Constraining Mean free path of ionizing photons during Helium reionization

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Cosmology With SKA (SPARC Workshop)

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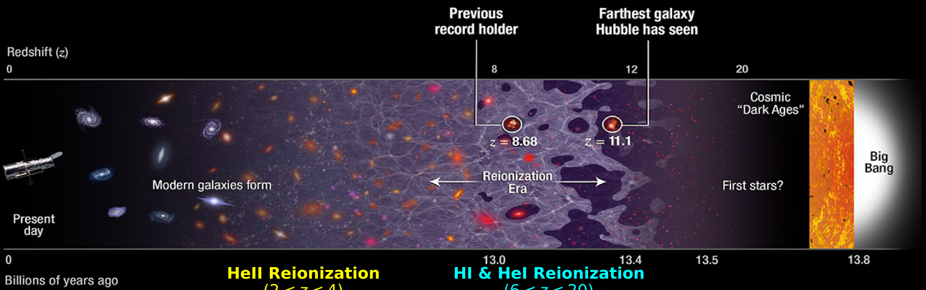
Outline

- Motivation
- Observations
- Simulations
- Results
- Summary

Introduction

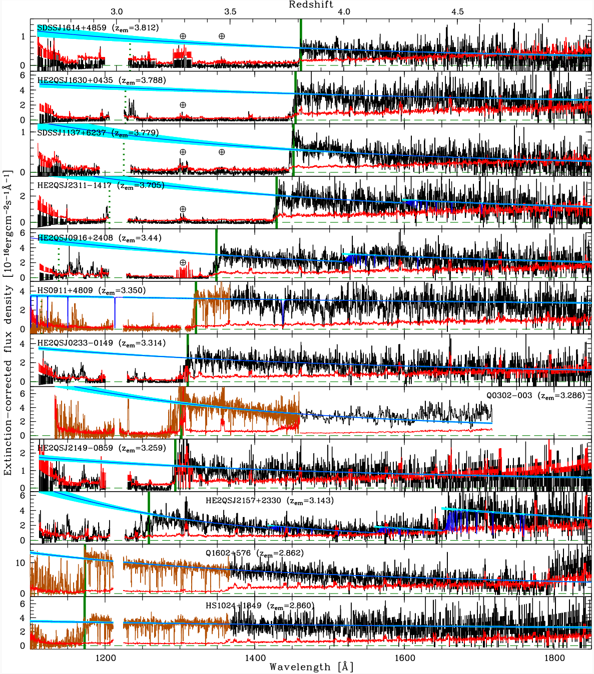


HeII Reionization
$(2 < z < 4)$
Quasars
HST-COS / Keck-HIRES
ESO-UVES / WEAVE-QSO

HI & HeI Reionization
$(6 < z < 20)$
Galaxies
XShooter / MIKE / JWST
21 cm : SKA / LOFAR

- Ionization of He II is the second major step in reionization.
- He II reionization: Quasars at $2 < z < 4$
- Observations of He II Lyα forest using HST-COS [Worseck+2014,2019]
- Uncertainity in He II reionization affects inferences of cosmological parameters from large scale surveys like eBOSS, DESI, WEAVE, SKA etc.

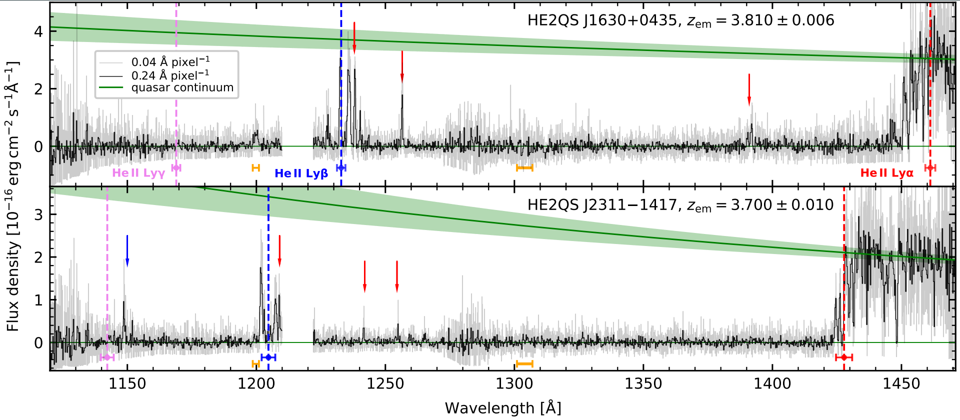
Observations



(Worsek+2018)

