



Illustris
simulation

BHs and AGN in 6 large-scale cosmological simulations

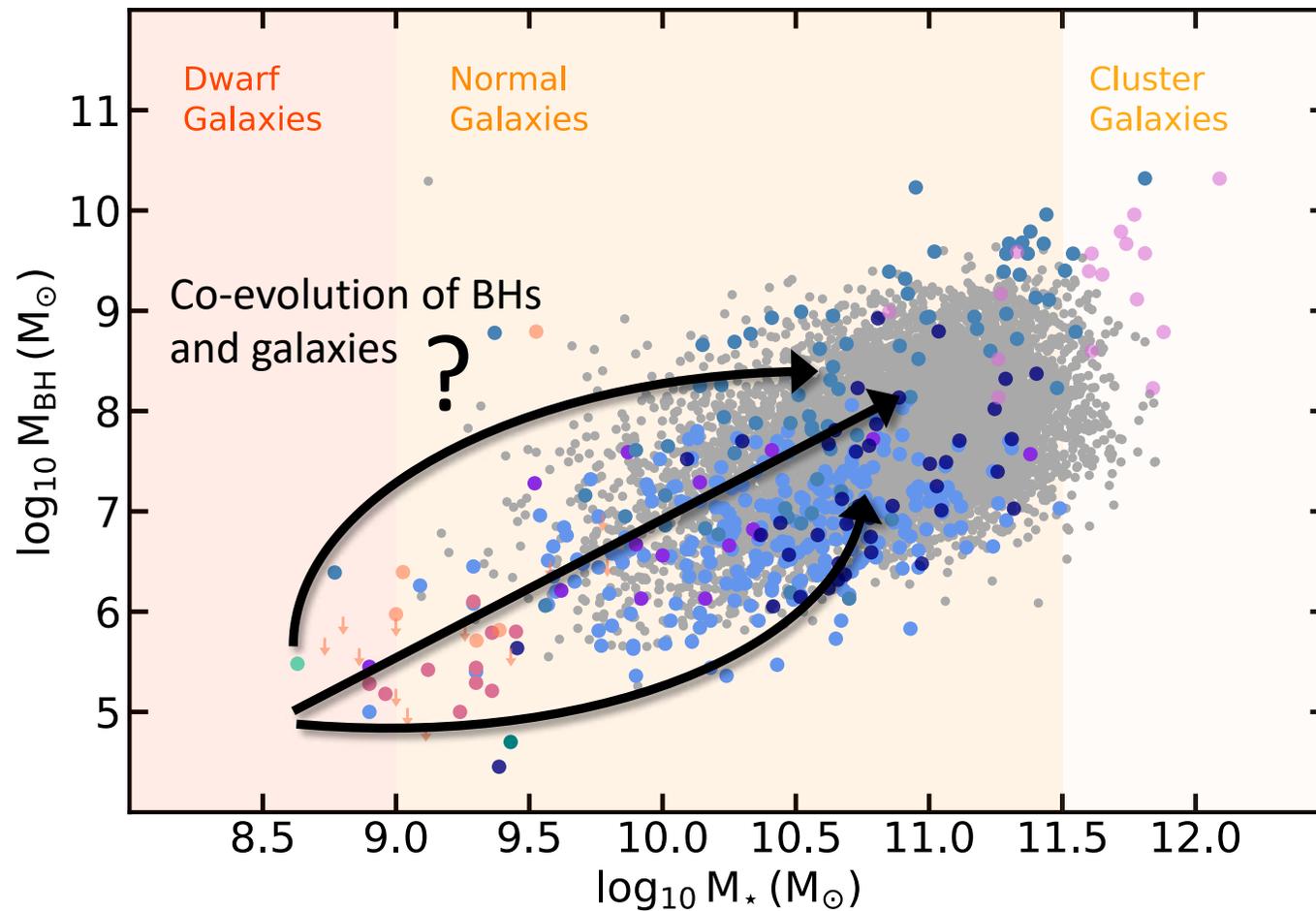
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Observations in the local Universe



Reines & Volonteri 15

- Dynamical mass measurements
 - Elliptical galaxies
 - S/SOs with classical bulges
 - S/SOs with pseudobulges

Reverberation-mapped AGN

Broad-line AGN

Dwarf galaxies

RGG118

Pox 52

Greene, Strader, Ho 19

Dwarf galaxies

Davis, Graham & Cameron 19

- Dynamical mass measurements
 - Spiral galaxies

Dogdan+ 18

BHs in BCGs

Baron & Menard 19

Obscured AGN (narrow line ratio)

A decade of large-scale cosmological hydro simulations to study galaxy formation.

