Astronomy 353

(Spring 2008)

ASTROPHYSICS: From Black Holes to the First Stars

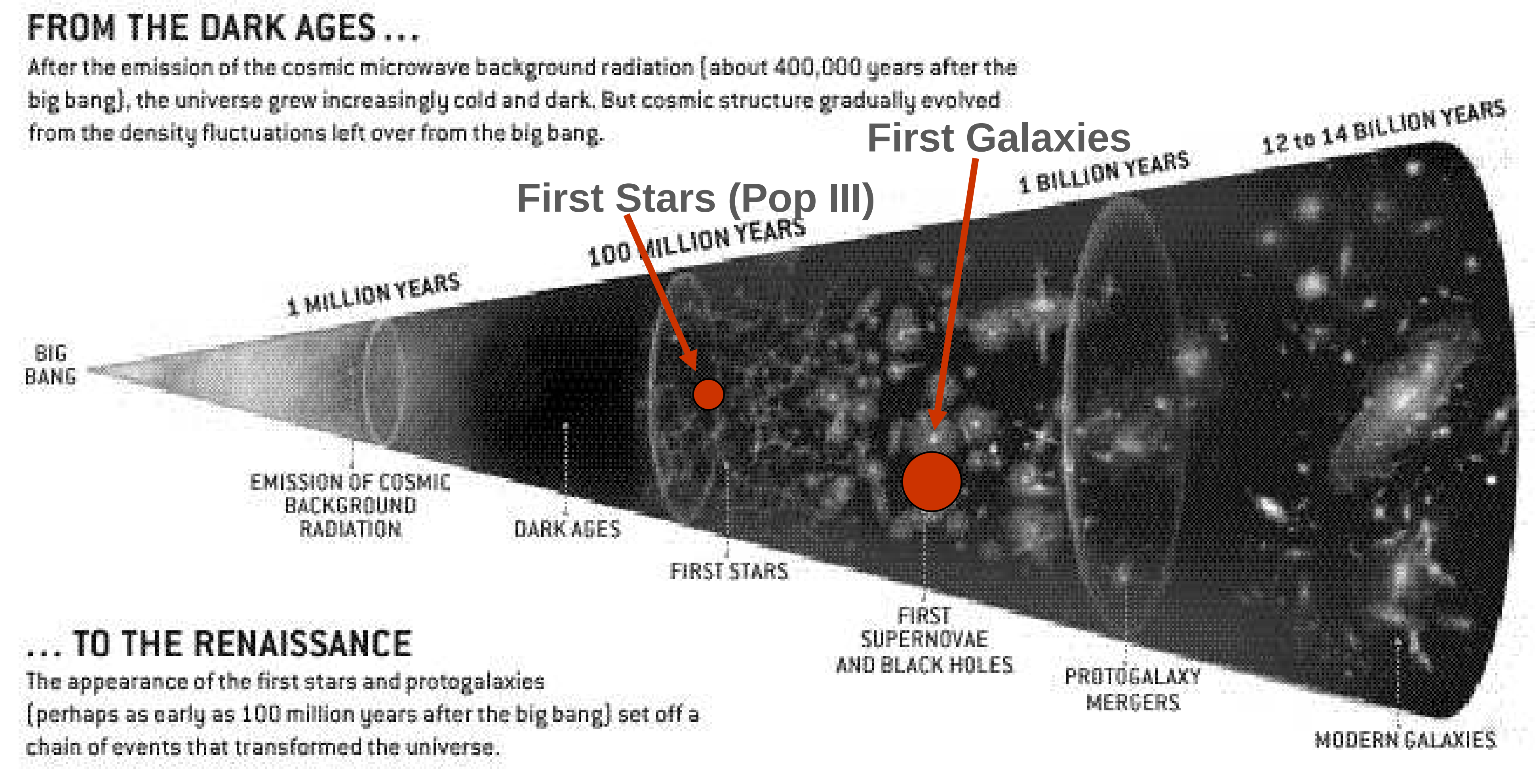
(Lecture 25: The First Stars: Effect on Cosmic Evolution)

Instructor: Volker Bromm

TA: Jarrett Johnson

The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance

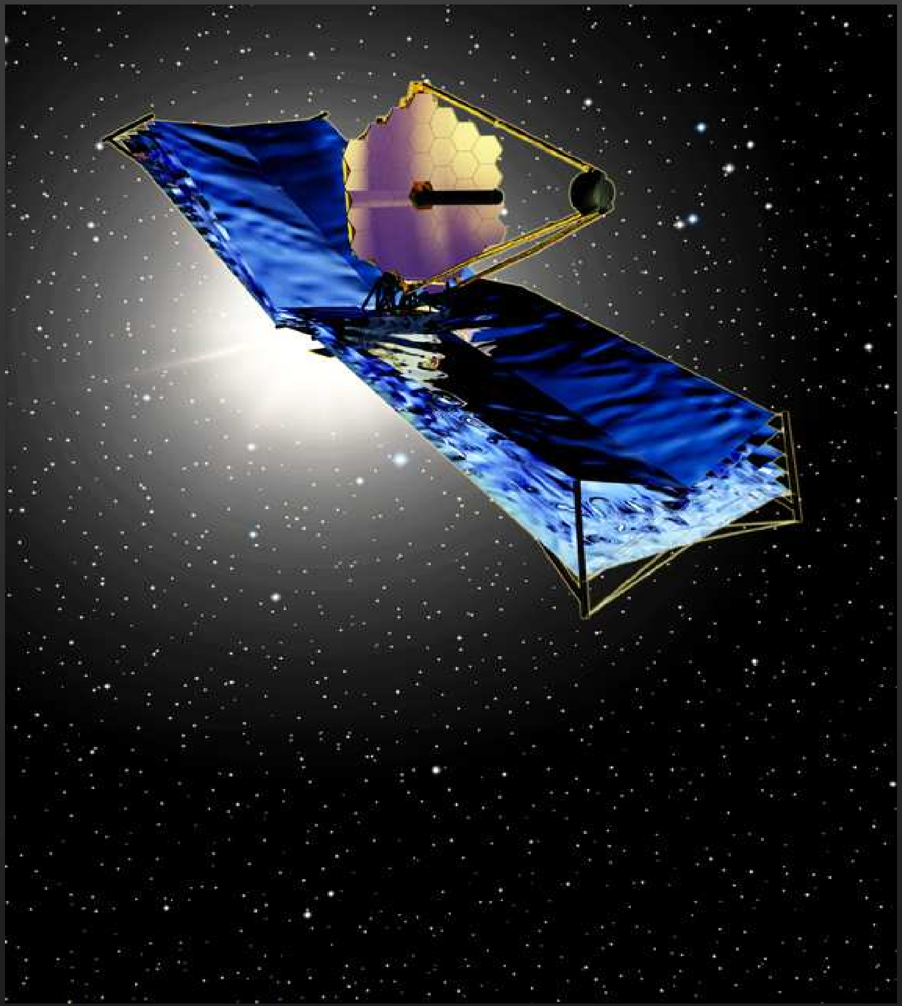


(Larson & Bromm, Scientific American, Dec. 2001)

- First Stars ⟶ Transition from Simplicity to Complexity

The James Webb Space Telescope:

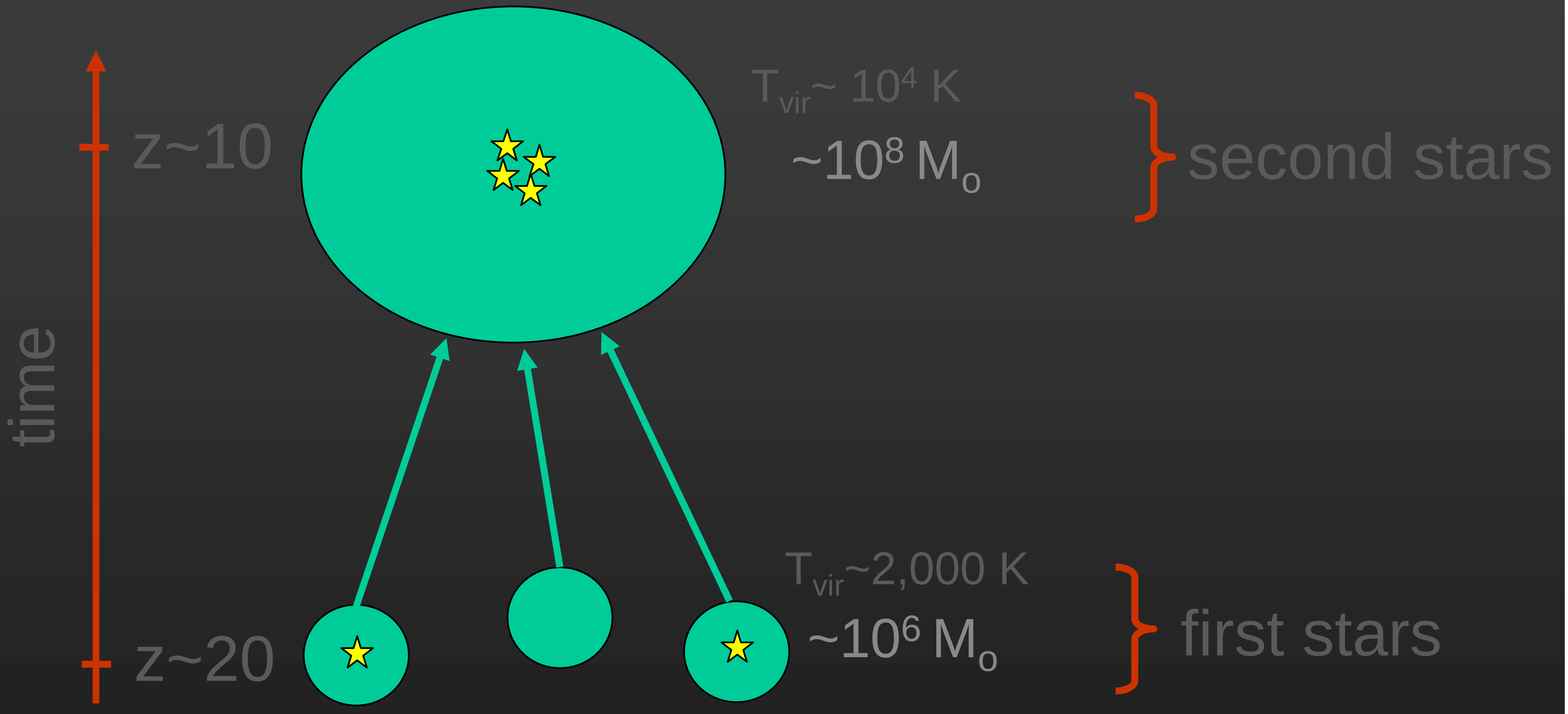
(NASA's successor to the *Hubble*)



