Too Hot to Handle

The Role of Supermassive Black Holes in Heating the Low Redshift Intergalactic Medium

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KITP - Galaxy Formation and Evolution in the Data Science Era 03/21/2023

Outline

- Why I love Simba and you should too!
- Why we need to model AGN feedback.
- Simba’s AGN feedback.
- The CAMELS Project: Exploring feedback models.
  - AGN feedback effects.
  - Stellar feedback effects.
- The interplay between stellar and AGN feedback.

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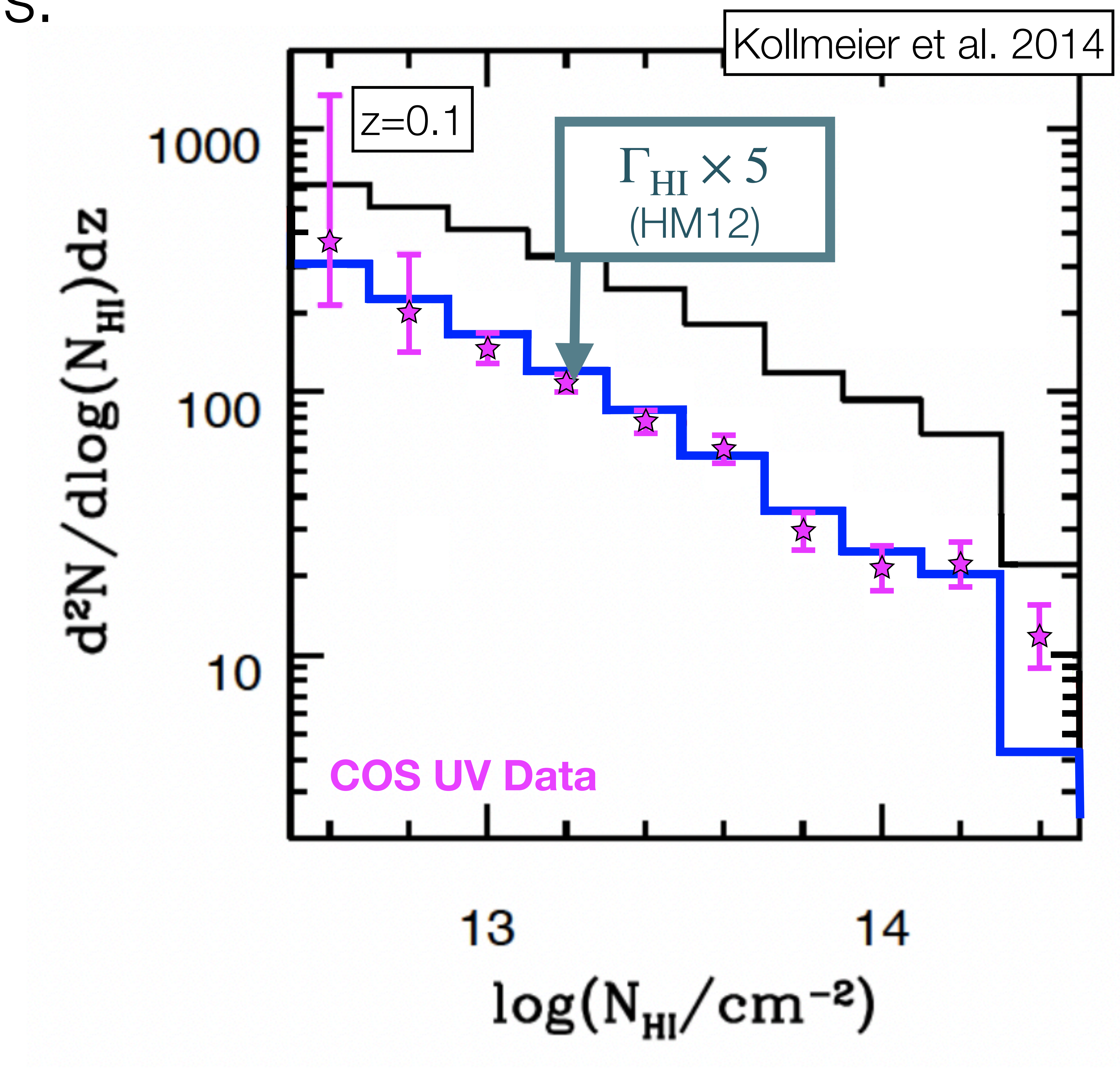
Recall: Low-z Lyman-α forest observations vs simulations

Mismatch between observed data and simulations.

- 5 times stronger UVB required at z=0.1

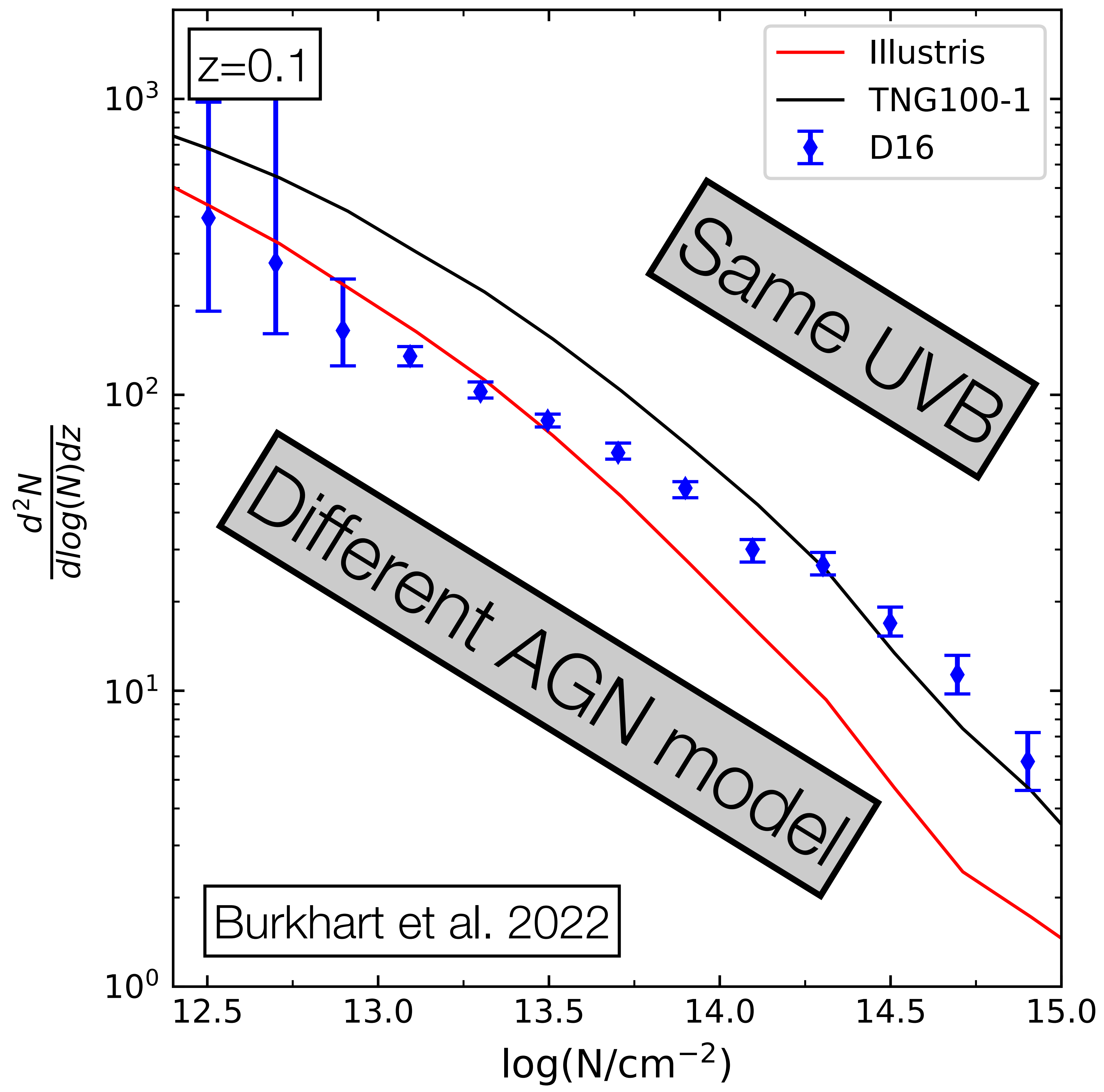


Recall: Low-z Lyman-α forest observations vs simulations

Mismatch between observed data and simulations.

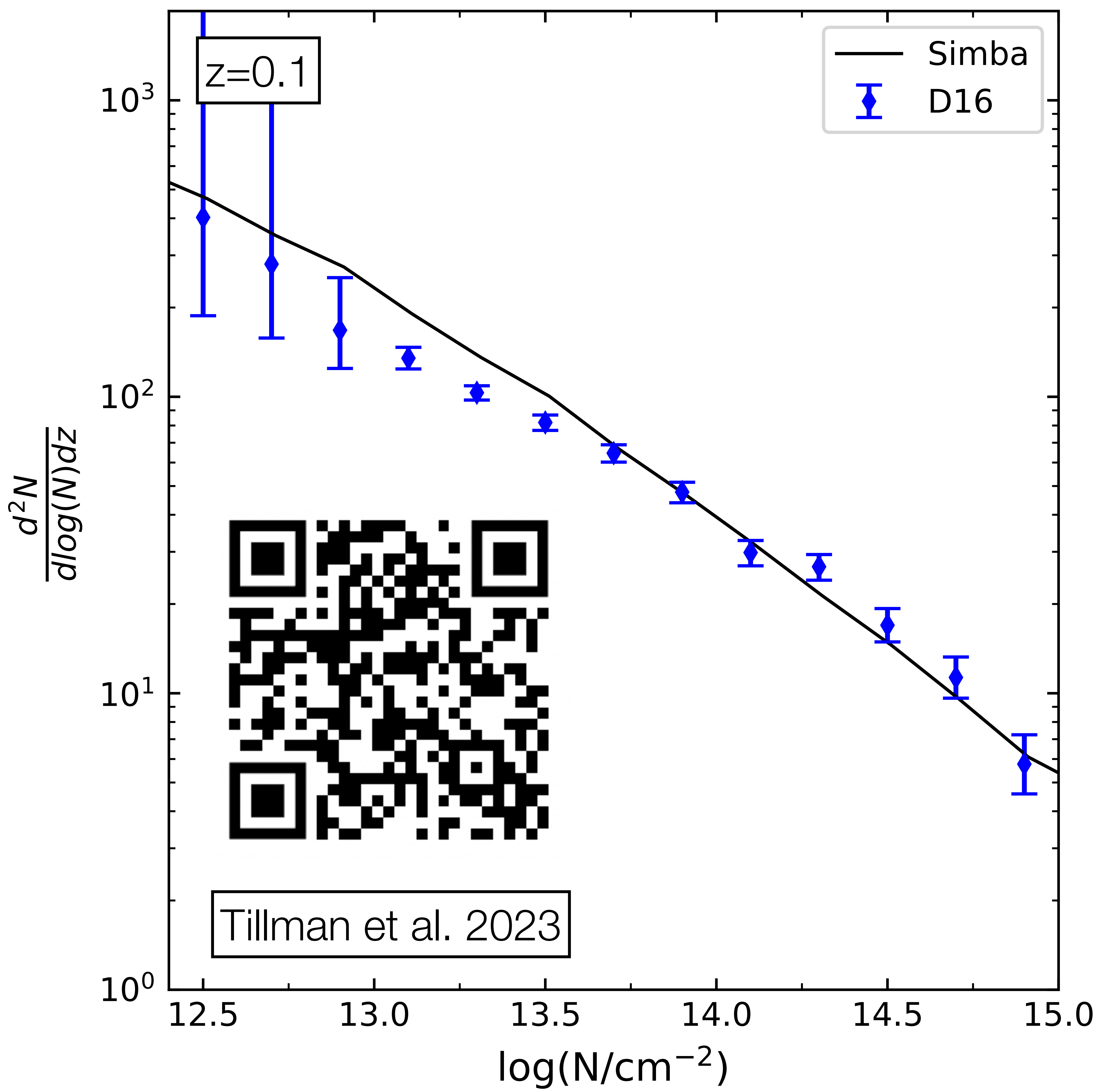
- 5 times stronger UVB required at z=0.1

The AGN feedback model can have an effect.



Why I love Simba and you should too!

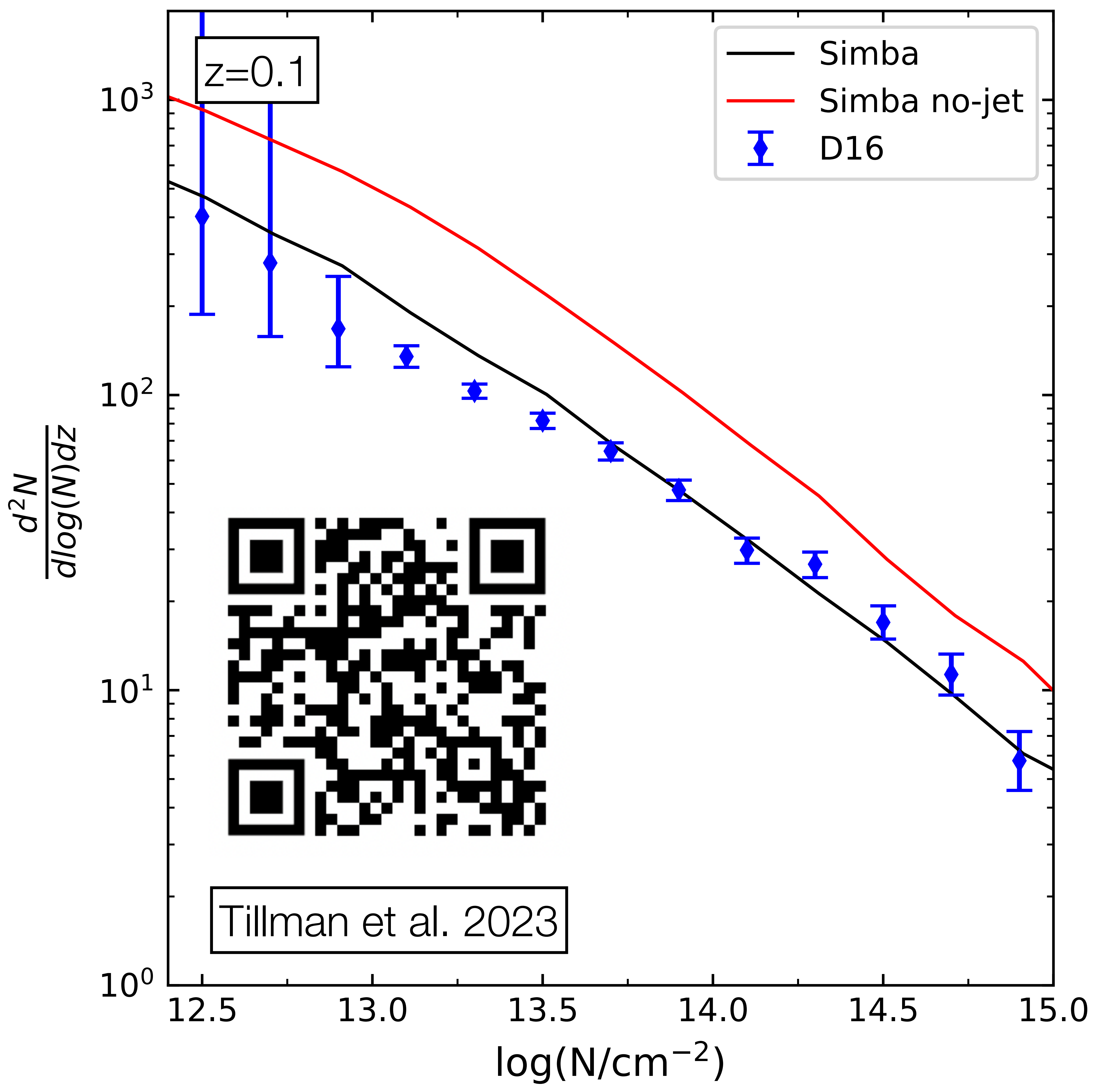
- The Simba simulation (Davé et al. 2016) provides a remarkable match to observed data.



