The Neutral Islands during the Late Epoch of Reionization

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  * The excursion set theory of reionization
* The Island Model
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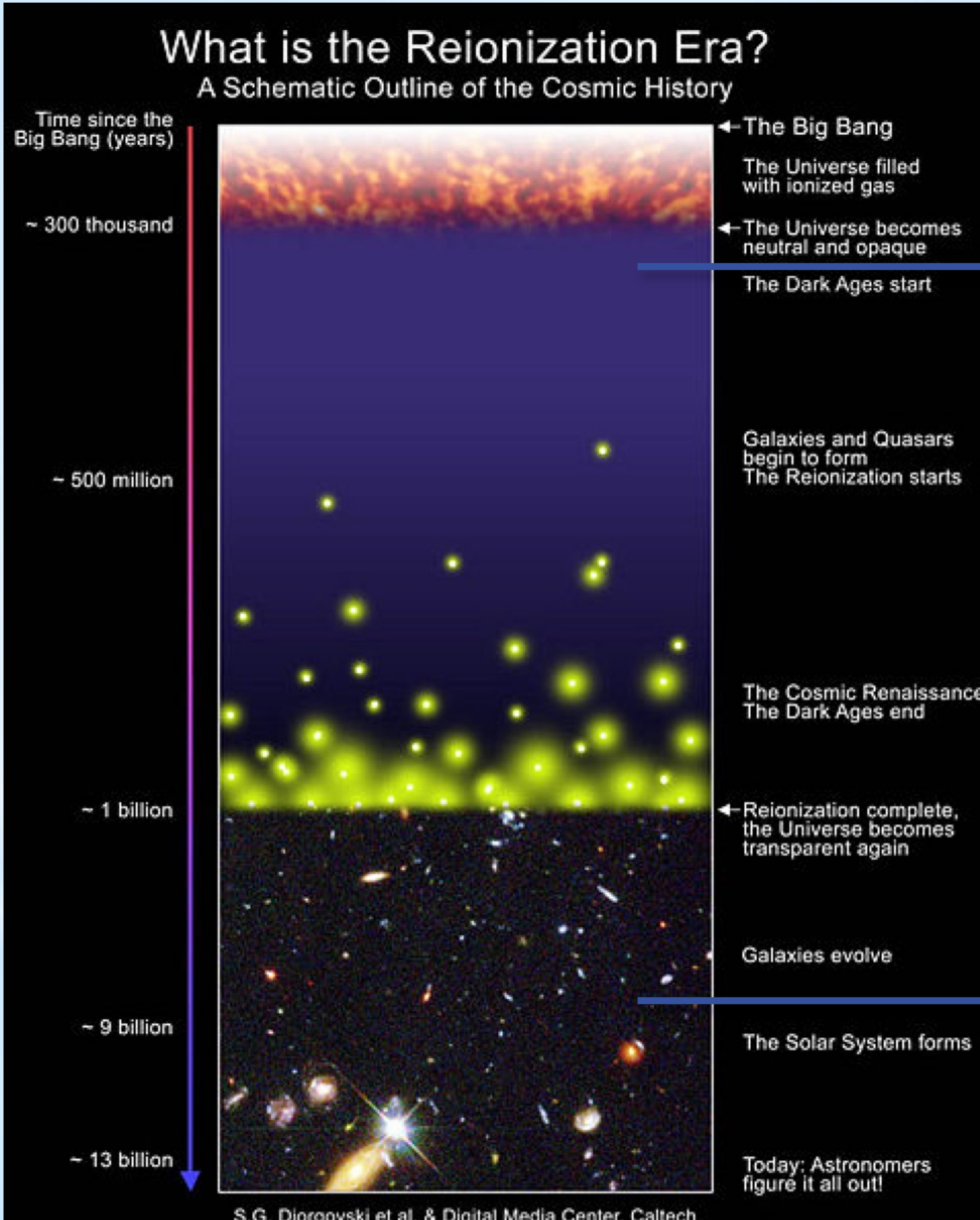
* Results
  * Size distribution & evolution of neutral islands
  * The evolution of ionizing background
* Summary and Outlook