- Launch in ~2013
- Near IR sensitivity of ~ 1 nJy
- ~ 4' x 4' FOV

→ **Direct Imaging of the First Galaxies**

Hierarchical (bottom-up) Structure Formation



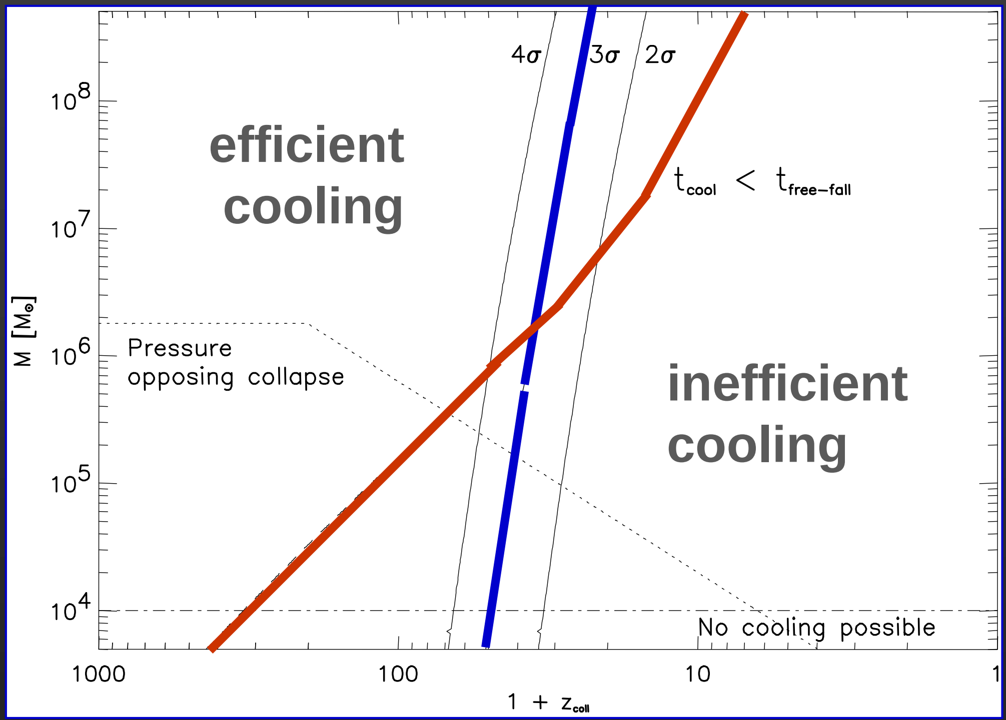
Cold Dark matter (CDM) halos

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)

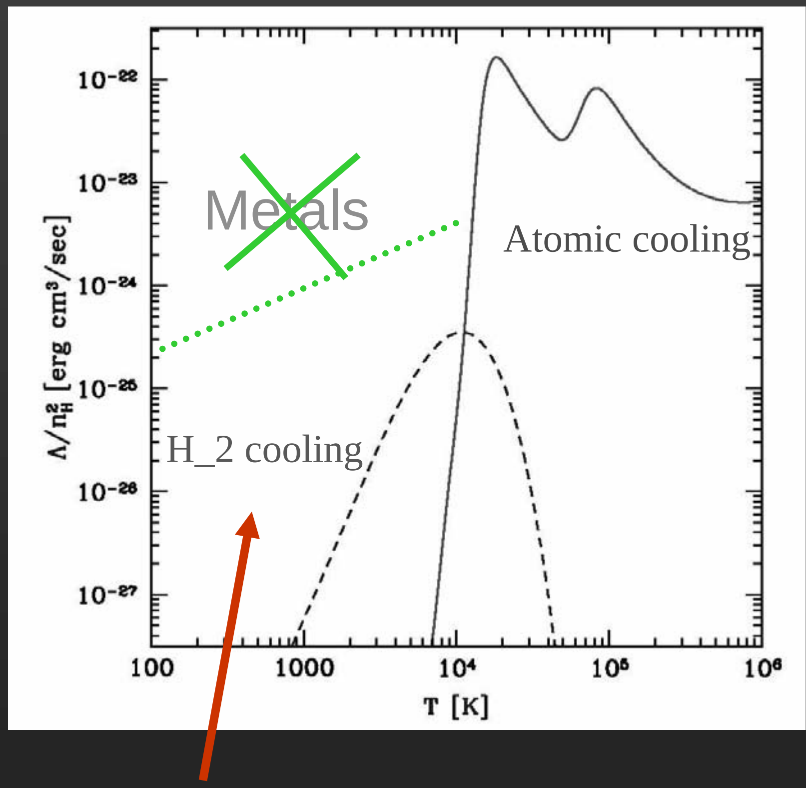


- Collapse of First Luminous Objects expected:
  - at: z_{coll} = 20 – 30
  - with total mass: $M \sim 10^6\ M_o$

``minihalos''

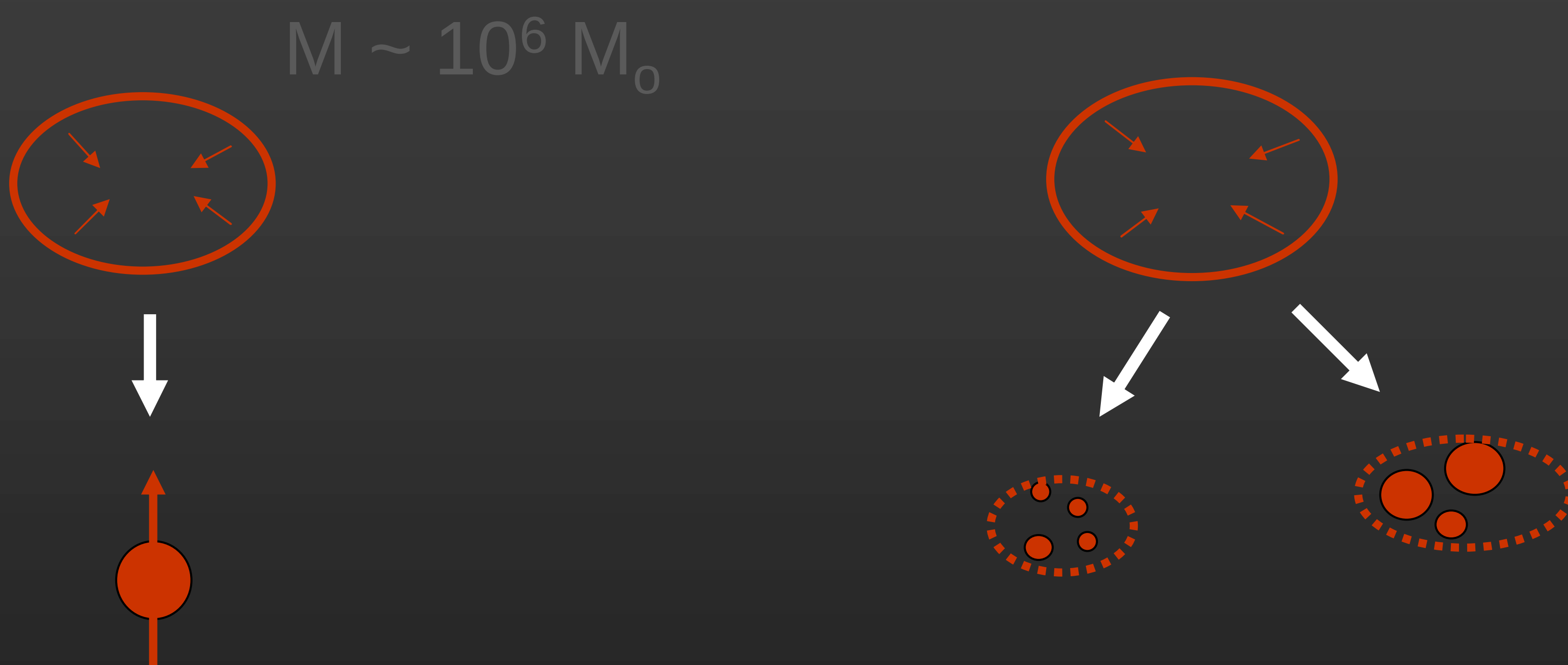
The Physics of Population III

- Simplified physics
  - No magnetic fields yet (?)
  - No metals ⟶ no dust
  - Initial conditions given by CDM
    - → Well-posed problem
- Problem:
  How to cool primordial gas?
  - No metals ⟶ different cooling
  - Below 10^4 K, main coolant is H_2
- H_2 chemistry
  - Cooling sensitive to H_2 abundance
  - H_2 formed in non-equilibrium
    - → Have to solve coupled set of rate equations



T_{vir} for Pop III

What happens inside primordial minihalos?



Single star

Multiple Stars

- **Most important question: How massive were the first stars?**

Simulating the First Stars and Galaxies:

- use state-of-the-art supercomputers
- multi-processor

(parallel)

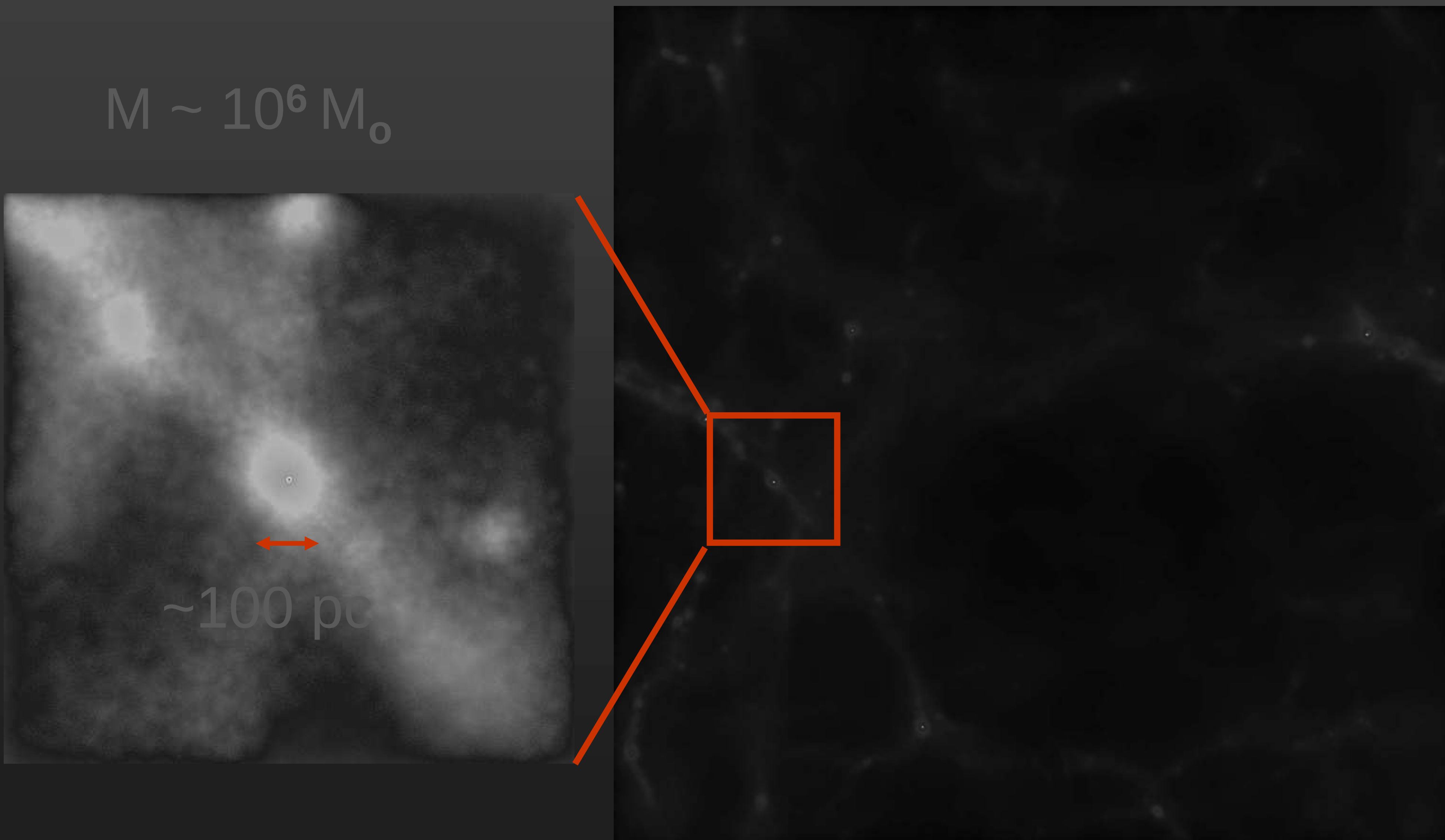
“Beowulf” machines

- “Lonestar” at Texas Advanced Computing Center
- UT Austin,
  J.J. Pickle Research Campus