Why I love Simba and you should too!

- The Simba simulation (Davé et al. 2016) provides a remarkable match to observed data.

- The AGN jet feedback plays a significant role in this match.



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Why we need to model AGN feedback.

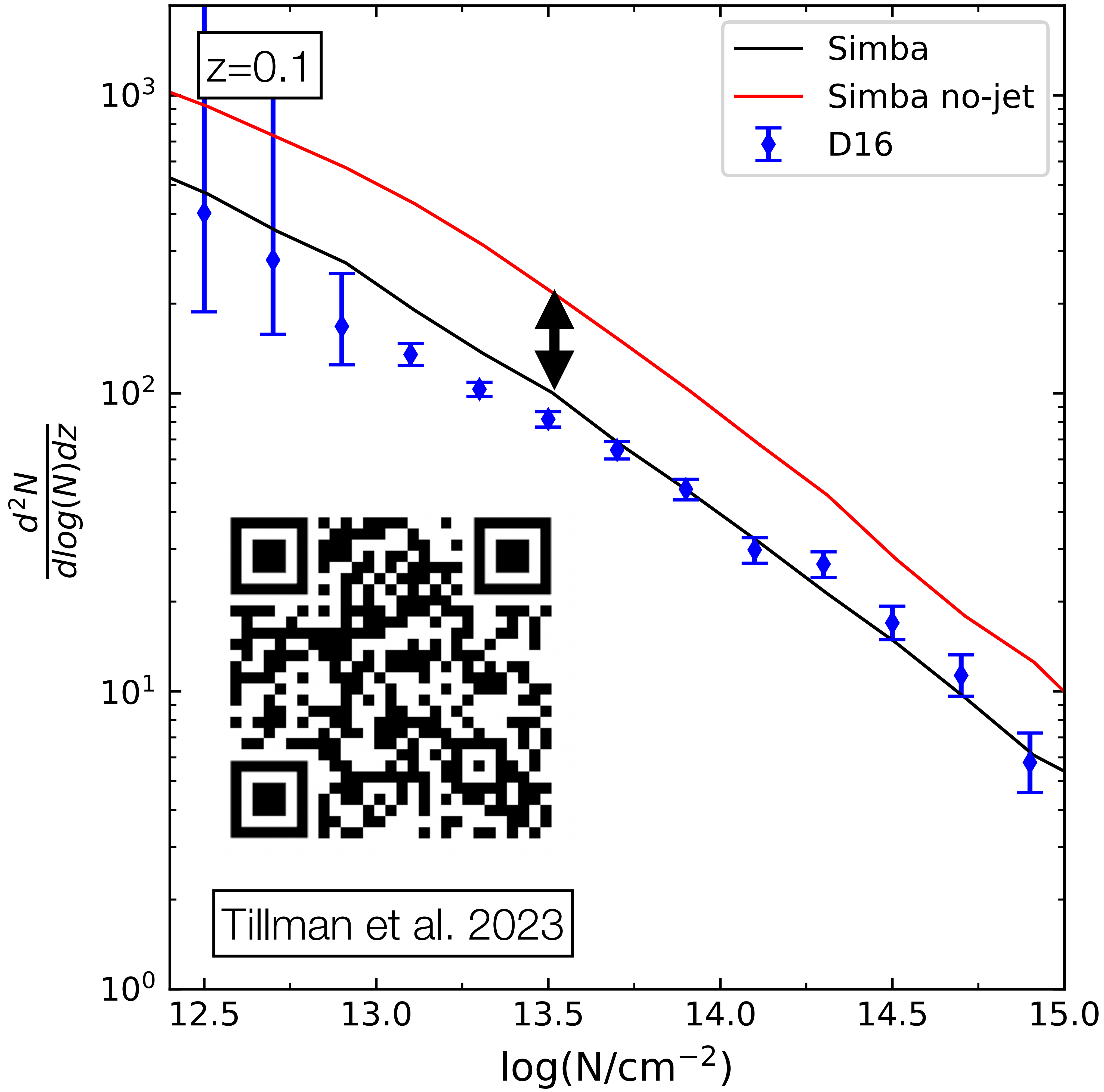
Can we lump this change into a UVB rescaling?

NO

Observations tell us there are jets.

Don't tunnel vision on a single statistic.

Simba's jet model affects the CDDF in ways the UVB does not.



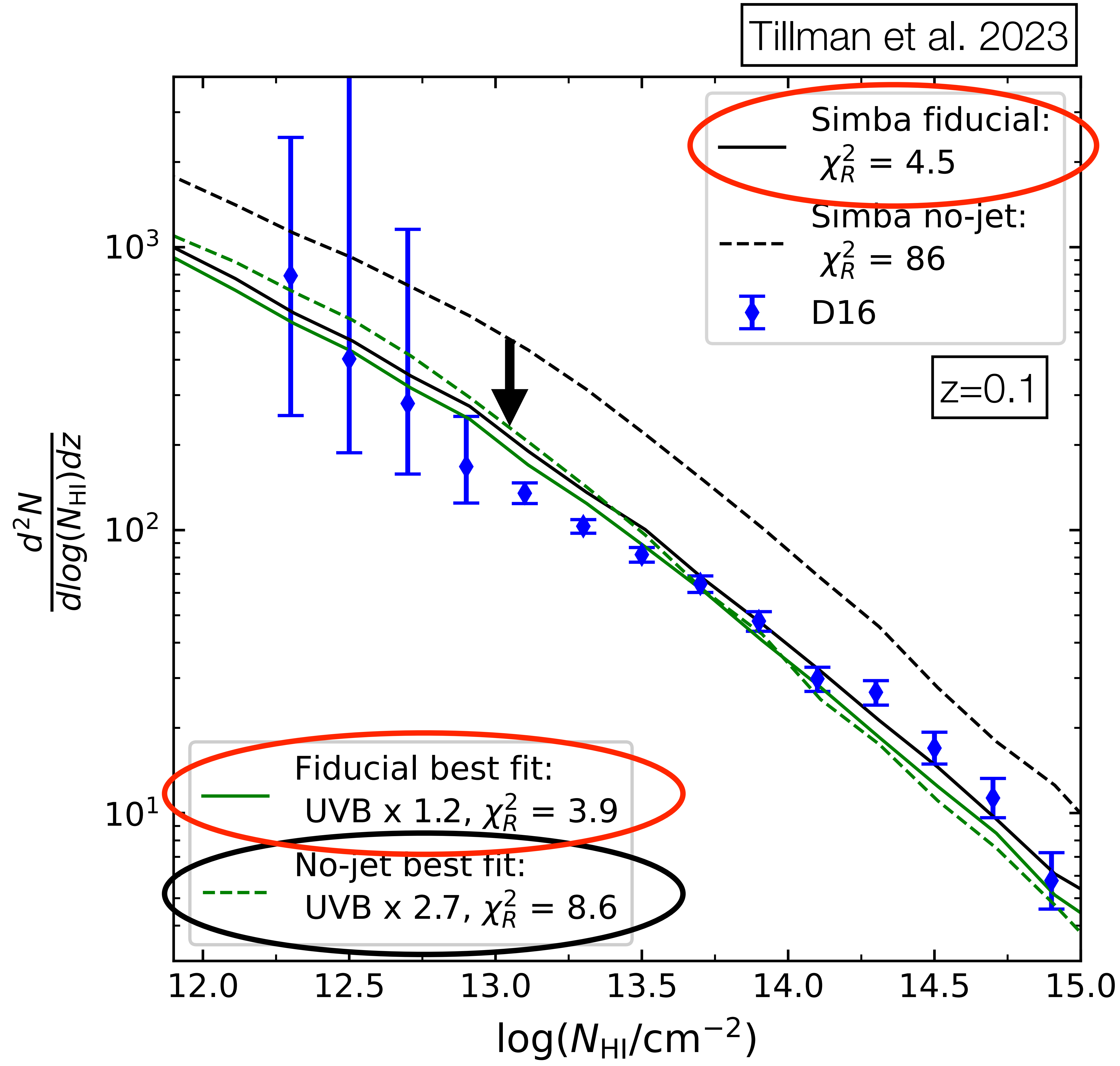
Why we need to model AGN feedback.

Rescaling the UVB in each case to find best fit.

Without jets requires a UVB 2.7 times stronger.

Best fit without jets is worse than even the fiducial results.

We **need** more observations!



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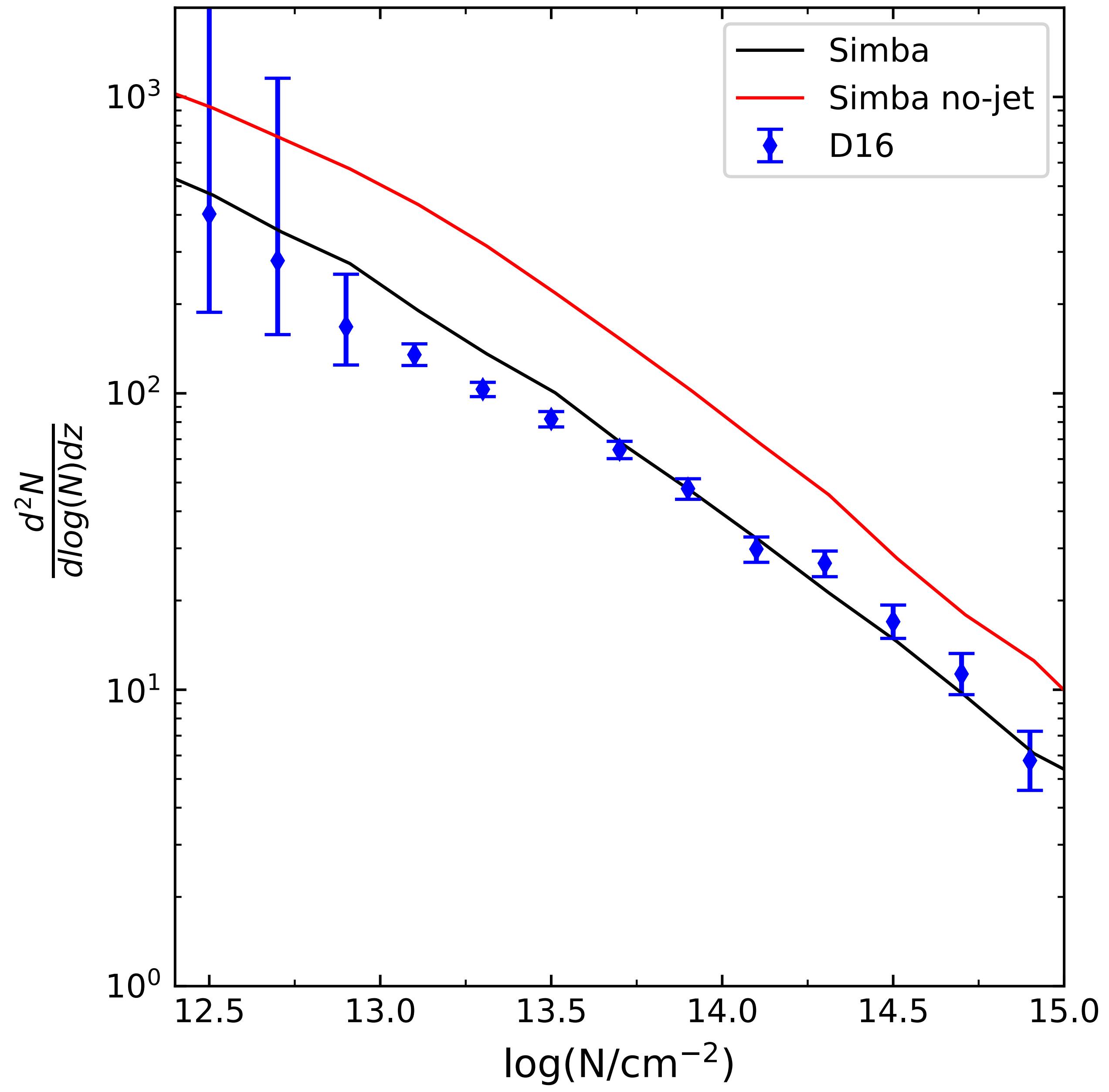
Simba's AGN feedback: What makes jets so effective?

Highly collimated - localized, not isotropic

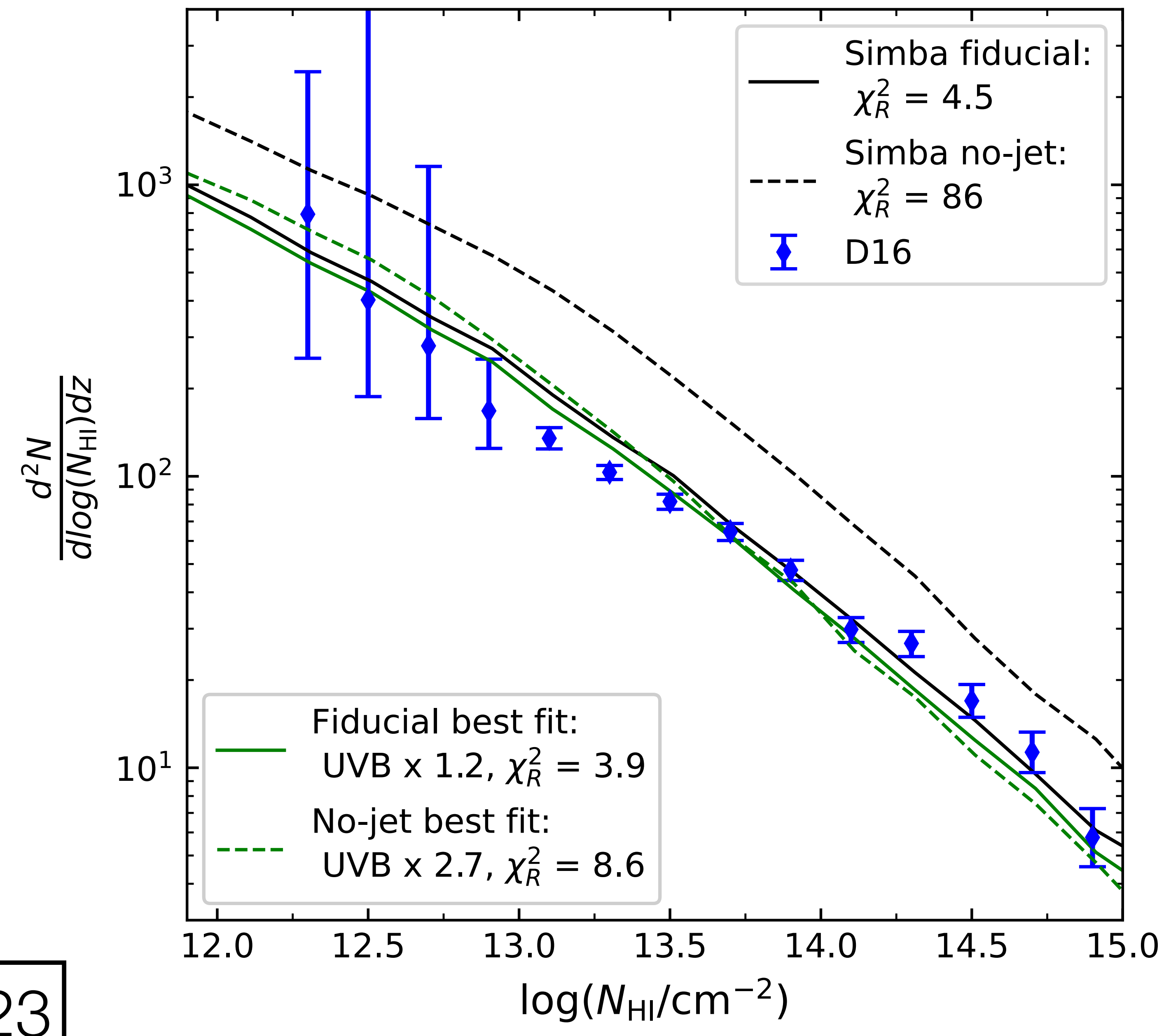
Includes a decoupling time - can escape the galaxy without being damped

