21cm線で探る初代星質量
Probe the first star mass using by 21cm line

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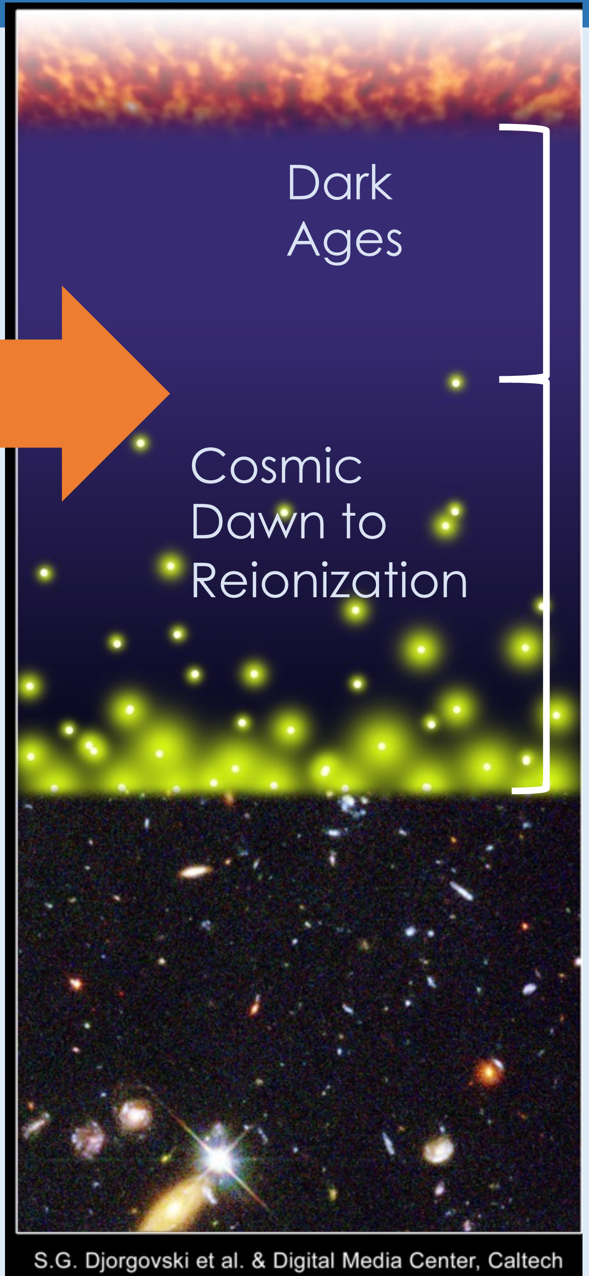
About First Star (Pop.III)

First Star

- The first luminous objects in the universe
- Formed in a halo consist of pristine gas, cooled by H_2, believed **typically massive**

First Stars formed

z=30 ~ z=20



Their Roles

- Providing Photons → Reionization (early)
- Producing Metal → Star formation(Pop.II, I)
- BH in early universe → Seed of SMBH？

First star is an important target related to various Cosmological topics

Background & Motivation

- Question
  - How much is the typical mass of the first stars?
  - How much is the abundance?
- Problems
  - Simulational results DON'T reach the consensus.
  - Little observational constraints about the mass

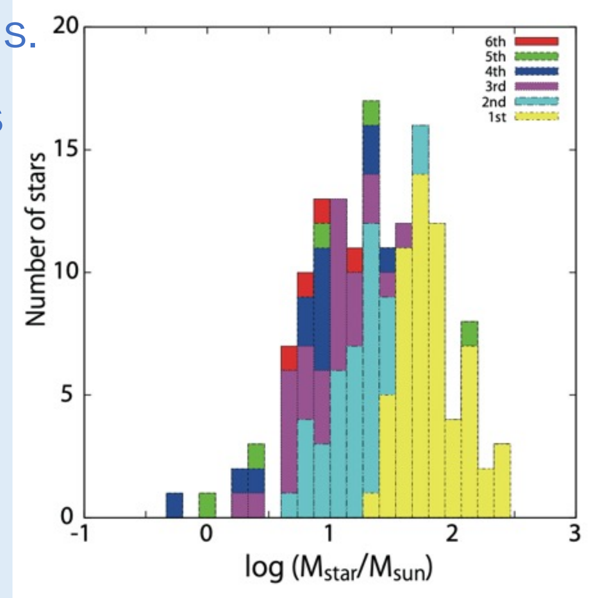
It's required a research that ties up simulations and observations

