Simulating galaxy populations

Schaye, J.

Simulating Galaxy Populations

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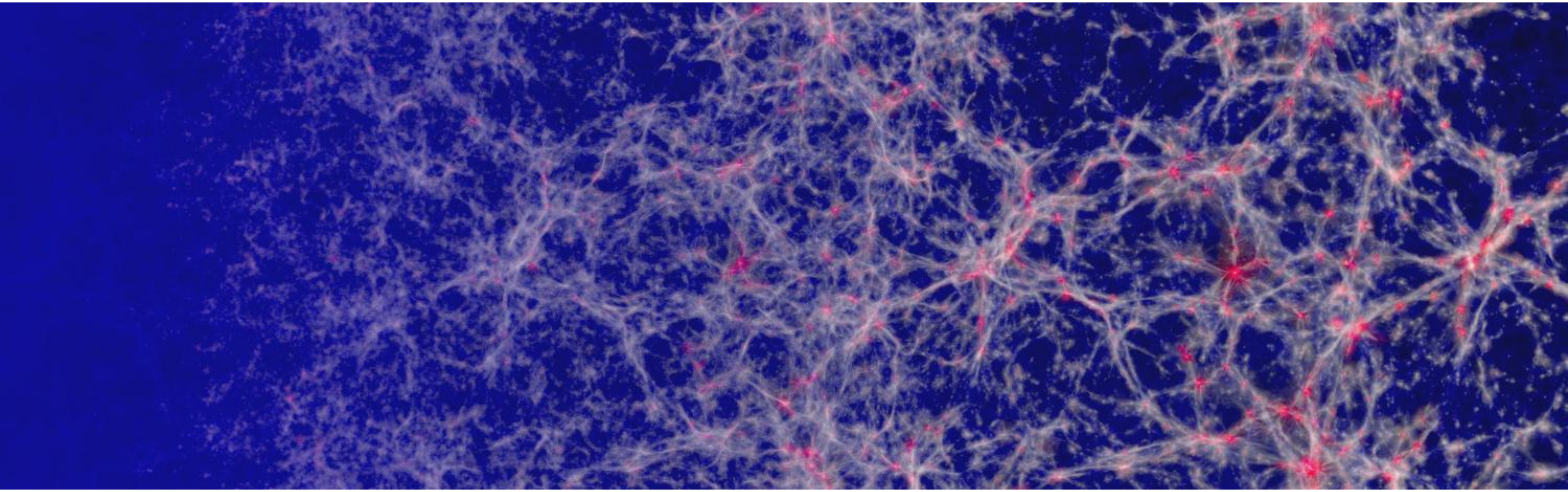


Modelling techniques

- Analytic theory
- Semi-empirical models
- Semi-analytic models
- **Hydrodynamical simulations**

Cosmological hydro simulations

- Evolution from z>~100 to z ~< 10 of a representative part of the universe
- Expansion solved analytically and scaled out
- Initial conditions from the CMB & LSS
- Boundary conditions: periodic
- Components: cold dark matter, gas, stars, radiation (optically thin)
- Discretizaton: time, mass (SPH) or length (AMR)
- Gravity and hydro solvers (and MHD, RT, …)
- Sub-grid modules are a crucial part of the game

Length Scales (cm)

Subgrid models

Directly simulated

10^{-8}	interparticle distance in stars
10^{0}	interparticle distance in ISM
10^{2}	interparticle distance in IGM
10^{11}	stellar radii
10^{18}	interstar distance
10^{20}	star clusters
10^{22}	galaxies
10^{24}	clusters of galaxies
10^{28}	observable universe

Common subgrid models

- Radiative cooling and heating
- Star formation
- Stellar mass loss (chemical evolution)
- Galactic winds driven by star formation
- Black hole formation, accretion and mergers
- AGN feedback

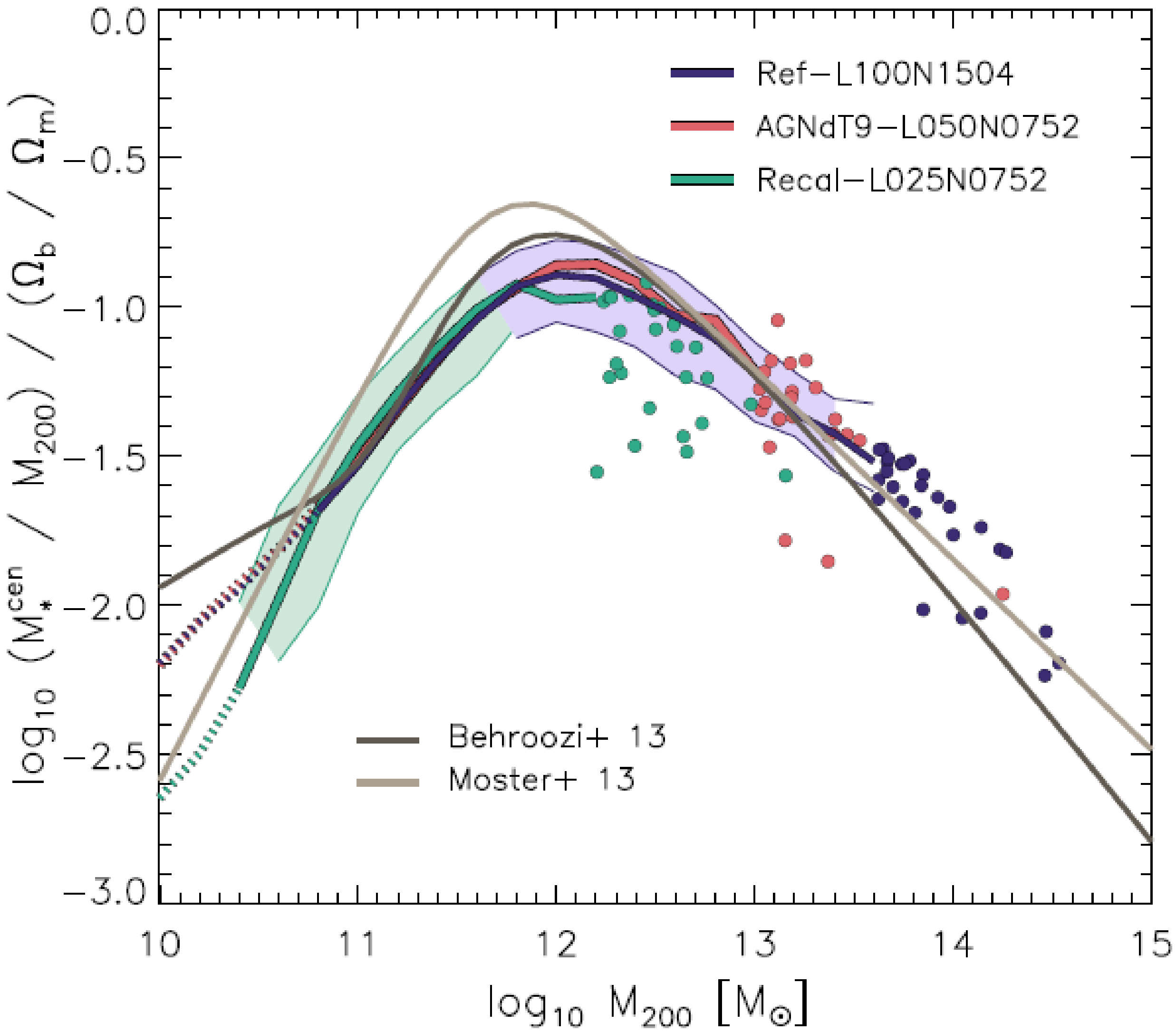
Galaxies in hydro simulations

- For many years galaxies in hydro simulations were:
  - Too massive
  - Too compact
  - Too old
  - Too bulgy/elliptical
- This changed thanks mainly to
  - Efficient, calibrated subgrid implementations of feedback from star formation
  - Inclusion of AGN feedback

Initial considerations

- Strong outflows at high redshift are necessary to obtain agreement with a diverse set of observations
- Maximum in stellar fraction – halo mass relation suggests that two types of feedback are needed

Galaxy formation efficiency



JS et al. (2015)

Initial considerations

- Strong outflows at high redshift are necessary to obtain agreement with a diverse set of observations
- Maximum in stellar fraction – halo mass relation suggests that two types of feedback are needed
- Cosmological simulations cannot resolve the cold ISM and hence cannot predict stellar masses and black hole masses accurately from first principles
- Some calibration necessary

  → require subgrid feedback that avoids numerical overcooling but whose efficiency can be controlled