Heated to the viral temperature - heats the gas at the recouping point



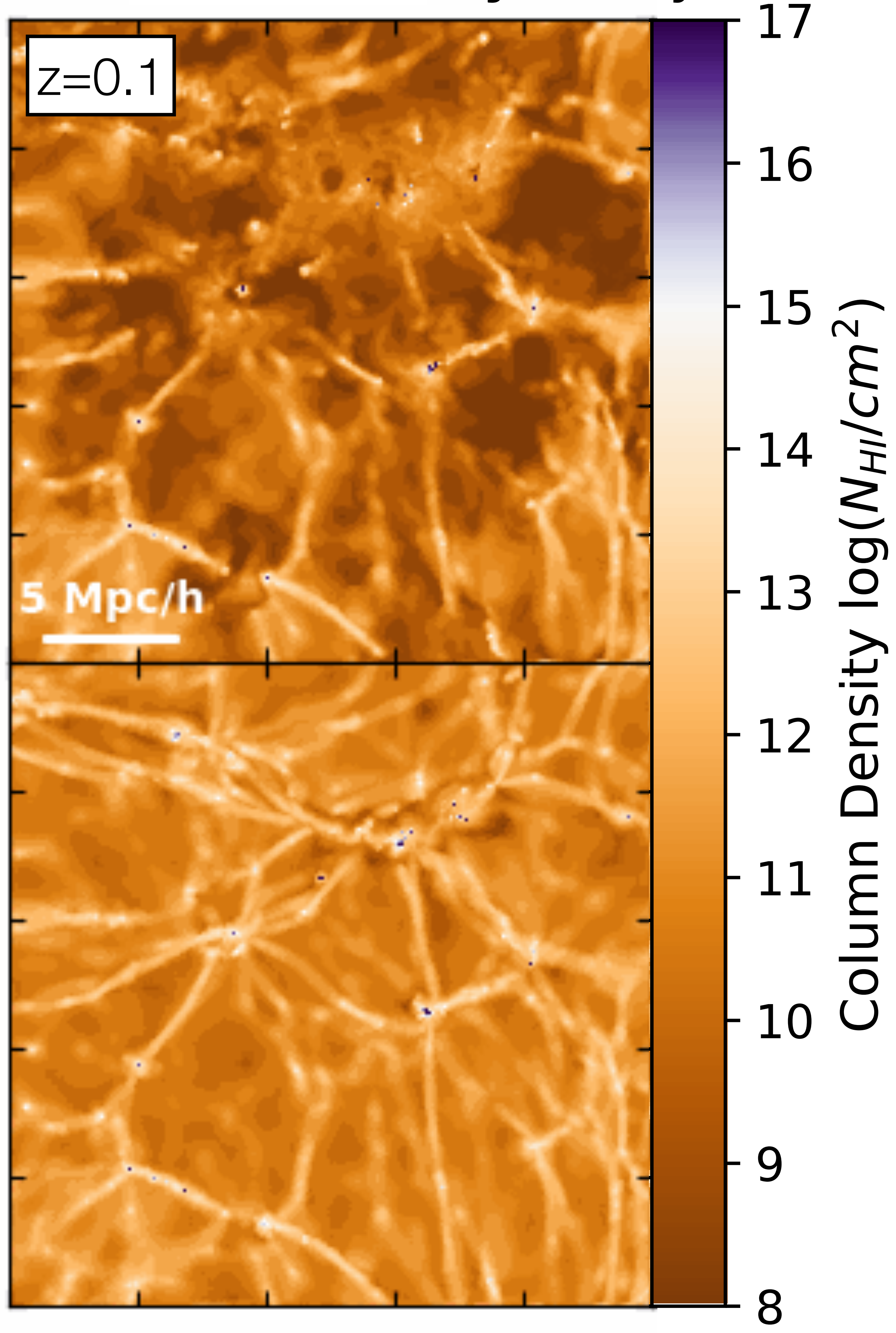
z=0.1

Tillman et al. 2023

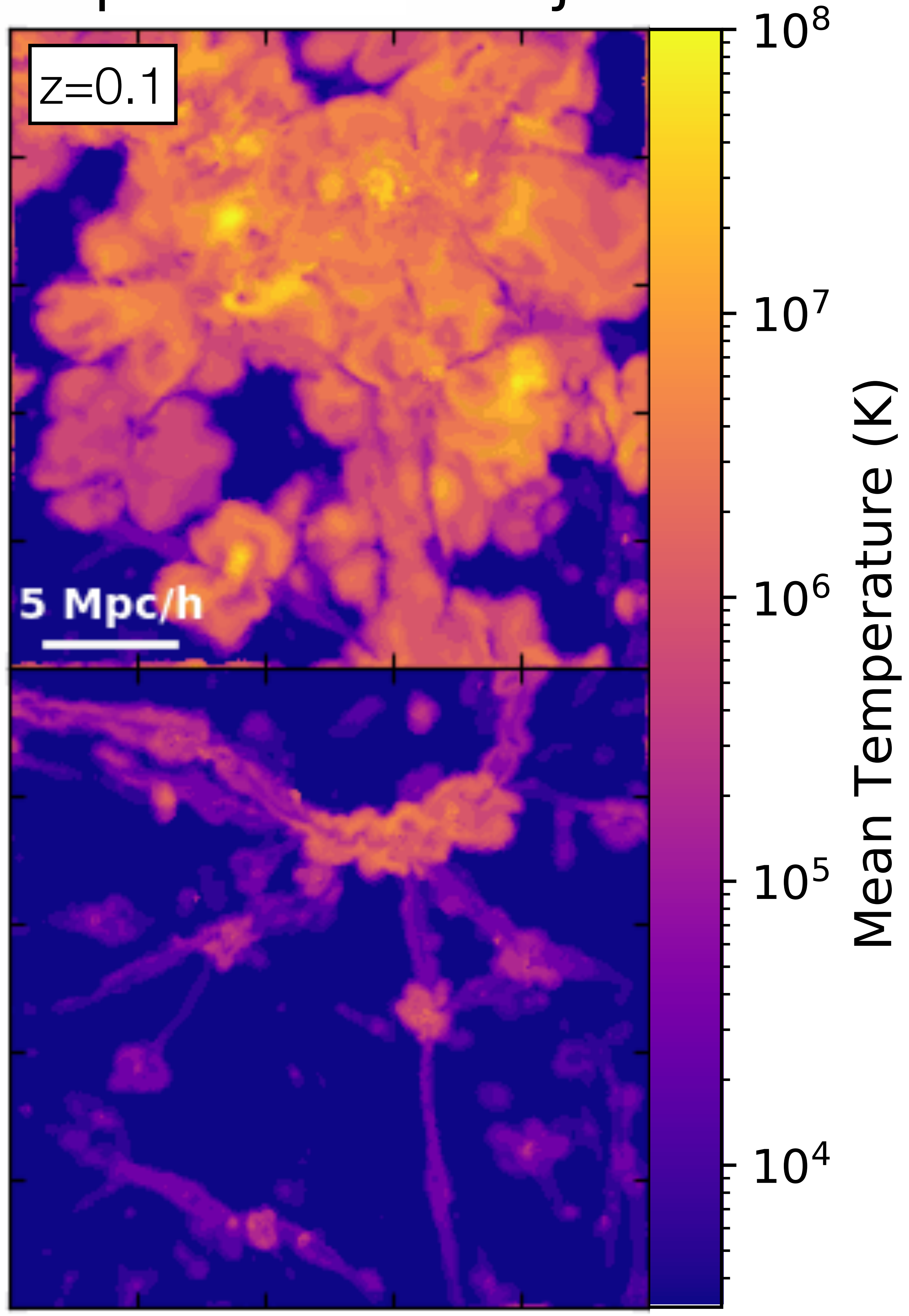


Simba’s AGN feedback: Visualizing AGN Jet Effects

HI Column Density Projection



Temperature Projection

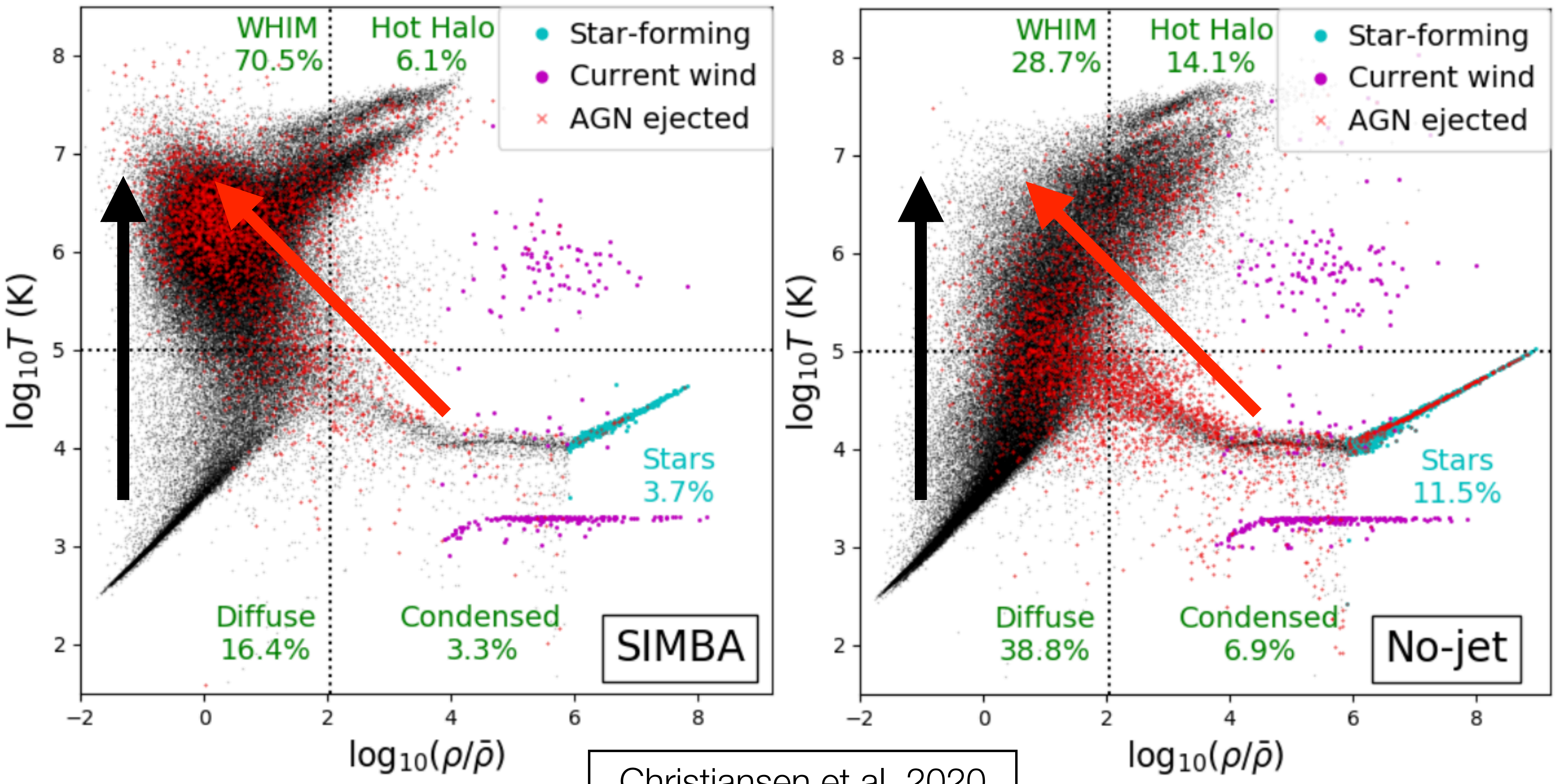


With jet feedback.

Simba simulations

Without jet feedback.

Simba’s AGN feedback: Heating and ejecting.



Christiansen et al. 2020

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The CAMELS Project

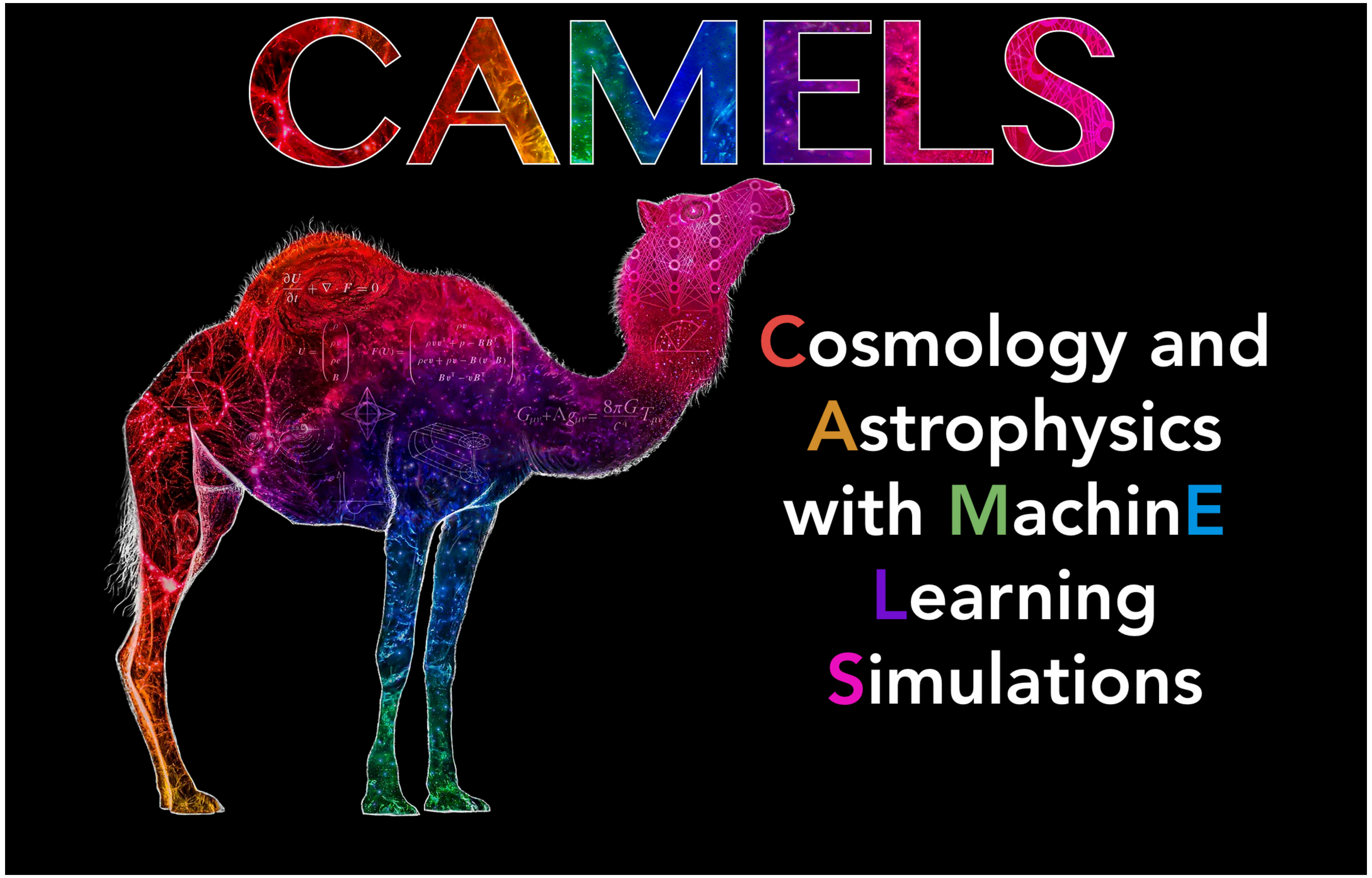
- Set of more than 10,000 simulations exploring parameter variations of the different simulations' sub-grid models (Villaescusa-Navarro et al. 2021).

25 Mpc/h boxes

256^3 particles

$1.27 \times 10^7 \ h^{-1} M_\odot$ mass resolution

- Allows us to explore variations of the Simba feedback sub-grid models.




Astrid
IllustrisTNG
SIMBA
$z = 9.94$
CAMELS
(Villaescusa-Navarro)


$z = 9.94$
CAMELS
(Villaescusa-Navarro)

The CAMELS Project: The Simba suite feedback.

