Astronomy 353

(Spring 2008)

ASTROPHYSICS: From Black Holes to the First Stars

(Lecture 22: The First Stars: Introductory Overview)

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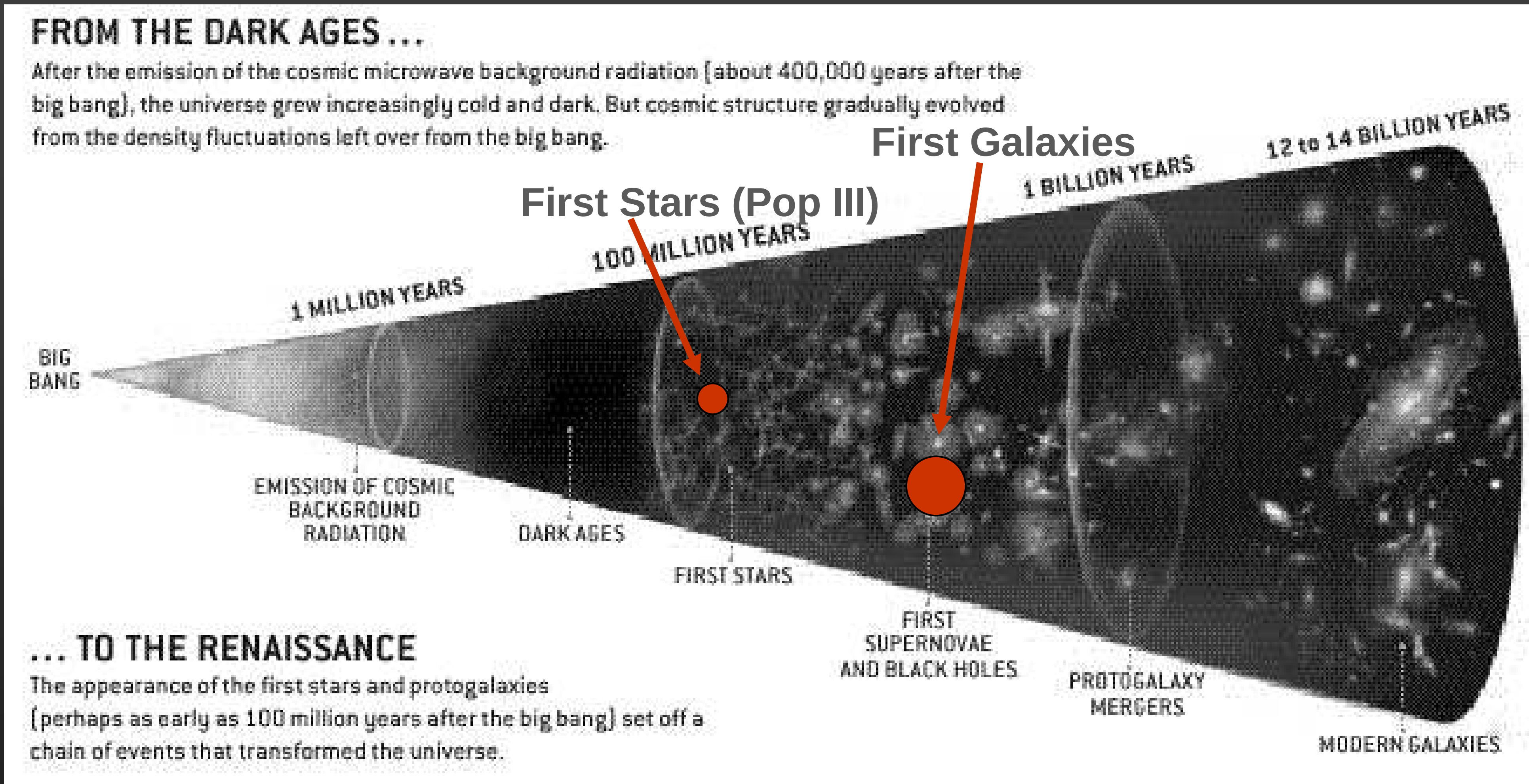
From the Dark Ages to the Cosmic Renaissance

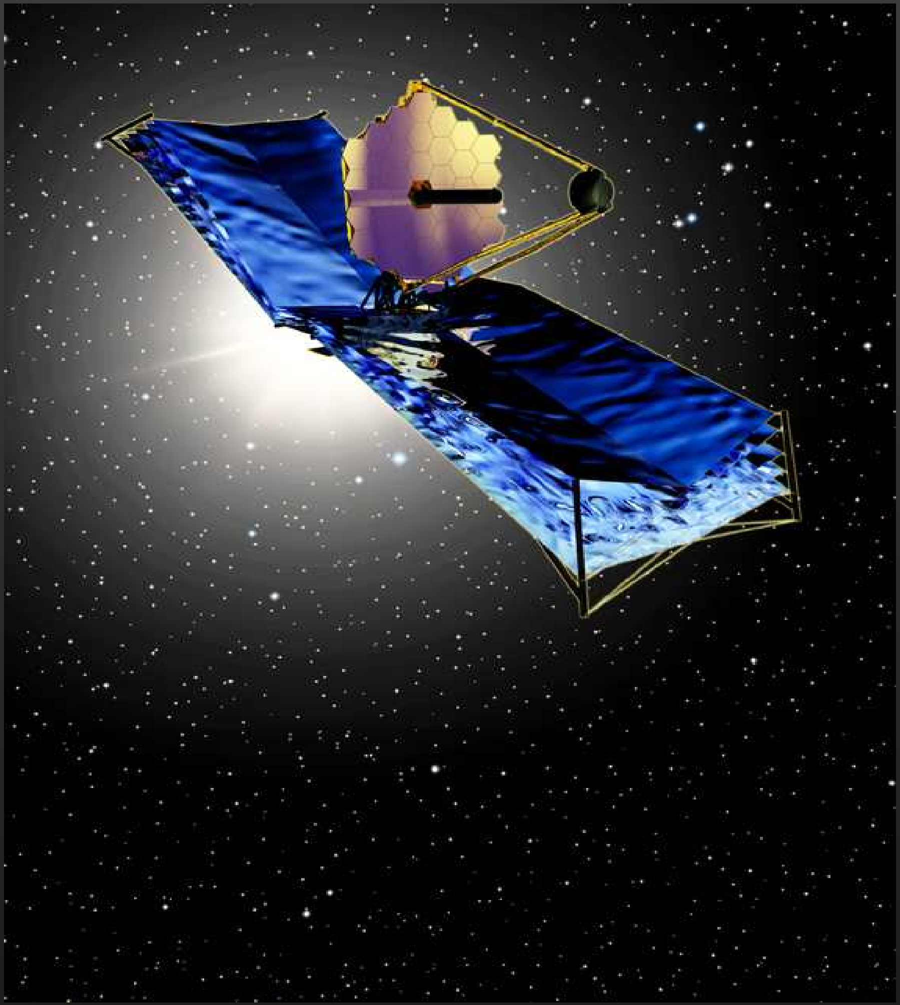


(Larson & Bromm, Scientific American, Dec. 2001)