  → need to compare to relevant observations

  → need to be clear about calibration input

Some take-away messages

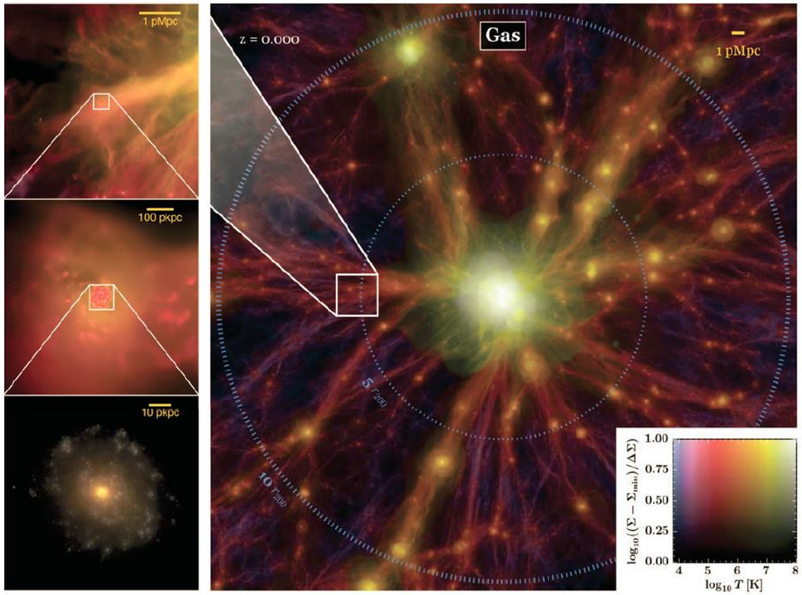
- Galaxy formation modelling is
  - Not fundamental theory
  - Generally better for qualitative than quantitative predictions
- Model calibration is not just tuning of free parameters:
  - (Subgrid) models contain free functions
  - A given amount of mass/energy can be injected in many ways
  - Motivated by discrepancies with data, simulations are modified from one generation to the next
  - Resolution dependence

Cosmological simulations: Complementary approaches

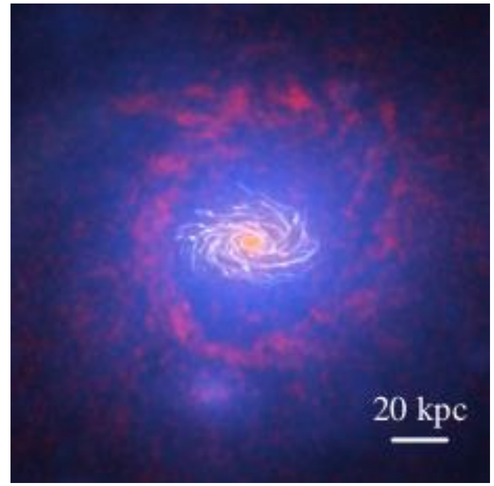
- Sets of zooms of haloes where resolution decreases with halo mass (e.g. FIRE, NIHAO)
  - Maximizes the range of halo masses
  - Maximizes the resolution at each mass scale
- Volumes of ~ 10^2 Mpc at a fixed maximum resolution (e.g. Illustris, EAGLE, Horizon, Simba)
  - No confusion between trends due to resolution and mass scale
  - Large numbers of objects
  - Representative range of environments
  - Easy to compare with observations
  - Intergalactic medium also included

