Constraints on photoionization rate and escape fraction at $z < 0.5$

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Plan of talk

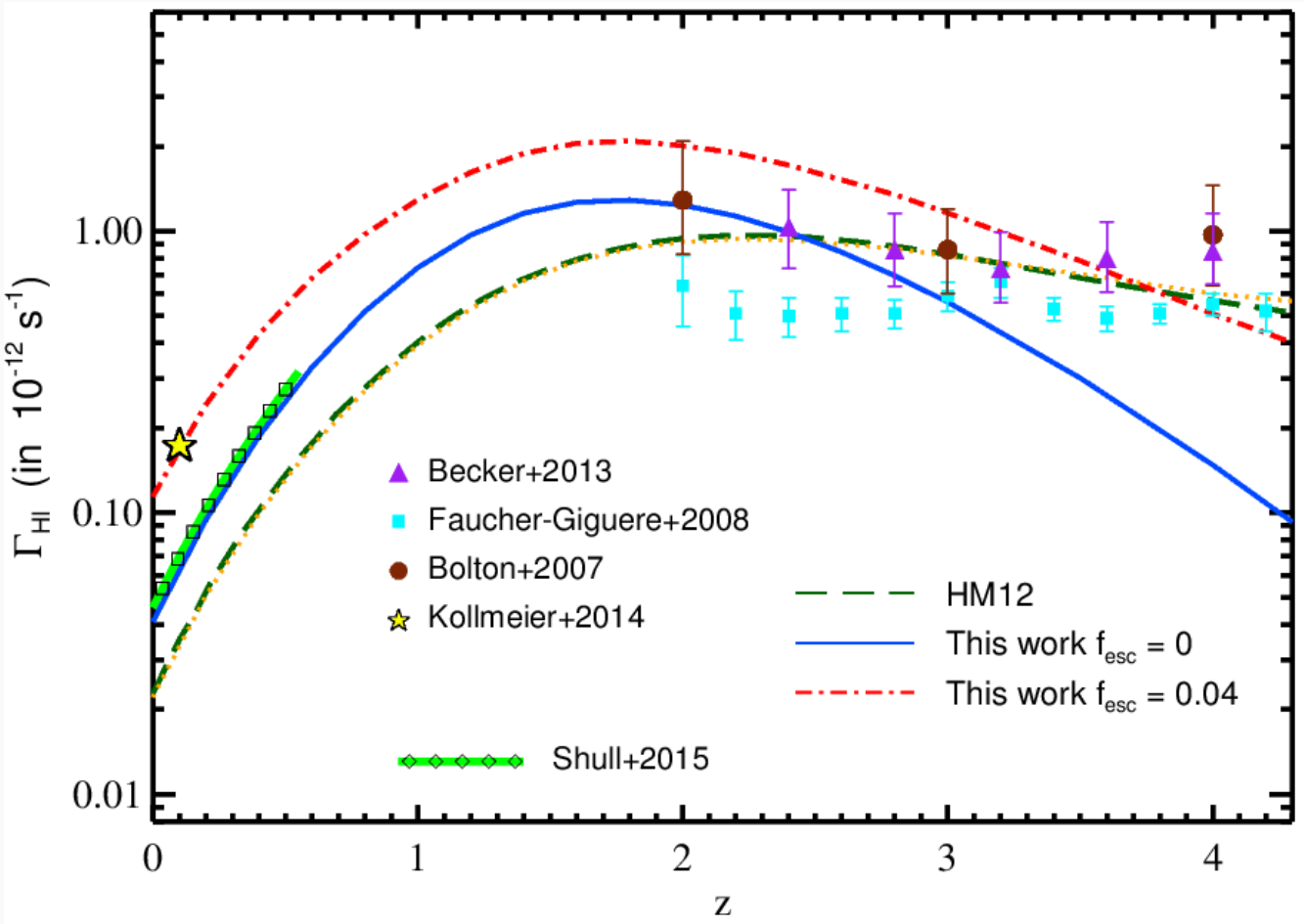
- Introduction
- Observation: HST-COS
- Simulation: CITE
- Method:
  - Flux PDF
  - Flux Power Spectrum
- Results:
  - $\Gamma_{\rm HI}$ constraint
  - $\Gamma_{\rm HI}$ Evolution
  - $f_{\rm esc}$ constraint
- Summary

Introduction

Introduction

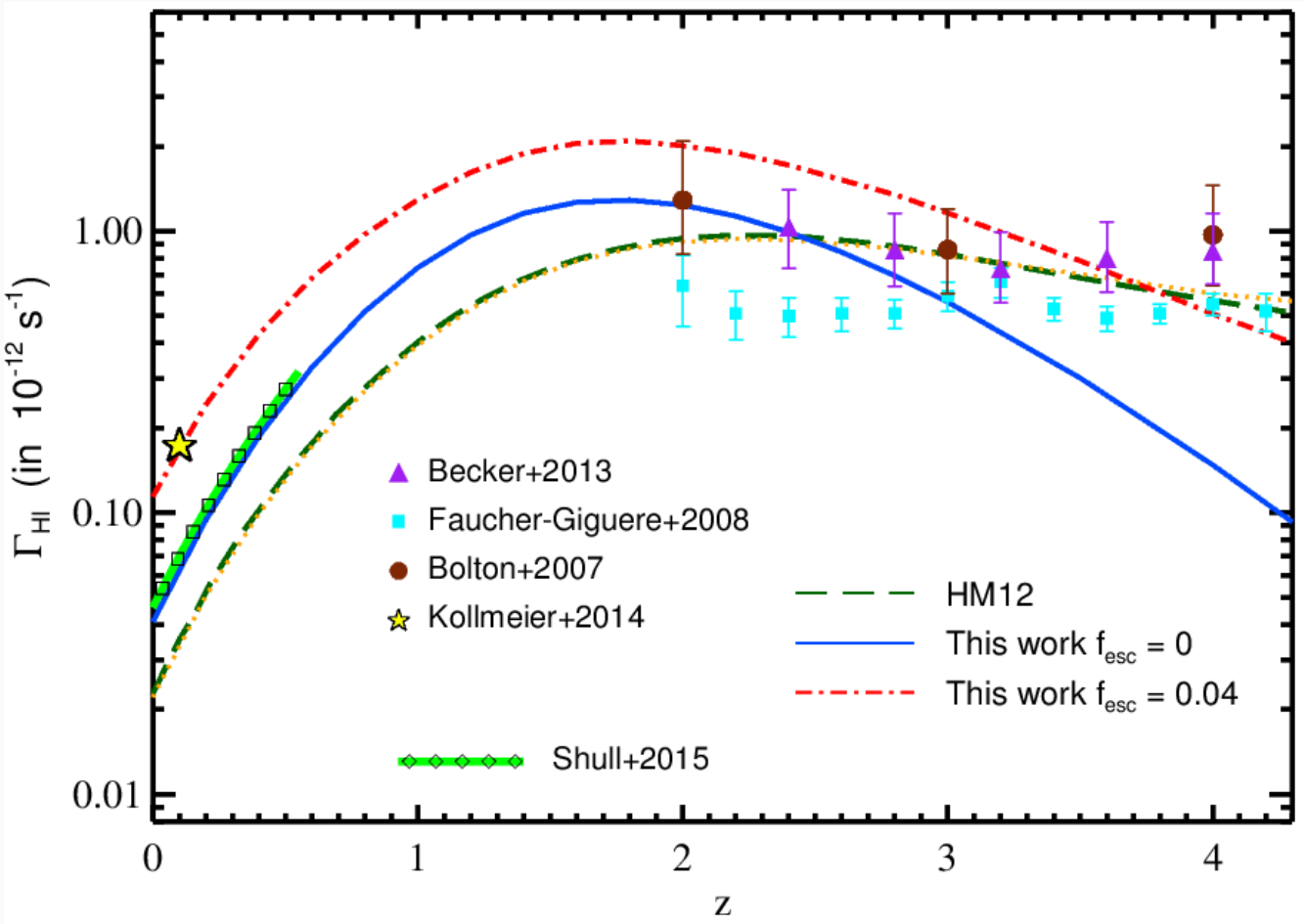
- QSO absorption spectra: Ly-α forest
  - IGM (Overdensity $\Delta \leq 10$)
  - Large redshift coverage
  - Thermal history
  - Ionization state
  - UV background (UVB)
- UVB sources:
  - Radiation from accretion of matter on to blackhole
  - Stellar contribution from galaxies
- Escape fraction ($f_{\rm esc}$):
  - Types of stars
  - Galaxy ISM: Gas distribution
- H I photoionization rate, $\Gamma_{\rm HI}$

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



- [Kollmeier et.al 2014] and [Shull et.al 2015]: HST-COS, same statistics, No errorbars
- [Kollmeier et.al 2014] $\Rightarrow f_{\rm esc} \sim 4\%$, [Shull et.al 2015] $\Rightarrow f_{\rm esc} \sim 0\%$
- 3σ upper limit from sample of galaxies at $z < 2$: $f_{\rm esc} \leq 2\%$ [Cowie et al. 2009]

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

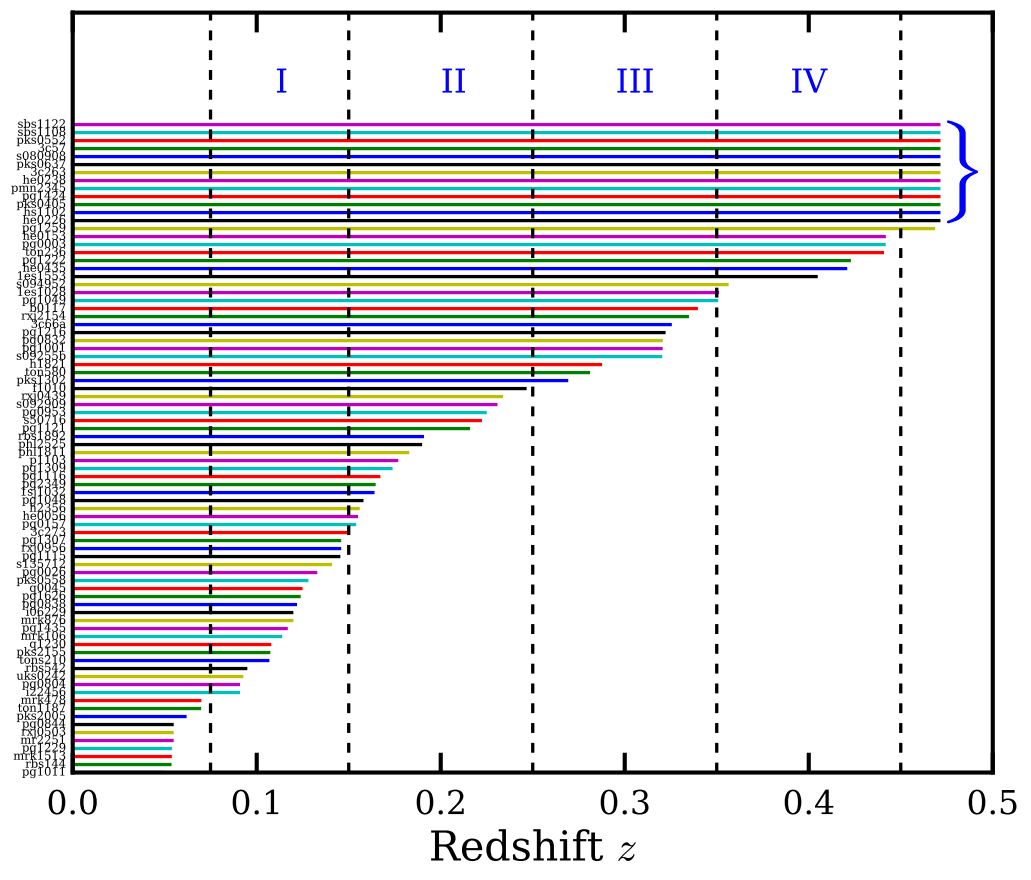


- $\Gamma_{\rm HI}$ with appropriate error bars at $z < 0.5$?
- Evolution of $\Gamma_{\rm HI}$ and Escape fraction $f_{\rm esc}$?
- HST-COS data, but different statistics

