

The Intergalactic Medium: a Weakly Collisional Plasma

Prakash Gaikwad

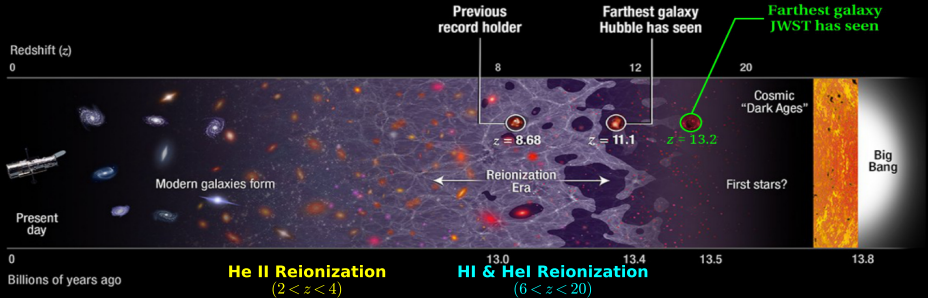
30 Jan, 2026



Introduction

What is the IGM?

Image : NASA, ESA, P. Oesch, B. Robertson and A. Fe



- Density fluctuations in the early universe ($z \sim 1100$, $t_{\text{age}} \sim 0.4 \text{ Myr} \sim 0.4 \times 10^6 \text{ yr}$)

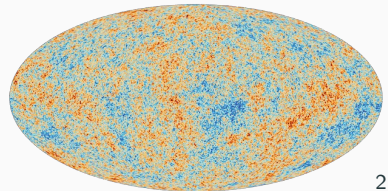
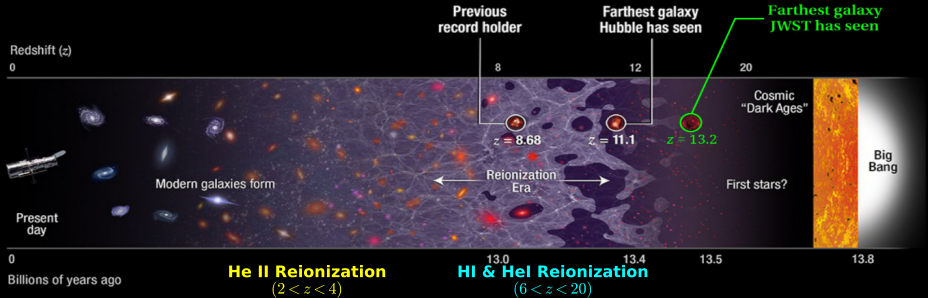
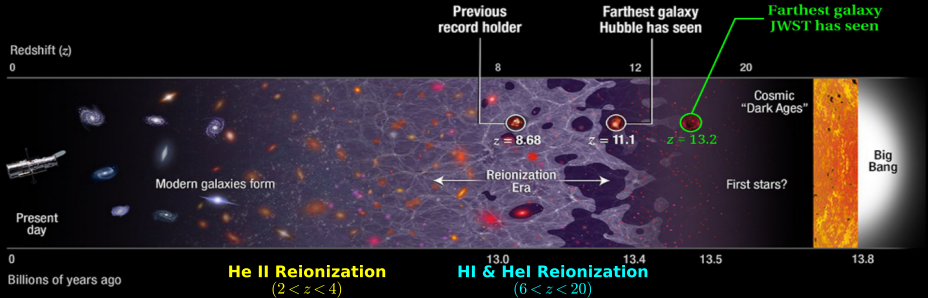


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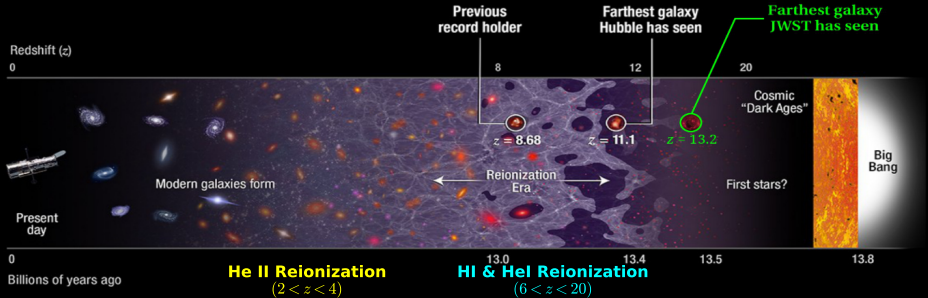
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- Overdense regions grow due to gravitational instability
- Collapsed structures: Formation of stars and Galaxies ($z < 20$, $t_{\text{age}} \sim 0.2 \text{ Gyr} \sim 0.2 \times 10^9 \text{ yr}$)

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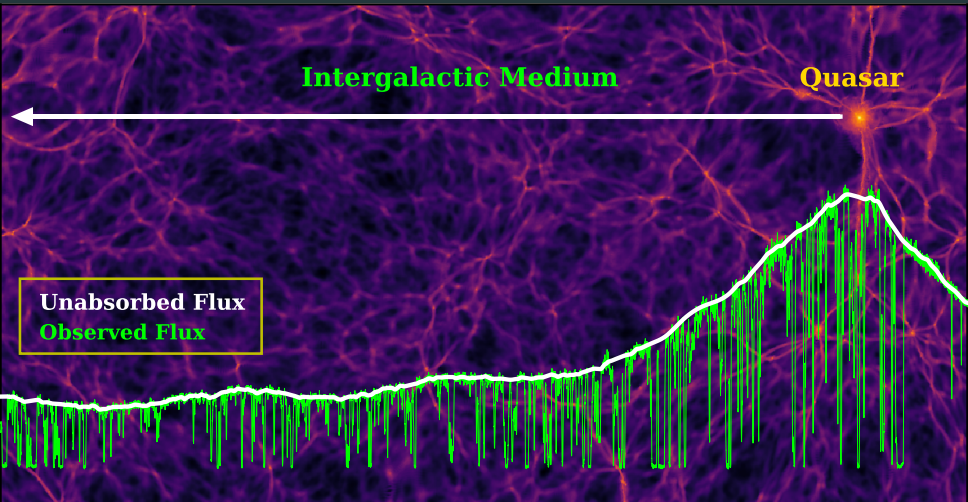


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- Intergalactic Medium: Diffuse gas that is not associated with collapsed objects
- IGM Features: (i) Large volume and (ii) Distinct filamentary structure

Image : NASA, ESA, P. Oesch, B. Robertson and A. Fe

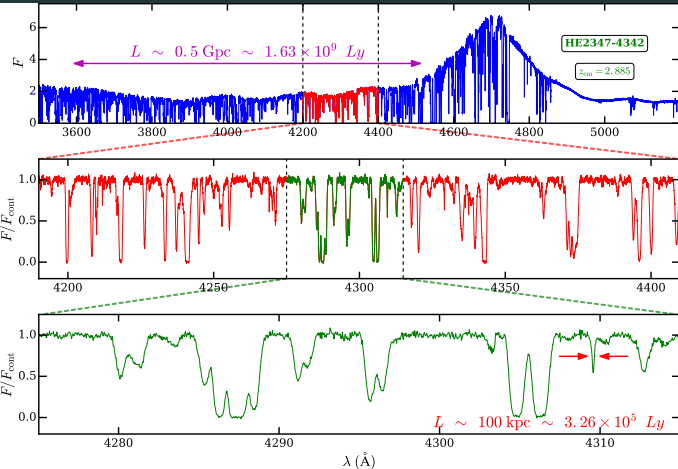


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- How do we probe the IGM?



- The set of characteristics absorption features are collectively known as $\text{Ly}\alpha$ forest
- Main focus of my work $\Rightarrow$ Observations + Simulations of $\text{Ly}\alpha$ forest
- Why is the quasar absorption spectroscopy important?

Advantages of Quasar absorption spectroscopy



Huge dynamic range

1. Cosmological Scales

Large scales $\sim 0.5 \text{ Gpc}$

Small scales $\sim 100 \text{ kpc}$

2. Cosmological Densities

Low density IGM

$n \sim 0.001 \text{ m}^{-3}$

High density IGM

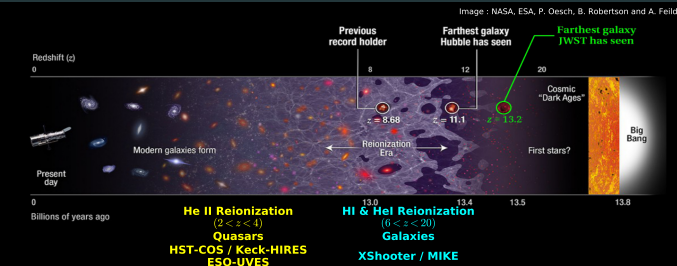
$n \sim 10 \text{ m}^{-3}$

Earth : 1 atm, 300 K

$n \sim 10^{25} \text{ m}^{-3}$

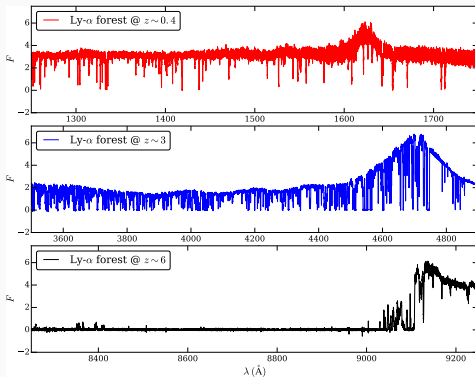
- Quasar absorption spectroscopy is a very sensitive probe of the IGM
- Suitable for studying both cosmology and astrophysics
- What is the physical state of the IGM?

Evolution of the IGM



How does Ly α forest look at different cosmic times?

Ly α forest observations



$t_{\text{age}} \sim 10 \text{ Gyr}$

Hubble Telescope
Gaikwad+2017a,b

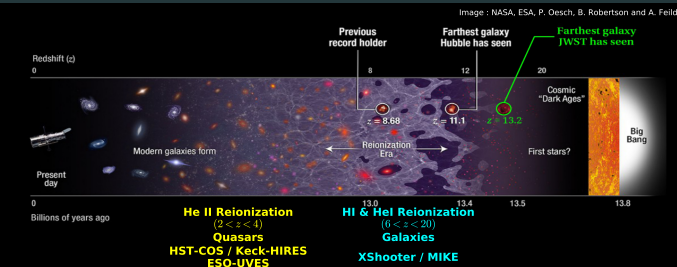
$t_{\text{age}} \sim 2 \text{ Gyr}$

Keck Telescope
Gaikwad+2021

$t_{\text{age}} \sim 1 \text{ Gyr}$

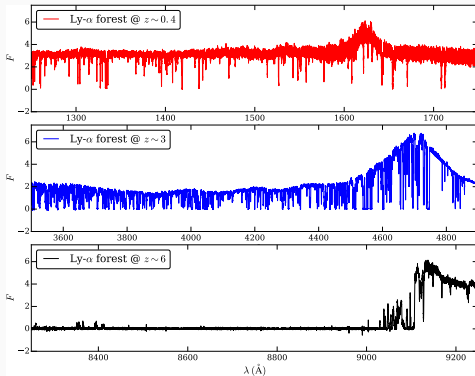
Magellan Telescope
Gaikwad+2020,23

Evolution of the IGM



How does Ly α forest look at different cosmic times?