Resolution of the simulations

Dark matter resolution of $6 \times 10^6 - 10^8 M_{\text{sun}}$.
Baryonic resolution of $2 \times 10^6 - 2 \times 10^7 M_{\text{sun}}$.
Spatial resolution 1-2 ckpc.
Box side length 100-300 cMpc.

Subgrid physics

Cooling + UV background.
Star formation.
Supernova feedback / Metal enrichment.

BH physics.

BH
formation

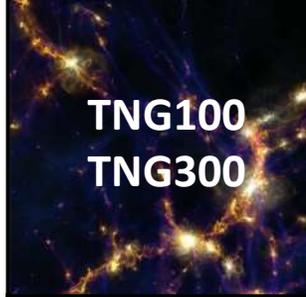
In massive halos/galaxies.
Fixed BH initial mass.
 $M_{\text{BH}} = 10^4 - 10^6 M_{\odot}$

BH
growth

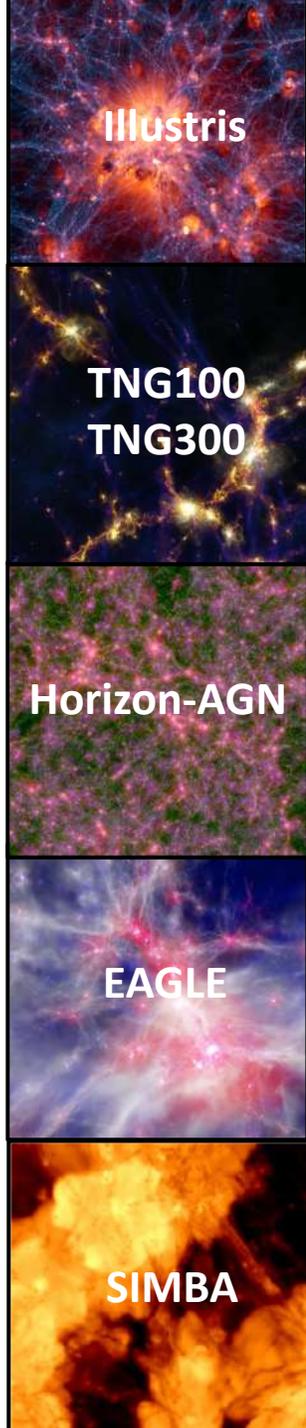
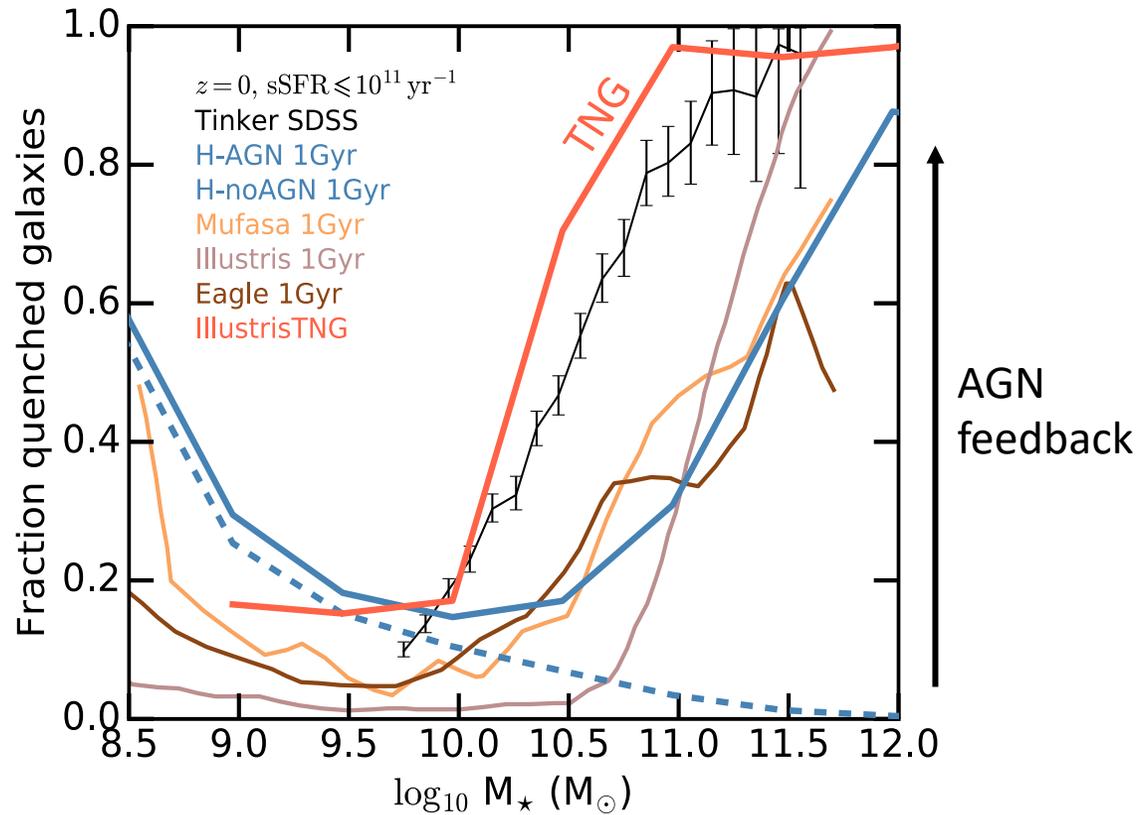
BH mergers,
gas accretion via Bondi formalism.

