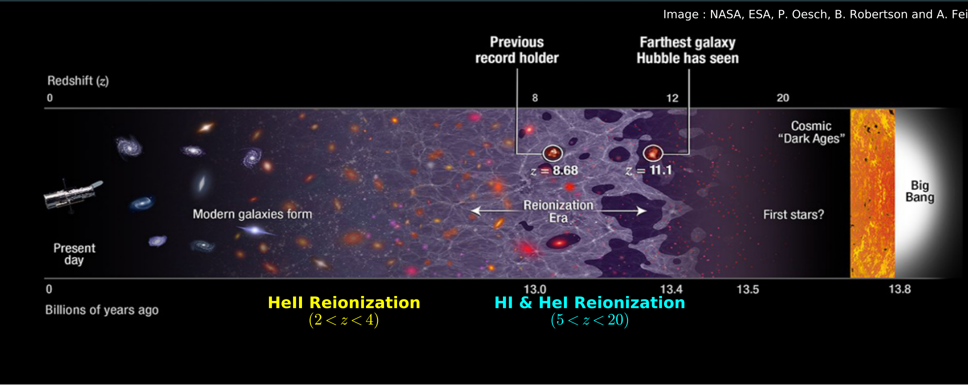
Physics of the Intergalactic Medium

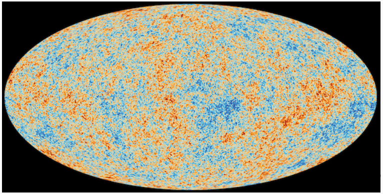
Prakash Gaikwad

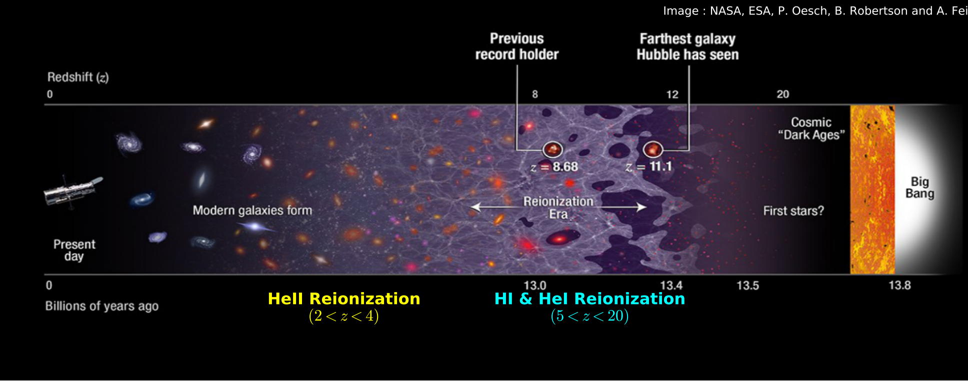
Dec, 2023

Outline

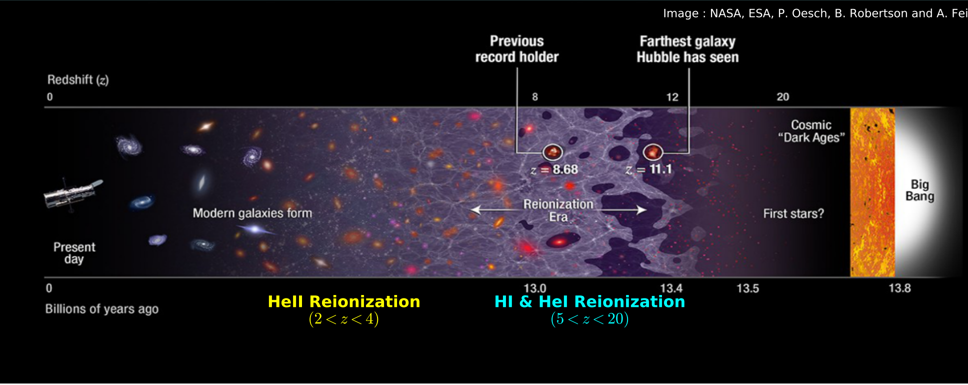


- Density fluctutations in the early universe ($z \sim 1100$)

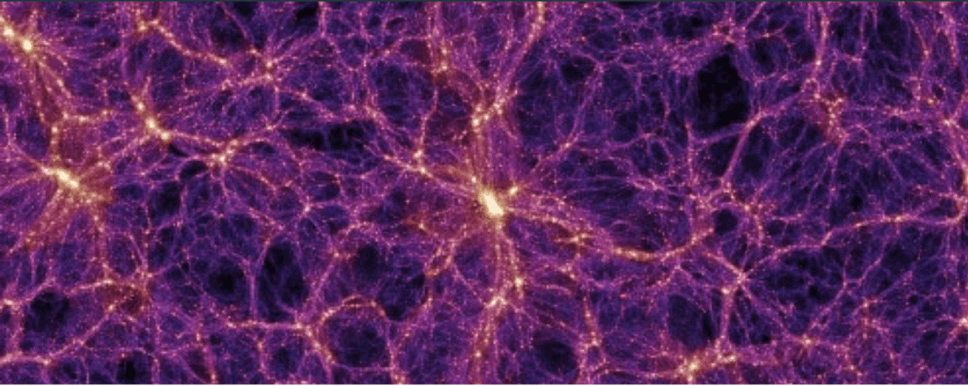




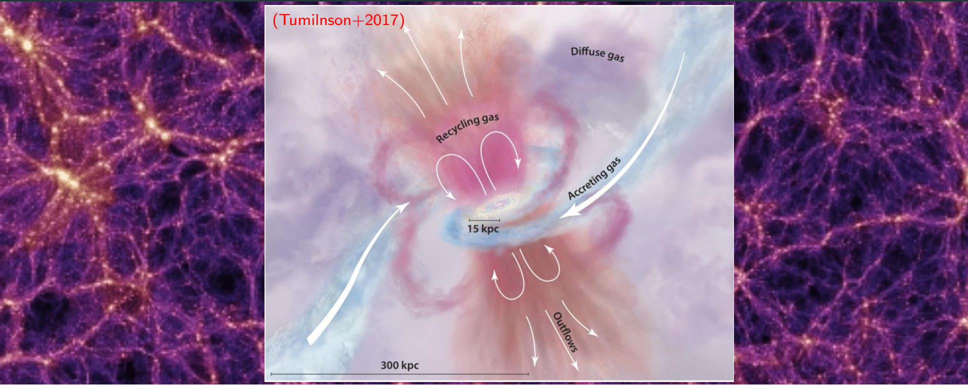
- Density fluctutations in the early universe ($z \sim 1100$)
- Overdense regions grow due to gravitational instability
- Collapsed structures: Formation of stars and Galaxies ($z < 20$)



