The processes that shape the galaxy population in numerical simulations

A flavour of how current simulations are set up, and the problems that can be addressed with them.

Rob Crain
Liverpool John Moores University
(with thanks to colleagues from the EAGLE team)

liverpool JMU

THE ROYAL SOCIETY

* Expectation management *

All models incorporate compromises. No single model will ever reproduce all observable properties of the population.

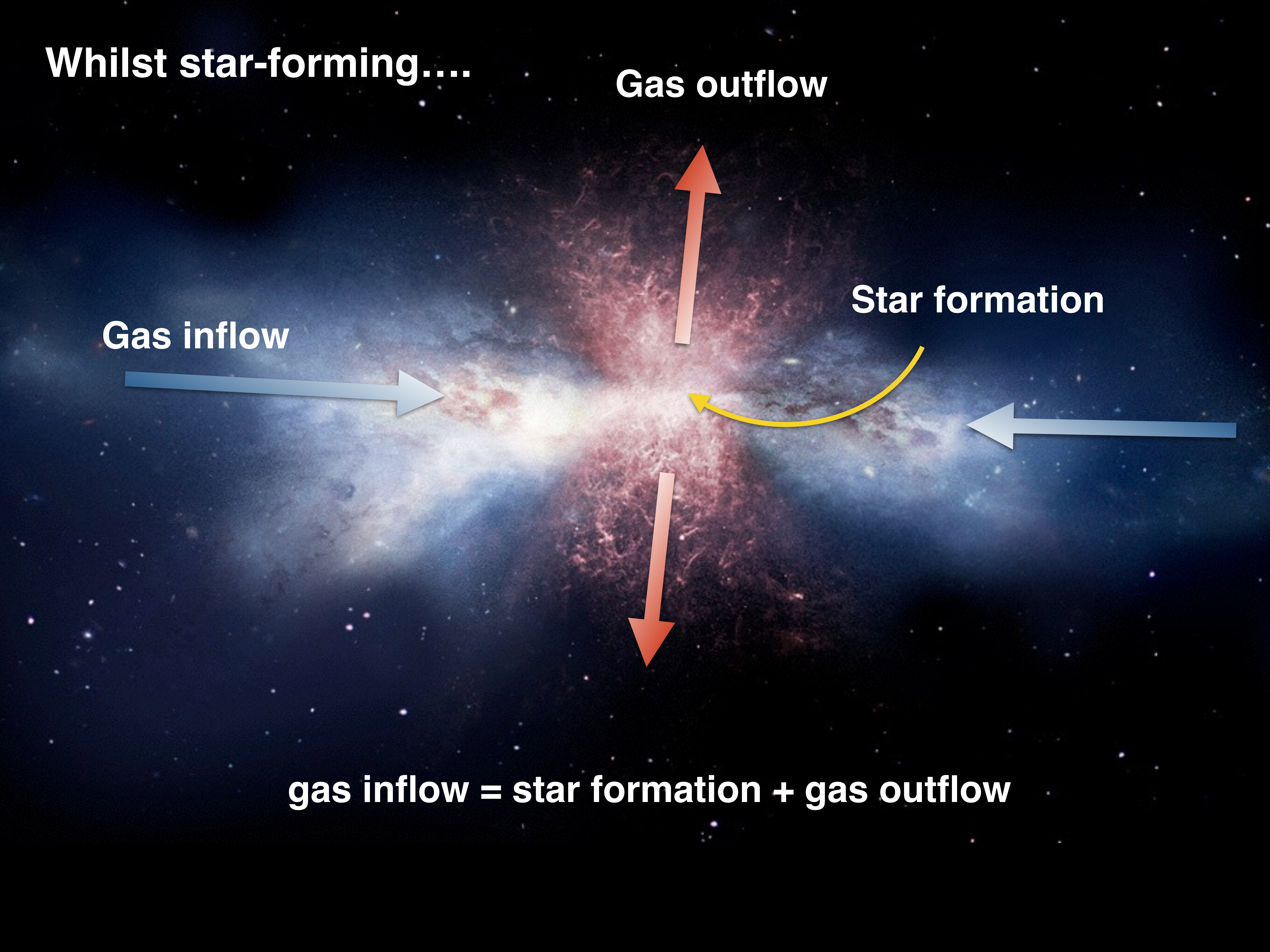
To model a representative galaxy population, we have to impose phenomenology when gas cools to $T \sim 10^4$K, at densities of $n_H \sim 0.1$ cm^{-3}, i.e. the photoionised ISM.

The Jeans length of such gas is $L \sim 1$kpc. Galaxy structure (esp. vertically) and kinematics will be unavoidably coarse.

Two main options:

1) Attack the myriad problems relating to the evolving, coarse properties of galaxies in a cosmological context.

2) Try to model colder, denser gas (and the associated additional physics) in idealised cases or individual zooms.


Whilst star-forming….
Gas outflow
Star formation
Gas inflow
gas inflow = star formation + gas outflow

On the road to quenching…

BH accretion = BH growth + rest mass-driven outflow

Consequences of these eqns.

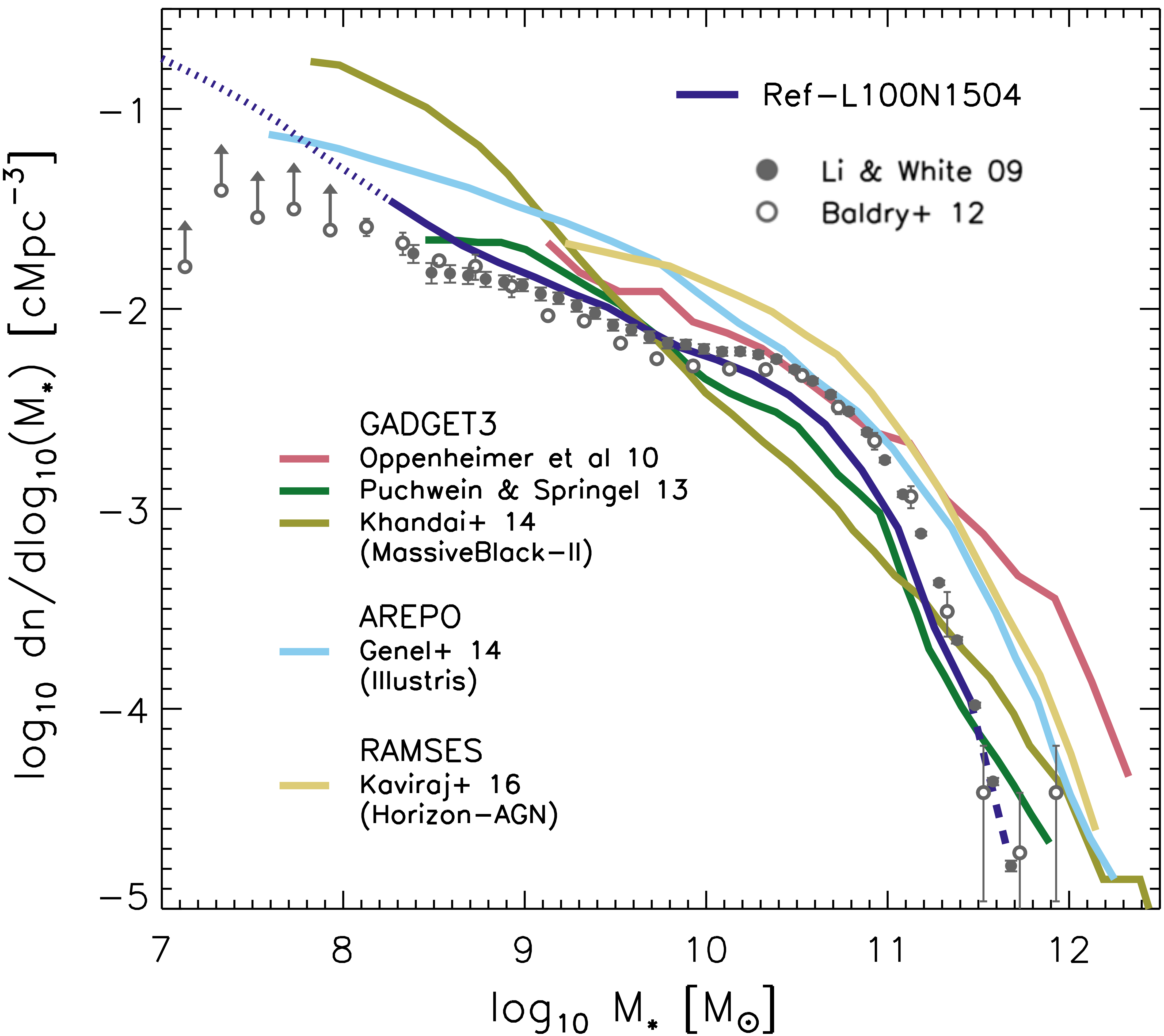
To predict the stellar mass of galaxies, we need to *know* the efficiency of the SF-driven feedback.

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

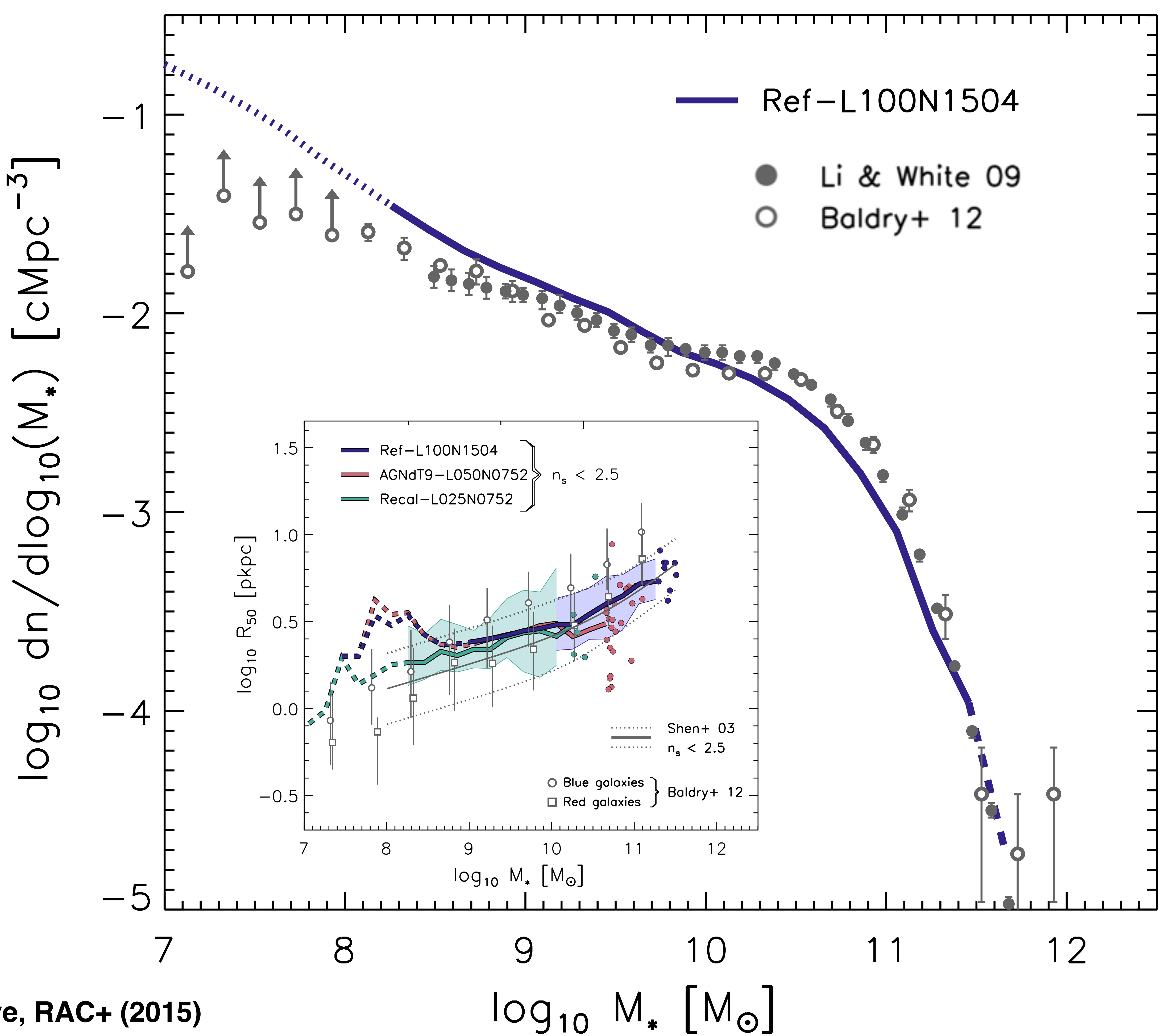
The efficiencies are determined by ISM microphysics: ab initio calculation is way beyond the scope of current simulations.

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

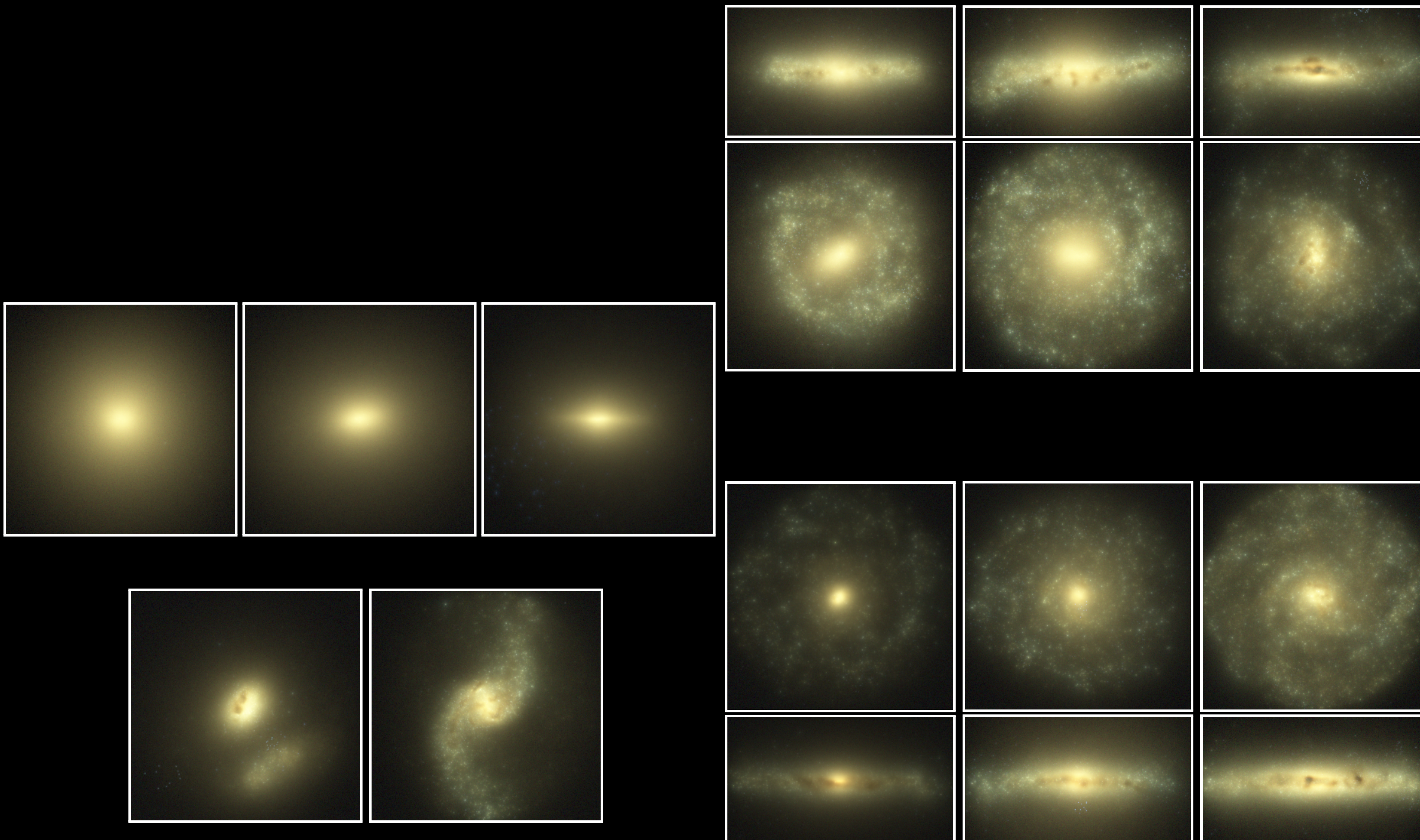
How well can we calibrate?



