Texas Cosmology Network

(Austin, September 2006)

The First Stars

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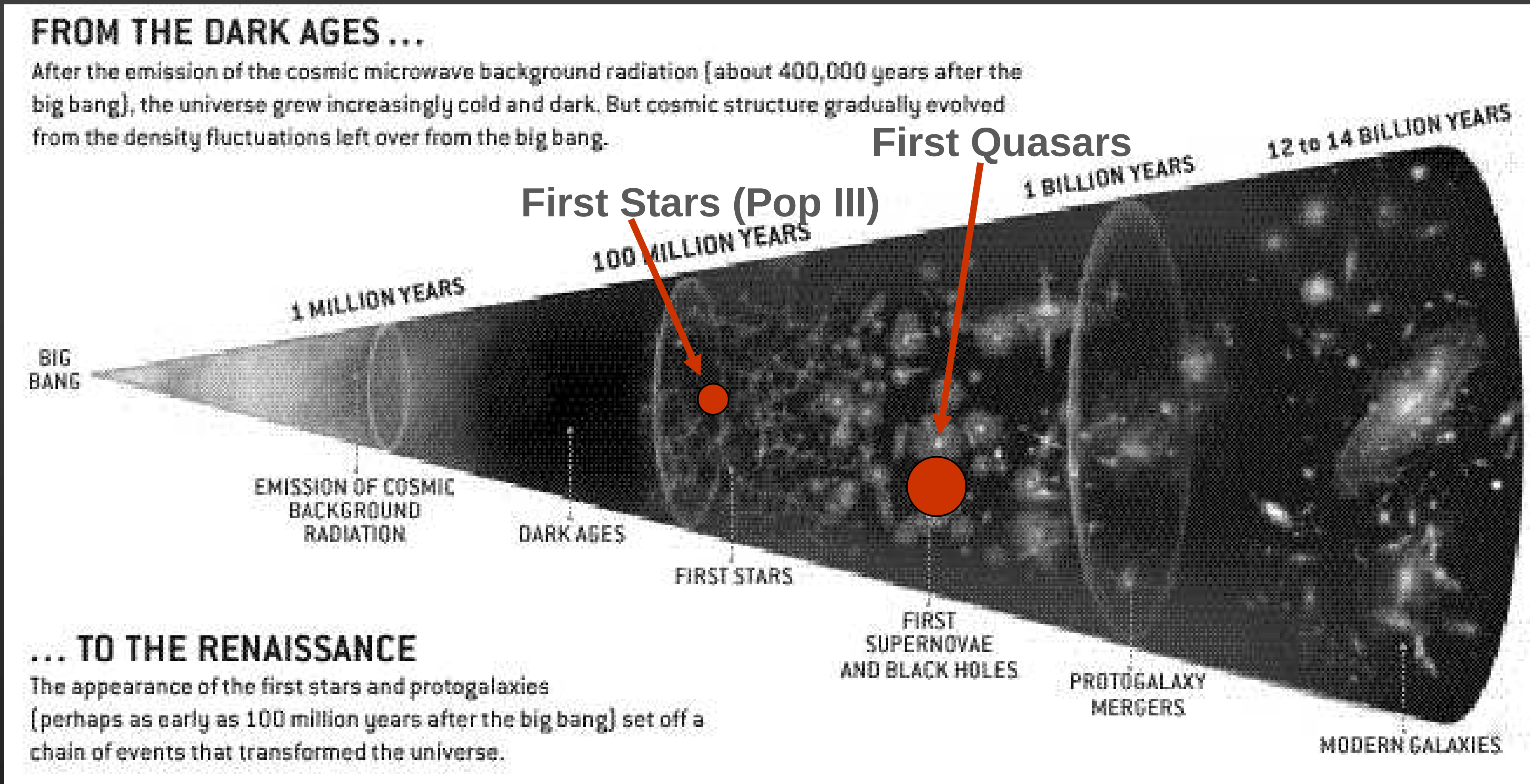
The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance

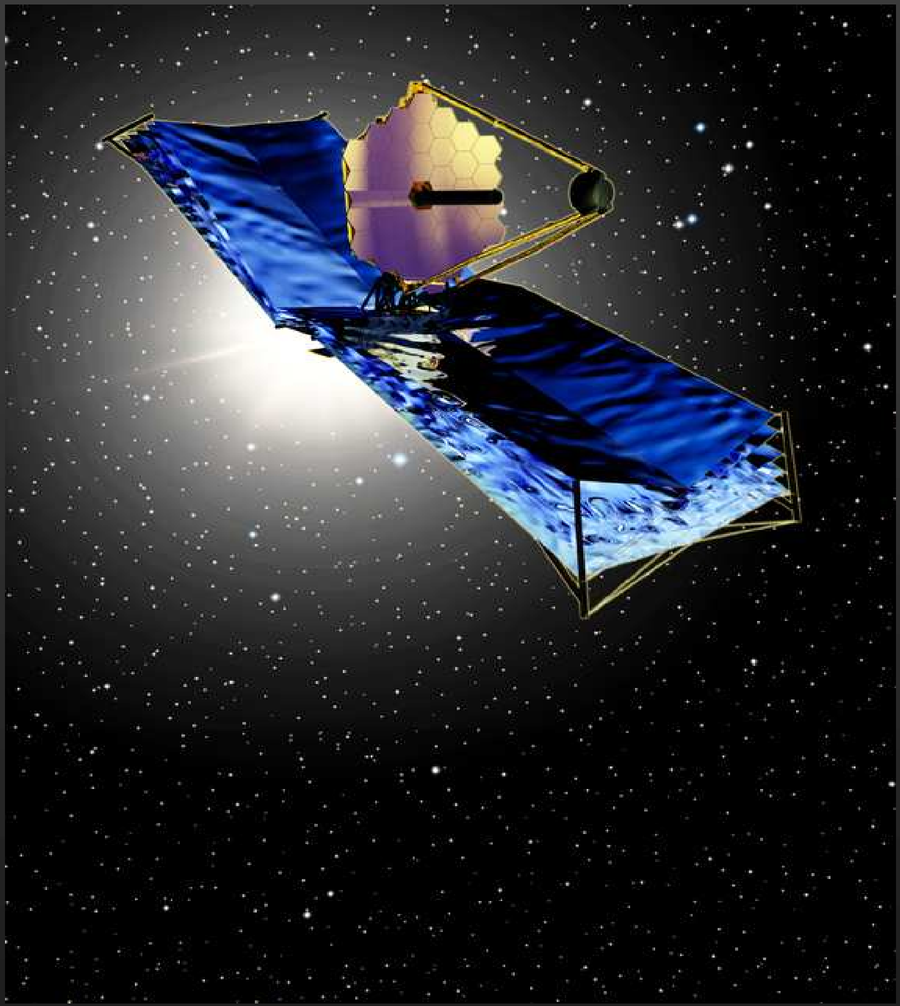


(Larson & Bromm, Scientific American, Dec. 2001)

- First Stars $\longrightarrow$ Transition from Simplicity to Complexity

The James Webb Space Telescope:

(Next Generation Space Telescope)

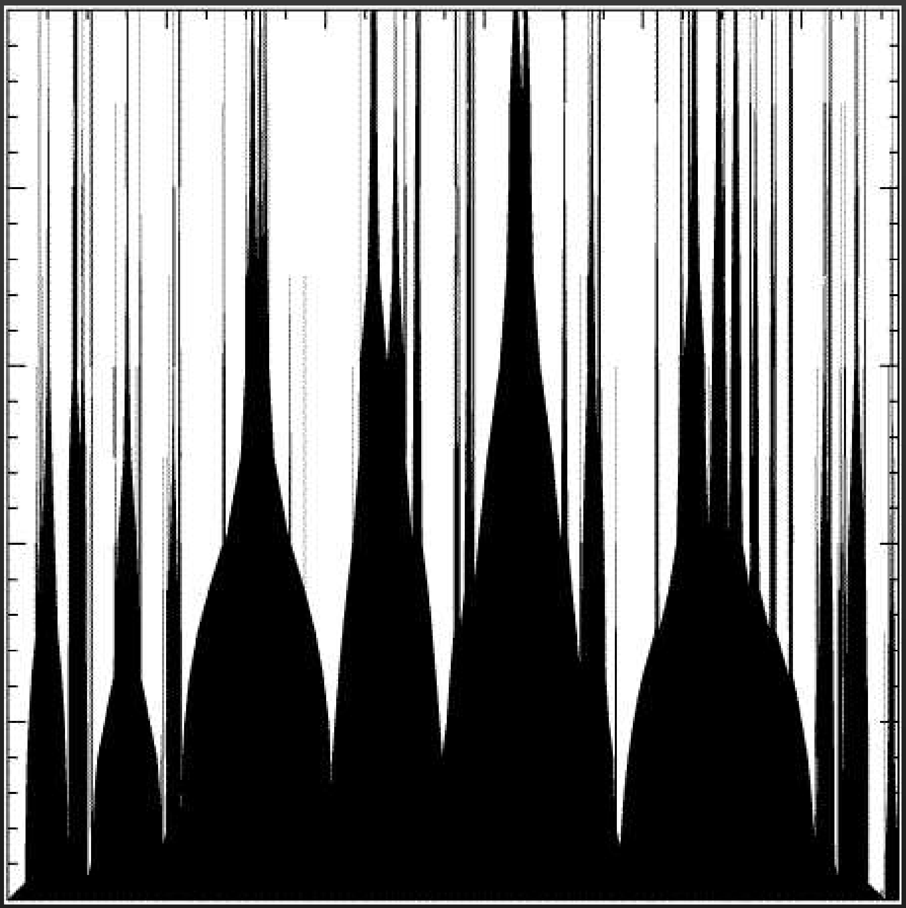


- Launch in ~2013
- Near IR sensitivity of ~ 1 nJy
- ~ 4’ x 4’ FOV

→ **Direct Imaging of the First Stars**

Hierarchical Structure Formation:

Merger tree



- Variant of CDM
- Typical mass scale of collapsed objects increases with time

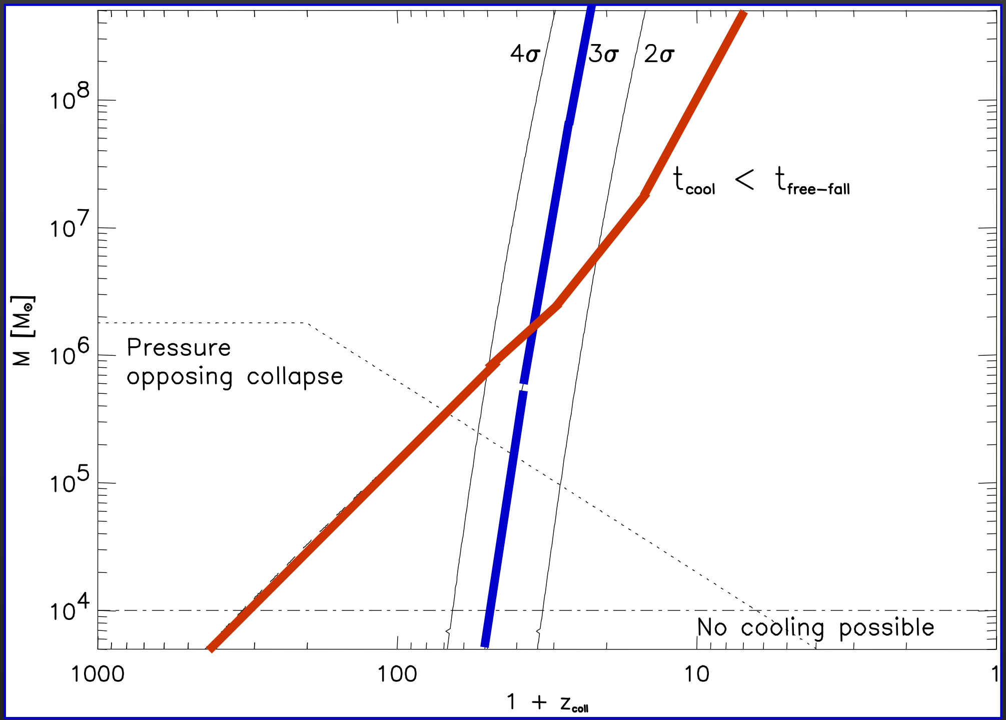
(Beasley et al. 2002, MNRAS, 333, 383)

Region of Primordial Star Formation

Mass vs. redshift

- Gravitational Evolution of DM
- Gas Microphysic:

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

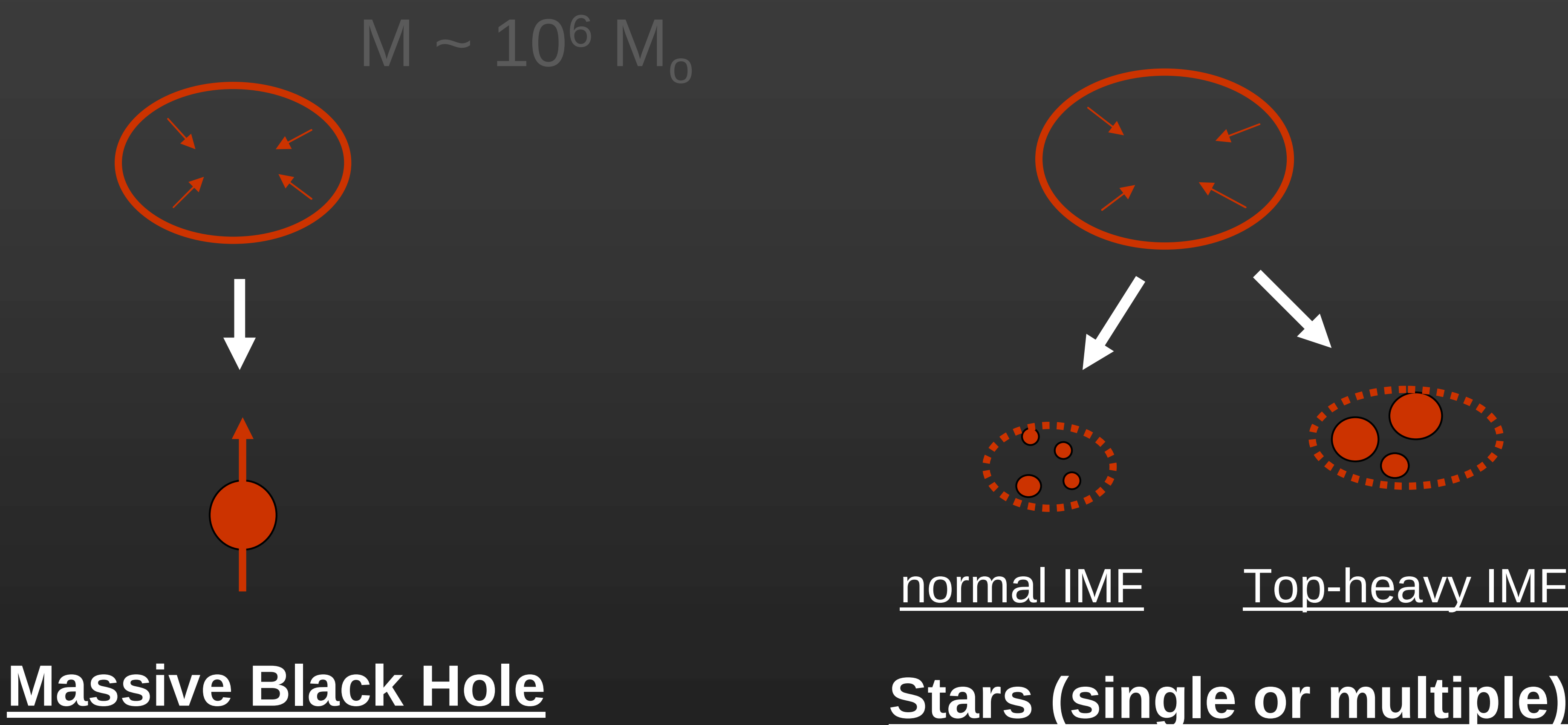


- Collapse of First Luminous Objects expected:

  - at: $z_{coll} = 20 – 30$

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

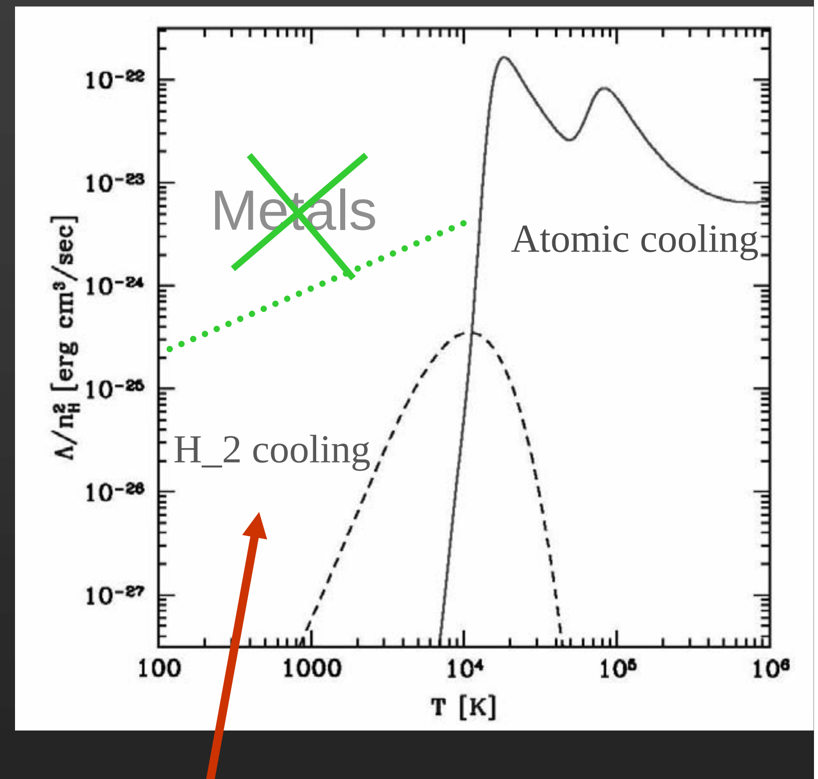
What happens inside primordial minihalos?



