The AGN population across cosmic time with Athena

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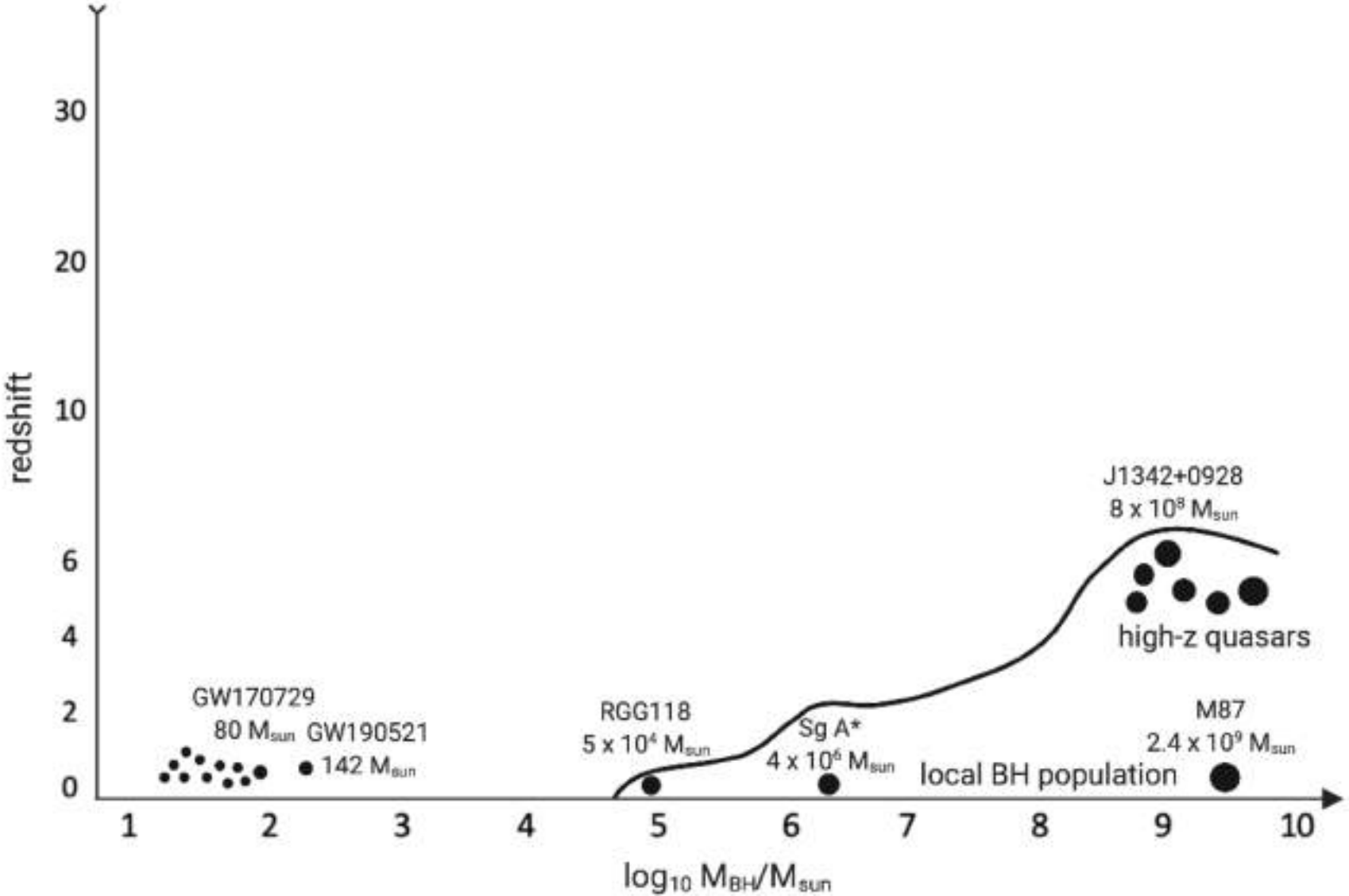
Athena X-ray Advances: ASST & ACO Science Webinars, *April 2022*

Population of massive black holes



Electromagnetic detections of BHs as of today.

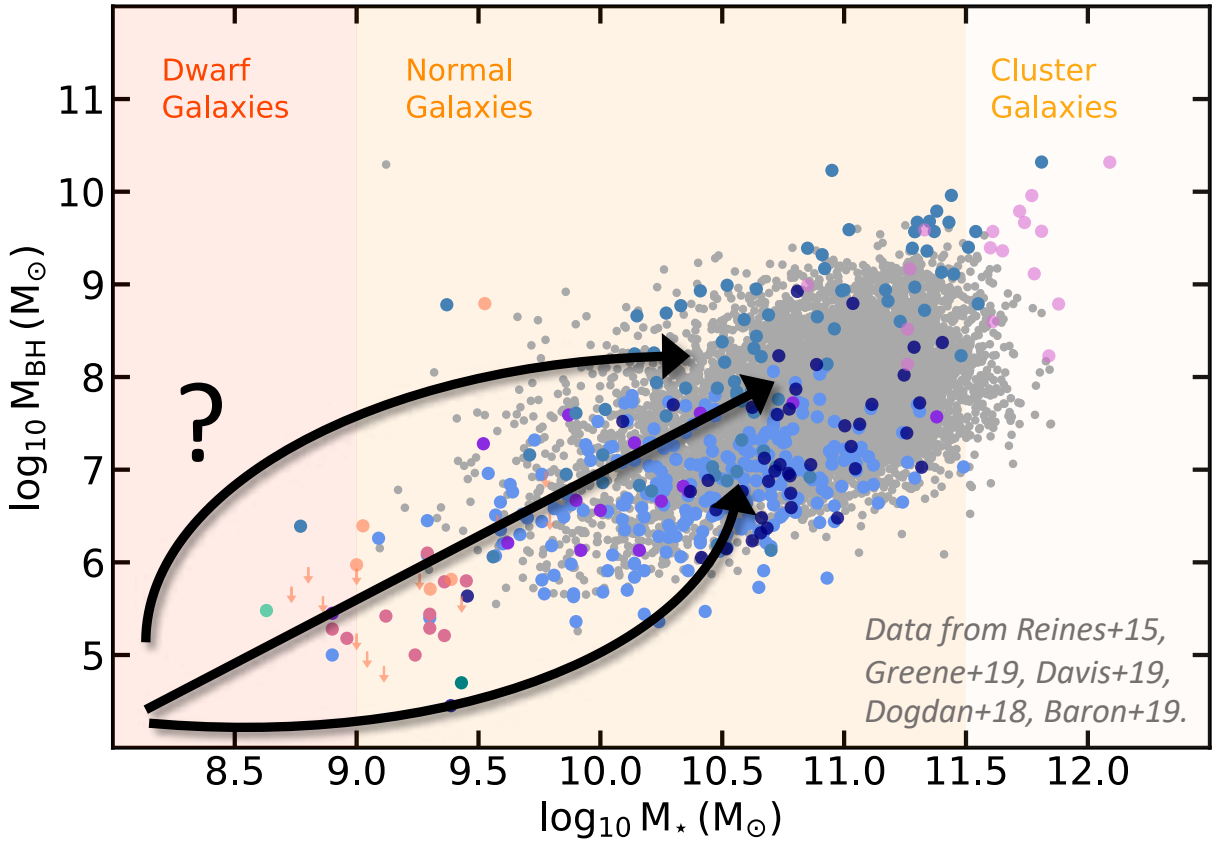
Population of massive black holes

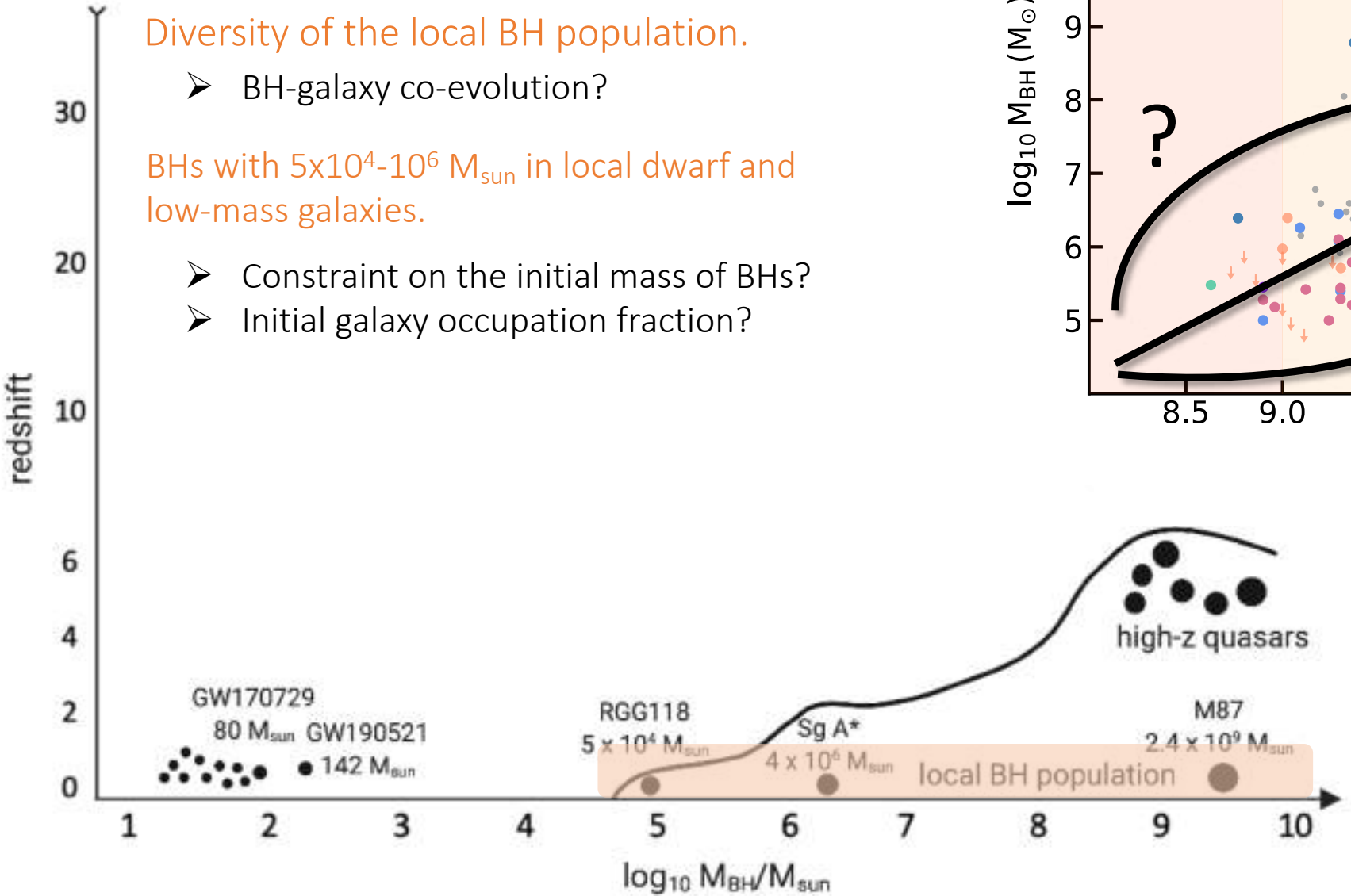
Diversity of the local BH population.

- BH-galaxy co-evolution?

BHs with 5×10^4-10^6 M_{sun} in local dwarf and low-mass galaxies.

- Constraint on the initial mass of BHs?
- Initial galaxy occupation fraction?