- **This research**

Focuses on the effects of the first stars on 21cm signal

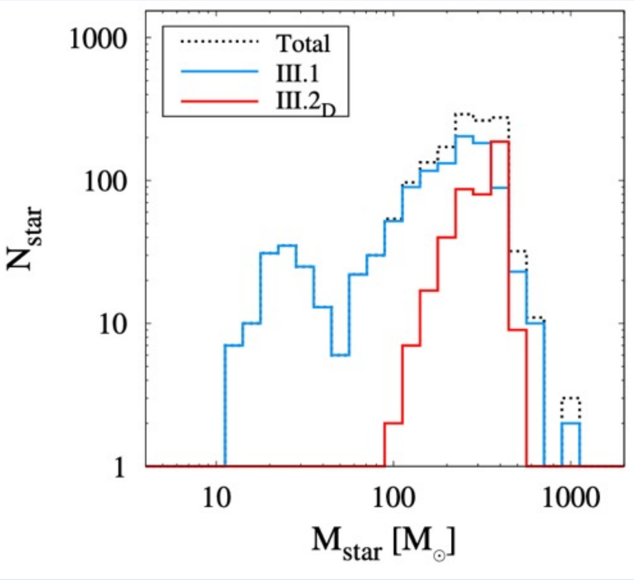
Simulates the statistical signature.

Typically several 10 $M_\odot$



Susa+ 2014

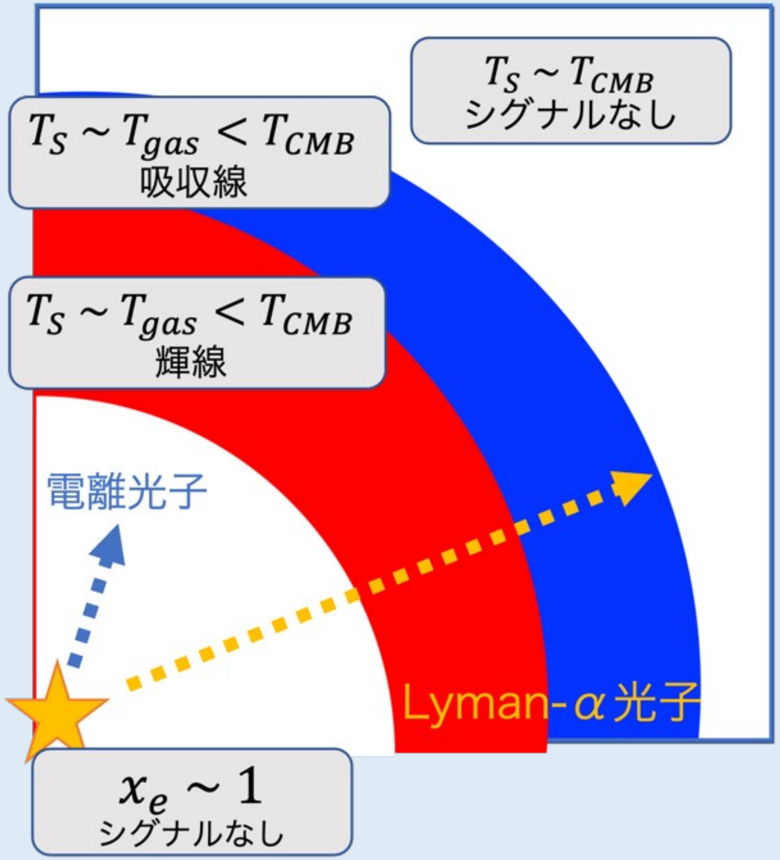
Typically several 100 $M_\odot$



Hirano+ 2015

How a first star effects on 21cm line?

Small-scale 21-cm signal
around a first star



21-cm line brightness temperature

$$\delta T_b = 27\,\mathrm{mK} \times (1 - x_e)(1 + \delta)\left(\frac{1+z}{20}\right)^{1/2}\left(\frac{T_S - T_{CMB}}{T_S}\right)$$

x_e ionized fraction
δ matter fluctuation
T_S spin temperature

21-cm line observed as emission/absorption in CMB
→ emission line
$T_S < T_{CMB}$ → absorption line

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

Gas temperature

Increases by UV heating

Wouthuysen-Field (WF) coupling coefficient

Spin temperature approaches gas temperature through absorption and re-emission of Ly-α photon by first star

Collisional coupling coefficient

How a first star effects on 21cm line?

