Korea Astronomy & Space Science Institute
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Recombination in Small-scale Structures During the Cosmic Reionization

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東京大学
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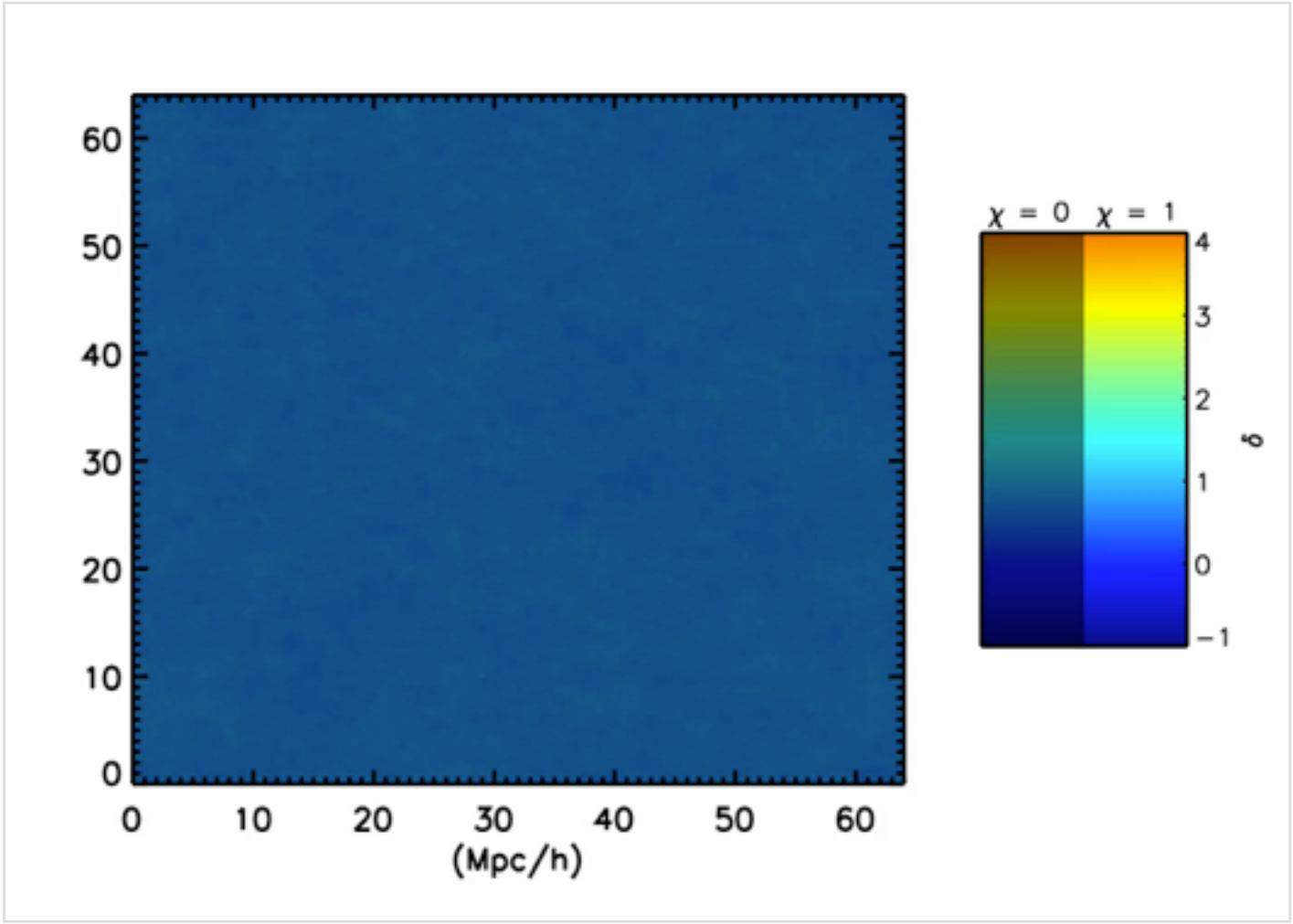
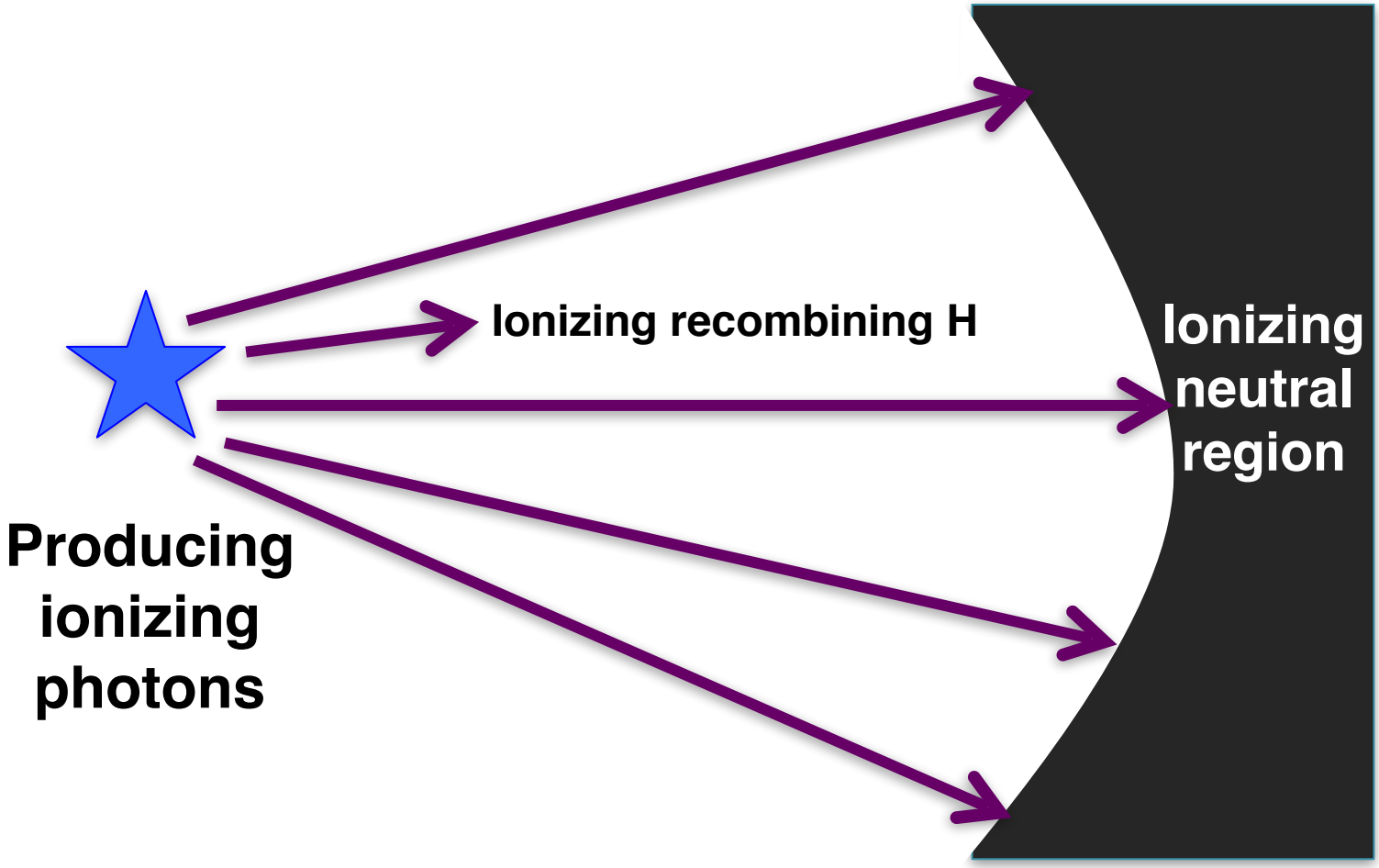
(Park et al. in preparation)