CAMELS
Cosmology and Astrophysics with MachinE Learning Simulations

AGN feedback parameters:

- Momentum Flux
- Jet Speed

$$\dot{P}_{\rm out} \equiv \dot{M}_{\rm out}\, v_{\rm out} = A_{\rm AGN1} \times 20\, L_{\rm bol}/c$$

$$v_{\rm rad} = 500 + 500(\log_{10}(M_{\rm BH}) - 6)/3 \ {\rm km\,s^{-1}}$$

$$v_{\rm jet} = 7000 \times \min[1, \log_{10}(0.2/\lambda_{\rm Edd})]\ {\rm km\,s^{-1}}$$

$$v_{\rm out} = \begin{cases} v_{\rm rad} + A_{\rm AGN2} \times v_{\rm jet} & \text{if } \begin{cases} \lambda_{\rm Edd} < 0.2 \\ M_{\rm BH} > 10^{7.5}\,{\rm M_\odot} \end{cases} \\ v_{\rm rad} & \text{otherwise,} \end{cases}$$

Stellar feedback parameters:

- Mass Loading
- Wind Speed

$$\eta \equiv \dot{M}_{\rm wind}/{\rm SFR}$$

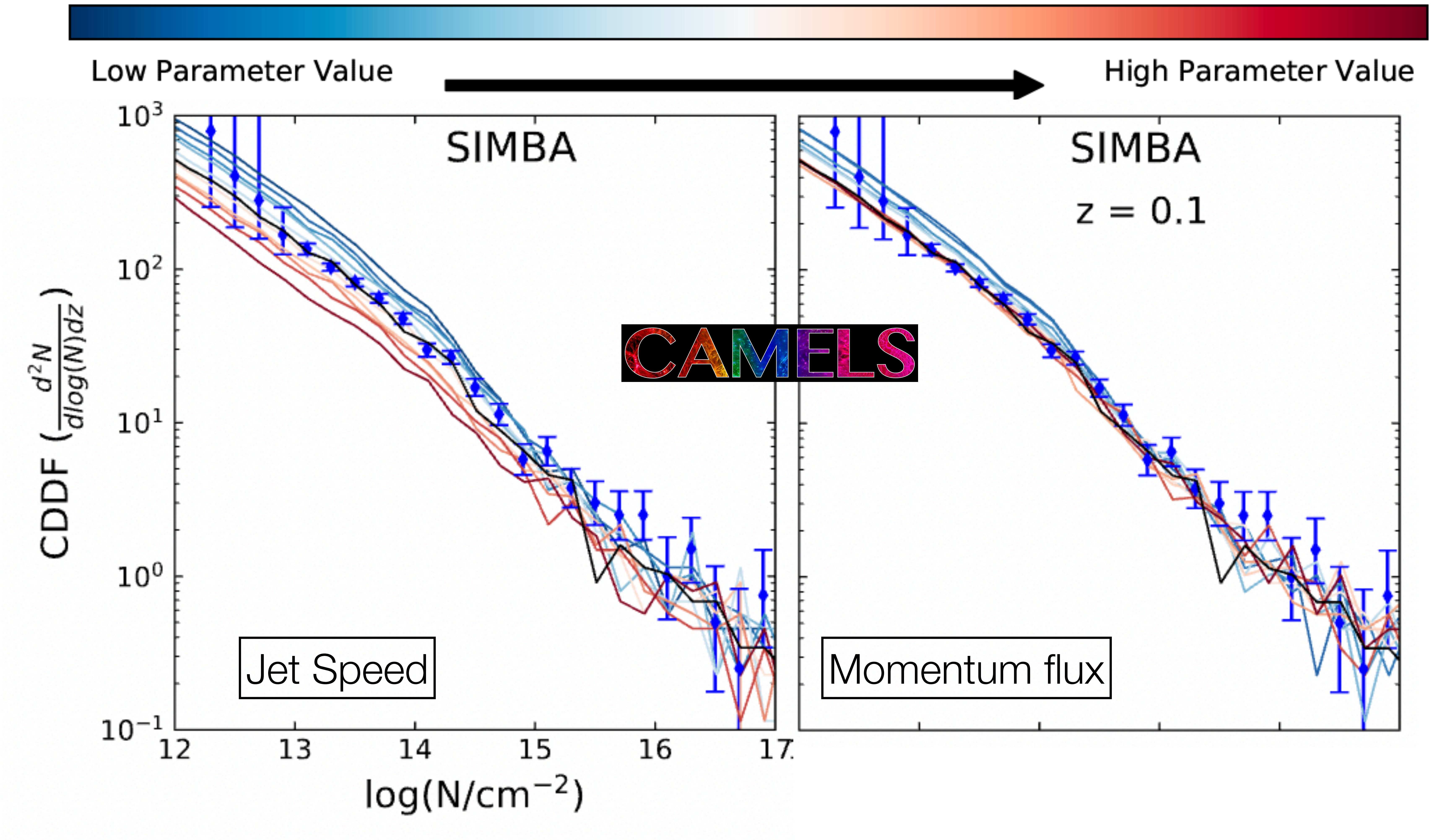
$$\eta(M_\star) = A_{\rm SN1} \times \begin{cases} 9\left(\frac{M_\star}{M_0}\right)^{-0.317}, & \text{if } M_\star < M_0 \\ 9\left(\frac{M_\star}{M_0}\right)^{-0.761}, & \text{if } M_\star > M_0 \end{cases} \qquad M_0 = 5.2 \times 10^9 M_\odot$$

$$v_{\rm w} = A_{\rm SN2} \times 1.6\left(\frac{v_{\rm circ}}{200\ {\rm km\,s^{-1}}}\right)^{0.12} v_{\rm circ} + \Delta v(0.25 R_{\rm vir})$$

The CAMELS Project: AGN Feedback Parameter Effects

Largest effects seen at lowest column densities.

Jet speed is the dominating factor.



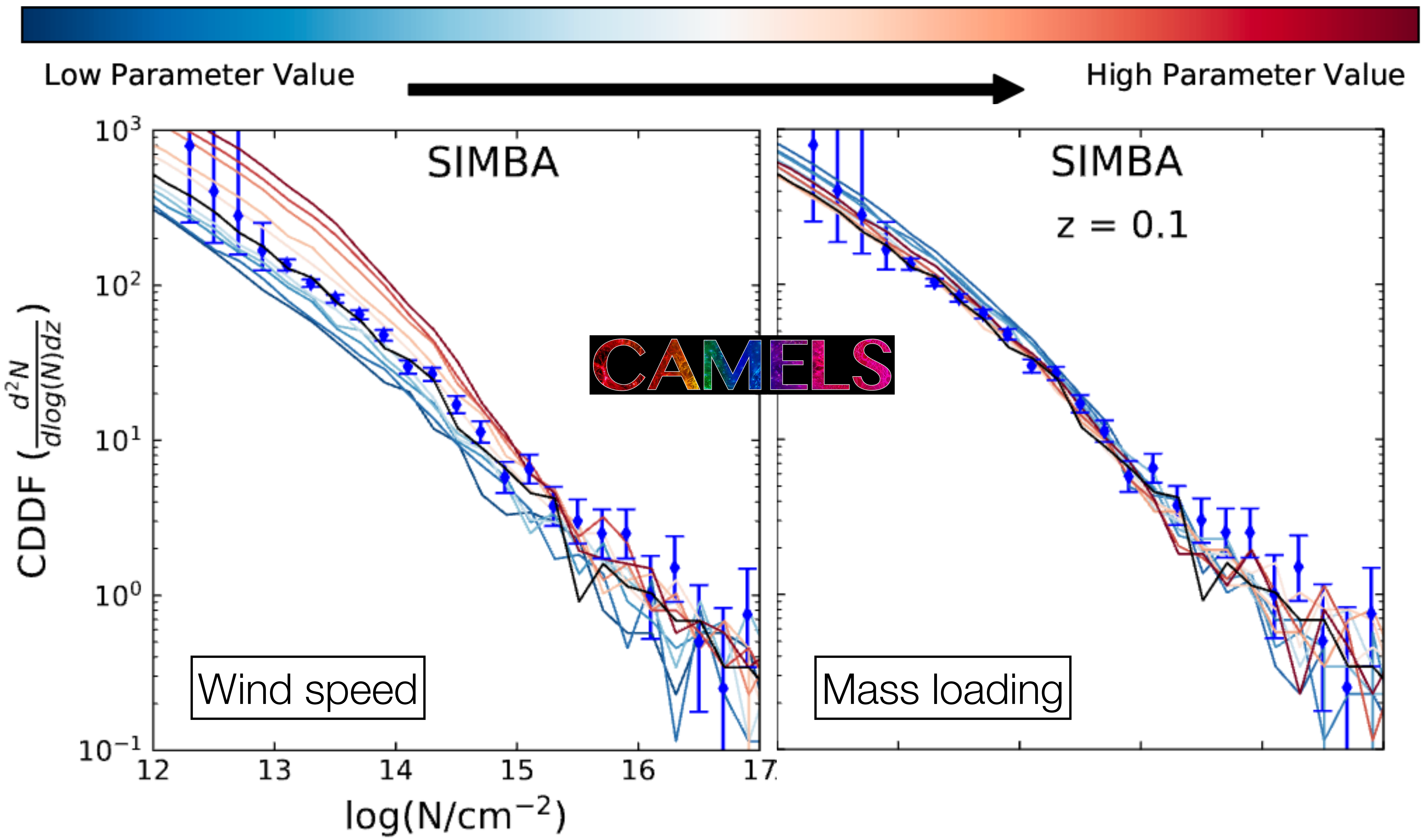
Tillman et al. in prep

The CAMELS Project: Stellar Feedback Parameter Effects

Similar to AGN feedback effects???

Strong stellar feedback could suppress SMBH growth.

Let's check.



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Tillman et al. in prep

The interplay between stellar and AGN feedback.

Statistics we look at:

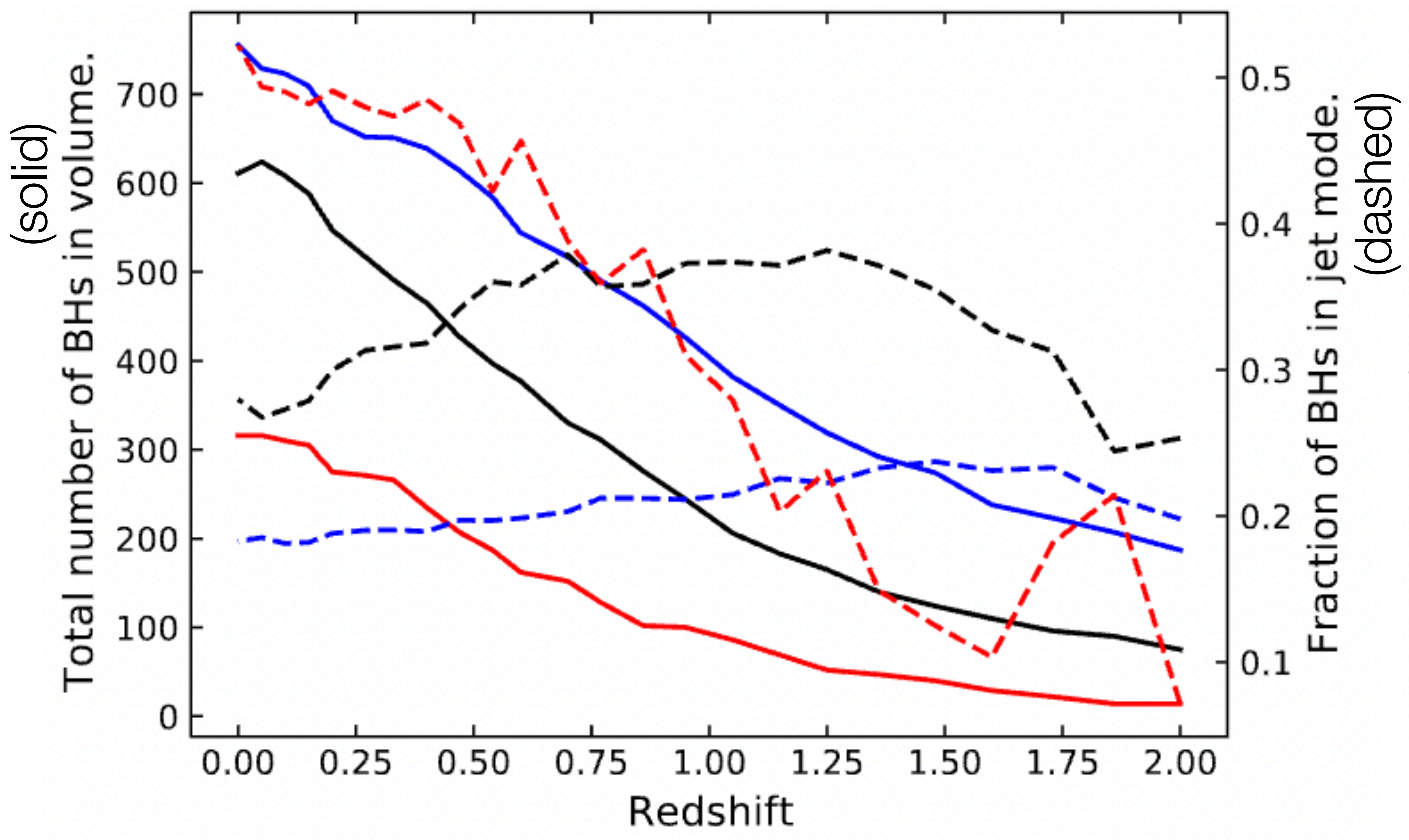
- Number of SMBHs in the simulation - SMBHs are seeded in galaxies with $M_* > 10^{9.5}\ M_\odot$ with mass $10^4\ M_\odot/h$.

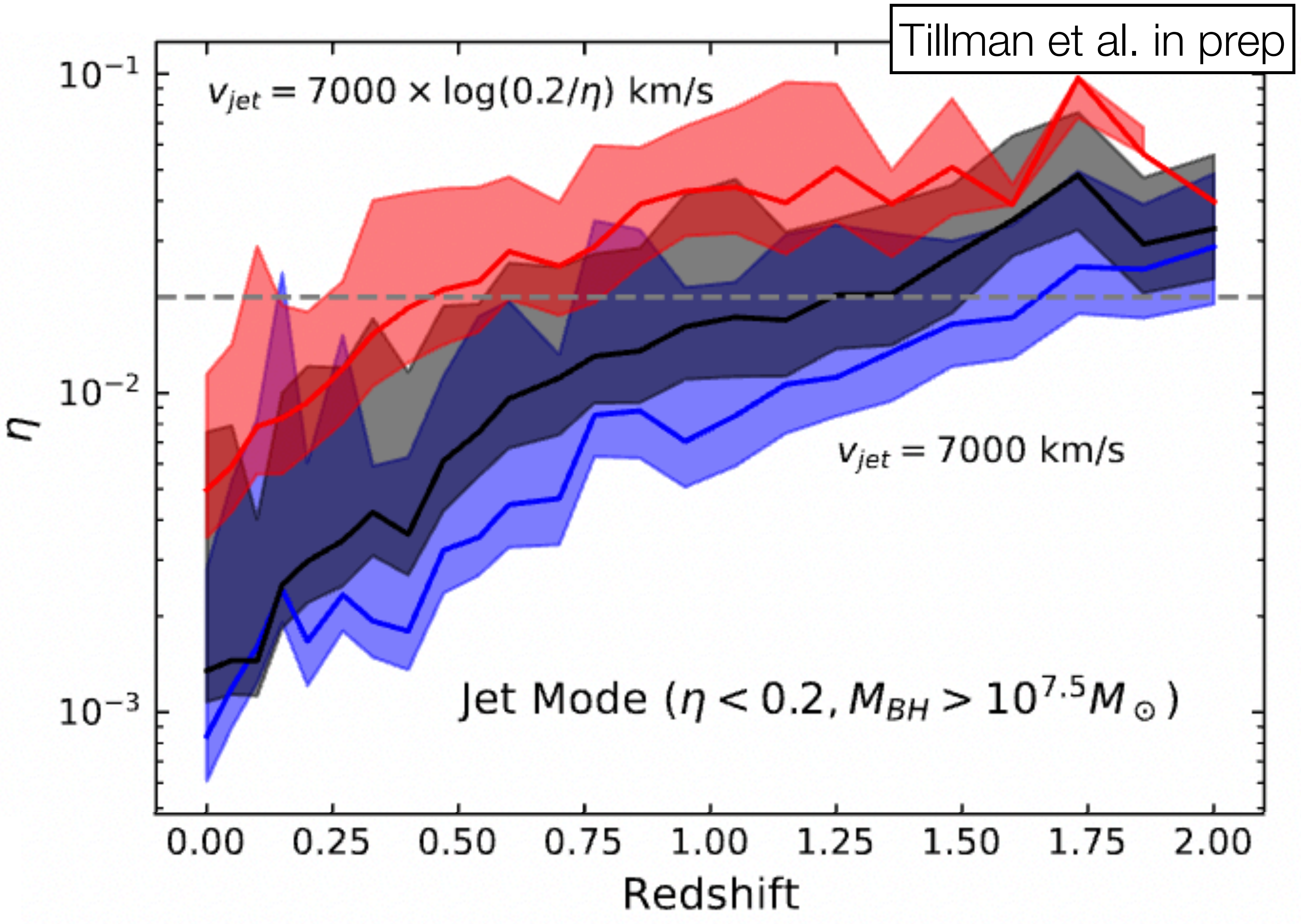
- Fraction of SMBHs in the jet mode - SMBHs with $\eta < 0.2$ and $M_{BH} > 10^{7.5}\ M_\odot$ produce jet mode feedback.