Ly α forest observations



Less absorption

$t_{\text{age}} \sim 10$ Gyr

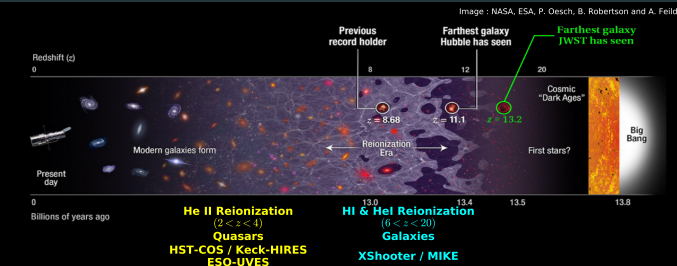
More absorption

$t_{\text{age}} \sim 2$ Gyr

High absorption

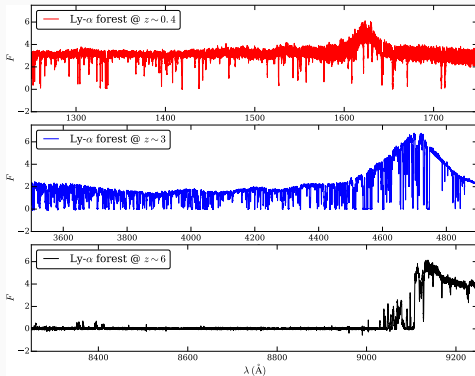
$t_{\text{age}} \sim 1$ Gyr

Evolution of the IGM



How does Ly α forest look at different cosmic times?

Ly α forest observations



Less absorption

$t_{\text{age}} \sim 10$ Gyr

Highly ionized

More absorption

$t_{\text{age}} \sim 2$ Gyr

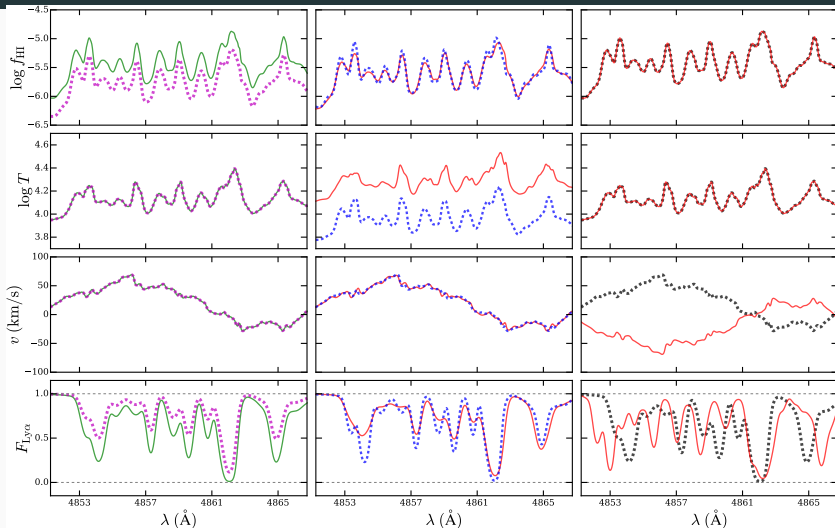
More neutral

High absorption

$t_{\text{age}} \sim 1$ Gyr

Highly neutral

Evidence of Cosmic Reionization



Depth of absorption lines

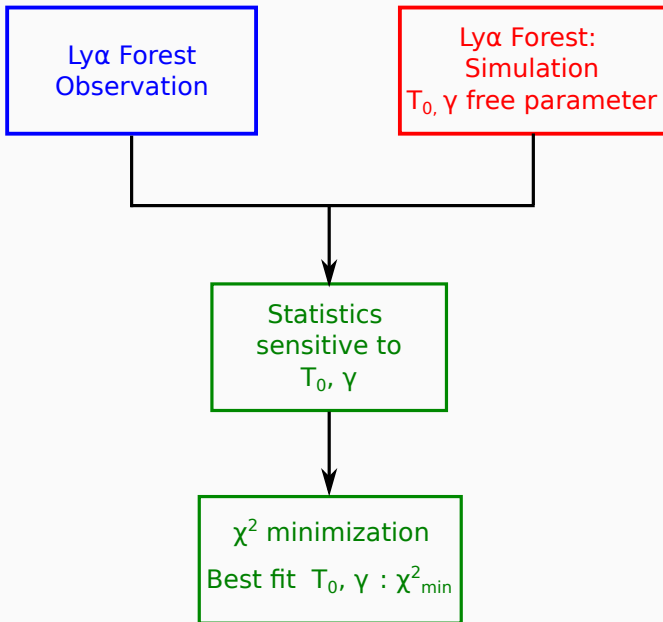
Width of absorption lines

Location of absorption lines

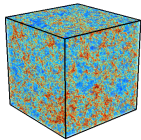
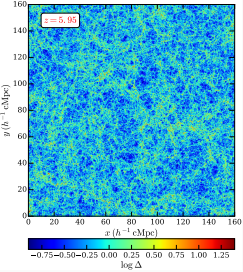
The process of reionization affects amount of neutral hydrogen and temperature

Velocities are affected by large scale structures formation

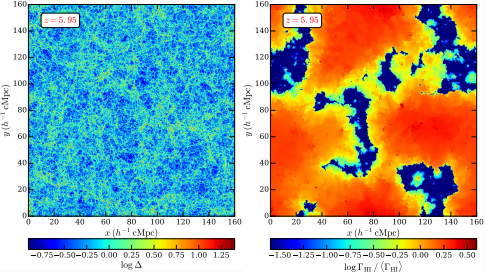
Method



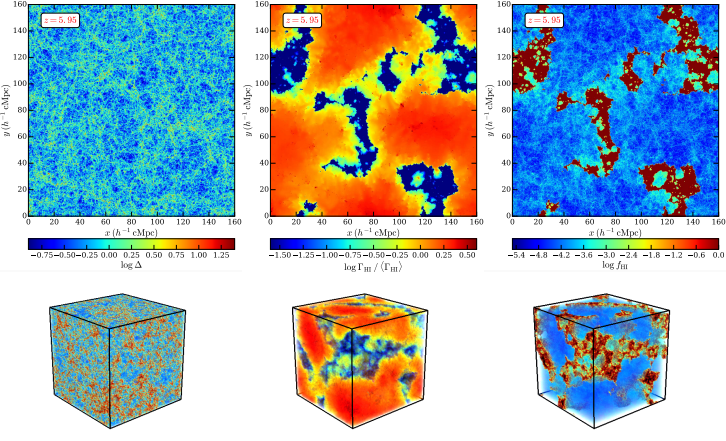
Simulations



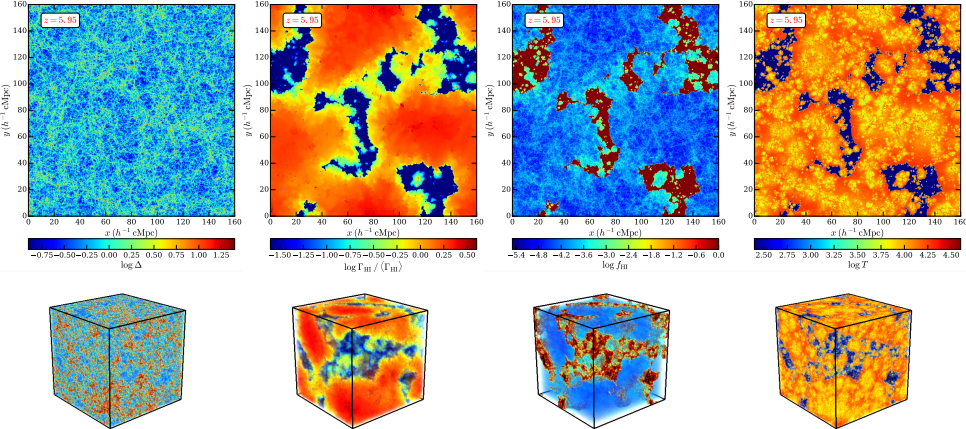
- Perform cosmological hydrodynamical simulation from $t = 10 \text{ Myr}$ to 1.2 Gyr ($2 < z < 100$)



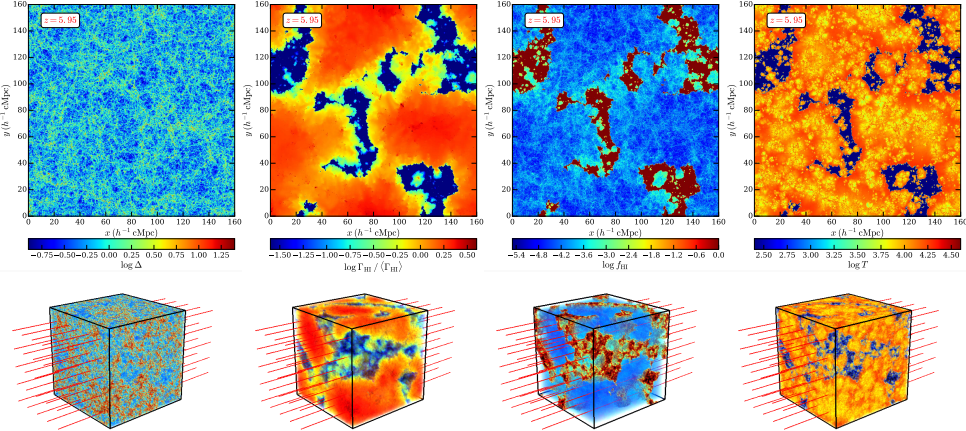
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- Solve radiative transfer equation that propagates ionizing radiation field to IGM



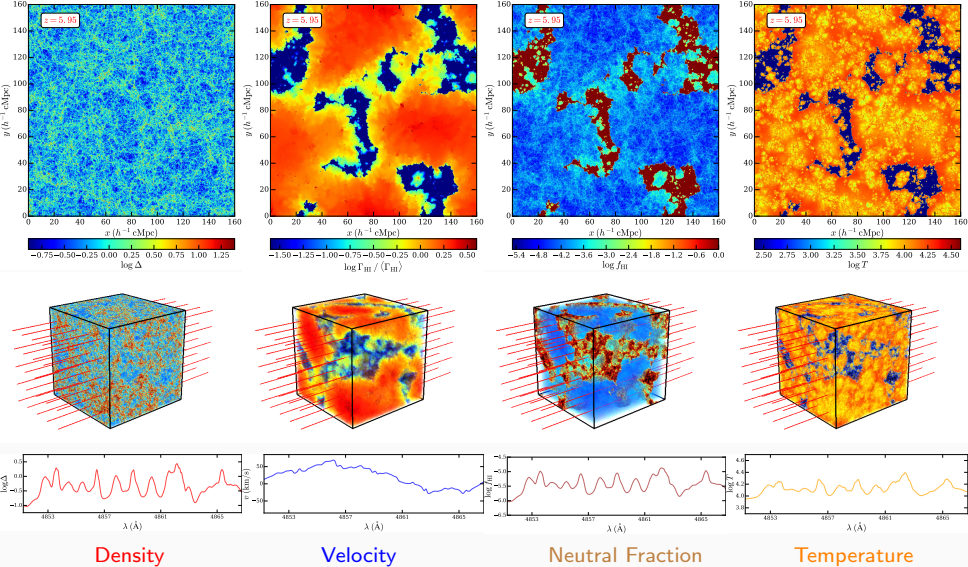
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- Solve non-equilibrium (chemistry) ionization evolution Equation for HI, Hel, Hell



