Illustris cosmological simulation of the Universe

Evidence for supermassive black hole binaries
RAS Specialist Discussion Meeting

Growth of Massive Black Holes over Cosmic Times

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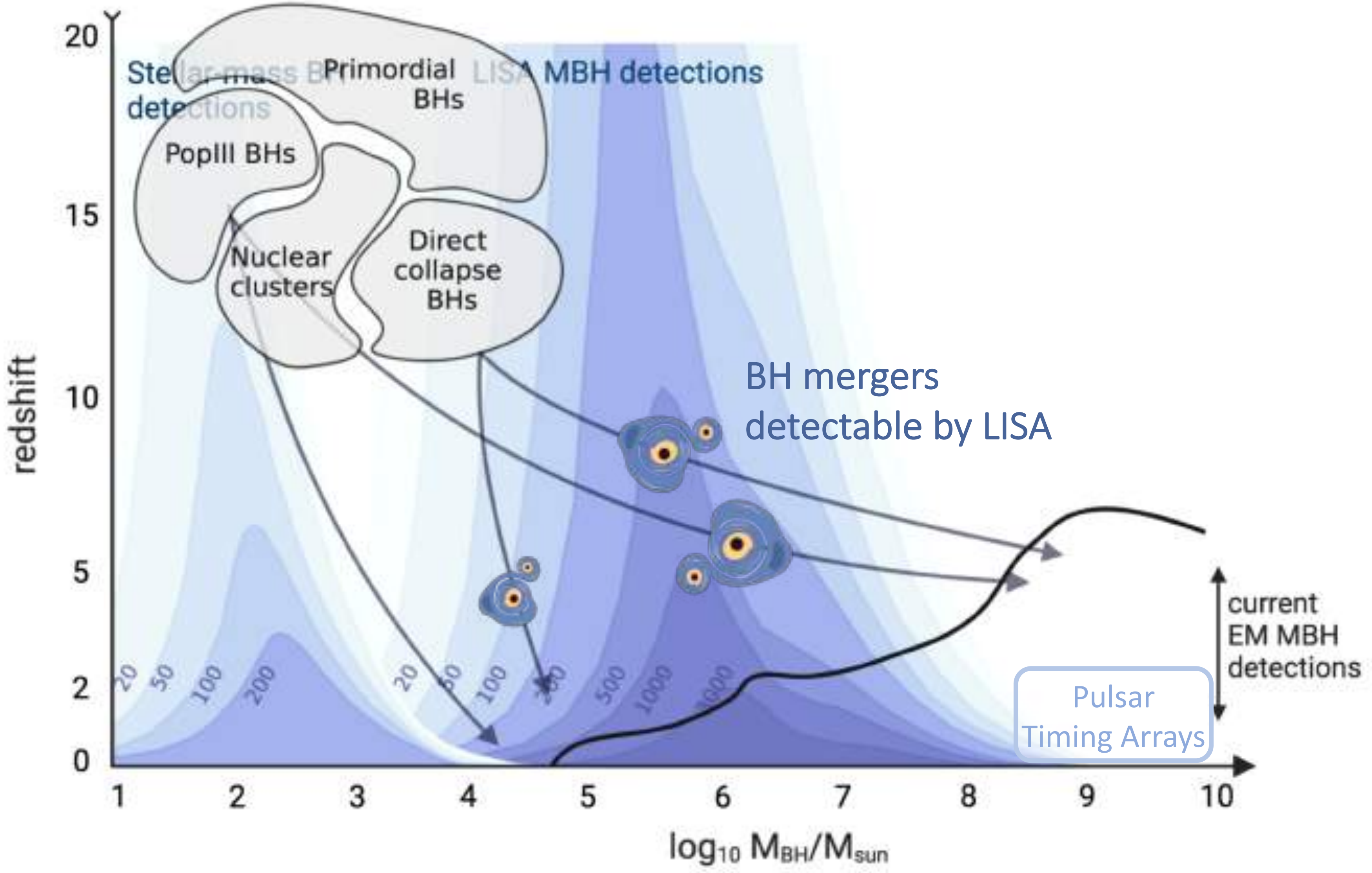
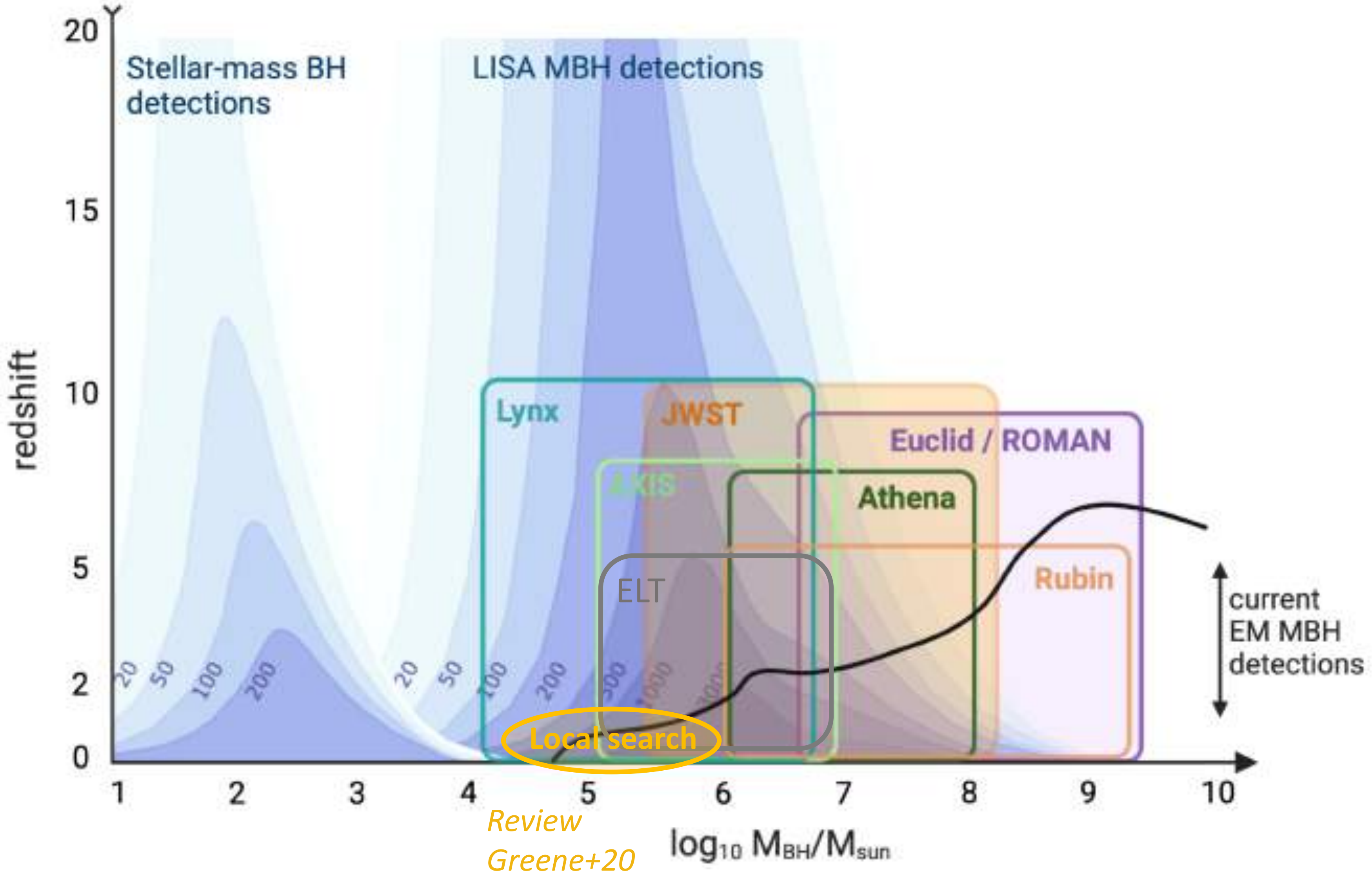
Golden age for observing early BHs with light and gravitational wave messengers



Adapted from Volonteri, MH, Colpi (Nature Physics Reviews, 2021) and LISA Living Review (LISA Astrophysics Working Group, 2023)

