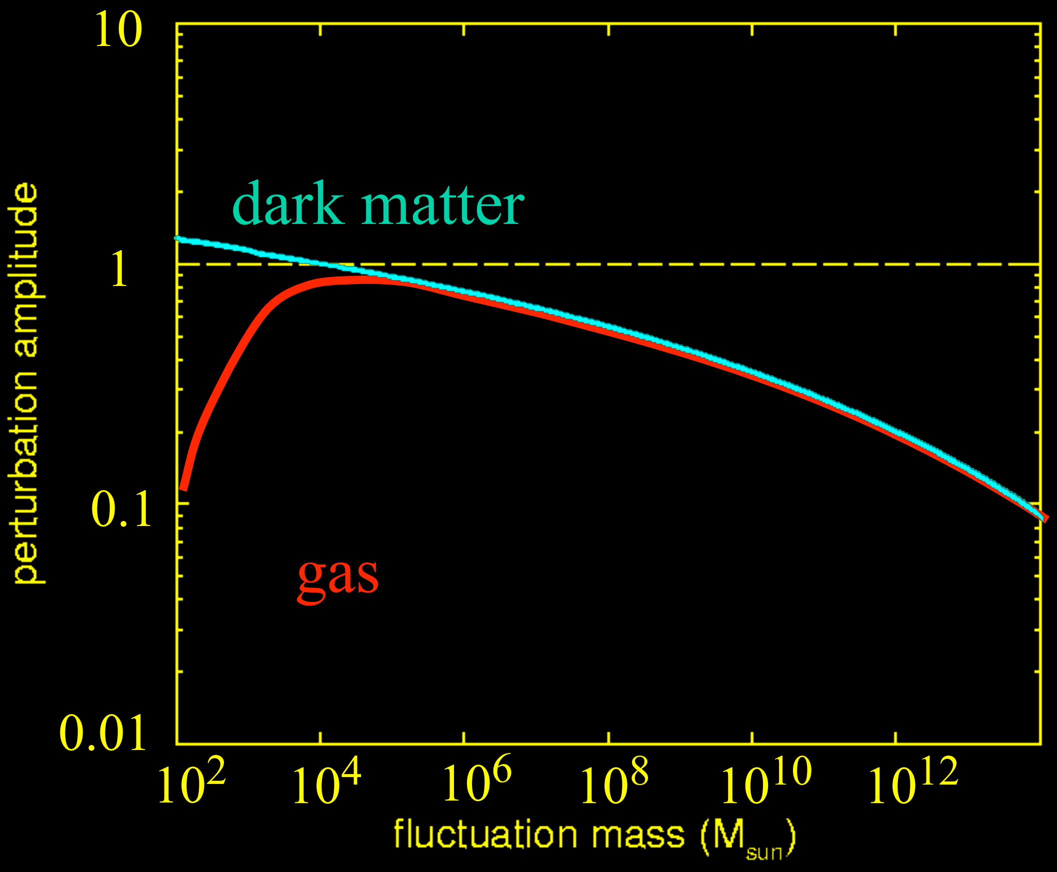
Outline

A. First star formation
B. First star feedback
C. Large-scale reionization
D. Open questions/simulations

Dark matter vs. gas

- Dark matter clumps on all scales
- Gas resists clumping below Jeans length
  (when thermal pressure balances gravity)
  - $M_J =$ $\sim 10^4\ M_{sun}$
- $M_{cloud} > M_J$ necessary



Dark matter vs. gas

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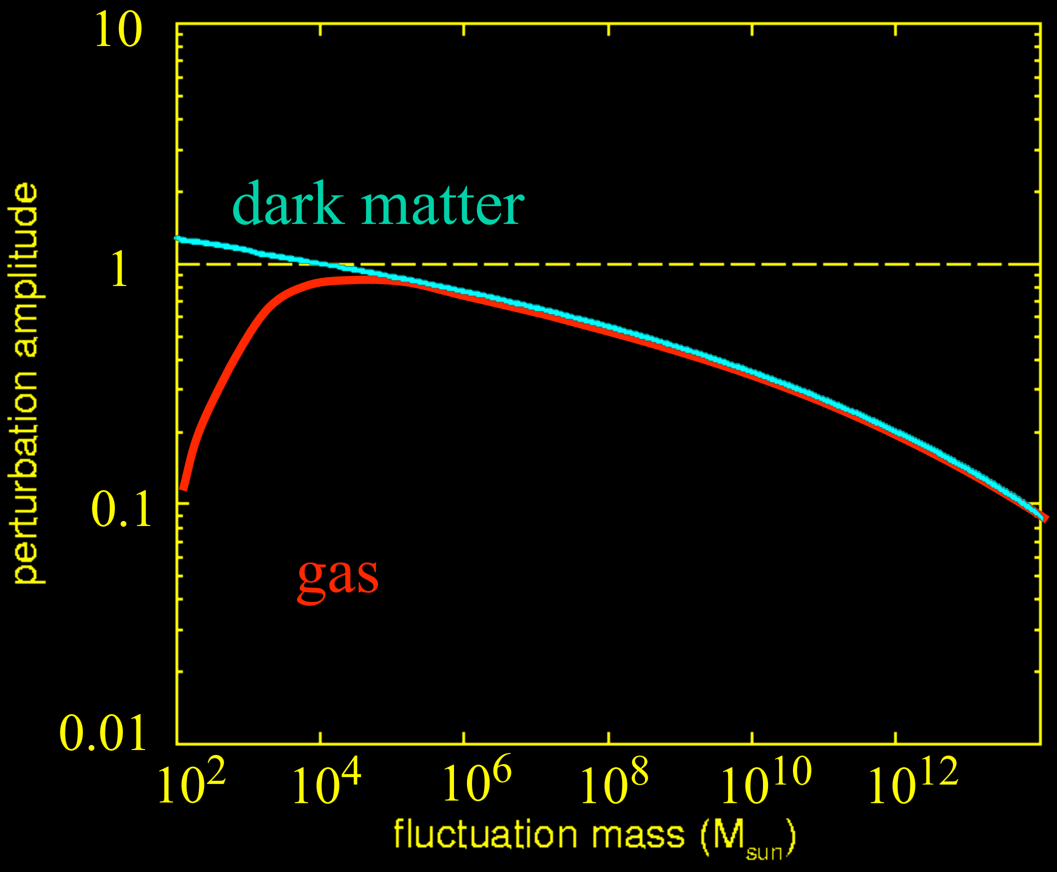
- Gas resists clumping below Jeans length
  (when thermal pressure balances gravity)
  - $M_J =$
    $\sim 10^4 M_{sun}$
- $M_{cloud} > M_J$ necessary but not sufficient
- Cloud must also <u>cool</u>:
  H_2



Cooling: Why H_2?

- No "heavy" molecules (e.g. CO)
- Cloud collapses (virializes): $T \sim T_{vir} \sim M^{2/3}(1+z)$
  - Set by initial conditions and dark matter
  - If $T_{vir} < 10^4$ K: No H line cooling, only H_2
  - If $T_{vir} > 10^4$ K: H line cooling dominates
- H_2 formed in gas phase (no dust)
  - catalyzed by free electrons, strongly T dependent

$$H + e^- \longrightarrow H^- + h\nu$$
$$H^- + H \longrightarrow H_2 + e^-$$

Cooling: Why H_2?

- Cooling efficiency depends on:
  - amount of H_2
  - Temperature (cooling rate $\sim T^4$)
- Minimum H_2 fraction for efficient cooling
  - $f(H_2) \sim 10^{-3}$
  - $T_{vir} \sim 1000$ K

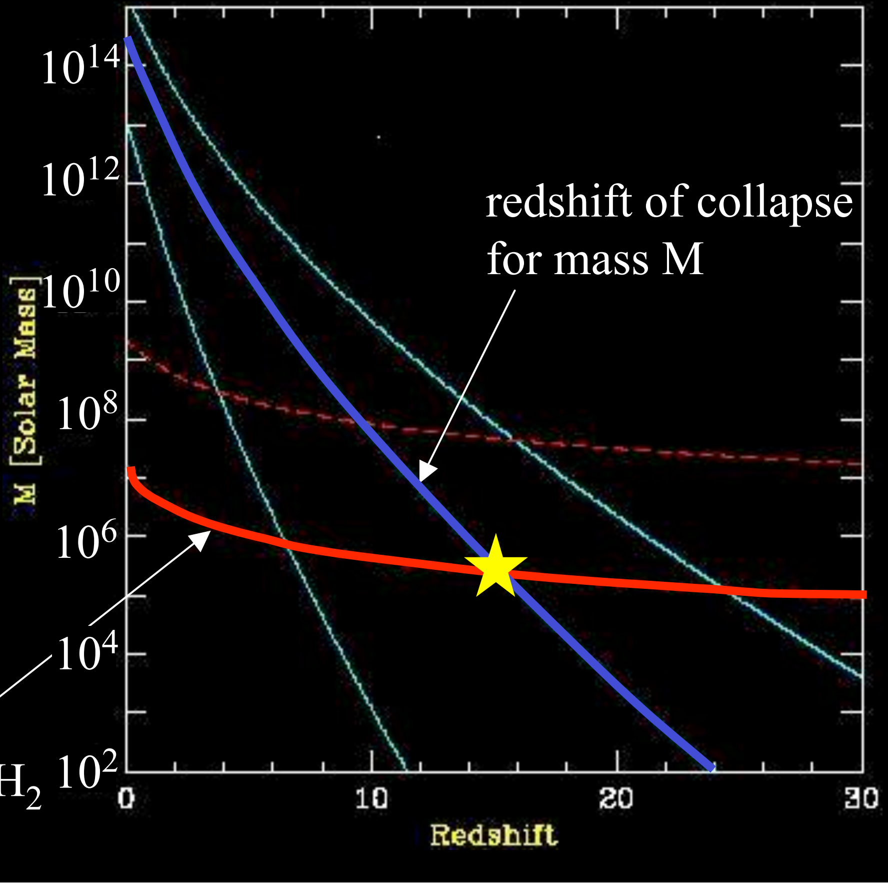
$t_{cool} = t_{age}$

First Stars: Two mass scales

(1) Overall mass of the “microgalaxy” (M_{cloud})

- $M_{cloud} \sim 10^6\ M_{sun}$ (minimum cooling scale)
  - z ~ 20
- Analytic approaches:
  - Tegmark et al. (1997)
  - Abel et al. (1998)
- Numerical simulation:
  - 1D: Haiman et al. (1996), Omukai & Nishi (1998)
  - 3D: Abel et al. (1998) Fuller & Couchman (2000)

