Physics of the Intergalactic Medium

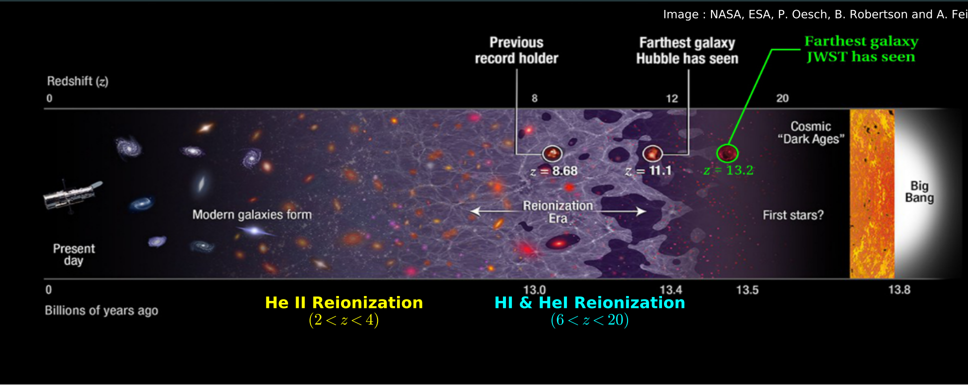
Prakash Gaikwad

Sept, 2024

Outline

- What is reionization?
- Why is reionization important?
- What is the current status of field?
- Projects
    1. Detecting Temperature Fluctuations
    2. Small scale structure in the IGM
    3. Metal ionizing background
- Summary

Introduction



- Epoch of recombination $z \sim 1100$
- Dark ages $20 < z < 1100$

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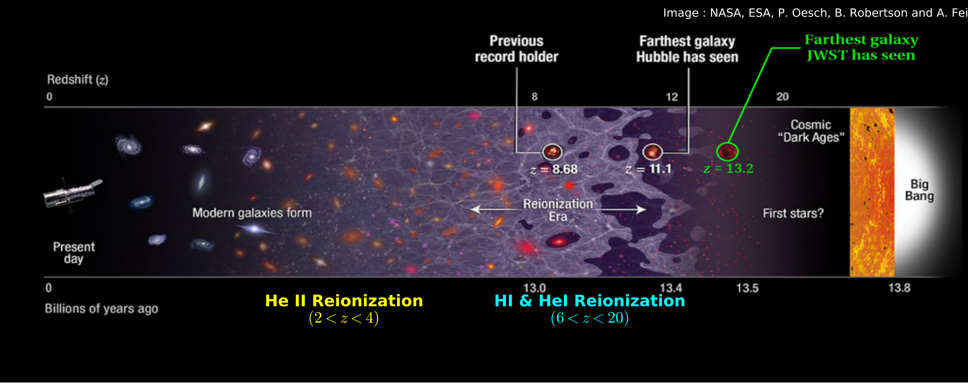

- Epoch of recombination $z \sim 1100$
- Dark ages $20 < z < 1100$
- Formation of first stars and Galaxies
- Ionization of the intergalactic medium (H I: $5 < z < 20$, He II: $2 < z < 4$)

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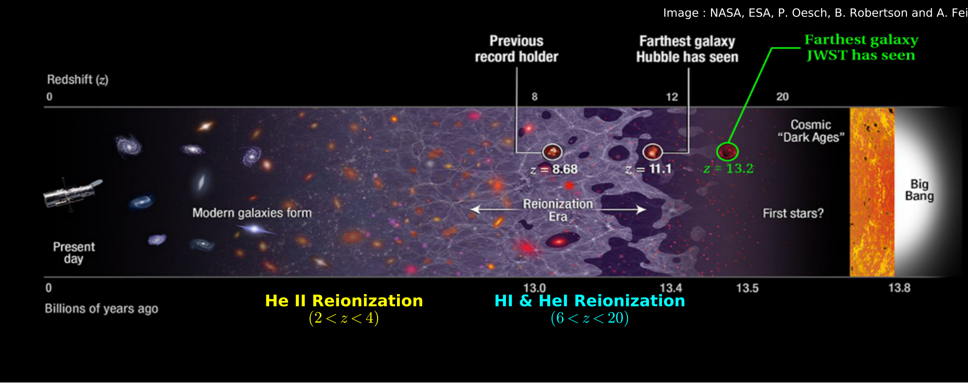

