Fermi/Swift GRBs 2012

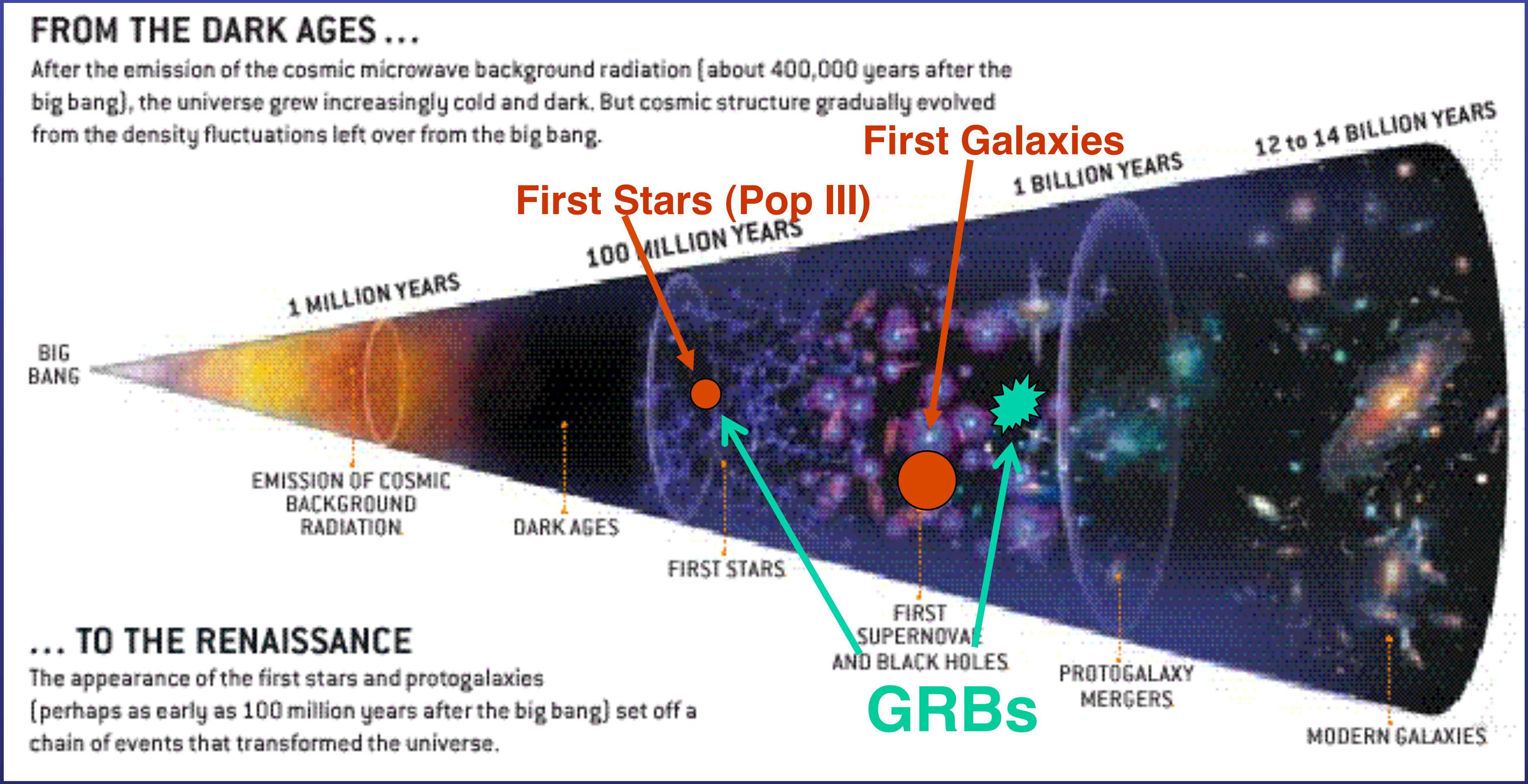
(Munich, May 2012)

Gamma-ray Bursts as Probes of the First Stars

Volker Bromm

The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance

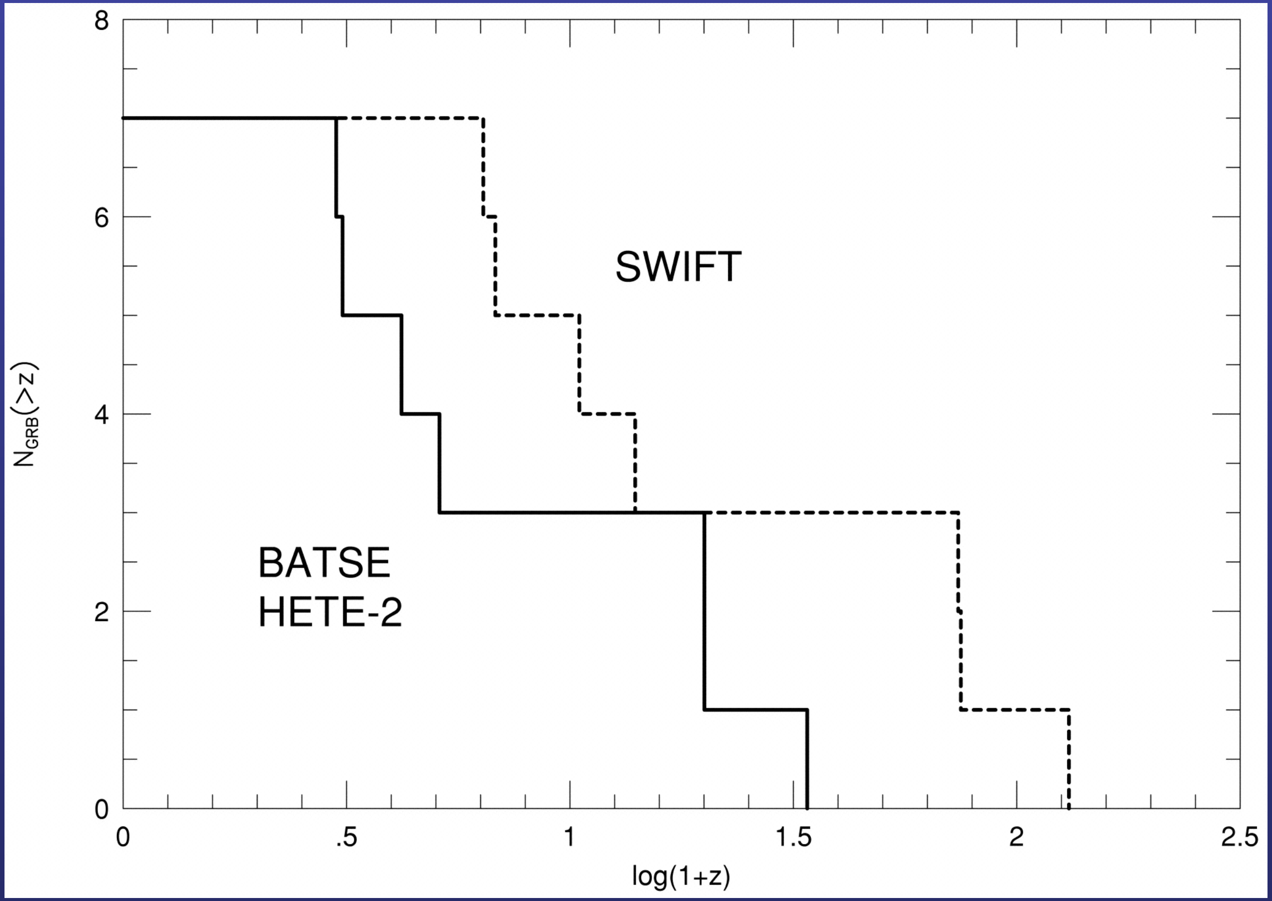


(Larson & Bromm, Scientific American)

- First Stars ⟶ Transition from Simplicity to Complexity

GRBs Probe the *Very* High Redshift Universe

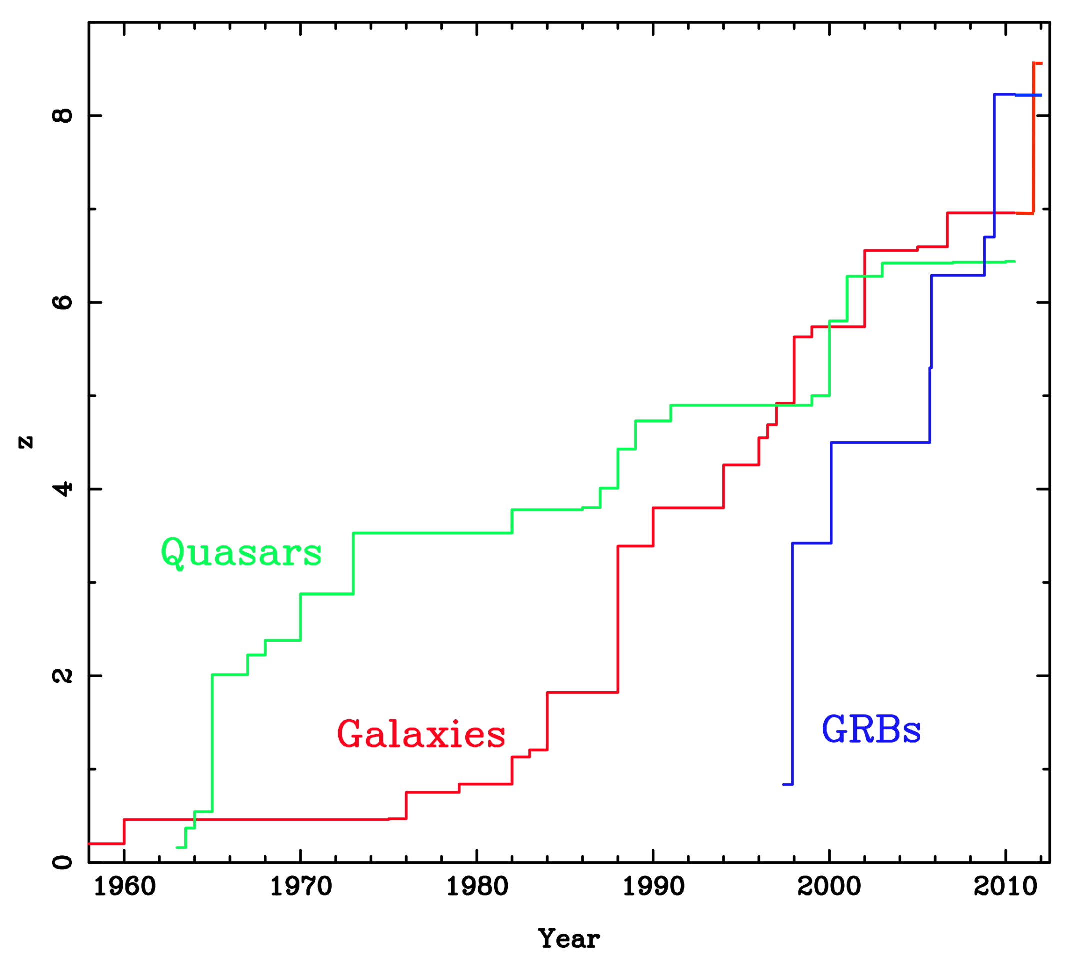
Number vs. Redshift



- Lamb & Reichart 2000

(also: Blain & Natarajan 2000; Bromm & Loeb 2002)

Extending the Redshift Barrier



(Courtesy: N. Tanvir)

- An ongoing race! GRBs likely to win!

Q: Are first stars suitable progenitors?