Ref−L100N1504
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
log10 dn/dlog10(M*) [cMpc−3]
log10 M* [M⊙]

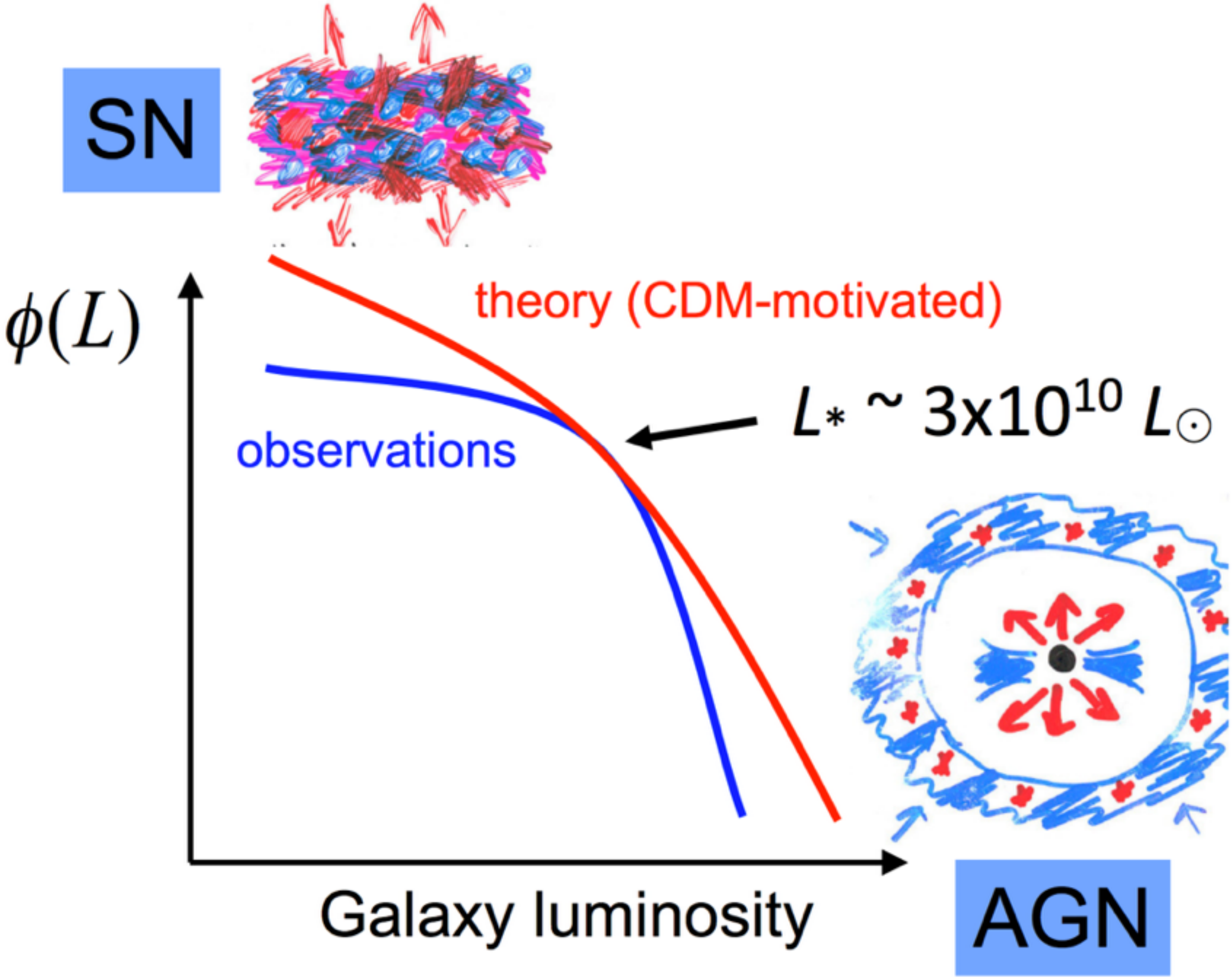


Schaye, RAC+ (2015)

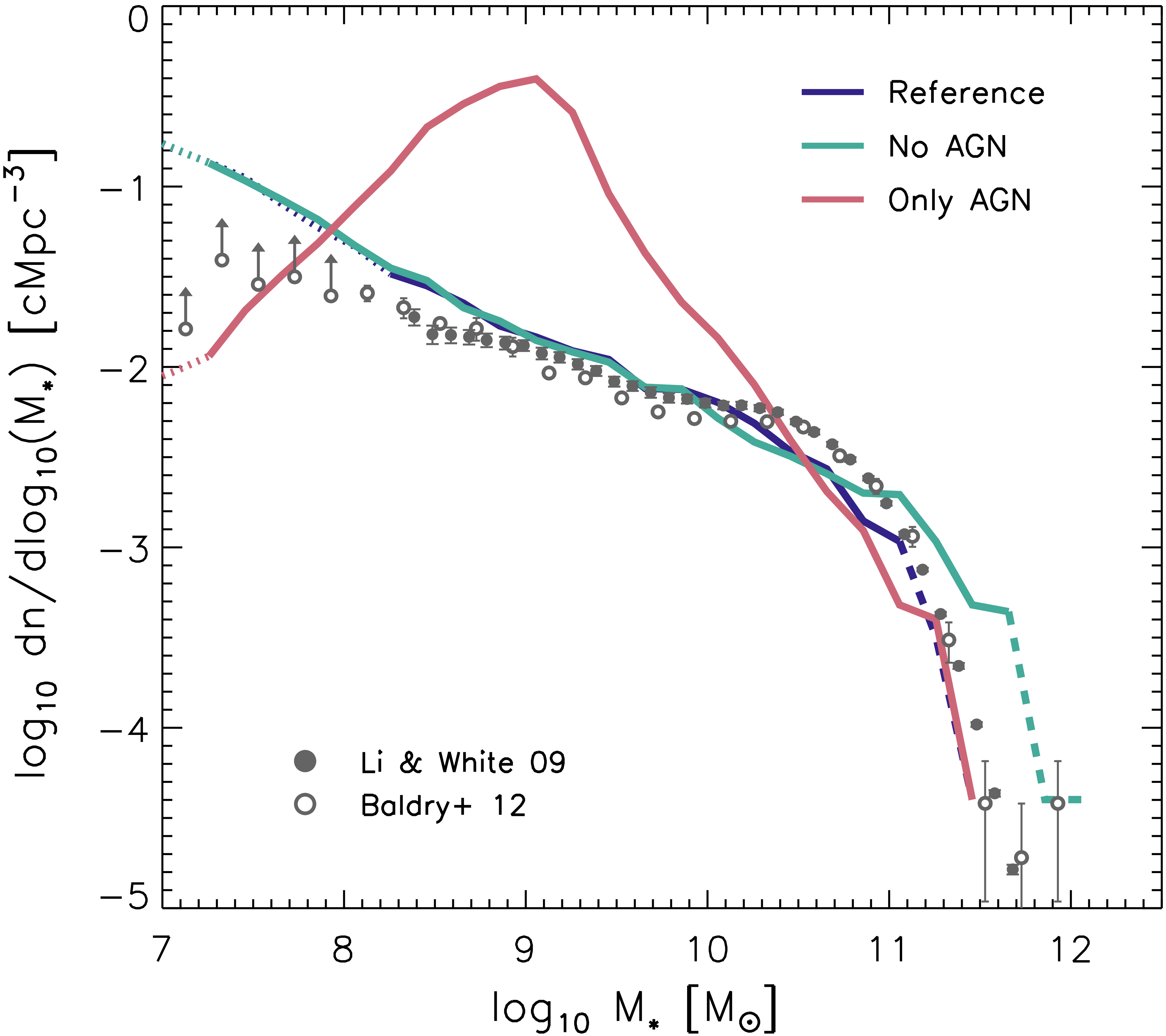


Schaye, RAC+ (2015)

The numerical laboratory



Silk & Mamon (2012)



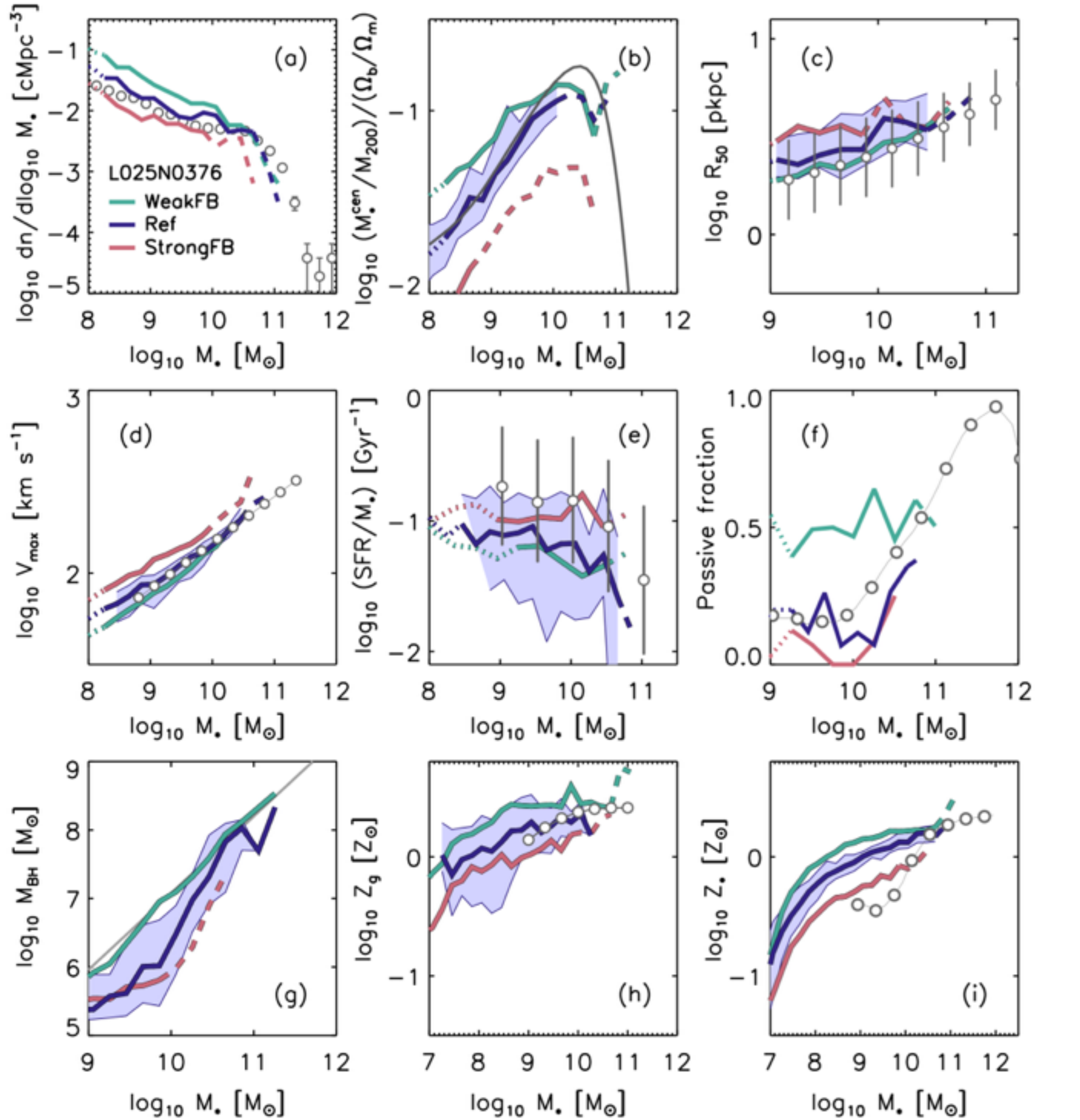
Reference
No AGN
Only AGN
Li & White 09
Baldry+ 12
log10 dn/dlog10(M*) [cMpc^-3]
log10 M* [M⊙]
0
−1
−2
−3
−4
−5
7
8
9
10
11
12

Varying SF-driven feedback efficiency by a factor of 2 has a dramatic influence on broad range of scaling relations.

Recall that this shifts the balance between star formation and gas ejection.

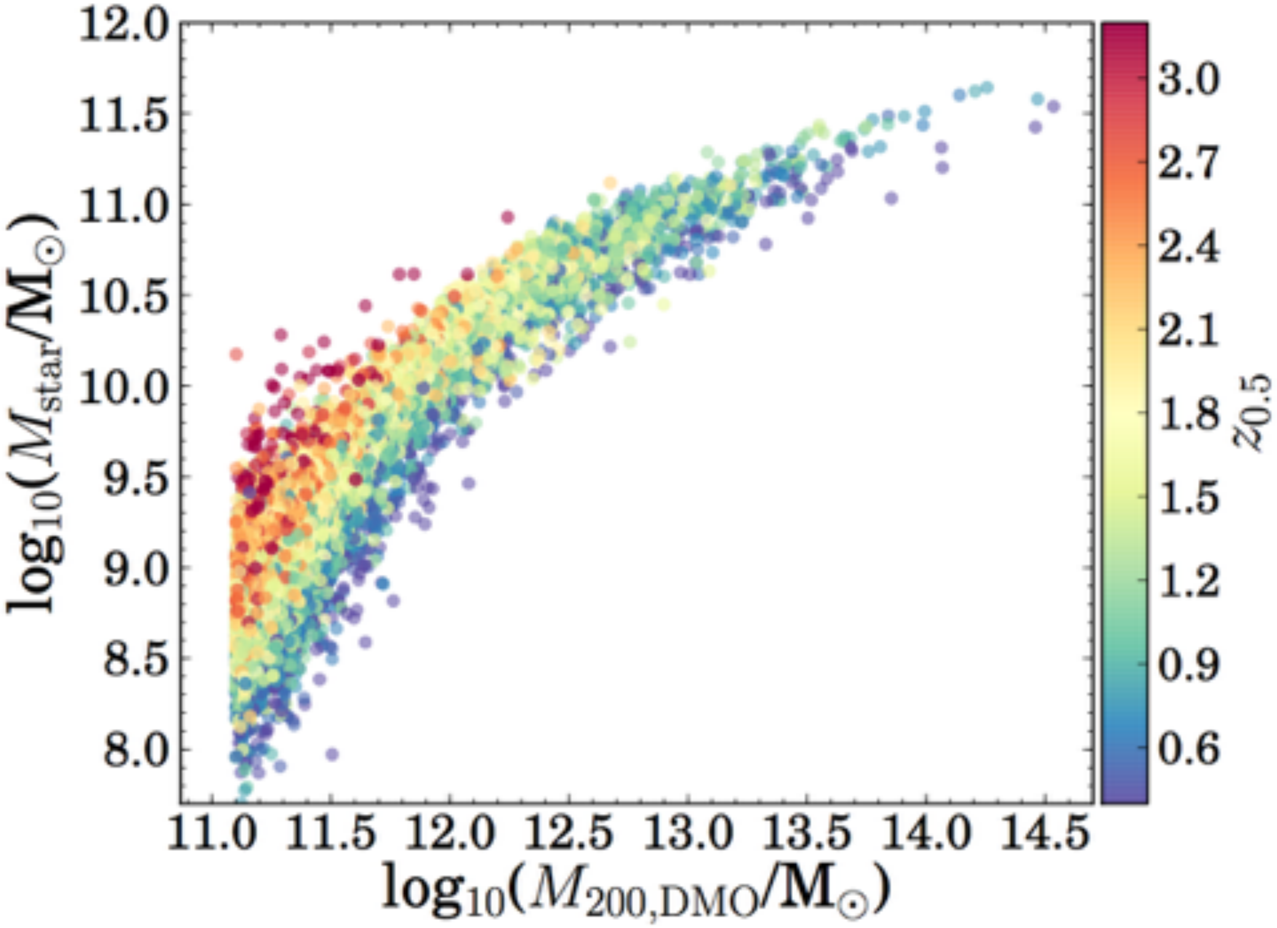
Relations have significant scatter:

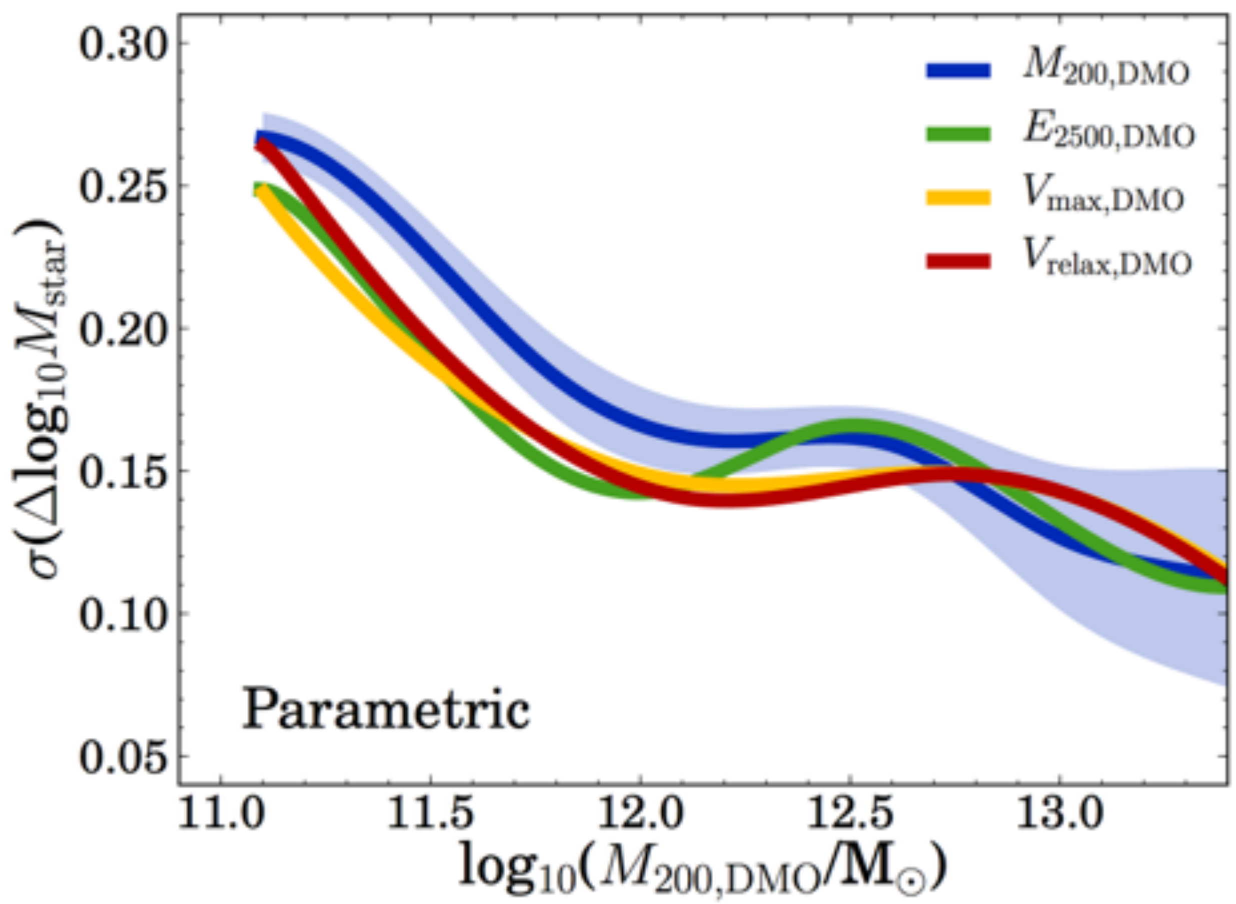
Focussing on zooms alone precludes examination of the origin of scatter, and offers no guarantee the candidate galaxy is representative.



RAC+ (2015)

Scatter in galaxy scaling relations





At fixed halo mass, galaxies form more stars if the halo collapses at higher redshift (and so has a higher concentration).

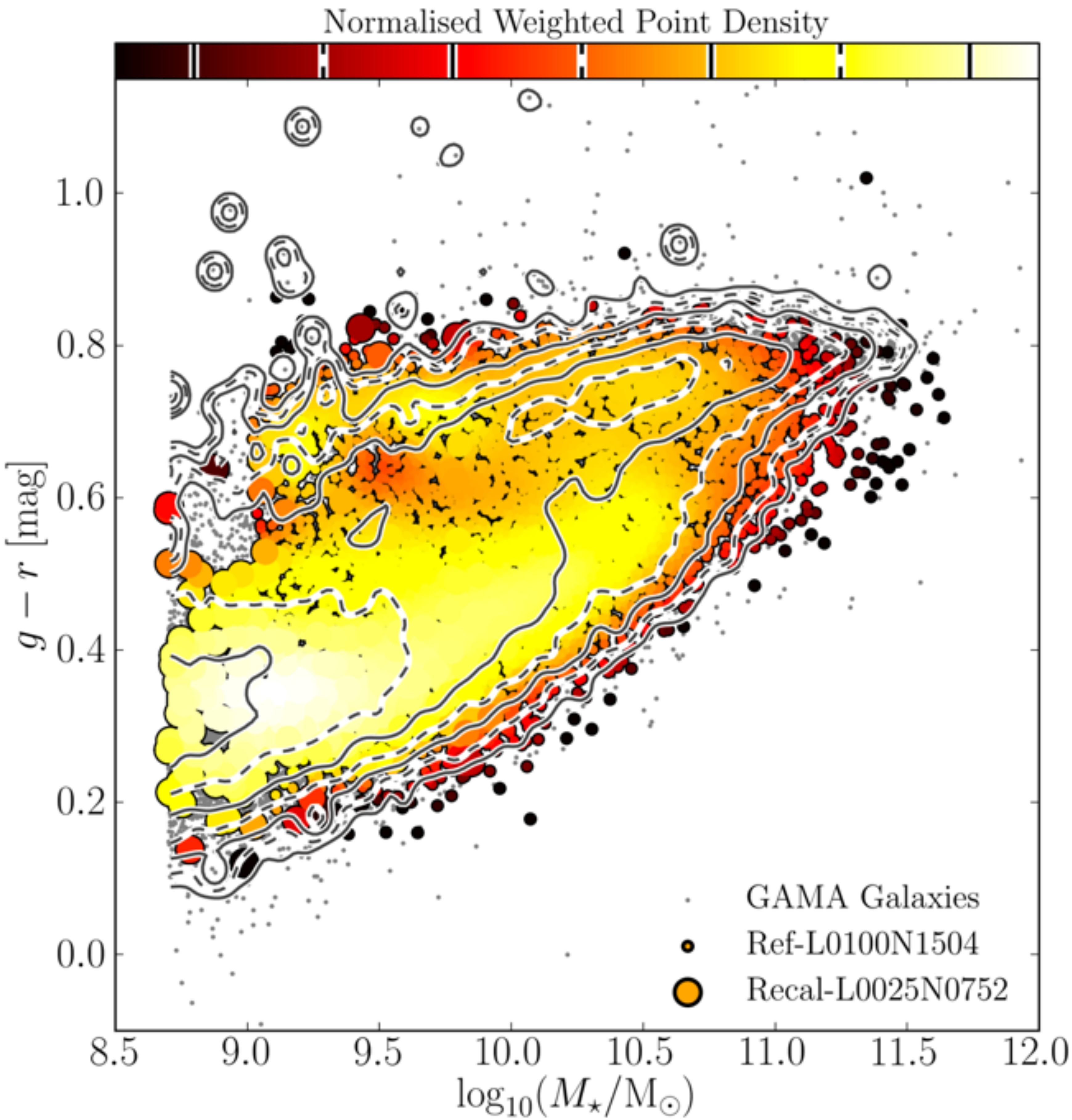
More time for stars to form, and the potential is deeper, making feedback less efficient.

Halo mass is a relatively poor 'predictor' of stellar mass: the scatter in $M_{\rm star}$ at fixed $M_{\rm halo}$ is significantly reduced if predicted from a fit to the $M_{\rm star}$ with some velocity-based quantity.

This is because such quantities are a combination of both mass and concentration.

Matthee, RAC+ (2016)

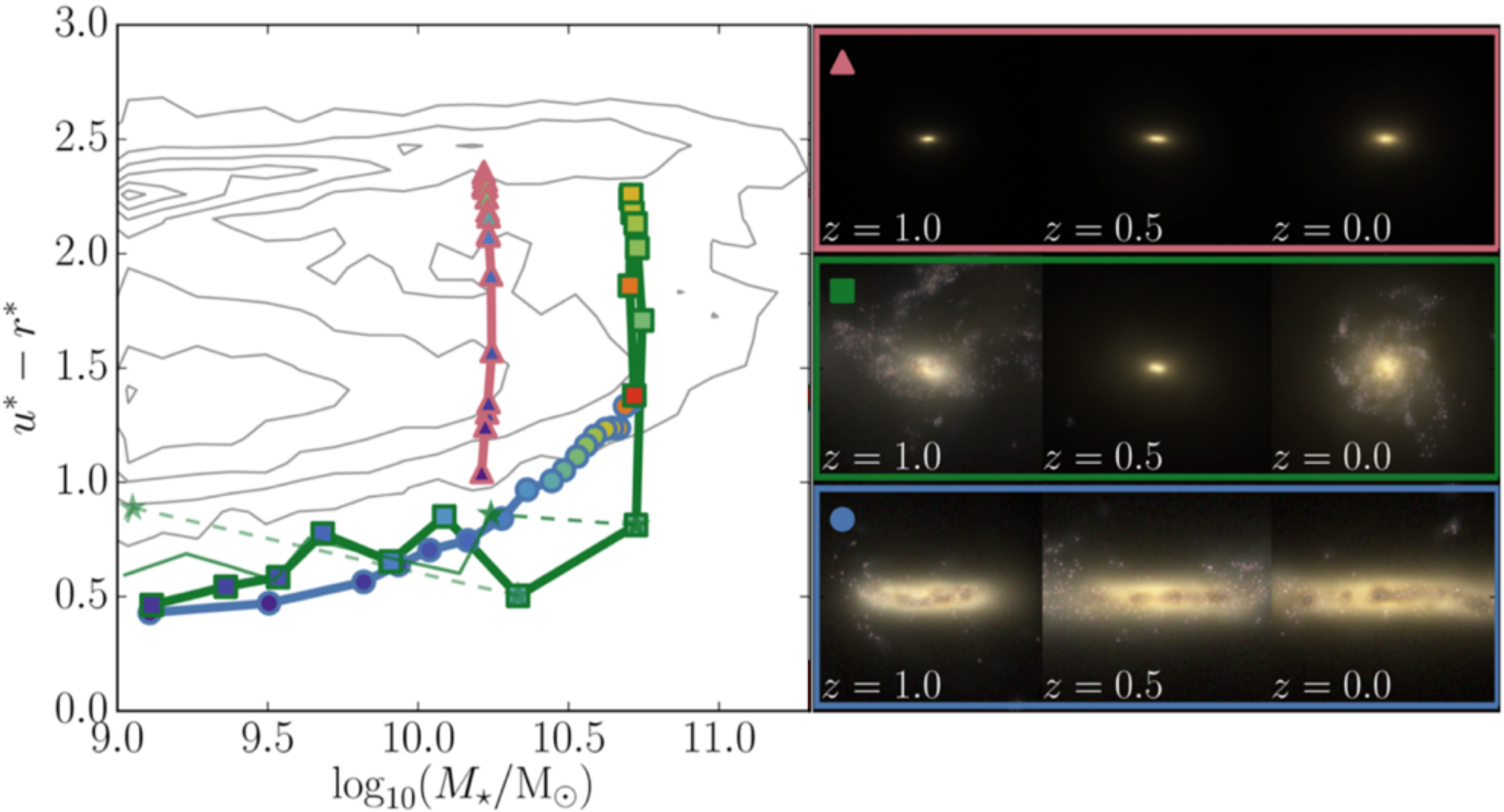
Changing faces



Trayford, RAC+ (2015)

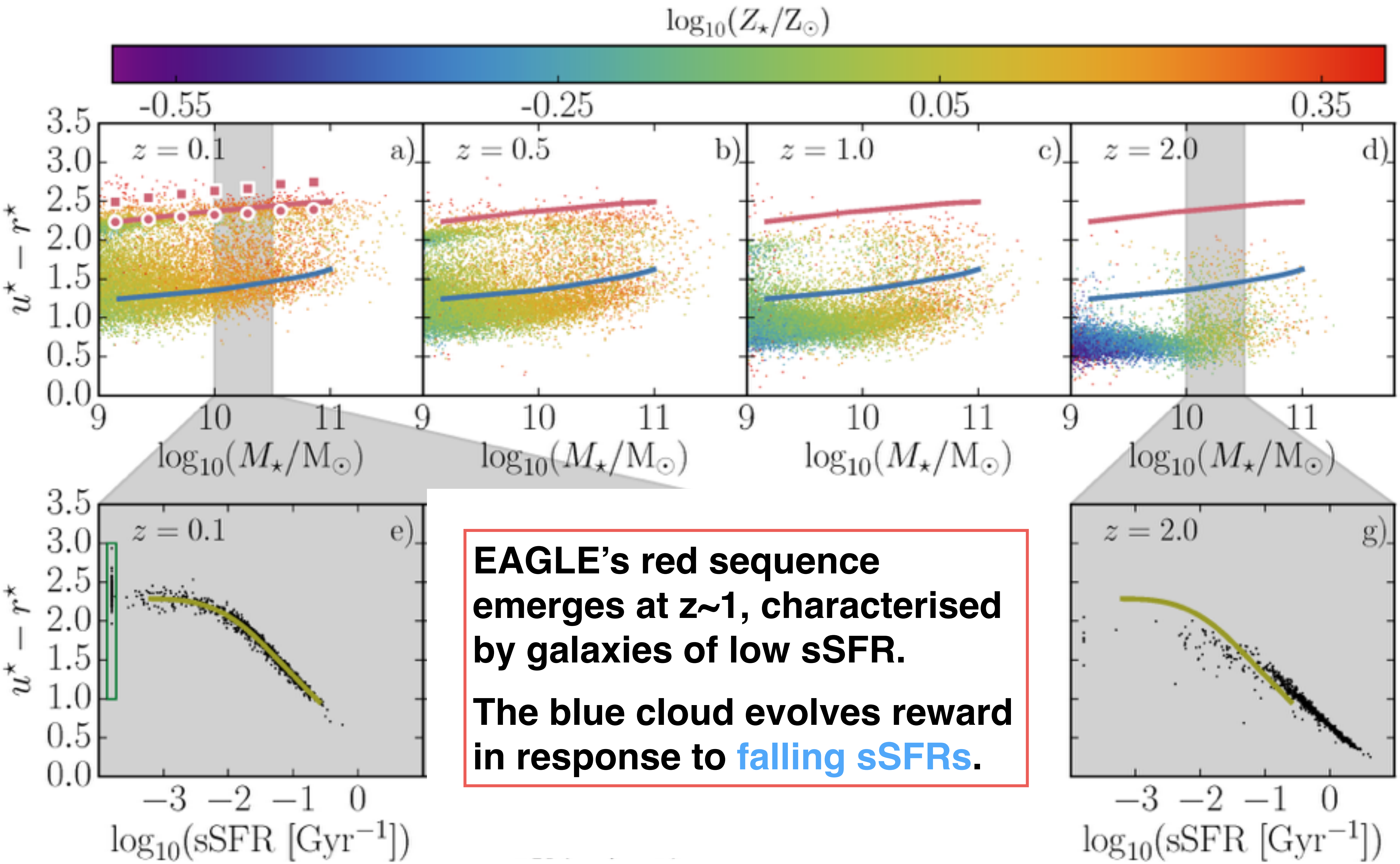
The diverse pathways by which faces change

Trayford, RAC+ (2016)



1) Disc galaxy remaining in the blue cloud (blue circles)
2) Quenching galaxy migrating onto the red sequence (red triangles);
3) Red sequence galaxy rejuvenating into the blue cloud (green squares).

