Evaluating the Formation and Evolution of Massive Black Holes at High Redshift

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What is a Massive Black Hole?

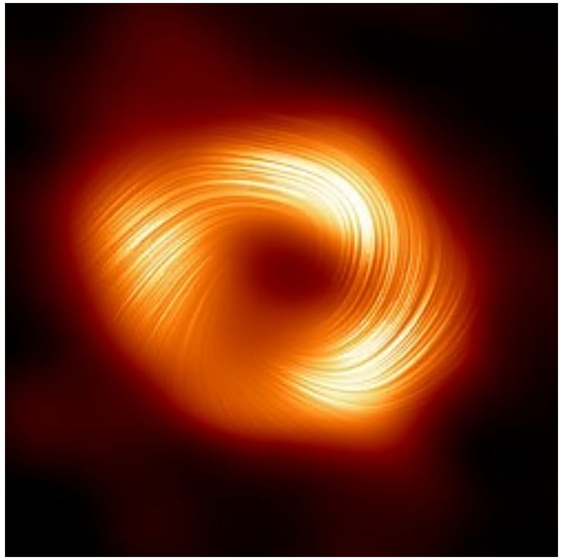
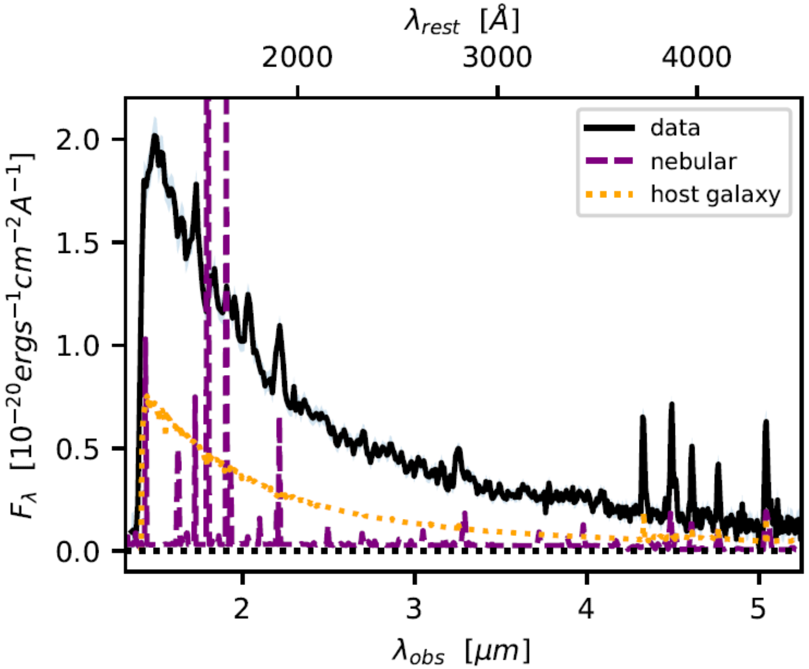
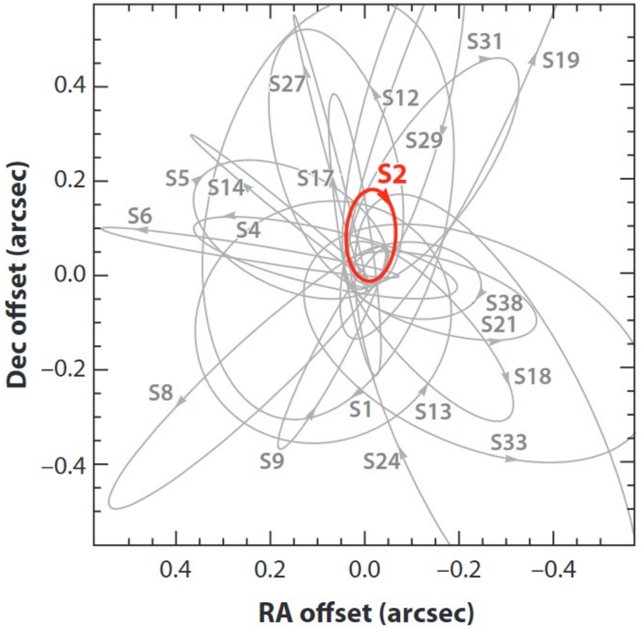


Image of Sagittarius A* by EHT



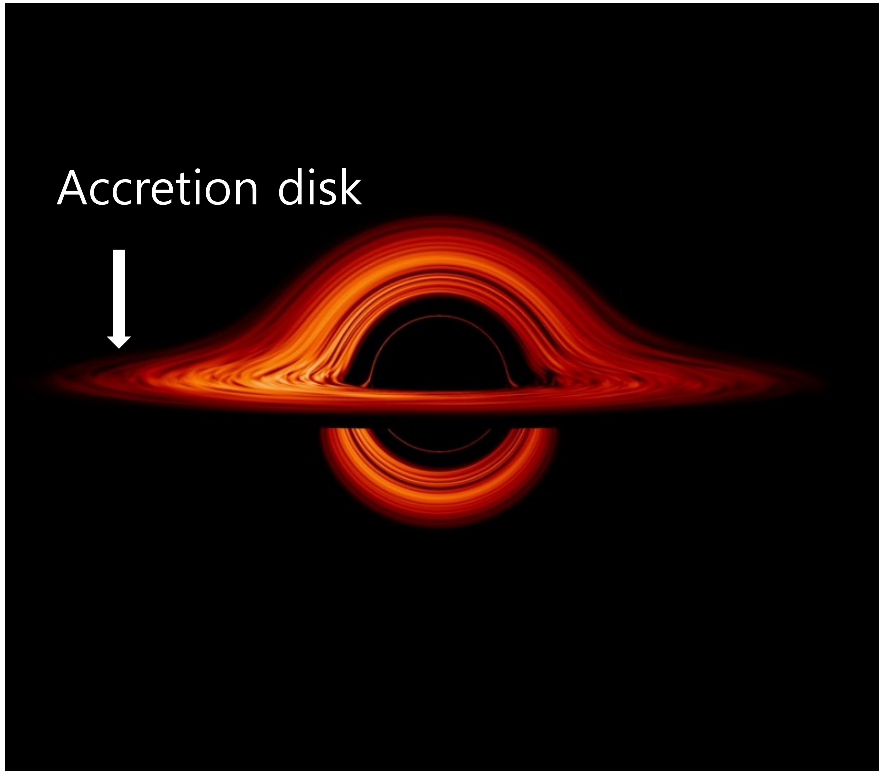
Maiolino et al. 2023



Kormendy and Ho 2013

- A massive black hole (MBH; a black hole with $M_{\mathrm{BH}} \gtrsim 10^6 \mathrm{M}_\odot$) is first introduced to explain abnormal brightness of the galaxy.
- They are now believed to exist at the center of most galaxies.

Gas Accretion and MBH Growth



Credit: NASA's Goddard Space Flight Center/Jeremy Schnittman

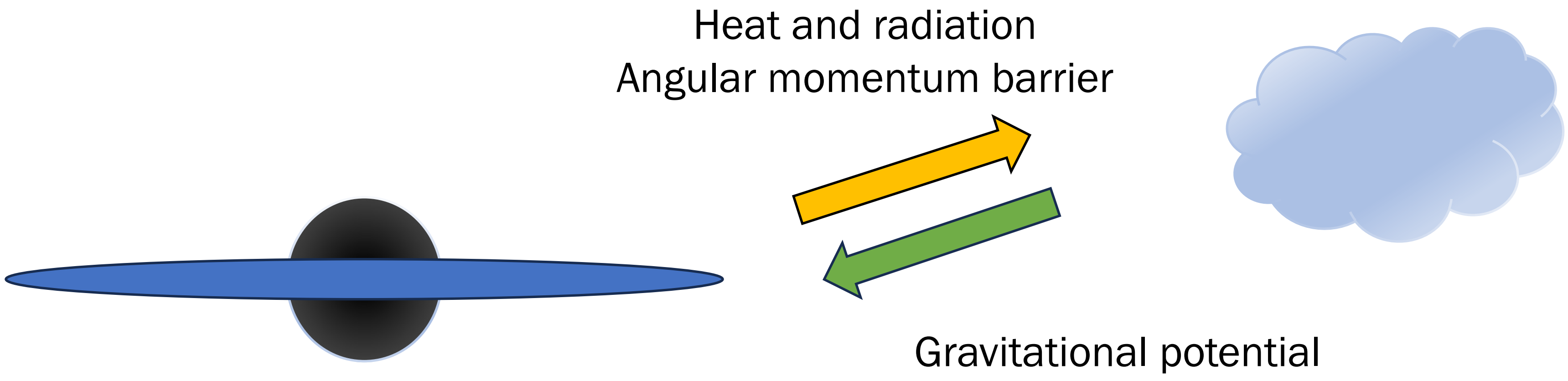
1. The infalling gas forms an accretion disk, accompanying a strong radiation.

