Observational Signatures of the First Galaxies

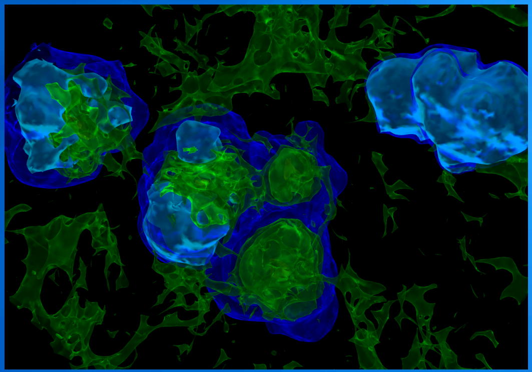
Jarrett L. Johnson

TMoCS
Theoretical Modeling of Cosmic Structures

MPE

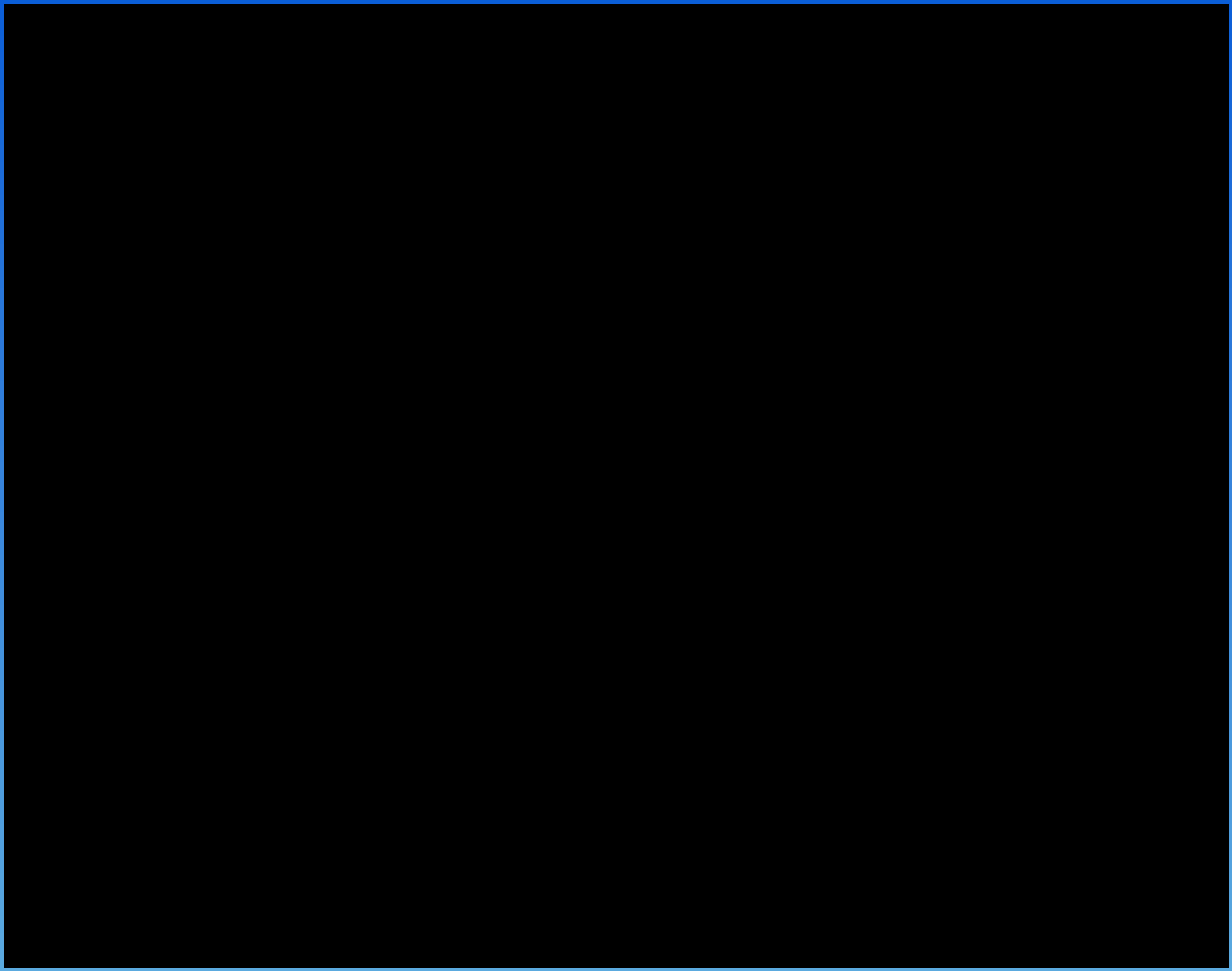
Key Questions

- How can we constrain the IMF of Pop III stars?
- Where should we expect to find Pop III star formation?
- Can we find metal-free stellar populations with the JWST?



Ionizing Radiation from the First Stars

- Radiation from the first stars heats and ionizes the primordial gas!
- *This impacts subsequent star formation, galaxy formation, and leads to strong nebular emission from H II regions*



- ionized gas
- molecule-rich gas

~ 30 kpc (physical)

JLJ, Greif & Bromm (2007)

Spectral Signatures of Pop III Star Formation

- Metal-free (Pop III) stars, and especially massive Pop III stars, are hot (e.g. 10^5 K)

Ezer & Cameron (1971); Castellani et al. (1983); El Eid et al. (1983); Bond et al. (1984); Eryurt-Ezer & Kiziloglu (1984);

- High UV flux leads to photoionization of primordial gas (H and He) and to strong recombination emission in Lya, Ha, and He II l1640

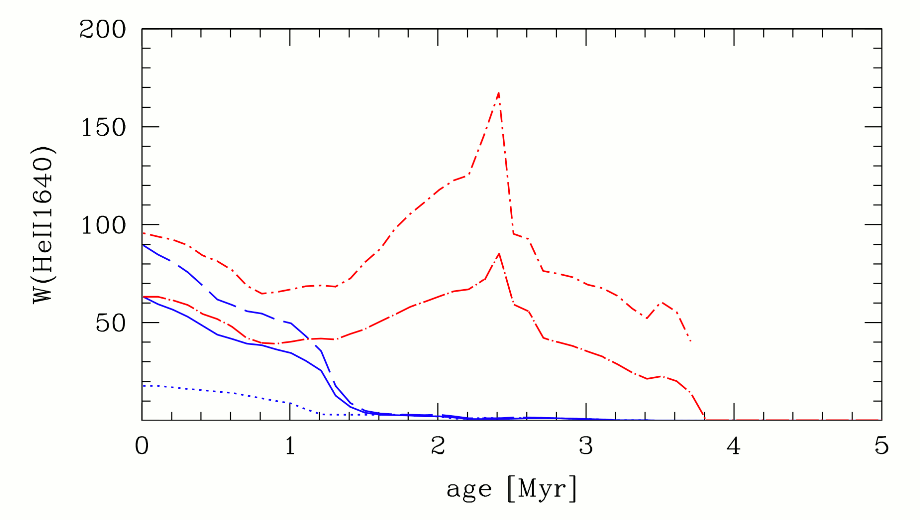
Bromm et al. (2001); Oh et al. (2001); Tumlinson et al. (2001); Schaerer (2002, 2003)

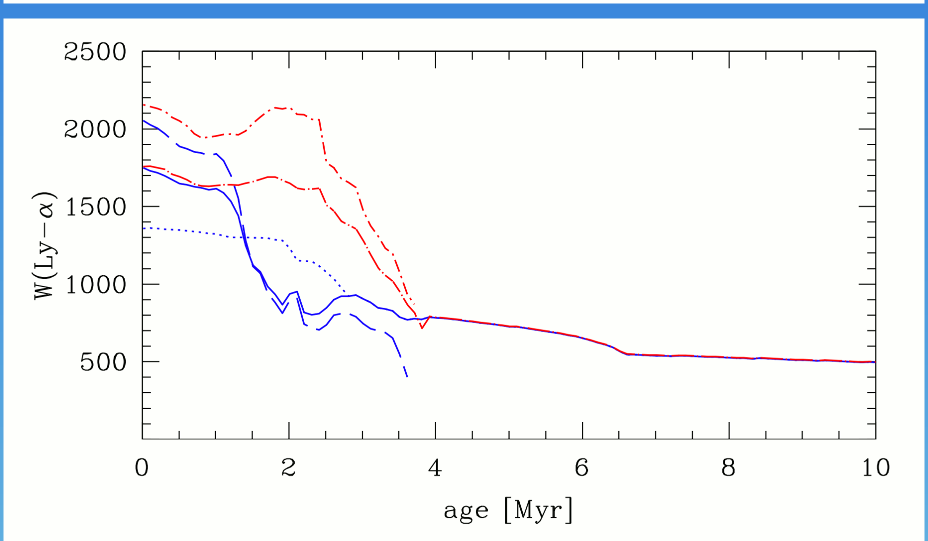
- *Strategies to identify Pop III star formation:*
  1) Look for galaxies with high He II l1640/Lya or He II l1640/Ha ratios
  2) Look for galaxies with high equivalent widths of Lya and He II l1640

Fosbury et al. (2003); Shapley et al. (2003) Dawson et al. (2004); Nagao et al. (2005, 2008); Prescott et al. (2009); Bouwens et al. (2009); Wang et al. (2009)

Spectral Signatures of Pop III Star Formation

- The spectral properties of Pop III stellar clusters change with time due to stellar evolution
- Model spectra including nebular emission, assuming static photoionized regions
- *Simulations capturing dynamical evolution of H II and He III regions are important complements to such models!*

