FTPI Workshop:

Early Structure Formation

(Minneapolis, October 2005)

The First Stars and their Impact on Cosmology

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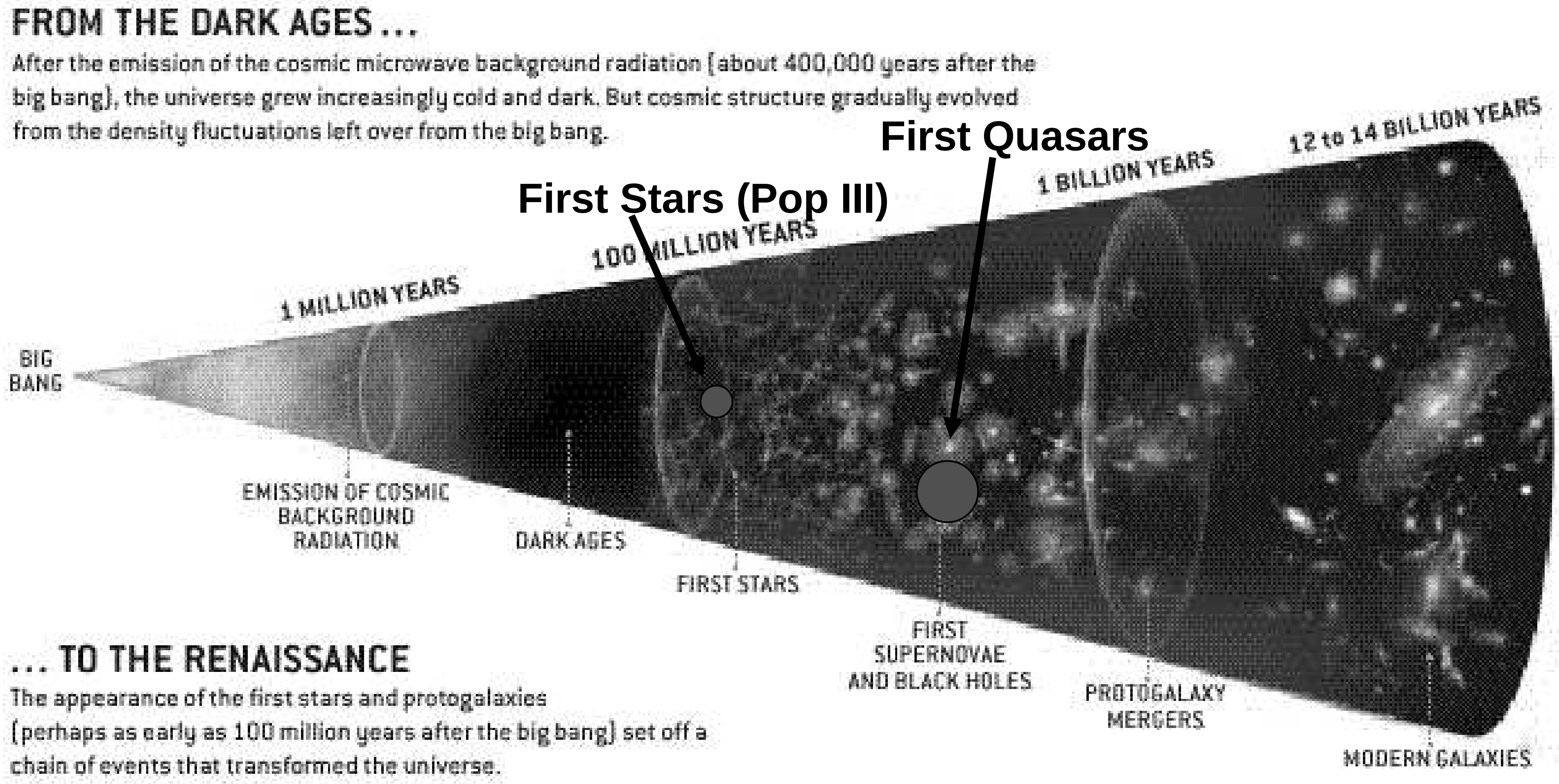
The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance



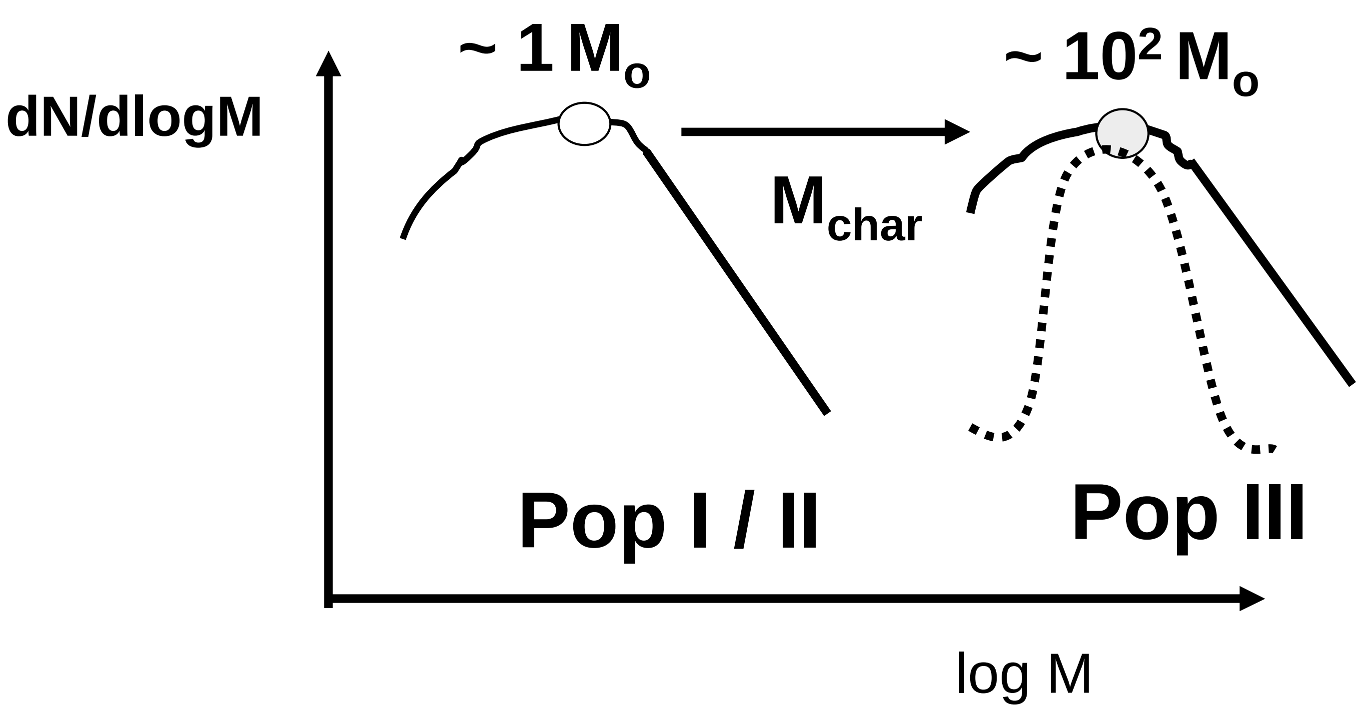
(Larson & Bromm, Scientific American, Dec. 2001)

- First Stars ⟶ Transition from Simplicity to Complexity

The First Stars: The "Standard" Model

- Numerical simulations
  - Bromm, Coppi, & Larson (1999, 2002)
  - Abel, Bryan, & Norman (2000, 2002)
  - Nakamura & Umemura (2001, 2002)

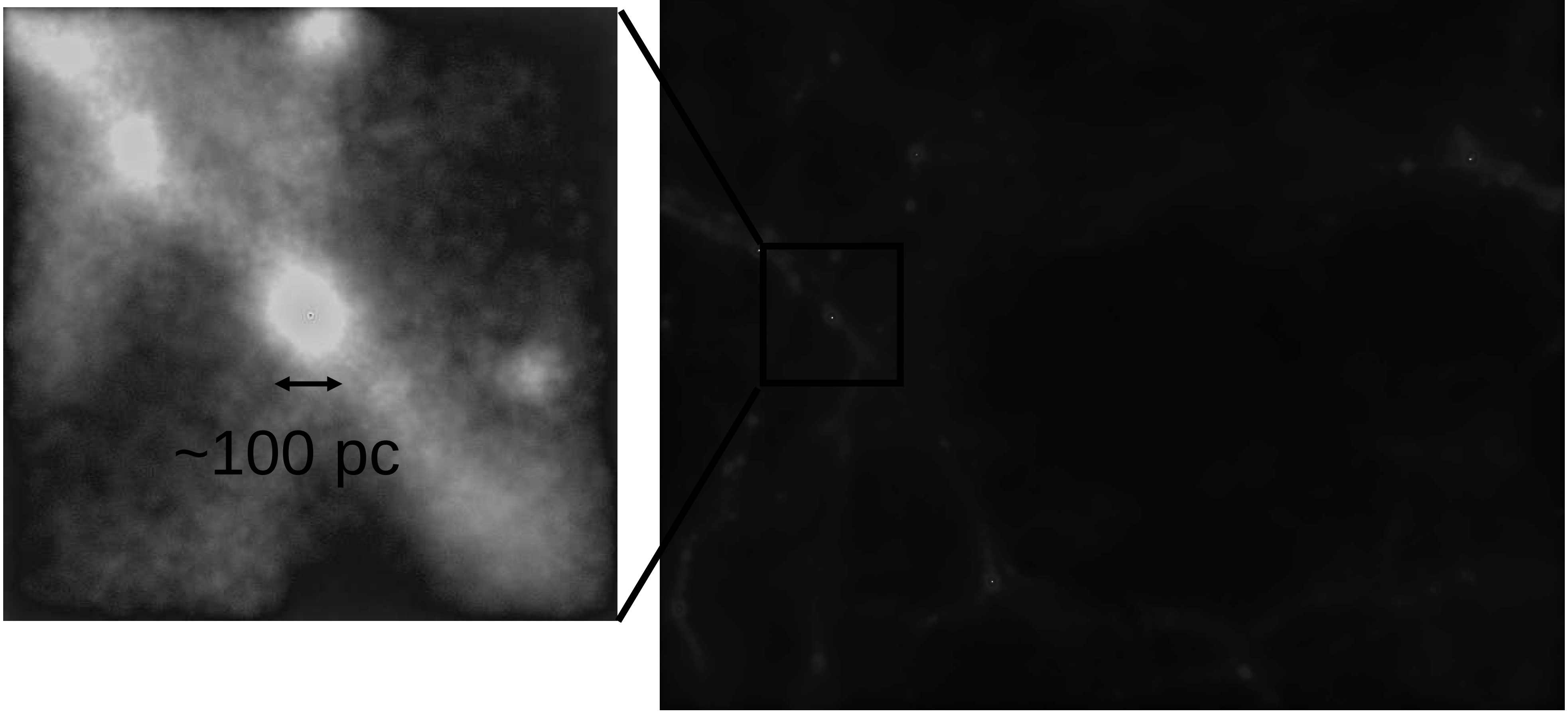
- Main Result: → **Top-heavy IMF**



The First Star-Forming Region ("minihalos")

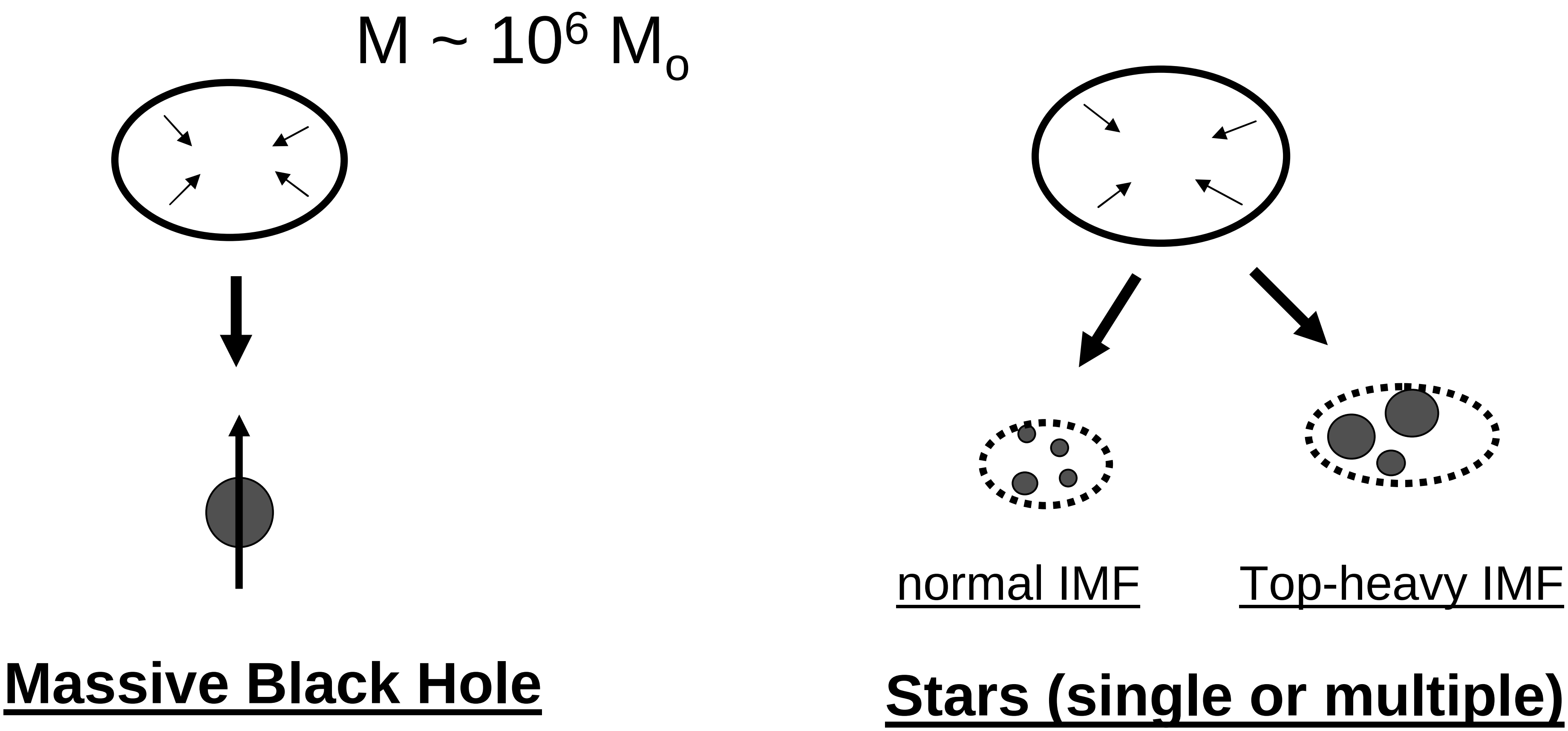
projected gas density at z=20

$M \sim 10^{6} M_{o}$



~ 7 kpc (proper)

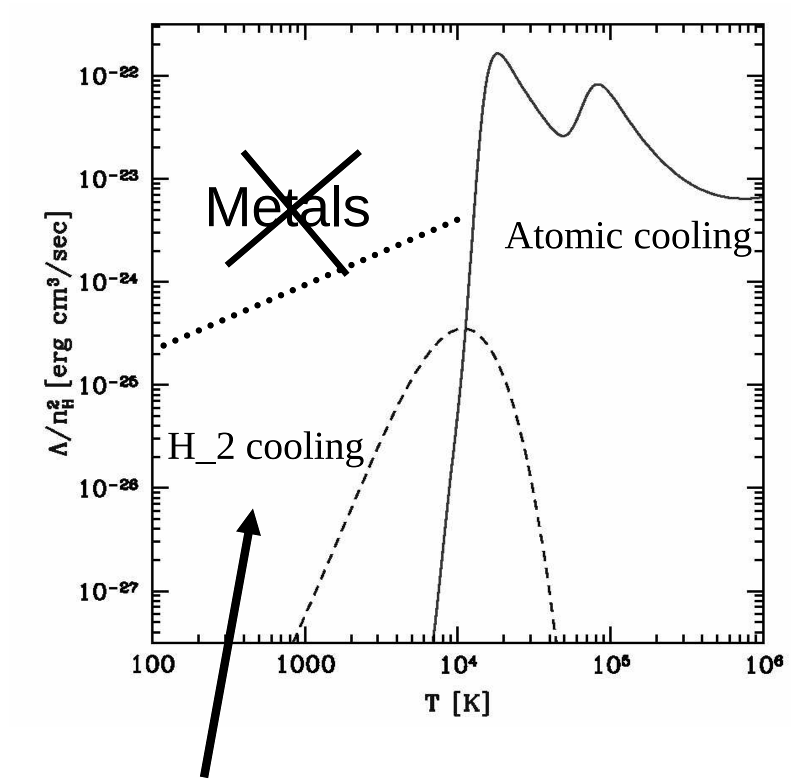
What happens inside primordial minihalos?



