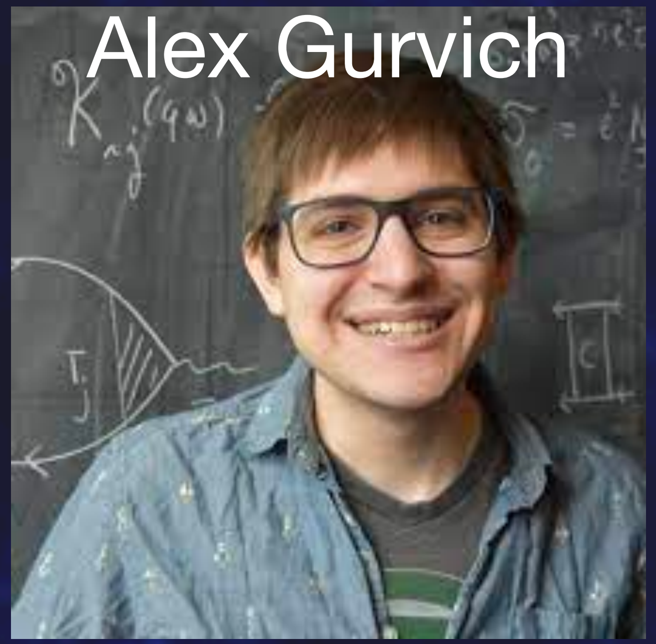
How Supermassive Black Holes Ignite the Intergalactic Medium: Tales from the Low Redshift Lyman-α Forest

Blakesley Burkhart
Rutgers/CCA



Outline

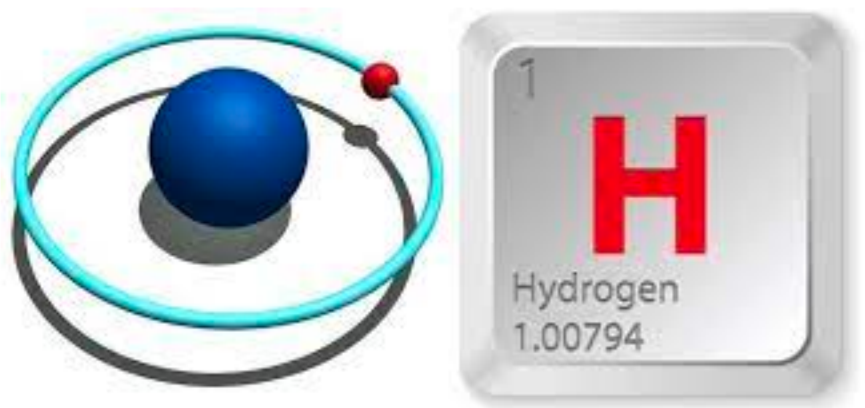
- What is the Ly-α Forest?

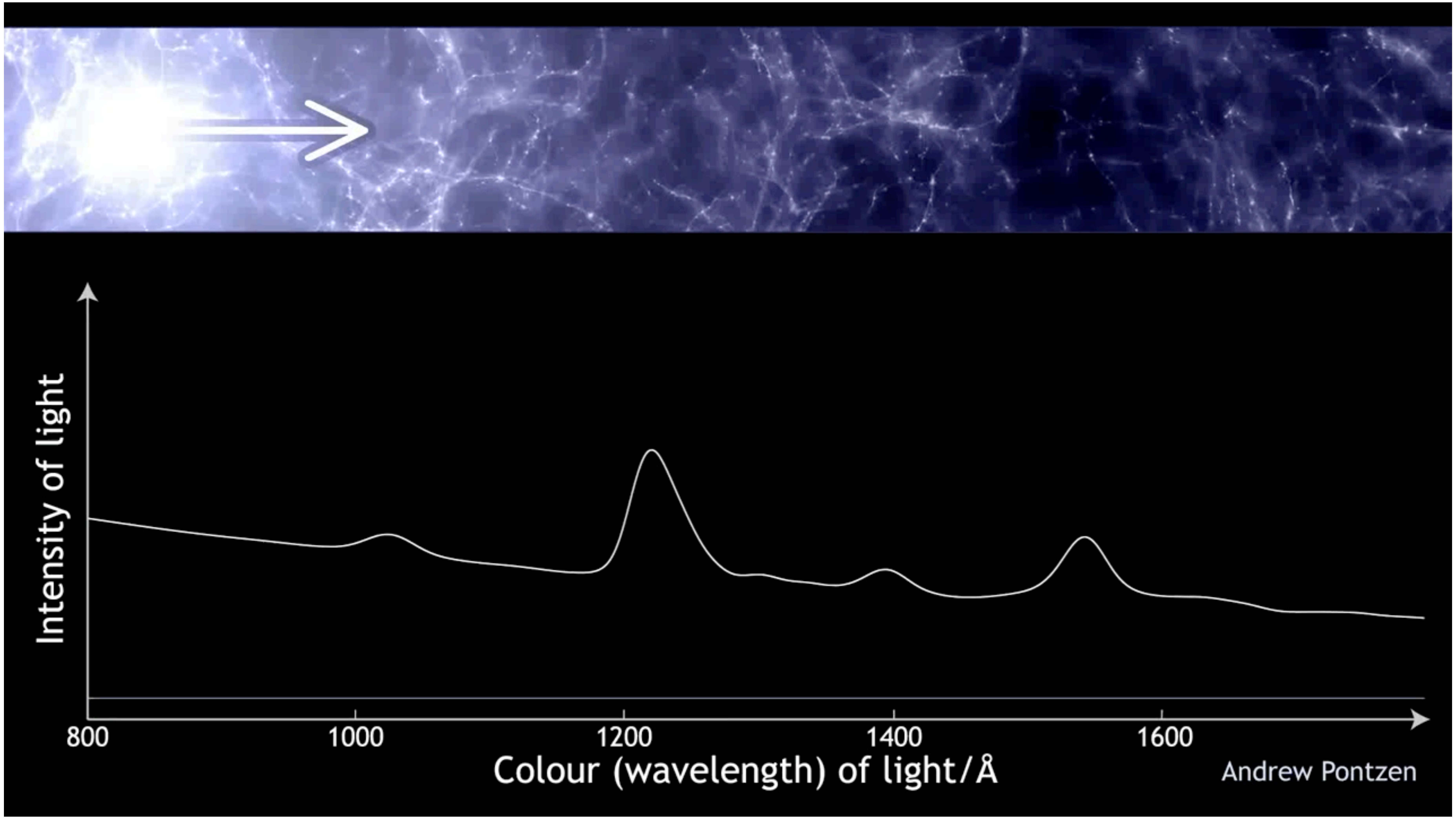
- The incredible observational and theoretical *successes* of the Ly-α Forest from 1.6<z<6: Providing insights into cosmology, the ultraviolet background, and the intergalactic medium

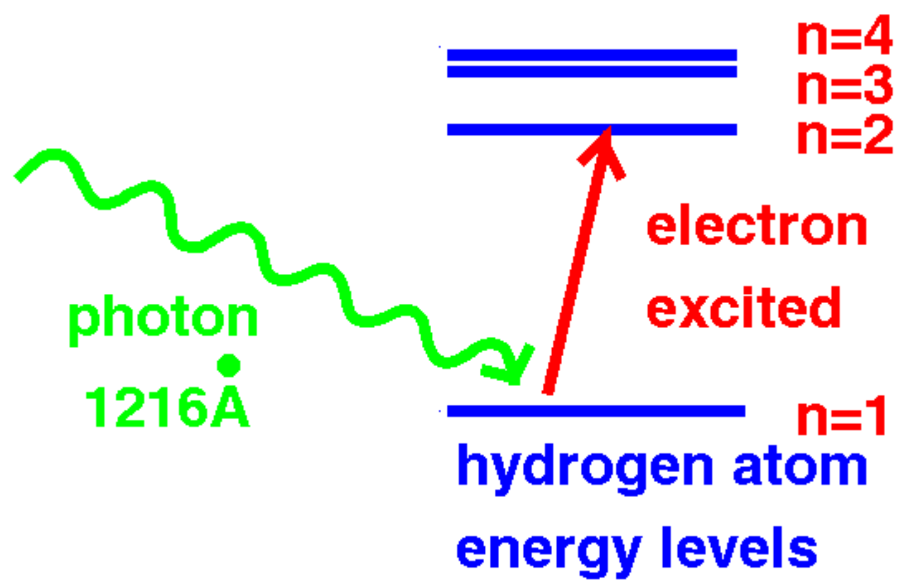
- The incredible observational and theoretical *mysteries* of the Ly-α Forest at z<1: cosmological simulations in crisis? New physics?

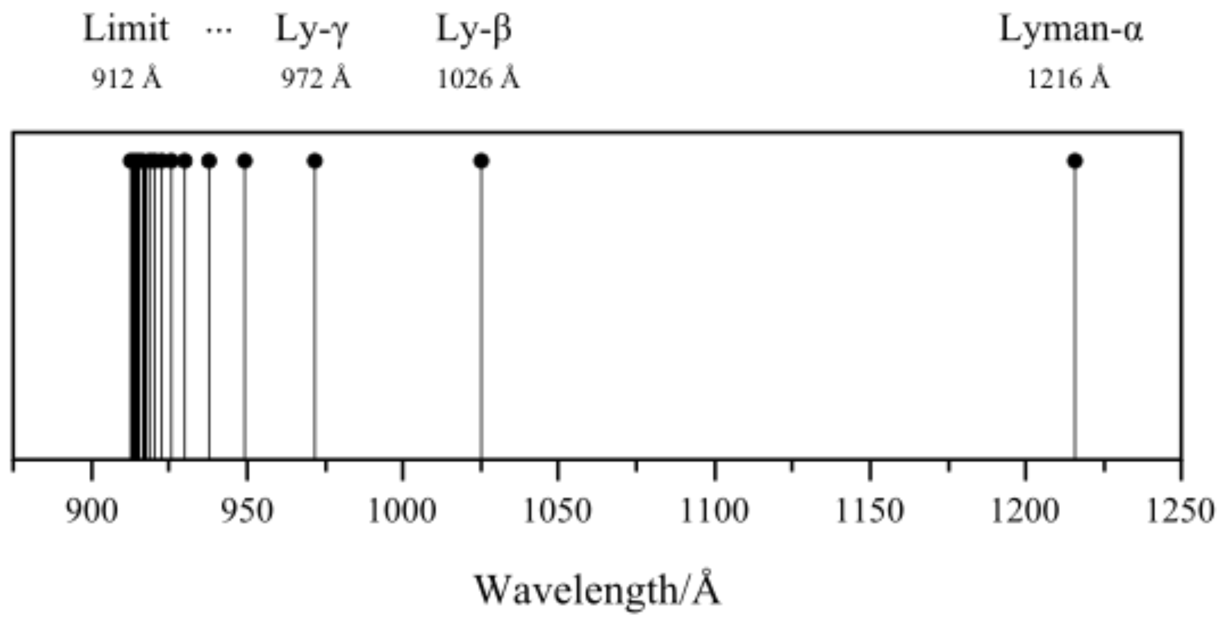
- How the growth of supermassive black holes heat up the IGM and alleviate (most) of the tension

Ly-α Forest: An Invaluable Tool for Studies of the IGM and Cosmology



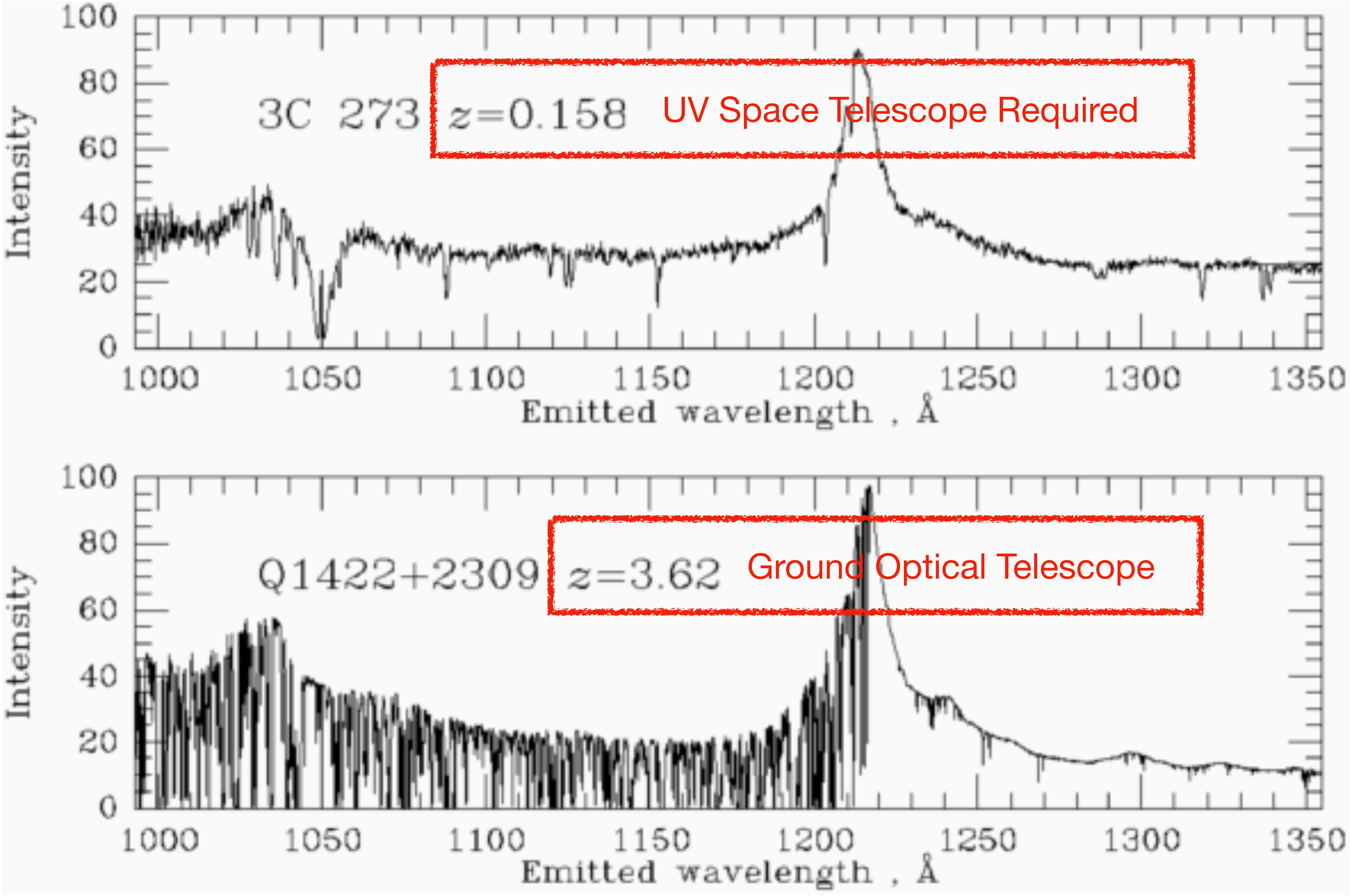






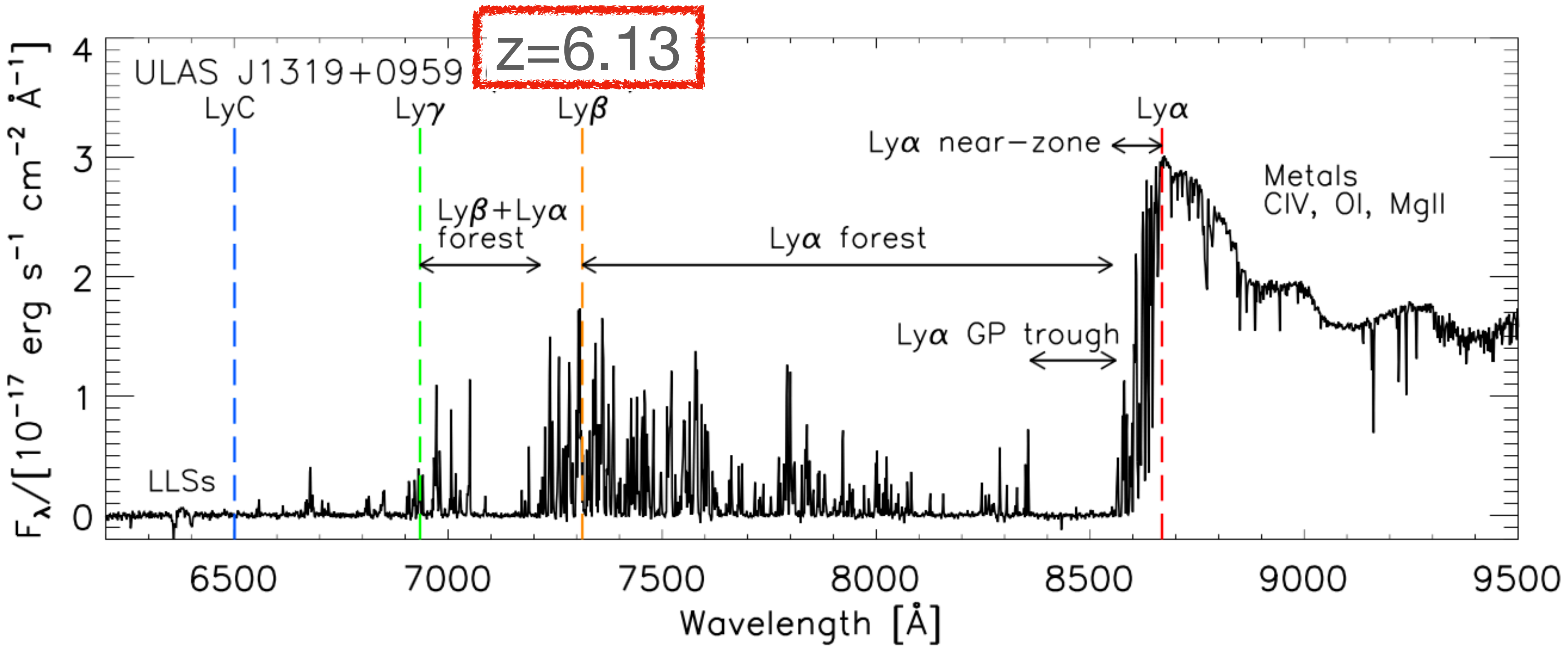
Gunn and Peterson (1965);
Bahcall and Salpeter (1965)

•What is the Ly-α Forest?



