Effect of non-equilibrium HeII reionization on IGM at $2 \leq z \leq 4$

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[4]University of California, Santa Barbara

Outline

- Introduction
- Modeling of He II reionization
- Uncertainties in modeling of He II reionization
- Effect on observables
- Comparison with Observations
- Summary

Introduction

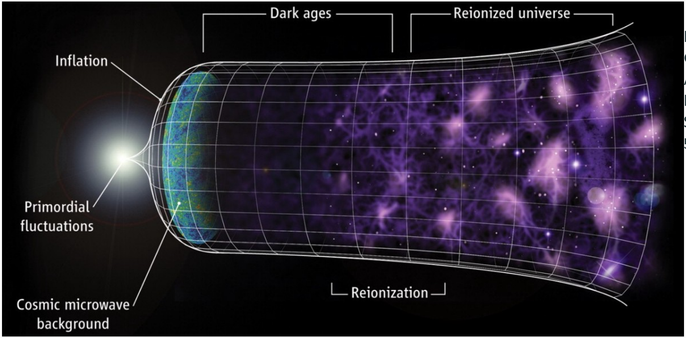

Image credit: C. Faucher-Gigure, A. Lidz, and L. Hernquist, Science 319, 5859 (47)

- CMB ($z \sim 1100$), Epoch of Reionization: Two step process
- H I (13.6 eV) and He I (24.6 eV) : $z \sim 6$, early type of stars and galaxies
- He II (54.4 eV) : $z \sim 3$, mainly QSOs
- Effect of thermal and ionization state during He II reionization?
- Epoch of He II reionization is observationally more accessible through H I Lyα forest (optical)
- Some questions about EoR.

Epoch of Reionization

- What are the sources?

Epoch of Reionization

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    - Galaxies and/or QSOs
    - Spectral Energy Distribution (SED) : $\mathcal{L}(L,\nu)\,d\nu$

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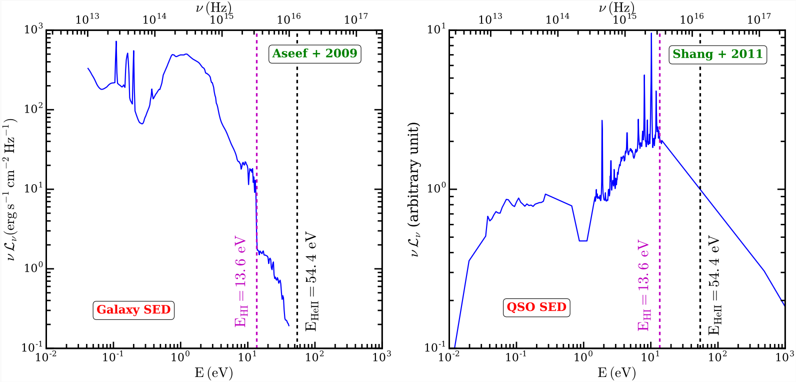

Epoch of Reionization

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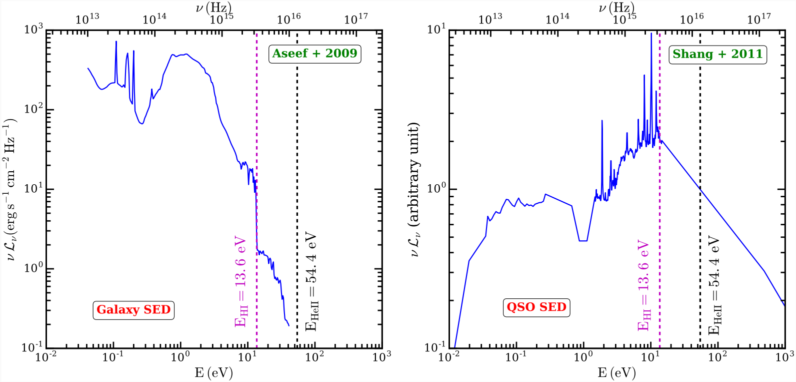
- How many of them are present?



Epoch of Reionization

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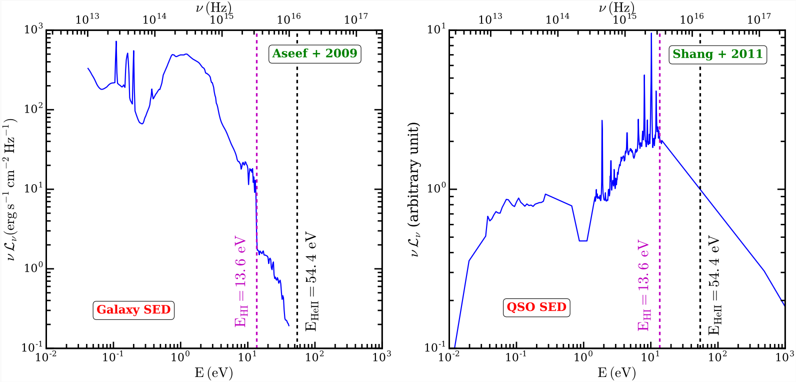
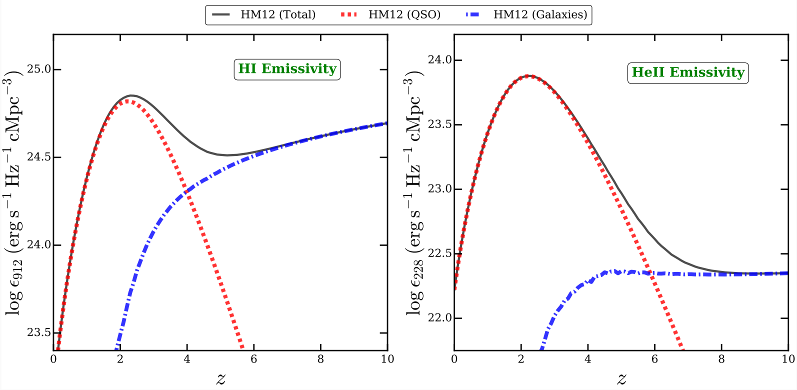
    - Spectral Energy Distribution (SED) : $\mathcal{L}(L, \nu)\, d\nu$
- How many of them are present?
    - Luminosity Function : $\Phi(L, z)\, dL$



Epoch of Reionization

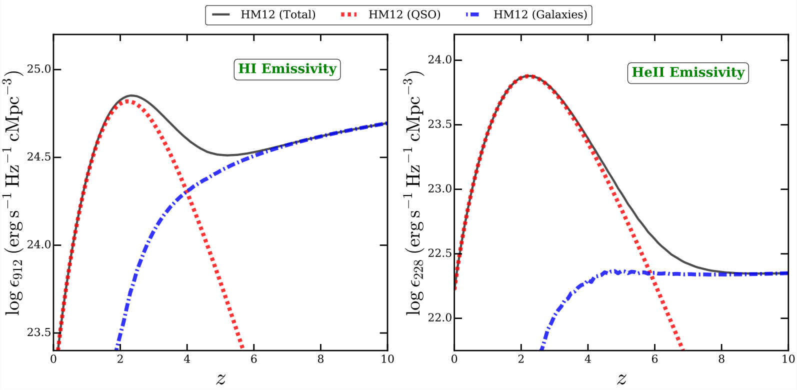
- What: Spectral Energy Distribution (SED) : $\mathcal{L}(L,\nu)\,d\nu$
- How many: Luminosity Function : $\Phi(L,z)\,dL$
- Emissivity:

$$\epsilon(\nu,z) = \int_{L_{\min}}^{L_{\max}} \underbrace{\mathcal{L}(L,\nu)}_{\text{What?}} \; \underbrace{\Phi(L,z)}_{\text{How many?}} \; dL$$



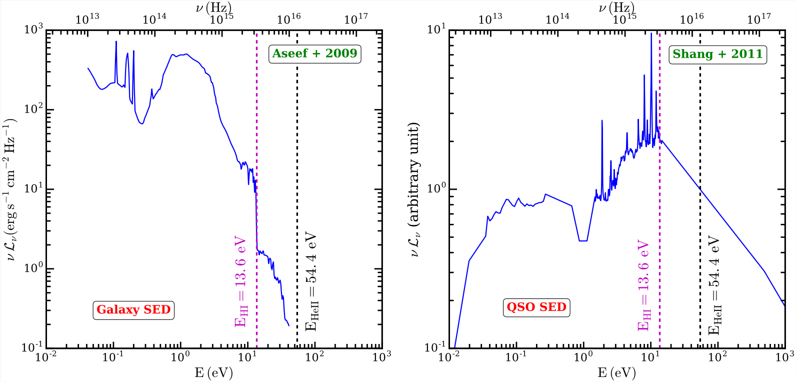
Epoch of Reionization

- H I emissivity (912 Å)
  - Galaxies: High at $z > 5$ due to SED and population
  - QSOs: Small at $z > 5$ due to decrease in their population
- He II emissivity (228 Å)
  - Galaxies: Small $2 < z < 4$ due to SED
  - QSOs: High at $2 < z < 4$ due to SED and population



Epoch of Reionization

- Emissivity: Total number of ionizing photons produced
- How many of these photons escaped in to IGM?
    - Galaxies: f_{esc} Uncertain
    - QSOs: $f_{\mathrm{esc}} \sim 0.8 - 1.0$
- How do photons ionize IGM? ⇒ Radiative Transfer



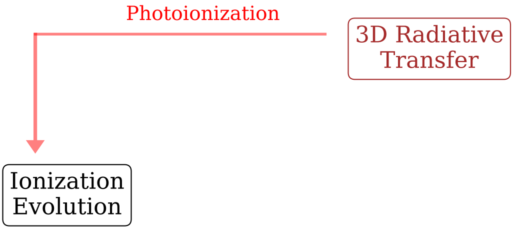
Radiative Hydrodynamics

3D Radiative Transfer

- Specific Intensity: $I_\nu(x, y, z, \theta, \phi, t)$
- Radiative Transfer Equation : Absorption, Emission, Scattering

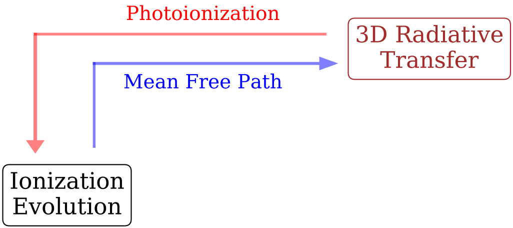
$$\frac{dI_\nu}{ds} = -I_\nu\,\alpha_\nu + j_\nu$$

Radiative Hydrodynamics



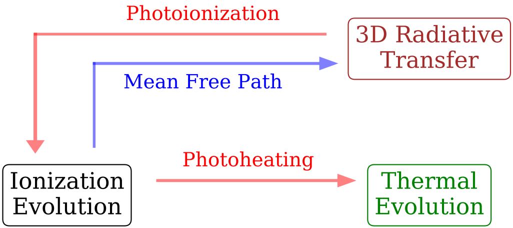
- Photoionization of He II $\Rightarrow$ He III

Radiative Hydrodynamics



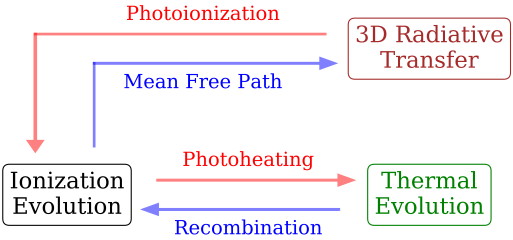
- Photoionization of He II ⇒ He III
- Large ionization fraction ⇒ larger mean free path

Radiative Hydrodynamics



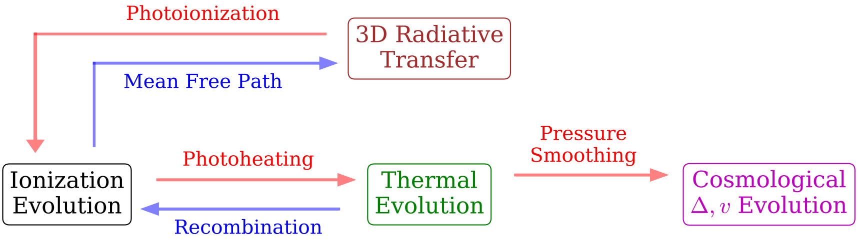
- Photoionization of He II $\Rightarrow$ He III
- Large ionization fraction $\Rightarrow$ larger mean free path
- Excess energy of ionizing photons carried away by electrons

Radiative Hydrodynamics



- Photoionization of He II ⇒ He III
- Large ionization fraction ⇒ larger mean free path
- Excess energy of ionizing photons carried away by electrons
- Larger temperature ⇒ Less probability of recombination.