Trayford, RAC+ (2016)



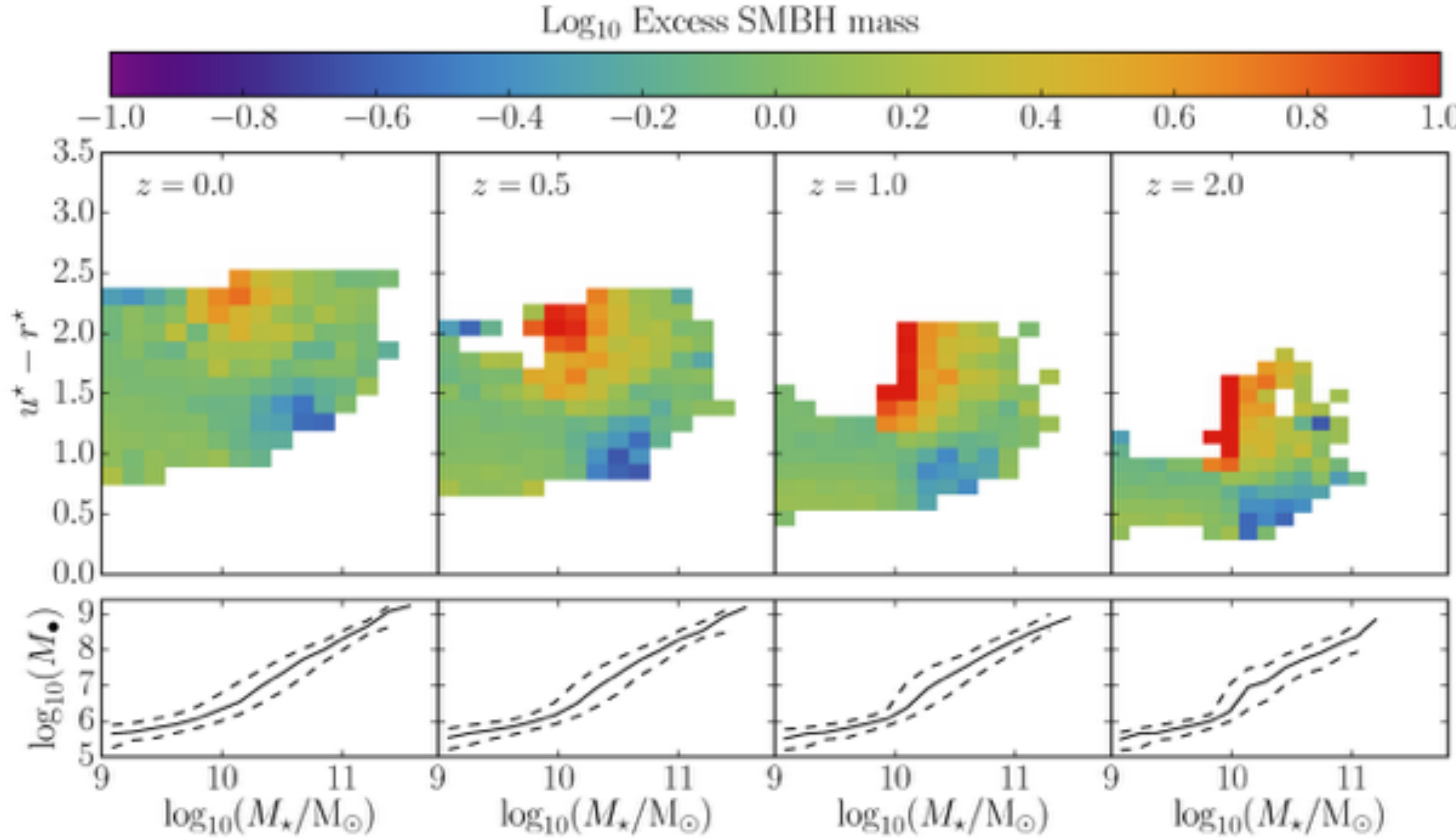
EAGLE's red sequence emerges at z~1, characterised by galaxies of low sSFR.

The blue cloud evolves reward in response to falling sSFRs.

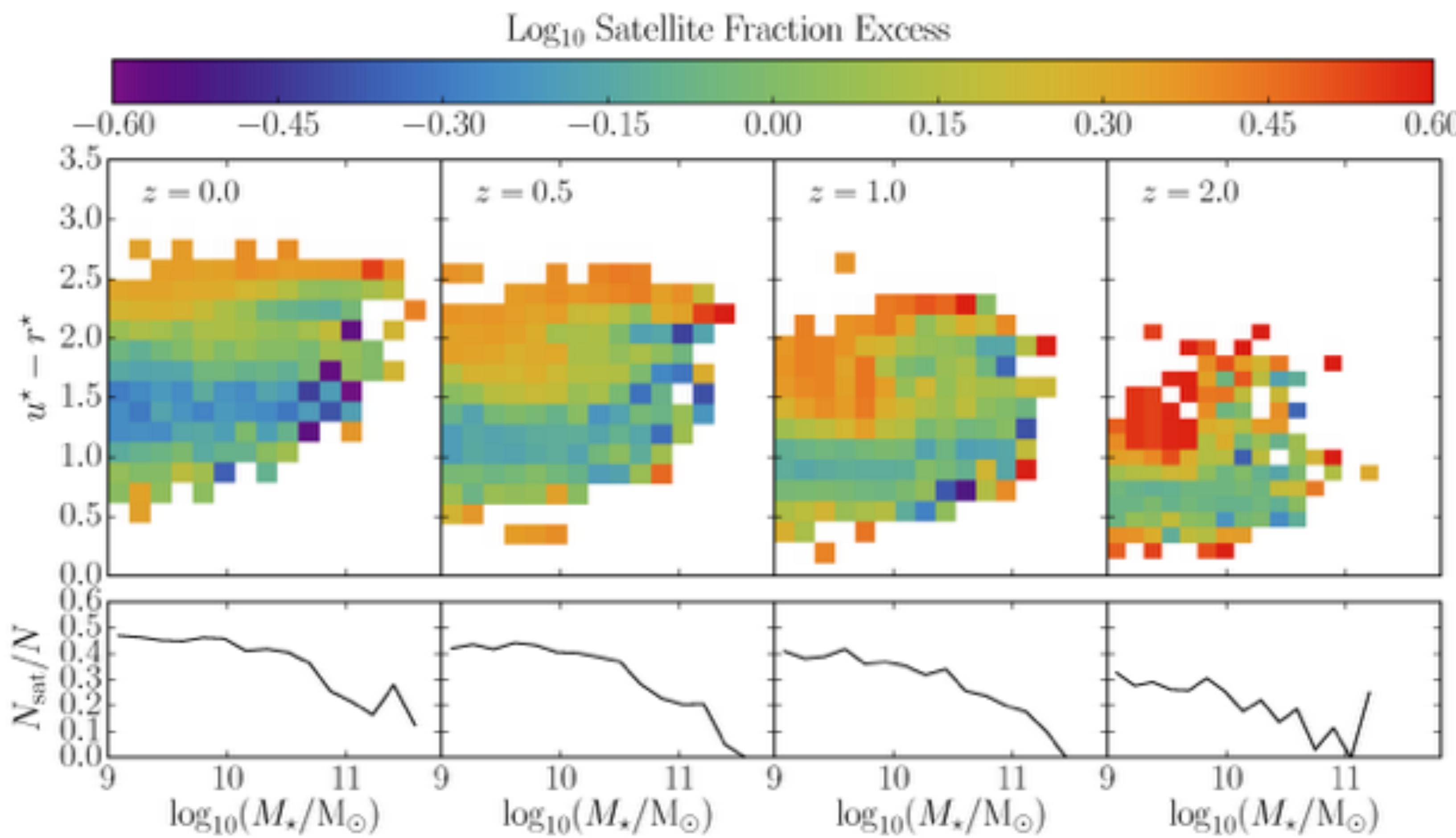
The red sequence builds up from both ends, indicating that low- and high-mass galaxies are quenching co-temporally. Why?

The high-mass passive galaxies host massive BHs.

The reddest examples have the most massive BHs.



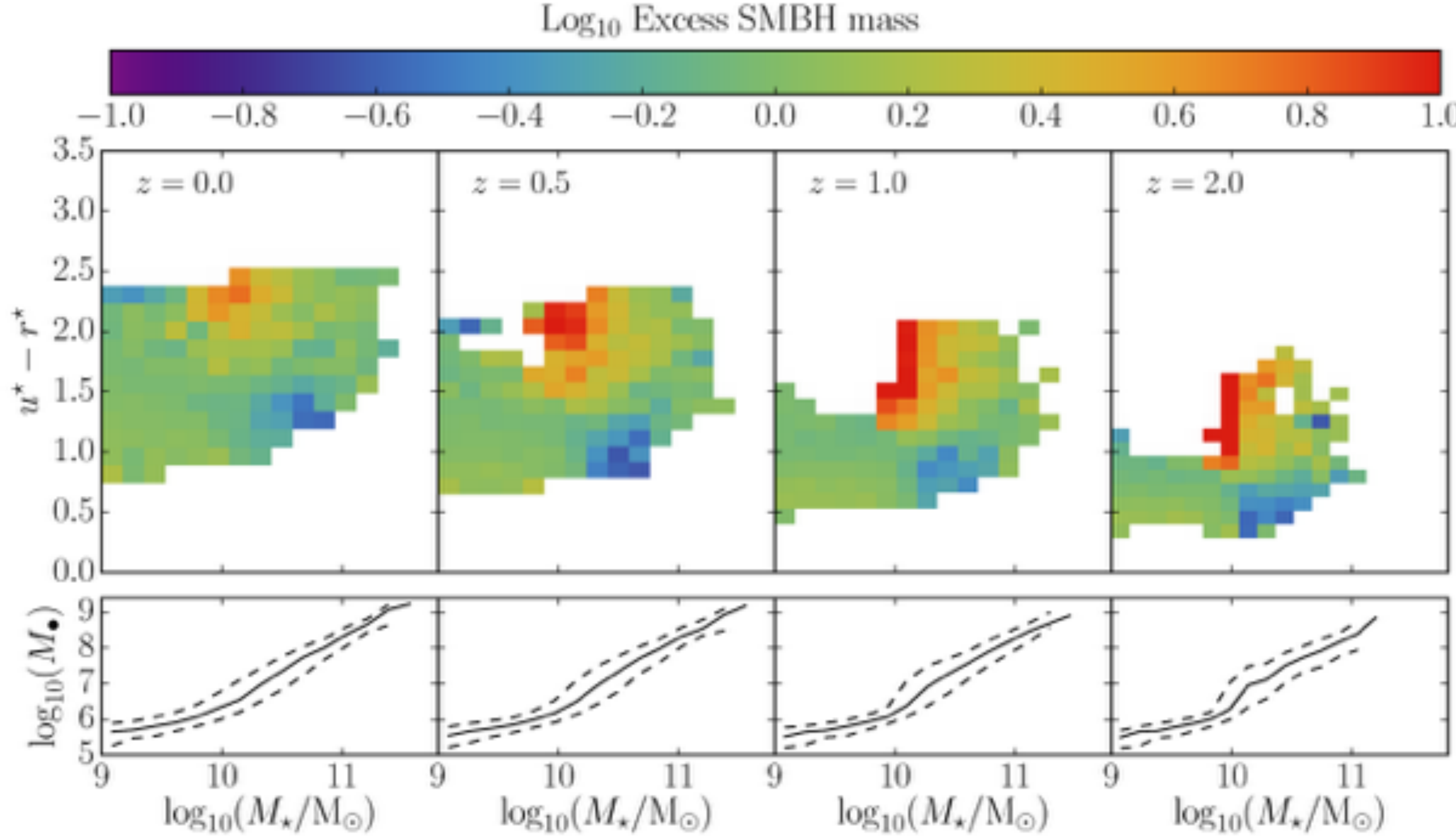
The low mass passive galaxies are predominantly satellites, implying environmental quenching.



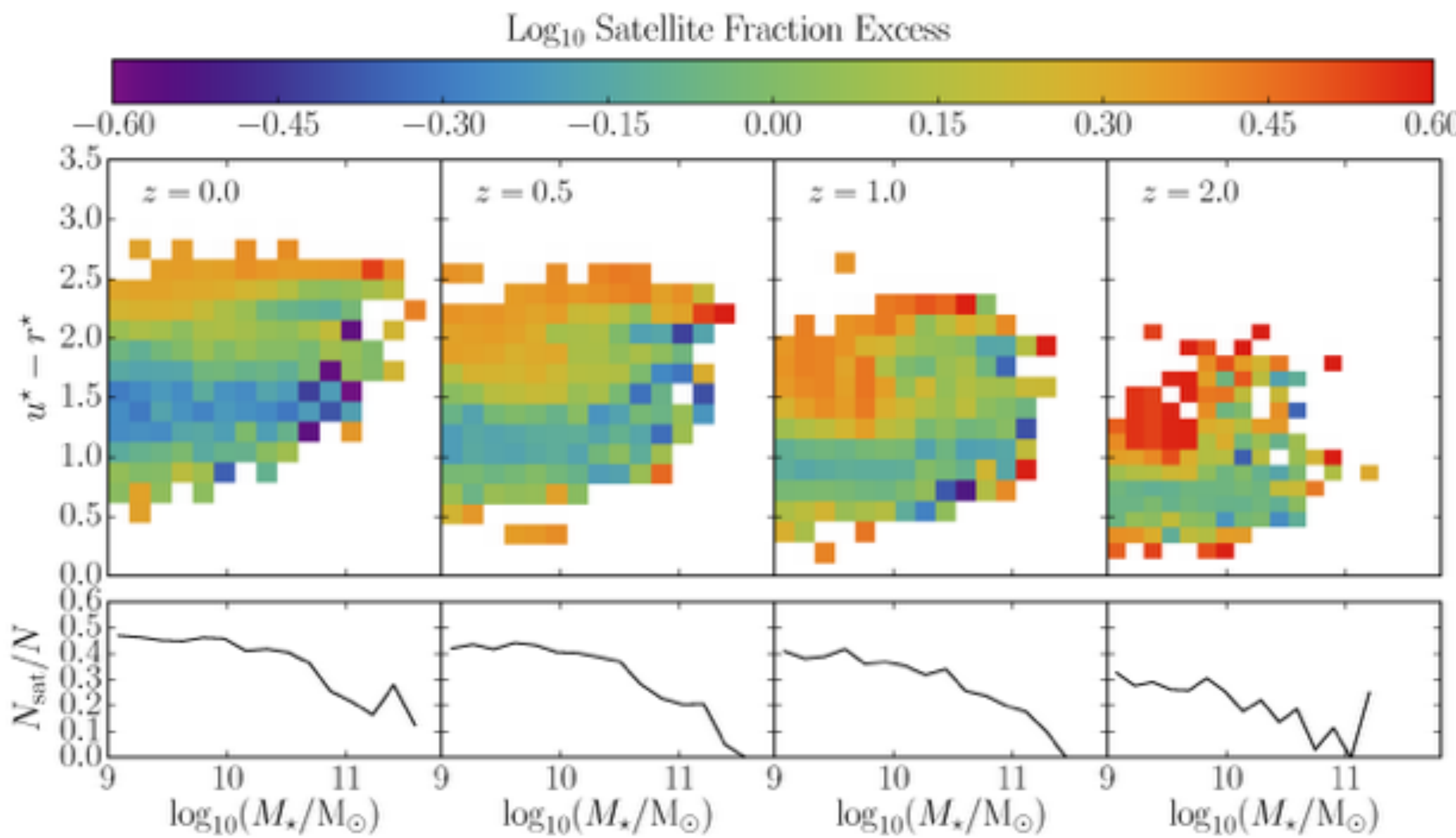
Trayford, RAC+ (2016)

The high-mass passive galaxies host massive BHs.

