Super-Eddington Accretion at z > 6

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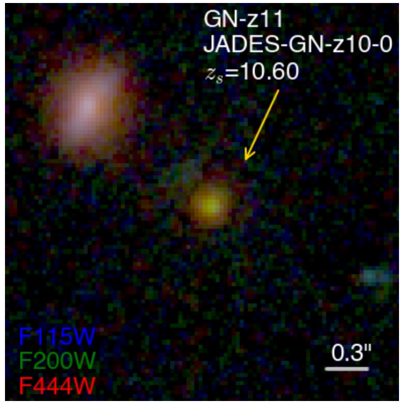
2024 Vienna: Building Galaxies from Scratch

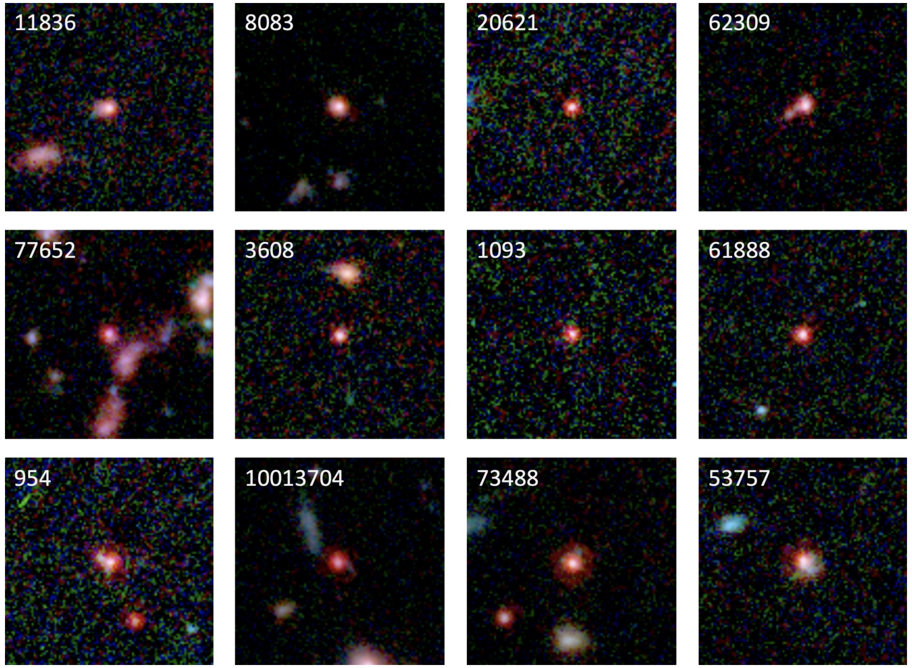
SMBHs with JWST

- Maiolino+2023: A small and vigorous black hole in the Early Universe
- Maiolino+2023: JADES. The diverse population of infant black holes at 4<z<7 (…)
- Matthee+2023: Little Red Dots: an abundant population of faint AGN at z>5
- Furtak+2023: A supermassive black hole in the early Universe growing in the shadows
- Juodžbalis+ in prep: A dormant, over massive black hole in the young universe: the tip of an iceberg
- Larsen+2023, Natarajan+2023, Goulding+2023, Mazzucchelli+2023, Bogdan+2023, Zhang+2023, …

Object	z	$\log M_{BH} [M_\odot]$
CEERS-1670	5.2	7.11
CEERS-3210	5.6	7.44
CEERS-00717	6.93	7.99
CEERS-1019	8.7	6.95
GS-3073	5.6	8.2
GNz-11	10.6	6.2
GOODS-N-4014	5.2	4.58
GOODS-N-9771	5.5	8.55