Cosmic Reionization



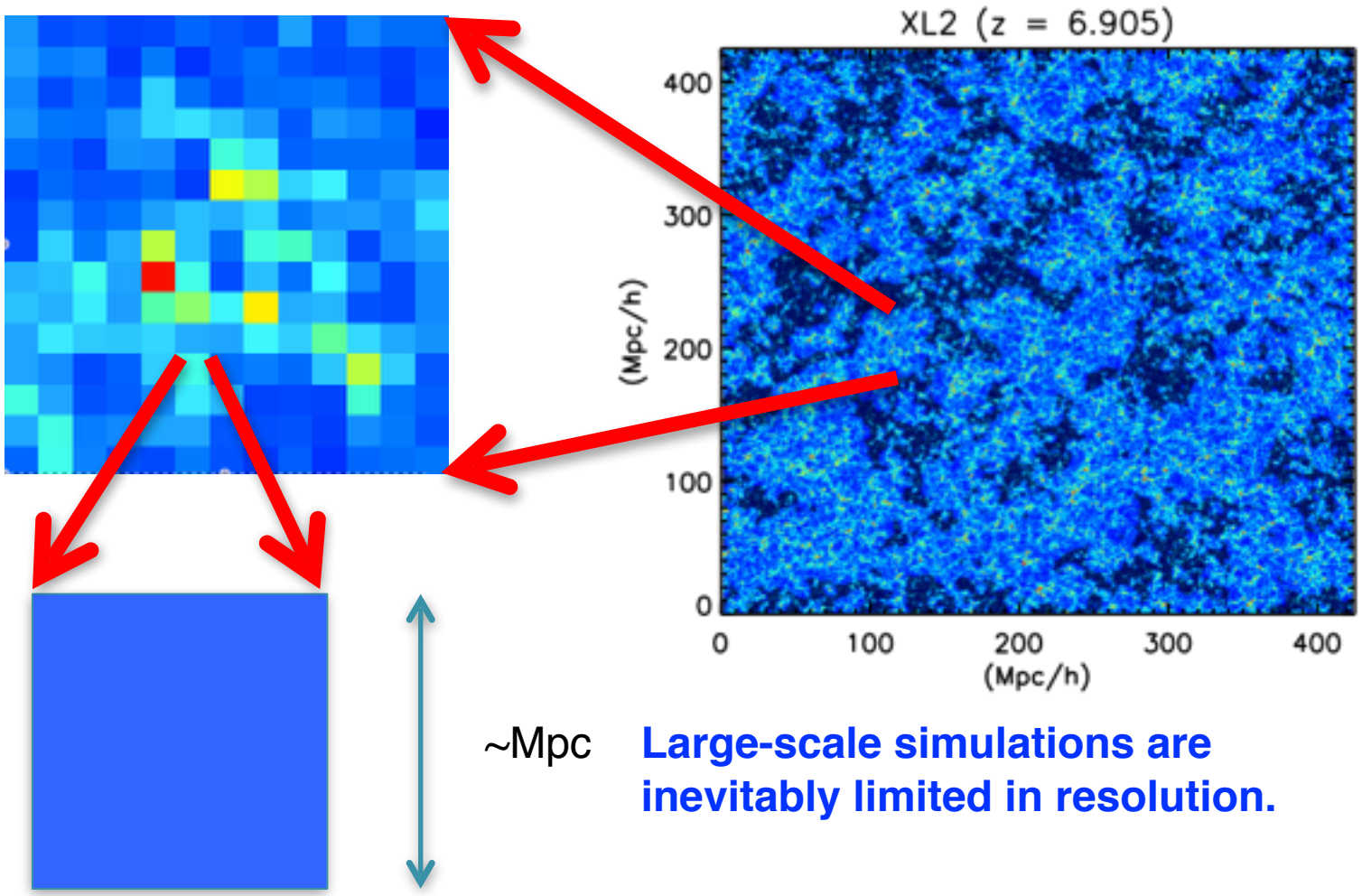
Galaxies produce ionizing (>13.6 eV) photons.
Those photons are consumed to ionize intergalactic gas.

Photon Consumption during Reionization



Ionizing photons are consumed to
(1) ionize HI in the neutral regions and
(2) recombining H in the ionized region.

Resolution Limit in Large-scale EoR Simulation

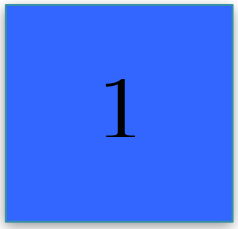
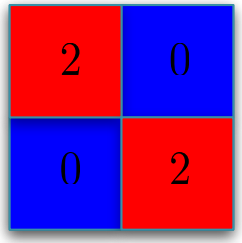


Large-scale simulations are inevitably limited in resolution.

Recombination & Clumping Factor

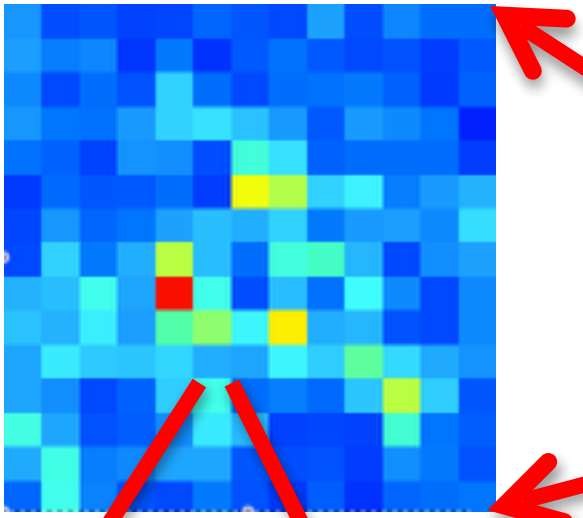
$$\langle R \rangle_V \propto \langle \rho^2 \rangle_V \neq \langle \rho \rangle_V^2$$

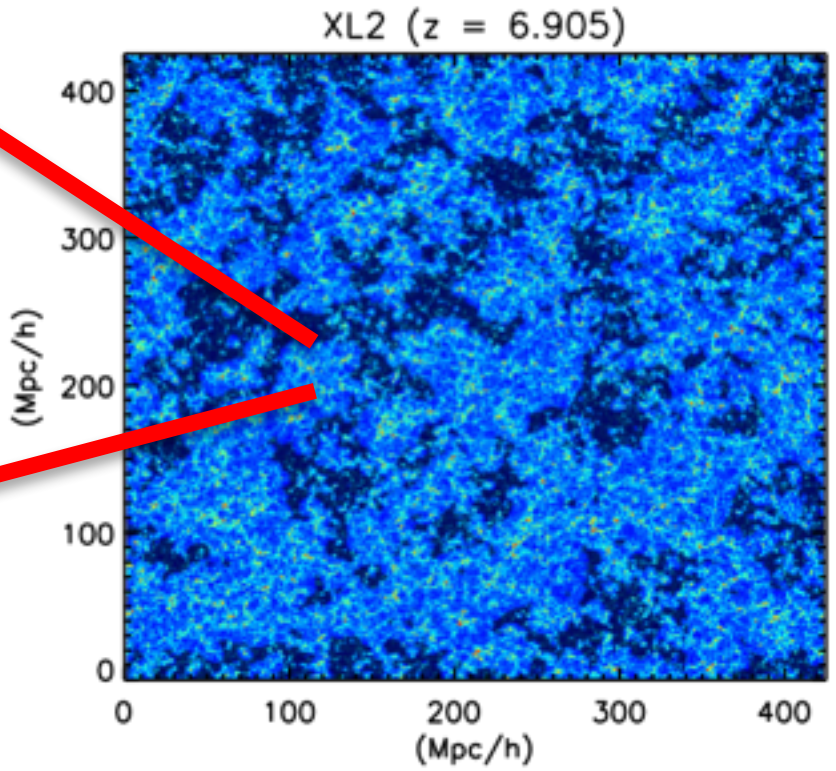
Square of average does not equal to average of square!

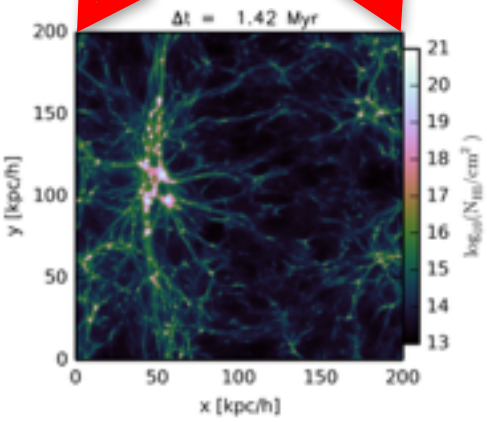
	
$\langle \rho^2 \rangle = \langle \rho \rangle^2 = 1$	$\langle \rho^2 \rangle = 2, \ \langle \rho \rangle^2 = 1$
$C \equiv \dfrac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \dfrac{(\text{Actual})}{(\text{Approximate})}$	
$C = 1$	$C = 2$

Clumping factor quantifies the underestimation of the recombination rate due to unresolved density fluctuations.

