Constraints on HI photoionization rate and escape fraction at $z < 0.5$ from Lyα forest

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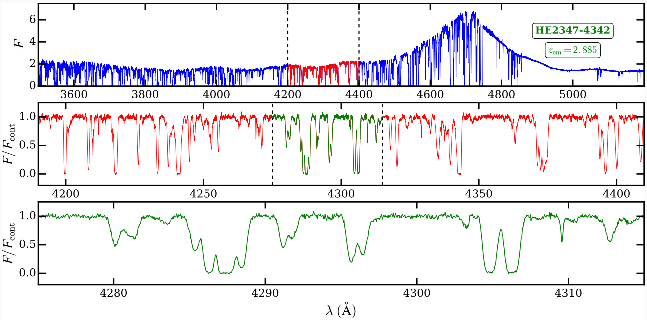
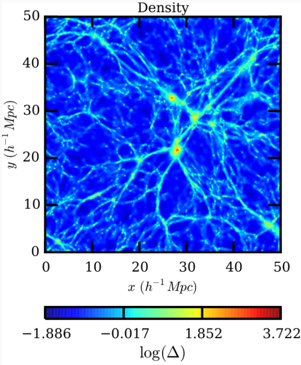
Outline

- Introduction
- Observations
- Simulations
- Result
- Summary

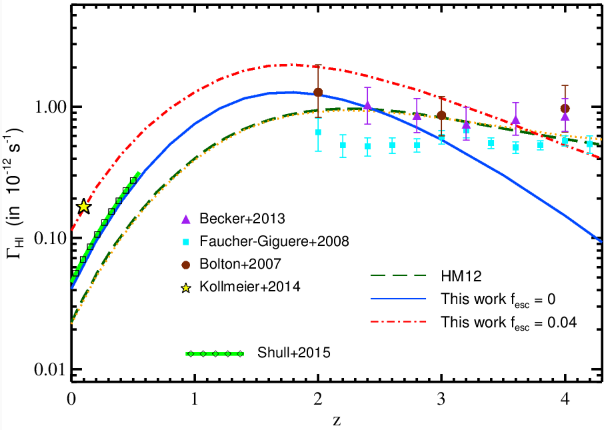
Introduction





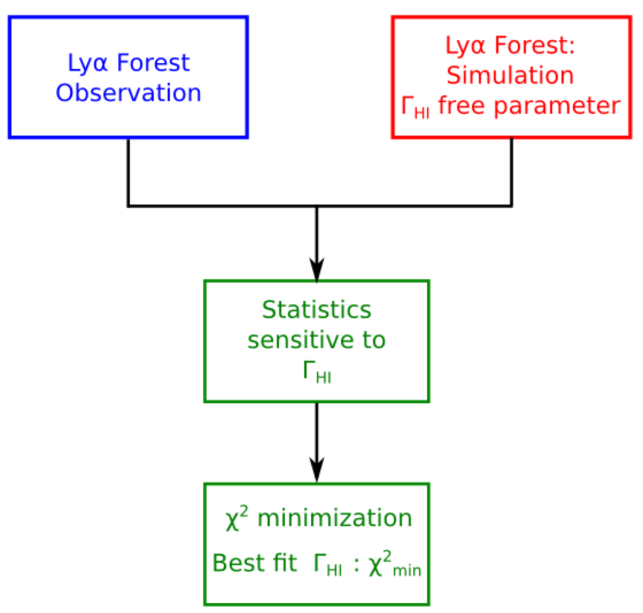
- The IGM is highly ionized at low-z.
- Ultra-Violet Background (UVB) at low-z ($z < 0.5$): QSO and/or Galaxies?
- Galaxy contribution to UVB, Escape fraction (f_{esc})?
- H I photoionization rate Γ_{HI}: Number of H I ionizing photons per unit time
- Ly-α forest: Fluctuations in cosmic density field, Thermal and Ionization state of IGM

H I Photoionization rate [Khaire & Srianand, 2015a], [Khaire et.al, 2015b]



- [Kollmeier et.al 2014] and [Shull et.al 2015]: HST-COS, CDDF, No errorbars
- [Kollmeier et.al 2014] $\Rightarrow f_{\rm esc} \sim 4\%$, [Shull et.al 2015] $\Rightarrow f_{\rm esc} \sim 0\%$
- $\Gamma_{\rm HI}$ with appropriate error bars at $z < 0.5$?
- Evolution of $\Gamma_{\rm HI}$ and Escape fraction $f_{\rm esc}$?