The First Star-Forming Region (“minihalos”)

projected gas density at z=20

$M \sim 10^6\ M_o$

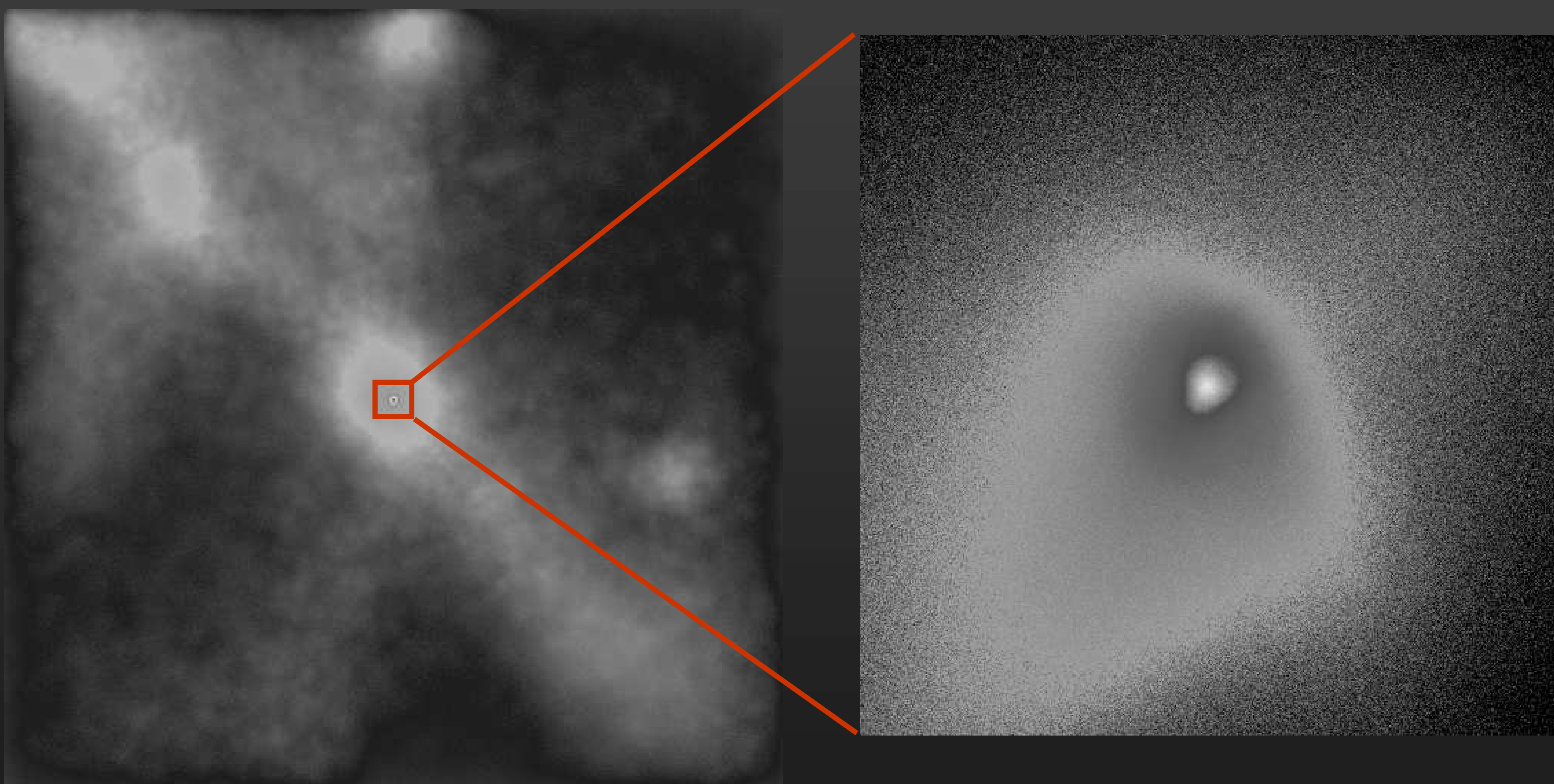


~ 7 kpc (proper)

Formation of a Population III Star

(Bromm, Coppi, & Larson 1999, 2002; Bromm & Loeb 2004)

$M_{halo} \sim 10^6\, M_o$ $M_{clump} \sim 10^3\, M_o$



~ 25 pc

1 kpc

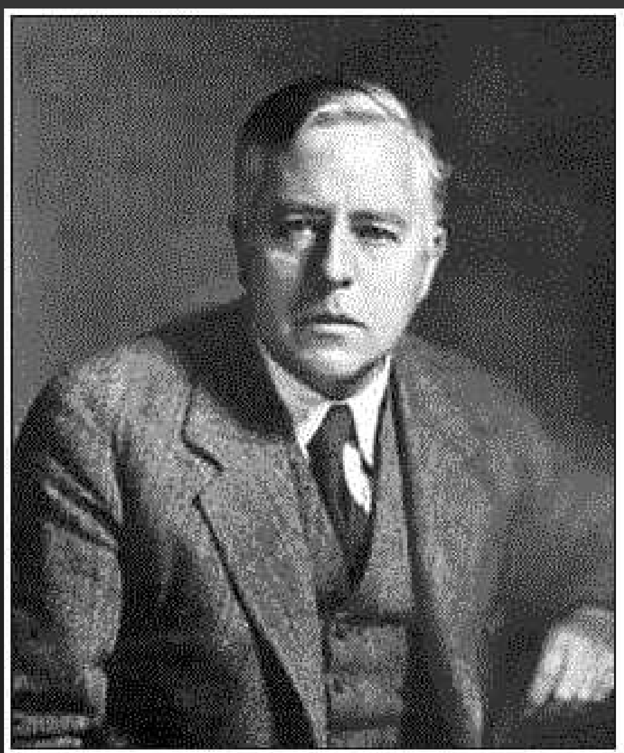
A Physical Explanation:

(Bromm, Coppi, & Larson 1999, 2002)

• Gravitational instability (Jeans 1902)

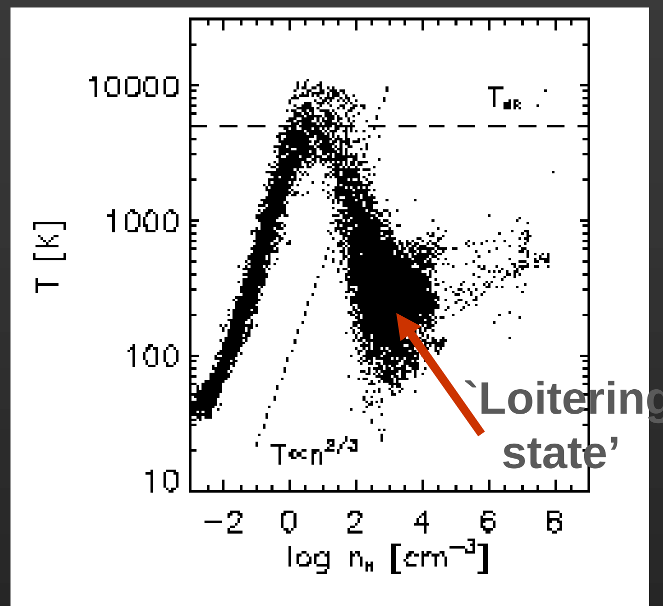
• Jeans mass:

$M_J \sim T^{1.5}\ n^{-0.5}$

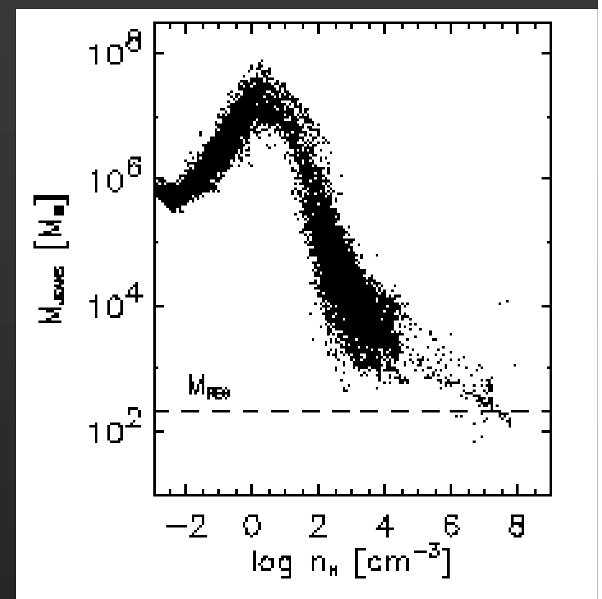


•Thermodynamics of primordial gas

T vs. n



M_J vs. n



•Two characteristic numbers in microphysics of H_2 cooling:

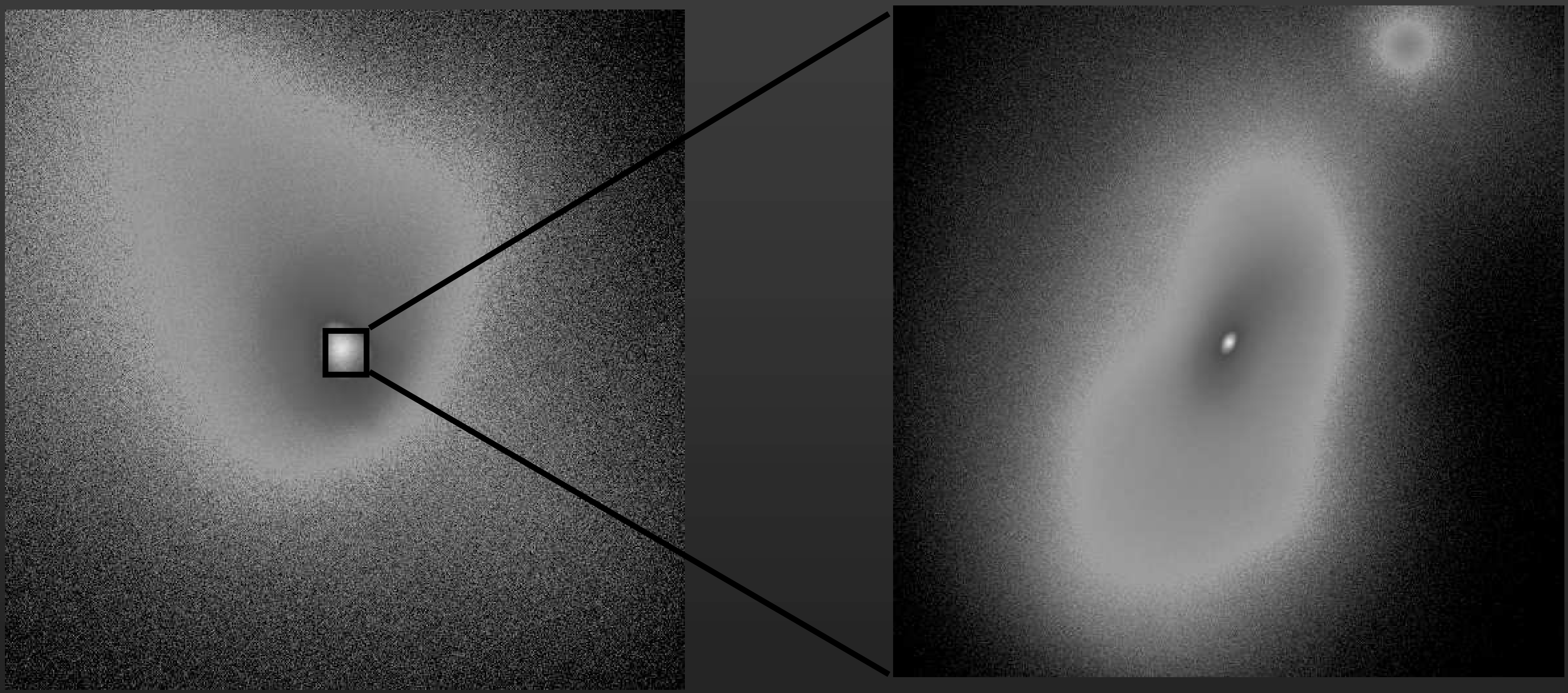
- $T_{min} \sim 200$ K
- $n_{crit} \sim 10^3$ - 10^4 cm^{-3} (NLTE → LTE)