Radiative Hydrodynamics



- Photoionization of He II $\Rightarrow$ He III
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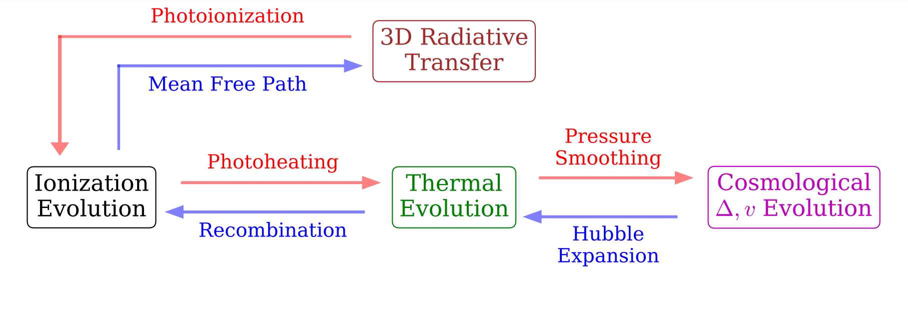
- Excess energy of ionizing photons carried away by electrons
- Larger temperature $\Rightarrow$ Less probability of recombination.
- Larger temperature $\Rightarrow$ Δ, v field smoothing

Radiative Hydrodynamics



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- Cooling due to Hubble expansion

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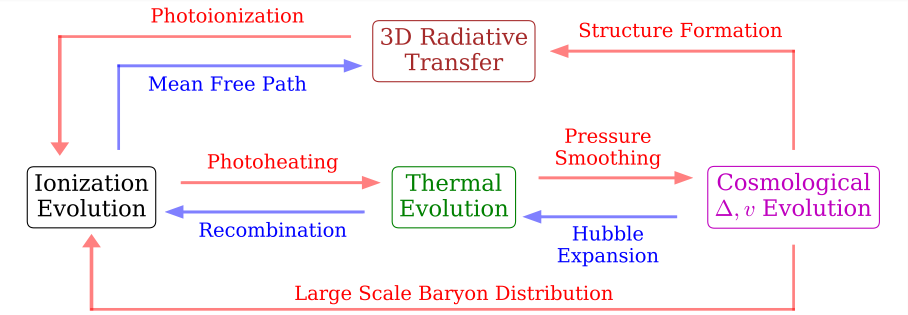
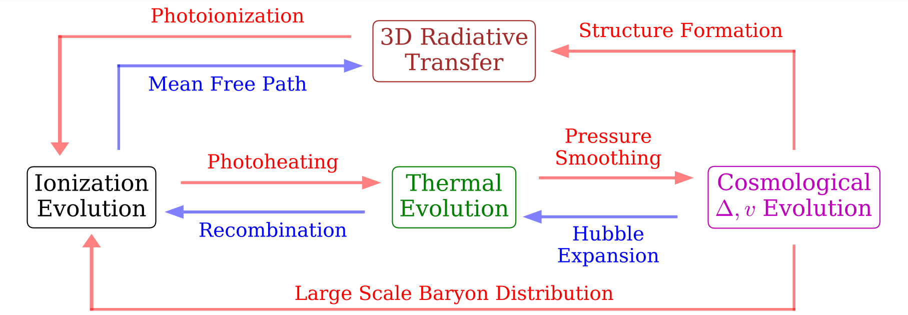


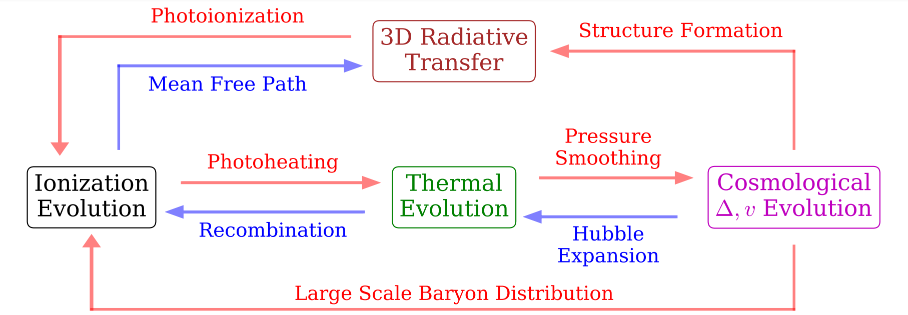
- Photoionization of He II $\Rightarrow$ He III
- Large ionization fraction $\Rightarrow$ larger mean free path
- Excess energy of ionizing photons carried away by electrons
- Larger temperature $\Rightarrow$ Less probability of recombination.
- Larger temperature $\Rightarrow$ Δ, v field smoothing
- Cooling due to Hubble expansion
- Distribution of gas in IGM and Galaxy formation and Evolution

Radiative Hydrodynamics



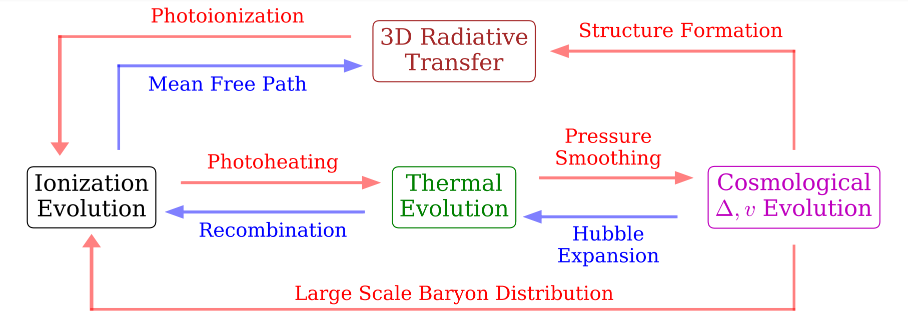
- Cosmological Radiative Hydrodynamics Simulation

Radiative Hydrodynamics



- Cosmological Radiative Hydrodynamics Simulation
- Computationally very expensive

Radiative Hydrodynamics



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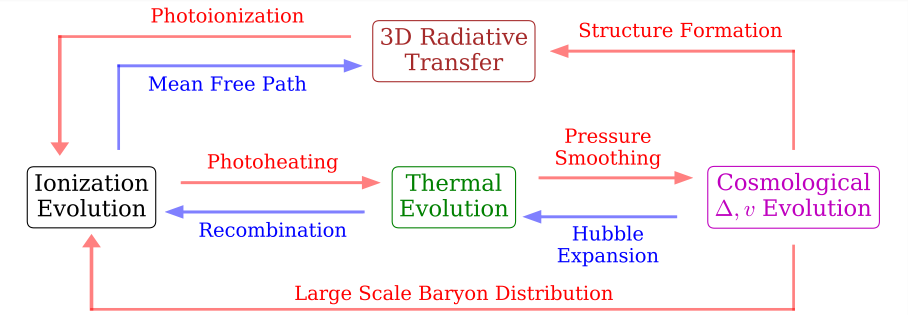
- Radiative Transfer Equation : Absorption, Emission, Scattering

$$\frac{dI_\nu}{ds} = -I_\nu \, \alpha_\nu + j_\nu$$

Radiative Hydrodynamics



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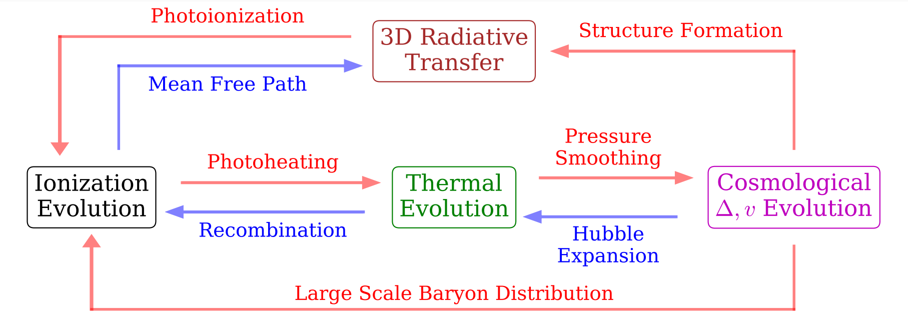
- $I_\nu(x, y, z, \theta, \phi, t)$: 7 Variables to discretize

Radiative Hydrodynamics



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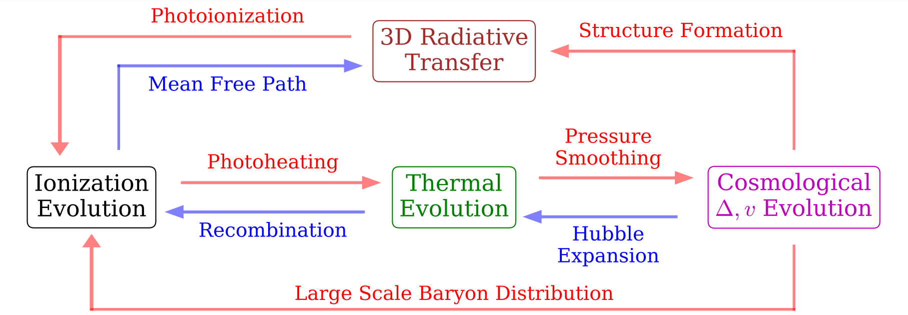
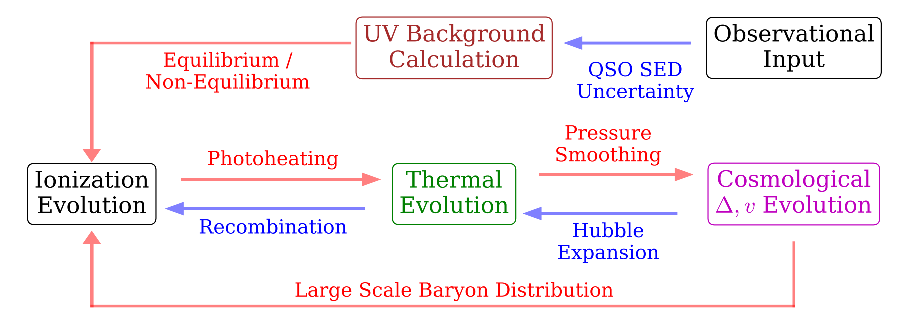
- $I_\nu(x, y, z, \theta, \phi, t)$: 7 Variables to discretize
- 1D Radiative Transfer Code : UVB Calculations

UV Background





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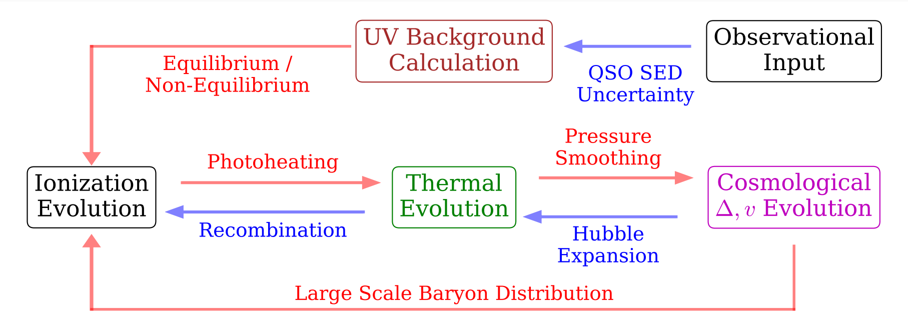
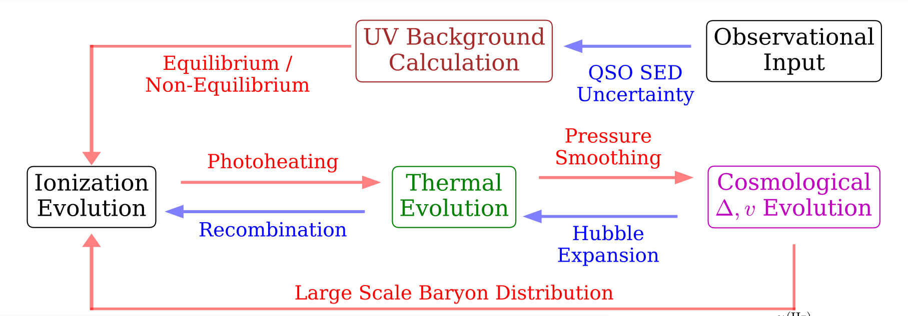


