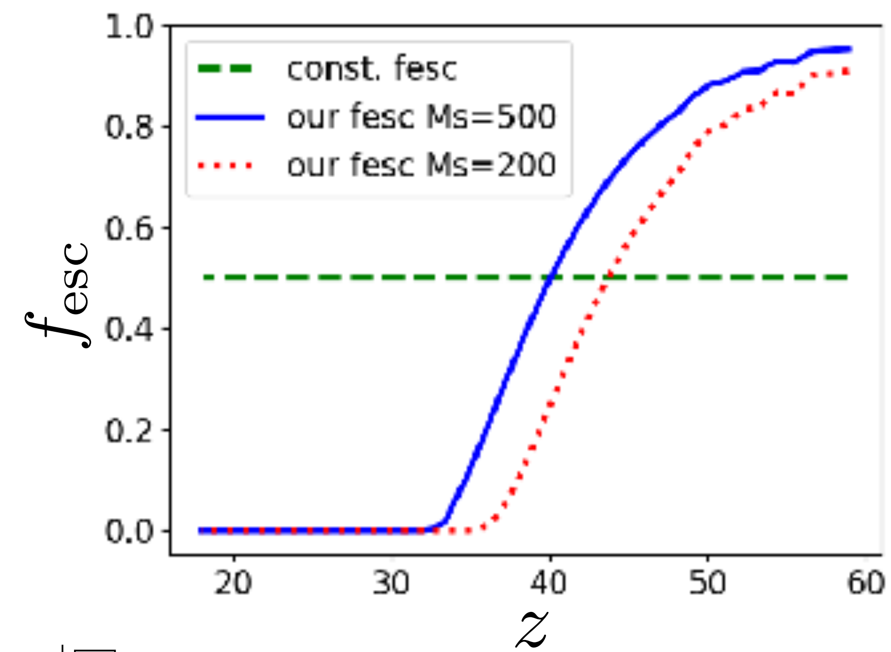
Cosmological 21-cm signal

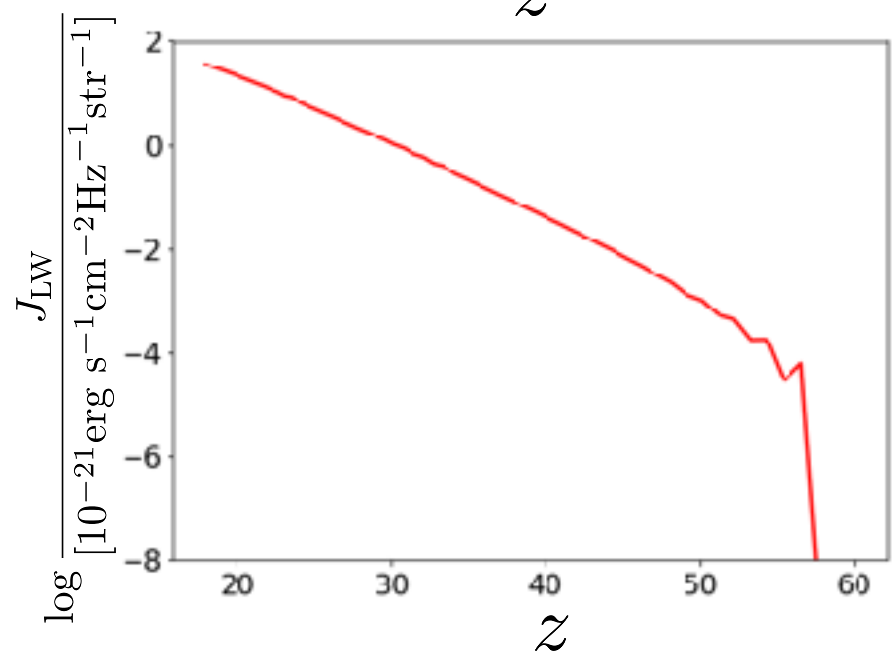
- Base code: 21cmFAST
- Box size: (128Mpc)^3
- Grid number: 128^3
- Start from z=60, end at z=18
- LW feedback and recombination added
- Inhomogeneous Lya coupling
- NO X-ray heating
- Assume all stars are PopIII