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

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

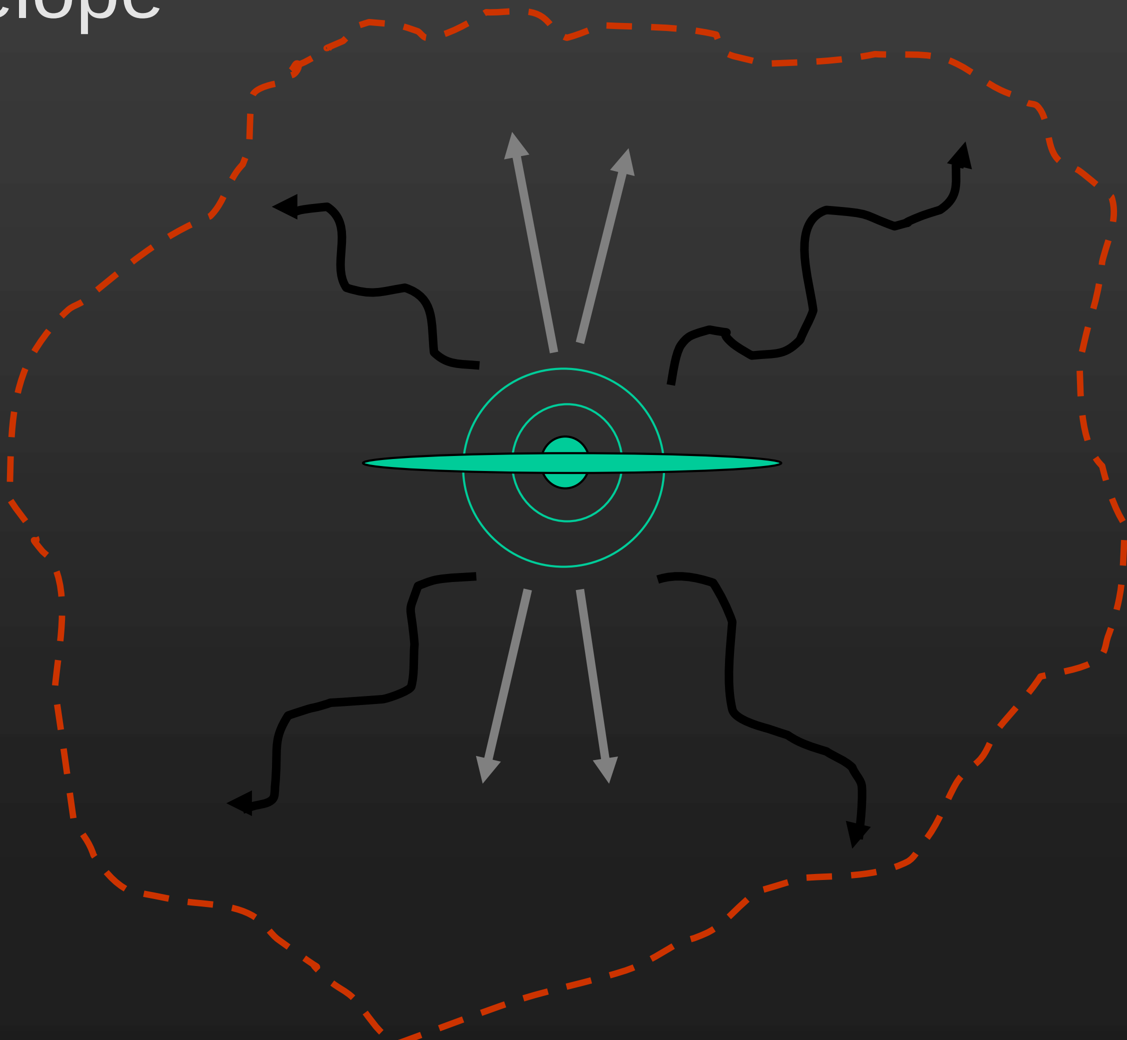
- Simulate further fate of the clump



25 pc 0.5 pc

The Crucial Role of Accretion

• Final mass depends on accretion from dust-free Envelope

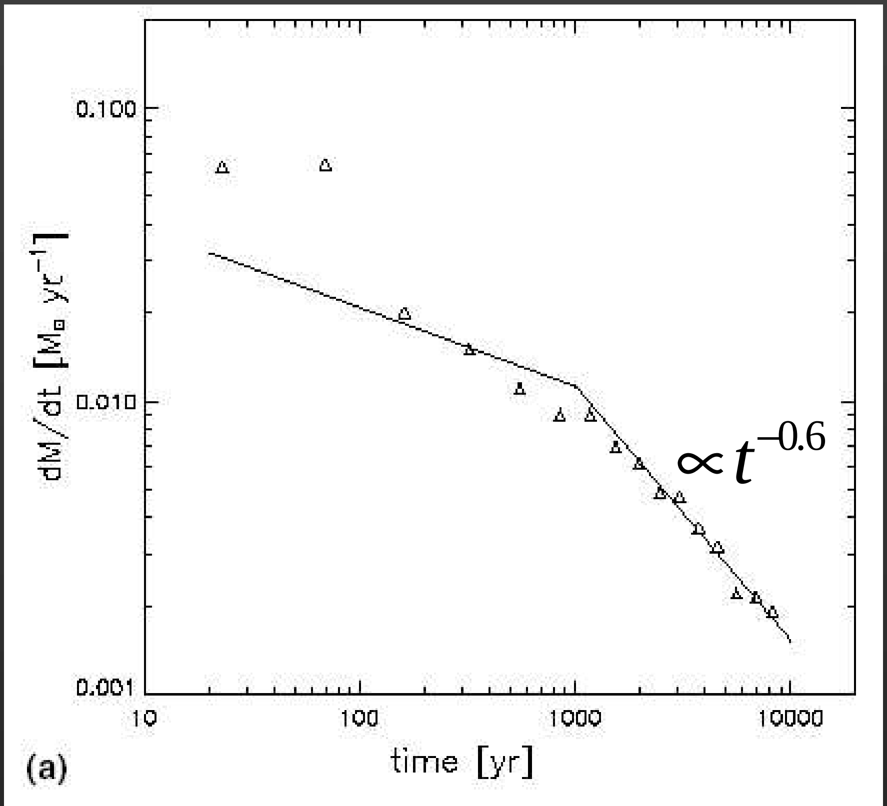


Clump:

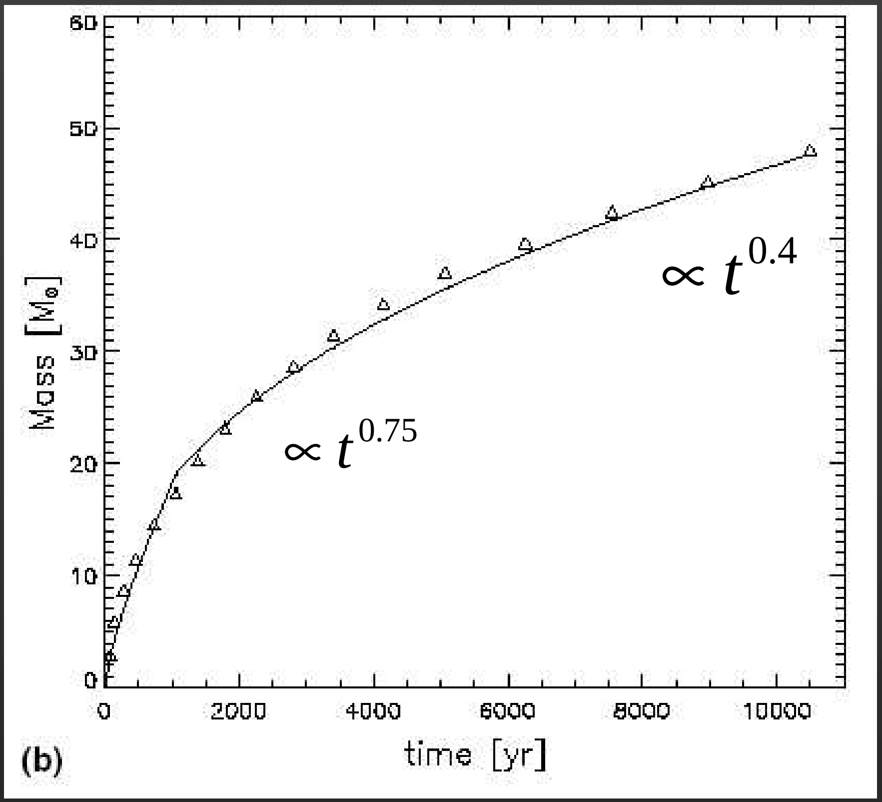
$M \sim M_J$

Accretion onto a Primordial Protostar

dM/dt vs. time



M vs. time



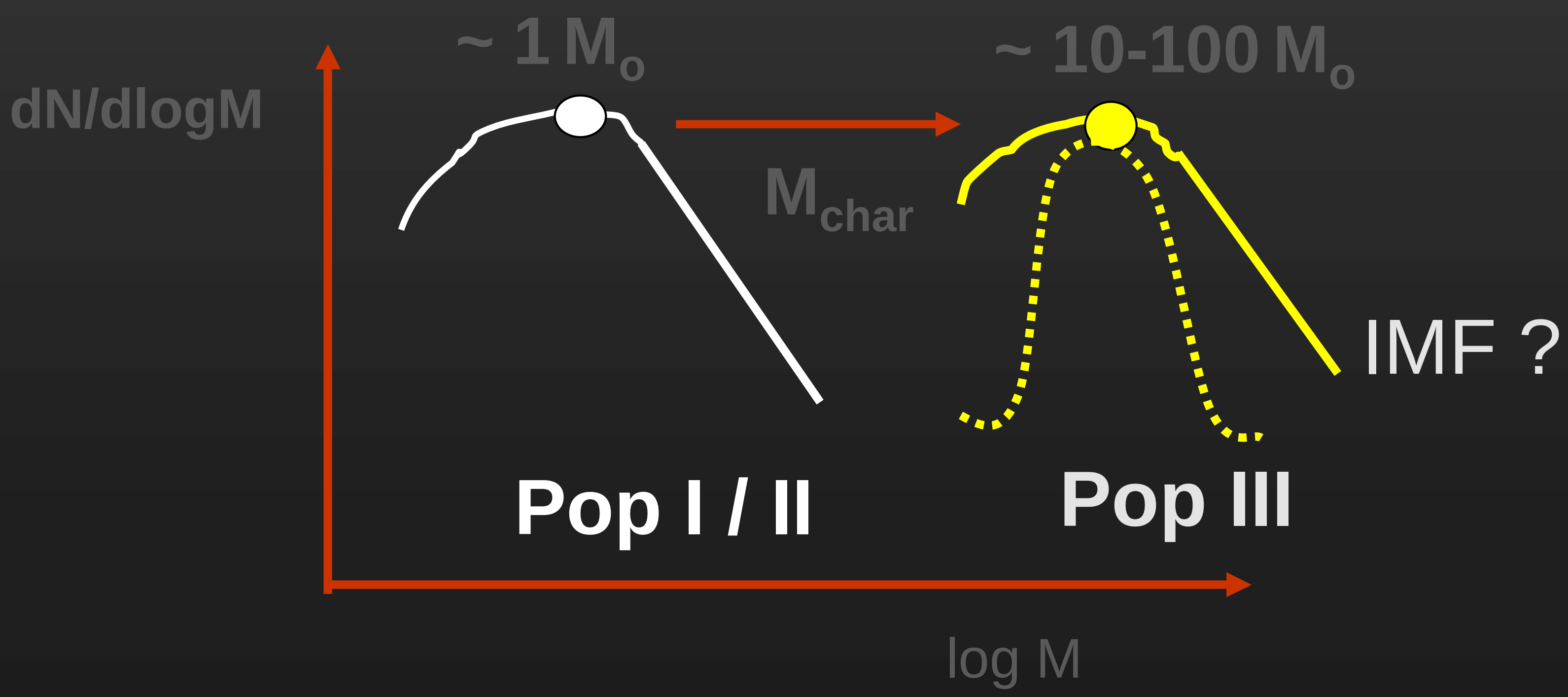
Upper limit: $M_*(t = 3\times10^{6}\,\mathrm{yr}) \approx 500\,M_\odot$