Barkana & Loeb 2001

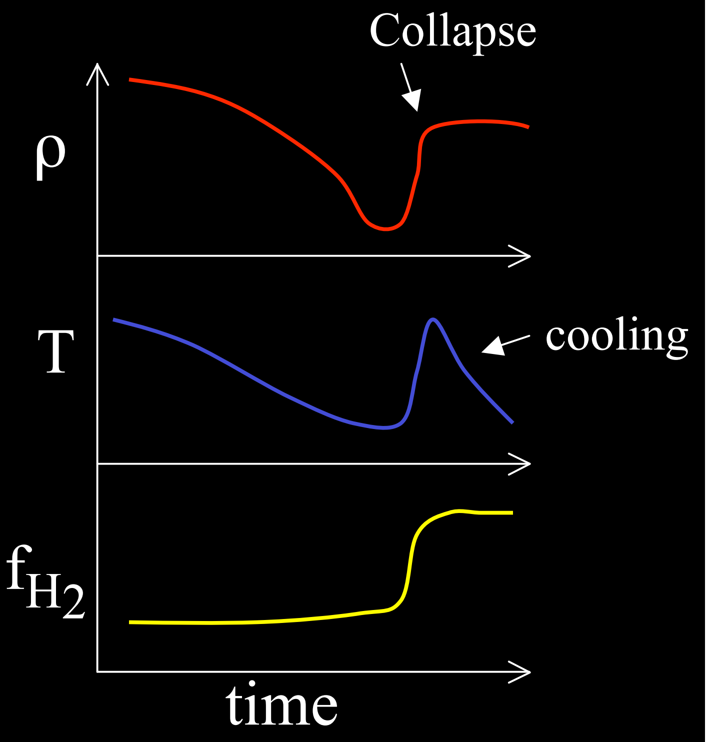


redshift of collapse for mass M

Minimum mass
For cooling via H_2

M_{cloud}: Analytic approach

- Guess M_{cloud} (M_{vir} & z_{vir})
- Assume spherical symmetry
  - Use "top-hat" solution: $\rho(z)$
- Calculate $n_{H_2}(z)$, $T(z)$
  - Solve rate equations for H_2
  - Solve heating/cooling rates
- Stop when $T(z=z_{cool})$ falls below $0.75T(z_{vir})$
- For given cosmology: find M_{vir} with smallest z_{cool}



First Stars: Two mass scales

(2) Stellar Mass (M_*) or IMF

- More difficult
  - substructure, fragmentation, H_2, multi-scale
- $M_* < 10^6\ M_{sun}$
- Analytically predicted M_*: $M_{planet} \rightarrow 10^6\ M_{sun}$
- Requires full numerical simulation
  - 1D: Haiman et. al (1996)
  - 2D: Nakamura & Umemura (2000)
  - 3D: Abel et. al (1998), Bromm et. al (1999), Abel et. al (2001), Bromm et. al (2003)

The first stars are different

	first generation of stars	present-day star formation
Coolant	H_2 (gas-phase)	CO, etc.
Equation of state	“adiabatic” (slow cooling)	isothermal (fast cooling)
Typical temperature	500 K	10 K
Initial conditions	well-prescribed	Uncertain
Magnetic fields	(probably) absent	dynamically important

Simulating the first stars

- Primordial star formation easier…
  - No heavy elements, ionizing radiation, magnetic fields
  - Primary coolant: H_2
    - T < 9000 K → H line cooling unimportant
- …but still hard:
  - H_2 abundance out of equilibrium
  - Resolution required: $L/r_{sun} \sim 10^{23}\mathrm{cm} / 10^{11}\mathrm{cm} \sim 10^{12}$
  - Fragmentation? ($M_{star} << M_{cloud}$)

The equations

1. Fluid equations

$$\begin{aligned}
\left(\frac{\partial \rho}{\partial t}\right)_r + \vec{v}\cdot\nabla_r \rho &= -\rho \nabla_r \cdot \vec{v}, \\
\left(\frac{\partial \vec{v}}{\partial t}\right)_r + (\vec{v}\cdot\nabla_r)\vec{v} &= -\frac{1}{\rho}\nabla_r p - \nabla_r \phi, \\
\left(\frac{\partial E}{\partial t}\right)_r + \vec{v}\cdot\nabla_r E &= -\frac{1}{\rho}\nabla_r \cdot (p\vec{v}) - \vec{v}\cdot\nabla_r \phi,
\end{aligned}$$

2. Ideal Gas

$$\begin{aligned}
E &= e + \frac{1}{2}\vec{v}\cdot\vec{v}, \\
e &= p/[(\gamma - 1)\rho],
\end{aligned}$$

3. Gravity

$$\nabla_r^2 \phi = 4\pi G(\rho_{total} + 3p_{total}/c^2) - \Lambda.$$

4. Dark matter

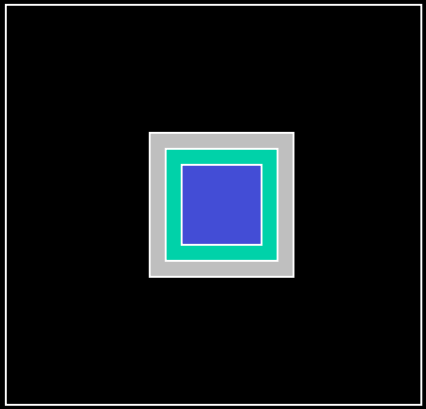
$$\rho_{total} = \rho_{gas} + \rho_{particles}$$

5. nine species: H, H^+, He, He^+, He^{++}, e^-, H^-, H^+, H_2

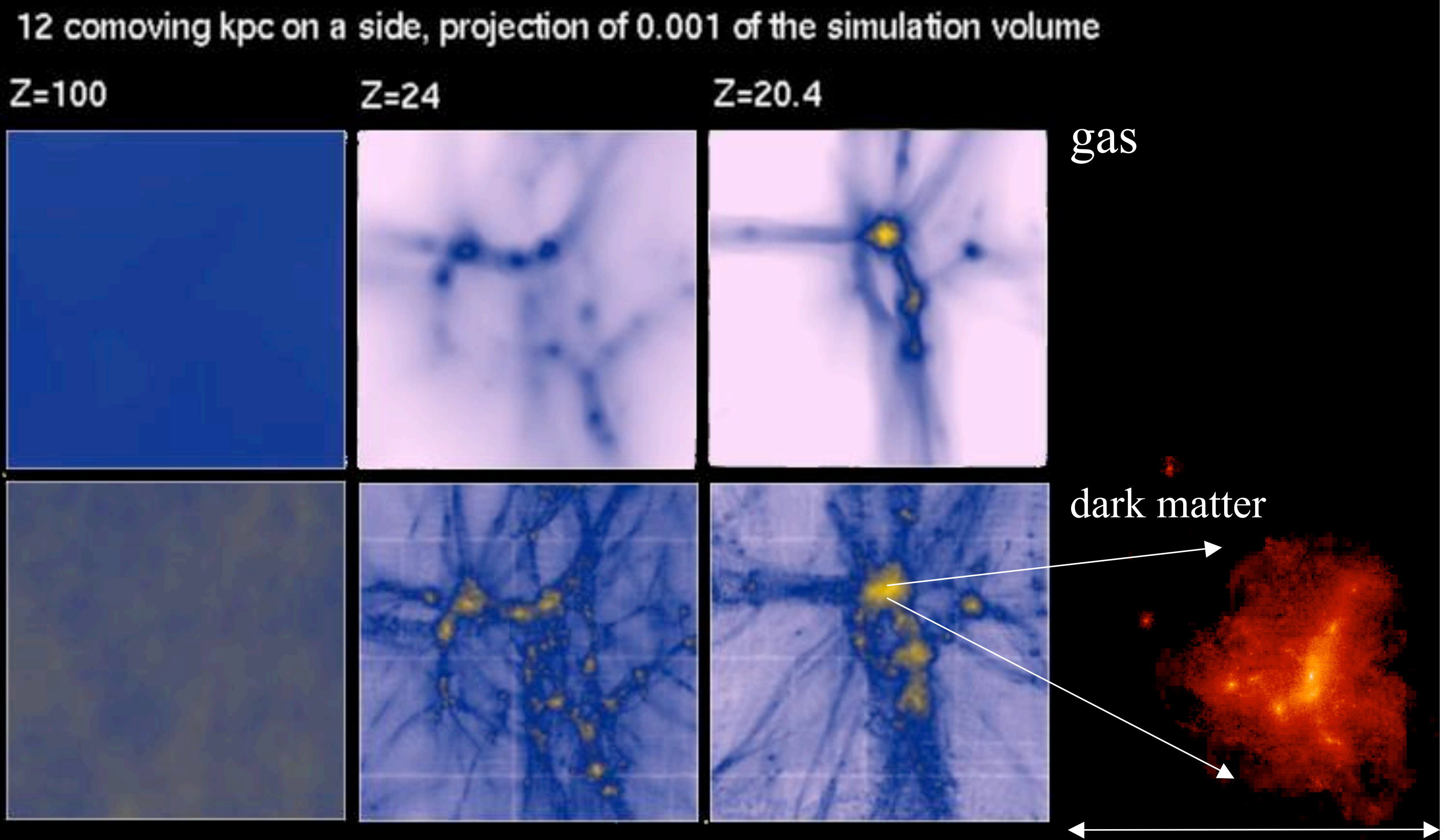
6. Radiative cooling/heating

The simulation: focus on one (2.5σ) halo

- L = 128 kpc, SCDM, $z_{init} = 100$
- 4 levels of AMR pre-refined:
  - $M_{DM} = 1\ M_{sun}$, $M_{gas} = 0.07\ M_{sun}$
- Refine up to 30 levels
- DM, gas, gravity
  - Non-equilibrium chemistry for 9 species
  - Cooling/heating from H_2, Compton, etc
- Refinement criteria:
  - (1) dm density, (2) gas density (3) $\Delta x < L_J/16$