“Sub-grid” Clumping Factor

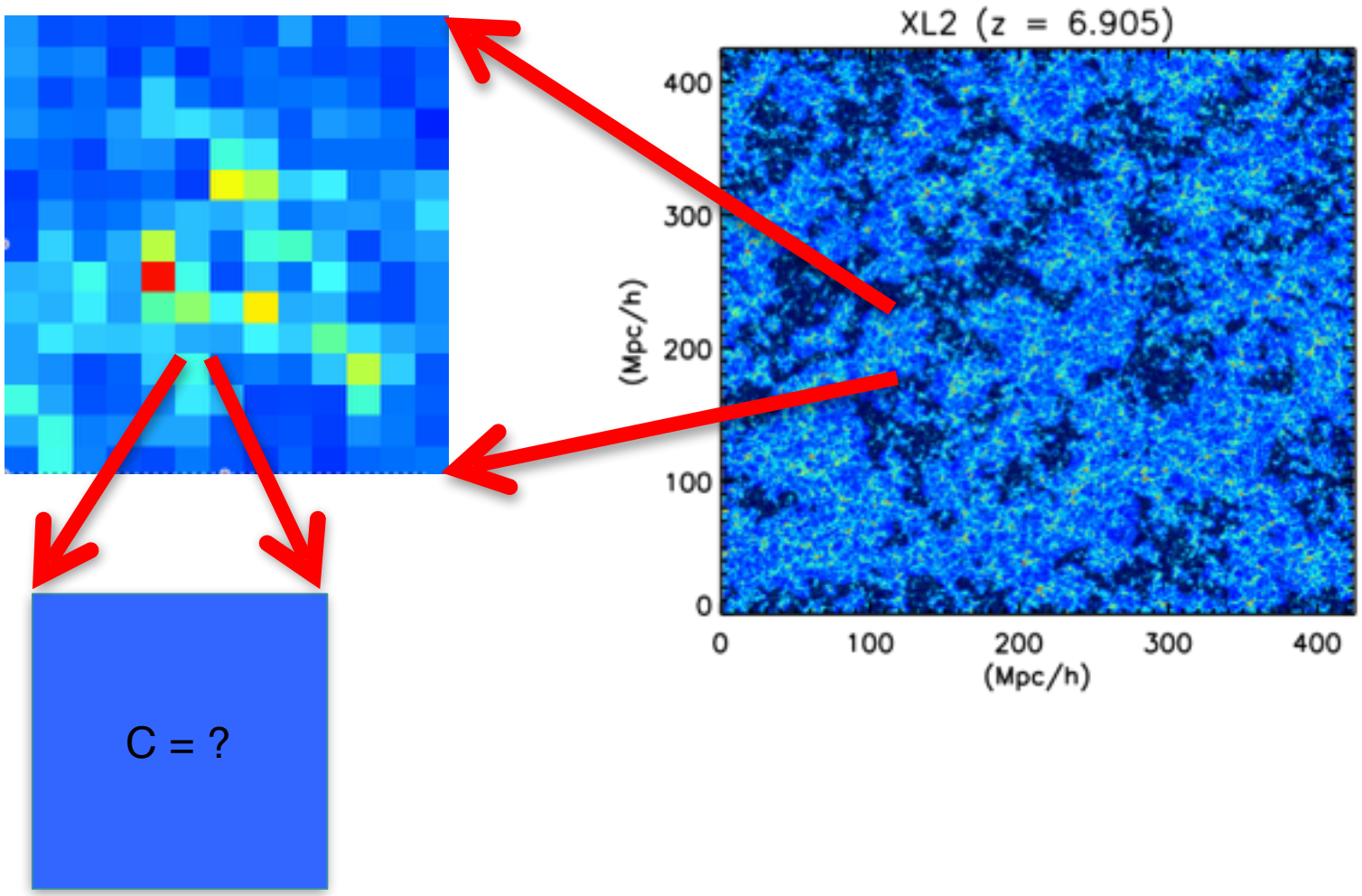






We shall model density structures in sub-Mpc to complement large-scale simulations.

“Sub-grid” Clumping Factor



Simulation Setup

Code : GADGET-3

Size : 200 kpc/h

Resolution : $M_{DM} = 51\ M_{\odot}$ ($N = 256^3$)

Star Formation : Suppressed by LW background

Ionizing Radiation :

Isotropic

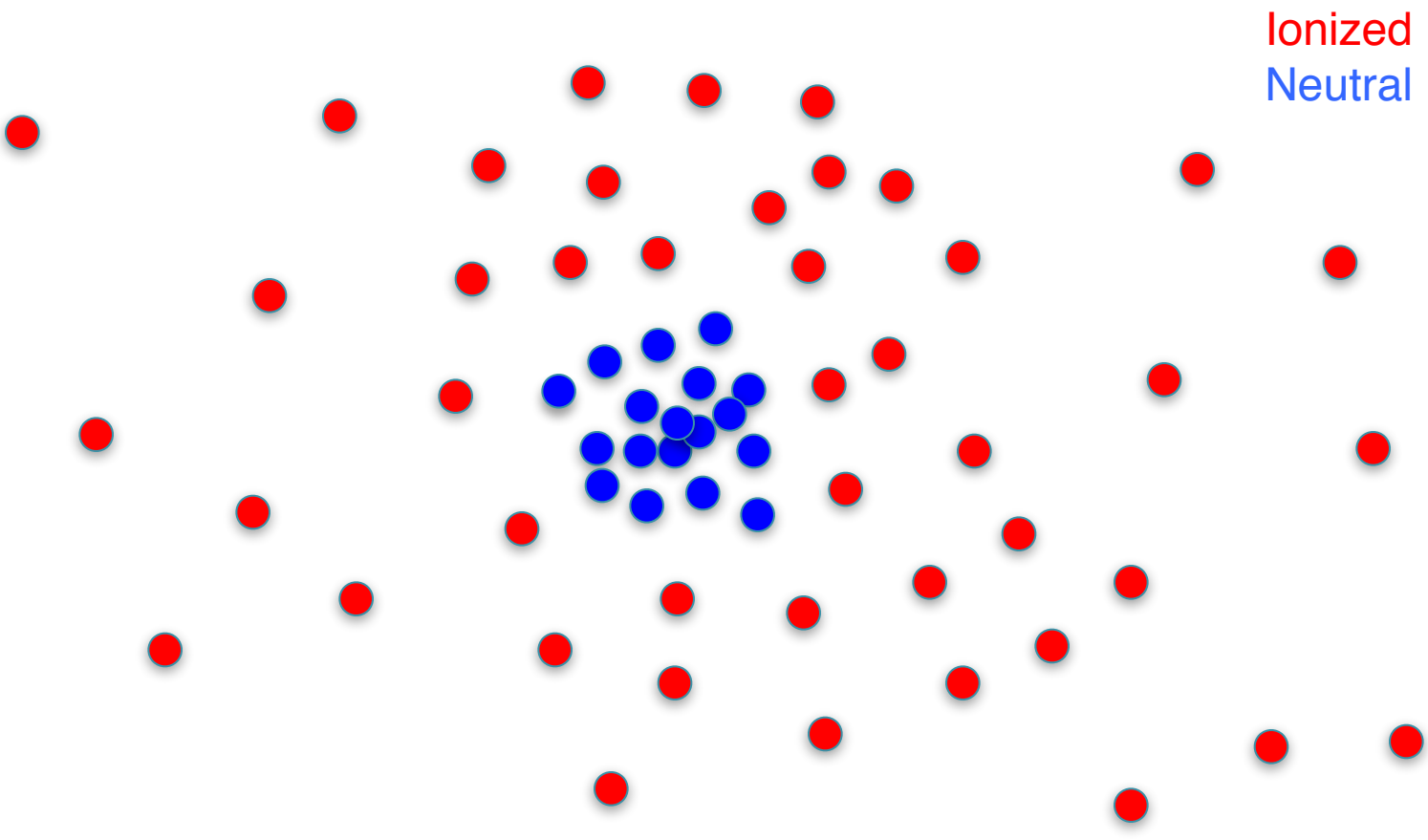
External Background

$T = 10^5$ K black-body with $J_{21} = 1, 0.3, 0.1$

Turned on at $z_i = 10, 9, 8$

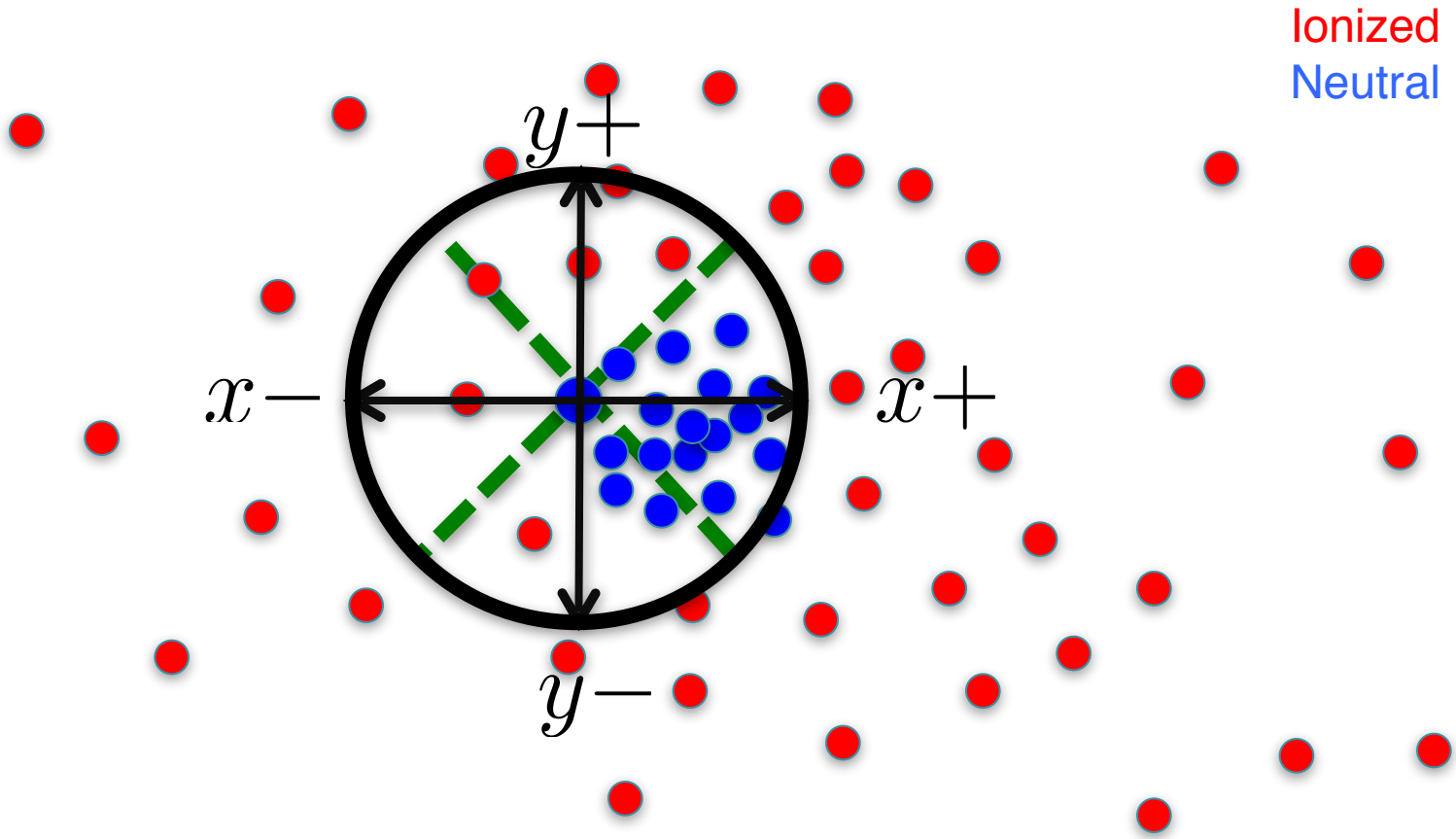
J_{21} : intensity in the unit of 10^{-21}(erg/s/Hz/std/cm^2)

