The Brightest Primordial Sources: Population III Galaxies and Accreting Black Holes

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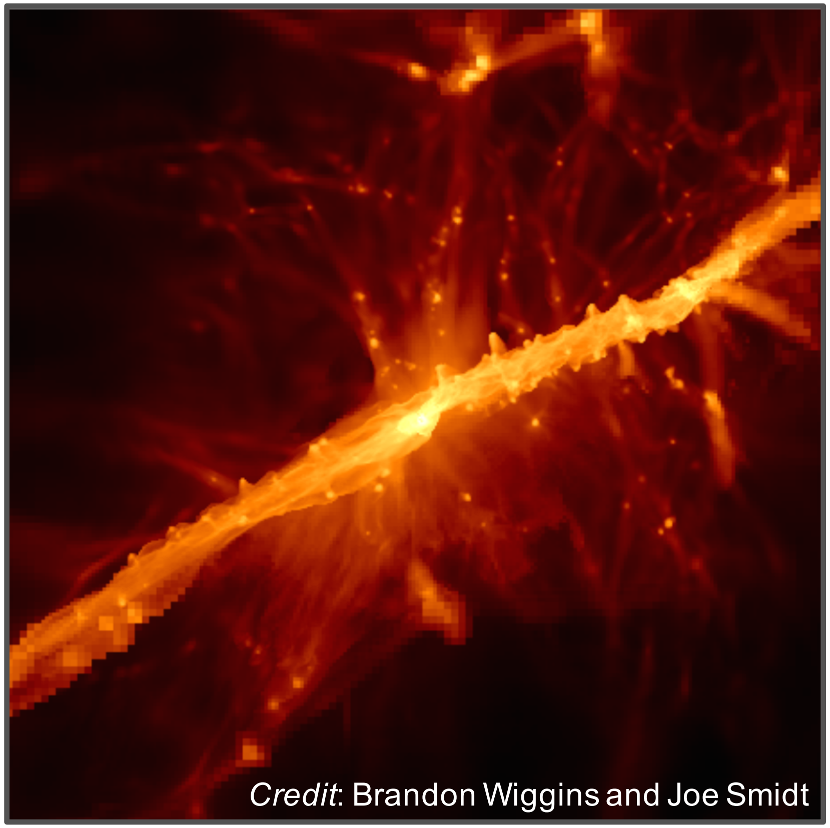
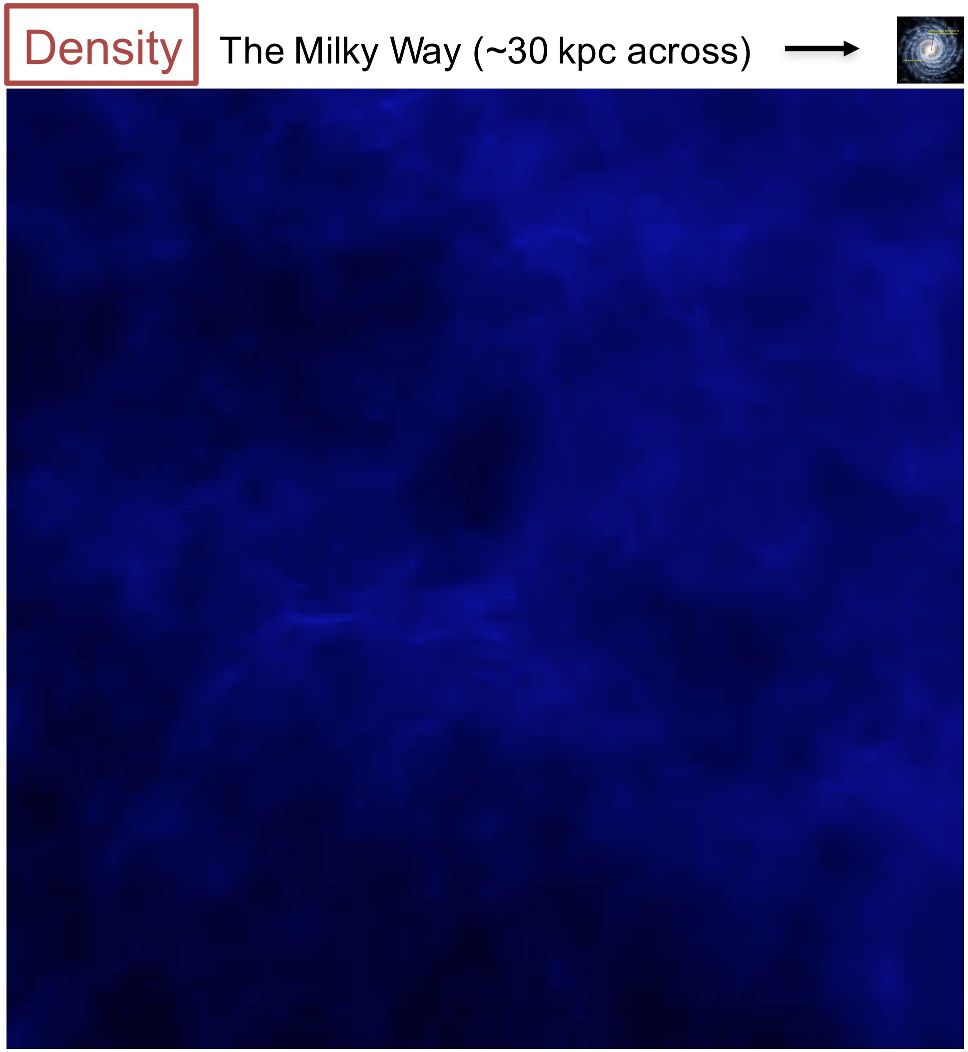