- Radiative Transfer Equation : Absorption, Emission, Scattering

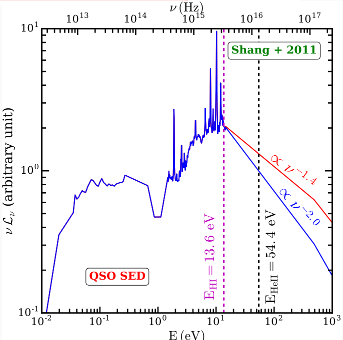
$$\frac{dI_\nu}{ds} = -I_\nu \, \alpha_\nu + j_\nu$$

- $I_\nu(x, y, z, \theta, \phi, t)$: 7 Variables to discretize
- Average over θ, ϕ, y, z
- Volume average emissivity: ϵ_ν (Sources + Recombination)
- Volume average emissivity: (Observational Input)

UV Background



- Emissivity: (What + How many)
- Emissivity: QSO SED
- Uncertainty in QSO SED index: Flatter ($\alpha \sim -1.4$) or Steeper ($\alpha \sim -2.0$)
- Aim-1: Effect of Uncertainty in QSO SED on Ionization and Thermal Evolution?



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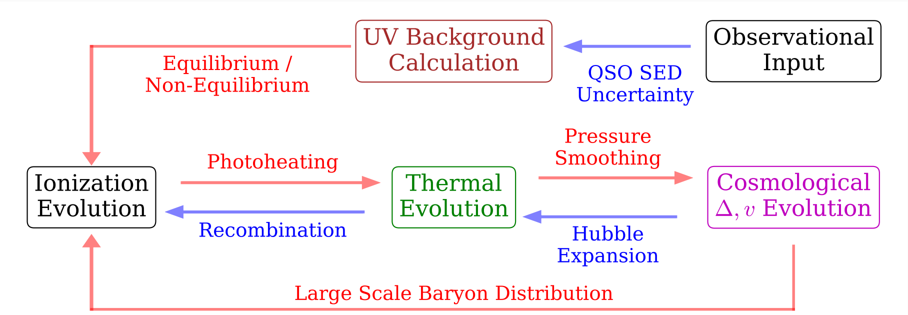
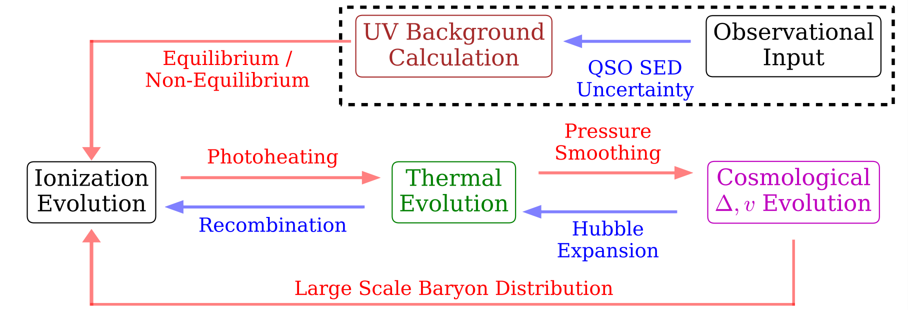


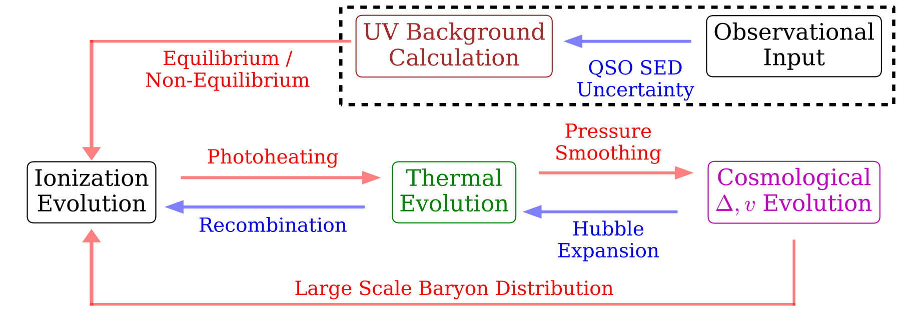
- How does ionization state of IGM evolve?
- Photo-ionization Equilibrium? Default in GADGET-3 (except Puchwein+2015)
- Eqbm $\Rightarrow$ Radiative time-scale $\leq$ Hubble or Dynamical timescale
- Photo-ionization Non-Equilibrium?
- Non-Eqbm $\Rightarrow$ Radiative time-scale $>$ Hubble or Dynamical timescale
- Aim-2: Effect of Eqbm/Non-Eqbm on Ionization and Thermal Evolution?

UV Background



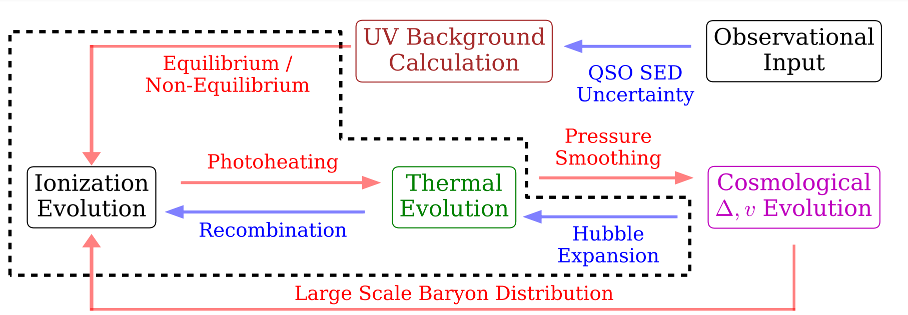
- Step-1: UVB Calculation with varying QSO SED indices

UV Background



- Step-1: UVB Calculation with varying QSO SED indices
- Step-2: Perform Cosmological hydrodynamical.
- Cosmological hydrodynamical simulations are still expensive.

UV Background



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- Step-2A: Code for Ionization and Temperature Evolution (CITE)

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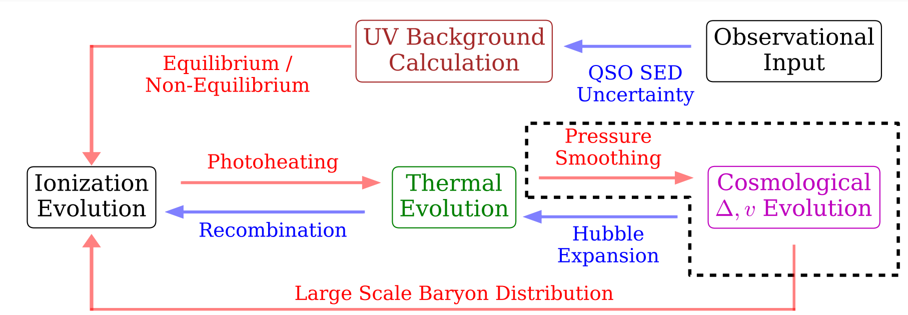

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- Cosmological hydrodynamical simulations are still expensive.
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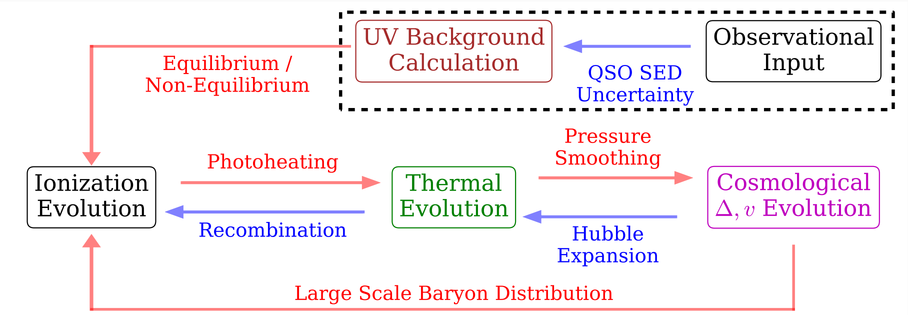
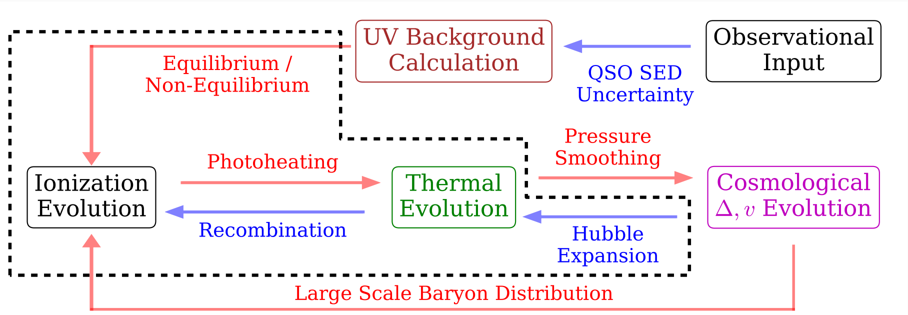
- Step-2B: Need to account for pressure smoothing effects
- Step-2B: Generating Ly-Alpha forest Spectra in Simulation (GLASS)

UV Background



- Step-1: UVB Calculation (PhD Thesis of Vikram Khaire)
- Khaire et.al. 2013,2015,2016,2017,2019 : PhD Thesis of Vikram Khaire

UV Background



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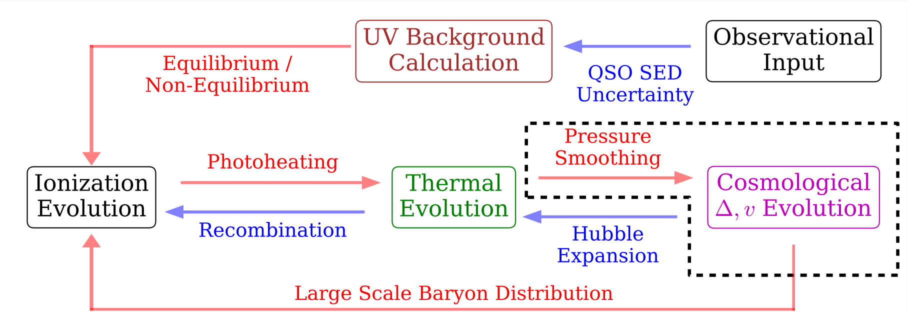
    - Step-2C: Constrain thermal and ionization evolution of IGM from observations

UV Background



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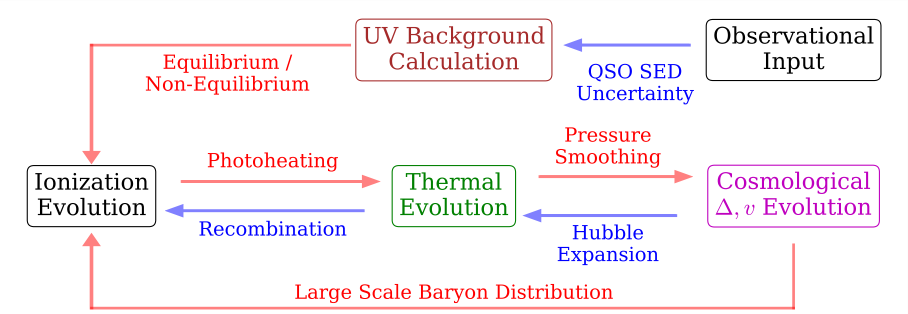
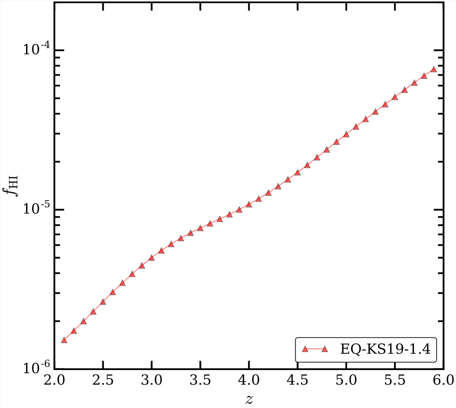
    - Step-2C: Constrain thermal and ionization evolution of IGM from observations
- Step-3: Constrain pressure smoothing scale from observations
  (Maitra+2019, PhD Thesis of Soumak Maitra, in progress)