Progenitor: Requirements for Collapsar Engine

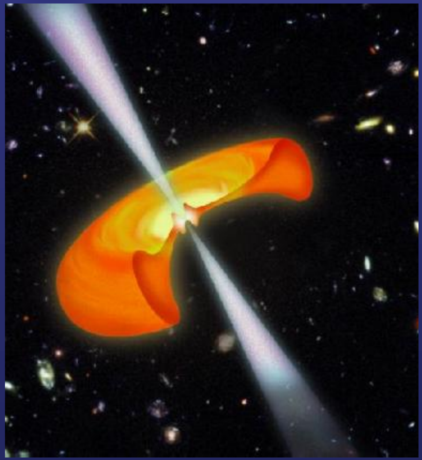
(for long/soft GRBs)

1. Sufficiently massive to form central BH

2. Central core has to retain enough spin

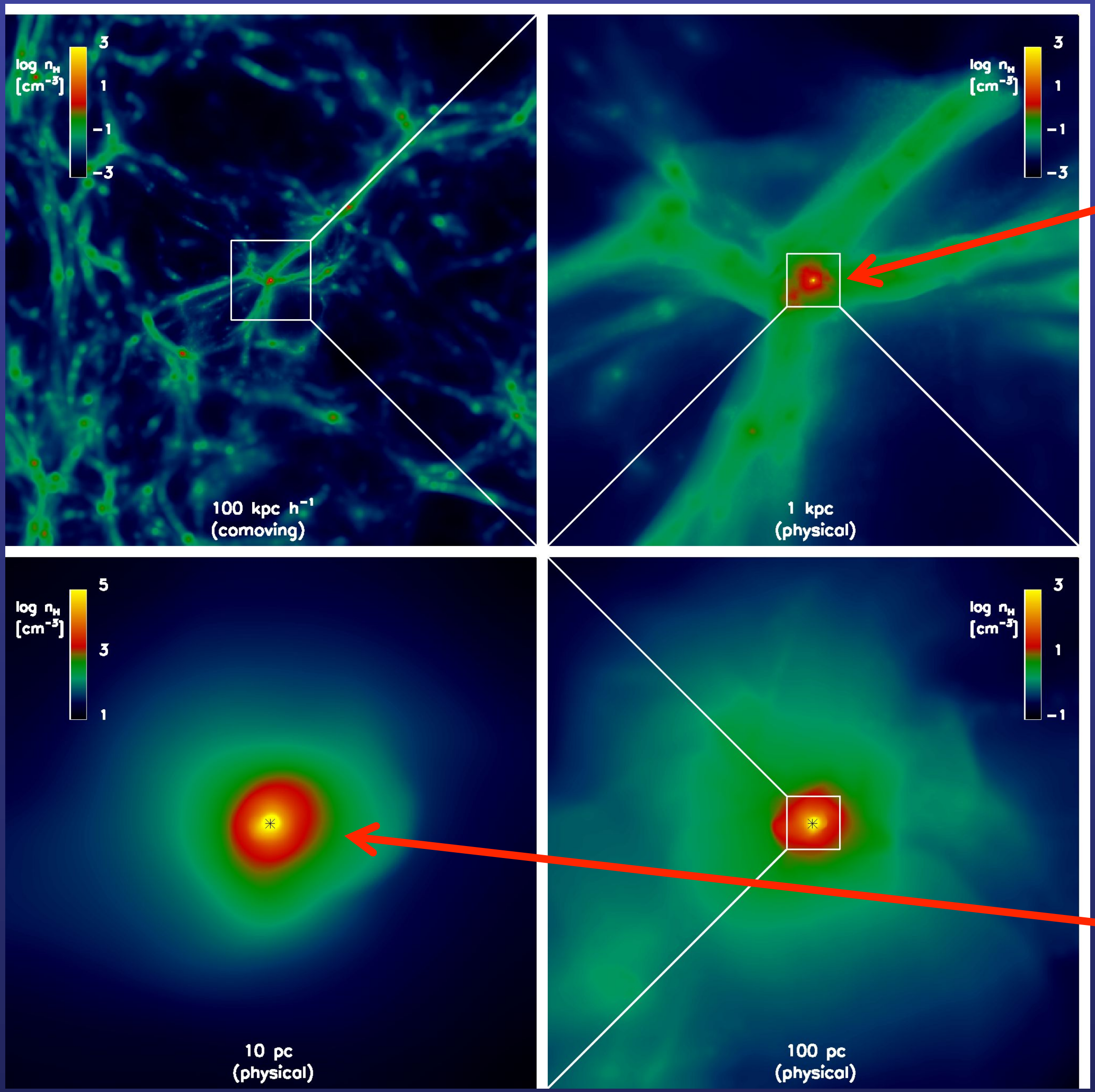
3. Loss of H/He envelope possible

   (But see: Suwa & Ioka 2011)



Formation of a Population III Star

(Stacy, Greif & Bromm 2010, MNRAS, 403, 45)



Minihalo:

$M \sim 10^6 M_o$

$R \sim 100$ pc

$z \sim 20$

Clump:

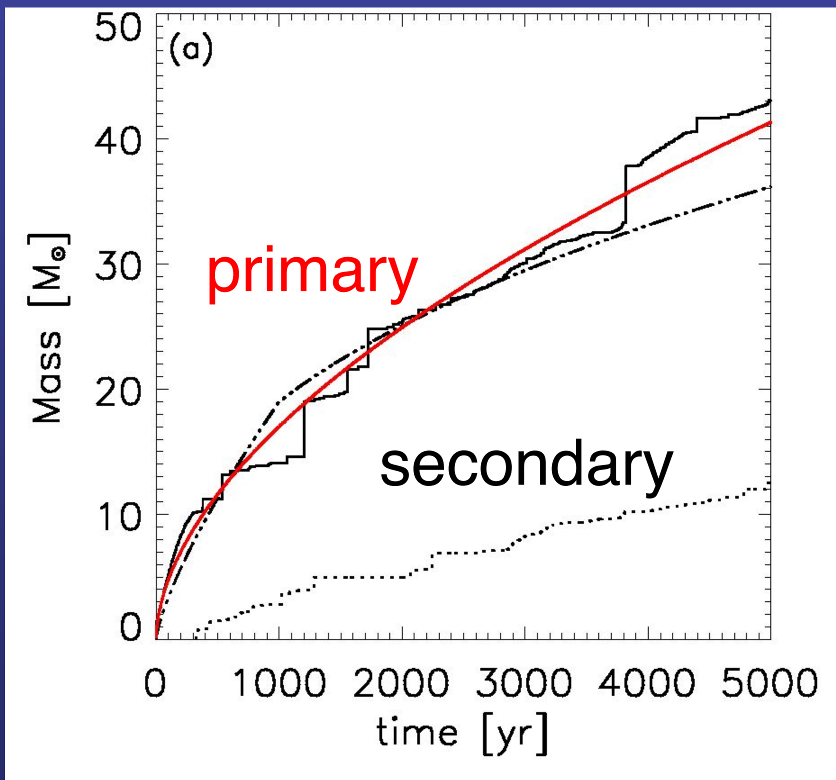
$M \sim 10^3 M_o$

$R \sim 1$ pc

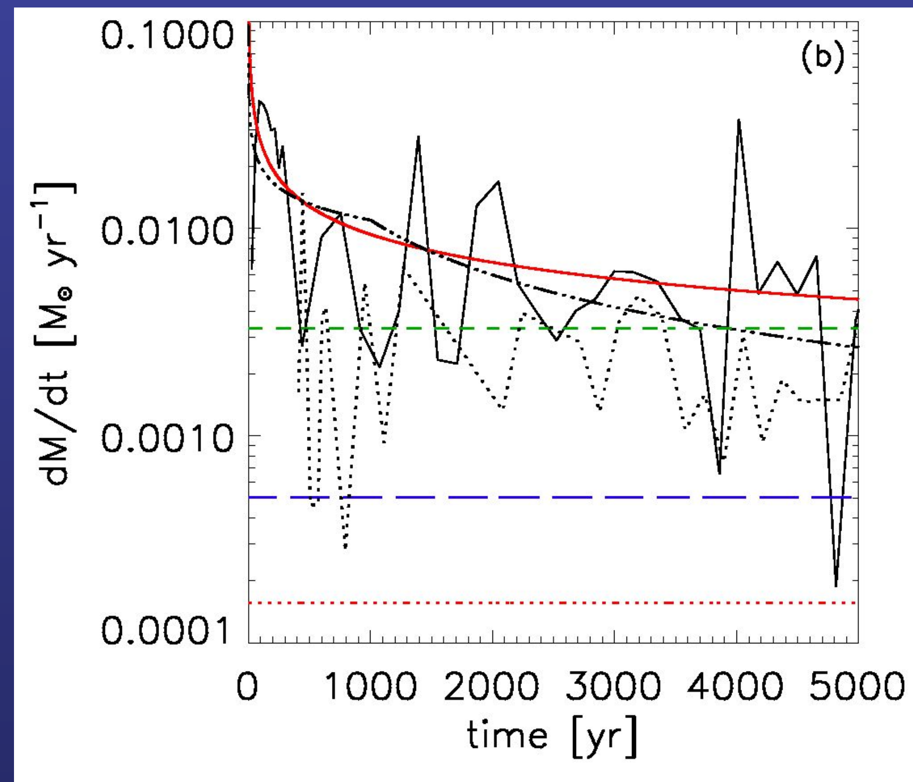
Pop III Star Formation: Growth by Accretion

(Stacy, Greif & Bromm 2010, MNRAS, 403, 45)