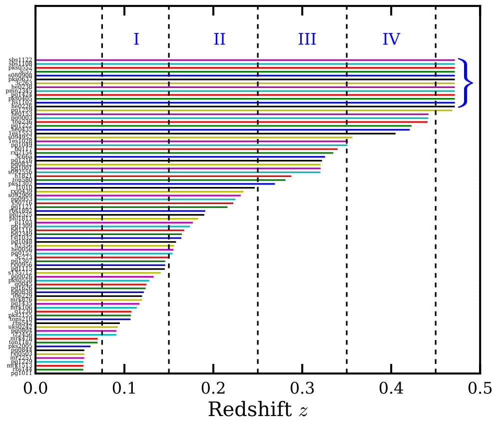
Basic idea



Lyα Forest
Observation
Lyα Forest:
Simulation
Γ_HI free parameter
Statistics
sensitive to
Γ_HI
χ² minimization
Best fit Γ_HI : χ²_min

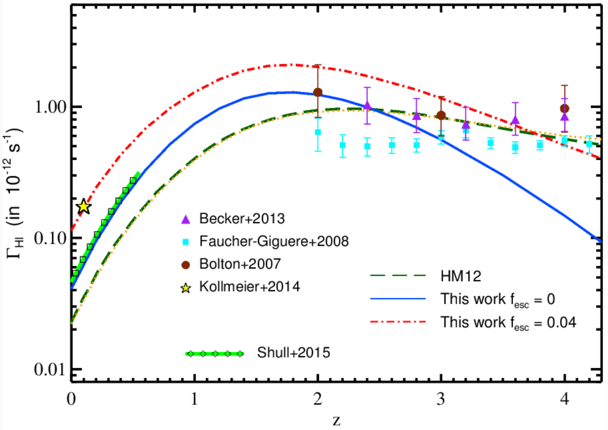
Observation Data

[Danforth et.al, 2015]



- Instrument: HST-COS
- Number of spectra: 82
- SNR : 4 to 16
- Resolution $\Delta v \sim 17 km/s$
- Instrumental Broadening: Not Gaussian
- Continuum Fitting
- Metal Lines and higher transition lines are removed
- QSO proximity zone : High ionization due to radiation from QSO itself ($\sim 25 h^{-1}$ Mpc)

H I Photoionization rate [Khaire & Srianand, 2015a], [Khaire et.al, 2015b]

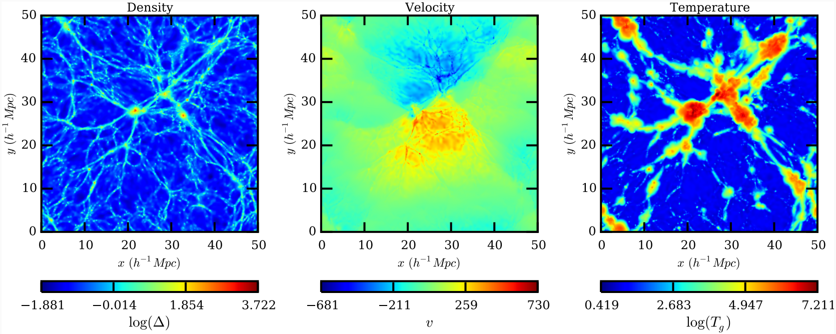


- Uncertainty in Γ_{HI} : Degeneracy with astrophysical parameters (T_0, γ)
- Performing a SPH simulation at $z \sim 0$ with different thermal history is computationally expensive
- Need a method to efficiently vary the thermal history.

Simulation

SPH Simulation

[Springel 2005, Gaikwad et.al. 2017a]

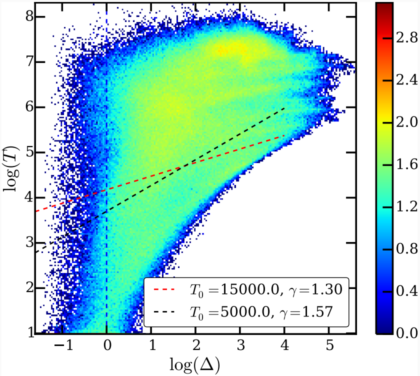


- GADGET-2 (SPH) : No AGN or Stellar feedbacks
- ΛCDM cosmology, $L_{\rm box} = 50h^{-1}$ cMpc, 2×512^3 DM + Baryons
- Snapshots are stored at $z = 2.1, 2.0, \cdots, 0.1, 0$
- Radiative heating and cooling processes are not included in GADGET-2

$$\underbrace{\frac{dT}{dt}}_{\text{Temperature evolution}} = \underbrace{-2HT}_{\text{Hubble expansion}} + \underbrace{\frac{2T}{3\Delta}\frac{d\Delta}{dt}}_{\text{Adiabatic Term}} + \underbrace{\frac{dT_{\rm shock}}{dt}}_{\text{Shock heating}} + \underbrace{\frac{2}{3k_B n_b}\frac{dQ}{dt}}_{\text{Radiative Heating / Cooling Processes}}$$

$T - \Delta$ Relation: CITE [Gaikwad et al. 2017a]

GADGET-2



$T - \Delta$ relation is not a power-law.