Evolution of the Cloud



gas

dark matter

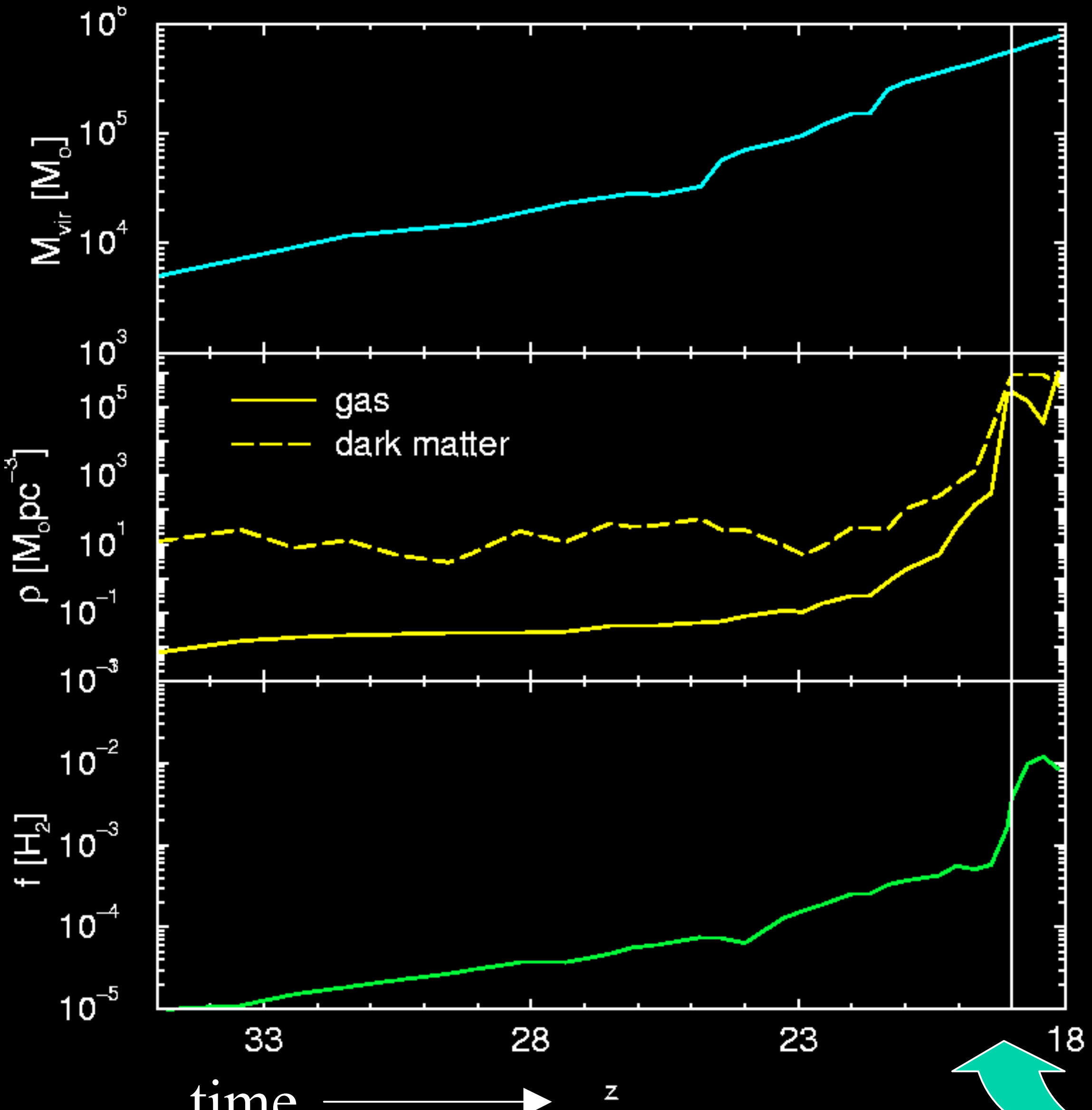
300 pc comoving

Primordial molecular cloud evolution

M_{cloud}

Central density

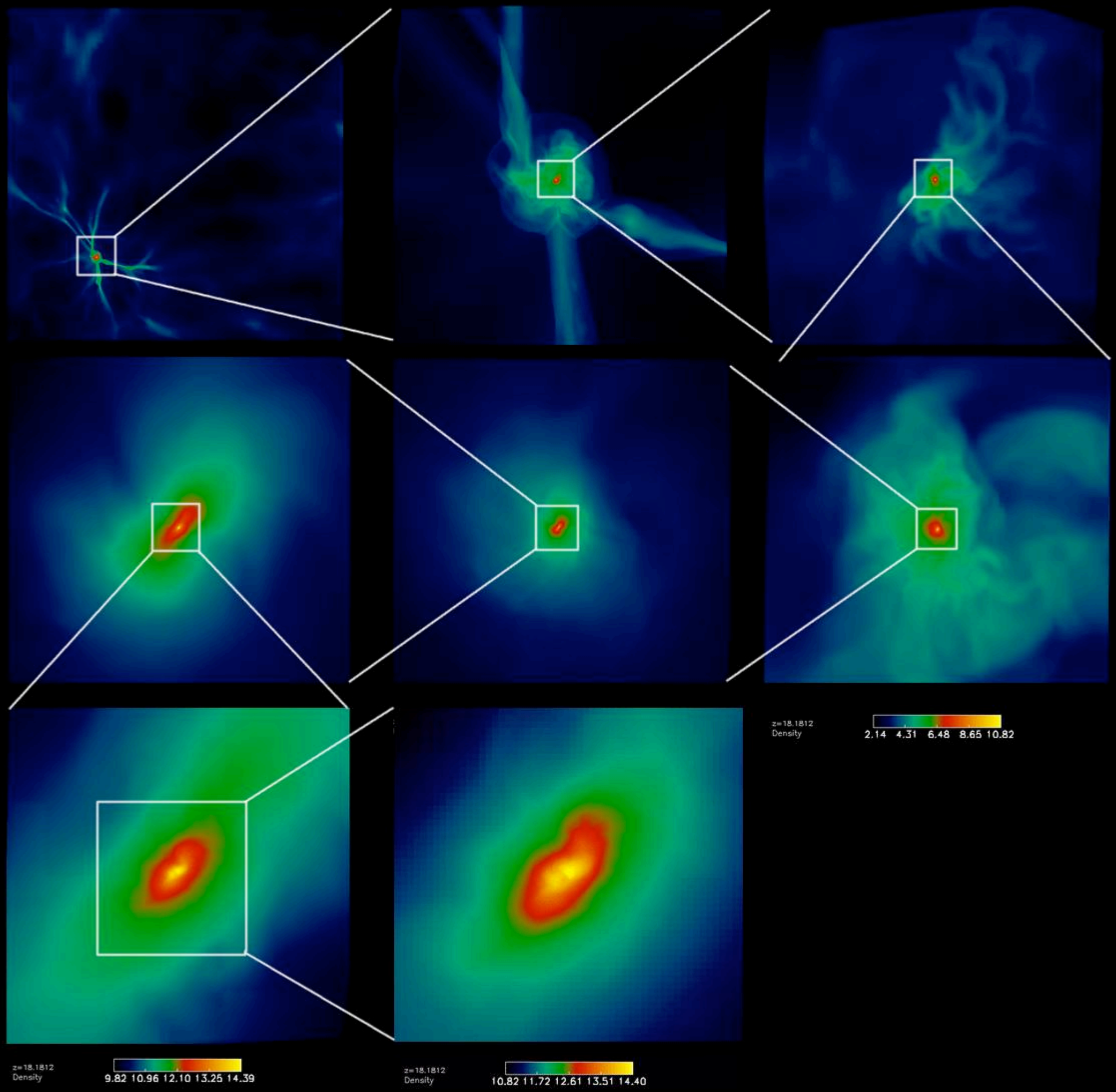
H_2 fraction



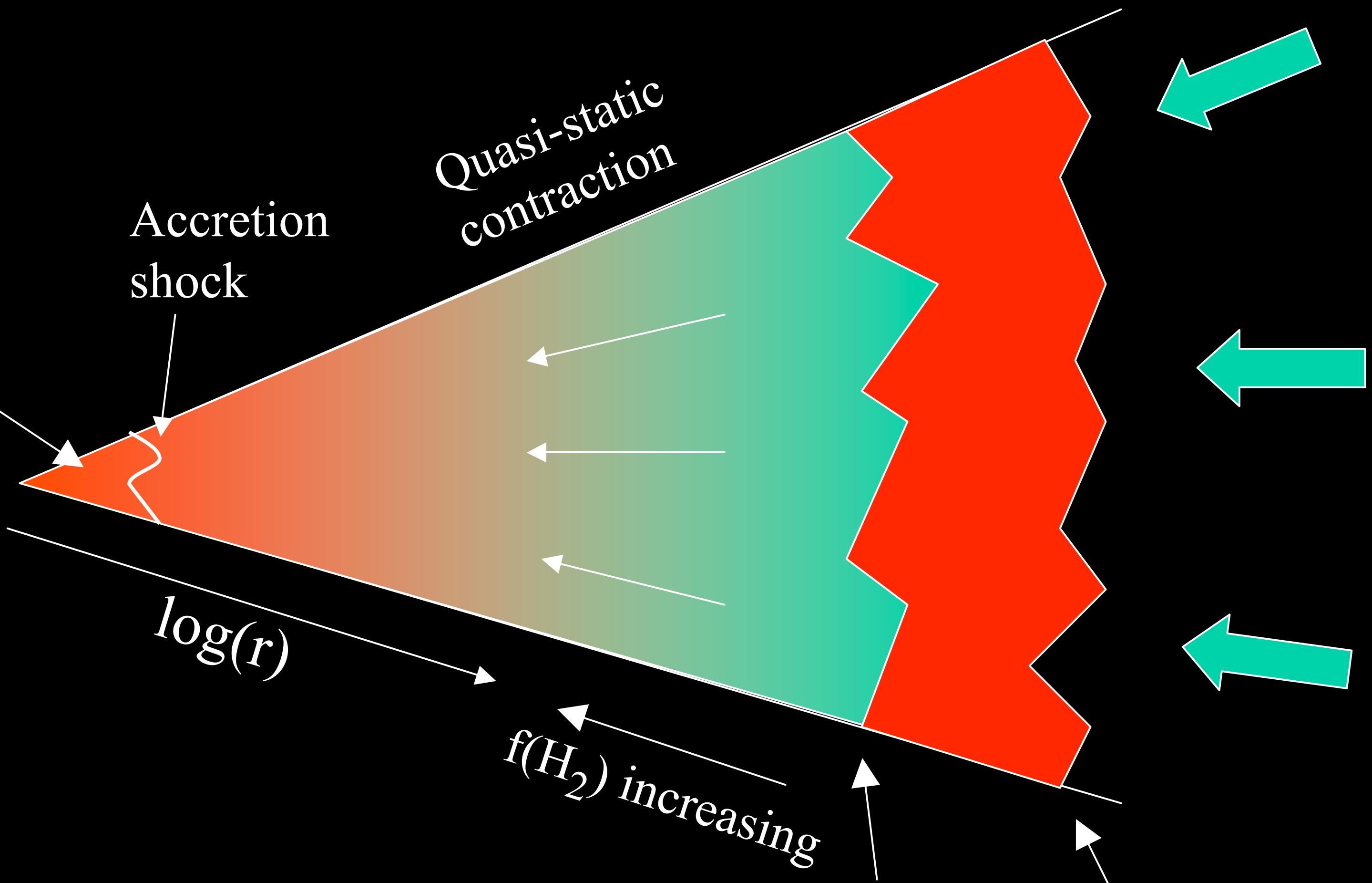
time →

collapse

First star formation



Microgalaxy structure



Fully
molecular
core

Accretion
shock

Quasi-static
contraction

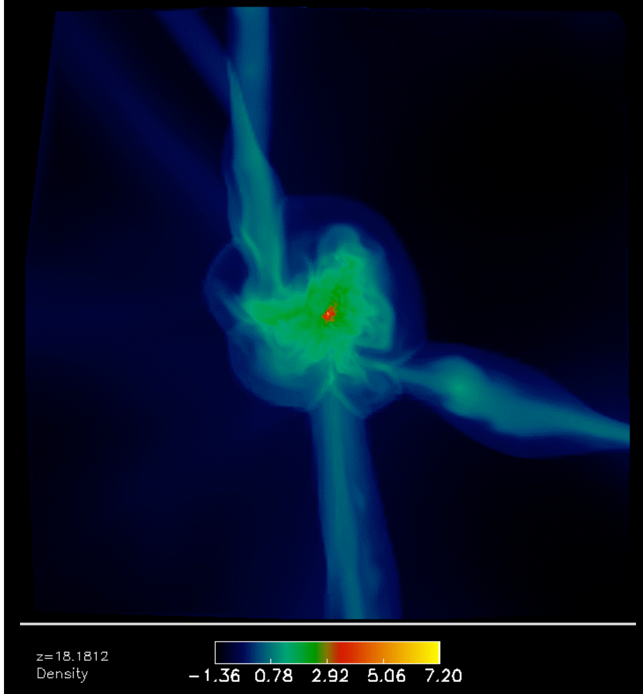
log(r)