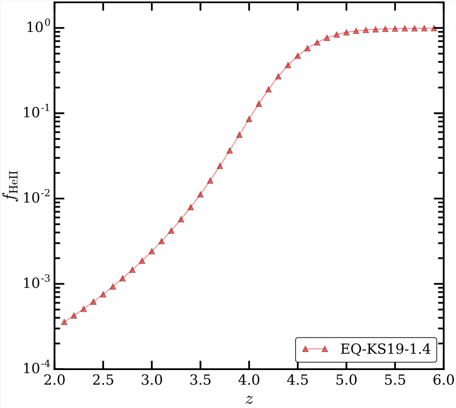
Effect on Ionization Evolution

UV Background



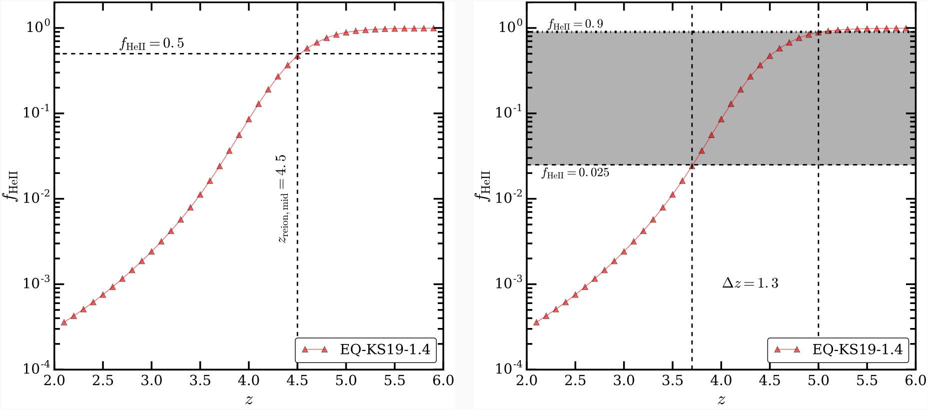
f_{HeII} Evolution: QSO SED index





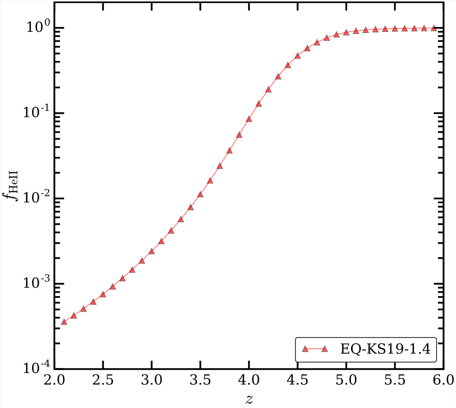
- At $2 \leq z \leq 5$: H I is highly ionized and is in photo-ionization equilibrium.
- Volume average He II fraction evolution : $f_{\mathrm{HeII}} \sim n_{\mathrm{HeII}}/n_{\mathrm{He}}$

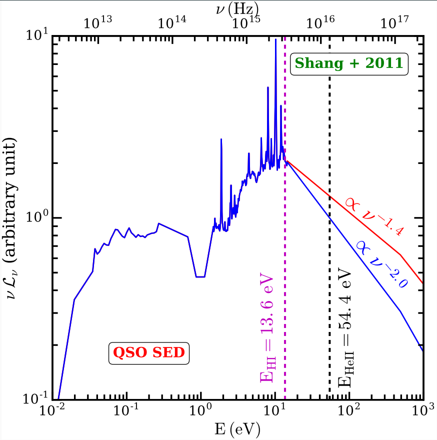
f_{HeII} Evolution: QSO SED index



- Redshift of He II reionization: z at $f_{\mathrm{HeII}} \sim 0.5$
- Duration/Extent of He II reionization: Δz for $0.025 \leq f_{\mathrm{HeII}} \leq 0.9$

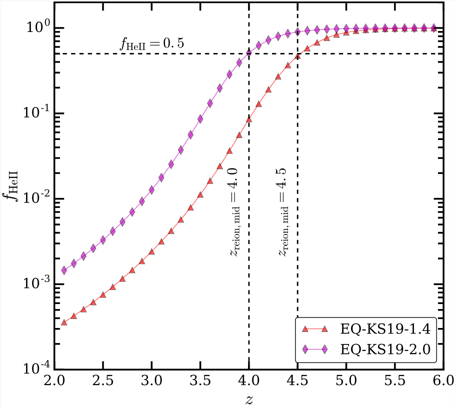
f_{HeII} Evolution: QSO SED index

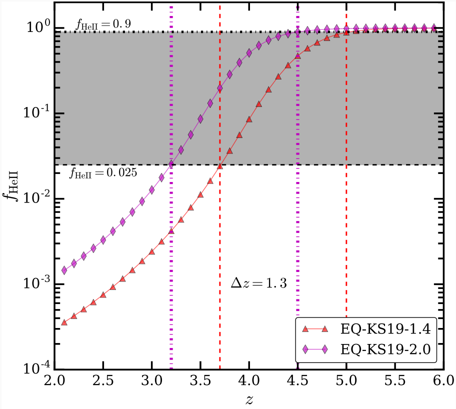




- Steeper QSO SED $\Rightarrow$ Less number of He II Ionizing photons
- Require more time to ionize intergalactic He II.
- Steeper QSO SED $\Rightarrow$ Late He II reionization.

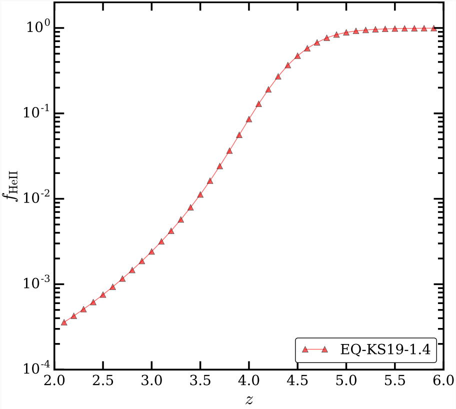
$f_{\rm HeII}$ Evolution: QSO SED index





- Steeper QSO SED $\Rightarrow z_{\rm reion,mid} \sim 4.0$
- Flatter QSO SED $\Rightarrow z_{\rm reion,mid} \sim 4.5$
- Duration of He II reionization ($\Delta z \sim 1.33$) is relatively same.
- Steeper QSO SED $\Rightarrow$ Late He II reionization.

f_{HeII} Evolution: Non-Equilibrium Effects

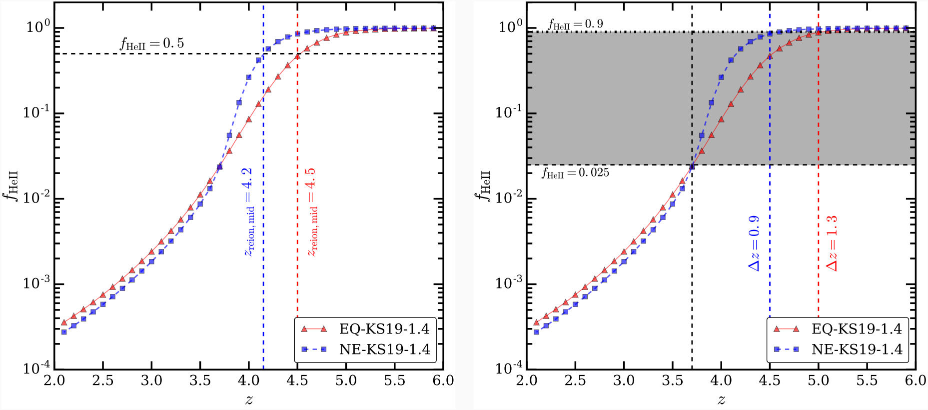


- Ionization evolution equation

$$\frac{d\mathrm{X}_i}{dt} = \alpha_{\mathrm{X}_{i+1}}(T)\, n_e\, \mathrm{X}_{i+1} \; - \; \mathrm{X}_i\, (\Gamma_{\gamma,\mathrm{X}_i} + \Gamma_{\mathrm{e},\mathrm{X}_i}\, n_{\mathrm{e}})$$

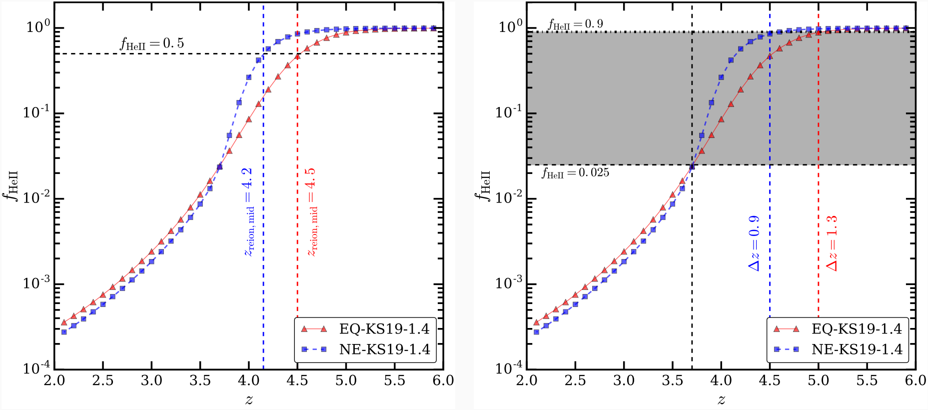
- Equilibrium Ionization evolution: $dX_{\mathrm{i}}/dt = 0$: (Default in GADGET-3)

f_{HeII} Evolution: Non-Equilibrium Effects



- Equilibrium Ionization evolution: Radiative processes time scales are short compared to dyanmical and Hubble time-scales.
- Non-Equilibrium Ionization evolution: Radiative processes time scales are no longer short compared to dyanmical and Hubble time-scales.

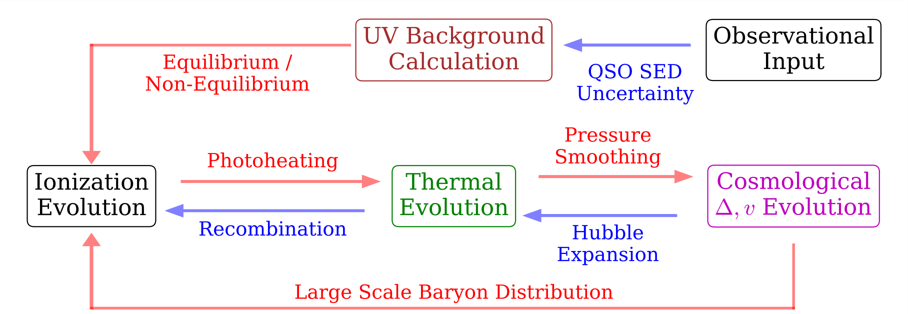
$f_{\rm HeII}$ Evolution: Non-Equilibrium Effects



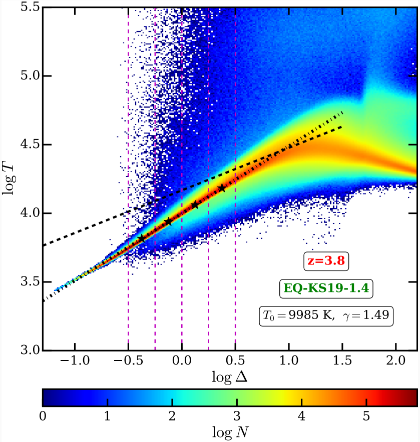
- Duration of He II reionization in Non-Eqbm ($\Delta z \sim 0.9$) is shorter than Eqbm ($\Delta z \sim 1.33$).
- $f_{\rm HeII}$ initially evolves slowly in Non-Eqbm. Eqbm is reached at $z \leq 3.7$.