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

The Physics of Population III

- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM
    → Well-posed problem
- <u>Problem:</u>
  How to cool primordial gas?
  - No metals → different cooling
  - Below 10^4 K, main coolant is H_2



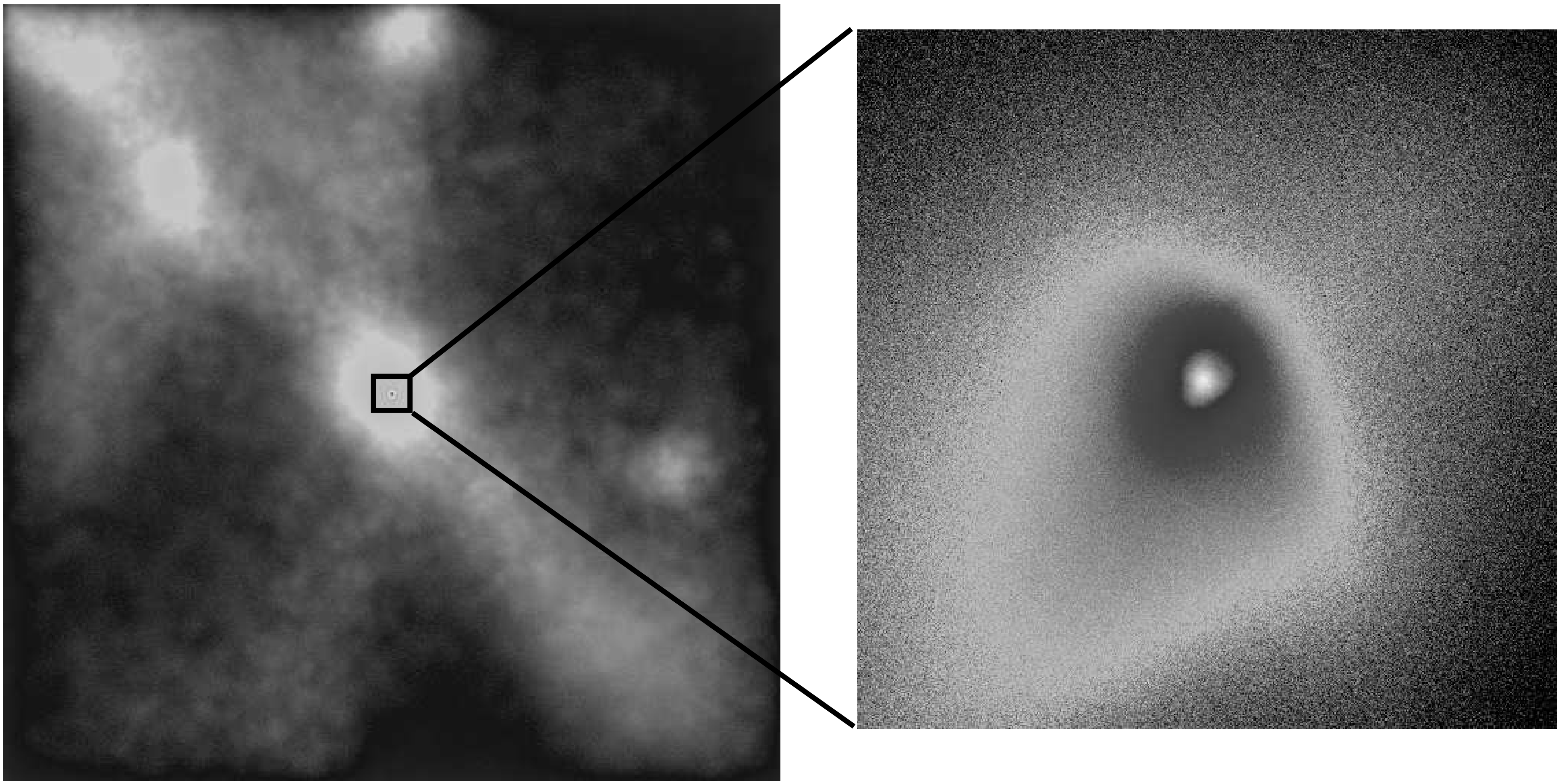
T_{vir} for Pop III

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

Formation of a Population III Star

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

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



~ 25 pc

1 kpc

A Physical Explanation:

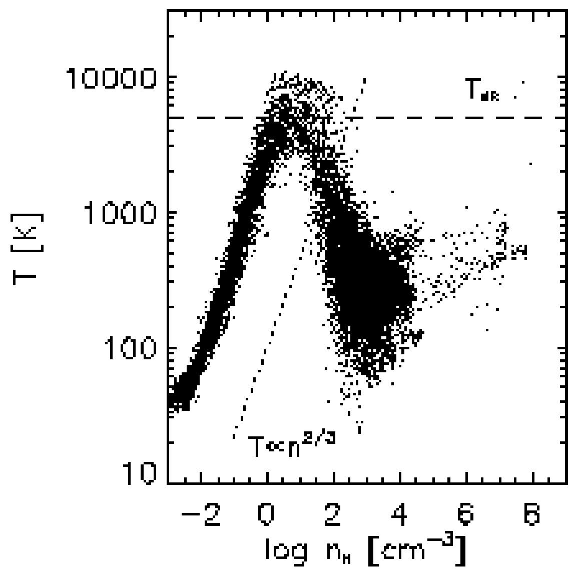
(Bromm, Coppi, & Larson 1999, 2002)

- Gravitational instability (Jeans 1902)
- Jeans mass:

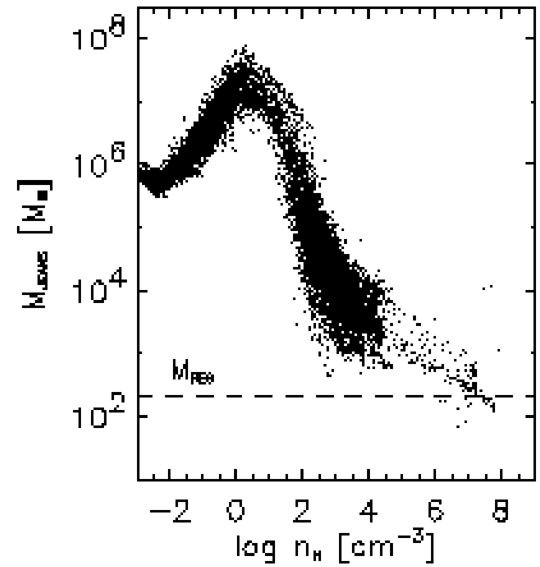
$M_J \sim T^{1.5}\, n^{-0.5}$

- Thermodynamics of primordial gas

T vs. n



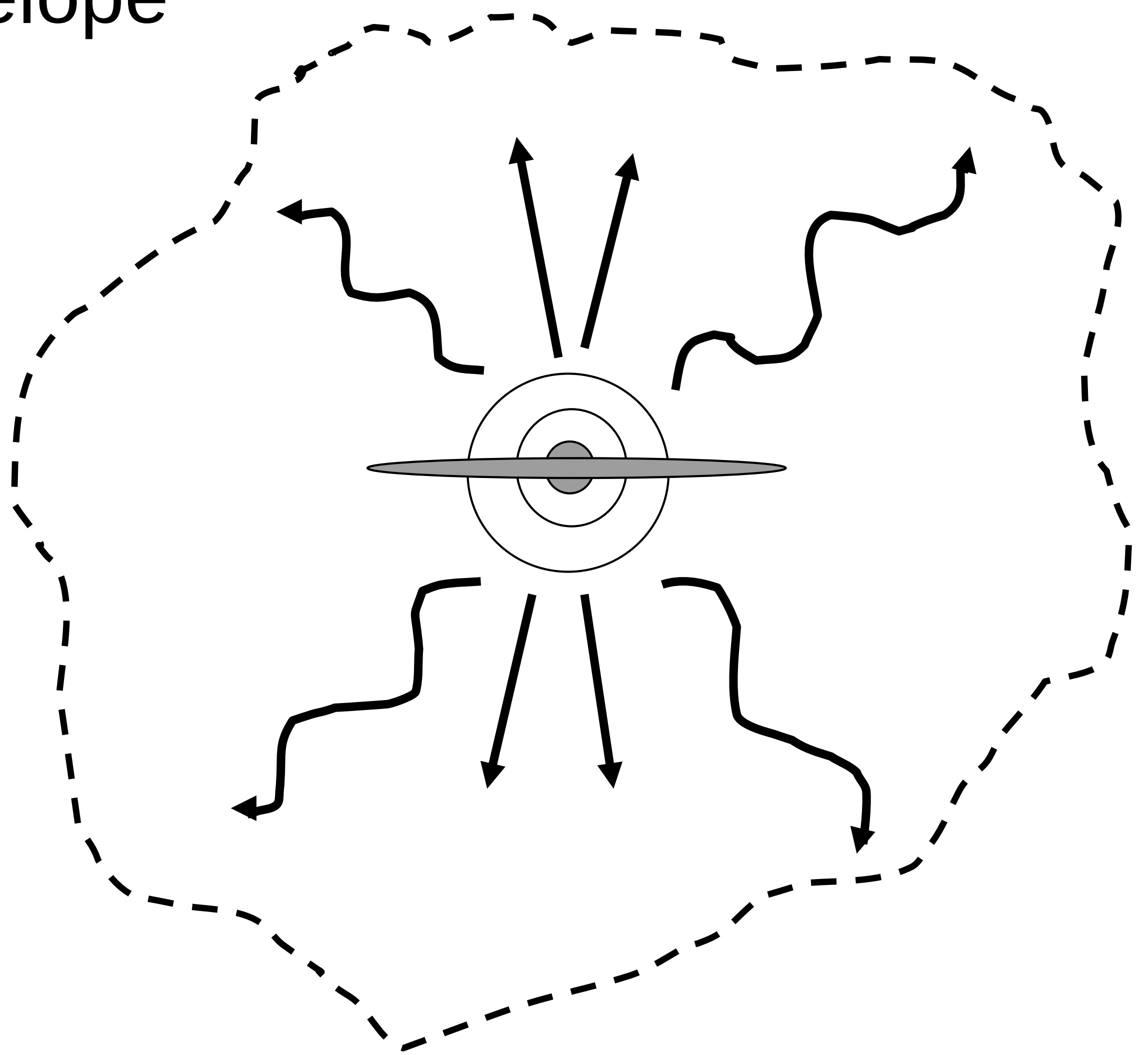
M_J vs. n



- 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!

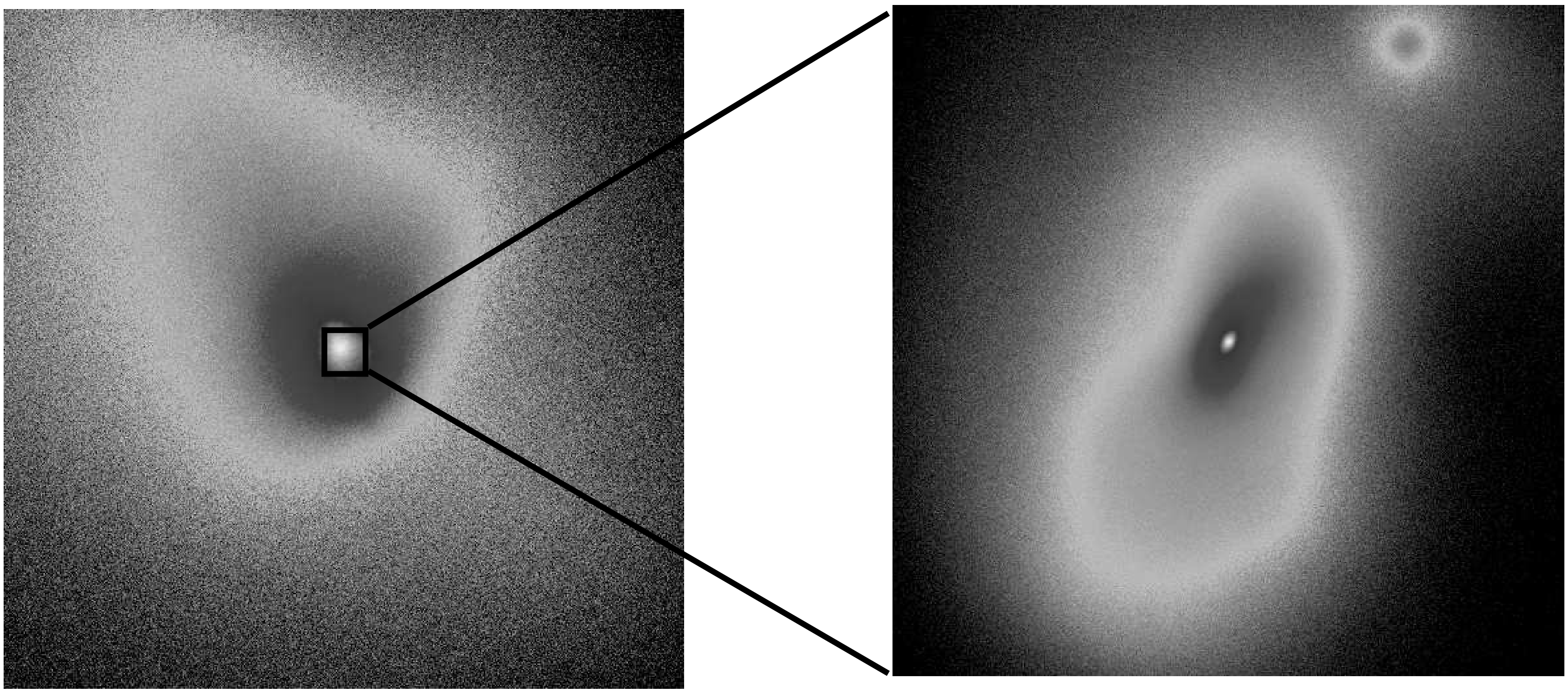
- $dM/dt_{acc} \sim M_J / t_{ff} \sim T^{3/2}$ (Pop I: T ~ 10 K, Pop III: T ~ 300 K)