-Similar range (~50 - ~ few 100 $M_\odot$) found by:

- Abel et al. 2002; Omukai & Palla 2003; Tan & McKee 2004; Yoshida et al. 2006; O'Shea & Norman 2007)

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)
- Main Result: → **Top-heavy initial mass function (IMF)**

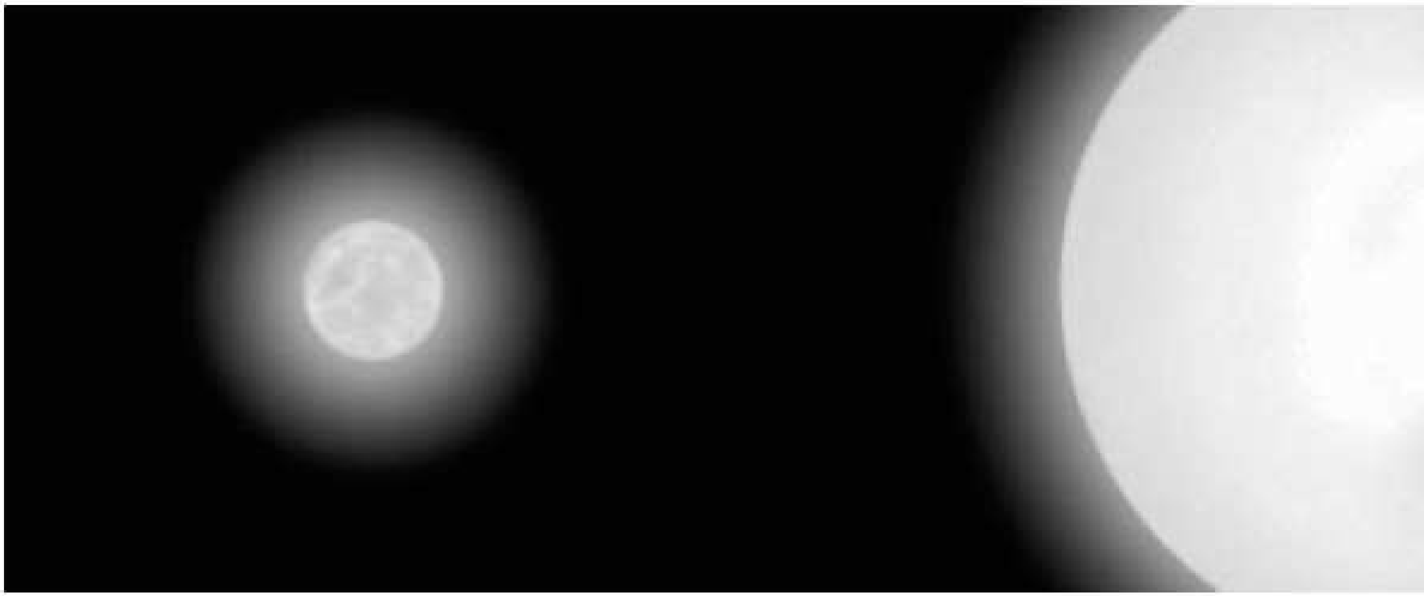


First Stars were Massive

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

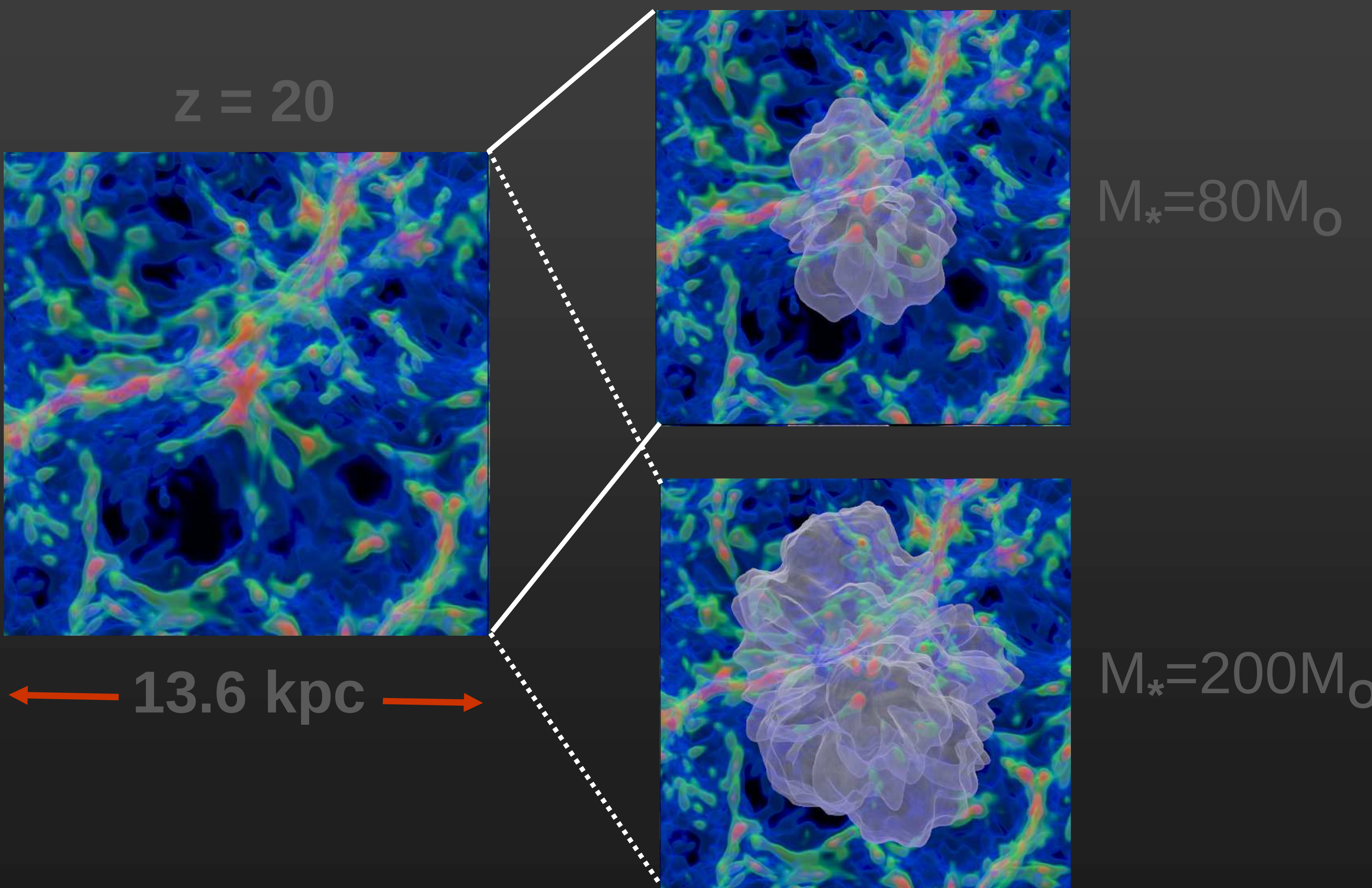
(Larson & Bromm, Scientific American, Dec. 2001)

