Accretion onto the first black holes formed by direct collapse

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with

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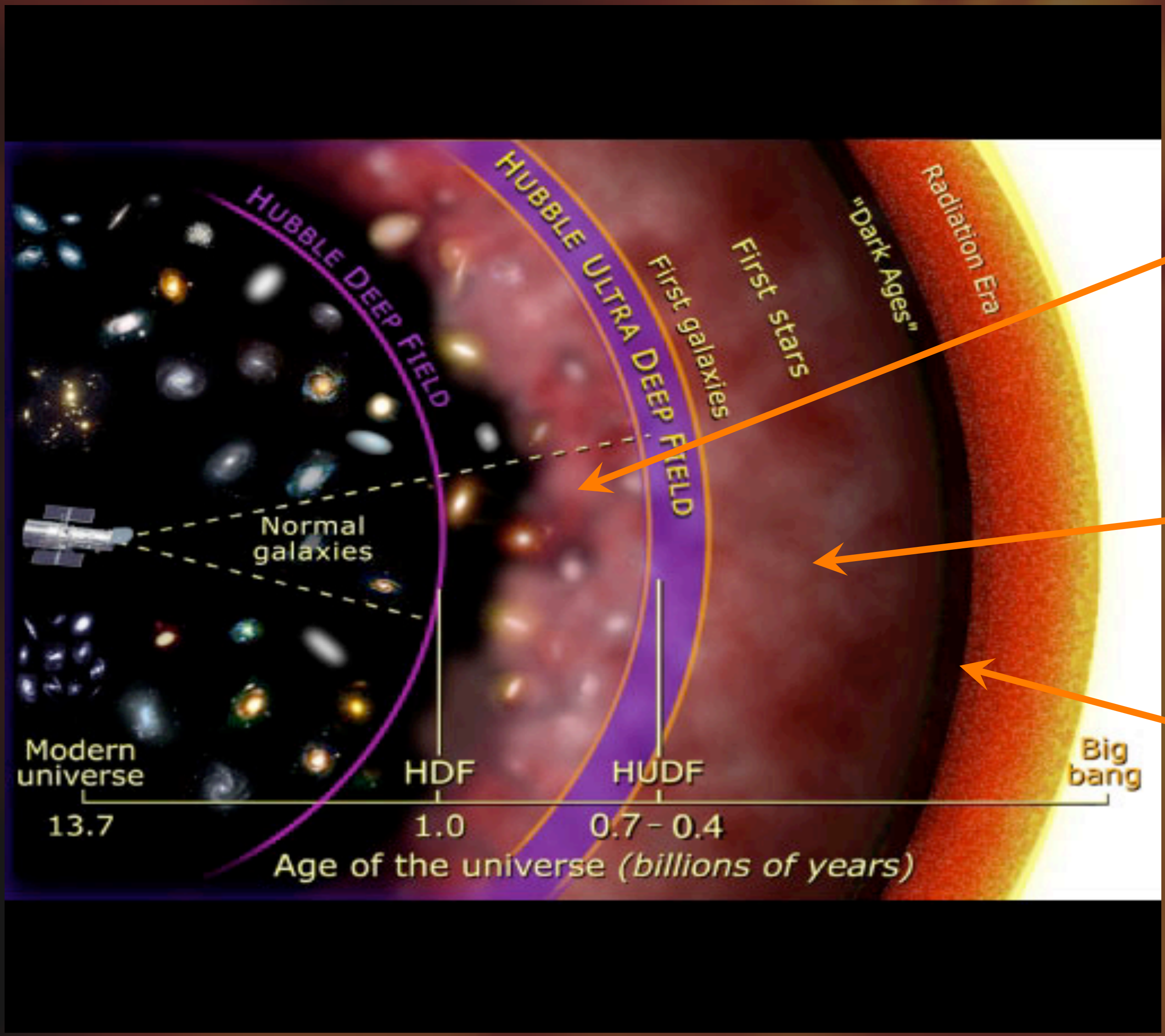
Theoretical Modeling of Cosmic Structures

Rapid Black Hole Growth in the Early Universe



Observed galaxies hosting 10^9 M_{sun} black holes

The first stars, seed BHs, and galaxies

Observations of the CMB give ICs for star, BH and galaxy formation

credit: firstgalaxies.org

Two Modes of Massive Black Hole Seed Formation

1) Relic Pop III BHs

(e.g. Madau & Rees 2001; Tanaka & Haiman 2009; Volonteri 2010 for a review)

- Initial mass ~ 100 M_{Sun}
- Typically form at z ~ 20
- Accretion limited by strong radiative feedback from the progenitor star (see Yoshida 2006; Johnson & Bromm 2007; Alvarez et al. 2009)