- 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**

Character of Population III Star Formation

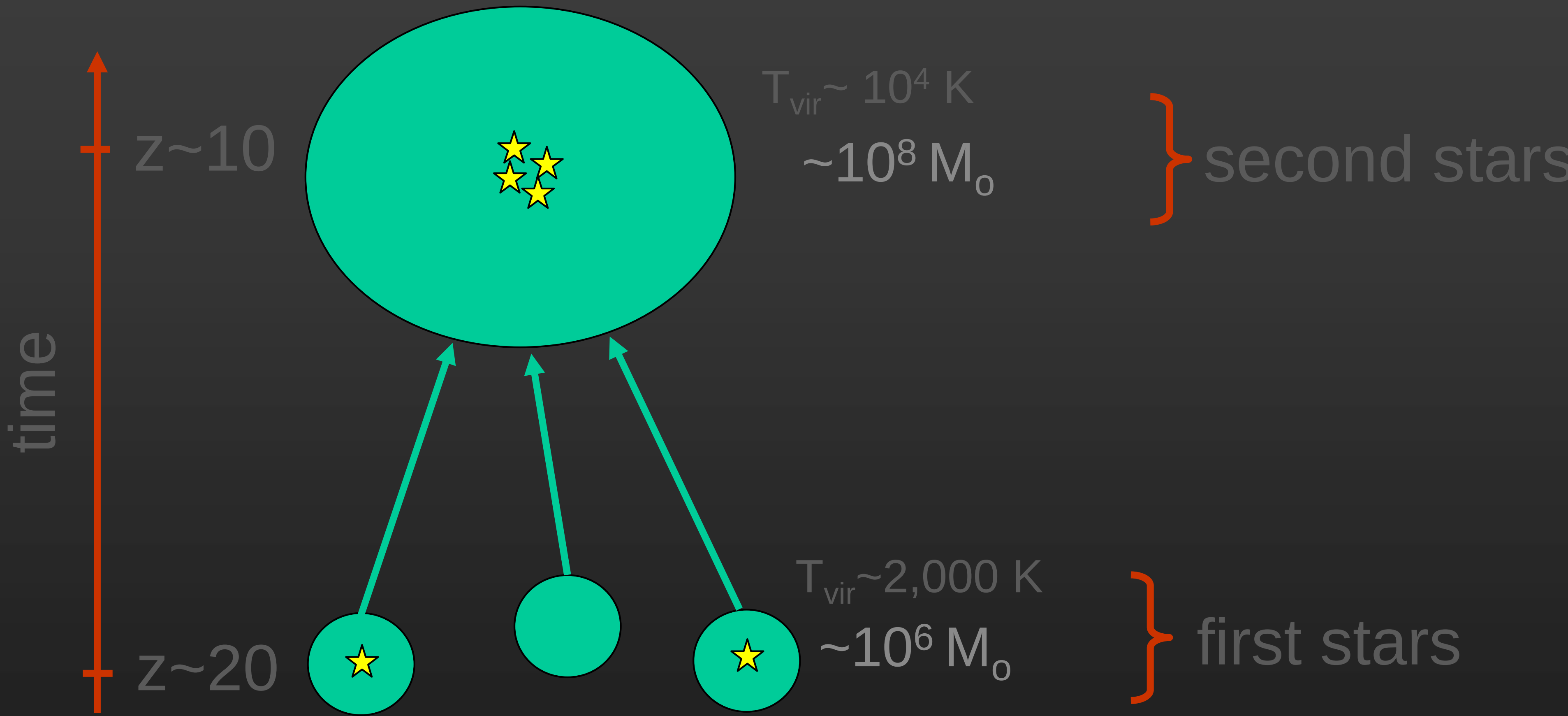
- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM cosmology

    → Well-posed problem

- First Stars = Cold dark matter (CDM)

  + atomic and molecular physics of H/D/He

Hierarchical (bottom-up) Structure Formation

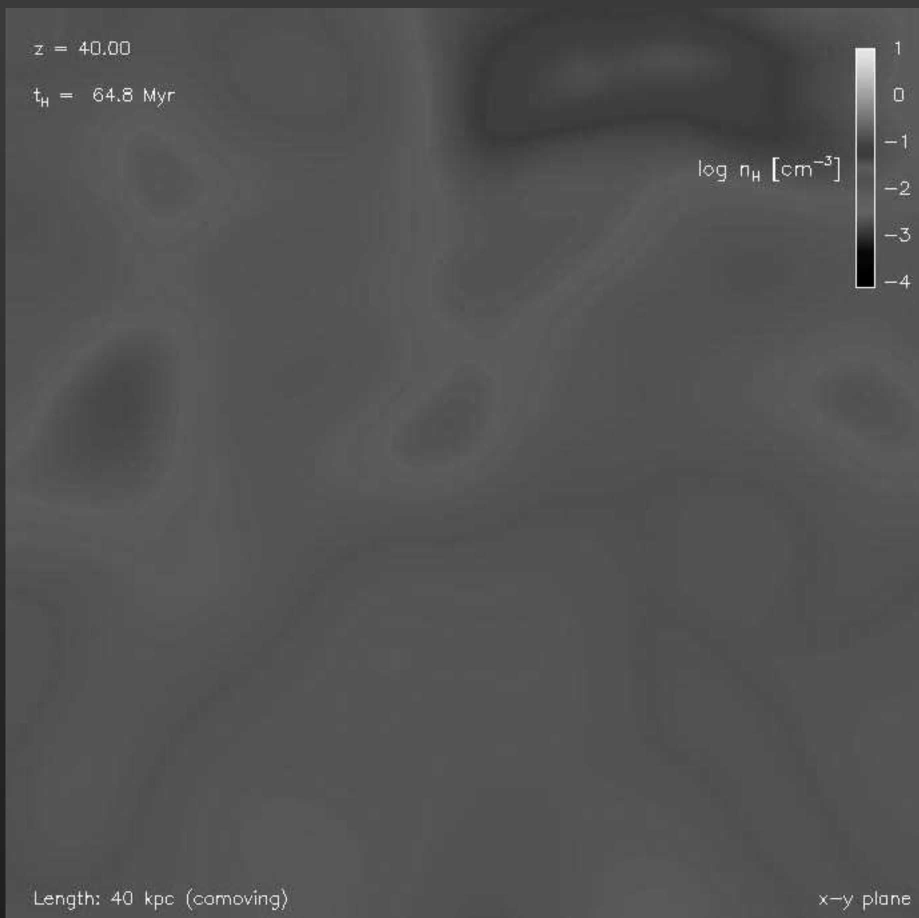


Cold Dark matter (CDM) halos

Hierarchical Structure Formation

(Greif, Johnson, Klessen & Bromm 2008, MNRAS, submitted; arXiv:0803.2237)

