Star Formation in Very Low Metallicity Gas

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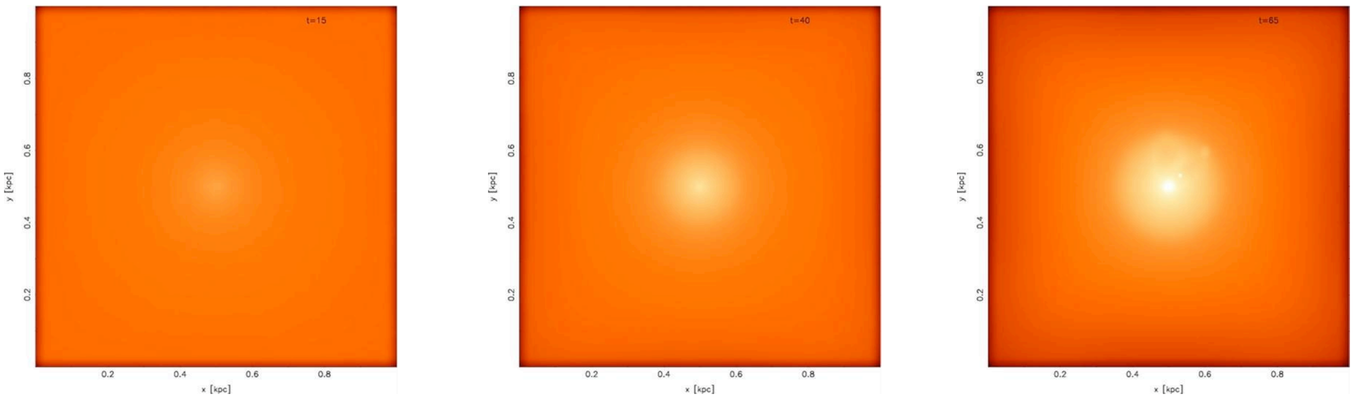

Collaborators

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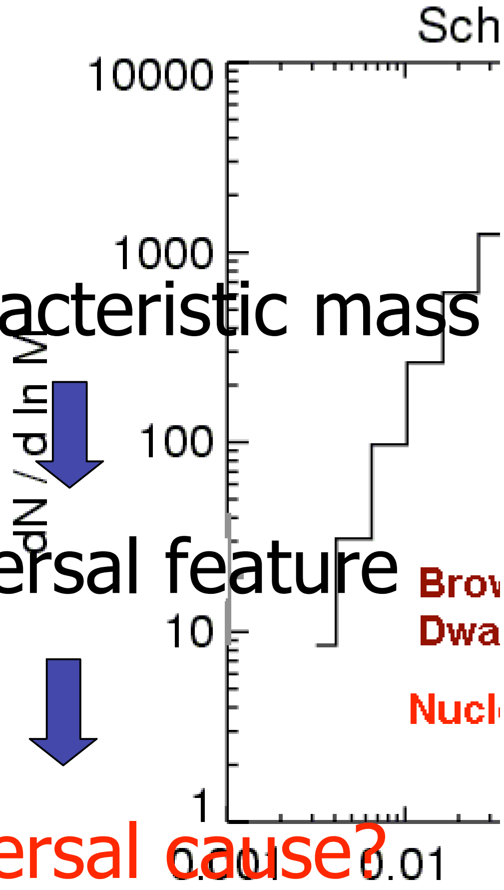
DFG

What determines the shape of the IMF?

- Fragmentation:
  - determines protostellar core mass function
- Accretion (modulated by feedback):
  - maps protostellar mass to final mass

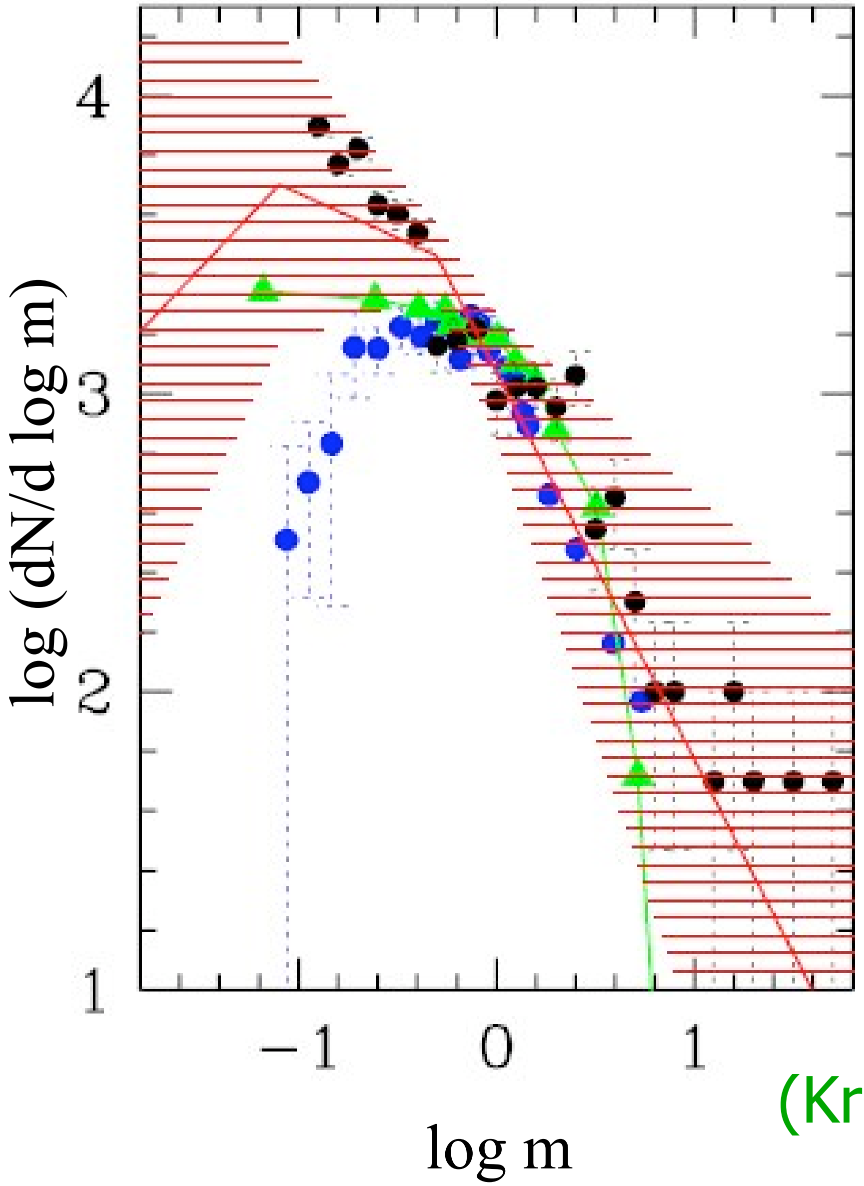
The Initial Mass Function - IMF



characteristic mass

universal feature

universal cause?



(Kroupa 02)

Thermal Properties of Star-Forming Clouds

Observations:

- balance: gravity and thermal pressure (Myers et al. 91)
- temperatures: 8 – 20 K
- heating and cooling processes

But in Simulations:

- isothermal approximation
- temperature: ~ 10 K

Fragmentation depends on Equation of State (EOS)

(Li et al. 03)

Piecewise Polytropic Equation of State

$$P = K_1 \rho^{\gamma_1} \qquad \rho < \rho_{crit}$$
$$P = K_2 \rho^{\gamma_2} \qquad \rho > \rho_{crit}$$

$\gamma_1 = 0.7$ $\qquad 4\text{x}10^{4}\ \text{cm}^{-3} < n_{crit} < 4\text{x}10^{7}\ \text{cm}^{-3}$

$\gamma_2 = 1.1$ $\qquad 1\text{x}10^{-19}\ \text{g/cm}^{3} < \rho_{crit} < 1\text{x}10^{-16}\ \text{g/cm}^{3}$

Is there a connection between ρ_{crit}
and a characteristic stellar mass ?

