銀河とブラックホールの共進化過程における種ブラックホール質量の影響

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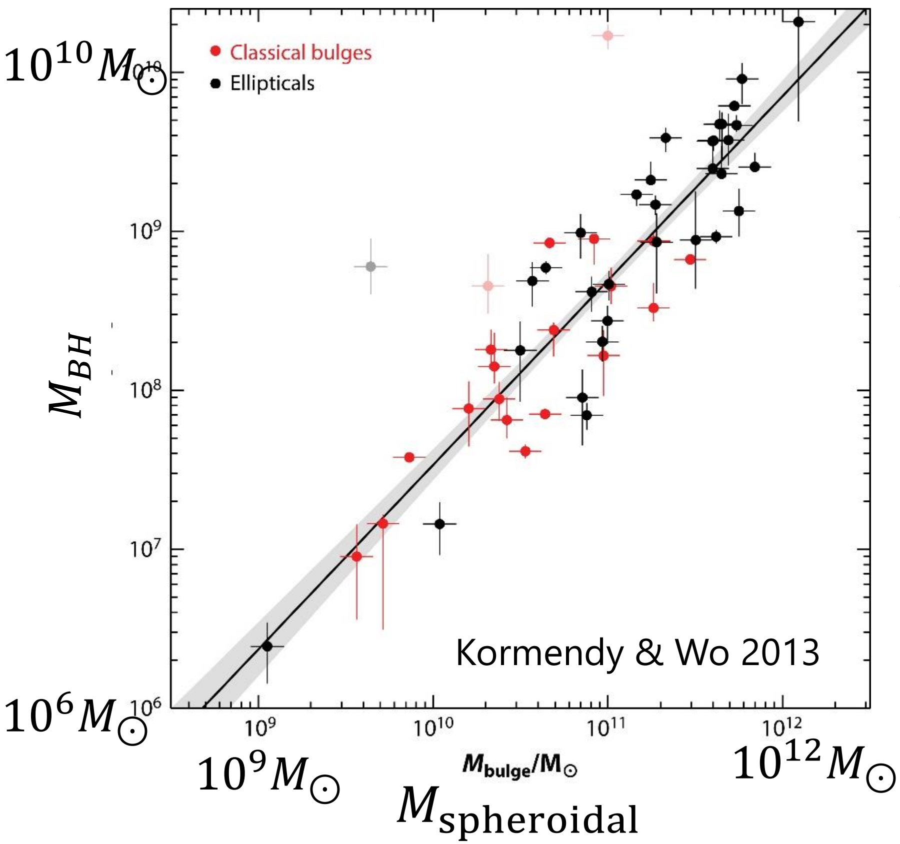
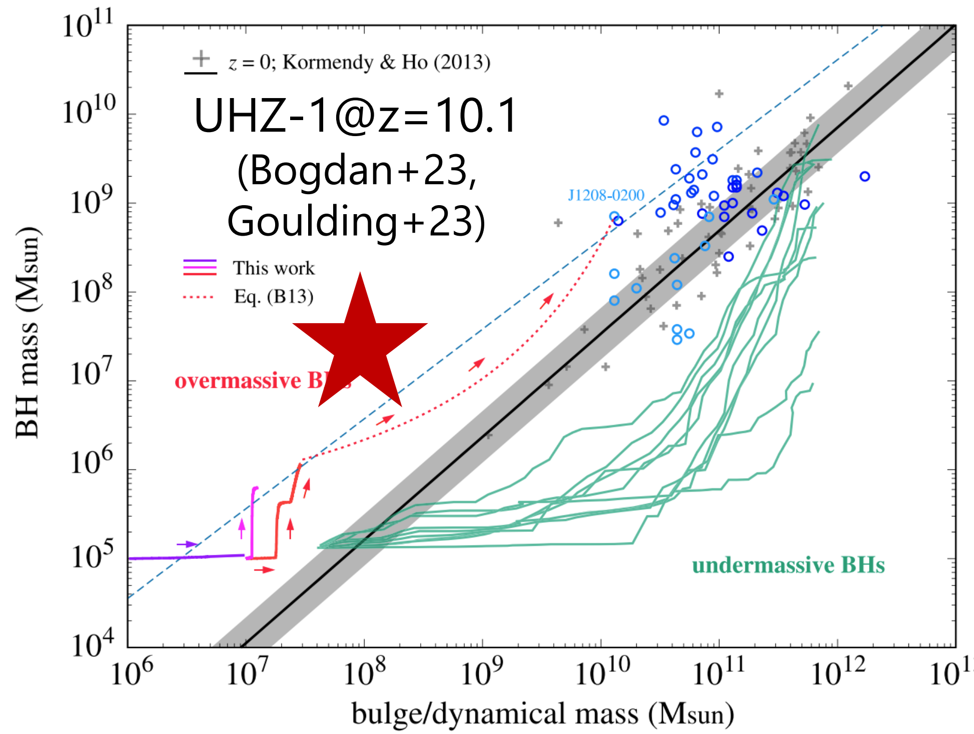
$M_{BH} - M_*$ relation

Magorrian relation, M-σ relation



high-z overmassive BHs



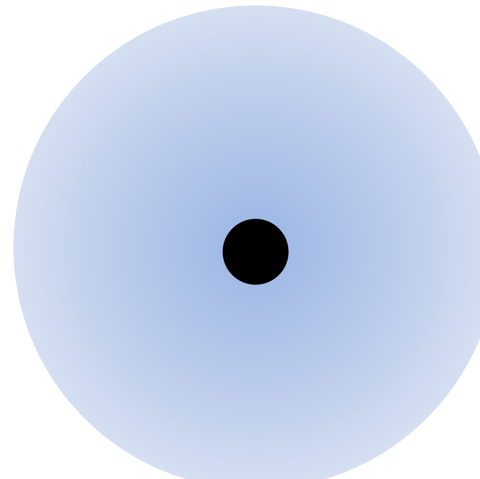
Inayoshi et al. 2022
(see 稲吉さん講演)

Requirement of overmassive seed?
How would they co-evolve in such a case?

