

Insights on the IGM and Reionization from quasar absorption spectroscopy

Prakash Gaikwad

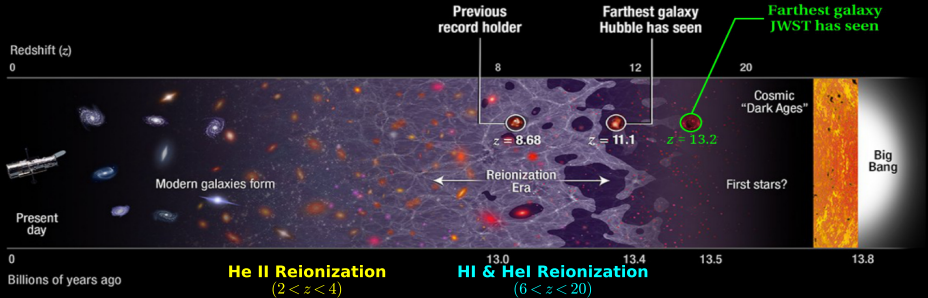
Nov, 2024

- What is the Intergalactic Medium (IGM)? Introduction
- Why the IGM is important? Motivation
- What are the main open problems in IGM? Reionization
- How do we study the IGM? Observations and Simulations
- What more can be learned from IGM? Future Work
- Summary

Introduction

What is the IGM?

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



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

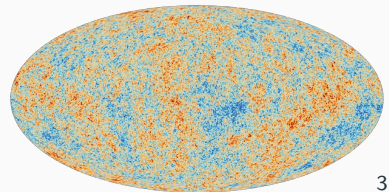
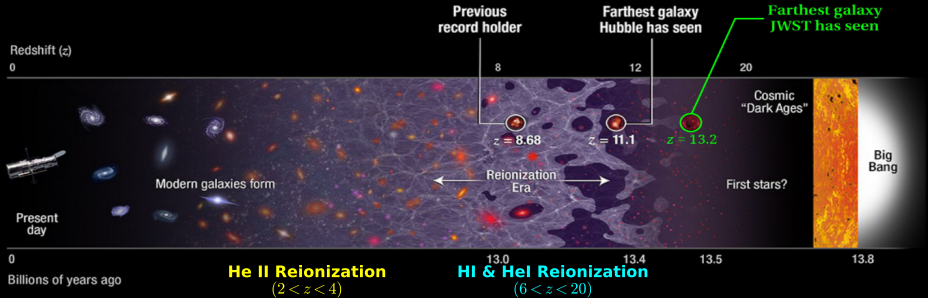
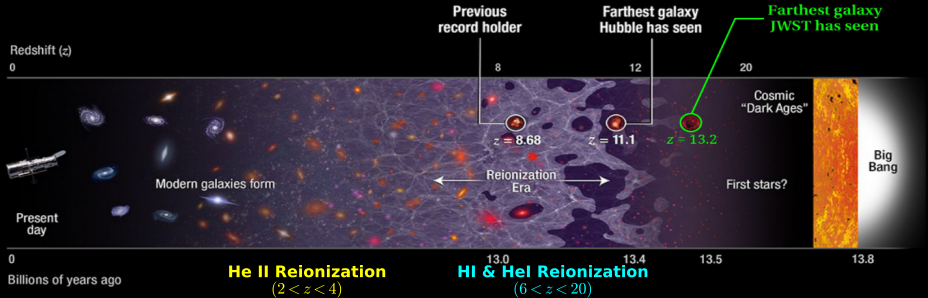


Image : NASA, ESA, P. Oesch, B. Robertson and A. Fei



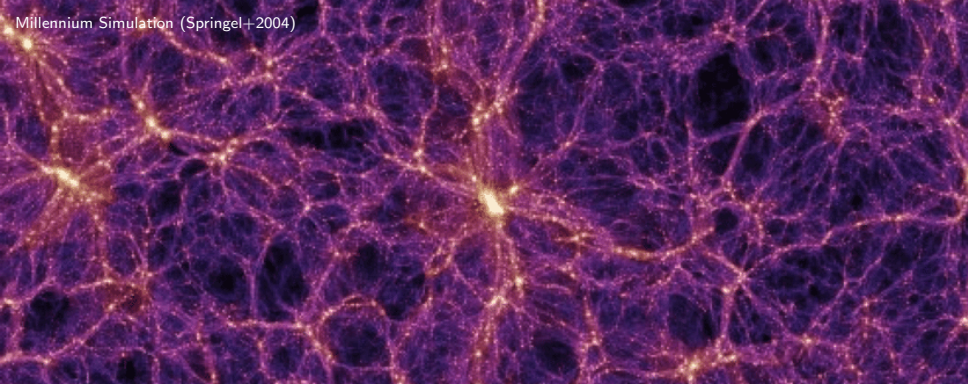
- Density fluctuations in the early universe ($z \sim 1100$, $t_{\text{age}} \sim 0.4 \text{ Myr} \sim 0.4 \times 10^6 \text{ yr}$)
- Overdense regions grow due to gravitational instability
- Collapsed structures: Formation of stars and Galaxies ($z < 20$, $t_{\text{age}} \sim 0.2 \text{ Gyr} \sim 0.2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

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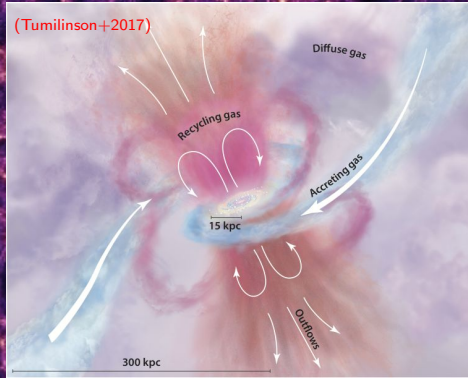


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- Intergalactic Medium: Diffuse gas that is not associated with collapsed objects
- IGM Features: (i) Large volume and (ii) Distinct filamentary structure

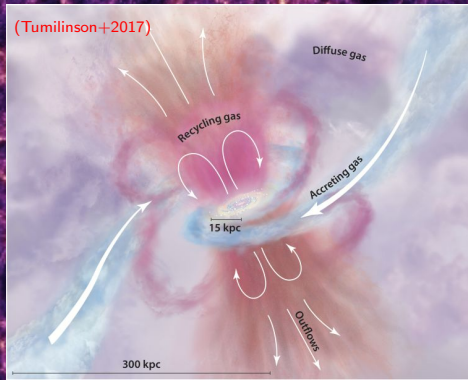
Millennium Simulation (Springel+2004)



- The cosmic web has imprints of cosmological initial conditions
- Galaxies during their life-time constantly interact with the IGM



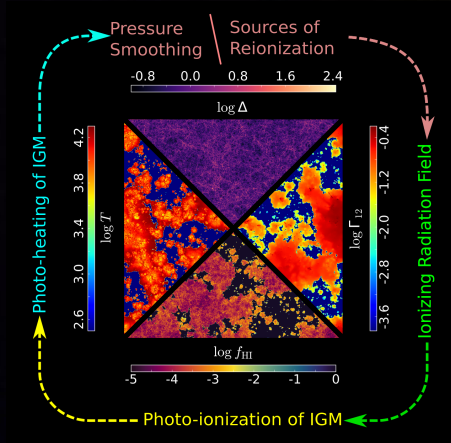
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- Inflow of pristine (H and He enriched) gas
- Outflow of non-pristine (recycled) gas



- The cosmic web has imprints of cosmological initial conditions
- Galaxies during their life-time constantly interact with the IGM
- Inflow of pristine (H and He enriched) gas
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- Radiation from Stars, Galaxies and AGN ionizes the IGM
- Rich information of Galaxy formation and Cosmological initial conditions

Open Problems in IGM (The big picture)

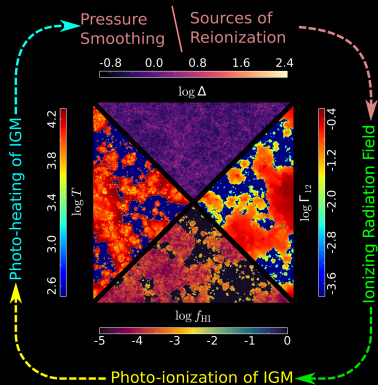
- Reionization:
 - When and How did reionization happen?
 - Nature of reionization? Morphology of reionization
- IGM - Galaxies connection:
 - Properties of early galaxies and AGN during reionization?
 - Feedback of reionization on galaxy formation?
- Cosmology :
 - Nature of dark matter and dark energy?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

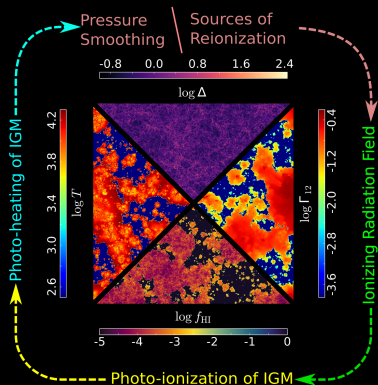
Why is reionization important?