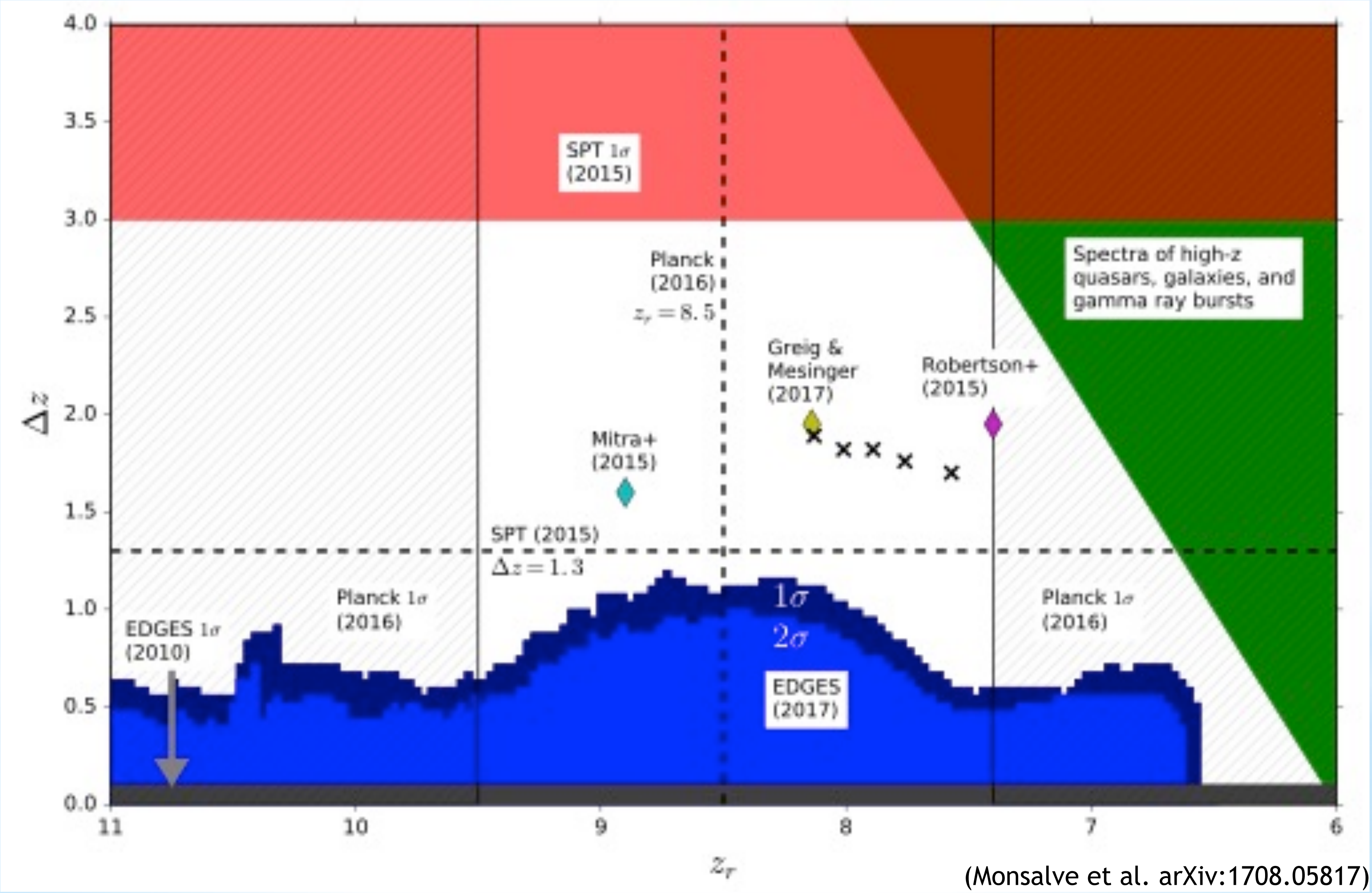


Neutral IGM after recombination

Epoch of reionization (EoR)

Ionized IGM indicated by quasar absorption spectra

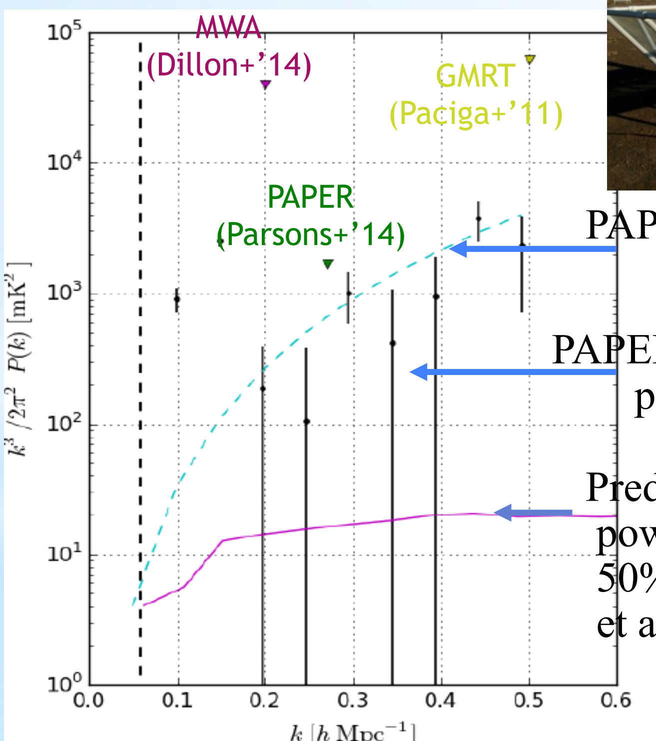
Observational Constraints



(Monsalve et al. arXiv:1708.05817)

Observational Constraints

- Upper limit on the 21cm power spectrum:
  - PAPER → $(22.4\ \mathrm{mK})^2$ at k=0.15 – 0.5 h Mpc^{-1} at z=8.4
  - LOFAR → $(79.6\ \mathrm{mK})^2$ at k = 0.053 h cMpc^{-1} in the range z = 9.6 – 10.6.

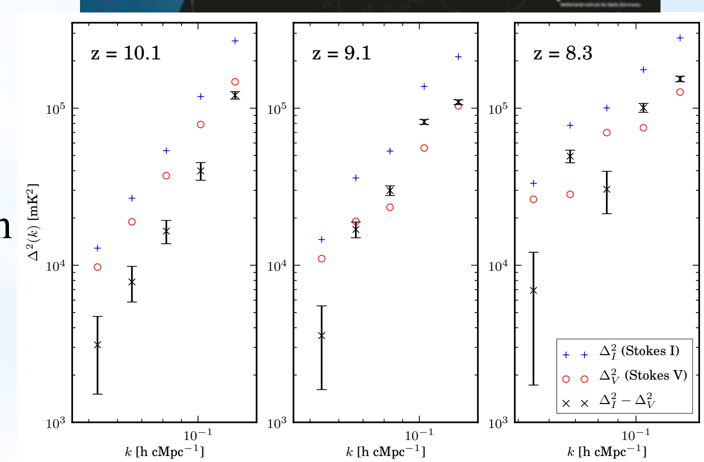


PAPER 2015 2σ upper limit

PAPER 2015 measured points

Predicted model 21 cm power spectrum at 50% ionization (Lidz et al. 2008).