BH seeding method in cosmological simulations

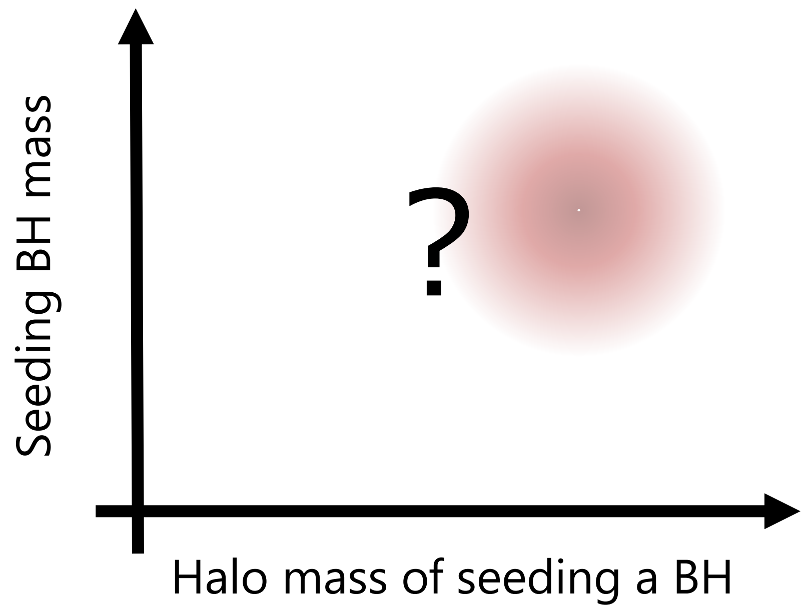
Placing a seed BH of a certain mass at the halo center when the halo mass reaches a certain value

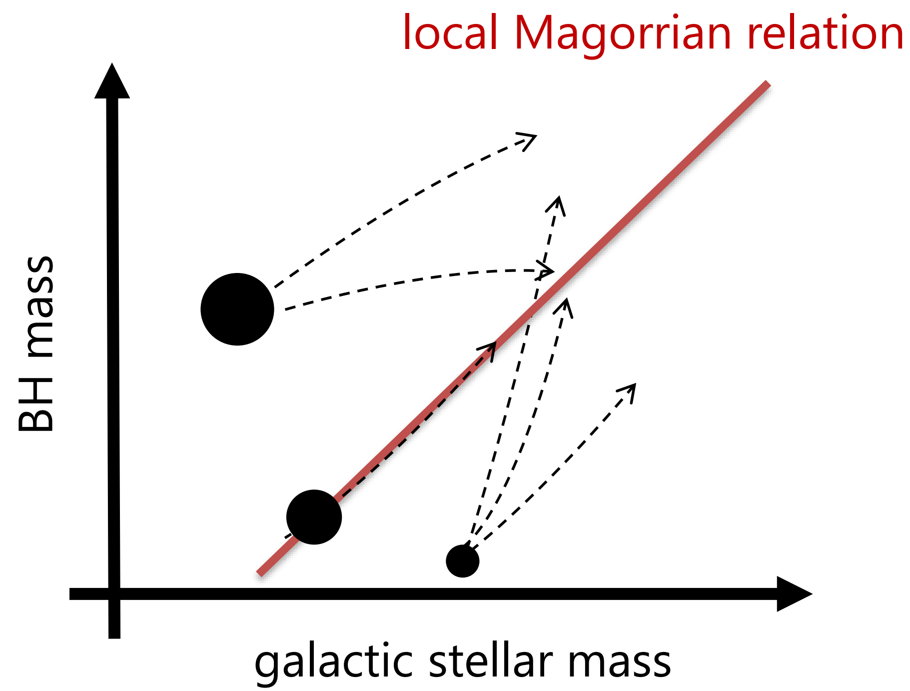
Project Name	Seed BH mass	Seeding Halo mass
-	[$h^{-1}\mathrm{M}_\odot$]	[$h^{-1}\mathrm{M}_\odot$]
Illustris	10^5	5×10^{10}
IllustrisTNG	8×10^5	5×10^{10}
EAGLE	10^5	10^{10}
SIMBA	10^4	$M_* > 10^{9.5}$
FOREVER22	10^5	10^{10}



Seeding method is one of the fundamental uncertainties

Motivation





We investigate which seeding strategies of BHs would facilitate the growth of MBHs using a suite of cosmological galaxy formation simulations.

Method

Cosmological simulation
with SPH (Smoothed particle hydrodynamics)