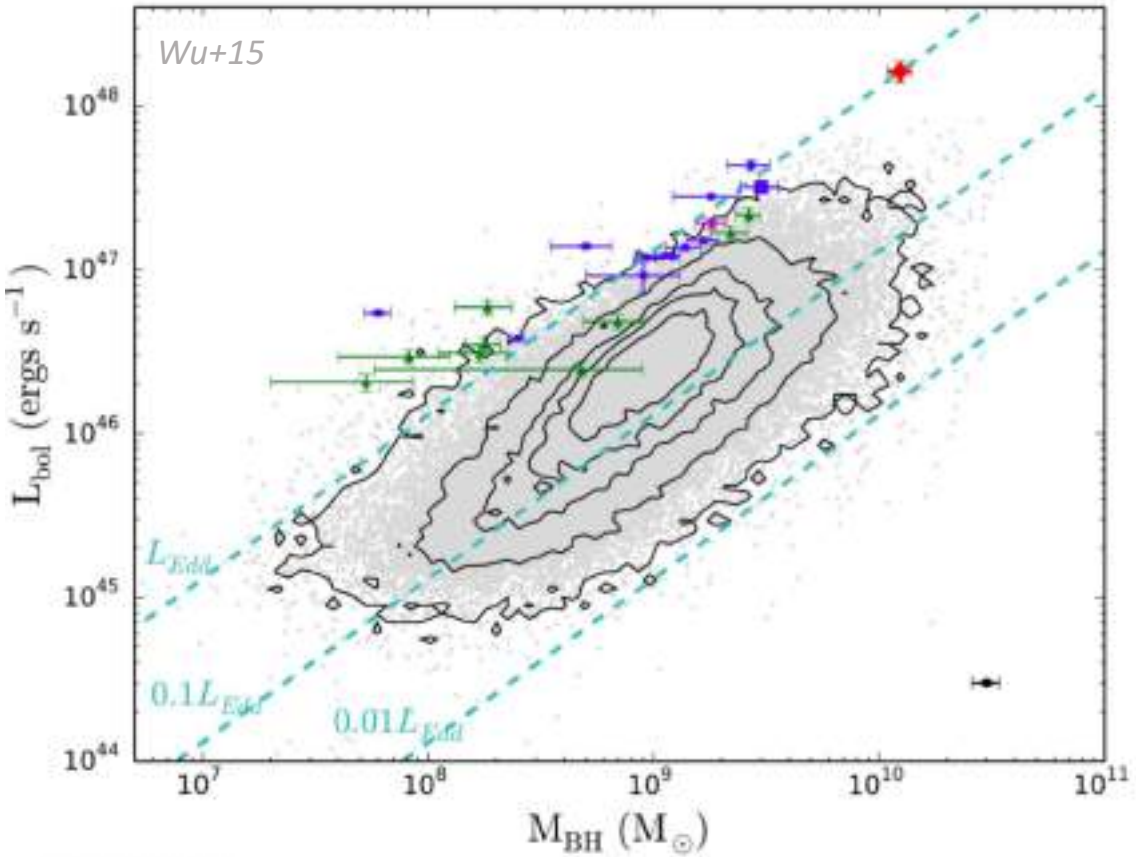


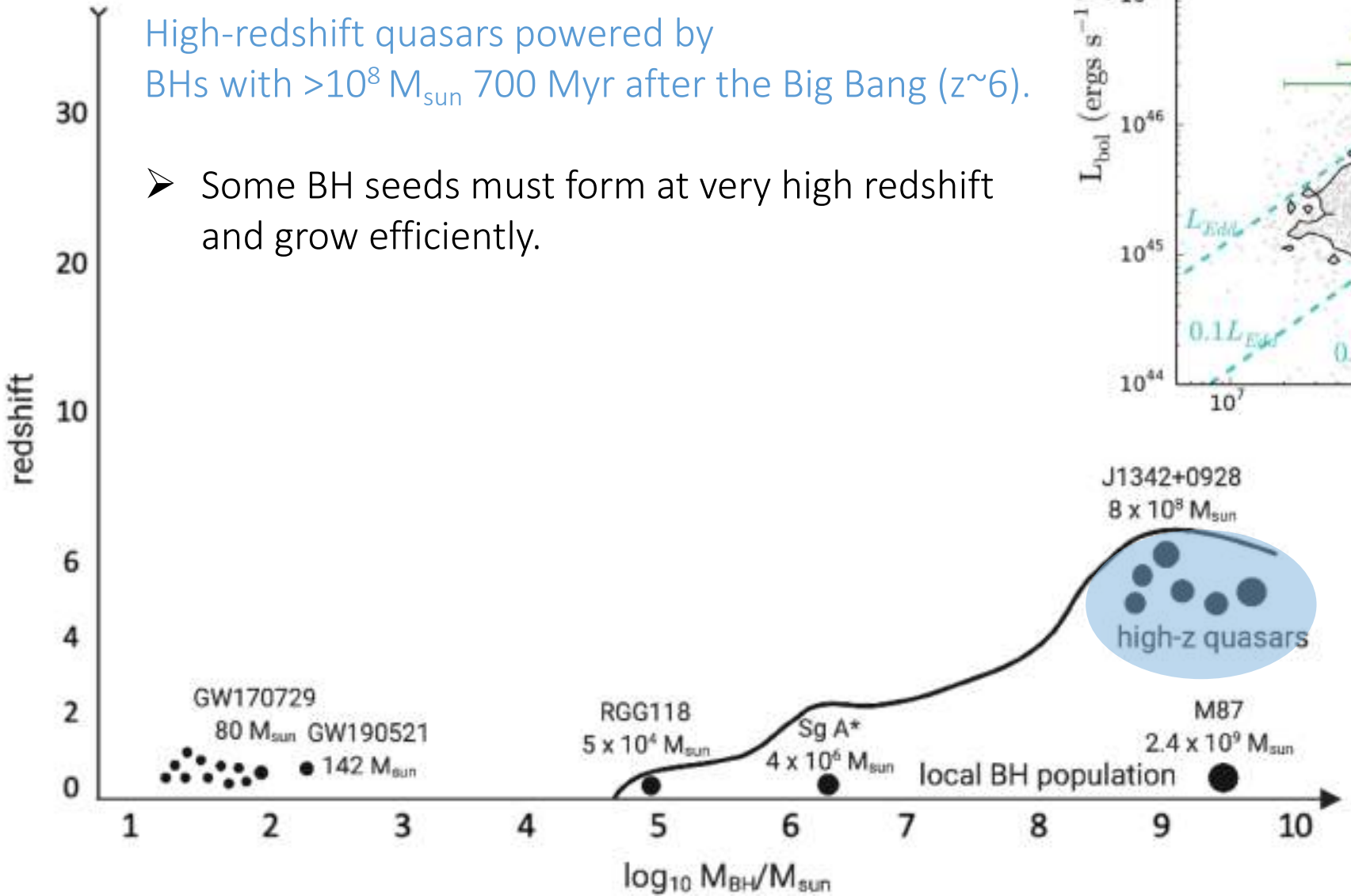
Greene & Ho04, Gallo+08
Dong, Greene & Ho12,
Aird+12,+18
Reines, Greene, Geha13,
Schramm & Silverman13
Reines+15, Miller+15,
Baldassare+16, Pardo+16,
Mezcua+16,+18, Chilingarian+18.

Population of massive black holes

High-redshift quasars powered by
BHs with >10^8 M_{sun} 700 Myr after the Big Bang (z~6).

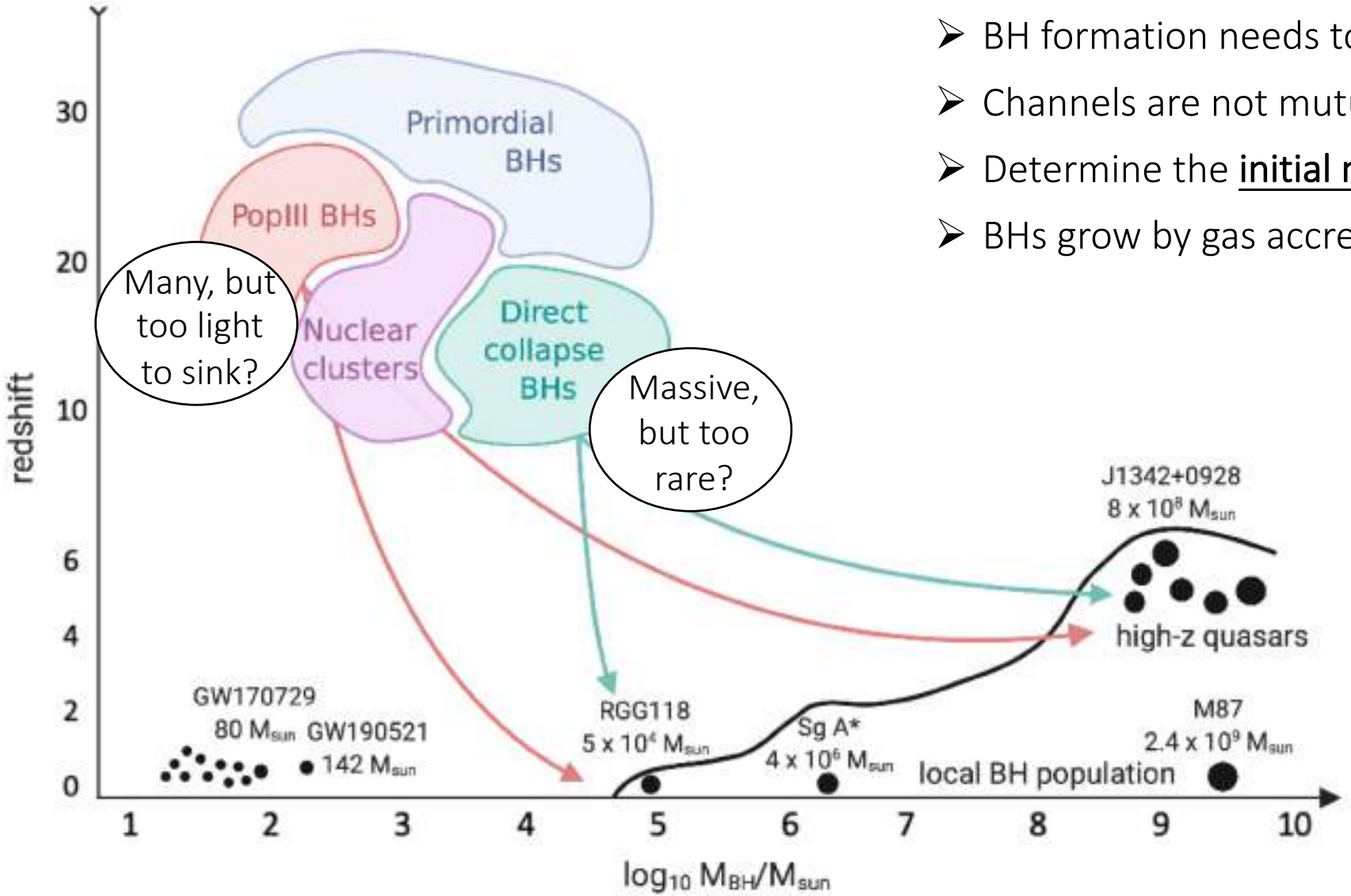
- Some BH seeds must form at very high redshift and grow efficiently.





Dietrich, Hamman04 Willott+07, Shields+06, Riechers+09, Fan+11, Jiang+07, Mortlock+11, Kurk+07, Maiolino+07, Wang+10, Willott+11, DeRosa+11, Wu+15, Matsuoka+16, Bañados+18, Onoue+19, Yang+20, Wang+21.