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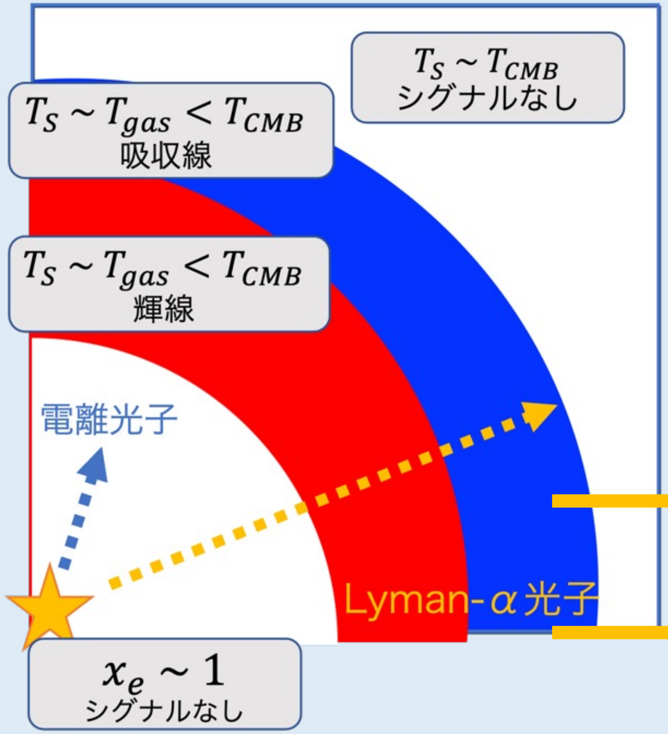


- There's a gap between the scale around a star and the scale photon reaches.
- To simulate 21-cm signal in Cosmological scale, required semi-analytical method.