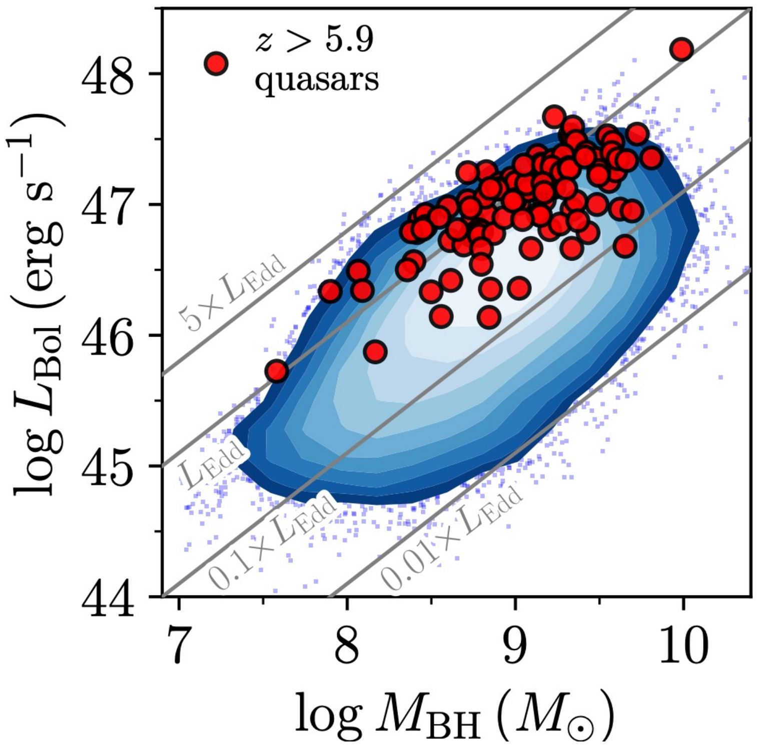
Tacchella+2023



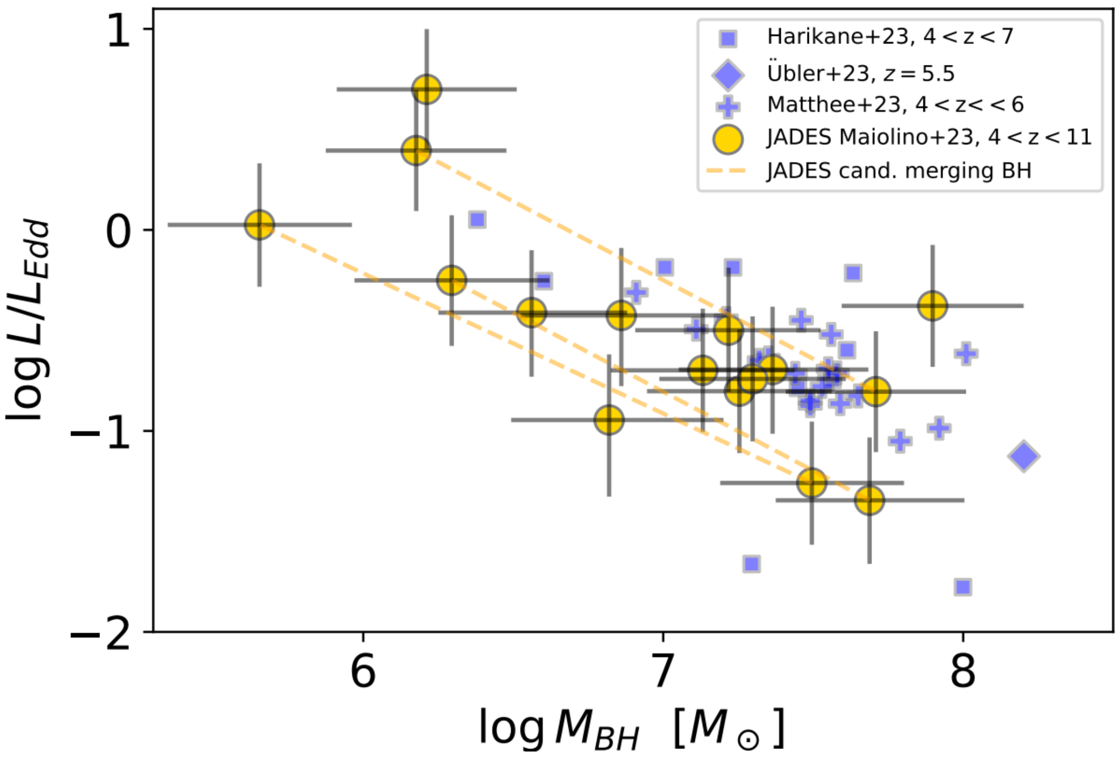
Maiolino+2023

Evidence for Super-Eddington Accretion?

Fan+2022



Maiolino+2023



Observations of black holes accreting at super-Eddington?

Rapid accretion rates to enable growth of quasars ($\sim 10^9 - 10^{10} M_\odot$)?

(Bennet+2024)

Goals

- How do (quasar) black holes form and grow at $z > 6$?
- How important and episodic is super-Eddington accretion?
- How does (super-Eddington) AGN feedback constrain galaxy evolution (e.g. star formation)?

FABLE

Feedback Acting on Baryons in Large-scale Environments

- AREPO moving mesh code with Illustris-like physics (Vogelsberger+2014)
  - ➢ star formation, stellar evolution, metal enrichment processes, radiative gas cooling, and UV background
- Updated SN and AGN (Sijacki+2015, Henden+2018) "subgrid" feedback models
  - ➢ Produces more reliable gas fractions in groups/clusters
- **NEW** 100 Mpc/h (Bigwood+, in prep) boxes

Seeding, Accretion, and Feedback

Black Hole Seeding

Seeds of $10^5 h^{-1} M_\odot$ for every halo above $5\times10^{10} h^{-1} M_\odot$

Realistically

- Population III remnants ($\sim10^2 M_\odot$)
- Runaway mergers ($\sim10^3 M_\odot$)
- Direct collapse ($\sim10^5 M_\odot$)

Bondi Accretion

$$\dot{M}_{Bondi} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

$$\dot{M}_{Edd} = \frac{4\pi G M_{BH} m_p}{\epsilon_r \sigma_T c}$$

$$\epsilon_r = 0.1$$

$$\dot{M}_{BH} = \max\left(\dot{M}_{Bondi}, \dot{M}_{Edd}\right)$$

Feedback

Quasar (“Thermal”) Mode

- ❖ $\dot{M}_{BH} > 0.01\ \dot{M}_{Edd}$
- ❖ Spherically-symmetric wind

Radio (“Kinetic”) Mode

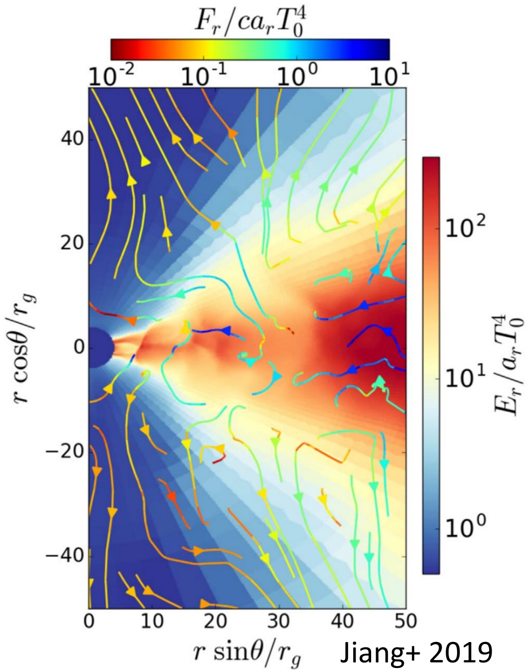
- ❖ $\dot{M}_{BH} < 0.01\ \dot{M}_{Edd}$
- ❖ AGN-driven radio bubble feedback