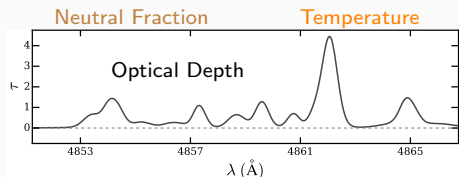
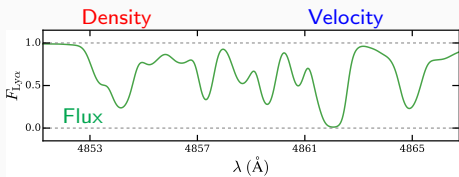
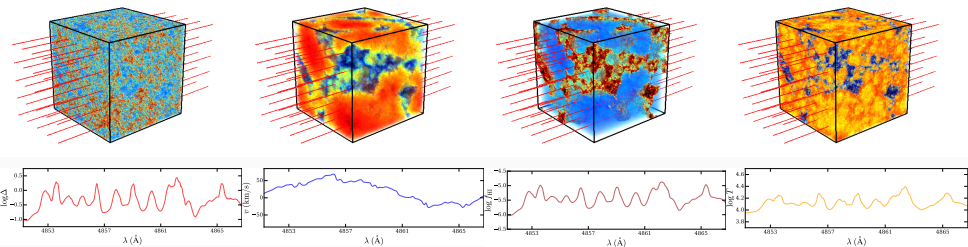
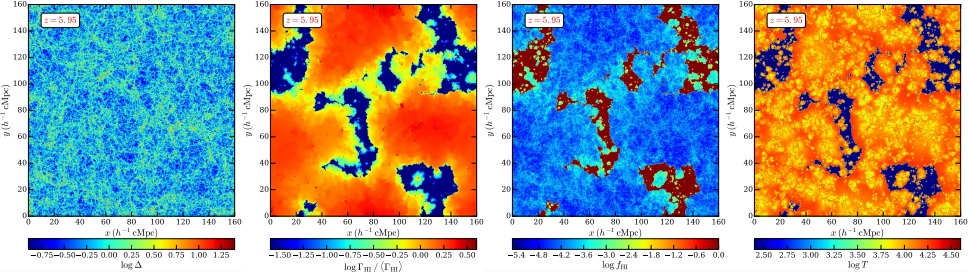
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- Step 2 to 4 are performed in post-processing of hydrodynamical simulations

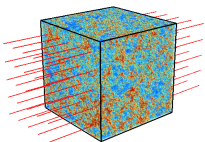
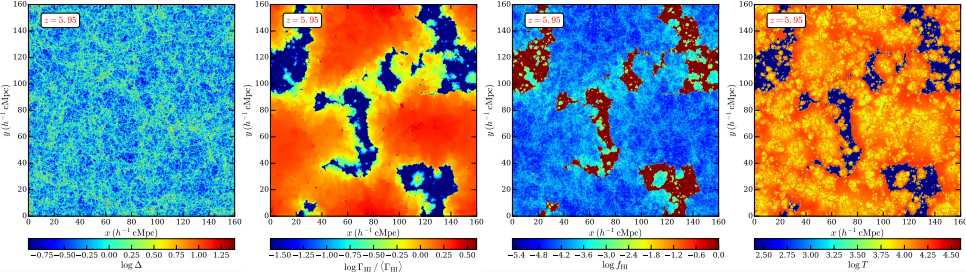


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- Step 2 to 4 are performed in post-processing of hydrodynamical simulations
- Randomly shoot sightlines to extract fields that probes different large scale structures.

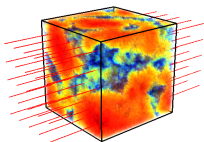


- Example of a sample sightline. The fields are then used to compute absorption spectrum.

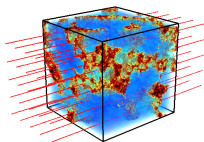




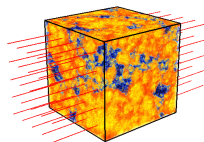
Fluid + Gravity



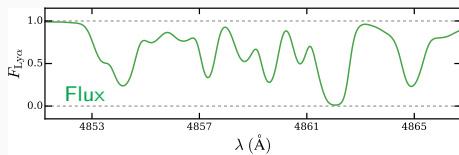
Radiative Transfer



Ionization Evolution



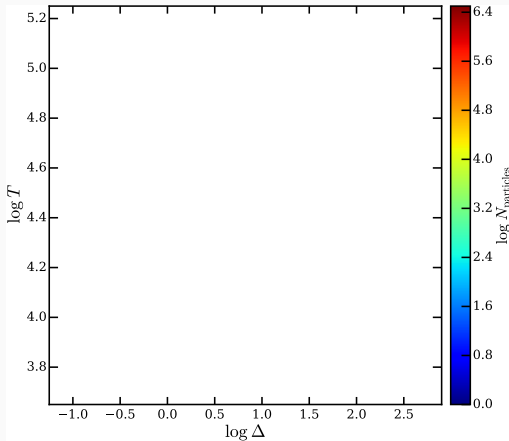
Temperature Evolution



Ly α line transfer

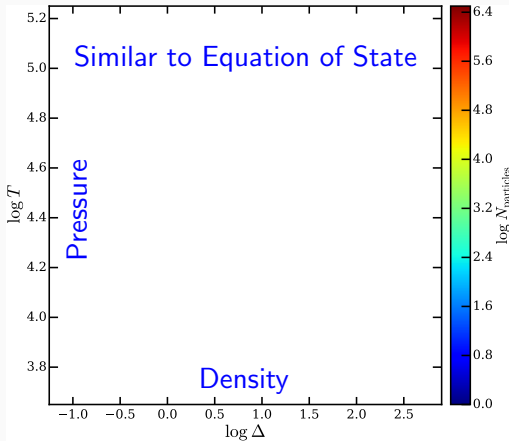
Results

Temperature-Density Relation



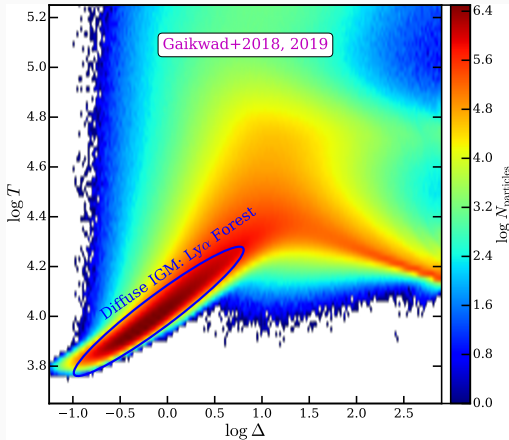
- IGM is low density medium. Essential to see how does temperature correlate with density

Temperature-Density Relation



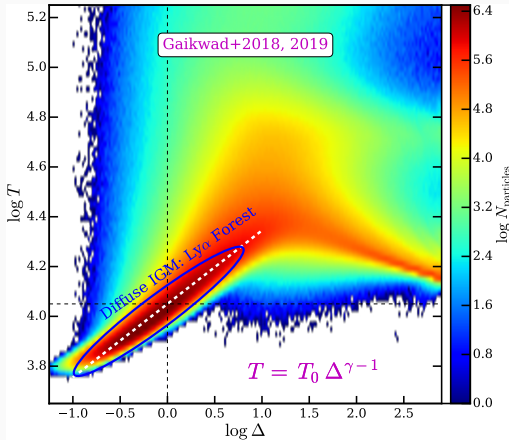
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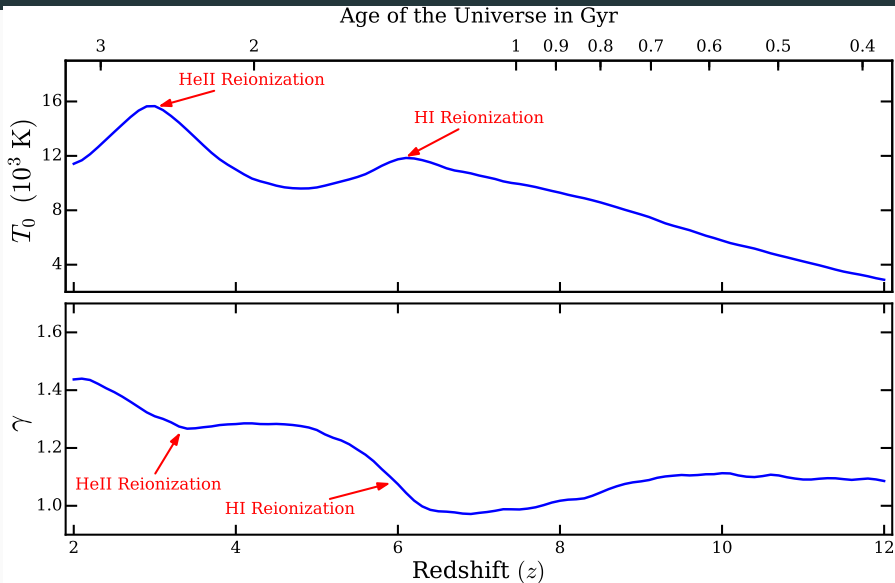
- IGM is low density medium. Essential to see how does temperature correlate with density
- Temperature density relation from cosmological hydrodynamical simulations
- In low density IGM, temperature and density are tightly correlated ($\Delta = \rho/\bar{\rho}$)

Temperature-Density Relation



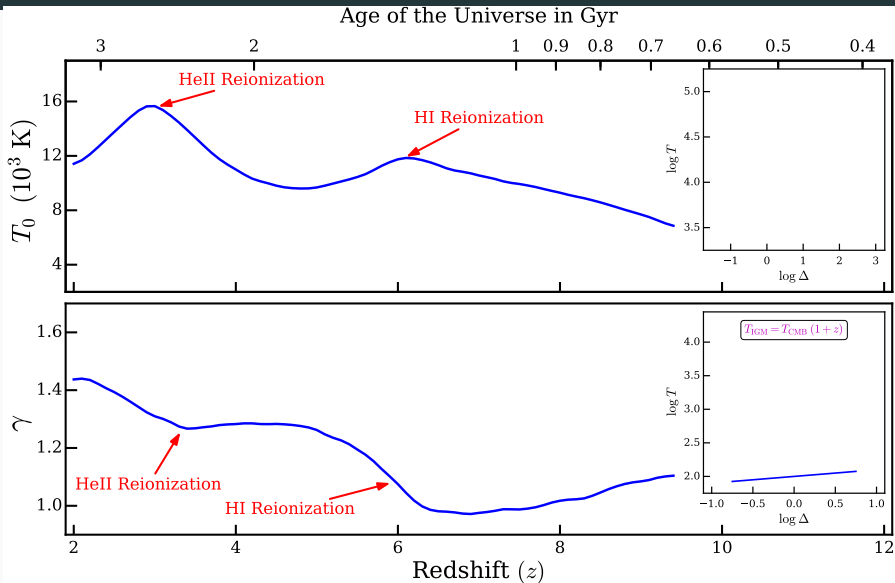
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- Temperature density relation from cosmological hydrodynamical simulations
- In low density IGM, temperature and density are tightly correlated ($\Delta = \rho/\bar{\rho}$)
- Temperature-Density relation is well described by the power-law
- Evolution of thermal parameters (T_0, γ) quantifies thermal state of the IGM.