Zoomed hydro simulations

Hydrangea/C-EAGLE



NIHAO

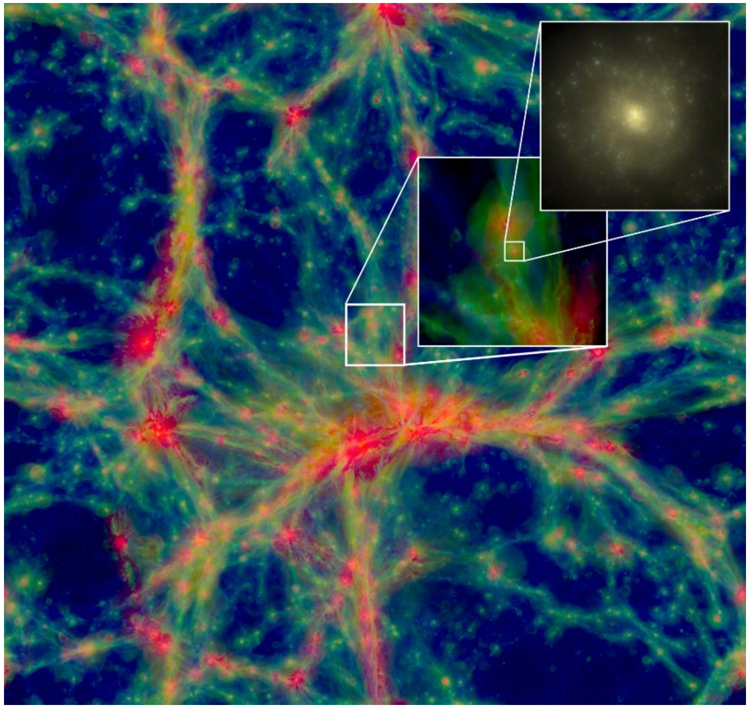


Auriga

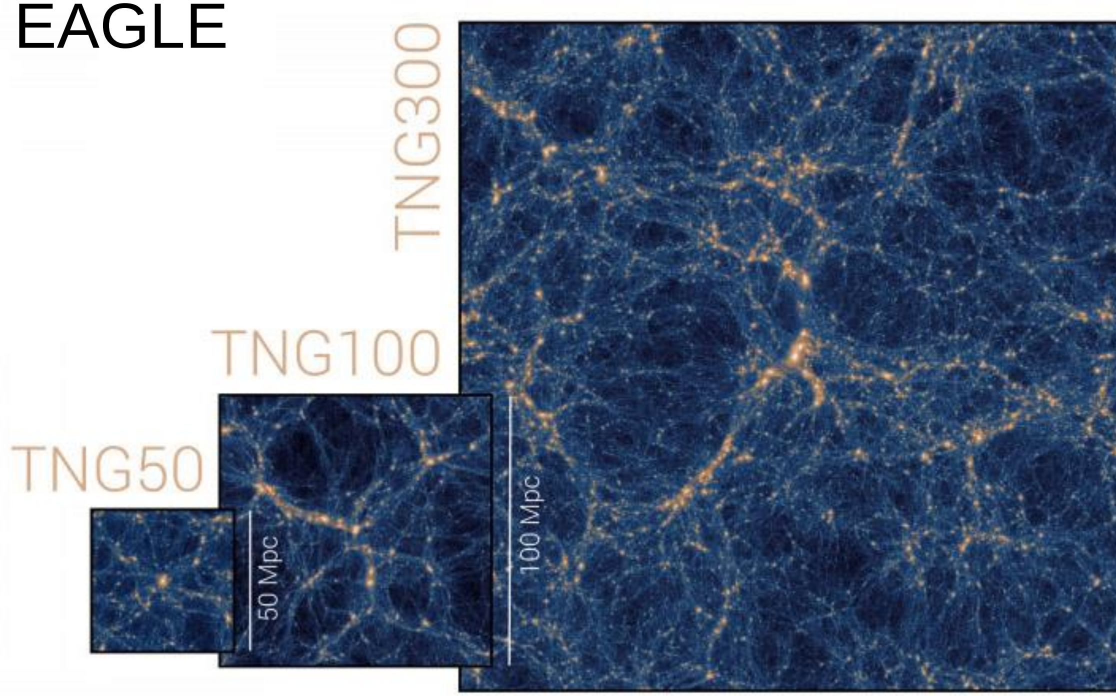
FIRE

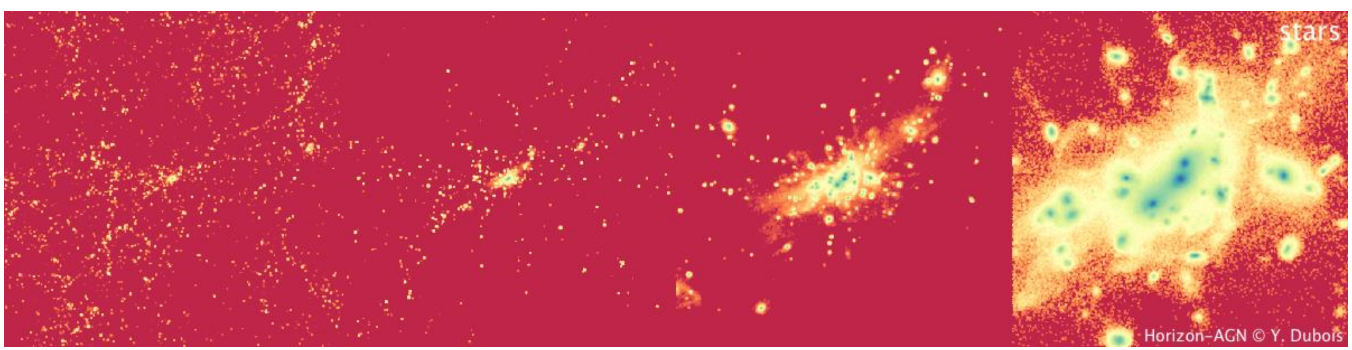
APOSTLE

Hydro simulations: Representative volumes



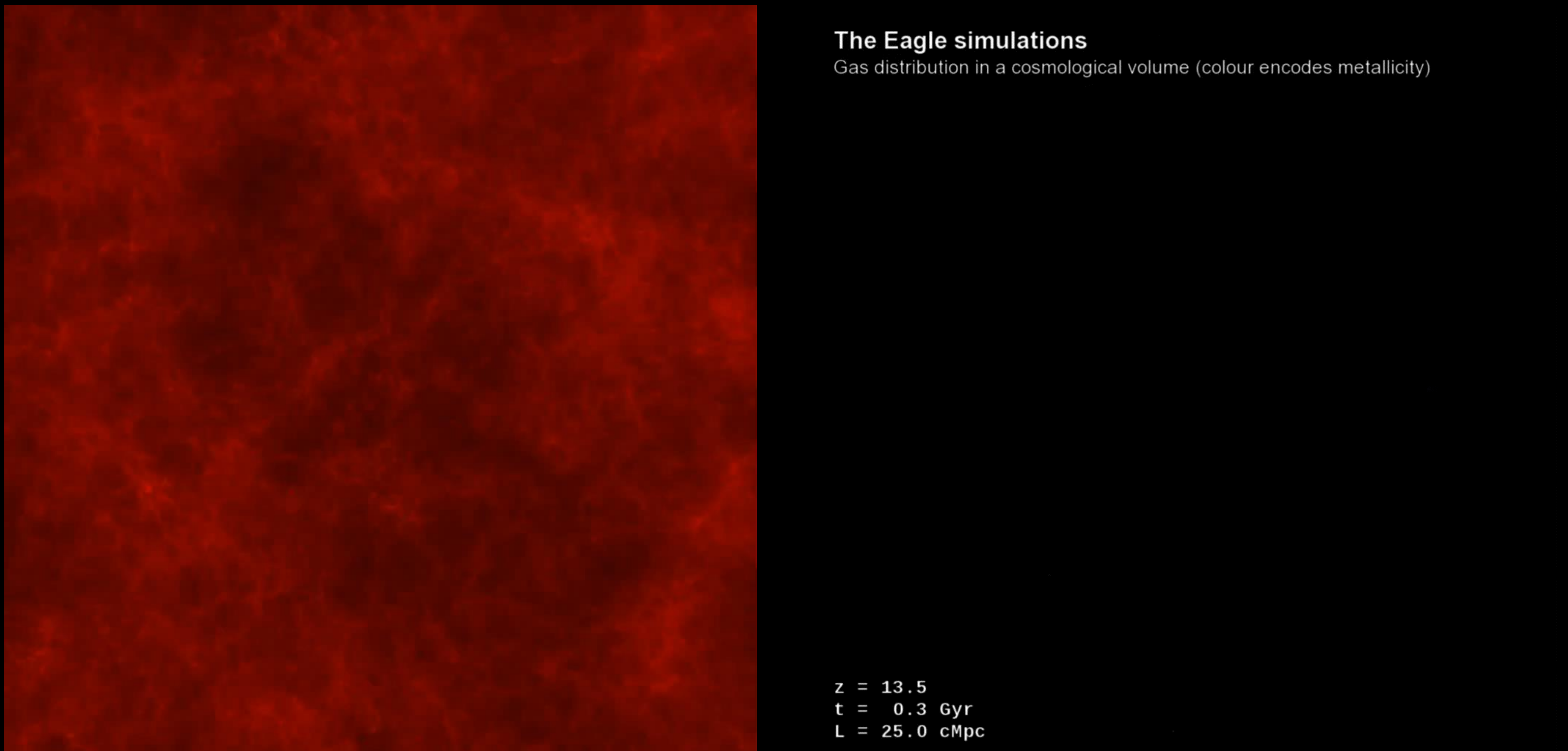
EAGLE





Horizon

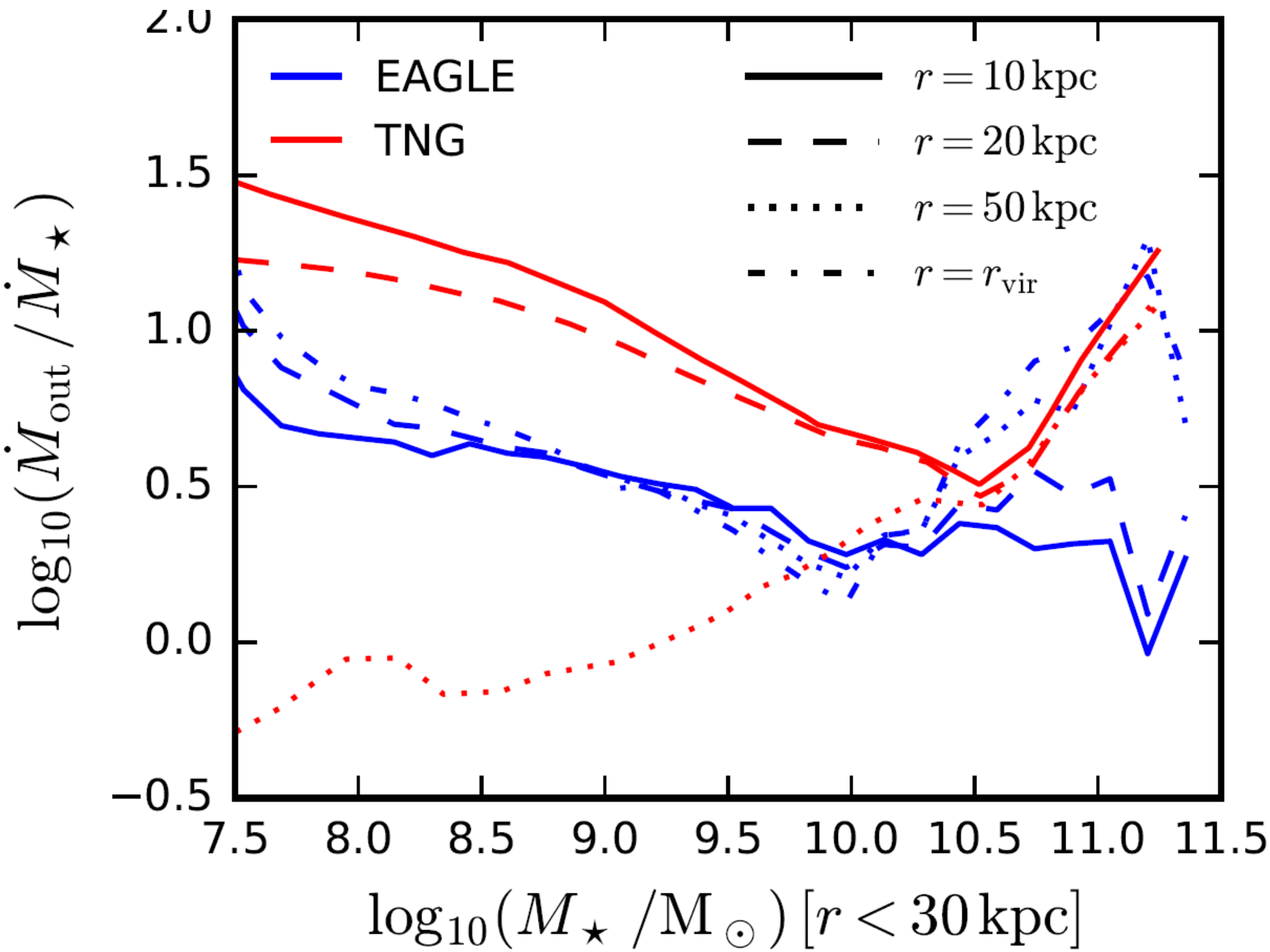
EAGLE T and Z evolution



JS, Crain+ (2015)

	EAGLE	ILLUSTRIS-TNG
Hydro solver	SPH	Moving mesh
Cold ISM phase	No	No
Effective resol.	~ 1 kpc	~ 1 kpc
Box size	~ 10^2 Mpc	~ 10^2 Mpc
Stellar feedback	Stochastic thermal, local. Constant heating temperature. Probability depends on local gas density (**tuned** to galaxy masses, sizes at z=0), metallicity.	Some thermal but mostly kinetic energy deposited in the CGM by turning off hydro forces within galaxies. Mass loading and velocity depend on dark matter velocity dispersion, redshift and metallicity (**tuned** to galaxy masses and sizes at z=0 and to the star formation history). Separate metal mass loading (**tuned** to galaxy metallicities)
AGN feedback	Stochastic thermal, local. Constant heating temperature. Efficiency **tuned** to BH masses.	Local thermal dump (quasar-mode) and local kinetic energy (radio-mode) at high/low accretion rates. In radio mode the energy per event scales with the virial temperature and depends on density. The critical Eddington ratio depends on BH mass (**tuned** to quenching mass). Efficiencies **tuned** to BH masses (quasar mode) and **tuned** to group CGM mass fractions (radio mode).

