3D RT calculation on Escape of ionizing photons from forming galaxies

★Hidenobu Yajima（University of Tsukuba）
M. Umemura(Univ. of Tsukuba), M. Mori（Univ. of Tsukuba）
T. Nakamoto（Tokyo Institute of Technology）

Outline

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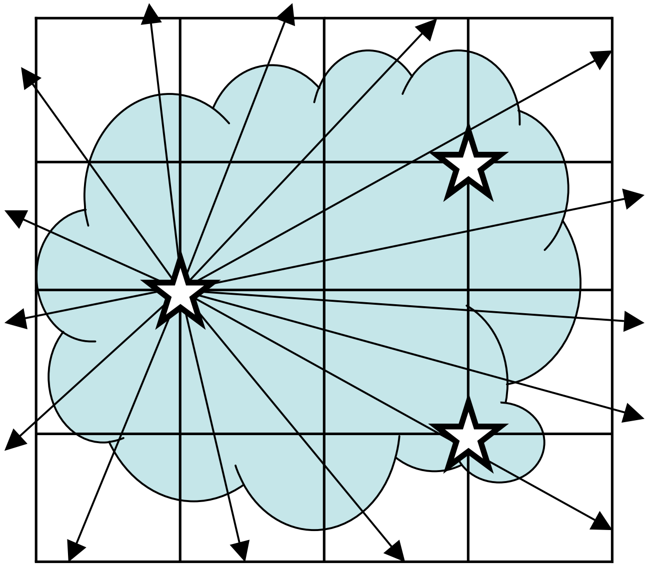
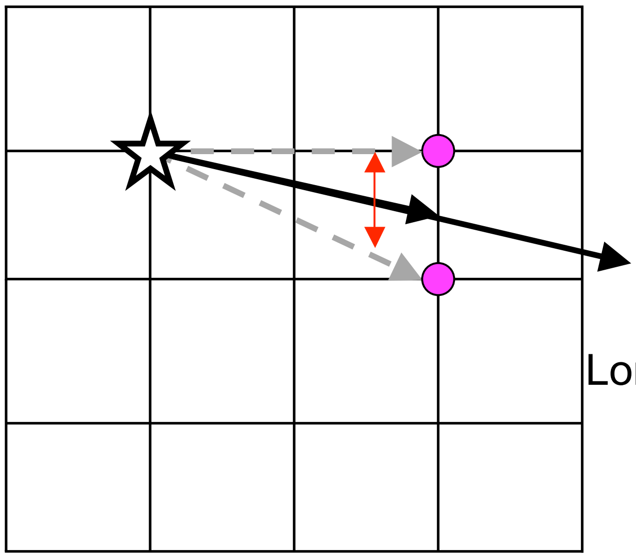
  - Our scheme (Authentic Ray Tracing method)
  - Cosmic reionization, Escape fraction
  - Previous works
- Model&Method
- Results
  - Ionization structure
  - Escape fraction
- Discussion
  - Can LAEs and LBGs ionize IGM at z=3~7 ?
- Summary

ART method





Authentic Ray Tracing Method

ART-type 1 (point source version)

(type2→Chizuru's talk!)

●Radiation meshes are arranged radially from each sources independently of fluid meshes.

●The radiation field on fluid meshes are estimated by interpolating from near radiation meshes.

●The order of calculation amount

$$N_{source} \times N_{\theta} \times N_{\phi} \times N_{path}$$

Long characteristic method: $N_{source} \times N_x \times N_y \times N_z \times N_{path}$

Basic equation: $$\frac{dI_\nu}{ds} = -\alpha_{\rm abs} I_\nu + \varepsilon_\nu$$

Test calculation

▪Stromgren sphere

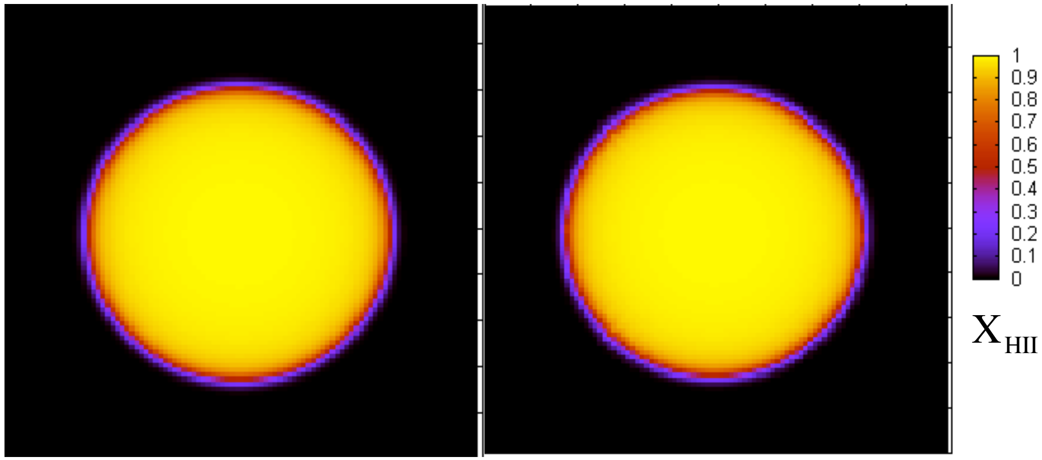
Hydrogen only

Uniform density → $n_{HI} = 1\ /cm^3$

Uniform temperature → $T = 10^4$ K

luminosity ： 6.9×10^{45} photon/s

SED：Black body (10^5K)