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

The 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

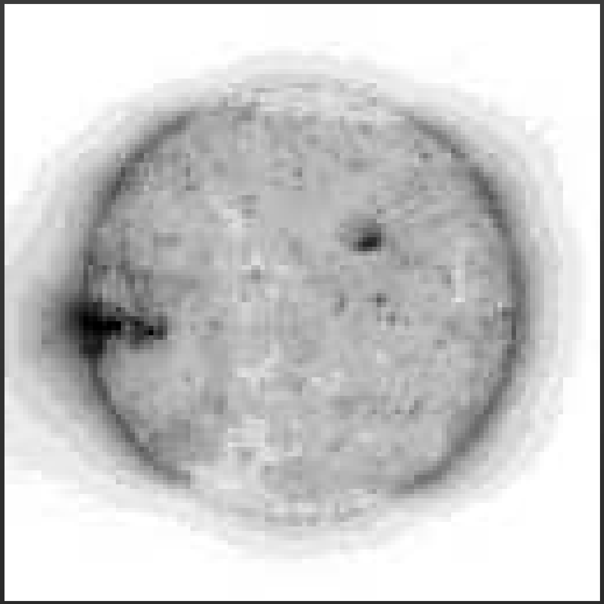


T_{vir} for Pop III

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

Simulating the Formation of the First Stars:

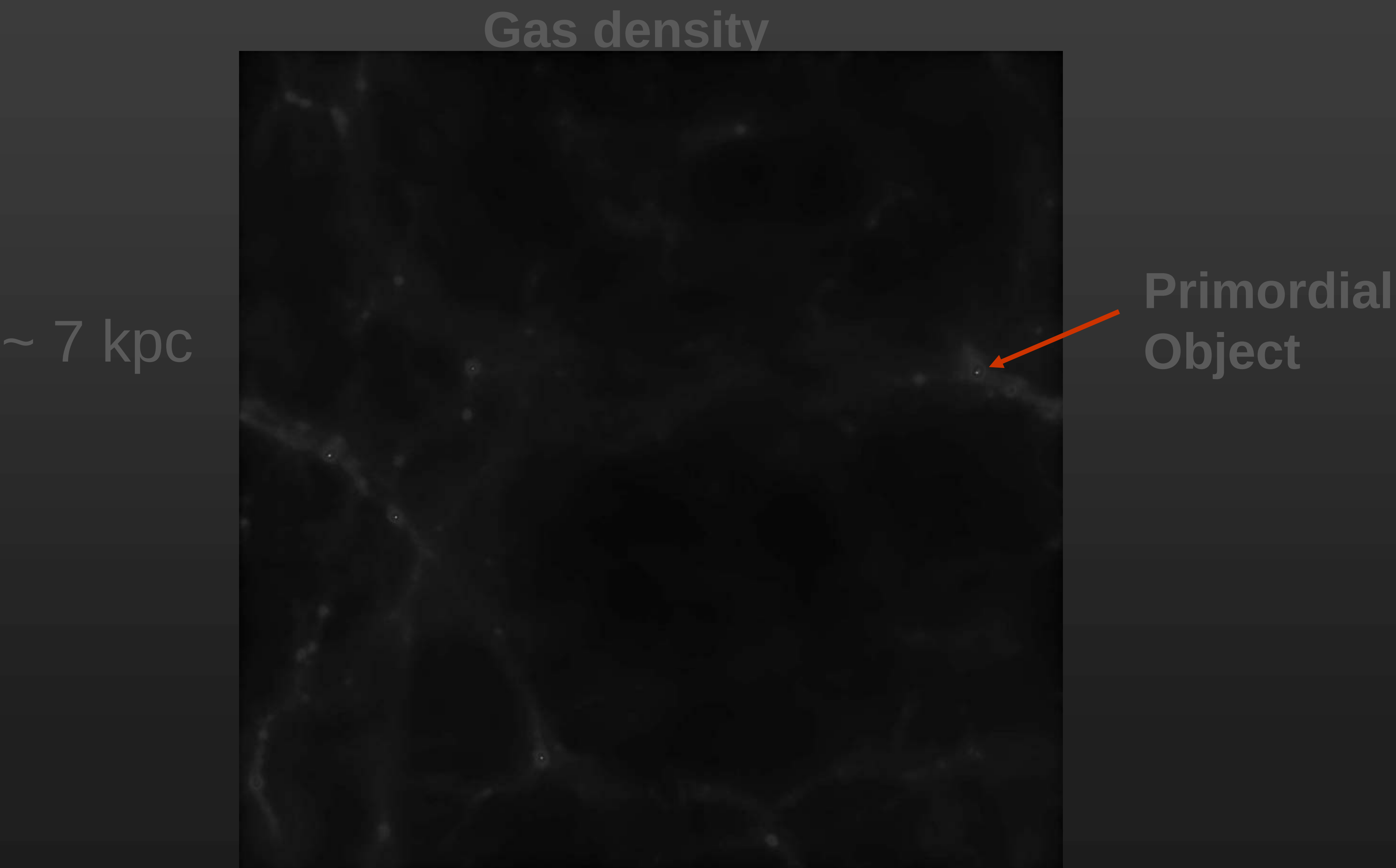
(Bromm, Coppi, & Larson and Bromm & Hernquist)



- Use TREESPH / Gadget
(both DM and gas)
- Radiative cooling of primordial gas
- Non-equilibrium chemistry
- Initial conditions: ΛCDM
- Modifications to SPH:
  - sink particles
  - particle splitting

Cosmological Initial Conditions

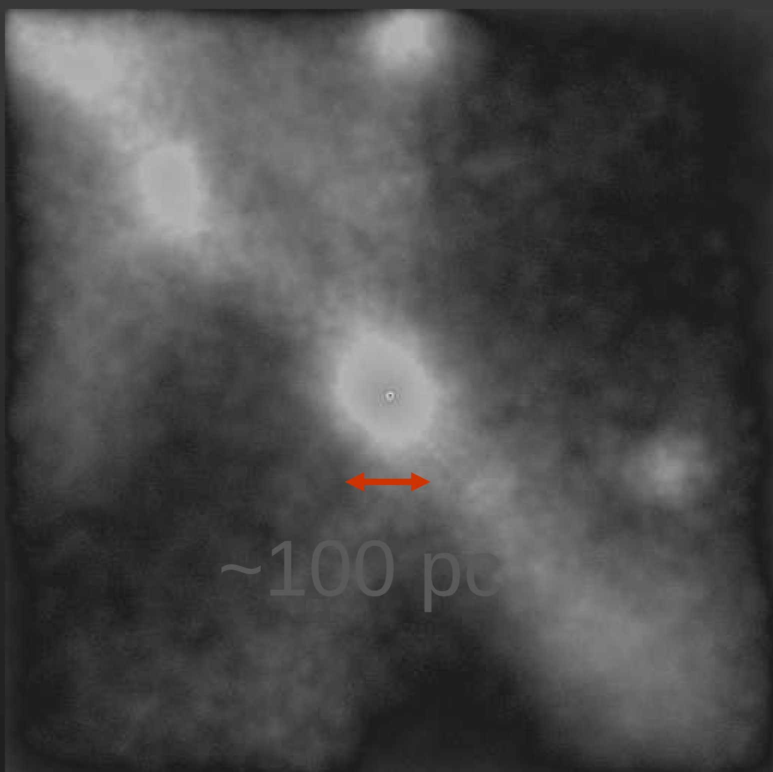
- Consider situation at **z = 20**

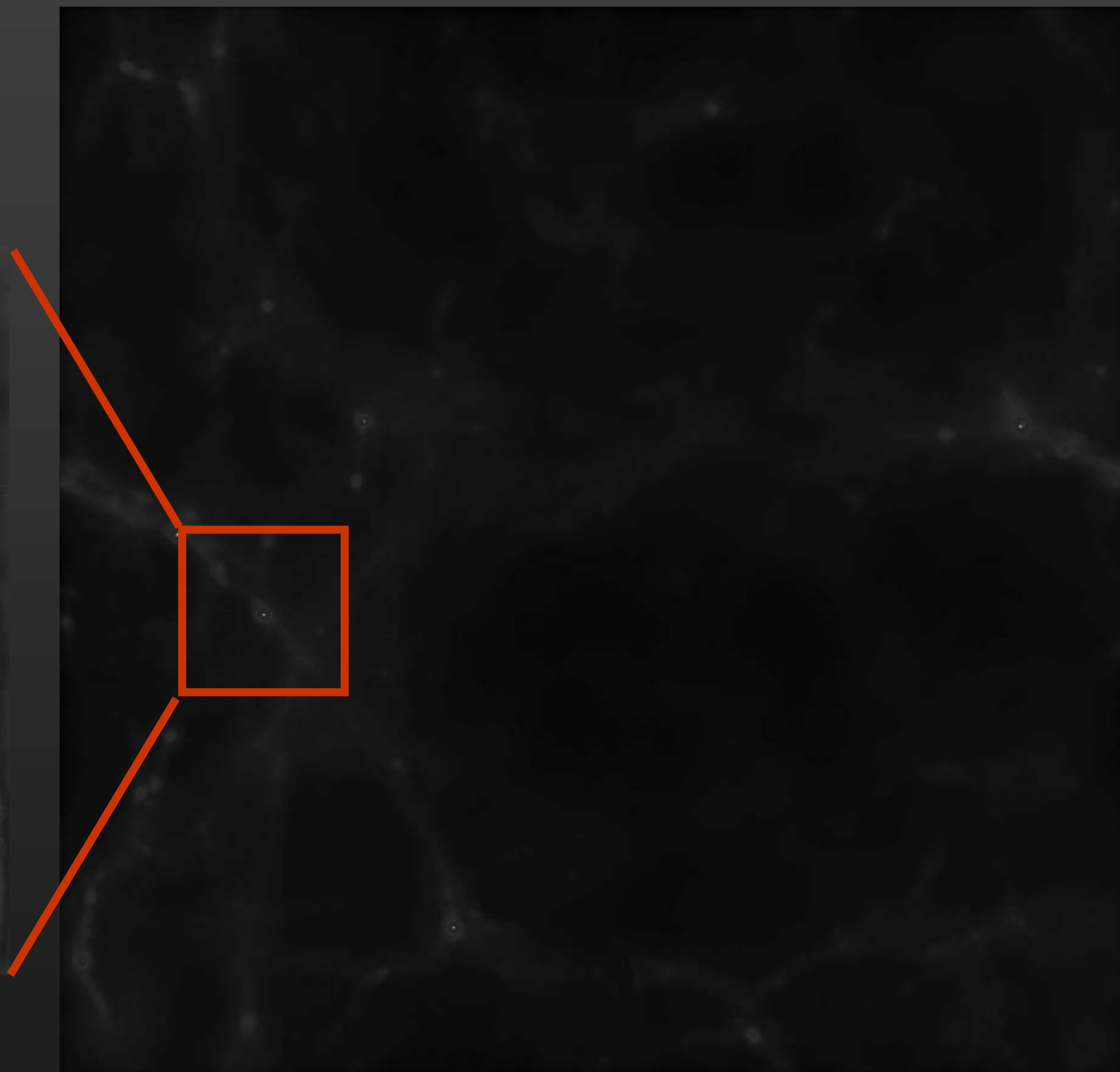


The First Star-Forming Region (“minihalos”)

projected gas density at z=20

$M \sim 10^6 M_o$



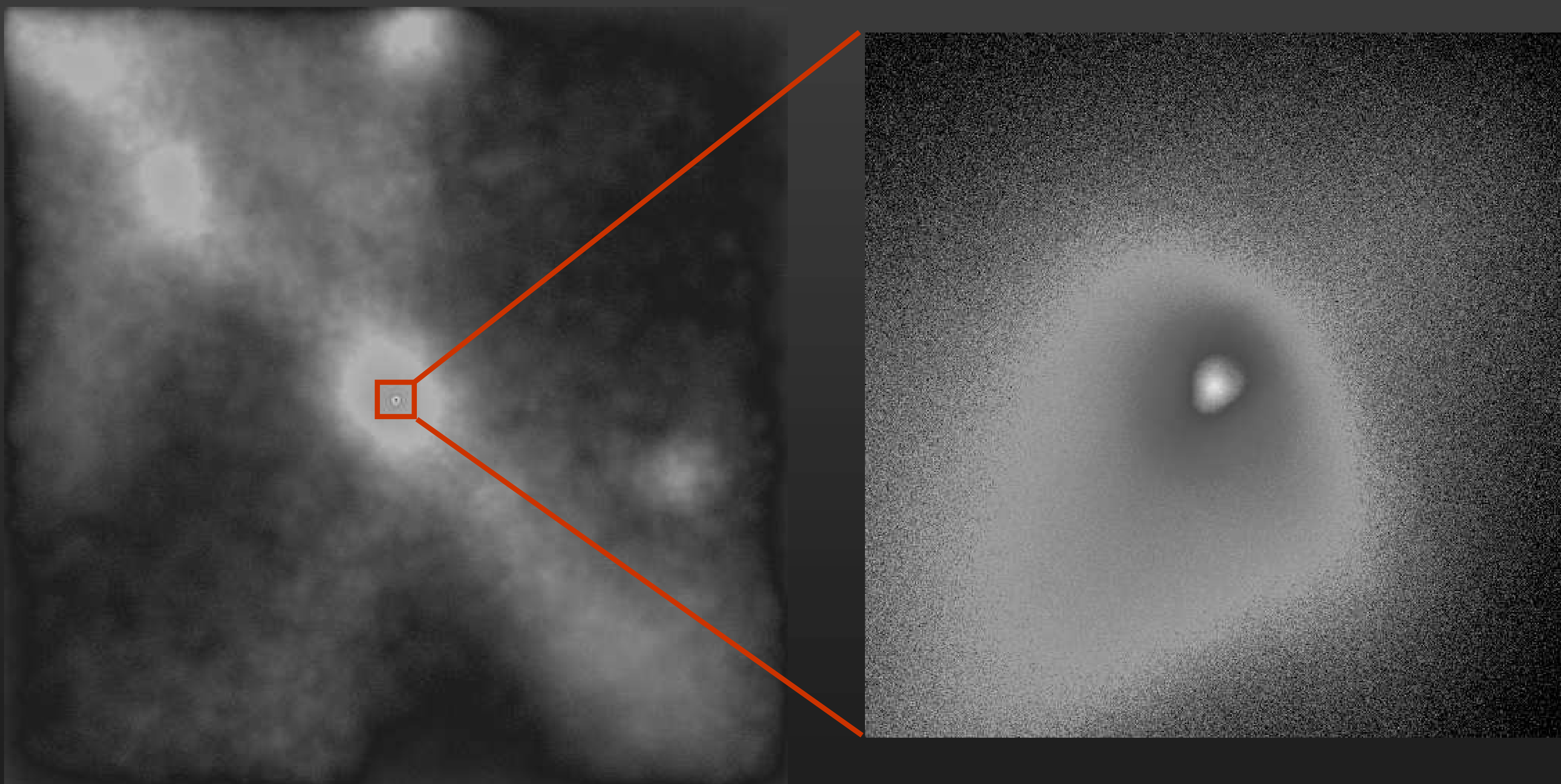


~ 7 kpc (proper)

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

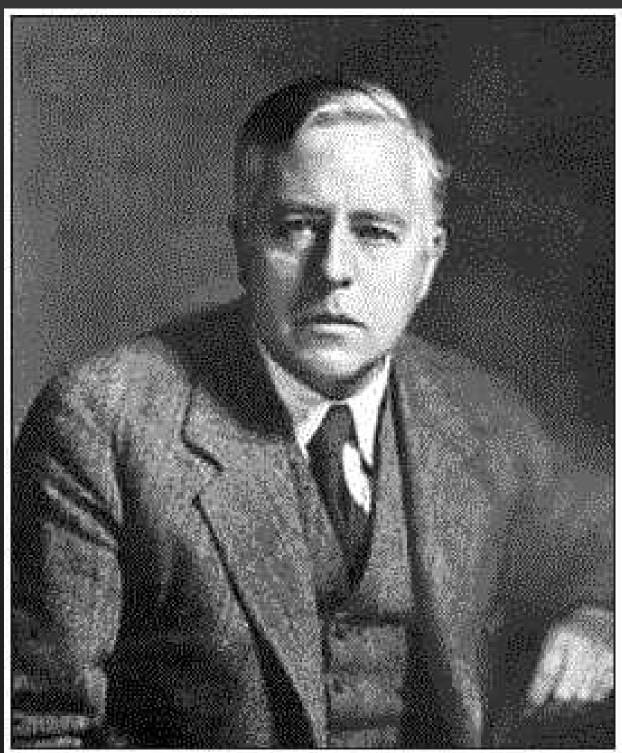
1 kpc

A Physical Explanation:

(Bromm, Coppi, & Larson 1999, 2002)

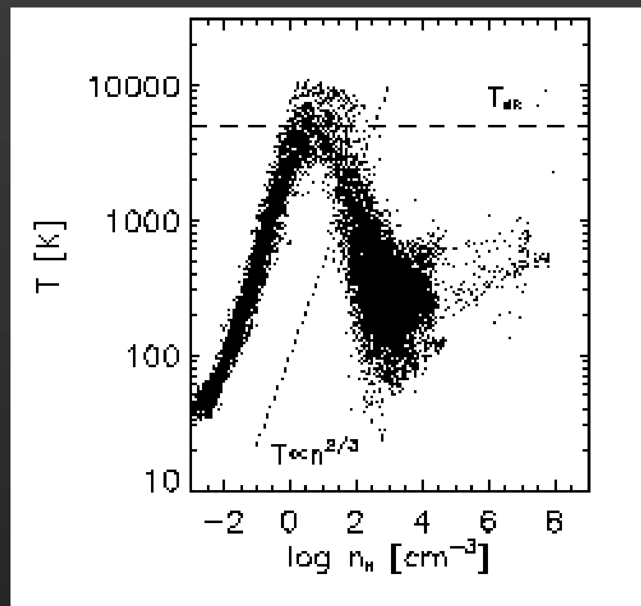
- Gravitational instability (Jeans 1902)
- Jeans mass:

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

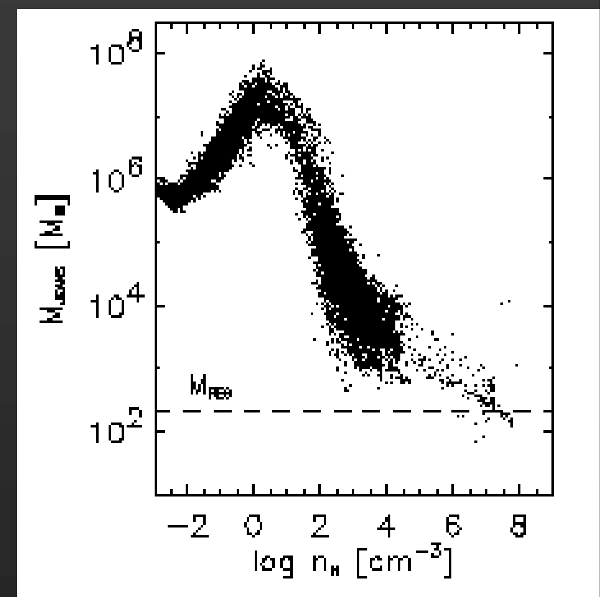


- Thermodynamics of primordial gas

T vs. n



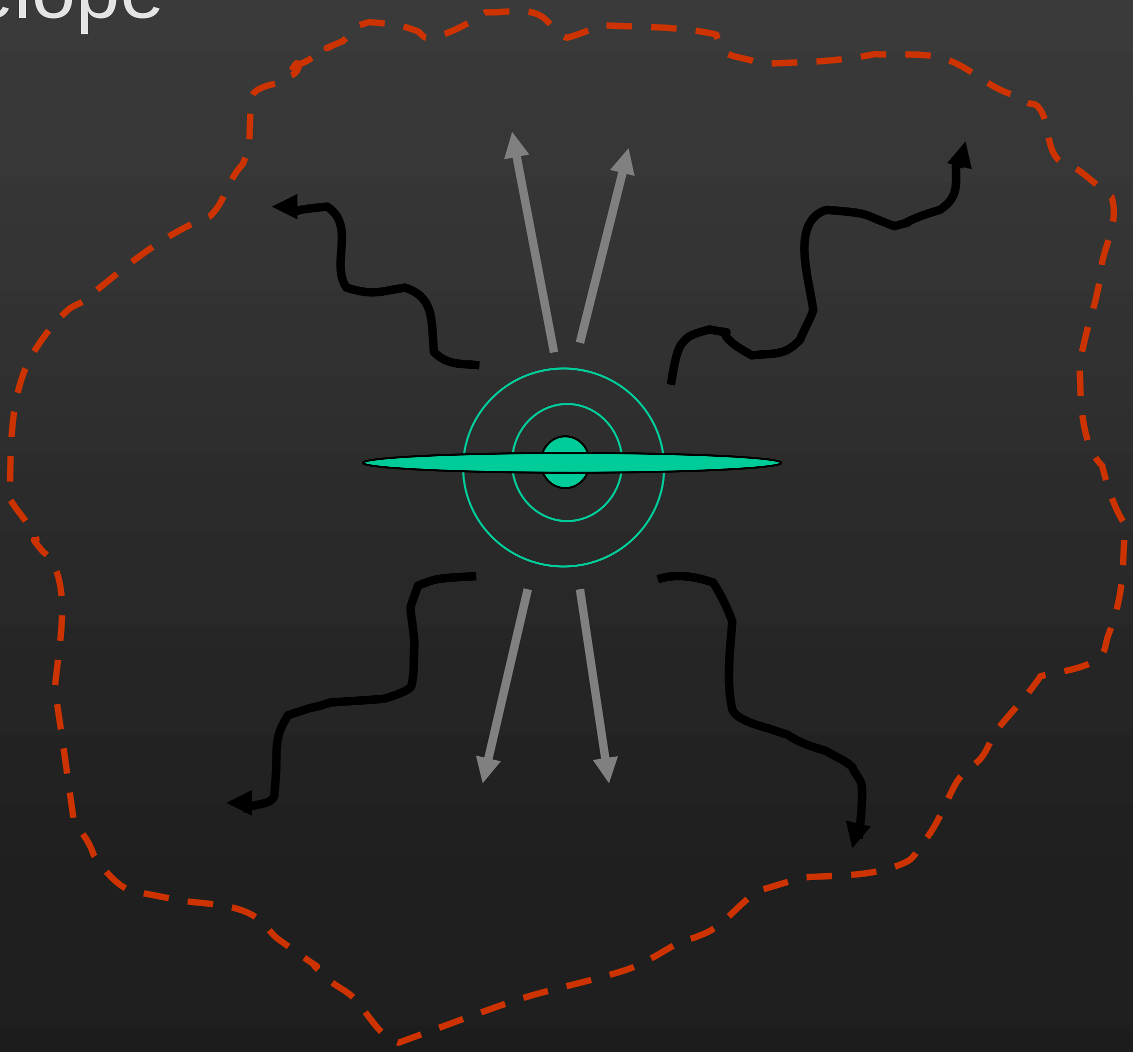
M_J vs. n



- 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!

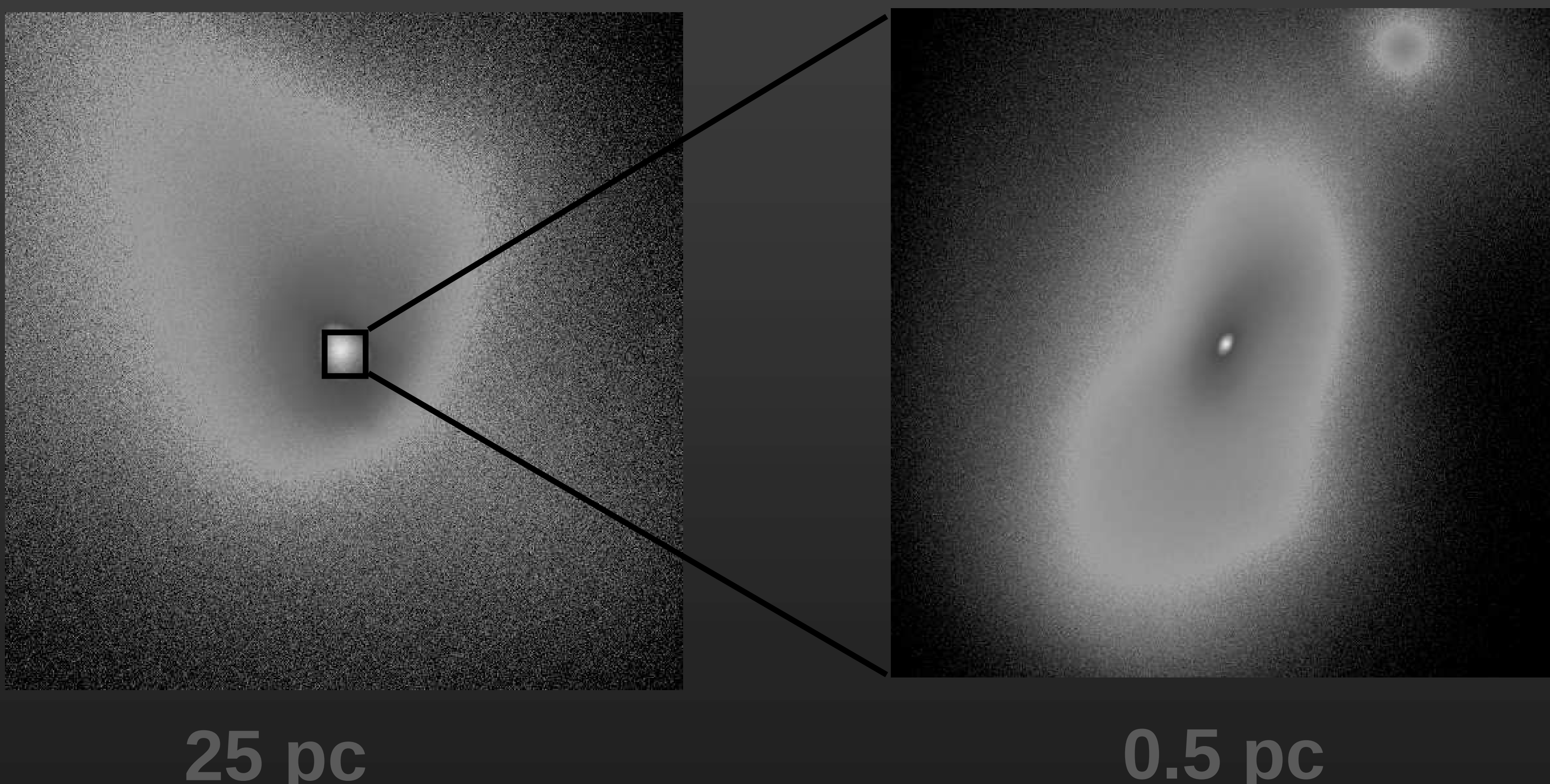
- $dM/dt_{acc} \sim M_J \,/\, t_{ff} \sim T^{3/2}$ (Pop I: T ~ 10 K, Pop III: T ~ 300 K)