Ali et al. (2015)



Patil et al. (2017)

The upcoming 21 cm experiments

Hydrogen Epoch of Reionization Array (HERA)

Analytical models of reionization

* Early stage – the “bubble model” (Furlanetto et al. 2004)

  -- growing ionized bubbles

* Late stage – the “island model” (Xu et al. 2014)

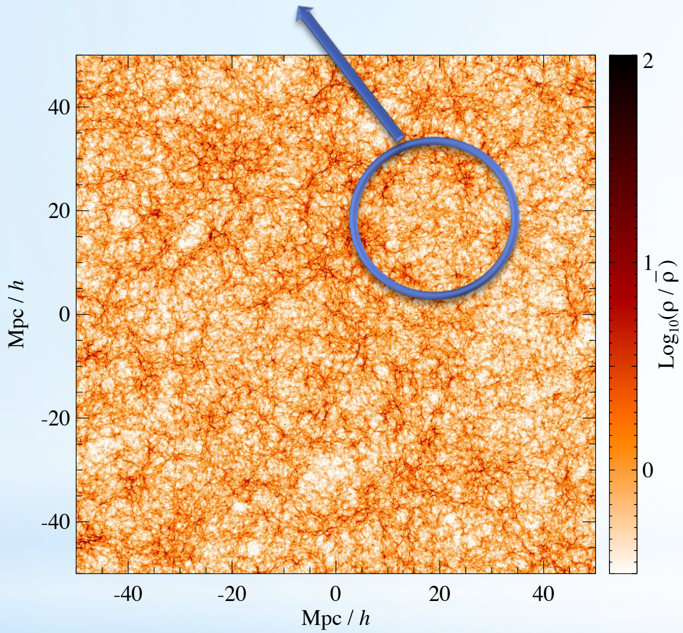
  -- shrinking neutral islands

→ ***Both based on the excursion set theory***

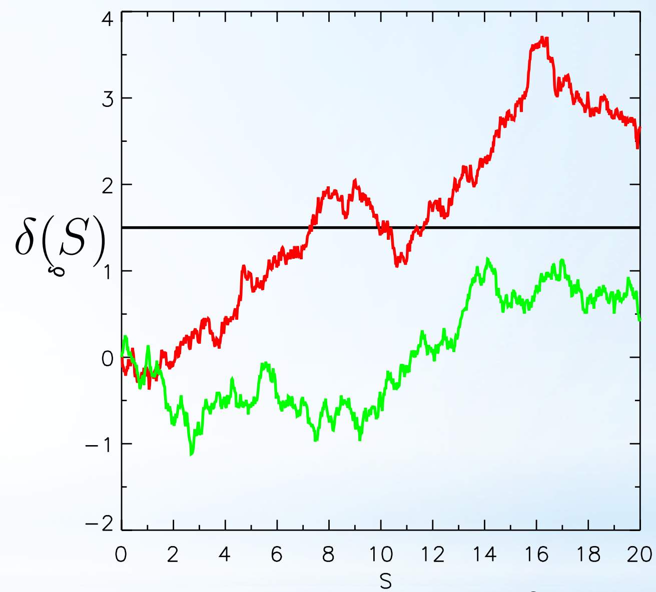
The Excursion Set Theory of Halo Model

(Bond et al. 1991, Lacey & Cole 1993)

$$\delta(\vec{x}; R) \equiv [\rho(\vec{x}) - \rho_{\rm M}]/\rho_{\rm M}$$



- Halo density barrier



$\delta(S)$

$S \equiv \sigma^2(R)$

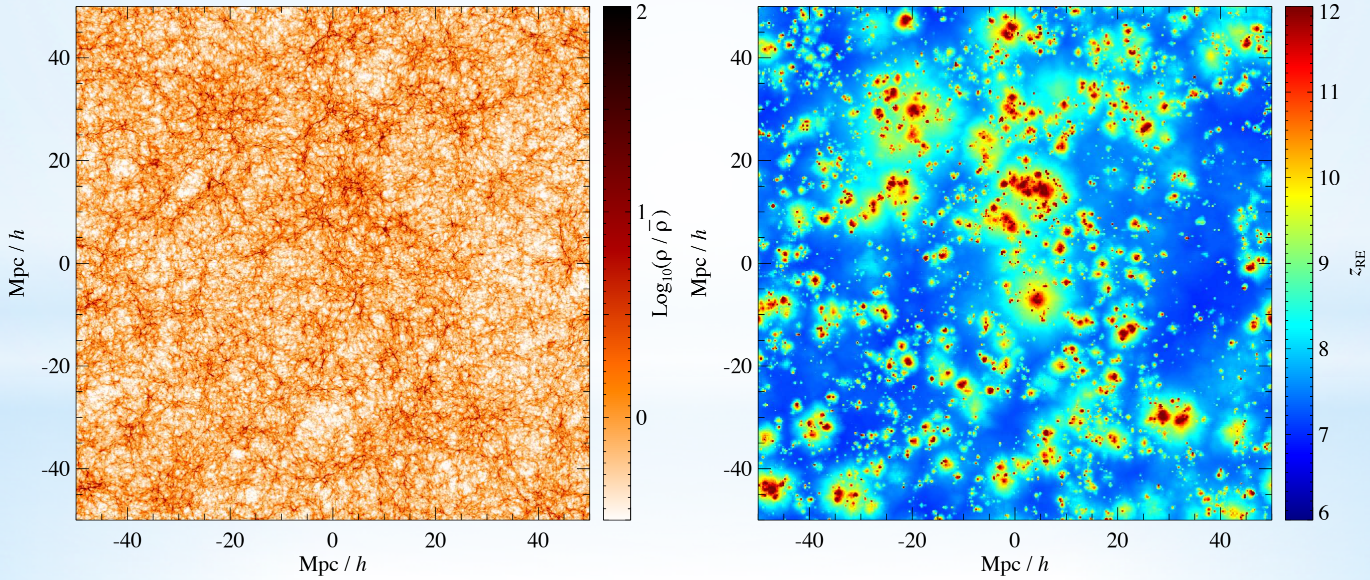
- Solving a diffusion equation → *"first-crossing distribution"*

  → halo mass function

Why excursion set theory?