- Average Eddington ratios - Jet speed is calculated based off the Eddington ratio η. The smaller η the larger the jet speed with a cap at $7000\ \mathrm{km/s}$.

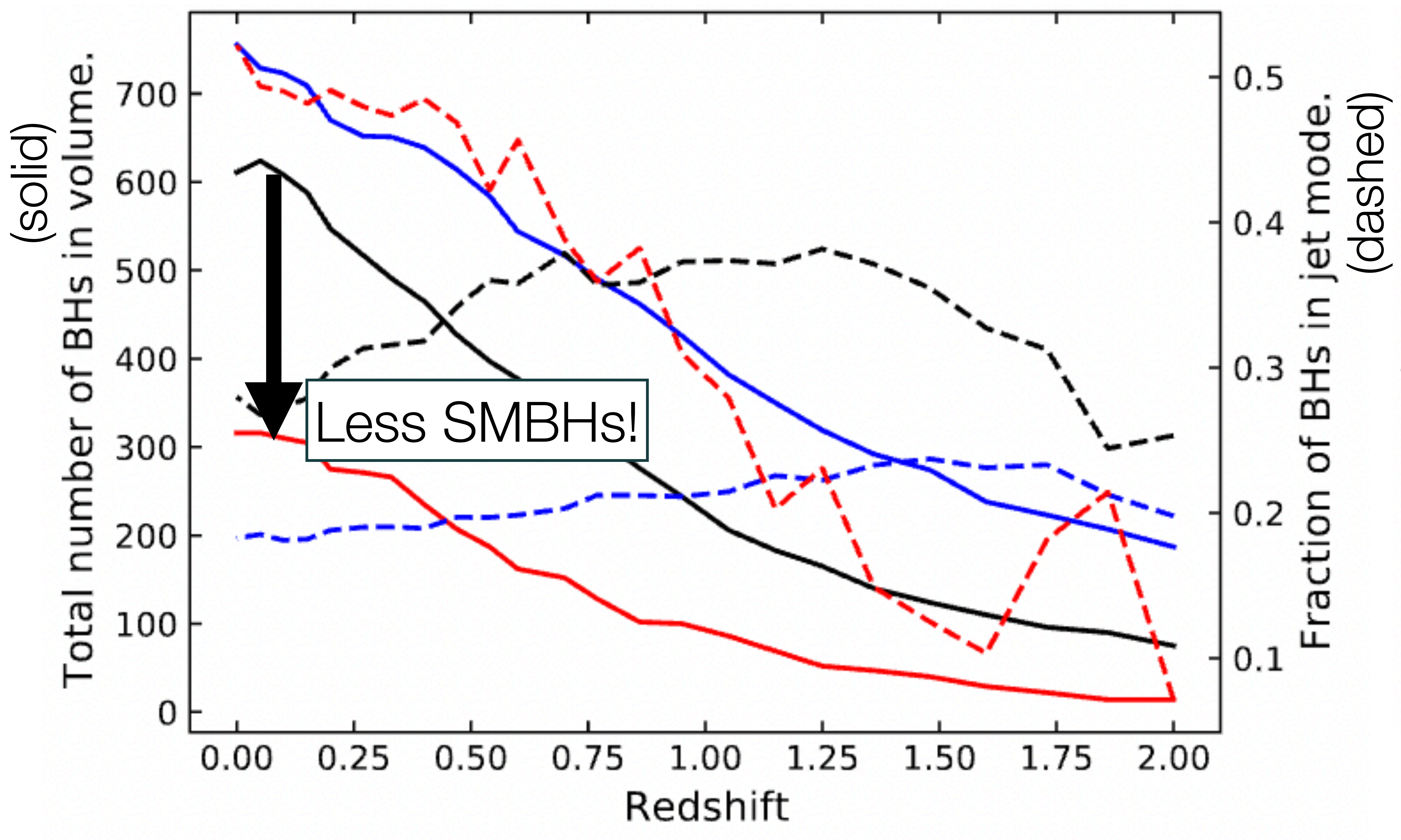
$$\eta = \dot{M}_{BH}/\dot{M}_{Edd}$$

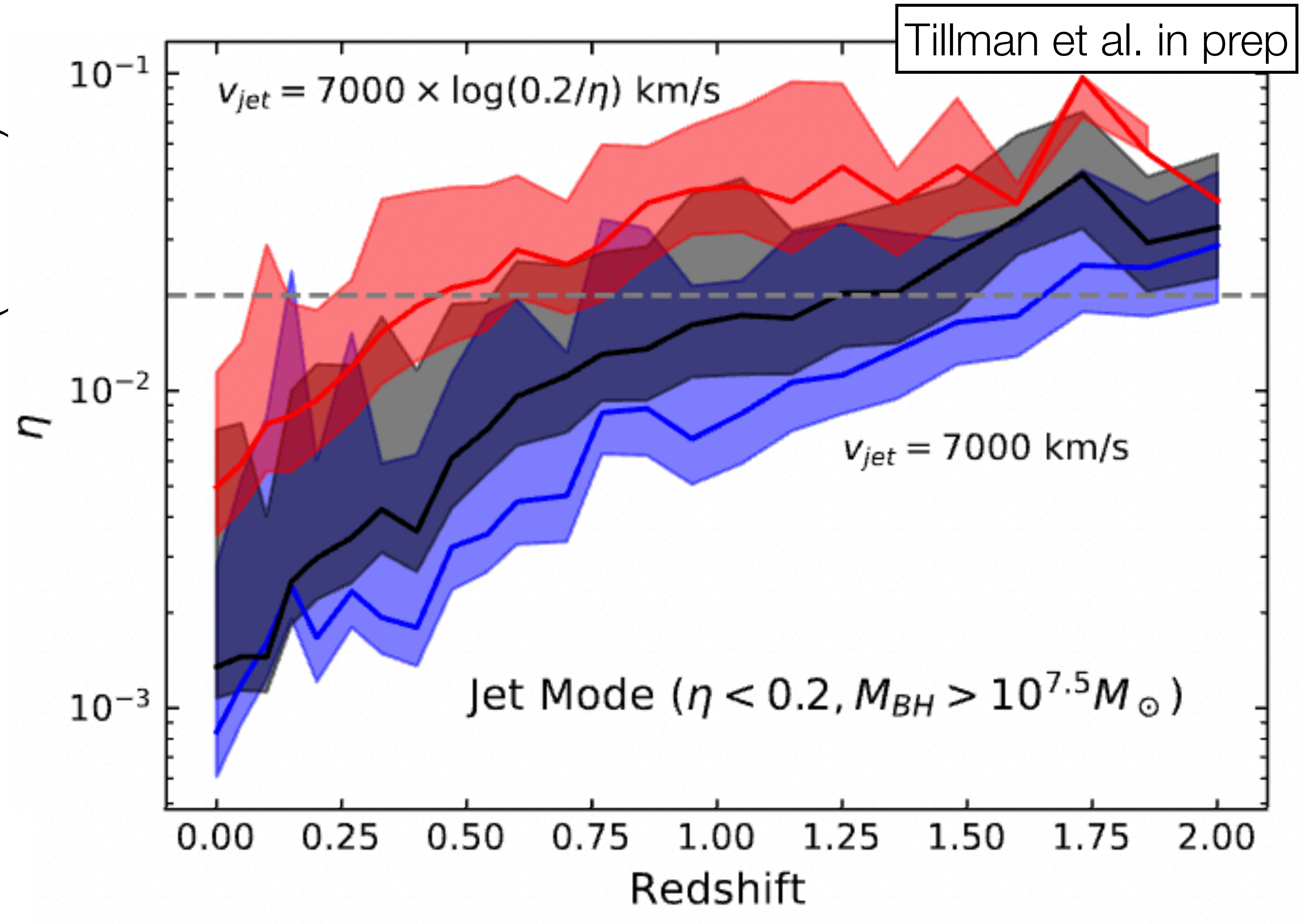
Stellar Feedback Parameter Effects: Mass Loading





Stellar Feedback Parameter Effects: Mass Loading





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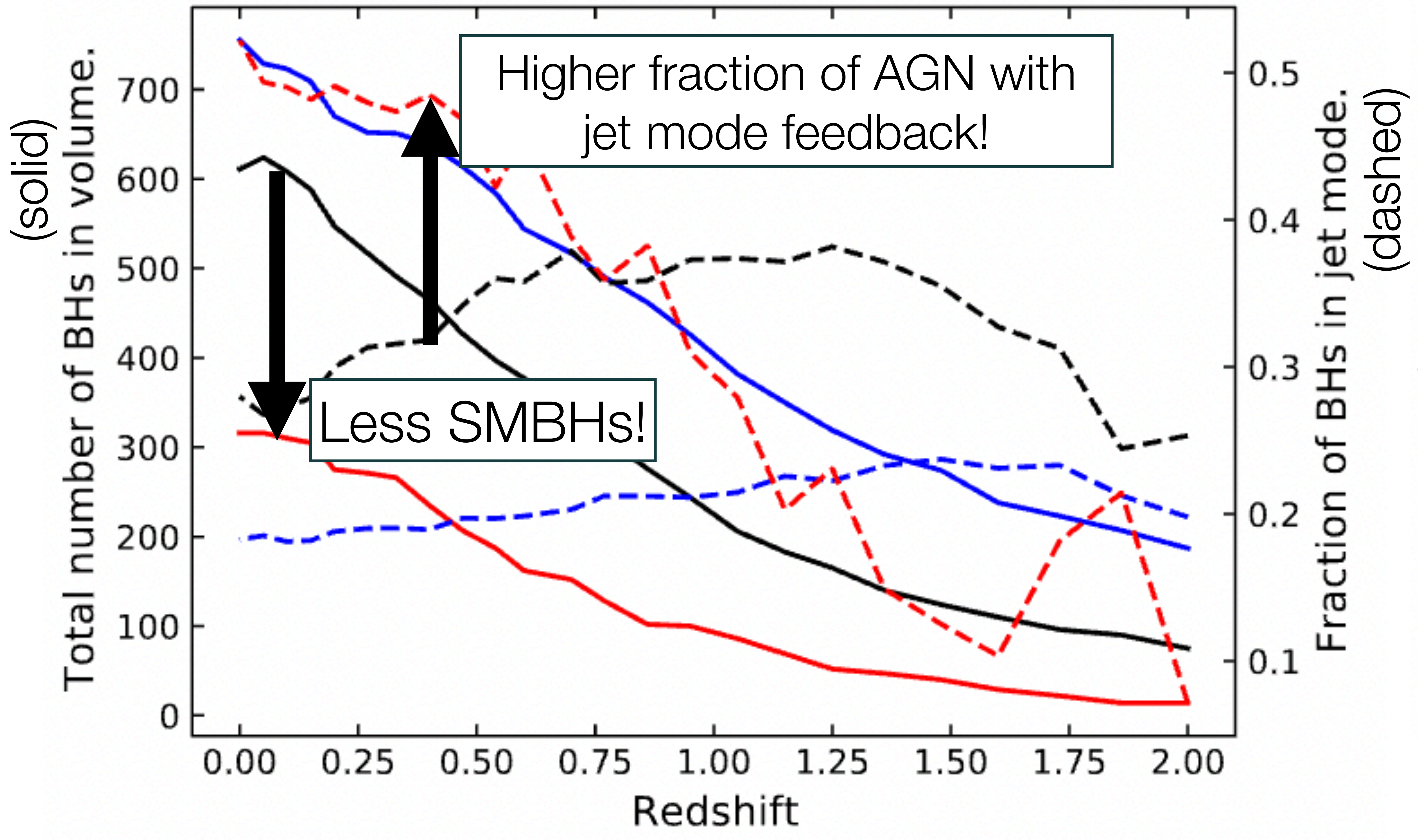