Credit: Brandon Wiggins and Joe Smidt

New Mexico Symposium
November 4, 2016

The Epoch of the First Galaxies



Credit: Claudio Dalla Vecchia (IAC)

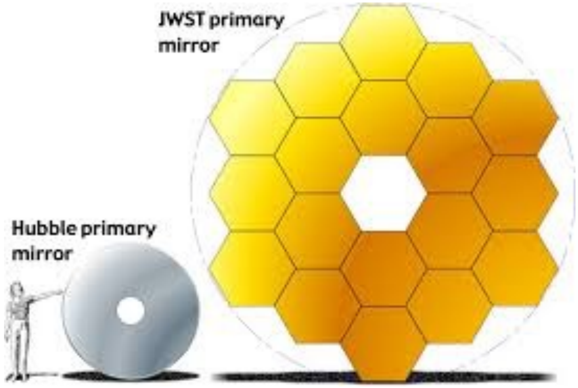
The first stars dramatically transformed the Universe.

The first supernovae ejected the first heavy elements far and wide.

High energy radiation from stars and accreting black holes shaped the formation of the first galaxies.

The Observational Frontier: Primordial Galaxies

The deepest
observations yet
of the high-z Universe
are on the way.



The James Webb Space Telescope
6.5m infrared telescope
Optimized for high-z science
First light in ~2019

Credit: jwst.nasa.gov

The Observational Frontier: Primordial Galaxies

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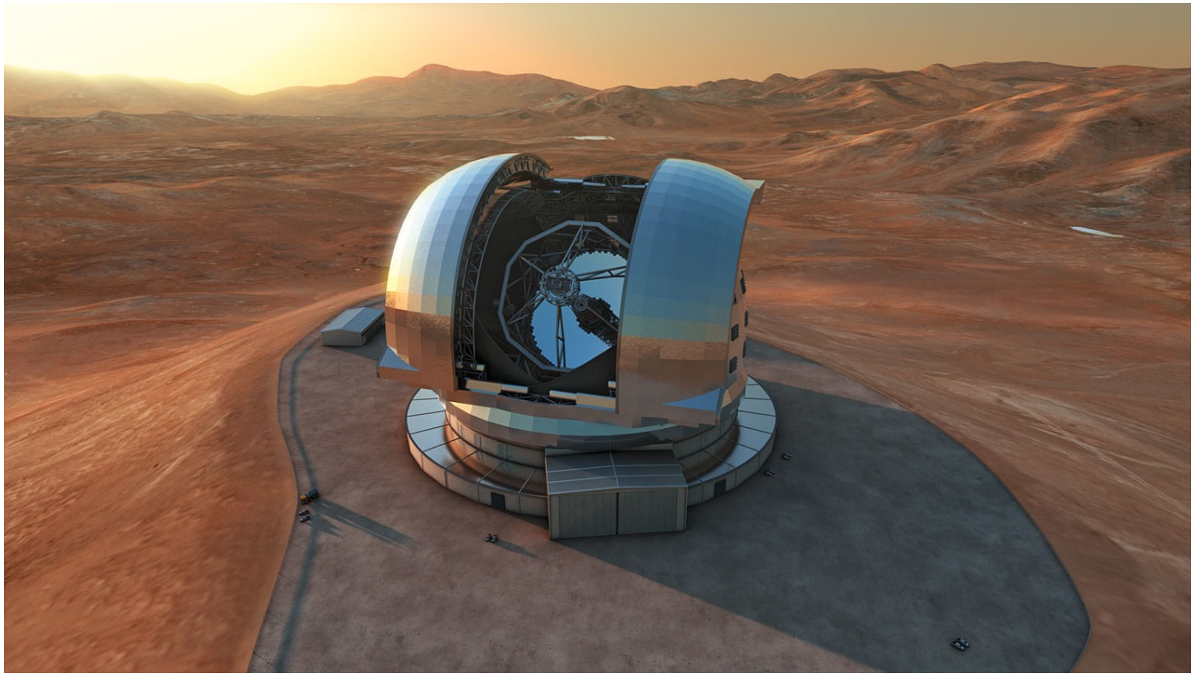


Illustration of a quasar at $z = 7.1$

The European Extremely Large Telescope
The first 40m class optical/infrared telescope
First light in ~2024

