

Kavli IPMU Colloquium (Oct 9th, 2020)

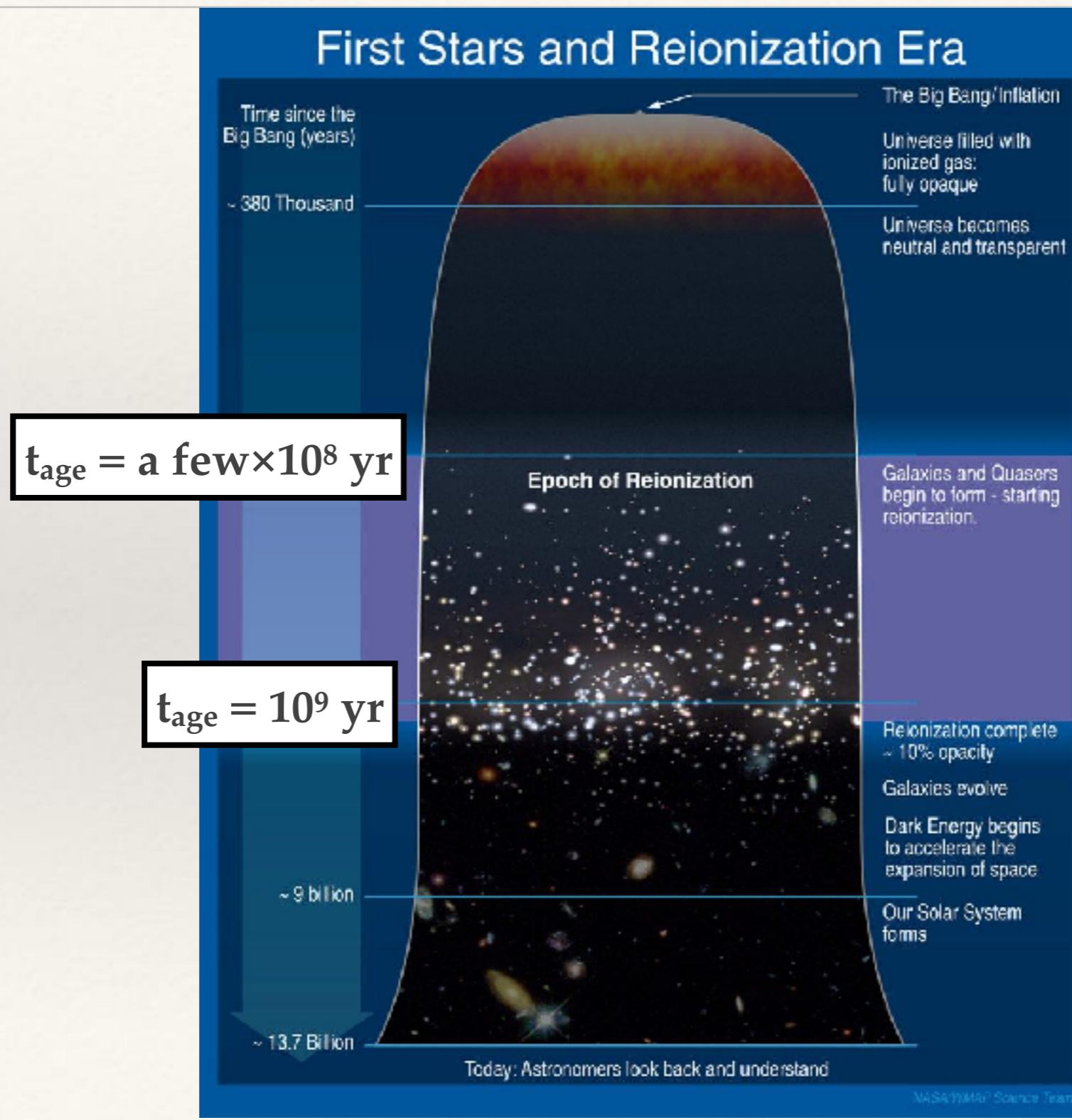
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## Scatter in Reionization History Induced by Baryon-Dark Matter Streaming Motion

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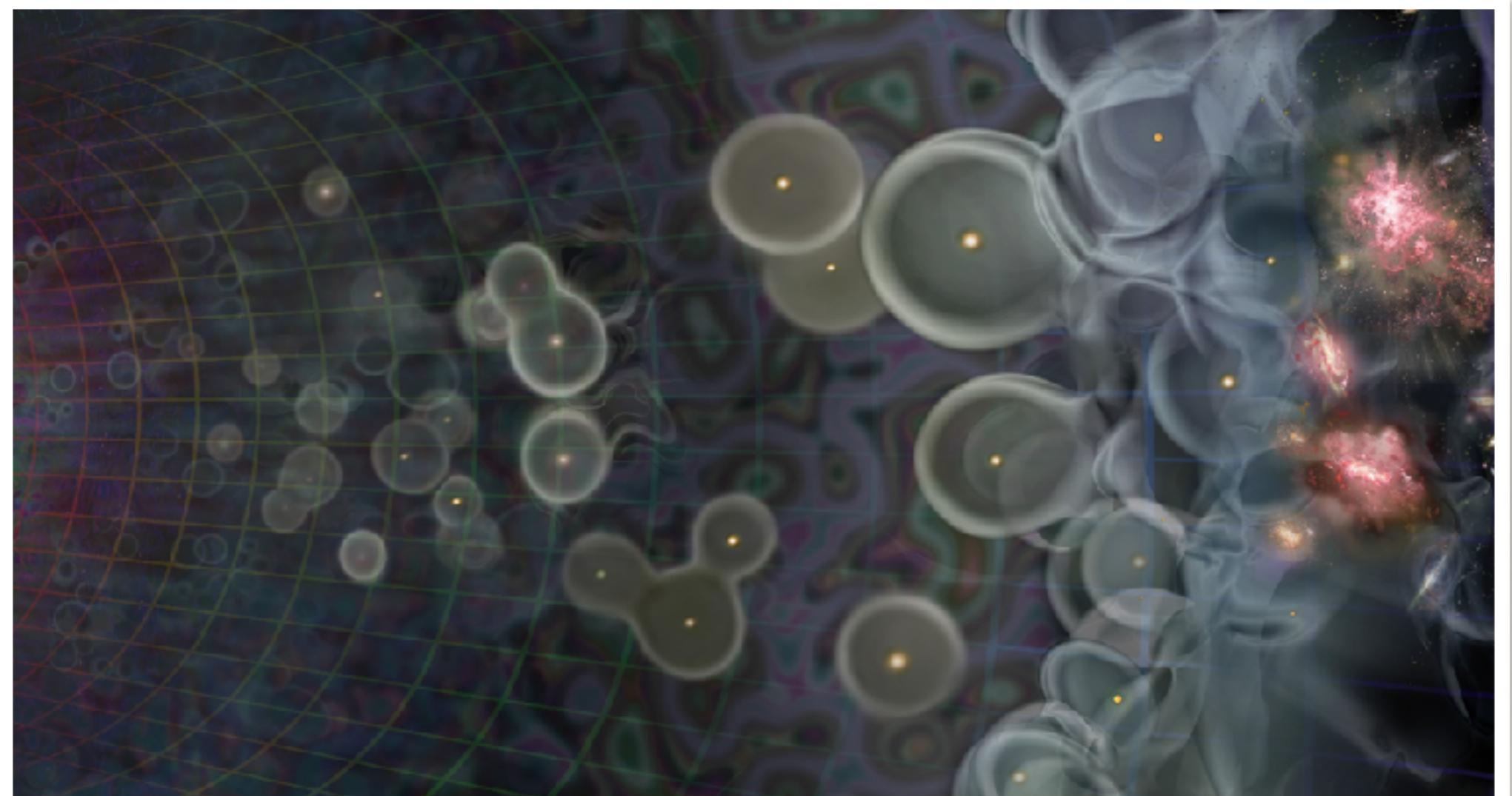
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# Reionization Era



# Epoch of Reionization

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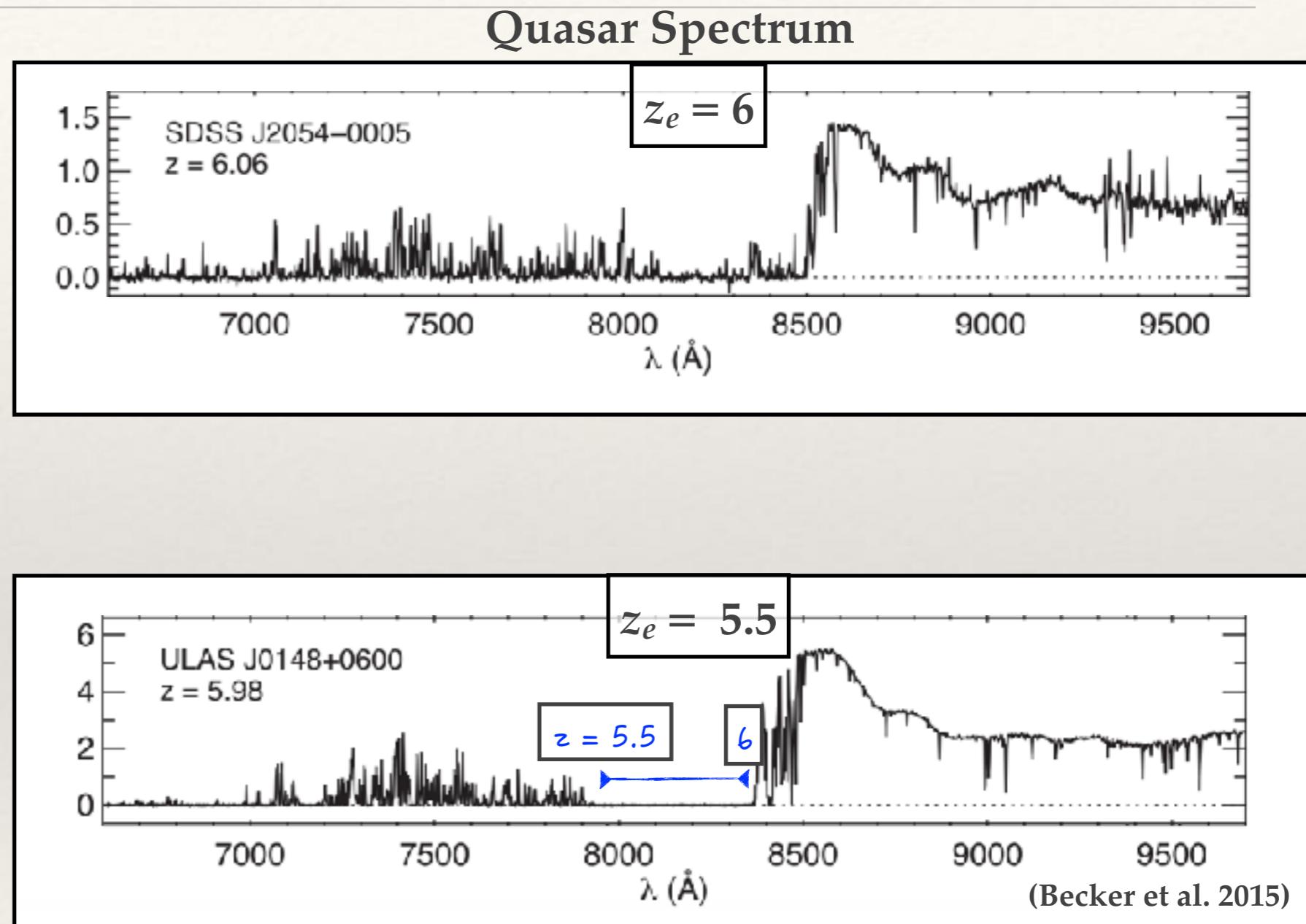
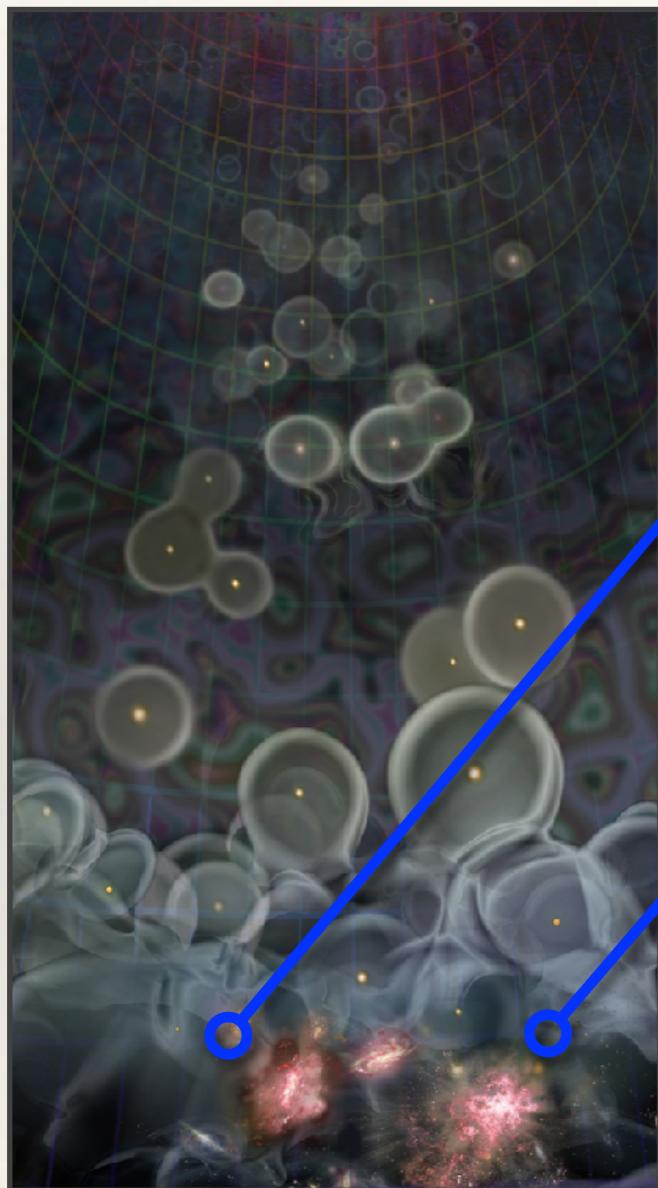
$t_{age} \sim$  a few  $\times 10^8$  yr