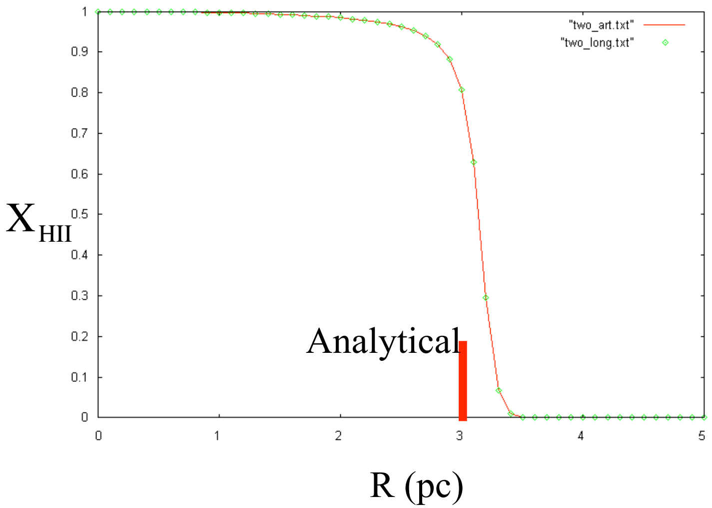


(Long) (ART)

Analytical solution

$$N_\gamma = \frac{4}{3}\pi\alpha_B n_H^2 r_s^3$$

$$r_s \cong 3.0\text{pc}$$



Test calculation

▪Effect of dust in HII region

Hydrogen + dust(dust-to-gas ratio = 0.01)

Uniform density → n_{HI}= 1 /cm^3

Uniform temperature → T = 10^4 K

luminosity : 5.5×10^{53} photon/s

SED : Black body (10^5K)

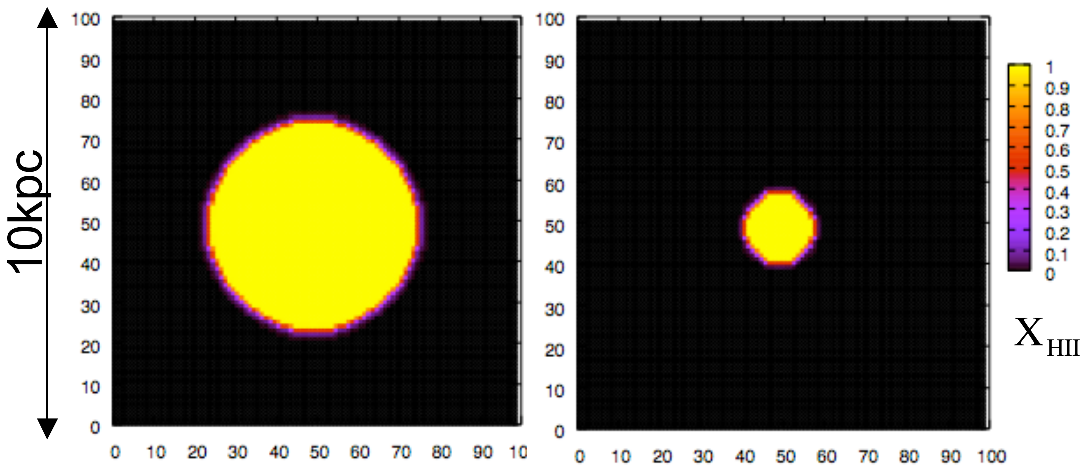
Analytical estimation
(Spitzer1977)