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

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

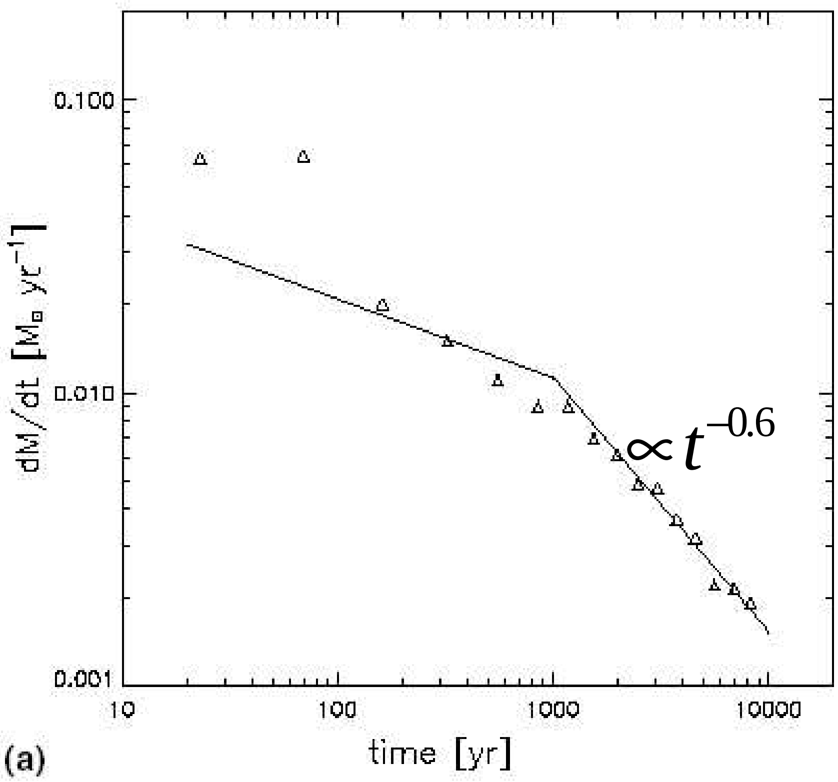
- Simulate further fate of the clump



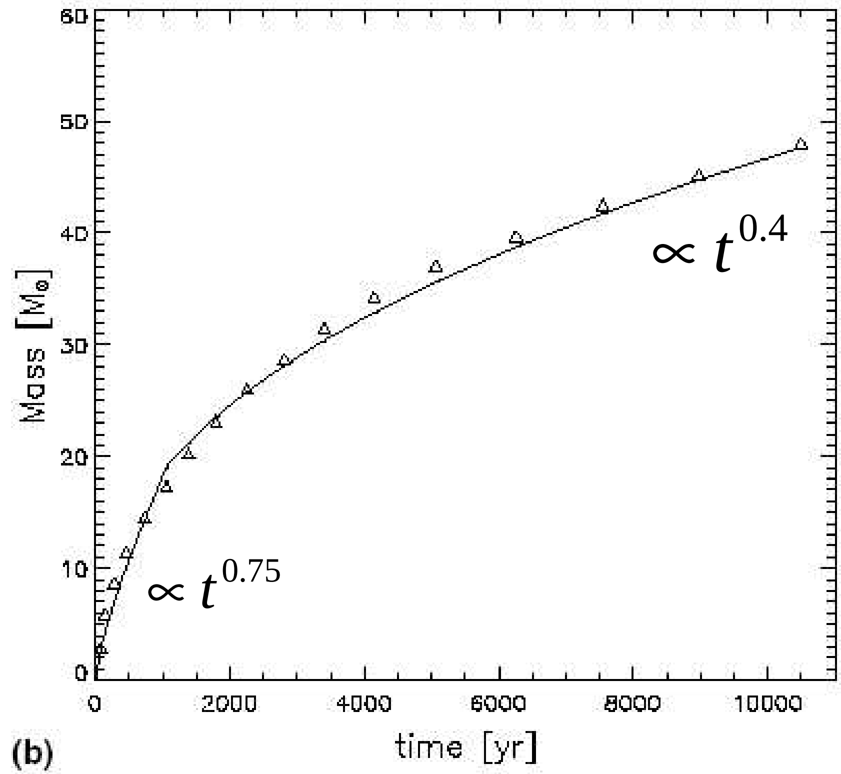
25 pc **0.5 pc**

Accretion onto a Primordial Protostar

dM/dt vs. time



M vs. time



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

Accretion onto a Primordial Protostar

Kelvin-Helmholtz time: $t_{KH} \sim GM^2/(LR) \sim 10^5$ yr

- Onset of nuclear fusion

- violent radiative feedback

→ accretion stops

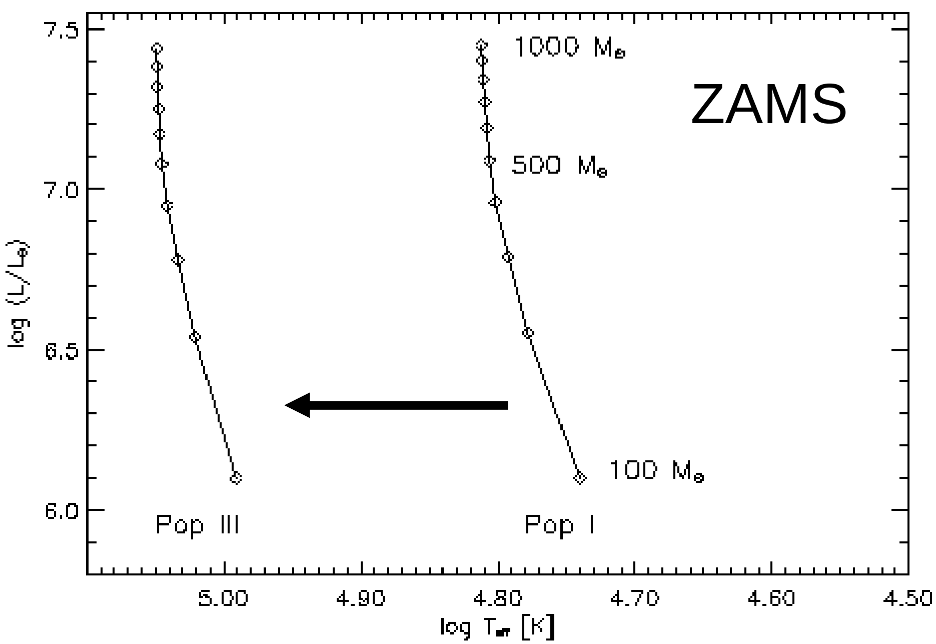
More realistic mass estimate: $M(t=t_{KH}) \sim 120\ M_{sun}$

Implications of a Heavy IMF For the First Stars

(Bromm, Kudritzki, Loeb 2001, ApJ, 552, 464)

- Consider: 100 M_o < M < 1000 M_o (VMO)
- Structure determined by:
  - Radiation pressure, Luminosity close to EDDINGTON limit

log L vs. log T_{eff}



- **For Pop III:**

  T_{eff} ~ 110,000 K

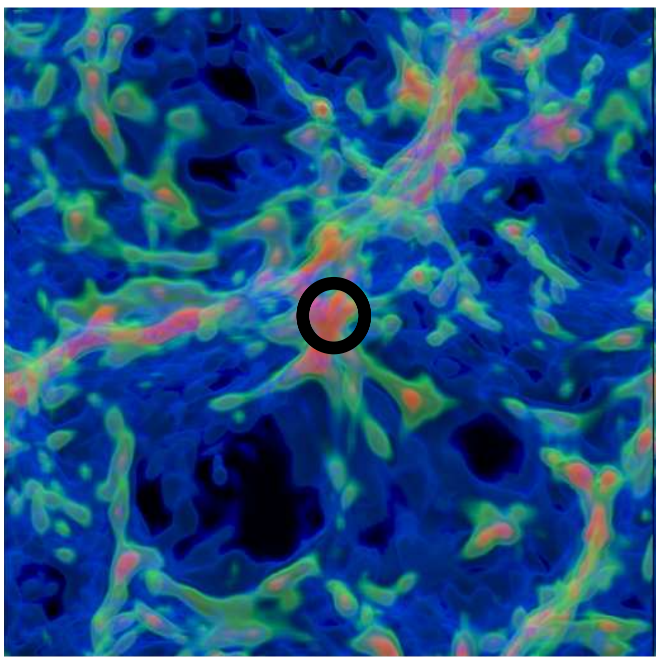
  → lambda peak ~ 250 Å

  (close to He II ionization edge)

Primordial HII Regions

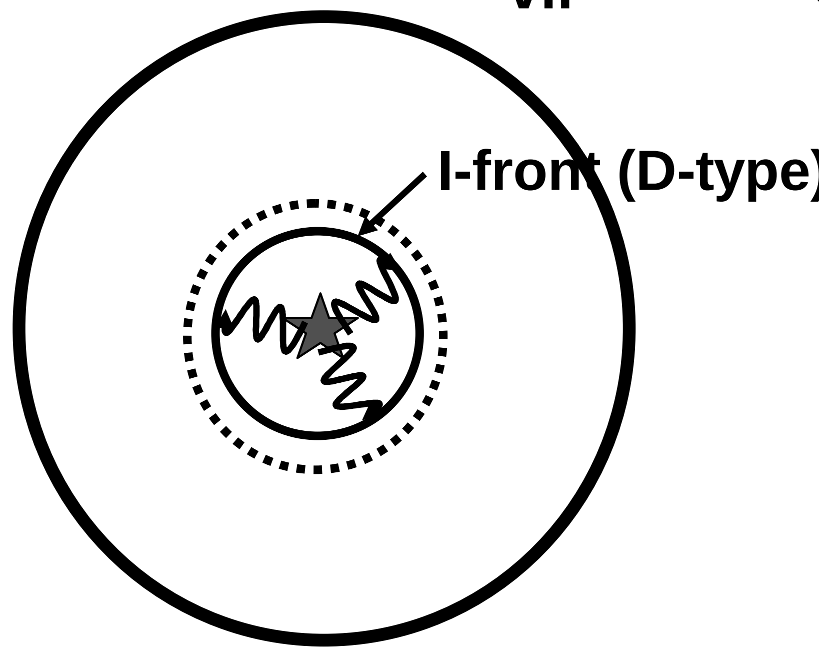
(Alvarez, Bromm, & Shapiro 2005; astro-ph/0507684)

z = 20



← 13.6 kpc →
(proper)

$M_{vir}=10^6 M_O$



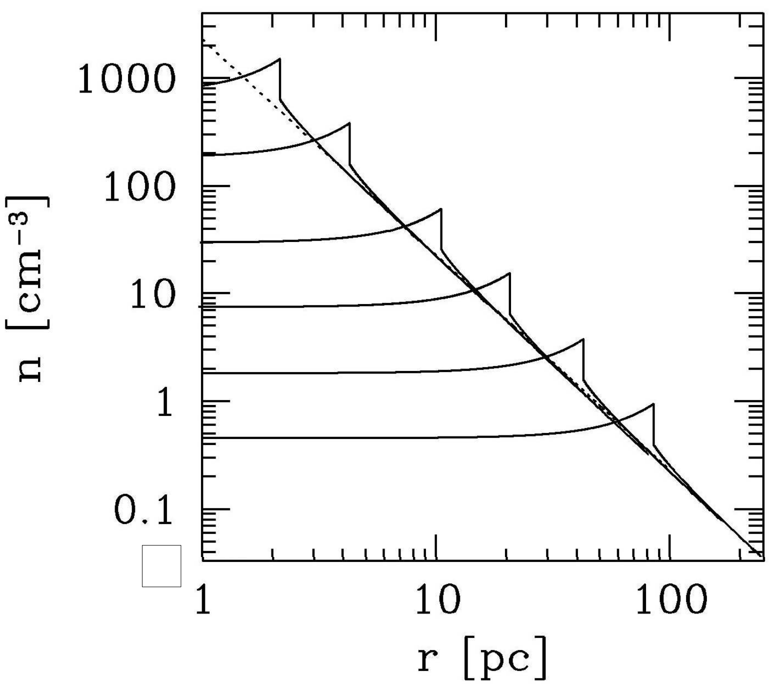
← 300 pc →

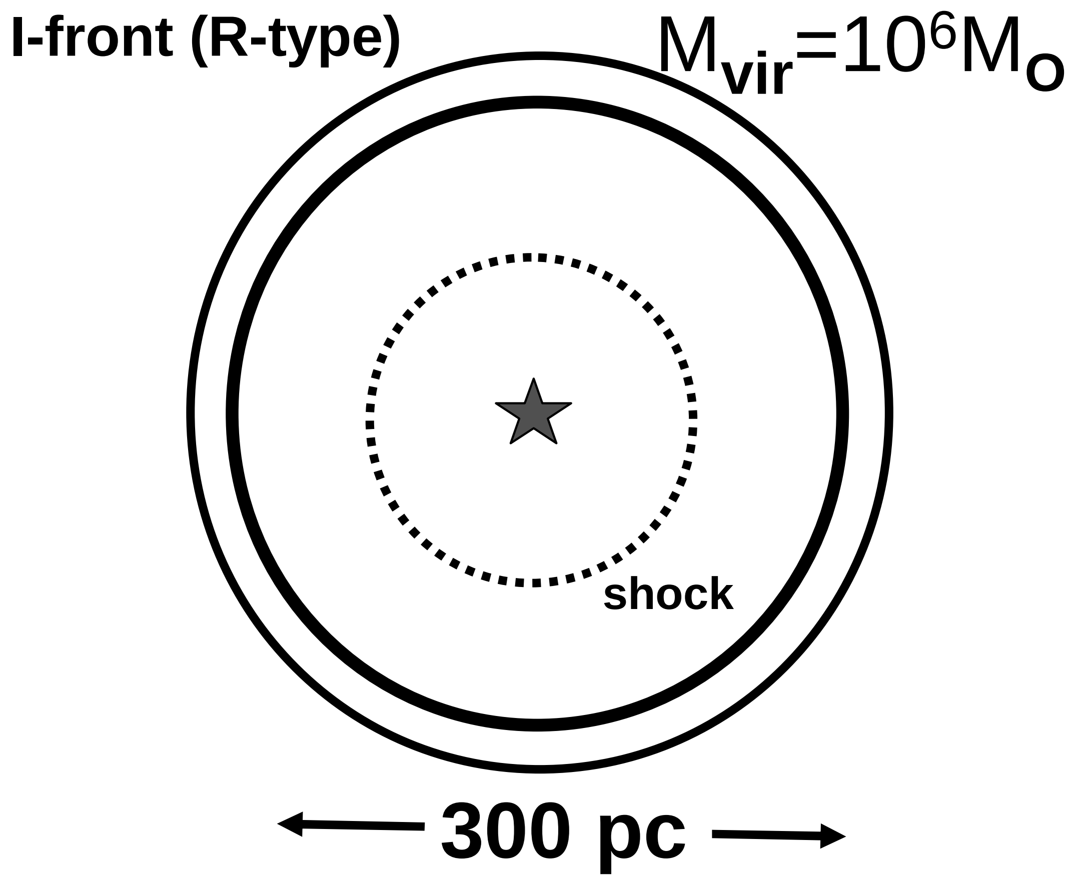
Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2005; astro-ph/0507684)

