New Measurement of the low-z IGM Thermal State Based On Density-Estimation Likelihood-Free Inference (DELFI)

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Outline

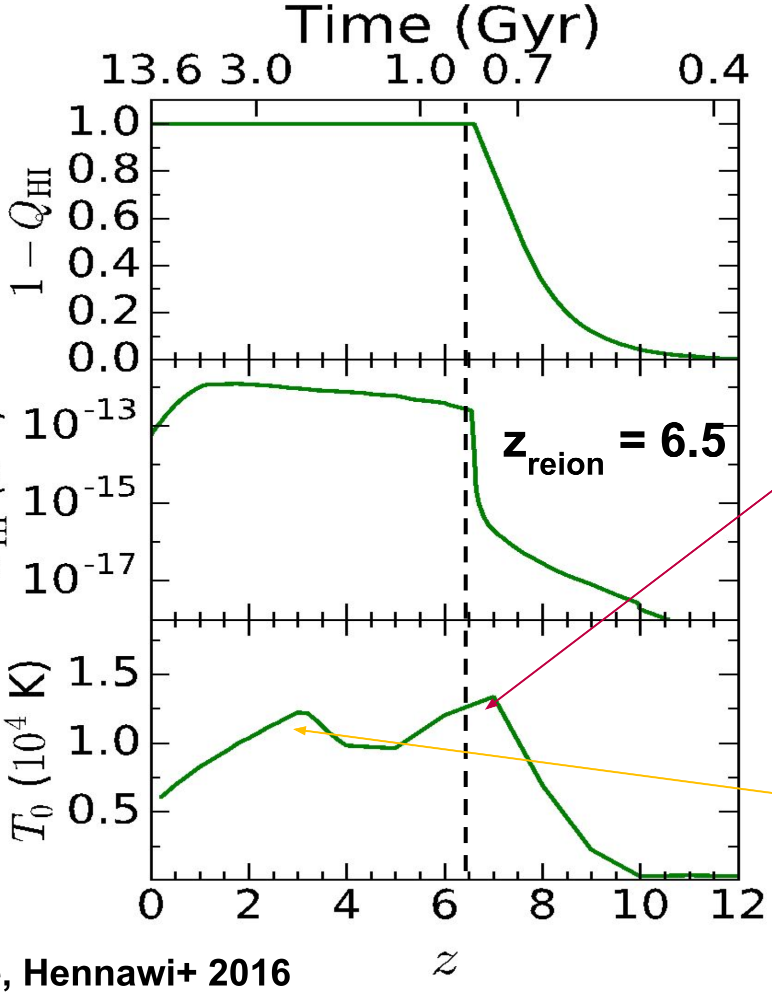
- New method to measure the IGM thermal state based on DELFI
- Preliminary result on Danforth2016 Data at z=0.1
- Implementation of the method on other simulations
- An alternative parameterization of the low z IGM

IGM Thermal History

Filling fraction of ionized regions

ionizing GUV

IGM temp. at mean density

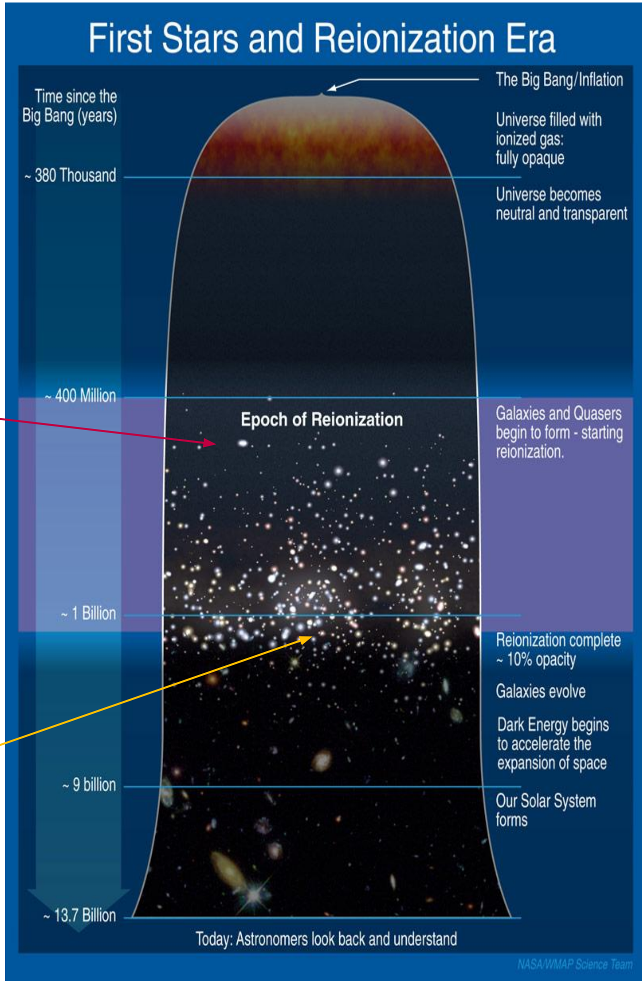


Oñorbe, Hennawi+ 2016

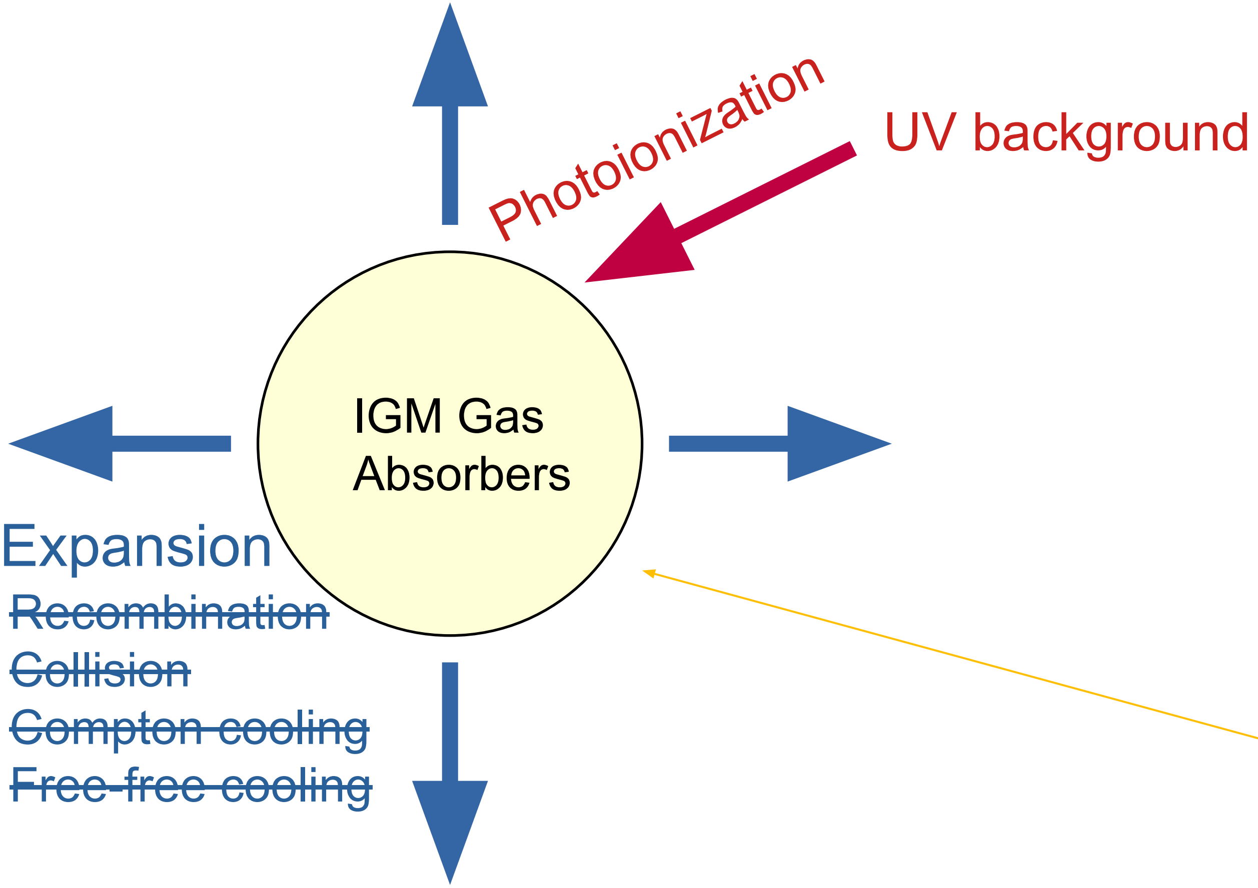
Two heating events

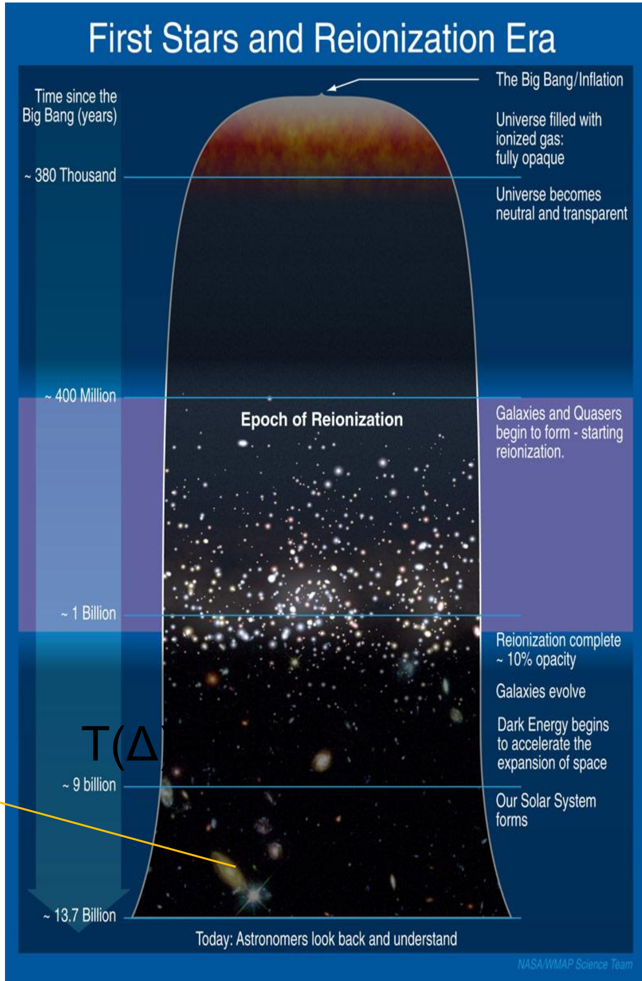
Reionization (Hydrogen)