Temperature-Density Relation



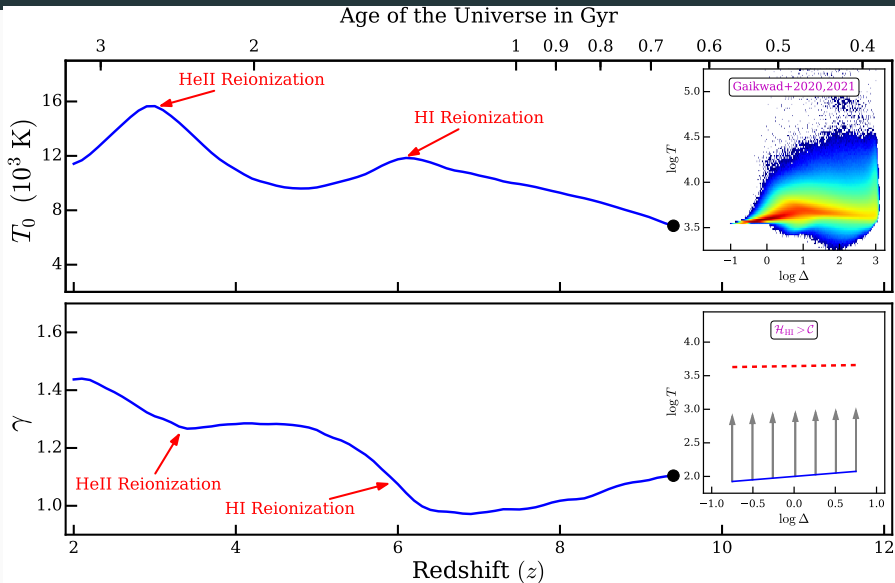
Evolution of thermal parameters

Temperature-Density Relation



Initially temperature of the IGM is similar to CMB temperature

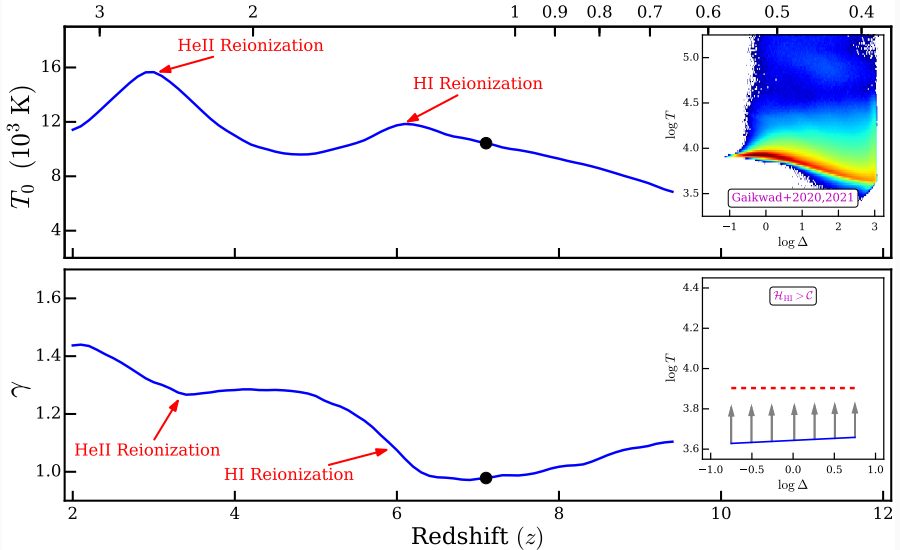
Temperature-Density Relation



During reionization, IGM starts to heat. Heating is more than cooling.

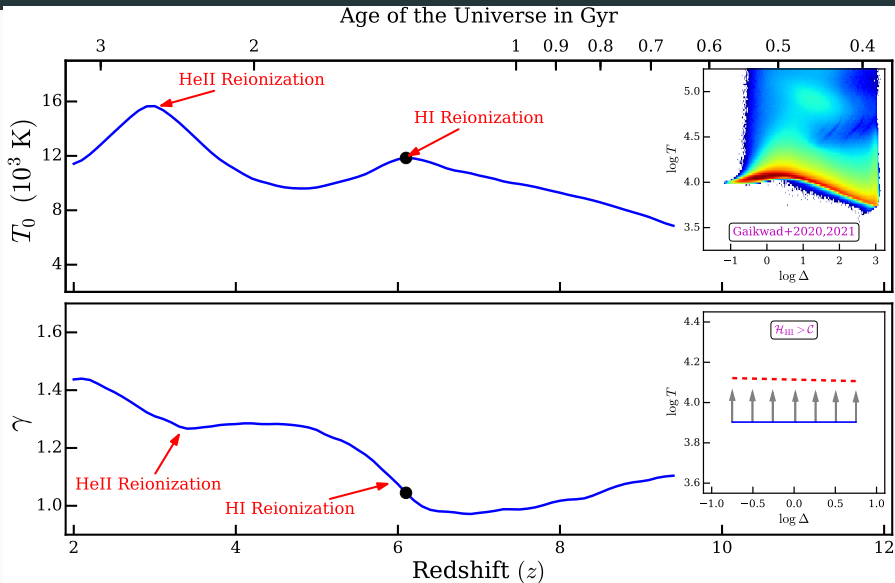
Temperature-Density Relation

Age of the Universe in Gyr



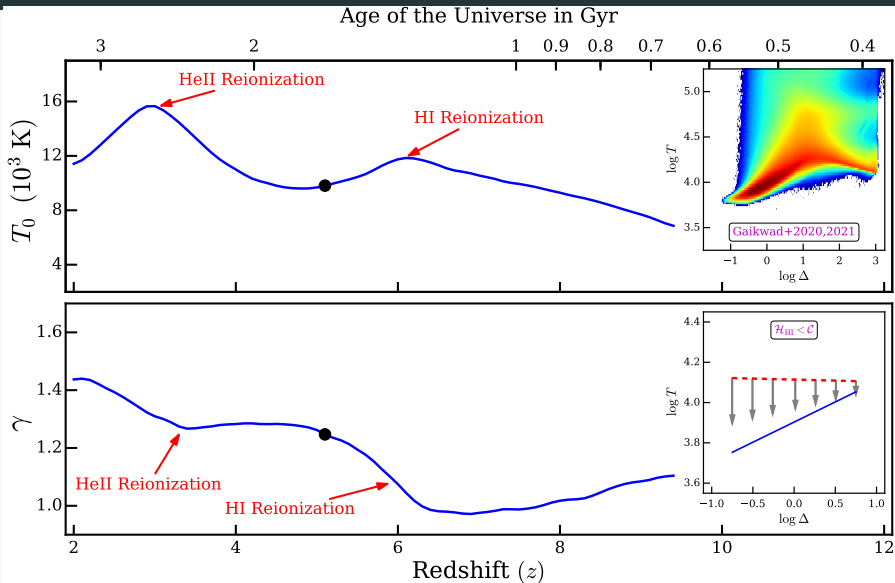
Heating is independent of density. So all the densities heated to similar temperature.

Temperature-Density Relation



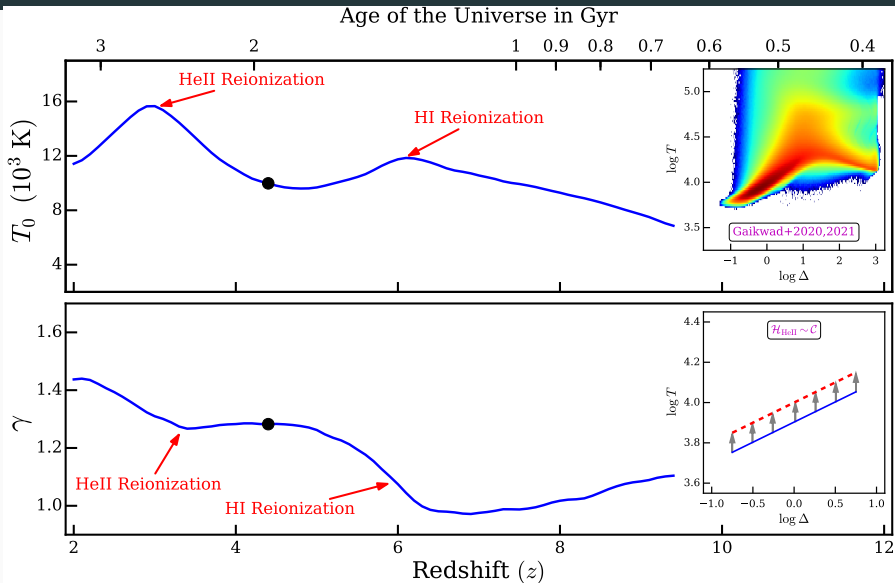
The reionization is in the last phase of completion. Cooling will start to dominate. 8

Temperature-Density Relation



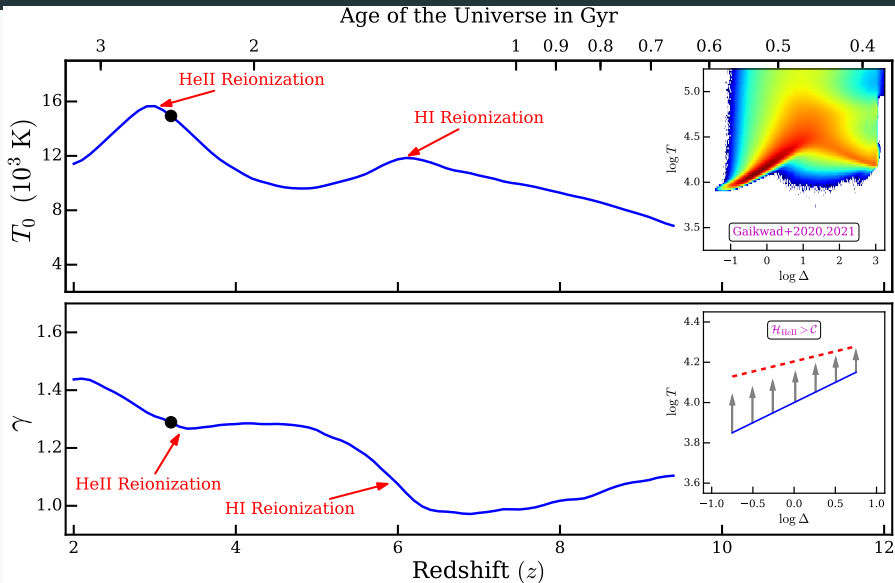
Cooling is density dependent. Hubble expansion, Compton cooling, Recombination cooling etc.

Temperature-Density Relation



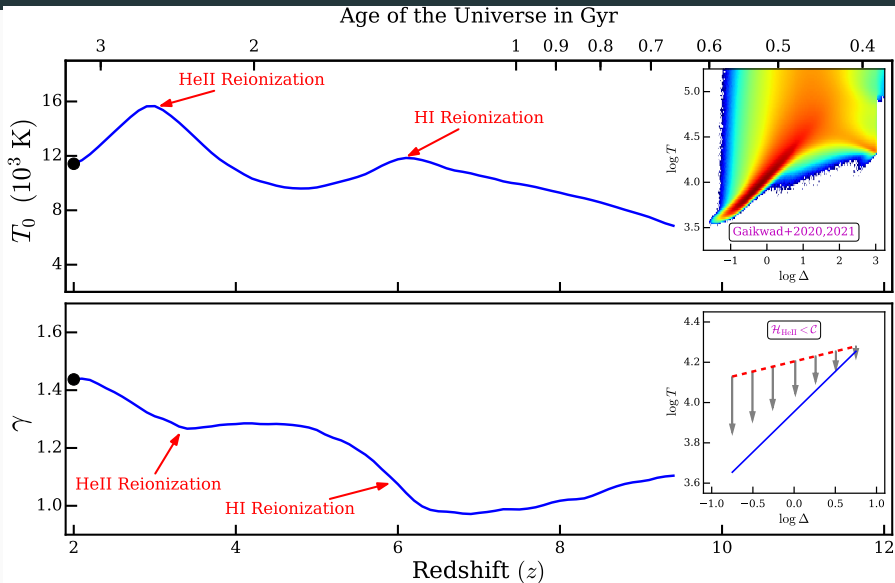
Heating due to HeII reionization starts. Quasar population starts to contribute.⁸

