Star Formation: Then and Now

KITP, Santa Barbara 2007

First Stars: Review of Theory

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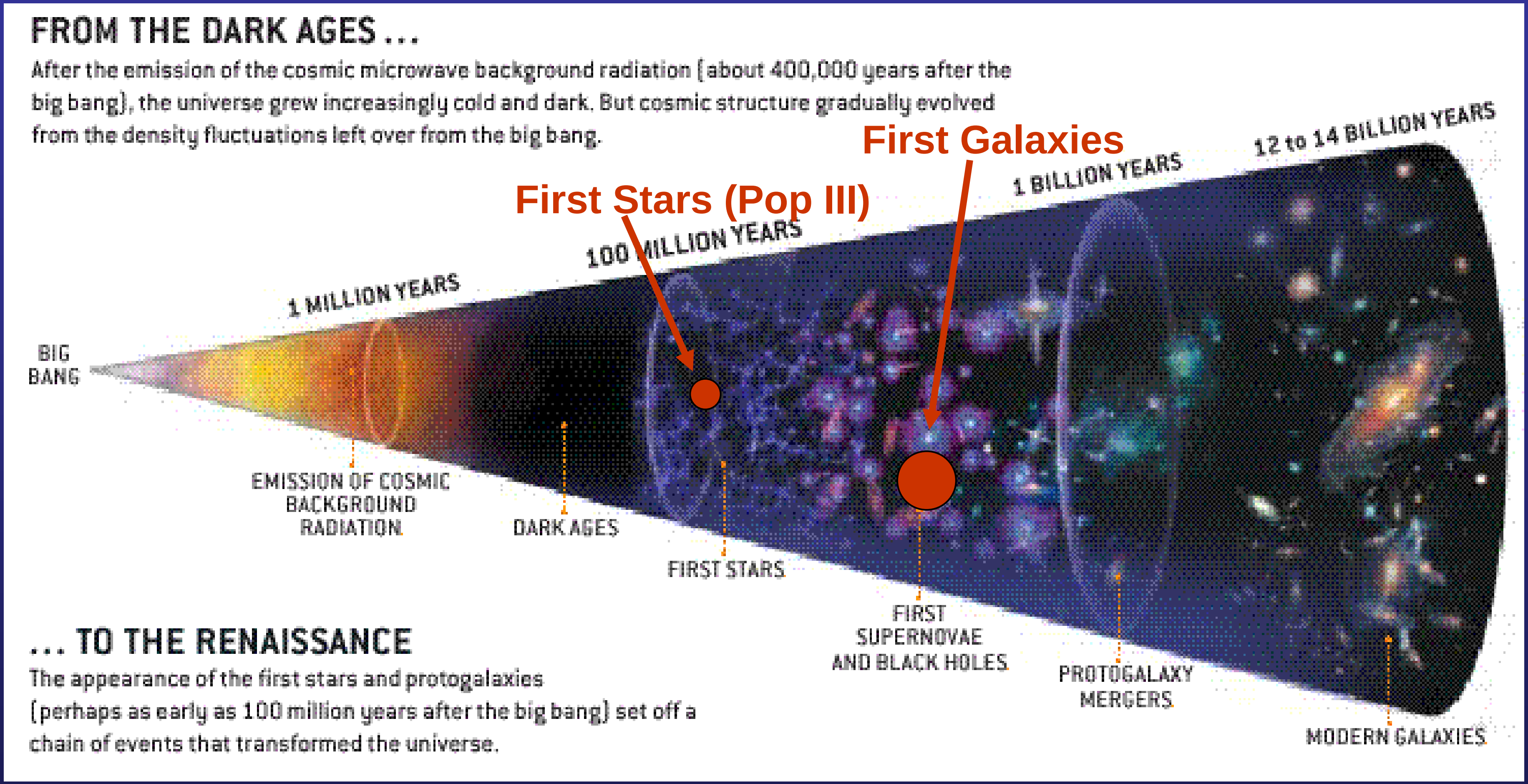
The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance



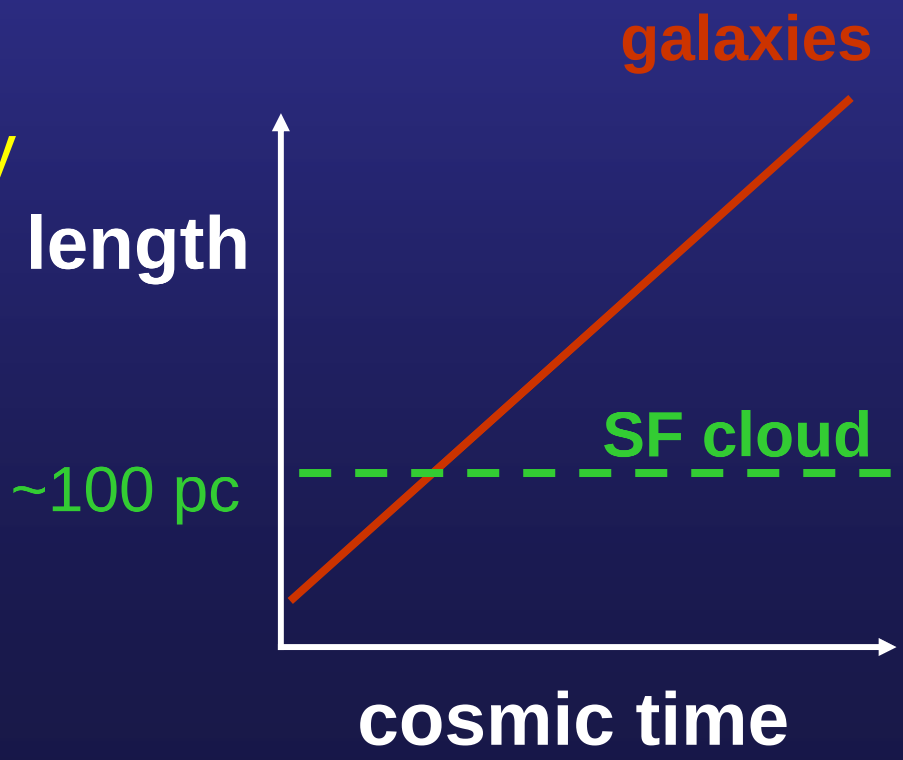
(Larson & Bromm, Scientific American, Dec. 2001)

- First Stars ⟶ Transition from Simplicity to Complexity

Why start with Population III ?

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

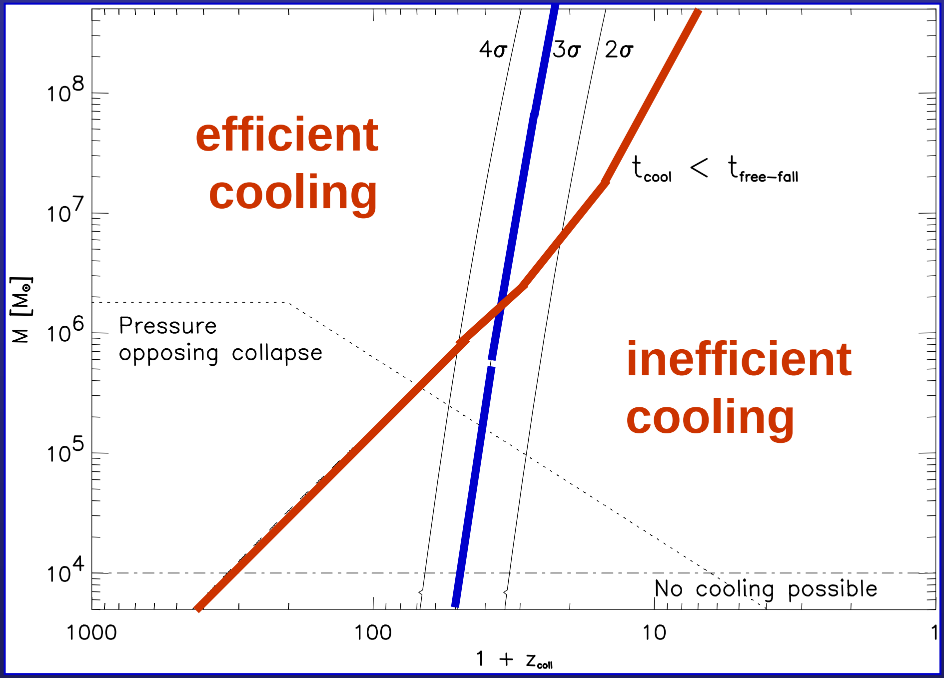
- Scales for star and galaxy formation overlap at earliest epochs



Region of Primordial Star Formation

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

Mass vs. redshift



- Gravitational Evolution of CDM

- Gas Microphysic:

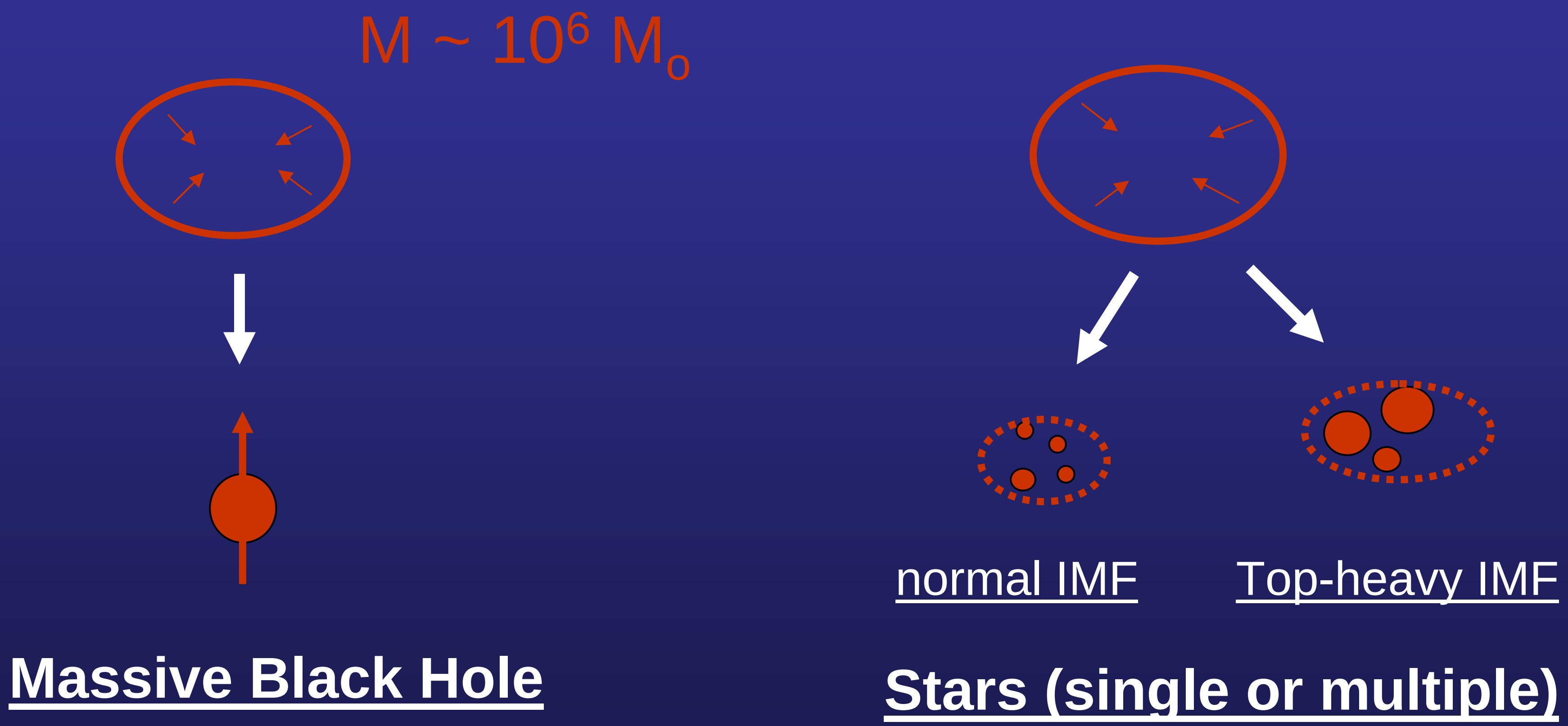
  - Can gas sufficiently cool?
  - $t_{cool} \lesssim t_{ff}$ (Rees-Ostriker)

- Collapse of First Luminous Objects expected:

  - at: $z_{coll} = 20 – 30$

  - with total mass: $M \sim 10^6\ M_o$

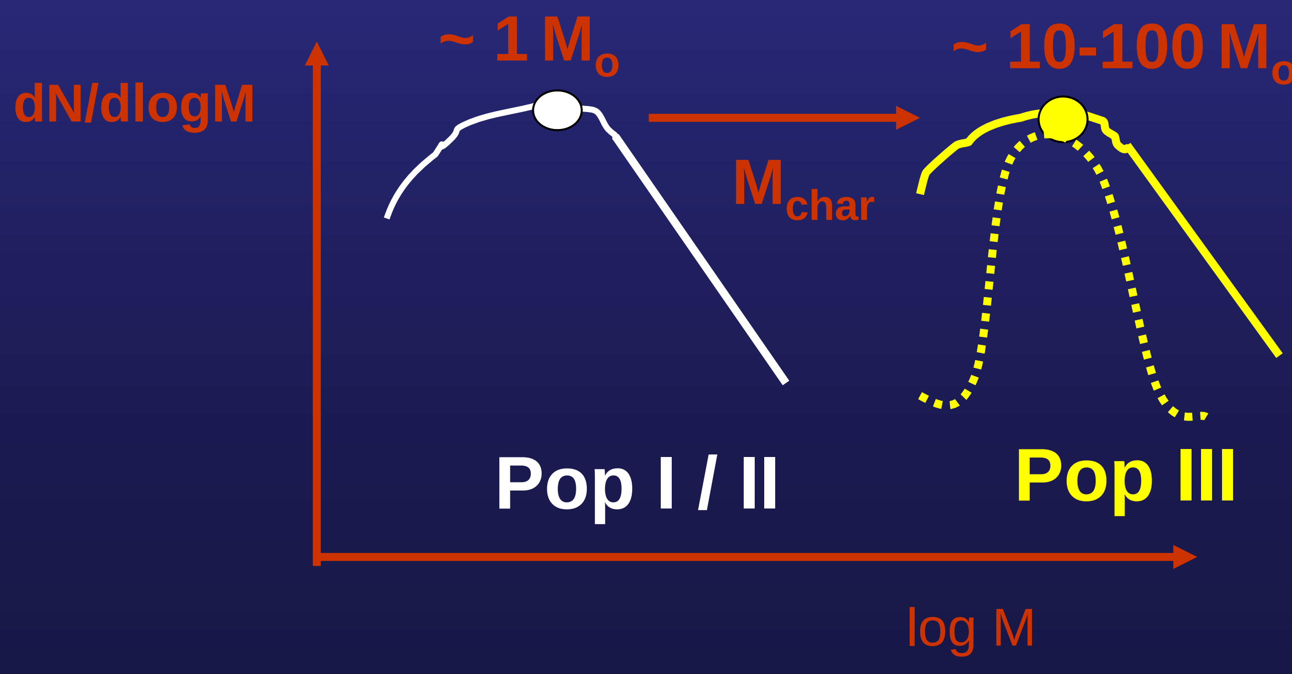
What happens inside primordial minihalos?