Golden age for observing early BHs with light and gravitational wave messengers



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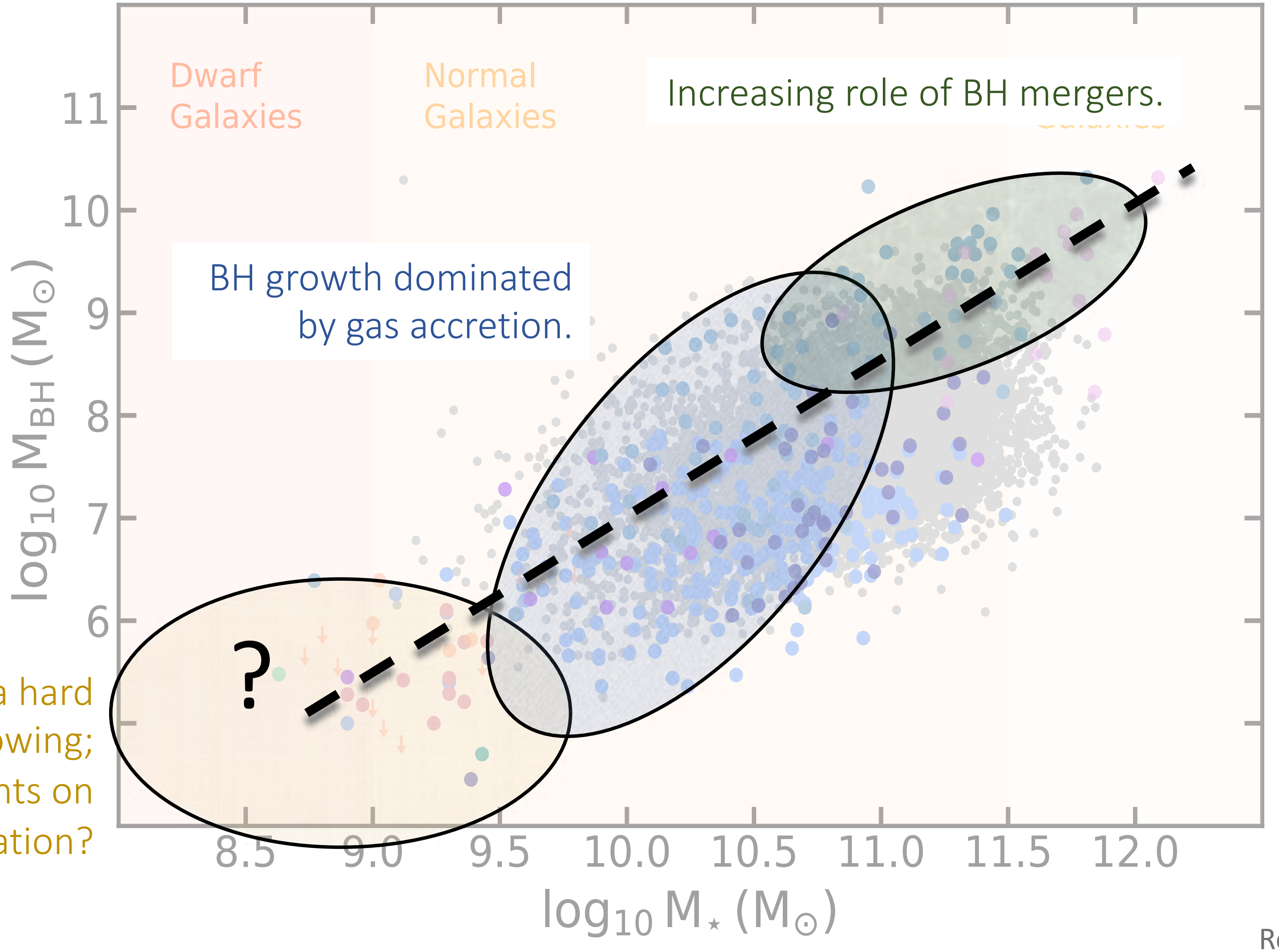
The population of massive black holes in the local Universe



BHs have a hard time growing; constraints on BH formation?

Scaling relation:

$$M_{BH} \propto 10^{-3} - 10^{-4}\, M_\star$$

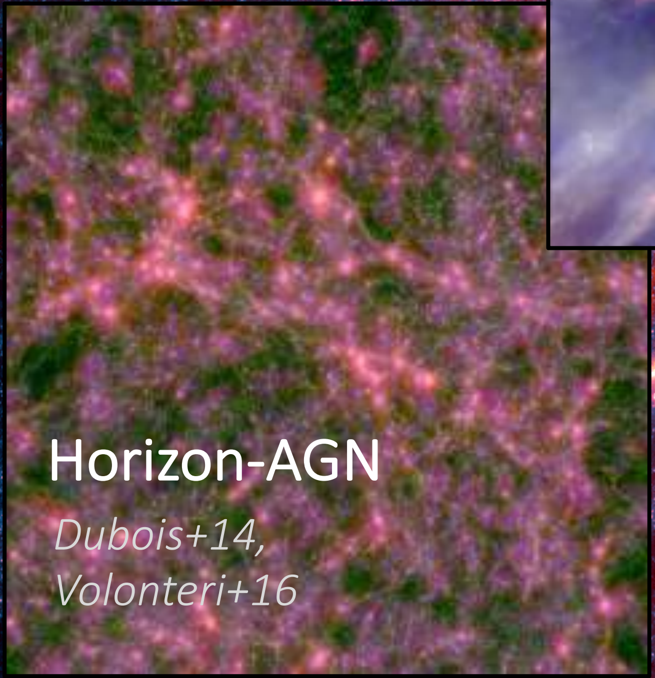
e.g., Magorrian+98, Ferrarese & Merritt 00, Haring & Rix 04, Gultekin+09, McConnell+11, Kormendy+13.

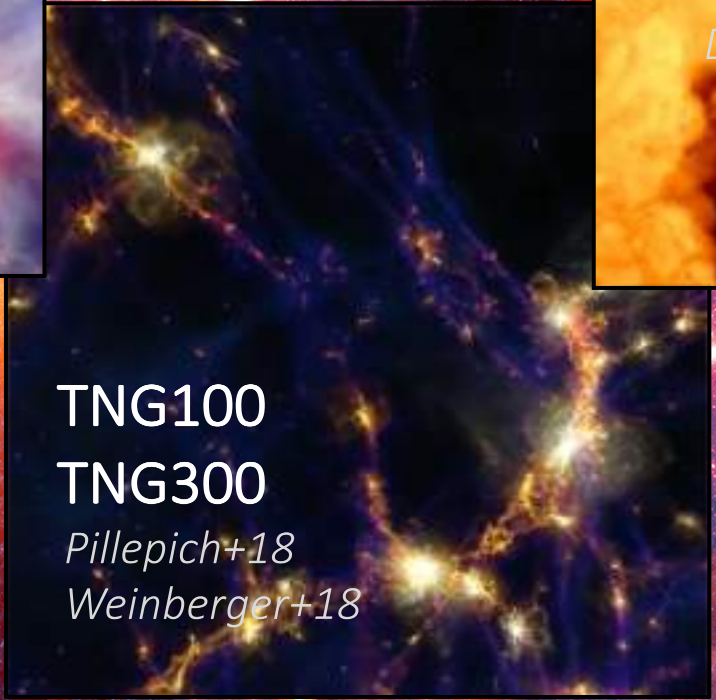
Results from cosmological simulations:
e.g., Habouzit+21, +17, Dubois+14+15, Sijacki+15, Bower+16, McAlpine+18, Weinberger+18.

Galaxy formation involves highly nonlinear processes, which can be captured in large-scale cosmological hydrodynamical simulations.

Illustris

Sijacki+15,
Genel+14,
Vogelsberger+14

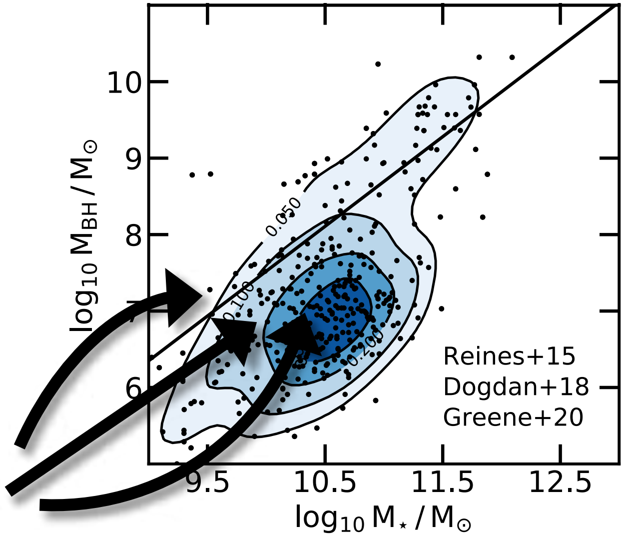




Di Matteo+08, Dubois+14,+15, Genel+14, Vogelsberger+14, Hirschmann+14, Sijacki+15, Schaye+15, Rosas-Guevara+15+16, Volonteri+16, Feng+16, Habouzit+17, Peirani+17, Tremmel+17, Di Matteo+17, McAlpine+17+18, Weinberger+17,+18, Pillepich+18,19, Davé+19, Thomas+19, Ni+22.