- Density fluctutations in the early universe ($z \sim 1100$)
- Overdense regions grow due to gravitational instability
- Collapsed structures: Formation of stars and Galaxies ($z < 20$)
- A significant fraction of diffuse gas that is not associated with these collapsed objects is known as Intergalactic Medium (IGM)
- IGM: Volume filling factor is very large and has distinct filamentary structure



- Filamentary structure has imprints of cosmlogical initial conditions
- Galaxies during their life-time constantly interact with the IGM



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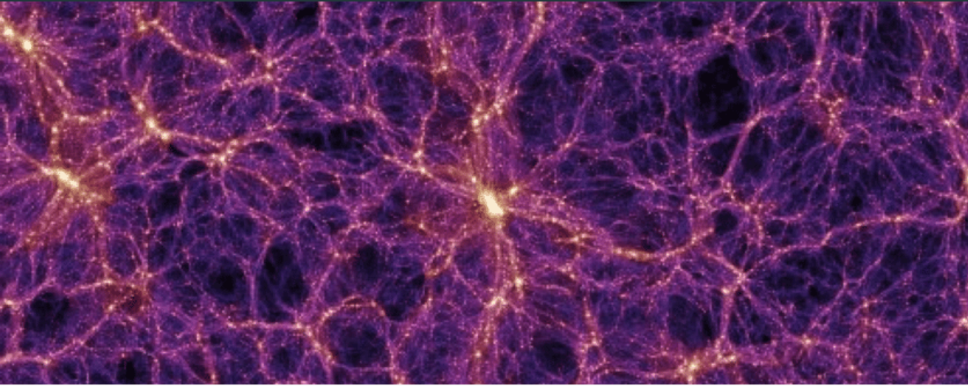
- Inflow of pristine (H and He enriched) gas
- Outflow of metal (elements heavier than He) enriched gas



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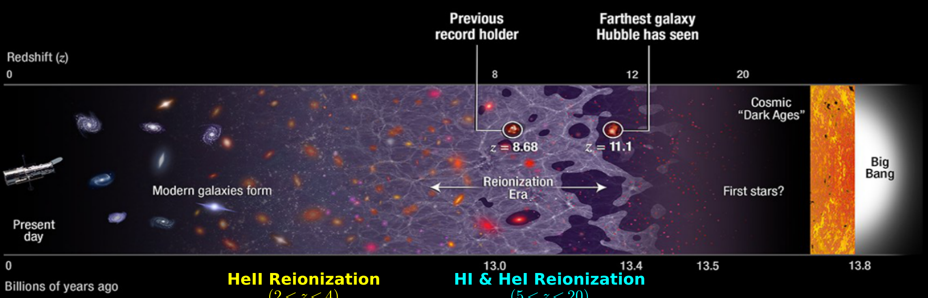
- Galaxies during their life-time constantly interact with the IGM
- Inflow of pristine (H and He enriched) gas
- Outflow of metal (elements heavier than He) enriched gas
- Reionization : Radiation from Stars, Galaxies and AGN ionizes the IGM
- Rich information of Galaxy formation and Cosmological initial conditions

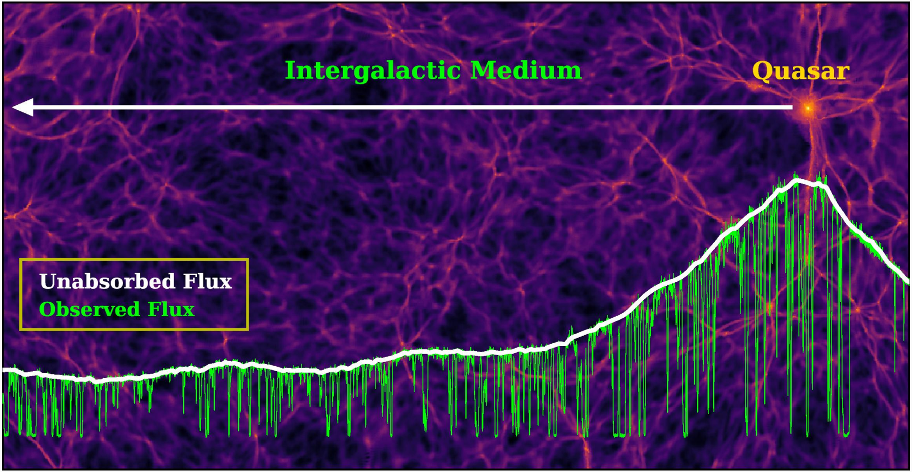
Image : NASA, ESA, P. Oesch, B. Robertson and A. Fei



HeII Reionization
$(2 < z < 4)$
Quasars
HST-COS / Keck-HIRES
ESO-UVES / WEAVE-QSO

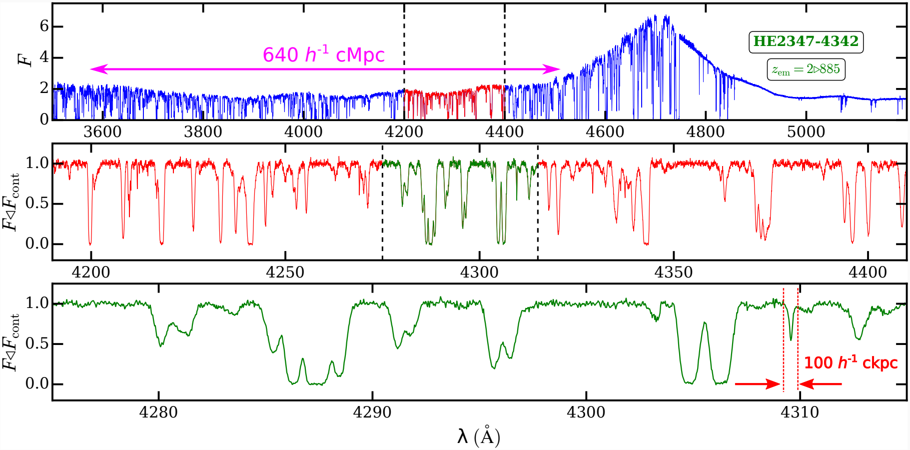
HI & HeI Reionization
$(5 < z < 20)$
Galaxies
XShooter / MIKE / JWST
21 cm : SKA / LOFAR

- Reionization is a two step process
- H I reionization $5 < z < 20$
- He II reionization $2 < z < 5$
- I am actively working on both H I and He II reionization.