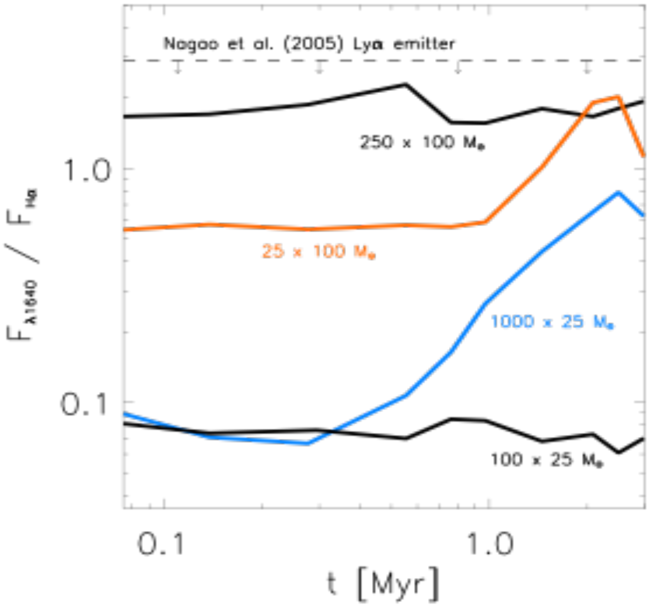
Credit: www.eso.org

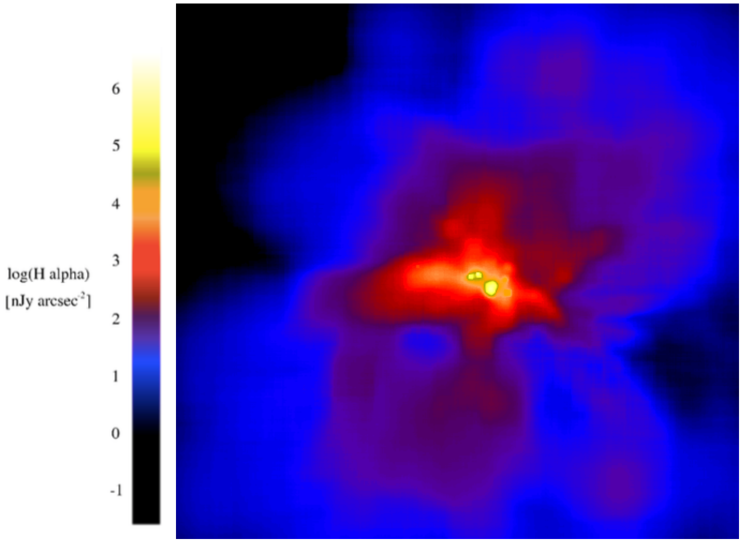
How will we know when we see the first stars?

Low opacity makes Pop III stars much hotter than metal-enriched stars

Lack of cooling species in primordial gas may lead to massive stars

These both suggest bright Lyman-α and He II 1640 angstrom emission
(e.g. Bromm et al. 2001; Oh et al. 2001; Tumlinson et al. 2001; Schaerer 2002)

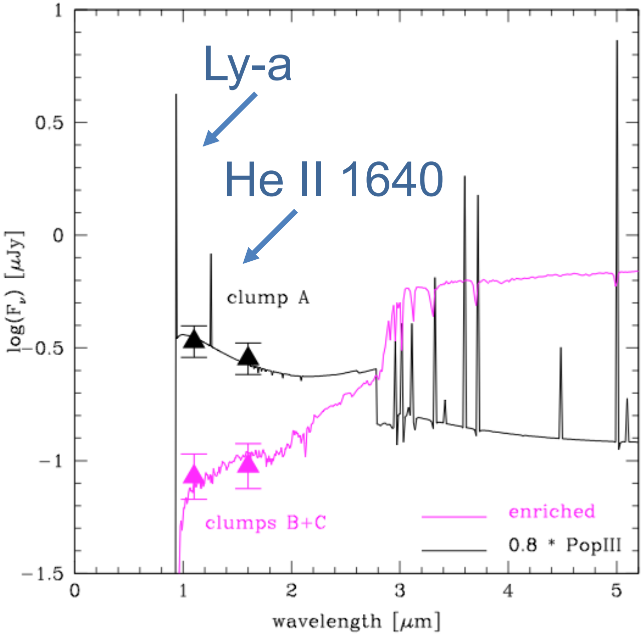




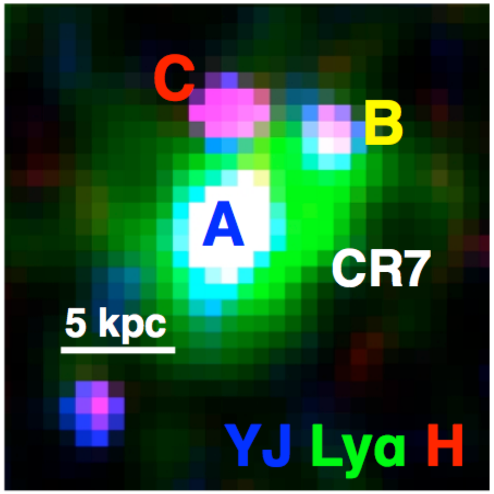
JLJ, Greif, Bromm, Klessen & Ippolito (2009)

A Candidate Primordial Galaxy in CR7

- The most luminous Ly-α emitter at z > 6 (Sobral et al. 2015)
- Low metallicity, but perhaps not primordial (Bowler et al. 2016; Hartwig et al. 2016)
- Luminosity of He II 1640 angstrom line suggests source is either primordial stars or an accreting black hole (Agarwal et al. 2015; Pallottini et al. 2015; Hartwig et al. 2015; Dijkstra et al. 2016; Smith et al. 2016)



H_2-dissociating radiation from sources **B** and **C** may have impacted formation of source **A**, at *z* > 10



Sobral et al. (2015)

CR7: Population III Galaxy or Accreting Black Hole?

Credit: *New York Times*, June 2015

Population III Stars

Stellar mass ~ 10^7 M_{Sun}

. . . if very top-heavy IMF

Stellar mass ~ 10^9 M_{Sun}

. . . if Saltpeter IMF

Star formation rate > 0.1 M_{Sun} yr^{-1}

(Sobral et al. 2015; Visbal et al. 2016; Xu et al. 2016)