2. The gas accretion is the main mass supply of the massive black hole

3. The gas accretion rate is well-approximated by Bondi-Holye accretion rate:

$$\dot{M}_{\mathrm{Bondi-Hoyle}} = \frac{\pi G^2 M_{\mathrm{BH}}^2 \rho_0}{c_s^3}.$$

The Limit of the MBH Growth

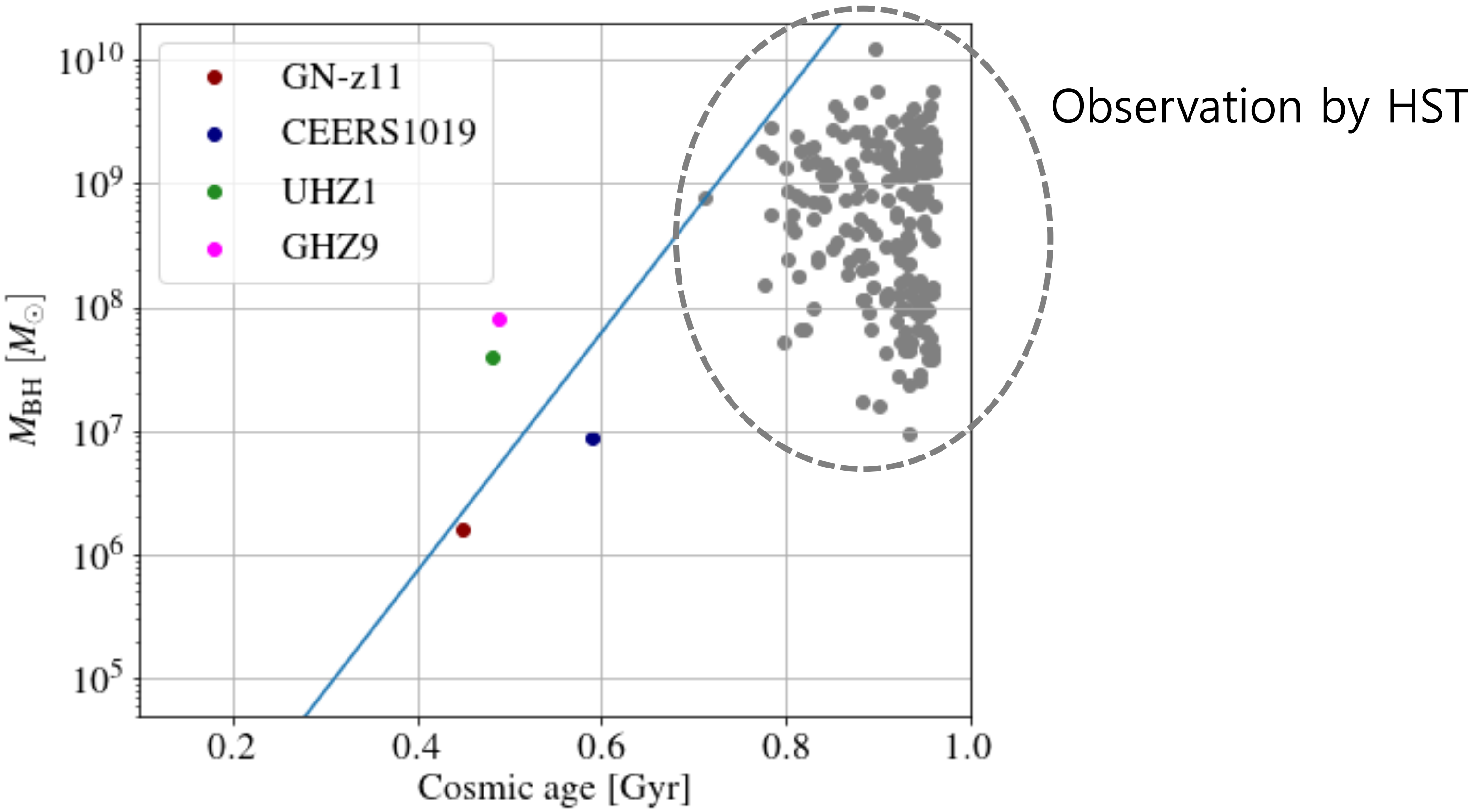


- The emitted radiation and heat limit the gas infall from the outer region of the galaxy by the Eddington rate:

$$\dot{M}_{\mathrm{Edd}} = \frac{4\pi G m_{\mathrm{p}}}{\eta \sigma_{\mathrm{T}} c} M_{\mathrm{BH}}.$$

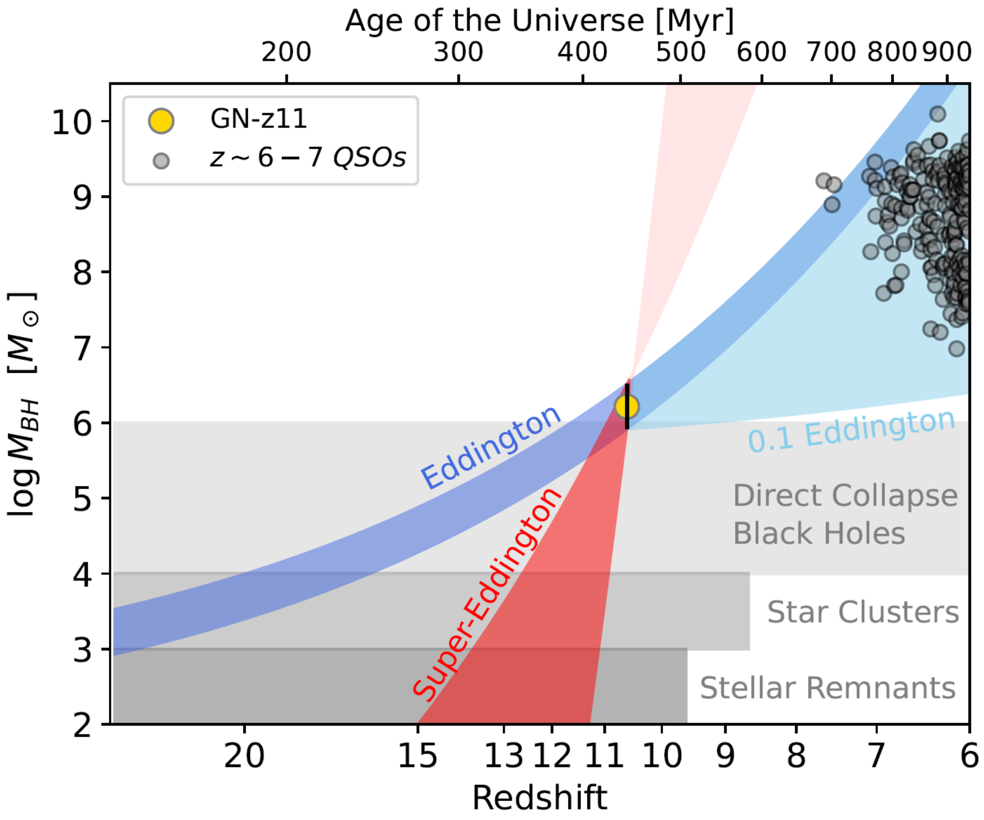
- It is also difficult to maintain full duty cycle in the whole life of MBHs.

Great Mystery of MBHs at $z \gtrsim 6$



The MBH evolution picture based on the Eddington limit hardly explains the high redshift ($z \gtrsim 6$) observations.

