EAGLE's HI Universe

Cold gas in calibrated cosmological simulations of galaxy formation

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Liverpool John Moores University

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THE
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SOCIETY

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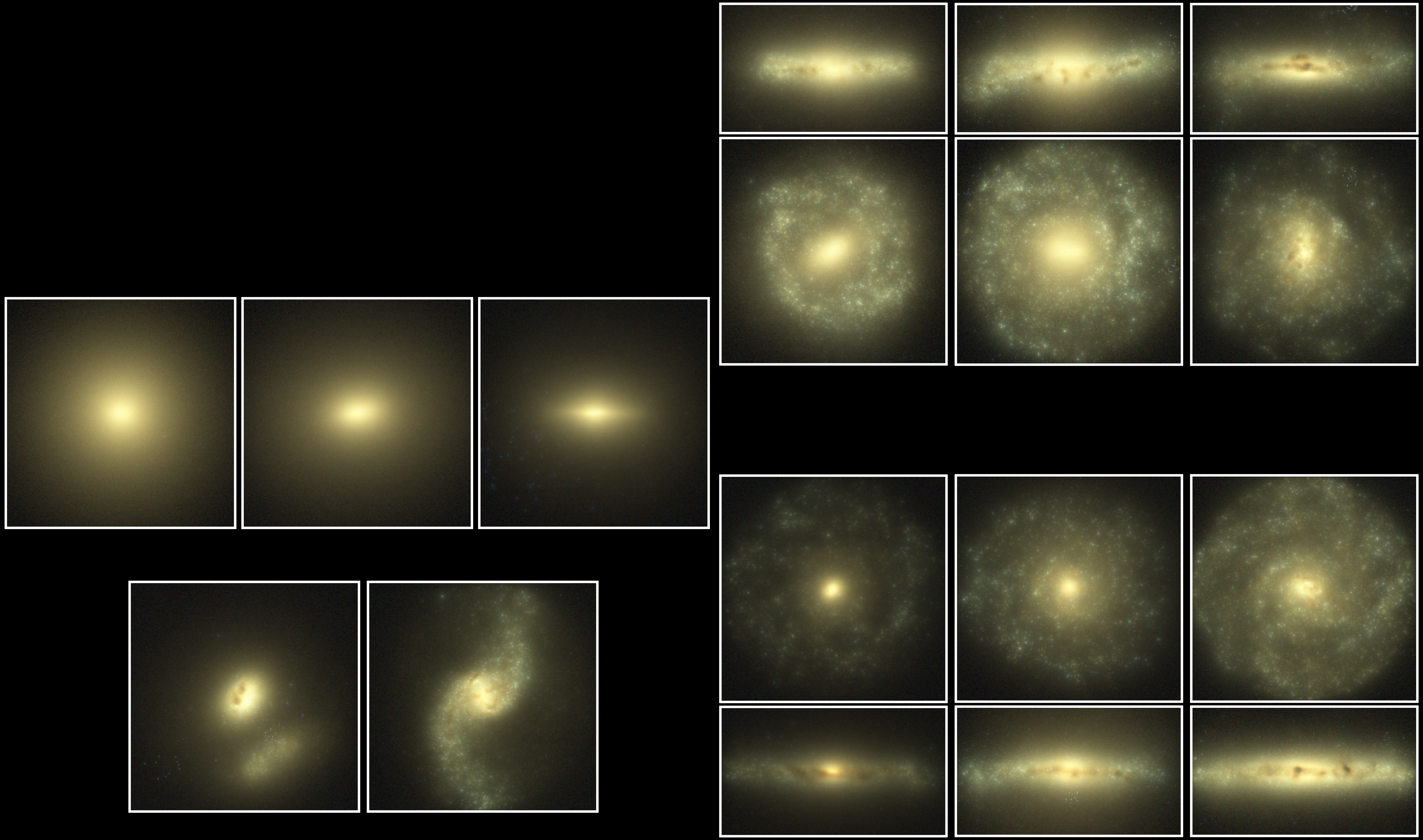
Major progress in cosmological simulations in recent years

It is possible to produce a realistic galaxy population in a LCDM Universe with energetically-feasible feedback.



Schaye, RAC+ (2015)

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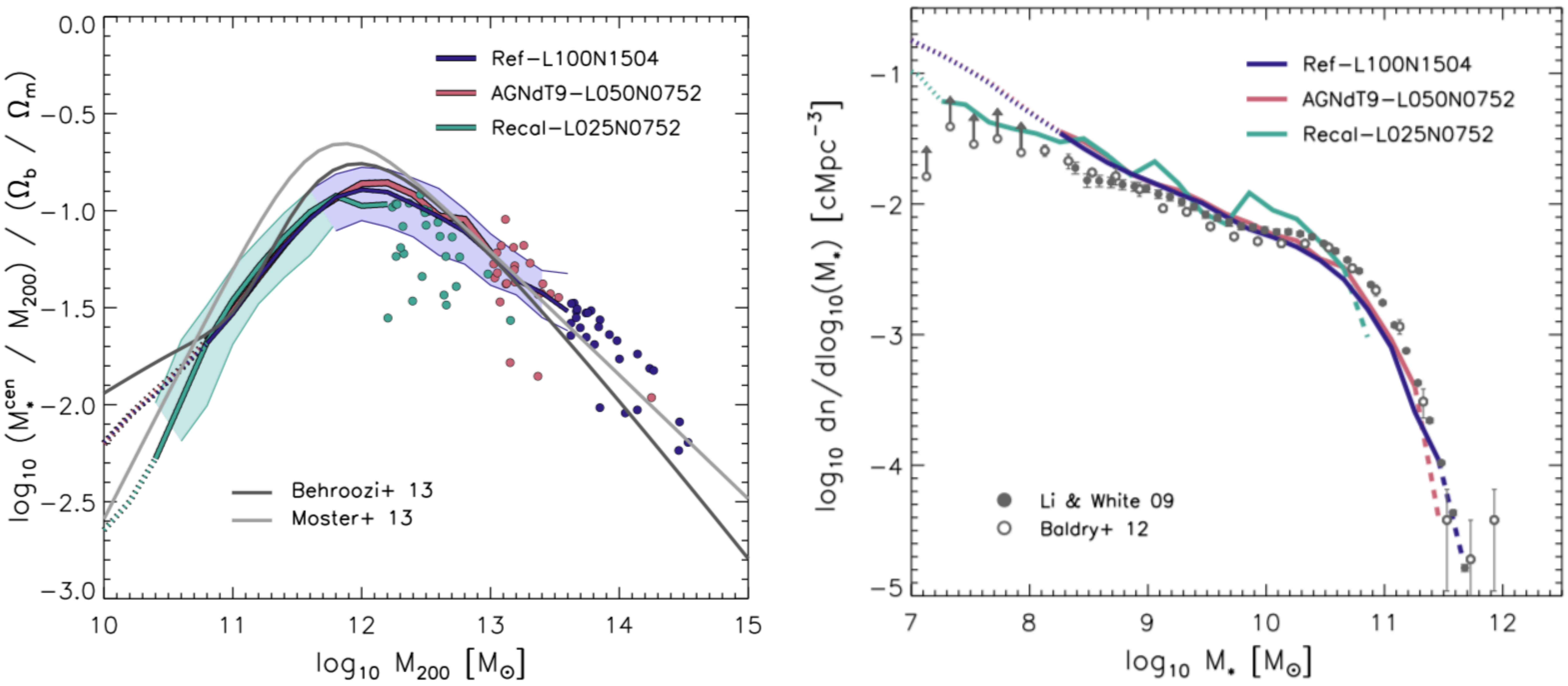
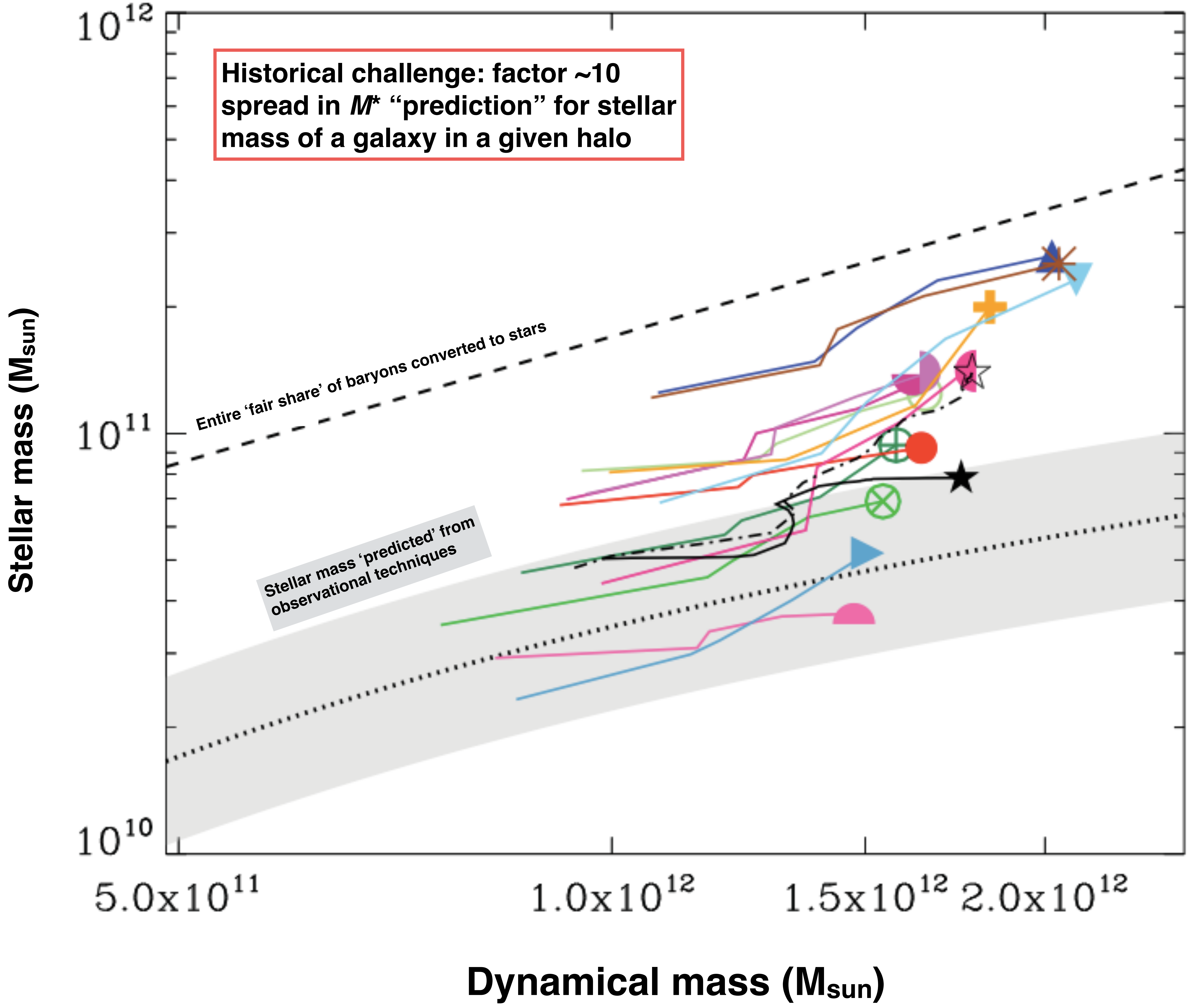


These simulations reproduce the observed galaxy stellar mass function (GSMF) and by construction broadly reproduce the M*-M200 relation.

Schaye, RAC+ (2015)



Historical challenge: factor ~10 spread in *M "prediction" for stellar mass of a galaxy in a given halo**

Scannapieco, RAC+ (2012)

Gas inflow = star formation + gas outflow

Gas outflow

Star formation

Gas inflow

NASA/JPL-Caltech/STScI/
CXC/UofA/ESA/AURA/JHU

BH accretion = BH growth + rest mass-driven outflow

Consequences of these equations.

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To predict the stellar mass of galaxies, we need to *know* the efficiency of the SF-driven feedback.

To predict the black hole mass of galaxies, we need to *know* the efficiency of AGN feedback.

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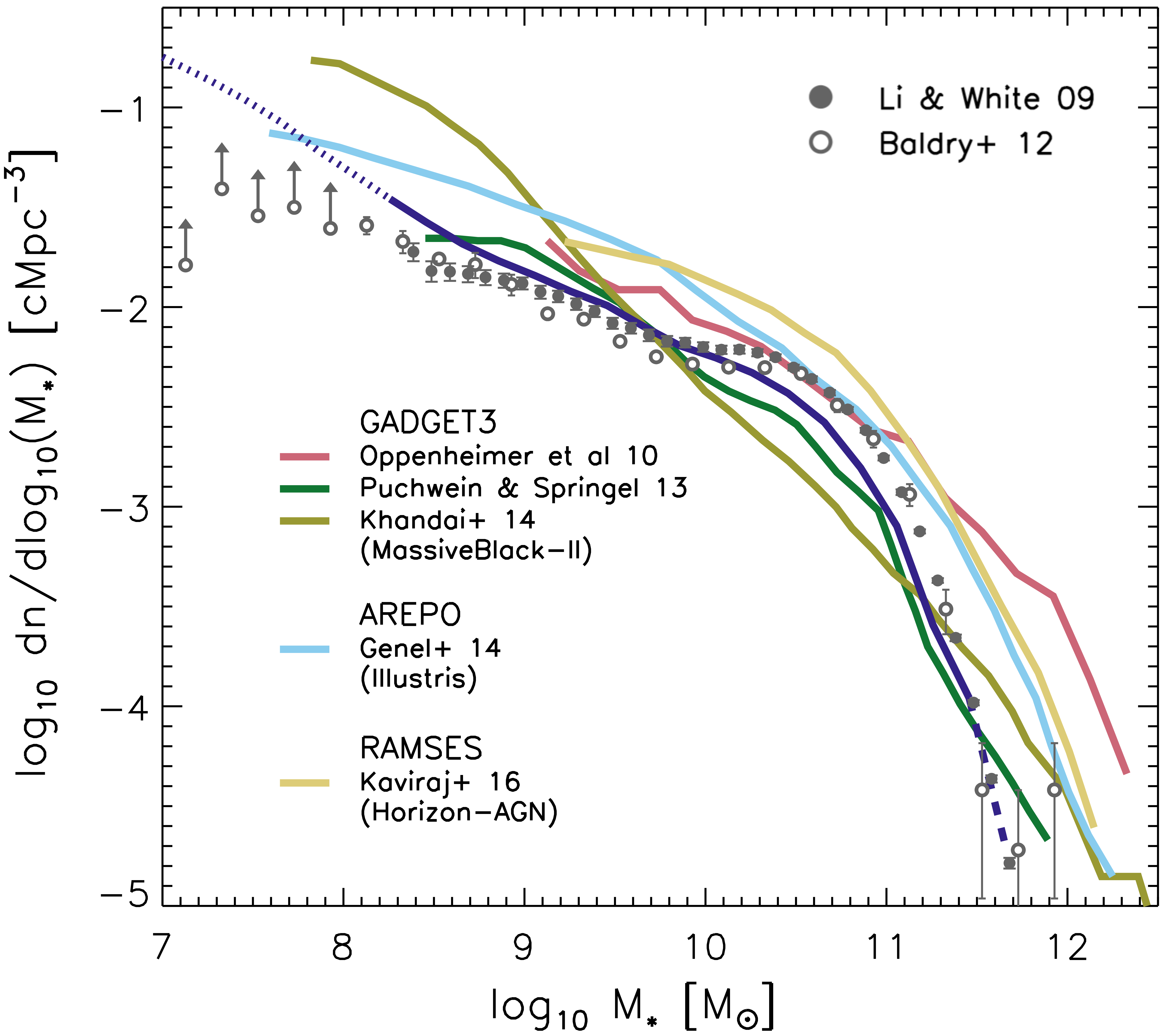
To predict the stellar mass of galaxies, we need to *know* the efficiency of the SF-driven feedback.

To predict the black hole mass of galaxies, we need to *know* the efficiency of AGN feedback.

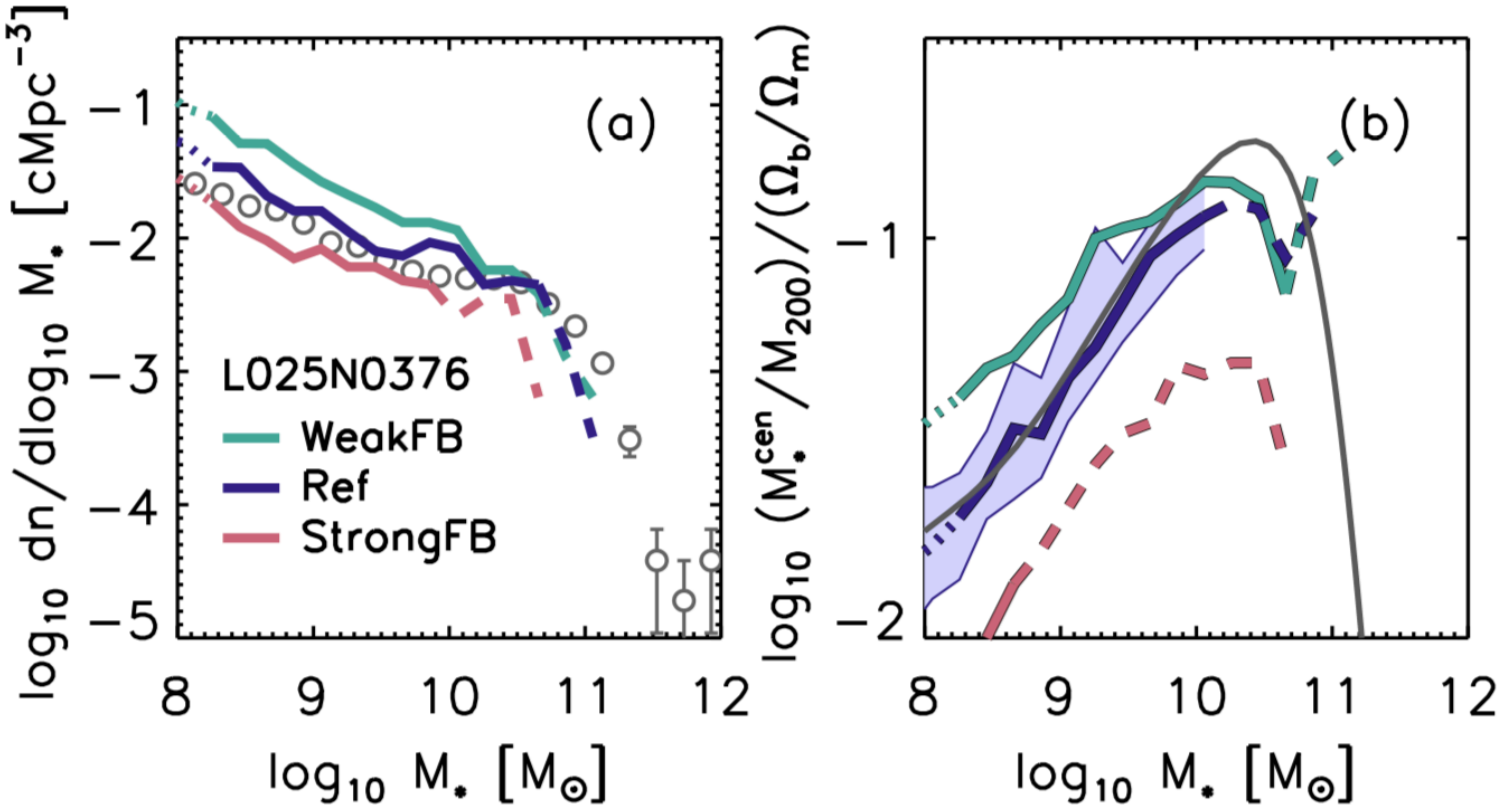
The efficiencies are determined by ISM microphysics: ab initio calculation is way beyond the scope of current simulations.

The only recourse is to calibrate the efficiencies, c.f. EAGLE, Horizon-AGN, Illustris.


Li & White 09
Baldry+ 12
GADGET3
Oppenheimer et al 10
Puchwein & Springel 13
Khandai+ 14
(MassiveBlack−II)
AREPO
Genel+ 14
(Illustris)
RAMSES
Kaviraj+ 16
(Horizon−AGN)
−1
−2
−3
−4
−5
7
8
9
10
11
12
$\log_{10}$ dn/d$\log_{10}$(M$_*$) [cMpc^{-3}]
$\log_{10}$ M$_*$ [M$_\odot$]

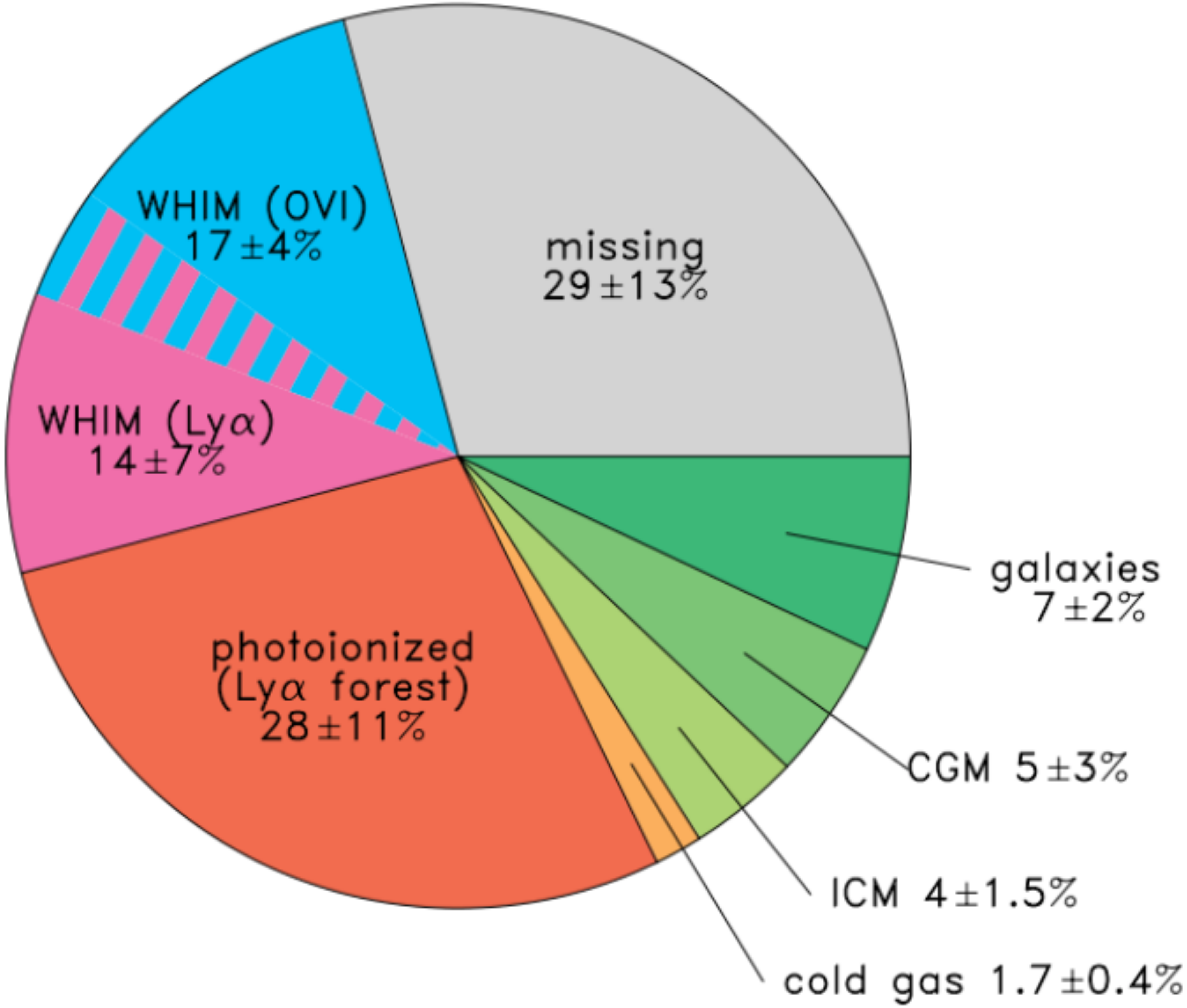
Major progress in cosmological simulations in recent years