Accreting Black Hole

Black hole mass > 10^6 M_{Sun}

Star formation suppressed

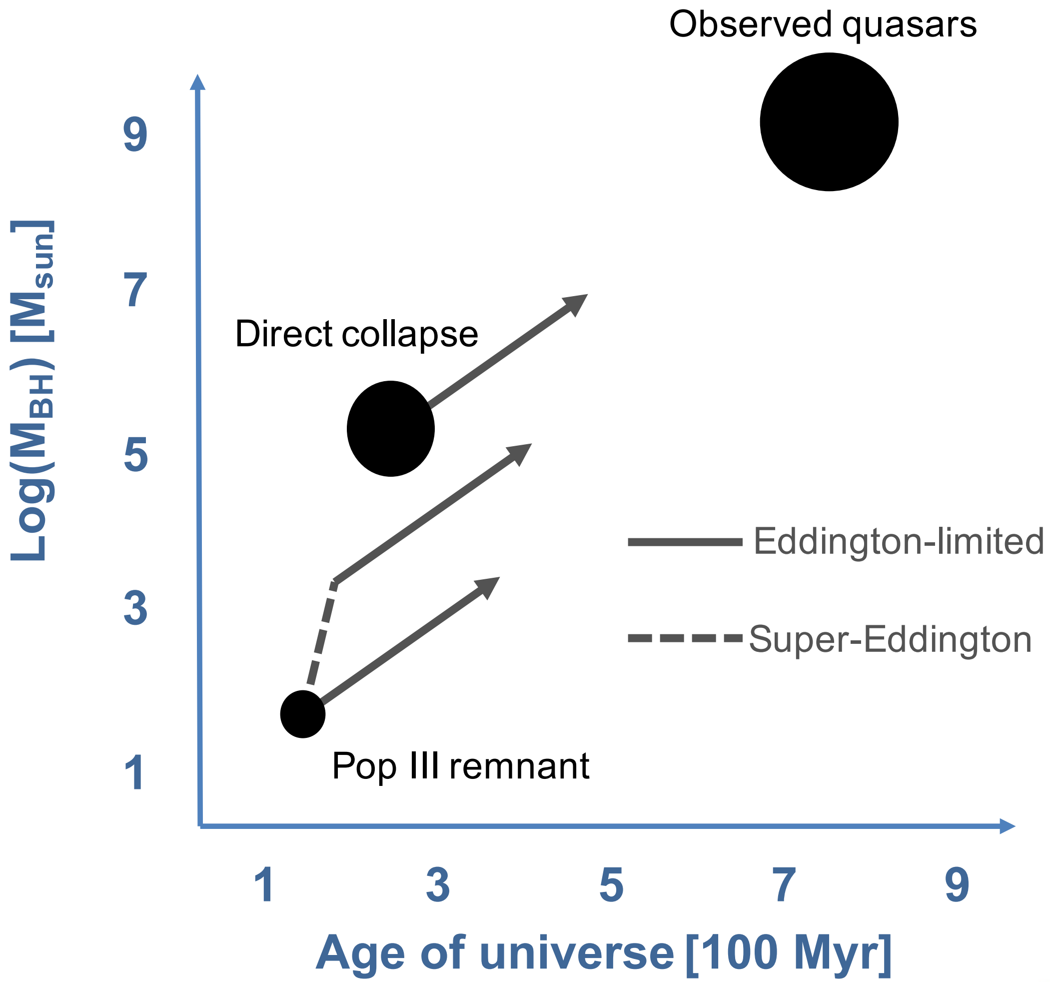
. . . to satisfy $Z < 10^{-2}$ Z_{Sun}

(Pallottini et al. 2015; Agarwal et al. 2016; Hartwig et al. 2016; Smidt et al. 2016; Smith et al. 2016; Dikjkstra et al. 2016; see also Bowler et al. 2016)

Formation and Growth of the First Black Holes

- Direct collapse BHs form in more massive dark matter halos than the first Pop III BHs, and so typically form later.

- The large initial masses of DCBHs ease the requirements on accretion rate and radiative efficiency implied by high-z quasars.



Reviews: Volonteri 2012; Haiman 2013; JLJ & Haardt 2016; Latif & Ferrara 2016

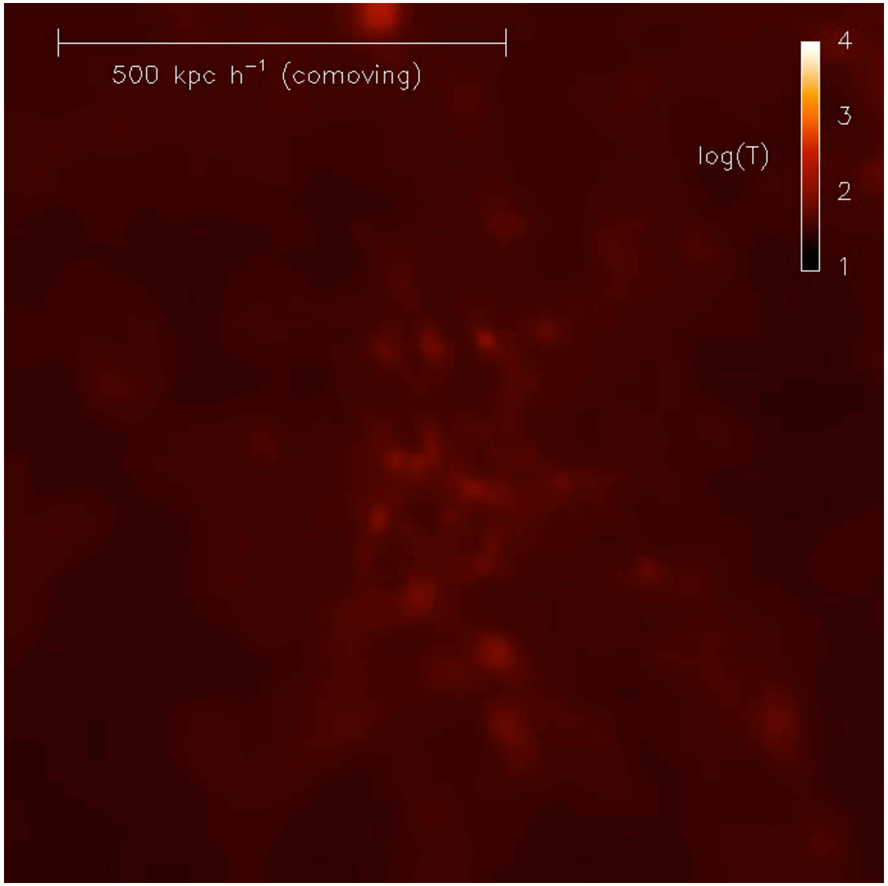
DCBH Formation from Hot Primordial Gas

- An elevated H_2-dissociating (LW) radiation field suppresses cooling of the primordial gas (e.g. Dijkstra et al. 2008; Agarwal et al. 2012; Sugimura et al. 2014; Visbal et al. 2014; Inayoshi et al. 2015; Regan et al. 2014, 2016)