- Opacity of He II increases with redshift as seen in absorption features

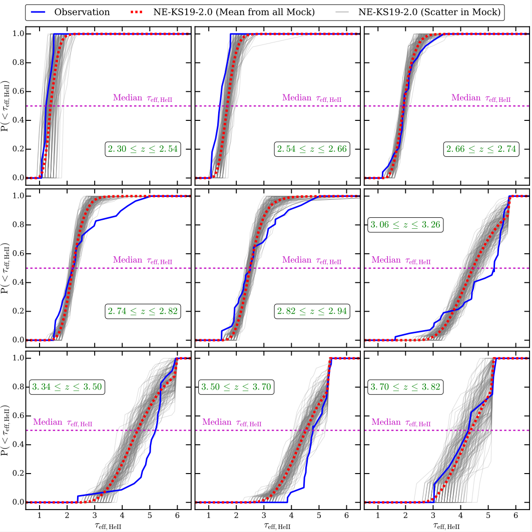
He II Lyα Forest at $z > 3$



- Example of He II Lyα forest spectra from Makan+2020
- Total of 24 He II Lyα forest Spectra are used in the analysis.
- Non-zero flux: Detection of transmission spikes
- Can we use this information to constrain nature of HeII reionization?

Patchy He II Reionization

[Worseck+2019,Gaikwad+2019]



Cumulative Distribution Function of He II effective optical depth

- Observations show large scatter in $\tau_{\rm eff,HeII}$
- More Opaque sightlines $\Rightarrow$ Large $\tau_{\rm eff,HeII}$
- More transperent sightlines $\Rightarrow$ Small $\tau_{\rm eff,HeII}$
- Uniform UVB model does not match observed $\tau_{\rm eff,HeII}$ CDF

Patchy He II Reionization

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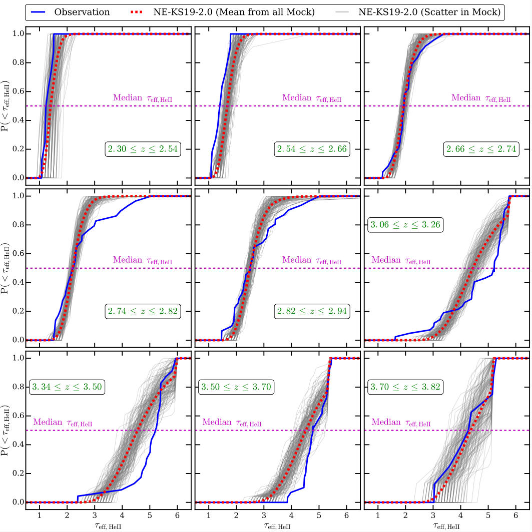

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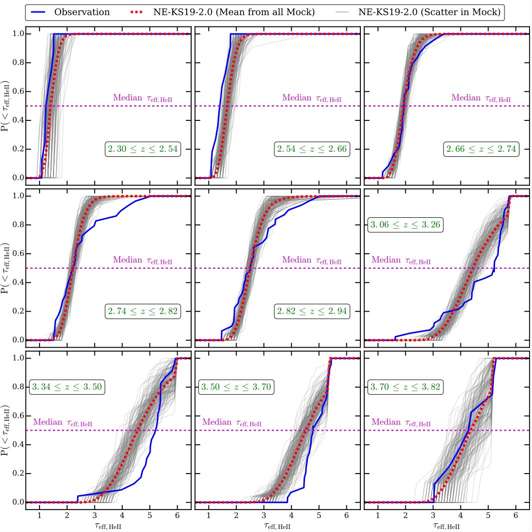
- Uniform UVB model does not match observed $\tau_{\rm eff,HeII}$ CDF
- Scatter in $\tau_{\rm eff,HeII}$ in uniform UVB model is mainly due to flucutations in cosmic density field.
- Patchy reionization ⇒ Fluctuations in ionizing radiation field

