The Influence of Metallicity on Star Formation in Protogalaxies

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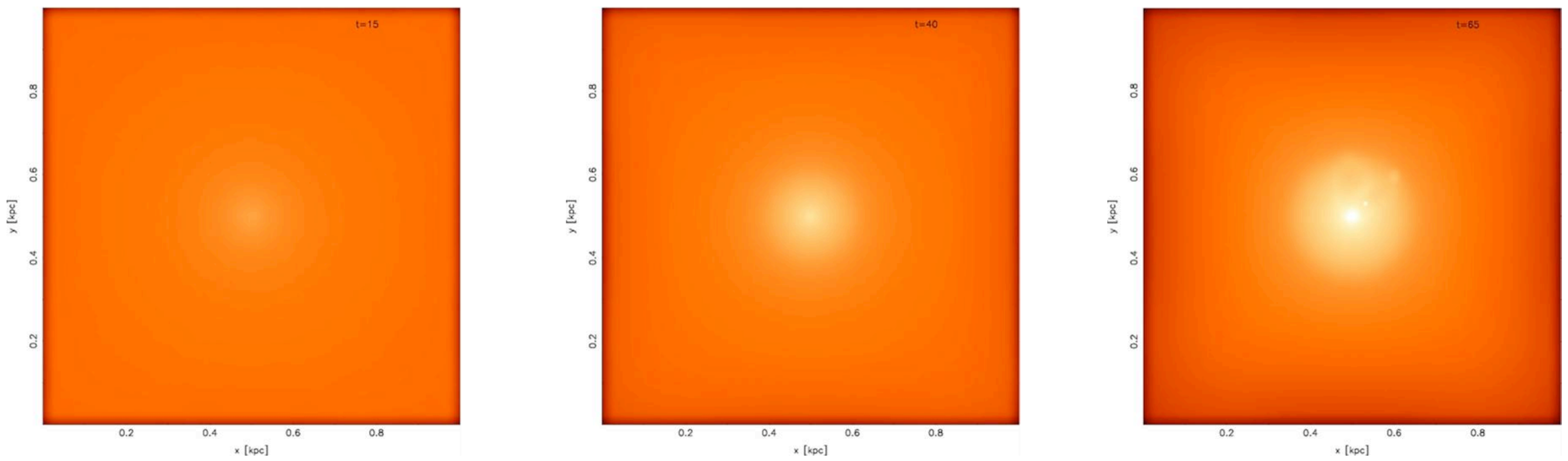

Collaborators

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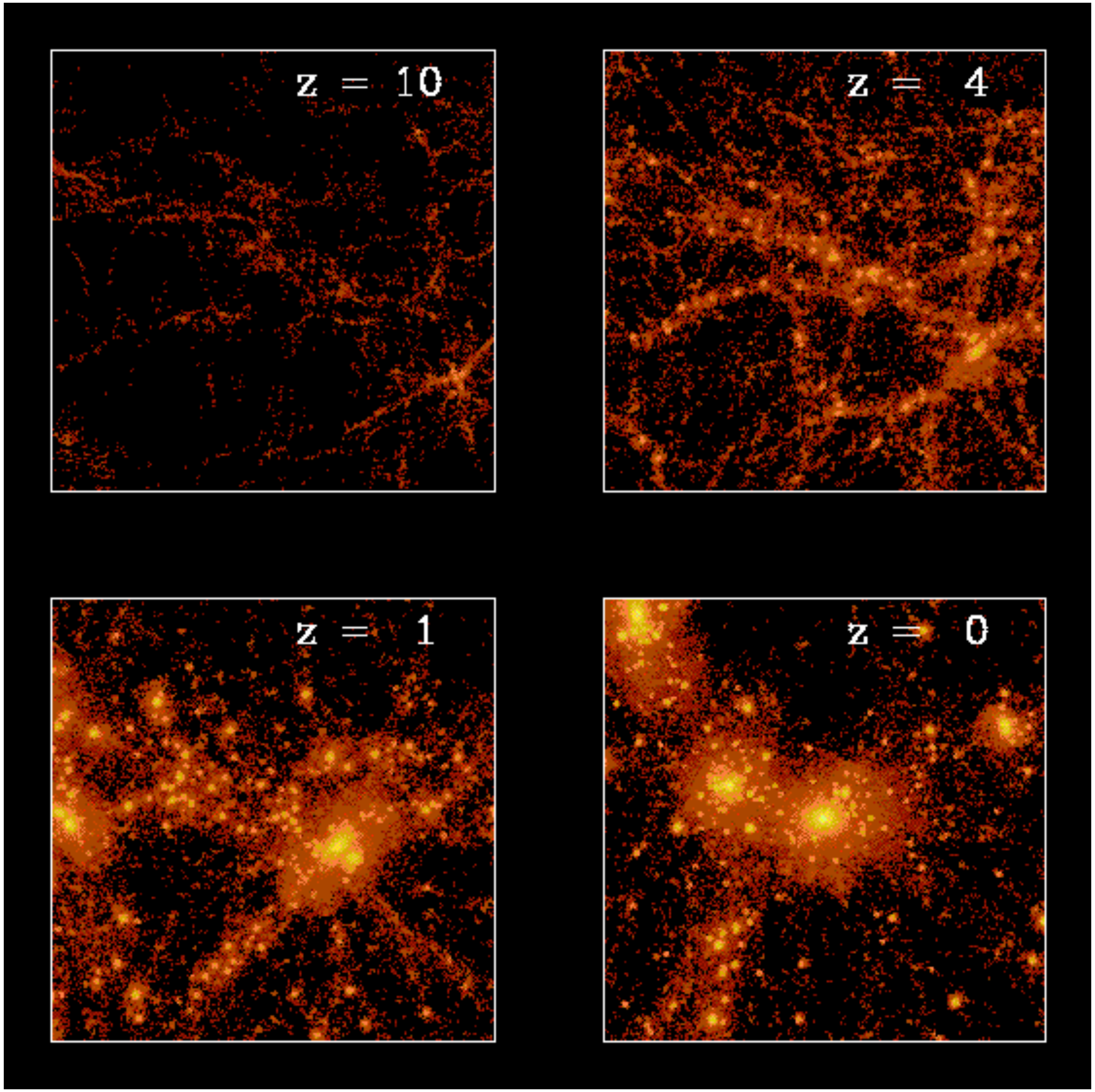
Spyridon Kitsionas – AIP, Potsdam, Germany