How Can We Boost the MBH Growth?

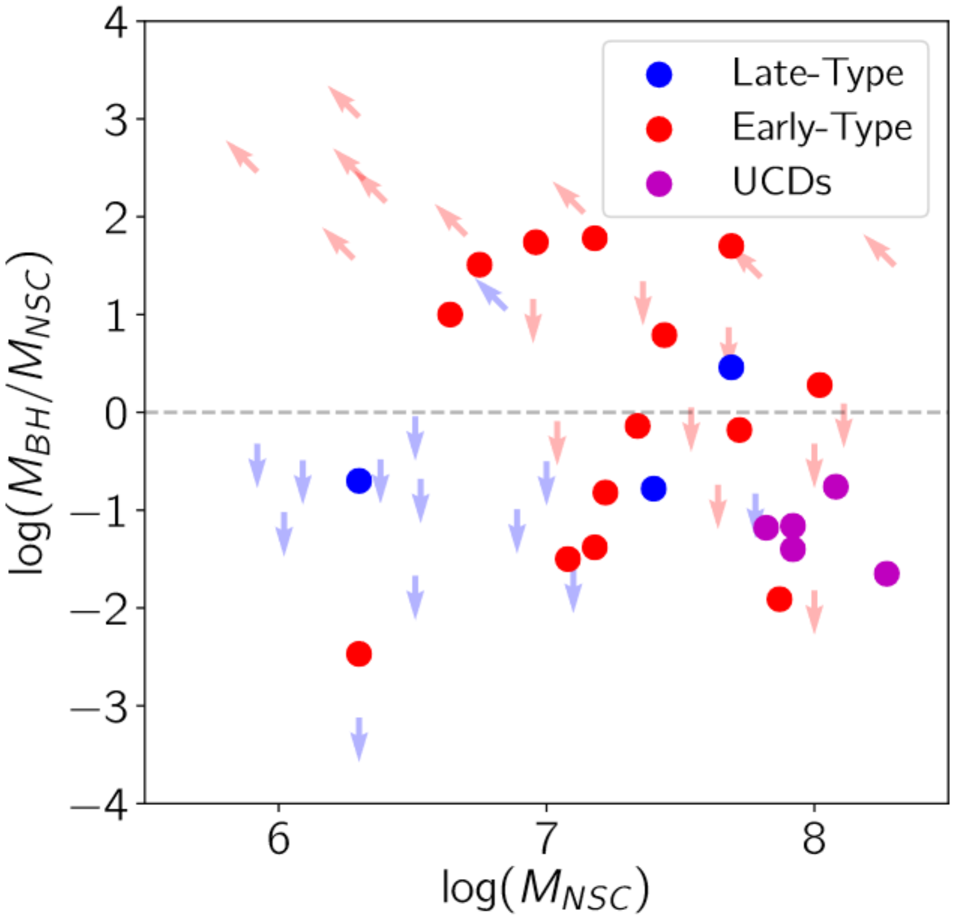


Maiolino et al. 2023

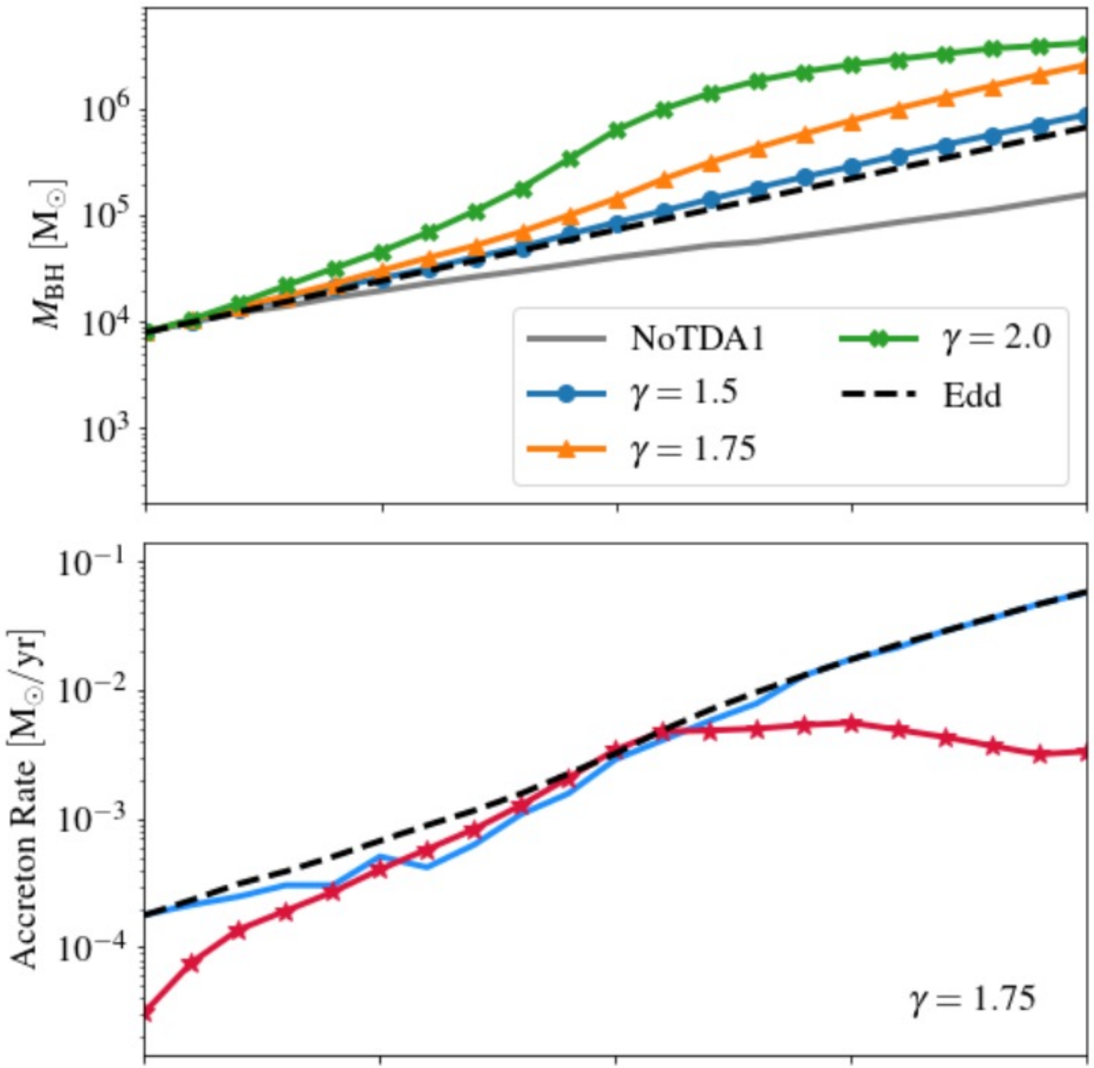
Radiatively inefficient accretion flow

- The gas accretion rate may increase above the Eddington limit!
- However, the super-Eddington is valid only under the assumption of a sufficient amount of gas supply from the galaxy.