Insights from these observations:

- **The IGM is Highly Ionized:** Gas between us and these quasars has low HI optical depths which is due to ionization by quasars and star forming galaxies.
- **The End of the epoch of reionization:** At highest redshifts observed (z~6), there are no more "trees in the forest" as optical depth increases due to natural fraction increasing (i.e. Gunn-Peterson Trough).



At low redshift, forest is less "thick" —> lower cosmic density (lower optical depth)

$$F = 1 - e^{-\tau}$$

•What is the Ly-α Forest?

Ionization Equilibrium of hydrogen with the background UV Field

$$n_{HI}\Gamma = n_{HII} n_e \alpha(T)$$

$$\tau_{IGM}(z_a) \approx 2[1 + \delta_b(z_a)]^2 \frac{\alpha_{rec}(T)}{\Gamma} \left(\frac{1 + z_a}{4}\right)^{4.5}$$

z_a	Redshift of absorbing gas
$\delta_b(z_a)$	baryonic overdensity of absorbing gas
T	temperature of absorbing gas
Γ	photoionization rate at absorbing gas = strength of ionizing BG.

Represents an important result as it links the observed opacity in Lya forest to

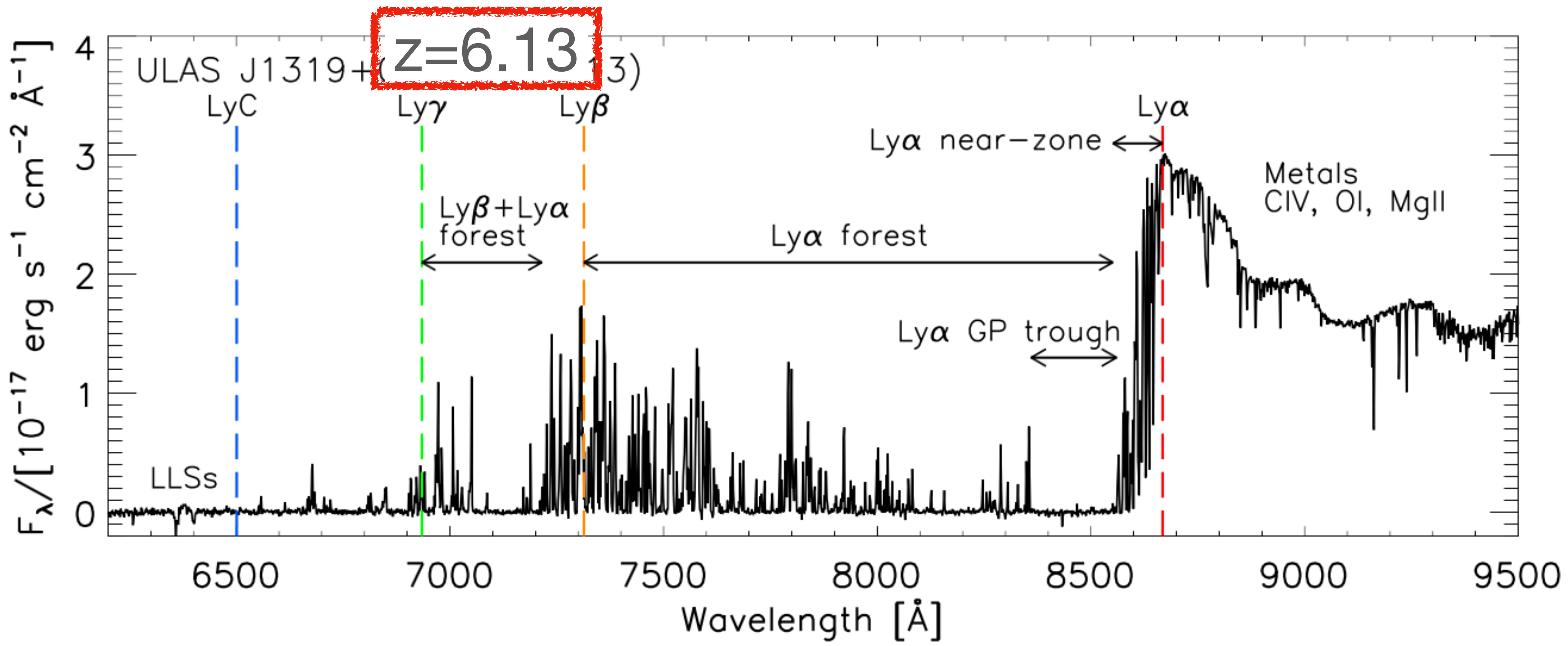
- density of the matter field
- temperature of the gas at that point
- ionizing radiation background.

Moreover, it enables us to understand & interpret basic observations of the Lyman alpha forest.

Insights from these observations:

- **The IGM is Highly Ionized:** Gas between us and these quasars has low HI optical depths.
- **The End of the epoch of reionization:** At highest redshifts observed (z~6), there are no more "trees in the forest" as optical depth increases due to natural fraction increasing (i.e. Gunn-Peterson Trough).
- **IGM Physics and Cosmology** science are possible via analysis of HI photoionization equilibrium.

$$F = 1 - e^{-\tau}$$



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- The incredible observational and theoretical *successes* of the Ly-α Forest from $1.6<z<6$: Providing insights into cosmology, the ultraviolet background, and the intergalactic medium
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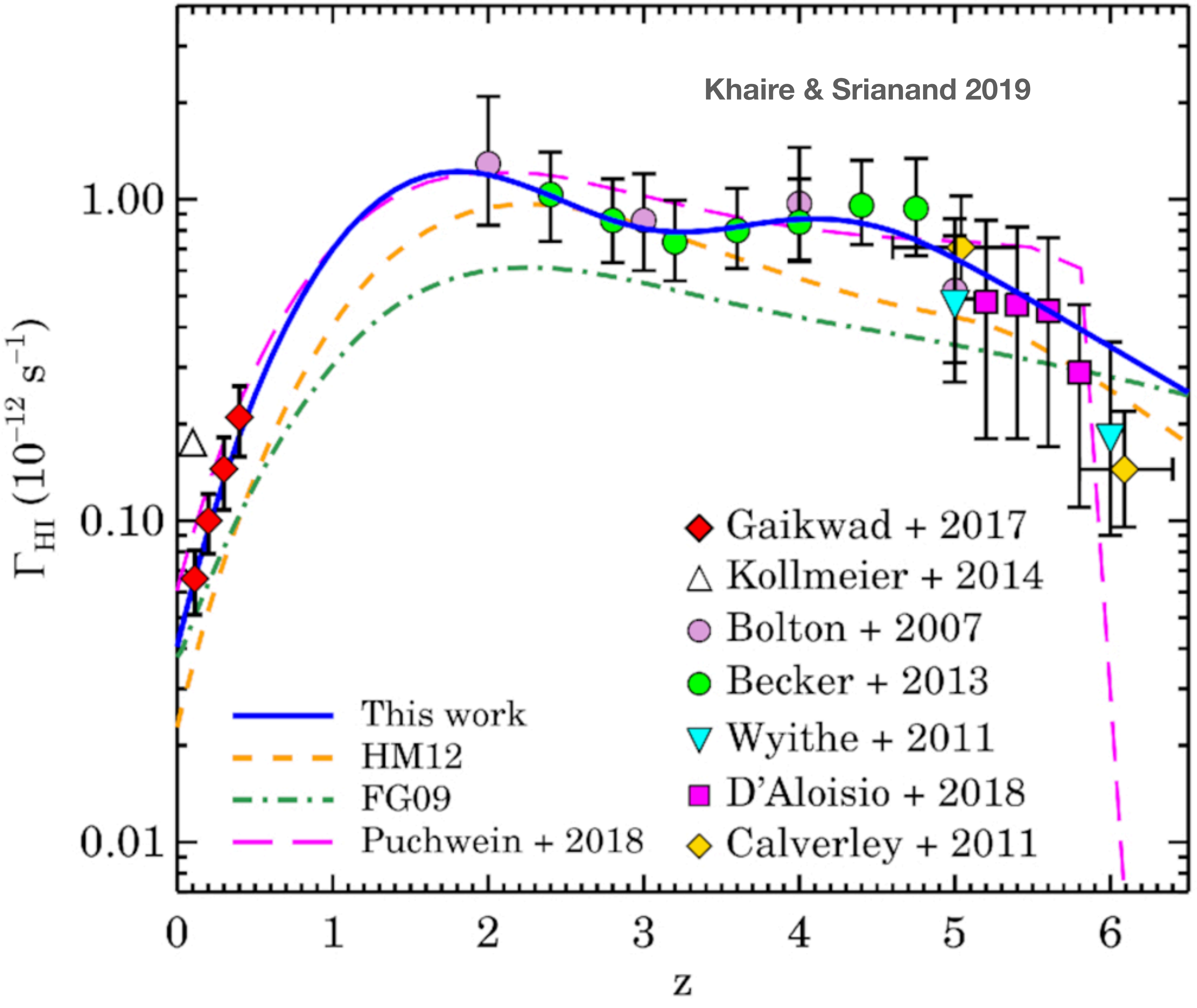
- Future outlook for low redshift 21-cm mapping and machine learning studies

•Ly-α Forest: provides ionizing background (UVB)



- Post-reionization: spatial uniformity of the UVB
- Census of ionizing photons and hardness of radiation from QSOs and galaxies (escape fractions)
- Photoionization equilibrium provides coupling of the HI column density to UVB
- Measuring column density distribution —> gives Gamma

$J_\nu \propto \nu^{-\alpha+3[\beta-1]}$ for $\partial^2\mathcal{N}/\partial x\partial N_{\rm HI} \propto N_{\rm HI}^{-\beta}$ and $\epsilon \propto \nu^{-\alpha}$.

$$\Gamma \equiv 4\pi \int_{\nu_{\rm HI}}^{\infty} \frac{d\nu}{h\nu}\sigma_{\rm HI}(\nu)J_\nu$$

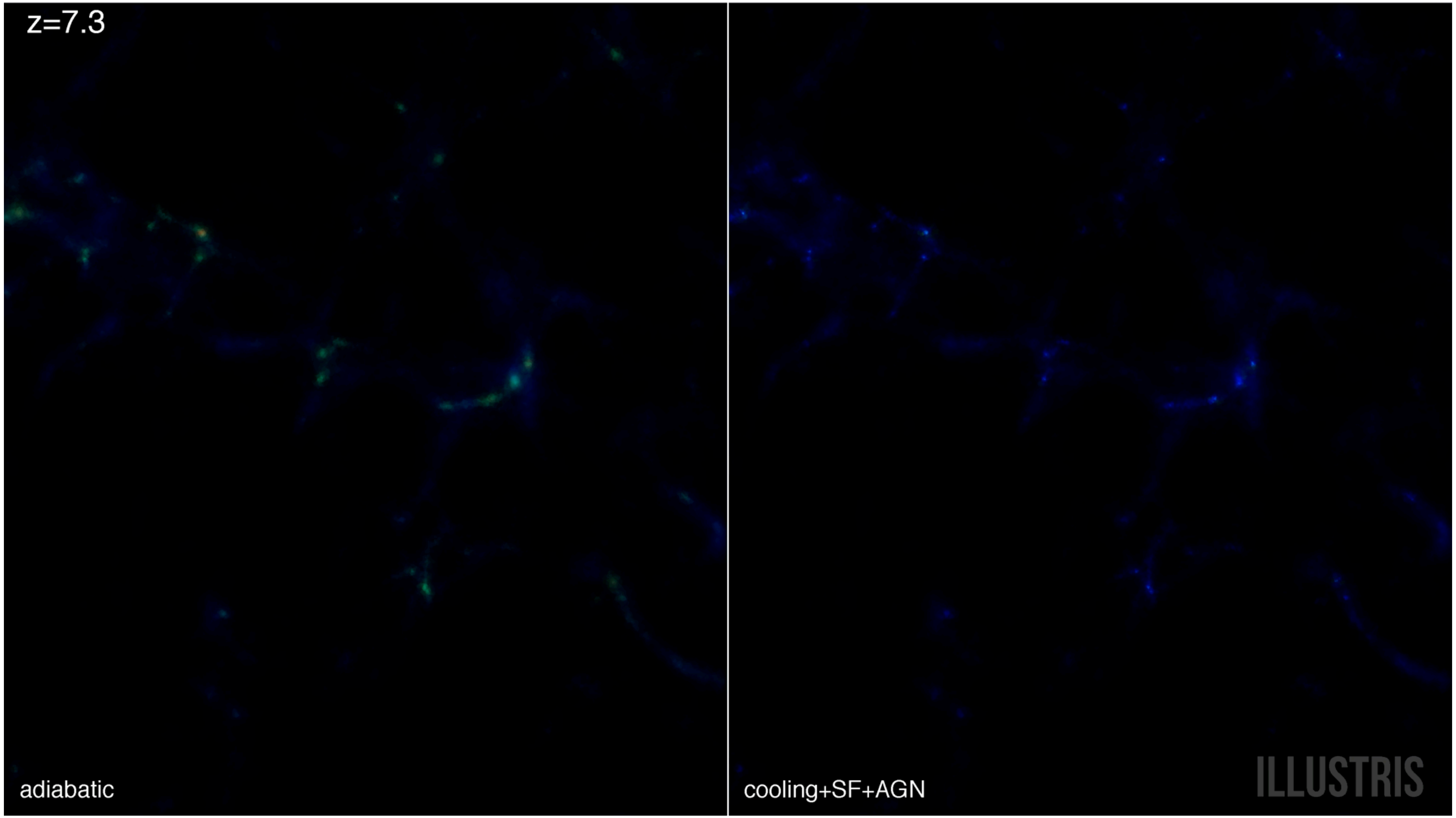
J_ν**:** angularly averaged specific intensity of ionizing background

Γ**:** photoionization rate of HI

z>2 Ly-α Forest: Observations and Numerical Simulations Agree!!

The beautiful match of LCDM cosmological hydro simulations with Ly-α Forest observations puts the cosmological paradigm on very firm footing!

Time evolution of a 10Mpc (comoving) over-dense region within a cosmological simulation.



Movie: Illustris Team

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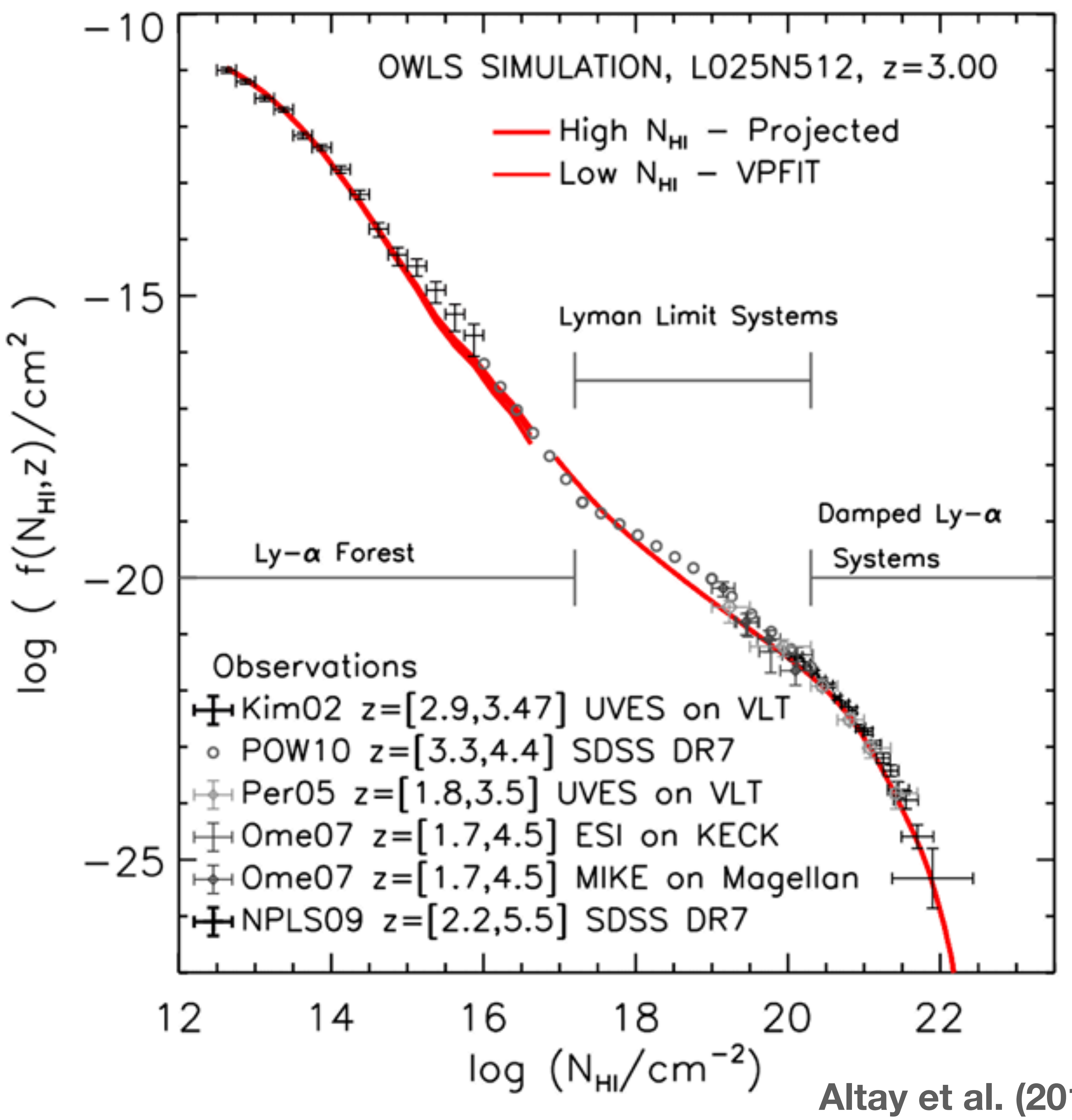
The column density distribution function (CDD) measures the fine-grained clumping and structure of the forest.

