11th NIC Symposium

(Heidelberg, July 2010)

Formation of the First Stars

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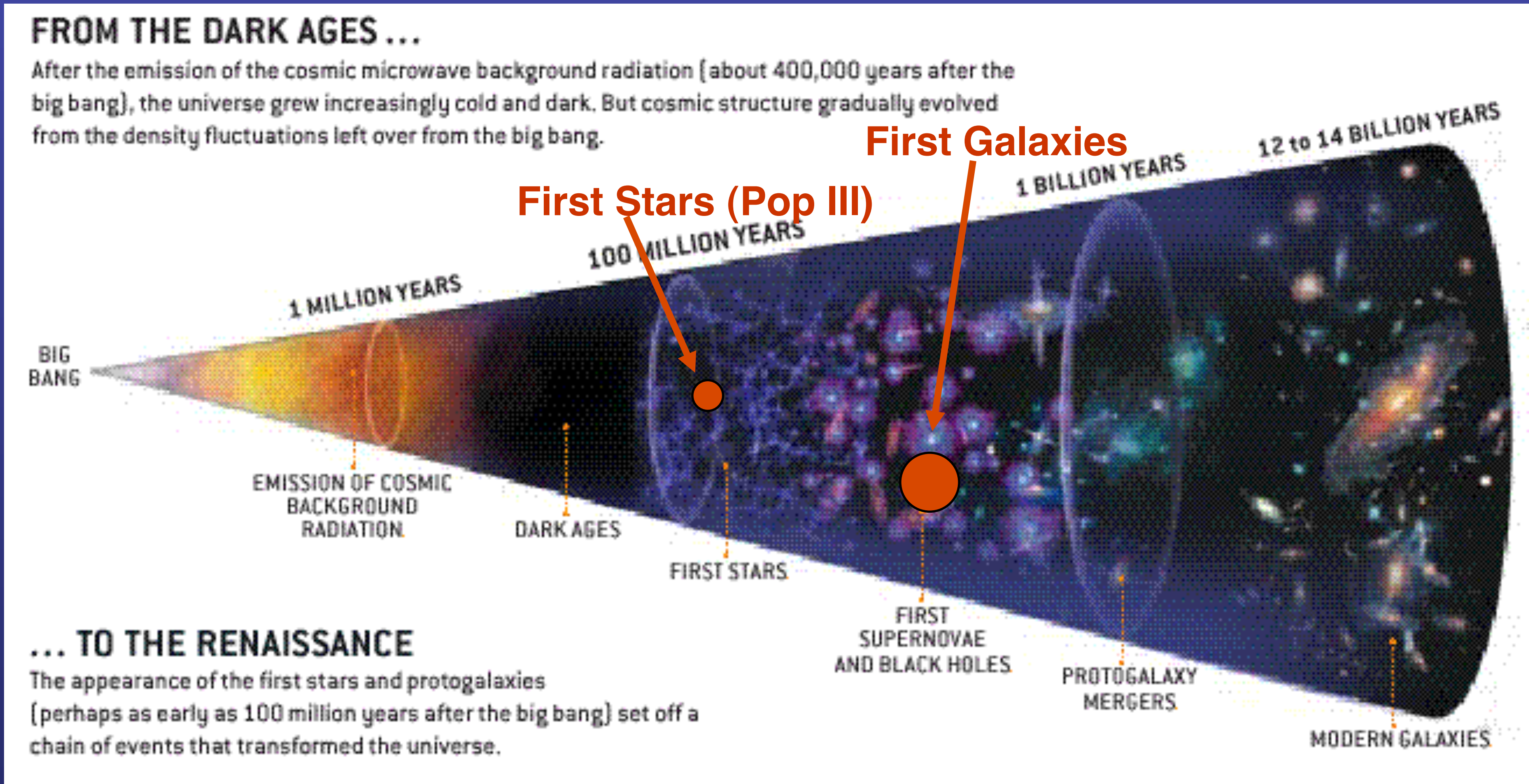
From the Dark Ages to the Cosmic Renaissance

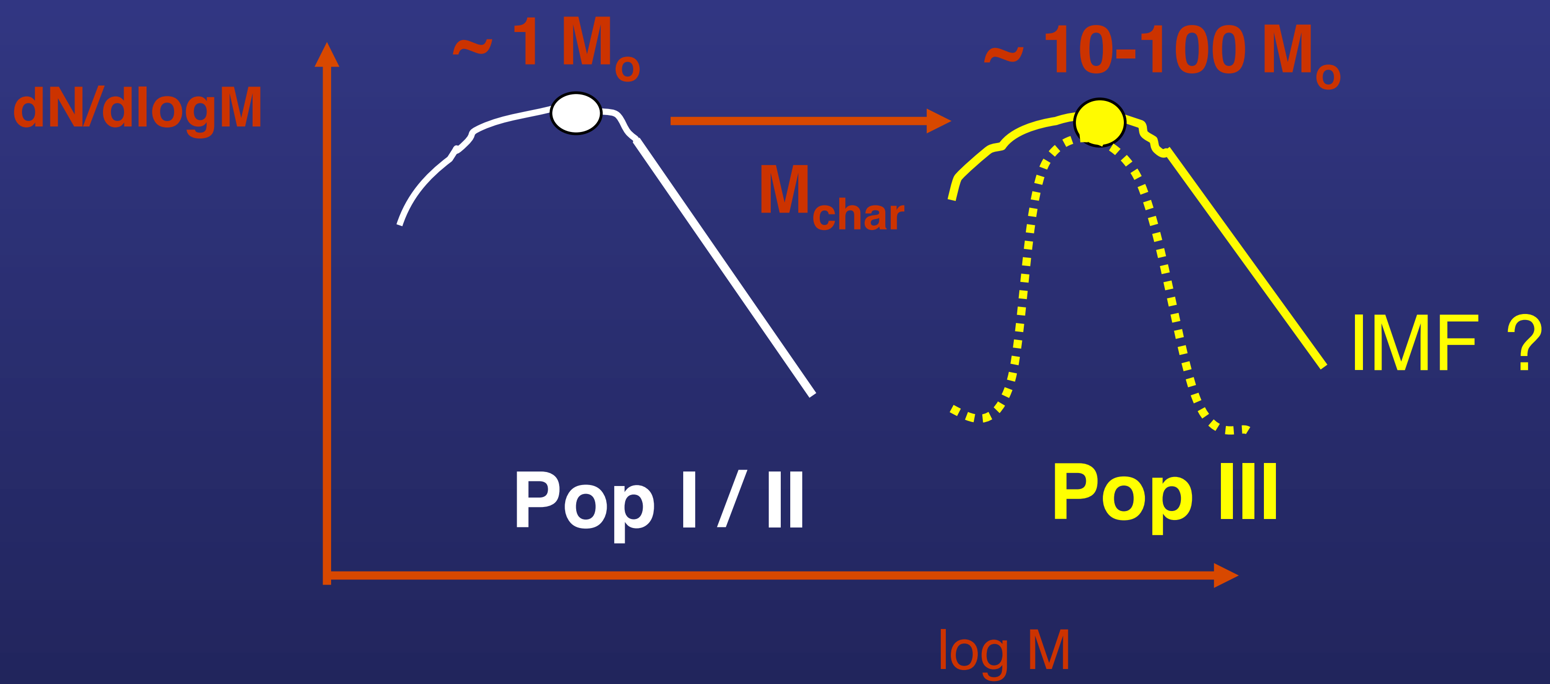


(Larson & Bromm, Scientific American)

- First Stars ⟶ Transition from Simplicity to Complexity

The First Stars: The "Standard" Model

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



Character of Population III Star Formation

- Simplified physics
  - No magnetic fields yet (?)
  - No metals $\rightarrow$ no dust
  - Initial conditions given by ΛCDM

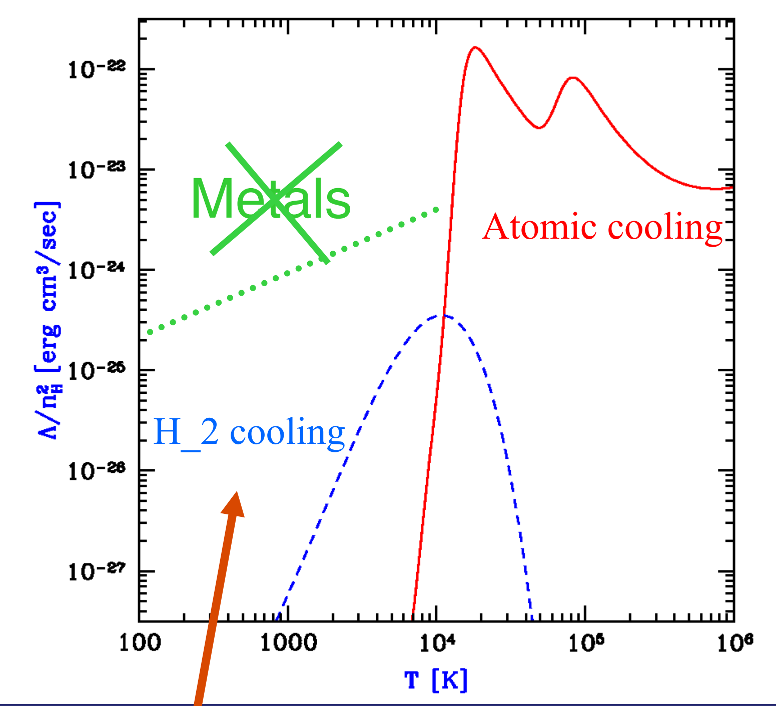
    $\rightarrow$ Well-posed problem

- First Stars = Cold dark matter (CDM)

  \+ atomic and molecular physics of H/D/He

Cooling Channels in the Early Universe

- First Stars:
  - formed in minihalos (~ $10^6 M_o$)
  - T_{vir} ~ few 1,000 K
  - cooling → molecular hydrogen
- First Galaxies:
  - formed in deeper potential wells (~ $10^8 M_o$)
  - $T_{vir} \gtrsim$ 10,000 K
  - cooling → atomic hydrogen



T_{vir} for Pop III

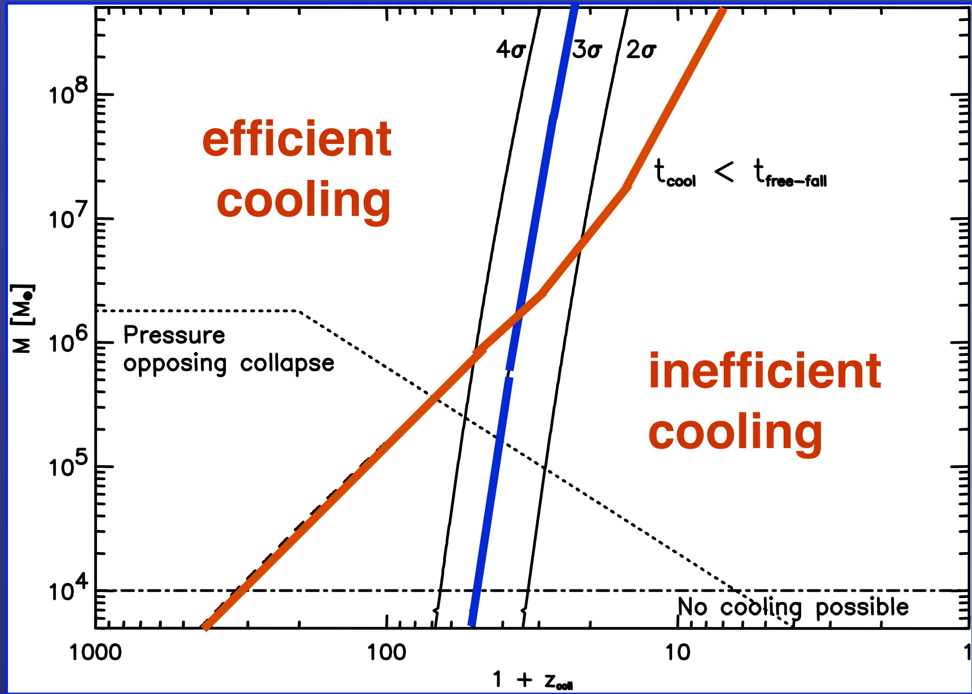
→Thermal evolution may be very different for the two regimes!