Stellar mass vs. time



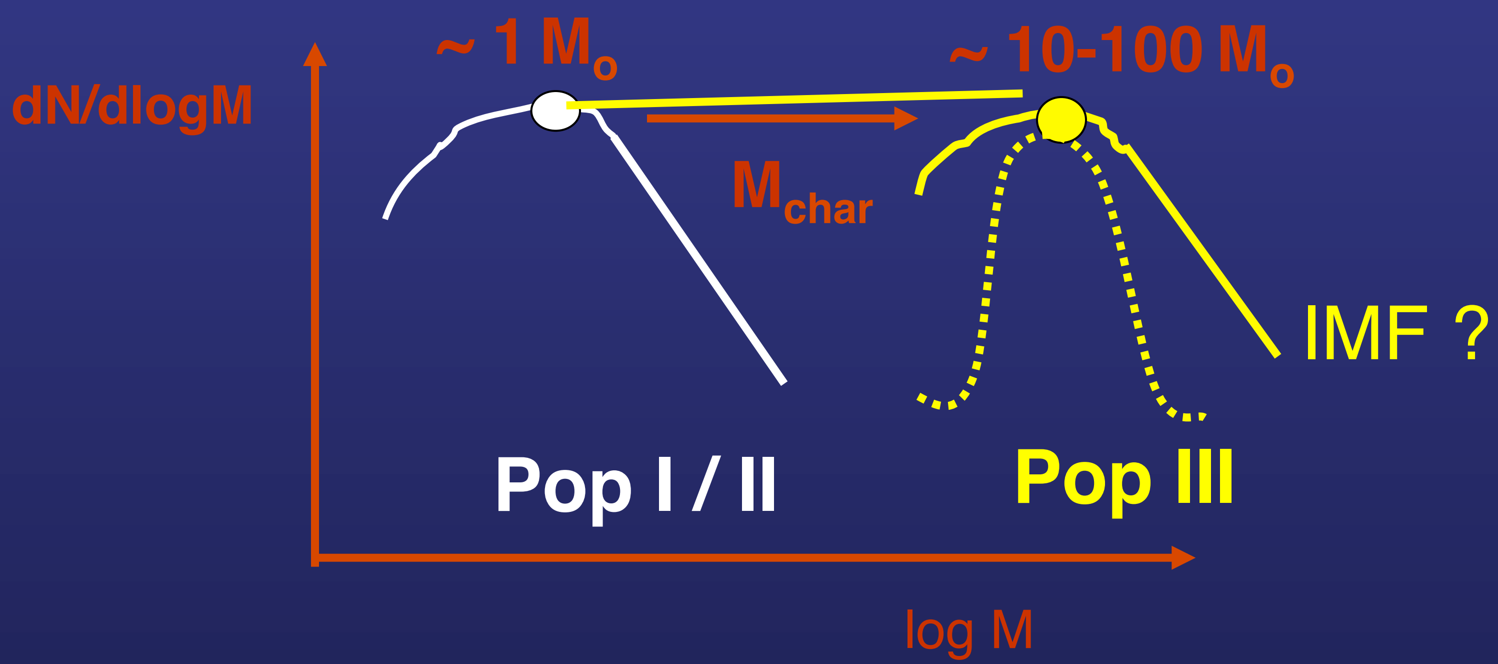
dM/dt vs. time



- a dominant binary has formed (~ 40 and ~10 M_O) after ~5,000 yr of accretion

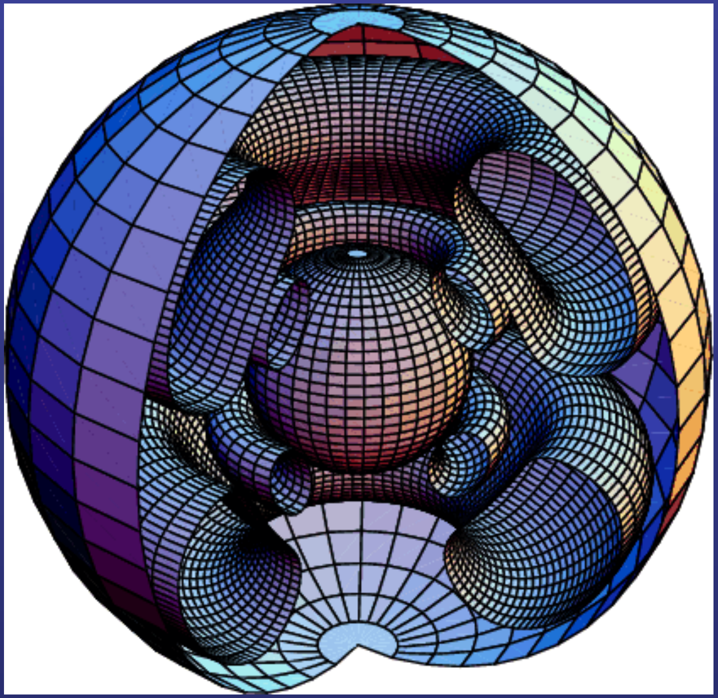
The First Stars: Final IMF

- Numerical simulations
  - Bromm, Coppi, & Larson (1999, 2002)
  - Abel, Bryan, & Norman (2000, 2002)
  - Nakamura & Umemura (2001, 2002)
  - Yoshida et al. (2006, 2008); O’Shea & Norman (2007); Gao et al. (2007); Clark et al. (2011); Greif et al. (2011)
- Likely Outcome: → **Top-heavy initial mass function (IMF)**

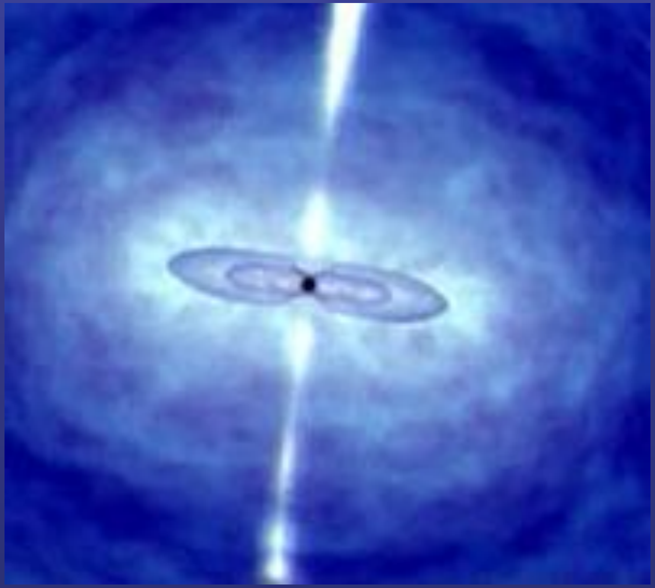


Rotation of Pop III Stars

- Poorly constrained
- After mass scale, most important parameter



Chemical mixing

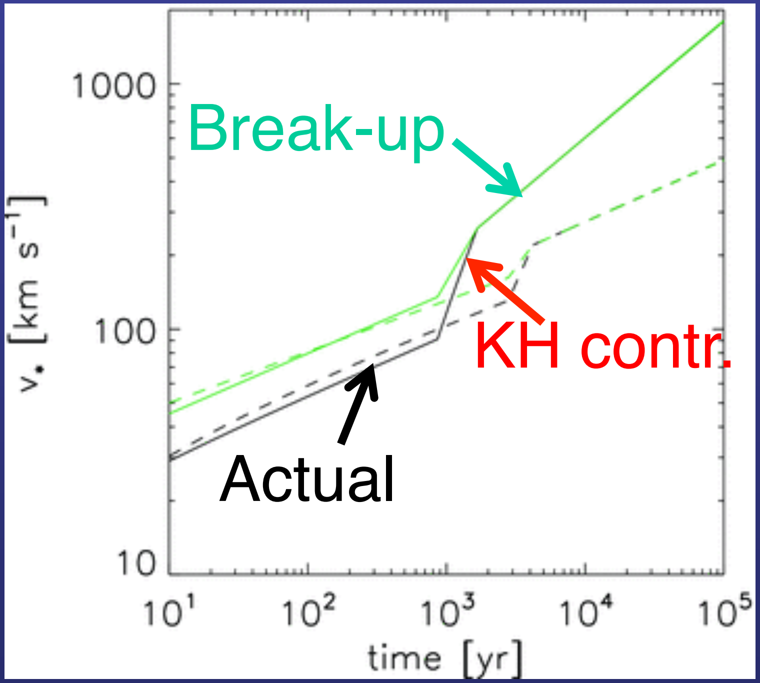


GRB collapsar

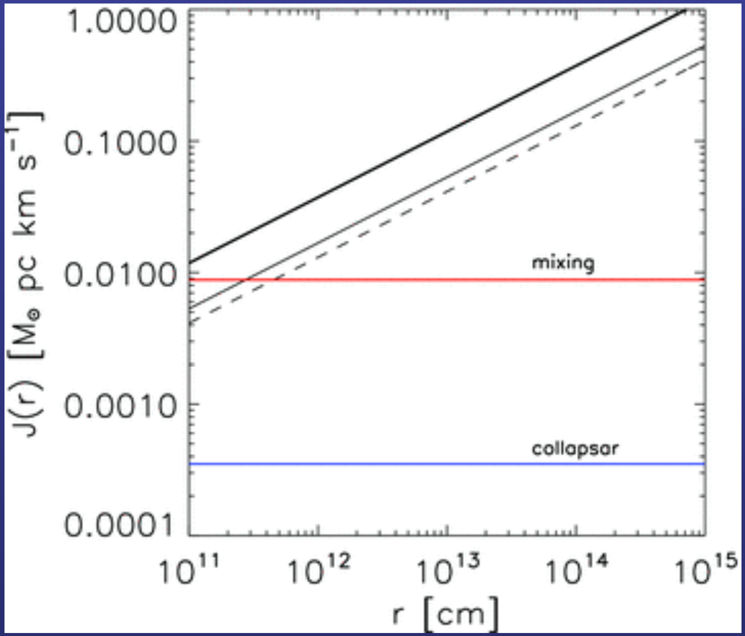
Rotation of Pop III Stars

(Stacy, Bromm & Loeb 2011, MNRAS, 413, 543)

Rot. Velocity vs time



J vs radius

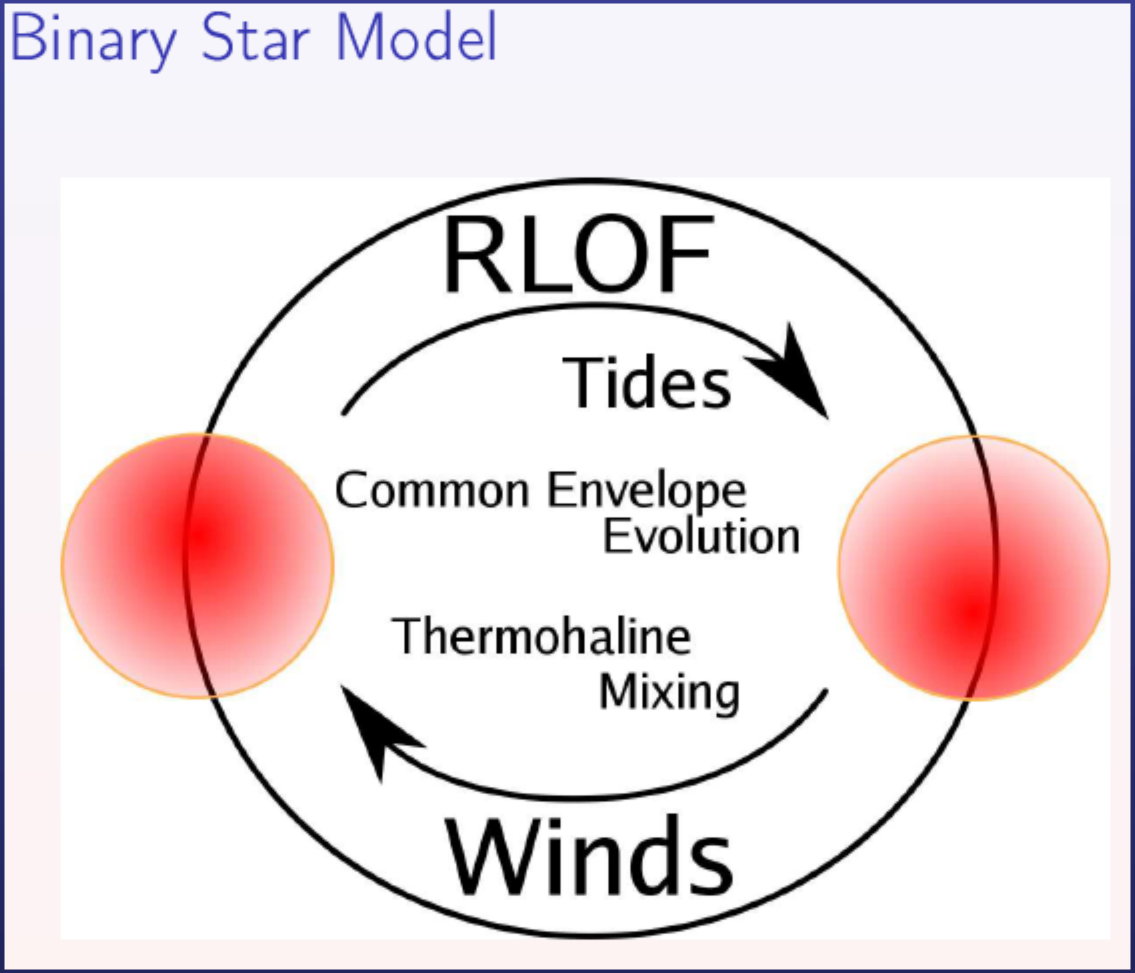


- Pop III stars may rotate at close to break-up speed
- May experience strong mixing and die as collapsar

Progenitor: Requirements for Collapsar Engine

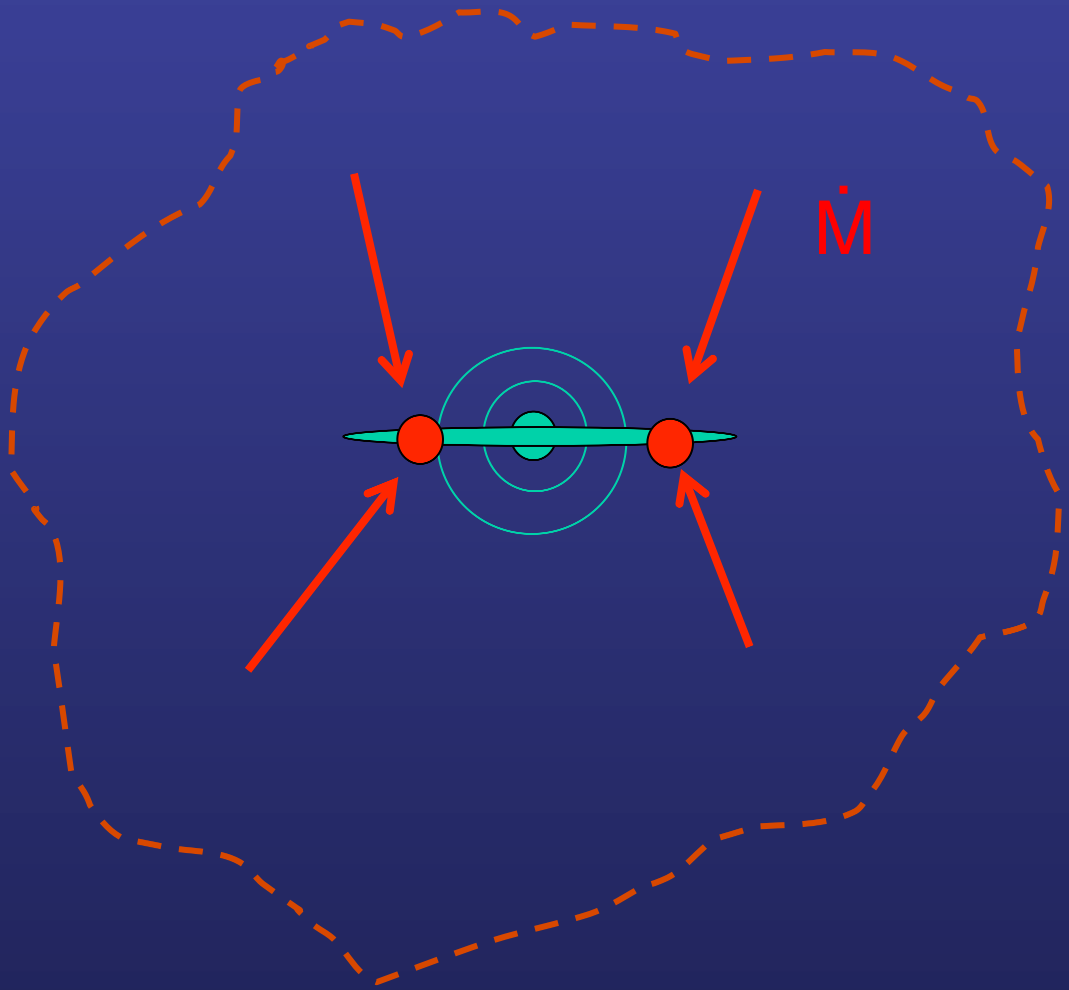
(for long/soft GRBs)