Code for Ionization and Temperature Evolution (CITE)

Initial Condition: $z = 2.1$ with $T_0 = 15000$ K and $\gamma = 1.3$ [Boera+2014]

Solve ionization evolution equation (Eqbm or Non-Eqbm), for each SPH particle

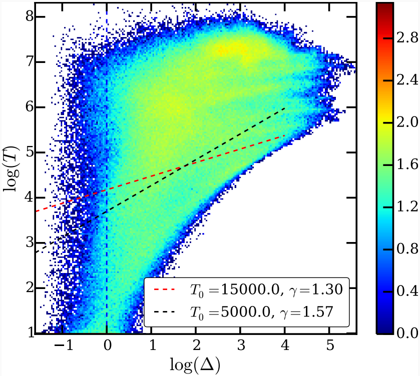
$$\frac{dX_i}{dt} = \alpha_{X_{i+1}}(T)\, n_e\, X_{i+1} - X_i\,(\Gamma_{\gamma,X_i} + \Gamma_{e,X_i}\, n_e)$$

Compute radiative heating/cooling term (dQ/dt).

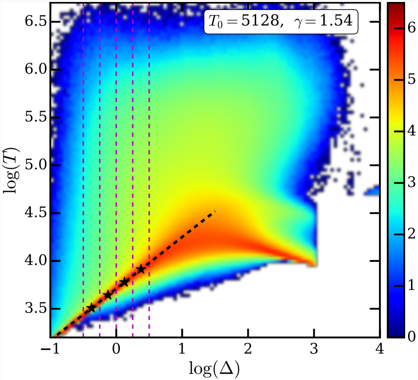
$$\underbrace{\frac{dT}{dt}}_{\text{Temperature evolution}} = \underbrace{-2HT}_{\text{Hubble expansion}} + \underbrace{\frac{2T}{3\Delta}\frac{d\Delta}{dt}}_{\text{Adiabatic Term}} + \underbrace{\frac{dT_{\text{shock}}}{dt}}_{\text{Shock heating}} + \underbrace{\frac{2}{3k_B n_b}\frac{dQ}{dt}}_{\text{Radiative Heating / Cooling Processes}}$$

$T - \Delta$ Relation: CITE [Gaikwad et al. 2017a]

GADGET-2



GADGET-2 + CITE

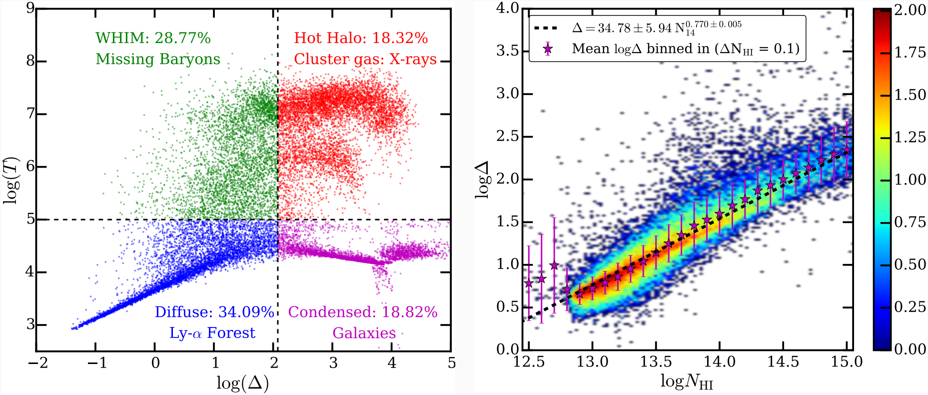


Different thermal history ⇒ Variation in Initial conditions at $z = 2.1$.

Different thermal history ⇒ $T_0 = 10000 - 20000$ K, $\gamma = 1.1 - 1.8$ at $z = 2.1$

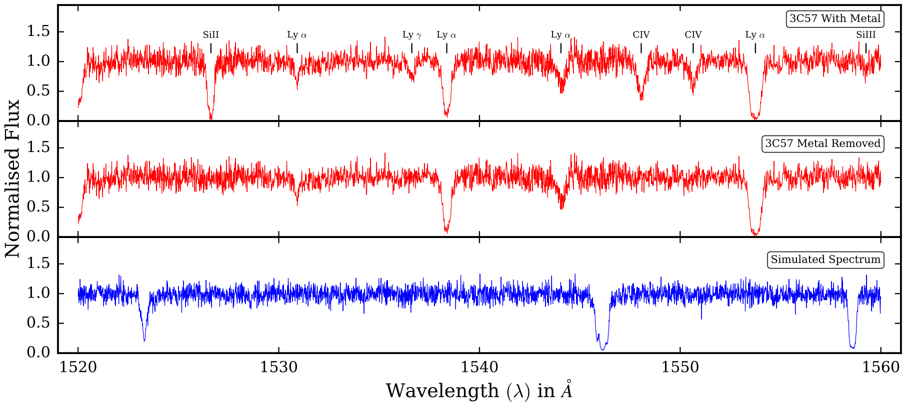
Advantage: Different thermal history without running full SPH simulation