Density of Cosmic Gas



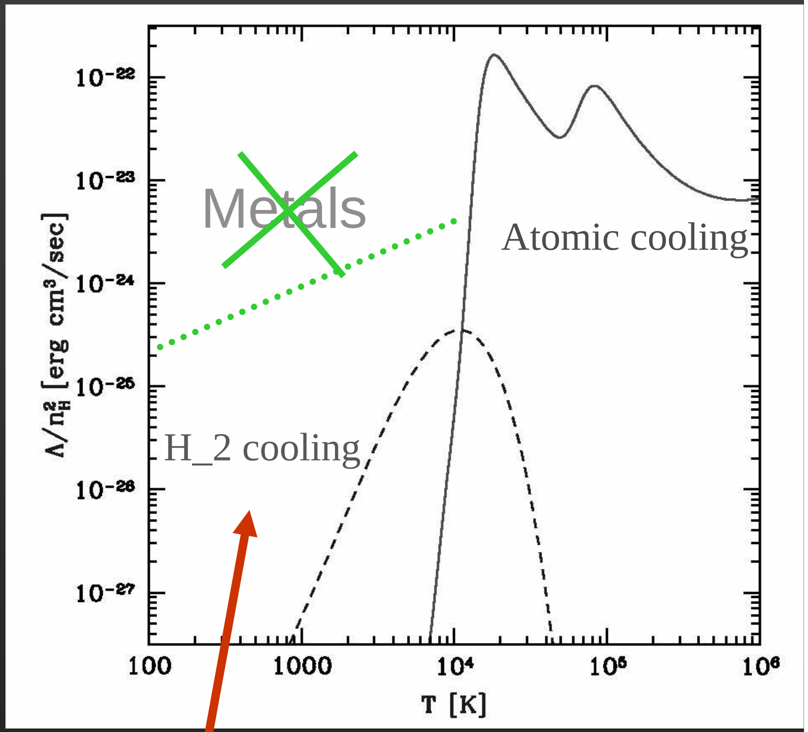
40 kpc (comoving)

Temperature of Cosmic Gas

40 kpc (comoving)

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



T_{vir} for Pop III

- H_2 chemistry
  - Cooling sensitive to H_2 abundance
  - H_2 formed in non-equilibrium
    - → Have to solve coupled set of rate equations

Region of Primordial Star Formation

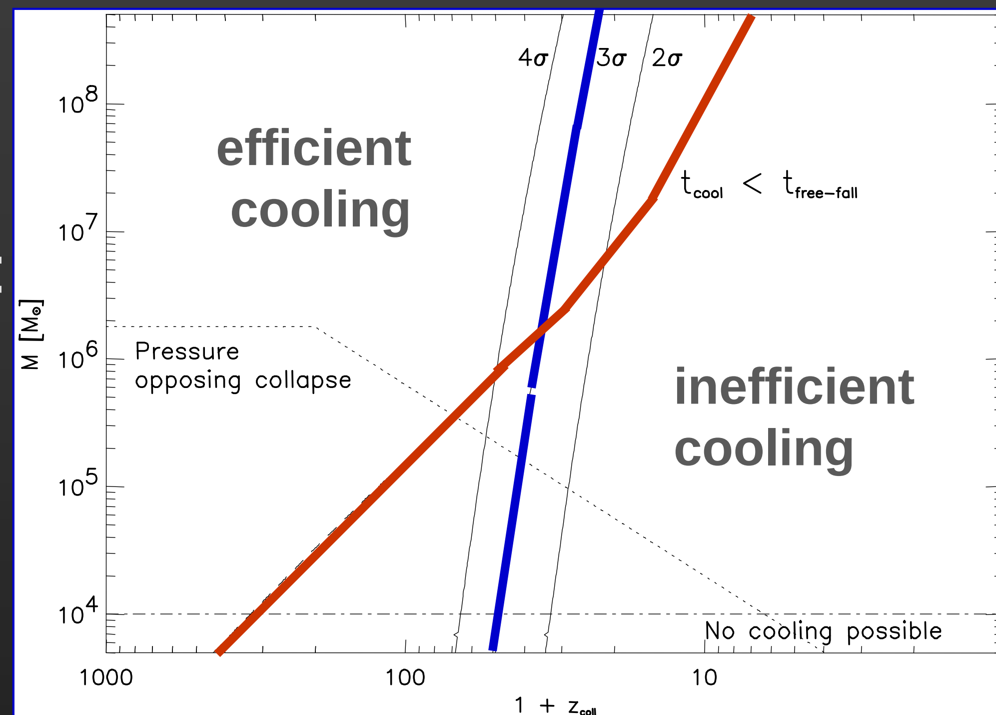
(e.g., Couchman & Rees 1986; Haiman et al. 1996; Tegmark et al. 1997)

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''

What happens inside primordial minihalos?