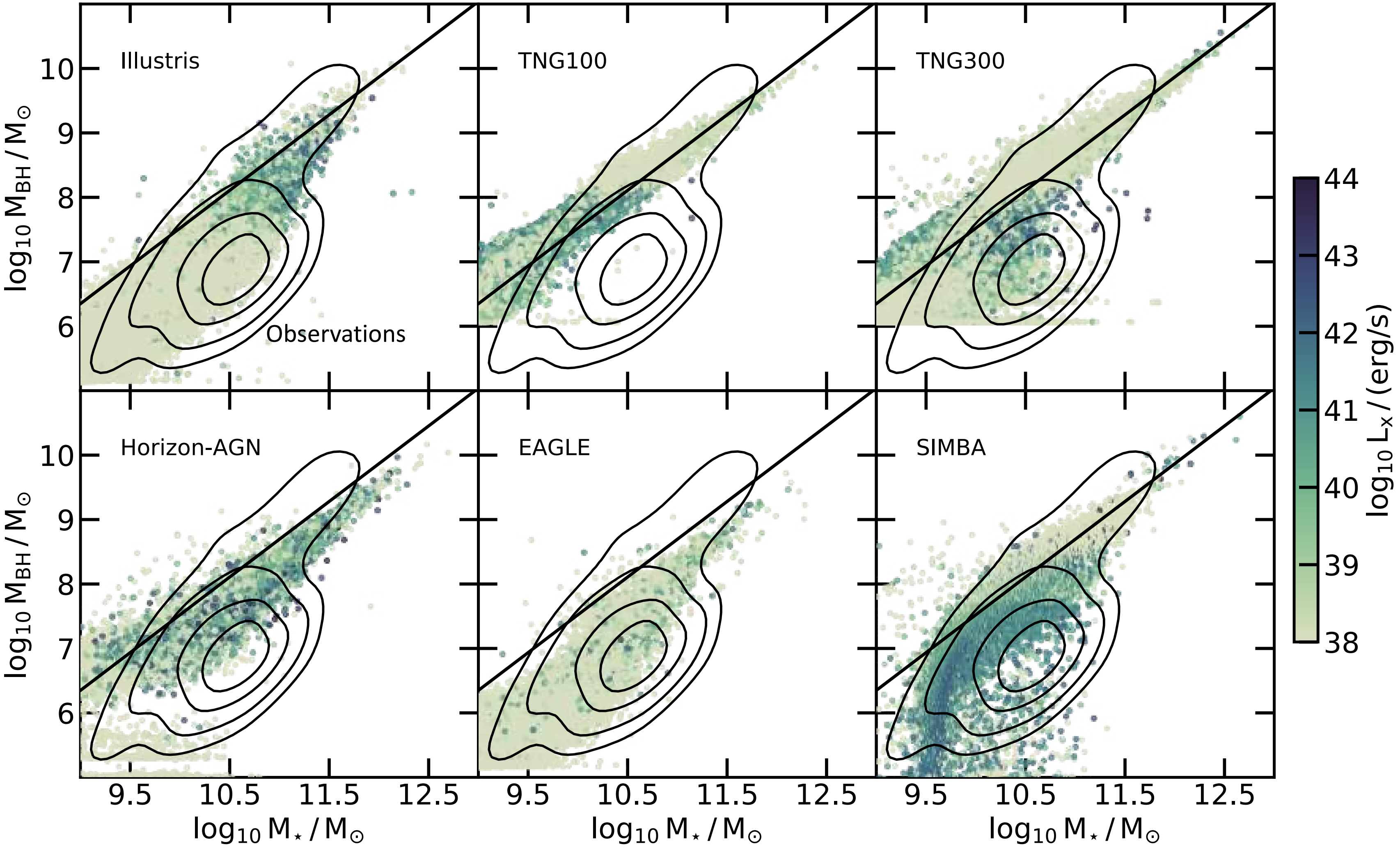
Habouzit+21

Observations in the local Universe



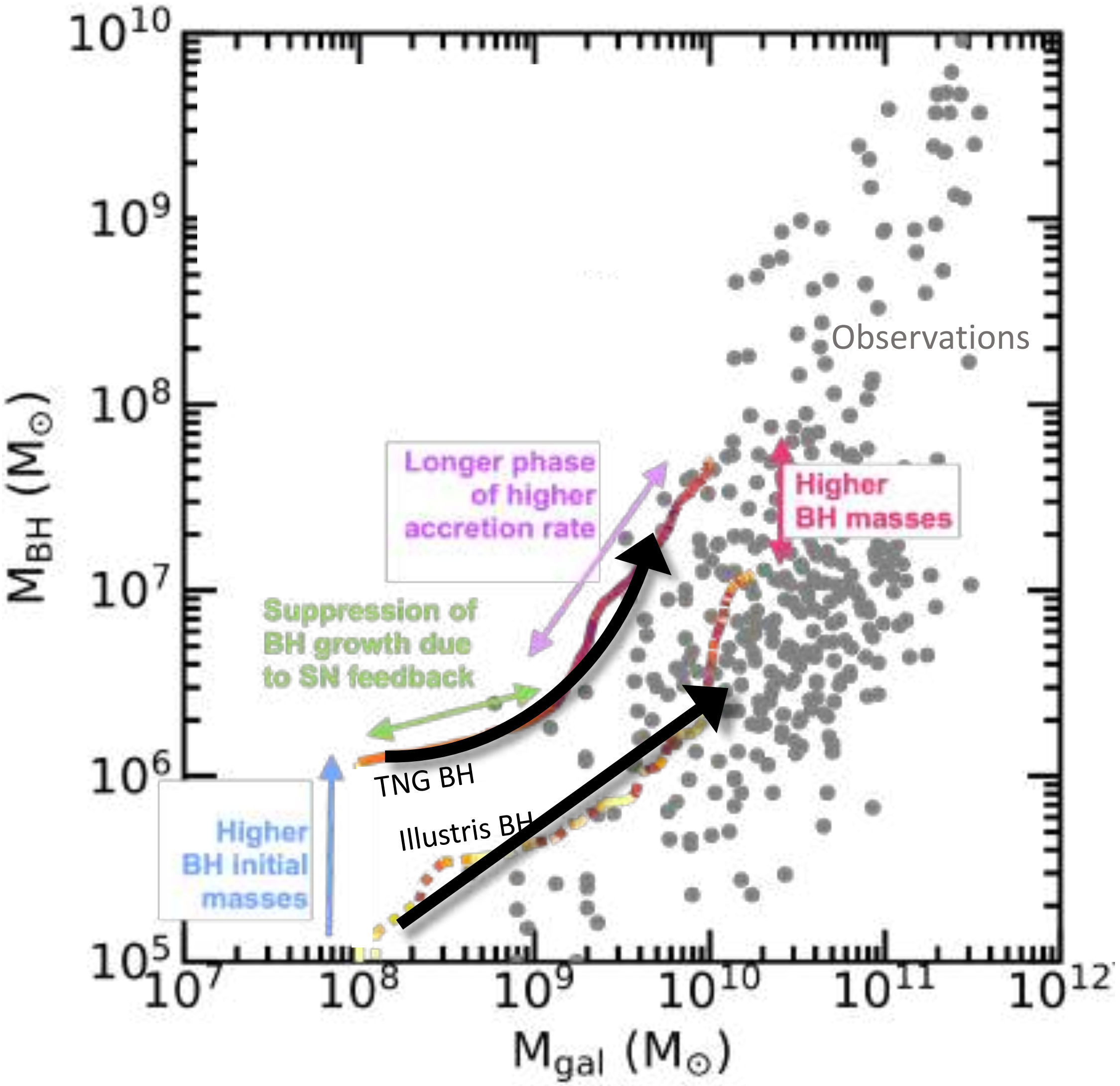
BH-galaxy co-evolution with time?

Cosmological simulations



Simulations produce different populations of BHs, not always in agreement with current observations.

Habouzit+21



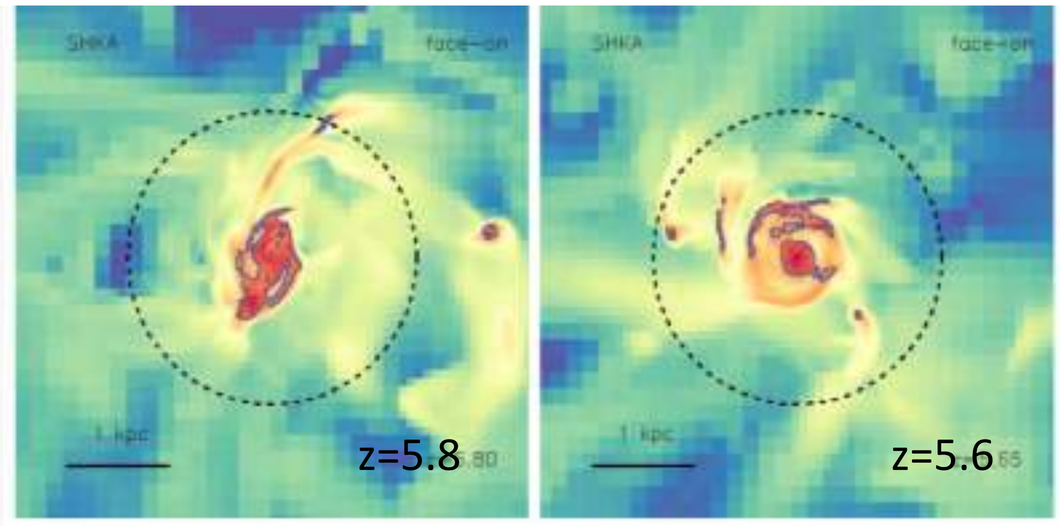
Modeling of BH and galaxy subgrid physics strongly impact BH and galaxy co-evolution.

Habouzit+17+21, Dubois+15, Fontanot+15, Anglés-Alcázar+17, Bower+17

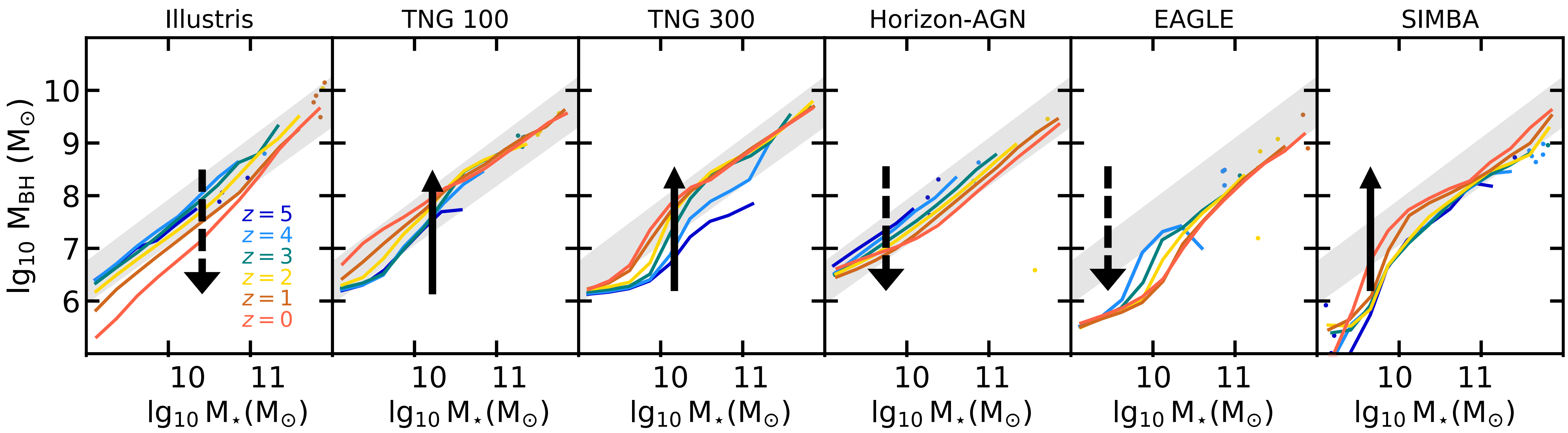
Also responsible for number of AGN in low-mass galaxies. *Haidar, MH+22, Koudmani+21 (role of AGN feedback)*