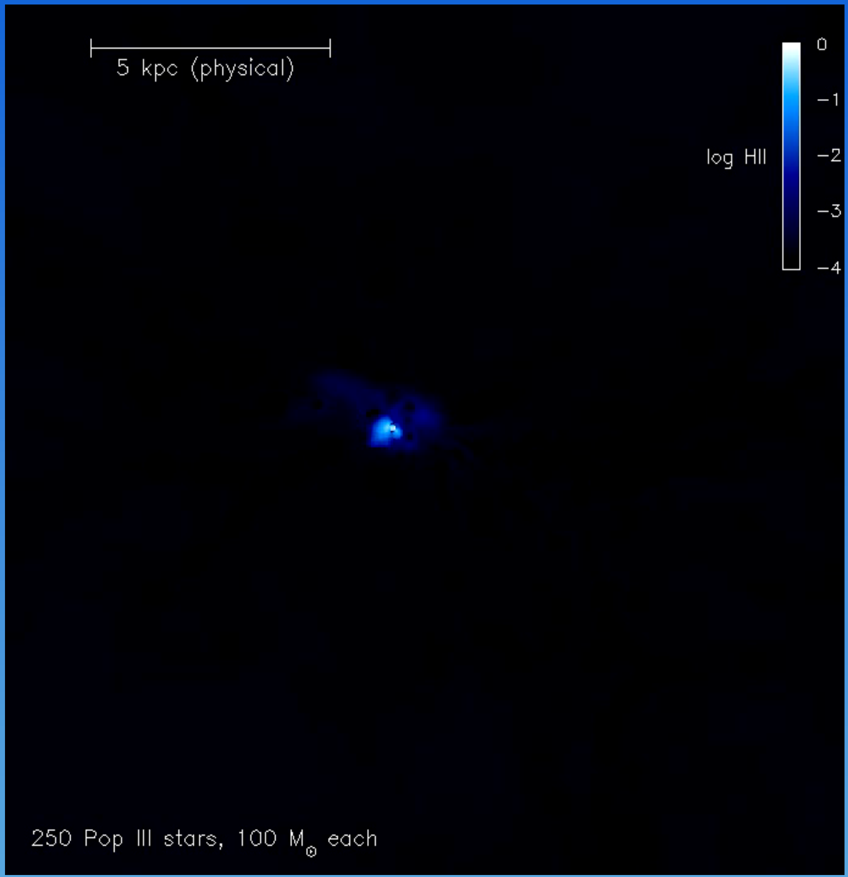




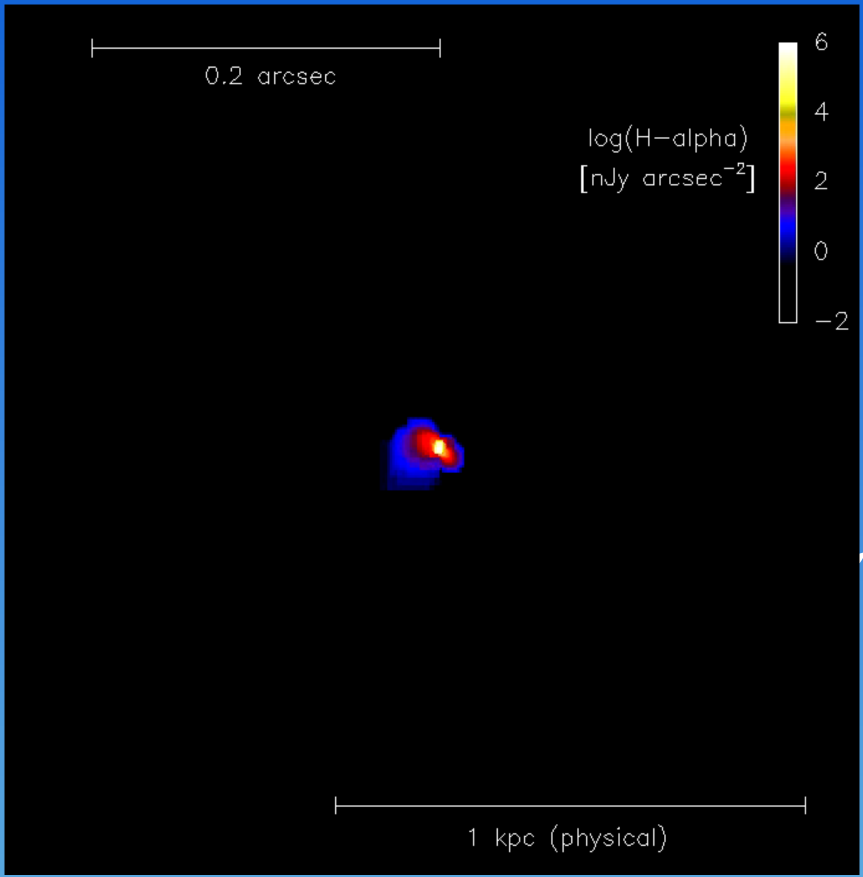
Schaerer (2002)