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

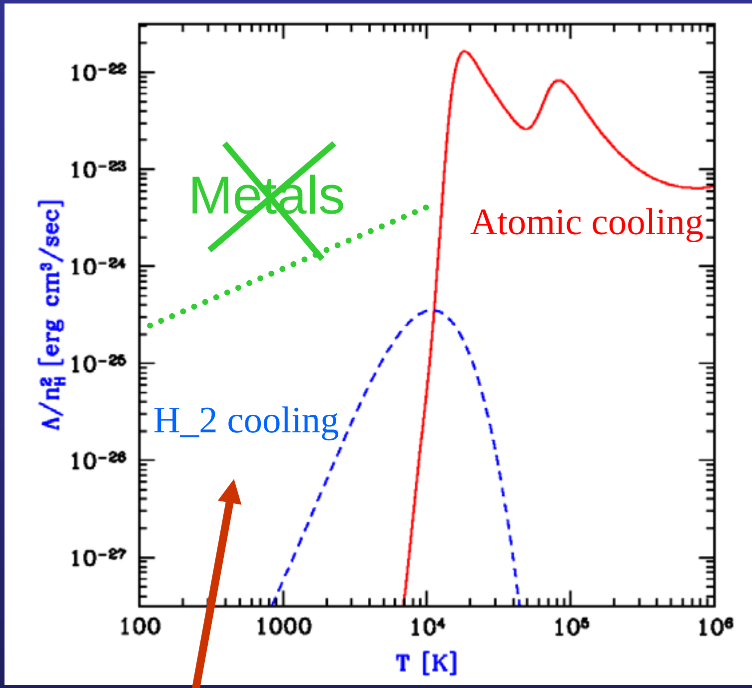
The First Stars: The "Standard" Model

- 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 IMF**



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

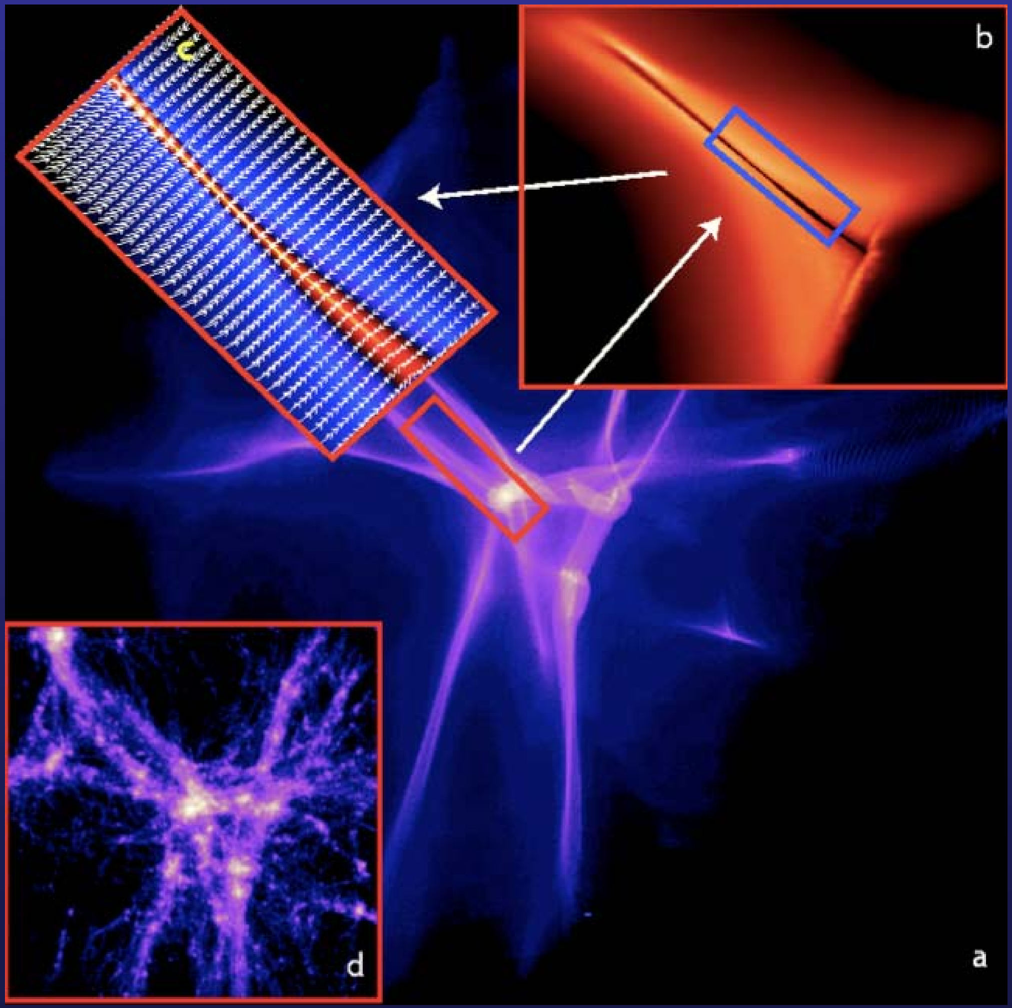


T_{vir} for Pop III

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

First Stars within WDM

Gao & Theuns 2007, to appear in *Science*



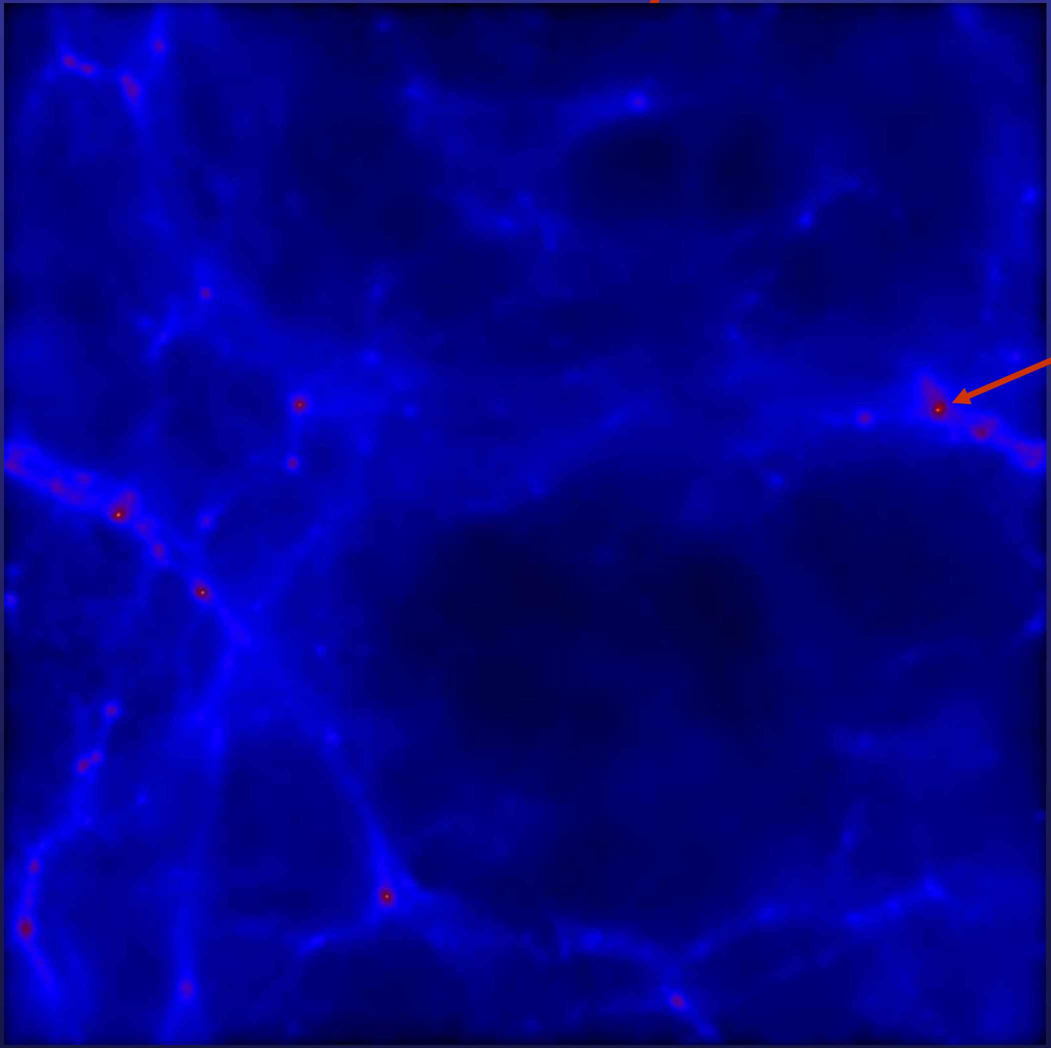
- Primordial gas first falls into filaments, not minihalos

Cosmological Initial Conditions

- Consider situation at **z = 20**

Gas density

~ 7 kpc

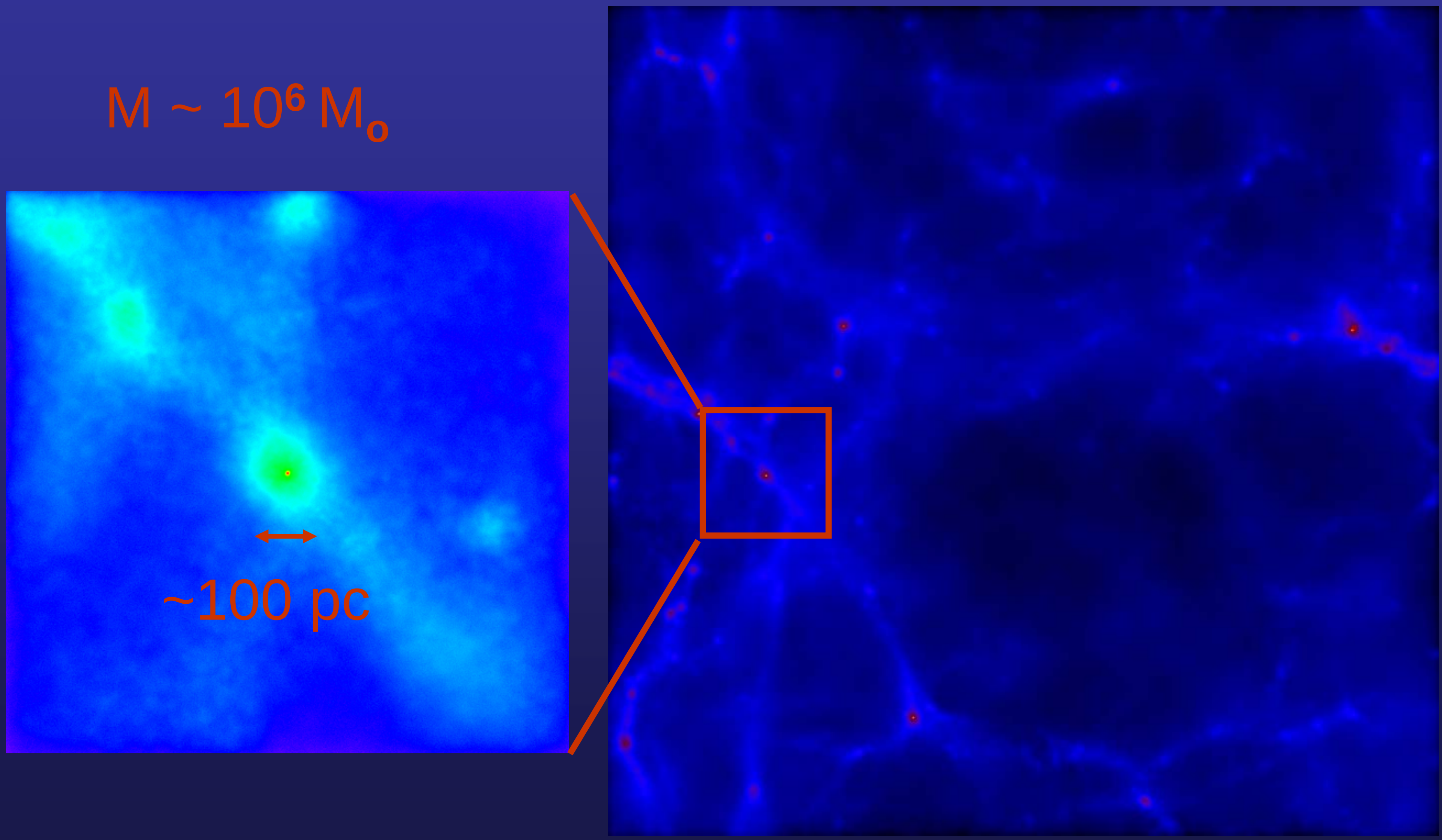


Primordial Object

The First Star-Forming Region ("minihalos")

projected gas density at z=20

$M \sim 10^6 M_o$



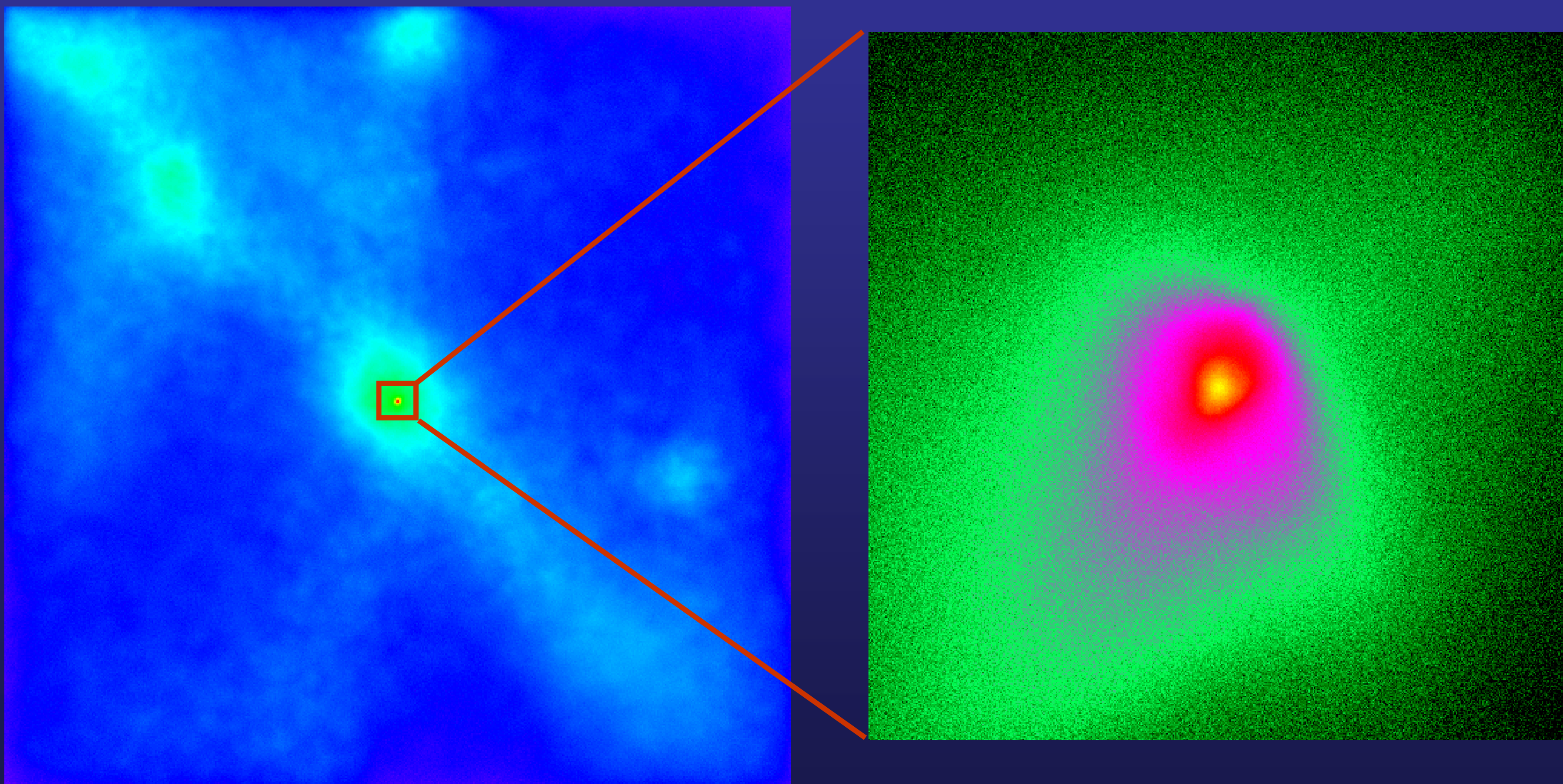
~ 7 kpc (proper)