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

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

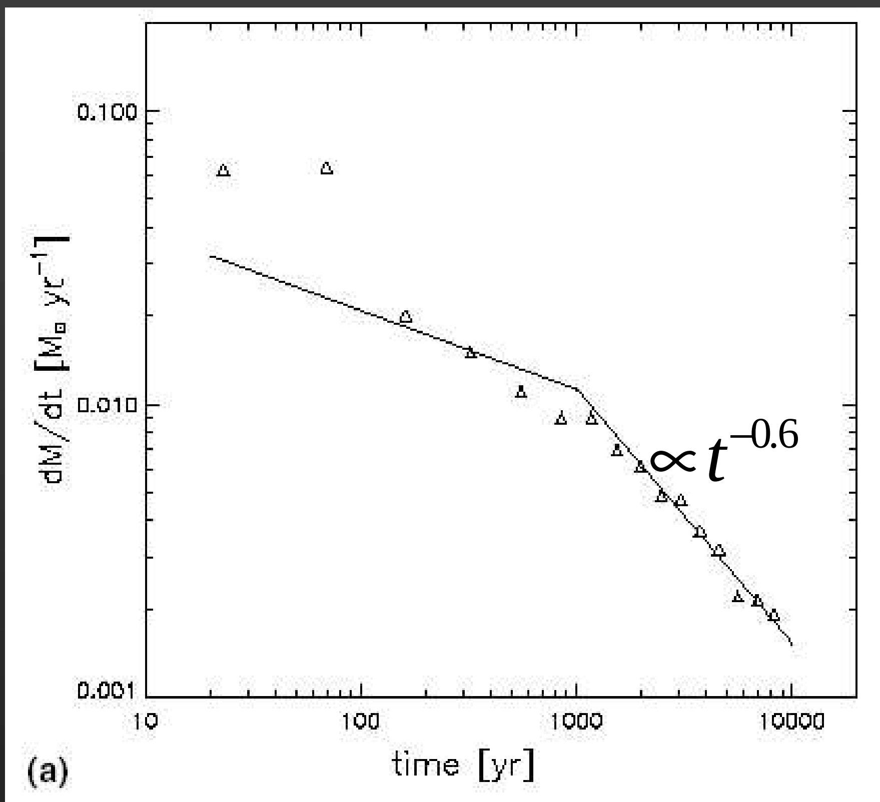
- Simulate further fate of the clump

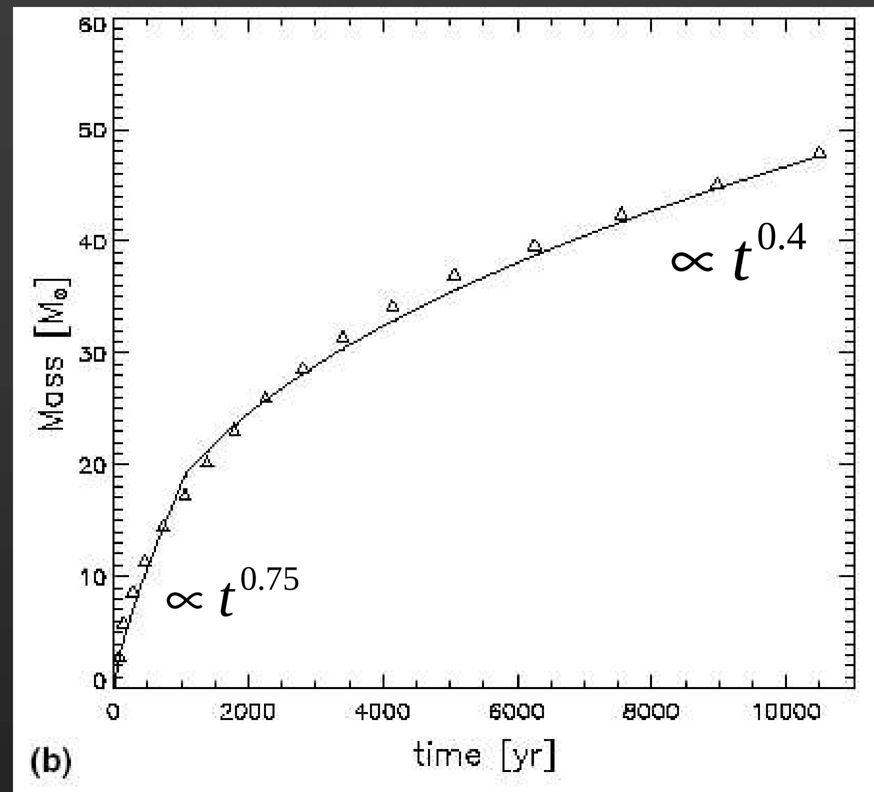


Accretion onto a Primordial Protostar

dM/dt vs. time

M vs. time





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

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

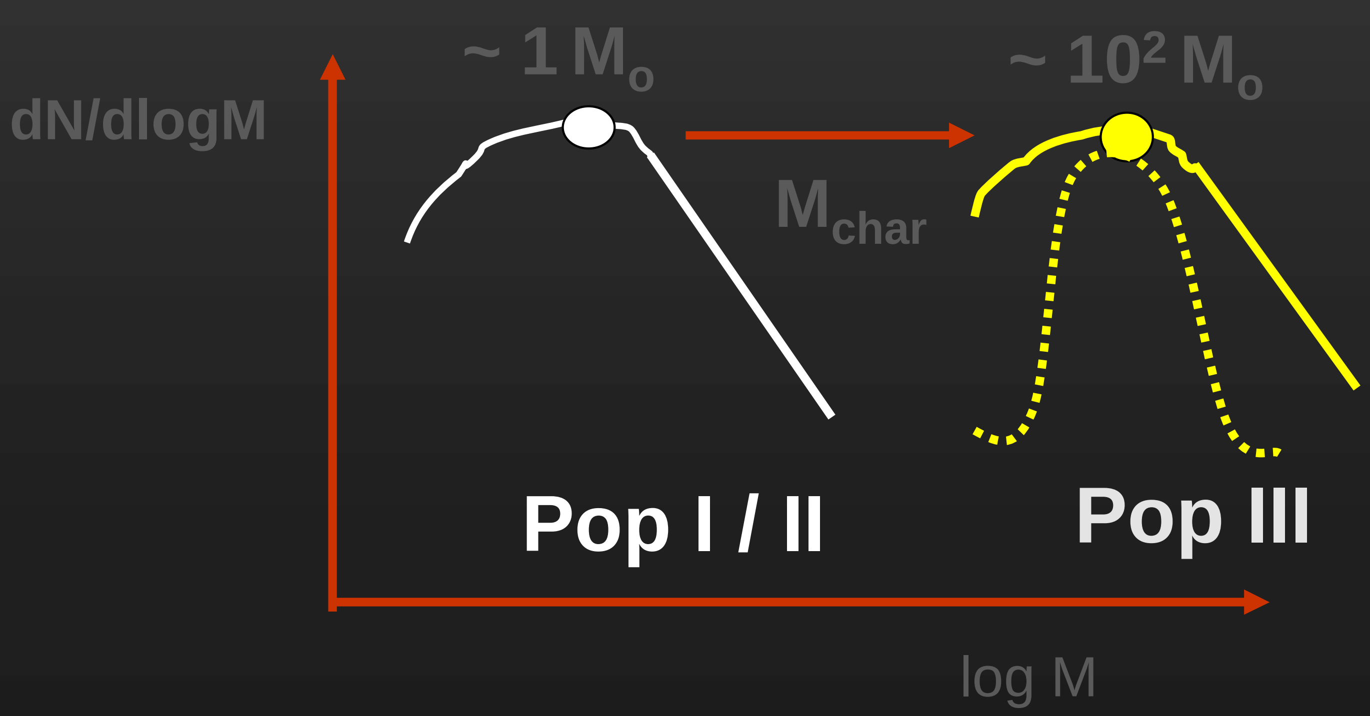
→ accretion stops

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

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**

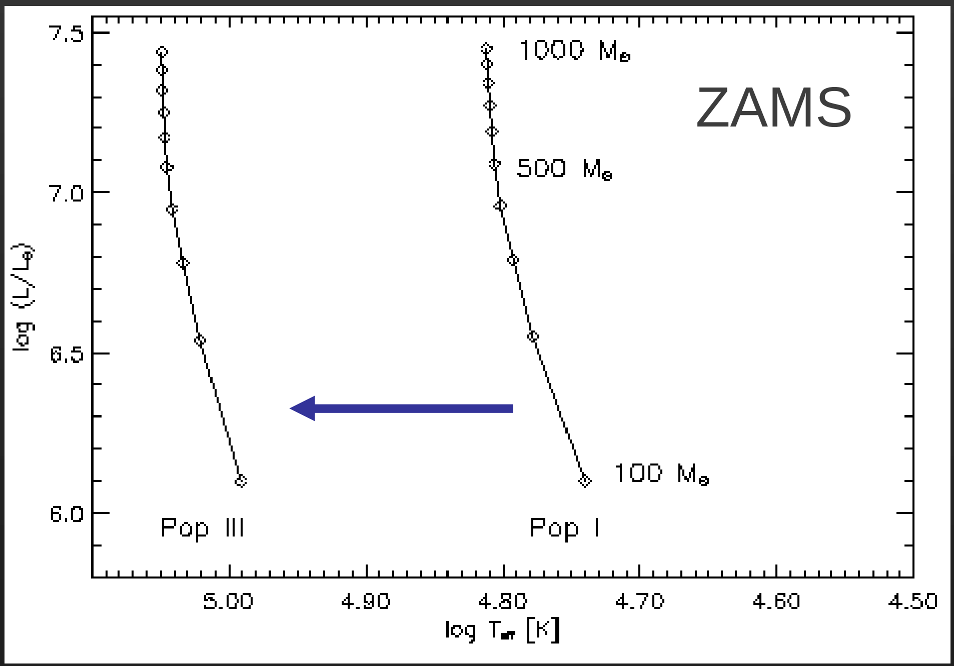


Implications of a Heavy IMF For the First Stars

(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}



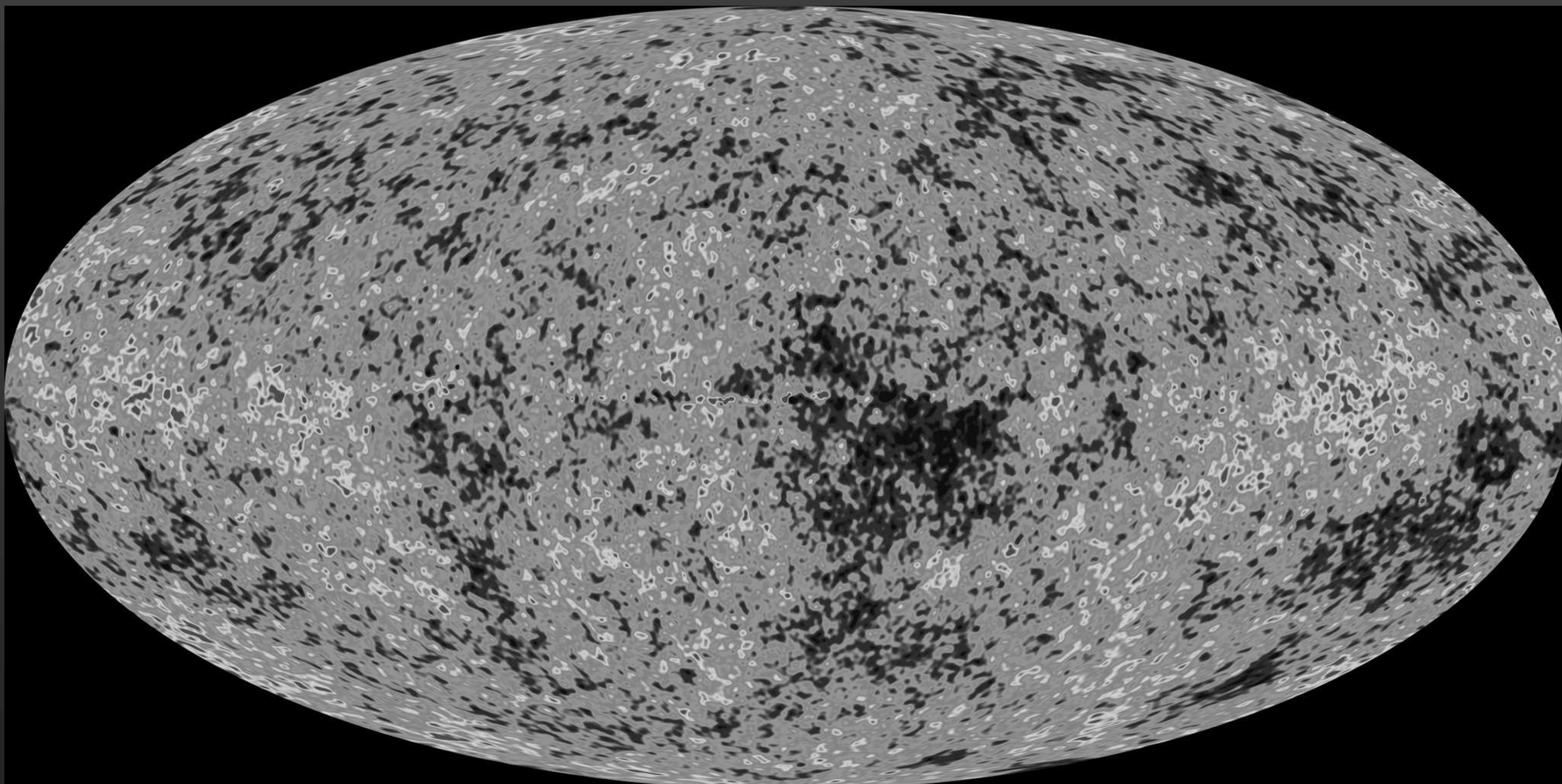
- **For Pop III:**

  T_{eff} ~ 110,000 K

  → lambda peak ~ 250 Å

  (close to He II ionization edge)

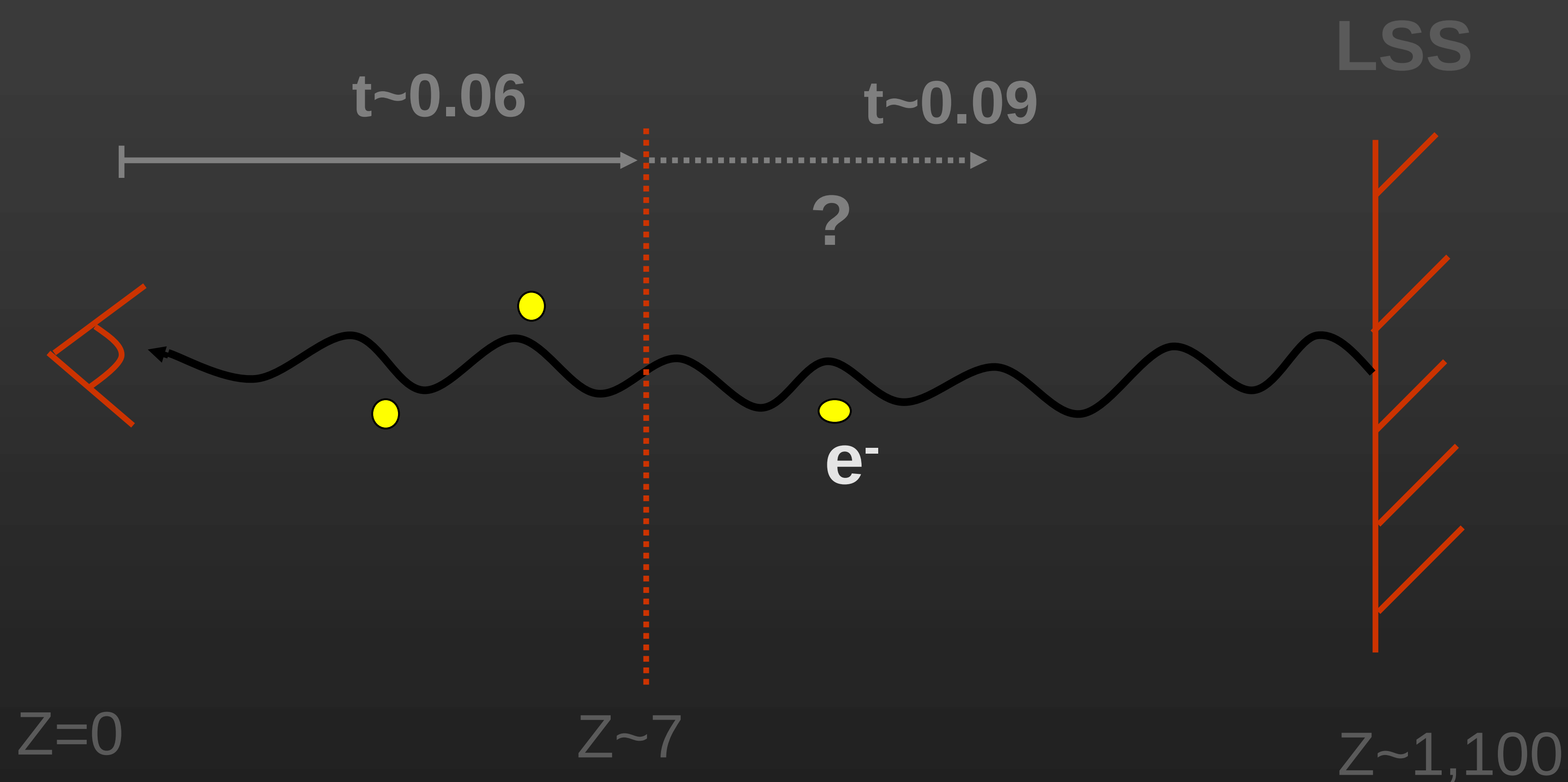
Wilkinson Microwave Anisotropy Probe:



Polarization → optical depth to Thomson scattering:

$(\tau = 0.09 \pm 0.04)$ → **Signature of the First Stars**

CMB photon-scattering from free electrons

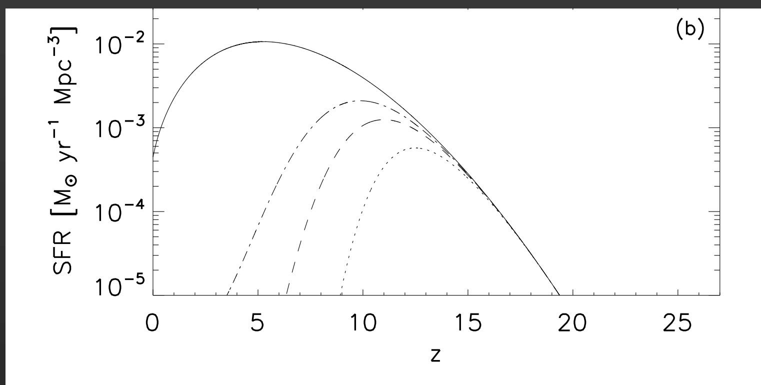


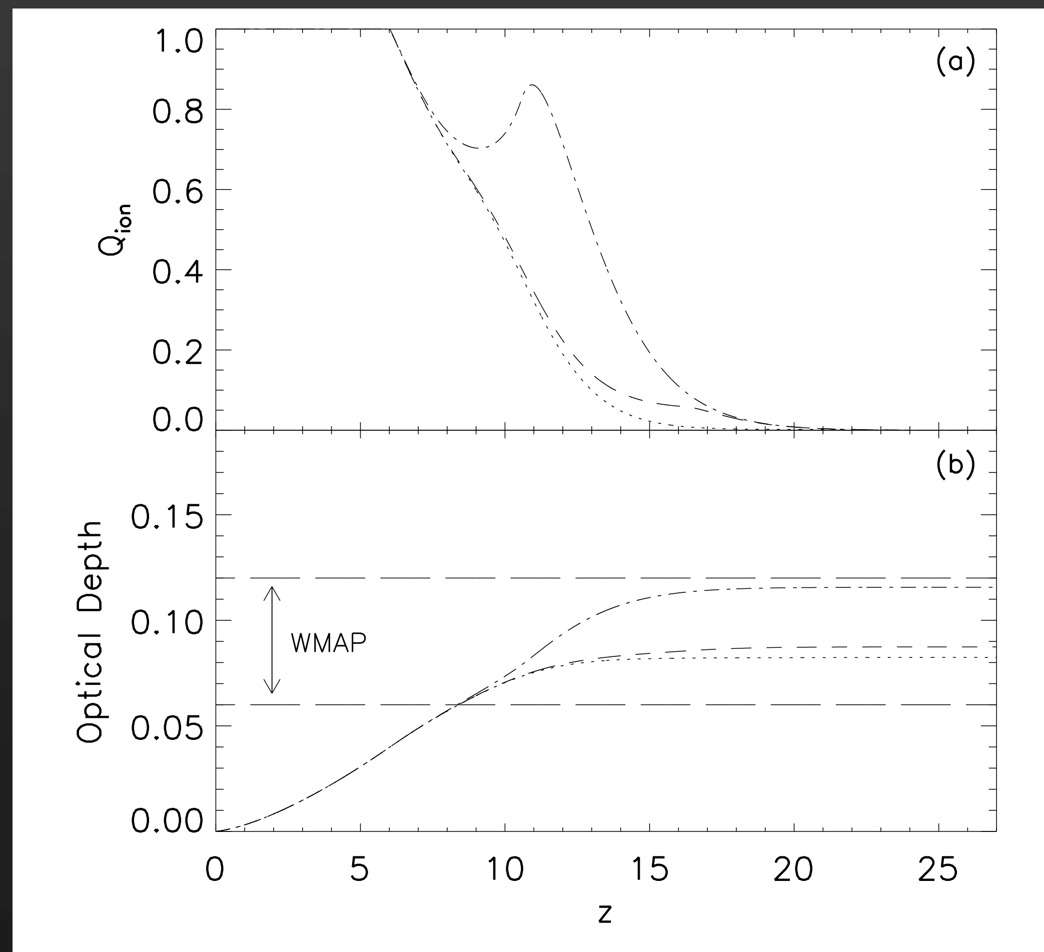
Ionization History of the Universe

(Greif & Bromm 2006; astro-ph/0604367)

SFR vs z

Ionized fraction vs z



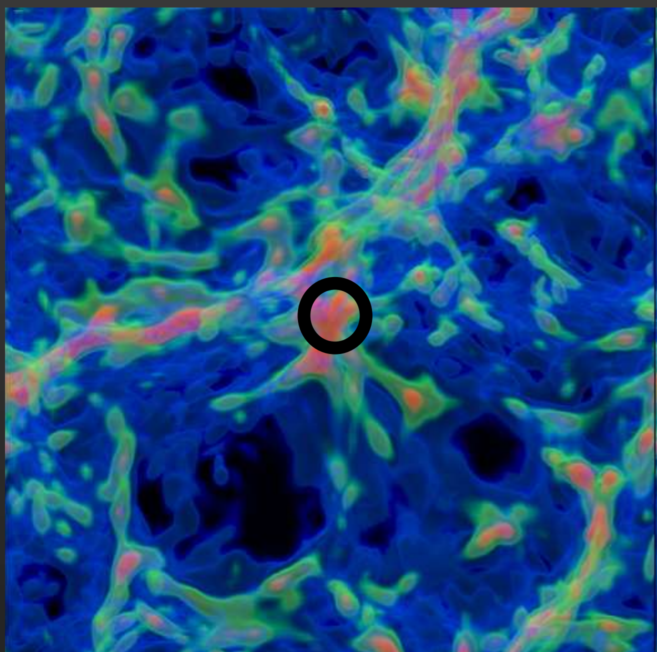


à Pop III star formation must have been terminated z≳10

Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)

z = 20



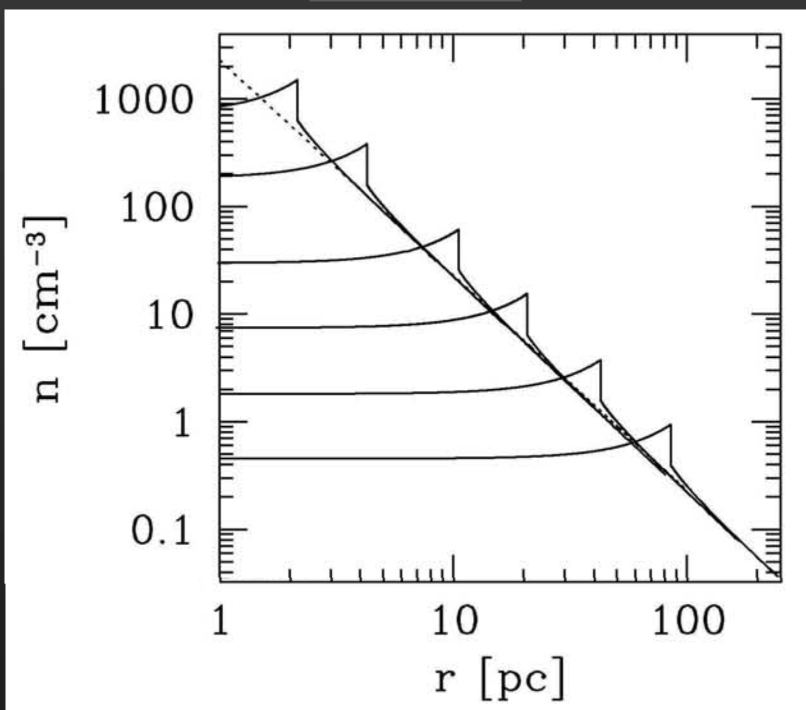
13.6 kpc
(proper)

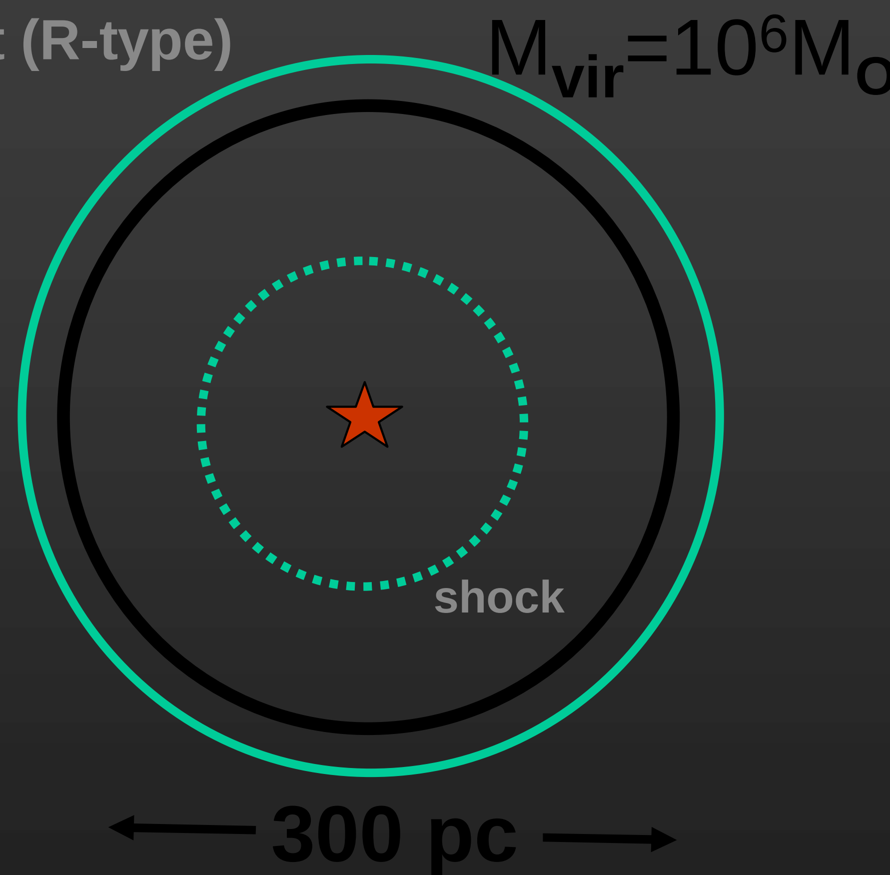
Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)