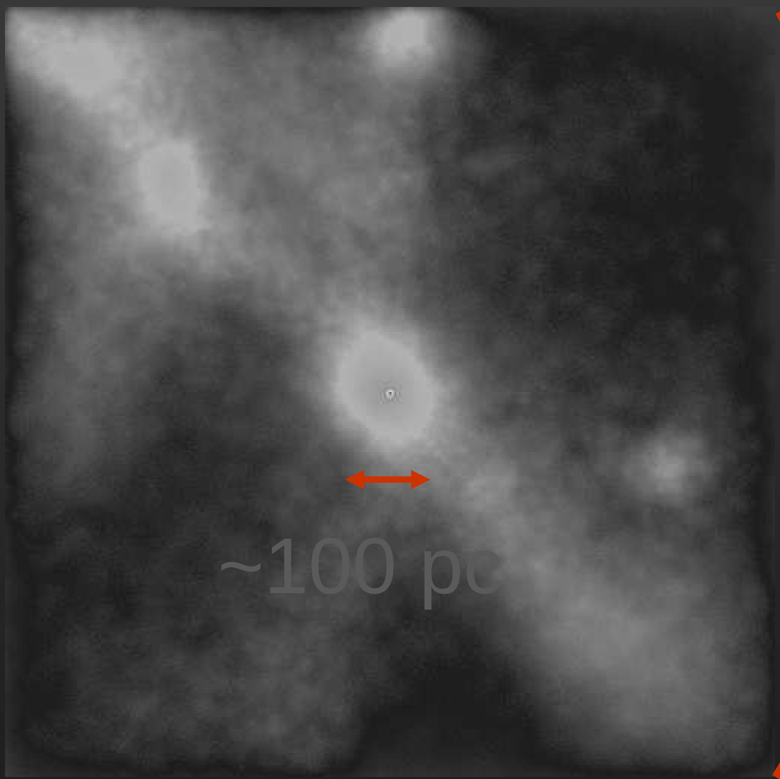
$M \sim 10^6 M_o$

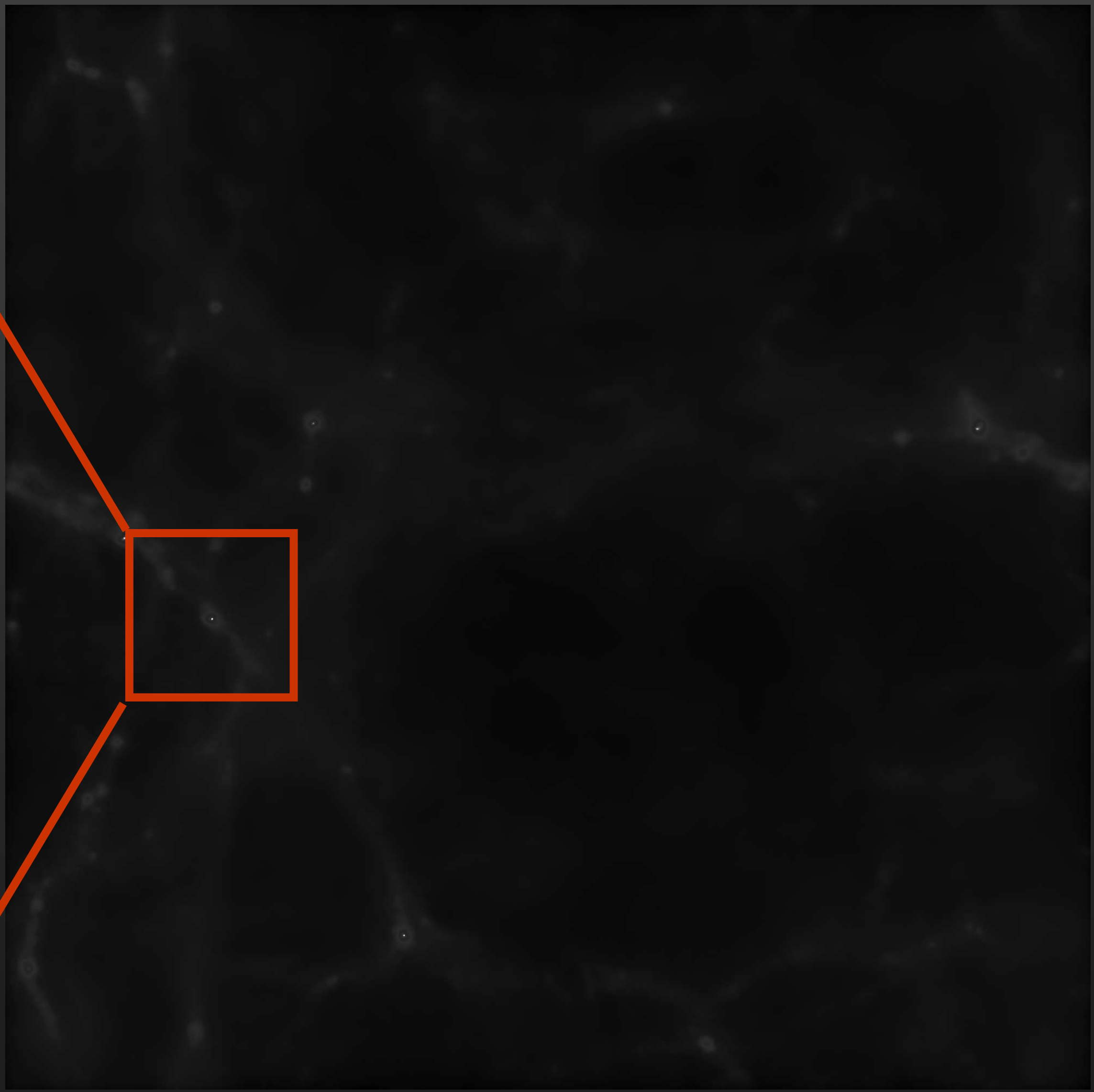
Single star

Multiple Stars

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

The First Star-Forming Region ("minihalos")