Observation

Data

[Danforth et.al, 2015]

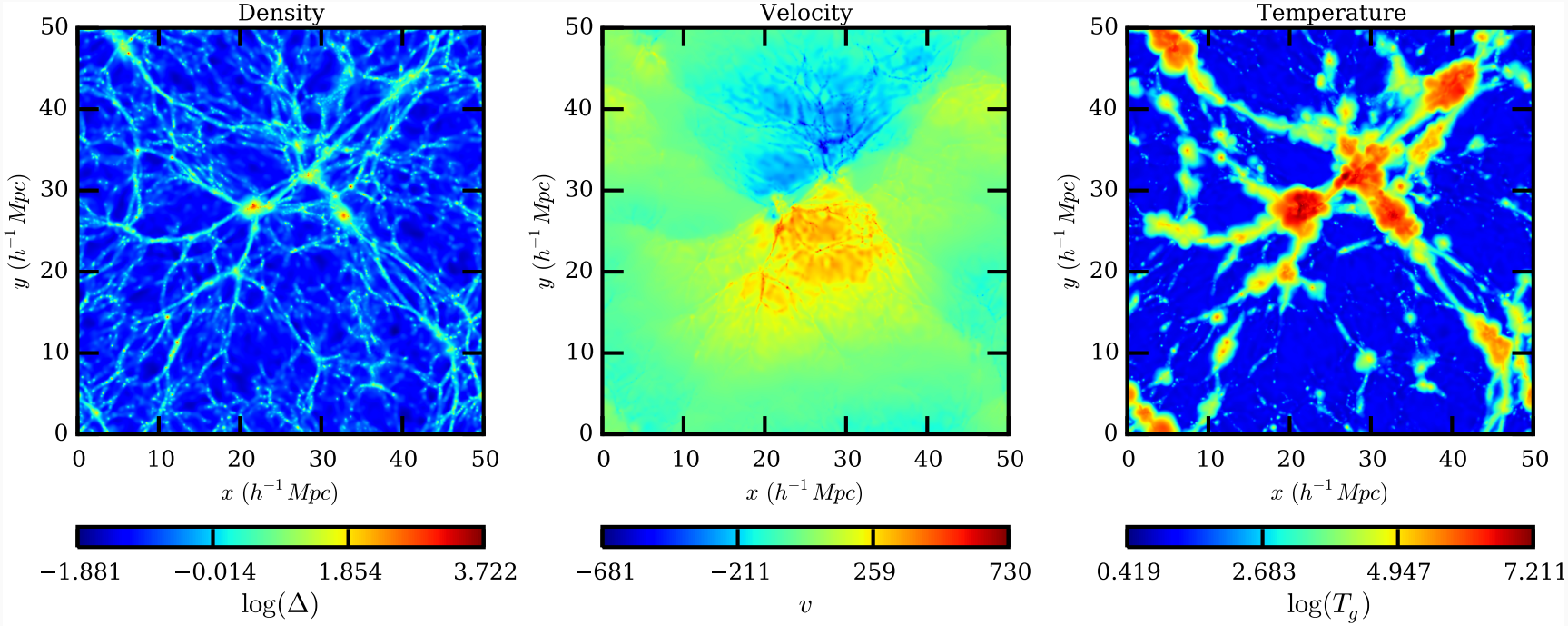


- Instrument: HST-COS
- Number of spectra: 82
- SNR : 4 to 16
- Resolution $\Delta v \sim 17 km/s$
- Instrumental Broadening: Not Gaussian
- Continuum Fitting
- Metal Lines and higher transition lines are removed
- QSO proximity zone : High ionization due to radiation from QSO itself ($\sim 25 h^{-1}\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

Simulation

SPH Simulation

[Springel, 2005]

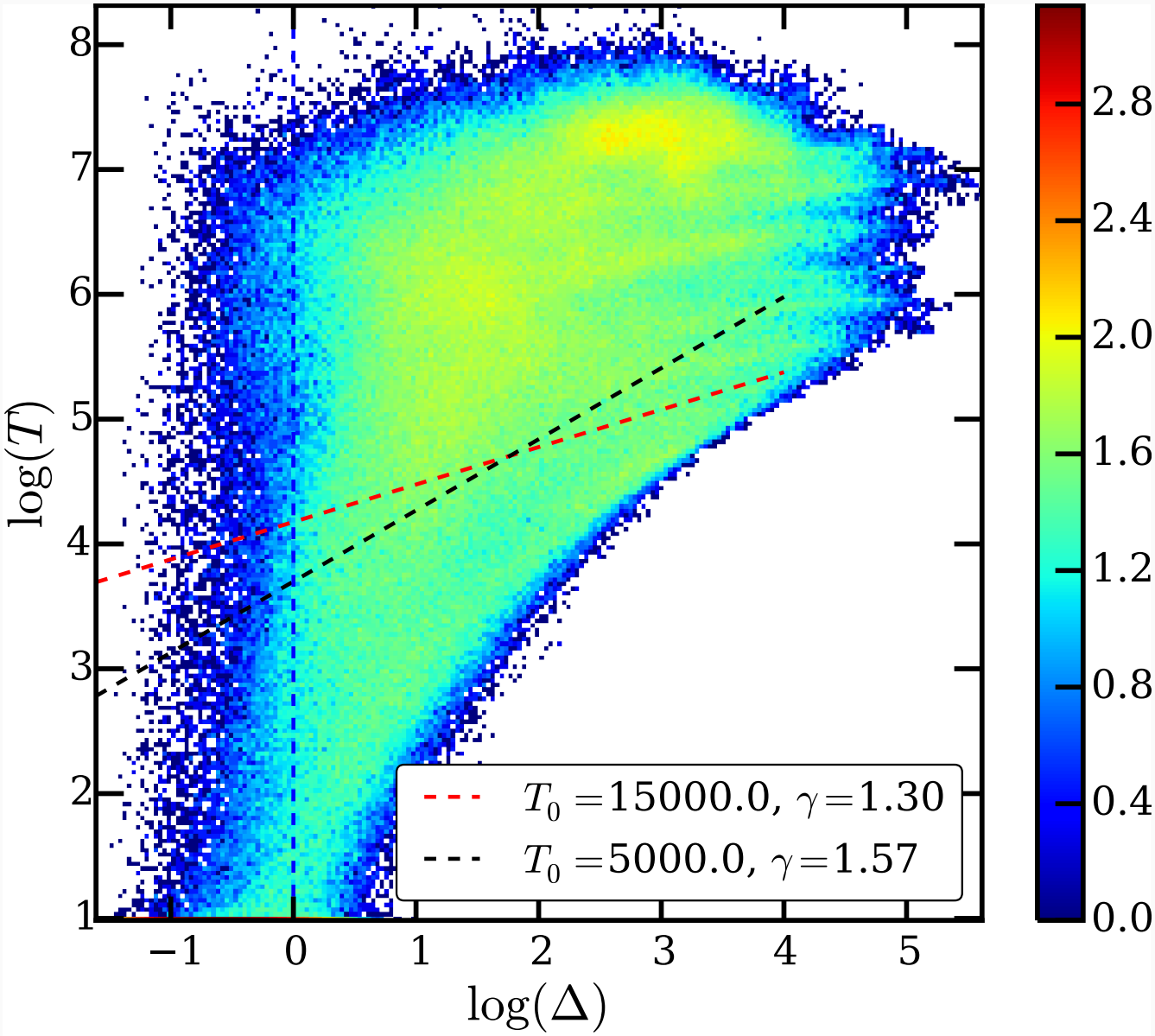


$$\tau_{\rm GP} \propto \frac{(\Omega_b\, h^2)^2\, \Omega_m^{-0.5}}{\Gamma_{HI}}\; T_0^{-0.7}\; \Delta^{2-0.7\gamma}\; (1+z)^6$$

- GADGET-2 SPH
- ΛCDM cosmology
- 2×512^3 DM + Baryons
- Box size: $50h^{-1}\,Mpc$

- Advantages : Parameter space
- Disadvantage: No ionization evolution
- Equation of state at high z: $T = T_0\, \Delta^{\gamma-1}$

GADGET-2: $T - \Delta$ Relation



Temperature Evolution Equation [Hui & Gnedin, 1997]

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

- Other heating / cooling processes term is not included in Gadget-2 except shock heating
- Other heating processes: Photo-heating
- Cooling processes: Recombination Cooling, Collisional ionization, Collisional excitation, Bremsstrahlung, Inverse Compton Cooling

Code for Ionization and Temperature Evolution (CITE)