3. Loss of H/He envelope?



New Picture for Pop III SF:

- (Ubiquitous) Disk Fragmentation → small multiple

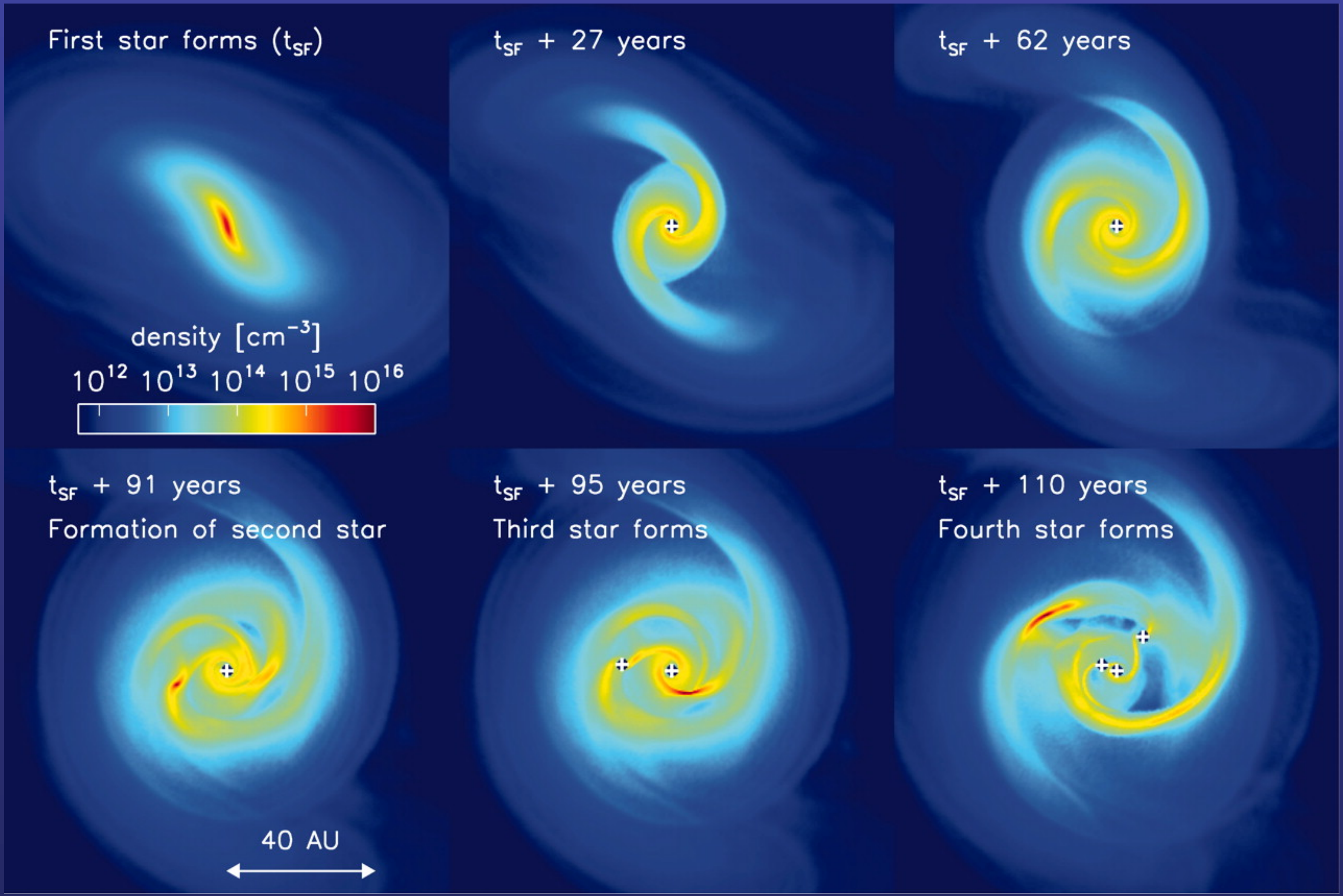


Clump:

$M \sim M_J$

Pop III Star Formation: Disk Fragmentation

(Clark, Glover, Smith, Greif, Klessen & Bromm 2011, Science, 331, 1040)



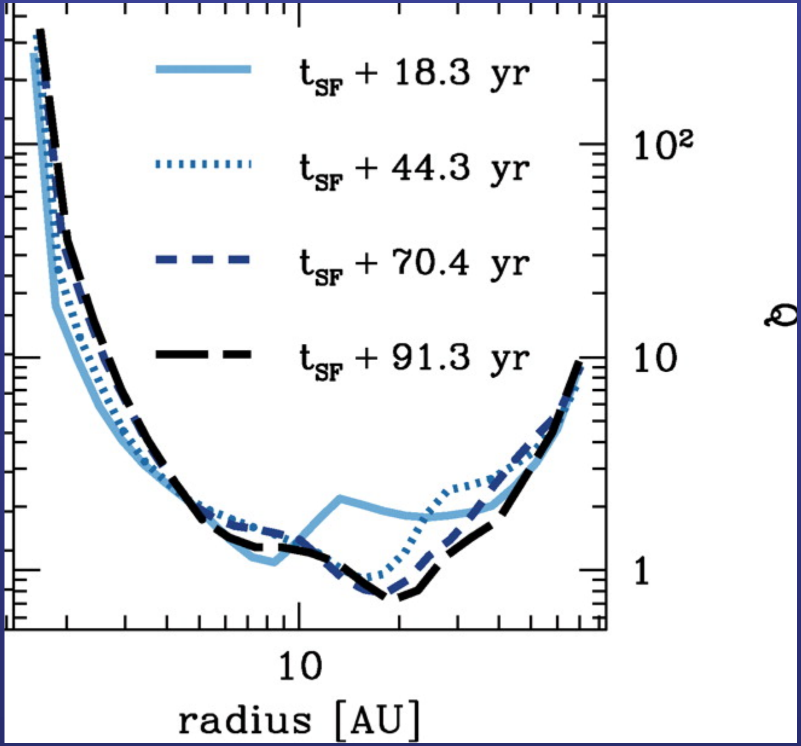
- Disk grows around primary sink

- Disk is gravitationally unstable: small multiple forms

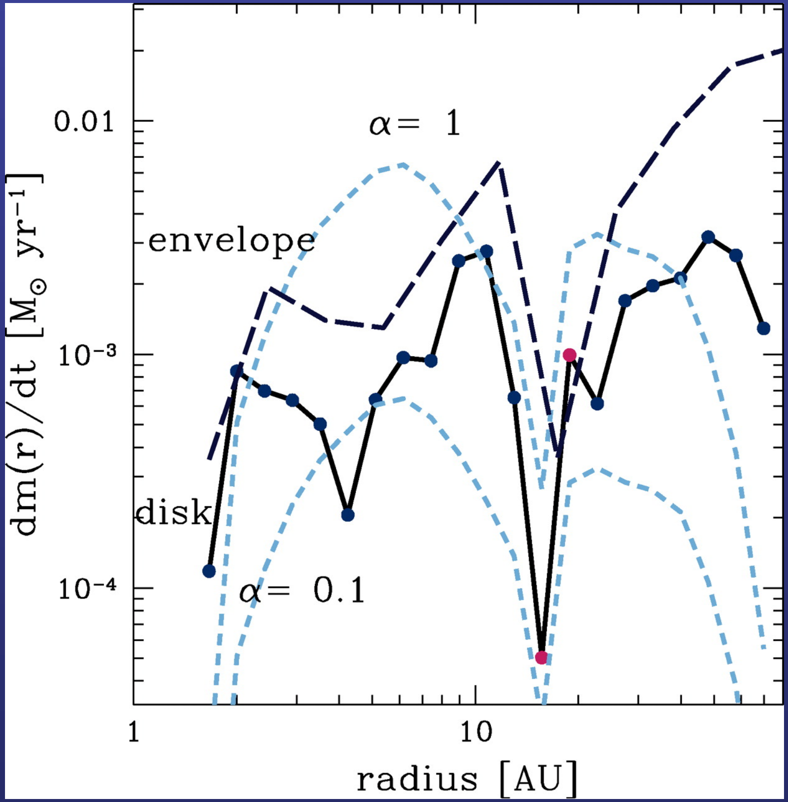
Pop III Star Formation: Disk Fragmentation

(Clark, Glover, Smith, Greif, Klessen & Bromm 2011, Science, 331, 1040)

Toomre Q vs. Radius



Mass transfer rate vs. Radius



- Disk is inevitably driven towards gravitational instability!

Q: How many bursts from high z?

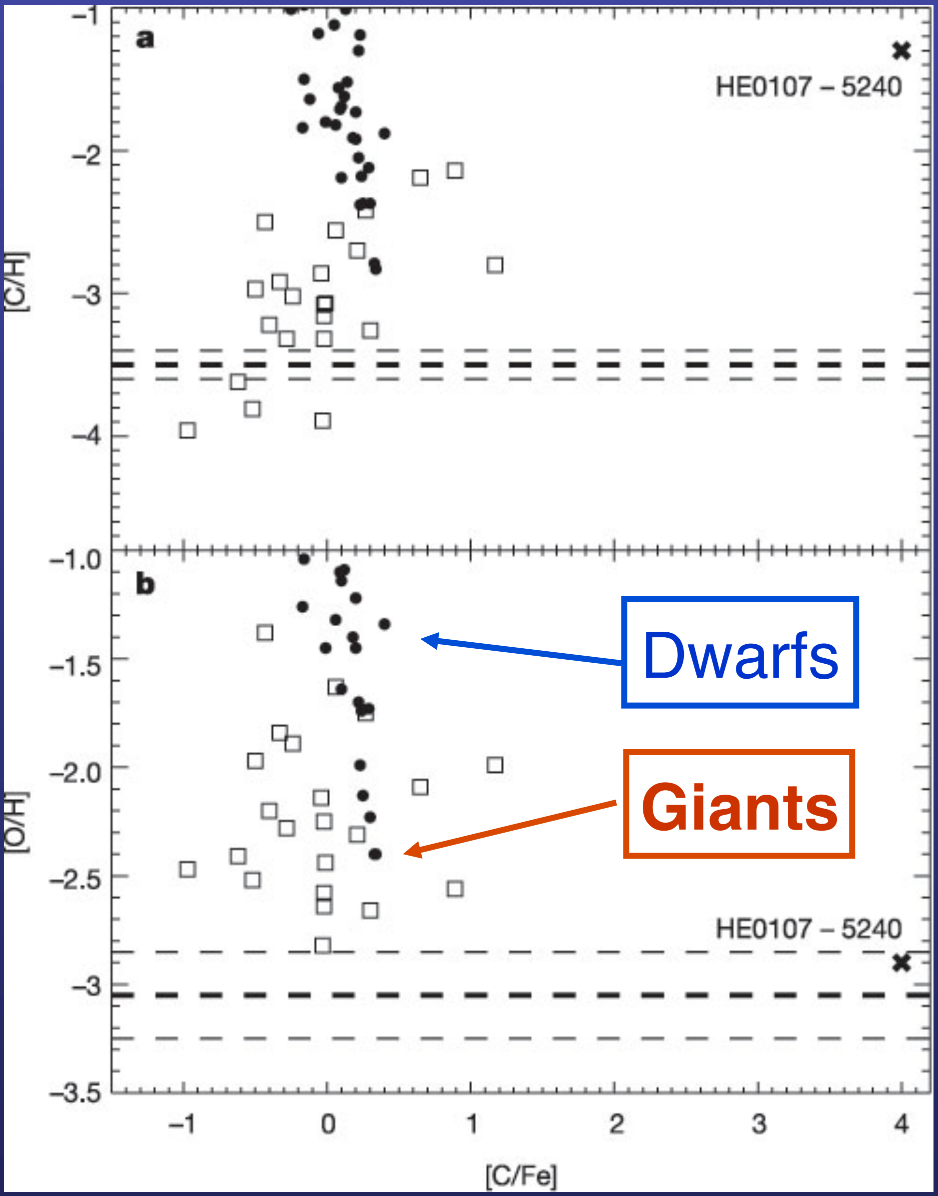
Critical Metallicity for Low-mass Star Formation:

(Bromm & Loeb 2003, Nature 425, 812)

- Abundance pattern:
  - HE0107-5240, 1327-2326
  - very Fe-poor
  - very C/O-rich

- Pop III ⟶ Pop II:
  - driven by: CII, OI (fine-structure transitions)

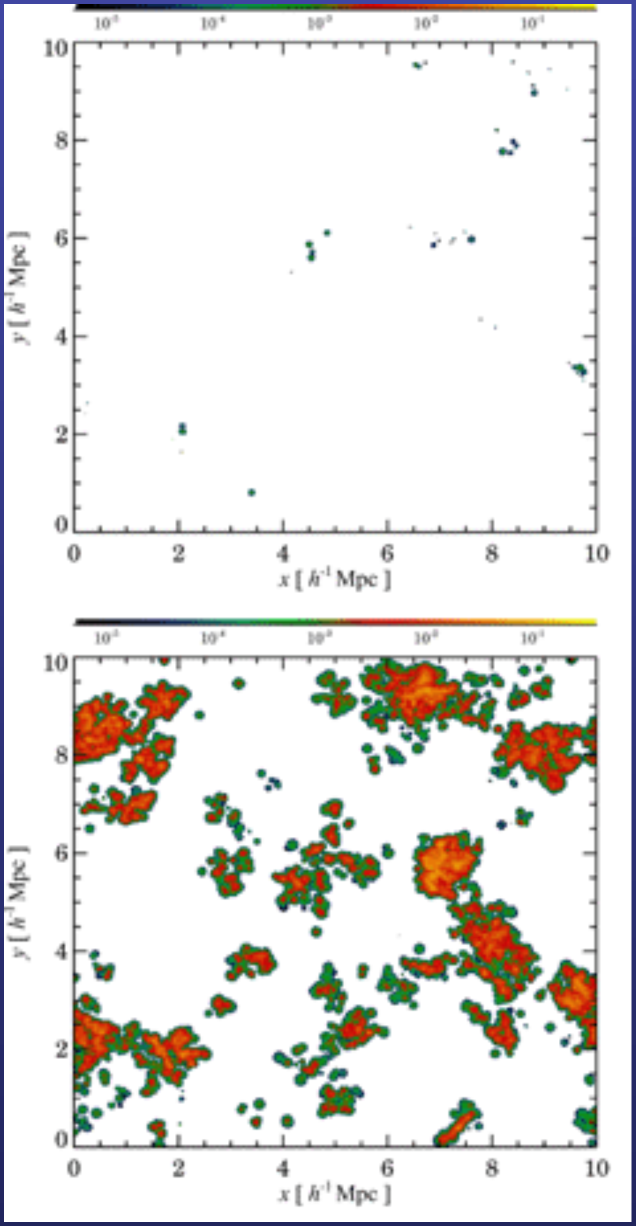
- Minimum abundances:
  - [C/H] ~ -3.5
  - [O/H] ~ -3.1
  - Identify truly 2nd gen. stars!



Chemical Feedback: Enriching Early Universe

z=10

z=5

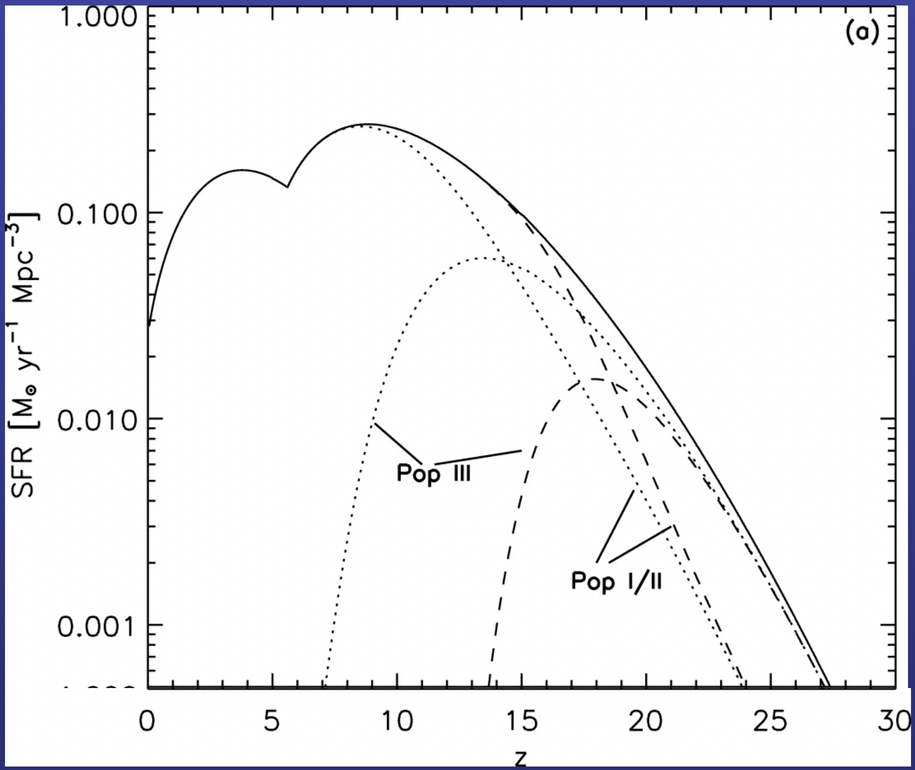


- Tornatore et al. 2007

- Metals comprise increasing volume fraction → Pop III mode extinguished!

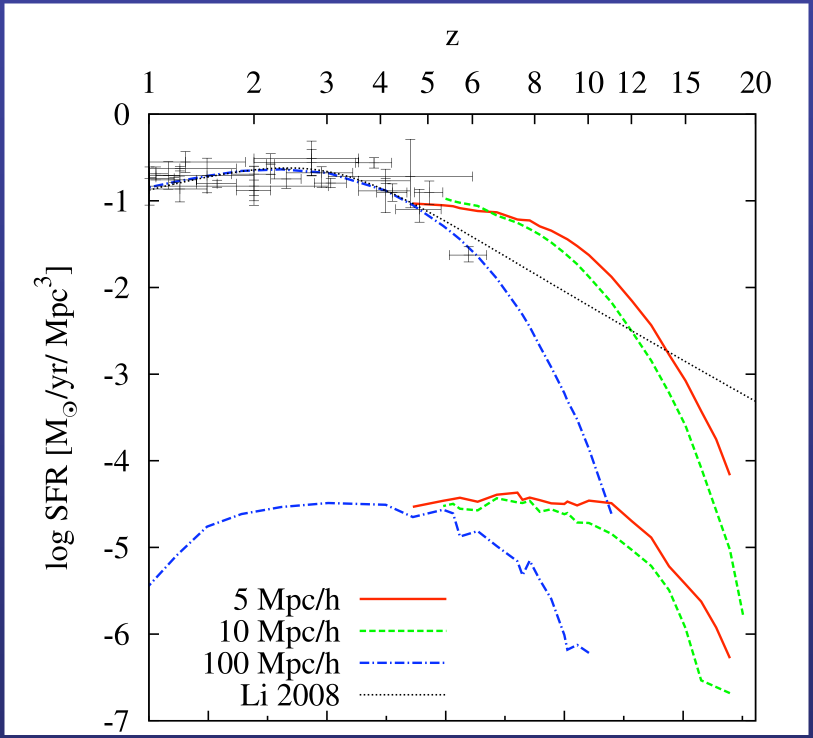
Modeling Cosmic SF History at High Redshift

SFR Density vs. z



(Bromm & Loeb 2006)

SFR Density vs. z



(Campisi et al. 2011)

- Pop III mode ⟶ Small fraction of total SFRD

Deriving GRB Redshift Distribution

- e.g.: Bromm & Loeb 2006

$$\frac{dN_{\rm GRB}^{\rm obs}}{dz} = \psi_{\rm GRB}^{\rm obs}(z)\,\frac{\Delta t_{\rm obs}}{(1+z)}\,\frac{dV}{dz}\,,$$

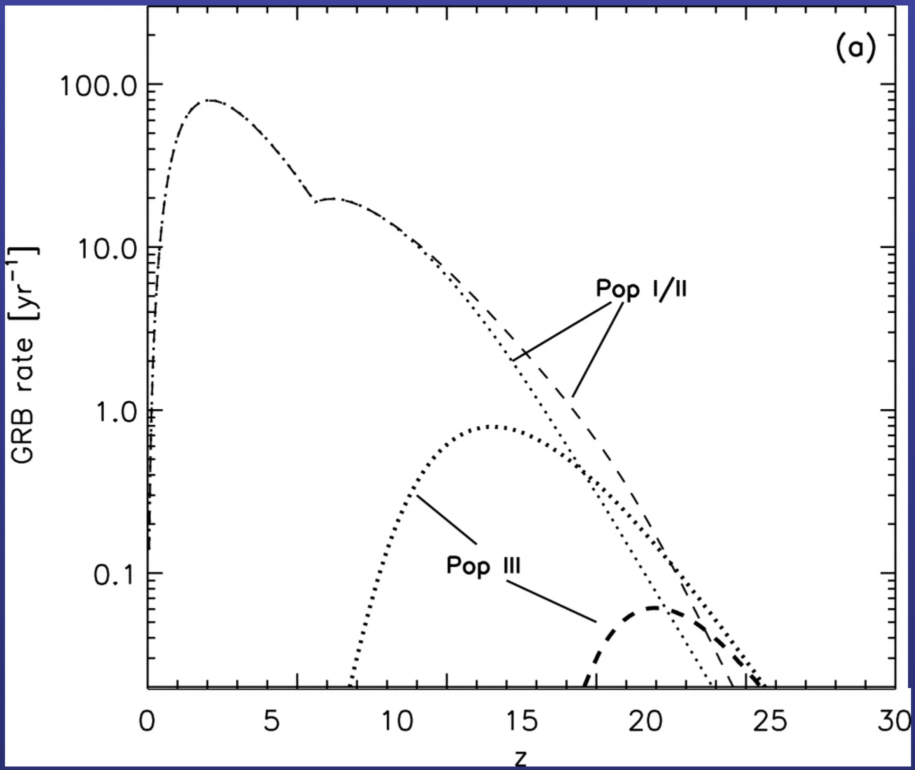
$$\psi_{\rm GRB}^{\rm obs}(z) = \eta_{\rm GRB}\,\psi_*(z)\int_{L_{\rm lim}(z)}^{\infty} p(L)\,dL.$$

GRB LF

GRB formation efficiency
(~10^{-9} bursts per solar mass)

GRB Redshift Distribution

***Swift* GRB rate vs. z**



(Bromm & Loeb 2006)

