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Recombination in Small-scale Structures during the Epoch of Reionization

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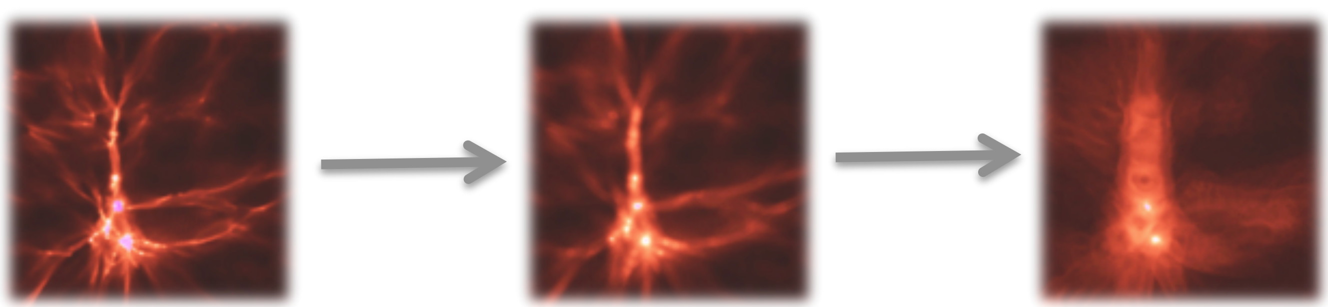


Introduction
Epoch of Reionization (EoR)

First billion years in the cosmic history that early generation of galaxies were ionizing IGM.

(1) Why care about recombination during EoR?

(2) Why care about small-scale structures?

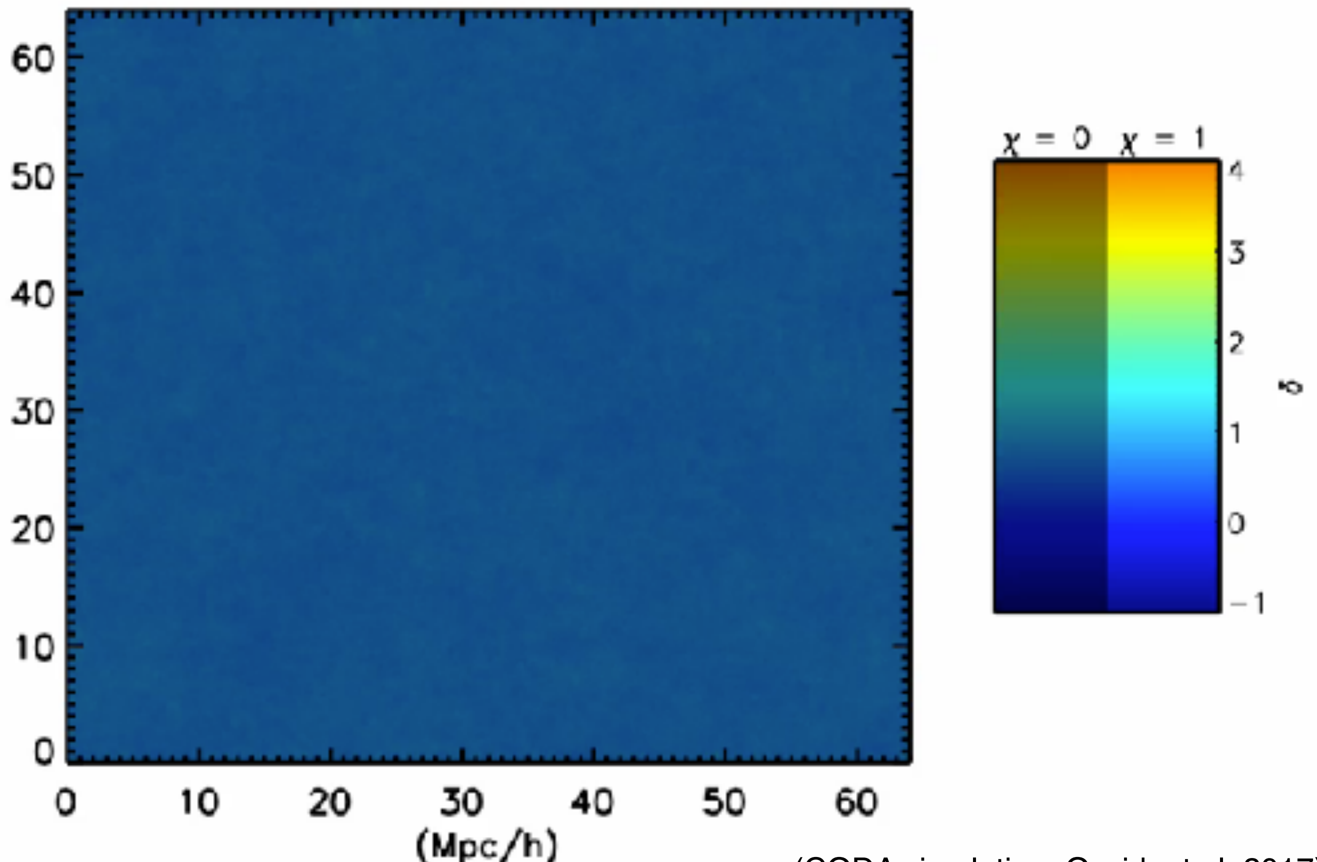
Introduction 1
Why care about recombination during reionization?

Because it is…

1) a key ingredient for reionization simulations.

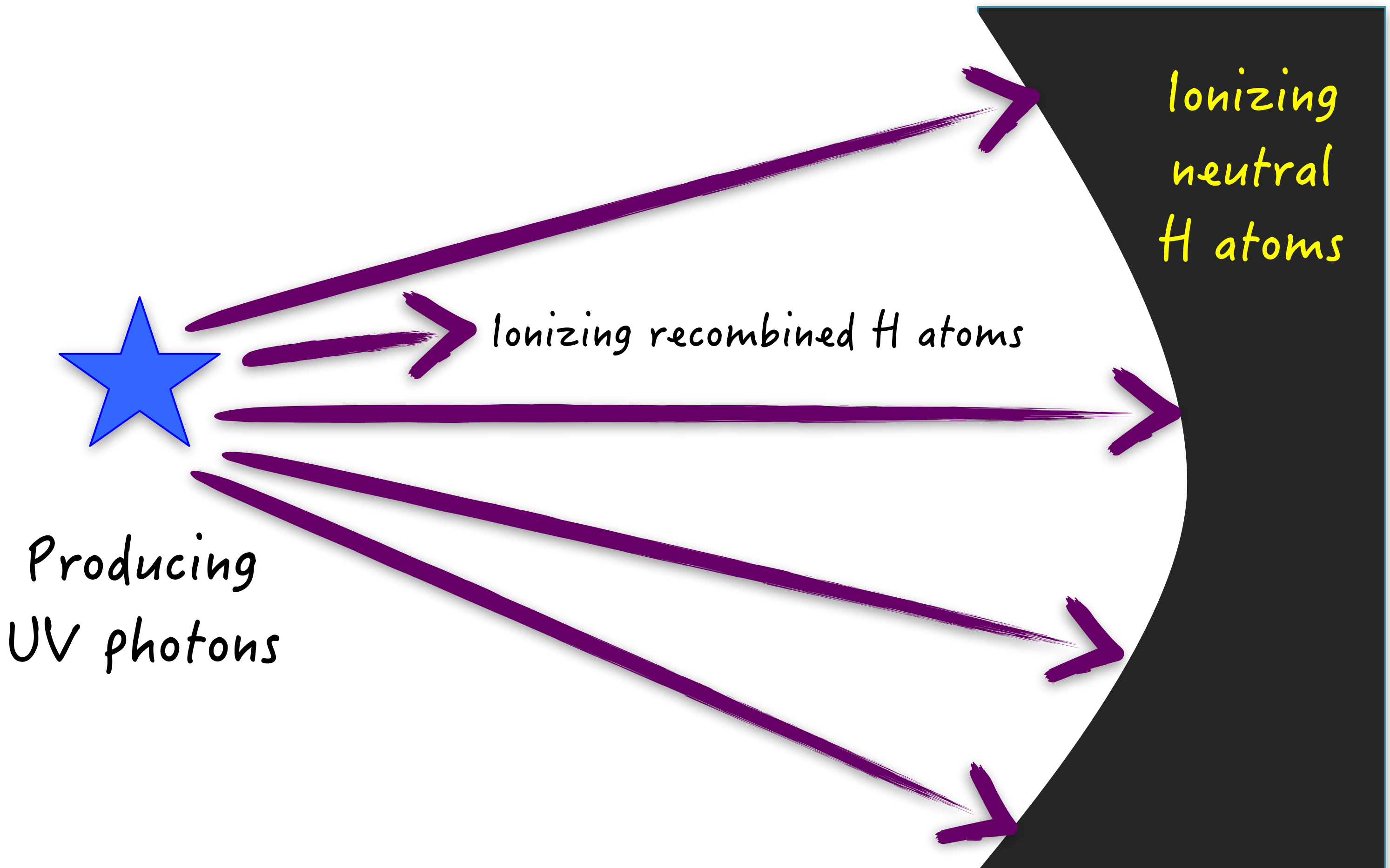
2) needed to account for the number of galaxies required to achieve reionization.

Intro 1) Recombination as an ingredient for reionization simulation



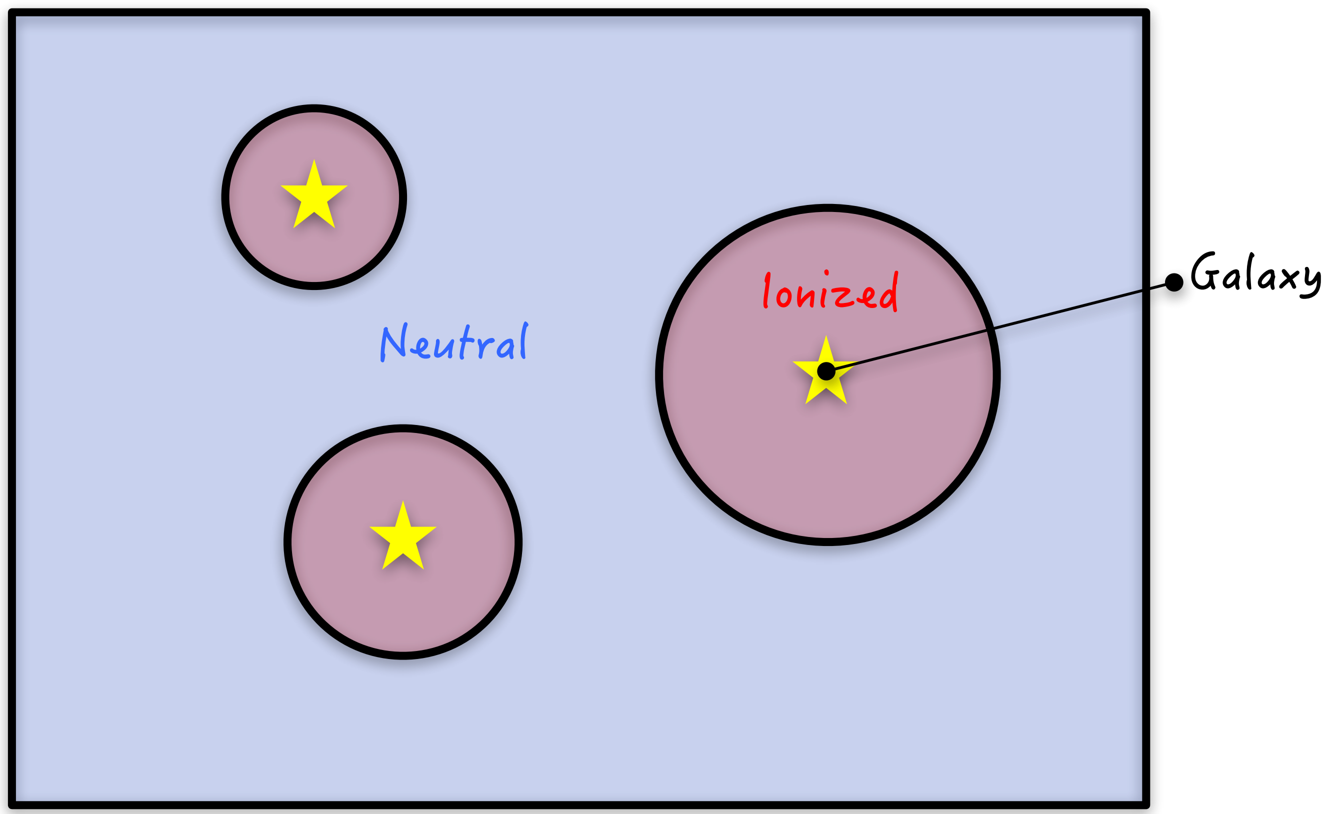
(CODA simulation; Ocvirk et al. 2017)

Intro 1) Recombination as an ingredient for reionization simulations



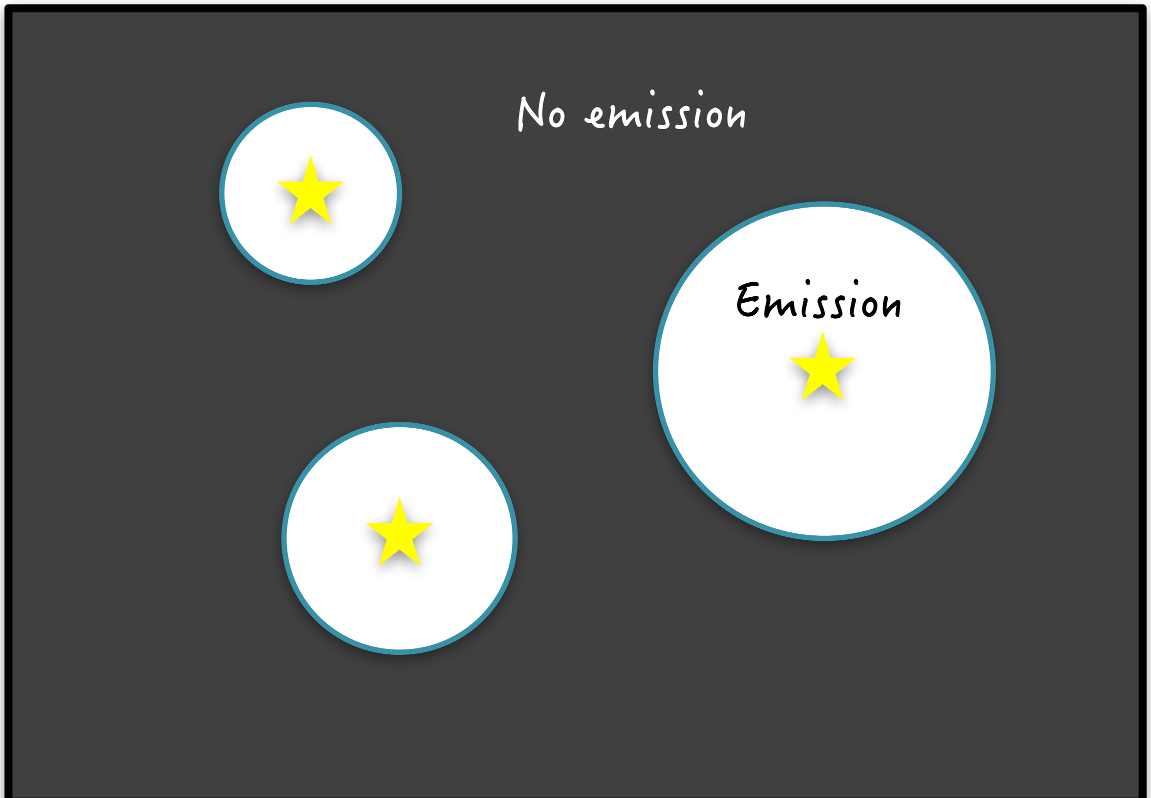
Ionizing photons are consumed to ionize
(1) H atoms in neutral region and
(2) <u>recombined H atoms in ionized region.</u>

Intro 1
Patchy Reionization



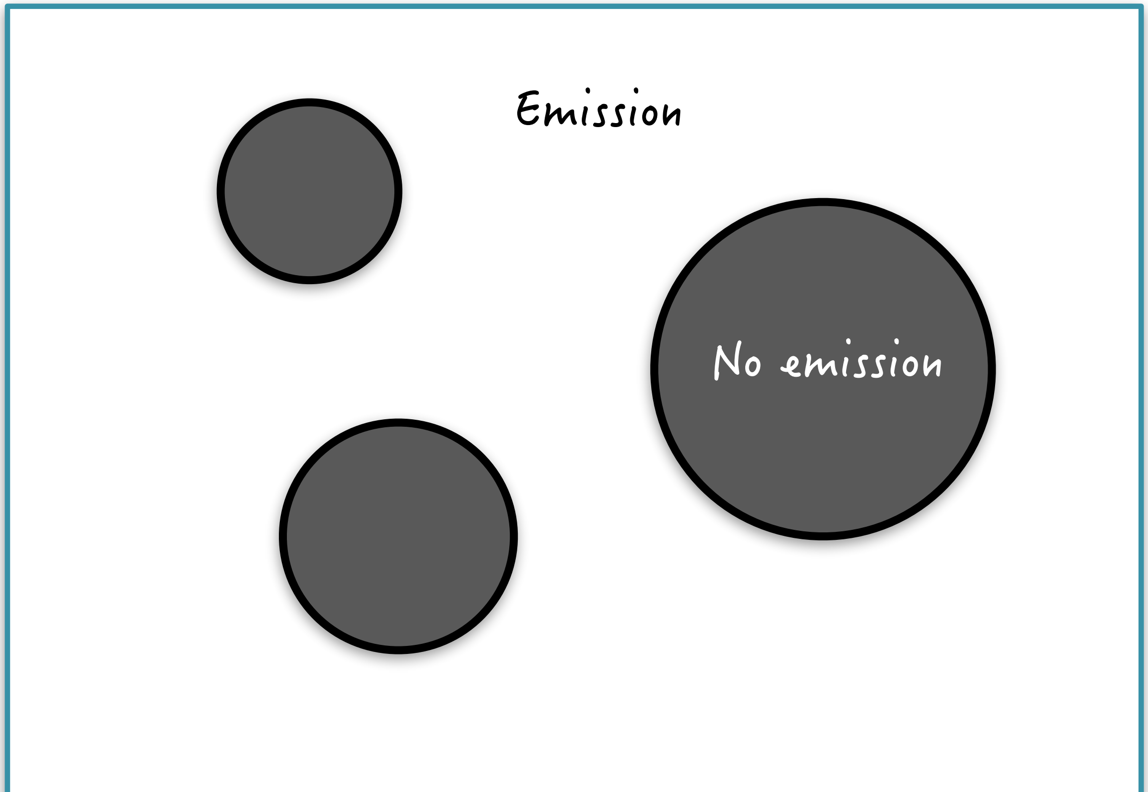
Ionization pattern of IGM provides a distinctive observational consequences

Observable of Patchy Reionization (1)
Cosmic Infrared Background



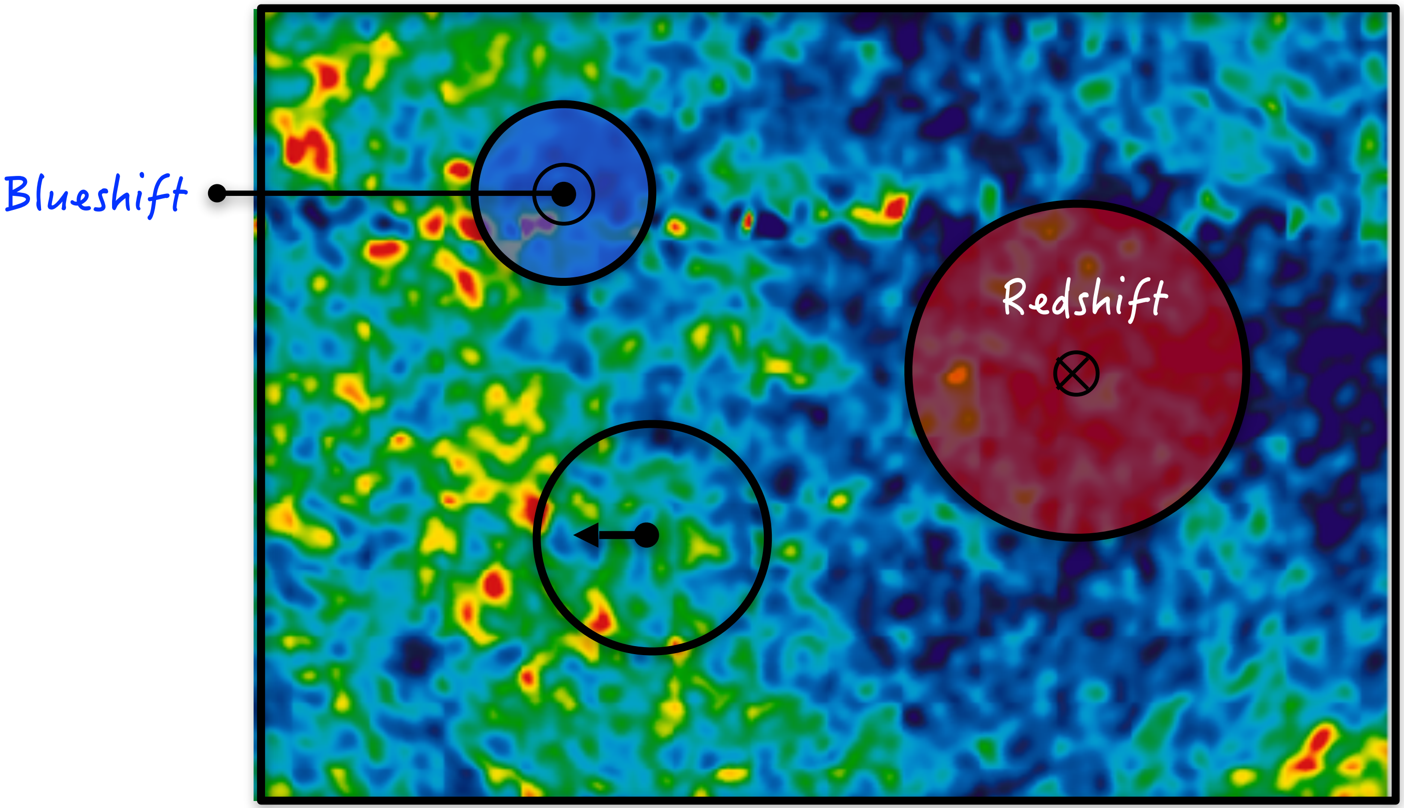
Optical light from galaxies and ionized regions is observed as a part of the infrared background in the present day universe.