Photoionized Regions in the First Galaxies

Ionized fraction



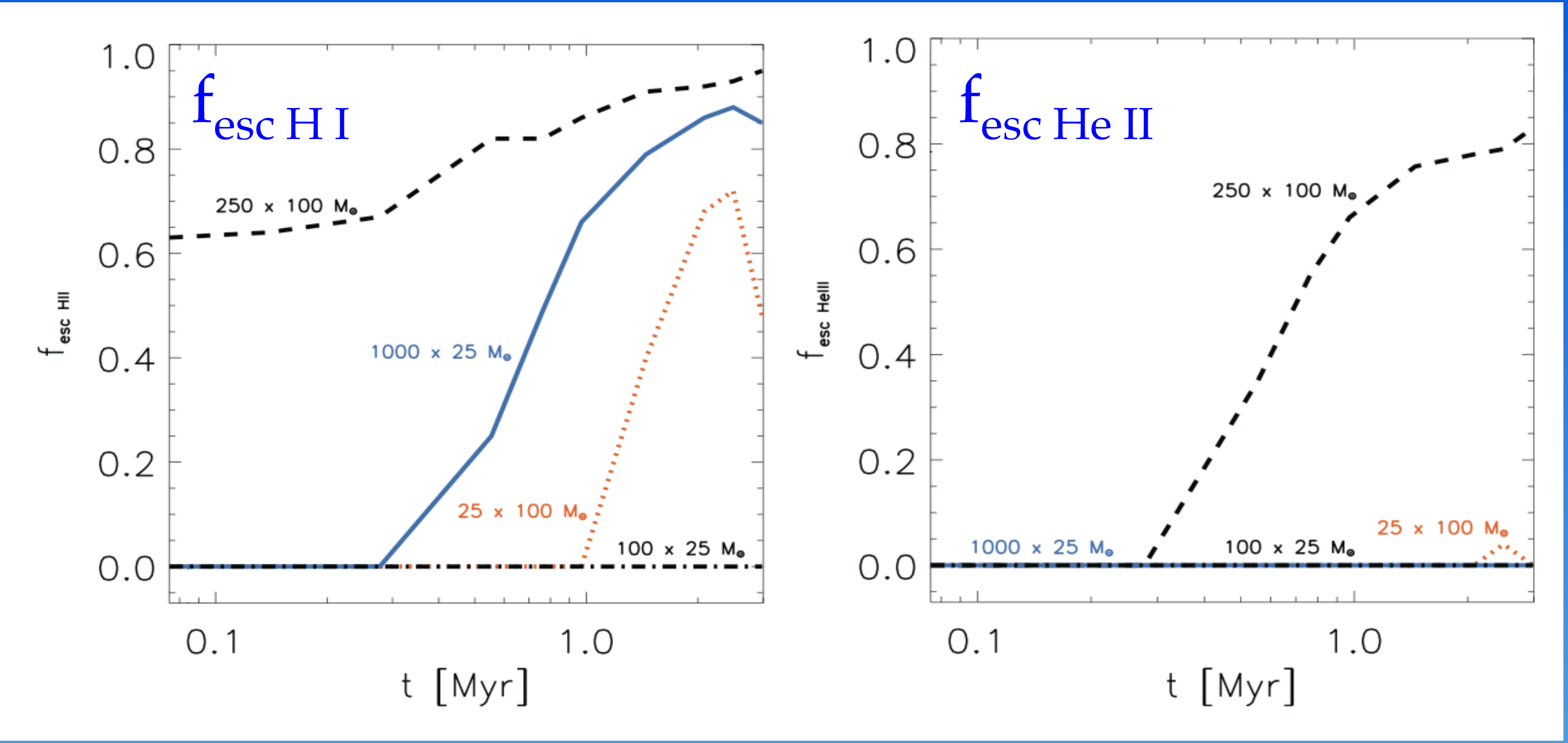
Observed flux in Hα



Cluster of 100 M_{sun} Pop III stars

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

Escape of Ionizing Photons from the First Galaxies



- Photoheating leads to *dynamical evolution of H II and He III regions*

⟶ Dramatic changes in f_{esc}

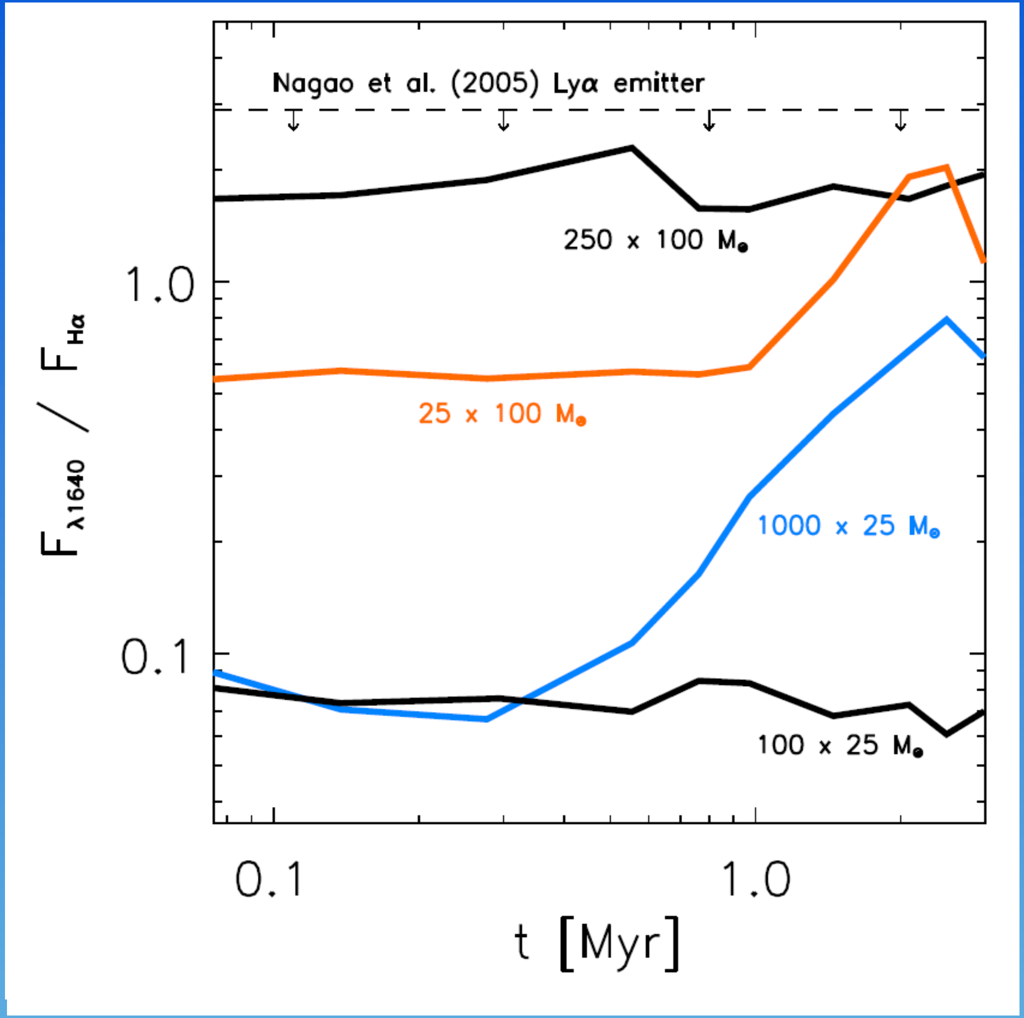
⟶ Large variation in nebular emission

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

Recombination Emission from the First Galaxies

- Temporal evolution of the stellar mass to light ratio

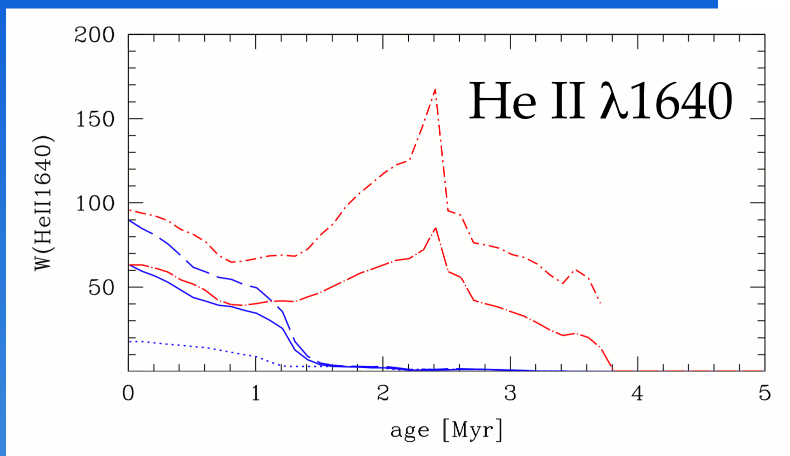
- Difficult to distinguish between different IMFs, total stellar masses using flux ratios

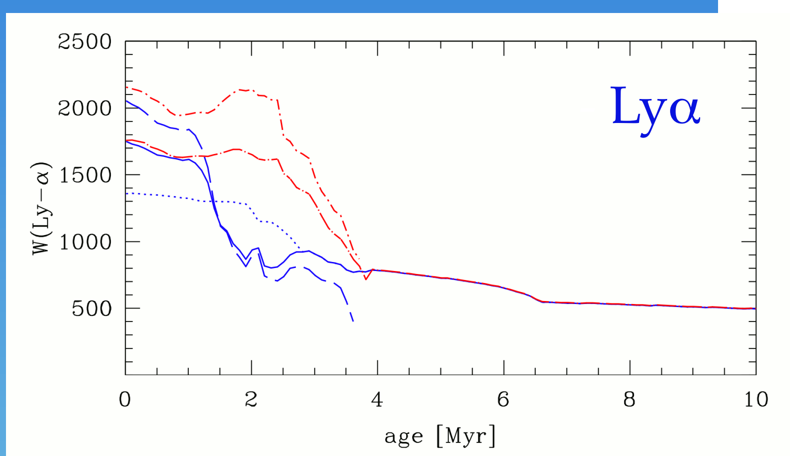


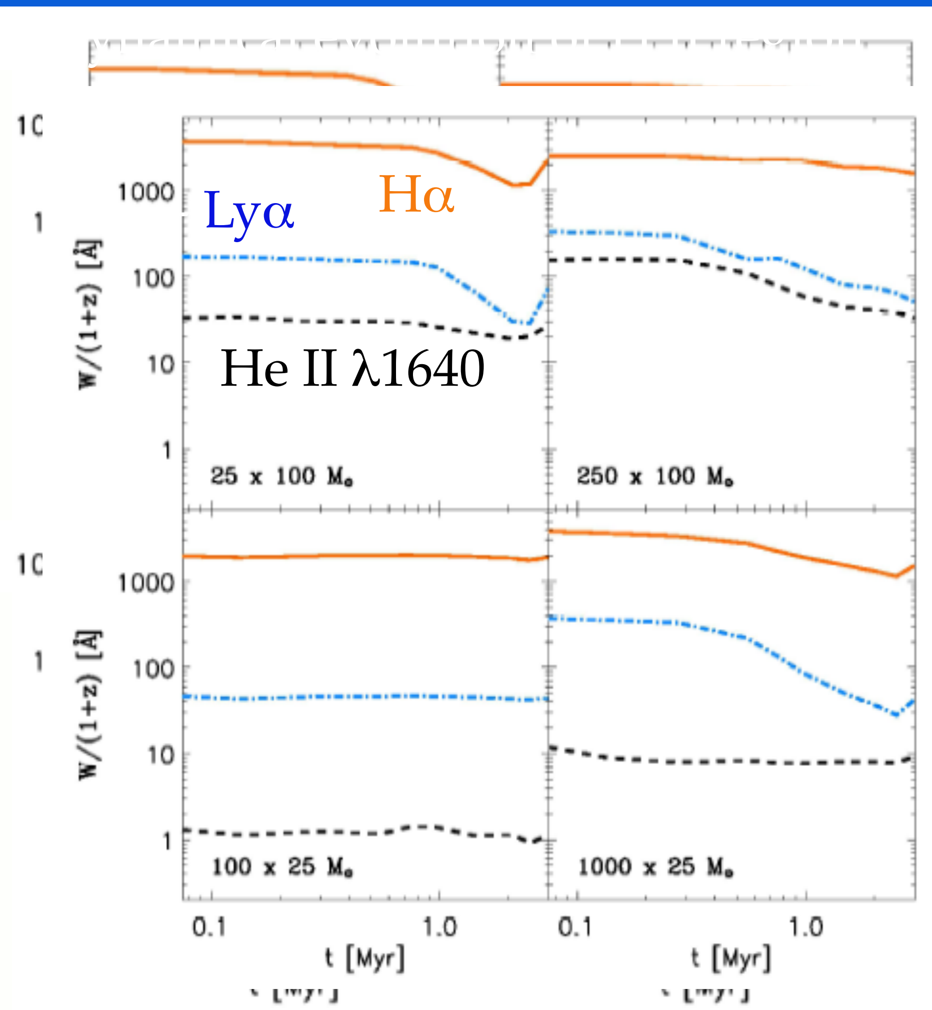
JLJ, Greif, Bromm, Klessen & Ippolito (2009)

Pop III Stellar IMF Indicators

Stellar evolution







Schaerer (2002)

JLJ et al. (2009)

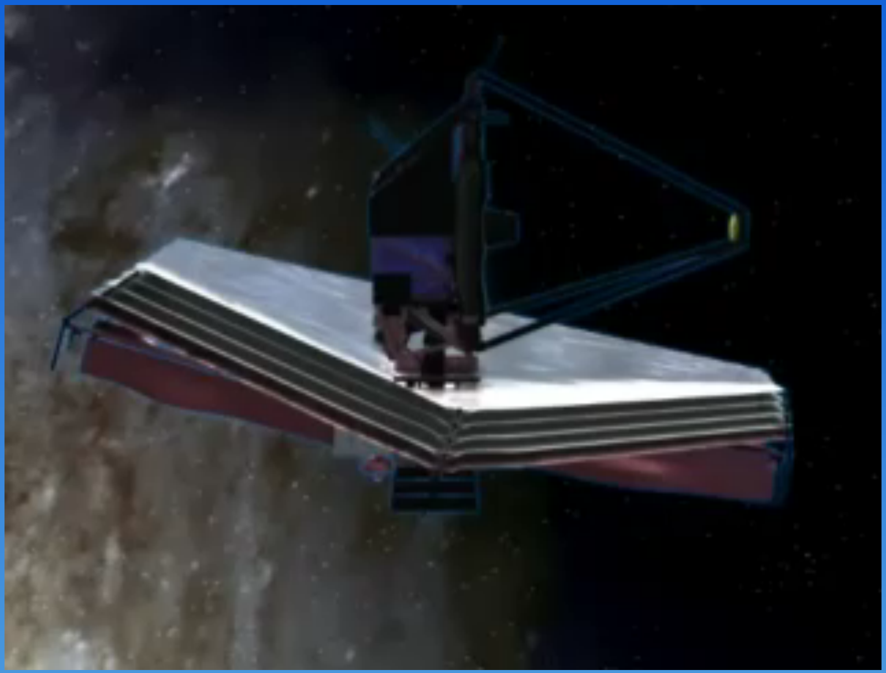
Finding Pop III Stars with the JWST

- The *first* stars and galaxies are likely to distant and faint for detection (e.g. Barkana & Loeb 2000; Gardner et al. 2006; Ricotti et al. 2008; JLJ et al. 2009)

- Pop III SNe (or GRBs) could be detected out to very high z (e.g. Weinmann & Lilly 2005; Wise & Abel 2005; Haiman 2008)