Super-Eddington Accretion

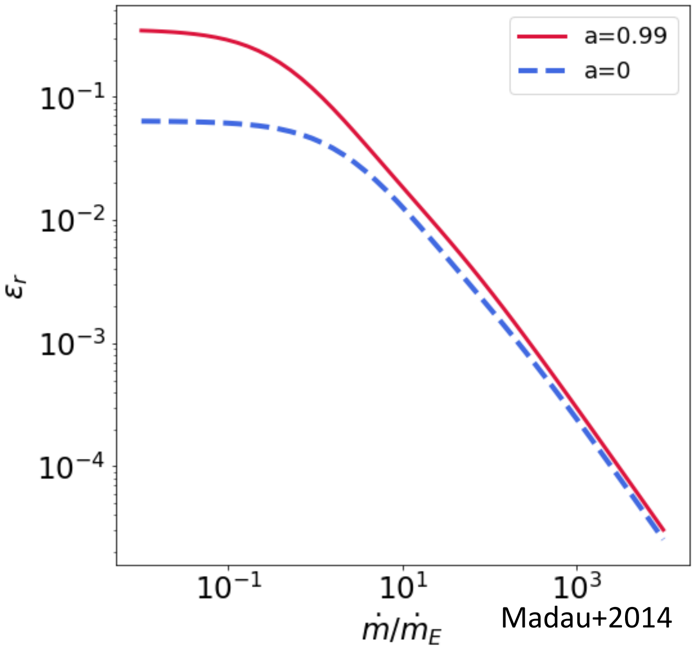
$\dot{M} > \dot{M}_{Edd}$?

- Asymmetric accretion
- Tidal disruption events (Rees 1988)
- Mergers (Schneider 2023)
- Magneto-rotational instability (Jiang 2019)

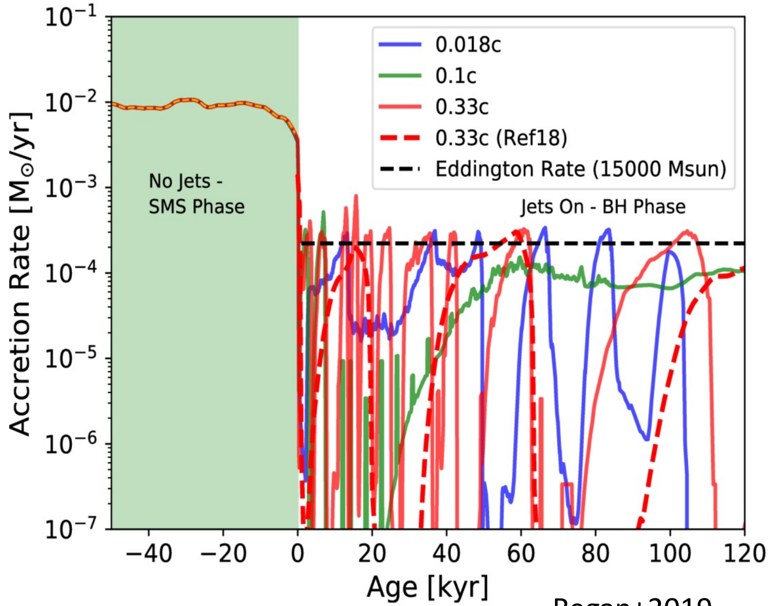
Generally, $\dot{M}_{\max} \gtrsim 10\ \dot{M}_{Edd}$ (Jiang 2019, Ricarte 2023, Schneider 2023)



