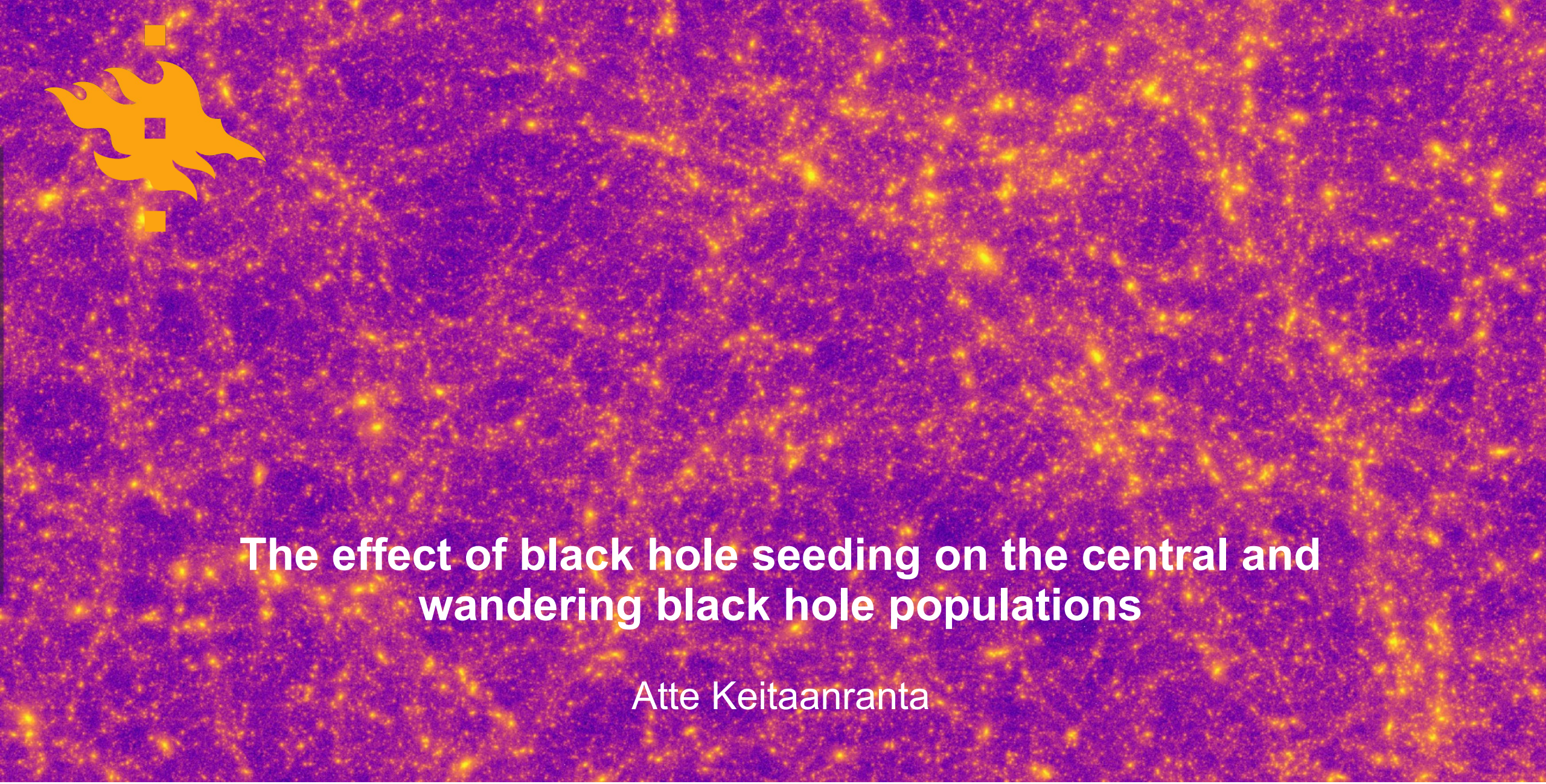
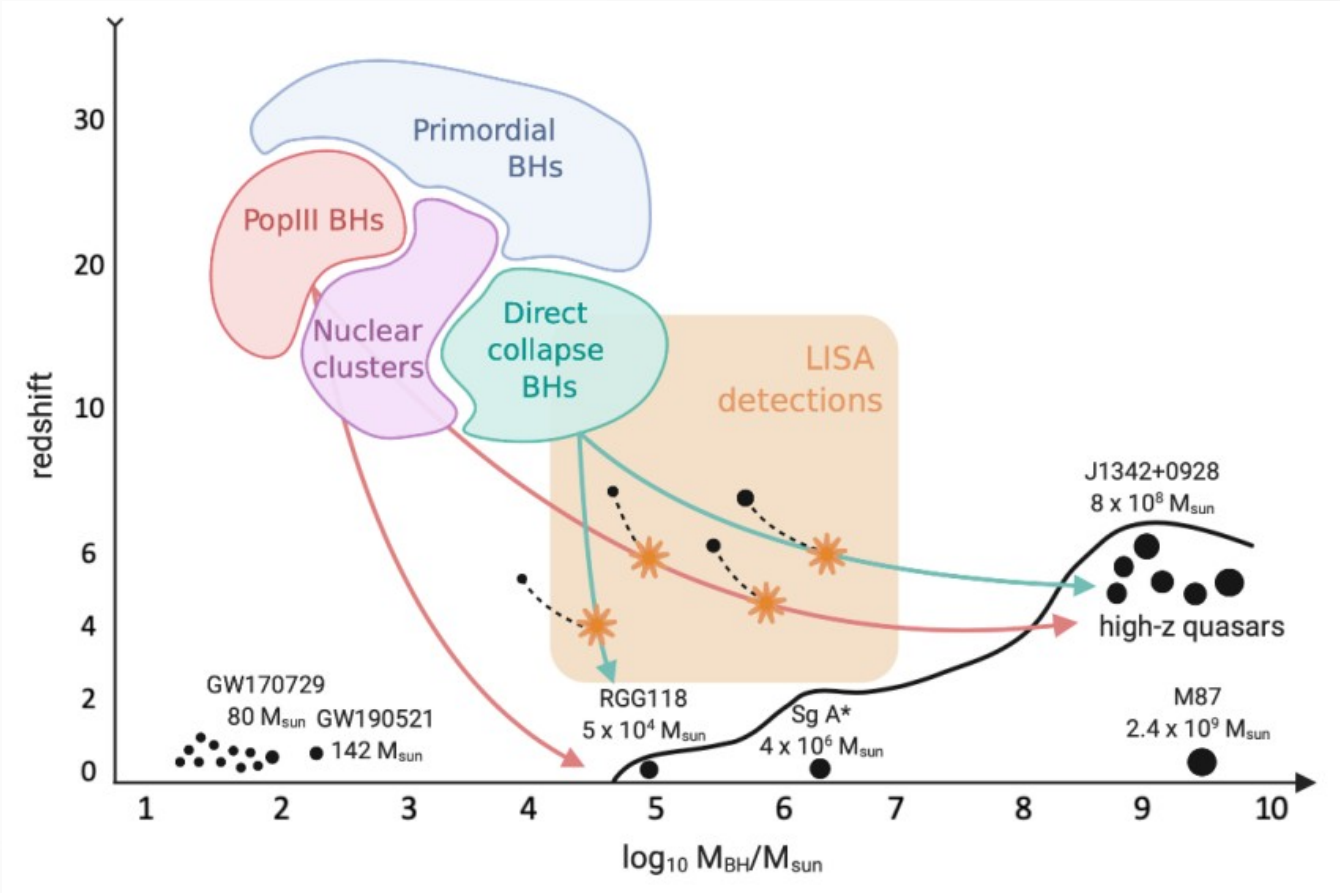