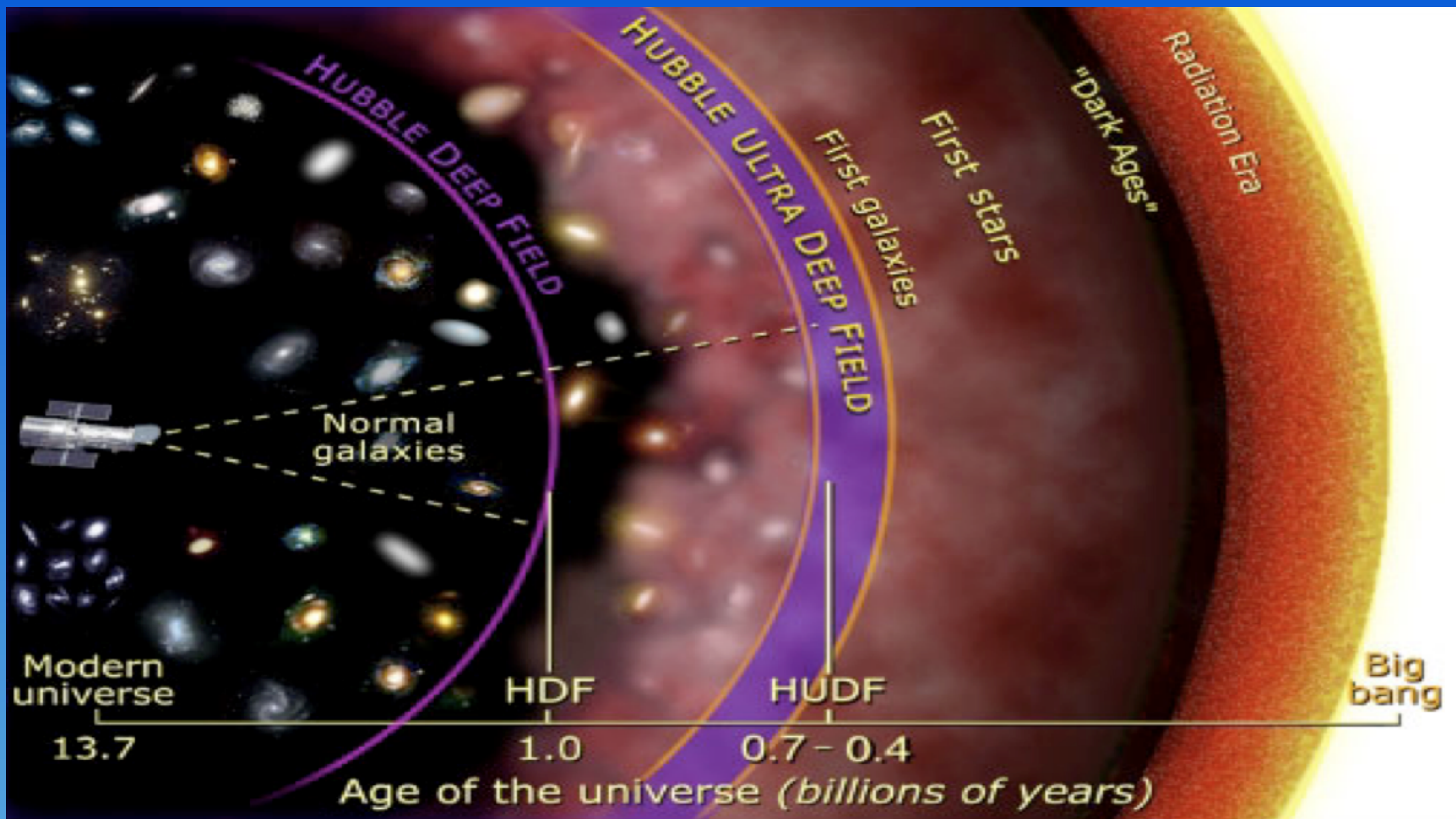
- Some sufficiently bright (massive) early galaxies may host some Pop III star formation (see e.g. Jimenez & Haiman 2006)

  \- *Requires inefficient mixing of metals with the primordial gas*



- *Can we use the JWST to find primordial stars and constrain the Pop III IMF?*

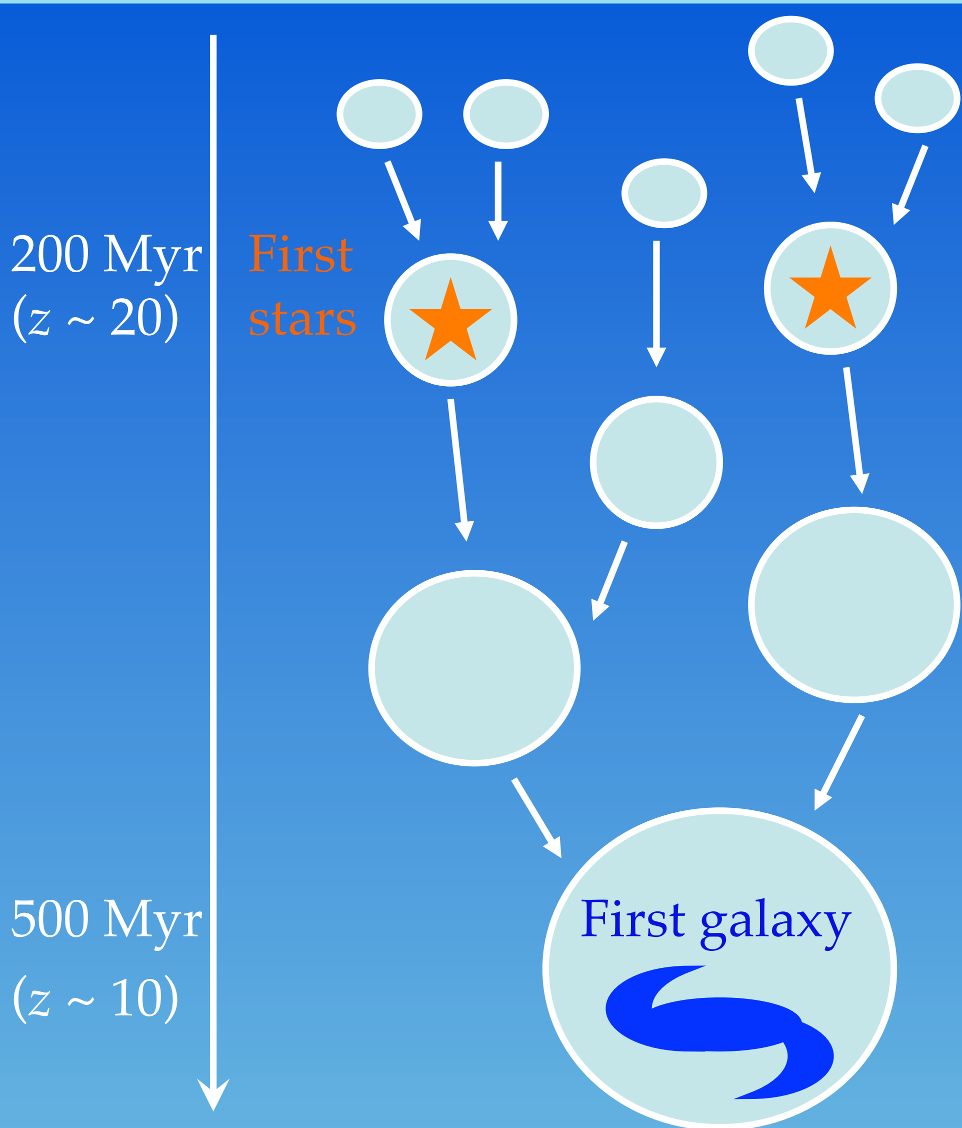
Finding Pop III Stars with the JWST



The epoch of Pop III star formation?

The first stars and galaxies

Formation of the First Galaxies

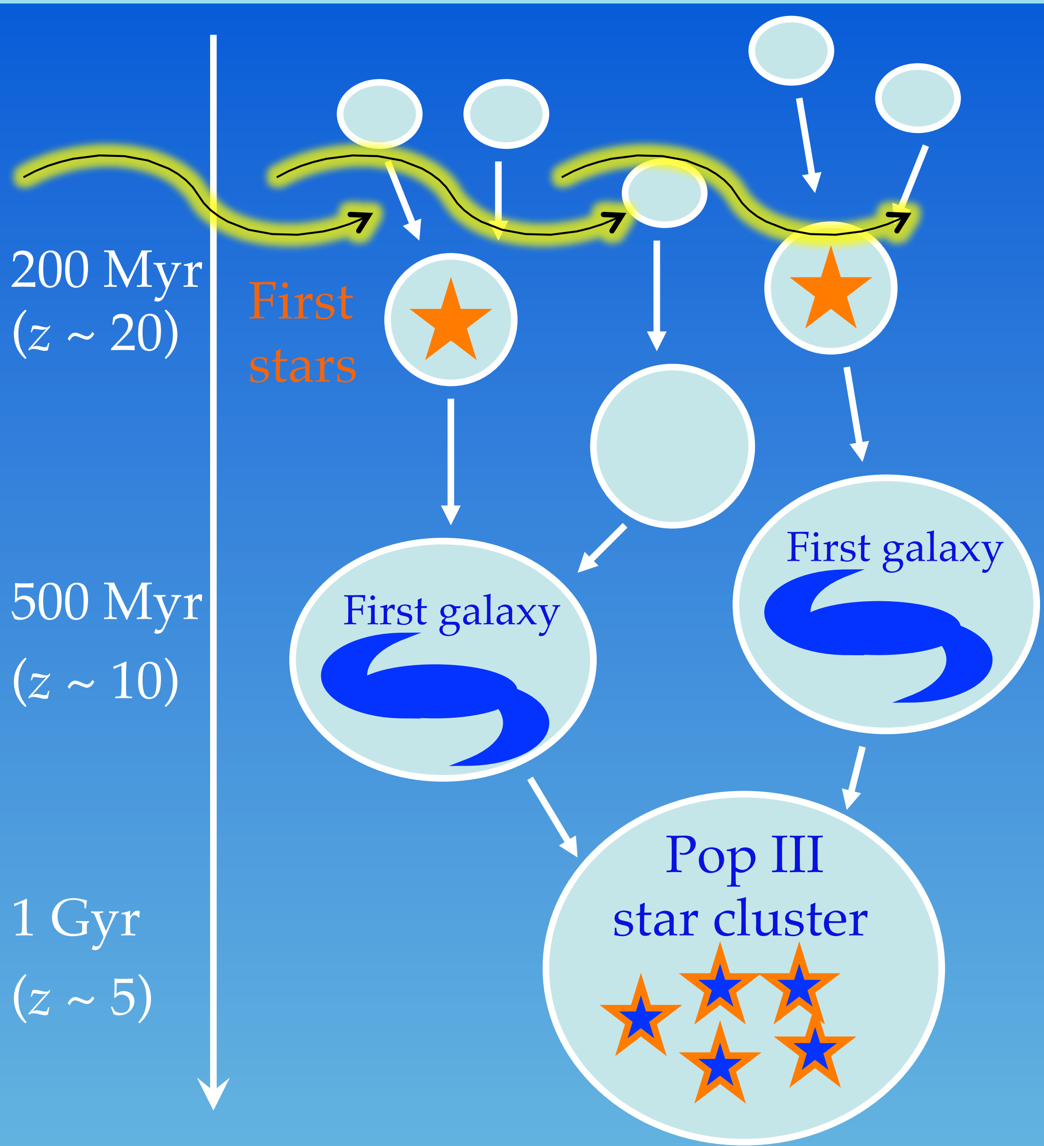


- Form from the mergers of dark matter minihalos (~ 10^6 M_{Sun}), which may host Pop III stars
- First dwarf galaxies form in dark matter halos of ~ 10^8 M_{sun}
- Properties of the first galaxies depend sensitively on:

  1) *IMF of the first stars*

  2) *Pop III SFR*

Pop III Star Formation after Reionization

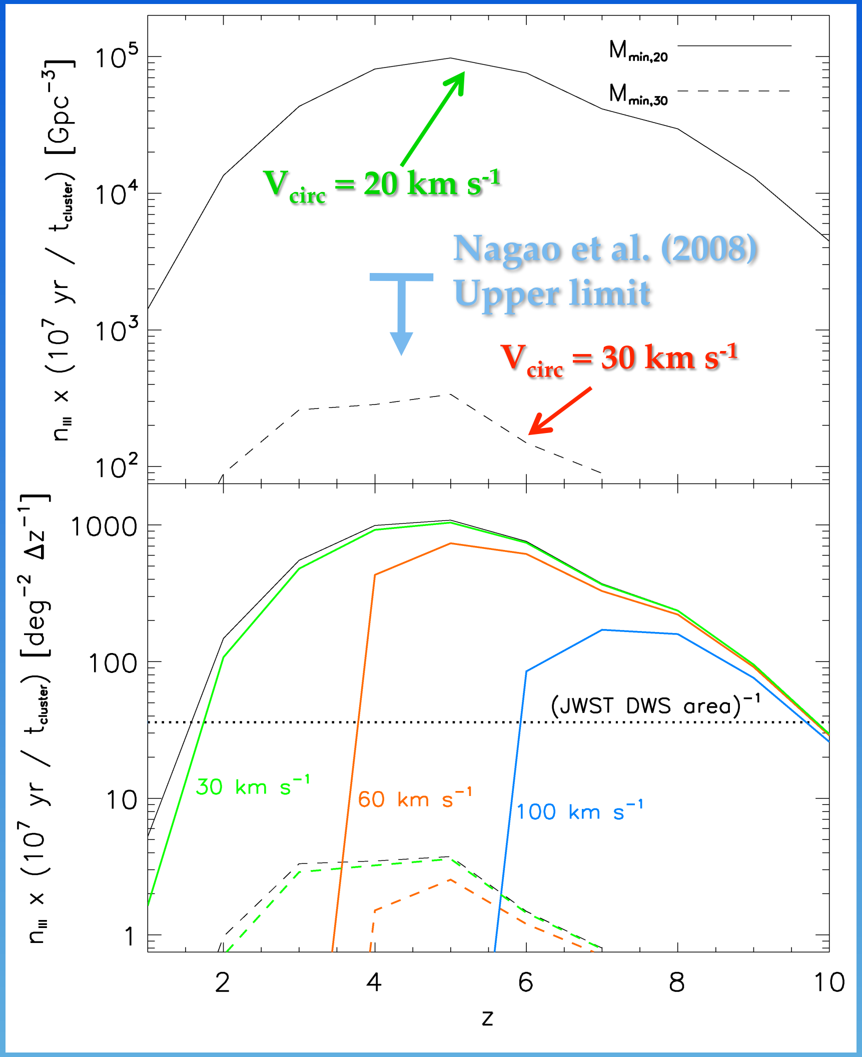


- Star formation may be prevented at z > 20 by photoionizing radiation during reionization
- DM Haloes with mass > 10^8 M_{sun} at z < 6 may remain pristine
- *Could the JWST detect Pop III clusters formed in these haloes?*

Pop III Star Formation after Reionization

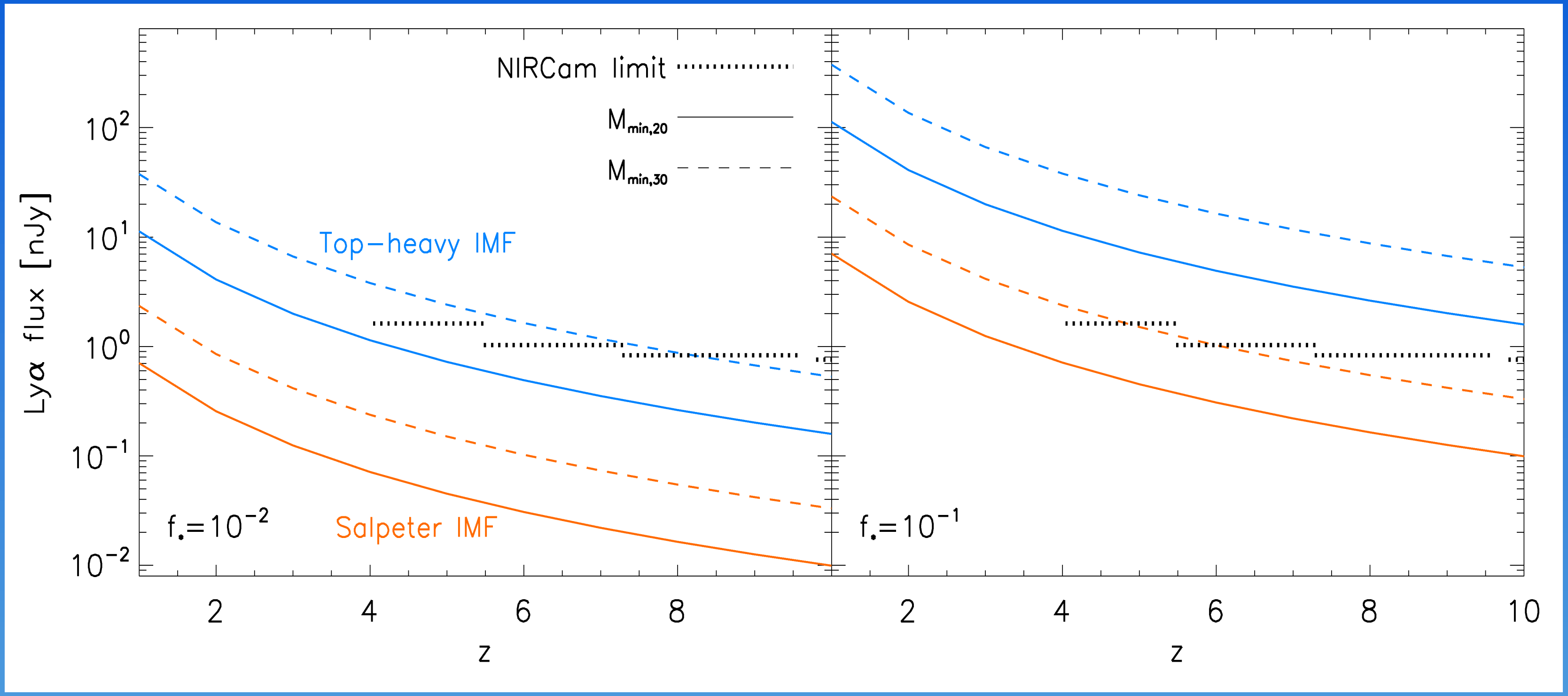
- The Pop III cluster abundance depends sensitively on:
  - The minimum halo mass for star formation
  - The cluster lifetime
  - Enrichment by galactic winds

- *There may be a sufficient abundance of Pop III clusters at z < 6 for detection in the JWST Deep-Wide Survey*



JLJ (2010)