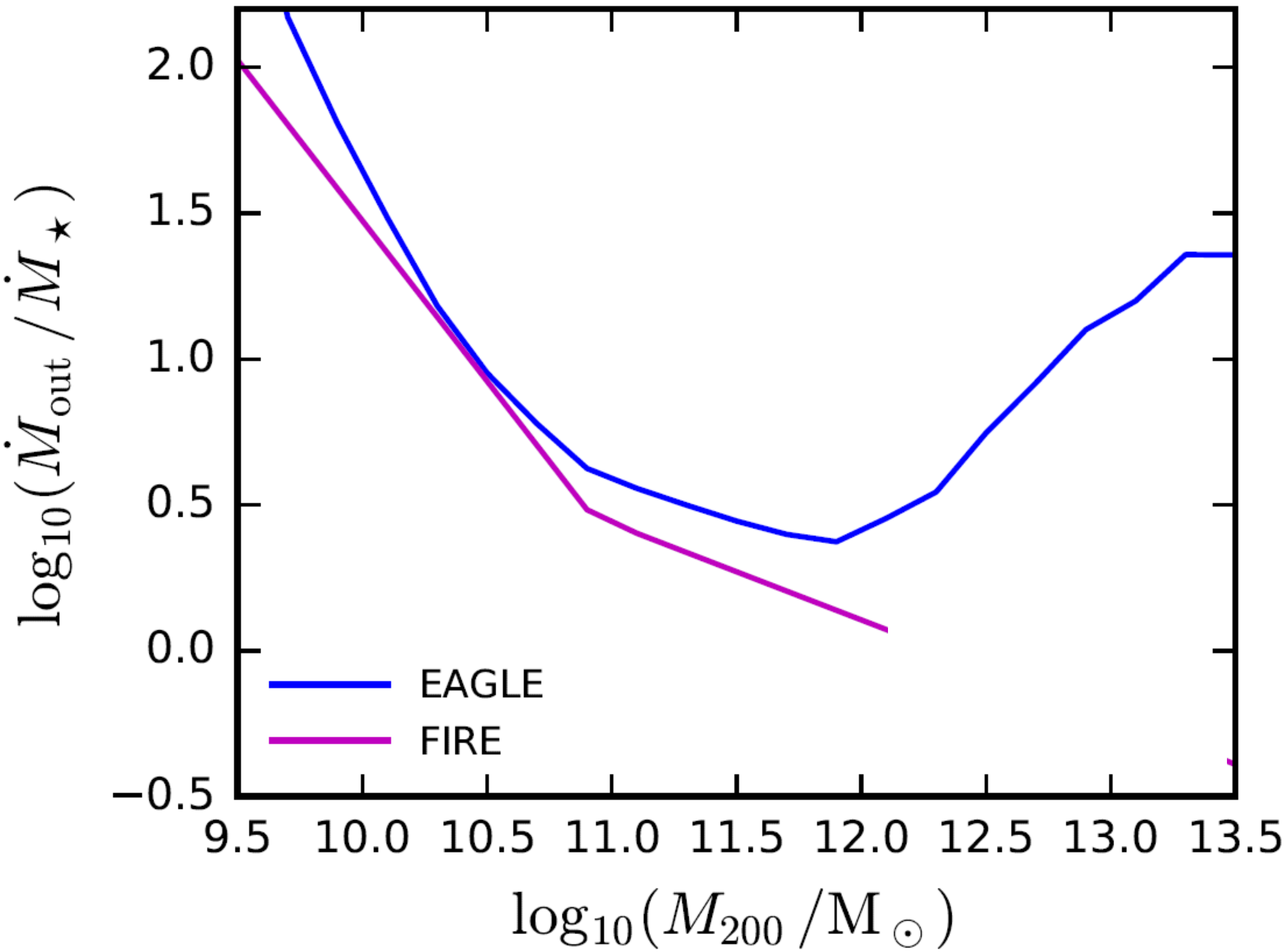
Wind mass loading vs stellar mass at z=2: Comparison of EAGLE and TNG



Mitchell, JS+ (2020)

Qualitatively similar at small r, but TNG higher
Strong reduction at large r for low-mass galaxies in TNG

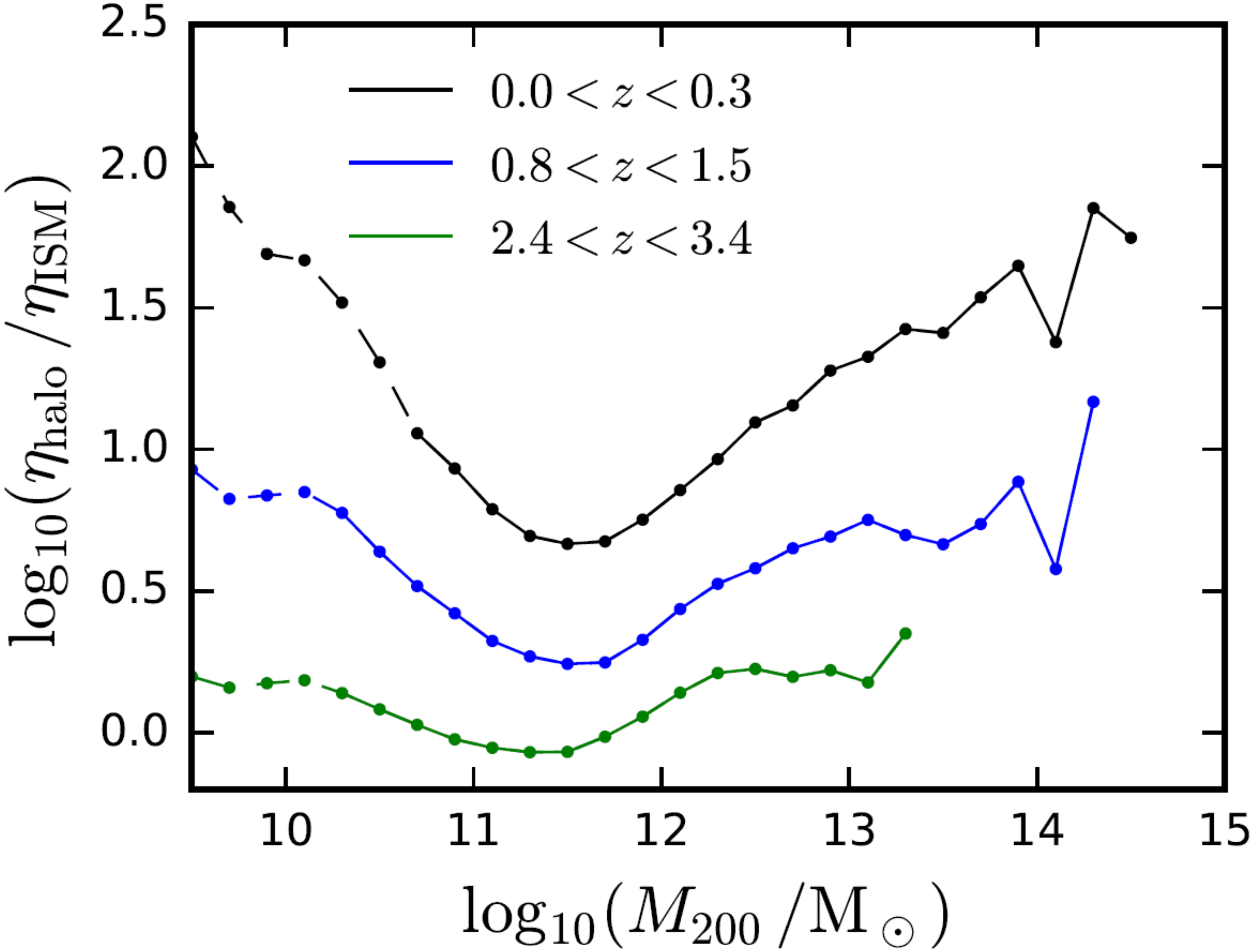
Wind mass loading vs halo mass at z=0.25: Comparison with FIRE



Very good agreement at low mass
FIRE much lower at high mass due to lack of AGN

Mitchell, JS+ (2020)