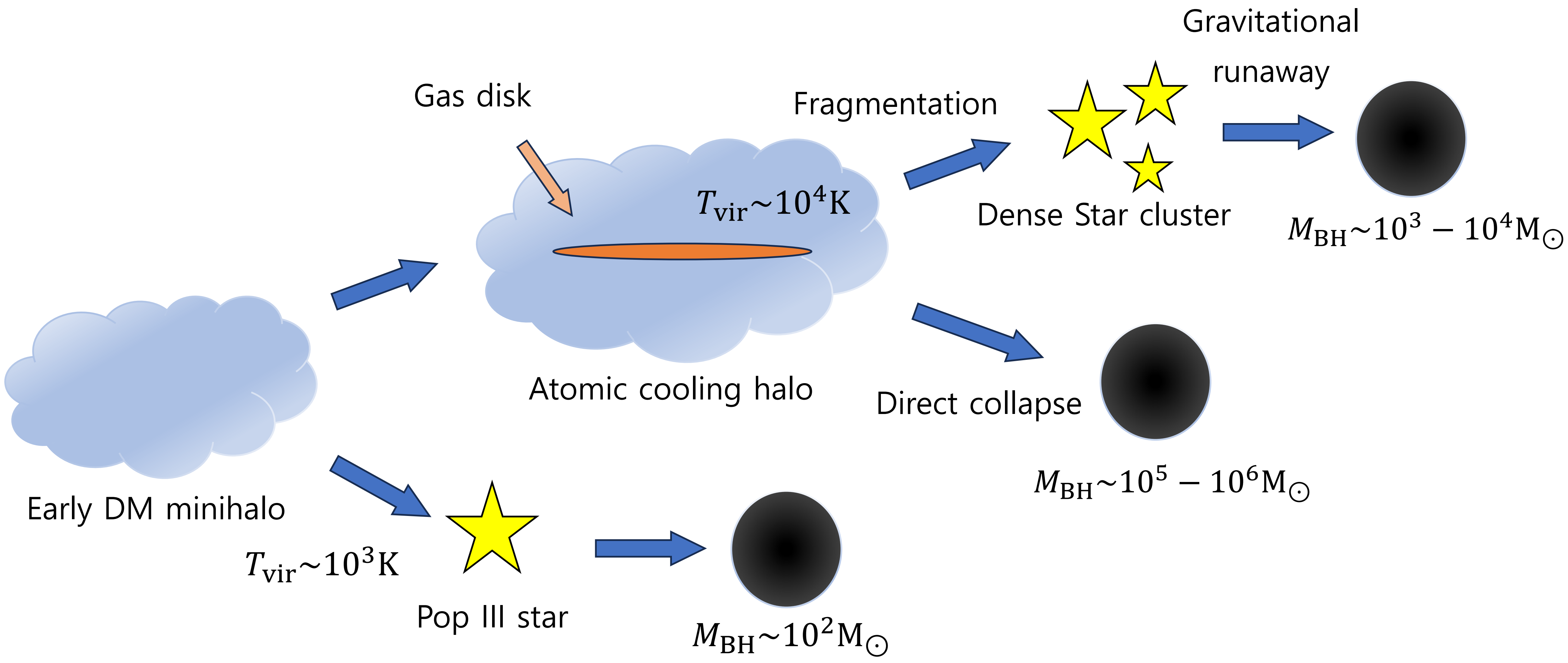
Additional Growth Channel?



Neumayer et al. 2020



A Head Start with a Massive Black Hole Seed



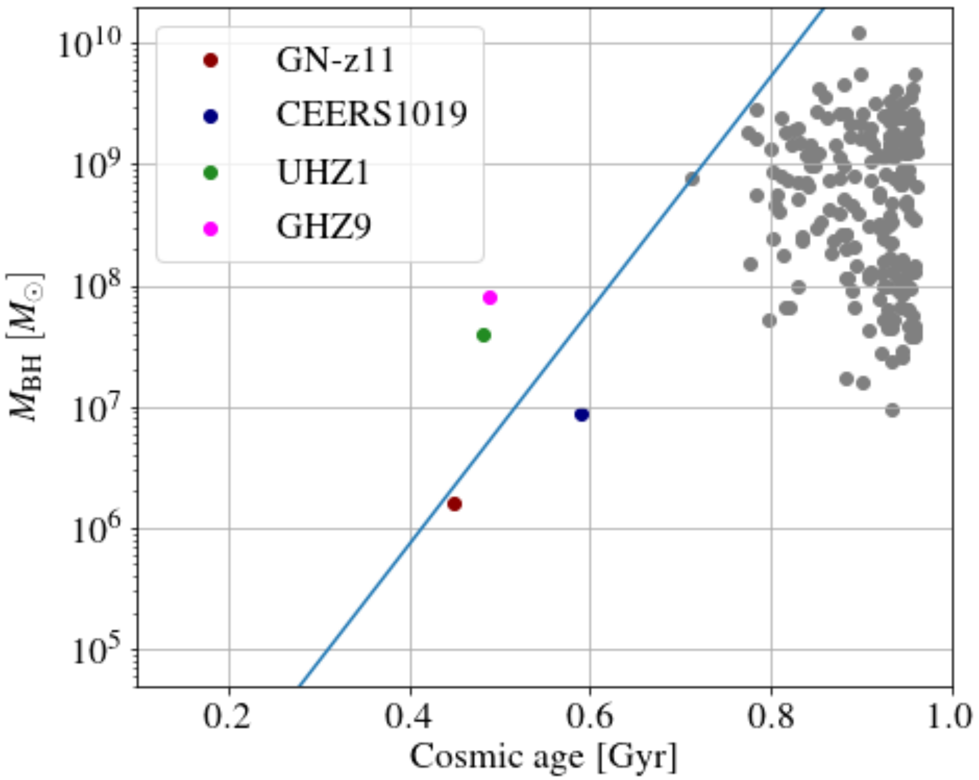
Questions:

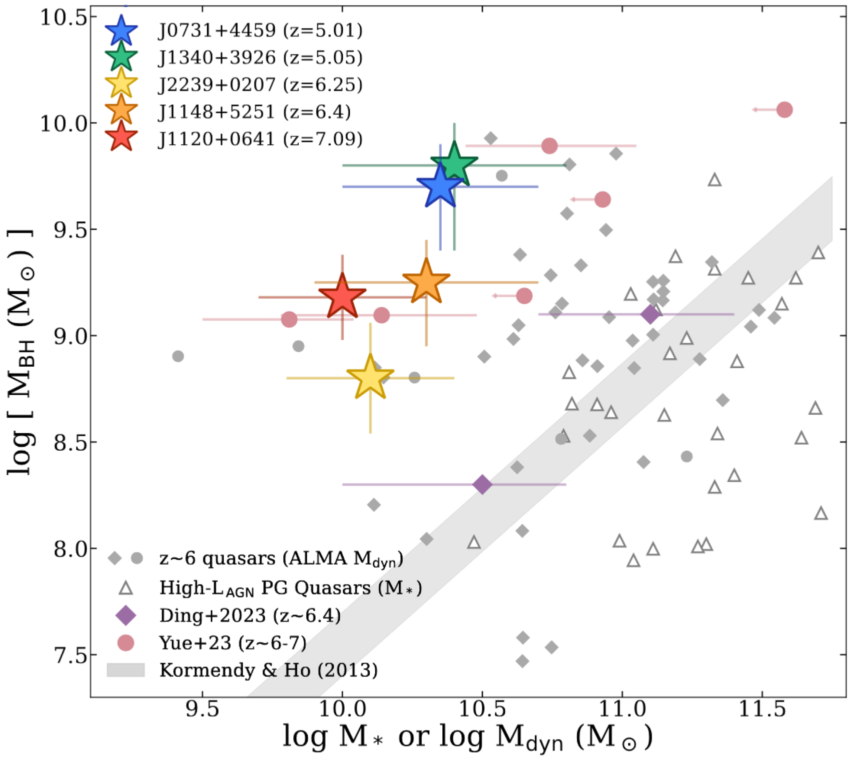
1. **Are the seeding scenarios good enough to explain the high-z observations?**
2. **Which scenario is more reasonable?**