Region of Primordial Star Formation

(e.g., Couchman & Rees 1986; Haiman et al. 1996; Tegmark et al. 1997)

Halo mass vs. redshift

- Gravitational Evolution of CDM
- Gas Microphysic (H_2 cooling):
  - Can gas sufficiently cool?
  - $t_{cool} \lesssim t_{ff}$ (Rees-Ostriker)

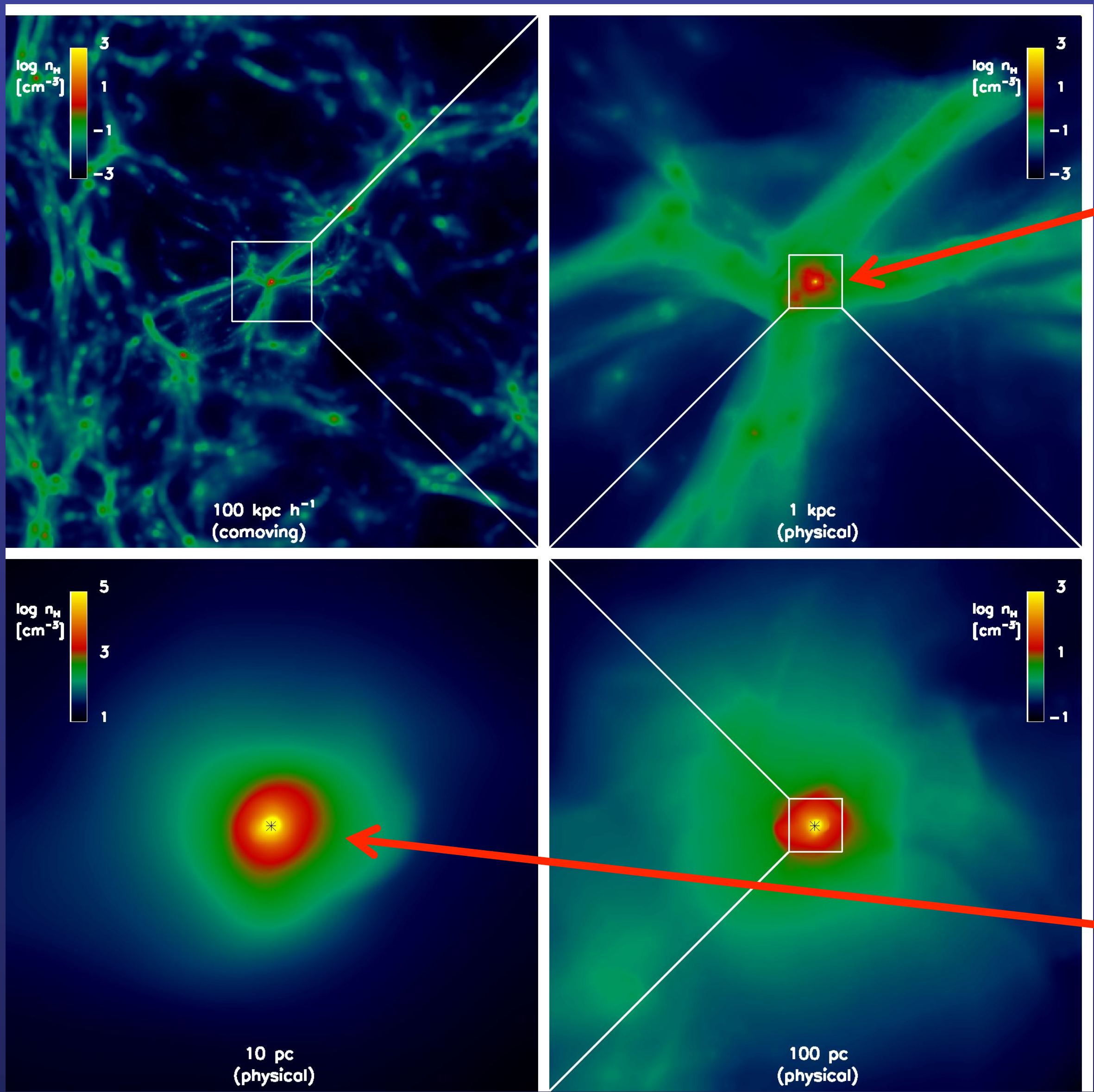


- Collapse of First Luminous Objects expected:
  - at: z_{coll} = 20 – 30
  - with total mass: $M \sim 10^6 M_o$

``minihalos''

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:

$M \sim 10^3 M_o$

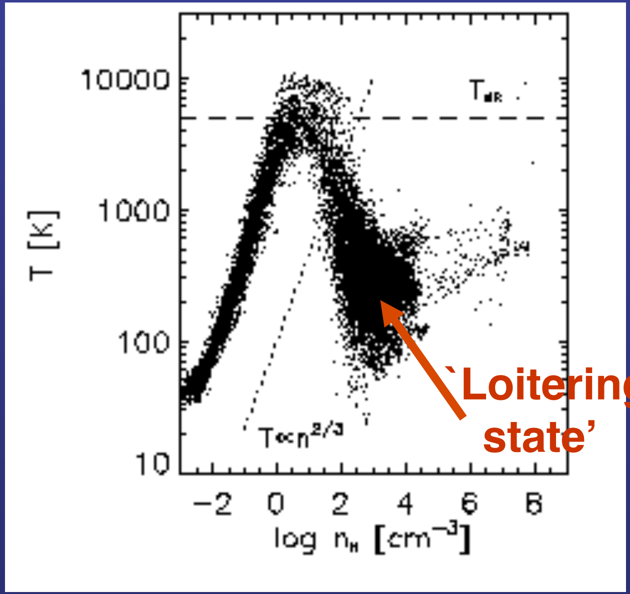
$R \sim 1$ pc

A Physical Explanation:
(Bromm, Coppi, & Larson 1999, 2002)

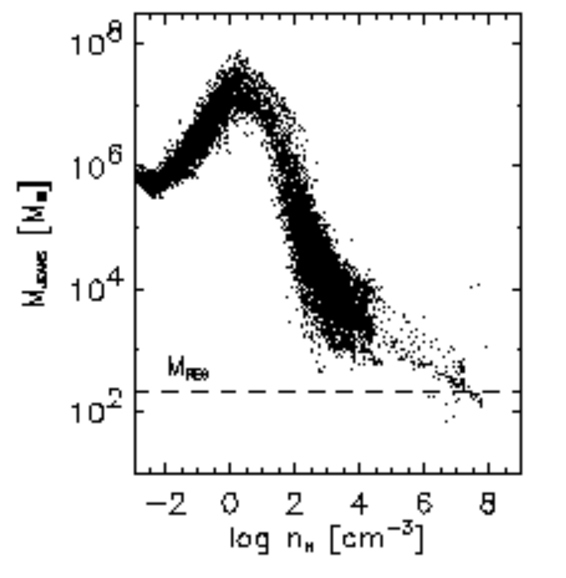
- Gravitational instability (Jeans 1902)
- Jeans mass: $M_J \sim T^{1.5}\, n^{-0.5}$

•Thermodynamics of primordial gas

T vs. n



M_J vs. n



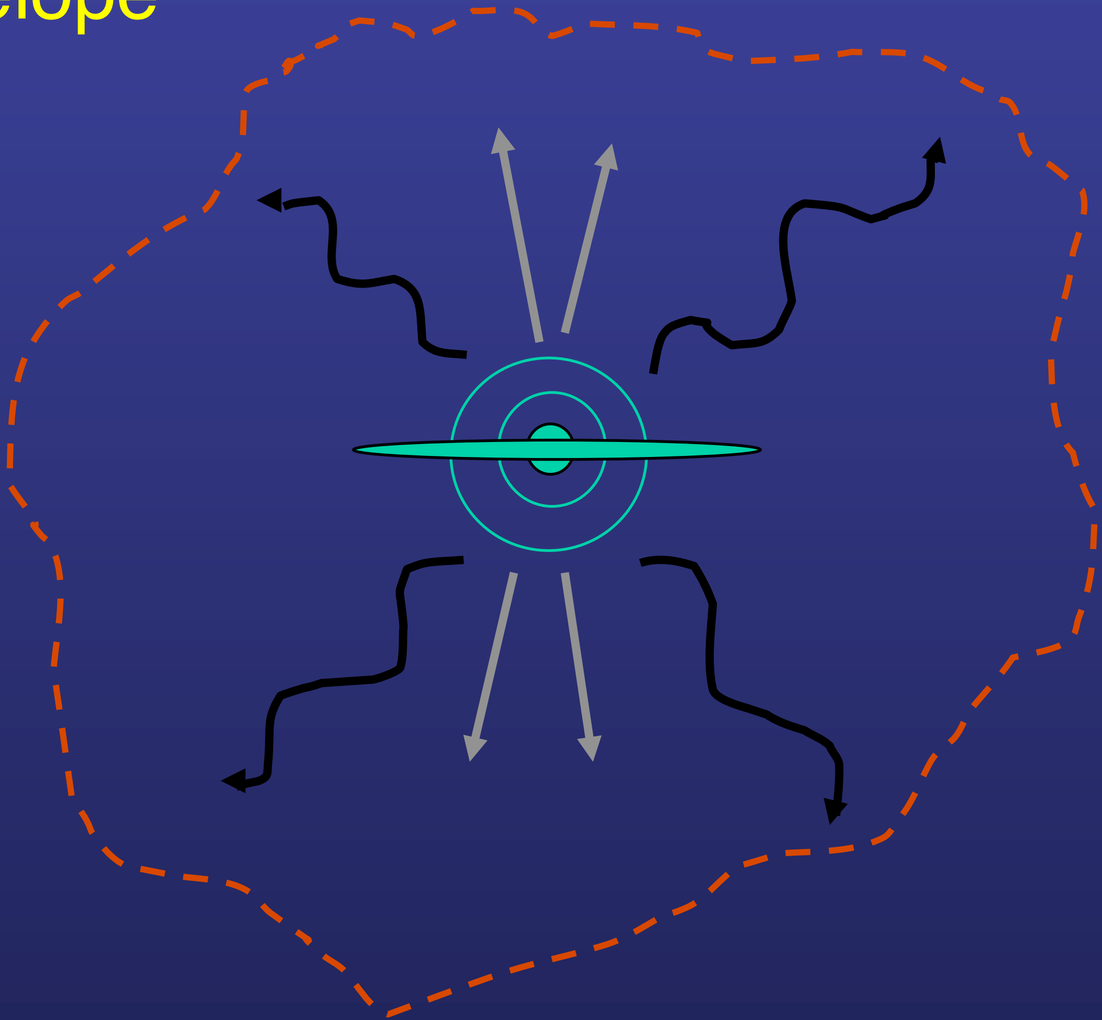
•Two characteristic numbers in microphysics of H_2 cooling:

- $T_{min} \sim 200$ K
- $n_{crit} \sim 10^3$ - 10^4 cm^{-3} (NLTE → LTE)

