Constructing a High Redshift Massive Black Hole Population with Renaissance

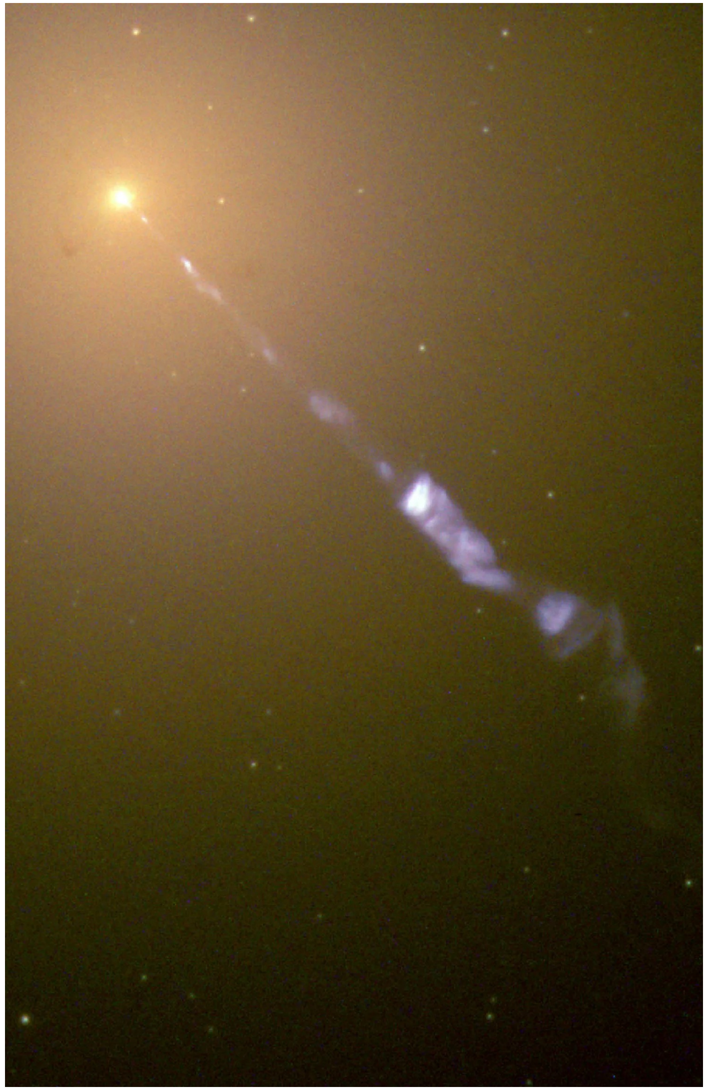
Joe McCaffrey, John Regan, John Wise, Britton Smith, Michael Norman, Brian O’Shea

Maynooth University
National University of Ireland Maynooth

LISA Astro Working Group 2024 Meeting, Garching

Introduction

- Existence of Supermassive Black Holes is evident in majority of galaxies.
- Unknown as to how these Black Holes reached the mass that they did.
- Grow through accretion and merging with other black holes.
- With the discovery of gravitational waves, we can probe the histories of these Black Holes through their merger events.
- Cosmological simulations can help predict black hole populations in the Universe.

