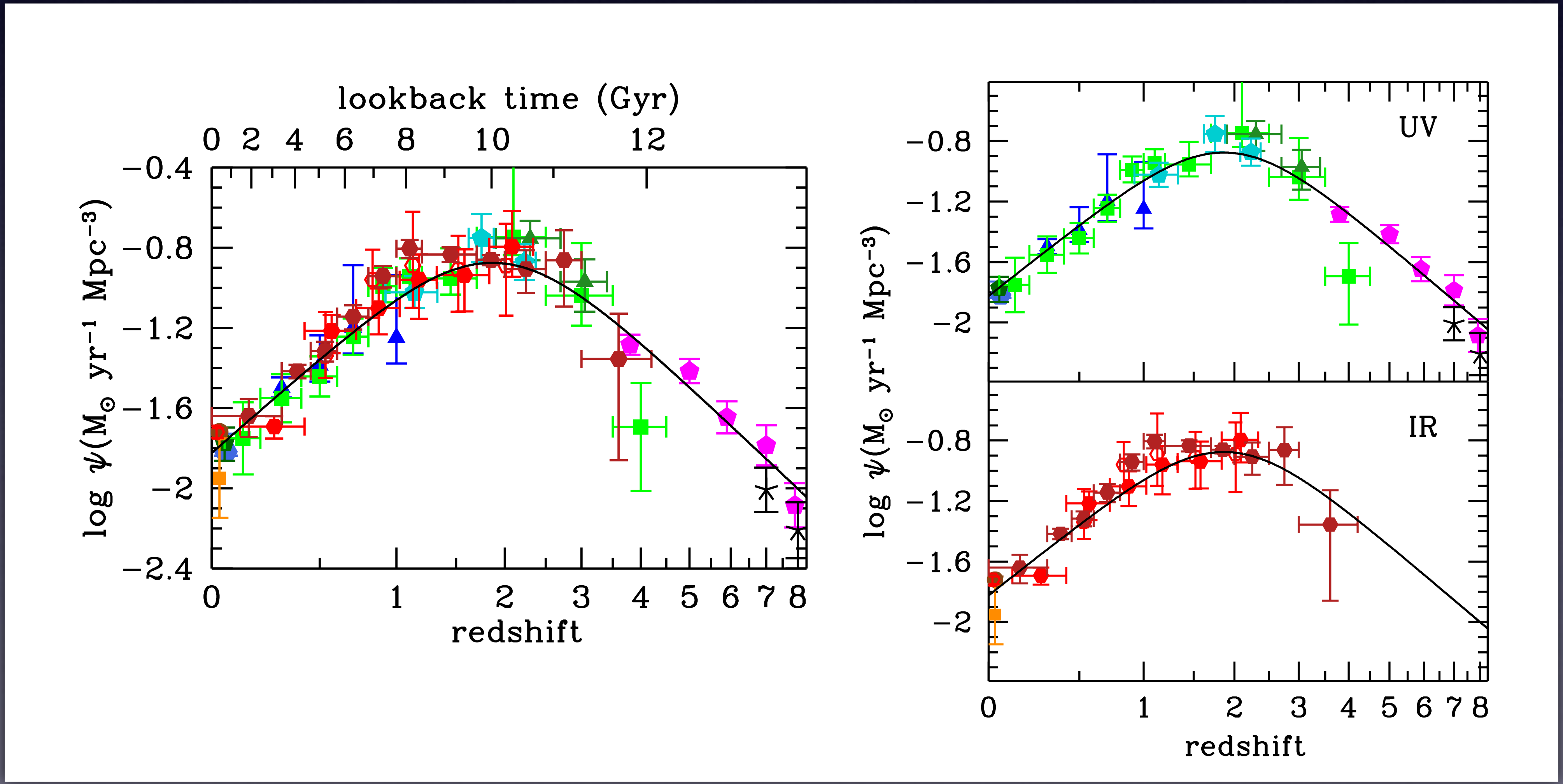
The first stars and galaxies through a gravitational wave lens

Stephen Fairhurst

with significant input from
Paul Clark and Tim Davis

Star formation history

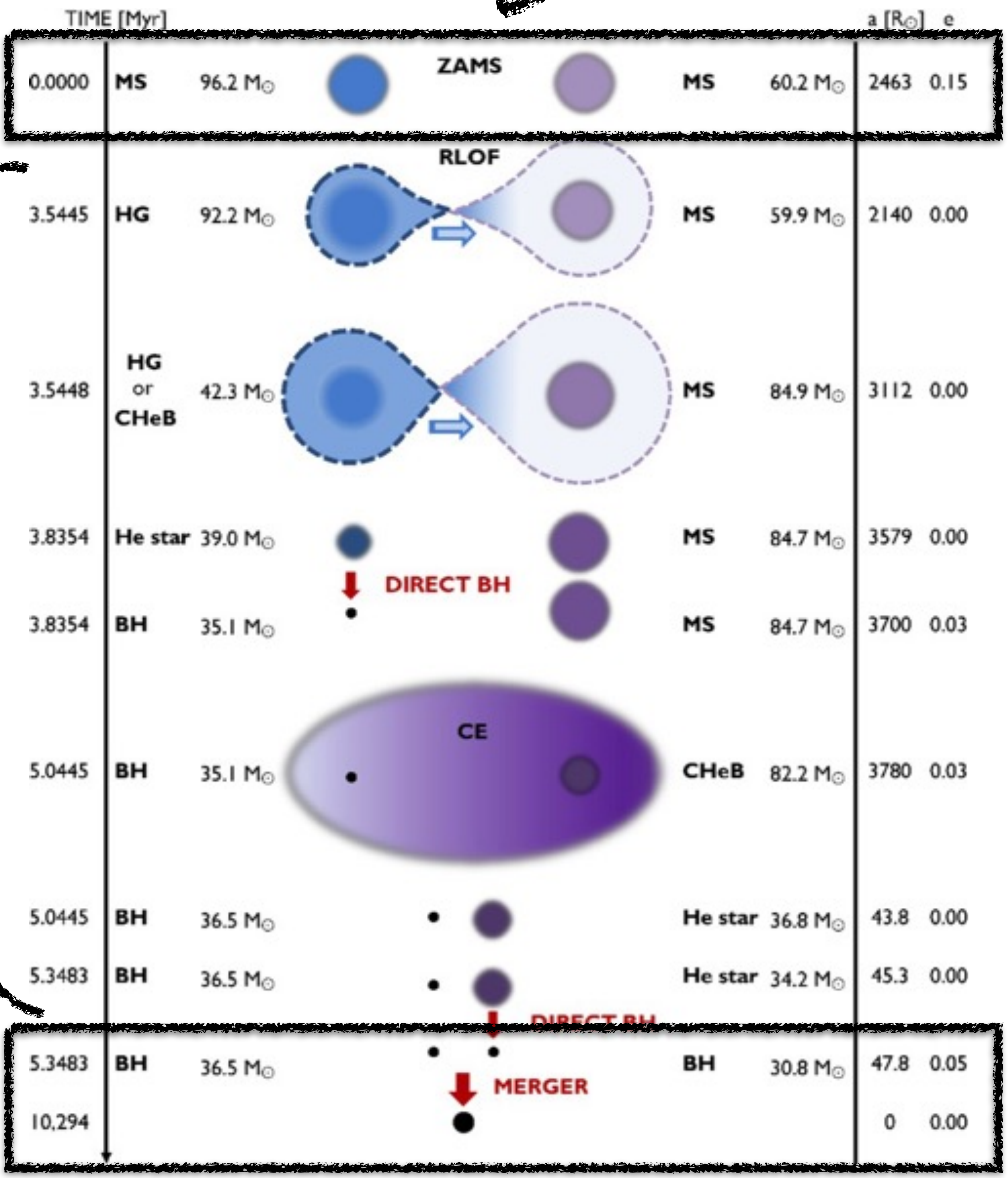
Consistent picture of star formation history emerging from multi-wavelength observations



From Madau and Dickinson, 2014

One way to get a binary black hole merger

Massive star formation



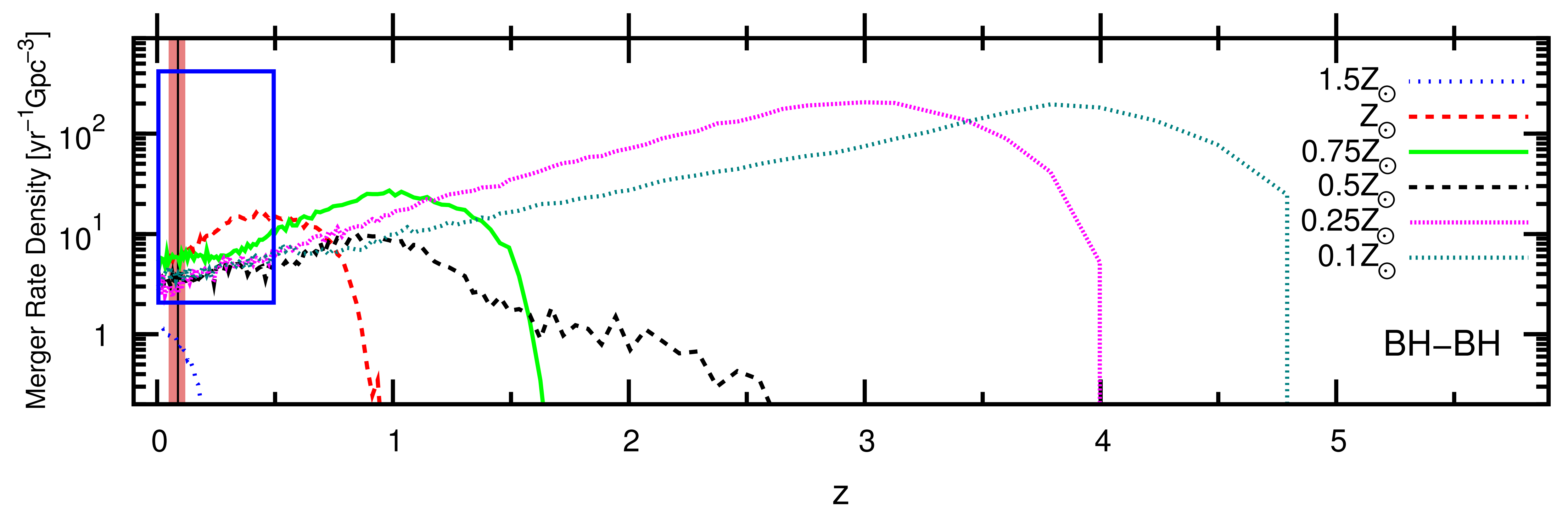
A few million years of complex astrophysics

Gravitational wave emission & observation

From Belczynski et al 2016

Merger rate density

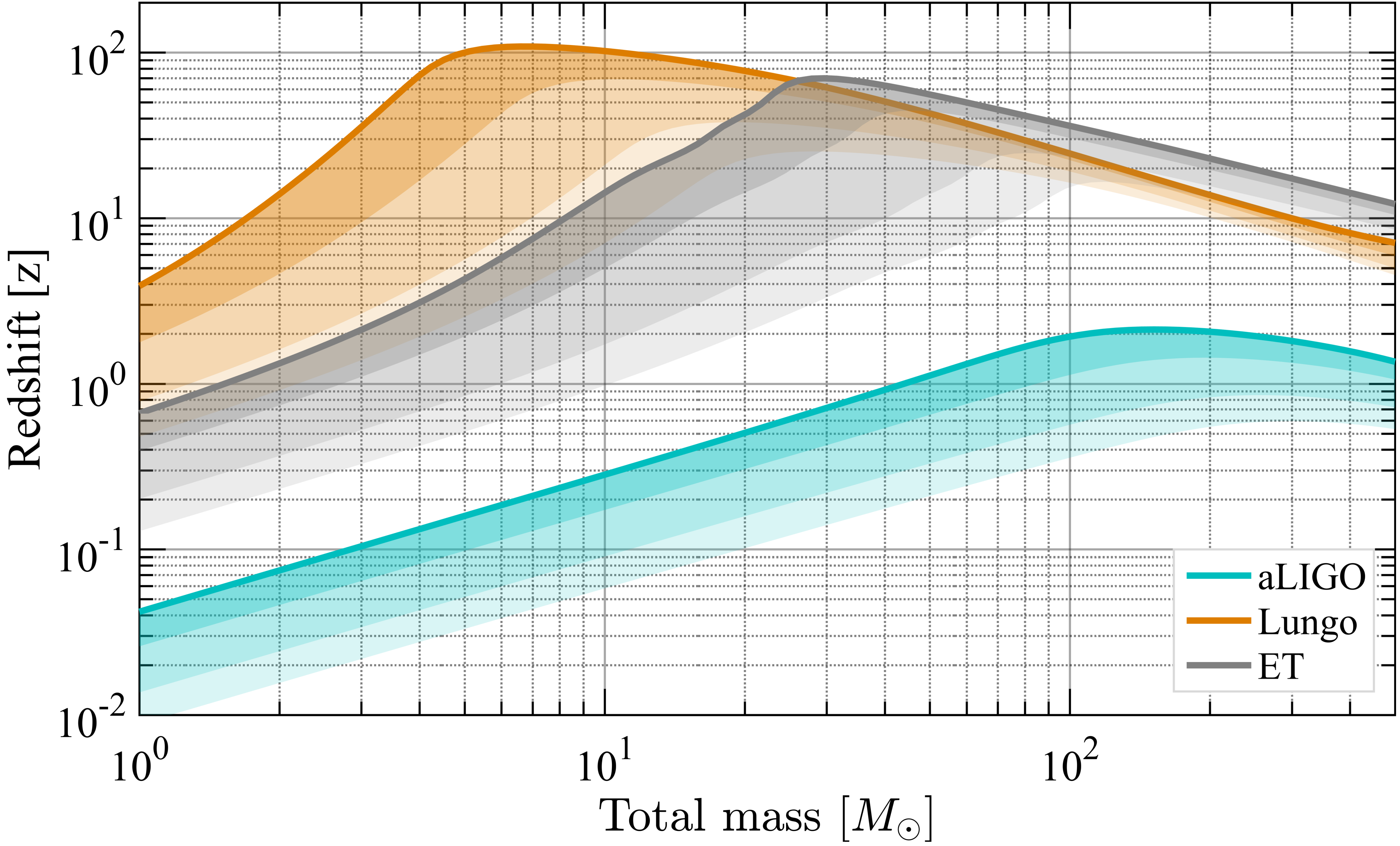
- BBH mergers offer an independent probe of high mass star formation
- Need to untangle complex astrophysics