GADGET-2 + CITE : Consistency



- Diffuse $\sim 37\%$, $\Delta = 38.9 \times \mathrm{N}_{14}^{0.74}$ [Dave+2009]
- Diffuse $\sim 40\%$, $\Delta = 36.9 \times \mathrm{N}_{14}^{0.65}$ [Smith+2011]
- For the resolution of our simulations, pressure smoothing effects are not so important.
- More details [Gaikwad+2017a, Gaikwad+2018]

Simulated Spectrum

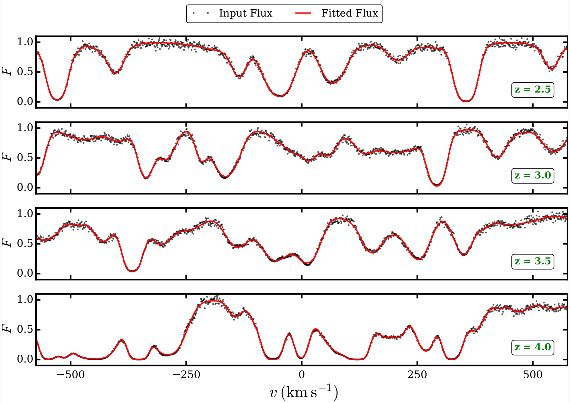


- Metal lines are replaced by continuum added with noise
- Convolved with instrumental broadening profile. (Not a Gaussian)
- Added SNR similar to observed spectra

- Flux Probability Distribution Function (FPDF):
- Flux Power Spectrum (FPS):
- Column Density Distribution Function: $\frac{\mathrm{d}^2 N}{\mathrm{dN_{HI}}\,\mathrm{d}z}$

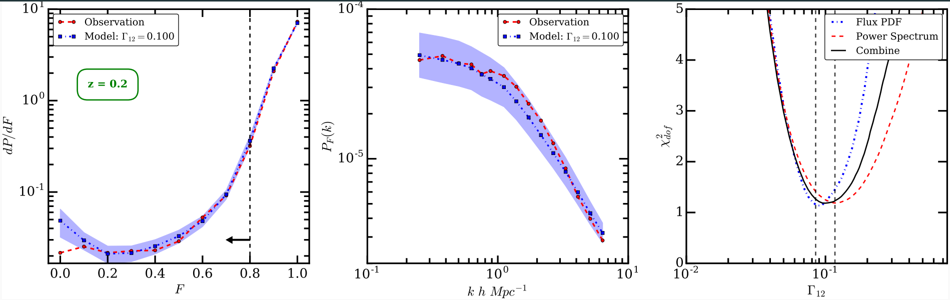
  Number of lines in $\mathrm{N_{HI}}$ to $\mathrm{N_{HI}} + \mathrm{dN_{HI}}$ and z to $z + \mathrm{d}z$

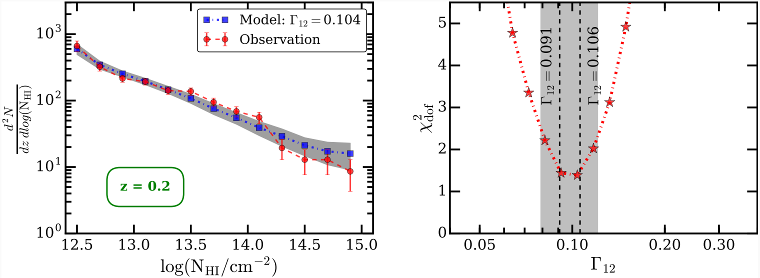
  VoIgt profile Parameter Estimation Routine (VIPER)