- Gas cools to only ~ 10^4 K by collisional excitation of hydrogen (e.g. Bromm & Loeb 2003; Wise et al. 2008; Regan & Haehnelt 2009; Shang et al. 2010; Latif et al. 2013; Becerra et al. 2015; Choi et al. 2015)

- *Gas collapses and accretes onto central supermassive star at ~ 0.1 – 1 M_{sun} yr^{-1}* (e.g. Begelman 2010; JLJ et al. 2012; Schleicher et al. 2013; Hosokawa et al. 2013; Sakurai et al. 2015; Pacucci & Ferrara 2015)

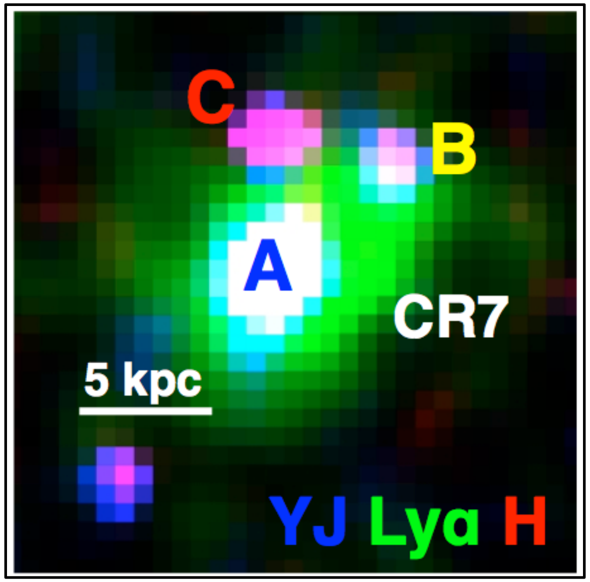
Gas temperature

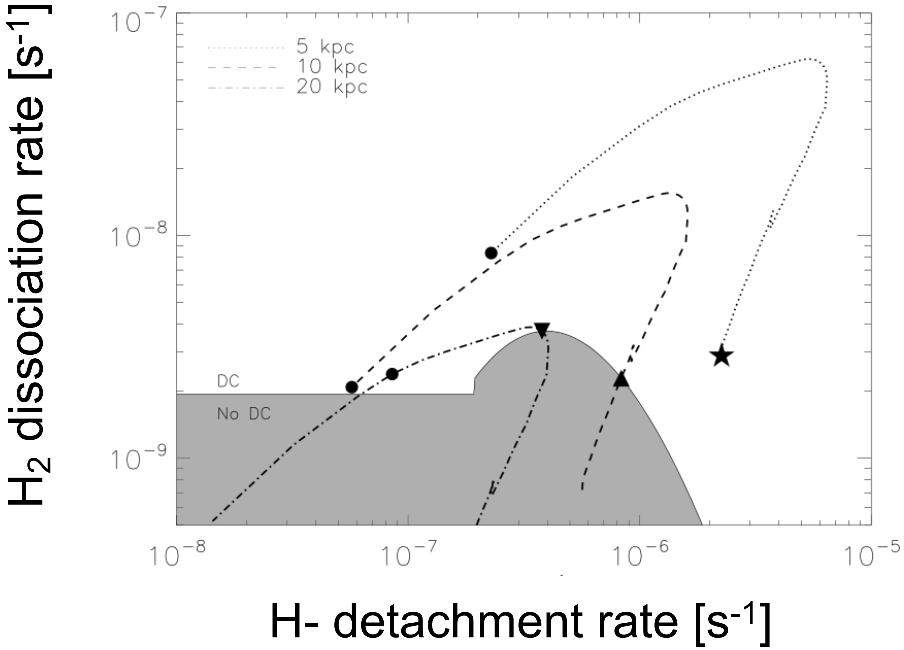


JLJ, Khochfar, Durier & Greif (2011)

Modeling the Origin of CR7 as a Black Hole

- Modeling of the star formation history in clumps B and C suggests that the LW flux is high enough for DCBH formation in clump A, if their separation is < 20 kpc





- DCBH host halo merges with nearby galaxy-hosting halo just prior to $z = 6.6$

Agarwal, JLJ, et al. (2016)