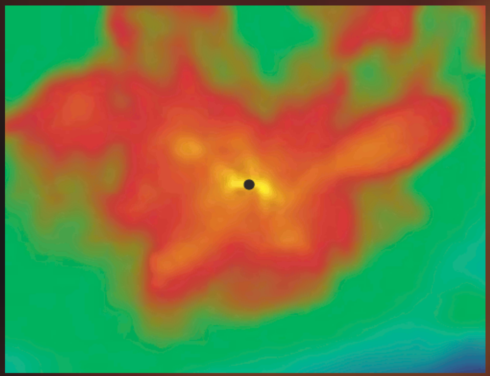
2) Direct collapse BHs

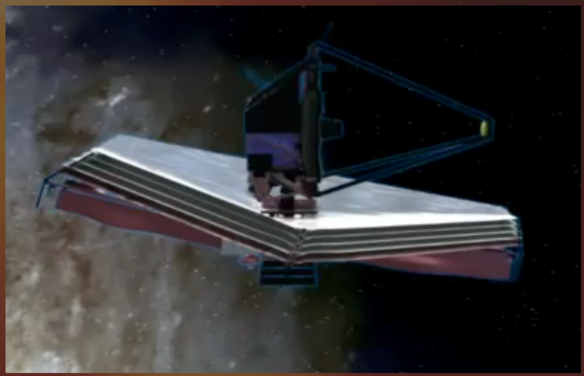
(e.g. Bromm & Loeb 2003; Begelman et al. 2006; Lodato & Natarajan 2006; Spaans & Silk 2006)

- Initial mass > 10^4 M_{Sun}
- Typically form at z ~ 15
- Form in atomic-cooling haloes subjected to high H_2-dissociating flux (e.g. Dijkstra et al. 2008; Shang et al. 2010)

Direct Collapse BHs: Two Key Questions

- How fast do black holes formed by direct collapse grow?
- What are the observable signatures of accretion onto such BHs that may be detected by e.g. the JWST?