The effect of black hole seeding on the central and wandering black hole populations

Atte Keitaanranta

Seeding

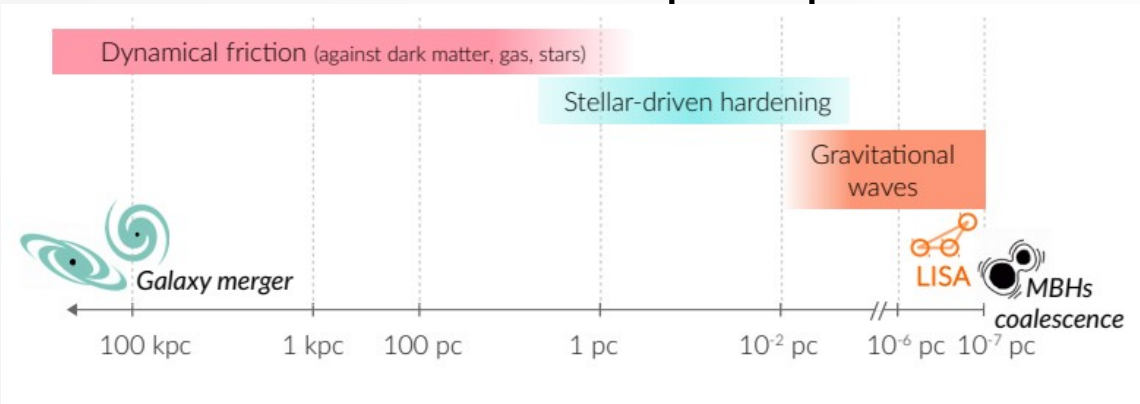
- Environments where BHs form (and BH masses) still uncertain
- In cosmological simulations, BHs are ”seeded” to haloes when they reach a mass threshold (ASTRID, EAGLE, IllustrisTNG, COLIBRE...)
- Used in various large simulations, seed mass usually $\sim 10^5 - 10^6\,\mathrm{M}_\odot$
- Seeding models taking into account e.g. gas properties also exist (ROMULUS, BRAHMA)