↓

Semi-Analytic Modeling

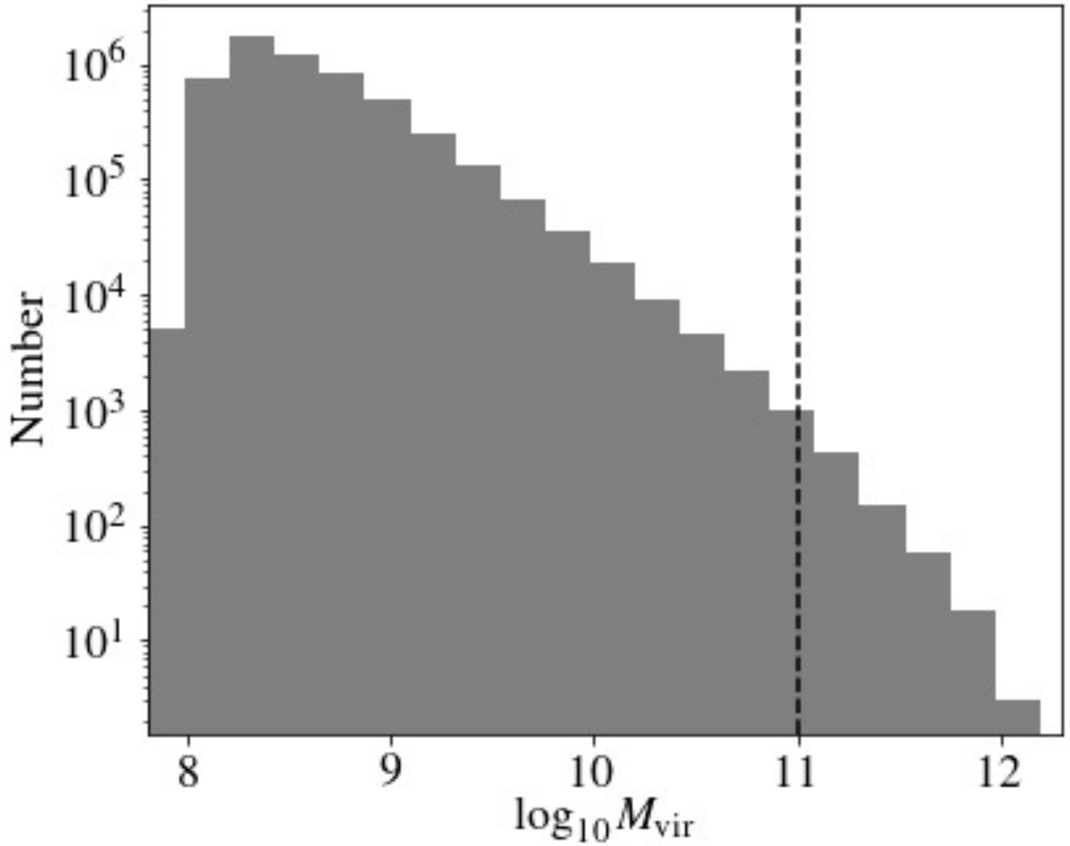
Constraints on the MBH Evolution History

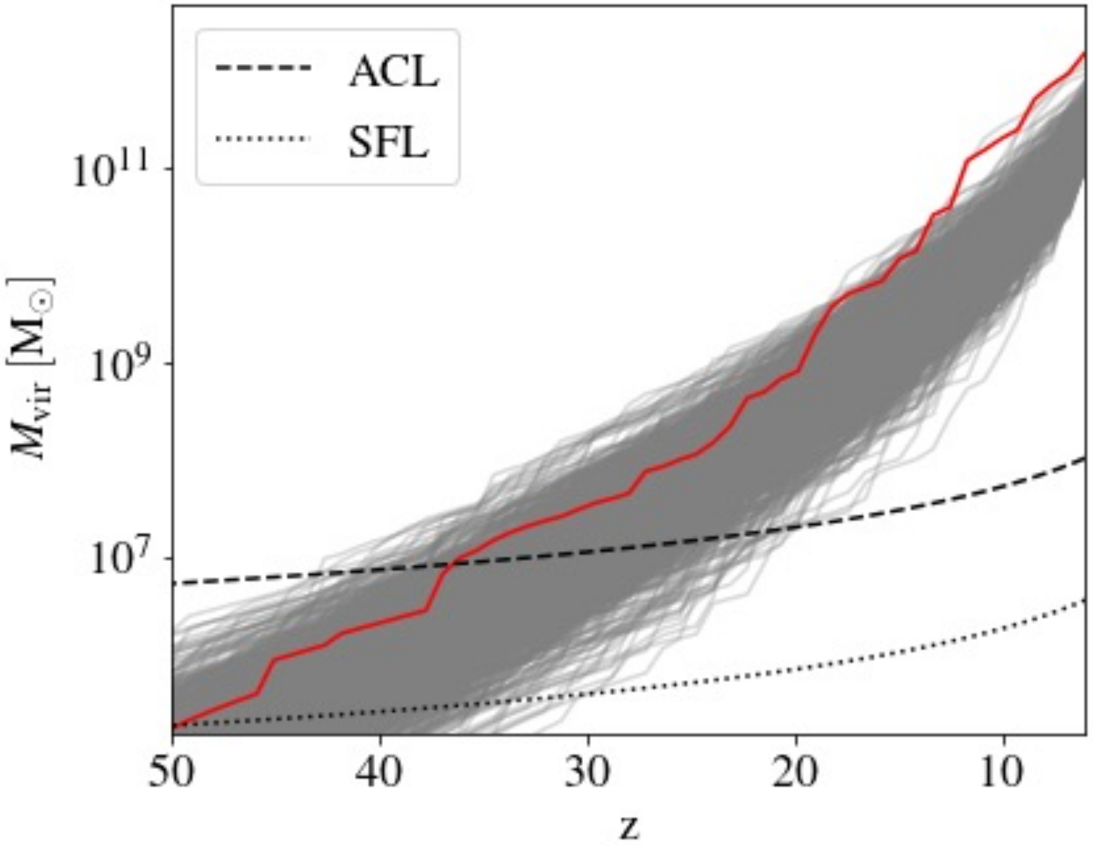




The high-z observation reveals that the $M_{\rm BH} - M_{\rm dyn}$ relation is offset from the local relation.

Halo Sampling and Merger History





- We select halos with $M_{\rm vir} > 10^{11}\ \rm M_\odot$ at $z = 6$ in TNG100 to generate a halo mass function.
- The merger history of each halo is generated by the code GALFORM semi-analytical algorithm (the extended Press-Schechter formalism).

Idealized Dark Matter Halo

Halo properties: (virial mass M_{vir} and angular momentum J at redshift z).

1. Virial radius:

$$R_{\mathrm{vir}} = \left(\frac{2GM_{\mathrm{vir}}}{\Delta_{\mathrm{c}} H_0^2 (1+z)^3}\right)^{1/3} \text{ where } \Delta_{\mathrm{c}} = 18\,\pi^2$$

2. Circular velocity:

$$V_{\mathrm{c}} = \left(\frac{GM_{\mathrm{vir}}}{R_{\mathrm{vir}}}\right)^{1/2}$$

3. Virial temperature:

$$T_{\mathrm{vir}} = \frac{\mu m_{\mathrm{P}} V_{\mathrm{c}}^2}{2k_{\mathrm{B}}}$$

4. Halo energy:

$$E = -\frac{GM_{\mathrm{vir}}}{2R_{\mathrm{vir}}} = -\frac{M_{\mathrm{vir}} V_{\mathrm{c}}^2}{2}$$

5. Spin parameter:

$$\lambda = \frac{J|E|^{1/2}}{GM_{\mathrm{vir}}^{5/2}}$$

Disk properties:

1. Mestel disk:

$$\Sigma(\mathrm{R}) = \Sigma_0 \left(\frac{R}{R_0}\right)^{-1}$$

with

$$\Sigma_0 = \frac{10 m_{\mathrm{d}} (m_{\mathrm{d}}/j_{\mathrm{d}})^2 H_{\mathrm{z}} V_{\mathrm{c}}}{16\pi G \lambda^2}$$