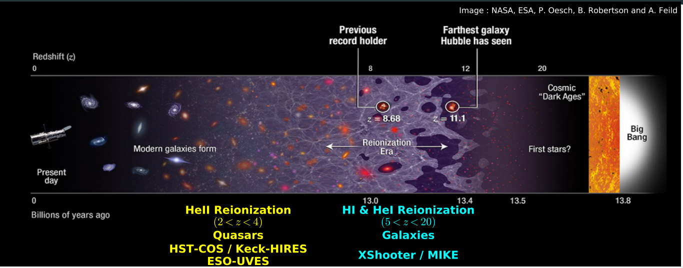
- Observations of distant bright QSOs
- Absorption features $\Rightarrow$ H I Lyα forest + Metals produced due to IGM
- Highly senstive to low density gas in IGM

Observations



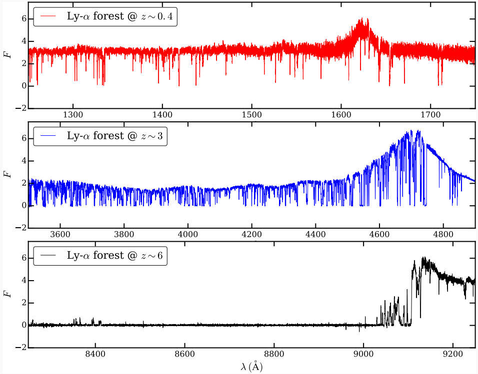
- Huge dynamic range
- $L_{\rm scale} \sim 100h^{-1}$ ckpc to $500h^{-1}$ cMpc
- $\mathrm{N_{HI}} \sim 10^{12}$ to 10^{21} cm^{-2}

Evolution of the IGM



How does Lyα forest look at various redshifts?

Lyα forest observations



Less absorption

$(z < 0.5)$

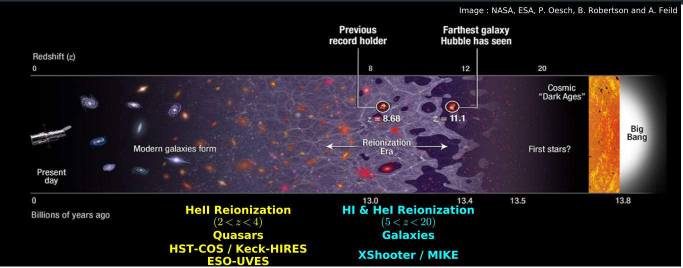
More absorption

$(2 < z < 4)$

High absorption

$(5 < z < 6)$

Evolution of the IGM



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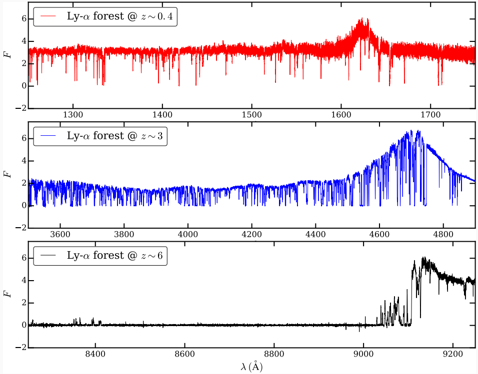
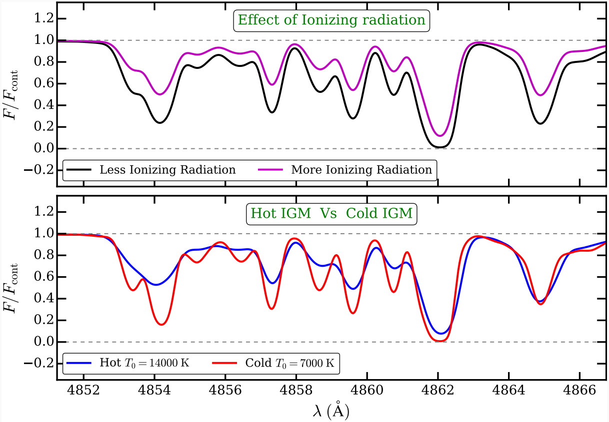


Less absorption $(z < 0.5)$ — Highly ionized

More absorption $(2 < z < 4)$ — More neutral

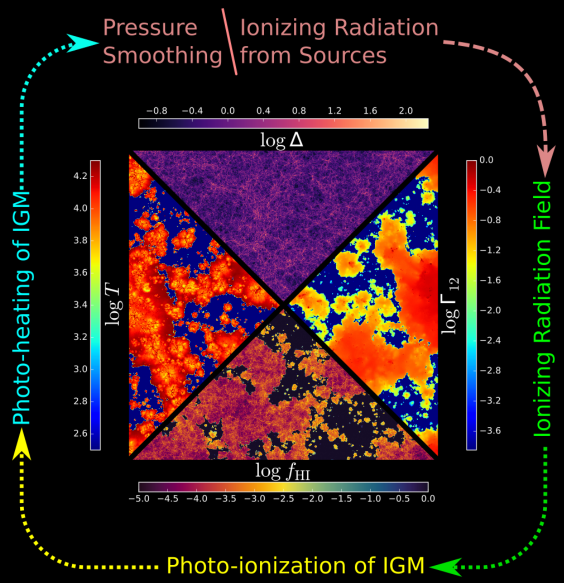
High absorption $(5 < z < 6)$ — Highly neutral

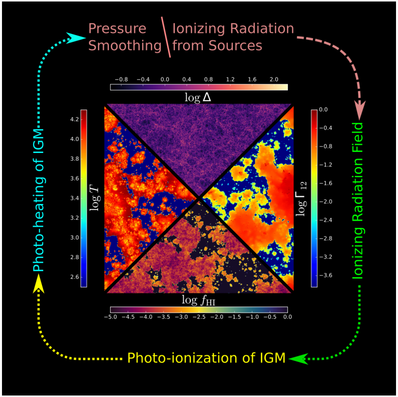
How hot and neutral IGM is?