Ratio of mass loading of halo and ISM winds in EAGLE



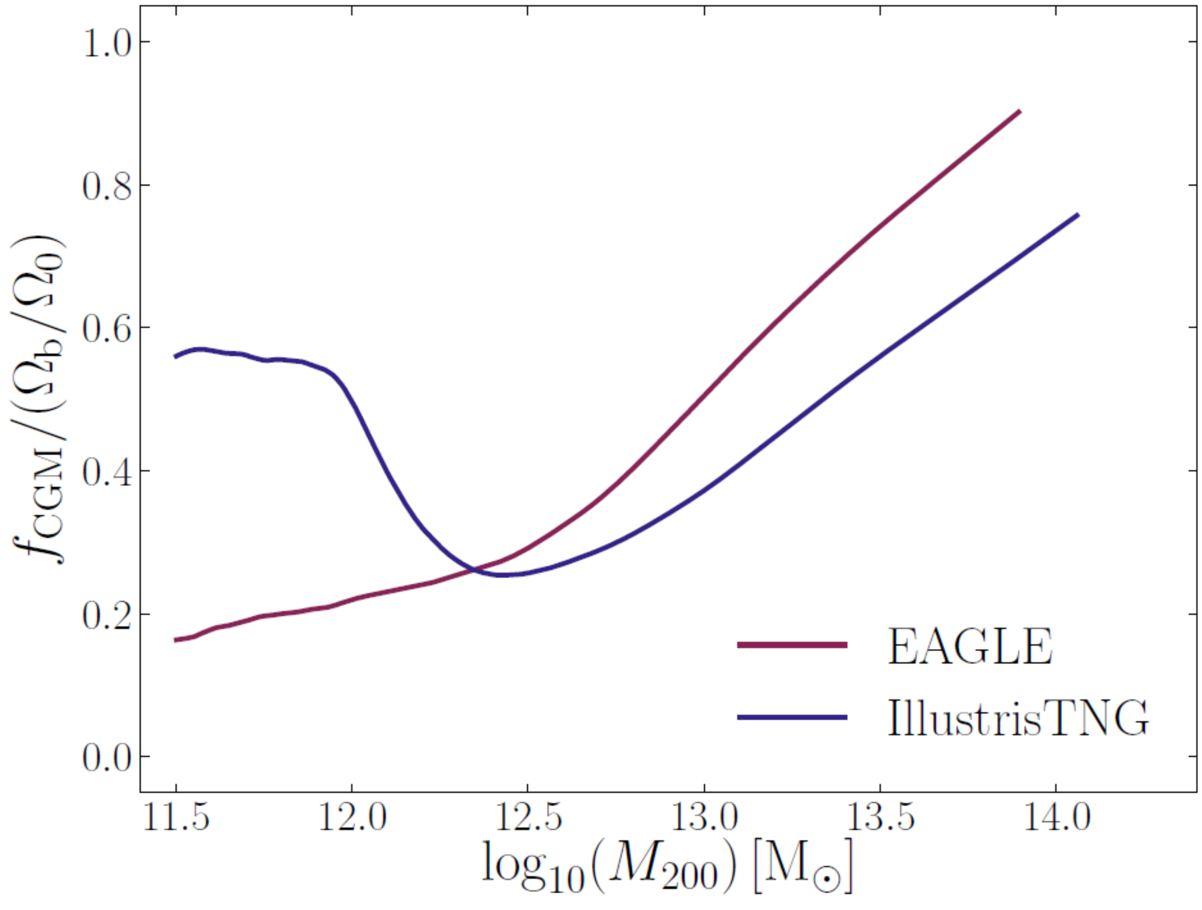
Large amount of mass loading in the CGM,
particularly at low-z and at low/high mass

Mitchell, JS+ (2020)

Galactic winds

- Emergent wind scaling relations: mass loading and velocity vary systematically with galaxy mass
- Mass loading minimum at L* in EAGLE & TNG
- In EAGLE mass loading strongly enhanced while traversing the CGM → preventative feedback important
- TNG mass loading higher (lower) at small (large) radii
- Good agreement between EAGLE and FIRE at small radii and low mass, but in FIRE outflows do not turn up at high mass due to lack of AGN

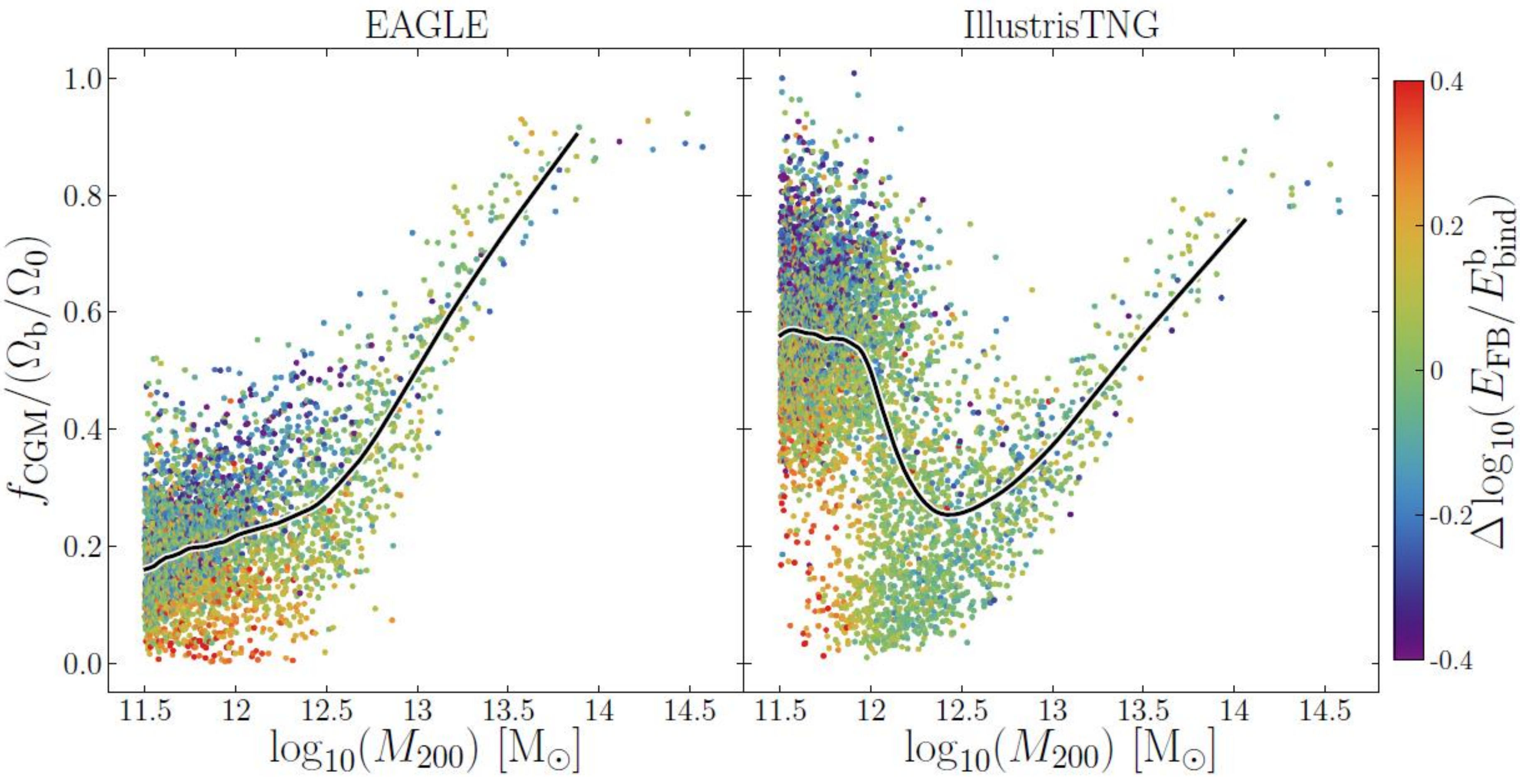
CGM mass fraction vs halo mass



- EAGLE and TNG predict very different $f_{CGM}(M_{200})$
- In TNG stellar feedback less efficient on CGM scales
- Drop in TNG corresponds to activation of quenching “radio-mode” AGN feedback at tuned mass scale

Davies+ (2020)

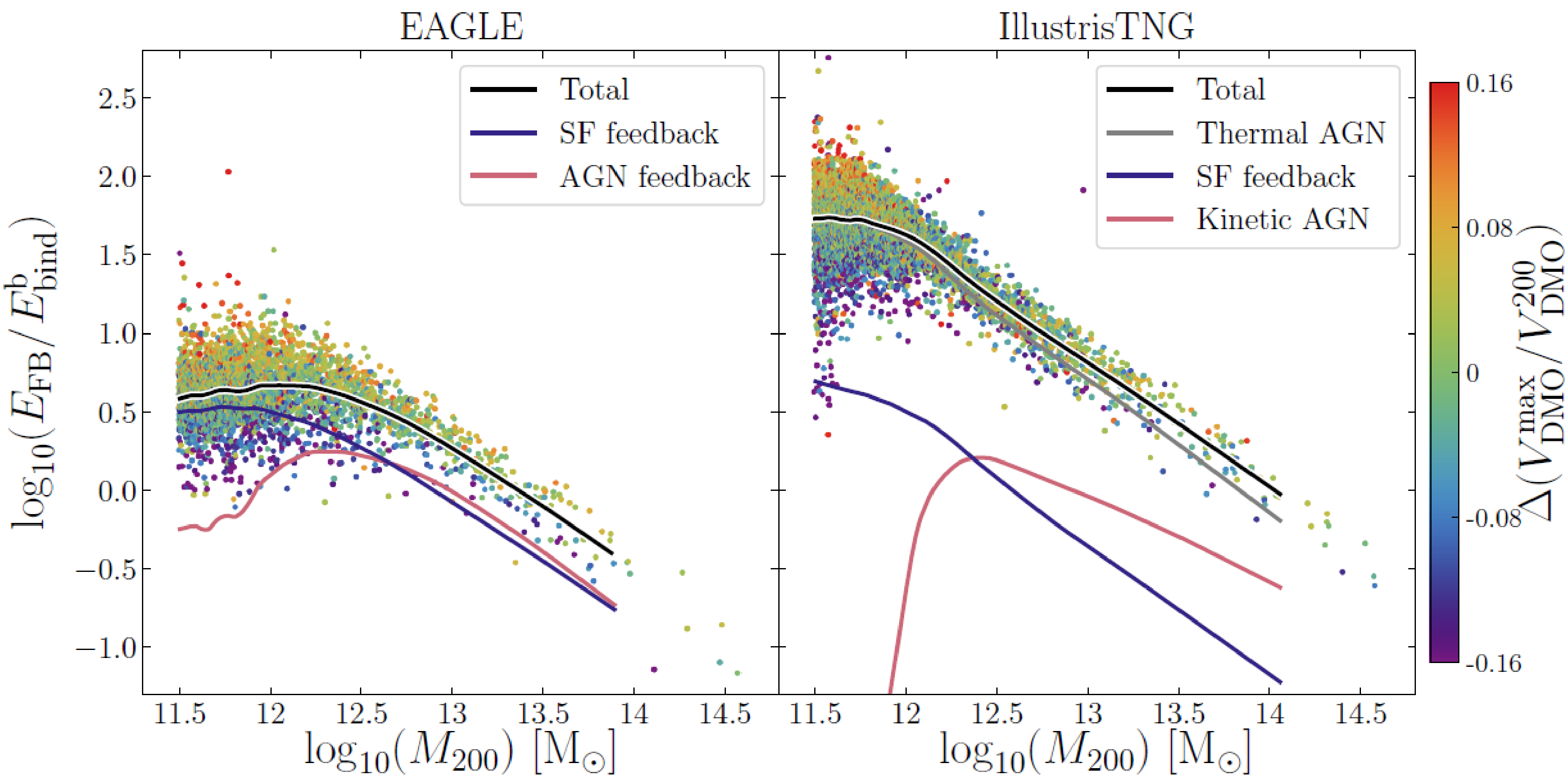
Scatter in $f_{CGM}(M_{200})$: Correlation with $\Delta(E_{fb}/E_b)$