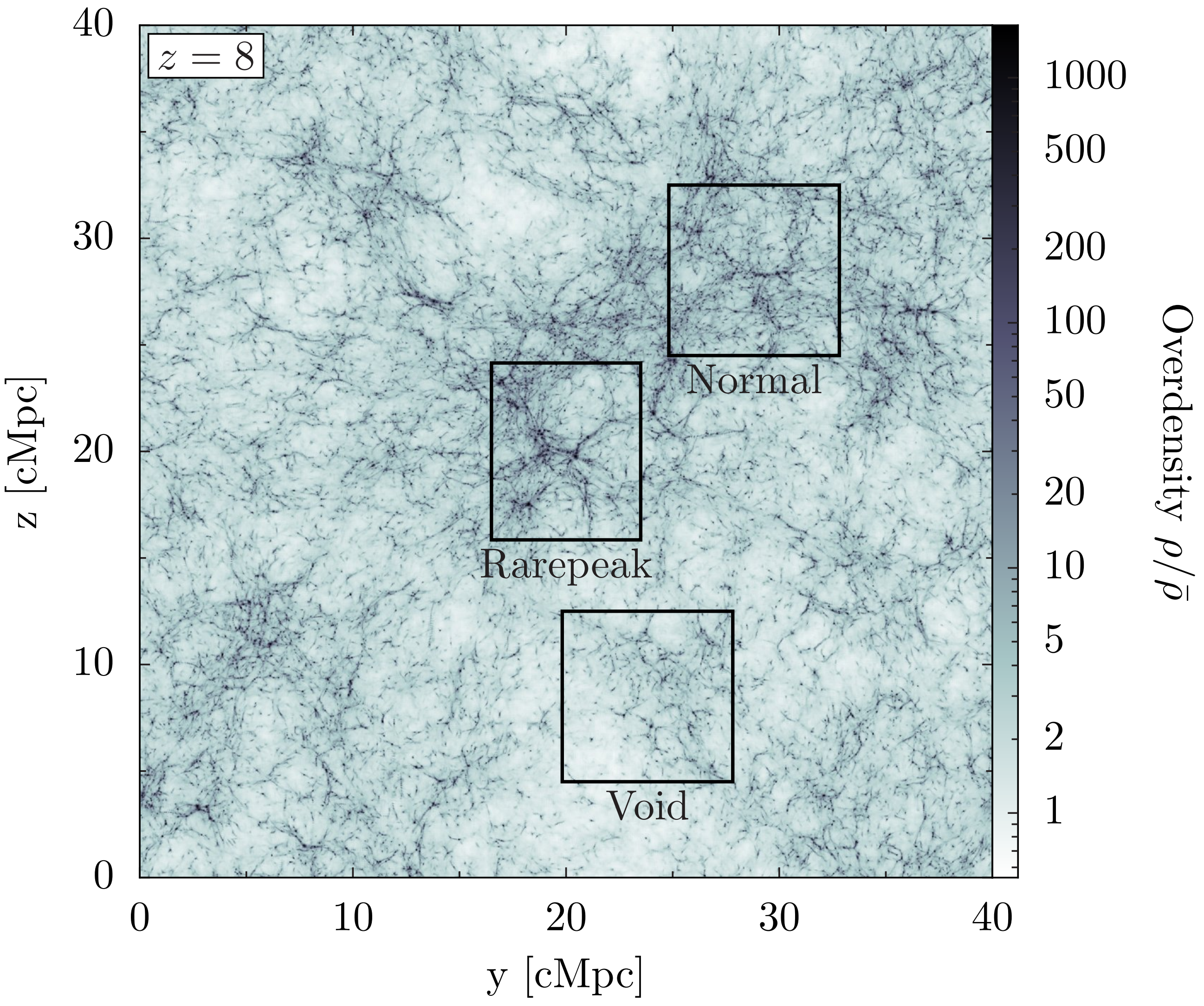


Credit: NASA and the Hubble Heritage Team (STScI/AURA)

Credit: EHT

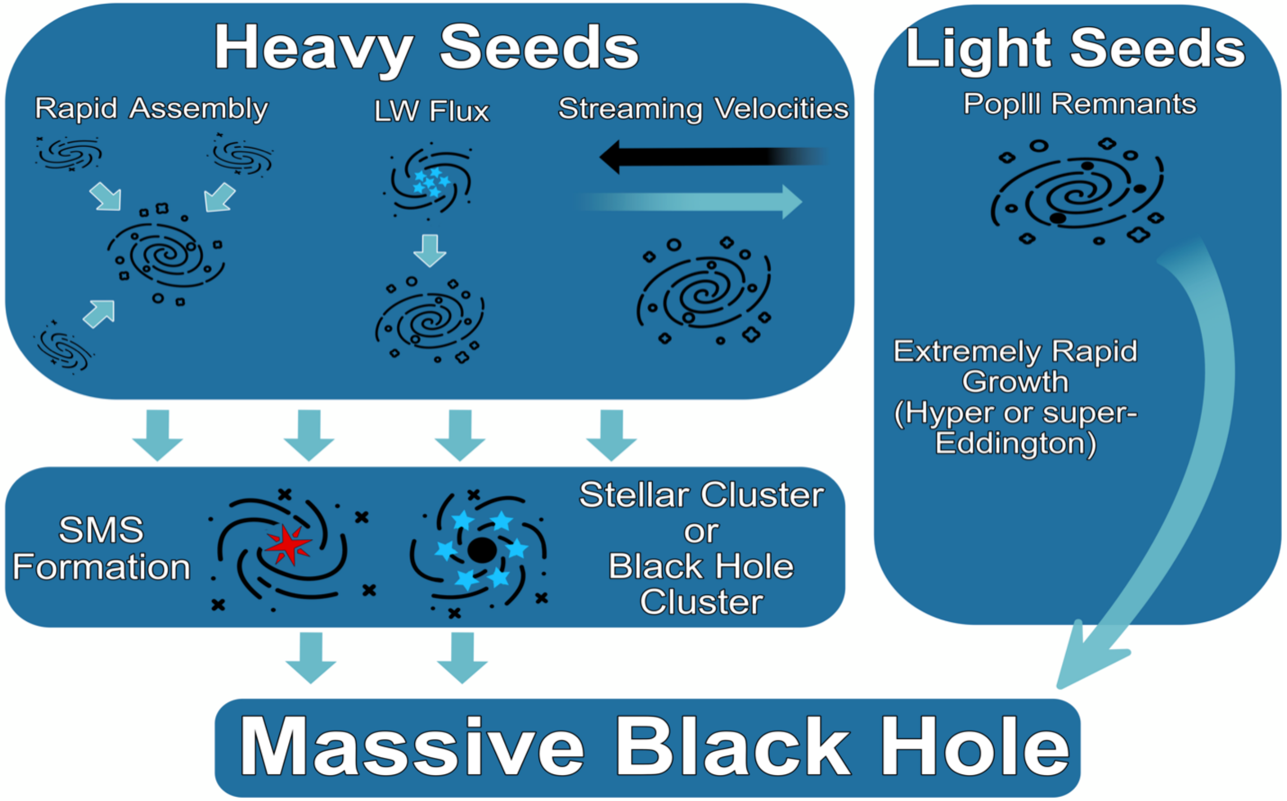
Renaissance Simulations

- Suite of 3 zoom-in regions of n-body hydrodynamic simulations which focus on galaxy formation.
- Regions consist of:
  - Rarepeak (RP), $z_{final} = 15$
  - Normal, $z_{final} = 11.6$
  - Void, $z_{final} = 8$
- Have prescriptions for the formation of PopIII and PopII stars (ie. The earliest stars in the Universe)



Xu et al. 2013; Chen et al. 2014; O'Shea et al. 2015; Smith et al. 2018; Wise et al. 2019, Xu et al 2016