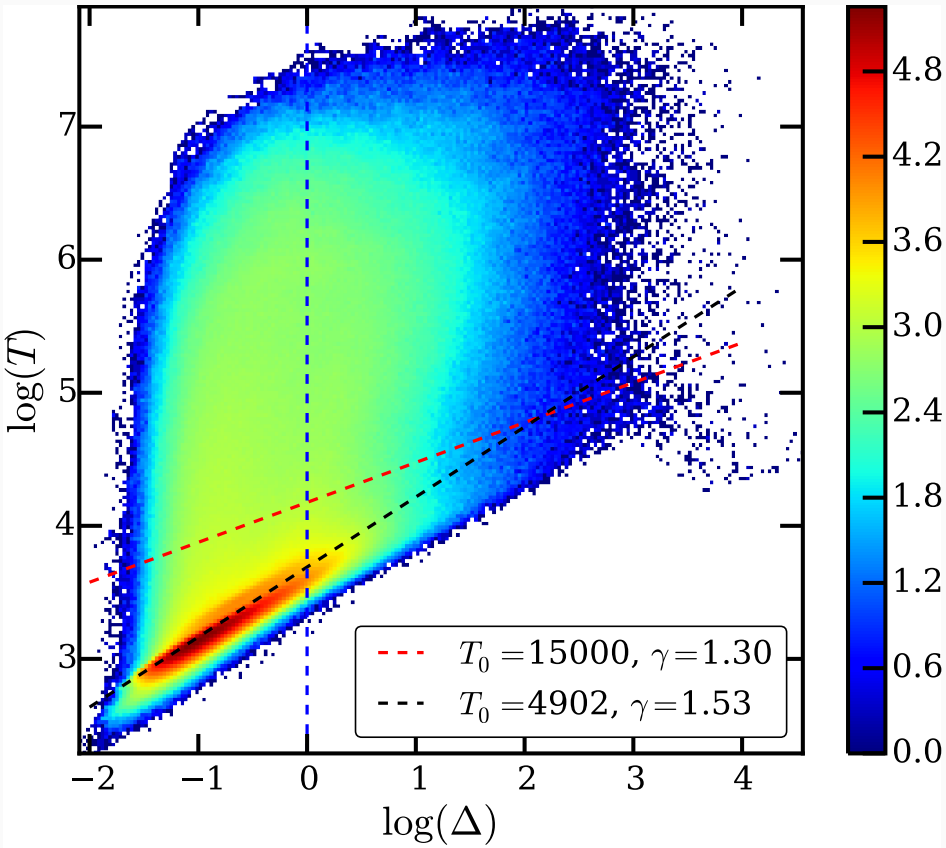
1. GADGET-2 snapshots stored at $z = 2.1, 2.0, 1.9, \cdots, 0.1, 0.0$
2. Assuming initial equation of state for $z = 2.1$ e.g. $T_0 = 15000\,\mathrm{K}$ and $\gamma = 1.3$.
3. Solve ionization evolution equation
4. Calculate photoheating and radiative cooling rates (dQ/dt).
5. Solve the temperature evolution equation for z_{prev} and get temperature for next step z_{next},

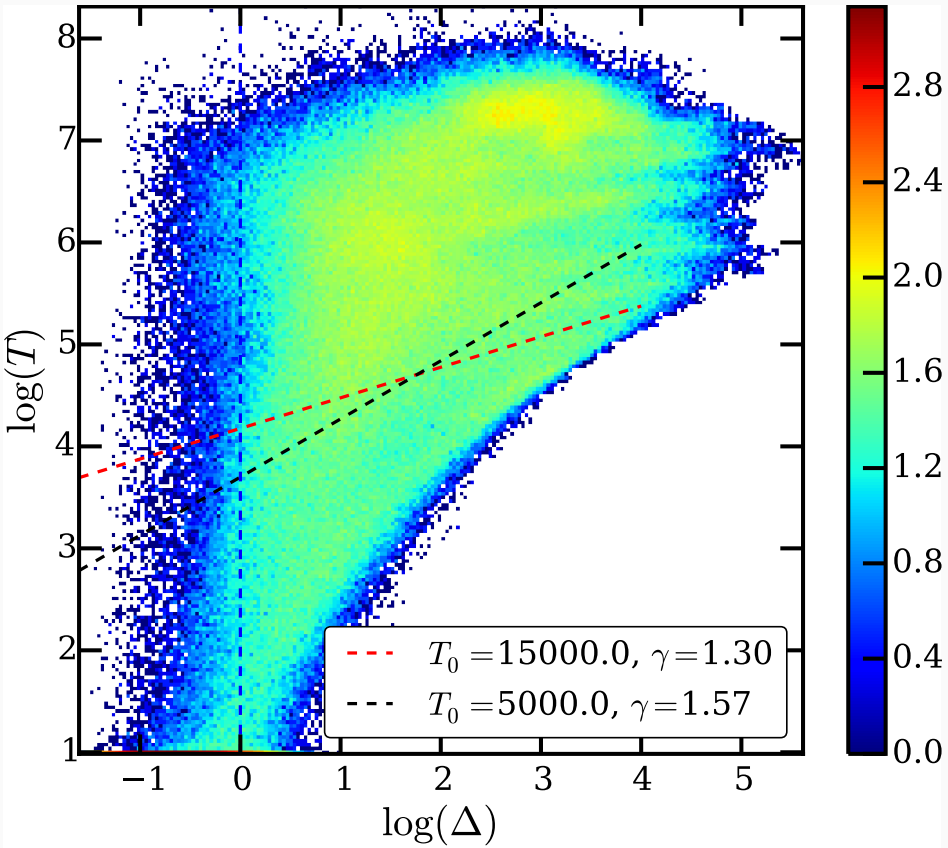
$$\frac{dT}{dt} = -2HT + \frac{2T}{3\Delta}\frac{d\Delta}{dt} + \frac{2}{3k_B n_b}\frac{dQ}{dt} + \left[\frac{dT}{dt}\right]_{\mathrm{shock}}$$

6. Repeat Step 3 to Step 5 for next redshift

Comparison with other simulation

$T - \Delta$ relation ($z = 0.3$)





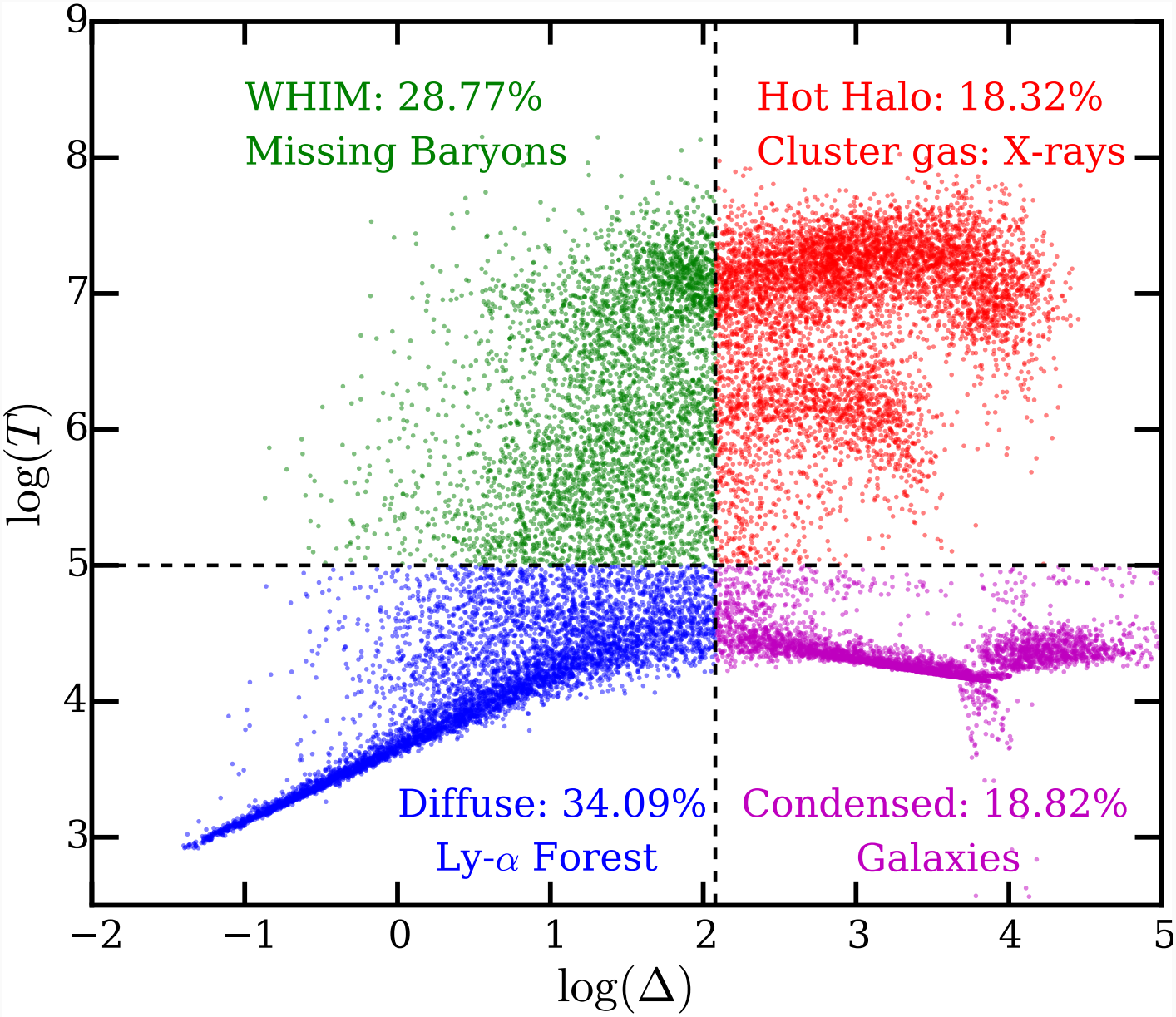
- Color represents density of points in log

