# The dark nemesis of galaxy formation: why hot haloes trigger black hole growth and bring star formation to an end

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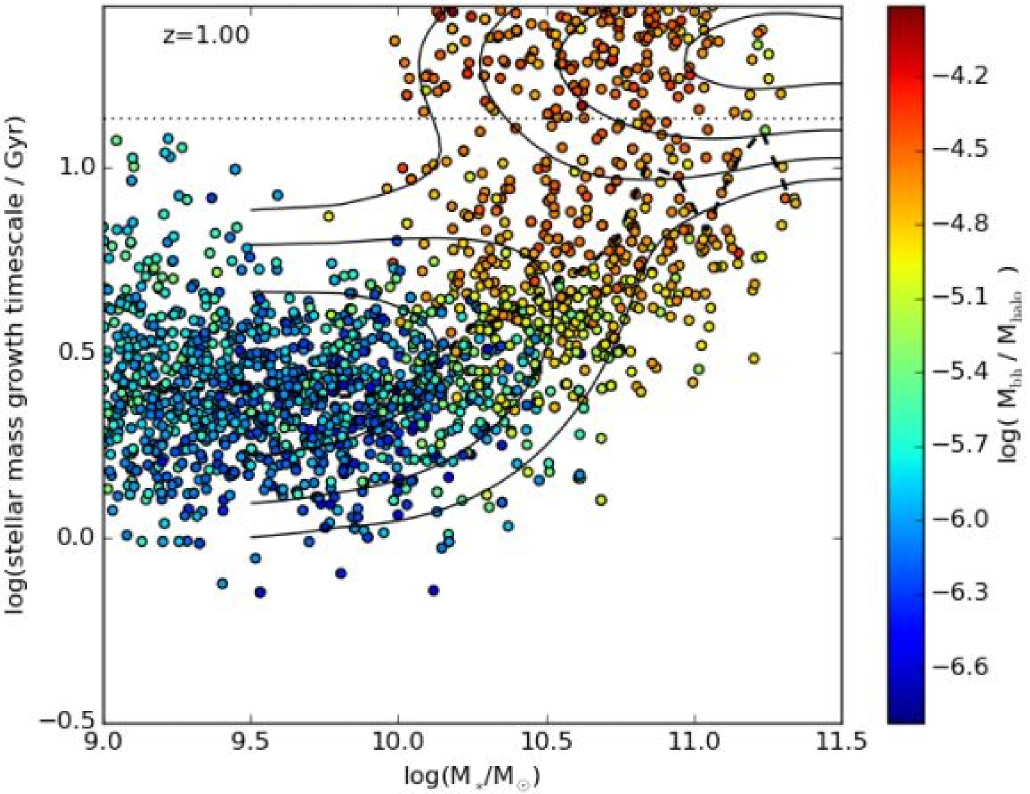
# Overview

- This paper proposes a theory for the existence of the transition mass scale that depends on a competition between black hole accretion into the center of a galaxy and star formation-driven outflow out of a galaxy
- They create a highly simplistic analytic model of this interaction and find support for their model from observational data as well as EAGLE simulations in which they vary a number of parameters to test the interaction