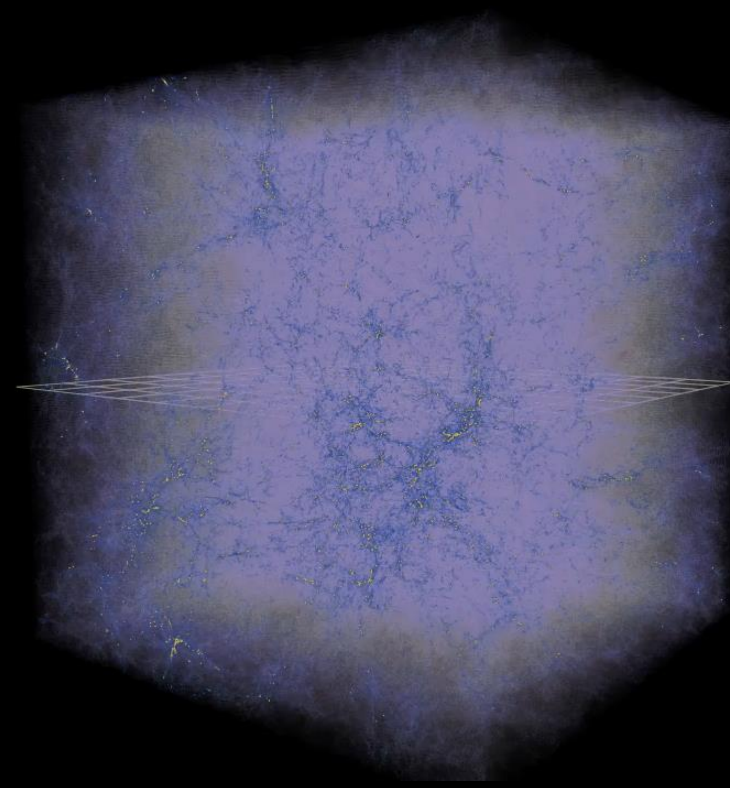
Code: Gadget3 (Springel 2005)
+OWLS project (Schaye+2010)

Originally developed for FOREVER22 project (Yajima et al. 2022)

Key Parameters

- ✓ BH seeding halo mass
  $10^9, 5\times10^9, 10^{10}, 5\times10^{10} M_\odot$/h
- ✓ Seed BH mass
  $10^4, 10^5, 10^6, 10^7 M_\odot$/h

We start simulations from the same initial condition(IC).



IC: 10 cMpc box @z=100
$N=256^3\times2$ (DM+gas)
created with MUSIC (Hahn & Abel 2011)

Finished at z=2

Gas accretion and feedback of BH

see Yajima et al. 2022 (FOREVER22 project)

Gas accretion model

Bondi-Hoyle accretion
(Bondi & Hoyle 1944)

$$\dot{m}_{\rm Bondi} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v_{\rm rel}^2)^{3/2}}$$

↓

$$\dot{m}_{\rm acc} = \dot{m}_{\rm Bondi} \times \min\left(C_{\rm visc}^{-1} (c_{\rm s}/V_\phi)^3, 1\right)$$

$$\leq \dot{m}_{\rm Edd} \left(\equiv \frac{4\pi G M_{\rm BH} m_{\rm p}}{f_{\rm r} \sigma_T c}\right)$$

AGN feedback model

Thermal feedback (QSO mode)

Released energy:

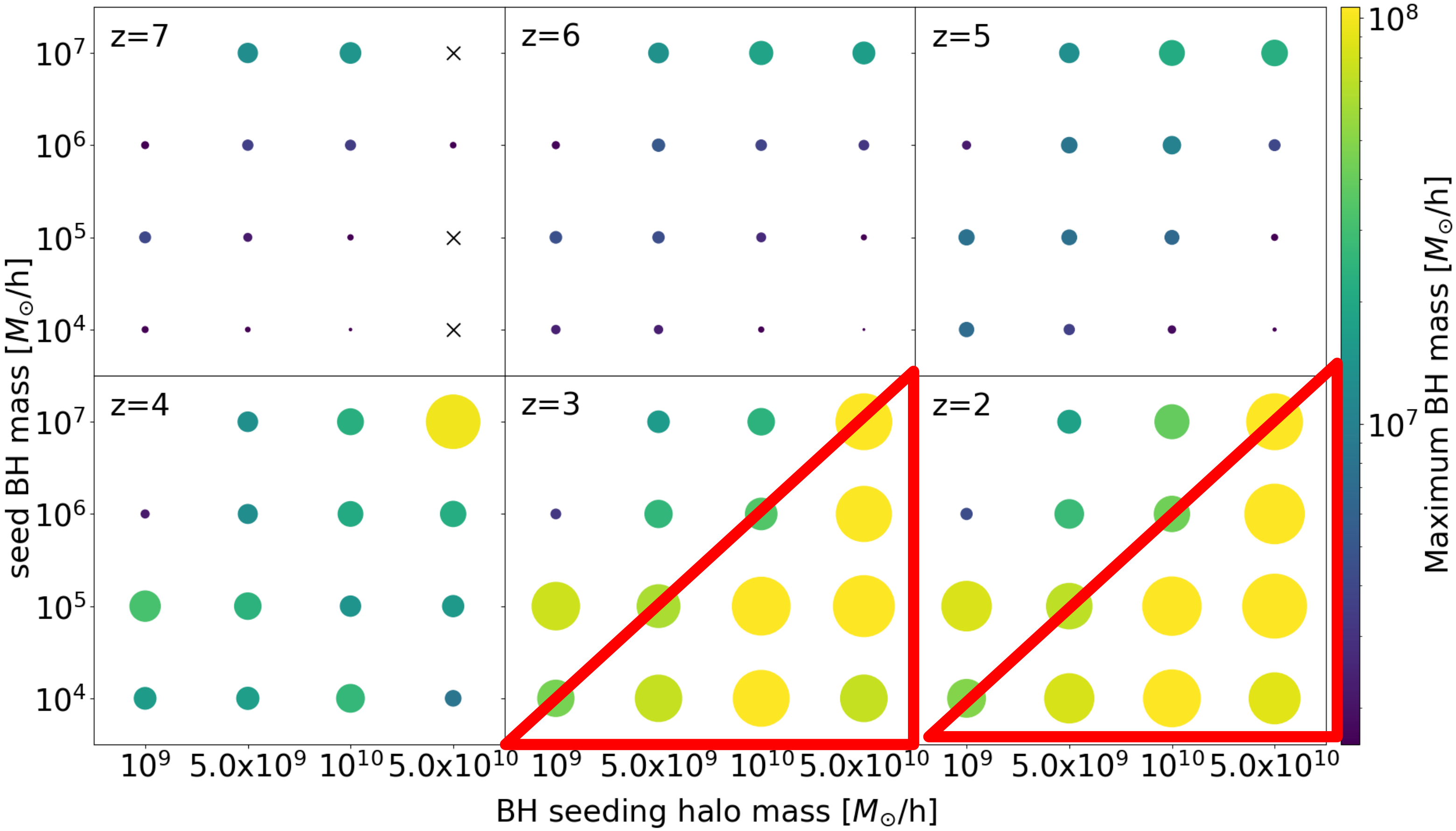
$$\Delta E = f_{\rm e} f_{\rm r} \dot{m}_{\rm acc} c^2$$