Hierarchical Structure Formation

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



Credit: S. Gottlöber (AIP)

Star Formation in the Early Universe

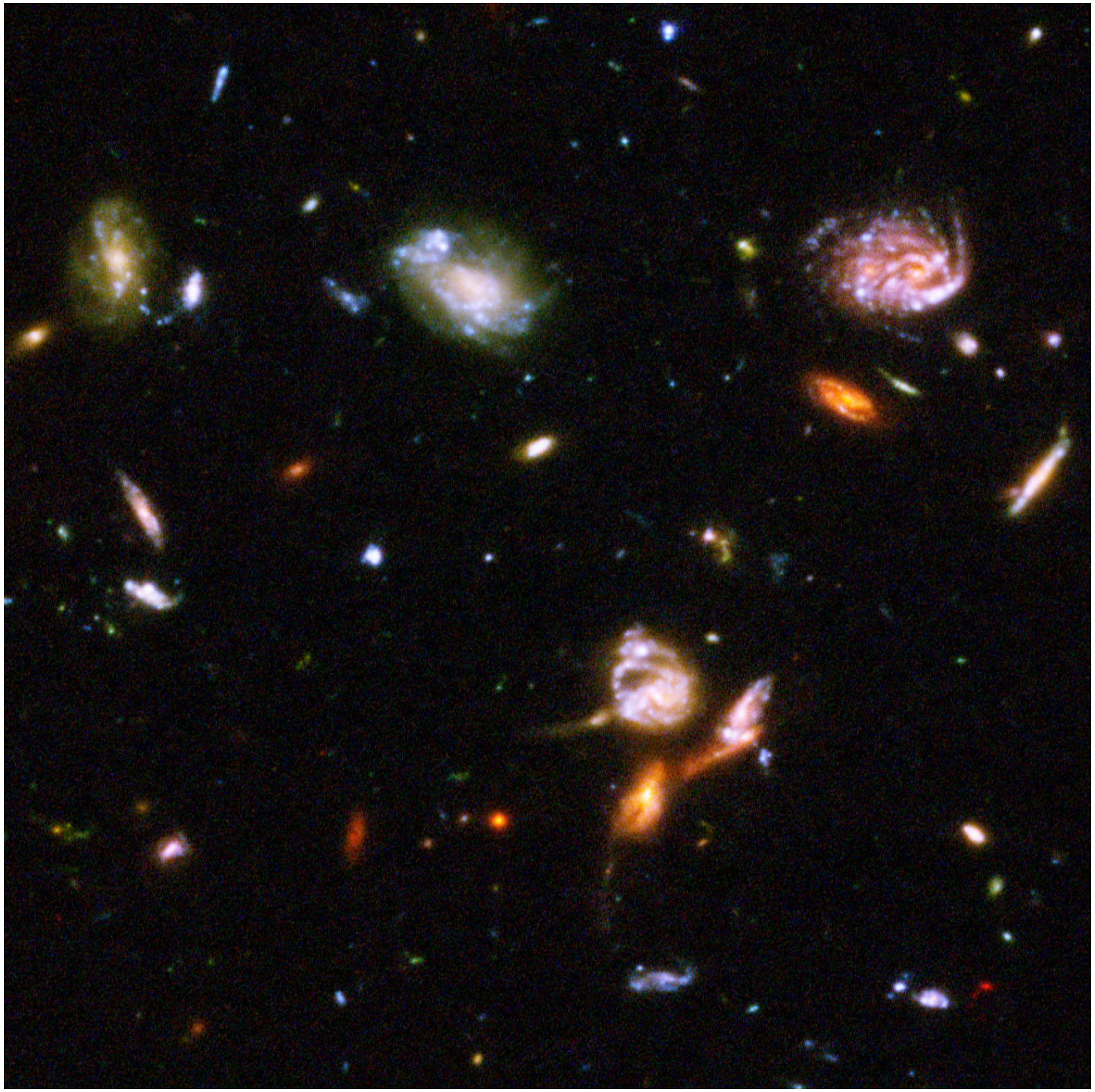
- Pop III stars

↓

- Metal enrichment
- UV photons contribute to reionization
- injection of entropy into IGM

↓ ?

- Pop II stars



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

The Questions

- What is the influence of low levels of metallicity on cooling and collapse of the gas?
- 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?
- What is a appropriate description of the initial conditions and the environment?

A Critical Metallicity?

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

C, O fine structure cooling

↓

$Z_{cr} \sim 10^{-3.5} Z_{sun}$

dust cooling

↓

$Z_{cr} \sim 10^{-5} Z_{sun}$

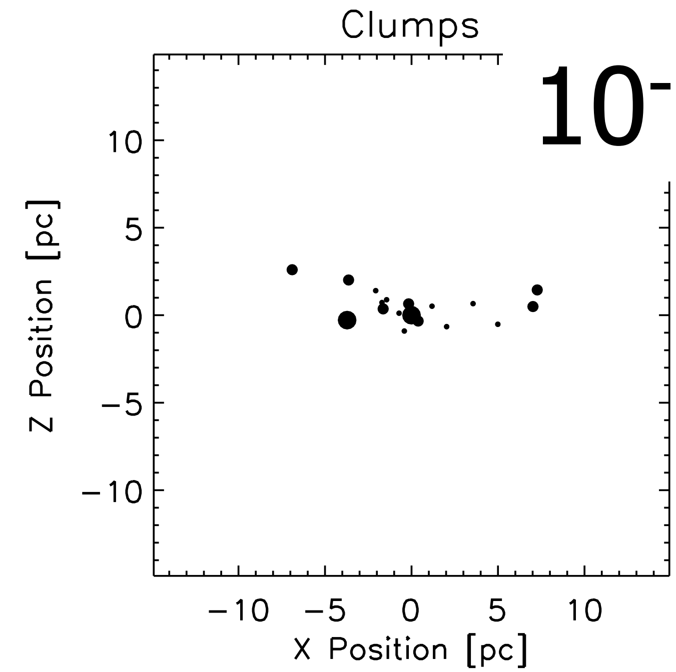
Different Studies

Bromm et al. (2001):