Population of massive black holes

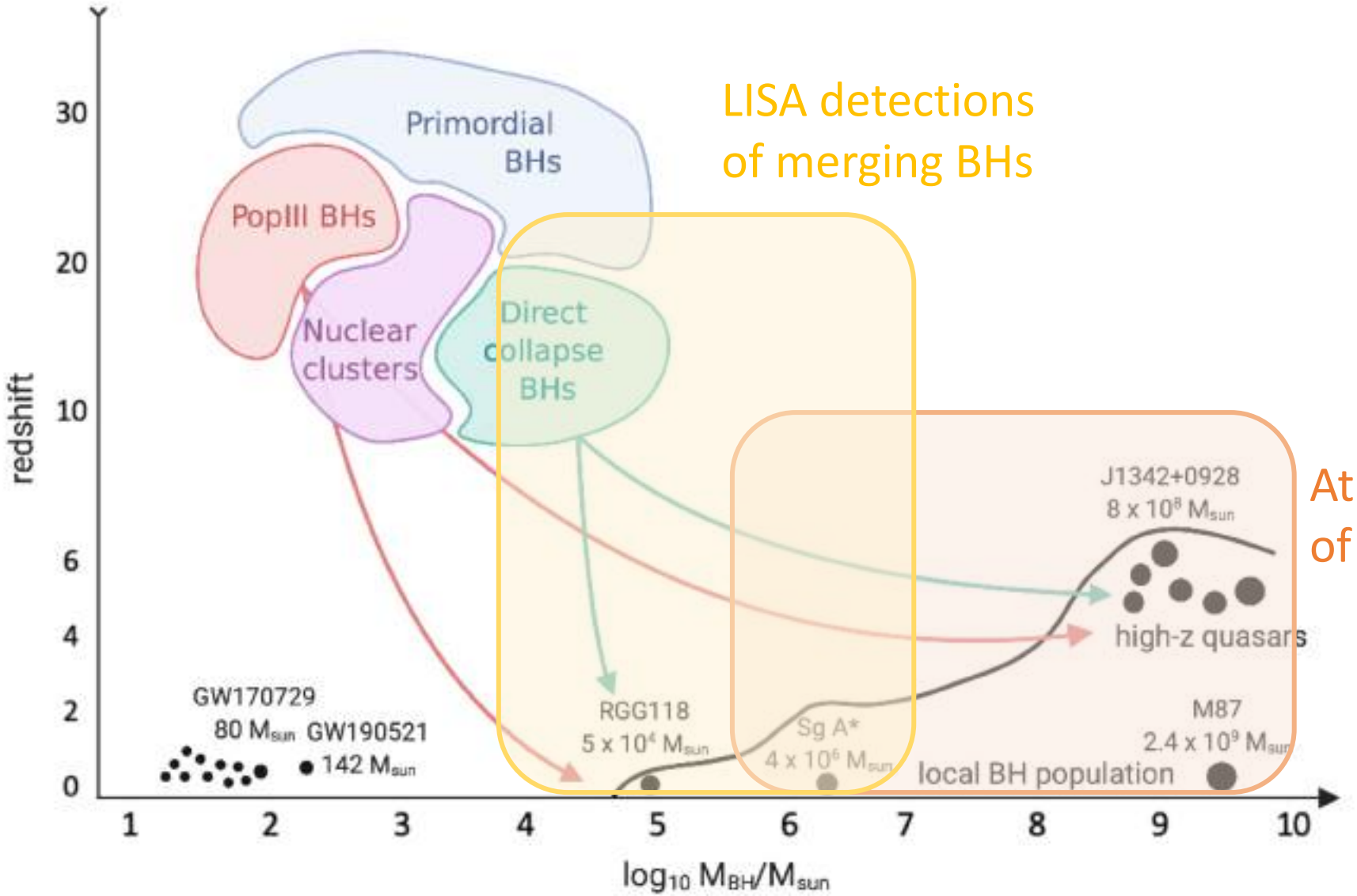


- BH formation needs to explain BH diversity.
- Channels are not mutually exclusive.
- Determine the **initial mass** and **abundance** of BHs.
- BHs grow by gas accretion and BH mergers.

Volonteri, MH, Colpi 2021 (Nature Physics Review)

Rees 78, Loeb & Rasio 94, Madau& Rees 01, Bromm & Loeb 03, Volonteri, Haardt, Madau 03 Spaans & Silk 06, Begelman+06, Lodato & Natarajan+06,07, Omukai, Schneider & Haiman 08, Devecchi & Volonteri 09, Regan & Haehnelt 09, Shang, Bryan, Haiman 10, Latif+13, Agarwal+12,14, Visbal+14+18, Katz, Sijacki & Haehnelt 15, Wise+19, Inayoshi+20, Lupi+21, Habouzit+16a,16b,17.

Population of massive black holes



LISA detections of merging BHs

Athena detections of active BHs

Large-scale cosmological hydrodynamical simulations to study galaxy formation

Resolution

- Dark matter resolution 6×10^6 - 10^8 M_{sun}.
- Baryonic resolution 10^6 - 10^7 M_{sun}.
- Spatial resolution 1-2 ckpc.
- Box side length 100-300 cMpc.
- Run down to z=0.

Subgrid physics

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

BH formation

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

BH growth

- BH mergers,
- gas accretion via Bondi formalism.

AGN feedback

- Injection of energy that couples to the gas.
- $\dot{E}_{\rm AGN} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{M}_{\rm BH}c^2$

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

Large-scale cosmological hydrodynamical simulations to study galaxy formation

AGN luminosity

- $\dot{M}_{BH}\,(M_\odot/yr) \longrightarrow L_{bol},\, L_{2-10\,kev}\,(erg/s)$
- AGN obscuration is done post-processing, but remains one of the biggest unknown.
- AGN short timescale variability is not captured by the simulations.

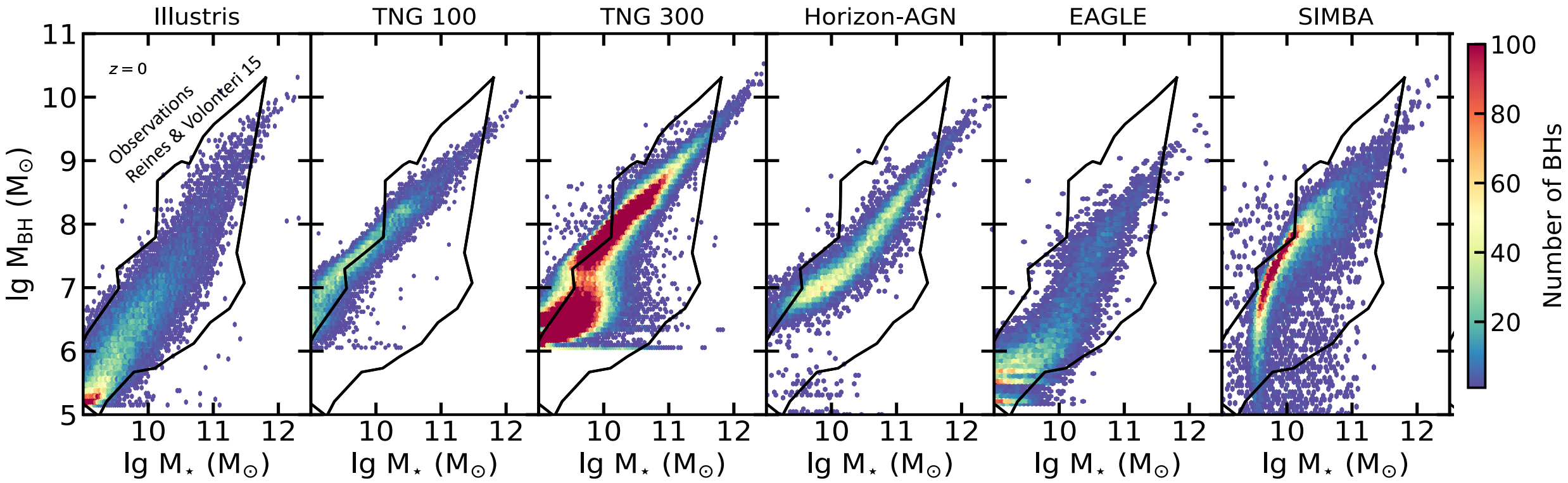
Simulated population of galaxies in good agreement with observations
(e.g., star-forming main sequence, galaxy morphologies, sizes, quenched galaxies).

Are the simulated BHs
in good agreement
with observations ?

Scaling relation in cosmological simulations

Melanie Habouzit

Habouzit+21
Haidar, MH+22



Broad agreement at z=0 with observations, but tighter relations in simulations.

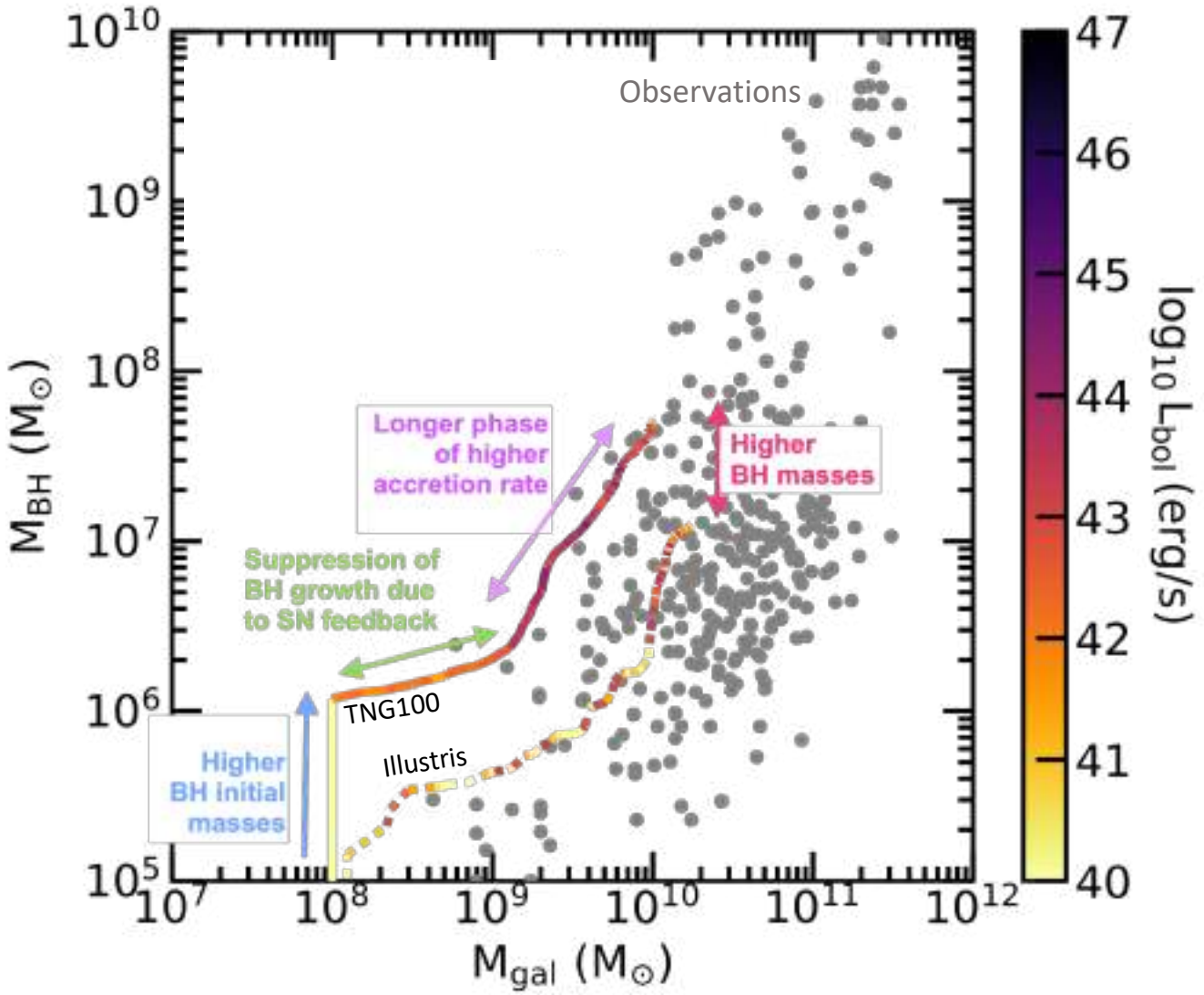
See also Sijacki+15, Pillepich+17, Weinberger+18, Volonteri+16, McAlpine+17,+18, Thomas+19, Li, MH+20.