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)

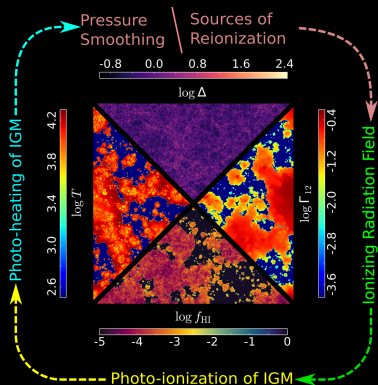


Small Scale Astrophysics

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

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Small Scale Astrophysics

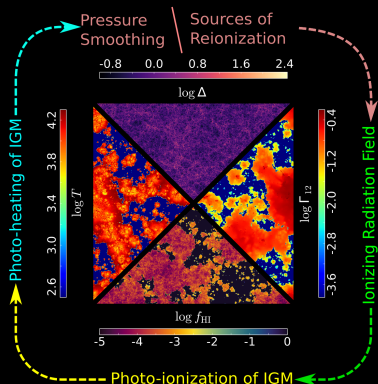
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Large Scale Structures

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

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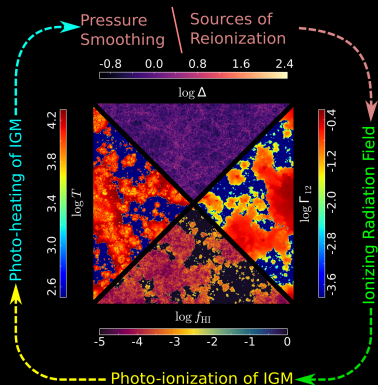
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Observational Challenges

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

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Modeling Challenges

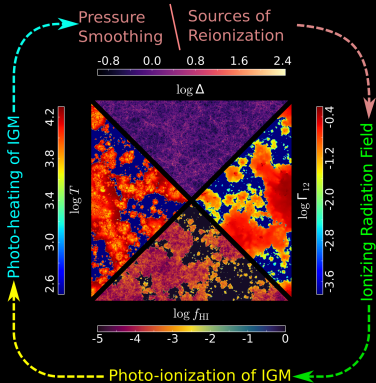
- Huge dynamic range of simulations
- Radiative Transfer Effects
- Galaxy formation sub-grid models

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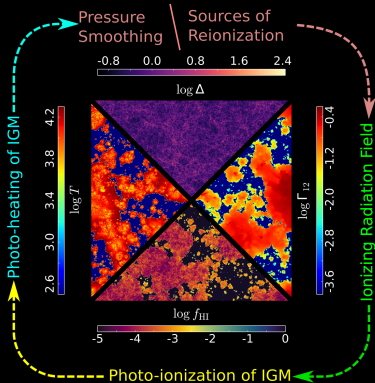
Observational Challenges

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The complexity of reionization makes it more interesting !

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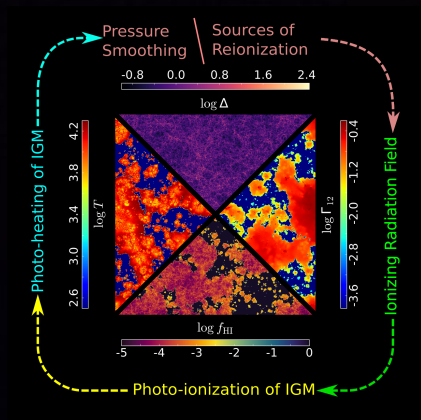
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Observational Challenges

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What are the main questions we want to answer about reionization?

Process of Reionization



Main questions

Sources of reionization?

Galaxies, Small or Large mass, f_{esc} ?

Nature of reionization?

Slow vs Rapid, Uniform vs Patchy

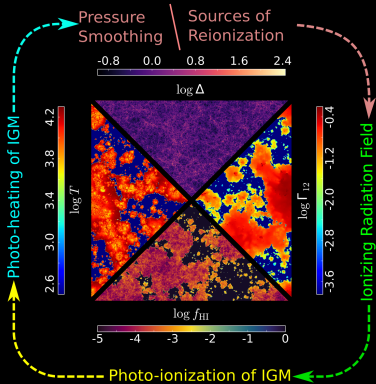
Timing of reionization?

Early vs Late reionization

Effects of reionization?

Feedback on Galaxy formation

Process of Reionization



Main questions

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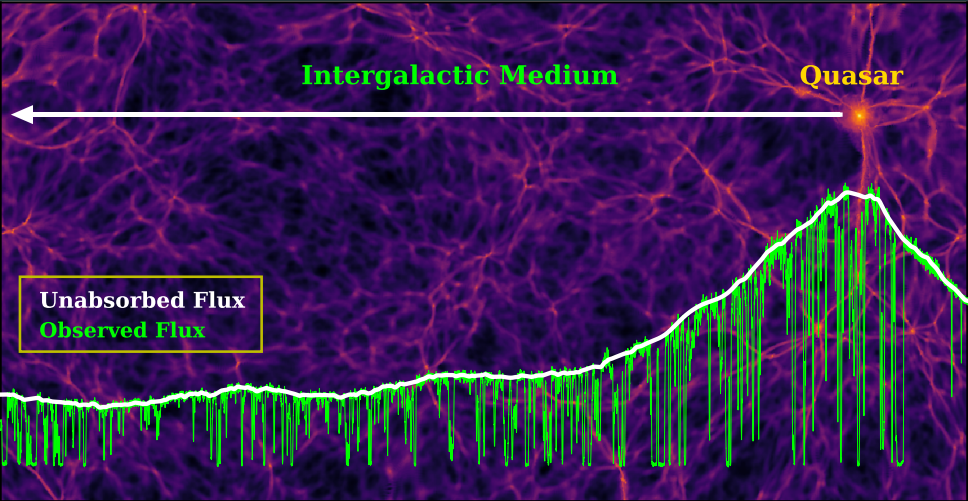
Feedback on Galaxy formation

Quasar Absorption Spectra $\Rightarrow$ Observations + Simulations

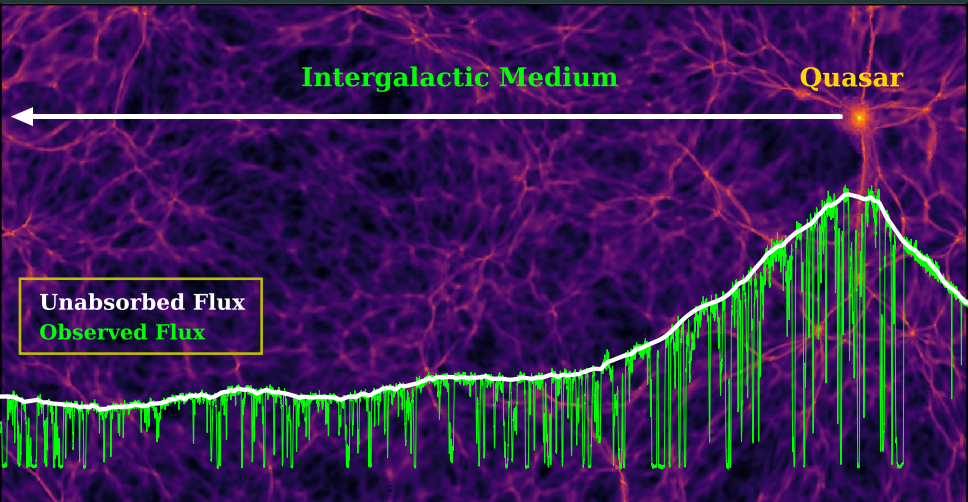
This talk $\Rightarrow$ Nature and Timing of H I Reionization

Introduction

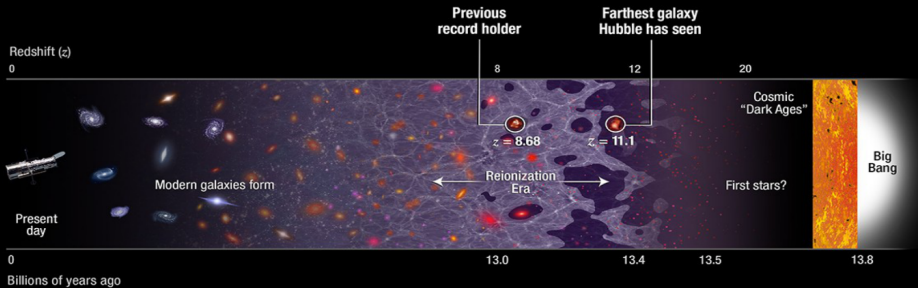
How can we observationally probe IGM?