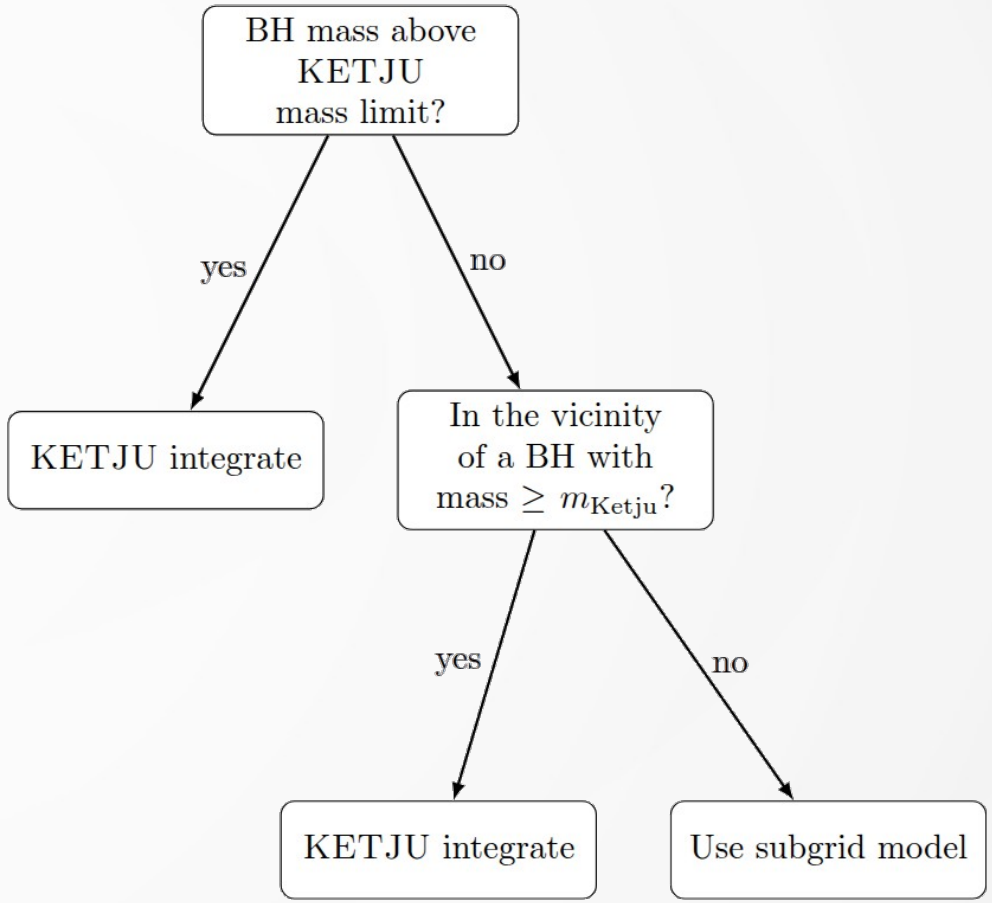
Amaro-Seoane et al. 2023

BH dynamics often not accounted for in cosmological simulations

- Mass resolution limits the modelling of BH dynamics, repositioning traditionally used (e.g. IllustrisTNG, EAGLE, COLIBRE)
- Some recent simulations apply a dynamical friction subgrid model for BHs
- KETJU: algorithmic regularization, models binaries to sub-pc separations



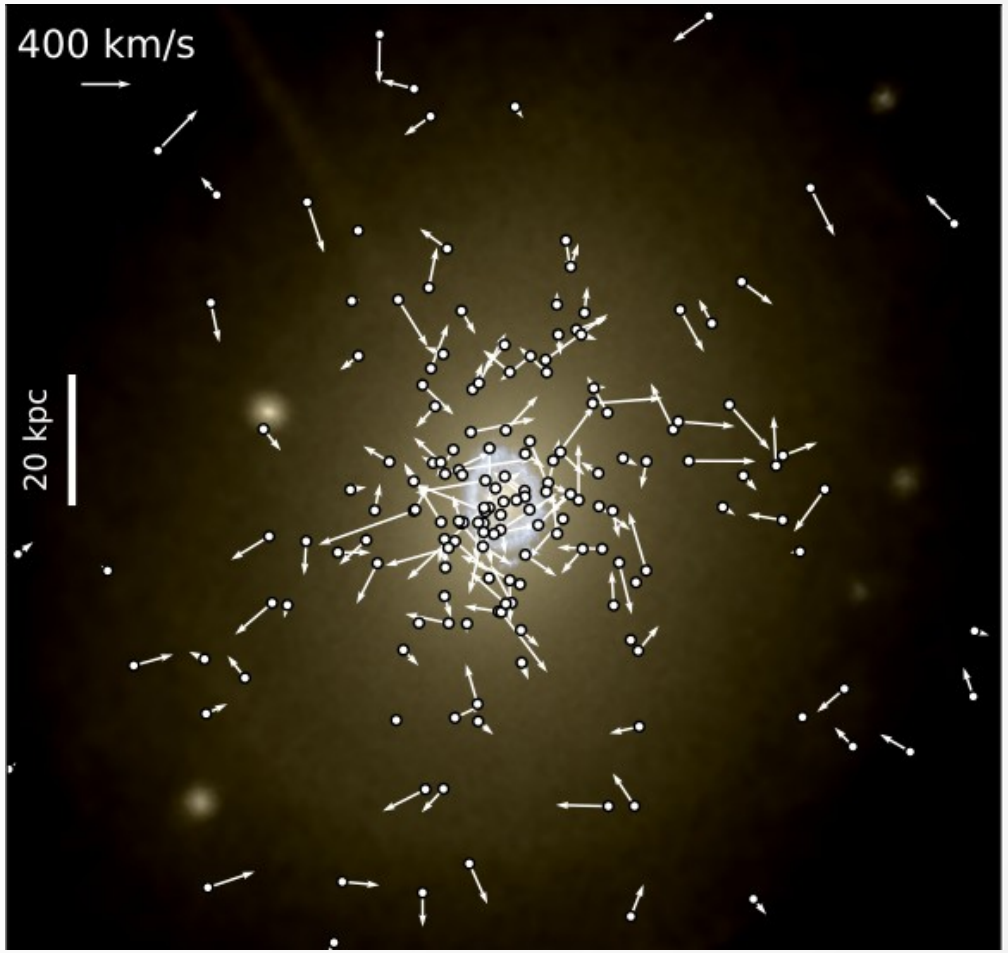
Adapted from Amaro-Seoane et al. 2023.