Observable of Patchy Reionization (2)
21cm Background



21cm emission from neutral regions are also the main target of future radio observation.

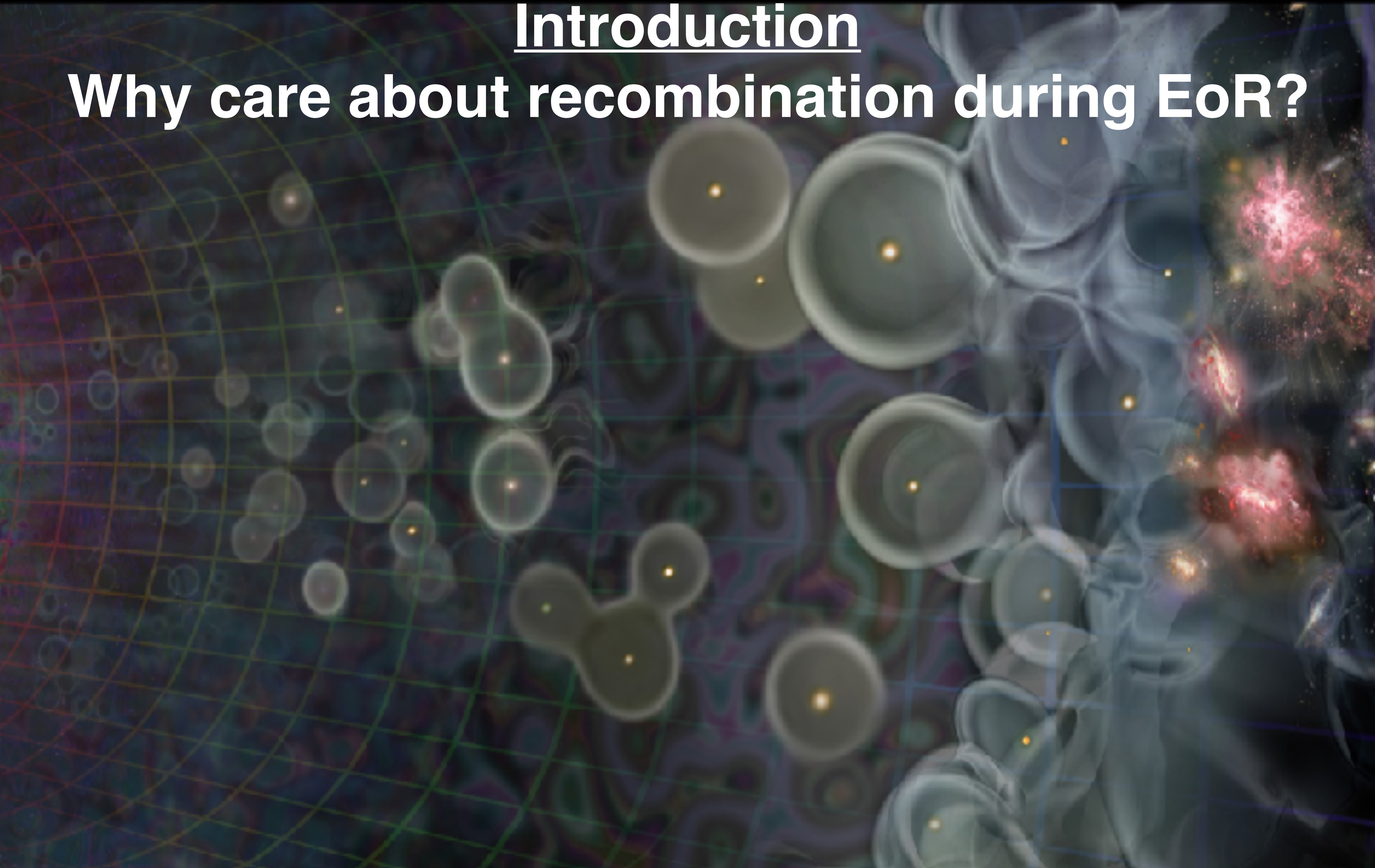
Observable of Patchy Reionization (3)
Kinetic Sunyaev-Zel'dovich Effect



Peculiar motion of ionized gas doppler shifts the CMB photons, adding to the secondary anisotropy of CMB.

Introduction

Why care about recombination during EoR?



We mostly believe star-light from galaxies have reionized the universe.

Intro 1
Ionization Photon Budget

# of UV photons produced

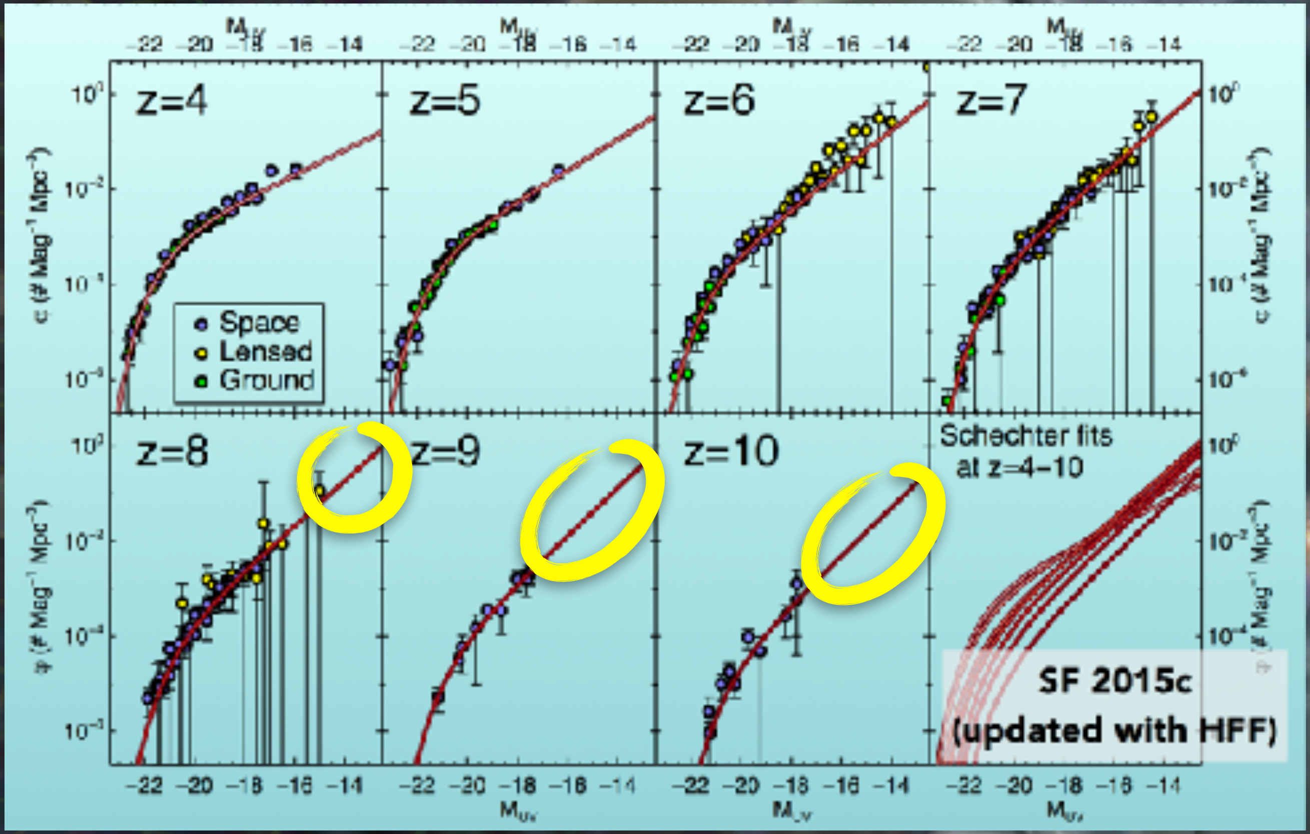
>

# of UV photons Needed

?

In order to confirm that, we need to account for the UV photons that ionized the universe.

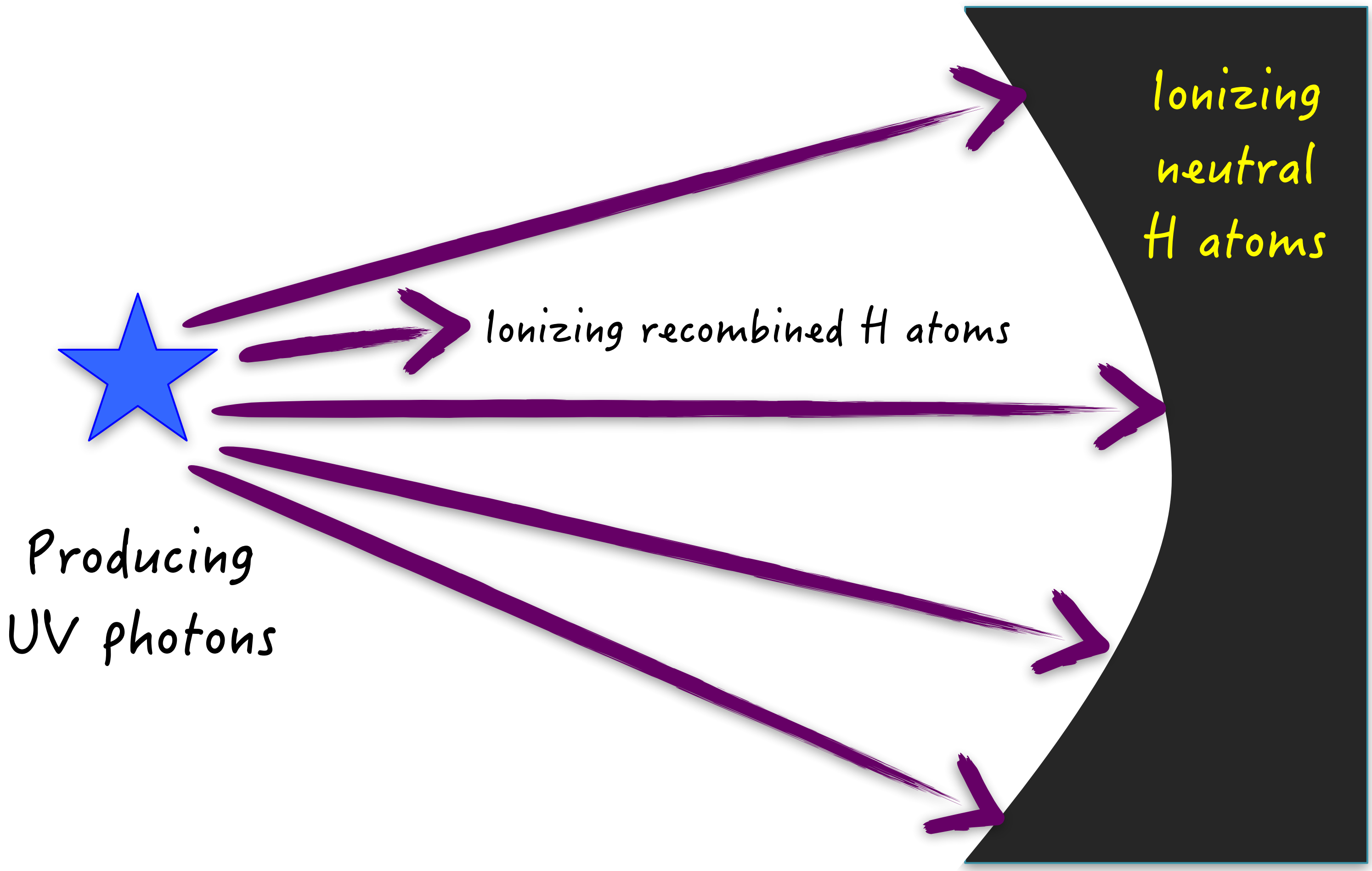
Intro 1
of produced photons



(From S. Finkelstein's slides)

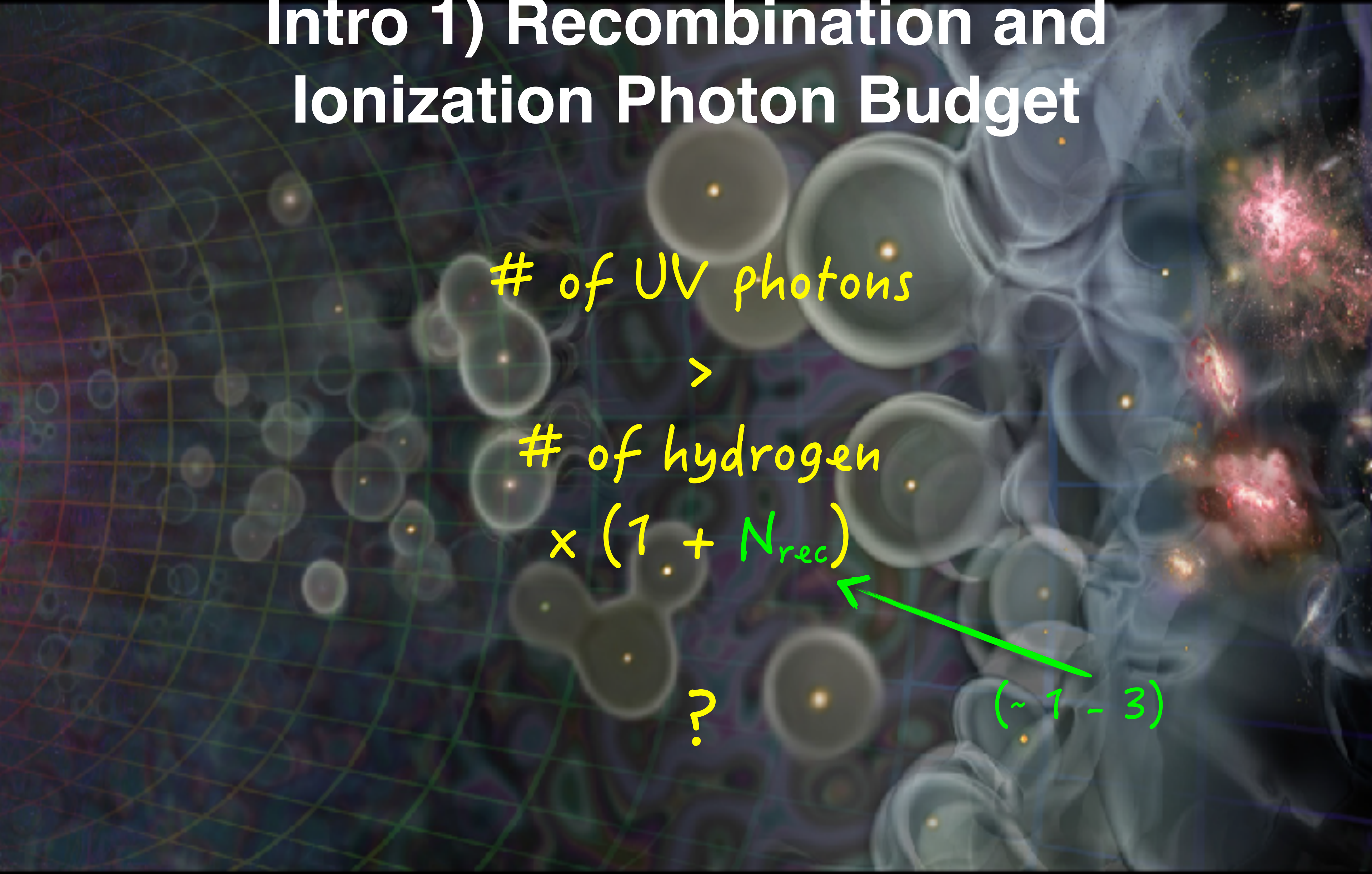
Observed galaxies do not account for them needed photons yet. Most of the photons are thought to have come from faint galaxies beyond the current detection limit.

of consumed photons



= # of atoms + # of recombination

Intro 1) Recombination and Ionization Photon Budget



$\#$ of UV photons

$>$

$\#$ of hydrogen

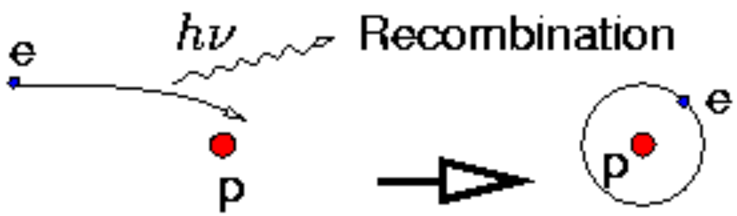
$\times\ (1 + N_{rec})$

?

(~ 1 - 3)

Recombination is another important factor in accounting for the reionization

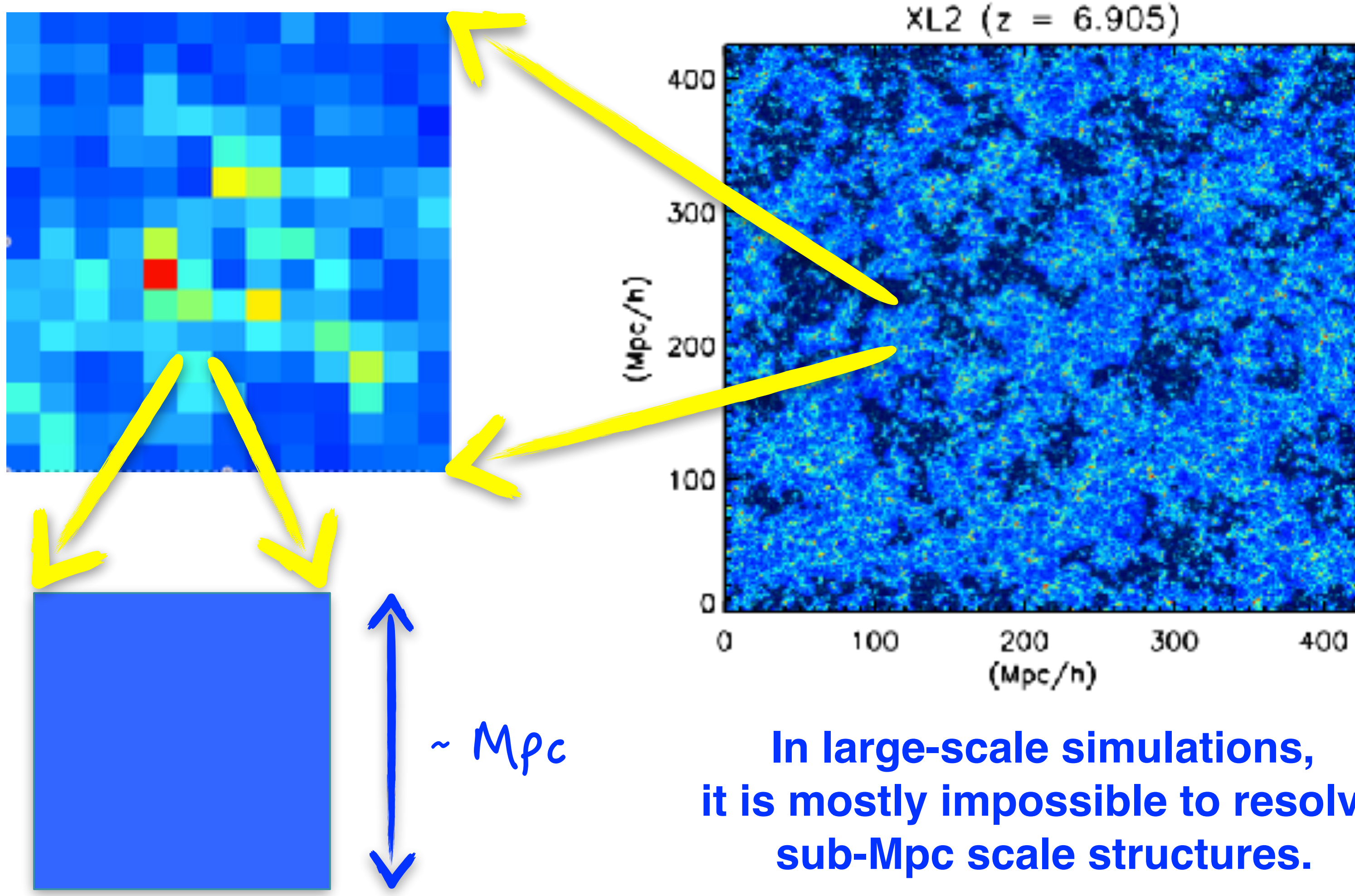
Introduction (2)
Why small-scale structure?



$$\mathcal{R} \propto n_e n_{\mathrm{HII}} (\propto \rho^2)$$

In fully ionized gas, the recombination rate goes nearly as the density squared.