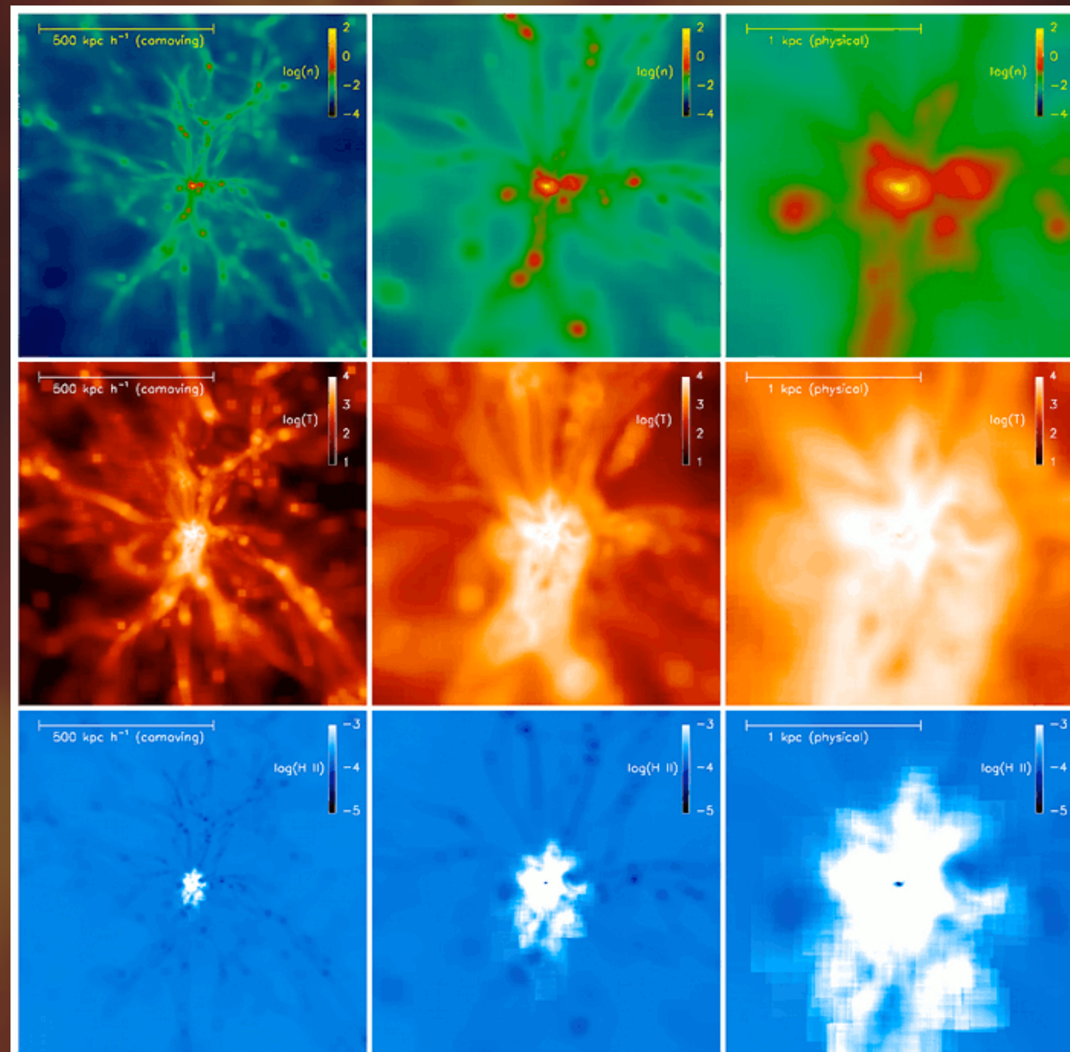




Credit: jwst.nasa.gov

Simulating the Formation of BHs by Direct Collapse

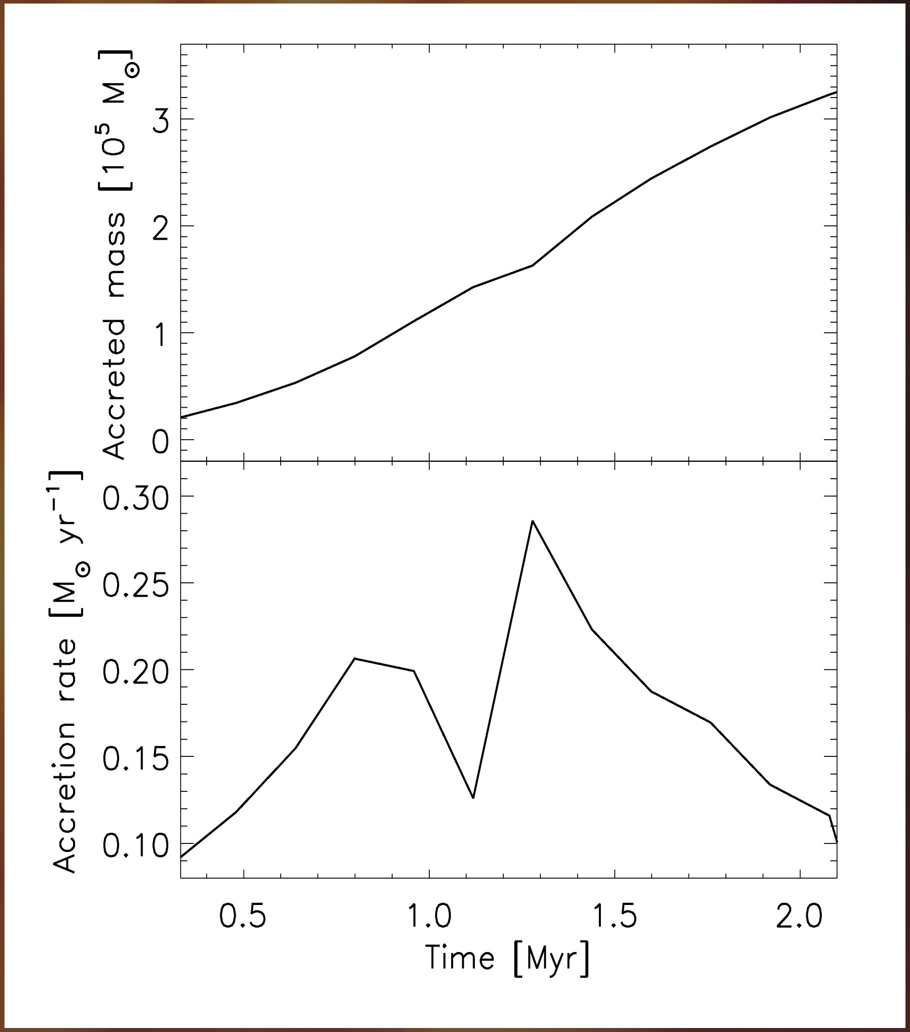
- A constant elevated H_2-dissociating radiation field assumed, to suppress cooling and star formation
- Canonical atomic-cooling halo forms at $z \sim 15$ with $T_{vir} \sim 10^4$ K and cooling by collisional excitation of hydrogen
- Similar results as found by previous studies of collapse of gas into atomic-cooling haloes (Wise et al. 2008; Regan & Haehnelt 2009; Shang et al. 2010)