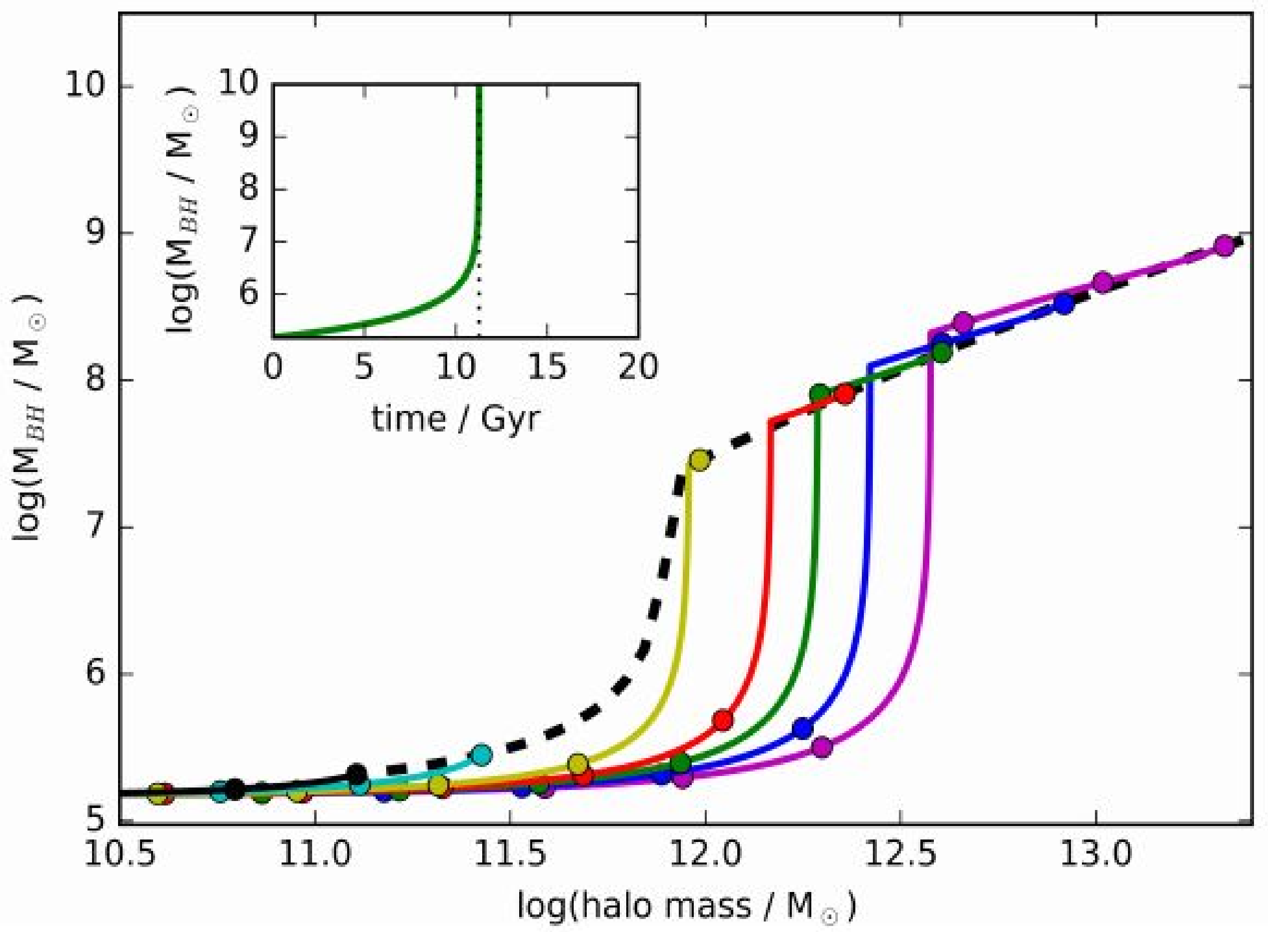
# Galaxy Bimodality

- Blue galaxies are younger and form stars relatively quickly
- Red galaxies are older and do not grow as quickly
- Galaxies tend to transition from blue to red sequence around 3e10 Msun



# Black holes in galaxy formation

- Put very simply, galaxy formation is a balance of outflows and inflows
  - Gas inflows are either used as fuel for star formation or counteracted by outflows from supernovae
- Black holes play a huge role in galaxy formation/evolution
  - BHs can produce large outflows, heating surrounding gas corona, and disrupting inflows
  - BHs can accrete large amounts of gas in the center of a galaxy, and grow rapidly as they do so



10
9
8
7
6
5
10.5
11.0
11.5
12.0
12.5
13.0
log(halo mass / $M_\odot$)
log($M_{BH}$ / $M_\odot$)
0
5
10
15
20
time / Gyr