- density suppression (photo-heating)

n vs r

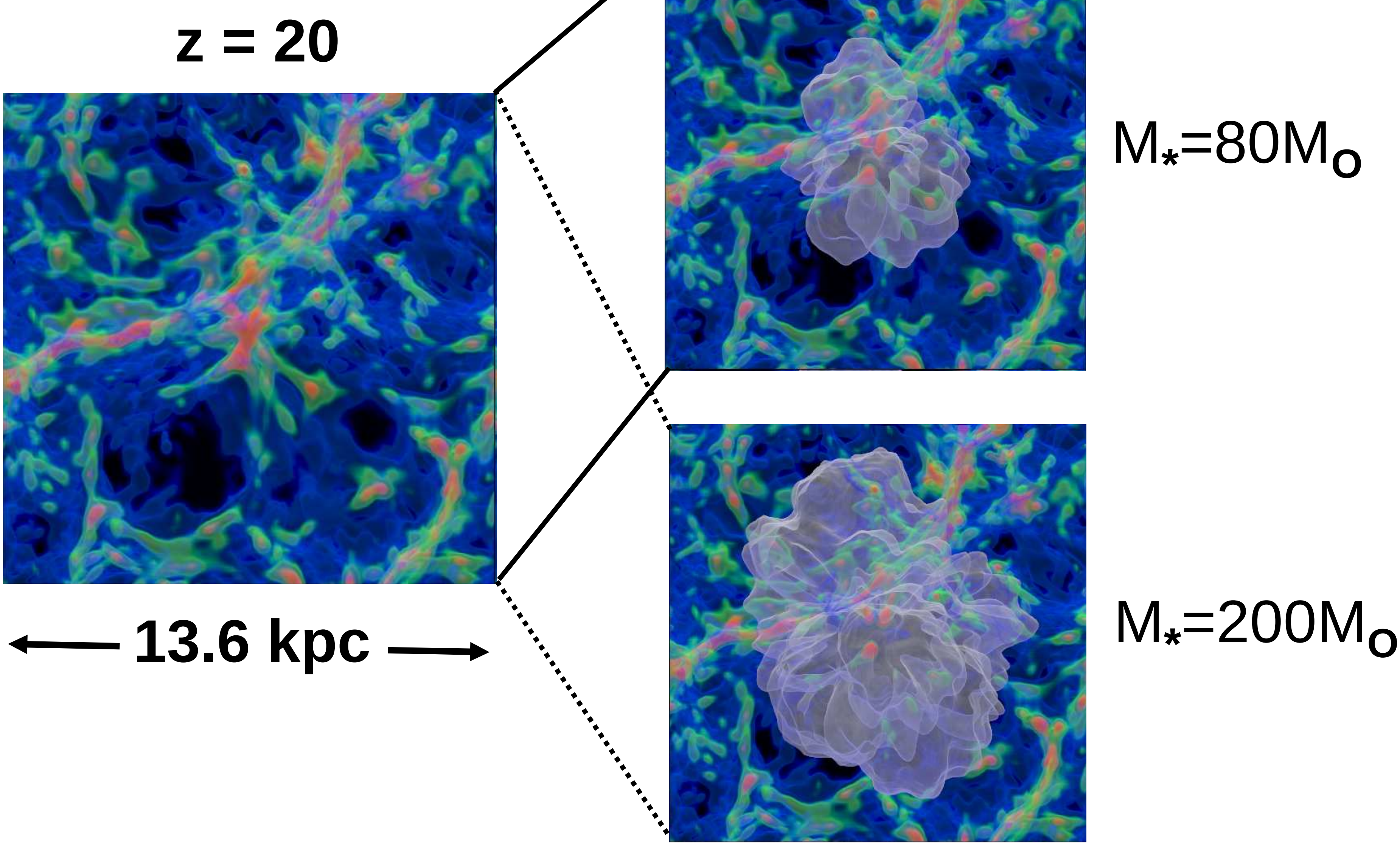




- self-similar “champagne flow” (Shu et al. 2002)

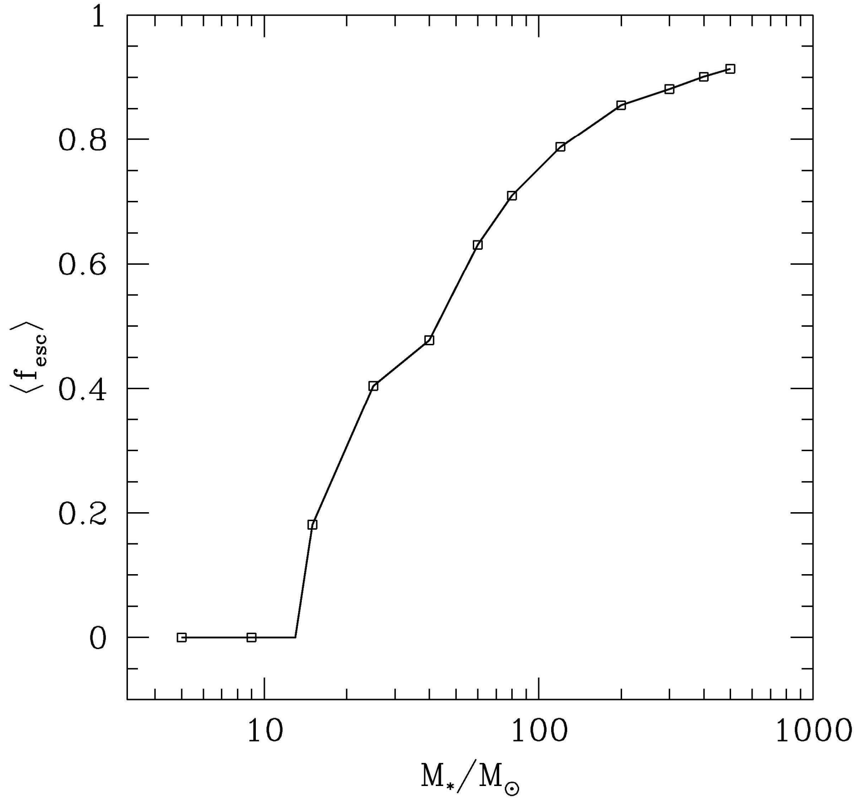
Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2005; astro-ph/0507684)

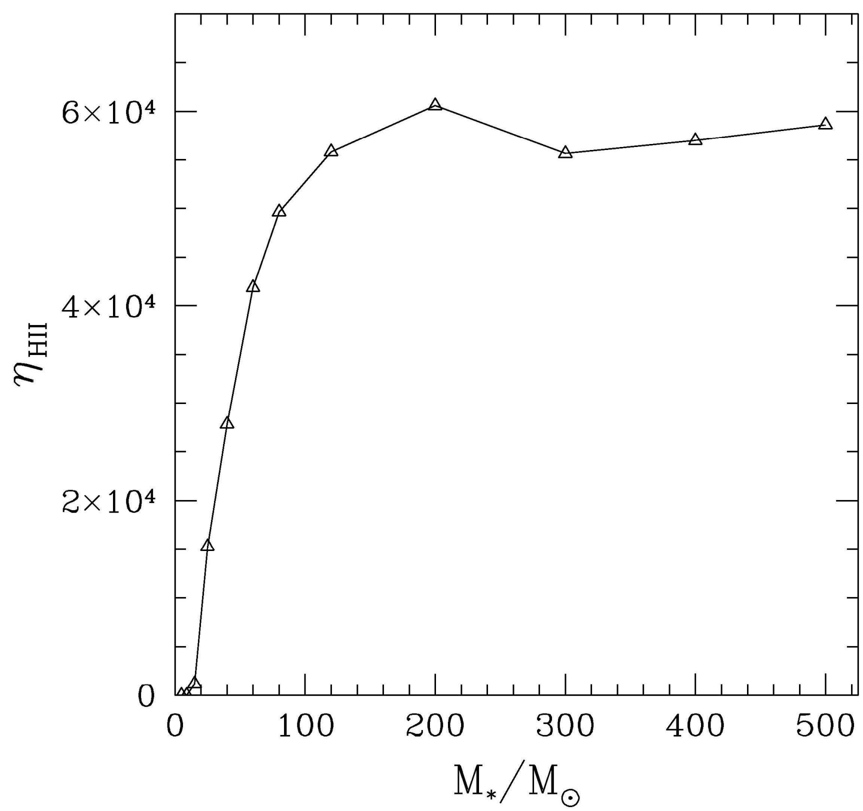


Primordial HII Regions

Average escape fraction vs. stellar mass



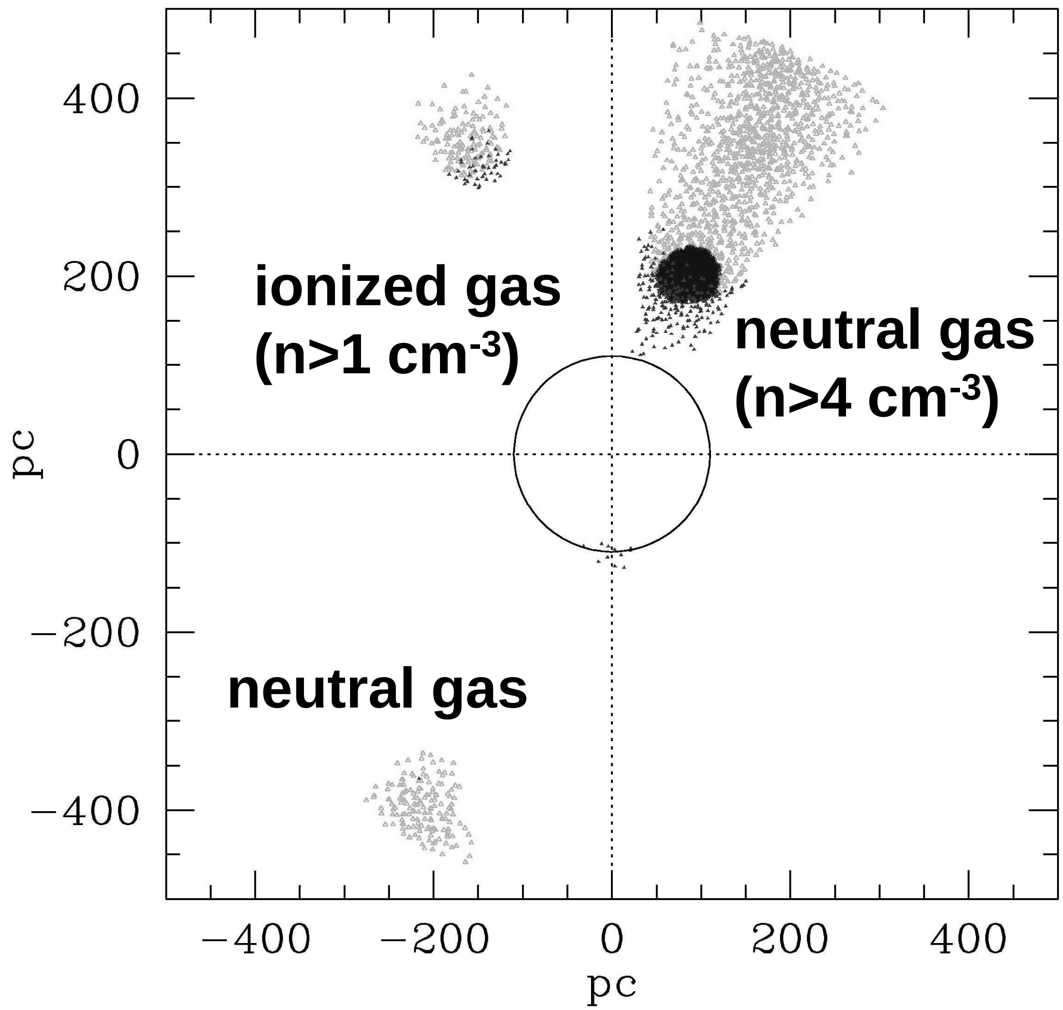
M_{ion}/M_{star} vs. stellar mass



- breakout for $M_{crit} \gtrsim 15\ M_\odot$ only!

Primordial HII Regions

- Impact on neighboring minihalos: Will they be completely ionized? à necessary condition for triggered formation of 2nd star (O'Shea et al. 2005)

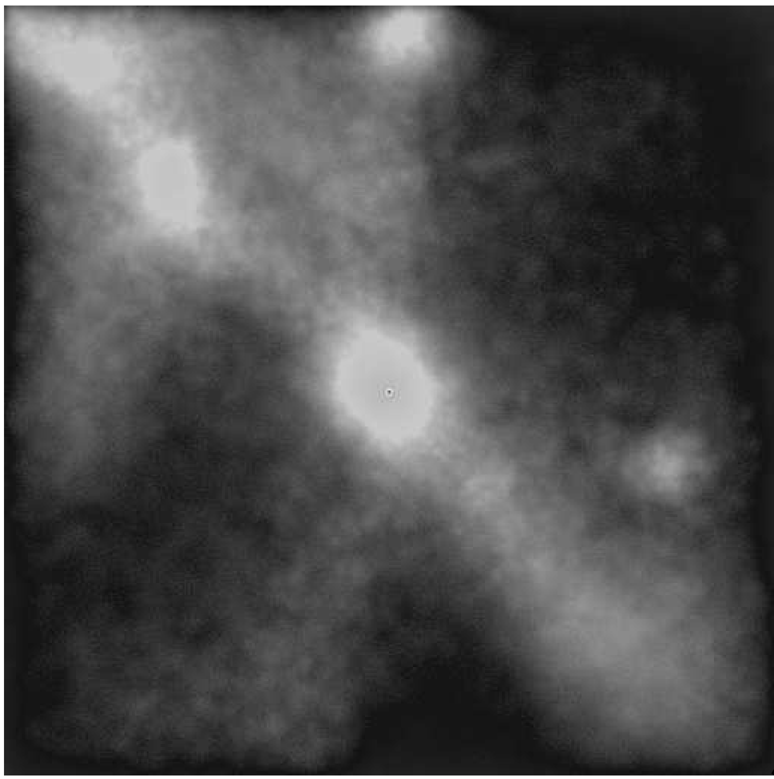


- nearest minihalo is able to self-shield
- *not* fully ionized
- triggered SF by relic HII region may not operate in general