From Abbott et al, ApJL 2016

Future prospects

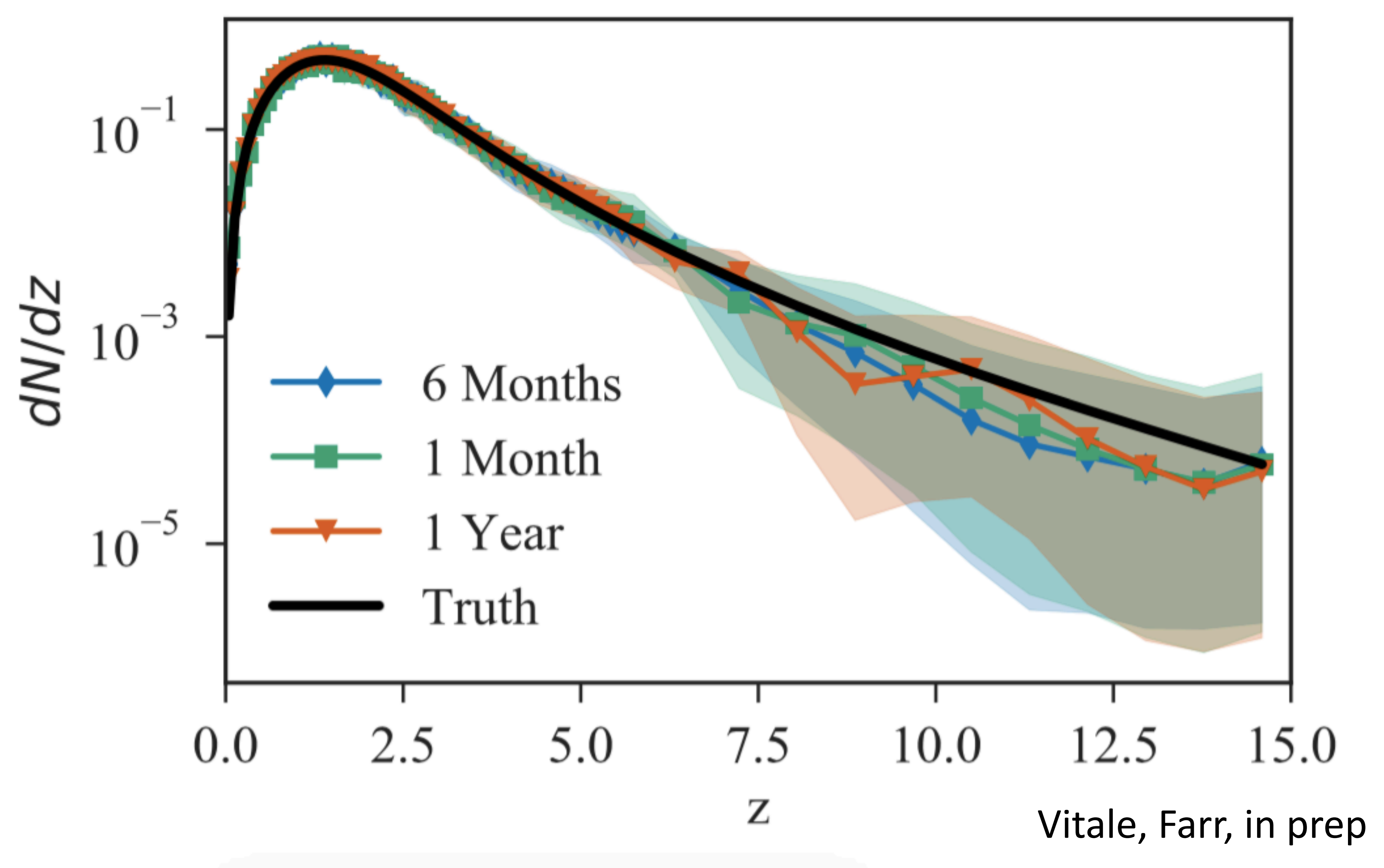
Horizon and 10, 50 and 75 % confidence levels



Measuring merger rate & star formation rate (Vitale & Farr)

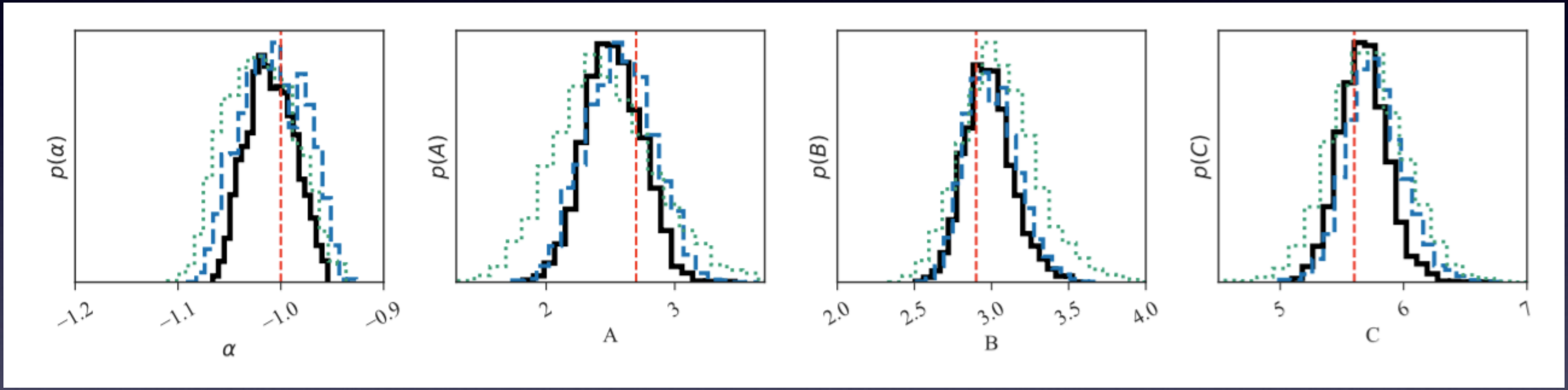
- Assume Madau-Dickinson star formation rate (SFR)
- Assume time delay between merger and formation goes as 1/t
- Formation rate proportional to SFR
- Generate 1, 6, 12 months worth of BBH detections by 3G detectors

Measuring merger rate density



Vitale, Farr, in prep

Star formation rate



Can measure the time delay power law coefficient and well as the parameters of the SFR

SFR template:

$$\psi_{MD}(z) = \nu \frac{(1+z)^A}{(1+\frac{1+z}{B})^C}$$

The First Stars

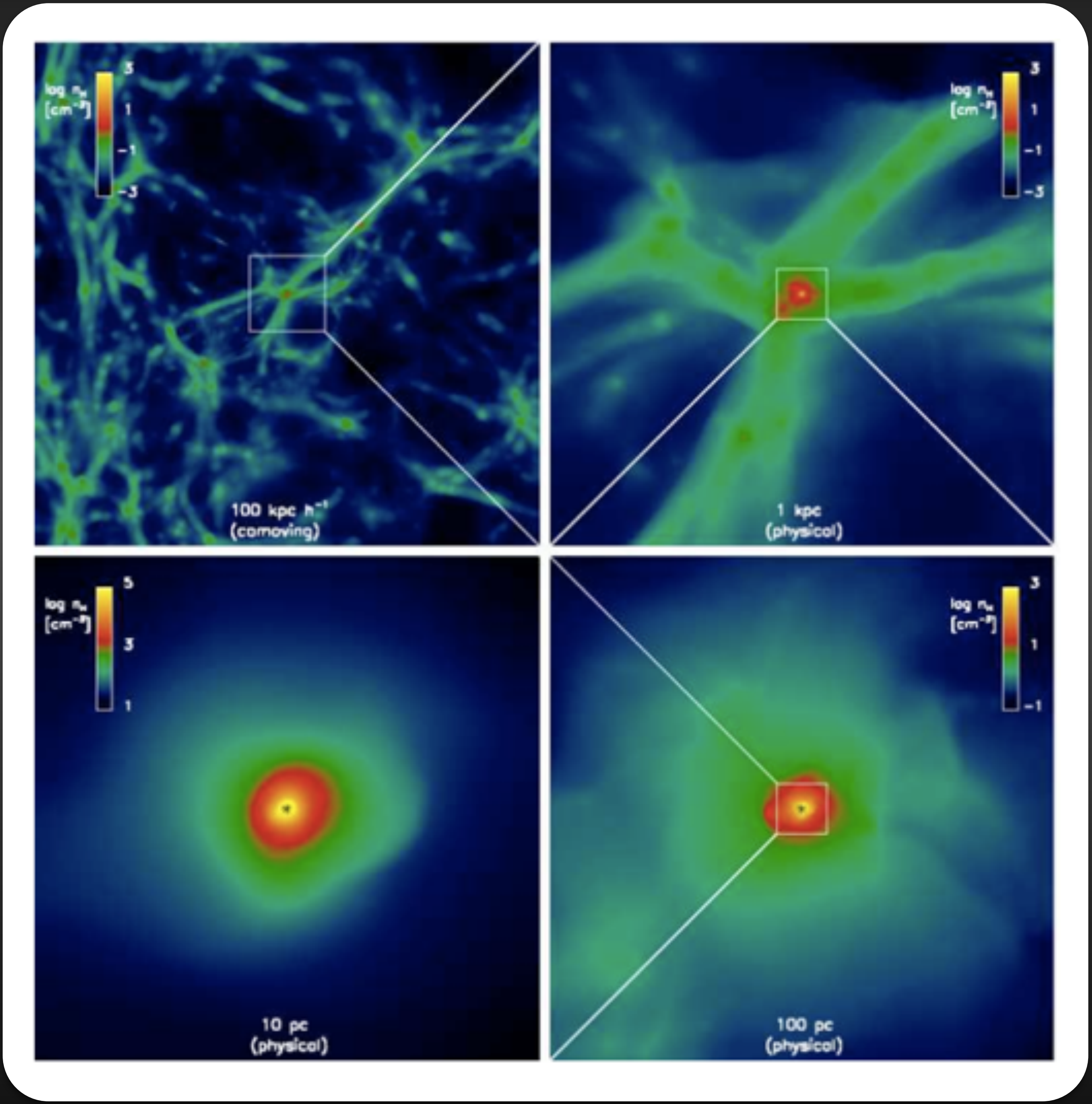
- Formation of the first stars
- Observational prospects
  - EM observations
  - GW observations
- Challenges for the 3G network

Where do Pop III stars form… and when?

- Form in dark matter minihalos with mass

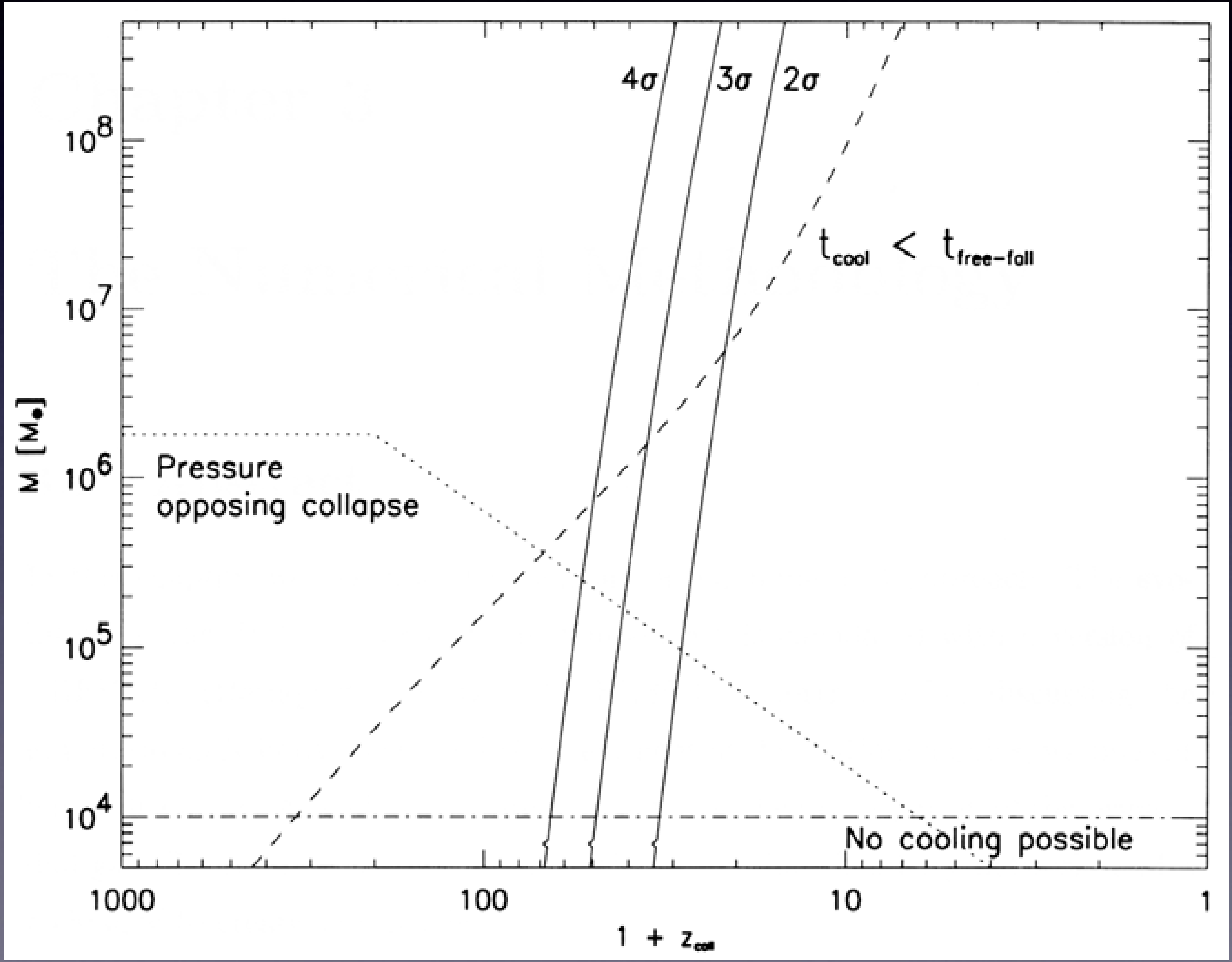
  $M_{halo} \gtrsim 5 \times 10^5 M_\odot$

- Redshift $z = 16 - 20$
- $T_{vir} \sim 1000$ K
- Gas density is around 1 cm^{-3}