Helium Reionization

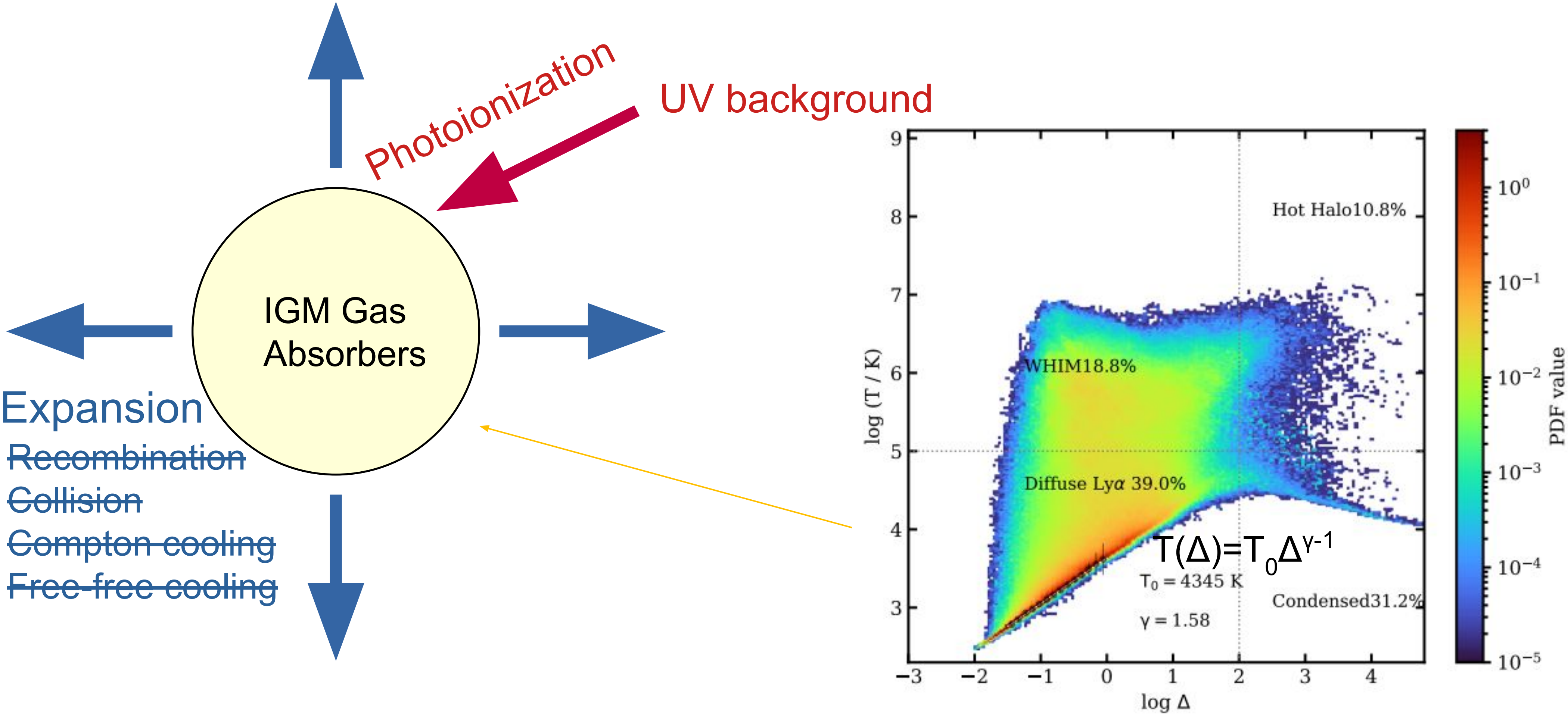


IGM Thermal History



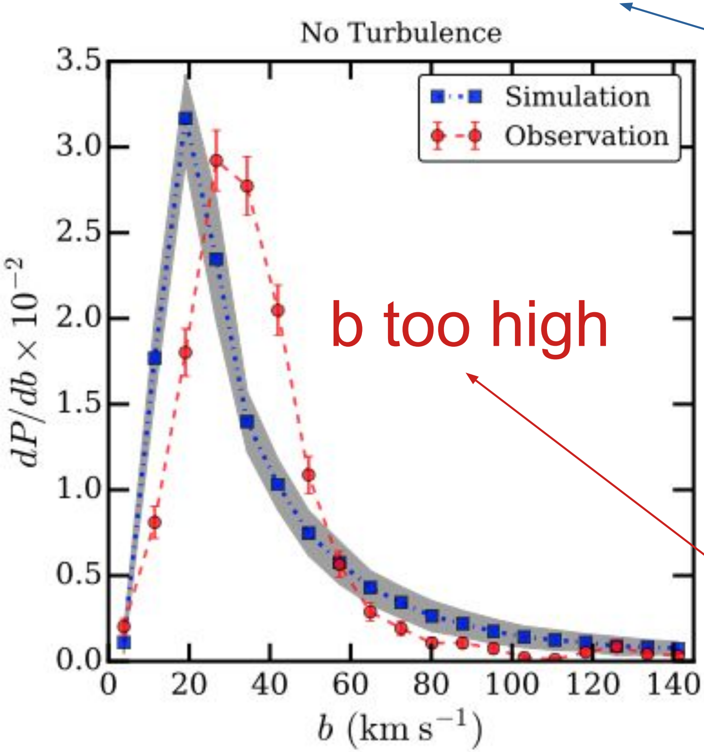


IGM Thermal History



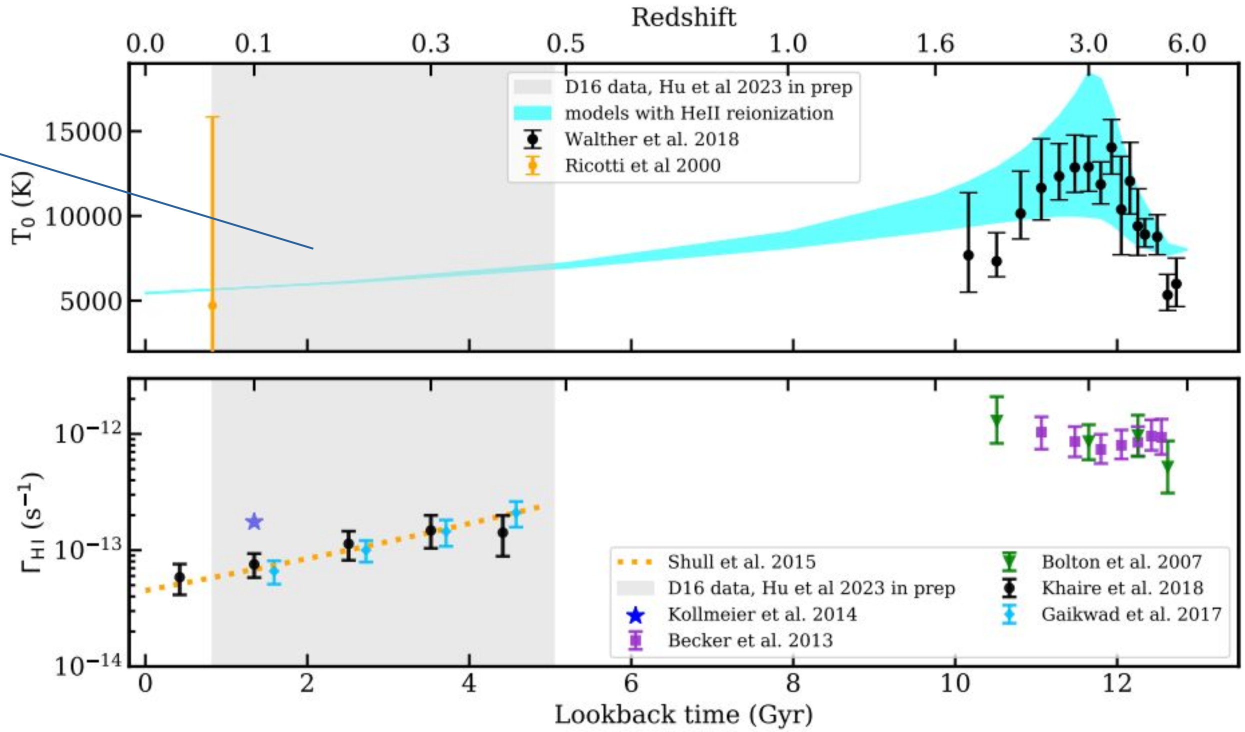
IGM Thermal History

Is the IGM too hot in low z?



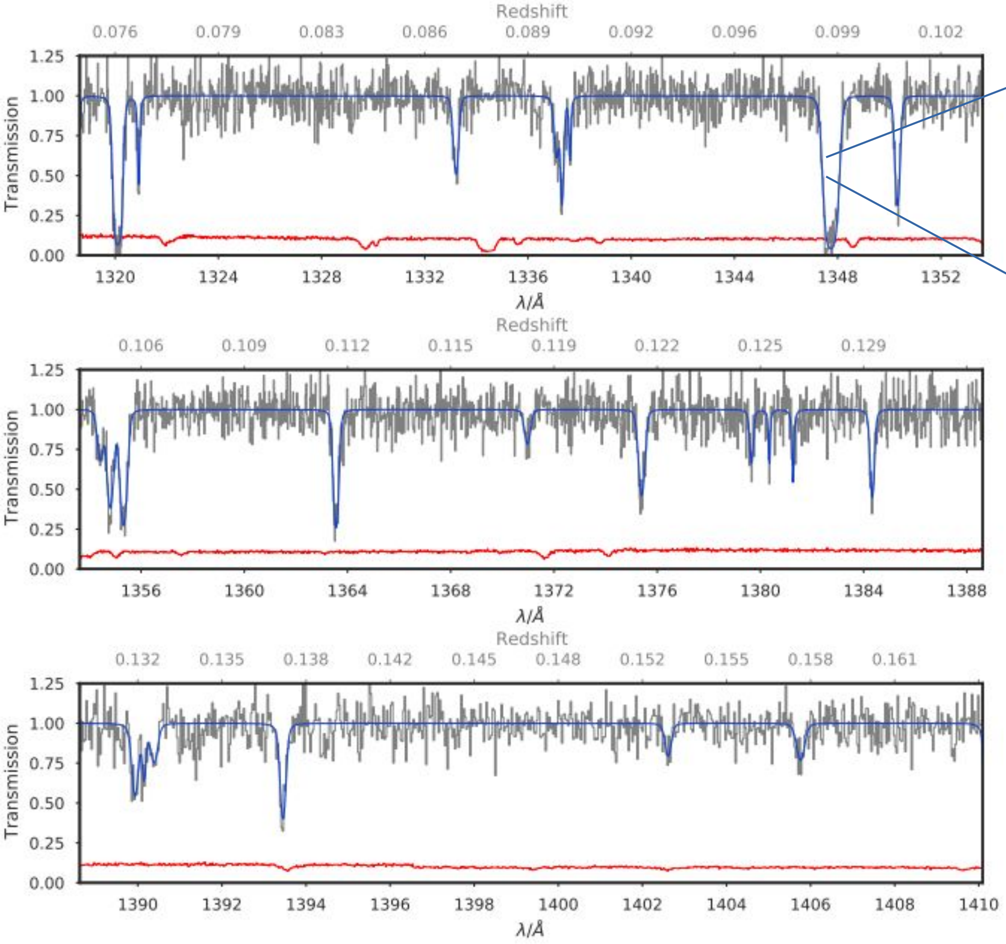
b too high

Gaikwad+2017



Recent researches suggest that the IGM might be much hotter (Gaikwad et al. 2017; Viel et al. 2017; Nasir et al. 2017

b-N distribution



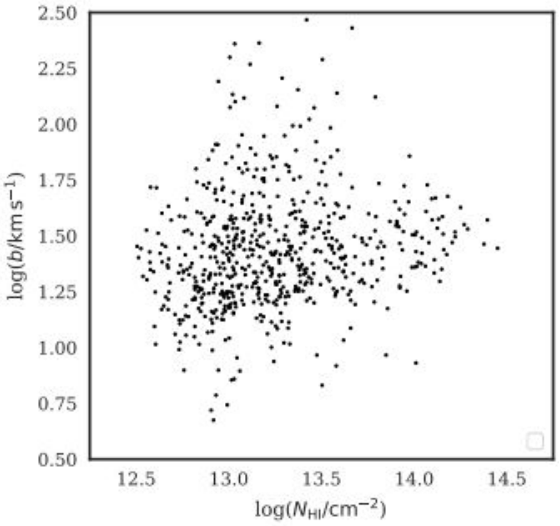
b: broadening parameter

Thermal → Relates to T_0 of IGM

Turbulence

N: HI Column density

(b,N) pairs



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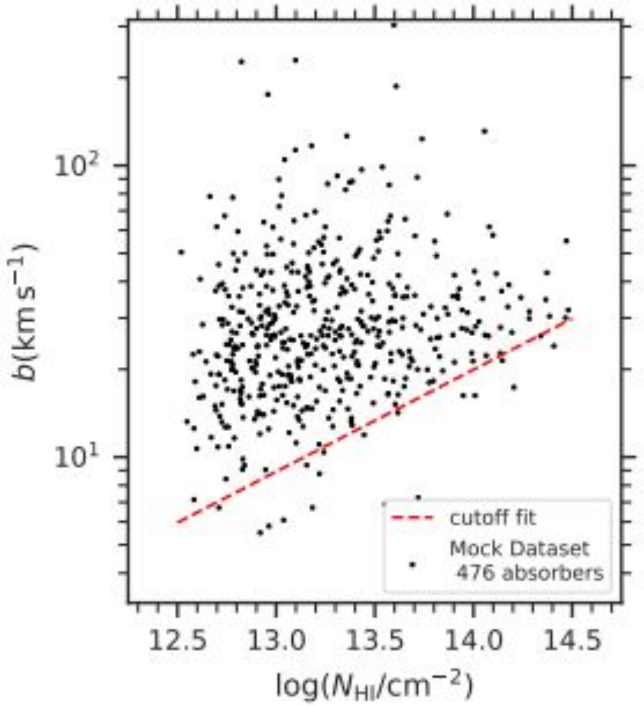
Previous work



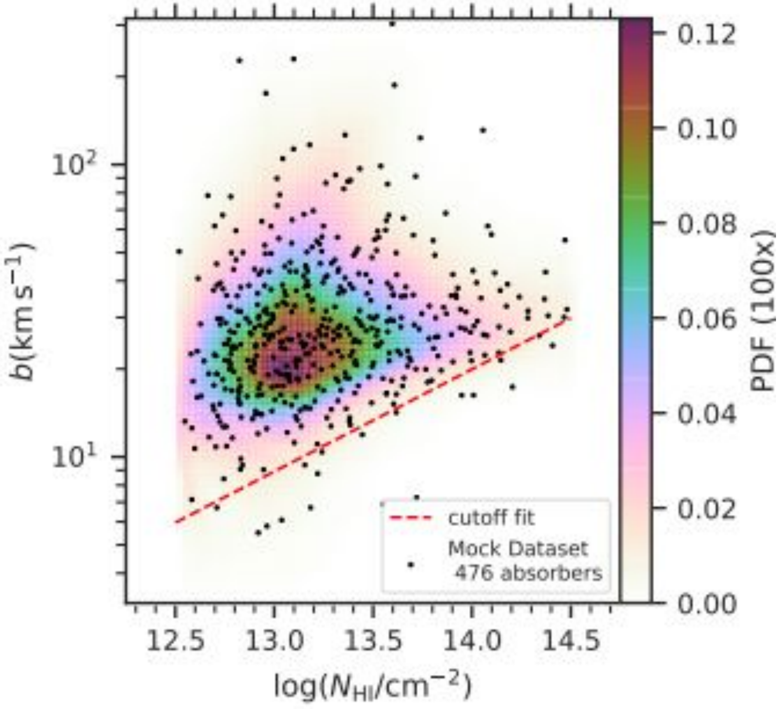
Fit b-N distribution by cutoff

Sensitive to noise and outliers

Not using all information
(Rorai et al. 2018; Hiss et al. 2019)

Schaye+1999,Ricotti+20000,Hiss2018

Full bN distribution

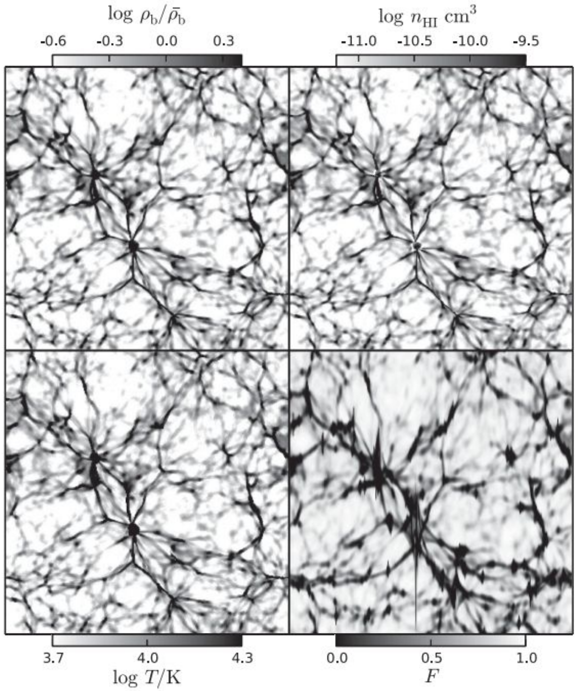


Fitting the full (b,N) distribution.

