

Evolution of the Intergalactic Medium in the past 12.8 billion years

Prakash Gaikwad

Dec, 2024

Scientific rationale of the conference

- What have we learned about the physical conditions, chemical enrichment, and kinematics of the diffuse baryons beyond galactic boundaries in the past two decades? How do these properties evolve with time and the environment?
What is IGM? Why the IGM is important?
- Have CGM studies truly fulfilled the promise of understanding galaxy evolution? How to make meaningful comparisons between observations and simulations?
How do we study IGM from observations and simulations?
- How do recent advancements in Integral Field Spectroscopy enhance our comprehension of the relationships between galaxies and baryonic matter?
Thermal and Ionization state of the IGM
- What novel ventures should both observers and simulators pursue to achieve a breakthrough in the coming years?

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Future work and Summary

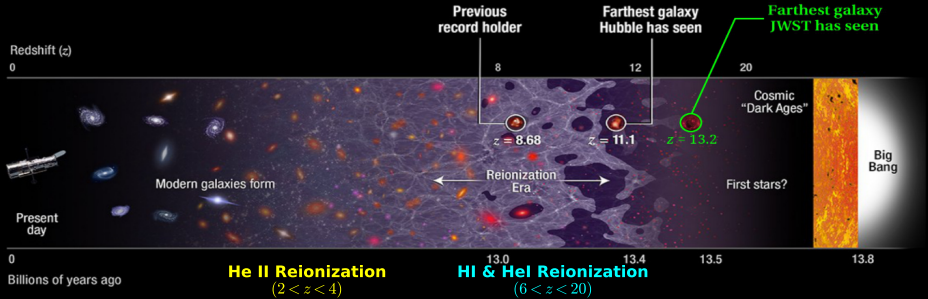
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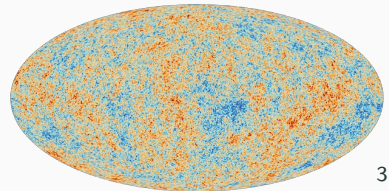
Introduction

What is the IGM?

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



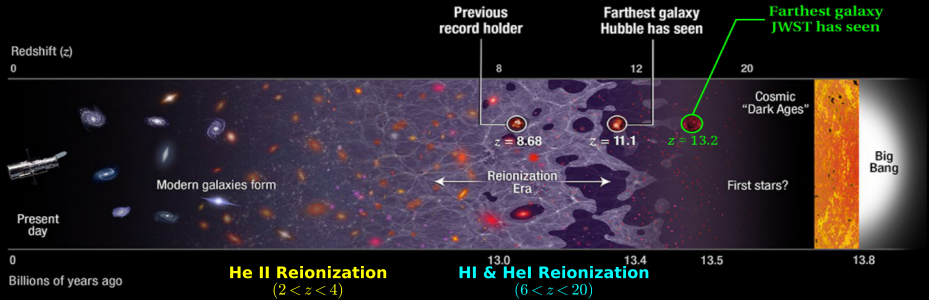
- Density fluctuations in the early universe ($z \sim 1100$, $t_{\text{age}} \sim 0.4 \text{ Myr} \sim 0.4 \times 10^6 \text{ yr}$)



Introduction

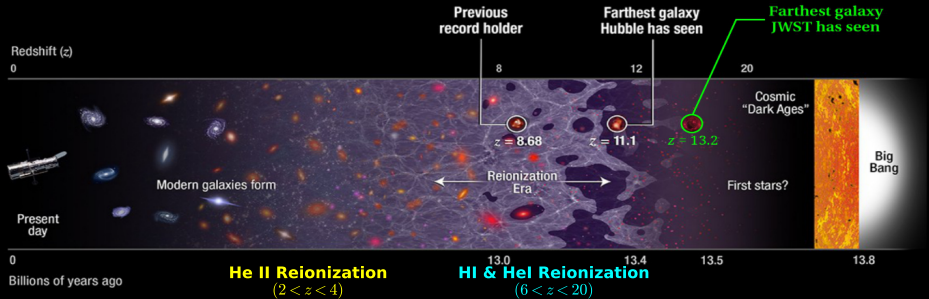
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- Density fluctuations in the early universe ($z \sim 1100$, $t_{\text{age}} \sim 0.4 \text{ Myr} \sim 0.4 \times 10^6 \text{ yr}$)
- Overdense regions grow due to gravitational instability
- Collapsed structures: Formation of stars and Galaxies ($z < 20$, $t_{\text{age}} \sim 0.2 \text{ Gyr} \sim 0.2 \times 10^9 \text{ yr}$)

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

Introduction

Why is the IGM important?

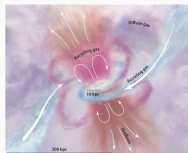
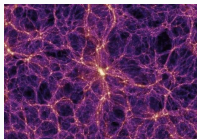
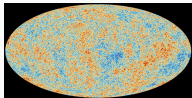
Cosmic
Microwave
Background

Intergalactic
Medium

Circumgalactic
Medium

Interstellar
Medium

Illustration



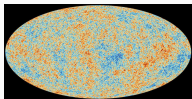
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Why is the IGM important?

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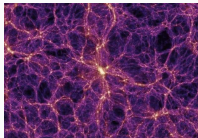
Densities

Cosmic
Microwave
Background



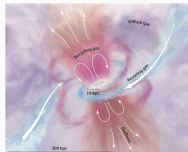
Linear
 $\Delta \sim 1$

Intergalactic
Medium



Mildly Non-Linear
 $\Delta \sim 1$ to 50

Circumgalactic
Medium



Non-Linear
 $\Delta \sim 100-500$

Interstellar
Medium



Highly Non-Linear
 $\Delta > 1000$

Introduction

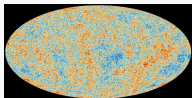
Why is the IGM important?

Illustration

Densities

Scales

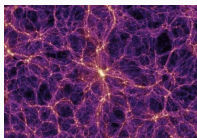
Cosmic
Microwave
Background



Linear
 $\Delta \sim 1$

Few Gpc

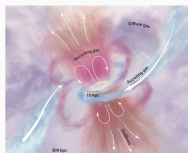
Intergalactic
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Few 100 Mpc

Circumgalactic
Medium



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 $\Delta \sim 100$ -500

Few 100 kpc

Interstellar
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 $\Delta > 1000$

< 100 kpc

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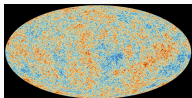
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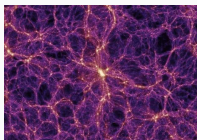
Scales

Physics

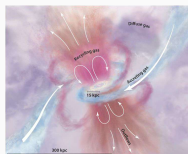
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Few Gpc

Few 100 Mpc

Few 100 kpc

< 100 kpc

Inflation
Dark Energy
Dark Matter
Particle physics

Reionization
Large Scale Structure
Dark Matter
Feedback & Metals

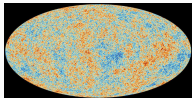
Galaxy Formation
AGN Feedback
Outflows (Metals)
Inflow (Accretion)

Star Formation
Stellar Feedback
Galaxy Type
Interaction (CGM)

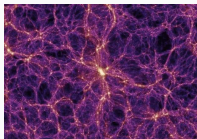
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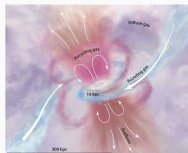
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Intergalactic Medium



Circumgalactic Medium



Interstellar Medium



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Few Gpc

Few 100 Mpc

Few 100 kpc

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Cosmology
Large Scale Structures



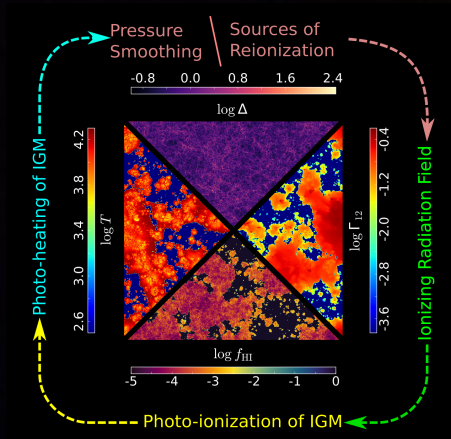
IGM



Astrophysics
Galaxy Formation and Evolution

Open Problems in IGM (The big picture)

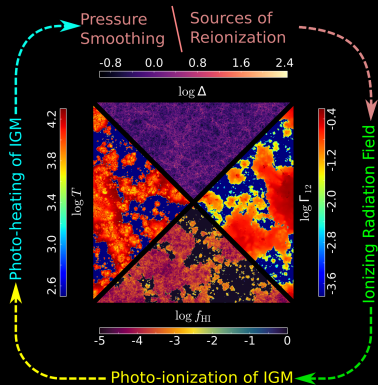
- Reionization:
 - When and How did reionization happen?
 - Nature of reionization? Morphology of reionization
- IGM - Galaxies connection:
 - Properties of early galaxies and AGN during reionization?
 - Feedback of reionization on galaxy formation?
- Cosmology :
 - Nature of dark matter and dark energy?
 - Evolution of large scale structure in the Universe?



- 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?

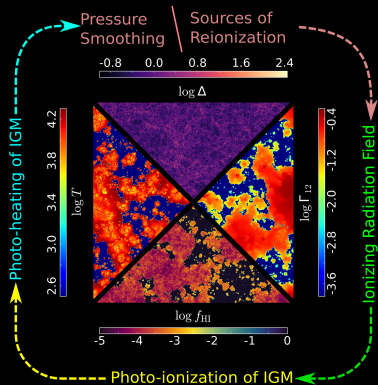
Why is reionization important?

Reionization connects small scales ($< 100 \text{ cMpc}$) with large scales ($> 100 \text{ cMpc}$)



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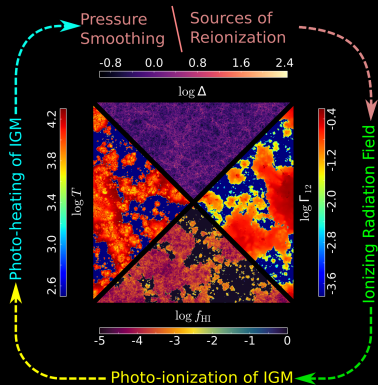


Small Scale Astrophysics

- Star formation and AGN activity
- Spectral Energy Distribution of Sources
- Escape of ionizing photons from Galaxies

Why is reionization important?