# Analytic Model - Black Hole Growth

- First, they assume a constant density medium
- The main factors that are considered in determining the growth rate of a BH are the density of gas surrounding it and the effective sound speed of the gas surrounding it
    - Density of surrounding gas is measured out to the Bondi radius

$$\dot{M}_{\rm bh} = 4\pi G^2 f_{\rm sup} \frac{M_{\rm bh}^2 \rho_{\rm bh}}{c_s^3}$$

- BH accretion is highly non-linear
    - Growth timescale decreases rapidly as BH grows
- BH growth is limited by exhaustion of surrounding material and binding energy within dark matter halo

$$t_\infty = \frac{1}{\kappa \rho_{\rm bh}^{1/2}}$$

# Analytic Model - Outflows

- The ability of outflow from star formation to carry away mass from the galaxy will affect BH growth
- Outflows create a corona which increases in density as the halo mass increases
    - As the corona mass becomes comparable to the mass of the outflow, a point is reached at which the outflowing gas no longer escapes and falls back into the galaxy
- The ability of the outflow to escape the galaxy completely is its buoyancy

# Analytic Model - Buoyancy

- They determine the buoyancy of an outflow as a ratio of its adiabat to that of the diffuse corona
- They calculate the adiabat of the outflow using assumptions about the ratio of energy from supernovae used to propel an outflow and assumptions about the galaxy disk size/mass relative to halo angular momentum/mass
  - Mass loading (change in outflow mass with respect to stellar mass) is a key variable in their calculation of the outflow adiabat
  - A critical outflow adiabat is reached by setting mass loading factor = 1

$$K = k_B T \left(\rho/\mu m_H\right)^{-2/3}$$

$$K_{\rm outflow} \sim 8\,\beta^{-1} \left(\frac{n_H^0}{0.1\,{\rm cm^{-3}}}\right)^{-2/3} \left(\frac{M_{\rm halo}}{10^{12}\,{\rm M_\odot}}\right)^{-2/9} \Delta_z^{-4/3}\,{\rm keV\,cm^2}$$

$$\beta = \dot{M}_{\rm outflow}/\dot{M}_*$$

$$K_{\rm crit} \equiv K_{\rm outflow}(\beta = 1).$$

# Analytic Model - Critical Mass

- Equating Kcrit = Khalo leads to an expression for a critical mass, Mcrit
- Systems with M < Mcrit have buoyant outflows, and systems with M > Mcrit do not
- They assume that, for haloes with M < Mcrit, the outflow will be *just* buoyant (Koutflow ~ Khalo)
- This allows them to determine an expression for the mass loading factor that depends on halo mass

$$K_{\rm halo} \sim 7 \left( \frac{M_{\rm halo}}{10^{12}\,{\rm M}_\odot} \right)^{2/3} \Delta_z^{-1}\,{\rm keV\,cm}^2$$