AGN
feedback

Injection of energy that couples to the gas.
 $\dot{E}_{\text{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2$



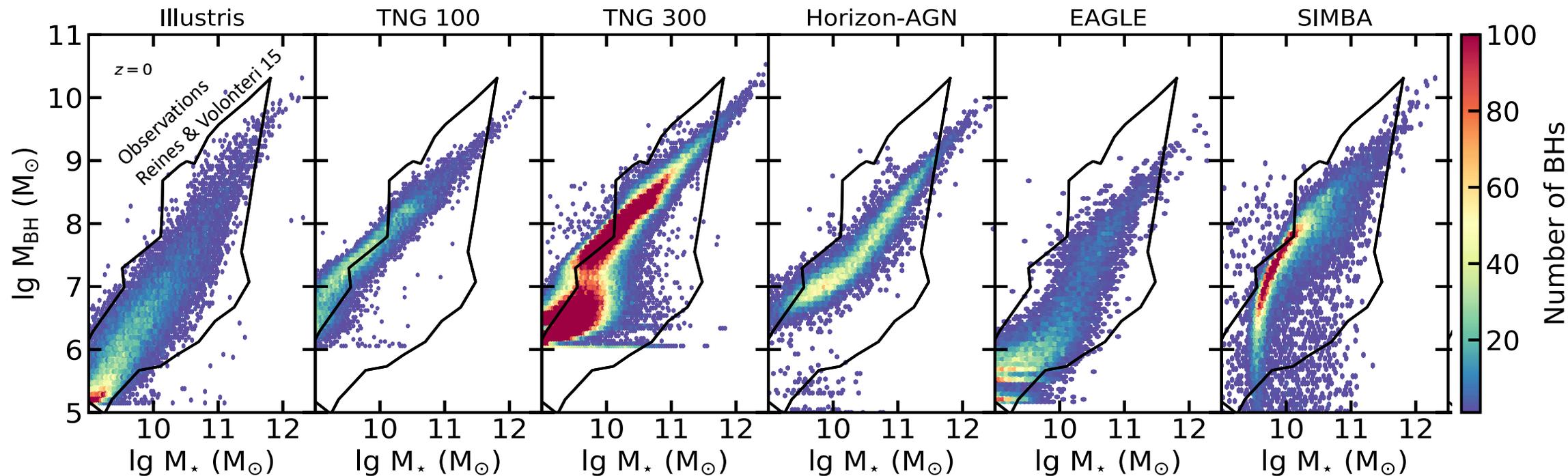
Large-scale cosmological hydrodynamical simulations to study galaxy formation



Simulated population of galaxies in good agreement with observations (e.g., star-forming main sequence, galaxy morphologies, sizes, quenched galaxies).