$z \sim 10 - 15$

$t_{age} \sim 10^9$  yr

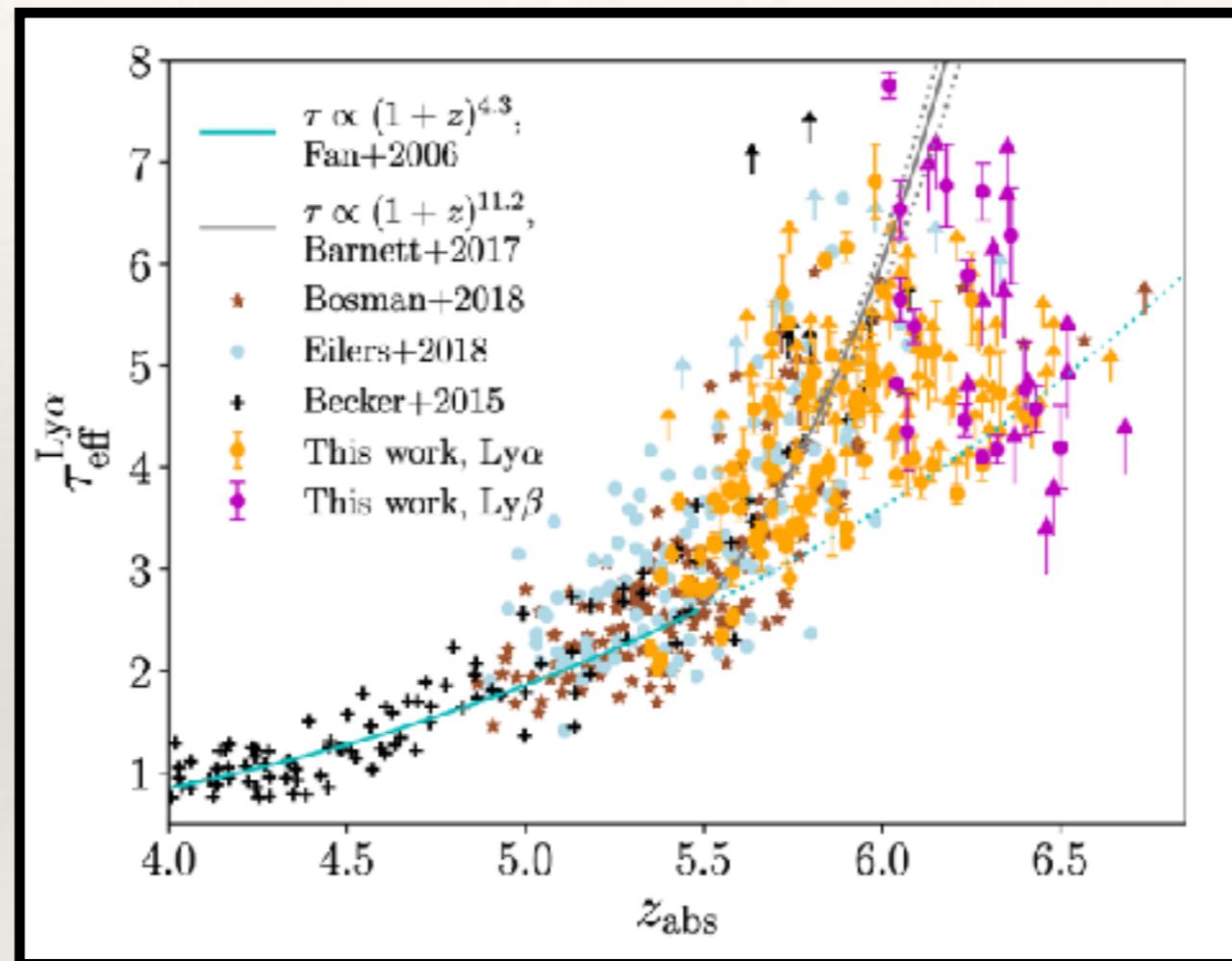
$z \sim 6$

# Multiplicity of the end-of-reionization



The reionization history seems to have a large scatter near the end.

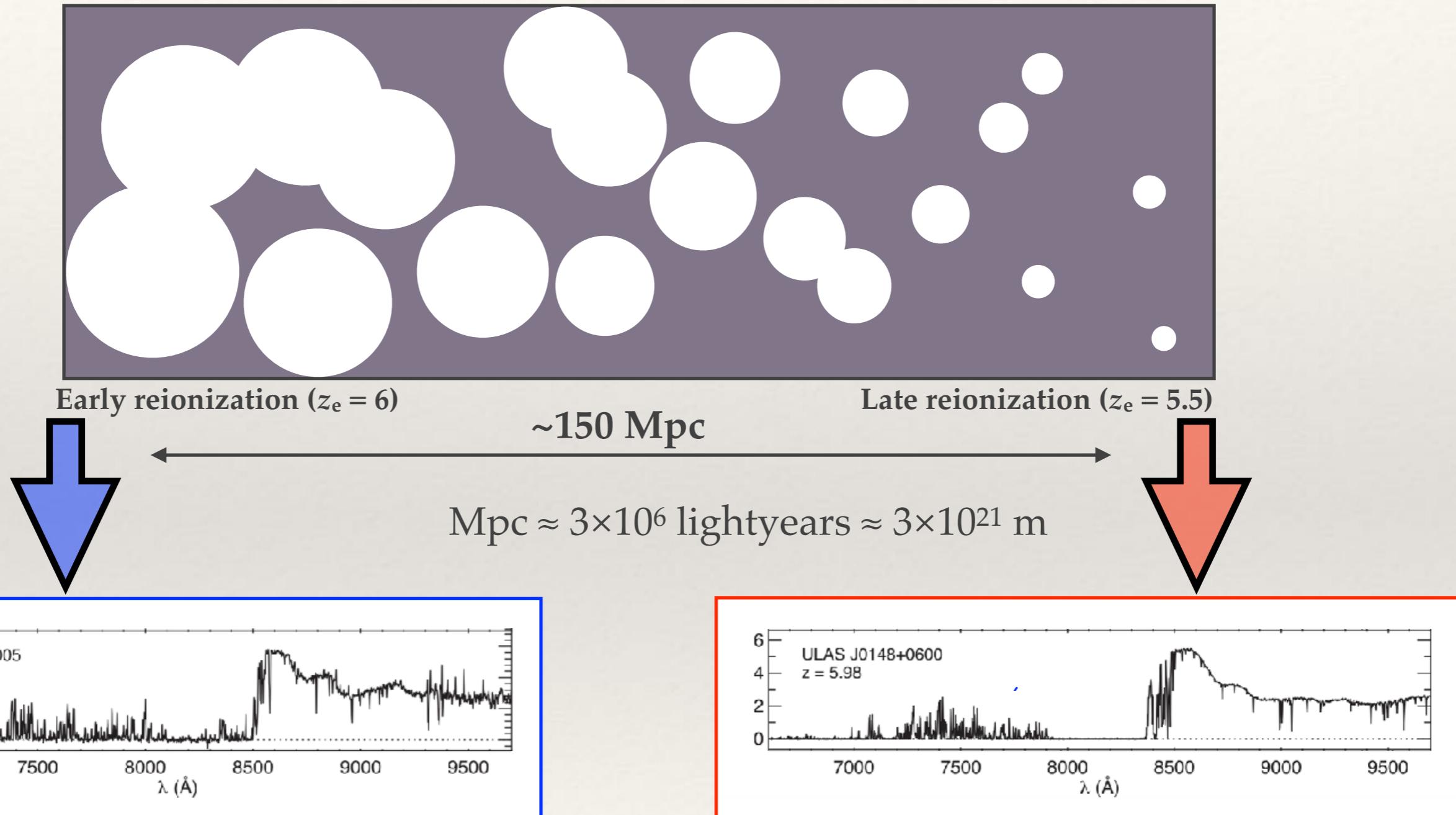
# Scatter in the Reionization History



(Yang+ 2020)

The reionization history seems to have a large scatter near the end.

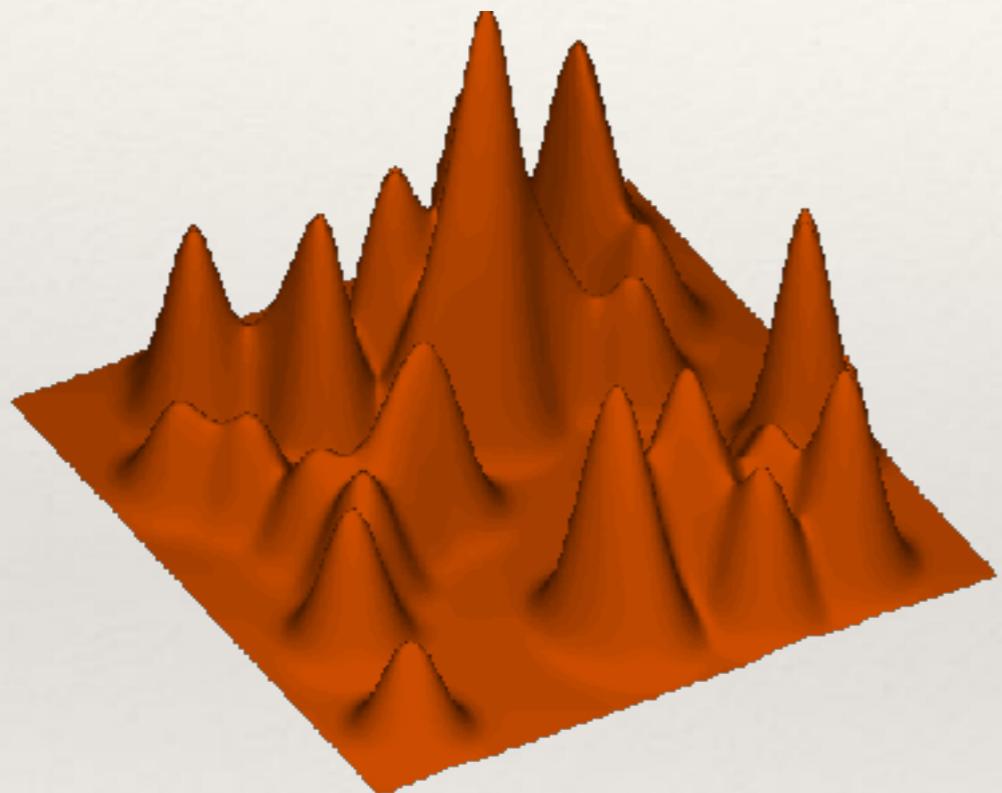
# Multiplicity of the end-of-reionization



The density fluctuations of the universe is small at scales of  $> 50$  Mpc.  
Difficult to explain the reionization process being inhomogeneous over  $\sim 150$  Mpc.

# Baryon-Dark Matter Streaming Motion

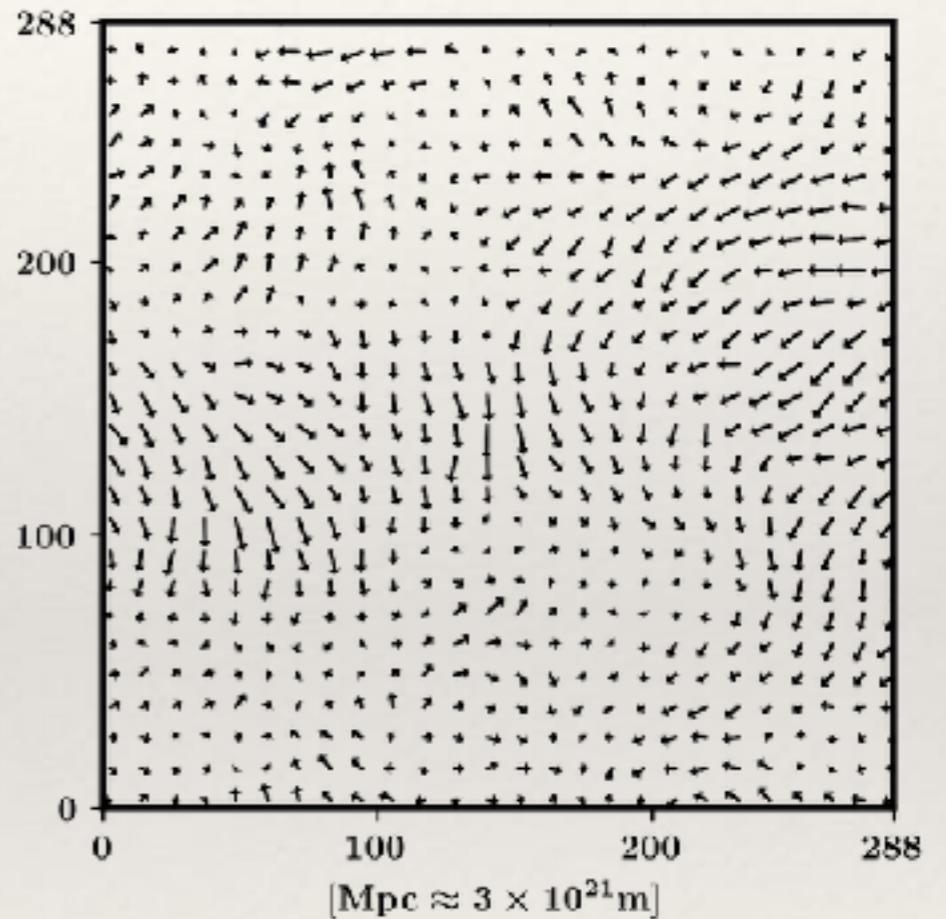
$z > 1090$  ( $t_{\text{age}} < 4 \times 10^5$  yrs)



... pressure of photon-baryon fluid generates  
the Baryonic Acoustic Oscillations.

This acoustic motion created a *relative motion*  
between baryon and dark matter.

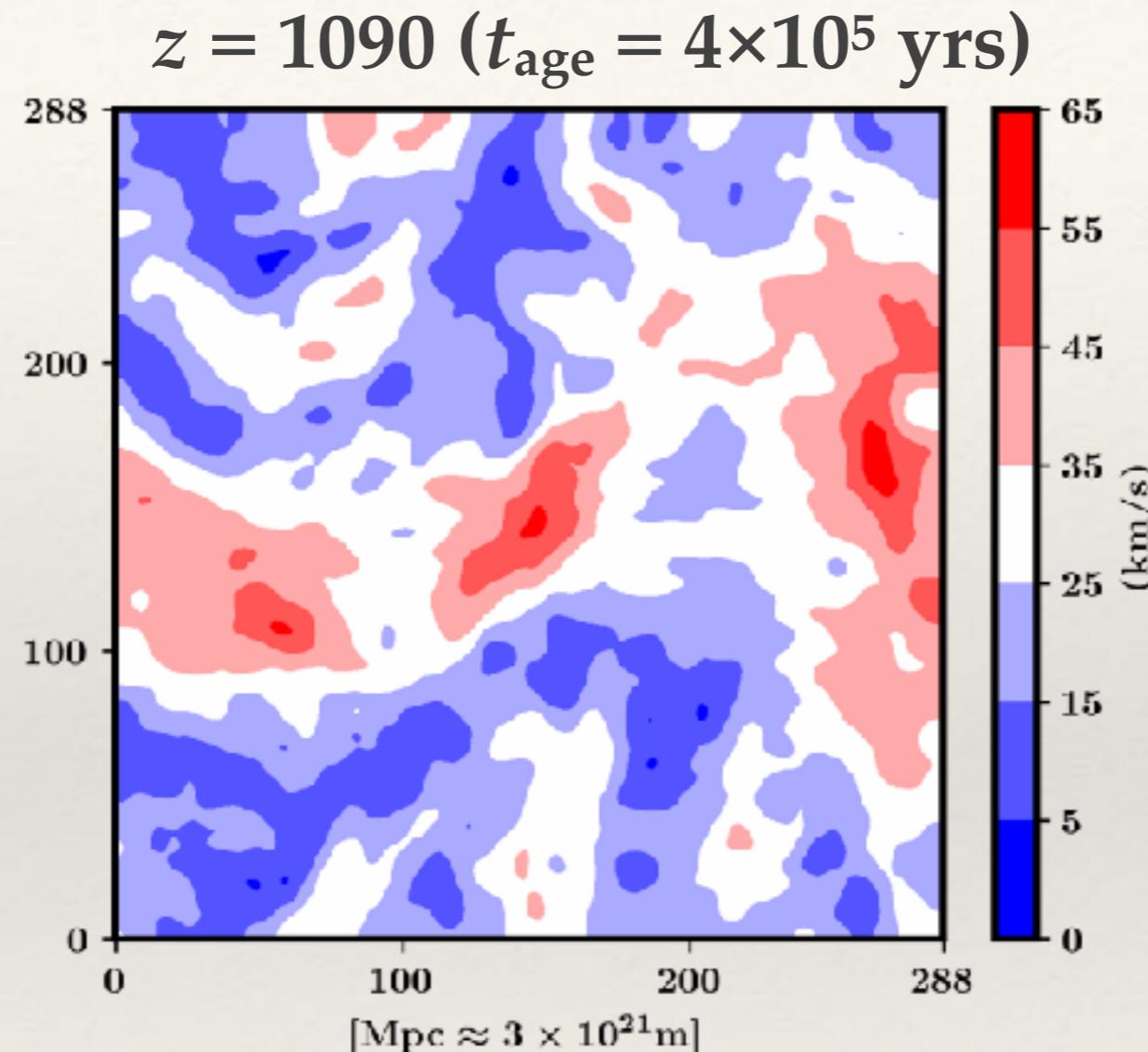
$z = 1090$  ( $t_{\text{age}} = 4 \times 10^5$  yrs)



... the streaming motion freezes out  
with the cosmic recombination.