$$r_s \cong 2.6\mathrm{kpc}$$

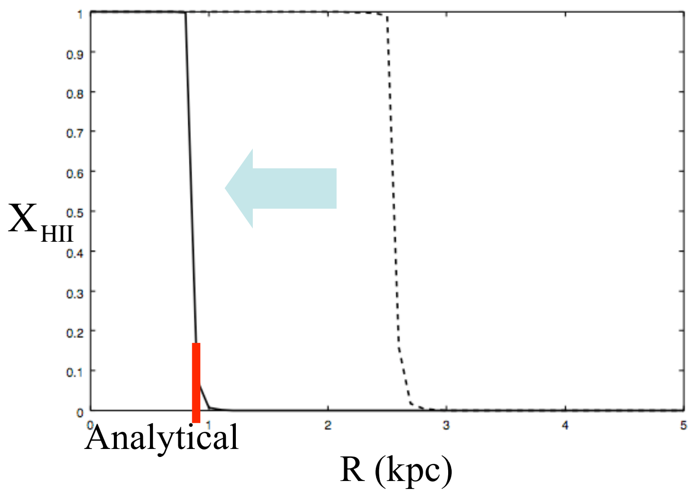
$$\tau_{sd} = 10$$

$$y = \frac{r_i}{r_s} = 0.37$$

$$r_i = 0.95\mathrm{kpc}$$



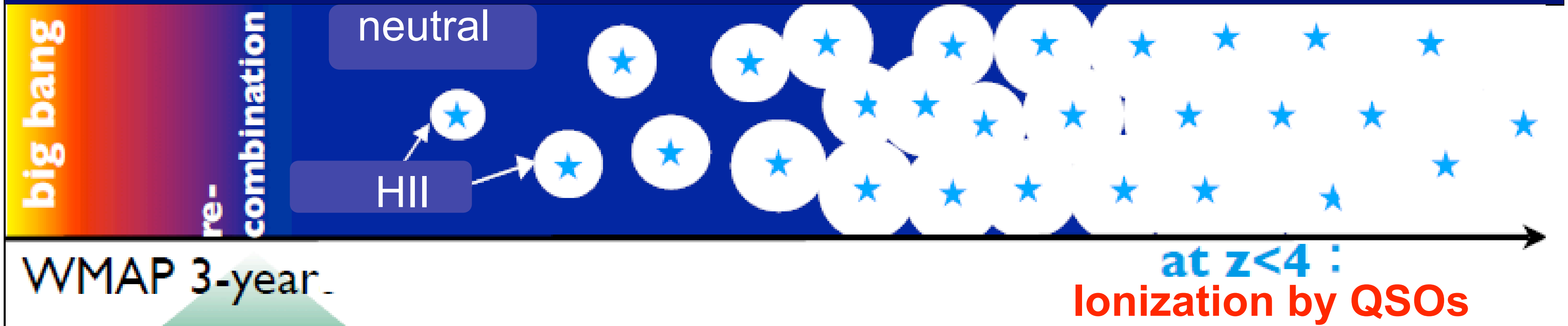
H only H+dust



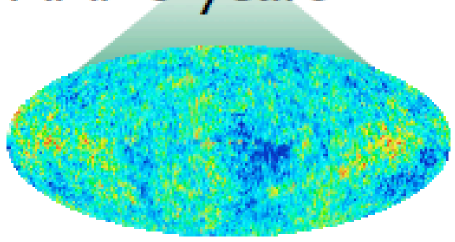
y~0.35

Application
to
ionization structure in forming galaxies

Cosmic Reionization



WMAP 3-year



$$\tau_e(z) = \int_0^z \sigma_T n_e(z') c \left| \frac{dt}{dz'} \right| dz'$$

Thomson scattering optical depth

$$\tau_e = 0.093 \pm 0.029$$

(Spergel et al. 2006)

reionization redshift

$$z_r = 10.9^{+2.7}_{-2.3}$$

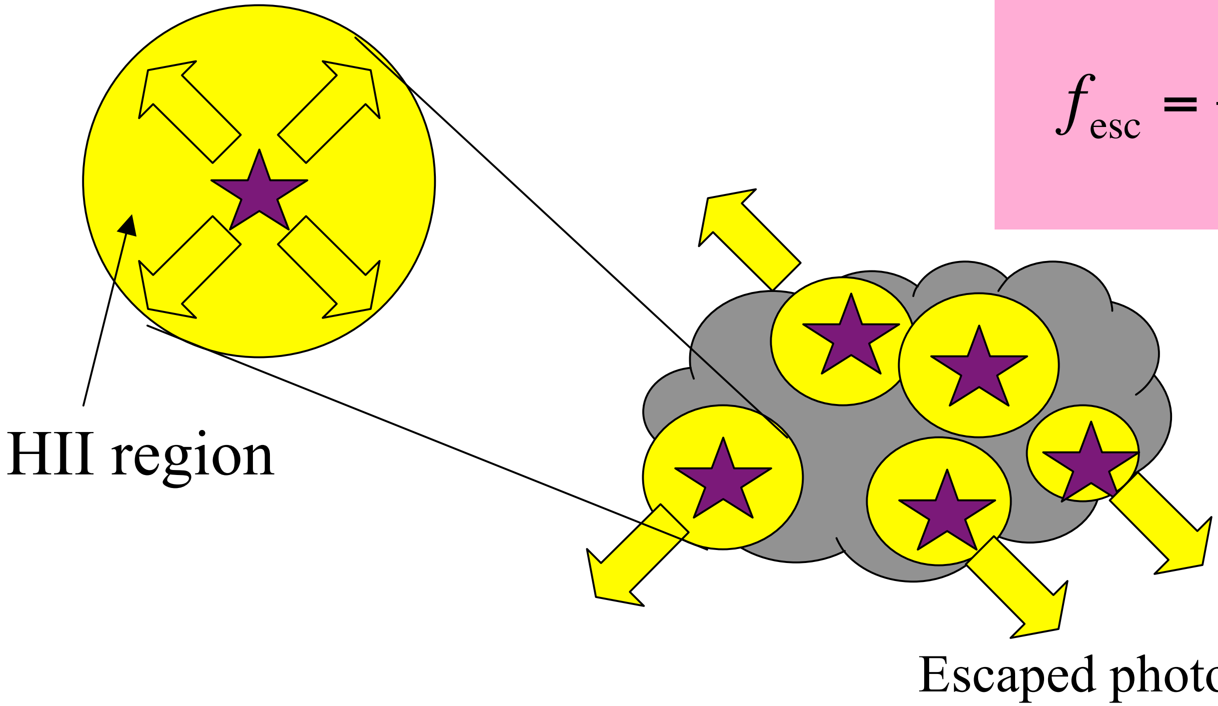
<u>What are the ionizing sources at z>4?</u>