• Corresponding Jeans mass: $M_J \sim 10^3\, M_o$

The Crucial Role of Accretion

• Final mass depends on accretion from dust-free Envelope



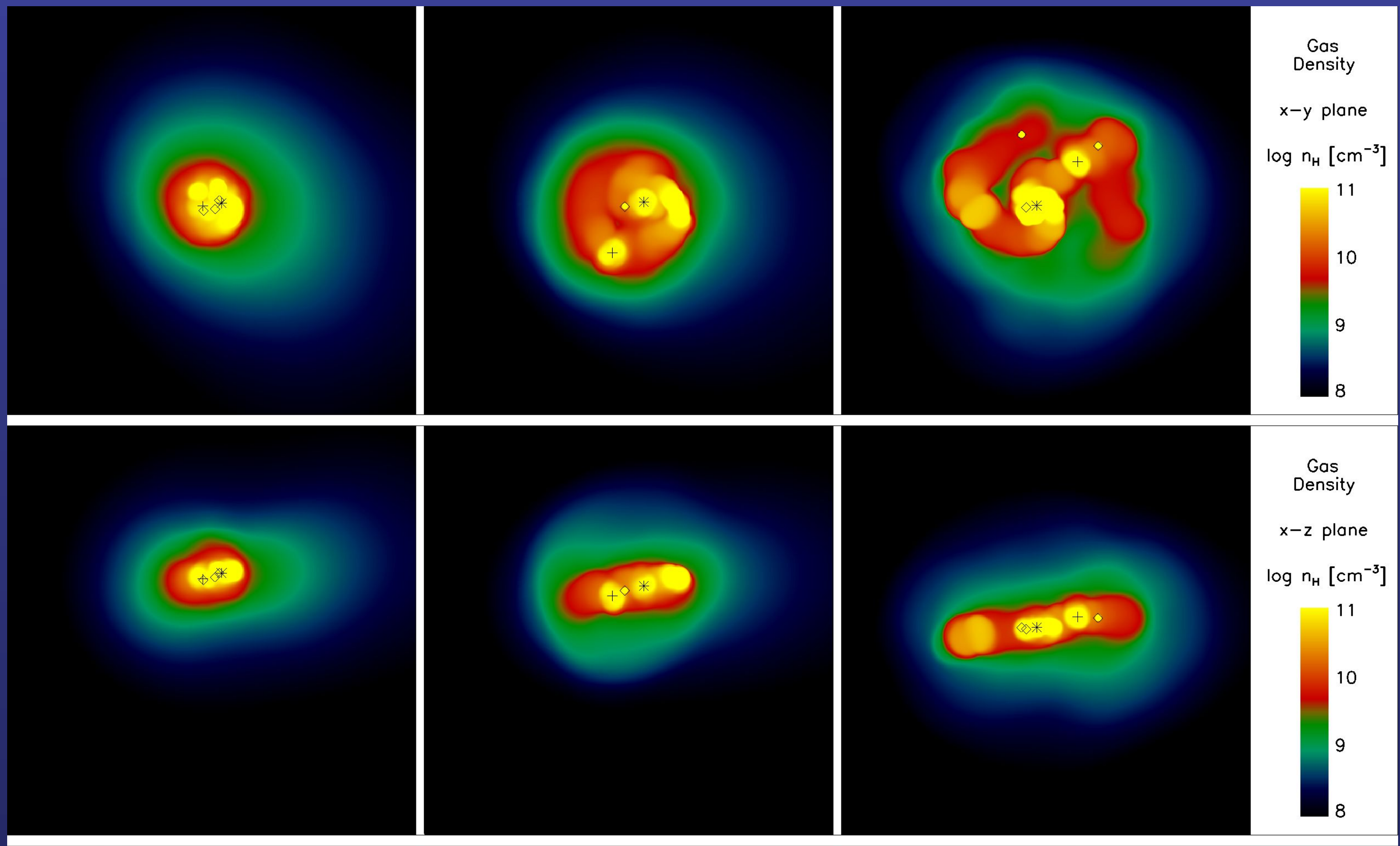
Clump:

$M \sim M_J$

Formation of a Pop III Star: Further Evolution

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

time



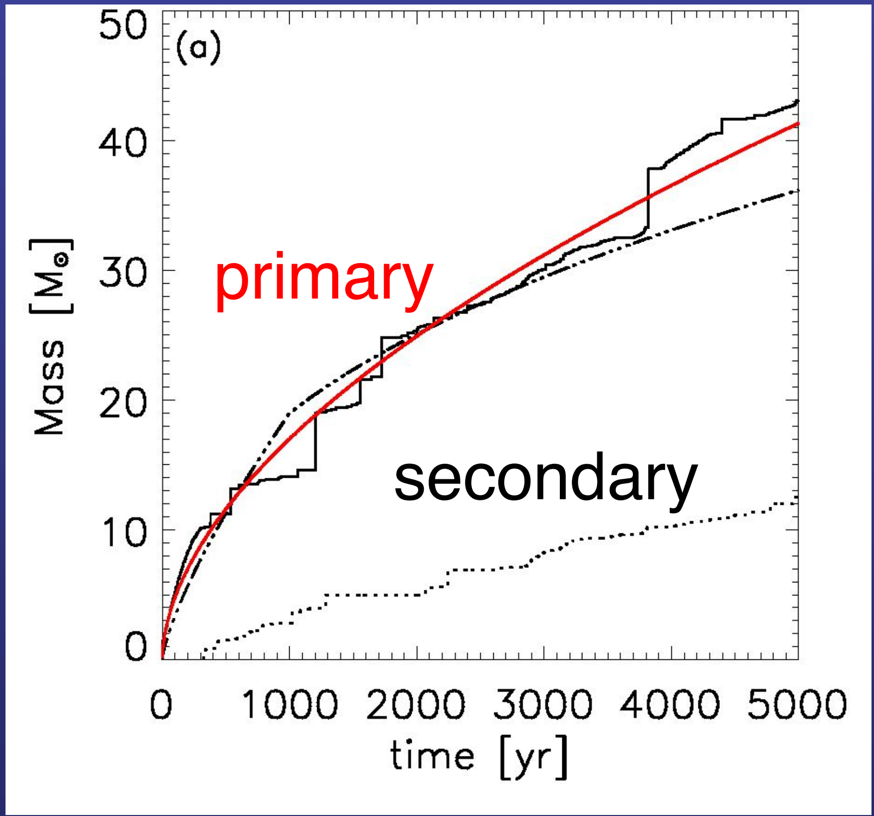
- Disk grows around primary sink

- Disk is gravitationally unstable: small multiple forms

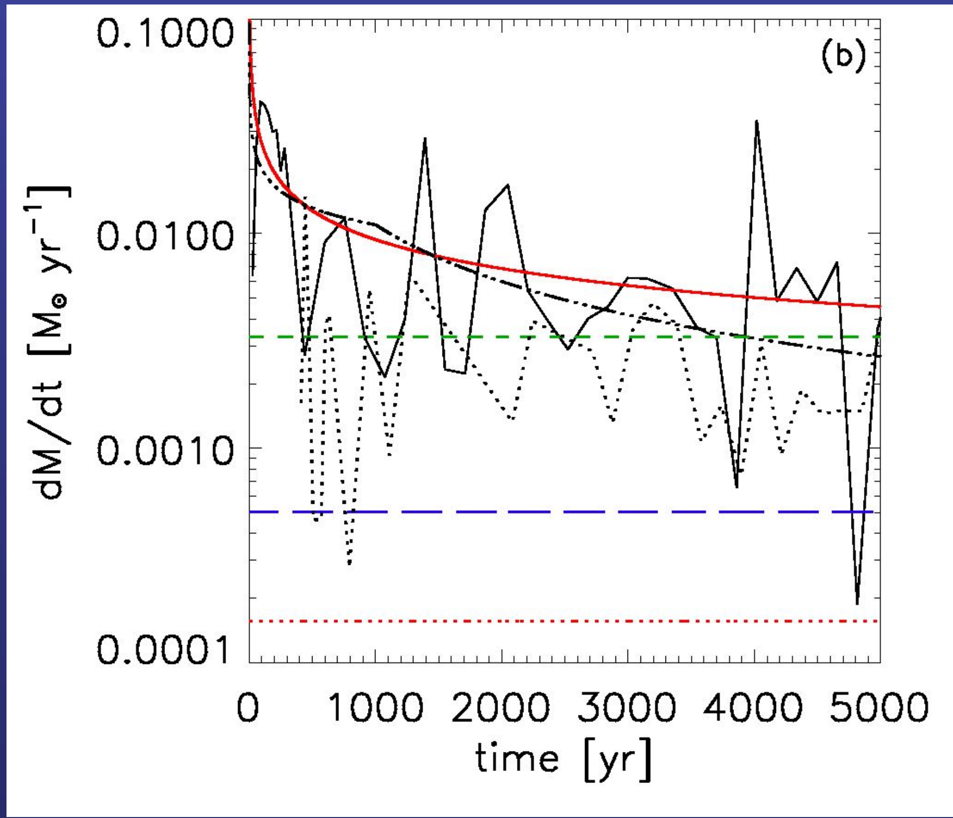
Formation of a Pop III Star: Growth by Accretion

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

Stellar mass vs. time



dM/dt vs. time

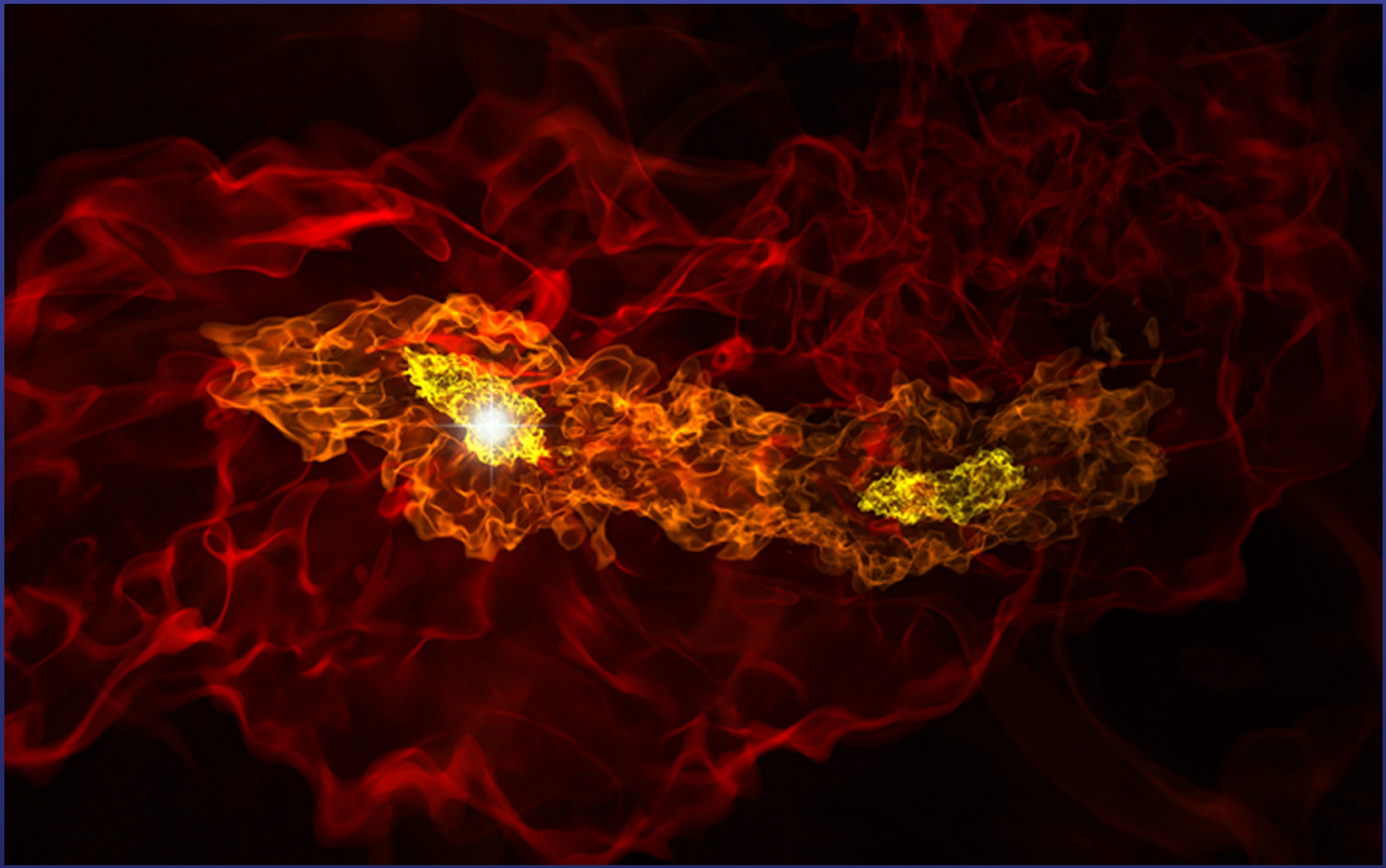


- a dominant binary has formed (~ 40 and ~10 M_O) after 5,000 yr of accretion

Formation of a Pop III BINARY?