Results: ionization history

- Compared with constant escape fraction model: fesc = 0.5



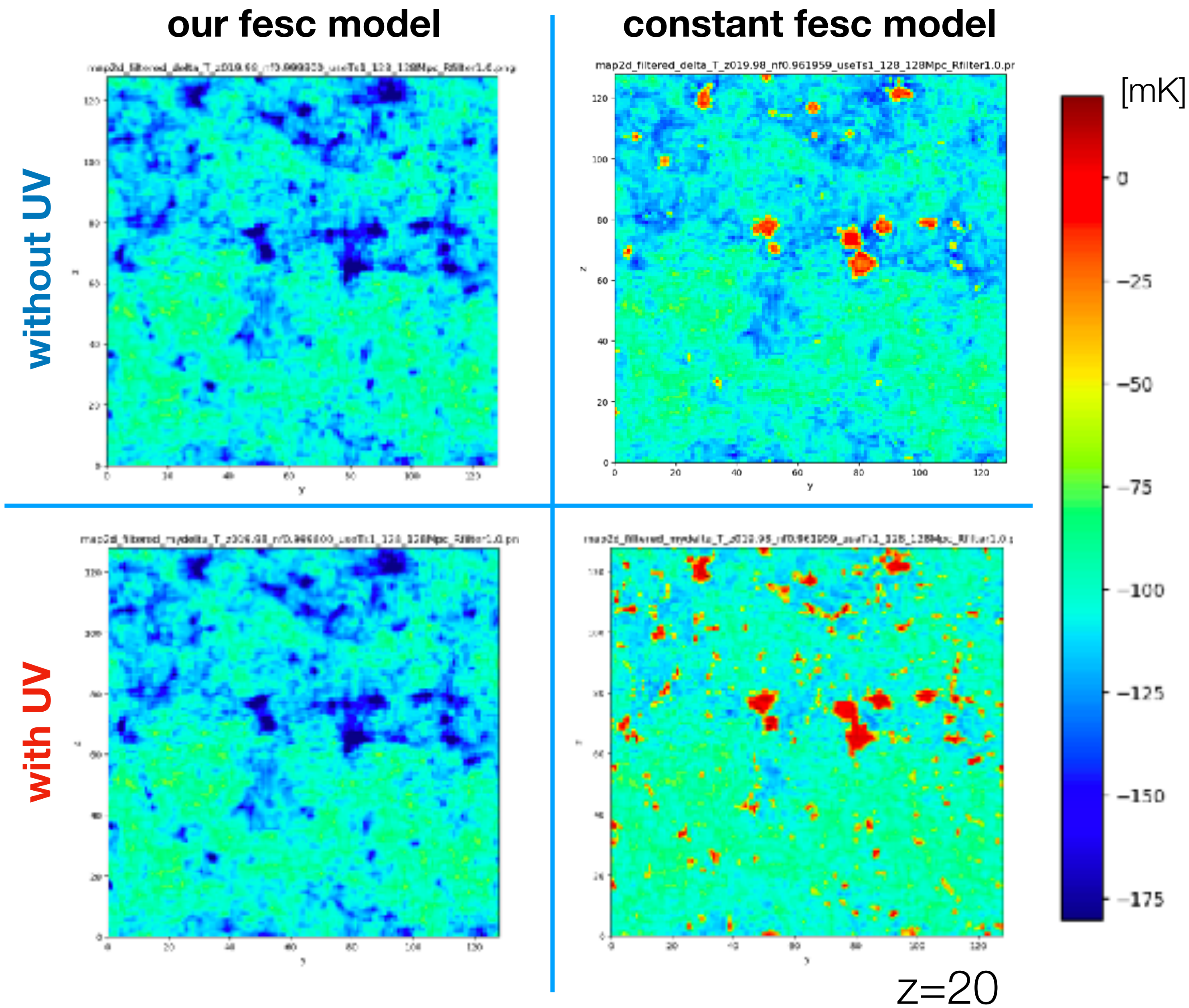


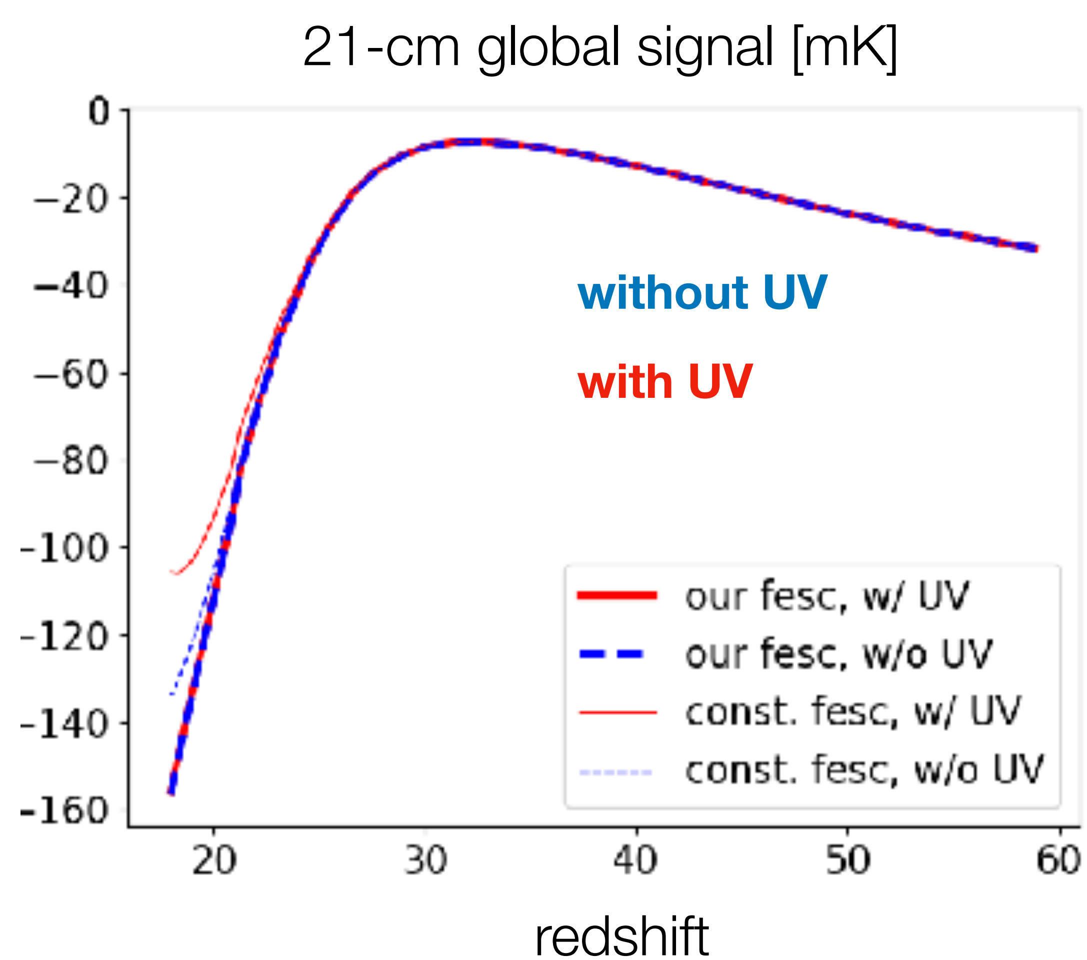


- Escape fraction become ~0 at z~35 because the minimum halo mass for star formation is increasing due to increasing LW intensity. Resultantly, **MH do not ionize IGM in our fesc model**. On the other hand, in const fesc case do ionize.