$f_e = 0.15$ (thermal coupling factor)
$f_r = 0.1$ (radiative efficiency factor)

Feedback energy is deposited into neighboring gas particles thermally and gas particles are heated up to $T = 10^9$ K

Based on the EAGLE simulation (Schaye+15)

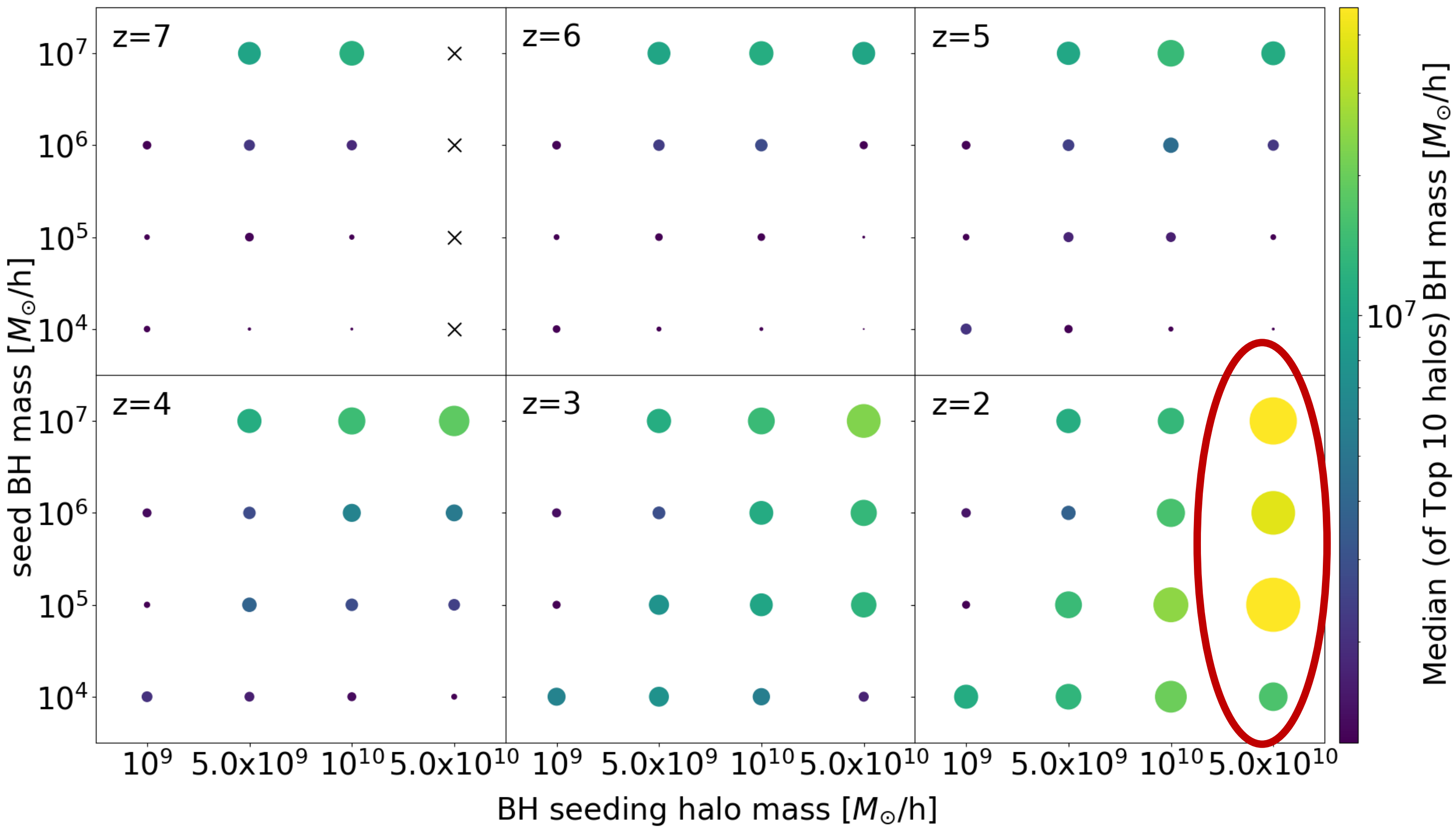
Sweet spot (Most massive BH)



At high-z (z≧5), BHs tend to grow faster when seeding a BH within a lighter halo. This is because the **elapsed time is shorter as the seeding halo mass is larger!** At low-z (z<4), on the other hand, a heavier BH forms when a relatively small BH is introduced into a relatively massive halo. (lower right triangle region)

Sweet spot (Median BH)