Reionization connects small scales (< 100 ckpc) with large scales (> 100 cMpc)



Small Scale Astrophysics

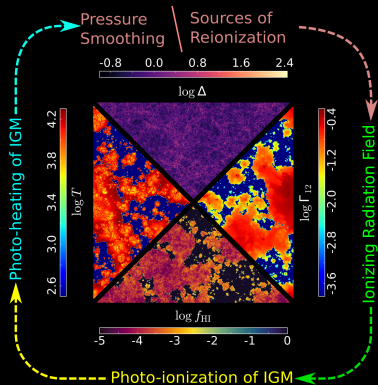
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Large Scale Structures

- Population of ionizing sources
- Distribution of ionizing sources
- Large scale ionization fluctuations

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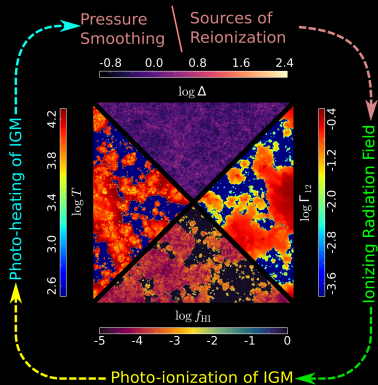
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Observational Challenges

- Identifying sources of reionization
- Measuring reionization history
- Morphology of reionization

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Modeling Challenges

- Huge dynamic range of simulations
- Radiative Transfer Effects
- Galaxy formation sub-grid models

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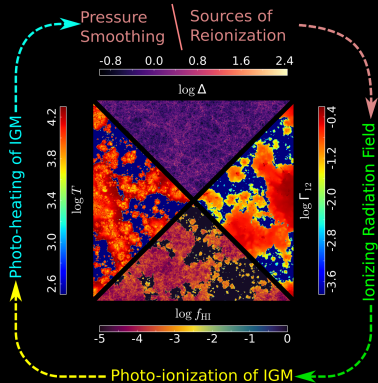
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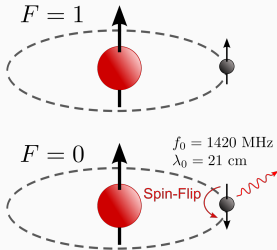
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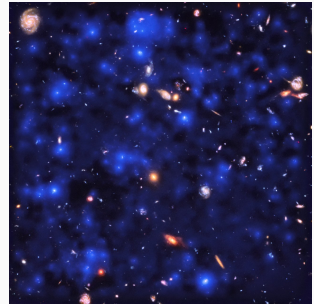
The complexity of reionization makes it more interesting !

Observations

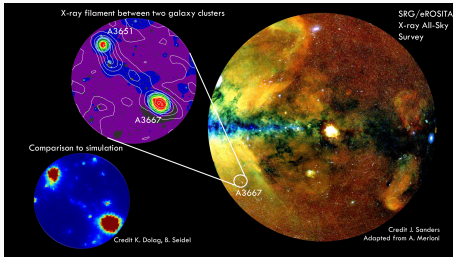
How can we observationally probe IGM?



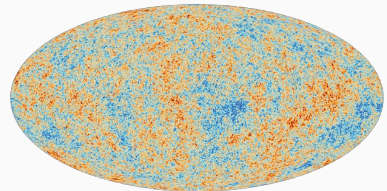
21cm Experiments



Diffuse Ly α emission



X-ray observations of filaments

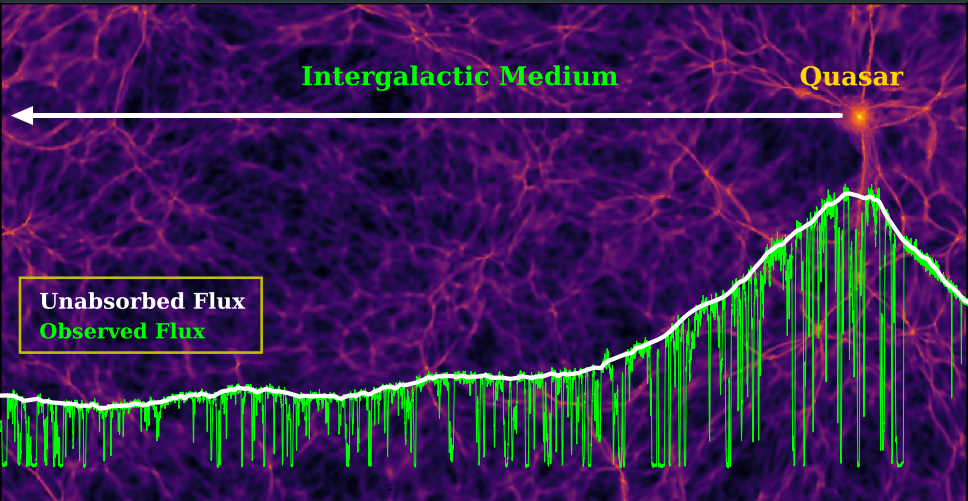


CMB (Thompson τ , Thermal SZ)

Transients (FRB, GRB)
Gravitational Lensing

Introduction

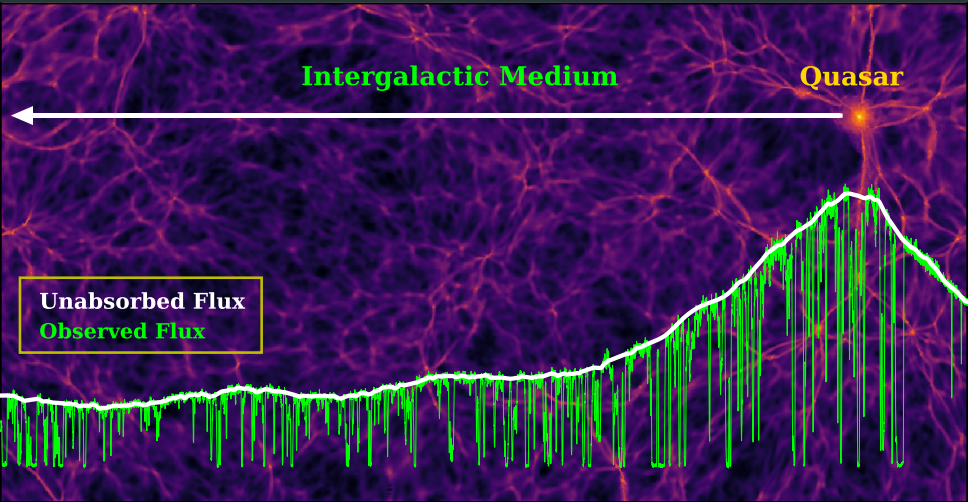
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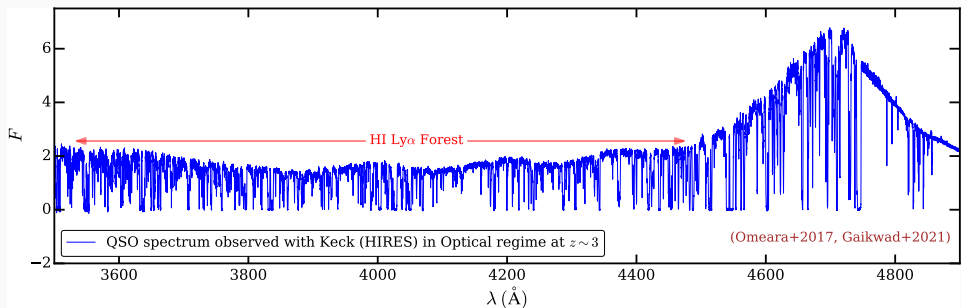
- The spectrum of distant bright objects (quasar) in the universe
- The set of absorption features are produced by IGM between us and the source

Introduction

How can we observationally probe IGM?



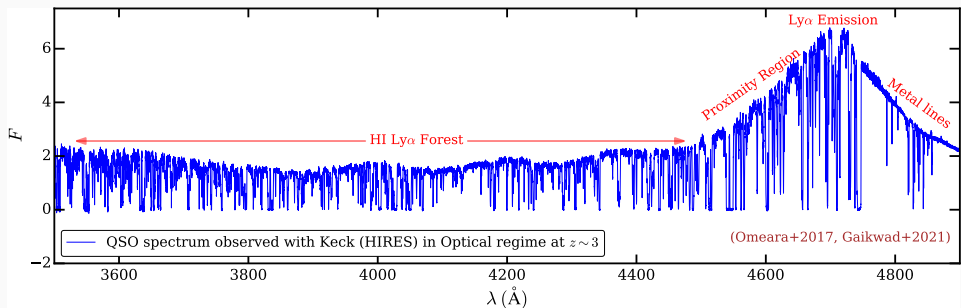
- The set of characteristic absorption features are collectively known as Ly α forest
- Main focus of this talk $\Rightarrow$ Observations + Simulations of Quasar Absorption Spectra
- Why is the quasar absorption spectroscopy important?



- Quasar spectra contains a lot of information about IGM.

- Ly α forest (Physical state of the IGM, mass of WDM)

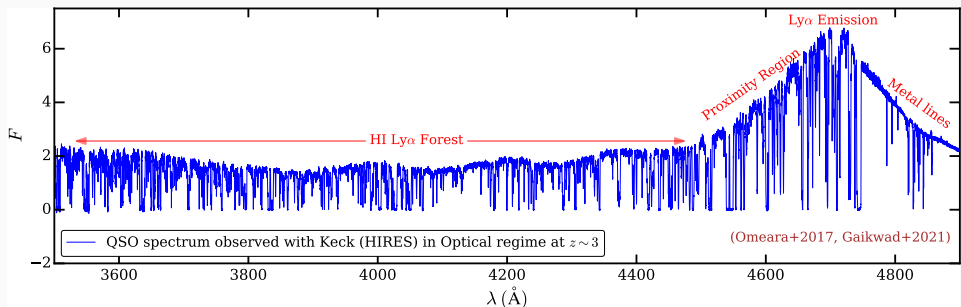
(Schaye+2001, Viel+2006, Becker+2011)



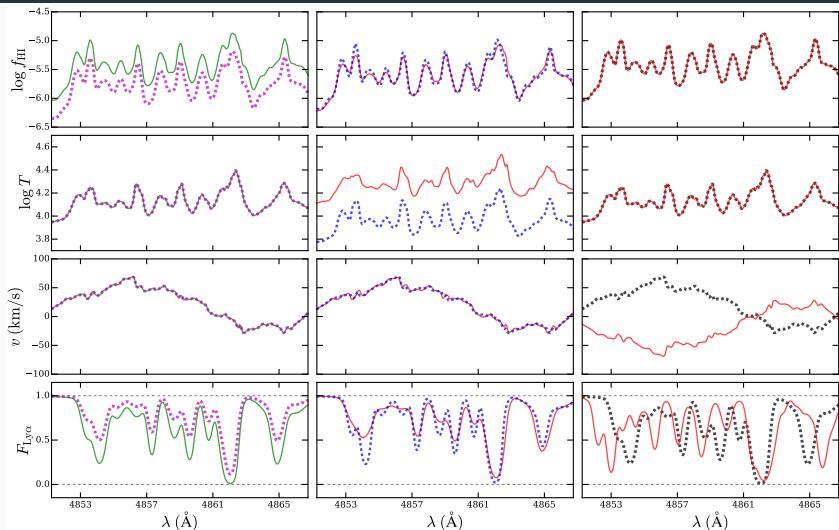
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- $\text{Ly}\alpha$ forest (Physical state of the IGM, mass of WDM) (Schaye+2001, Viel+2006, Becker+2011)
- Proximity region of Quasars
 - Quasar properties and environment (Khrykin+2021, Eilers+2021, Soltinsky+2021, Sindhu+2023,2024)
 - Damping wings at $z > 6$ (Greig+2017,2018, Davies+2018, Keating+2024, Spina+2024, Zhu+2024)

Introduction

How can we use Quasar absorption spectra to study IGM?