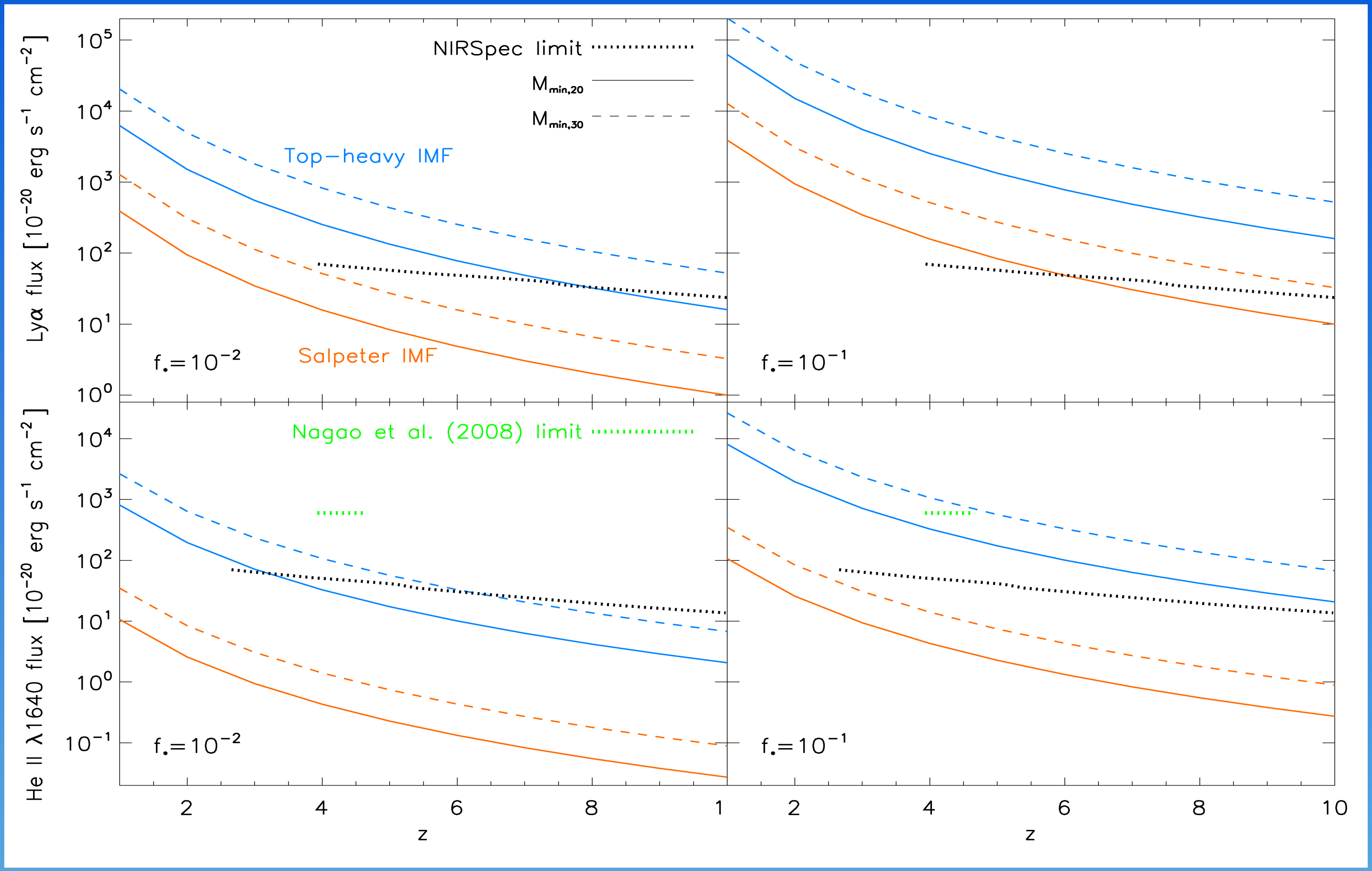
Pop III Star Formation after Reionization



- Depending on the star formation efficiency and the IMF, the Near-Infrared Camera aboard the JWST could detect Pop III clusters in the Deep-Wide Survey

JLJ (2010)

Pop III Star Formation after Reionization



- Detection of Lya and He II l1640 would allow for direct constraints on the Pop III IMF (at low z)

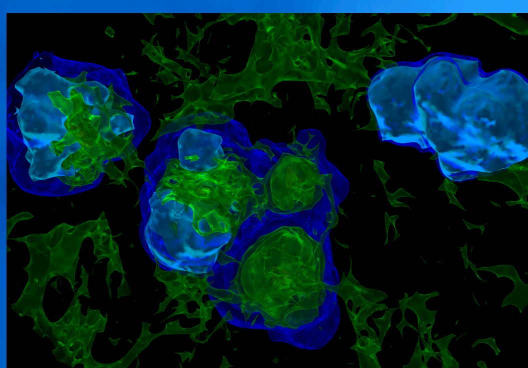
JLJ (2010)

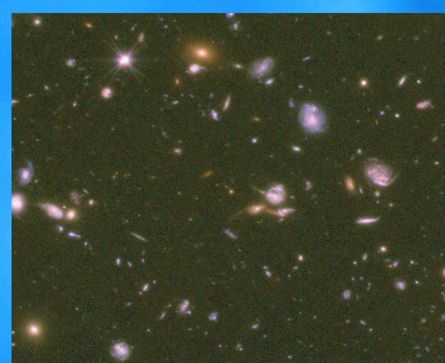
Summary

- The Pop III IMF can be constrained with detection of helium recombination emission (He II l1640)
  - Varies due to both stellar evolution and evolution of photoionized regions

- In rare regions, Pop III star formation may extend well beyond the epoch of the first galaxies

- Planned JWST surveys may detect Pop III stellar clusters at redshift $z < 6$ and place constraints on the IMF





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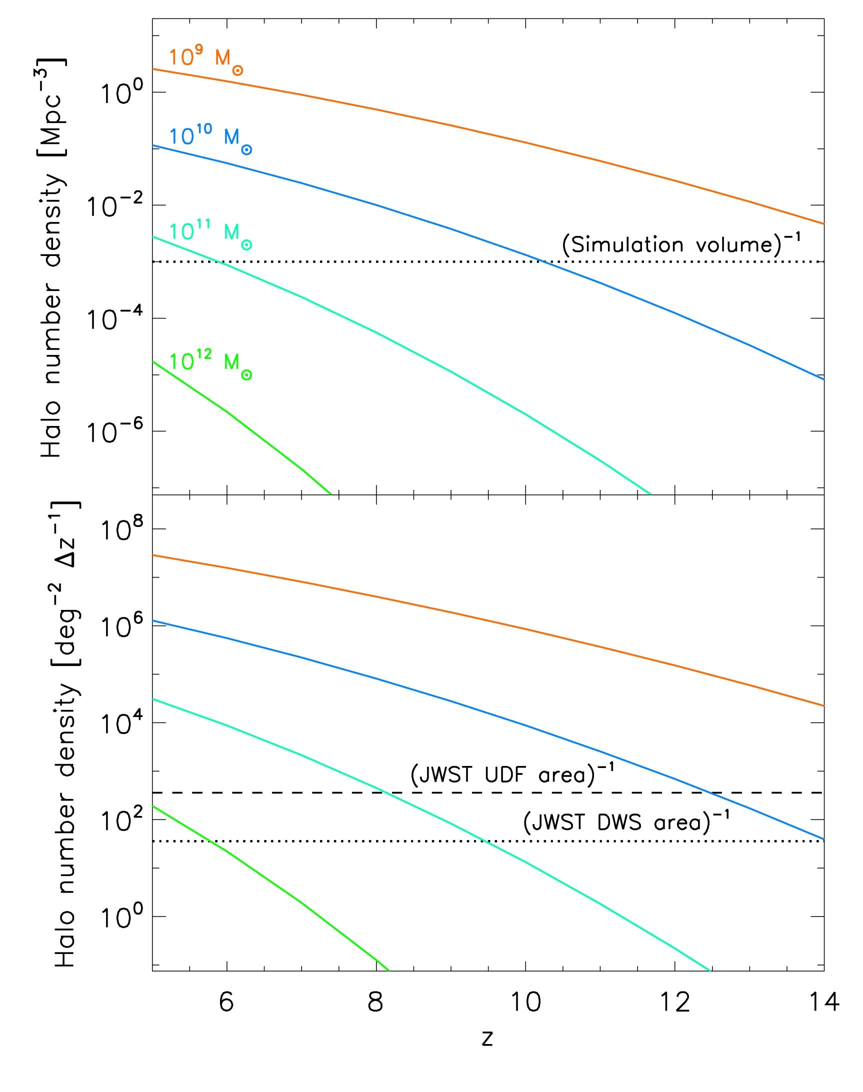
- Detection of Lya and He II l1640



The Formation of Primordial Galaxies

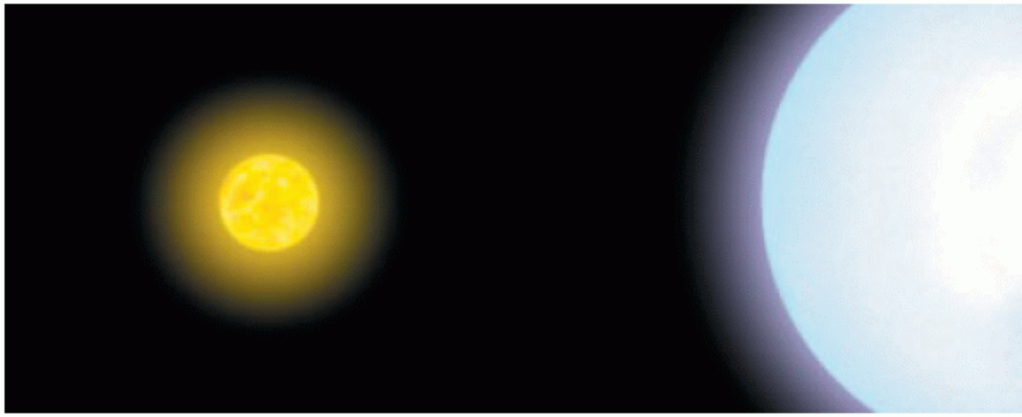
- Is hindered by the early enrichment of the gas by the first stars formed during the assembly of the first galaxies (JLJ, et al. 2008; Omukai, et al. 2008 (check these!!); Trenti, et al. 2009;

Radiation from the First Stars

STAR STATS

COMPARING CHARACTERISTICS

Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.