$$M_{\rm crit} \sim 10^{12} \Delta_z^{-3/8}\,{\rm M}_\odot$$

$$\beta \sim \left( \frac{M_{\rm halo}}{M_{\rm crit}} \right)^{-8/9}$$

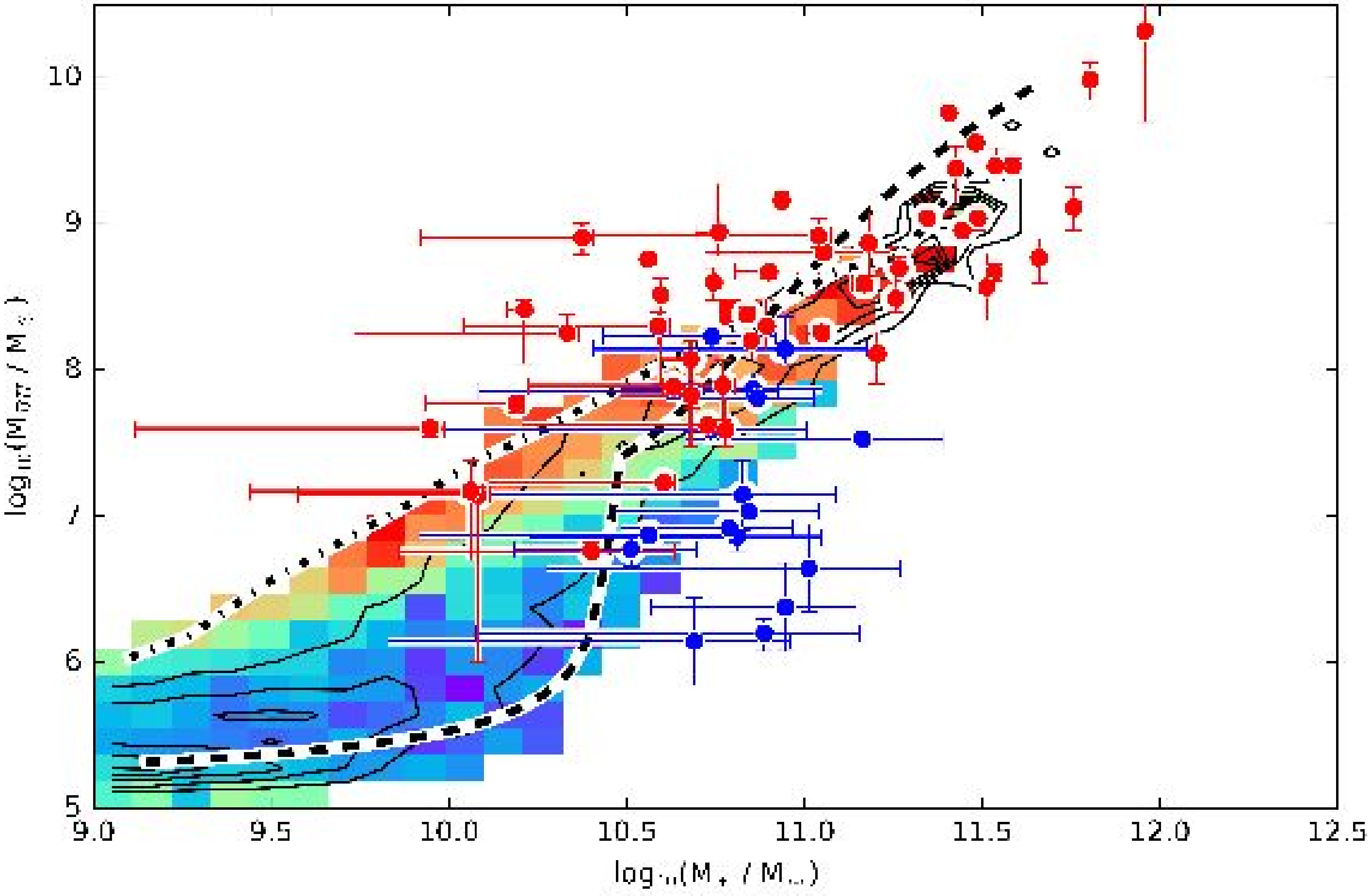
# Analytic Model - BH mass and Halo mass

- They determine an expression for the density of gas around a BH as it relates to the efficiency of the outflow
    - Amount of gas in central regions is inversely proportional to the mass loading factor

$$n_{\rm bh} = n^0_{\rm bh}\left(\frac{M_{\rm halo}}{M_{\rm crit}}\right)^{8/9}\left(\frac{M_{\rm halo}}{10^{12}\,{\rm M}_\odot}\right)^{1/3}\Delta_z^2$$
$$\sim n^0_{\rm bh}\left(\frac{M_{\rm halo}}{10^{12}\,{\rm M}_\odot}\right)^{4/3}\Delta_z^{5/2}.$$