- density suppression (photo-heating)

n vs r

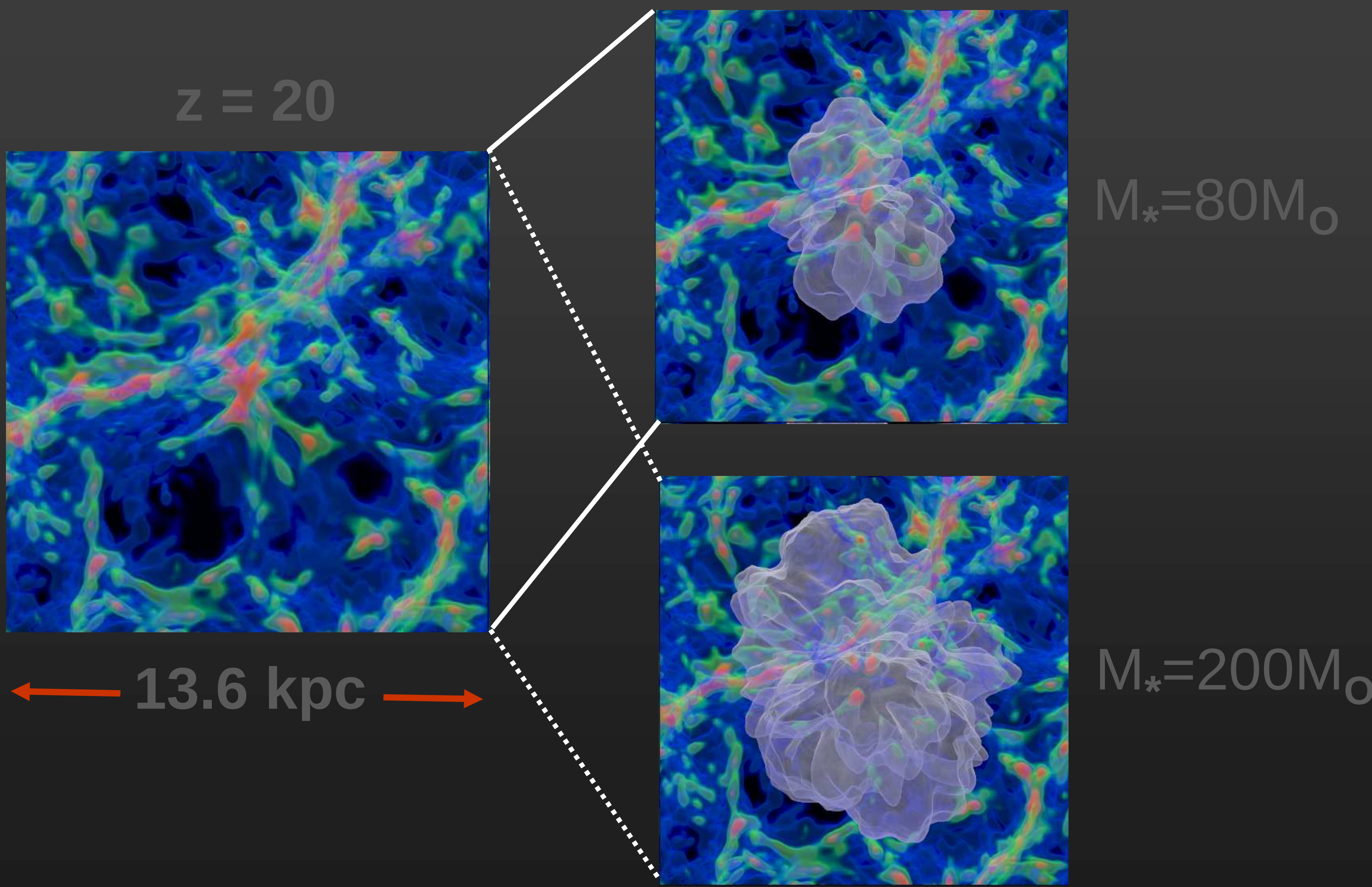




- self-similar “champagne flow” (Shu et al. 2002)

Primordial HII Regions

(Alvarez, Bromm, & Shapiro 2006; astro-ph/0507684)



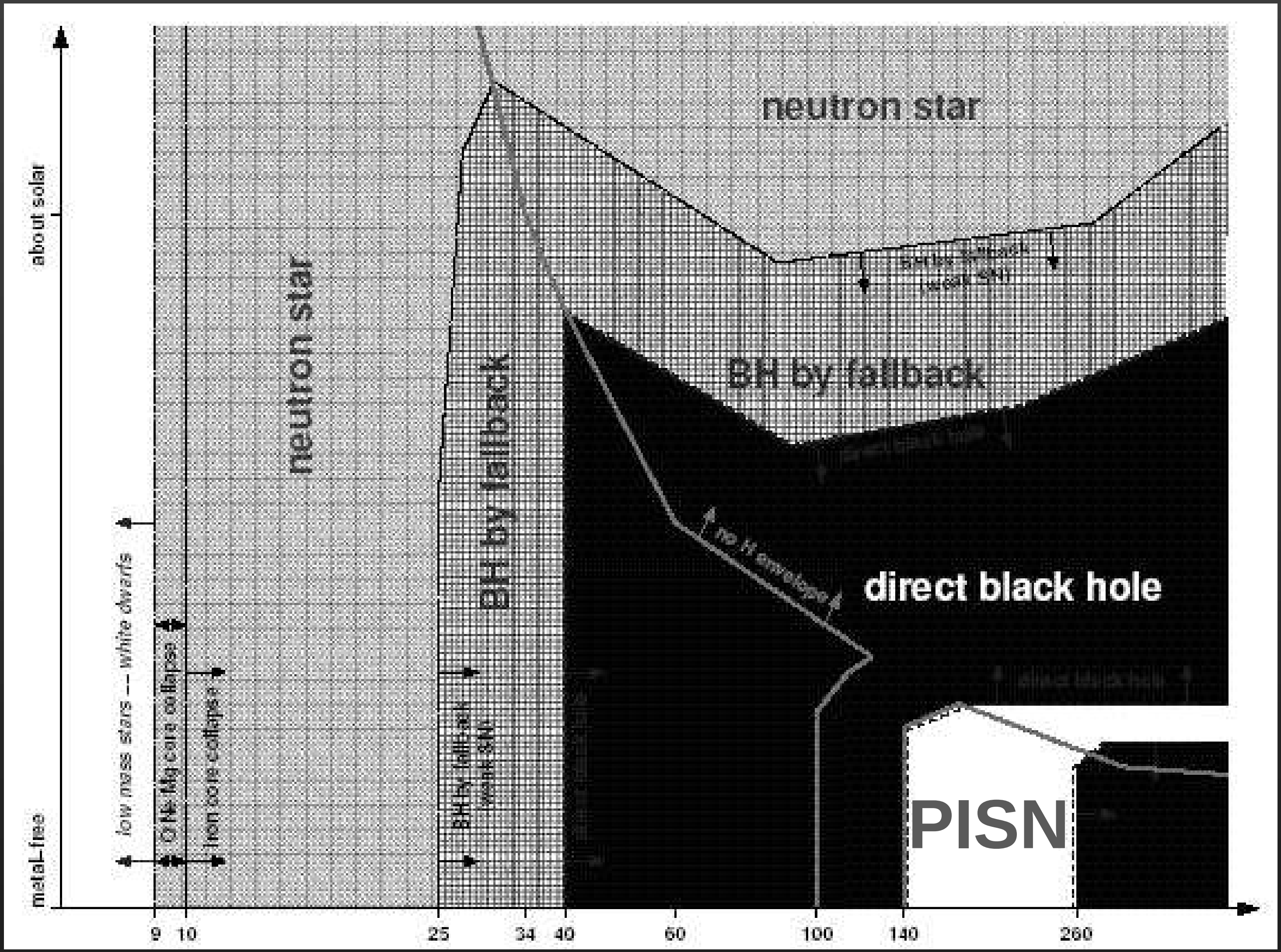
The Death of the First Stars:

(Heger et al. 2003)