$f(H_2)$ increasing

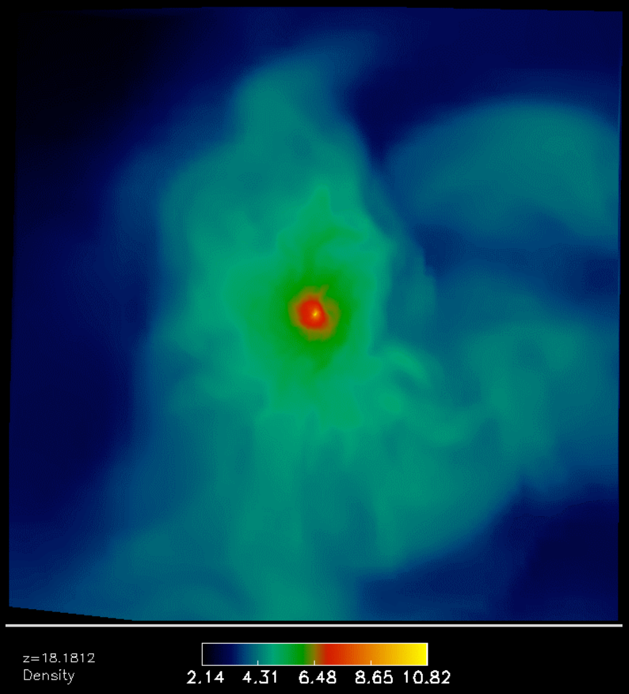
Cooling
front

Accretion
shock

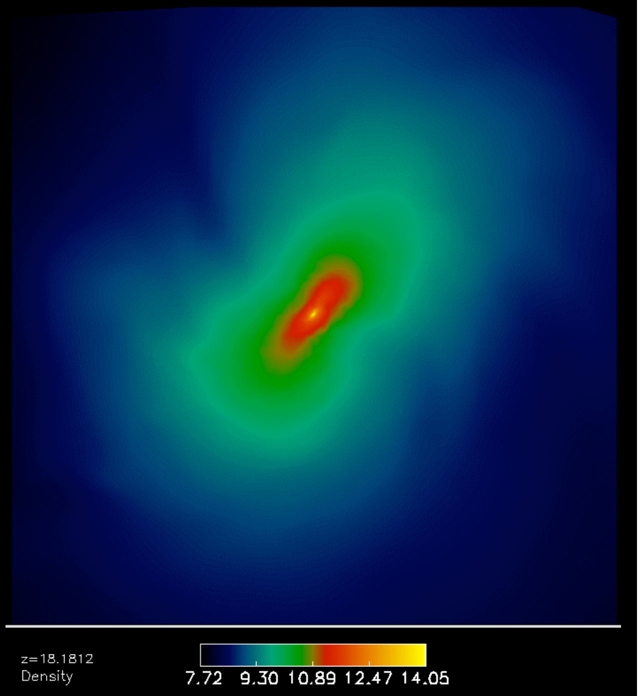
Density slice (z=18.2)



600 pc

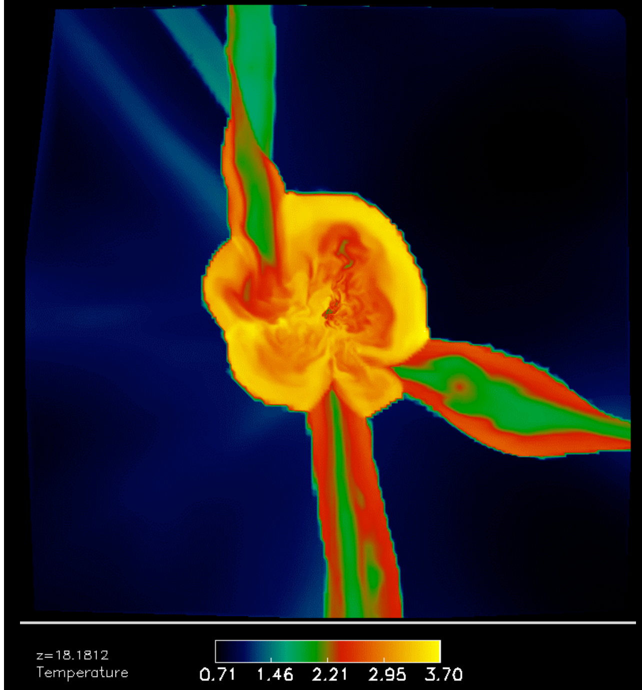


6 pc

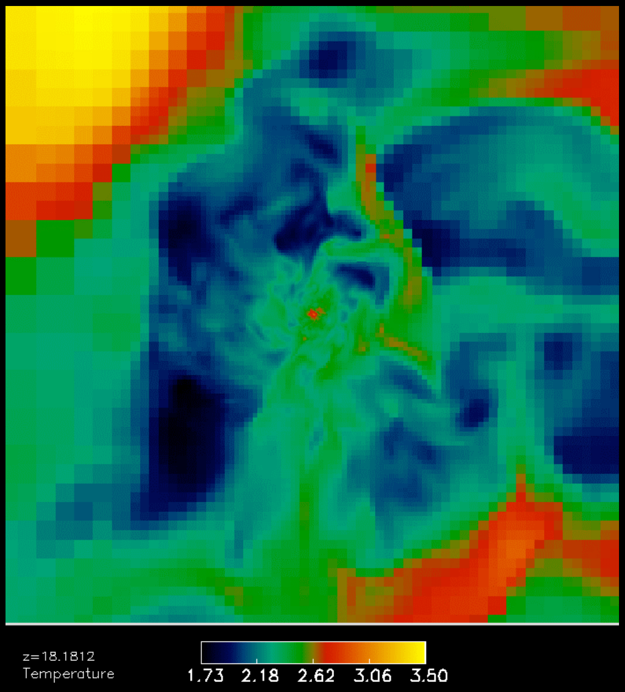


0.06 pc

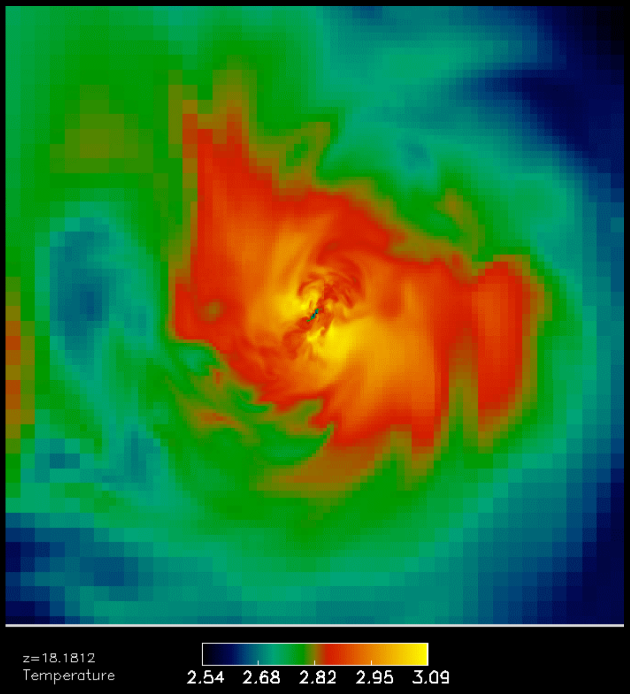
Temperature slice (z=18.2)



600 pc



6 pc



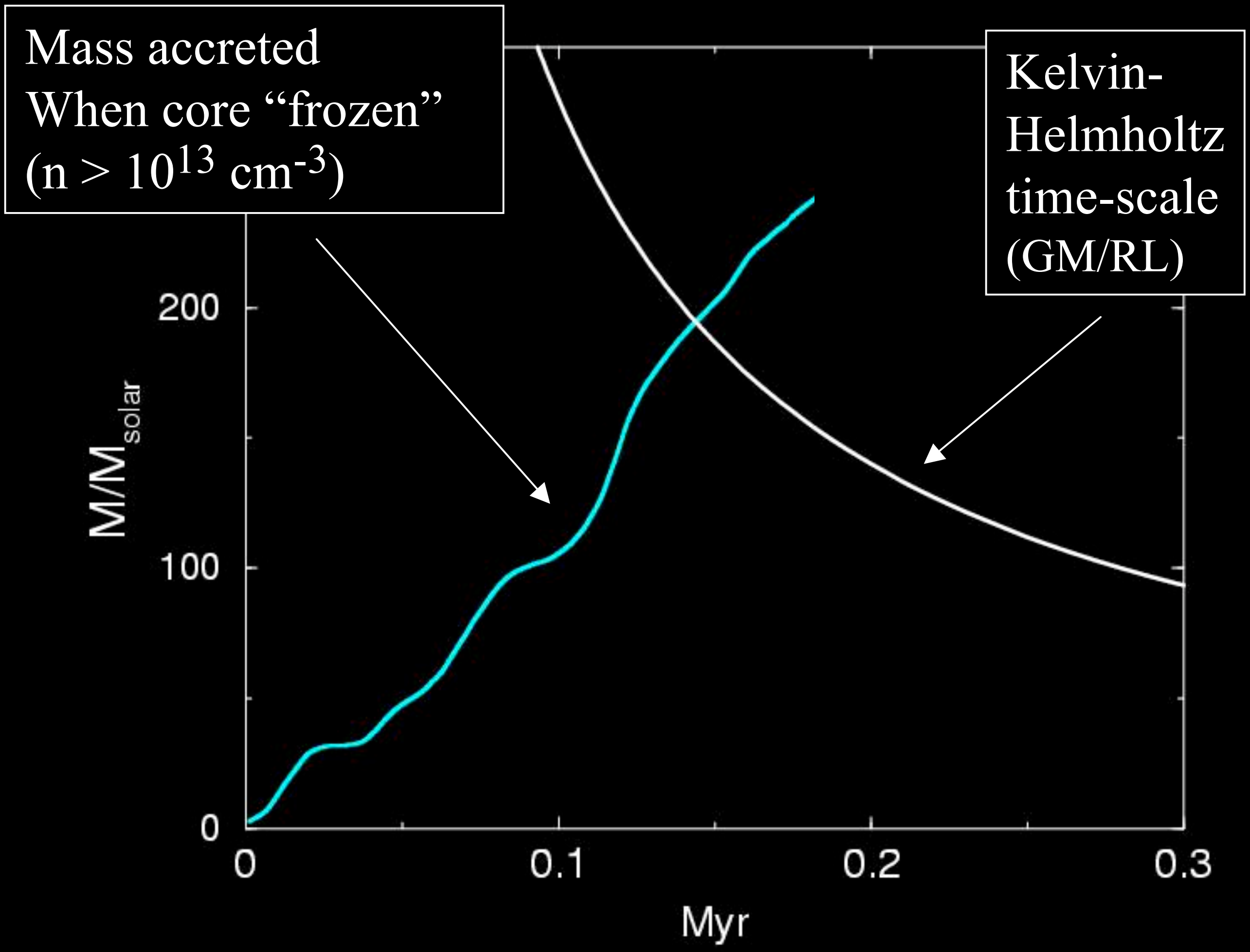
0.06 pc

What are the masses of the first stars?