Weaker SN feedback

Zoom-in (Dubois+15)



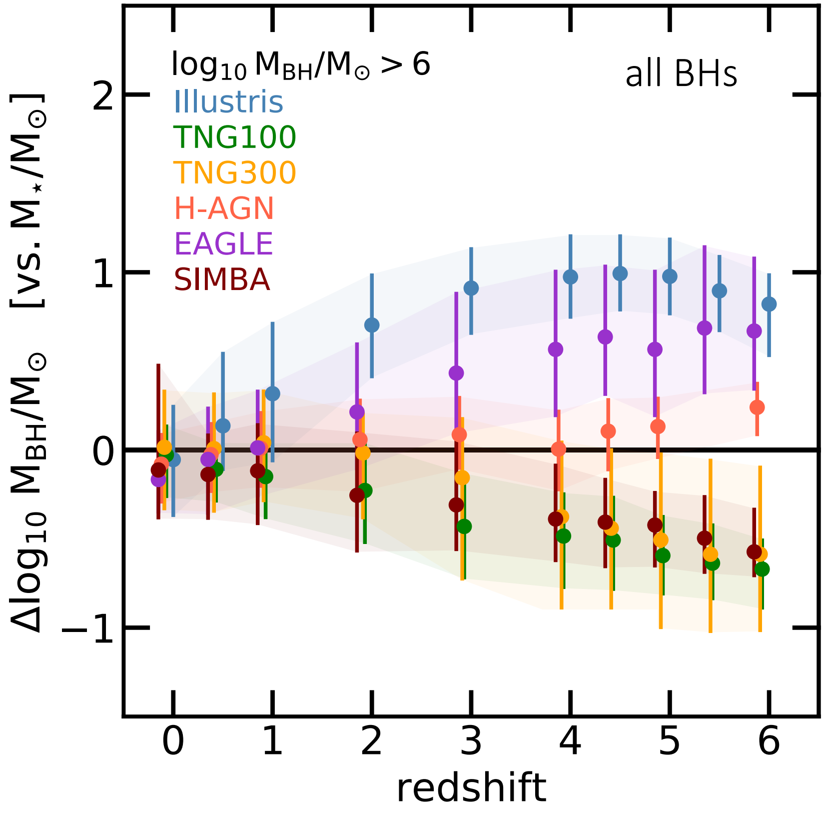
Habouzit+21



No consensus on the shape of the scaling relation
nor on its build-up with time, i.e. whether BHs are more massive at higher redshift.

Observational constraints (z<2, M_{star}>10^{10} M_{sun}): Shields+03, Jahnke+09, Mullaney+12, Schramm+13, Cisternas+11, Sun+15, Suh+19, but McLure+06, Ding+19+22.

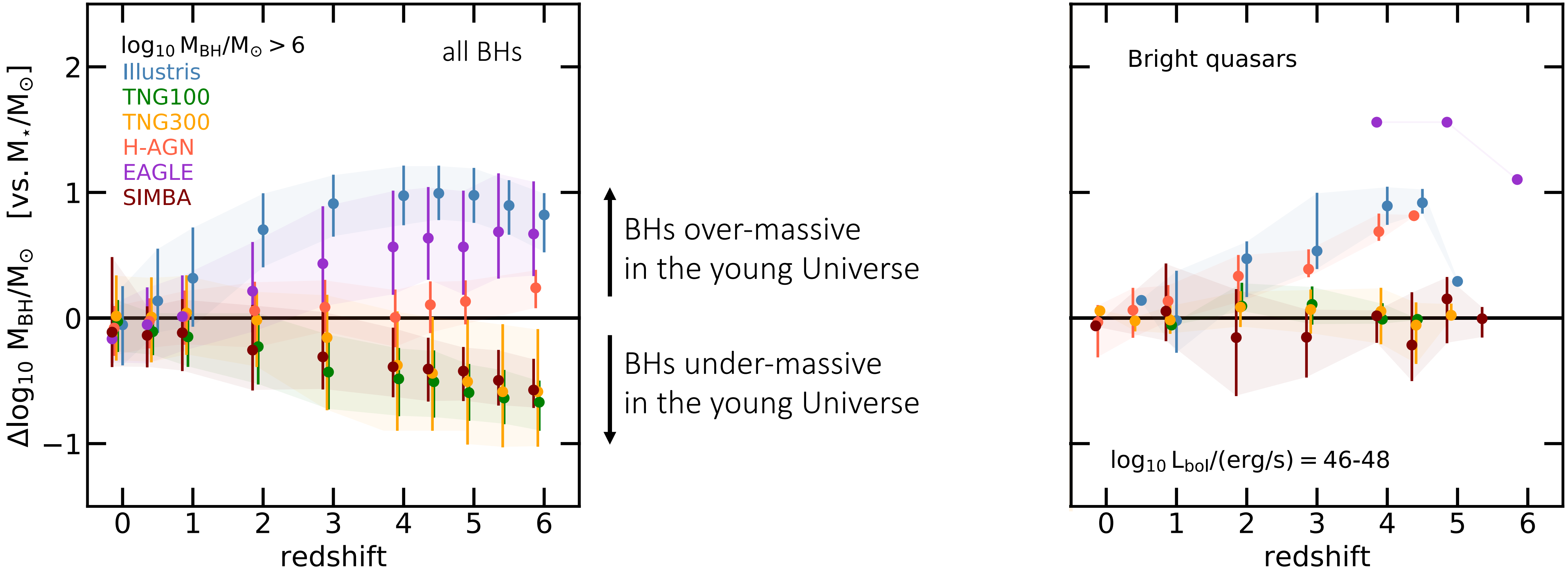
Habouzit, Onoue, Banados+22b



BHs over-massive in the young Universe

BHs under-massive in the young Universe

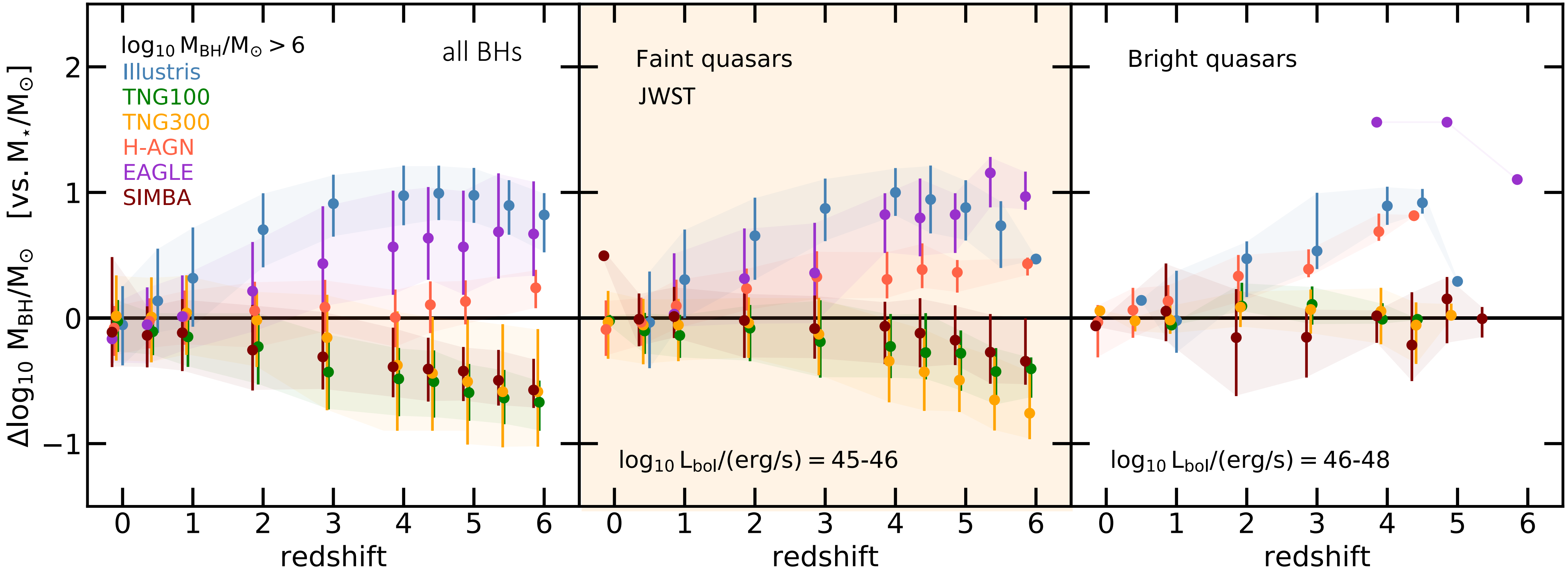
Habouzit, Onoue, Banados+22b



BHs over-massive in the young Universe

BHs under-massive in the young Universe

Habouzit, Onoue, Banados+22b



Characterizing faint quasars 1 Gyr after the Big Bang
can constrain the build-up of the M_{BH}-M_{star} relation.