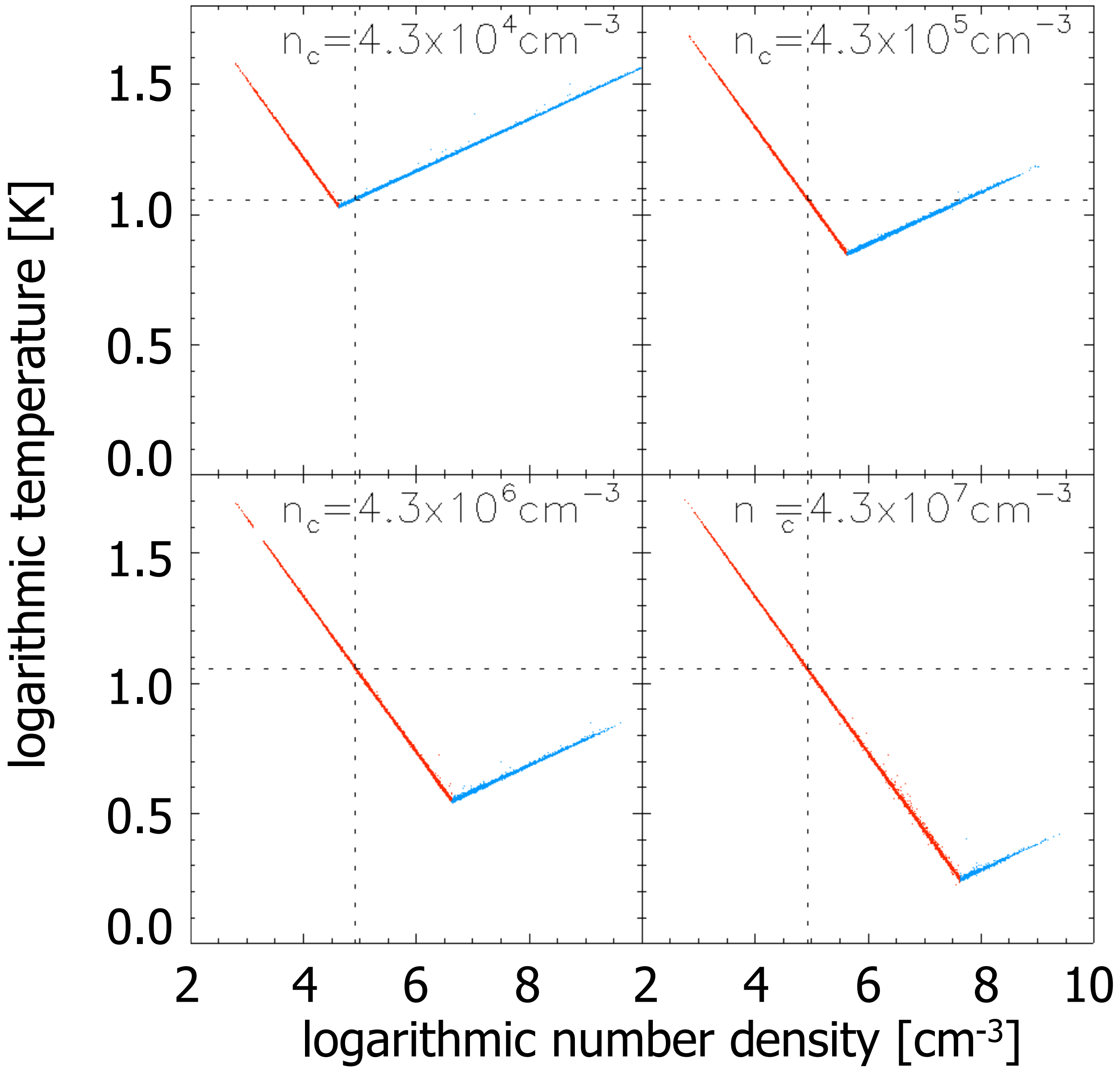
Temperature as a Function of Density

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

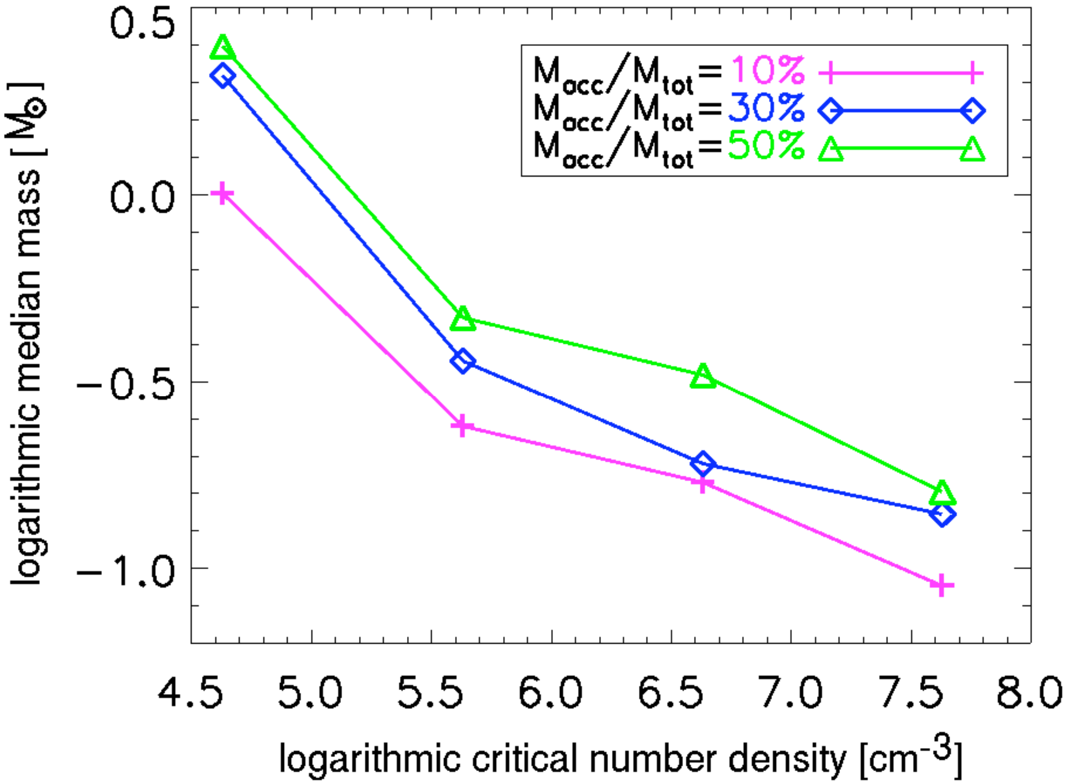
$\boxed{T \sim \rho^{\gamma-1}}$

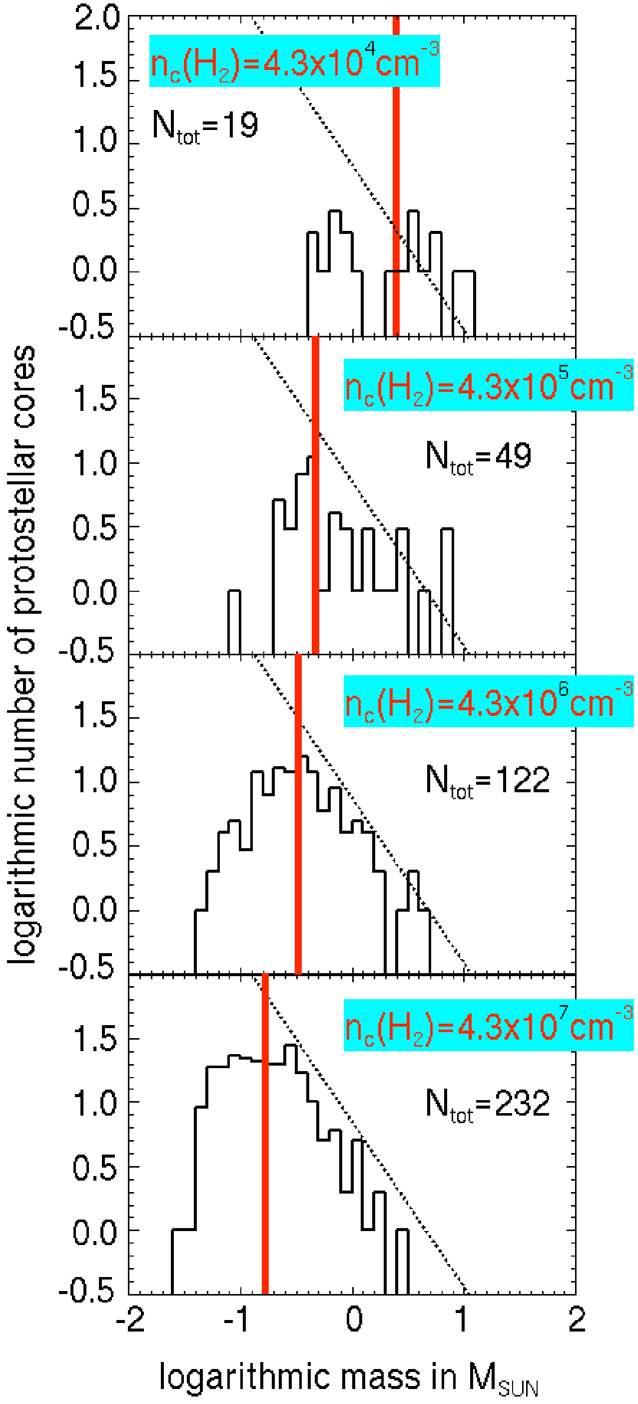
(Jappsen et al 2005)



Mass Spectra of Protostellar Cores

- 50% gas accreted
- median mass





Polytropic Equation of State

- Fragmentation requires soft equation of state

$$\boxed{T \sim \rho^{\gamma-1}}$$

- effective polytropic index $\gamma \leq 1.0$

- Once EOS stiffens → fragmentation stops

(e.g. Larson 05, Jappsen et al. 05)

- In primordial gas, this occurs at $T \sim 200$ K, $n \sim 10^4$ cm^{-3}
- Resulting fragment mass: few hundred M_{SUN}

Star Formation in the Early Universe

Polytropic Equation of State?