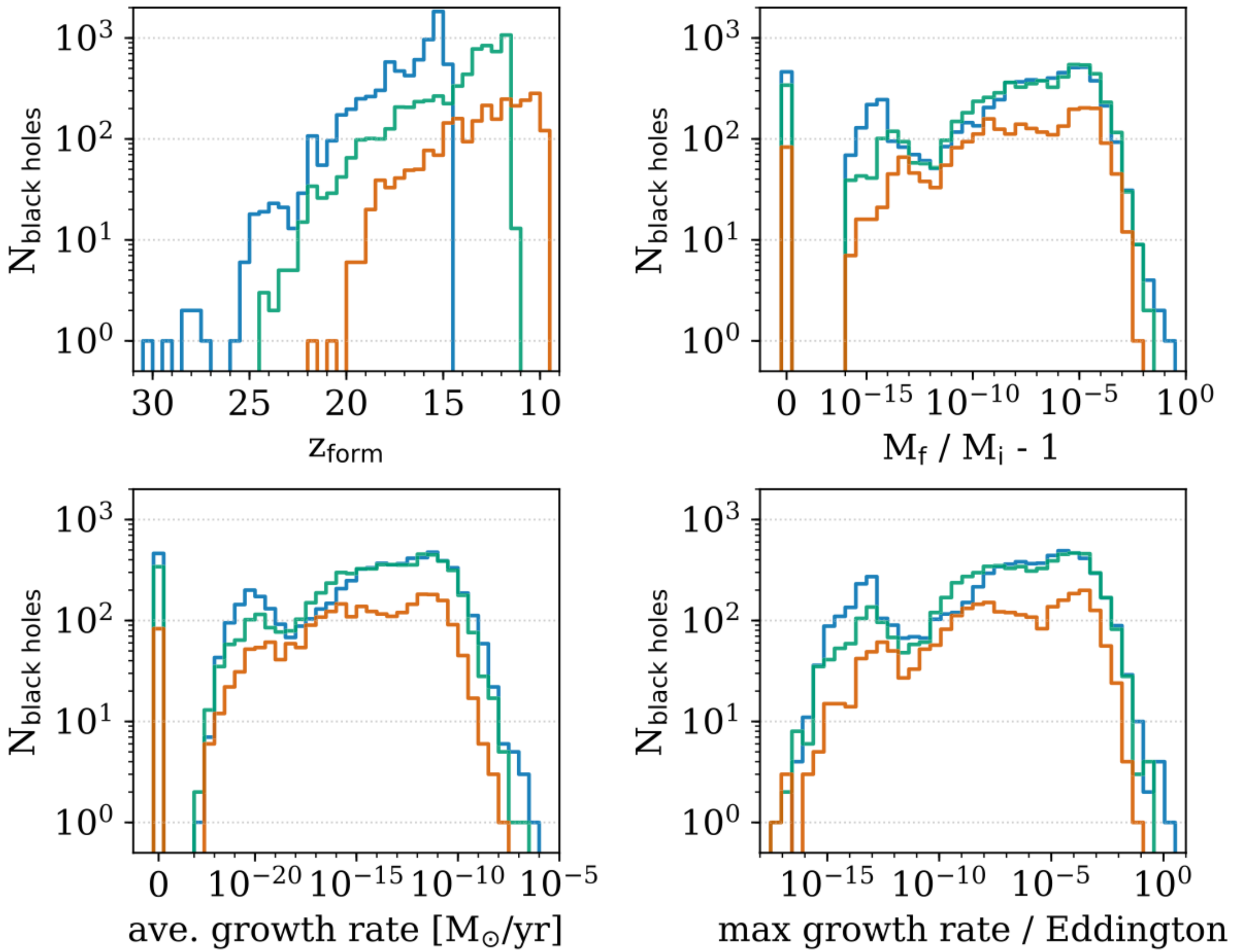
Seed Pathways



- Two possible seed pathways: Heavy seeds and Light seeds
- Light seed requires vast amounts of accretion to reach sufficient masses.
- Heavy seeds give a headstart in the black hole's lifetime: growing through moderate accretion and mergers.

Light Seed Growth

- Smith et al 2018 used Renaissance to investigate the growth of Light seed black holes.
- Light seeds – the remnants of the PopIII stars born in Renaissance.
- Growth was very low, Black holes never reached sufficient accretion values.



Smith et al 2018

Heavy Seed Formation

- Other simulations seed black hole when halo reaches certain mass.

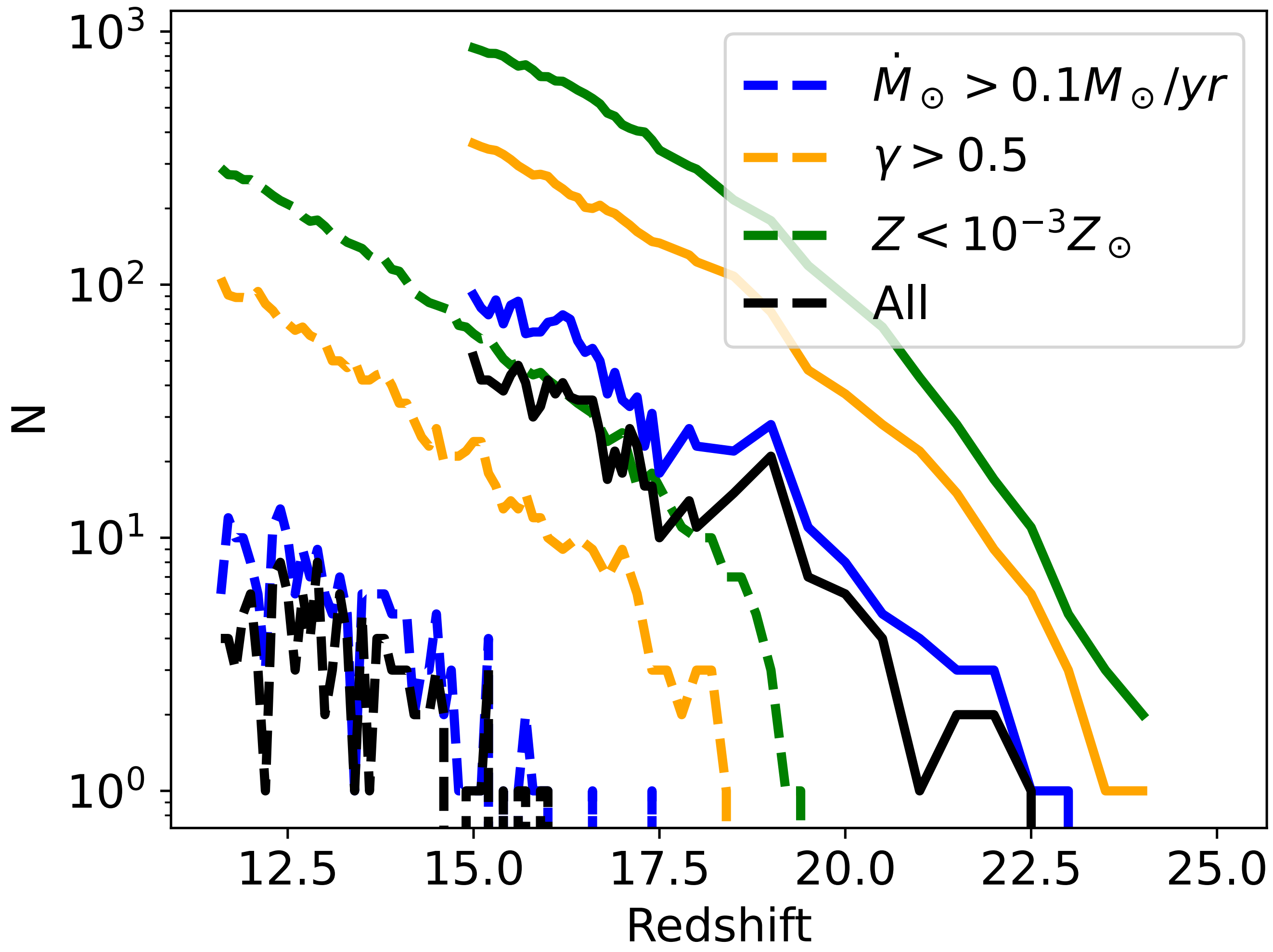
- We add more constraints:

  - The halo has metallicity $< 10^{-3} Z_{\odot}$ - leading to less fragmentation.

  - Inflow rate > 0.1 solar masses per year

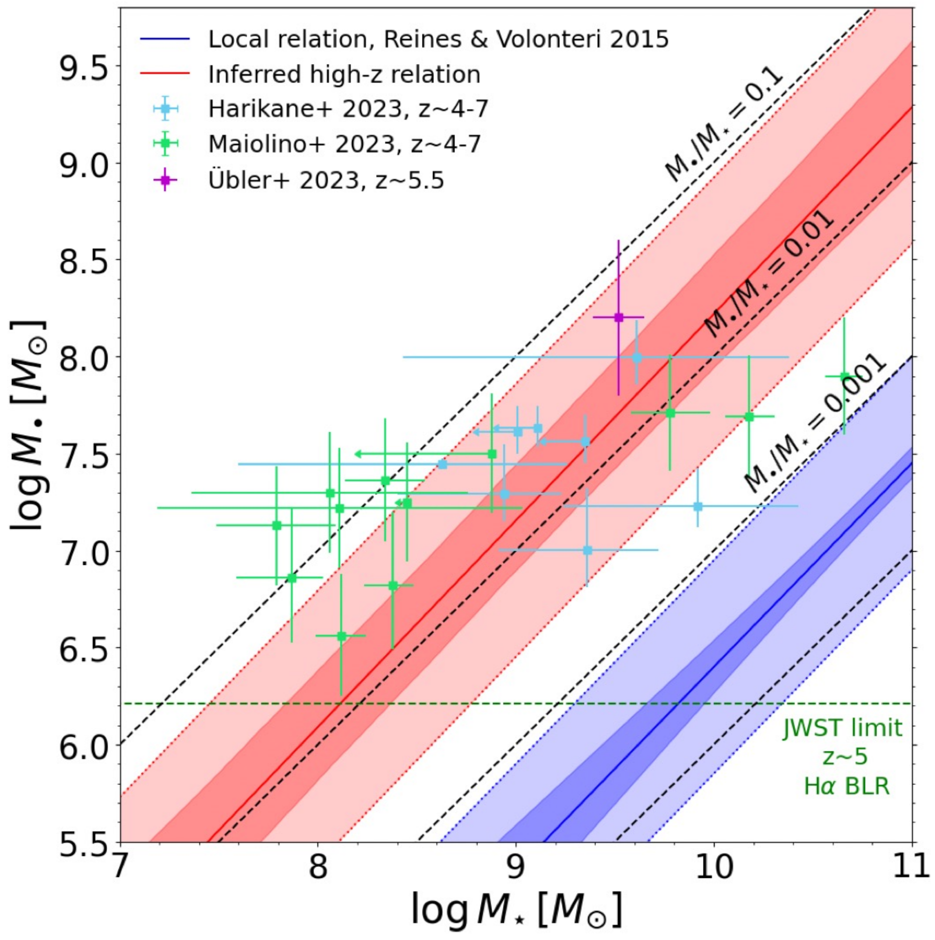
  - ”Compactness”, γ – flag for a collapsing halo