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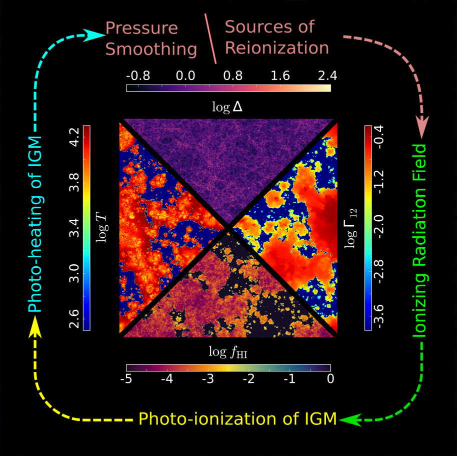
- Dark ages $20 < z < 1100$
- Formation of first stars and Galaxies
- Ionization of the intergalactic medium (H I: $5 < z < 20$, He II: $2 < z < 4$)
- Post-reionization IGM: Cosmic filaments and cosmic web

Process of Reionization

(Gaikwad+2023)

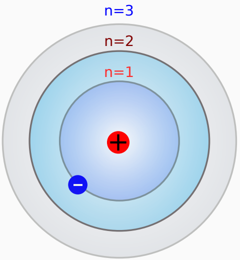


- Gravitational collapse leads to formation of stars and Galaxies
- Galaxies emit ionizing radiation that travels to the IGM
- IGM is photo-ionized and maintain photo-ionization equilibrium
- Excess energy carried away by free electrons that photo-heats the IGM
- Why is it important to study the reionization?

Observations

Origin of absorption lines

[Gaikwad+2020,2021]



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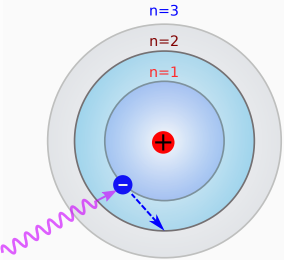

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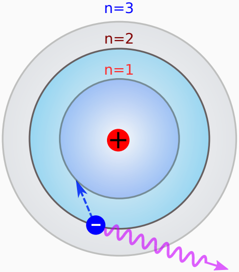

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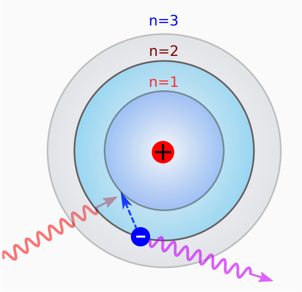

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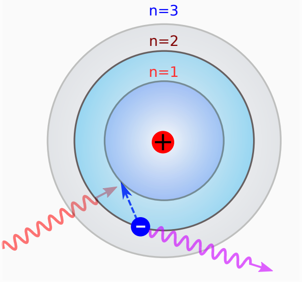

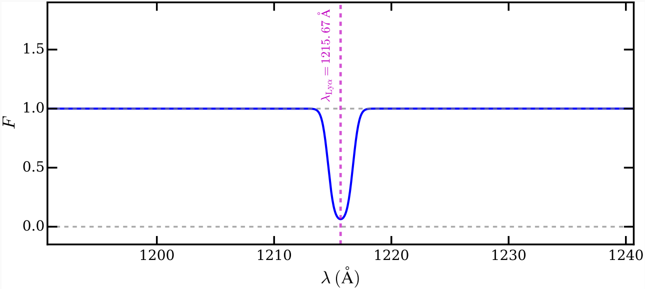

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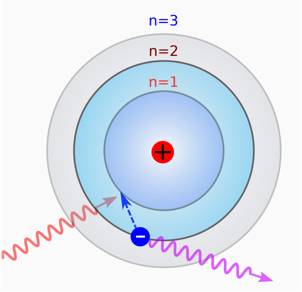