Keitaanranta et al. 2026

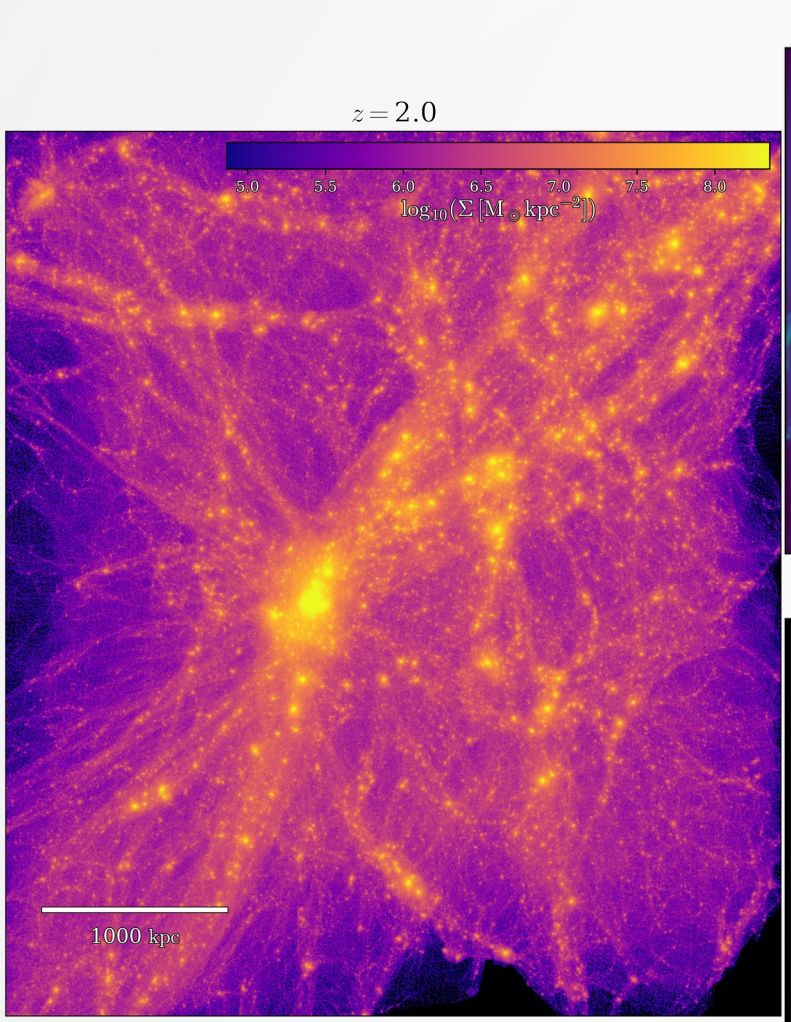
Wandering BHs and simulation setup

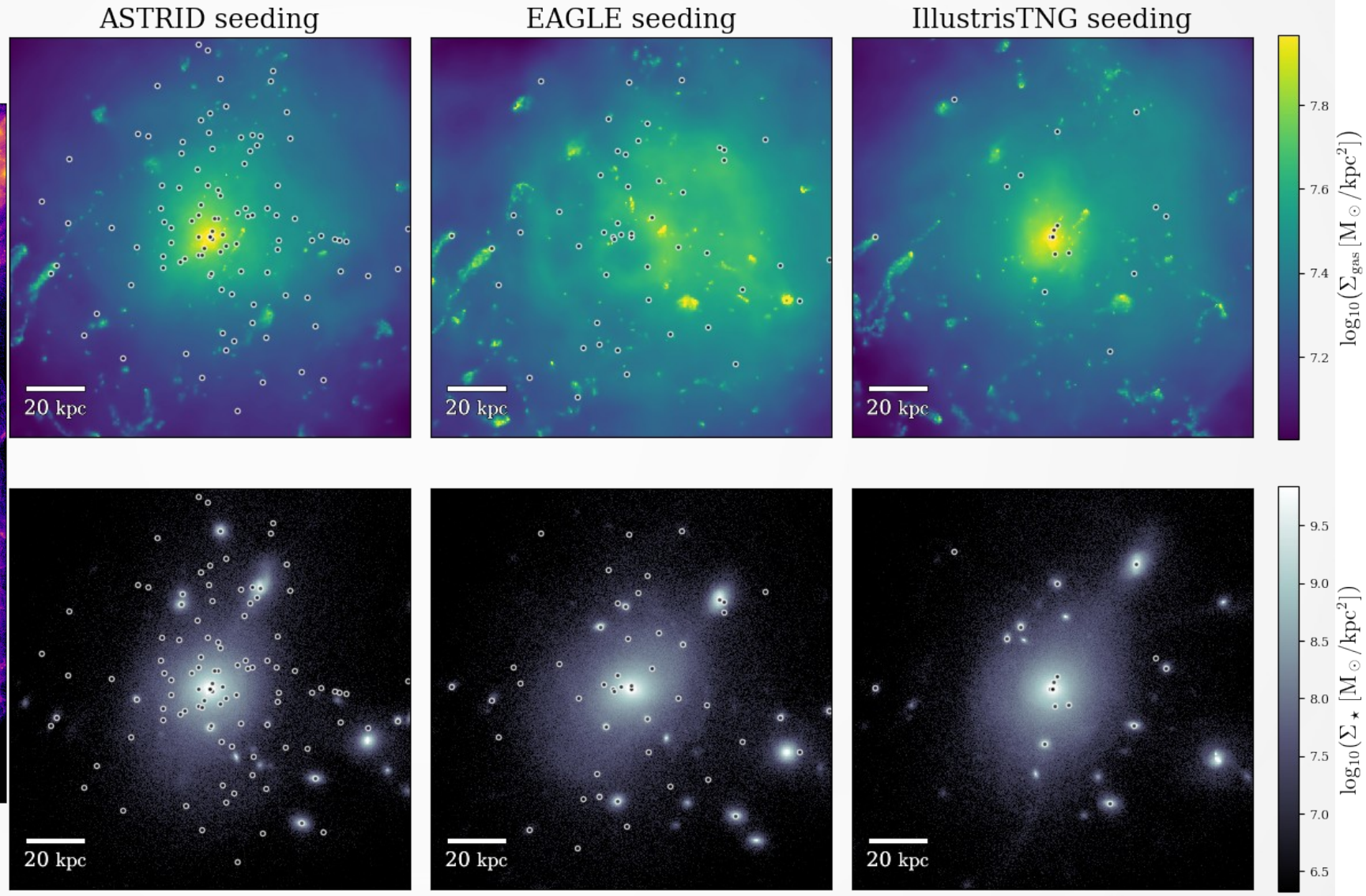
- ASTRID and ROMULUS simulations predict hundreds of BHs in the most massive galaxies
- Goal: run three simulations with different halo mass criteria for BH seeding and see how the BH population is affected
- Zoom-in simulations with (15 cMpc)^3 volume
- Seeding limits taken from ASTRID, EAGLE and IllustrisTNG