- Calculation stopped when core is optically thick to H_2 line cooling
  - Protostar is final state of this calculation
- What can we say about final stellar mass?
  - M_* depends on accretion and radiative transfer
  - 1D Radiative transfer calculations imply that

    M_* limited by accretion
    - Omukai & Nishi (1998), Ripamonti et al. (2001)
- No fragmentation so far

What are the masses of the first stars?



Mass accreted
When core "frozen"
($n > 10^{13}$ cm^{-3})

Kelvin-Helmholtz time-scale (GM/RL)

This mass scale is set by the Jeans mass at $n_{crit} \sim 10^4$ cm^{-3}

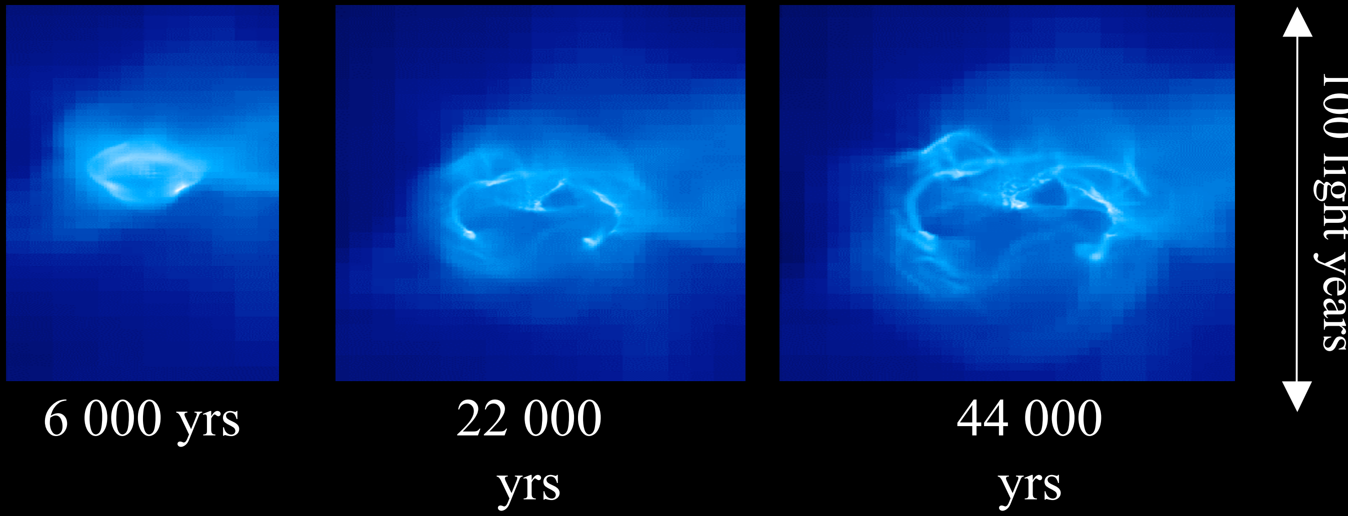
For H_2 cooling:

$n < n_{crit} \rightarrow t_{cool} \sim n^{-1}$

$n > n_{crit} \rightarrow t_{cool} \sim$ constant

What is the "Initial Mass Function" of the first stars?

- What about other objects in cloud?
  - – Can they form before 1st goes SN?
  - – No: only one object per cloud
    - Only 1 clump in cloud after a few Myr
    - 1 Supernova can unbind cloud
- Only one (massive) star produced per microgalaxy!



Have pop III stars been found locally?

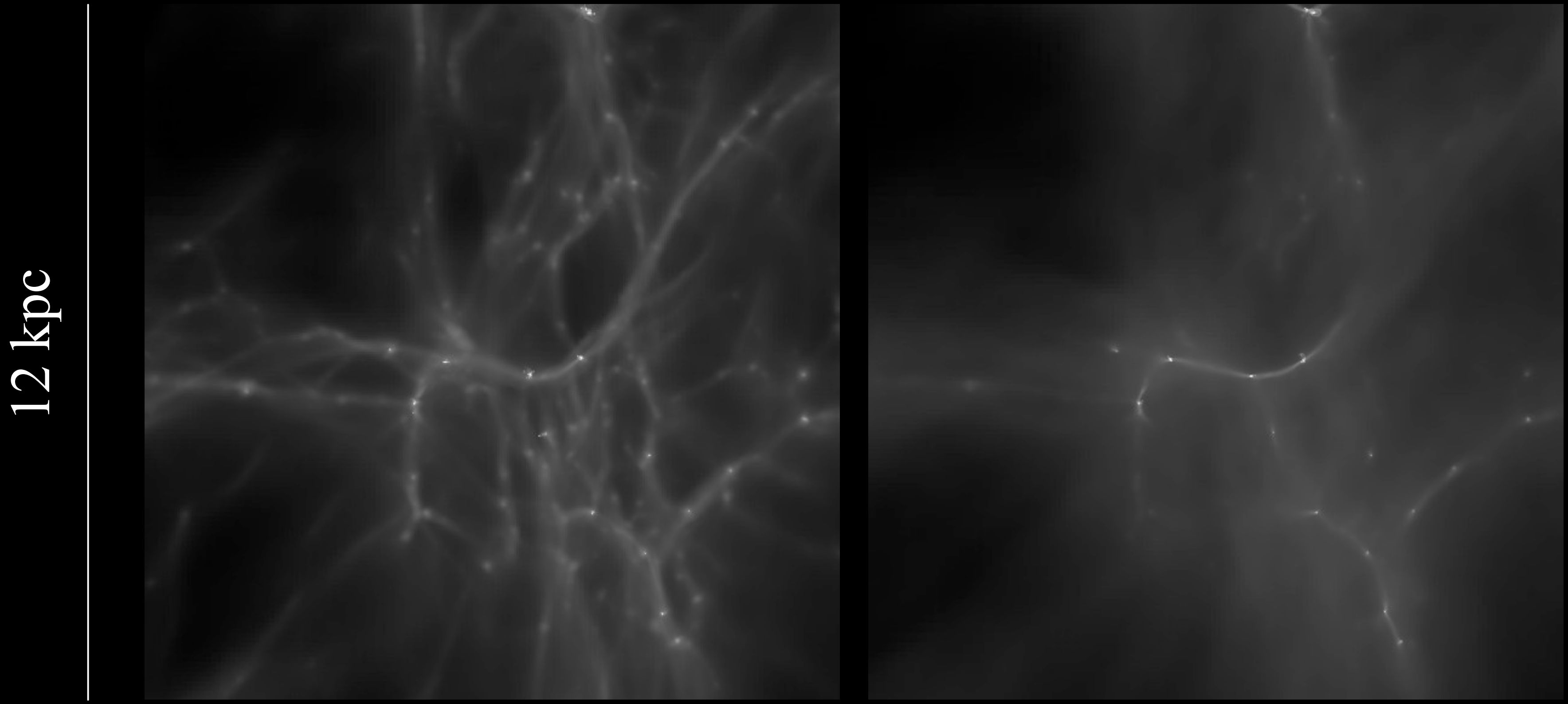
- Extremely low metallicity stars have been found
  - [Fe/H] = -5.2 (HE0107-5240; Chriestleb et al 2002)
  - [Fe/H] = -5.4 (HE1327-2326; Frebel et al. 2005)
  - Both are low mass stars
- Is this star:
  - Pop III with accretion (binary?)
  - Pop II with a small amount of pre-enrichment
    - (e.g. Iwamoto et al 2005)
- Both stars have relatively high C abundance
  - Cooling comes mostly from CII

B. Feedback from the first stars

1. H_2 Photo-dissociating flux (11-13 eV)
   - Suppresses new "first" star formation
2. Ionizing radiation from the first stars:
   - Positive? (more stars, leading to runaway)
     - Ionization → free e- → more H_2 → more cooling (Haiman, Rees & Loeb 1996)
   - Negative? (fewer stars, self-suppression)
     - Ionization → heating → outflows → lower density gas
3. Impact of the first supernovae
   - Metals: "regular" star formation mode ($[Z_{crit}] = -3.5$)
     - Produces smaller stars (like sun)
     - Due to more efficient cooling (particularly Carbon)
   - Energy