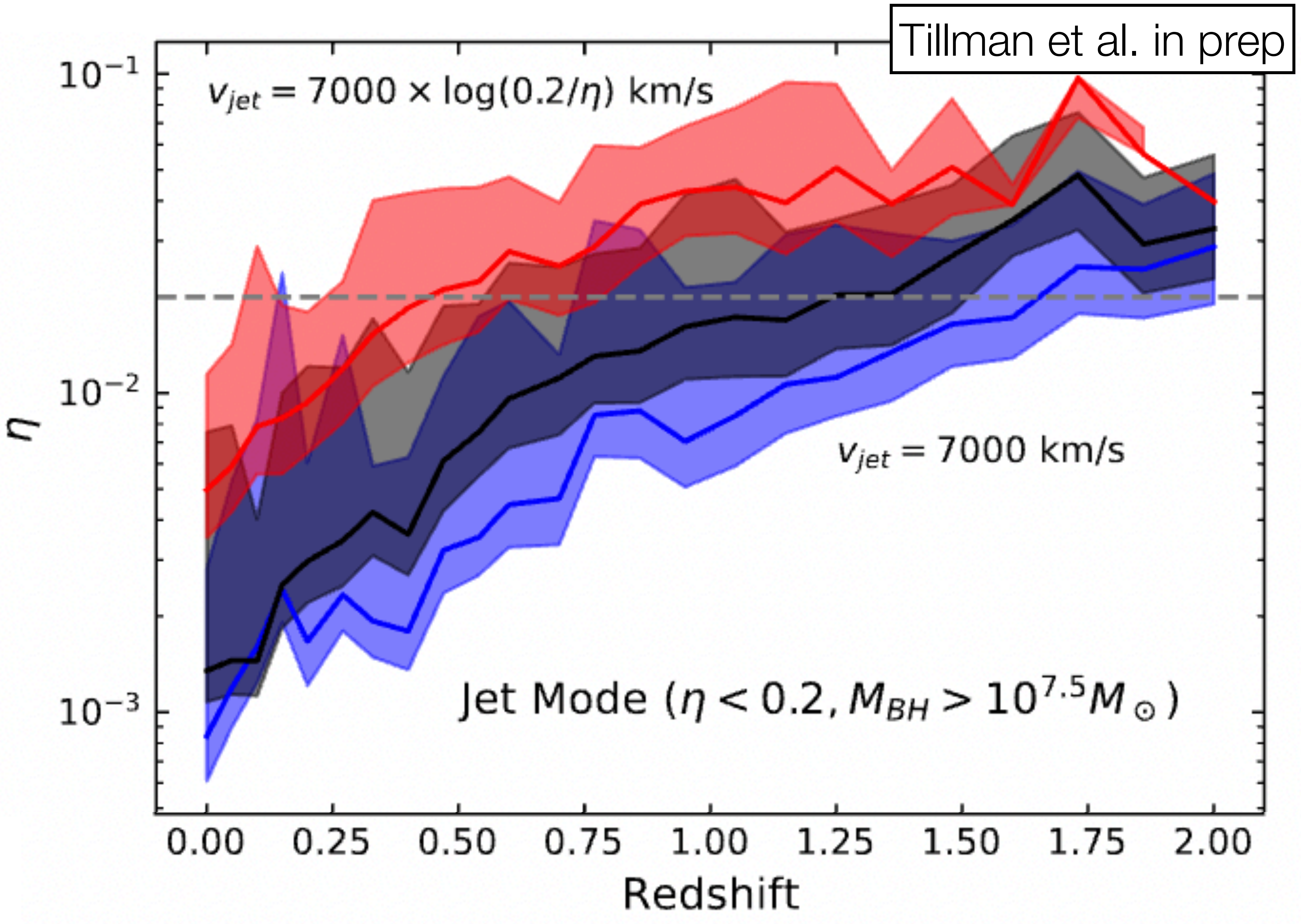

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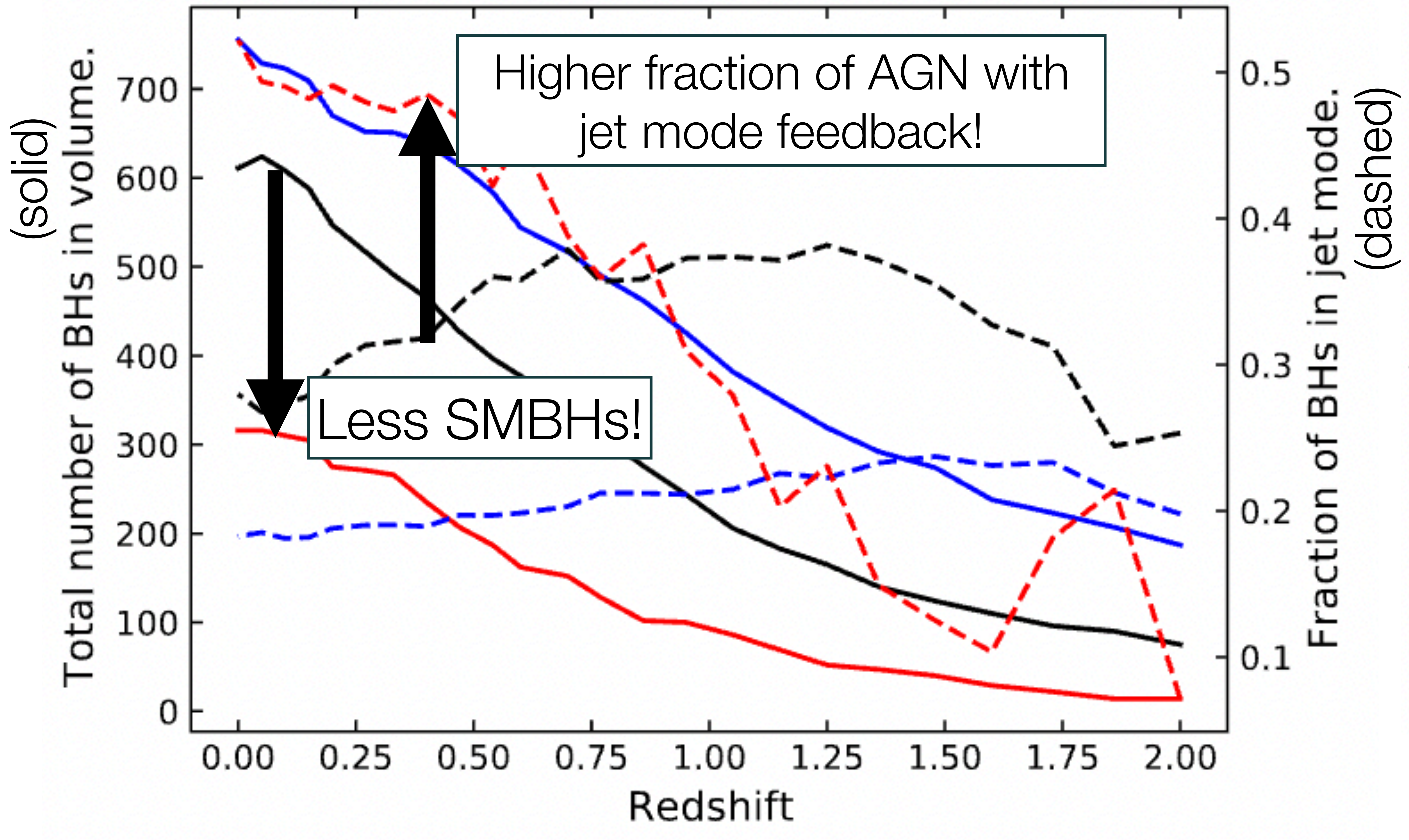

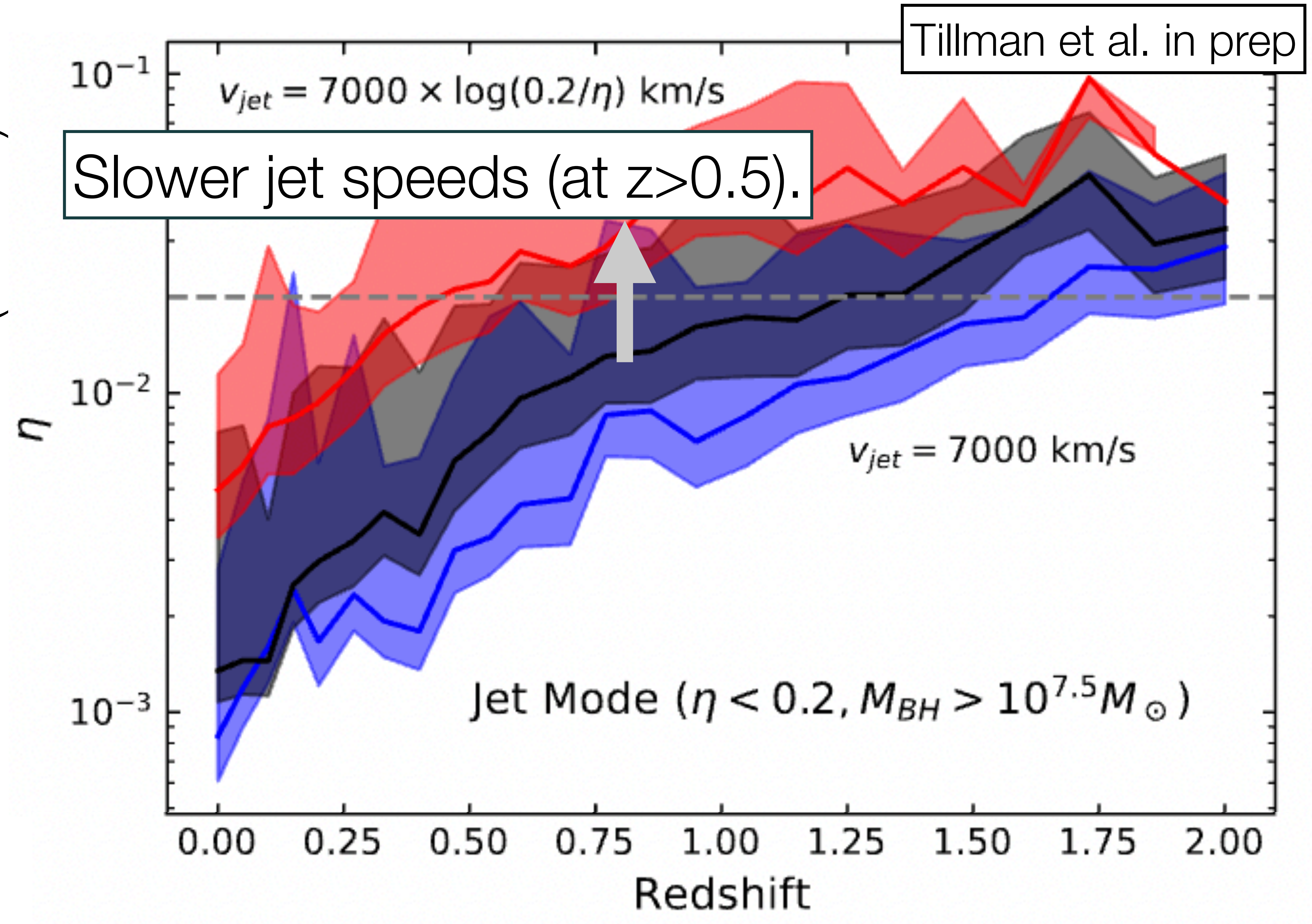

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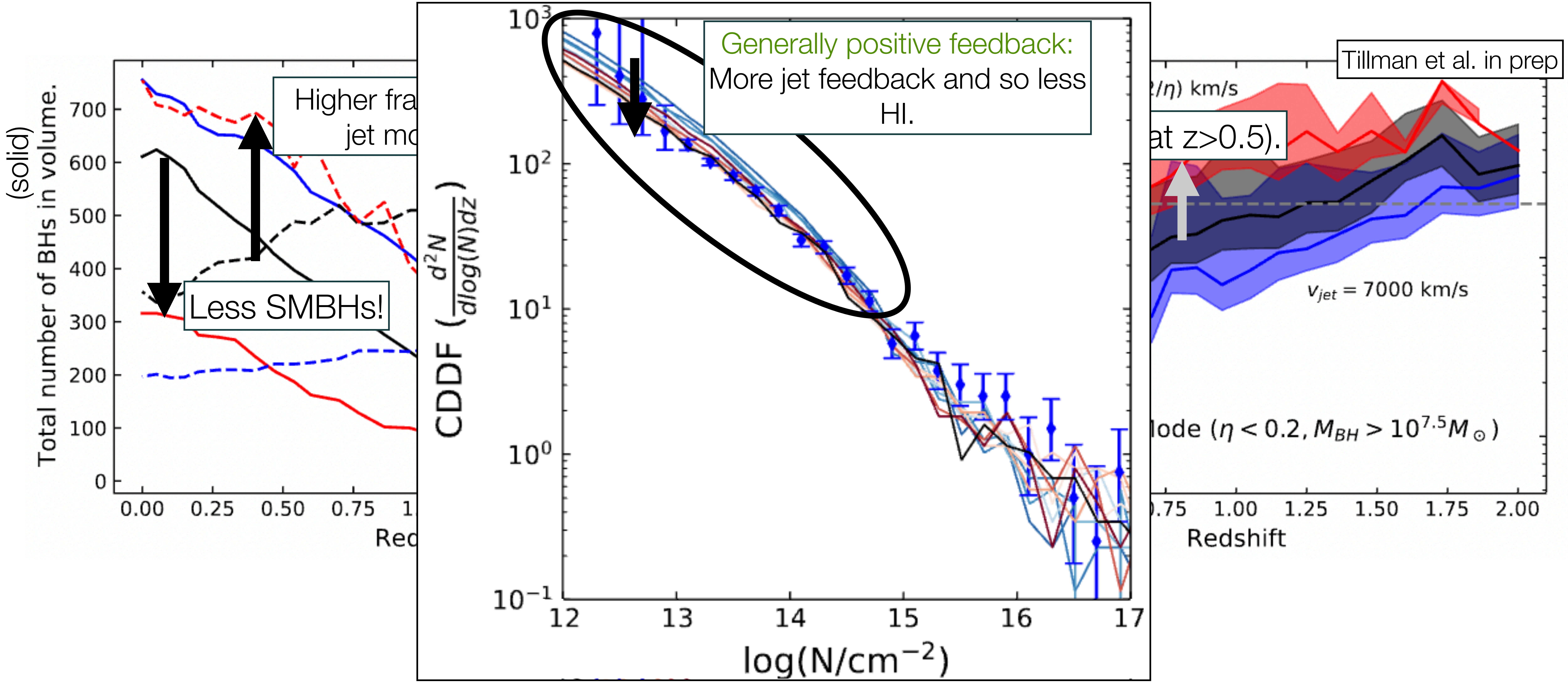
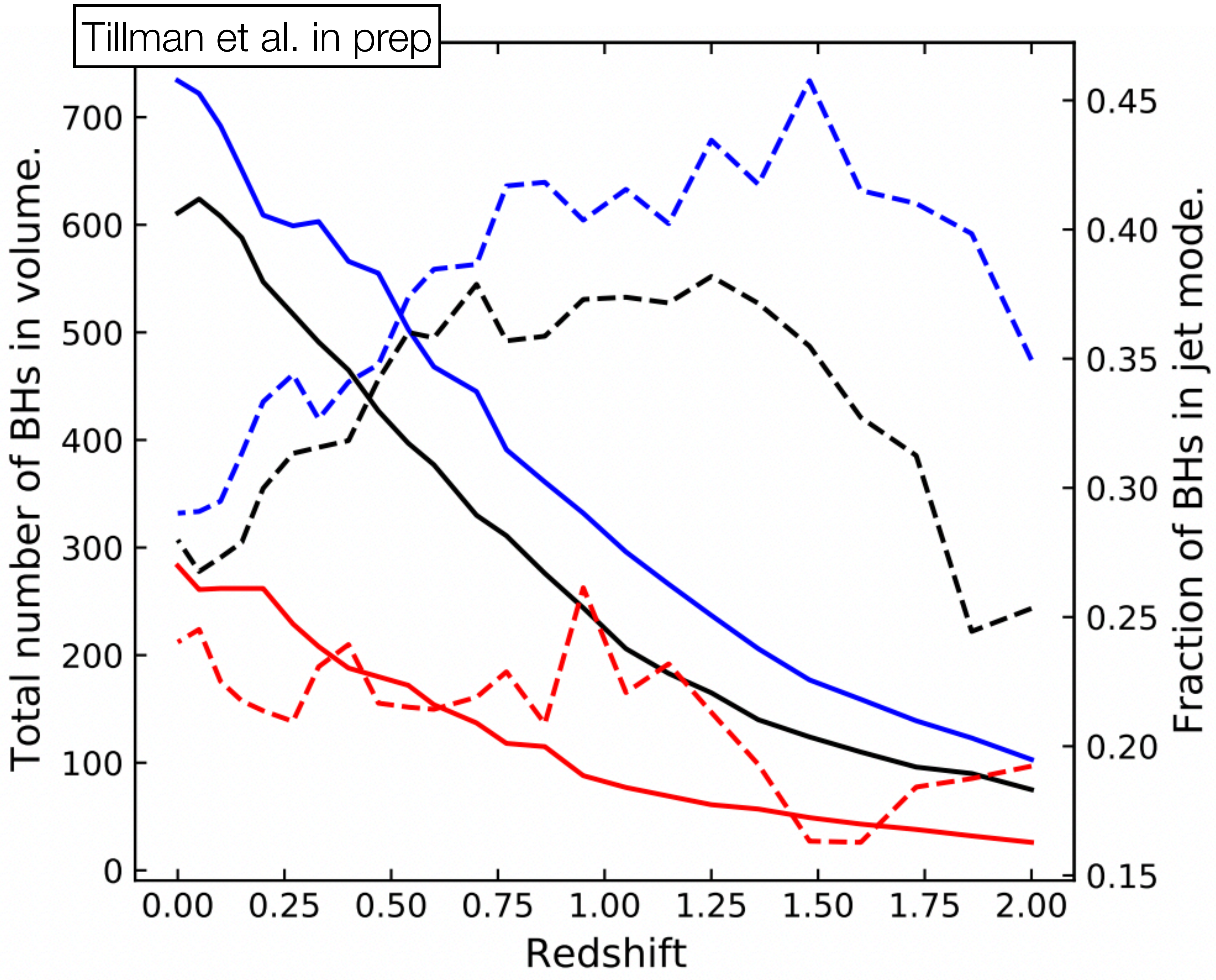