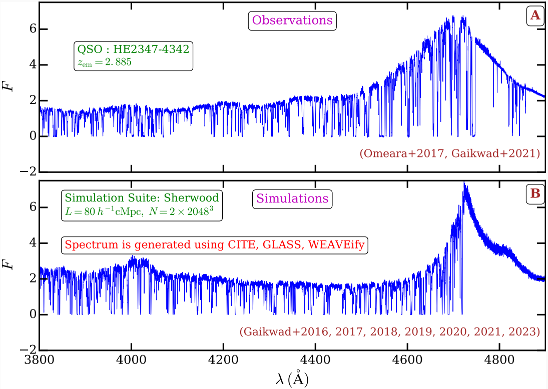


- Lyα forest is sensitive to temperature and ionizing radiation field of IGM
- Small ionizing radiation field shows systematically more absorption in Lyα forest
- Hotter IGM shows systematically broder absorption lines in Lyα forest
- $\Gamma_{\rm HI} \Rightarrow$ Photo-ionization rate (Number of ionizing photons per unit time)
- $T_0 \Rightarrow$ Temperature of IGM at cosmic mean density ($\Delta = 1,\ T = T_0\,\Delta^{\gamma-1}$)

Process of Reionization



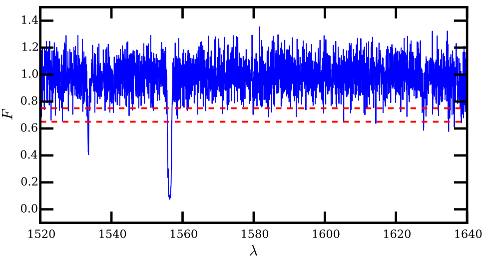


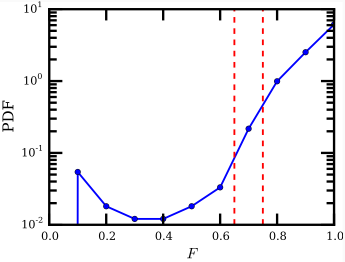


- I have developed codes to model effect of reionization on QSO absorption spectra
- EX-CITE, GLASS, WEAVEIFY, VIPER, SPECRED, HEART (Available on Bitbucke
- All codes are written in Python using MPI-HPC and CUDA-GPU
- Need summary statistics to compare simulations with observations.

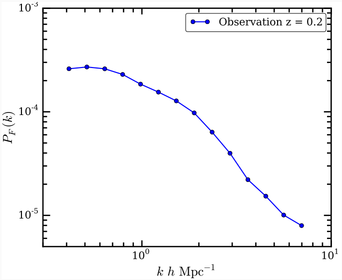
Summary Statistics (Gaikwad+2016,2017,2021)

- Flux Probability Distribution Function (Flux PDF):





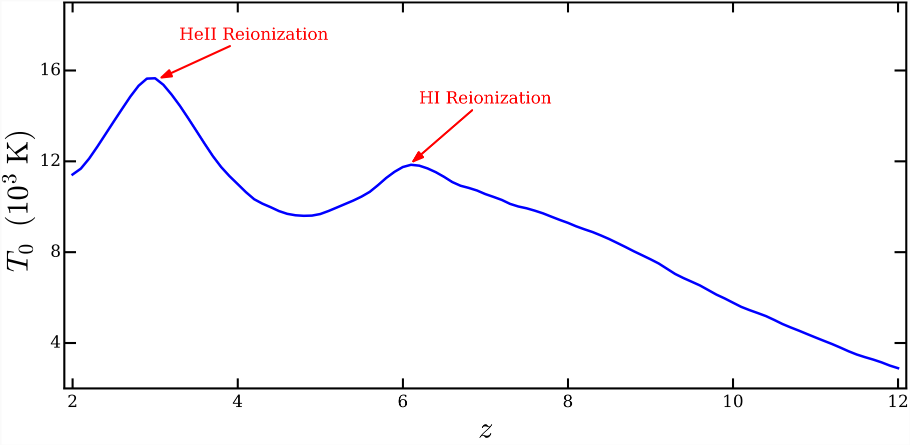
- Flux Power Spectrum:
  - $P_F(k) = |\mathscr{F}[F(x)]|^2$
  - $\sigma_F^2 = \int_{-\infty}^{\infty} P_F(k)\, dk\, /2\pi$



- Flux PDF $\Rightarrow$ Ionization state of IGM Γ_{HI}
- Flux PS $\Rightarrow$ Thermal state of IGM T_0

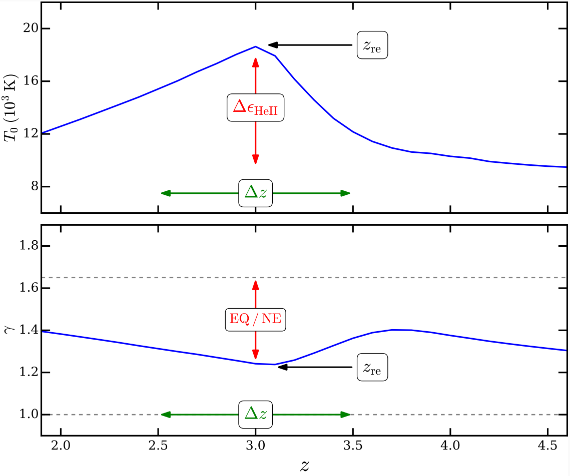
What is the temperature of IGM?