The reddest examples have the most massive BHs.



The low mass passive galaxies are predominantly satellites, implying environmental quenching.

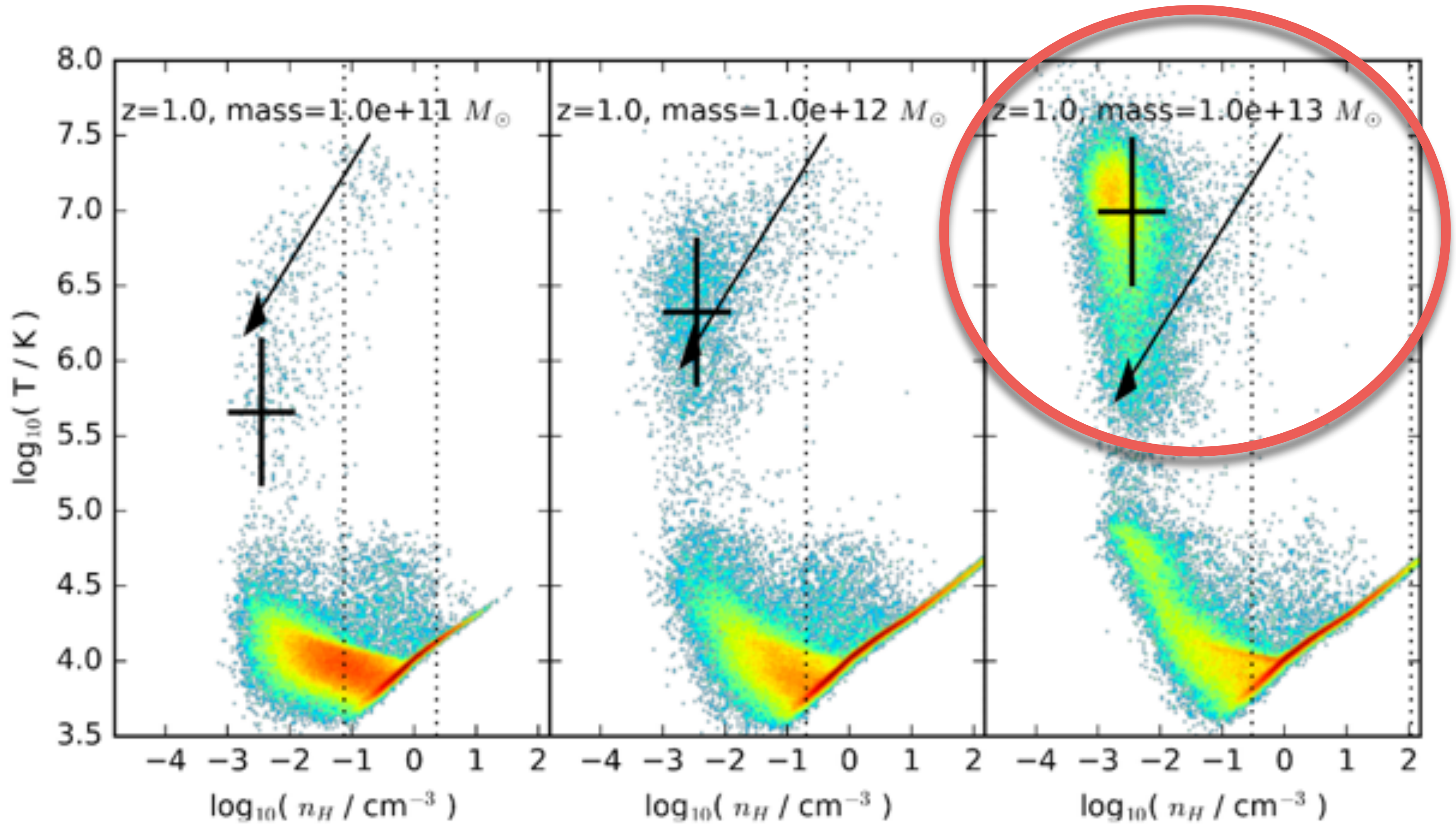


Trayford, RAC+ (2016)

BHs are the nemesis of galaxy growth!

BHs grow when feedback from star formation is no longer able to eject low-*j* gas from galaxy haloes.

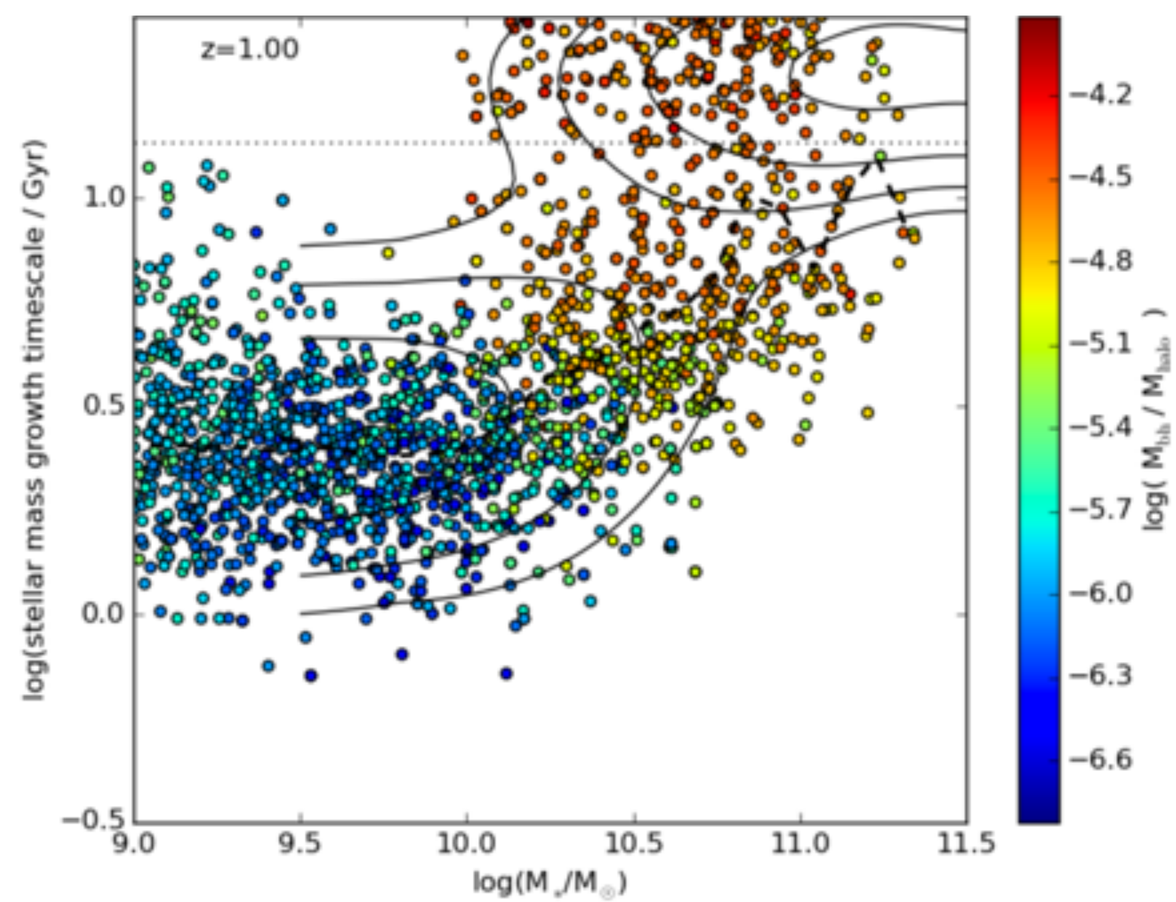
A hot, diffuse corona of low-*j* gas builds in massive haloes, efficiently feeding the BH.



When the Eddington rate of BH becomes sufficient[1], it to regulate its own growth, and that of the entire galaxy, by heating gas that cools out of the hot halo to high entropy.

c.f COSMOS growth timescale measurements by Ilbert+ (2016), shown as black contours.

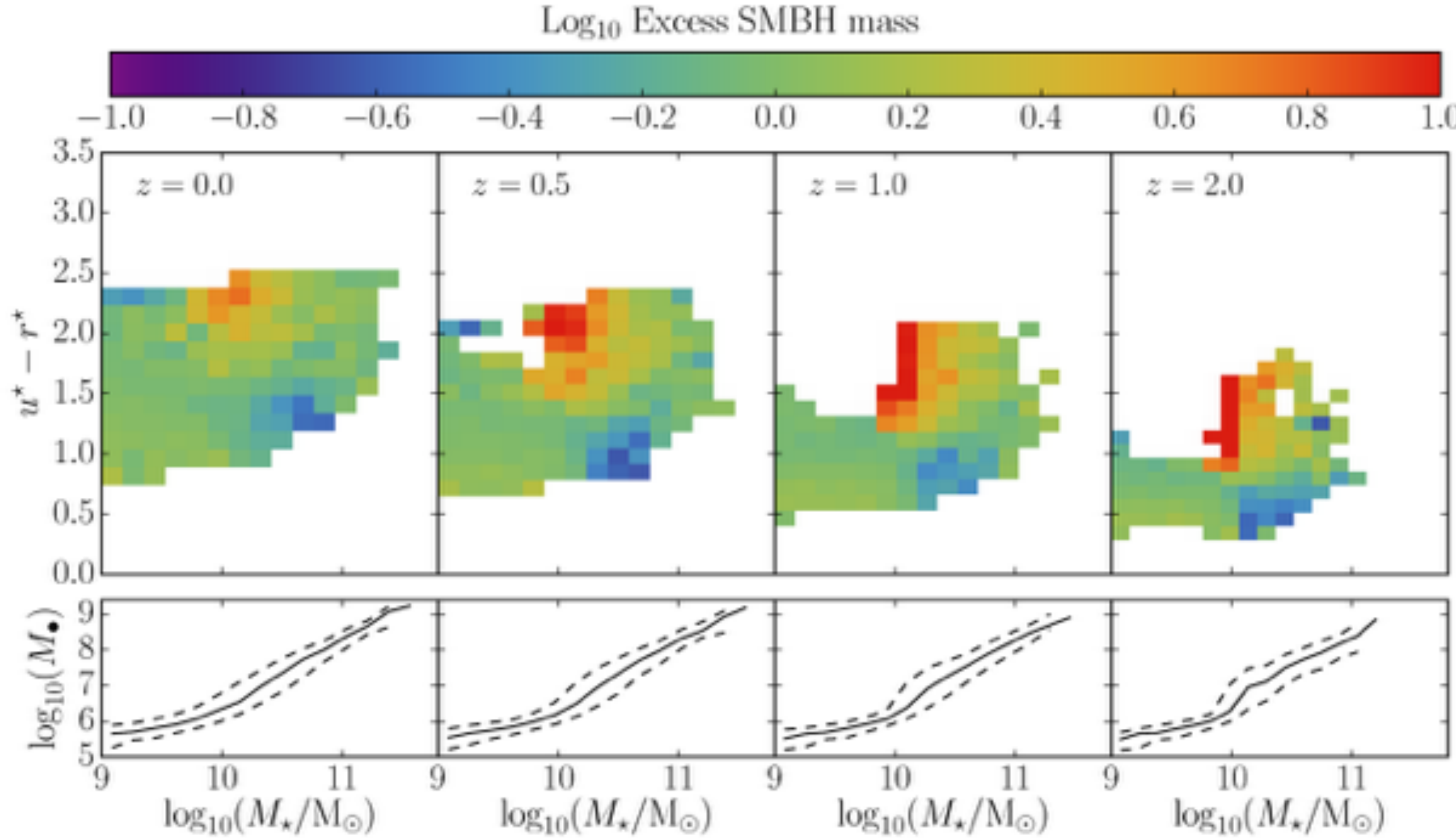
[1]L_{edd} scales as m_{BH}



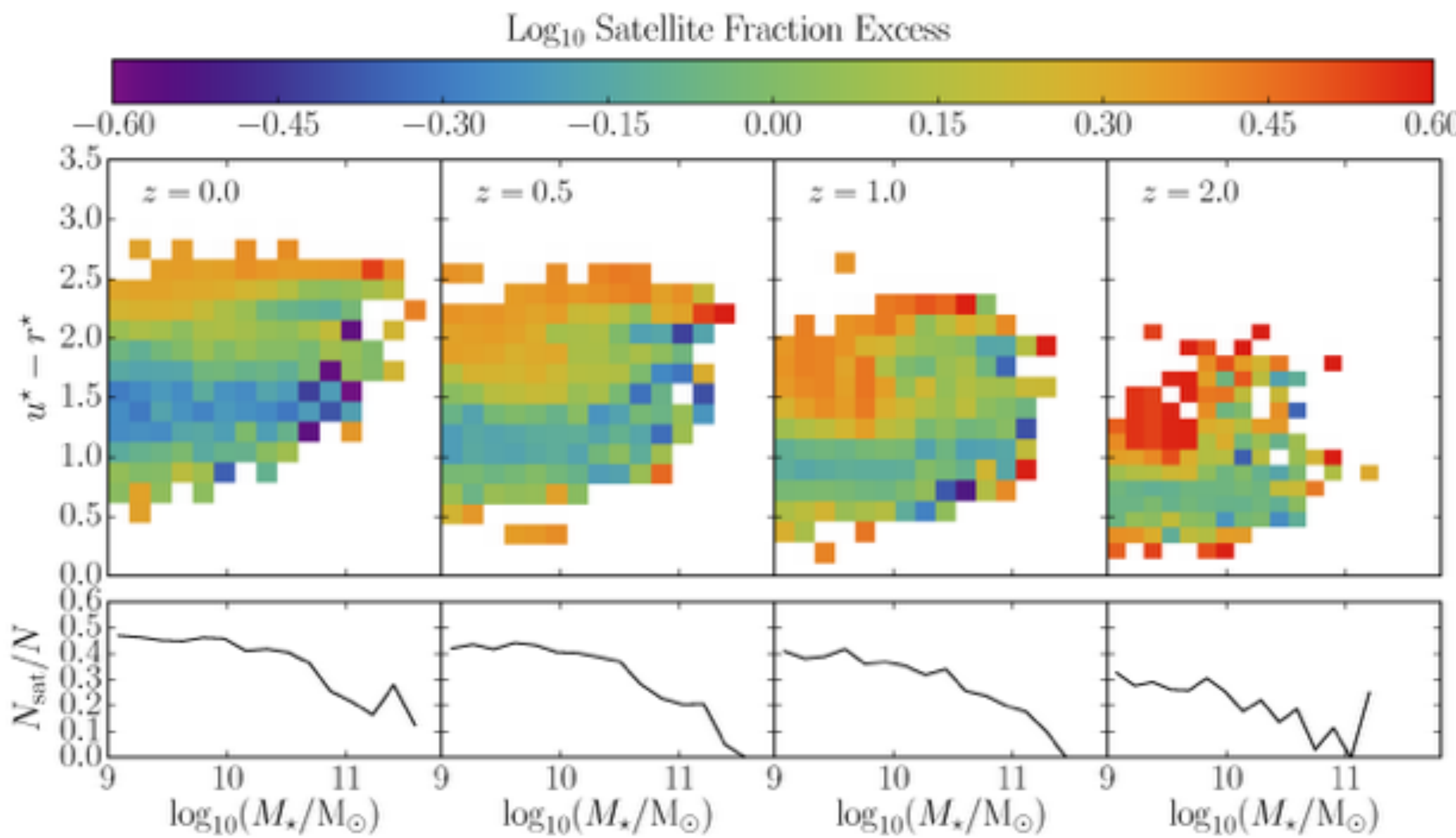
Bower, RAC+ (2016)

The high-mass passive galaxies host massive BHs.

The reddest examples have the most massive BHs.