Shielding Algorithm for Minihalos



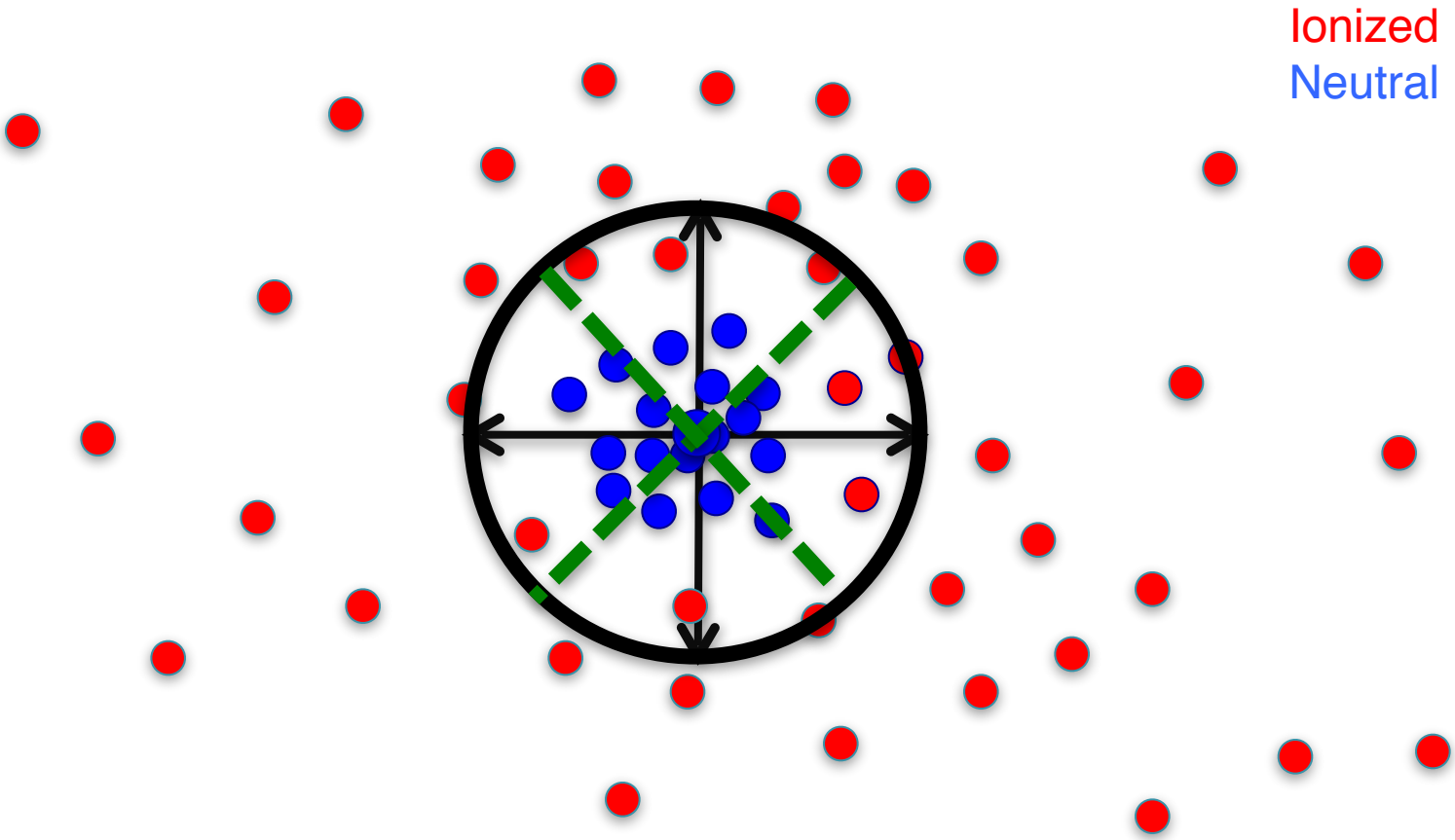
Most gas will ionized immediate except dense gas in minihalos that will be able to shield against the external background.

Shielding Algorithm for Minihalos



1) Search for neutral particles within 200 kpc/h physical.
2) Attenuation using neutral column density in 6 directions.
(+x, -x, +y, -y, +z, -z)

Shielding Algorithm for Minihalos



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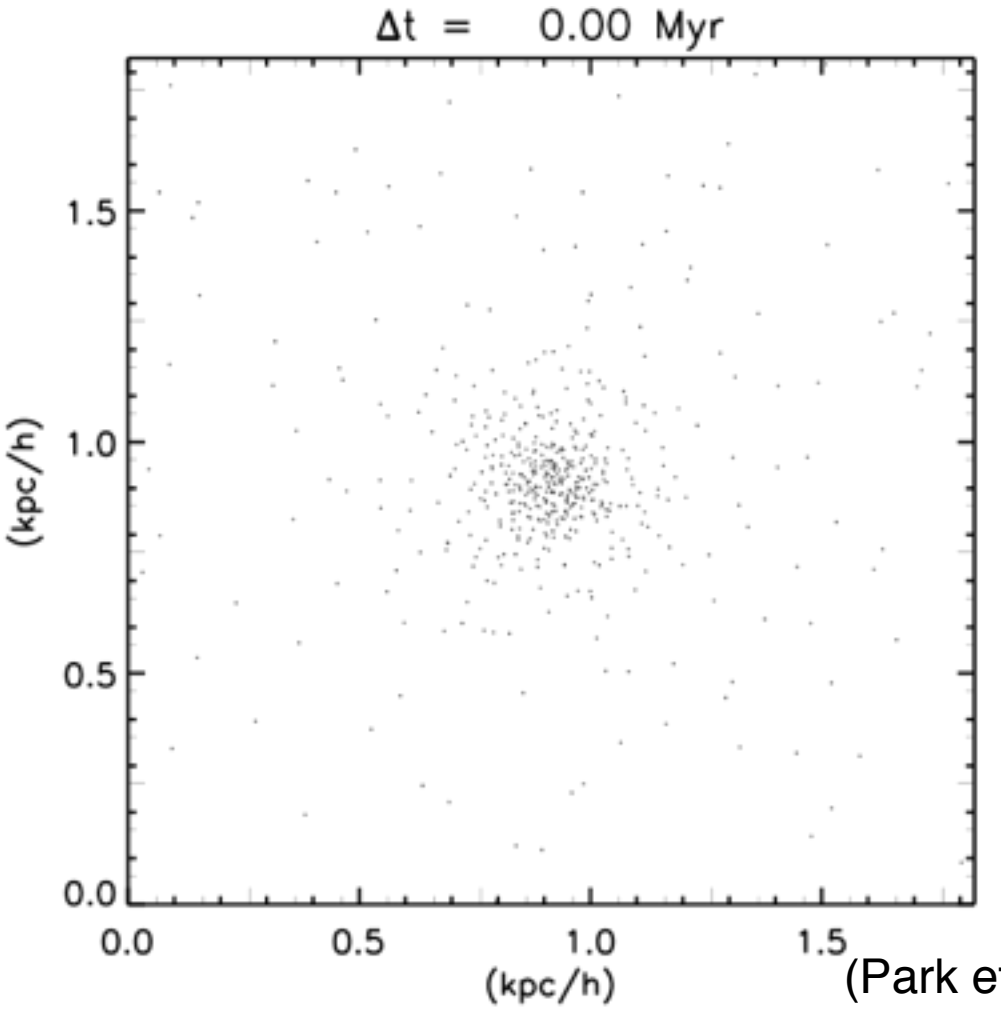
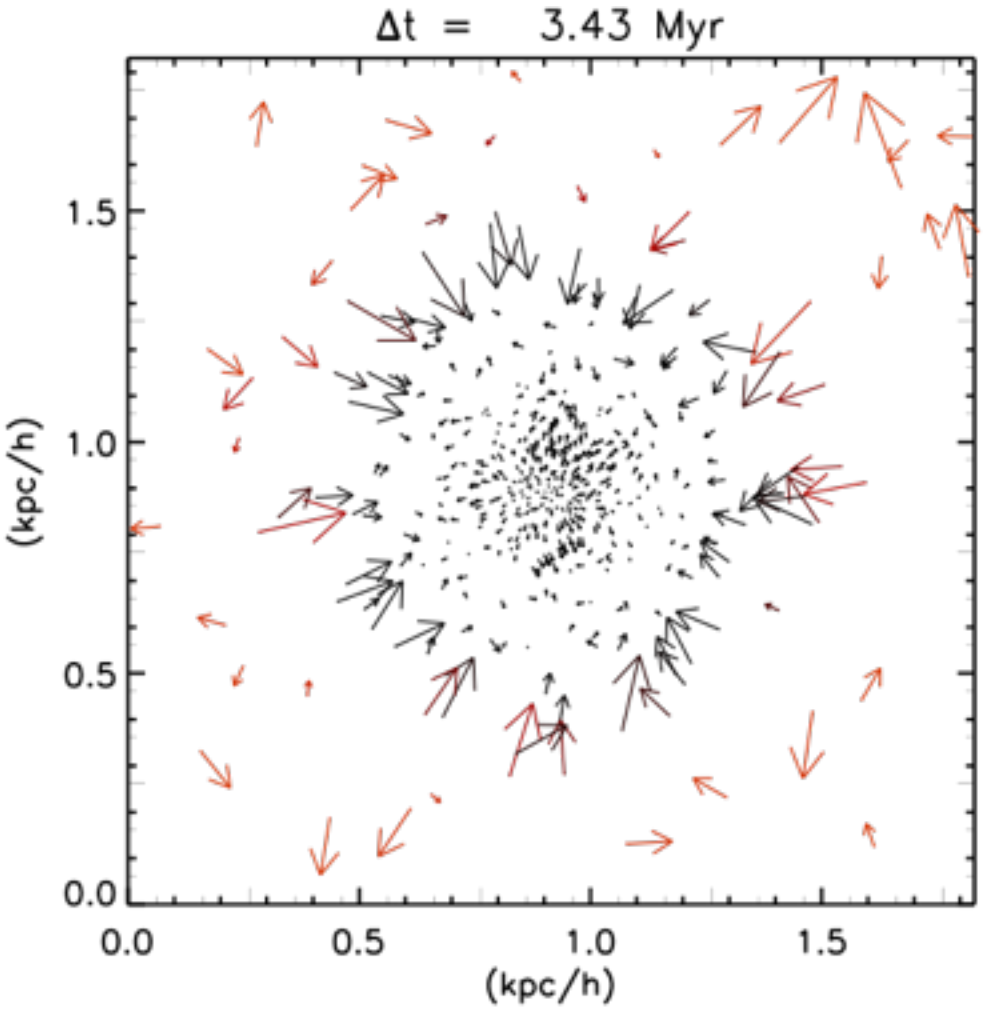
Test Problem : Spherically Symmetric Halo