Patchy He II Reionization

[Worseck+2019,Gaikwad+2019]



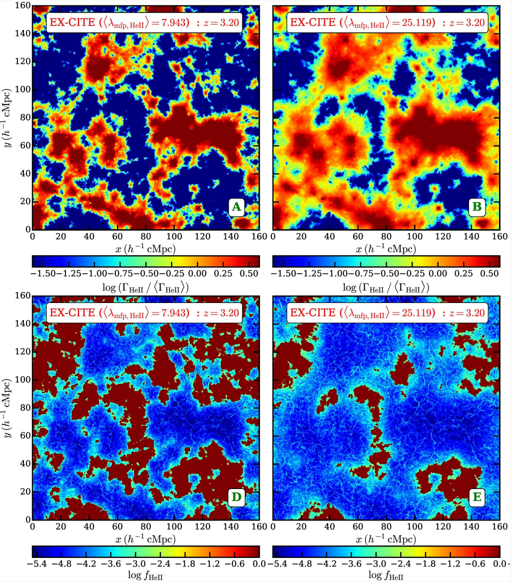
Cumulative Distribution Function of He II effective optical depth

- How to simulate patchy reionization?
- Radiative transfer simulations
  Computationally expensive, not suitable for parameter exploration
- Semi numerical simulations:
  Less accurate but efficient for parameter exploration
- Patchy Reionization $\Rightarrow$ Fluctuating mean free path model [Davies+2015]

Simulations

Patchy Reionization using EX-CITE

[Davies+2015]



Small $\langle\lambda_{\rm mfp,HeII}\rangle$ Large $\langle\lambda_{\rm mfp,HeII}\rangle$

- Photo-ionization rate fluctuations depend on mean free path along sightline to sources

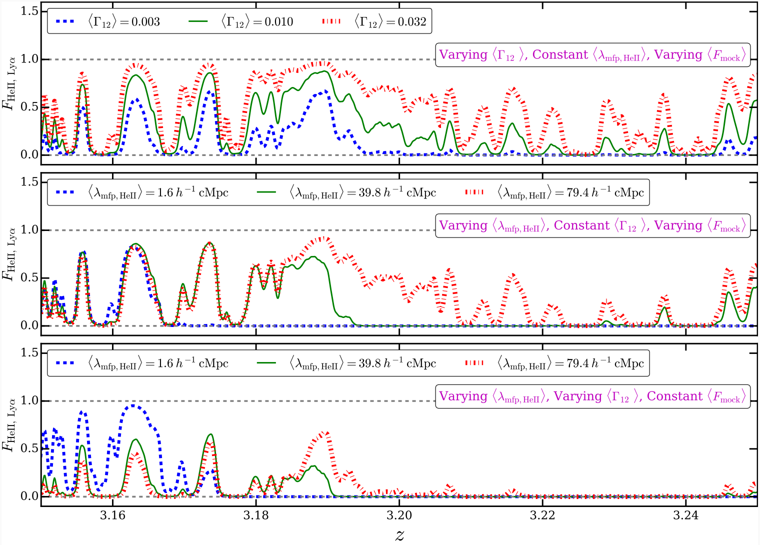
$$\frac{\Gamma_{\rm HeII,j}}{\langle\Gamma_{\rm HeII}\rangle} = \sum_{\rm i=1,i\neq j}^{N_{\rm source}} \frac{w_{\rm halo,i}}{(4\,\pi\, r_{\rm ij})^2}\ \exp\left[-\int_{r_i}^{r_j} \frac{dx}{\lambda(x)}\right]$$

- Mean free path depends on local photo-ionization rate fluctuations

$$\lambda(x) = \langle\lambda_{\rm mfp,HeII}\rangle\ \Delta^{-1}\ \left[\frac{\Gamma_{\rm HeII}(x)}{\langle\Gamma_{\rm HeII}\rangle}\right]^{2/3}$$