→ ***Full RT-simulations are computationally expensive***

→ ***The reionization field follows the density field on large scales (Battaglia et al. 2013)***



(From Battaglia et al. 2013 ApJ, 776, 81)

The Excursion Set Approach for ionized bubbles
– The bubble model of reionization

(Furlanetto et al. 2004)

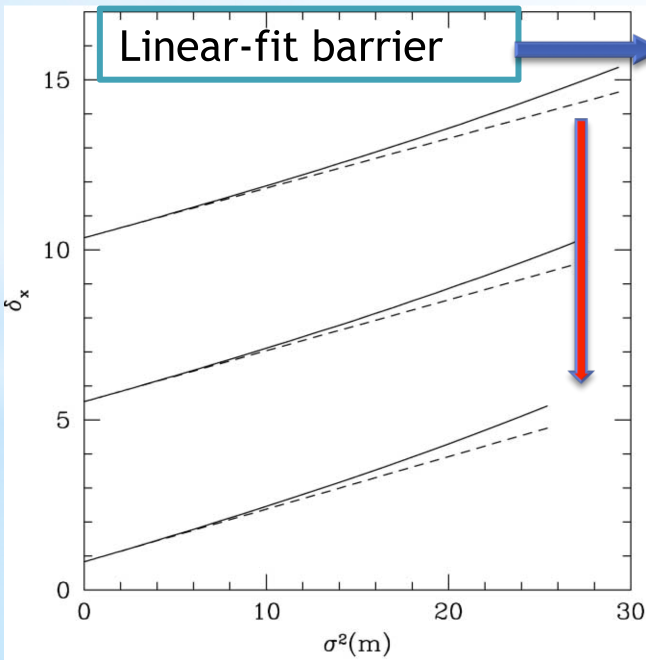
* Relate the ionization field to the initial density field
* Ask whether an isolated region of mass M can be fully self-ionized.

$$f_{\rm coll} \geq f_x \equiv \zeta^{-1}.$$ → $$\delta_m \geq \delta_x(m,z) \equiv \delta_c(z) - \sqrt{2}K(\zeta)[\sigma^2_{\rm min} - \sigma^2(m)]^{1/2}$$

$$K(\zeta) = {\rm erf}^{-1}(1 - \zeta^{-1}).$$

The bubble barrier

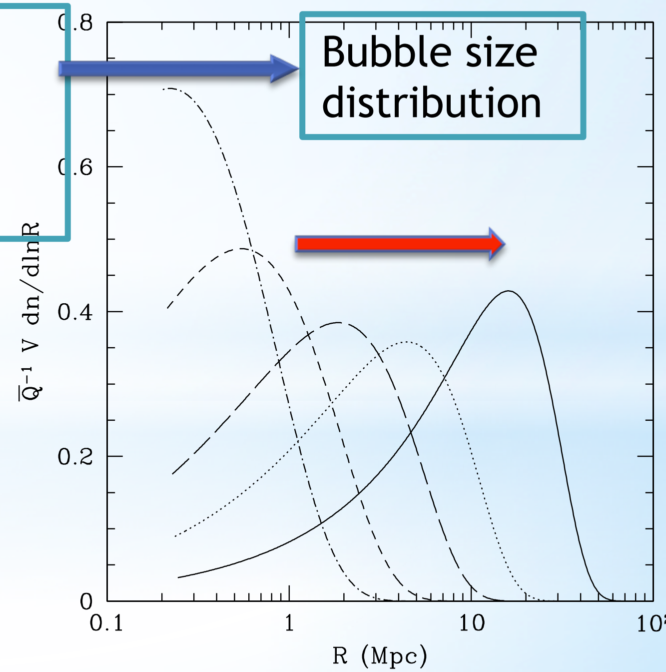
Linear-fit barrier →



First-up-crossing distribution (analytical) →

Bubble-in-bubble problem

Bubble size distribution



However, after percolation…

1. The isolated and spherical assumption for the ionized bubbles breaks down

   ➔ the neutral islands are more isolated

2. The existence of an ionizing background

   ➔ the shape of barriers could be changed

   (the linear fit may not apply)

The island model

It would be relatively easier for the upcoming instruments to probe the signal at the late reionization stages.

The Island Model

(Xu et al. 2014)

* Negative island barrier ("inside-out" reionization)
* Island mass scales are identified by ***first-down-crossings*** through the island barrier (but not the "never-up-crossing" distribution).
* With the inclusion of an ionizing background, the condition of keeping from being ionized:

$$\xi f_{\rm coll}(\delta_{\rm M}; M, z) + \frac{\Omega_m}{\Omega_b} \frac{N_{\rm back} m_{\rm H}}{M X_{\rm H}(1+\bar{n}_{\rm rec})} < 1,$$

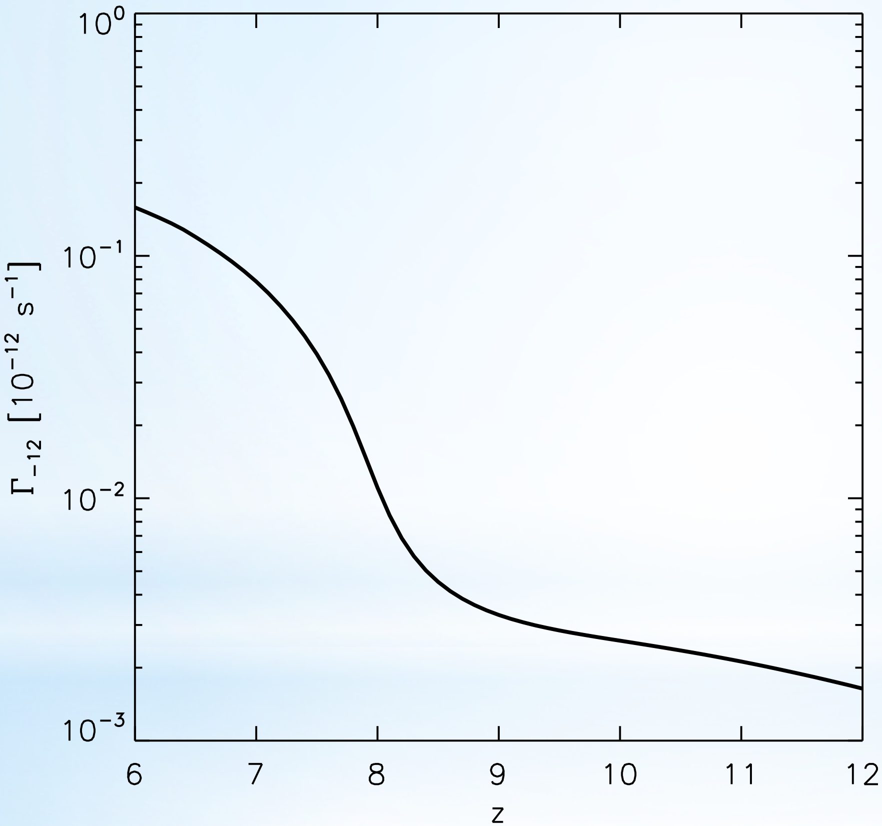
The contribution of background ionizing photons