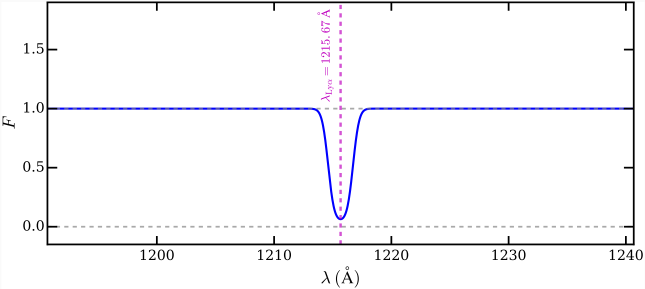

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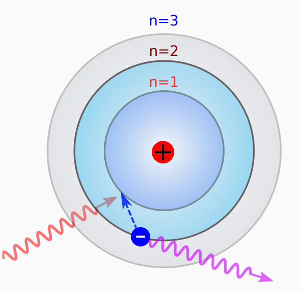

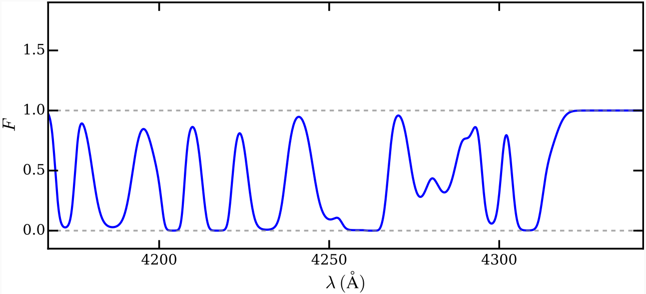

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- IGM consists of the field of neutral hydrogen distributed on cosmological scales.
- Photons redshift due to the expansion of the universe
- 'Locally', only those photons are absorbed that have been redshifted to energies of $\sim 10.2eV$.

Origin of absorption lines

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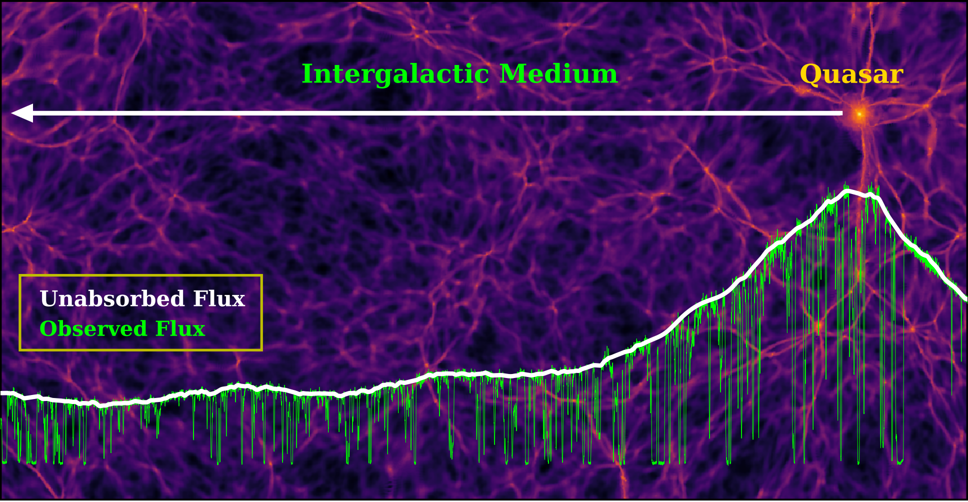
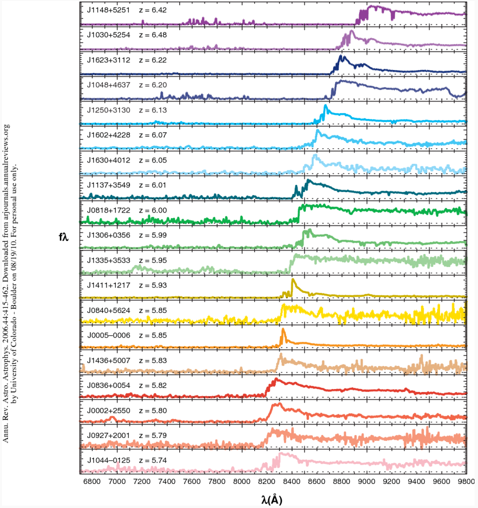
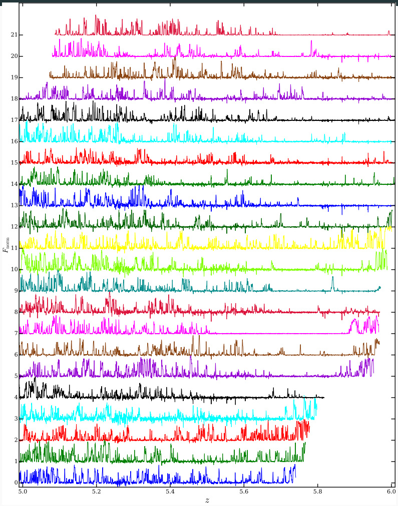