Effect on Thermal Evolution

UV Background

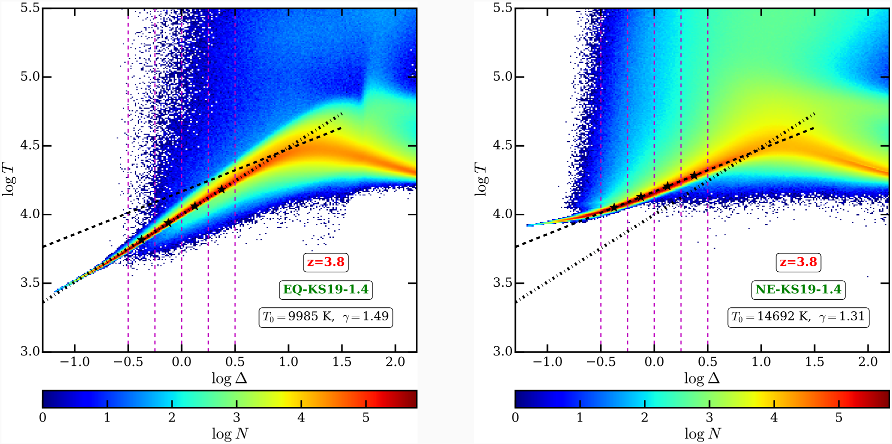


Temperature-Density Relation



- Low density gas in IGM follows power-law TDR $T = T_0\,\Delta^{\gamma-1}$
- Evolution of T_0 and γ can be used to constrain timing and nature of He II reionization.
- What is the effect of Non-eqbm ionization evolution?
- T_0 (γ) is higher (lower) in Non-eqbm model compared to Eqbm model.

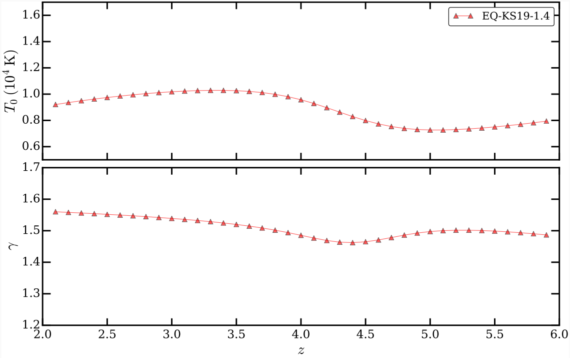
Temperature-Density Relation



- Low density gas in IGM follows power-law TDR $T = T_0\,\Delta^{\gamma-1}$
- Evolution of T_0 and γ can be used to constrain timing and nature of He II reionization.
- What is the effect of Non-eqbm ionization evolution?
- T_0 (γ) is higher (lower) in Non-eqbm model compared to Eqbm model.

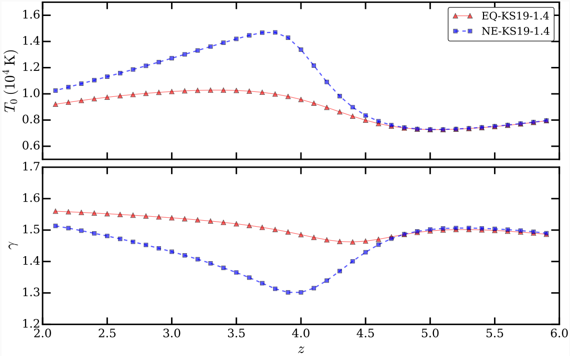
Link

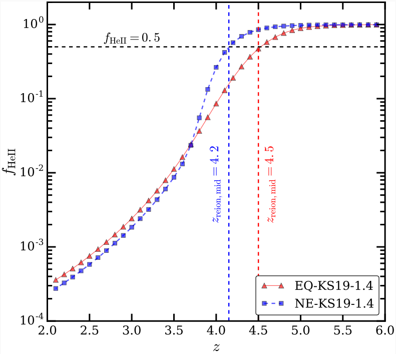
Thermal Parameter Evolution



- Evolution of T_0 and γ in Eqbm model

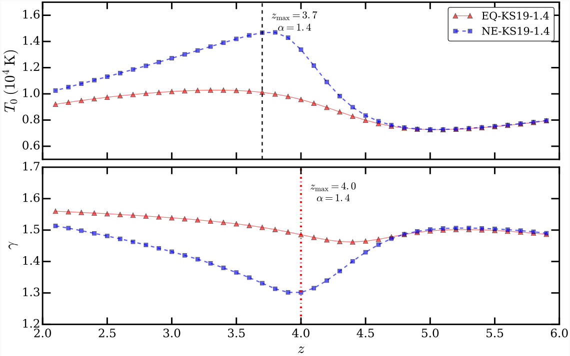
Thermal Parameter Evolution

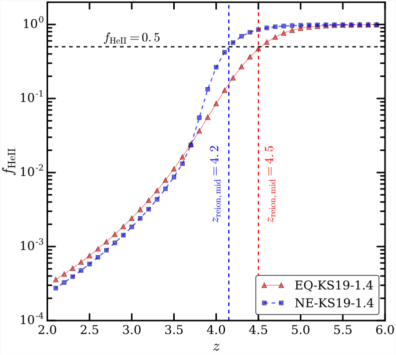




- Evolution of T_0 and γ in Eqbm model
- T_0 higher in Non-Eqbm model
- Heating rate: $\mathcal{H} \approx \epsilon_{\rm HeII}\, f_{\rm HeII}$
- Larger heating $\Rightarrow$ Higher Temperature
- Higher $T_0 \Rightarrow$ Flatter TDR (small γ)
- Heating is independent of density

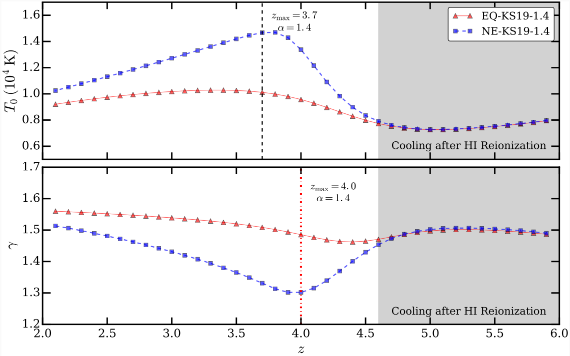
Thermal Parameter Evolution

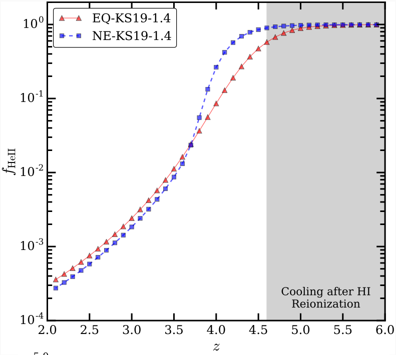




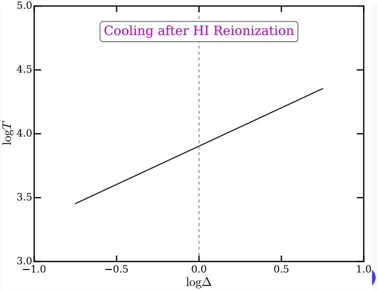
- The maxima in T_0 occurs at $z \sim 3.7$
- The minima in γ occurs at $z \sim 4.0$
- Evolution of $T_0 - \gamma$ closely related to f_{HeII}

Thermal Parameter Evolution

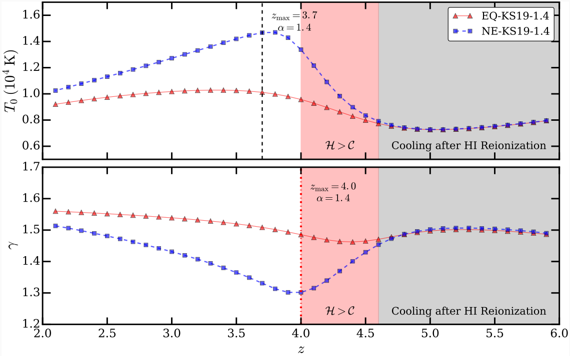


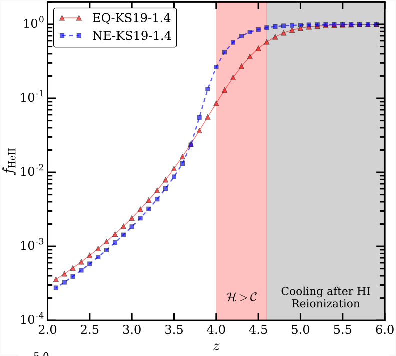


- Adiabatic cooling after H I reionization
- $T_0 \sim 8000$, $\gamma \sim 1.55$ [Macquinn+2015]

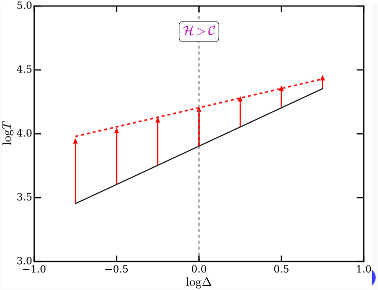


Thermal Parameter Evolution

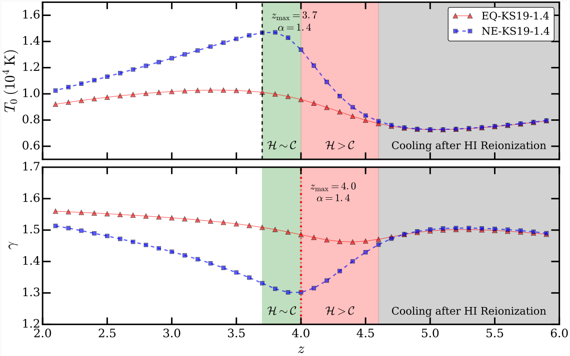


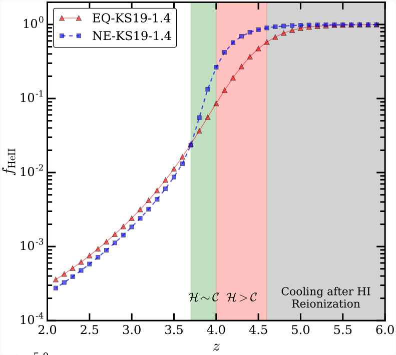


- He II ionization starts heating IGM
- Heating independent of density
- T_0 increases, γ decreases (flat TDR)

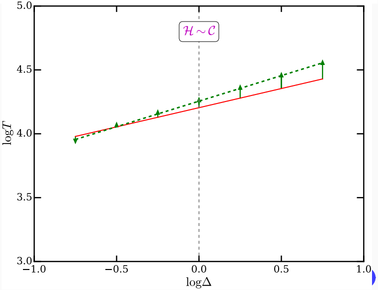


Thermal Parameter Evolution

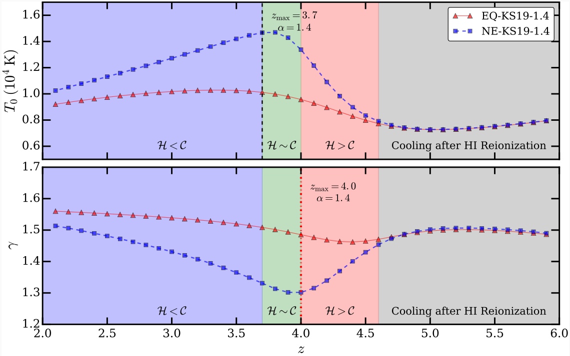


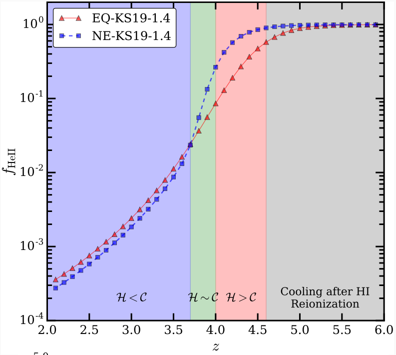


- Cooling and Heating are comparable
- Low density IGM freely expands with Universe
- Hubble expansion effective in low density IGM
- Slightly overdense regions responds lately to Hubble expansion
- T_0 increases, γ increases (steep TDR)