➔ The island barrier:

$$\delta_{\rm M} < \delta_{\rm I}(M,z) \equiv \delta_c(z) - \sqrt{2[S_{\rm max} - S(M)]}\, {\rm erfc}^{-1}\left[K(M,z)\right],$$

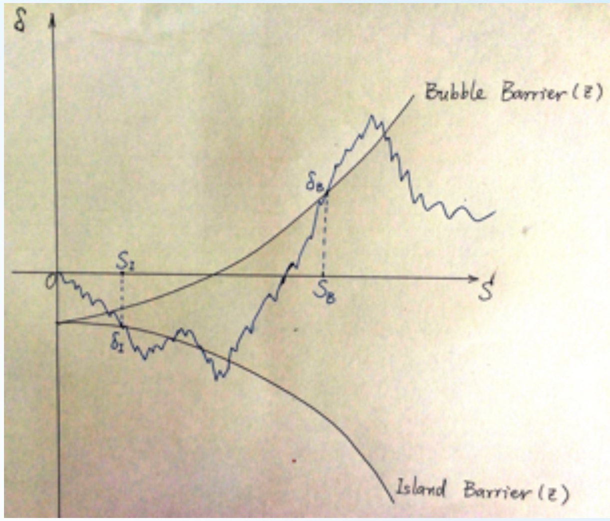
$$K(M,z) = \xi^{-1}\left[1 - N_{\rm back}(1+\bar{n}_{\rm rec})^{-1} \frac{m_{\rm H}}{M(\Omega_b/\Omega_m)X_{\rm H}}\right].$$

The ionizing background



- Considering the effect of ***Lyman limit systems*** on the mean free path of ionizing photons
- Scaling the hydrogen photoionization rate to be $\Gamma_{HI} = 10^{-12.8}$ s^{-1} at redshift 6, as suggested by recent measurements from the Ly-α forest (Wyithe & Bolton 2011; Calverley et al. 2011)
- Consistent with our definition of the "background onset time"

The bubbles-in-island effect (Xu et al. 2014)



* Solving for a two-barrier problem:

1 - The first down-crossing distribution of random walks w.r.t. ***island barrier***:

$$f_{\rm I}(S_{\rm I}, z)$$

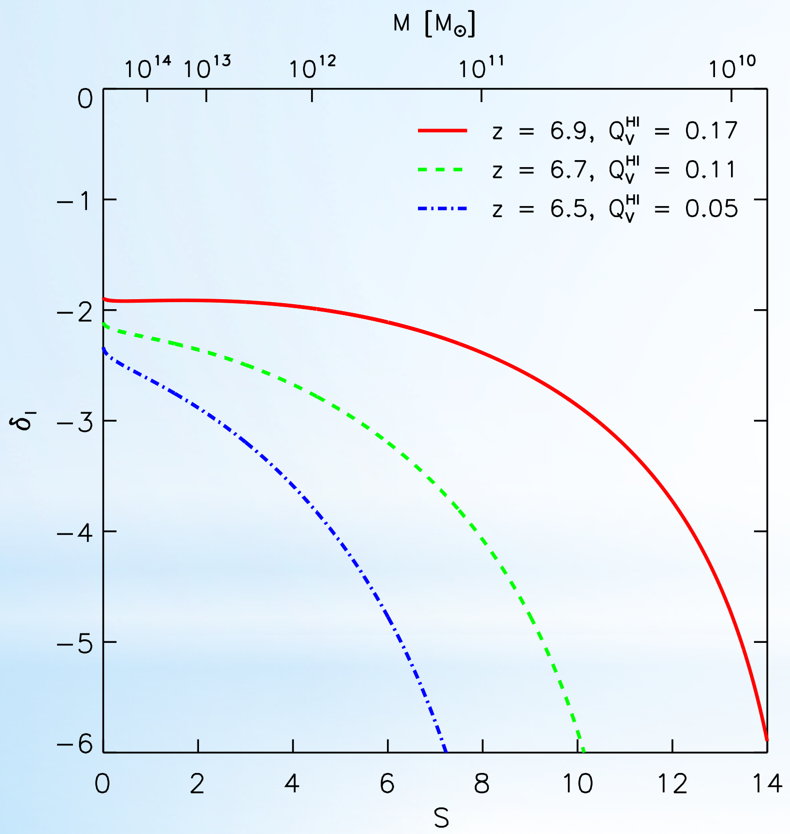
2 - The conditional first up-crossing distribution w.r.t. ***bubble barrier***: $f_{\rm B}[S_{\rm B}, \delta_{\rm B} | S_{\rm I}, \delta_{\rm I}]$

* The effective bubble barrier:

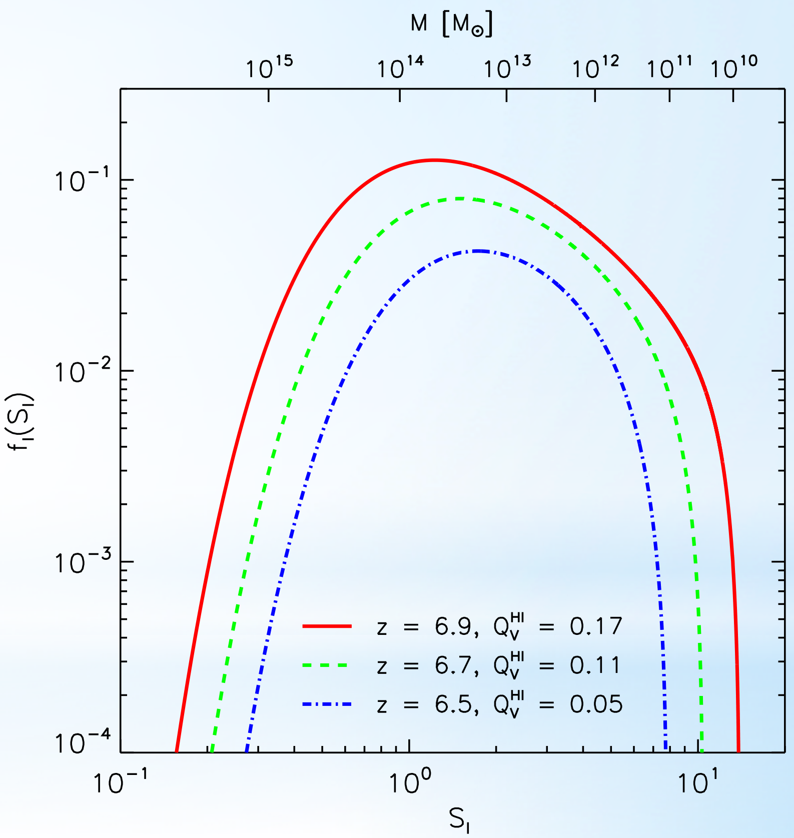
$$\delta'_{\rm B} = \delta_{\rm B}(S + S_{\rm I}) - \delta_{\rm I}(S_{\rm I}) \qquad \text{where } S = S_{\rm B} - S_{\rm I}.$$

The island-vS model – varying surface area

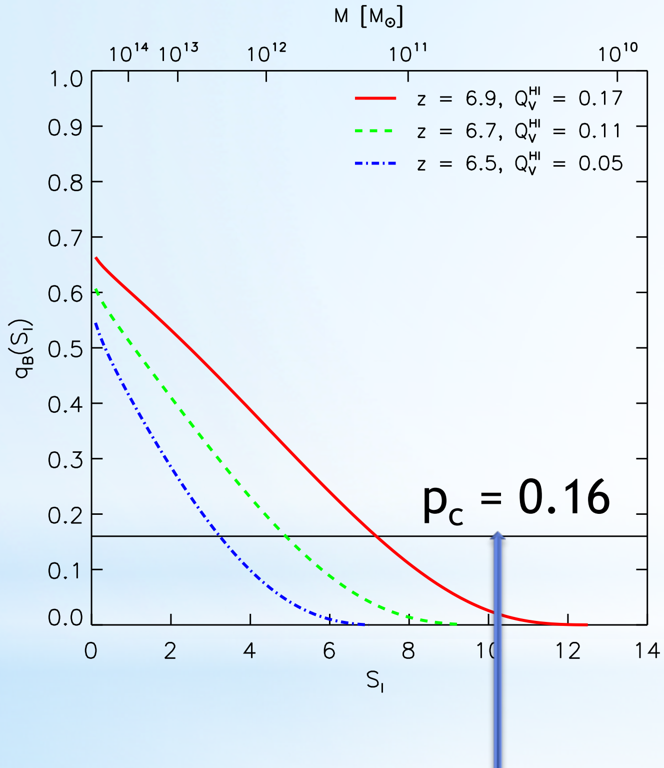
island barrier



first down-crossing distribution



The problem of large bubbles-in-island fraction



for Gaussian random fields

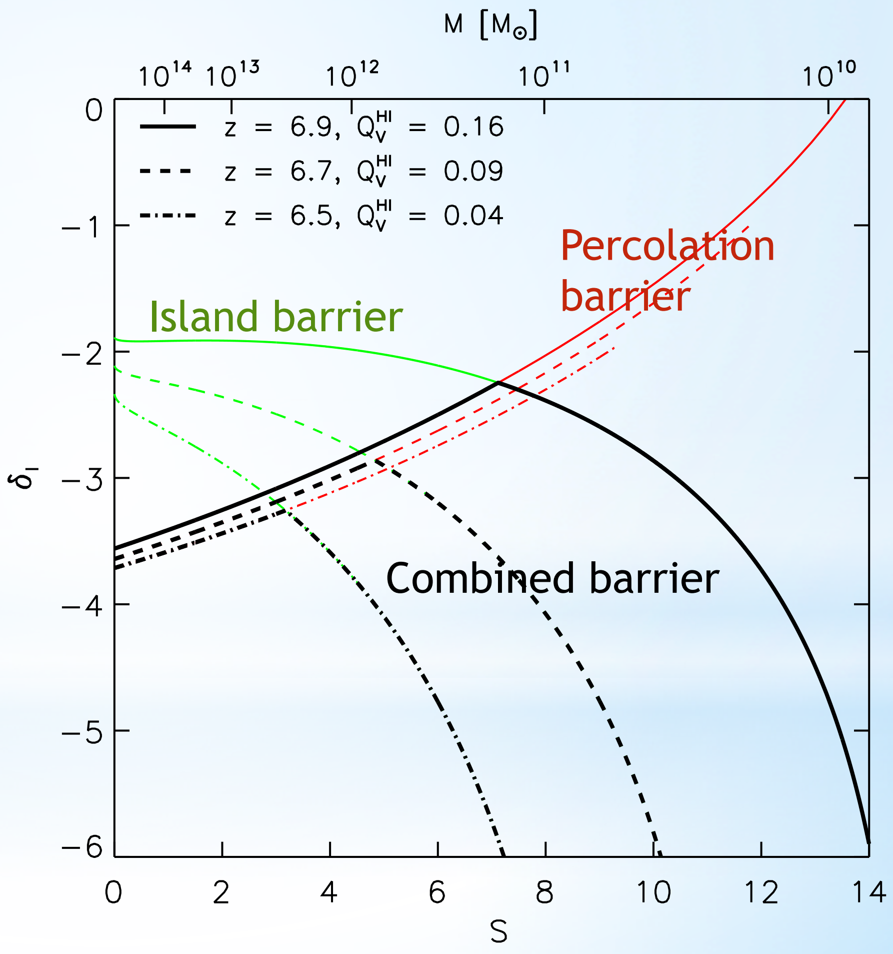
- Host islands → overestimate the neutral fraction
- Neutral islands → not the real image
- Difficult to visually identify the host islands
- Break down of bubble model inside islands