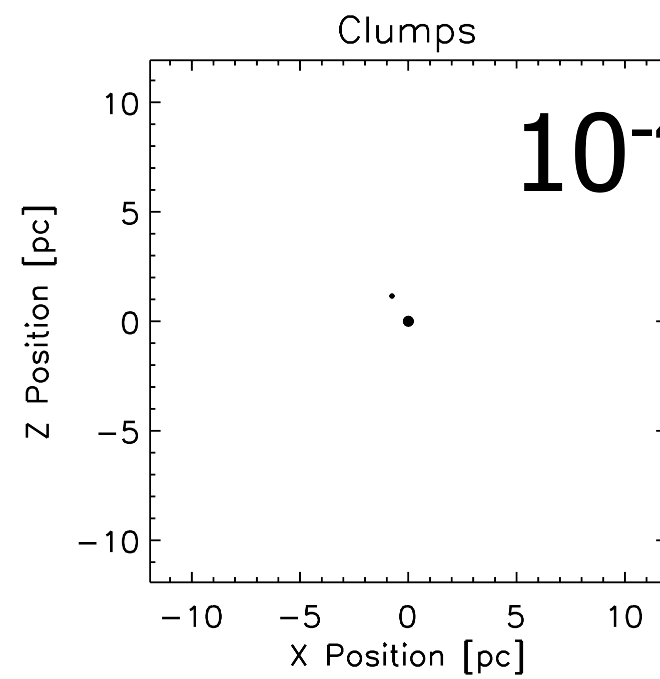
• SPH simulations of collapsing dark matter mini-halos