James Webb Space Telescope (JWST, near-IR/mid-IR)

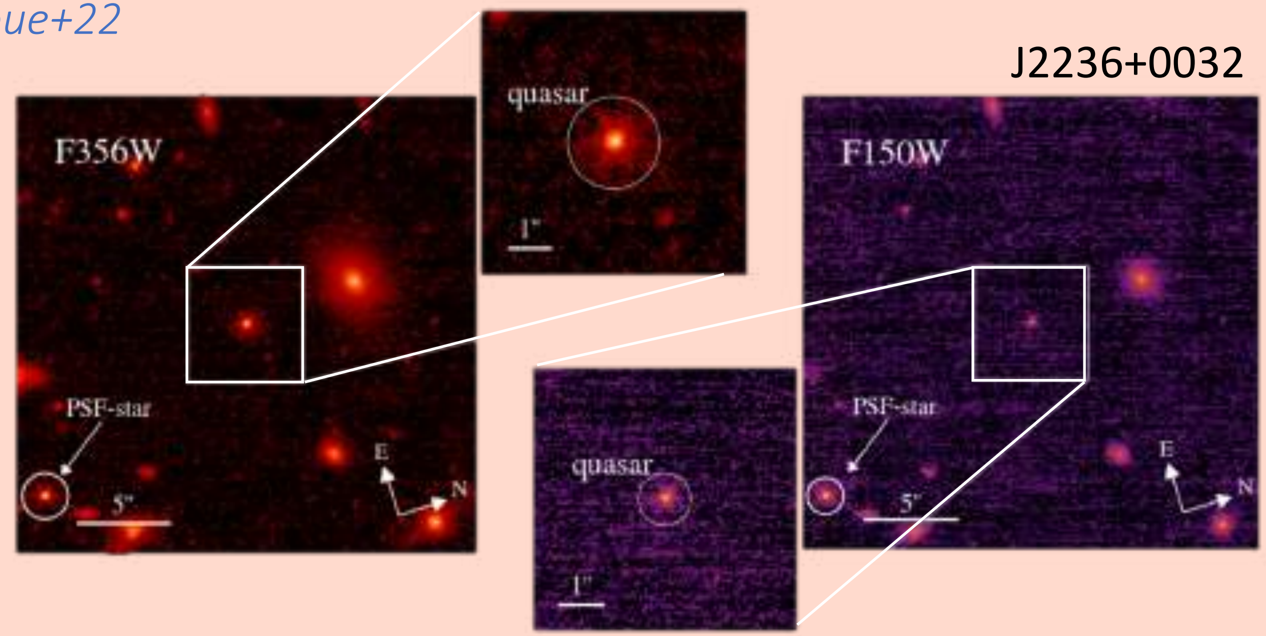
What's next: Indirectly constraining the bulk of the BH population with faint quasars.

- Theoretical predictions *Habouzit, Onoue, Eduardo+22b*.
- JWST GO1967 (PI: M. Onoue, incl. MH) Observation of 15 faint quasars 1 Gyr after the Big Bang.
  (More precise BH mass measurements with Hbeta, M_{star} instead of M_{dyn}).

First detection of stellar light from quasar host galaxies!

Ding, Onoue+22

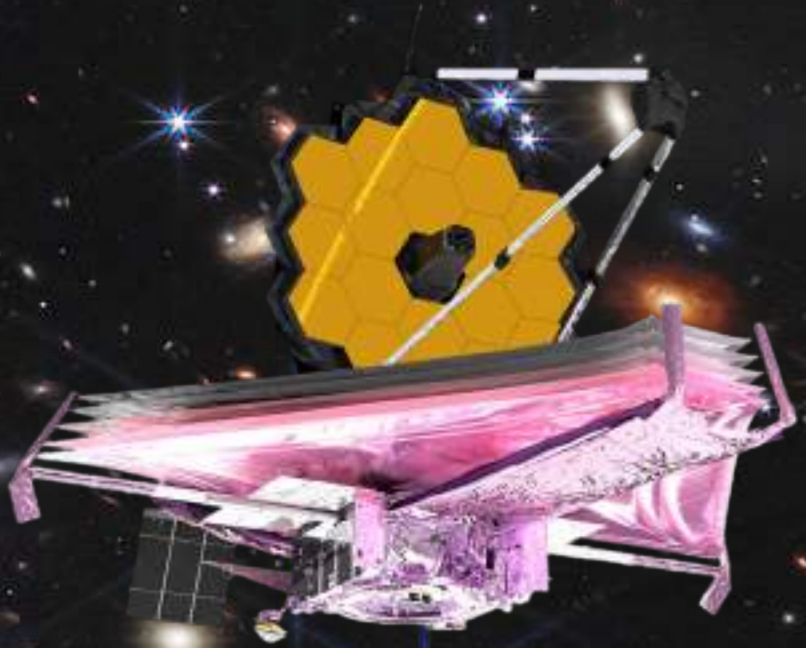
J2236+0032



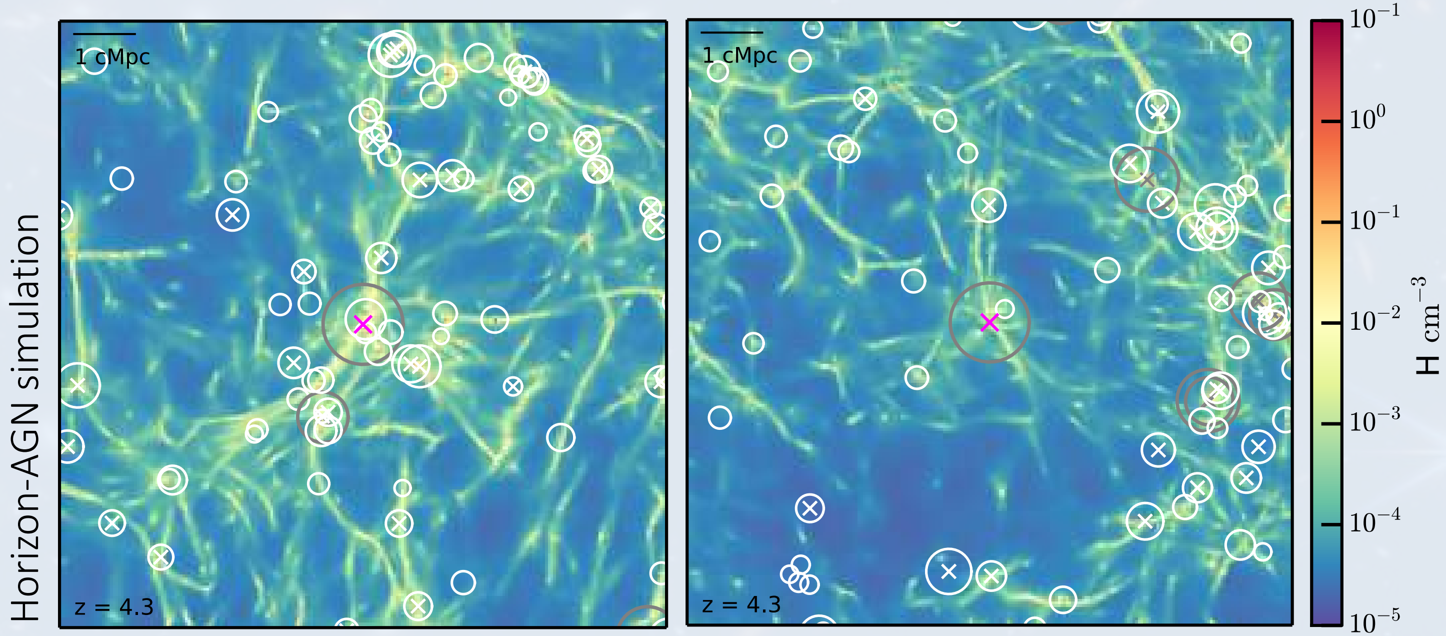
James Webb Space Telescope (JWST, near-IR/mid-IR)

What's next: Constraining the assembly of quasars with their environments.

- **JWST GO2078** (PI: F. Wang, incl. MH) A spectroscopic survey of biased halos In the reionization era. 25 FoV at 6.5 < z < 6.8 *Wang+23, Yang+23*
- **JWST GO1764** (PI: Xiaohui Fan, incl. MH) Observations of the 3 most distant quasars.



- Theoretical predictions from *Habouzit+19 / Costa+15*

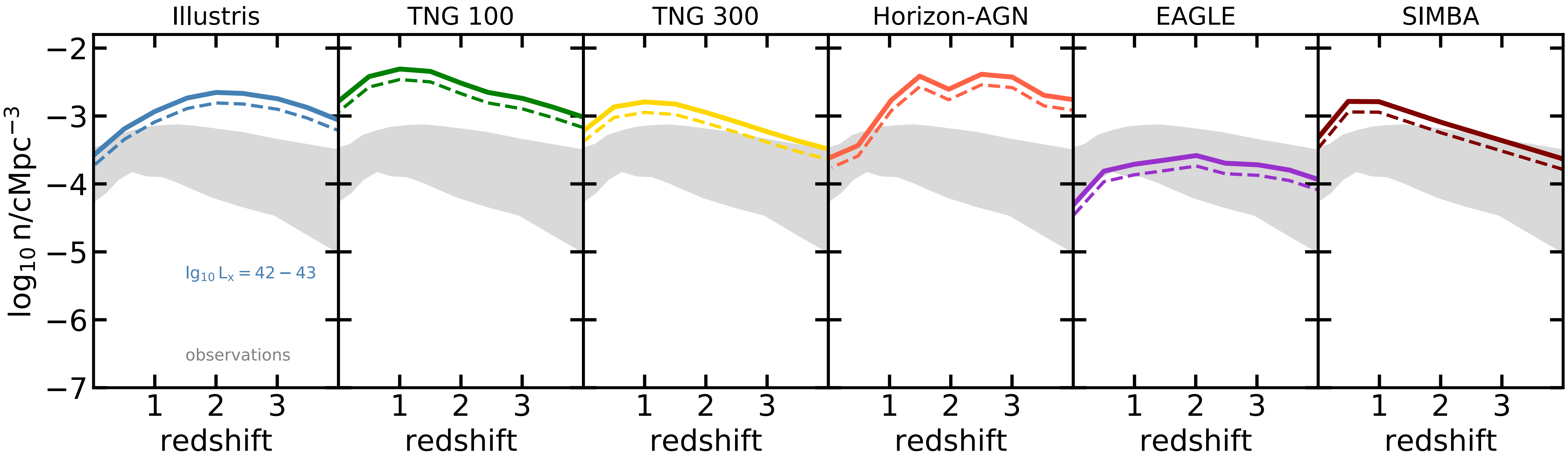


AGN population across cosmic times

No calibration with AGN properties.
→ predictions from the simulations!