Lyman series reaches ~ several 100 Mpc

LW photon reaches~ several 10 Mpc

Virial radius ~1 kpc

Ionized region ~10 kpc

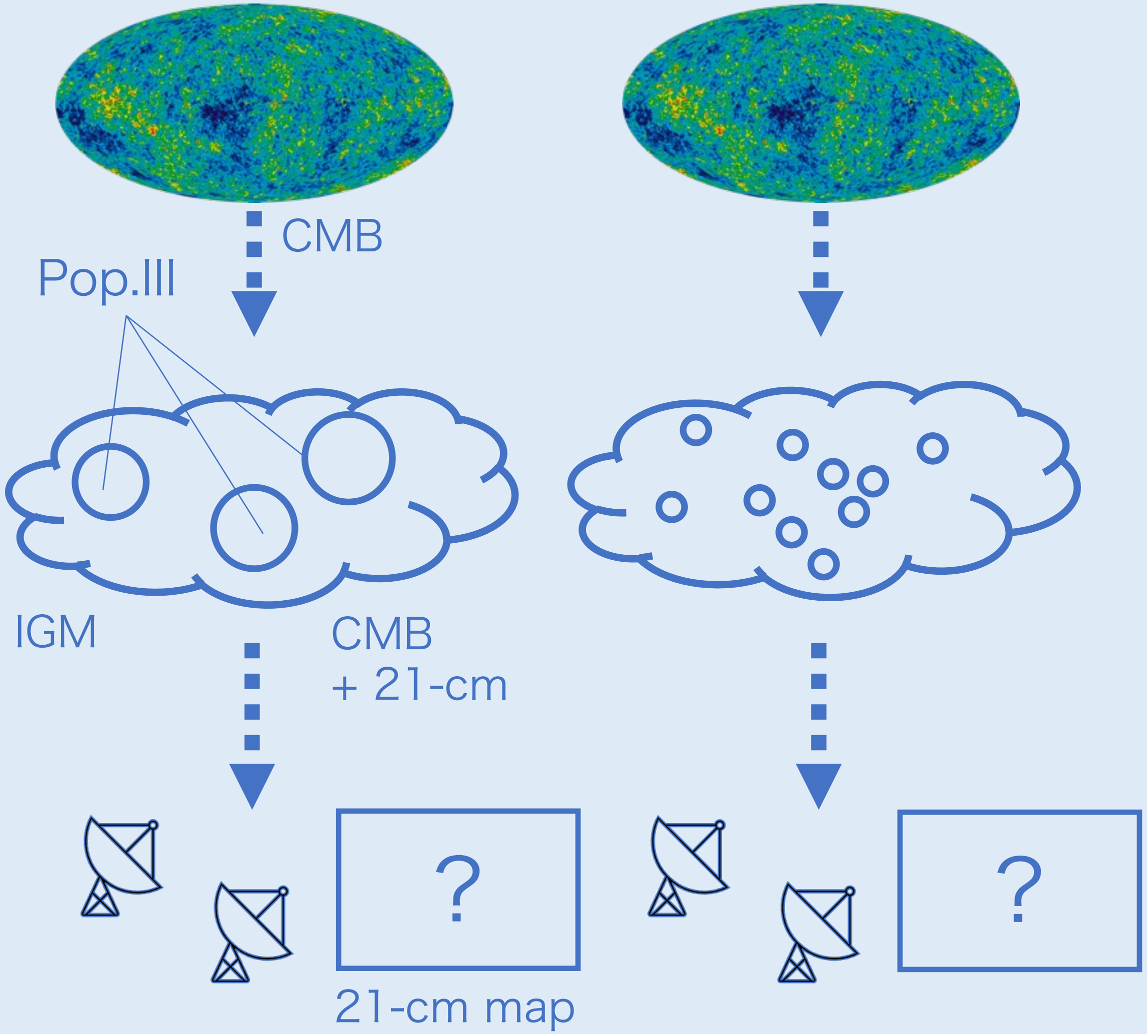
Emission region~100 kpc

Absorption region ~ several 100 kpc

Resolution of the simulation=1Mpc

Motivation

- M_S:Mass of single star and
  f_*: Stellar baryon fraction
  simulate the 21cm signal intensity map
- Analyze global signal and power spectrum
- Find the signature reflects the parameters



>>> In near future, compare with observations and determine the mass and abundance of first stars!

Simulation flow

Base software: 21cmFAST
(Messinger, Furlanetto, and Cen 2010)

1. Generate density fluctuation $\delta(\boldsymbol{x}, z_{int}), v(\boldsymbol{x}, z_{int})$
2. Make the fluctuation $\delta(\boldsymbol{x}, z)$ grow up
3. Estimate the stellar fraction in each grid
4. Calculate $x_e, T_{gas}, x_C, x_\alpha, T_S$
5. Calculate brightness temperature $\delta T_b(\boldsymbol{x}, z)$

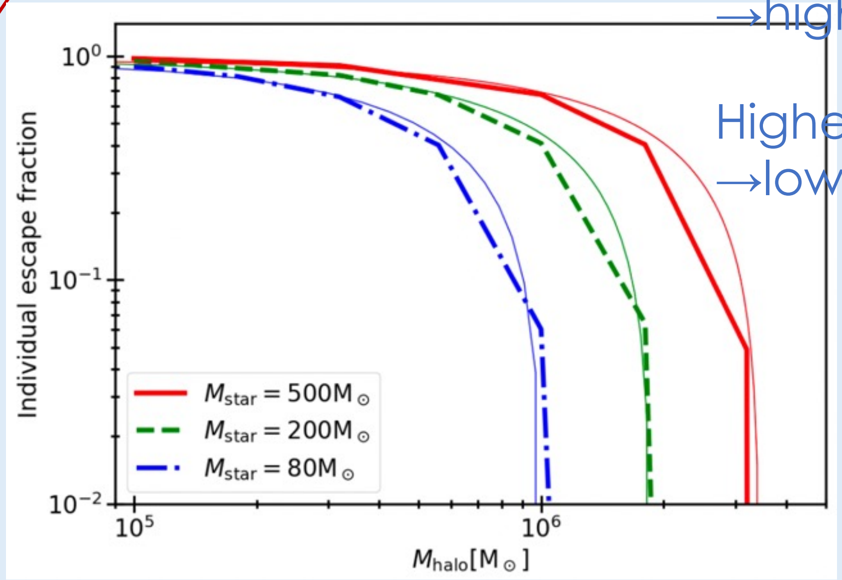
$$= 27\ \mathrm{mK} \times (1 - x_e)(1 + \delta)\left(\frac{1+z}{20}\right)^{1/2}\left(\frac{T_S - T_{CMB}}{T_S}\right)$$

Take first stars into account as ionizing & heating source

1. Single star mass dependence of ionizing photon escape fraction
2. UV heating in small-scale

<u>higher single star mass</u>
→higher escape fraction

Higher host halo mass
→lower escape fraction



(Tanaka+ 2018)