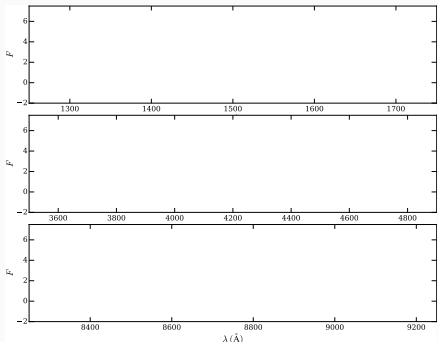
- The spectrum of distant bright objects (quasar) in the universe
- The set of absorption features are produced by IGM between us and the source



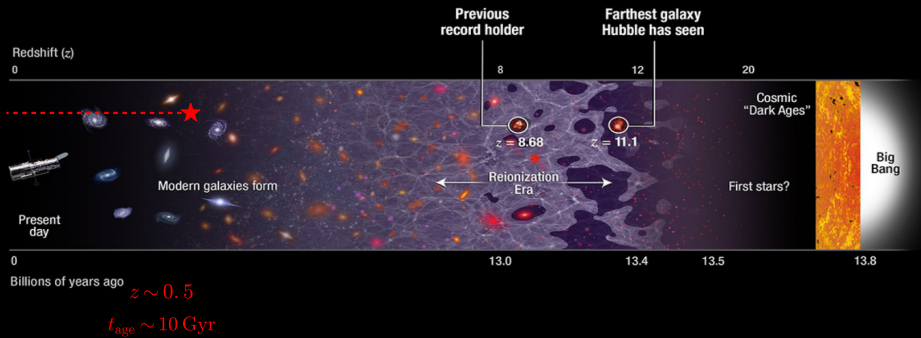
- The set of characteristic absorption features are collectively known as $\text{Ly}\alpha$ forest
- Main focus of this talk $\Rightarrow$ Observations + Simulations of Quasar Absorption Spectra
- Why is the quasar absorption spectroscopy important?



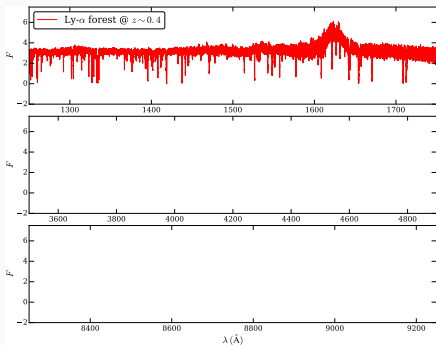
$\text{Ly}\alpha$ forest observations



How can Quasar absorption spectroscopy be used to study the history of our universe?

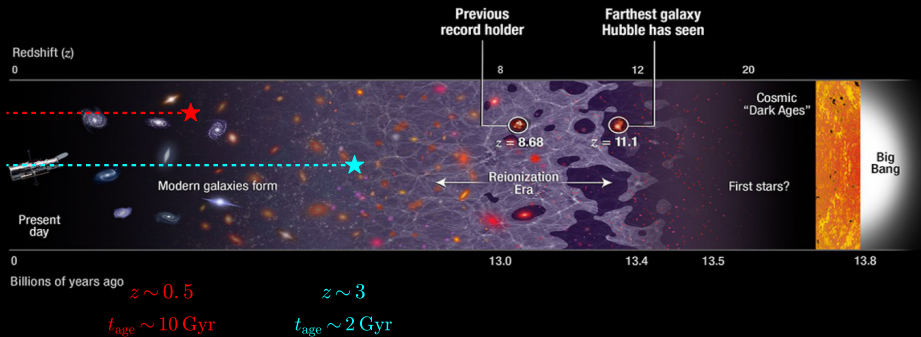
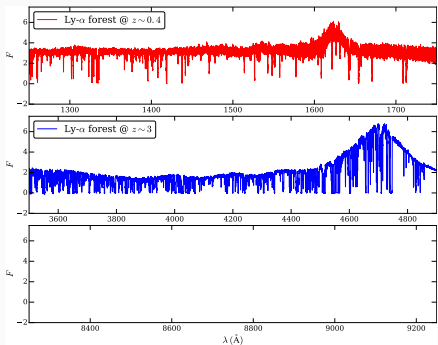


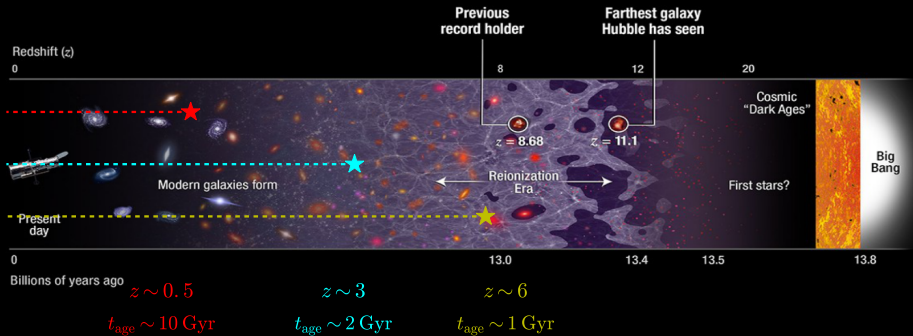
Ly α forest observations



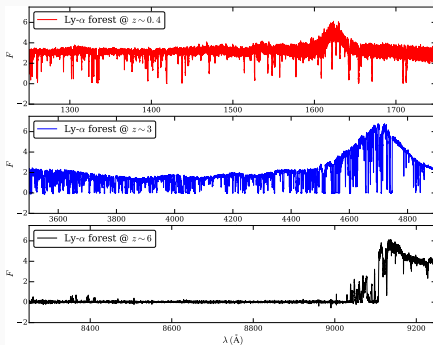
$t_{\text{age}} \sim 10 \text{ Gyr}$

Hubble Telescope
Gaikwad+2017a,b

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



Ly α forest observations



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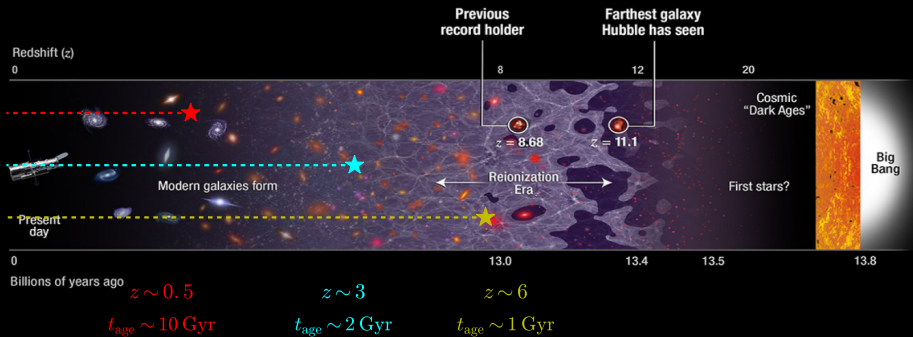
Hubble Telescope
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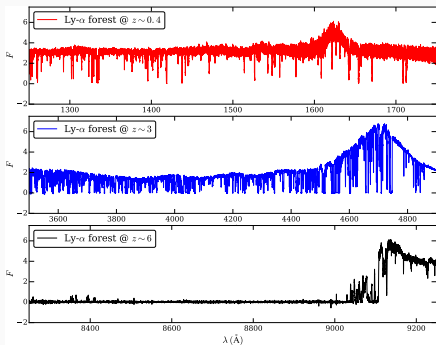
Keck Telescope
Gaikwad+2021

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

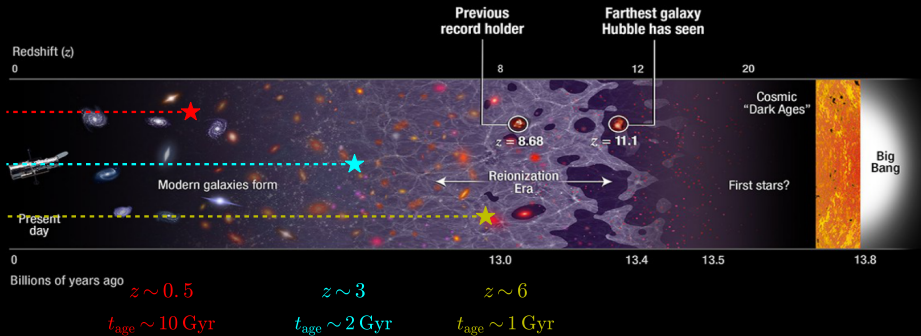
Magellan Telescope
Gaikwad+2020,23



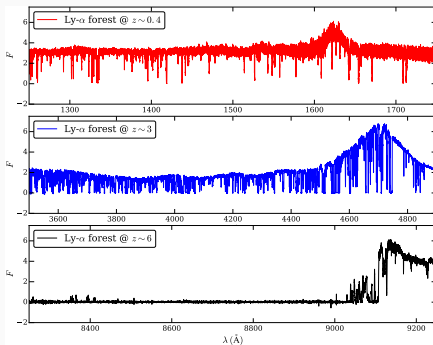
Ly α forest observations



Quasar absorption spectroscopy can be used to study the history of universe in the distant past.