Scaling relation in cosmological simulations

Melanie Habouzit

Habouzit+21

Dubois+15, Fontanot+15, Anglés-Alcázar+17, Habouzit+17, Bower+17, McAlpine+18, Dekel+19 for the role of SN feedback.



BH and galaxy subgrid physics strongly impact the BH and galaxy co-evolution and the number of AGN.

Scaling relation in cosmological simulations

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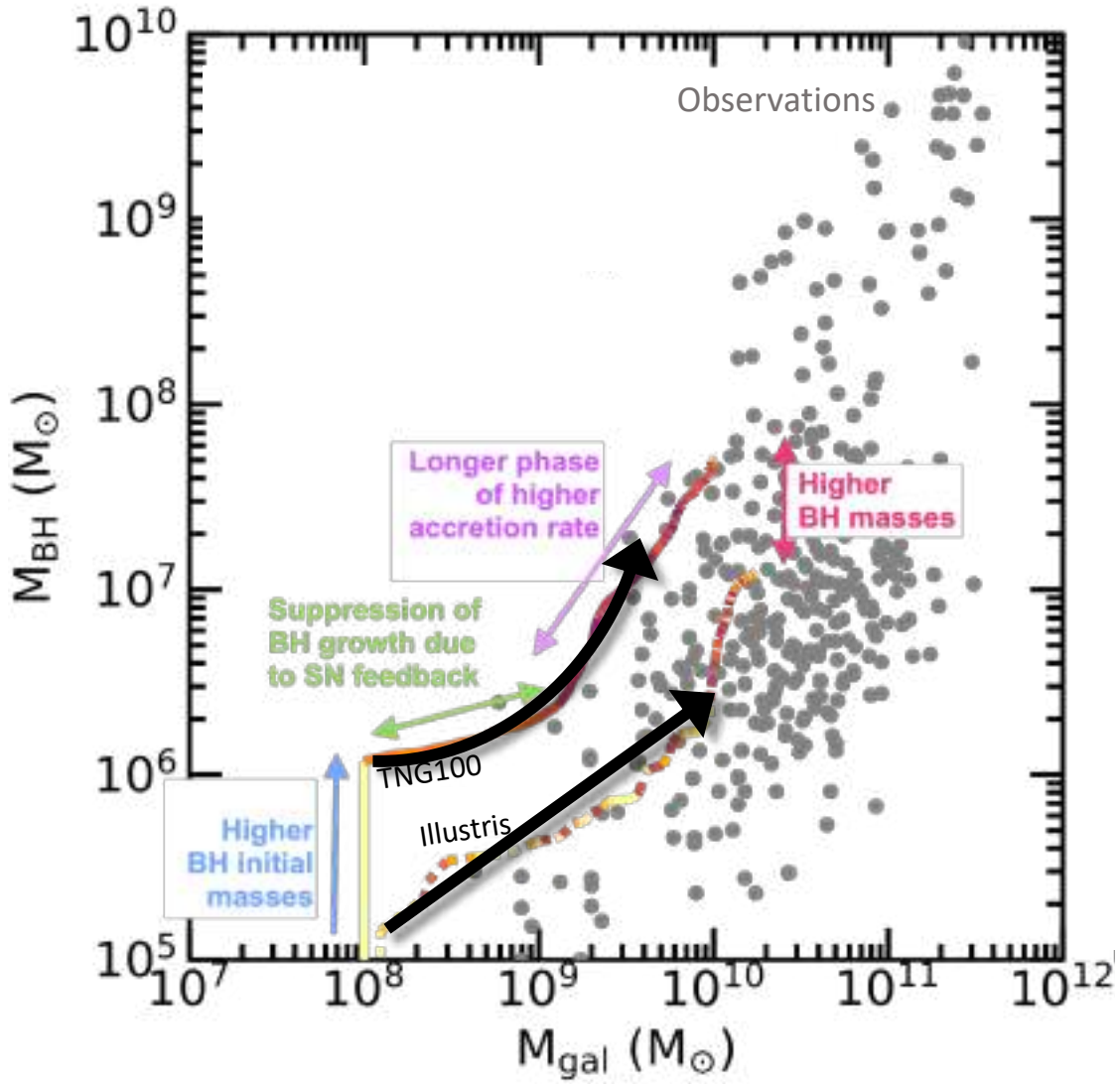
Habouzit+21



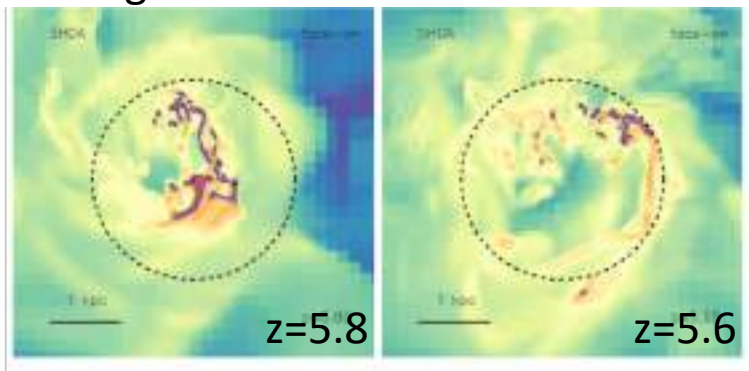
Dubois+15

Set of high-resolution zoom-in simulations.

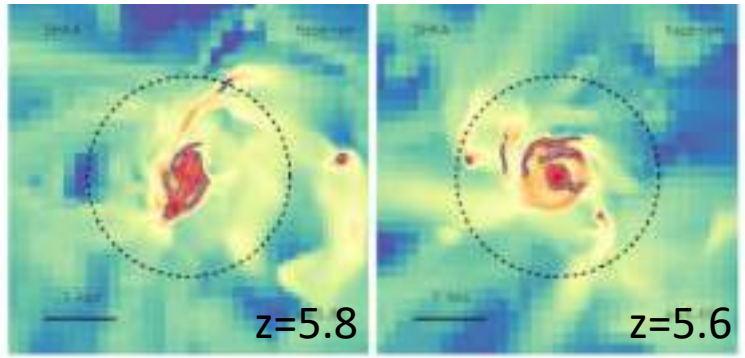
Dark matter resolution 2 x 10^5 $M_\odot$.

Spatial resolution ~10-35 pc.

Strong SN feedback



Weaker SN feedback



BH and galaxy subgrid physics strongly impact the BH and galaxy co-evolution and the number of AGN.

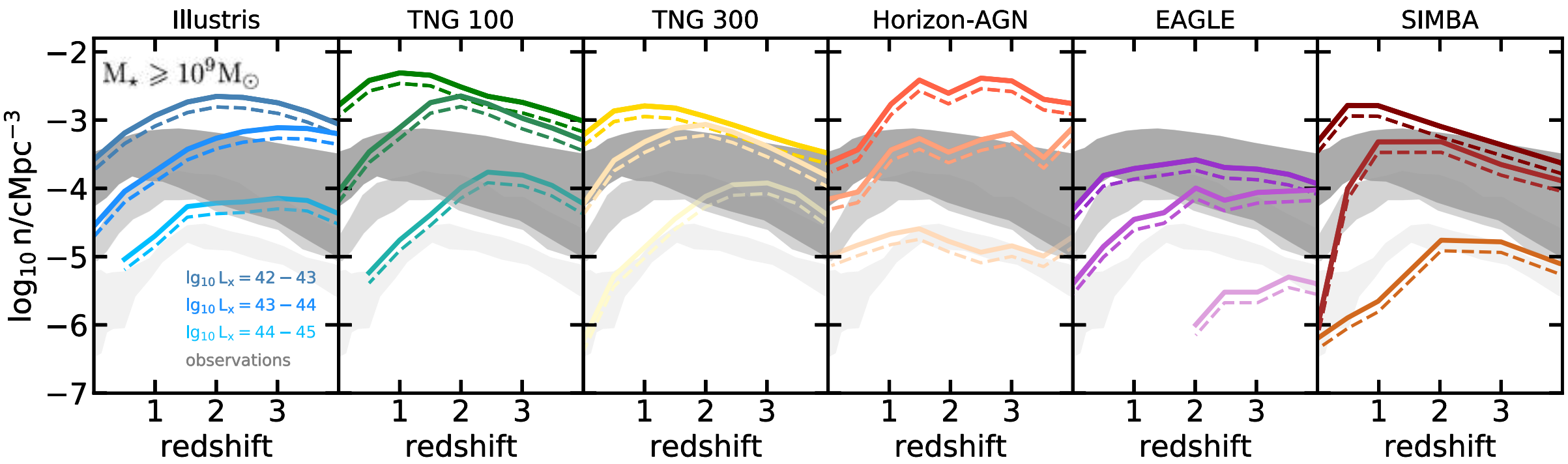
Is the AGN population produced by
large-scale cosmological simulations
in good agreement with current observations?

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

AGN population in simulations (2-10 keV luminosity)

Melanie Habouzit

Habouzit+22a, see also Rosas-Guevara+16 for EAGLE



- 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 population in simulations (2-10 keV luminosity)

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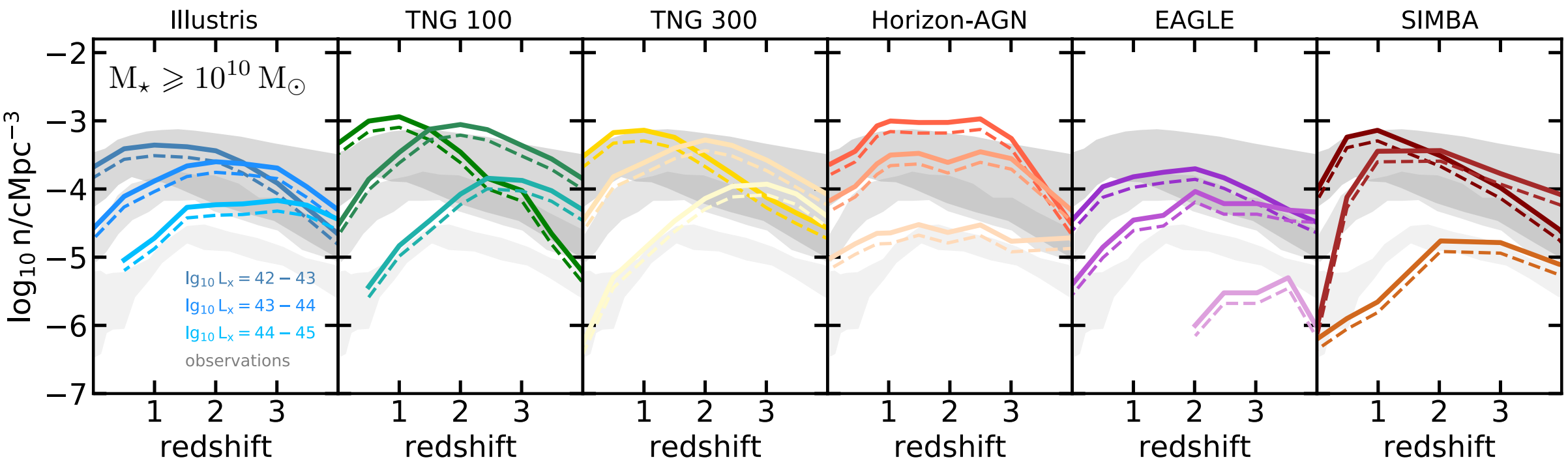
Habouzit+22a, see also Rosas-Guevara+16 for EAGLE