Setting

- Range and resolution
  - Grid size: $(1\ \mathrm{Mpc})^3$. Box size: $(256\ \mathrm{Mpc})^{\mathbf{3}}$
  - $z = 60 \sim z = 18$
- Assumption
  - Without other species (pop.II, galaxy, etc.)
  - All first stars have same stellar mass
- Parameters
  - $M_S = 500, 200, 80\ [M_\odot]$
  - $f_* = 0.001, 0.01, 0.1$

Result: 21-cm Power spectrum

Upper: $Ms = 500\ M_{\odot},\ \ f_* = 0.001, 0.01, 0.1$

Higher stellar baryon fraction deepen the absorption.

Lyman α dominant → T_S and T_{gas} strongly coupled

→ In this epoch, $T_{CMB} > T_{gas}$, absorption

Bottom: $f_* = 0.01$, $M_S = 500, 200, 80\ [M_{\odot}]$

Higher single star mass weaken the absorption.

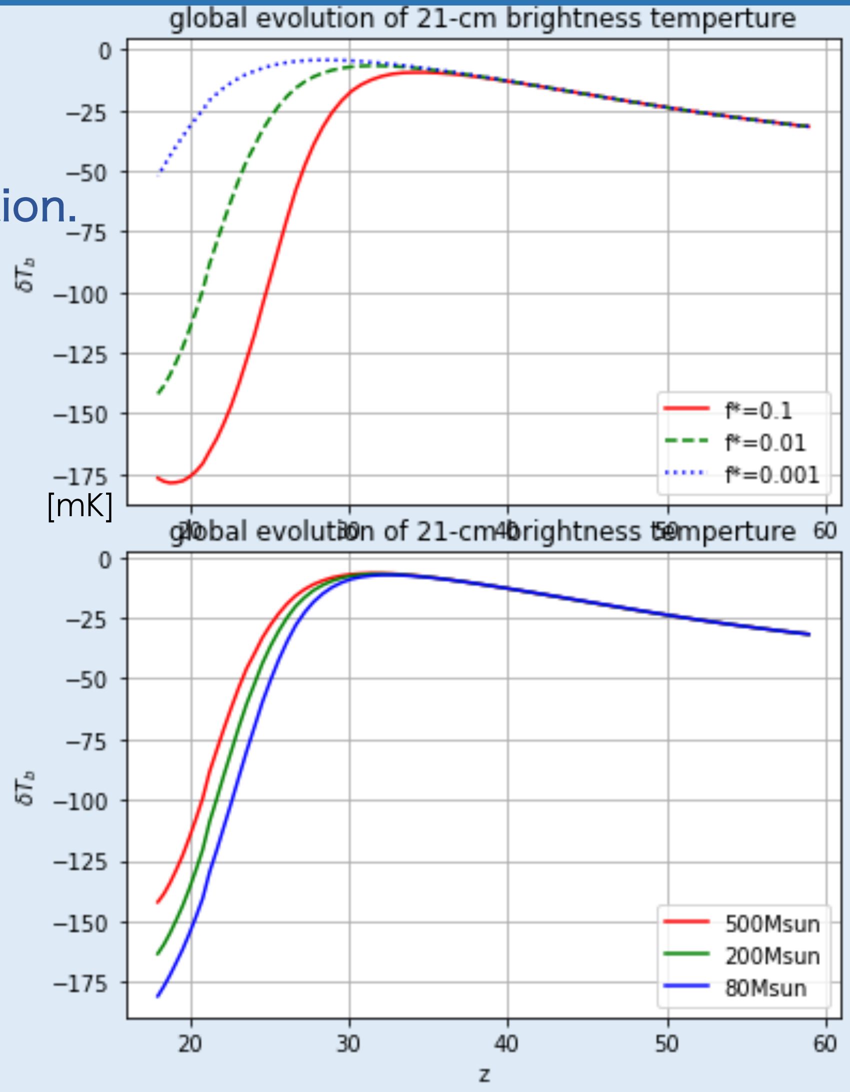
f_{esc} high →Ionizing photon high

→ gas temperature increases by UV heating

→absorption weaken

f_*, M_S both change the depth of the absorption in GS

So they may degenerate for GS observation



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

Result: 21-cm Power spectrum

Blue: absorption
Red: emission
white: ionized
or coupled with CMB

$Ms = 200\ M_\odot$ fixed, $f_* = 0.001, 0.01, 0.1$

<u>Higher f*, weaken the large-scale correlation.</u>

Large-scale correlation of 21cm, are made by fluctuation of Lyman alpha flux.