Use Density-Estimation Likelihood-Free Inference (DELFI) to emulate
$P\,(b,N|T_0,\gamma,\Gamma_{HI})$

Hiss2019, Hu+2022

Nyx Simulation



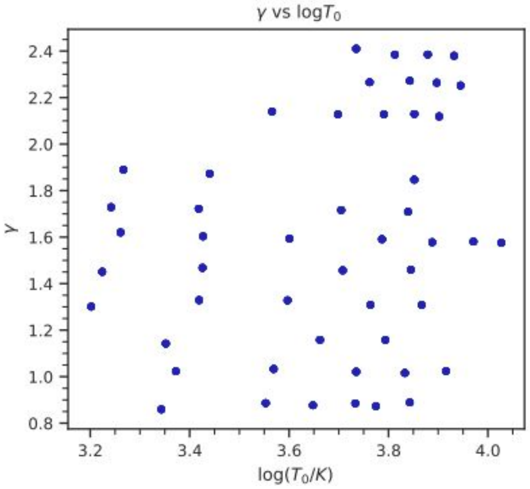
Box size 20 cMpc/h with 1024^3 grids

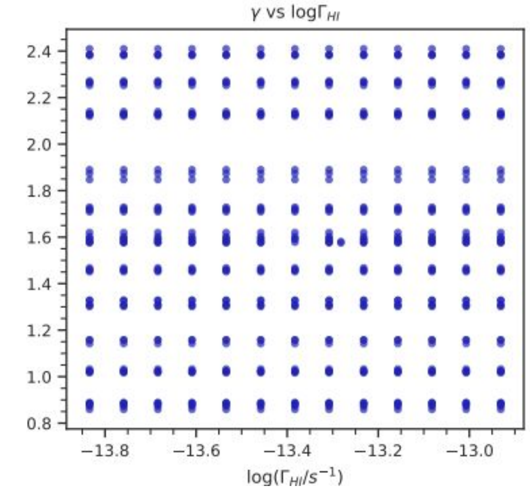
No feedback or galaxy formation

Thermal History and Evolution in Reionization Models of Absorption Lines (THERMAL) suite of Nyx simulation

50 models on T_0-γ plane

50 x13 = 650 models in total.





Zarija Lukic et al 2015

Nyx Simulation

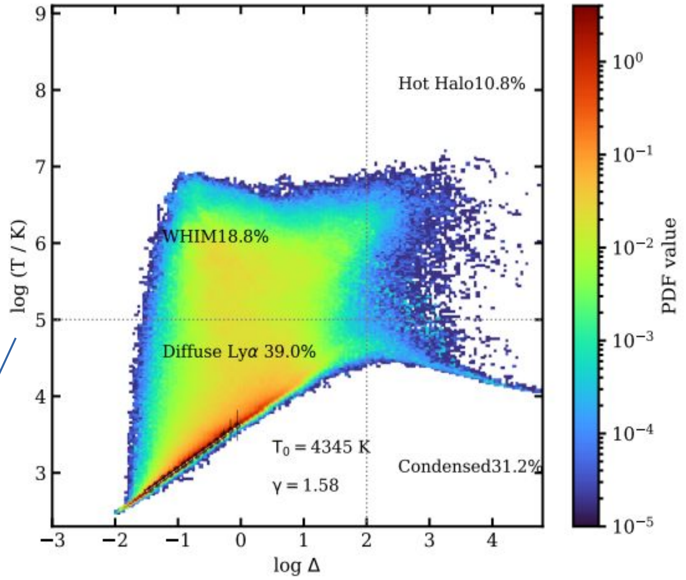
Fit the density-Temperature relationship

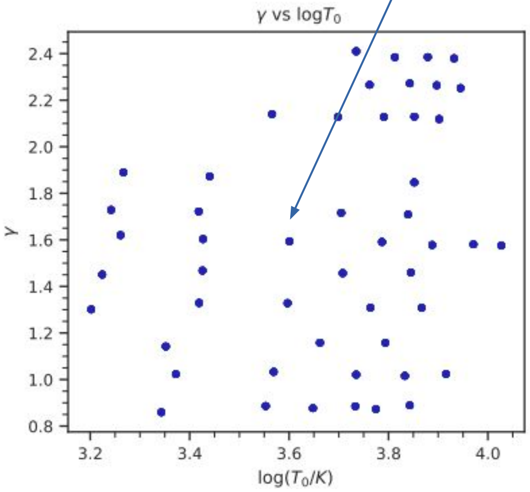
$$T(\Delta)=T_0\Delta^{\gamma-1}$$

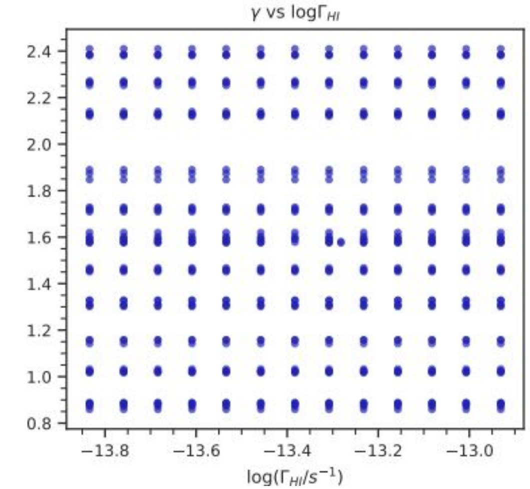
Models are generated by setting different photoheating rate

$$\varepsilon = A\Delta^B\varepsilon_0$$

T_0, γ

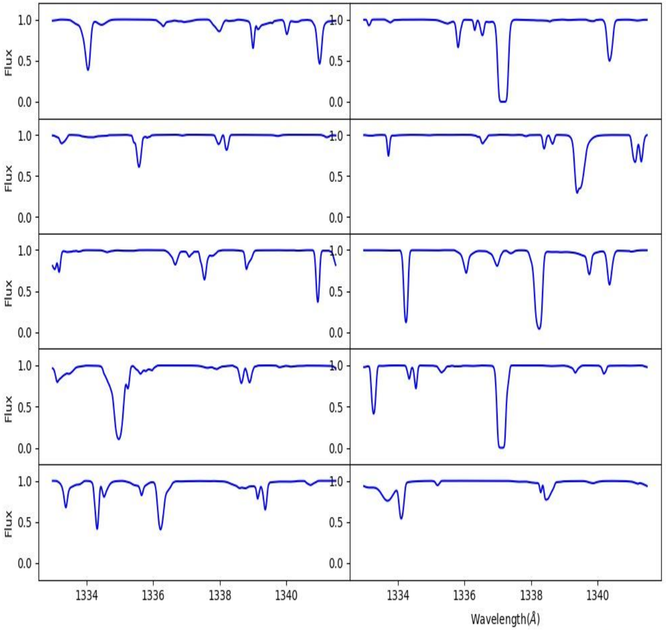






Zarija Lukic et al 2015

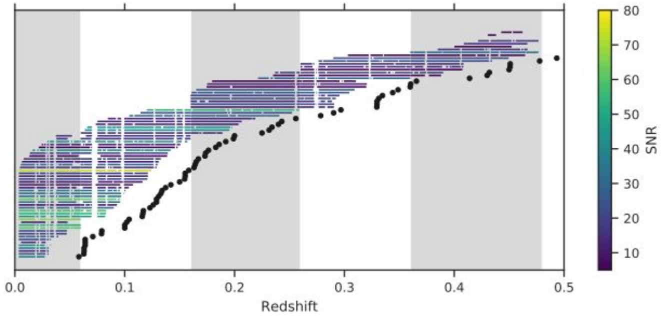
Forward-modeling and VPFIT



Stitched skewers

Forward-modeling
HST COS LSF

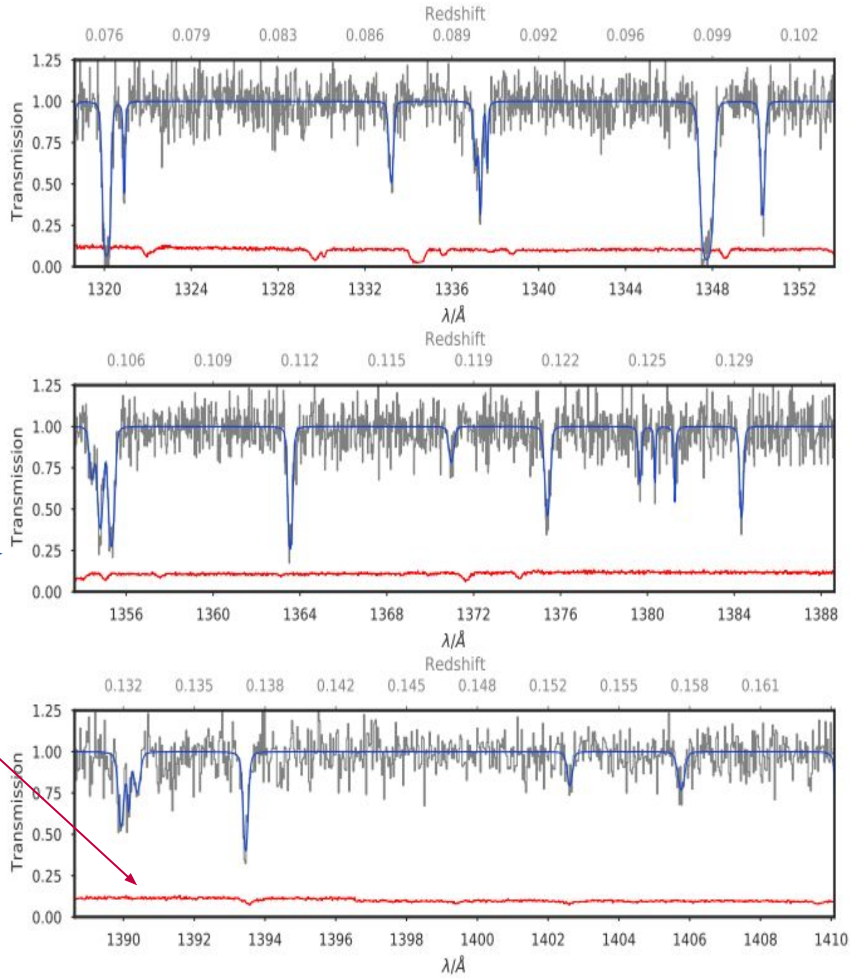
Wavelength and
noise vectors



Danforth et al. 2016
Z=0.1 HST COS data
34 spectra

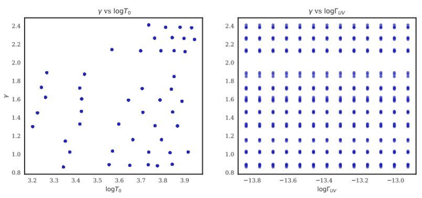
Teng Hu et al 2023 in prep

VPFIT based on COS LSF



b-N emulator

- Hiss+2019,Alsing+2019, Hu+2022



Models with thermal parameters $[T_0, \gamma, \Gamma_{HI}]$

Masked Autoregressive Flow neural density estimator

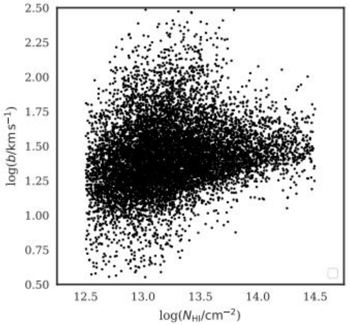
Distribution of (b-N) pairs for any given $[T_0, \gamma, \Gamma_{HI}]$