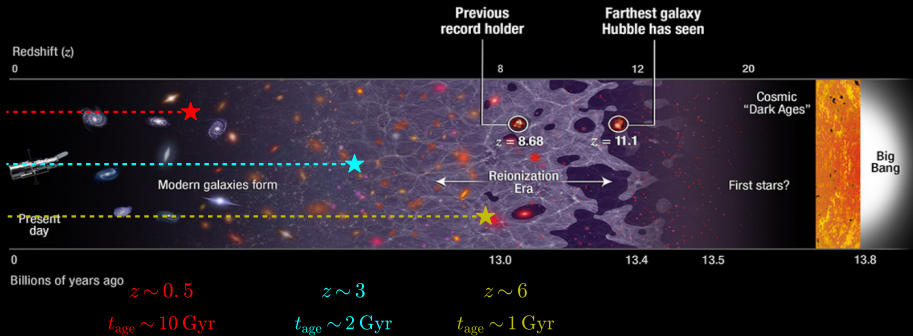


Ly α forest observations

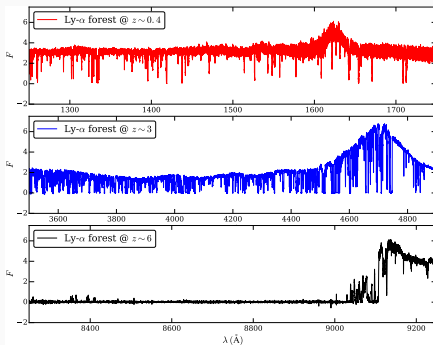


Quasar absorption spectroscopy can be used to study the history of universe in the distant past.

Suitable for studying both cosmology and astrophysics



Ly α forest observations



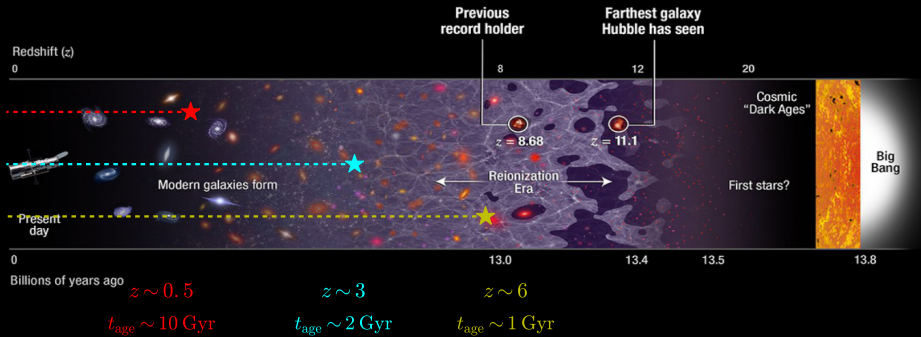
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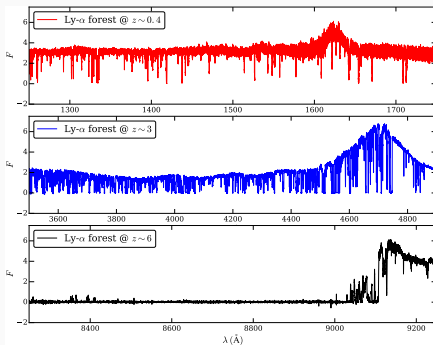
Astrophysics: Reionization, Matter around Galaxies

Cosmology: Cosmological parameters,

Constraints on nature of dark matter

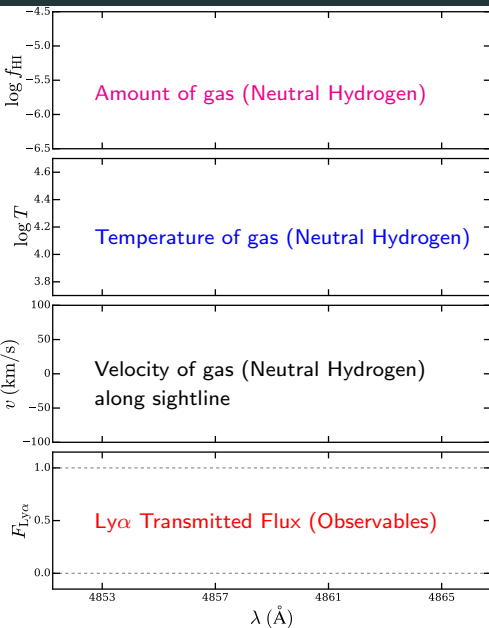


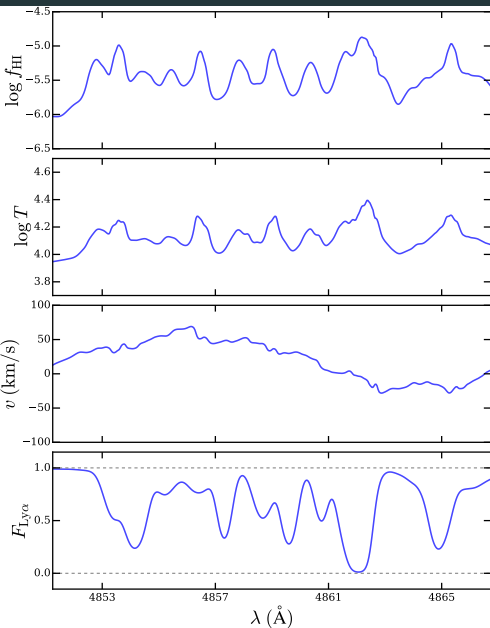
Ly α forest observations



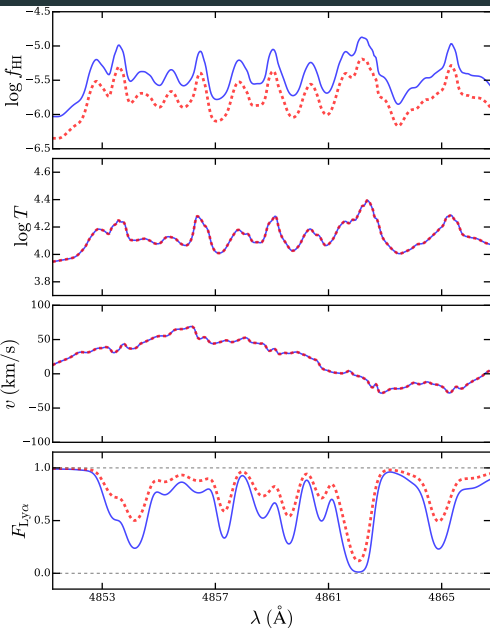
Quasar absorption spectroscopy can be used to study the history of universe in the distant past.

Quasar absorption spectra traces Physical conditions of the IGM: How?

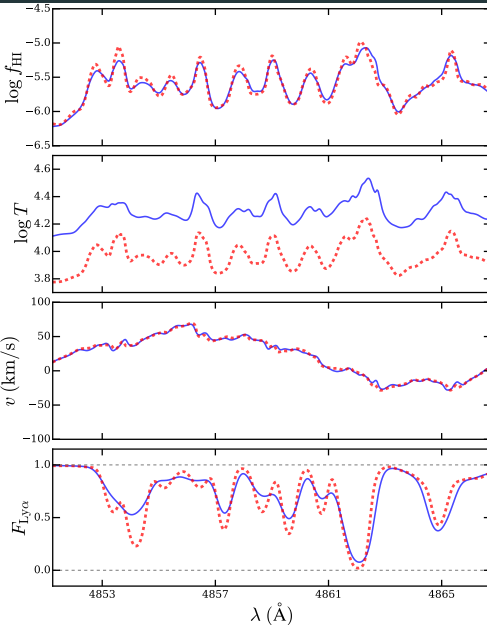




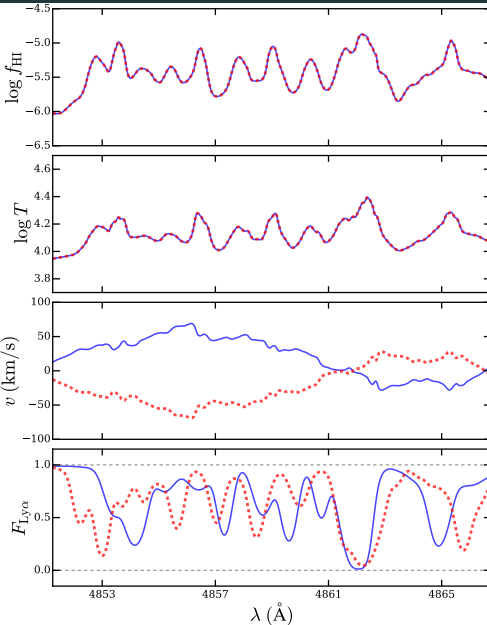
- Absorption occurs in region with where amount of neutral hydrogen is large