Jiang+ 2019



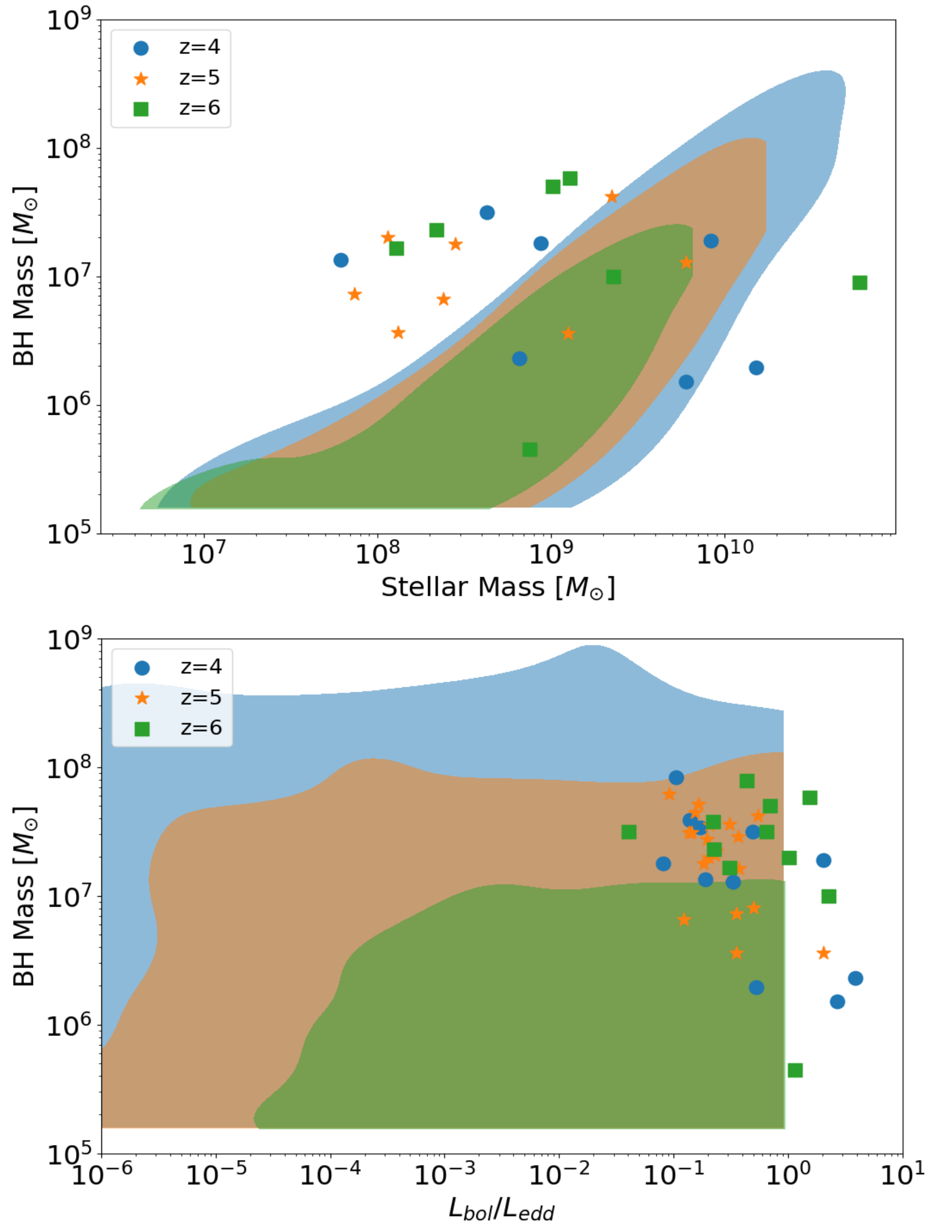
Madau+2014



Regan+2019

Properties

- $\frac{P_{rad}}{P_g} \sim 10^4$
- Thick, advection-dominated disk (photon trapping)
- Bursty
- Spin-jet-disk interactions



High Luminosity Black Holes

Fiducial FABLE model:

Significant population of observed high-mass black holes accreting at high Eddington ratios not reproduced by simulations

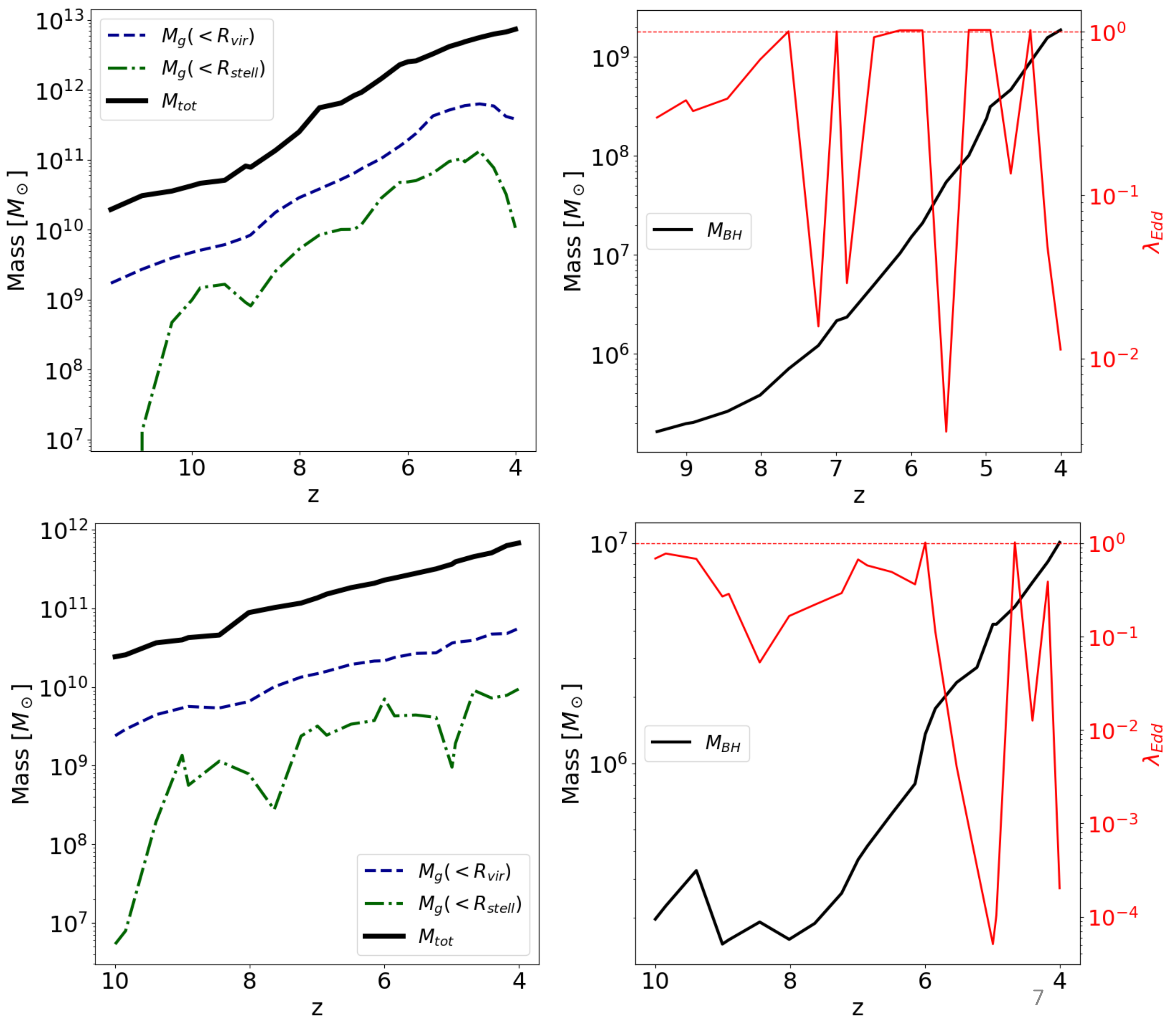
Existence of simulated objects accreting at $\dot{M}_{Edd}$ => abundant gas reservoirs?