(Turk, Abel & O'Shea 2009, Science, 325, 601)

800 AU



~ 10 M_{sun} ~ 6 M_{sun}

Neglected Processes

- Magnetic fields (MHD effects, MRI, dynamos, jets…)

  -- E.g., Tan & Blackman 2004; Machida et al. 2006; Silk & Langer 2006

- Cosmic Rays (ionization, heating, chemistry…)

  -- E.g. Shchekinov & Vasiliev 2004; Rollinde et al. 2005, 2006; Jasche et al. 2007; Stacy & Bromm 2007

→ might lead to lower Pop III masses!

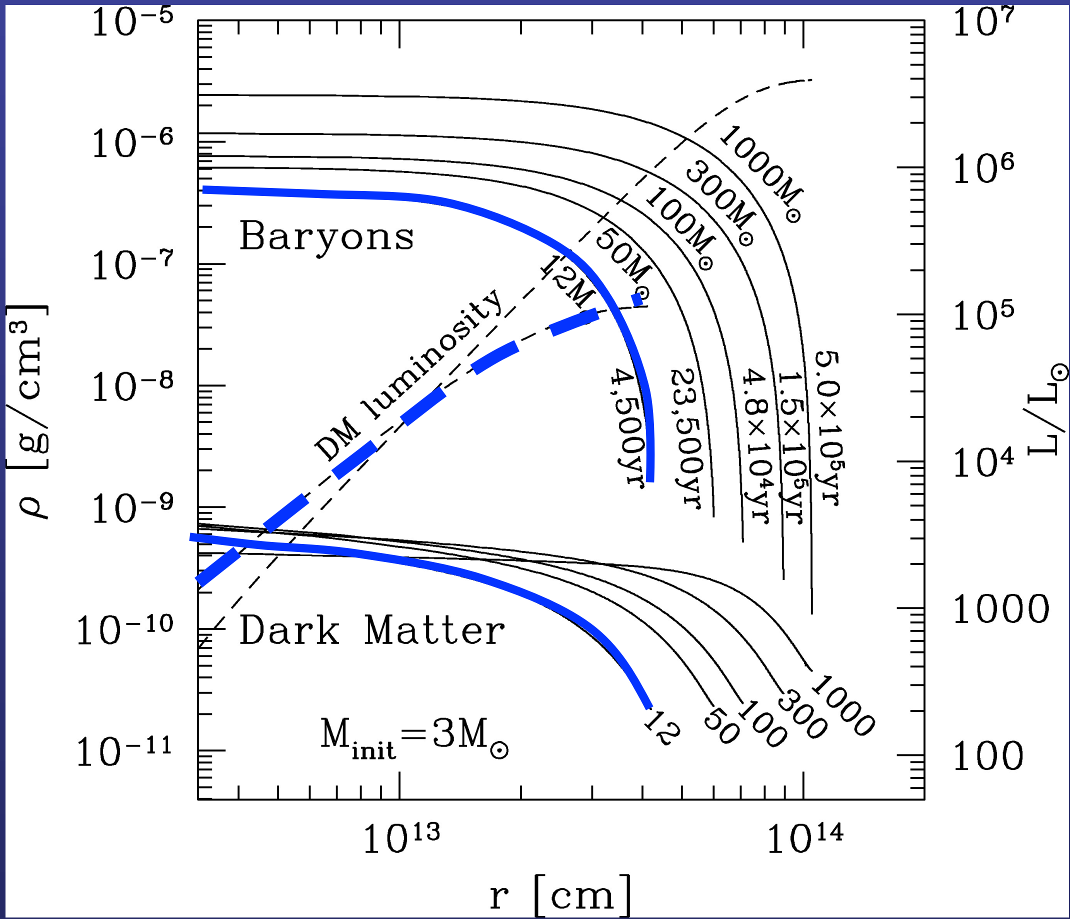
- Possible modifications to CDM (WDM, annihalation heating…)

  -- E.g. Yoshida et al. 2003; Gao & Theuns 2007; Spolyar et al. 2008

Dark-Matter powered Stars: "Dark Stars"

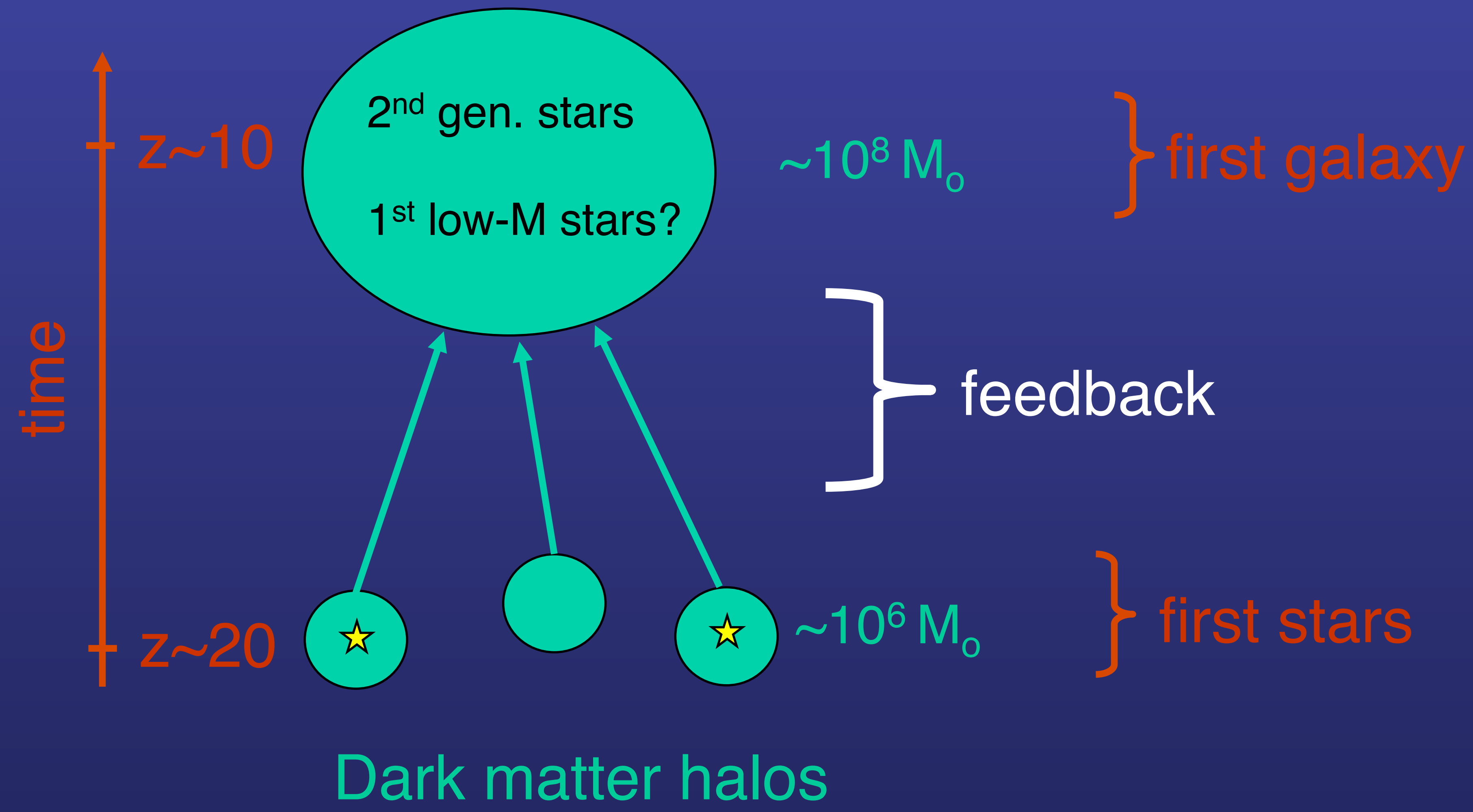
(Spolyar, Freese & Gondolo 2008; Freese et al. 2008; Iocco et al.)

- self-annihilating WIMP DM heats stellar interior !



→A red supergiant (~1,000 R_{sun}) Pop III?

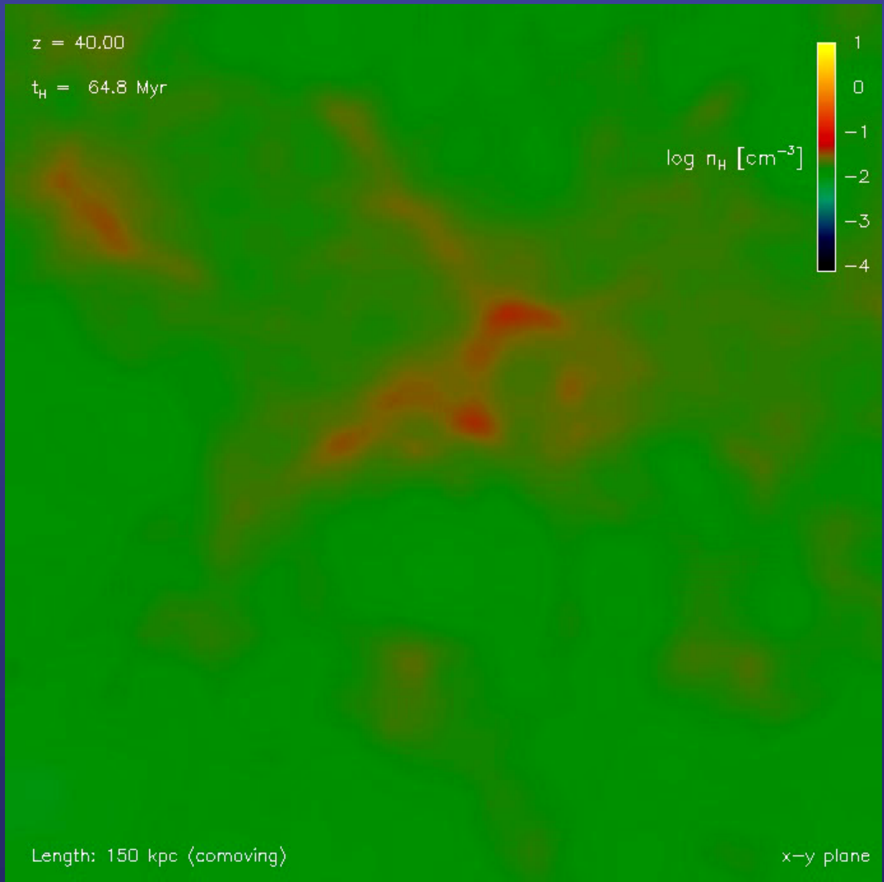
Assembly of the First Galaxies

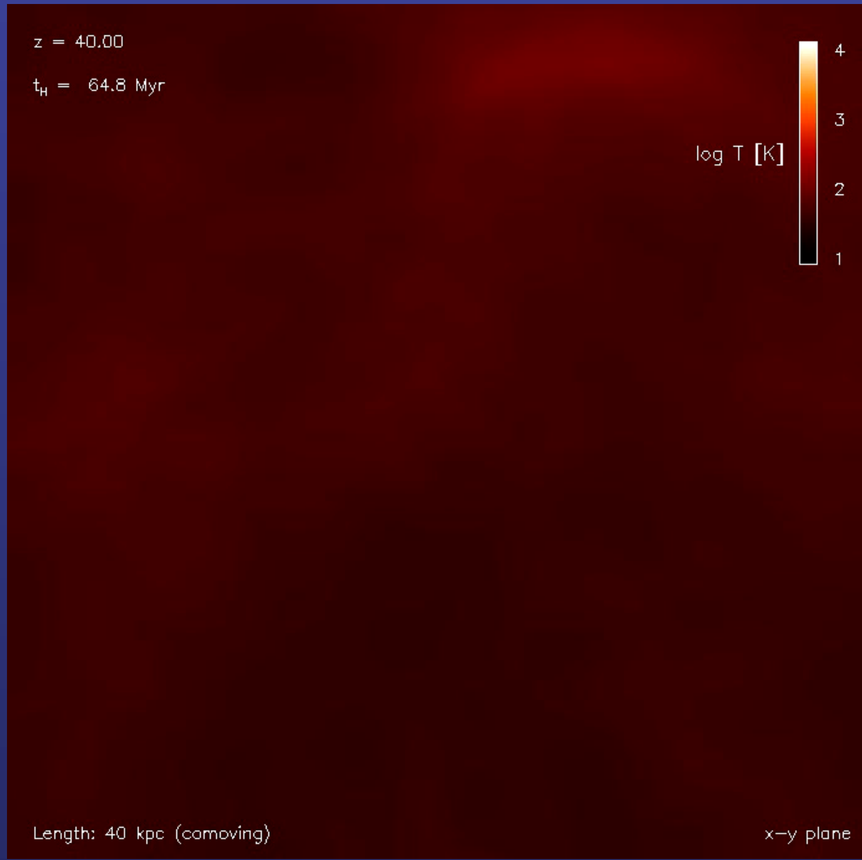


First Galaxies: Onset of Turbulence

(Greif, Johnson, Klessen & Bromm 2008, MNRAS, 387, 1021)