- This leads to a relationship between BH mass and halo mass
    - They have a good estimate for halo growth rate, which tells them how the gas around a BH changes, which tells them how the BH grows

$$\dot{M}_{\rm halo} = 7\times10^{10}\left(\frac{M_{\rm halo}}{10^{12}\,{\rm M}_\odot}\right)(0.51+0.75z)\Delta_z^{3/2}\,{\rm M}_\odot\,{\rm Gyr}^{-1}.$$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# EAGLE Simulations

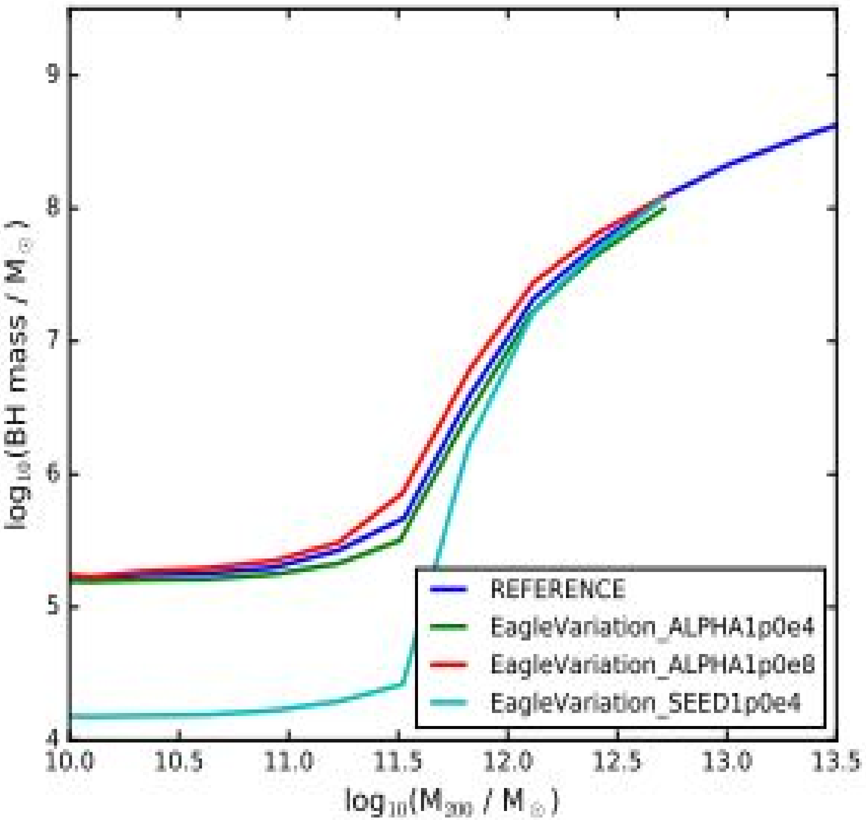
- The EAGLE simulations contain a large number of hydrodynamical simulations of galaxy formation
- The simulations are known to successfully reproduce key observational properties of galaxies, such as evolution of galaxy size and the stellar mass function, and the transition mass scale
- BH accretion is determined by a sub-grid model that considers mean density, sound speed, and relative motion/angular momentum of surrounding gas