Observations: Maiolino+2023, Kokorev+2023, Lukas+2023, Green+2023, Harikane+2023, Fan+2023, Eilers+2023, Larson+2023, Kocevski+2023

Subhalo Evolution

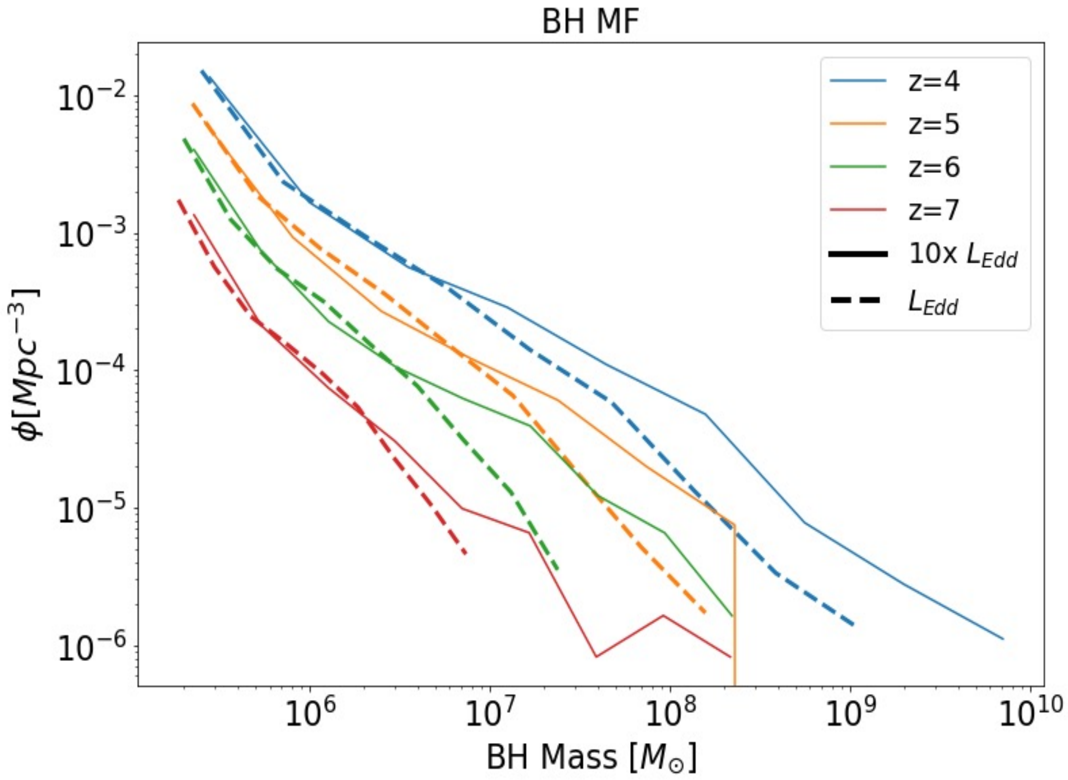
- Merger tree reconstruction (Rodriguez-Gomez+2015) to track halo evolutionary histories
- Identified halos with
  i. High gas fractions $\frac{M_g}{M_{tot}}$
  ii. High Eddington ratios

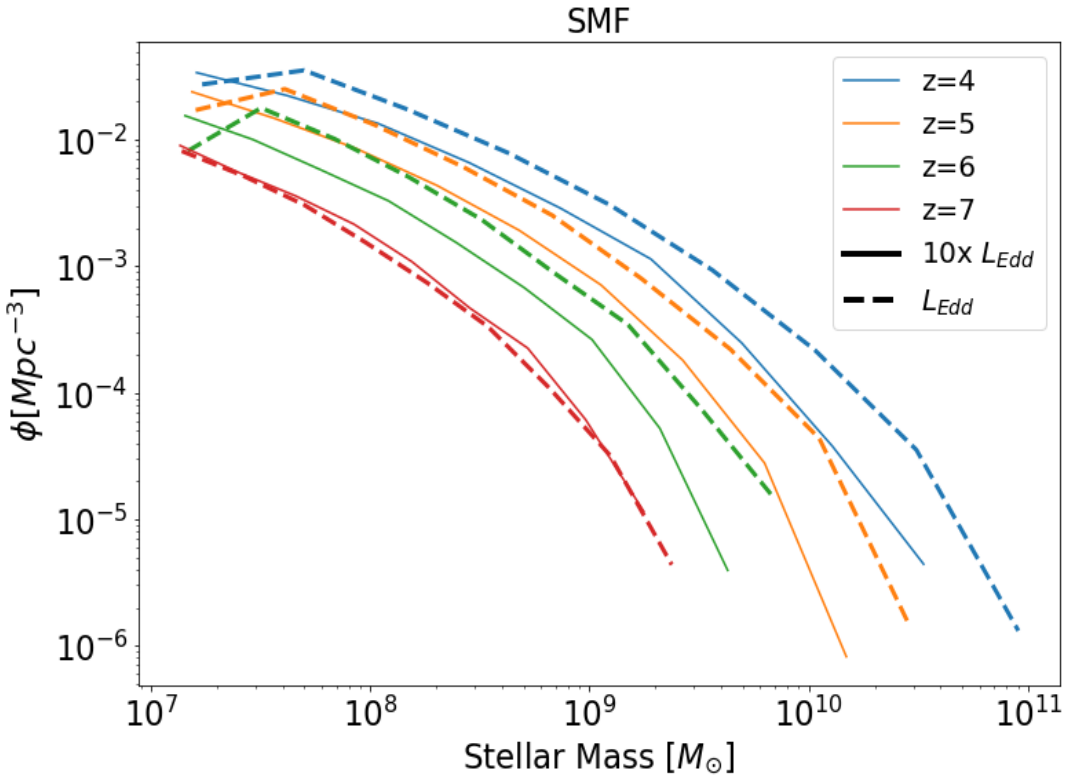
$$\lambda_{Edd} = \frac{L_{bol}}{L_{Edd}}$$