The major candidates of ionizing sources are Lyman alpha emitters(**LAEs**) and Lyman break galaxies(**LBGs**).

Escape fraction

Escape fraction(f_{esc}) ･･･ The ratio of photon number escaped from a galaxy to photon number radiated by stars.

$$f_{\mathrm{esc}} = \frac{N^{\gamma}_{\mathrm{int}} - N^{\gamma}_{\mathrm{abs,HI}} - N^{\gamma}_{\mathrm{abs,DUST}}}{N^{\gamma}_{\mathrm{int}}}$$



The escape fraction of ionizing photons can control the UV background intensity and hence has a close relation to the cosmic reionization process.

Previous works(Observation)

There are some observational estimations of escape fraction at z~3.

(Steidel et al. 2001)	$f_{\mathrm{esc}} \sim 60\%$	(stack data)
(Giallongo et al. 2002)	$f_{\mathrm{esc}} \leq 5\%$	(no detection → upper limit)
(Inoue et al. 2005)	$f_{\mathrm{esc}} \leq 38\%$	(no detection → upper limit)
(Shapley et al. 2006)	$f_{\mathrm{esc}} \sim 14\%$	(2 object)
(Iwata et al. 2008)	$f_{\mathrm{esc}} \geq 15\%$	(16 object)

However detected young galaxies with ionizing photons are few.
(Shapley et al. 2006, Iwata et al. 2008)

⇨ **The typical value of escape fraction of high-z galaxis has not been understood yet.**

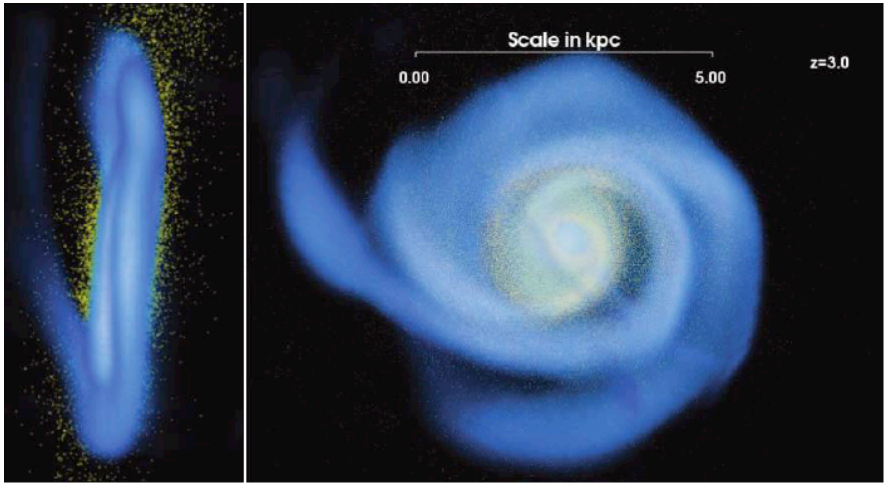
Previous works(Simulation)&Objective

Previous works(simulation)

Gnedin et al. 2008

$$\longrightarrow f_{esc} \leq 3\%$$

Their model galaxies are disk galaxies (see also Lazoumov et al. 2006, 2007).



	Disk	Irregular
f_{esc}	~3%	?

LAEs and LBGs may be irregular galaxies(Mori&Umemura2006).