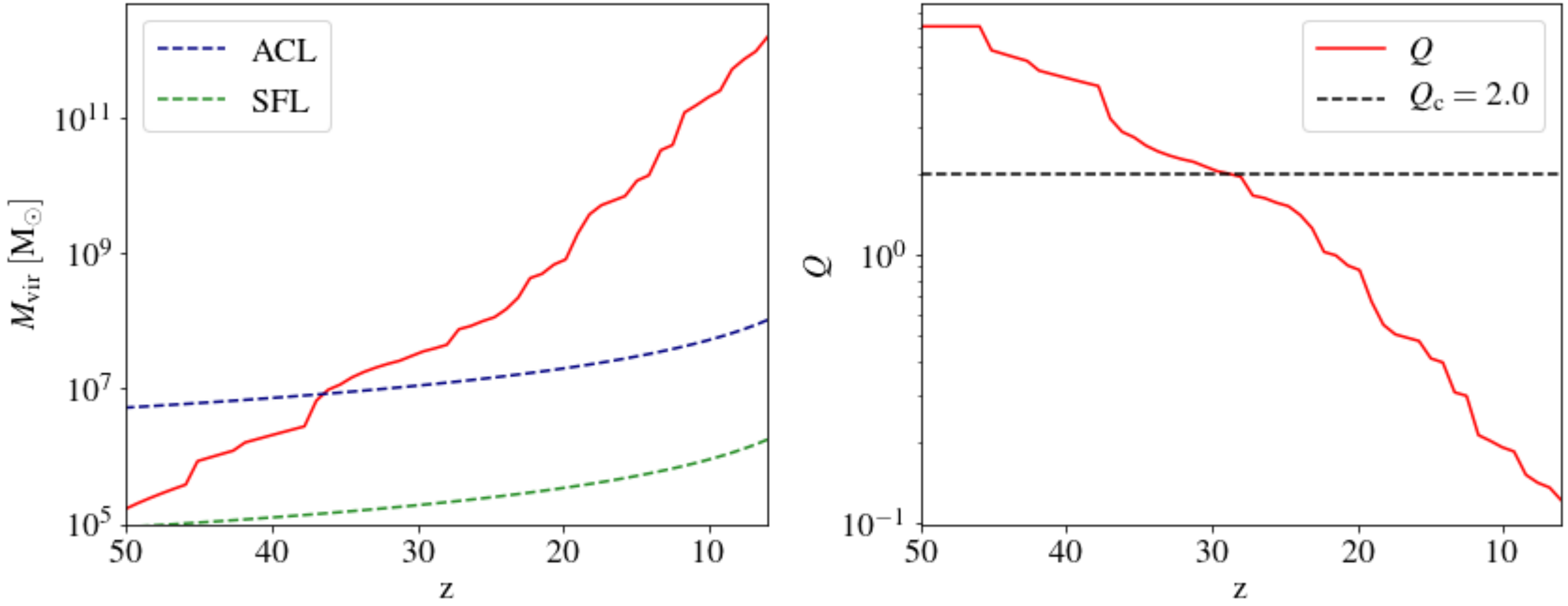
$$R_0 = 2\sqrt{2}(j_{\mathrm{d}}/m_{\mathrm{d}})\lambda R_{\mathrm{vir}}$$

2. Disk stability:

$$Q = \frac{c_{\mathrm{s}}\kappa}{\pi G \Sigma} = \frac{\sqrt{2} c_{\mathrm{s}} V_{\mathrm{c}}}{\pi G \Sigma R}$$

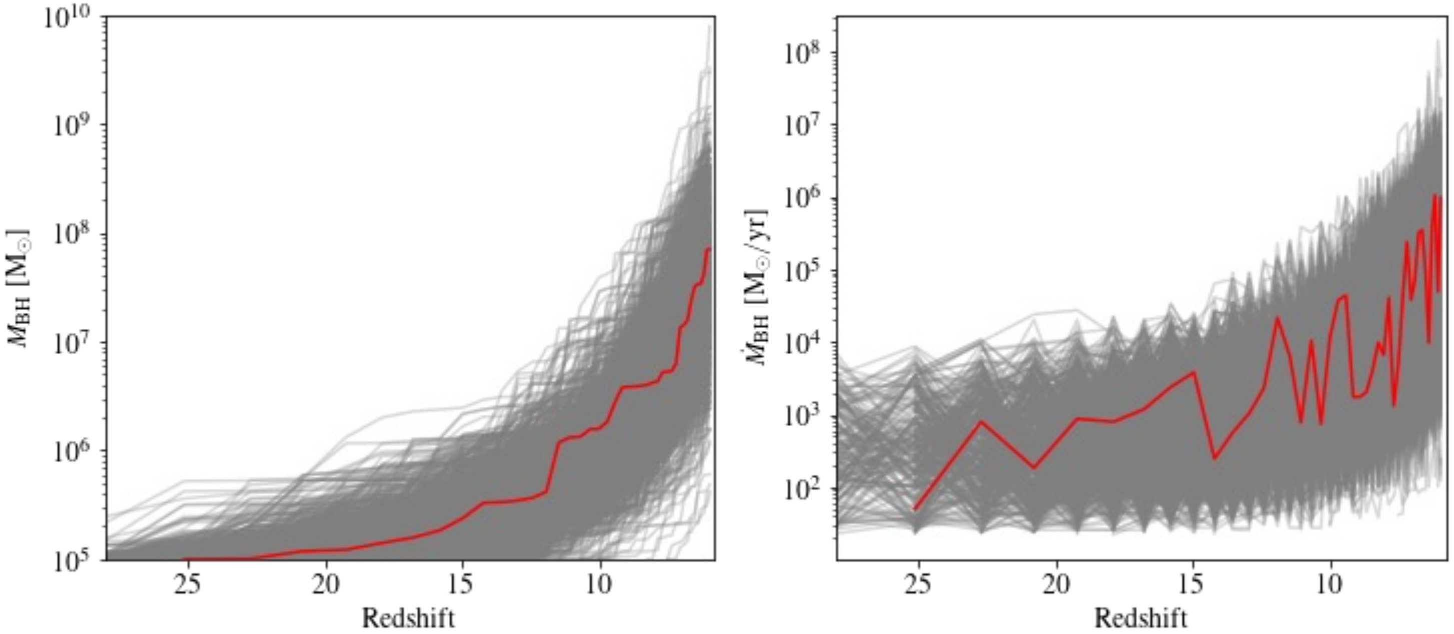
If $Q < Q_{\mathrm{c}}$, we regard the disk unstable.

MBH Seeding Strategy



	$M_{\rm Seed}$	Seeding criteria
Pop III	100 $M_\odot$	$M_{\rm vir} > M_{\rm SFL}$
Direct collapse	10^5 $M_\odot$	$M_{\rm vir} > M_{\rm ACL}$, $Q < Q_c$
Gravitational runaway	10^3 $M_\odot$	$M_{\rm vir} > M_{\rm ACL}$, $Q < Q_c$

MBH Growth via Gas Accretion



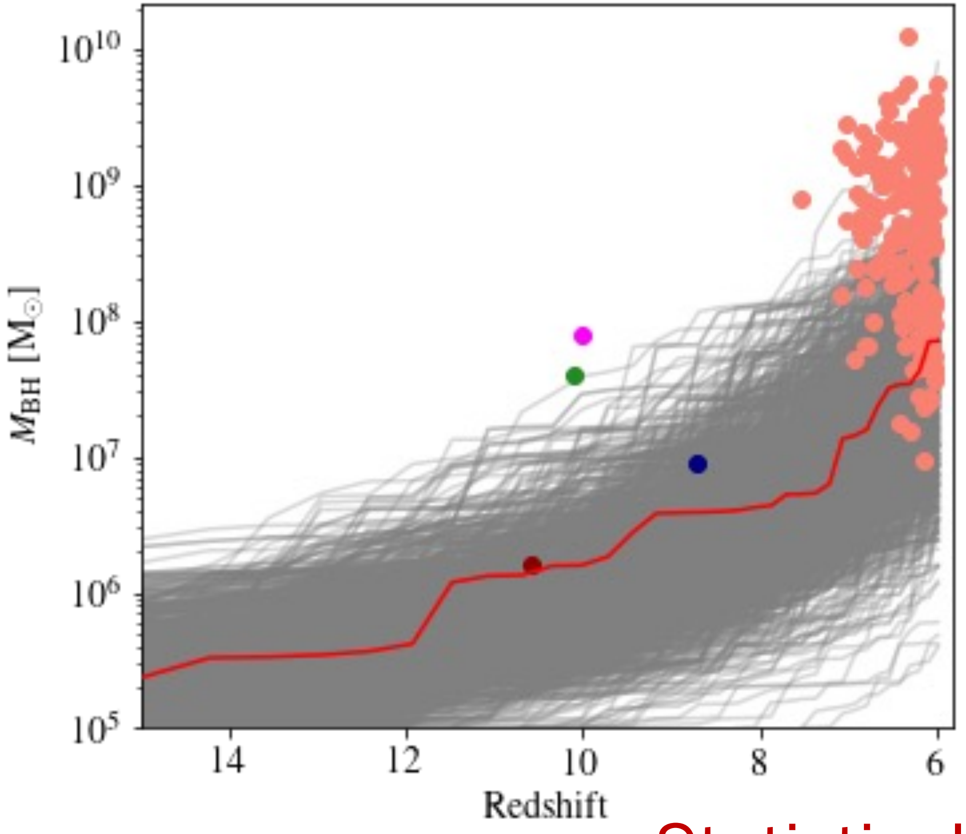
1. Eddington ratio distribution function (ERDF):