Habouzit+22a

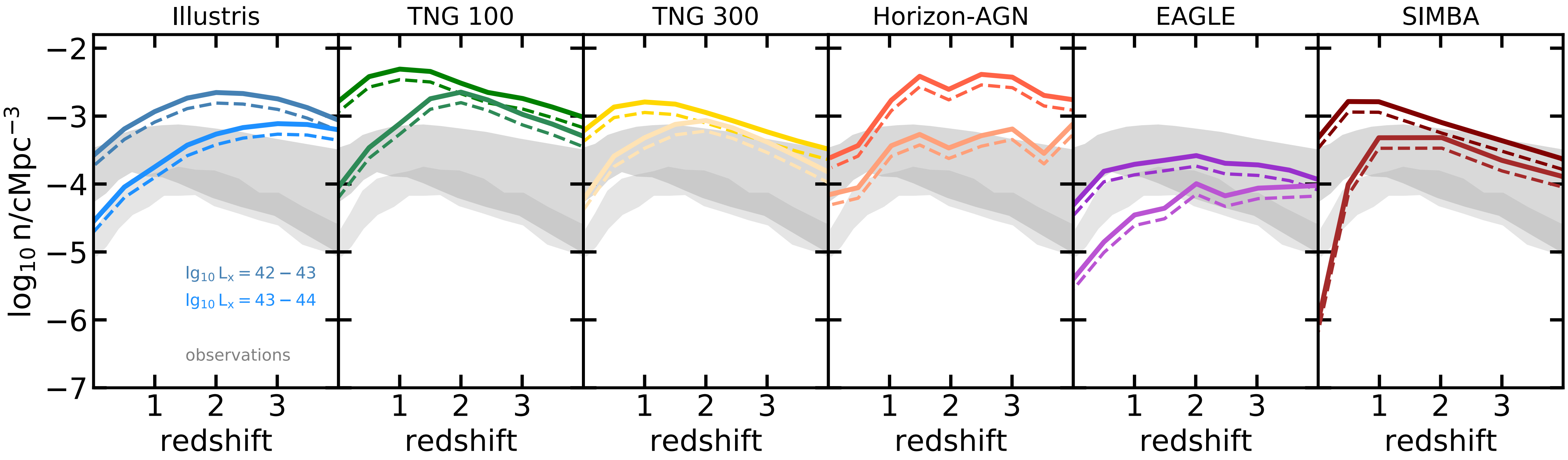
See Rosas-Guevara+16 for the EAGLE simulation.



Shaded regions combine the observational constraints of *Ueda+14*, *Aird+15*, *Buchner+15*.

Habouzit+22a

See Rosas-Guevara+16 for the EAGLE simulation.



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Habouzit+22a

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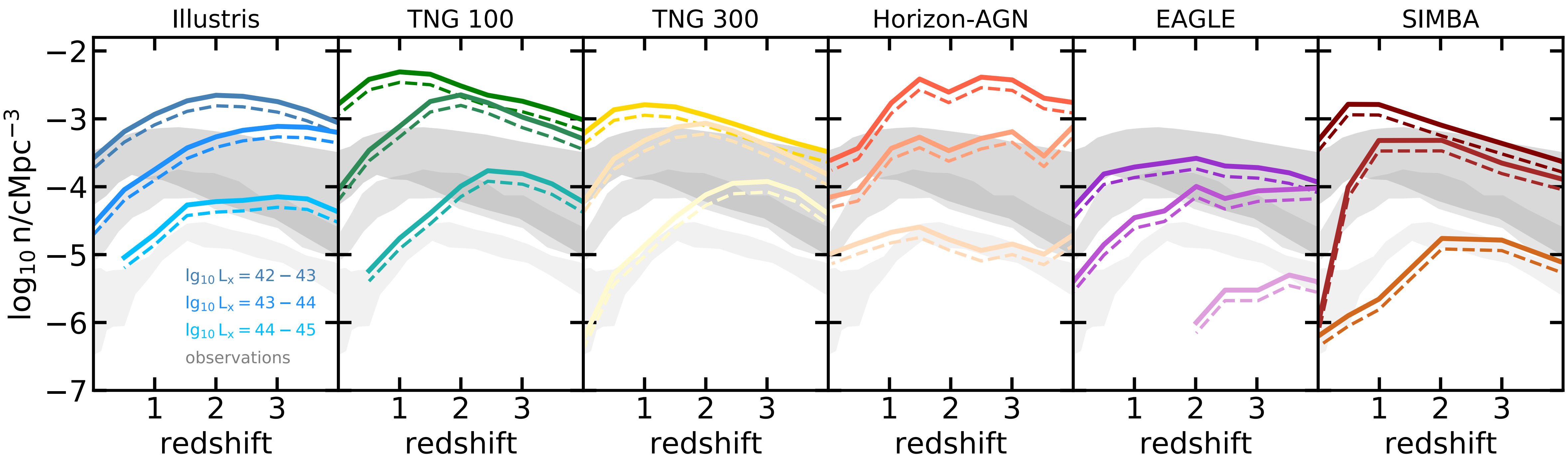
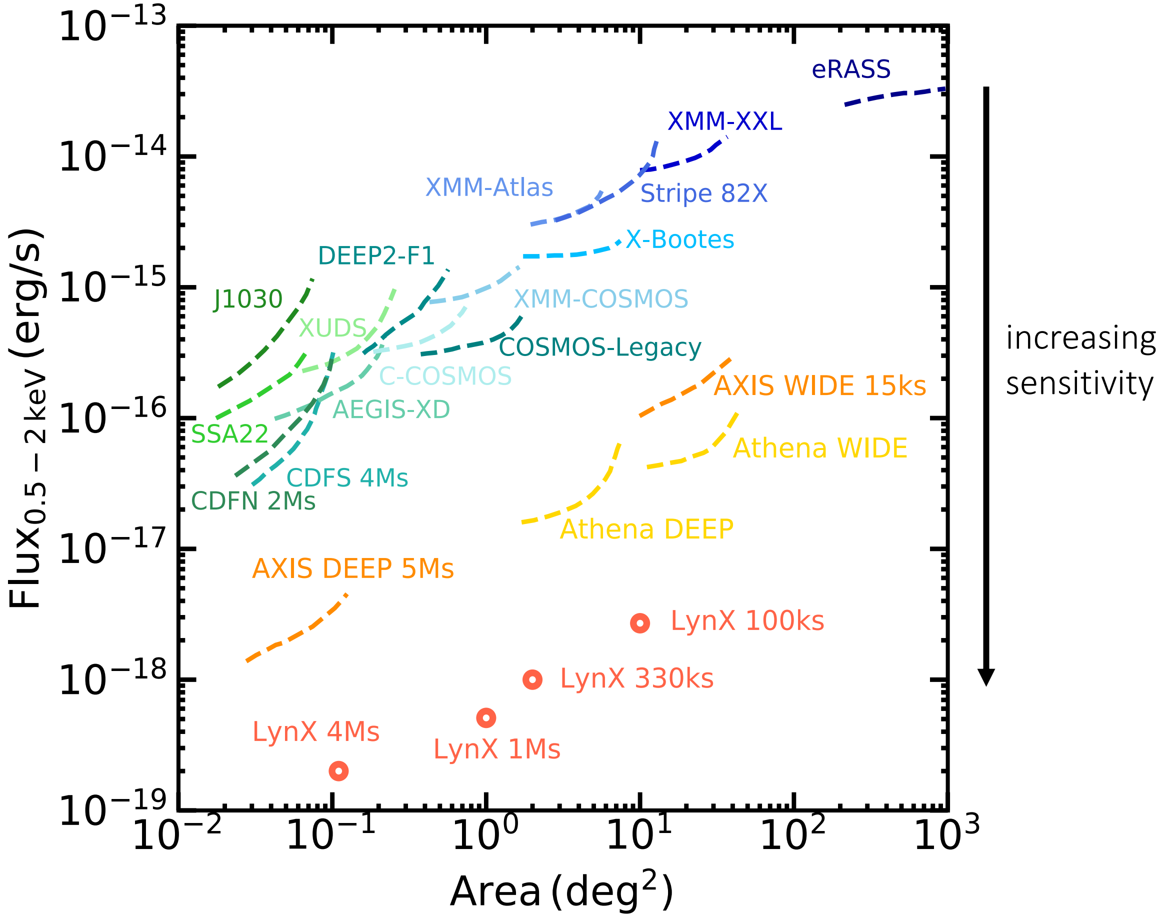
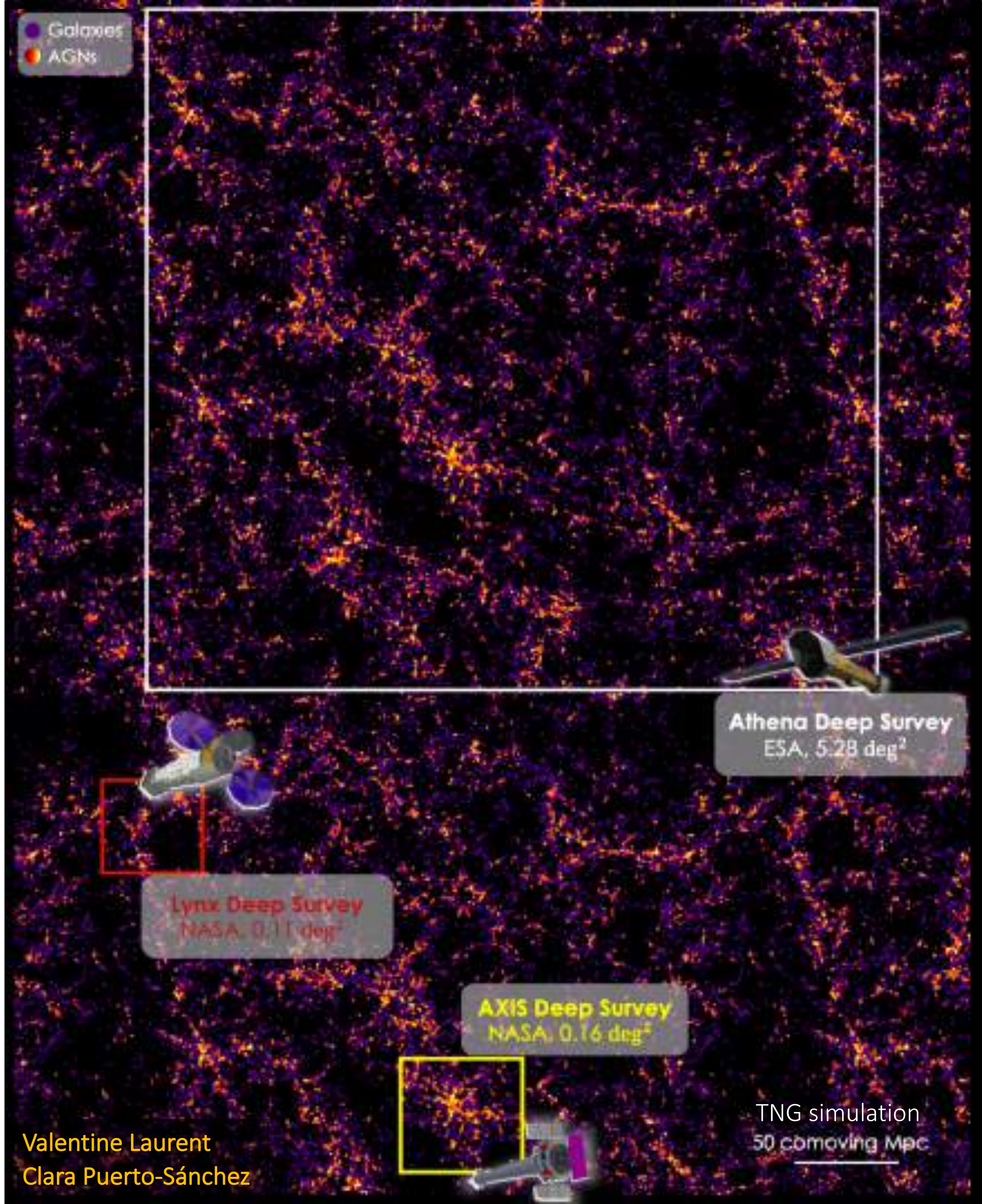