Thermal state of IGM



- If there was no reionization, IGM would cool adiabatically (Hubble Expansion)
- Peak in temperature due to H I and He II reionization

Thermal state of IGM



- Redshift of reionization $z_{\rm re}$ ($f_{\rm HeII} \sim 0.5$)
- Spectral Energy Distribution of sources $\Delta\epsilon_{\rm HeII}$
- Duration of reionization Δz
- Nature of Process: Equilibrium vs Non-Equilibrium
- Thermal Parameters T_0, γ:

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

- If there was no reionization, IGM would cool adiabatically (Hubble Expansion)
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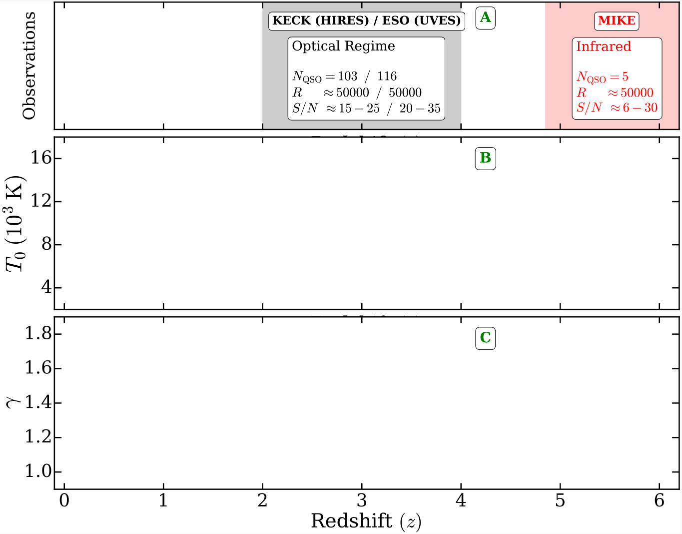
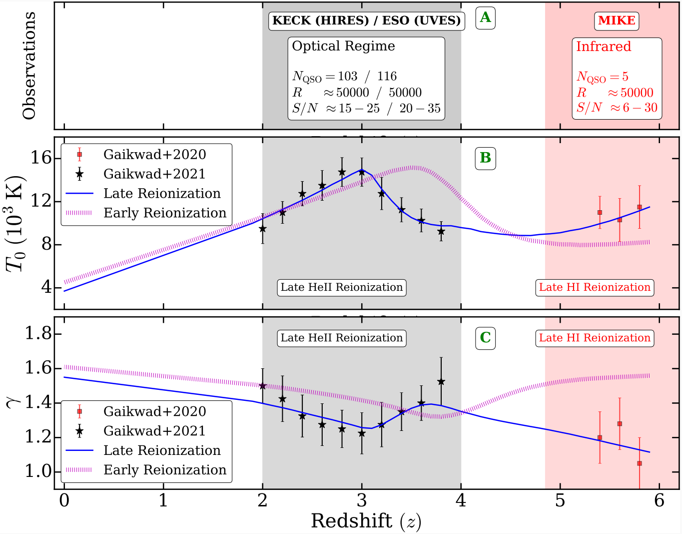
Temperature Measurements



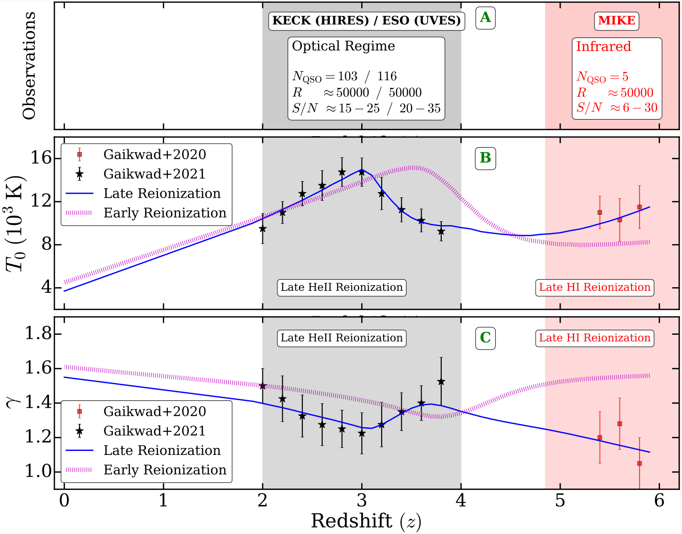
- Measurement of thermal parameters at $2 < z < 6$
- QSO absorption spectra obtained from different telescopes
- Observational systematics are quite different

Temperature Measurements



- Extreamly challenging measurements: Observation Systematics + Very careful Modeling
- $5 < z < 6 \Rightarrow$ First measurement of IGM temperatures at $z > 5$
- $2 < z < 4 \Rightarrow$ Most robust and consistent measurement of IGM temperature

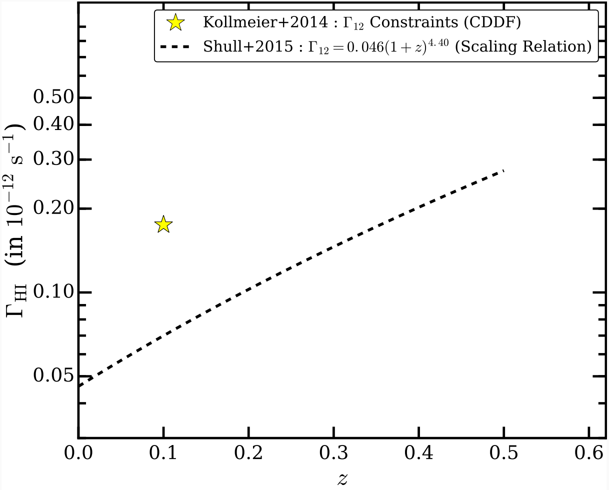
Temperature Measurements



- There is a clear peak in IGM temperature at $z \sim 3 \Rightarrow$ He II reionization
- Late reionization $z_{\rm re}$, Rapid reionization (Δz), Non-equilbrium and Softer SED
- These measurements established the late H I and He II reionization scenario