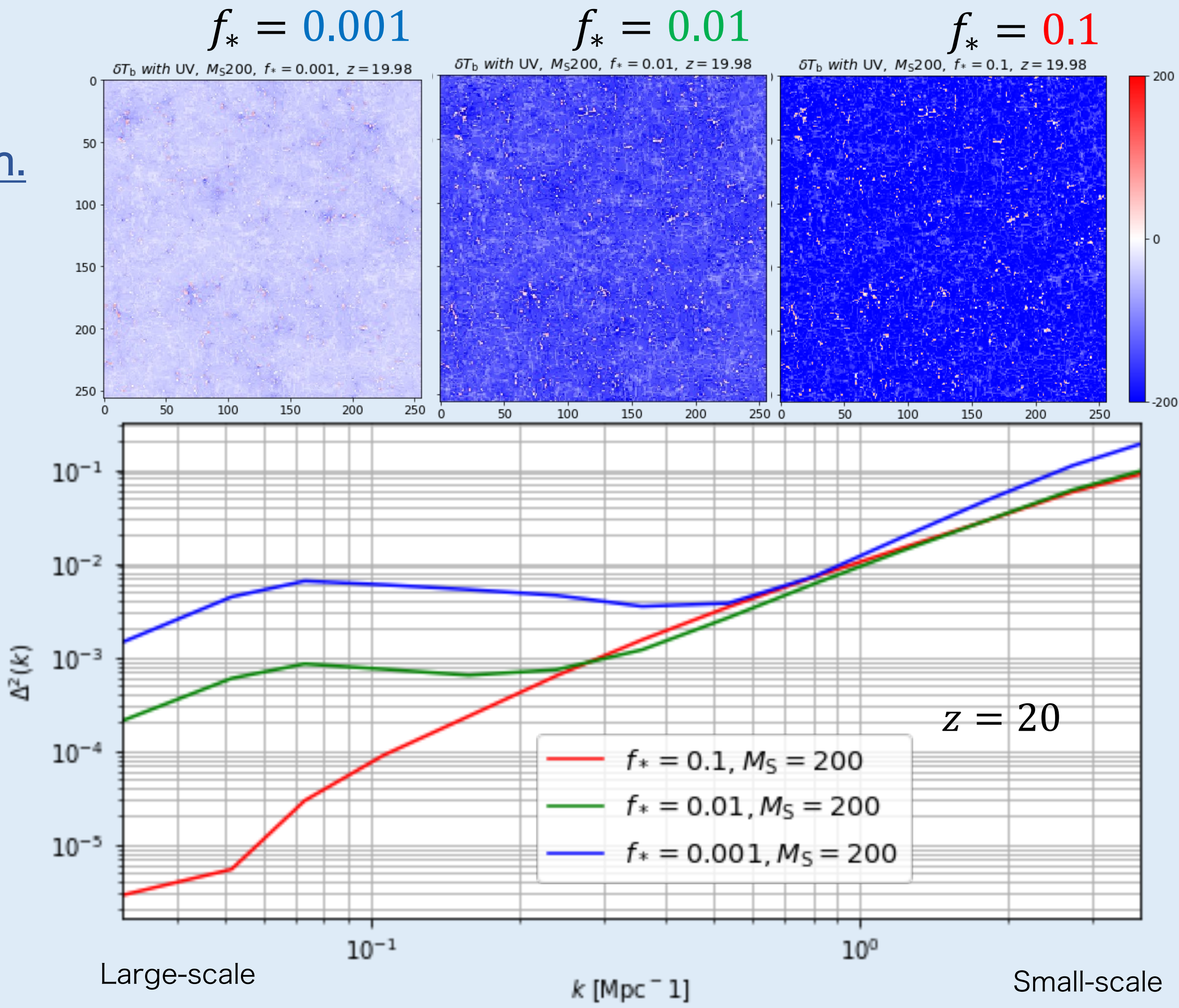
→under sufficient star forming,

Lyman α coupling saturates and the fluctuation fade,

T_S reaches T_{gas} in entire region.