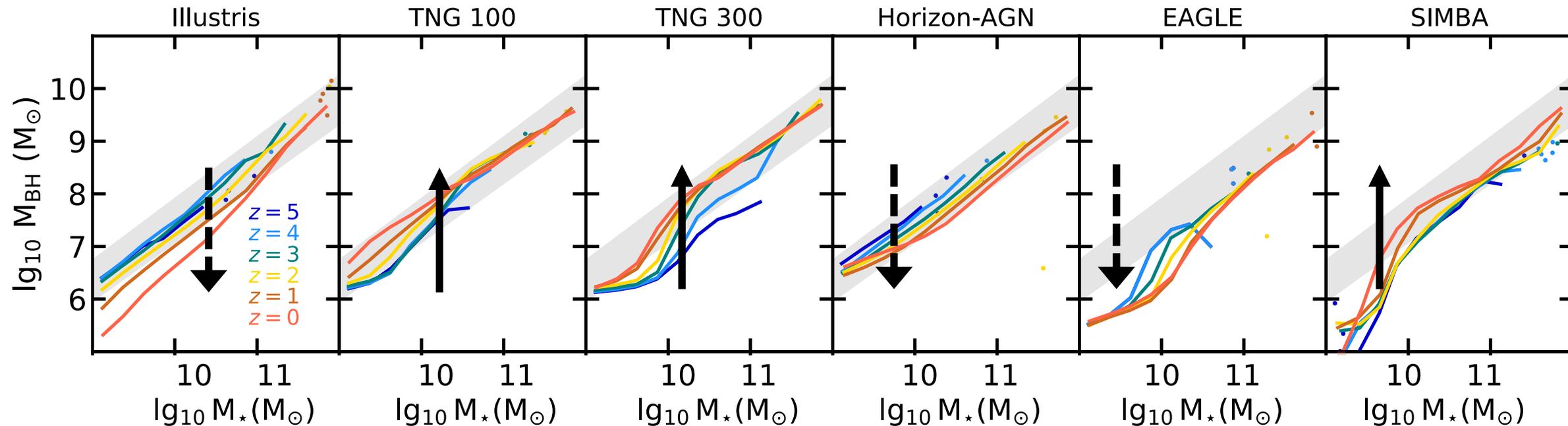
e.g., Dubois+14,+15, Genel+14, Vogelsberger+14, Schaye+15, Pillepich+18, MH+19a, Davé+19.

Are the simulated BHs
in good agreement
with observations ?



- Broad agreement at $z=0$ due to calibration.
Haring+04, McConnell+11, Kormendy+13
- Tighter relation in simulations than in observations.
see also Li, Habouzit+20

- a) Seeding
- b) Lack of stochasticity in subgrid models
- c) SN feedback
- d) BH spin *e.g., Dubois+14, Bustamante+19, Trebitsch+20*
- e) Radiative efficiency, AGN feedback