JLJ et al. 2010

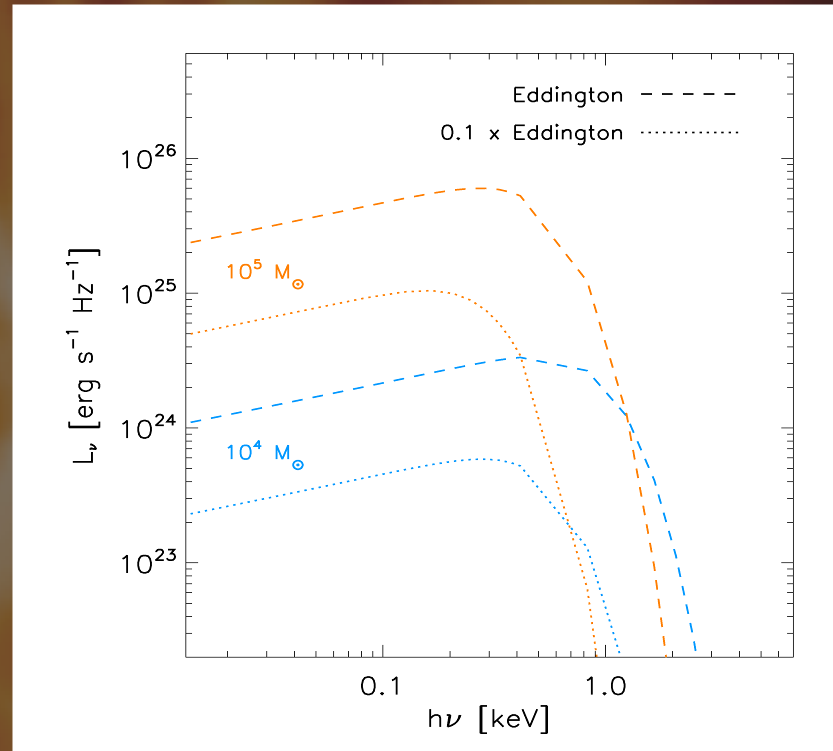
An Upper Limit to the Accretion Rate

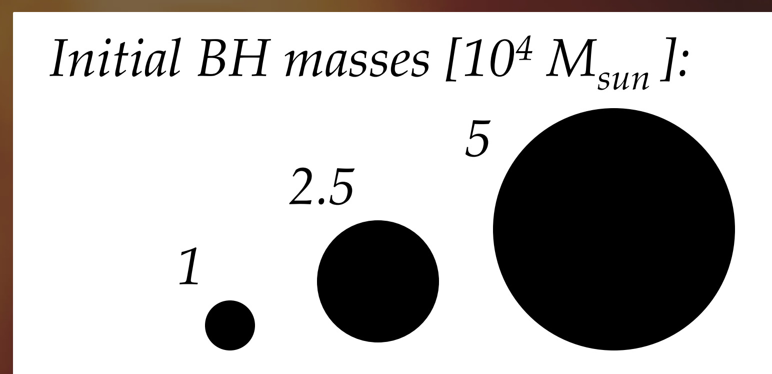
- Immediate BH progenitor (a supermassive star) represented by an accreting sink particle *without radiative feedback*
- Gas falls inward at roughly the sound speed
- Accretion rate onto sink particle is ~ 0.1 – 0.3 M_{sun} yr^{-1}
- Within ~ 2 Myr lifetime of the SMS, 3 x 10^5 M_{sun} is accreted
  - Upper limit to final mass



Modeling BH Accretion and Feedback Together

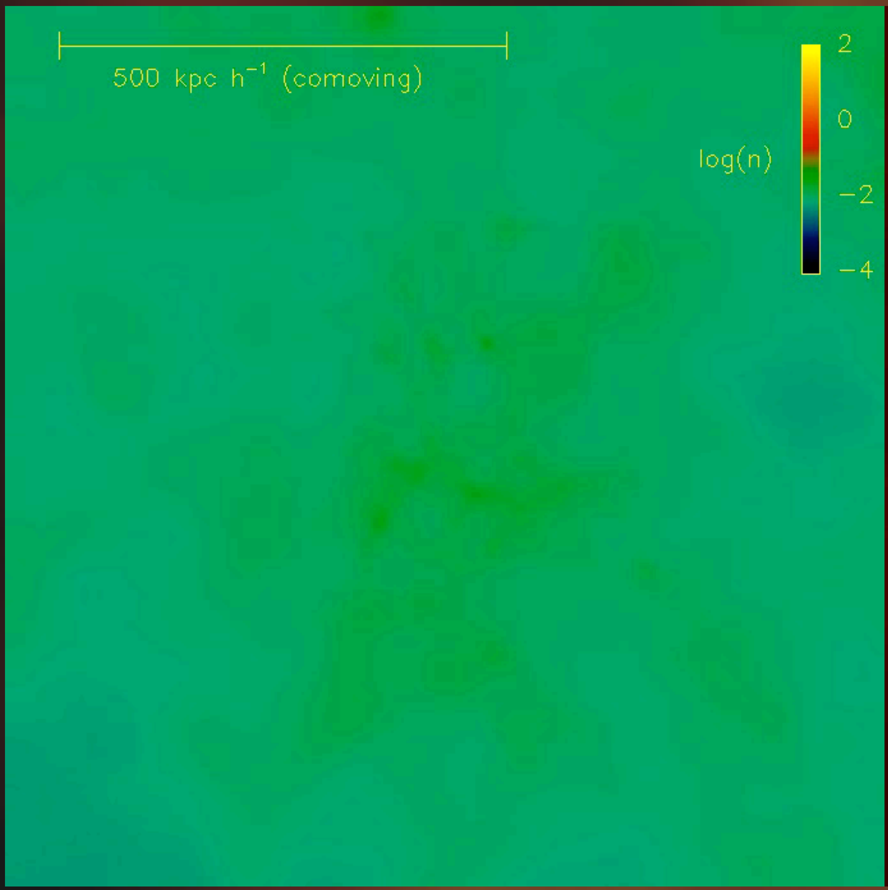
- Resolve Bondi radius, and use Bondi accretion rate
  - Gas is largely pressure-supported
- Use multi-color accretion disk model to couple accretion rate to radiative output
- Use ray-tracing algorithm to track propagation of ionizing radiation
- Account for photoheating, radiation pressure feedback