Not possible since gas not necessarily in thermal equilibrium

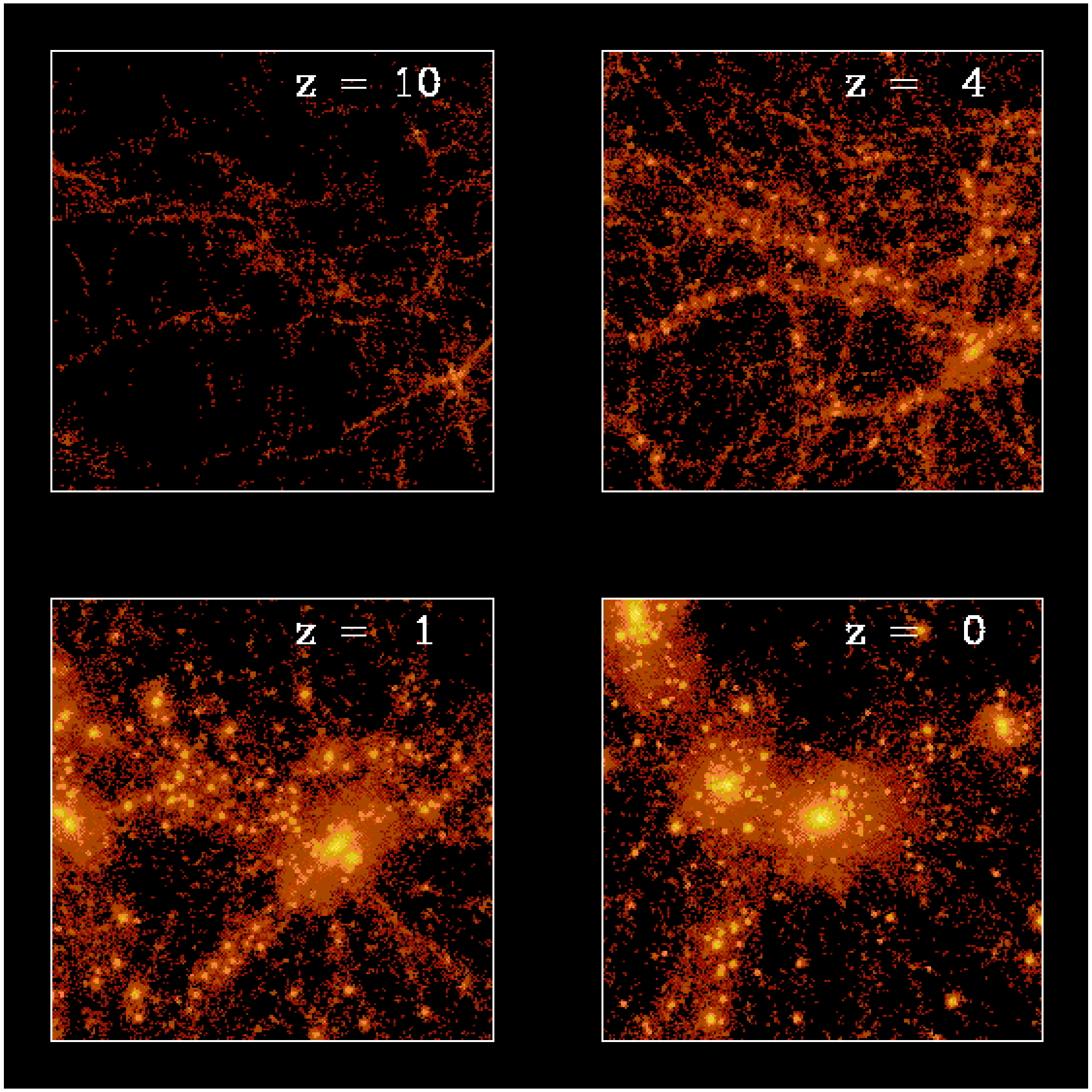
➡ Follow coupling of:
- chemistry
- thermal balance (cooling and heating)
- dynamics

No observational evidence – so far!

➡ Parameter study needed

Hierarchical Structure Formation

- cold dark matter
- smallest regions collapse first
- “bottom-up” formation



Credit: S. Gottlöber (AIP)

Star Formation in the Early Universe

- Pop III stars

↓

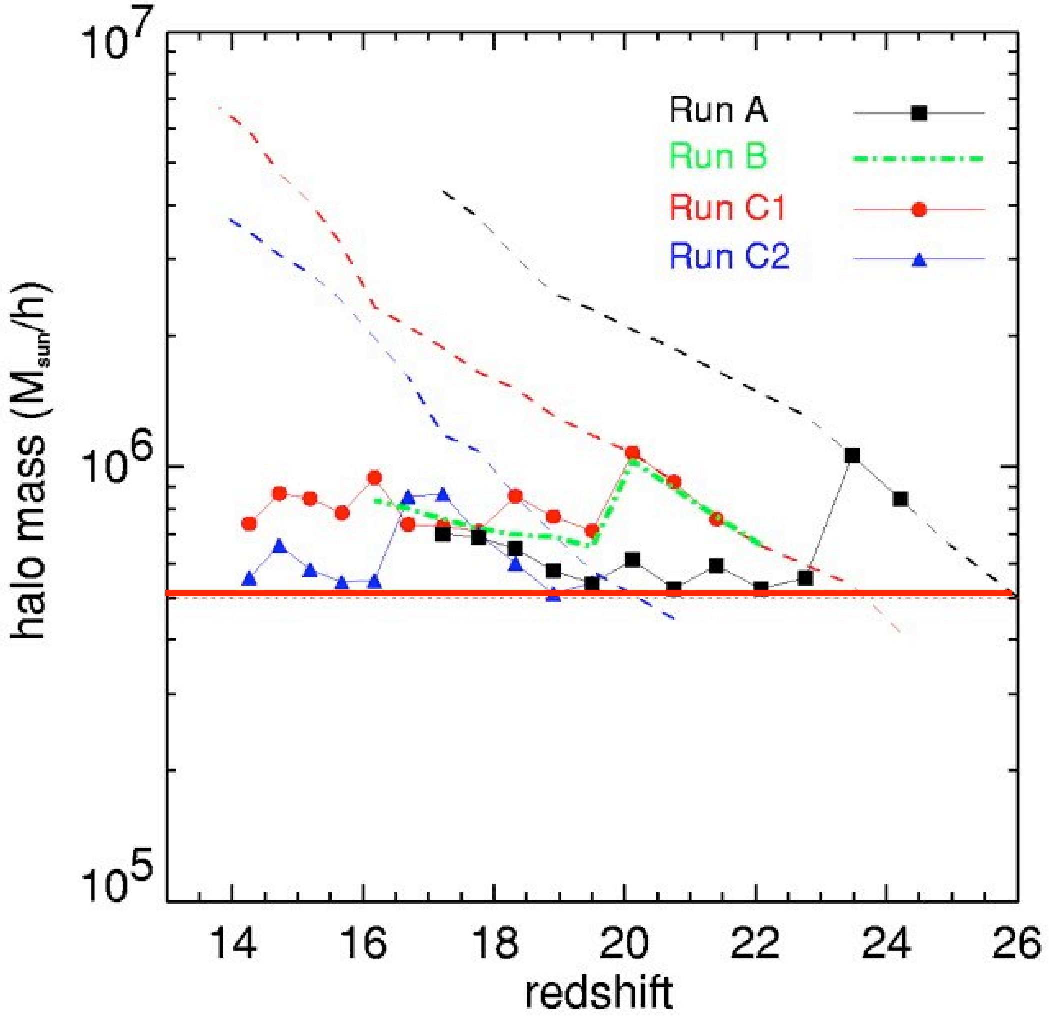
- Metal Enrichment
- Ionization

↓ ?