Ricarte et al. 2021

Seeding greatly affects wandering BHs

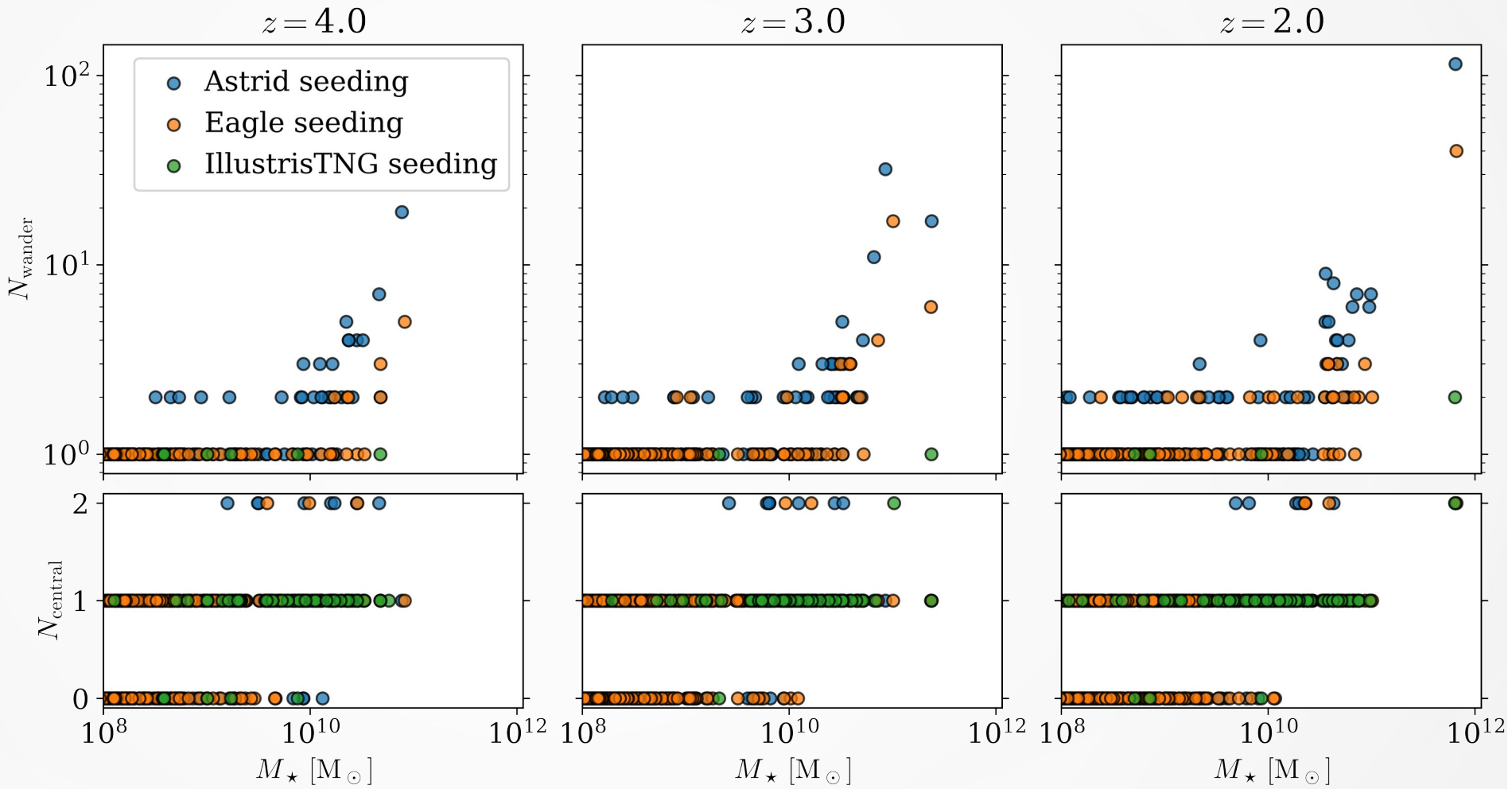




Keitaanranta et al., in prep.