Intro 2) Why small-scale structure?

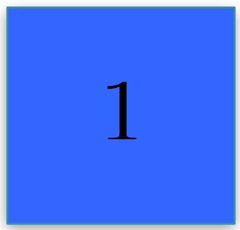
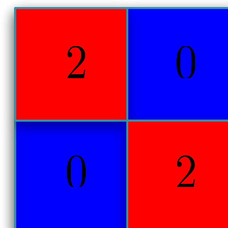


In large-scale simulations, it is mostly impossible to resolve sub-Mpc scale structures.

Intro 2
Clumping Factor

$$\langle R \rangle_V \propto \langle \rho^2 \rangle_V \neq \langle \rho \rangle_V^2$$

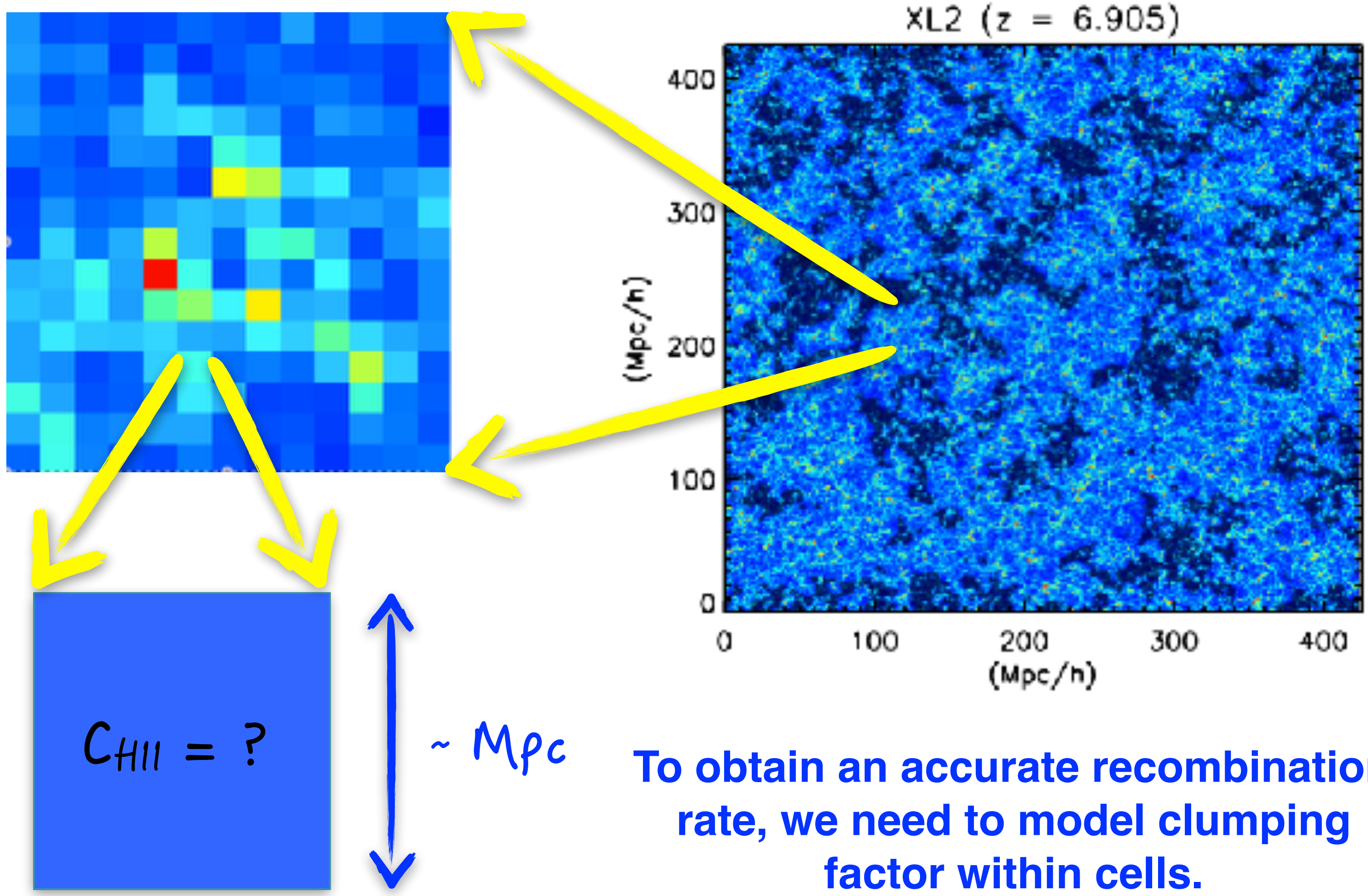
Square of average does not equal to average of square!

	
$\langle \rho^2 \rangle = 1 = \langle \rho \rangle^2$	$\langle \rho^2 \rangle = 2 \neq 1 = \langle \rho \rangle^2$
$C = 1$	$C = 2$

$$C \equiv \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \frac{(\text{Actual})}{(\text{Approximate})}$$

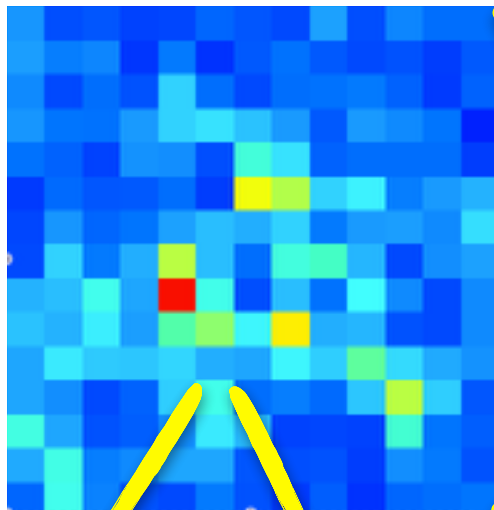
Neglecting density distribution within a volume underestimates the recombination rate by the clumping factor, C.

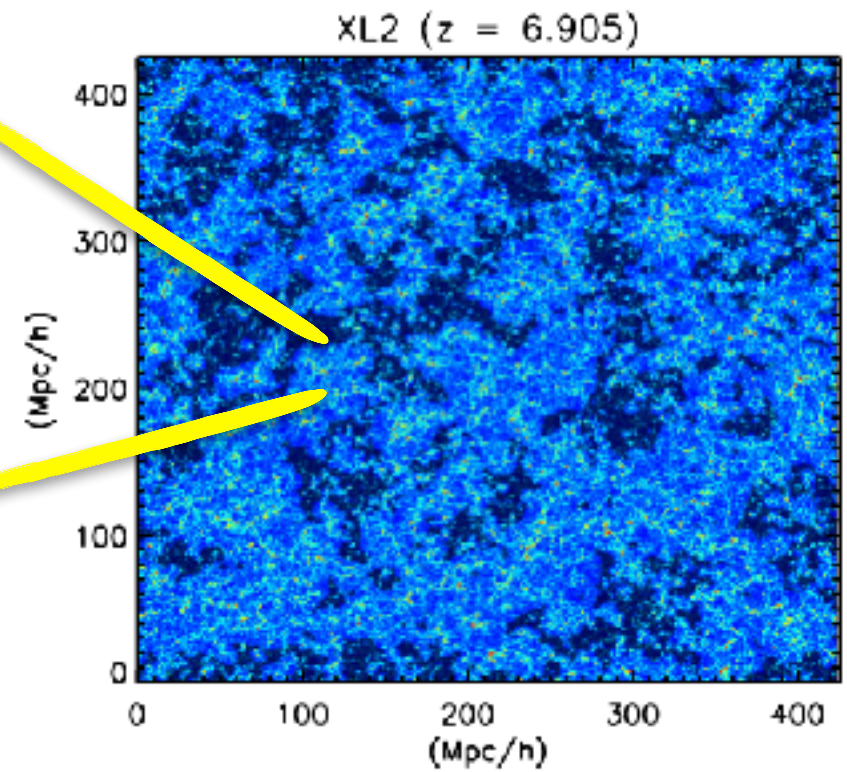
Intro 2)“Sub-grid” Clumping Factor

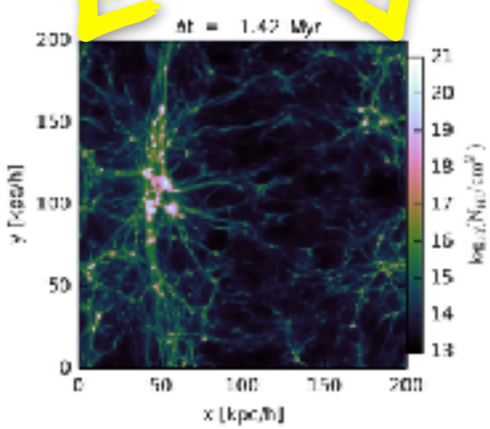


To obtain an accurate recombination rate, we need to model clumping factor within cells.

Intro 2)“Sub-grid” Clumping Factor



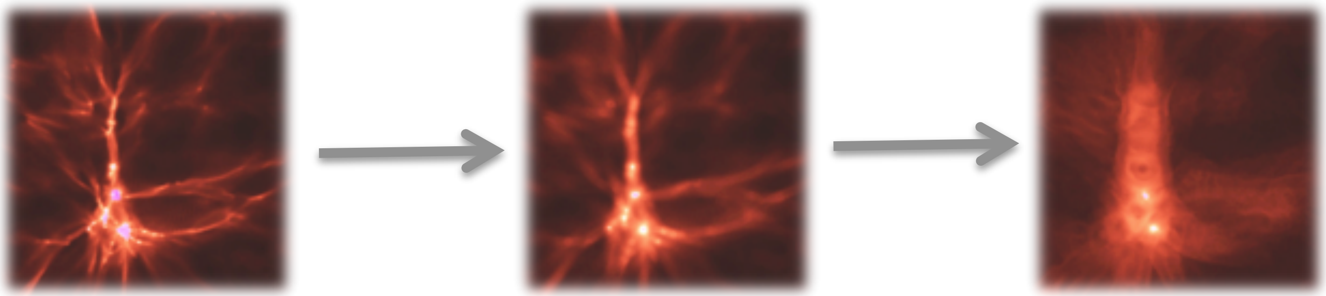




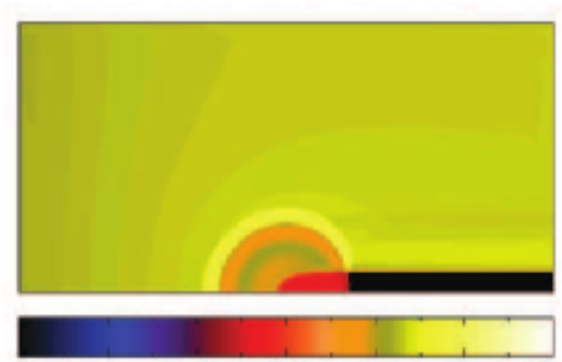
To do so, we shall simulate “small-scale structures” in such cells.

Methodology
Key physics for small-scale structure

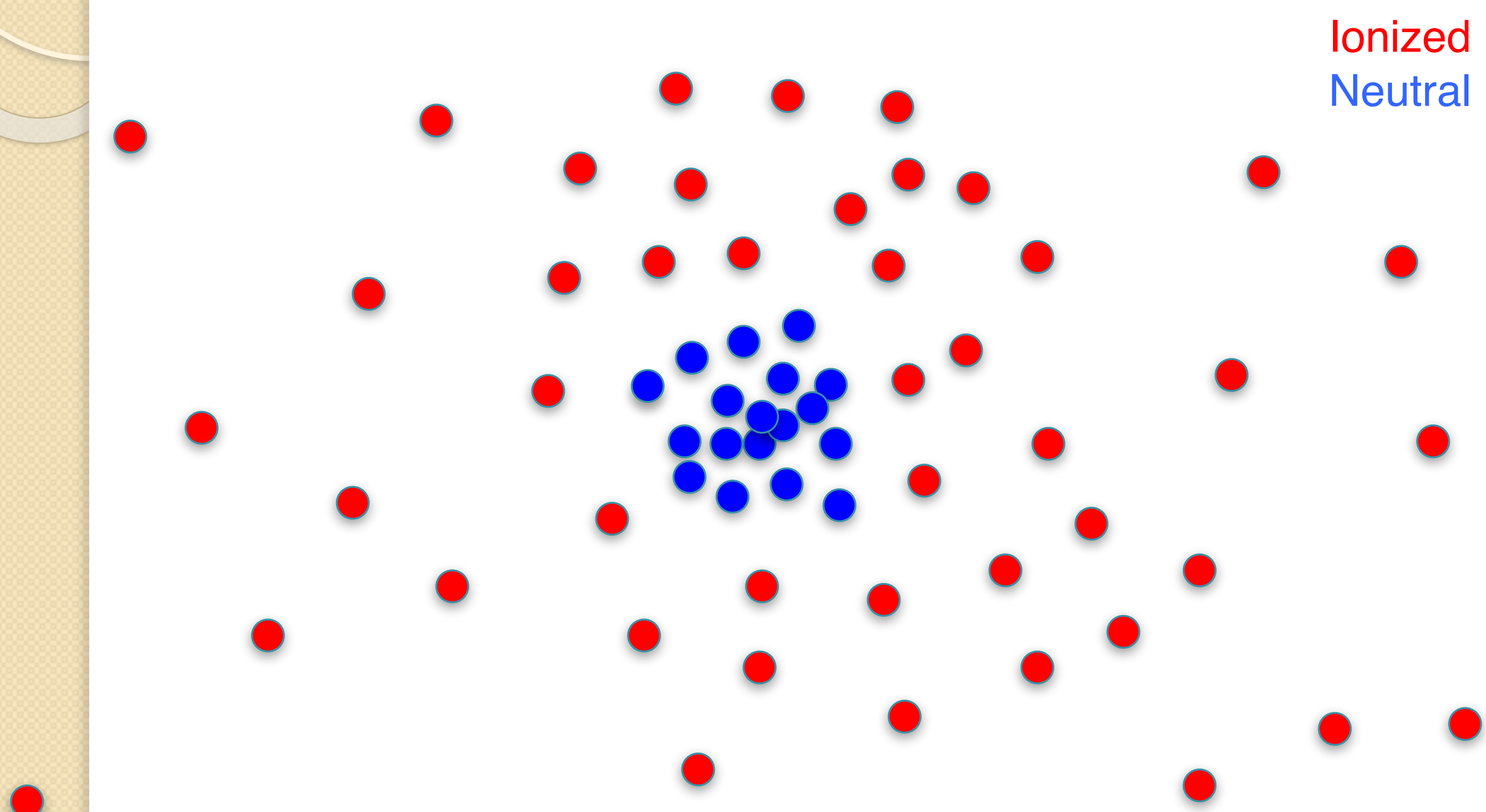
Hydrodynamic back-reaction of photo-ionization on small-scale structures



Self-shielding of dense minihalos against ionizing radiation

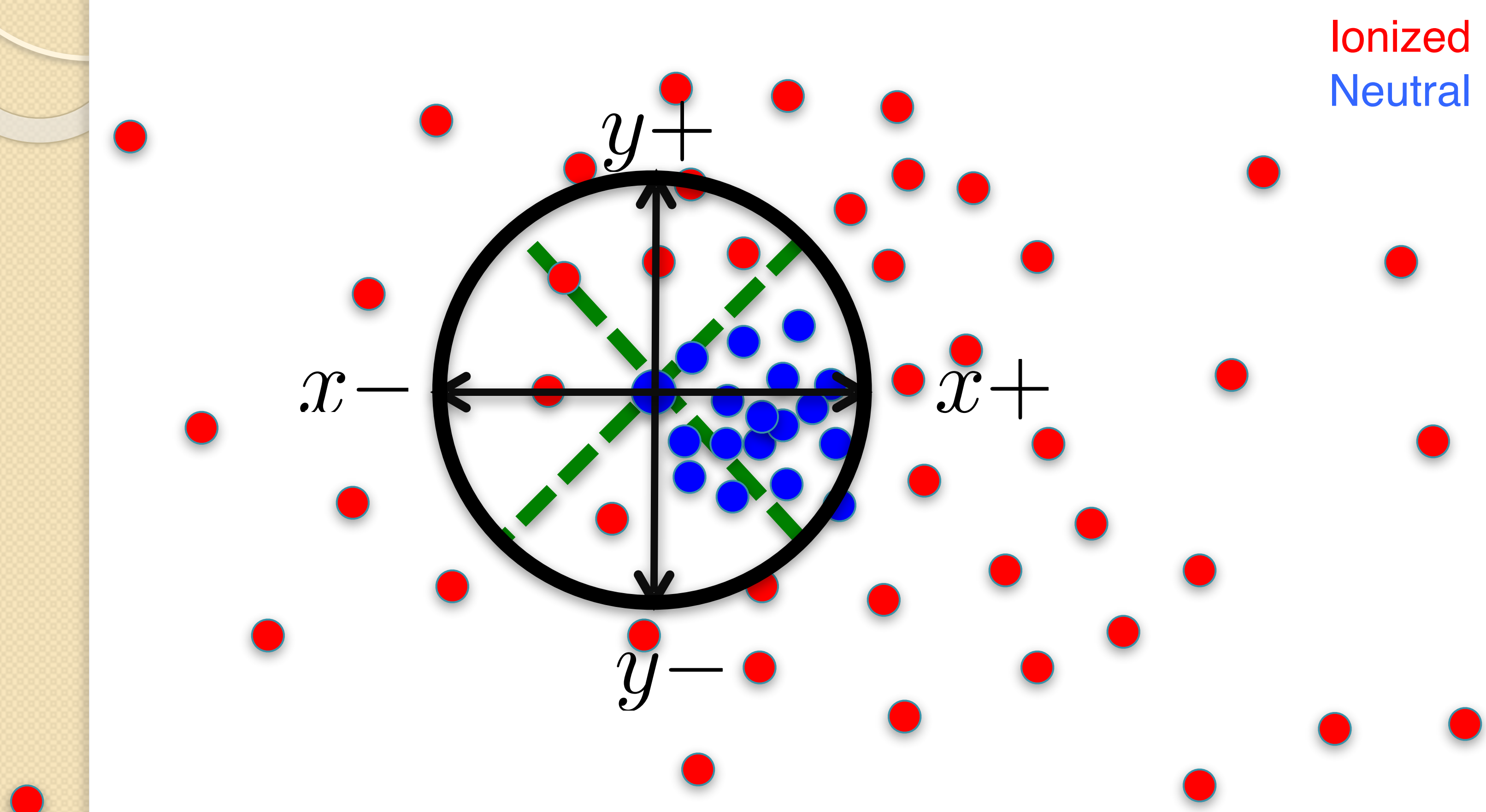


Shielding against Ionizing Radiation



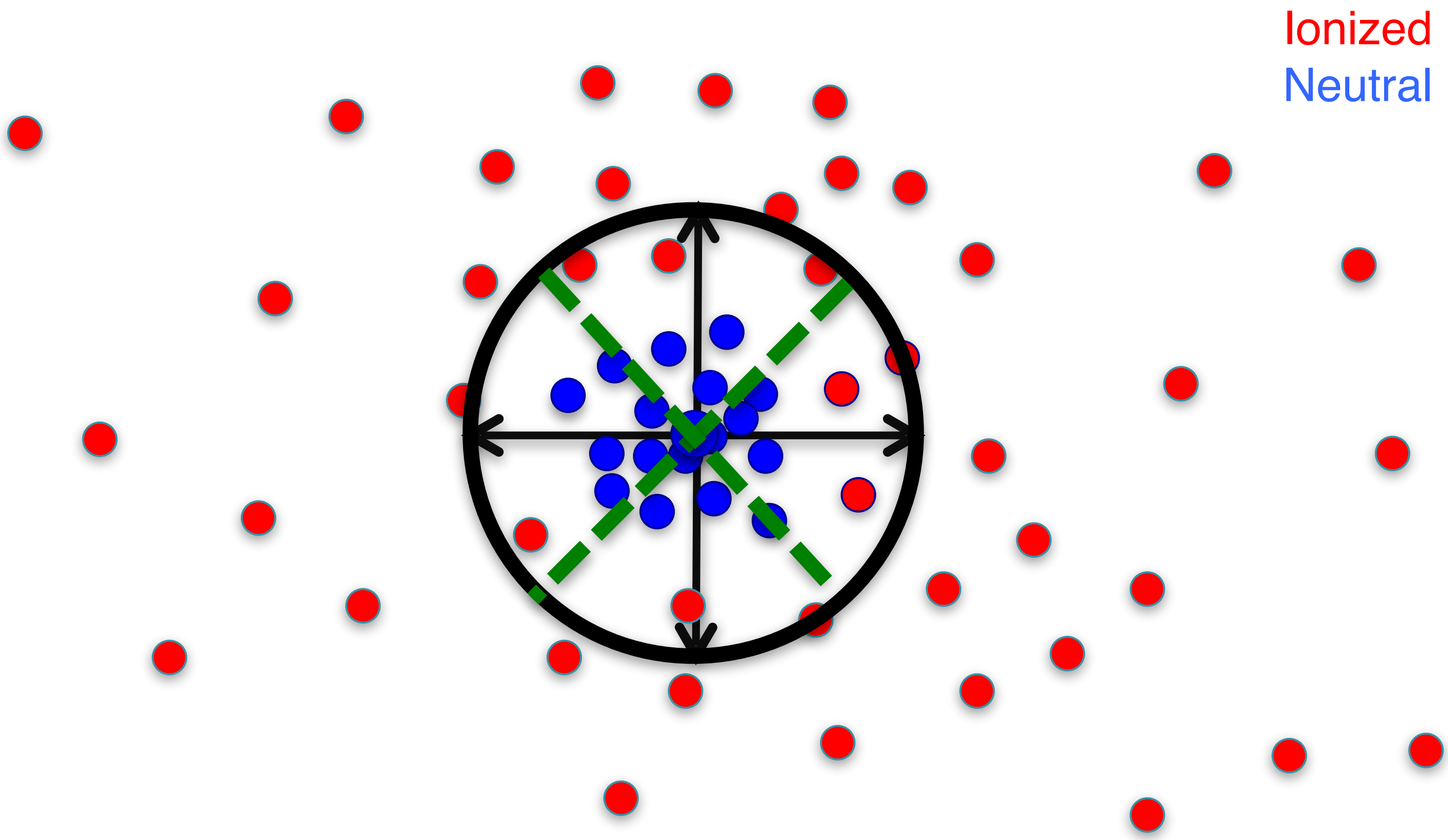
Most gas will be ionized immediately except dense gas in minihalos that will be able to shield against the external background.