- At fixed halo mass, more feedback energy relative to binding energy reduces f_{CGM} (and sSFR)

Davies+ (2020)

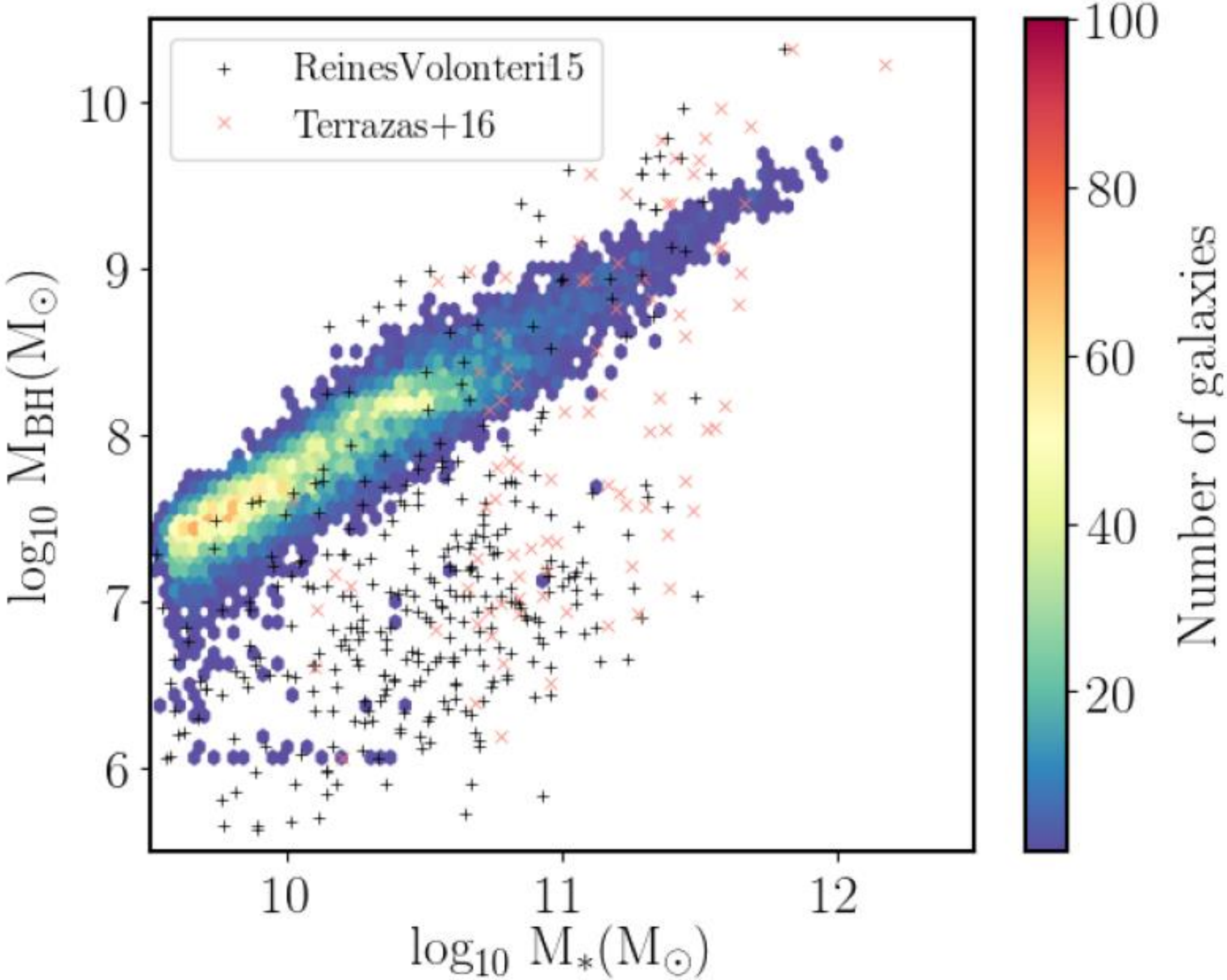
Contributions from different feedback channels to the energy budget



- EAGLE: SF (AGN) feedback dominates at low (high) mass
- TNG: Quasar-mode AGN totally dominates at all masses, Radio mode sets in at (tuned) mass scale and is then more important than SF

Davies+ (2020)