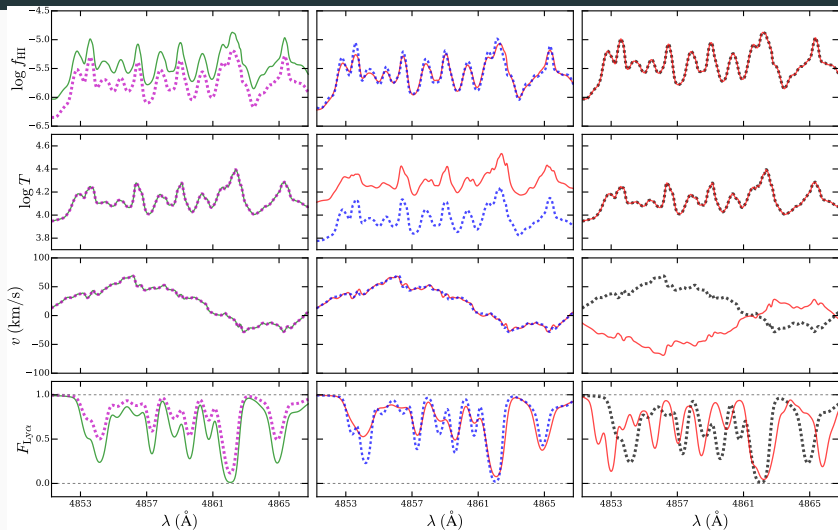
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- With the decrease in temperature, width of the absorption line changes due to doppler broadening
 $T \sim 10^4 \text{ K} \Rightarrow b \sim 12.8 \text{ km/s}$



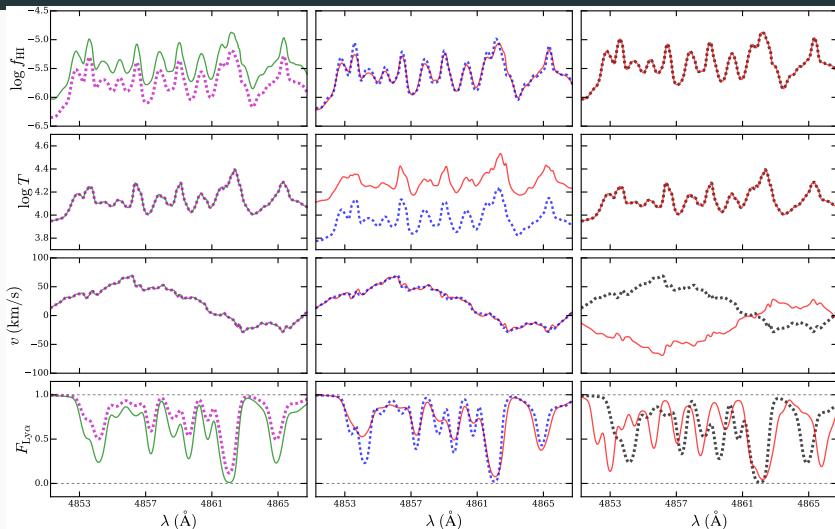
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- Velocity (Bulk) field produce a systematic shift in absorption profiles and small change in shape of the absorption profiles



Depth of absorption lines

Width of absorption lines

Location of absorption lines



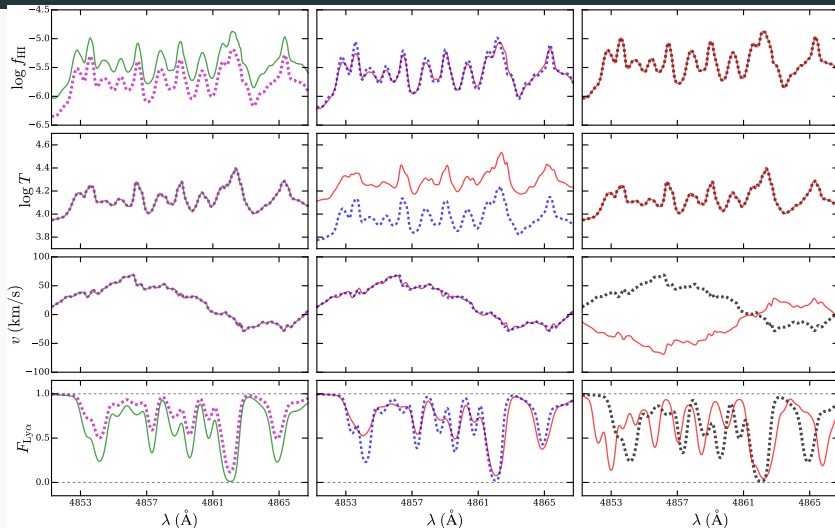
Depth of absorption lines

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

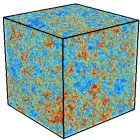
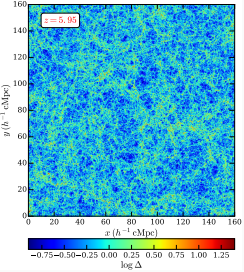
Photo-ionization rate

Temperature of IGM

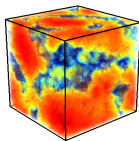
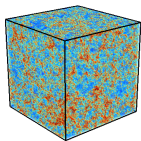
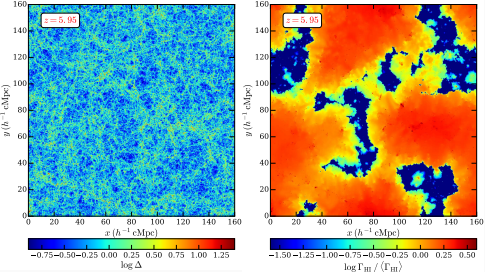
Mean Free Path

Free streaming length of WDM

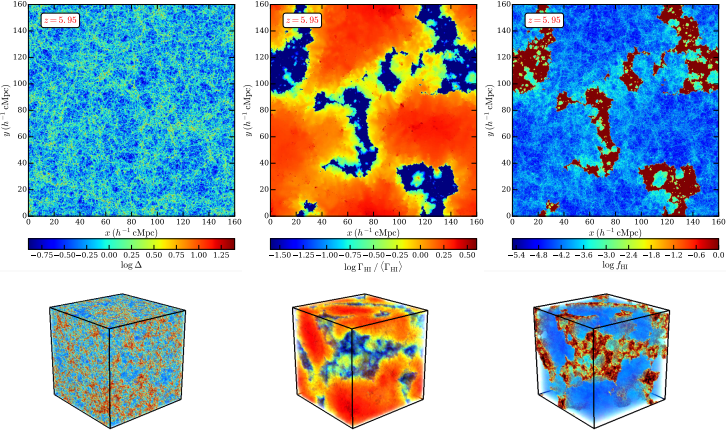
Simulations



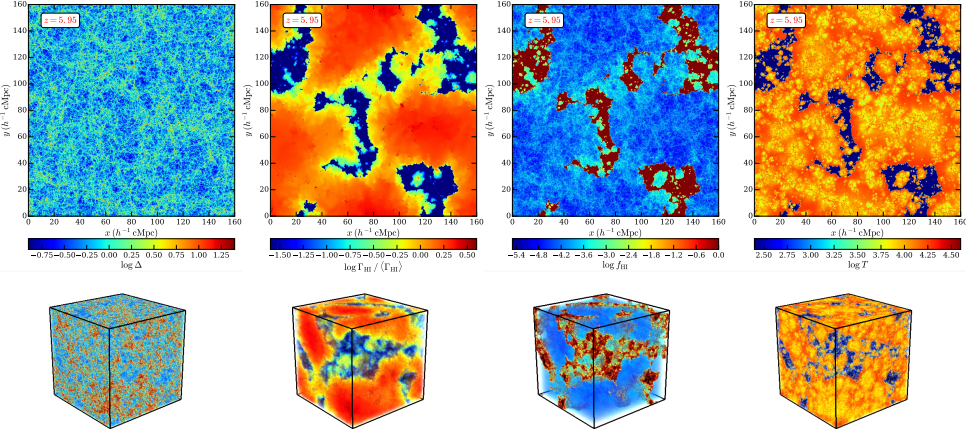
- Perform cosmological hydrodynamical simulation (Formation of Galaxies)



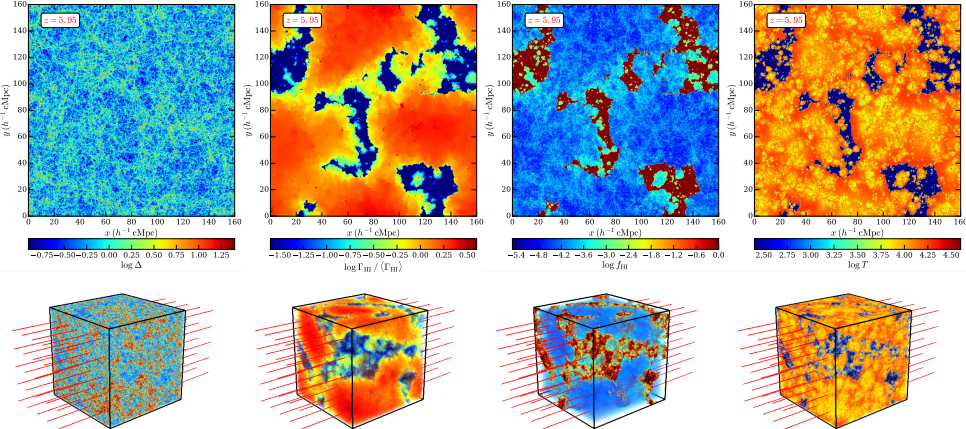
- Perform cosmological hydrodynamical simulation (Formation of Galaxies)
- Solve radiative transfer equation (Radiation propagation from Galaxies)