The calibration of feedback efficiencies is a necessary evil

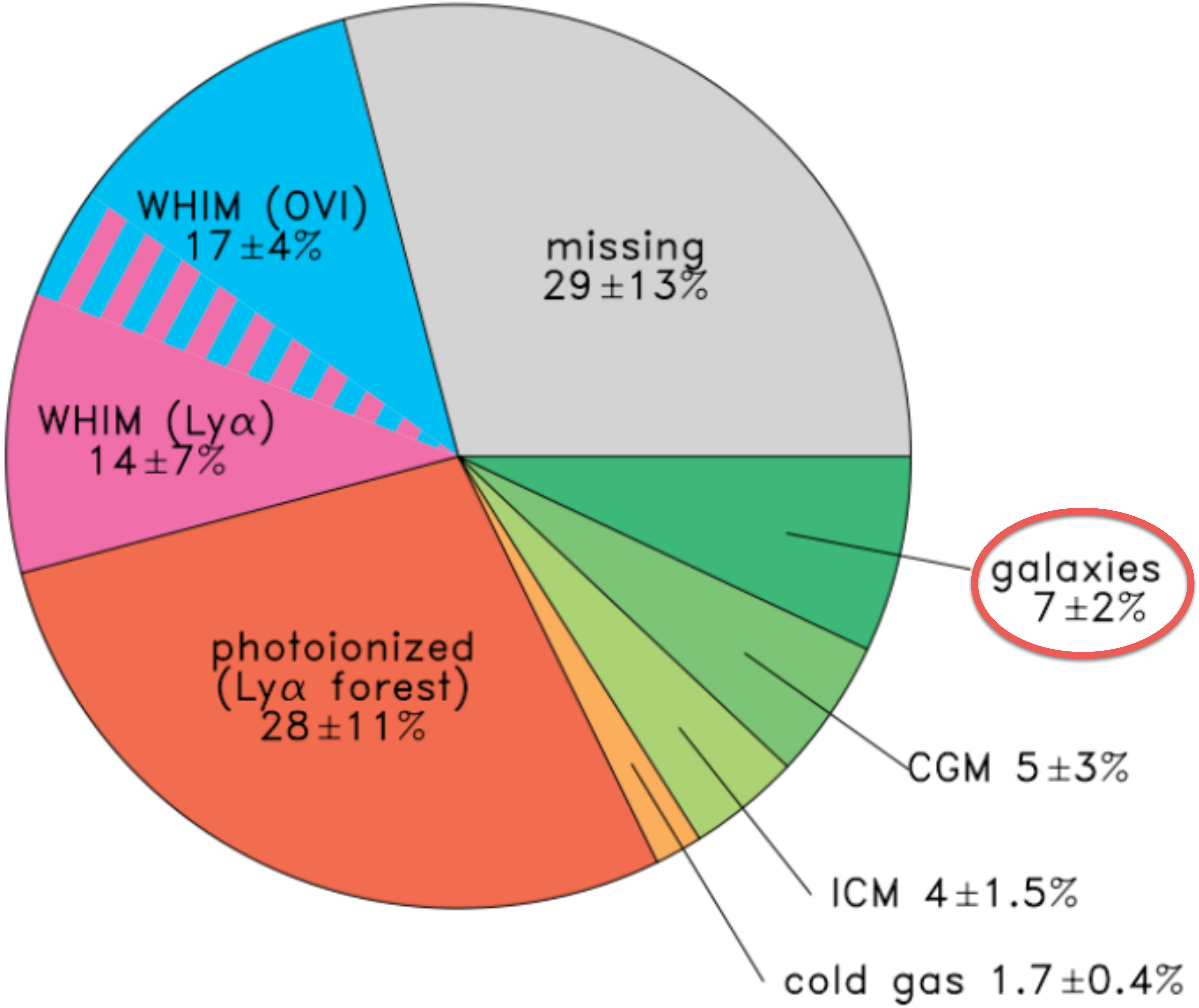


Dialling the feedback to 50% or 200% of fiducial efficiency dramatically alters the galaxy population, also in size, morphology, colour, SF history…

RAC+ (2015)

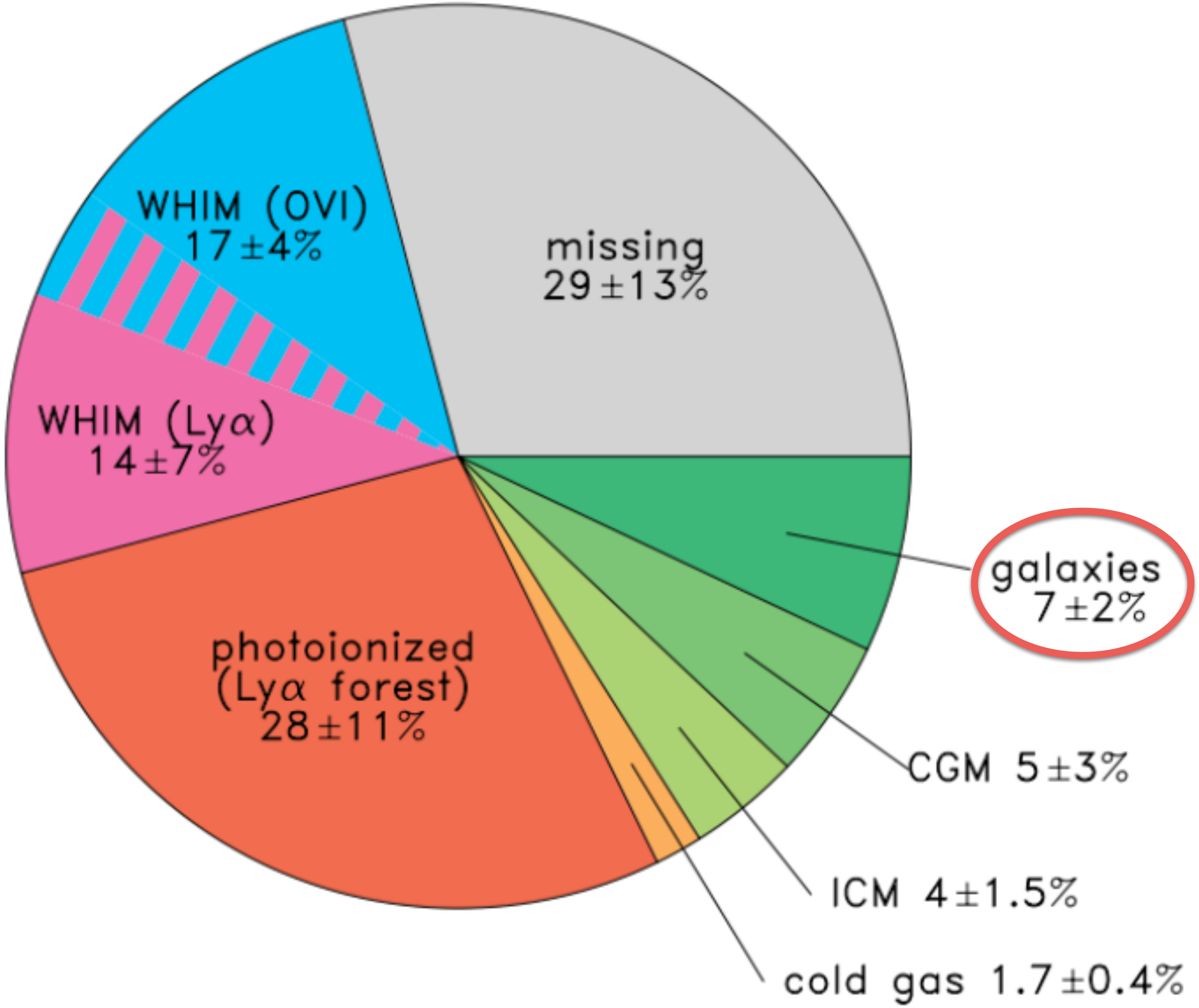


Shull, Smith & Danforth (2012)



Shull, Smith &
Danforth (2012)

Having calibrated feedback using only the stars, gas properties are effectively "predictions".



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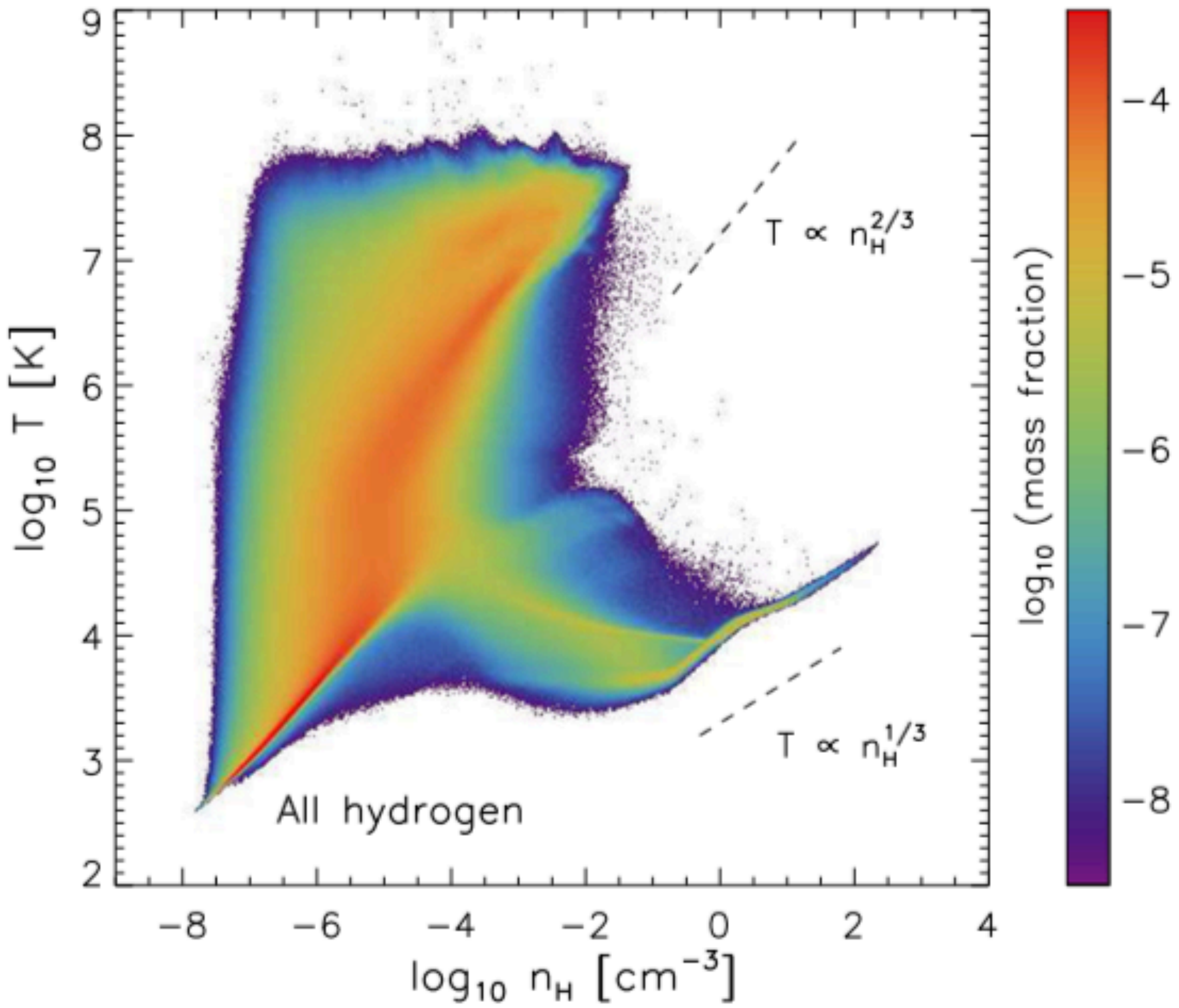
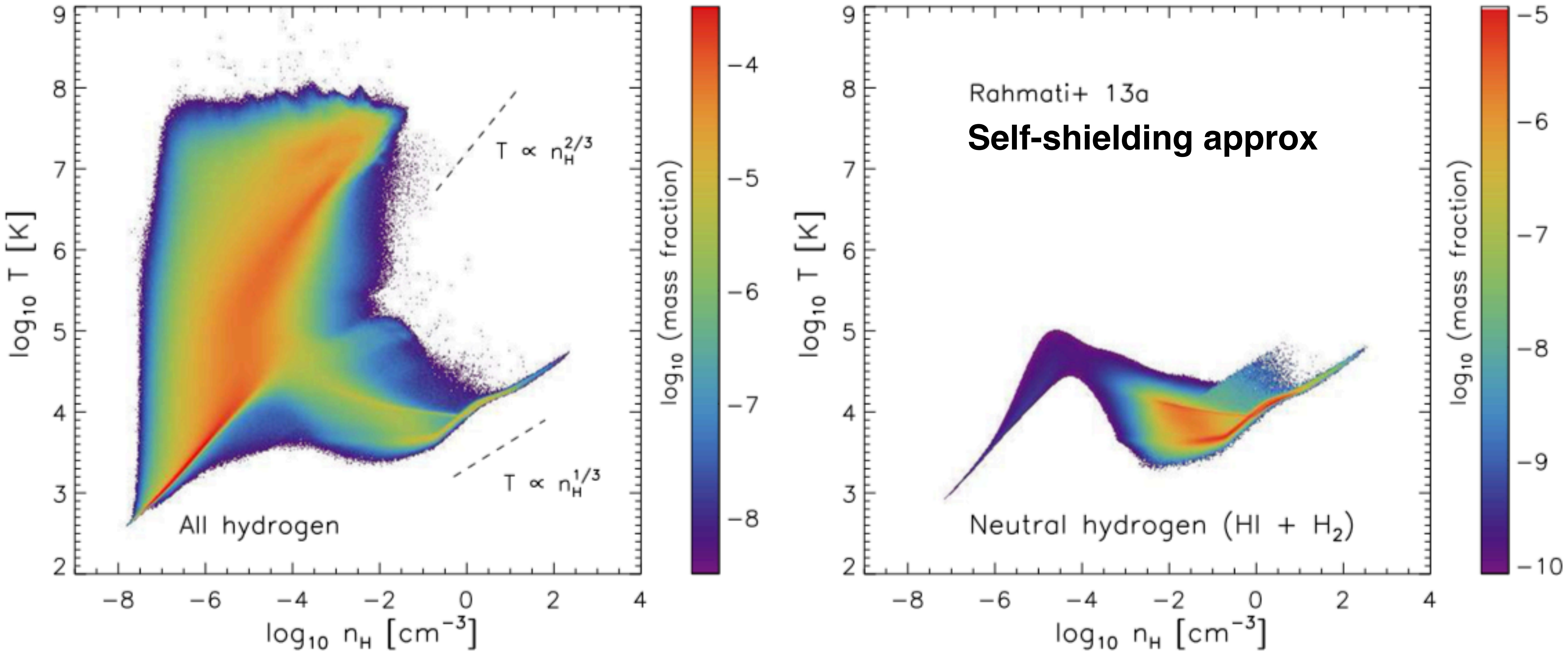
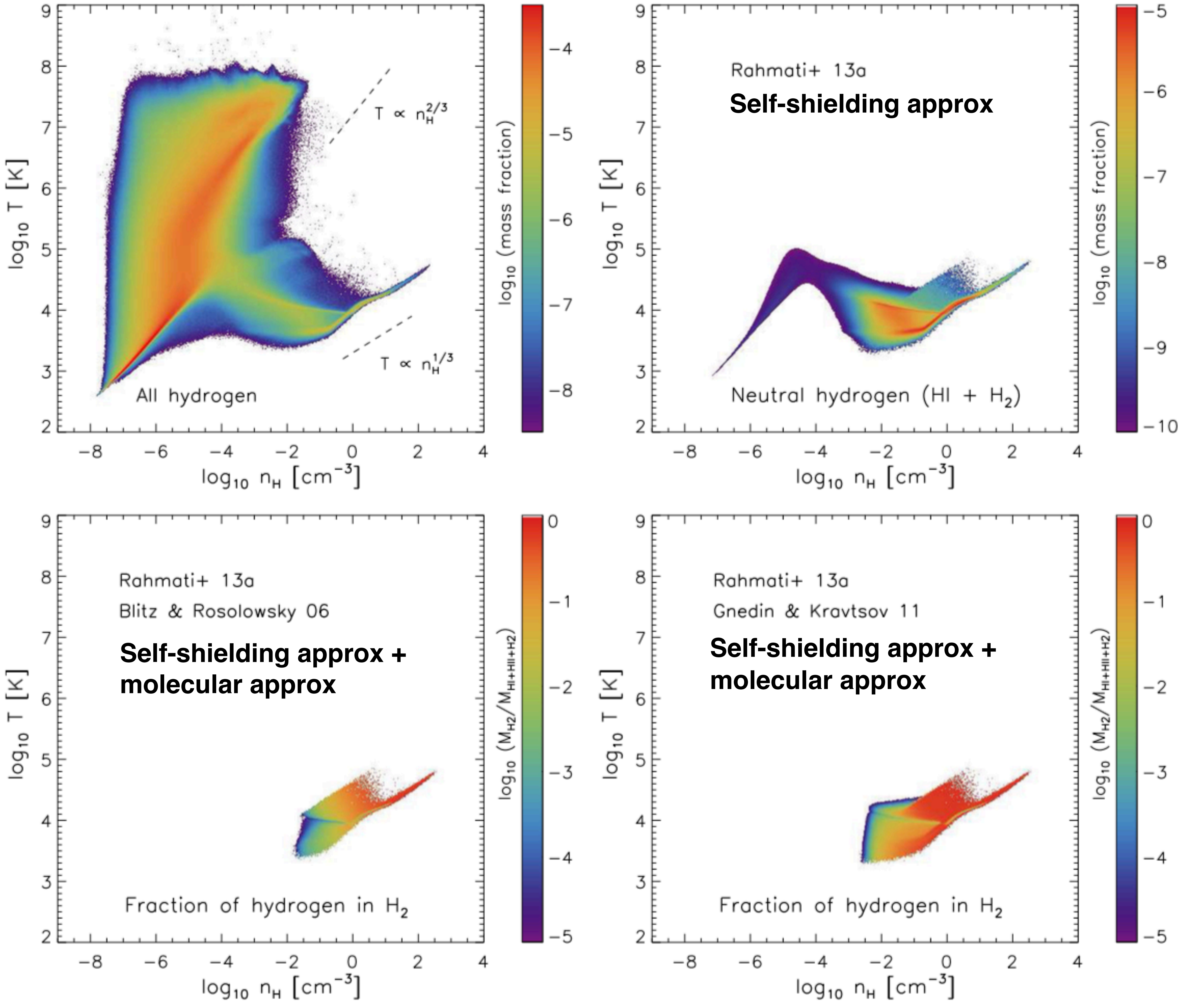

9
8
7
6
5
4
3
2
$\log_{10}$ T [K]
$T \propto n_H^{2/3}$
$T \propto n_H^{1/3}$
All hydrogen
−8
−6
−4
−2
0
2
4
$\log_{10}$ n_H [cm^{-3}]
−4
−5
−6
−7
−8
$\log_{10}$ (mass fraction)

RAC+ (2017)



Self-shielding approx

RAC+ (2017)



Self-shielding approx

Self-shielding approx +
molecular approx

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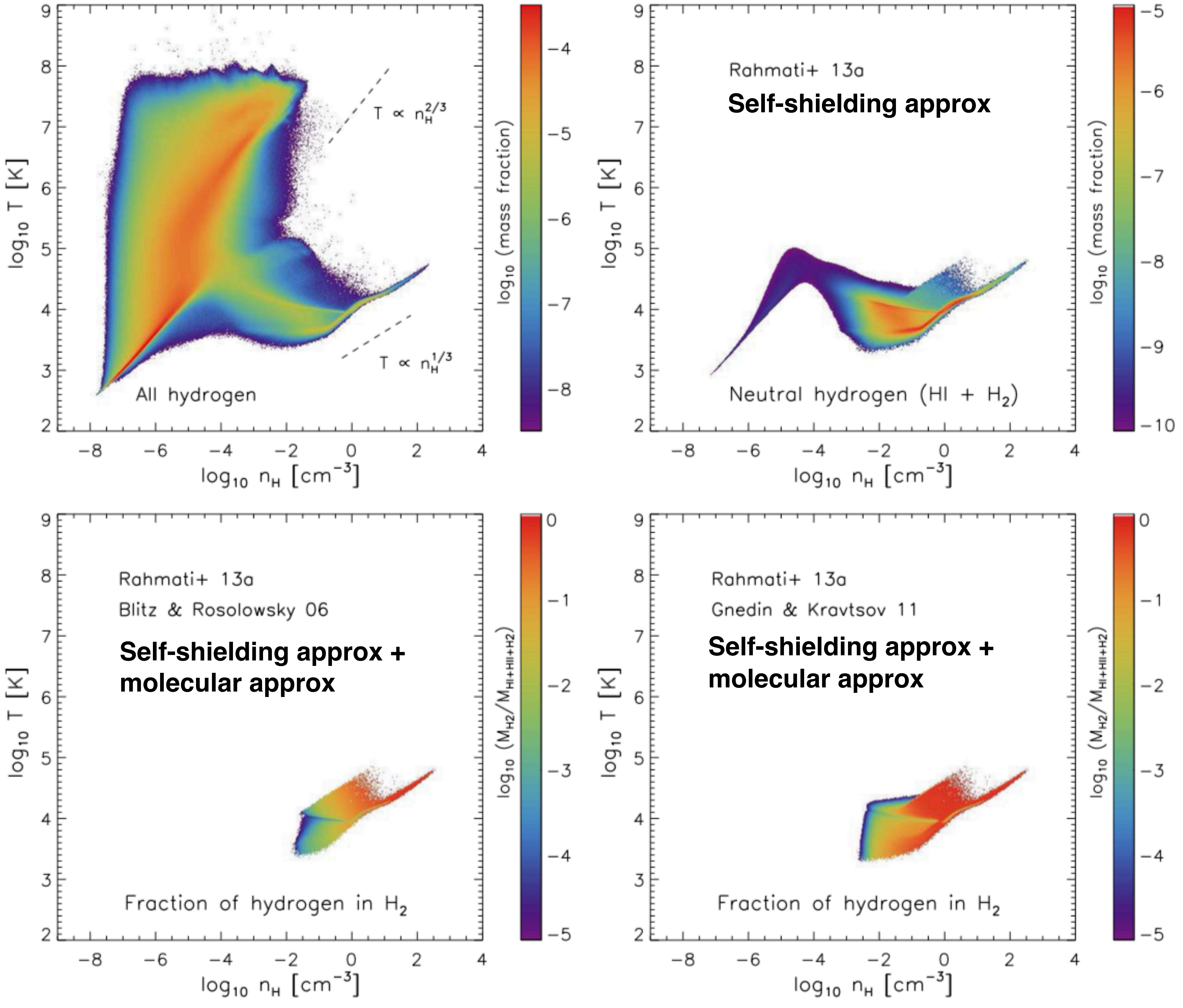
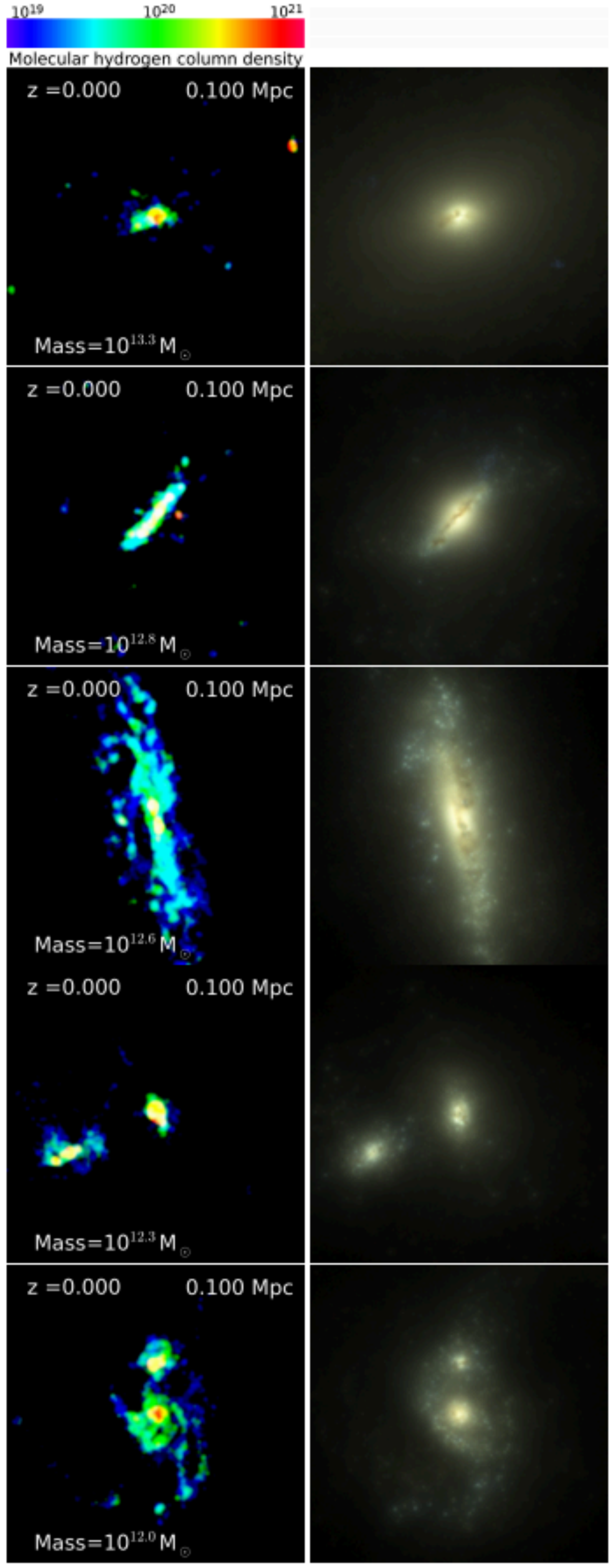
molecular approx

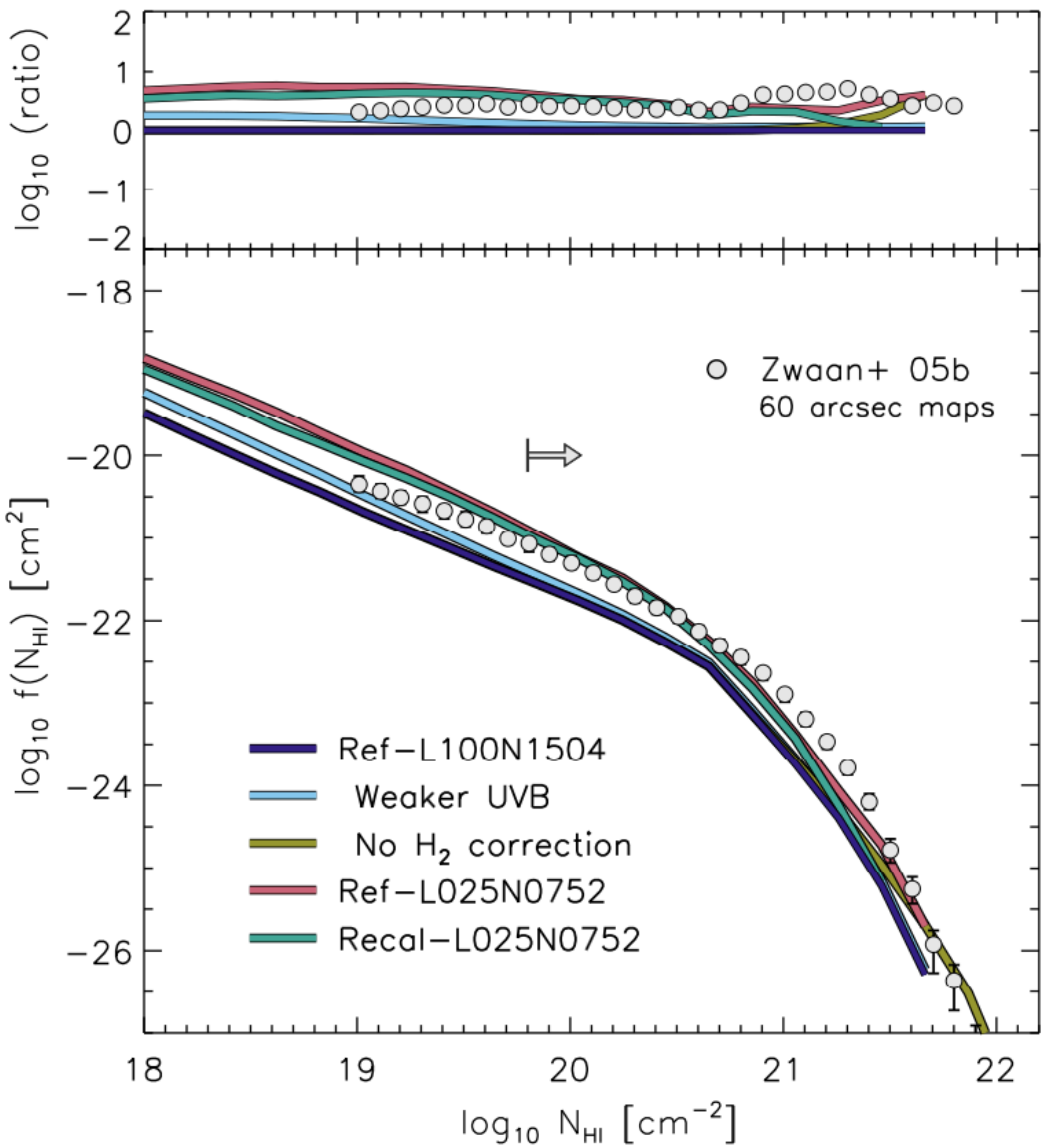
RAC+ (2017)



RAC+ (2017)



Lagos, RAC+ (2016)



Cosmological simulations probe a huge dynamic range in HI columns.