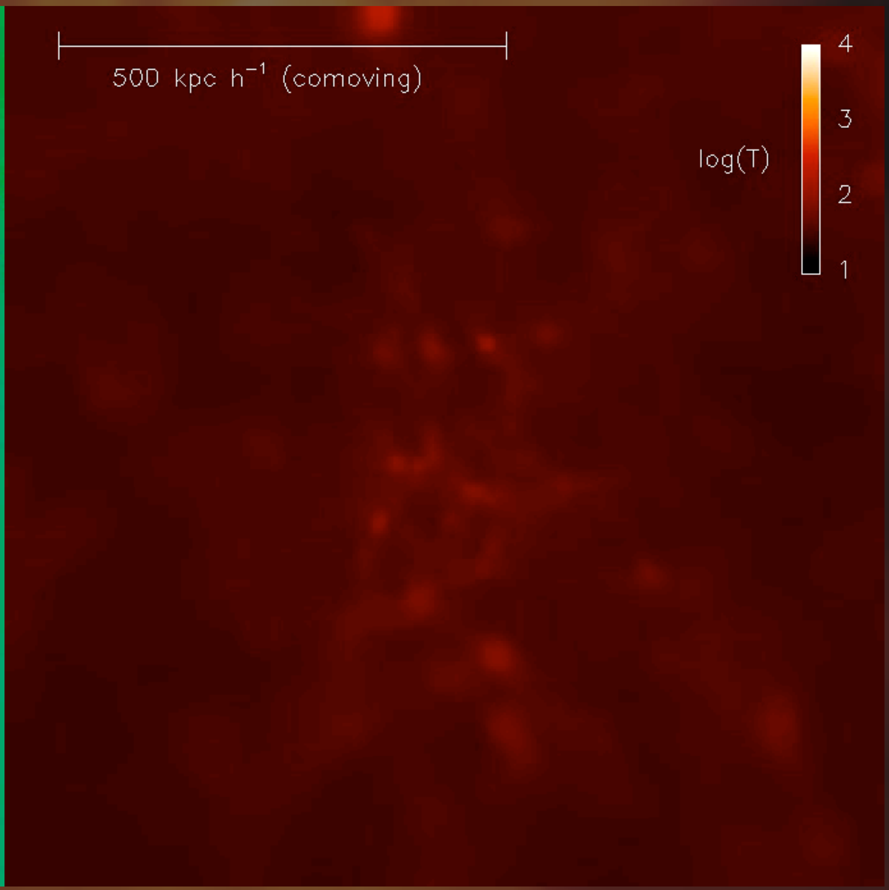


BH Accretion with Radiative Feedback

Density

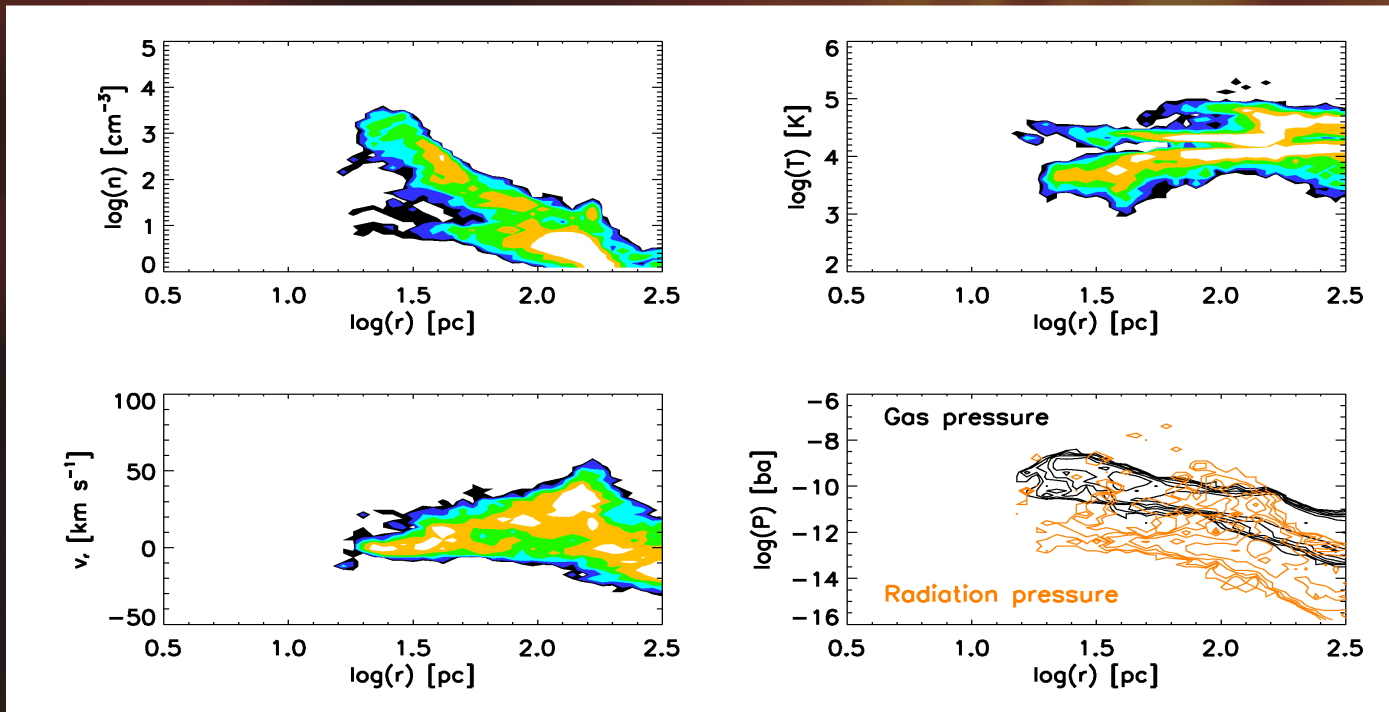


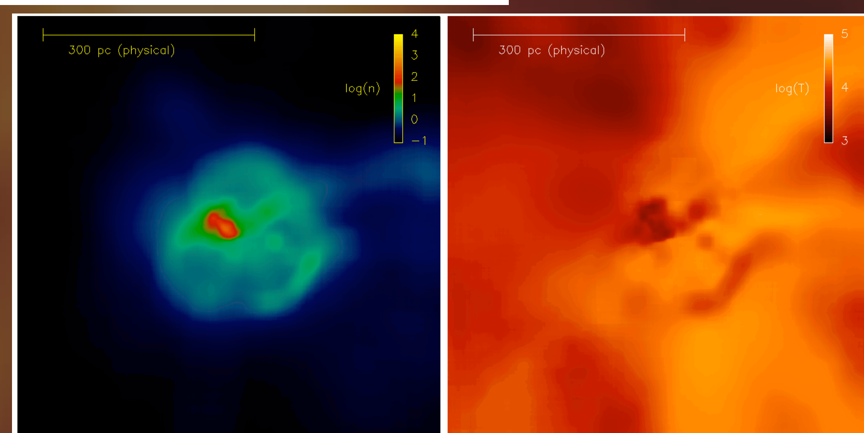
Temperature



- BH forms at z ~ 15
- $M_{BH,init} = 2.5 \times 10^4\ M_{sun}$

Evolution of the Gas with Feedback

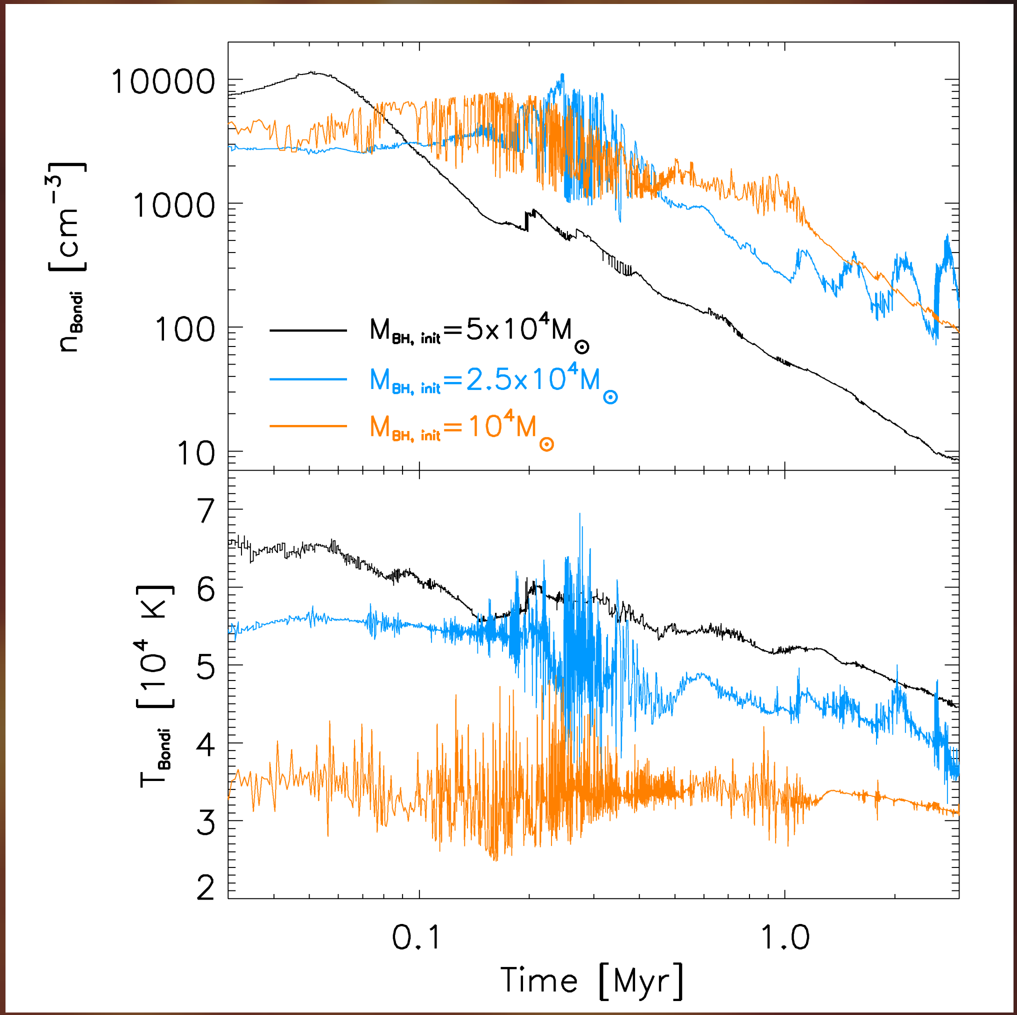




- 3 Myr after BH formation
- BH mass = 2.5×10^4 M_{Sun}

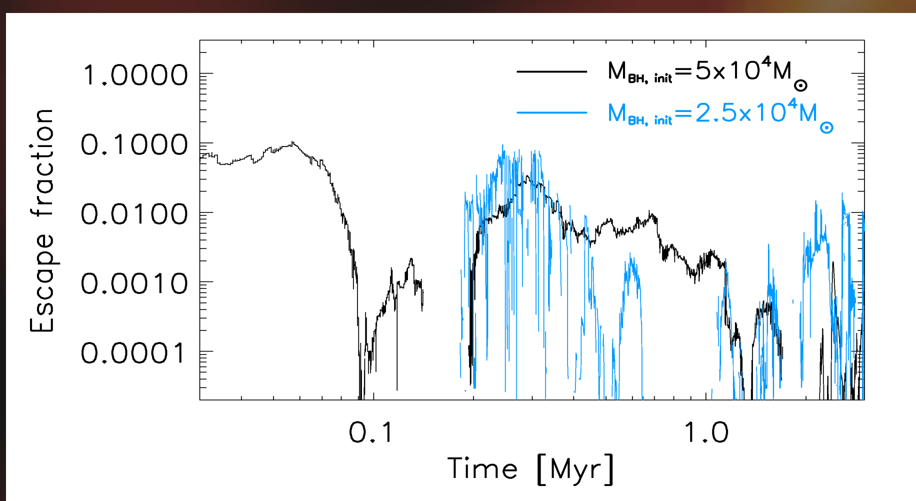