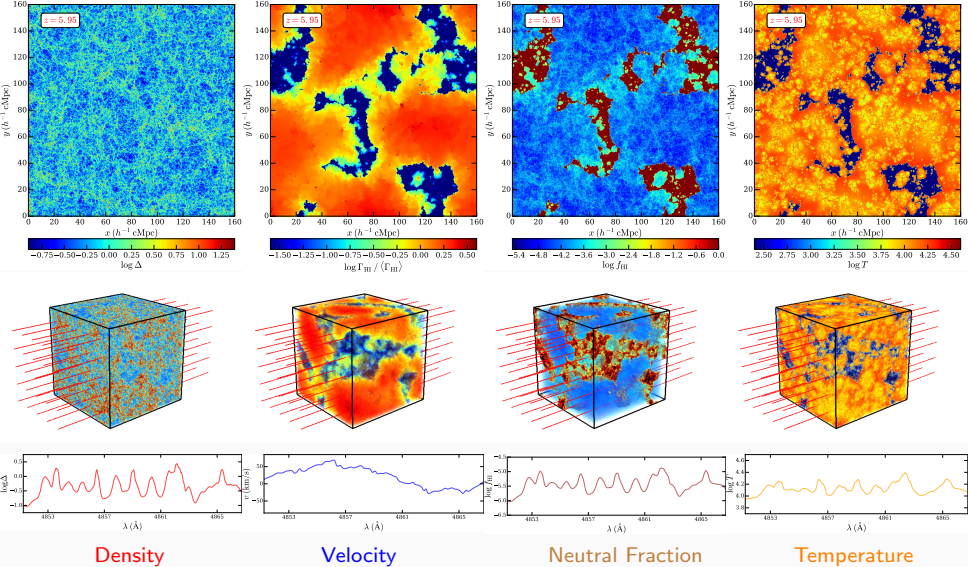
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- Solve radiative transfer equation (Radiation propagation from Galaxies)
- Solve chemical evolution Equation (Reionization of IGM)



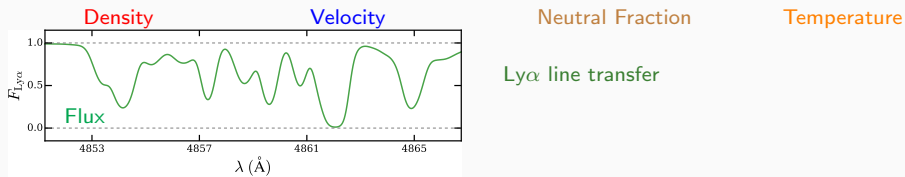
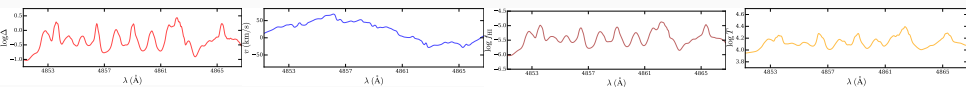
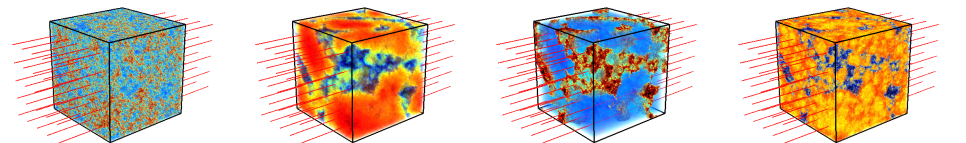
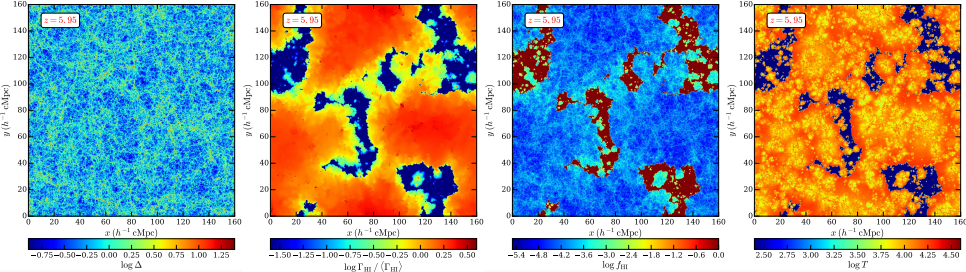
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- Solve radiative transfer equation (Radiation propagation from Galaxies)
- Solve chemical evolution Equation (Reionization of IGM)
- Solve temperature evolution Equation. (Photo-heating of IGM)

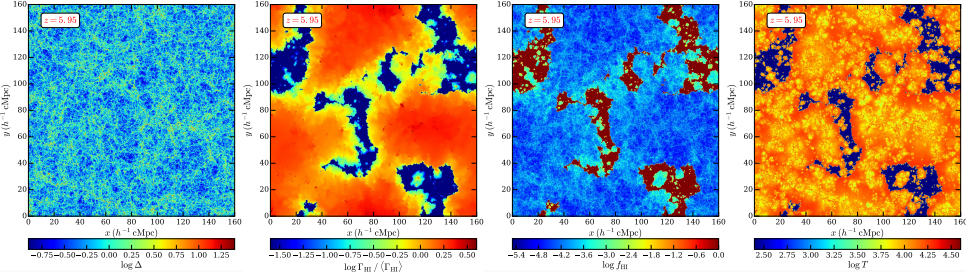


- Perform cosmological hydrodynamical simulation (Formation of Galaxies)
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- Randomly shoot sightlines to extract fields that probes different large scale structures.



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



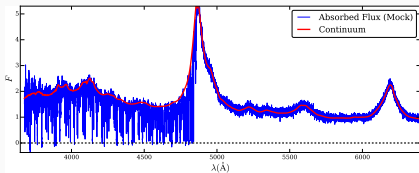


Fluid + Gravity

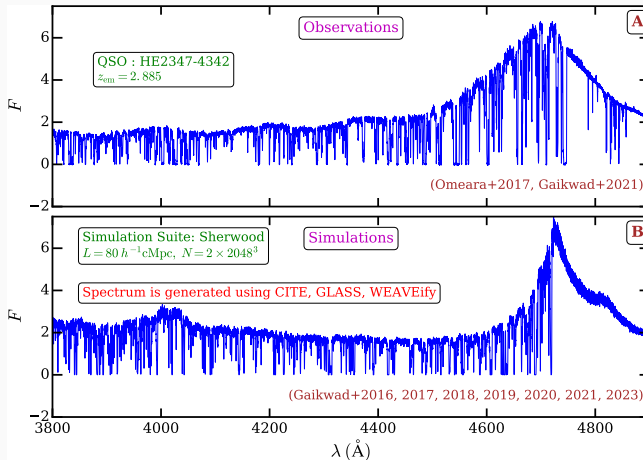
Radiative Transfer

Ionization Evolution

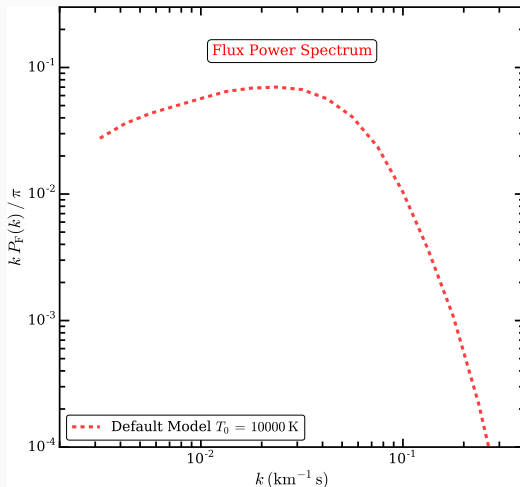
Temperature Evolution



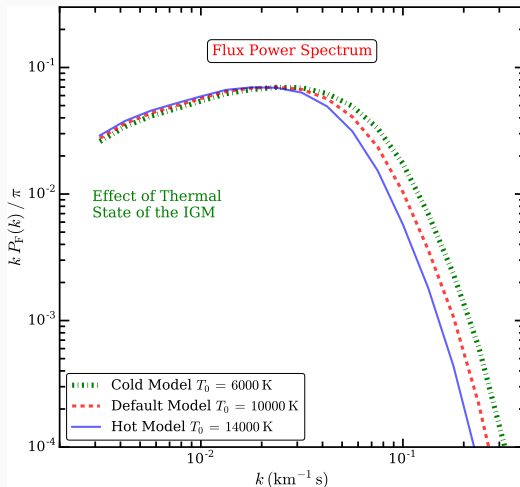
WEAVEIFY: To mimic observational properties



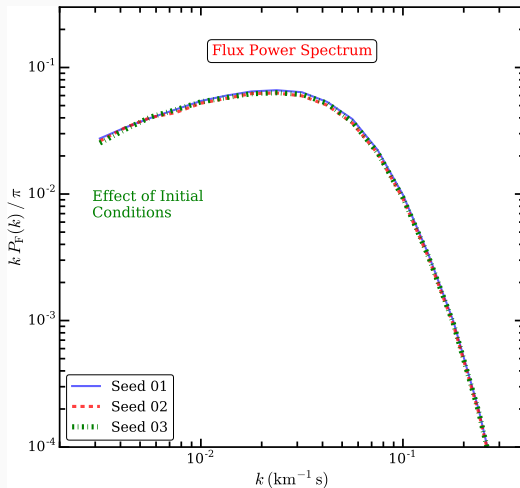
- One can not compare simulated spectra with observed spectra directly.
- Need to extract information from observation and simulation for comparison
- Our statistics should depend on only parameters of our interest and not on initial conditions.
- Fourier analysis of the flux field: Flux Power Spectrum