Shaded regions combine the observational constraints of *Ueda+14*, *Aird+15*, *Buchner+15*.

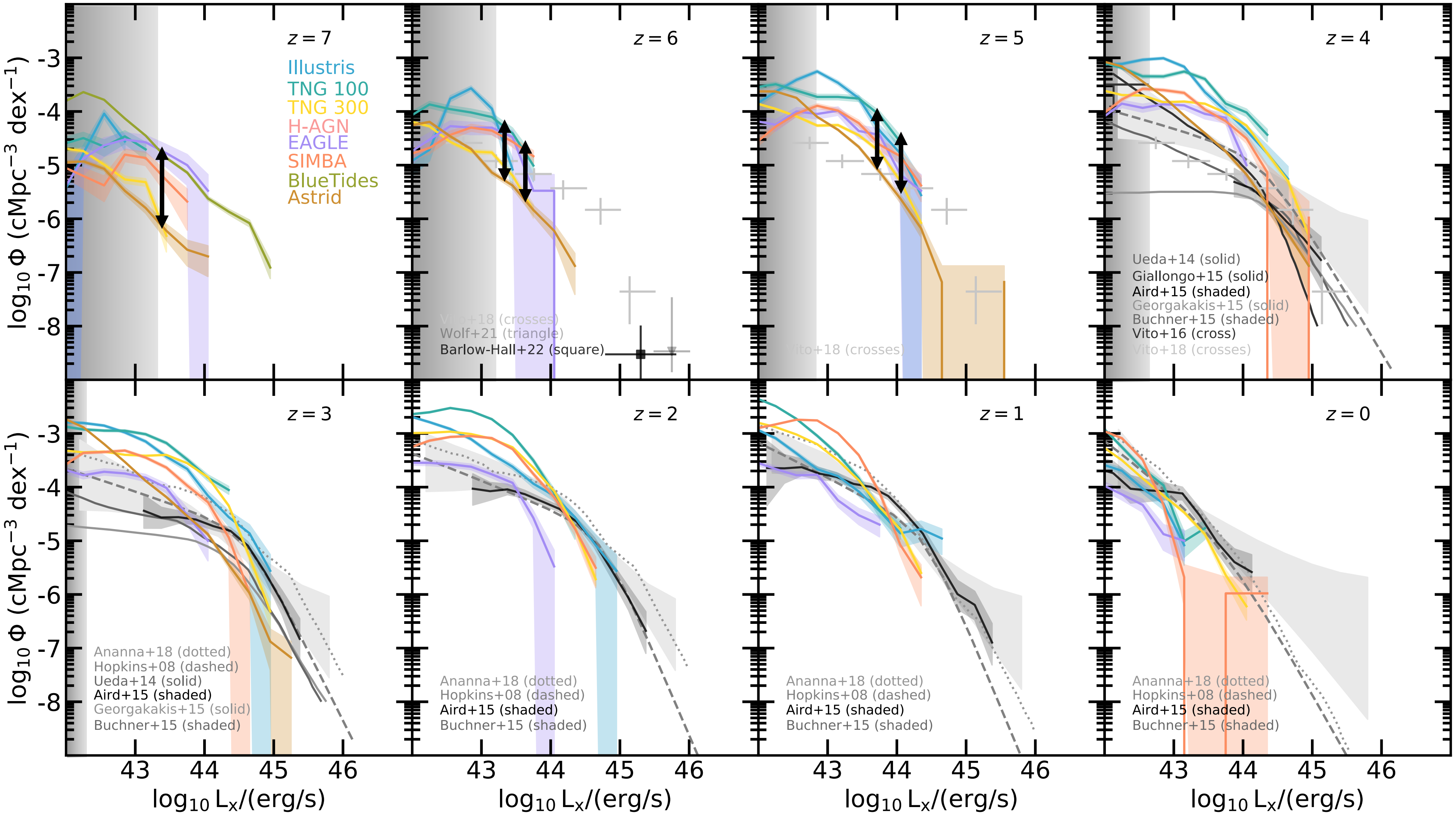
- ➢ Simulations produce different populations of AGN.
- ➢ Have a hard time reproducing both the ***faint & bright*** and ***low-z & high-z*** **AGN** number densities.

Constraining the bulk of the BH population with future X-ray observatories (Athena, AXIS, Lynx)