The percolation criterion

* The additional barrier is obtained by solving

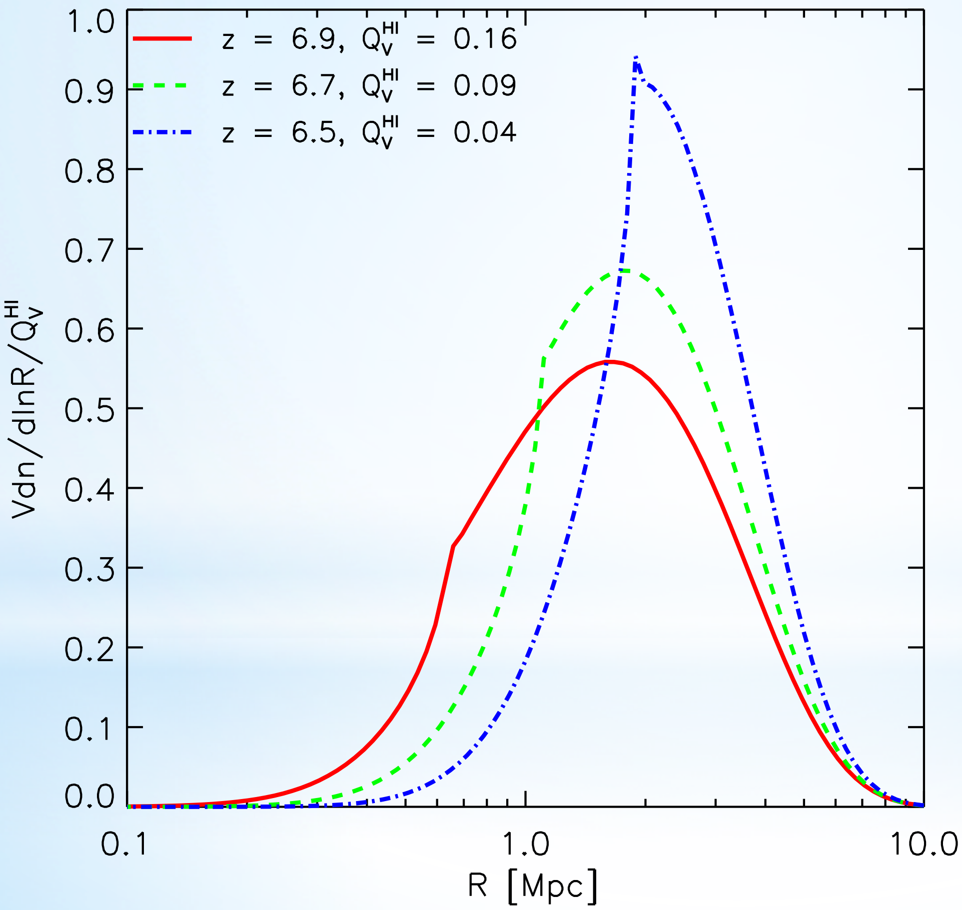
  $q_B(S_I, \delta_I; z) < p_c$

* p_c = 0.16 for Gaussian random fields



Results

– the size distribution with p_c cutoff



A characteristic scale that does not change much with redshift!

(Xu et al. 2014)

Semi-numerical simulation – islandFAST

(Xu et al. 2017)

* Initial ionization field at z >~ z_{back} generated by the 21cmFAST
* A ***two-step*** filtering algorithm

  1 – Based on the excursion set theory, we filter the evolved density field and ***find host islands*** with the island barrier including an ionizing background.

  2 – ***Find bubbles in islands*** with the bubble barrier without an ionizing background.

* A self-consistent treatment for the ionizing background taking into account the effect of absorption systems

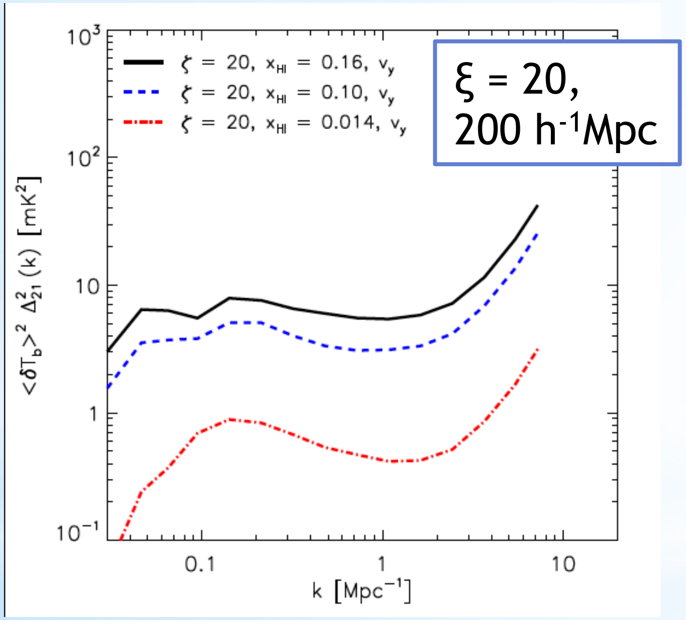
$$\lambda_{\rm mfp}^{-1}(z) = \lambda_{\rm I}^{-1}(z) + \lambda_{\rm abs}^{-1}(z).$$

* An ***iterative*** procedure and ***adaptive*** redshift steps.