Halos Satisfying Conditions



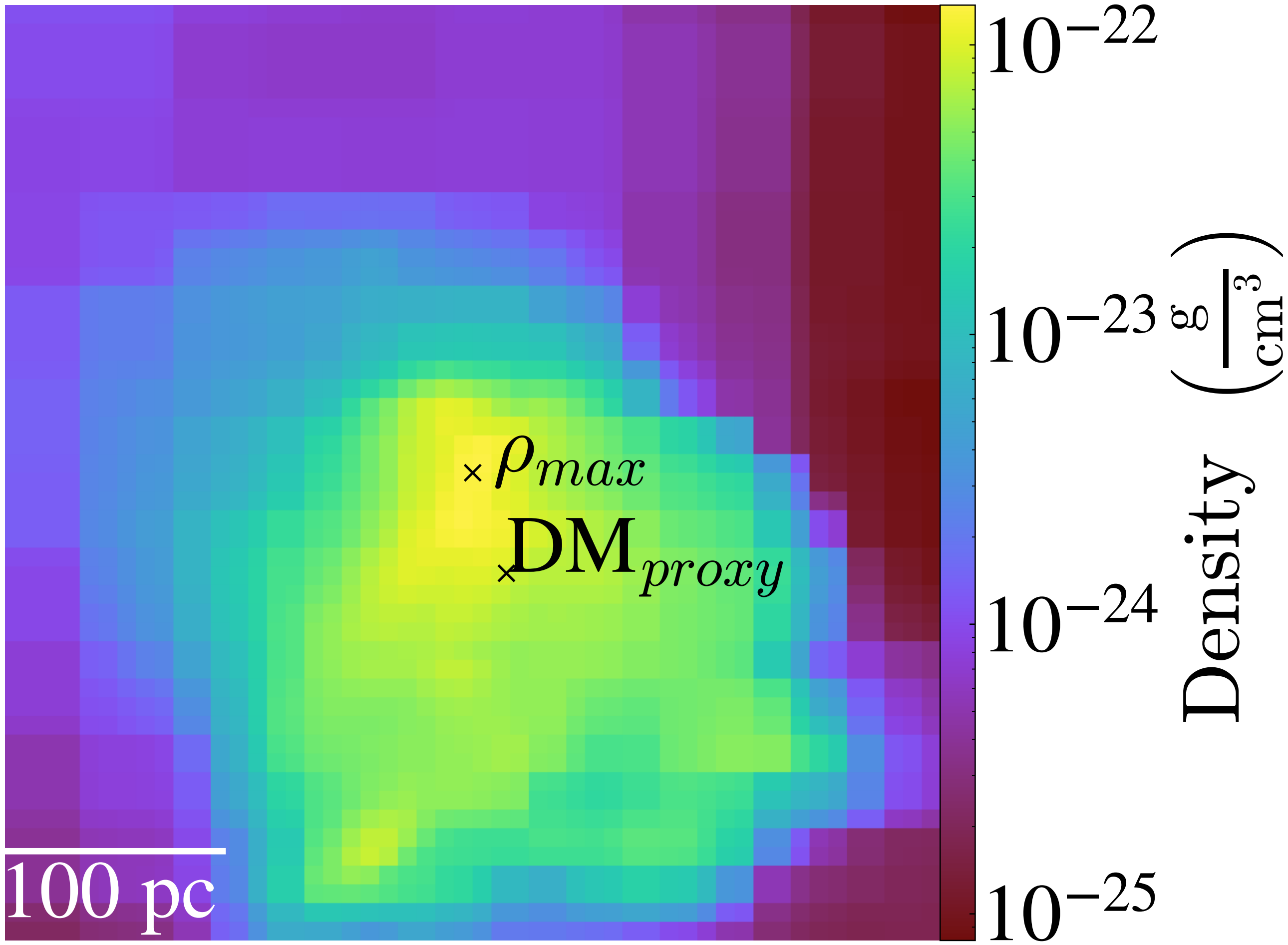
Black Hole Masses

- IMF for these epoch of the Universe unconstrained.
- JWST is starting to discover black holes which are overmassive with respect to their host galaxies.
- Relation derived by Reines et al 2015 (local relation) and Pacucci et al 2023 (overmassive high-z) between Stellar mass and Black hole mass.
- Relation does not account for halos with no stellar mass