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

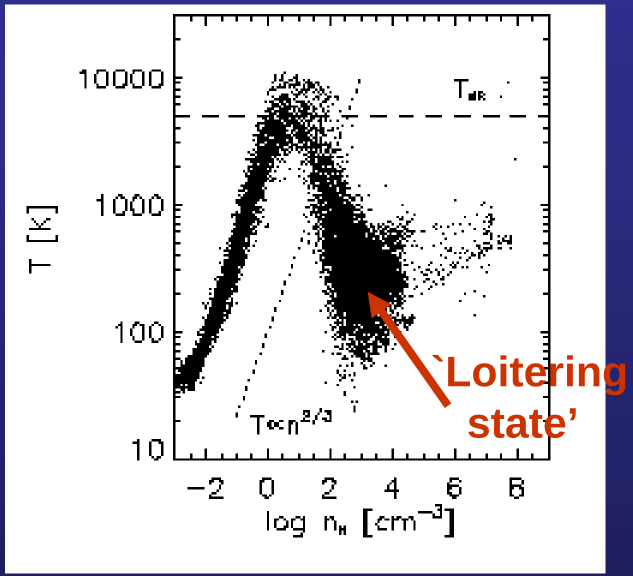
1 kpc

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

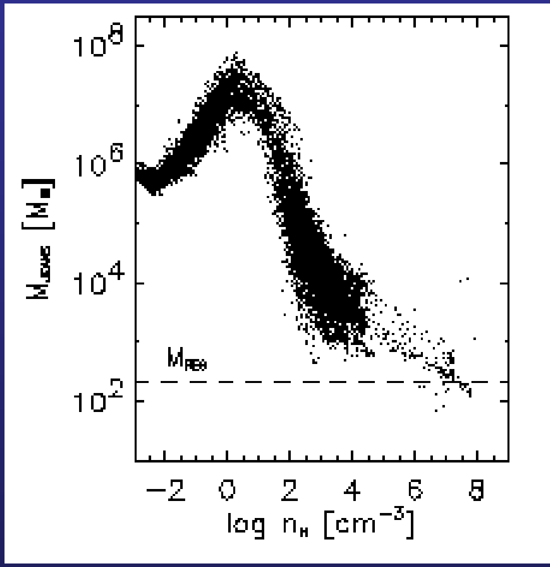
- Gravitational instability (Jeans 1902)
- Jeans mass: $M_J \sim T^{1.5}\, n^{-0.5}$

- Thermodynamics of primordial gas

T vs. n



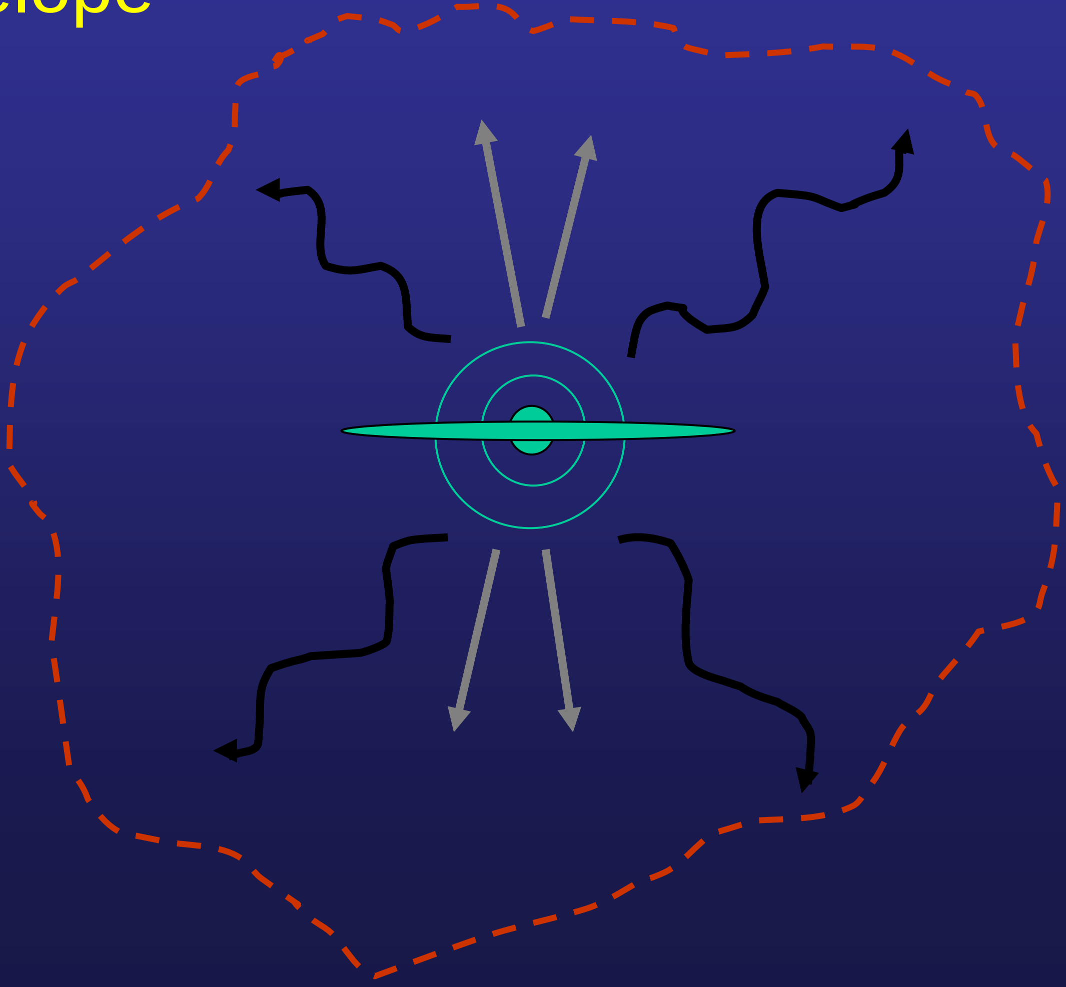
M_J vs. n



- 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: $M_J \sim 10^3\, M_o$

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!

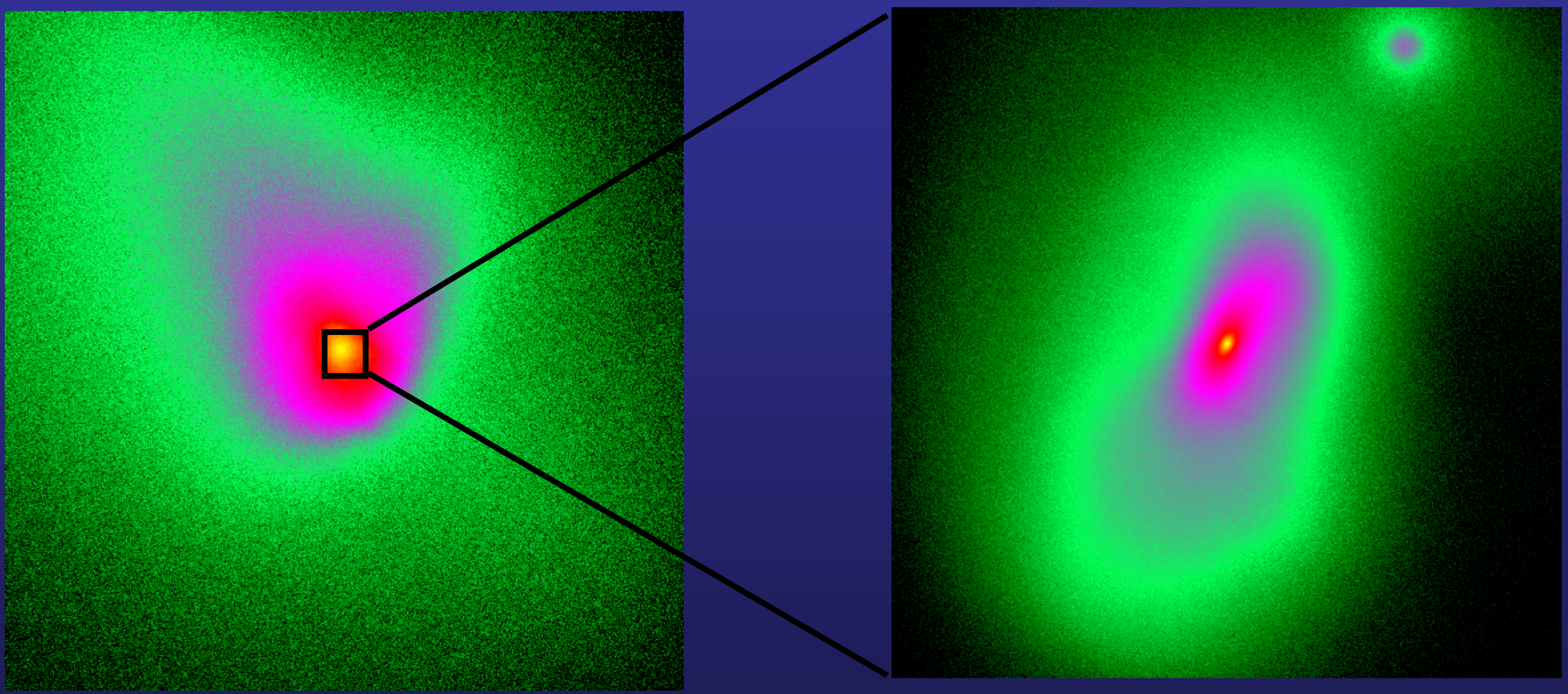
- $dM/dt_{acc} \sim M_J / t_{ff} \sim T^{3/2}$ (Pop I: T ~ 10 K, Pop III: T ~ 300 K)

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

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

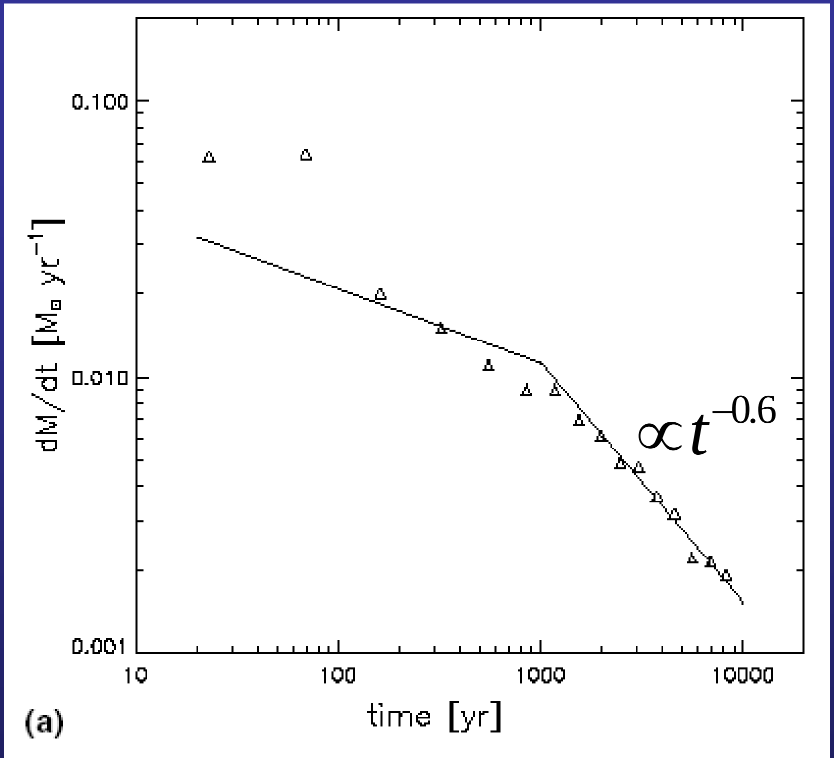
- Simulate further fate of the clump



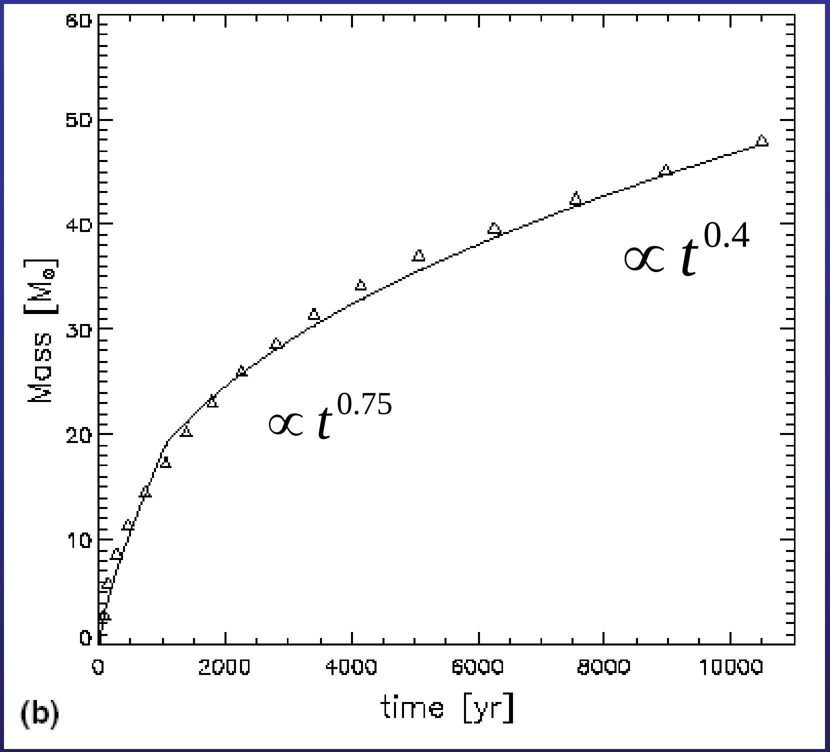
25 pc　　　　0.5 pc

Accretion onto a Primordial Protostar

dM/dt vs. time



M vs. time

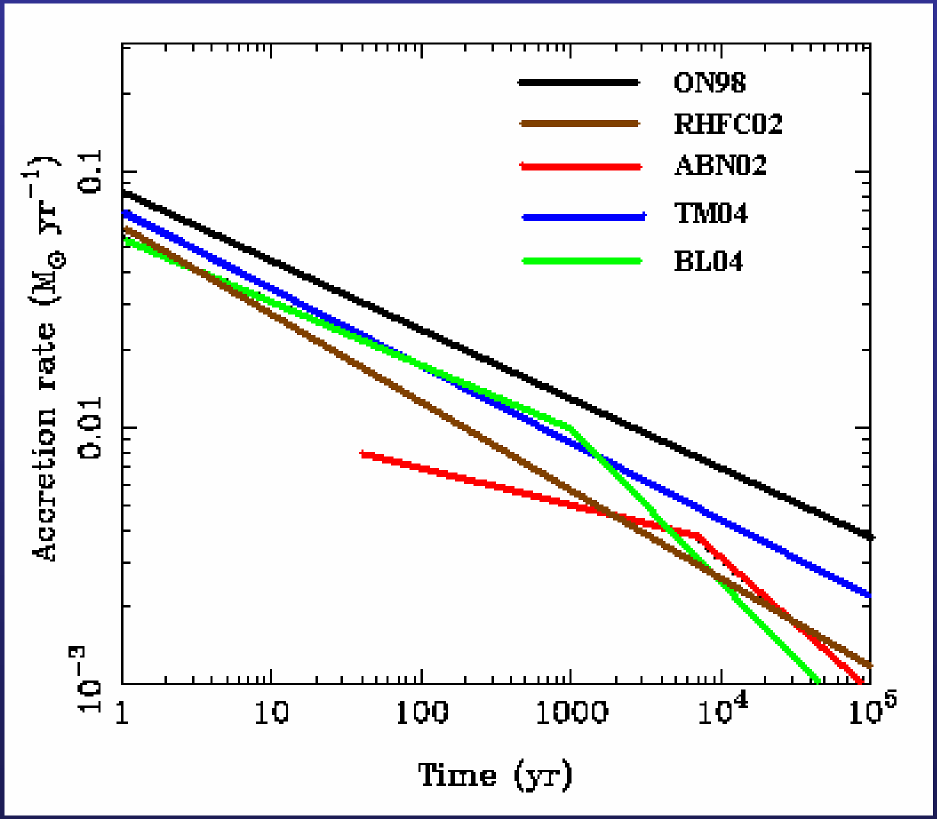


Upper limit: $M_* \, (t = 3 \times 10^6 \, \mathrm{yr}) \approx 500 \, M_\odot$

-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)

