

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 using 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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How do we study IGM? Data, observation, and simulation?

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Future goals and Summary

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Thermal and Ionization state of the IGM?

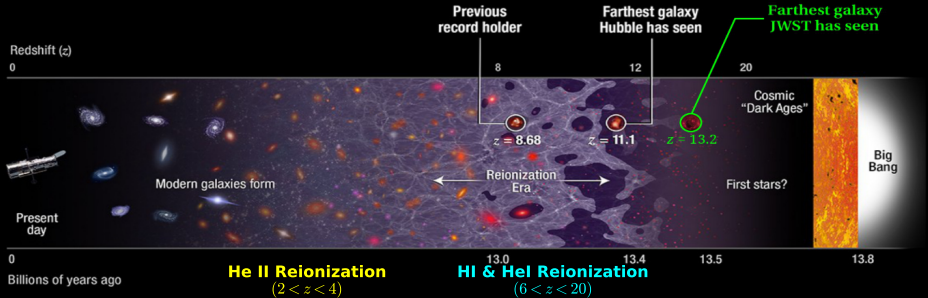
- What novel ventures should both observers and simulators pursue to achieve a breakthrough in the coming years?

Future work and Summary

Introduction

What is the IGM?

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



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

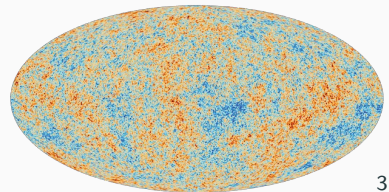
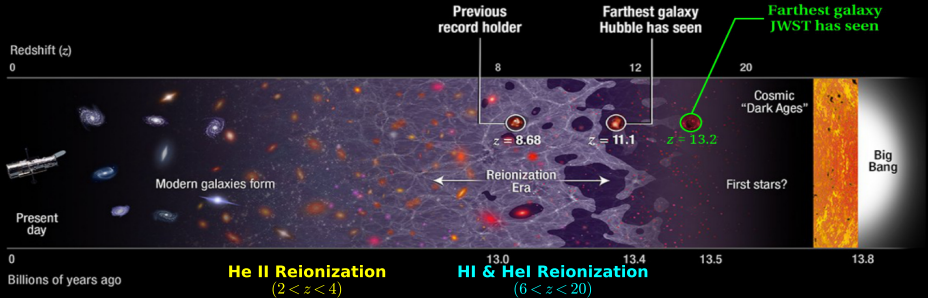
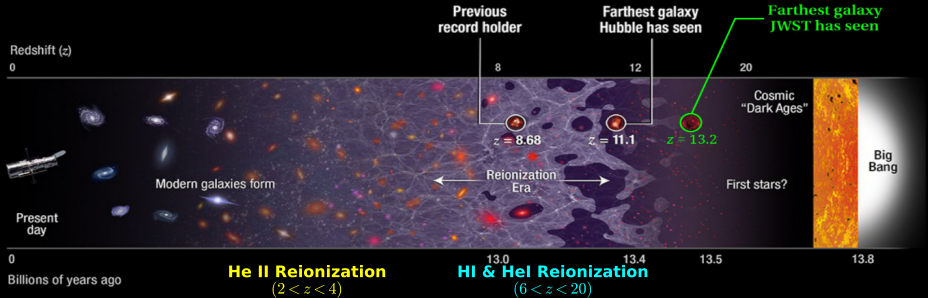


Image : NASA, ESA, P. Oesch, B. Robertson and A. Fei



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

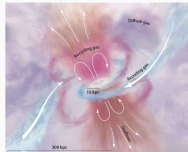
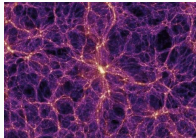
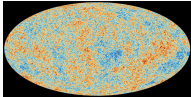
Cosmic
Microwave
Background

Intergalactic
Medium

Circumgalactic
Medium

Interstellar
Medium

Illustration



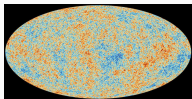
Introduction

Why is the IGM important?

Illustration

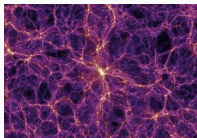
Densities

Cosmic
Microwave
Background



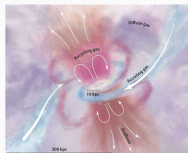
Linear
 $\Delta \sim 1$

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

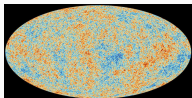
Why is the IGM important?

Illustration

Densities

Scales

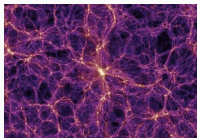
Cosmic
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Linear
 $\Delta \sim 1$

Few Gpc

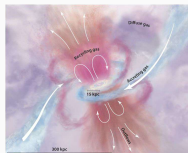
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Few 100 Mpc

Circumgalactic
Medium



Non-Linear
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Few 100 kpc

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 $\Delta > 1000$

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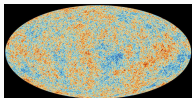
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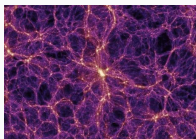
Scales

Physics

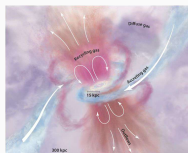
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Few 100 Mpc

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)

Introduction

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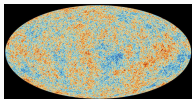
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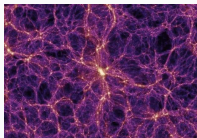
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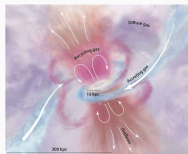
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Cosmology
Large Scale Structures



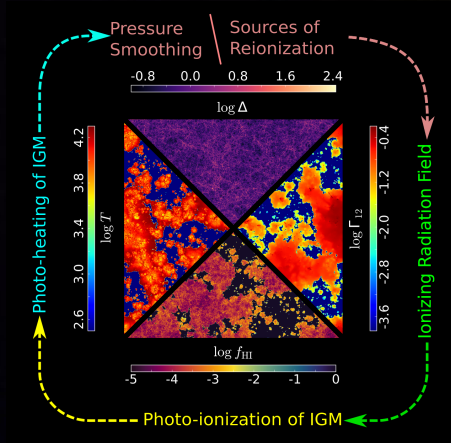
IGM



Astrophysics
Galaxy Formation and Evolution

Open Problems in IGM (The big picture)

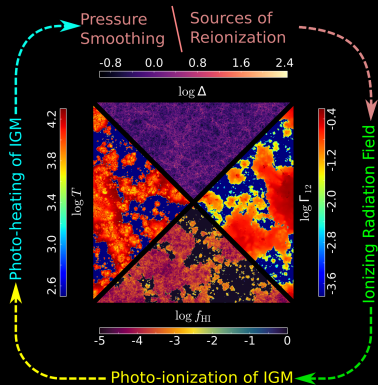
- Reionization:
 - When and How did reionization happen?
 - Nature of reionization? Morphology of reionization
- IGM - Galaxies connection:
 - Properties of early galaxies and AGN during reionization?
 - Feedback of reionization on galaxy formation?
- Cosmology :
 - Nature of dark matter and dark energy?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

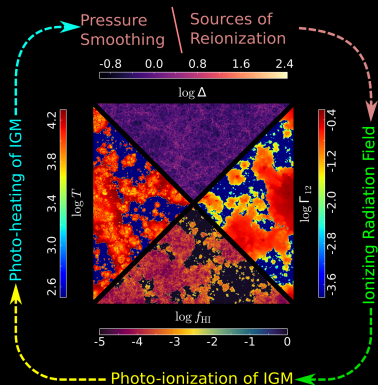
Why is reionization important?

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



Why is reionization important?

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

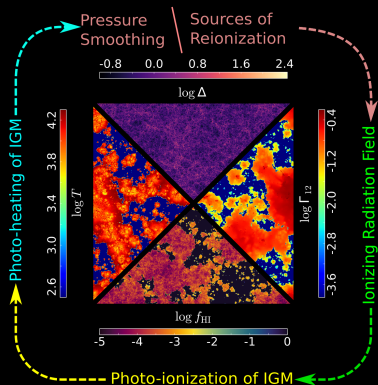


Small Scale Astrophysics

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

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Small Scale Astrophysics

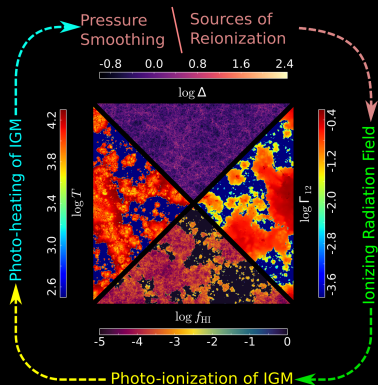
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Large Scale Structures

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

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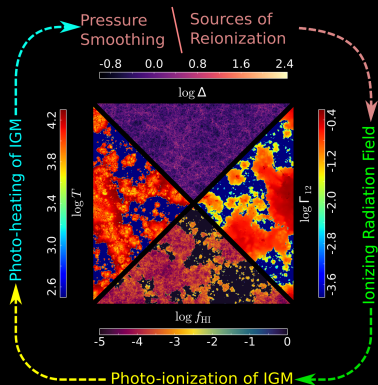
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Observational Challenges

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

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Modeling Challenges

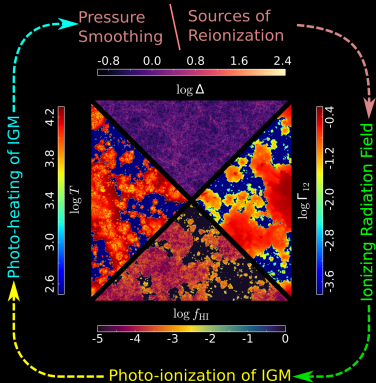
- Huge dynamic range of simulations
- Radiative Transfer Effects
- Galaxy formation sub-grid models

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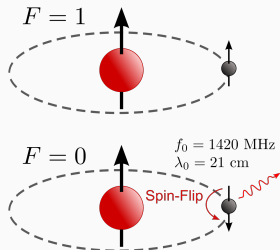
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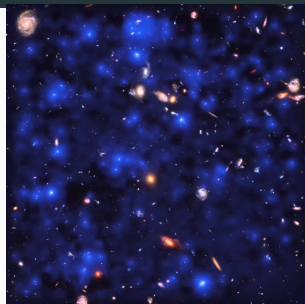
The complexity of reionization makes it more interesting !