- EX-CITE solves coupled equations using Octree method.
- 2 parameters that constrain patchy reionization: $\langle\Gamma_{\rm HeII}\rangle - \langle\lambda_{\rm mfp,HeII}\rangle$

Effect of $\Gamma_{\rm HeII}$ and $\lambda_{\rm mfp,HeII}$ on Lyα forest

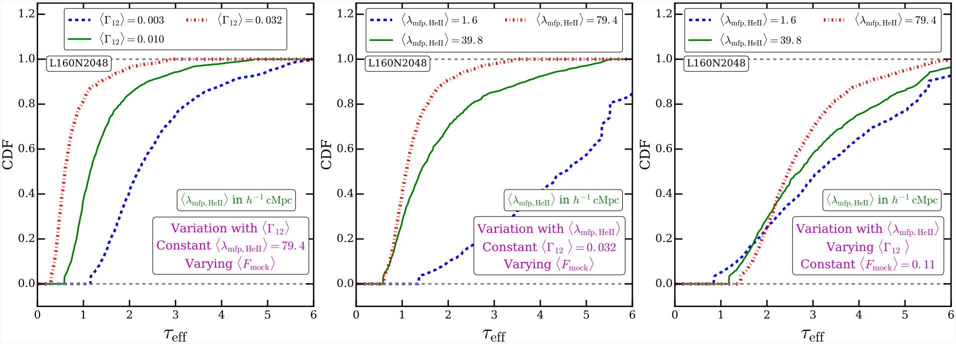


$\Gamma_{\rm HeII}$ Variation

$\lambda_{\rm mfp,HeII}$ Variation

- Variation in $\Gamma_{\rm HeII}$ affects the overall flux level
- Variation in $\lambda_{\rm mfp,HeII}$ affects location of transmission spikes

Effect of Γ_{HeII} and $\lambda_{\mathrm{mfp,HeII}}$ on Lyα forest



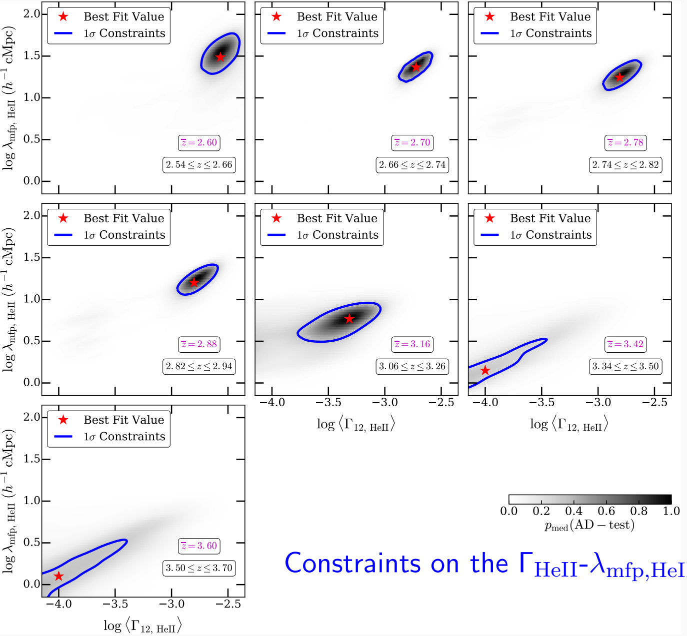
Γ_{HeII} Variation

$\lambda_{\mathrm{mfp,HeII}}$ Variation

- Variation in Γ_{HeII} affects median of the $\tau_{\mathrm{eff,HeII}}$ distribution
- Variation in $\lambda_{\mathrm{mfp,HeII}}$ affects scatter of the $\tau_{\mathrm{eff,HeII}}$ distribution
- Using these properties, we constrain $\Gamma_{\mathrm{HeII}} - \lambda_{\mathrm{mfp,HeII}}$ simultaneously
- Statistics : Two Sample Anderson-Darling Test