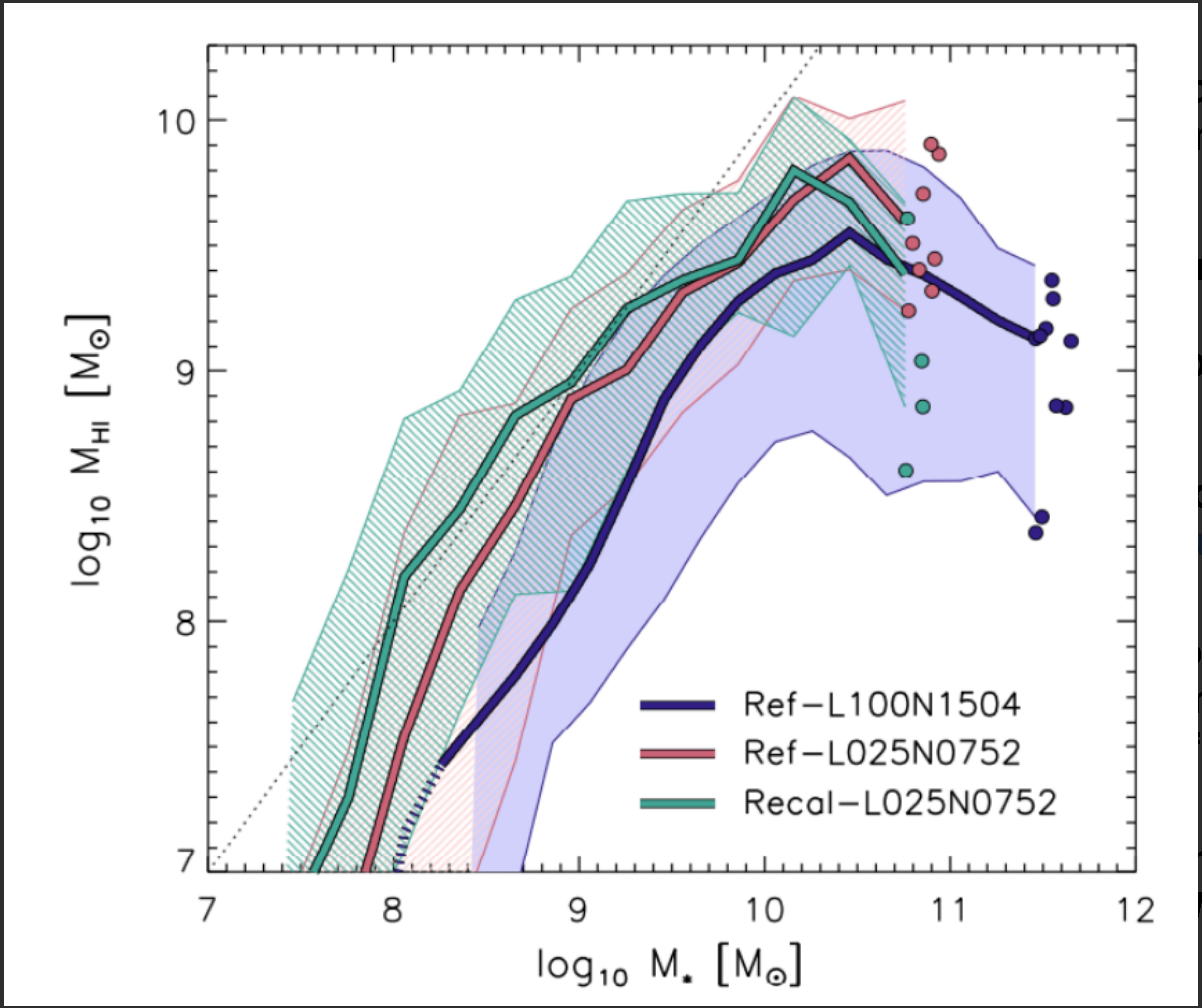
EAGLE's largest volume (dark blue) reproduces the form of the 21-cm emission CDDF, but offset low by ~0.3 dex in column.

This is not driven by uncertainty in the UVB (c.f light blue curve).

Higher resolution runs fare better; at low columns small numbers of particles can make significant difference

Prescription for converting HI into H2 only influences $N_{HI} > 10^{-21.5}$ cm^{-2}.

RAC+ (2017)



In the very high column density regime…

The resolution sensitivity is clear when looking at the mass of HI bound to central galaxies…

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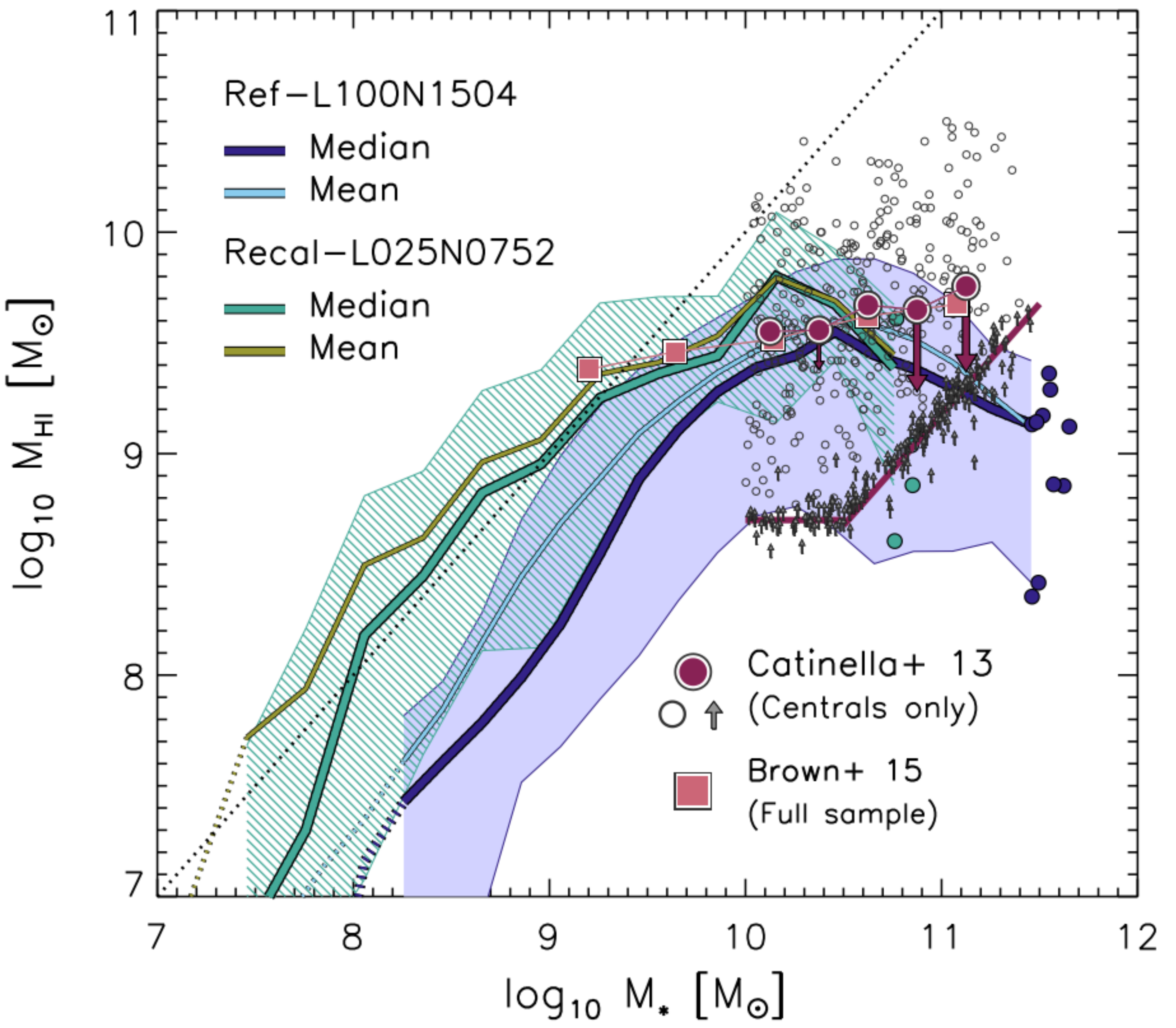
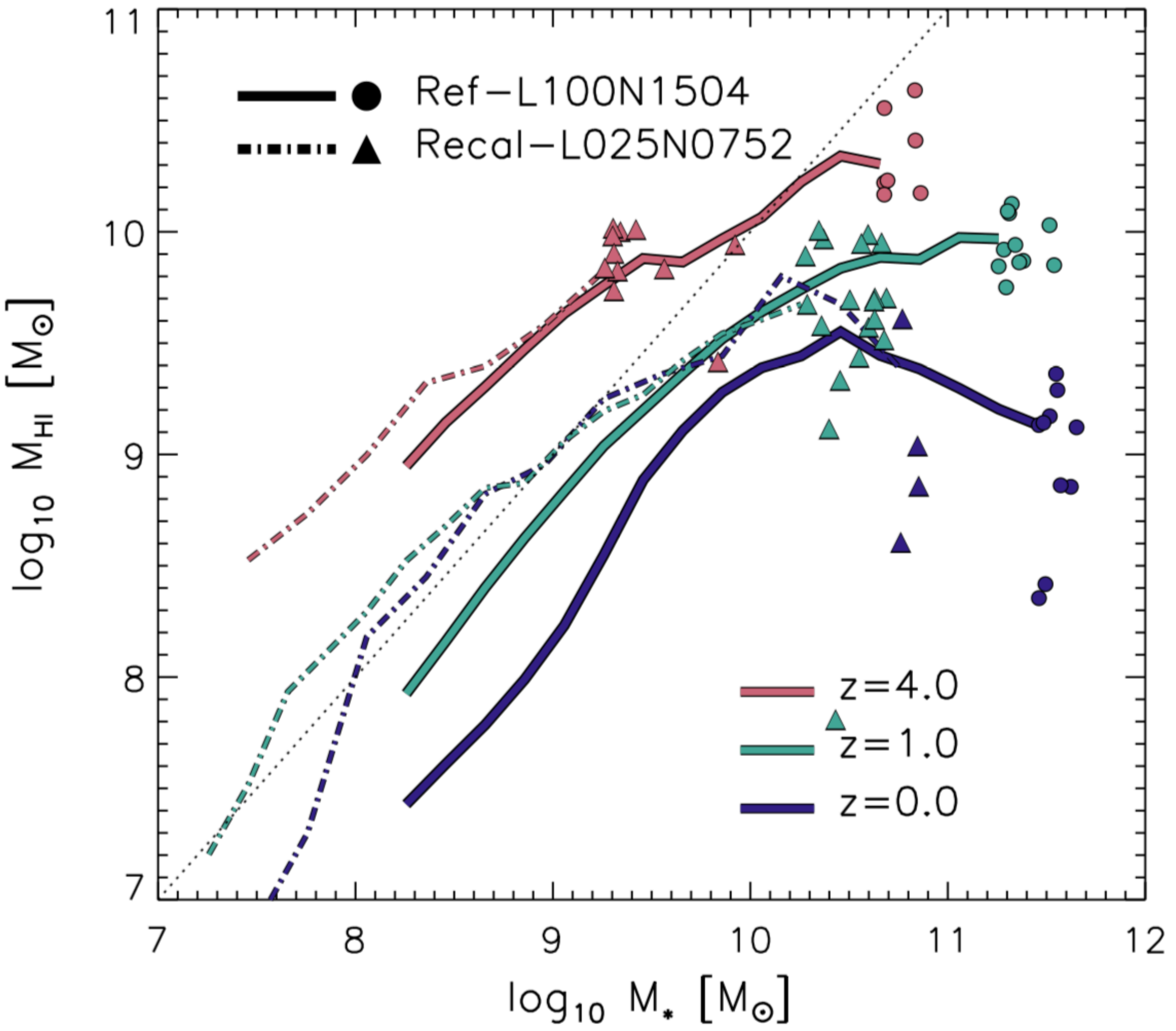
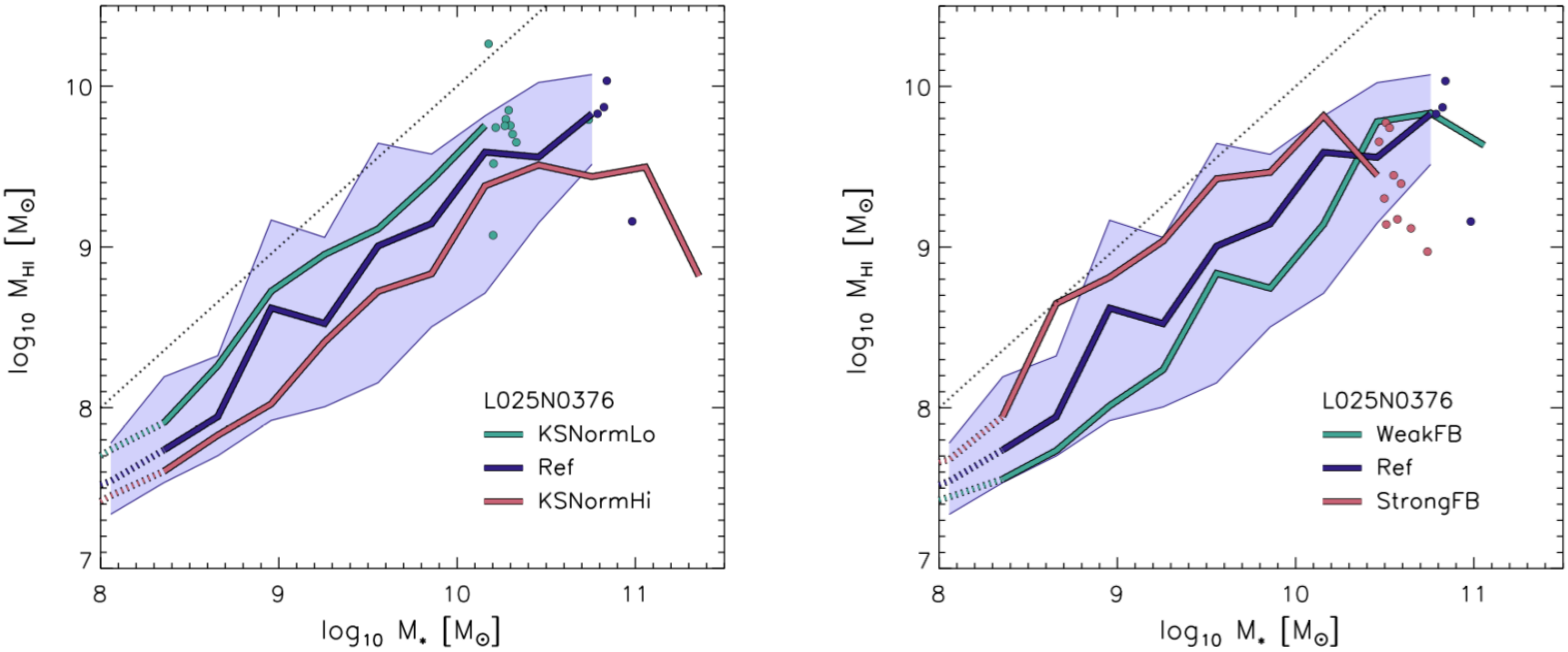


Standard and high-res EAGLE runs are broadly compatible with e.g. GASS for $M^* > 10^{10}$ M_{sun}, but too little HI at lower masses n standard res runs.

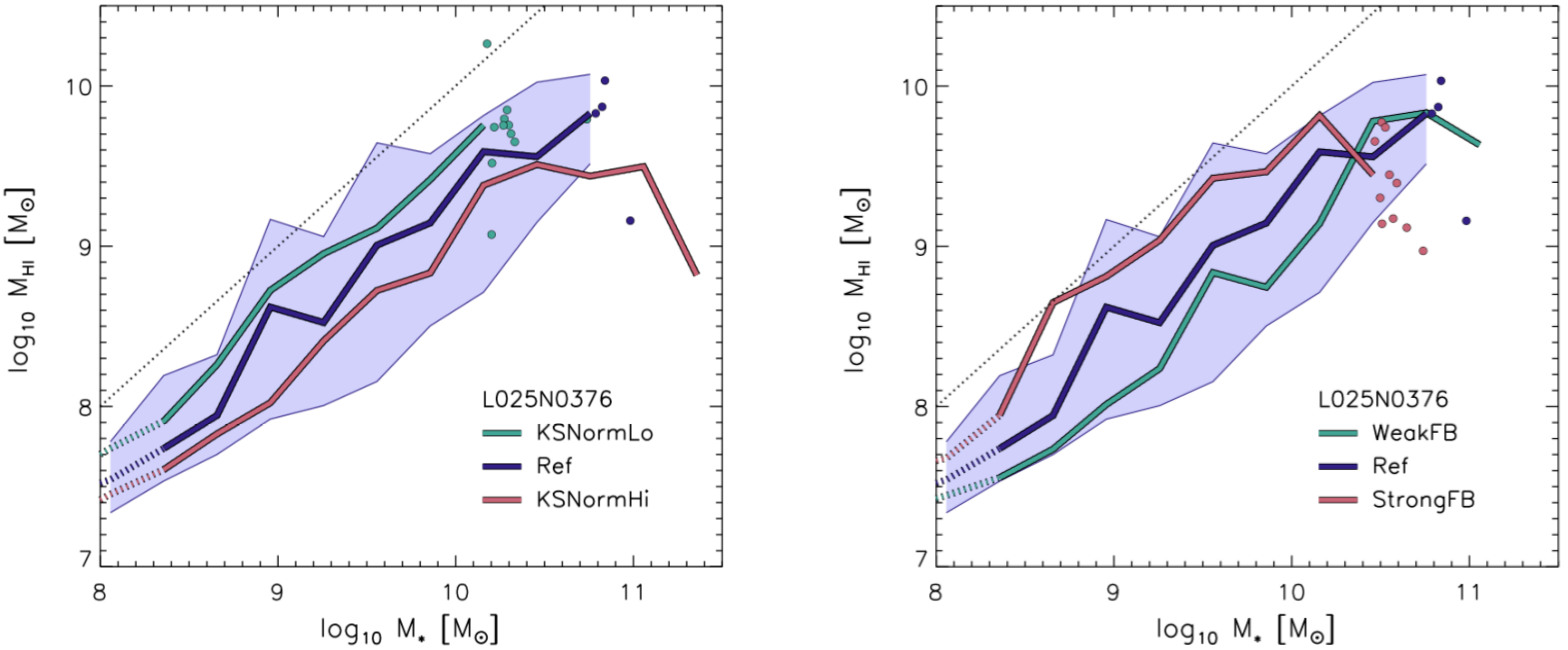


HI fractions at fixed M* are greater at earlier cosmic epochs due to higher inflow rate.

RAC+ (2017)



Dialling the efficiency of SF and feedback influences M_{HI} at fixed M* because of self-regulation.



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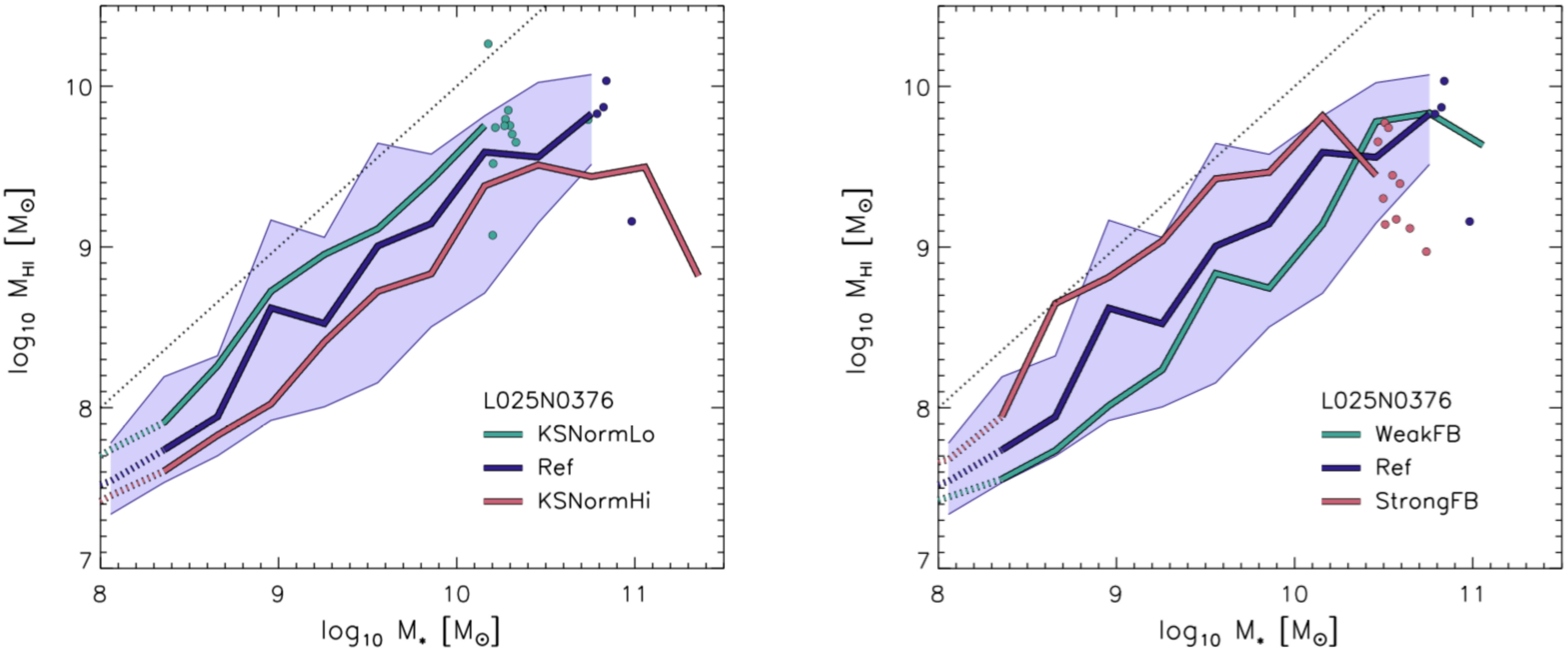
Lower SF efficiency: requires accumulation of a larger gas reservoir to yield the SF and SF-driven feedback required to balance the large-scale inflow: M_{HI} goes up.