Observations

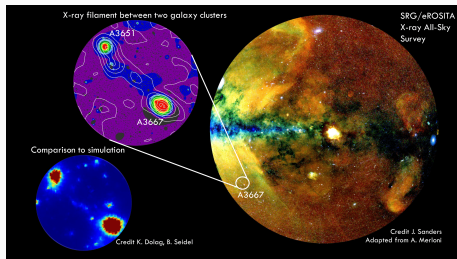
How can we observationally probe IGM?



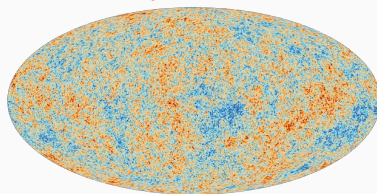
21cm Experiments



Diffuse Ly α emission



X-ray observations of filaments

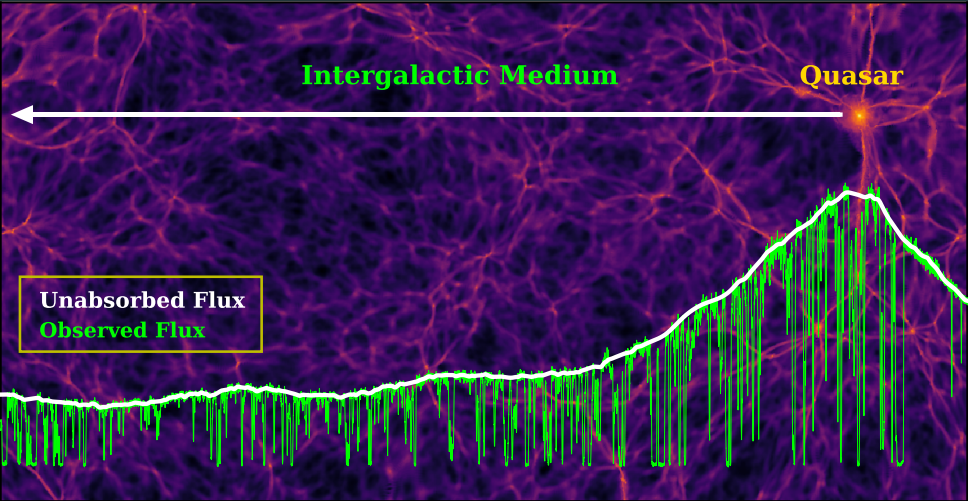


CMB (Thompson τ , Thermal SZ)

Transients (FRB, GRB)
Gravitational Lensing

Introduction

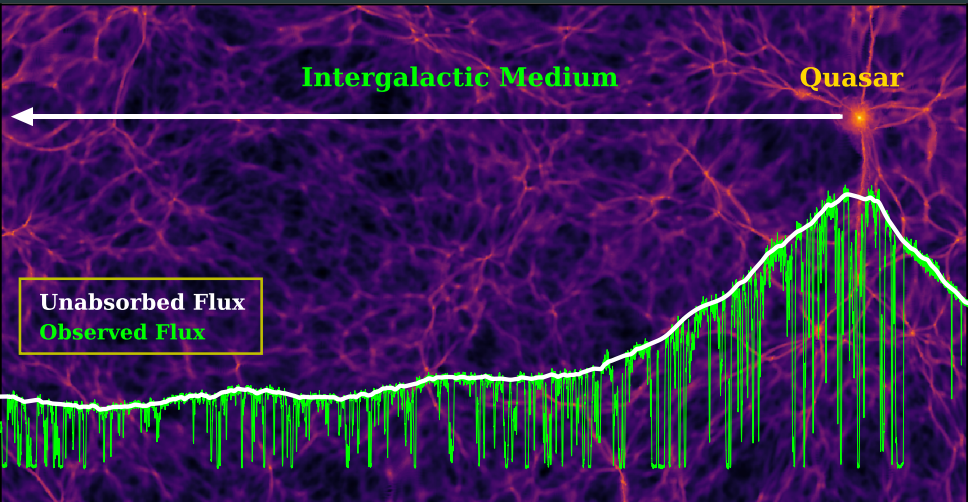
How can we observationally probe IGM?



- 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

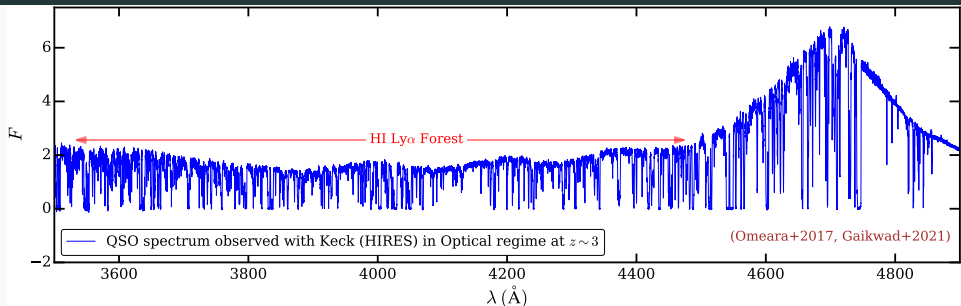
How can we observationally probe IGM?



- The set of characteristics 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?

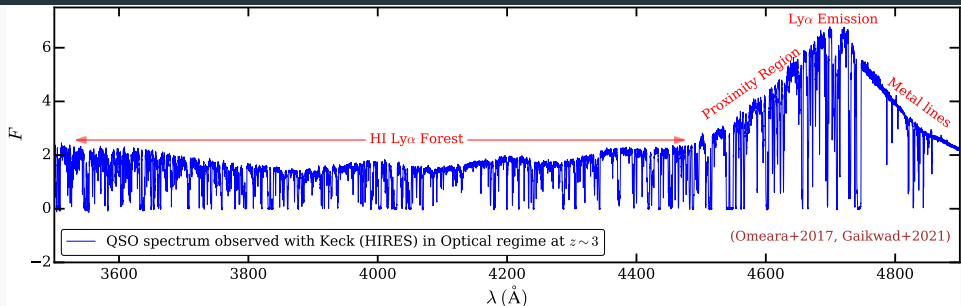
Introduction

How can we use Quasar absorption spectra to study IGM?



- Quasar spectra contains a lot of information about IGM.
- Ly α forest (Thermal and Ionization state of the IGM)

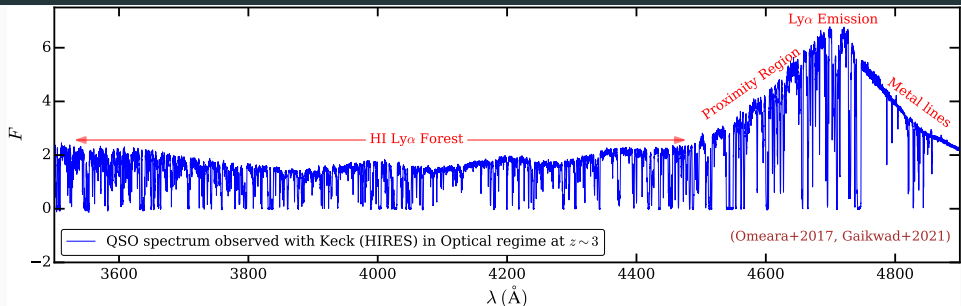
(Schaye+2001, Lidz+2010, Becker+2011)



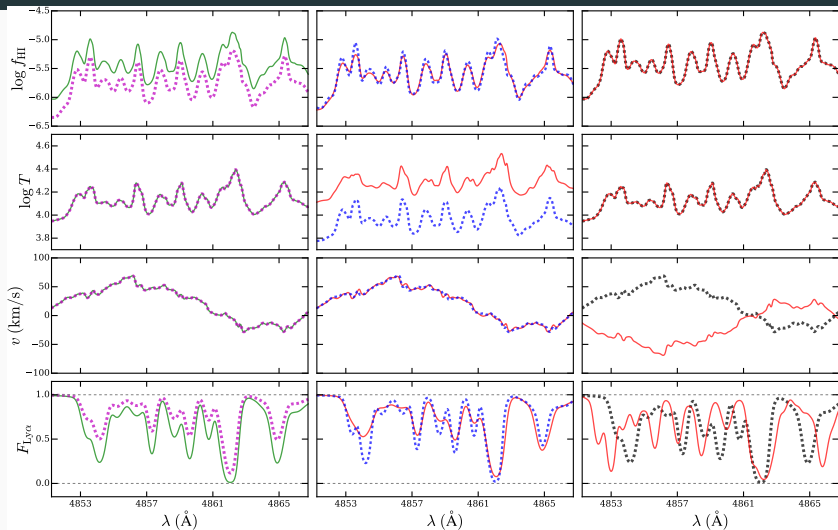
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- $\text{Ly}\alpha$ forest (Thermal and Ionization state of the IGM) (Schaye+2001, Lidz+2010, Becker+2011)
- Proximity region of Quasars
 - Quasar properties and environment (Khrykin+2021, Eilers+2021, Soltinsky+2021, Sindhu+2023,2024)
 - Damping wings at $z > 6$ (Greig+2017,2018, Davies+2018, Keating+2024, Spina+2024, Zhu+2024)