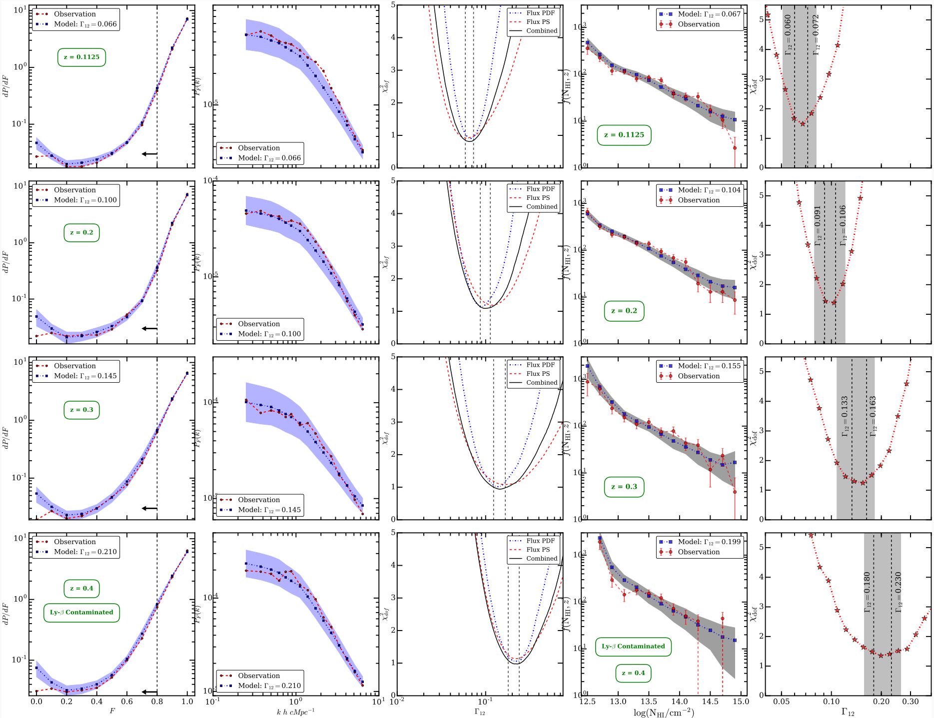
Result: Γ_{HI} Constraint

$\Gamma_{\rm HI}$ Constraint: Flux PDF, Flux PS, CDDF [Gaikwad et.al. 2017a,b]





- (CDDF) Sensitivity curve : Incompleteness of the sample is accounted for.

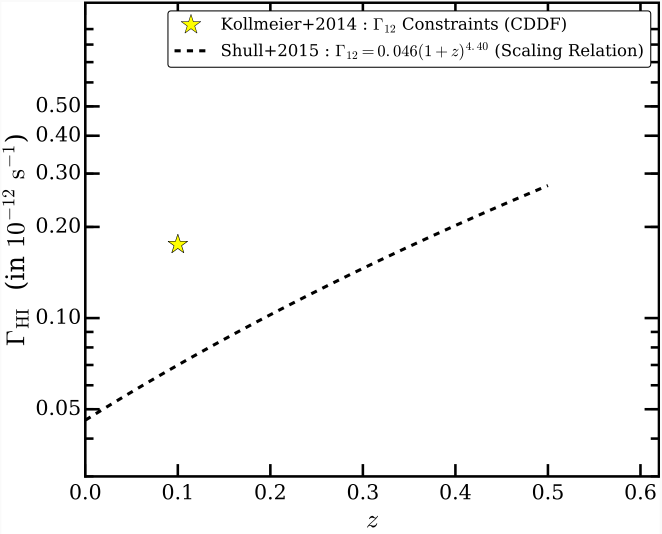


Observation
Model: Γ12 = 0.066
z = 0.1125
Model: Γ12 = 0.100
z = 0.2
Model: Γ12 = 0.145
z = 0.3
Model: Γ12 = 0.210
z = 0.4
Ly-β Contaminated
dP/dF
F
P_F(k)
k h cMpc^-1
Flux PDF
Flux PS
Combined
χ²_dof
Γ12
Model: Γ12 = 0.067
Model: Γ12 = 0.104
Model: Γ12 = 0.155
Model: Γ12 = 0.199
f(N_HI, z)
log(N_HI/cm^-2)
Γ12 = 0.060
Γ12 = 0.072
Γ12 = 0.091
Γ12 = 0.106
Γ12 = 0.133
Γ12 = 0.163
Γ12 = 0.180
Γ12 = 0.230

Total Γ_{HI} Error Budget: Systematic and Statistical Uncertainty

Redshift ⇒	0.1125	0.2	0.3	0.4
Type of simulated spectra ⇒	Ly-α forest	Ly-α forest	Ly-α forest	Ly-α forest
Best Fit Γ_{12}	0.066	0.100	0.145	0.155
Statistical Uncertainty	± 0.007	± 0.013	± 0.022	± 0.030
Cosmological parameters (∼ 10%)	± 0.007	± 0.010	± 0.015	± 0.021
Cosmic Variance (∼ 3%)	± 0.002	± 0.003	± 0.004	± 0.006
Total statistical errors	± 0.010	± 0.016	± 0.027	± 0.037
Continuum uncertainty (systematic)	± 0.005	± 0.005	± 0.010	± 0.015
Total error	± 0.015	± 0.021	± 0.037	± 0.052