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

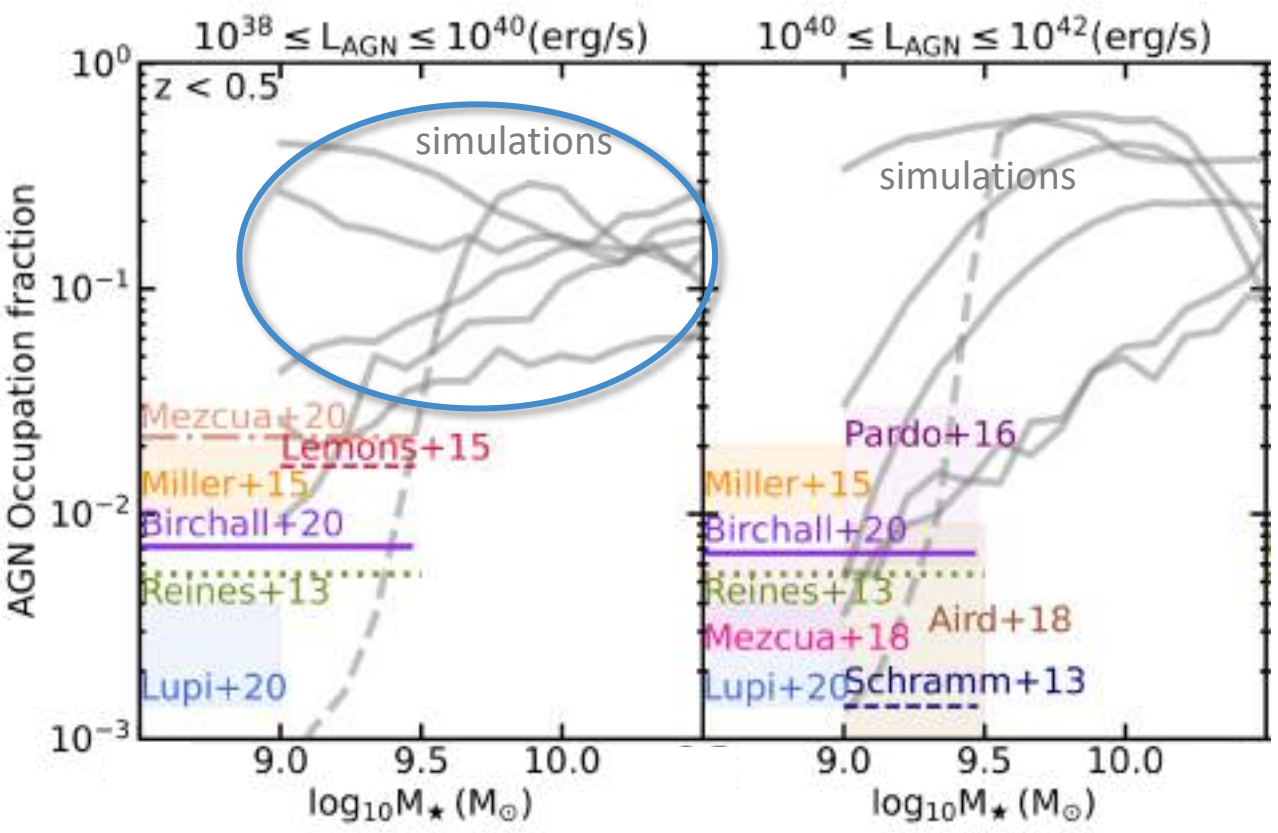
- Too many AGN in low-mass galaxies? Too weak SN feedback?

AGN population in simulations (2-10 keV luminosity)

Melanie Habouzit

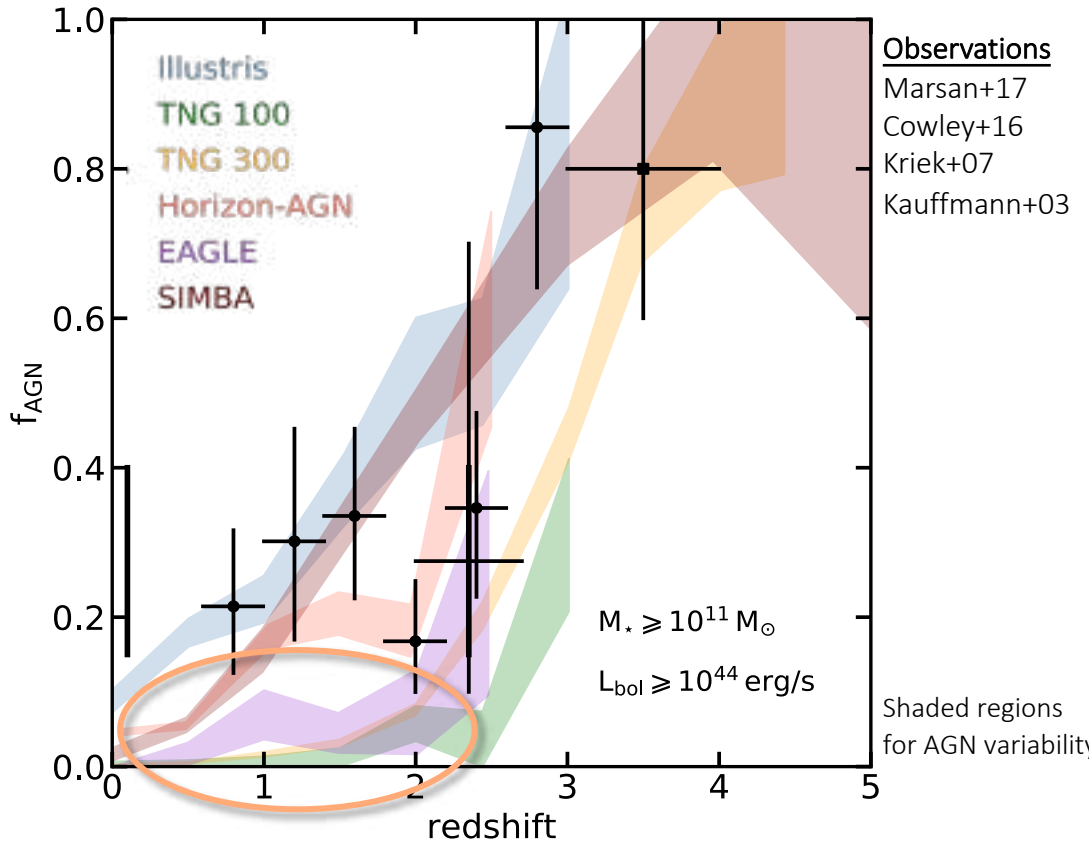
Low-mass local galaxies:
higher AGN fractions compared to observations.
- ➢ too weak SN feedback?
- ➢ too massive BHs?

Houda Haidar, MH+22 *(see also Koudmani+21)*



Massive low-redshift galaxies:
lower AGN fractions compared to observations.
- ➢ too strong AGN feedback?

Habouzit+22a, Habouzit+19a.

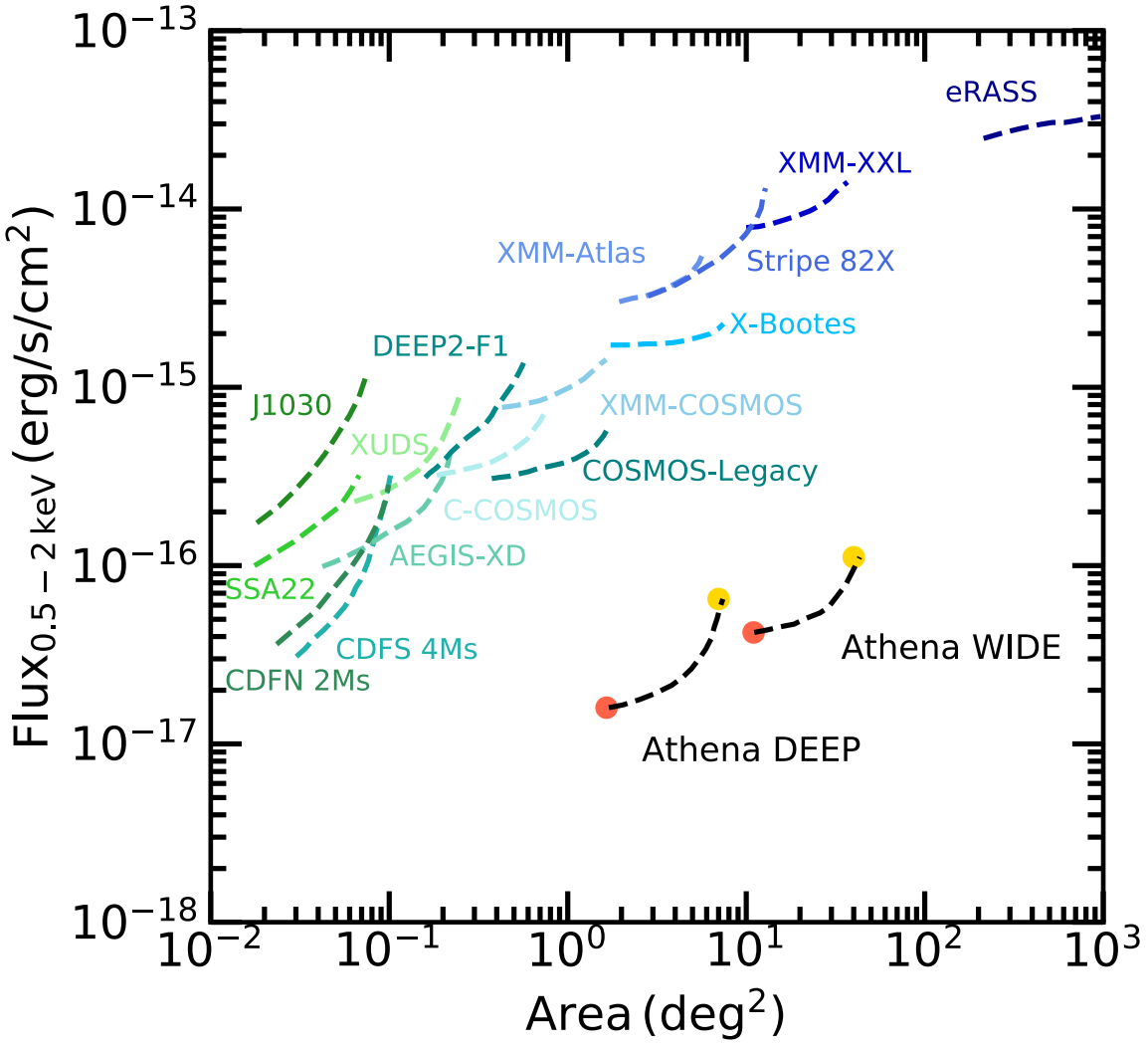


Some discrepancies between the observed
and simulated populations of BHs and AGN.

Comparing all the state-of-the-art simulations allows us
to capture modeling uncertainties
and to assess their impact on AGN predictions.

Needed to maximize the
scientific return of Athena.

Habouzit+22a



Surveys	Area ($\mathrm{deg^2}$)	F ($\mathrm{erg/s/cm^2}$)
Athena DEEP	5.28	$1.6 - 6.5 \times 10^{-17}$
Athena WIDE	47.52	$4.2 - 11. \times 10^{-17}$

1/ How much of the AGN luminosity distribution will cover Athena?