Pacucci et al 2023

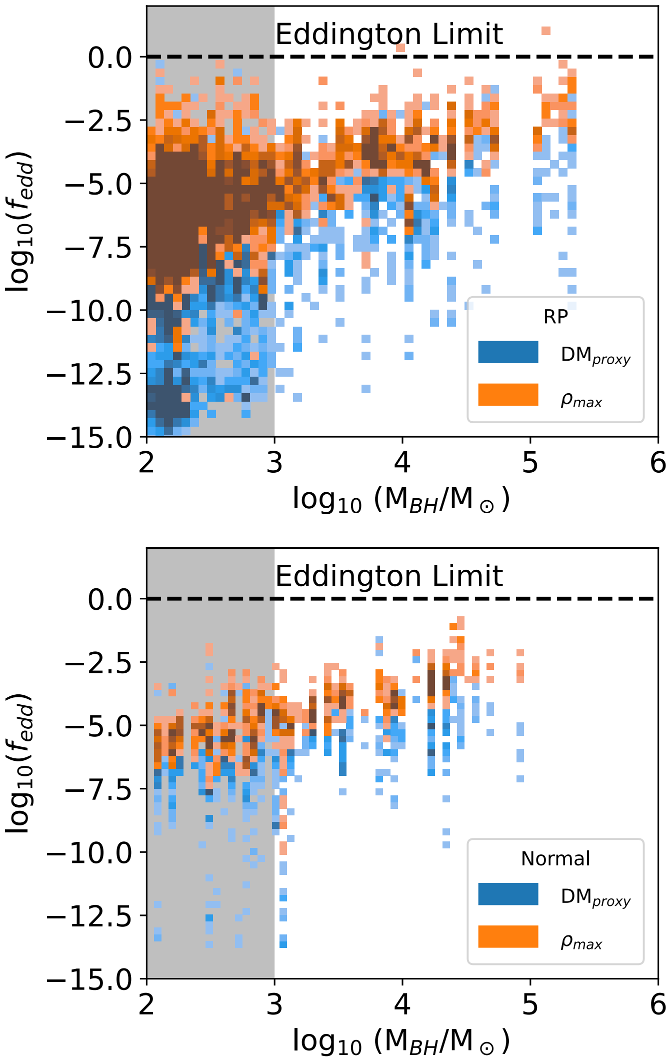
Accretion onto the Black Holes



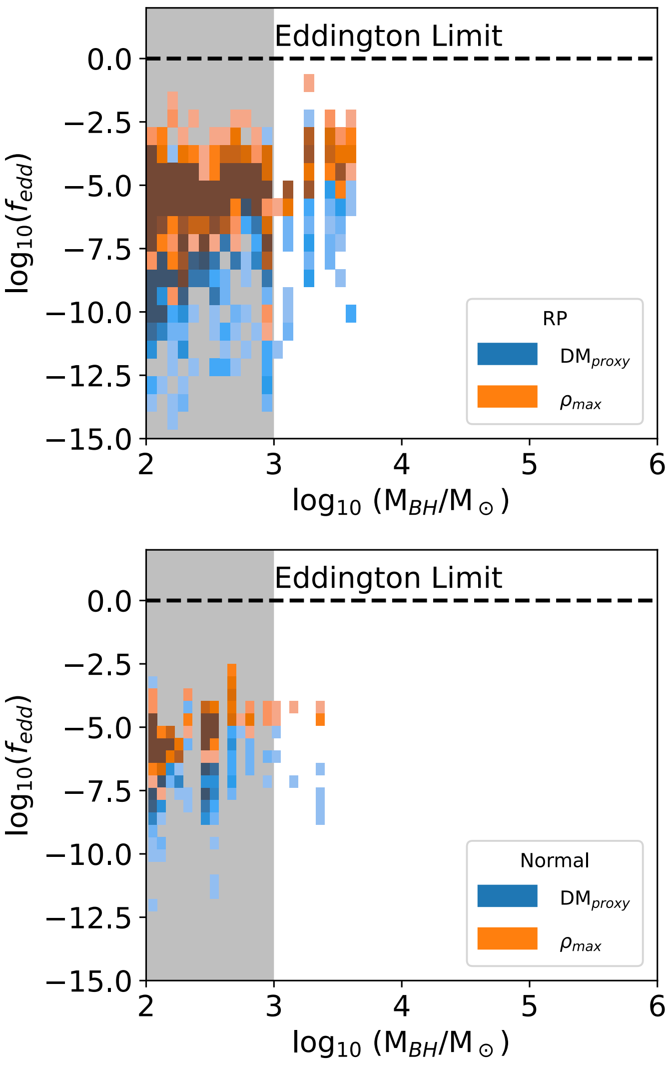
- Used Bondi-Hoyle mechanism for accretion:

$$\dot{M} = \frac{\pi G^2 M_{BH}^2 \rho}{\max(v, c_s)^3}$$

- Optimistic scenario of black holes being situated at the highest density point of the halo
- Apply another accretion method whereby a nearby dark matter particle is used a proxy for the black hole, to provide more realistic values for the accretion.