The CDD depends on the **photoionization rate, density,** and the **temperature of the IGM.**

All these components are well understood at z>7 in LCDM and included in cosmo-sims:

Photoionization from quasars (z<4) and star forming galaxies (z>4), temperature set by heating (photoheating) balancing cooling (adiabatic expansion), and **density set by the dark matter distribution**



Altay et al. (2011)

Red simulation lines are not a fit to the data!

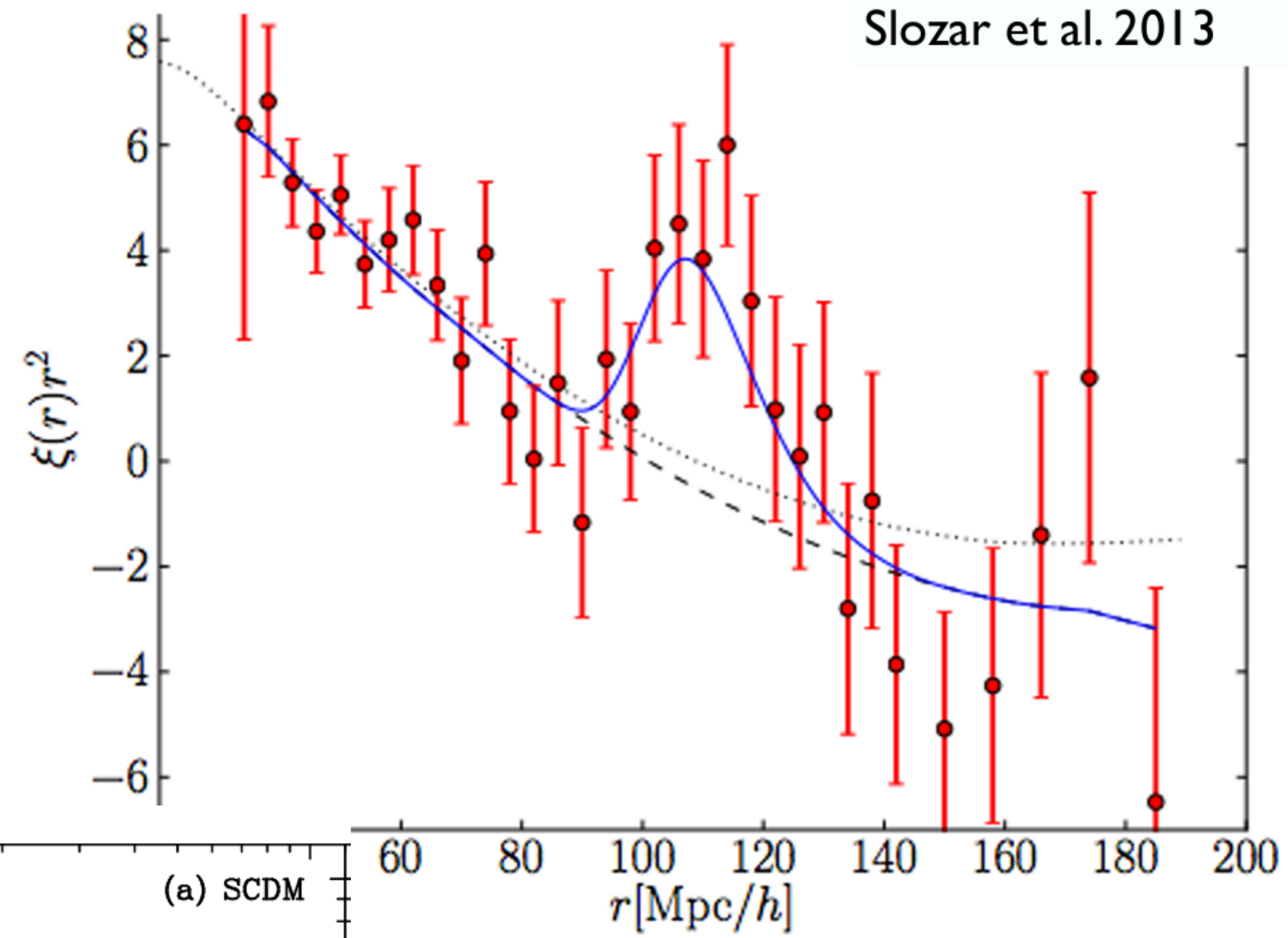
Amazing correspondence for LCDM cosmo-sims at z=3!

z>2 Ly-α Forest: A Tool for Precision Cosmology

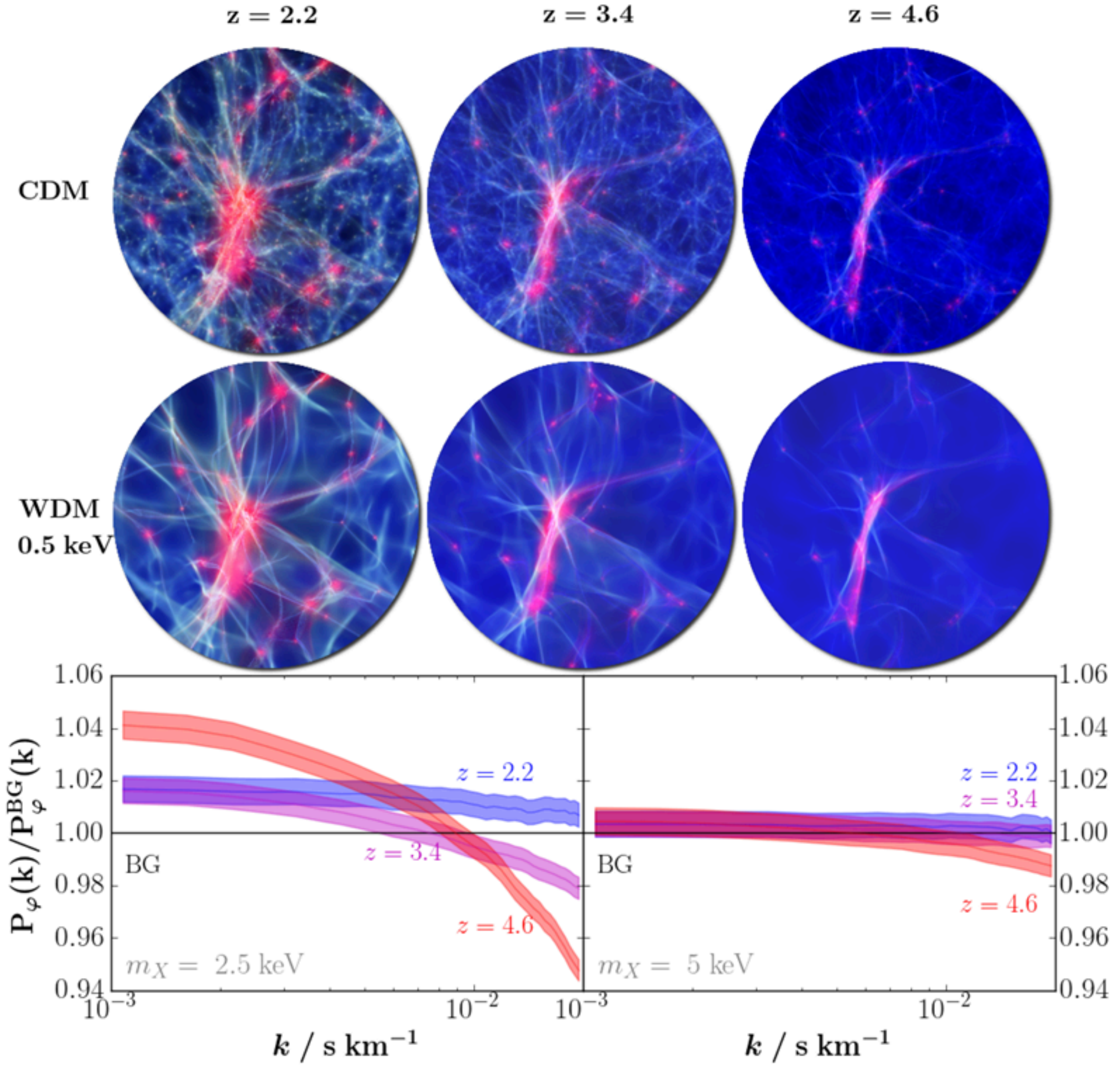
The beautiful match of LCDM cosmological hydro simulations with Ly-α Forest observations puts the cosmological paradigm on very firm footing!

Acoustic Peak in Lya Forest.

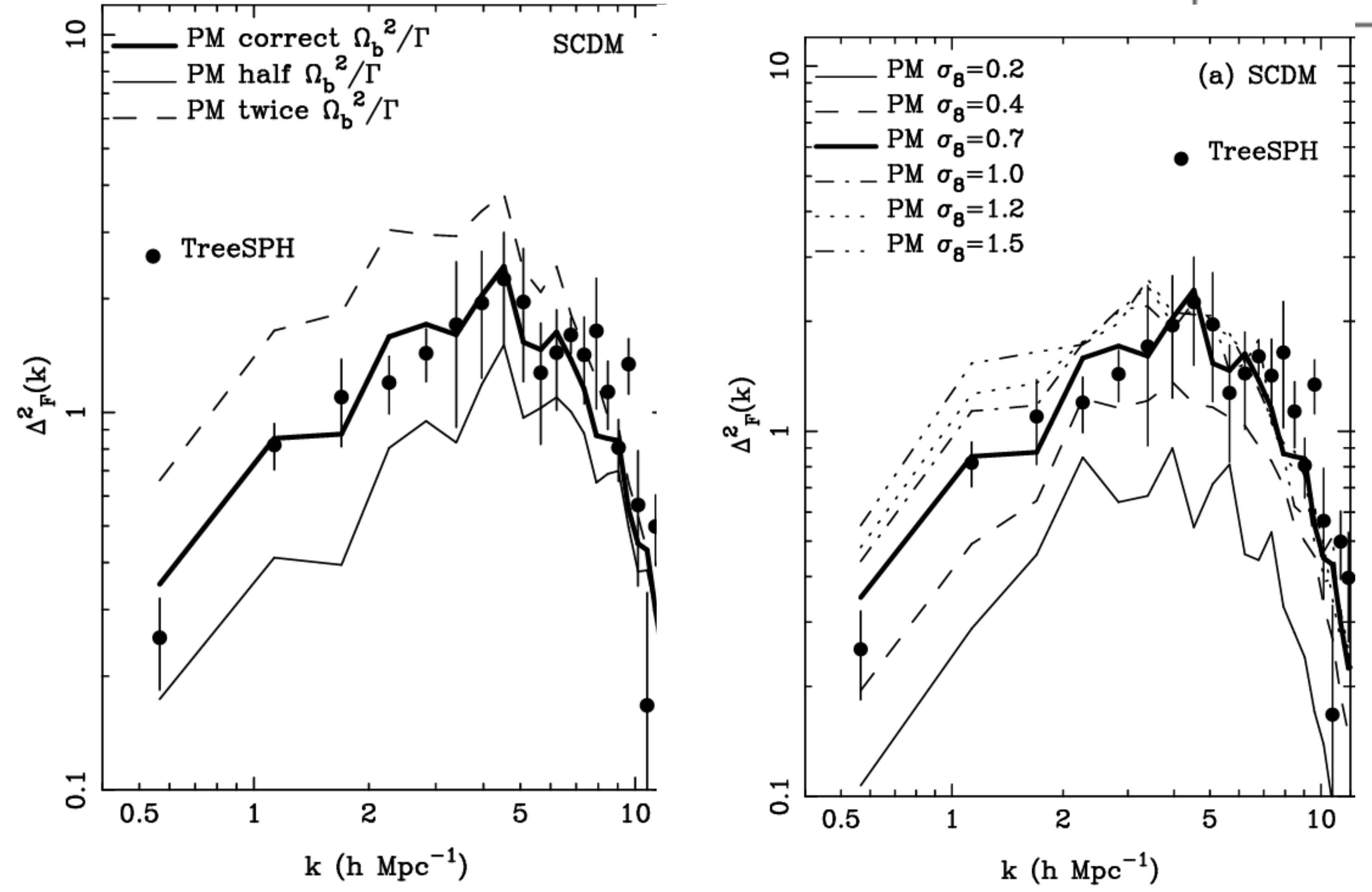
Recent Lyman alpha forest measurements (BOSS) have uncovered the acoustic peak in the matter power spectrum (i.e. the acoustic peak imprints itself also in Lyman alpha forest)



Ratio of the WDM to the CDM Ly-α transmitted flux power spectra at redshifts z = 2.2,3.4 and 4.6



Baur et al. 2016



Flux power spectrum to matter power spectrum Croft et al. 1998

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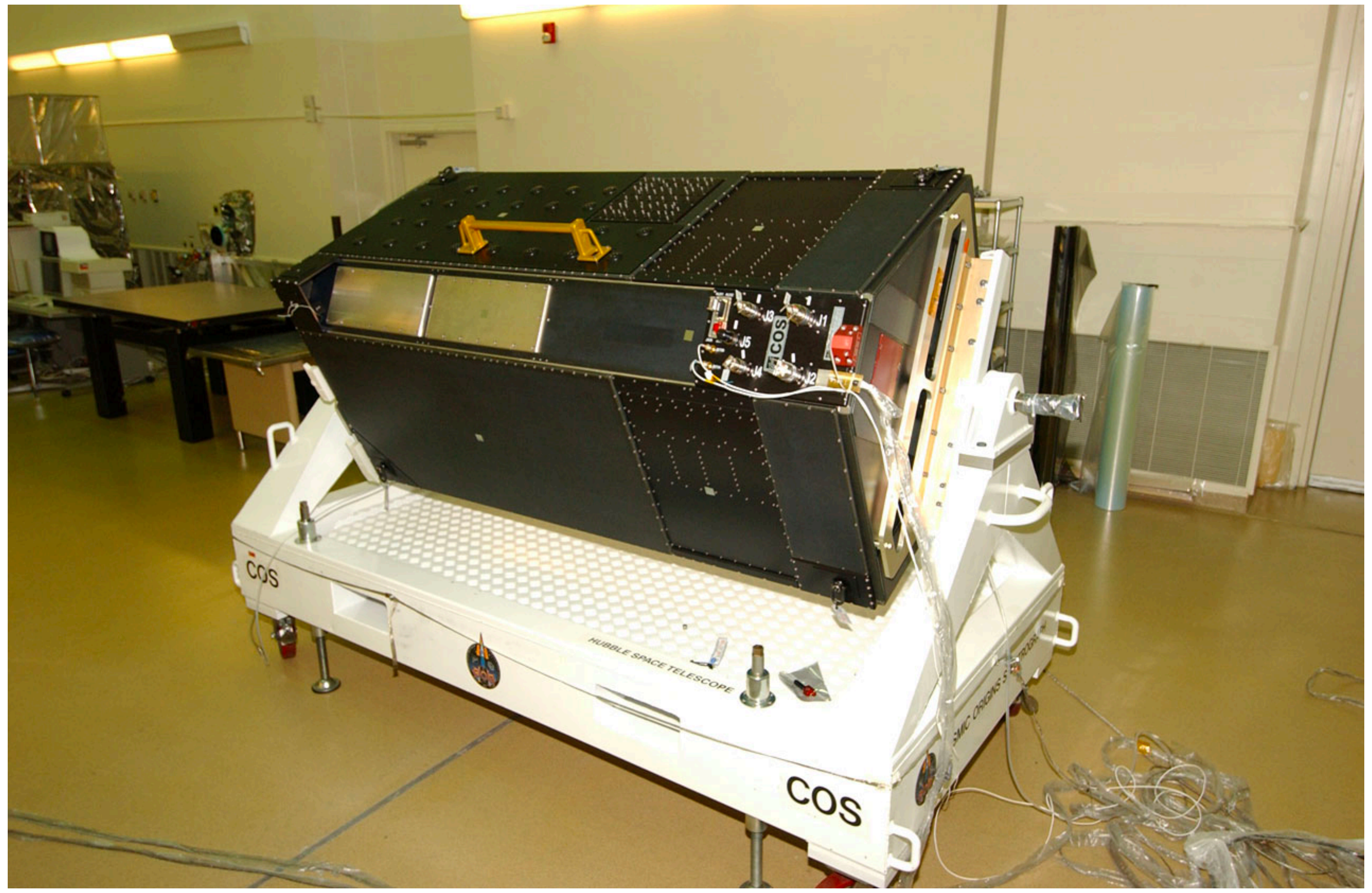
Low Redshift Lyman-α forest

Why care? "New physics is at high redshift" -Sultan



Most baryons are in the IGM:

Even after nearly 14 Gyr of evolution, only a small fraction of baryonic matter has collapsed into luminous objects (galaxies, groups, clusters) while ~ 80% are in the IGM!