- Pop II stars

Credit: NASA, ESA, S. Beckwith (STScI)
and the HUDF Team

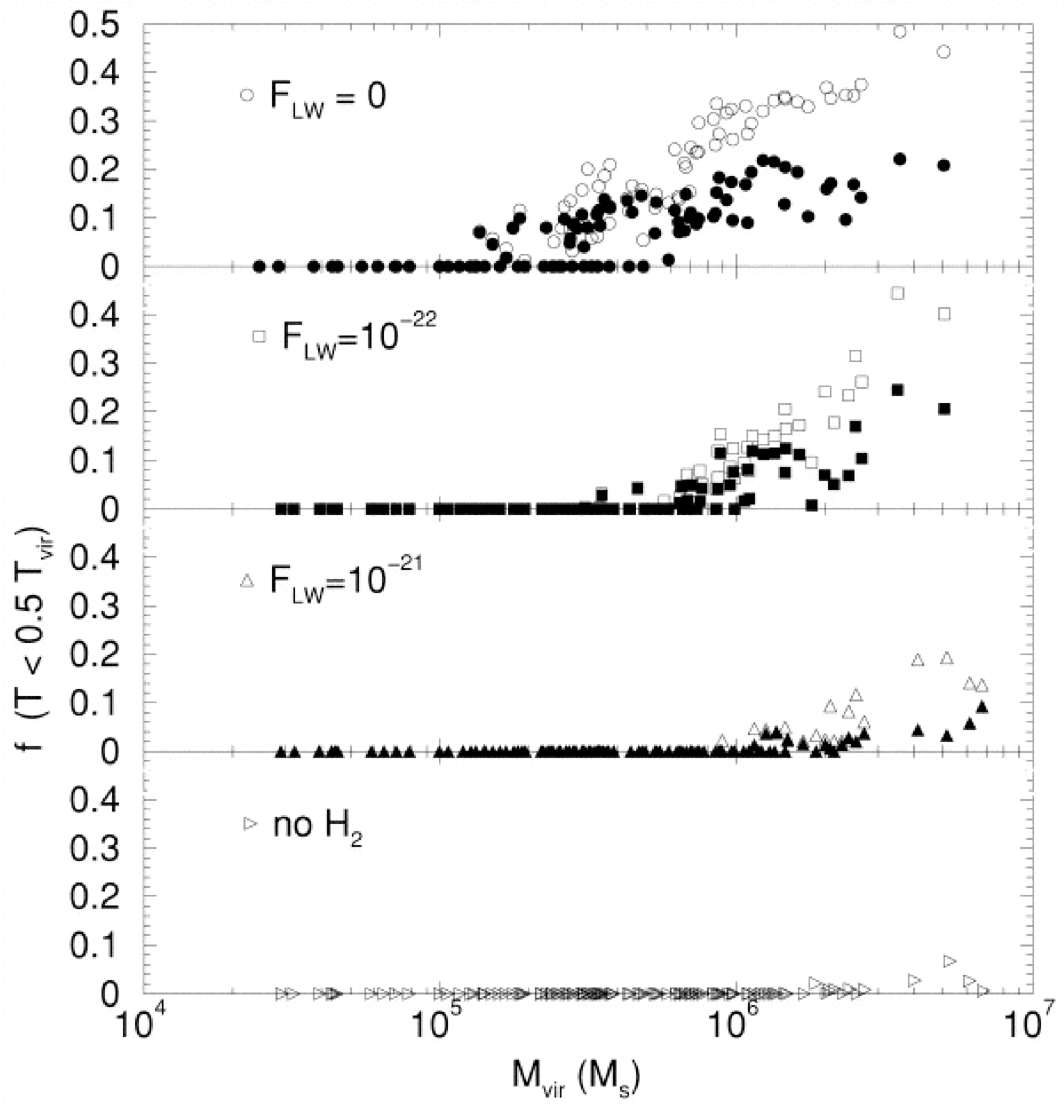
Primordial Gas Cloud Formation



Critical Halo Mass

(Yoshida et al. 2003)

UV Background



(Machacek et al 2001)

$J_{21} = 0$

$J_{21} = 10^{-2}$

$J_{21} = 10^{-1}$

UVB delays
cooling and collapse

The Questions

- Does metallicity make a difference?
- What about fragmentation? How small can the objects be that form - IMF?
- What is the role of the UV background?
- What are the time scales?
- How much cool gas?

How significant are small halos for the formation of stars?

A Critical Metallicity?

- A minimal level of enrichment is required before metals can contribute significantly to the cooling

- The size of this minimal level depends on coolant in question:

  - $Z_{cr} \sim 10^{-3.5}\ Z_{sun}$ for C, O fine structure cooling

  - $Z_{cr} \sim 10^{-5.0}\ Z_{sun}$ for dust cooling

What happens once $Z > Z_{cr}$?

- Bromm et al. (2001) examine effects of C, O fine structure cooling, in absence of H_2
  - gas cools to T_{cmb} by $n \sim 10^4$ cm^{-3}
  - fragmentation forms multiple clumps
  - minimum clump mass ~ 100 $M_{sun}=M_{res}$
  - Bromm et al. argue that smaller clumps would form in a higher resolution simulation

What happens once $Z > Z_{cr}$?

- Tsuribe & Omukai (2006) study dust-induced fragmentation in dense, non-rotating cores
- Temperature evolution approximated with tabulated EOS, based on Omukai et al. (2005)
  - Oblate cores do not fragment
  - Prolate cores fragment at $n \sim 10^{16}$ cm^{-3}

Technical challenges

- Dynamical range
- Chemical complexity
- Optical depth effects
- Initial conditions

Hydrodynamic Equations

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = -\rho \nabla \cdot \mathbf{v}$$

continuity equation

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla \Phi$$

Euler equation

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{\partial \epsilon}{\partial t} + \mathbf{v} \cdot \nabla \epsilon = -\frac{P}{\rho} \nabla \cdot \mathbf{v} - \frac{\Lambda(\epsilon, \rho)}{\rho}$$

energy eq.

$$\Delta \Phi = 4\pi G \rho$$

Poisson equation

$$P(\rho, T)$$

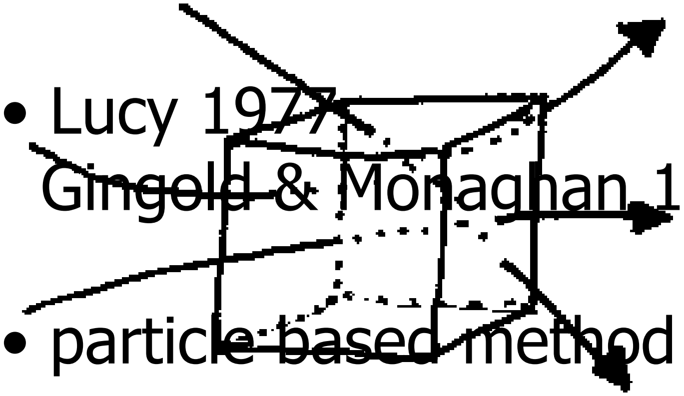
equation of state

Numerical Method

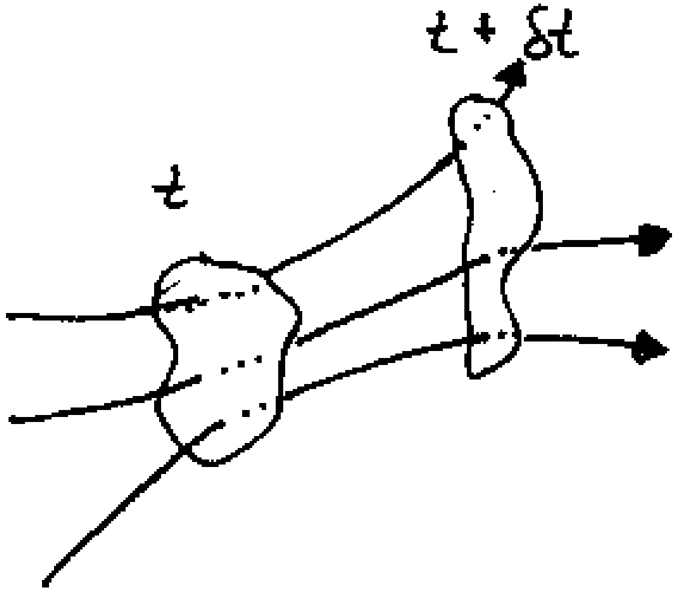
- smoothed particle hydrodynamics
  (Gadget - Springel et al. 01)
- sink particles (Bate et al. 95)
- chemistry and cooling
- dark matter density profile (Navarro et al. 97)
- “periodic boundaries”