2. The impact of ionization on the first stars

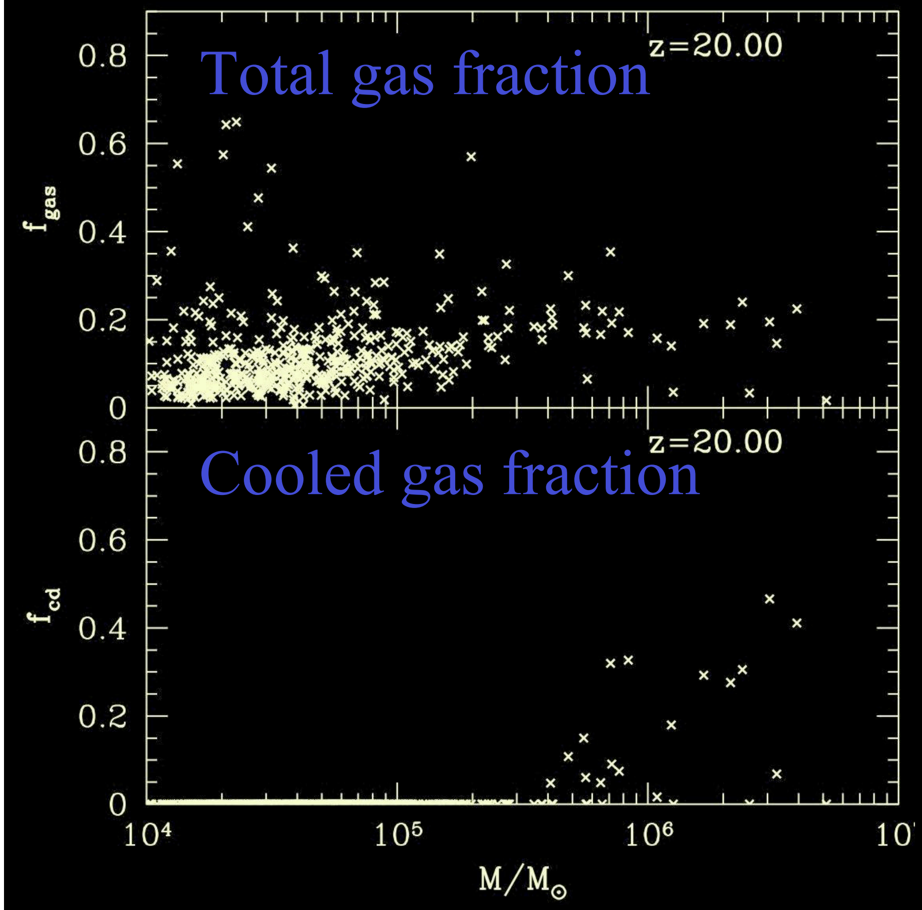
Log density at z=17.5



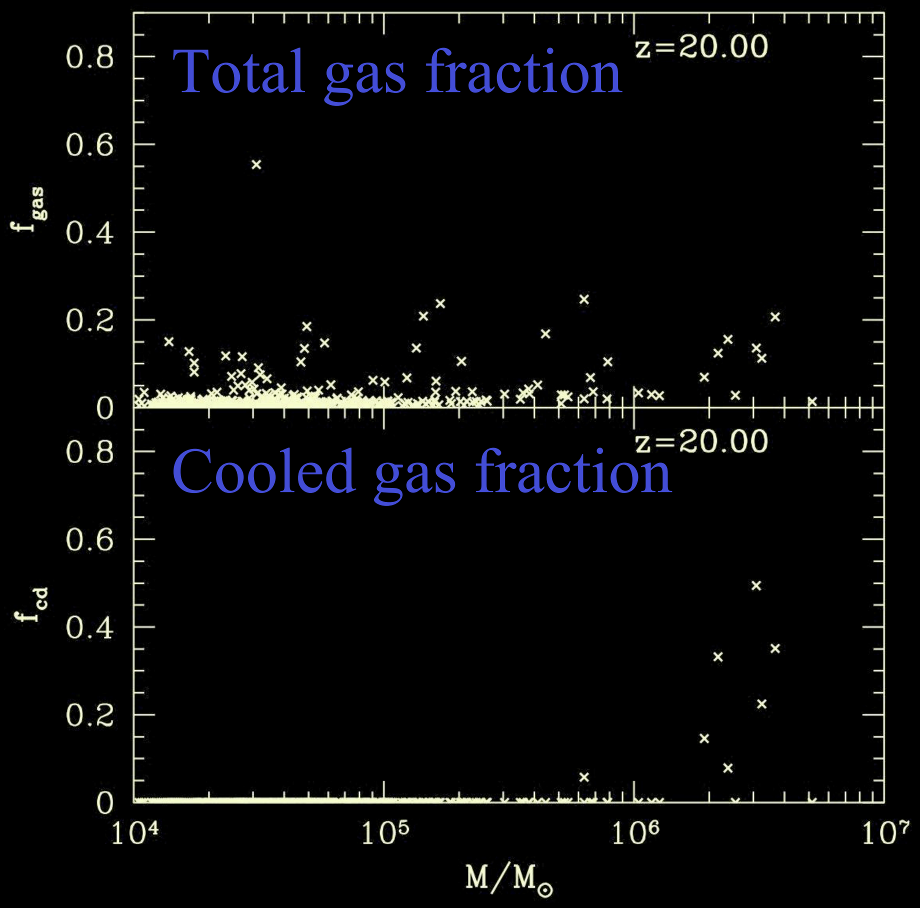
No ionizing flux

With ionizing flux
(F$_{21}$ = 10 for 3 Myr at z=25)

Impact of Reionization



No ionizing flux



With ionizing flux

(F_{21} = 10 for 3 Myr at z=25)

Why is there no fragmentation?

- Fragmentation criteria:
  - $t_{cool} < t_{dyn}$ $(t_{dyn} \sim n^{-1/2})$
- At low densities, H_2 is mostly in ground state
  - $t_{cool} \sim n^{-1}$
- At high densities ($n > 10^4$ cm^{-3})
  - Excited states populated
  - t_{cool} is constant

Imprints mass scale of ~ 200 M_{solar}

(Jeans mass at $n \sim 10^4$ cm^{-3} and $T \sim 300$ K)

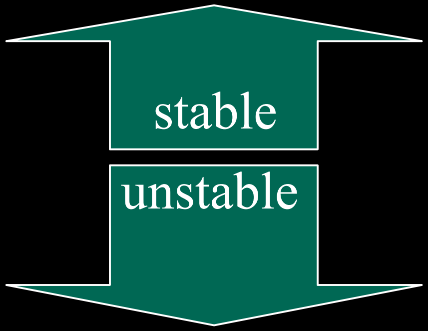
Why is there no fragmentation?

- Thermally unstable?

$$\rho \frac{dL}{d\rho}\bigg|_T - T\frac{dL}{dT}\bigg|_\rho + L(\rho,T) > 0$$

(Hunter 1970)

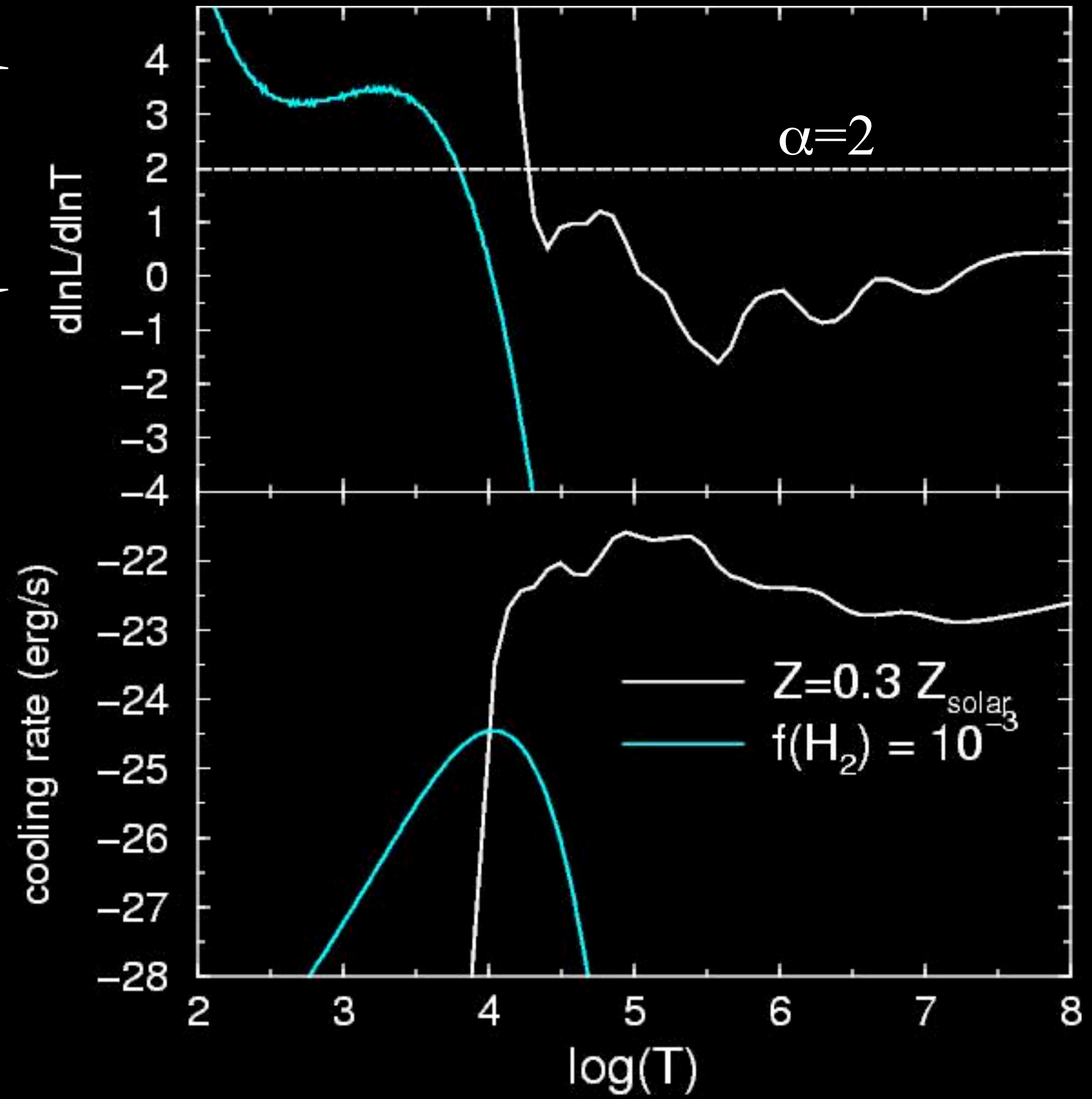
- If cooling rate per unit mass is:
  $L = A\rho T^{\alpha}$
- unstable if $\alpha < 2$