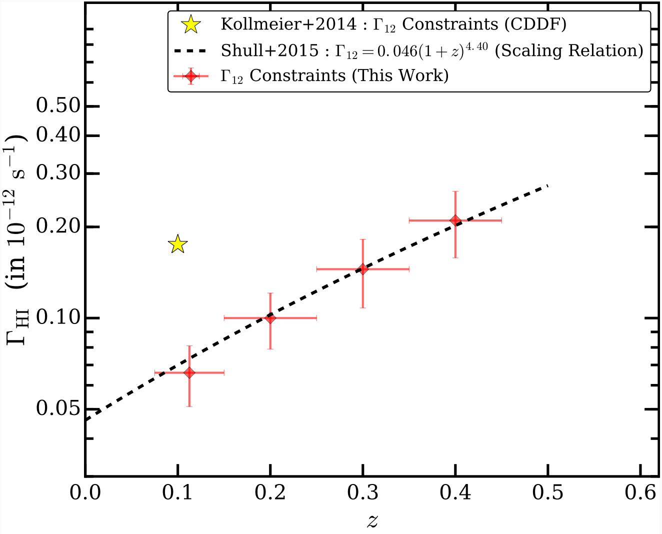
- Statistical Uncertainty: Includes uncertainty in initial T_0 and γ
  Flexibility of CITE allowed us to vary thermal history.
- Cosmic Variance: Identical cosmological parameters but different initial conditions.
- Cosmological Parameters: Ω_m, $\Omega_b\, h^2$, n_s,σ_8



Previous $\Gamma_{\rm HI}$ measurements

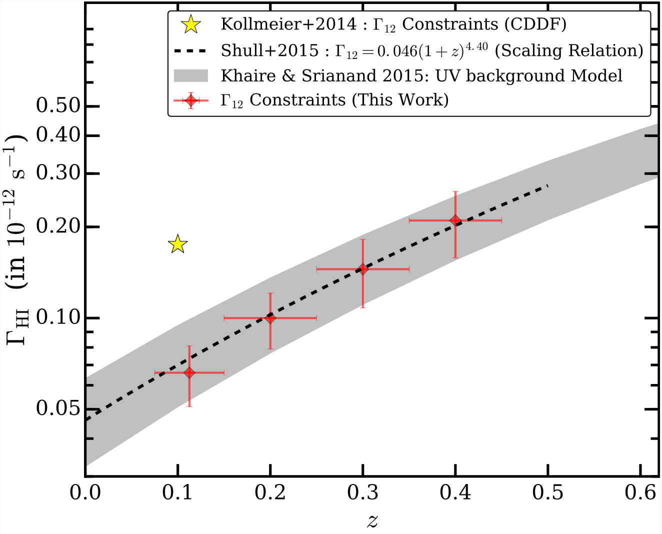
$\Gamma_{\rm HI}$ Evolution:

[Gaikwad et.al. 2017a,b]

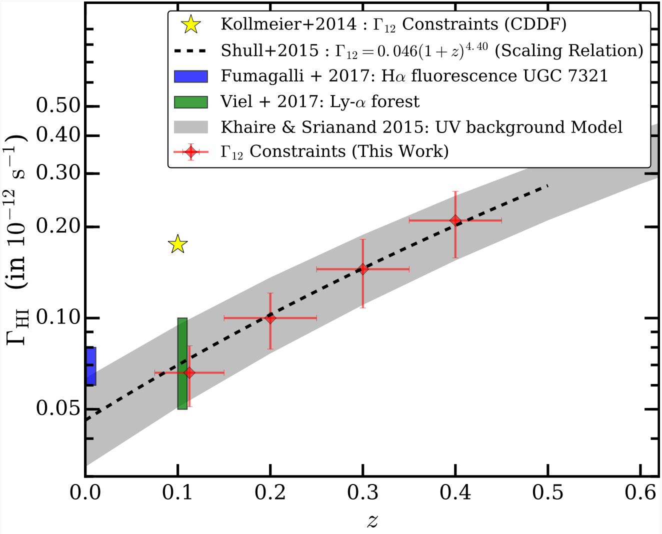


$\Gamma_{\rm HI}$ uncertainty: Thermal history parameters, Cosmic variance, Continuum fitting and Cosmological parameter uncertainty

$\Gamma_{\rm HI}$ Evolution: [Gaikwad et.al. 2017a,b]



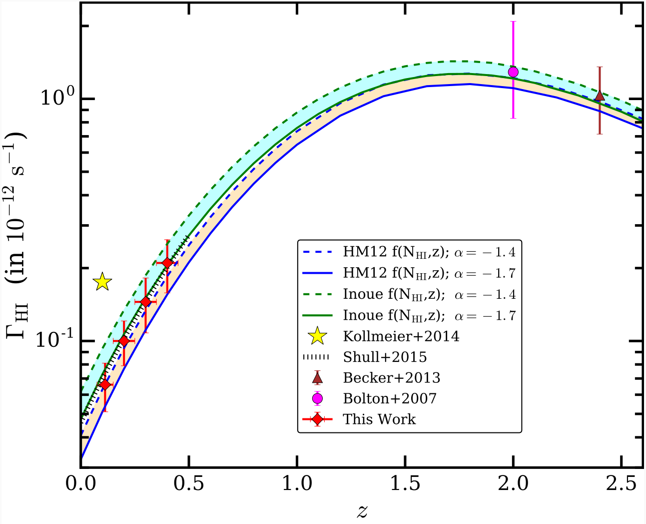
UVB at $z \leq 0.5$ is dominated by QSO i.e. $f_{\rm esc} = 0\%$