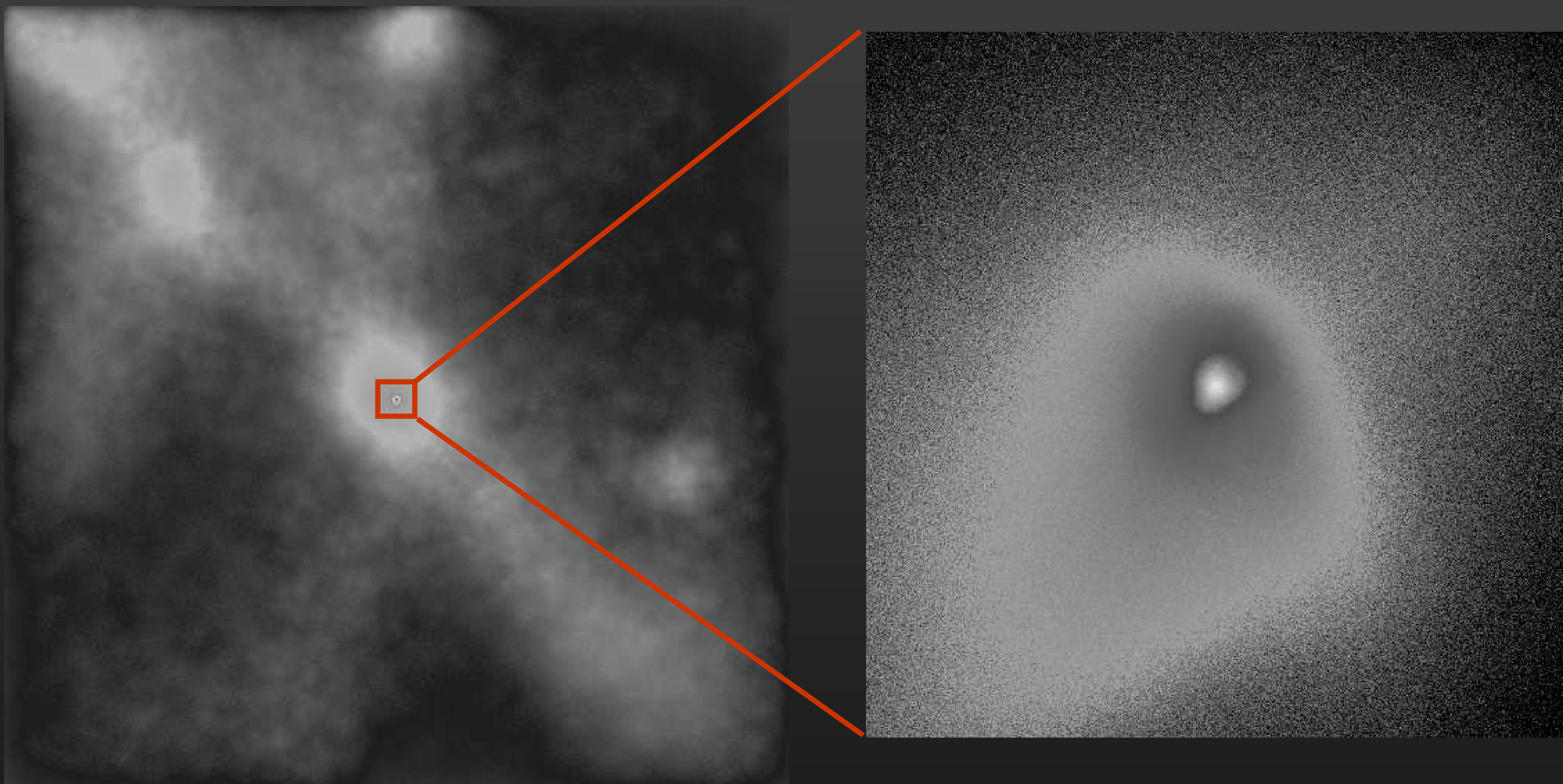


Formation of a Population III Star

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

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

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



~ 25 pc

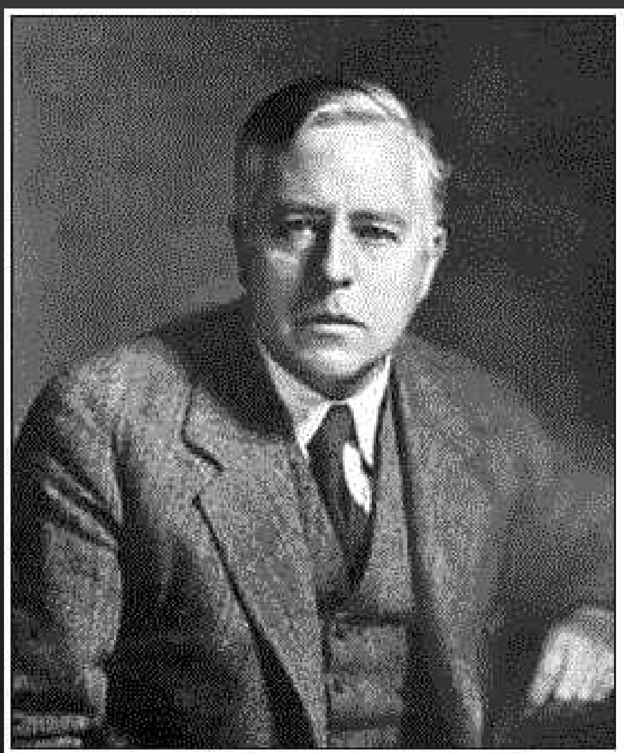
1 kpc

A Physical Explanation:

(Bromm, Coppi, & Larson 1999, 2002)

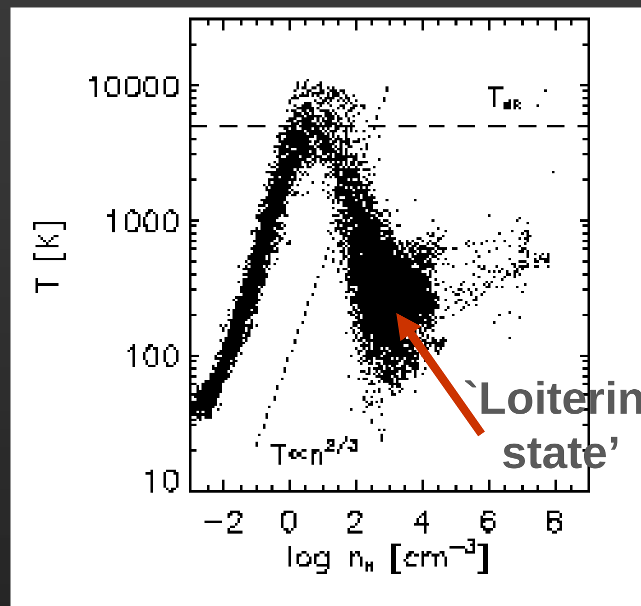
- Gravitational instability (Jeans 1902)
- Jeans mass:

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



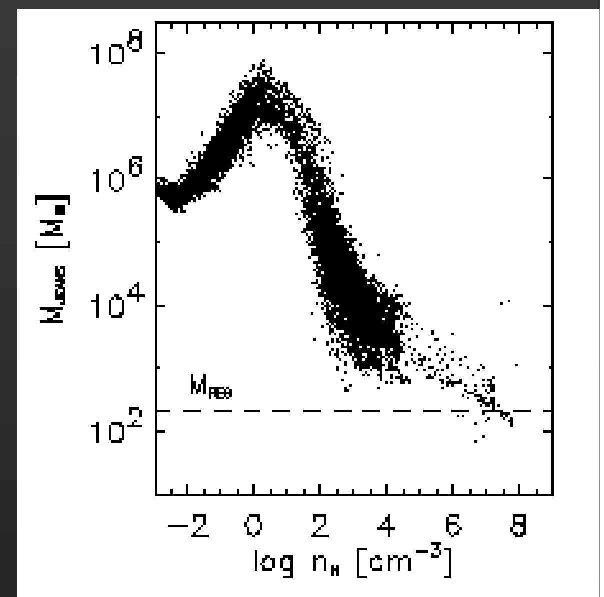
- Thermodynamics of primordial gas

T vs. n



`Loitering state'