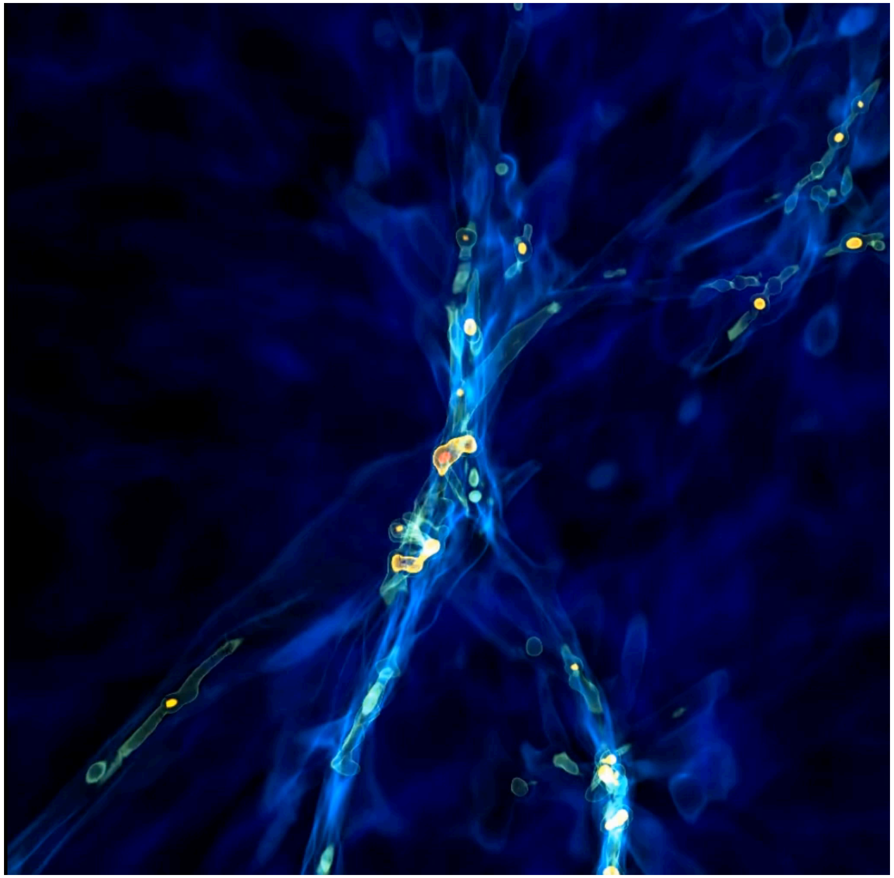
Cosmological Simulations of CR7 as an Active Black Hole

- Our *Enzo* simulations start at $z = 15$, when halo is seeded at atomic cooling threshold; ends at redshift of CR7, $z = 6.6$

- Here we focus on an isolated ~ 3×10^{10} M_{sun} halo (e.g. Agarwal et al. 2015), neglecting the neighboring clumps B and C that produce LW radiation

- We account for a background LW radiation field with $J_{21} = 10^4$ as a simplification

Density

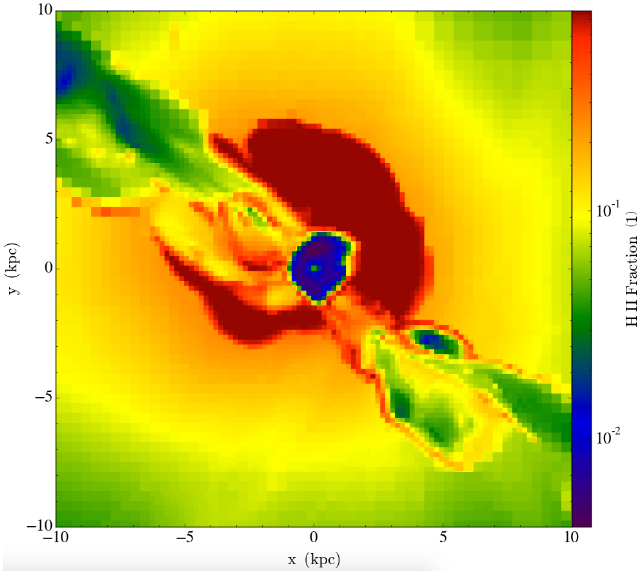


Credit: Joe Smidt

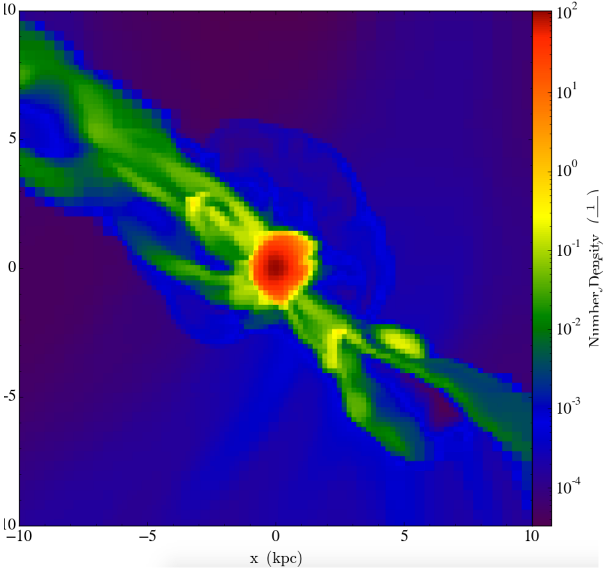
Smidt, Wiggins & JLJ (2016)

Modeling X-ray Feedback from the BH in CR7

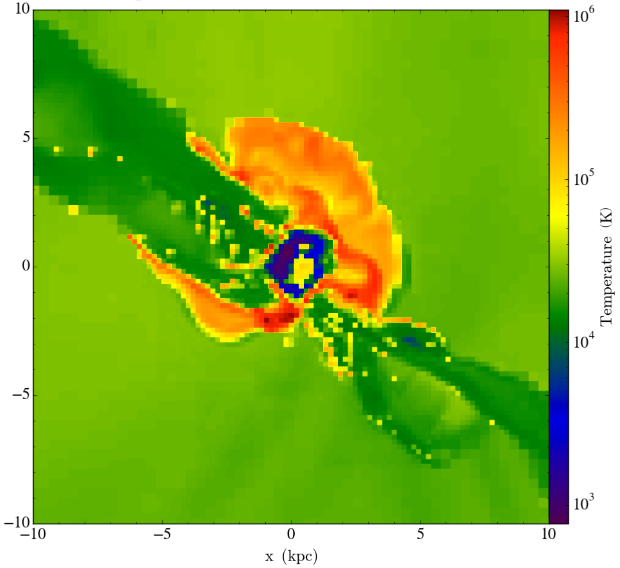
Ionized fraction



Density



Temperature



Properties of the black hole at z = 6.6:

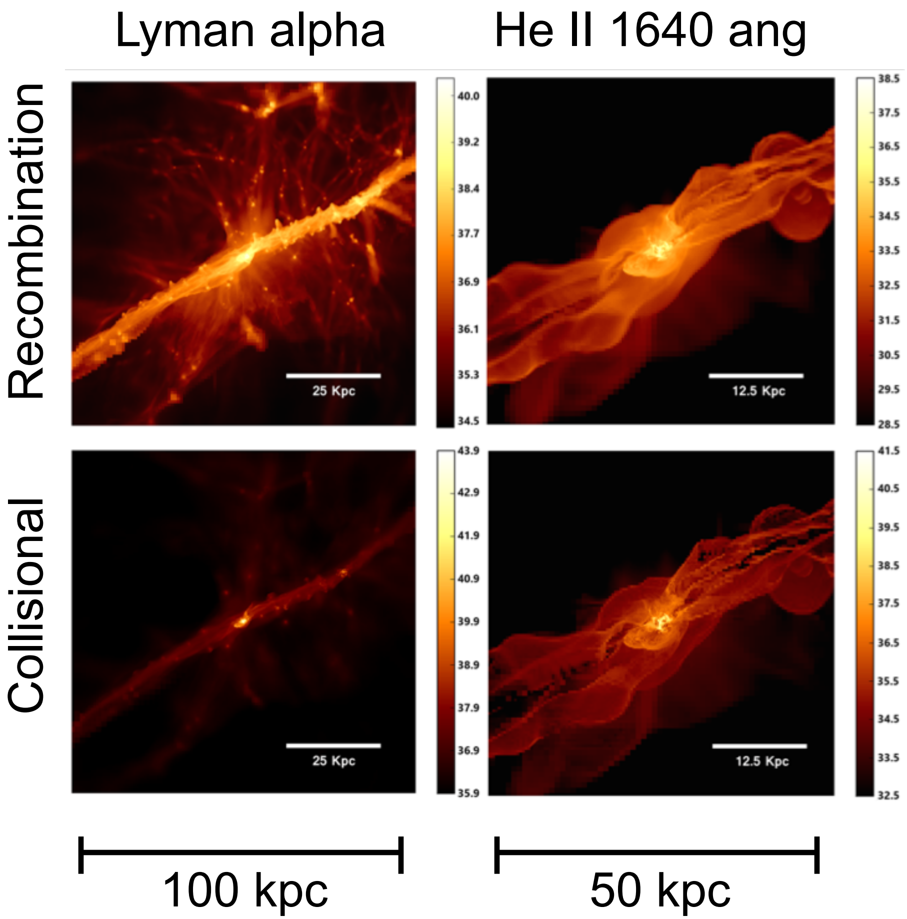
M_{BH} ~ 2 x 10^7 M_{sun}
dM_{BH}/dt ~ 0.16 M_{sun} yr^{-1} (0.25 Eddington)
Accretion rate varies on ~ 10^3 yr timescales

Smidt, Wiggins & JLJ (2016)

Modeling the Nebular Emission from CR7

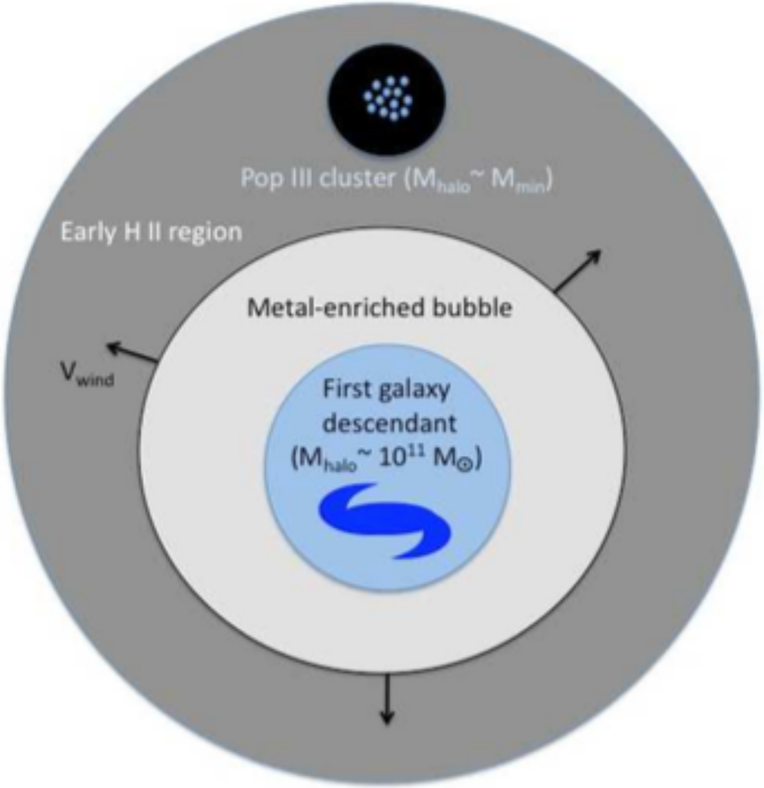
- UV radiation ionizes the gas, which then emits via recombination.
- X-rays heat the gas, but only partially ionize, leading to emission from collisionally-excited species (see also Smith et al. 2016)
- Slightly low luminosities suggest that the halo hosting clump A in CR7 may be > 3 x 10^{10} M_{sun}

	Obs	Sim
Lyα [10^{43} erg s^{-1}]	> 8.3	50
He II 1640 [10^{43} erg s^{-1}]	2	2.3
Width He II 1640 [km s^{-1}]	130	210
Width Lyman-α [km s^{-1}]	260	270