Pop I

Z

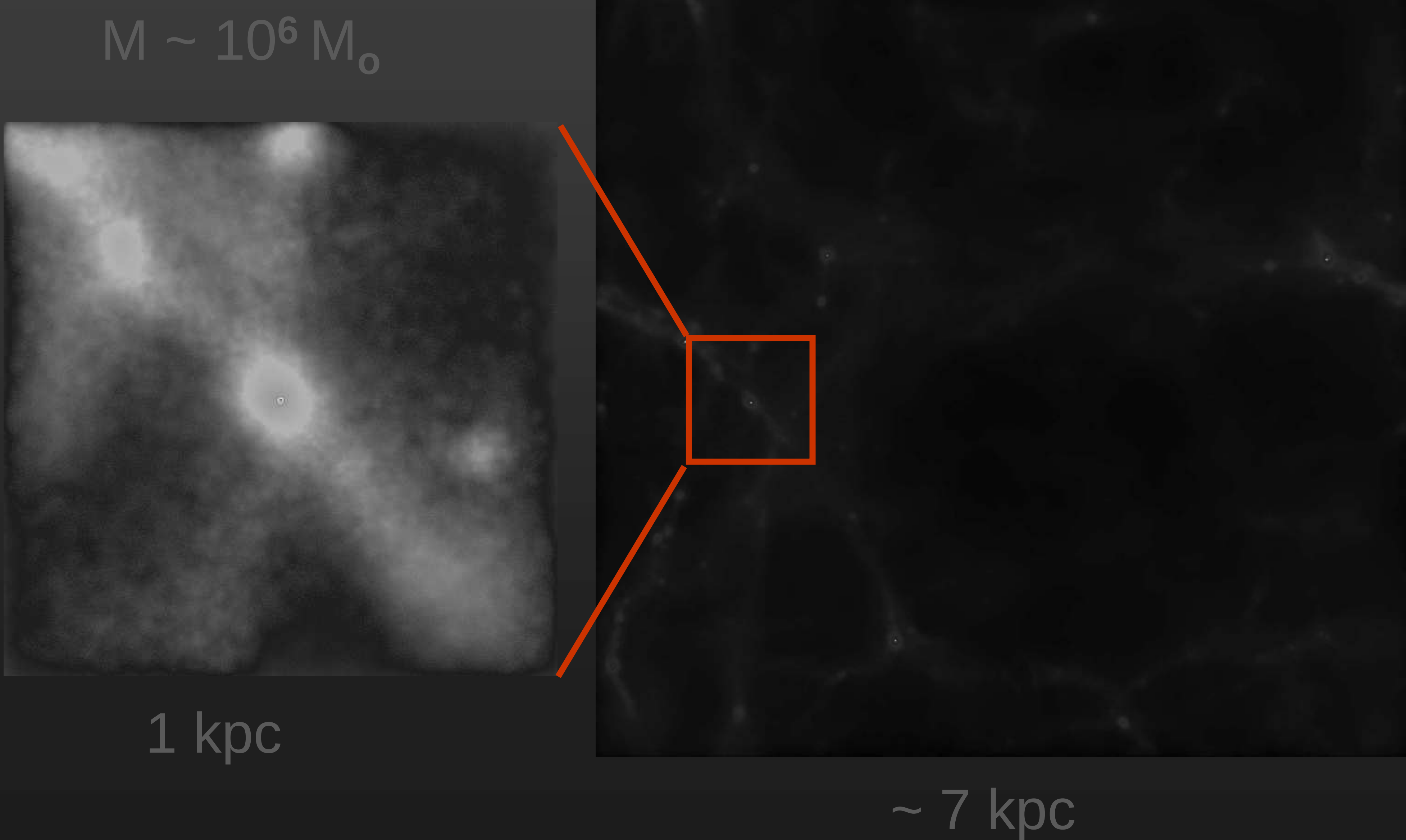
Pop III



Initial Stellar Mass

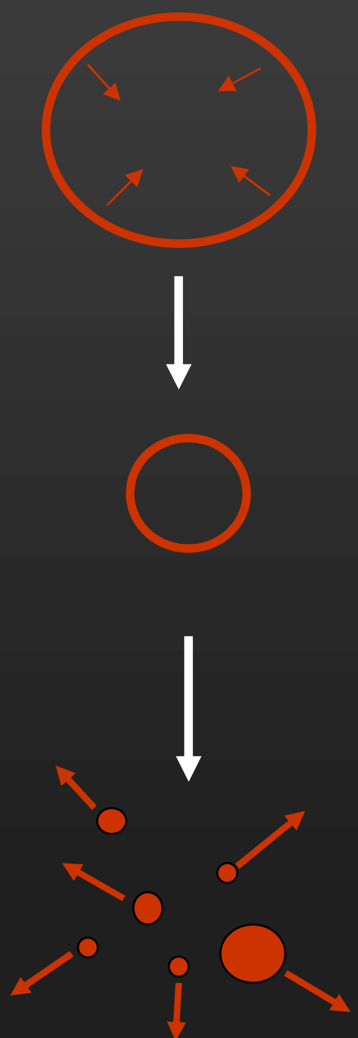
The First Supernova Explosions

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



Physics of Pair-instability Supernovae

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

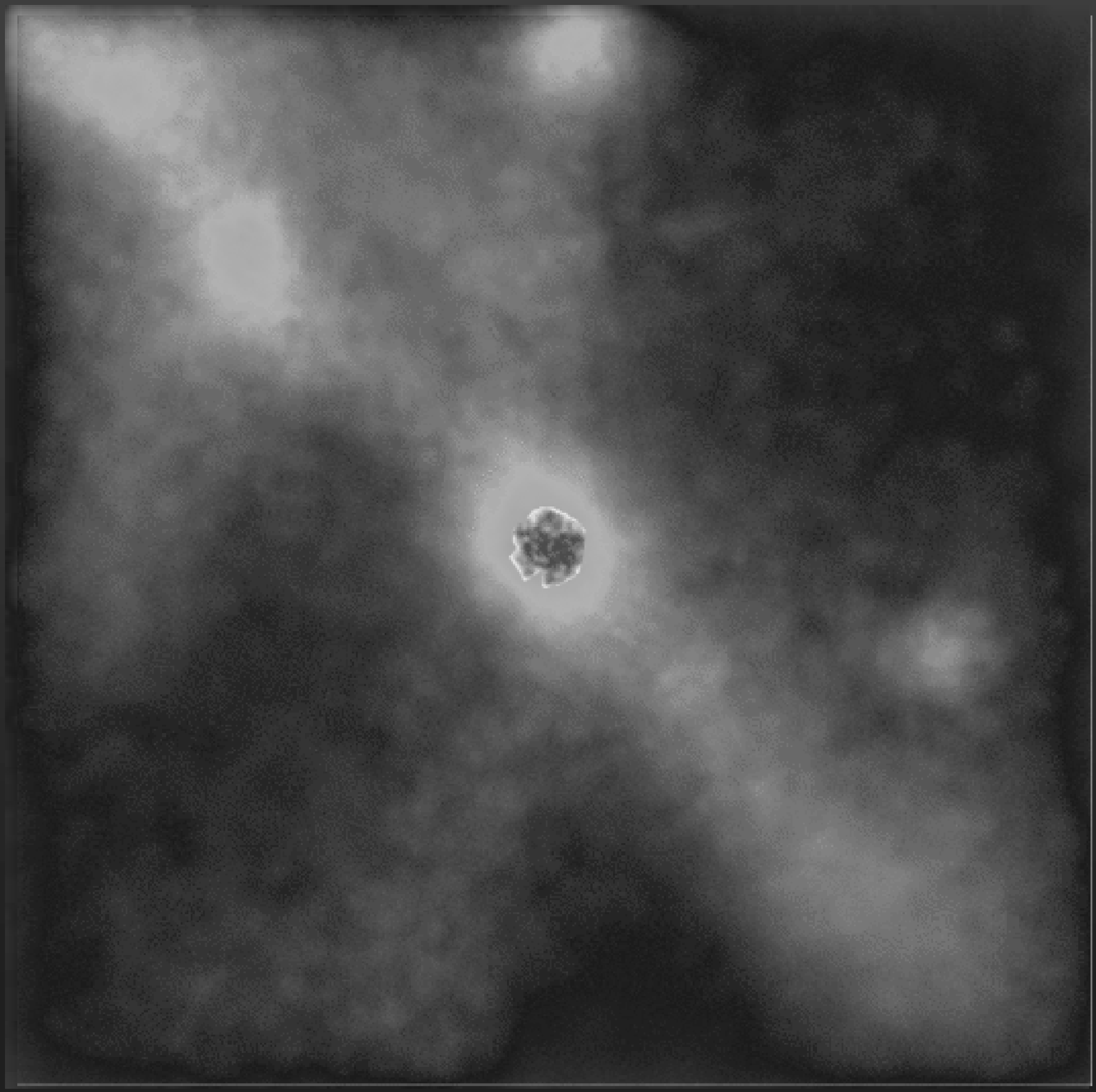


- $T > 10^9 K$
- ph+ph → $e^- e^+$
- grav. runaway collapse

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

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

HII Regions around the First Stars

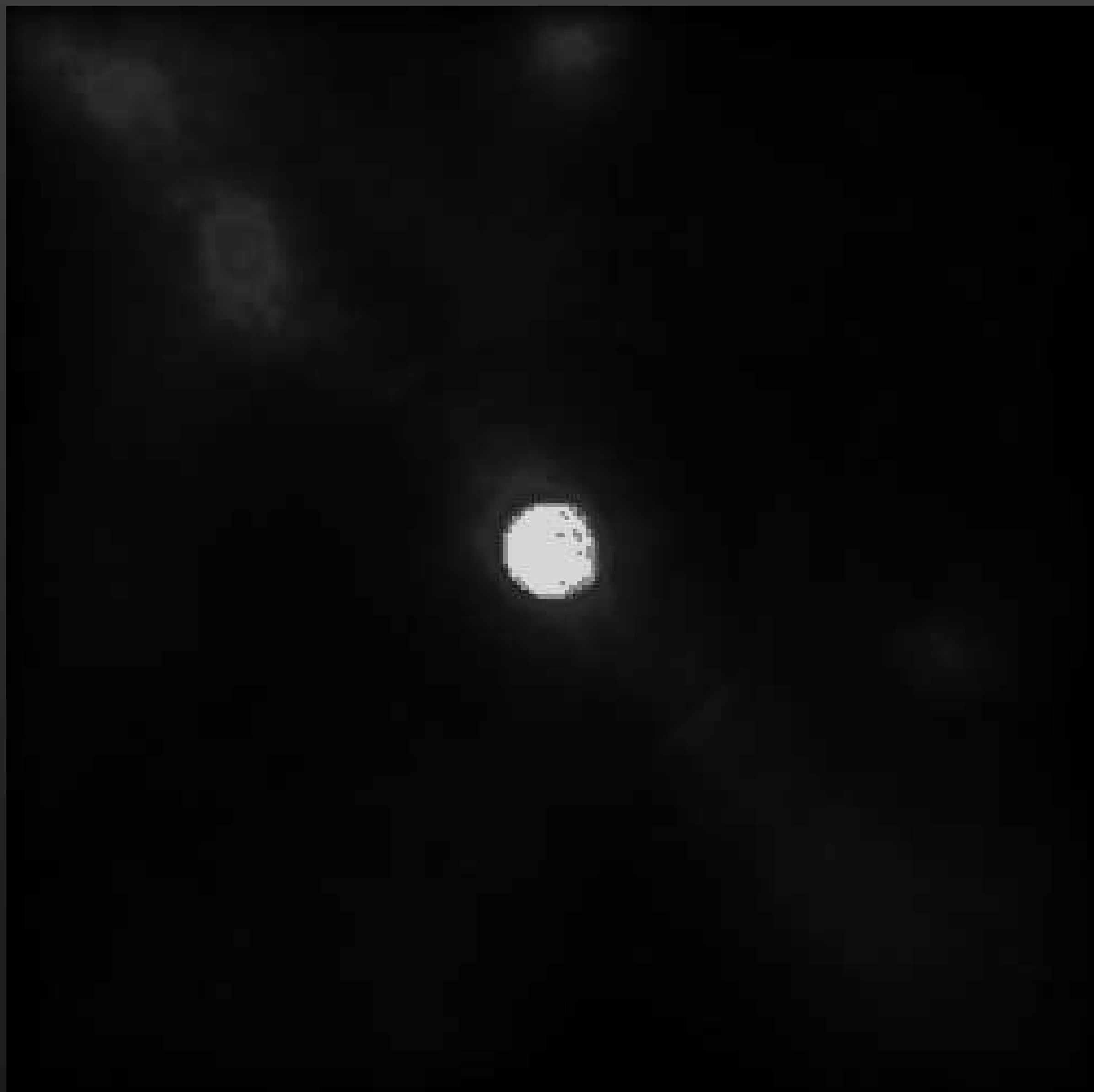


1 kpc

The First Supernova-Explosion

Gas density

~ 1 kpc

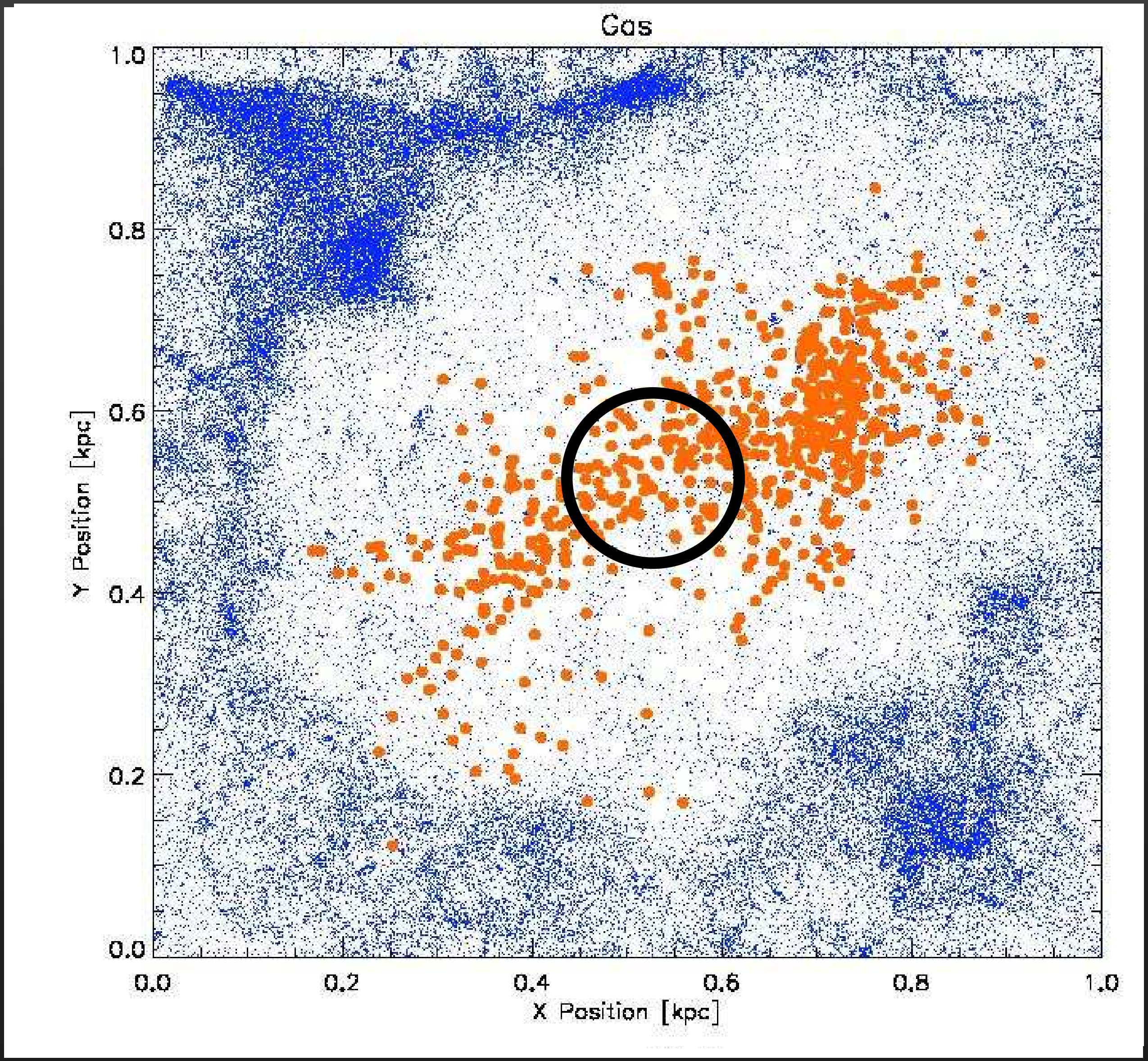


- E_{SN}~10^{53}ergs
- Complete Disruption (PISN)

The First Supernova-Explosion

Metal Distribution

~ 1 kpc

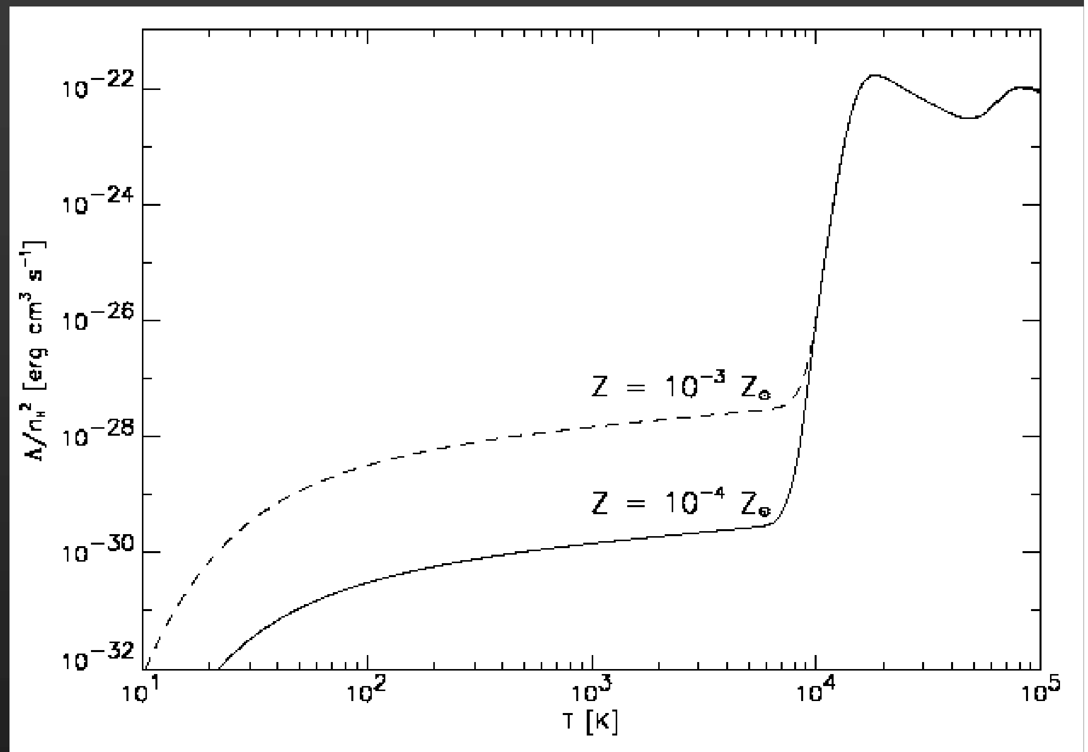


Paradise Lost: The Transition to Population II

(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

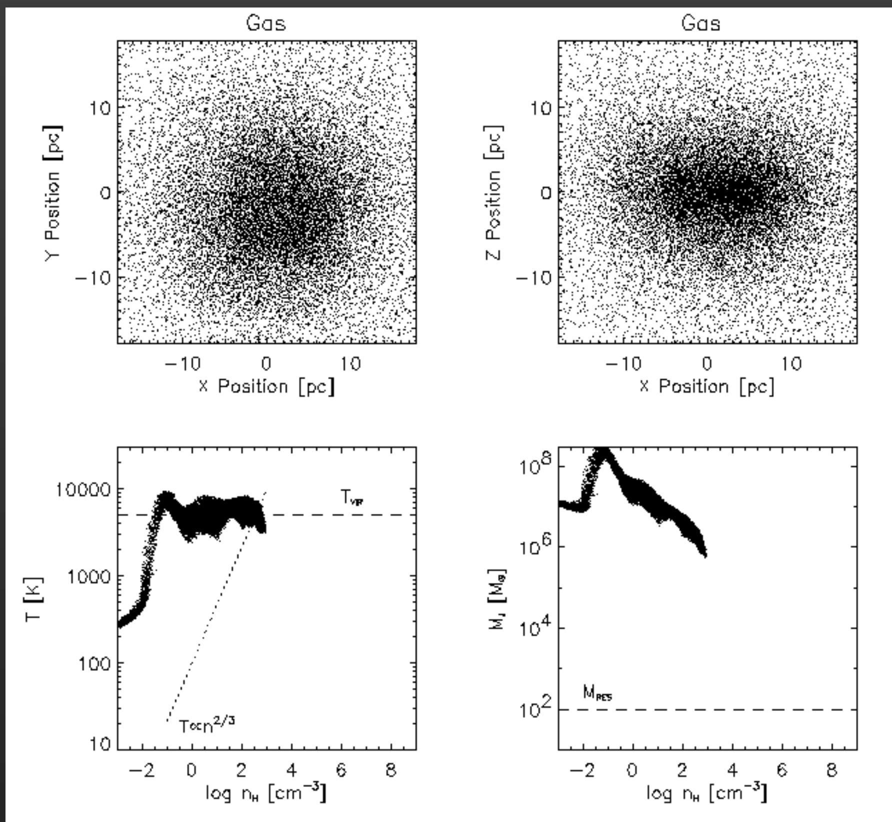
Cooling Rate vs. T



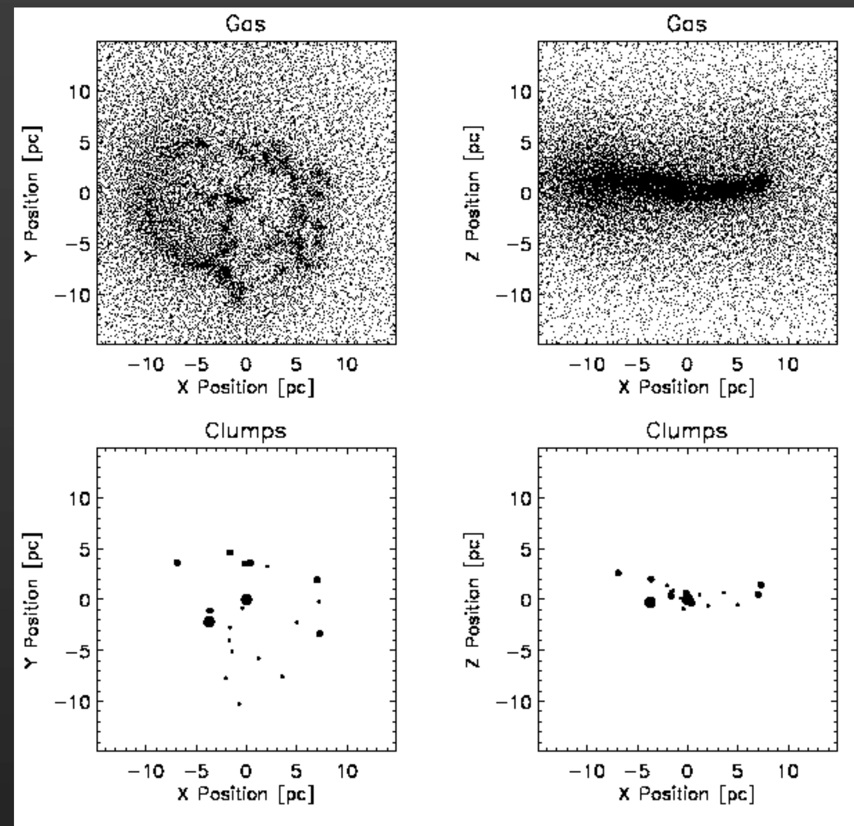
→ Consider two identical (other than Z) simulations !

Effect of Metallicity:

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



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



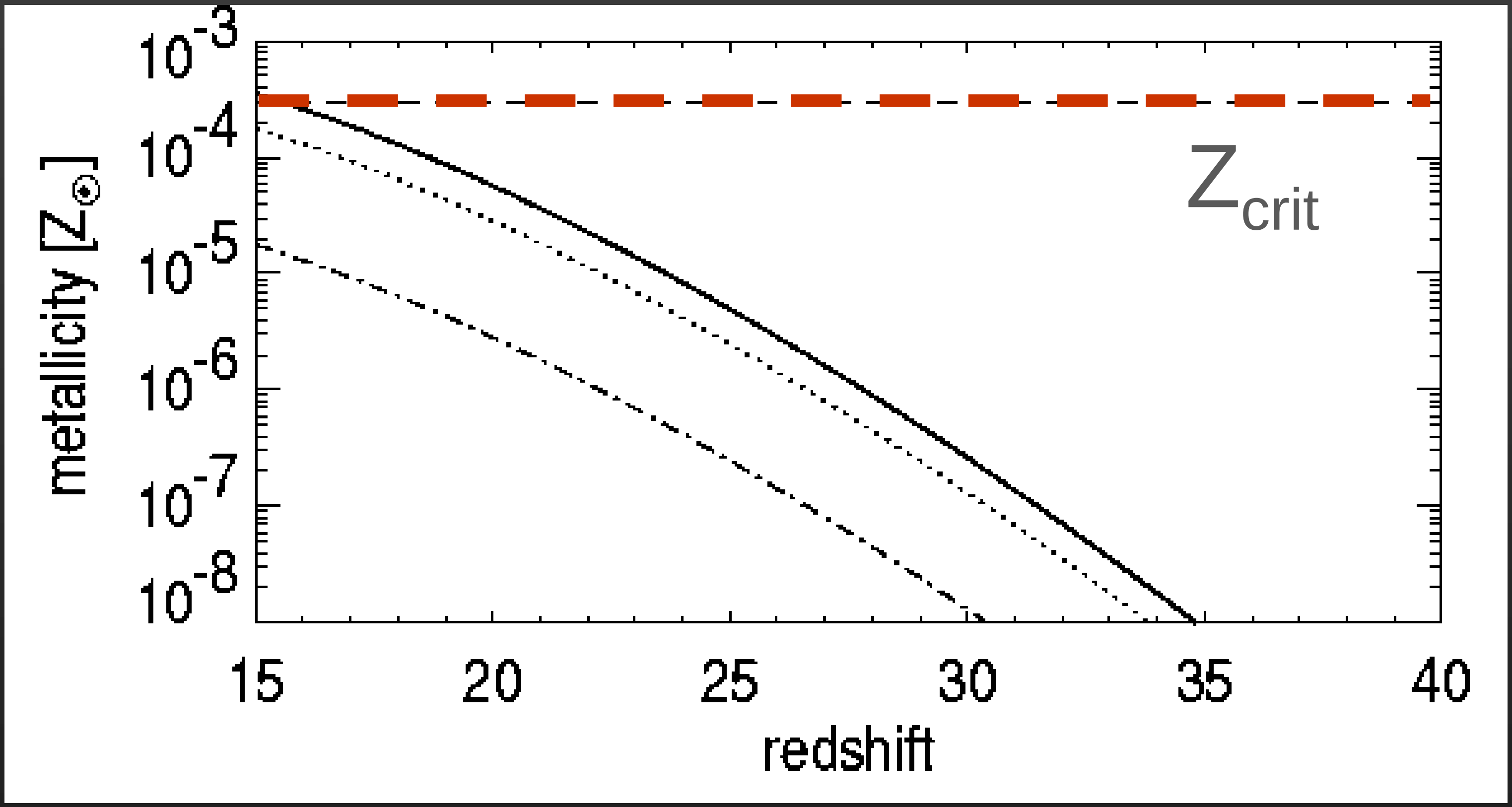
- Insufficient cooling
- Vigorous fragmentation

→ 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

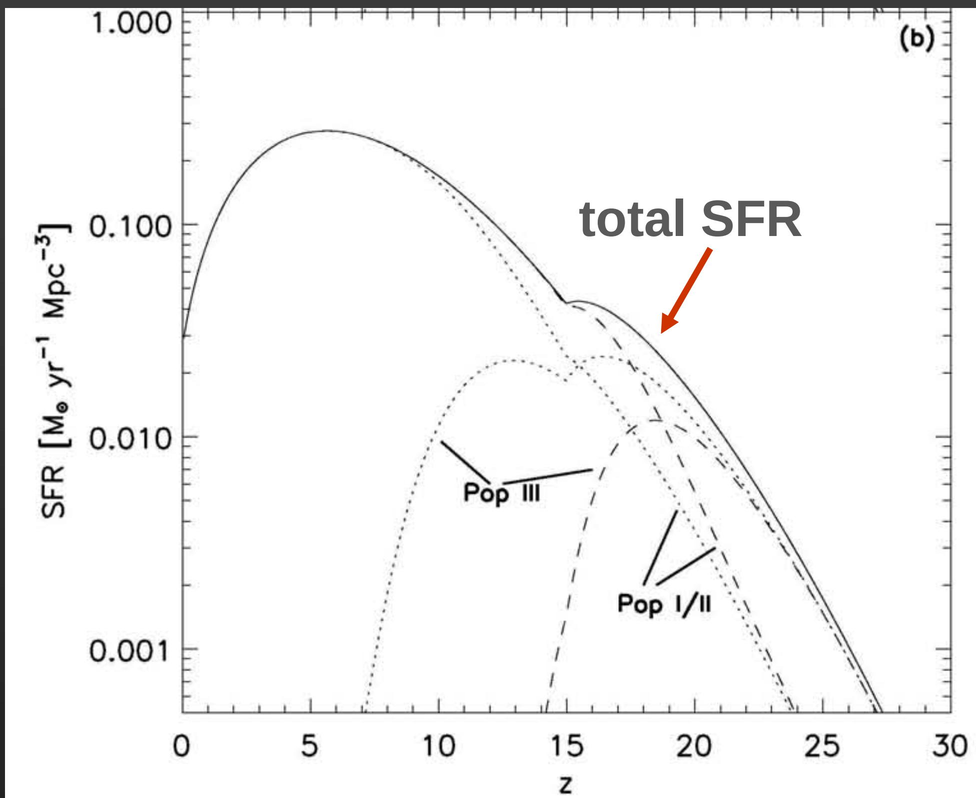


$z_{tran} \sim 15 \pm 5$

Chemical Feedback: Pop III à Pop II transition

(Bromm & Loeb 2006; astro-ph/0509303)