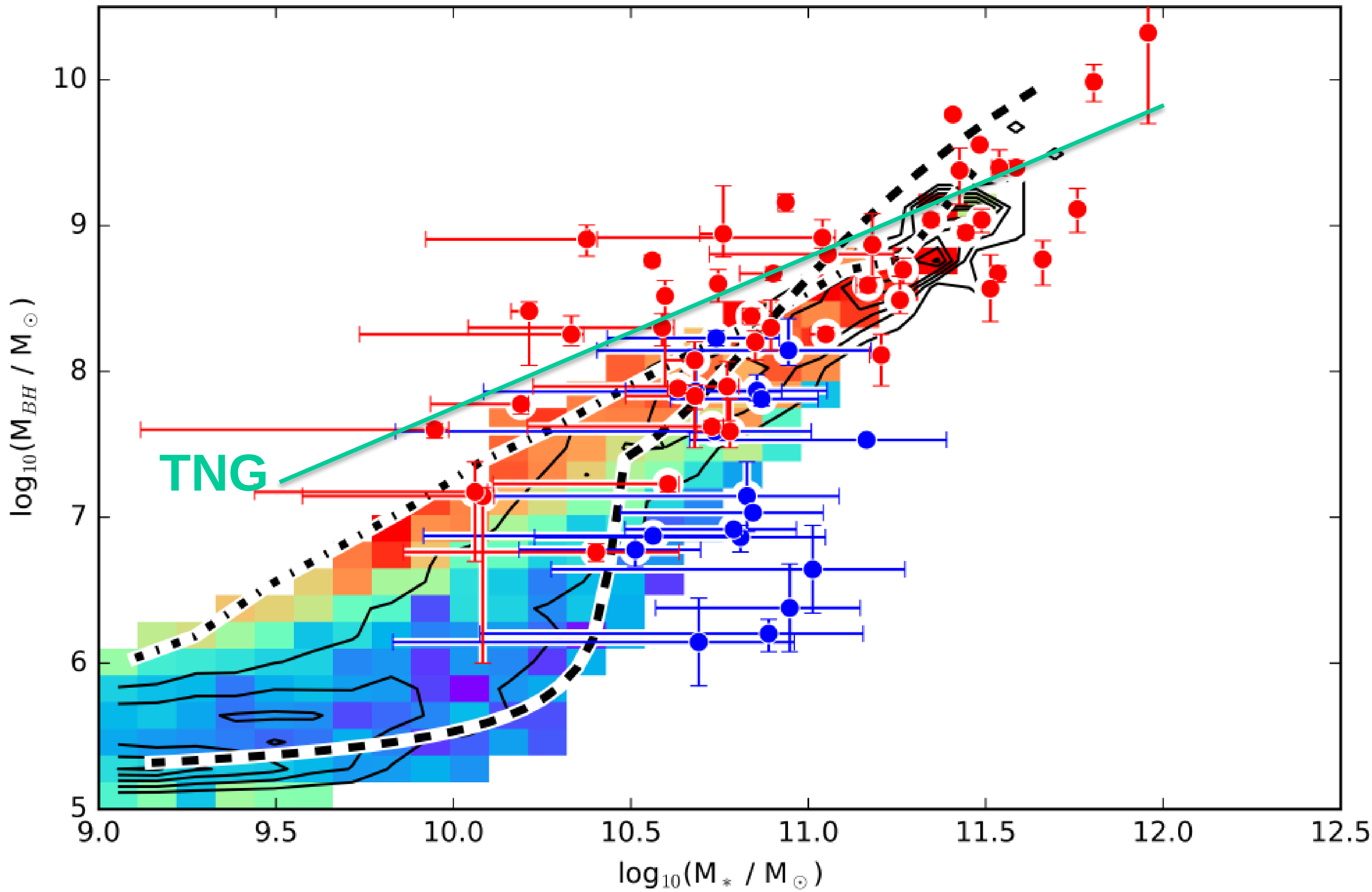
BH – Stellar mass relation: TNG



TNG: Single power-law M_{BH}-M_* relation down to low mass

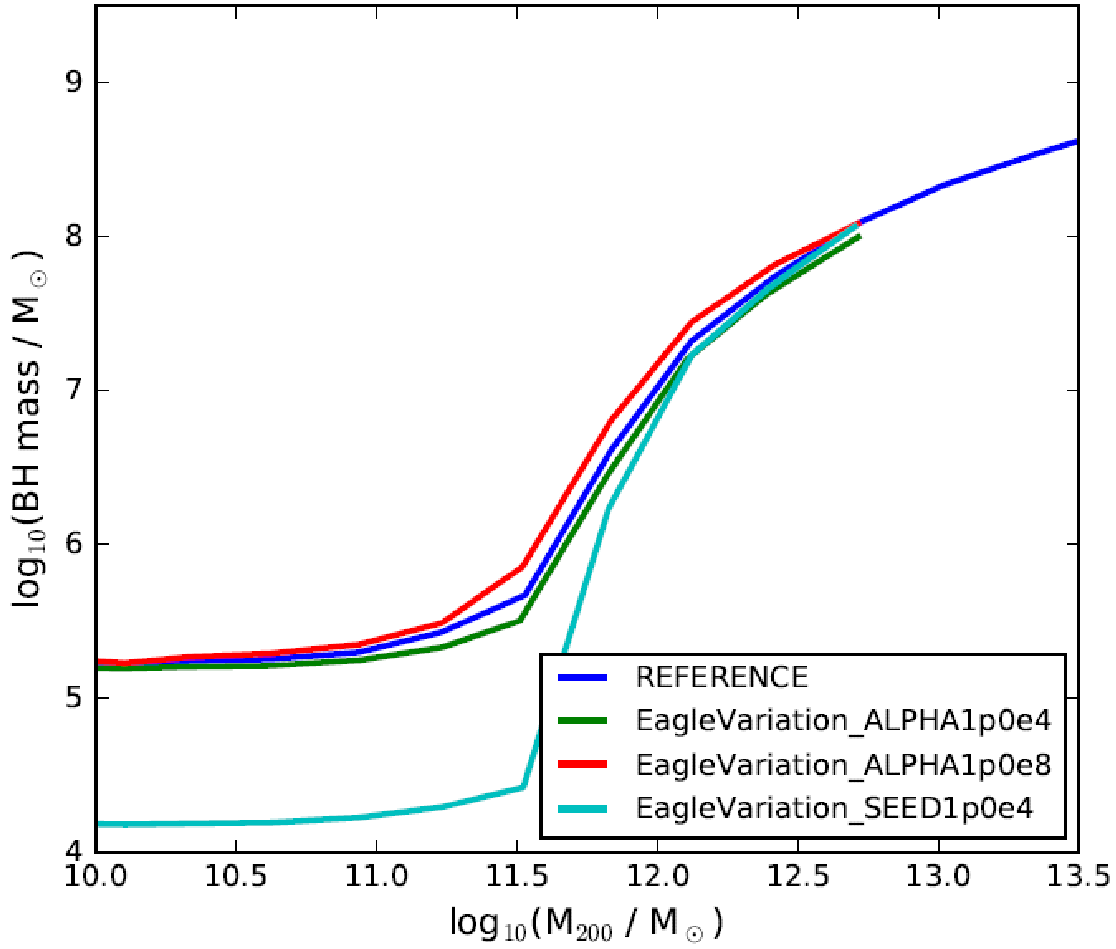
Li+ (2019)

BH – Stellar mass relation in EAGLE



Bower, JS+ (2017)

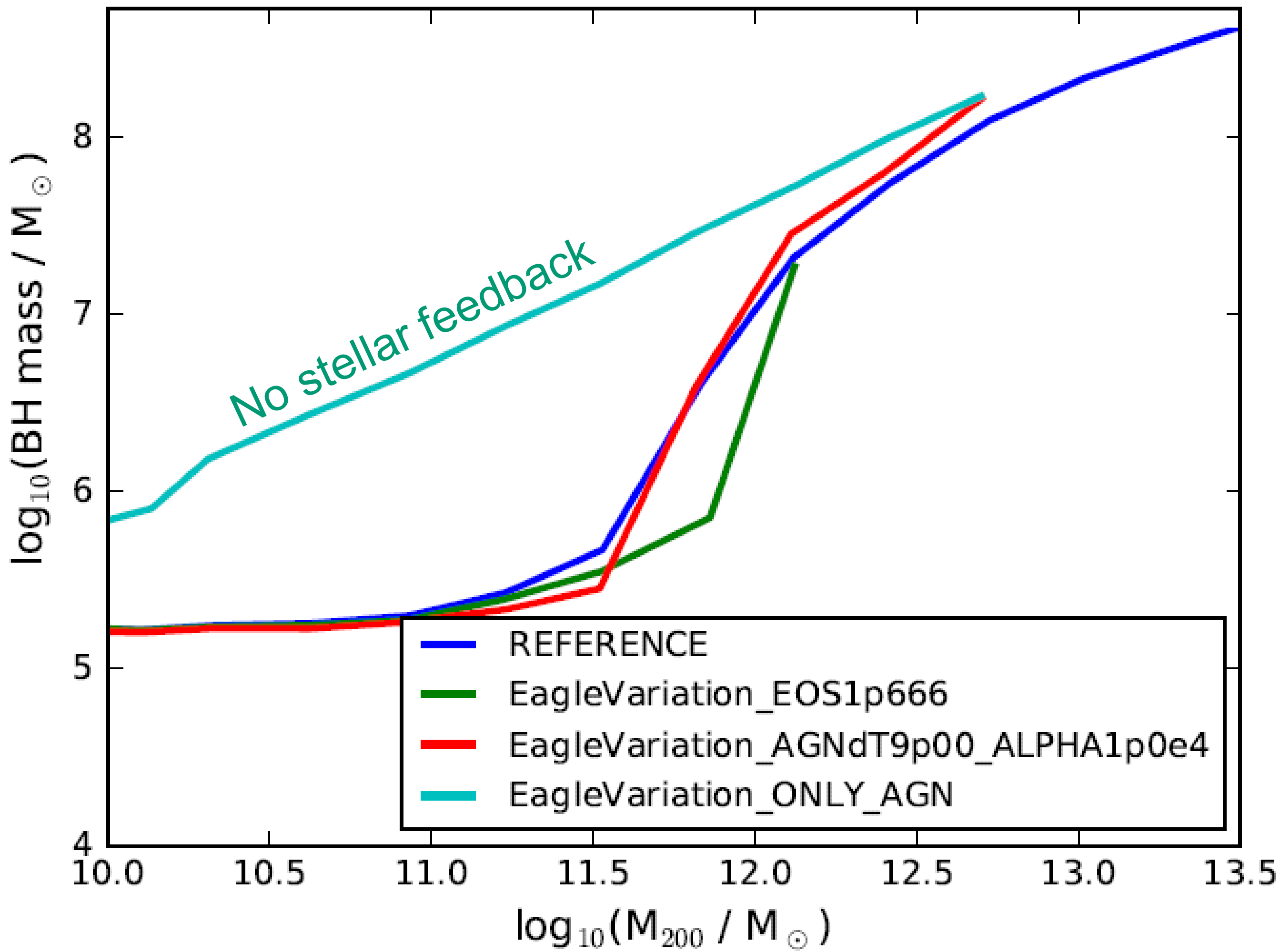
BH – Stellar mass relation in EAGLE



The critical mass scale is neither set by the subgrid BH accretion model nor by the BH seed mass

Bower, JS+ (2017)