  Red ⇒ high density of points,

  Blue ⇒ low density of points

- T_0 and γ are in agreement with those from simulations in literature

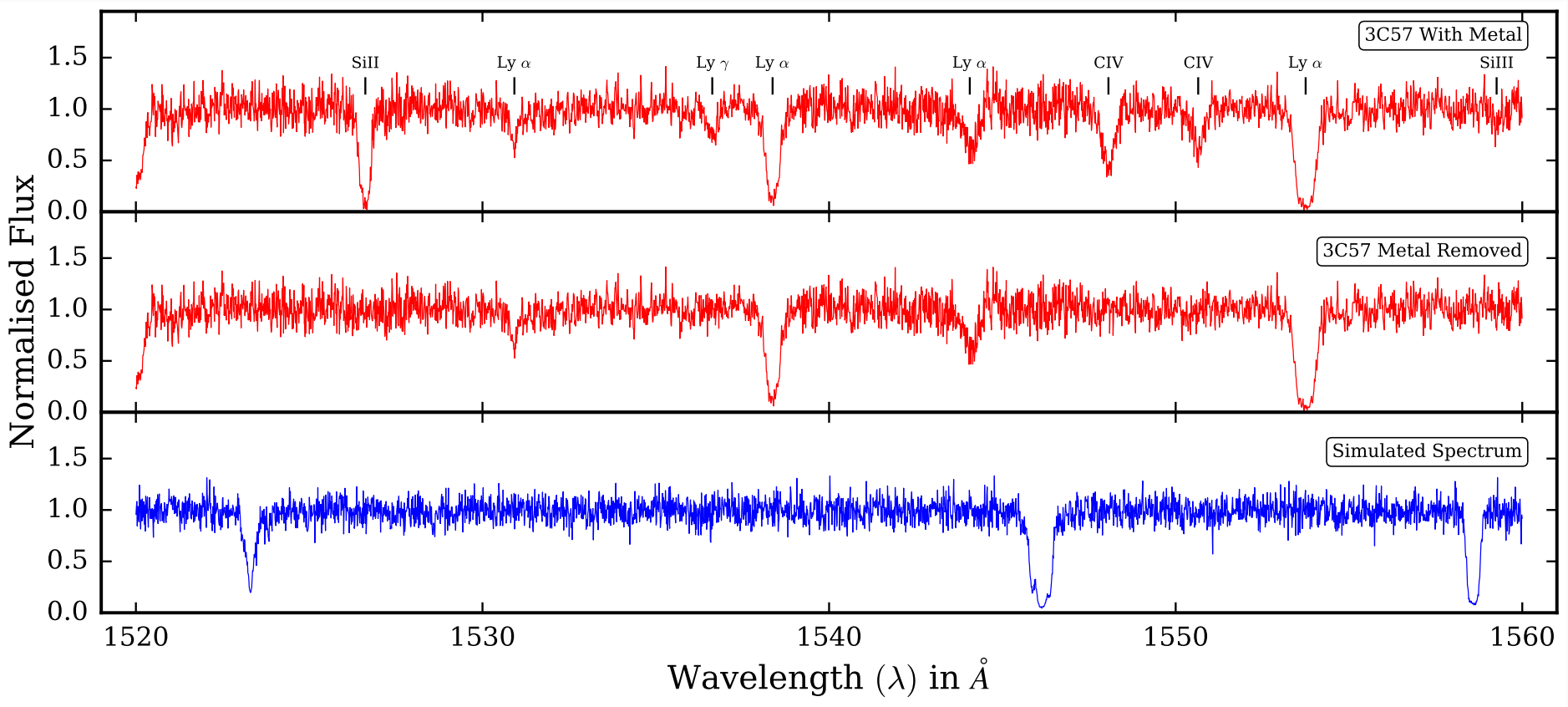
Phase Distribution of Baryons ($z = 0$)



Fractions consistent with those from simulations in the literature

Method

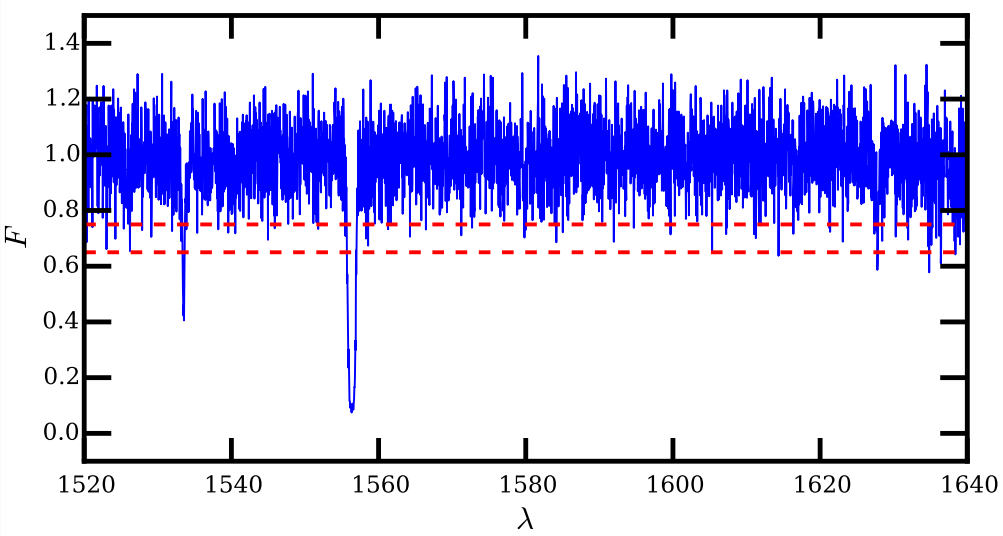
Simulated Spectrum

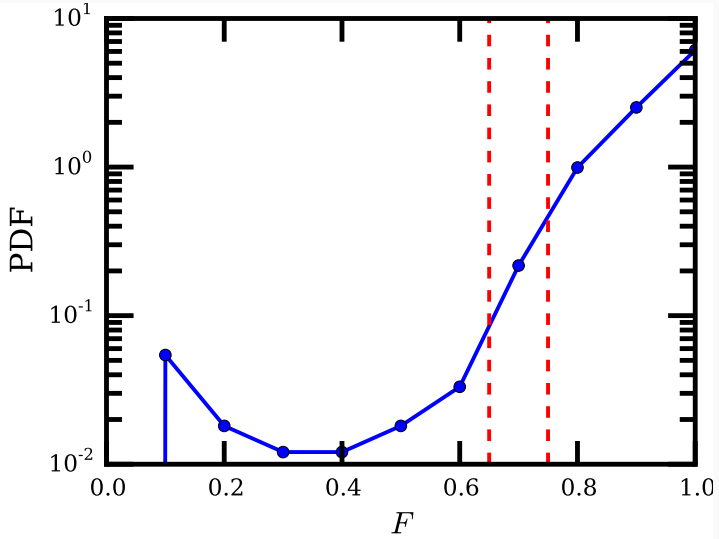


- Metal lines are replaced by continuum added with noise
- Convolved with instrumental broadening profile. (Not a Gaussian)
- Added SNR similar to observed spectra

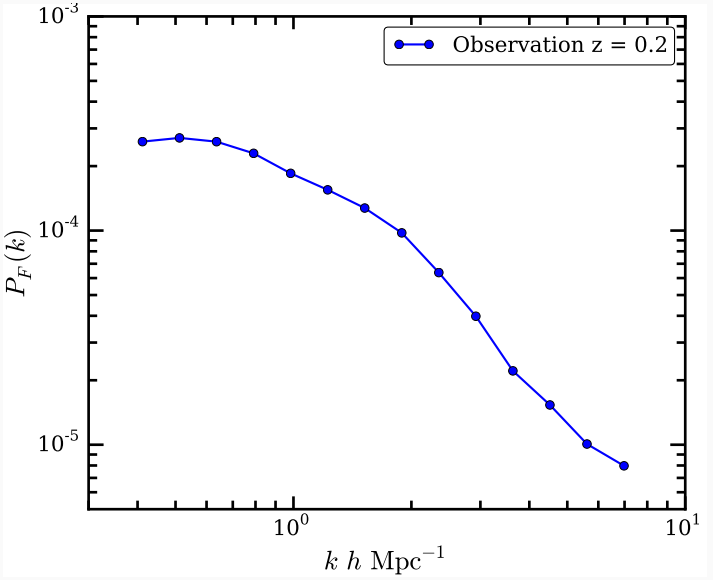
3 Statistics

- Flux Probability Distribution Function (Flux PDF):





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



Matching Simulation with Observation

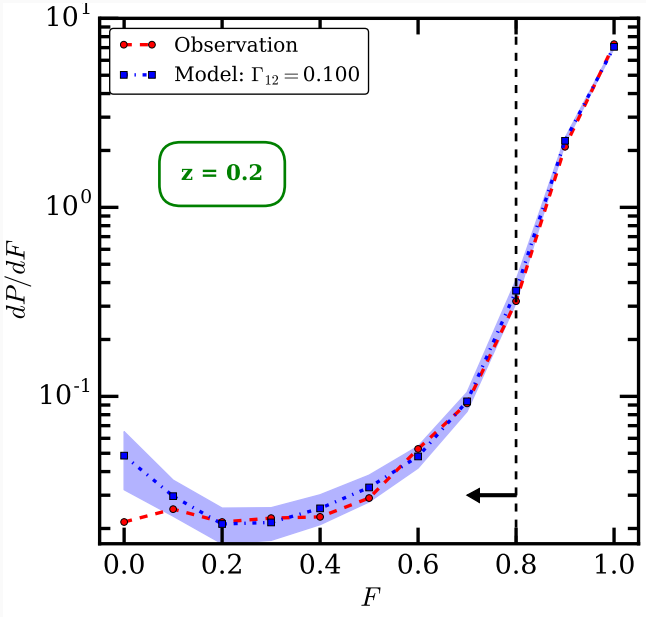
- Simulation: $\Gamma_{\rm HI}$ as free parameter.

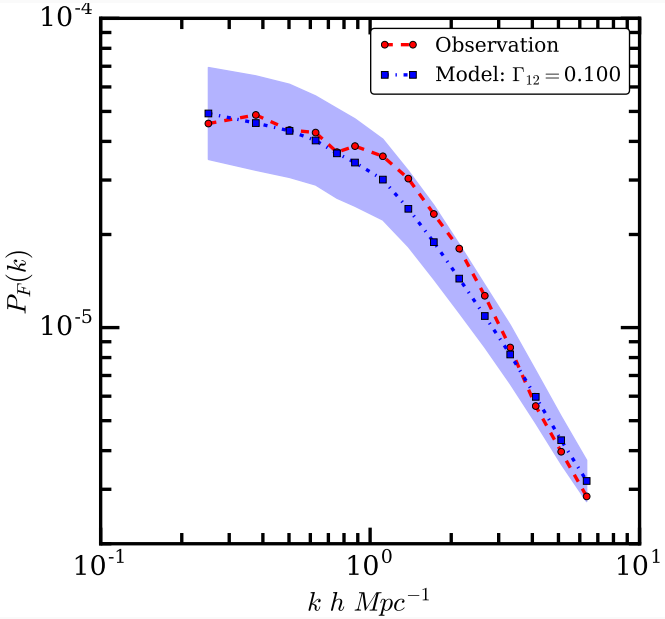
$$\chi^2 = [P_{\rm obs} - P_{\rm sim}]\ {\rm C}^{-1}\ [P_{\rm obs} - P_{\rm sim}]^{\rm T}$$

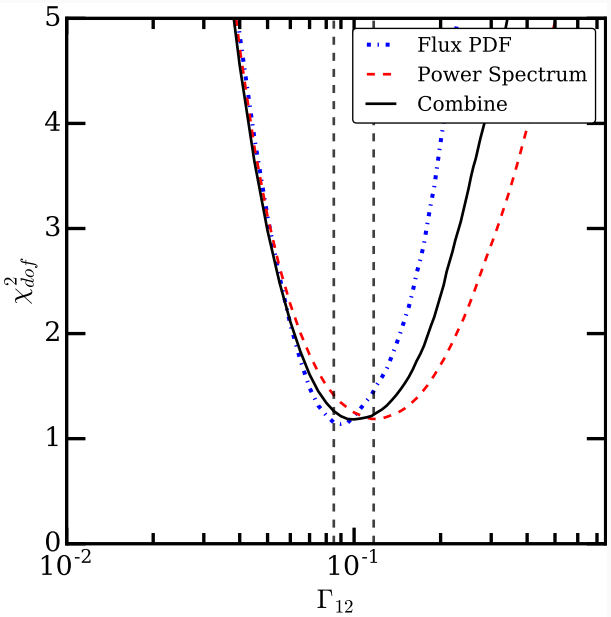
- How to estimate Covariance Matrix $\rm C$?
  - Observation: Jackknife Estimation? $\Rightarrow$ Underestimated
  - Simulation $\Rightarrow$ Converge [Rollinde et.al. 2013]
  - Recovery using 2 statistics is well.