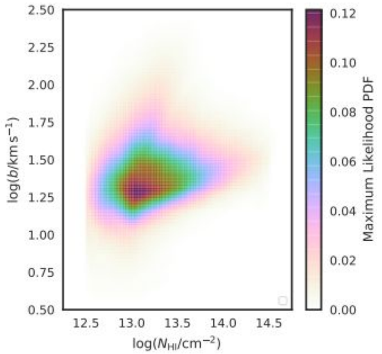
Training data $\{(b,N),\theta\}$

DELFI

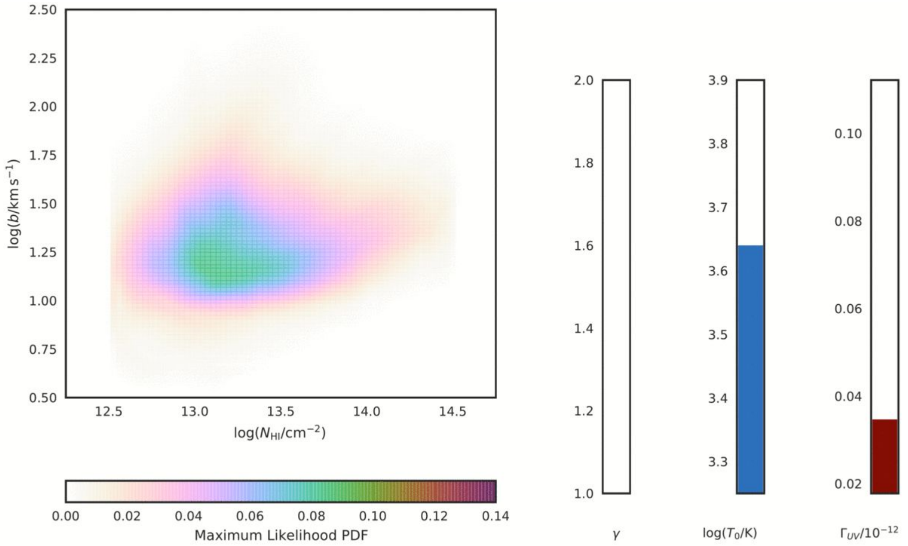
$p(b,N|\theta)$

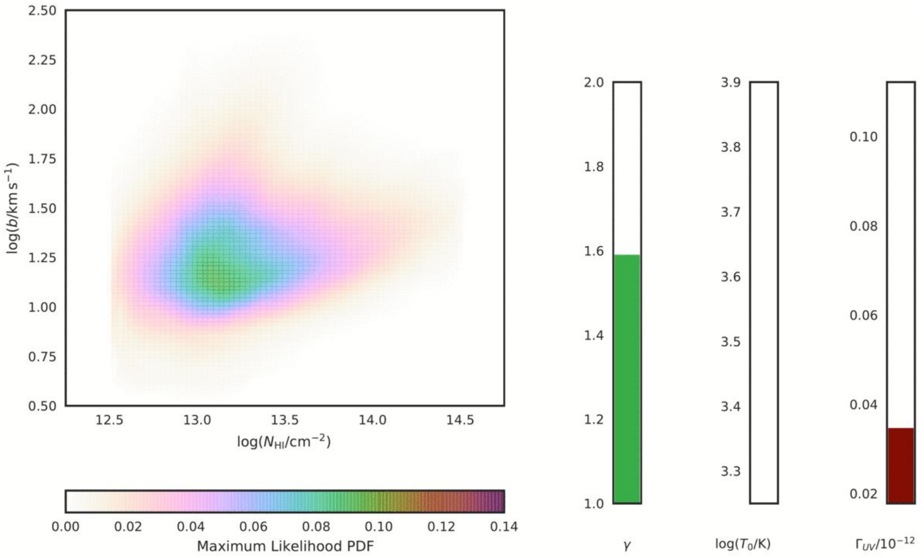
(b,N) pairs from each model, labeled by $[T_0, \gamma, \Gamma_{HI}]$

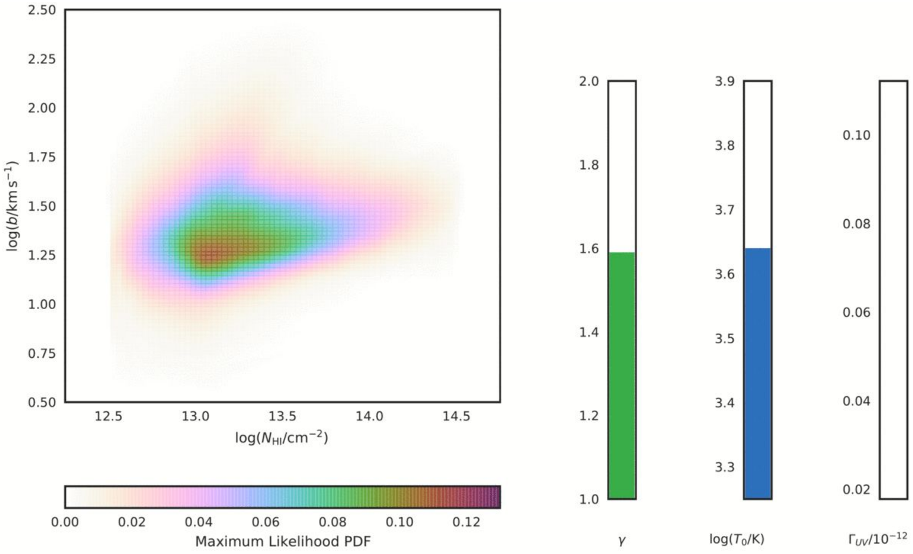




Emulated b-N distribution

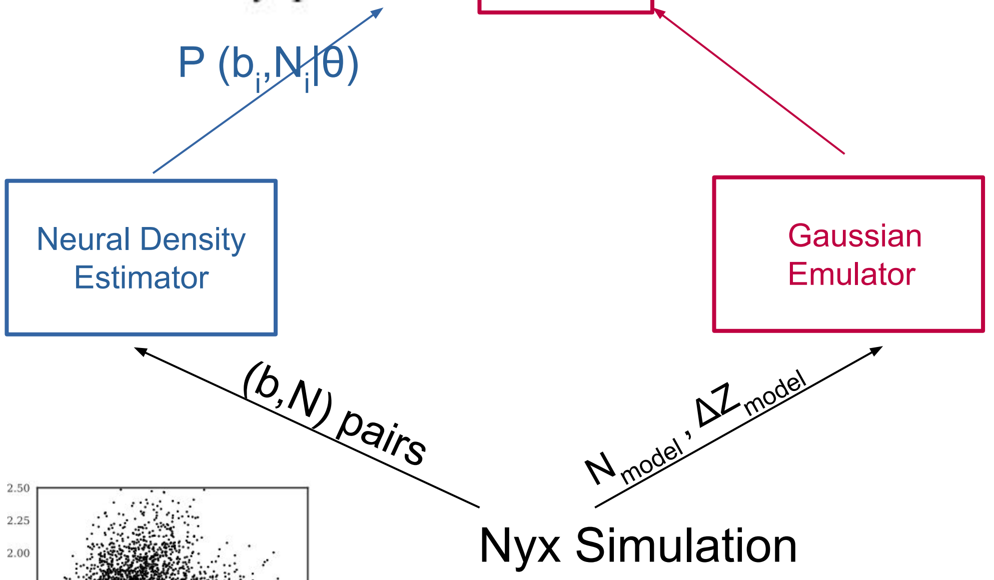


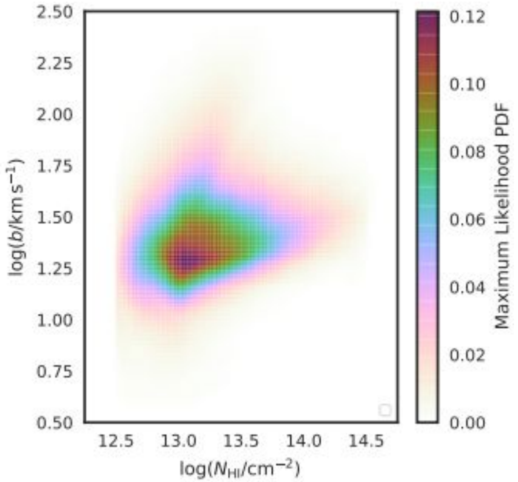


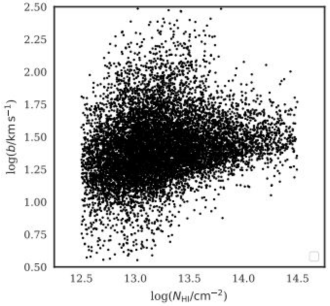


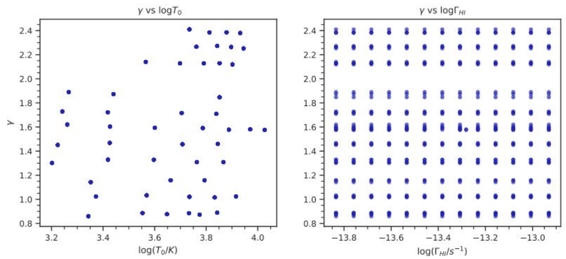
Likelihood emulator

$$\ln \mathcal{L} = \sum_{i=1}^{n} \ln(\boxed{\mu_i}) - \boxed{\frac{N_{\mathrm{model}}}{\Delta z_{\mathrm{model}}}} \Delta z_{\mathrm{data}},$$