• no H_2 or other molecules
• no dust
• only C and O atomic cooling

$10^{-4} Z_{sun} < Z_{cr} < 10^{-3} Z_{sun}$



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

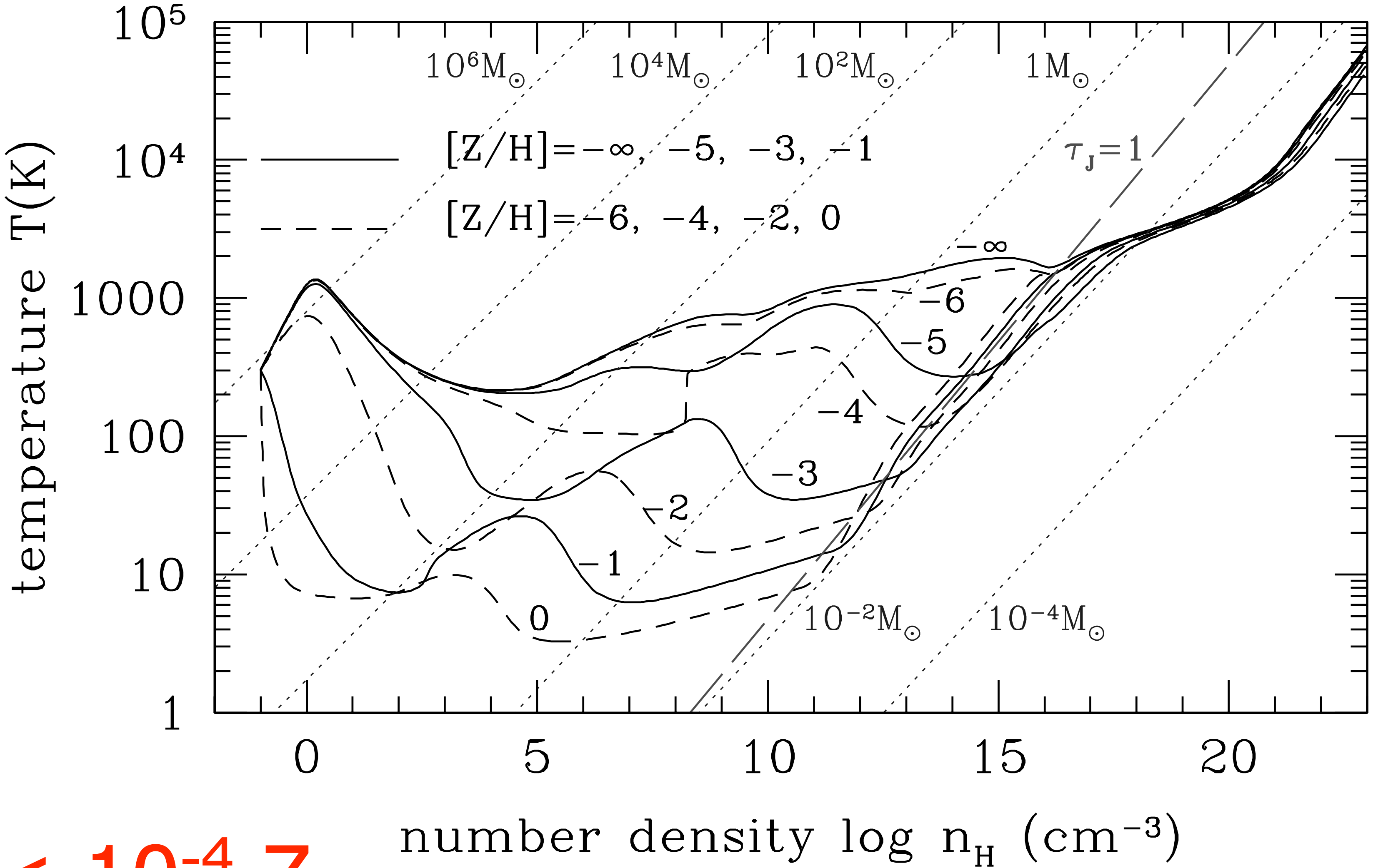


$10^{-4} Z_{sun}$

Different Studies

Omukai et al. (2005): one zone model

H_2, HD and other molecules,
metal cooling,
dust cooling



$10^{-6}\ Z_{sun} < Z_{cr} < 10^{-4}\ Z_{sun}$

Different Studies

Omukai et al. (2005): one zone model

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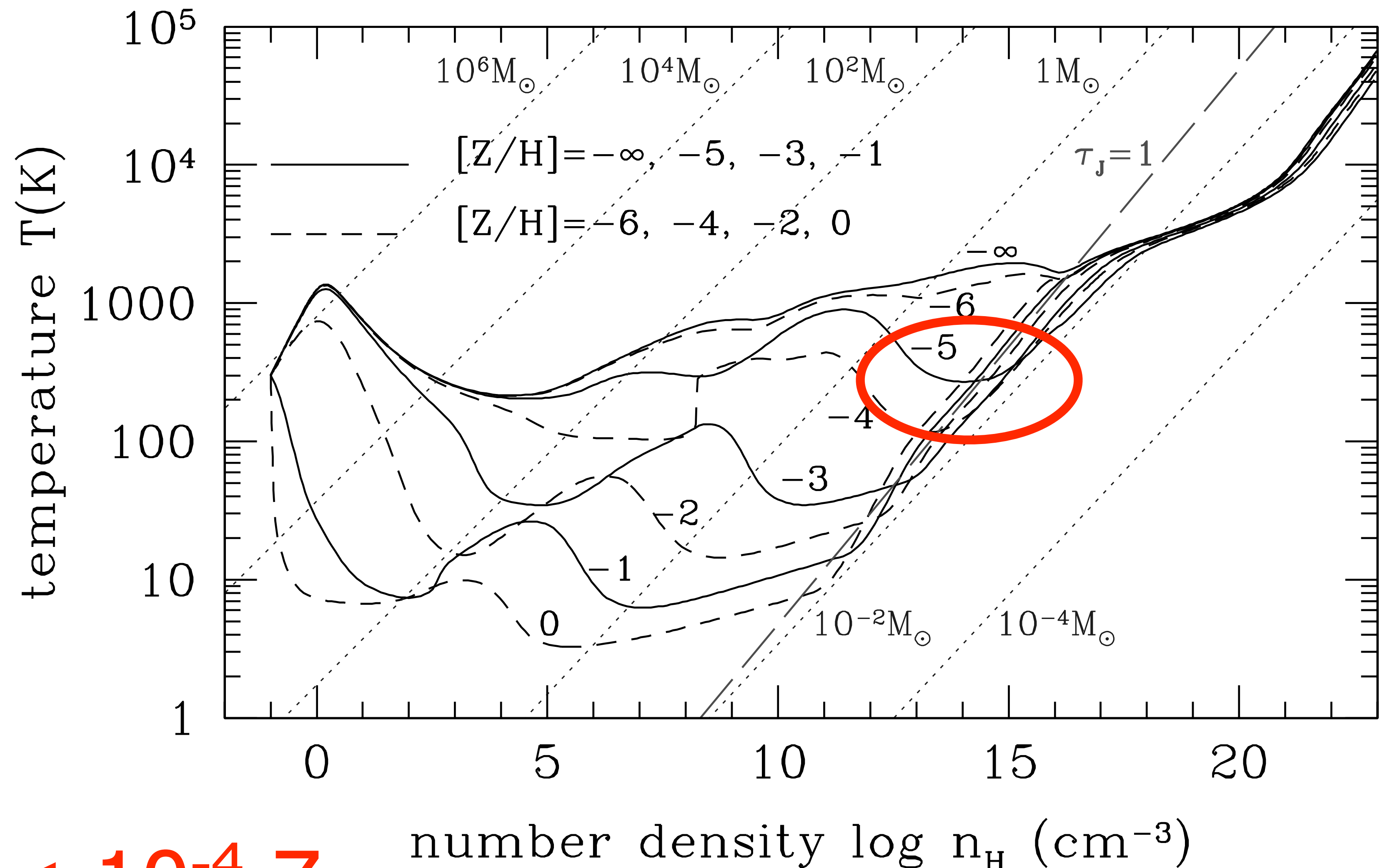


$10^{-6} Z_{sun} < Z_{cr} < 10^{-4} Z_{sun}$

Numerical Method

- smoothed particle hydrodynamics
  (Gadget1 & Gadget2 - Springel et al. 01, 05)
- sink particles (Bate et al. 95)
- chemistry and cooling
- particle splitting (Kitsionas & Whitworth 02)
- different initial conditions

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

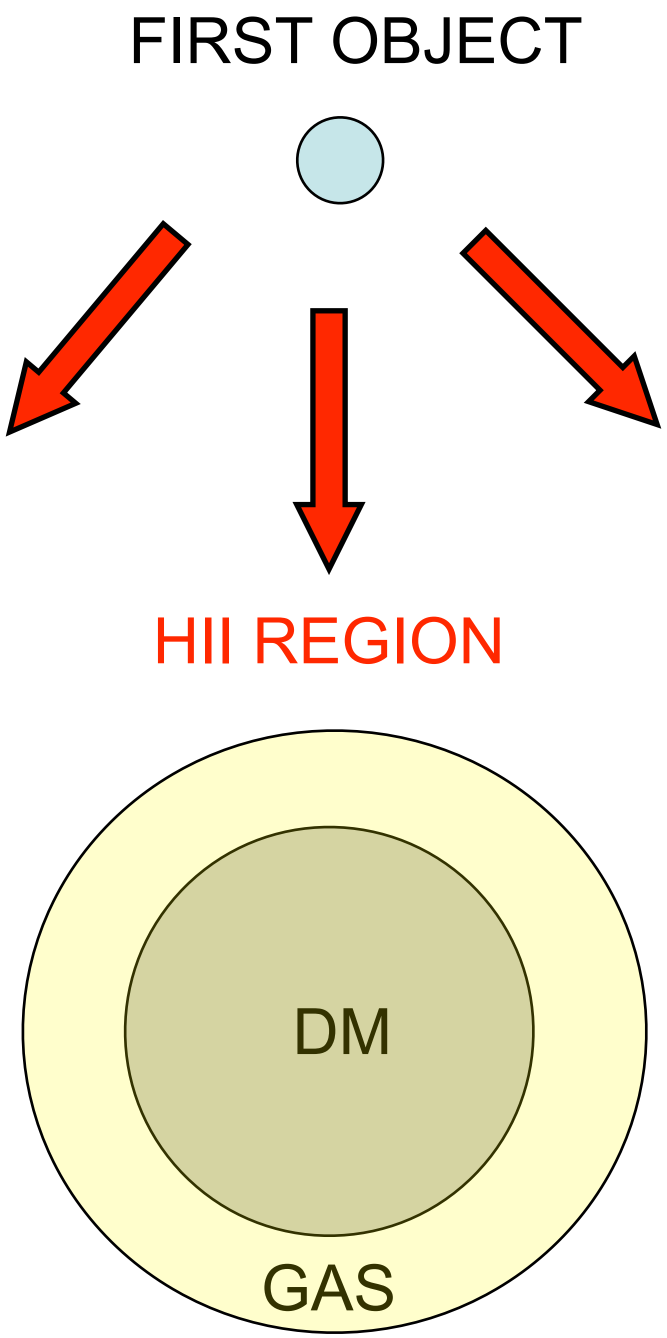
(Jappsen et al. 06)