- The set of characteristics absorption features are collectively known as Lyα forest
- Main focus of my work $\Rightarrow$ Observations + Simulations of Lyα forest

XQR-30 sample

(D'odorico+2023)





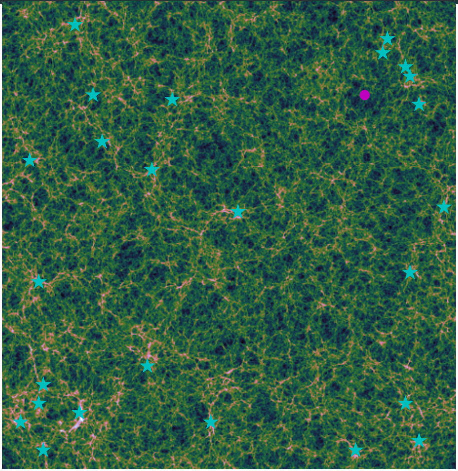
SDSS quasar Spectra [Fan+2006]

Few XQR-30 Spectra

- XQR-30 large program spectra are of unprecedented quality

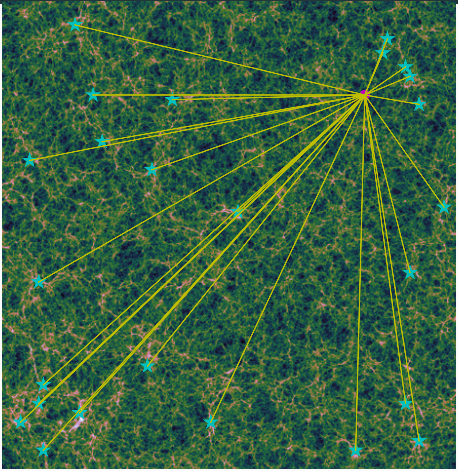
Simulations

Modeling Patchy Reionization



- Starting from initial condition at $z \sim 100$, cosmological fields are evolved to $z \sim 5$
- Stars and Galaxies (sources of reionization) are formed in the high density regions
- How much is the ionizing radiation field at a given point due to all sources?

Modeling Patchy Reionization

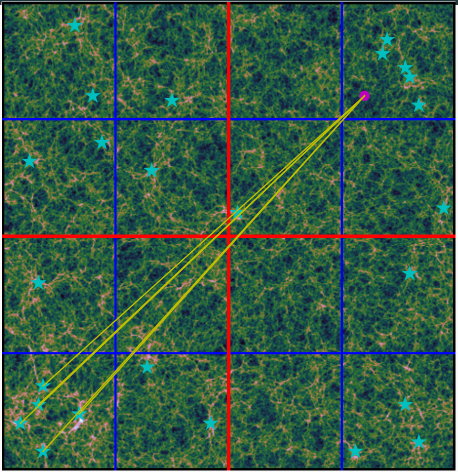


$$\Gamma_{\rm HI,j} = \frac{\sigma_{\rm HI}(\nu)}{t_*} \sum_{\rm i=1,i\neq j}^{N_{\rm source}} \frac{N_{\rm ion,i}}{4\,\pi\, r_{\rm ij}^2}\ {\rm e}^{-\tau}$$