M_J vs. n

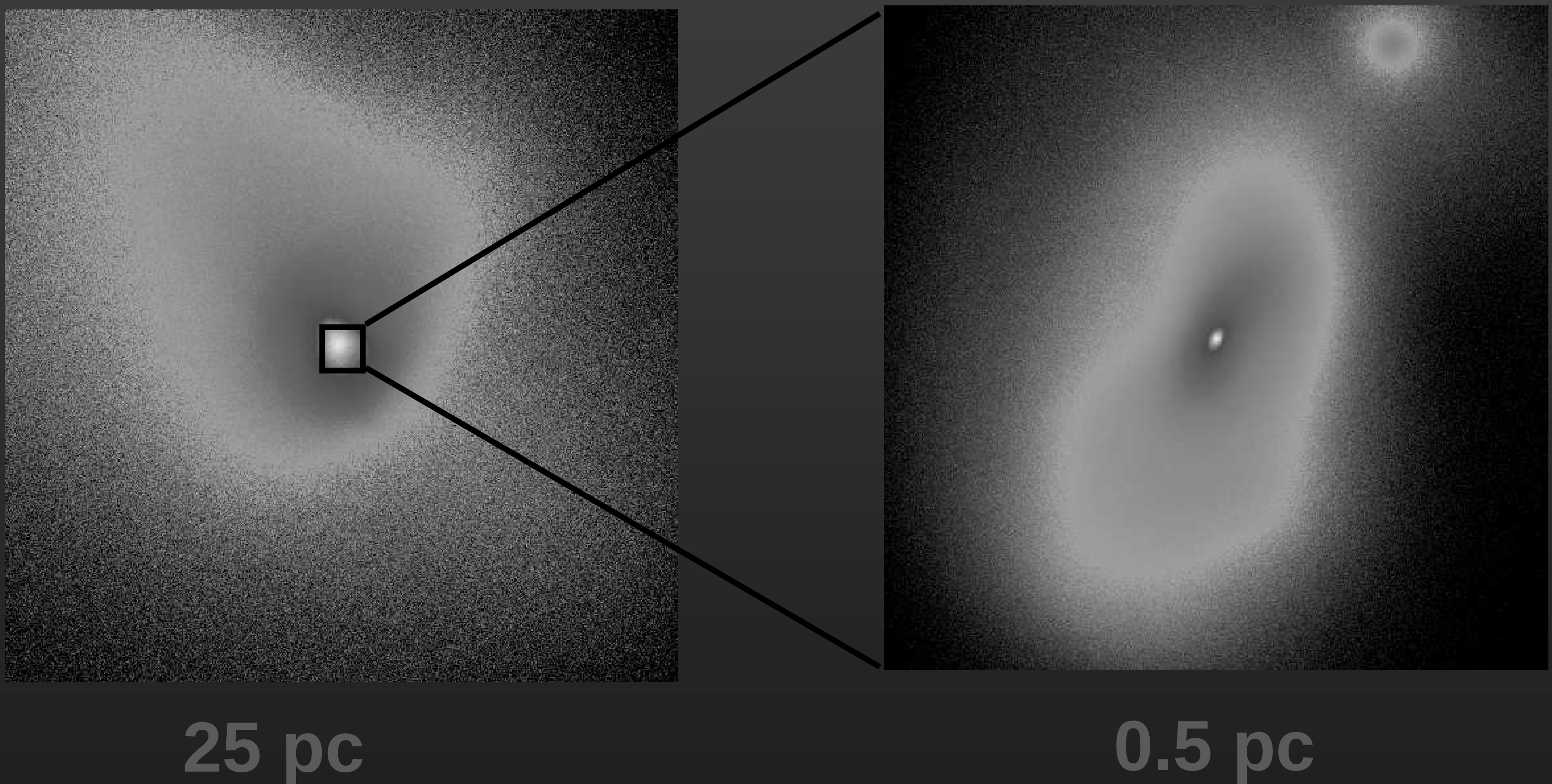


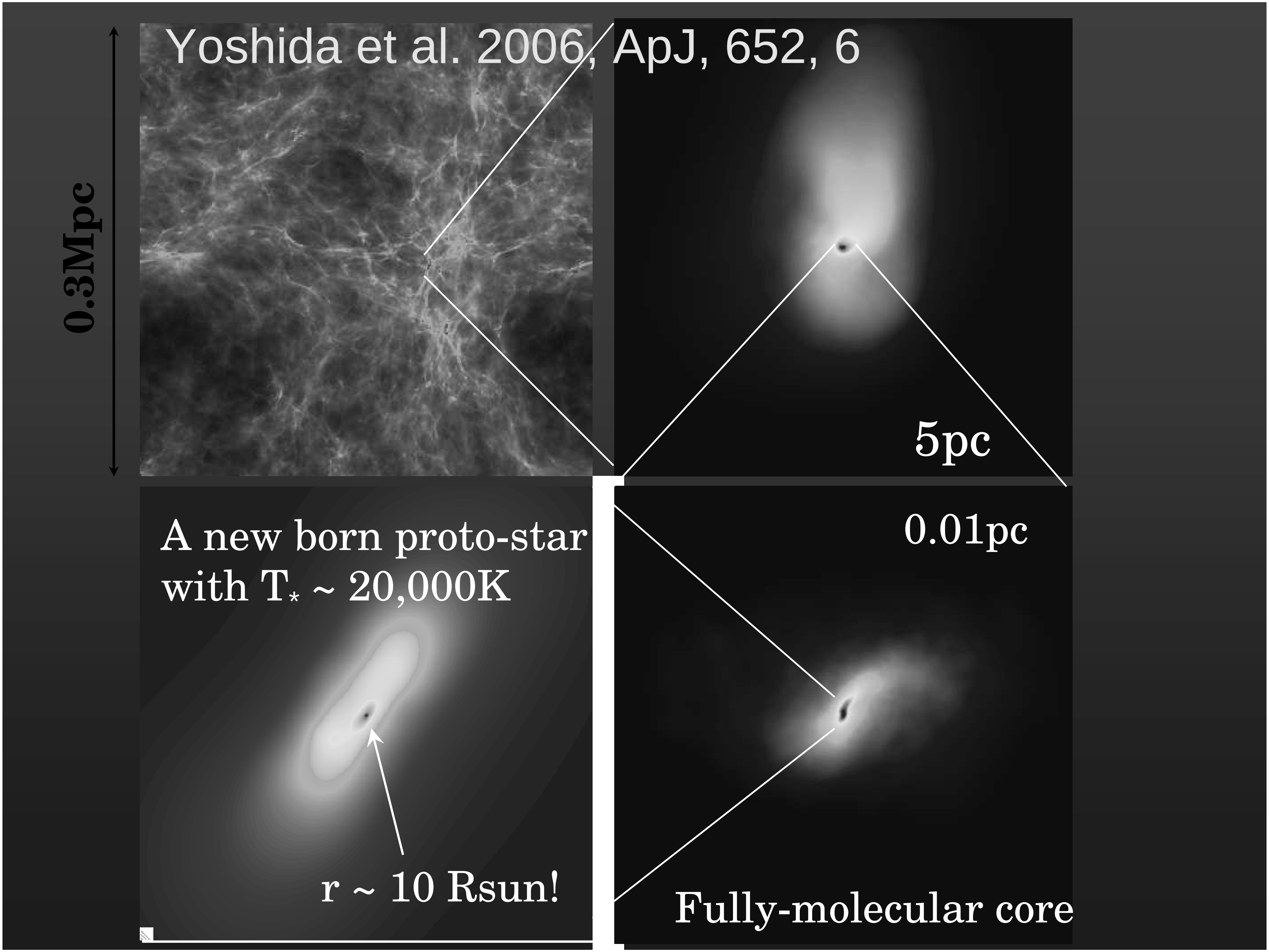
- Two characteristic numbers in microphysics of H_2 cooling:
  - $T_{min} \sim 200$ K
  - $n_{crit} \sim 10^3 - 10^4\ cm^{-3}$ (NLTE → LTE)
- Corresponding Jeans mass: $M_J \sim 10^3\ M_o$