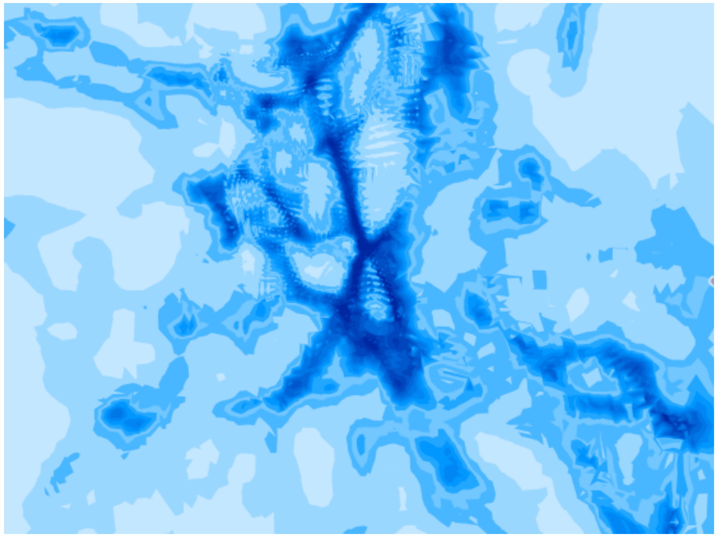


Smidt, Wiggins & JLJ (2016)

Formation of Massive Population III Galaxies



Collapsing photo-heated gas

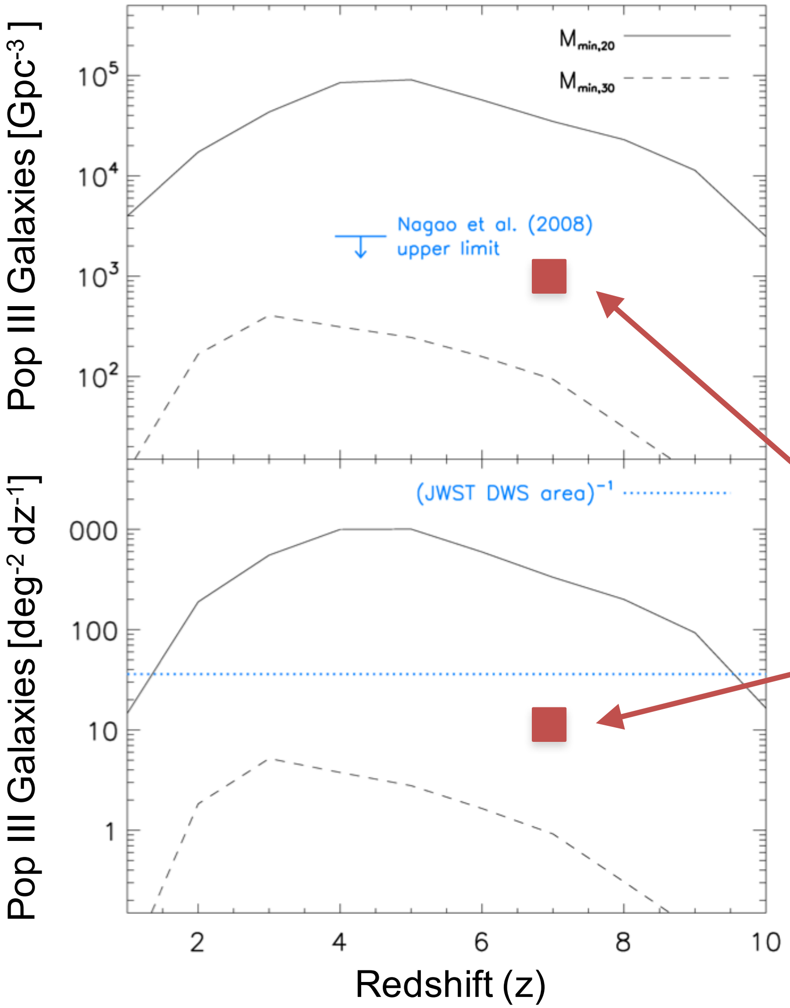


Primordial haloes subjected to strong ionizing radiation collapse at large mass scales $M_{halo} \sim 10^9\ M_{Sun}$.
(e.g. Dijkstra et al. 2004)

This could set stage for a Pop III starburst.

JLJ 2010; JLJ, Whalen et al. 2014; also Visbal et al. 2016

Population III Stars: An Explanation for CR7



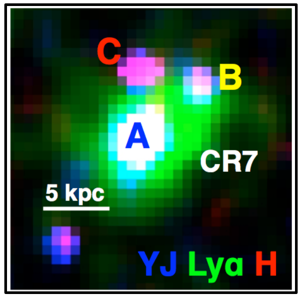
JLJ (2010)

- Bright Population III galaxies may form in ~ 10^9 M_{sun} halos at modest redshifts, due to photoheating of IGM during reionization (JLJ 2010; see also Trenti et al. 2009 on LW feedback)

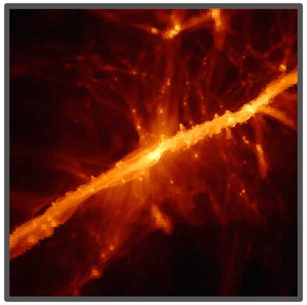
Revisited: Visbal et al. (2016) have now applied this theory to model CR7, finding a similar cosmic abundance of Pop III-powered galaxies

*A star formation efficiency of ~ 0.07, assuming a very top-heavy IMF, is required

-Note also that Smith et al. (2016) find that this model doesn't produce the observed Lyα velocity offest.



The Brightest Primordial Sources: Summary



- The deepest observations ever of the first galaxies are coming soon.
- We have observations of one candidate primordial galaxy already in CR7.
- This is likely powered by an accreting black hole, but could also be a massive cluster of Population III stars.
- The most massive Population III galaxies may be found in the vicinity of high-*z* galaxies which photoheat the IGM to high temperatures.