Seeding greatly affects wandering BHs

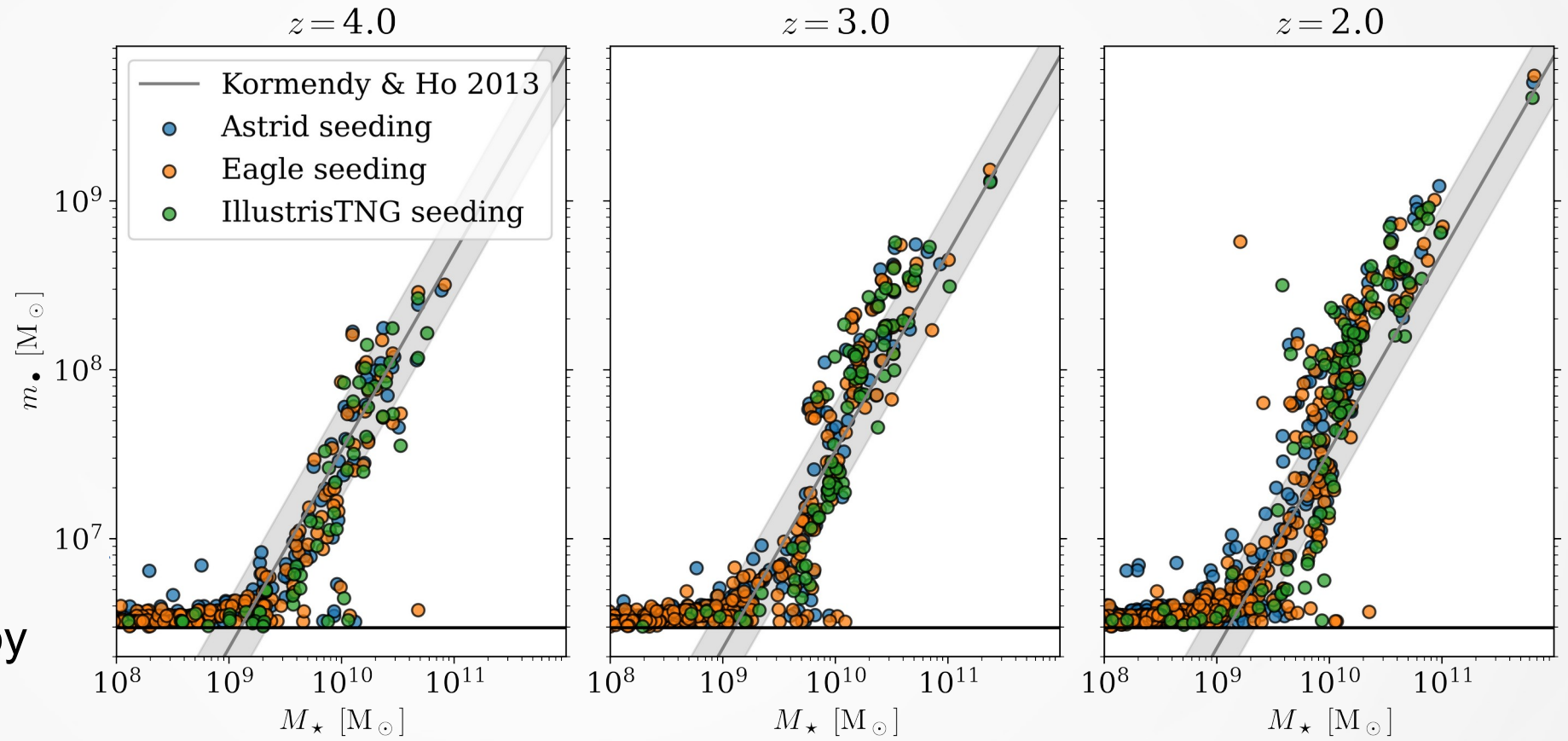
- IllustrisTNG seeding results in nearly zero wandering BHs, ASTRID has >100 in the most massive galaxy
- Wandering BHs also common with EAGLE seeding
- No significant evolution with redshift
- All wanderers are ~seed mass BHs



Keitaanranta et al., in prep.