SF History



strength of chemical feedback

weak strong

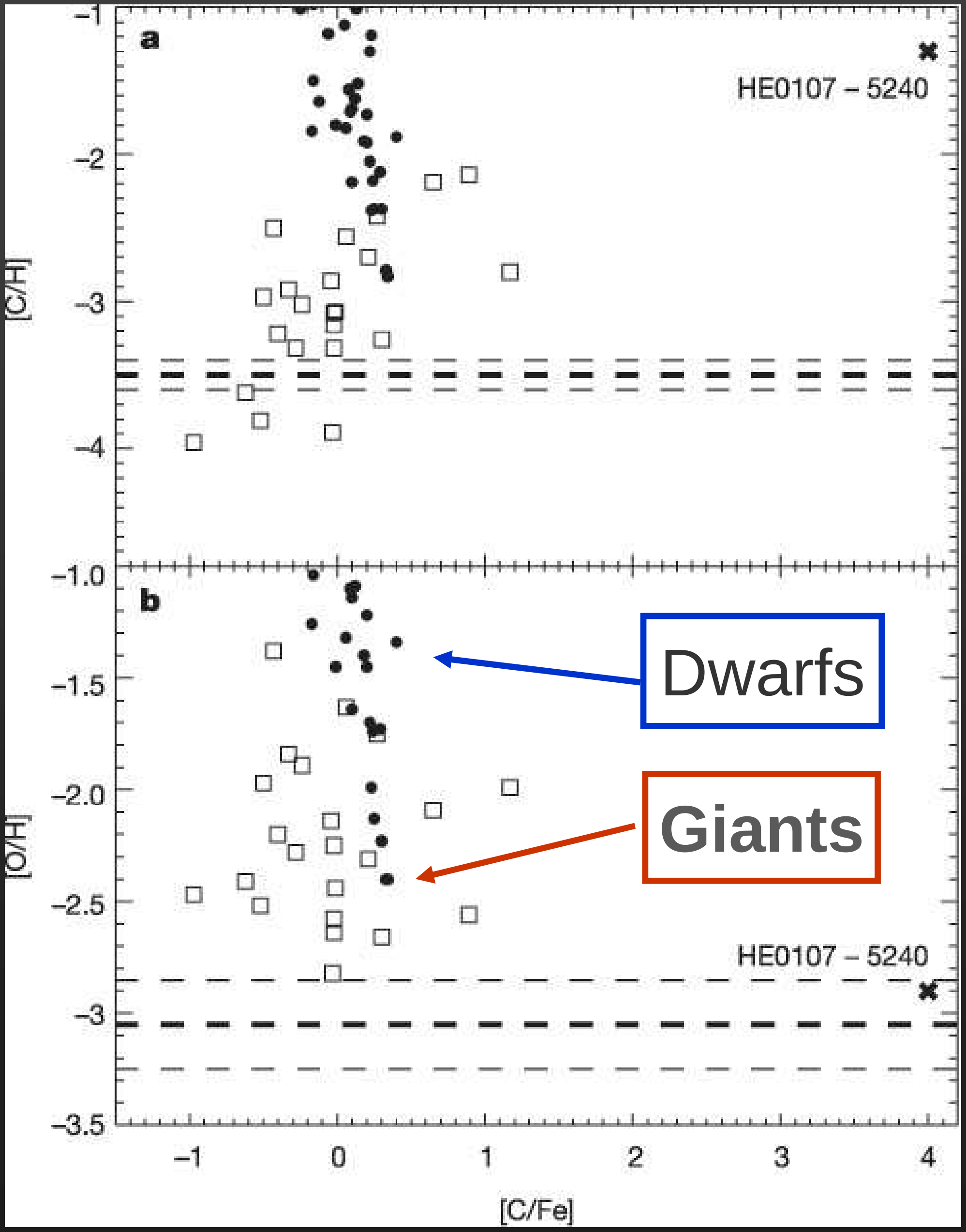
(cf. Scannapieco, Schneider, & Ferrara 2003)

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

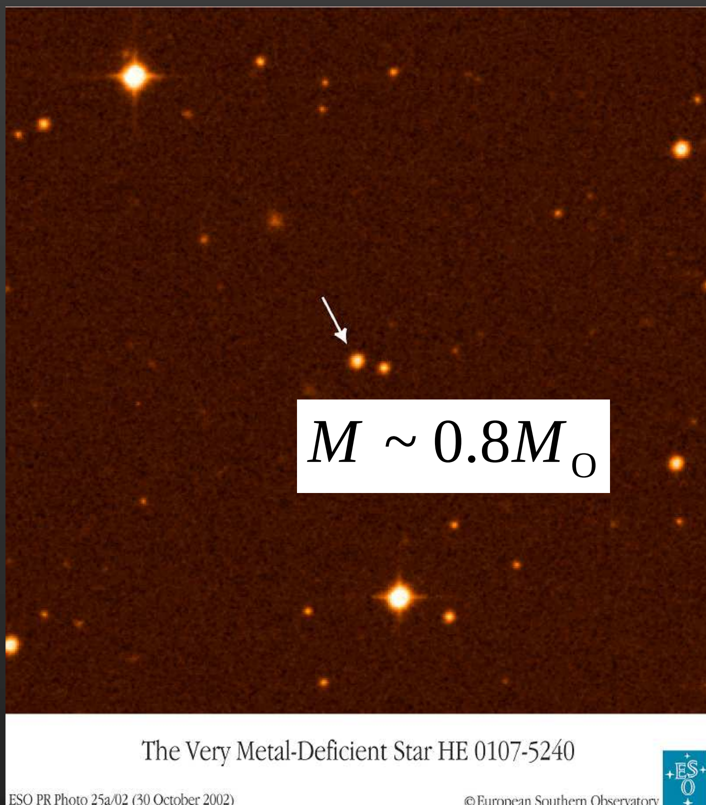
- Pop III → Pop II:
  - driven by: CII, OI (fine-structure transitions)

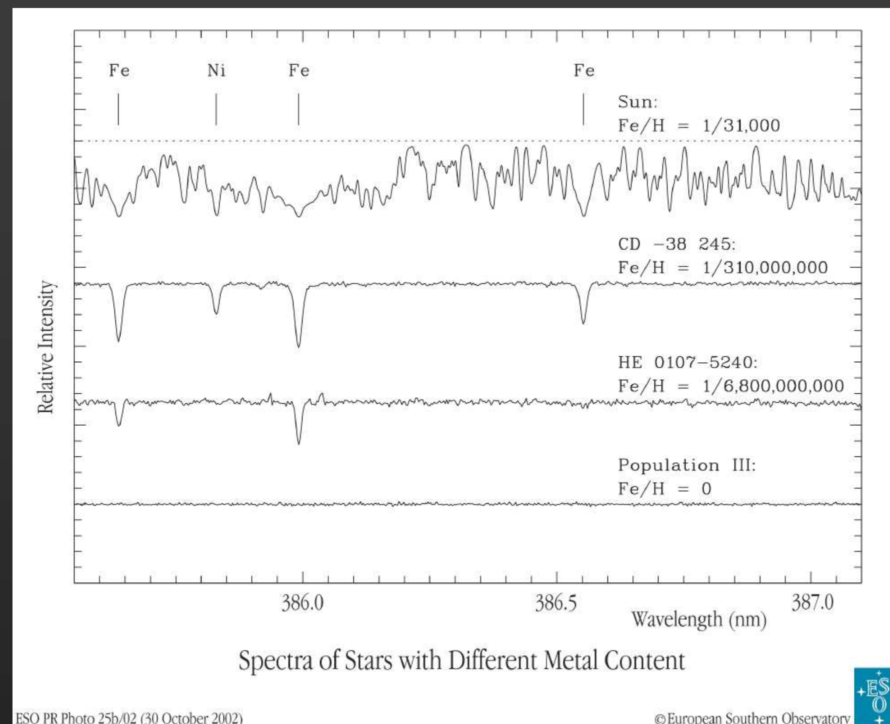
- Minimum abundances:
  - [C/H] ~ -3.5
  - [O/H] ~ -3.1
  - Identify truly 2nd gen. stars!



Relic from the Dawn of Time:

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





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

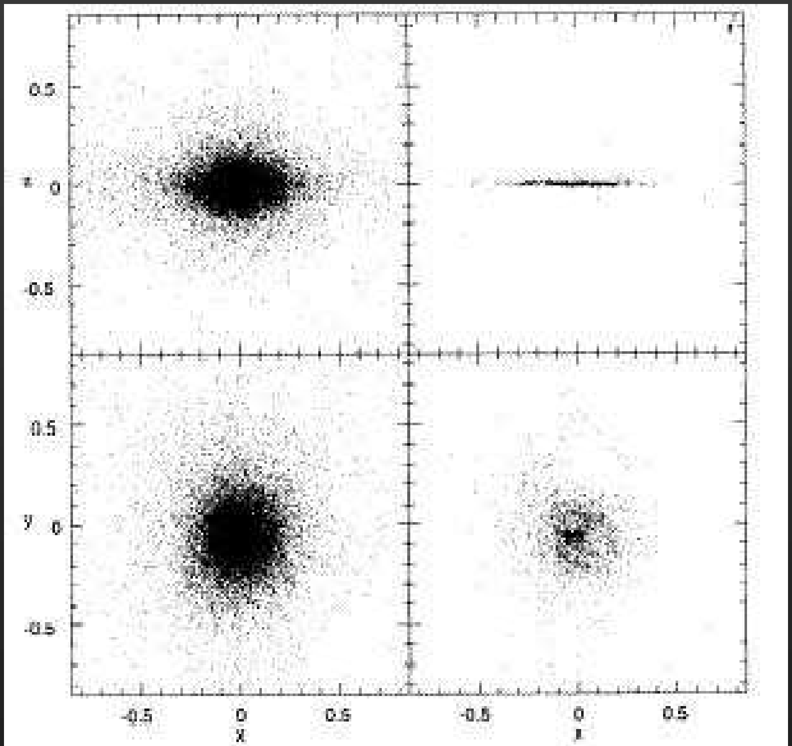
Formation of the First Quasars

(Bromm & Loeb 2003, ApJ, 596, 34)

- Seed BH by direct collapse of primordial gas cloud

(Loeb & Rasio 1994, ApJ, 432, 52)

Stars **Gas**



- **Problem**:

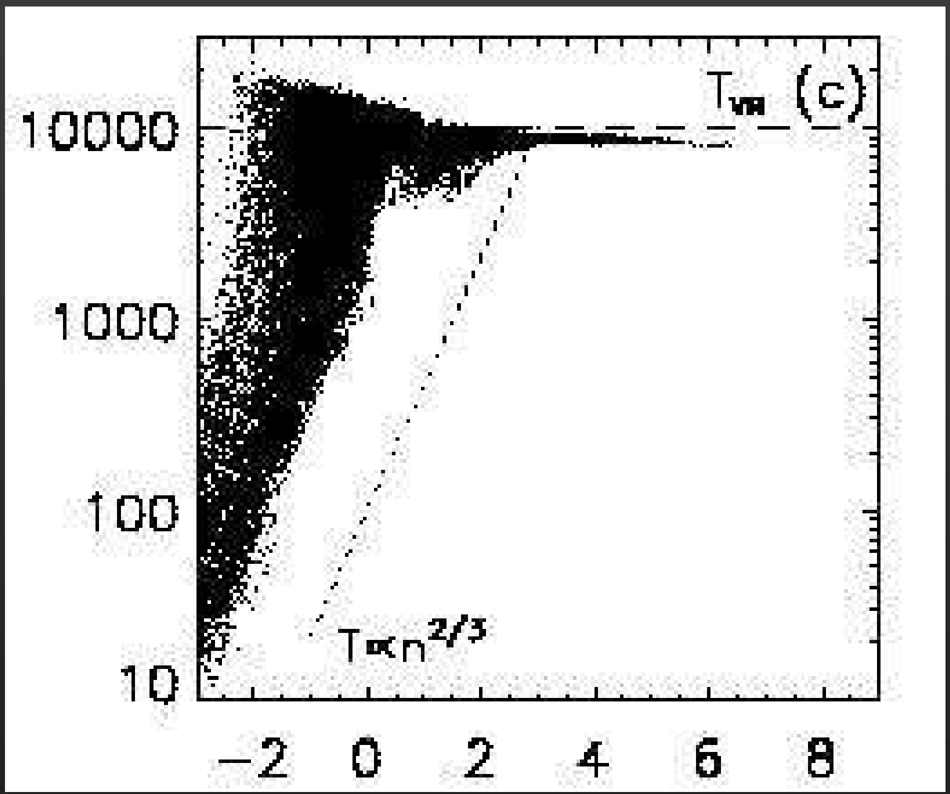
  - Gas cooling
  - Fragmentation
  - Star Formation
  - Negative Feedback (SNe)

→ **No compact central object!**

Mass ~ 10^9 M_o, R ~ 1 kpc
zvir = 5, no DM

First Dwarf Galaxies as Sites of BH Formation

T vs. log n



$T_{vir} \sim 10^4$ K

- **2 sigma peak**
- **$M \sim 10^8\ M_0$, $z_{vir} \sim 10$**
- **$T_{vir} \sim 10^4$ K**

→ Cooling possible due to atomic H

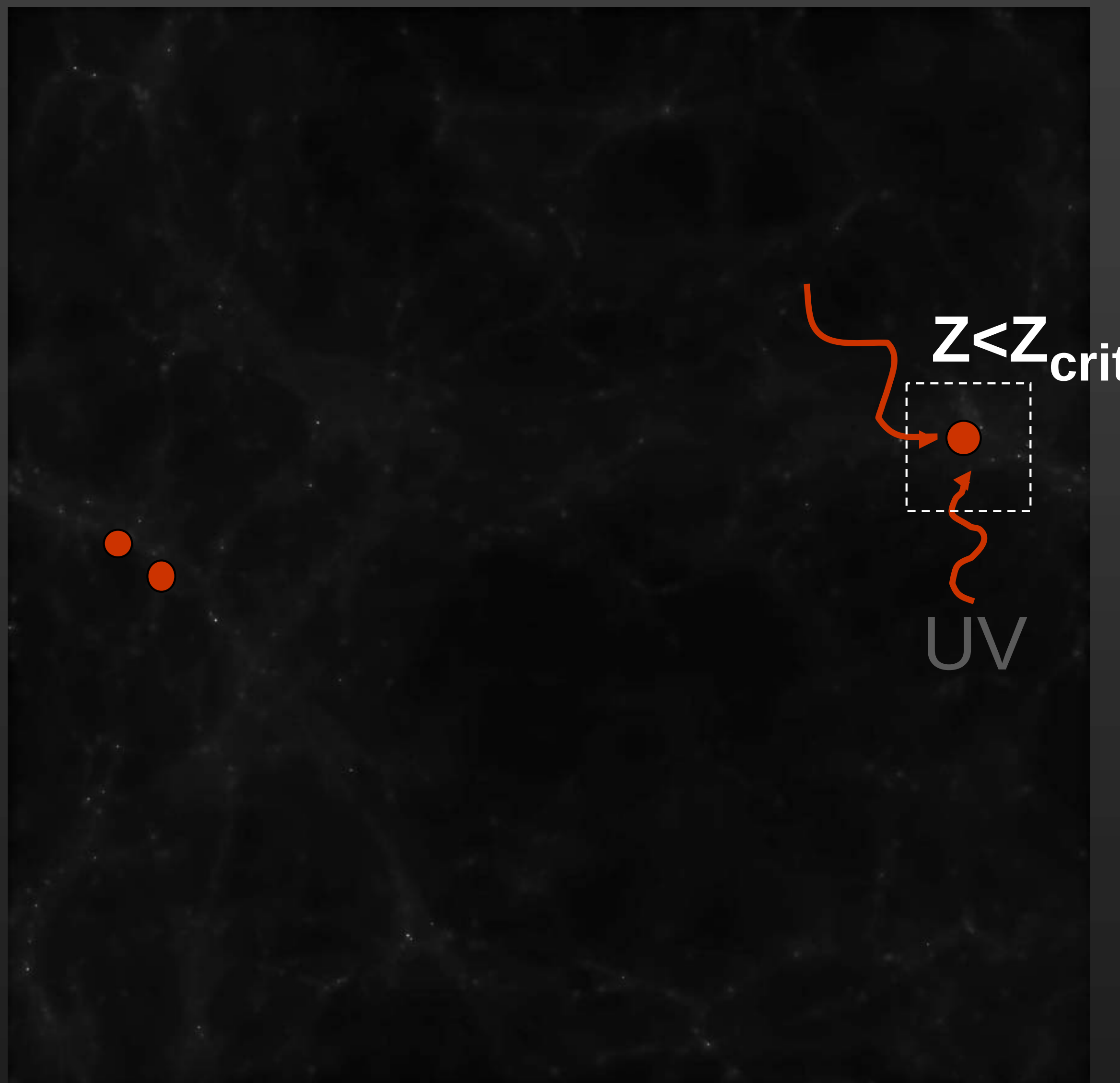
- Suppress star formation:
  - Photo-dissociation of H_2:

    $H2 + h\ nu \longrightarrow 2\ H$

  - Lyman – Werner photons:

    $h\ nu = 11.2 – 13.6$ eV

Cosmological Context



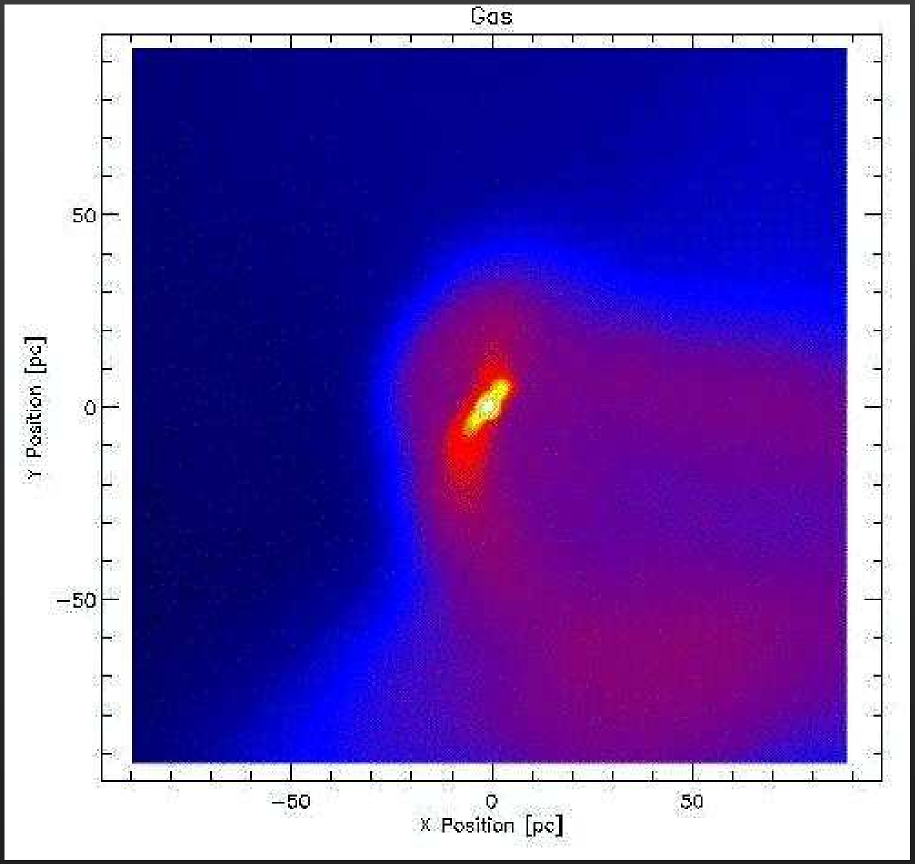
Z = 10

1 co-moving Mpc

En Route to a Supermassive Black Hole?