Stellar Feedback Parameter Effects: Wind Speed



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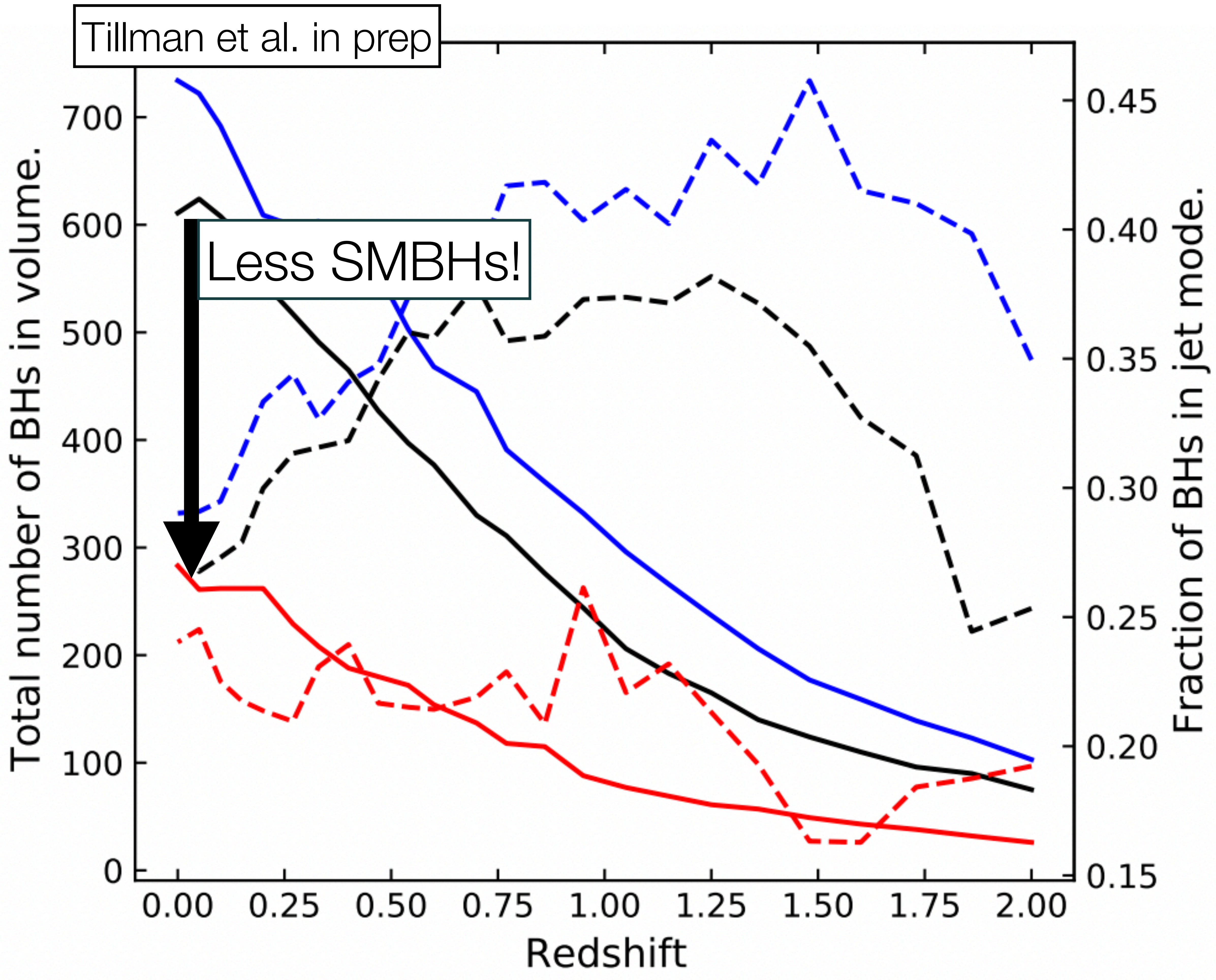

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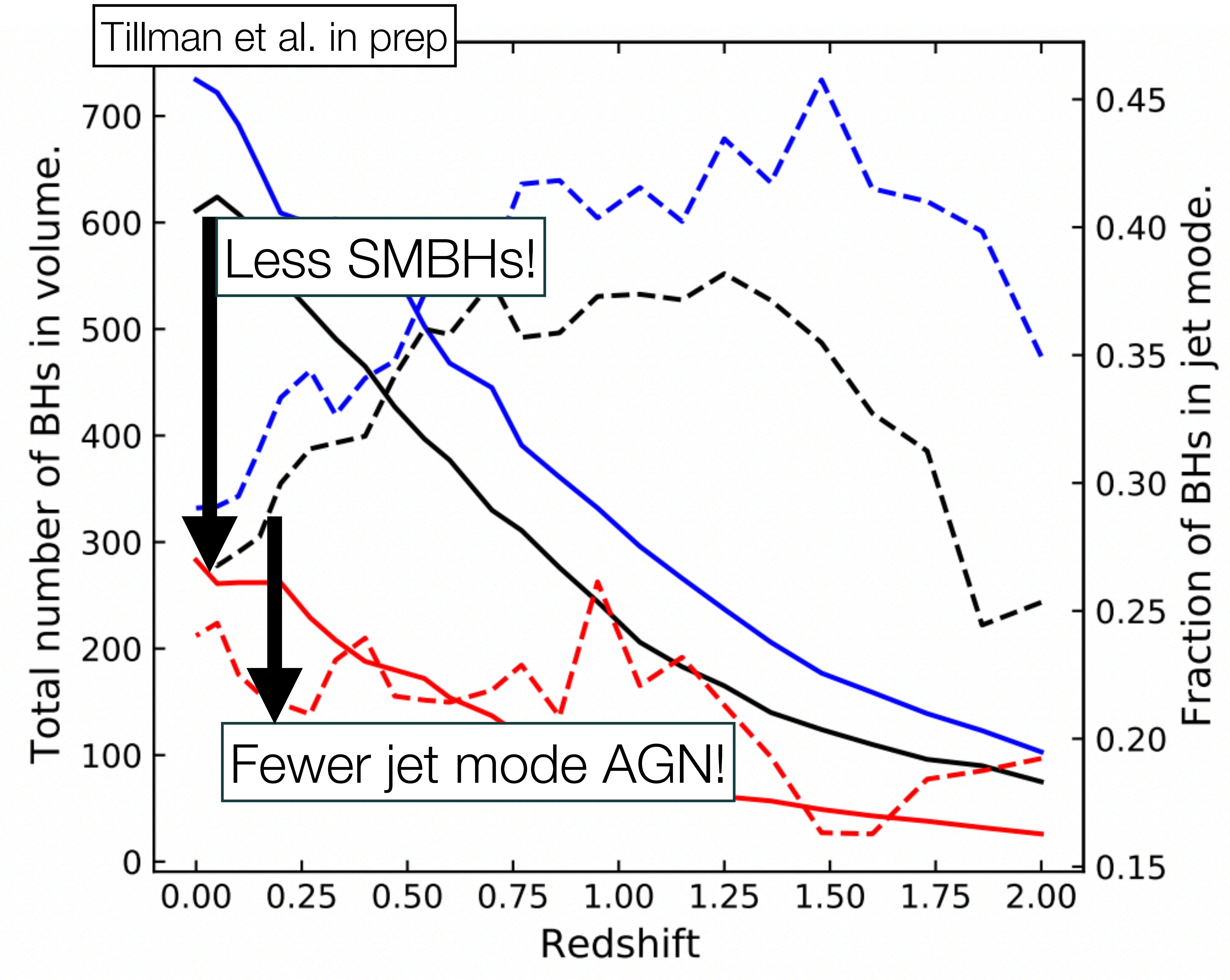

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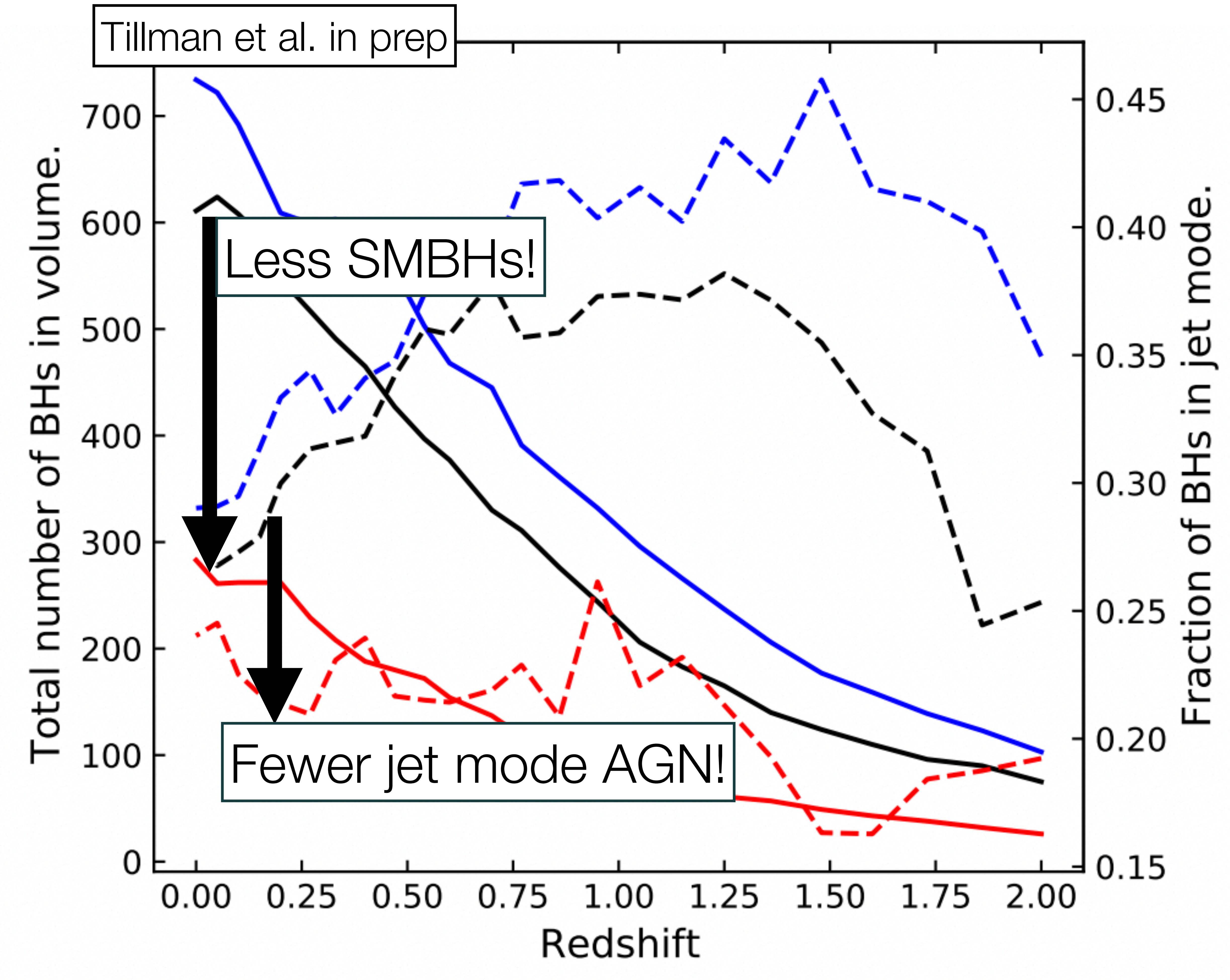
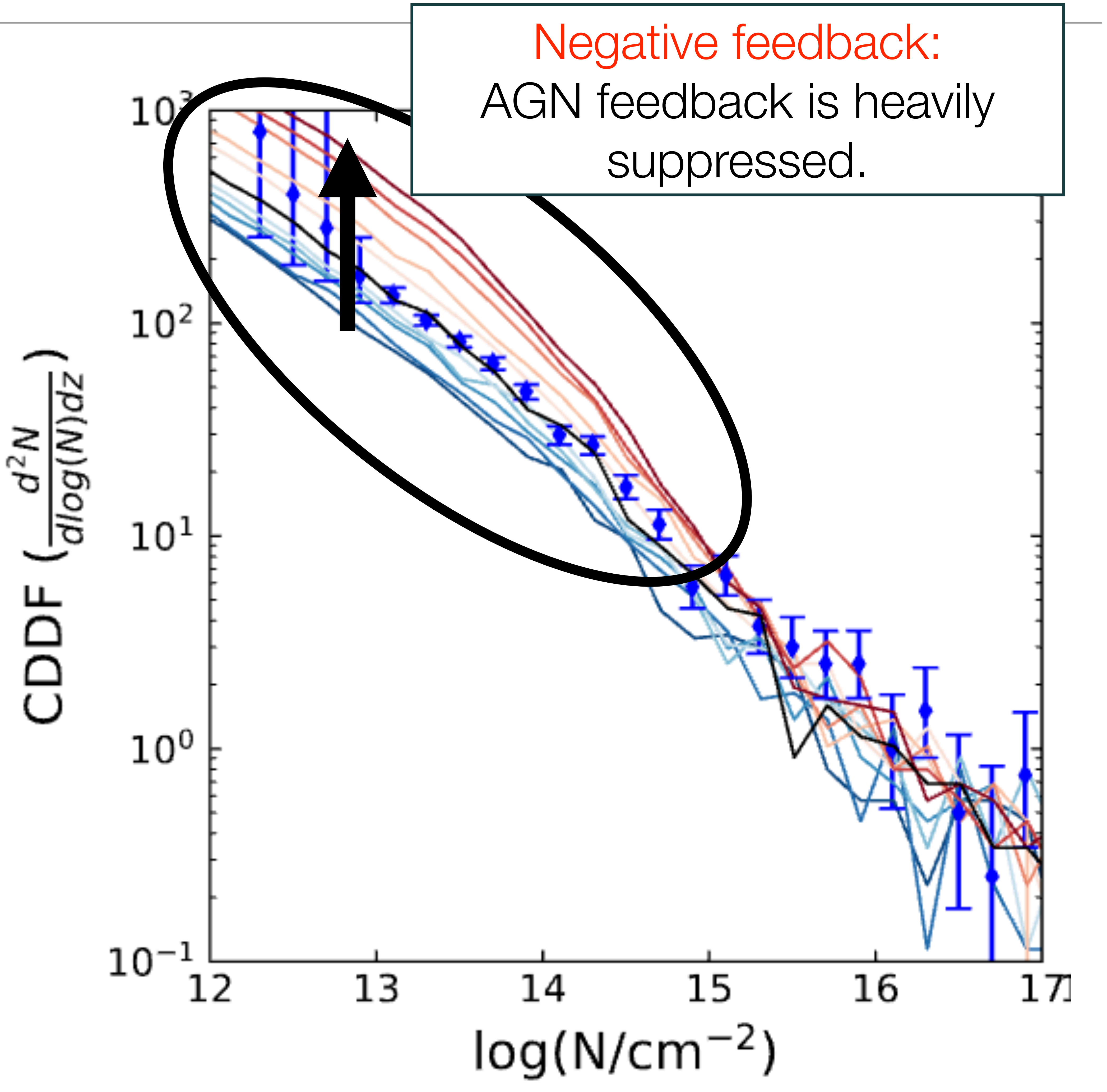
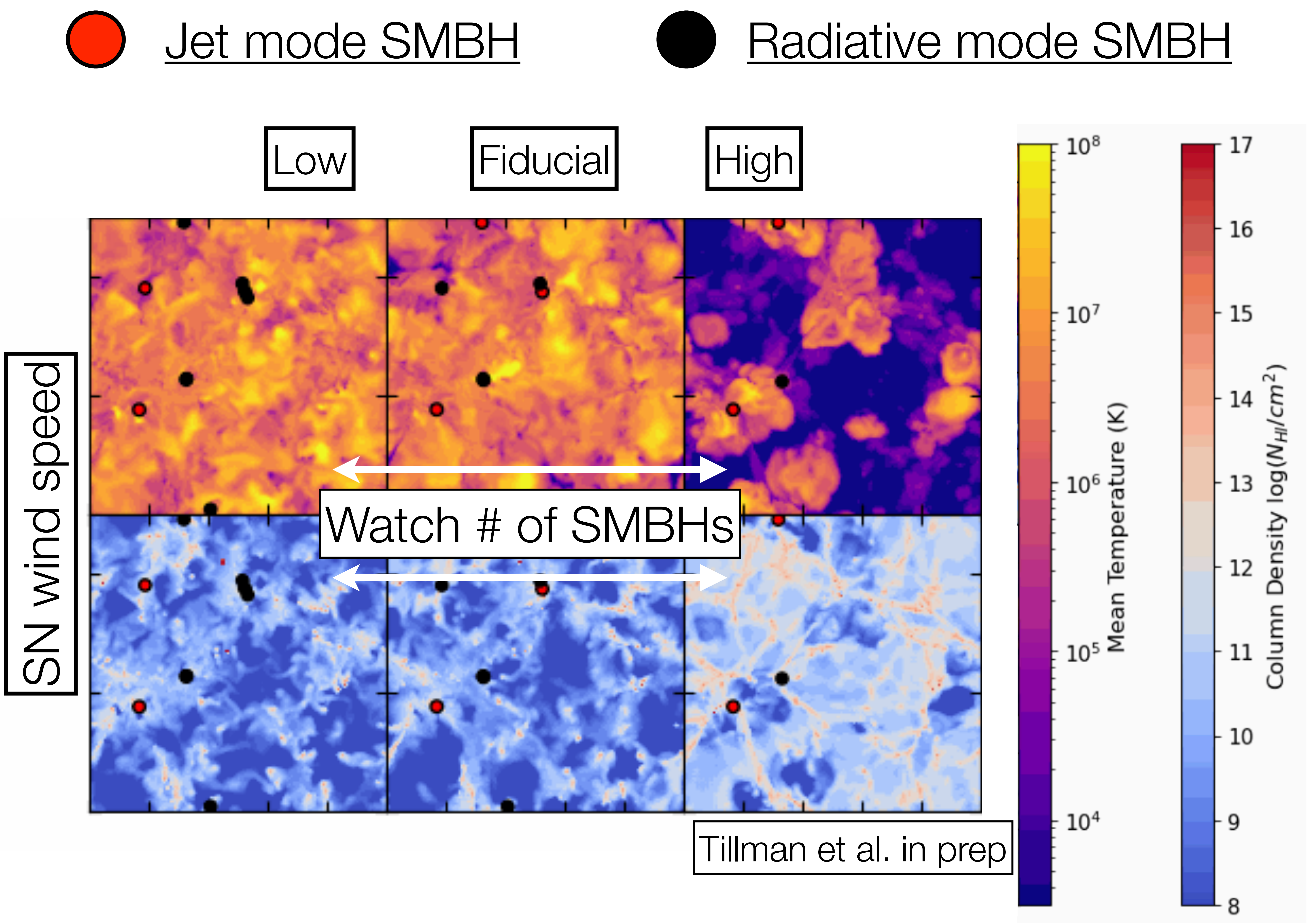