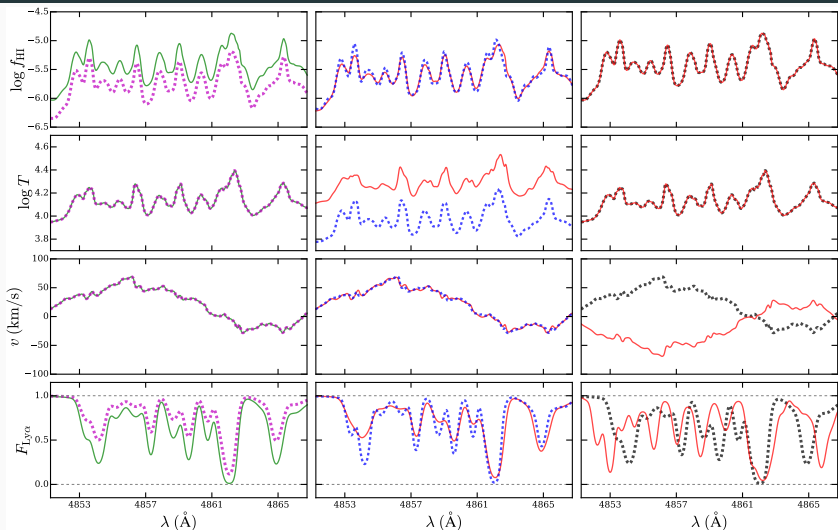
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 - Damping wings at $z > 3$ (Greig+2017,2018, Davies+2018, Keating+2024, Spina+2024, Zhu+2024)
- IGM Metal lines:
 - Feedback of Galaxies enriches IGM with metals (Talks presented in conference)
- How can we extract information from quasar absorption spectra?



Depth of absorption lines

Width of absorption lines

Location of absorption lines



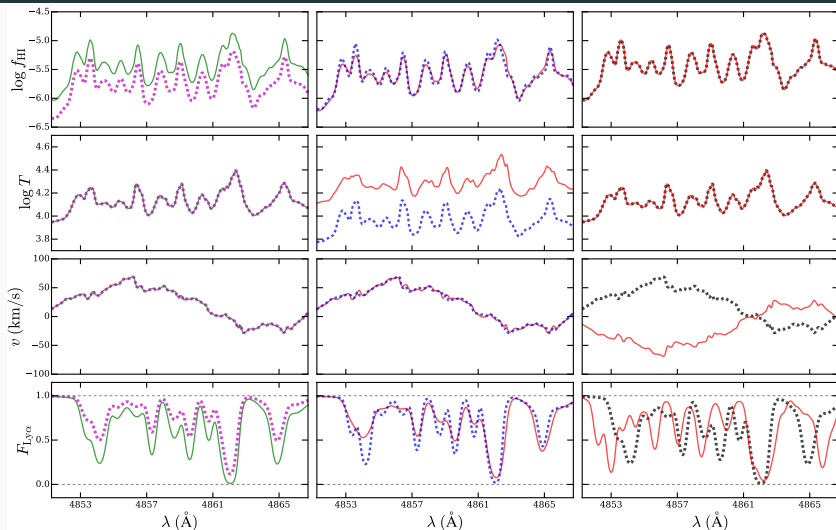
Depth of absorption lines

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



Depth of absorption lines

Width of absorption lines

Location of absorption lines

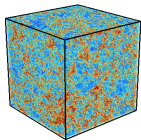
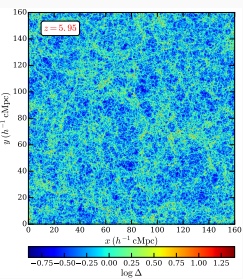
Photo-ionization rate

Temperature of IGM

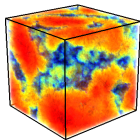
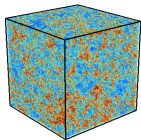
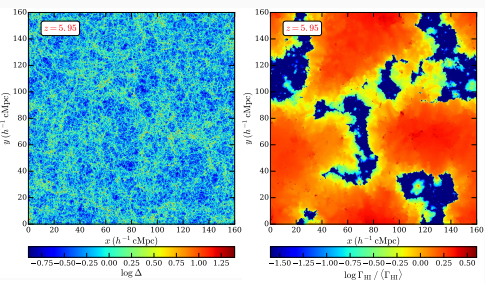
Mean Free Path

Free streaming length of WDM

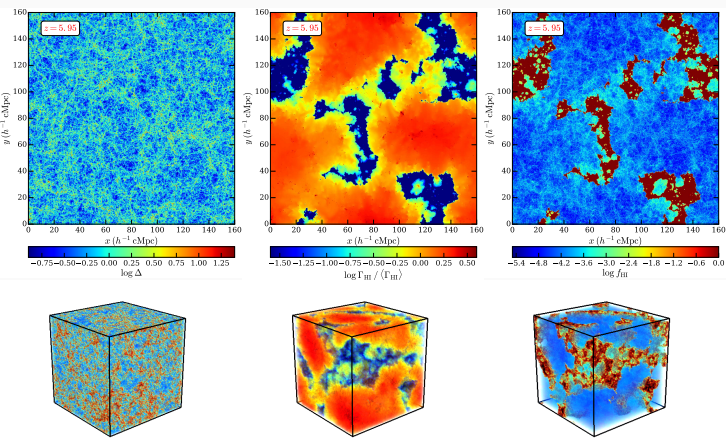
Simulations



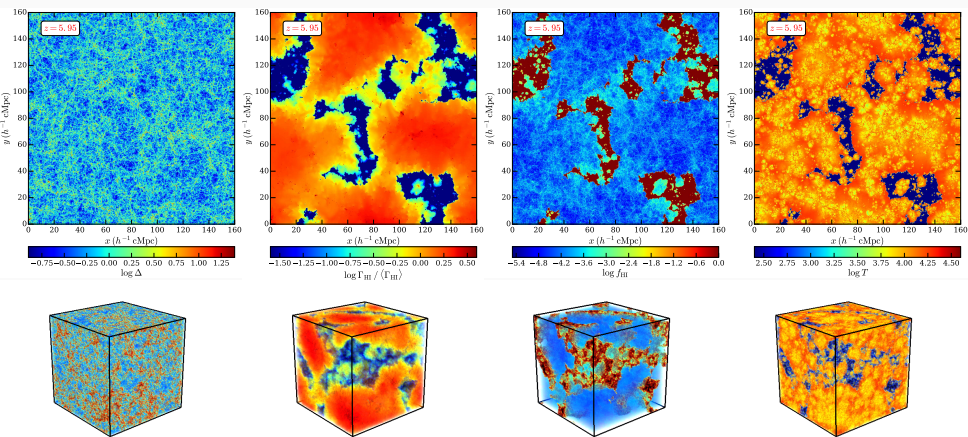
- Perform cosmological hydrodynamical simulation (Formation of Galaxies)



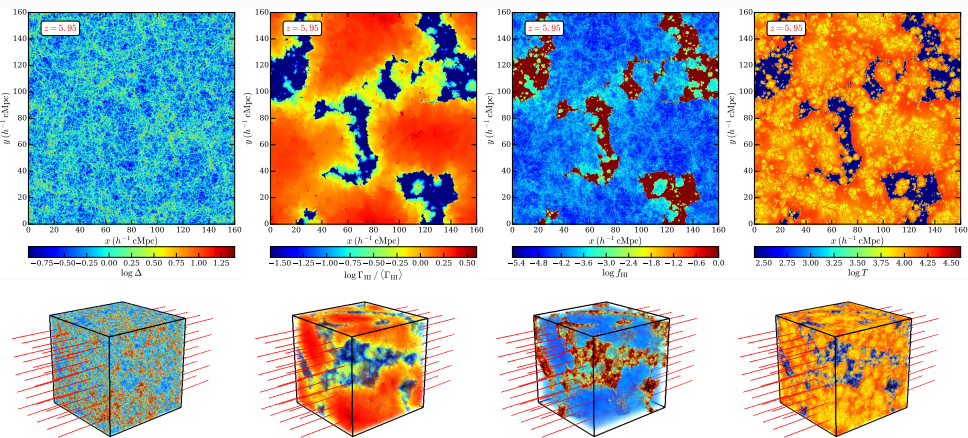
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- Solve radiative transfer equation (Radiation propagation from Galaxies)



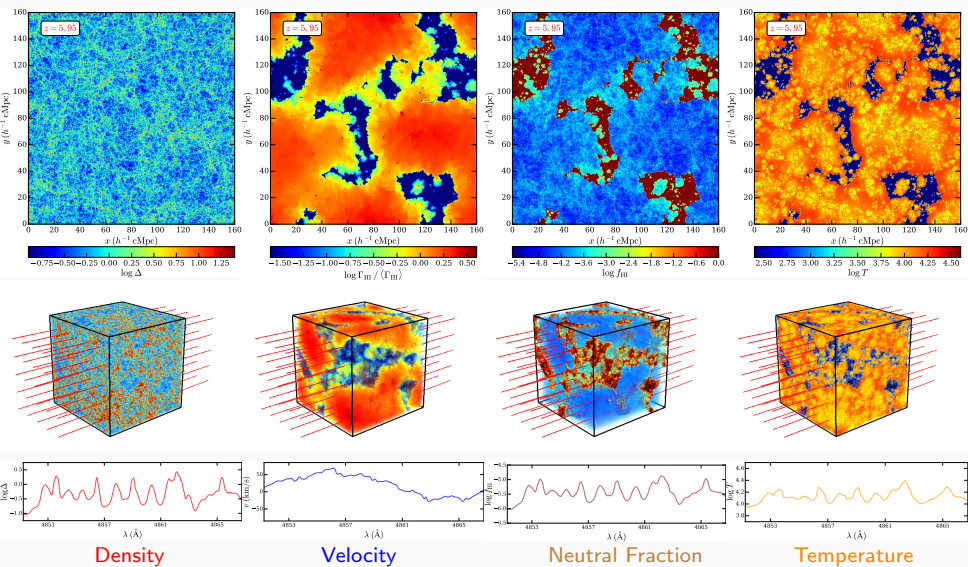
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- Solve chemical evolution Equation (Reionization of IGM)