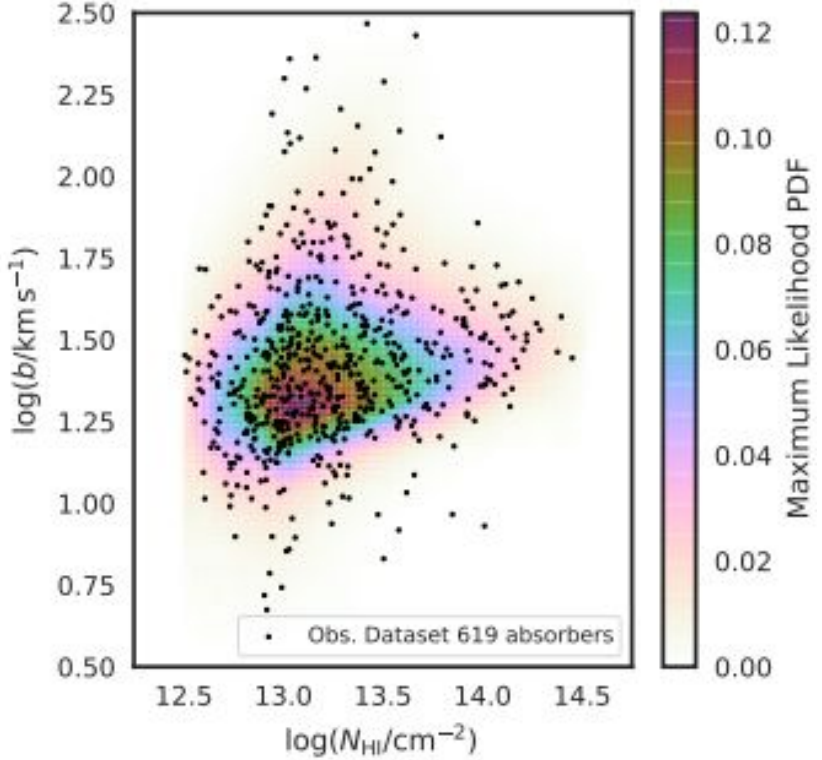


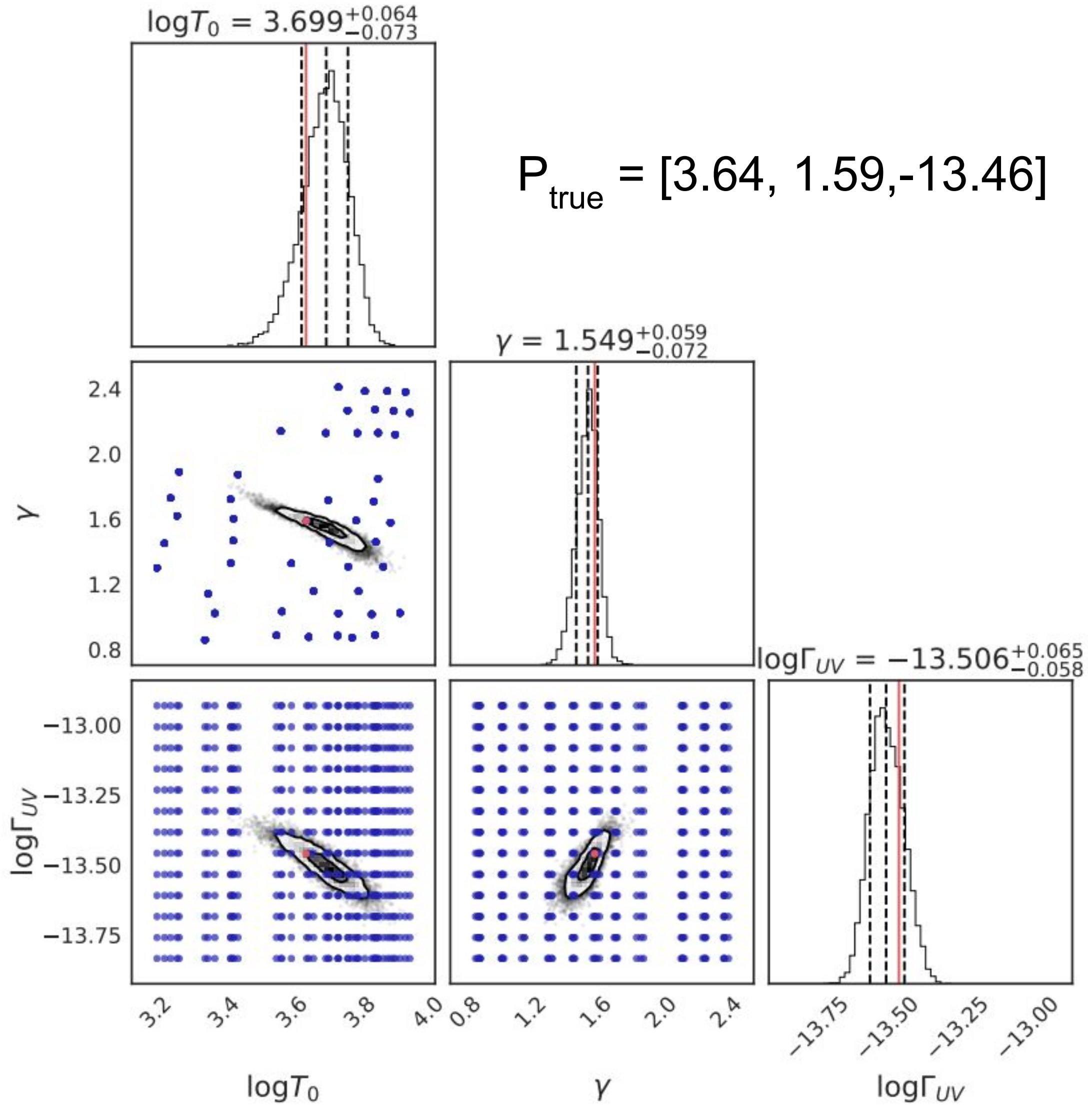




Hu+2022

Mock data analysis





P_{true} = [3.64, 1.59,-13.46]

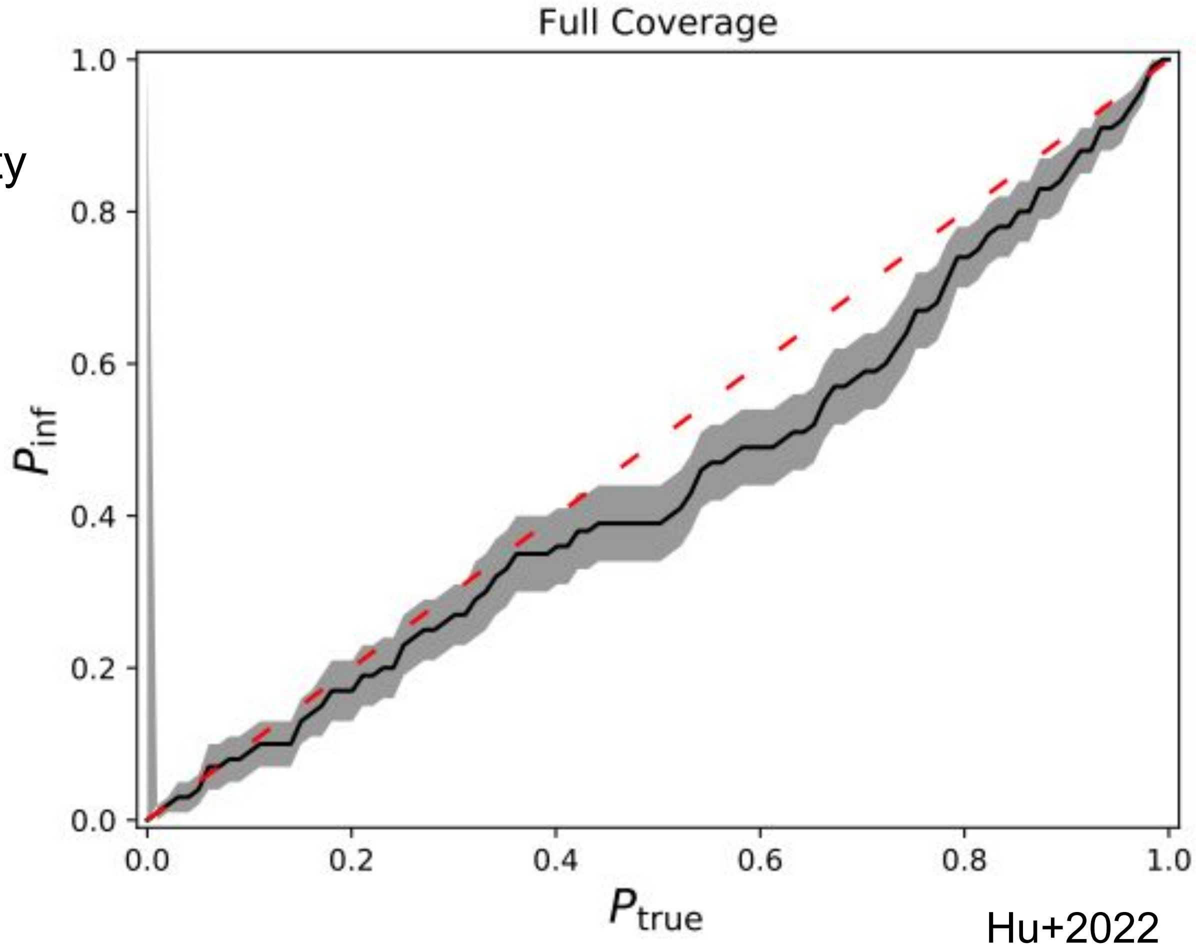
Hu+ 2022

Inference Test

- Check if the inference method returns valid posterior probability distributions.

- Coverage probability $\boldsymbol{P}_{inf}$: the proportion of the time that the true parameters of interest are contained within a certain likelihood contour

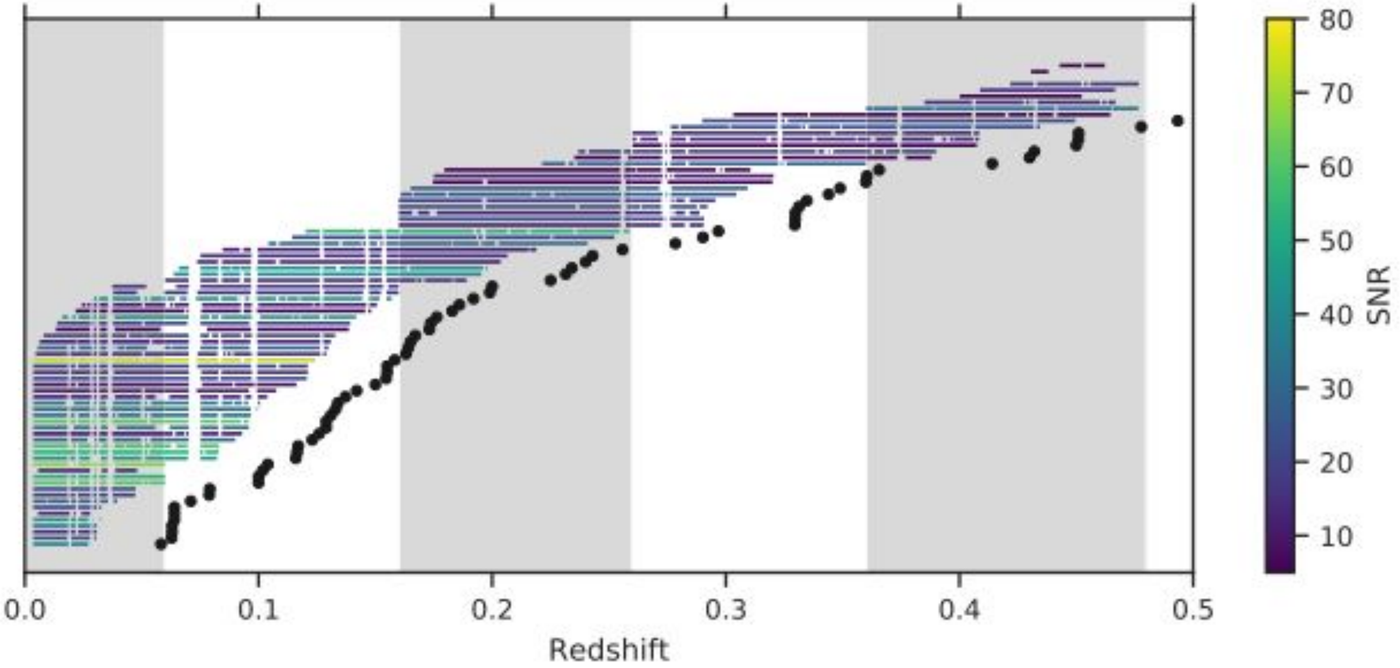
- 100 realizations based on realistic mock dataset.



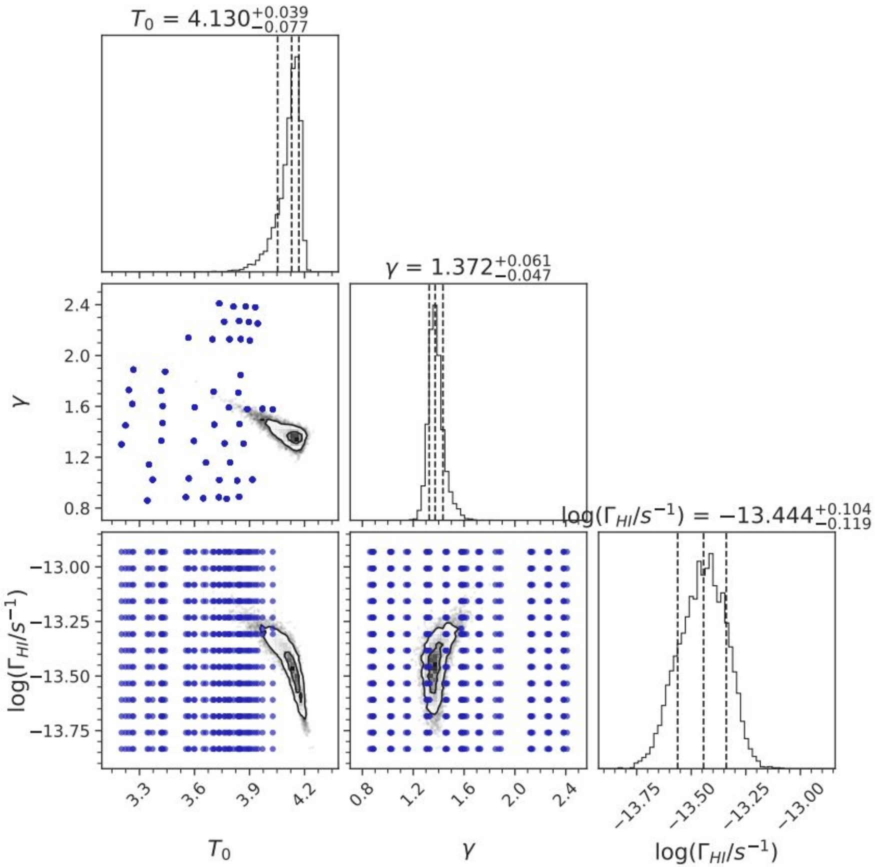
Hu+2022

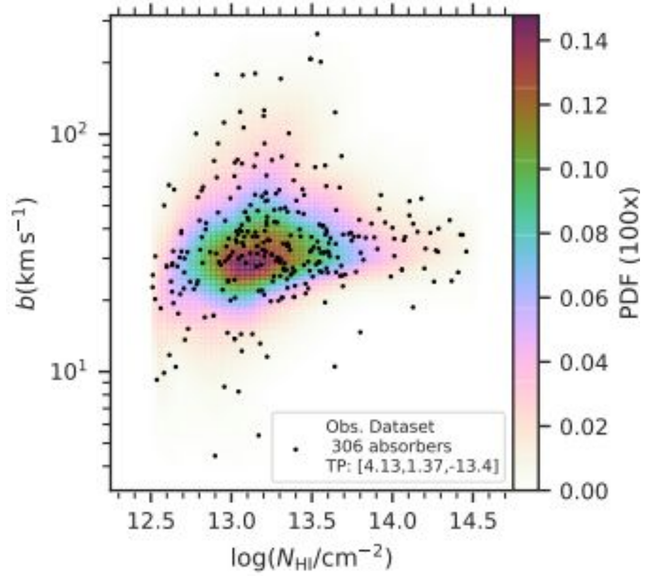
Danforth 2016 data

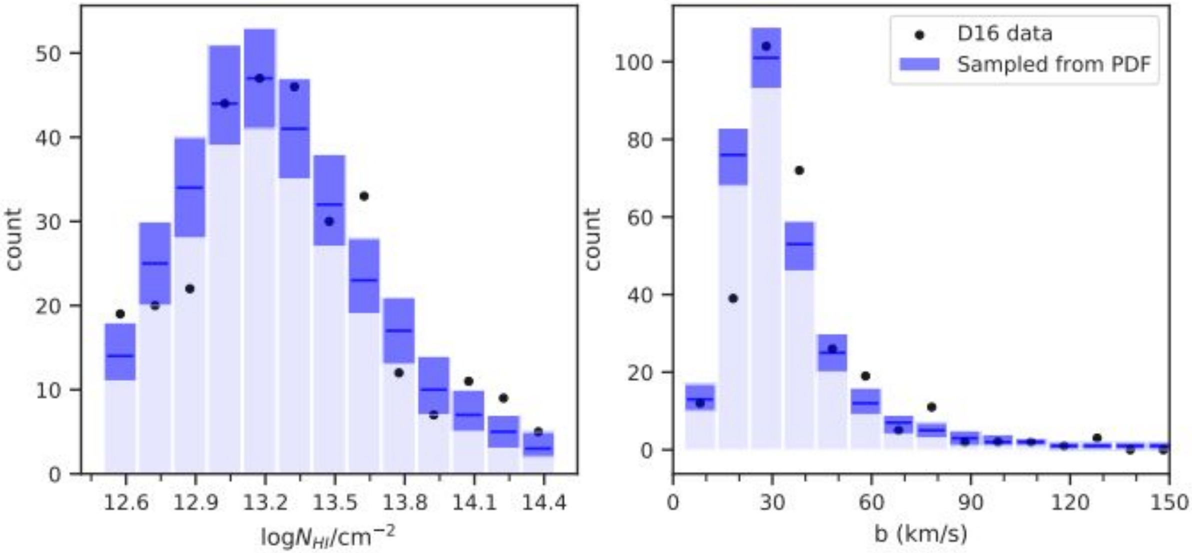
- Danforth et al. 2016
- Z=0.06-0.48 HST COS data
- 82 Spectra