# Comparing Analytic and Numerical Models

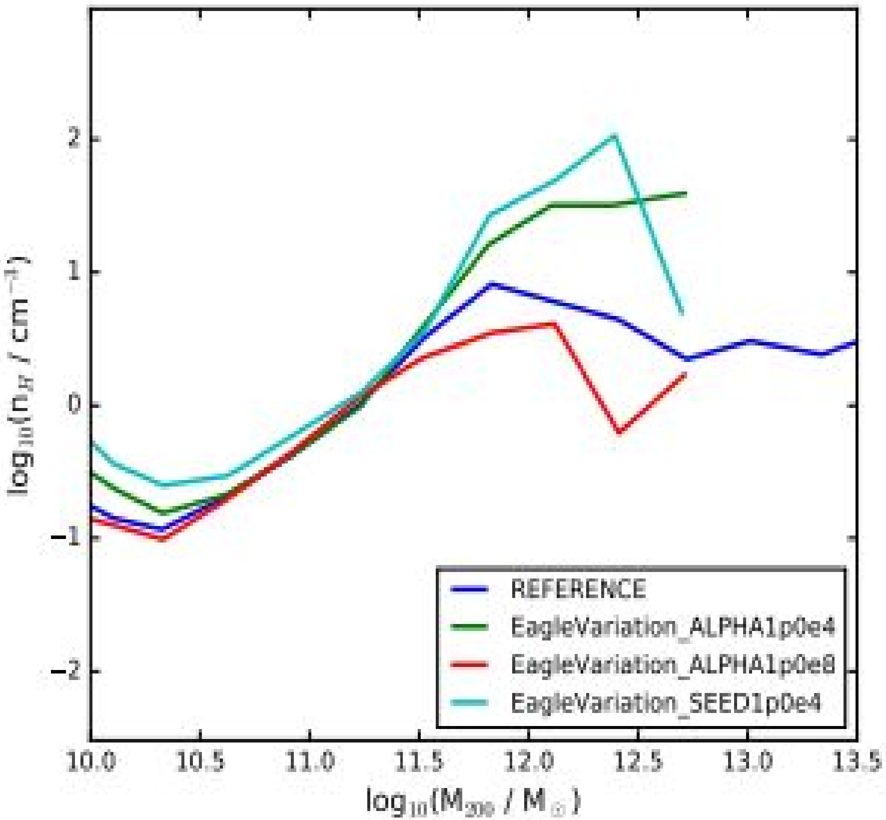
- Generally, they find that their analytic model, although quite crude, is supported by simulations
- When including maximally accurate BH effects, they still find that the simulations have the observed transition mass scale
- Their REFERENCE simulation supports their analytic model, so they proceed to vary parameters in order to test relationships.

# Varying Parameters

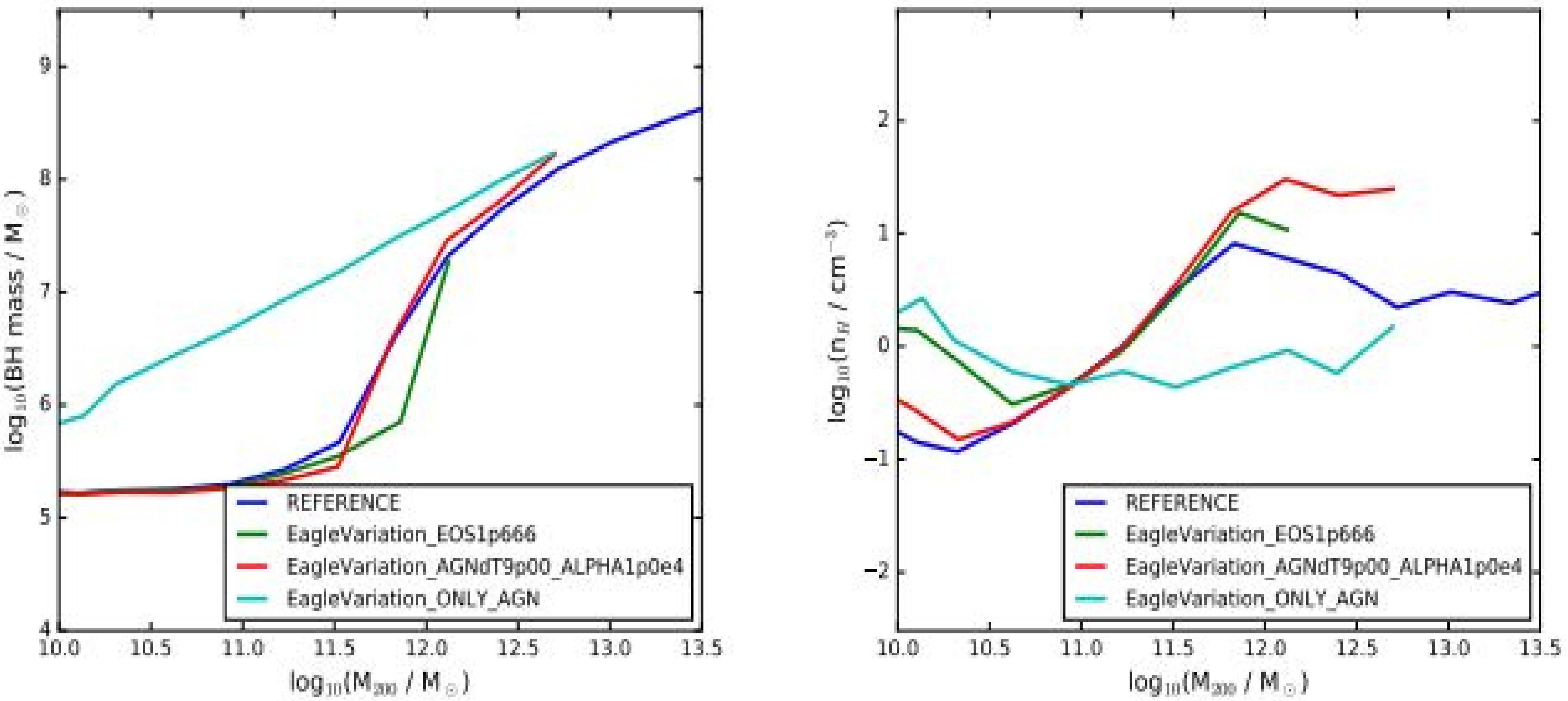
- The key aspect of the simulations for this group is that they can vary the parameters
    - This allows them to test different parameters to more accurately draw conclusions about the effect of the BH and gas outflows on the transition mass scale
- They find that varying the AGN accretion parameter,  the BH seed mass, the exponent on the ISM equation of state, and the relation of angular momentum to BH accretion rate all produce results that are similar to their reference simulation, with little change in the transition mass scale
- Their key finding is that switching off stellar feedback completely changes the BH evolution and the transition mass scale disappears