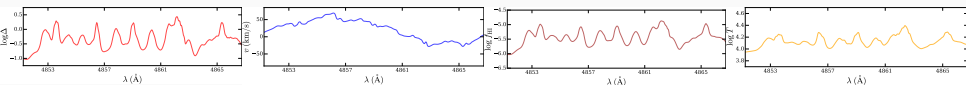
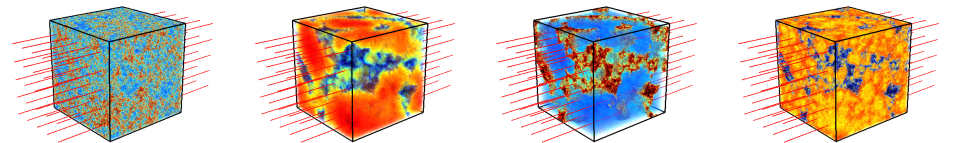
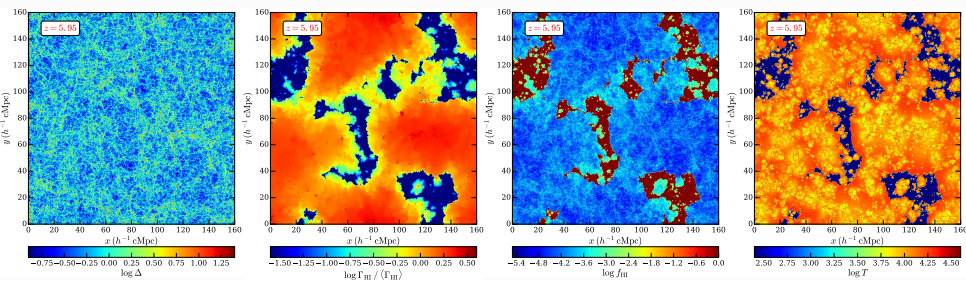
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- Solve temperature evolution Equation. (Photo-heating of IGM)



- Perform cosmological hydrodynamical simulation (Formation of Galaxies)
- Solve radiative transfer equation (Radiation propagation from Galaxies)
- Solve chemical evolution Equation (Reionization of IGM)
- Solve temperature evolution Equation. (Photo-heating of IGM)
- 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.

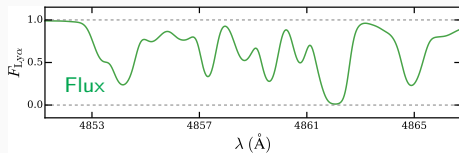


Density

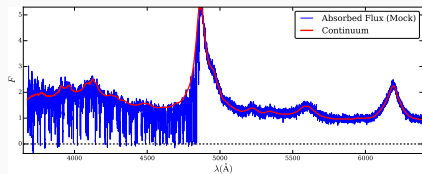
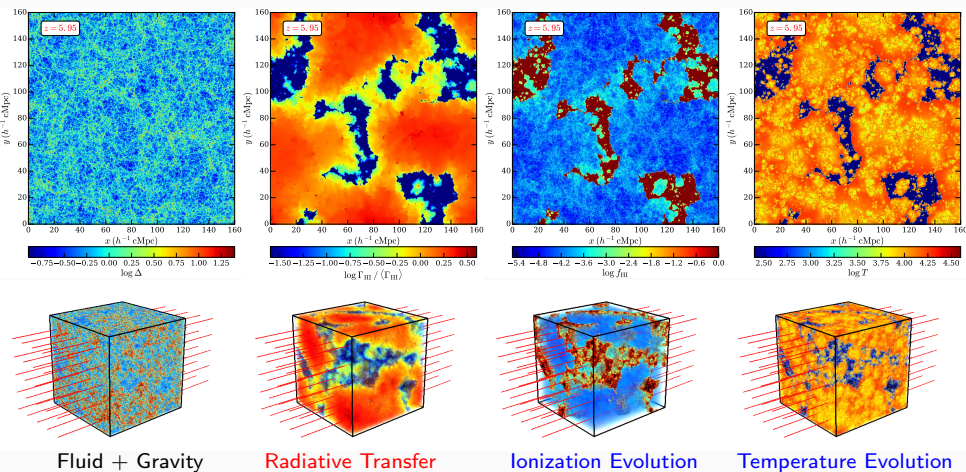
Velocity

Neutral Fraction

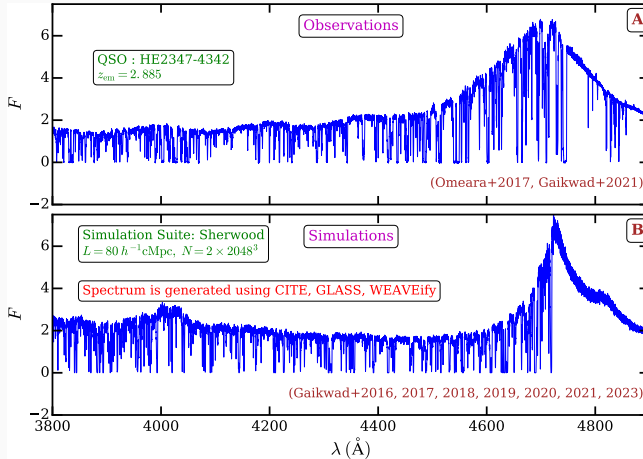
Temperature



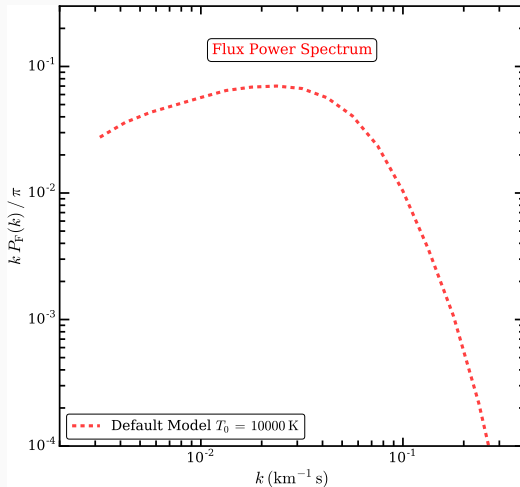
Ly α line transfer



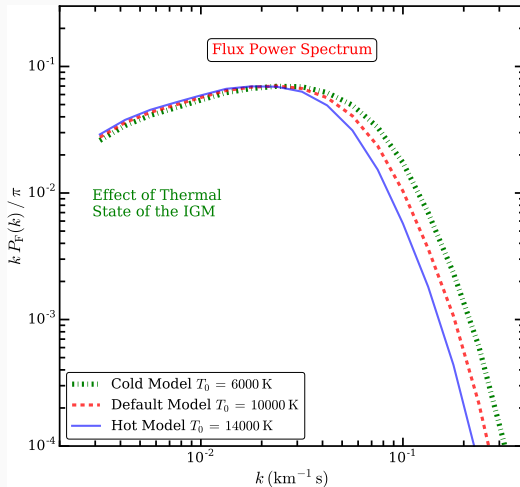
WEAVEIFY: To mimic observational properties



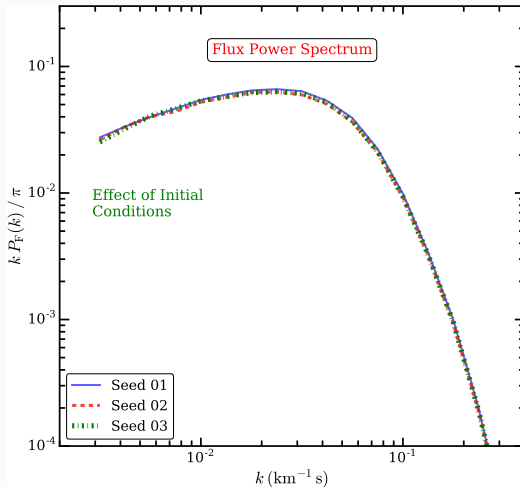
- One can not compare simulated spectra with observed spectra directly.
- Need to extract information from observation and simulation for comparison
- Our statistics should depend on only parameters of our interest and not on initial conditions.
- Fourier analysis of the flux field: Flux Power Spectrum, (Machine Learning, Soumak's Talk)



- $k = 2\pi/\nu$, Small $k \Rightarrow$ Large Scales, Large $k \Rightarrow$ Small Scales
- $k < 0.03 \Rightarrow$ Large scale variation in density field
- $k > 0.03 \Rightarrow$ Turn over due to temperature of the IGM



- $k = 2\pi/\nu$, Small $k \Rightarrow$ Large Scales, Large $k \Rightarrow$ Small Scales
- Flux PS is sensitive to the temperature of the IGM
- Hotter IGM $\Rightarrow$ More smoothing of Flux $\Rightarrow$ Less Power



- $k = 2\pi/\nu$, Small $k \Rightarrow$ Large Scales, Large $k \Rightarrow$ Small Scales
- Flux PS is similar even if initial conditions are different
- All other parameters kept same. Flux Power Spectrum can be used to measure temperature¹³

Statistical Inferences

- Model Fitting (Accounting for correlation between neighboring bins):

$$\chi^2(p) = [D - M(p)] \quad C^{-1} \quad [D - M(p)]^T$$
$$\text{Scalar} = [1 \times N_{\text{bins}}] \quad [N_{\text{bins}} \times N_{\text{bins}}] \quad [N_{\text{bins}} \times 1]$$

- D is observed data, M is model that depends on set of parameters p .
- C is covariance matrix. Very important because bins of the statistics are correlated. (Gaikwad+2017,2020,2020)
- Likelihood : $\mathcal{L} \propto e^{-\chi^2/2}$ $\Leftarrow$ We maximize this function.
- 1σ uncertainty : 68% of region around the best fit (Maximum $\mathcal{L}$)