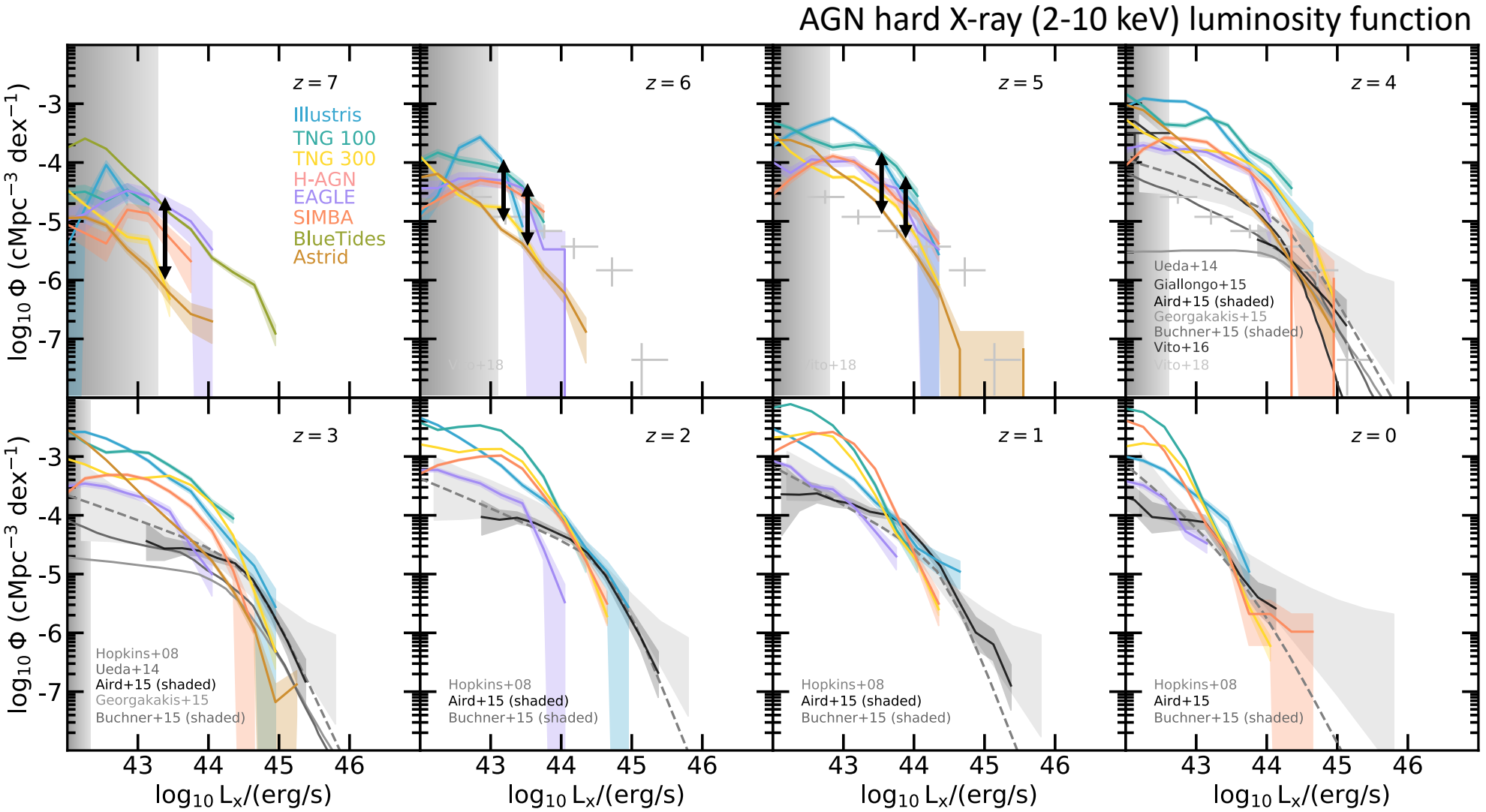
2/ What BH population power the AGN detectable by Athena?

3/ In which galaxies are located these AGN?

The Athena AGN population

Melanie Habouzit

Habouzit+22a, Habouzit (in prep)



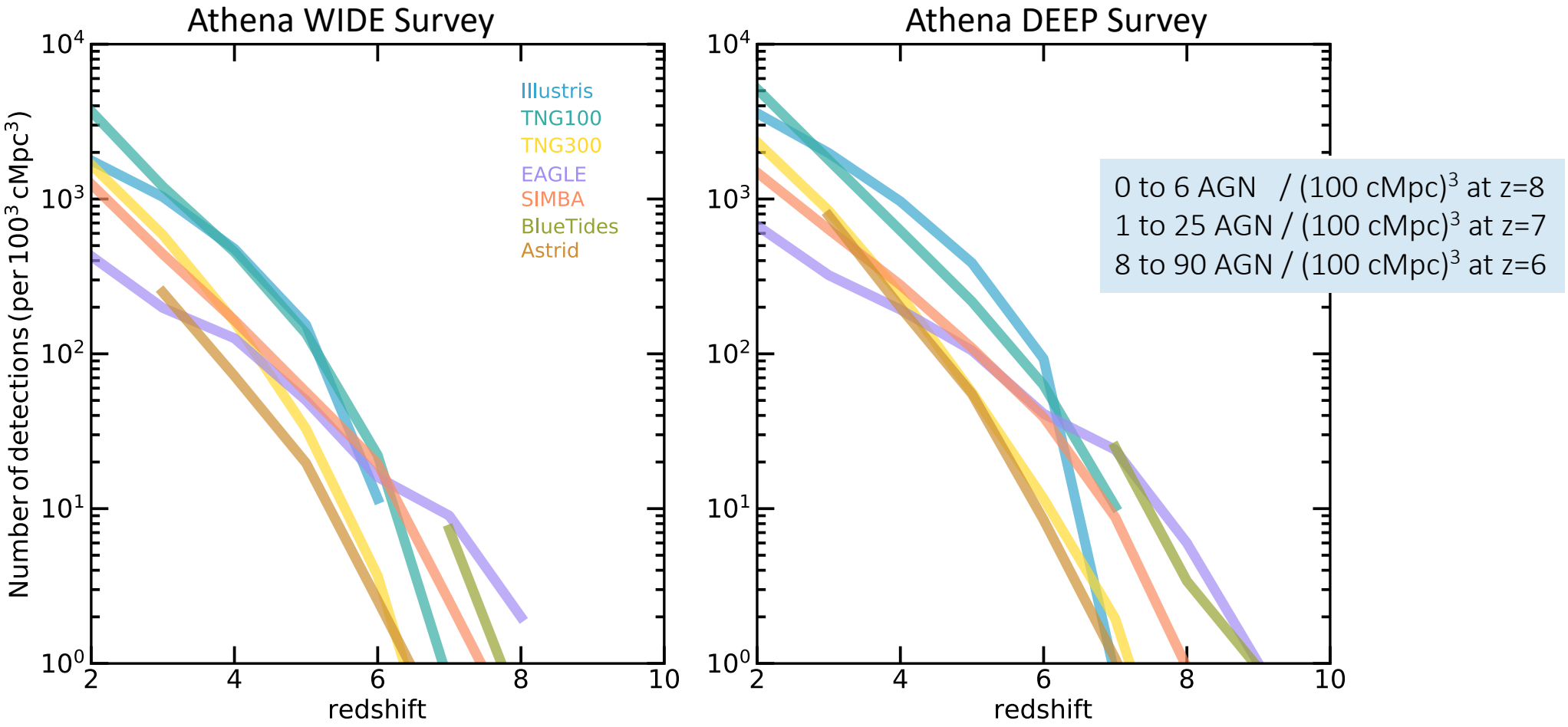
➢ Athena will observe a significant fraction of the AGN population across cosmic time.

The Athena AGN population

Melanie Habouzit

Habouzit (in prep)
Habouzit+22a for AGN obscuration uncertainty (0.5 dex)

see also Marchesi+20

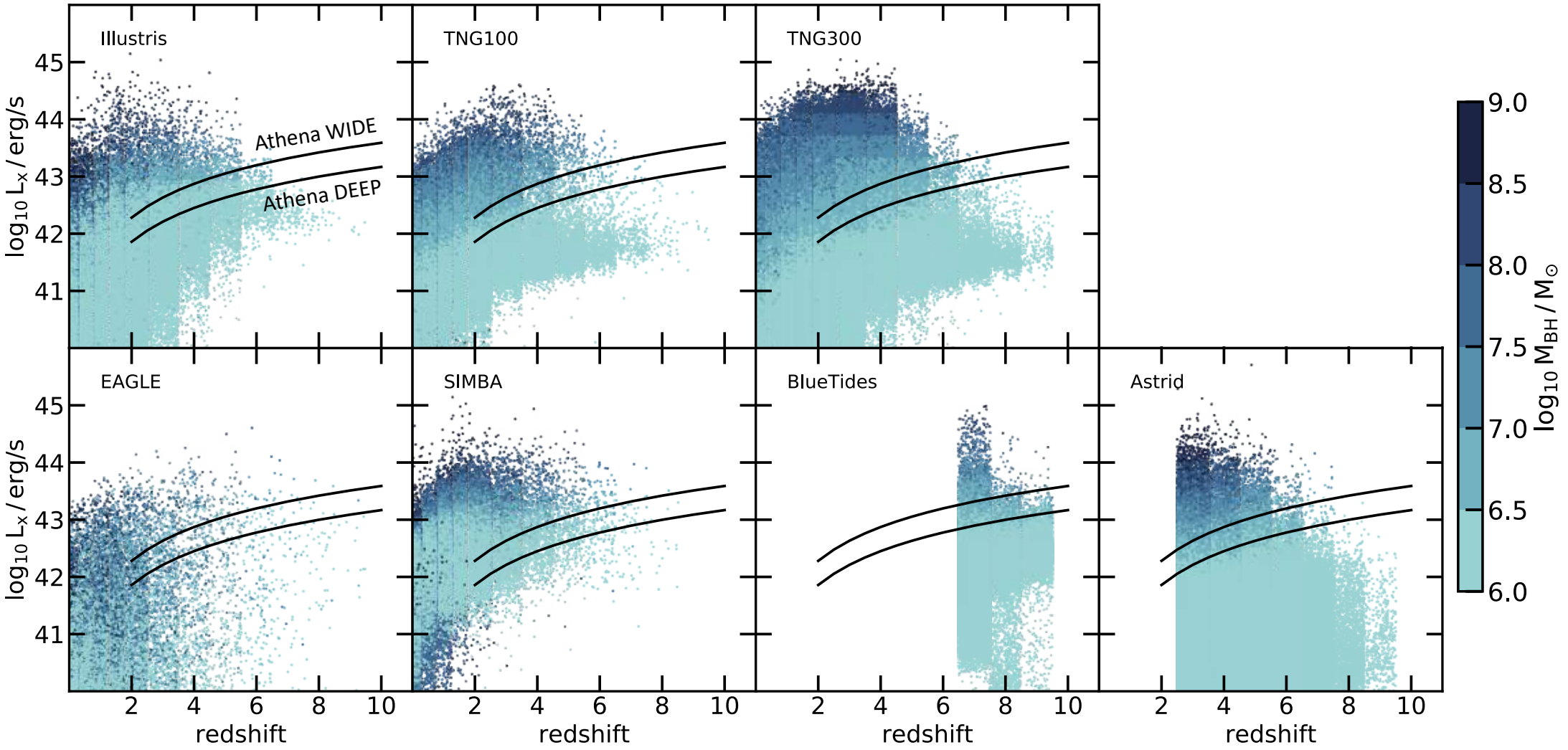


➢ Likely enough detections to disentangle the simulations with Athena.

The Athena AGN population

Melanie Habouzit

Habouzit (in prep)



- At high redshift, Athena will detect BHs with $M_{BH} > 10^6$ Msun (DEEP survey) and $>10^{6.5}$ Msun (WIDE survey).
- Athena will miss the newly formed BHs with $M_{BH} < 10^6$ Msun.