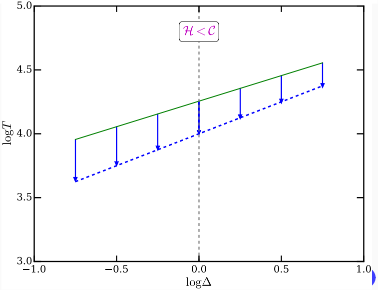


Thermal Parameter Evolution

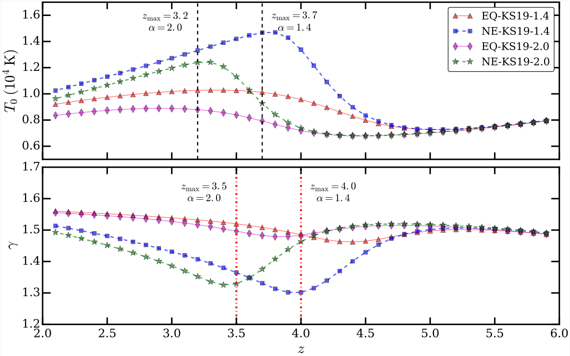


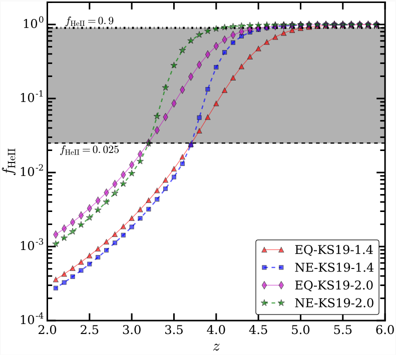


- No more photo-heating from He II ionization
- IGM is now in photo-ionization Eqbm
- All densities ($\Delta < 10$) cool by Hubble expansion
- T_0 decreases, γ increases (steep TDR)
- Similar to cooling of IGM after H I reionization



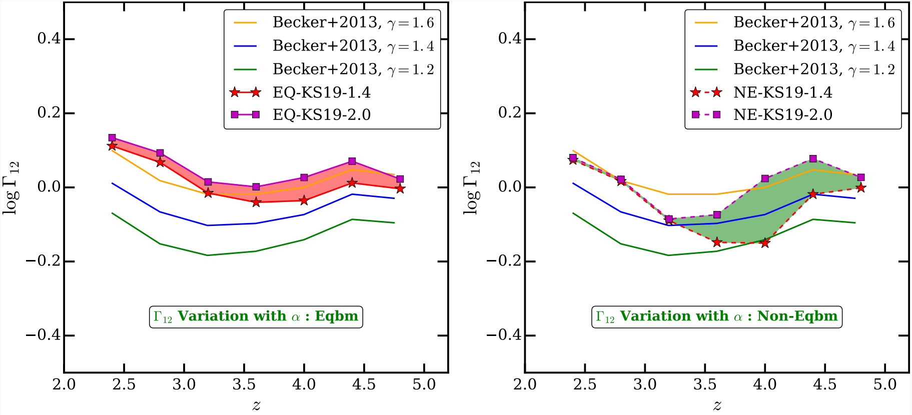
Thermal Parameter Evolution





- T_0 is systematically smaller in steeper QSO SED than flatter QSO SED.
- What is the effect of T_0 and γ evolution on H I Lyα forest?
- Photo-ionization rates derived from H I Lyα forest assume evolution of T_0 and γ.

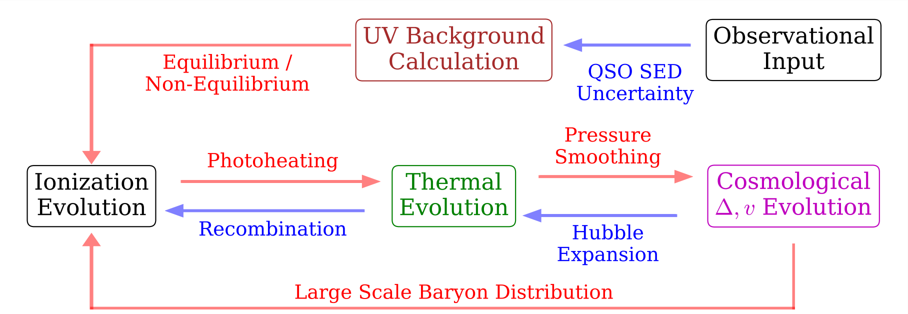
HI Photo-ionization rate



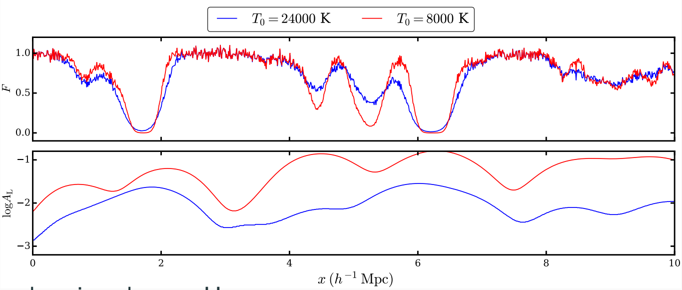
- The derived Γ_{HI} evolution is different for Equilibrium and Non-equilibrium evolution.

Observations: Thermal Evolution

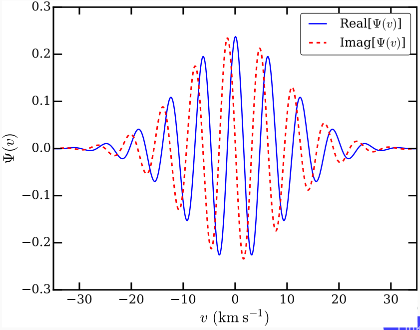
UV Background



$T_0 - \gamma$ Evolution

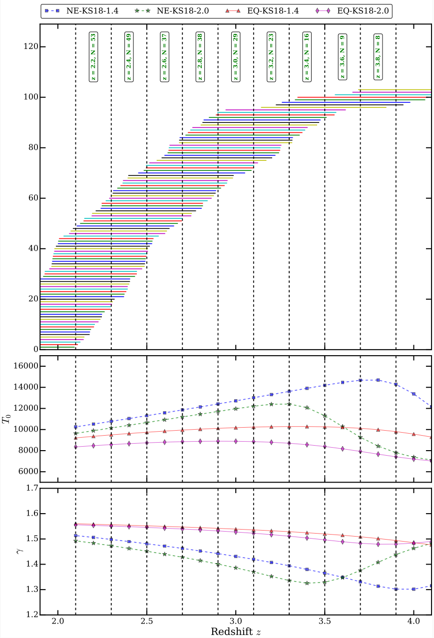


- Photo-heating due to He II reionization $\Rightarrow$ T_0 increases
- H I is in photo-ionization equilibrium
- Width of absorption line in H I Lyα forest increases systematically
- Convolve with wavelet of suitable scale and calculate PDF to constrain the temperature.



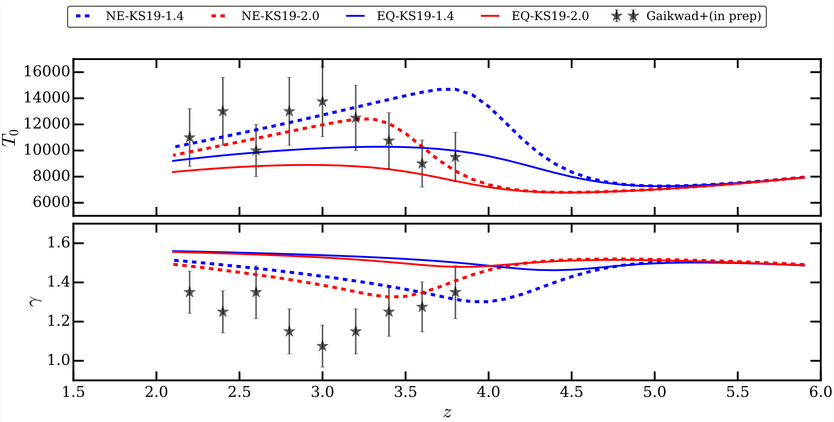
$T_0 - \gamma$ Evolution

[Omeara+2017]



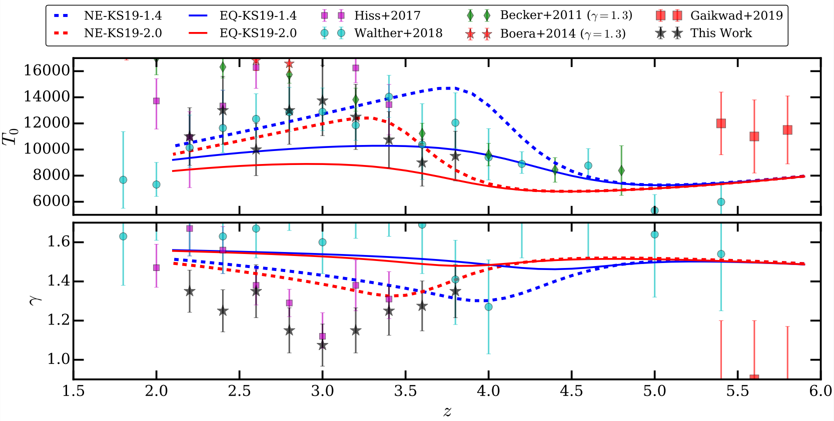
- KODIAQ DR2 Sample
- 296 QSO absorption spectra
- 106 QSO absorption spectra after removing DLA, LLS, sub-DLA
- Velocity resolution: $\Delta v \sim 6$ $\mathrm{km\,s^{-1}}$, $b_{\mathrm{HI}} \sim 12.8$ $\mathrm{km\,s^{-1}}$
- SNR per pixel $\sim 6 - 52$

$T_0 - \gamma$ Evolution



- Constraints on $T_0 - \gamma$ using wavelet statistics from 106 QSO sample.
- T_0 evolution is roughly consistent with steeper QSO SED ($\alpha \sim -2.0$) model
- Work in progress: Other statistics to constrain T_0 and γ.

$T_0 - \gamma$ Evolution

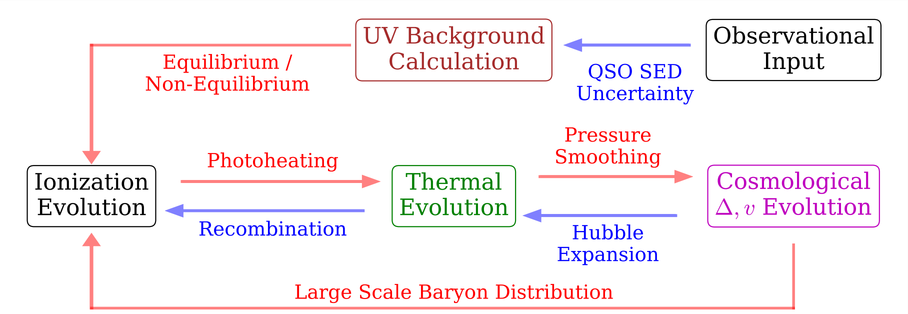


- $T_0 - \gamma$ evolution from literature.