The Super-Eddington Regime

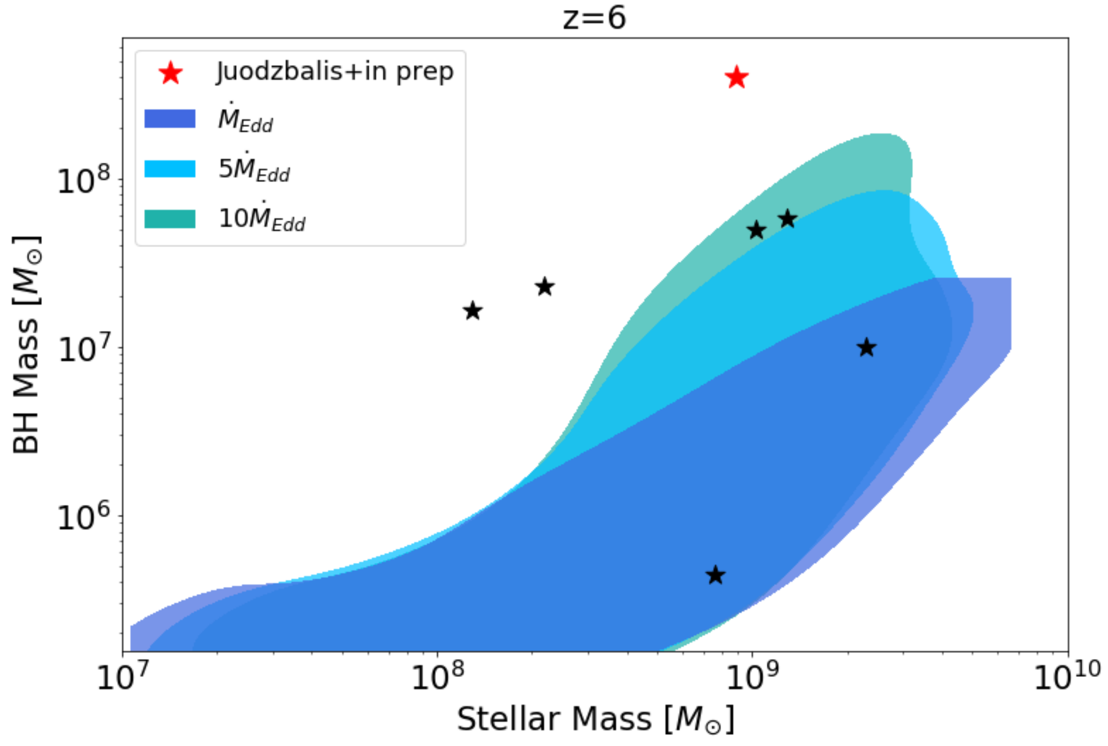
We allow the maximum accretion rates be 1, 5, 10x $\dot{M}_{Edd}$, resulting in suppressed star formation and more higher mass black holes.