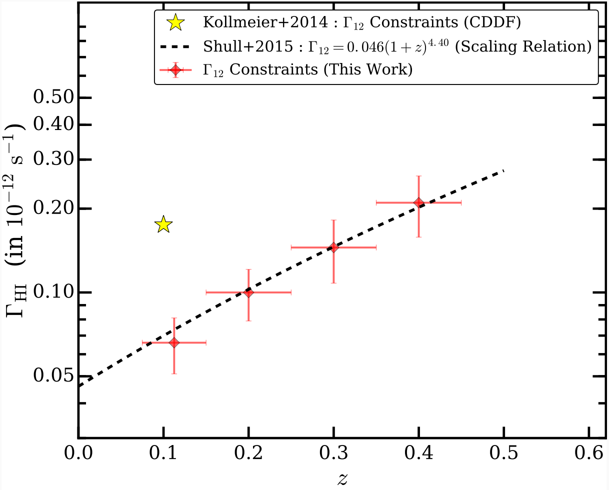
Ionization State of the IGM

Photon-Underproduction Crises



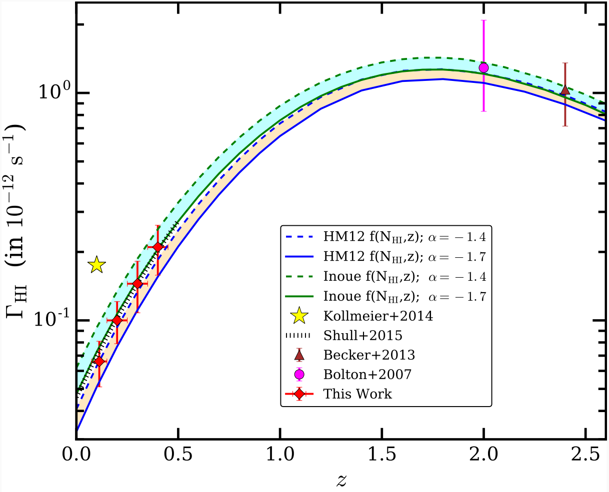
- Problem: Number of ionizing photons needed for IGM $>>$ Number of ionizing photons counted from astrophysical sources.
- Hypothesis : Contribution by some non-astrophysical sources (Dark Matter annihilation)

Photon-Underproduction Crises



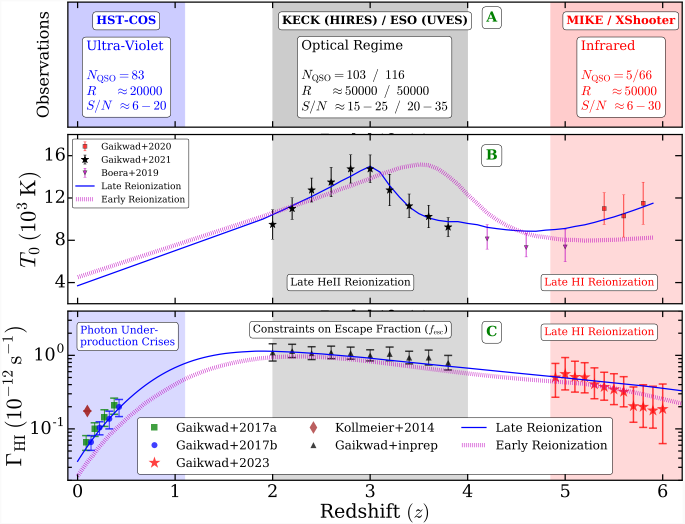
- Problem: Number of ionizing photons needed for IGM $>>$ Number of ionizing photons counted from astrophysical sources.
- Hypothesis : Contribution by some non-astrophysical sources (Dark Matter annihilation)
- We resolve the issue of PUC by measuring the photo-ionization rate from HST-COS Lyα forest

Photon-Underproduction Crises

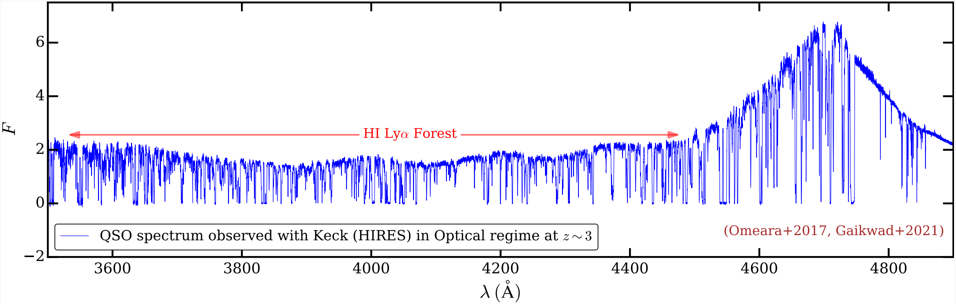


- $\Gamma_{\rm HI}$ is measured from a sample of 83 HST-COS (UV Spectrograph) Lyα forest spectra
- The evolution of measured $\Gamma_{\rm HI}$ is consistent with those from standard astrophysical sources
- We put the 3σ upper limit on Galaxy escape fraction to be $f_{\rm esc} < 0.08\%$

Summary of Previous Work

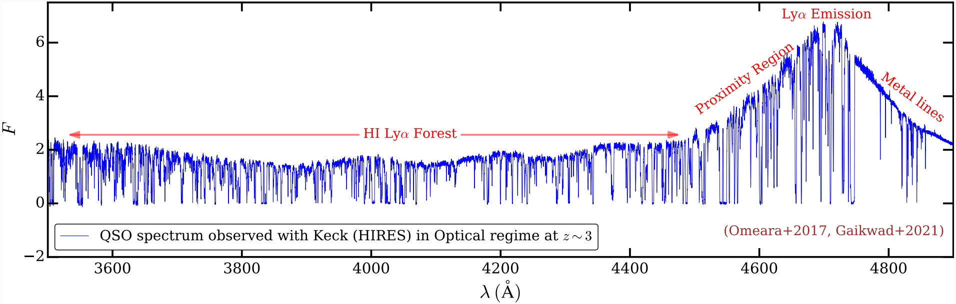


- $5 < z < 6 \Rightarrow$ First measurement of Γ_{HI} accounting for patchy reionization
- Evidence for late H I and He II reionization



- The main results were obtained from Lyα forest

Future Work (Astrophysics) [Galaxy Formation and Evolution]



- The main results were obtained from Lyα forest
- Other regions in absorption spectra: Proximity Region and IGM Metal lines