Shielding against Ionizing Radiation



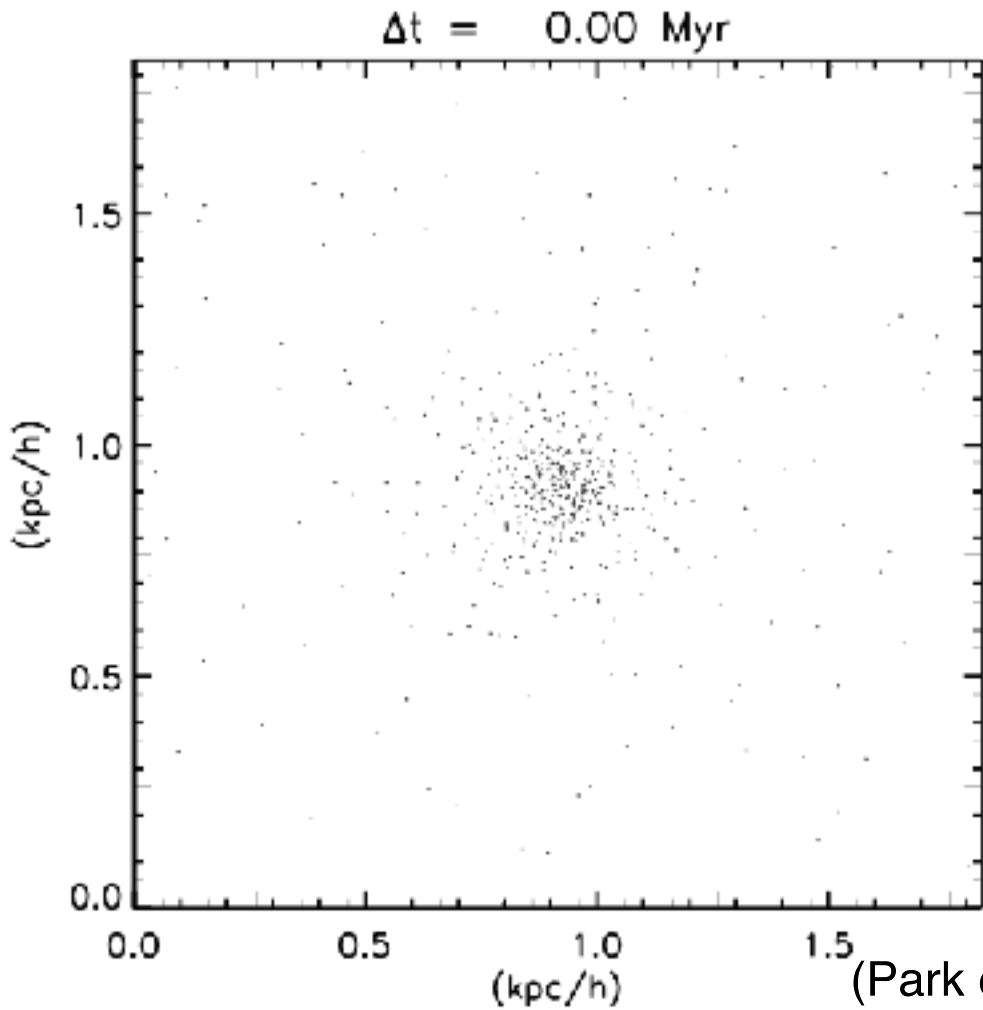
1) Search for neutral particles within 200 physical pc.
2) Attenuate radiation using neutral column densities in 6 directions.
(+x, -x, +y, -y, +z, -z)

Shielding against Ionizing Radiation



1) Search for neutral particles within 200 physical pc.
This uses the pre-constructed tree structure for gravity solver.
2) Attenuate radiation using neutral column densities in 6 directions.
(+x, -x, +y, -y, +z, -z)

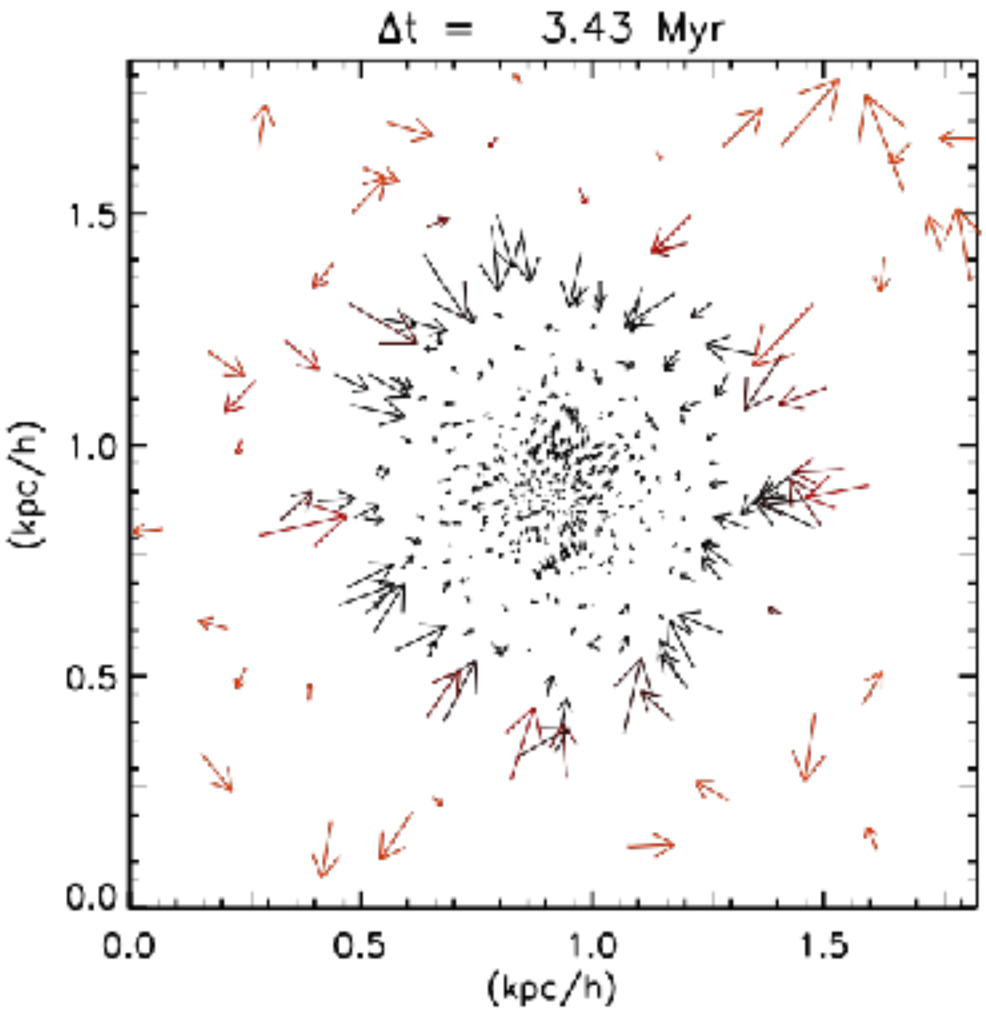
Test Problem : Spherically Symmetric Halo



(Park et al. 2016)

We test our shielding algorithm against the 1D rad-hydro code of Ahn et al. (2007).

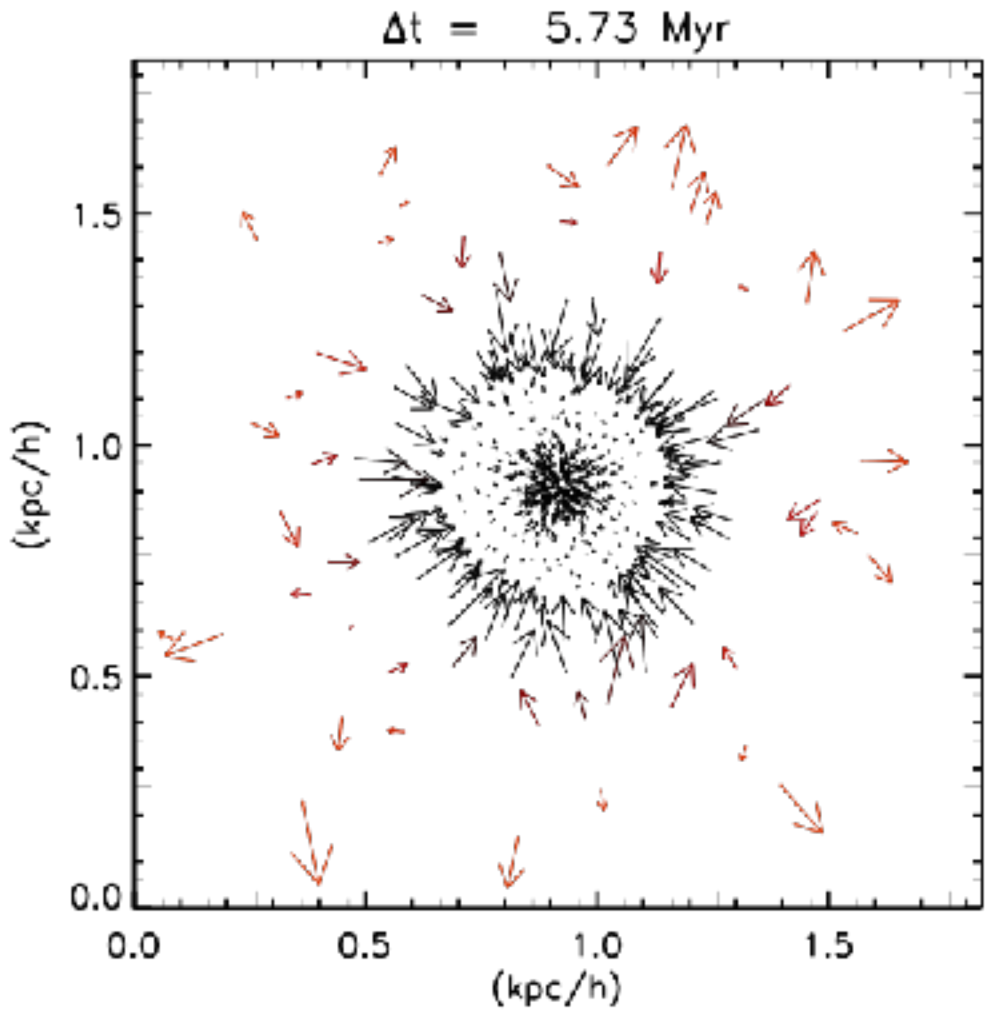
Test Problem : Spherically Symmetric Halo



Ionized

Neutral

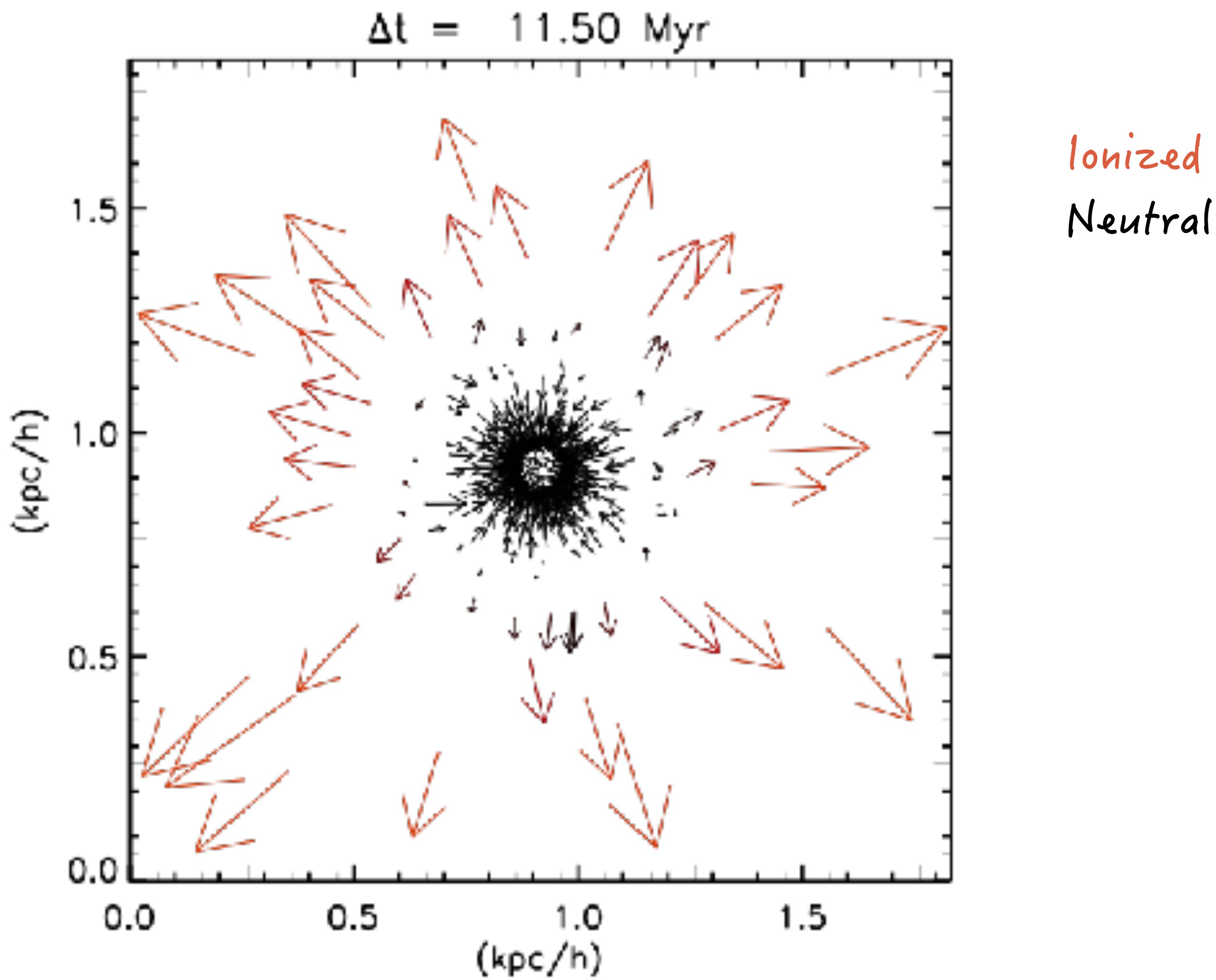
Test Problem : Spherically Symmetric Halo



Ionized

Neutral

Test Problem : Spherically Symmetric Halo

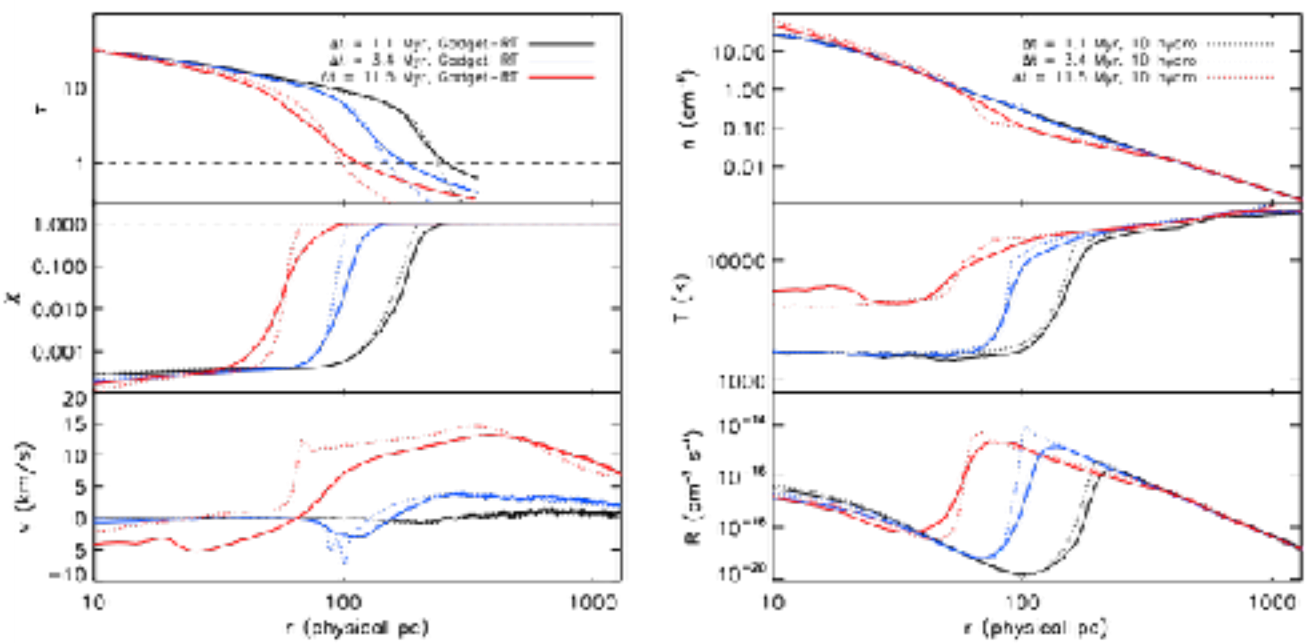


Test Result:
Radial Profiles of Physical Quantities

Optical depth

Ionized Fraction

Radial Velocity



Density

Temperature

Recombination Rate

(Park et al. 2016)

The algorithm reproduces the result of Ahn et al. (2007) very well.