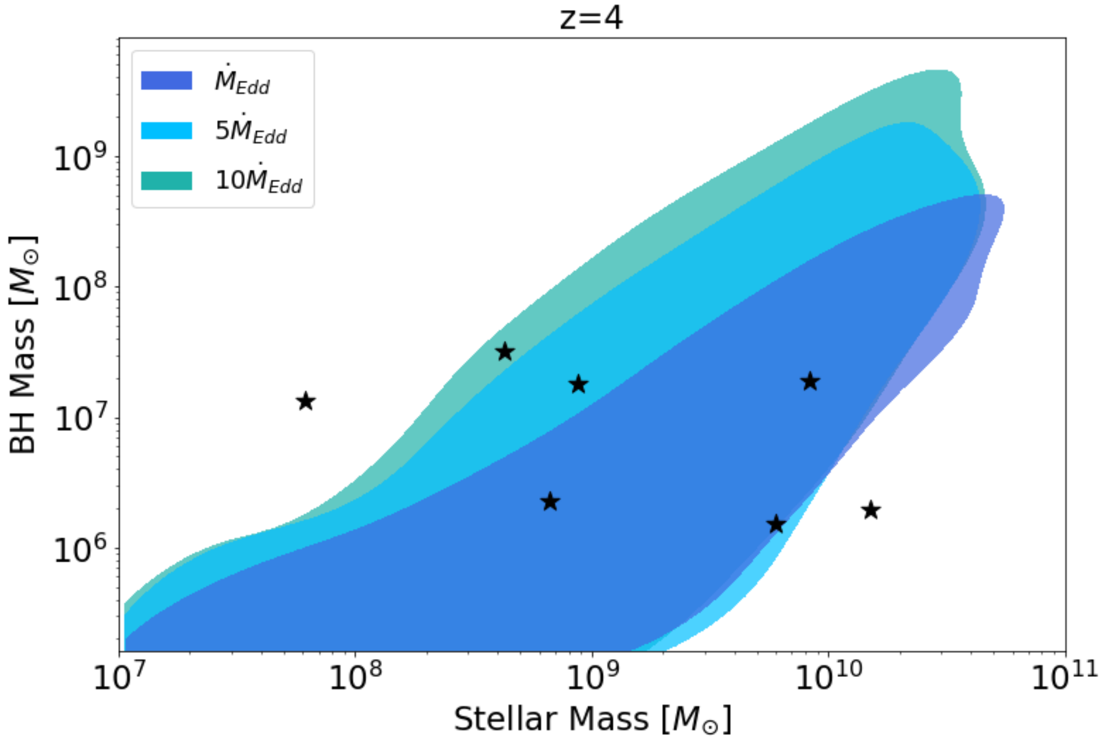




Black hole v Stellar masses

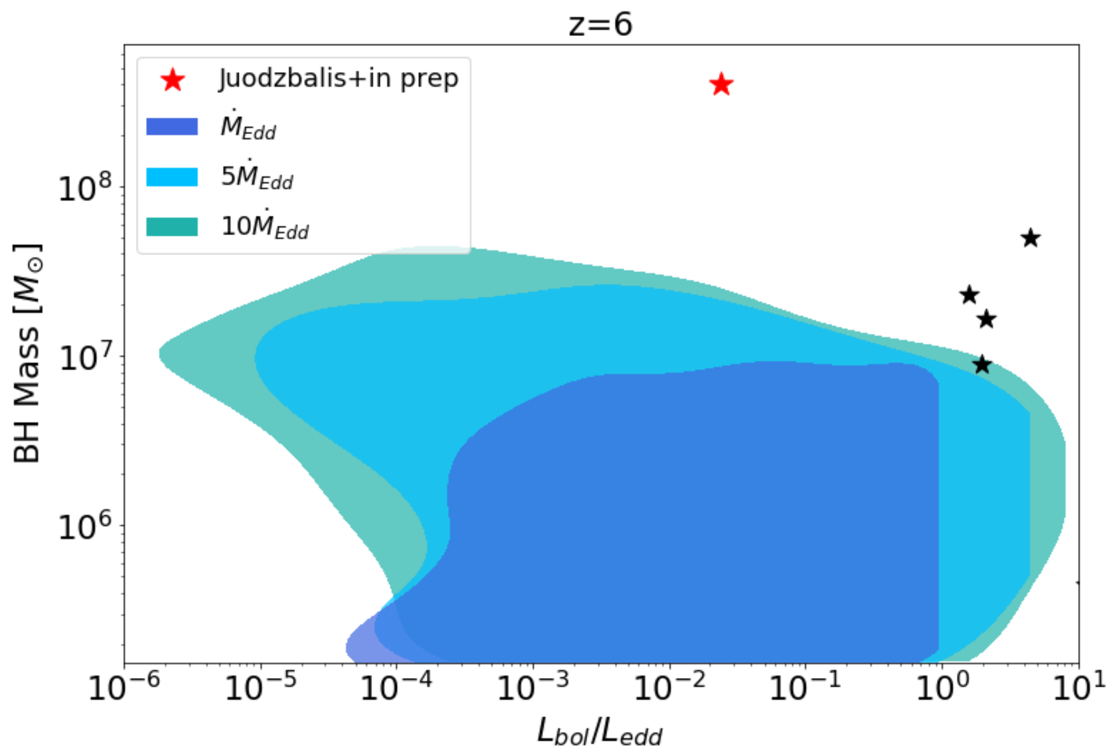
Black hole and stellar masses better match observations at higher maximum accretion rates.
Enhanced accretion and feedback is permitted by the high availability of gas.