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

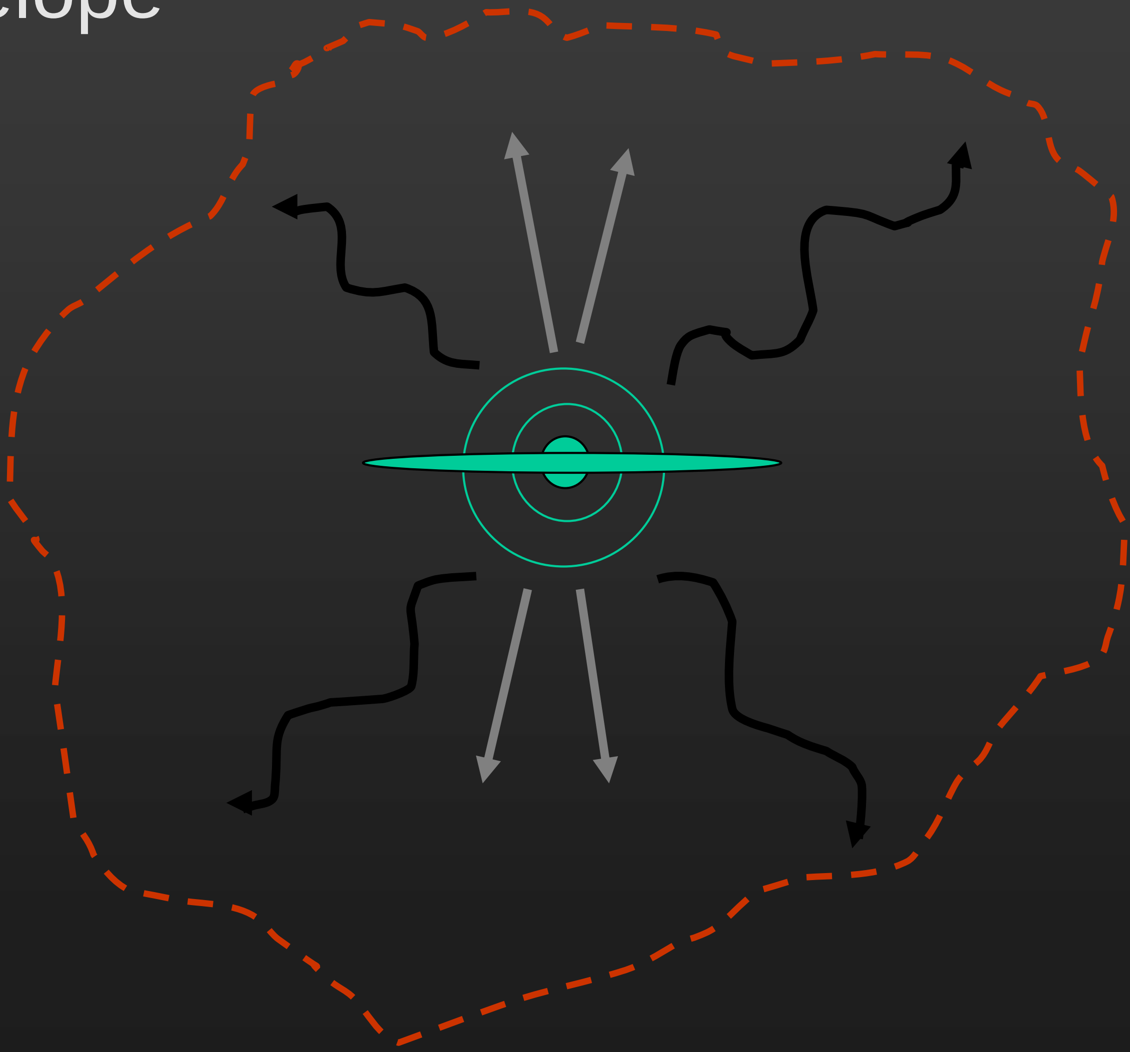
- Simulate further fate of the clump




Yoshida et al. 2006, ApJ, 652, 6
0.3Mpc
5pc
0.01pc
A new born proto-star
with T* ~ 20,000K
r ~ 10 Rsun!
Fully-molecular core

The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope



Clump:

$M \sim M_J$

The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope

- Development of core-envelope structure
  - Omukai & Nishi 1998 , Ripamonti et al. 2002

- $M_{core} \sim 10^{-3}\, M_o$ → very similar to Pop. I

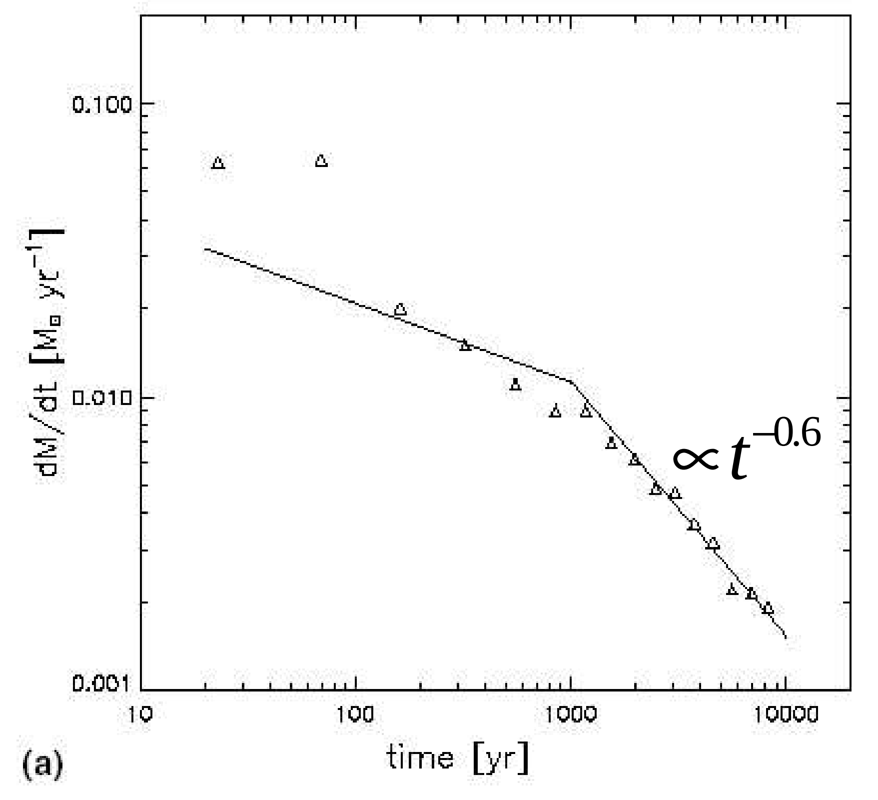
- Accretion onto core → very different!