Introduction

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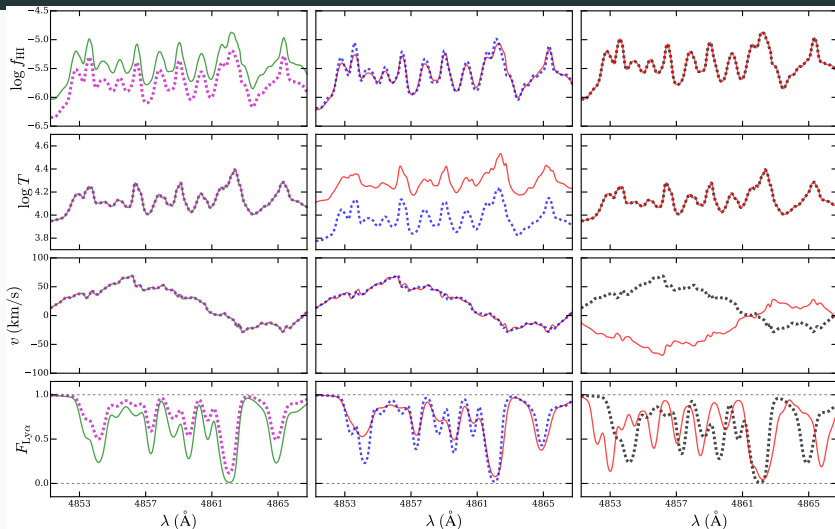
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 - Damping wings at $z > 6$ (Greig+2017,2018, Davies+2018, Keating+2024, Spina+2024, Zhu+2024)
- IGM Metal lines:
 - Feedback of Galaxies enriches IGM with metals (Talks presented in conference)
- How can we extract information from quasar absorption spectra?



Depth of absorption lines

Width of absorption lines

Location of absorption lines



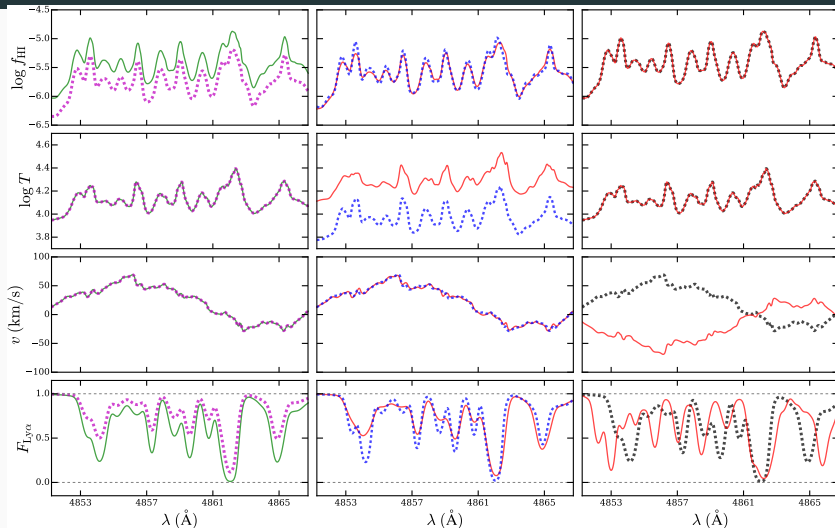
Depth of absorption lines

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

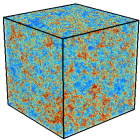
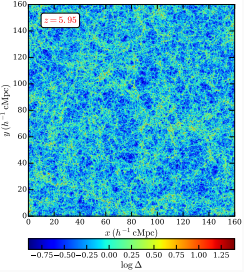
Photo-ionization rate

Temperature of IGM

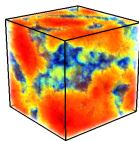
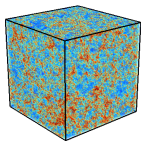
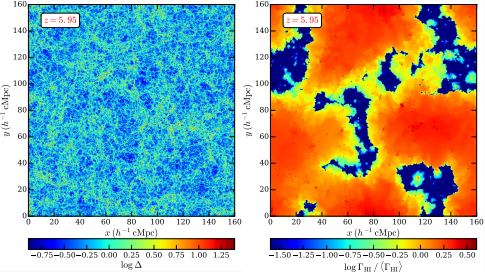
Mean Free Path

Free streaming length of WDM

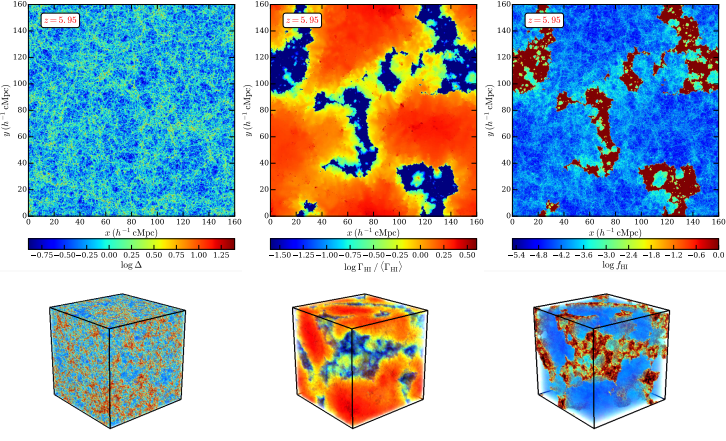
Simulations



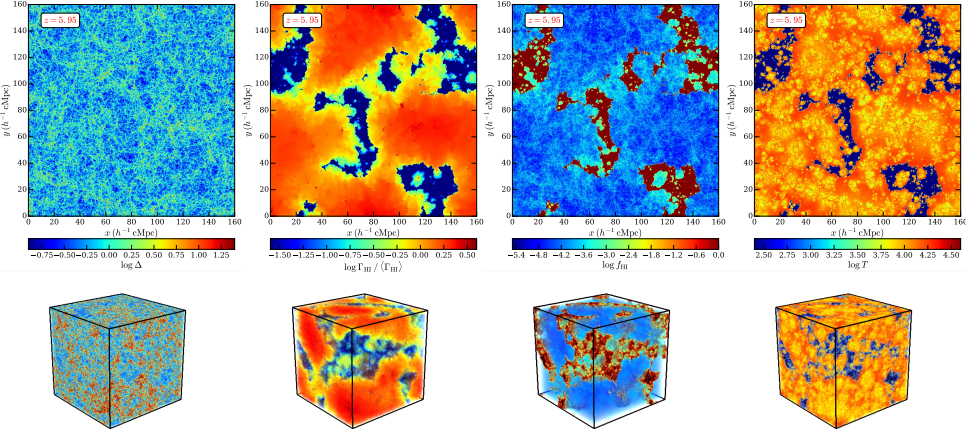
- Perform cosmological hydrodynamical simulation (Formation of Galaxies)



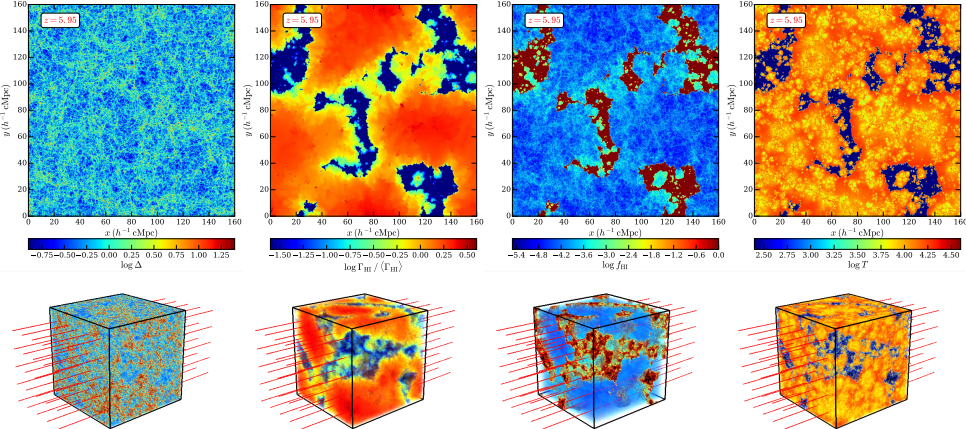
- Perform cosmological hydrodynamical simulation (Formation of Galaxies)
- Solve radiative transfer equation (Radiation propagation from Galaxies)



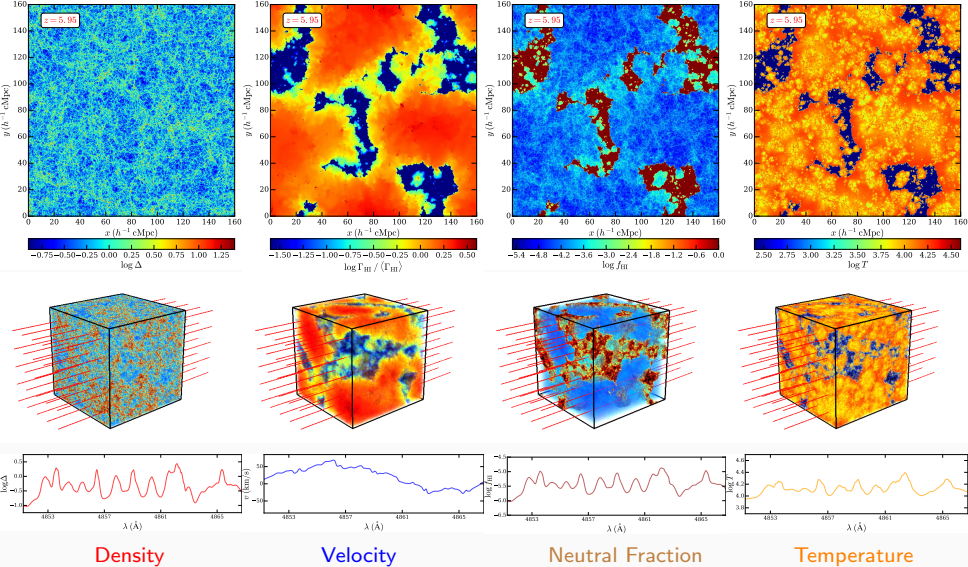
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- Solve chemical evolution Equation (Reionization of IGM)