(Park et al. 2015 in prep.)

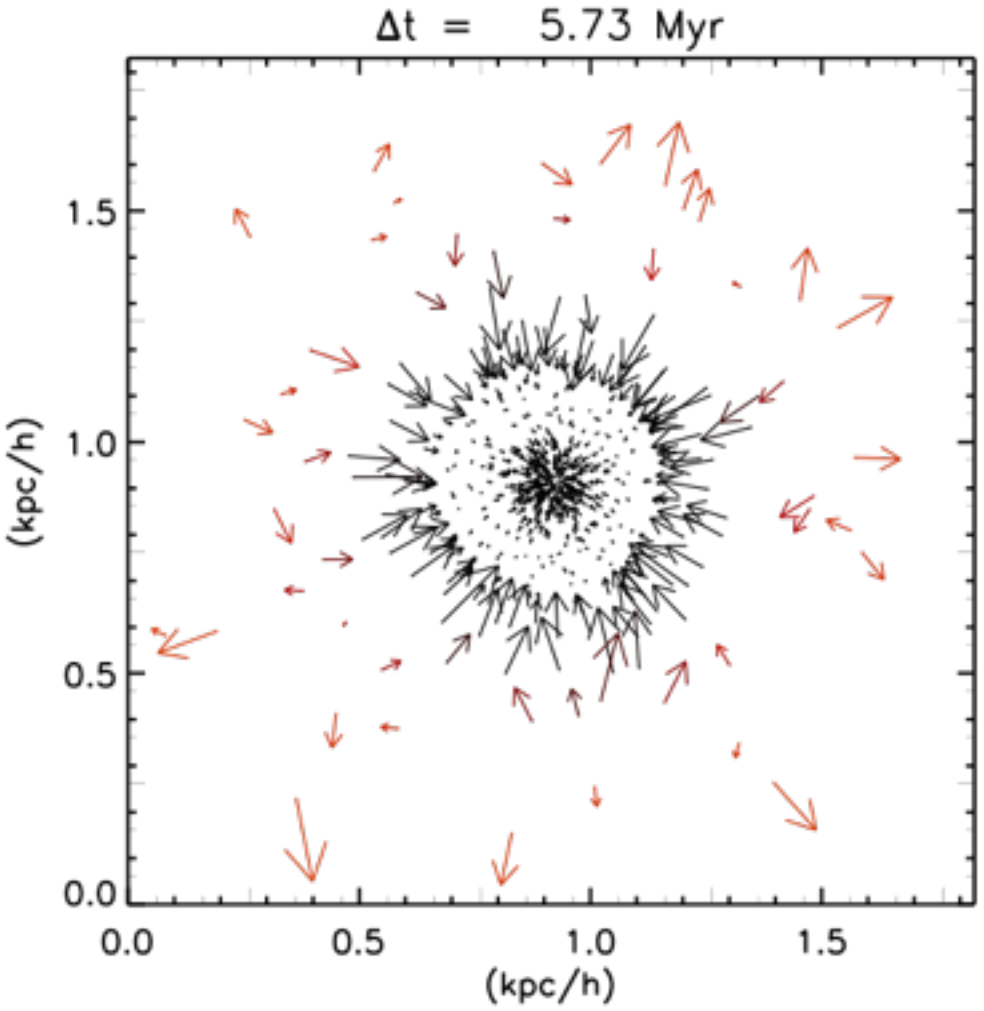
We test our shielding algorithm again the 1D rad-hydro code of Ahn et al. (2007).

Test Problem : Spherically Symmetric Halo



Ionized
Neutral

Test Problem : Spherically Symmetric Halo



Ionized
Neutral

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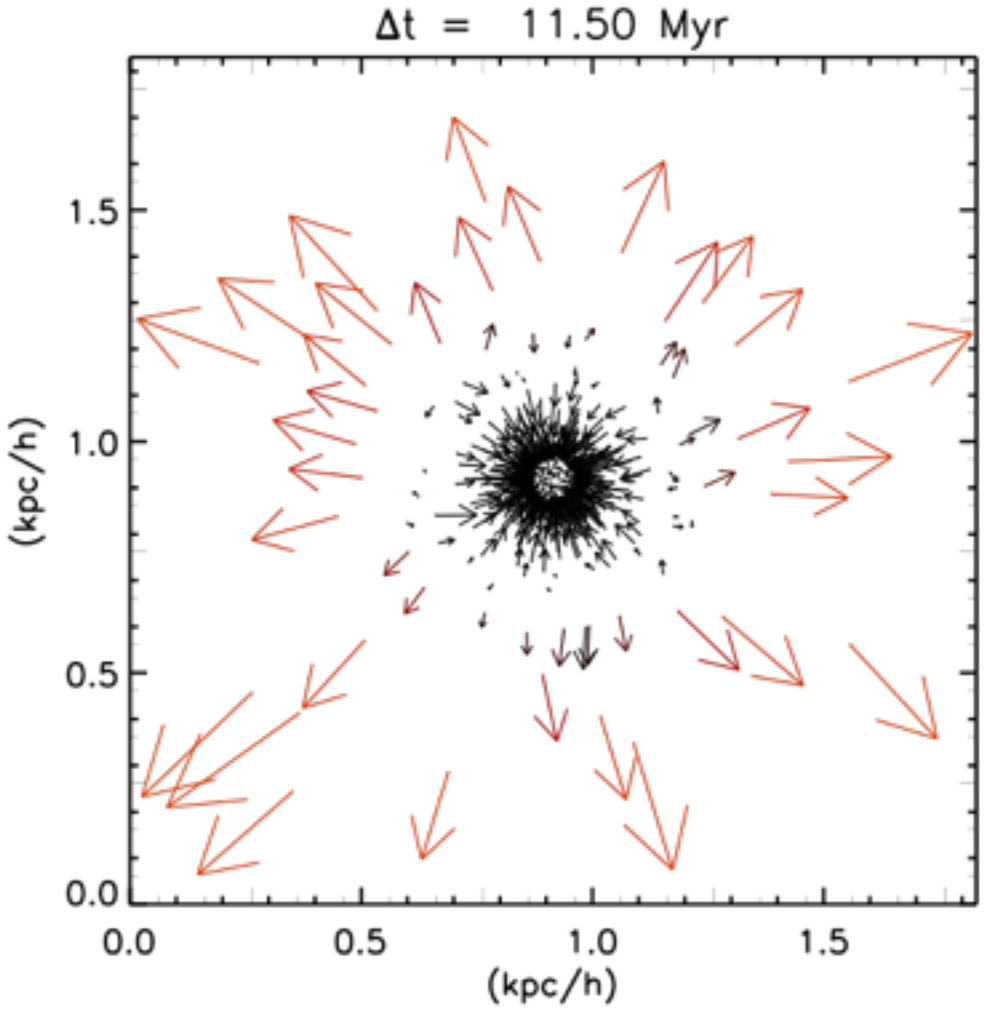