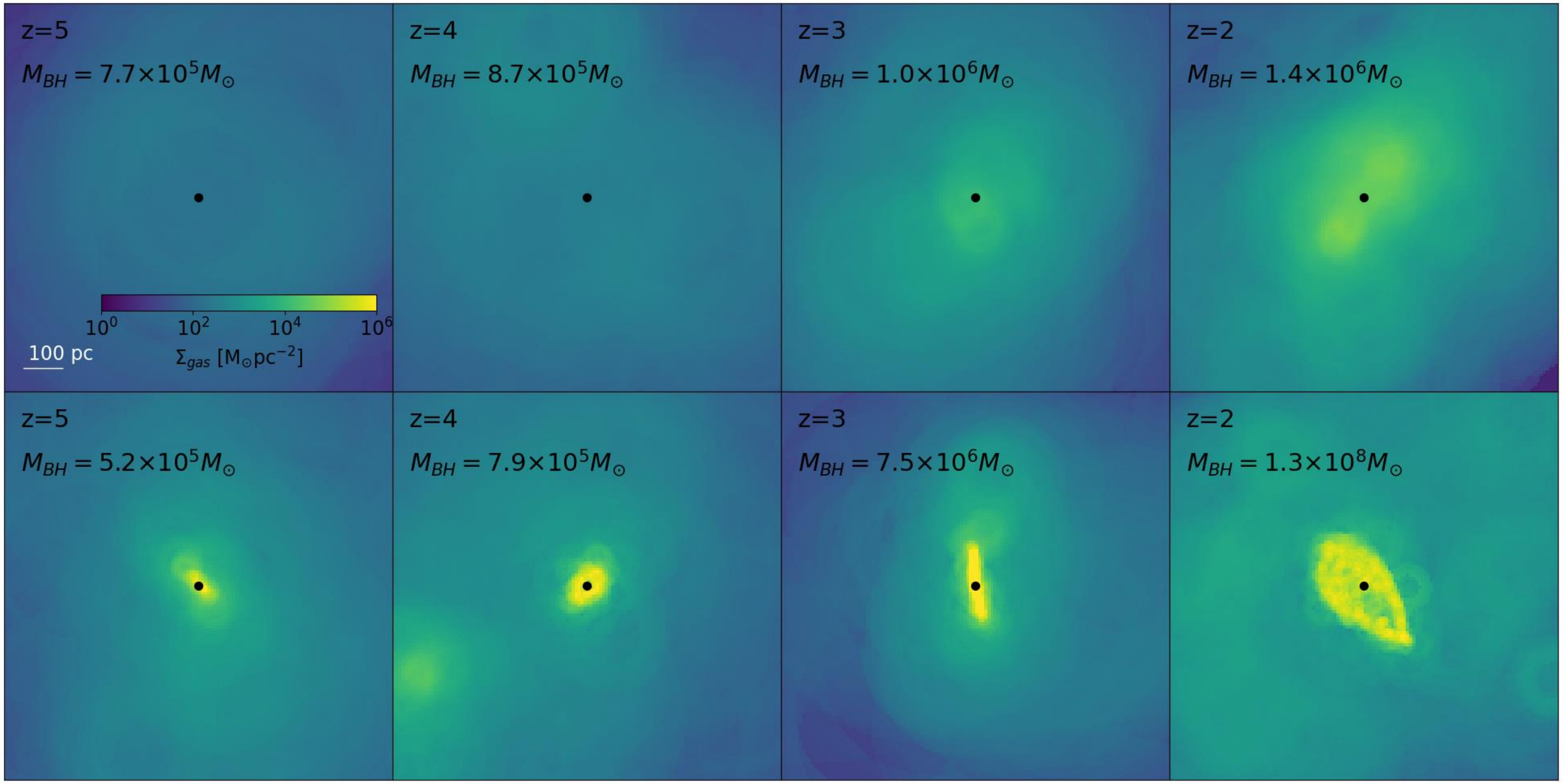
of top 10 massive halos



- ✓ At z=2, BH grows the most when we seed a BH to a halo mass of $5 \times 10^{10} M_\odot$.
- ✓ There is little dependence on the seeding BH mass.
- ✓ Introduction of a light BH into a less massive halo and the introduction of a heavy BH into a massive halo are completely different.

Gas distribution in the vicinity of a BH

Seed BH mass: $10^5 M_\odot$
Seeding halo mass **top : $10^9 M_\odot$, bottom: $5 \times 10^{10} M_\odot$**