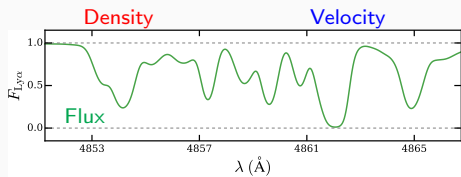
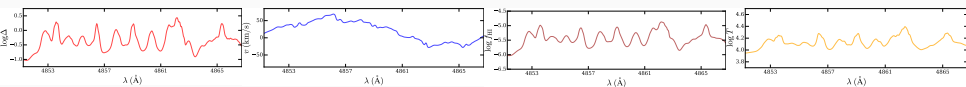
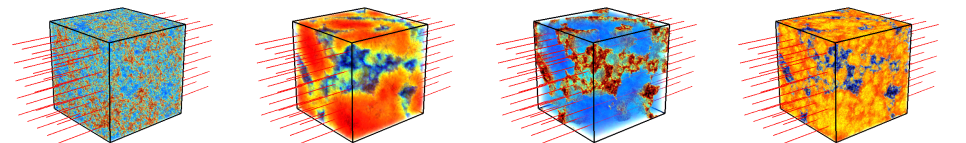
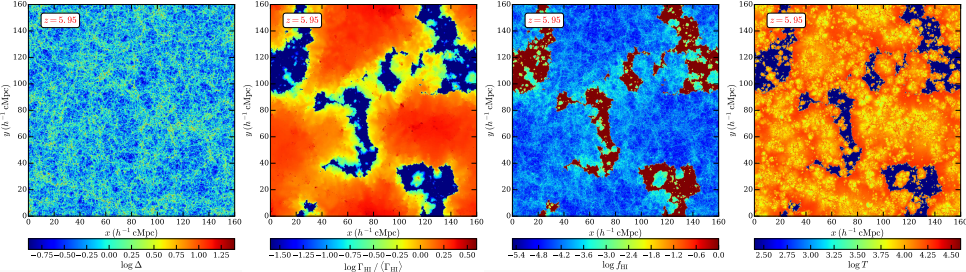
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- Solve temperature evolution Equation. (Photo-heating of IGM)



- 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.

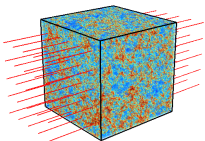
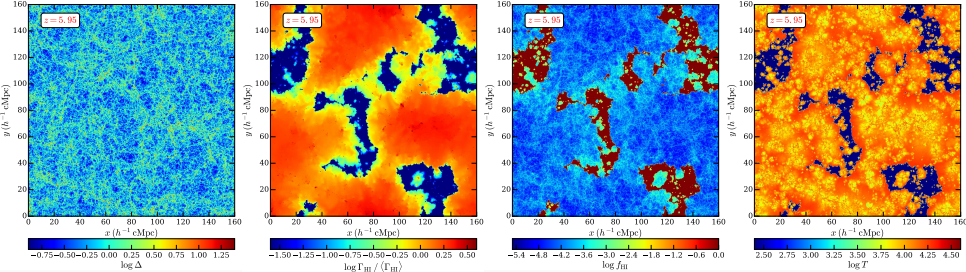


- Example of a sample sightline. The fields are then used to compute absorption spectrum.

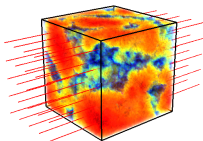


Density Velocity Neutral Fraction Temperature

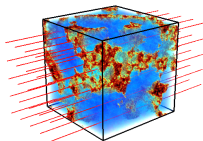
Ly α line transfer



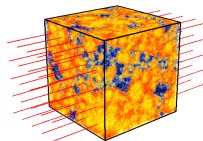
Fluid + Gravity



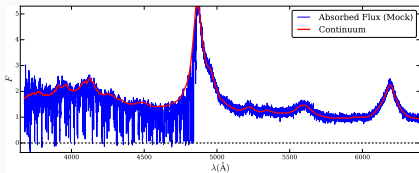
Radiative Transfer



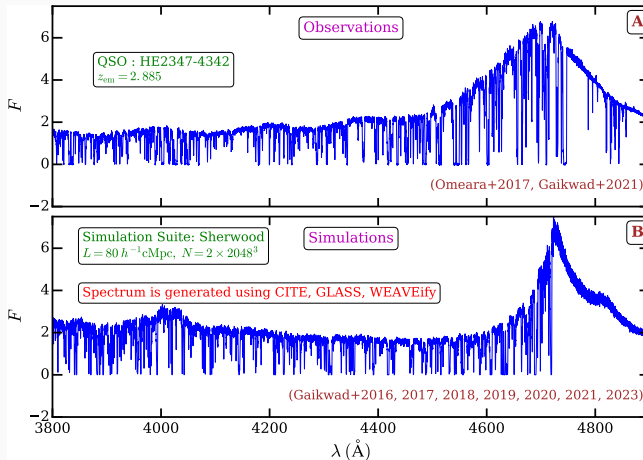
Ionization Evolution



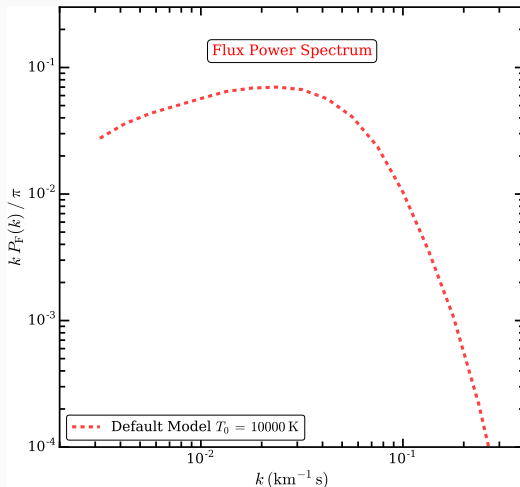
Temperature Evolution



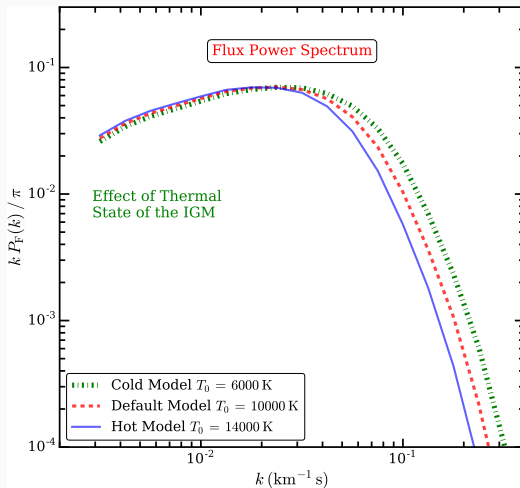
WEAVEIFY: To mimic observational properties



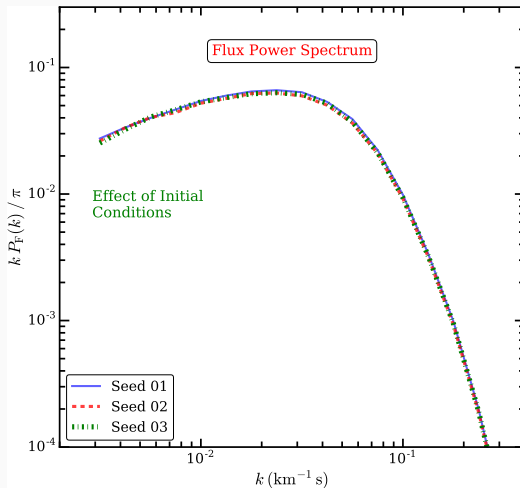
- One can not compare simulated spectra with observed spectra directly.
- Need to extract information from observation and simulation for comparison
- Our statistics should depend on only parameters of our interest and not on initial conditions.
- Fourier analysis of the flux field: Flux Power Spectrum



- $k = 2\pi/\nu$, 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 temperature

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

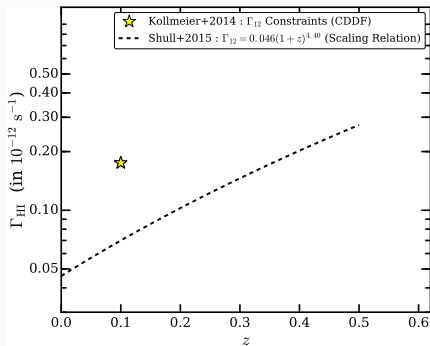
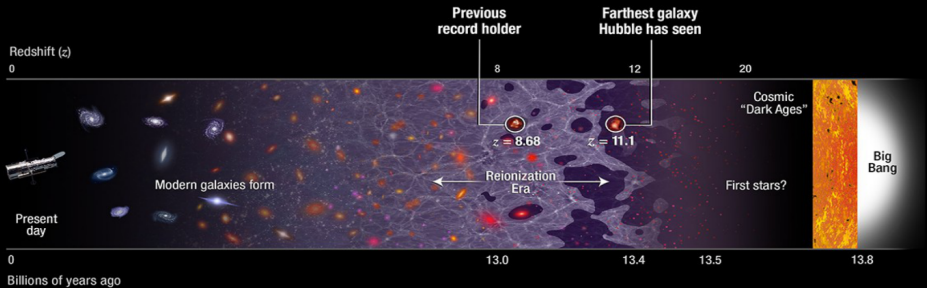
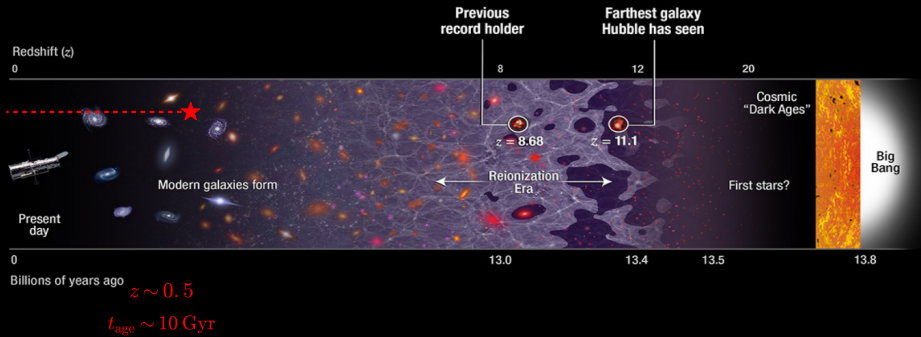
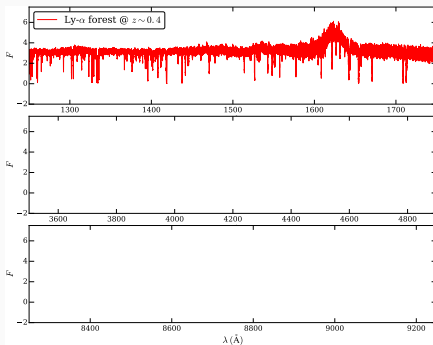