Massive central BHs hardly change with seeding

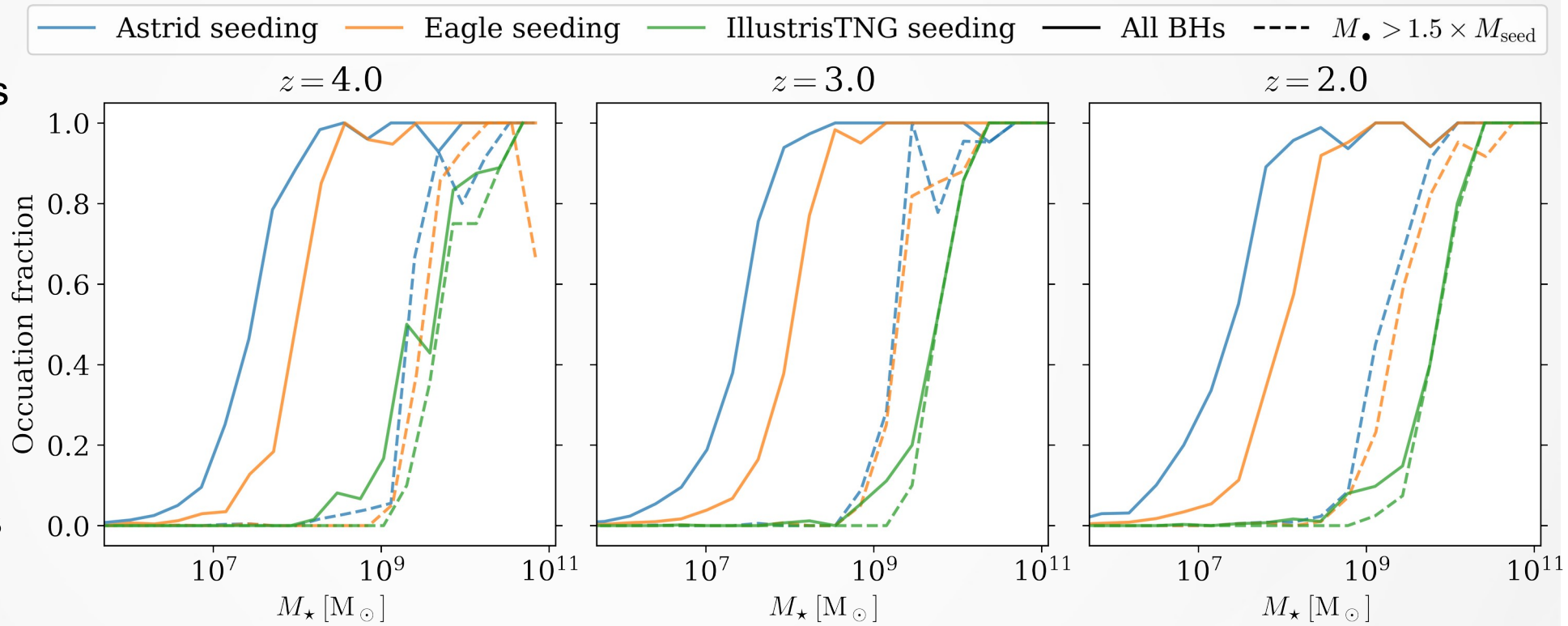
- All simulations result in galaxies following observed relation between stellar and BH mass
- Relation matched already at high redshifts
- Growth dominated by self-regulated BH feedback and accretion



Keitaanranta et al., in prep.

Constraining seeding models: occupation fractions

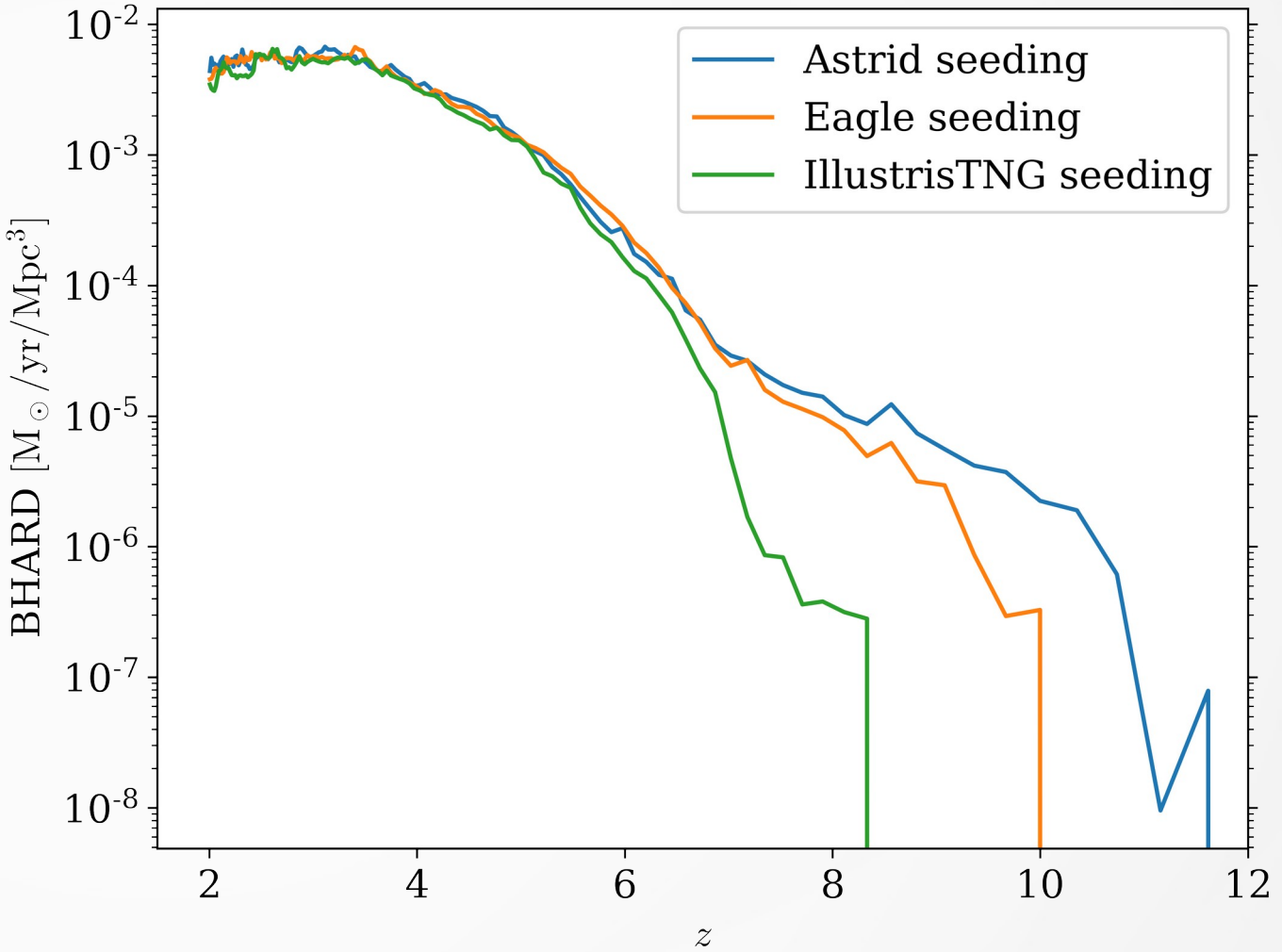
- Occupation fraction of ”grown” BHs hardly varies between simulations
- Notable differences in the full population of BHs
- Observing occupation fractions of low-mass galaxies (even at low redshifts) could constrain seeding models



Keitaanranta et al., in prep.