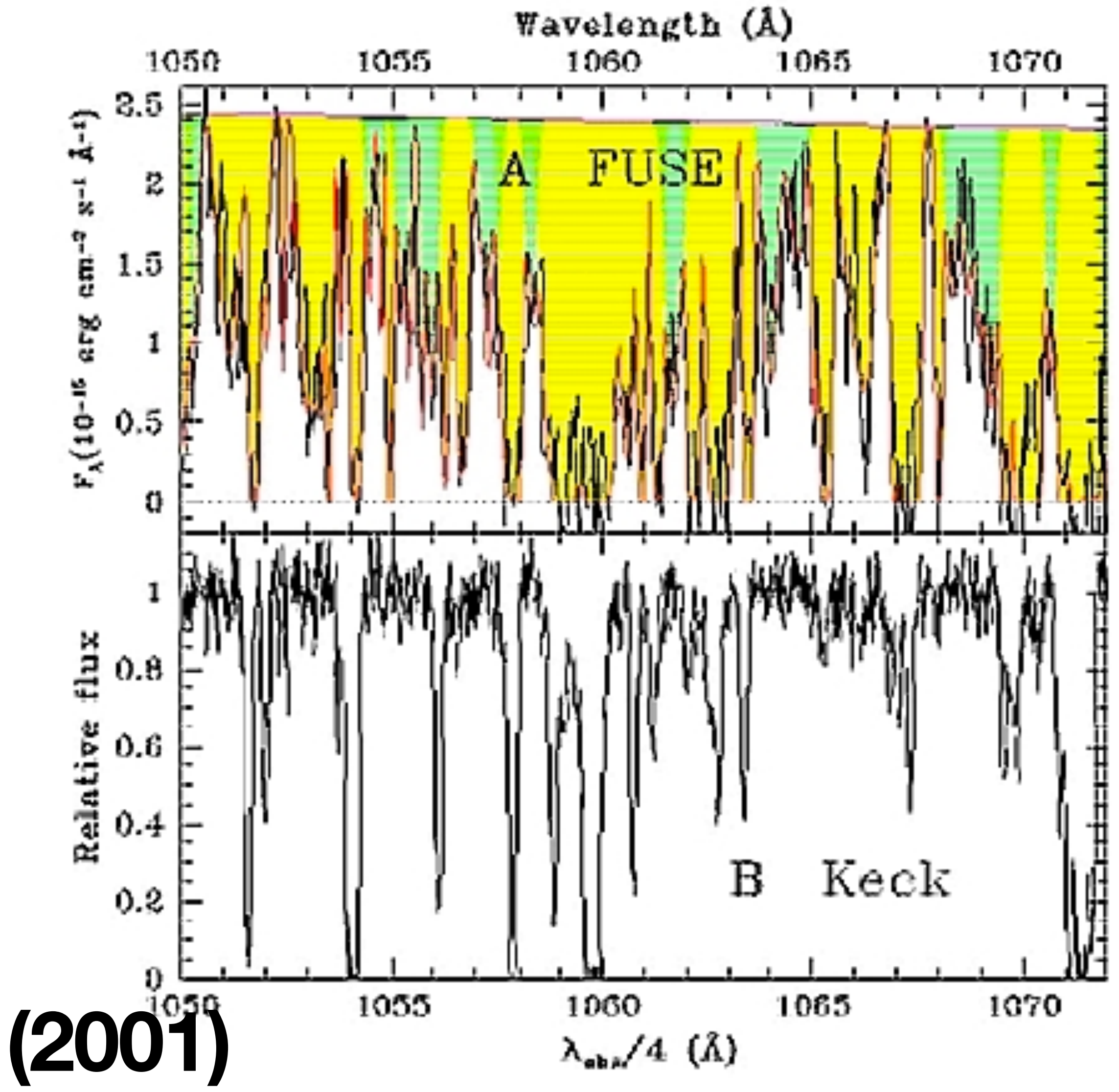
Low z Forest is Hard:

1) From 1>z>2 we have no good tracers of the Forest

2) z<1 requires space based UV instrumentation
   - COS
   - FUSE
   - GALAX

   Landmark study Danforth et al. 2016: largest sample of low-z absorbers to date and is more sensitive than previous studies.

3) Cosmological simulations: baryonic feedback effects become more important and non-standard heating sources can be present (e.g. shocks)



Kriss et al. (2001)

Low Redshift Lyman-α forest: observations vs simulations

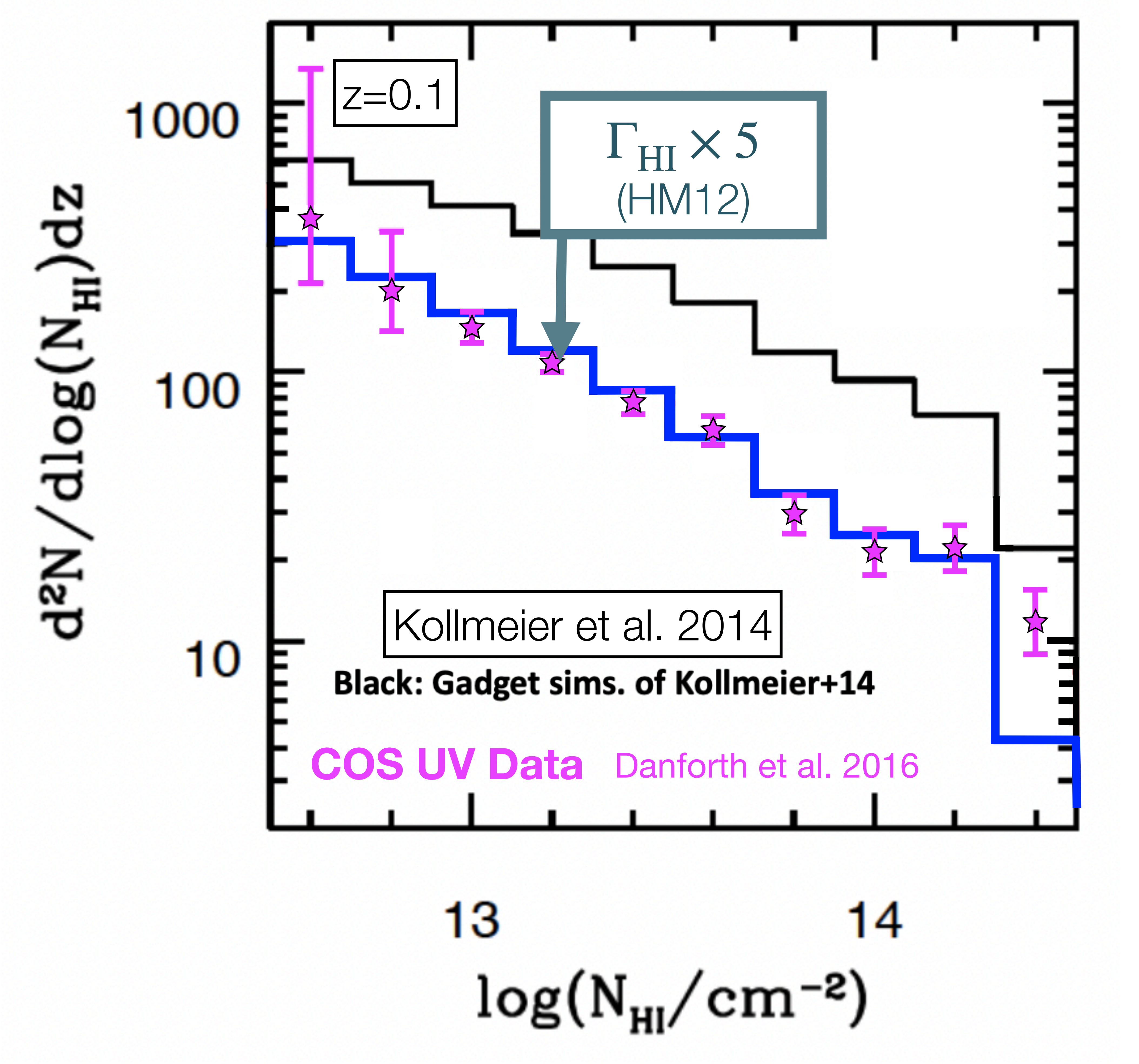
Mismatch between observed data and simulations.

- 5 times stronger UVB required at z=0.1!

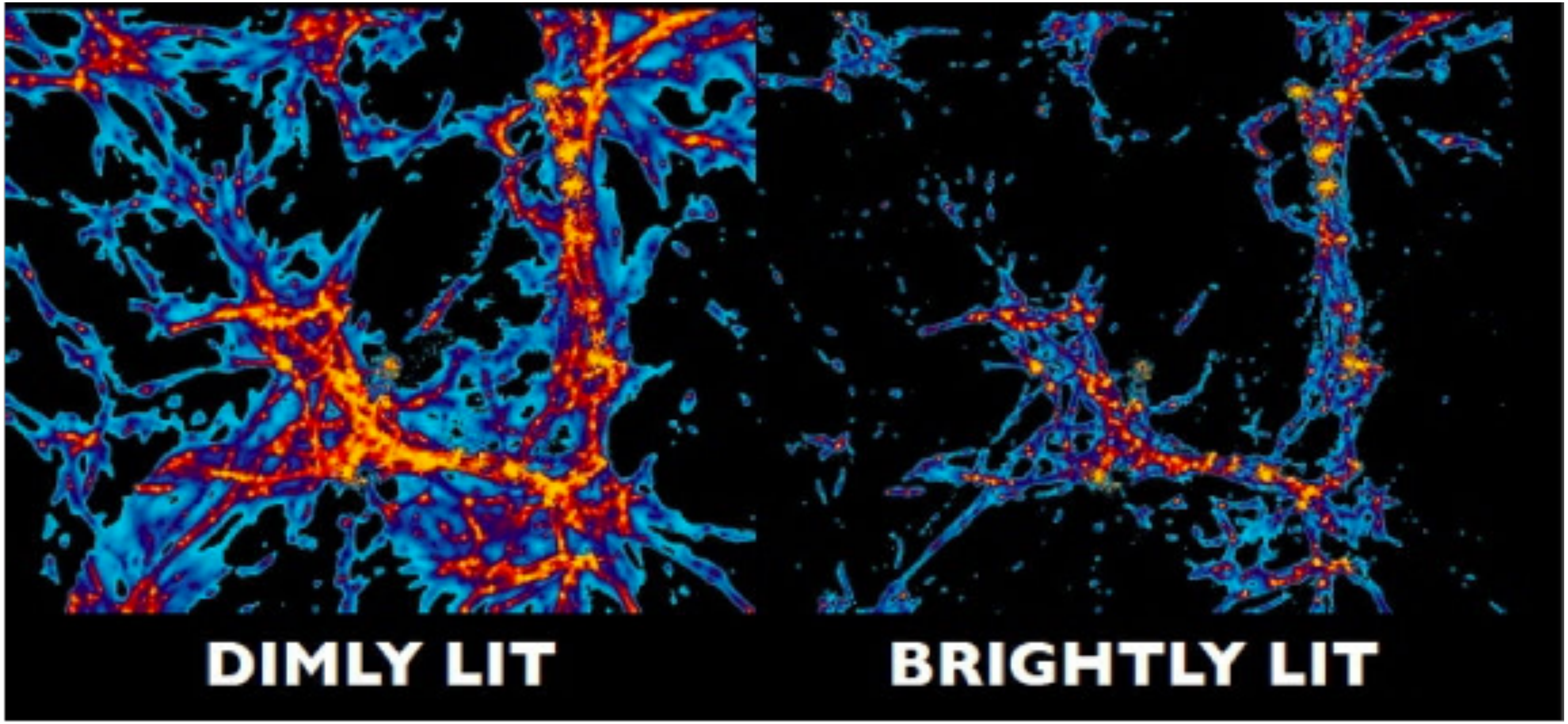
Kollmeier et al. 2014 first reported a discrepancy in the column density distribution at z=0.1 with simulations which include the Haardt & Madau (2012) UV-background model.

To achieve the correct UVB the ionizing photons must be increased by a factor of 5 over HM12!

The column density distribution function (CDD)



IGM with x5 different ionizing photons: dramatically different IGM



$$\tau \propto n_{\rm HI} \propto \rho^2 T^{-0.7} \Gamma^{-1}$$

Kollmeier et al. 2014

Initial ideas as to what could be going on..

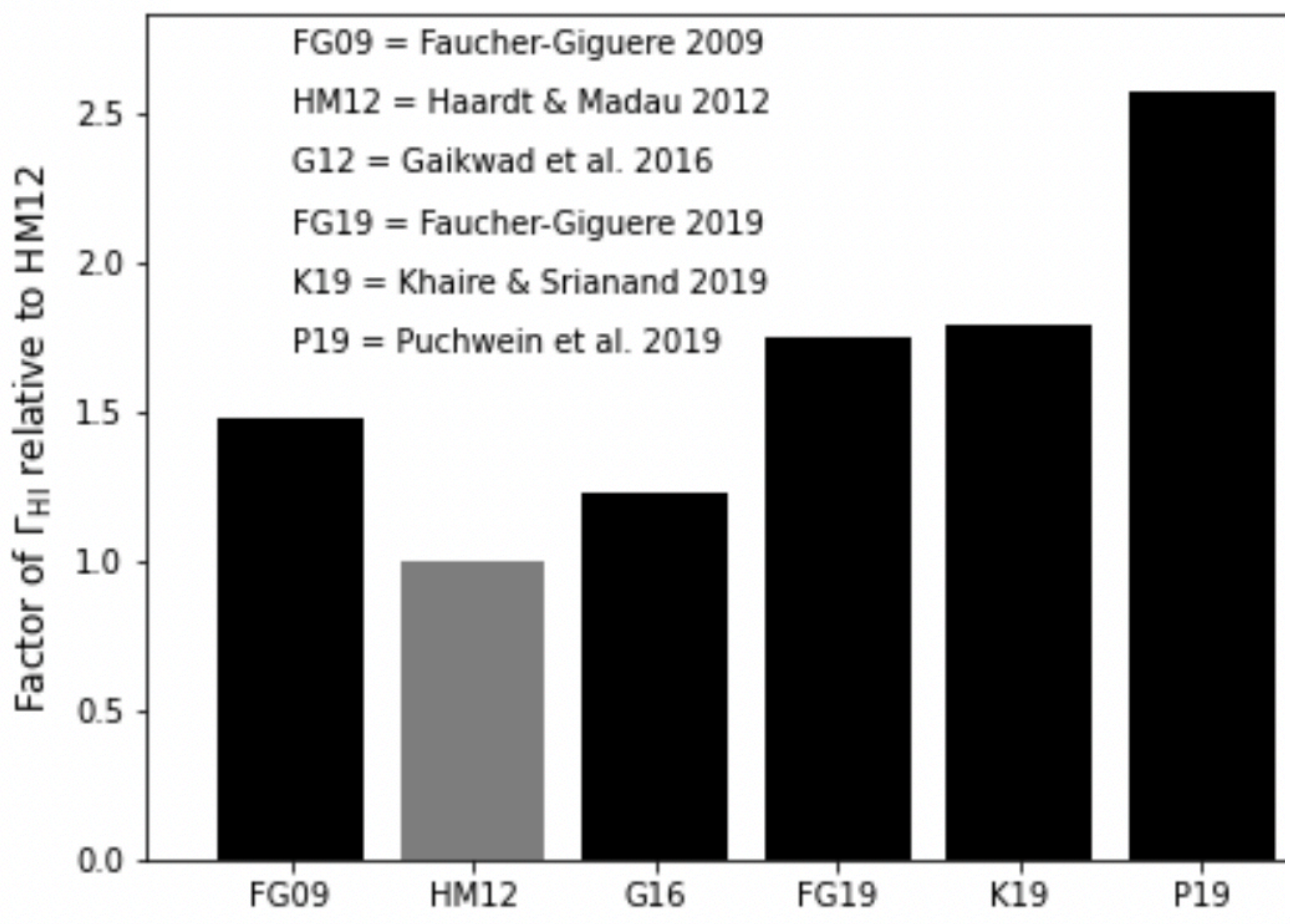
- Not enough photons are accounted for in the simulations? UV Background is actually higher (factor of 5).
- Galaxy escape fractions/quasar luminosity boosted ?
- Extra heating terms?
- Exotic sources of photons like DM decay?
- Some combination of the above?

Comparison of Low-Redshift Lyman-α Forest Observations to Hydrodynamical Simulations with Dark Photon Dark Matter

Show affiliations

Bolton, James S. ; Caputo, Andrea ; Liu, Hongwan ; Viel, Matteo

Can Updated UVB Models Save the Day?