The Athena AGN population

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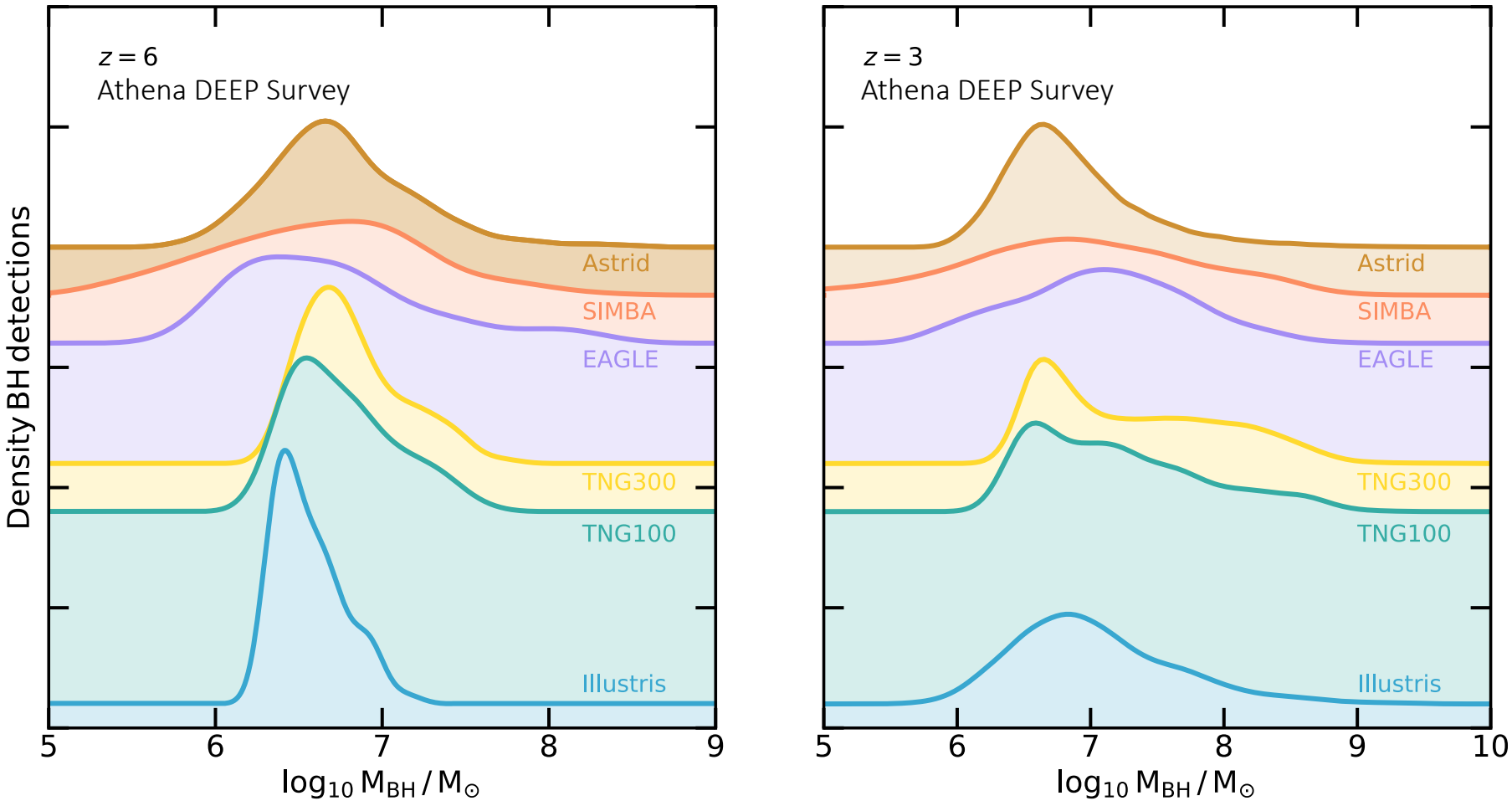
Habouzit (in prep)

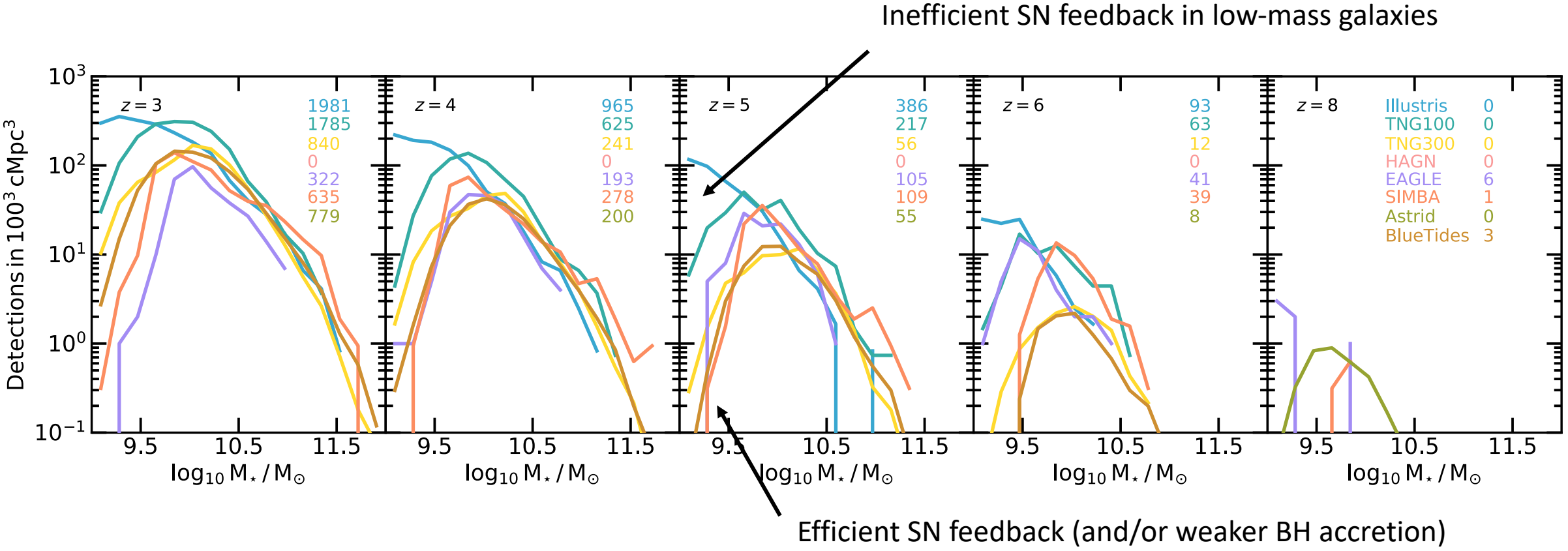


➢ Differences among the simulations on the population of BHs to be discovered.

The Athena AGN population

Melanie Habouzit

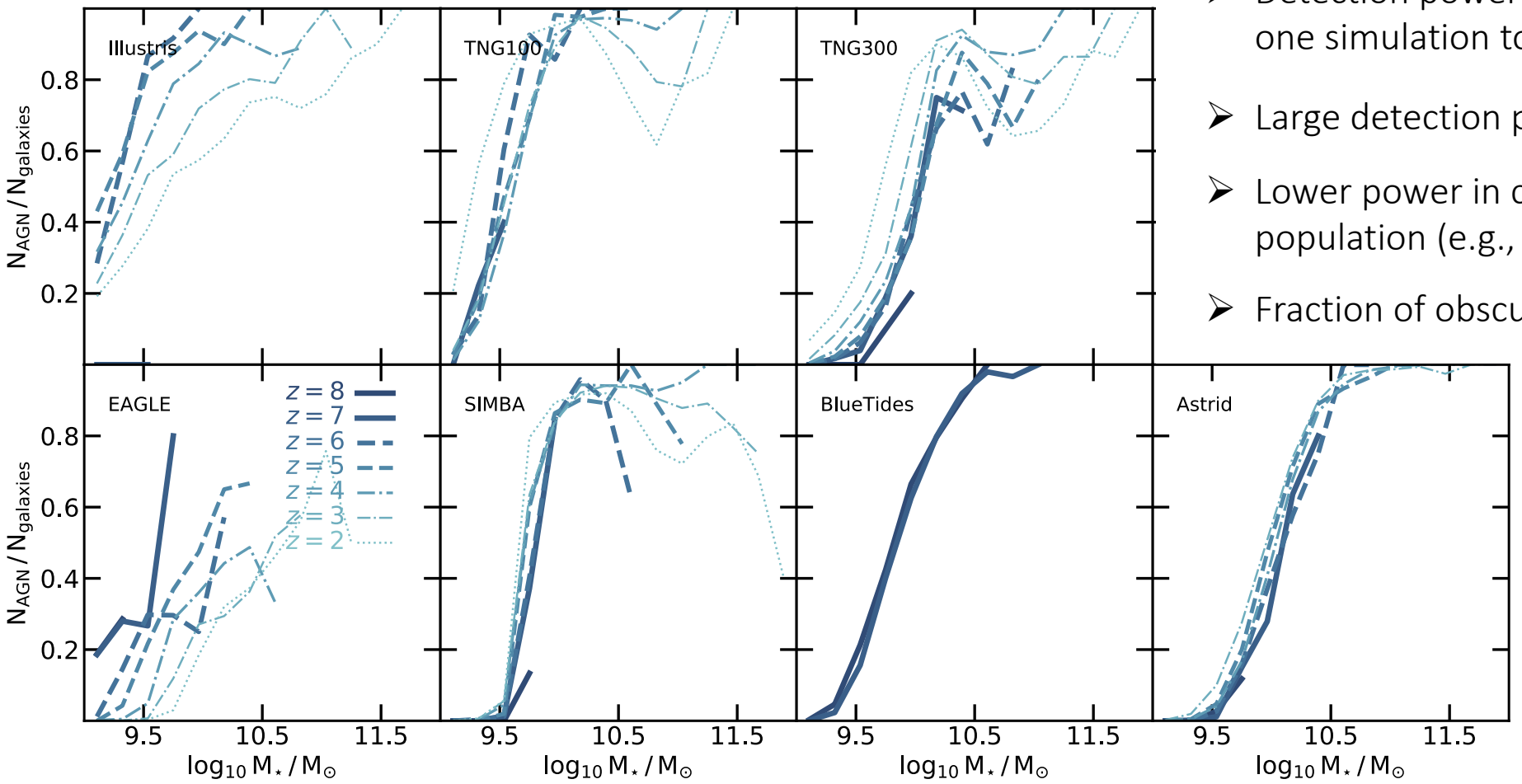
Habouzit (in prep)



- Athena will mostly detect AGN in galaxies with $10^{9.5} < M_{star} < 10^{10.5}$ M_{sun}.
- More detections in low-mass galaxies ($M_{star} < 10^{9.5}$ M_{sun}) if SN feedback is relatively inefficient at quenching BH growth.
- Athena will constrain a combination of BH/galaxy physics (BH formation efficiency, BH accretion, SN feedback).

Habouzit (in prep)

Detection power = Number of detectable AGN / Total number of galaxies in Mstar bins.