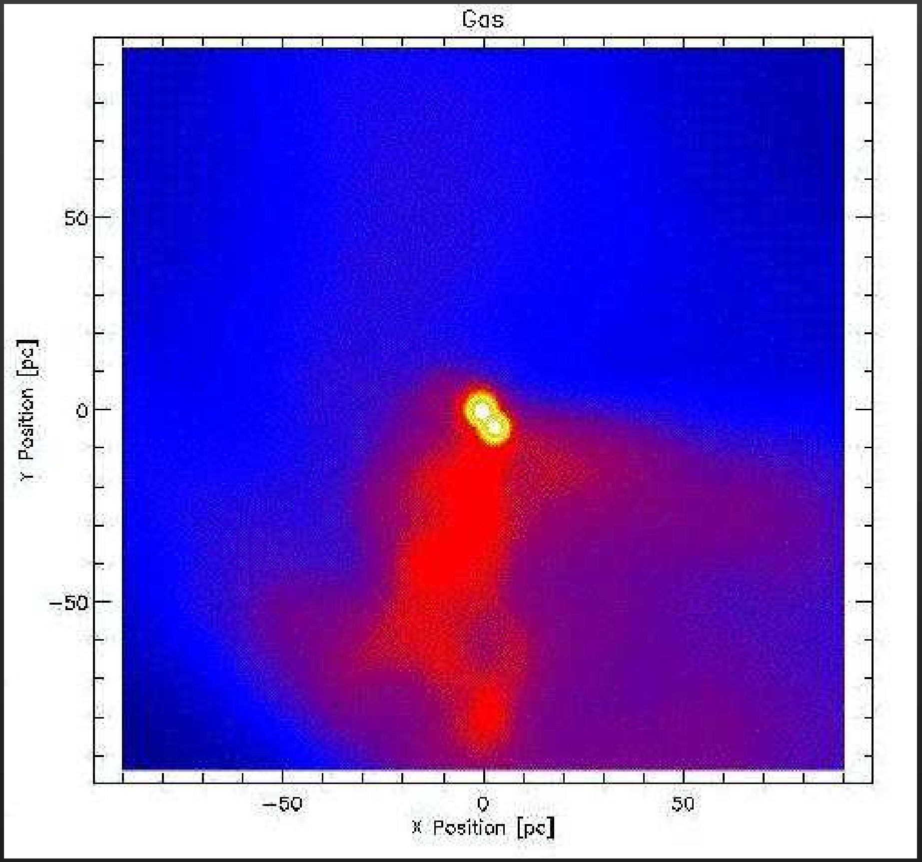
- Consider gas distribution in central 100 pc

Low-spin



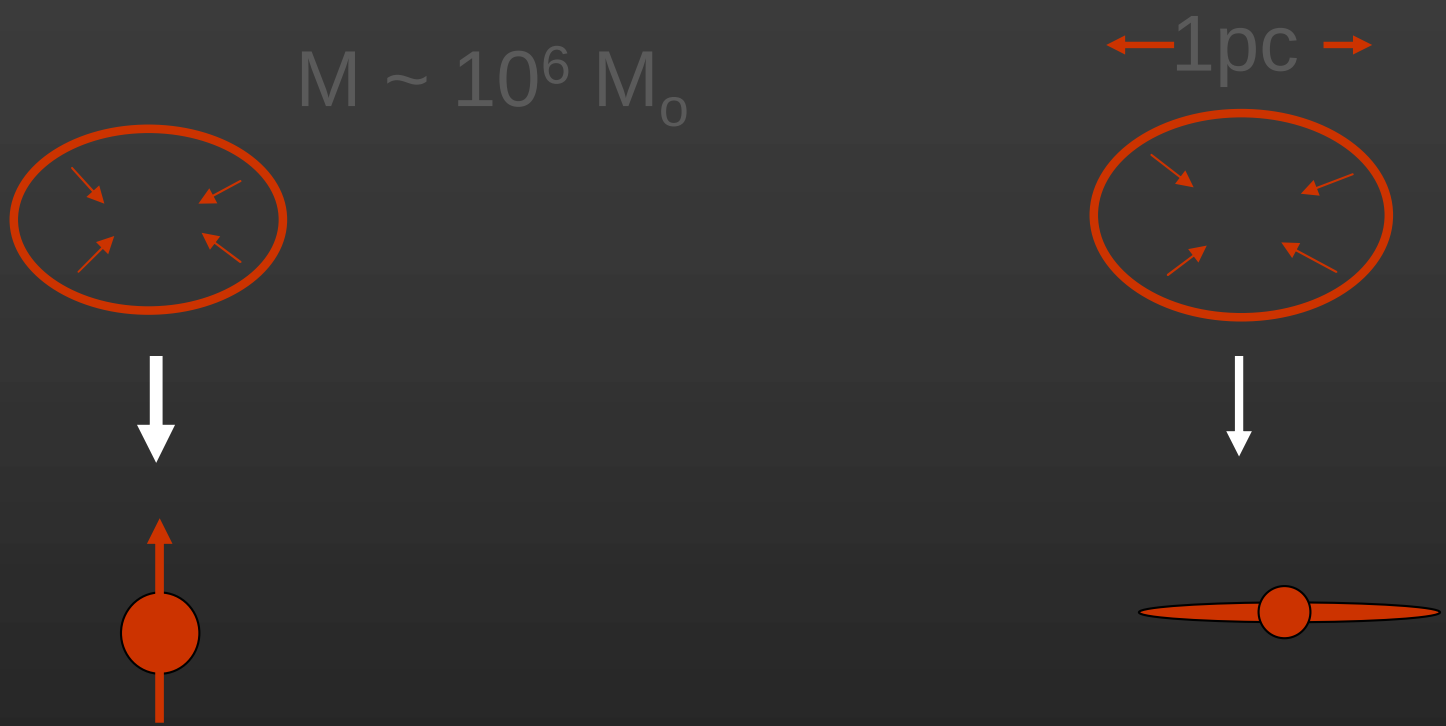
Single object: M ~ 10^6 M_o

High-spin



Binary: $M_{1,2}$ ~ 10^6 M_0

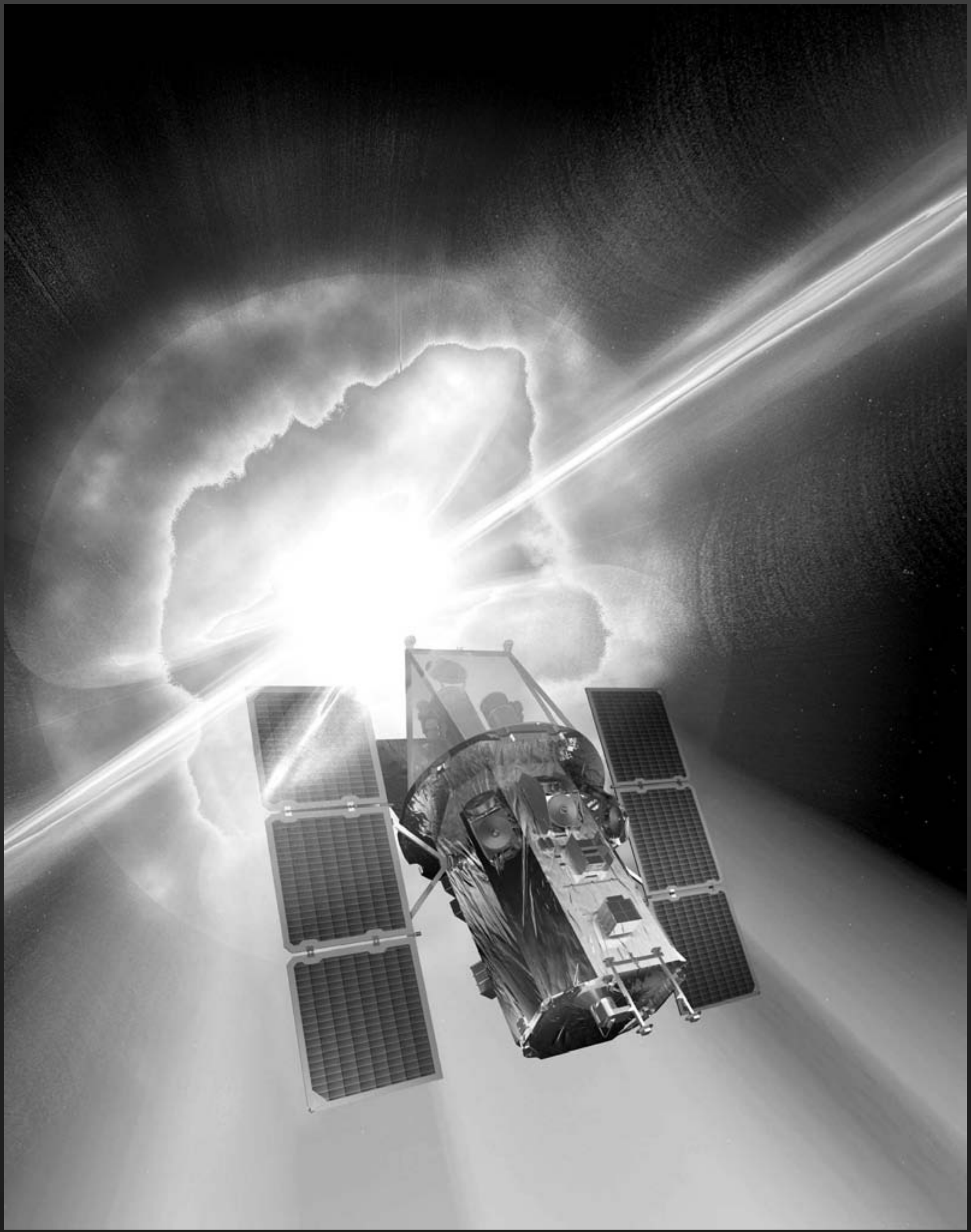
What is further fate of gas cloud?



Supermassive Star **Supermassive Disk**

- Radiation-pressure supported: $t_{cool} >> t_{ff}$
- Supermassive star or disk: $t_{vis} < t_{cool}$ → **SMS?**

Gamma-Ray Bursts as Probes of the First Stars:



• GRB progenitors → massive stars

• GRBs expected to trace cosmic SFH

• *Swift* mission:

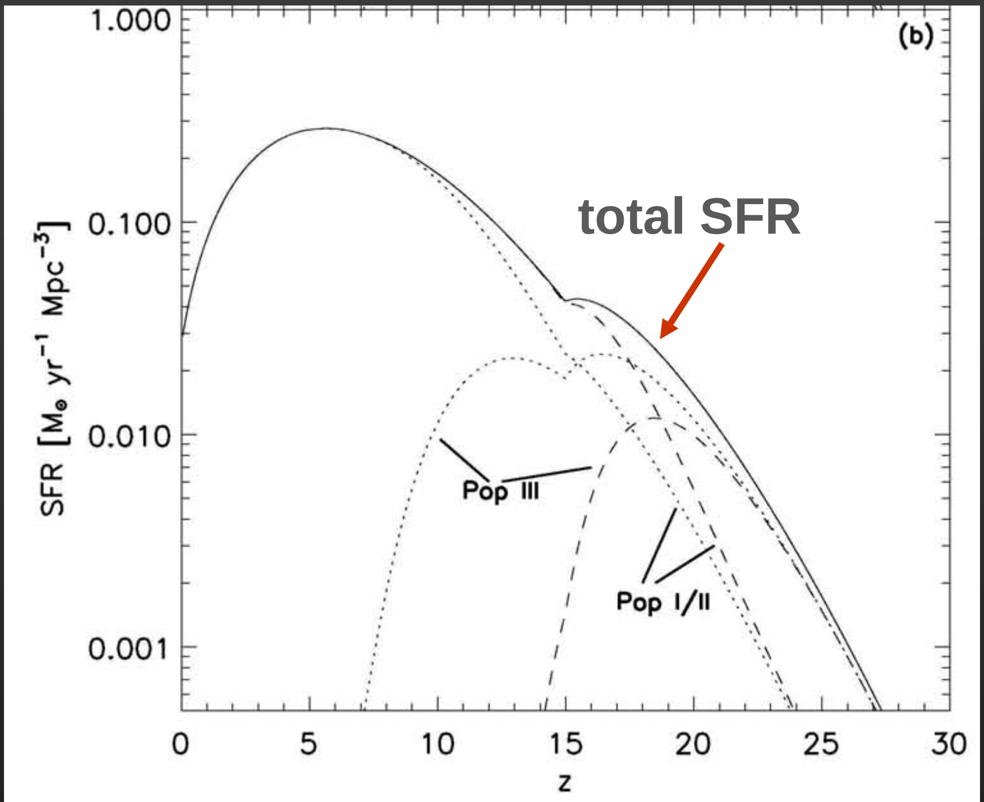
- Launched in 2004

- Sensitivity → GRBs from z > 15

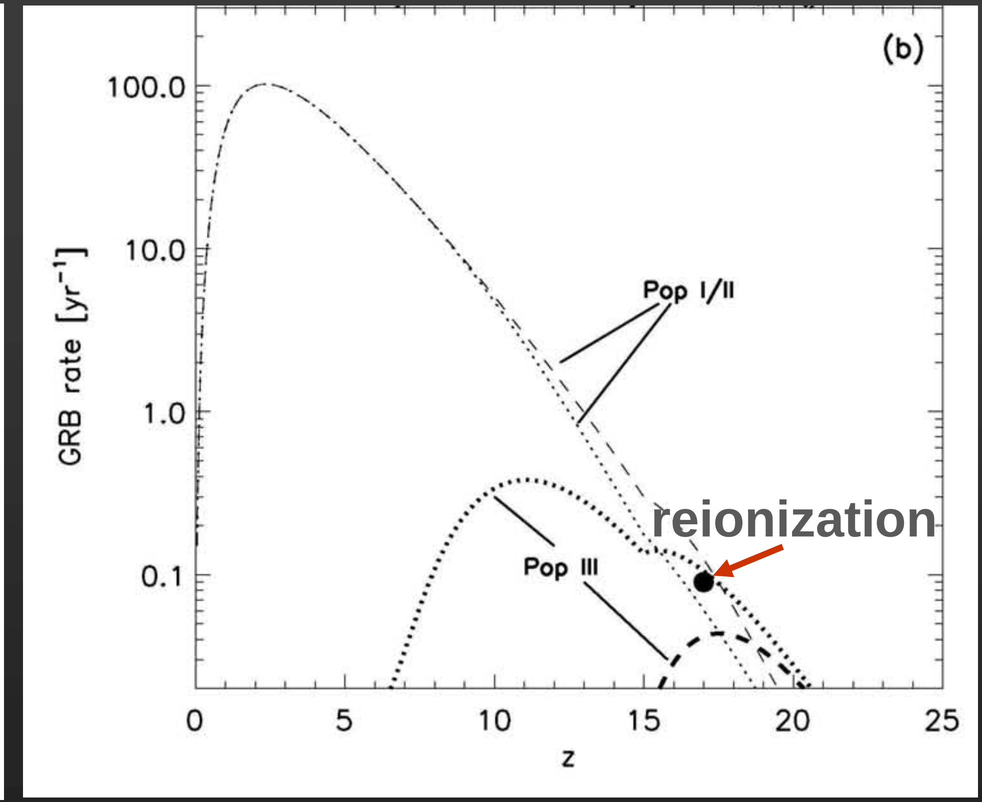
High-z GRBs from Population III Progenitors:

(Bromm & Loeb 2006; astro-ph/0509303)

SF History



GRB Redshift Distribution



- 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: $M_J \sim 10^3 M_o$

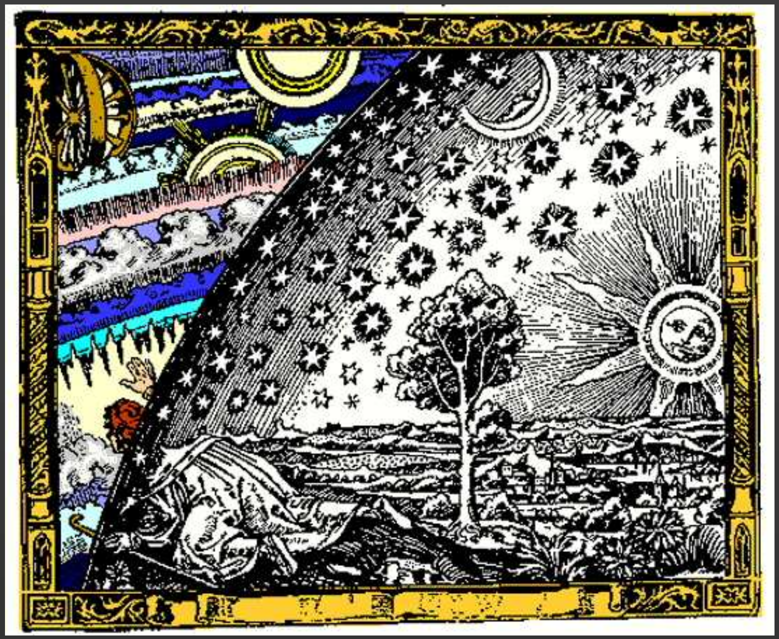
• Pop III SF might have favored *very massive stars*

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