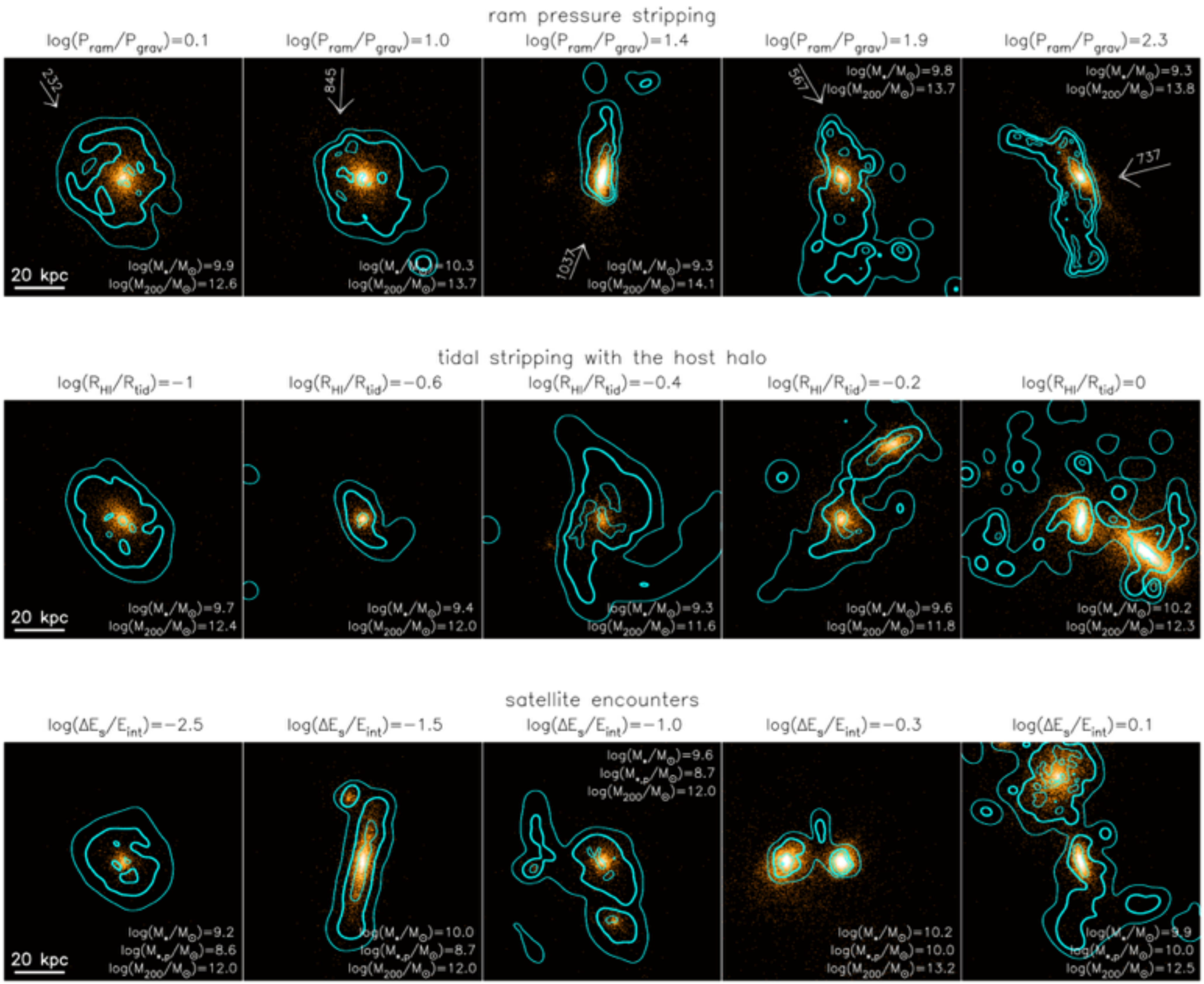
The low mass passive galaxies are predominantly satellites, implying environmental quenching.



Trayford, RAC+ (2016)

Environmental influences on atomic gas in present-day galaxies.

Weak influence



Strong influence

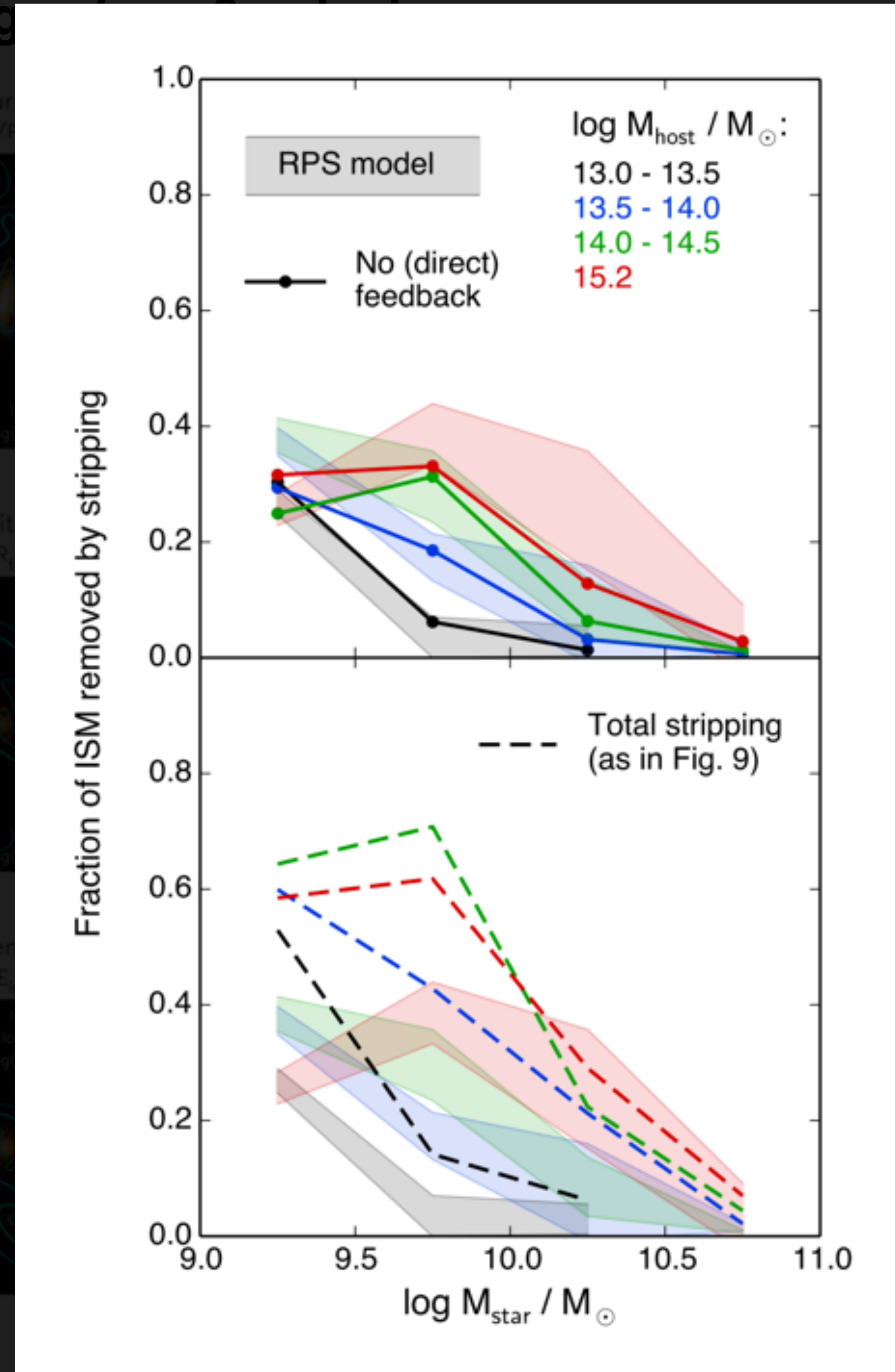
Marasco, RAC+ (2016)

Environmental influences on atomic g

Bahe & McCarthy (2015) show that the mass of gas stripped from satellites galaxies in hydro simulations is ~twice the quantity expected from the classical Gunn & Gott calculation.

Winds driven by internal feedback processes puff up the gas distribution, drastically lowering its gravitational restoring force.

c.f. Nichols & Bland-Hawthorn (2011)

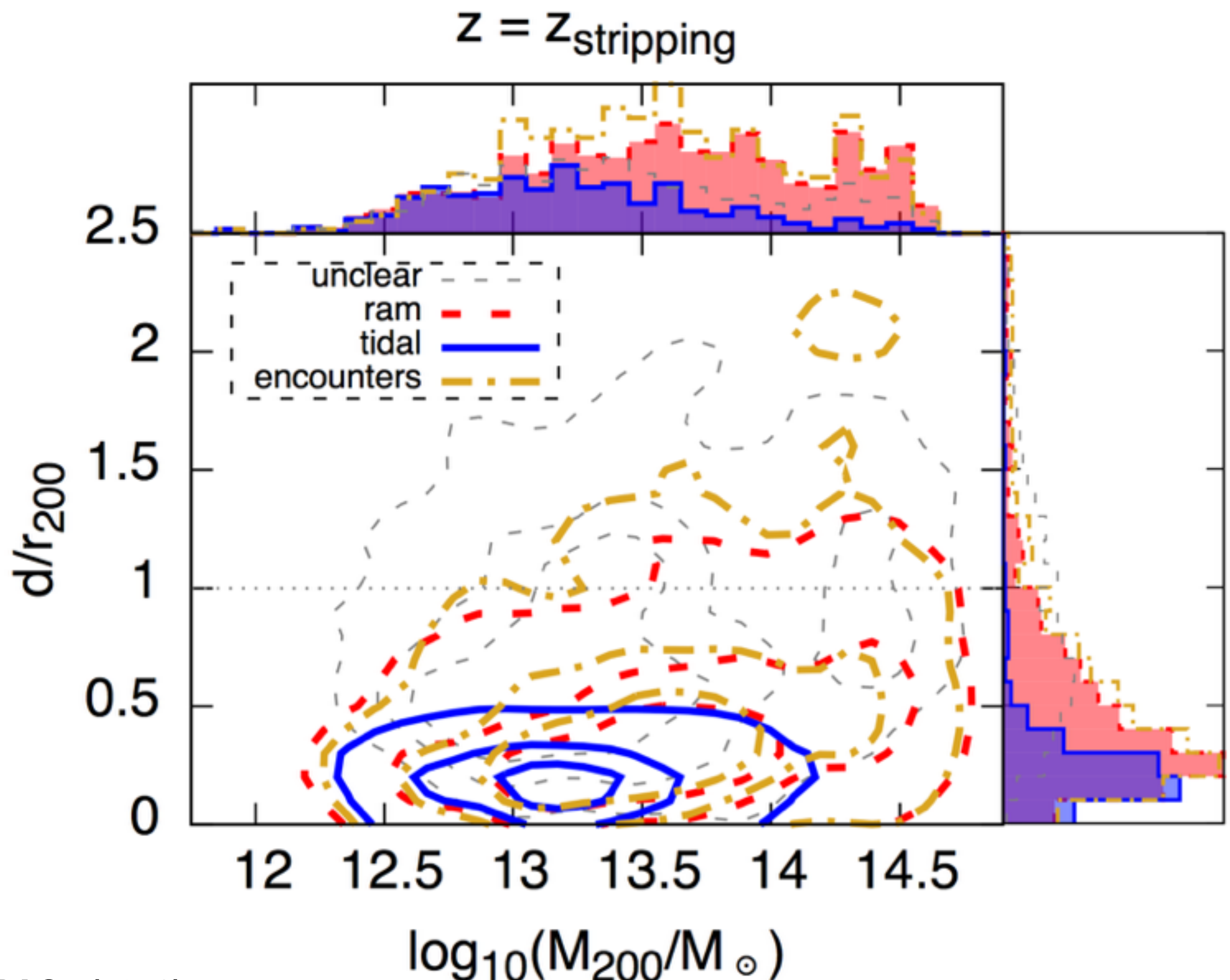


Marasco, RAC+ (2016)

A quantitative prediction for how today's HI-poor galaxies lost their gas.

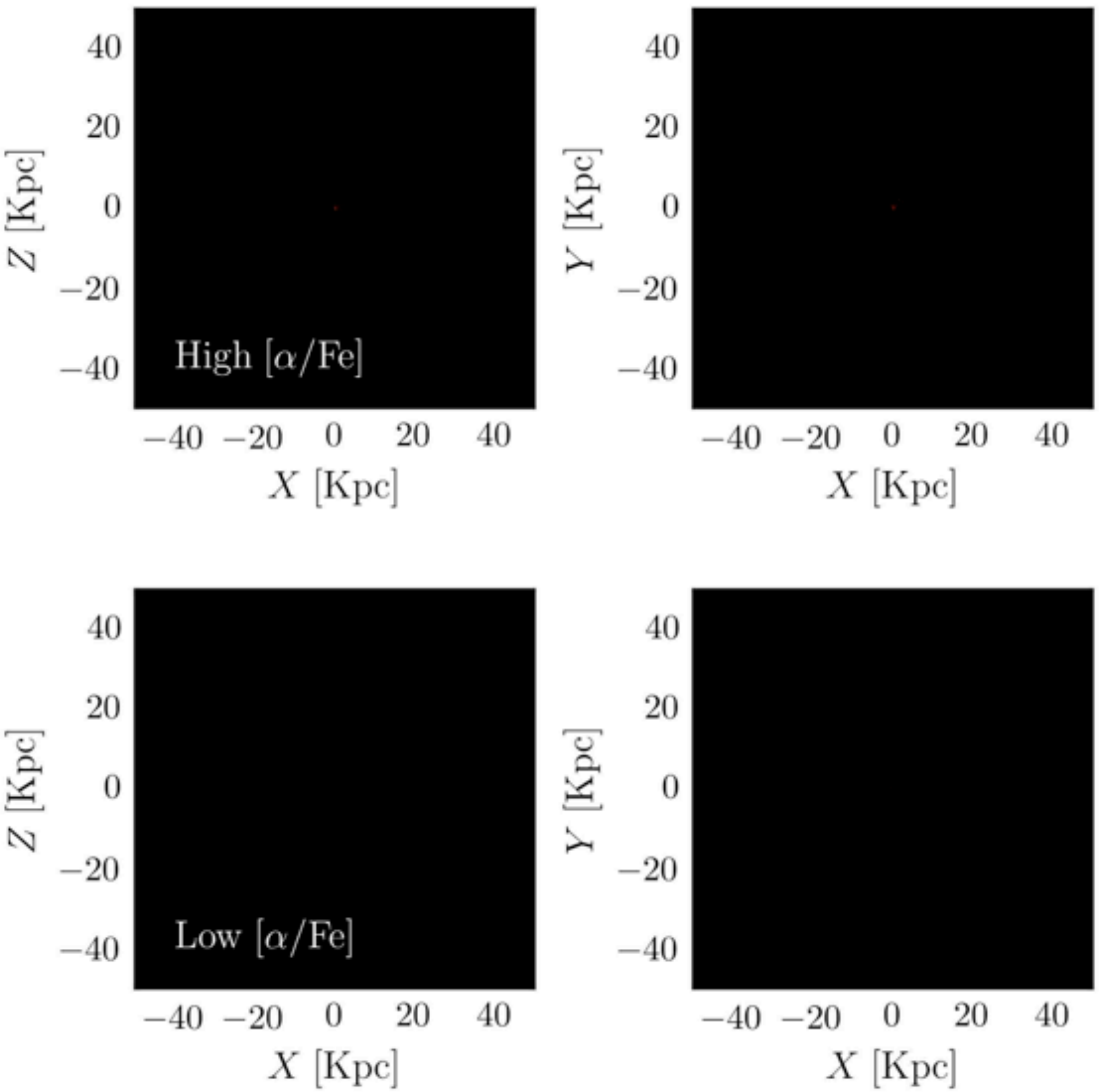
Most common cause (across all redshifts) is satellite-satellite encounters

Looking only at z=0 stripping, ram pressure dominates.