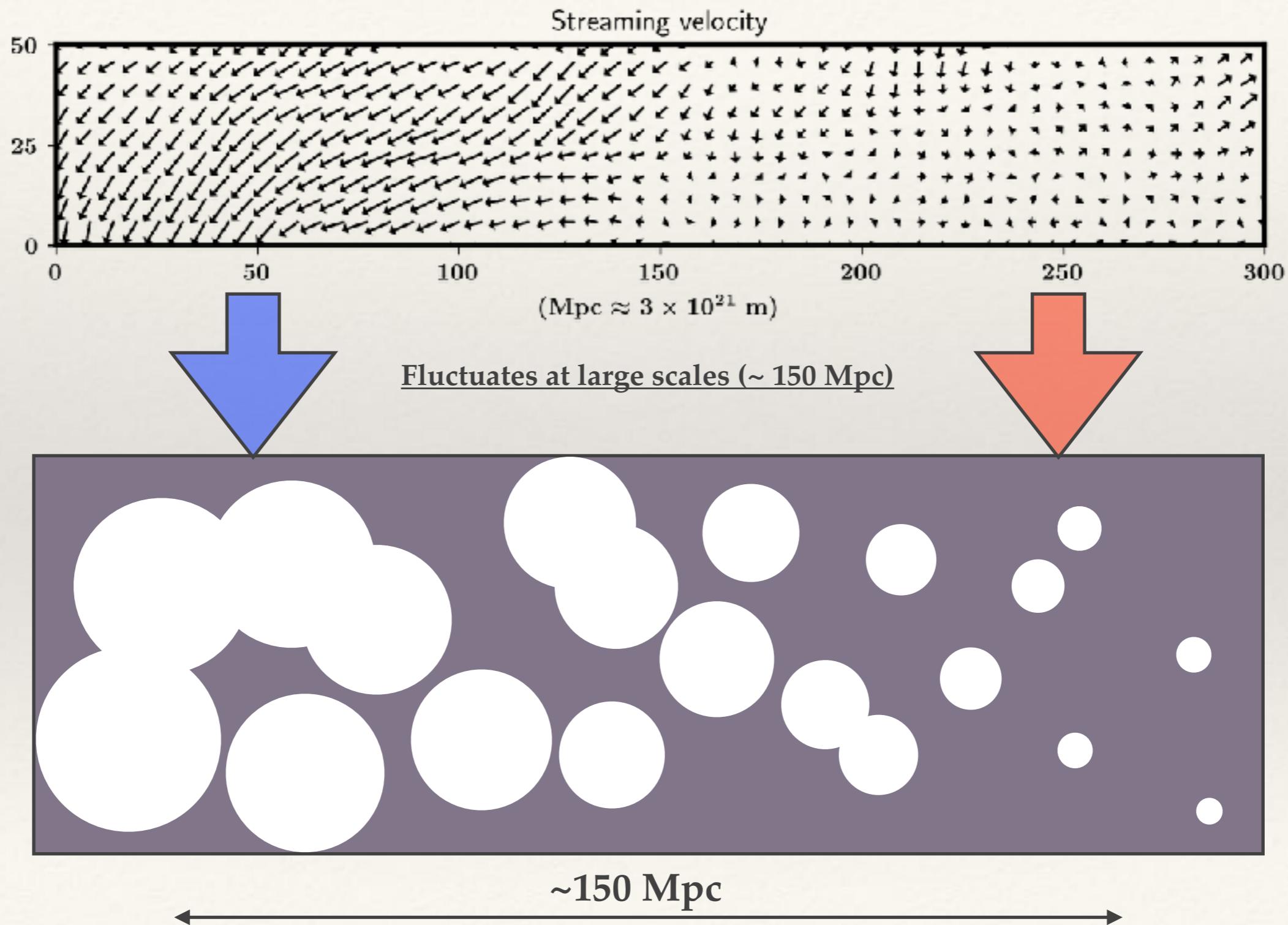
(Tseliakhovich and Hirata 2010)

# Baryon-Dark Matter Streaming Motion

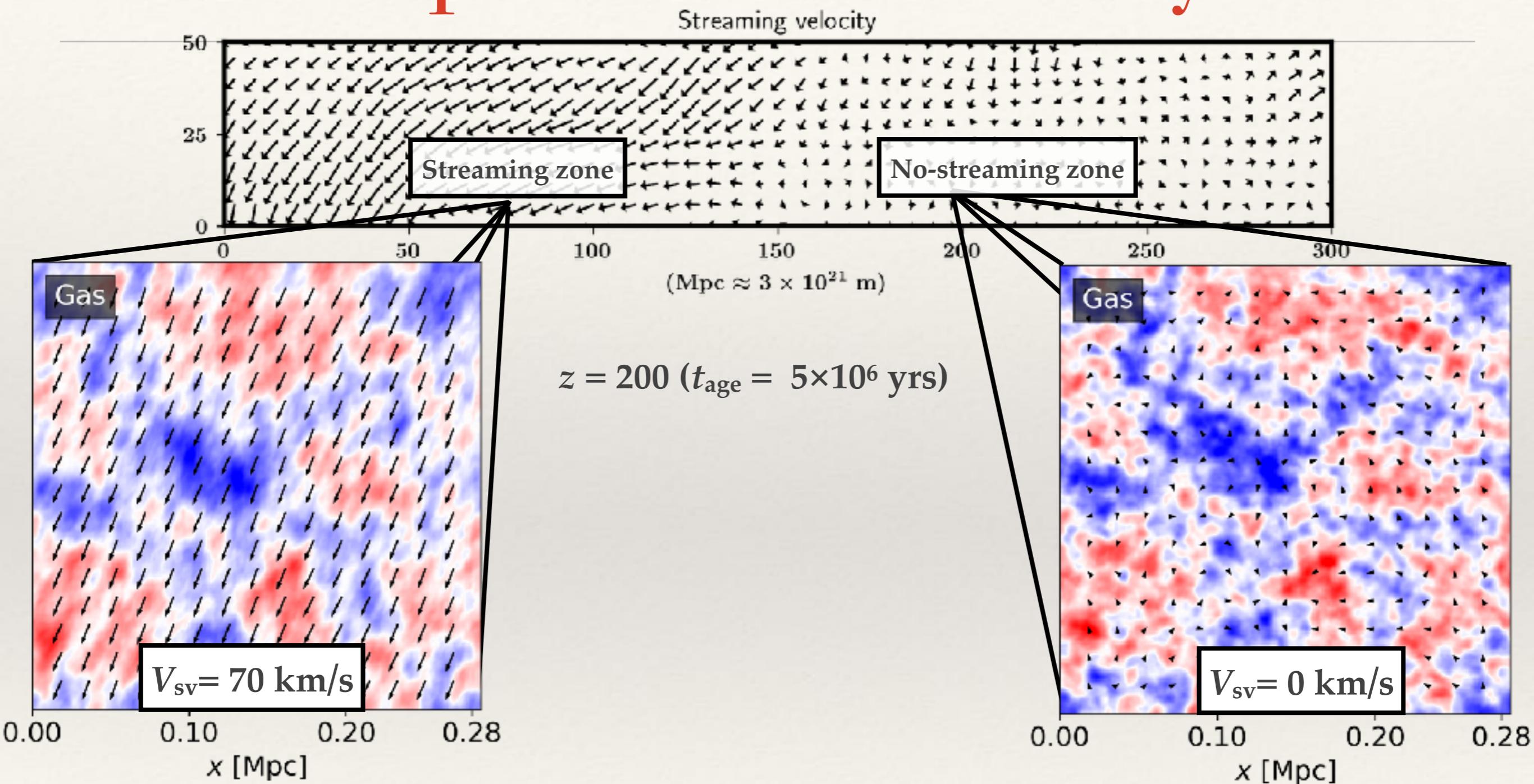


- Mostly (98%) ranges between 5 - 55 km/s.
- Decays as  $(1+z)$ . Unimportant at the late time in cosmic history.
- Fluctuates at large scales ( $\sim 150$  Mpc).

# Motivation: Can streaming motion affect reionization?



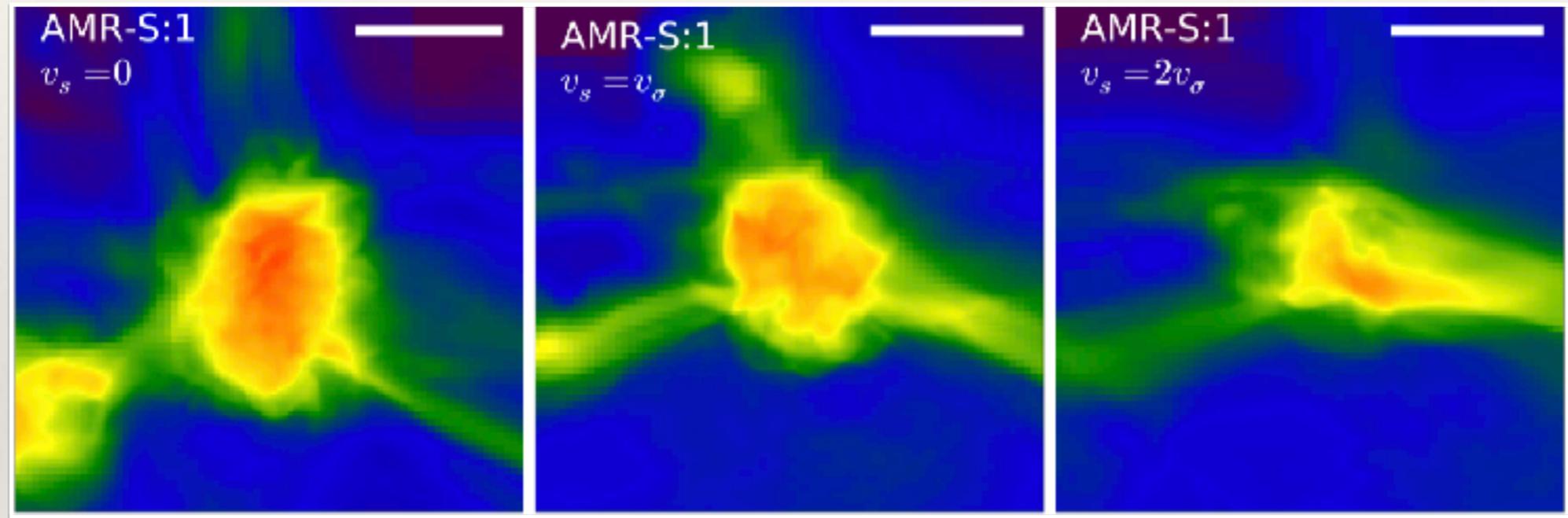
# Impact on Gas Density



Gas density gets smoothed by the streaming motion.

# Impact on Halos in the Early Universe

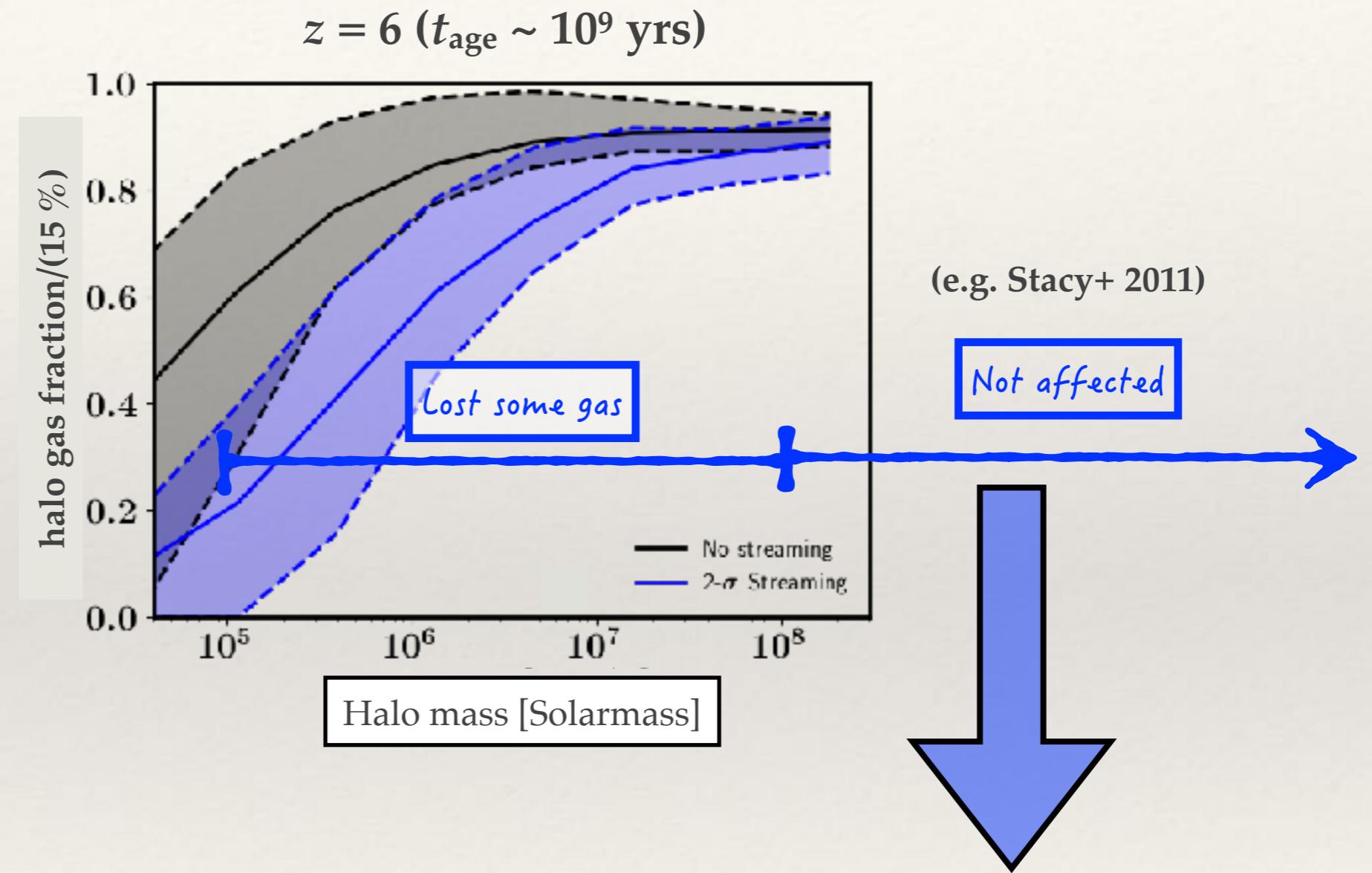
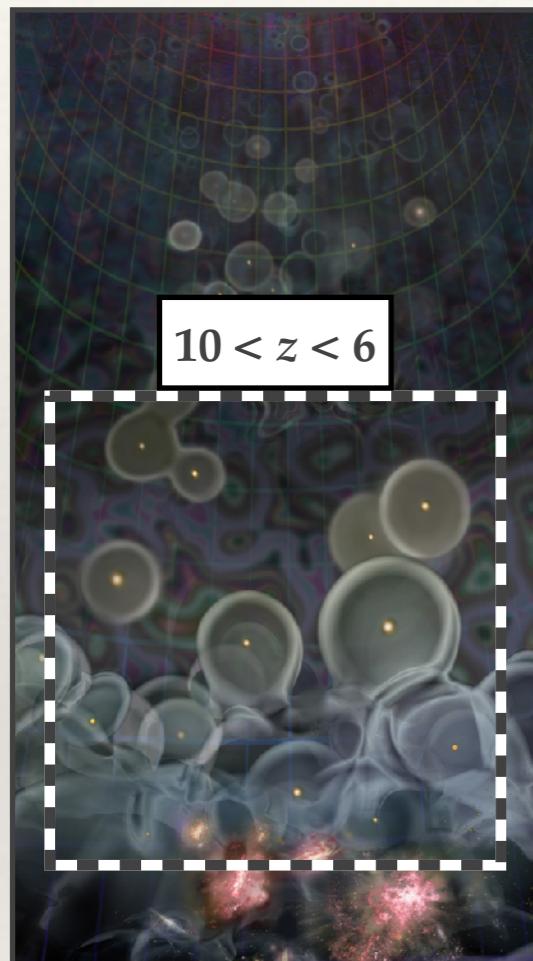
$z < 20$  ( $t_{\text{age}} > 10^8$  yrs)