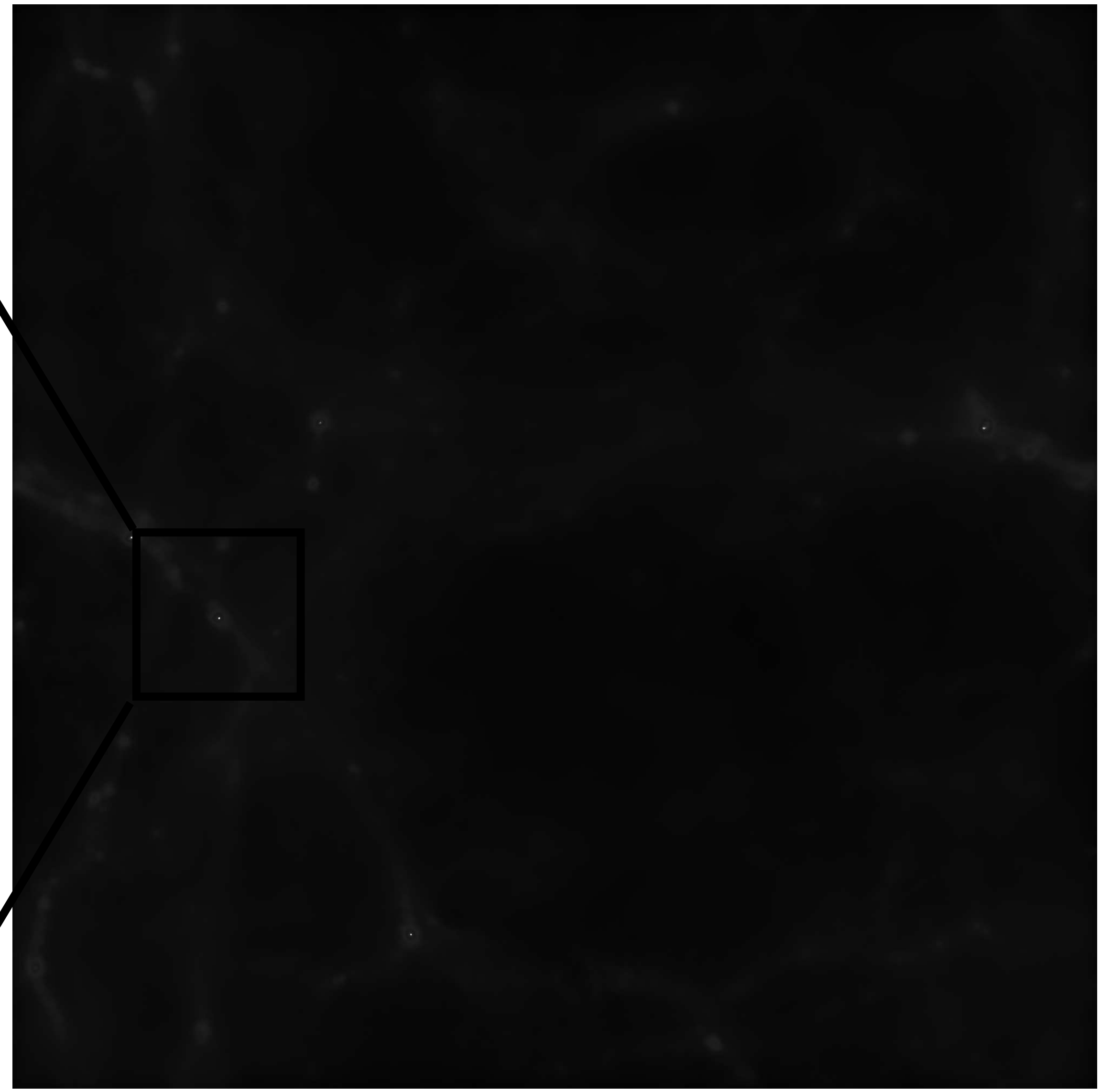
The First Supernova Explosions

(Bromm, Yoshida & Hernquist 2003, ApJ, 596, L135)

$M \sim 10^{6} M_{o}$

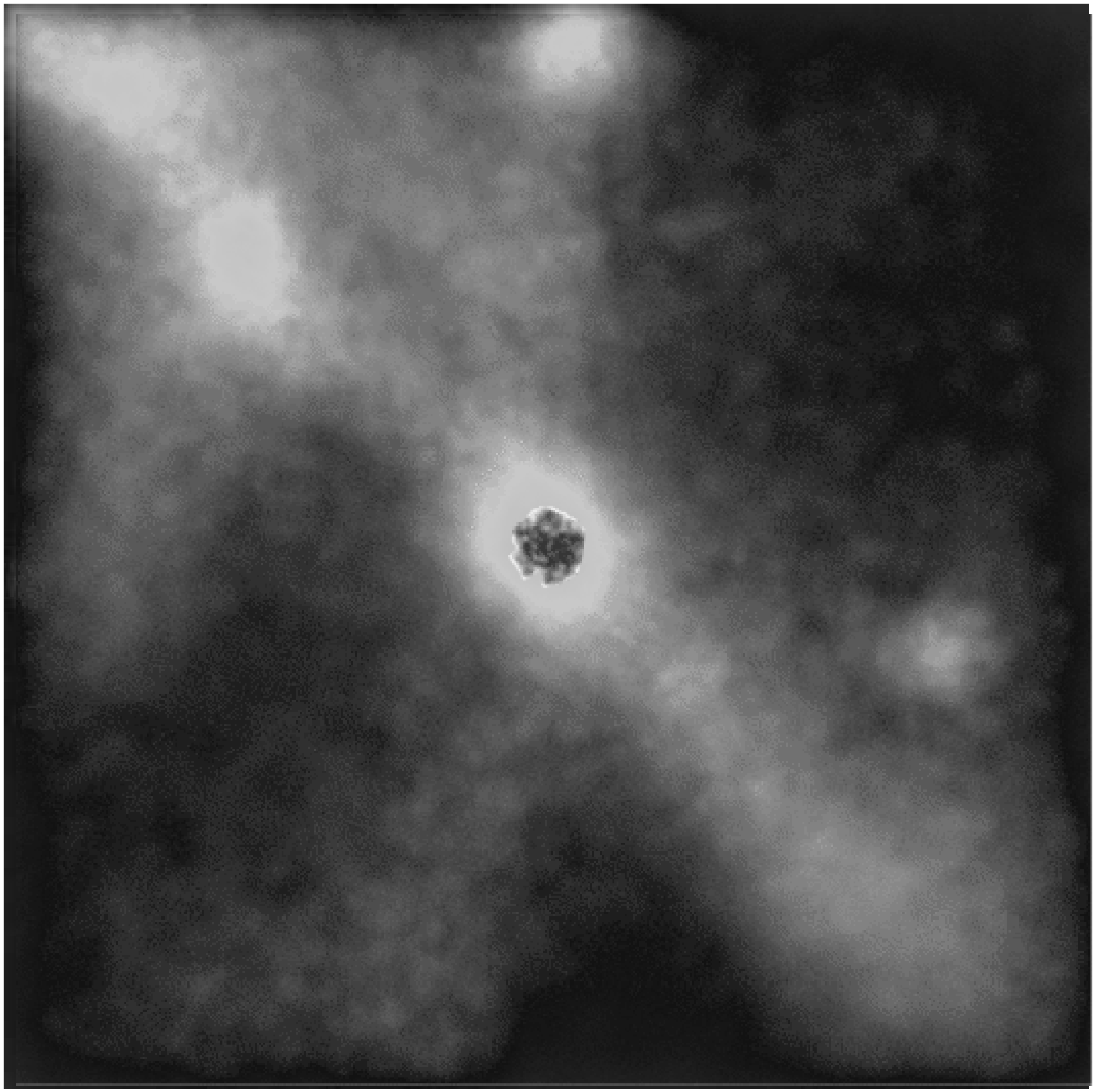


1 kpc



~ 7 kpc

HII Regions around the First Stars

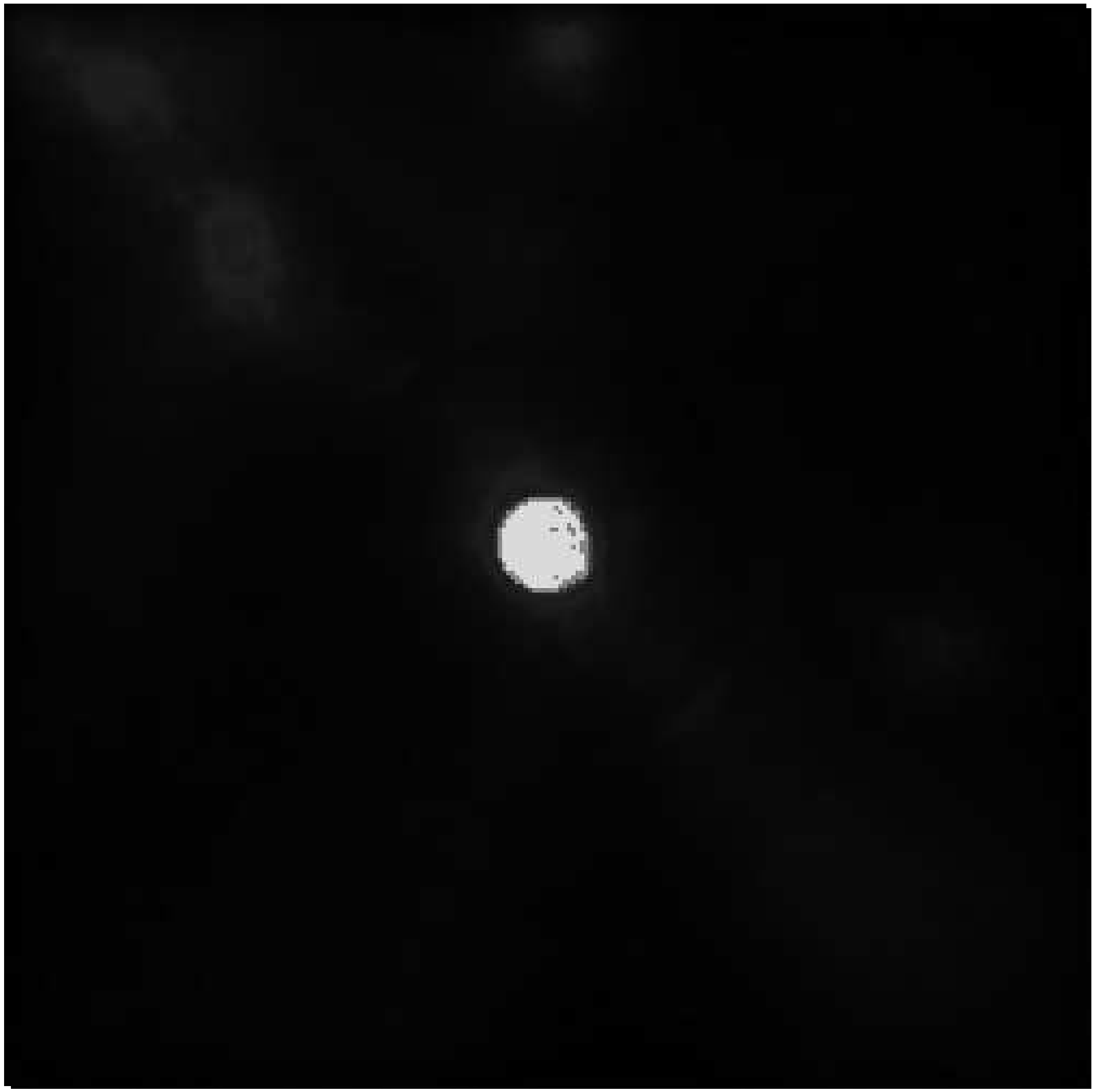


1 kpc

The First Supernova-Explosion

Gas density

~ 1 kpc

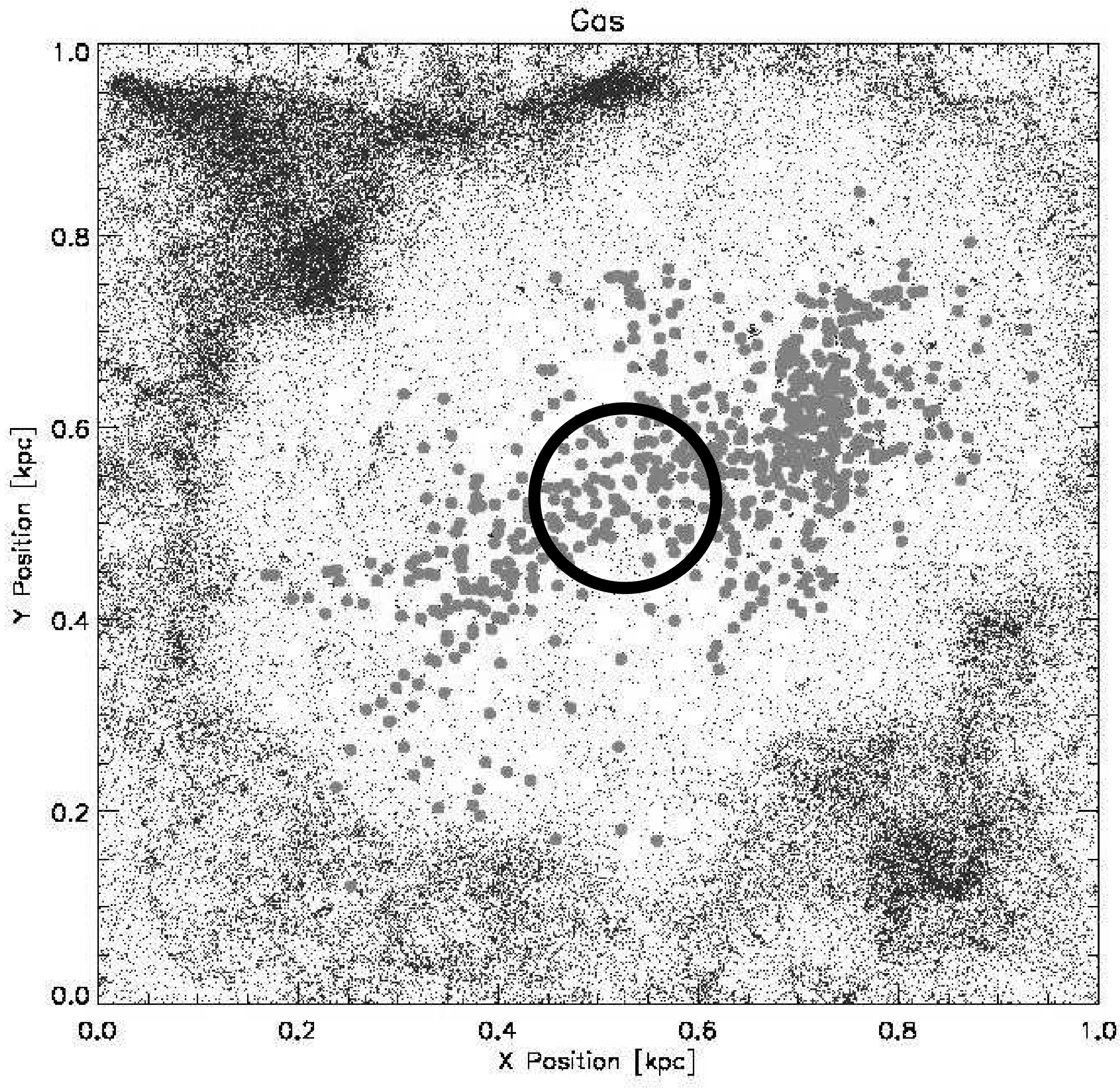


- E_{SN}~10^{53}ergs
- Complete Disruption (PISN)