Temperature-Density Relation



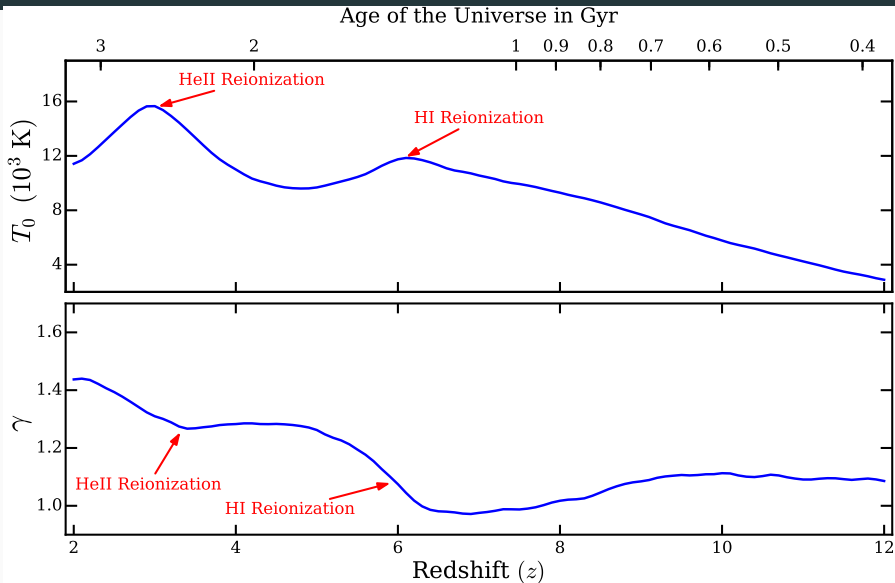
The rise in temperature is high. Quasars are more energetic.

Temperature-Density Relation



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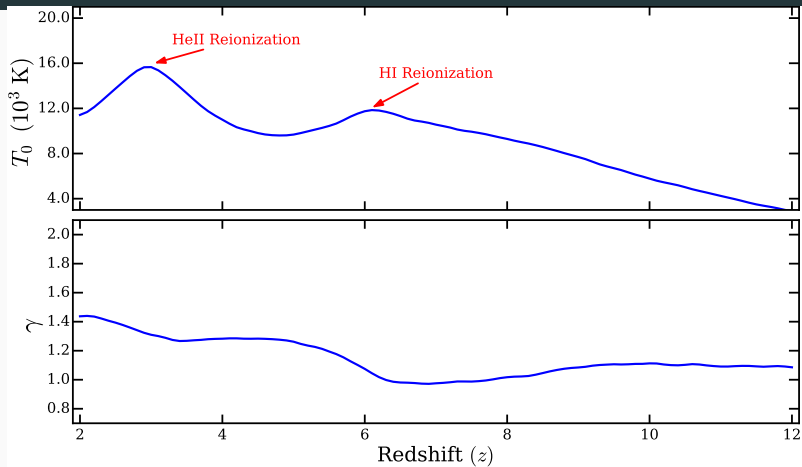
Temperature-Density Relation

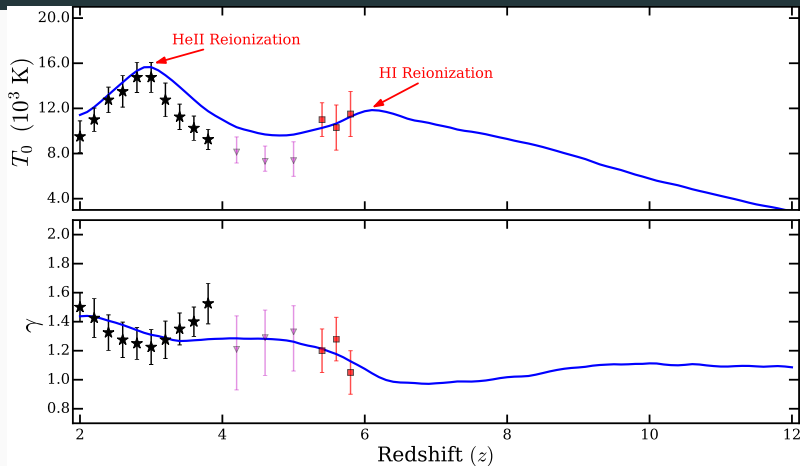


Aim: To measure the evolution of thermal parameters from observations

Evolution of the thermal state of the IGM

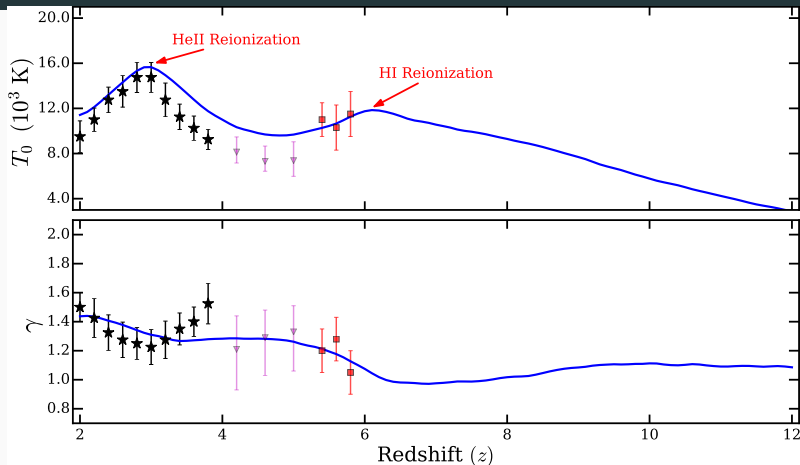
(Gaikwad+2020,2021)



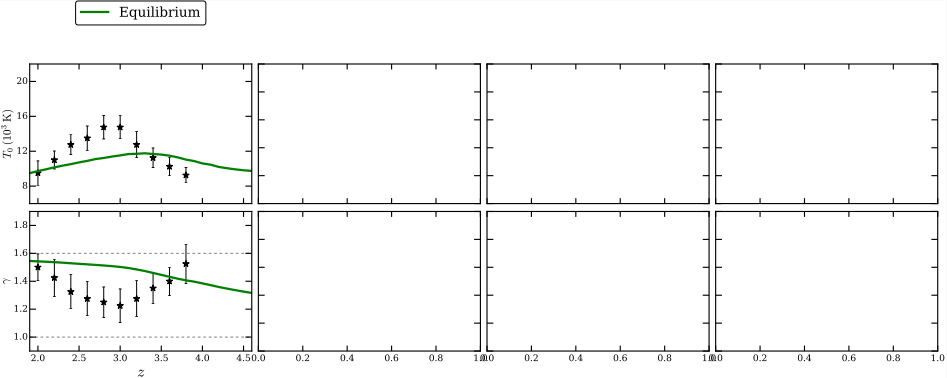


- Gaikwad+2021 and Gaikwad+2020 measurements are shown by black stars and red squares.

Measuring T_0, γ from observations is extremely challenging!

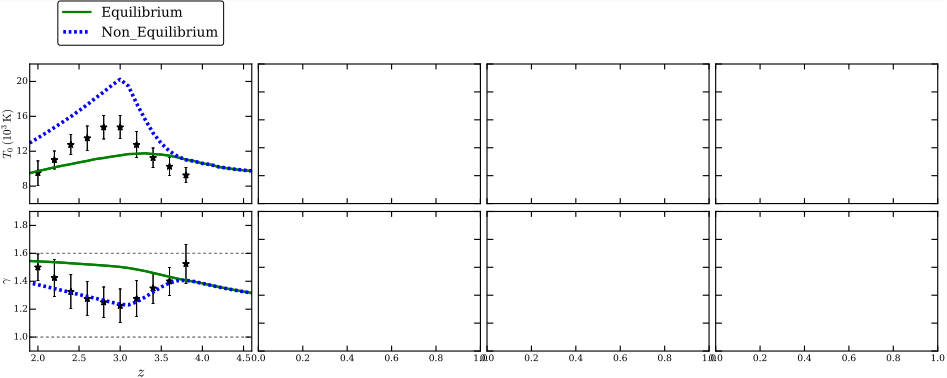


- Measured thermal parameter evolution is in better agreement with models at $z > 5$
- Models do not agree well with the thermal parameter evolution at $z < 5$. Why?



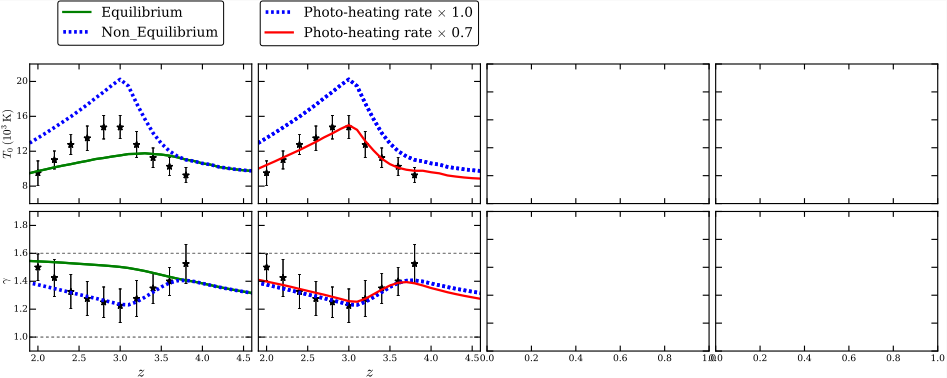
$$\frac{df_{\text{XI}}}{dt} = \alpha_{\text{XII}} n_e f_{\text{XII}} - f_{\text{XI}} (\Gamma_{\text{XI}}^p + \Gamma_{\text{XI}}^c n_e) = 0$$

- Equilibrium ionization evolution does not match the measurements

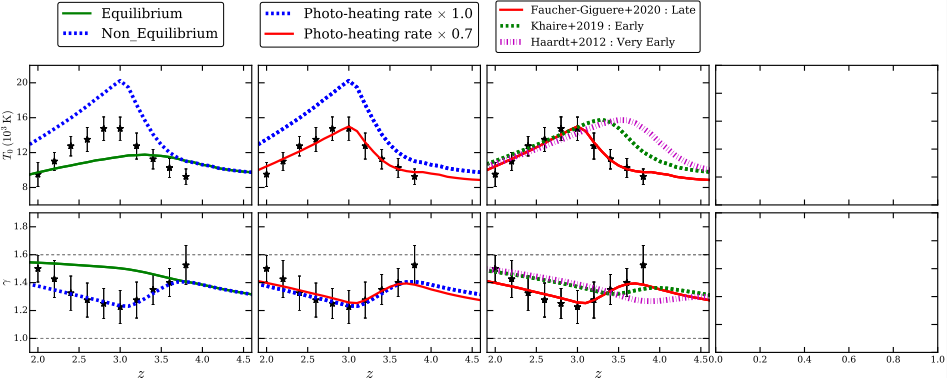


$$\frac{df_{\text{XI}}}{dt} = \alpha_{\text{XII}} n_e f_{\text{XII}} - f_{\text{XI}} (\Gamma_{\text{XI}}^p + \Gamma_{\text{XI}}^c n_e) \neq 0$$