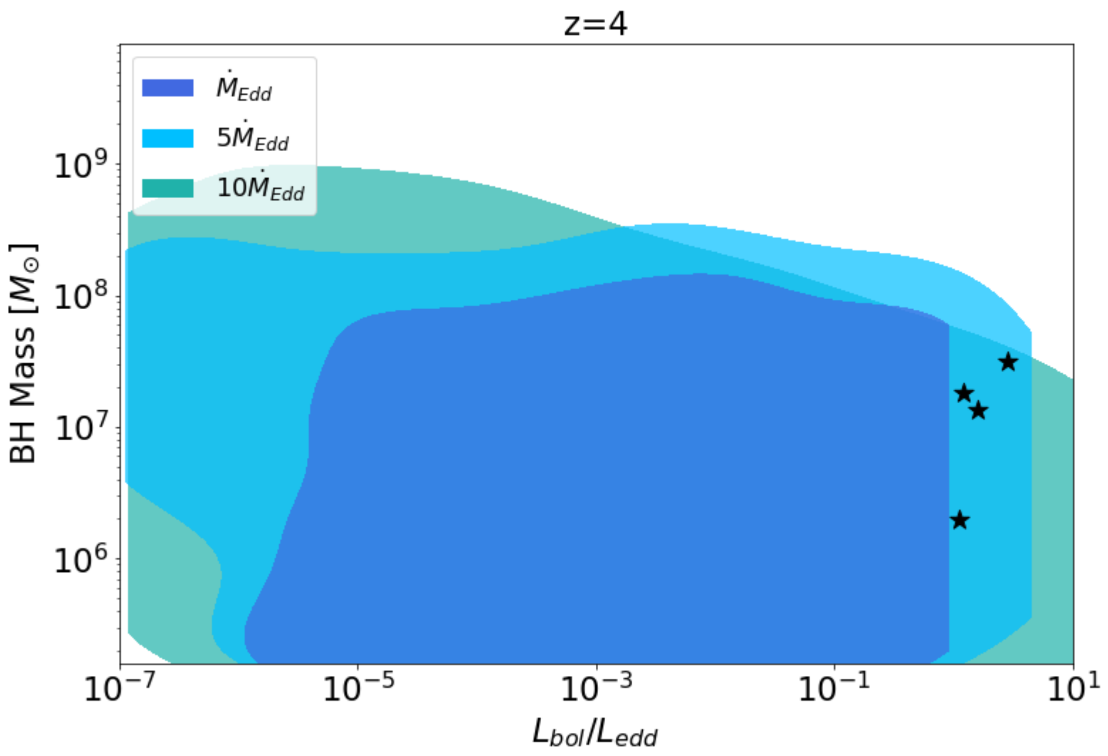




Black hole mass v λ_{Edd}

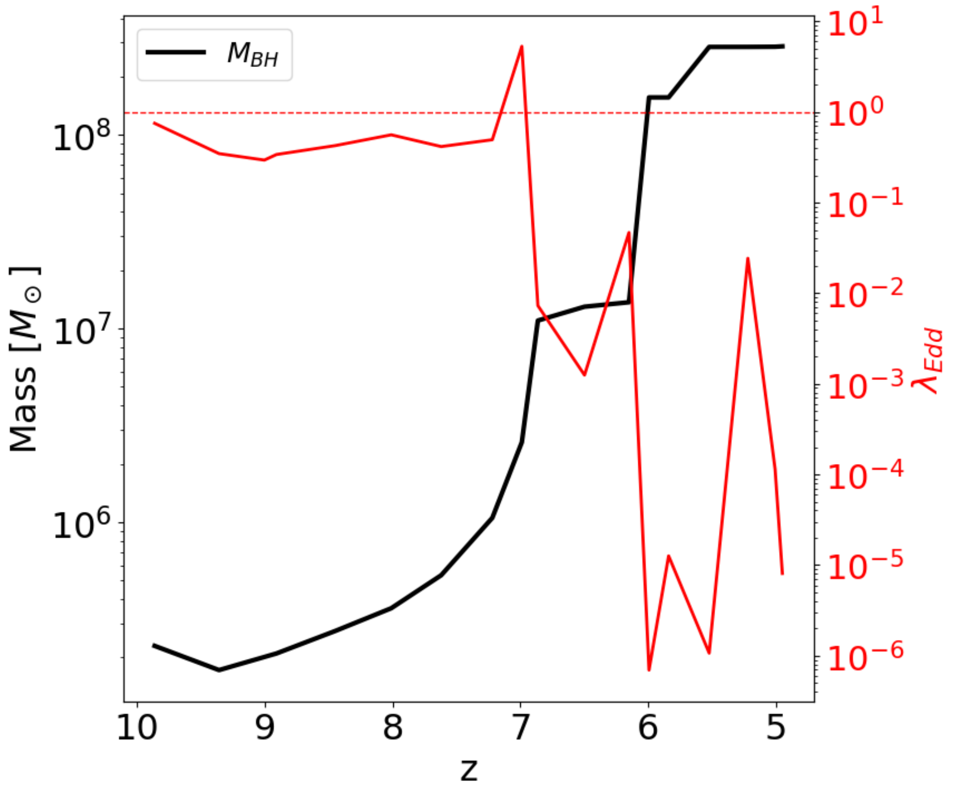
Black holes accreting at up to $10\times\dot{M}_{Edd}$ are produced, consistent with observations.
Abundant gas implies results are sensitive to the choice of the upper accretion limit.

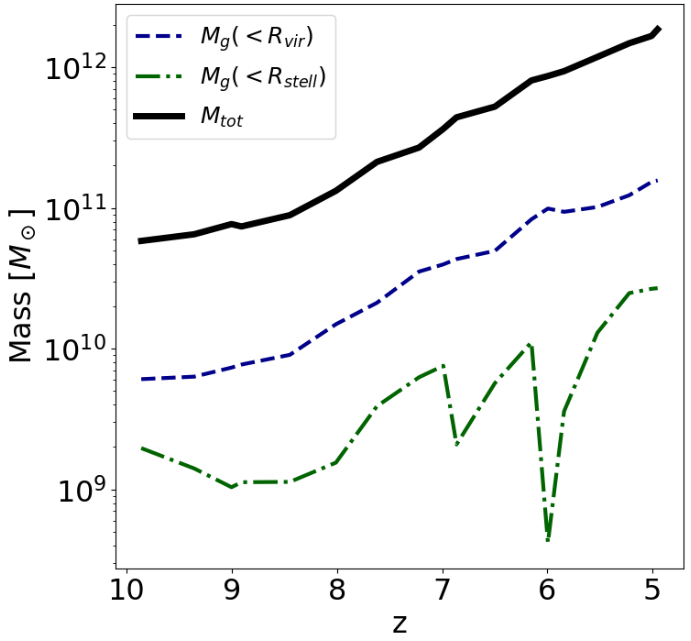


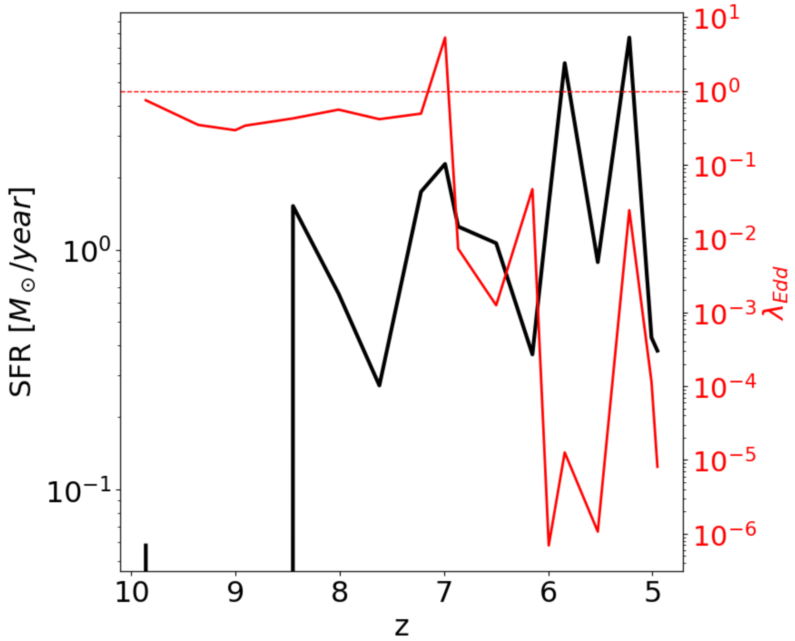


Merger tree reconstruction 10x $\dot{M}_{Edd}$

Transient super-Eddington accretion is accompanied by temporary depletion of gas reservoirs. Strong shocks in radio mode induce star formation







Conclusions

- JWST has revolutionized the landscape of SMBH at high redshifts with the discovery of objects that grow very rapidly in limited time

- We apply the FABLE simulations where super-Eddington growth at 5 and $10 \times \dot{M}_{Edd}$ is allowed

- Significant increase in black hole masses; existence of gas expulsion and star formation suppression. High Eddington rates are in accordance with observations

- Future work: implementation of (weaker) super-Eddington feedback, zoom-in simulations with more realistic sub-kpc physics