Result

$\Gamma_{\rm HI}$ Constraint: Flux PDF and Flux Power Spectrum







- Flux PDF: Range: $0 \leq F \leq 0.8$
- Covariance Matrix from mock samples
- Flux Power spectrum
- $\Gamma_{12} \Rightarrow \Gamma_{\rm HI}$ in units of 10^{-12} s^{-1}
- Smooth χ^2 parabola $\Rightarrow$ No instability in statistics
- Statistical uncertainty: $\chi^2_{1\sigma} = \chi^2_{min} + \Delta\chi^2_{1\sigma}$

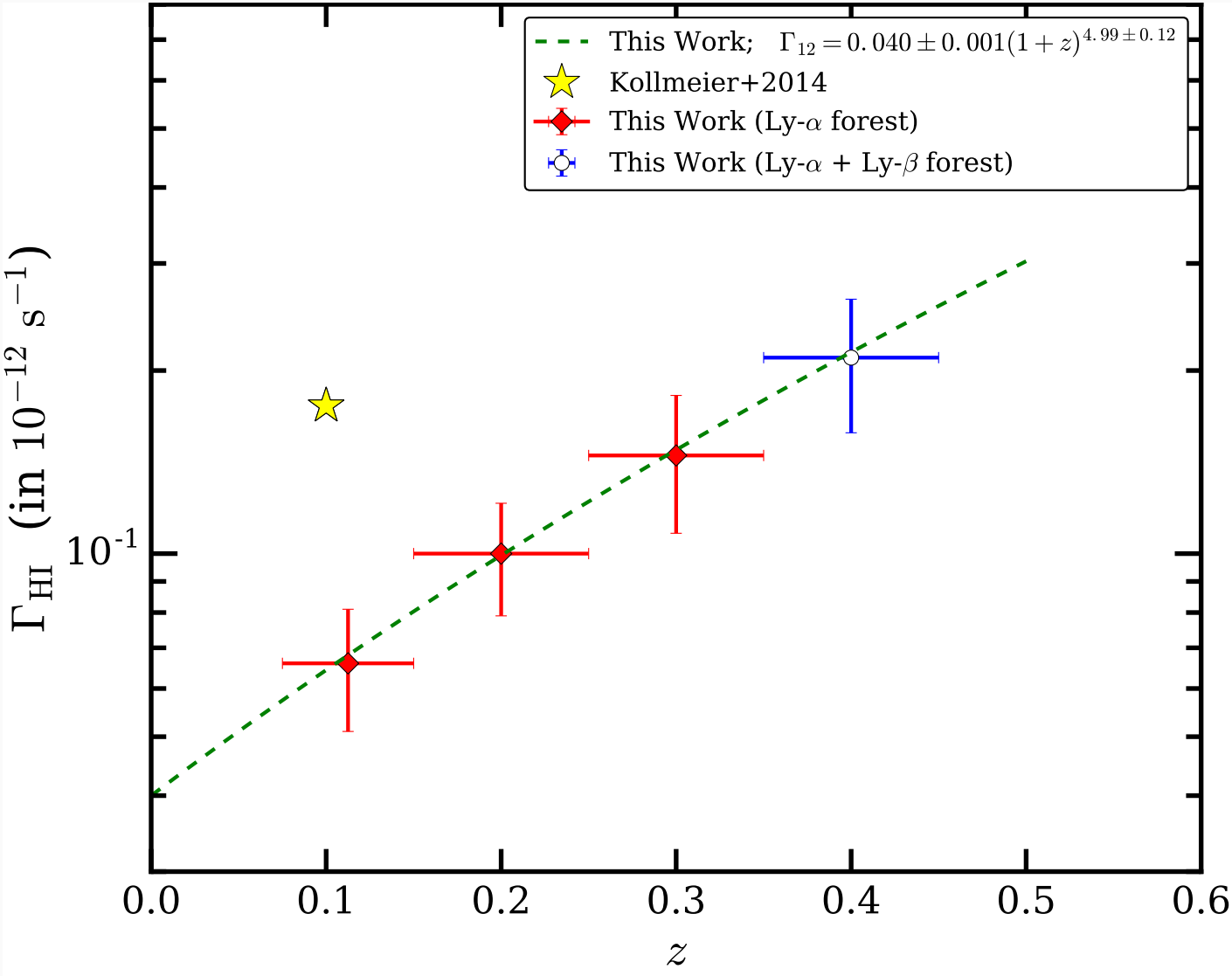
Total $\Gamma_{\rm HI}$ Error Budget: Systematic and Statistical Uncertainty

Redshift $\Rightarrow$	0.1125	0.2	0.3	0.4
Type of simulated spectra $\Rightarrow$	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	$\pm$ 0.007	$\pm$ 0.013	$\pm$ 0.022	$\pm$ 0.030
Cosmological parameters ($\sim$ 10%)	$\pm$ 0.007	$\pm$ 0.010	$\pm$ 0.015	$\pm$ 0.021
Cosmic Variance ($\sim$ 3%)	$\pm$ 0.002	$\pm$ 0.003	$\pm$ 0.004	$\pm$ 0.006
Total statistical errors	$\pm$ 0.010	$\pm$ 0.016	$\pm$ 0.027	$\pm$ 0.037
Continuum uncertainty (systematic)	$\pm$ 0.005	$\pm$ 0.005	$\pm$ 0.010	$\pm$ 0.015
Total error	$\pm$ 0.015	$\pm$ 0.021	$\pm$ 0.037	$\pm$ 0.052

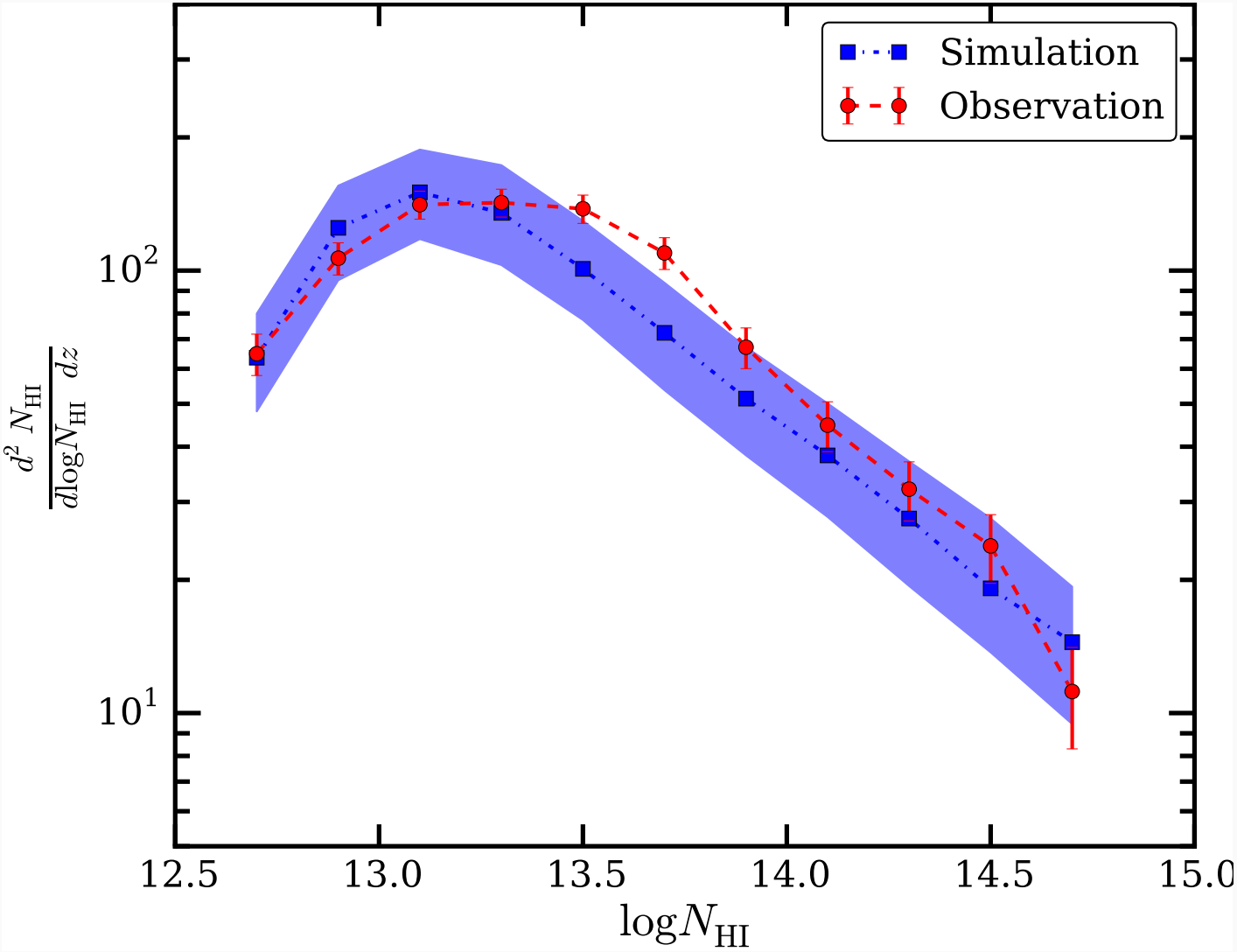
- Statistical Uncertainty: Includes uncertainty in initial T_0 and γ
- Cosmic Variance: Identical cosmological parameters but different initial conditions.
- Cosmological Parameters: Ω_m, $\Omega_b\, h^2$, n_s,σ_8

$$\tau_{\rm GP} \propto \frac{(\Omega_b\, h^2)^2\, \Omega_m^{-0.5}}{\Gamma_{HI}}\; T_0^{-0.7}\; \Delta^{2-0.7\gamma}\; (1+z)^6$$

$\Gamma_{\rm HI}$ Evolution:

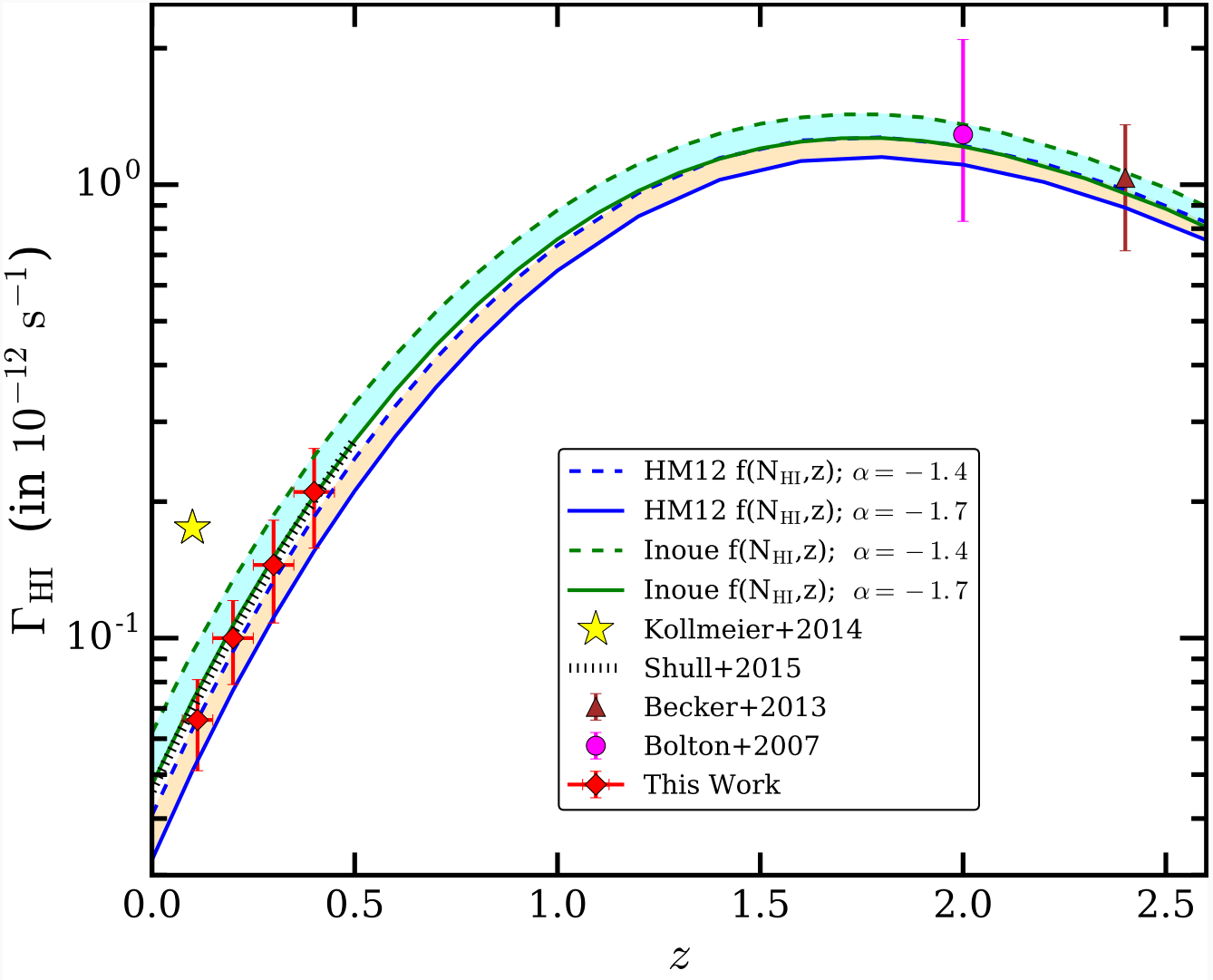


Column Density Distribution: $\Gamma_{\rm HI}$ consistency



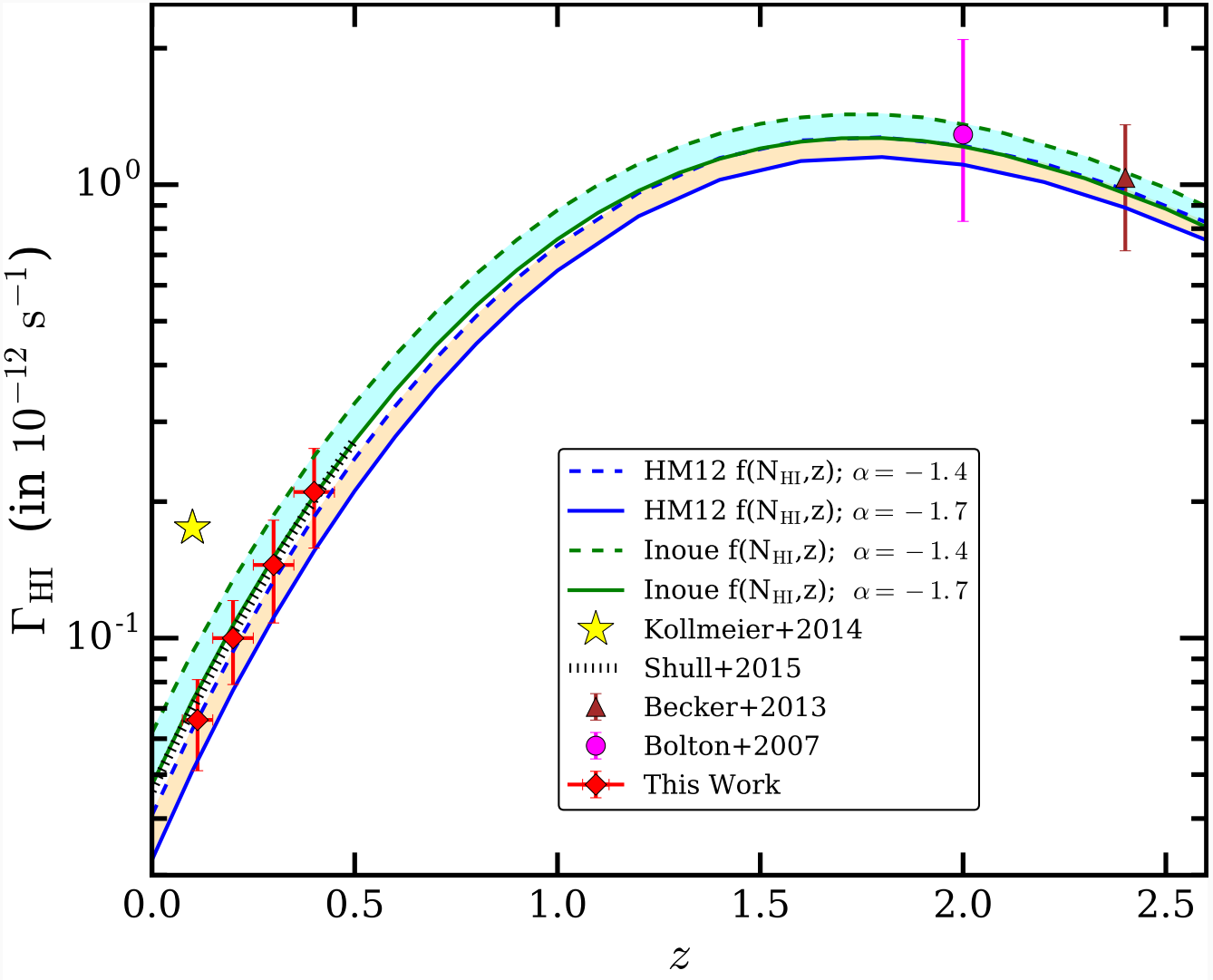
$$\chi^2_{\rm dof} = 1.15$$

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]



3σ upper limit on f_{esc} is 0.8% $\Rightarrow$ Low mass galaxy contribution to UVB is negligible

Summary

Summary

- Observation : Analysis of 82 HST-COS quasar absorption spectra
- CITE:
  - $T_0 \sim 4000 - 5000$K, $\gamma \sim 1.6$
  - Phase diagram: Diffuse phase $\sim 30 - 40\%$, WHIM $\sim 40 - 25\%$
  - Computationally less expensive
- Method
  - 2 Statistics: Flux PDF and Flux power spectrum
  - Covariance Matrix is calculated from Simulation
- Result
  - $\Gamma_{\rm HI}$ constraints in 4 redshift bins.
  - Uncertainty: Systematic and Statistical
  - $\Gamma_{\rm HI}$ constraints consistent with CDDF
  - Evolution of Γ_{12} is consistent with $f_{\rm esc} = 0\%$
  - 3σ upper limit on $f_{\rm esc} = 0.8\%$ $\Rightarrow$ Low mass galaxy contribution negligible

Acknowledgement

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  (IUCAA)

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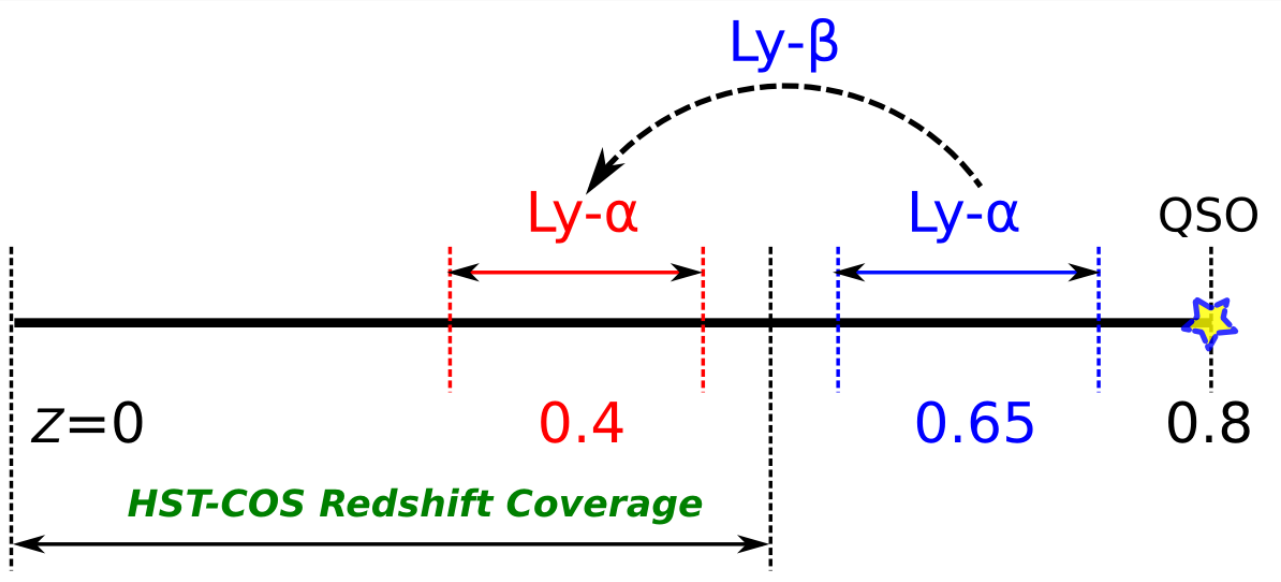
- Charles Danforth
  (Department of Astrophysical & Planetary Science, University of Colorado)