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 I

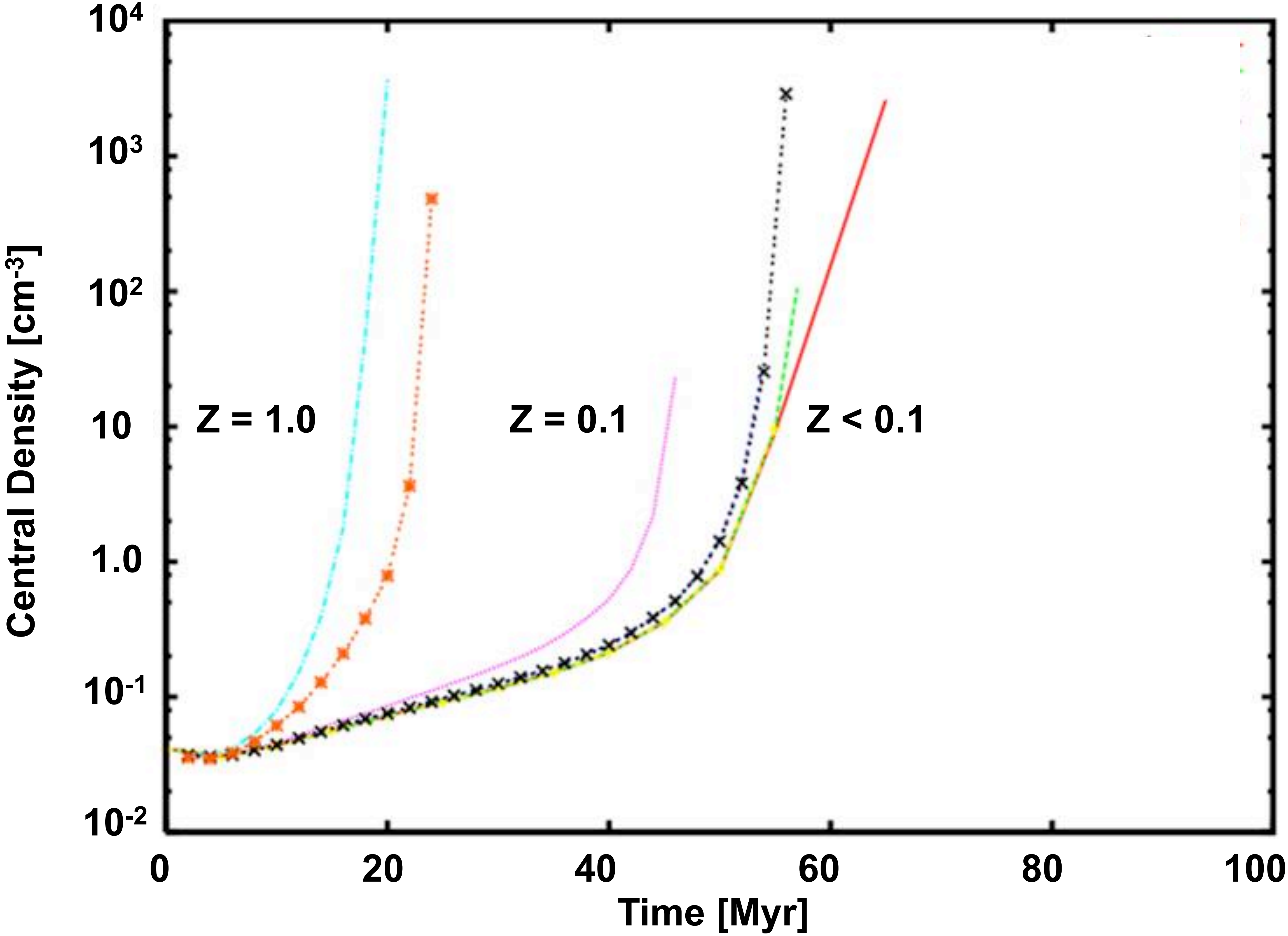


- gas fully ionized
- initial temperature: 10000 K
- volume: (0.5) kpc^3 - (4.0) kpc^3
- contained gas mass: 17% of DM Mass
- number of gas particles: 10^5 - 4 x 10^6
- resolution limit: 2 M_{SUN} – 400 M_{SUN}

(Jappsen et al. 07)