- $dM/dt_{acc} \sim M_J / t_{ff} \sim T^{3/2}$ (Pop I: T ~ 10 K, Pop III: T ~ 300 K)

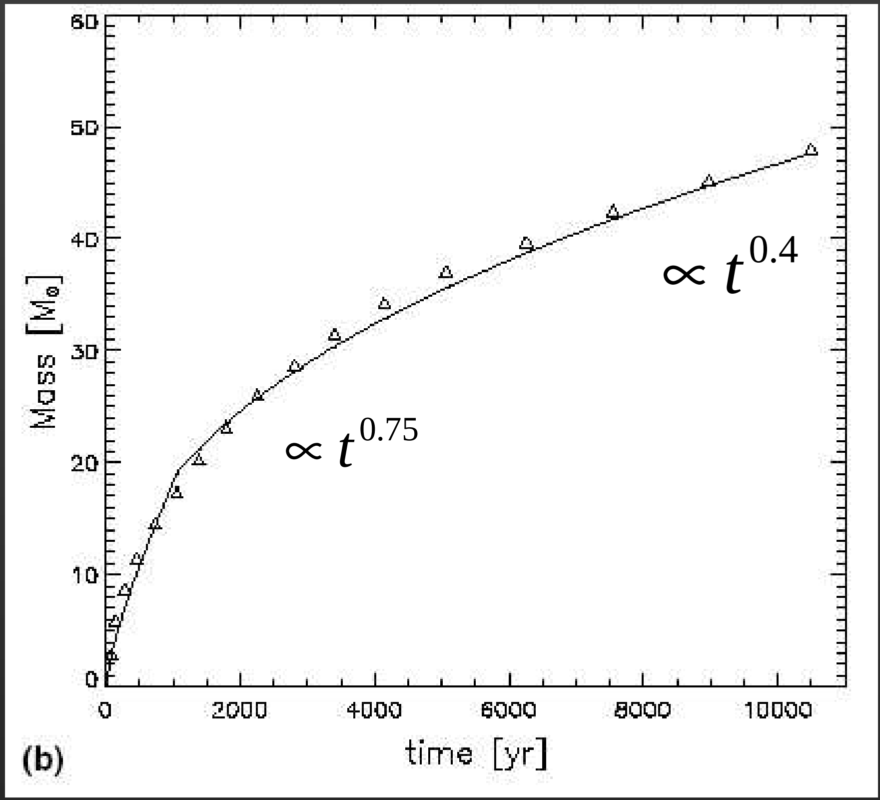
- Can the accretion be shut off in the absence of dust?

Accretion onto a Primordial Protostar

dM/dt vs. time



M vs. time



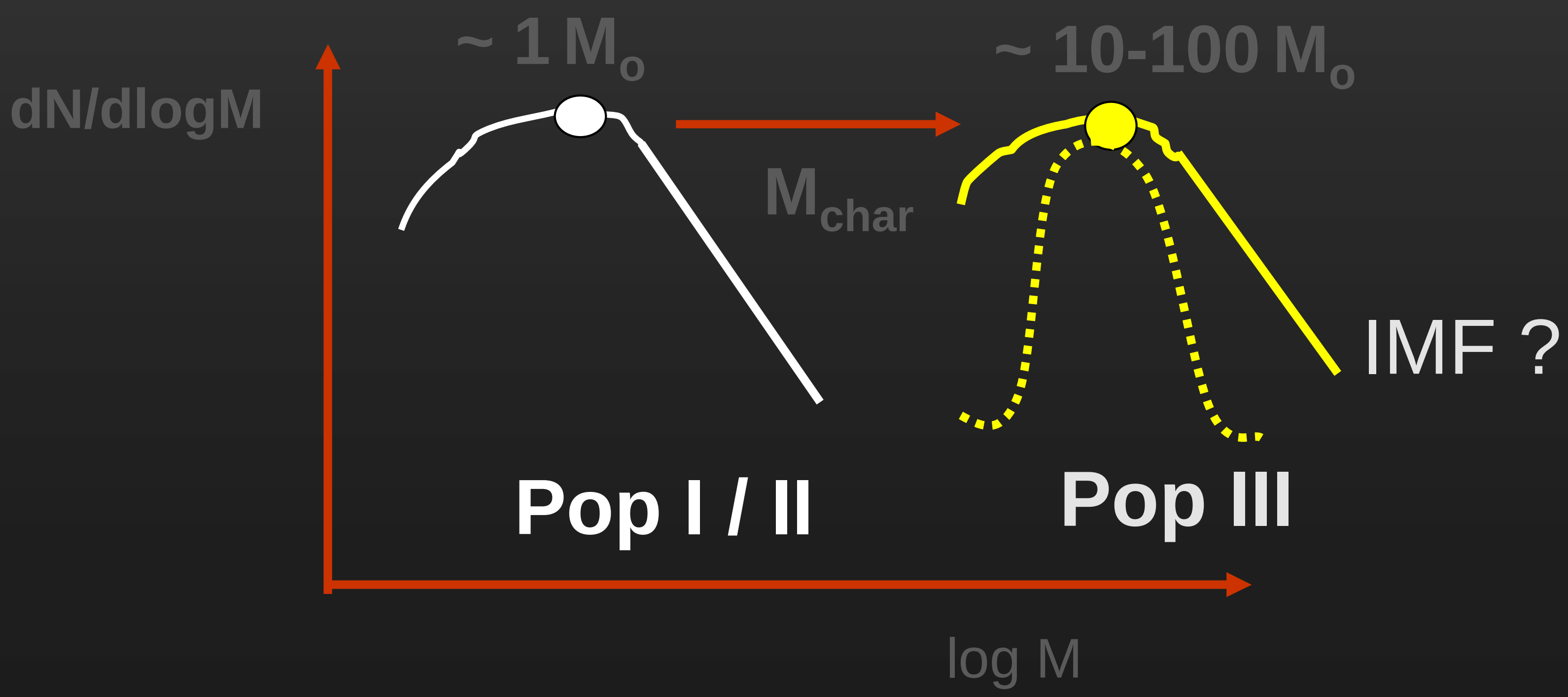
Upper limit: $M_*\ (t = 3\times 10^{6}\ \mathrm{yr}) \approx 500\ M_\odot$

-Similar range (~50 - ~ few 100 M_O) 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)**



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

à 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. 2007