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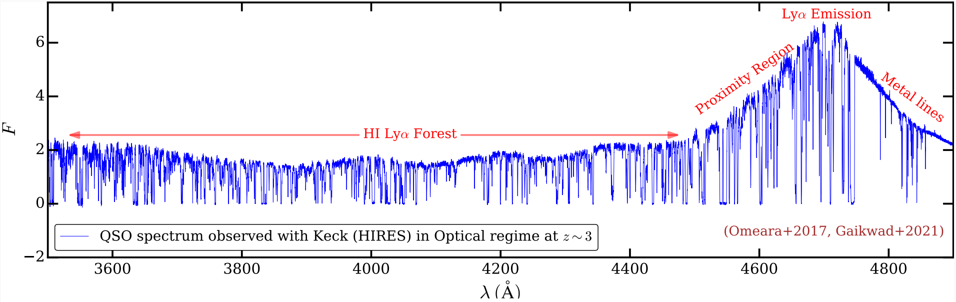
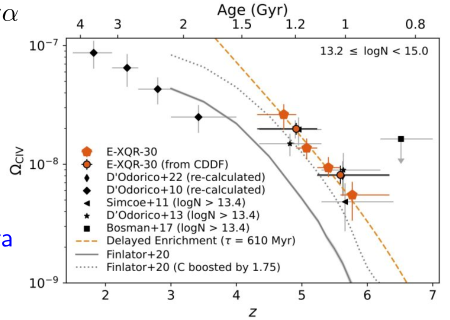
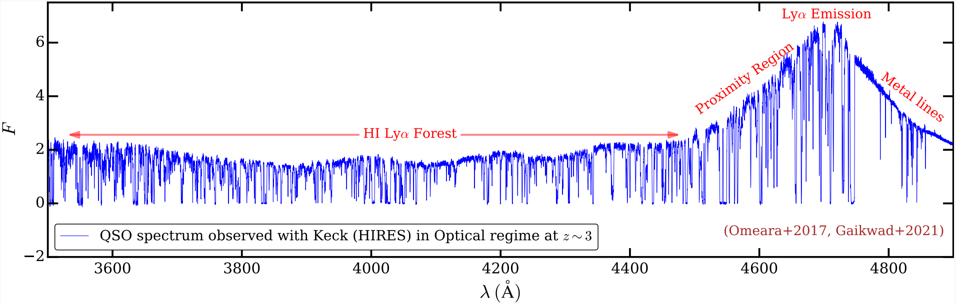


- The main results were obtained from Lyα forest
- Other regions in absorption spectra: Proximity Region and IGM Metal lines
- Metal lines: Feedback of Galaxies to metal enrichment of IGM
- Damping Wing with JWST galaxy spectra

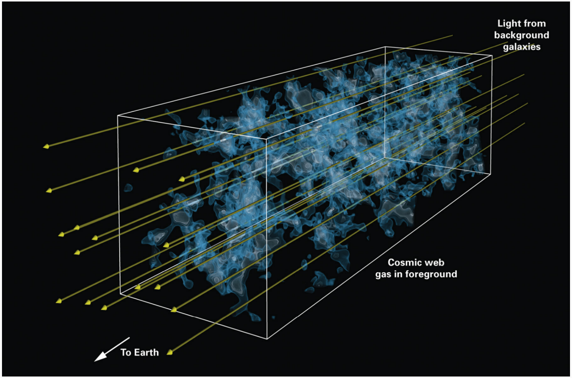


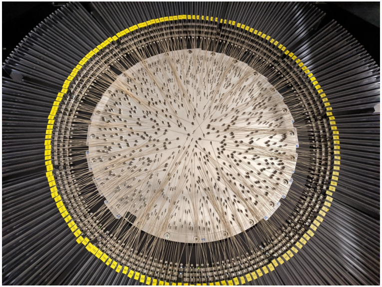
Future Work (Cosmology)



- Main limitations of QSO absorption spectra: 1D probe of IGM along sightline

Future Work (Cosmology) [IGM Tomography]

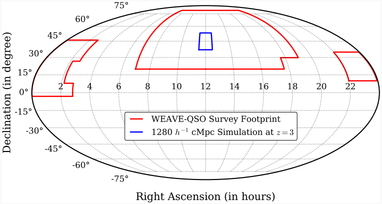




Robotic Arm Fiber plate arrangement

- WEAVE QSO absorption spectra survey: Planning to observe ∼ 0.5 million QSO
- WEAVE-QSO survey builder

WEAVE survey footprint



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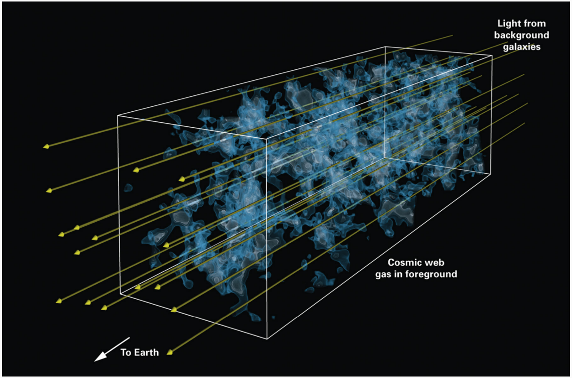
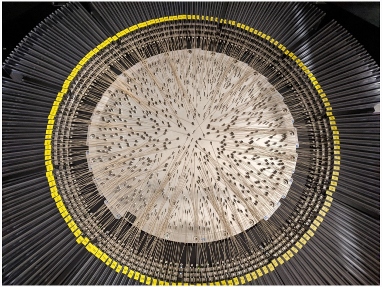
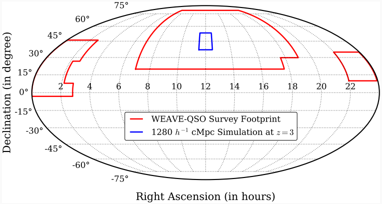