Γ_{HI} constraints from other studies

$\Gamma_{\rm HI}$ Evolution:

[Gaikwad et.al. 2017a,b]

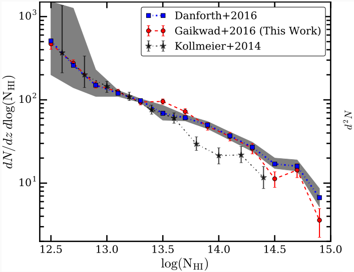


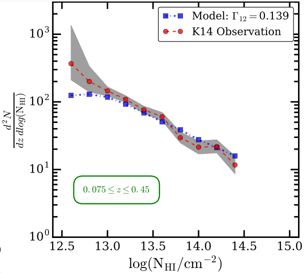
UVB at $z \leq 2.5$ is dominated by QSO i.e. $f_{\rm esc} = 0\%$

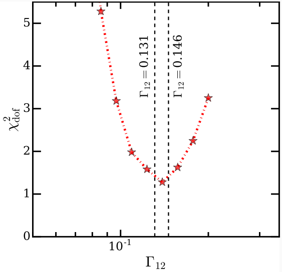
Summary

- Observation : Analysis of 82 HST-COS quasar absorption spectra
- Simulation: GADGET-2 + CITE $\Longrightarrow$ Ly-α forest
  - $T_0 \sim 4000 - 5000$K, $\gamma \sim 1.6$
  - Phase diagram: Diffuse phase $\sim 30 - 40\%$, WHIM $\sim 40 - 25\%$
  - Computationally less expensive
- Method
  - 3 Statistics: Flux PDF, Flux PS and CDDF (VIPER)
  - Covariance Matrix is calculated from Simulation
- Result
  - $\Gamma_{\rm HI}$ constraints in 4 redshift bins.
  - Uncertainty: Systematic and Statistical
  - Evolution of Γ_{12} is consistent with $f_{\rm esc} = 0\%$

Γ_{12} constraints from K14 data







For K14 data and using model Ly-α forest from G17 simulations at $z = 0.1$

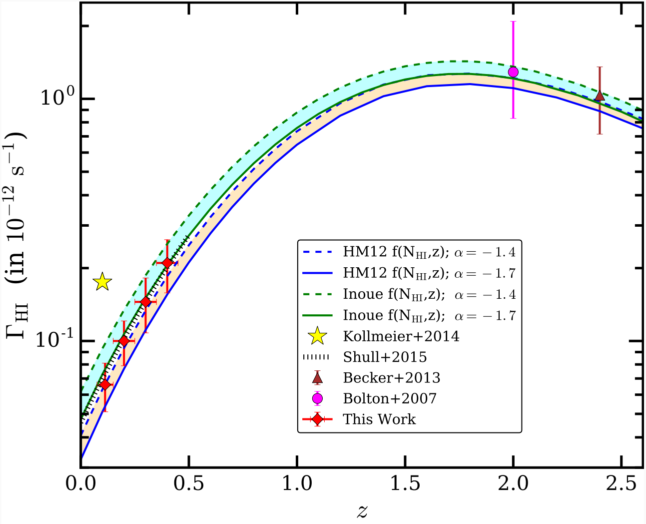
$$[\Gamma_{12}]_{\text{G17}} = 0.138 \pm 0.007 \approx (3.9 \pm 0.2) \times [\Gamma_{12}]_{\text{HM12}}$$

If we account for the differences in K14 and G17 simulation,

$$[\Gamma_{12}]_{\text{K14}} = 1.2353 \times [\Gamma_{12}]_{\text{G17}} = 1.2353 \times (0.138 \pm 0.007)$$

$$[\Gamma_{12}]_{\text{K14}} = 0.170 \pm 0.009 \approx (4.80 \pm 0.25) \times [\Gamma_{12}]_{\text{HM12}}$$

UV background model: [Khaire & Srianand, 2015a], [Khaire et.al, 2015b]