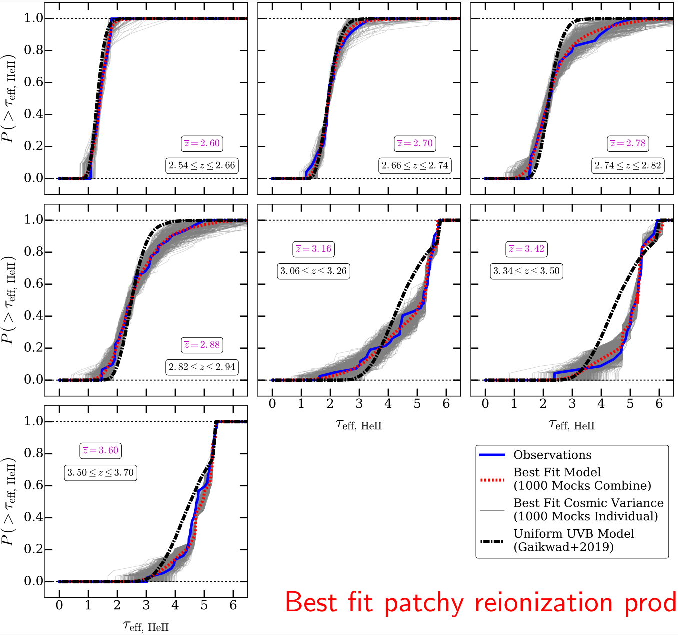
Results

Measurement of $\Gamma_{\rm HeII}$ and $\lambda_{\rm mfp,HeII}$ from $\tau_{\rm eff,HeII}$ CDF



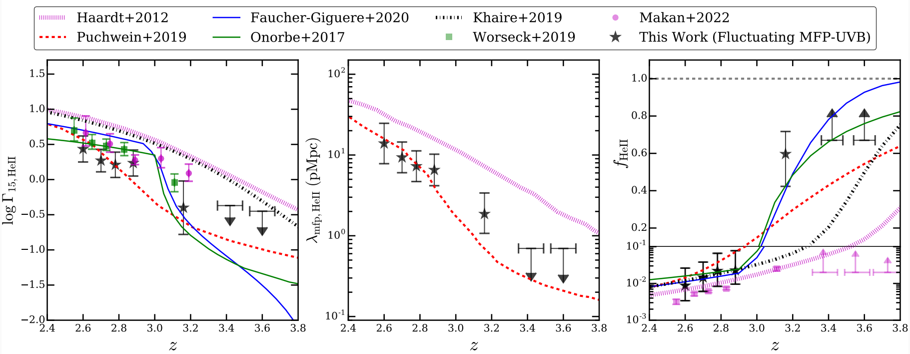
Constraints on the $\Gamma_{\rm HeII}$-$\lambda_{\rm mfp,HeII}$ from observations

Measurement of $\Gamma_{\rm HeII}$ and $\lambda_{\rm mfp,HeII}$ from $\tau_{\rm eff,HeII}$ CDF



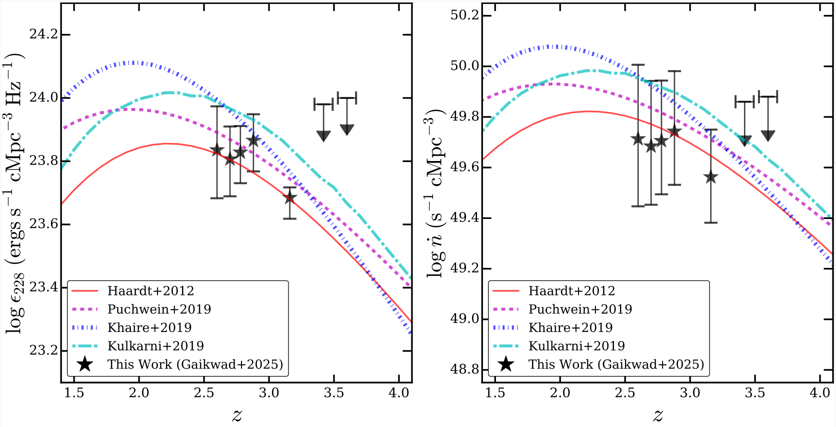
Best fit patchy reionization produces $\tau_{\rm eff,HeII}$ scatter