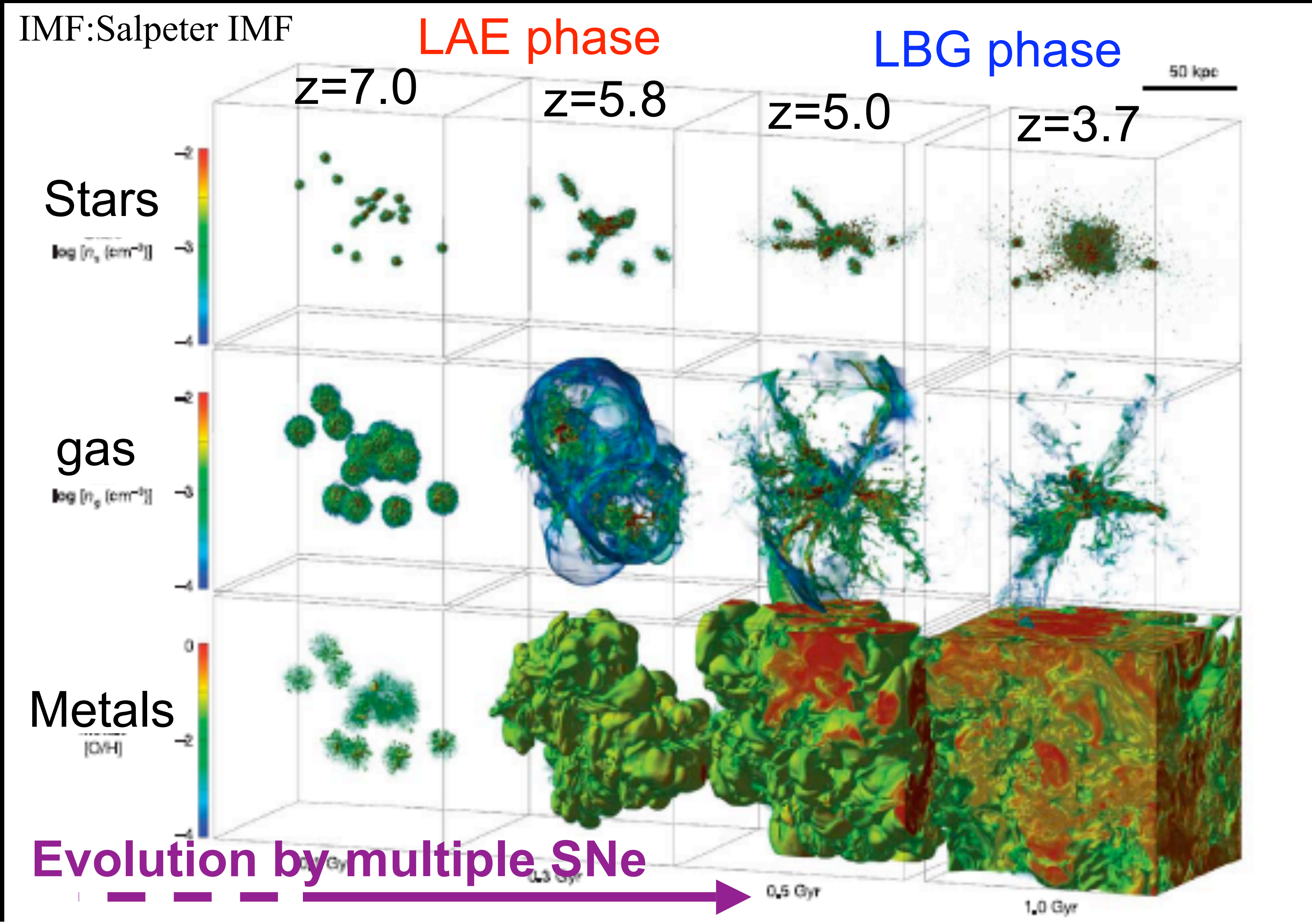
Our objective

We calculate the escape fraction to LAEs and LBGs with precise radiation transfer calculation.

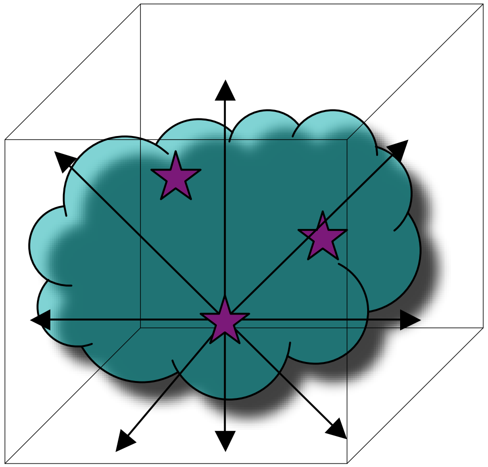
Model galaxy

$M_{DM}=10^{11}M_{sun}$

(Mori&Umemura2006)



Method



The calculation box is composed of 128^3 cells.