(Richardson+ 2012)

Harder for halos to accrete gas.

# Impact on Reionization

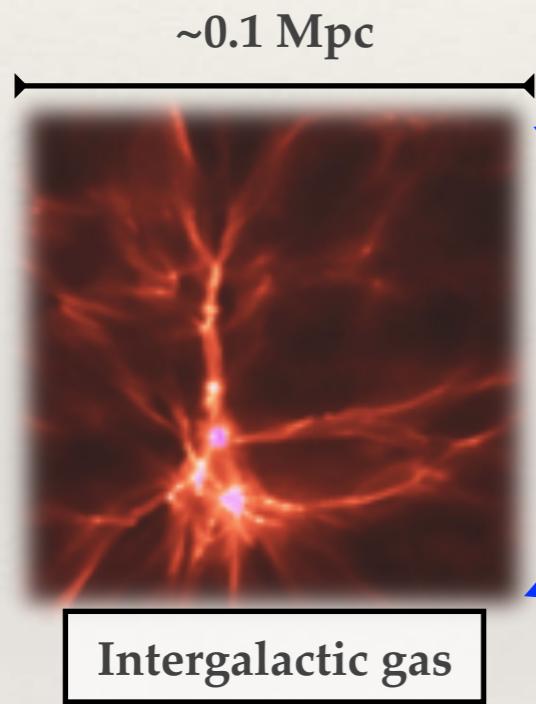


Reionization is driven by massive ( $> 10^8$  solarmass) halos.  
But, these halos are not affected.

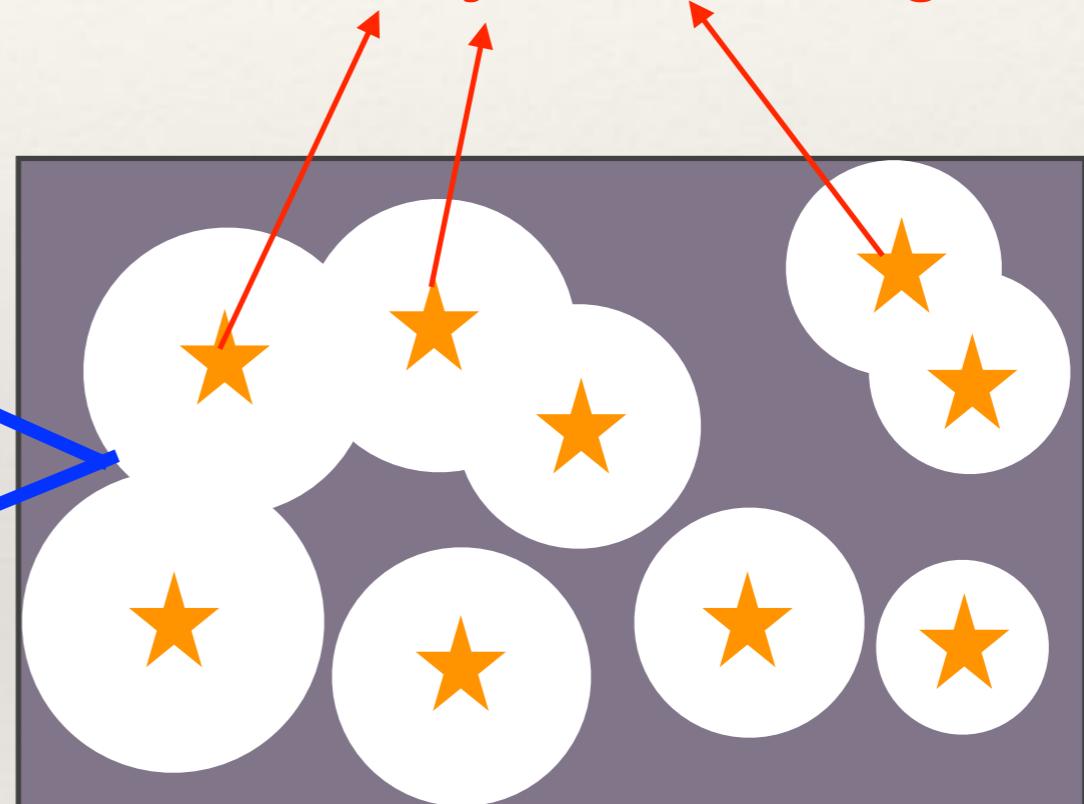
# Small-scale Gas Structure during Reionization

$$\bar{n}_H \dot{Q}_{\text{HII}} = \langle \mathcal{I} \rangle - \langle \mathcal{R} \rangle$$

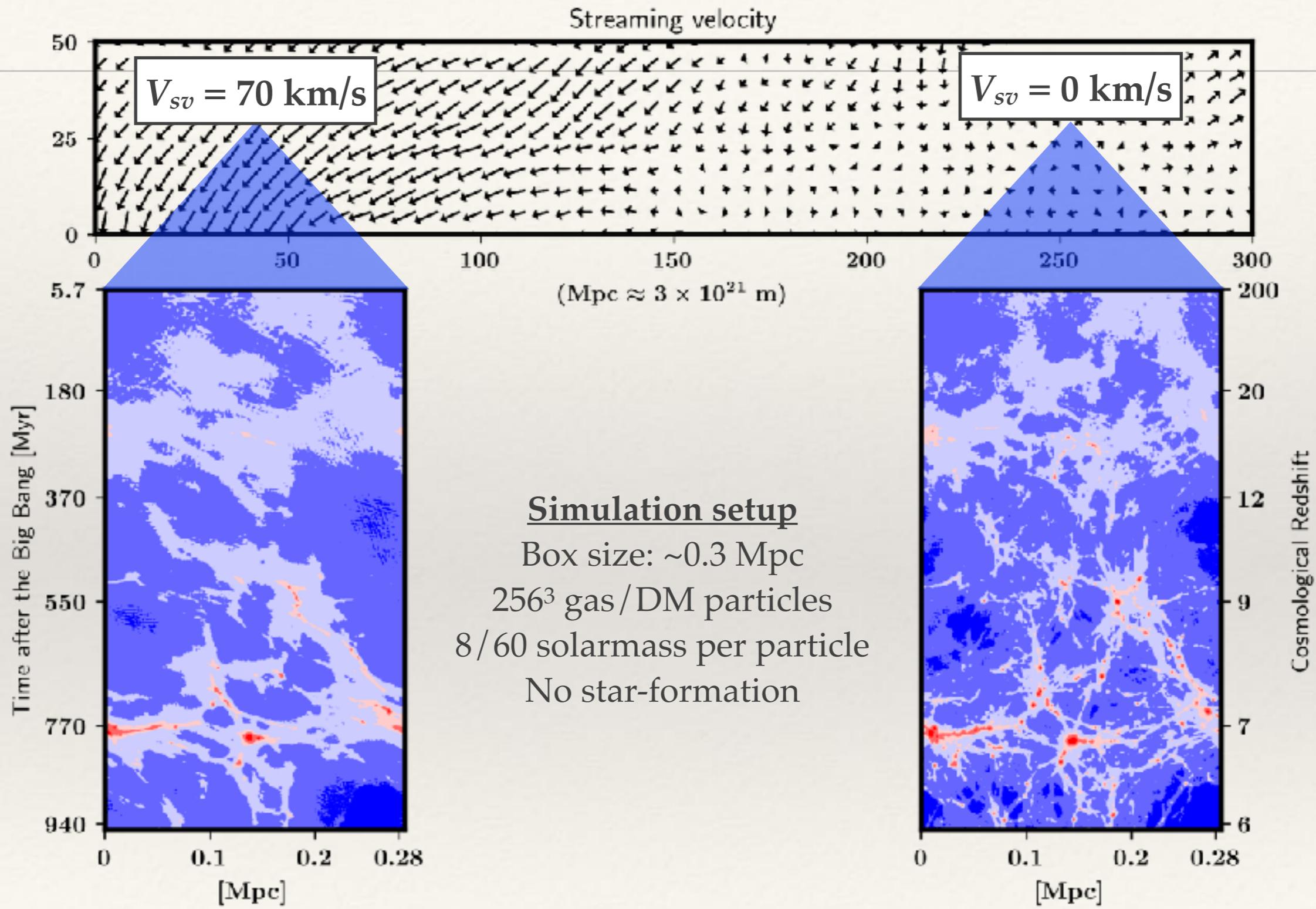
Net Ionization      Production by galaxies      Recombination by gas structures



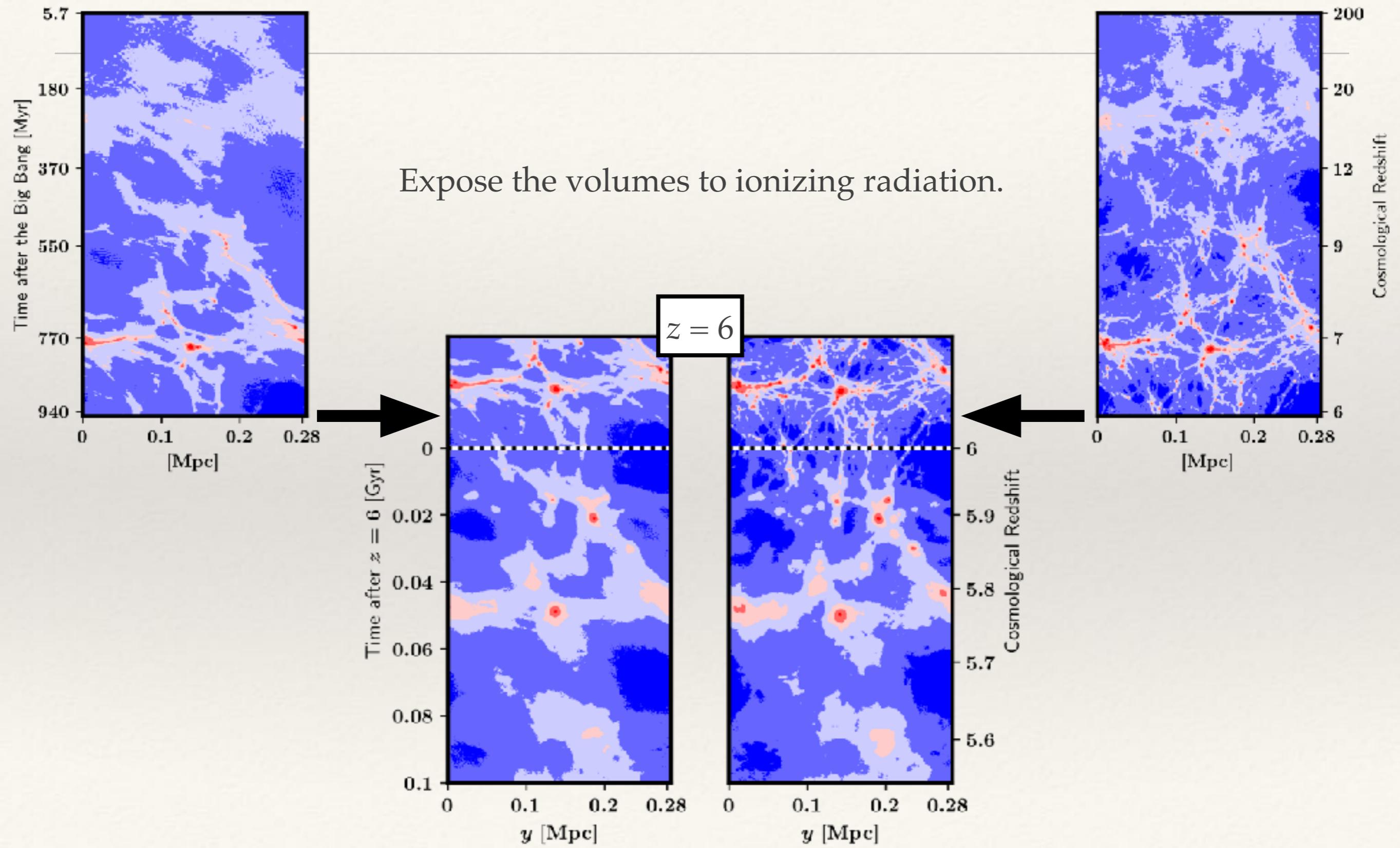
**$M > 10^8$  solarmasses galaxies**  
**Not affected by the streaming motion**