See also:
- Daigne et al. 2006
- Langer & Norman 2006
- de Souza et al. 2011
- Campisi et al. 2011
- Ishida et al. 2011
- Elliott et al. 2012

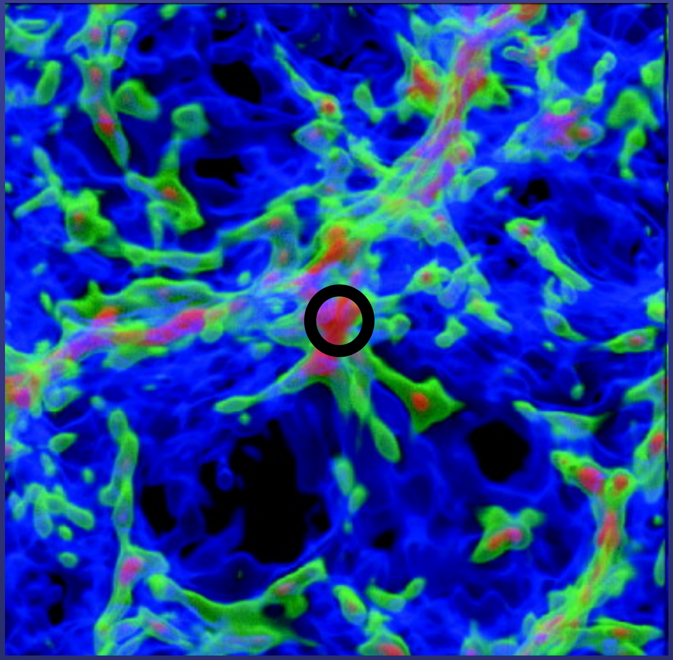
- ~10% of Swift bursts from z>5
- Expect of order 0.1 Pop III bursts per year

Q: Pop III circumburst environment?

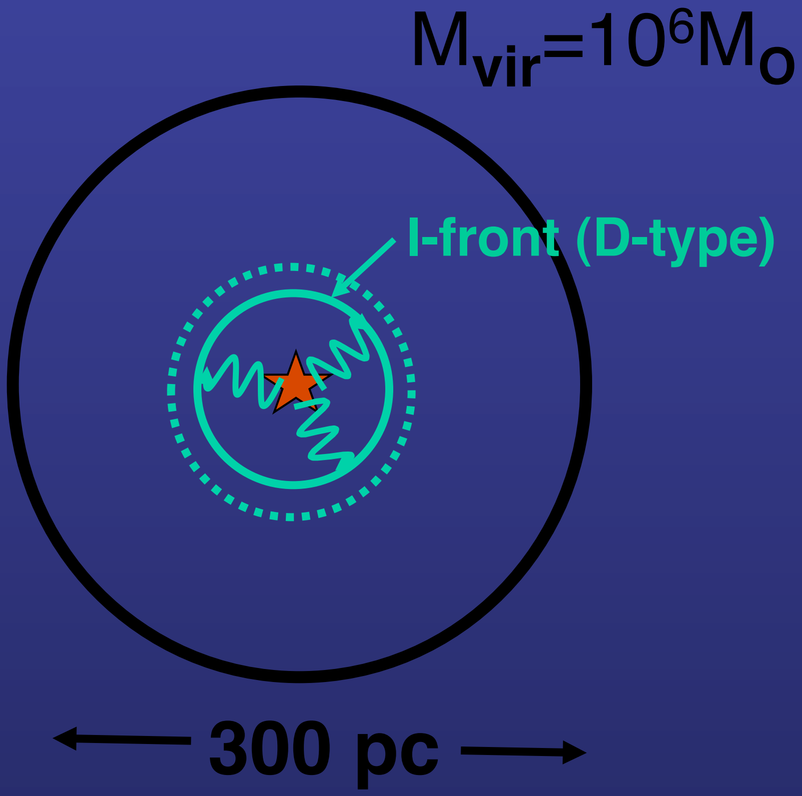
Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2006, ApJ, 639, 621)

z = 20



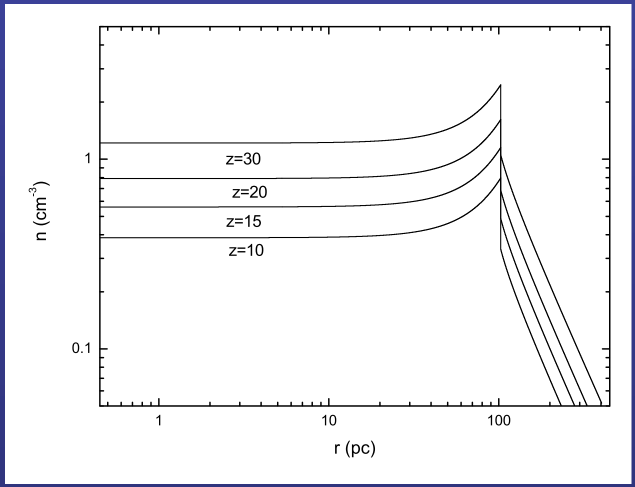
← 13.6 kpc →
(proper)



Pop III circumburst density

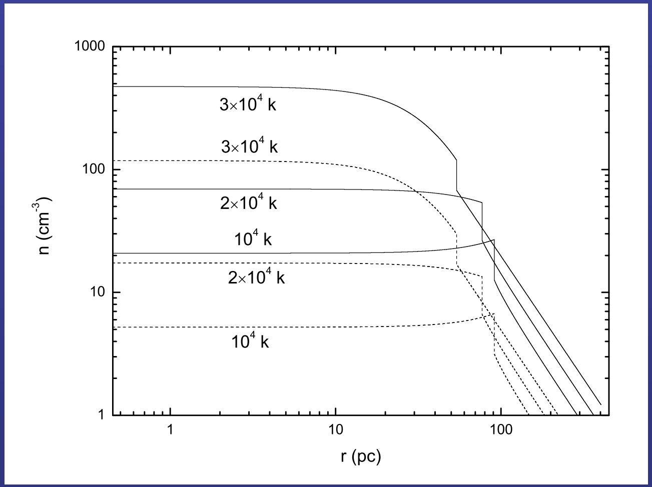
(Wang et al. 2012, to be submitted)

n vs. radius



Minihalo case

n vs. radius



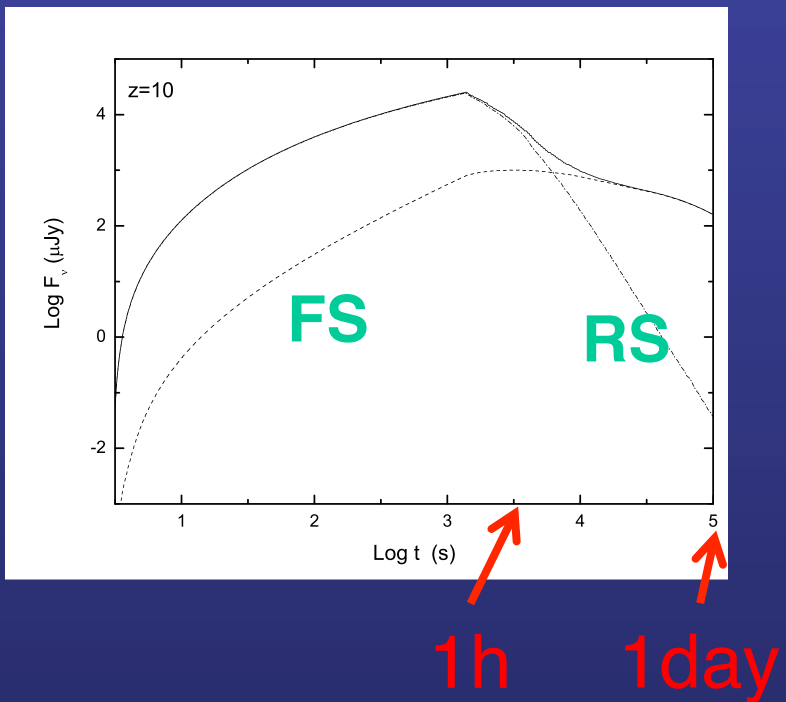
First-galaxy case

- In minihalos (Pop III.1): $n \lesssim 1$ cm^{-3}
- In atomic cooling halos (Pop III.2): $n > 10$ cm^{-3}

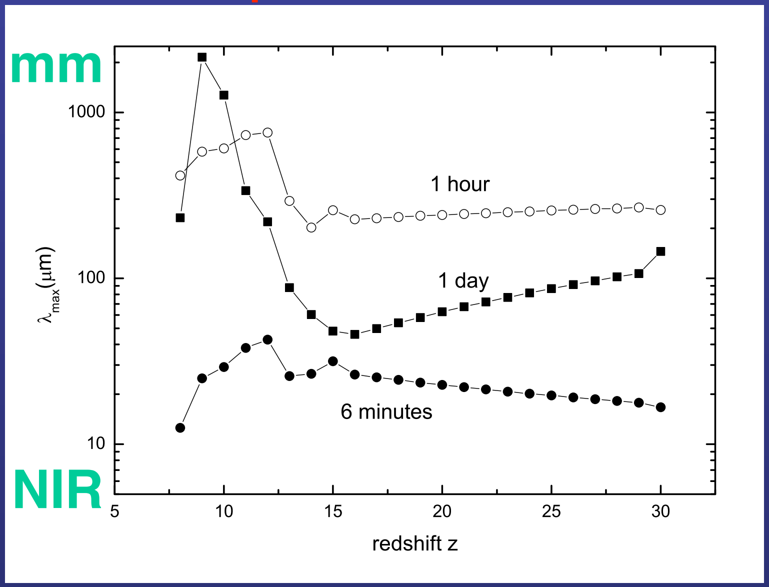
Pop III GRB Afterglow

(Wang et al. 2012, to be submitted;
see also: Gou et al. 2004, Inoue et al. 2007)

F_{obs} (M-Band) vs. t_{obs}



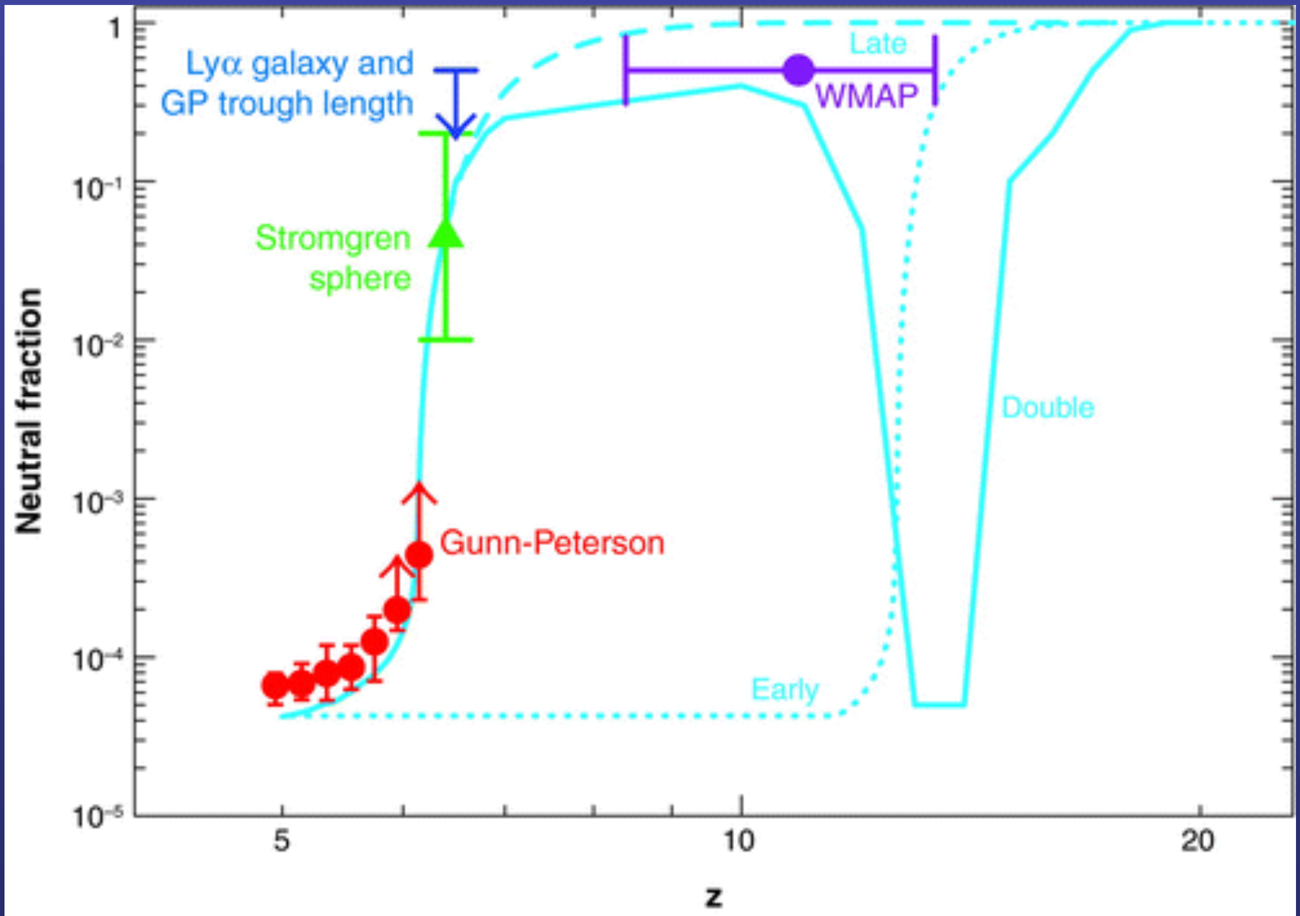
λ_{peak} vs. z



- Assume standard shocked synchrotron theory
- Pop III bursts very bright, but no unique features

Q: How to probe early IGM?