Stacy, Greif and Bromm (2010)

Required halo mass



The ‘classical’ picture of Pop III collapse

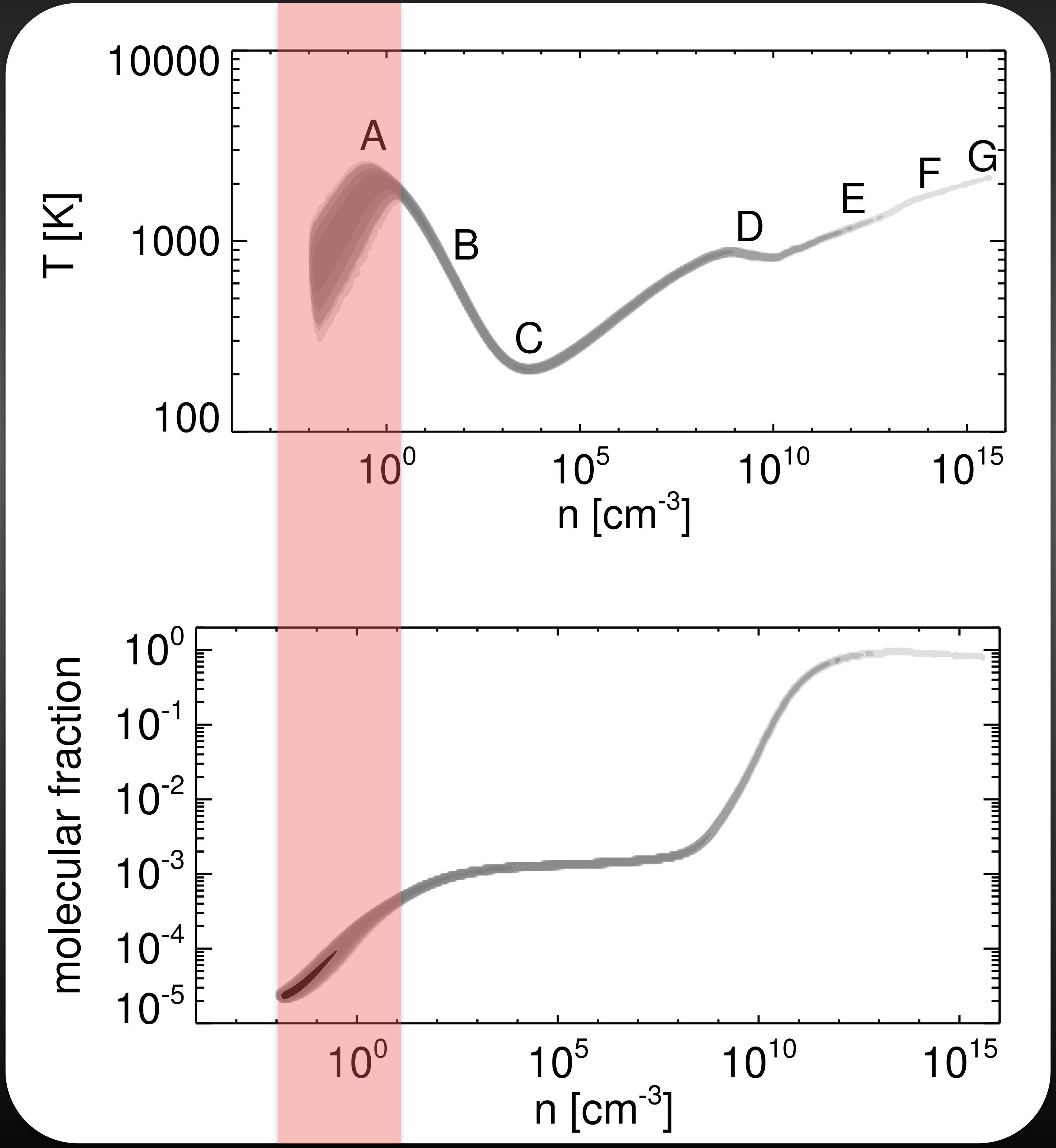
Bromm et al. 2002
Abel et al. 2002
Omukai 2001; 2005
Bromm & Larson 2004
Yoshida et al. 2006

The classic picture of Pop III collapse

- Gas falls into minihalo and heats up to virial temperature via compression

- H_2 formation is enhanced by the temperature increase

Yoshida et al. 2006

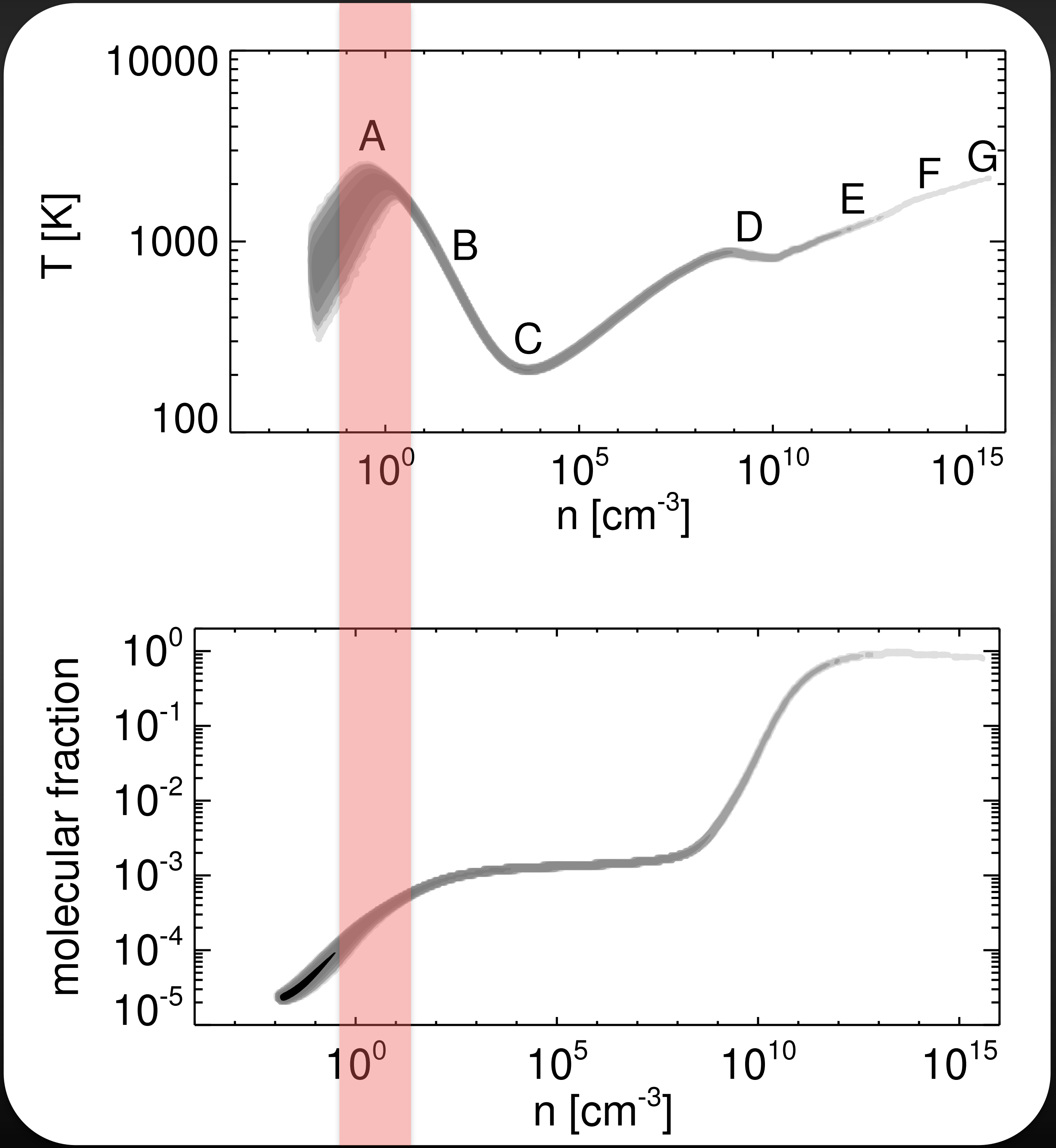


The classic picture of Pop III collapse

- H_2 cooling counteracts heating and the gas starts to cool

- H_2 formation continues

Yoshida et al. 2006

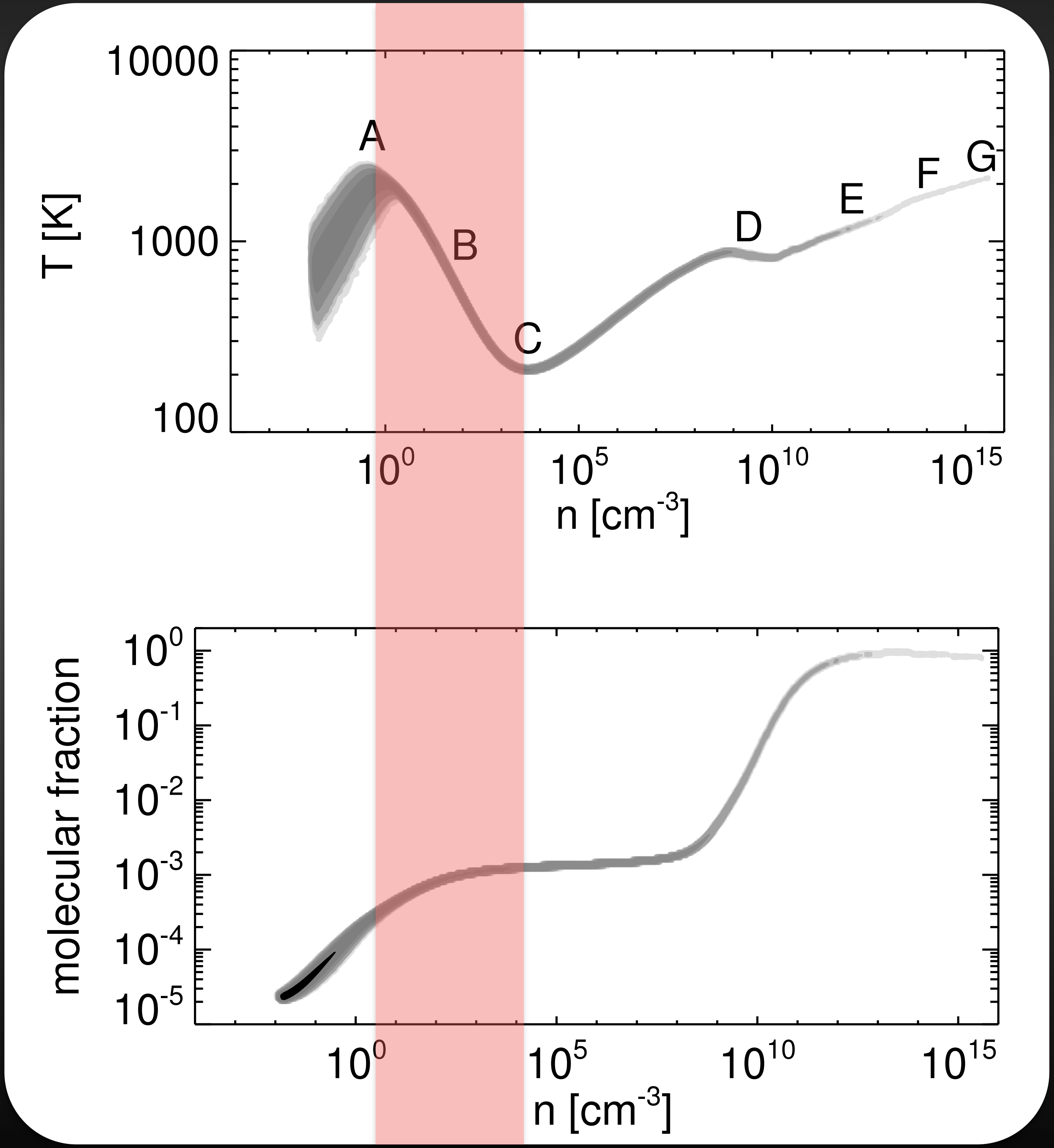


The classic picture of Pop III collapse

- Gas starts to collapse under gravity. Cooling rate is faster than associated compressional heating rate