Photo-Underproduction Crisis at $z < 0.5$

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

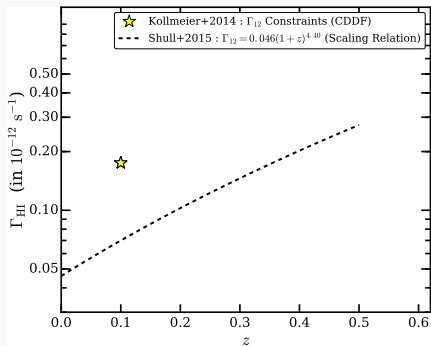
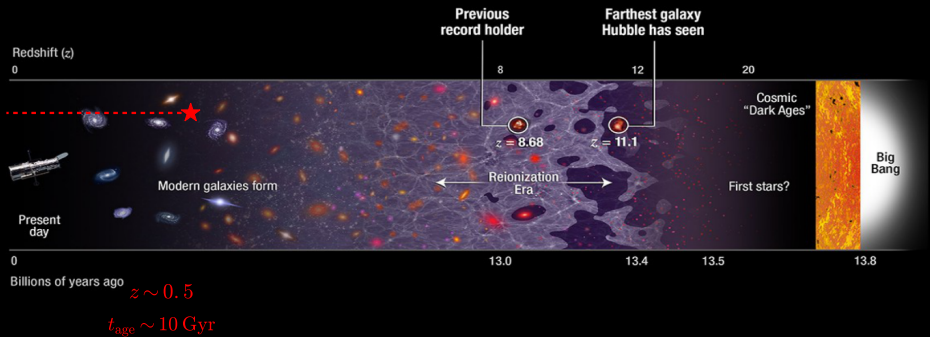


Hubble Telescope

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

Gaikwad+2017a,b

84 HST-COS spectra (Danforth+2014)

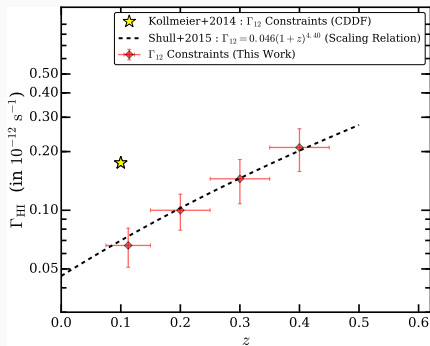
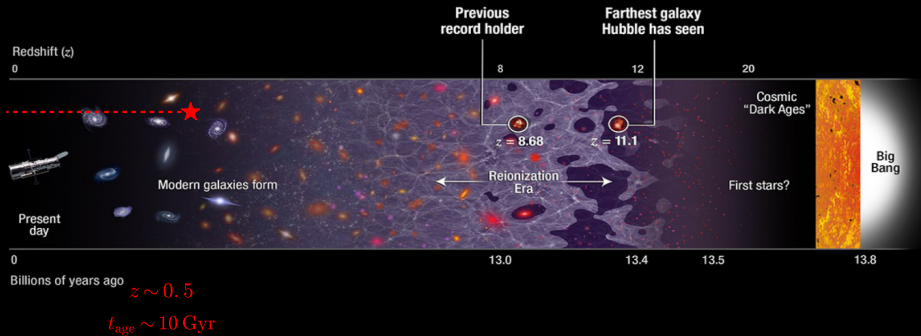


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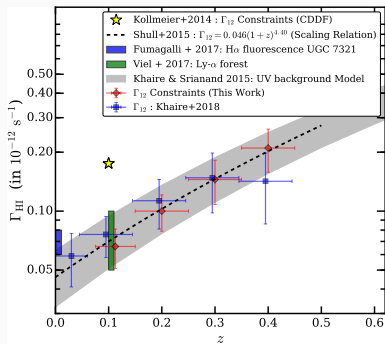
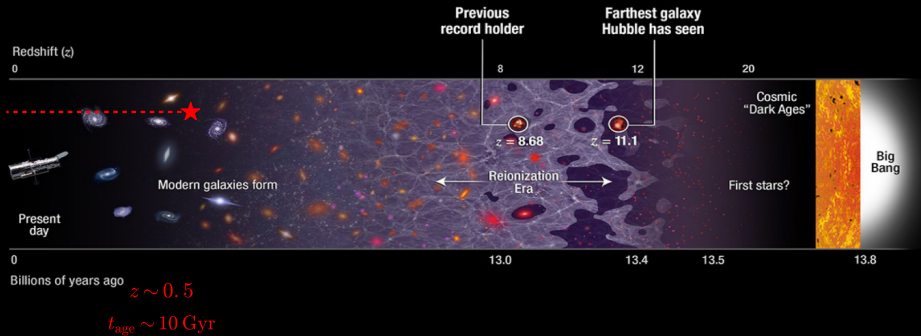
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Gaikwad+2017a,b

84 HST-COS spectra (Danforth+2014)

Modeling and Statistical inference from $\text{Ly}\alpha$

forest in SPH simulations (Gaikwad+2017a,b)



Hubble Telescope

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

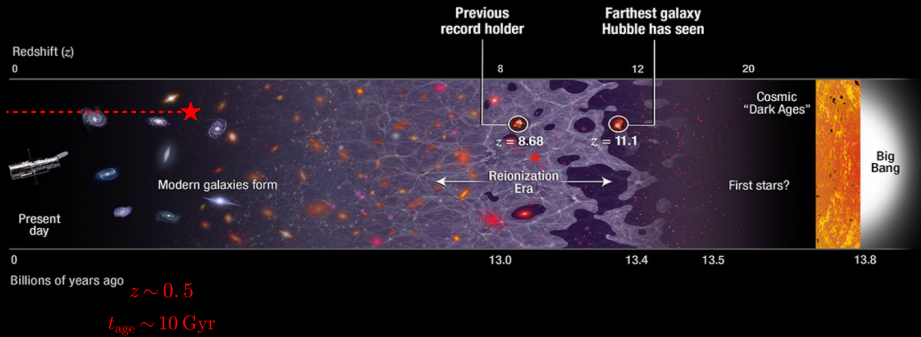
Gaikwad+2017a,b

84 HST-COS spectra (Danforth+2014)

Modeling and Statistical inference from $\text{Ly}\alpha$ forest in SPH simulations (Gaikwad+2017a,b)

No Photon Underproduction Crisis!

Galaxy escape fraction $< 0.08\%$



Ly α forest observations

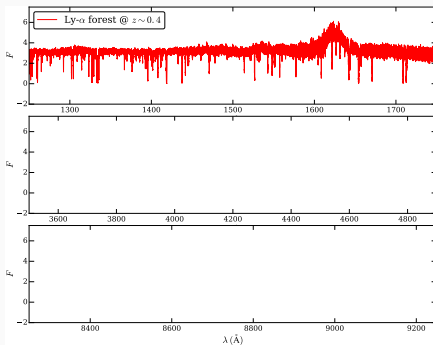
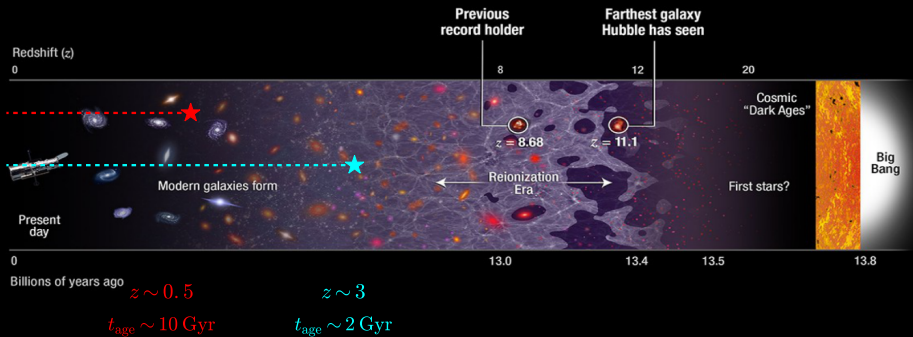
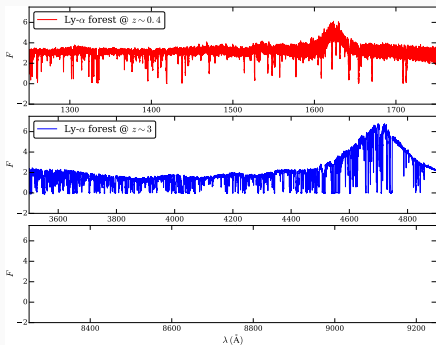


Photo-heating of IGM due to He II reionization

What is the thermal state of the IGM?