Probing the History of Reionization

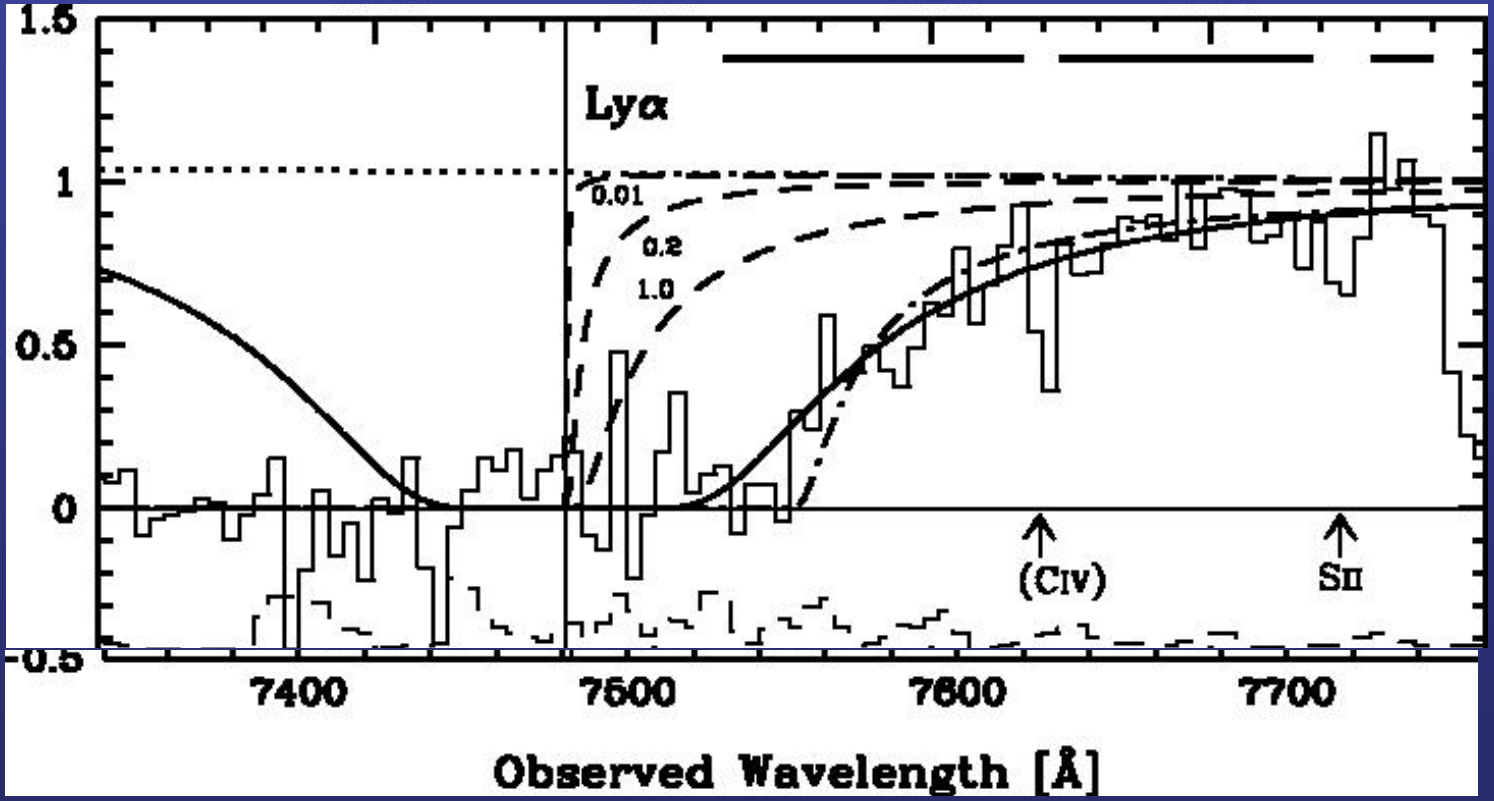


Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62

Probing the History of Reionization

-Use absorption in red damping wing of Lyα

(Barkana & Loeb 2004)

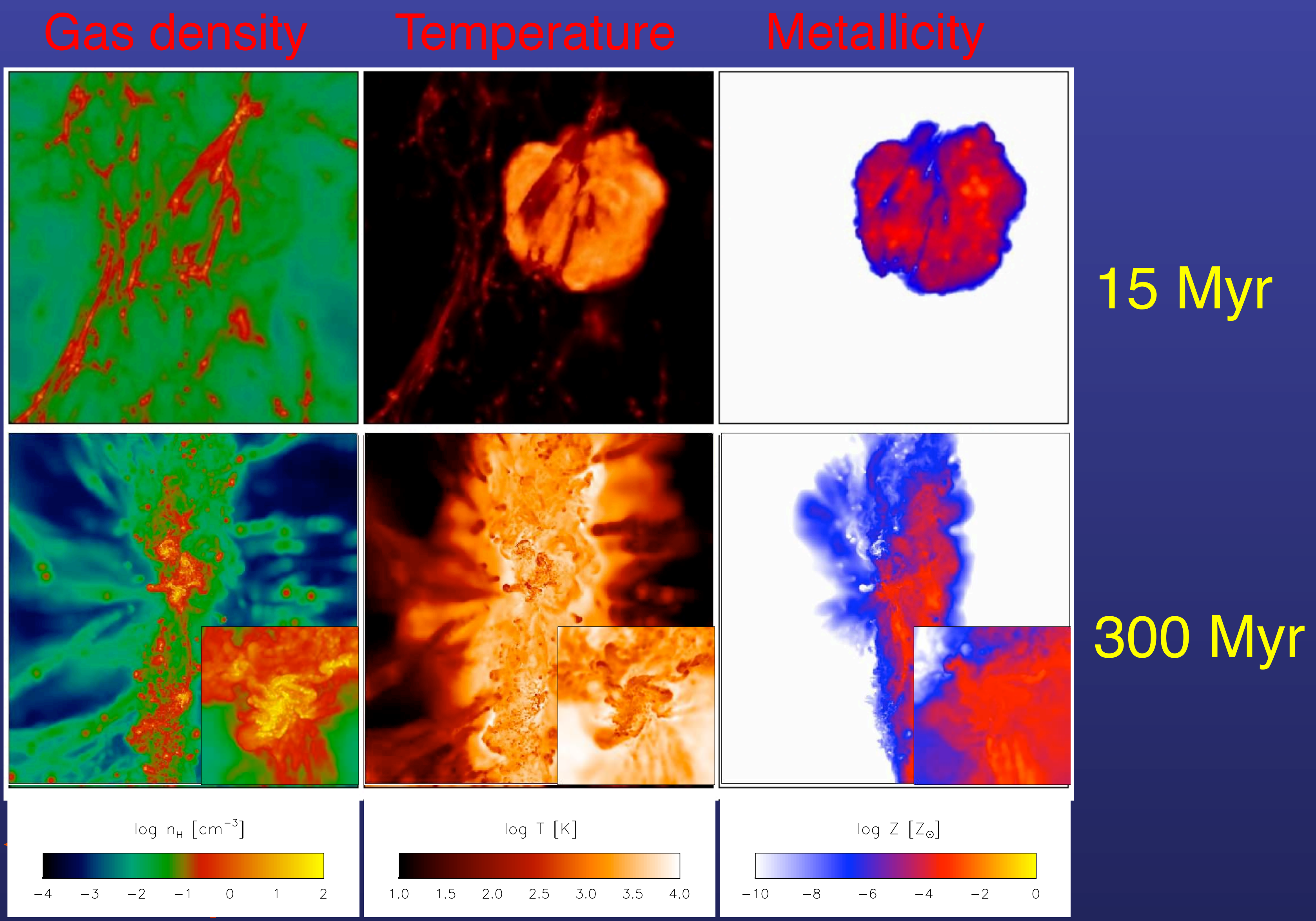


- GRB 050904 (z=6.3): Totani et al. 2006

- Problem: Intrinsic (DLA) absorption may dominate

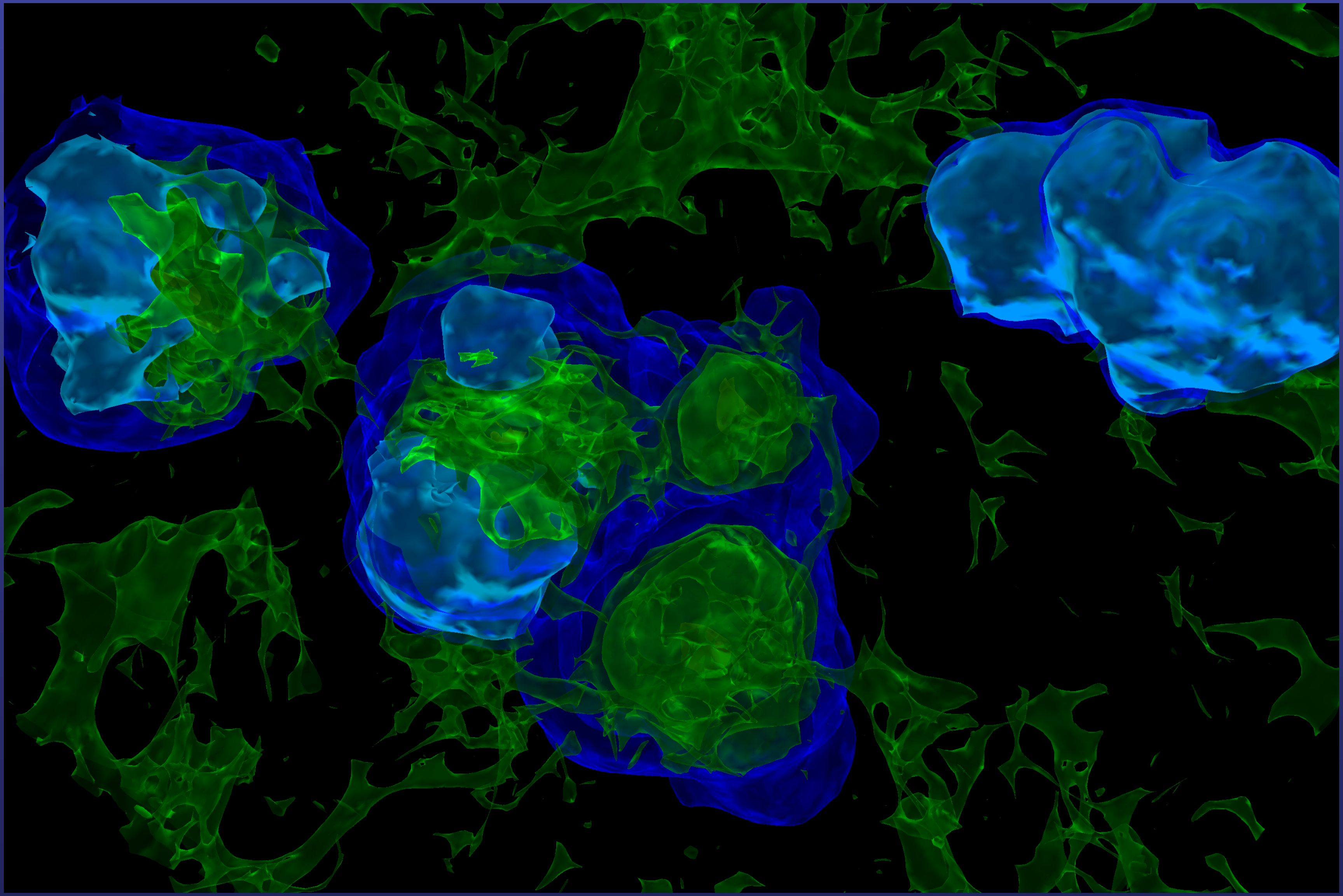
Pre-galactic Metal Enrichment

(Greif et al. 2010, ApJ, 716, 510)