The number of angular bins is 128^2 per source.

$$f_{\rm esc} = \frac{N^{\gamma}_{\rm esc}}{N^{\gamma}_{\rm intrinsic}}$$

- Dust distribution

$$m_{\rm dust} = f_{\rm dust} \frac{Z}{Z_{\rm sun}} m_{\rm H}$$

Radiative transfer equation

$$\frac{dI_{\nu}}{ds} = -(\alpha_{\rm abs,HI} + \alpha_{\rm abs,DUST}) I_{\nu}$$

I_{ν} : intensity

$\alpha_{\rm abs}$: absorption cofficient

ε_{ν} : emissivity

Equation of ionization degree in equilibrium state.

$$0 = \Gamma^{\gamma} \cdot n_{\rm HI} + \Gamma^{\rm C} \cdot n_{\rm e} \cdot n_{\rm HI} - \alpha_{\rm rec} \cdot n_{\rm e} \cdot n_{\rm HII}$$

Γ^{γ} : photo ionization ratio , $\Gamma^{\rm C}$: collisional ionization ratio

$n_{\rm HI}$: number density of hydrogen, $n_{\rm e}$: number density of electron

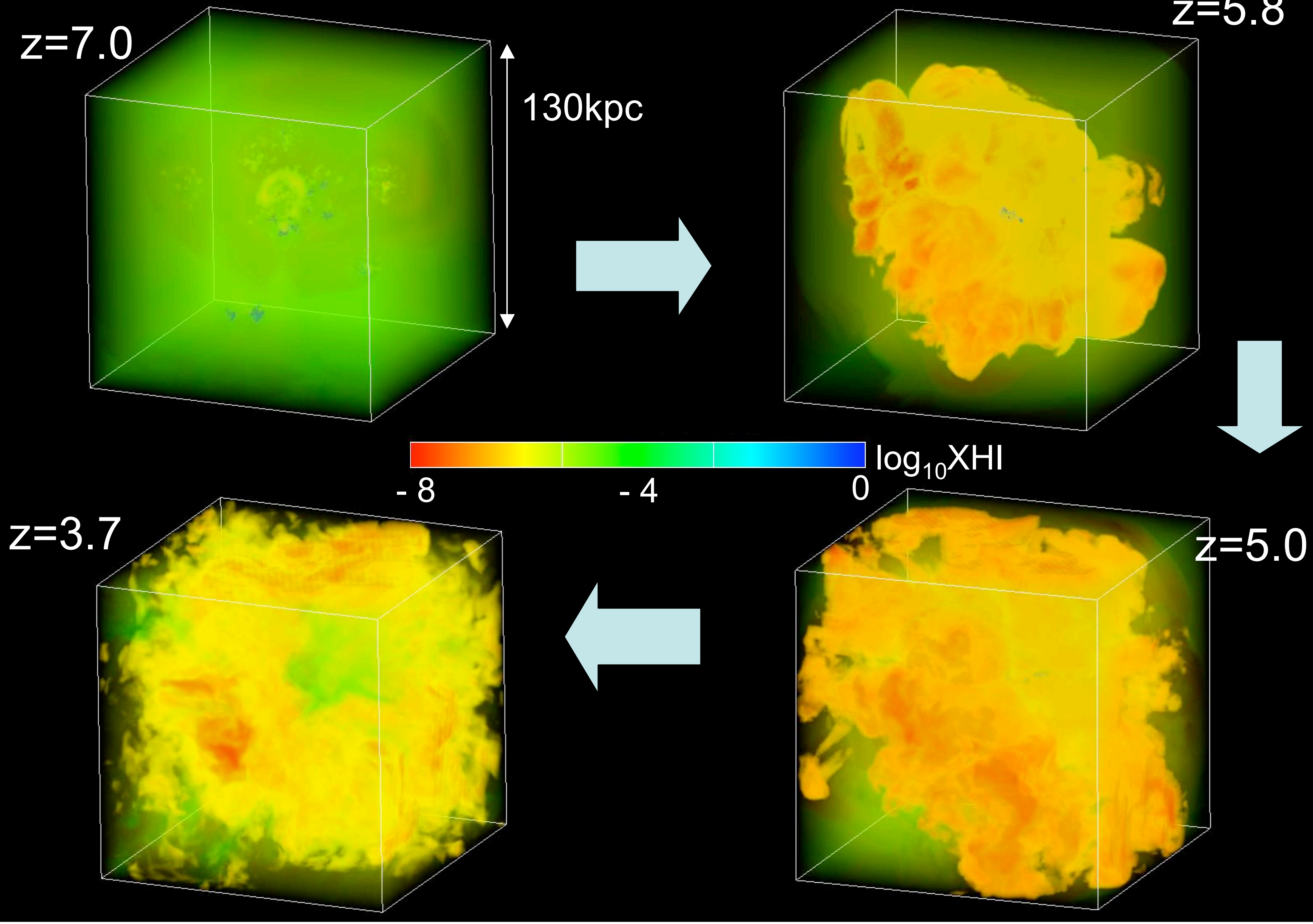
$\alpha_{\rm rec}$: recombination cofficient(caseB)