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



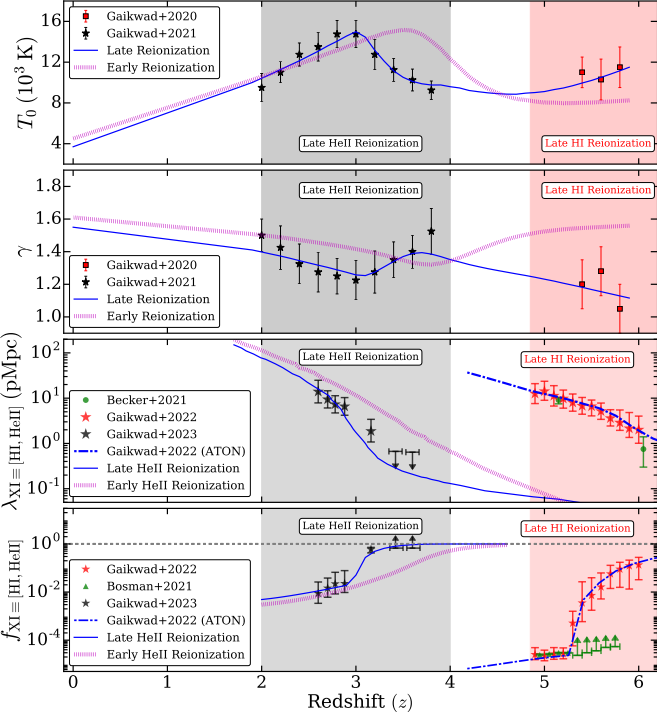
- $k = 2\pi/\nu$, Small $k \Rightarrow$ Large Scales, Large $k \Rightarrow$ Small Scales
- Flux PS is similar even if initial conditions are different
- All other parameters kept same. Flux Power Spectrum can be used to measure temperature

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 $\mathcal{L}$)



Thermal state of IGM

Ionization state of IGM

Implication for Cosmology

Thermal relics warm dark matter

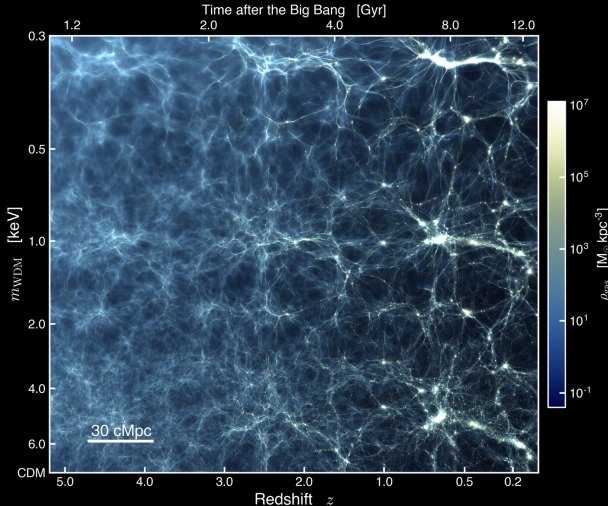
- Cold Dark Matter is successful in reproducing most of the observations
- Some of the predictions of CDM are not consistent with observations
- For example, missing satellite problem, Cusp vs core problem

Thermal relics warm dark matter

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- For example, missing satellite problem, Cusp vs core problem
- Alternative hypothesis : May be the dark matter is not that cold
- Thermal relic warm dark matter (few KeV, from particle physics)
- What is the signature of thermal Warm dark matter?

Thermal relics warm dark matter

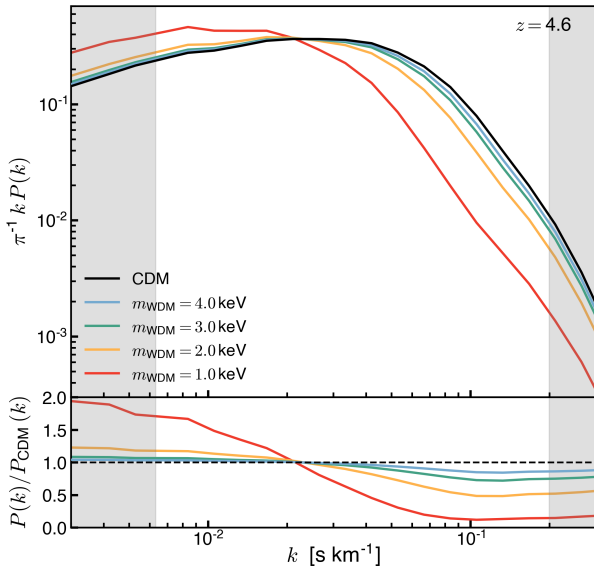
(Viel+2005)



$\lambda_{\text{FS}} \approx (0.95 \text{ Mpc}) \left(\frac{1 \text{ keV}}{m_{\text{wdm}}} \right)$, λ_{FS} is free streaming length below which structures are smoothed

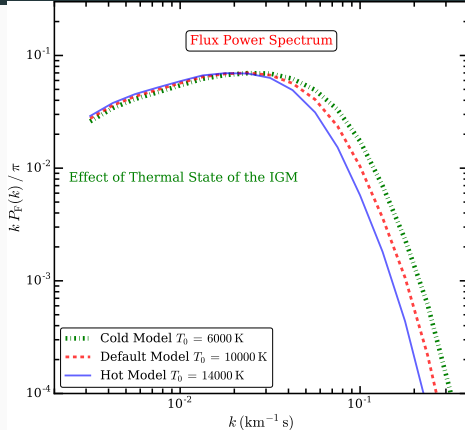
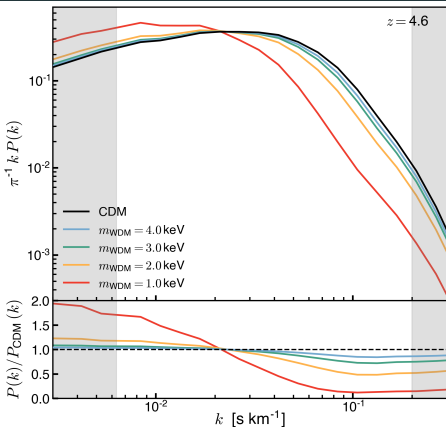
- Warm dark matter suppresses small scale fluctuations in density (Villasenor+2022)

Thermal relics warm dark matter



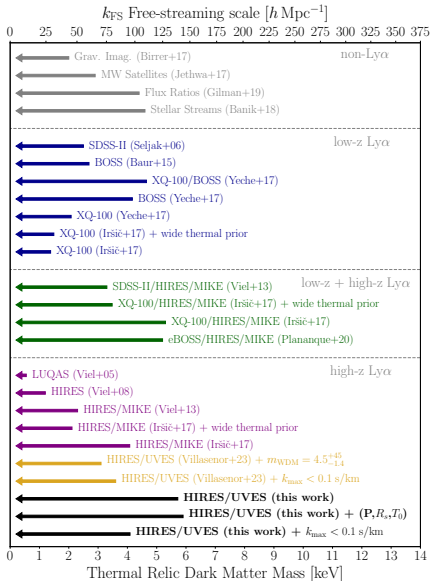
- Warm dark matter mass can be constrained from Ly α forest (Villasenor+2022,Irsic+2023)

Thermal relics warm dark matter



- The same effect can also be produced by temperature of IGM
- For realistic constraints on mass of warm dark matter, one need to marginalize the uncertainty stemming from thermal state of the IGM
- Thus our IGM temperature measurements become important when one wants to constrain mass of warm dark matter from $\text{Ly}\alpha$ forest data.