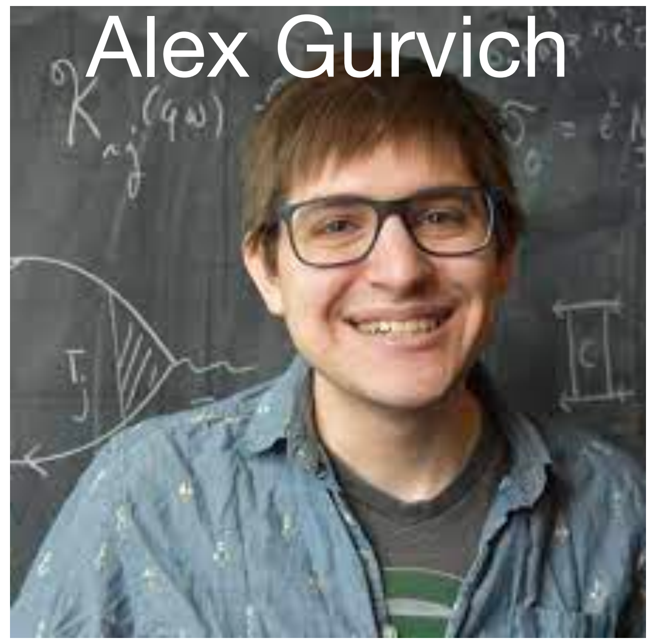


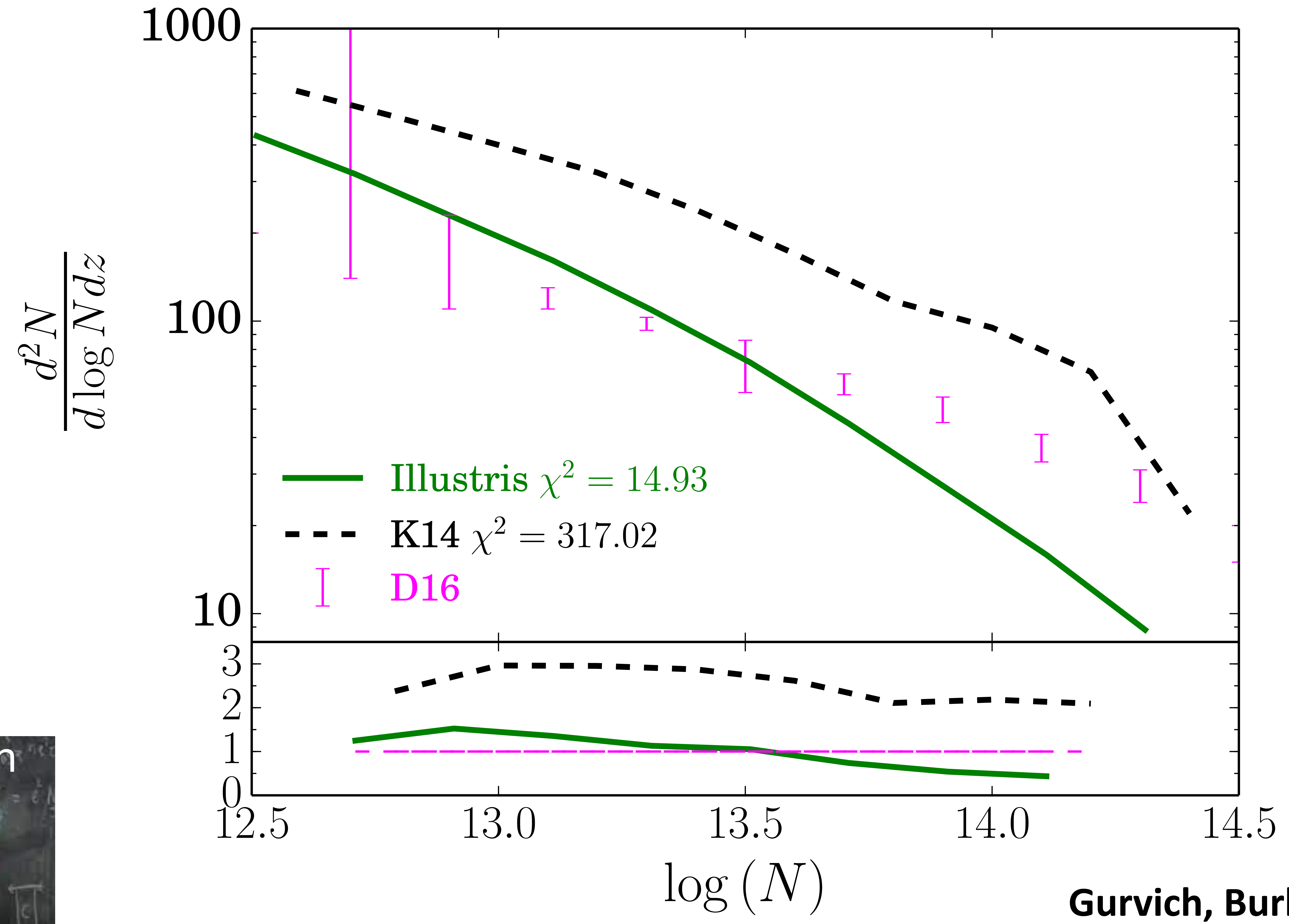
UVB models since Kollmeier et al. 2014 provide at most factor of 2.5x more ionizing photons than HM12

Illustris Cosmological Simulation (full physics)

Column Density Distribution performs much better (at low column density) than expected for the FG09 UVB!

Extra heating?



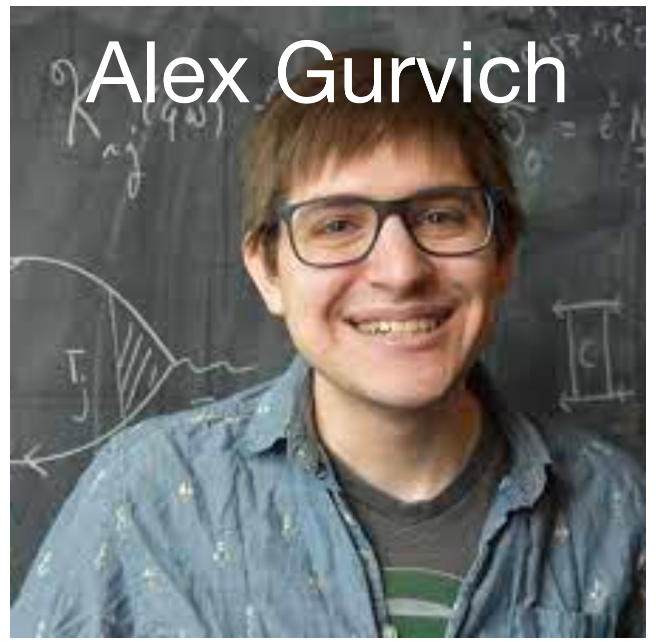


Gurvich, Burkhart & Bird 2017

Why does the CDD in Illustris fit the COS data better?

Our 2017 study addressed the effects of:

- UV Background (UVB) ?
- Resolution?
- Hydrodynamics?
- Stellar Winds?
- AGN Feedback?



The Effect of AGN Heating on the Low-redshift Lyα Forest

Alex Gurvich[1], Blakesley Burkhart[2], and Simeon Bird[3]

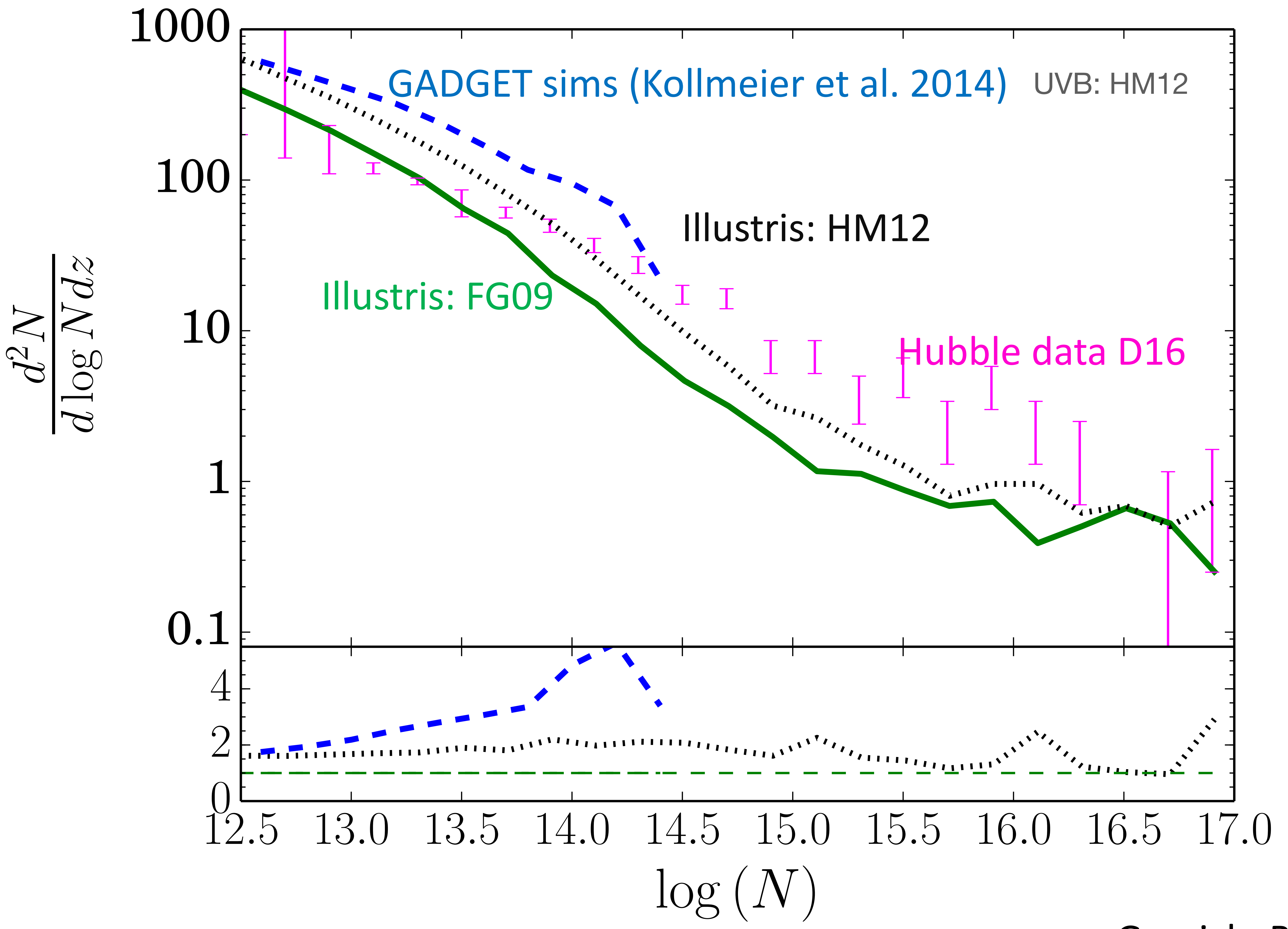
Published 2017 January 30 •

The Astrophysical Journal, Volume 835, Number 2

Citation Alex Gurvich *et al* 2017 *ApJ* **835** 175

DOI 10.3847/1538-4357/835/2/175

UV Background Effect

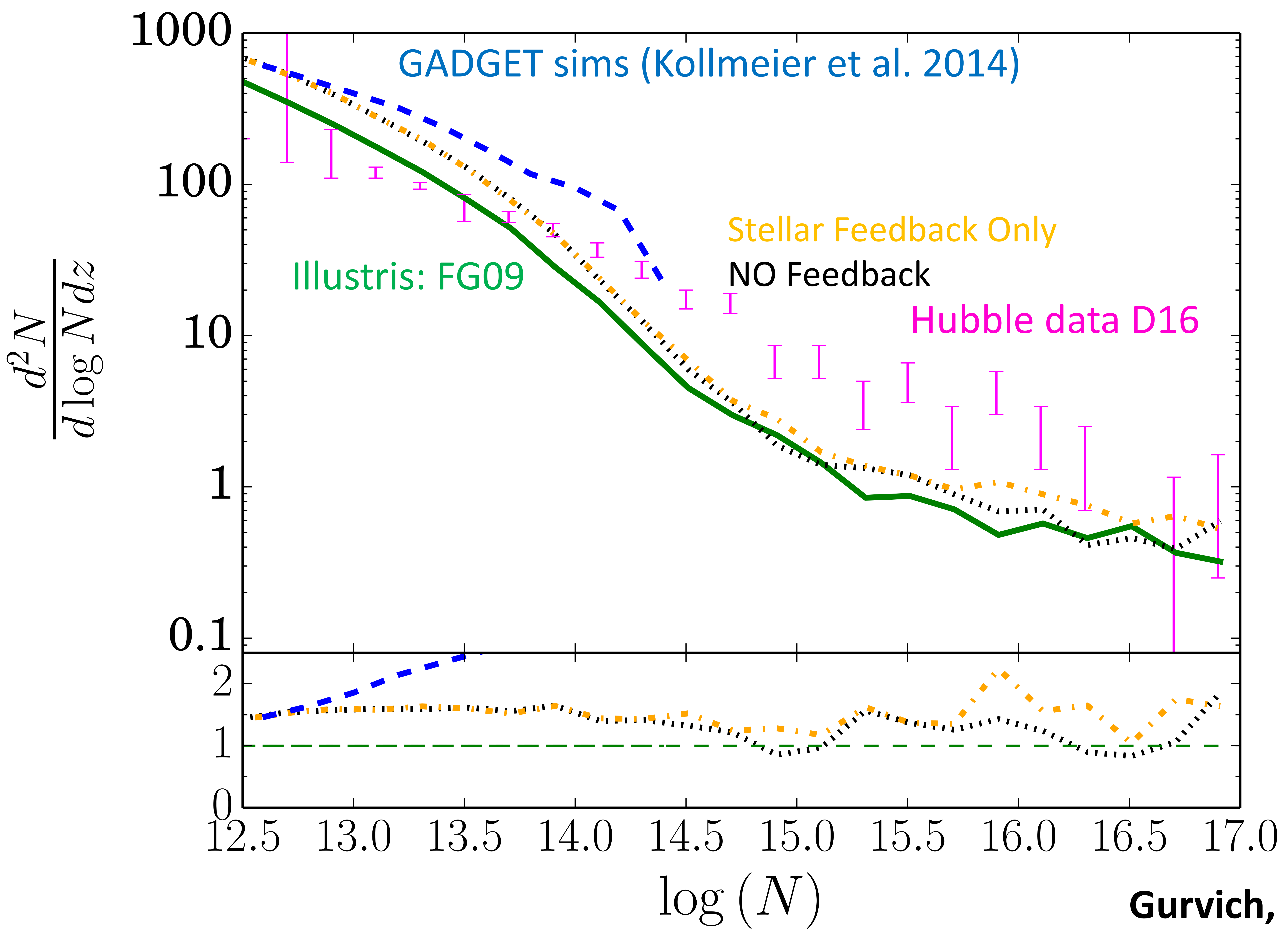


As expected, FG09 UVB isn't enough to fully solve the discrepancy

More ionizing UVB + additional heating needed

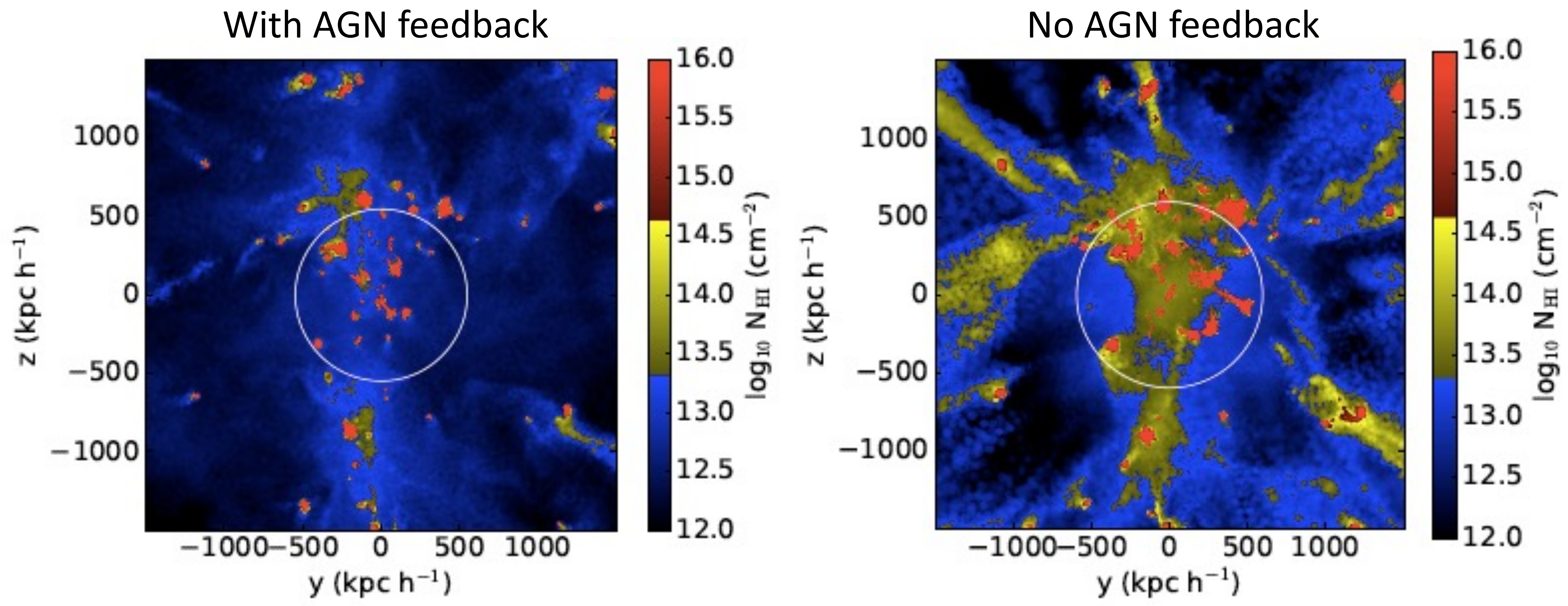
Gurvich, Burkhart & Bird 2017

Stellar Feedback



Gurvich, Burkhart & Bird 2017

AGN Feedback and the Column Density Distribution in Illustris



$$\tau \propto n_{\mathrm{HI}} \propto \rho^2 T^{-0.7} \Gamma^{-1}$$

Increase in UVB will decrease NHI
Increase in temperature will decrease NHI

Gurvich, Burkhart & Bird 2017

<u>Subsequent papers confirmed the importance of AGN feedback for the low redshift Lyman:</u>