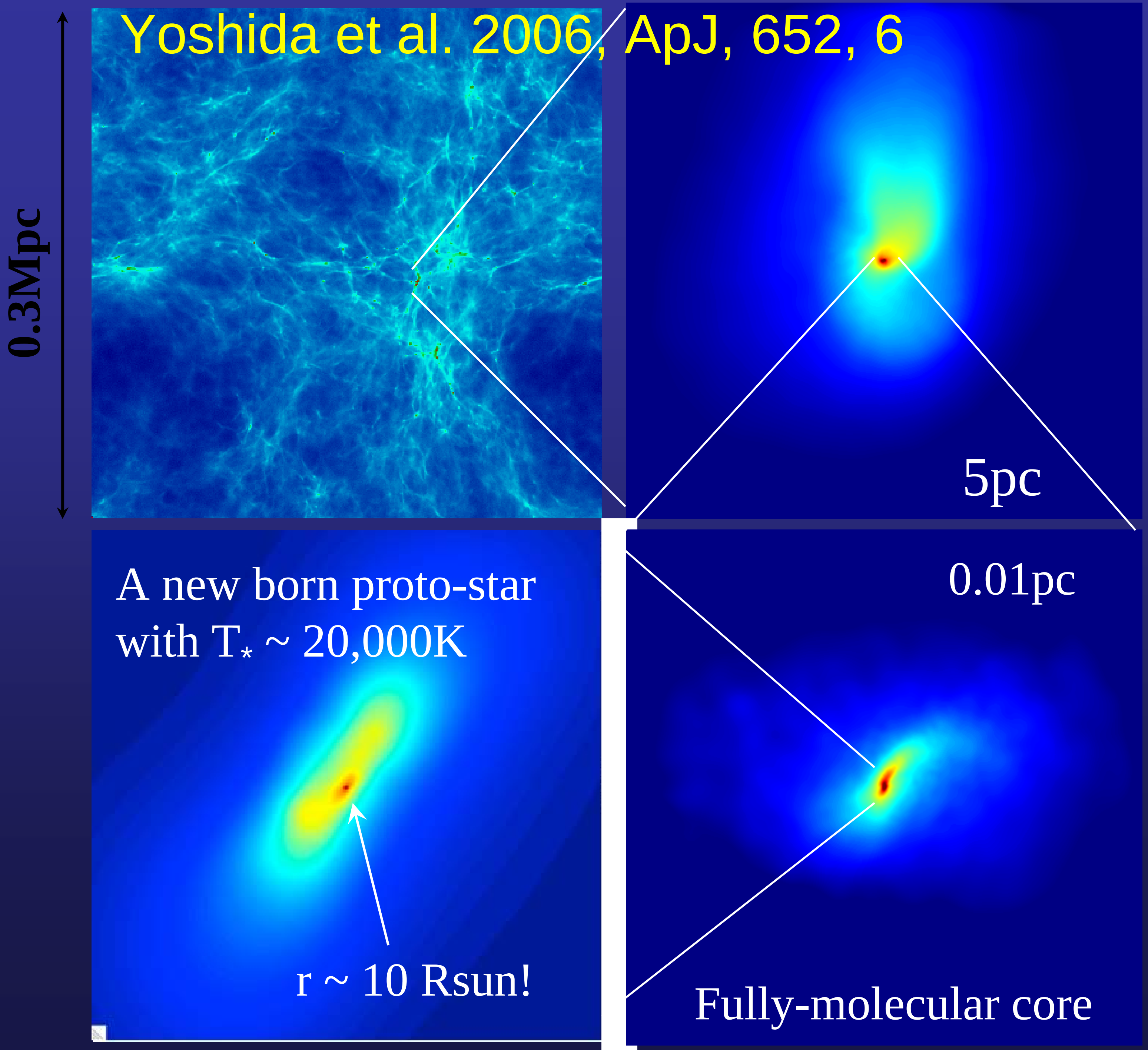
Protostellar Accretion Rates



Glover (2005)

Several groups found similar accretion rates.

- The rate is very high $\sim 0.01 M_{sun}/yr$ because of high prestellar temperature ~300 K ($c.f. 10^{-6}$-$10^{-5} M_{sun}/yr$ for the present-day case)
- The rate decreases with time.


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

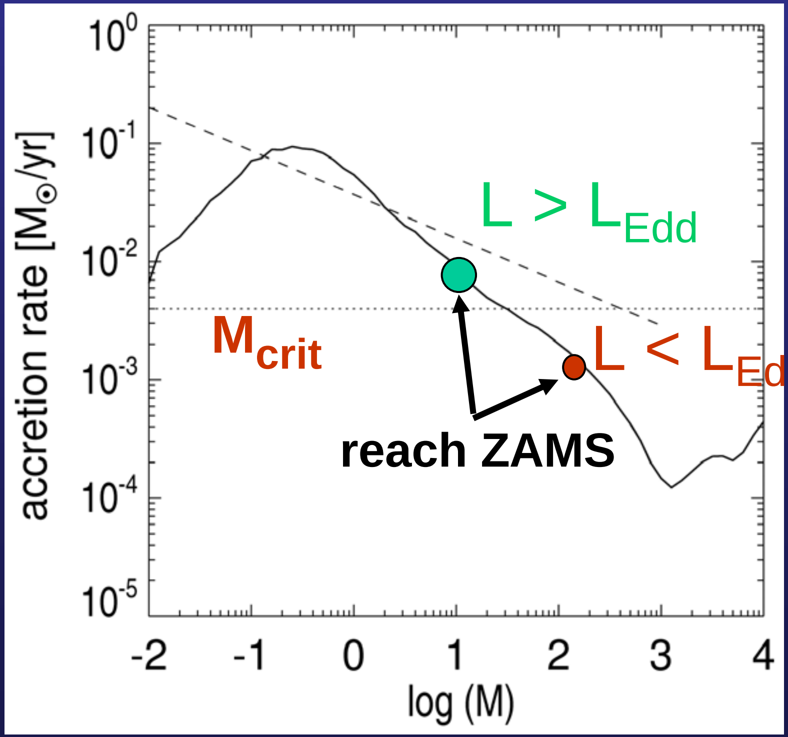
Protostellar Collapse: Mass accretion

(Yoshida et al. 2006, ApJ, 652, 6)

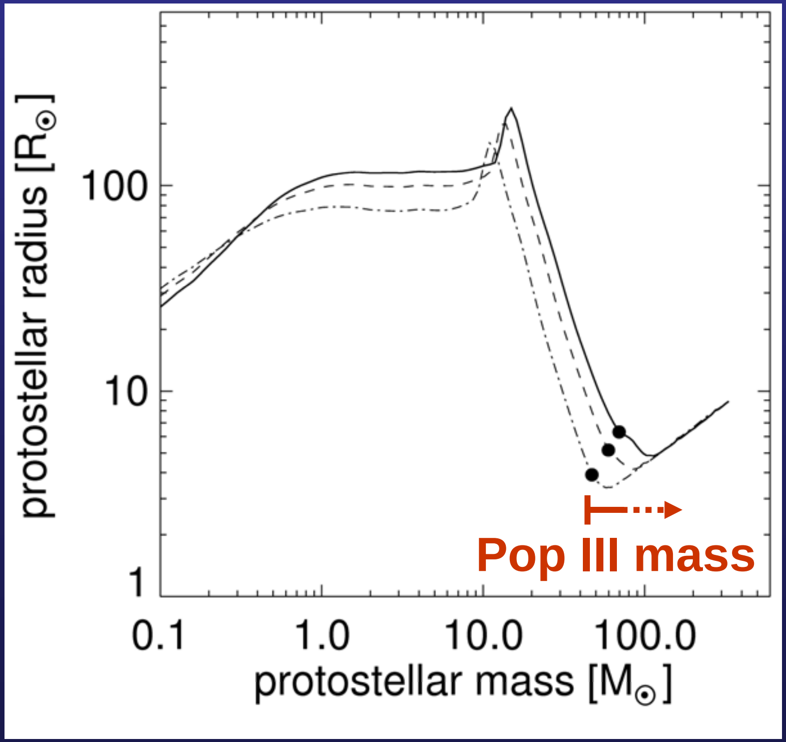
- For continued accretion, need: $L = L_* + L_{acc} < L_{Edd}$

  $\rightarrow M_{crit} \sim 5 \times 10^{-3}\, M_\odot\, yr^{-1}$

Accretion rate vs. mass



Radius vs. mass

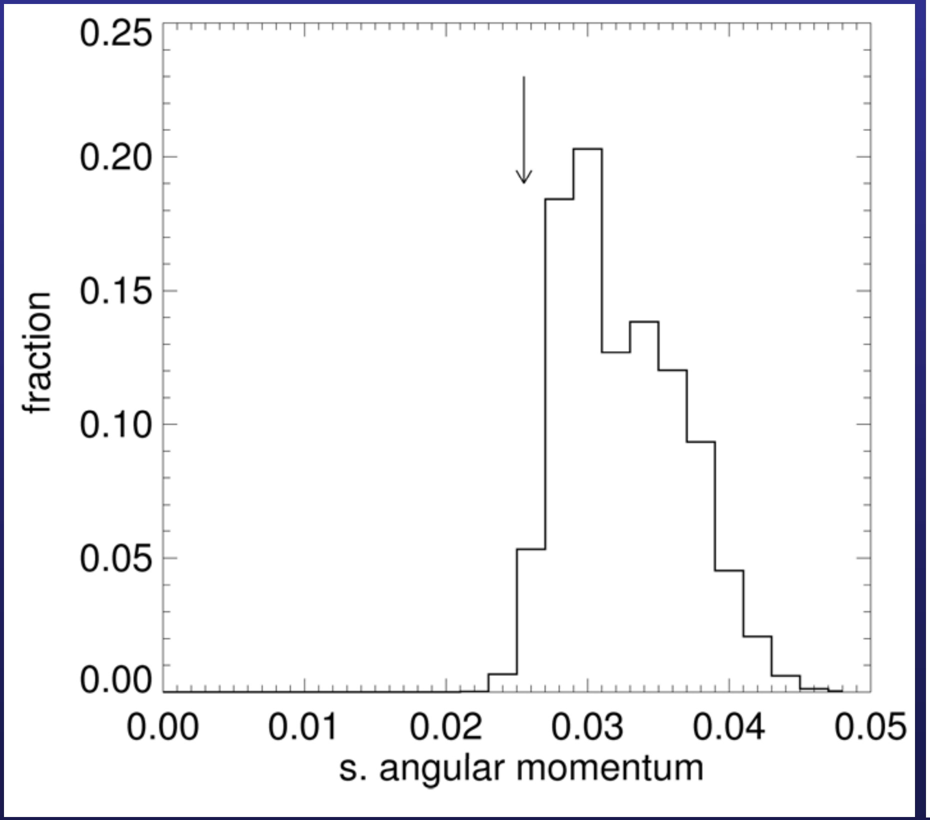


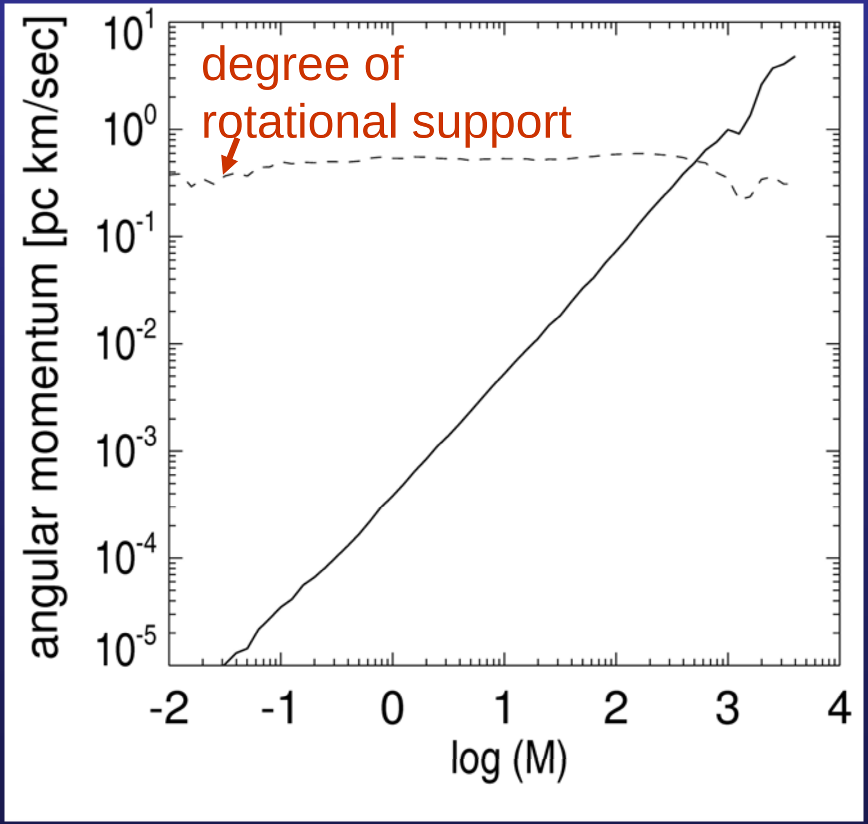
$\rightarrow$ See also: Tan & McKee: ~ 30 – 100 $M_\odot$

Protostellar Collapse: Angular Momentum

(Yoshida et al. 2006, ApJ, 652, 6)

- Lowest specific angular momentum gas collapses first!





Pre-collapse

Post-collapse

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!