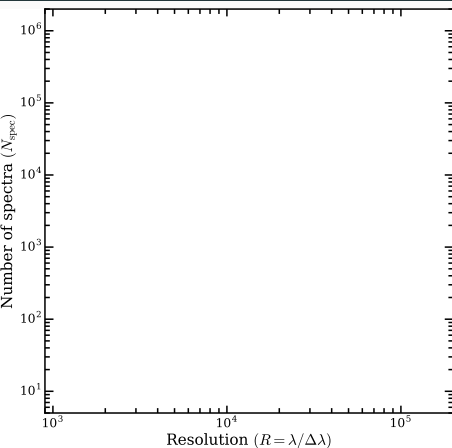
Thermal relics warm dark matter



- Constraints on mass of warm dark matter particle (Irsic+2023, including PG)
- Arrows indicate 2σ exclusion limit on the mass of WDM in keV
- **Ly α forest provides better constraints than non- $\text{Ly}\alpha$ forest probes**
- Thermal parameter measurements help to get better constraints on mass of WDM
- Patchy reionization, resolution correction and T_0 prior

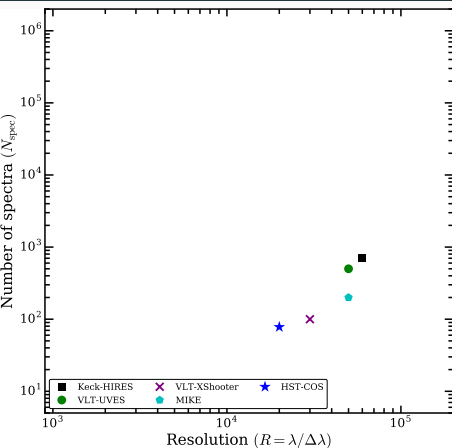
Future Work

Future Work (Observations)



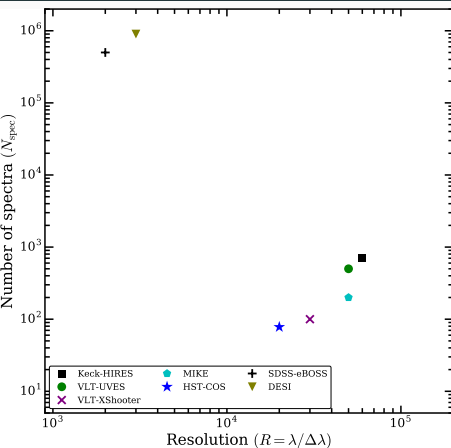
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- $R \Rightarrow$ Quality of spectra

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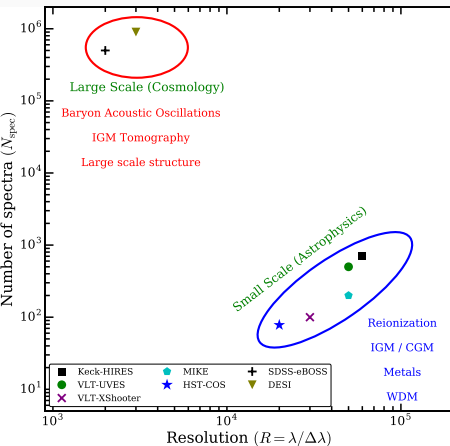
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 - * Target based studies
 - * Echelle Spectroscopy
 - * Detailed information on small scales ($S/N > 10$)

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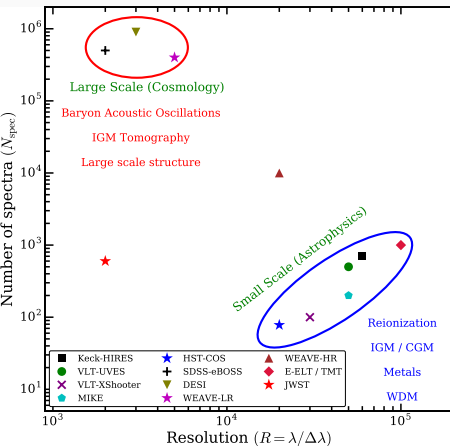
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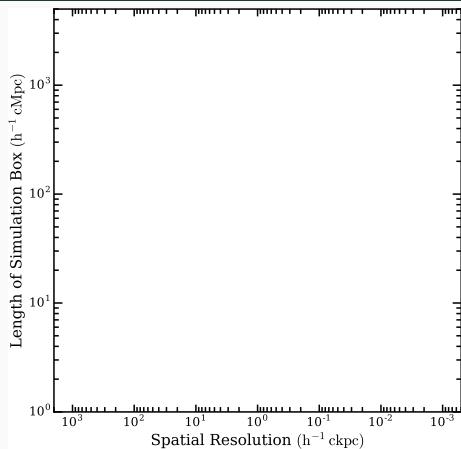


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- Astrophysics : Reionization, IGM / CGM, Metal distribution, Nature of Dark Matter
- Upcoming Facilities: 30m class telescopes, TMT, E-ELT ANDES
- Cosmology : Large scale structures, BAO, IGM tomography, Nature of Dark Energy
- Upcoming Surveys :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

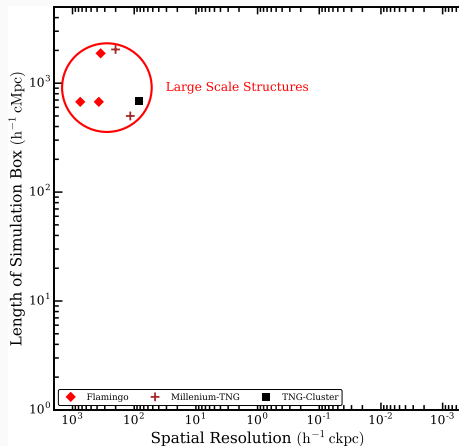
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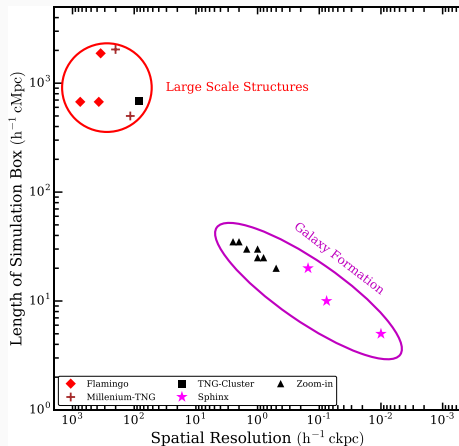
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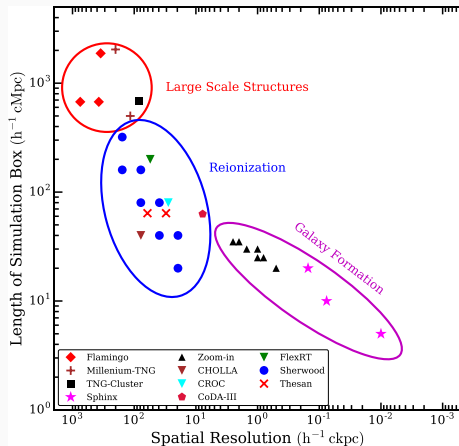
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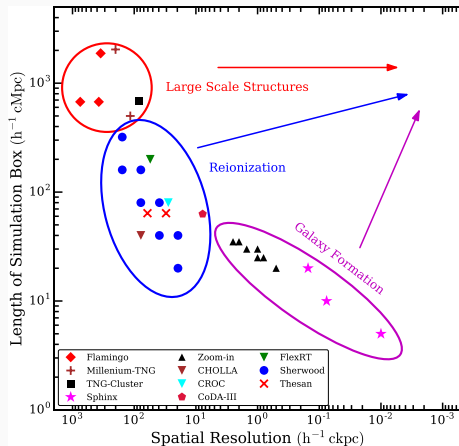
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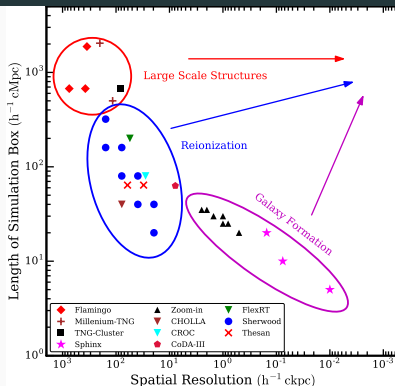
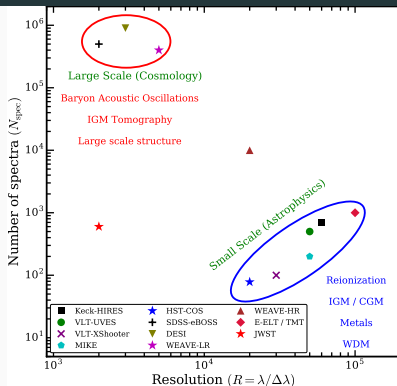
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- Goal of scientific community
 - * Efficient Algorithms / techniques
 - * GPU Acceleration
 - * Machine Learning techniques

Future Work

Observations



Simulations

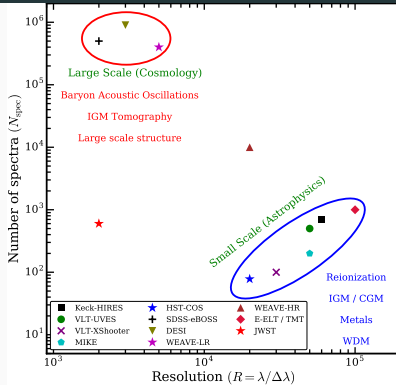
Observations:

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

Wealth of observational data is / will be available

Future Work

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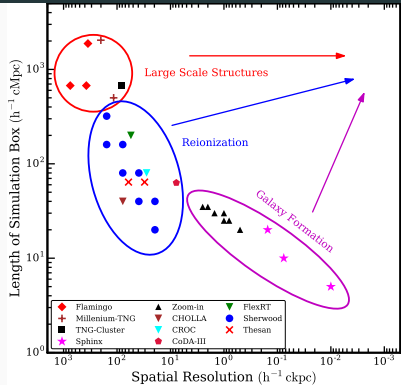


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Simulations:

- 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