Parameter Study

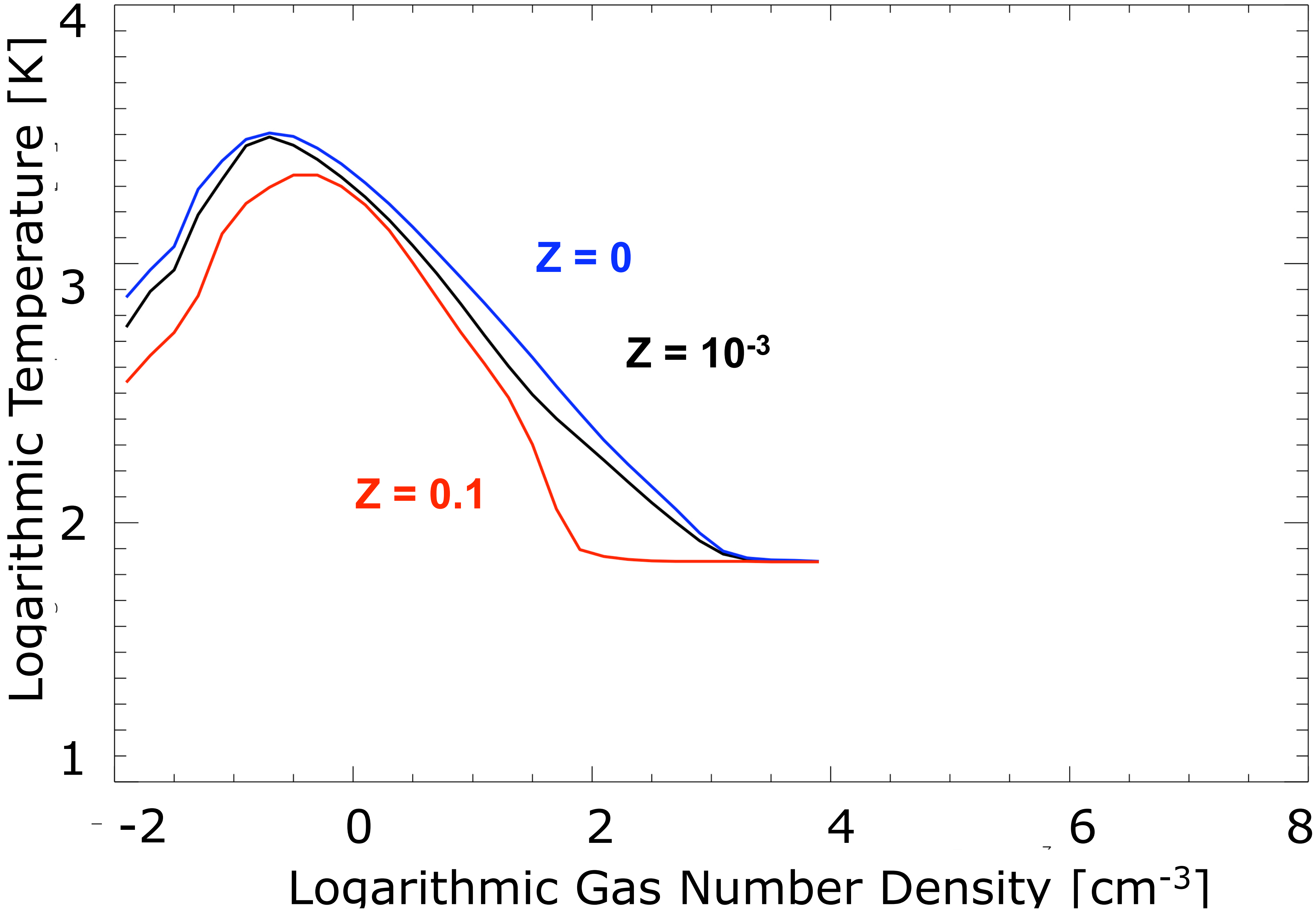
- halo size: $5 \times 10^4\,M_{sun}$ - $10^7\,M_{sun}$
- redshift: 15, 20, 25, 30
- metallicity: zero, $10^{-4}\,Z_{sun}$ - Z_{sun}
- UV background: $J_{21} = 0, 10^{-2}, 10^{-1}$
- dust: yes or no