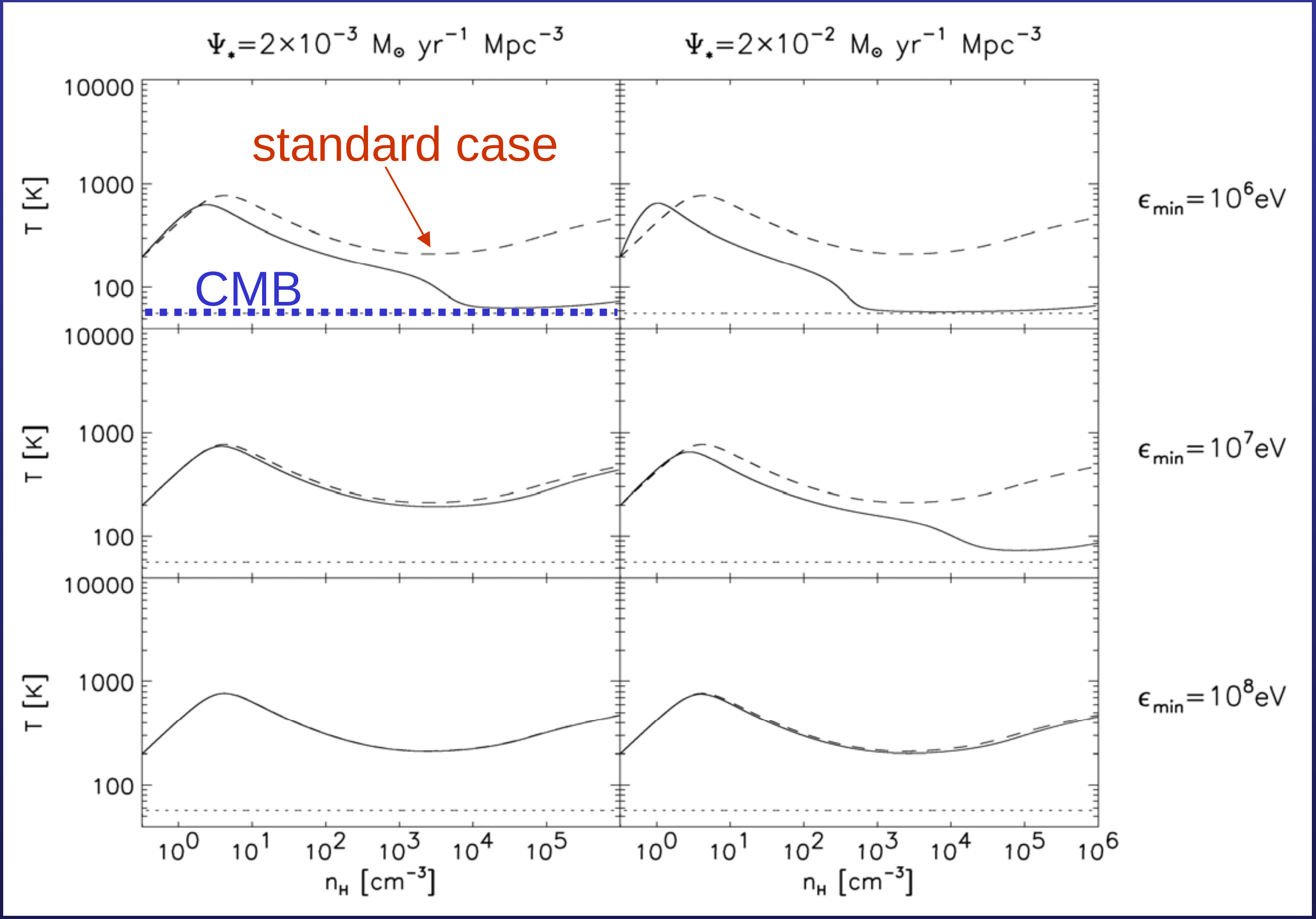
- Possible modifications to CDM (WDM, annihalation heating…)

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

  Spolyar et al. 2007

Impact of Cosmic Rays on Pop III Star Formation

(Stacy & Bromm 2007, MNRAS, in press, arXiv:0705.3634)



→lowering Pop III mass scale?

(see also: Jasche, Ciardi & Ensslin 2007)

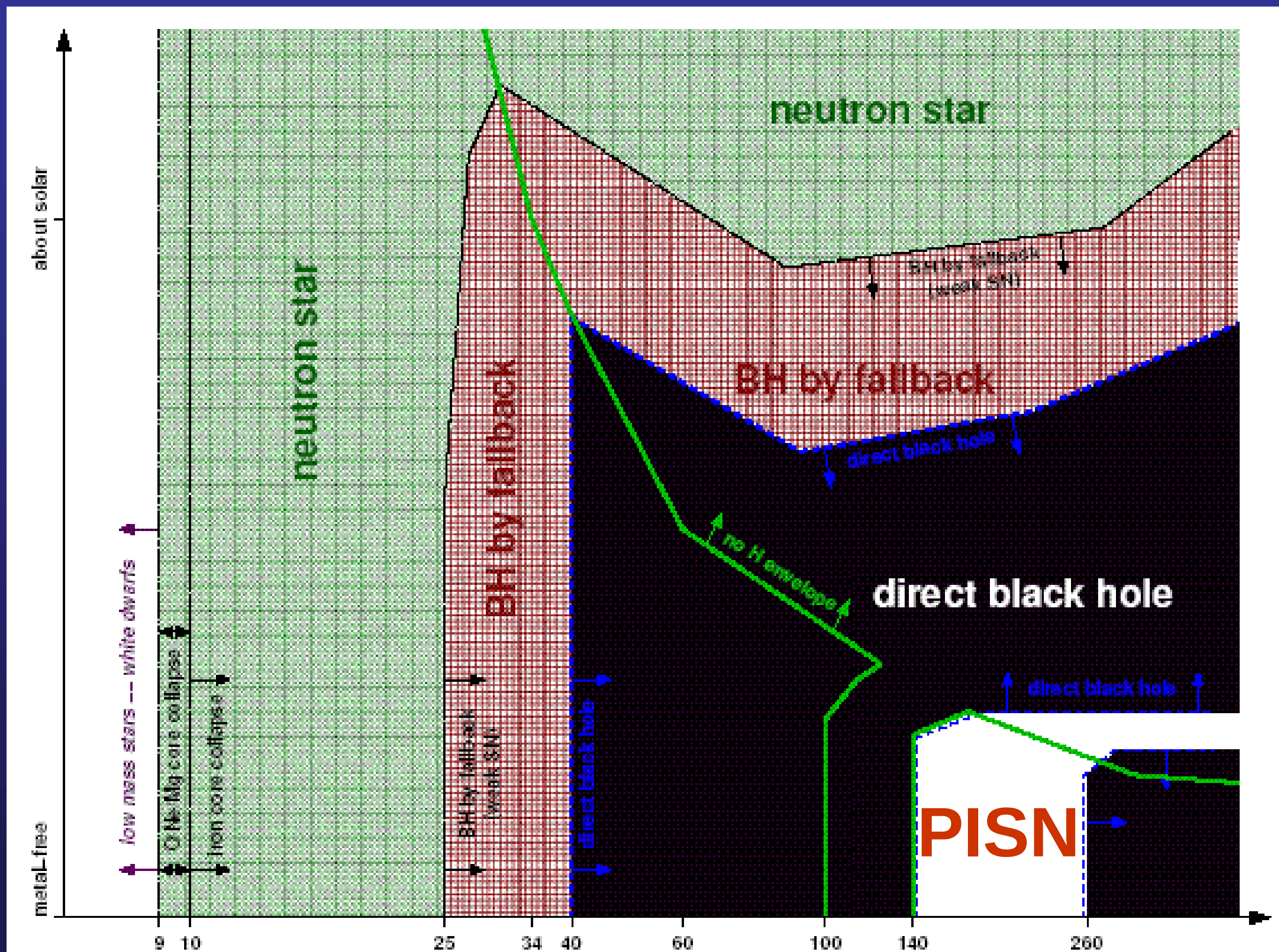
The Death of the First Stars:

(Heger et al. 2003)

Pop I

Z

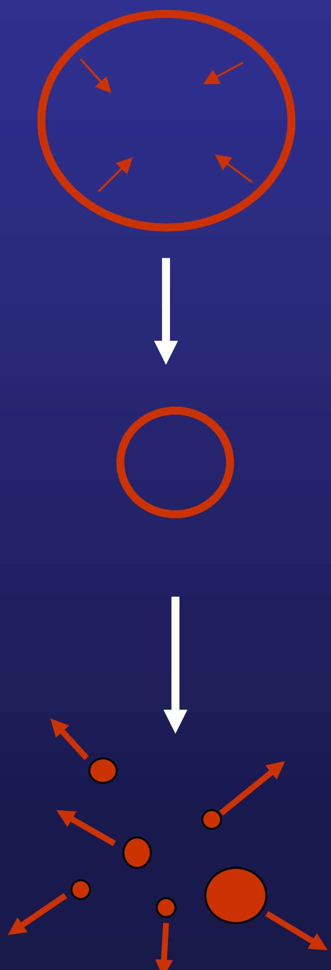
Pop III



Initial Stellar Mass

Physics of Pair-instability Supernovae

$M \sim 140 - 260\ M_o$



-T>10^9K

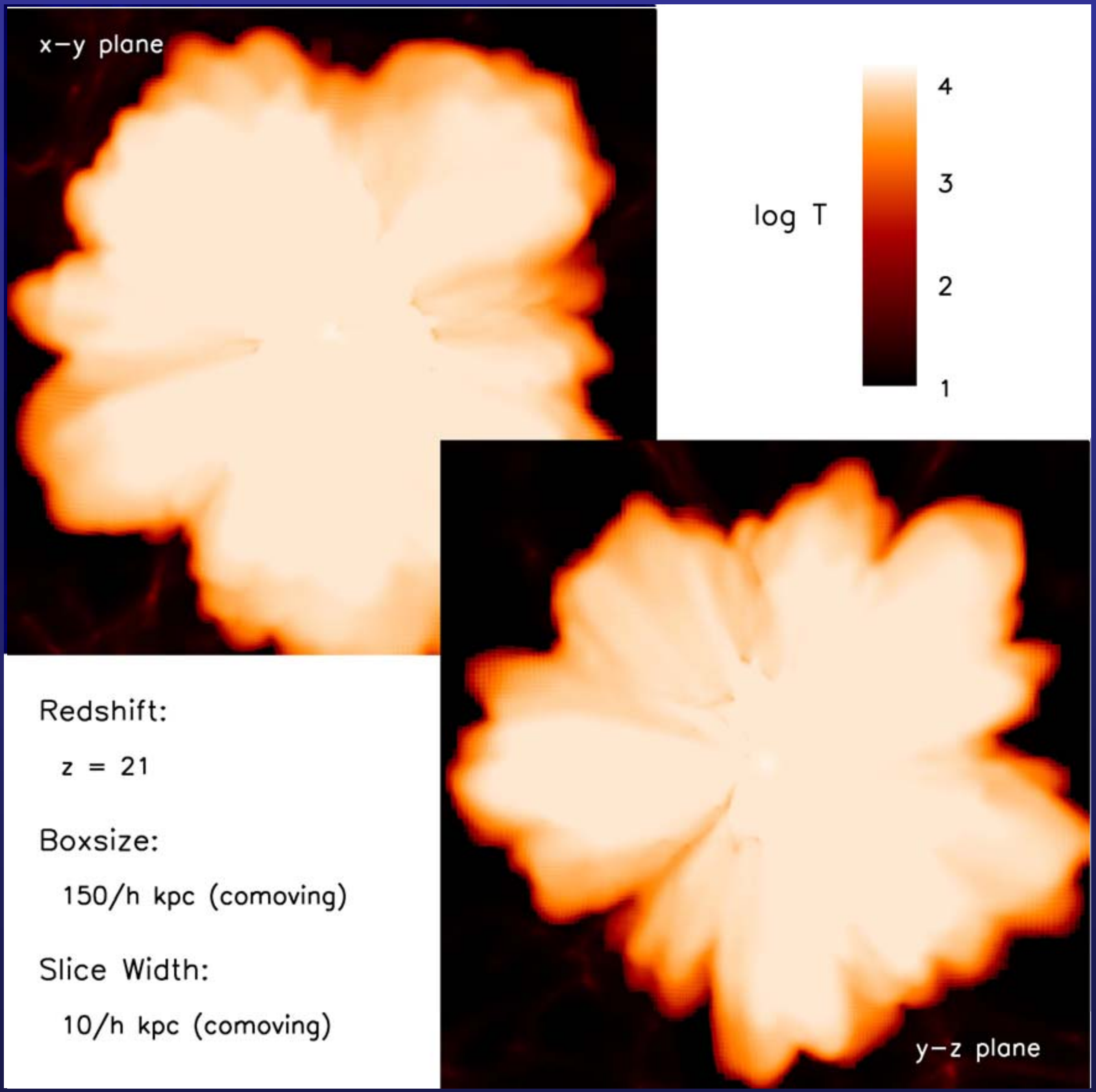
- ph+ph → $e^- e^+$
- grav. runaway collapse

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

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

The First Supernova Explosions

(Greif, Johnson, Bromm & Klessen 2007, ApJ, in press; arXiv:0705.3048)

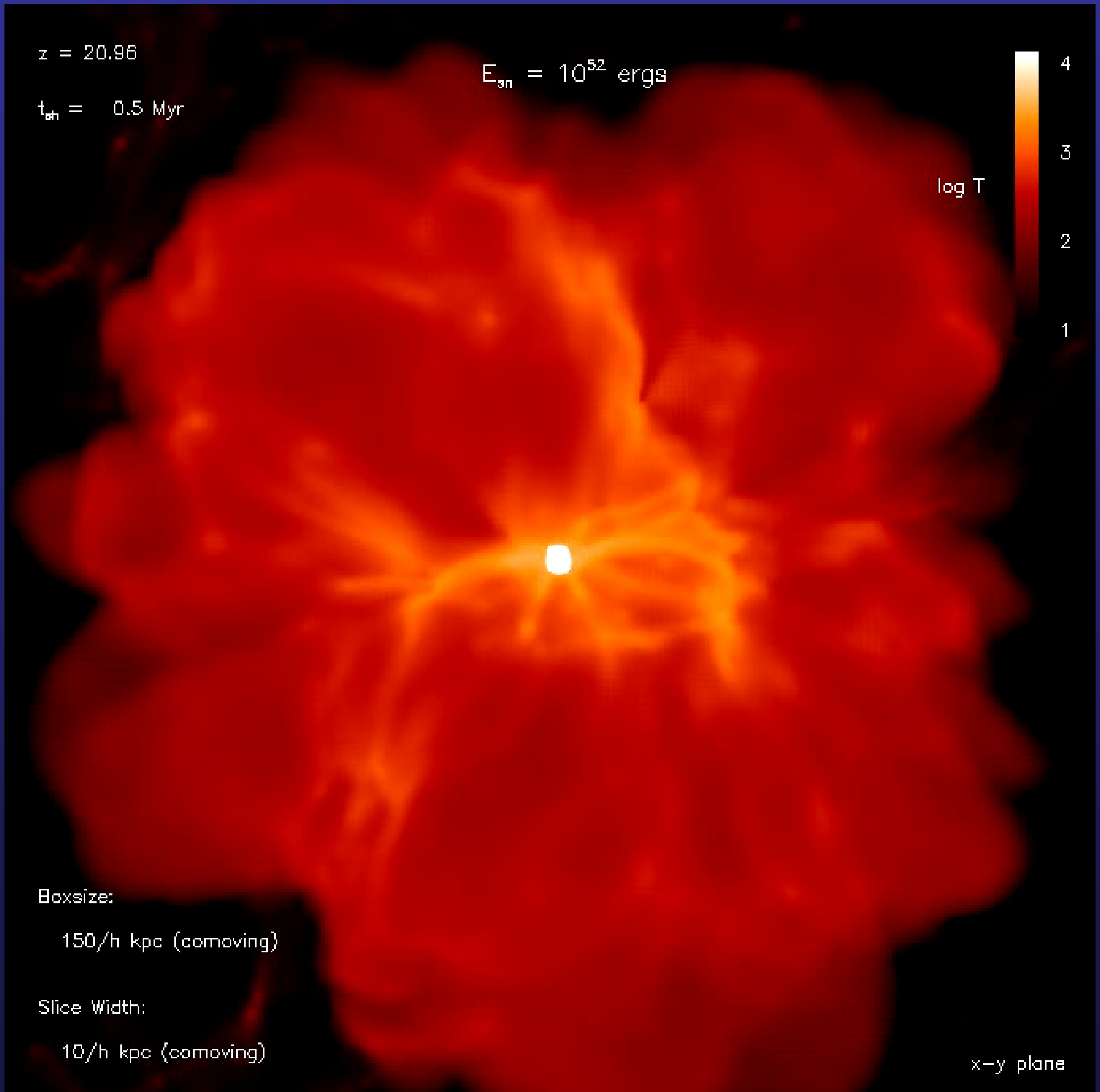


(See also: Bromm, Yoshida & Hernquist 2003, ApJ, 596, L135)