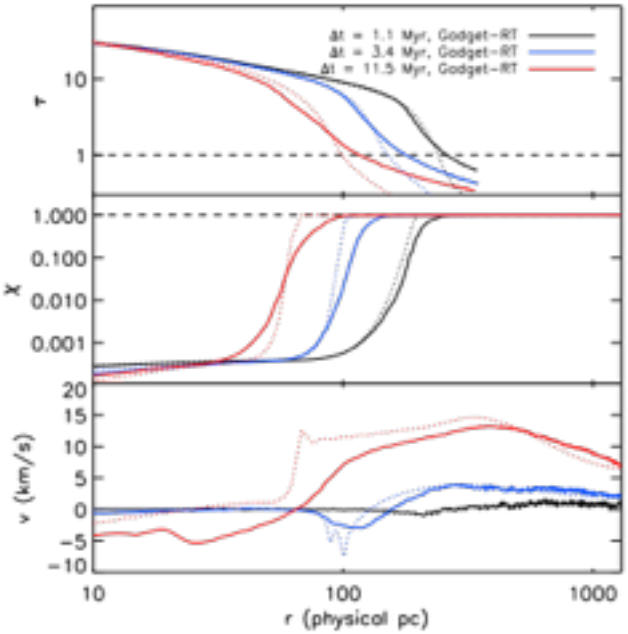
Ionized
Neutral

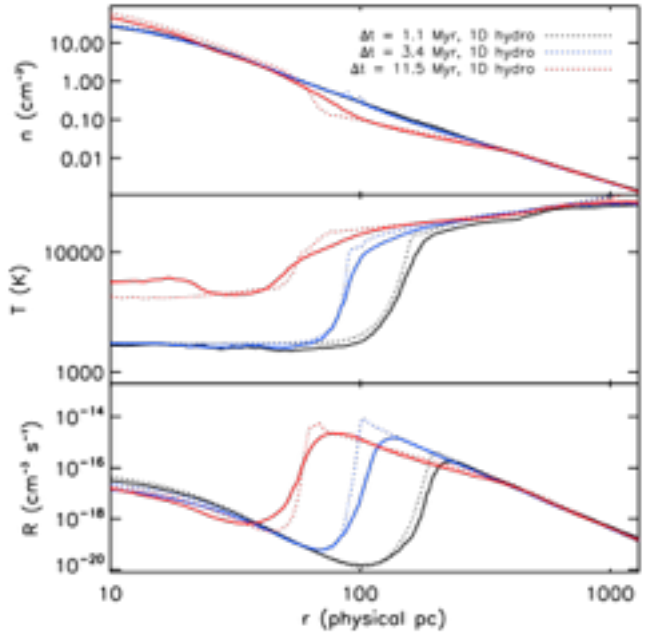
Test Result:
Radial Profiles of Physical Quantities

Optical depth

Ionized Fraction

Radial Velocity





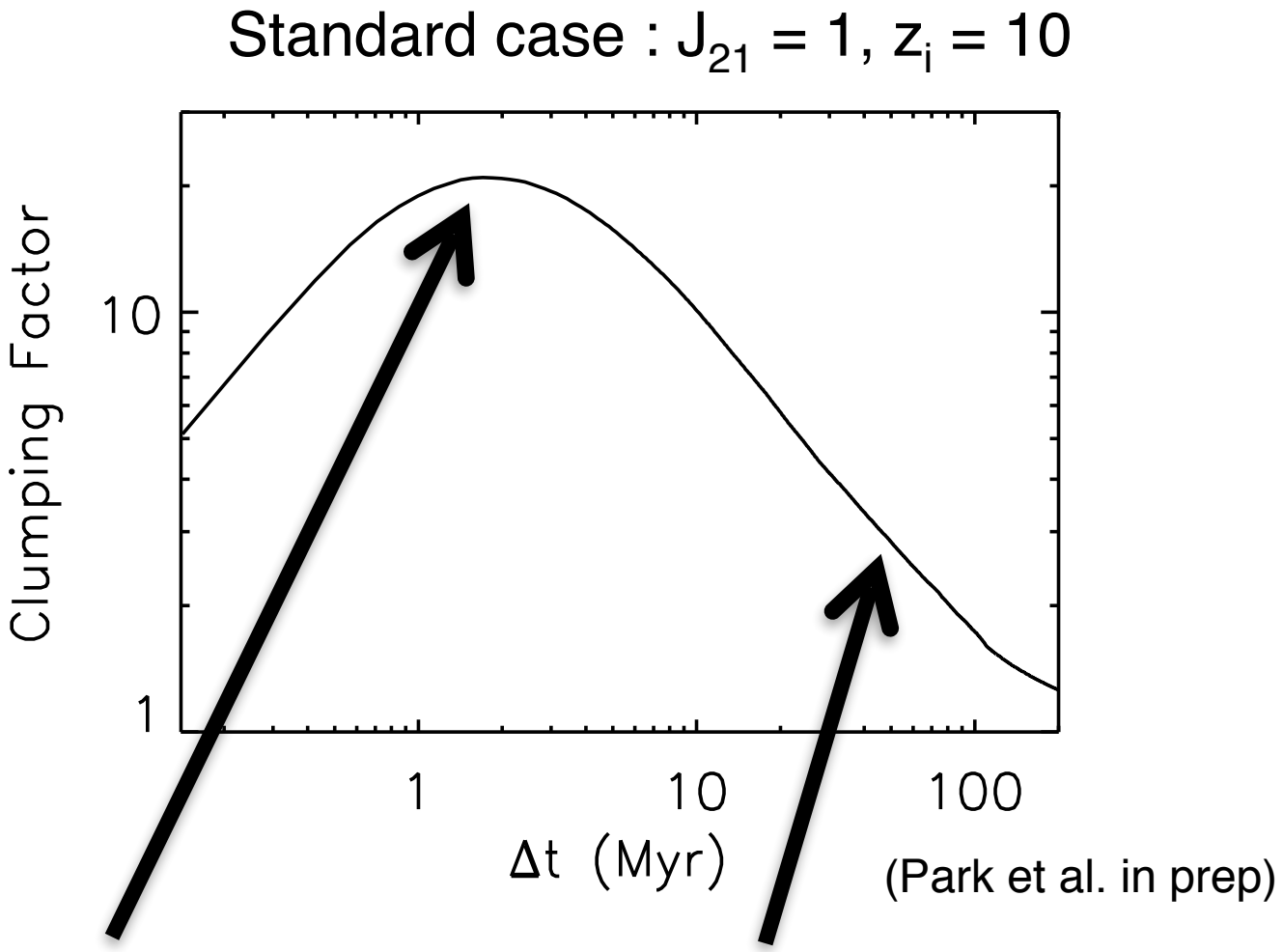
Density

Temperature

Recombination Rate

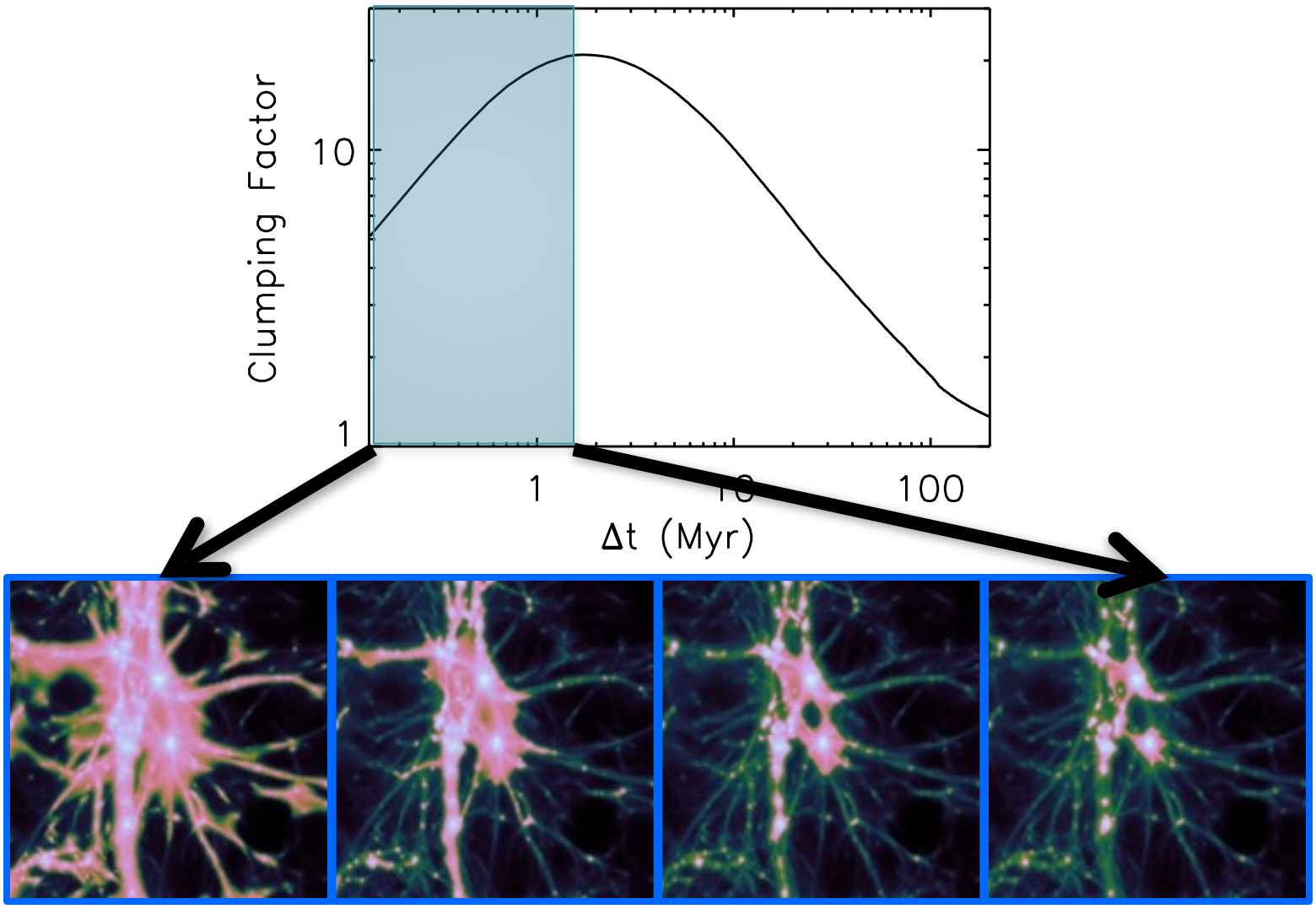
We agree very well with the 1D code of Ahn et al. (2007).