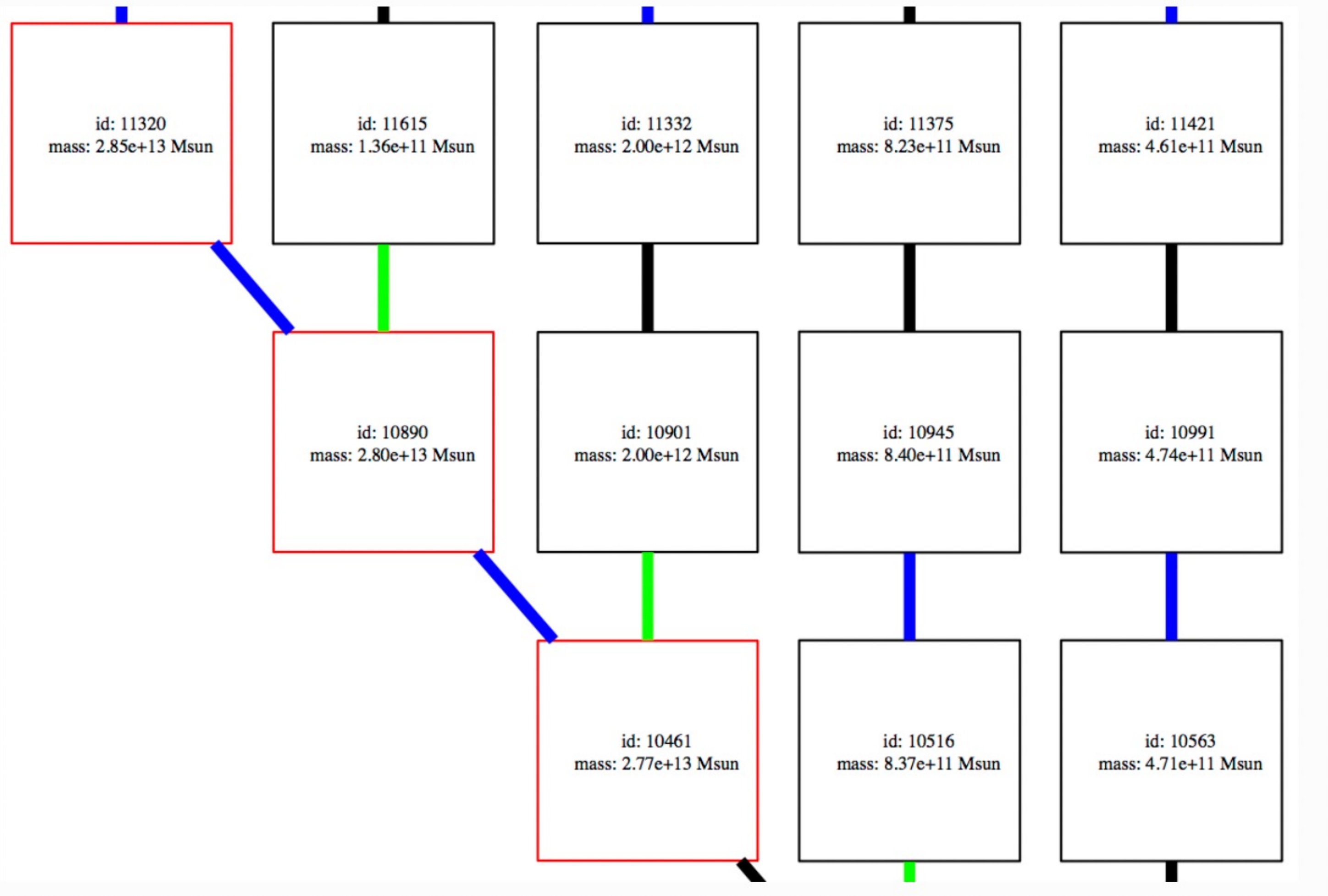
Seeded with Paccuci et al 2023 relation



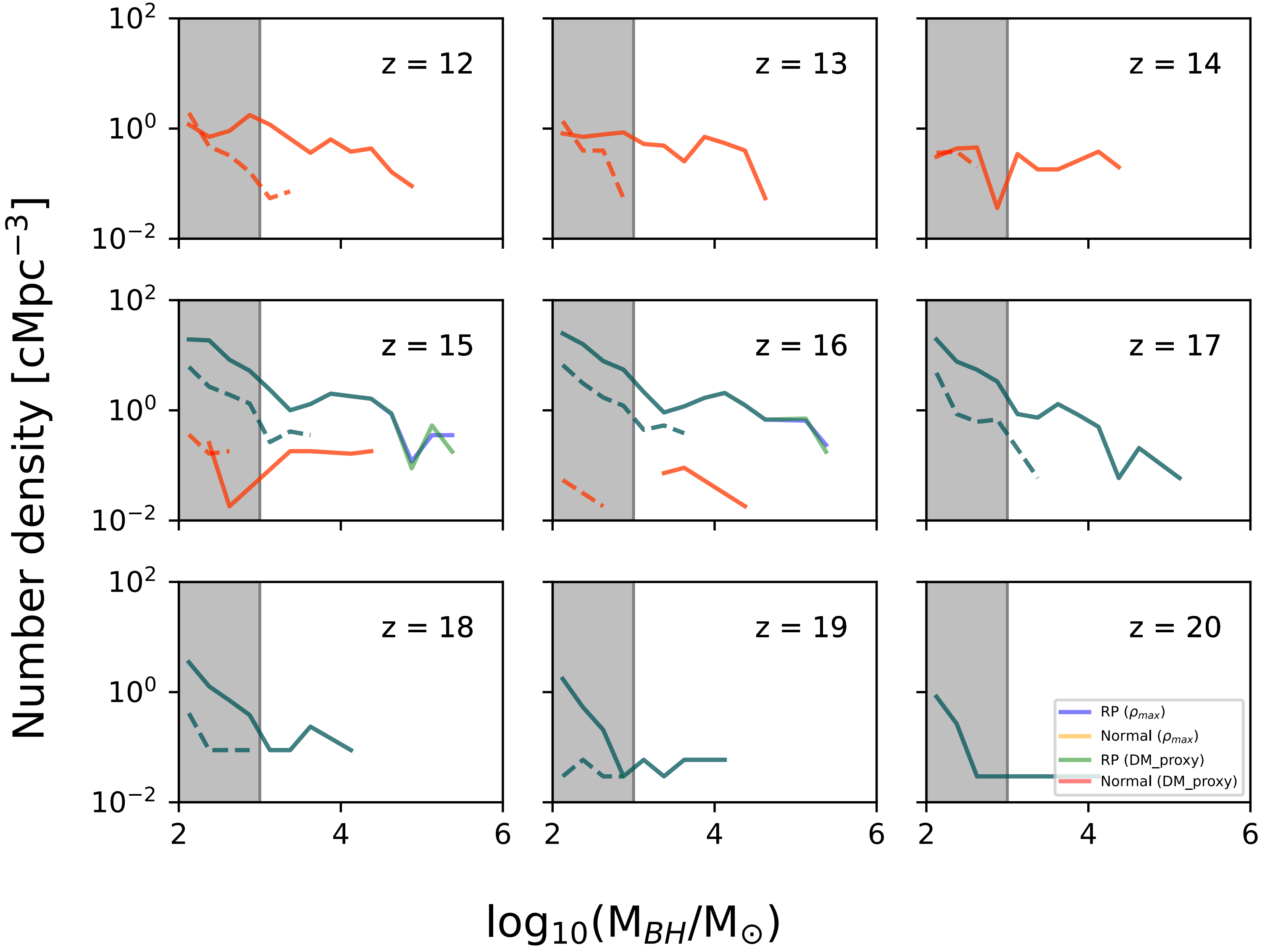
Seeded with Reines & Volonteri 2015 relation

Mergers

- Halo Trees allow us to track mergers of halos throughout the simulation.
- The current prescription for the black hole mergers is that they merge immediately
- We can add a delay based on dynamical friction.
- Percentage of mass gained from mergers to mass accreted is around 1-10%.