Jet mode SMBH
Radiative mode SMBH
Low
Fiducial
High
SN wind speed
Watch # of SMBHs
Tillman et al. in prep
Mean Temperature (K)
10^8
10^7
10^6
10^5
10^4
Column Density $\log(N_{HI}/cm^2)$
17
16
15
14
13
12
11
10
9
8

Conclusions and Outlook

AGN **Jet** Feedback can have a significant, and unique (from the UVB), effect on the low-z Lyman-α forest.

- Exploration of current and new AGN jet feedback models could be vital for the forest and further observations are needed for constraint.

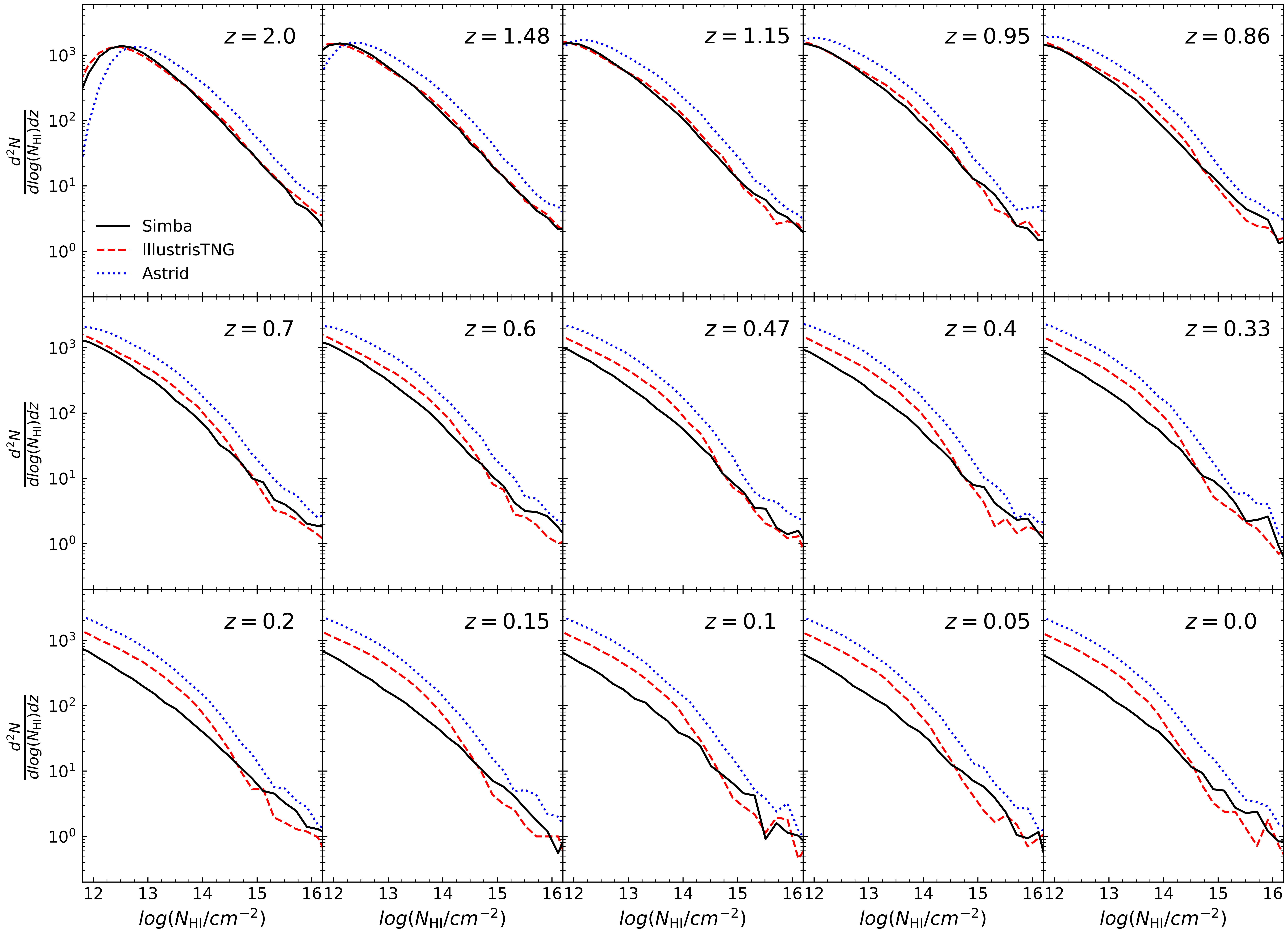
In order for jets to be effective in hydrodynamic cosmological simulations, certain conditions must be met.

- Dampening in particular is a huge issue for low resolution galaxies.

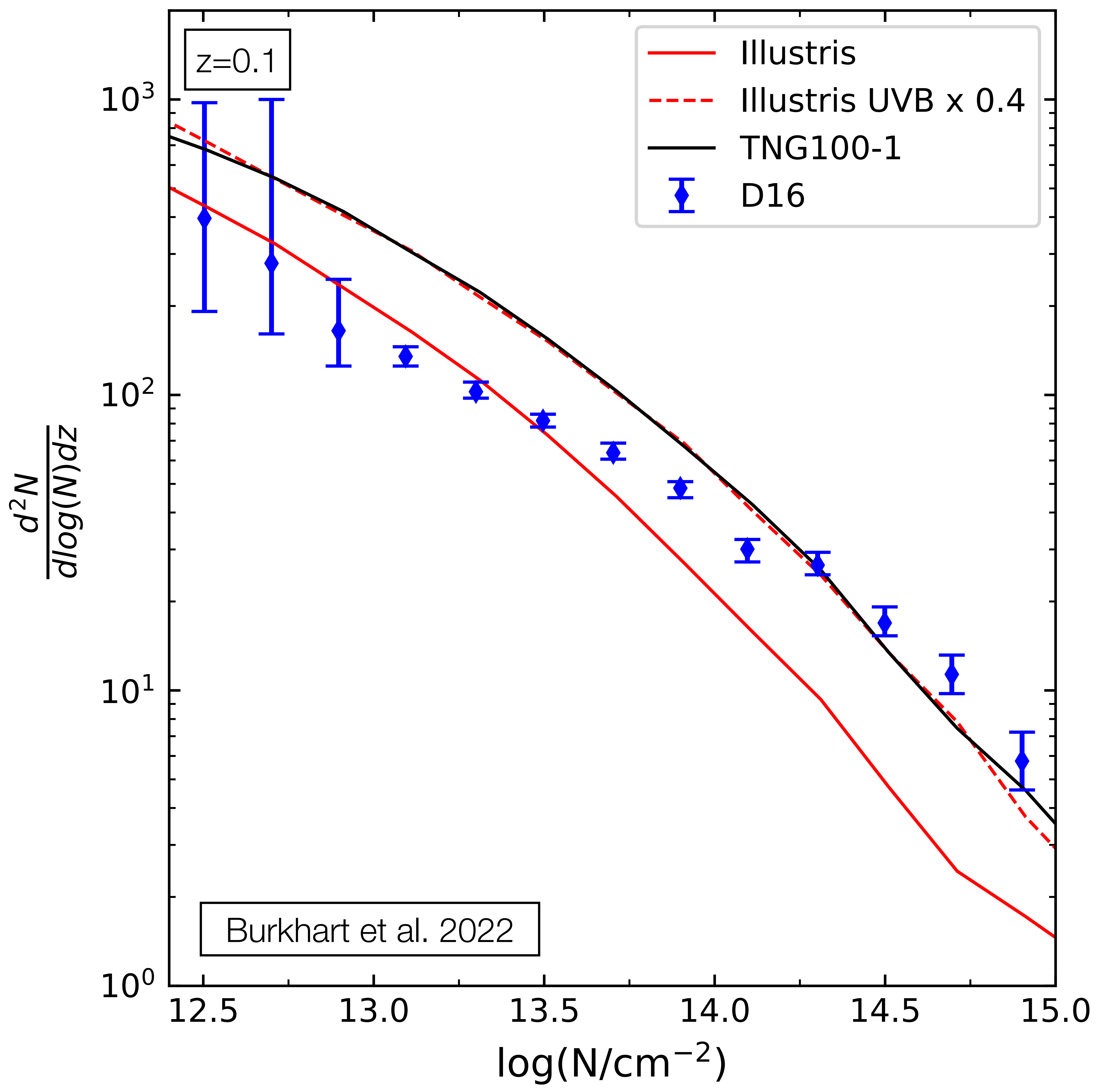
The CAMELS project provides a unique opportunity to explore stellar and AGN feedback by applying ML techniques.

- e.g. predicting the temperature density relation from Lyα statistics with ML, done before with MCMC (Hiss et al. 2019).

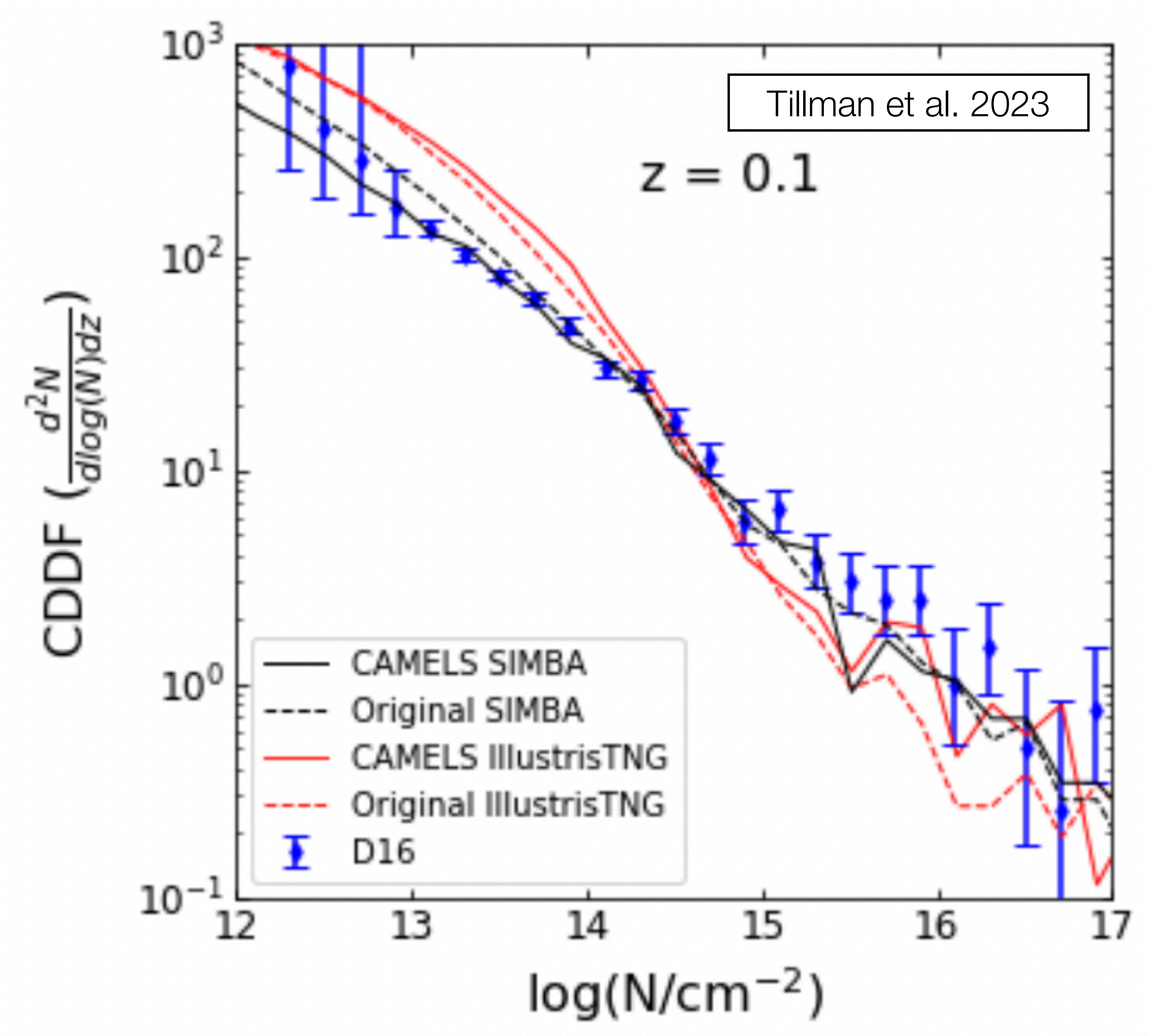
Extra Slides



z = 2.0
z = 1.48
z = 1.15
z = 0.95
z = 0.86
z = 0.7
z = 0.6
z = 0.47
z = 0.4
z = 0.33
z = 0.2
z = 0.15
z = 0.1
z = 0.05
z = 0.0
Simba
IllustrisTNG
Astrid
$\frac{d^2N}{dlog(N_{HI})dz}$
$log(N_{HI}/cm^{-2})$
10^0 10^1 10^2 10^3
12 13 14 15 16



z=0.1
Illustris
Illustris UVB x 0.4
TNG100-1
D16
Burkhart et al. 2022
$\frac{d^2N}{dlog(N)dz}$
$\log(N/cm^{-2})$
10^0
10^1
10^2
10^3
12.5
13.0
13.5
14.0
14.5
15.0


Tillman et al. 2023
z = 0.1
CDDF ($\frac{d^2N}{dlog(N)dz}$)
log(N/cm^{-2})
CAMELS SIMBA
Original SIMBA
CAMELS IllustrisTNG
Original IllustrisTNG
D16
10^3
10^2
10^1
10^0
10^{-1}
12
13
14
15
16
17

Jet mode SMBH

Radiative mode SMBH