- H_2 formation drops to zero due to limitations of the reaction network

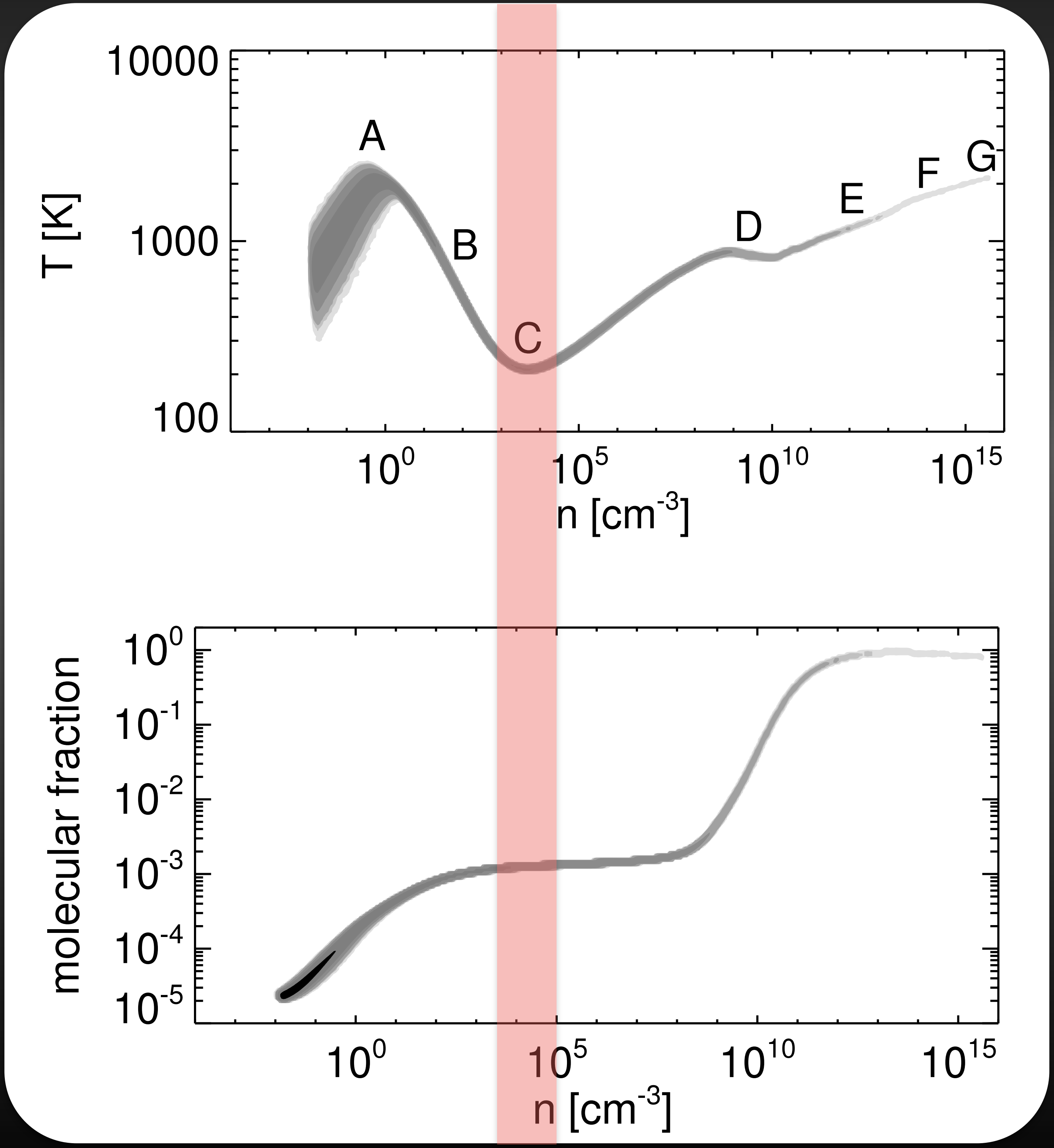
Yoshida et al. 2006



The classic picture of Pop III collapse

- Temperature drops to around 200K, below which H_2 cooling is ineffective

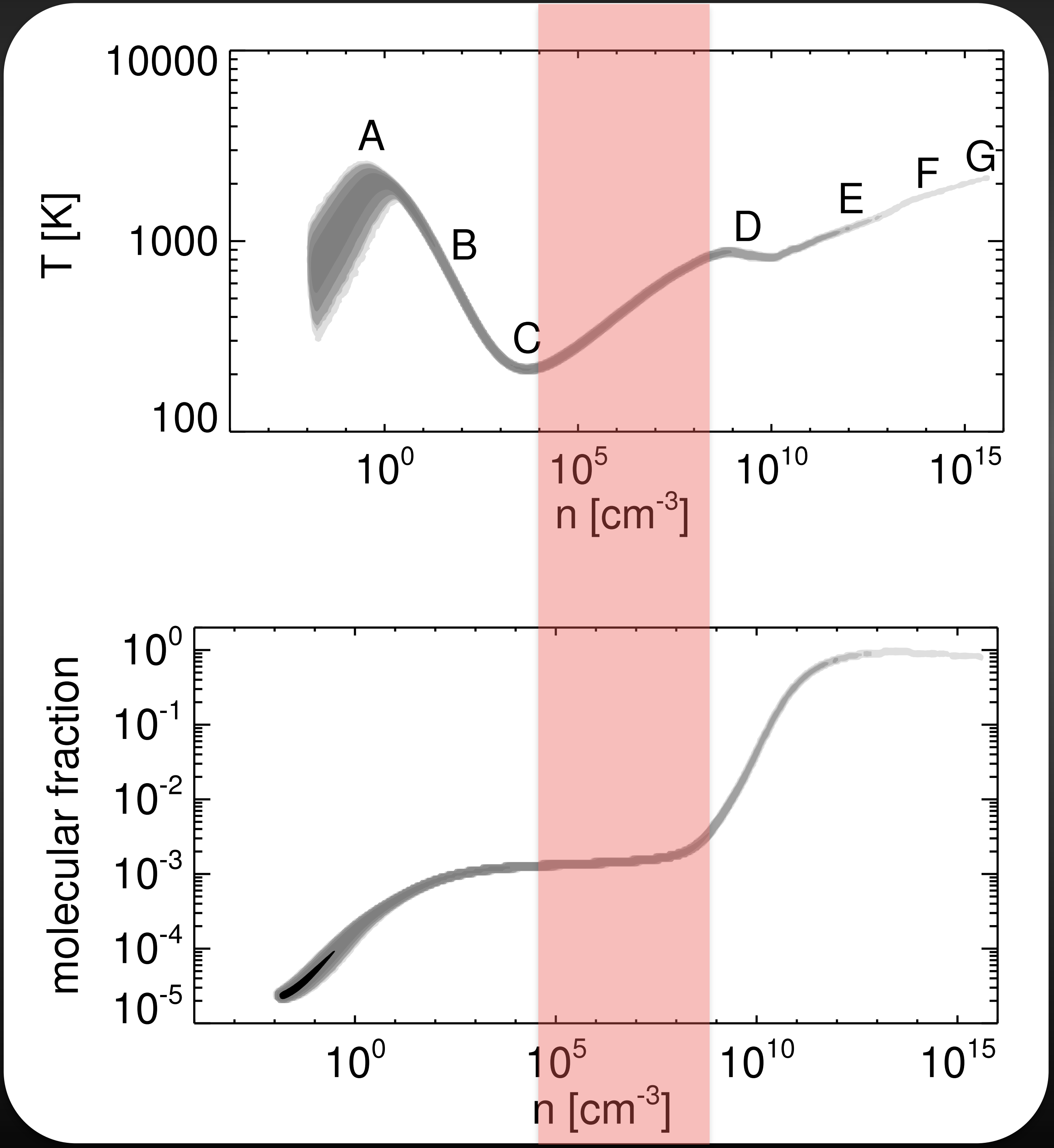
Yoshida et al. 2006



The classic picture of Pop III collapse

- H_2 reaches critical density and levels go into Local Thermodynamic Equilibrium.

Yoshida et al. 2006

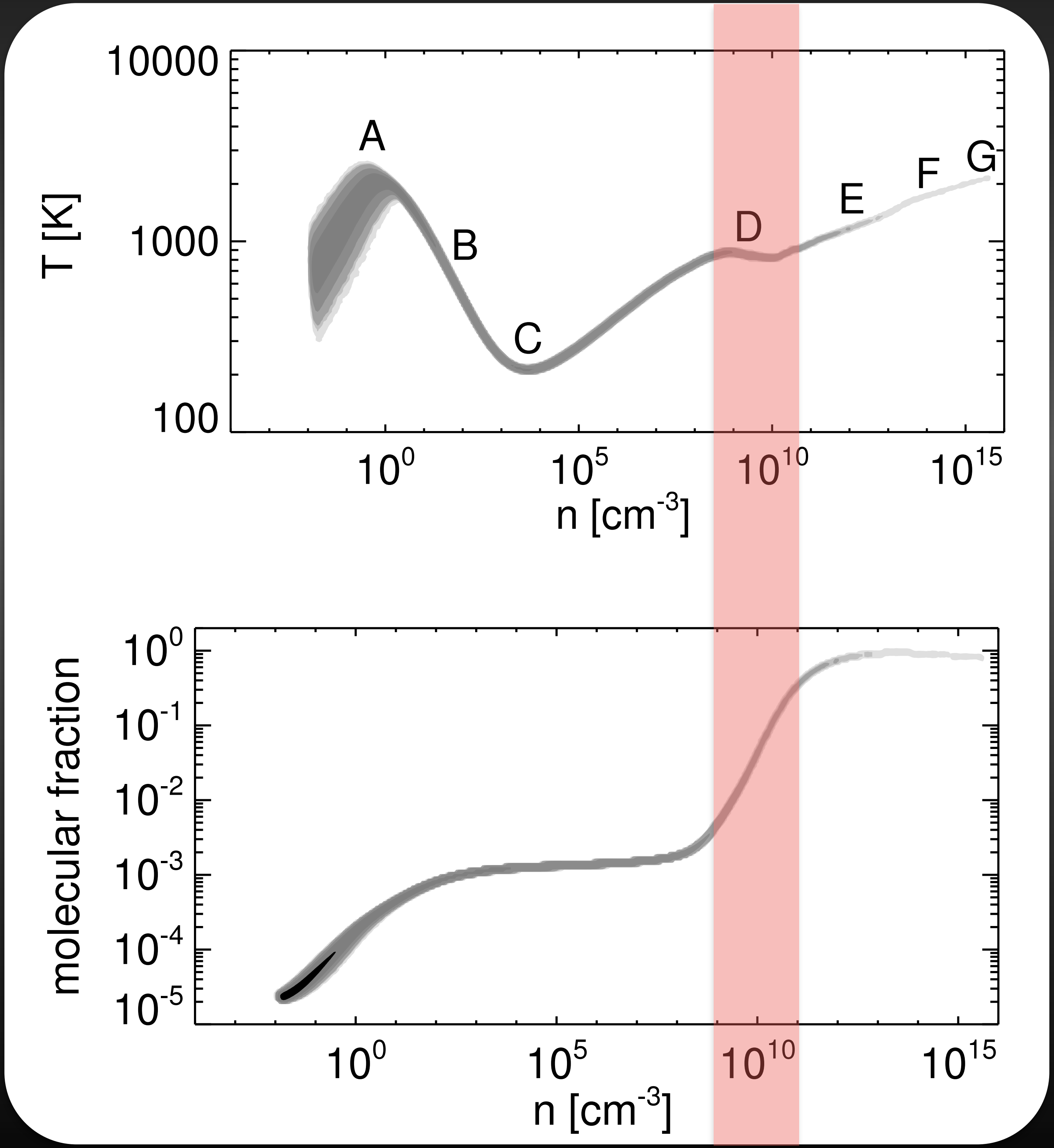


The classic picture of Pop III collapse

- Rapid rise in the H_2 fraction due to 3-body reactions

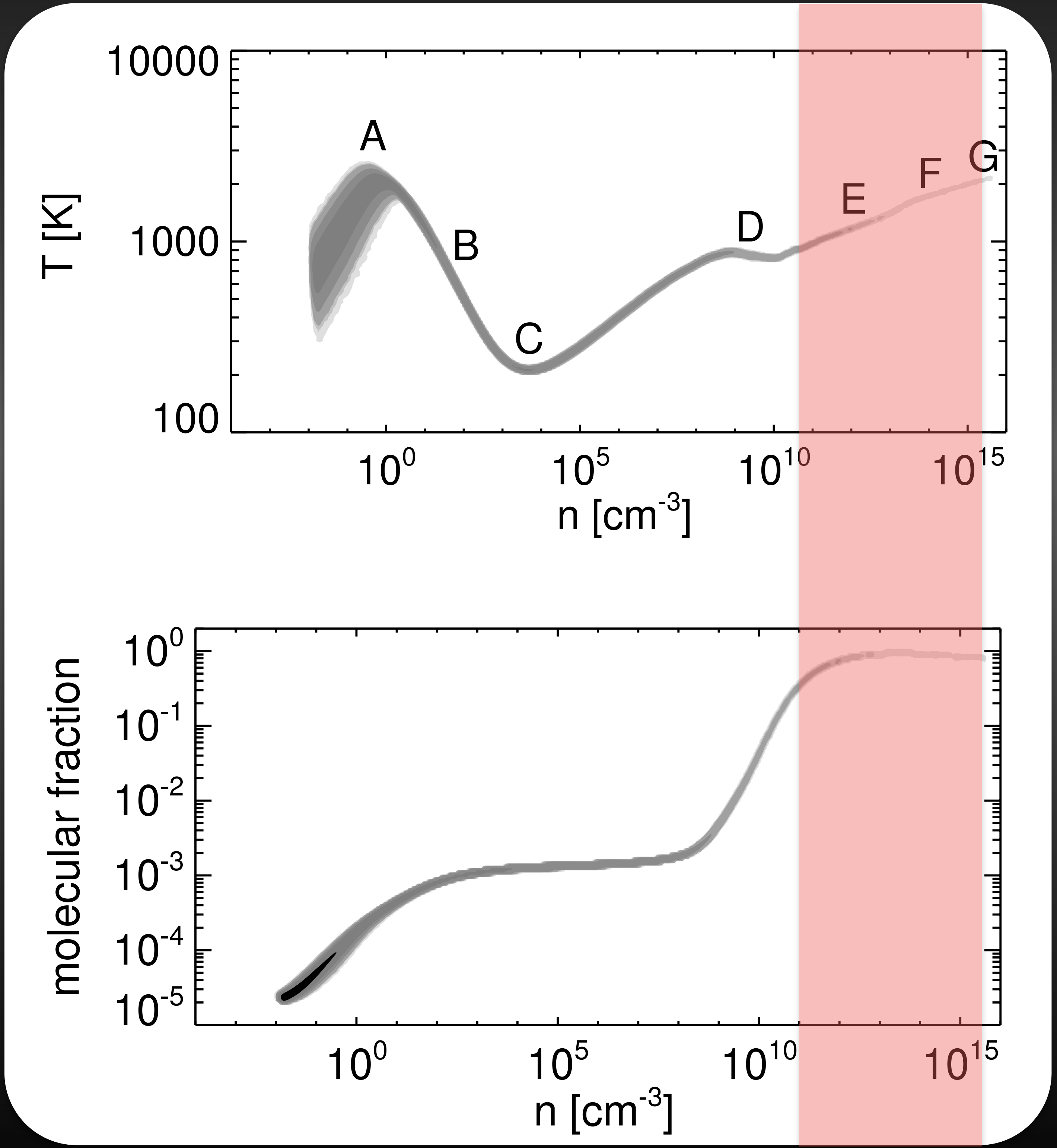
- Accompanied by formation heating + enhanced cooling (due to elevated H_2 abundance)