Density of Cosmic Gas   Temperature of Cosmic Gas



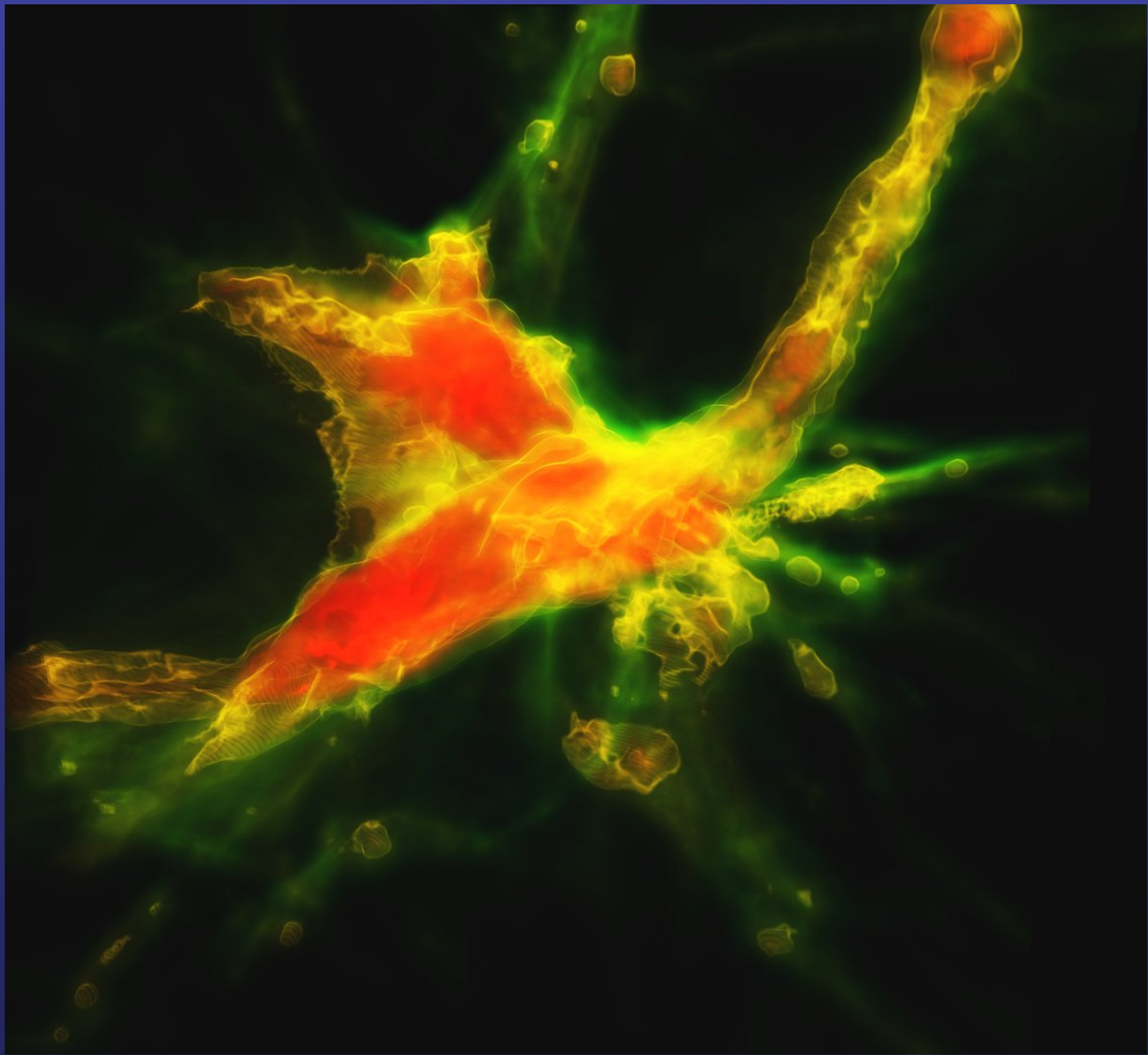


150 kpc (comoving)   40 kpc (comoving)

The First Galaxies: Assembly Process

(Greif, Johnson, Klessen & Bromm 2008, MNRAS, 387, 1021)

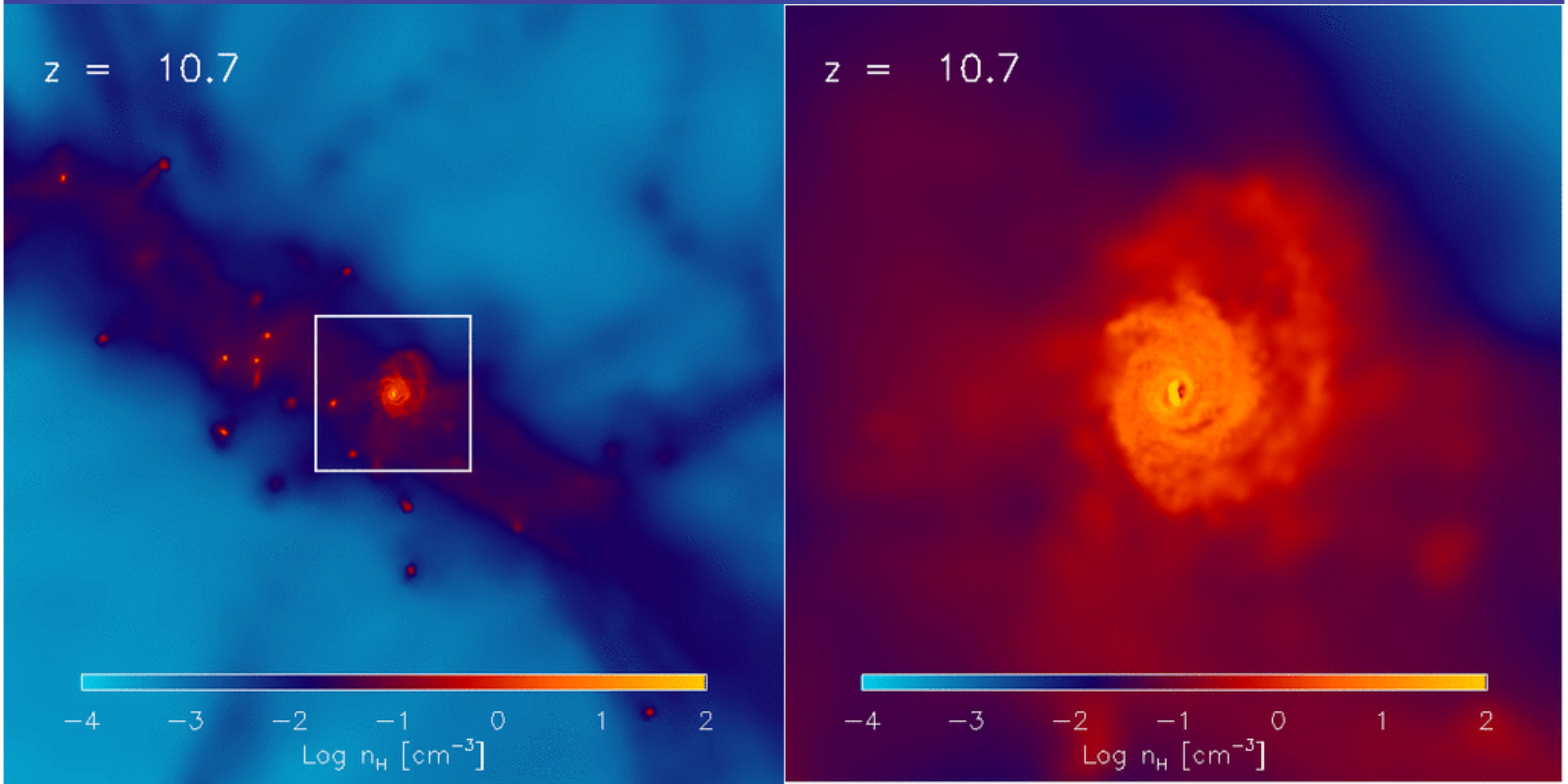
~ 10 kpc



- color indicates temperature (bright red = 10^4 K)

Emergence of Disk Galaxies

(Pawlik, Milosavljevic, & Bromm 2010, in prep.)