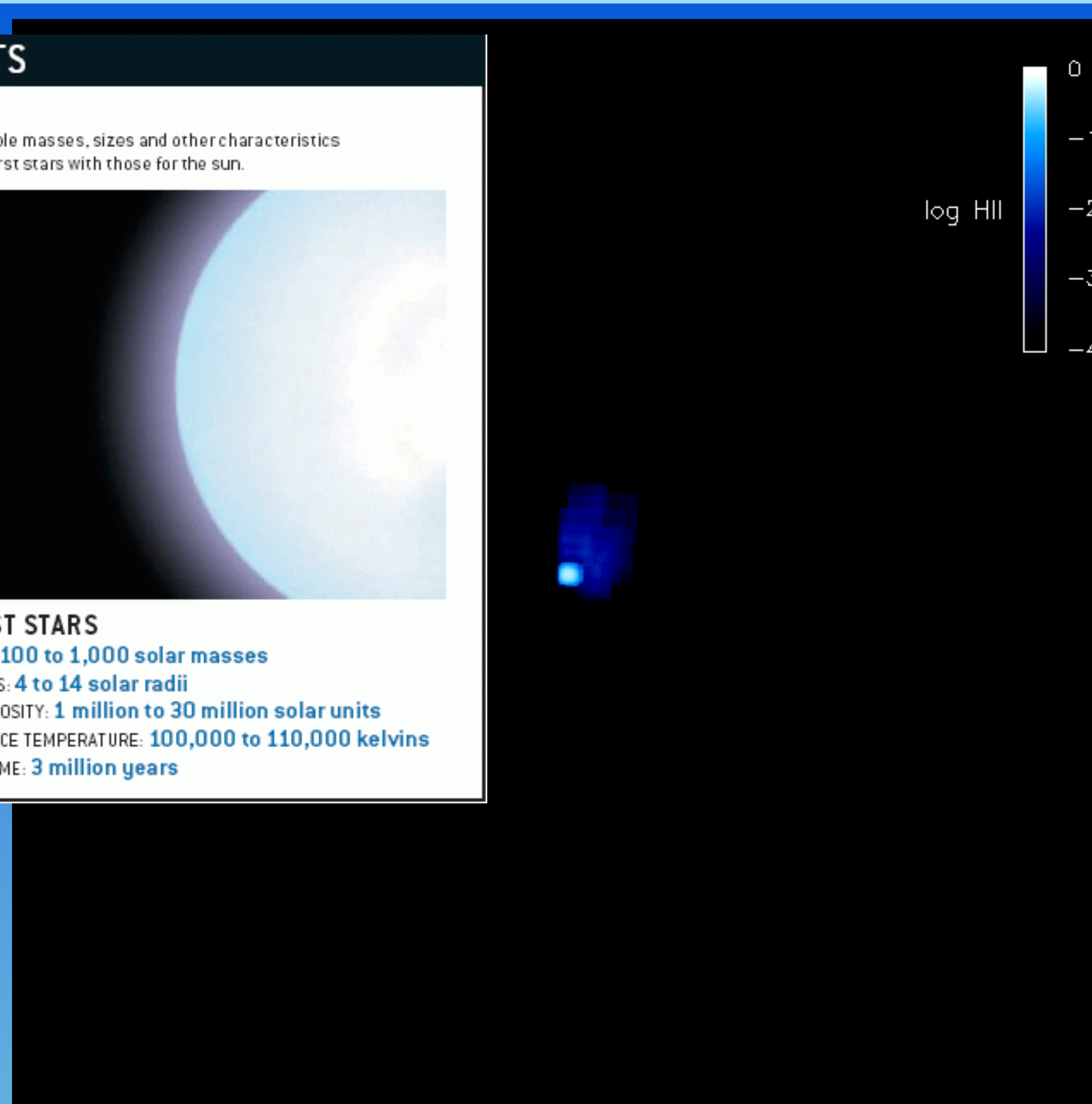


SUN

MASS: 1.989×10^{30} kilograms
RADIUS: 696,000 kilometers
LUMINOSITY: 3.85×10^{23} kilowatts
SURFACE TEMPERATURE: 5,780 kelvins
LIFETIME: 10 billion years

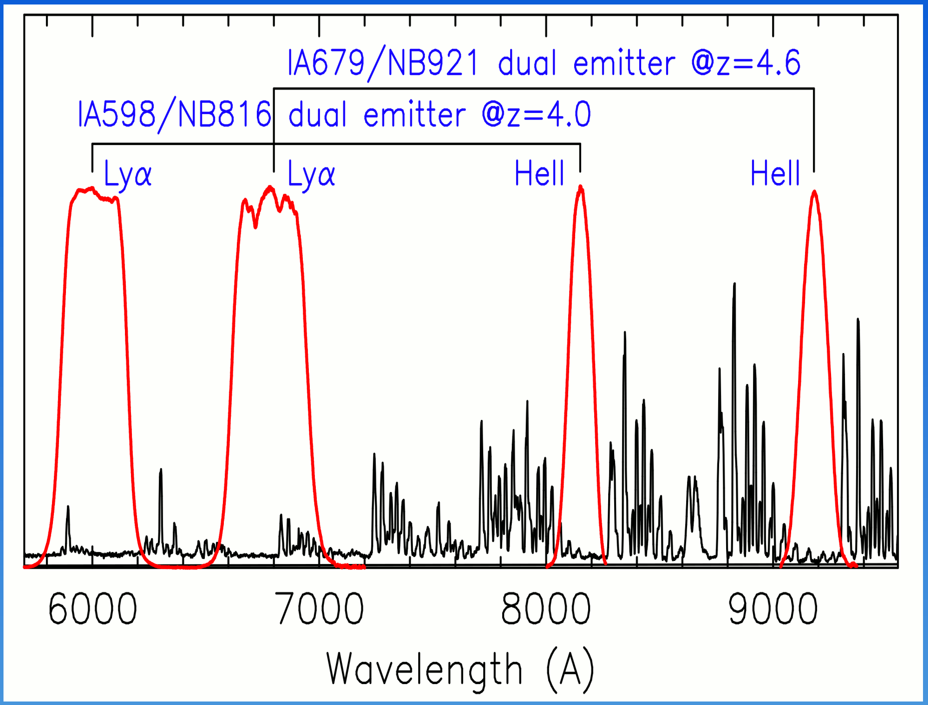
FIRST STARS

MASS: 100 to 1,000 solar masses
RADIUS: 4 to 14 solar radii
LUMINOSITY: 1 million to 30 million solar units
SURFACE TEMPERATURE: 100,000 to 110,000 kelvins
LIFETIME: 3 million years



Searches for Pop III Star-forming Galaxies

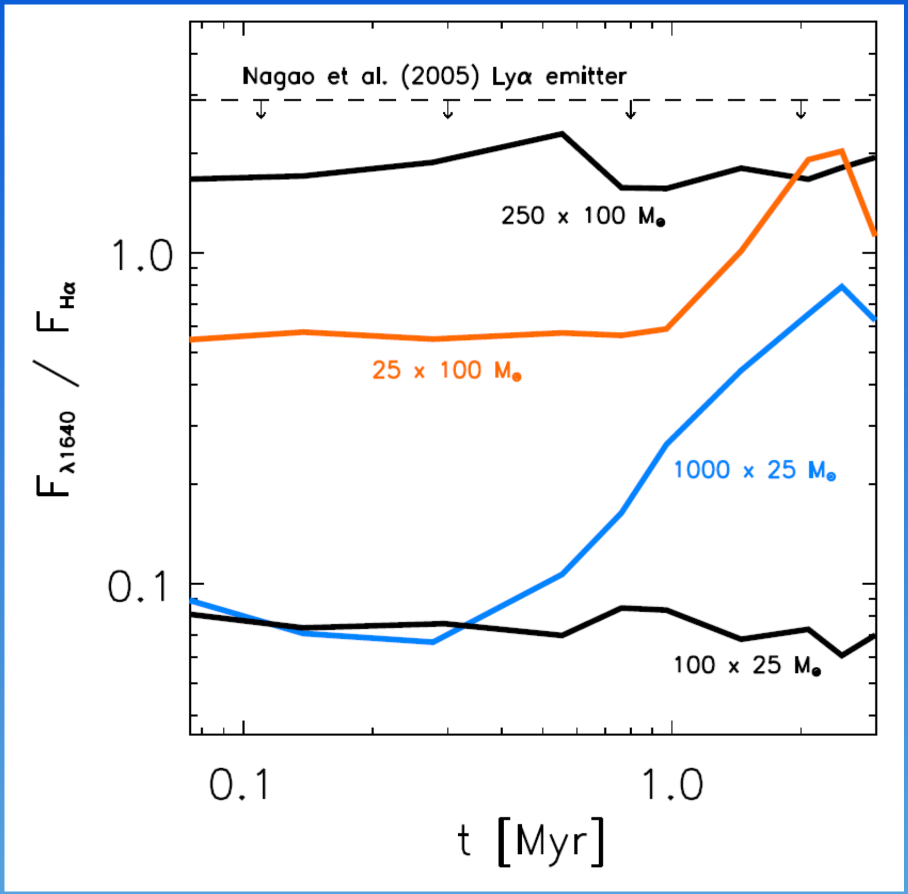
- Searches have focused on strong emission in Lya and He II l1640 (e.g. Nagao et al. 2005; 2008)



Nagao, et al. (2008)