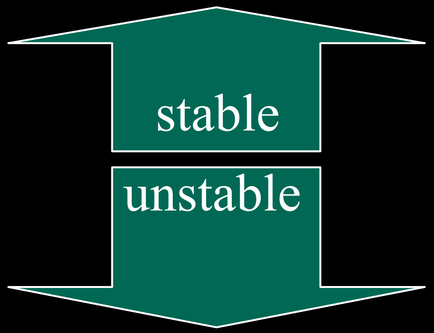


stable

unstable

Thermal (cooling) instability




stable

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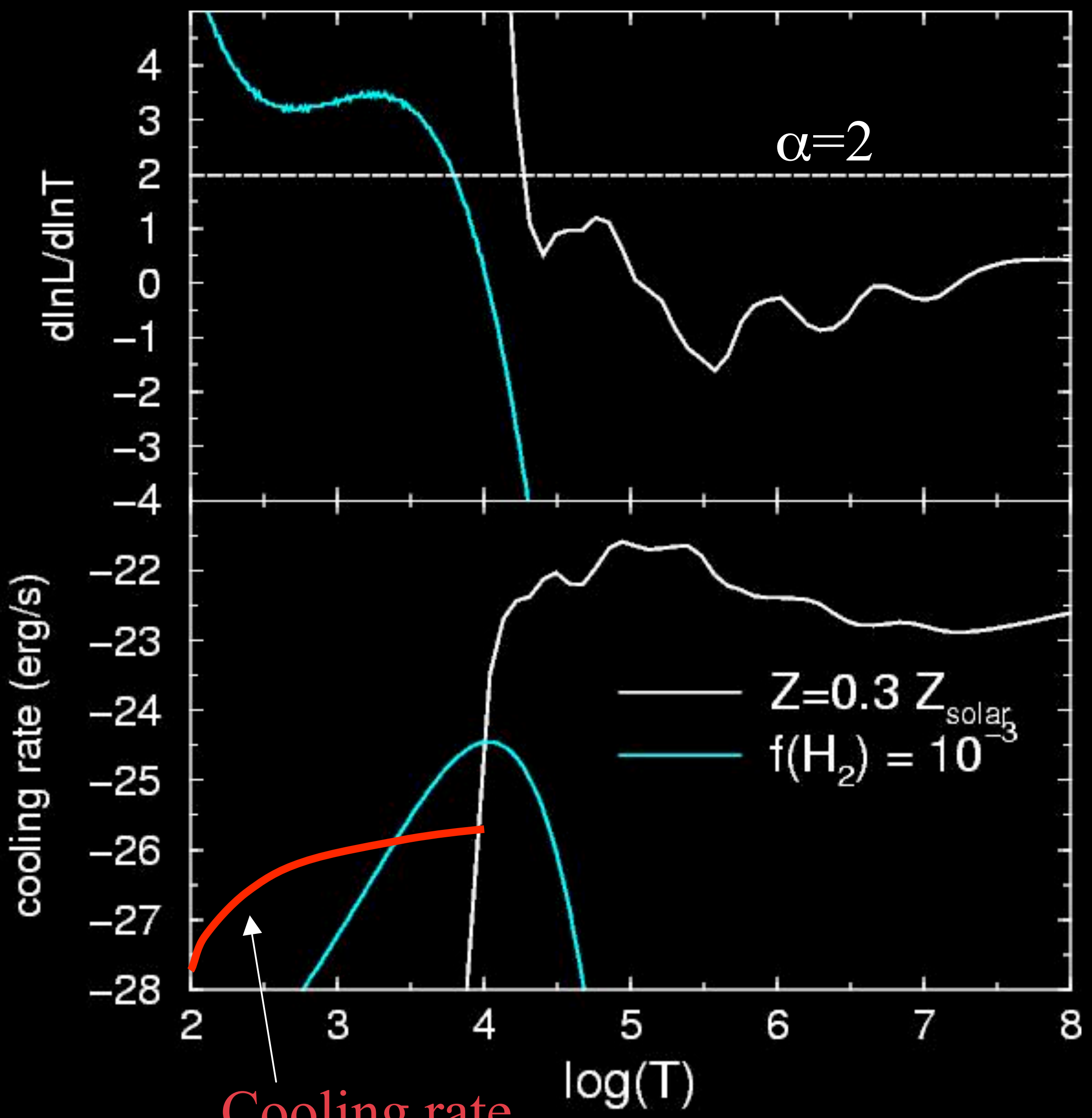
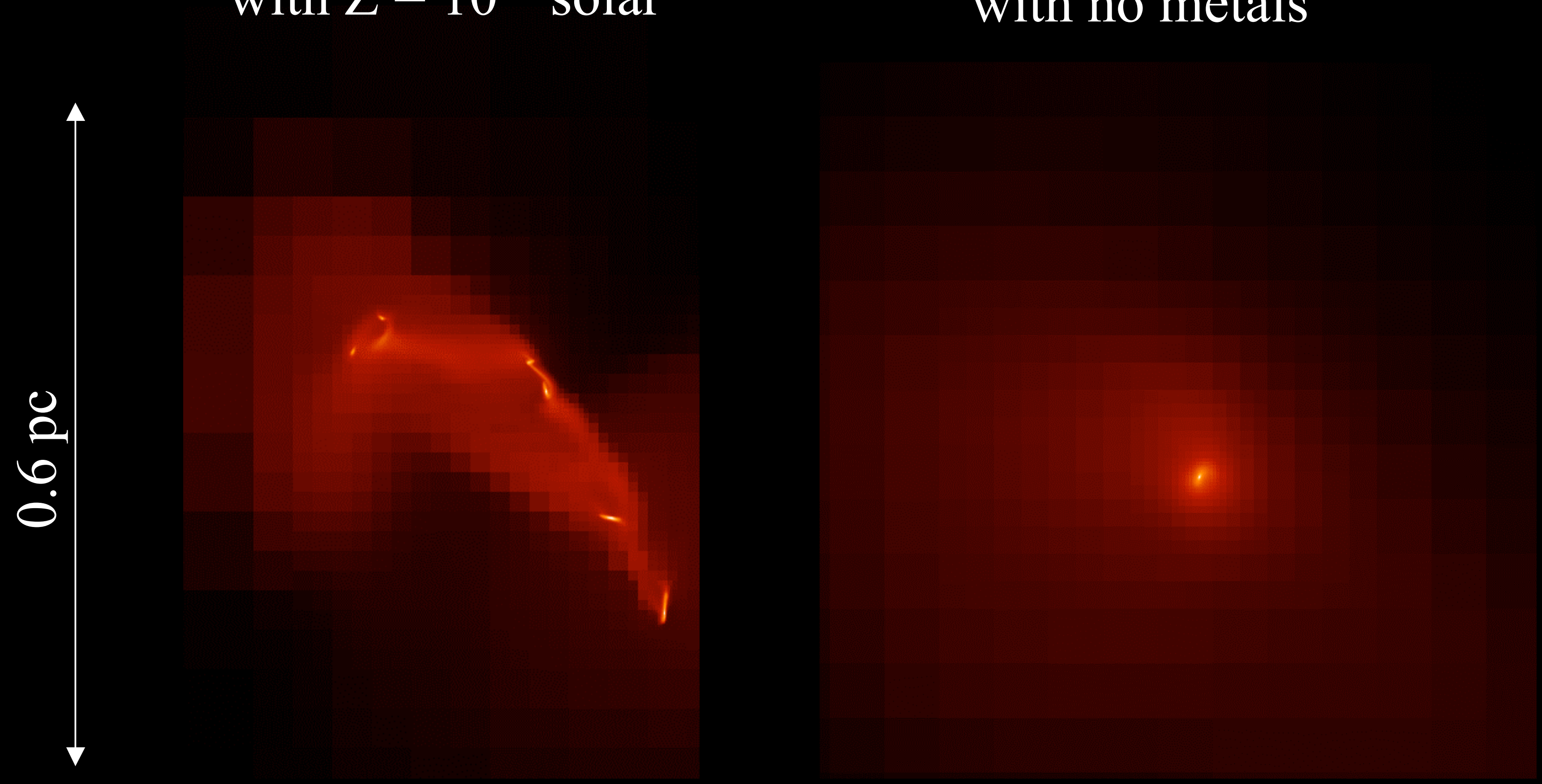


Cooling rate
For gas with $Z = 10^{-3}$ solar

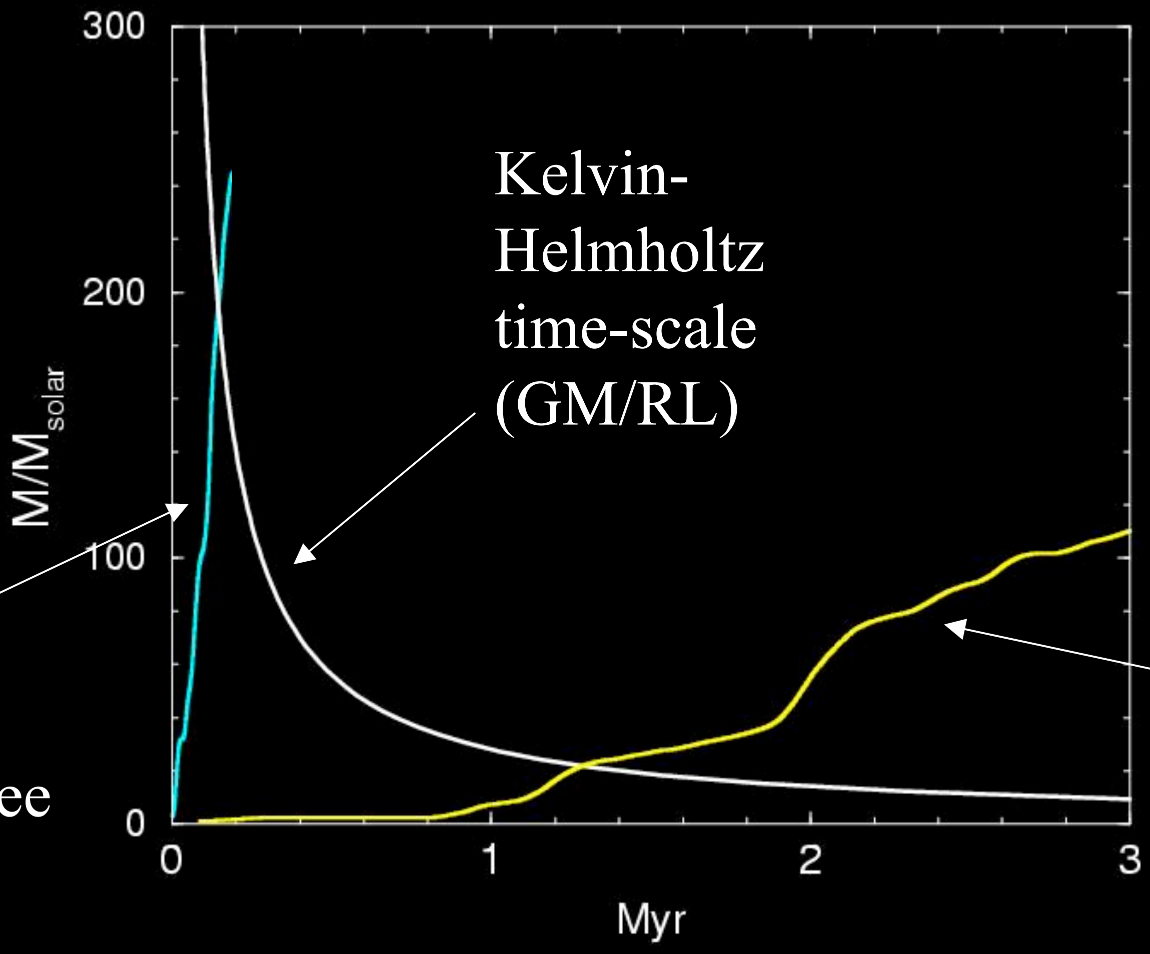
Primordial star formation



with Z = 10^{-3} solar

with no metals

Metal cooling reduces the resulting masses



Kelvin-Helmholtz time-scale (GM/RL)