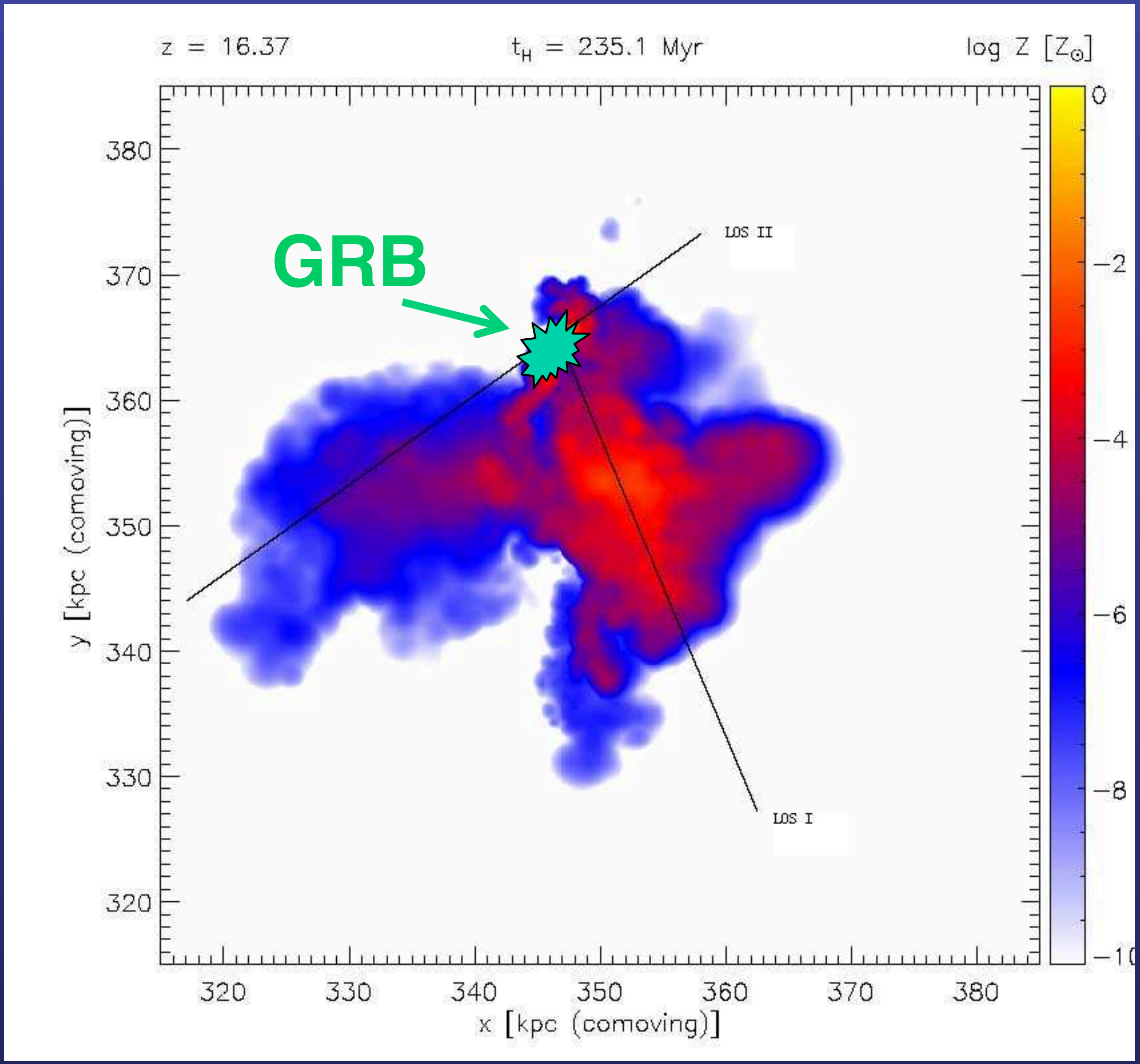
First Star Formation is highly clustered!

(Johnson, Greif, & Bromm 2007, ApJ, 665, 85)



Probing Pre-galactic Metal Enrichment

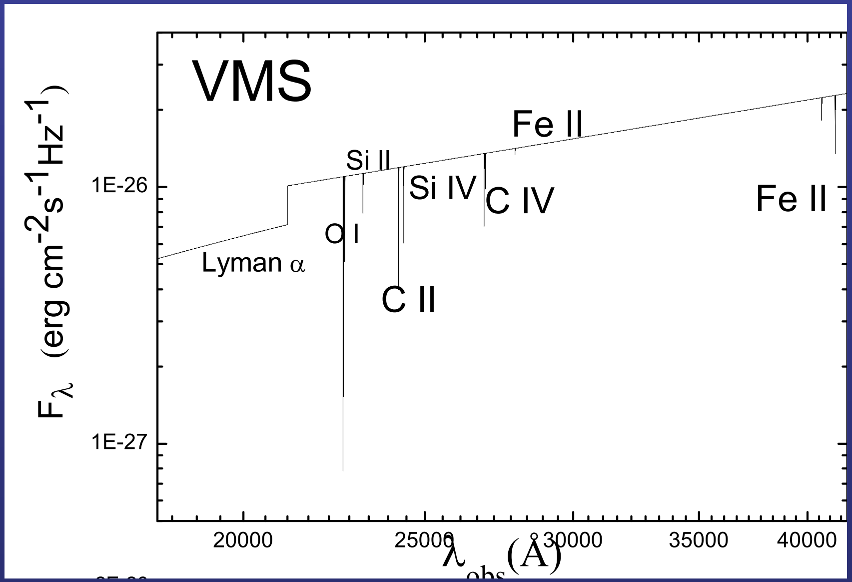
(Wang et al. 2012, to be submitted)



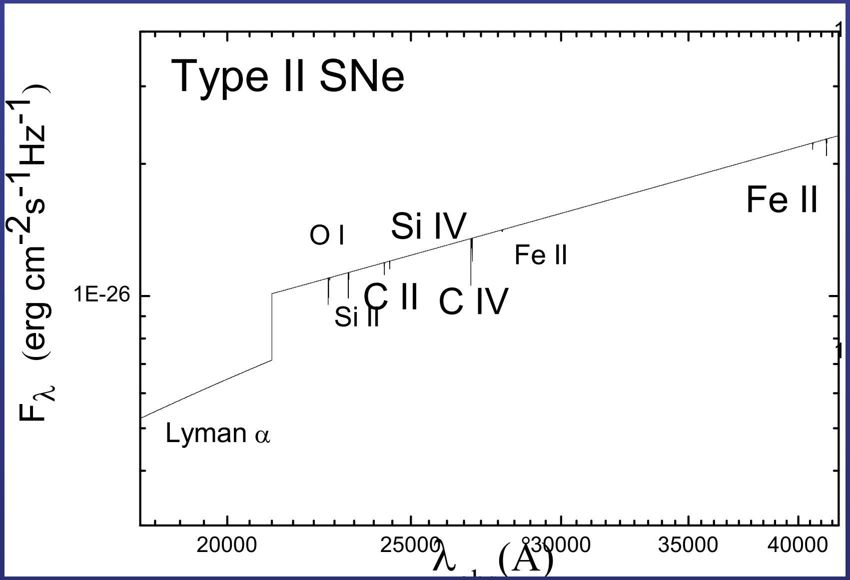
Probing Pre-galactic Metal Enrichment

(Wang et al. 2012, to be submitted)

PISN (VMS) case

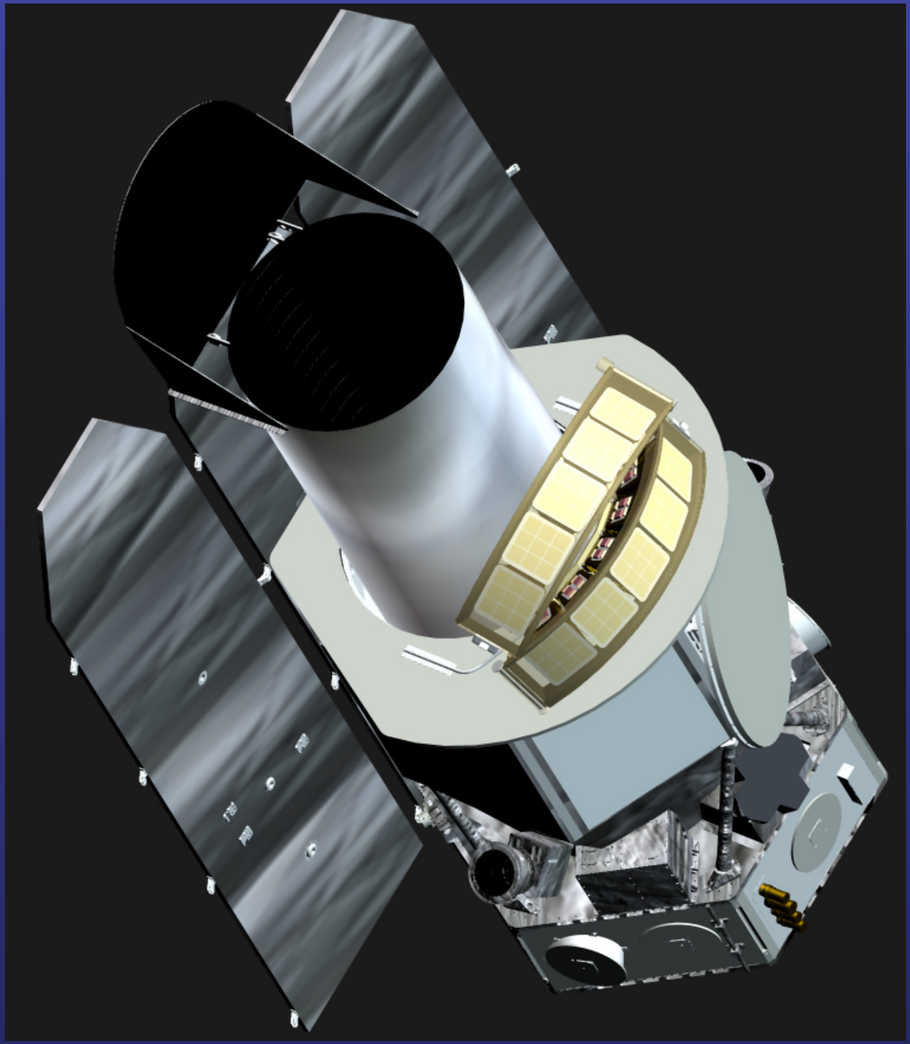


Core-collapse case



- Even Pop III spectra likely show strong metal lines
- Can distinguish between different Pop III SNe

The JANUS Mission (Lobster, SVOM, Origin)



- GRB locator
- On-board NIR telescope (+low-res spectroscopy)

→ **Hunting down high-z GRBs**

Perspectives:

- GRB cosmology holds tremendous promise
- Ideal signposts of the first stars and galaxies
- Ideal probes of early IGM
- *Swift* successor mission vitally important