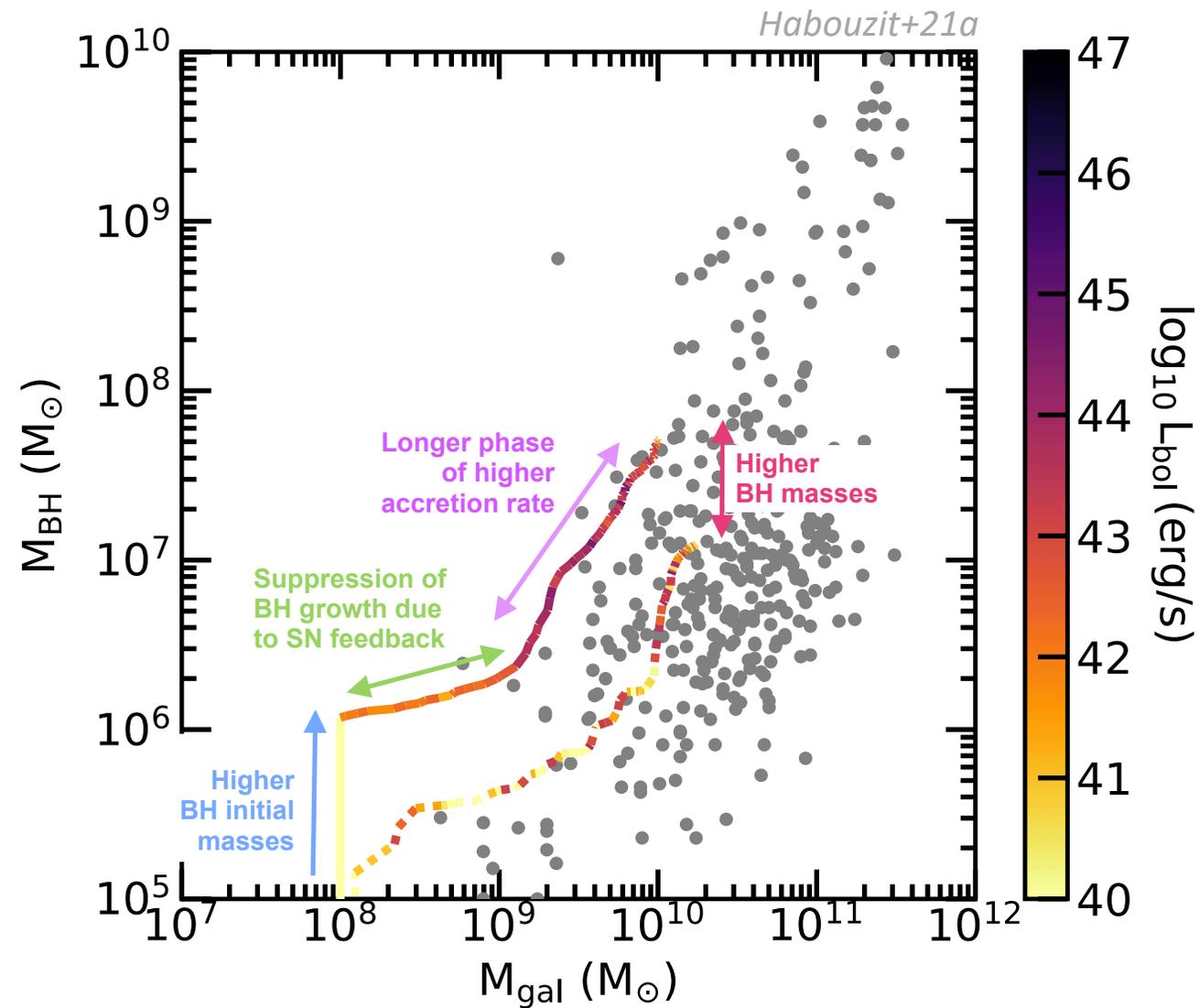
- Mild time evolution (within 1 dex of BH mass).
- Agreement with observations for $0 < z < 2$ ($M_{\text{star}} > 10^{10} M_{\text{sun}}$).
e.g., Shields+03, Jahnke+09, Mullaney+12, Schramm&Silverman+13, Cisternas+11, Sun+15, Suh+19, but McLure+06, Ding+19.

No consensus in cosmological simulations on whether BHs are more massive at high redshift.

The high-redshift regime can be constrained with *faint high-redshift quasars* with JWST (MH, Onoue, Banados+2021).

→ Cycle 1 JWST program, PI: M. Onoue.