- Calculation scheme

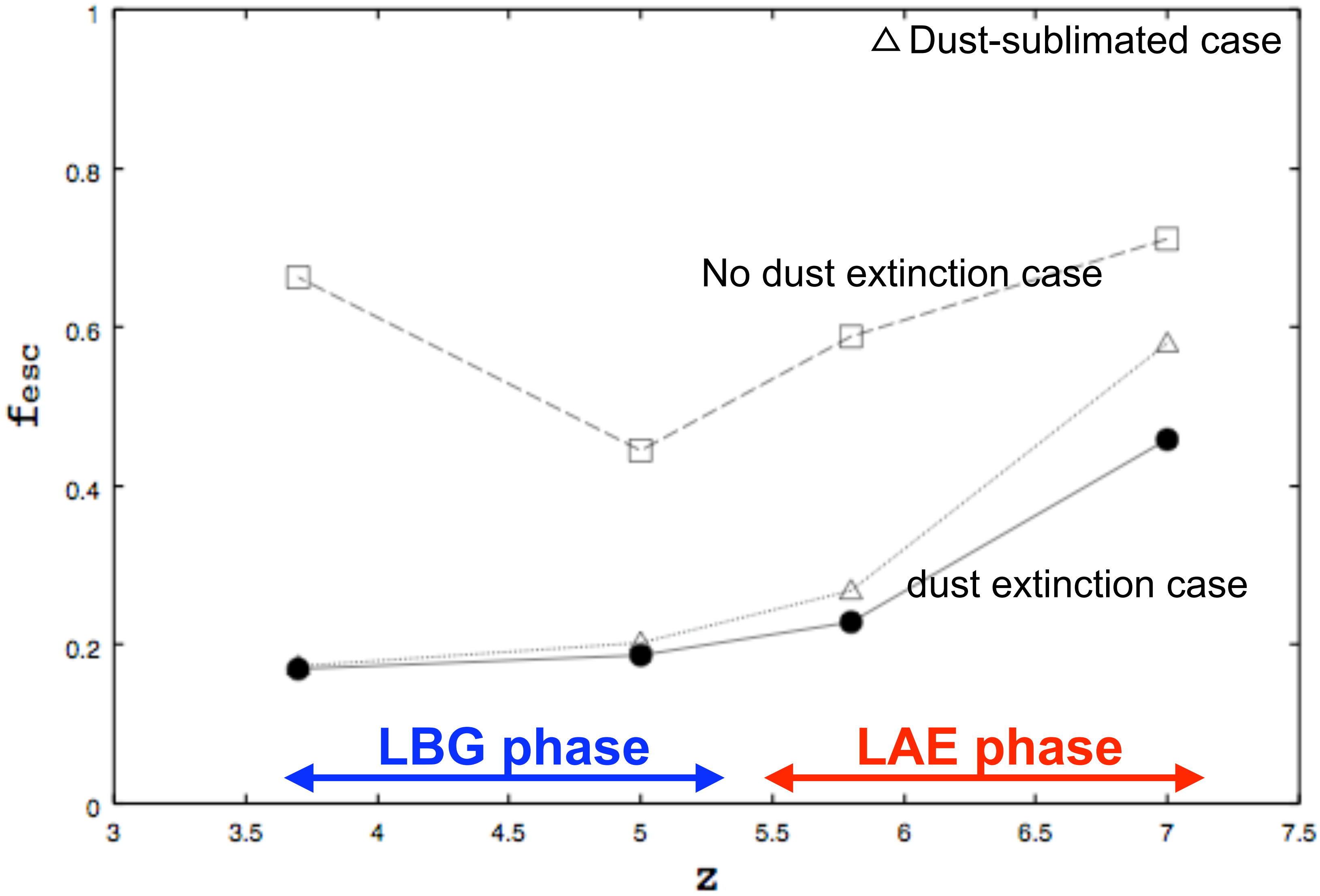
:ART method
(Nakamoto et al. 2001, Iliev et al. 2006)

- on-the-spot approximation
(Osterbrock 1989)

Ionization Structure



Escape fraction



Are LAEs and LBGs ionizing sources ?