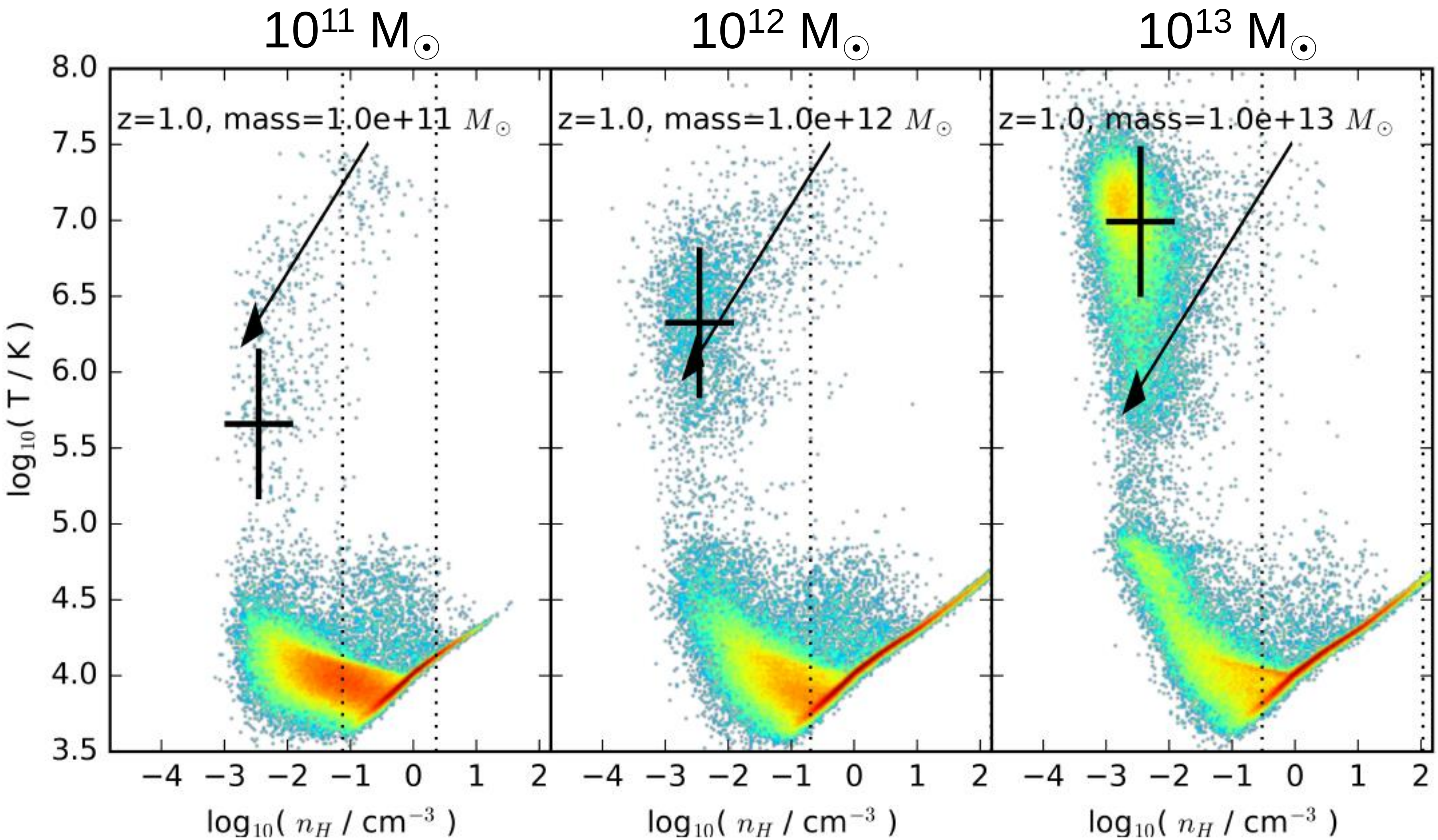
BH – Stellar mass relation in EAGLE



Stellar feedback suppresses BH growth for $M_{200} < 10^{12}\ M_{\odot}$
But why this mass?

Bower, JS+ (2017)

Are the winds buoyant?



Wind fluid not buoyant for $M_{200} > 10^{12}$ $M_\odot$

Formation of hot halo quenches galactic winds

Bower, JS+ (2017)

Quenching in EAGLE

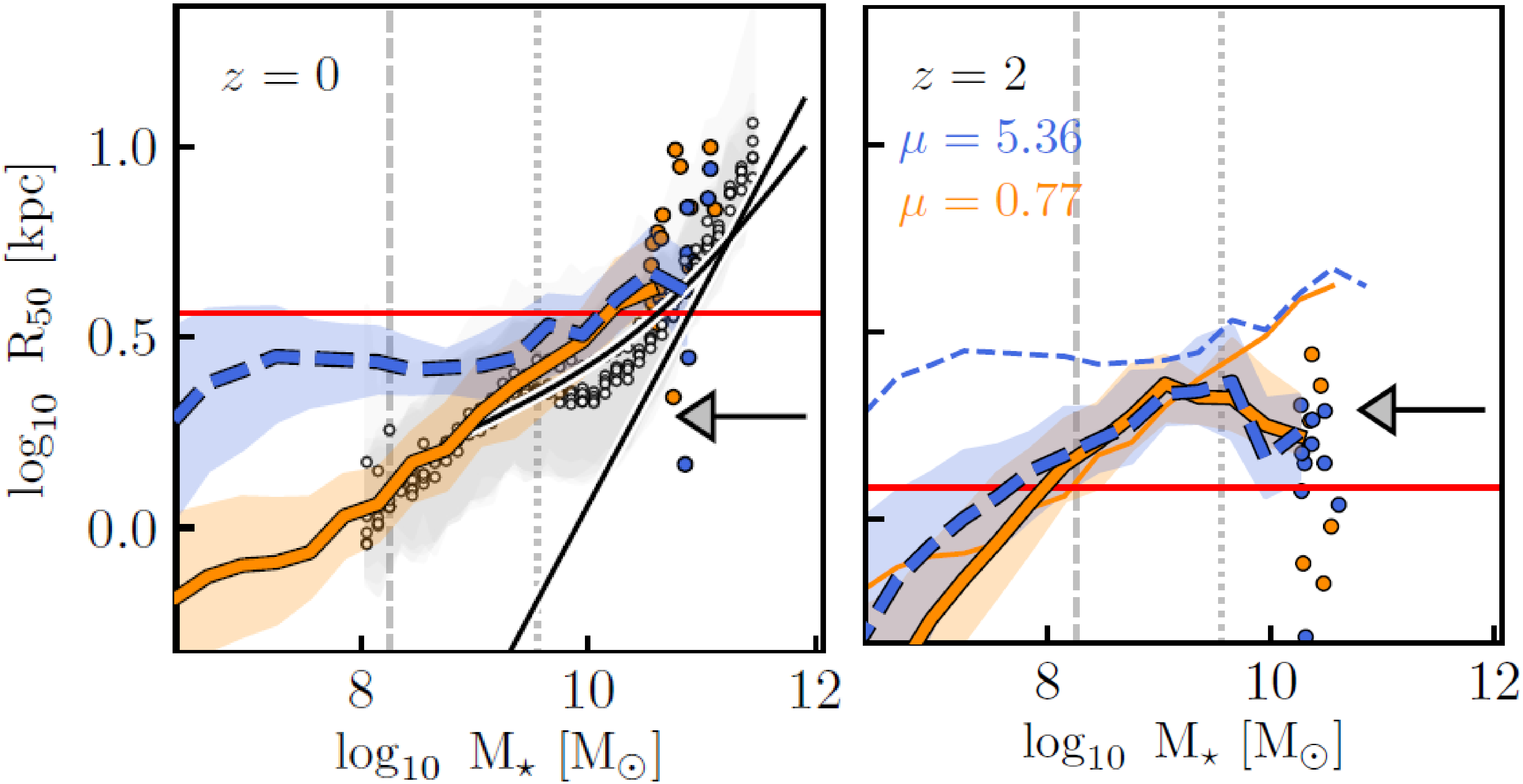
- At low galaxy mass stellar feedback keeps the nuclear ISM dilute and hot, preventing BH gas accretion
- Once a hot halo forms at $M_{200} \sim 10^{12}\ M_{\odot}$, stellar feedback is halted since the hot wind bubbles are not buoyant
- Once stellar feedback becomes inefficient, the BH grows rapidly until its luminosity is sufficiently high to halt gas accretion, eject part of the CGM and quench the galaxy

Bower, JS+ (2017)

Quenching in TNG (my interpretation)

- Stellar feedback does not prevent BH growth because the winds are decoupled from the hydrodynamics → mass is removed without heating/stirring the ISM
- Quasar mode uses thermal dump → overcooling → cannot stop gas accretion onto galaxy
- → BH and galaxy grow in lockstep at all masses
- Radio mode is explosive (similar to EAGLE), but only activated below a critical Eddington ratio
- Radio mode quenches galaxy by halting gas accretion and ejecting part of the CGM
- Mass at which switch to radio mode occurs is tuned by making the critical Eddington ratio mass dependent
- Runaway radio-mode feedback is prevented by halting it below a second (lower) critical Eddington ratio

Numerical can effects also matter: Evolution of the galaxy size-mass relation



- Spurious energy transfer from DM to stars unless equal mass particles are used
- Softening scale does NOT necessarily set the resolution

Ludlow, JS, Schaller, Richings (2019)