The First Supernova-Explosion

Metal Distribution

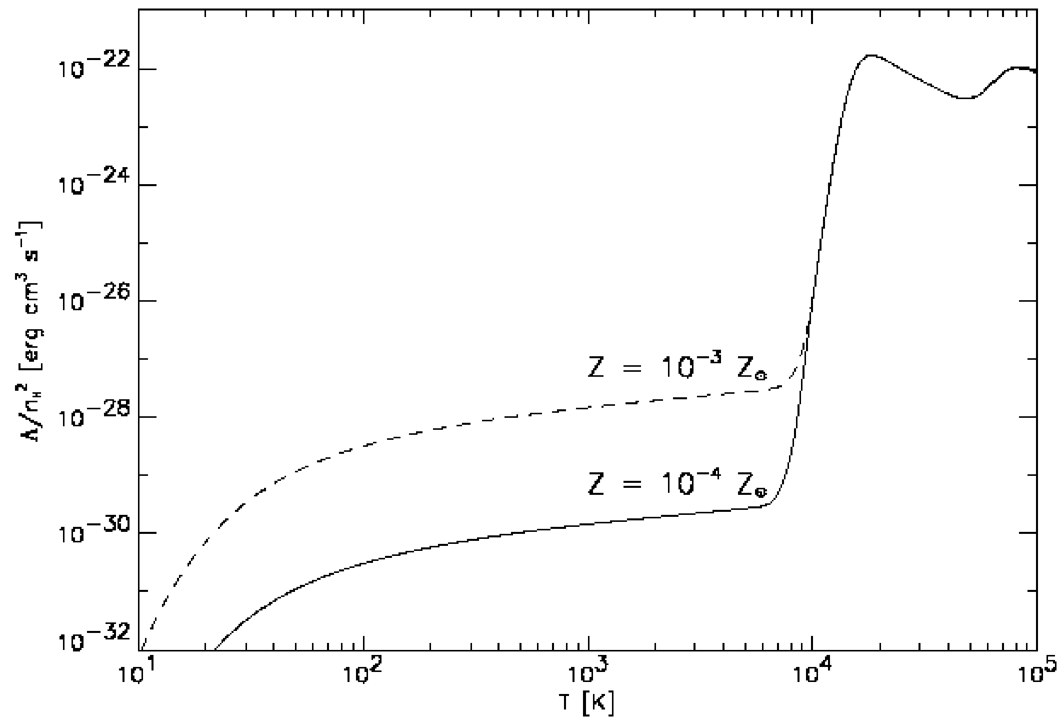
~ 1 kpc



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

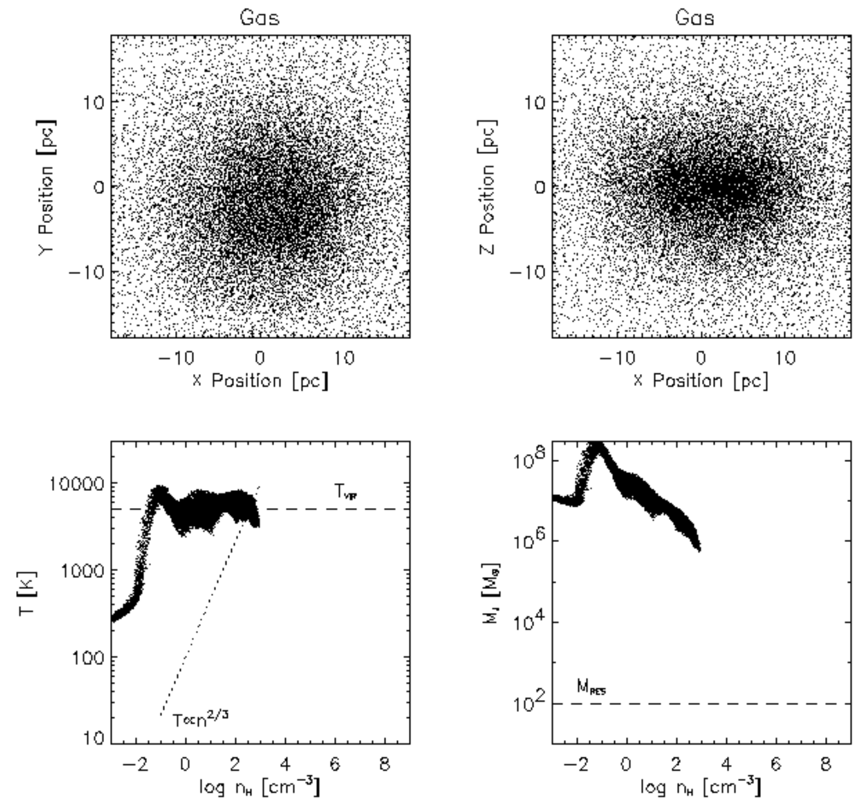
Cooling Rate vs. T



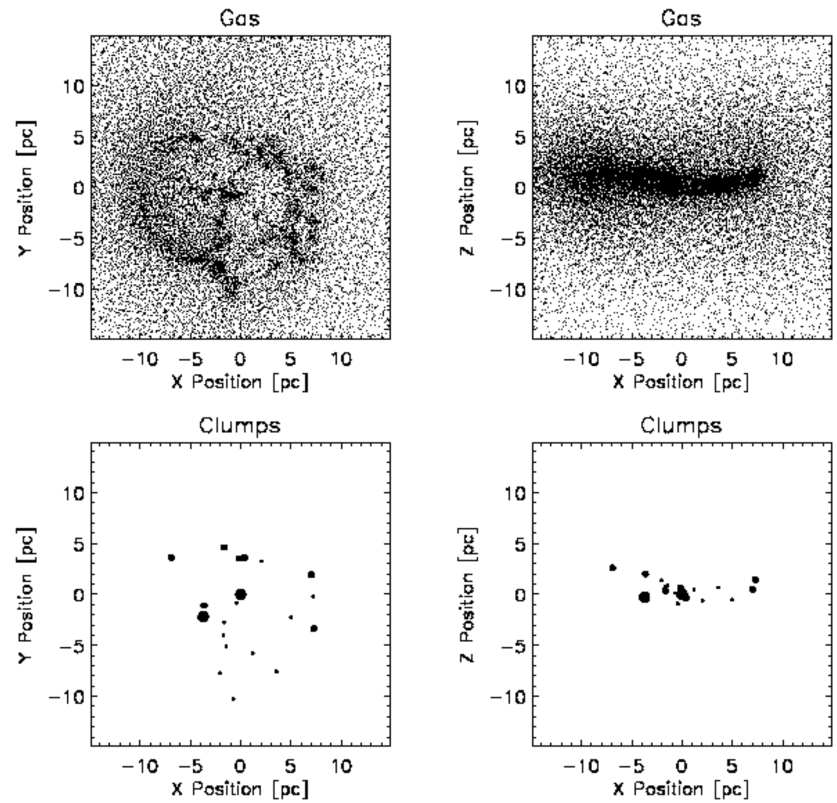
⟶ Consider two identical (other than Z) simulations !

Effect of Metallicity:

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



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



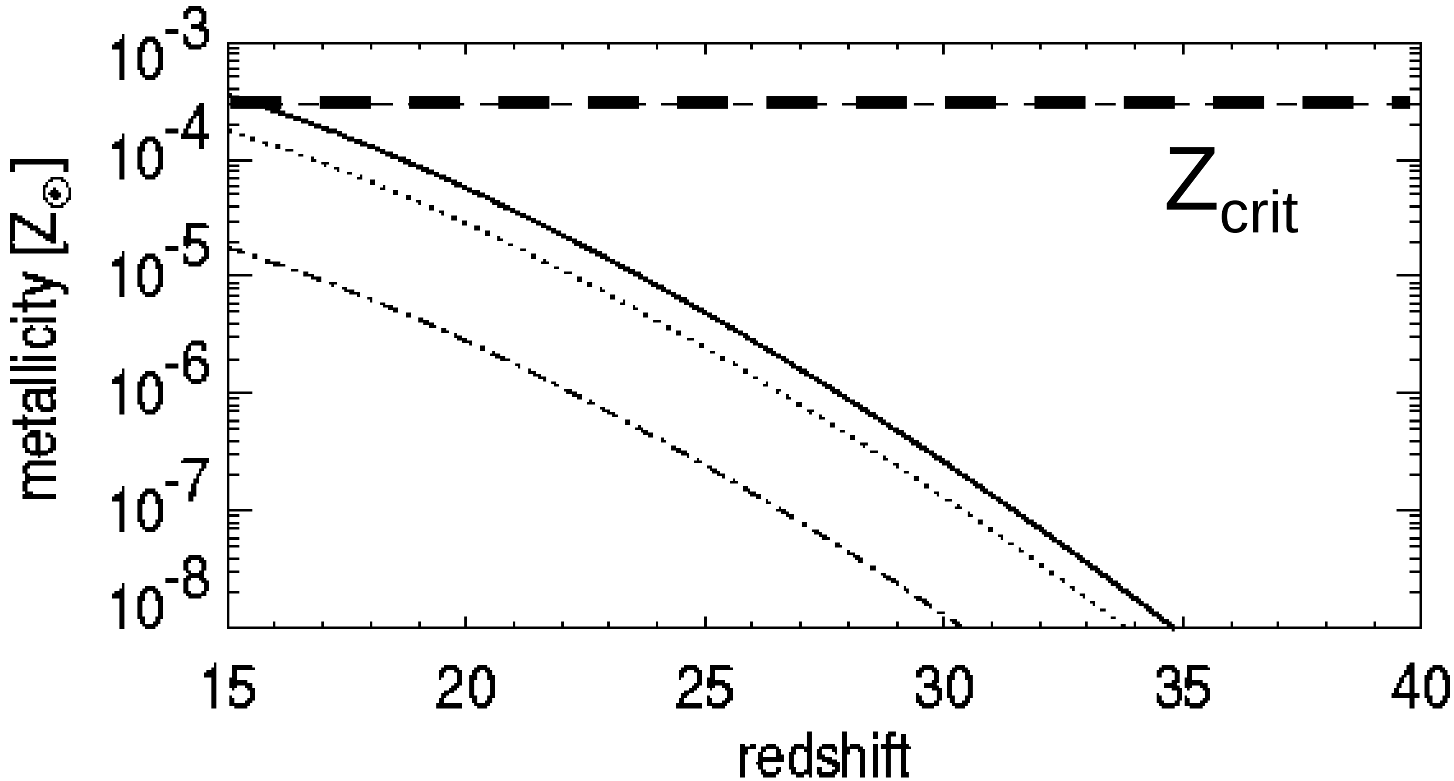
- Insufficient cooling
- Vigorous fragmentation

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

The Pop III ⟶ Pop II Transition

(Yoshida, Bromm & Hernquist 2004, ApJ, 605, 579)

IGM Metallicity vs. redshift

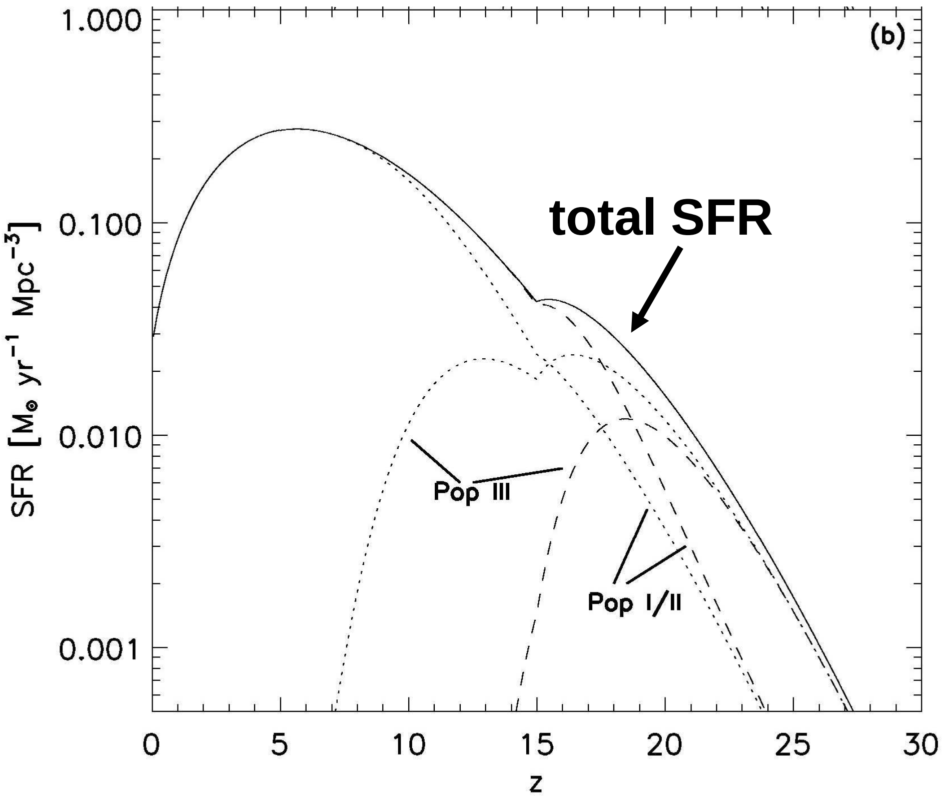


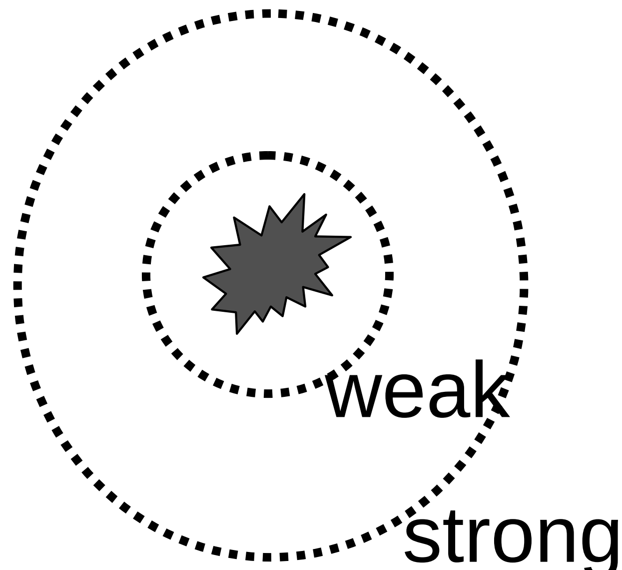
$z_{\mathbf{tran}}$~ 15 +- 5

Chemical Feedback: Pop III à Pop II transition

(Bromm & Loeb 2005; astro-ph/0509303)

SF History





(cf. Scannapieco, Schneider, & Ferrara 2003)

strength of chemical feedback

weak strong

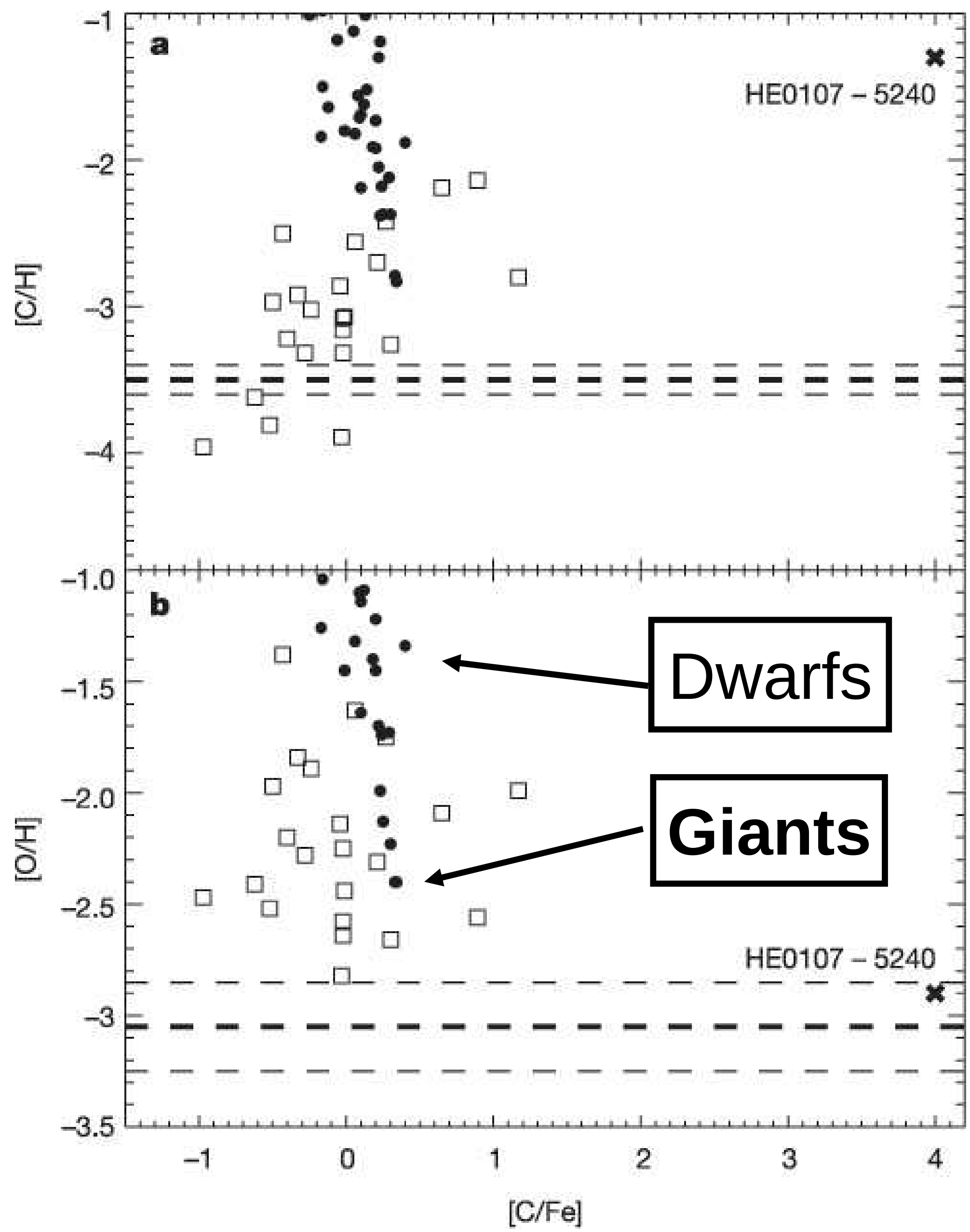
Forming the First Low-mass Stars:

(Bromm & Loeb 2003, Nature 425, 812)

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

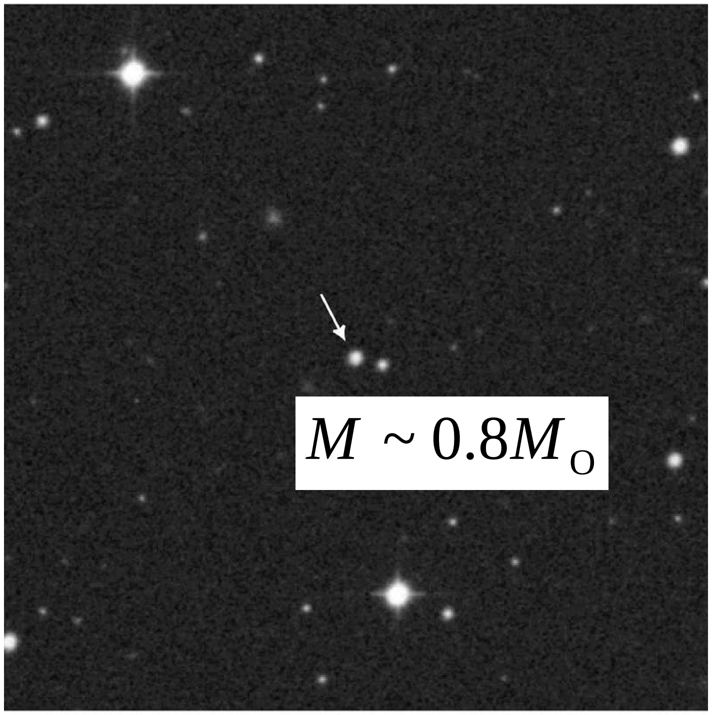
- Pop III ⟶ Pop II:
  - driven by: CII, OI (fine-structure transitions)

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



Relic from the Dawn of Time:

- **HE0107-5240**: [Fe/H] = - 5.3 (Christlieb et al. 2002)



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)

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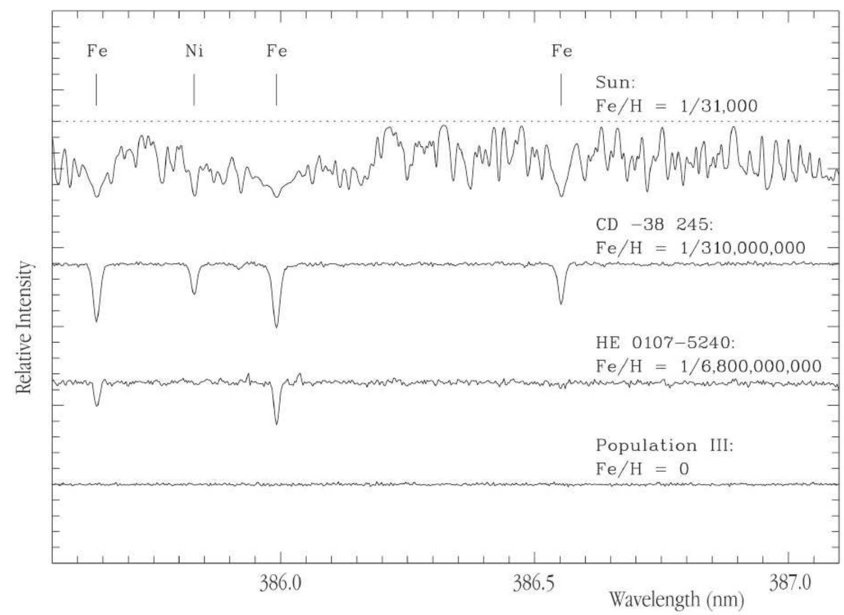


Spectra of Stars with Different Metal Content

ESO PR Photo 25b/02 (30 October 2002)

©European Southern Observatory

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

Fate of shock-heated primordial gas

(Johnson & Bromm 2005, astro-ph/0505304)

- How to account for abundance pattern in C-rich UMP stars (e.g., HE0107-5240, HE1327-2326)?

- BH-forming SNe with progenitor masses $\gtrsim 25\ M_\odot$

(Umeda & Nomoto 2002, 2003)

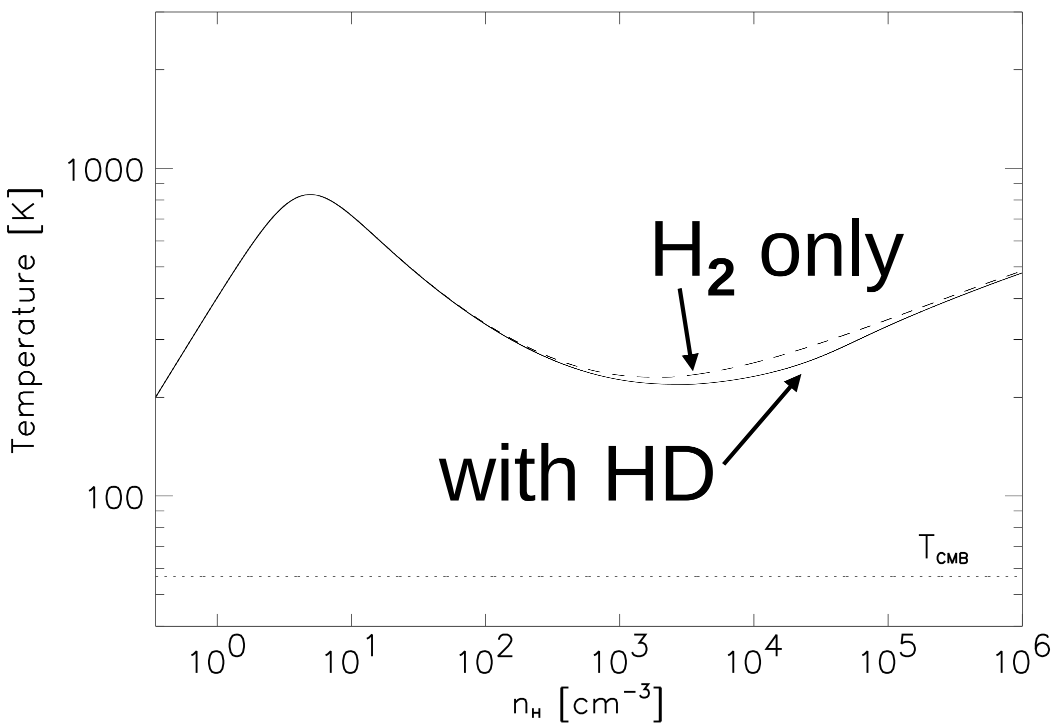
- Our suggestion: "Population II.5 stars"
  - almost metal-free
  - $M_{char} \sim$ few 10 $M_\odot$ (cf. Pop III: $M_{char} \sim$ few 100 $M_\odot$)

(see Mackey, Bromm, & Hernquist 2003)

Fate of shock-heated primordial gas

(Johnson & Bromm 2005, astro-ph/0505304)

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

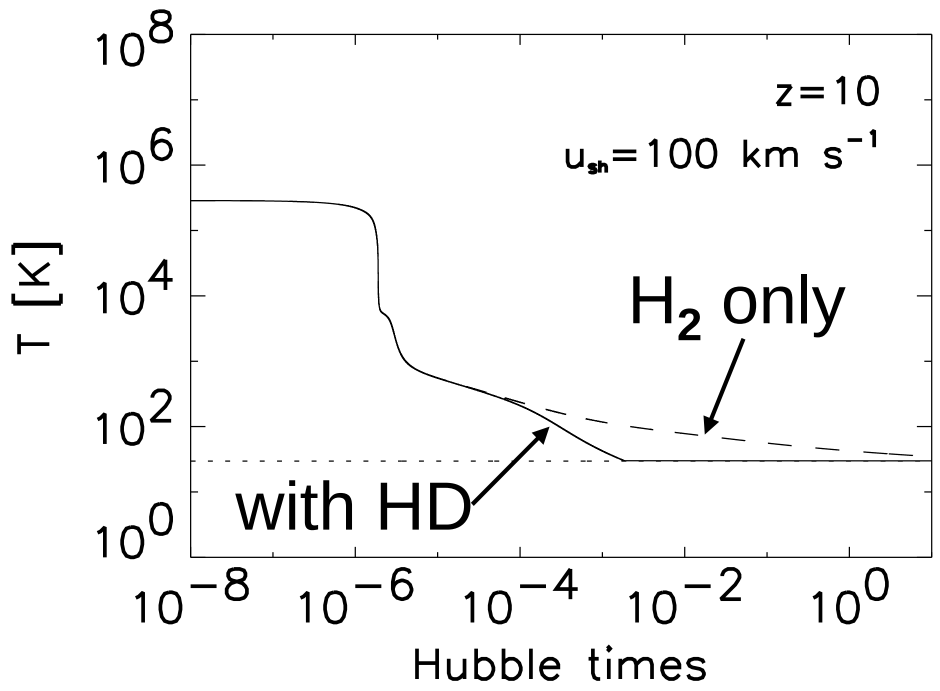


- HD makes no difference! (M_{char}~ few 100 $M_{\odot}$)

Fate of shock-heated primordial gas

(Johnson & Bromm 2005, astro-ph/0505304)

2) Shocked-case (T_{vir} > 10,000 K): Pop II.5

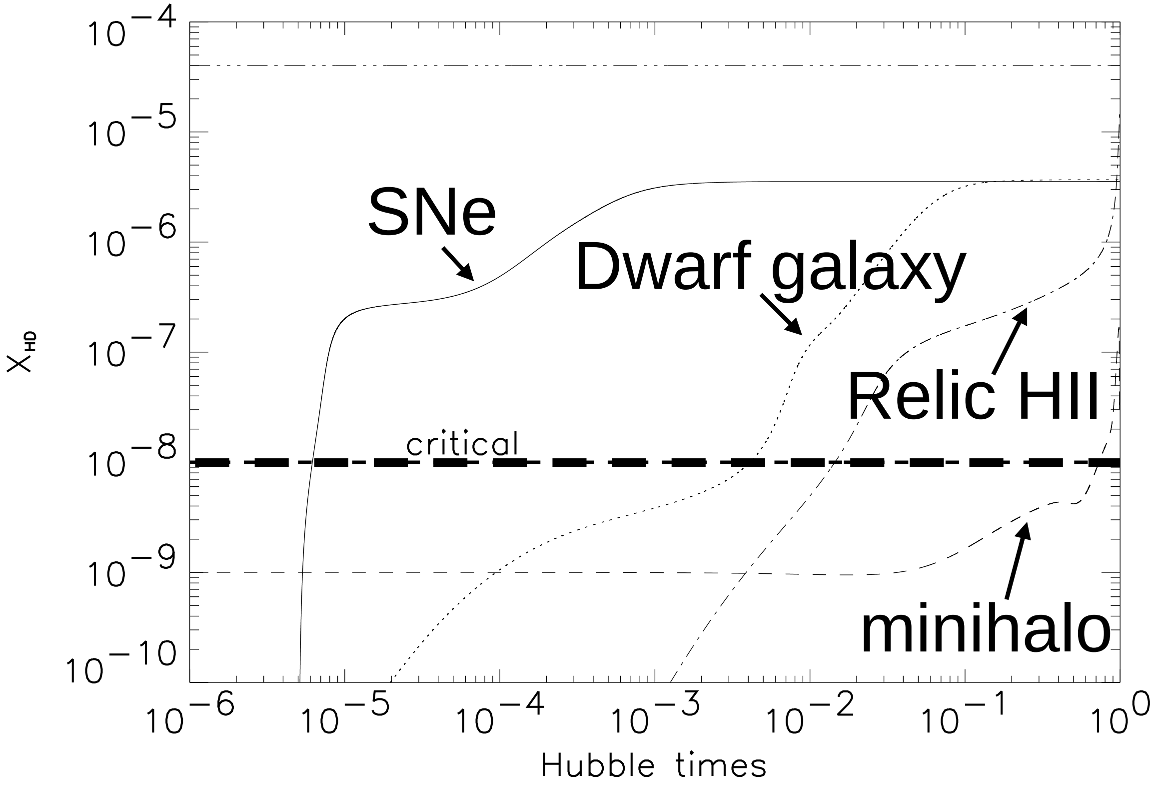


- HD may make difference! (M_{char}~ few 10 $M_{\odot}$)

Fate of shock-heated primordial gas

(Johnson & Bromm 2005, astro-ph/0505304)

HD abundance vs time

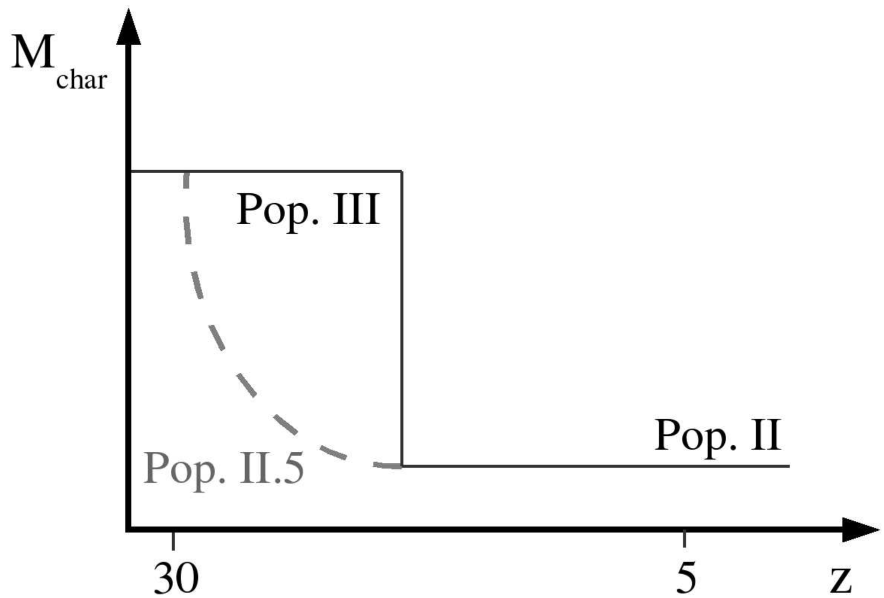


- Successful cooling to CMB: $X_{\mathbf{HD}} > X_{\mathbf{HD,crit}} \sim 10^{-8}$