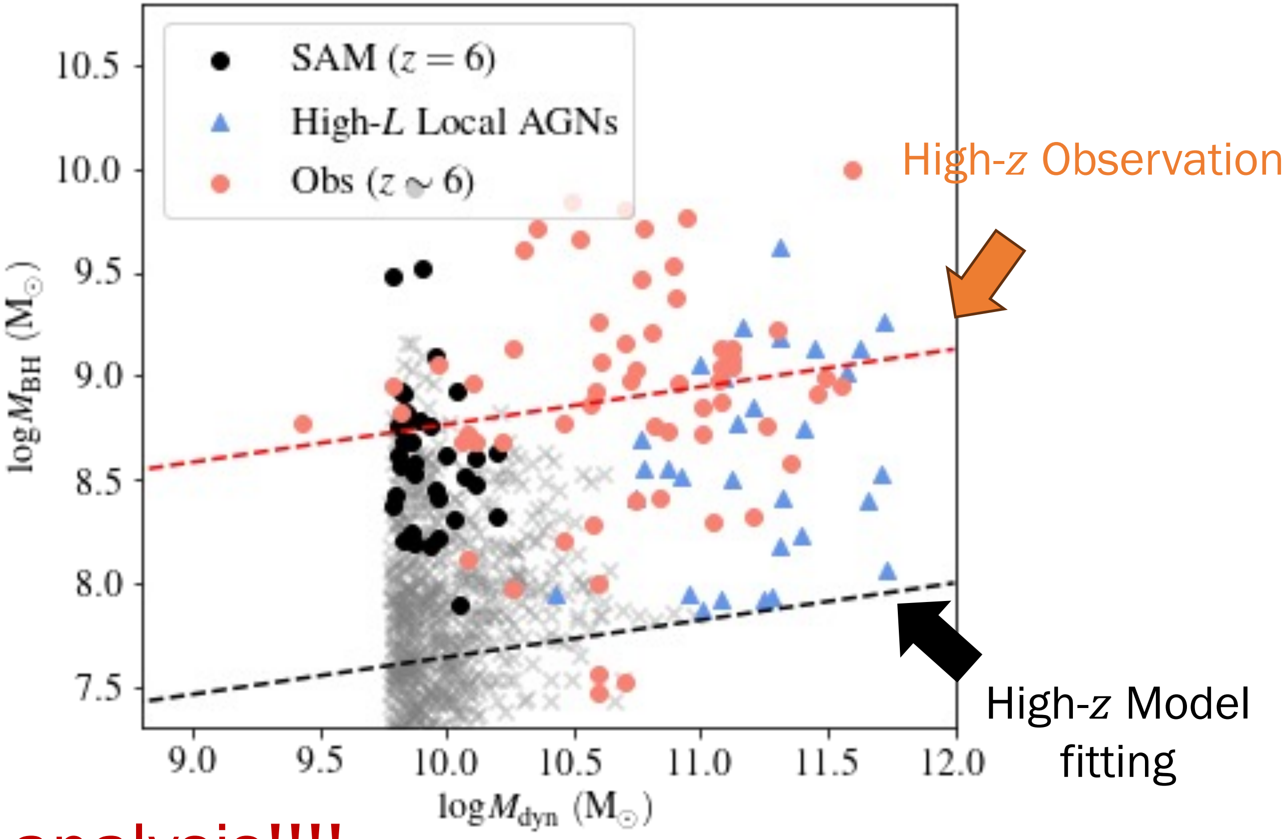
$$\frac{\mathrm{d}P}{\mathrm{d}\ln\lambda} \propto \left(\frac{\lambda}{\lambda_0}\right)^{\alpha} \exp\left(-\frac{\lambda}{\lambda_0}\right).$$

with $\alpha = -0.06$, $\lambda_0 = 0.96$. (Motivated by Zhang et al. 2022, 2023, and Li et al. 2023)

2. We then assume $\dot{M}_{\rm BH} = \lambda\, \dot{M}_{\rm Edd}$ and re-sample λ after the duration time $\tau = 23.13$ Myr .