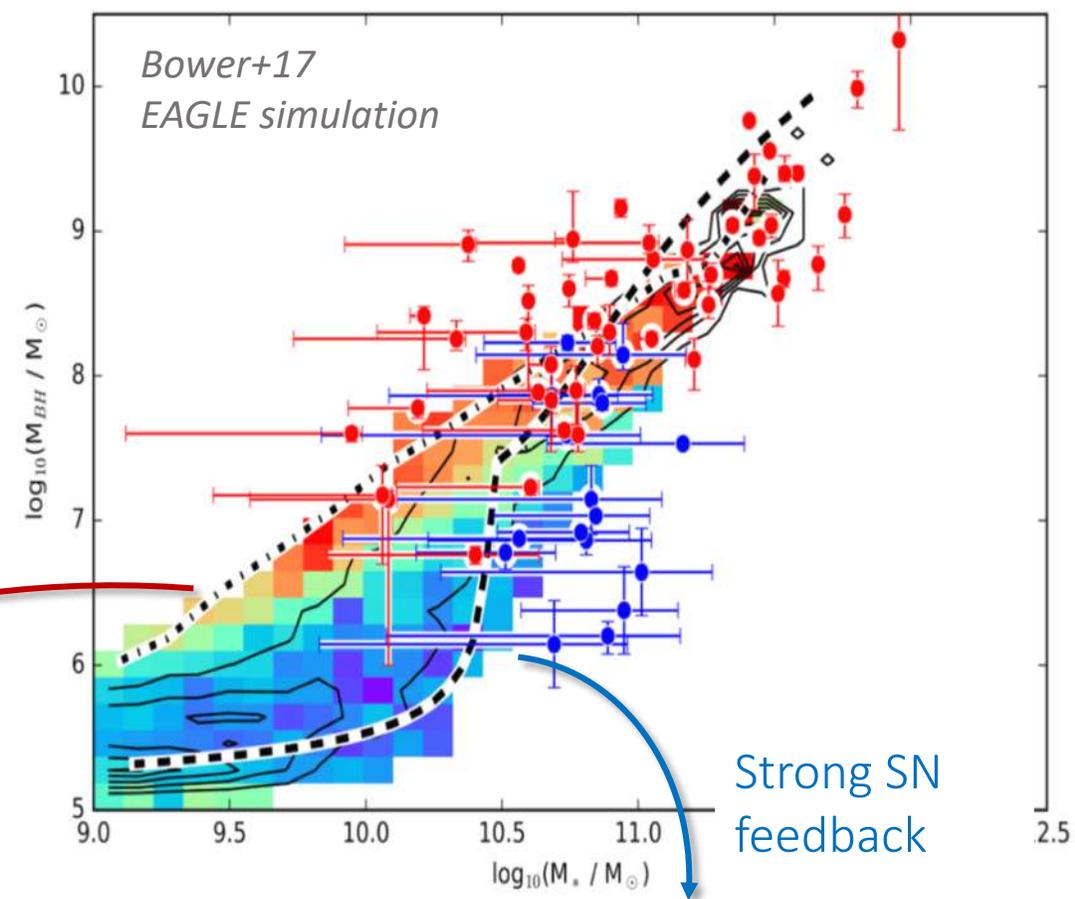
Two matched BHs
in TNG and Illustris



Subgrid models strongly impact BH growth

SN feedback can stunt BH growth in low-mass galaxies.

Dubois+15, Anglés-Alcázar+17, Habouzit+17,+21a, Bower+17, McAlpine+18, Dekel+19.
See also Fontanot+15 for SAMs.



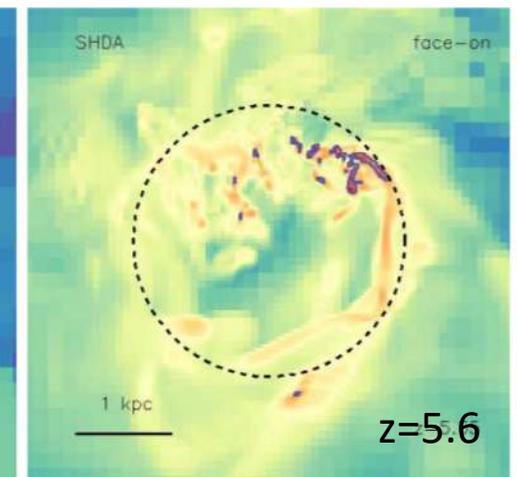
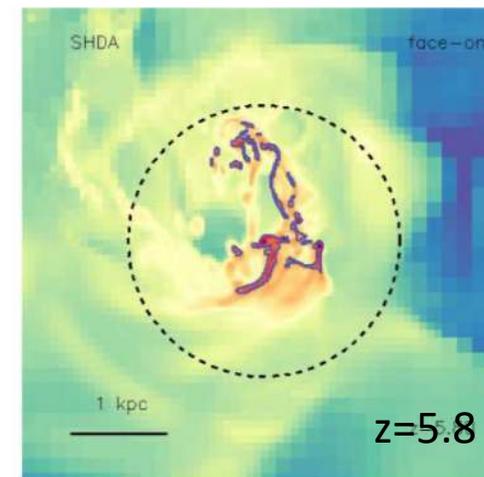
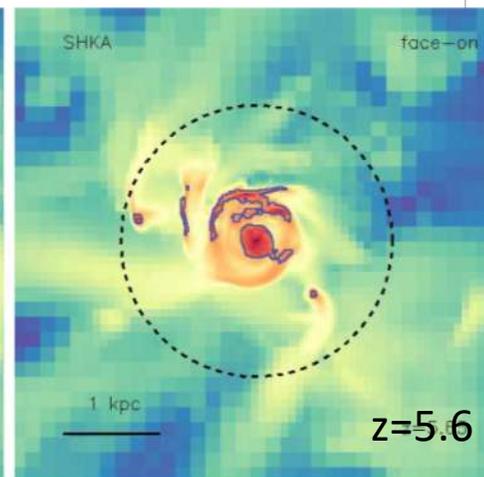
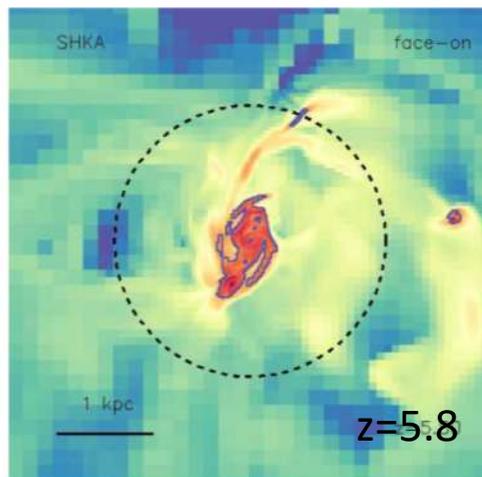
Weak SN feedback