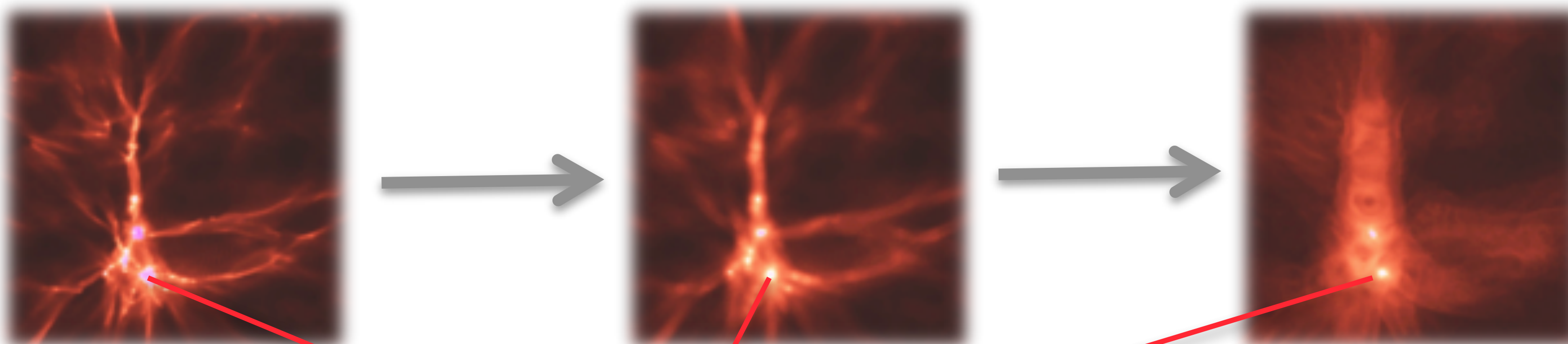
Resolution to use

Previous Works	DM particle mass
Pawlik et al. 2015	$> 1\times10^6$ $M_\odot/h$
So et al. 2014	5×10^5 $M_\odot/h$
Kaurov & Gnedin 2014	7×10^6 $M_\odot/h$
Shull et al. 2012	7×10^6 $M_\odot/h$
Finlator et al. 2012	1×10^6 $M_\odot/h$
Raicevic & Theuns 2011	6×10^5 $M_\odot/h$
Pawlik et al. 2009	$> 8\times10^5$ $M_\odot/h$
Iliev et al. 2008	1×10^6 $M_\odot/h$
Trac & Cen 2007	3×10^6 $M_\odot/h$
Gnedin & Ostriker 1997	3.7×10^5 $M_\odot/h$

- **Previous studies used $\sim10^6\ M_\odot$ DM particles to resolve down to $\sim10^8\ M_\odot$, covering structures with $T_{vir} > 10000$ K.**
- **They found C ~ 3.**

Recombination in Small-scale (< $10^8 M_\odot$) Structures

Previous works: Small-scales structures will be destroyed quickly by hydrodynamic feedback and we can ignore them.



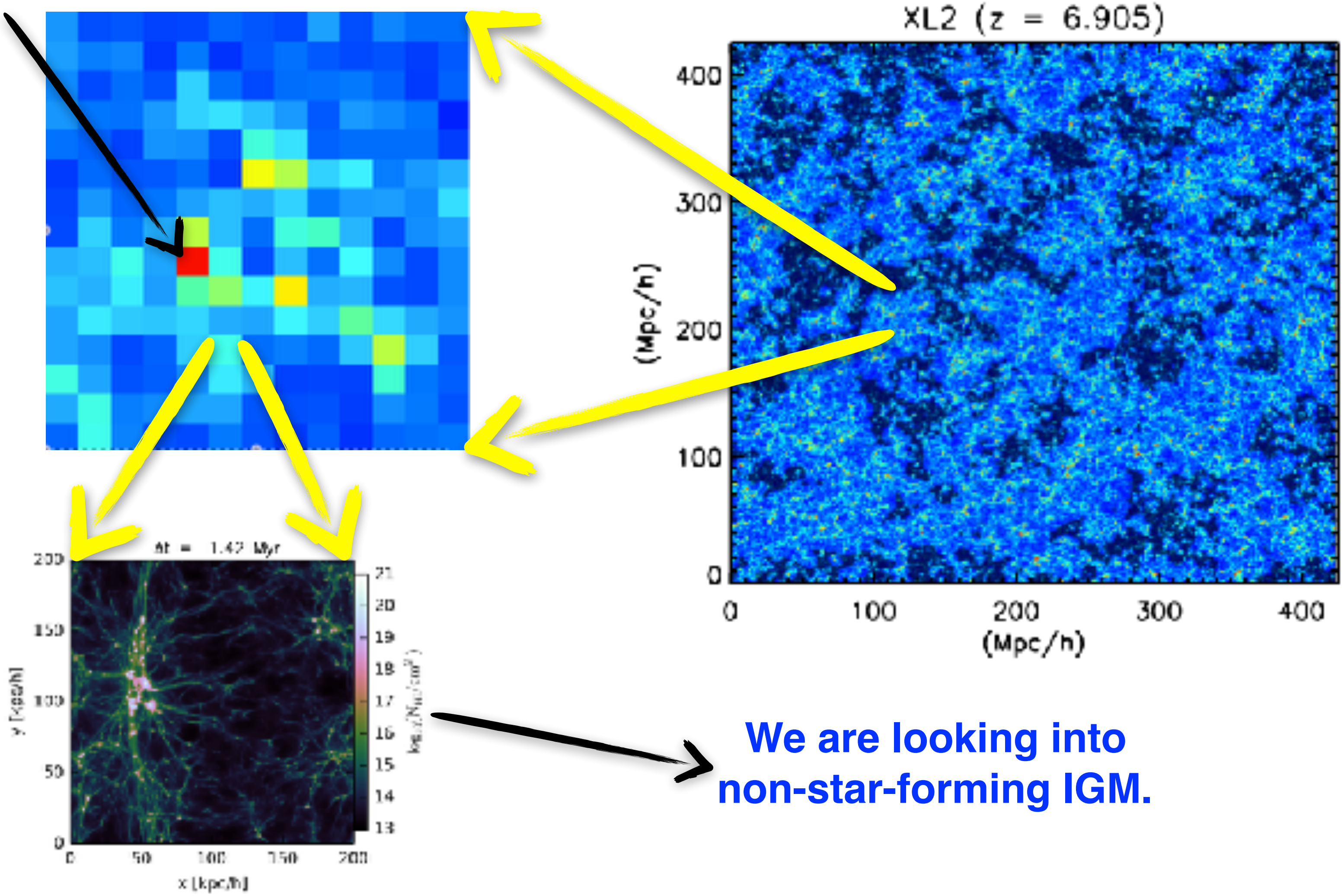
Minihalo gas can consume ~10 photons per atom. (Iliev et al. 2005; Shapiro et al. 2004)

At least in the early time before hydro feedback kicks in, using ~50 $M_\odot$ DM particles gives C > 10. (Emberson et al. 2013)

→ Our goal is to model the clumping factor with 50 $M_\odot$ DM particles with hydrodynamics.

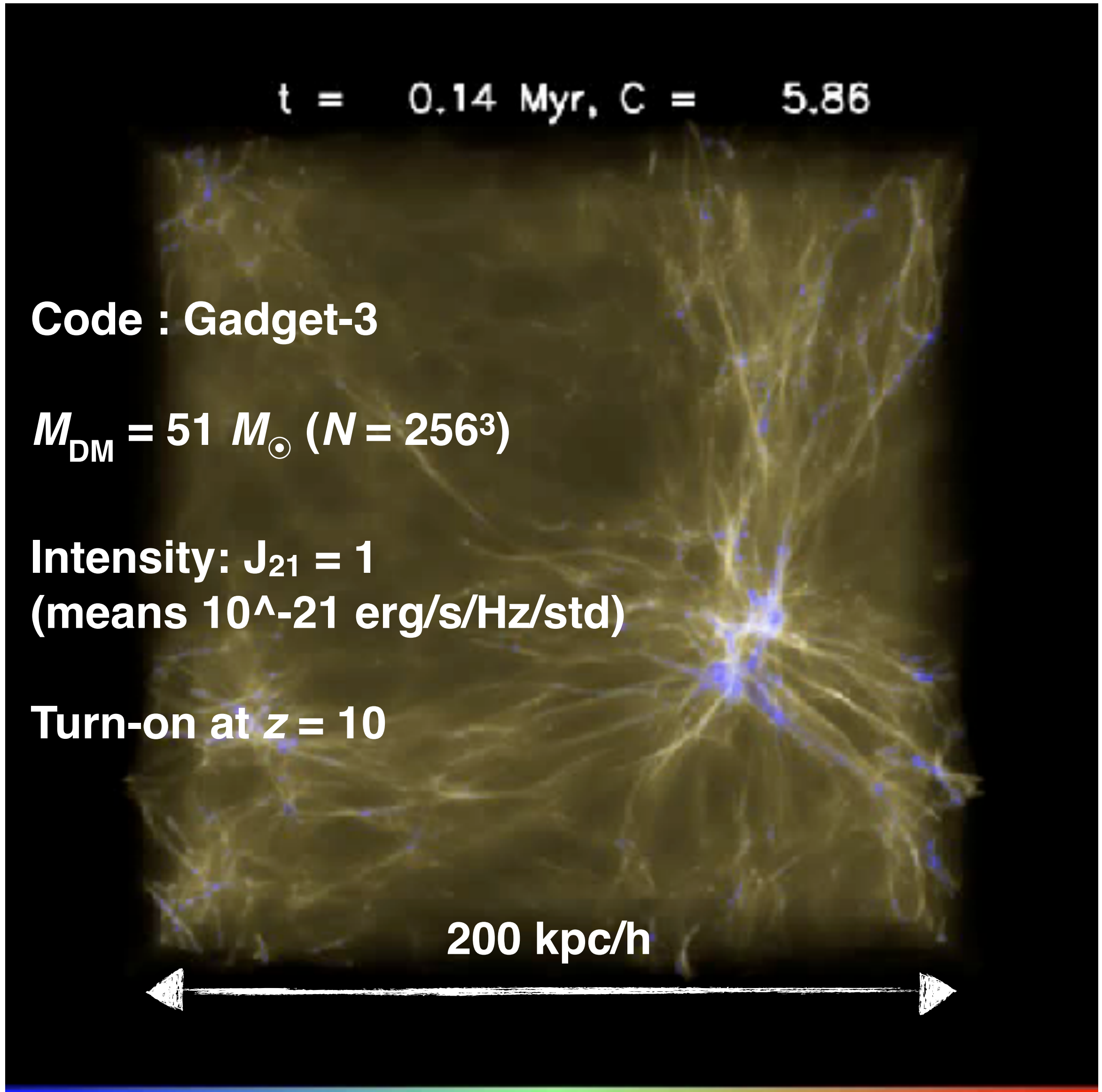
Simulation Setup (2)
No Star-formation

Star-formation happening here

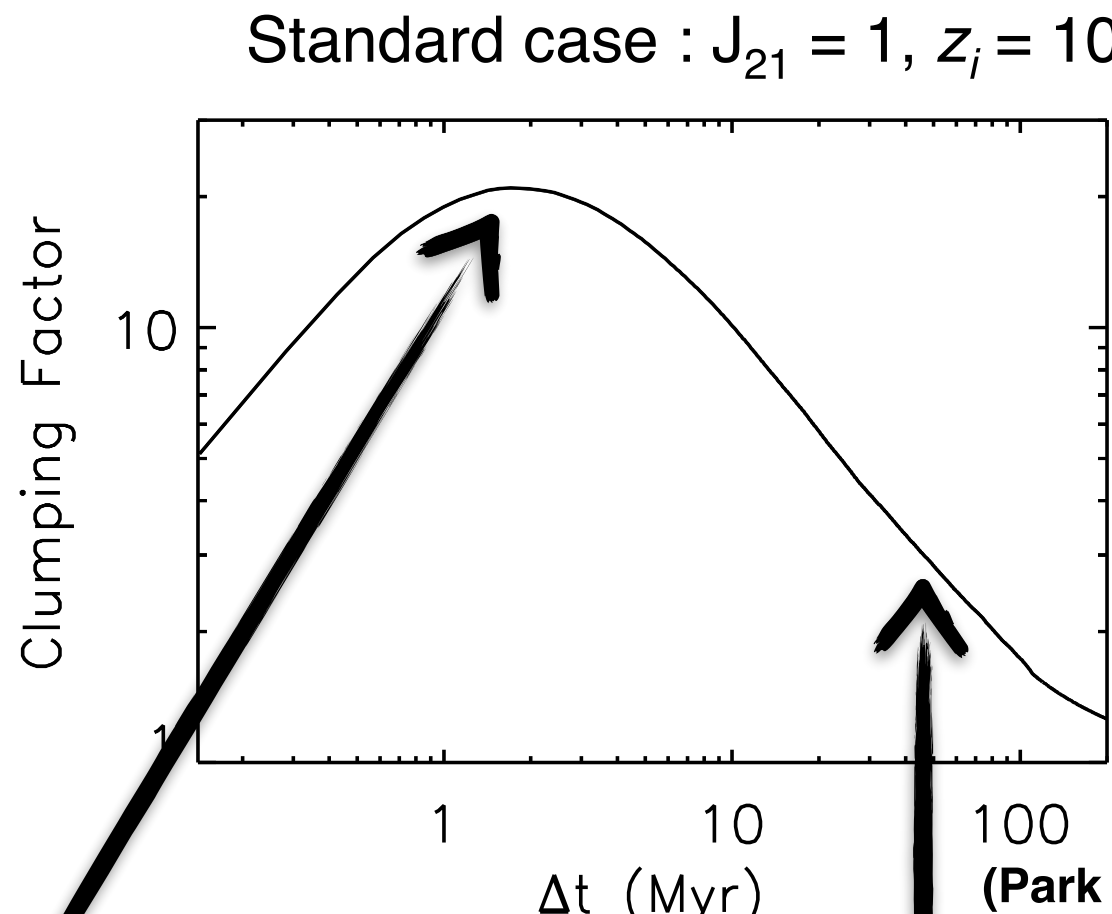


We are looking into non-star-forming IGM.

Result: Simulation Overview



Result : Clumping Factor

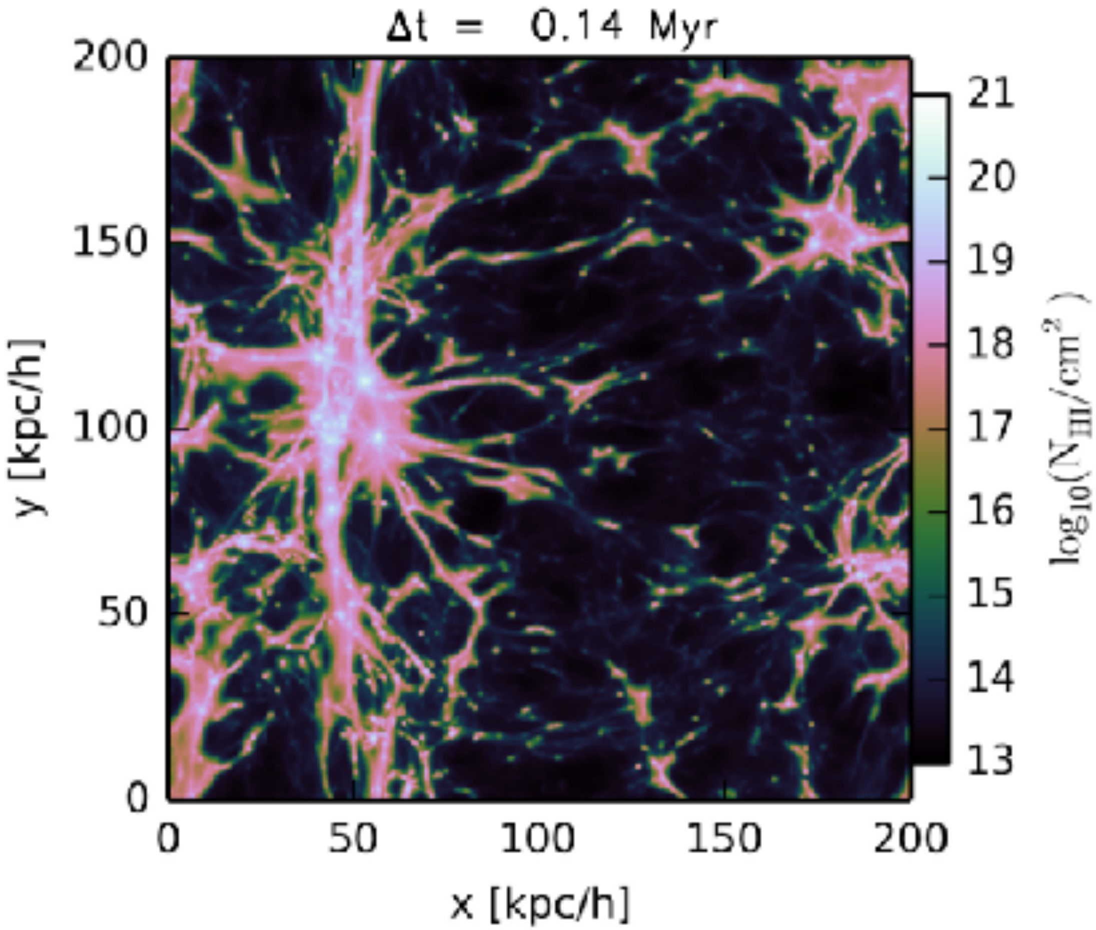


(Park et al. 2016)

High clumping factor in early time and low clumping factor in late time.

Result : Column Density Map

Standard case : $J_{21} = 1$, $z_i = 10$



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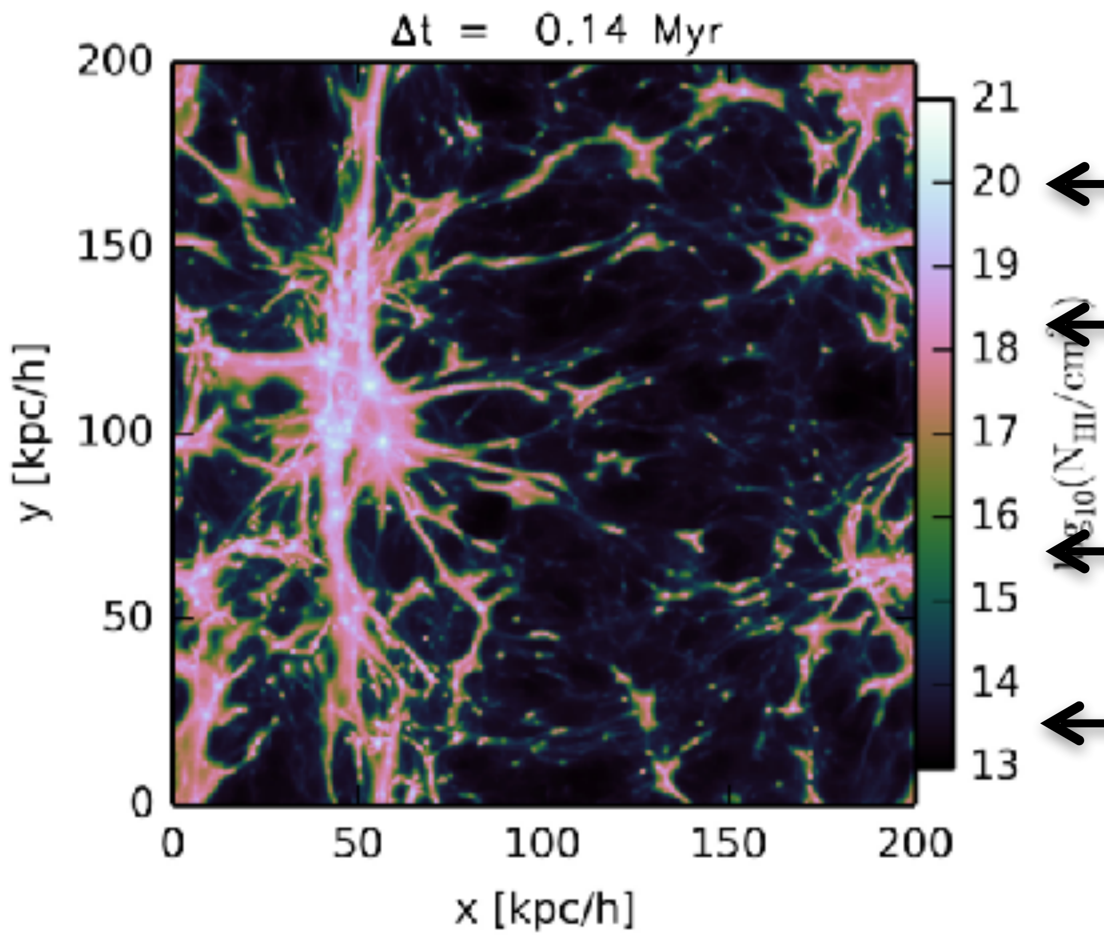