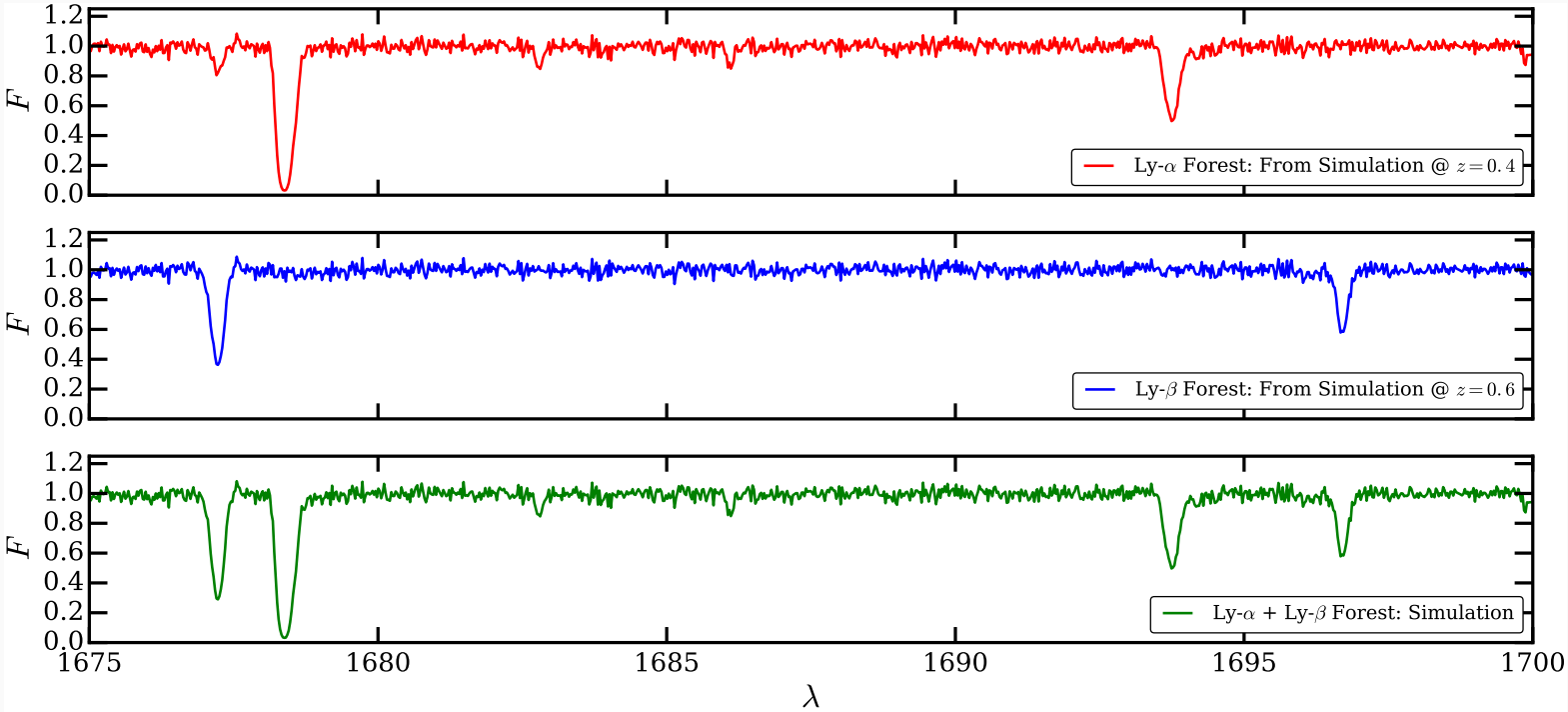
Computing Facility

- HPC Cluster (NCRA)
- Perseus Cluster (IUCAA)
- Ganga (NCRA)

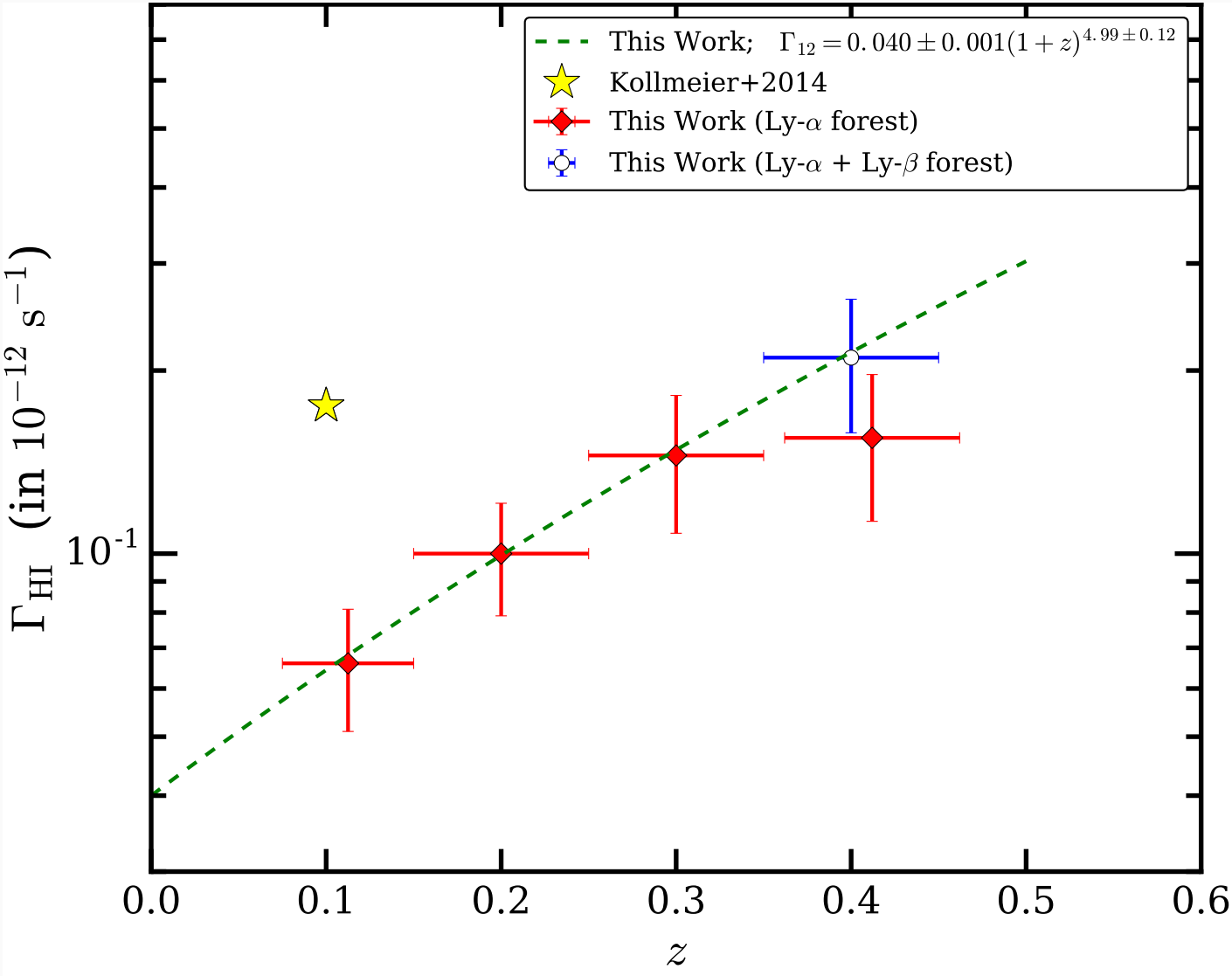
HI Interlopers:



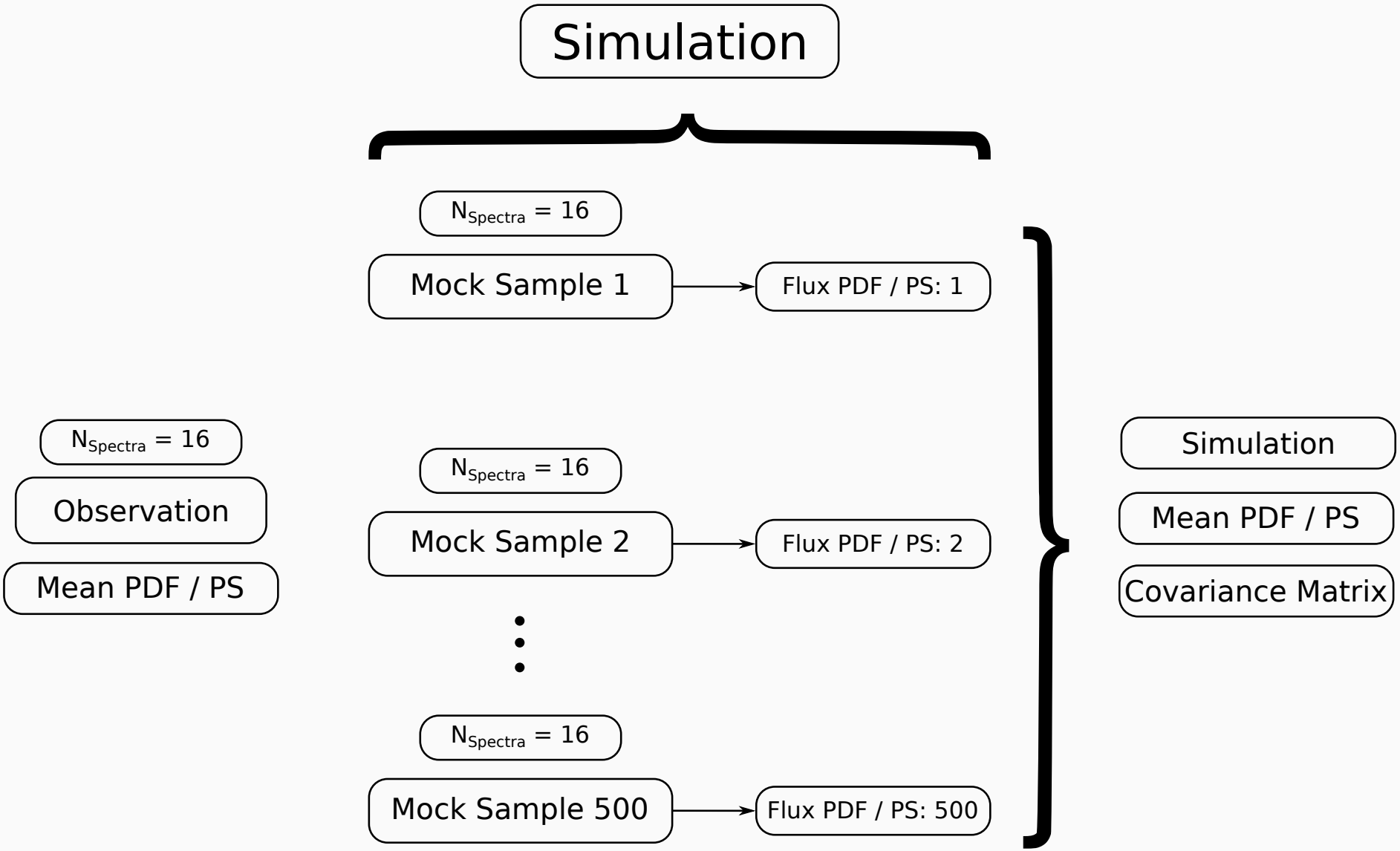
Line	λ in Å	Strength
Ly-α	1215.6701	1
Ly-β	1025.7223	6.17^{-1}
Ly-γ	972.5368	17.78^{-1}
Ly-δ	949.7431	38.02^{-1}
Ly-ω	937.8035	69.18^{-1}