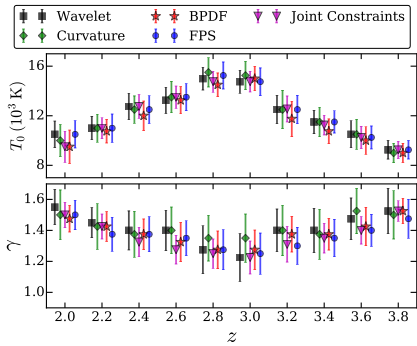
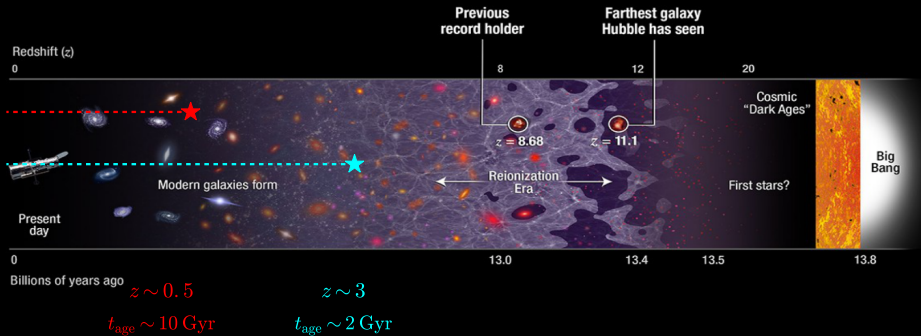
Ly α forest observations



Keck Telescope
Gaikwad+2021

104 Keck-HIRES spectra (Omeara+2017),

$$T = T_0 \Delta\gamma^{-1}$$



Keck Telescope

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

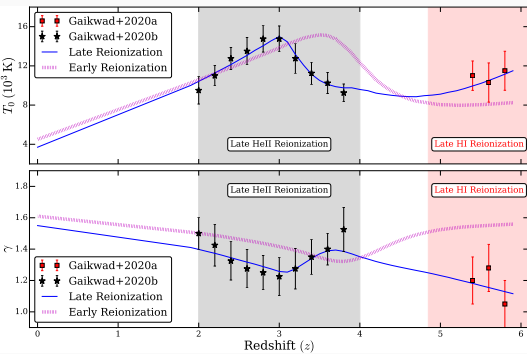
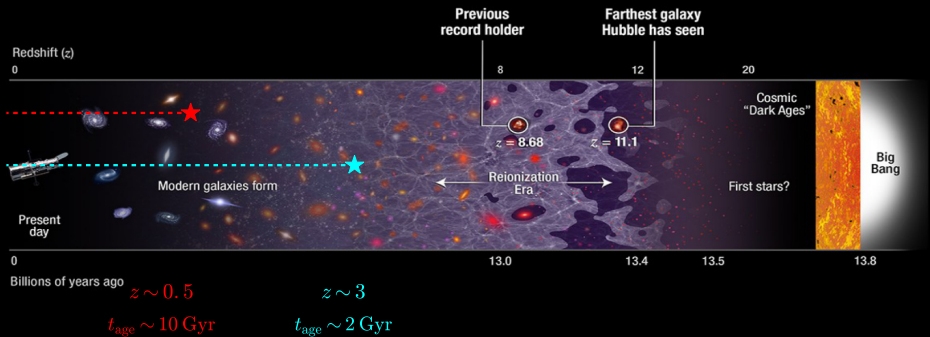
Gaikwad+2021

104 Keck-HIRES spectra (Omeara+2017),

$$T = T_0 \Delta\gamma^{-1}$$

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

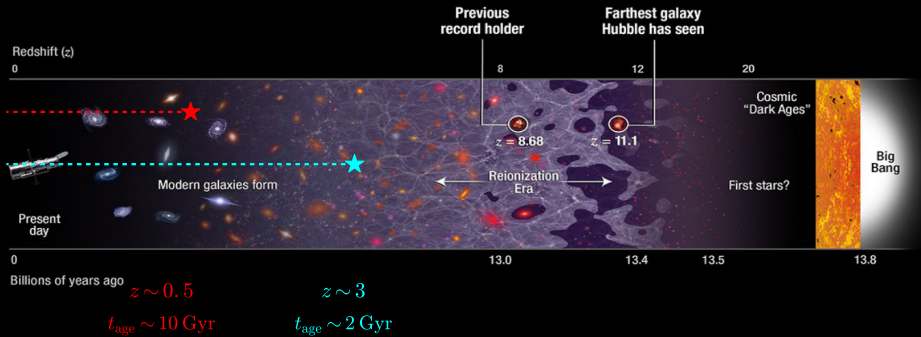
Most robust and consistent measurements of
thermal parameters



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 $\alpha \sim -1.8$

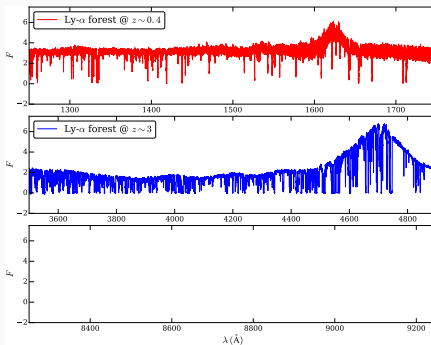
WDM mass constraints $> 4.1 \text{ keV}$
(Irsic+2024)