- $N_{\rm ion} \Rightarrow$ Cumulative number of photons
- $1/(4\pi\, r_{ij}^2) \Rightarrow$ Flux dilation factor
- ${\rm e}^{-\tau} \Rightarrow$ IGM attenuation
- $t_* \Rightarrow$ Time scale, $L(\nu) = h\,\nu\, N_{{\rm ion},\nu}/t_*$

- The equations are coupled in non-linear way!
- Optical Depth: $\tau = \int_{\rm los} n_{\rm HI}\,\sigma_{\rm HI}\, dx$, H I number density : $n_{\rm HI} \propto \Gamma_{\rm HI}^{-1}$
- Direct summation is computationally expensive, $N_{\rm operations} \sim \mathcal{O}(N^2)$, $N \sim 1024^3$

Modeling Patchy Reionization using EX-CITE (Gaikwad+2023)



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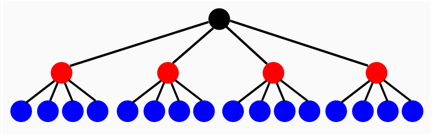
$$\tau = \int n_{\mathrm{HI}}\,\sigma_{\mathrm{HI}}\,dx = \int dx/\lambda(x)$$



- Tree search operation $\mathcal{O}(\log N)$
- Number of locations to evaluate $\mathcal{O}(N)$
- EX-CITE scales as $\mathcal{O}(N \log N)$

- Construct a source octree by recursively dividing cube in to (8) sub-cubes
- Assign total ionizing emissivity to tree node.
- Effectively treat as a single source. Compute IGM attenuation between location and center of subcubes (Far away criteria: $s/r_{ij} < 0.7$, standard in gravity tree codes)

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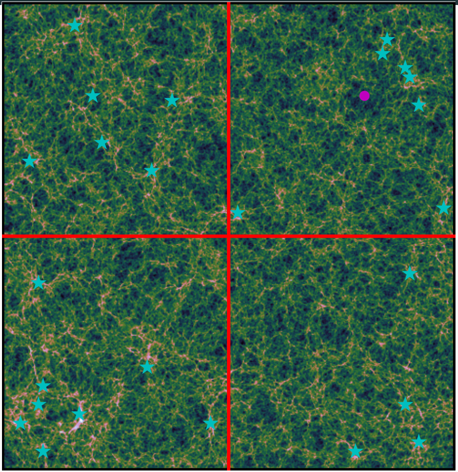

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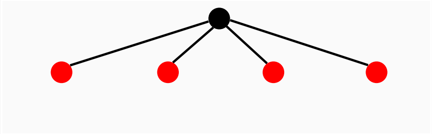

- 1D $\Rightarrow$ Binary Tree
- 2D $\Rightarrow$ Quadtree
- 3D $\Rightarrow$ Octree

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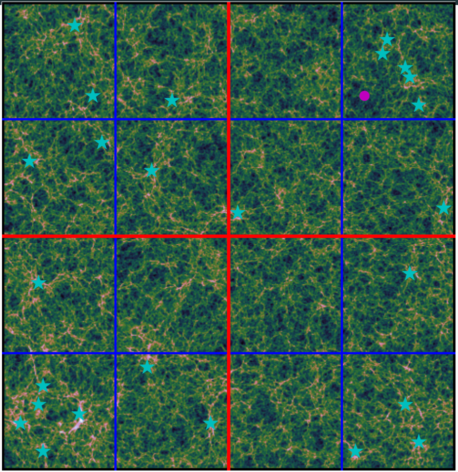

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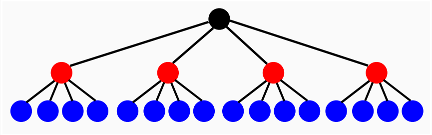