$\Gamma_{\rm HI}$ Evolution:

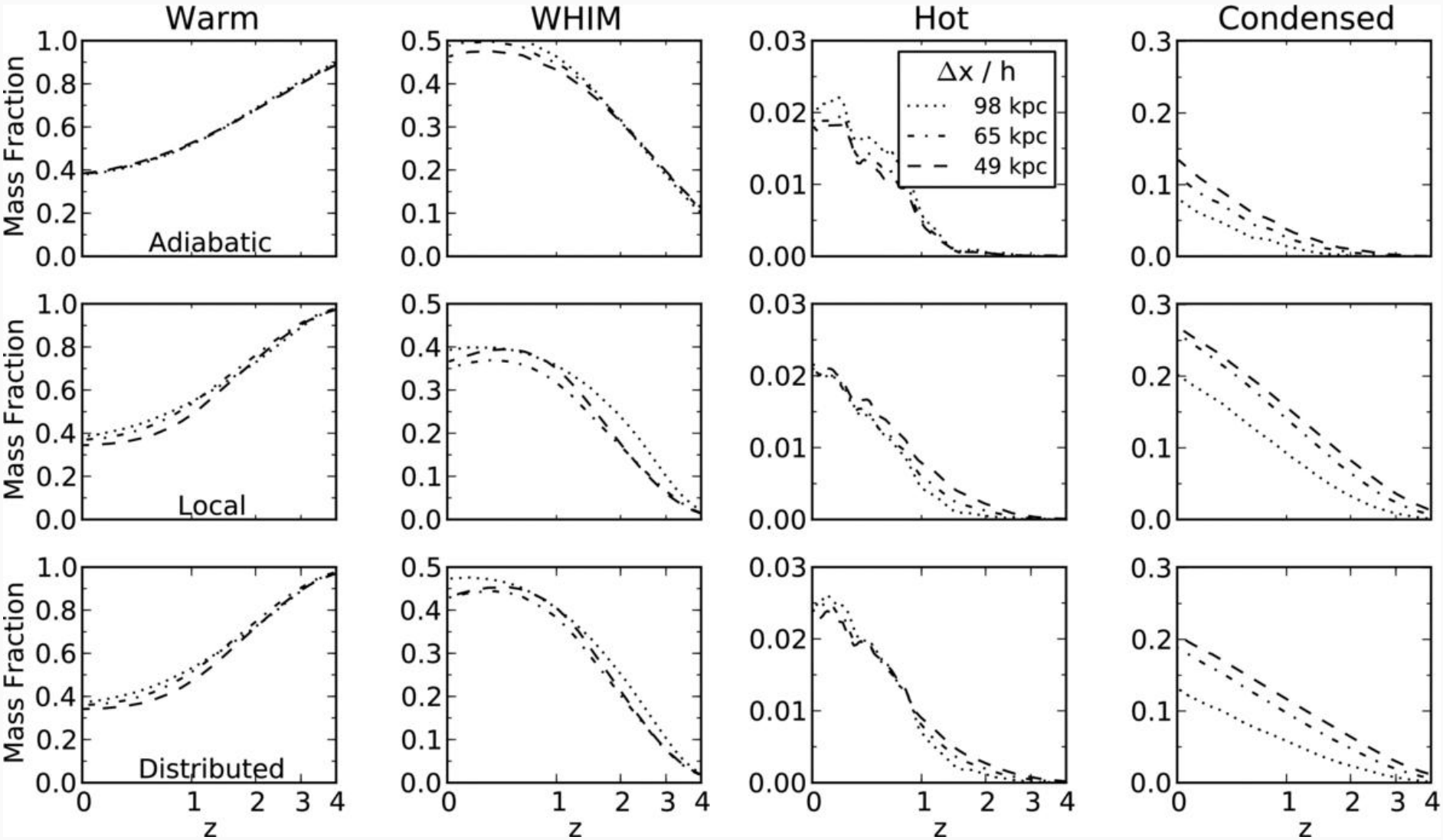


Covariance Matrix

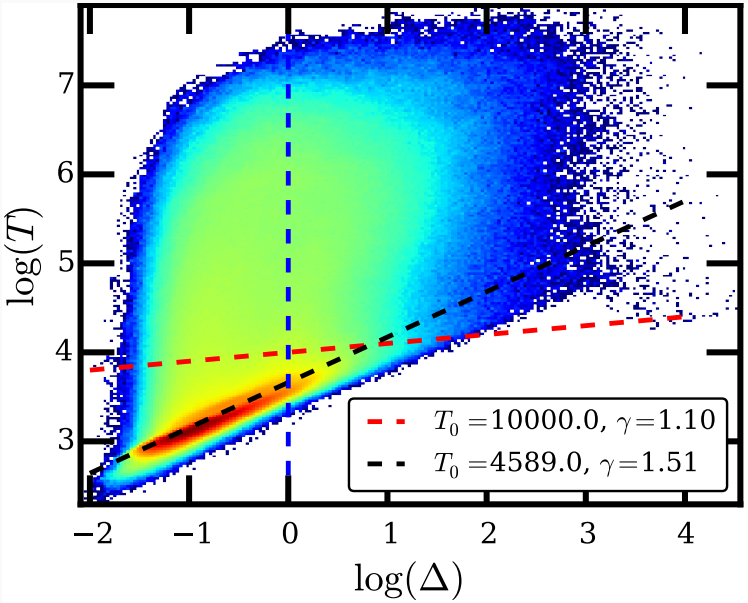


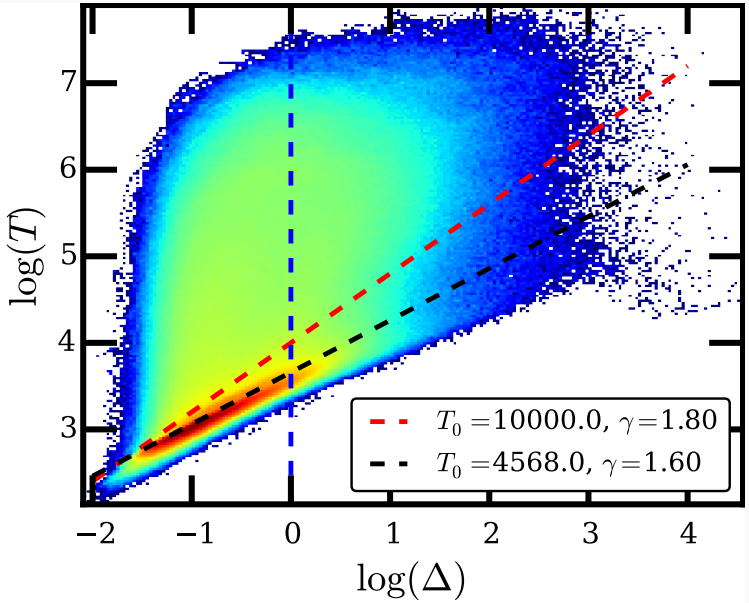
Effect of Feedback:

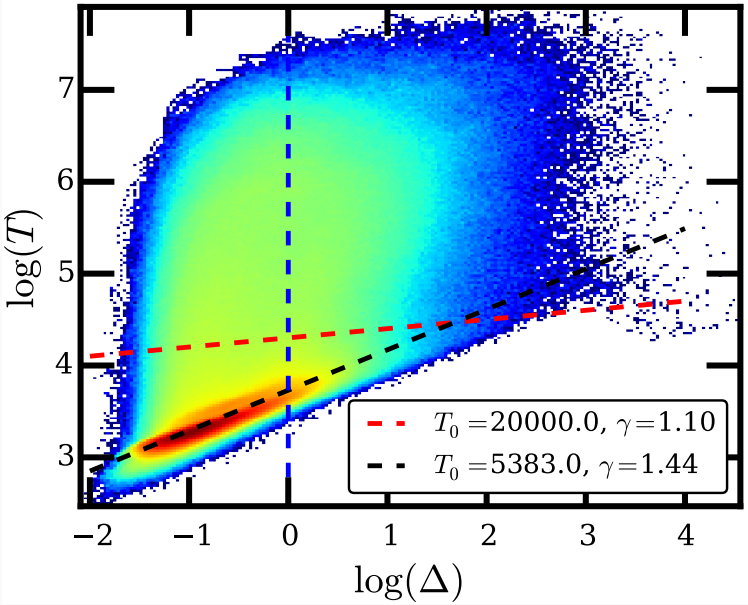
[Smith et. al. 2011]

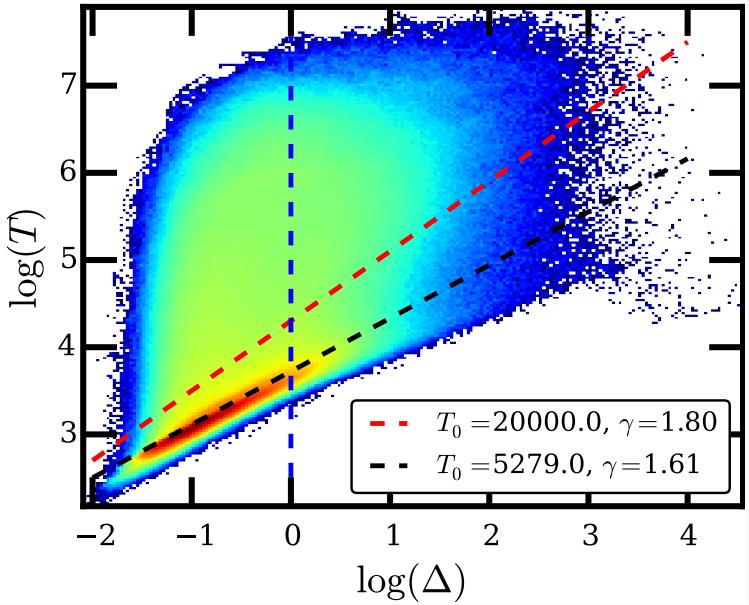


Effect of initial T_0 and γ









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]