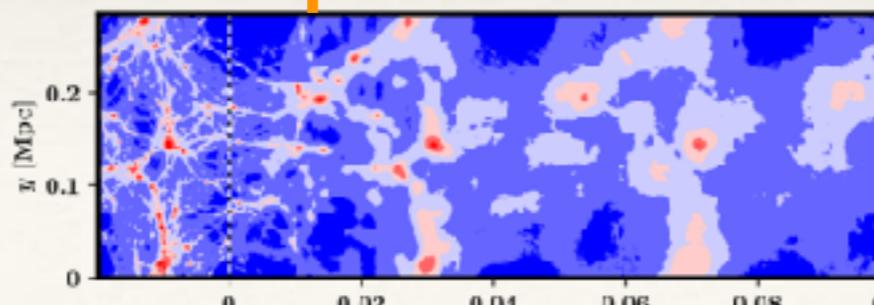
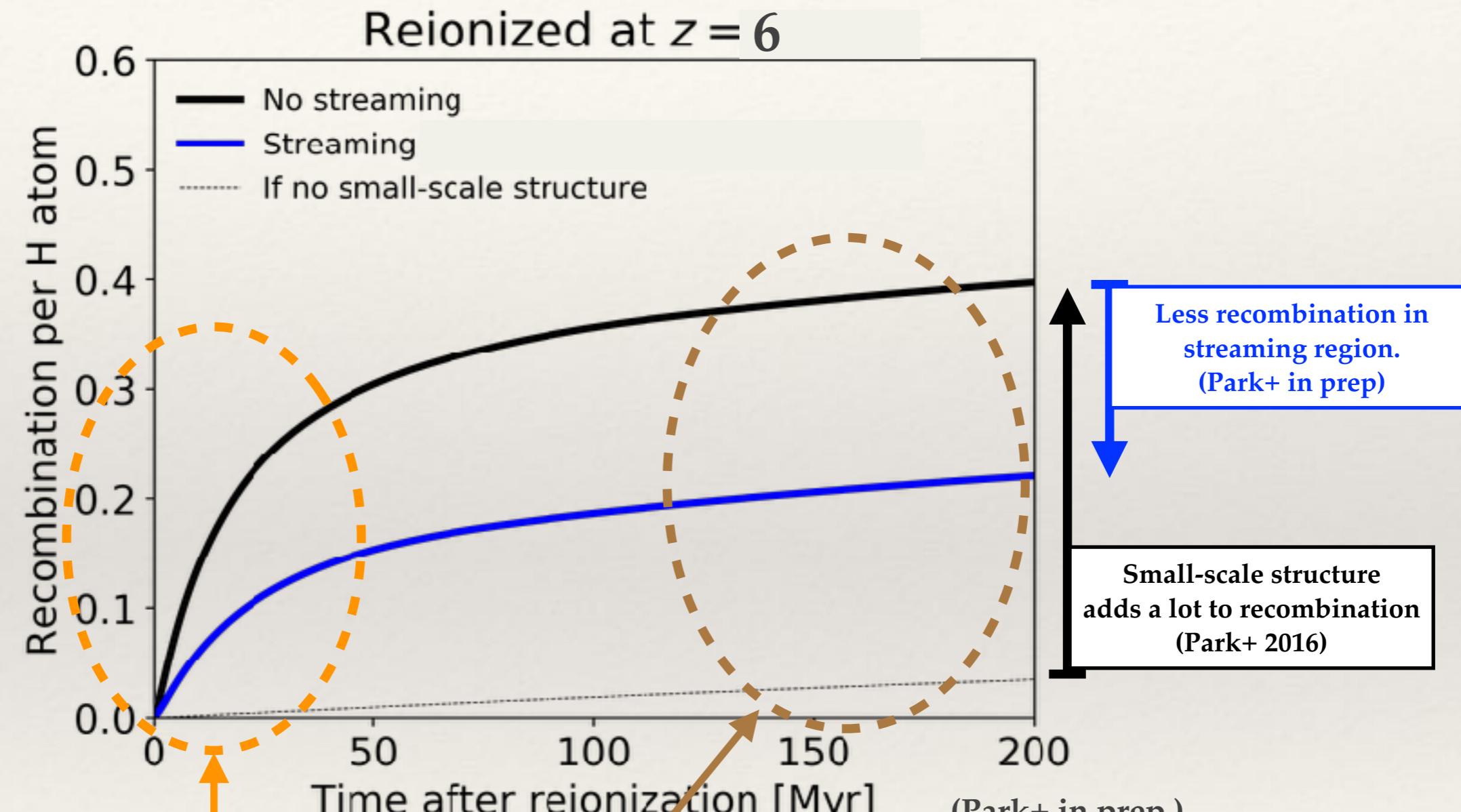
Intergalactic gas structures consumes extra photons.  
They are mostly  $M << 10^8$  solarmasses.  
Maybe affected by the streaming motion?

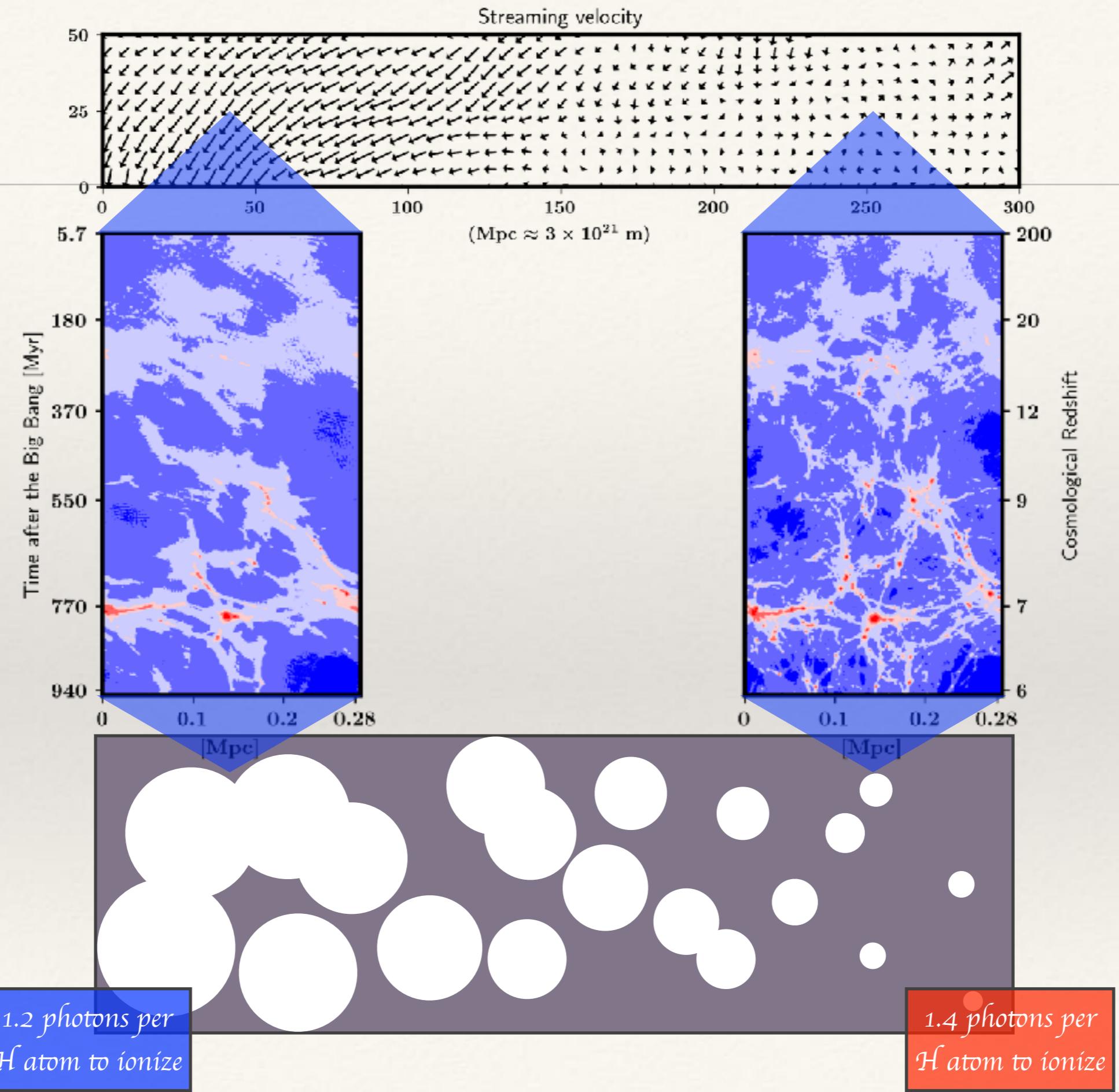


**Small-scale ( $< 10^7 \text{ M}_\odot$ ) structures strongly suppressed by the streaming V.**



# Recombination in Small-scale Gas Structure





# Variation in Reionization History

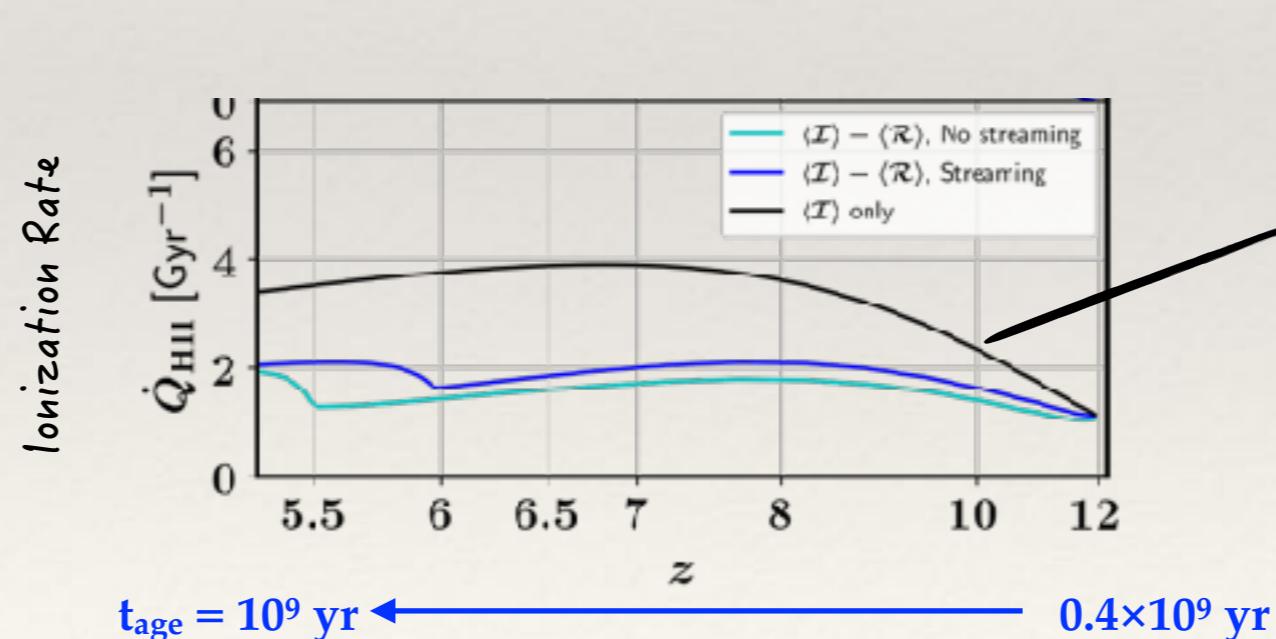
$Q_{\text{HII}}(z)$ : Global mean ionized fraction

$$\bar{n}_{\text{H}} \dot{Q}_{\text{HII}} = \langle \mathcal{I} \rangle - \langle \mathcal{R} \rangle$$

Net Ionization

Production  
by galaxies

Recombination  
by gas structures



Similar to the model of  
Finkelstein et al. 2019

# Scatter in Reionization History

Scatter in End-of-reionization

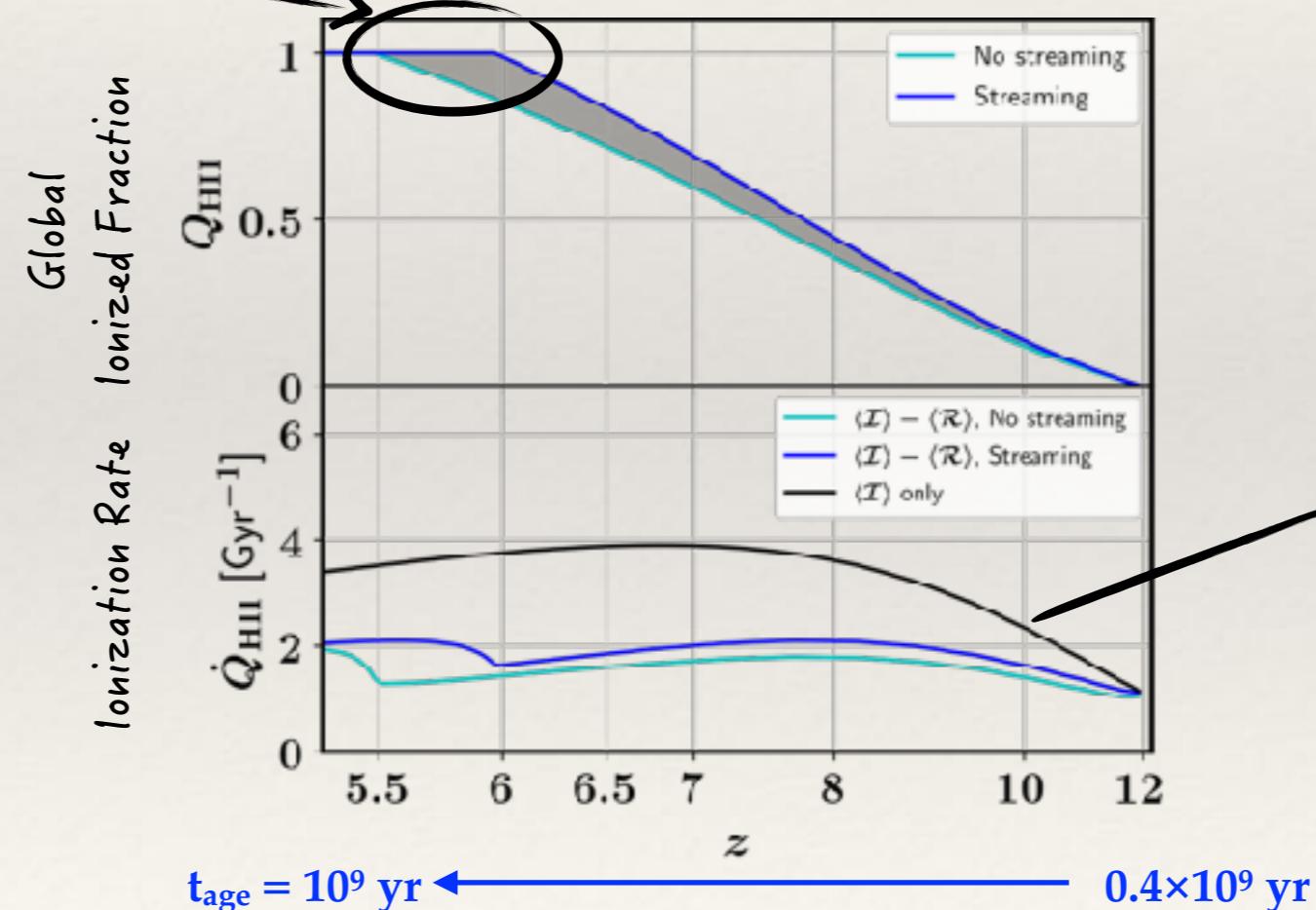
$$z_e = 5.5 - 6$$

$$\bar{n}_H \dot{Q}_{\text{HII}} = \langle \mathcal{I} \rangle - \langle \mathcal{R} \rangle$$