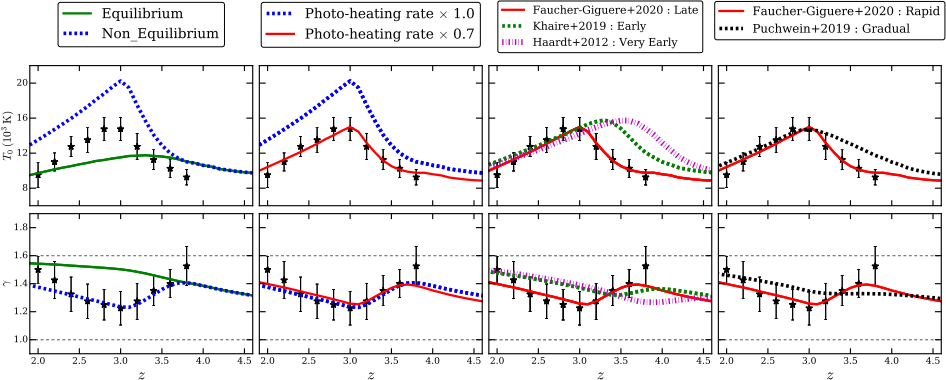
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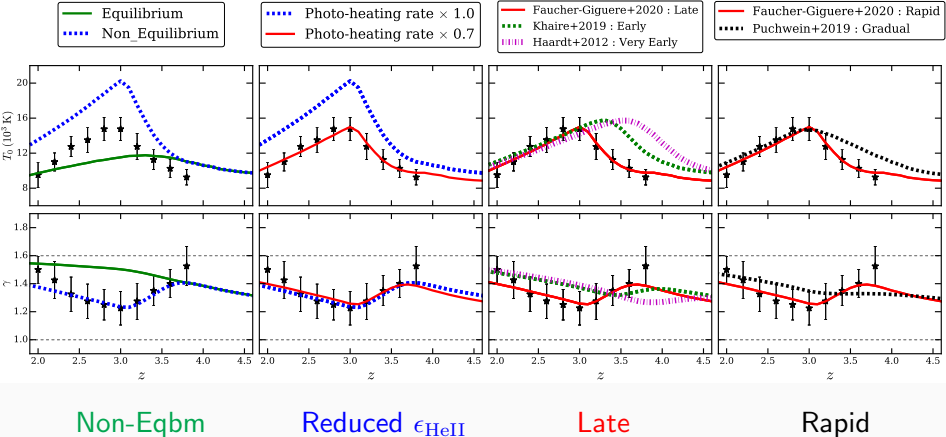
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- Early He II reionization models are ruled out by the measurements



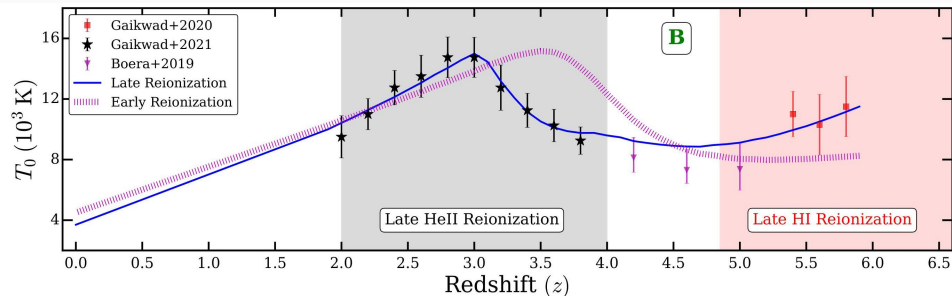
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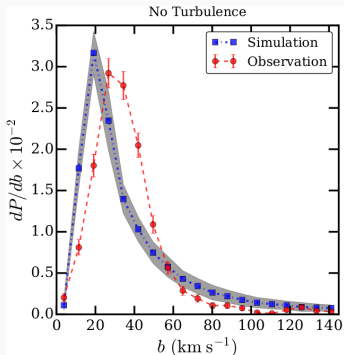
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Is everything understood?

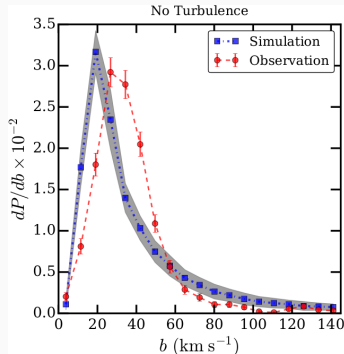
(Gaikwad+2017)



- We understand the evolution of thermal state of IGM at $z > 2$
- What about at $z < 0.5$? Models seems to converge to $T_0 \sim 5000$ K



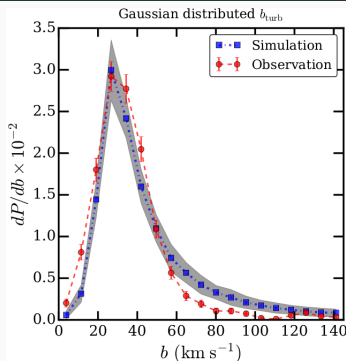
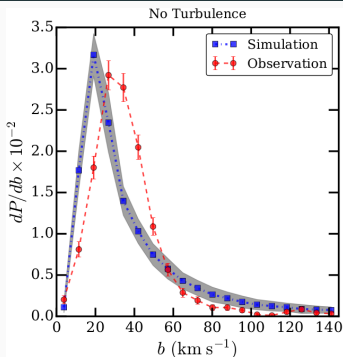
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- Observation Systematics? Ruled out $\Rightarrow$ Careful analysis of instrumental broadening
- Thermal: Heating source? Possibly No $\Rightarrow$ Conflict with Ionizing photon budget

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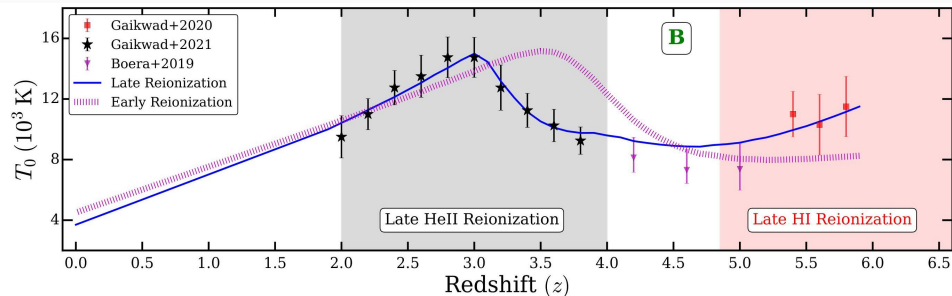
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- Non-Thermal: $b_{\text{turb}} \sim 10 \text{ km s}^{-1} \Rightarrow$ Interesting question for Plasma community

Is everything understood?

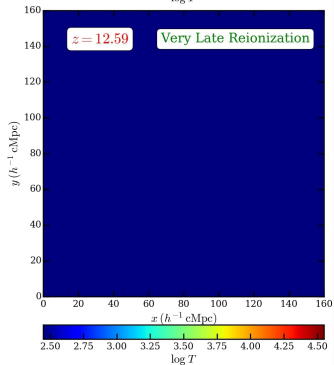
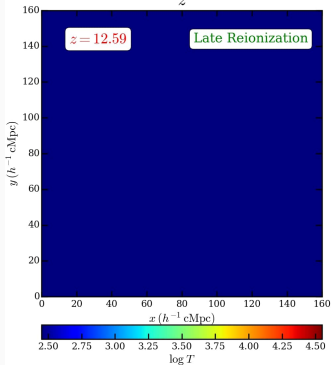
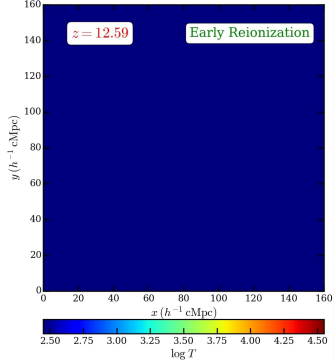
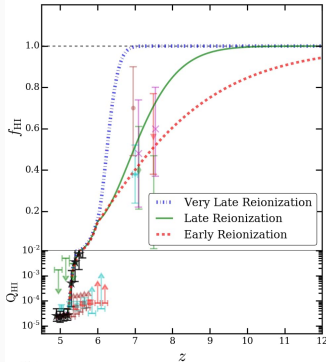
(Gaikwad+2017)



- What about $4 < z < 5$, do we understand thermal state of IGM better?

Temperature Fluctuations

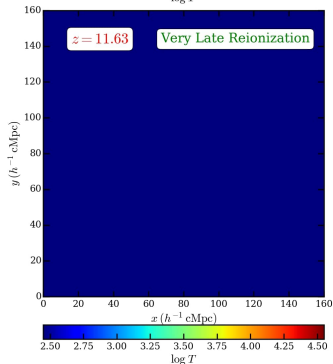
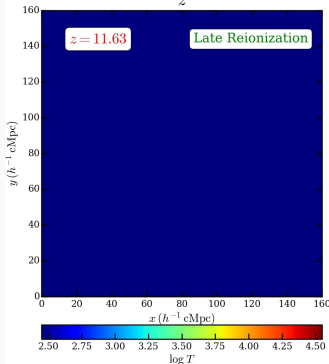
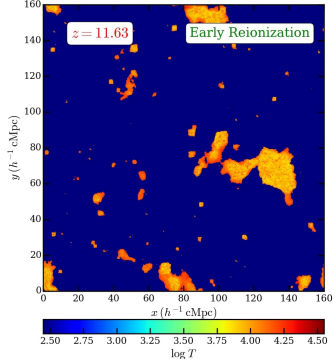
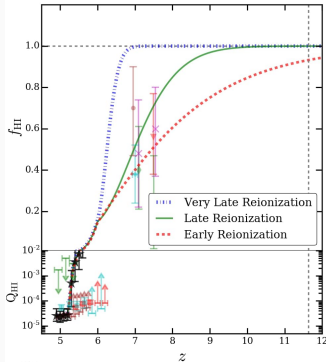
Reionization starts at $z \sim 13$



Temperature Fluctuations

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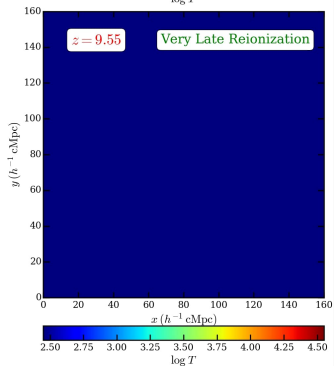
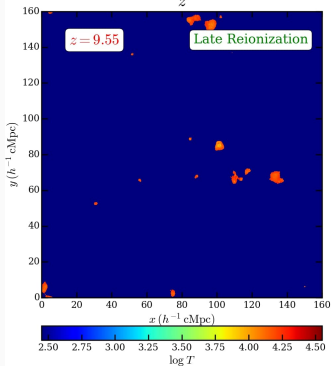
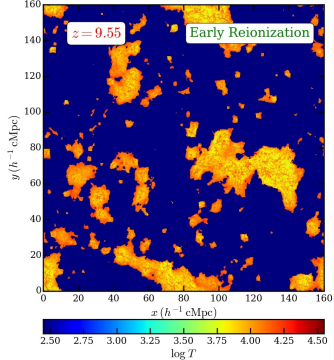
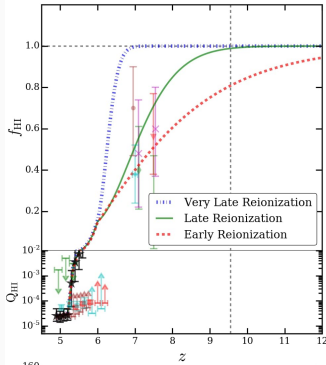
Region close to sources
ionizes and increases IGM
temperature