→Large-scale correlation decreases.

$$T_S^{-1} = \frac{T_{CMB}^{-1} + (x_c + x_\alpha) T_{gas}^{-1}}{1 + x_C + x_\alpha}$$



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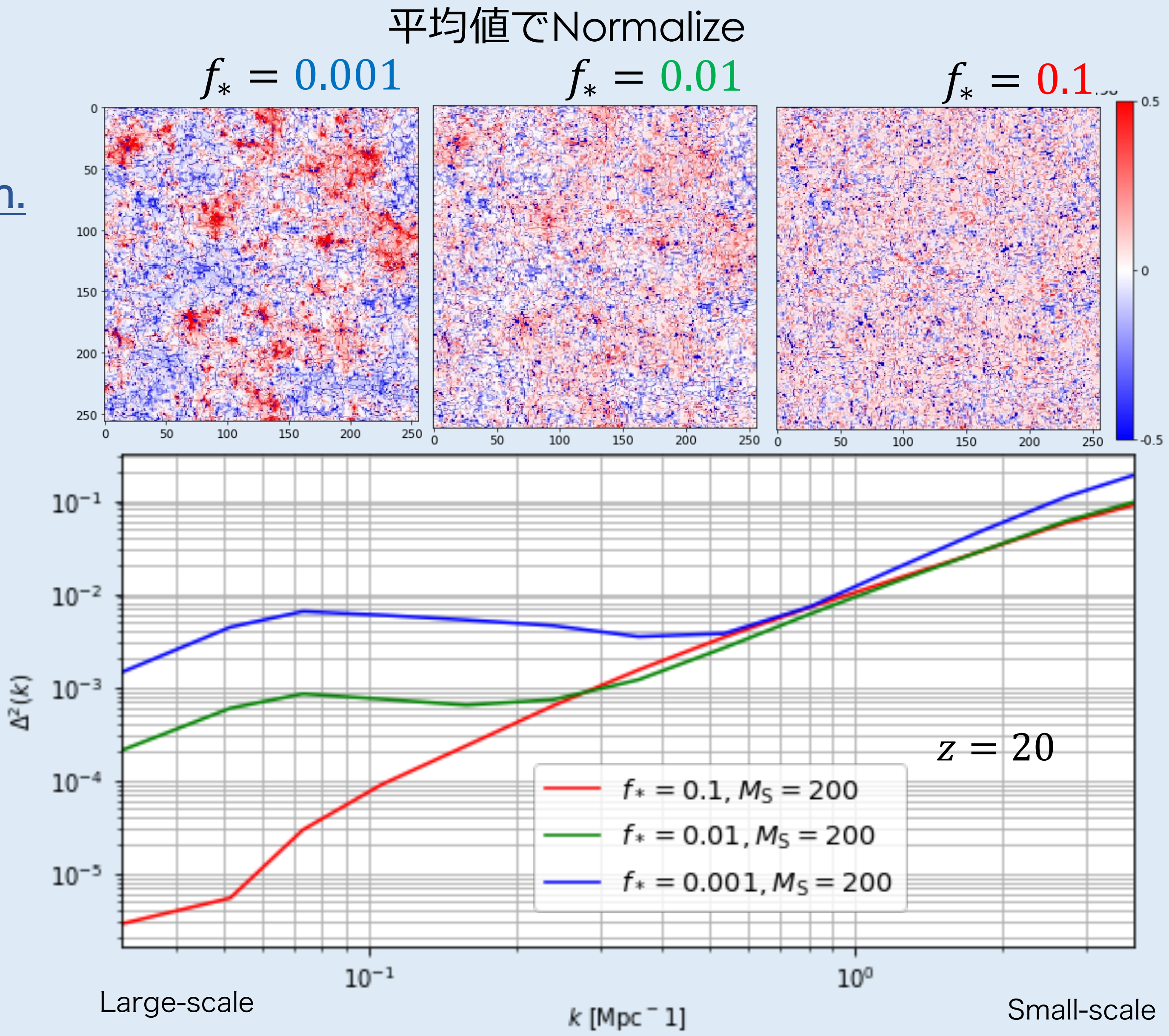