Viel et al. 2017
Tonnesen et al. 2017
Nasir et al. 2017
Christiansen et al. 2020

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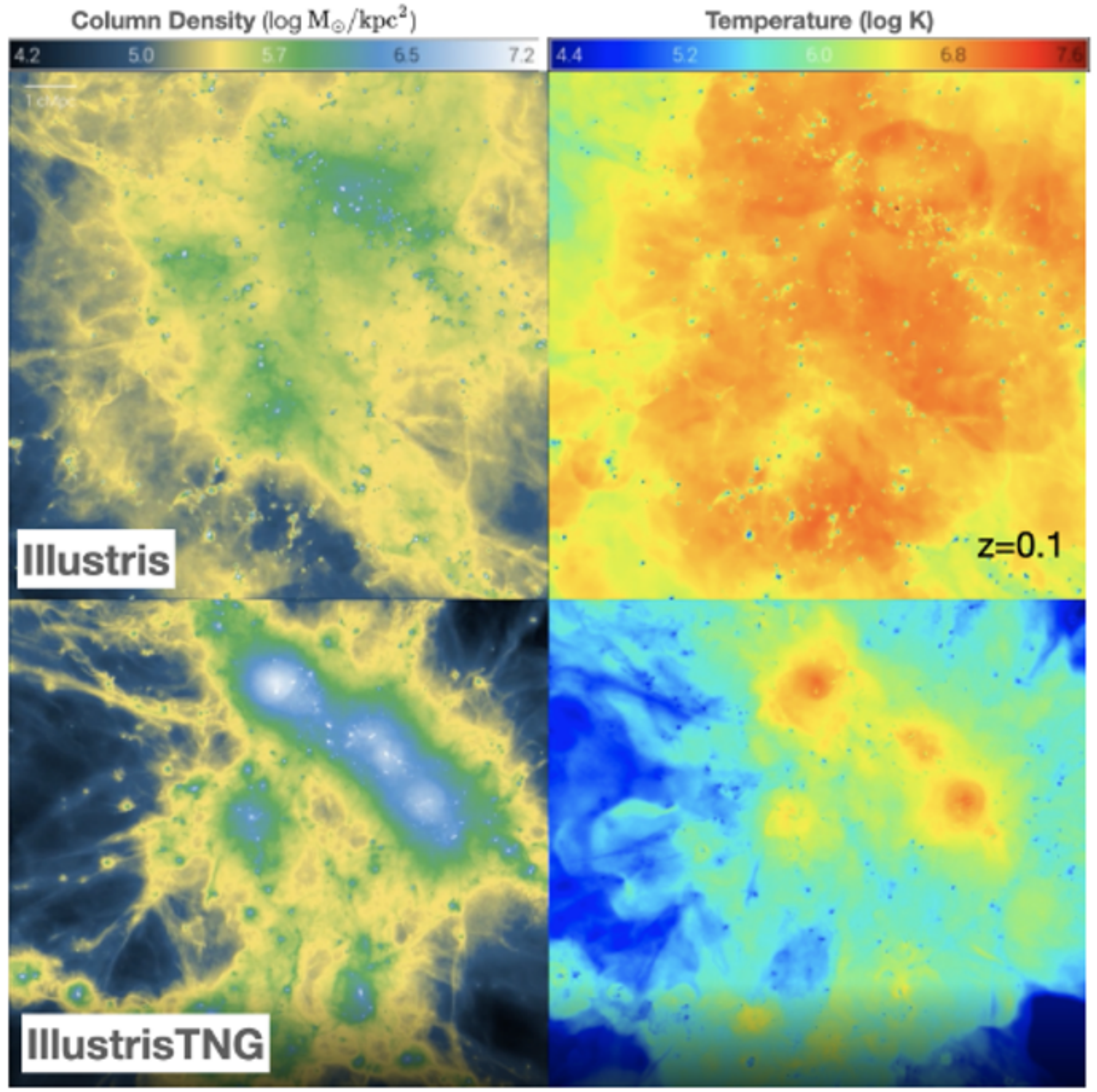
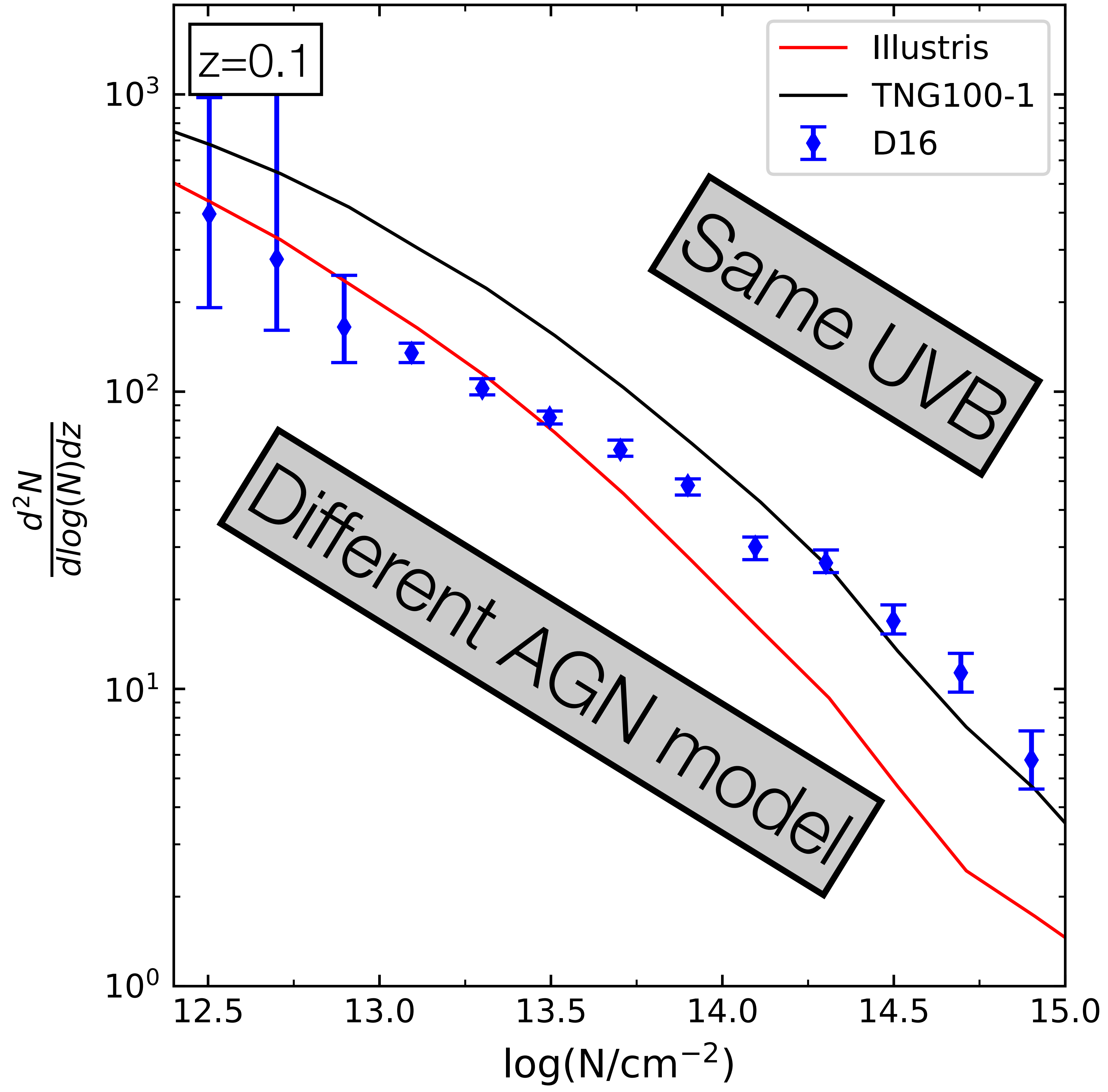
Low Redshift Lyman-α forest: observations vs simulations

The AGN feedback model can have a major effect.

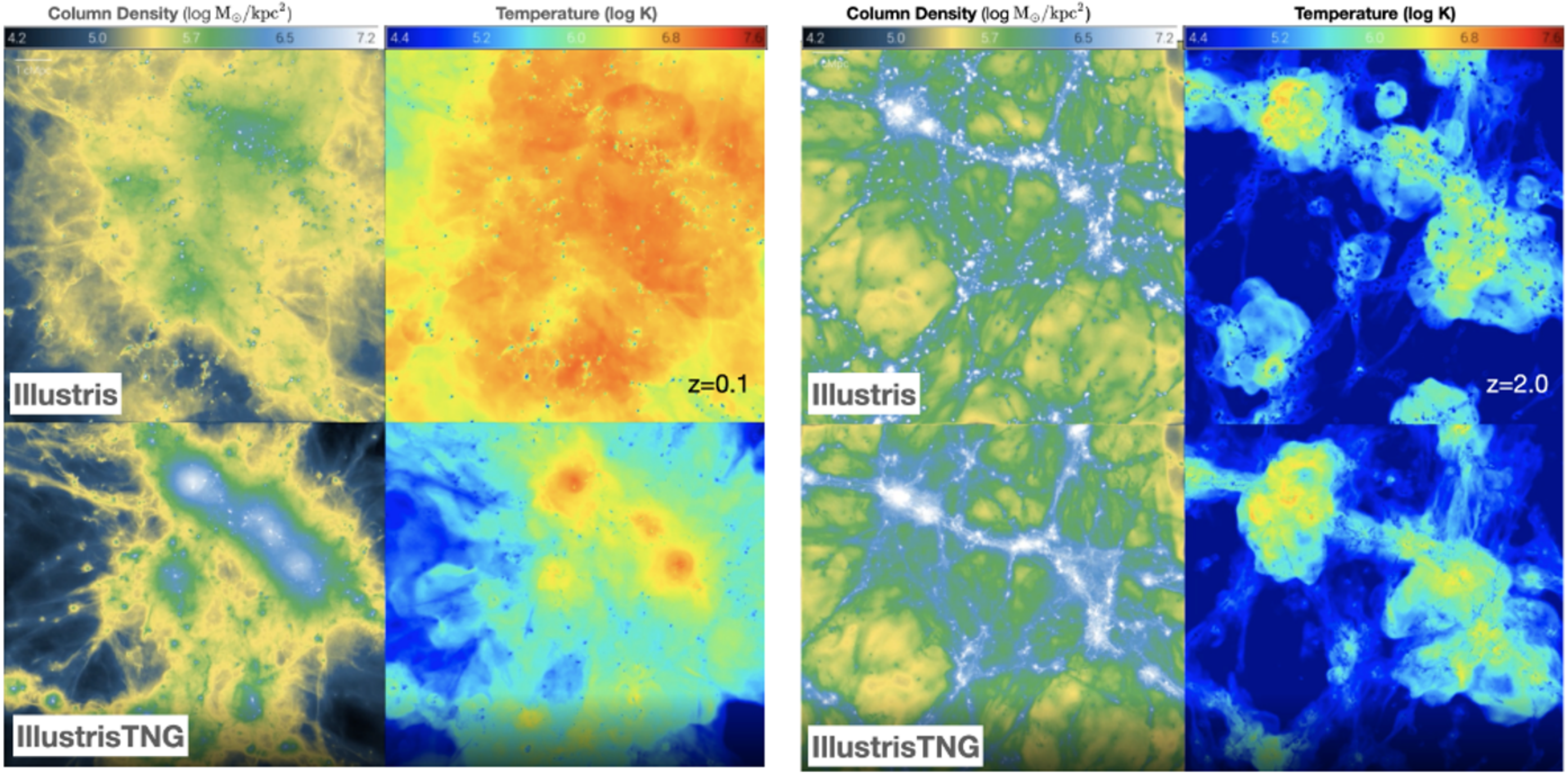


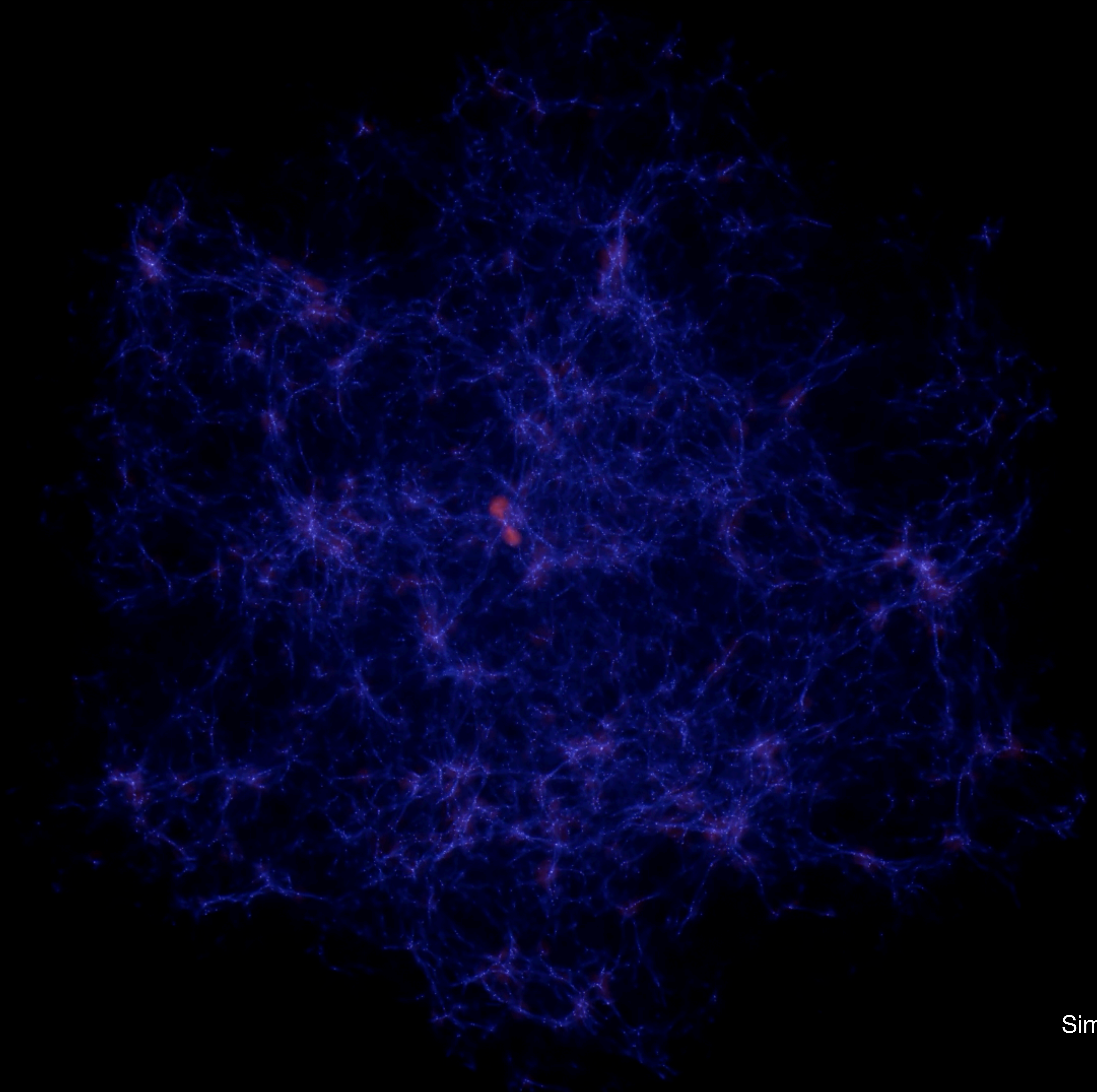


Burkhart et al. 2022

Why is this not a problem at z>2?

Growth of blackholes and AGN heating not significant (volume filling) until lower redshift