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

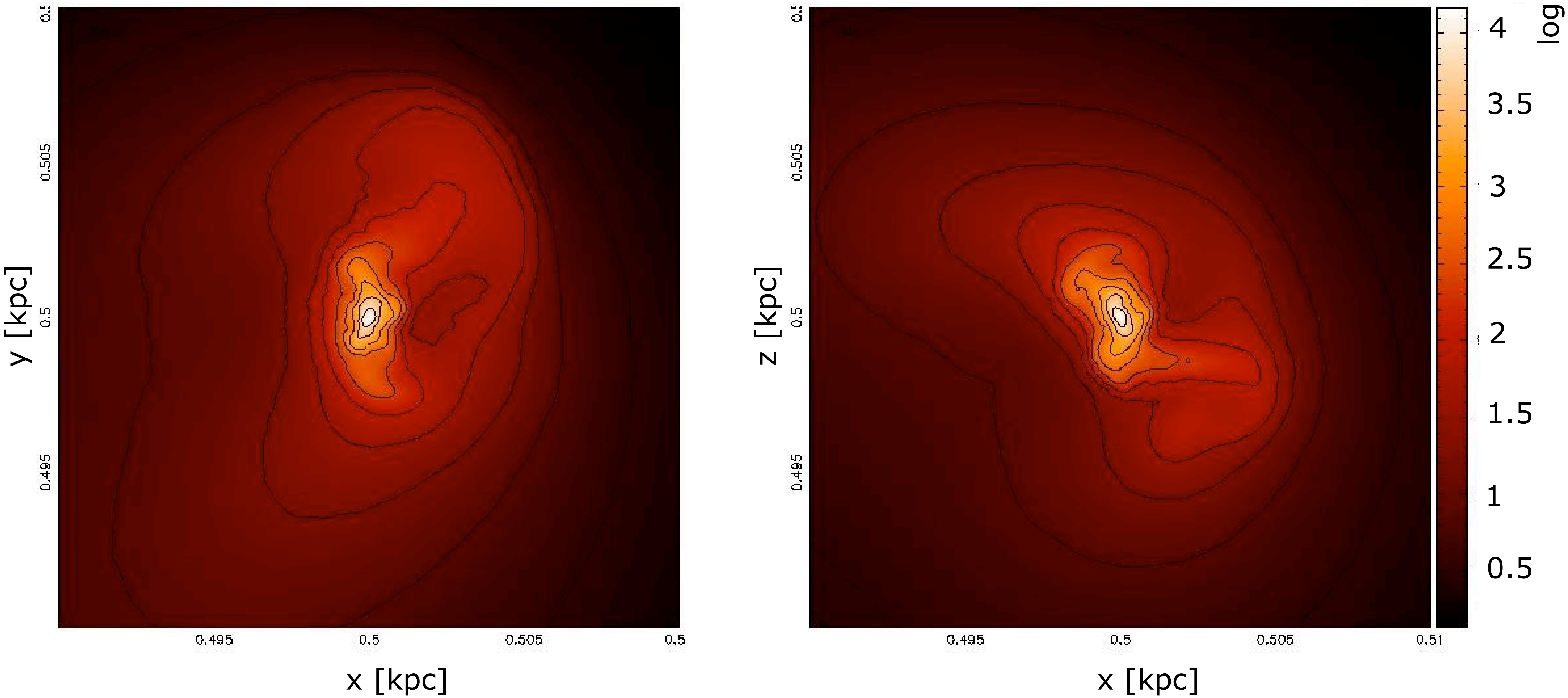
Higher Resolution Simulations

Temperature versus Density

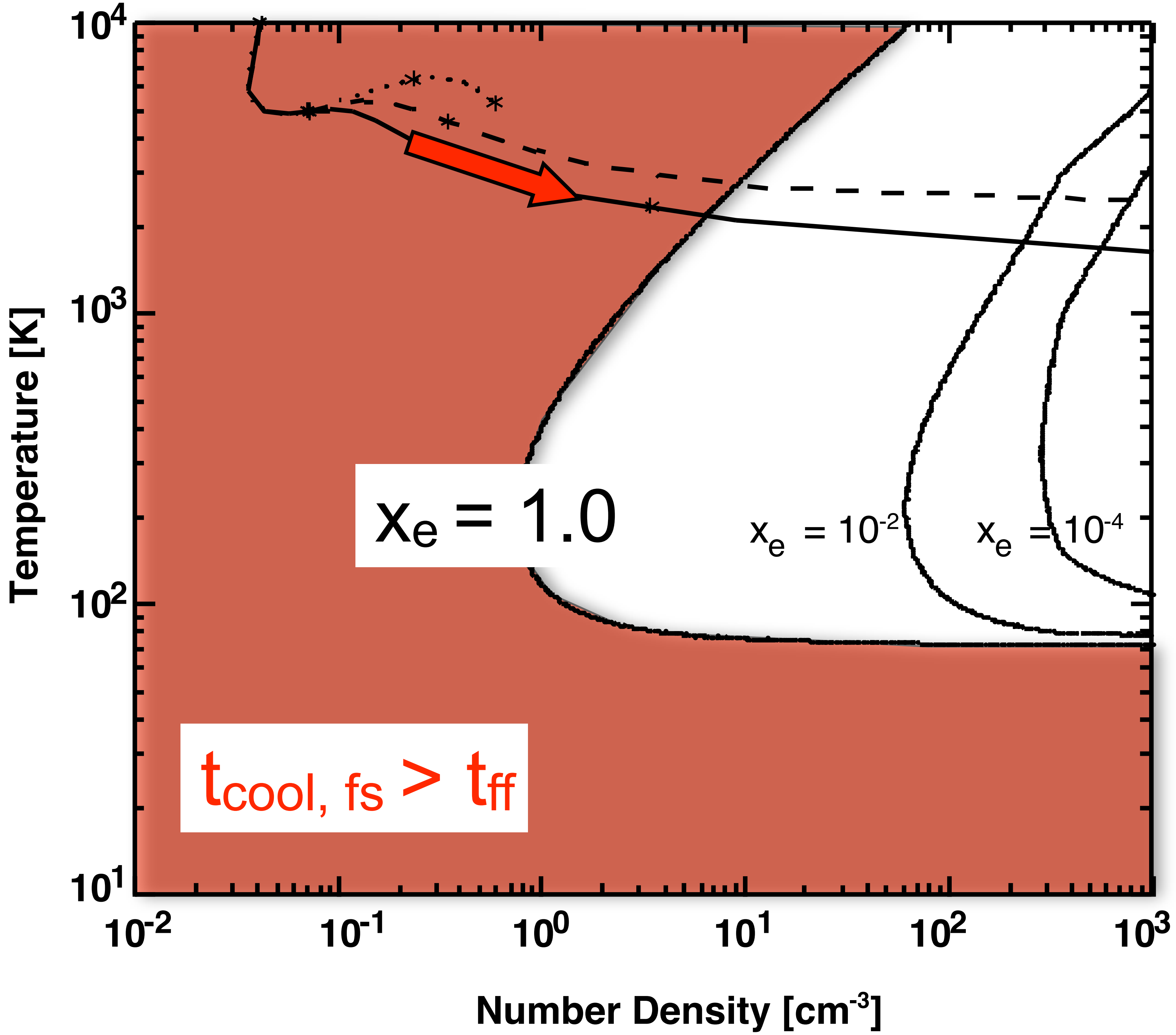


Higher Resolution Simulations