The Accretion Rate

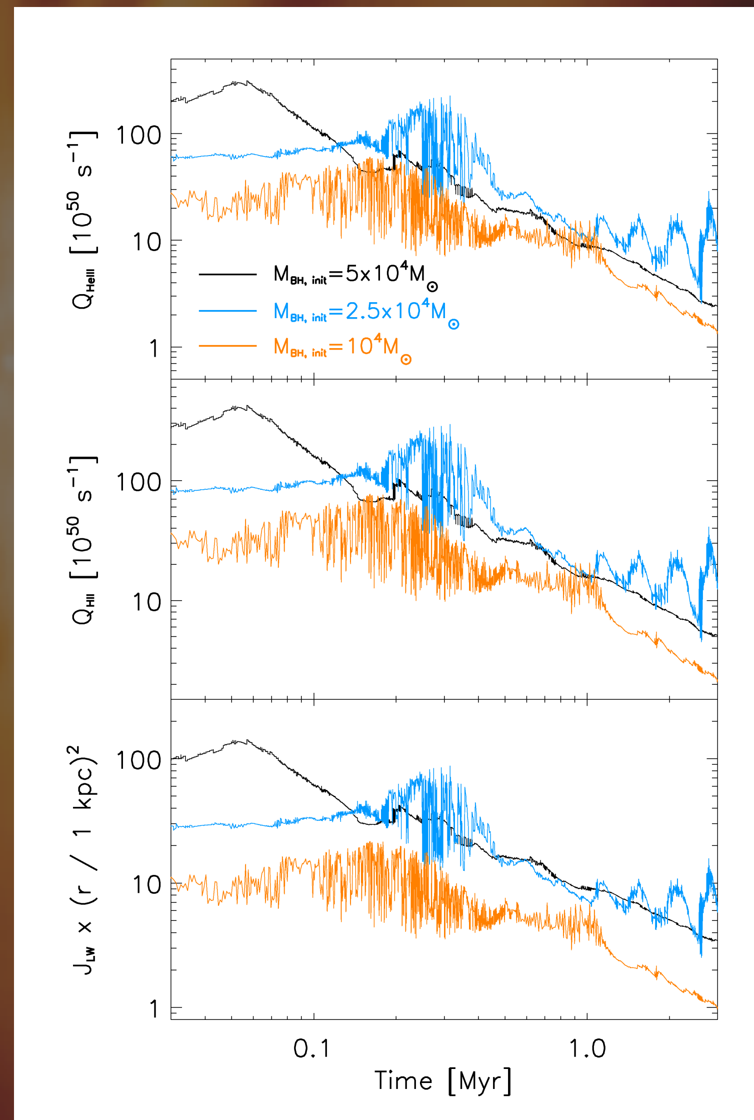
- Accretion rate initially approaches Eddington limit
- Time-averaged Eddington factor drops to < 0.1
- This is due to gas expansion, outflow from photoheating and photoionization pressure



Ionizing and H_2-Dissociating Radiation

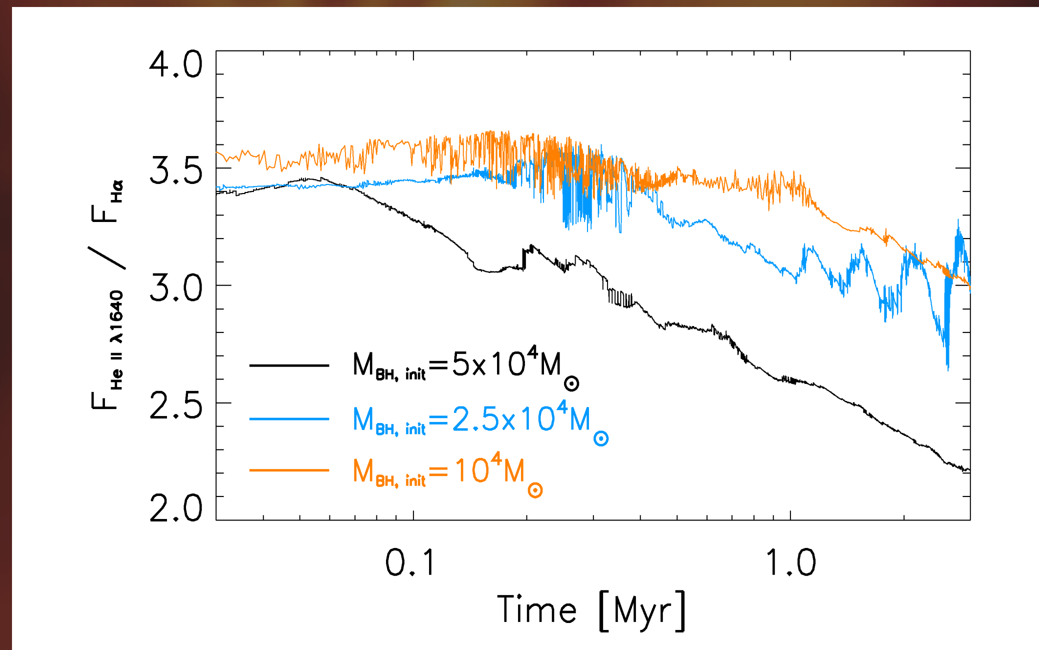
- High energy photon output closely tracks the accretion rate
- With a low escape fraction, ionizing radiation is reprocessed into nebular recombination emission





An Observable Signature of BH Accretion

- Hard spectra from accretion disk yields large He II-ionizing photon output
- Ratio of fluxes in He II λ1640 to Hα higher than even very massive Pop III stars



- Nebular emission due to $> 10^{4\text{-}5}$ M_{sun} BHs at $z < 10$ marginally detectable by NIRSpec on JWST

Credit: jwst.nasa.gov

Summary

- Upper limit to the initial BH mass of ~ $3 \times 10^5\ M_{sun}$
- Accretion rates onto BHs formed by direct collapse, initially near the Eddington rate, drop by an order of magnitude after ~ 10^6 yr

  - A deeper potential needed for efficient accretion

- One observable signature of BH accretion, as opposed to very massive Pop III star formation, is a ratio $L_{\mathrm{He\ II}\ \lambda 1640} / L_{\mathrm{H}\alpha} > 2$

  - This could be detected by the JWST