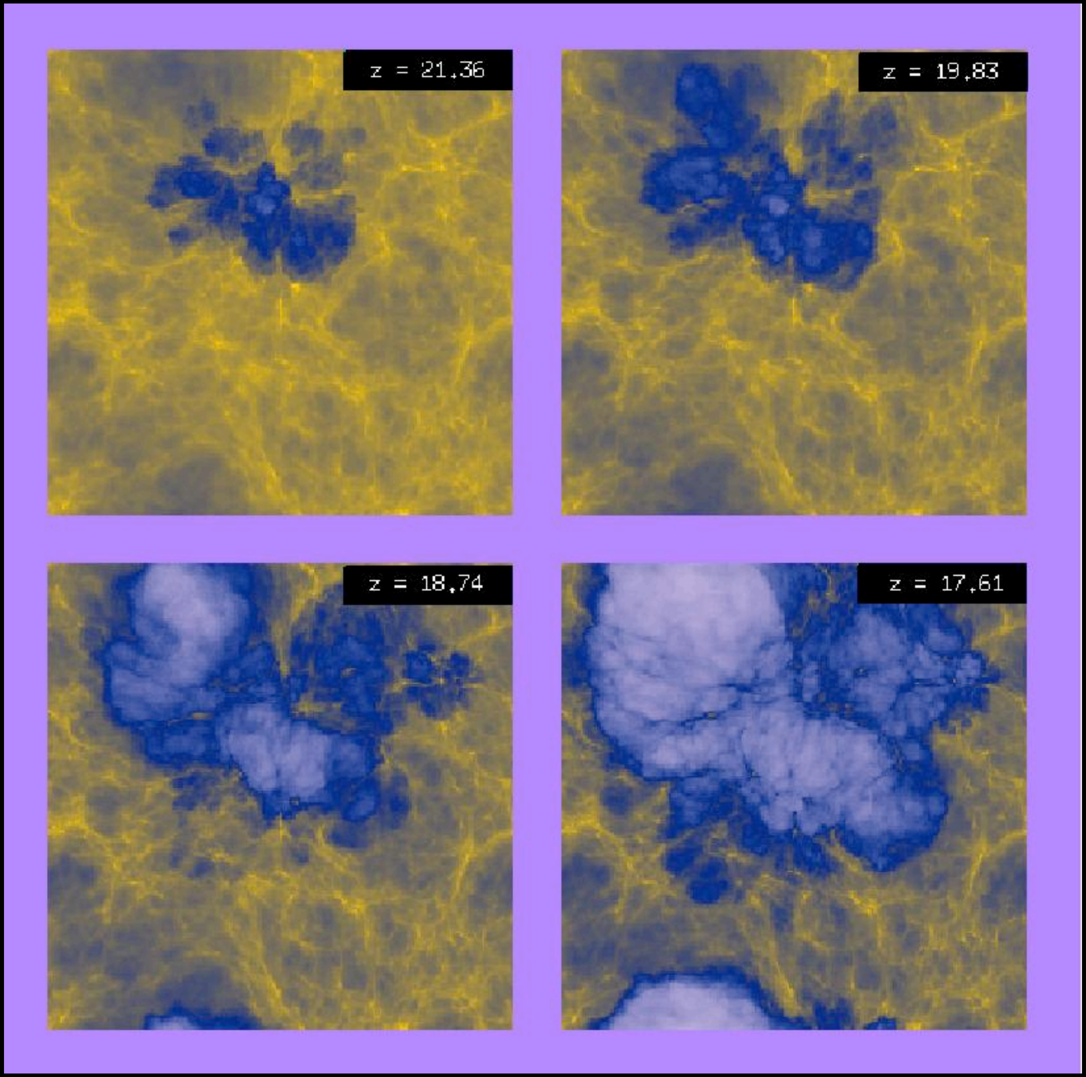
Mass accreted in metal-free case

Mass accreted with Z = 10^{-3} of solar

C. Large-scale reionization

- Current state-of-the art:
  - Freeze hydro, do “radiative transfer”
  - “I-front” tracking
- Radiative transfer hard
  - Ray tracing
  - moment-method
- Reionization difficult because of source clustering
  - L(bubble) ~ 10+ Mpc

Reionization by the First stars?

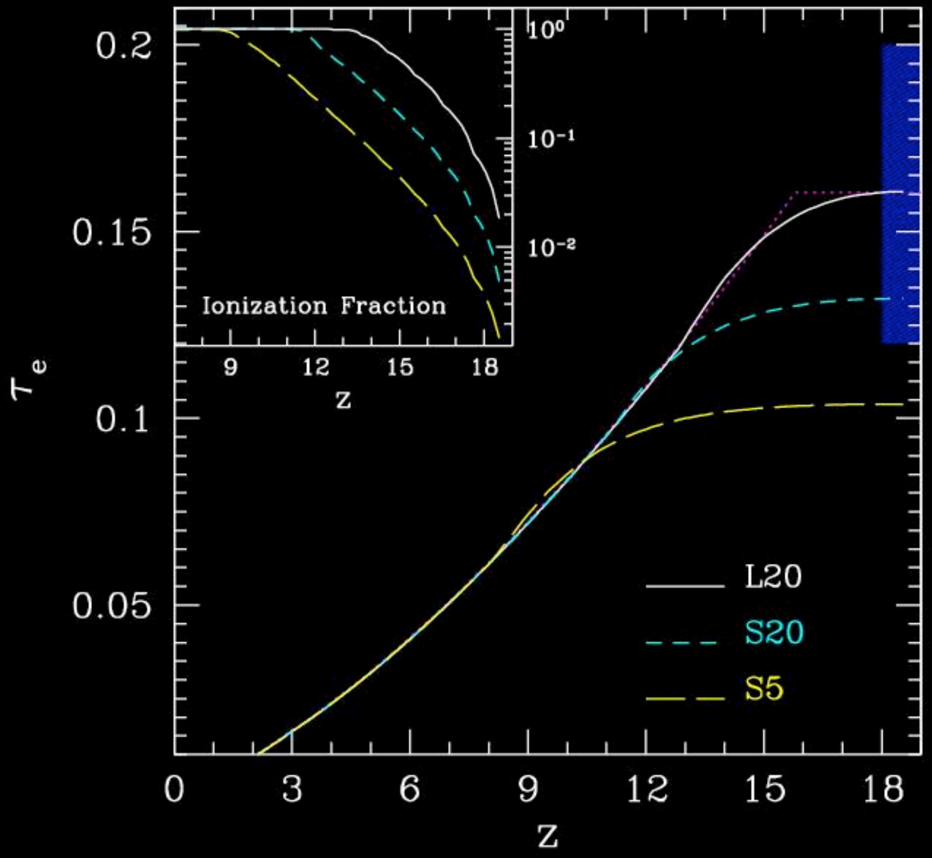


Sokasian et al (2003)

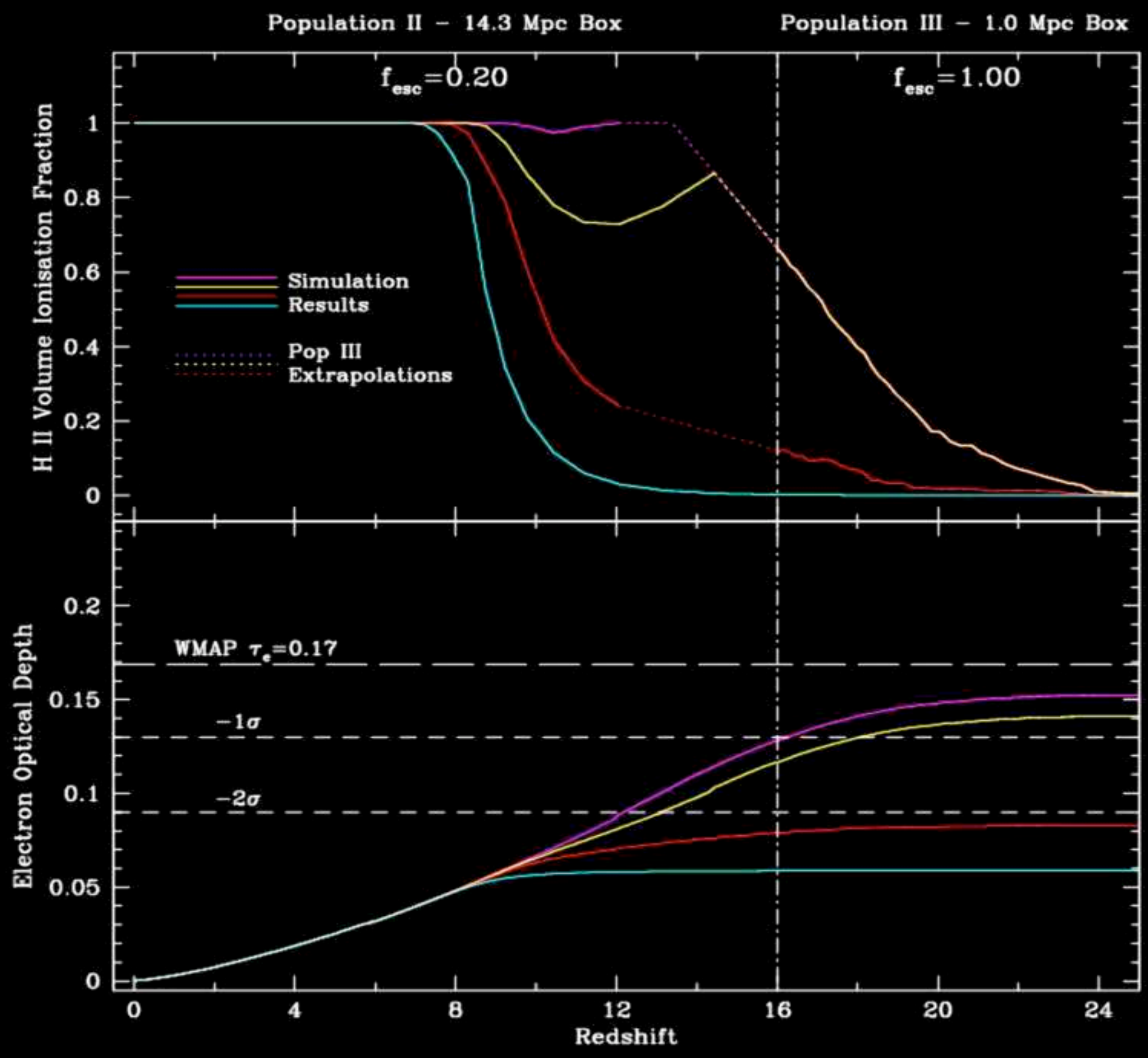
WMAP τ value was larger than expected

- Pre-WMAP predictions around τ~0.08
- Difficult to get τ=0.17 with standard IMF
- One way to get earlier reionization is with a top-heavy IMF as produced by the first stars

Ciardi, Ferrara & White (2003)



Reionization by the First stars?



Sokasian et al (2003)

D. Open questions

- Impact of ionizing bubbles on later star formation
  - Increase entropy in “fossil HII regions”
  - Increase e- and hence H_2 and cooling
  - HD enhancement (lower mass stars?)
- First SN: Metal mixing
  - When does “first” star mode end?
- First SN: impact of blast waves
  - Fragmention? (HD)
- Star formation in Type II halos ($T > 10^4$ K)
  - HI line cooling (fragmentation?)
  - Escape fraction?
  - Number of stars/halo?
- Reionization
  - How does it occur? How does it impact star formation?

D. Simulations

- Type II (10^8 solar mass, T ~ 10^4 K) halo
  - Refined region: L ~ 1 Mpc with M_{sun} resolution
  - All physics
    - H2 photodissociating flux
    - Small-scale Ionizing “bubbles”
    - Metal ejection and mixing
    - blastwaves
- Reionization
  - L = 50-100 Mpc (minimum) for biasing
  - Study 21 cm tomography