$\log_{10}$(BH mass / $M_\odot$)
$\log_{10}(M_{200} / M_\odot)$
REFERENCE
EagleVariation_ALPHA1p0e4
EagleVariation_ALPHA1p0e8
EagleVariation_SEED1p0e4

$\log_{10}(n_H / cm^{-3})$
$\log_{10}(M_{200} / M_\odot)$
REFERENCE
EagleVariation_ALPHA1p0e4
EagleVariation_ALPHA1p0e8
EagleVariation_SEED1p0e4



REFERENCE
EagleVariation_EOS1p666
EagleVariation_AGNdT9p00_ALPHA1p0e4
EagleVariation_ONLY_AGN
log10(BH mass / M☉)
log10(M200 / M☉)
log10(nH / cm−3)

# Conclusions

- They state that a transition from blue to red sequence occurs on a galaxy mass scale of 3e10 Msun, and a halo mass scale of 1e12 Msun
- They conclude that their model, in which BHs and star formation compete to regulate gas content of a galaxy, is comparable and supported by already established EAGLE simulations
- They conclude that the causal connections implied by their simple analytic model are confirmed by their findings when varying parameters in the simulations

# Conclusions

- By eliminating stellar outflow they are unable to reproduce properties of observed galaxies, and thus conclude that black hole growth is related to stellar feedback, especially below the transition mass scale
- Ultimately, they conclude that their simple analytic model in which BH growth regulates star formation-driven outflow is supported by observational data and numerical simulations.
- Thus, they have presented a reasonable new way of understanding the transition mass scale, and by extension, the bimodality of galaxies

# References


Bower et al https://arxiv.org/pdf/1607.07445.pdf

EAGLE simulation website http://icc.dur.ac.uk/Eagle/

https://en.wikipedia.org/wiki/Adiabatic_process

Bondi et al http://mnras.oxfordjournals.org/content/104/5/273