Yoshida et al. 2006



The classic picture of Pop III collapse

Yoshida et al. 2006



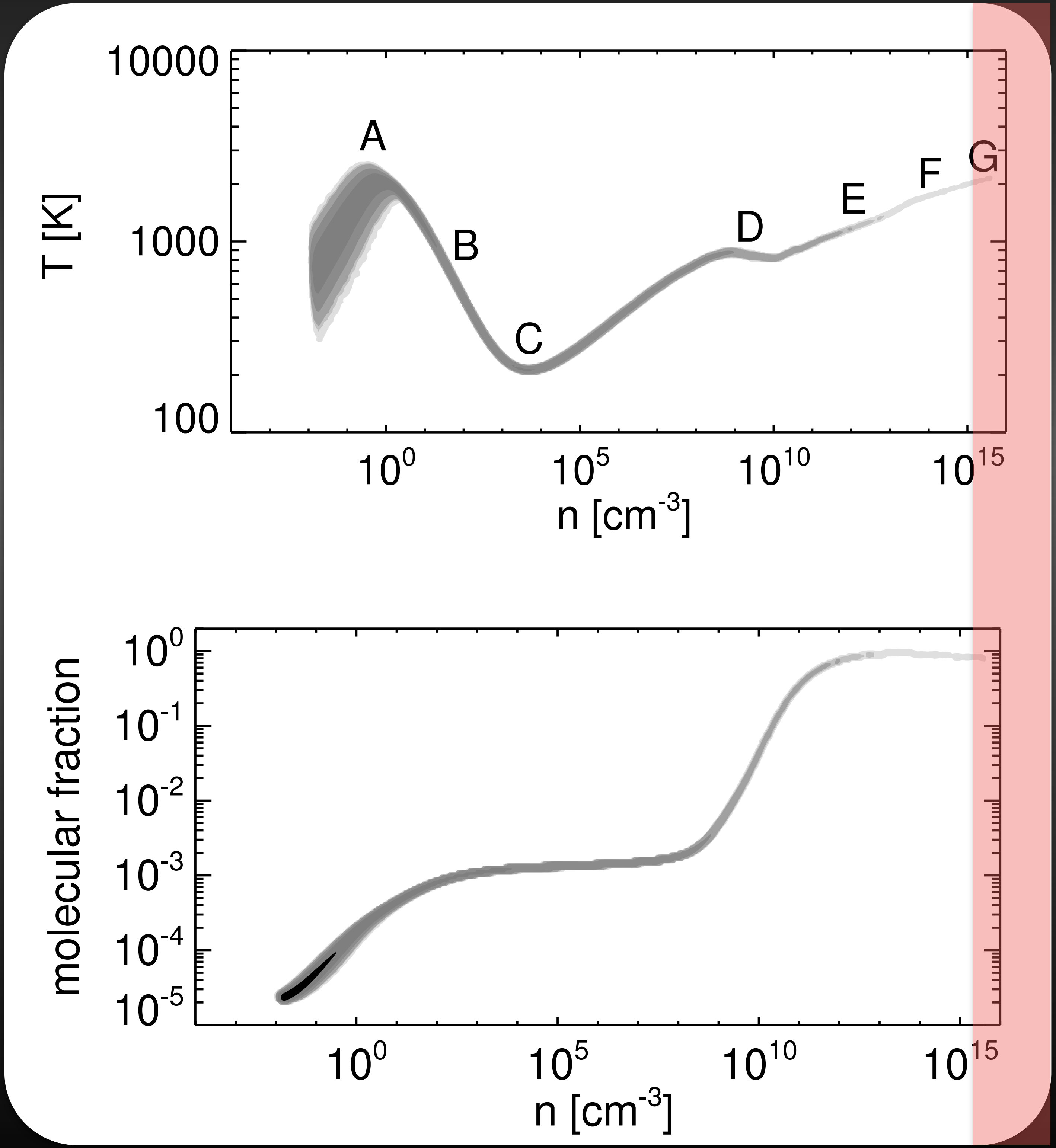
- H_2 cooling starts to become increasingly optically thick!
- Becomes less effective as a coolant.

The classical picture of Pop III collapse

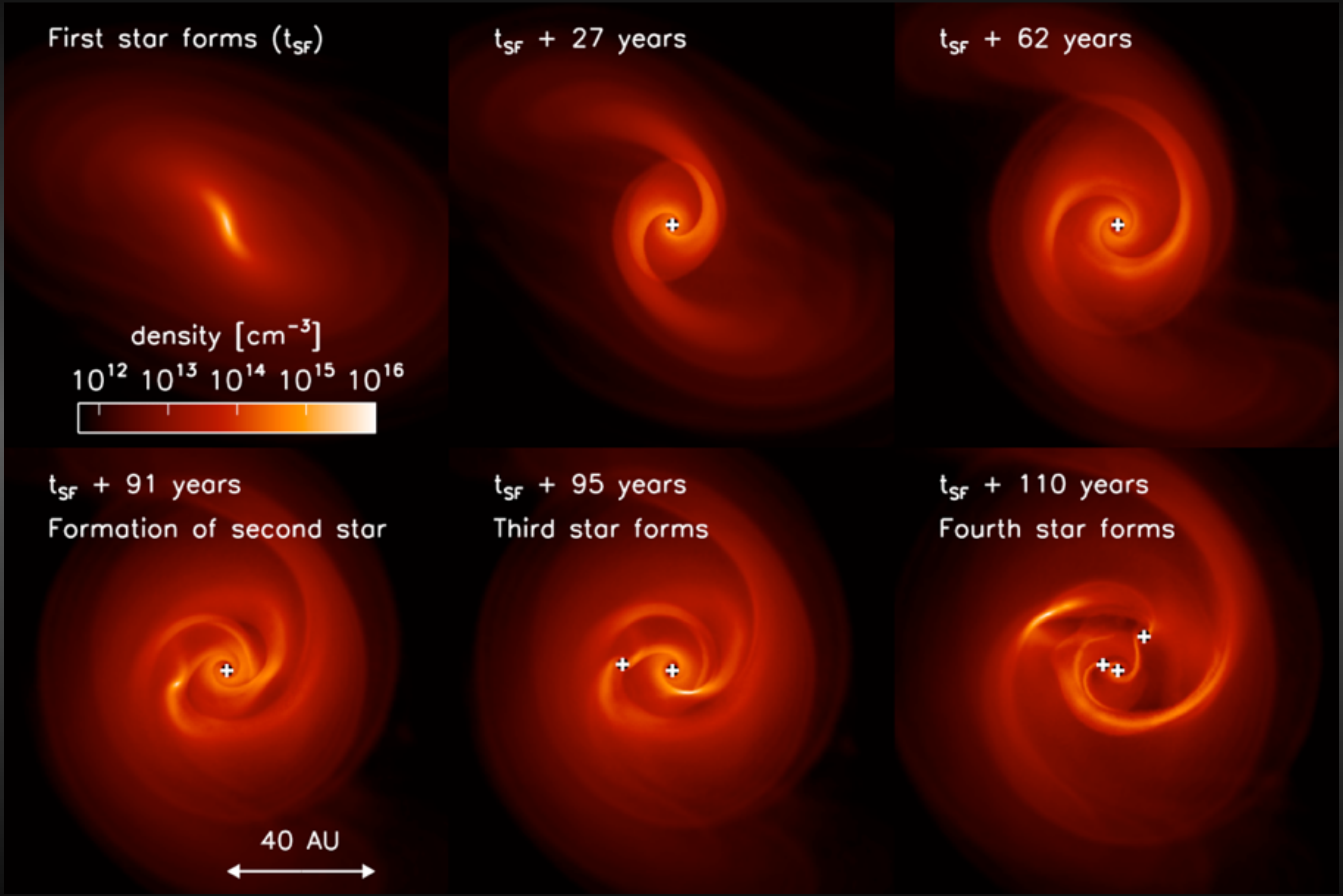
- Collision induced emission (CIE: (Frommhold 1994) takes over around densities of 10^{13} -10^{15} cm^{-3} (Omukai 2001)

- It too becomes optically thick after this density regime, and the gas relies on H_2 dissociation cooling.

Yoshida et al. 2006



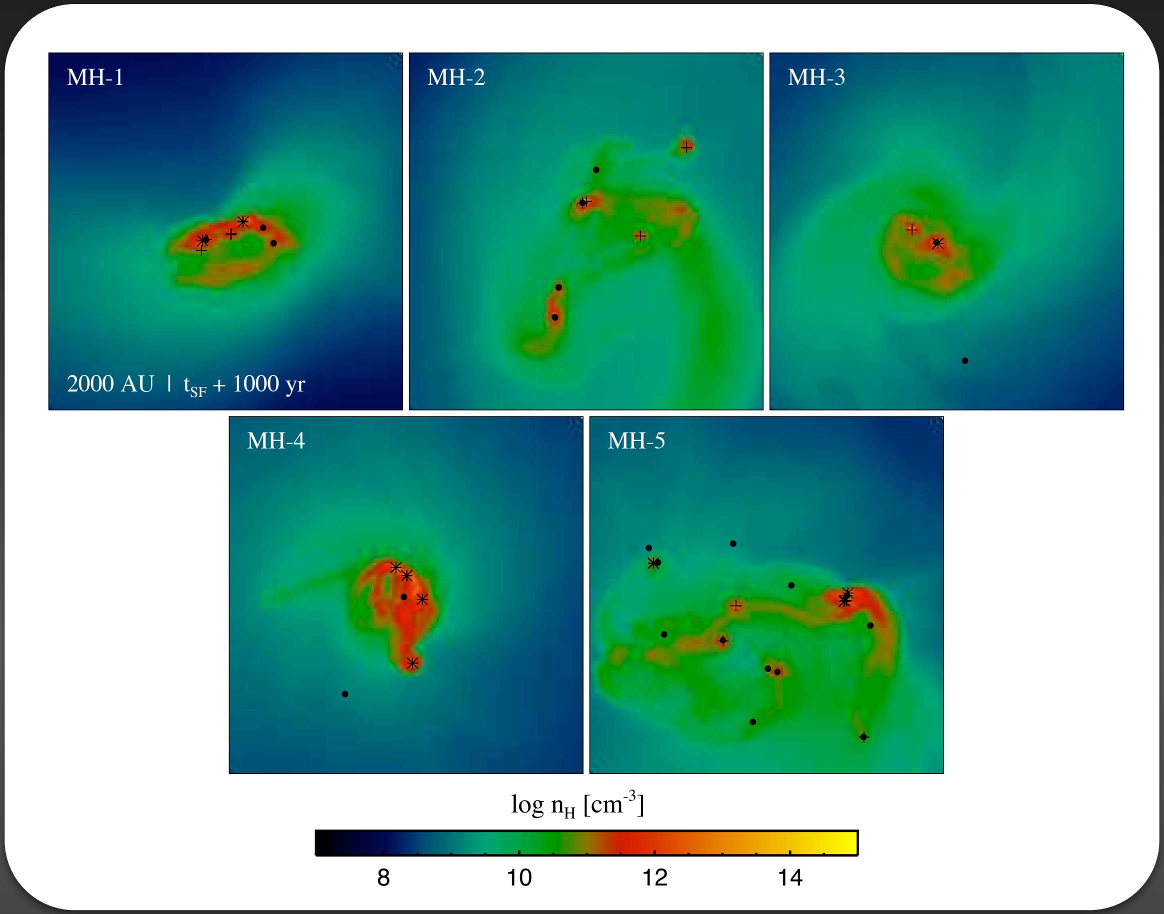
Fragmentation of protostellar Pop III discs



Clark et al. (2011b)

Multiplicity = Ejection

- 3 - body dynamics in inherently unstable
- If the gas really does fragment, then ejections from the halos will be common
- Normally the least-massive member is ejected
- High mass binary remains

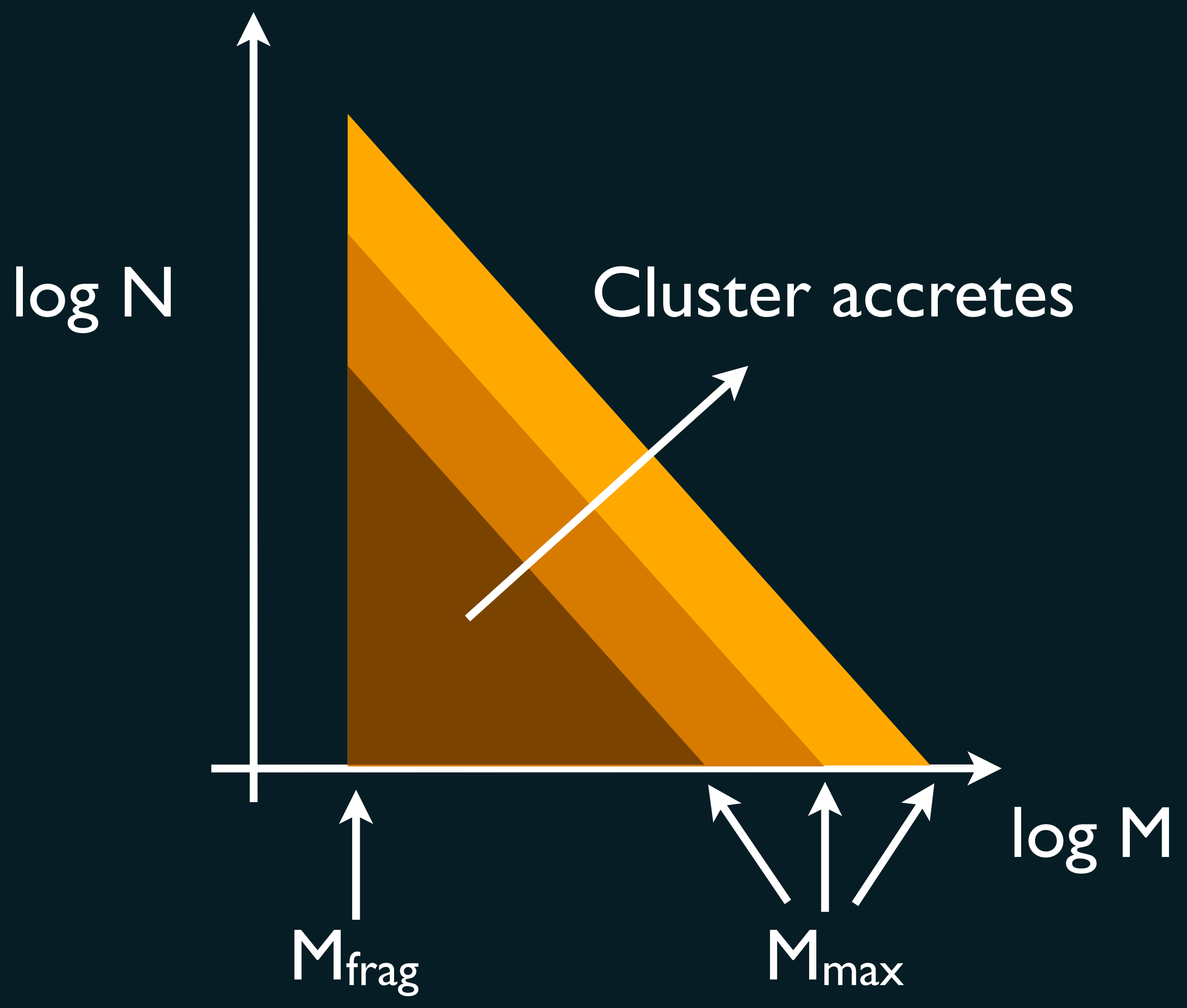


Greif et al. (2011), Smith et al. (2011)