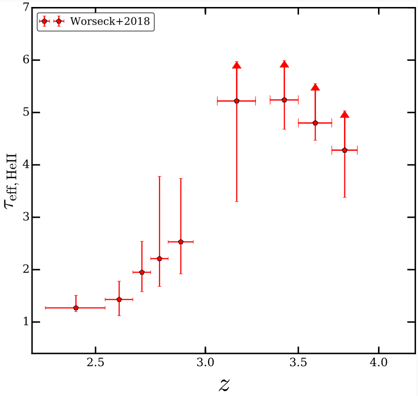
Link

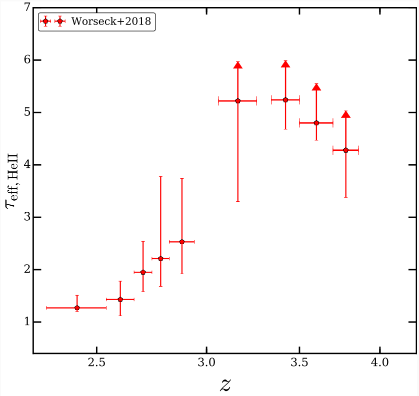
Observations: Ionization Evolution

UV Background



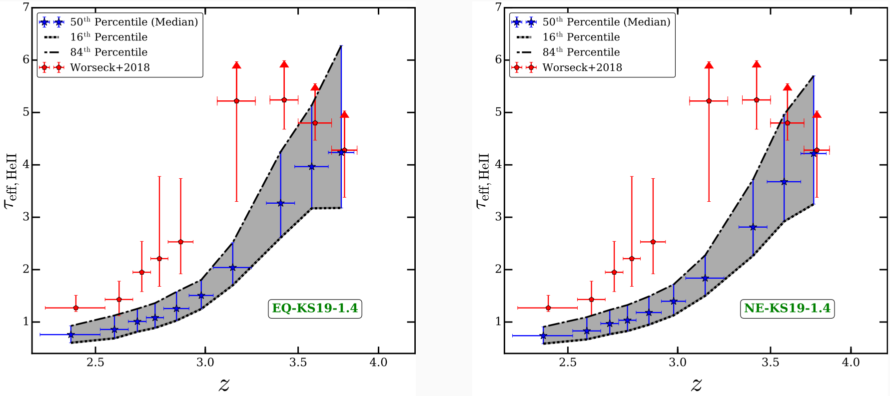
He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution





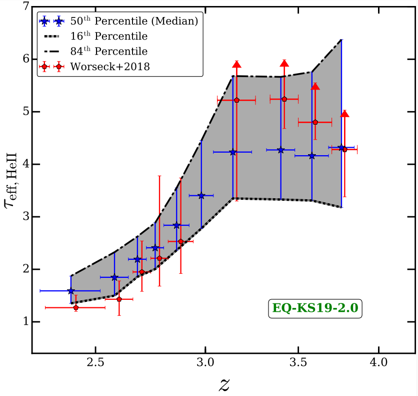
- He II Lyα forest is in UV: HST-COS spectra
- Effective optical depth $\tau_{\mathrm{eff,HeII}} = -\ln\langle F\rangle$
- Effective optical depth: Robust quantity
- Effective optical depth: Less effect of resolution
- $T \sim 10^4$ K, $b_{\mathrm{HI}} \sim 12.8\ \mathrm{km\,s^{-1}}$, $b_{\mathrm{HeII}} \sim 6.4\ \mathrm{km\,s^{-1}}$
- Best HST-COS resolution (G130M) is $\sim 17\ \mathrm{km\,s^{-1}}$

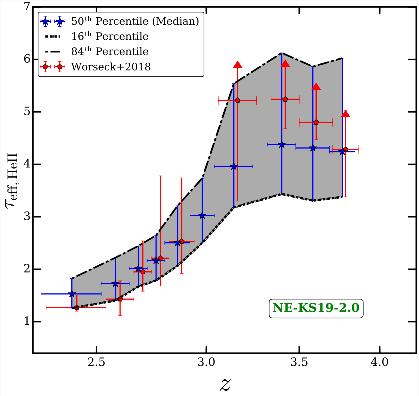
He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution



- He II Lyα forest generate from simulation
- Accounted for following effects
  - Pressure smoothing (GLASS)
  - LSF of HST-COS: Not Gaussian
  - Finite SNR: Sensitivity limit for $\tau_{\mathrm{eff,HeII}}$ measurements
- Flatter QSO SED ($\alpha \sim -1.4$) models are not consistent with observations

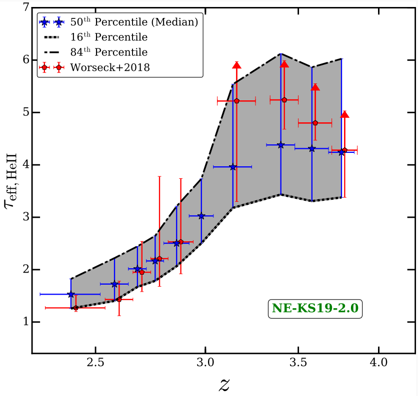
He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution

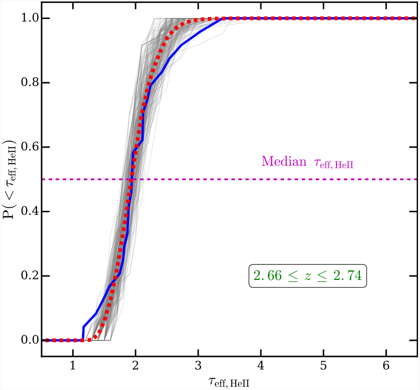




- Steeper QSO SED ($\alpha \sim -2.0$) models are consistent with observations
- At $z \leq 3$
  - Non-Equilibrium model with $\alpha \sim -2.0$ is in better agreement with data
  - Equilibrium model with $\alpha \sim -1.9$ is in better agreement with data
- At $z > 3$ observed $\tau_{\mathrm{eff,HeII}}$ is systematically larger than model. Why?

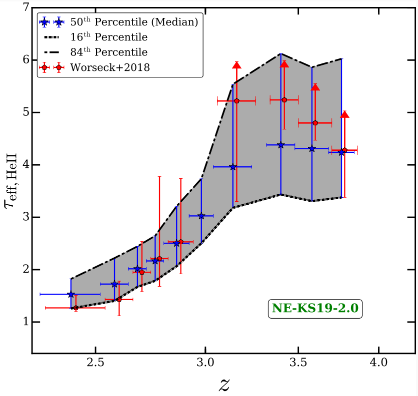
He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution

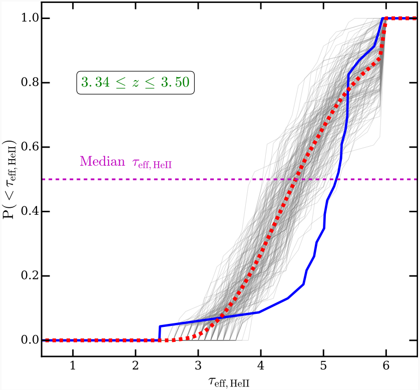




- Simulated $\tau_{\mathrm{eff,HeII}}$ CDF is consistent with observed $\tau_{\mathrm{eff,HeII}}$ CDF at $2.66 \leq z \leq 2.74$
- Blue curve $\Rightarrow$ $\tau_{\mathrm{eff,HeII}}$ CDF from Observations
- Red curve $\Rightarrow$ mean $\tau_{\mathrm{eff,HeII}}$ CDF from Simulations
- Gray curves $\Rightarrow$ $\tau_{\mathrm{eff,HeII}}$ CDF from each mock sample (Simulation)

He II Effective Optical Depth ($\tau_{\rm eff,HeII}$) Evolution

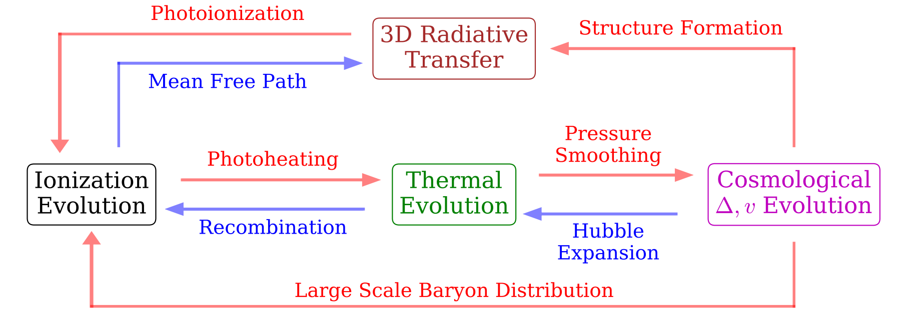


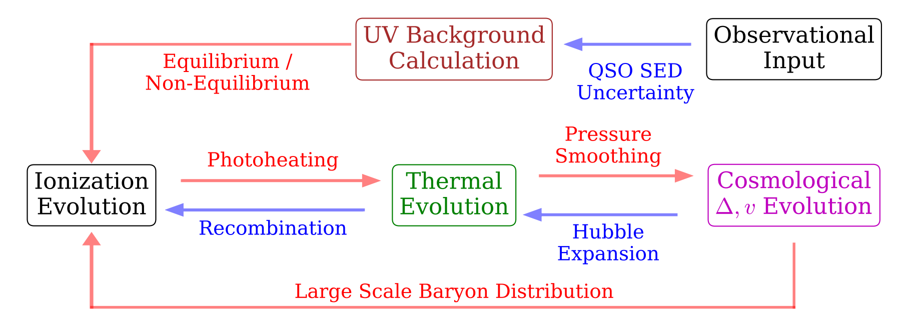


- Simulated $\tau_{\rm eff,HeII}$ CDF is not in agreement with observed $\tau_{\rm eff,HeII}$ CDF at $3.34 \le z \le 3.50$
- Our model reproduces lower limit on $\tau_{\rm eff,HeII}$ very well
- Our model does not produce scatter in $\tau_{\rm eff,HeII}$.
- Fluctuations in $\Gamma_{\rm HeII}$ are important at $z > 3$.
- Our model do not include fluctuations in $\Gamma_{\rm HeII}$.

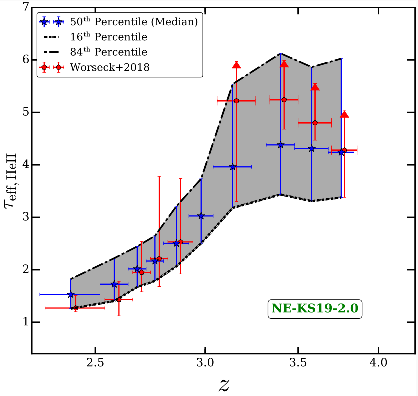
Link

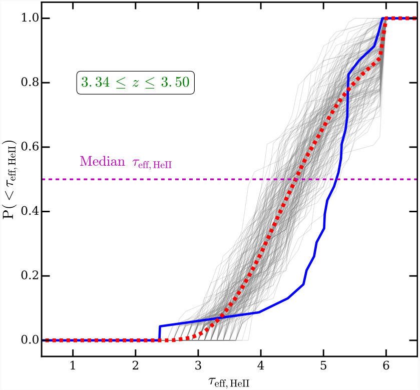
He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution





He II Effective Optical Depth ($\tau_{\mathrm{eff,HeII}}$) Evolution

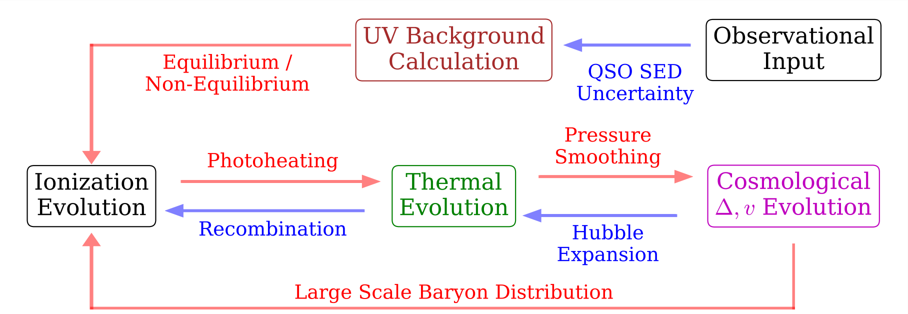




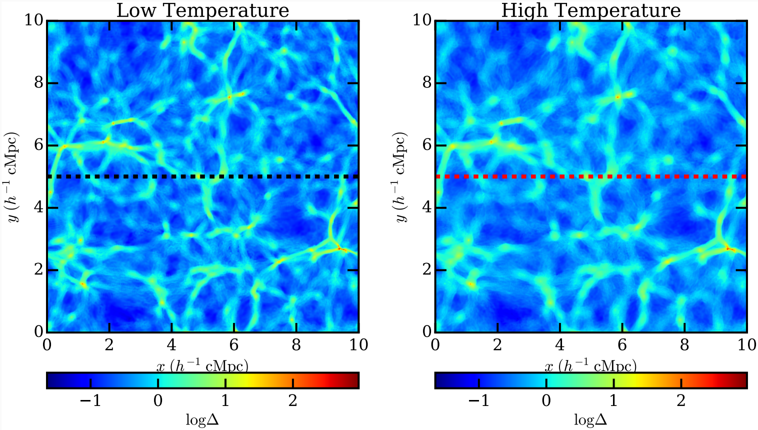
- It is important to account for fluctuations in Γ_{HeII} to explain scatter in observed $\tau_{\mathrm{eff,HeII}}$.
- Such fluctuations in Γ_{HeII} can also lead to systematics in BAO using Lyα forest measurements.