Result : Clumping Factor

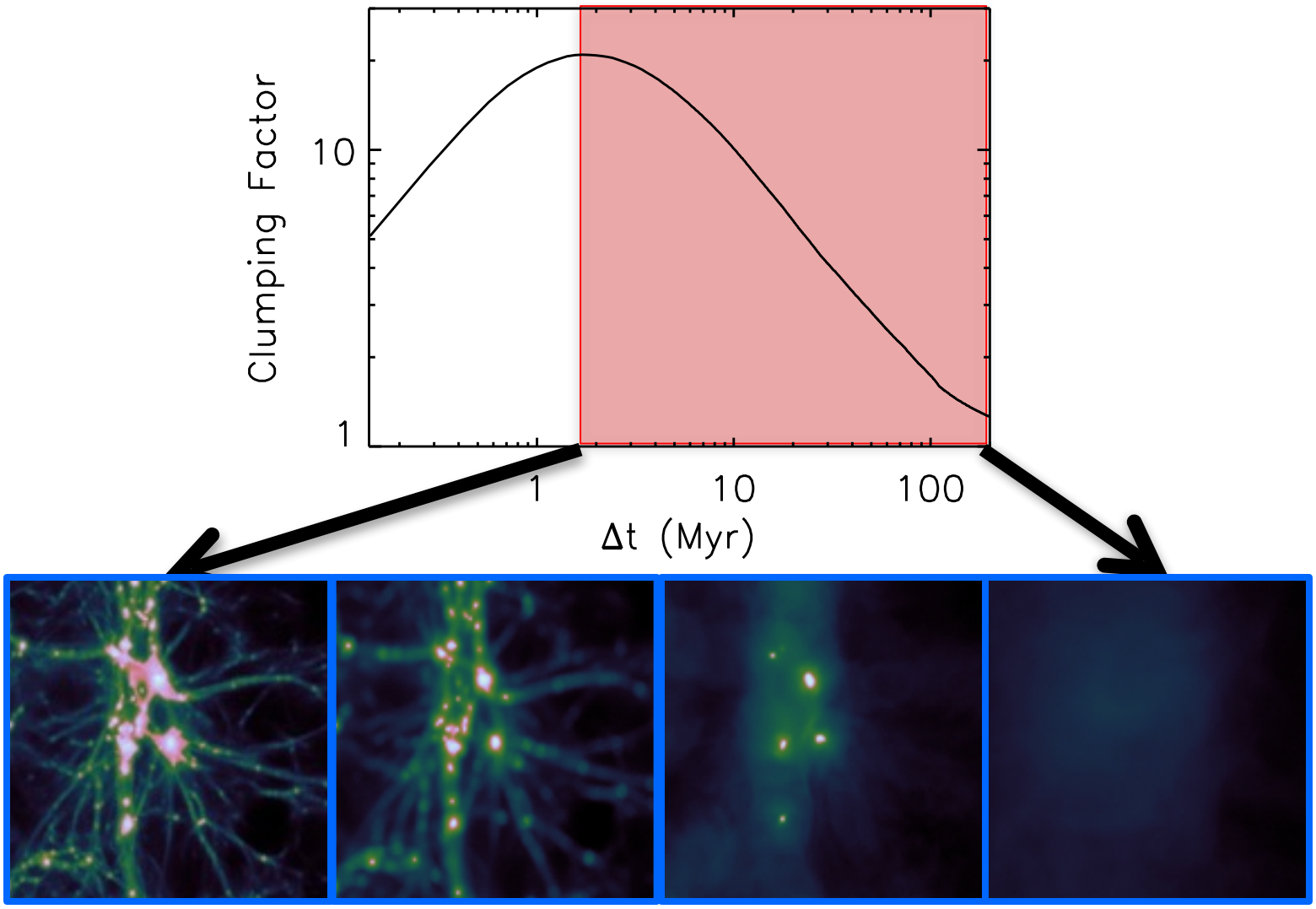


High clumping factor early and low clumping factor later.

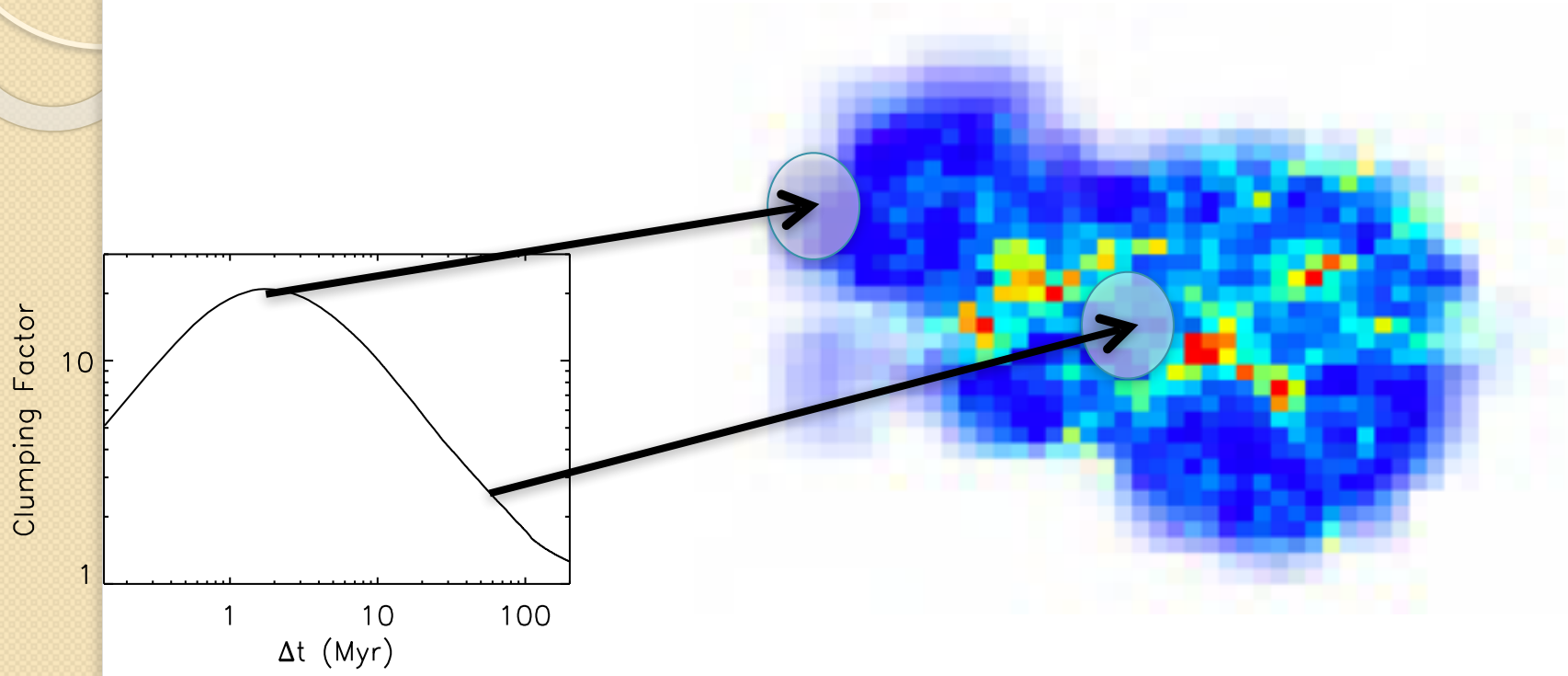
Clumping Factor at Early Time: Static Density Field