The First Supernova-Explosion

(Greif et al. 2007; arXiv:0705.3048)

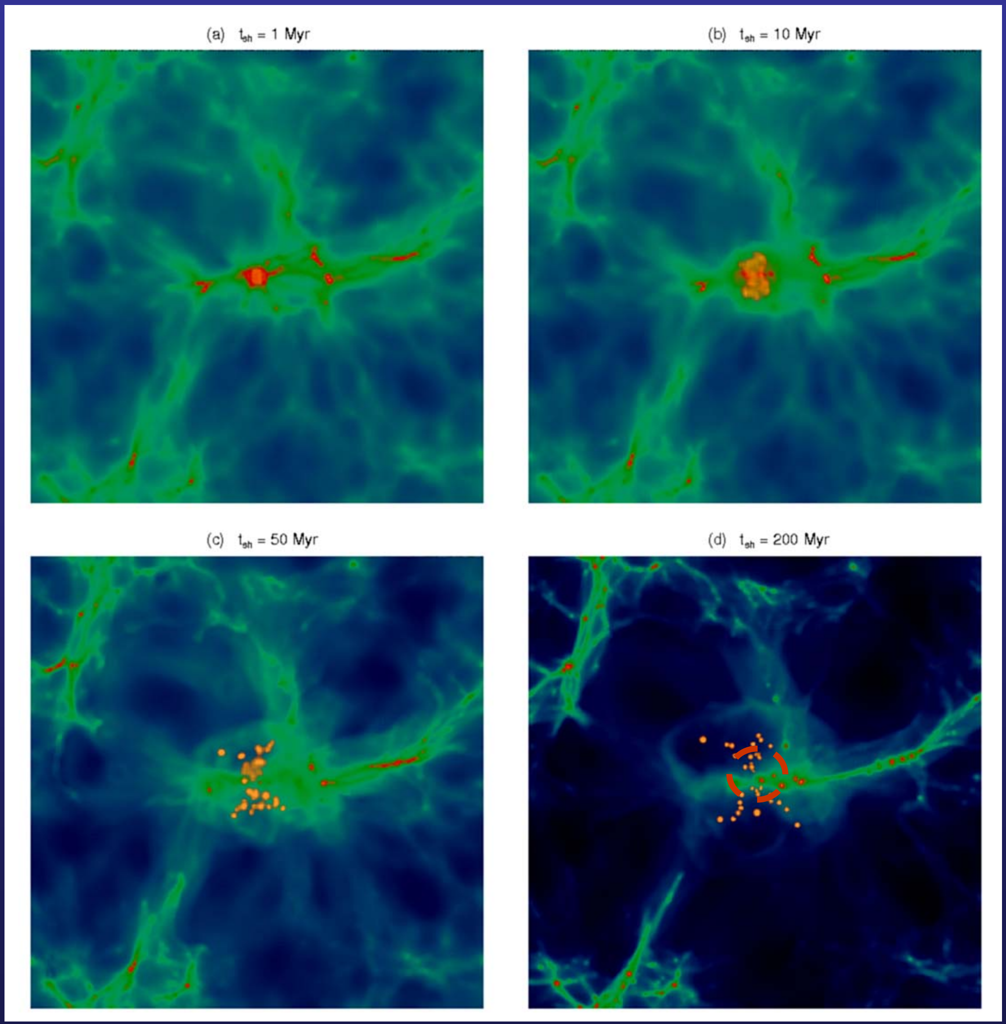
Temperature



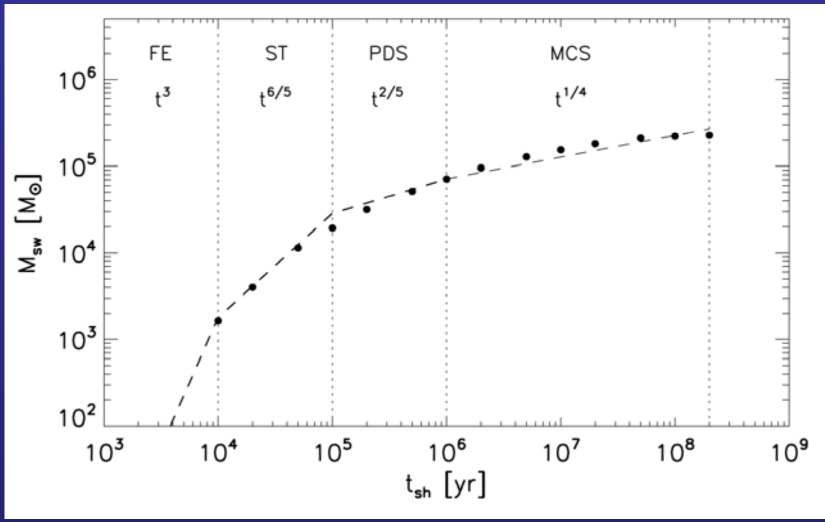
- E_{SN}~10^{52}ergs
- Complete Disruption (PISN)

The First Supernova-Explosion

(Greif et al. 2007; arXiv:0705.3048)



215 kpc



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

Paradise Lost: The Transition to Population II

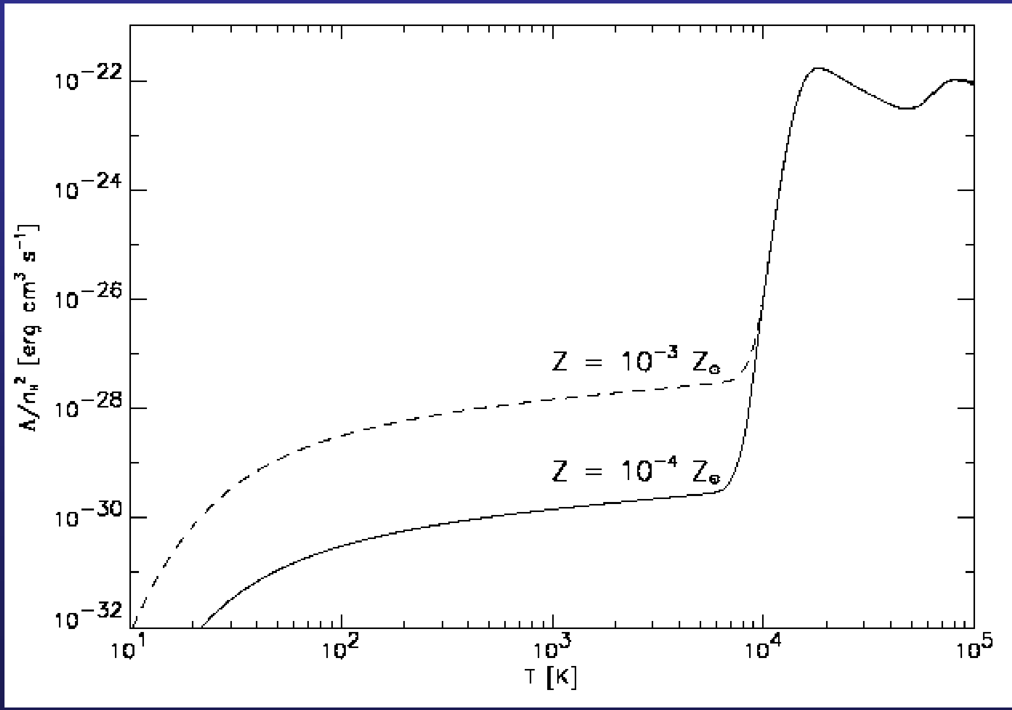
(Bromm, Ferrara, Coppi, & Larson 2001, MNRAS, 328, 969)

- Add trace amount of metals

- Limiting case of no H_2

- Heating by photoelectric effect on dust grains

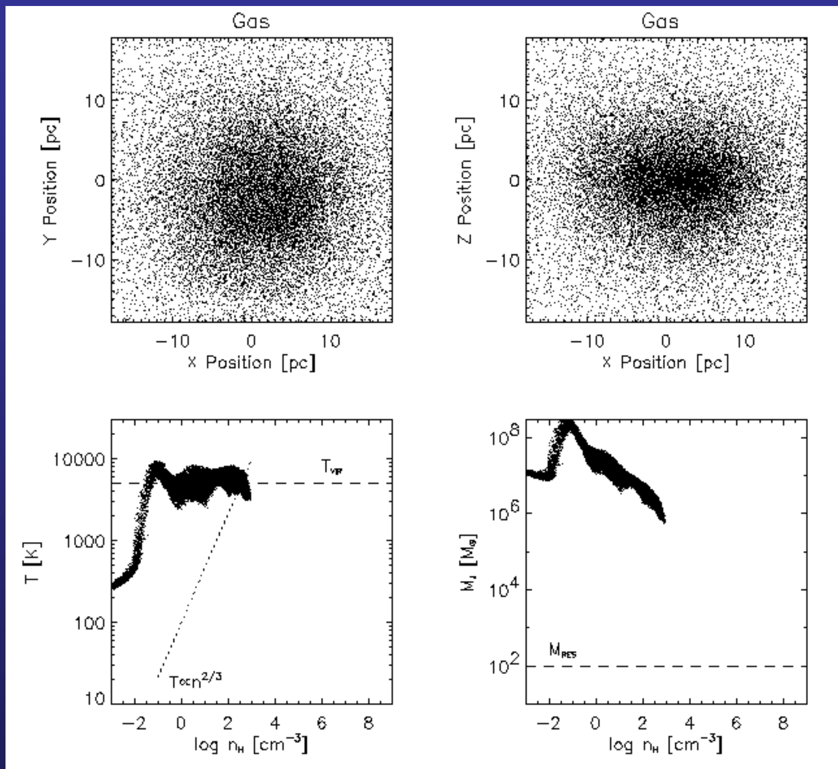
Cooling Rate vs. T



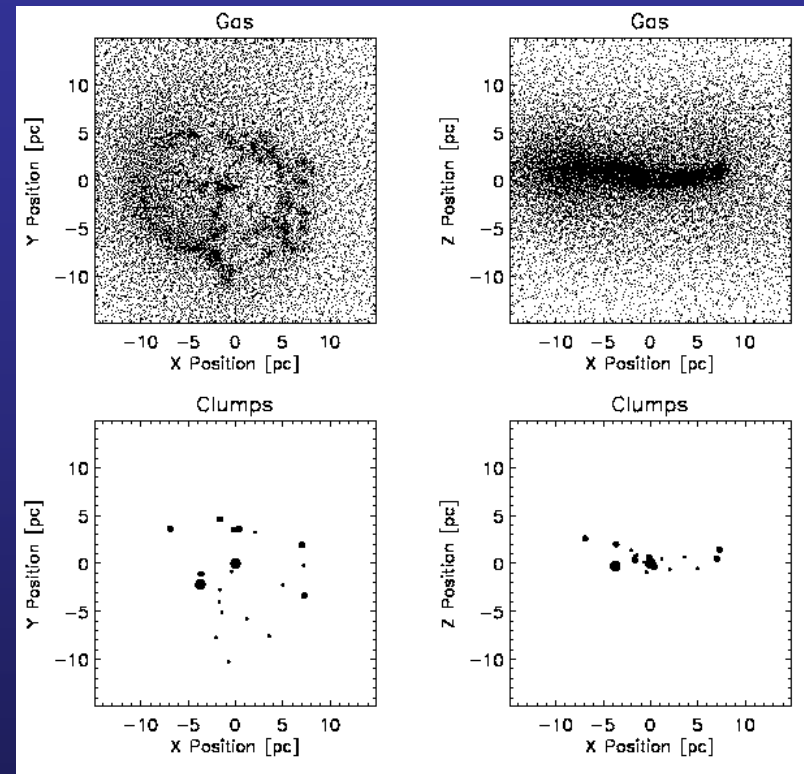
⟶ Consider two identical (other than Z) simulations !

Effect of Metallicity:

$Z = 10^{-4}\ Z_o$



$Z = 10^{-3}\ Z_o$



- Insufficient cooling
- Vigorous fragmentation

→ Critical metallicity: $Z_{crit} \sim 5 \times 10^{-4}\ Z_o$

→ Recently confirmed by Smith & Sigurdsson (2007)

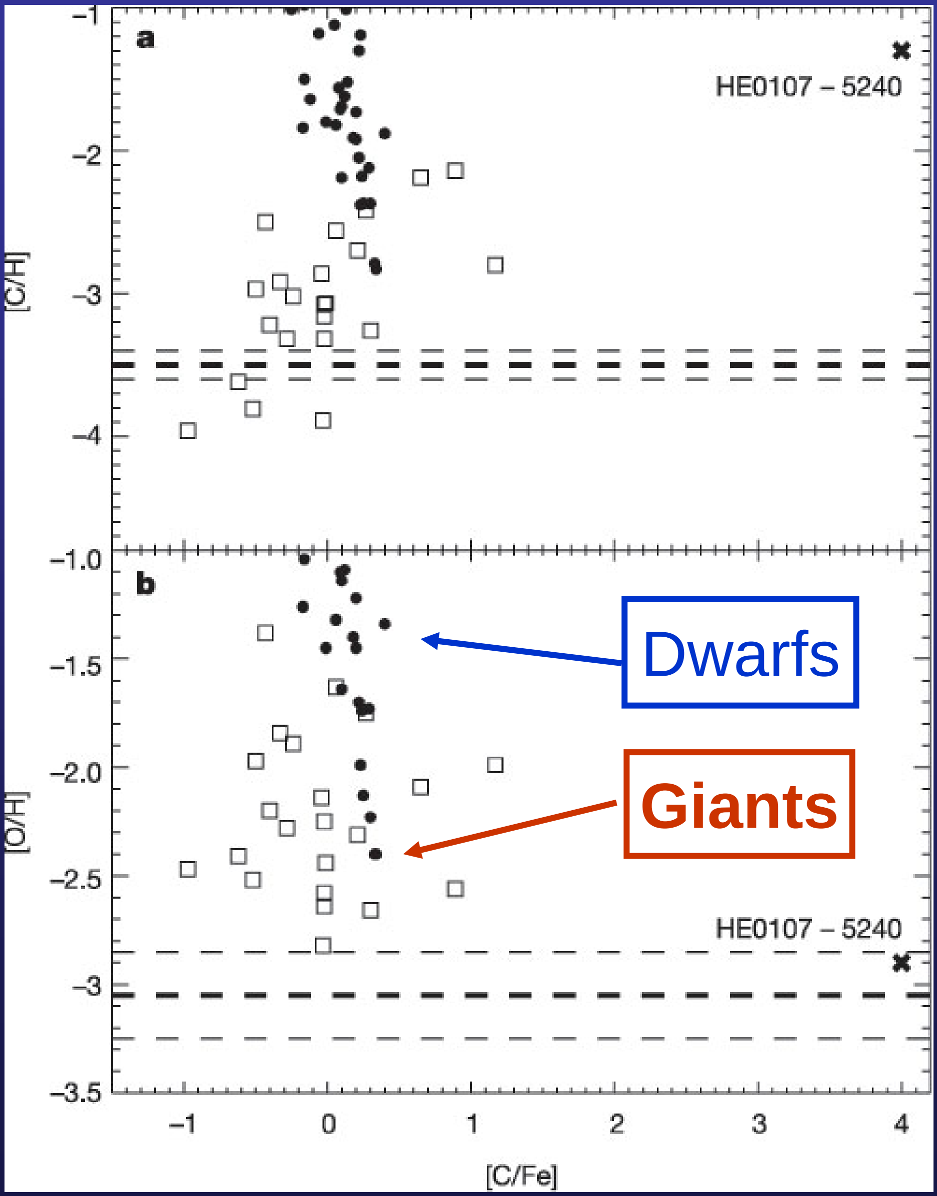
Forming the First Low-mass Stars:

(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:

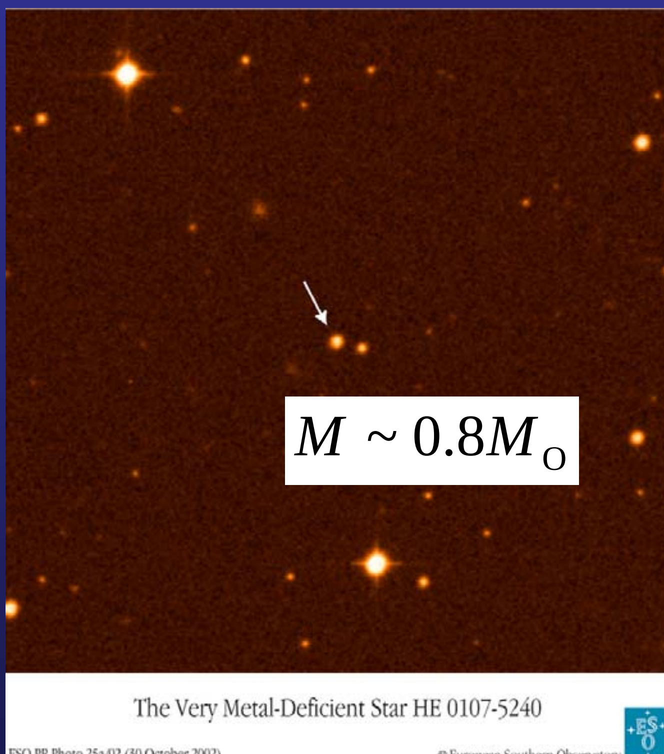
→ Highly complex!