Smoothed Particle Hydrodynamics

Eulerian



Lagrangian

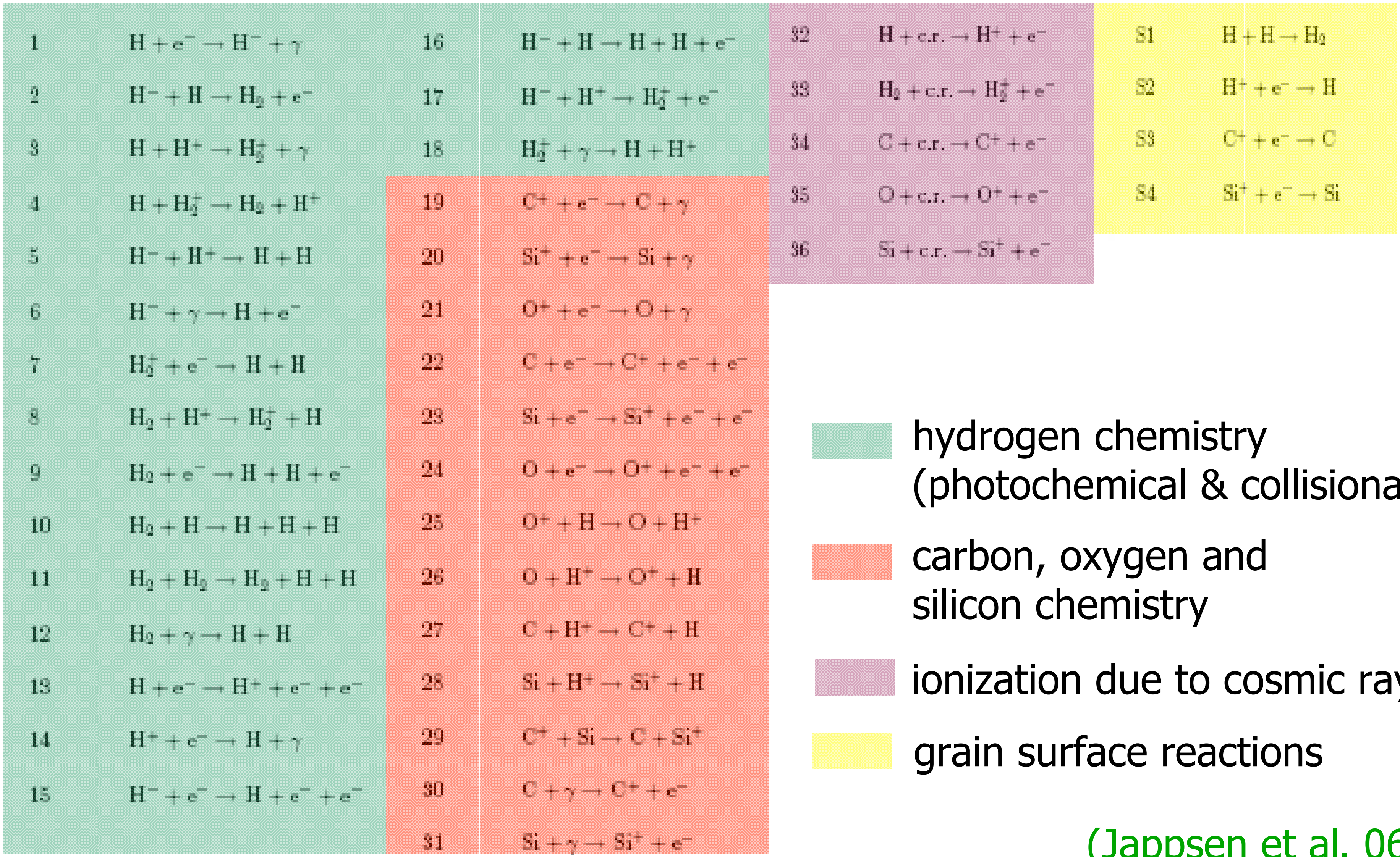


- Lucy 1977
  Gingold & Monaghan 1977
- particle-based method
- resolution follows density
- well suited for our problem

Sink Particles

- replace gas core by single, non-gaseous, massive sink particle
- fixed radius – Jeans radius of core
- inherit masses, linear momenta, “spin“
- accrete gas particles
- boundary corrections

Chemical Model



1	$H + e^- \rightarrow H^- + \gamma$
2	$H^- + H \rightarrow H_2 + e^-$
3	$H + H^+ \rightarrow H_2^+ + \gamma$
4	$H + H_2^+ \rightarrow H_2 + H^+$
5	$H^- + H^+ \rightarrow H + H$
6	$H^- + \gamma \rightarrow H + e^-$
7	$H_2^+ + e^- \rightarrow H + H$
8	$H_2 + H^+ \rightarrow H_2^+ + H$
9	$H_2 + e^- \rightarrow H + H + e^-$
10	$H_2 + H \rightarrow H + H + H$
11	$H_2 + H_2 \rightarrow H_2 + H + H$
12	$H_2 + \gamma \rightarrow H + H$
13	$H + e^- \rightarrow H^+ + e^- + e^-$
14	$H^+ + e^- \rightarrow H + \gamma$
15	$H^- + e^- \rightarrow H + e^- + e^-$
16	$H^- + H \rightarrow H + H + e^-$
17	$H^- + H^+ \rightarrow H_2^+ + e^-$
18	$H_2^+ + \gamma \rightarrow H + H^+$
19	$C^+ + e^- \rightarrow C + \gamma$
20	$Si^+ + e^- \rightarrow Si + \gamma$
21	$O^+ + e^- \rightarrow O + \gamma$
22	$C + e^- \rightarrow C^+ + e^- + e^-$
23	$Si + e^- \rightarrow Si^+ + e^- + e^-$
24	$O + e^- \rightarrow O^+ + e^- + e^-$
25	$O^+ + H \rightarrow O + H^+$
26	$O + H^+ \rightarrow O^+ + H$
27	$C + H^+ \rightarrow C^+ + H$
28	$Si + H^+ \rightarrow Si^+ + H$
29	$C^+ + Si \rightarrow C + Si^+$
30	$C + \gamma \rightarrow C^+ + e^-$
31	$Si + \gamma \rightarrow Si^+ + e^-$
32	$H + c.r. \rightarrow H^+ + e^-$
33	$H_2 + c.r. \rightarrow H_2^+ + e^-$
34	$C + c.r. \rightarrow C^+ + e^-$
35	$O + c.r. \rightarrow O^+ + e^-$
36	$Si + c.r. \rightarrow Si^+ + e^-$
S1	$H + H \rightarrow H_2$
S2	$H^+ + e^- \rightarrow H$
S3	$C^+ + e^- \rightarrow C$
S4	$Si^+ + e^- \rightarrow Si$

🟩 hydrogen chemistry (photochemical & collisional)

🟥 carbon, oxygen and silicon chemistry

🟪 ionization due to cosmic rays

🟨 grain surface reactions

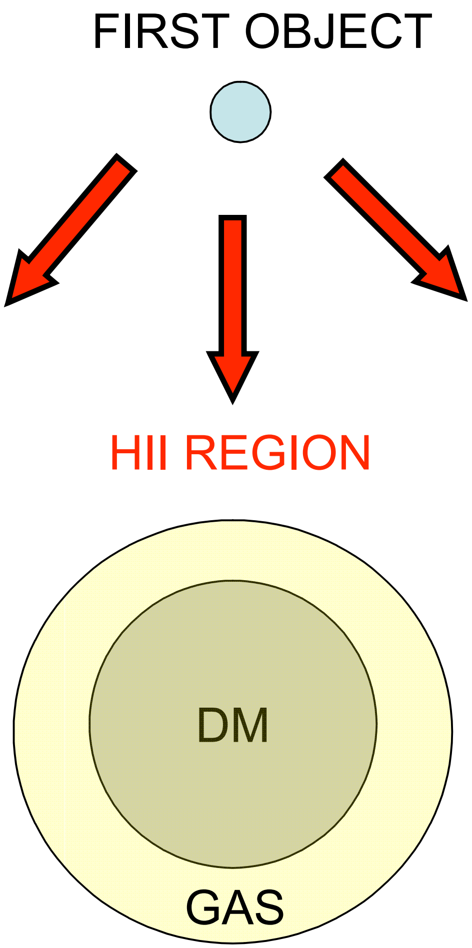
(Jappsen et al. 06)

Cooling and Heating

- gas-grain energy transfer
- H collisional ionization
- H^+ recombination
- H_2 rovibrational lines
- H_2 collisional dissociation
- Ly-alpha and Compton cooling
- Fine structure cooling from C, O, Si

- photoelectric effect
- H_2 photodissociation
- UV pumping of H_2
- H_2 formation on dust grains