Neutral high-density

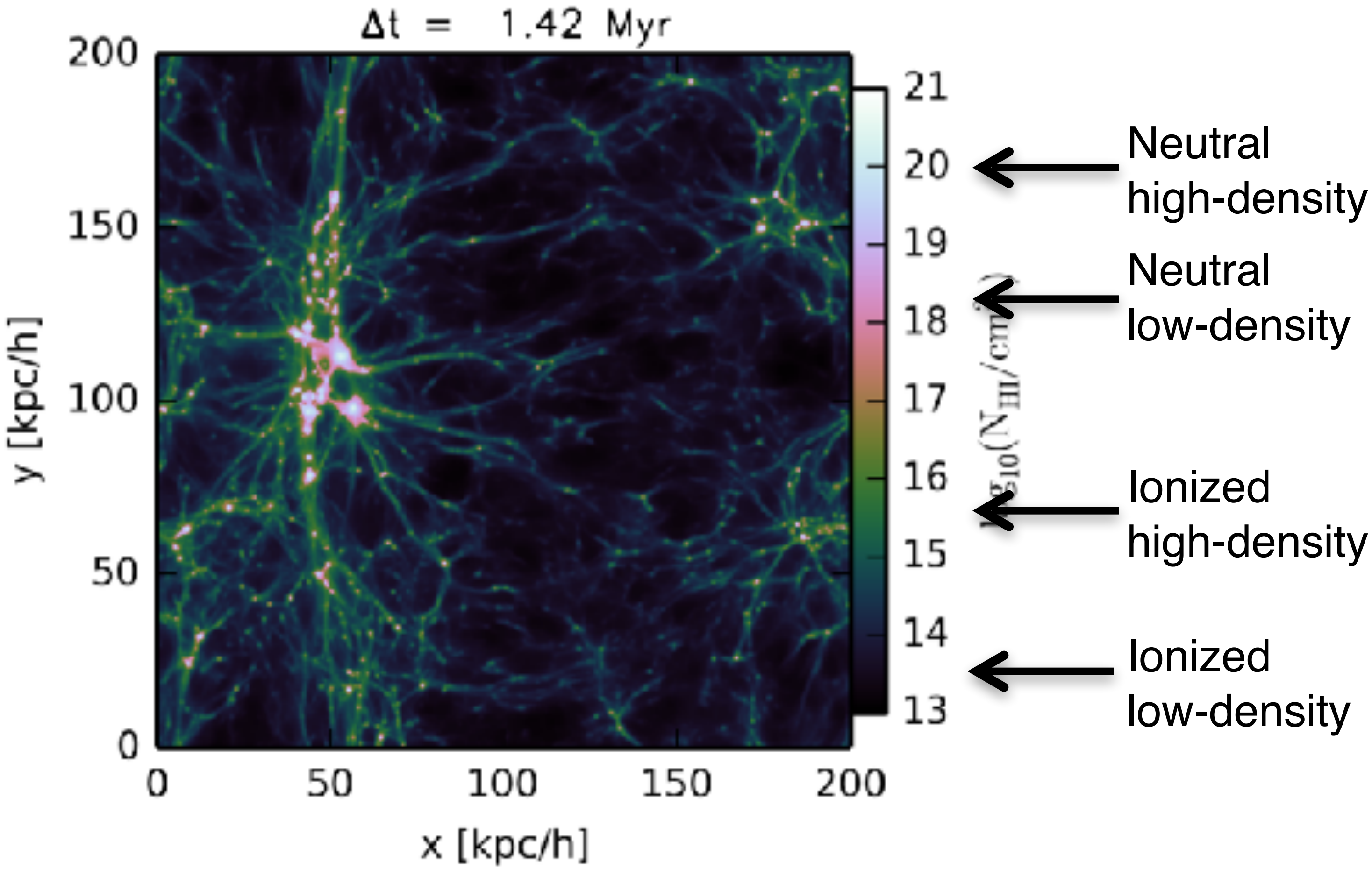
Neutral low-density

Ionized high-density

Ionized low-density

Result : Column Density Map

Standard case : $J_{21} = 1$, $z_i = 10$



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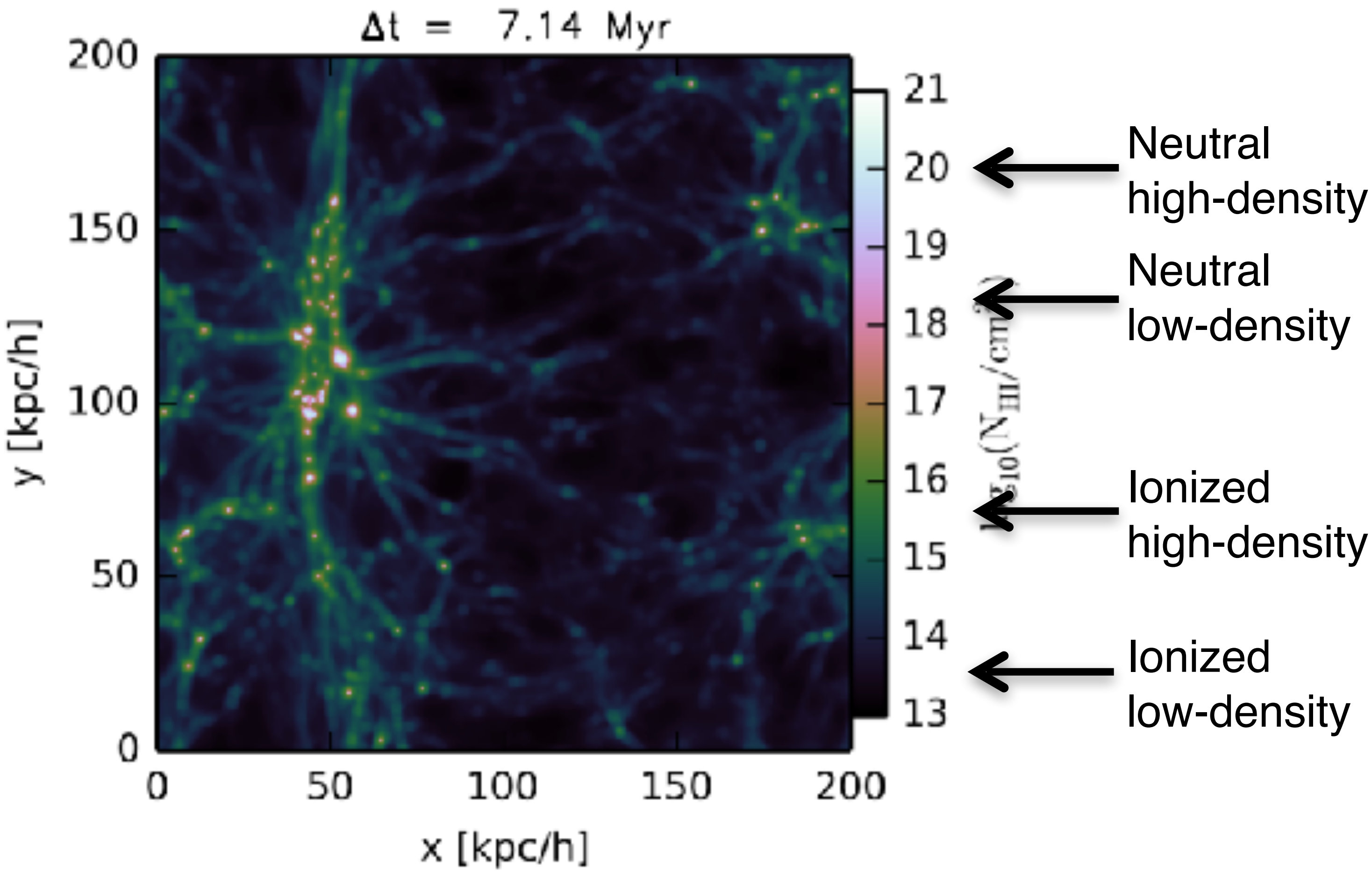

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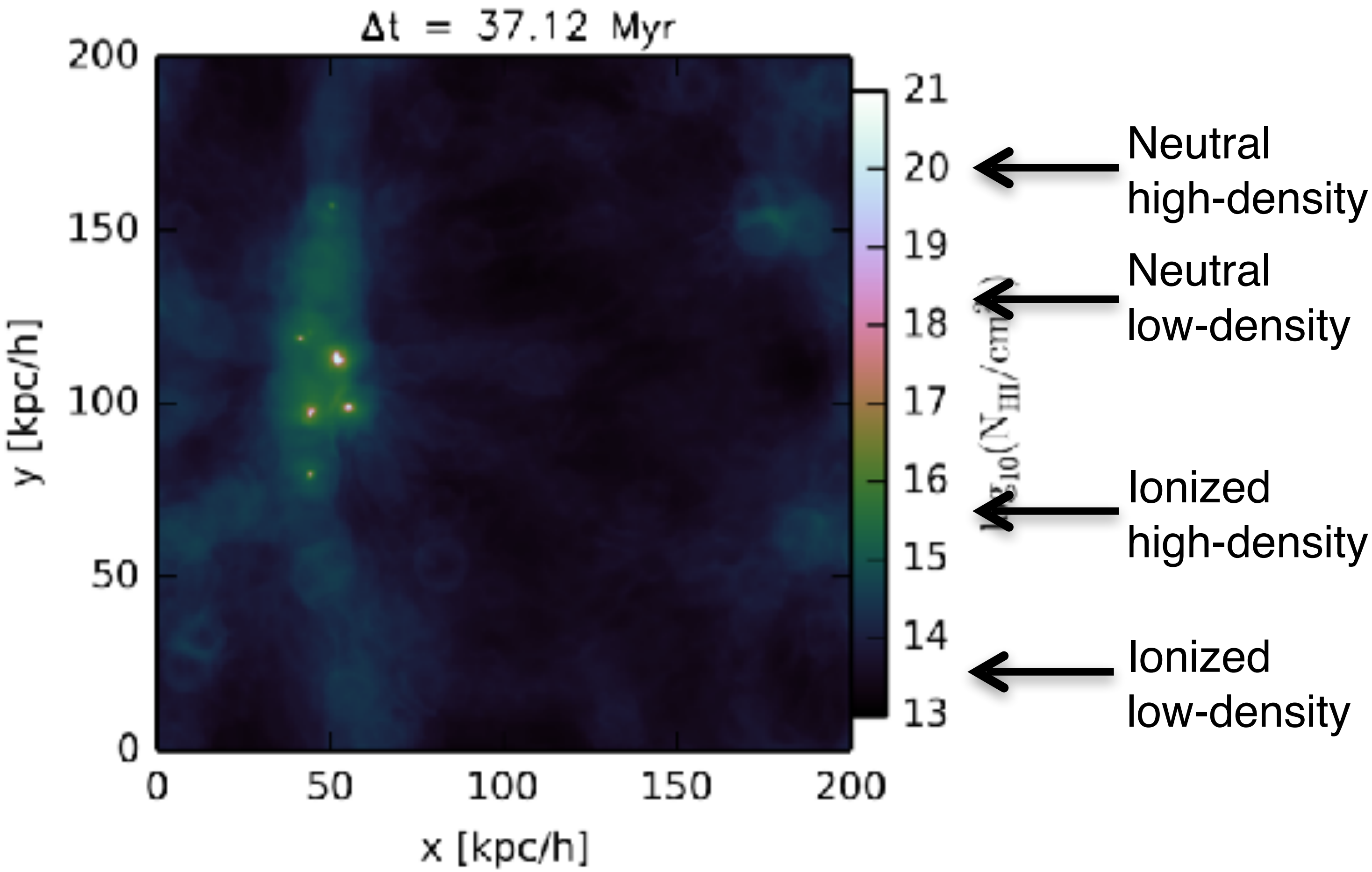
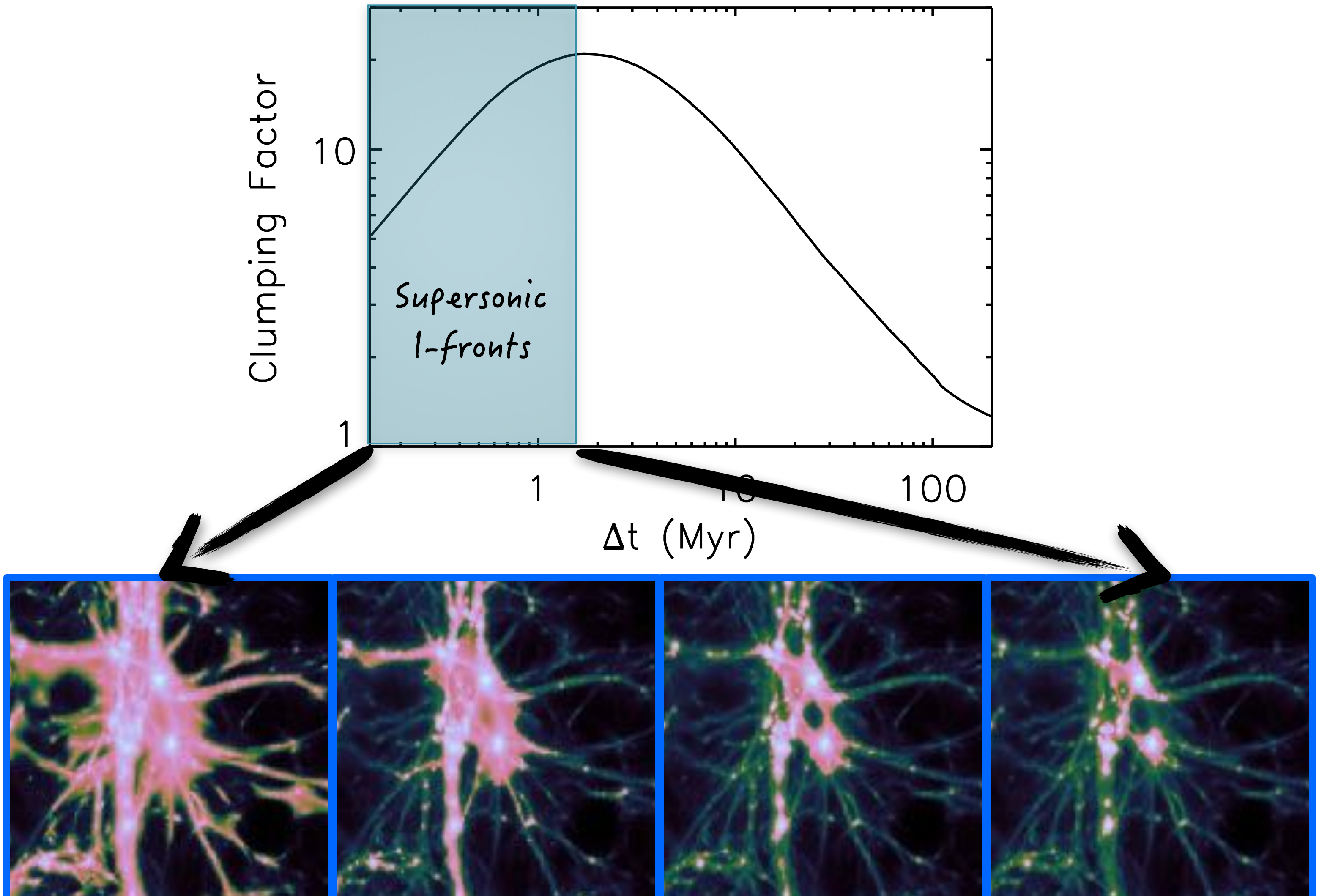
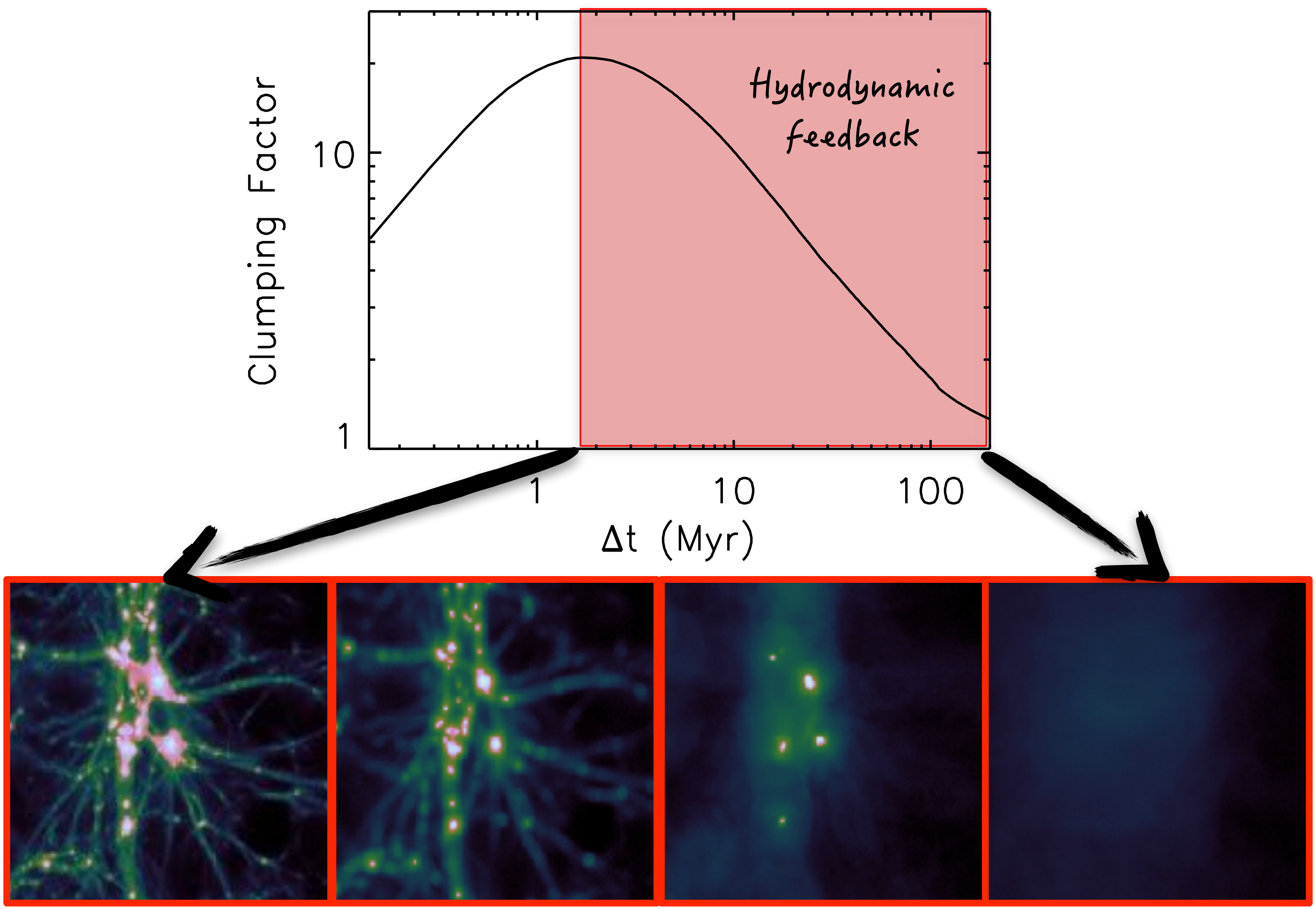