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

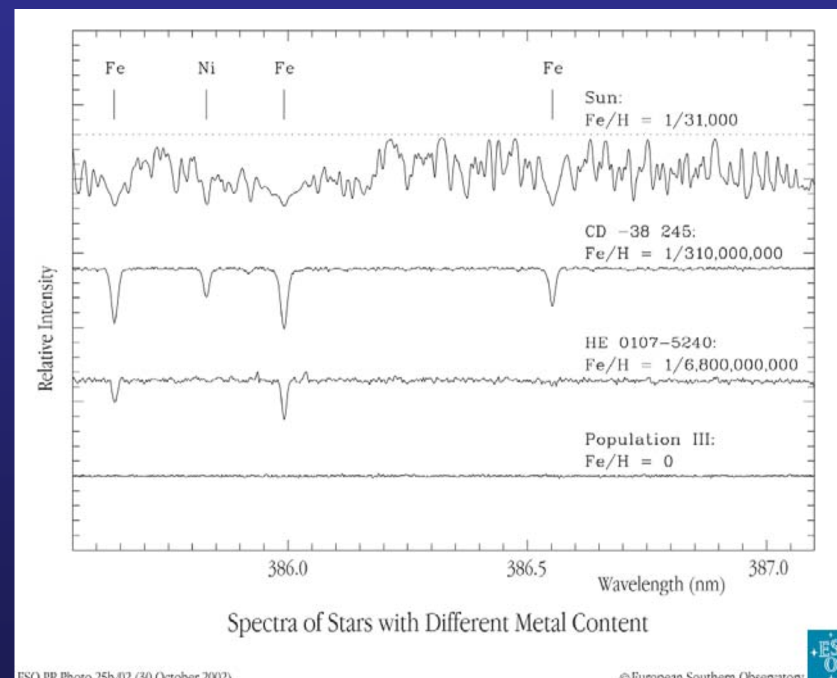
- Z_{crit} = f (environment, formation history,…)
  → Realistic Initial Conditions are crucial!

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)



The Very Metal-Deficient Star HE 0107-5240



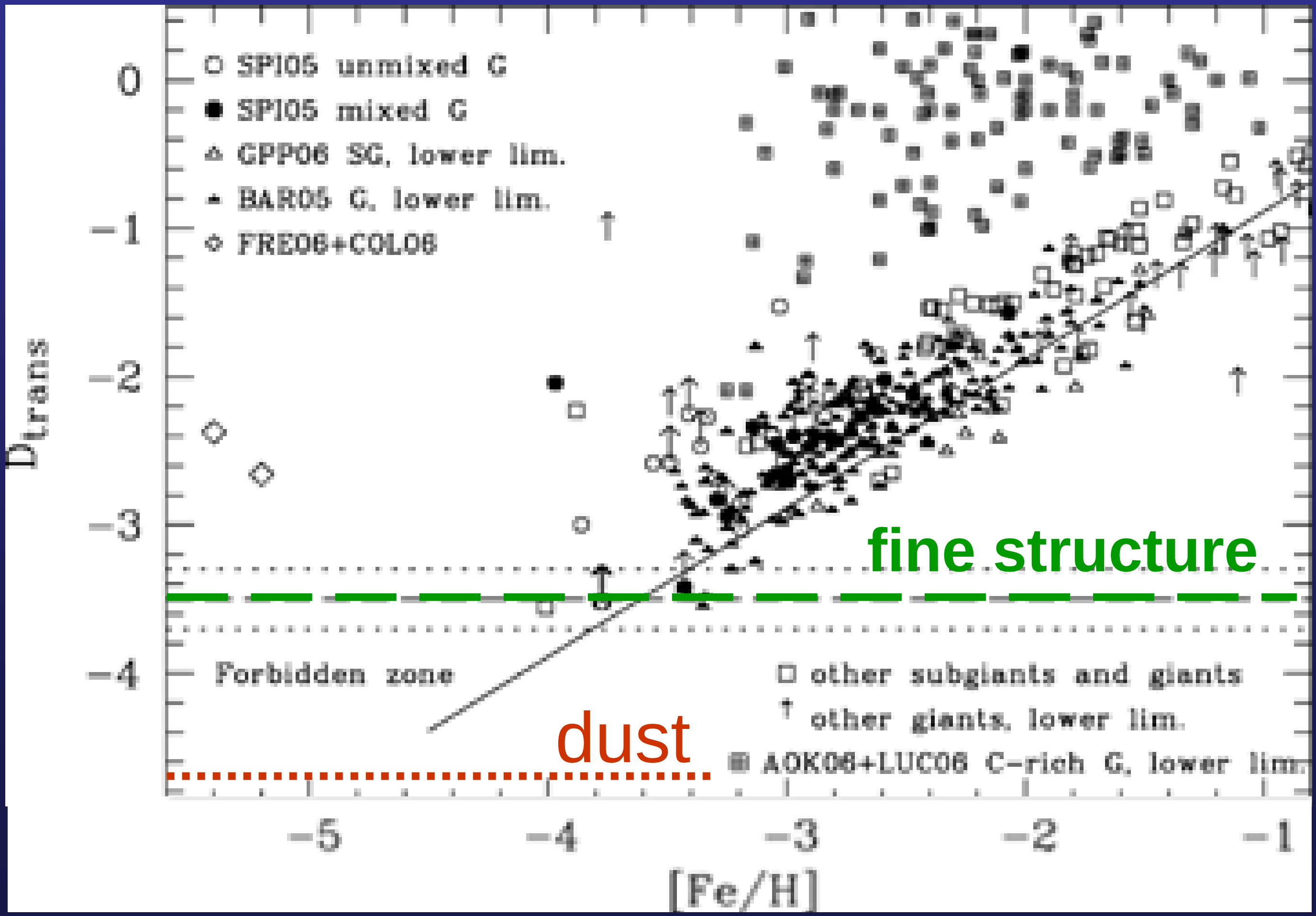
Spectra of Stars with Different Metal Content

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

Forming the First Low-mass Stars:

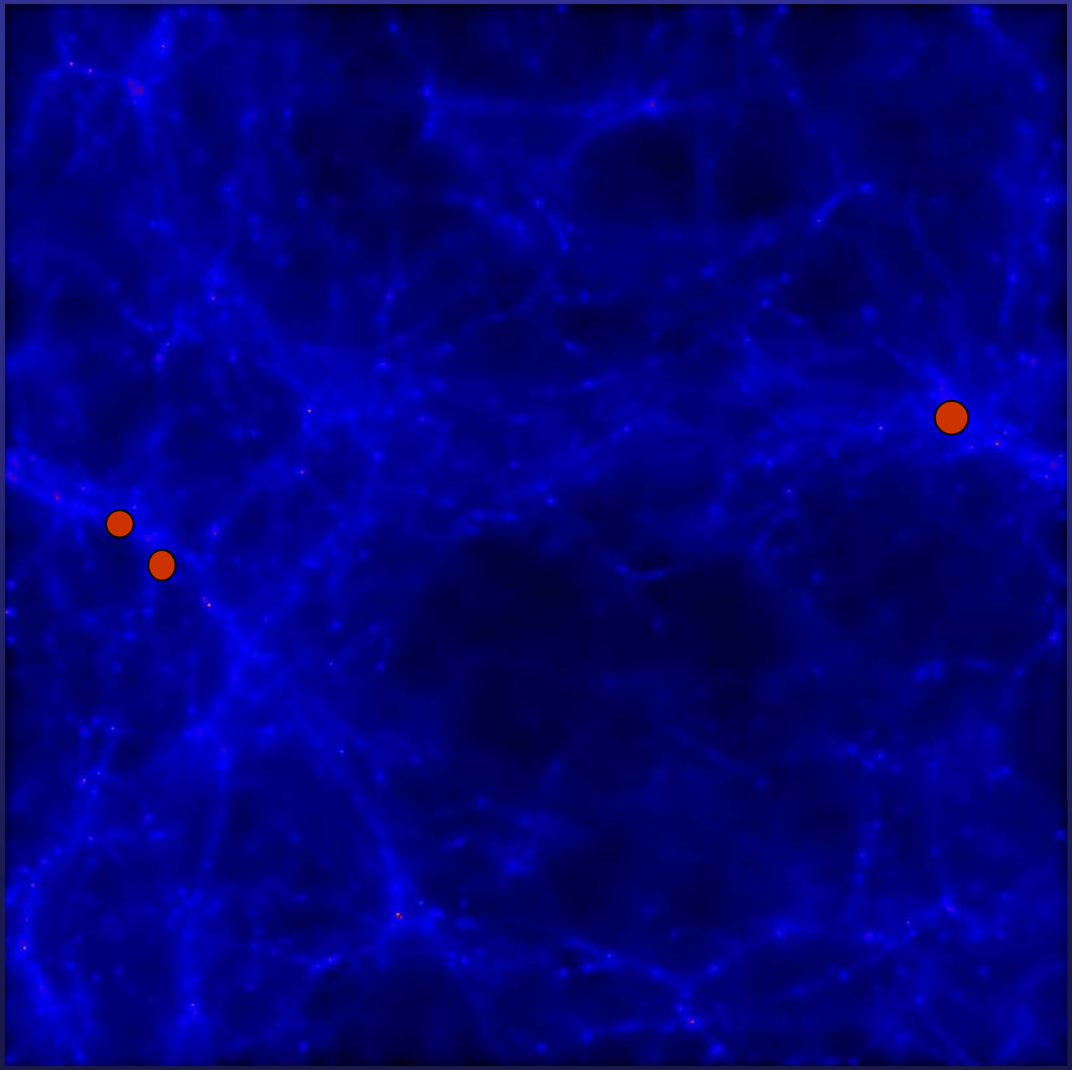
(Frebel, Johnson & Bromm 2007, MNRAS, in press; astro-ph/0701395)

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



The First Dwarf Galaxies

- What is character of star formation?



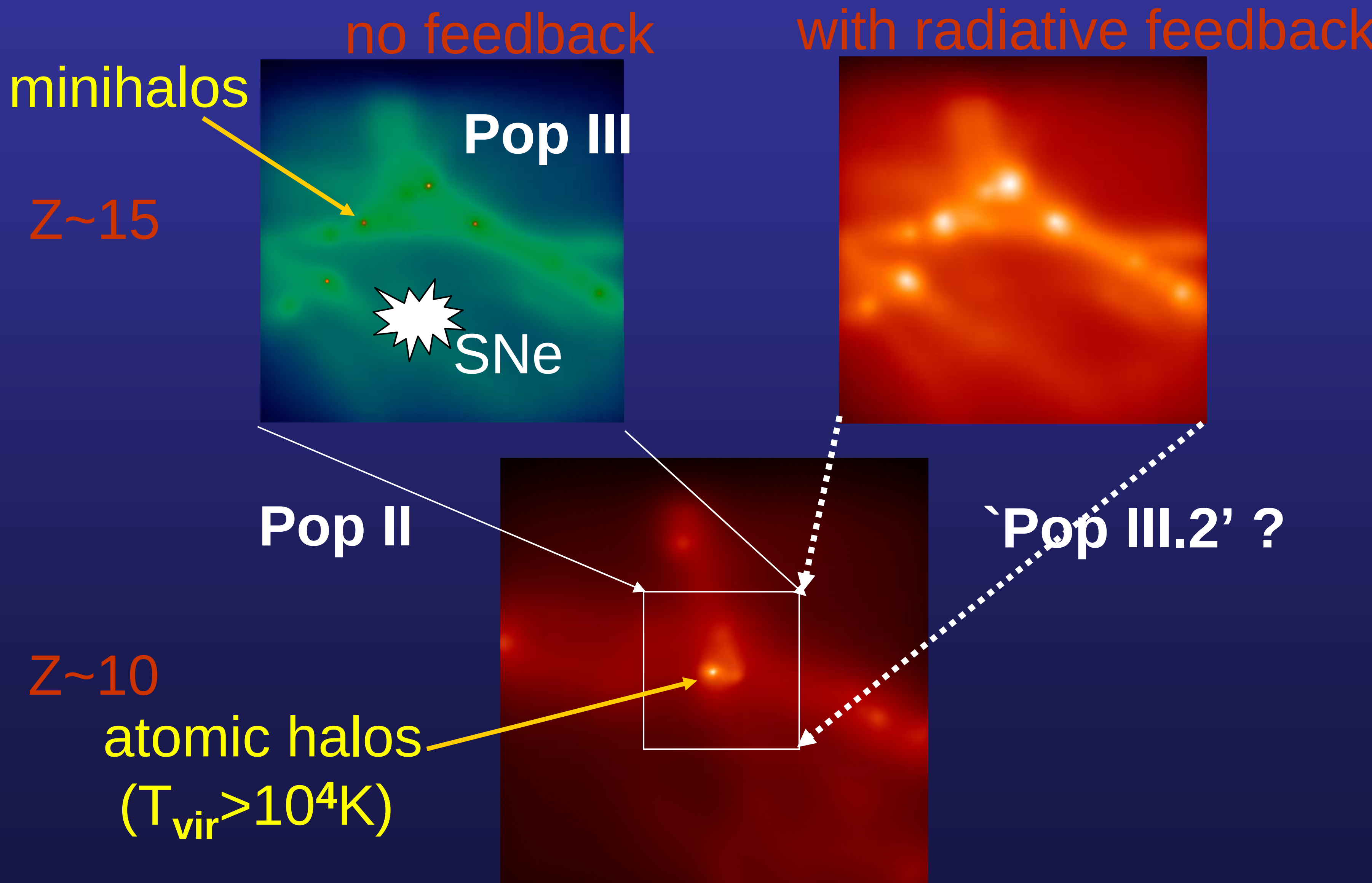
1 co-moving Mpc

- 2 sigma peak
- $M \sim 10^8 M_o$, $z \sim 10$
- $T_{vir} > 10^4 K$

→ Cooling possible
Due to atomic H

Setting the Stage for Pop II Star Formation:

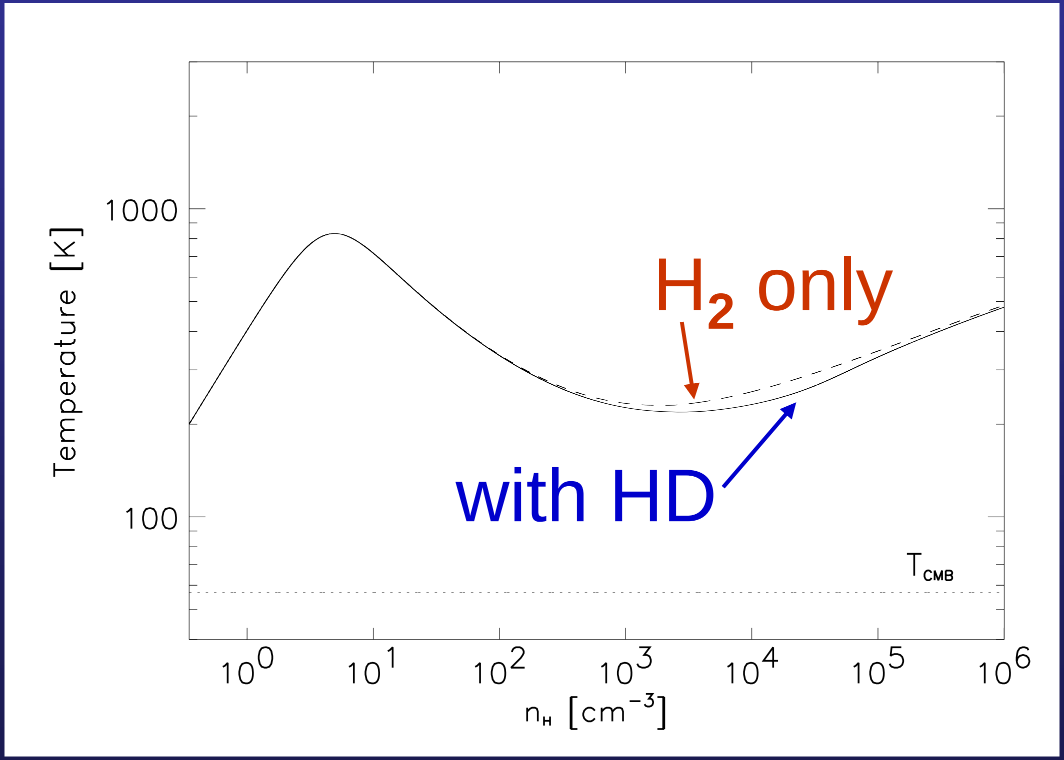
- **Influence of previous episodes of star formation**



Fate of shock-heated primordial gas

(Johnson & Bromm 2006, MNRAS, 366, 247)

1) Minihalo-case (T_{vir} ~ few 1,000 K): Pop III

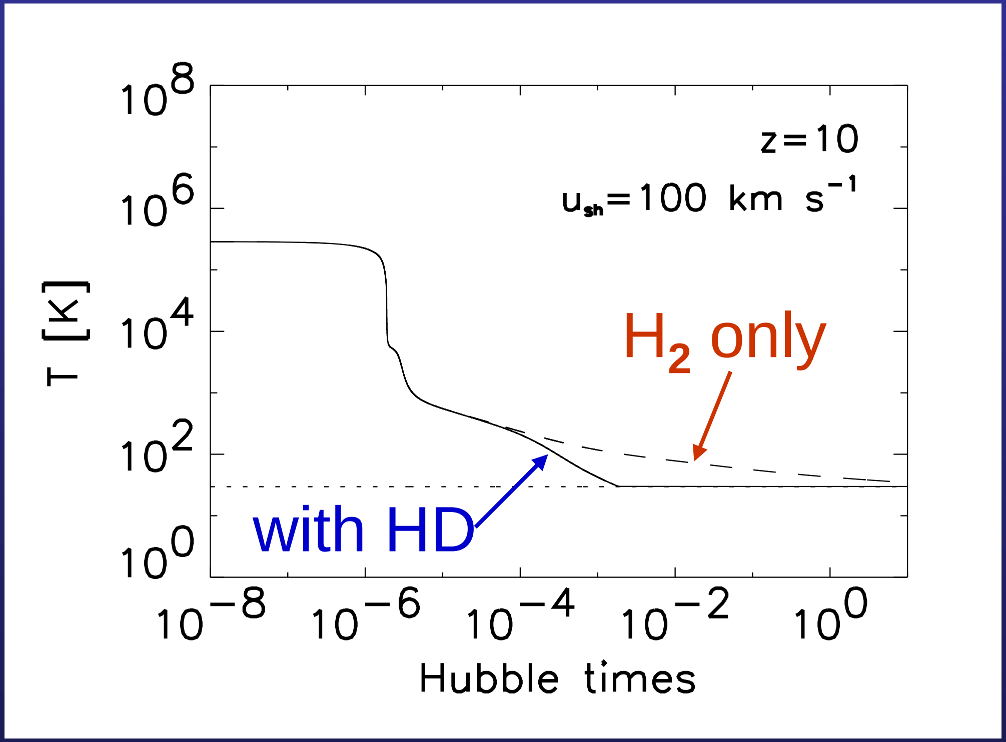


- HD makes no difference! (M_{char}~ few 100 $M_{\odot}$)

Fate of shock-heated primordial gas

(Johnson & Bromm 2006, 366, 247)

2) Shocked-case (T_{vir} > 10,000 K): Pop III.2

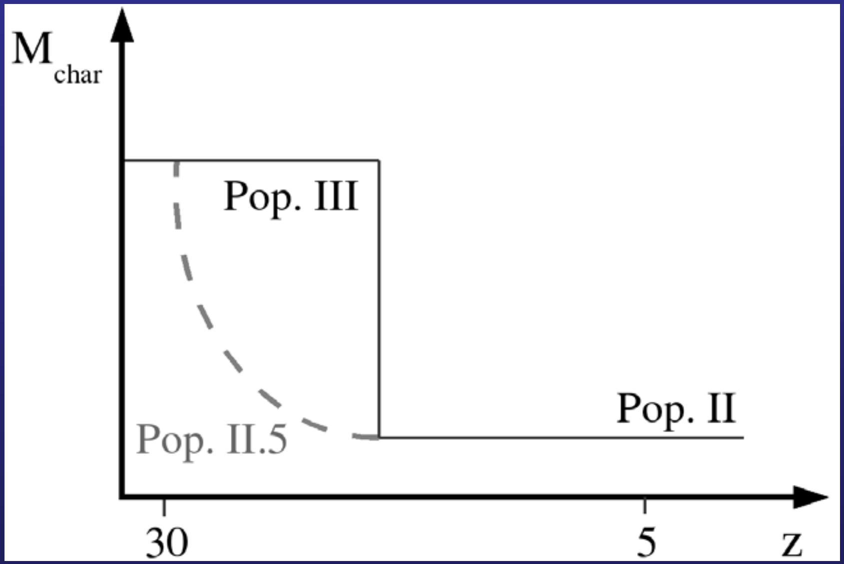


- HD may make difference! (M_{char}~ few 10 $M_{\odot}$)

Fate of shock-heated primordial gas

(Johnson & Bromm 2006, MNRAS, 366, 247)

• Star formation in high-z universe:



• Pop III:
  - M_{char} ~ few 100 $M_{\odot}$

• Pop III.2:
  - M_{char} ~ few 10 $M_{\odot}$

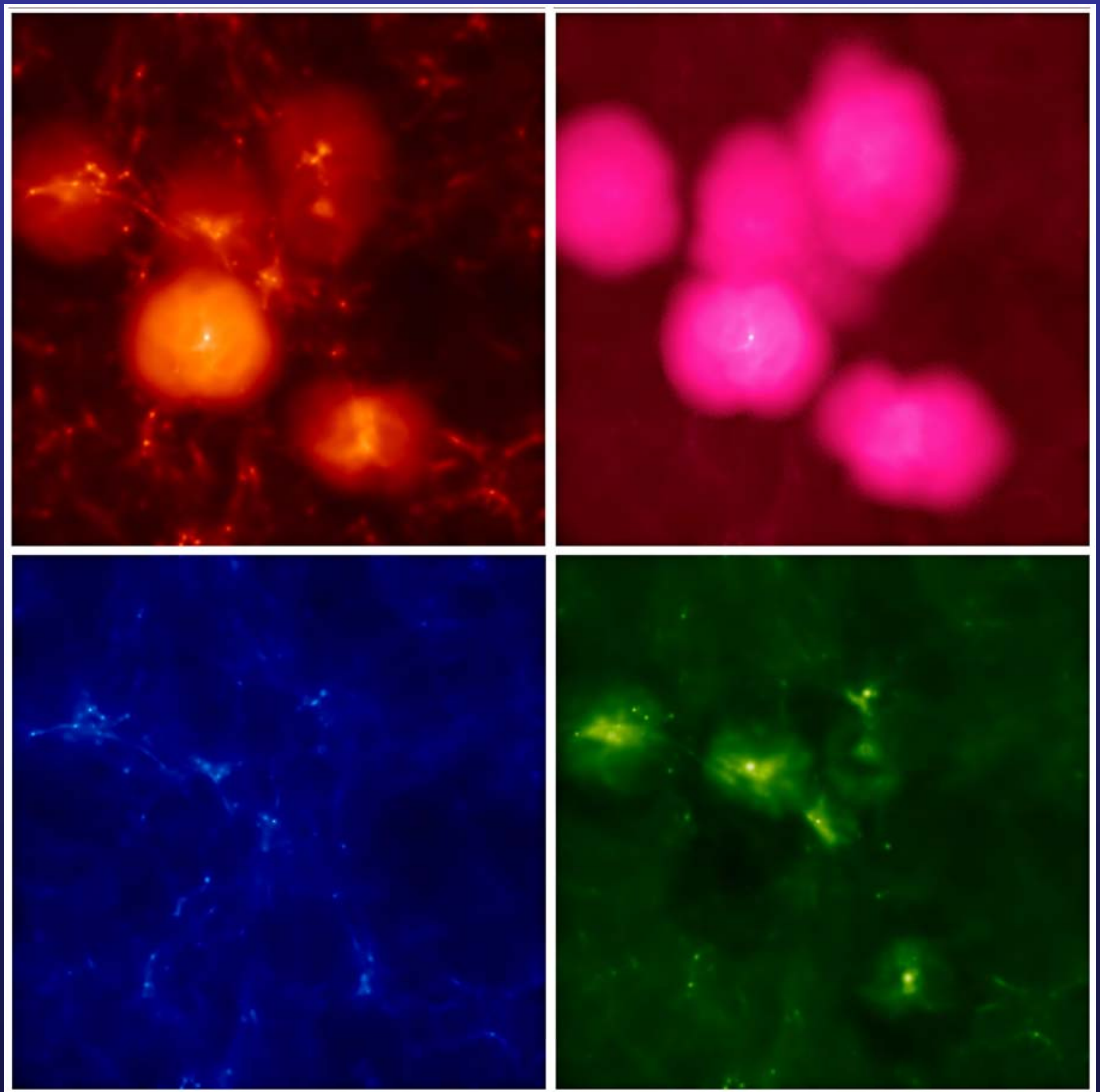
• Pop II:
  - M_{char} ~ few 1 $M_{\odot}$

time

• How abrupt is Pop III ⟶ Pop II transition?

Towards the First Dwarf Galaxies

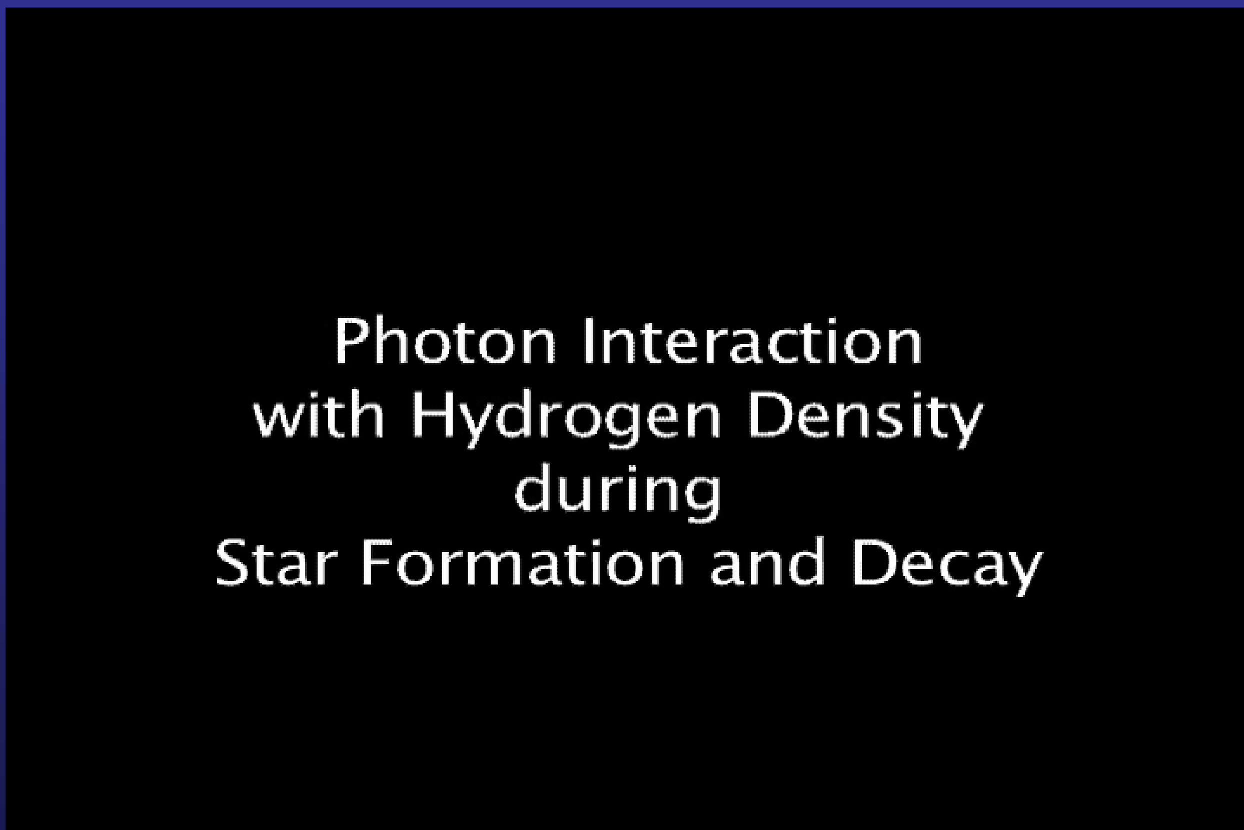
(Johnson, Greif, & Bromm 2007, ApJ, 665, 85)



Towards the First Dwarf Galaxies

(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)

Summary

- Primordial gas typically attains:

    - T ~ 200 – 300 K

    - n ~ 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} ~ 15 +- 5)

- PISNe completely disrupt mini-halos and enriches surroundings

- 2^{nd} generation of intermediate-mass stars (“Pop III.2”)

Perspectives:

- Further fate of clumps
  - Feedback of protostar on its envelope
  - Inclusion of opacity effects (radiative transfer)
- The ``Second Generation of Stars'' (high-z dwarf glaxies)
- SN feedback and metal enrichment from the first stars
- What were the seeds for the first quasars?
- When did QSO activity first begin?