Strong SN feedback

Dubois+15

Set of zoom-in cosmological simulations with high resolution.

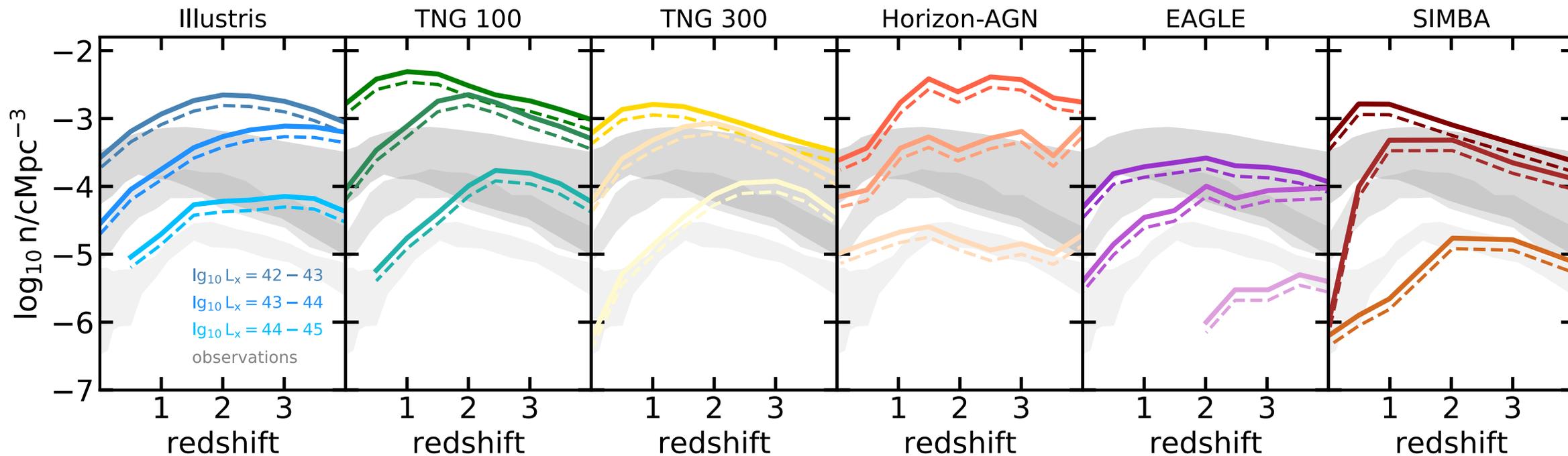
Dark matter resolution
2 × 10⁵ M_⊙.
Spatial resolution ~10-35 pc.



Are the simulated AGN
in good agreement
with observations ?