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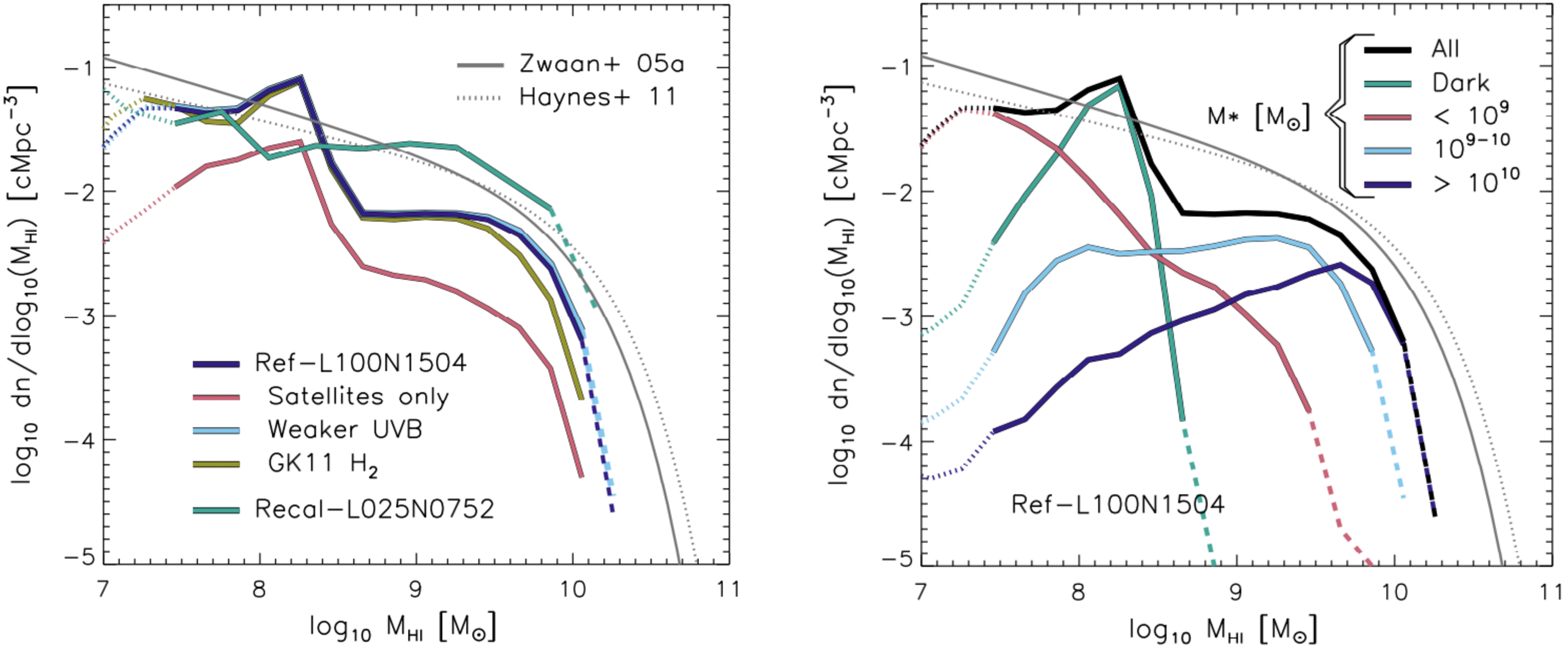
Lower SF efficiency: requires accumulation of a larger gas reservoir to yield the SF and SF-driven feedback required to balance the large-scale inflow: M_{HI} goes up.

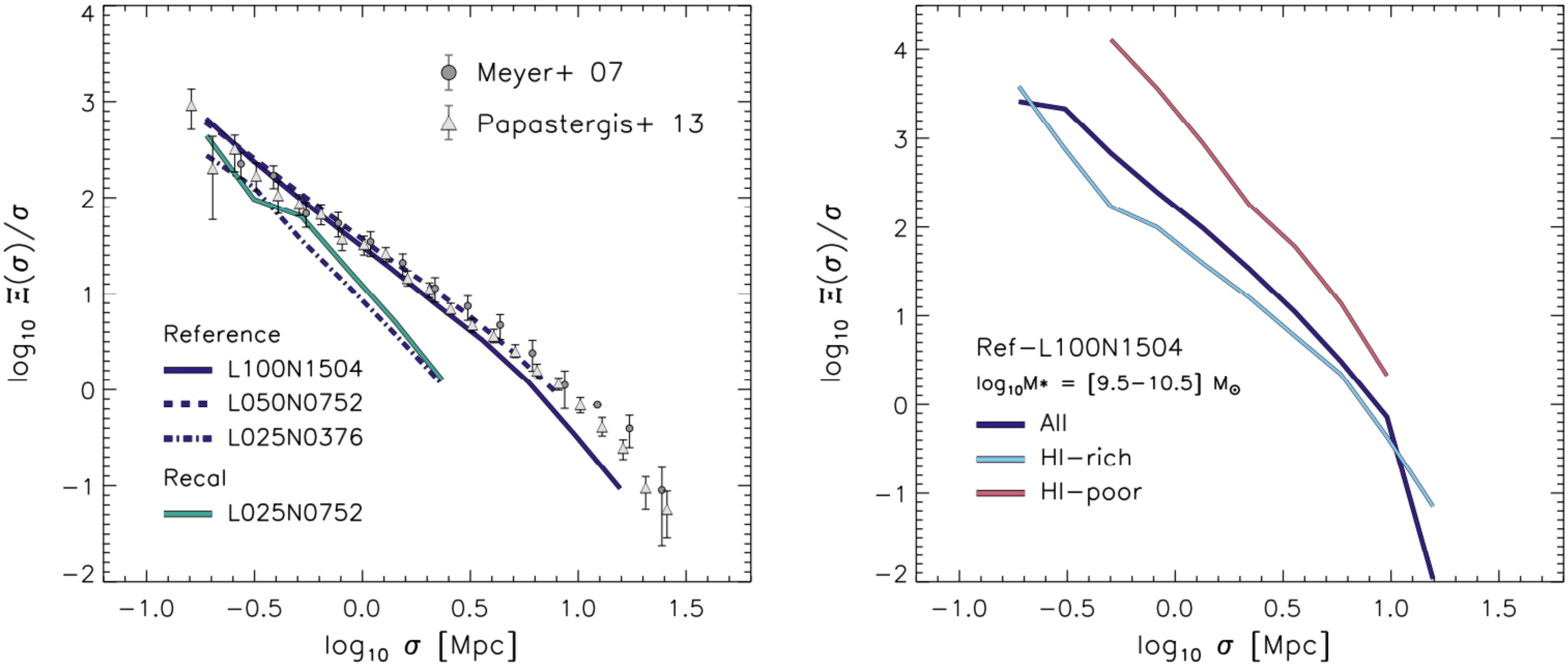
Lower feedback efficiency: enables galaxies of fixed M^* to form in haloes of lower M_{200} with lower inflow rates, requiring a smaller gas reservoir to give the necessary SF: M_{HI} goes down.



The HI mass function at standard res is not a huge success!

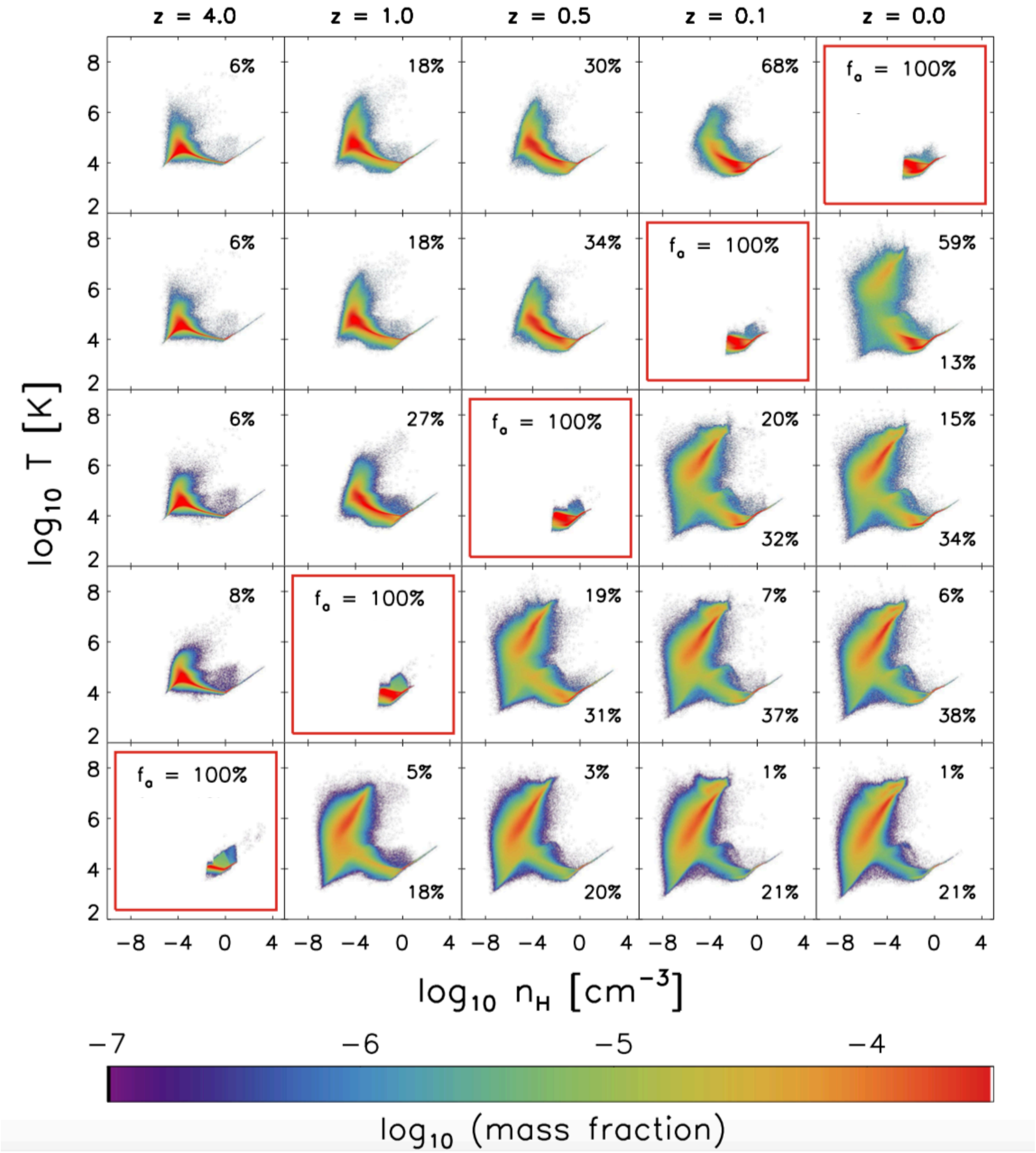
HI masses slightly too low (need shifting right). Also a lot of HI accumulates in poorly-sampled haloes that might have formed <~ mgas of stars but got unlucky in the stochastic SF lottery.

This problem almost absent at 8x better mass resolution, but we have only a *L*=25 Mpc box.

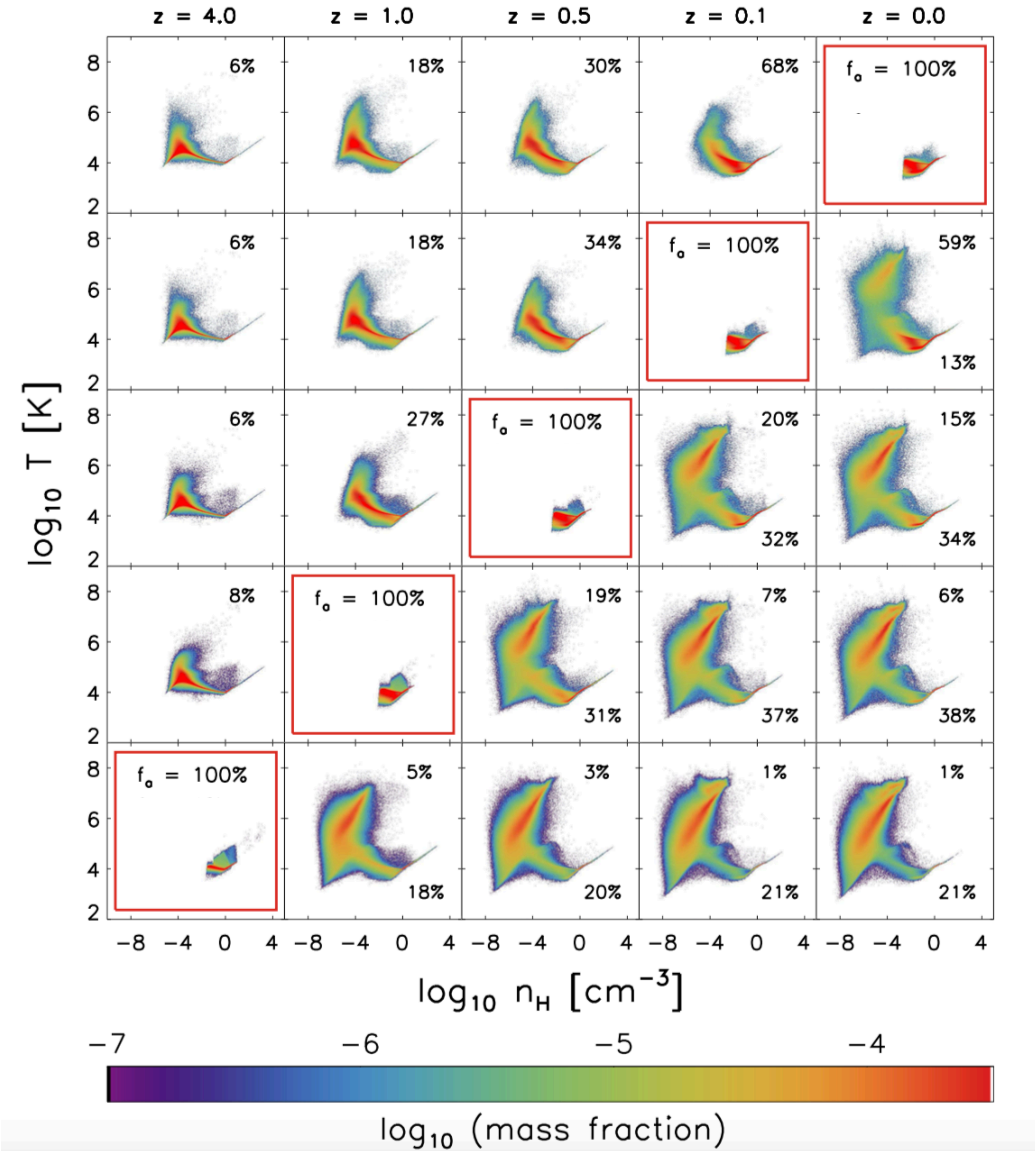


Clustering of HI-detected sources is better: the correct haloes are populated with HI.

HI-rich sources are less-clustered, and HI-poor sources are more-clustered, than average.



Simulations enable us to track the past history and future destiny of the gas in the form of HI at any given epoch.



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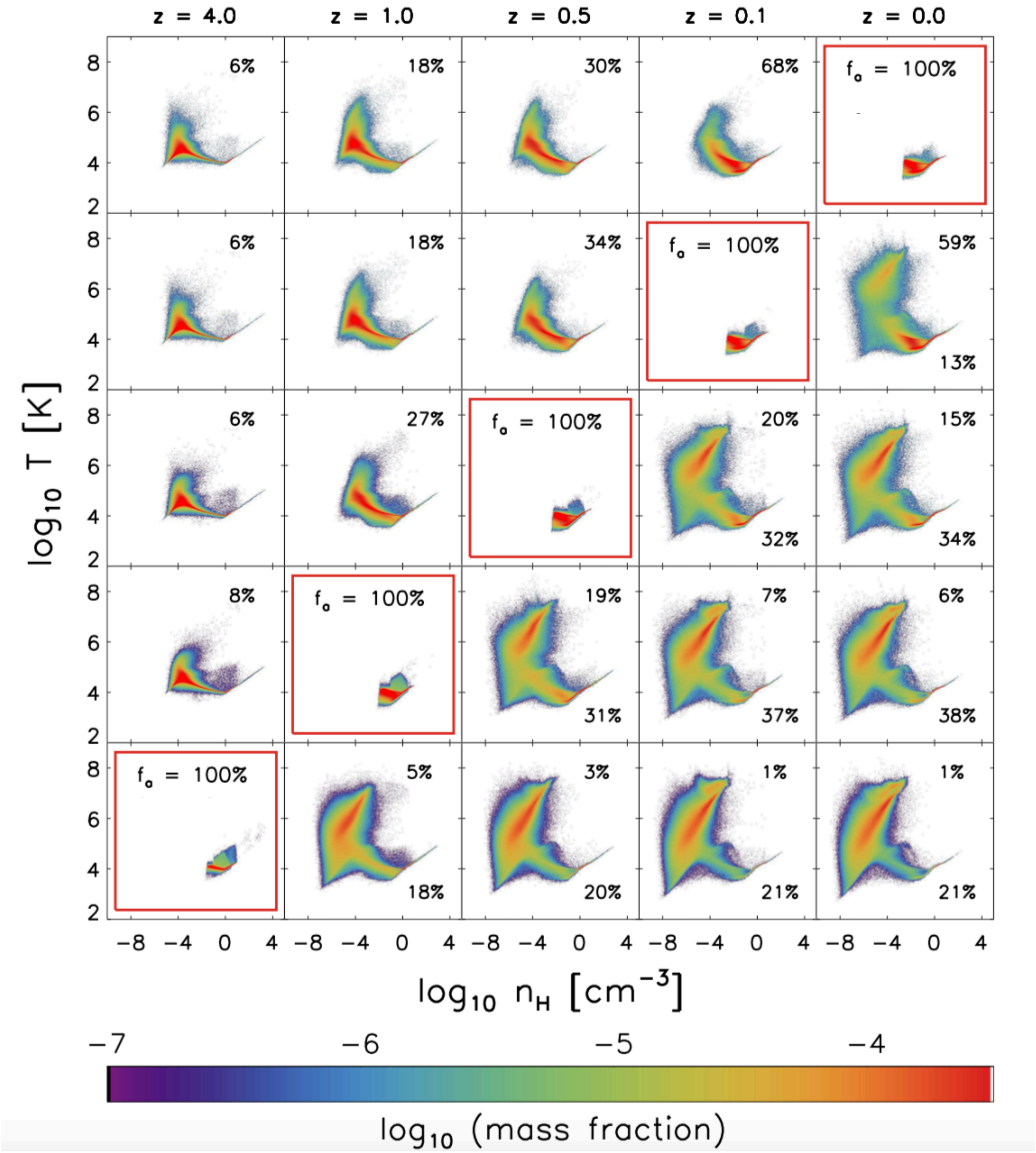
Top row: past history of today's HI.

Middle row: history & destiny of z=0.5 HI.

Bottom row: future destiny of z=4 HI.

Top #: fraction of selection in HI at that time

Bottom #: fraction of selection in stars at that time



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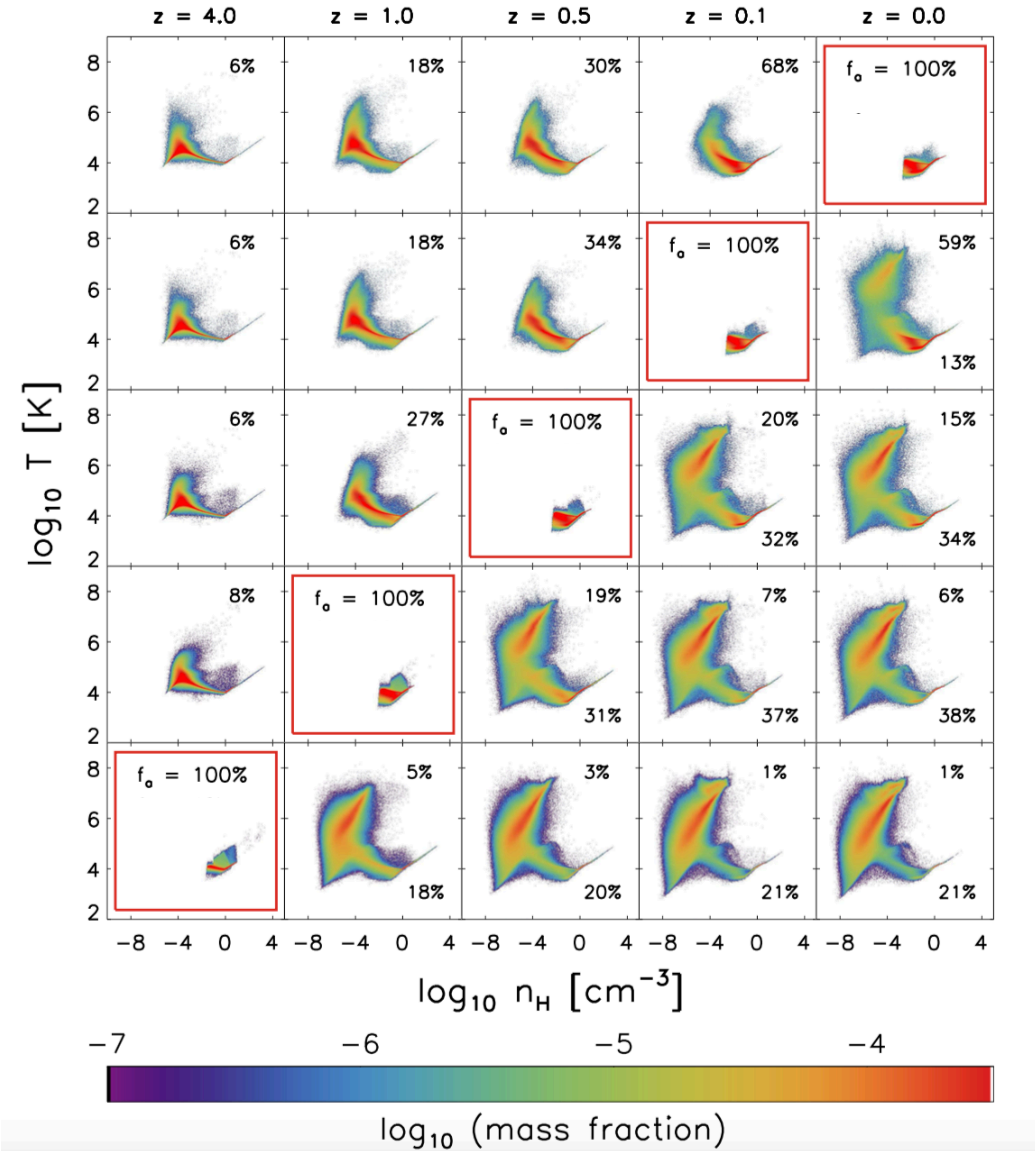
Today's HI could be largely found in the IGM or cold-phase CGM in the past. Most transited CGM without strong heating or recycling.



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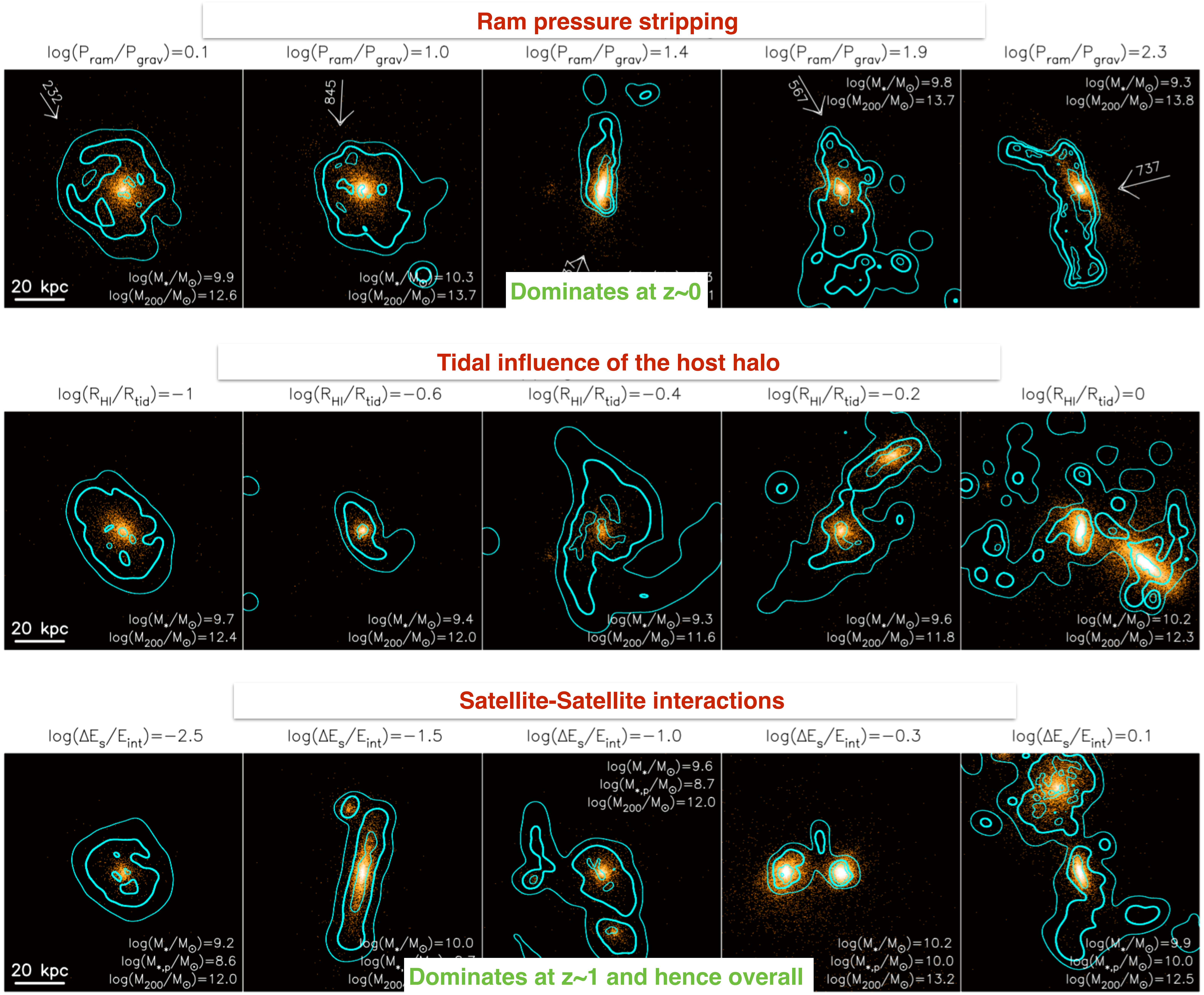
Atom of HI does not stay as such for long: governed by consumption and feedback times.