Results: Evolution of the IGM

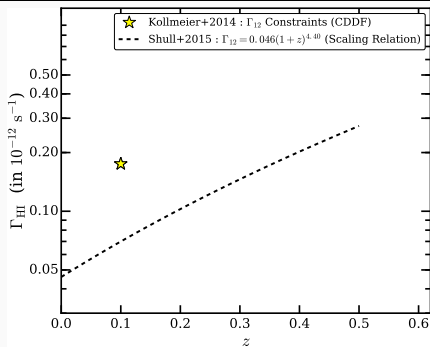
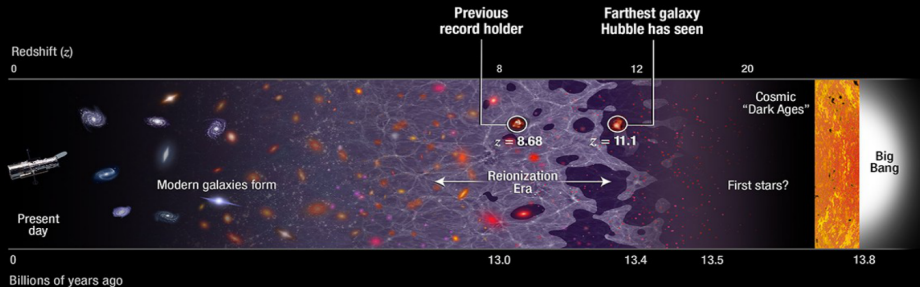
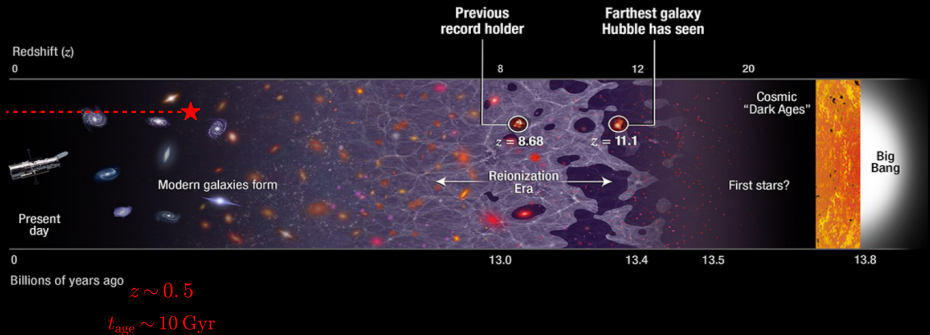
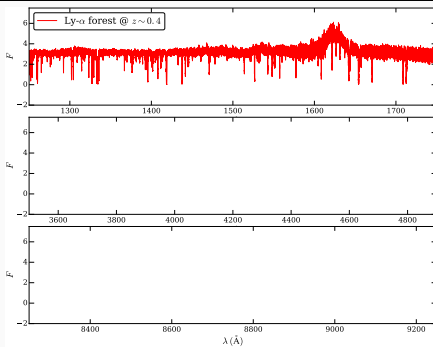


Photo-Underproduction Crisis at $z < 0.5$

Problem: Number of ionizing photons needed to maintain ionization state of the IGM $\gg$ Number of ionizing photons counted from astrophysical sources.



Ly α forest observations

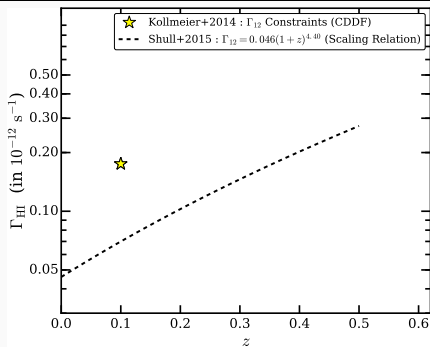
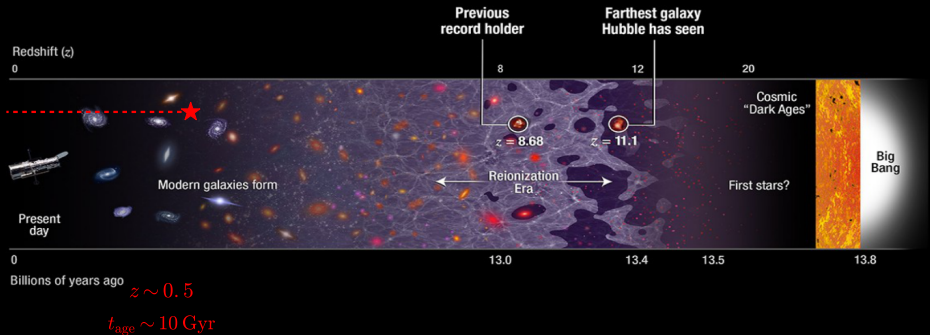


Hubble Telescope

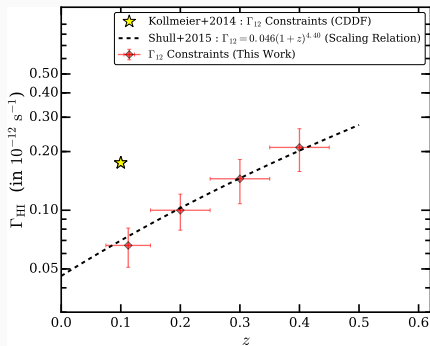
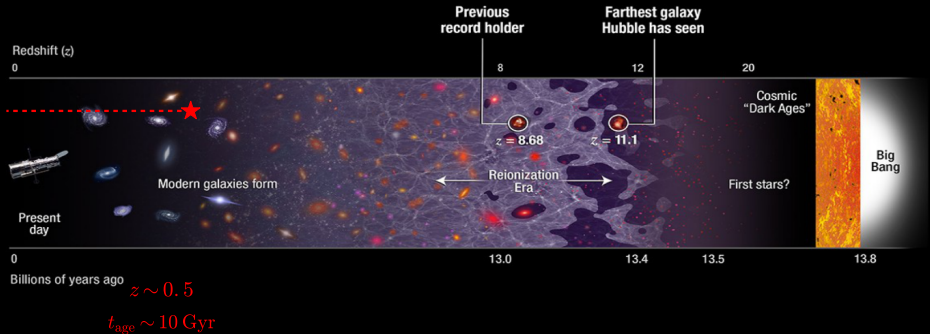
$t_{\text{age}} \sim 10 \text{ Gyr}$

Gaikwad+2017a,b

84 HST-COS spectra (Danforth+2014)



$t_{\text{age}} \sim 10 \text{ Gyr}$
 Hubble Telescope
 Gaikwad+2017a,b
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 Modeling and Statistical inference from $\text{Ly}\alpha$
 forest in SPH simulations (Gaikwad+2017a,b)



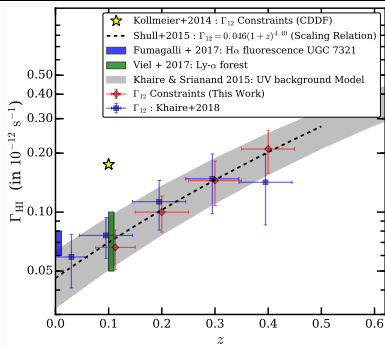
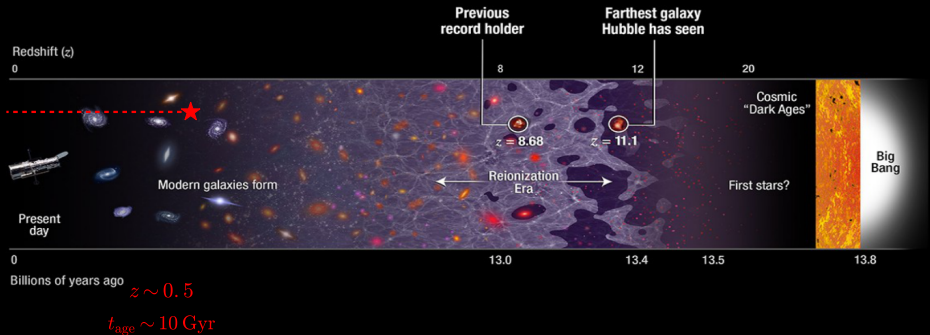
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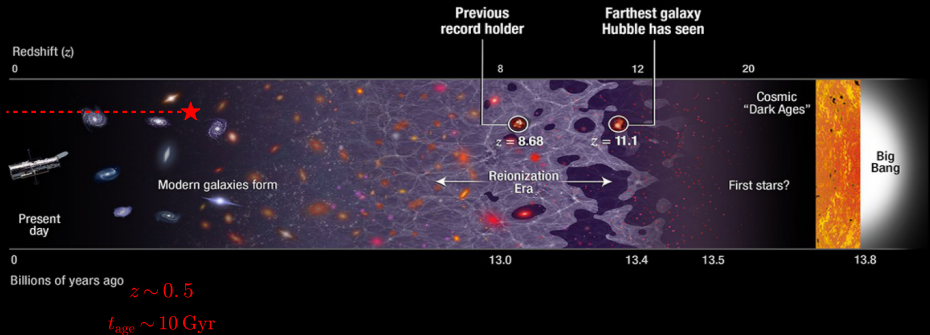
Hubble Telescope
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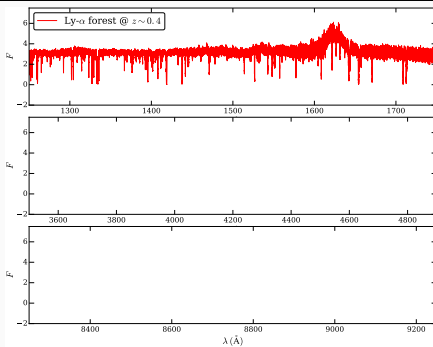
Modeling and Statistical inference from Ly α
 forest in SPH simulations (Gaikwad+2017a,b)

No Photon Underproduction Crisis!

Galaxy escape fraction $< 0.08\%$

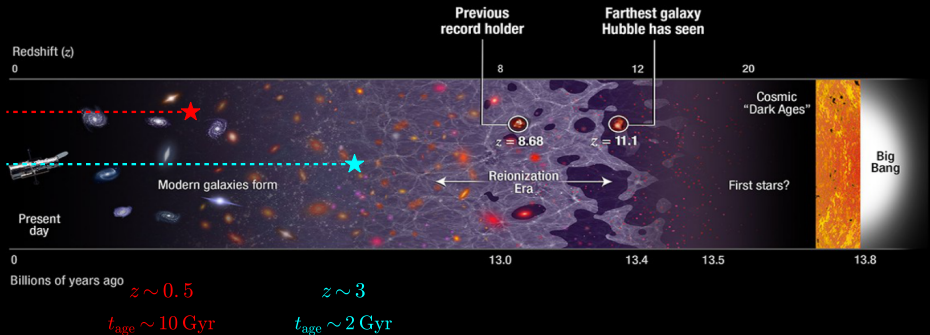


Ly α forest observations

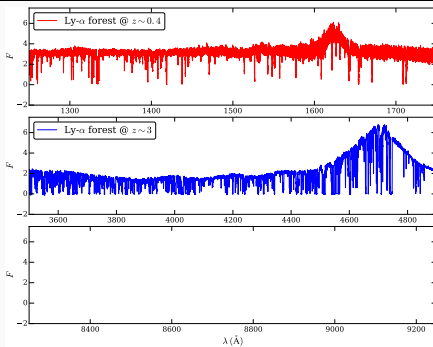


Reionization: H I ($5 < z < 20$), He II ($2 < z < 4$)

What is the thermal state of the IGM at $2 < z < 4$?