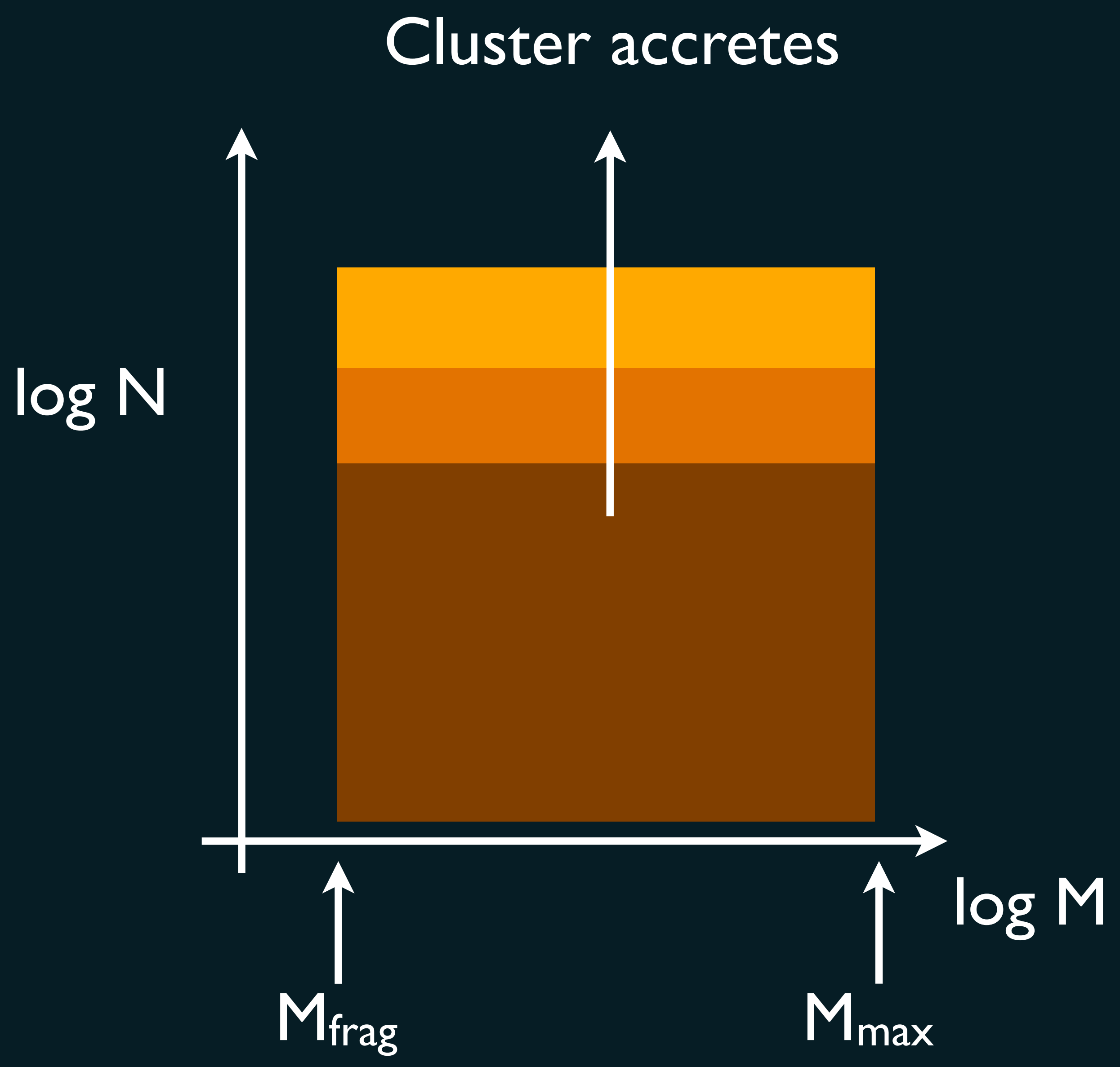
- However if there are lots of stars, then high-mass ejections will also be common
- We see these in the local universe (“runaways”)

We really do not understand the Pop III IMF!

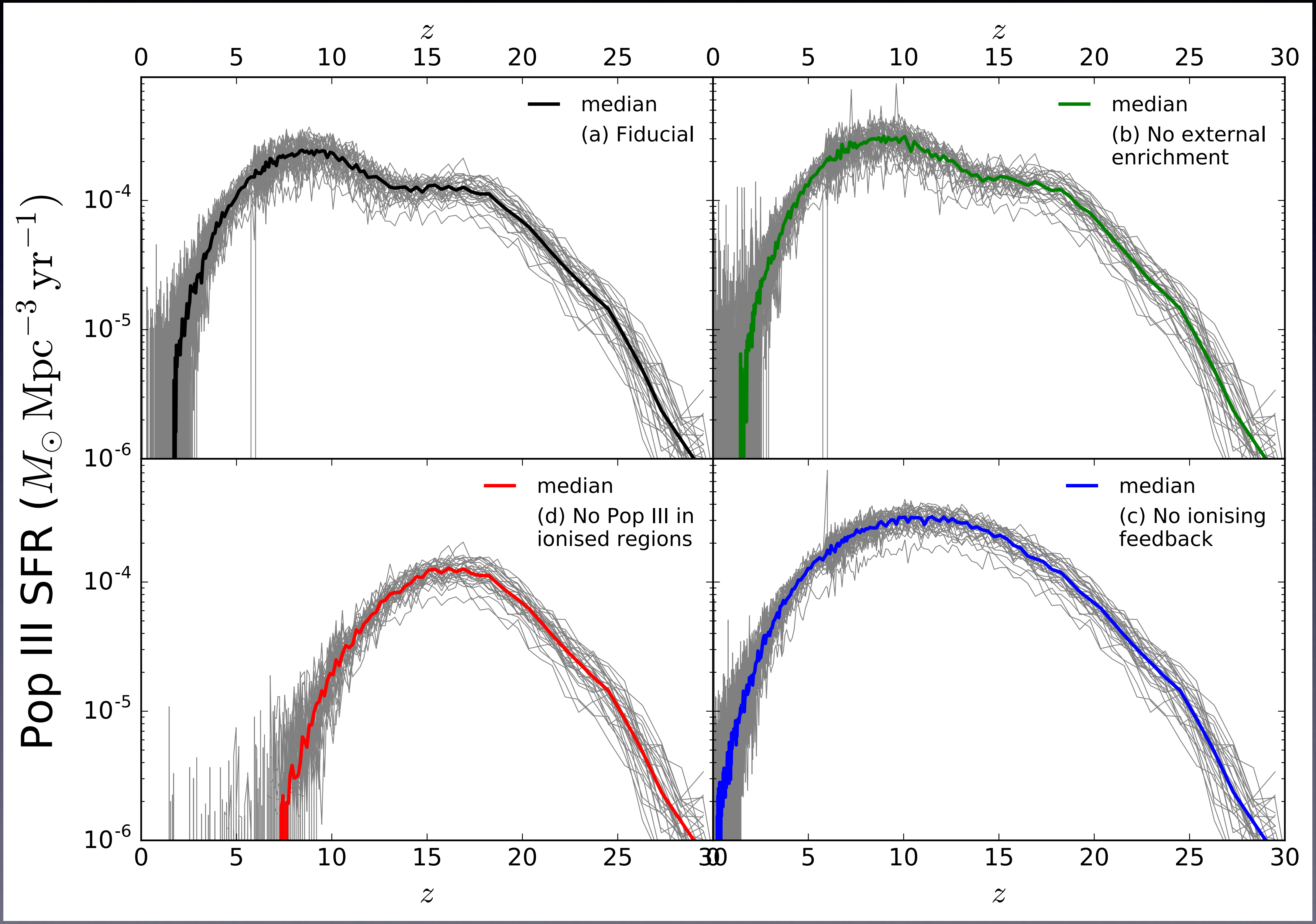
Imagine we have a standard power-law mass function:



Now imagine a flat mass function:

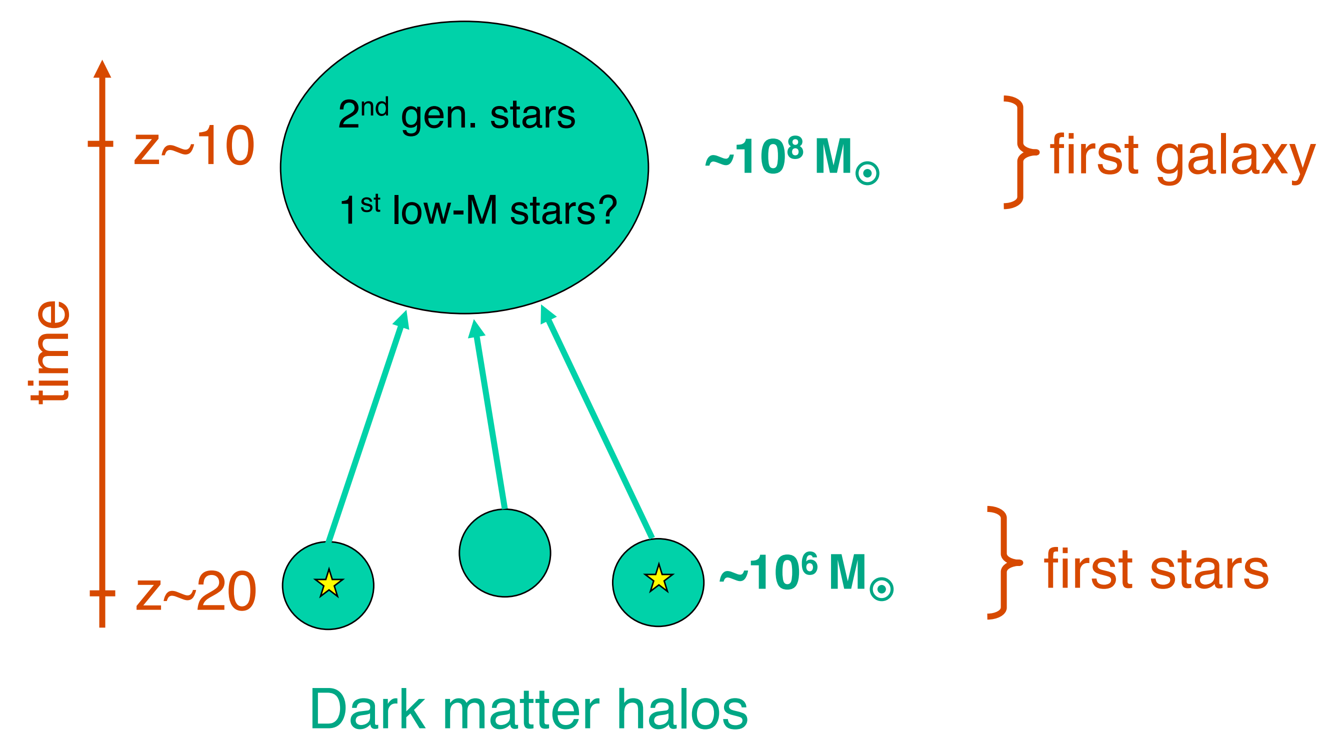


Pop III Star formation rate



Magg et al. (2017)

First galaxies and Pop II stars

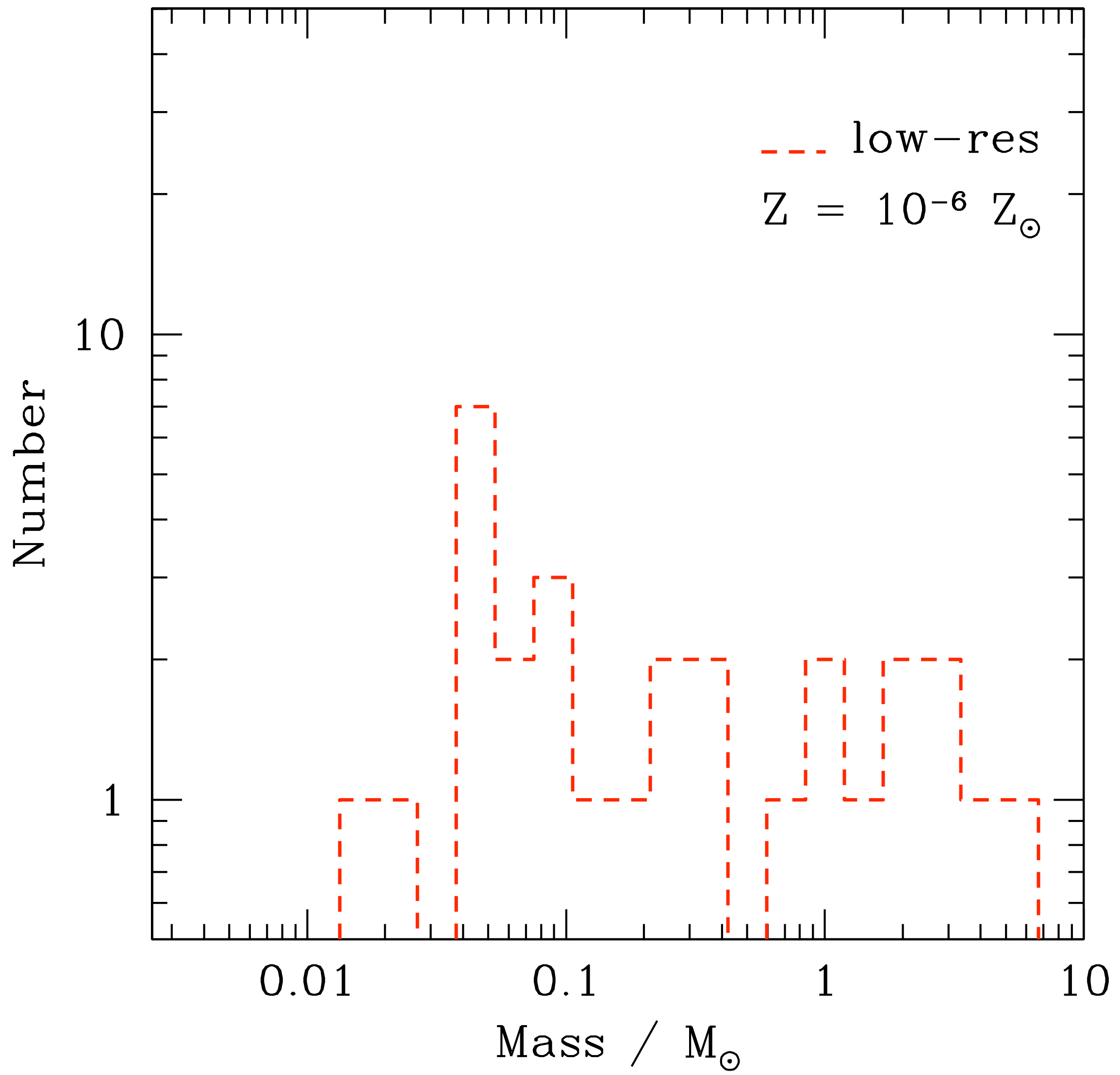


- Formation of 2nd generation stars delayed by radiation from 1st
- Form in presence of dust and metals (from SNe of Pop III)
- Even at $Z = 10^{-4}\ Z_\odot$, get different IMF