Preliminary Result at z=0.1

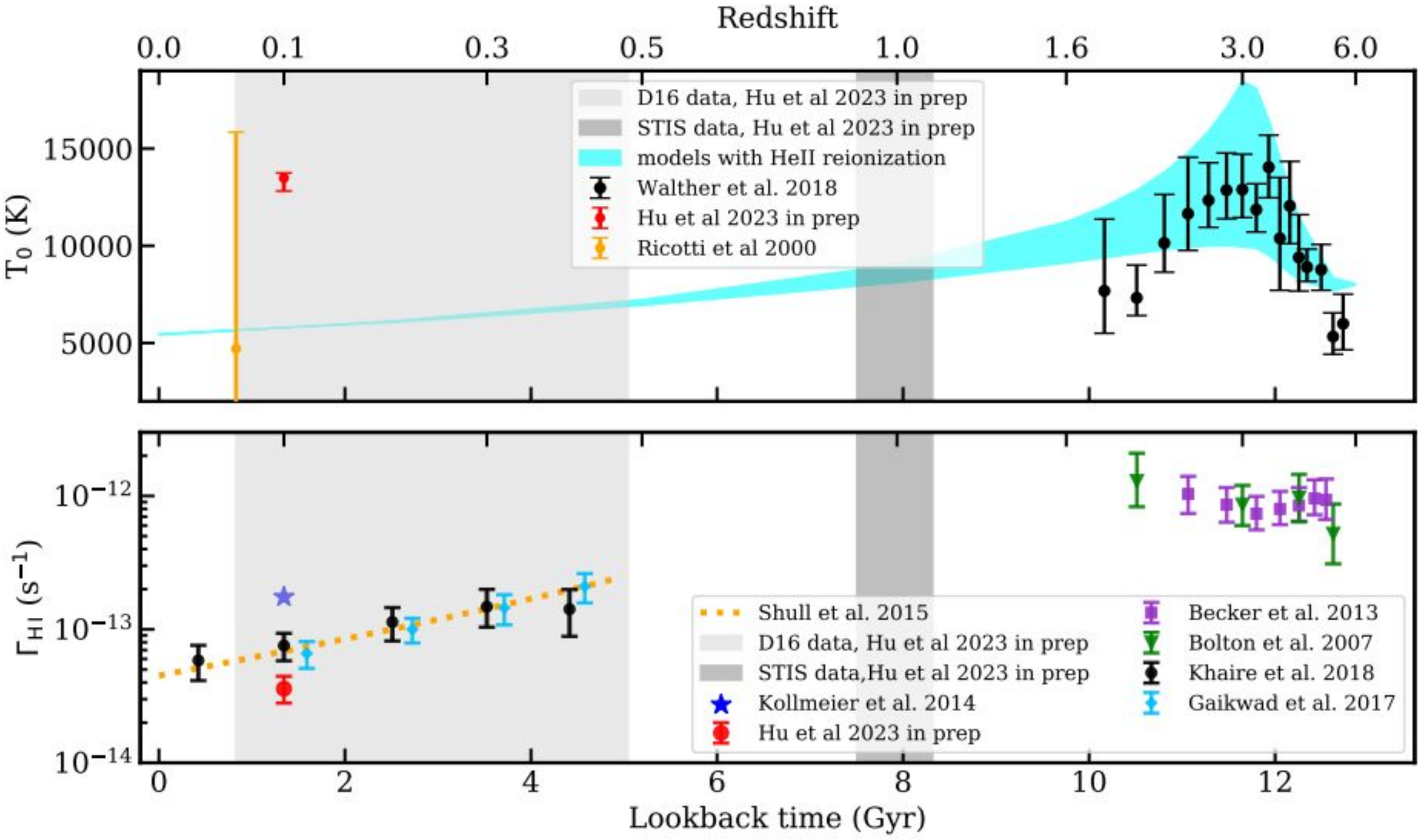




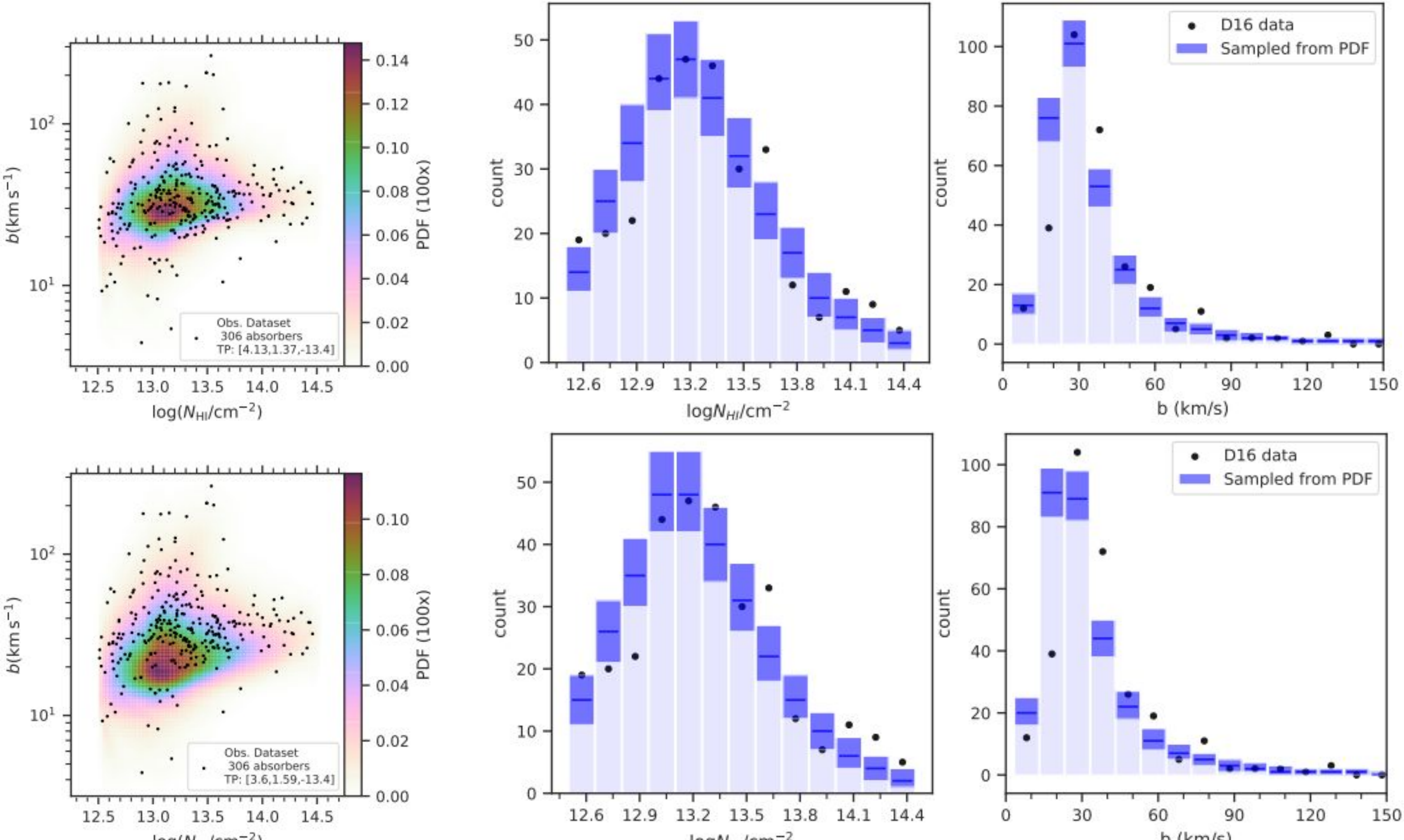


Hu+2023 in prep -b

T_0 too high?



Hu+2023 in prep -b



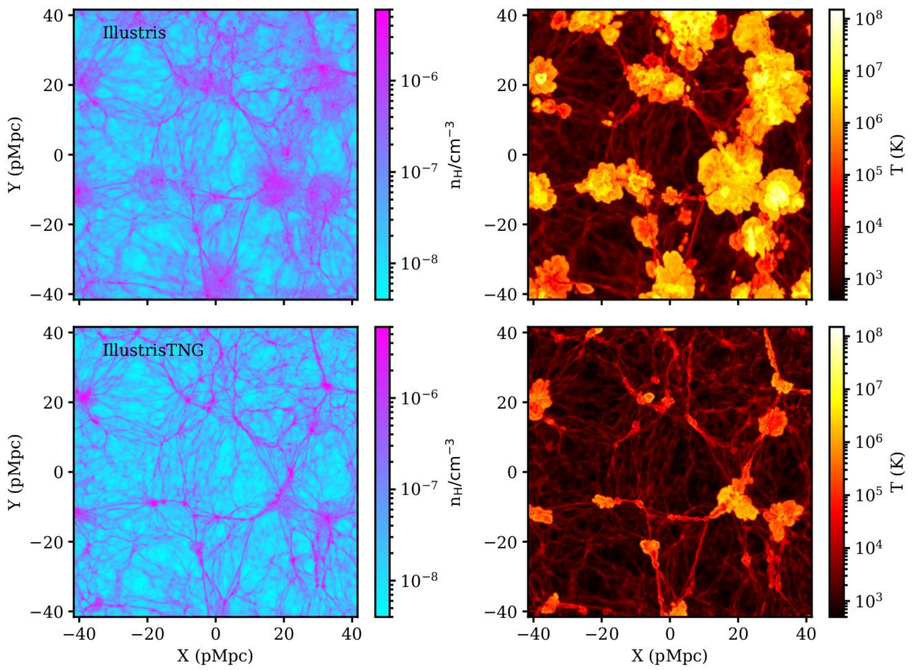
Obs. Dataset
306 absorbers
TP: [4.13,1.37,-13.4]
PDF (100x)
b(km s^-1)
log(N_HI/cm^-2)
count
logN_HI/cm^-2
D16 data
Sampled from PDF
b (km/s)
Obs. Dataset
306 absorbers
TP: [3.6,1.59,-13.4]
PDF (100x)
b(km s^-1)
log(N_HI/cm^-2)
count
logN_HI/cm^-2
D16 data
Sampled from PDF
b (km/s)

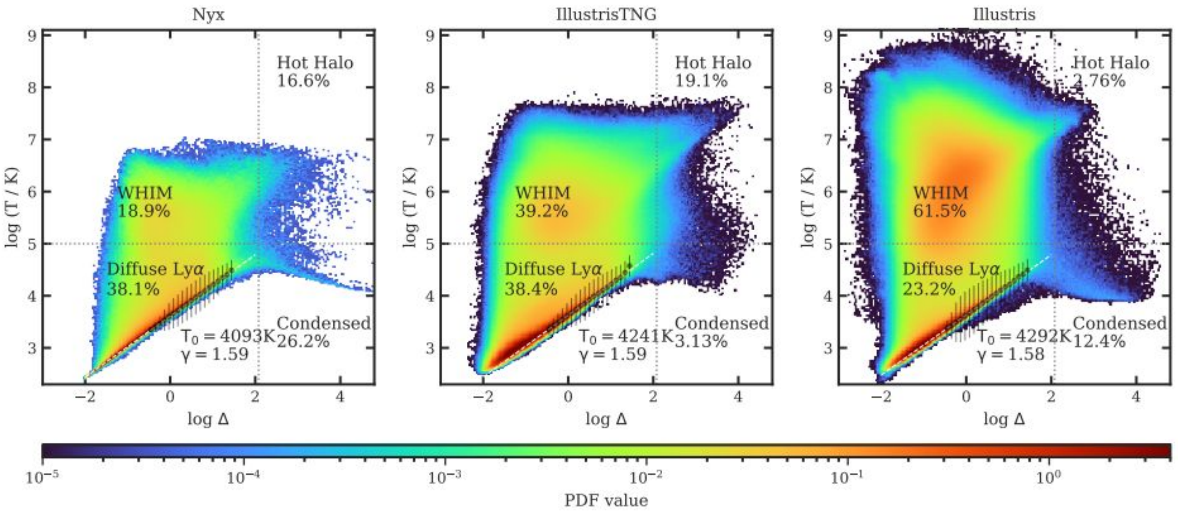
Illustris(TNG)