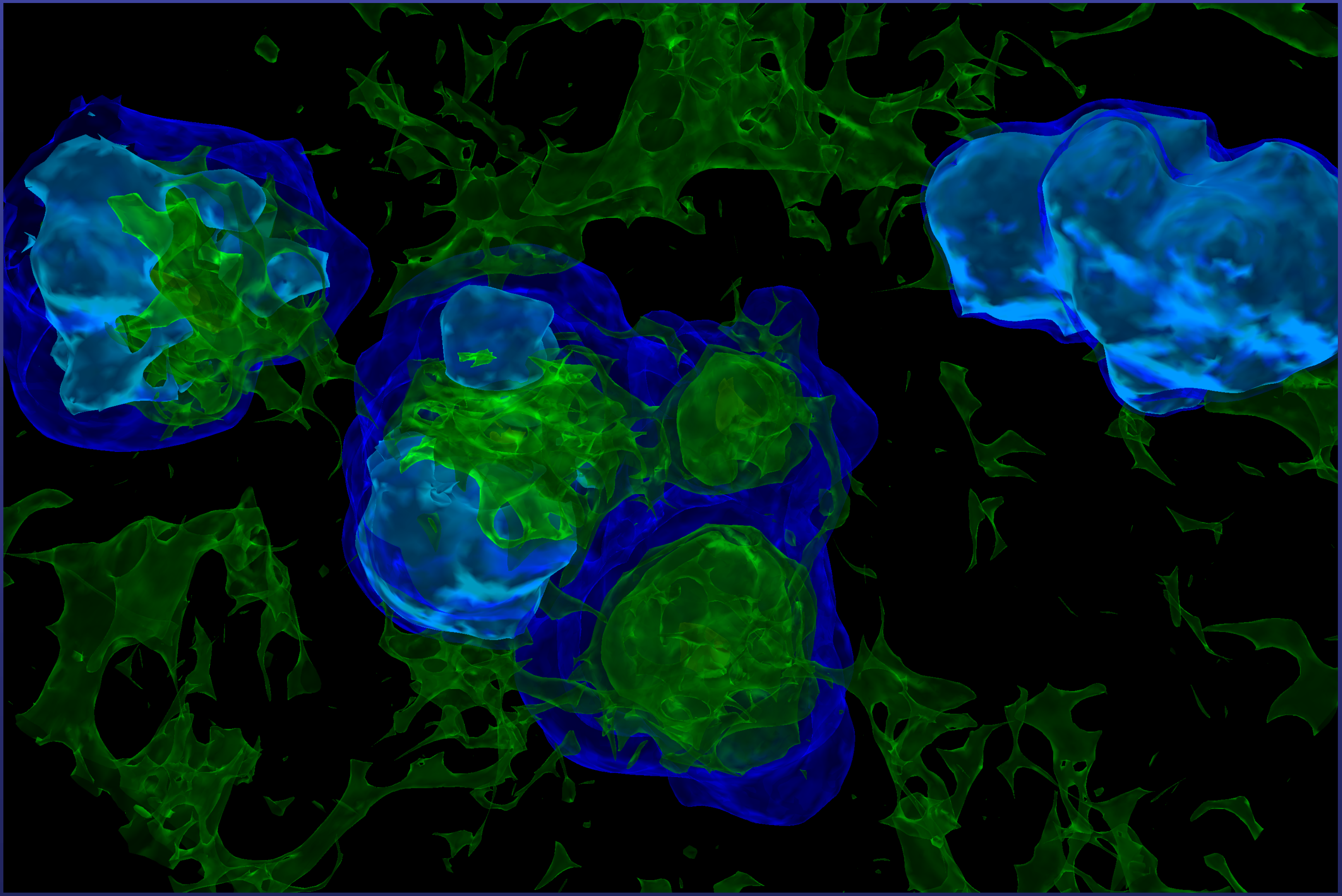


The Role of Feedback

- Various forms:
  - Radiative: ionizing and LW photons
  - Mechanical: SN blastwaves, winds, outflows
  - Chemical: more efficient cooling in enriched material

Feedback from the First Stars

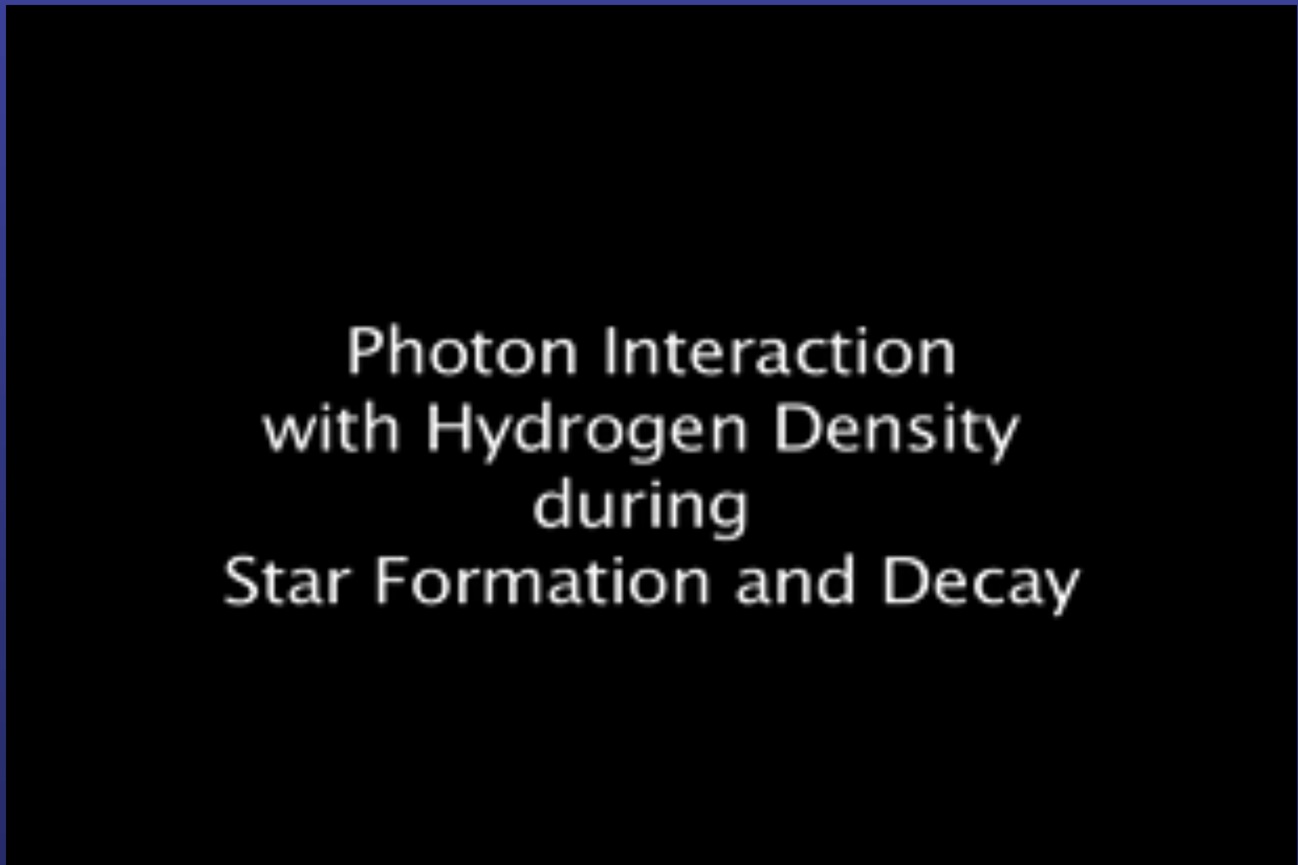
(Johnson, Greif, & Bromm 2007, ApJ, 665, 85)



LW Feedback: ``Phoenix Effect''

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

H_2 abundance (green color)



~ 660 kpc (comoving)

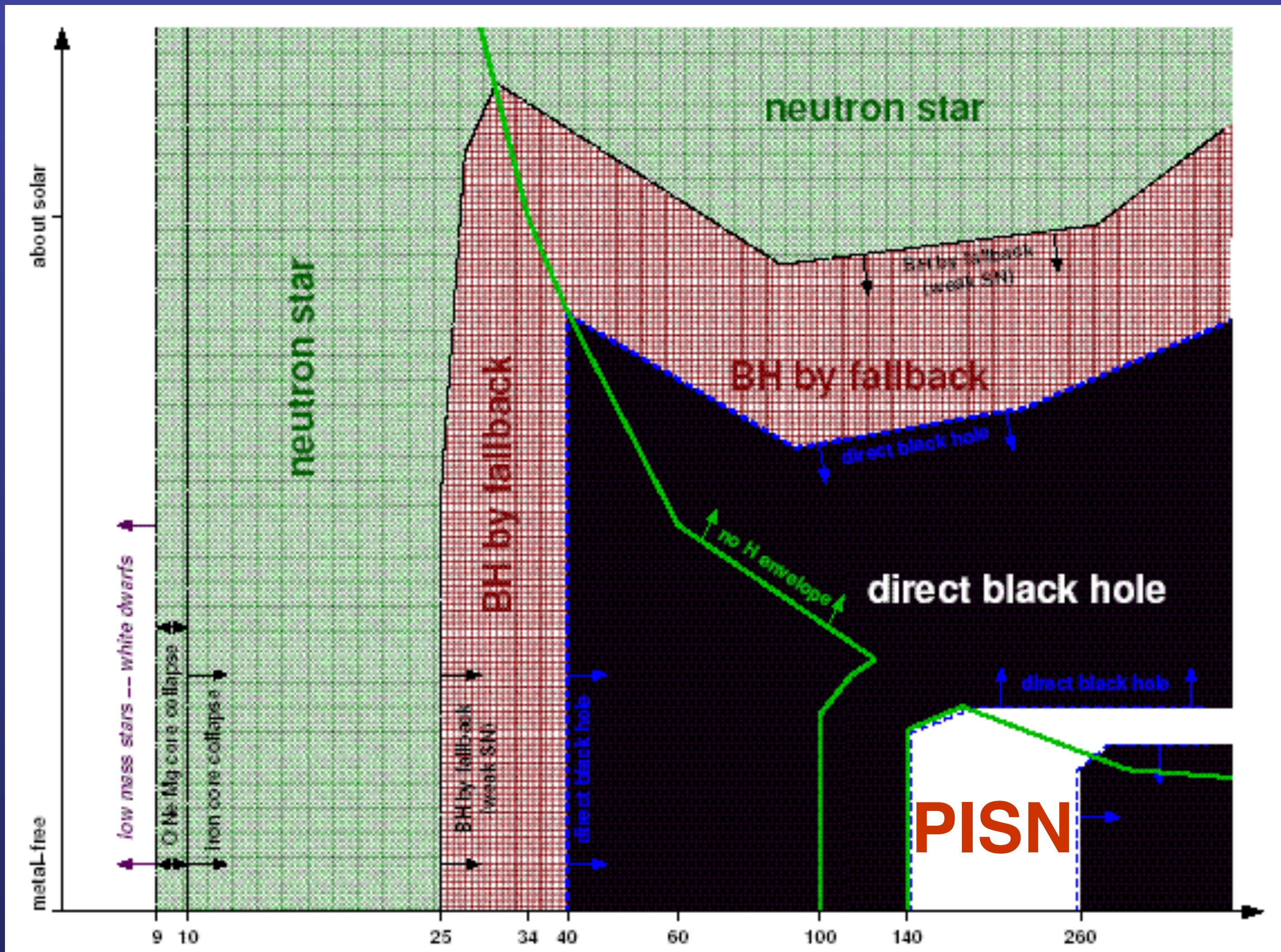
- HII regions:

white-gray overlay

- Movie credit:
  - Paul Navratil (Texas Advanced Computing Center)

The Death of the First Stars:

(Heger et al. 2003)