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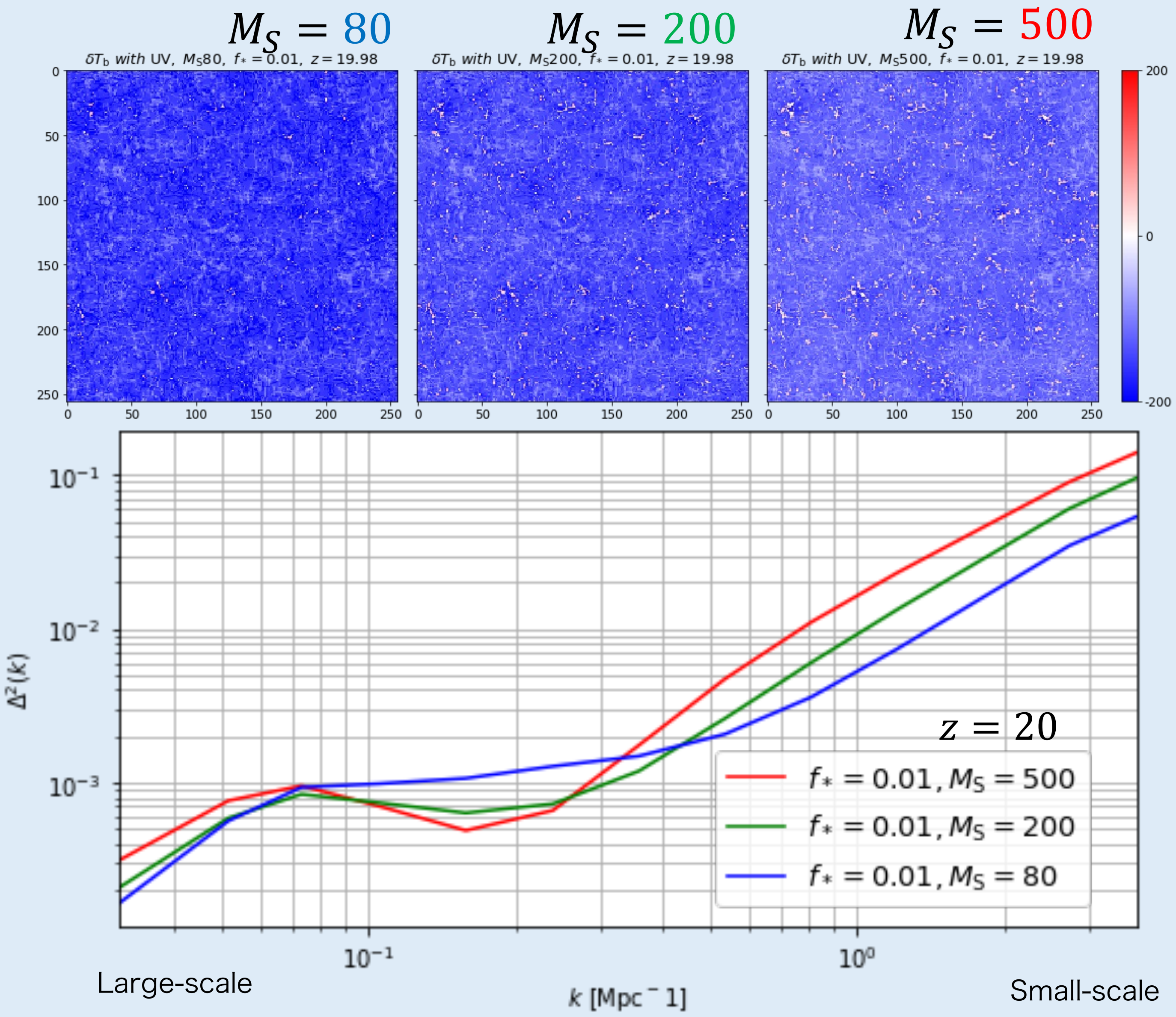
More massive single star mass, strengthen small-scale correlation.

Small-scale structure of 21-cm signal consist of ionized & heated region.
→massive star more ionize and heat the IGM for their higher escape fraction.

Conclusion

Single star mass Ms & stellar baryon fraction affect 21-cm signal different scales.

→Observing the 21-cm PS,
we maybe able to constrain both parameters.



Summary

- Simulate 21-cm signal map and its statistics
  changing Single star mass M_s Stellar baryon fraction f_*
- Newly, Introduce the effects of
  1. M_s dependence of ionizing photon escape fraction
  2. UV heating in small-scale
- Global signal
  Both M_s *and* f_* affect the depth of the absorption, these parameters can degenerate.
- Power spectrum
  M_s *and* f_* affect small and large scale respectively,
  we maybe able to distinguish the effects.
- Future prospects
  - Decomposition 21-cm PS with other PS(ionized fraction, coupling coefficient etc.) and estimate its contributions.
  - Construct more realistic model including other species.