Constraining seeding models: early accretion

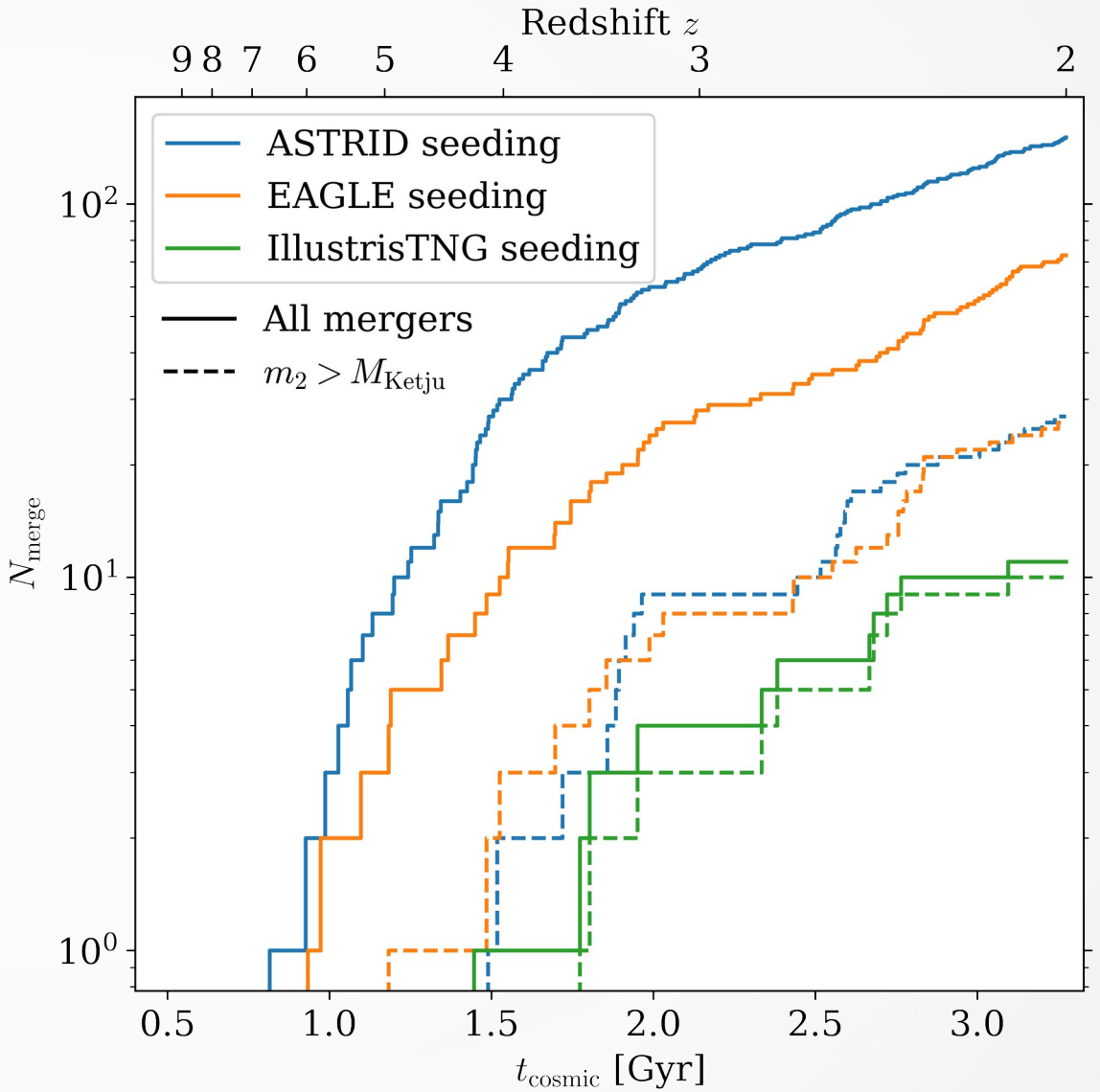
- BH accretion rate density converges at low redshifts
- At z>6, the onset of accretion occurs at different times
- Simulations not a full cosmological volume



Keitaanranta et al., in prep.

Constraining seeding models: mergers

- More than an order of magnitude difference in the amount of mergers
- Seeding has a smaller effect on mergers including very massive SMBHs
- LISA will be vital in constraining seeding models



Keitaanranta et al., in prep.

Summary

- The prediction of wandering BHs is not only due to moving away from repositioning, heavily affected by seeding
- BH merger rate also drastically changes for low-mass binaries
- Possible constrains to seeding models from future observations of BH binaires, occupation fractions and high-redshift accretion rate densities
- GADGET4 version of KETJU publicly available: https://www.mv.helsinki.fi/home/phjohans/ketju/