- 75 cMpc/h boxes with 1820^3 baryon and dark matter particles
- Includes feedback including galaxy formation and AGN.
- dN/dz matched by adjusting Γ_{HI}

Illustris

IllustrisTNG





Different simulations, similar T_0, γ

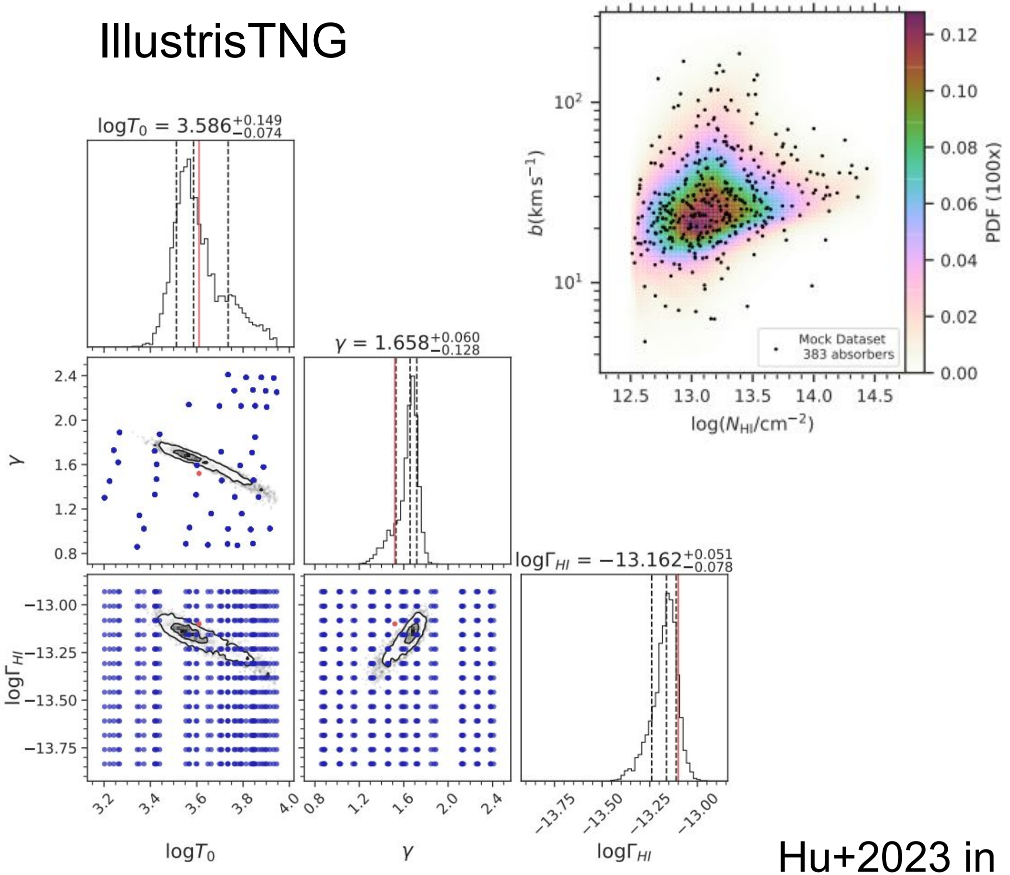
Illustris(TNG) are used as mock observation data, whereas DELFI is trained on Nyx.

Khaire, Hu +2023 in prep

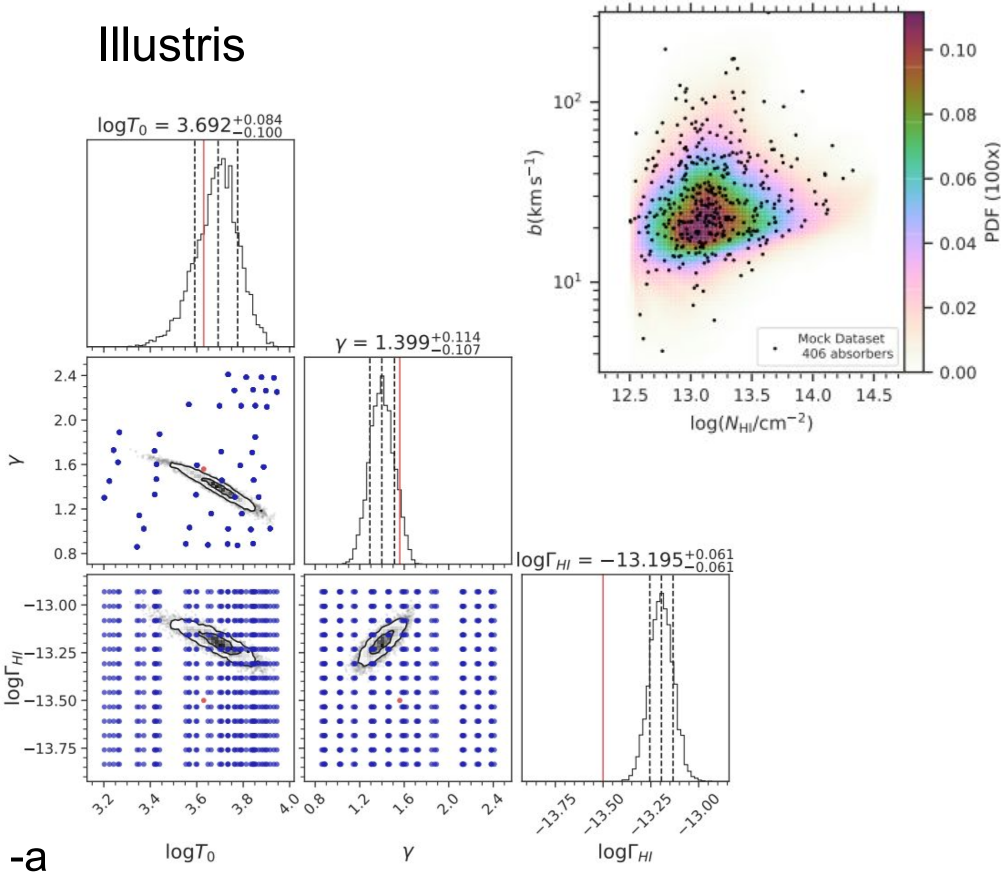
Illustris(TNG) Results

The result is decent, but does not pass the inference test.