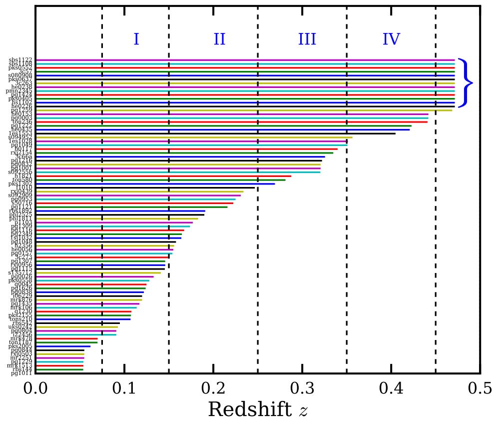
UVB at $z \leq 2.5$ is dominated by QSO i.e. $f_{\rm esc} = 0\%$

UV background model: [Khaire & Srianand, 2015a], [Khaire et.al, 2015b]

- Source Term 1: Galaxy Contribution (Stellar Light)
  - Free parameter: Escape fraction $f_{\rm esc}$
- Source Term 2: QSO contribution (Blackhole accretion)
  - Uncertainty in Spectral Energy Distribution index: α
  - $\alpha = -1.4$ [Stevans et al. 2014]
  - $\alpha = -1.7$ [Lusso et al. 2014]
- Sink Term: IGM attenuation ($\tau_{\rm eff}$)
  - Cloud distribution $f(N_{\rm HI}, z)$
  - HM12: $f(N_{\rm HI}, z)$ [Haardt & Madau 2012]
  - Inoue: $f(N_{\rm HI}, z)$ [Inoue et.al 2014]

Observation Data

[Danforth et.al, 2015]



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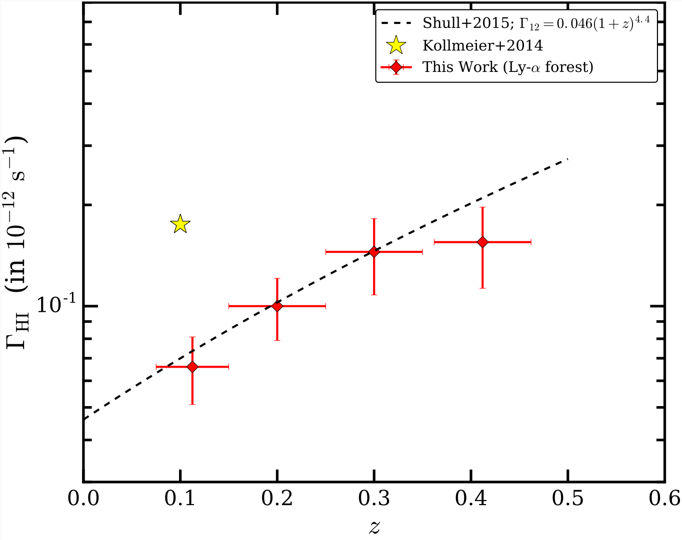
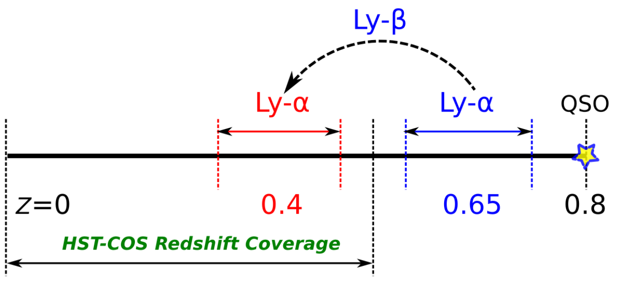
$\Gamma_{\rm HI}$ Evolution

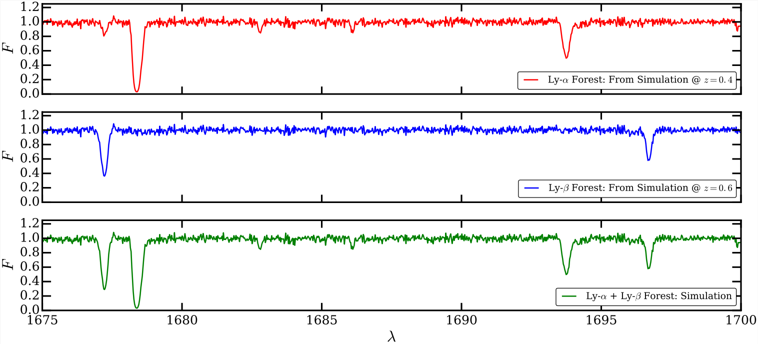


$\Gamma_{\rm HI}$ at $z = 0.4$, Real or Artifact?

HI Interlopers: Contamination due to Ly-β forest



Line	λ in Å	Strength
Ly-α	1215.6701	1
Ly-β	1025.7223	6.17^{-1}
Ly-γ	972.5368	17.78^{-1}
Ly-δ	949.7431	38.02^{-1}
Ly-ω	937.8035	69.18^{-1}



$\Gamma_{\rm HI}$ Evolution: Effect of Ly-β contamination at $z = 0.4$