Net Ionization

Production

Recombination

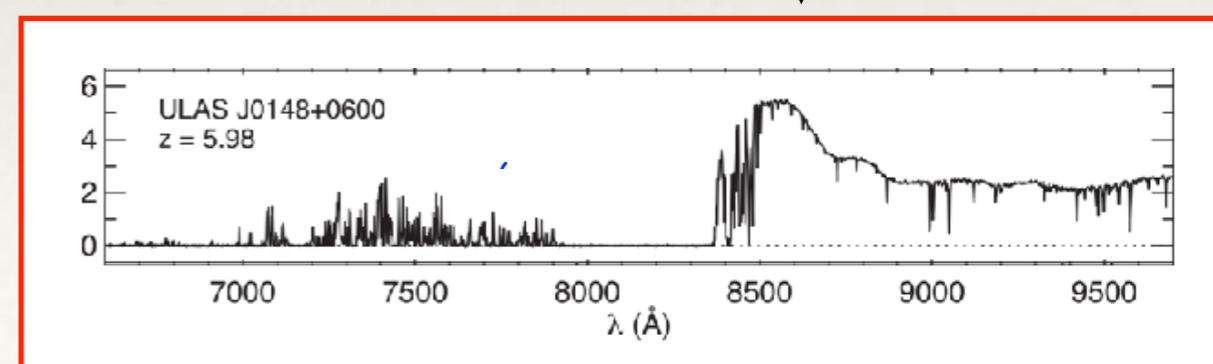
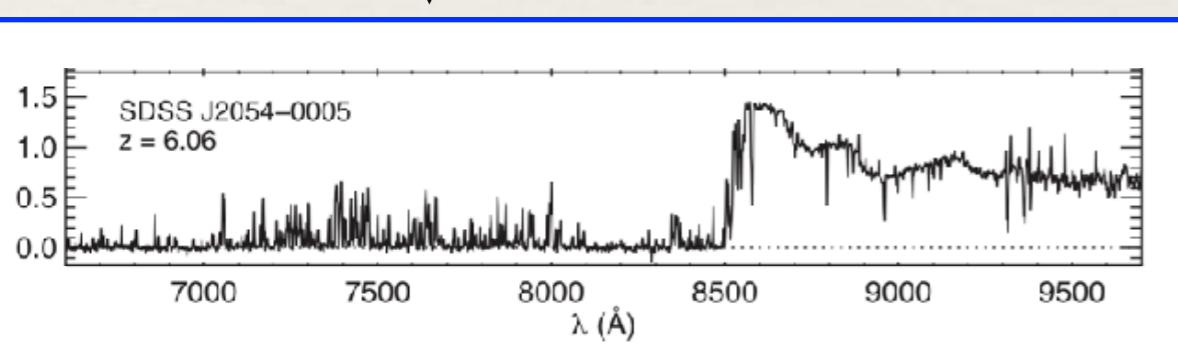
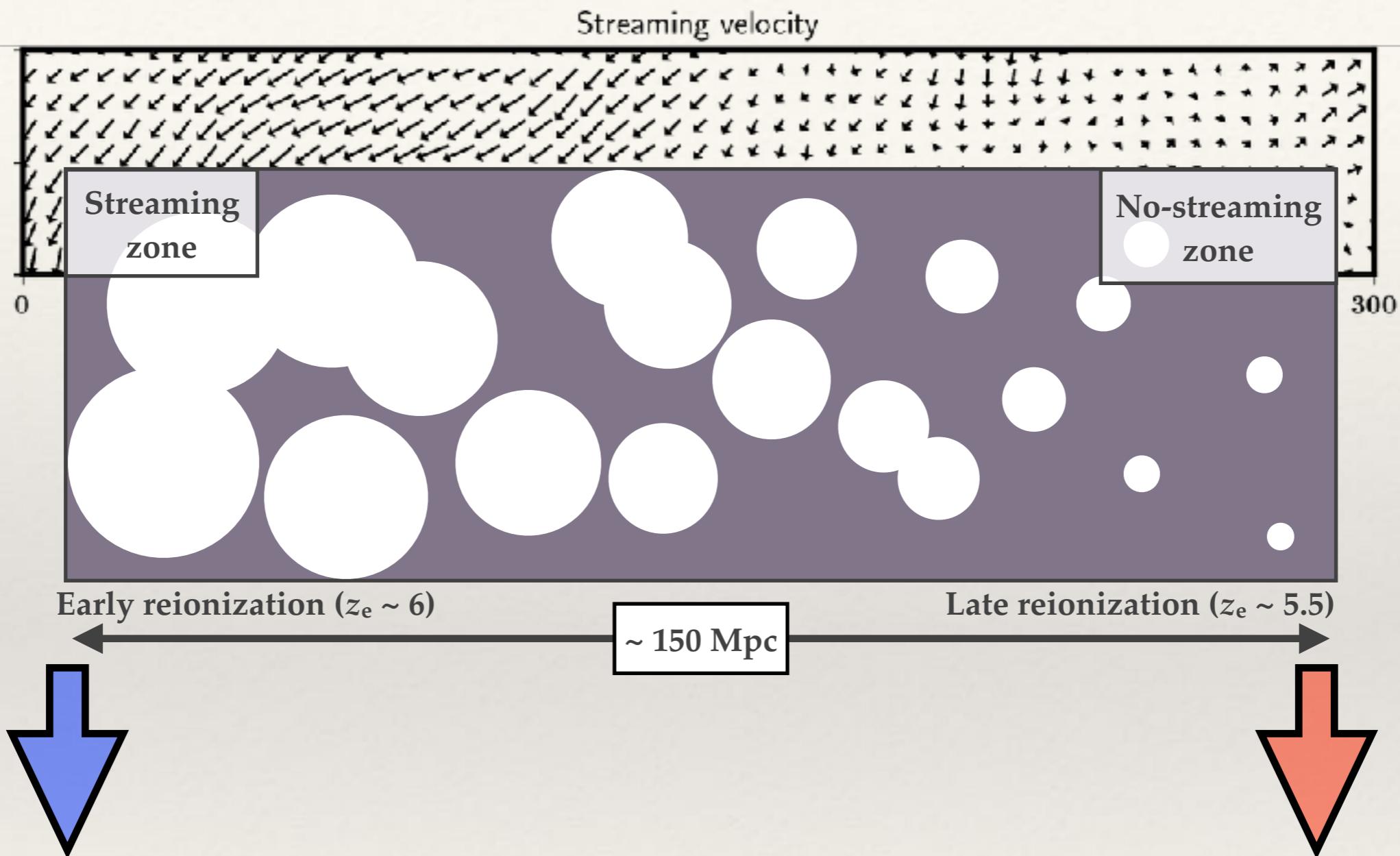


Similar to the model of  
Finkelstein et al. 2019

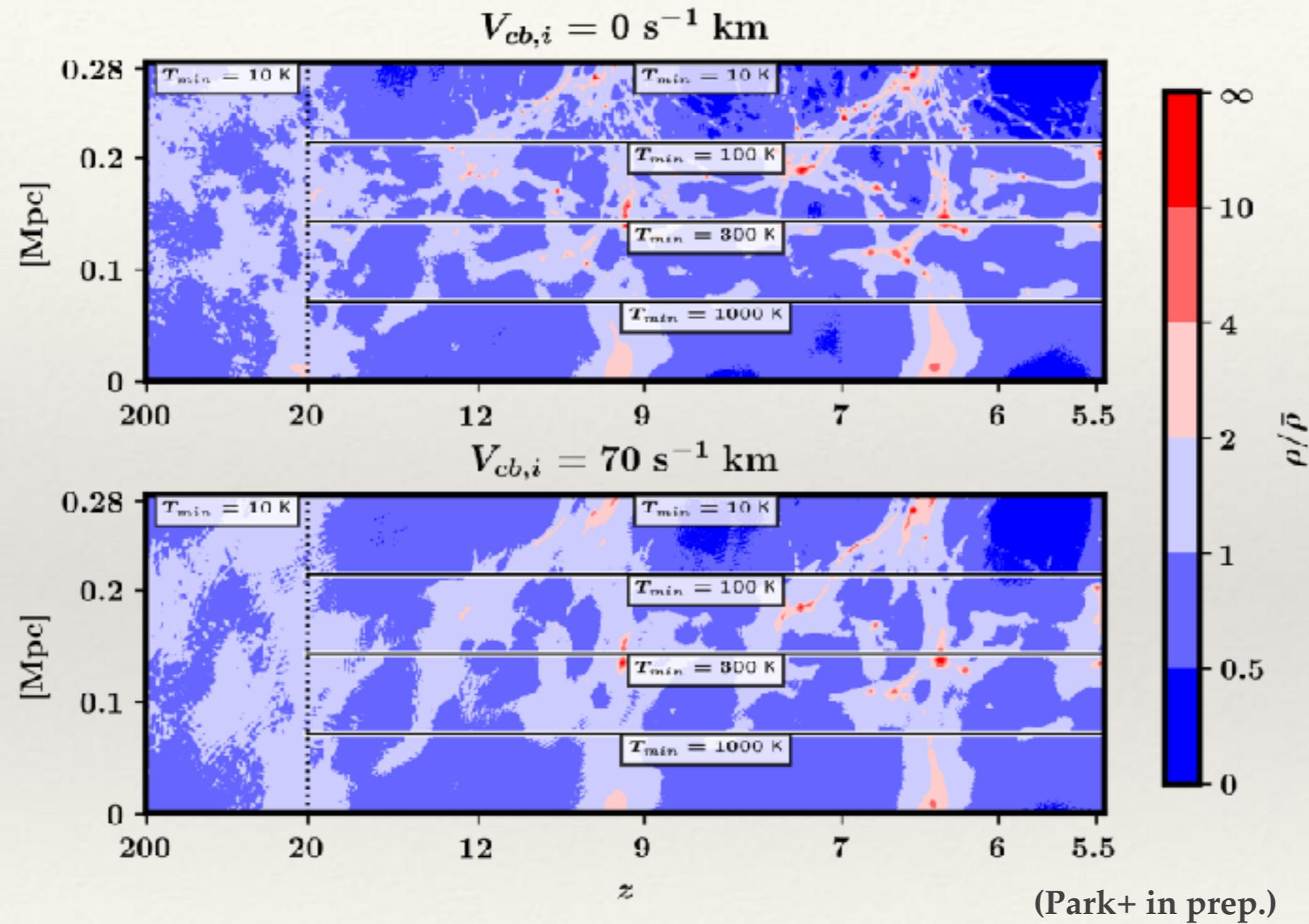
End of reionization scattered by  $\Delta z = 0.5!$

## Results

# Potential Explanation for the end-of-reionization scatter



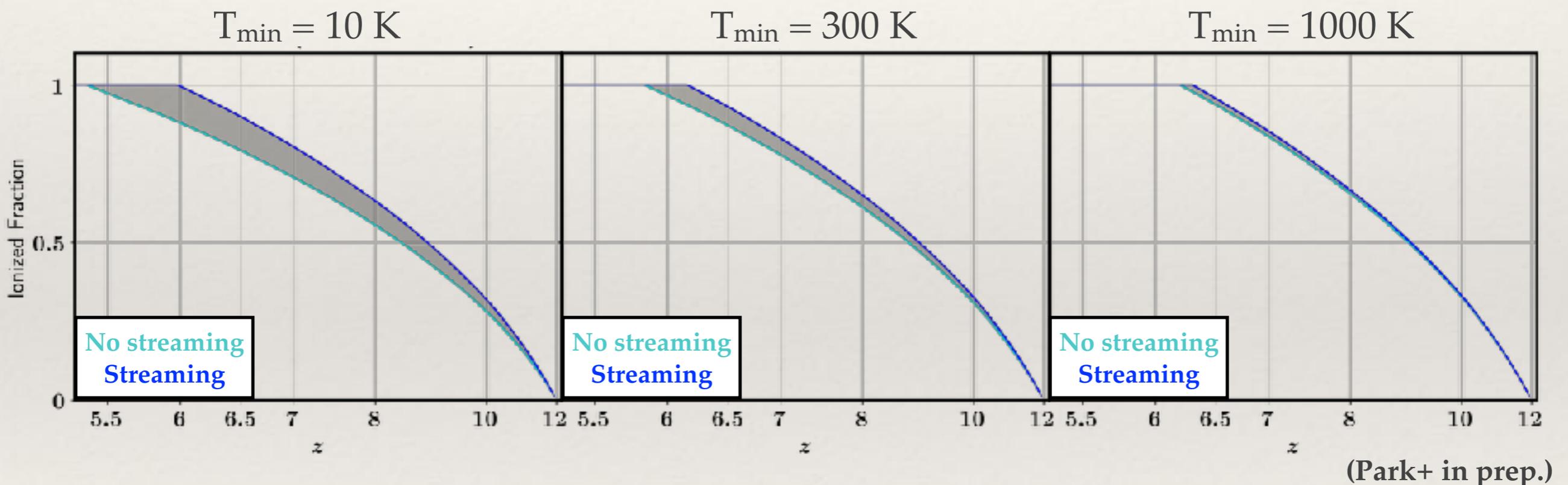
# Impact of X-ray Preheating



(Park+ in prep.)

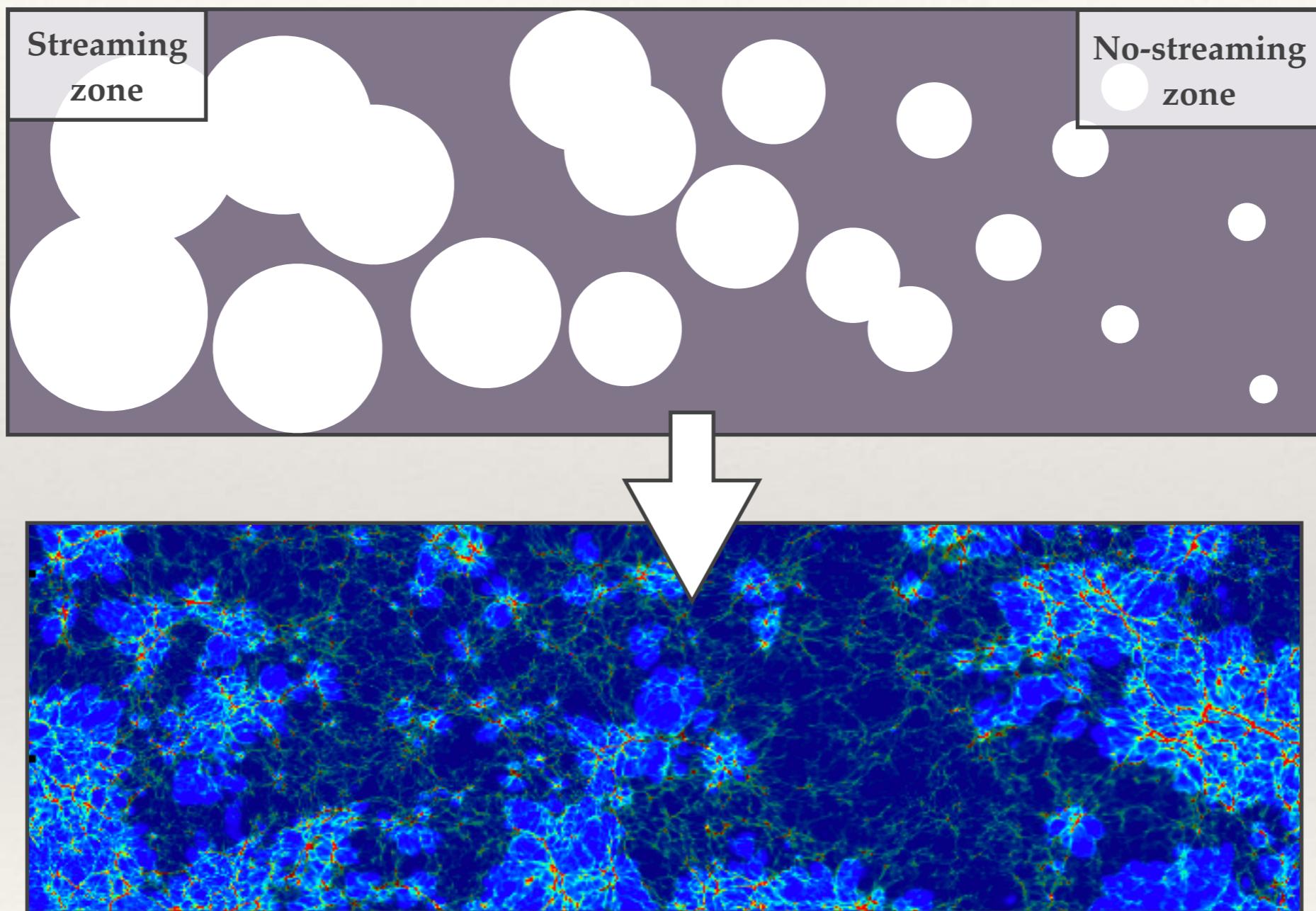
X-ray preheating also erases the small-scale structures.