Fate of shock-heated primordial gas

(Johnson & Bromm 2005, astro-ph/0505304)

- Star formation in high-z universe:

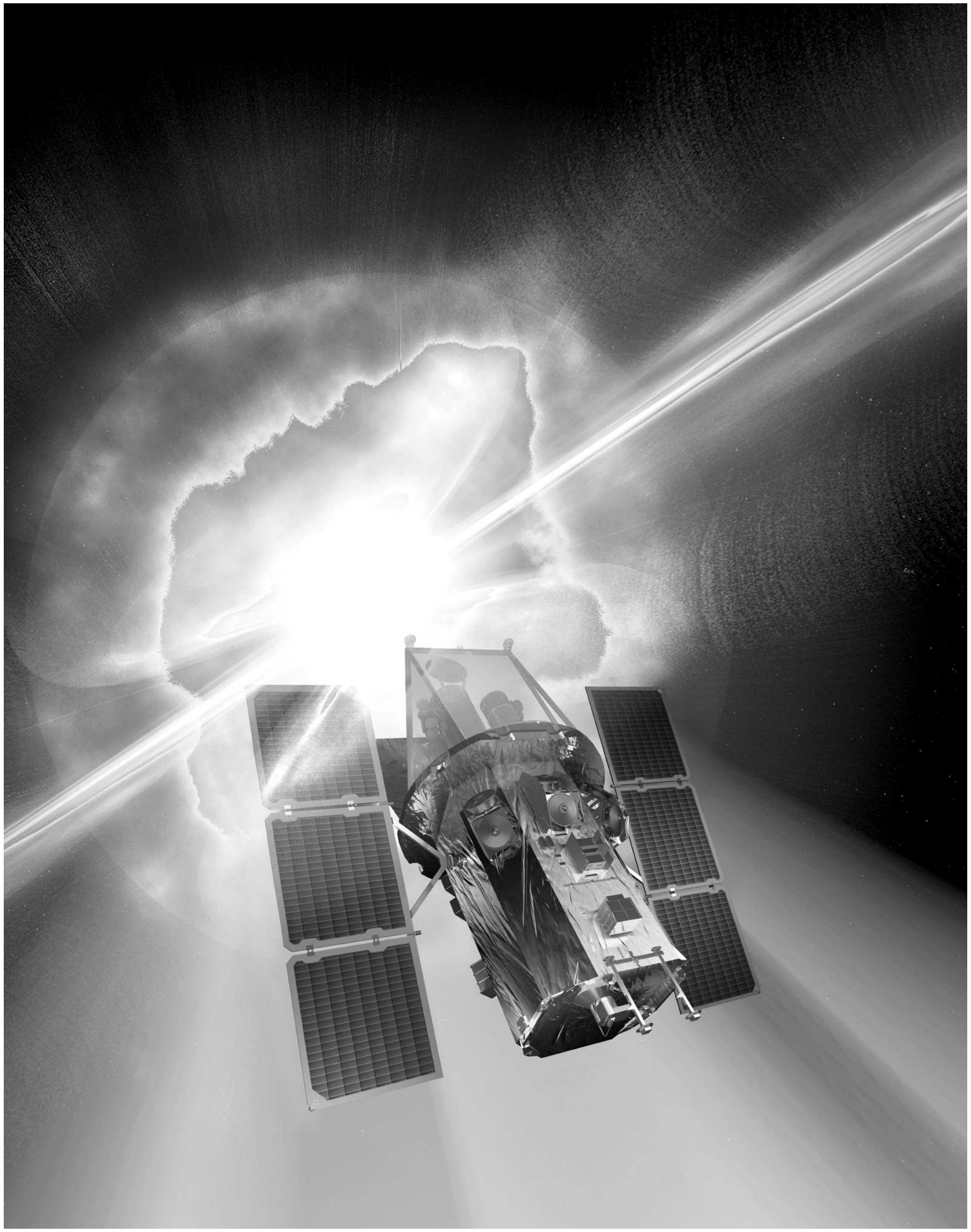


- Pop III:
  - $M_{\mathbf{char}}$ ~ few 100 $M_{\odot}$
- Pop II.5:
  - $M_{\mathbf{char}}$ ~ few 10 $M_{\odot}$
- Pop II:
  - $M_{\mathbf{char}}$ ~ few 1 $M_{\odot}$

time

- How abrupt is Pop III ⟶ Pop II transition?

Gamma-Ray Bursts as Probes of the First Stars:

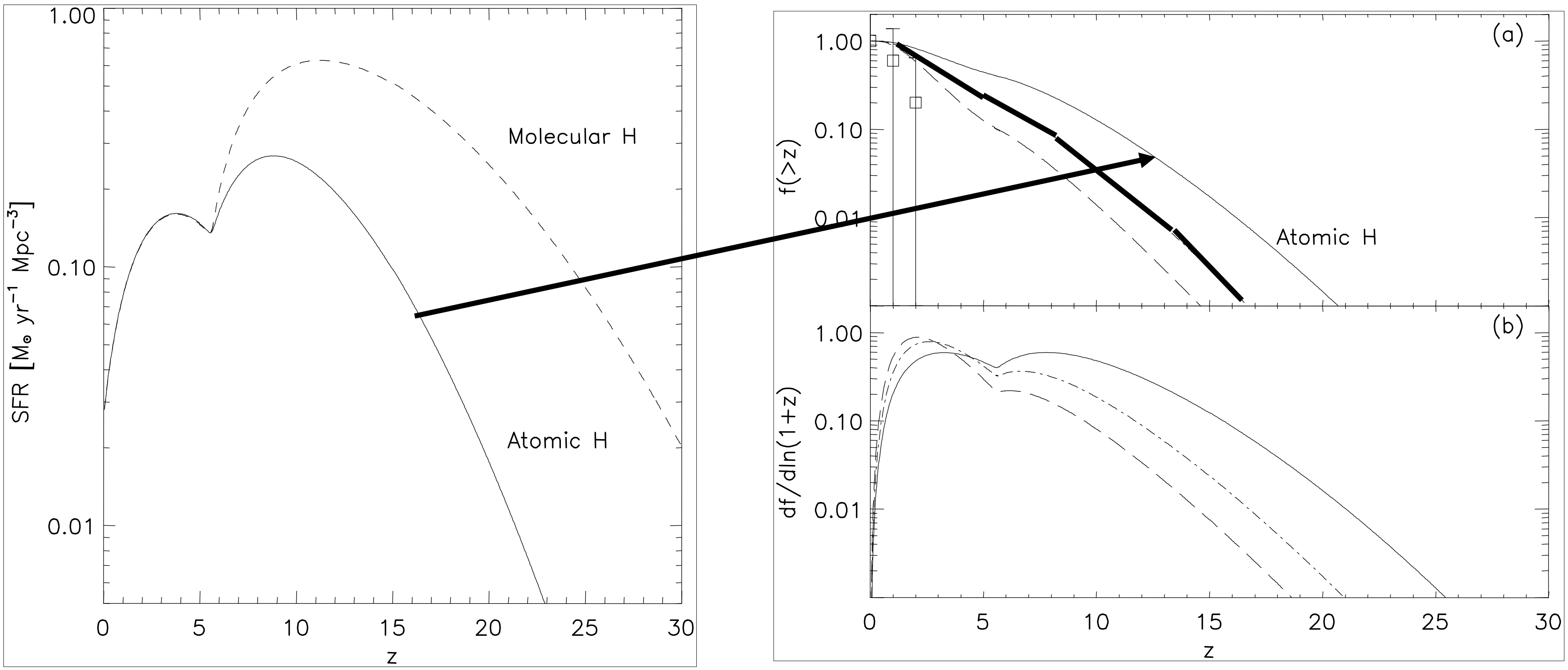


- GRB progenitors → massive stars
- GRBs expected to trace cosmic SFH
- *Swift* mission:
  - Launched in 2004
  - Sensitivity → GRBs from $z > 15$

Expected Redshift Distribution of GRBs:

(Bromm & Loeb 2002, ApJ, 575, 111)

SF History / GRB Redshift Distribution



(Cf. Barkana & Loeb 2000, ApJ, 539, 20)

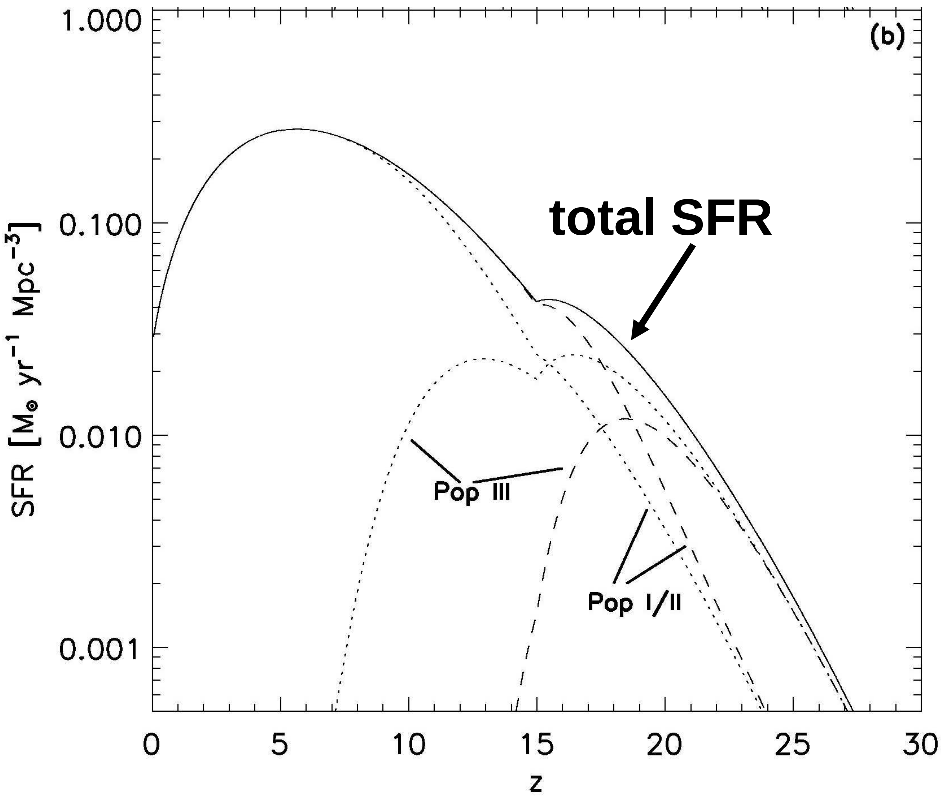
(see also Lamb & Reichart 2000)

- Fraction of *all* burst from z > 5: ~ 50%
- Fraction of GRBs detected by *Swift* from z > 5: ~25%

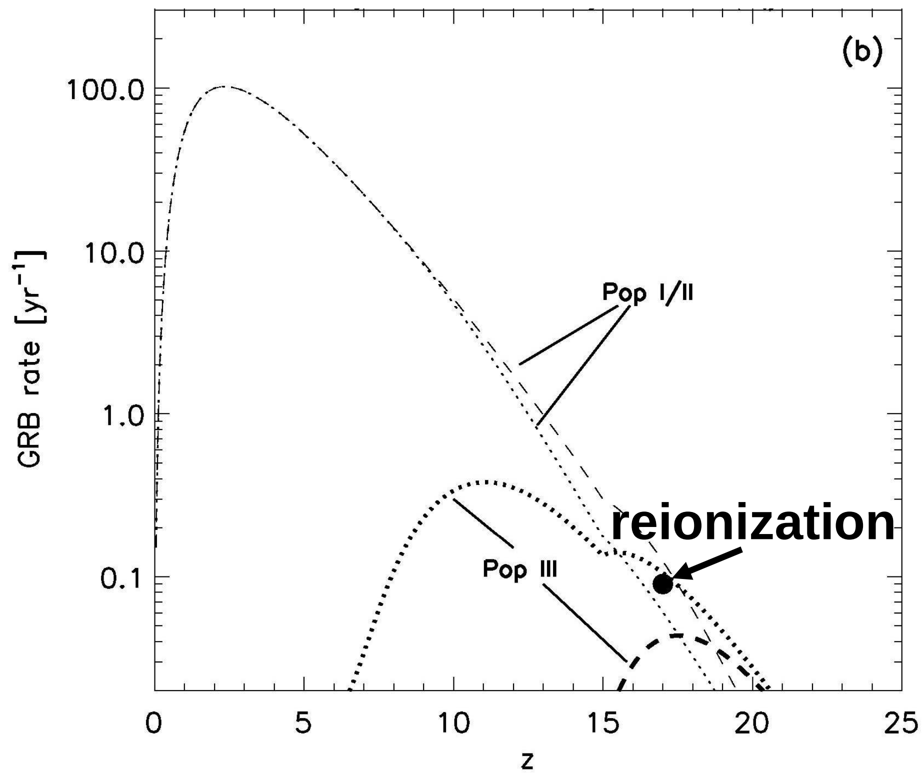
High-z GRBs from Population III Progenitors:

(Bromm & Loeb 2005; astro-ph/0509303)

<u>SF History</u>



<u>GRB Redshift Distribution</u>



- expect only small number of Pop III bursts over ~5 yr *Swift* mission
- Fraction of GRBs detected by *Swift* from z > 5: ~10%

Summary

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

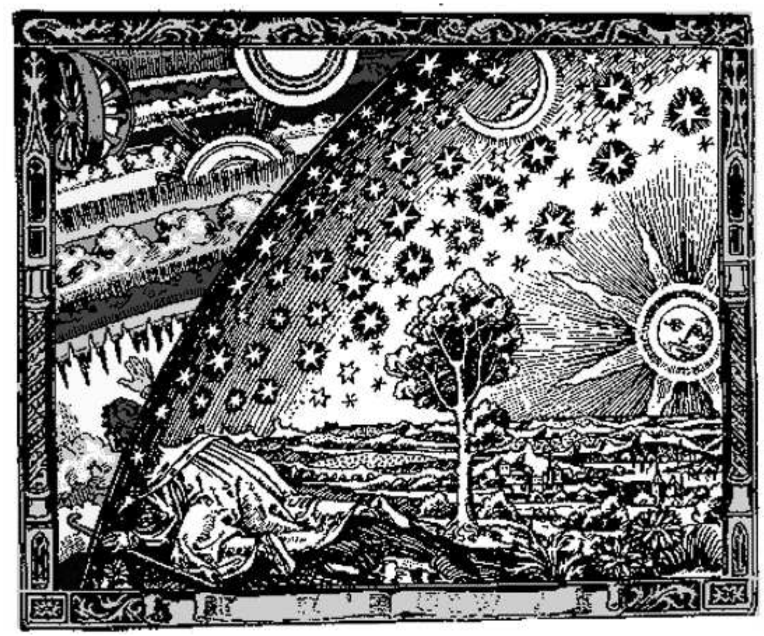
- Pop III SF might have favored *very massive stars*

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

- PISNe completely disrupt mini-halos and enriches surroundings

- 2nd generation of intermediate-mass stars ("Pop II.5")

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?