Parameter Evolution



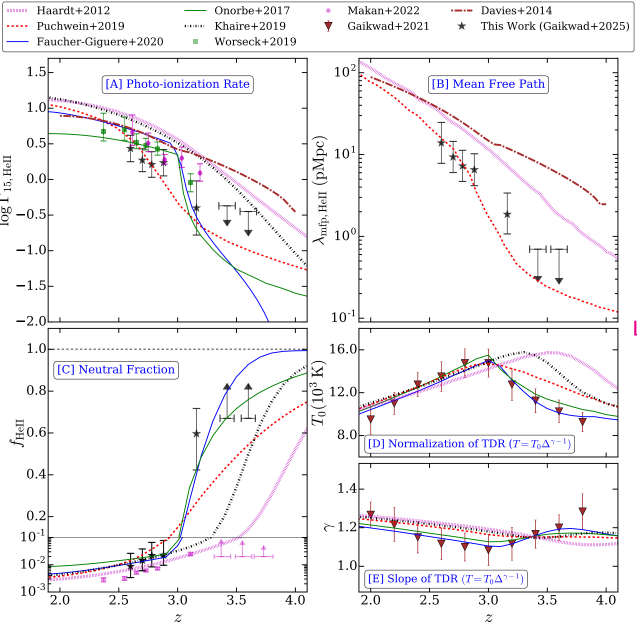
- Modeling and observational uncertainties are accounted for in the final measurements of Γ_{HeII} and $\lambda_{\mathrm{mfp,HeII}}$.
- Larger uncertainty in Γ_{HeII} is due to finite $\lambda_{\mathrm{mfp,HeII}}$.
- First measurements of the $\lambda_{\mathrm{mfp,HeII}}$ from observations
- Previous neutral fractions constraints were from uniform UVB models.
- Γ_{HeII} and $\lambda_{\mathrm{mfp,HeII}}$ favors late and rapid He II reionization scenario.

Emissivity Evolution



- Absorption Limited Approximation
- Constraints on Emissivity and Photon Emission Rate for He II
- Good agreement with Galaxy and QSO surveys

Coherent Picture

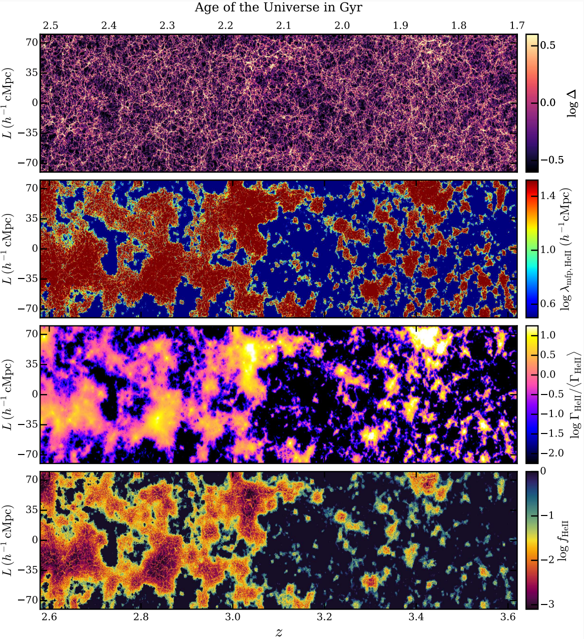


Ionization Parameters (Gaikwad+2025)

Late and Rapid He II Reionization

Thermal Parameters (Gaikwad+2021)

Summary



He II Lyα forest at $2 < z < 4$

Patchy He II reionization Simulations

Constraints on Γ_{HeII}, $\lambda_{\mathrm{mfp,HeII}}$, f_{HeII}, ϵ_{228} and $\dot{n}_{\mathrm{HeII}}$ at $2 < z < 4$

Complementary to and Consistent with thermal parameter ($T_0 - \gamma$) evolution from H I Lyα forest

All parameter evolution favors late He II reionization models.