Temperature Fluctuations

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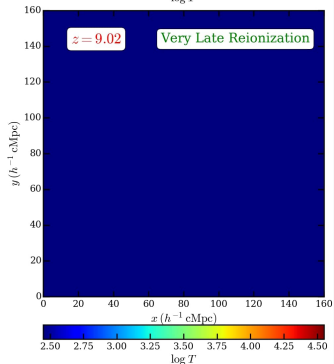
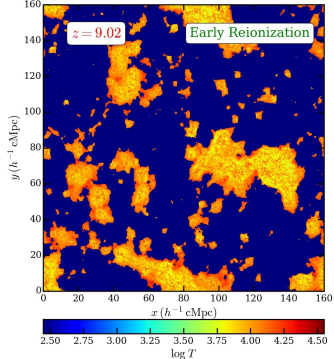
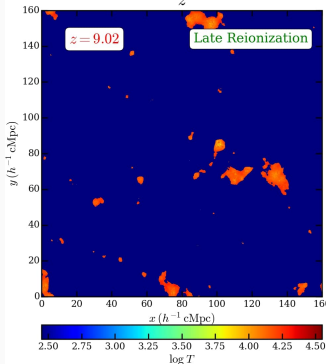
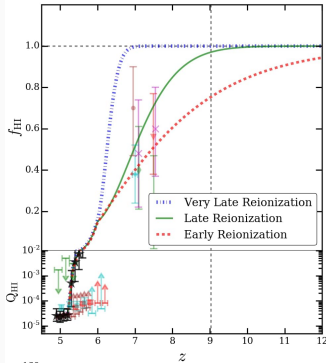
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Temperature Fluctuations

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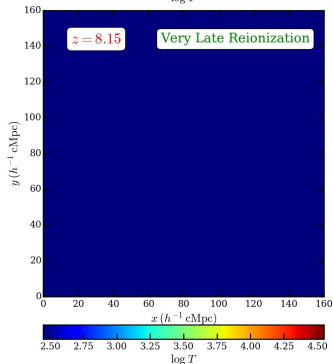
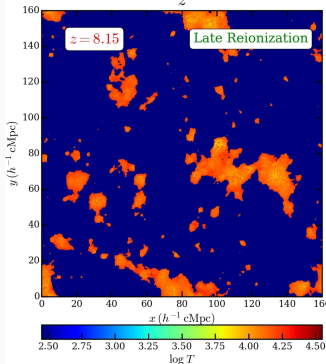
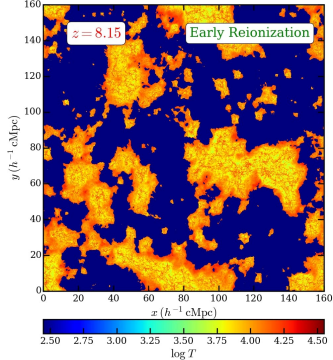
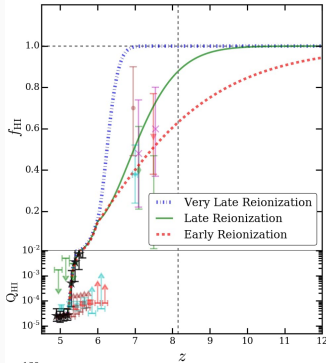
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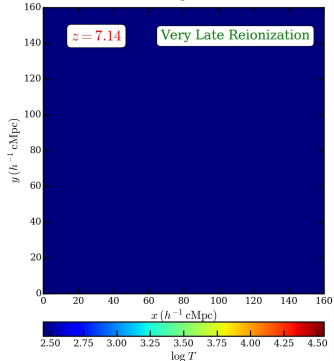
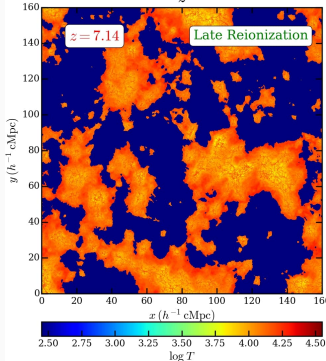
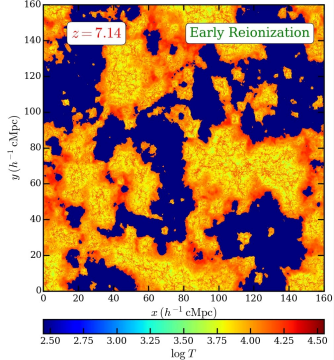
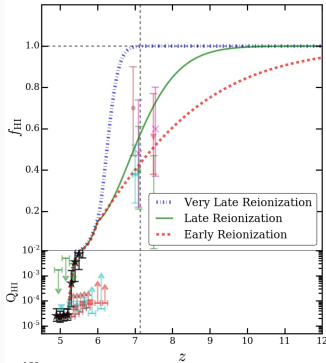
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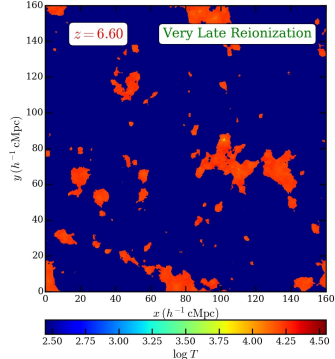
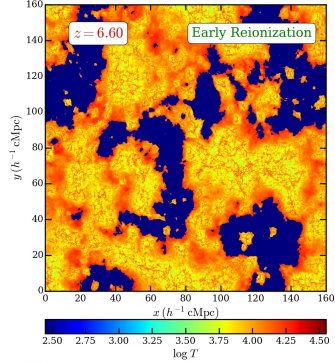
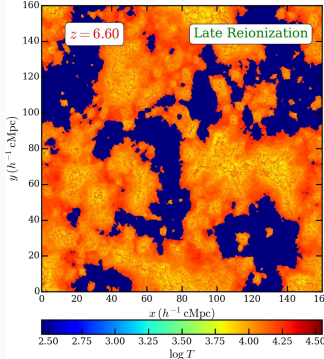
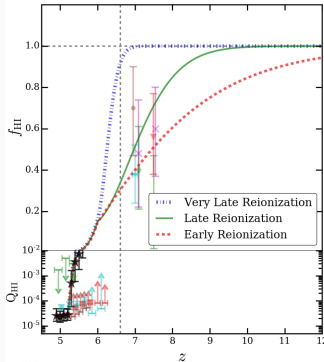


Temperature Fluctuations

Reionization starts at $z \sim 13$

Region close to sources
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Regions ionized earlier starts
to cool down due to cooling
processes and Hubble
expansion

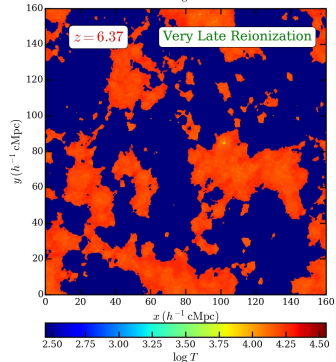
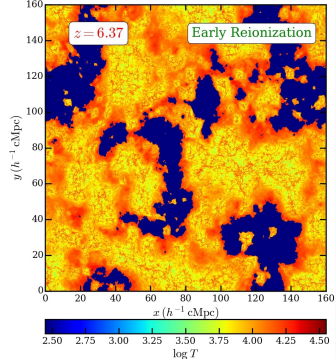
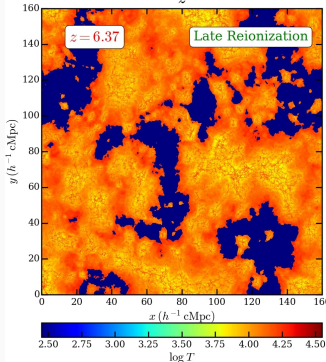
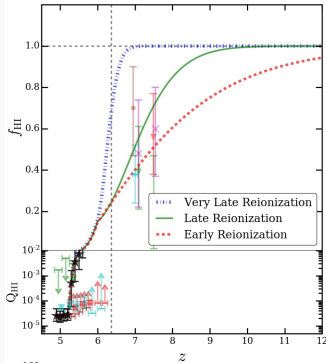


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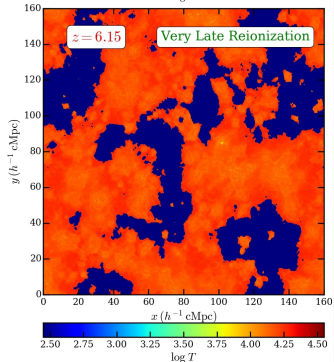
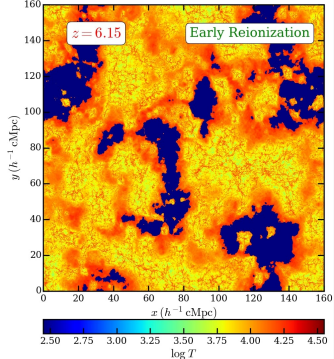
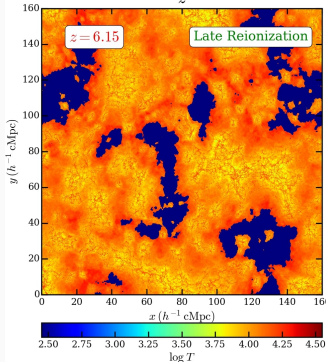
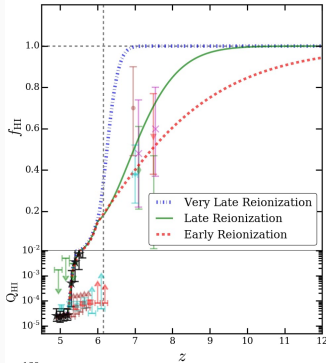