# Impact of X-ray Preheating



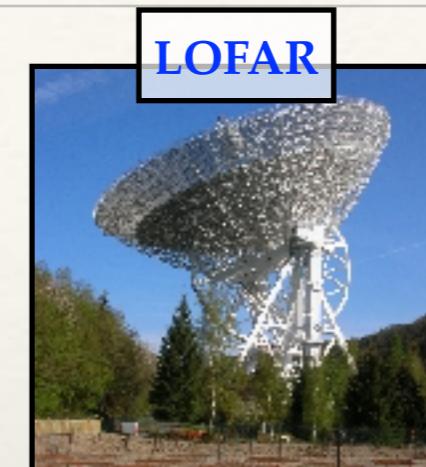
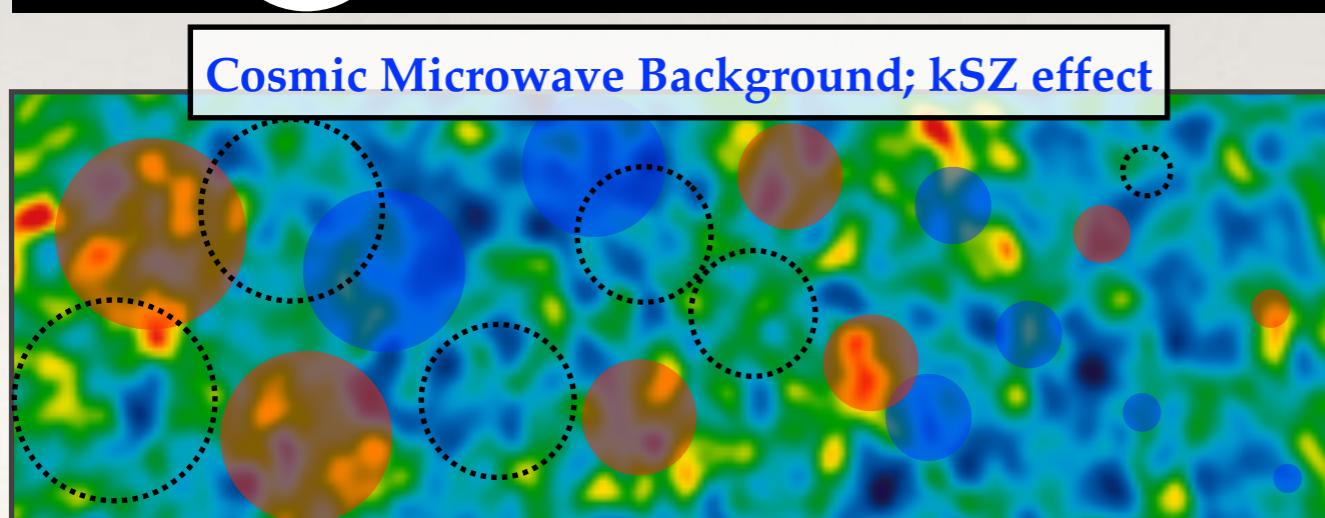
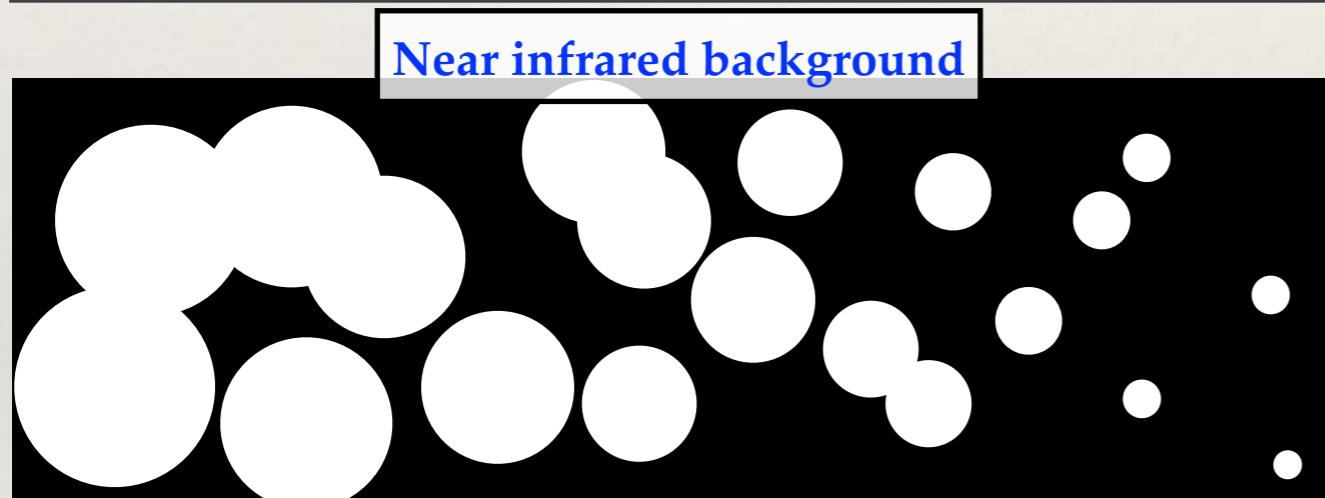
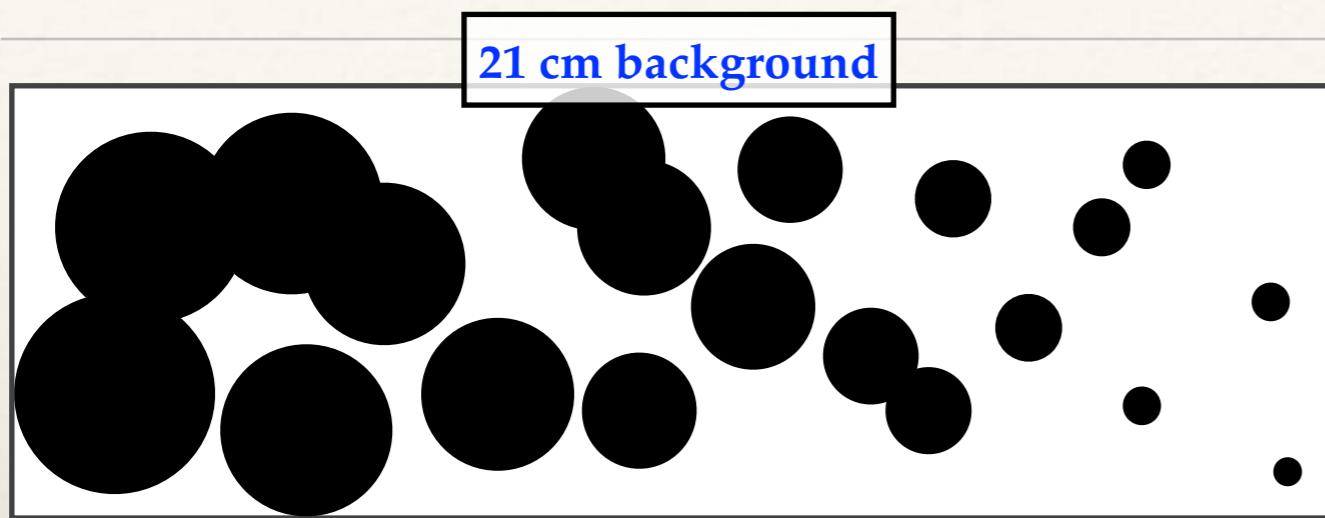
Scatter in reionization history is suppressed!  
However, the X-ray preheating may also fluctuate!

# [Wish List 1] Reionization Map with Streaming Effect

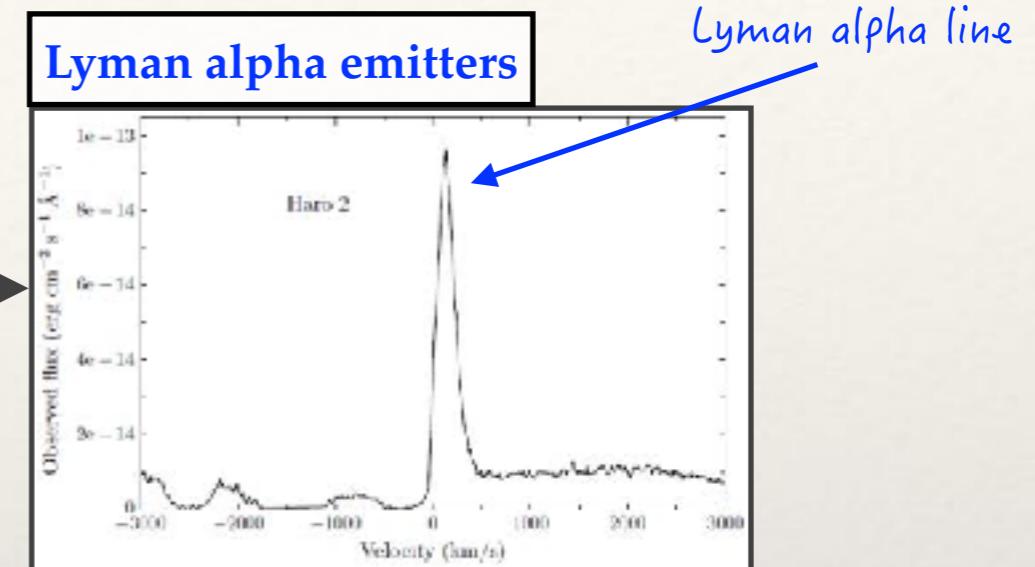
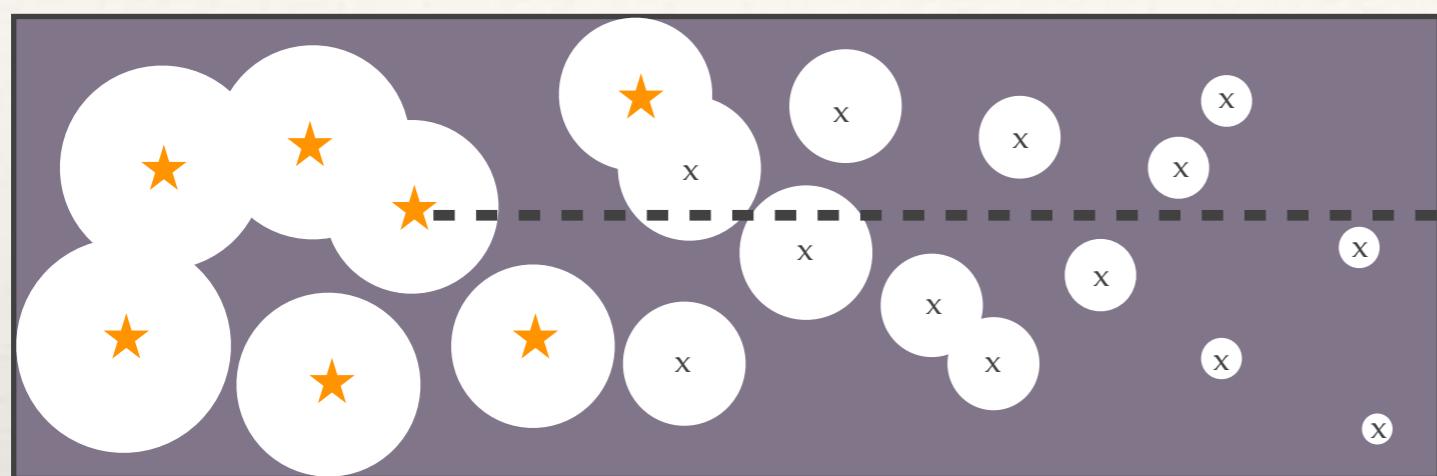


Make realistic reionization model with the streaming effect.