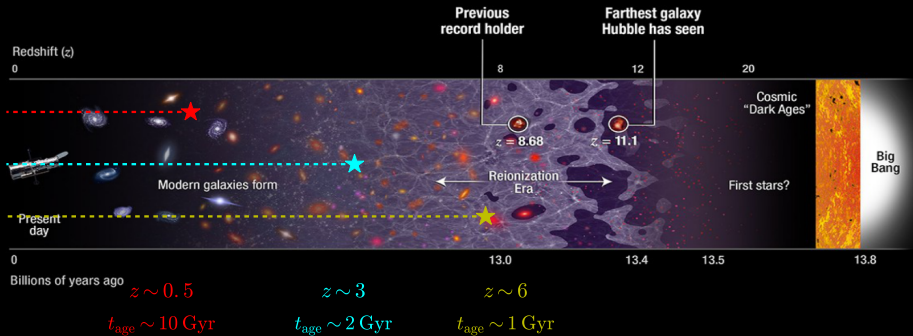


Ly α forest observations

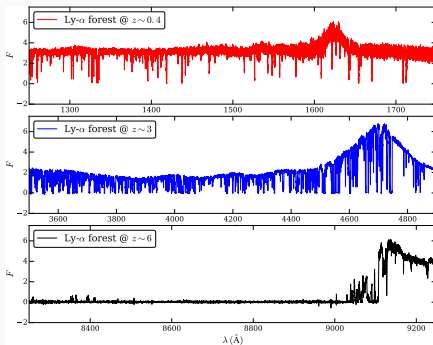
Ionization state of the IGM at $z > 5$

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





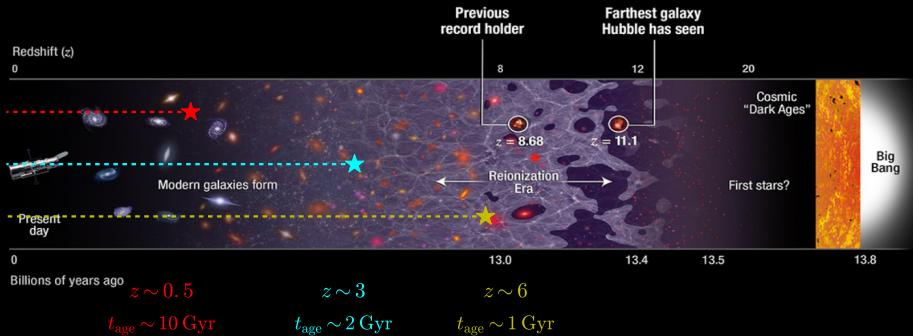
Ly α forest observations



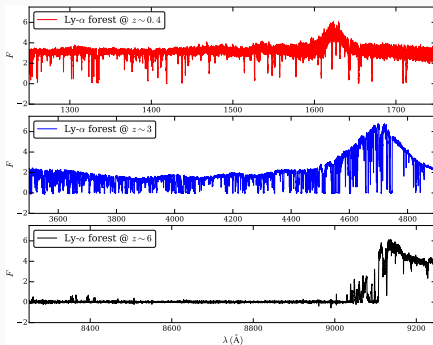
Very Large Telescope
Gaikwad+2023

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

60 VLT-XShooter spectra (D'odorico+2014)



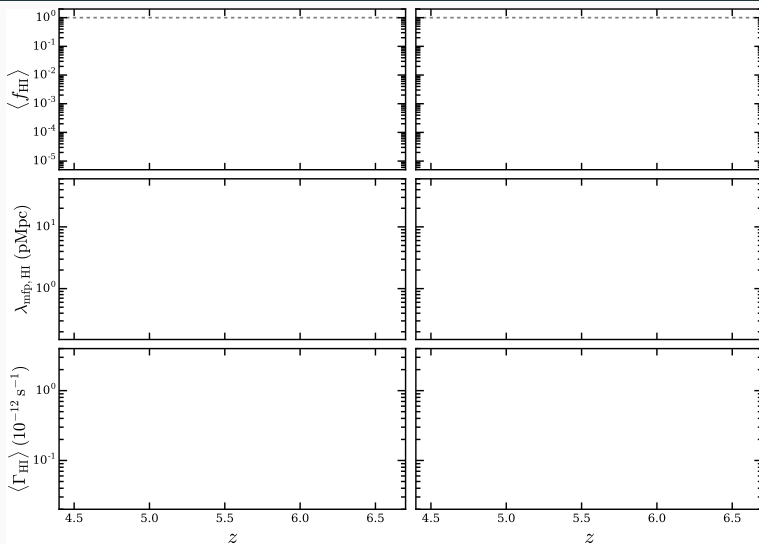
Ly α forest observations

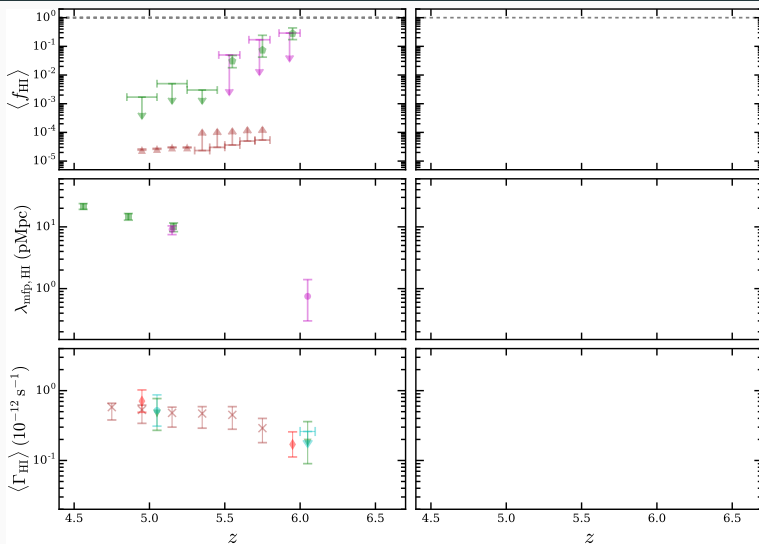


Very Large Telescope
Gaikwad+2023
 $t_{\text{age}} \sim 1 \text{ Gyr}$
60 VLT-XShooter spectra (D'odorico+2014)

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

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

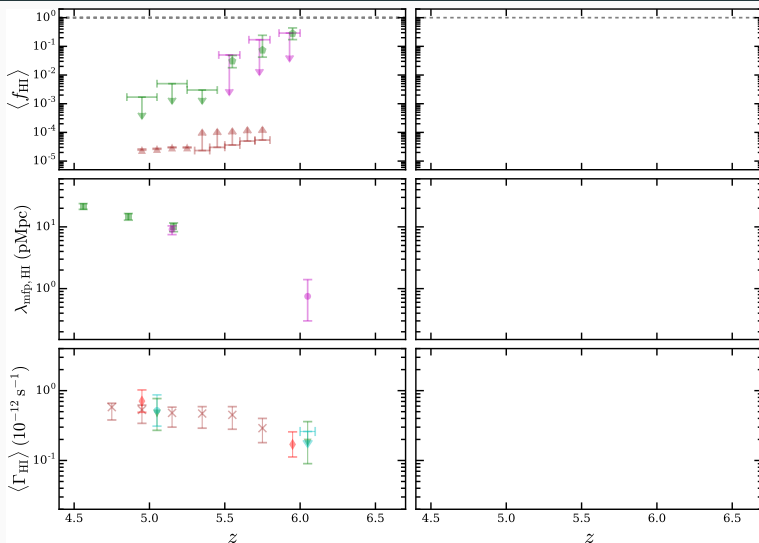




f_{HI} : [Mcgreer+2015](#), [Choudhury+2021](#), [Bosman+2022](#)

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

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

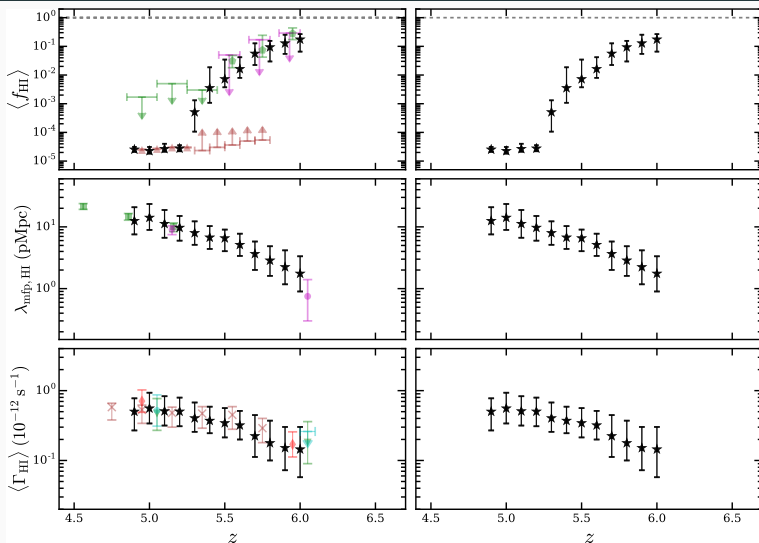


f_{HI} : Only limits on the amount of the neutral hydrogen

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

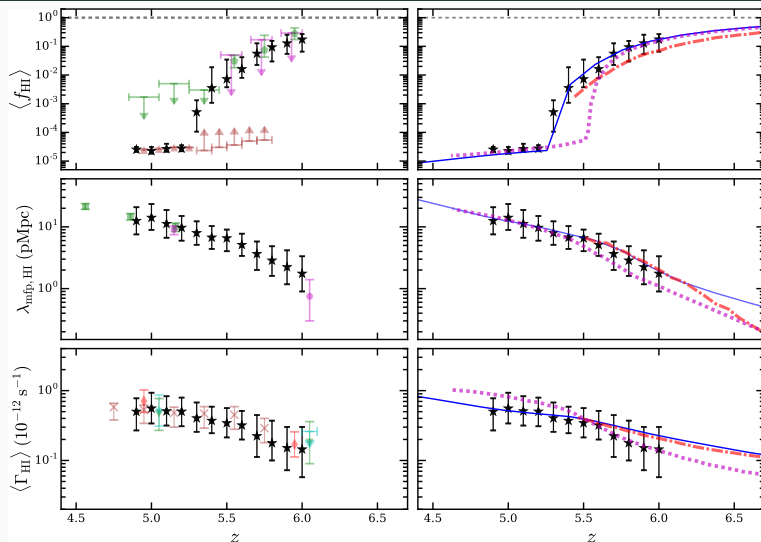
Γ_{HI} : Previous measurements did not account for patchy reionization

Comparison with previous constraints



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

Comparison with previous constraints

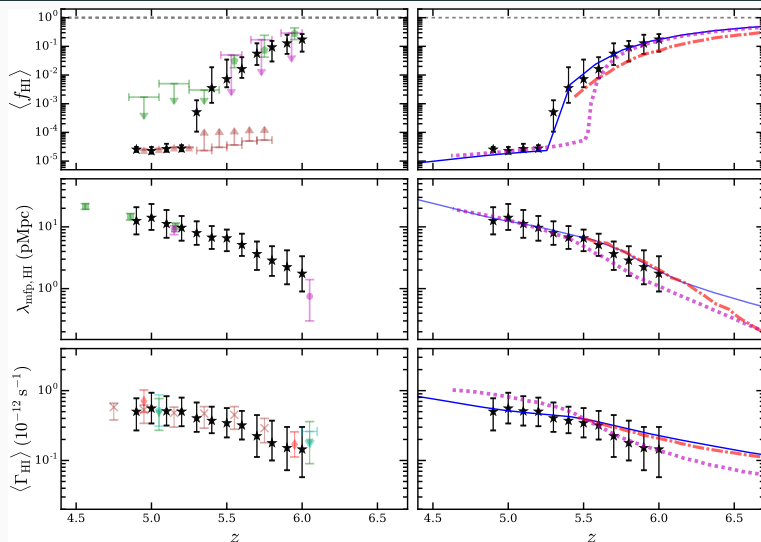


Comparison with radiative transfer models

Radiative Transfer Models (Time Evolution)

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

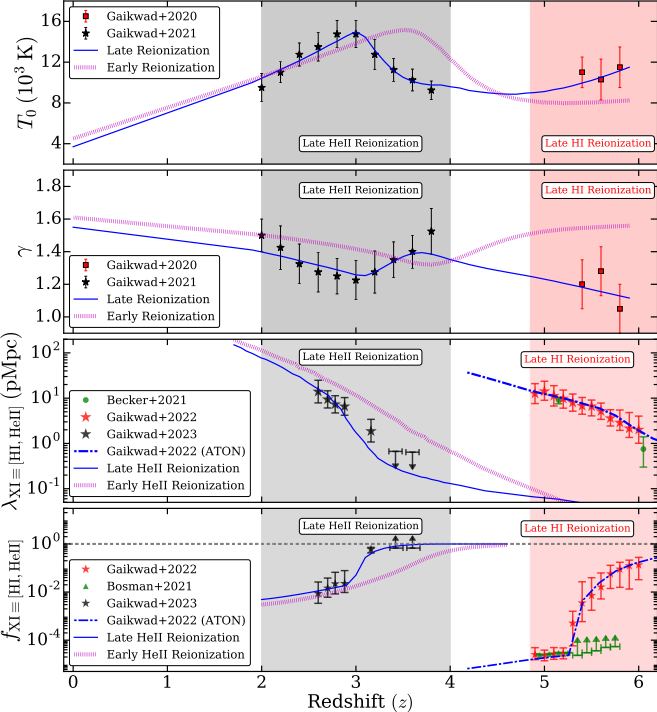
Comparison with previous constraints



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.