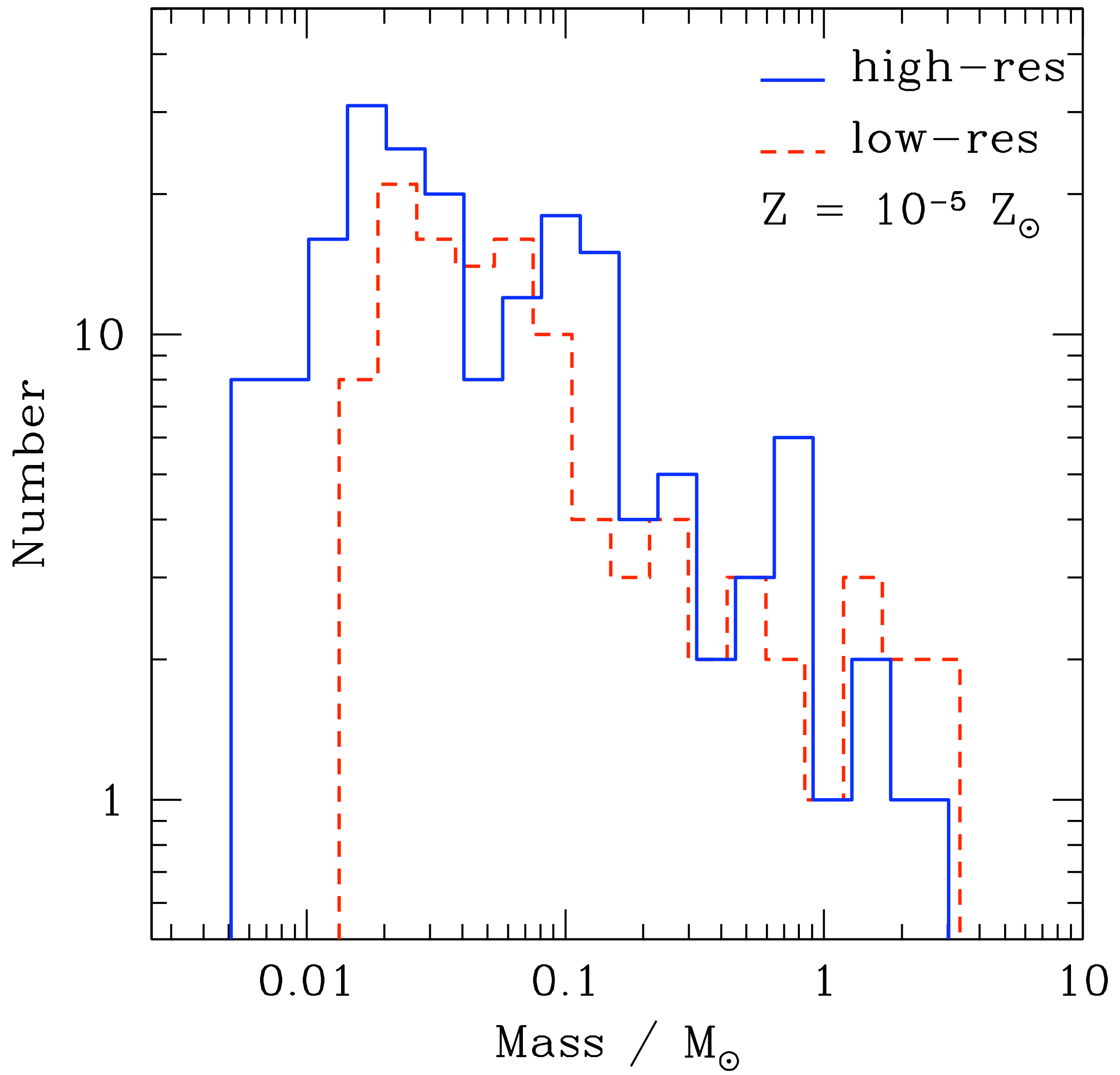
IMF

Transition to present-day IMF?

Clark, Glover & Klessen (2008)



Z = 10^{-6} $Z_\odot$



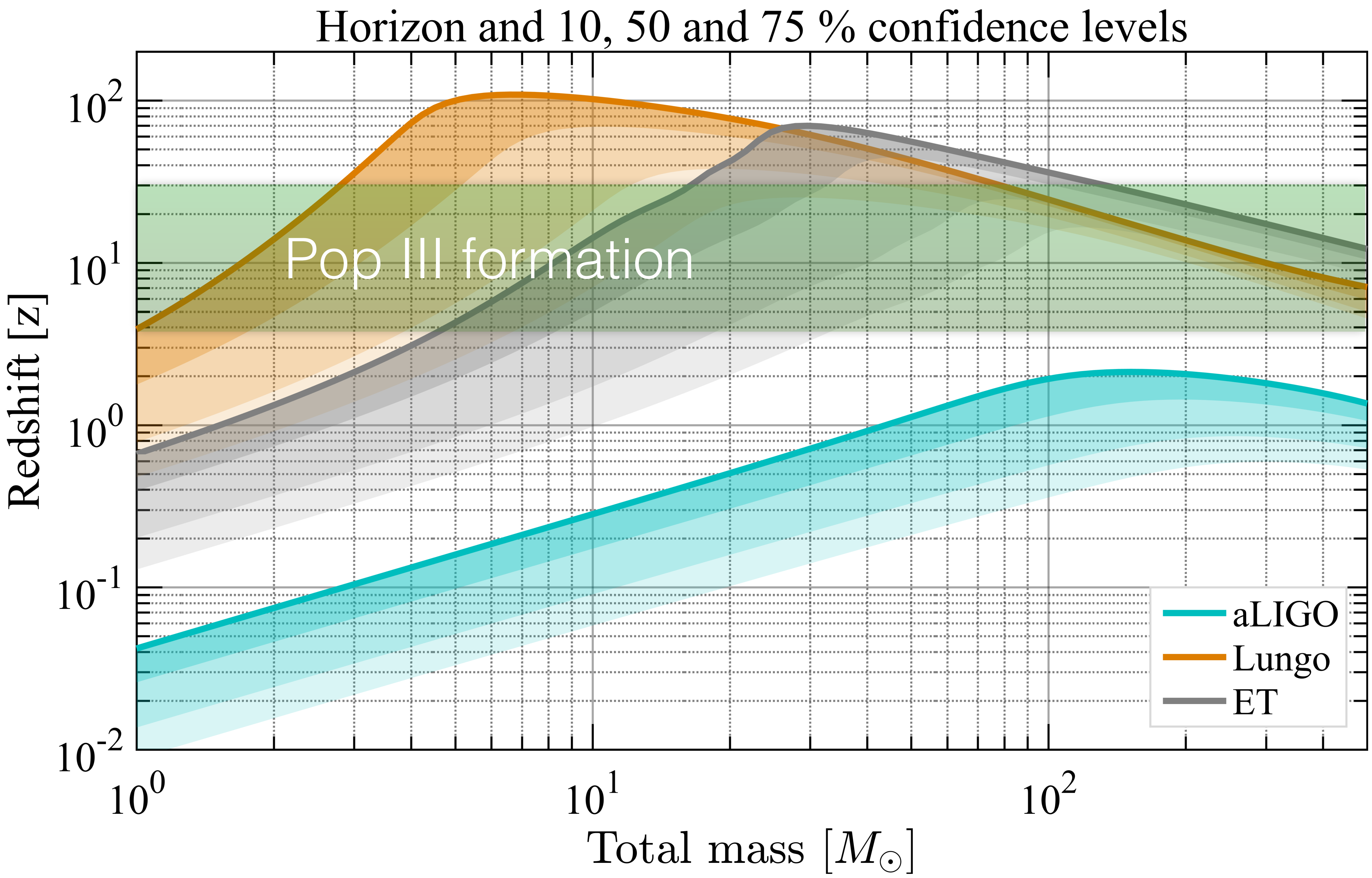
Z = 10^{-5} $Z_\odot$

Observational Prospects

- Not possible to directly observe Pop III stars, even with JWST, Euclid, E-ELT, …
- Observe Supernovae and GRBs associated to explosive death
    - SNe to z=10
    - PISNe to higher redshifts, but very rare
    - GRBs, possibly with clear Pop III signature
- Observations of extremely old, metal poor stars
- Black hole remnants

Broom (2013)

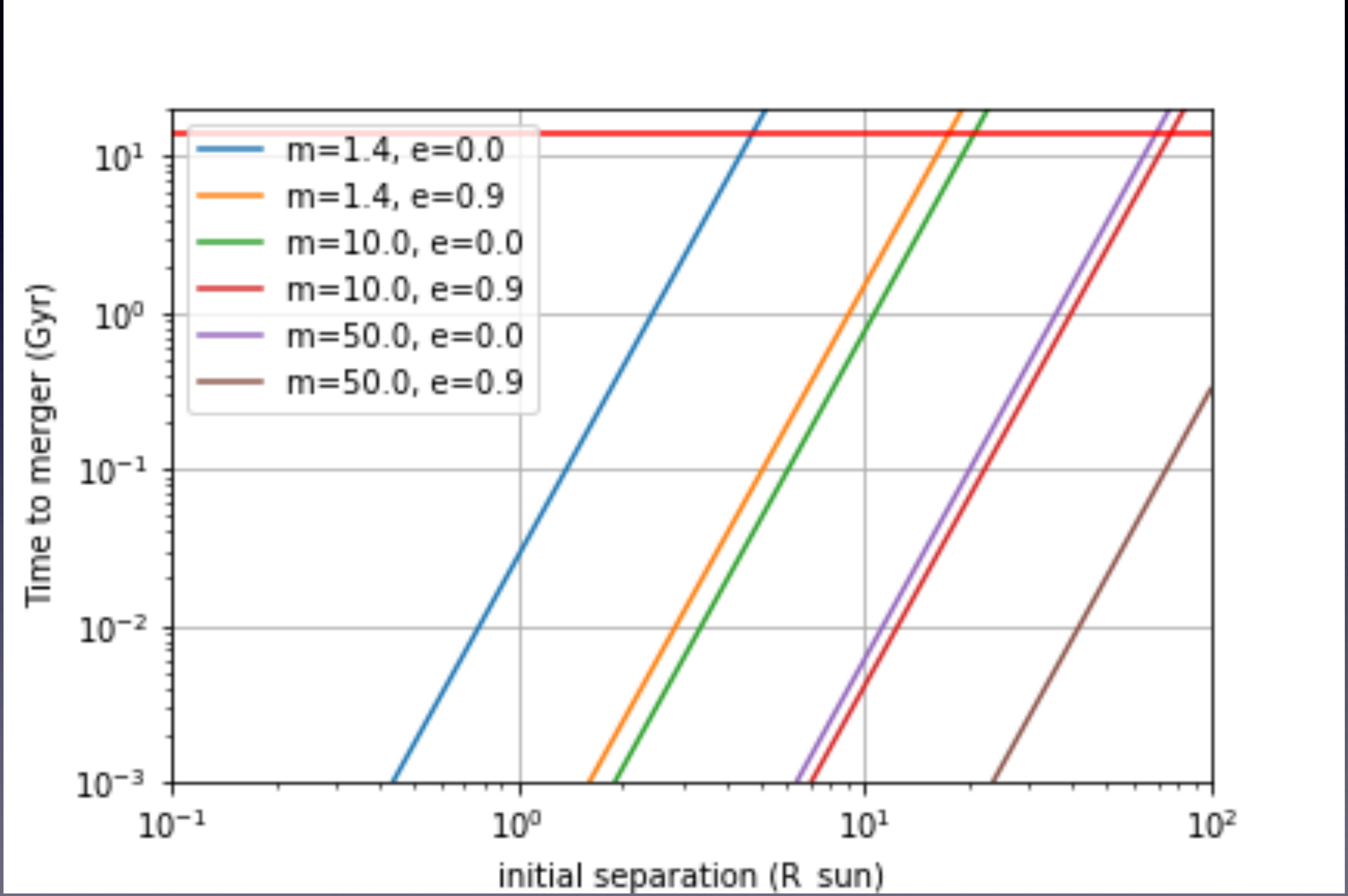
GW observations of Pop III?