Pop I

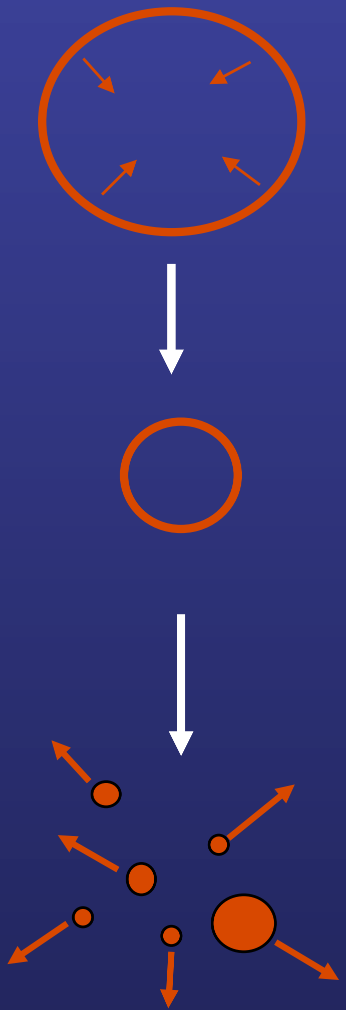
Z

Pop III

Initial Stellar Mass

Physics of Pair-instability Supernovae

$M \sim 140 - 260\ M_{\odot}$



-T>10^9K

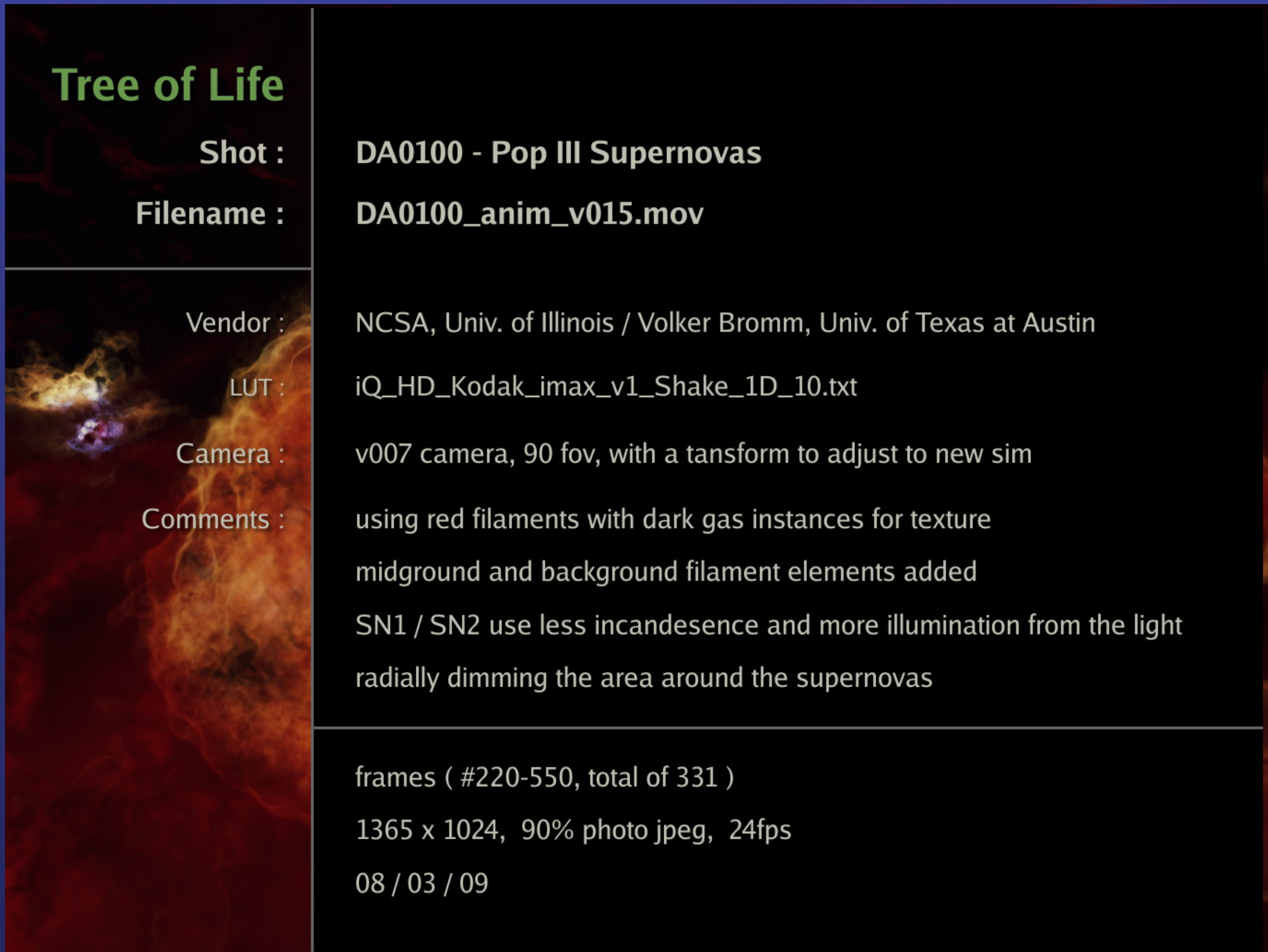
- ph+ph → e^- e^+
- grav. runaway collapse

- large jump in core T
- explosive nuclear burning
- implosion ⟶ explosion

- no compact remnant
- all heavy elements dispersed
- distinct nucleosynthetic pattern

The First Supernova-Explosion

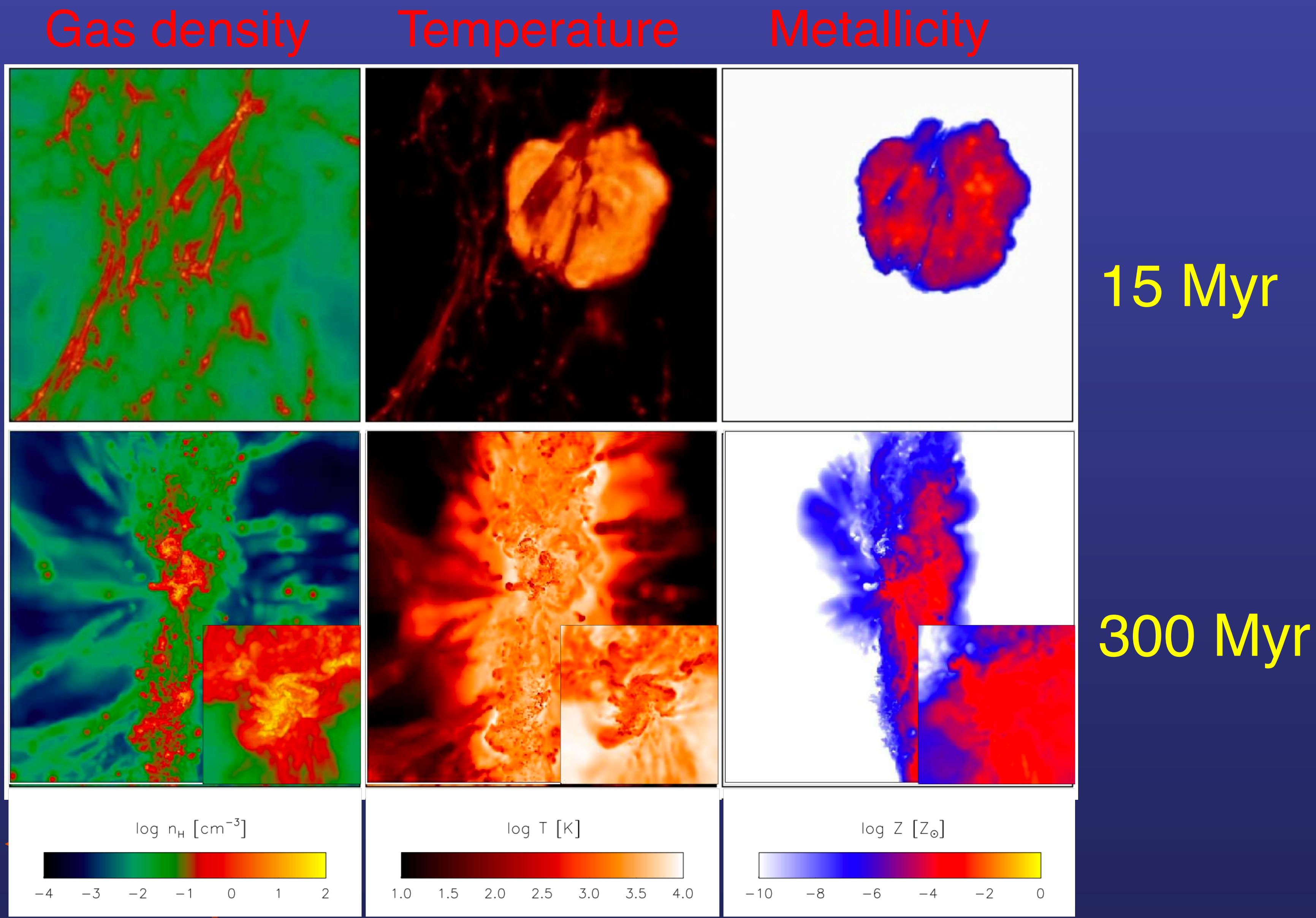
(Greif et al. 2010, ApJ, 716, 510)



- $E_{SN} \sim 10^{52}$ergs
- Complete Disruption (PISN)

Pre-galactic Metal Enrichment

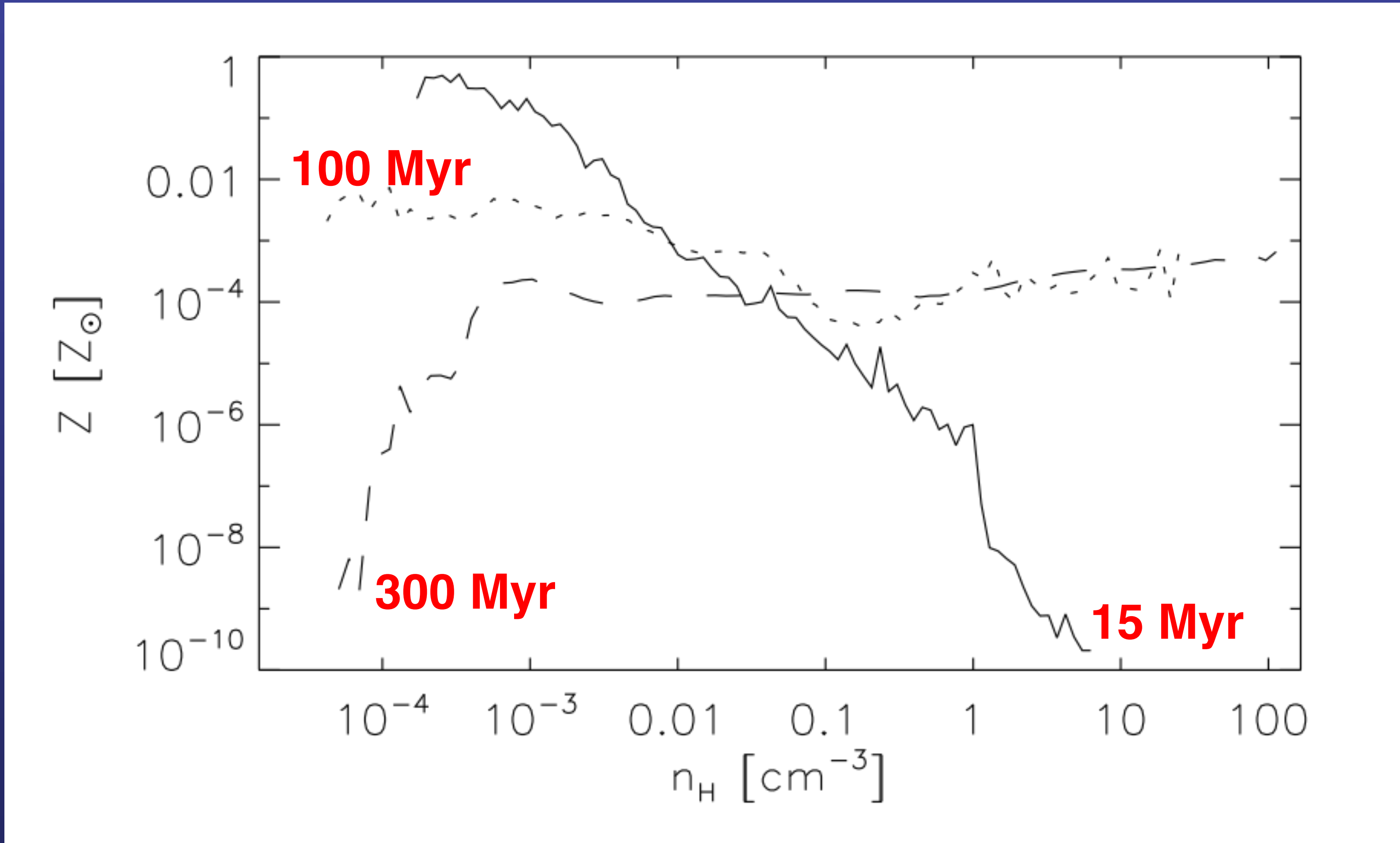
(Greif et al. 2010, ApJ, 716, 510)