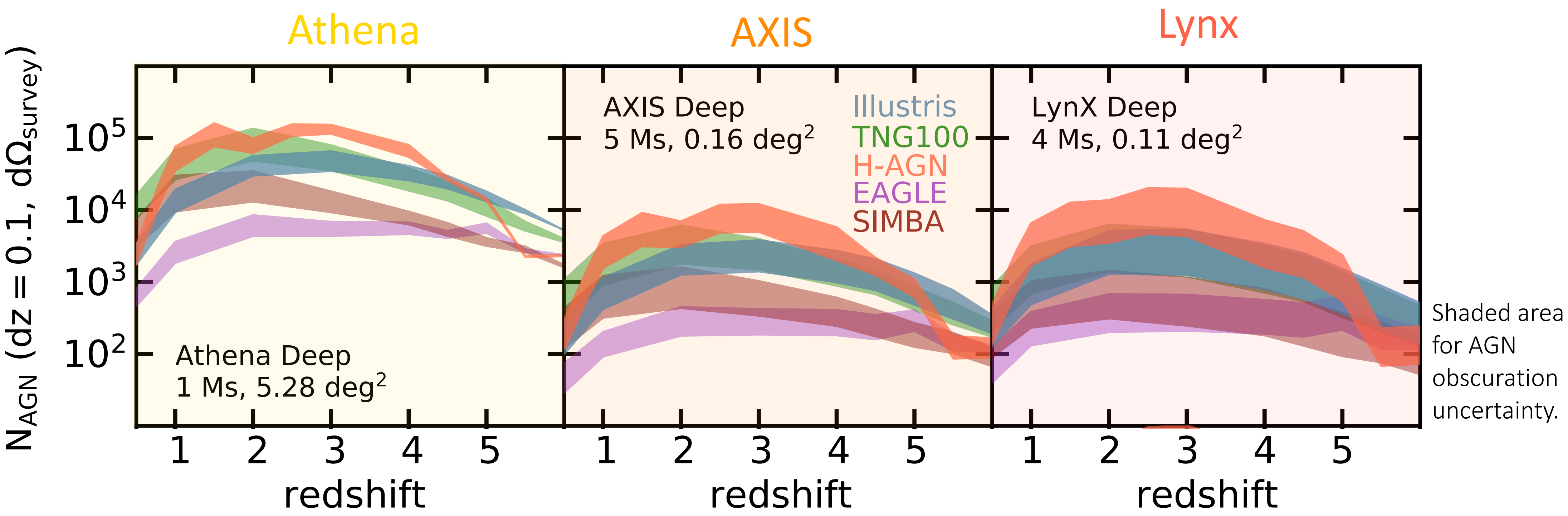


Nandra+13, Aird+13, LynX Team Report 2018, Mushotzky+19, Marchesi+20



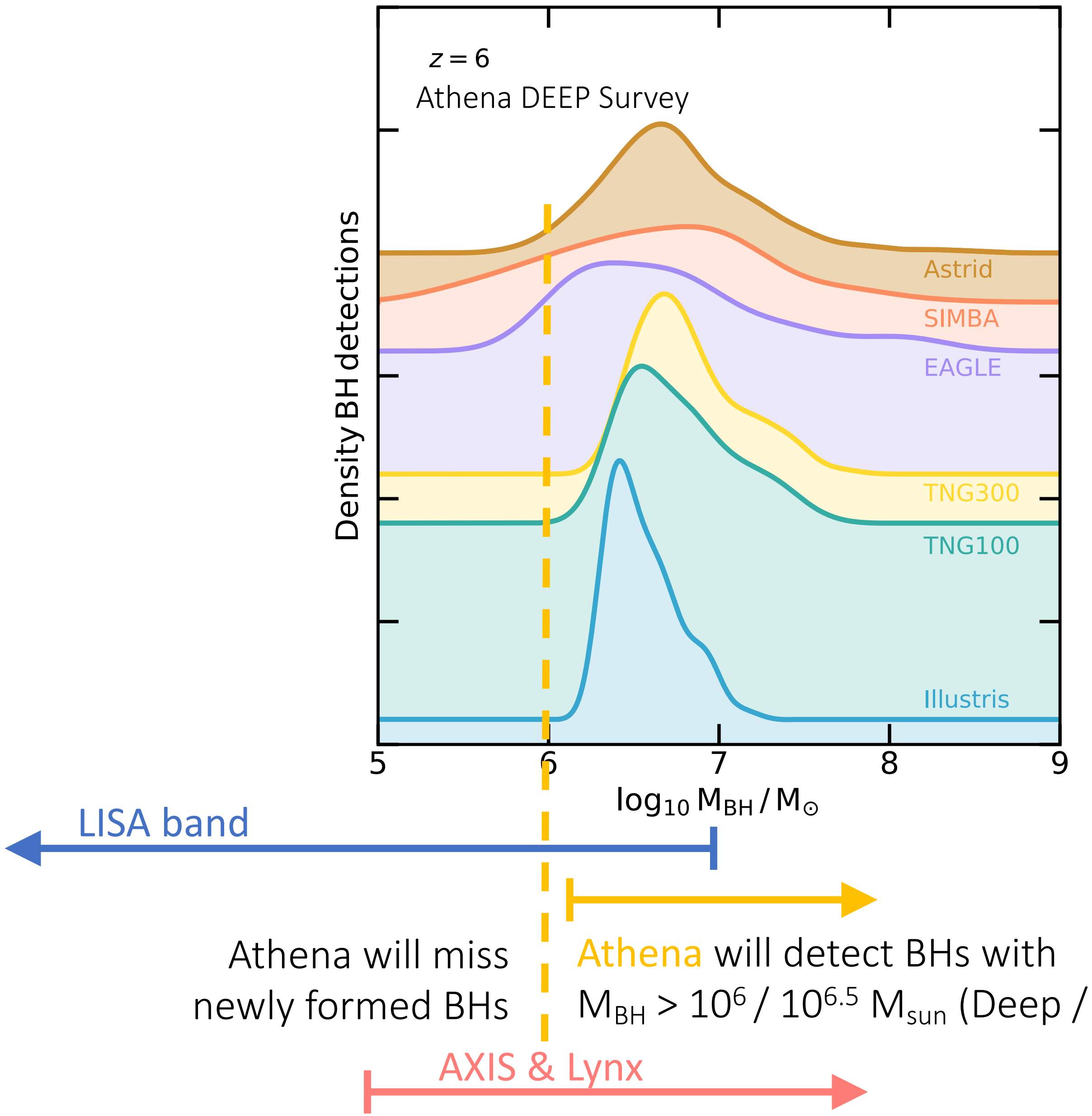
➢ Athena (AXIS/Lynx) will observe a significant fraction of the AGN population at high redshift.

Habouzit+22a



An order of magnitude discrepancy between the simulations for the number of detectable AGN.

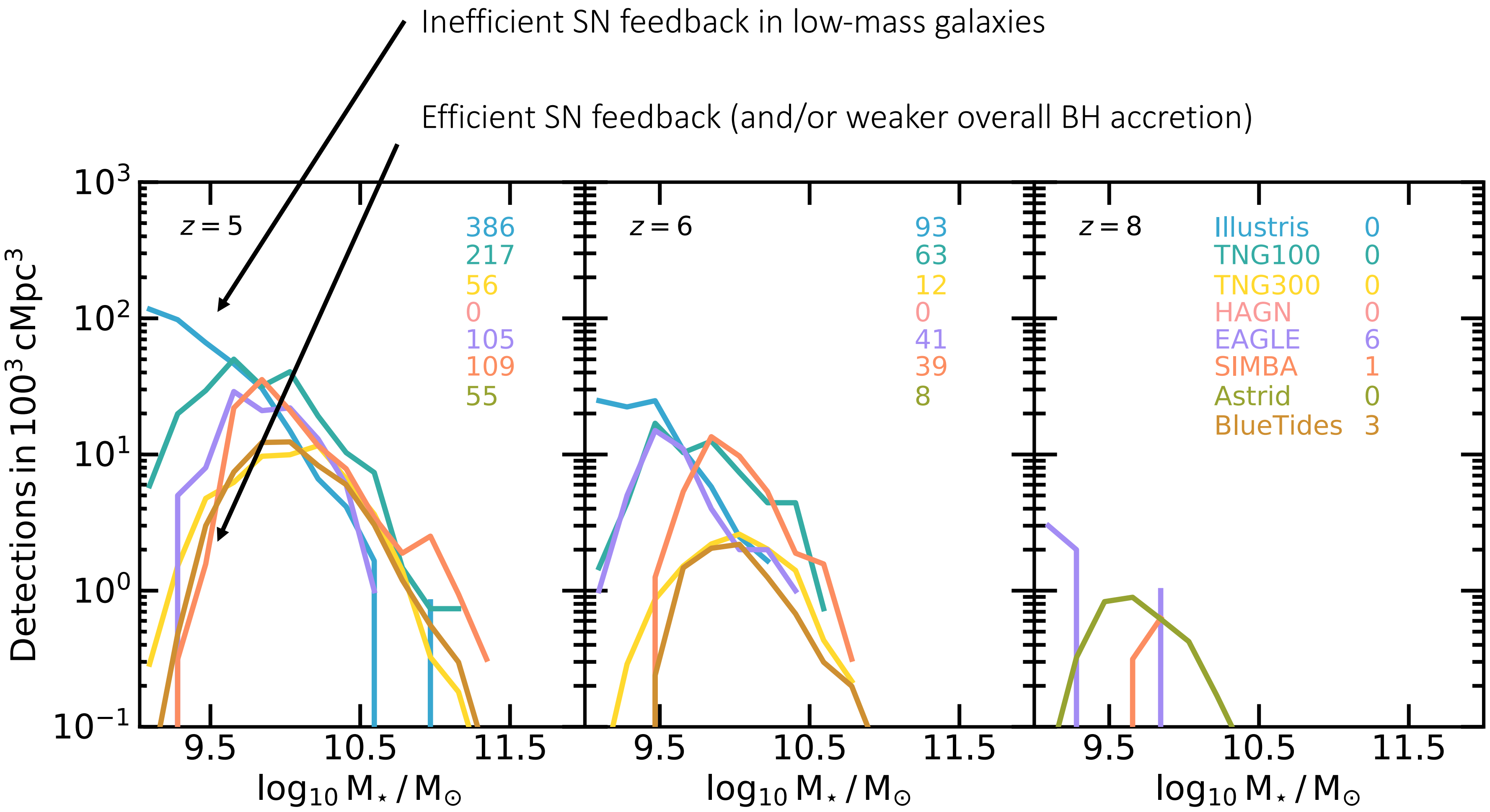
see also Marchesi+20 for Athena/AXIS



Athena will miss newly formed BHs

Athena will detect BHs with $M_{BH} > 10^6 / 10^{6.5}\ M_{sun}$ (Deep / Wide surveys)

Habouzit+22a, Habouzit+ (in prep)



Athena's AGN located in galaxies with $M_{star} = 10^{9.5} - 10^{10.5}$ M_{sun}.

More detections in lower-mass galaxies if weaker SN feedback.

Will constrain a combination of BH/galaxy physics (BH seeding, BH accretion, SN/AGN feedback).

Galaxy surveys: PRIMER, FRESCO, WDEEP, COSMOS Web.

Large-scale cosmological simulations

- No consensus on BH, AGN, and dual AGN populations across cosmic times.
- Key to prepare new observatories and maximize their scientific return.

JWST

- Constraints on the assembly of high-redshift quasars (BH and galaxy properties, environments).
- Constraints BH-galaxy co-evolution and bulk of the BH population ?

Athena, AXIS, LynX

- Constraints on the bulk of the BH population (M_{BH}>10^6 M_{sun}, >10^5 M_{sun}).
- Could constrain simulations‘ BH and galaxy subgrid physics if combined with future galaxy surveys.