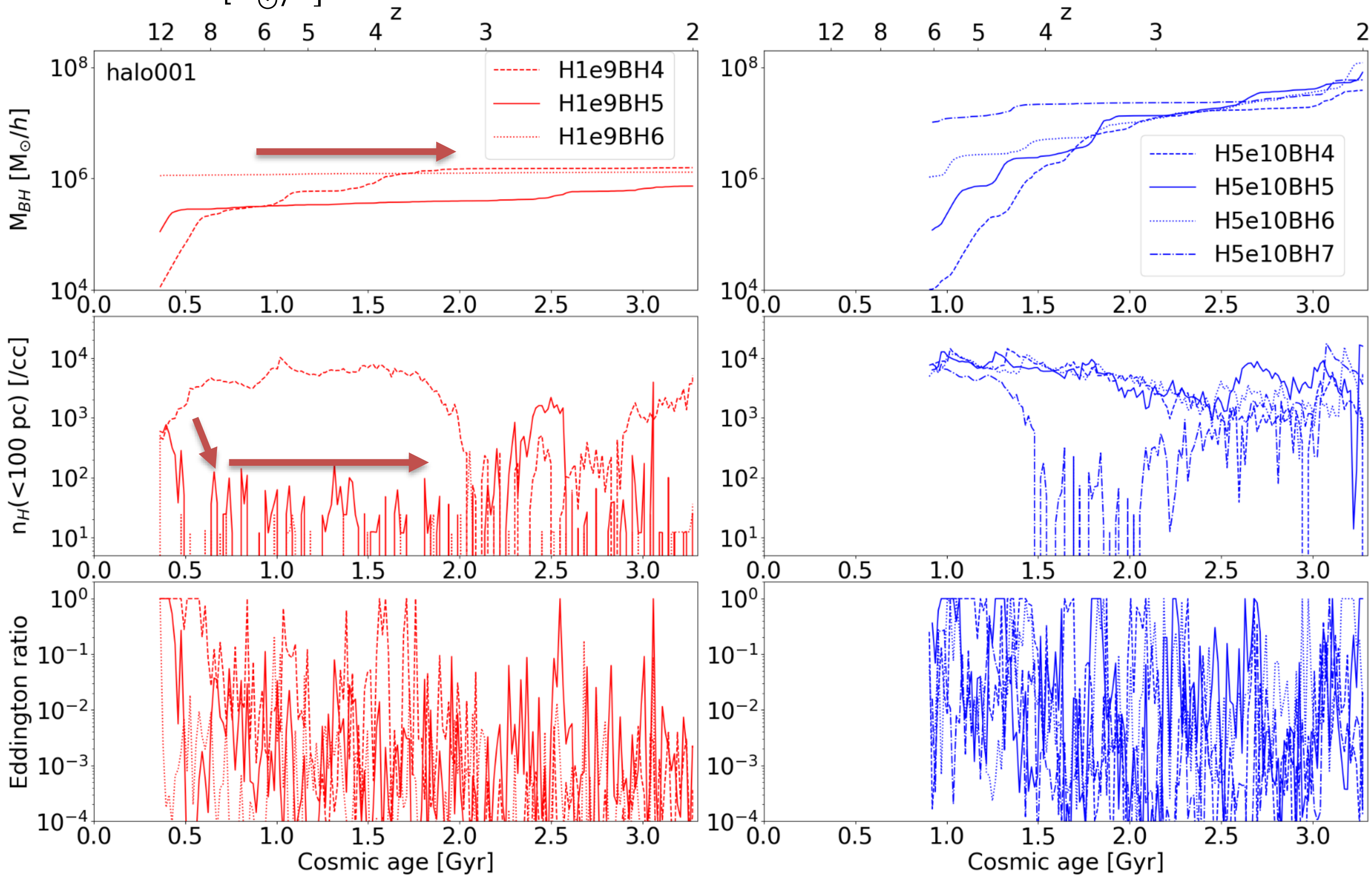
Effect of AGN feedback occurring in the early phase that removes the surrounding gas continues for a long time.