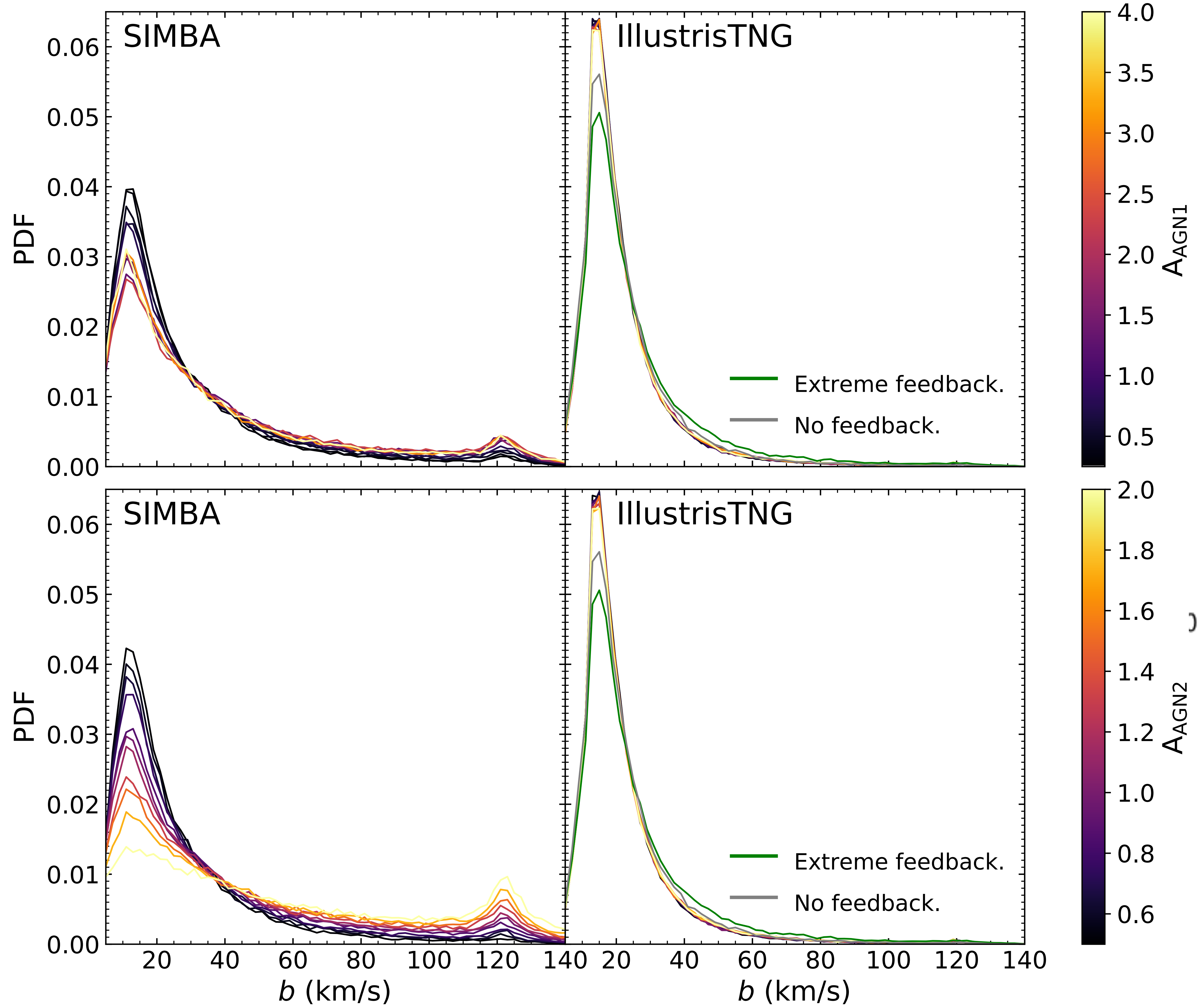


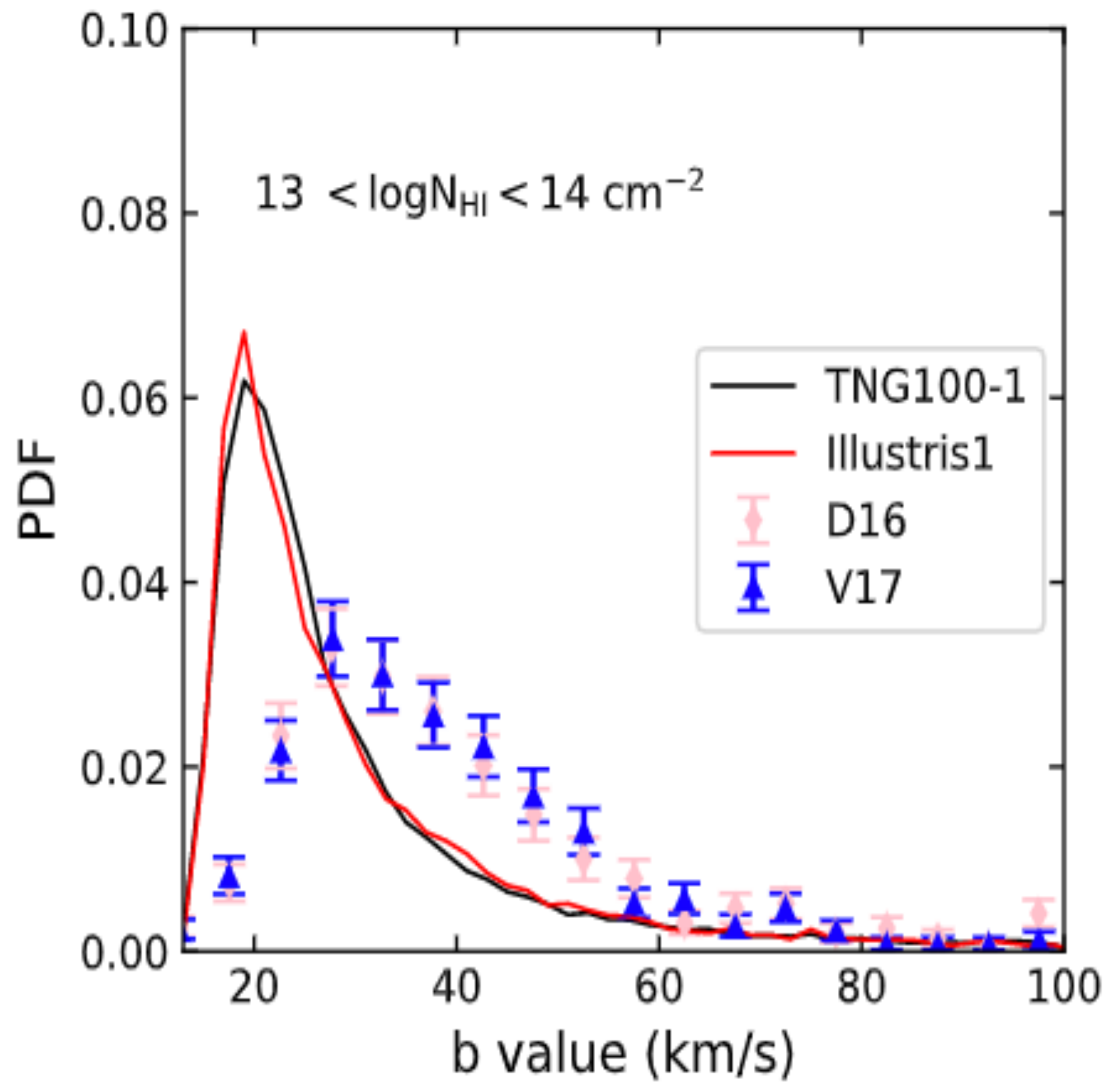


$z = 5.04$

Simba cosmological simulation
Christiansen et al. (2020)

Other Statistics: b distribution





$$b^2_{\rm turb} = b^2_{\rm obs} - b^2_{\rm noturb}$$

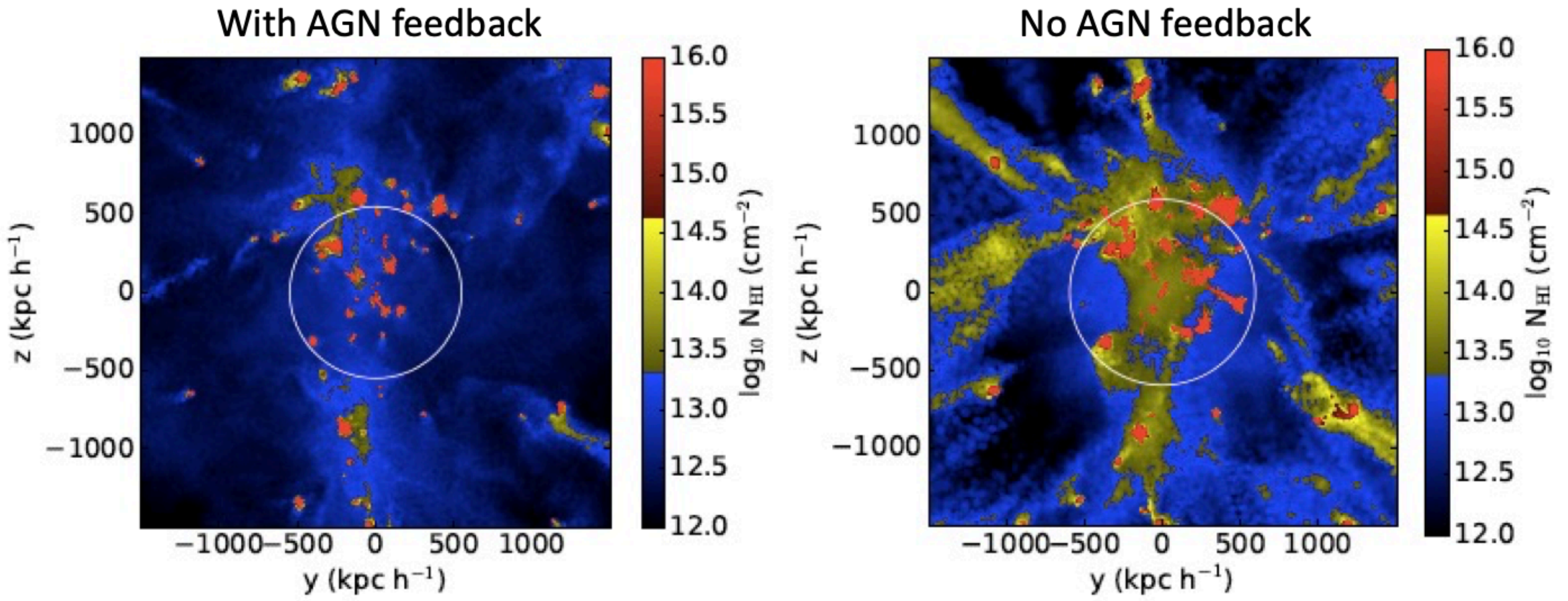
- TNG and Illustris are too narrow compared to COS!
- Could be unresolved turbulence?
- Likely not jeans broadening- widths in the diffuse IGM at z ~0.1 have a minimal contribution from Jeans smoothing since $b^2_{\rm Jeans} \propto \Delta^{-1}$ and Δ=10 at z=0.1

$$b_{\rm obs}/b_{\rm therm} \simeq 1.24$$

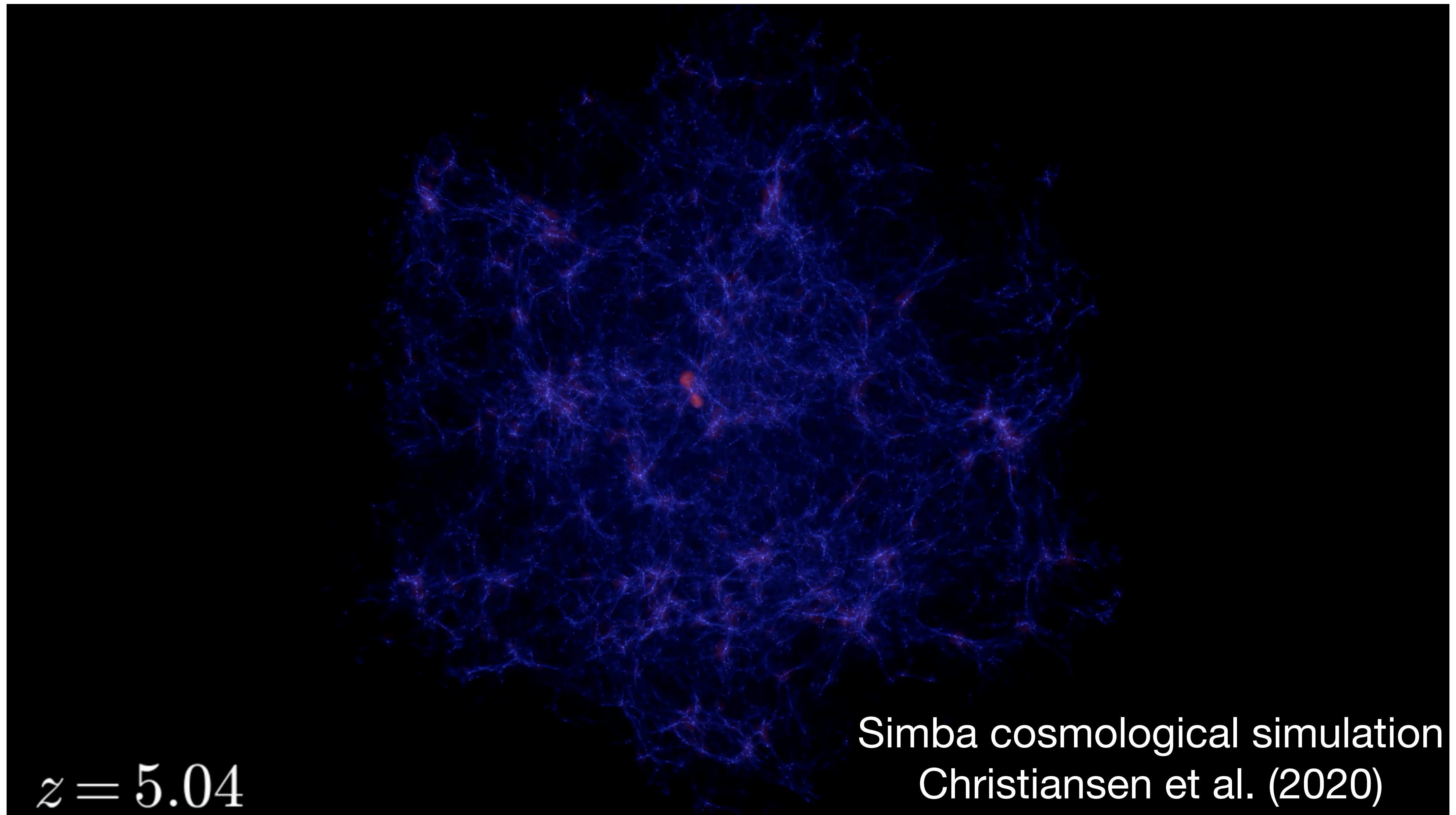
$$b_{\rm turb} \simeq 0.73 b_{\rm therm}$$

Conclusions

- High-z Ly-α Forest: a happy place for cosmologists where baryons are well-behaved (i.e., follow dark matter and equilibrium)
- Low-z Ly-α Forest: Ly-α Forest baryons are no longer following the classic paradigm. AGN Feedback can have a significant impact on the low-z Ly-α forest via heating and matter redistribution (a “Forest Fire!”).
- The *particulars of the AGN feedback model* have a dramatic effect on the Ly-α forest (i.e., TNG vs Illustris vs Simba etc.).
- Bad news: UVB measurements from Ly-α forest are dangerous at low z!
- Good news: We can calibrate feedback models on z=0.1 forest!
- The AGN "Forest Fire” begins around z=1 (sooner for damped Lyman-α systems).
- Machine learning can likely help disentangle the parameters (let’s discuss more!)