EAGLE predicts 41% of z=0.1 HI already gone: 13% in stars and 23% in the multi-phase CGM.

Environmental influences are treated self-consistently



Ram pressure stripping

Dominates at z~0

Tidal influence of the host halo

Satellite-Satellite interactions

Dominates at z~1 and hence overall

Weak influence

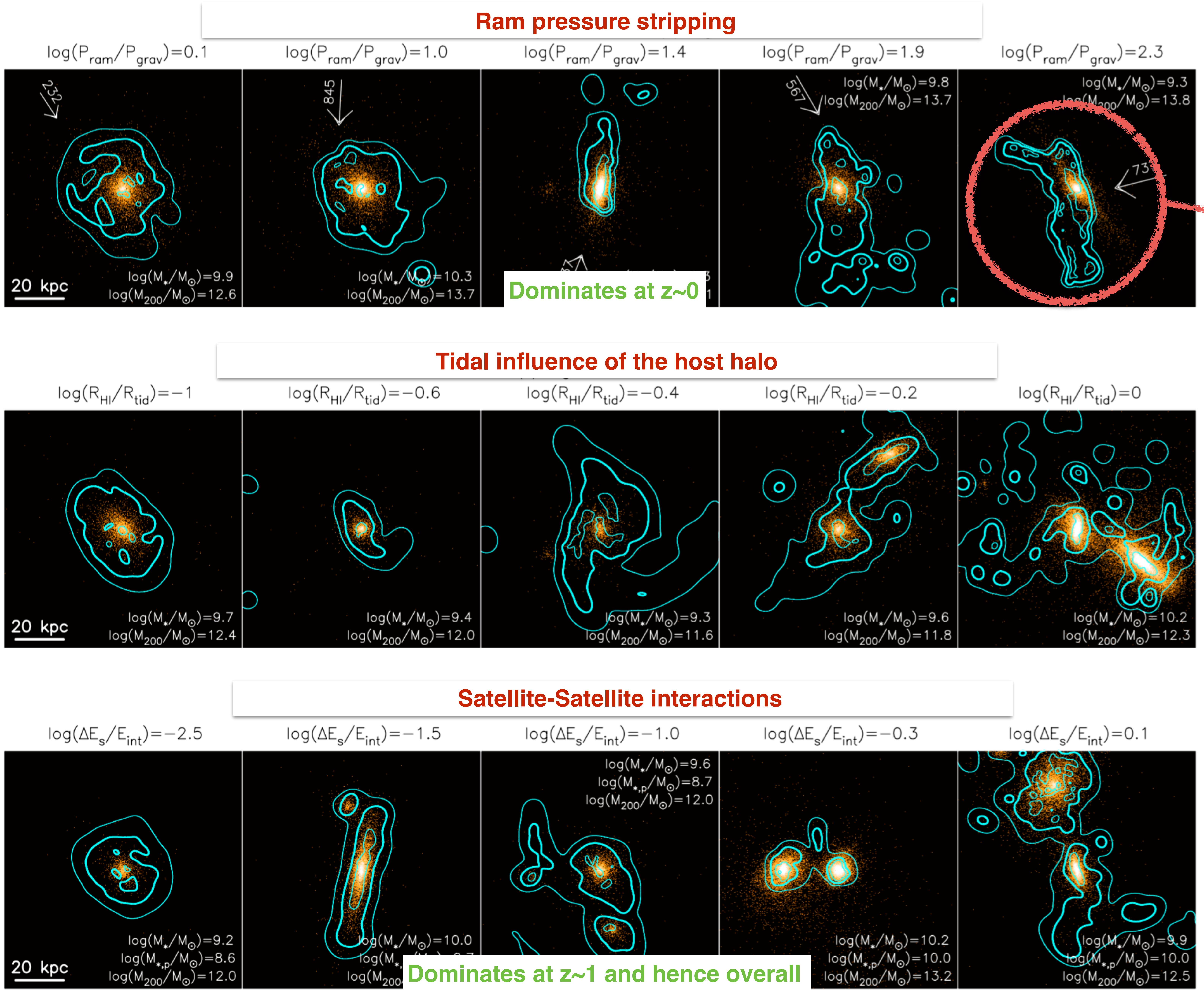
Strong influence

Antonino showed ram-pressure stripping is main way that HI is lost environmentally at z=0.

But! Environmental 'damage' was more prevalent in the past, and was dominated by tidal stripping and interactions between satellites.

Marasco, RAC+ (2016)

Weak influence



Dominates at z~0

Dominates at z~1 and hence overall

Look at that bow feature!

Strong influence

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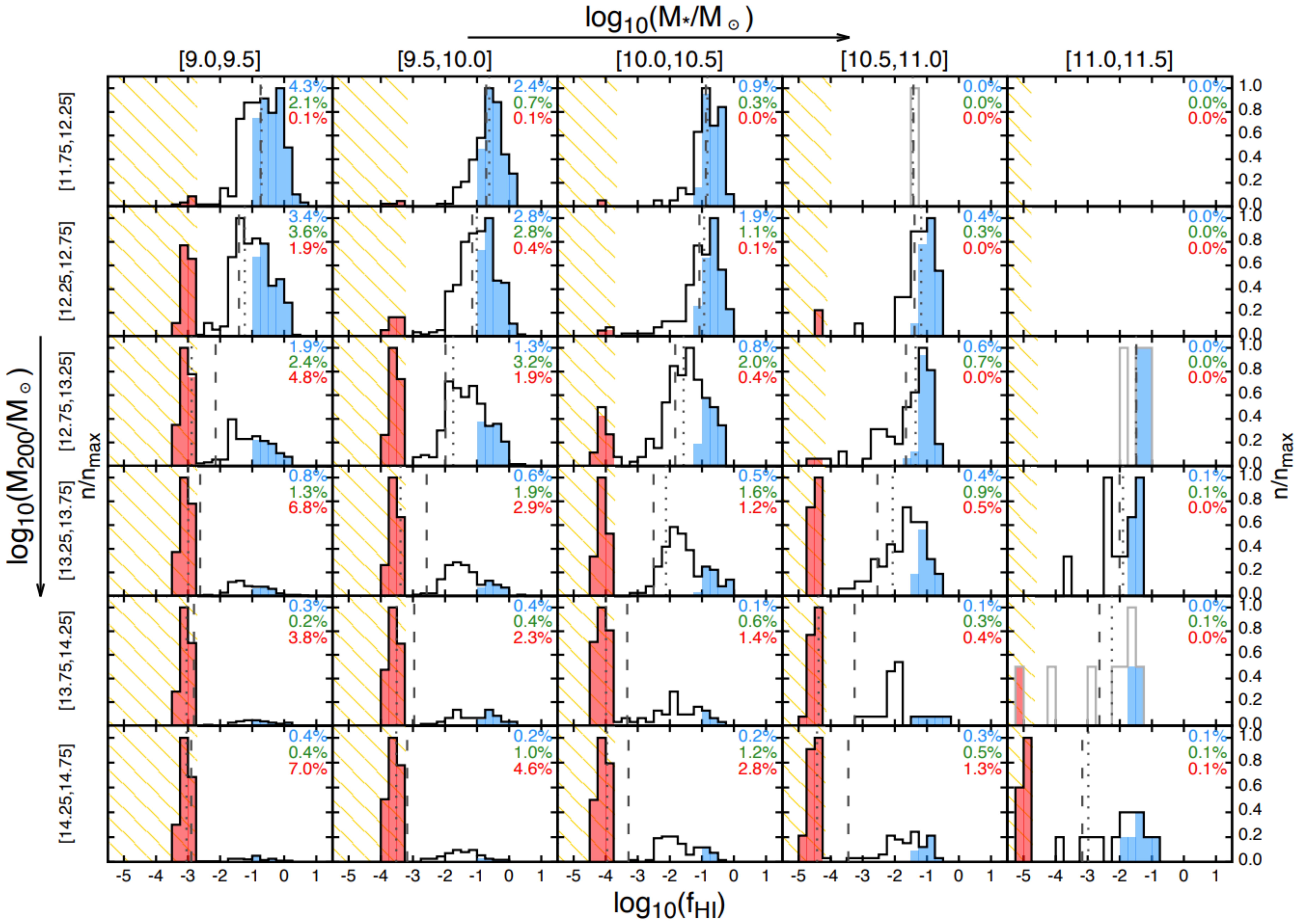


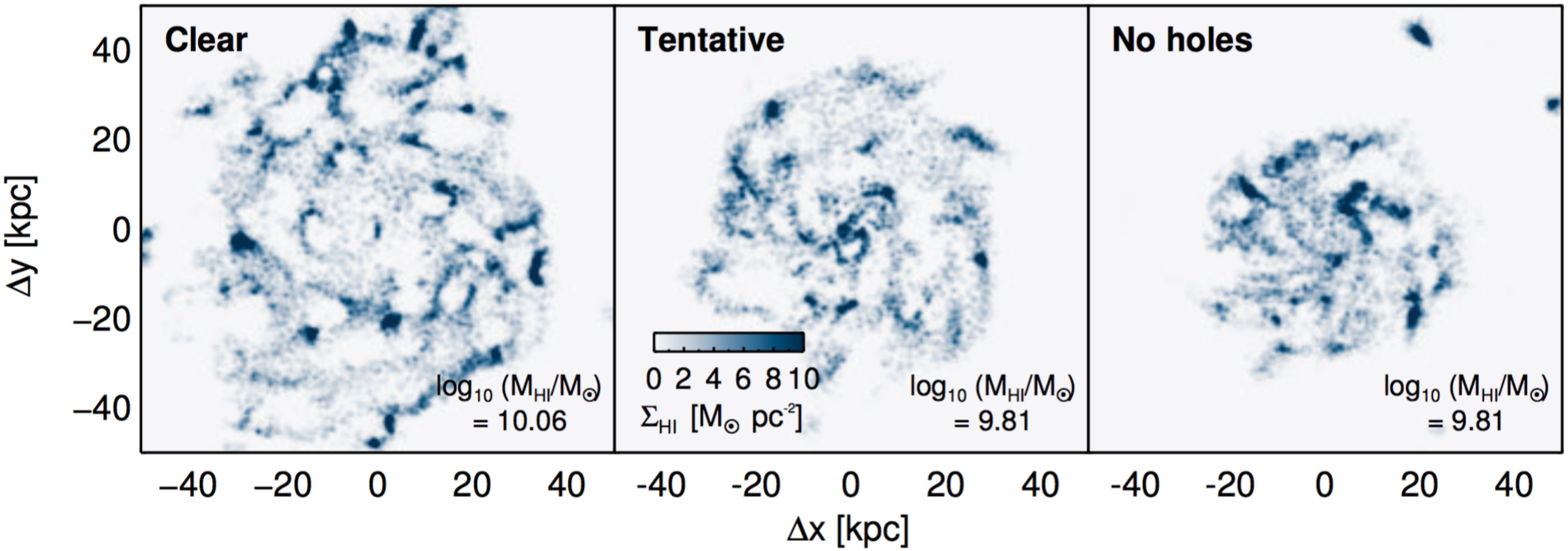
Antonino showed that EAGLE reproduces observed trends well.

Environment acts (to 1st order) as on/off switch in HI.

At fixed *M, HI-poor fraction of galaxies correlates with halo mass: *M*$_{200}$ is proxy for environment.**

At fixed *M*$_{200}$, HI-poor fraction anti-correlates with *M: bigger galaxies have more HI and are more resilient.**

Marasco, RAC+ (2016)



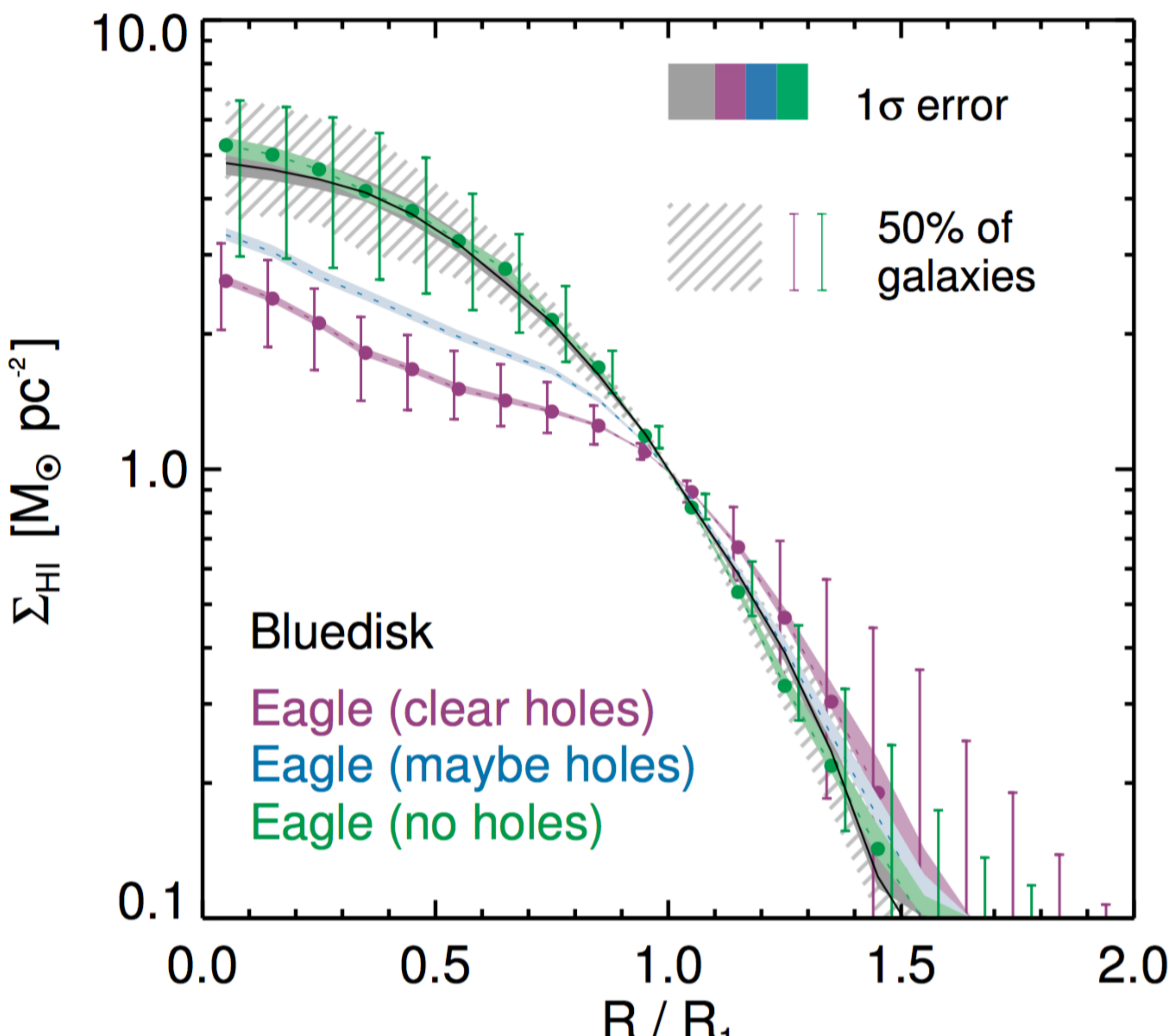
Bahe, RAC+ (2016)

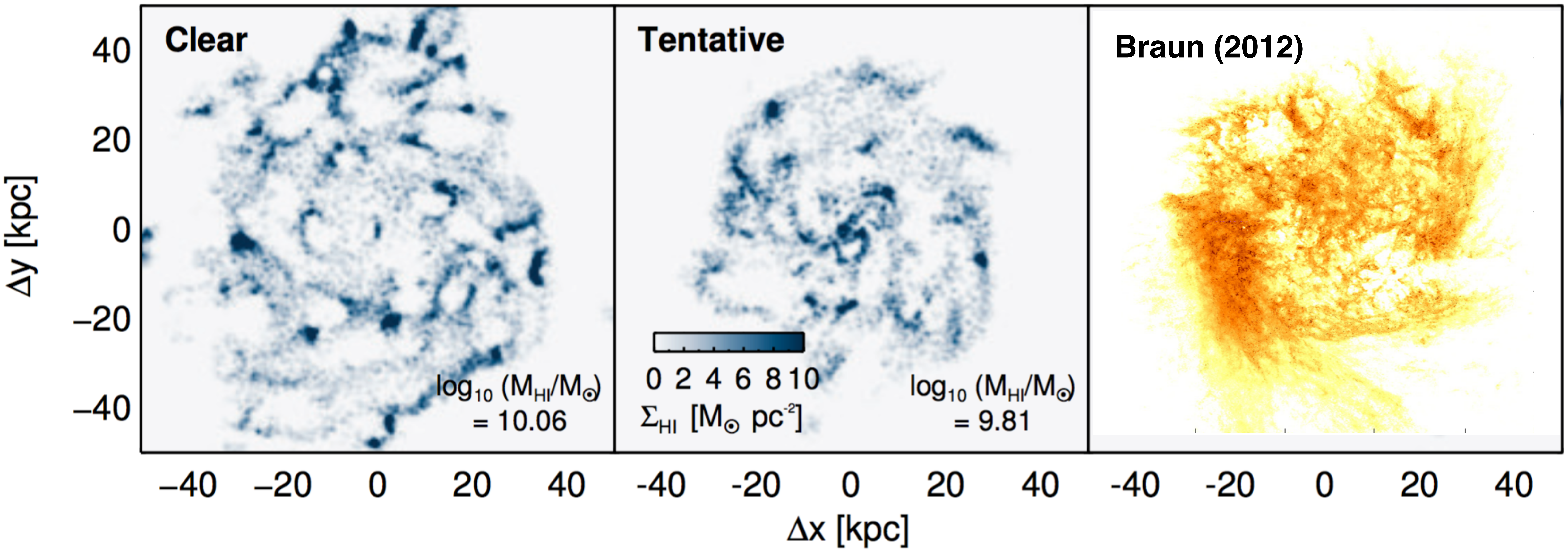
Detailed comparisons reveal tangible differences:

Each feedback heating event in EAGLE (standard-res) injects energy of ~10^4 SNe.

Injection creates short-lived holes in HI distribution that are much larger than those typical of observed galaxies.

Yannick Bahe showed that galaxies with holes tend to exhibit HI profiles that are centrally suppressed.





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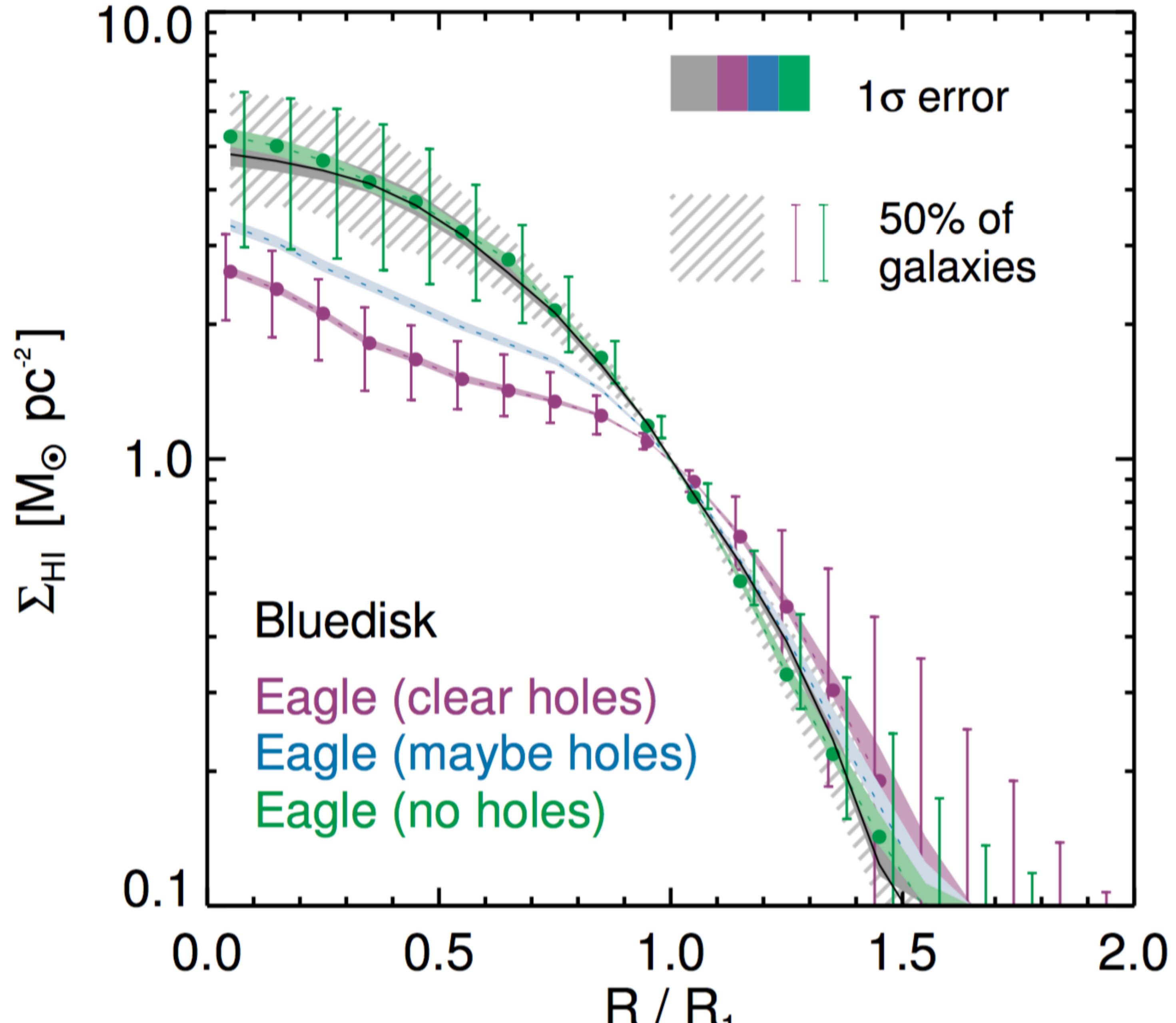

Heading further afield: the CGM traced by metal lines

Simulations can reproduce the OVI-sSFR bimodality seen by COS-Halos in different ways

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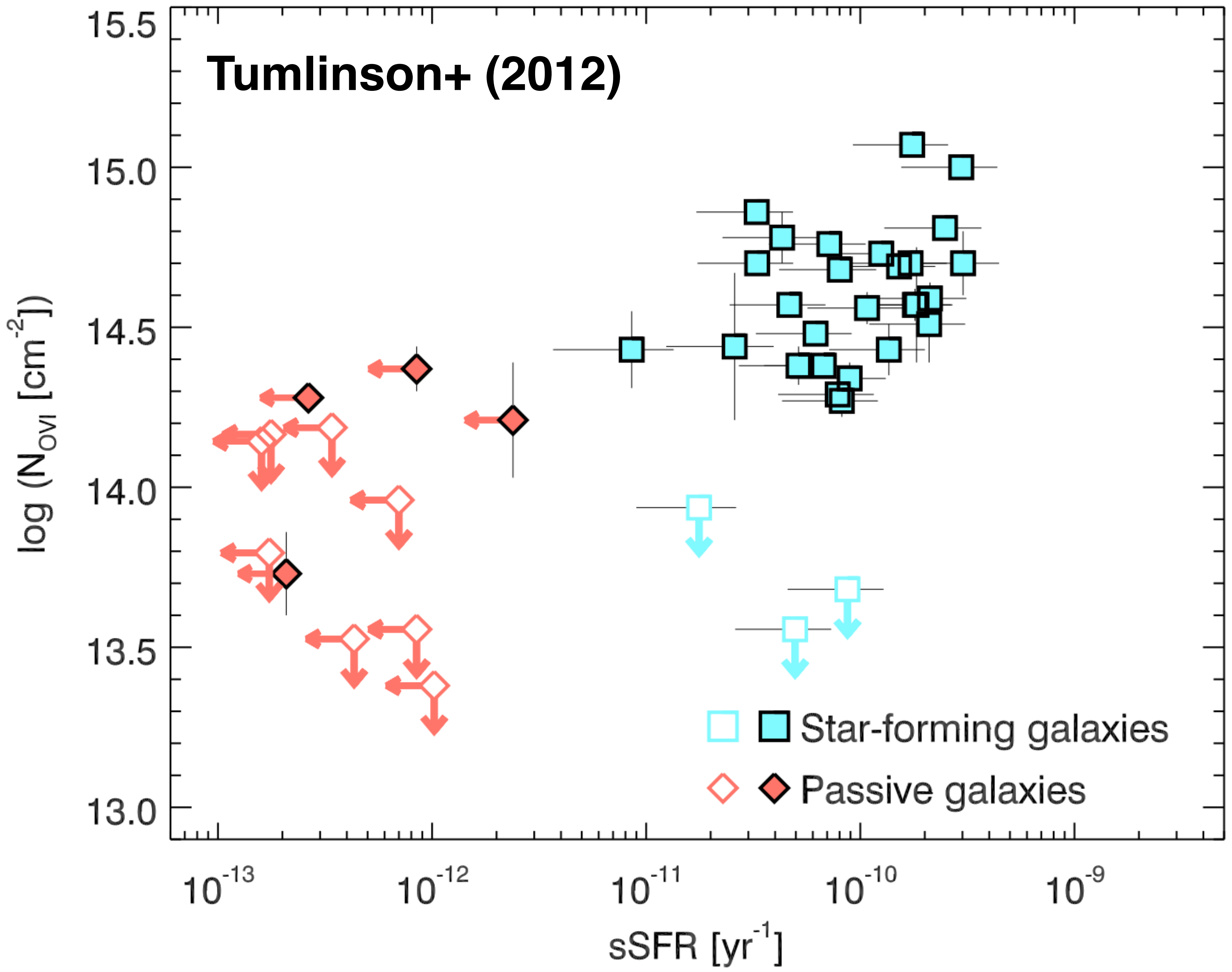

COS-Halo reveal a striking dichotomy in the OVI column densities of star forming and passive galaxies.