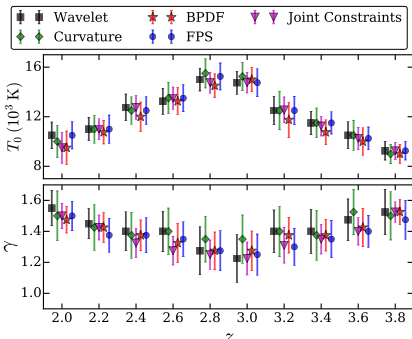
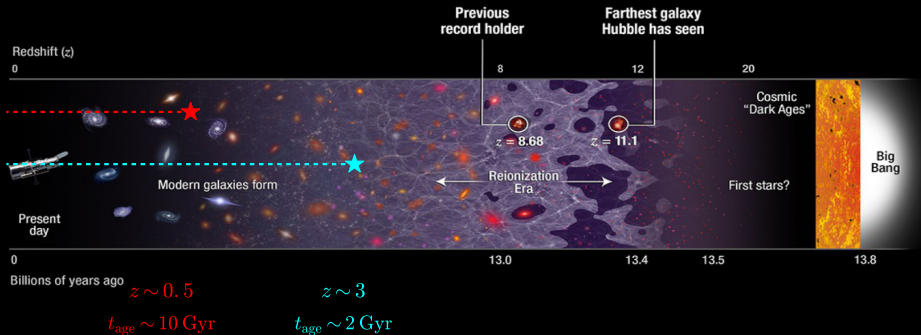


Ly α forest observations



Keck Telescope
Gaikwad+2021

104 Keck-HIRES spectra (Omeara+2017),
 $T = T_0 \Delta\gamma^{-1}$, (Sergio's Talk)



Keck Telescope

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

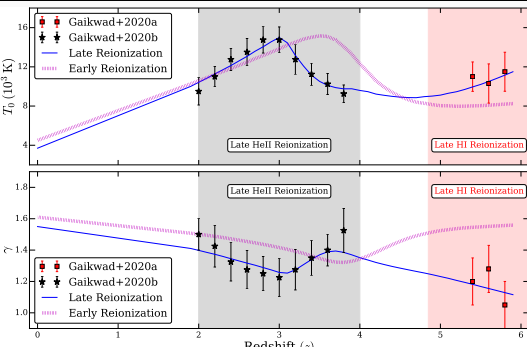
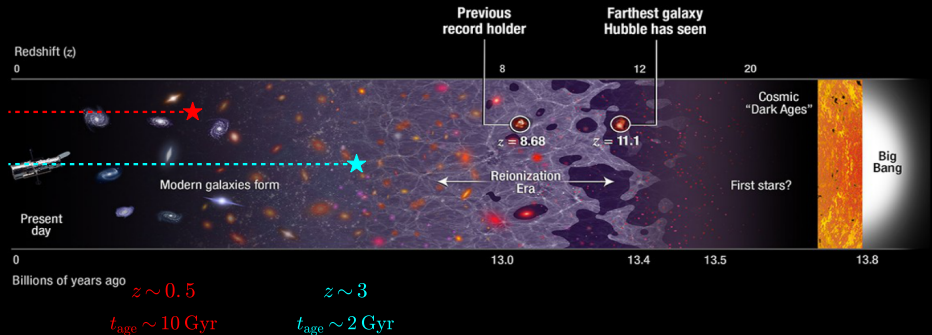
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Modeling and Statistical inference of $\text{Ly}\alpha$ forest
 from 4 statistics (Gaikwad+2021)

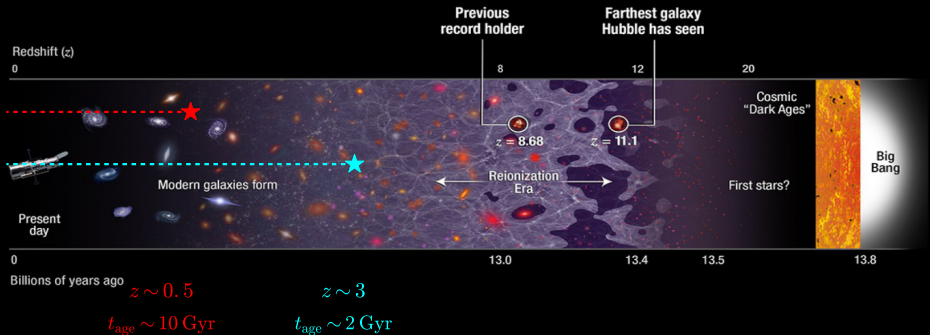
Most robust and consistent measurements of
 thermal parameters



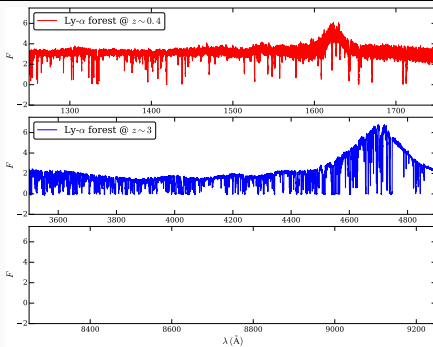
Similar analysis of Ly α forest at $5 < z < 6$
using spike statistics (Gaikwad+2020)

Favors Late H I and He II Reionization
AGN Spectral slope $\alpha \sim -1.8$

WDM mass constraints $> 4.1 \text{ keV}$
(Irsic+2024)

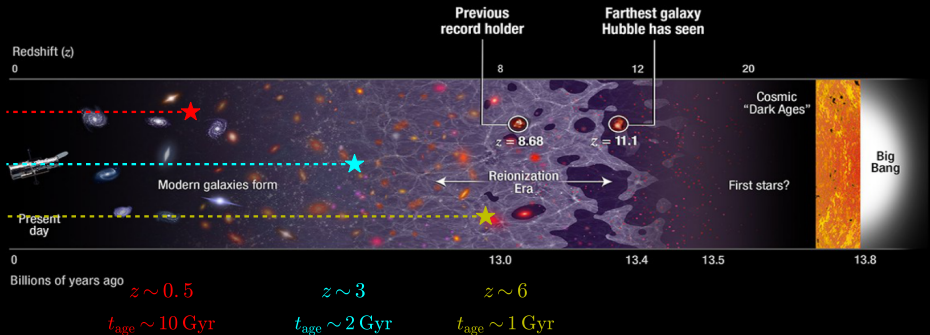
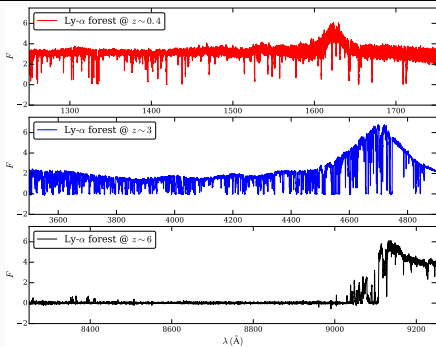


Ly α forest observations



Ionization state of the IGM at $z > 5$

Ly α line saturates quickly but observations show occurrence of transmission spikes