Feedback from the First Stars

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

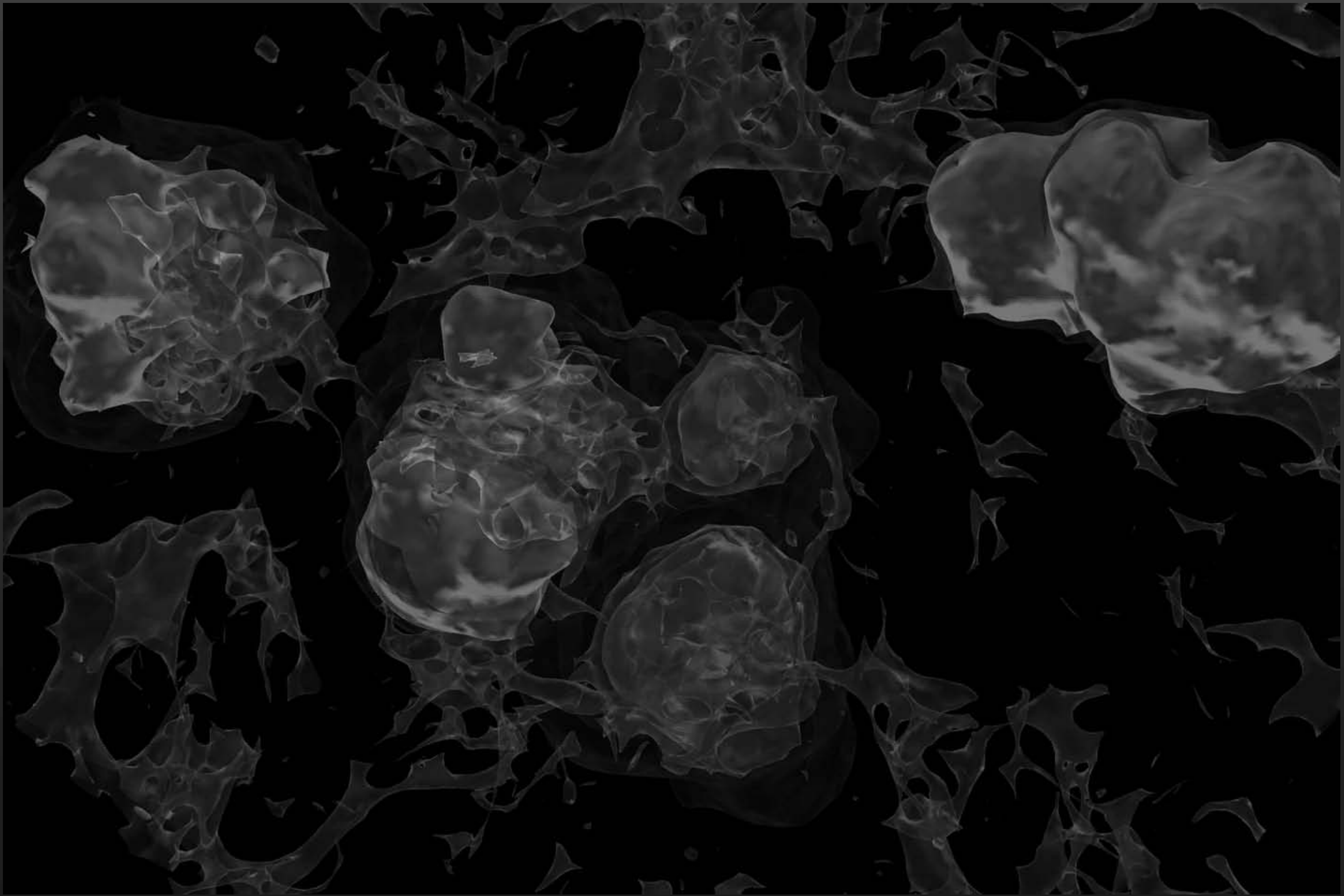
Primordial HII Regions

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



Radiative Feedback from the First Stars

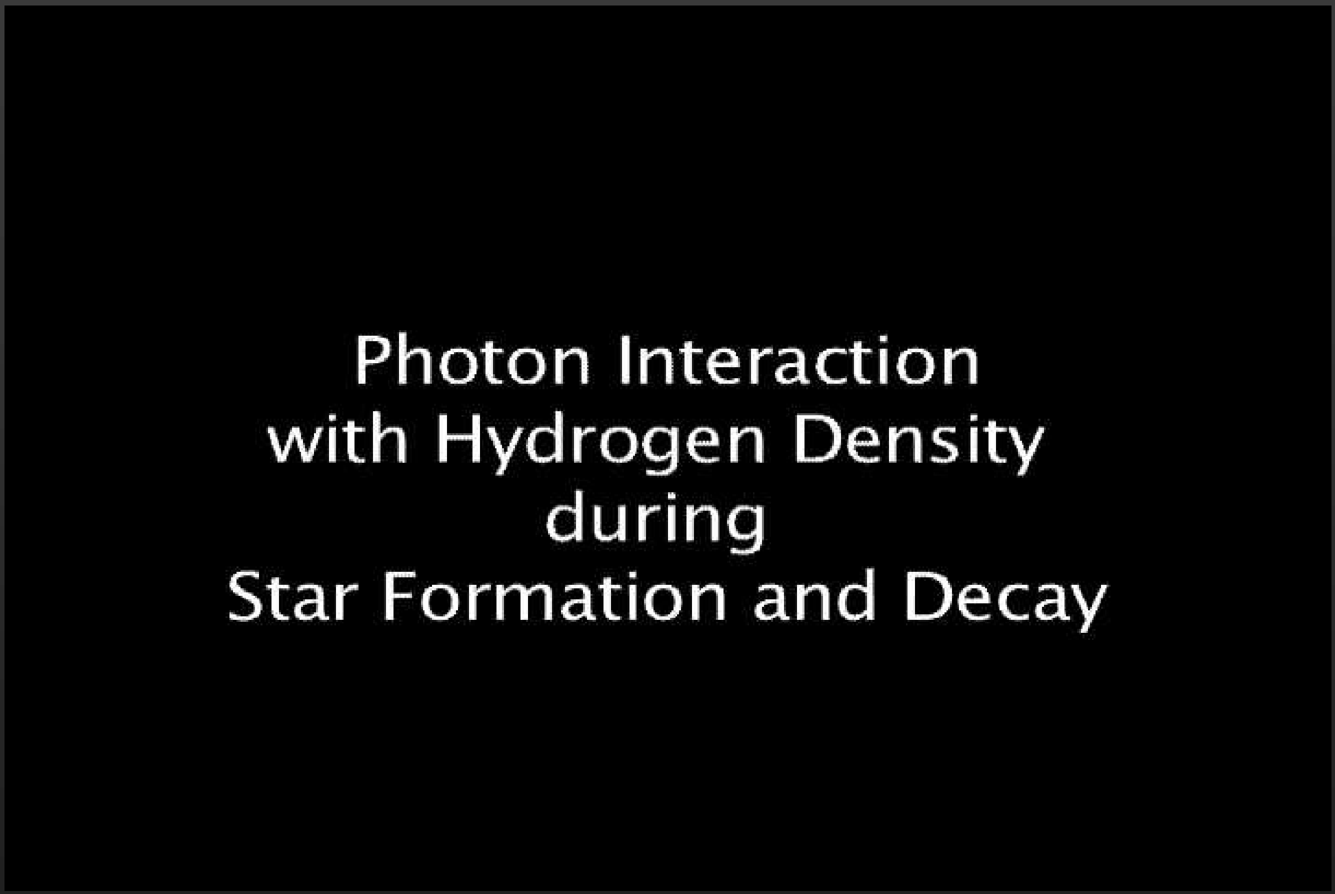
(Johnson, Greif, & Bromm 2007, ApJ, 665, 85)



LW Feedback: ``Phoenix Effect''

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

H_2 abundance (green color)



- HII regions:

white-gray overlay

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

~ 660 kpc (comoving)

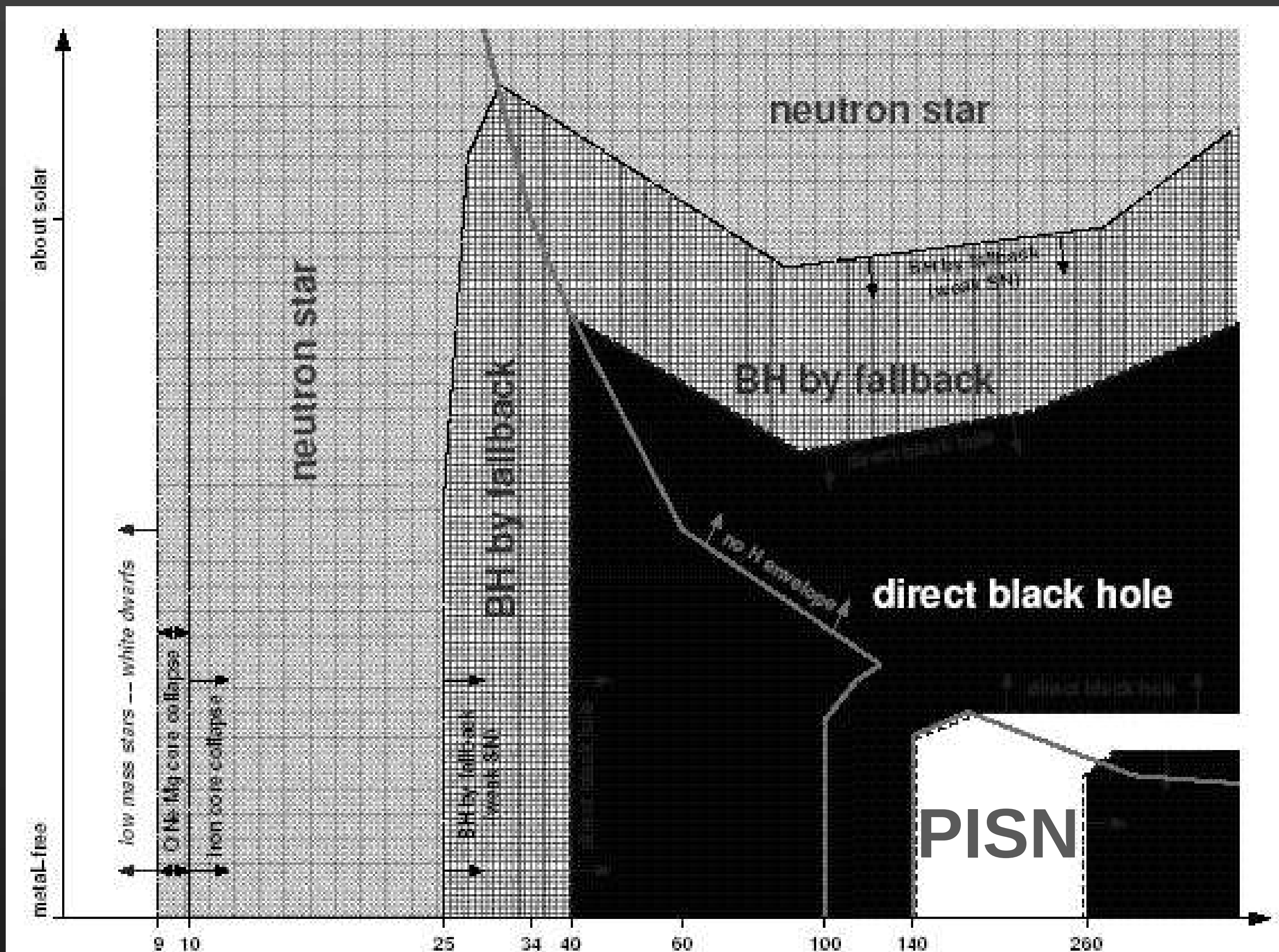
The Death of the First Stars:

(Heger et al. 2003)

Pop I

Z

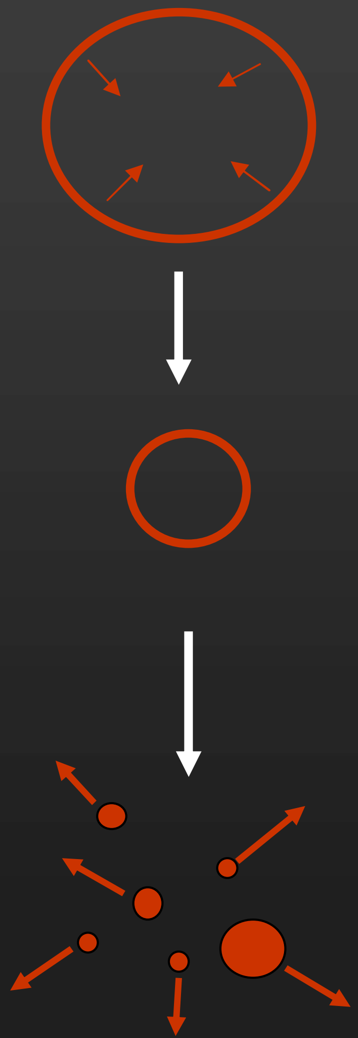
Pop III



Initial Stellar Mass

Physics of Pair-instability Supernovae

$M \sim 140 - 260\ M_o$



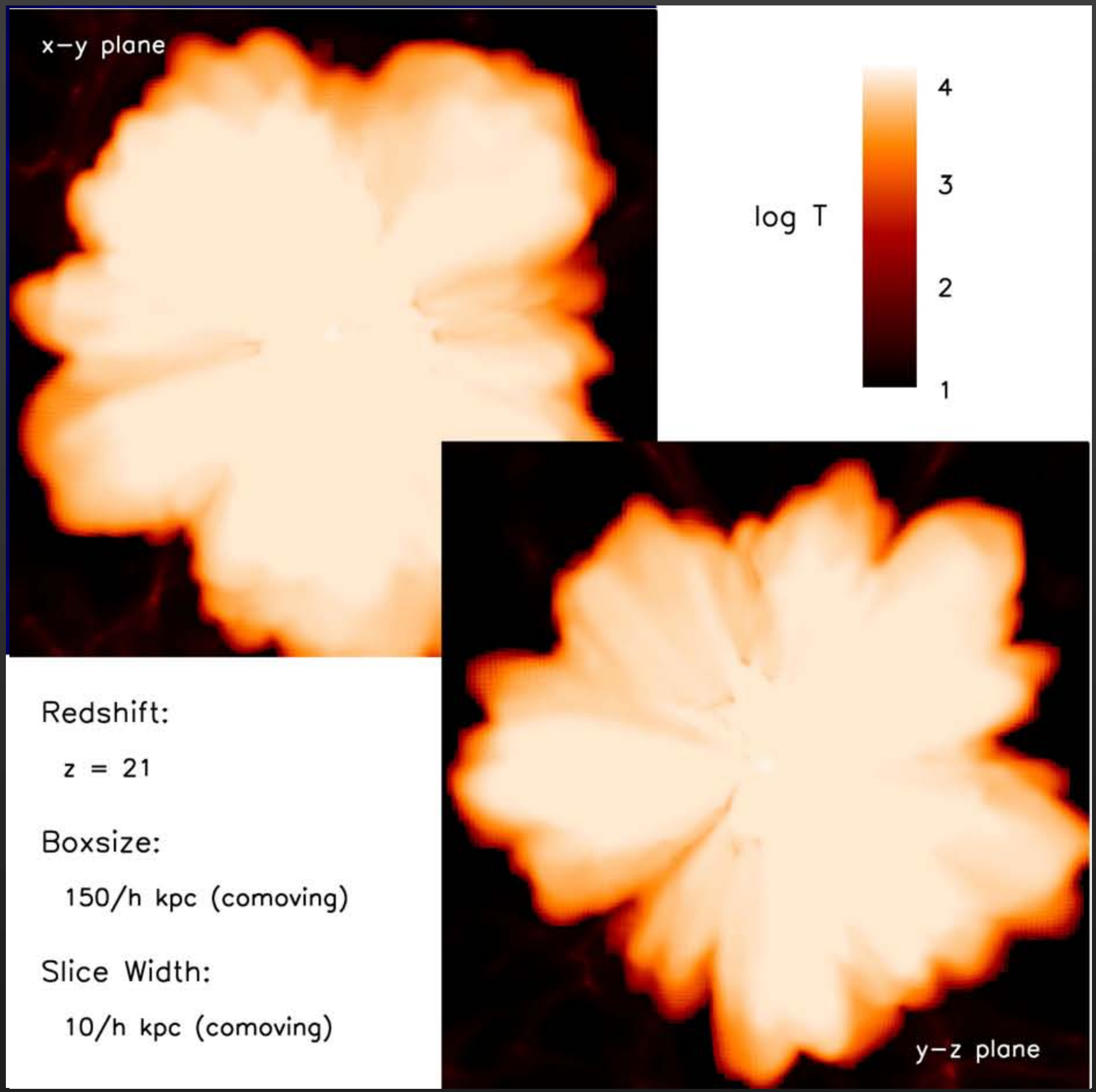
- $T > 10^9 K$
- ph+ph → $e^- e^+$
- grav. runaway collapse