halo mass of seeding a BH $[M_\odot/h]$

H1e9BH4

seed BH mass 10^4 $[M_\odot/h]$

Mass accretion and feedback on a BH of a **common** halo

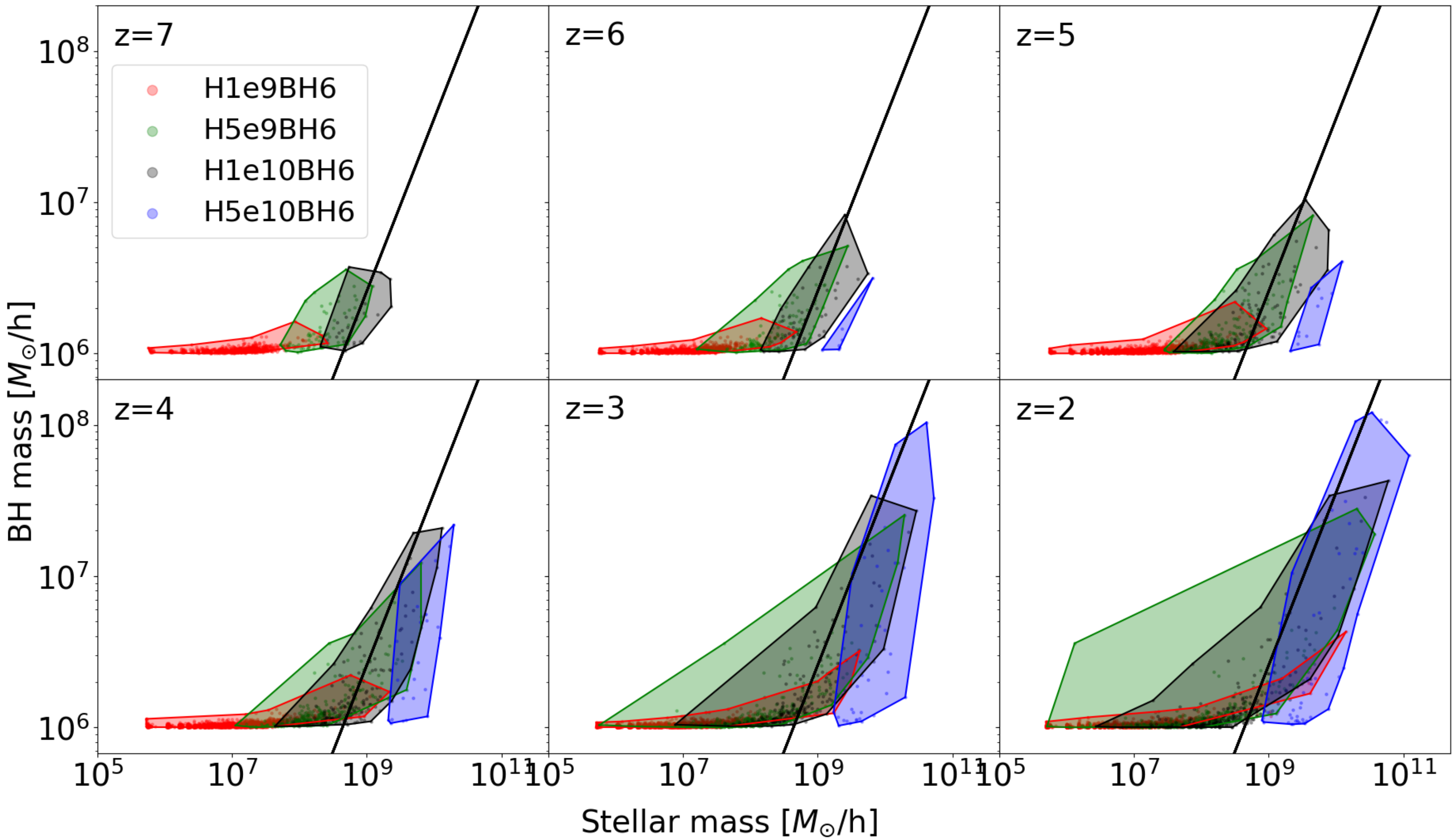


BHs can hardly accrete mass if they are seeded with a less-massive phase of the halo evolution.
(Right) BH can continue to accrete gas with little reduction in the gas density around the BHs.

halo mass of seeding a BH $[M_\odot/h]$

H1e9BH4

$M_* - M_{BH}$ ($10^6 M_\odot$ seed)



$10^9 M_\odot$ halo: All BHs do not grow sufficiently up to z=2.

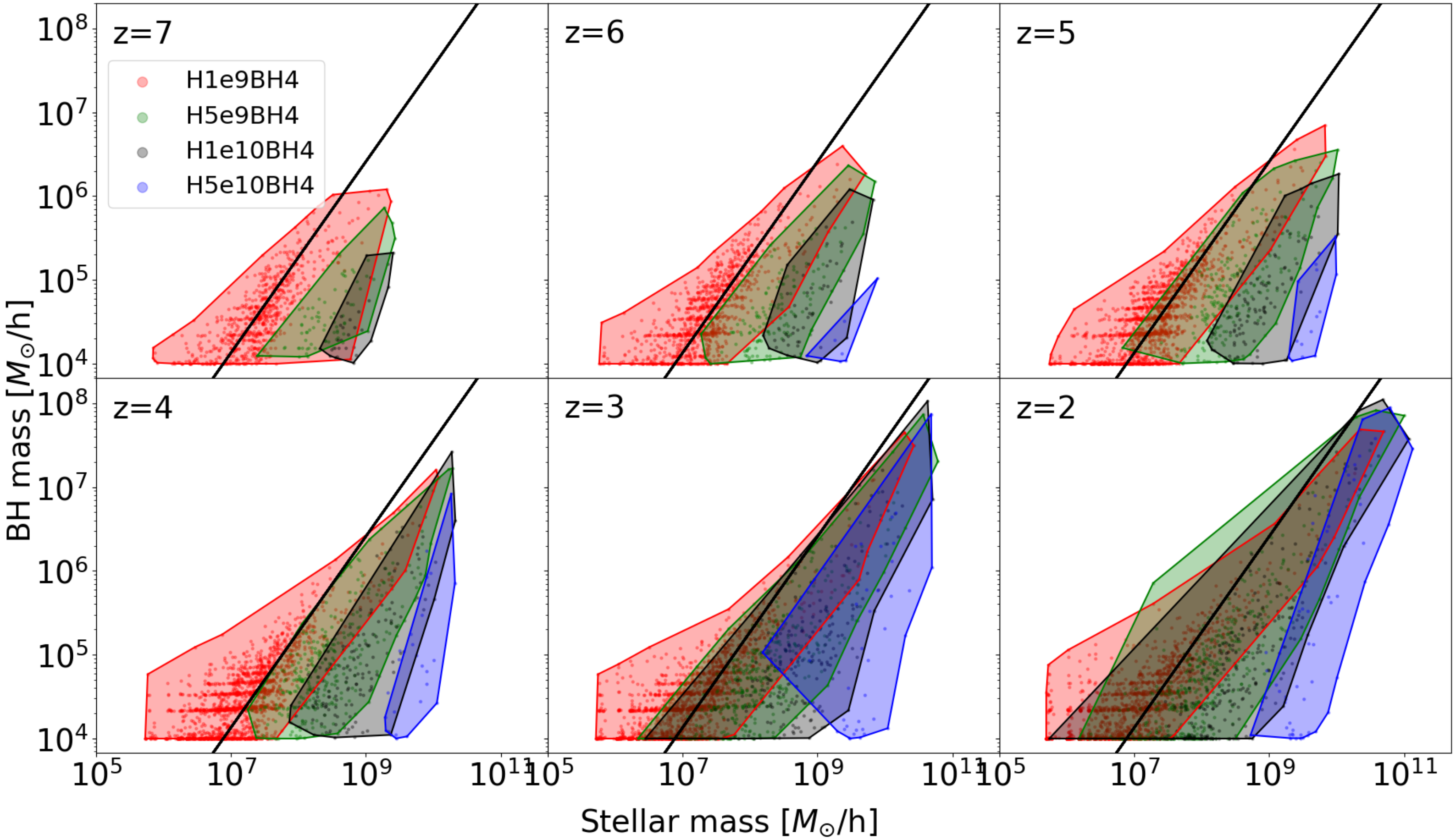
M_* grows reasonably well. A bit small relative to the other models until z=2.