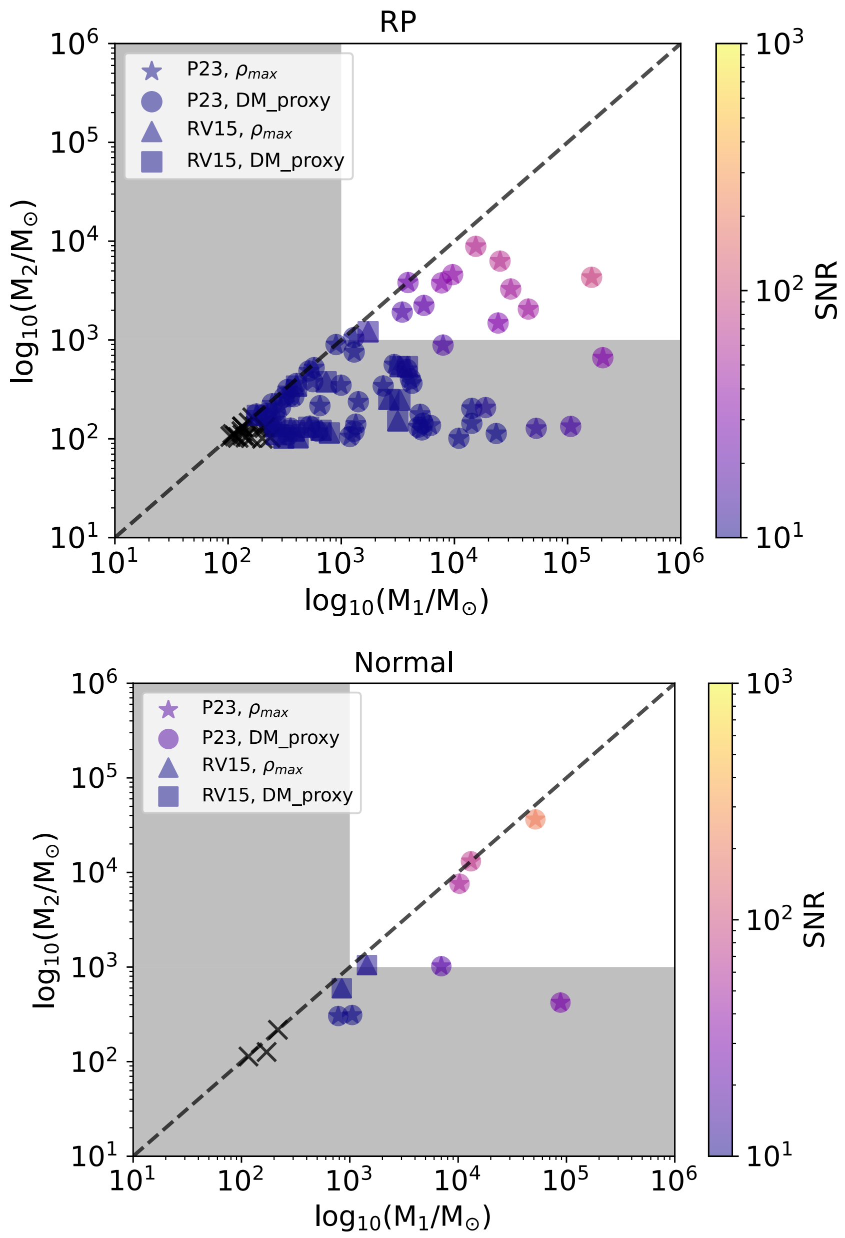
Source: https://ytree.readthedocs.io



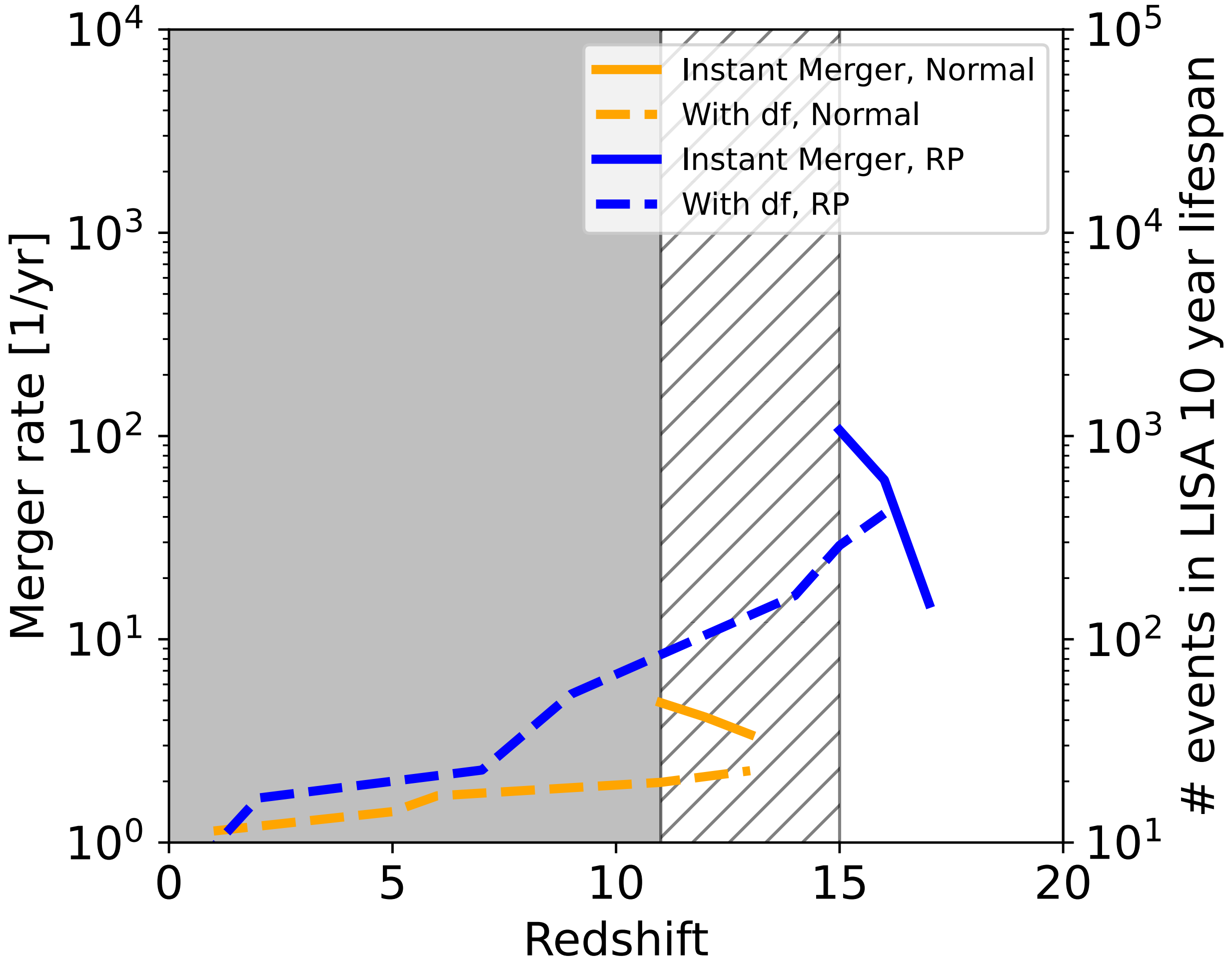
- Dashed line represents black holes seeded with masses from using Reines & Volonteri 2015 relation.
- Solid Line from Paccuci et al 2023.

Mergers

- With the caveat of instant mergers, signal to Noise ratio of these events can reach up to 100.
- If delays drastically extend the merger time, the signal would become even stronger



Predicted Merger Rate



Conclusions

- Growth of black holes from accretion and mergers negligible.
- Merger events of these black holes can be probed with LISA.

Link to Paper:
https://arxiv.org/pdf/2409.16413

Thank you!