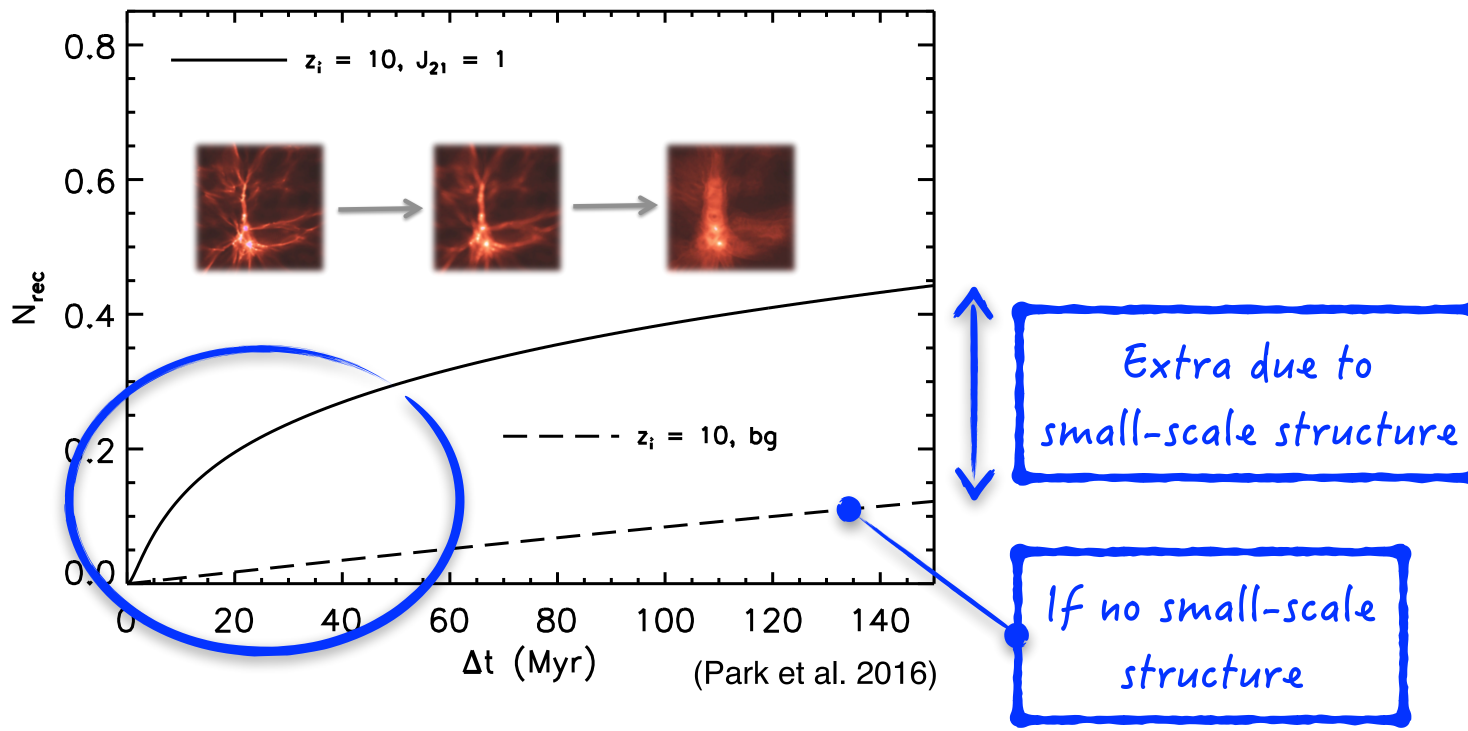
Clumping Factor at Early Time



Clumping Factor at Late Time

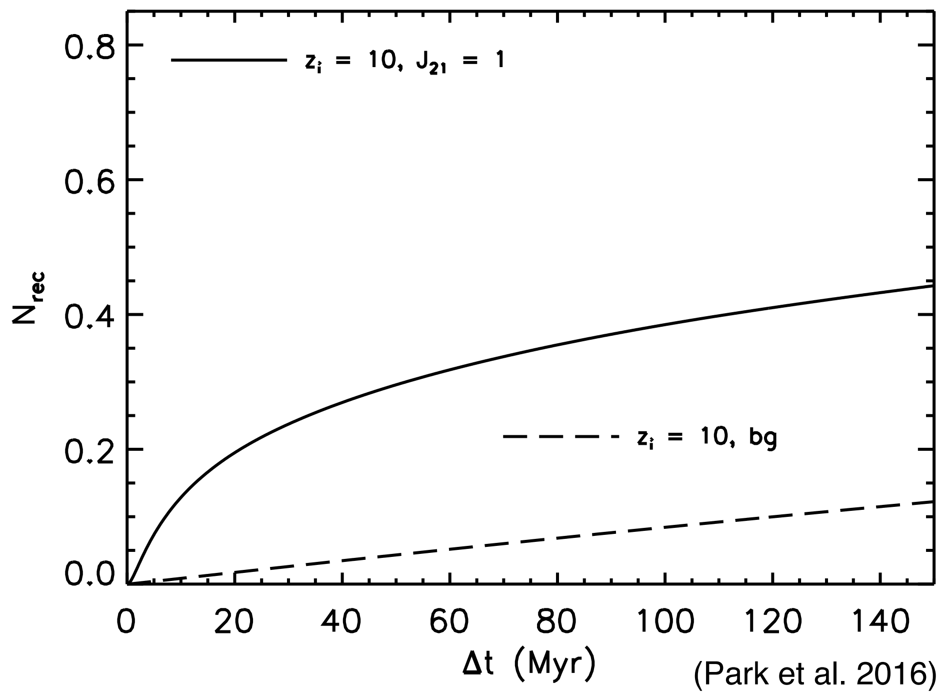


Result) Extra Photon Consumption due to Small-scale Structures



Initially high clumping factor results in extra photon consumption.

Result) Extra Photon Consumption due to Small-scale Structures

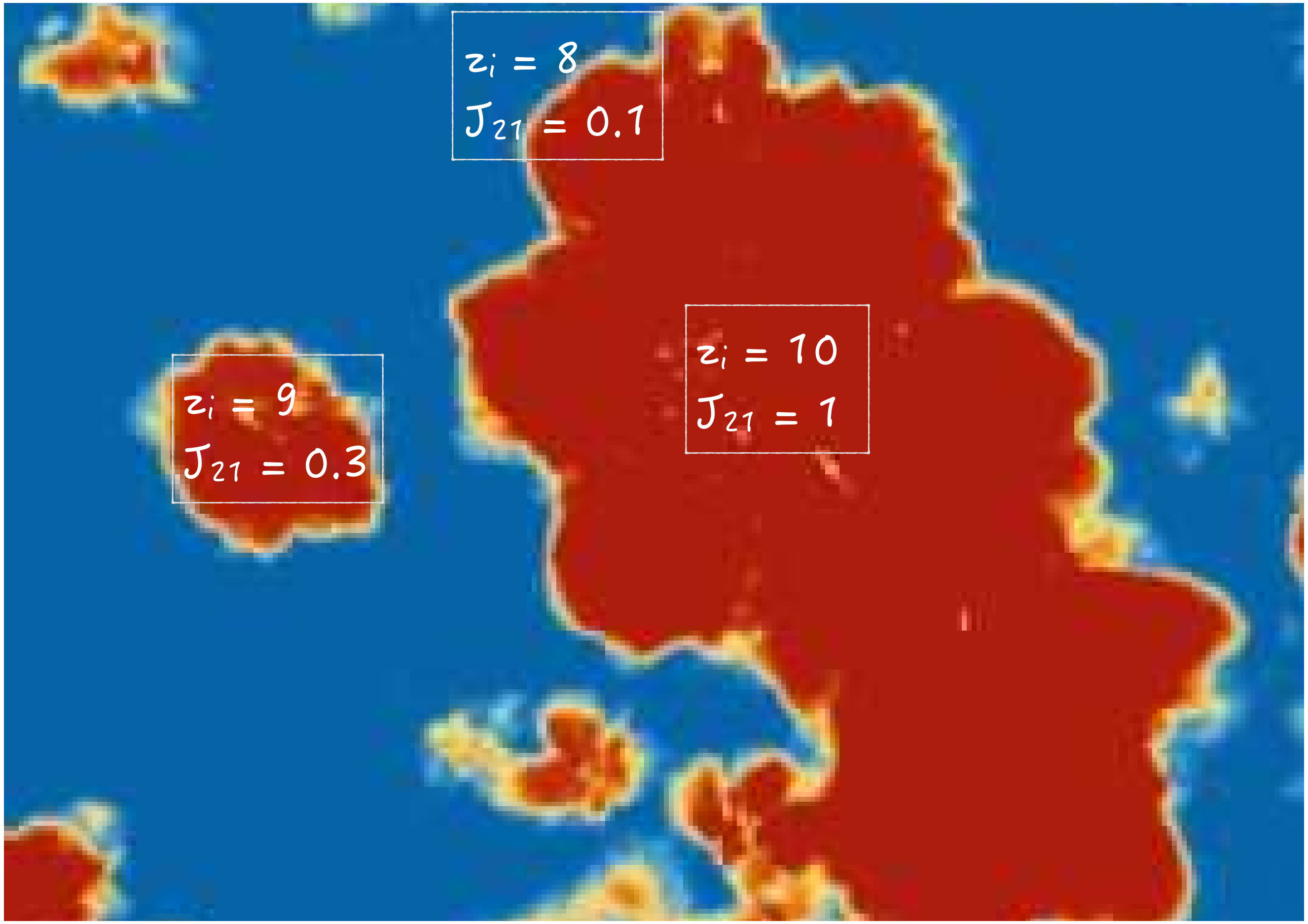


(Park et al. 2016)

$$N_{\rm rec}^{\rm add} = 0.32$$

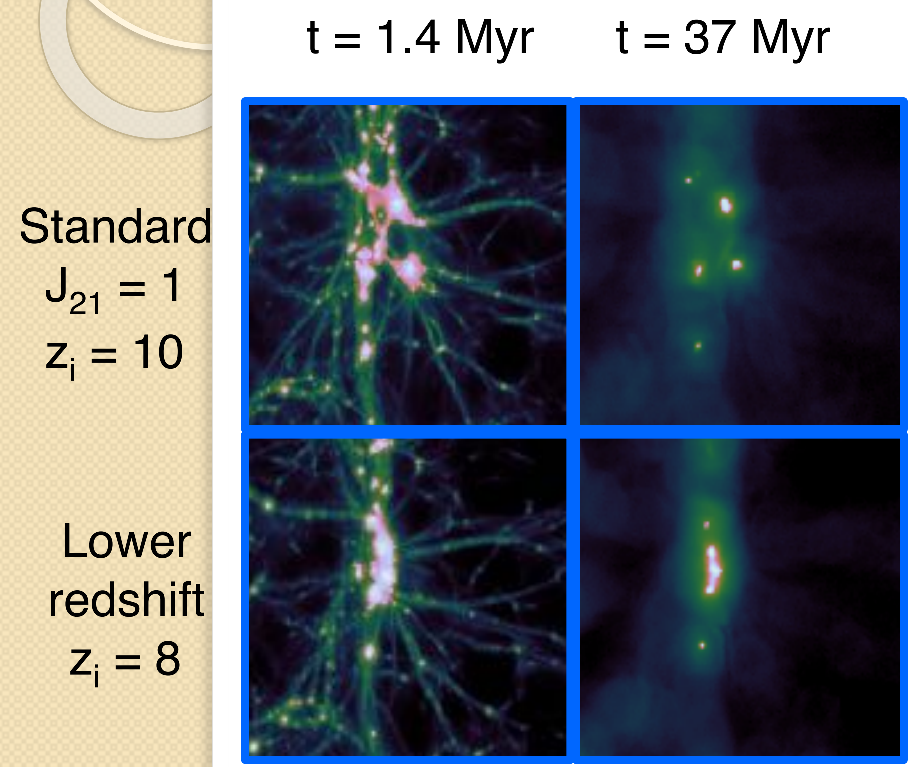
Initially high clumping factor results in extra photon consumption.

Dependence on arrival timing and intensity of ionizing radiation

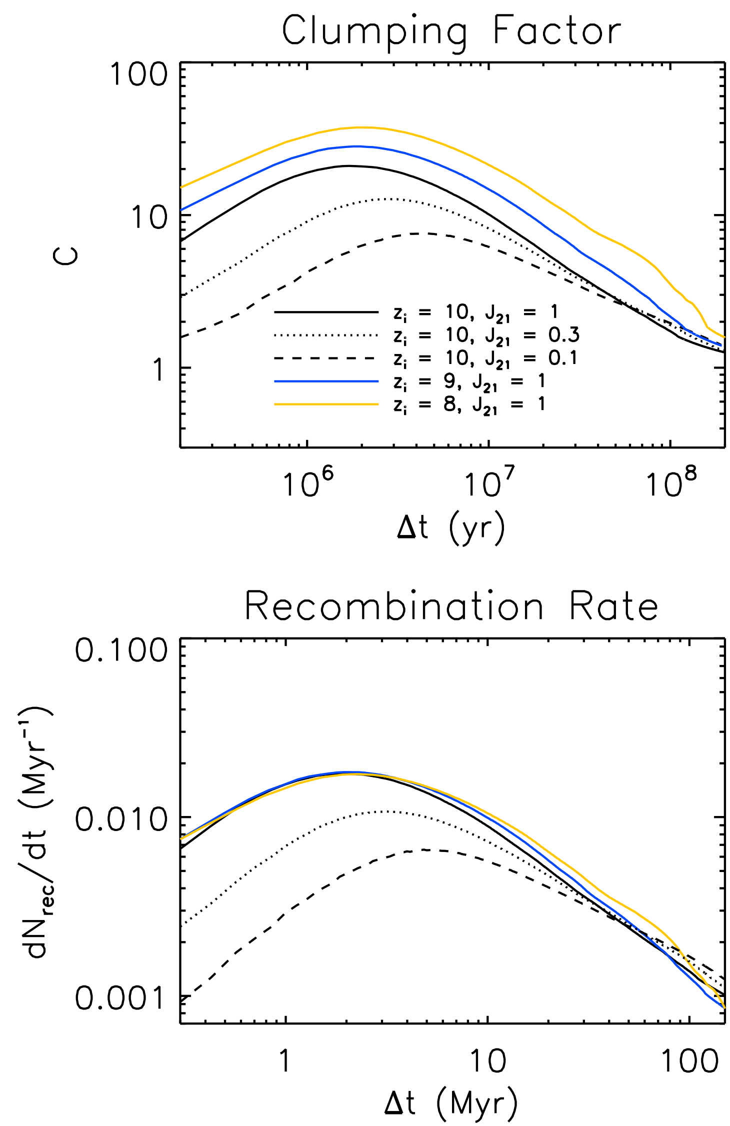


In large scale, sub-Mpc volumes are ionized at different times with different intensities depending on their environments.

Dependence on timing of ionization



At a lower *z*, more recombination due to more collapsed structures.

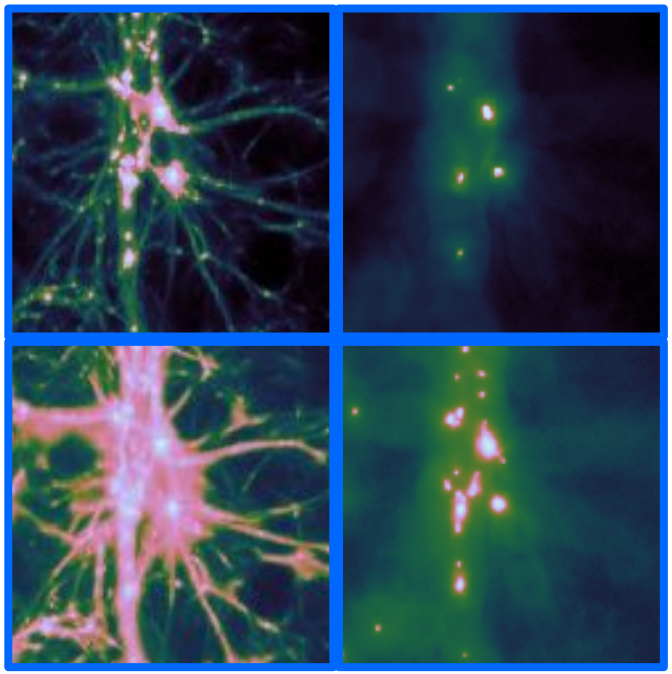


(Park et al. 2016)

Dependence on the intensity

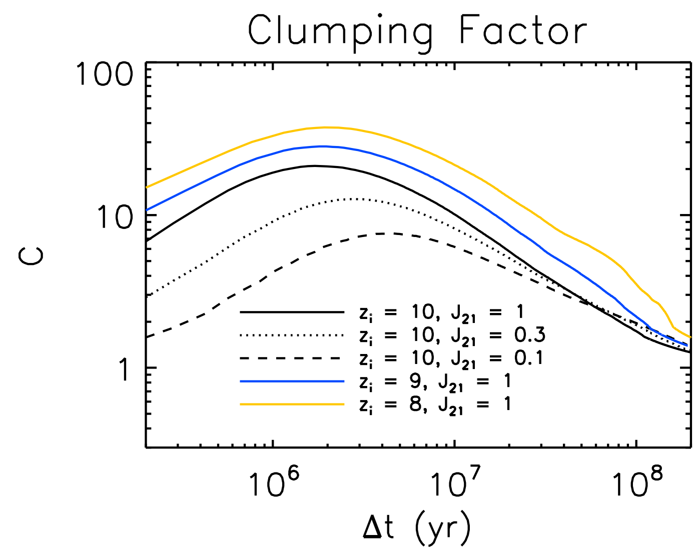
t = 1.4 Myr   t = 37 Myr

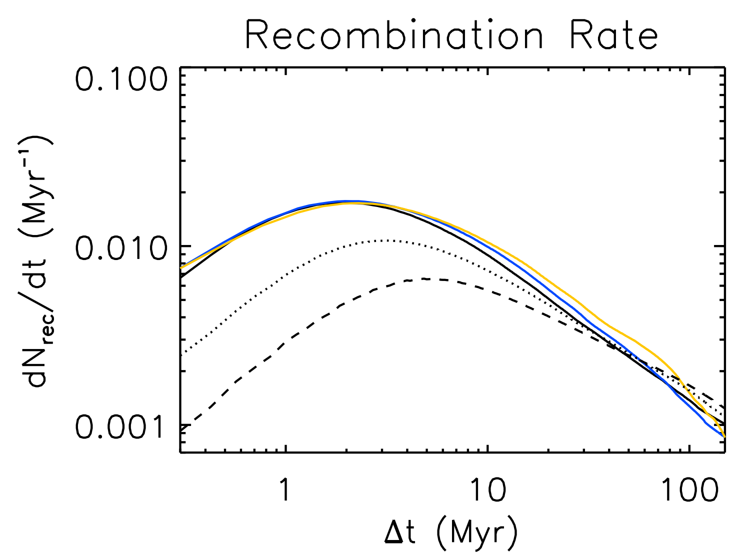
Standard
$J_{21} = 1$
$z_i = 10$



Weaker intensity
$J_{21} = 0.1$

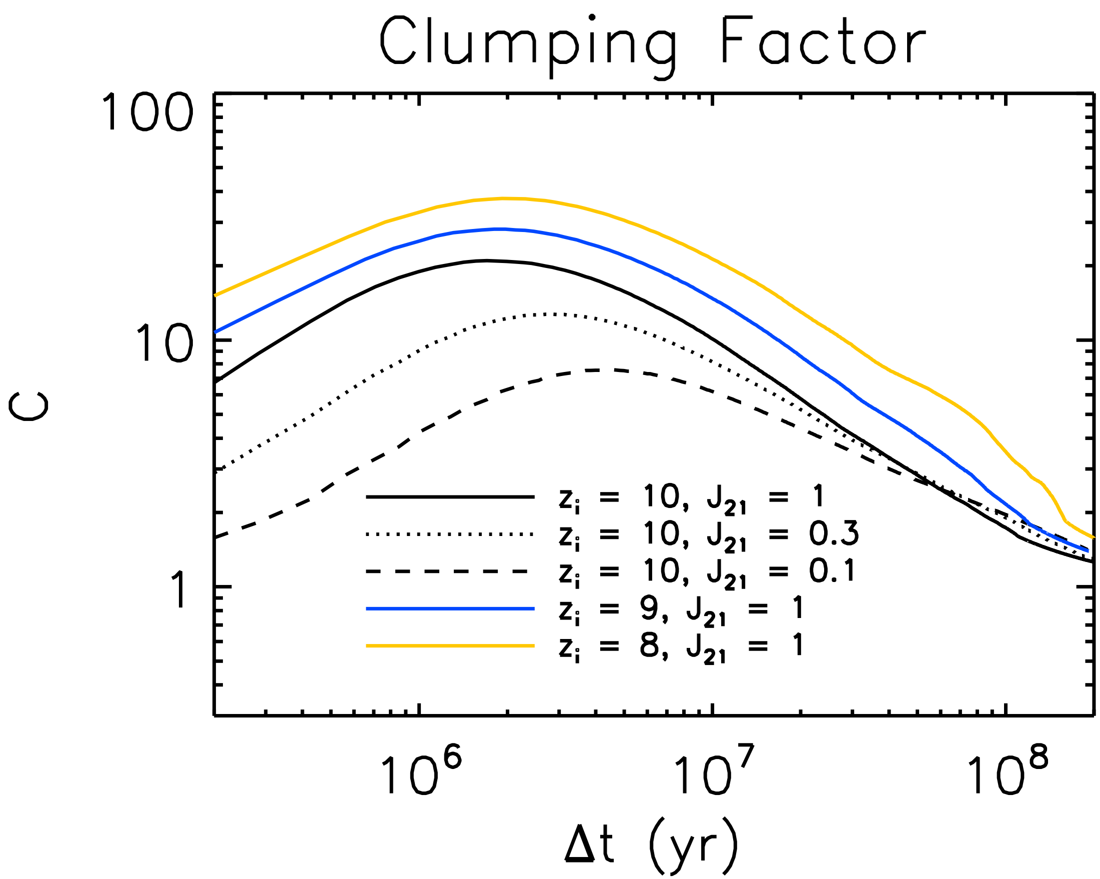
With weaker intensity, less recombination due to not being able to ionized as dense as before.