$5 \times 10^{10} M_\odot$ halo: BH grows quickly. Star formation does not occur very efficiently during the rapid growth of BHs.

halo mass of seeding a BH $[M_\odot/h]$

H1e9BH4

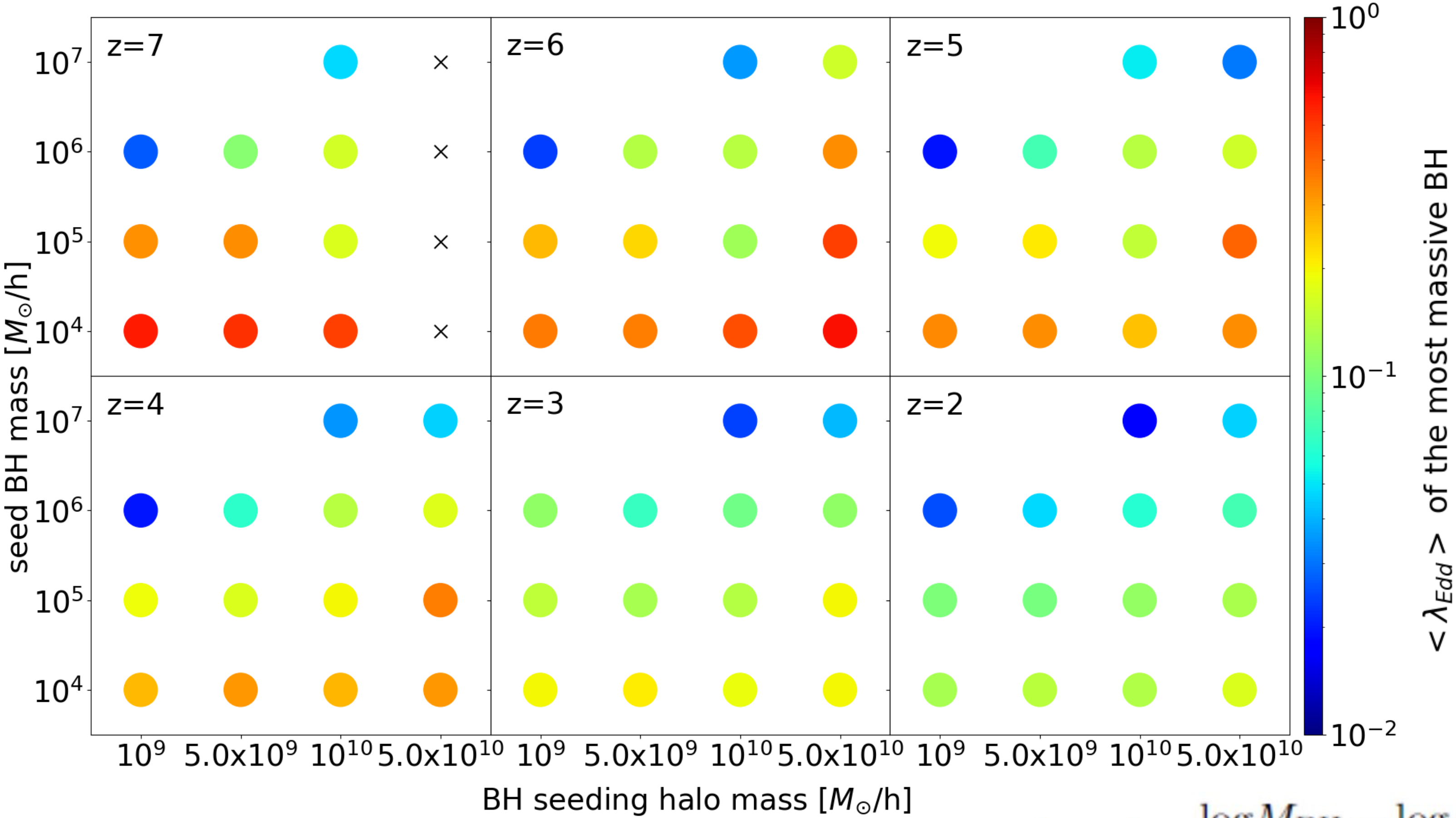
$M_* - M_{BH}(10^4 M_\odot$ seed)



$10^9 M_\odot$halo: the BHs are roughly located on the local Magorrian at the seeding epoch.
Subsequent evolution proceeds along the Magorrian relation.

$5 \times 10^{10} M_\odot$halo: BH grows quickly. Star formation does not occur very efficiently during the rapid growth of BHs.

$\langle \lambda_{\mathrm{Edd}} \rangle$ of the most massive BH



$$\langle \lambda_{\mathrm{Edd}} \rangle = \frac{\log M_{\mathrm{BH}} - \log M_{\mathrm{seed}}}{\dot{m}_{\mathrm{Edd}} \Delta t}$$

Average eddington factor is high for a low-mass seed.
$10^4 M_\odot$seed: At high-z, $\langle \lambda_{Edd} \rangle$>0.5. At low-z, $\langle \lambda_{Edd} \rangle \sim 0.1$.

Summary

- MBHs lurk at the centers of galaxies, and MBHs and galaxies are believed to have co-evolved.
- Recent QSO observations at high-z with the ALMA telescope have revealed that numerous MBHs are overmassive by an order of magnitude in BH mass compared to the Magorrian relation.
- To understand the growth of SMBHs in the coevolutionary process of MBHs and galaxies, we investigate which seeding strategies of BHs would facilitate the growth of MBHs.
- We conduct a suite of cosmological galaxy formation simulations in which we systematically vary both the mass of the galactic halo and BH in seeding a BH into a galaxy.
- **We find that more BHs tend to grow easier at z=2 if the seed BHs are introduced after the halo mass becomes larger, regardless of the mass of the seed BHs.**
- If the seed BH is more massive than the Magorrian relation, the subsequent BH growth is significantly inhibited.
- Our results suggest that installing a relatively massive BH in the most massive halos that exist as high the redshift as possible could help explain the observed overmassive BHs at high redshifts.