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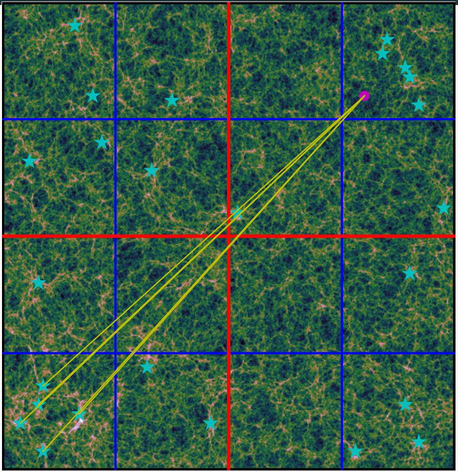

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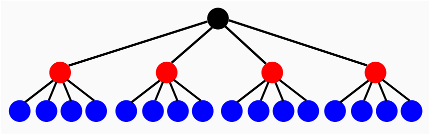

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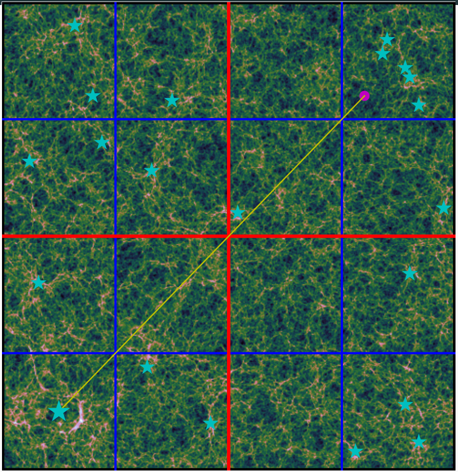

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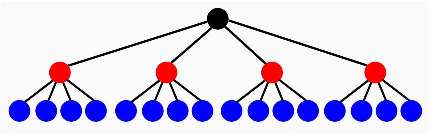

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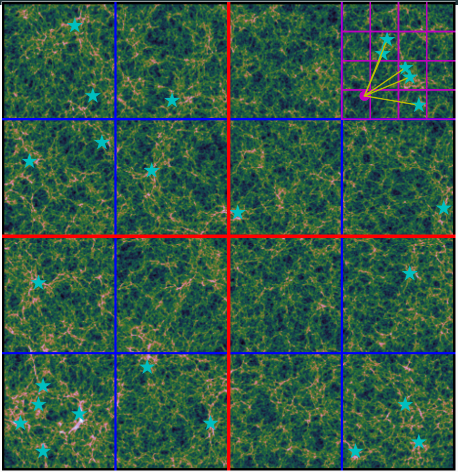

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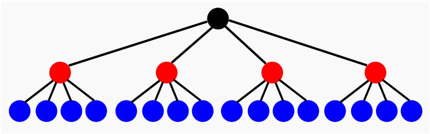

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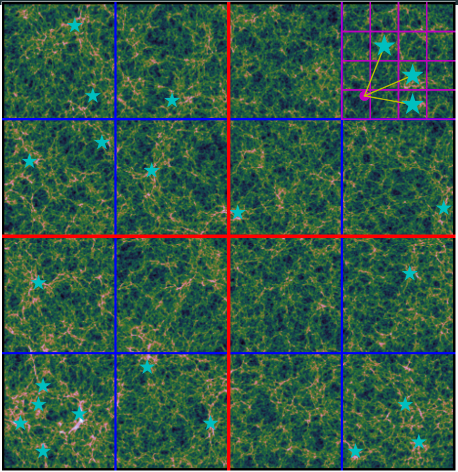

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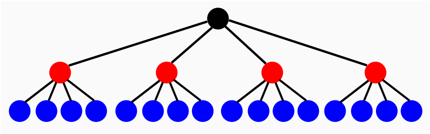