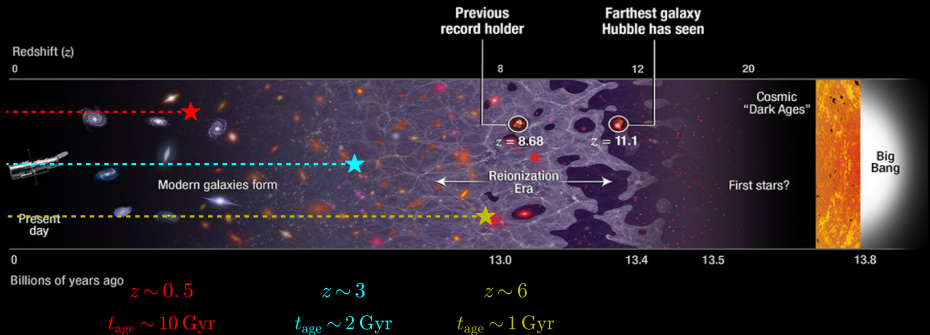
Ly α forest observations

Very Large Telescope

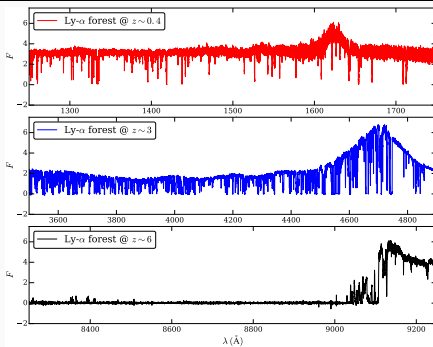
Gaikwad+2023

60 VLT-XShooter spectra (D'odorico+2024)

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



Ly α forest observations



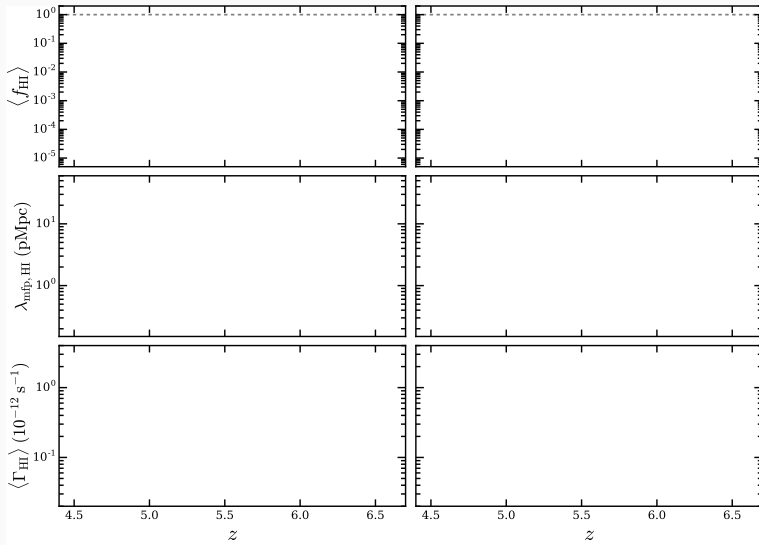
Very Large Telescope
Gaikwad+2023

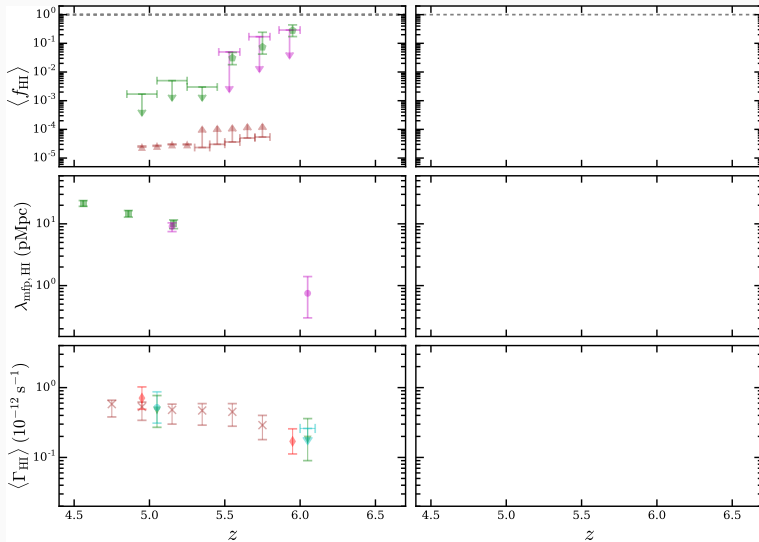
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60 VLT-XShooter spectra (D'odorico+2024)

Modeling of patchy reionization using
Ray-Tracing ExCITE (Davies+2016, Gaikwad+2023)

Constraints of photo-ionization rate, mean free
path and neutral fraction

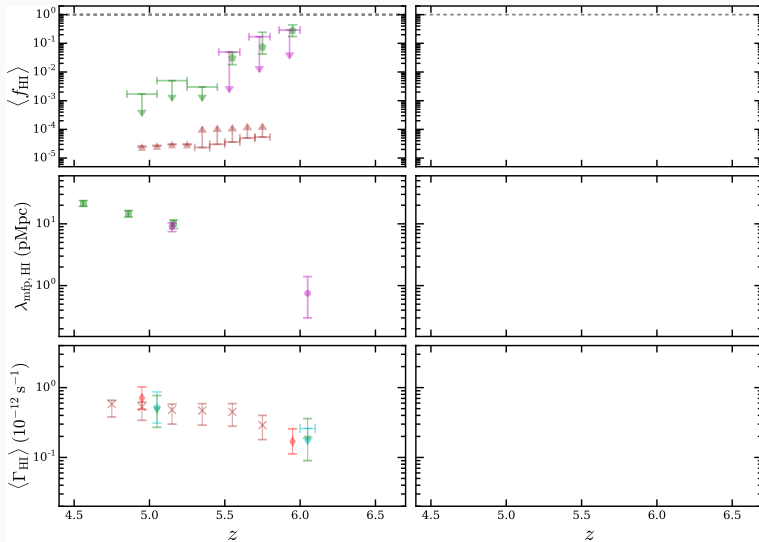




f_{HI} : [Mcgreer+2015](#), [Choudhury+2021](#), [Bosman+2022](#)

$\lambda_{\text{mfp, HI}}$: [Becker+2021](#), [Worseck+2014](#)

Γ_{HI} : [Calverley+2011](#), [Wyithe+2011](#), [D'aloisio+2018](#), [Bolton+2007](#)

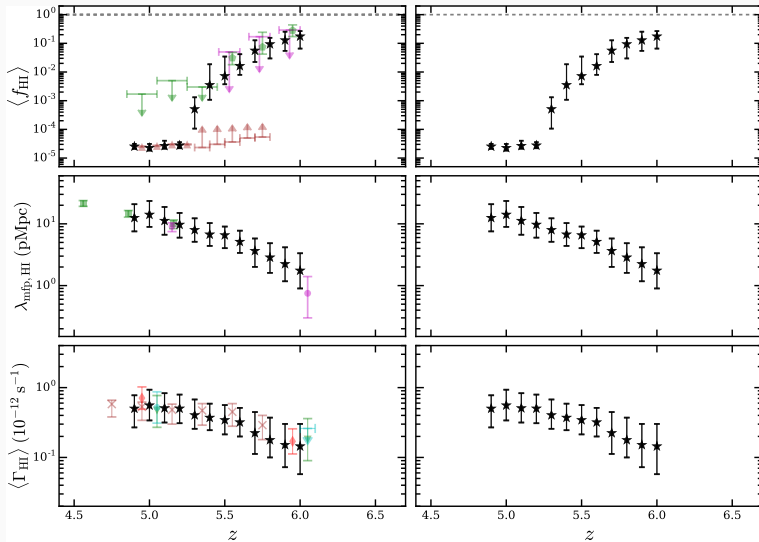


f_{HI} : Uniform UVB: limits on the amount of the neutral hydrogen

$\lambda_{\text{mfp, HI}}$: No measurements at $5 < z < 6$, MFP at $z \sim 6$ is too short.

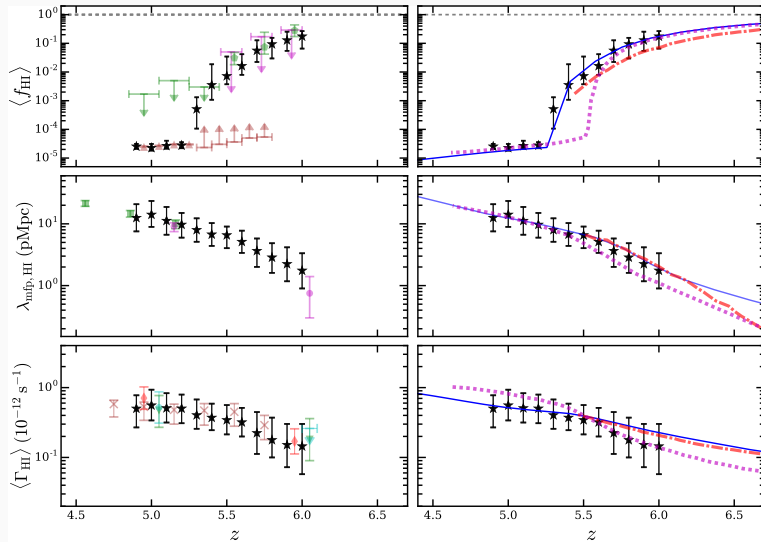
Γ_{HI} : Previous measurements did not account for patchy reionization

Comparison with previous constraints



Evolution of f_{HI} , $\lambda_{\text{mfp, HI}}$, Γ_{HI} : Accounts for observational and modeling uncertainties

Comparison with previous constraints

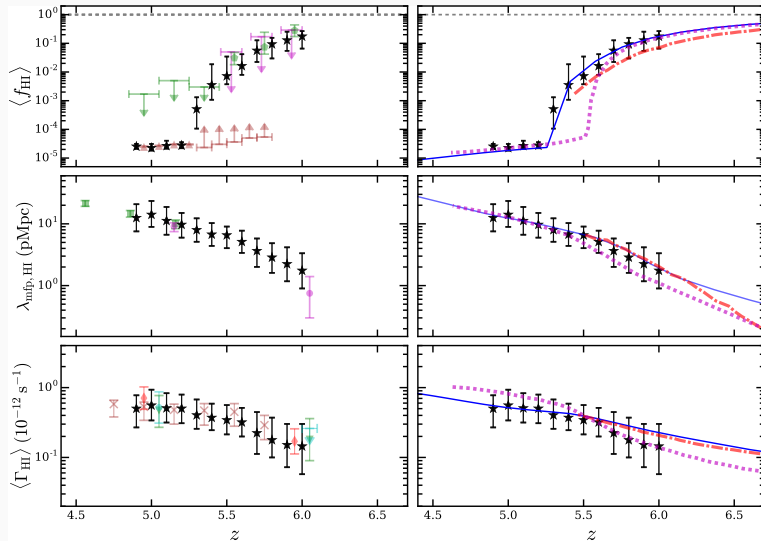


Comparison with radiative transfer models

Radiative Transfer Models (Time Evolution)

ATON model (Gaikwad+2023), CODA-III (Lewis+2022), THESAN (Garaldi+2022)

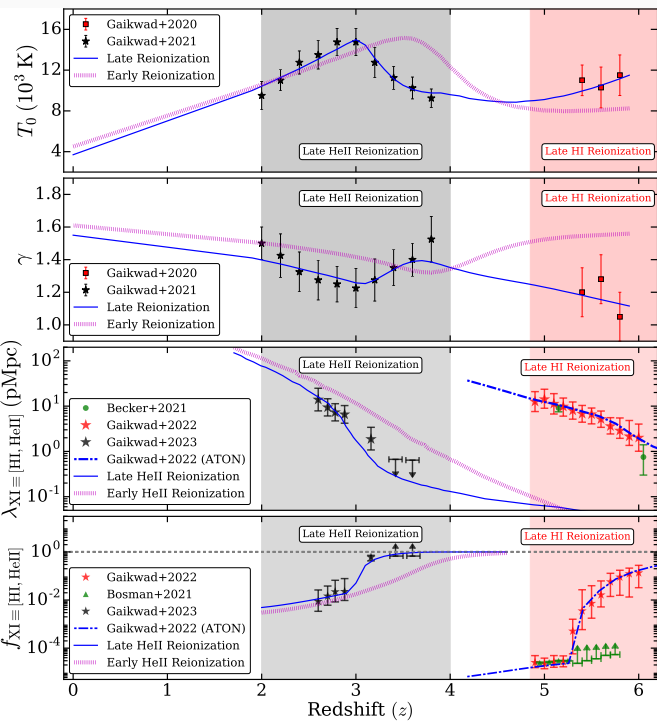
Comparison with previous constraints



Comparison with radiative transfer models

ATON model : Late reionization completed by $z \sim 5.2$

Too rapid models like CODA-III are disfavoured by our measurements.