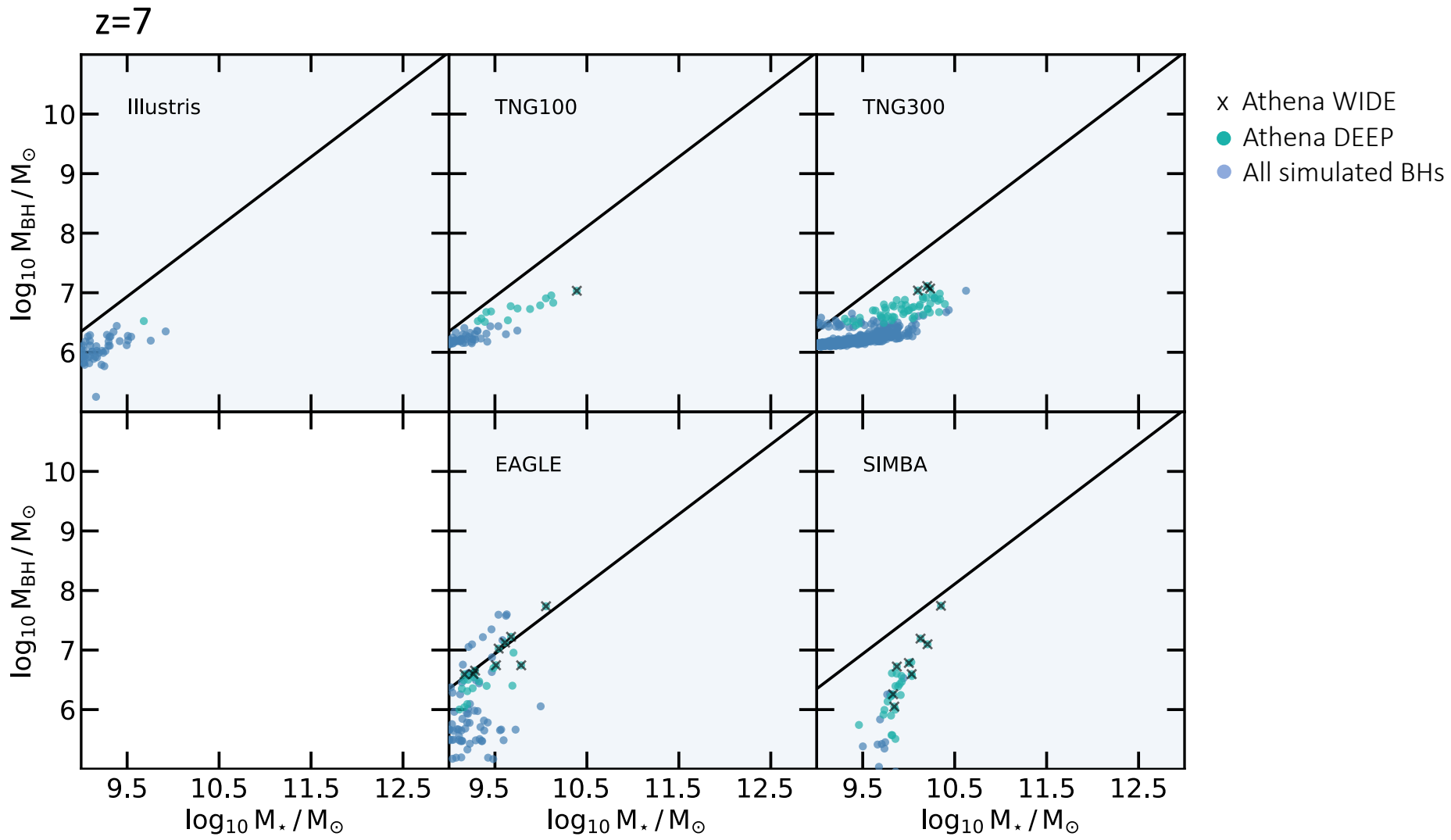


- Detection power varies significantly from one simulation to another.
- Large detection power for Mstar ~ 10^{10} M_{sun}.
- Lower power in case of an overall faint AGN population (e.g., EAGLE).
- Fraction of obscured AGN?

The Athena AGN population

Melanie Habouzit

Habouzit (in prep)



The Athena AGN population

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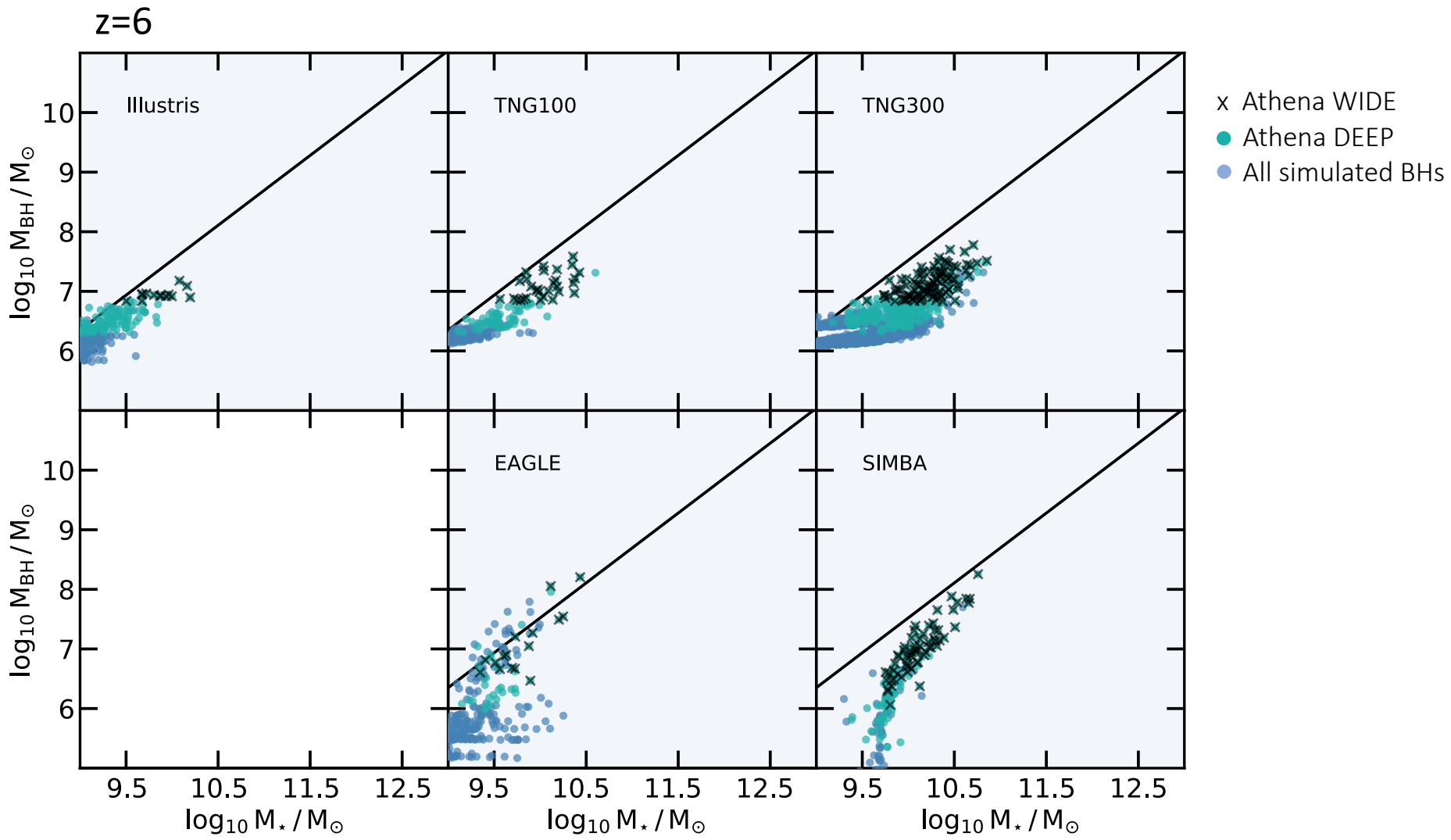
Habouzit (in prep)



The Athena AGN population

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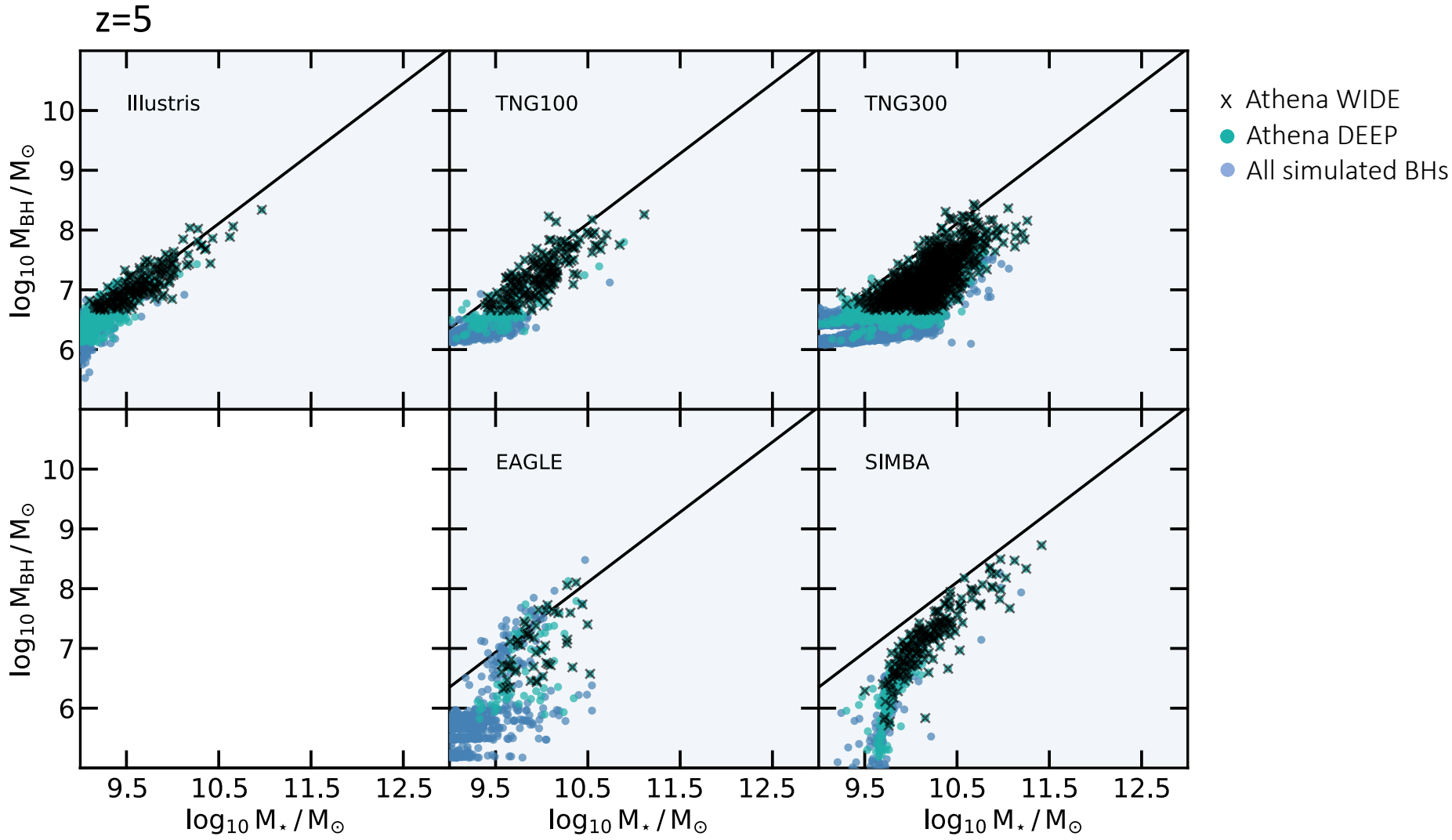

Large-scale cosmological hydrodynamical simulations

2021MNRAS.503.1940H
2022MNRAS.509.3015H

- To study BH evolution and interplay with host galaxies.
- Produce different populations of BHs and AGN.
- Not always in agreement with current observations.
- Key to prepare new observational missions and later maximize their scientific return.

The Athena mission

2022MNRAS.509.3015H
Habouzit (in prep)

- Will observe a significant fraction of the simulated AGN populations.
- Mostly BHs with $>10^6$ M_{sun} in galaxies with $M_{star} \sim 10^{10}$ M_{sun}.
- Missing newly formed and lower-mass BHs.
- Will detect AGN in galaxies of $M_{star}=10^9$ - 10^{10} M_{sun} if SN feedback is relatively inefficient at quenching BH growth.
- Good understanding of the M_{BH}-M_{star} relation if we get the properties of the host galaxies.