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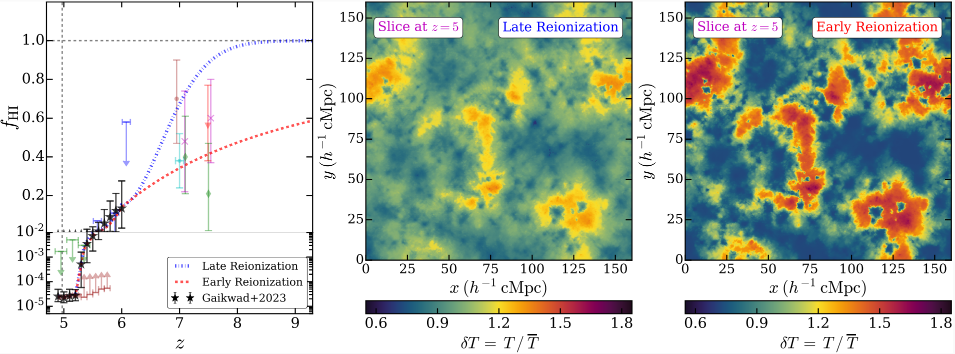
- Add contribution when sources are sufficiently far away (All this is for 1 iteration)



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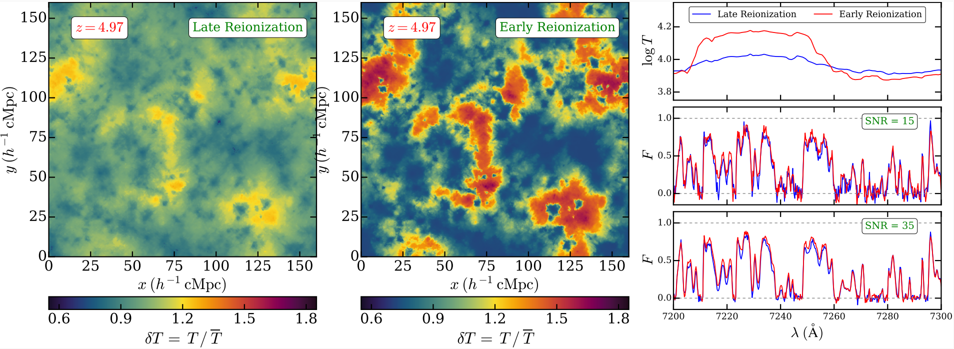
- Regions that ionize early $\Rightarrow$ Have long time to cool $\Rightarrow$ More T Fluctuations



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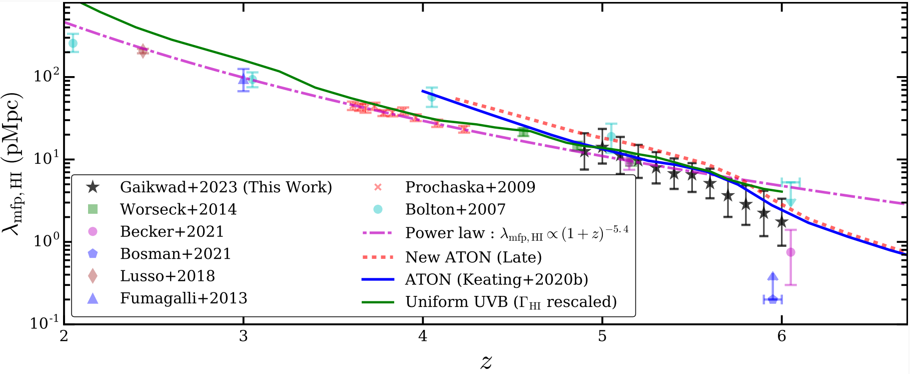
- Aim: To detect the temperature fluctuations in observations
- Method: Machine Learning with Lyα forest
- Application to data from onging GHOSTly survey data



- In simulations we find, more resolution $\Rightarrow$ IGM is more clumpy
- Clumpy IGM $\Rightarrow$ More density fluctuations $\Rightarrow$ More Recombinations
- More Recombinations $\Rightarrow$ More number ionizing photons
- More Recombinations $\Rightarrow$ Short Mean Free Path