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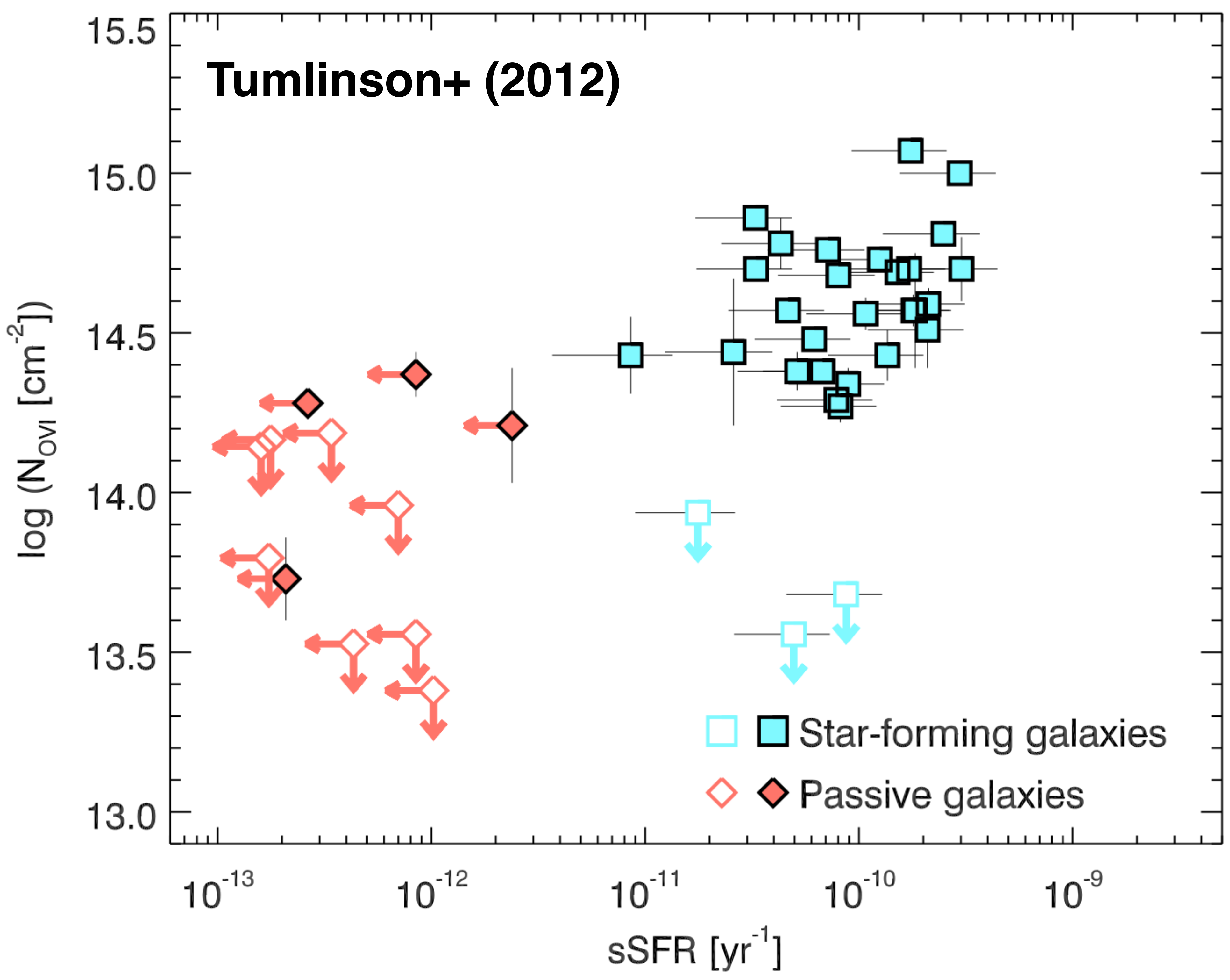

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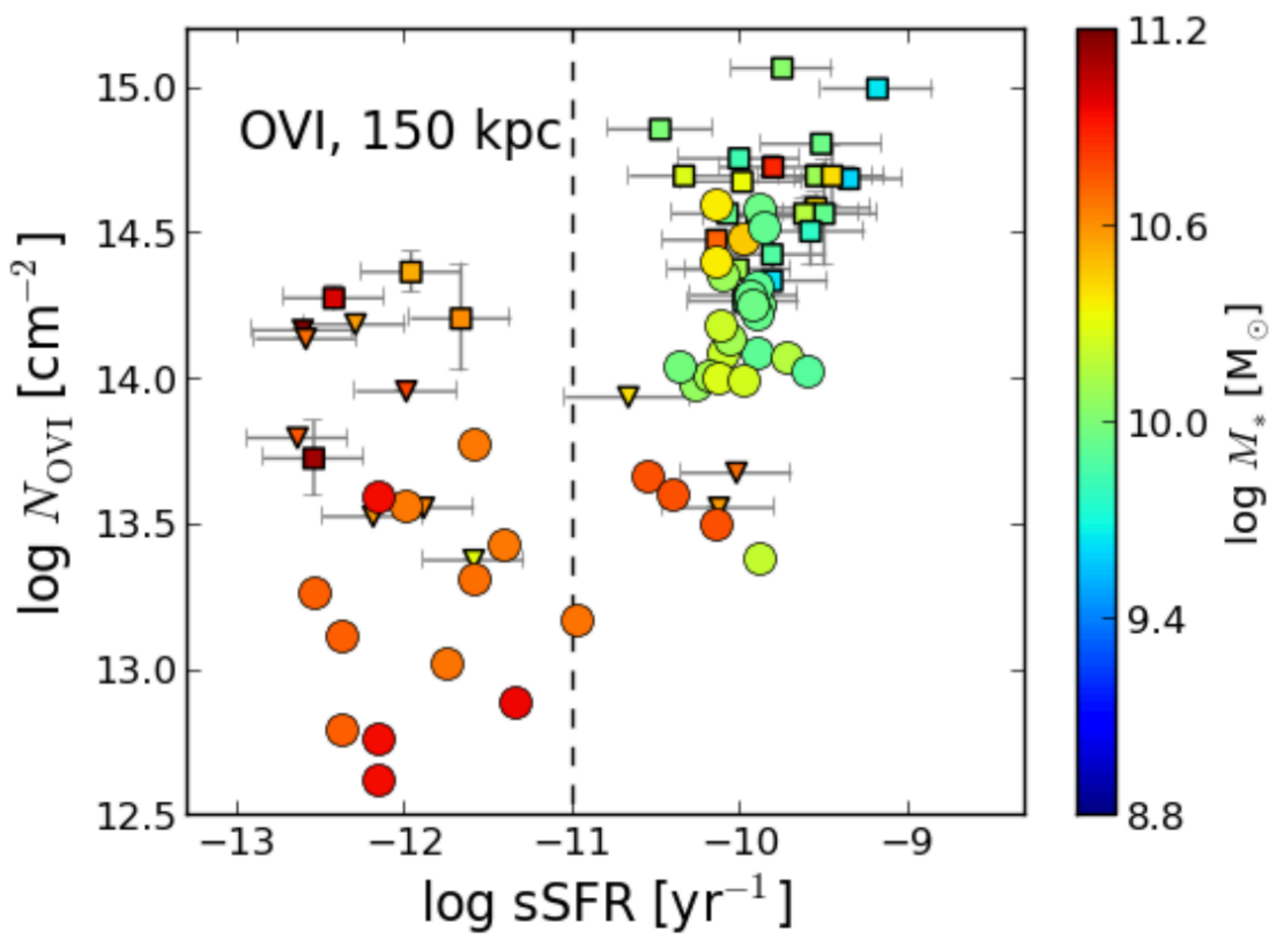
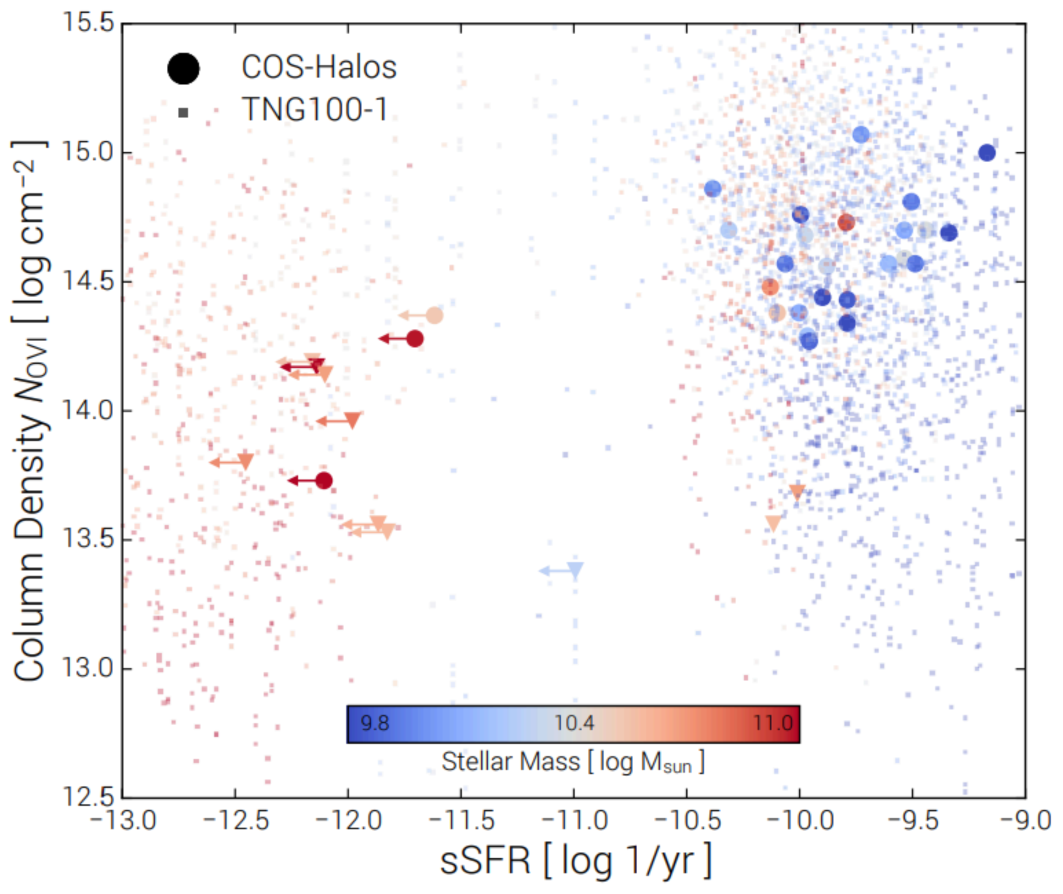


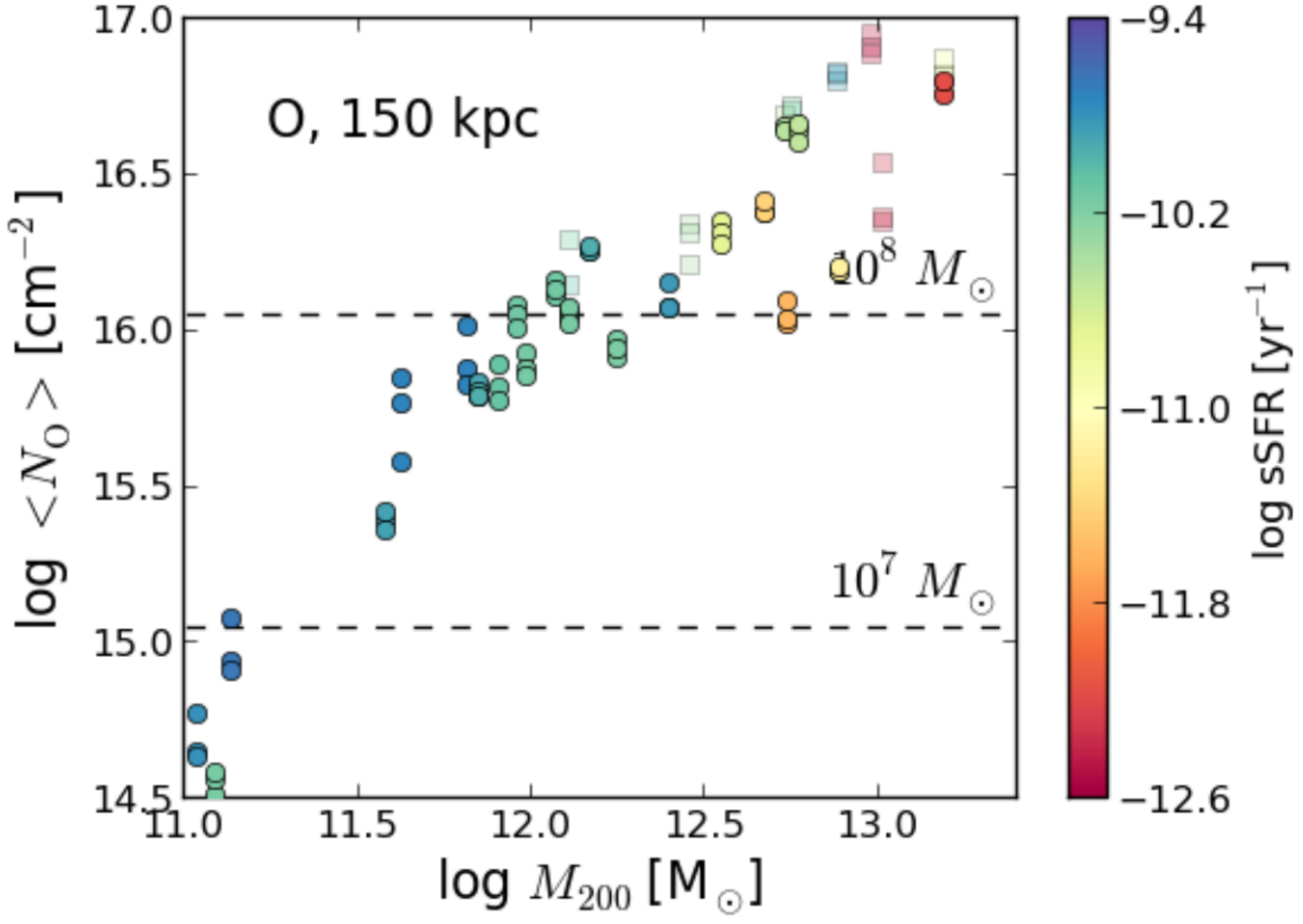
EAGLE: Oppenheimer,RAC+ (2016)



IllustrisTNG: Nelson+ (2018)

Heading further afield: the CGM traced by metal lines

EAGLE: passive galaxies occupy more massive, hotter haloes



Oxygen column density is a monotonic function of halo mass.

Passive galaxies associated with massive haloes hence have high oxygen column.

Oppenheimer, RAC+ (2016)

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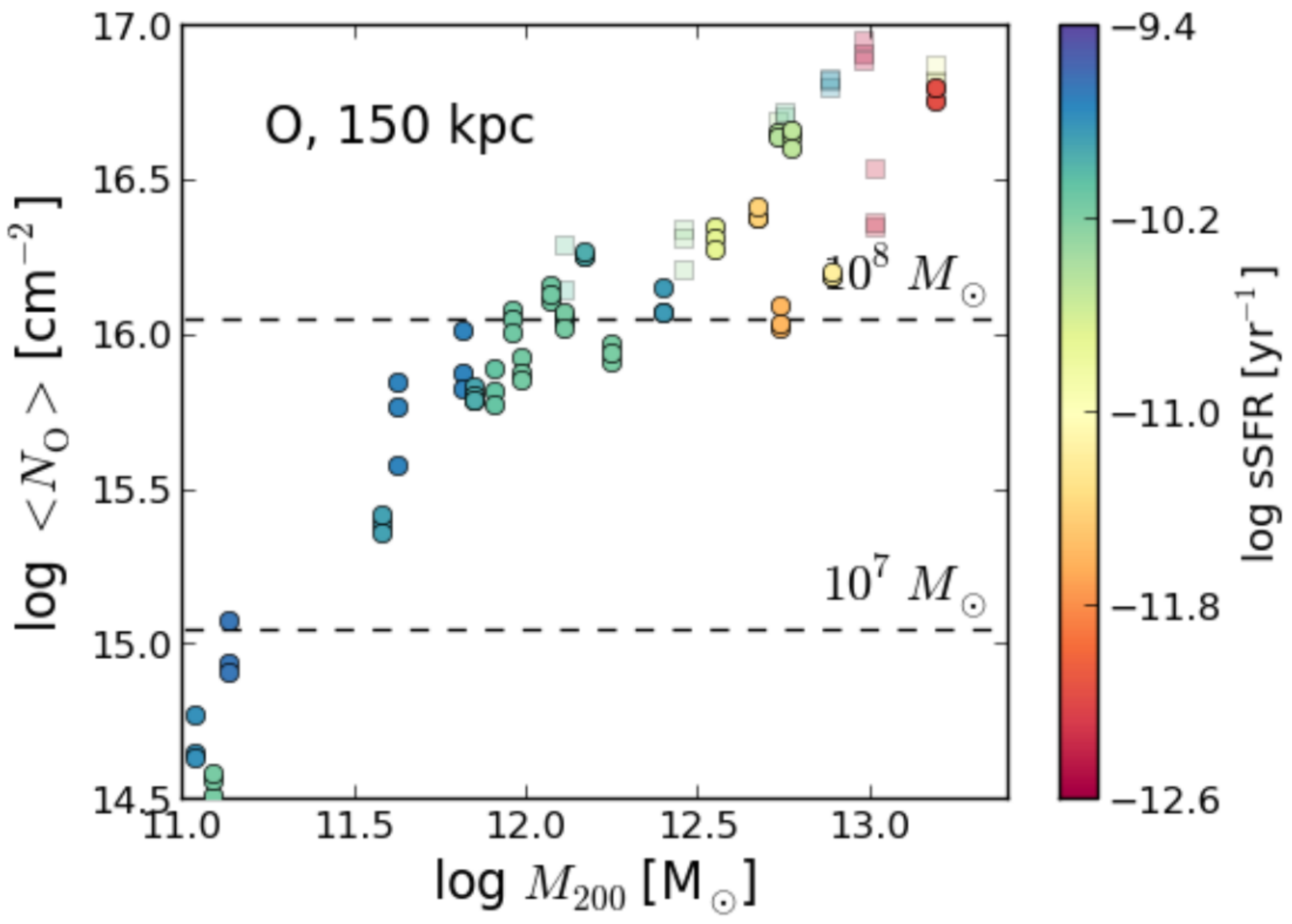

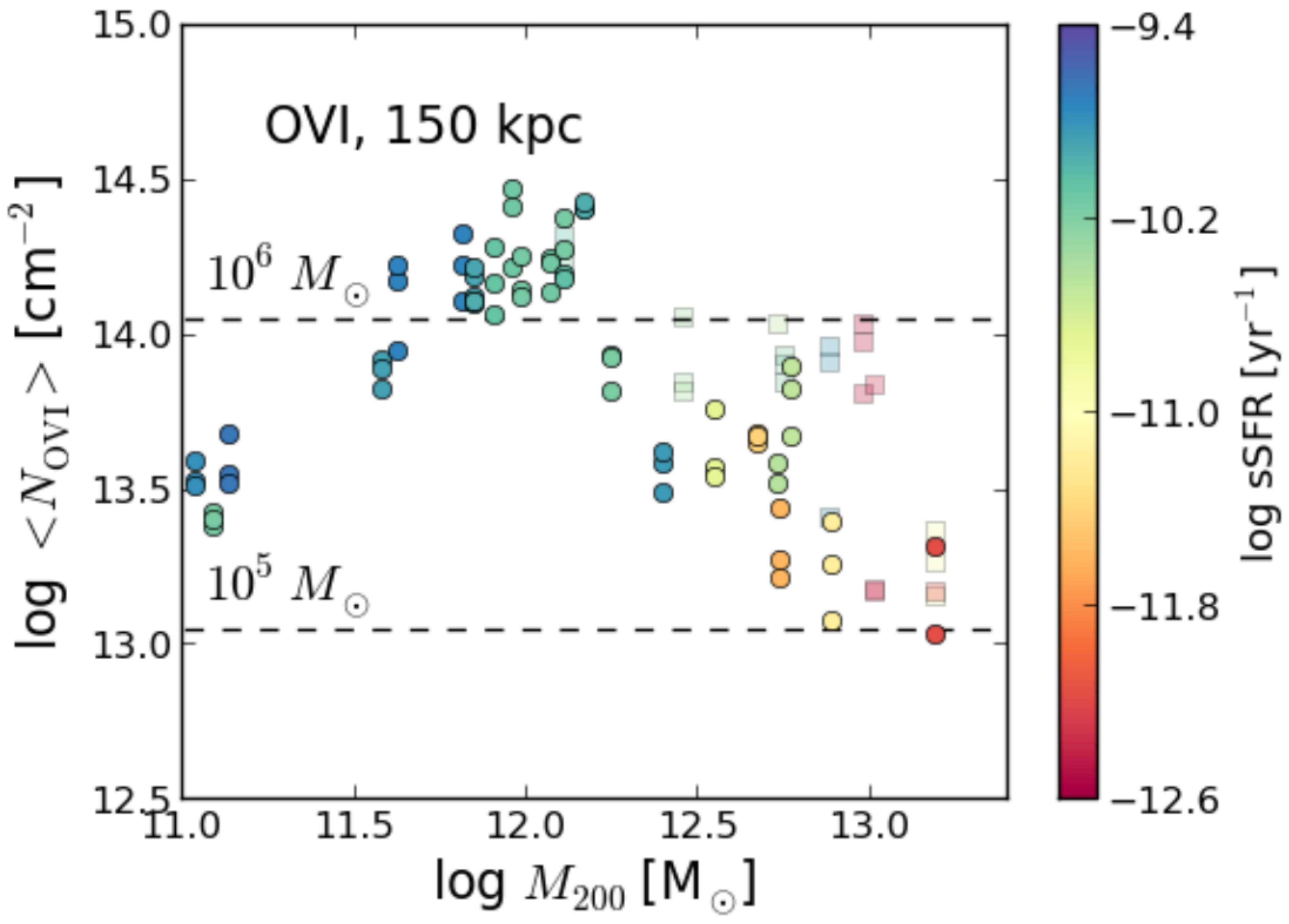

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Passive galaxies associated with massive haloes hence have high oxygen column.

Ionisation conditions in these haloes favour OVII over OVI, giving passive galaxies less OVI.

NB: Tripp+ (2008) report kinematically-coincident OVI and HI in some absorbers: missing microphysics?