Initial Conditions

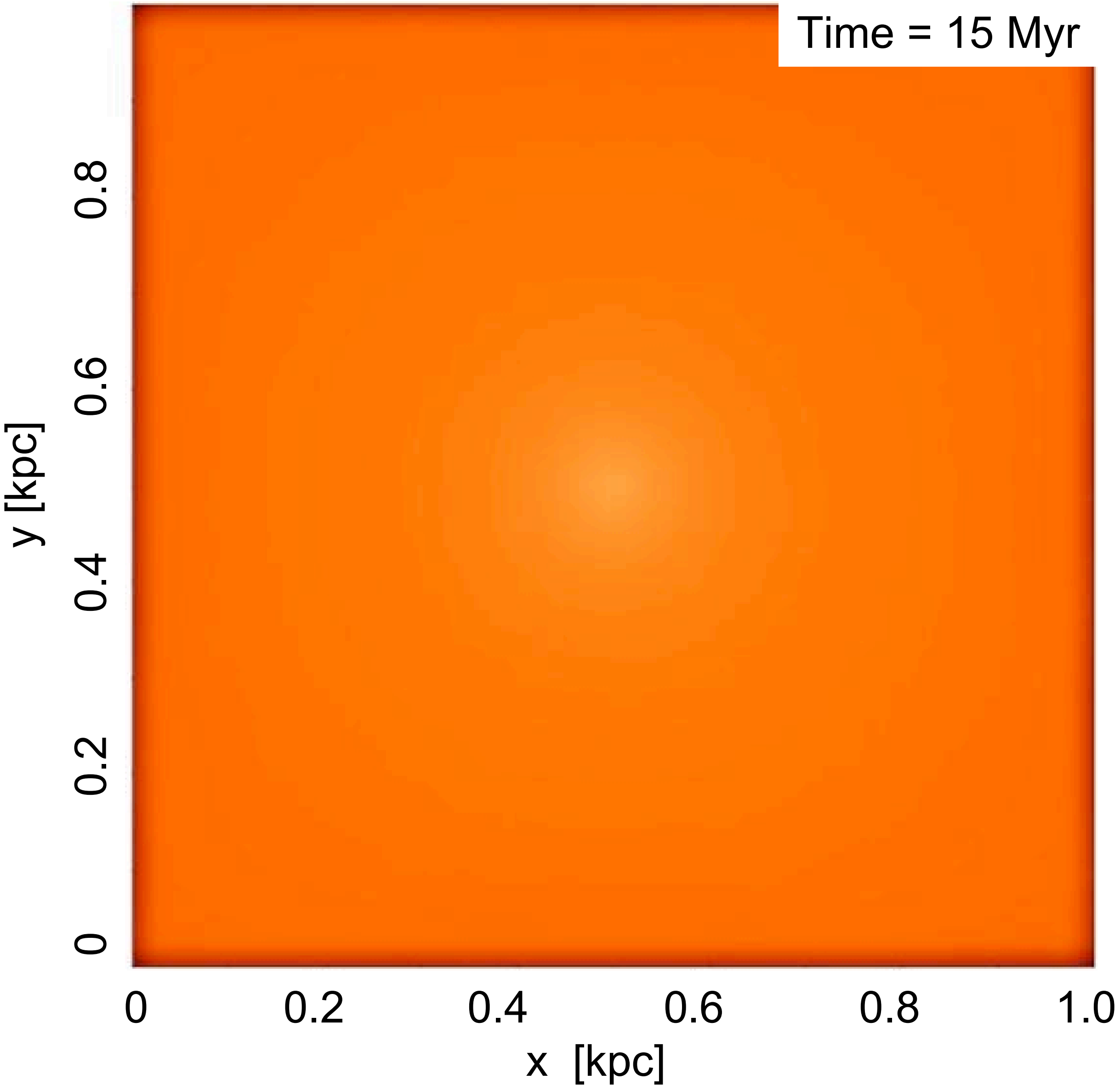


- gas fully ionized
- initial temperature: 10000 K
- volume: (0.5) kpc^3 - (4.0) kpc^3
- contained gas mass: 17% of DM Mass
- number of gas particles: 10^5 - 10^6
- resolution limit: $20\ M_{SUN} - 400\ M_{SUN}$

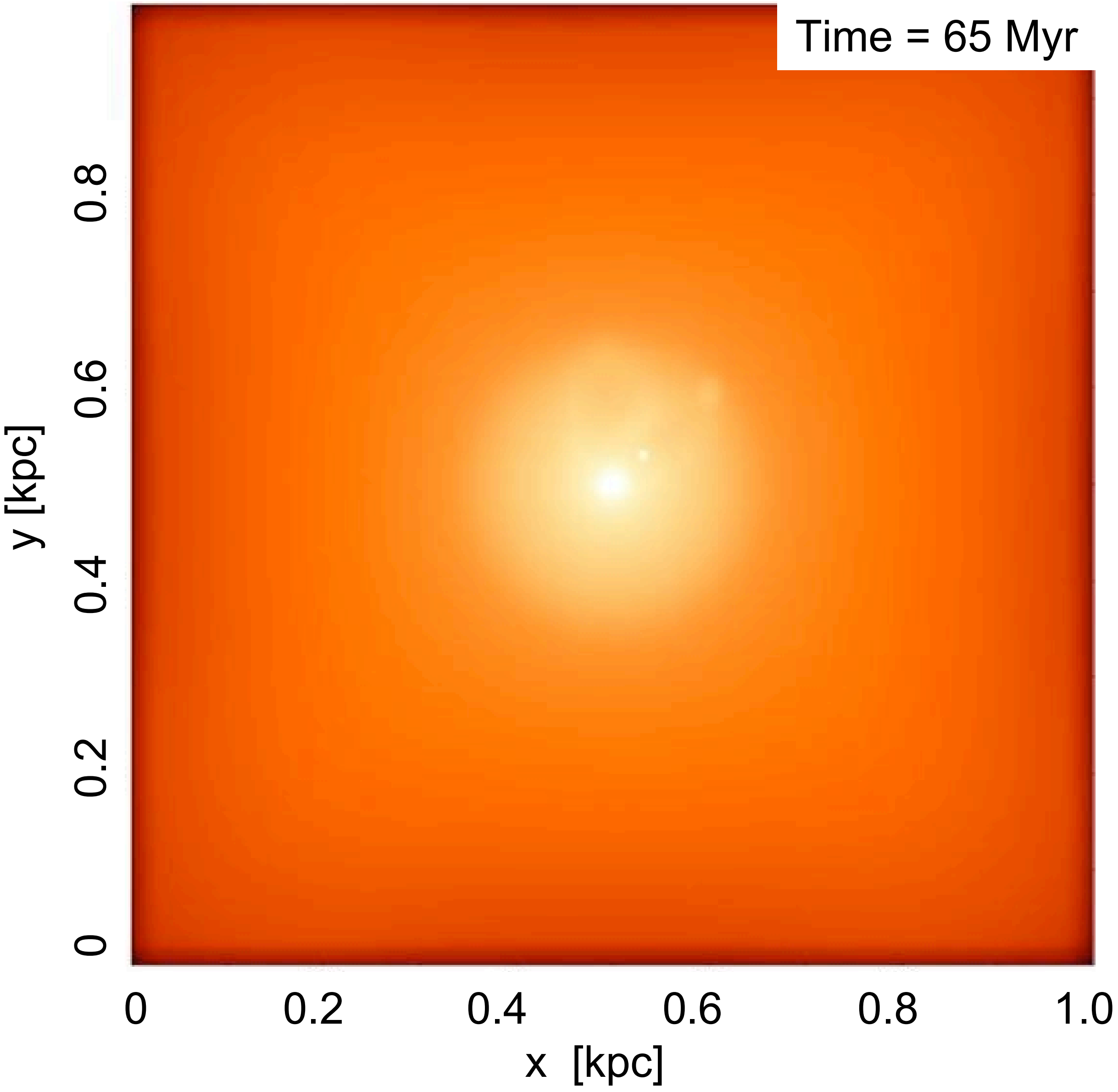
Parameter Study

- halo size: $5 \times 10^4 M_{sun}$ - $10^7 M_{sun}$
- redshift: 15, 20, 25, 30
- metallicity: zero, $10^{-4} Z_{sun}$ - Z_{sun}
- UV background: $J_{21} = 0, 10^{-2}, 10^{-1}$
- dust: yes or no