Number density of AGN for different AGN luminosity bins (hard 2-10 keV)

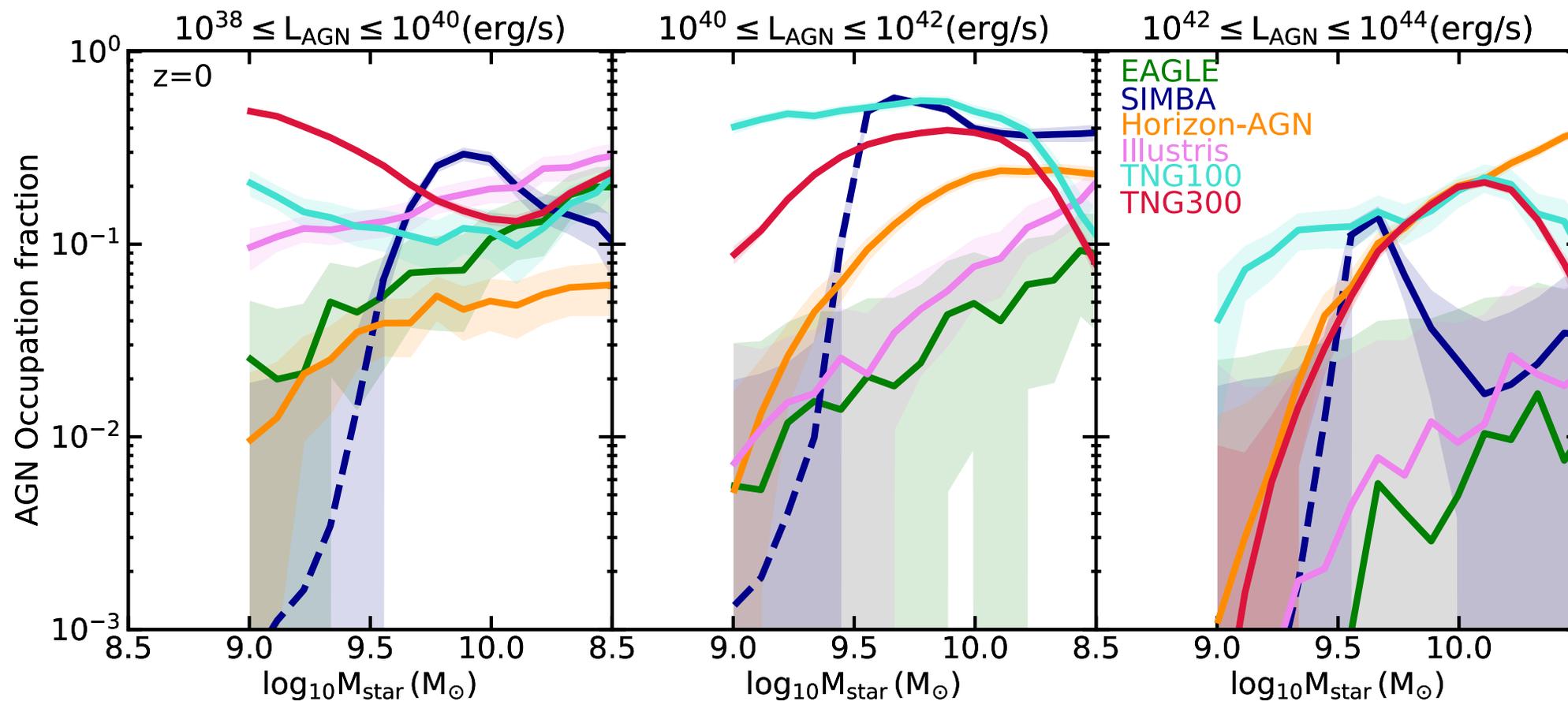
Habouzit+21b, see also Rosas-Guevara+16.



- Shaded regions combine the observational constraints of *Ueda+14, Aird+15, Buchner+15*.
- Simulations produce different populations of AGN.
- Have a hard time reproducing both the *faint & bright* and *low-z & high-z* AGN number densities.

AGN fractions constrain a combination of: a) seeding, b) accretion, c) SN feedback.

Some simulations likely produce too many AGN in low-mass galaxies.



Interplay between massive black holes and their host galaxies

➤ In some simulations, AGN are too strongly regulated by AGN feedback in massive low-z galaxies.

➤ By design, AGN feedback regulates star formation in massive galaxies.

➤ Supernova feedback regulates BH growth in low-mass galaxies.
➤ Shape the $M_{\text{BH}}-M_{\text{star}}$ relation

➤ Different AGN fractions in low-mass local galaxies.
➤ Too many AGN in some simulations?