Robotic Arm Fiber plate arrangement

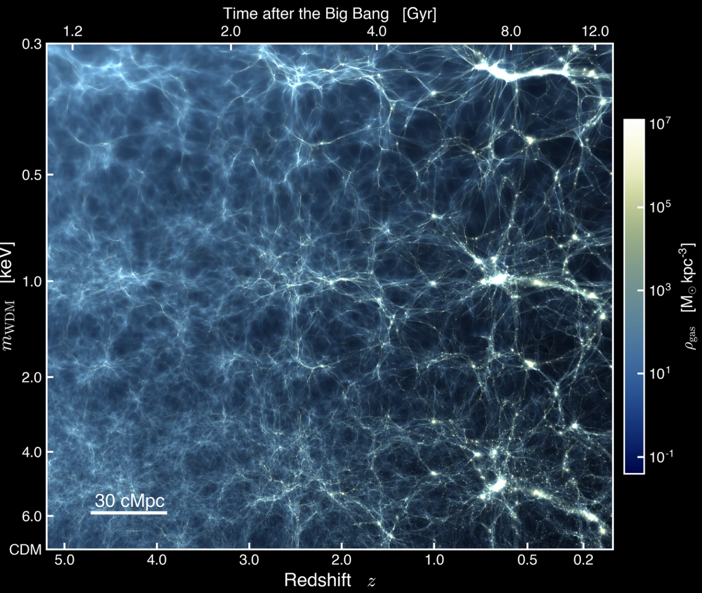
- WEAVE QSO absorption spectra survey: Planning to observe $\sim$ 0.5 million QSO
- WEAVE-QSO survey builder
- To perform 3D IGM tomography
- Nature of DM: P3D and P1D measurement
- Suppression in small scale fluctuations

WEAVE survey footprint



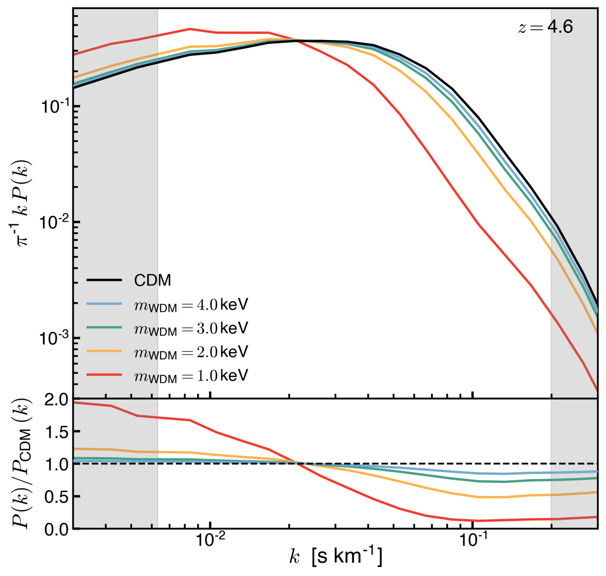
Future Work (Cosmology)

[IGM Tomography]



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

Future Work (Cosmology)



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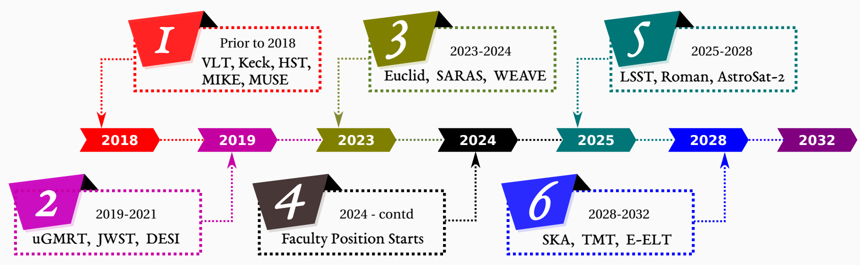
Future Work



- Indian Observatories:
  - uGMRT (Observations of Radio Loud QSO for 21cm forest)
  - AstroSat-2 (Cosmic web in X-ray emission)
- Indian involvement in Mega-Science Projects
  - SKA (HI intenesity mapping, cross-correlation with IGM tomography)
  - TMT (Galaxy Spectra at $z > 6$)
- Exisiting Collaboration:
  - JWST (QSO Light-Echo to study QSO emission properties)
  - WEAVE (Nature of dark matter P1d, IGM tomography, High Column Density Absorber

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, Huge dynamic range
- How hot and neutral IGM is?
  - Tharmal 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
  - Mega Science Projects, Indian observatories, Existing collaboration WEAVE, JWST

Main Presentation Links

Appendix Slides Links

1. Why IISc?
2. Teaching Plan
3. SW Analysis
4. IGM Problems
5. Astronomy Problems
6. Career Goals
7. Next 5-10 Years
8. Resources

Why IISc?

- Research Enviornment
  - Dedicated Astronomy Department
  - Students and Postdocs
- Resources for Research
  - CRAY (SAHASRAT) HPC system
  - Initial startup grant
- Interdisciplinary Collaborations
  - Particle Physics
  - Thoretical Sciences
- Location of IISc
  - Other Research Institutes : IIA, RRI, ICTS
  - Space Science Institutes : ISRO Headquater
  - Bangalore Metropolitan Multi-Cultural City

Teaching Plan

- JAP Courses
  - Fundamentals of Astrophysics
  - Galaxies and the Interstellar Medium
  - Astronomical Techniques
  - Radiative Processes in Astrophysics
  - General Relativity and Cosmology
  - Fluid Mechanics and Plasma Physics
  - More topics on Exo-Planet and Star Formation
- General Physics Courses
  - Computational Physics
  - Advanced Mathematical and Numerical Methods in Physics
  - Classical Mechanics
  - Quantum Mechanics
  - Statistical Mechanics
  - General Physics Lab

Teaching Plan

- Basics of Astronomy (35% of Time)
    - How to locate astronomical objects? Co-ordinate Systems
    - How far astronomical objects are? Distance and Time Scales
    - Units in Astronomy, Importance of order of magnitude
    - Fluxes, Colors, Magnitude, Extinction, Photometric systems
    - Observational techniques: Imaging, Photometry, Spectroscopy
    - Telescope: Types, Mounts, Modern design, Ground vs Space
    - Electromagentic spectrum: Gamma-ray, X-ray, UV, Optical, Infrared, Radio
    - Gravitational Wave (Qualitative, no tensor algebra)
- Stars and Planets (20%)
- Galaxies Formation, Evolution and Dynamics (20%)
- Cosmology (20%)
- Summary + Open Research Problems + Student Difficulty (5%)