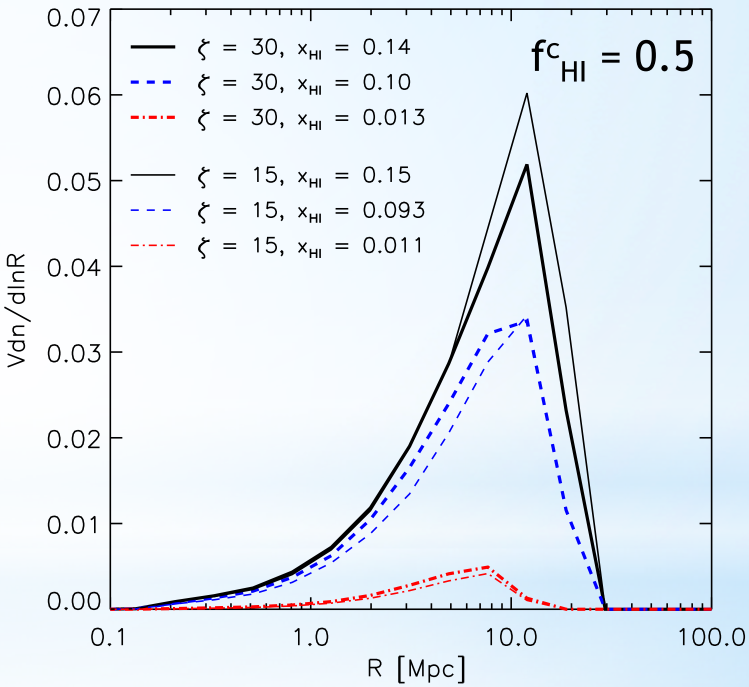
Semi-numerical simulation – islandFAST

Semi-numerical simulation – islandFAST

* The 21 cm power spectrum

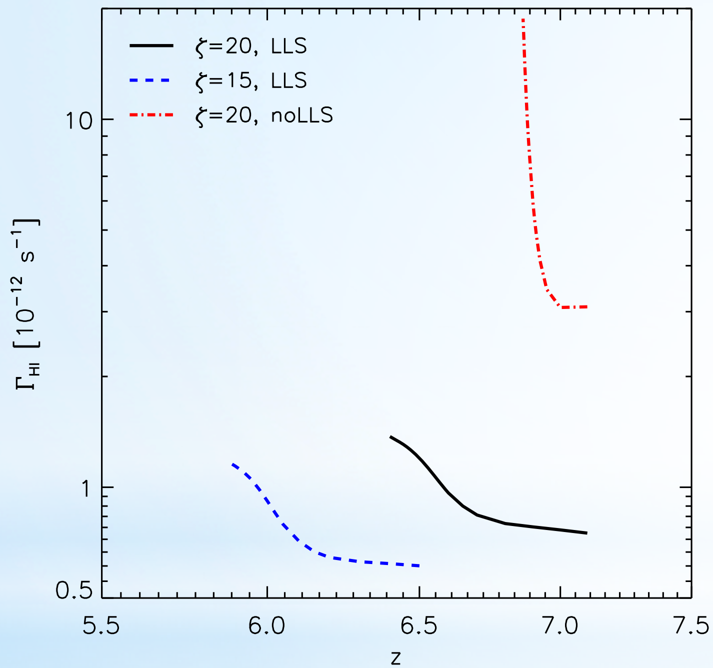


* The size distribution of islands

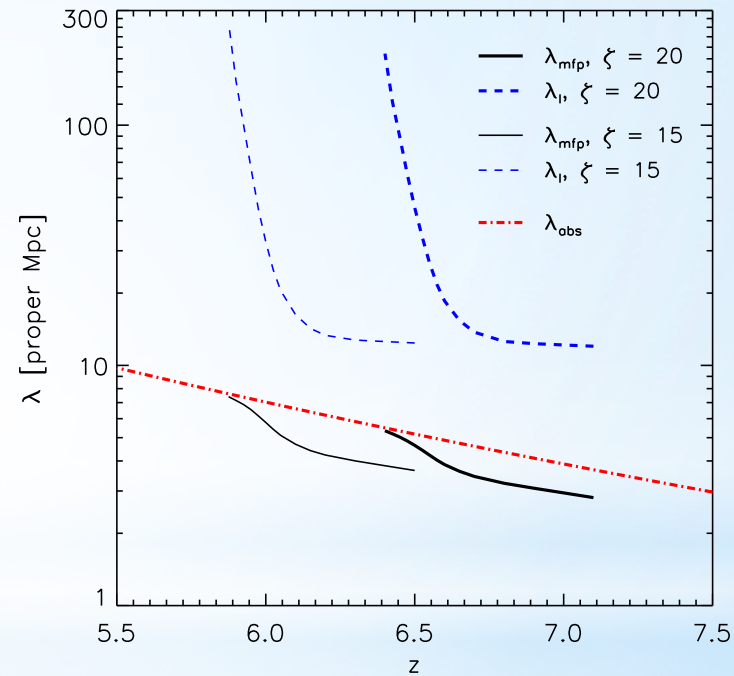


The role of small absorbers vs. large islands

* The ionizing background



* The MFP of ionizing photons



- The large-scale islands dominate the morphology of the ionization field
- The small-scale absorbers dominate the opacity of the IGM, and they delay and prolong the reionization process significantly.

Summary

Before percolation

* Early EoR
* Isolated and spherical bubbles
* No UVB in model
* First-up-crossing distribution
* Linear-fitted barrier with analytical solution

After percolation

* Late EoR
* Isolated and spherical islands
* With UVB
* First-down-crossing distribution
* Arbitrary shaped barriers with numerical solution
* Bubbles-in-island effect

* **Bubble model vs. Island model**

Summary

- islandFAST – a semi-numerical tool to ...

* Simulate the later part of EoR
* Model the effect of different absorbers
  - The large-scale islands dominate the morphology of the ionization field
  - The small-scale absorbers dominate the opacity of the IGM, and they delay and prolong the reionization process significantly.
* Generate synthesis signals from the late EoR
* ……

THANK YOU!