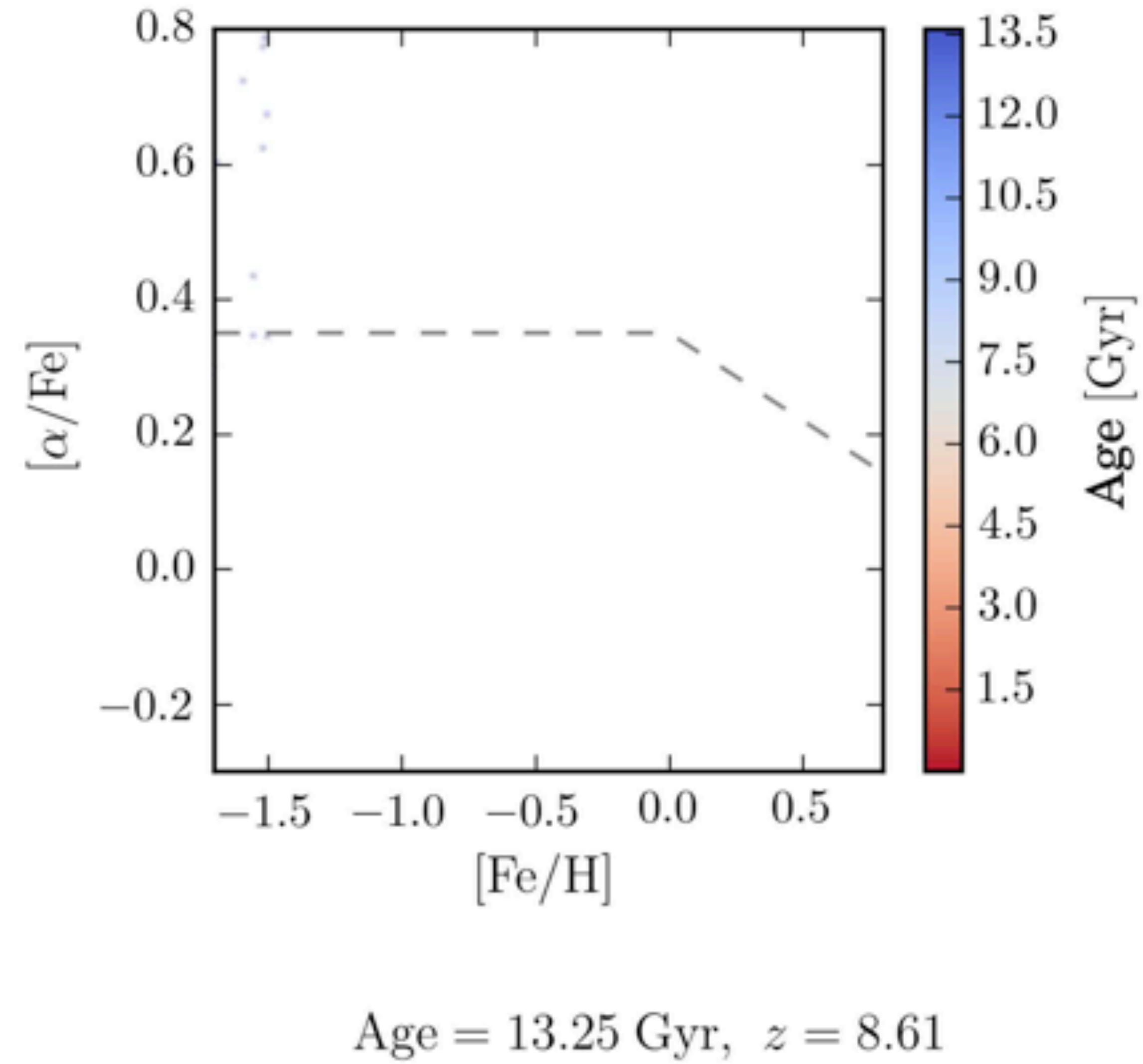


Marasco, RAC+ (2016)

The assembly of the Galaxy and its chemical structure.



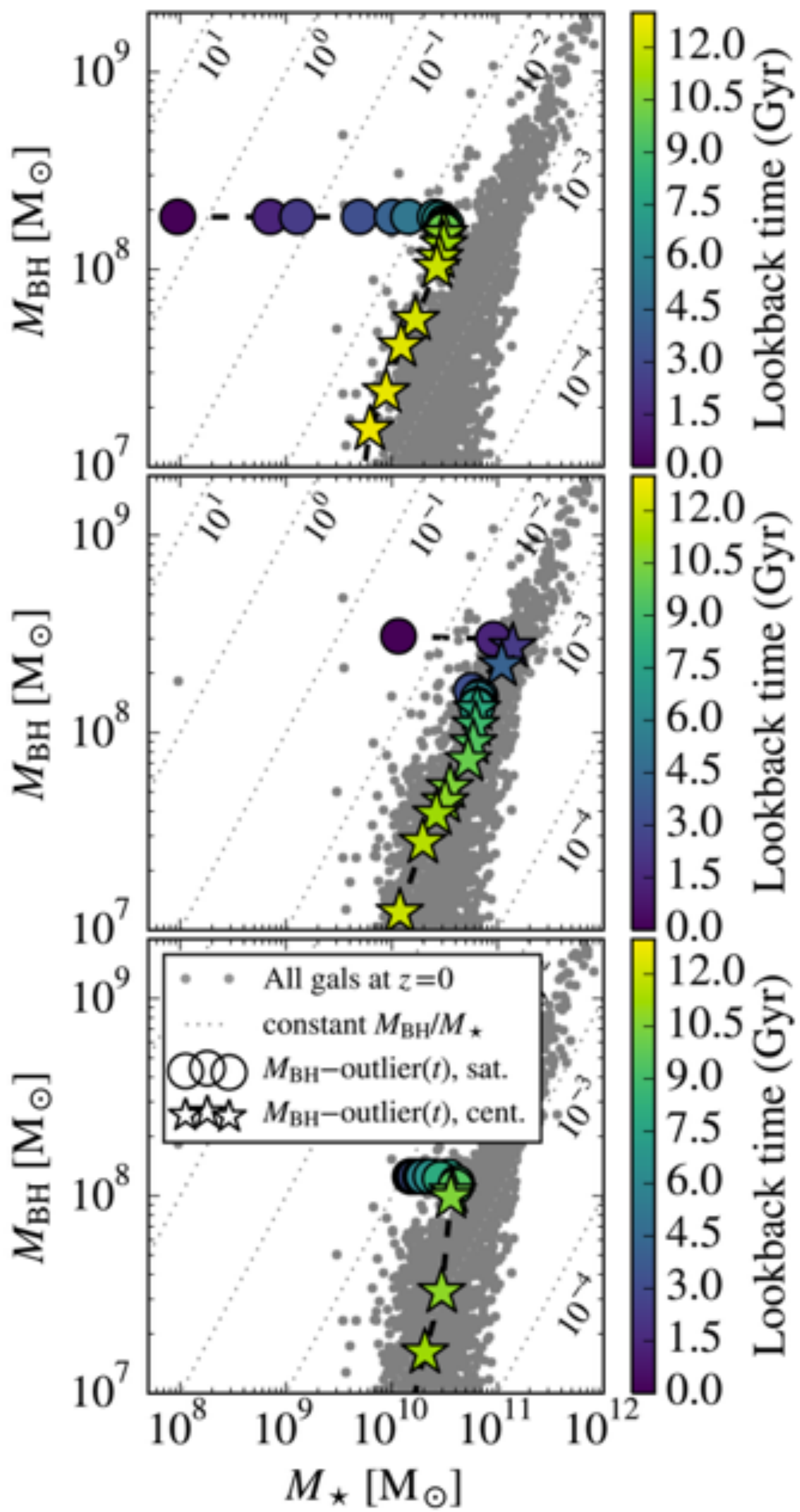
High-alpha stars form early in the bulge, low-alpha stars form later and are mostly in the disc.



Find bimodality of [alpha/Fe] at fixed [Fe/H], as seen in APOGEE (Hayden+ 2015), in ~25% of EAGLE's MW-mass galaxies.

Mackereth, RAC+ (in prep)

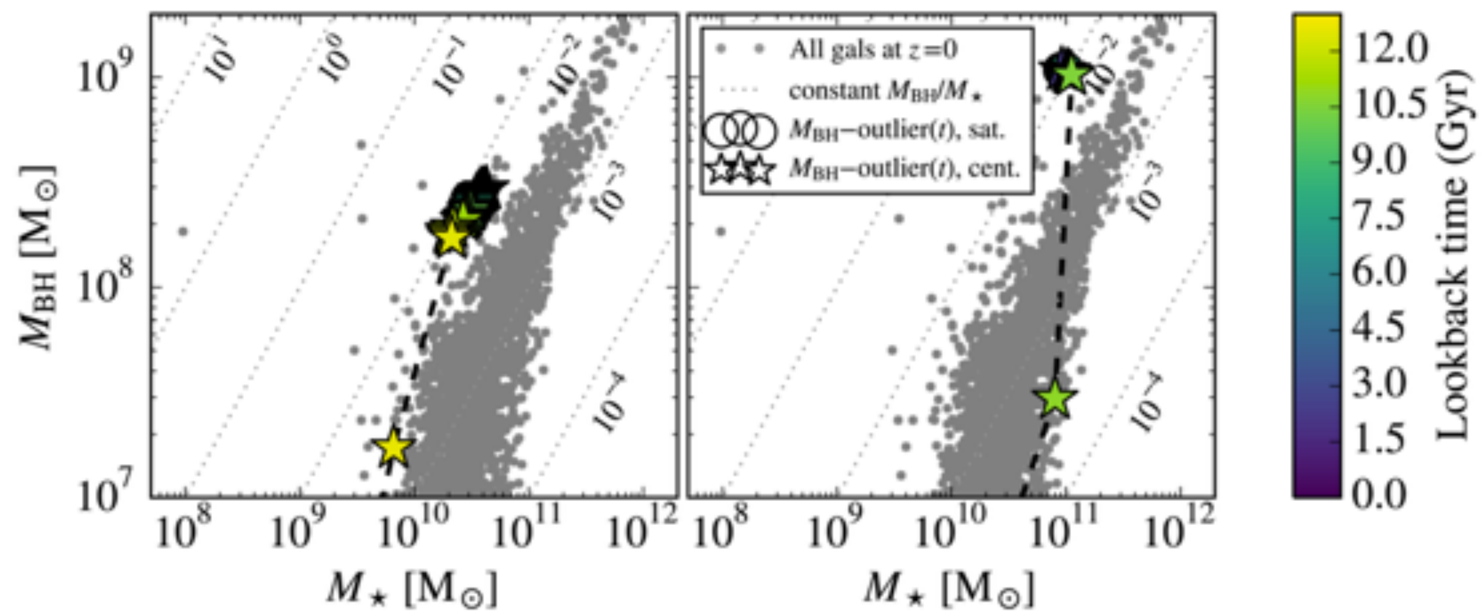
Tidally-stripped galaxies



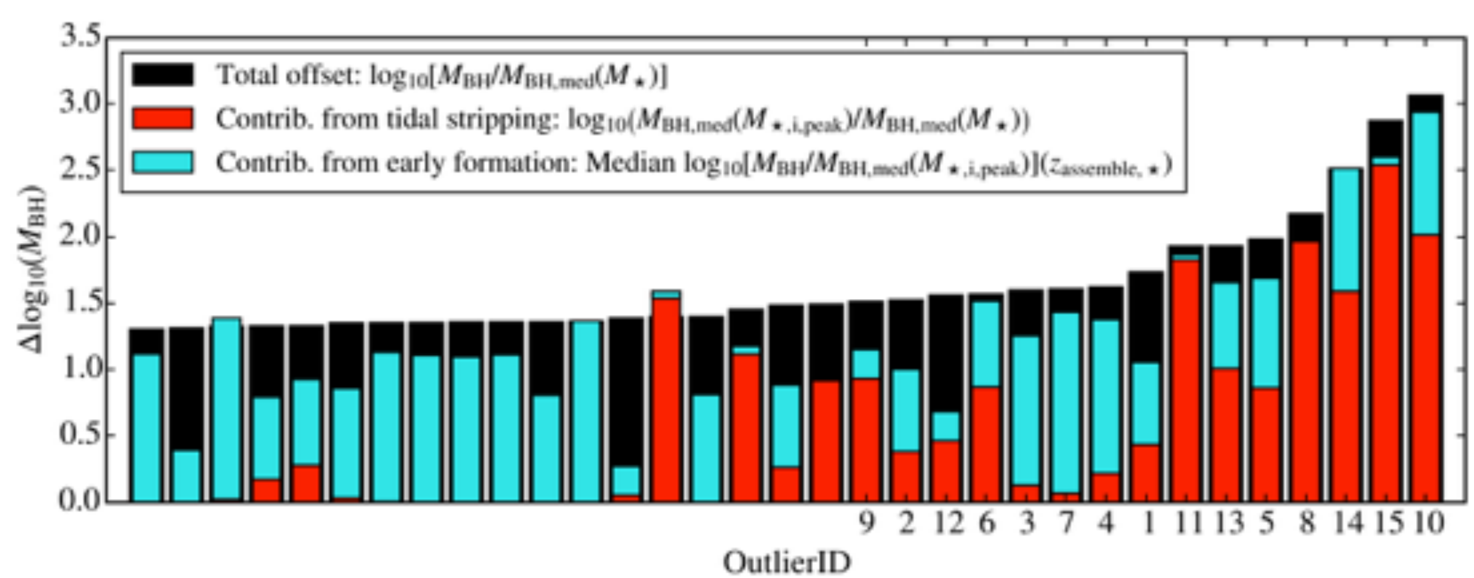
EAGLE has a population of galaxies with BHs that are outliers from M_{BH}-M_* relation, as observed.

Two formation mechanisms: stripping of stellar mass in satellites (left, c.f M60-UCD1), and early formation and rapid growth of the BH (above, c.f NGC1277?).

Early growers

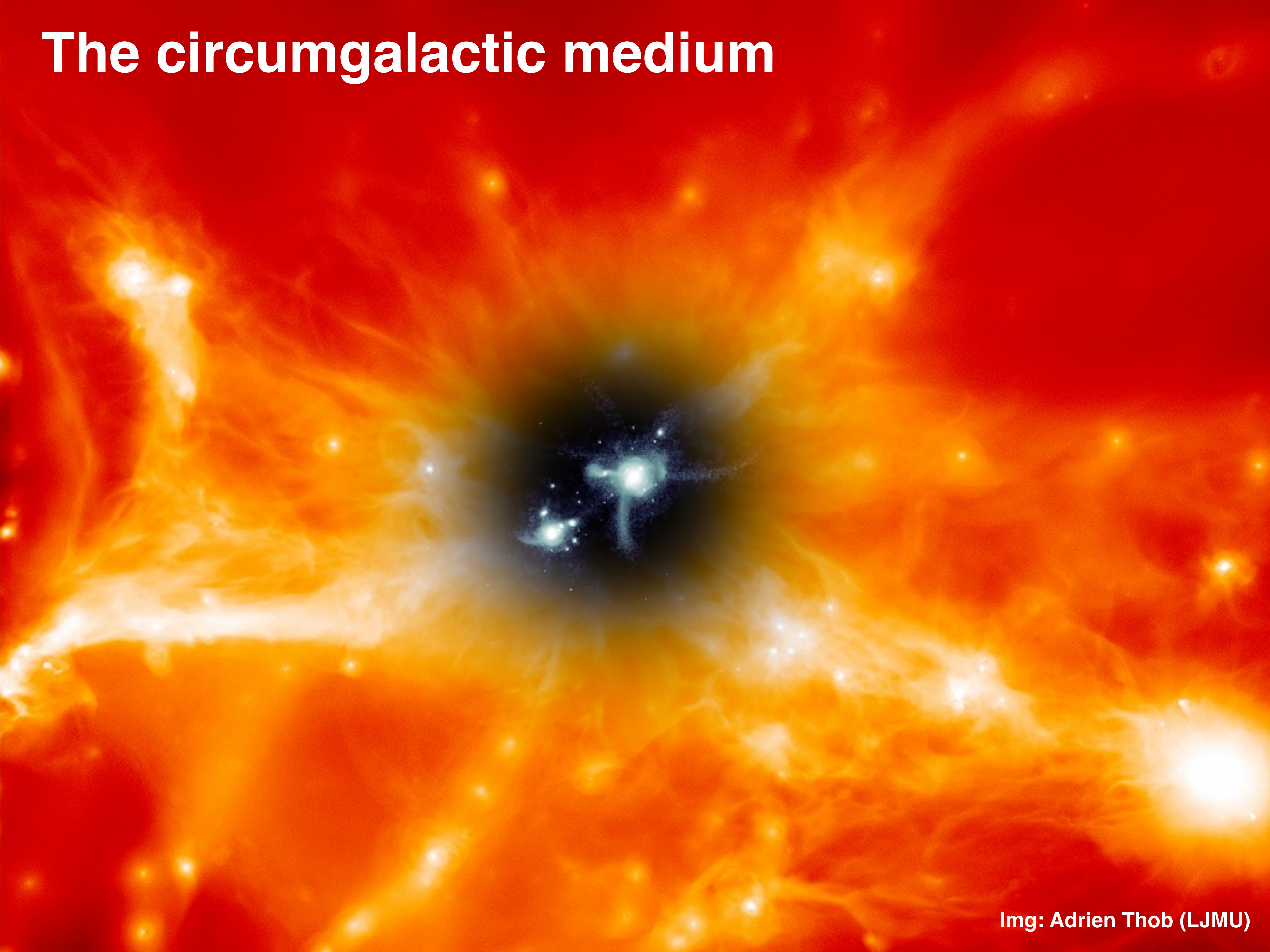


The most dramatic outliers experience both processes.