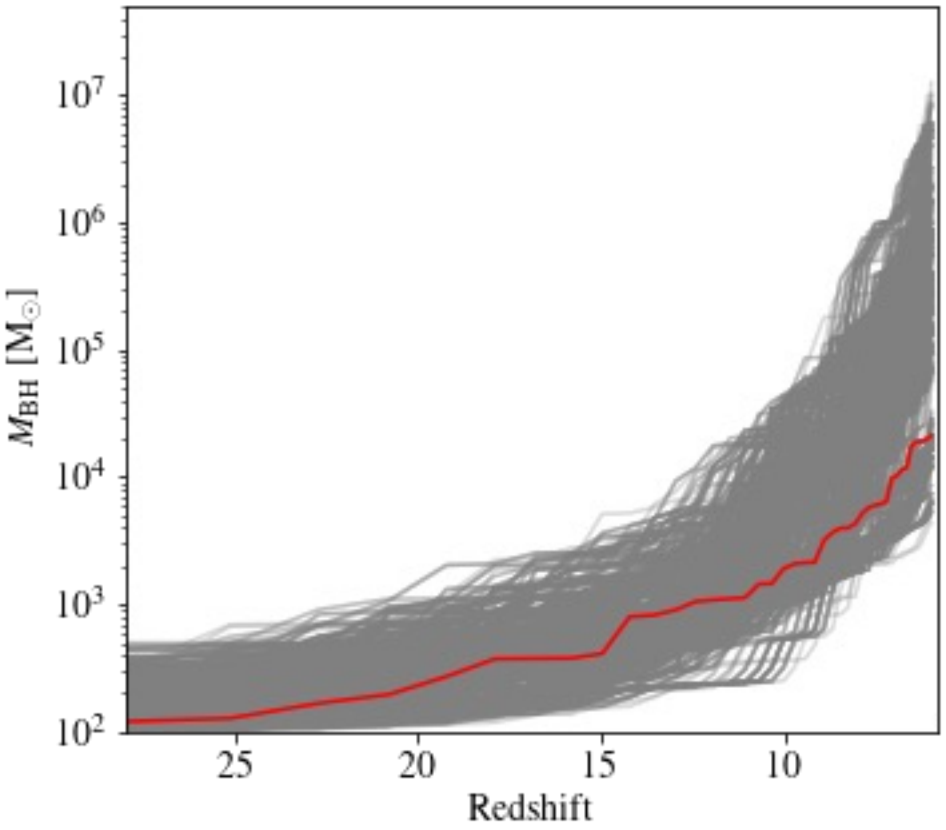
Comparison: SAM vs. Observation

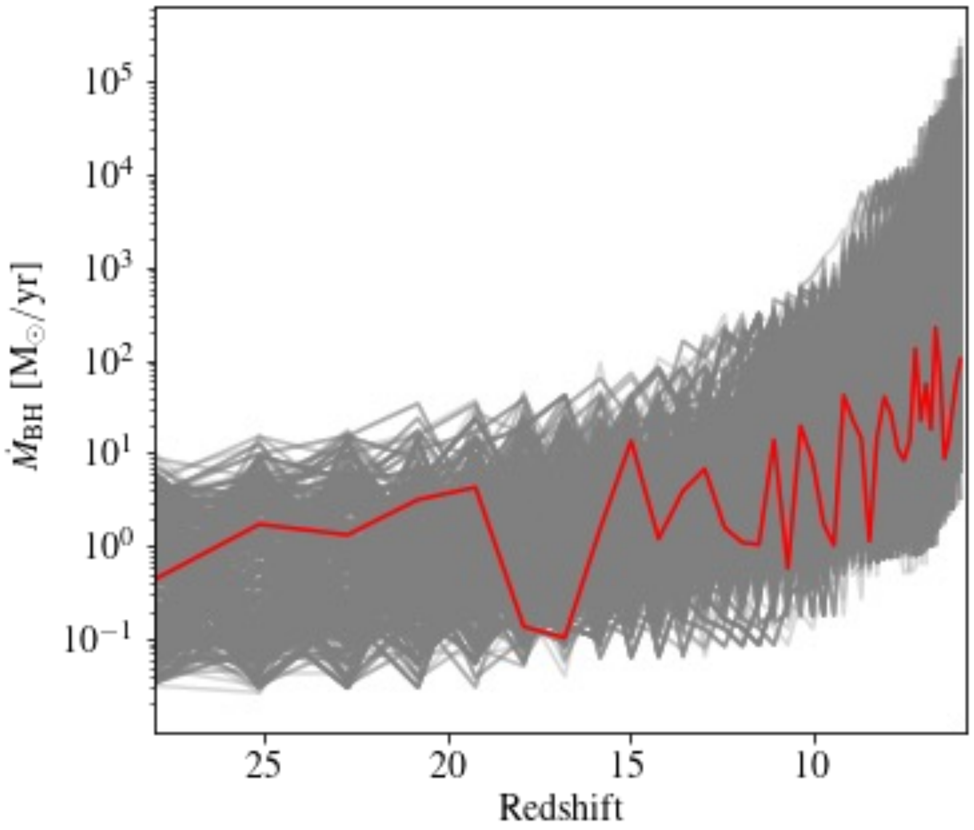




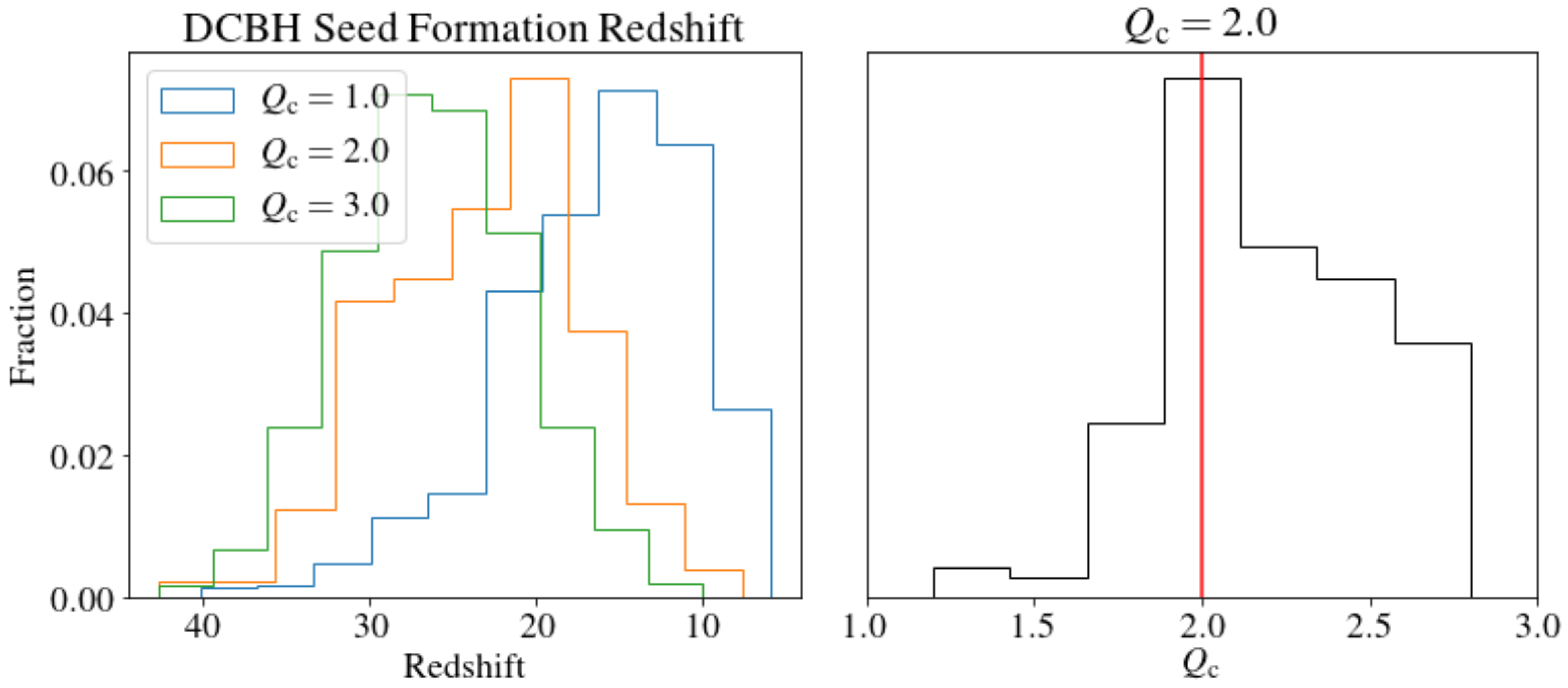
Statistical analysis!!!!

Comparison: SAM vs. Observation (Pop III)





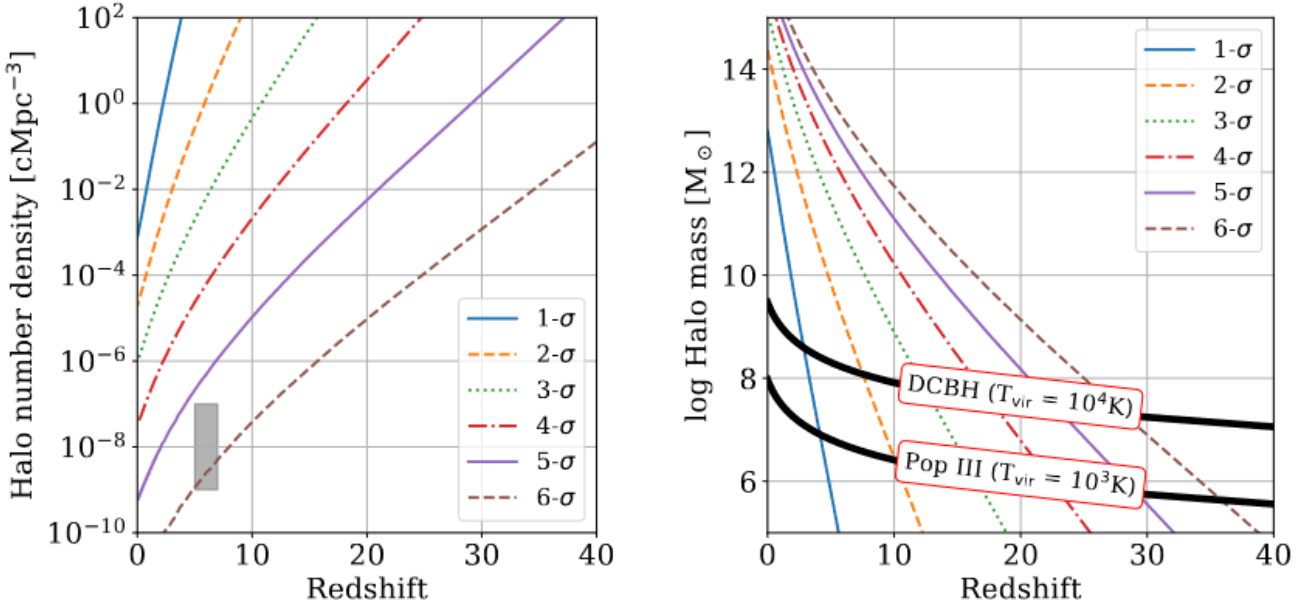
Parameter Tuning Based on MCMC



Hurdles & Caveats

1. More elaborated MBH seeding & growth models

2. Insufficient high mass halo samples



3. Other physics? e.g.) BH mergers

Summary & Conclusion

1. In this study, we aim to devise a MBH evolution model satisfying the observational constraints such as the $M_{\rm BH} - M_{\rm dyn}$ relations.

2. Given a typical MBH growth mechanism, the direct collapse BH better explains the high-z observations than the BH formed via Pop III stars.

3. However, some physics which are not incorporated in our model may change our conclusion.