Merger time

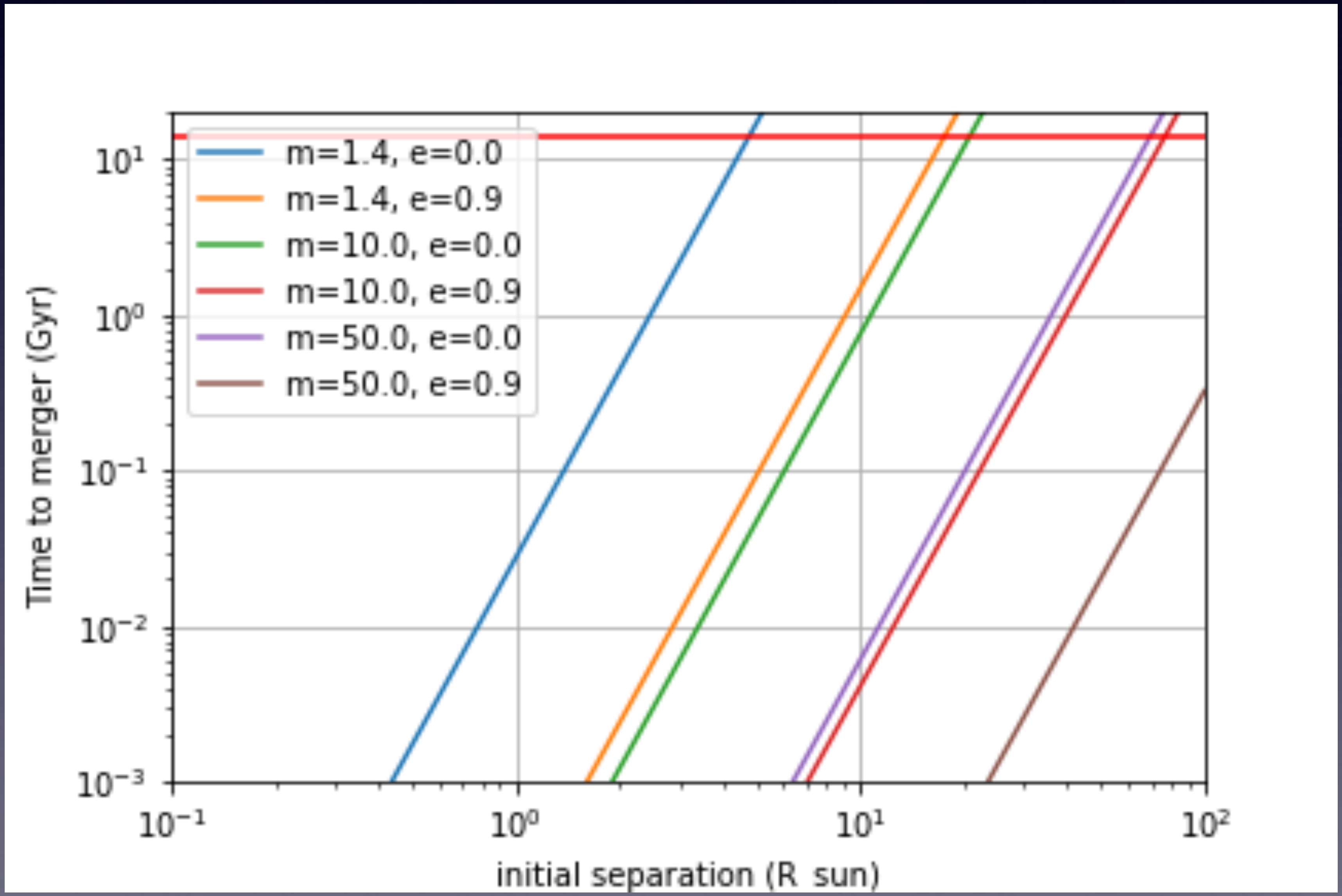
- Depends upon lifetime of the stars
  - few Myr to 50 Myr (depending upon mass)
  - equivalent to redshift $\Delta z < 0.1$
- Depends upon time for GW inspiral/merger
  - steep dependence on separation and eccentricity after 2nd NS/BH forms

Delay times



using results from Peters (1963)

Delay times



0

4

11

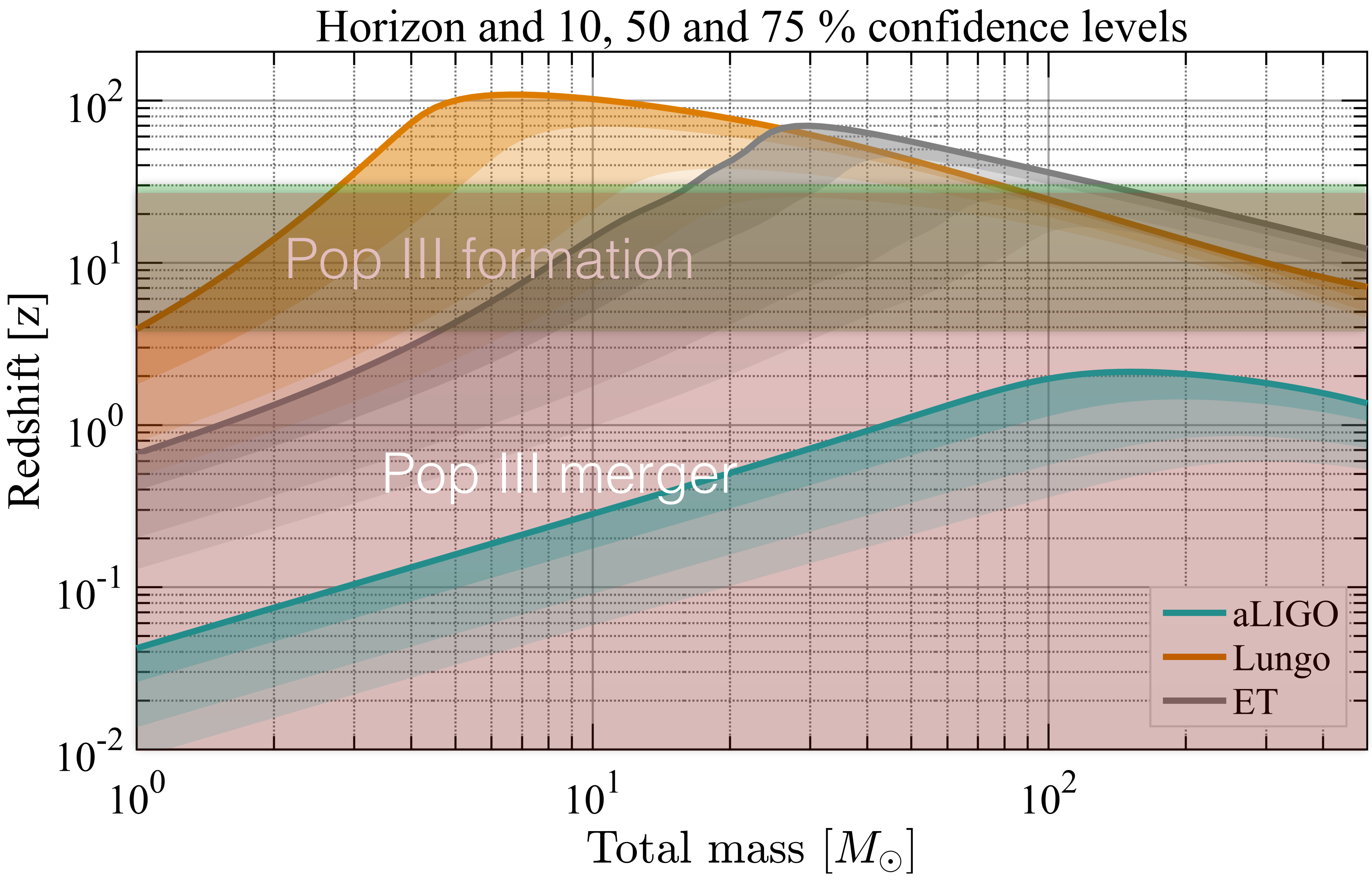
13.7

13.9

Assume 2nd
compact object
formation
at z = 14

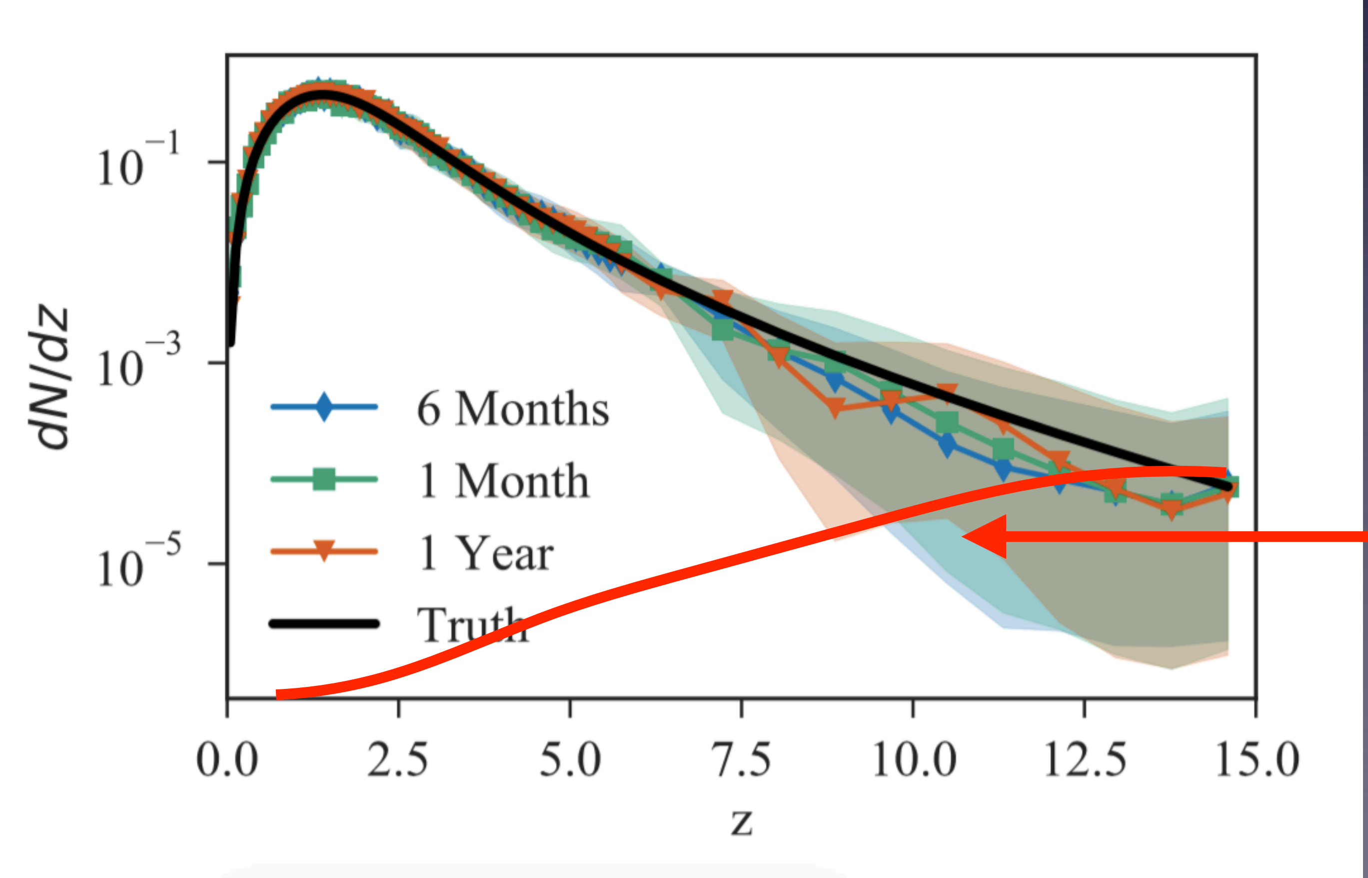
Merger
redshift

Future prospects



Evidence of Pop III origin?

- Unlikely on event by event basis
- likely to require identification of a population within the observed mergers, e.g.



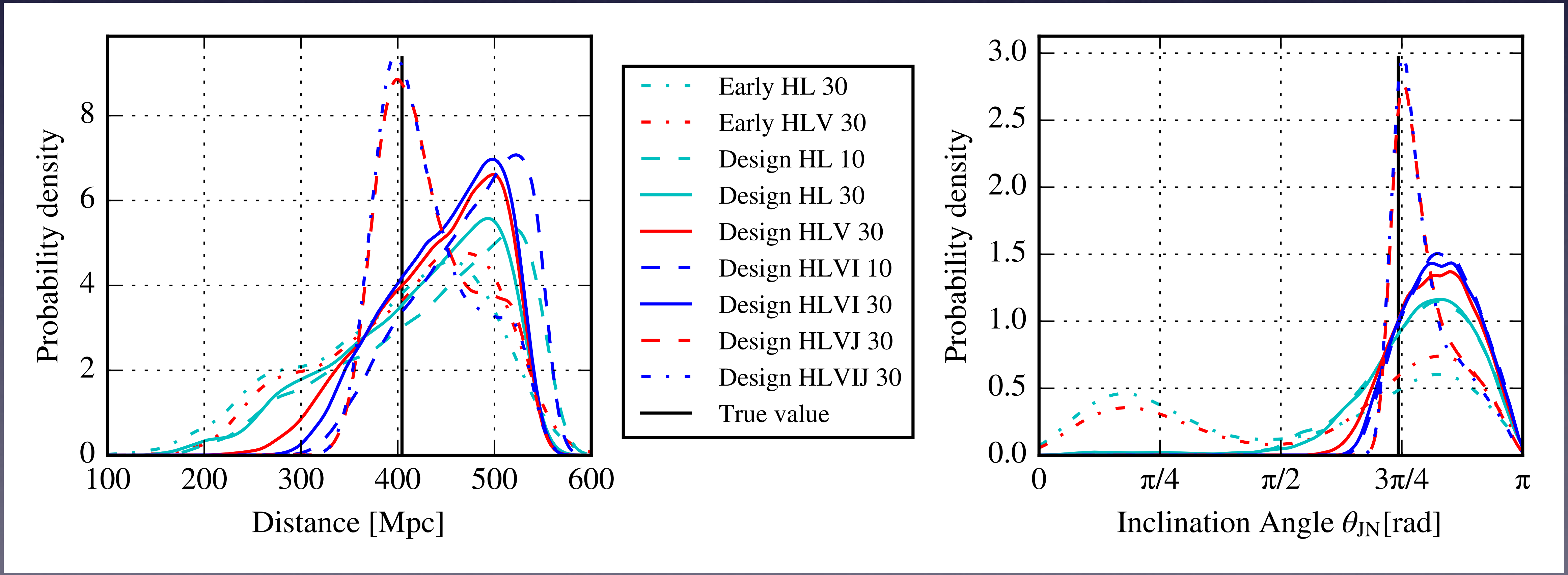
Pop III contribution

Measuring redshift & mass

- Uncertainty in distance leads to uncertainty in redshift and consequently mass
- Already seen in GW151226 — chirp mass measurement limited by distance uncertainty
- Impact on early universe measurements. Assume similar distance error: 50%
  - Source of mass 50 $M_{\odot}$ at z= 10 (D_L = 100GPc)
  - Observed to be between D_L=50 and D_L=150 GPc
    - z between 5 and 13.5
    - inferred masses between 25 $M_{\odot}$ and 70 $M_{\odot}$ — due to distance error alone

Measuring redshift & mass

- Require a network of detectors
- Better localisation and measurement of both polarizations improves distance measurement



Gaebel & Veitch (2017)

Summary

- Expect Pop III stars to be massive (flat/top-heavy IMF) and to form in close, multiple systems
- Third generation GW detectors will have sufficient sensitivity to measure NS and BH mergers of Pop III stars
- Challenge is to separate a Pop III component from the observed merger rate vs redshift
- 3G network likely to provide more accurate measurement of distance/redshift -> mass than a single detector