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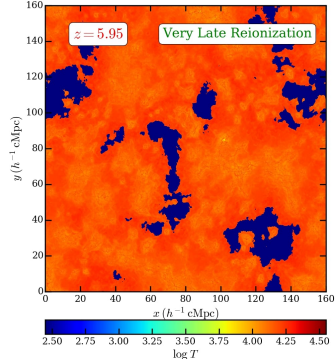
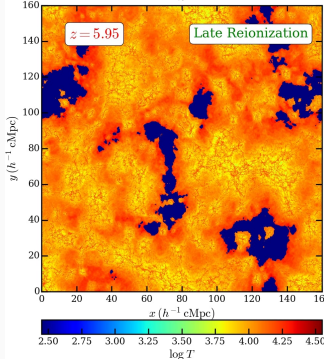
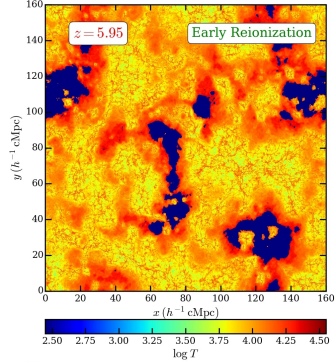
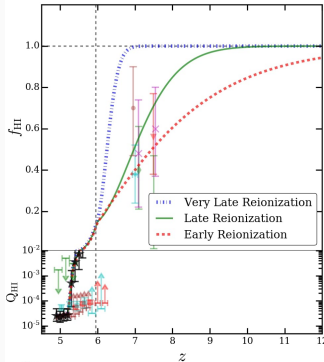
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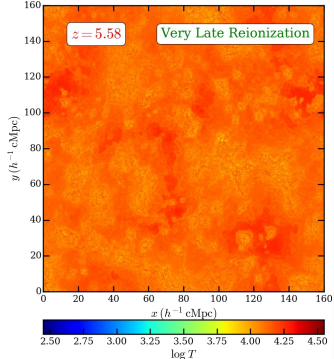
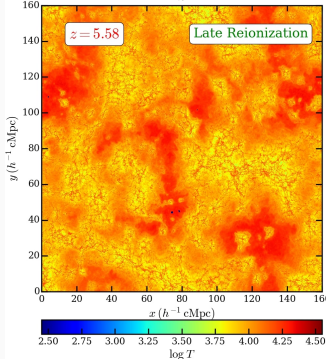
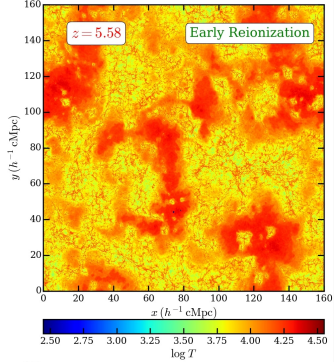
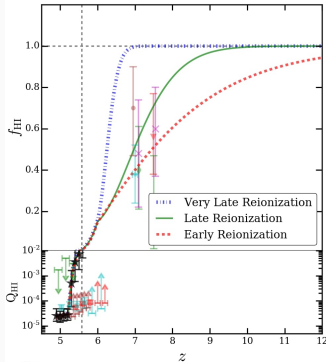
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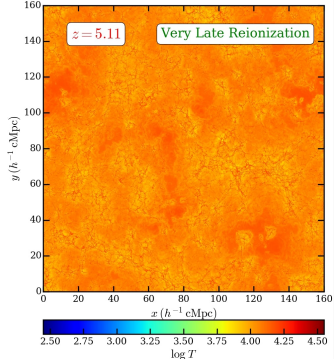
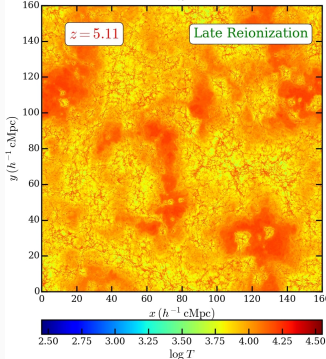
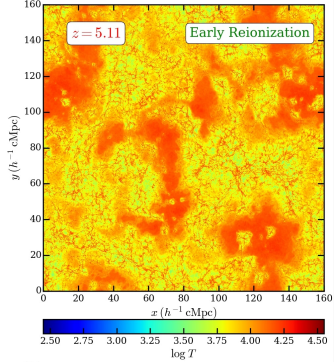
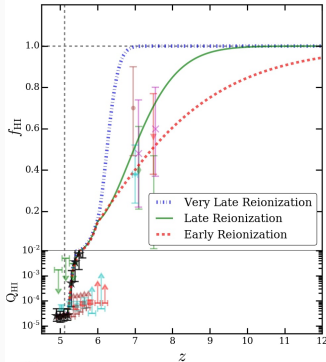
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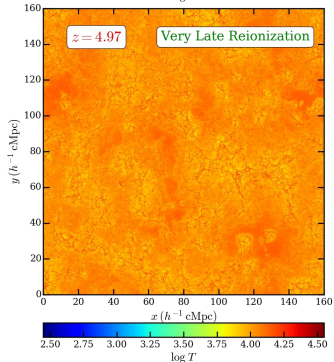
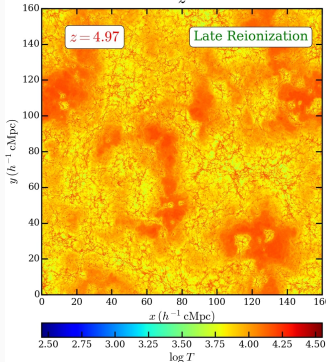
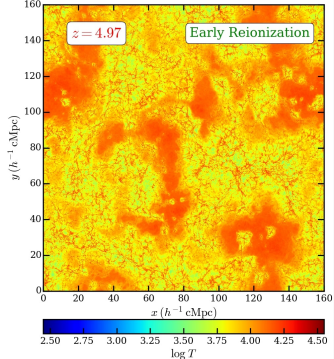
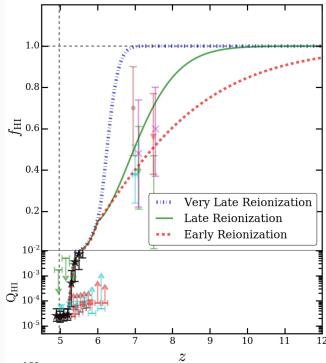
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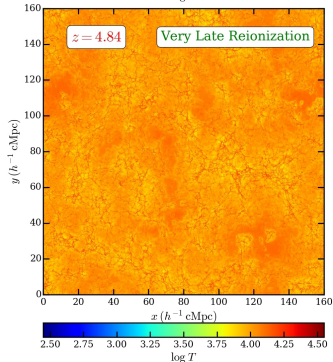
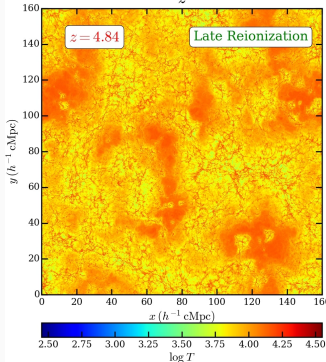
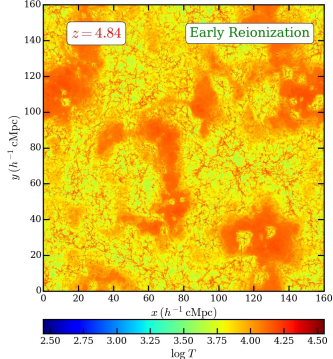
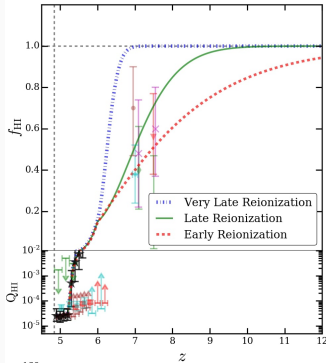
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This leads to temperature fluctuations that persists down to $z < 5$



Temperature Fluctuations

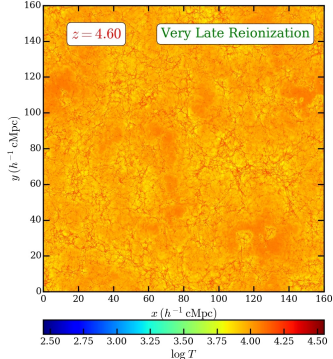
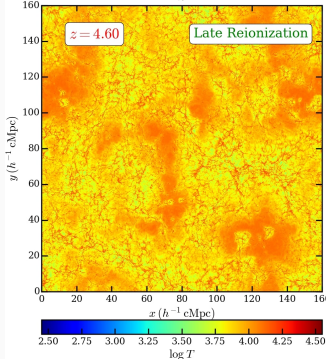
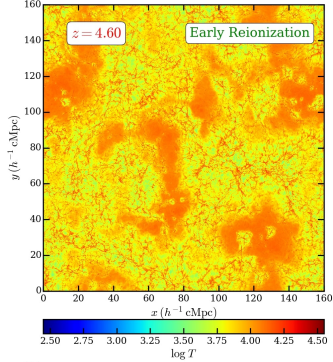
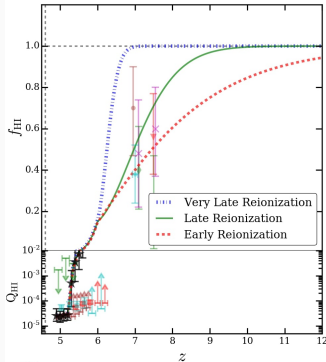
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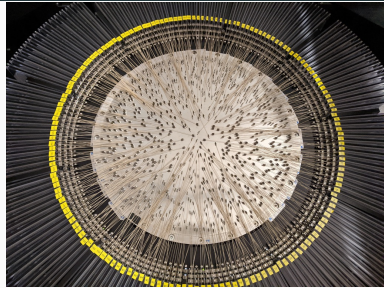
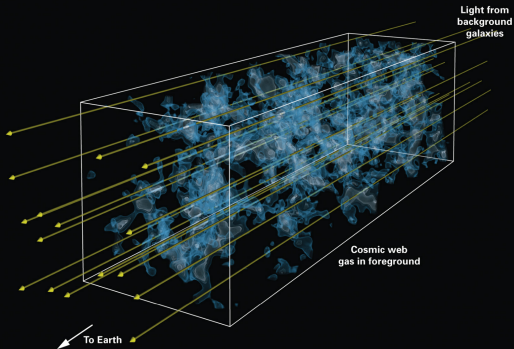
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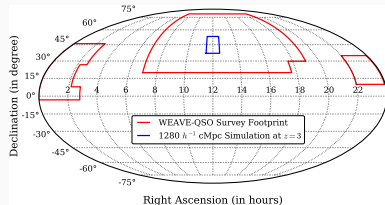
Future Work



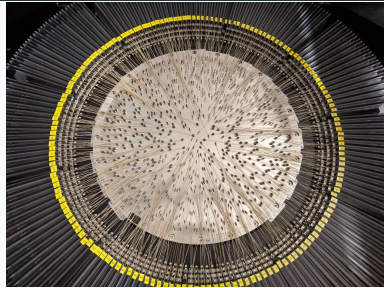
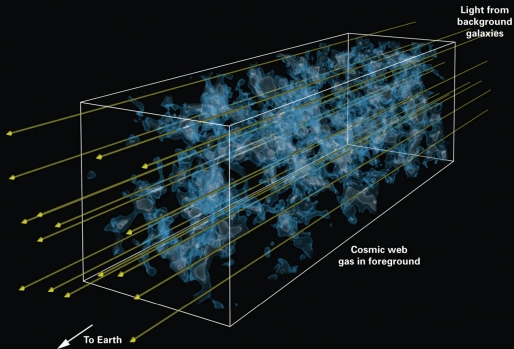
Robotic Arm Fiber plate arrangement

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- $R = 5000, 20000$ factor 2, 4 better than eBOSS
- 3 Main Science Goals
- 1. Cosmology : LSS, BAO, 3D IGM tomography
- 2. Nature of DM: P3D and P1D measurement
- 3. IGM/CGM Connections : Galactic feedback

WEAVE survey footprint



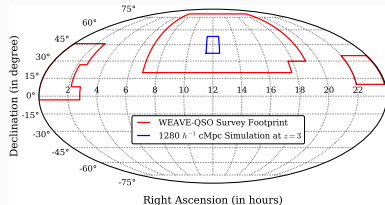
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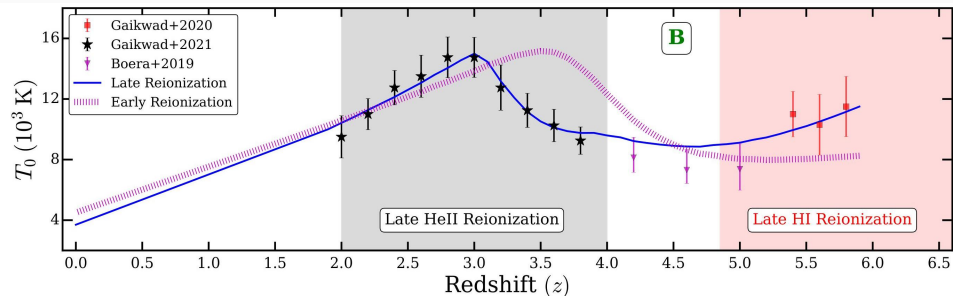
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- To detect, temperature fluctuations on large scale

WEAVE survey footprint



Summary



- IGM is highly ionized at $z < 5$
- The thermal state of IGM can be measured from observations of quasar absorption spectra
- Requires Non-Equilibrium ionization evolution to explain evolution of thermal state of IGM
- Observations hint the presence of non-thermal broadening of lines in IGM at $z < 0.5$
- Next generation observations are trying to detect the temperature fluctuations