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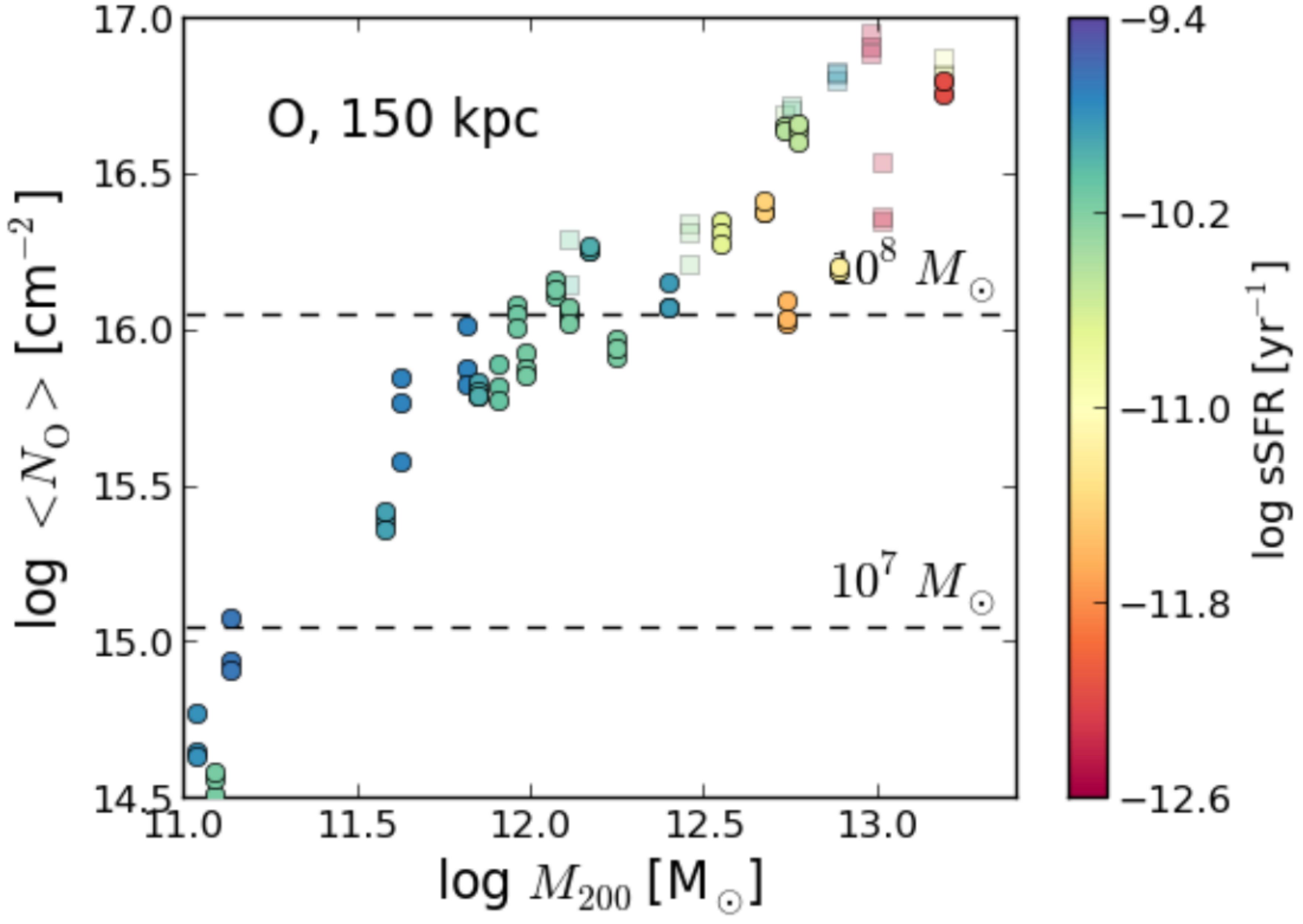

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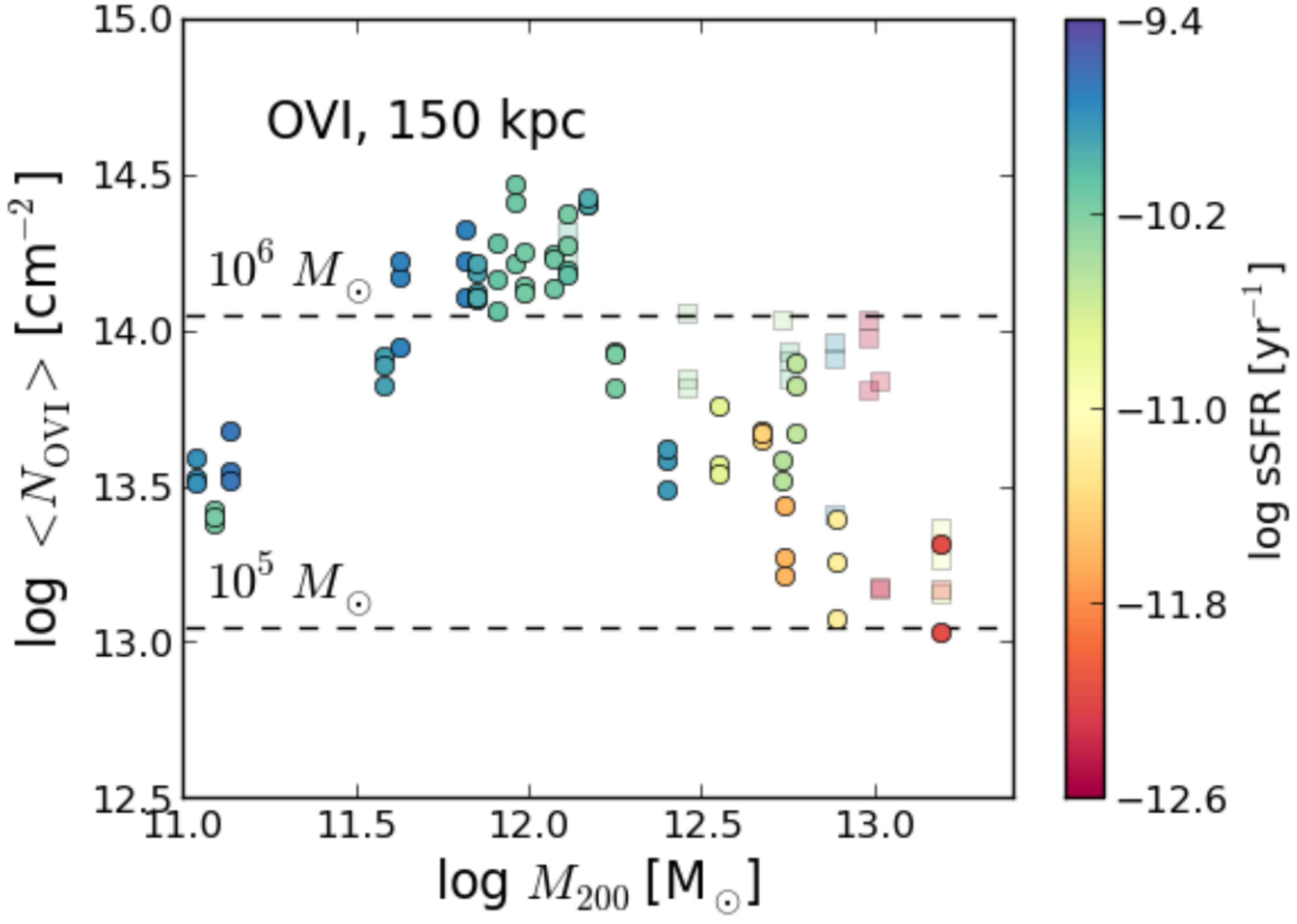
$T \sim 10^{5.5}$K



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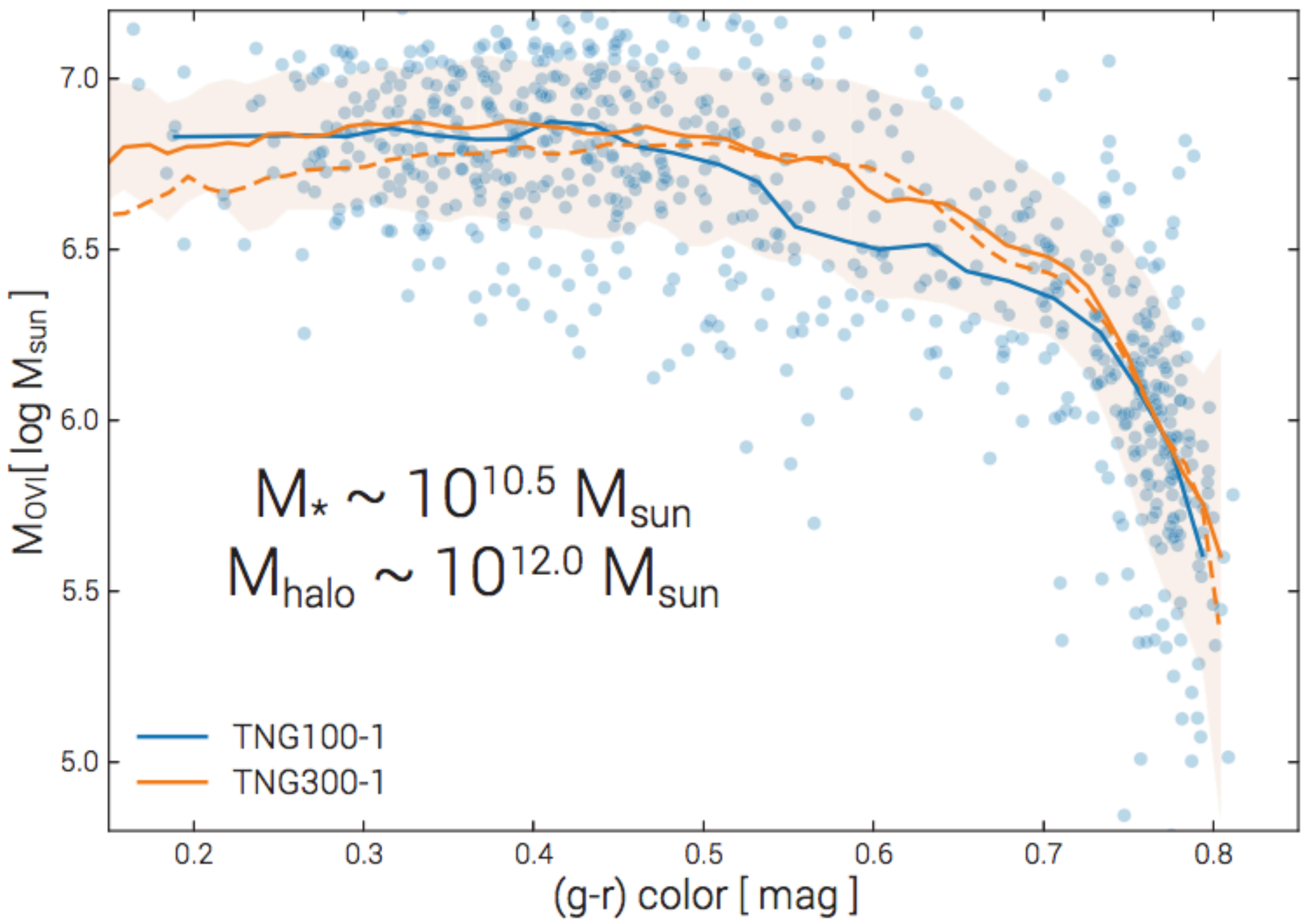
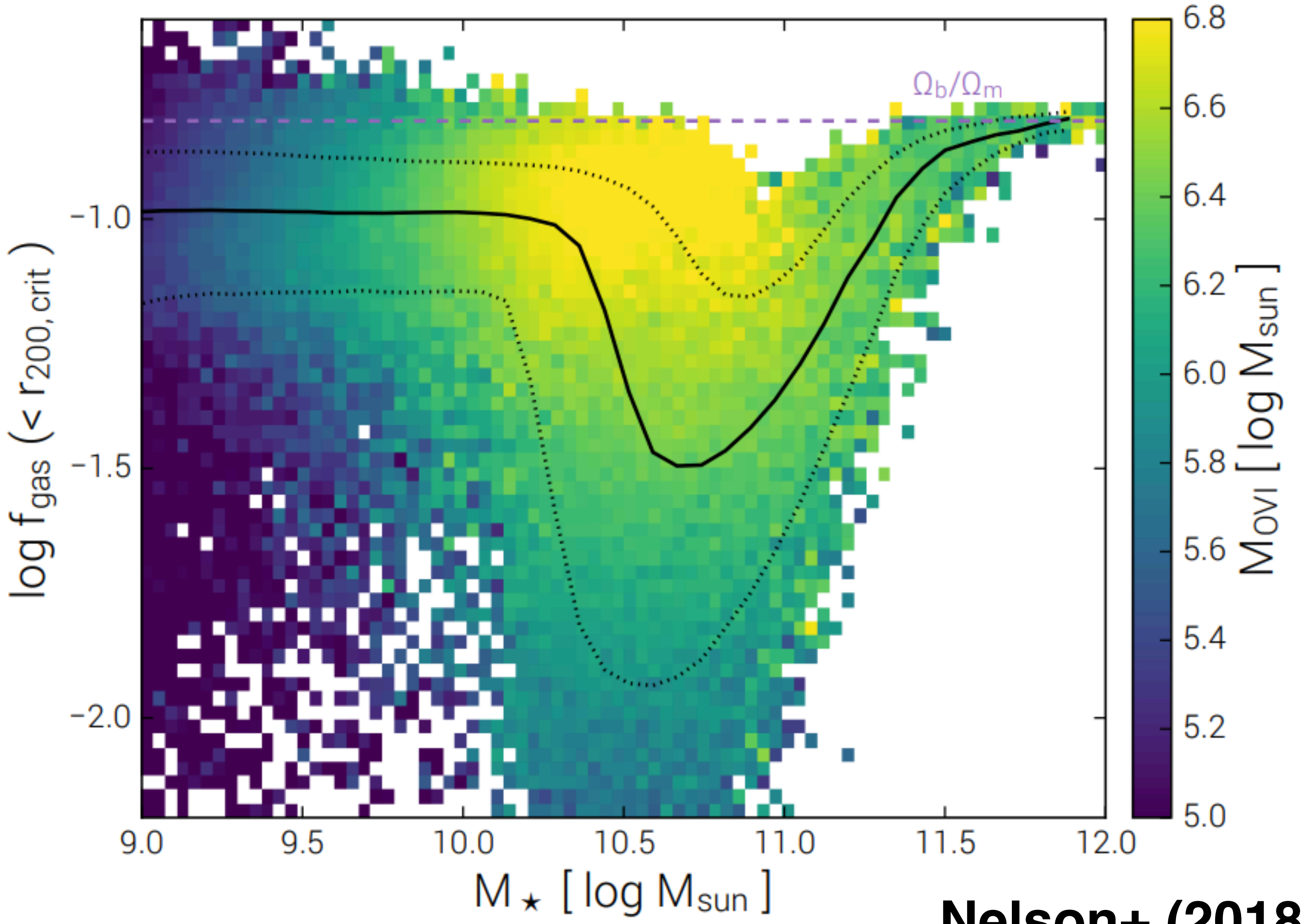
Illustris-TNG: bimodality is a signature of metal ejection by central AGN





Nelson+ (2018)

IllustrisTNG reveals a strong trend of CGM OVI mass with colour at *fixed mass* (*~L).**

Diversity of OVI mass reflects diversity of halo gas fractions, which are driven by low-redshift behaviour of the AGN.

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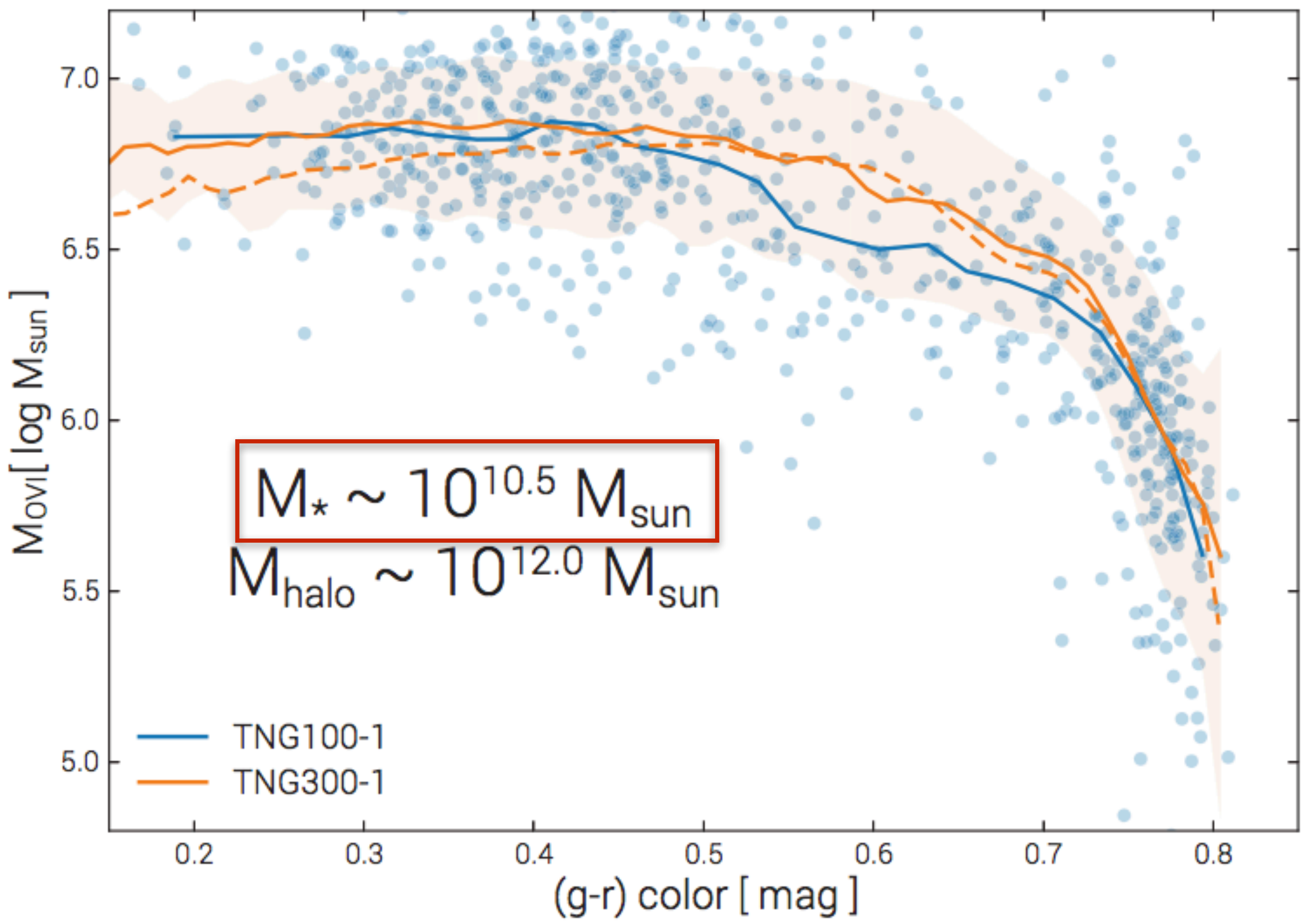
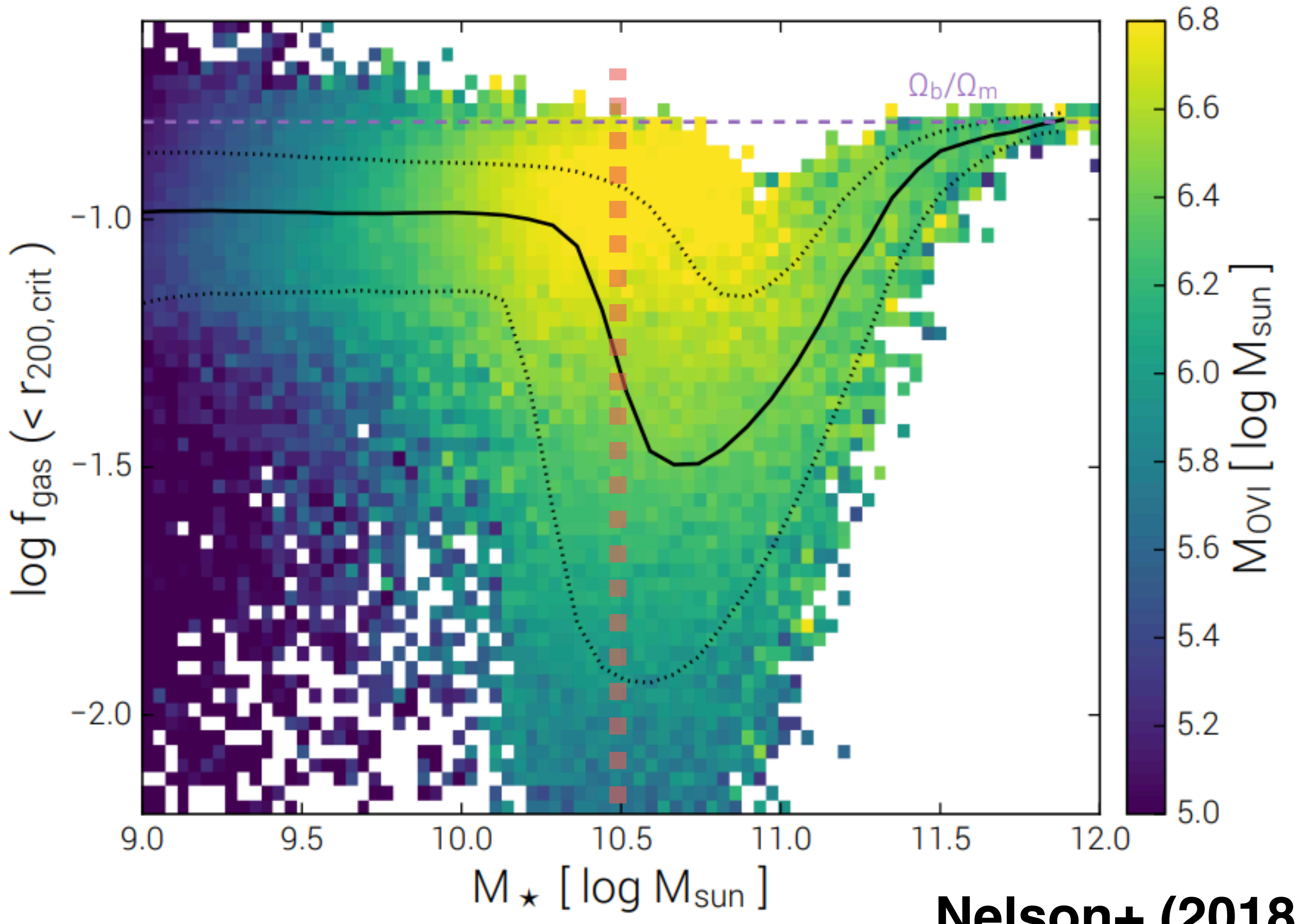
Illustris-TNG: bimodality is a signature of metal ejection by central AGN





Nelson+ (2018)

IllustrisTNG reveals a strong trend of CGM OVI mass with colour at *fixed mass* (*~L).**

Diversity of OVI mass reflects diversity of halo gas fractions, which are driven by low-redshift behaviour of the AGN.

Heading further afield: the CGM traced by metal lines

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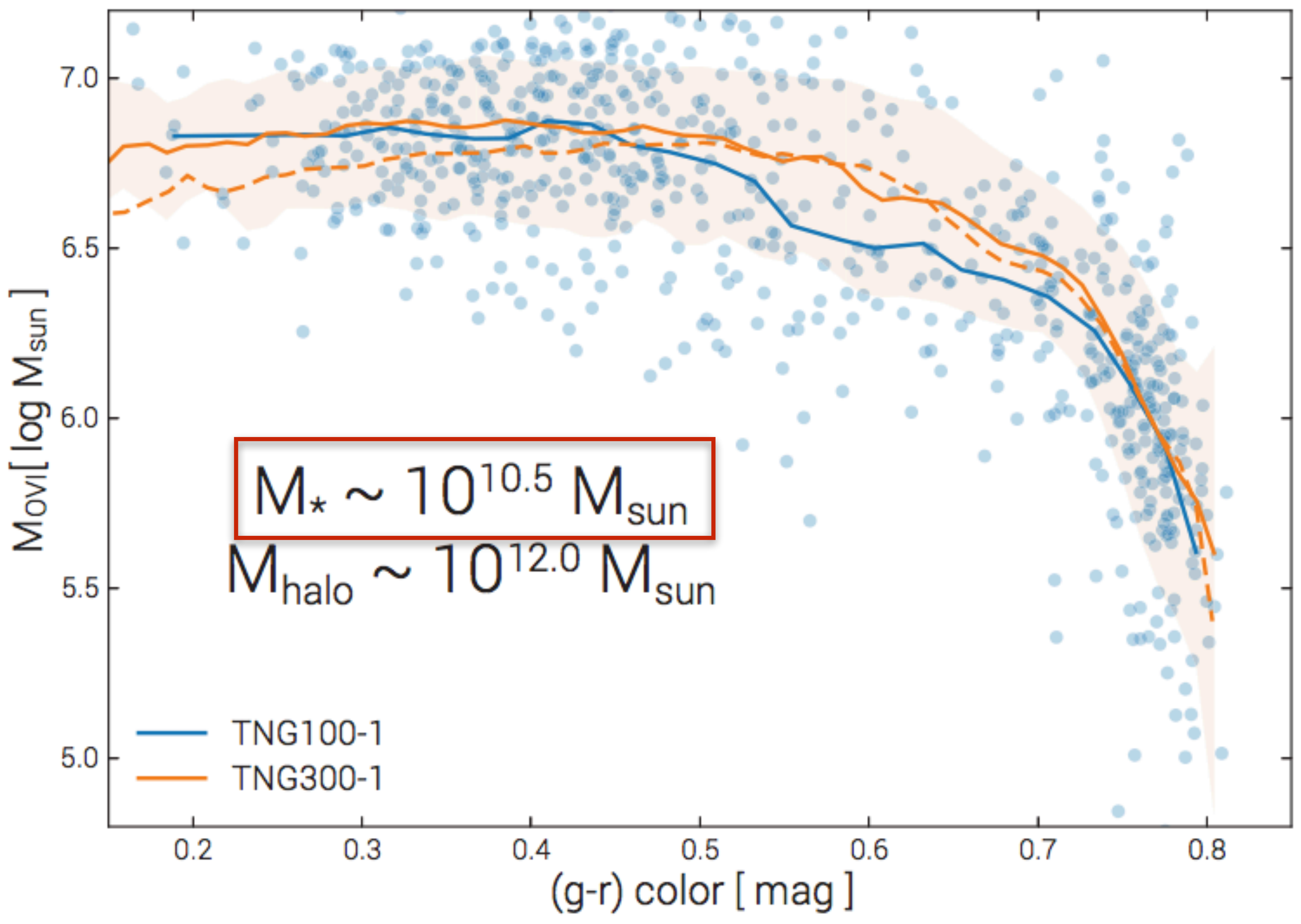