# [Wish List 2] Model Observables



# [Wish List 2] Model Observables



Subaru+Hyper Suprime-Cam



Keck+MOSFIRE



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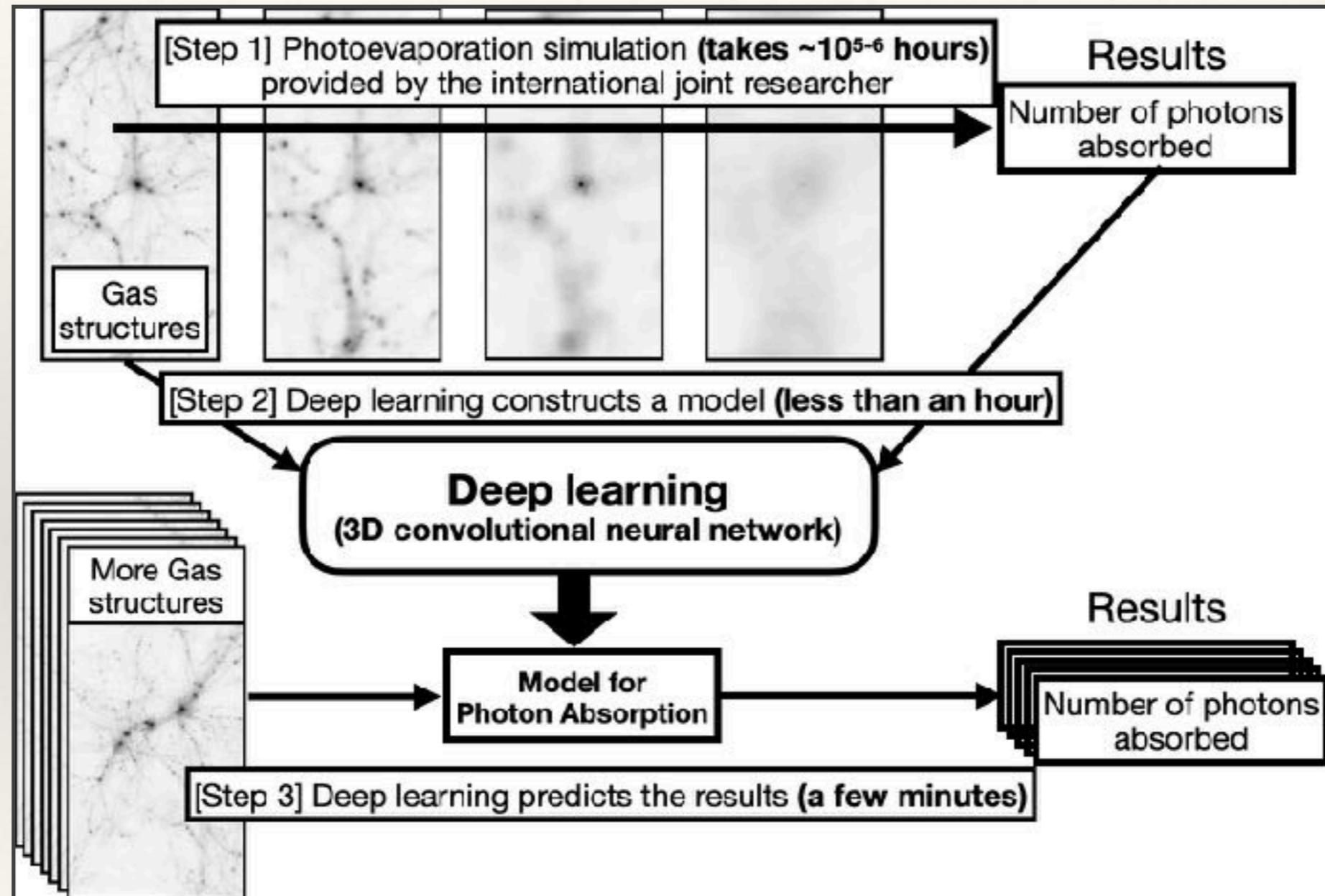
# Summary

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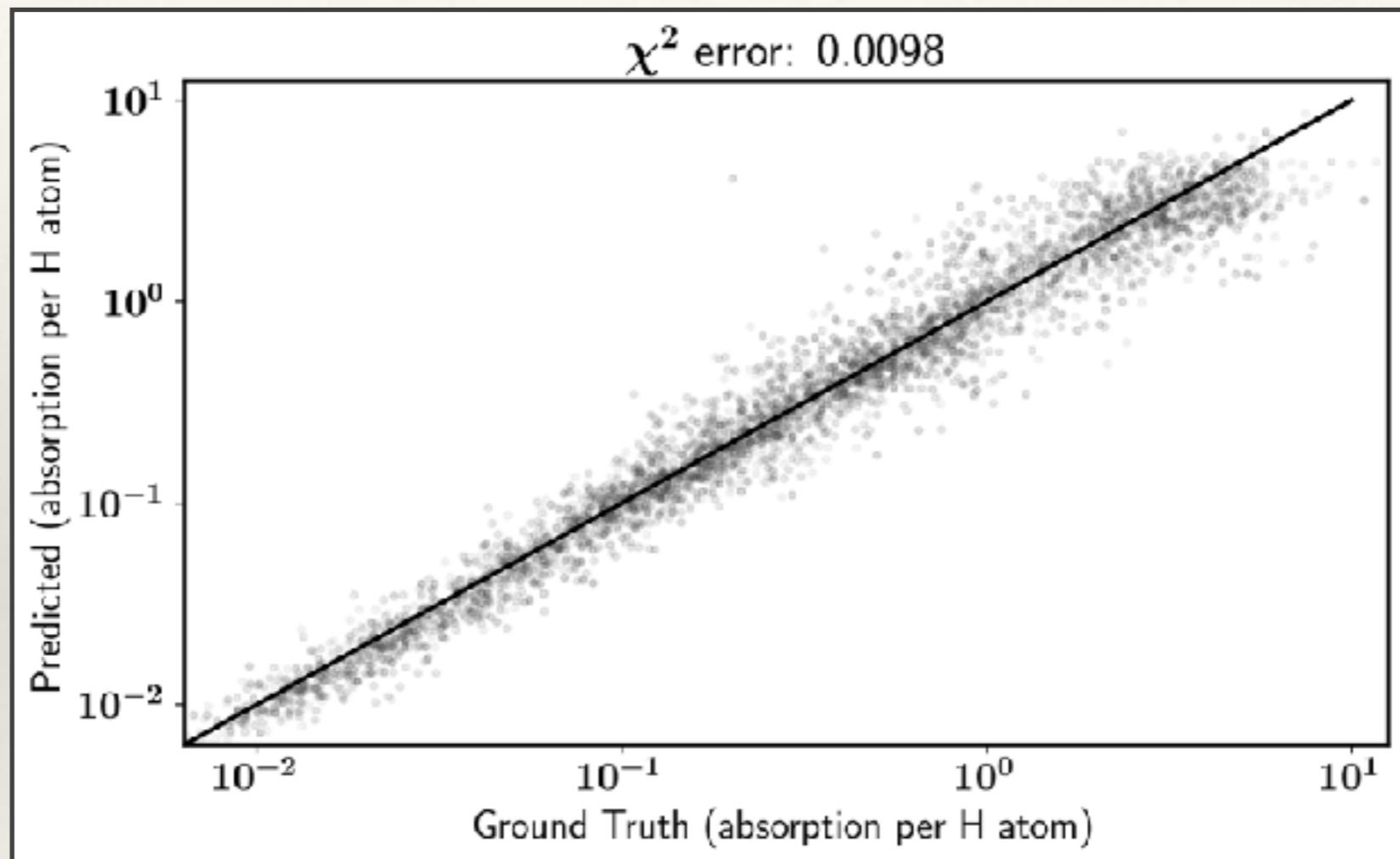
## Baryon-dark matter streaming motion...

- suppresses small-scale gas structures at  $z \sim 6$ .
- adds a scatter in the end-of-reionization redshift of up to  $\Delta z = 0.5$ .
- might explain the observed scatter in end-of-reionization.
- will impact the observables of the reionization era. (21cm, NIR, CMB, LAE)
- X-ray preheating is another important fact.

# [Wish List 3] Utilize Deep Learning



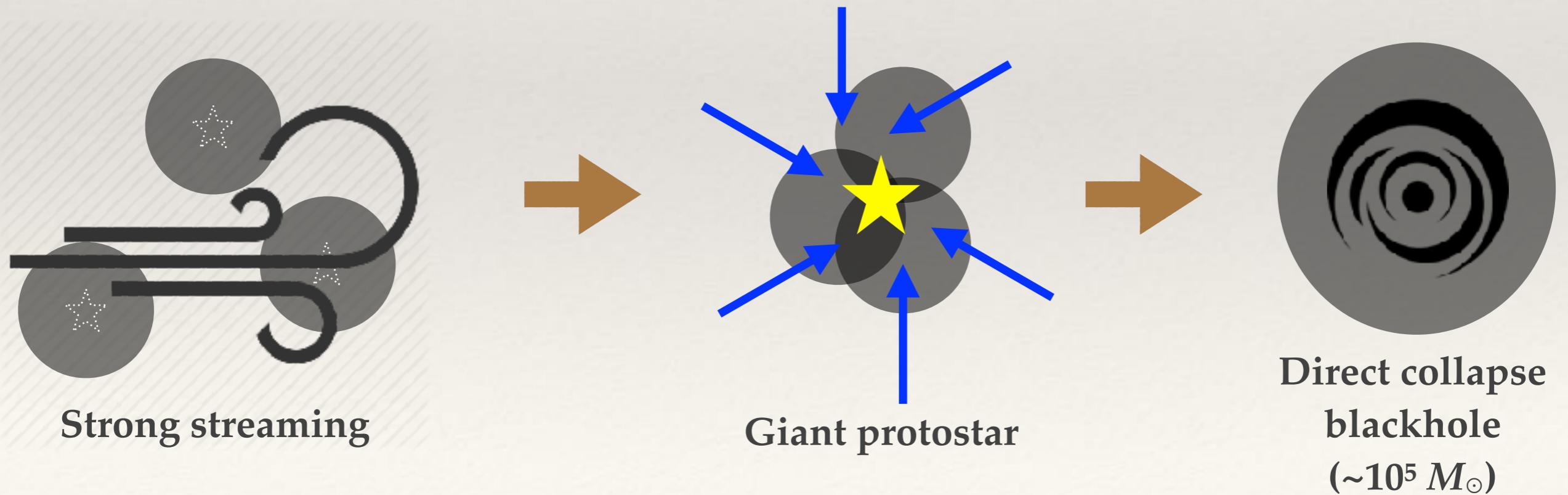
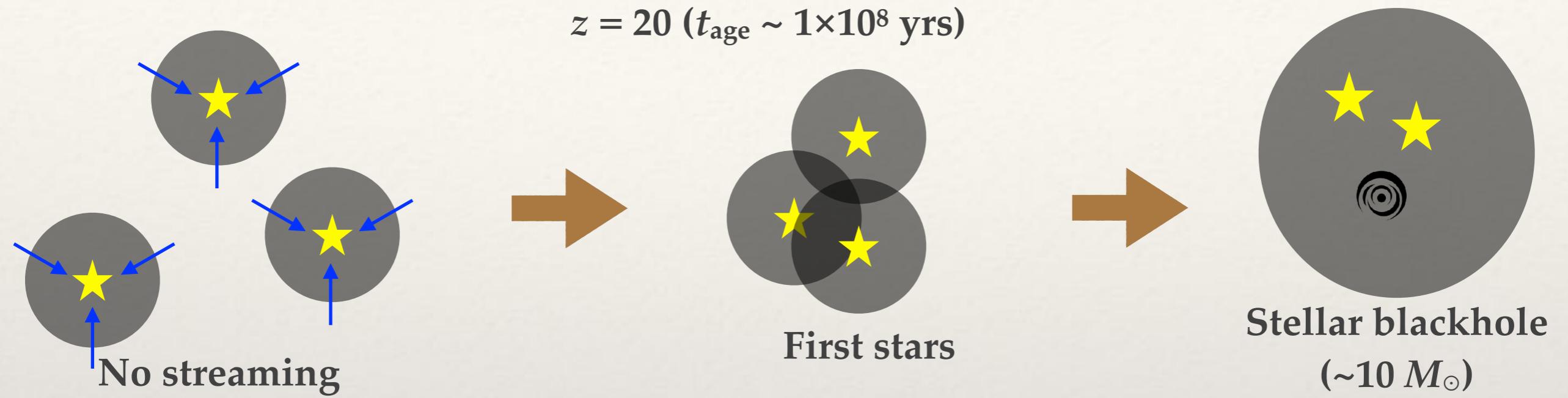
# [Wish List 3] Utilize Deep Learning



We are getting some promising preliminary results!  
(Sorry Tilman! I will keep working!)

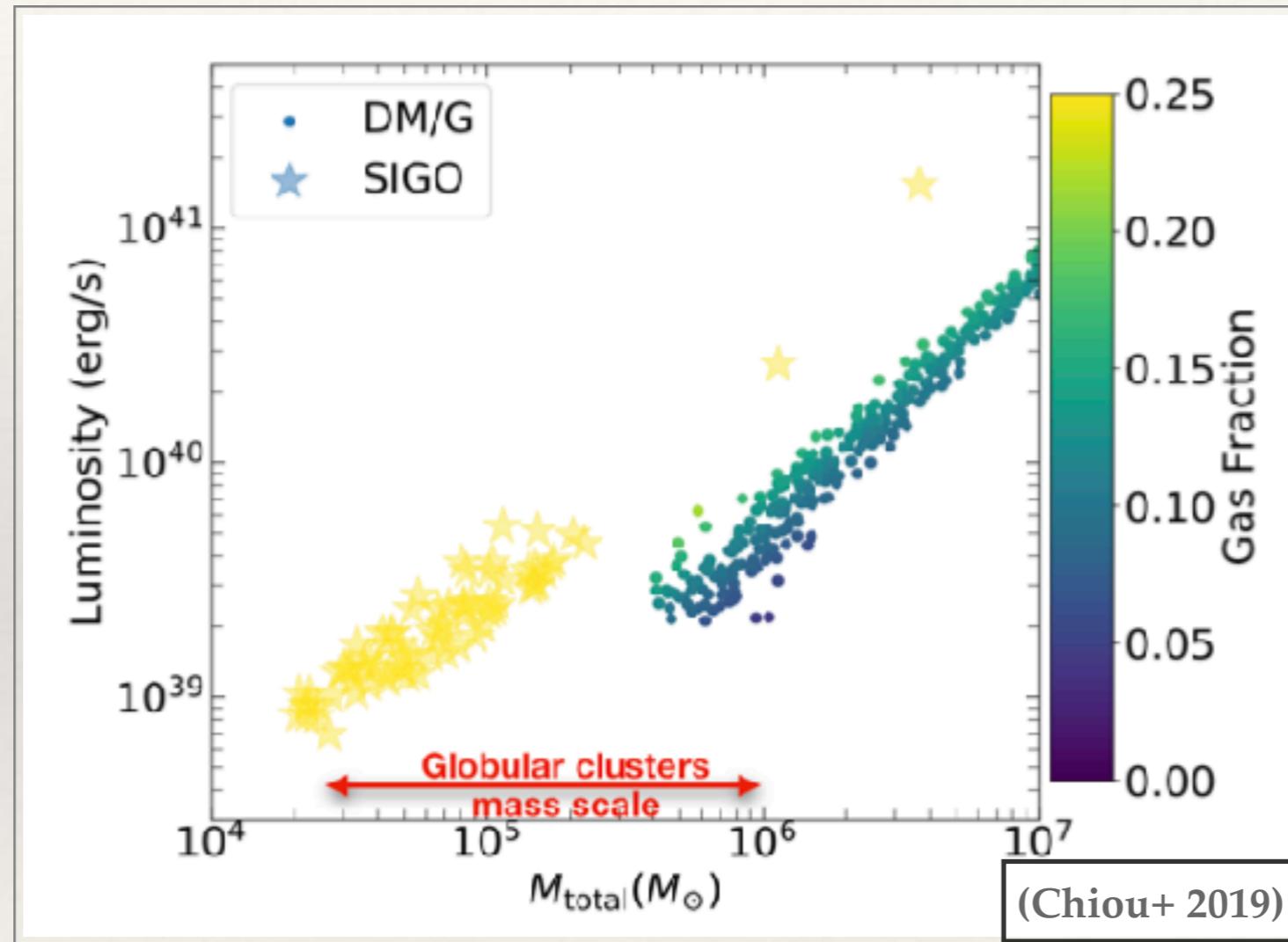
# Direct Collapse Blackhole Scenario

(Hirano et al. 2017)



# Origin of Globular Cluster?

$z = 20$  ( $t_{\text{age}} \sim 1 \times 10^8$  yrs)



Gas-free DM clumps  $\rightarrow$  Missing satellite (?)  
DM-free gas clumps  $\rightarrow$  Globular cluster (?)

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Thank you so much!