Results: 21-cm brightness temperature

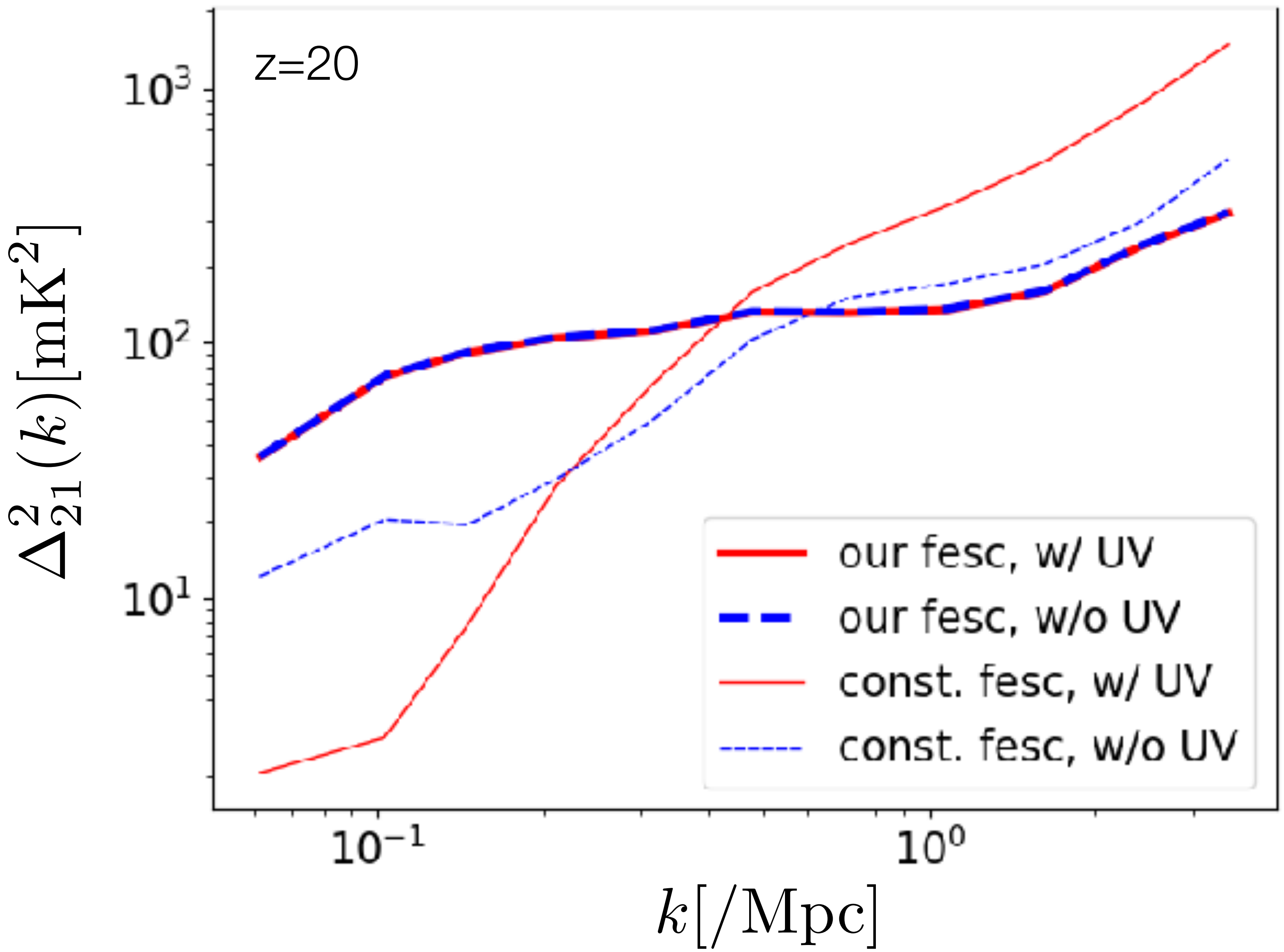
2D slice of 21-cm brightness temperature





- In our fesc model, MH do not ionize and heat IGM but Lya coupling occurs, which results in the deep absorption signal. In const. fesc model, IGM is ionized and heated by UV photons, which results in shallower absorption signal.

Results: 21-cm powerspectrum



- In our model, UV heating does not affect because of small ionization fraction.
- In constant fesc model, ionization and UV heating results in larger power at small scales.

Summary

What we did:

- We developed **detailed PopIII model** focusing on **escape fraction of ionizing photons** and **UV heating effect** on IGM. Then, **investigated these impacts on cosmological 21-cm signal**.

What we found:

- **PopIII stars hardly ionize IGM** because LW feedback boost minimum halo mass for PopIII star formation so that the escape fraction rapidly drops. (We assume 1 star per halo)
- In the case of constant escape fraction, we found that **UV heating has non-negligible impact on 21-cm signal**: raising the bottom of absorption of the global signal and increasing the power at small scale in fluctuation signal.