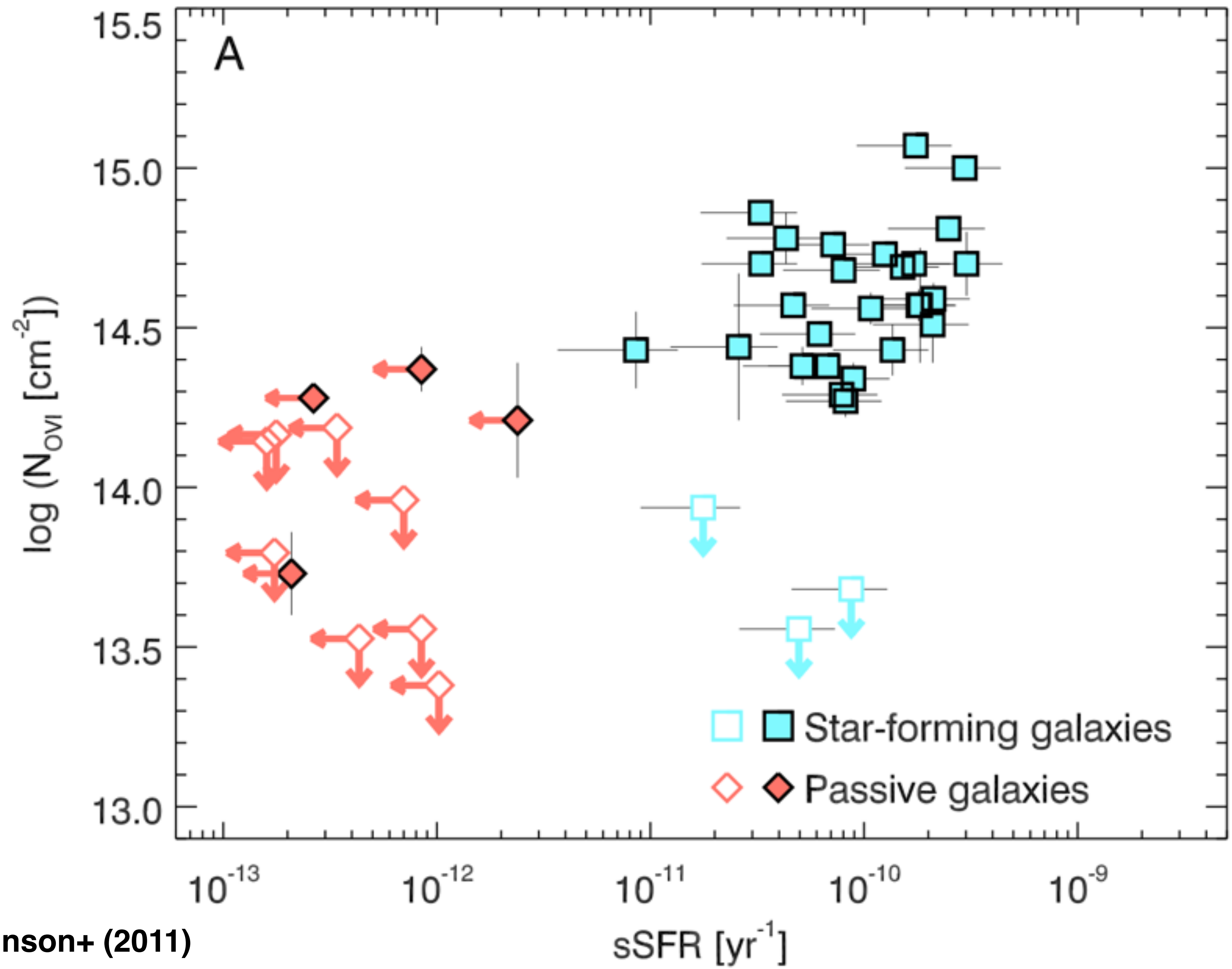
Barber, RAC+ (2016)

The circumgalactic medium



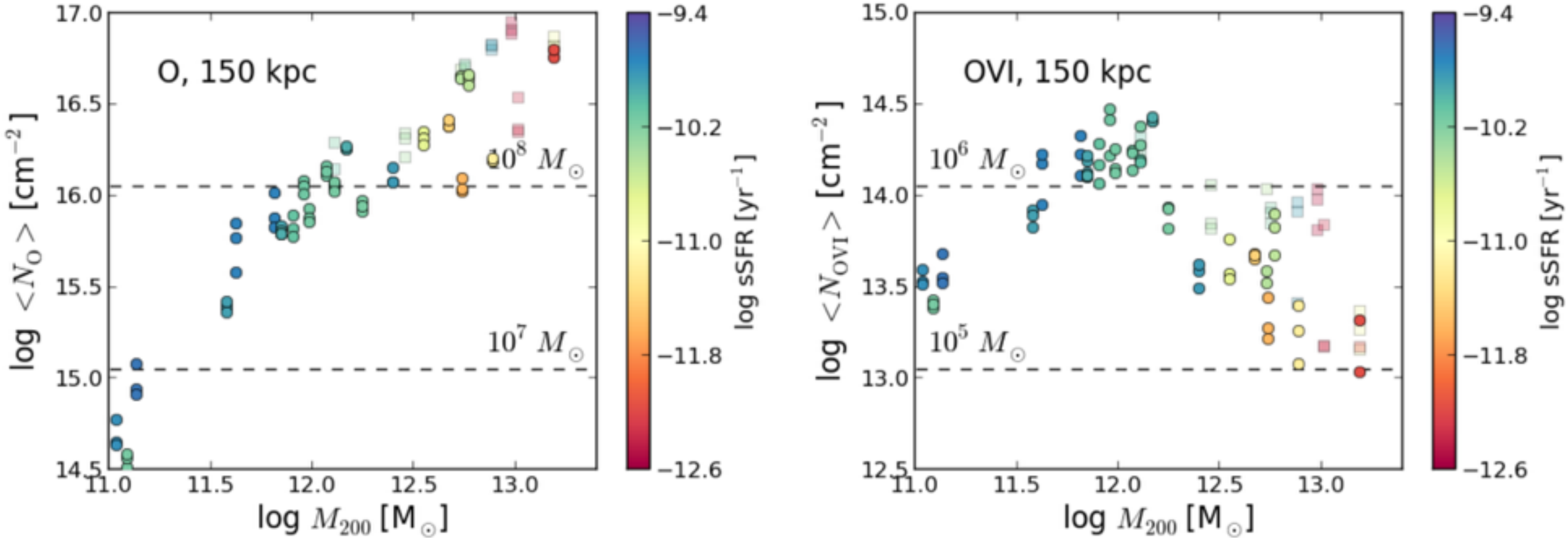
Img: Adrien Thob (LJMU)

COS-Halos reveals a striking correlation between galaxy's sSFR and the collissionally-ionized oxygen in its CGM



Tumlinson+ (2011)

Simulations highlight that the correlation is not causal!



Low-sSFR galaxies in COS-Halos occupy more massive haloes.

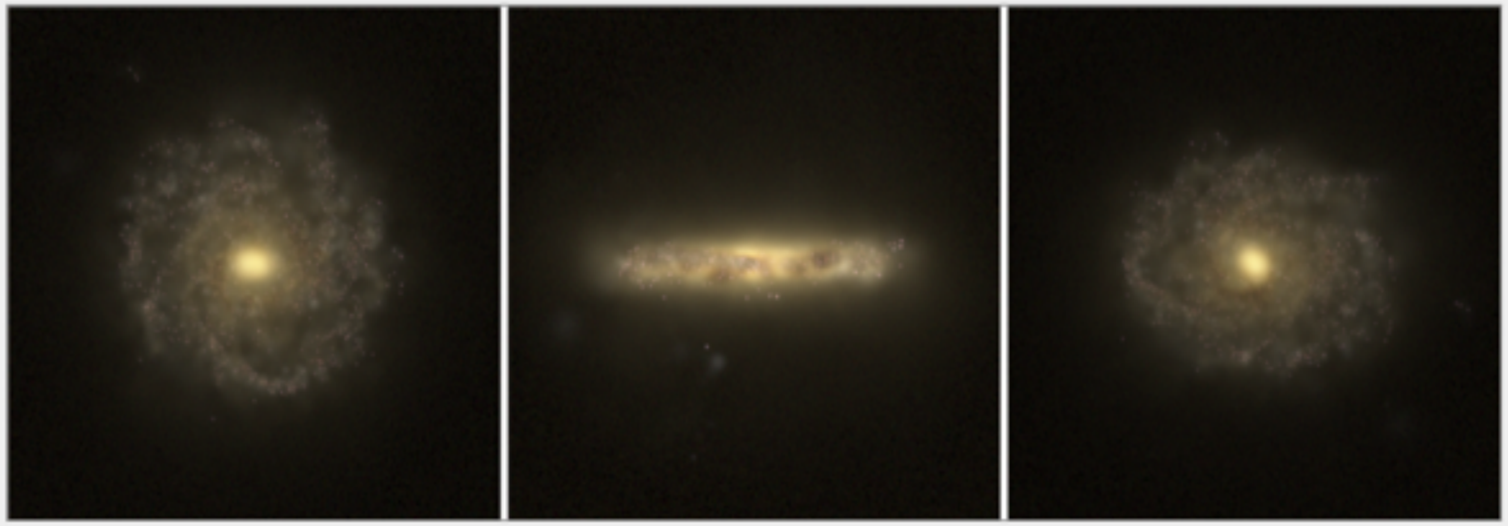
The column density of all oxygen rises linearly with M_{halo}, but the fraction in the form of OVI plummets above ~$10^{12}M_{sun}$: it becomes OVII!

EAGLE indicates that the oxygen was put into the CGM at z~1.

Oppenheimer, RAC+ (2016)

EAGLE Public Database

Welcome to the public database containing galaxy properties (such as masses, star formation rates, luminosites and metallicities), merger histories and images for more than 1,000,000 simulated galaxies spanning the whole observable redshift range in the EAGLE Universe !



Access and Documentation

If you already have an account, follow this link to access the data or register via the form below.

Documentation can be found on the database itself or in the release paper and the python module to connect directly to the database described in the paper is available here and the example plotting the galaxy stellar mass function here.

Registration

To gain access to the EAGLE database, please fill the following form. Credentials will be sent back to you by email. Your request will go via a human for verification, so there will be a short delay from the request to when you actually get access.

Firstname:

Lastname:

Institution:

E-mail:

Security question:

Type the text

Privacy & Terms

reCAPTCHA

Register

Durham University ICC DiRAC Science & Technology Facilities Council Universiteit Leiden erc CHARM

Astronomy and Computing

Volume 15, April 2016, Pages 72–89

ELSEVIER

Full length article

The EAGLE simulations of galaxy formation: Public release of halo and galaxy catalogues ☆

S. McAlpine[a], J.C. Helly[a], M. Schaller[a], J.W. Trayford[a], Y. Qu[a], M. Furlong[a], R.G. Bower[a], R.A. Crain[b], J. Schaye[c], T. Theuns[a], C. Dalla Vecchia[d, e], C.S. Frenk[a], I.G. McCarthy[b], A. Jenkins[a], Y. Rosas-Guevara[f], S.D.M. White[g], M. Baes[h], P. Camps[h], G. Lemson[i]

Show more

doi:10.1016/j.ascom.2016.02.004

Get rights and content

Abstract

We present the public data release of halo and galaxy catalogues extracted from the EAGLE suite of cosmological hydrodynamical simulations of galaxy formation. These simulations were performed with an enhanced version of the GADGET code that includes a modified hydrodynamics solver, time-step limiter and subgrid treatments of baryonic

```
import eagleSqlTools as sql
import numpy as np
import matplotlib.pyplot as plt

# Array of chosen simulations. Entries refer to the simulation name and comoving box length.
mySims          = np.array([('RefL0100N1504', 100.), ('AGNdT9L0050N0752', 50.), ('RecalL0025N0752', 25.)])

# This uses the eagleSqlTools module to connect to the database with your username and password.
# If the password is not given, the module will prompt for it.
con             = sql.connect("<username>", password="<password>")

for sim_name, sim_size in mySims:

        print sim_name

        # Construct and execute query for each simulation. This query returns the number of galaxies
        # for a given 30 pkpc aperture stellar mass bin (centered with 0.2 dex width).
        myQuery = 'SELECT \
                        0.1+floor(log10(AP.Mass_Star)/0.2)*0.2 as mass, \
                        count(*) as num \
                    FROM \
                        %s_SubHalo as SH, \
                        %s_Aperture as AP \
                    WHERE \
                        SH.GalaxyID = AP.GalaxyID and \
                        AP.ApertureSize =  30 and \
                        AP.Mass_Star > 1e8 and \
                        SH.SnapNum = 27 \
                    GROUP BY \
                        0.1+floor(log10(AP.Mass_Star)/0.2)*0.2 \
                    ORDER BY \
                        mass"%(sim_name, sim_name)

        # Execute query.
        myData  = sql.execute_query(con, myQuery)

        # Normalize by volume and bin width.
        hist = myData['num'][:] / float(sim_size)**3.
        hist = hist / 0.2

        plt.plot(myData['mass'], np.log10(hist), label=sim_name, linewidth=2)

# Label plot.
plt.xlabel(r'log$_{10}$ M$_{*}$ [M$_{\odot}$]', fontsize=20)
plt.ylabel(r'log$_{10}$ dn/dlog$_{10}$(M$_{*}$) [cMpc$^{-3}$]', fontsize=20)
plt.tight_layout()
plt.legend()

plt.savefig('GSMF.png')
plt.close()
```


Thanks to the organisers for a great week!

Summary

Cosmological simulations are the premier tool with which to connect & interpret multi-epoch observations of galaxy evolution.

We are primarily limited by our limited understanding of the physics of feedback associated with stars, SNe and BHs.

However, calibrating feedback efficiencies enables the reproduction of wide range of observed galaxy and IGM scaling relations: a new era for the realism of cosmological models.

Detailed studies of internal structure and kinematics await the development of cosmological simulations with a multiphase ISM. Nonetheless, for many applications this is not problematic.

We are getting to grips with making data public and accessible to the community (some better than others!), enabling the widest use these models - often in ways we didn't envisage.