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

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

The First Supernova Explosions

(Greif, Johnson, Bromm & Klessen 2007, ApJ, 670, 1)

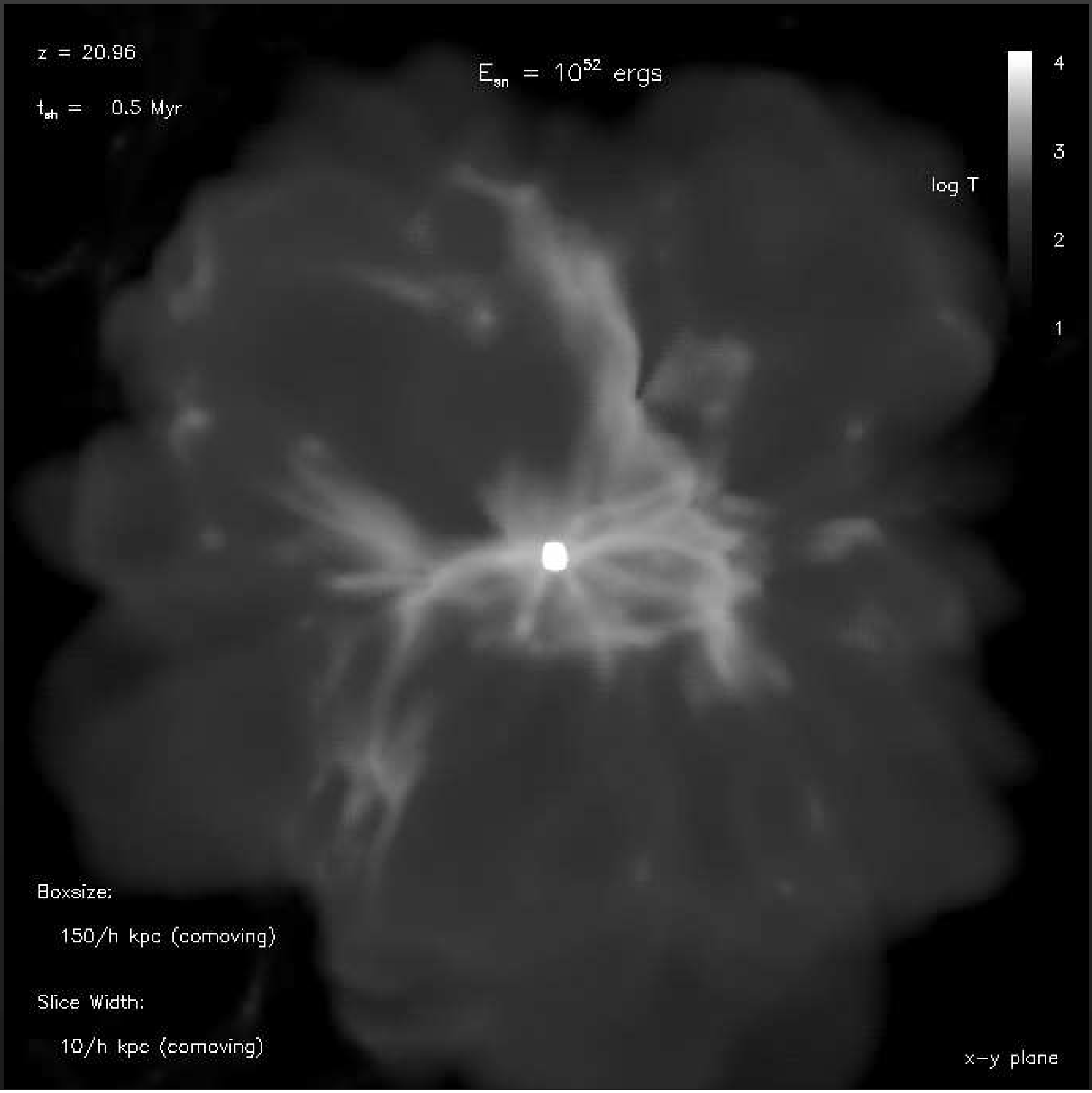


(See also: Bromm, Yoshida & Hernquist 2003, ApJ, 596, L135)

The First Supernova-Explosion

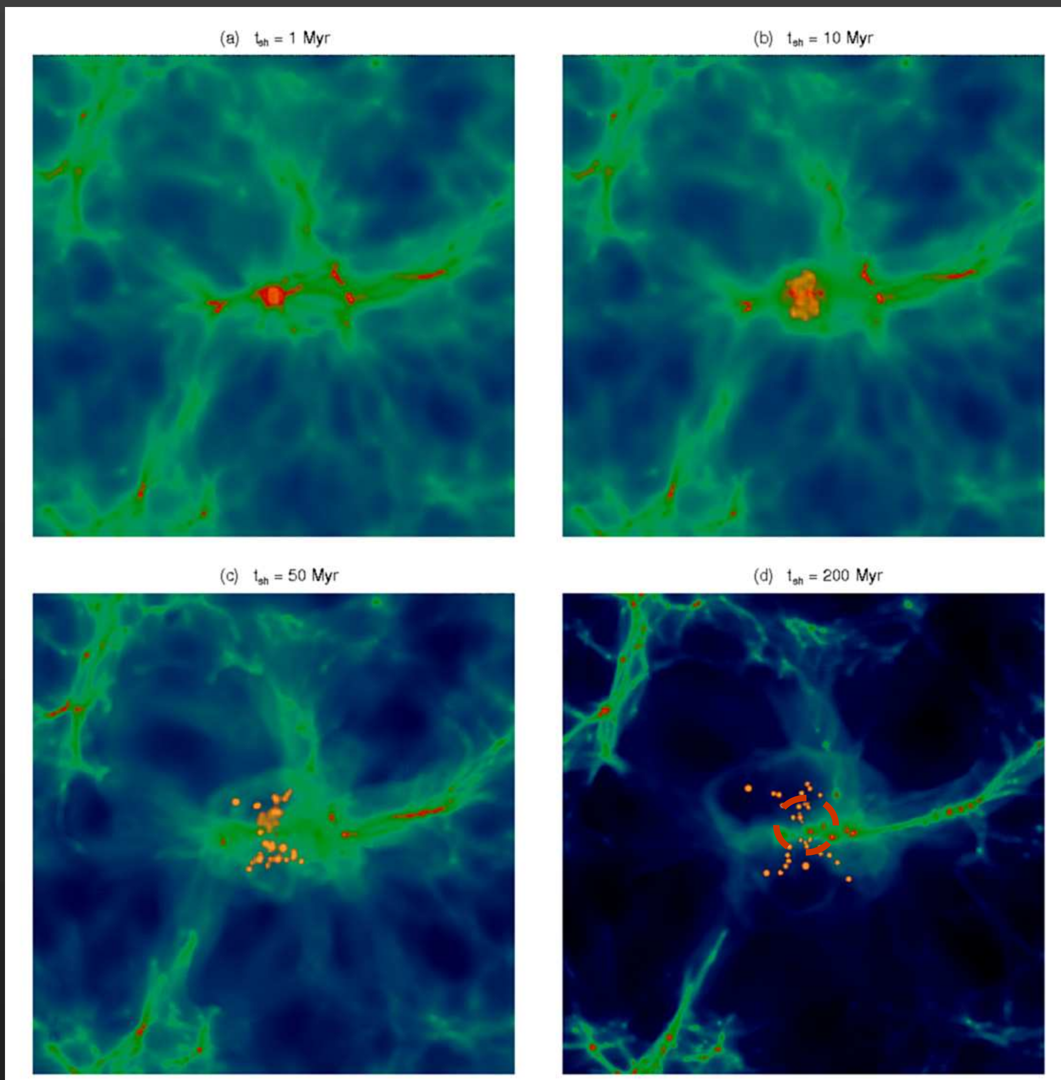
(Greif et al. 2007, ApJ, 670, 1)

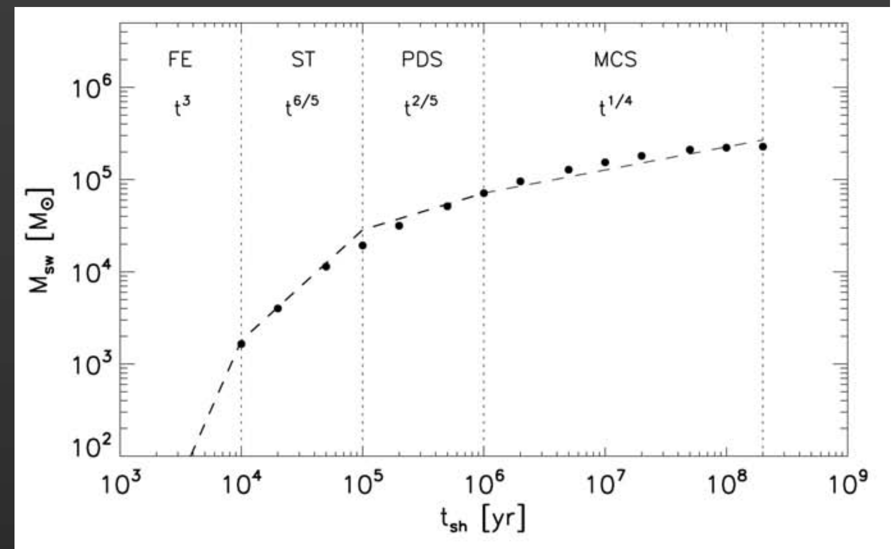
Temperature



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

The First Supernova-Explosion
(Greif et al. 2007, ApJ, 670, 1)