IllustrisTNG

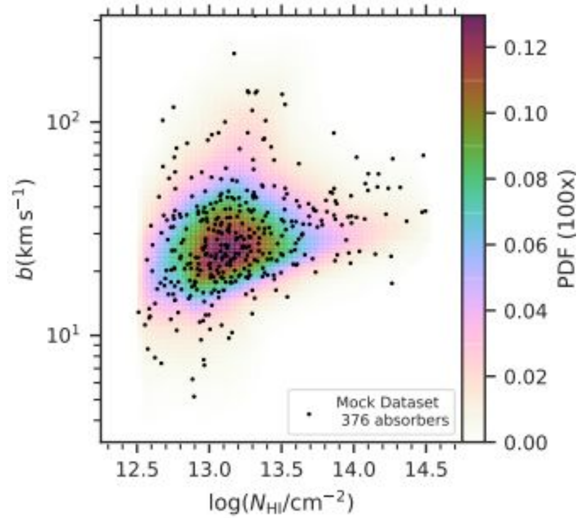


Illustris

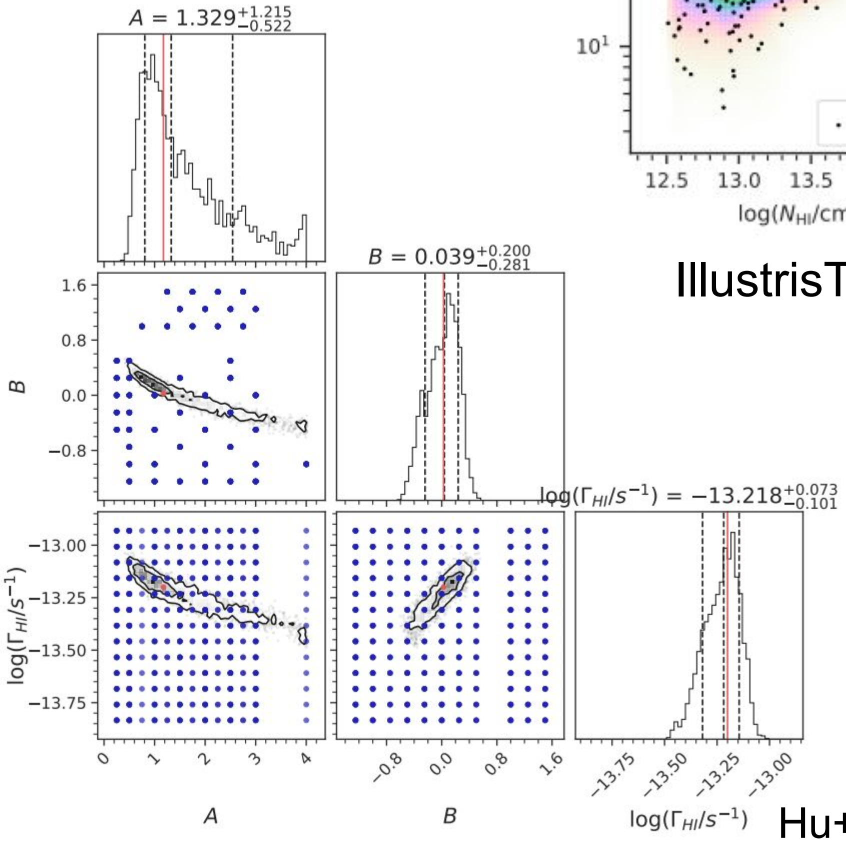


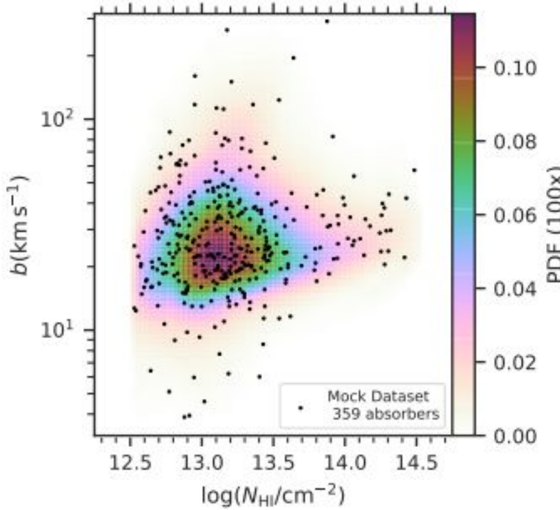
Hu+2023 in prep -a

An alternative parameterization of the IGM

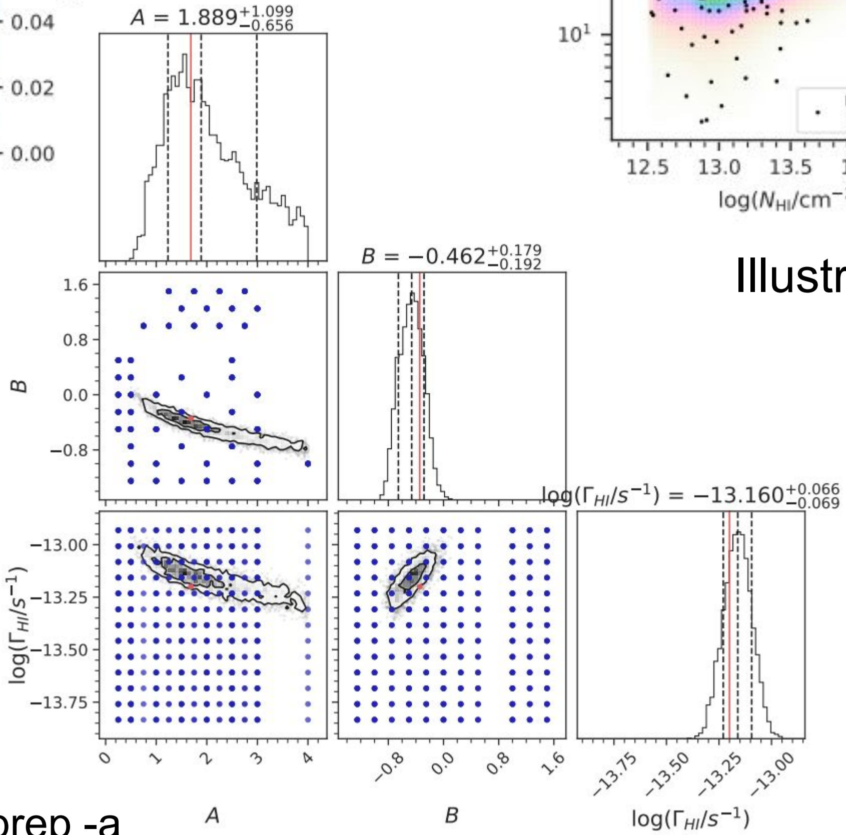


IllustrisTNG





Illustris



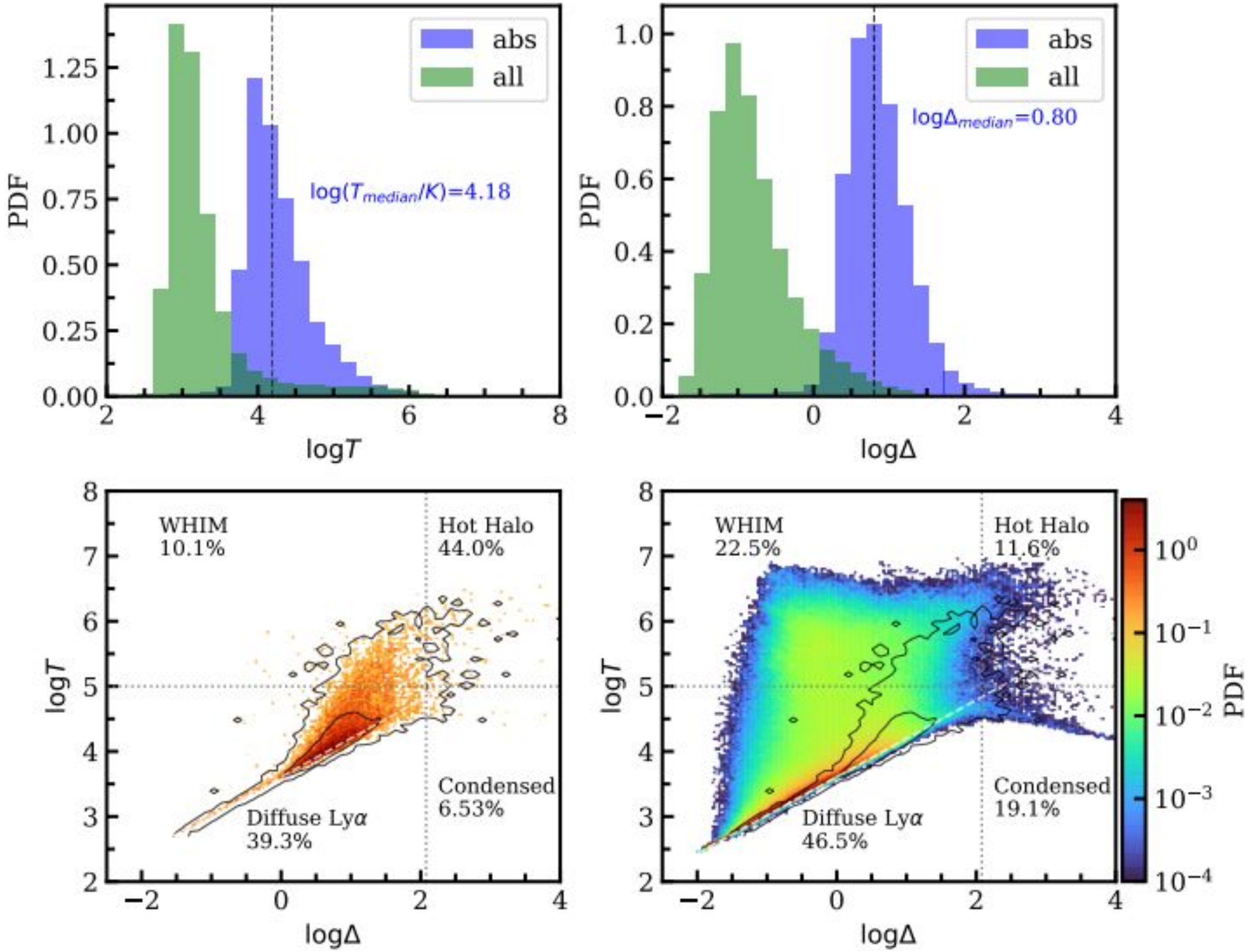
Hu+2023 in prep -a

An alternative Parameterization

- Shock heating in low z causes dispersion in the IGM Δ-T distribution, resulting in the inefficiency of the thermal state [T_0, γ] in the parameterization of the IGM.

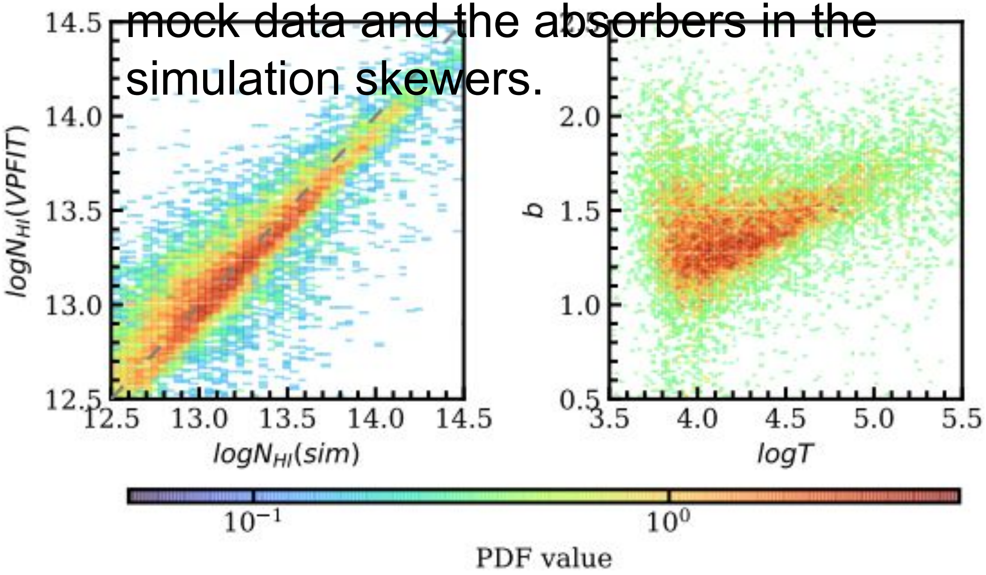
- By paring the absorbers in the simulation to the corresponding lines in mock spectra, we find the low z Lyα absorber does not follow the power-law Δ-T relationship rigiously.

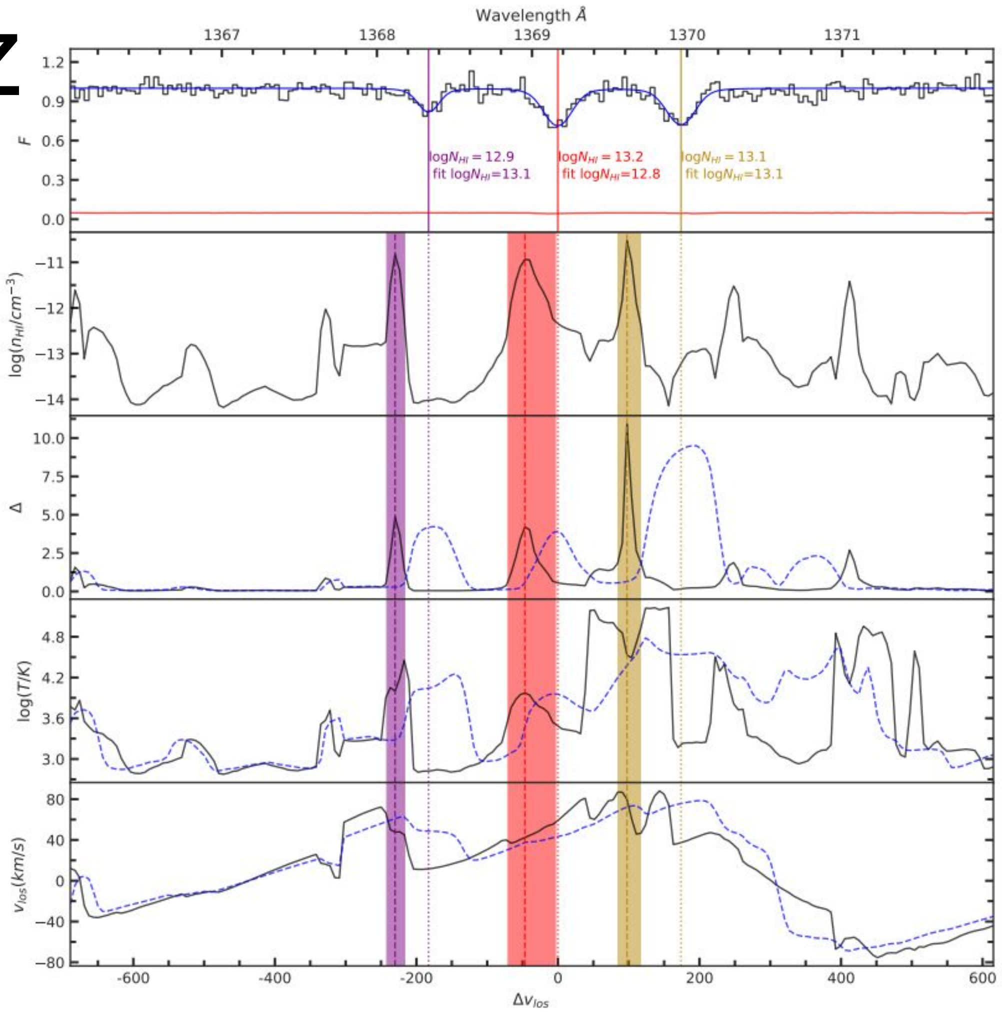
Hu+ 2023 in prep -a



Absorbers in low z

Establish one-to-one correspondence between the absorbers identified in mock data and the absorbers in the simulation skewers.

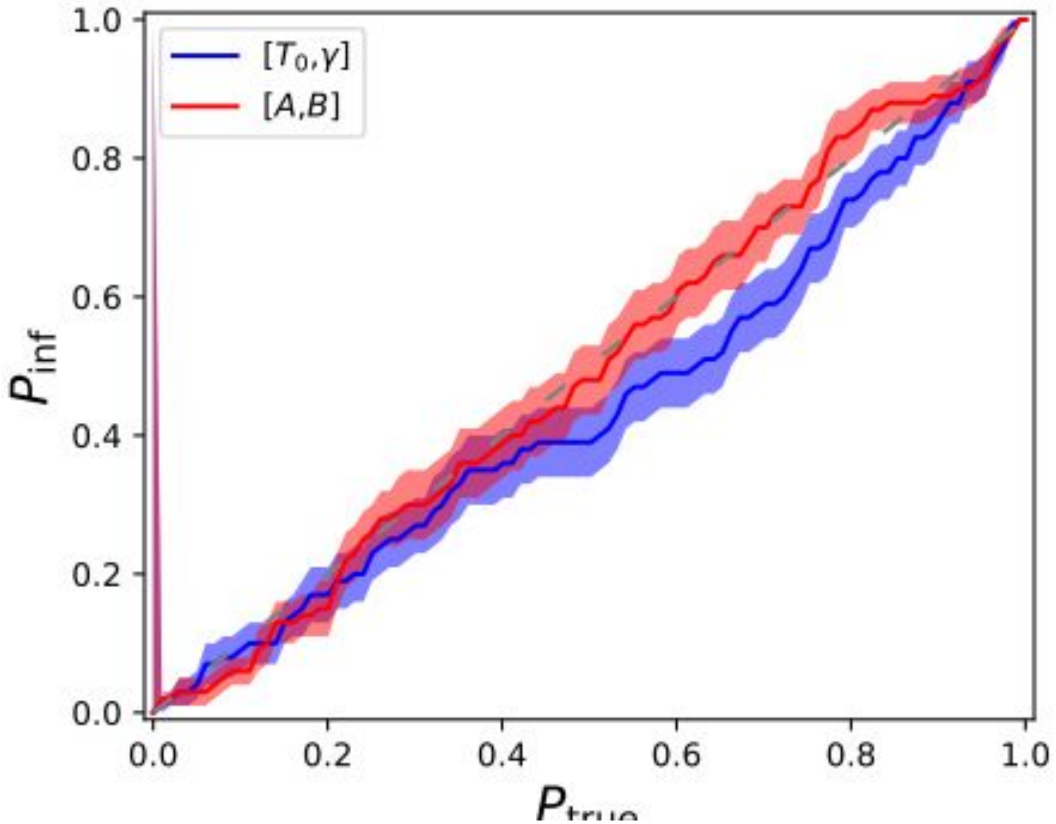




Hu+ 2023 in prep -a

Parameterization

- Using photoheating parameters [A,B] improves the inference test



Hu+ 2023 in prep -a

Summary

- Our inference method measure the IGM thermal state with very high accuracy. By using D16 data, it finds that the low z IGM seems too hot with $T_0 \sim 10^4$K.
- The inference method can be applied to other simulations, giving reasonable result, which however can not pass inference test due to varies reasons, e.g. the dispersion in Δ-T relationship in low z, different physics of the simulations, stochasticity caused by the early-stopping of the training.
- The conventional parameterization [T_0, γ] of the low z IGM is inefficient due to the dispersion in the Δ-T distribution caused by shock heating in low z.
- We employ the photoheating coefficient [A,B] for Nyx simulation as our fiducial labels for the IGM, which improves the performance of the inference test, and gives reasonable result on Illustris(TNG) simulations. ($A_{TNG} \sim 1.2$, $A_{ILL} \sim 1.7$)