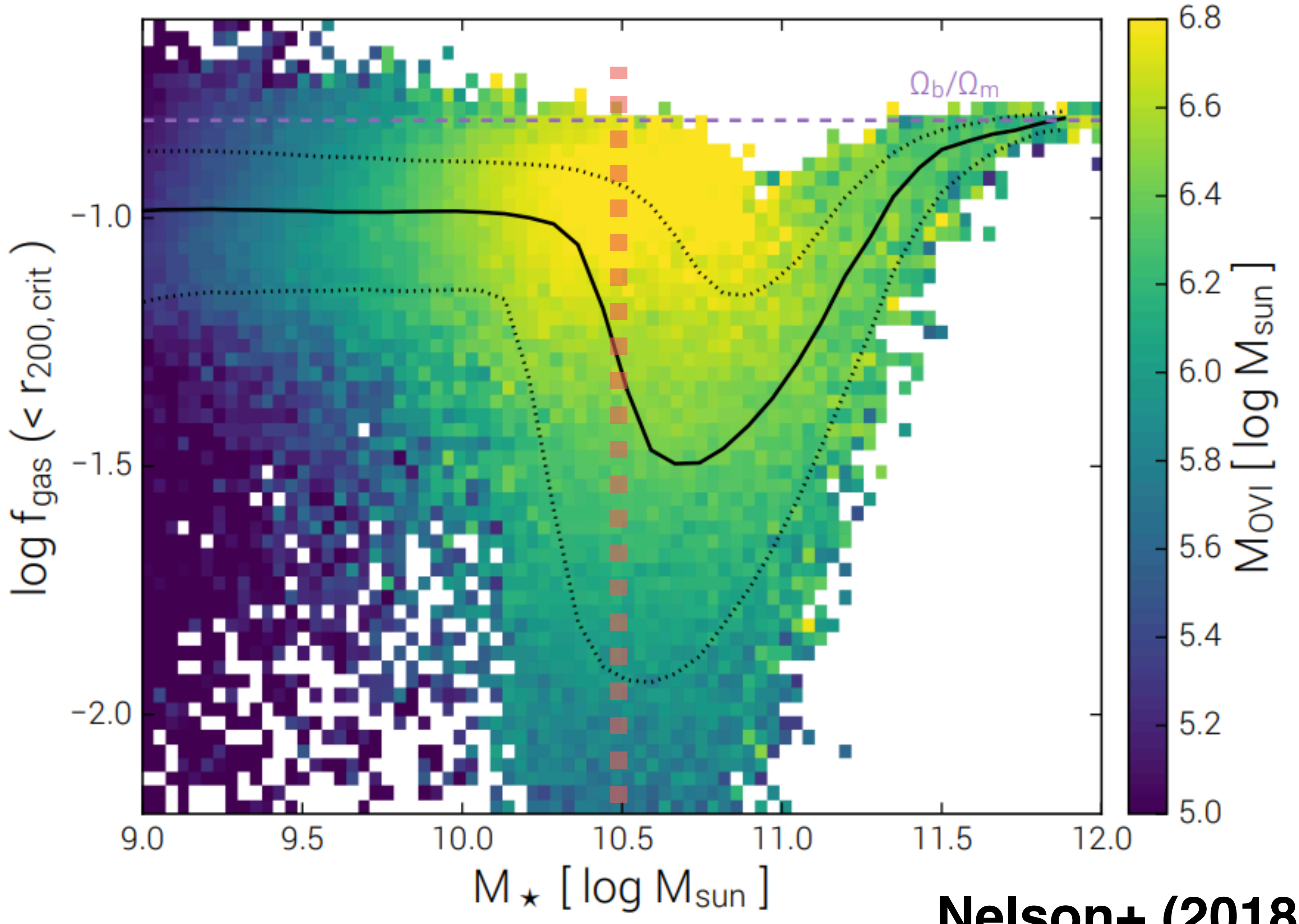

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Diversity of OVI mass reflects diversity of halo gas fractions, which are driven by low-redshift behaviour of the AGN.

In neither case is the OVI a signature of *recent* star formation. These are *predictions* of the simulations, testable with f_{gas} measurements.

A closer look at influences on the halo gas fraction in EAGLE

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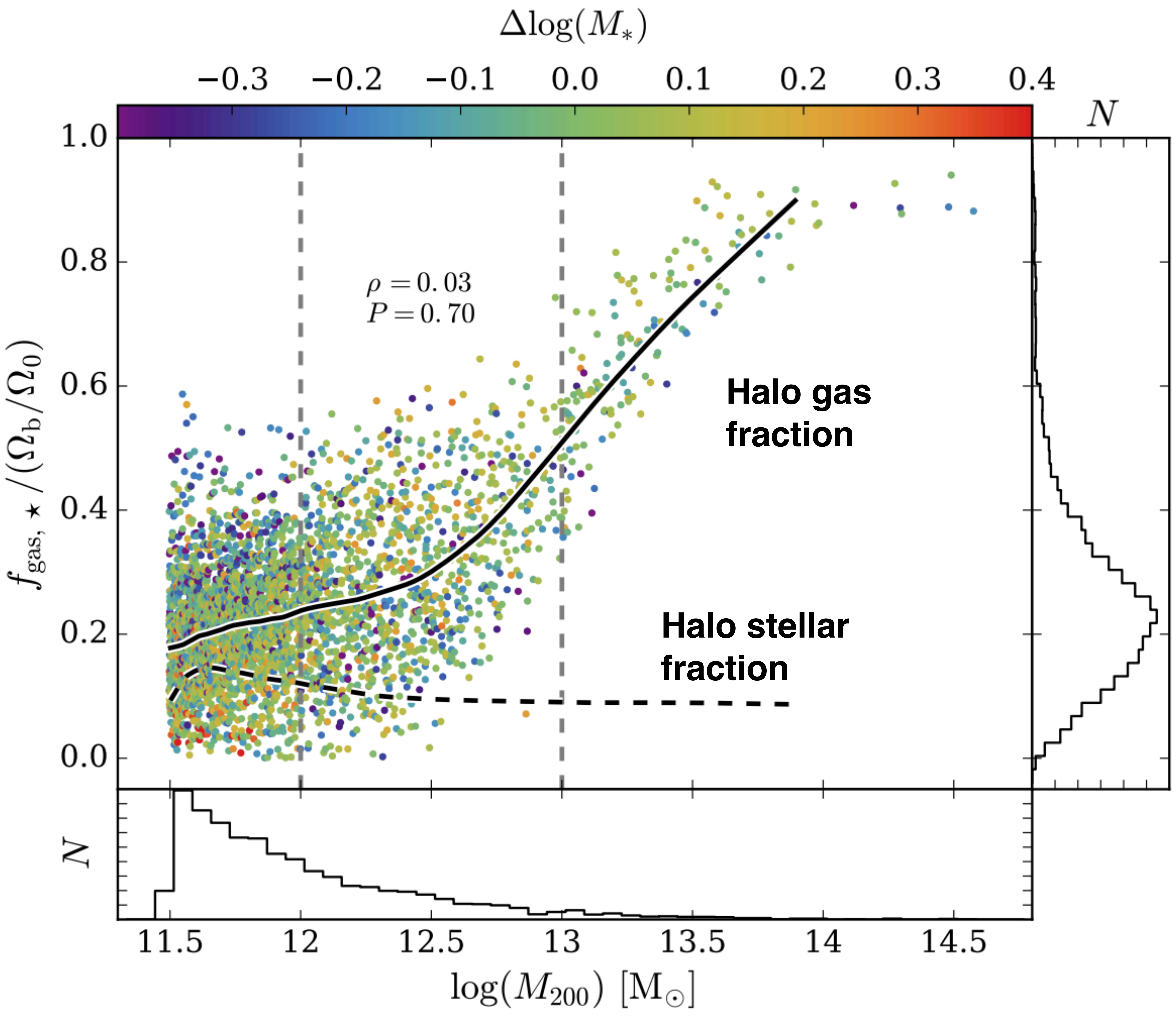

EAGLE haloes are baryon depleted below $M_{200} \sim 10^{14} M_{\rm Sun}$. Very definitely not closed-boxes.

Ejection of baryons is key to EAGLE's regulation and quenching of star formation.

Deviations of $f_{\rm gas}$ from the running-median at fixed M_{200} do not correlate with stellar mass.

In general, more gas is ejected than turns into stars.

Jon Davies, RAC *in prep*

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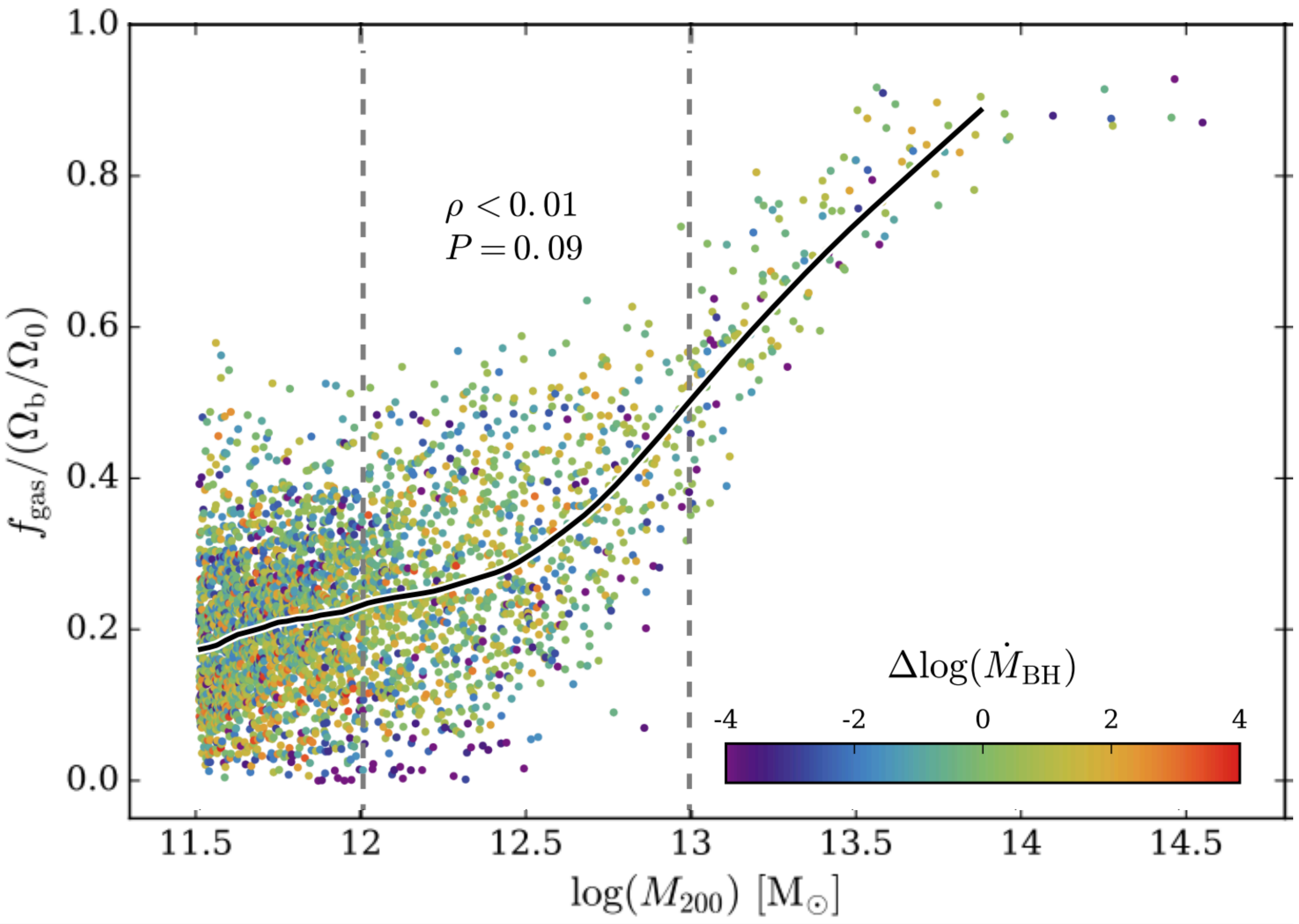

Interestingly the deviations do not correlate with the black accretion rate either (i.e. the rate of energy injection from the central AGN).

NB: this is consistent with recent findings of COS-AGN survey (Berg et al. 2018).

Jon Davies, RAC *in prep*

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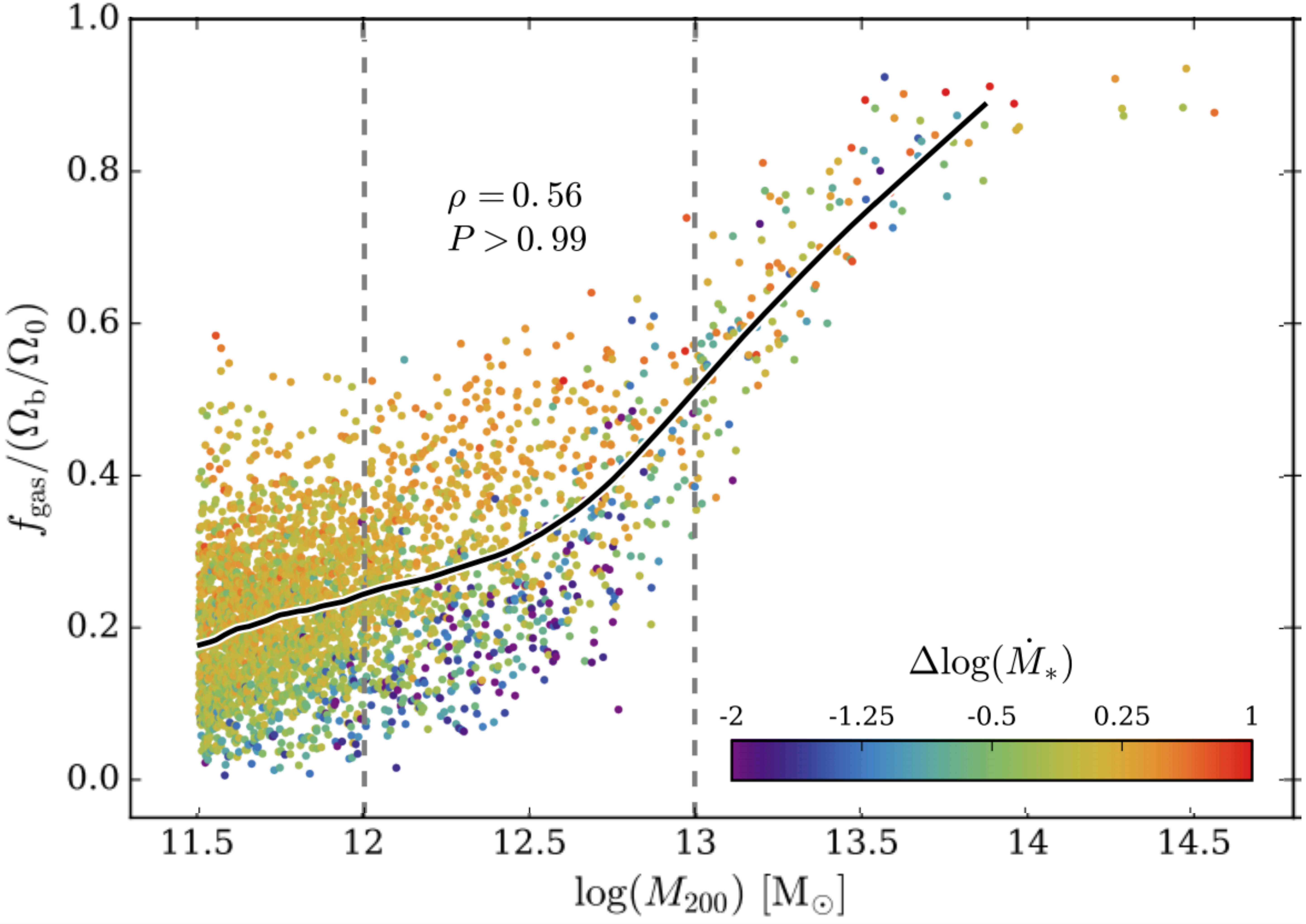

The deviations do correlate with the SFR (and hence SF-driven feedback)…

…interestingly the correlation is *positive*.

Galaxies with more SF, and so more SF-feedback, have *higher* gas fractions.

Jon Davies, RAC *in prep*

A closer look at influences on the halo gas fraction in EAGLE

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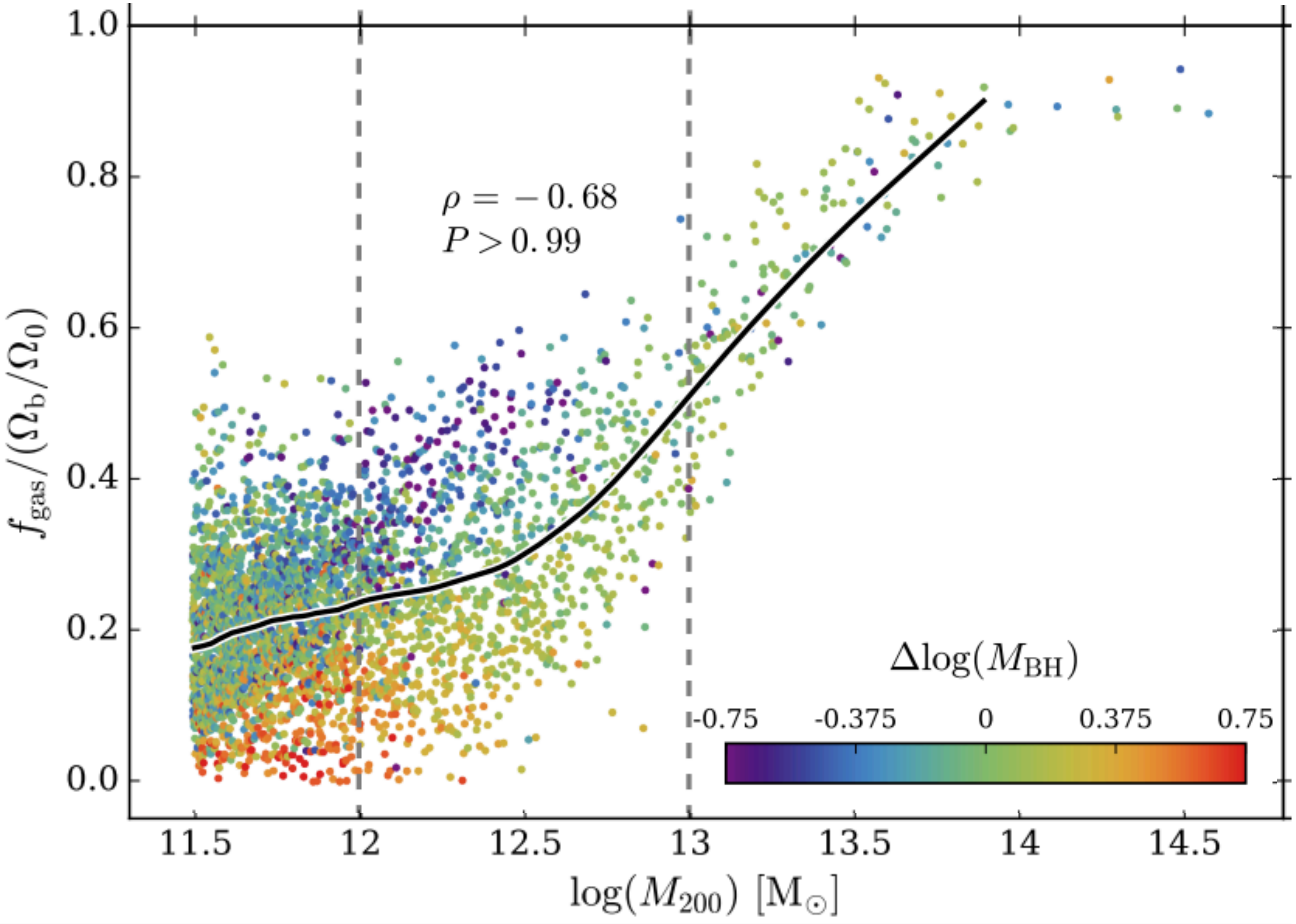


Higher SFR is a *consequence* of the galaxy/halo being gas-rich.

These systems are necessarily regulated by SF because their BHs are underweight and AGN feedback is ineffective.

Conversely the central galaxies of gas-poor haloes host atypically-massive BHs.

The diversity of BH masses at fixed M_{200} is governed by halo concentration & collapse time.

The gas fraction tells you when the halo collapsed (!!!).

Summary

Now in an era where cosmological simulations reproduce the basic demographics the galaxy population (NB based on KS law!)

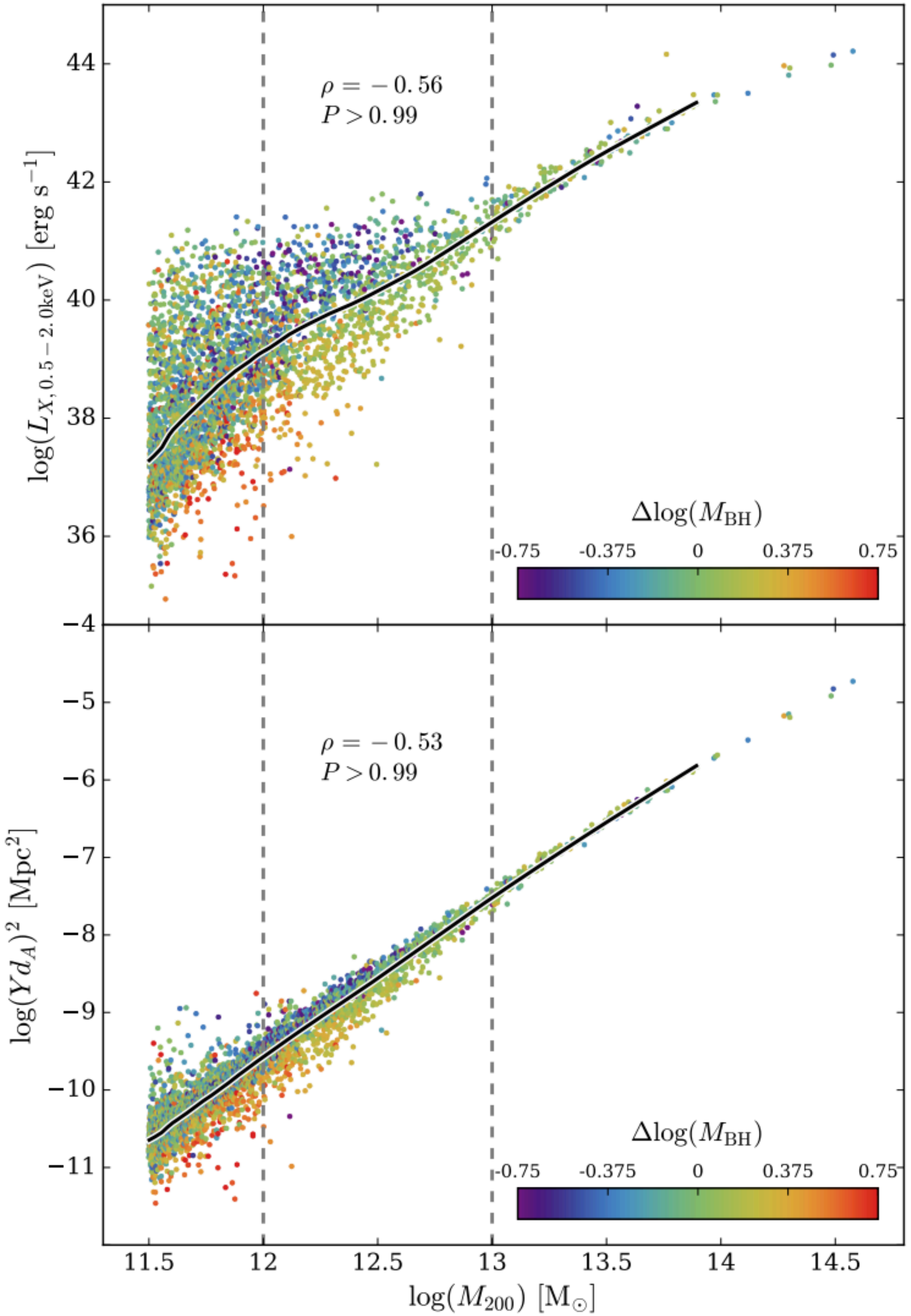
Success of current generation of galaxy population simulations built on well-posed initial conditions and calibration of feedback efficiencies.

ISM properties require higher-resol than stellar properties to realise realistic and converged properties in low-mass galaxies e.g. M_{HI}-M^*, HIMF.

Particular strengths of numerical approach is examination of sensitivities of scaling relations and impact environmental influences.

CGM harbours discriminatory power, e.g. EAGLE and Illustris-TNG reproduce (with calibration) the N_{OVI}-sSFR distribution for different reasons.

EAGLE shows scatter in halo gas fractions (which govern inflow rate) at fixed halo mass is set by BH mass.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$P > 0.99$
$\log(L_{X,0.5-2.0\mathrm{keV}})$ [erg s^{-1}]
44
42
40
38
36
$\Delta\log(M_{\rm BH})$
-0.75
-0.375
0
0.375
0.75
$\rho = -0.53$
$P > 0.99$
$\log(Y d_A)^2$ [Mpc^2]
−4
−5
−6
−7
−8
−9
−10
−11
$\Delta\log(M_{\rm BH})$
-0.75
-0.375
0
0.375
0.75
11.5
12
12.5
13
13.5
14
14.5
$\log(M_{200})$ [M$_\odot$]