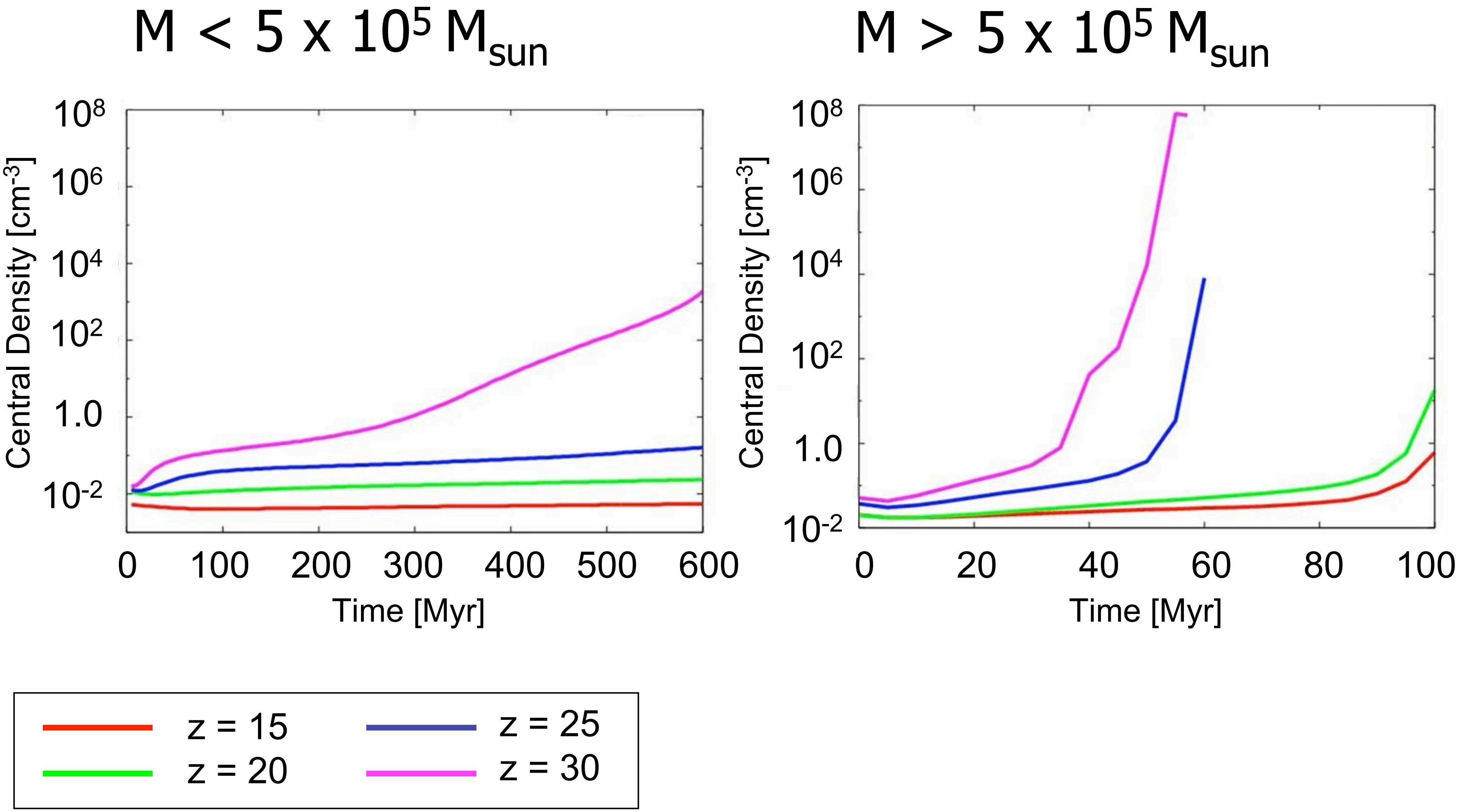
Initial Conditions



Gas Collapse

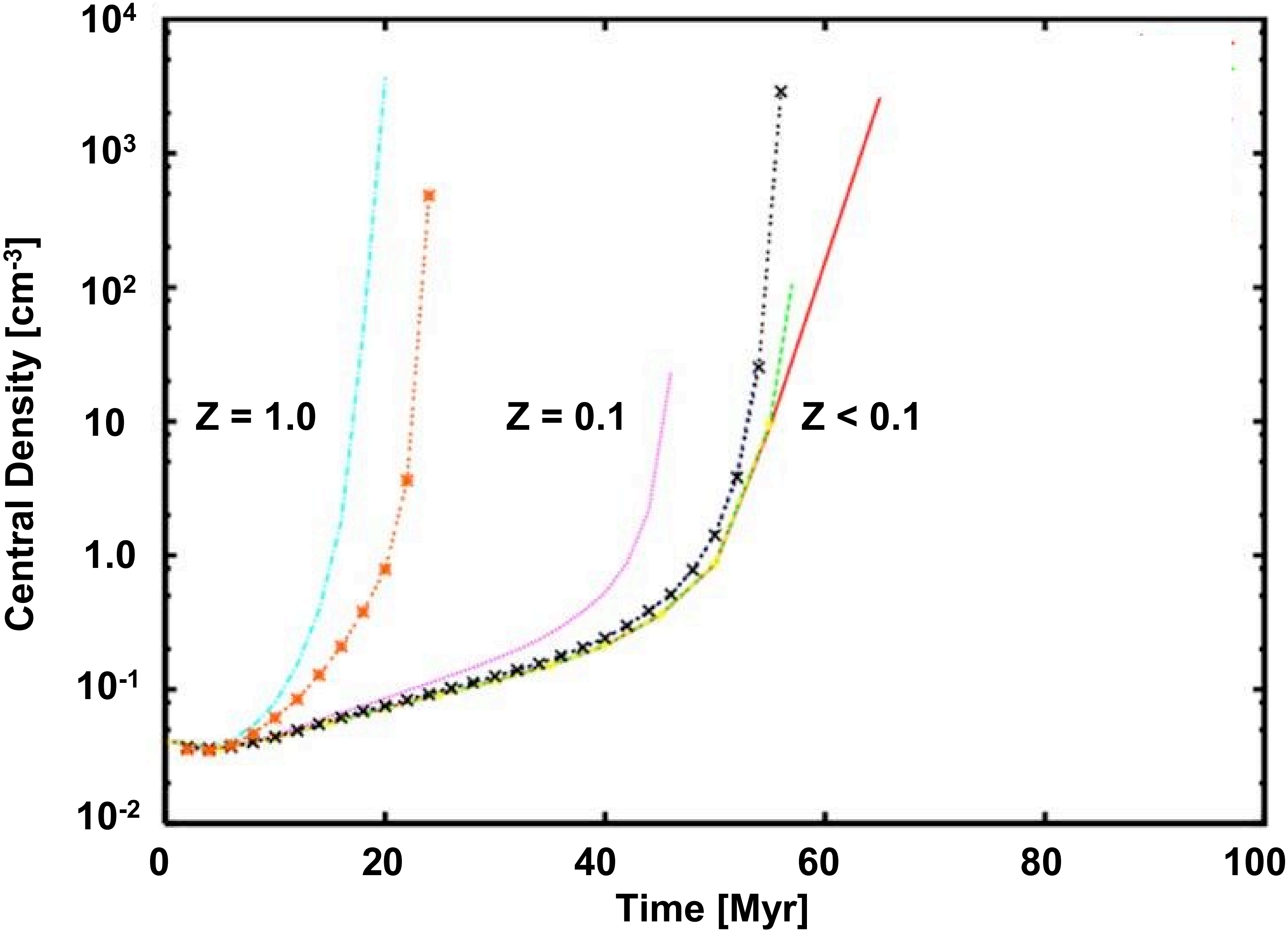


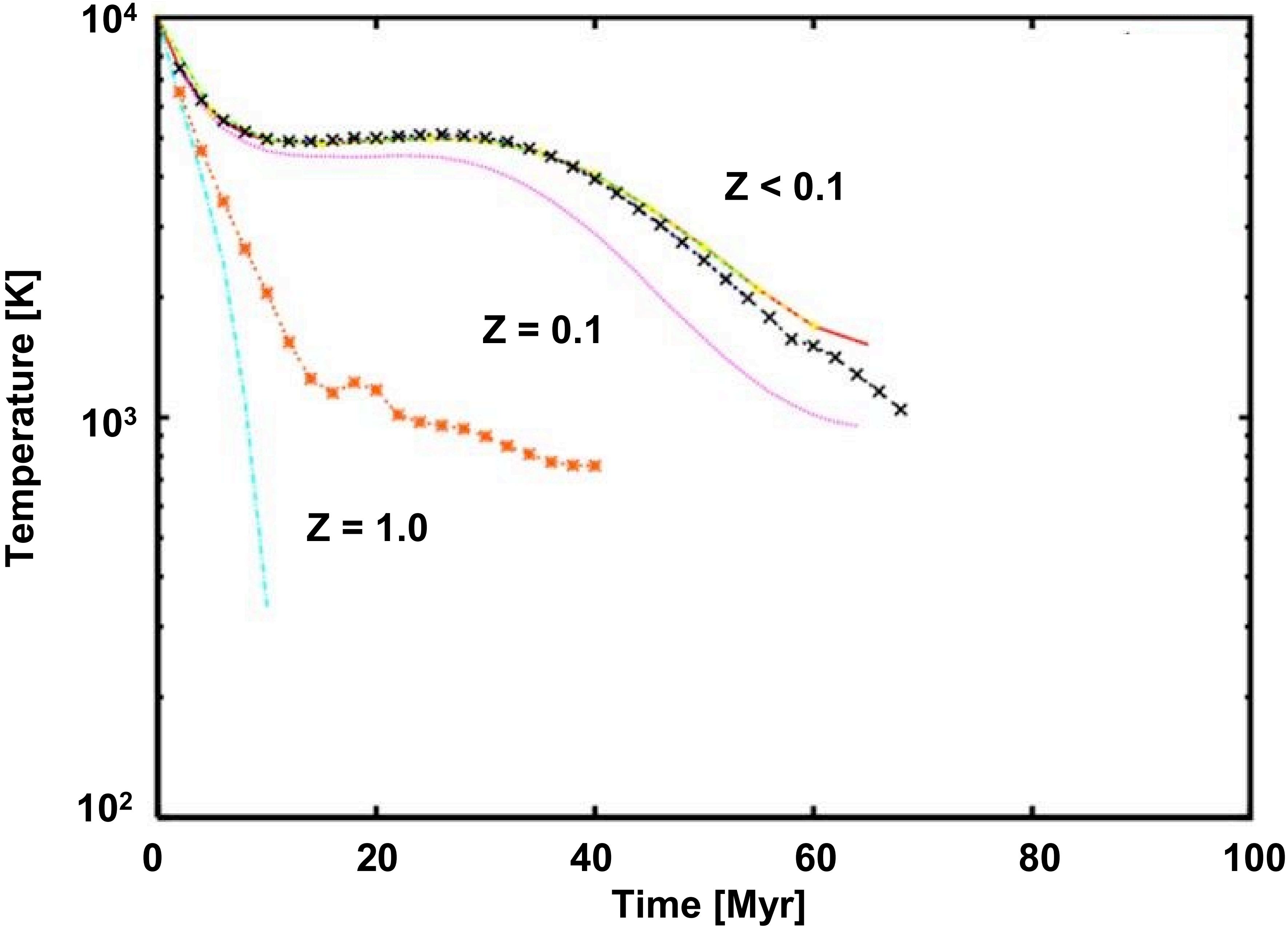
Zero Metallicity



$M < 5 \times 10^5 M_{sun}$

$M > 5 \times 10^5 M_{sun}$

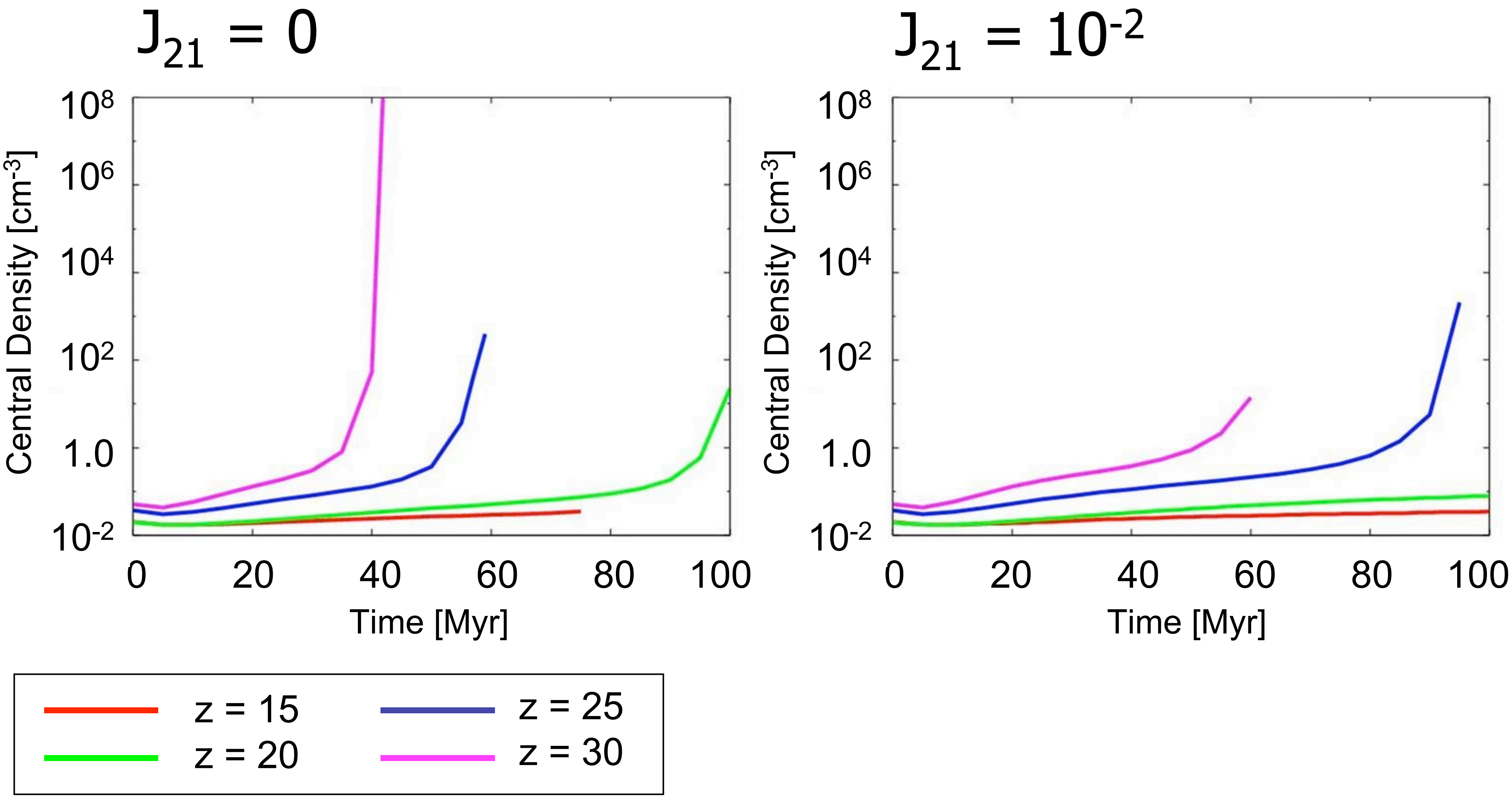

10^4
10^3
10^2
10
1.0
10^-1
10^-2
Central Density [cm^-3]
Z = 1.0
Z = 0.1
Z < 0.1
0
20
40
60
80
100
Time [Myr]



Temperature [K]
10^4
10^3
10^2
Time [Myr]
0
20
40
60
80
100
Z < 0.1
Z = 0.1
Z = 1.0

UV Background + Low Metallicity

$Z=10^{-3} Z_{sun}$

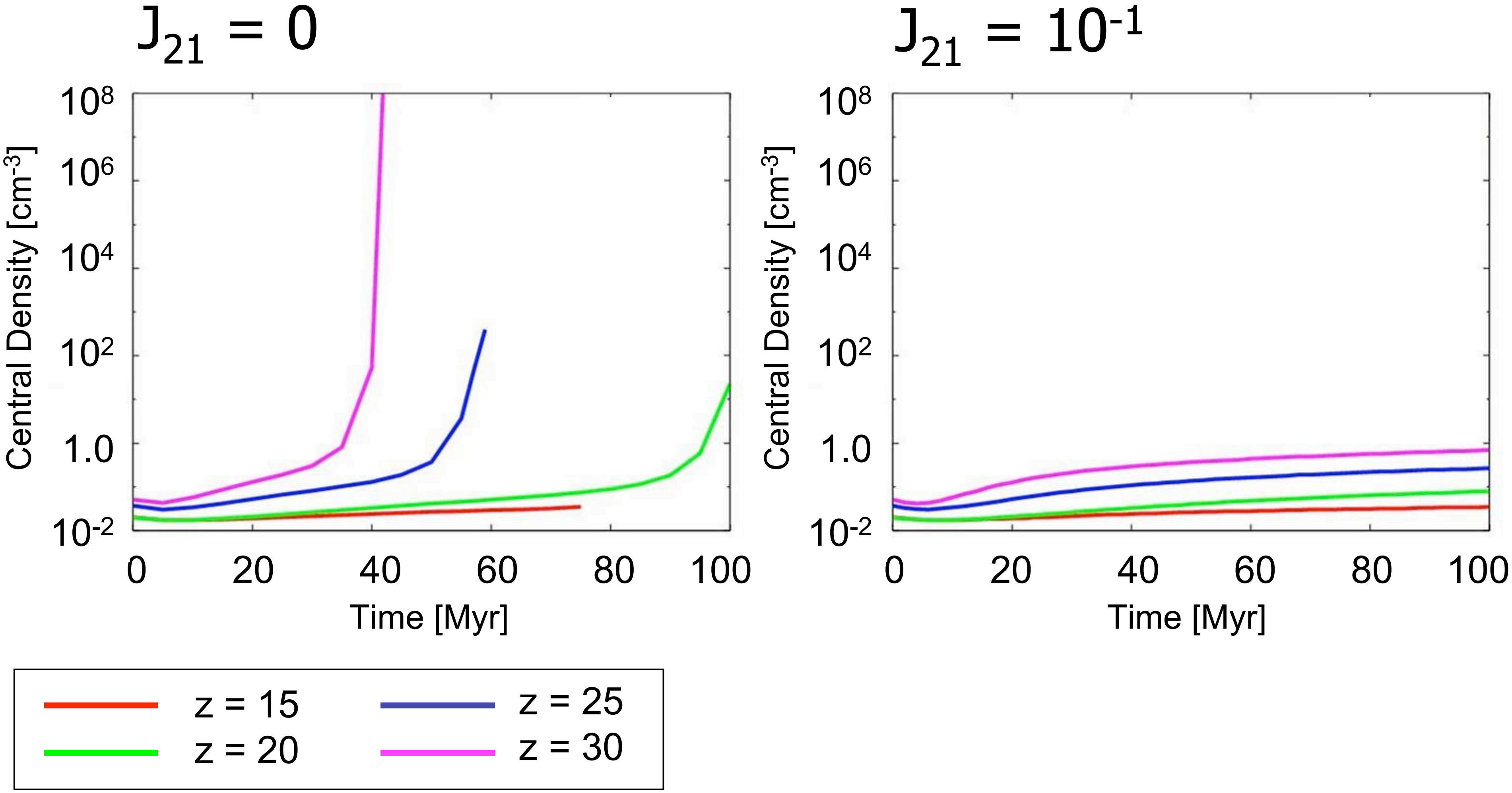


$J_{21} = 0$

$J_{21} = 10^{-2}$

UV Background + Low Metallicity

$Z=10^{-3}\,Z_{sun}$



$J_{21} = 0$

$J_{21} = 10^{-1}$

Results

- H_2 dominant & most effective coolant
- For $n < 100\ \mathrm{cm}^{-3}$: evolution of n and T not changed by metallicity below 10% solar
- UVB delays or suppresses cooling and collapse of the gas
- Influence of metallicity on fragmentation at higher densities?

⇨ High resolution simulations in progress

Conclusions

- 3D simulations of very low metallicity gas are:
  - technically feasible
  - necessary for studying the IMF
- Initial conditions remain largest area of uncertainty
- We should learn far more about the 2nd generation of stars over the next few years