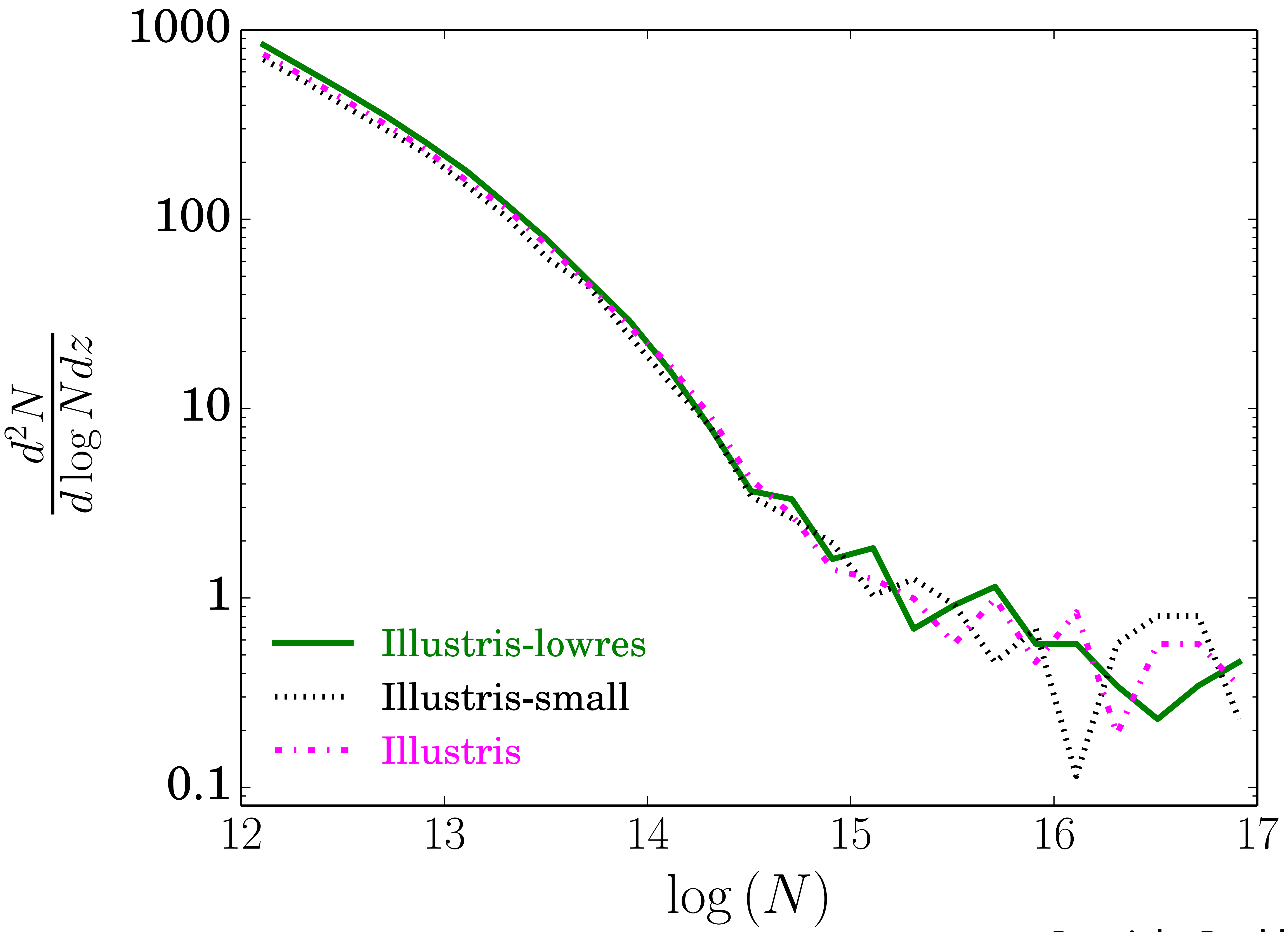


Gurvich, Burkhart & Bird 2017



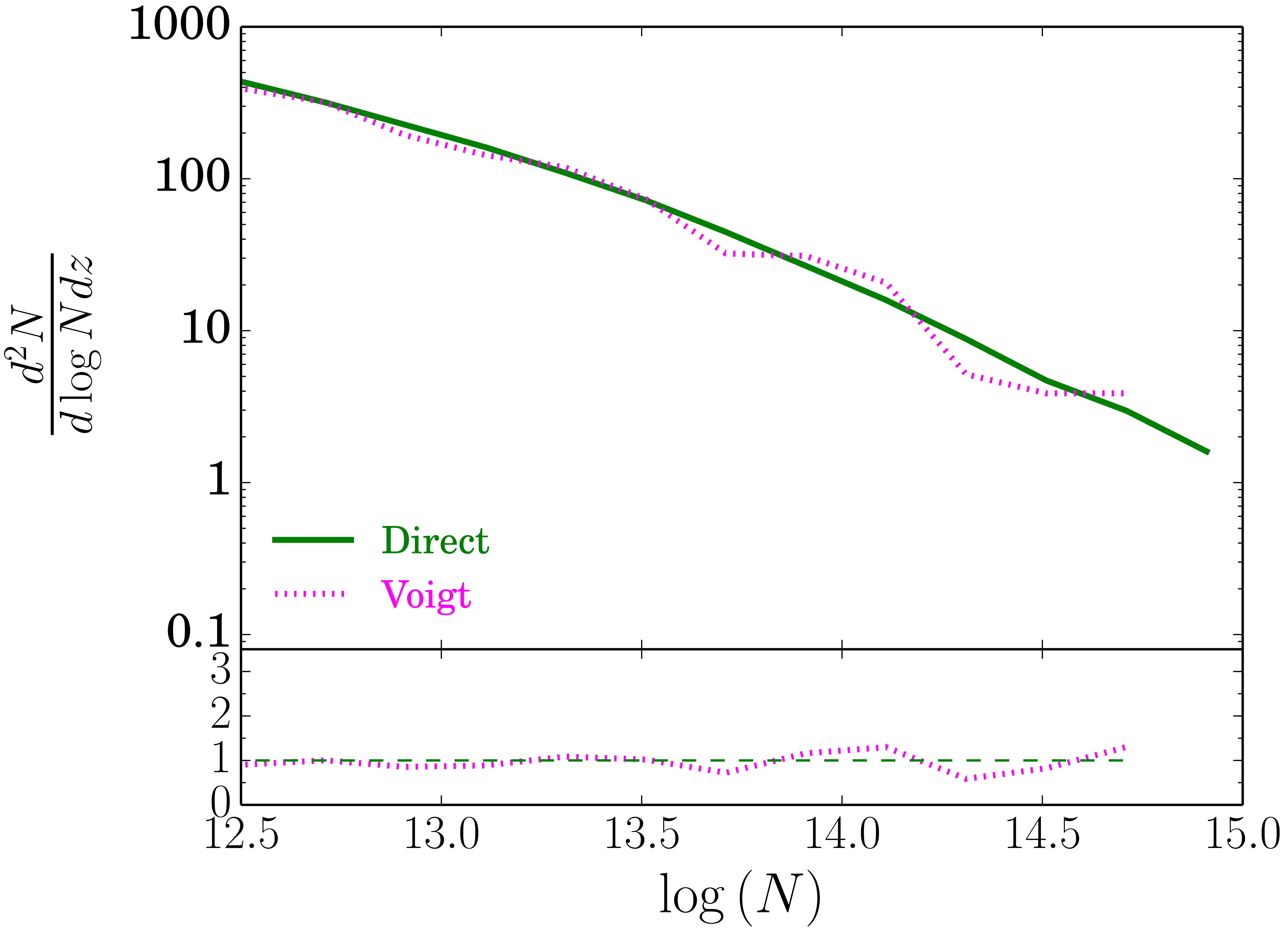
Simba cosmological simulation
Christiansen et al. (2020)

Resolution

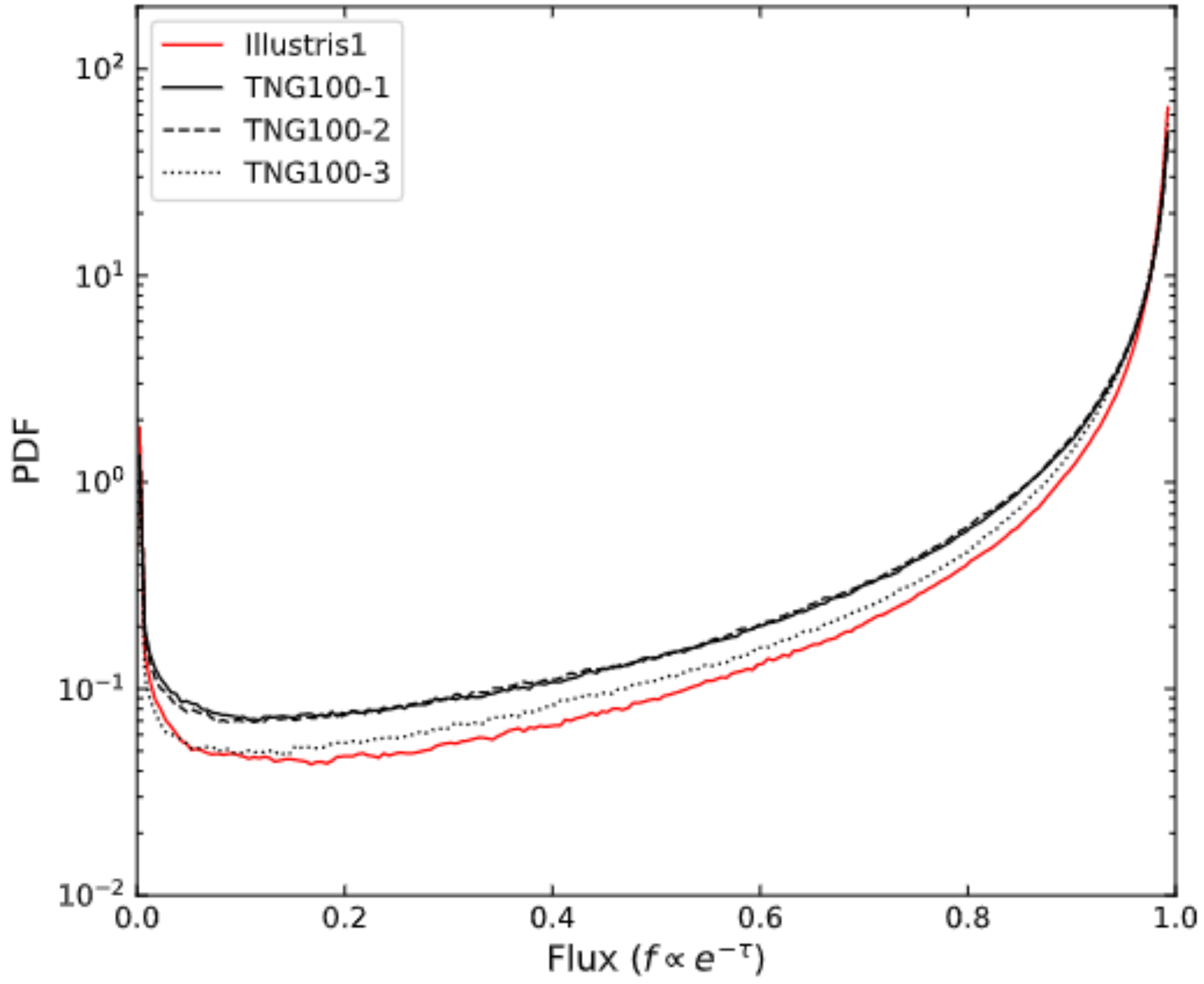


Gurvich, Burkhart & Bird 2017

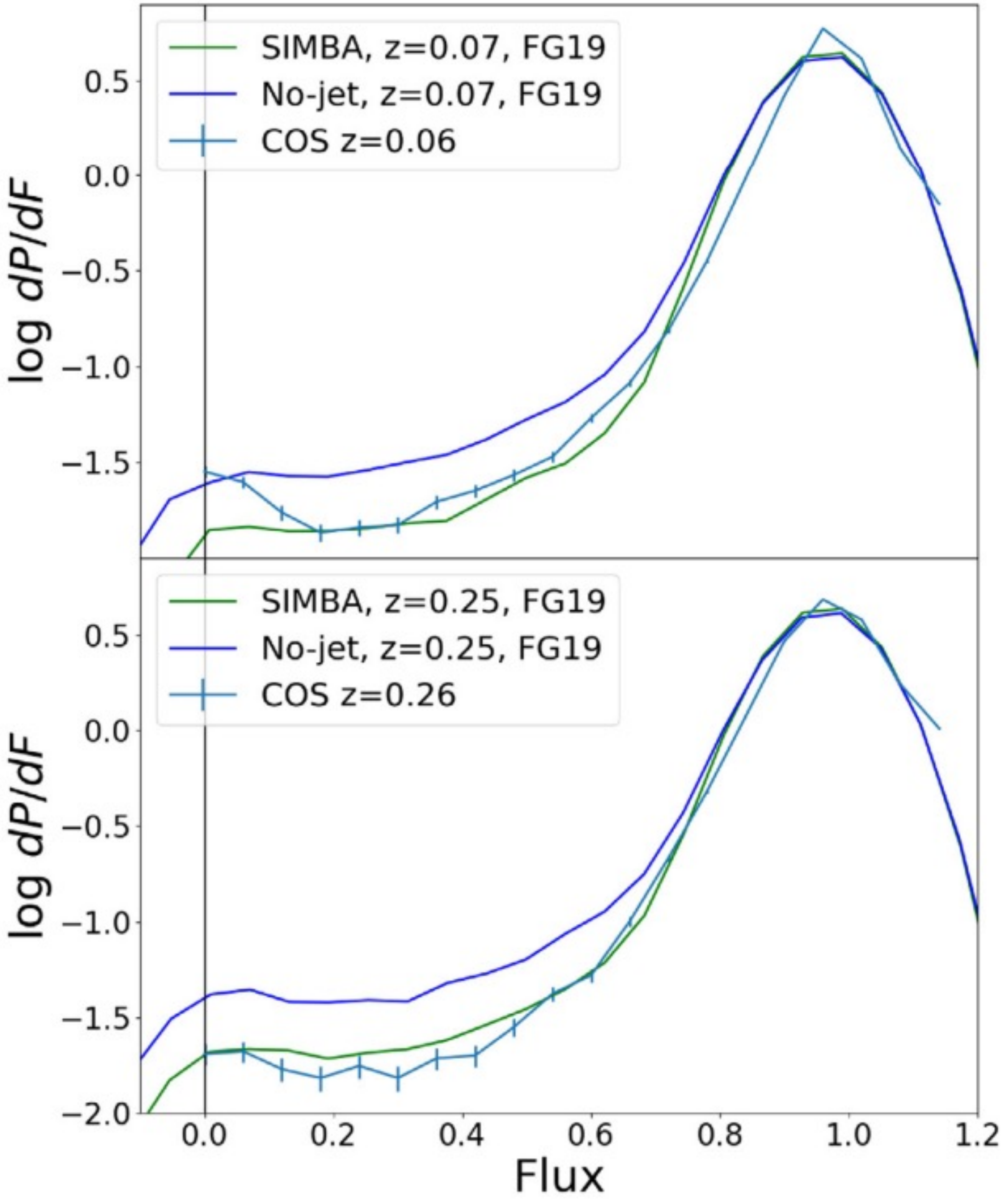
Voigt vs. Direct Calculation



Flux PDF



Illustris1
TNG100-1
TNG100-2
TNG100-3
PDF
Flux ($f \propto e^{-\tau}$)



SIMBA, z=0.07, FG19
No-jet, z=0.07, FG19
COS z=0.06
SIMBA, z=0.25, FG19
No-jet, z=0.25, FG19
COS z=0.26
log dP/dF
Flux

	Illustris	Illustris – TNG *
Black Hole Formation	$M_{BH} = 10^5 M_\odot$ seeded inside all haloes with	
Black Hole Growth $\dot{M}_{BH}$	All accretion rates Eddington limited: $\dot{M}_{eff} = \min$	
	$100\,\dot{M}_{Bondi}$	$\dot{M}_{Bondi} \max\left(1, \frac{M_{BH}}{M_{pivot}}\right)$
Quasar Feedback (rapid growth)	$\dot{M}_{eff} > 0.01\dot{M}_{Edd}$	$\dot{M}_{eff} > 0.05\dot{M}_{Edd}$
	$\dot{E} = \epsilon_f \epsilon_r \dot{M}_{eff} c^2$ distributed isotropically	

Courtesy of C. Popa

	Illustris	Illustris – TNG
	$\dot{M}_{eff} < 0.01\dot{M}_{Edd}$	$\dot{M}_{eff} < 0.05\dot{M}_{Edd}$

Radio Feedback
(slow growth)

$$\dot{E} = \epsilon_f \epsilon_r \dot{M}_{eff} c^2$$

$\epsilon_f = 0.35$

$\epsilon_f = 0.07$

$\epsilon_f = 0.1$

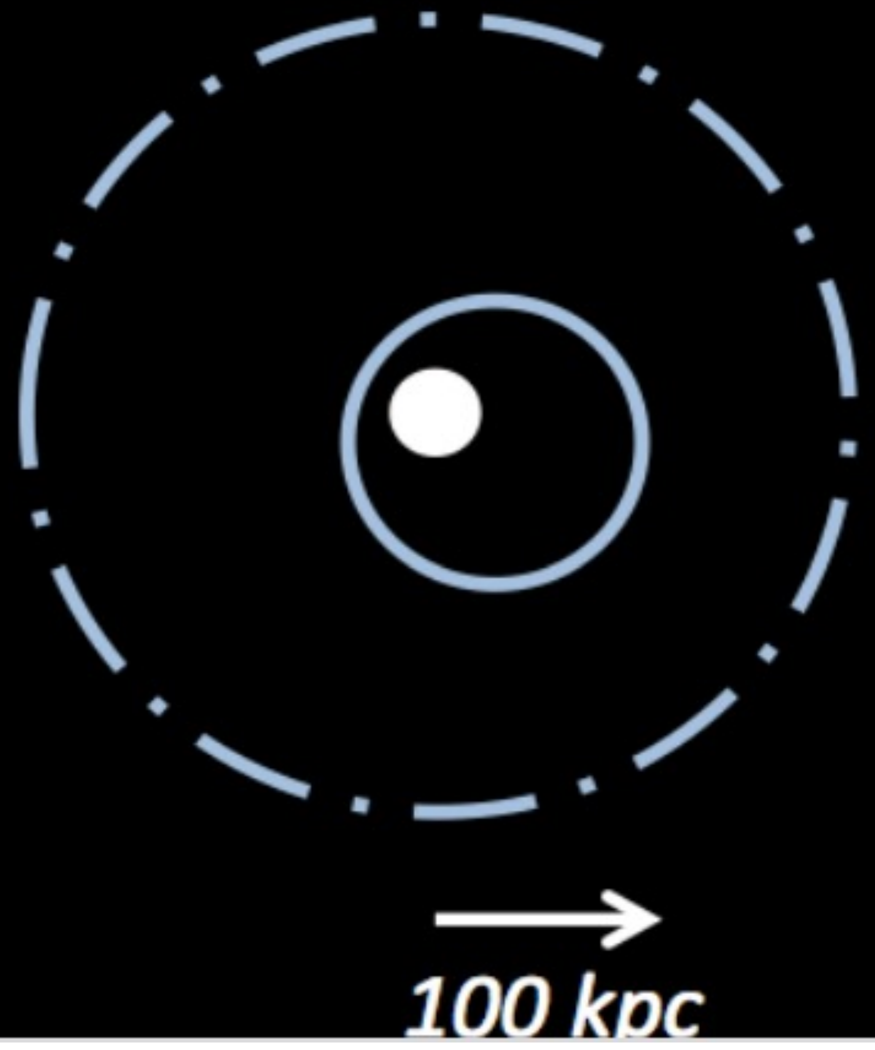
Illustris

Thermal feedback

inflates 1 hot bubble

$$R = R_0 \left(\frac{E/E_0}{\rho_{gas}/\rho_0} \right)^{1/5}$$

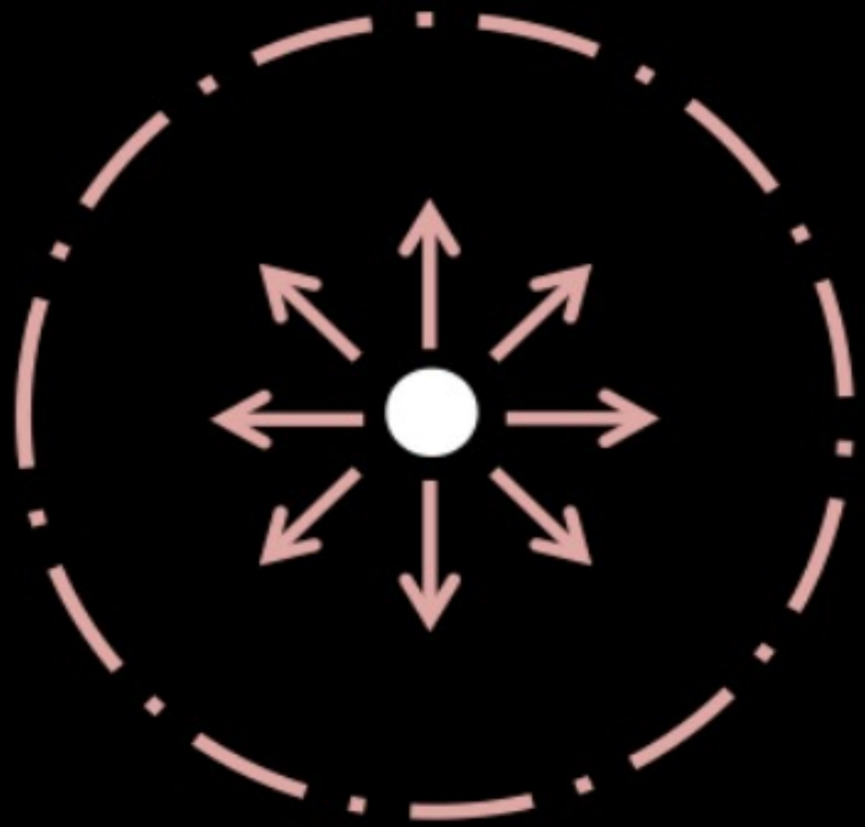
$$E = \epsilon_f \epsilon_r c^2 \delta M_{BH}$$



Illustris – TNG

Kinetic feedback

momentum distributed isotropically to neighboring gas cells



Courtesy of C. Popa