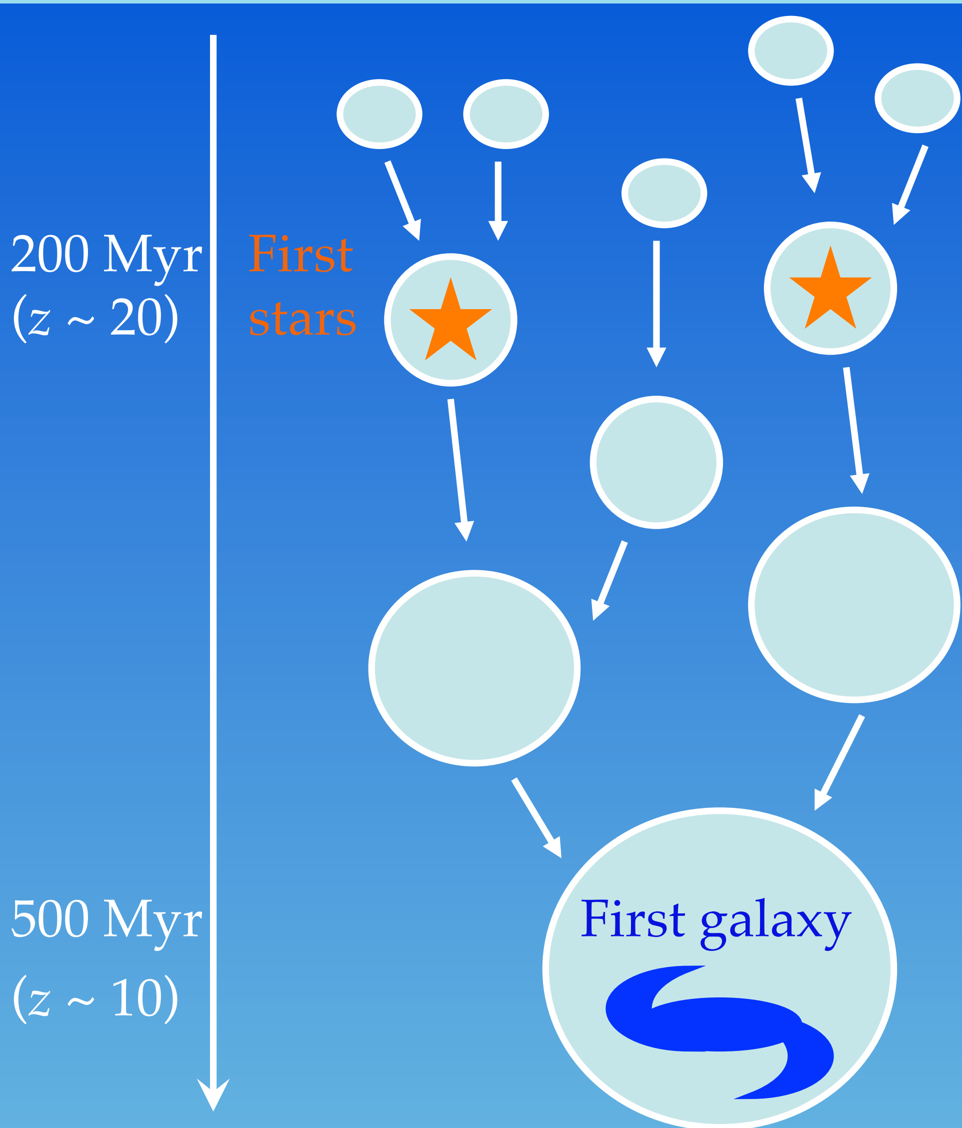
Pop III Stellar IMF Indicators

- The



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

The Formation of the First Galaxies



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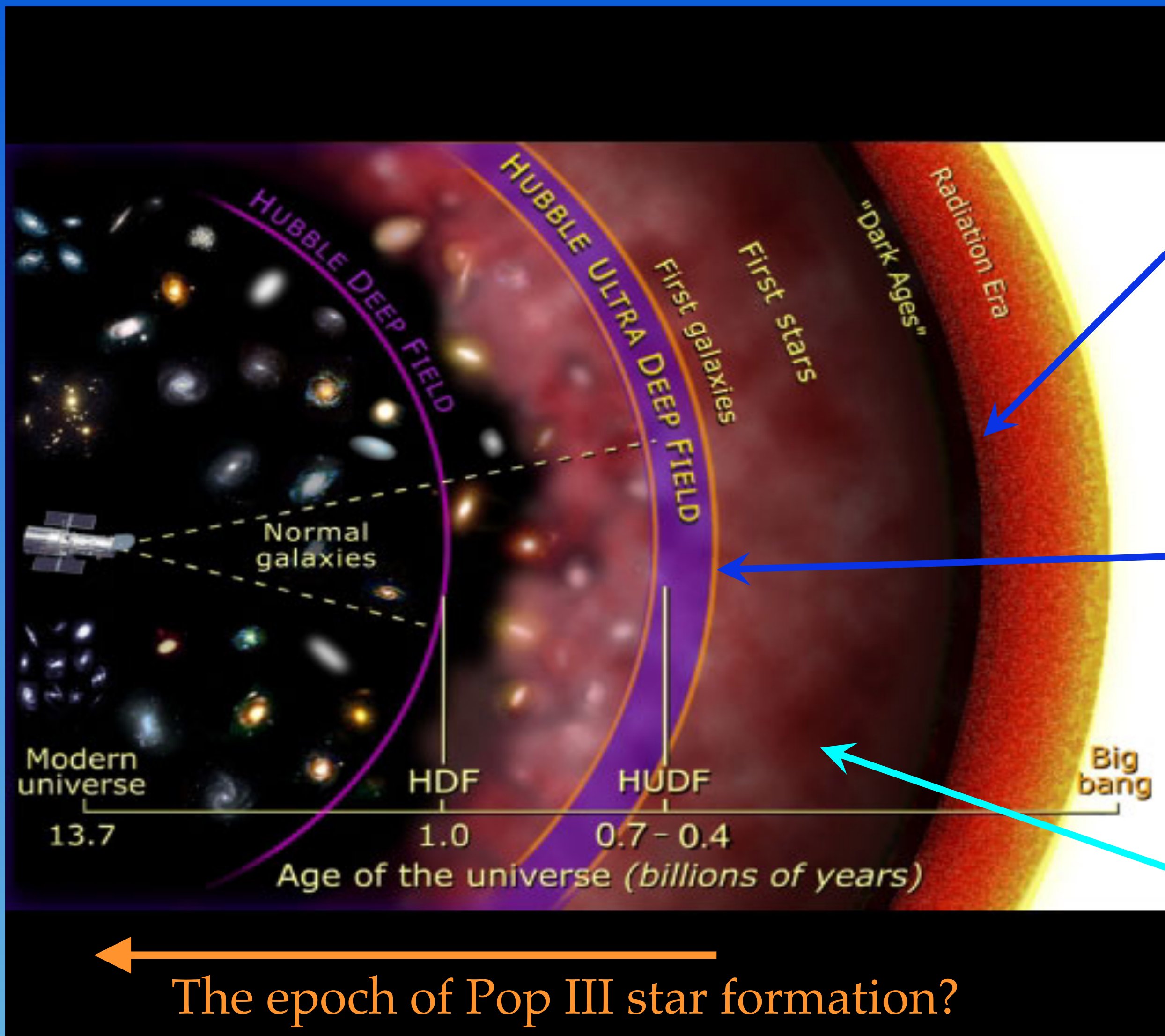
The Frontier of the First Galaxies



The cosmic microwave background is emitted

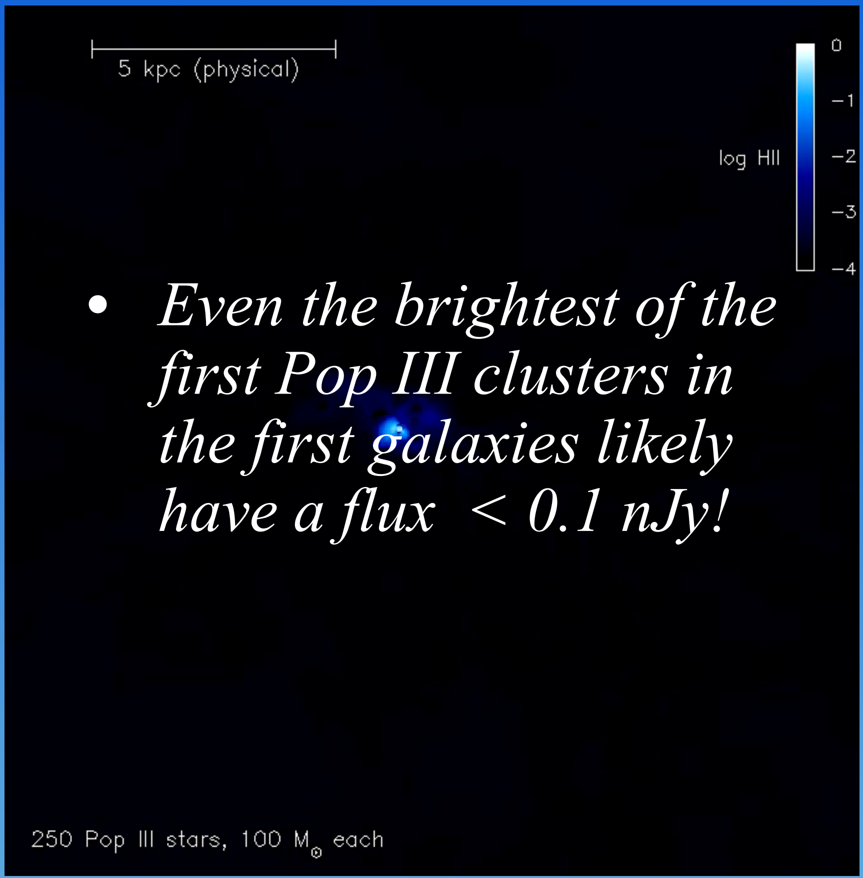
The most distant galaxies (and GRBs!) observed so far

The first stars and galaxies form *in between*

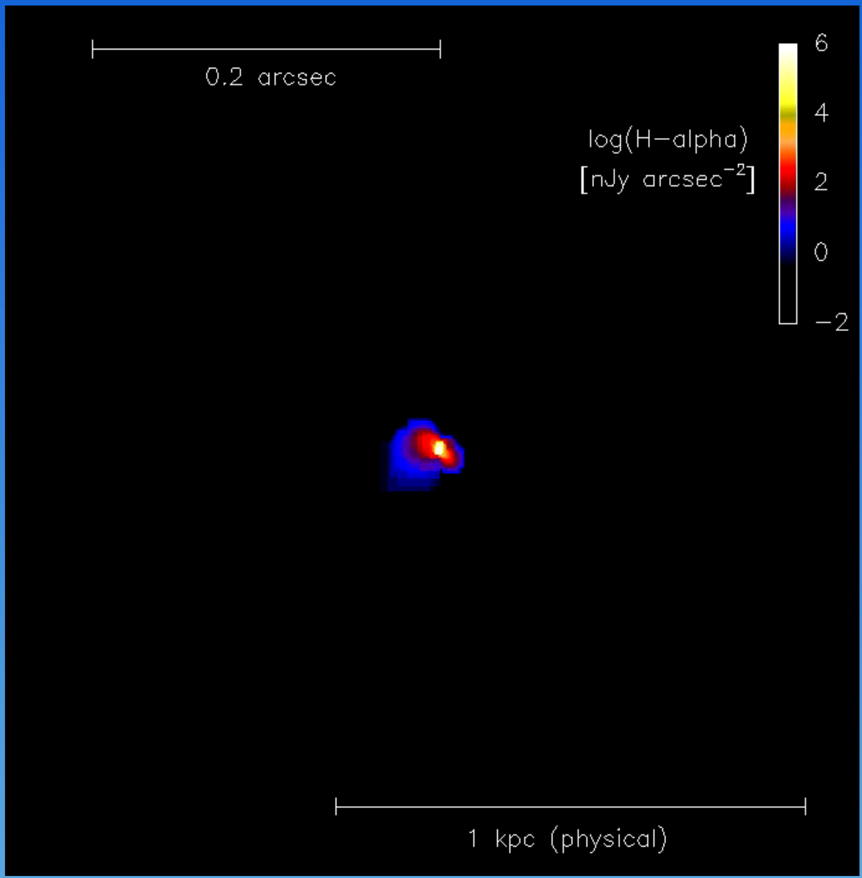
credit: firstgalaxies.org

Recombination Emission from the First Galaxies

Ionized fraction



Observed flux in Hα



Cluster of 100 M_{sun} Pop III stars

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