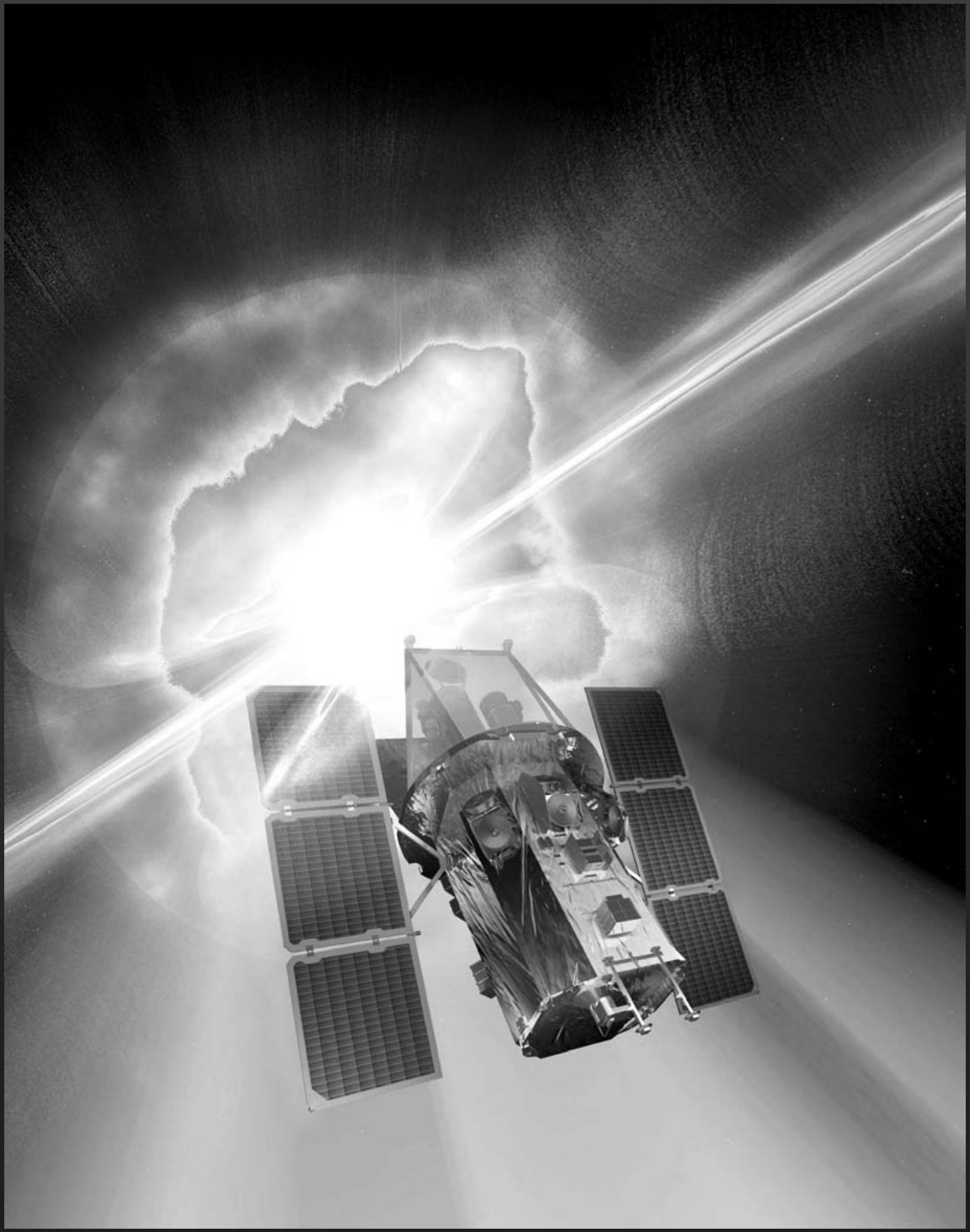




à $\langle Z \rangle \sim 10^{-4}$ - 10^{-3} Z_O

215 kpc

Gamma-Ray Bursts as Probes of the First Stars:



• GRB progenitors → massive stars

• GRBs expected to trace star formation

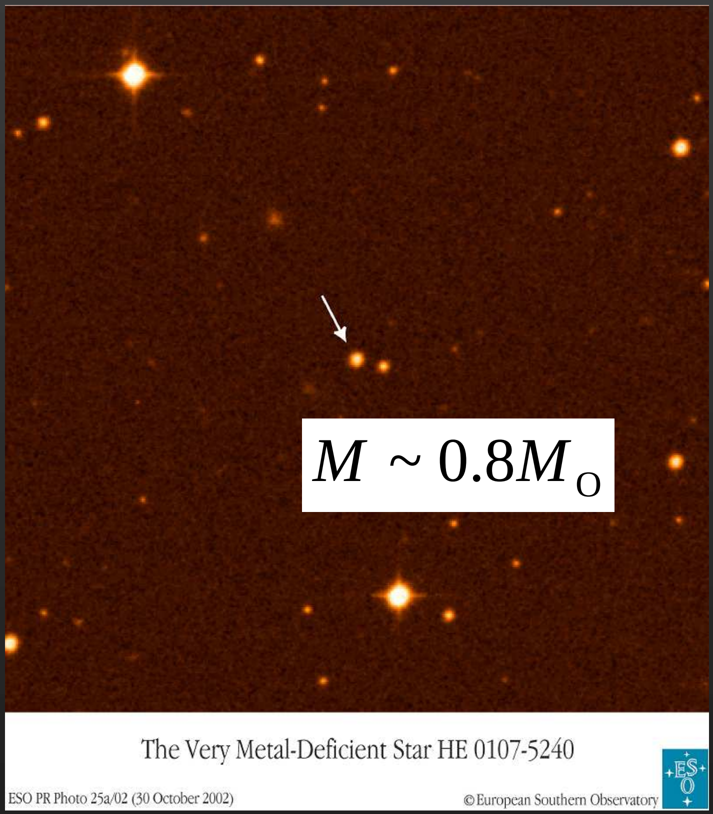
• *Swift* mission:

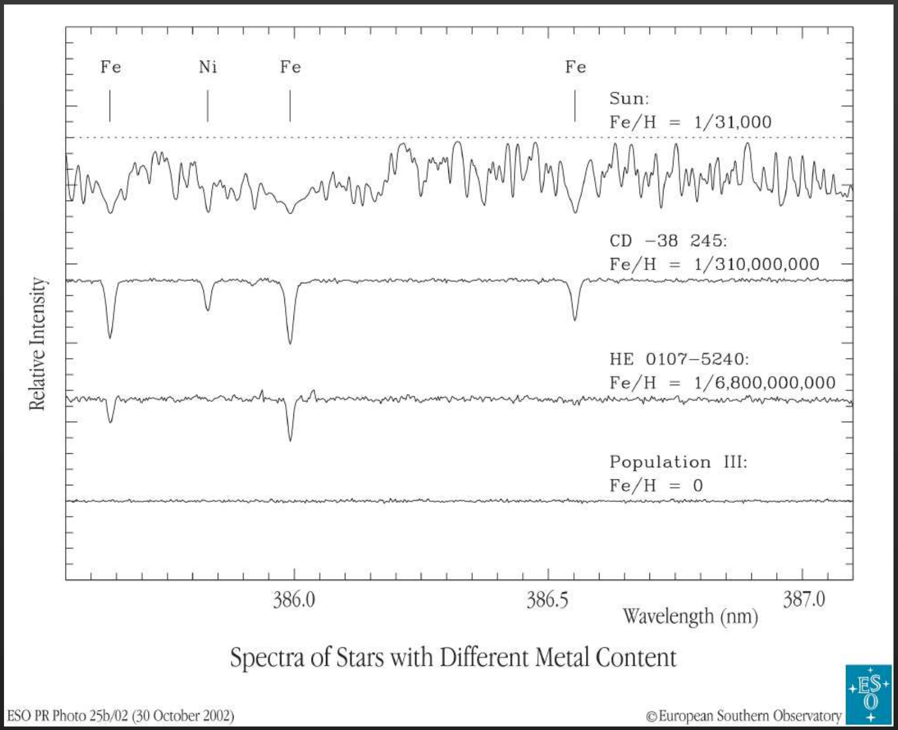
- Launched in 2004

- Sensitivity → GRBs from $z > 15$

Relics from the Dawn of Time:

- **HE0107-5240**: [Fe/H] = - 5.2 (Christlieb et al. 2002)
- **HE1327-2326**: [Fe/H] = - 5.4 (Frebel et al. 2005)

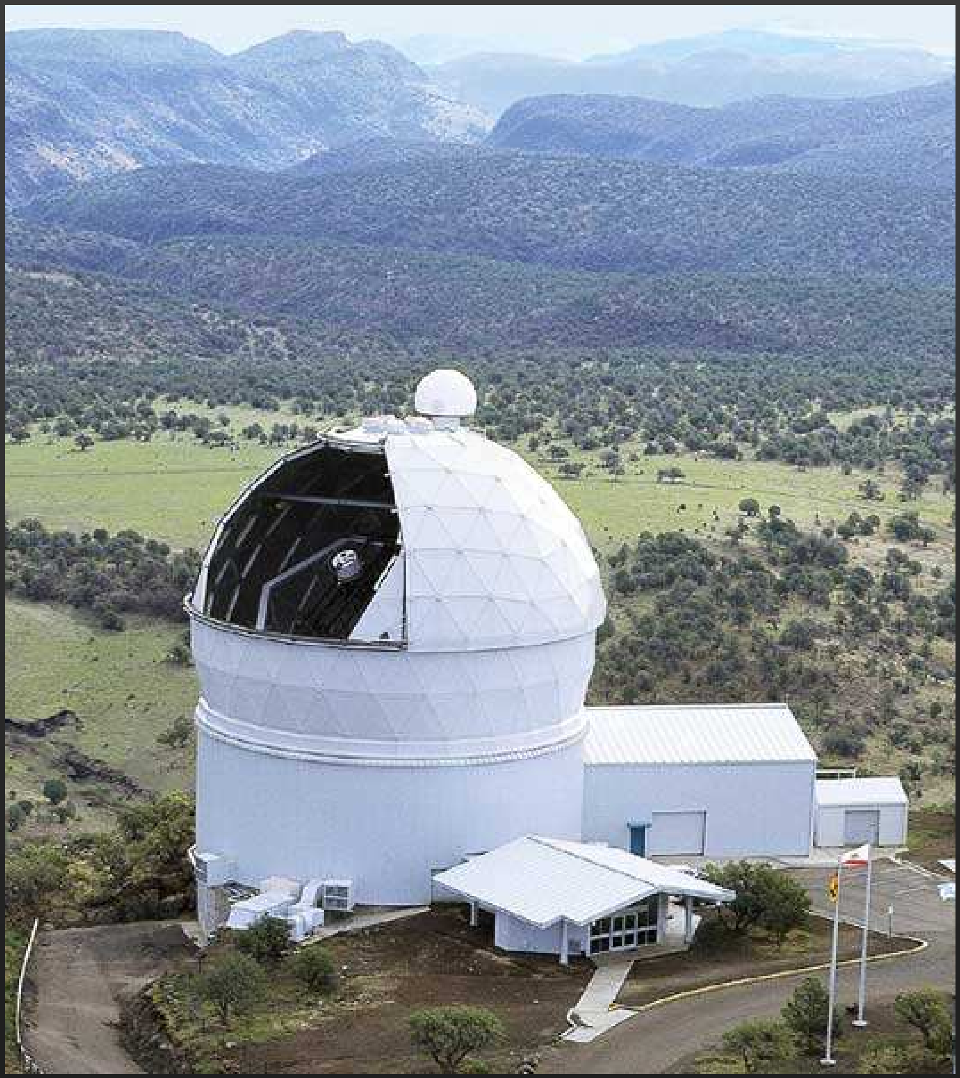




- How could such a low-mass star have formed ?

Probing the First Stars: Hobby-Eberly Telescope

à Extending famous Sloan Sky Survey!

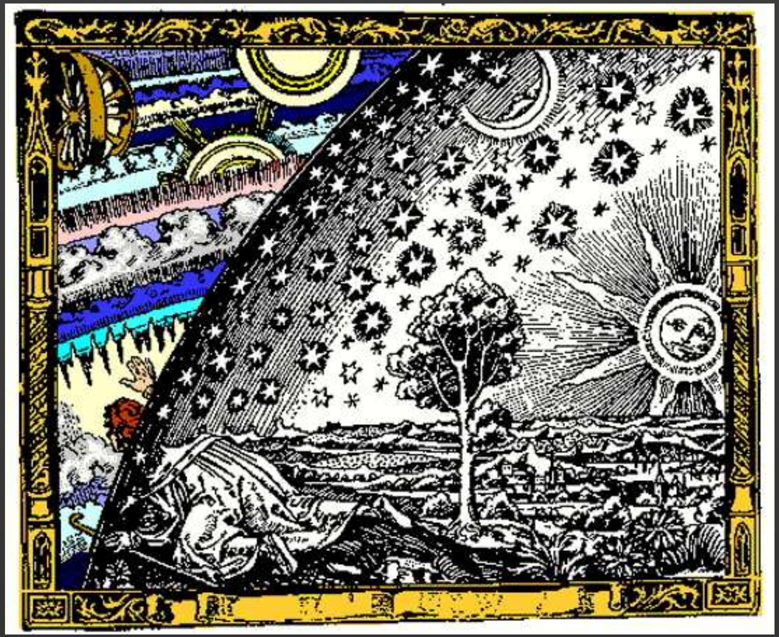


• High-resolution →

Spectra of oldest stars in our Milky Way

• pattern of chemical elements tells us about first stars and supernovae

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?