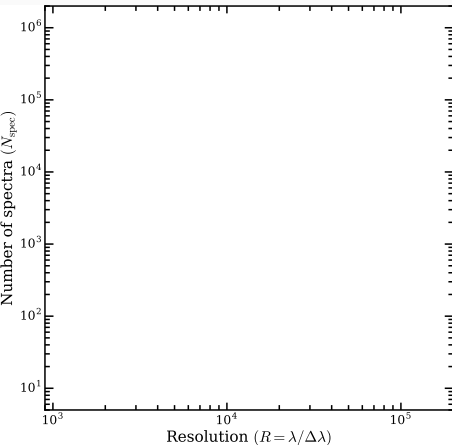


Thermal state of IGM

Ionization state of IGM

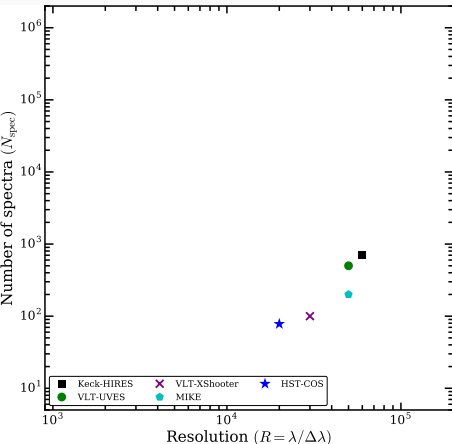
Future Work

Future Work (Observations)



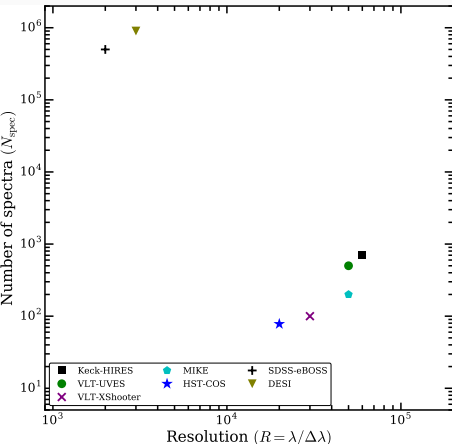
- $N_{\text{spec}} \Rightarrow$ Quantity of Spectra
- $R \Rightarrow$ Quality of spectra

Future Work (Observations)



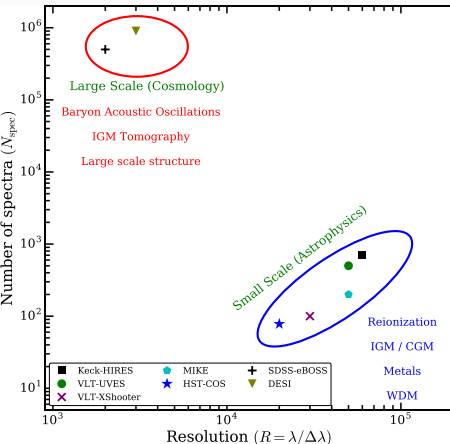
- $N_{\text{spec}} \Rightarrow$ Quantity of Spectra
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- High quality limited quantity
 - * Target based studies
 - * Echelle Spectroscopy
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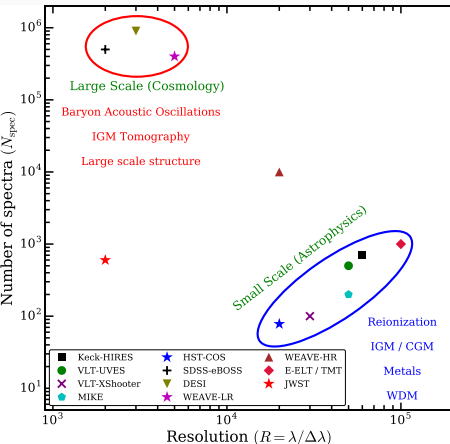
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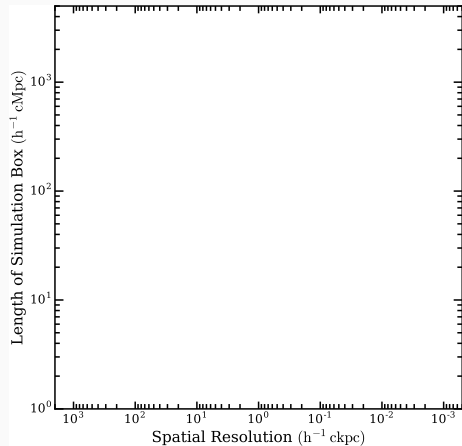


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- Astrophysics : Reionization, IGM / CGM, Metal distribution, Nature of Dark Matter
- Upcoming Facilities: 30m class telescopes, TMT, E-ELT ANDES
- Cosmology : Large scale structures, BAO, IGM tomography, Nature of Dark Energy
- Upcoming Surveys : WEAVE Low resolution and High resolution

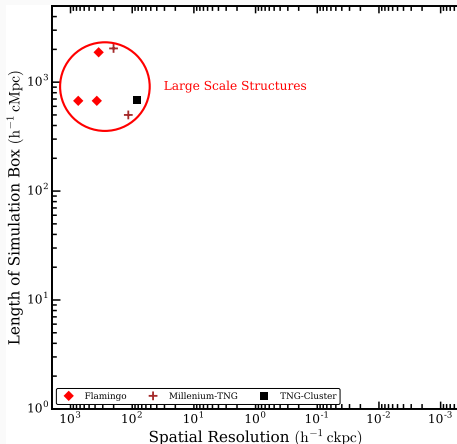
Future Work (Simulations)

- $L_{\text{box}}^3 \Rightarrow$ Volume of the Simulation box
- $dx \Rightarrow$ Resolution of the simulation box



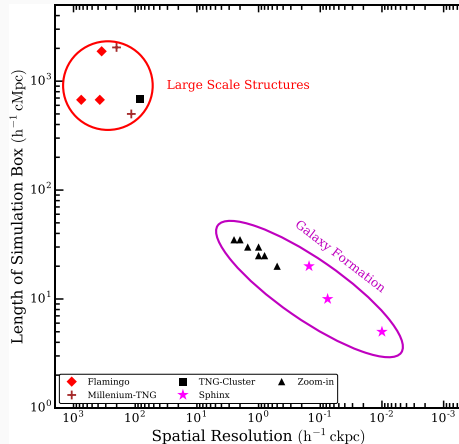
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 - * Do not solve radiative transfer



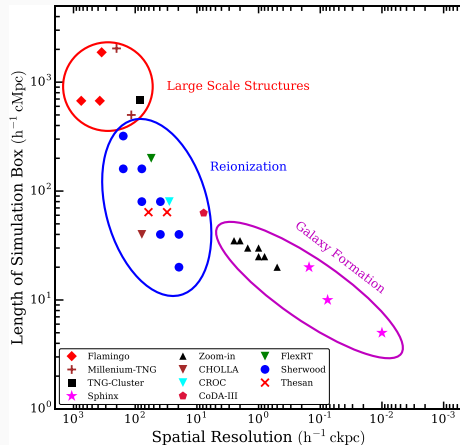
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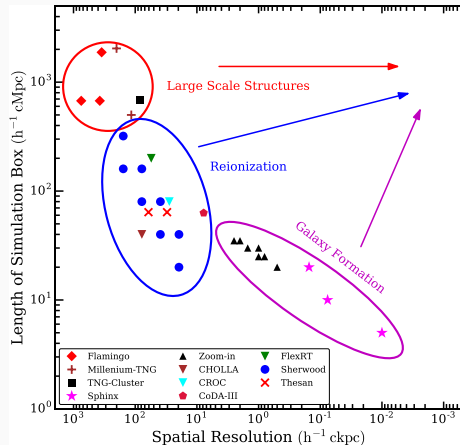
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Future Work (Simulations)

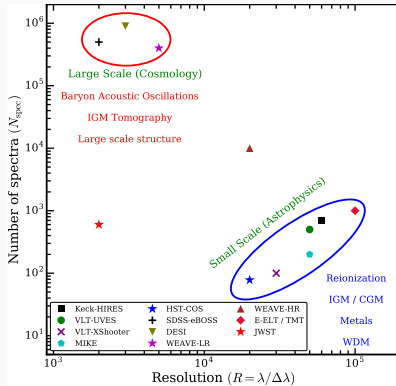
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- Goal of scientific community
 - * Efficient Algorithms / techniques
 - * GPU Acceleration
 - * Machine Learning techniques

Future Work

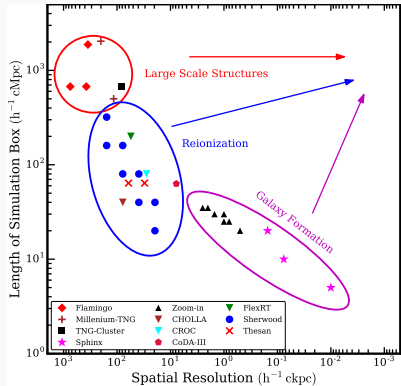
Observations



Observations:

- **Upcoming data:** UVES, GHOST, ESPRESSO, MUSE, WEAVE
- **Future observatories :** TMT, SKA, E-ELT

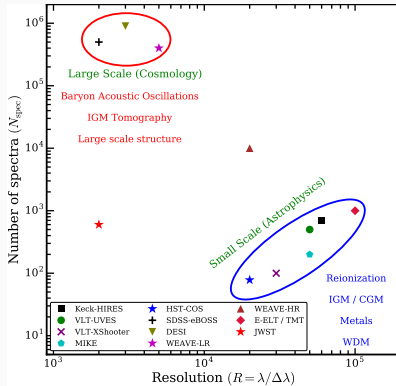
Wealth of observational data is / will be available



Simulations

Future Work

Observations

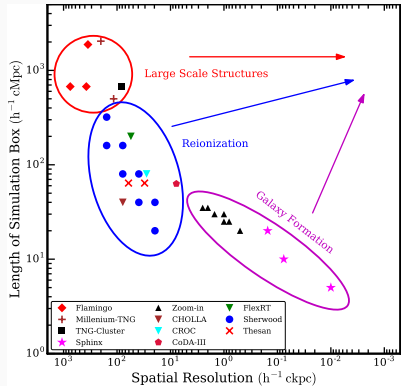


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Simulations:

- **Goals of community:** Efficient methods, GPU acceleration, Machine Learning approaches



Simulations

Wealth of observational data is / will be available

Repository of simulation data is available

Summary

- What is IGM?
 - Diffuse gas in cosmic filaments but not associated with Galaxies
- Why is IGM important?
 - IGM has imprints of cosmological initial conditions and processes of galaxy formation
- How do we study IGM?
 - Quasar Absorption Spectroscopy Observations (Challenging), Huge dynamic range
 - Cosmological hydrodynamical + Radiative Transfer Simulations (Expensive, HPC)
- How hot and neutral IGM is?
 - Thermal and Ionization state of IGM suggest reionization is rapid and late
(Gaikwad+2016, Gaikwad+2017, Gaikwad+2018, Gaikwad+2019, Gaikwad+2020, Gaikwad+2021, Gaikwad+2023)
- Future work
 - Significant developments going on in both Simulations and Observations of IGM