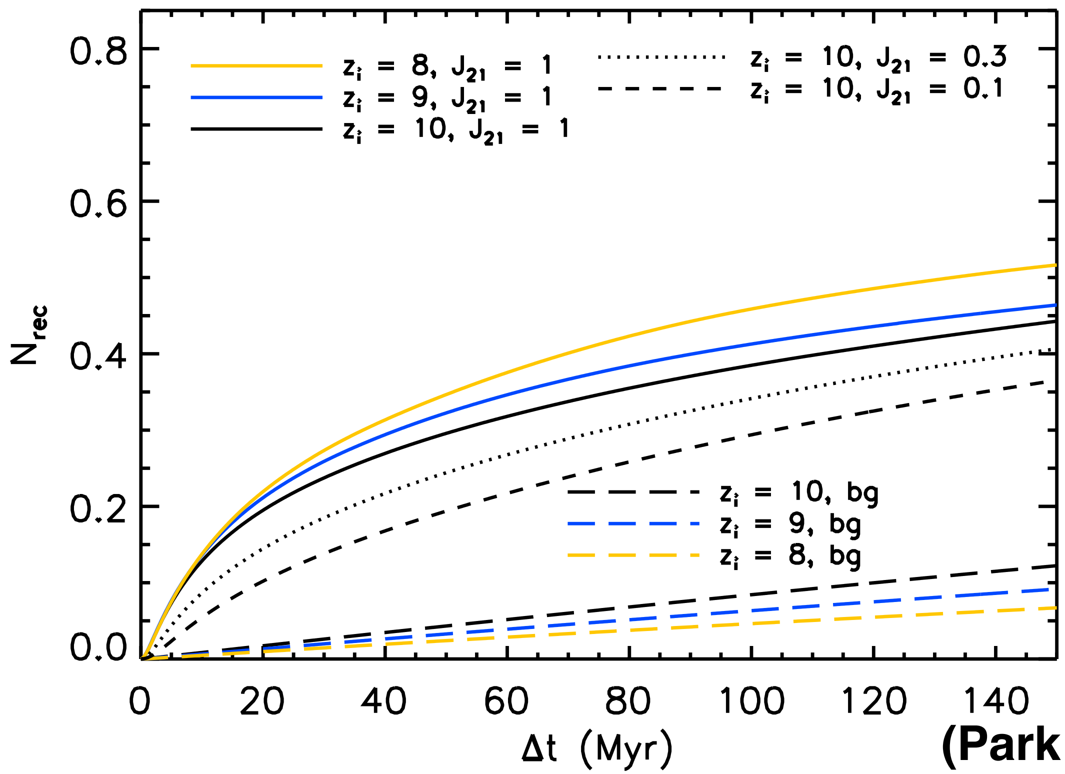
(Park et al. 2016)

For different J_{21}'s and z_i's



Higher recombination for lower z_i and higher J_{21}.

Result:
Scaling for J_{21} and z_i



(Park et al. 2016)

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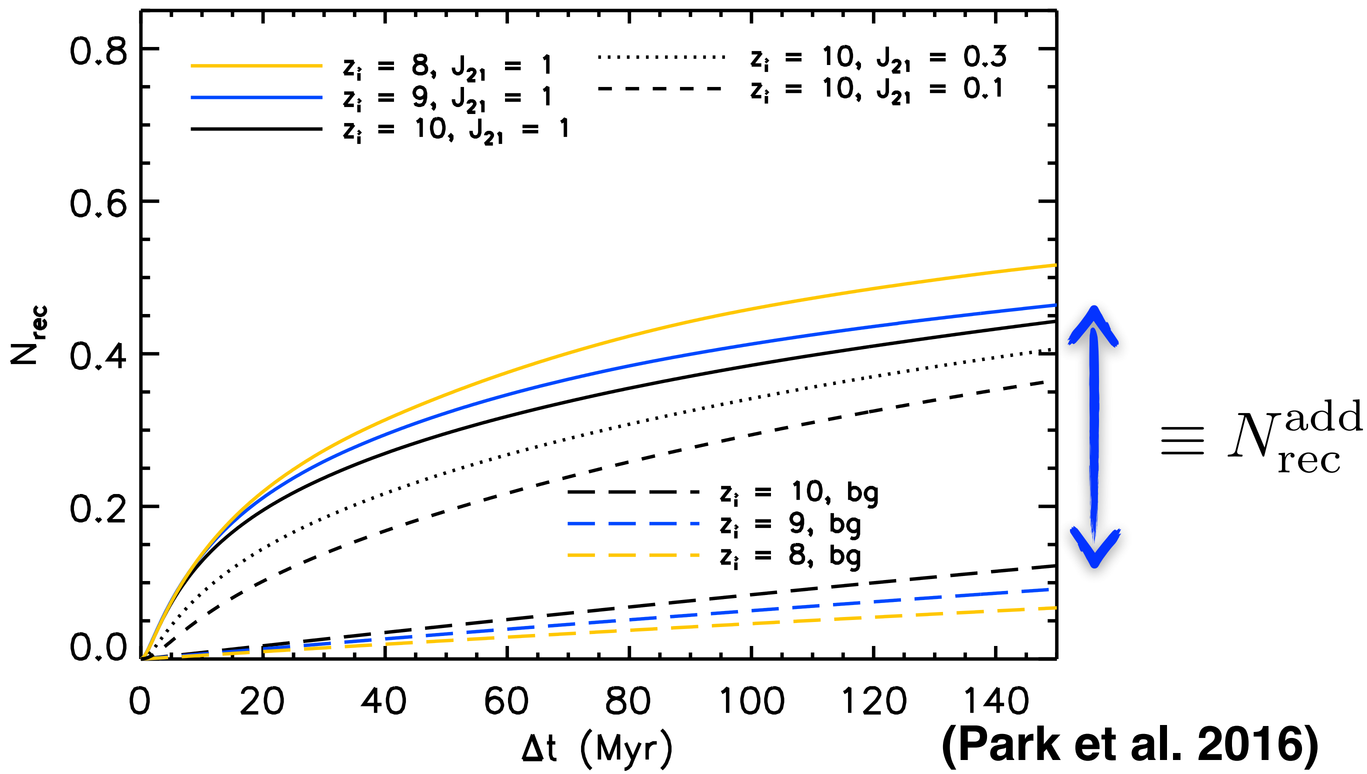
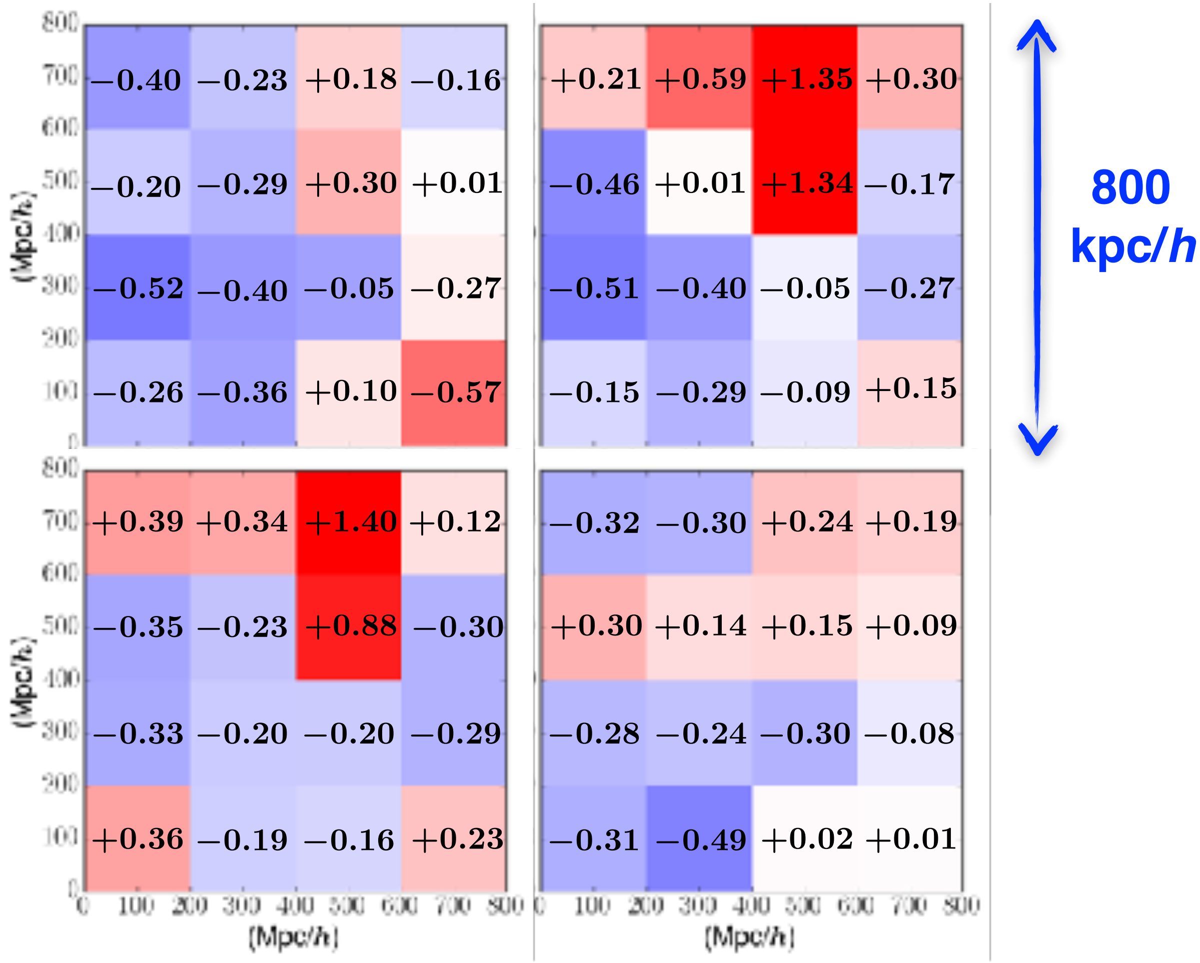


(Park et al. 2016)

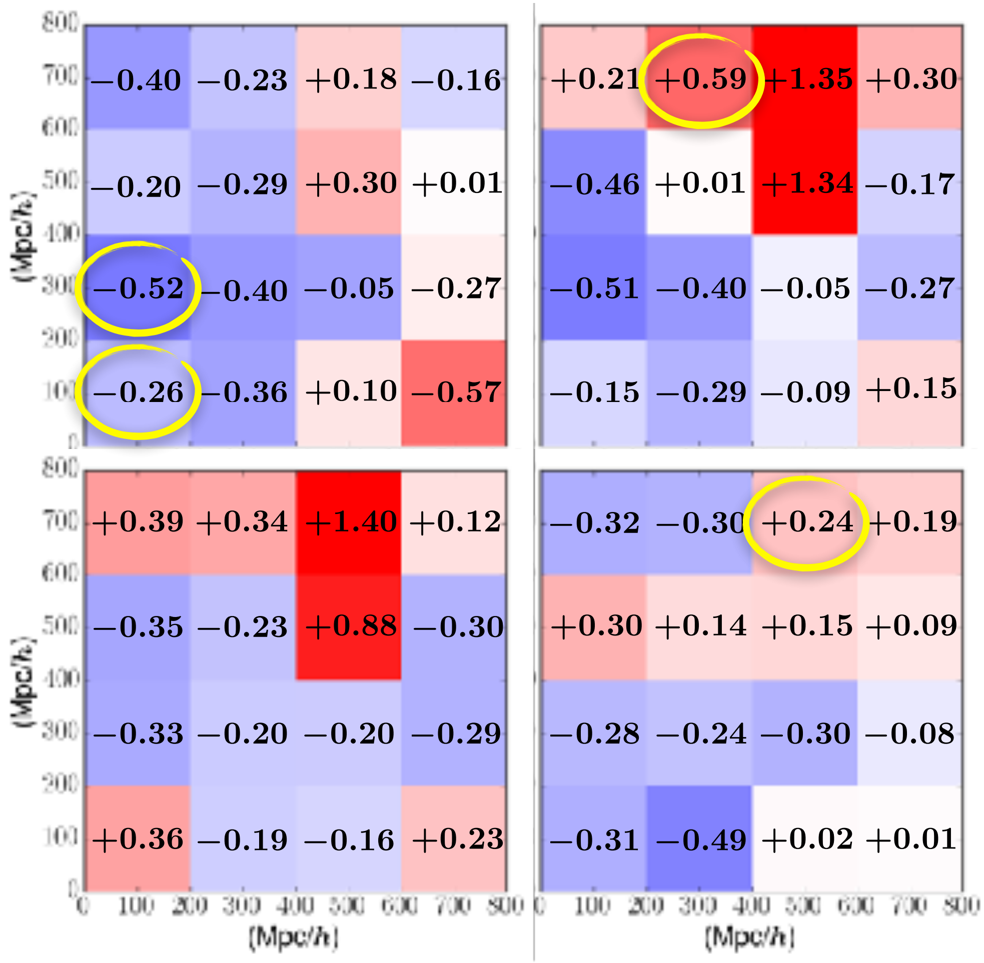
$$N_{\rm rec}^{\rm add} = 0.32 \times [J_{21}]^{0.12} \left(\frac{1+z_i}{11} \right)^{-1.7}$$

Dependence on local overdensity



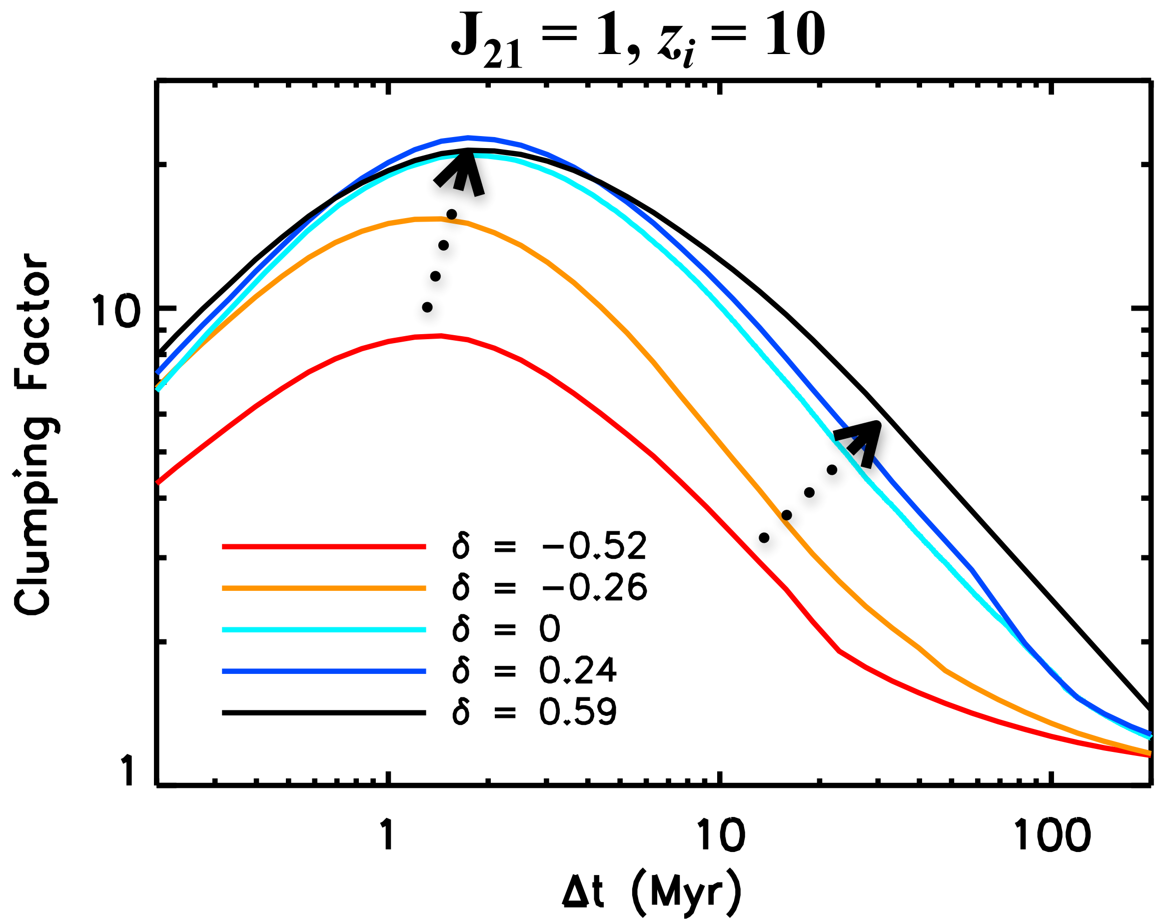
Our result from a 200 kpc/h-box with cosmic mean density is *not* representative sample of the universe.

Dependence on local overdensity



We sample sub-cubes of a 800 kpc/*h* box that δ = -0.52, -0.26, 0.24, & 0.59.

Dependence on δ



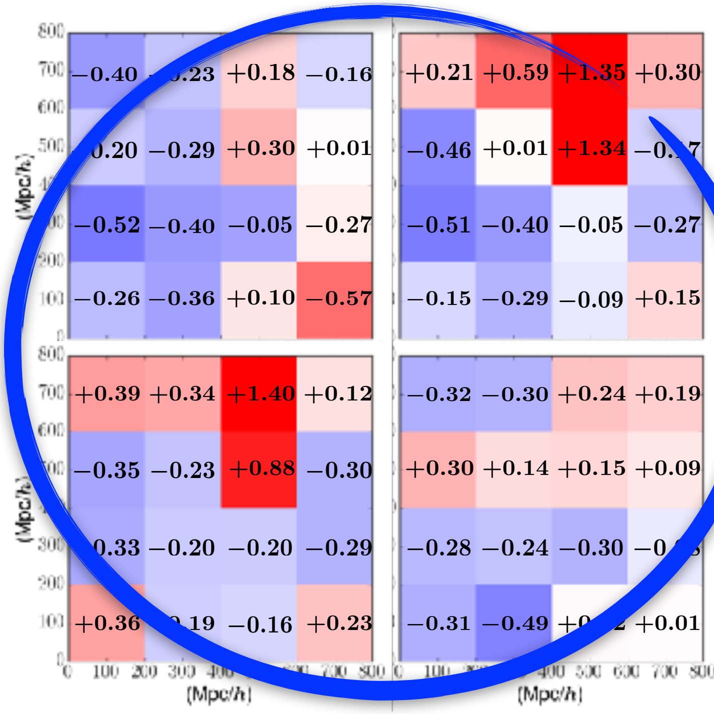
$$N_{\rm rec}^{\rm add} = 0.32 \times [J_{21}]^{0.12} \left(\frac{1+z_i}{11}\right)^{-1.7} \left[1+\bar{\delta}\right]^{2.5}$$

Extra photon budget for the $(800\ \mathrm{kpc}/h)^3$

$$N_{\rm rec}^{\rm add} = 0.32 \times \cancel{[J_{21}]^{0.12}} \cancel{\left(\frac{1+z_i}{11}\right)^{-1.7}} [1+\bar{\delta}]^{2.5}$$

$J_{21} = 1$

$z_i = 10$



$$\langle N_{\rm rec}^{\rm add} \rangle_{800\ {\rm kpc}/h} = \frac{1}{64}\sum_{i}^{64}[1+\bar{\delta}_i]N_{\rm rec,i}^{\rm add} = \frac{1}{64}\sum_{i}^{64} 0.32[1+\bar{\delta}_i]^{3.5} = 0.67$$

Ionizing photon budget

1 for ionizing first time

+

1 - 3 for recombination in large-scale structure

+

If $J_{21} = 1$ & $z_i = 10$

$\geq$ 0.67 due to recombination in small-scale structure

Significantly large!

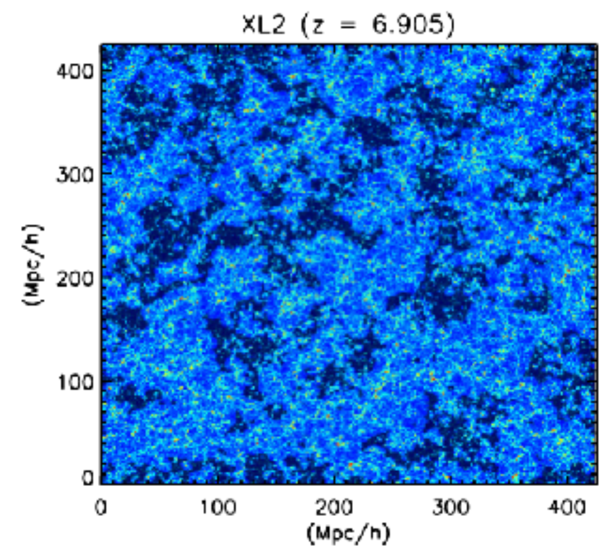
For more realistic global recombination rate, we need to apply our results to large-scale simulations.

Next step

- Implement the small-scale recombination in large-scale simulations.

  - Obtain more realistic global ionization budget

  - Update details of patchy reionization and change prediction for the observables.



Possible improvements to be made for this work

- Larger volume
- Lower (< 10) turn-on redshift
- Uni-directional ionizing radiation

Other physics that may matter

- Streaming velocity between dark matter and baryon would suppress small-scale structures.
- X-ray background may pre-heat the IGM and suppress small-scale structures.

Summary

- We find that small-scale structure add

$$N_{\rm rec}^{\rm add} = 0.32 \times [J_{21}]^{0.12} \left(\frac{1+z_i}{11}\right)^{-1.7} \left[1+\bar{\delta}\right]^{2.5}$$

  recombination per H atom. This is significant enough to change the history of reionization.

- Ultimately, we want to apply our result in large-scale simulations as sub-grid prescription to make more precise observable prediction.