Pre-galactic Metal Enrichment

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

Average Metallicity vs.Gas Density



Inside the first galaxies: $Z > 10^{-3}\ Z_{\odot}$

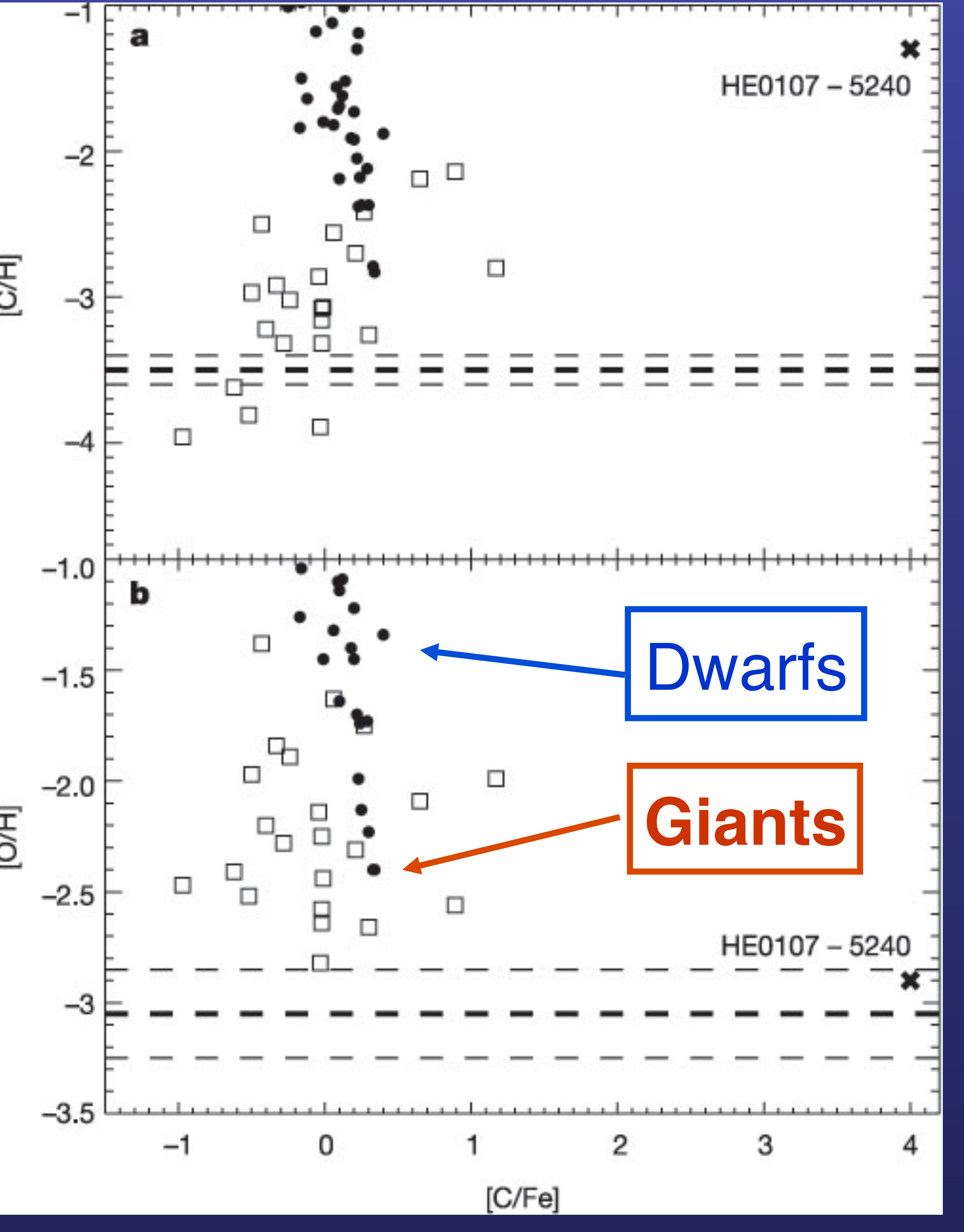
Critical Metallicity for Low-mass Star Formation:

(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!



Physics of the Critical Metallicity:

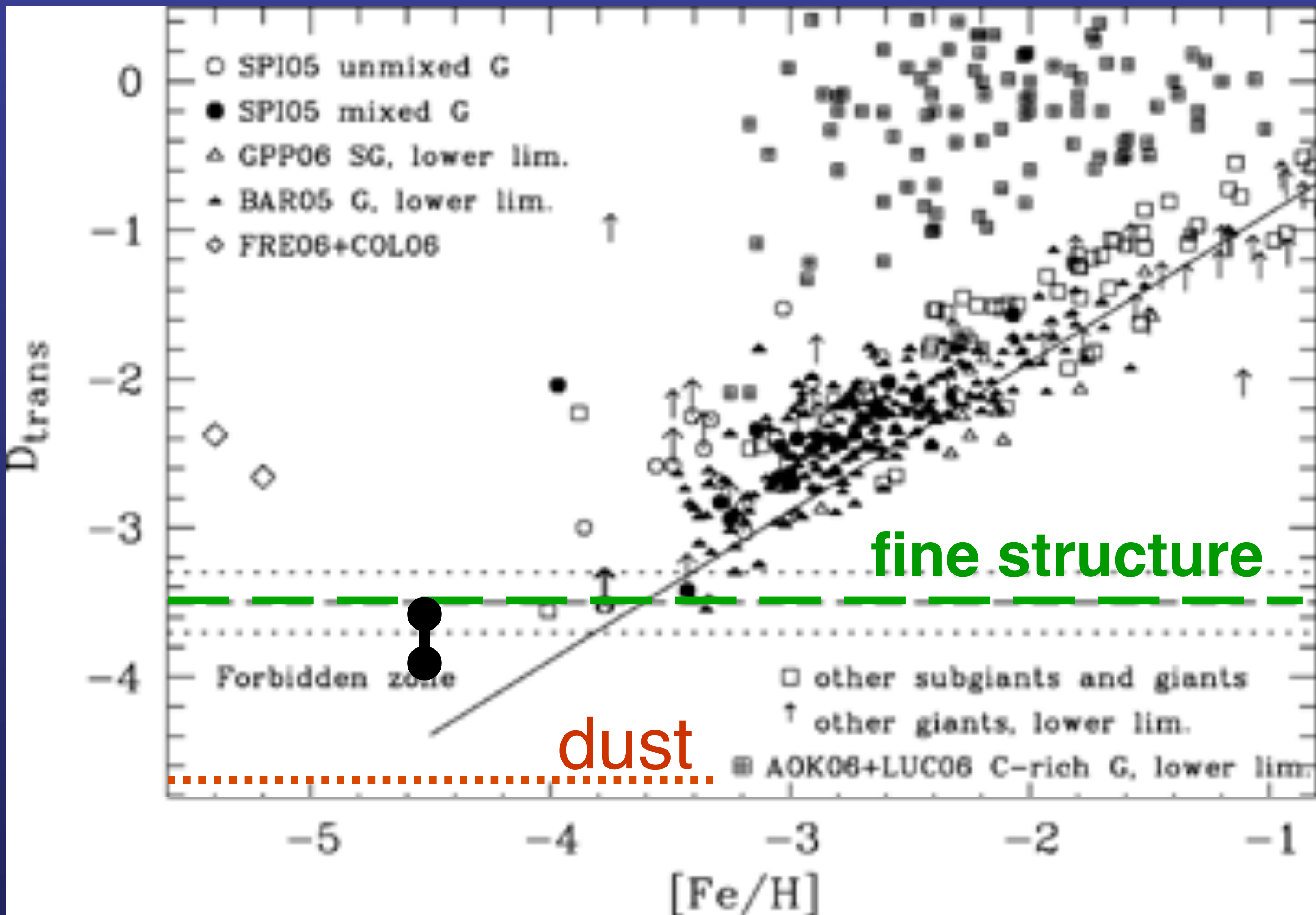
→ Highly complex!

- What is primary coolant?
  - Dust (e.g., Schneider et al. 2006; Clarke et al. 2007)
    vs. fine-structure cooling?
  - Molecules (CO…)?
  - Fine-structure cooling: Which elements? (C, O, Si, Fe,…)
    → Bromm & Loeb (2003); Santoro & Shull (2006)
  - Is fine-structure cooling relevant? (Jappsen et al. 2007, 2008)
  - Equation of state arguments:
    → e.g., Omukai (2000); Omukai et al. (2005); Spaans & Silk (2005)

- Z_{crit} = f (environment, formation history,…)
  → Realistic Initial Conditions are crucial!
  → non-uniqueness
  → robust temperature floor set by CMB (Larson 1998)

Forming the First Low-mass Stars:
(Frebel, Johnson & Bromm 2007, MNRAS, 380, L40)

`Transition discriminant' (D_{trans}): C + O abundance



Summary

- Primordial gas typically attains:
  - **$T \sim 200 - 300$ K**
  - **$n \sim 10^3 - 10^4$ cm^{-3}**
- Corresponding Jeans mass: **$M_J \sim 10^3 M_o$**

- Pop III SF might have favored *very massive stars*

- Transition to Pop II driven by presence of metals
  ($z_{trans} \sim 15$ +- 5)

- PISNe completely disrupt mini-halos and enriches surroundings

- First galaxies were already metal-enriched!

Perspectives:

- Very dynamic, rapidly developing field

- Closing the final gap in our worldview

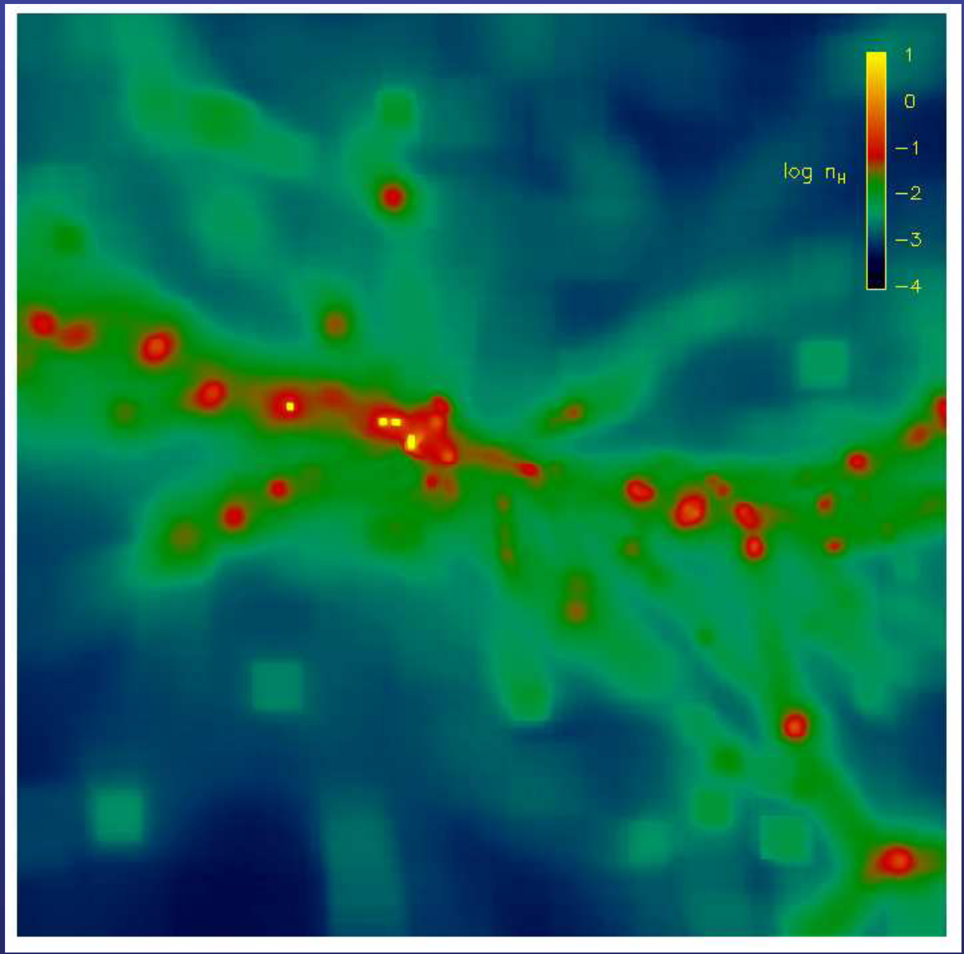
- Driven by supercomputers and our best telescopes

- The high-redshift frontier: How did it all begin?

Feedback: LW background delays SF

(Johnson, Greif, & Bromm 2008, MNRAS, 388, 26)

H number density



~ 10 kpc (proper)

- with $J_{LW} = 0.04 \times 10^{-21}$ erg s^{-1} cm^{-2} Hz^{-1} sr^{-1} present:

→ Only allow 4 Pop III stars to form (out of 10 possible)!