Clumping Factor at Late Time: Hydrodynamic Feedback

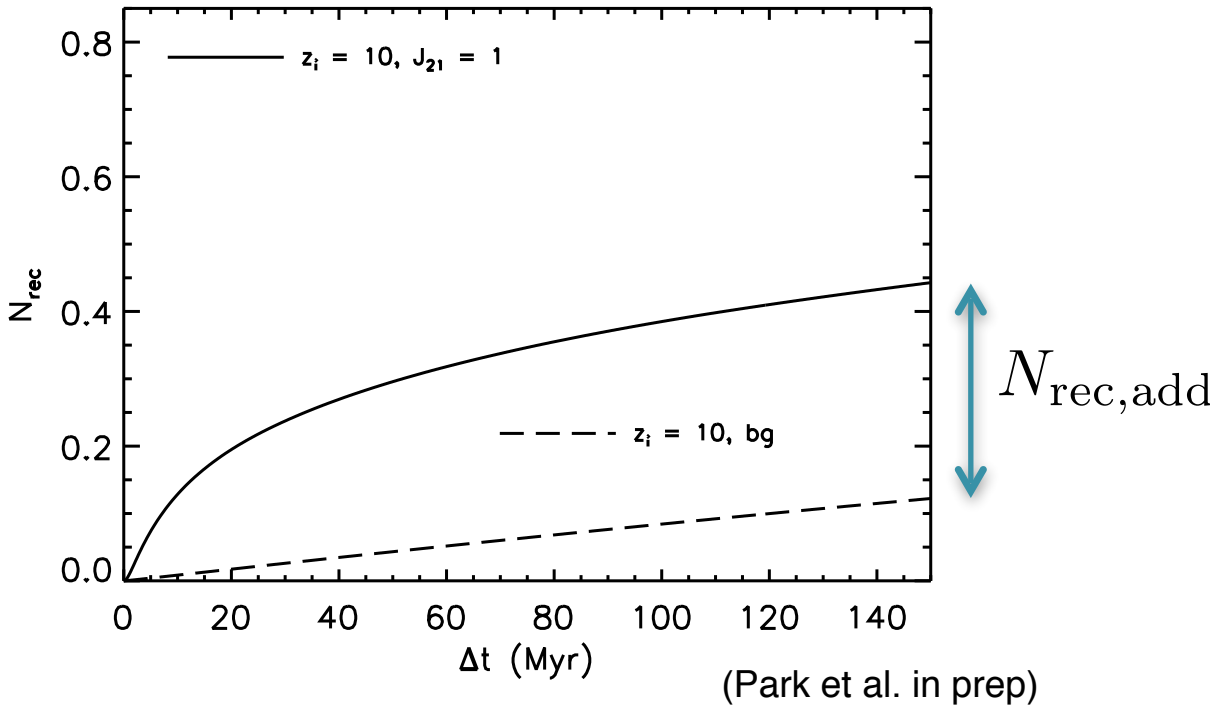


Impact 1: Bubble Growth



The outer part of HII regions will consume more photon.
Bubble growth rate will change!

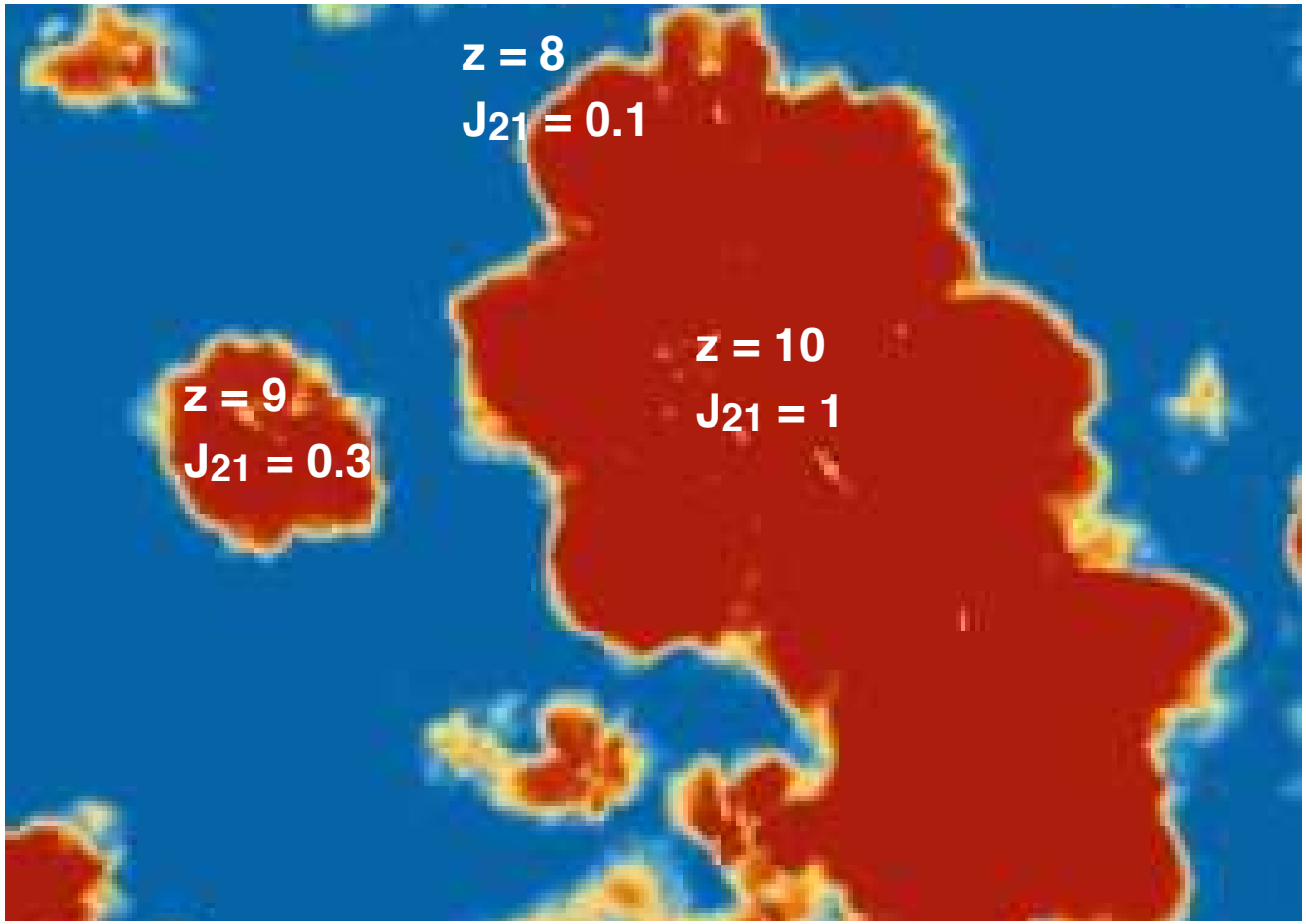
Impact 2: Photon Budget for Reionization



(Park et al. in prep)

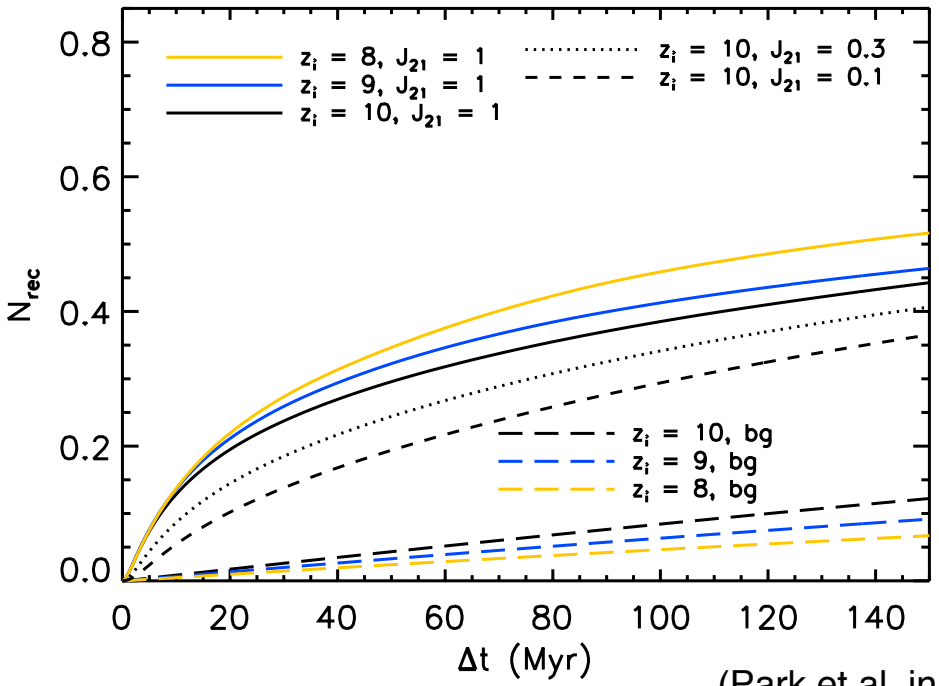
Small-scale structures end up with 0.3 recombination per HI.

Parameters for a sub-Mpc volume



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

N_{rec} as the Functions of z and J_{21}



(Park et al. in prep)

$$N_{\rm rec,add} \approx 0.3 \times J_{21}^{0.15} \left(\frac{z+1}{11} \right)^{-1.6}$$

Later reionization and higher intensity lead to more recombination.

Summary & Conclusion

Small-scales structures would…

- add 0.2~0.5 more recombination per HI. More photons (i.e. more galaxies) needed to achieve the cosmic reionization.
- would boost recombination in the outer part of HII regions. Observational features from HII bubbles will be impacted.

Thank you !