Observations: Pressure Smoothing

UV Background

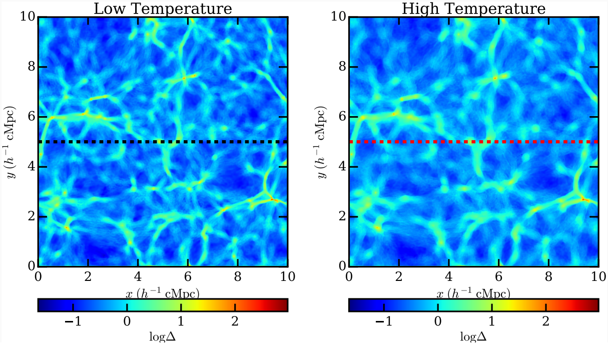


Pressure Smoothing



- Smoothing of density and velocity field due to increase in temperature
- Pressure smoothing scale can be observationally constrained
- Correlation of pixels/absorbers along sightline (Longitudinal)
- Correlation of pixels/absorbers in transverse direction: QSO doublet or triplet

Pressure Smoothing



Three- and two-point spatial correlations of intergalactic medium at $z \sim 2$ using projected quasar triplets

Soumak Maitra,[1★] Raghunathan Srianand,[1] Patrick Petitjean[2], Hadi Rahmani[3], Prakash Gaikwad[4,5], Tirthankar Roy Choudhury[6] & Christophe Pichon[2,7]

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[2] *Institut d'Astrophysique de Paris, CNRS-SU, UMR 7095, 98bis bd Arago, 75014, Paris, France*
[3] *GEPI, Observatoire de Paris, PSL Universite, CNRS, 5 Place Jules Janssen, 92190 Meudon, France*
[4] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK*
[5] *Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK*
[6] *National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune 411007, India*
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Summary

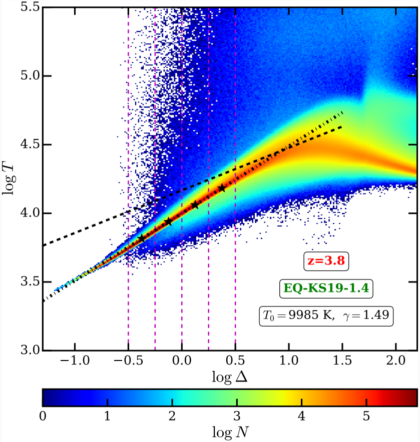
Summary

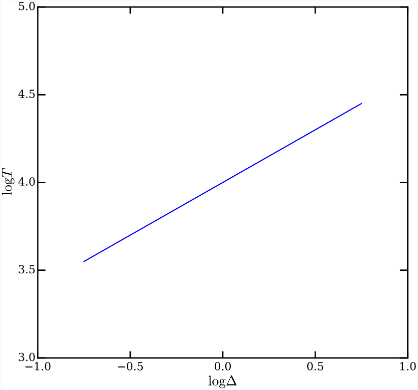
- Cosmological radiative hydrodynamical simulations are very expensive
- UV background calculation + Cosmological hydrodynamical simulations
- Cosmological hydrodynamical simulations: CITE + GLASS
- Uncertainty in UVB calculation: QSO SED index
- Ionization Evolution: Eqbm or Non-Eqbm
- Thermal ($T_0 - \gamma$) Evolution:
    - Constraints on $T_0 - \gamma$ from sample of KODIAQ-DR2 106 QSO spectra
    - Steeper QSO SED index and Non-Eqbm evolution
- Ionization Evolution:
    - $\tau_{\mathrm{eff,HeII}}$ Evolution $\Rightarrow$ Steeper QSO SED index
    - $\tau_{\mathrm{eff,HeII}}$ Evolution at $z > 3$ $\Rightarrow$ Fluctuations in UVB are important
- Pressure Smoothing:
    - QSO doublet and triplet

Index

- $\mathrm{T} - \Delta$ Relation
- $\mathrm{T}_0 - \gamma$ Evolution
- Radiative Hydrodynamics
- $\tau_{\mathrm{eff,HeII}}$ Evolution

Temperature-Density Relation





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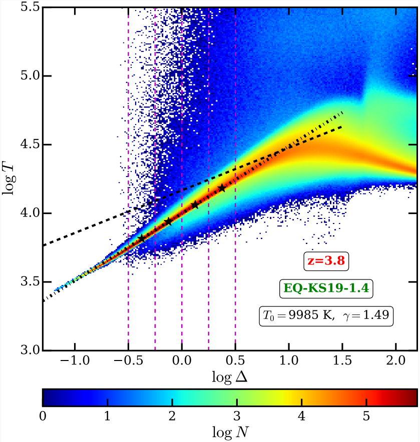
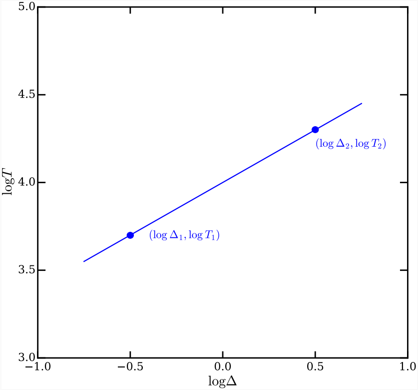
Temperature-Density Relation





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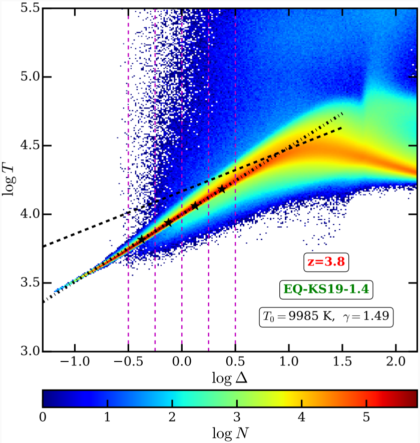
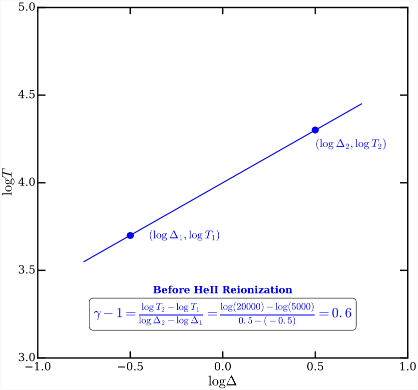
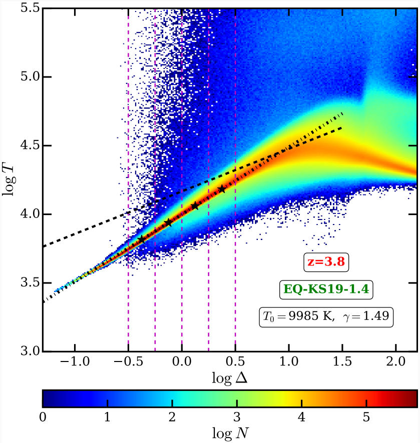
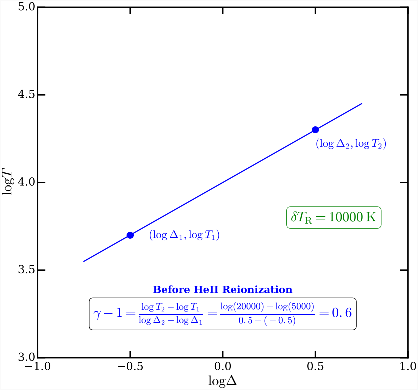




Temperature-Density Relation





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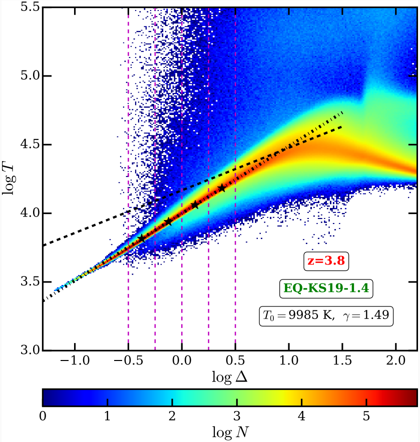
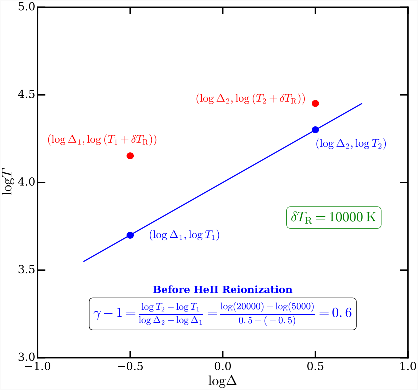
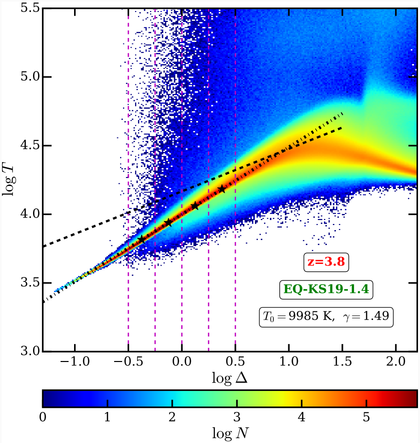
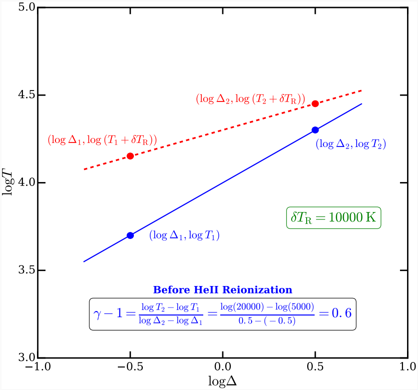




Link

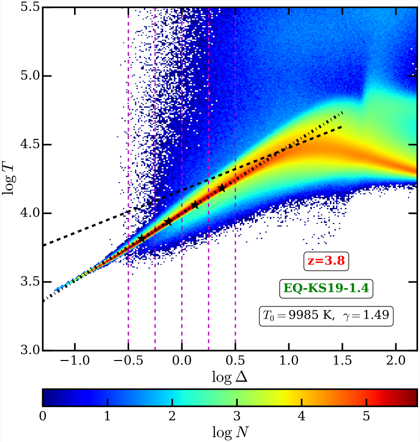
Temperature-Density Relation

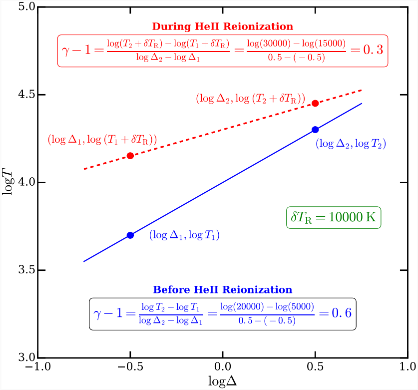




Link

Temperature-Density Relation





Link