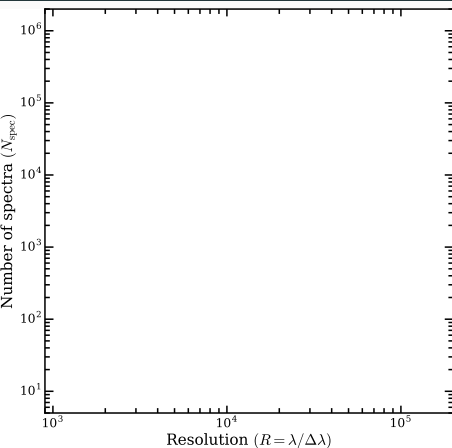


Thermal state of IGM

Ionization state of IGM

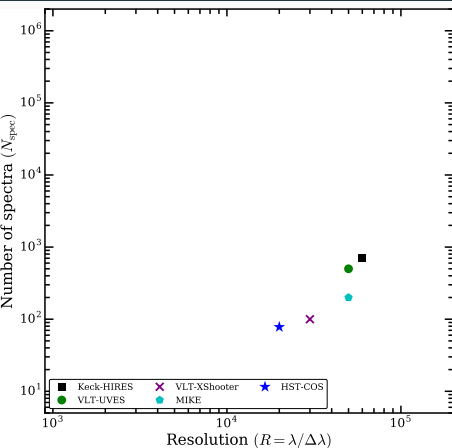
Future Work

Future Work (Observations)



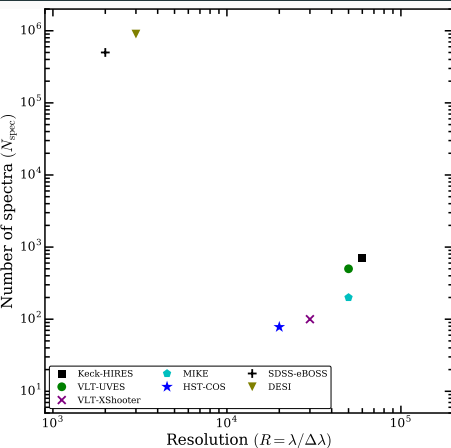
- $N_{\text{spec}} \Rightarrow$ Quantity of Spectra
- $R \Rightarrow$ Quality of spectra

Future Work (Observations)



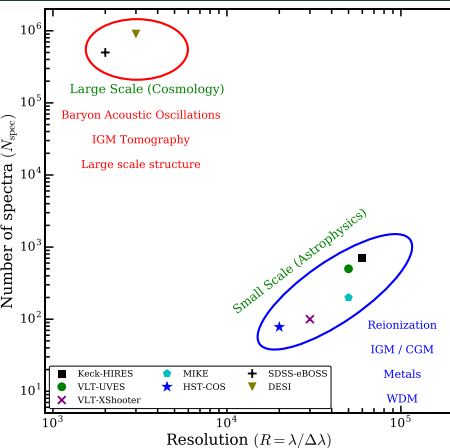
- $N_{\text{spec}} \Rightarrow$ Quantity of Spectra
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- High quality limited quantity
 - * Target based studies
 - * Echelle Spectroscopy
 - * Detailed information on small scales ($S/N > 10$)

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 - * Fibre Spectroscopy
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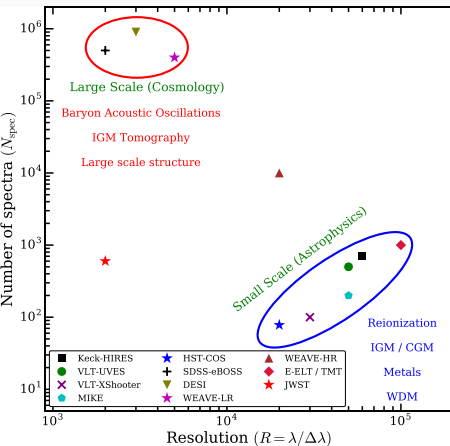
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- Cosmology : Large scale structures, BAO, IGM tomography, Nature of Dark Energy

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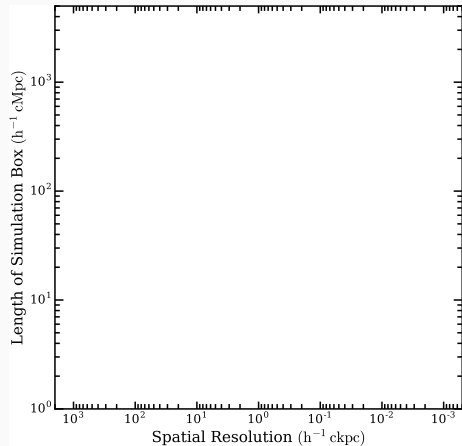


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- Astrophysics : Reionization, IGM / CGM, Metal distribution, Nature of Dark Matter
- Upcoming Facilities: 30m class telescopes, TMT, E-ELT ANDES
- Cosmology : Large scale structures, BAO, IGM tomography, Nature of Dark Energy
- Upcoming Surveys :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

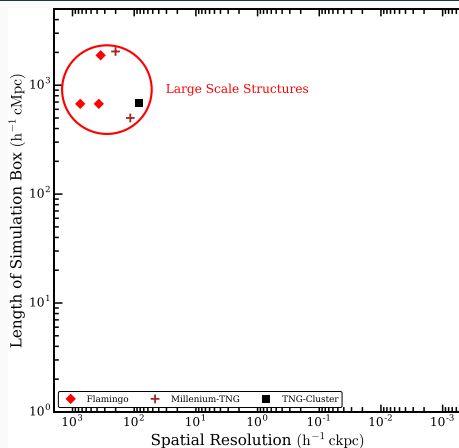
Future Work (Simulations)

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



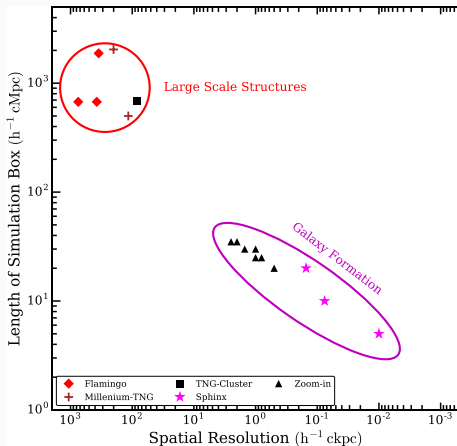
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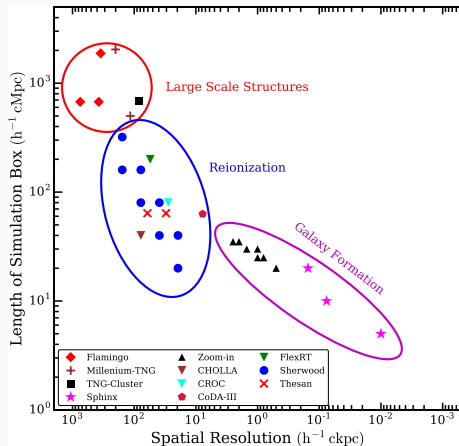
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 - * Very expensive few months per simulation



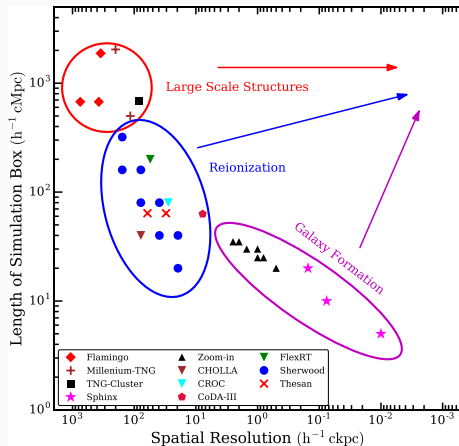
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Future Work (Simulations)

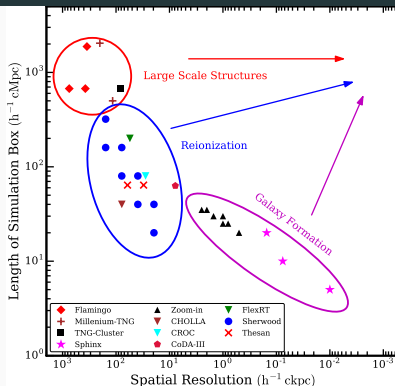
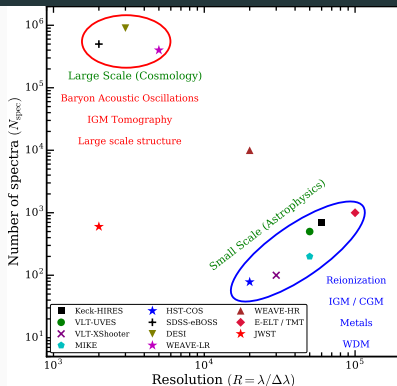
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- Goal of scientific community
 - * Efficient Algorithms / techniques
 - * GPU Acceleration
 - * Machine Learning techniques

Future Work

Observations



Simulations

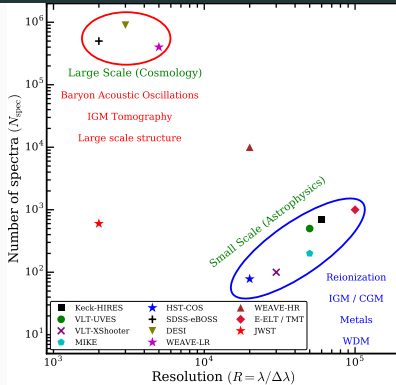
Observations:

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

Wealth of observational data is / will be available

Future Work

Observations

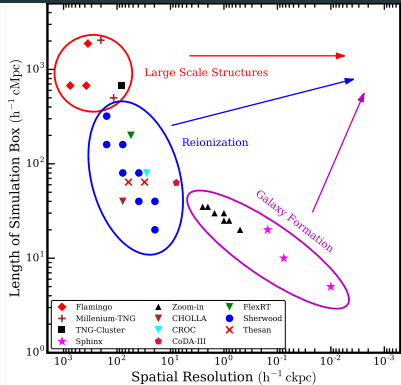


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Simulations:

- 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