<u>Can LAEs and LBGs ionize IGM?</u>

① Necessary photon number to ionize the IGM

$$N_{\mathrm{ion}}(z) = (10^{51.2}\,\mathrm{s}^{-1}\mathrm{Mpc}^{-3})C_{30}\left(\frac{1+z}{6}\right)^{3}\left(\frac{\Omega_{\mathrm{b}}h_{50}^{2}}{0.08}\right)^{2}$$

(Madau et al. 1999)

(C_{30}:clumpiness factor)

VS

② Photon number radiated by LAEs and LBGs

$$N_{\mathrm{ion}}(z) = \left(10^{53.1}\,\mathrm{s}^{-1}\mathrm{Mpc}^{-3}\right) \times \underbrace{SFRD(z)}_{\text{Observation data}} \times \underbrace{f_{\mathrm{esc}}}_{\text{Our results !}}$$

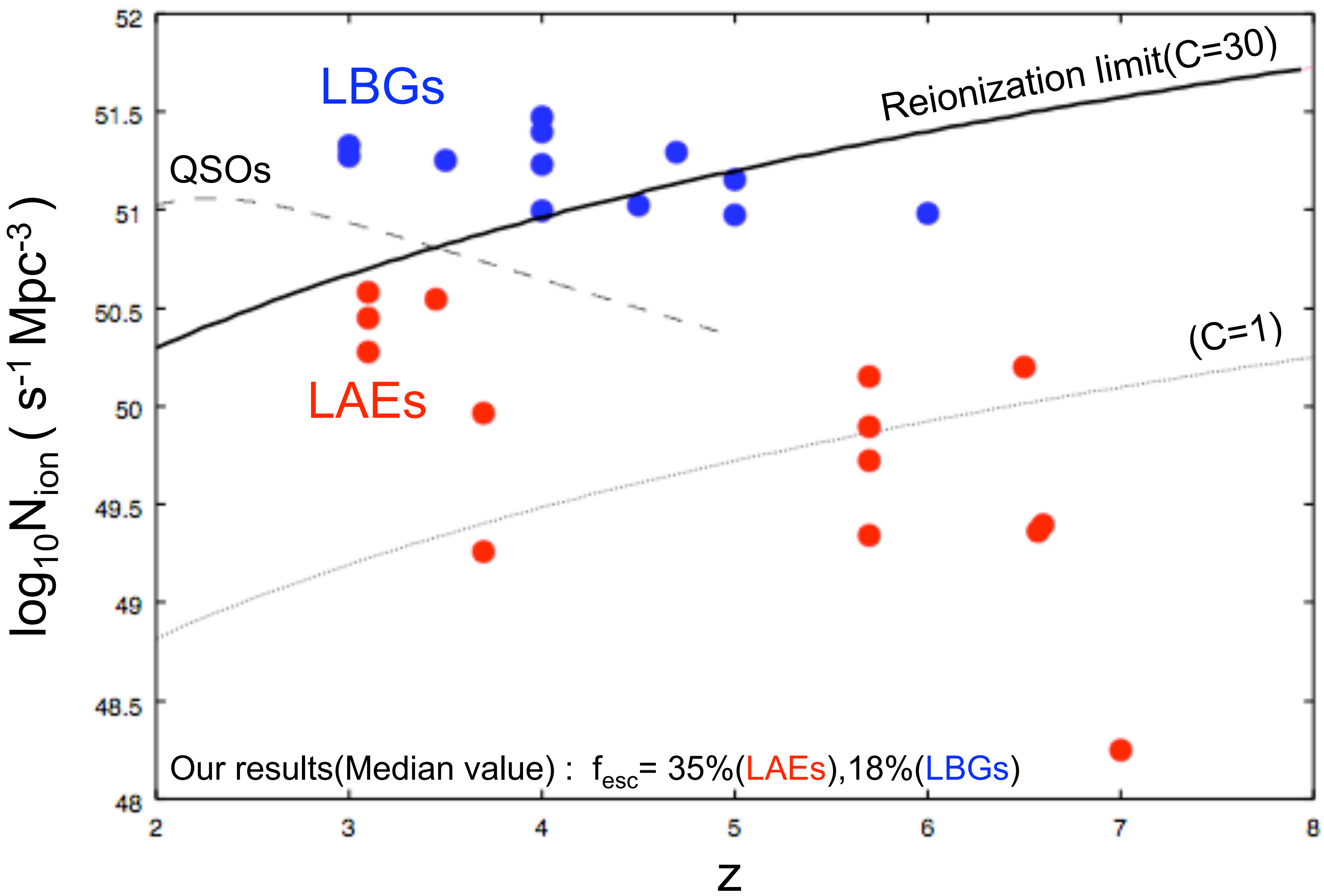
(Madau et al. 1999)

Observation data

Our results !

SFRD : star formation rate density
f_{esc} : escape fraction

Photon number radiated by LAEs and LBGs



SUMMARY

- LAEs and LBGs have a large escape fraction (17% ~ 47%). (theoretical previous works → ~3%)
- Escape fraction can largely vary by considering dust extinction.
- LBGs can ionize the IGM at z=3~5. However only LAEs and LBGs can not ionize the IGM at z≧6.

END