No Fragmentation at a Metallicity of $Z=10^{-3}\,Z_{sun}$



Cooling Time vs. Free-fall Time



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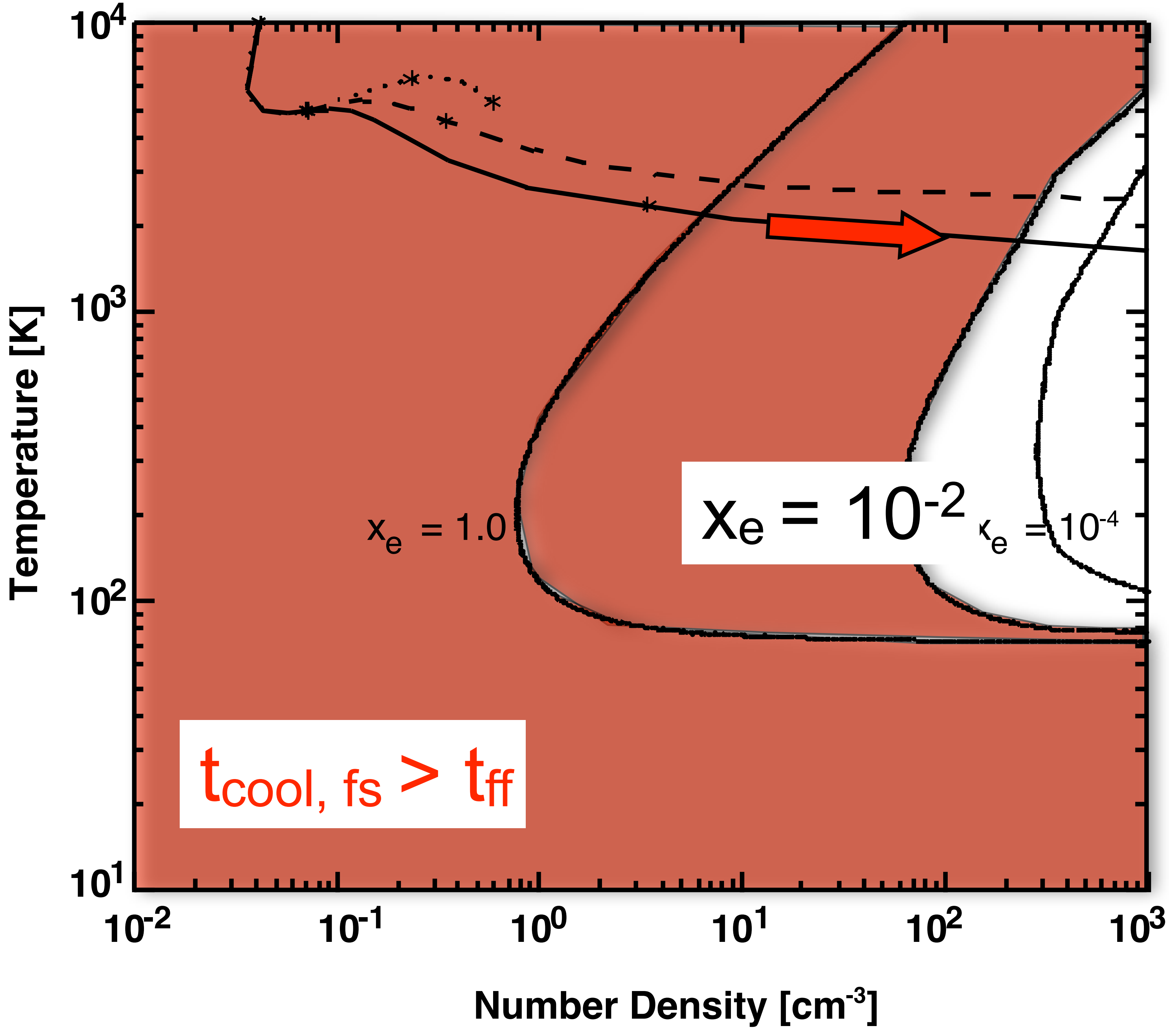

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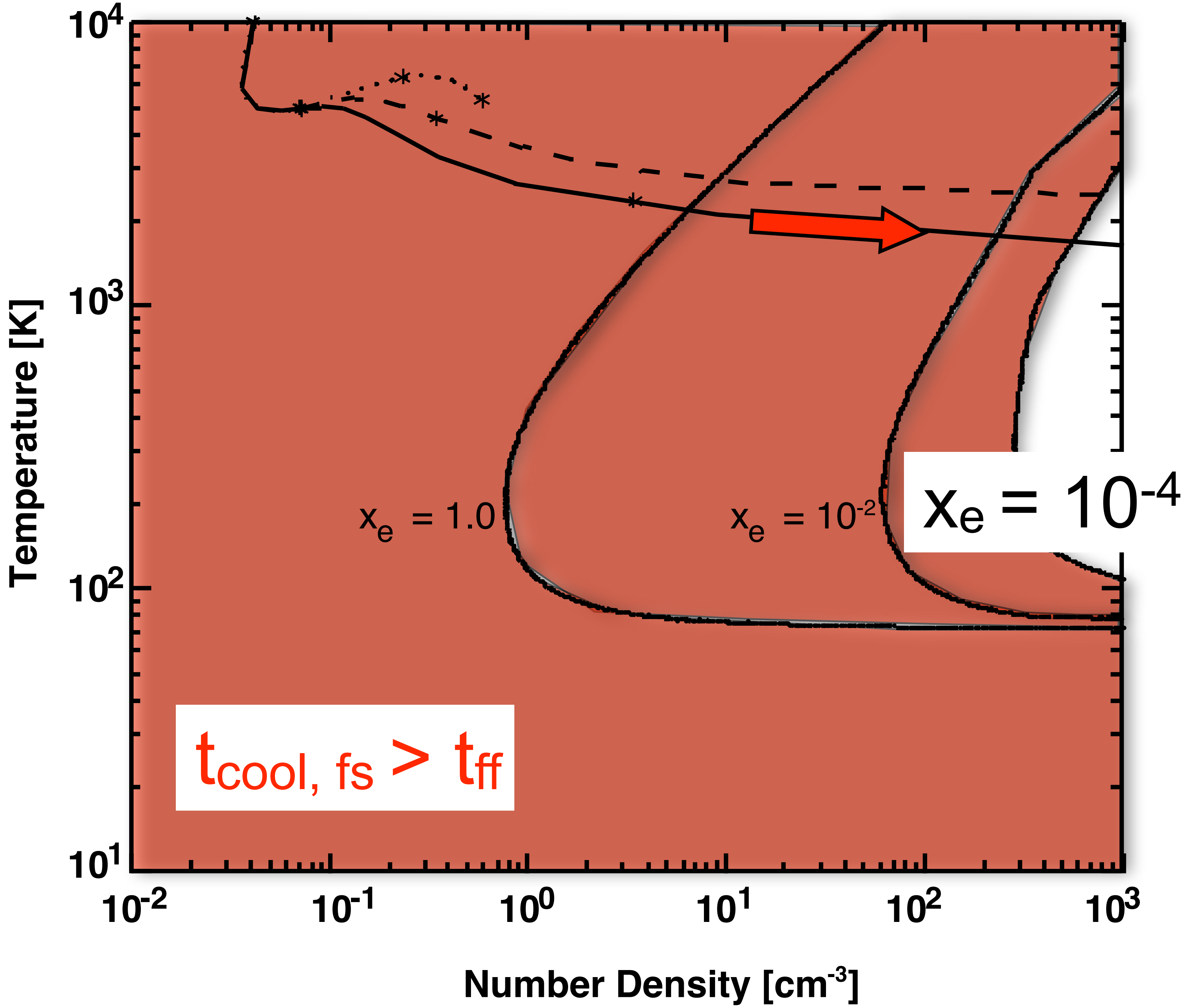
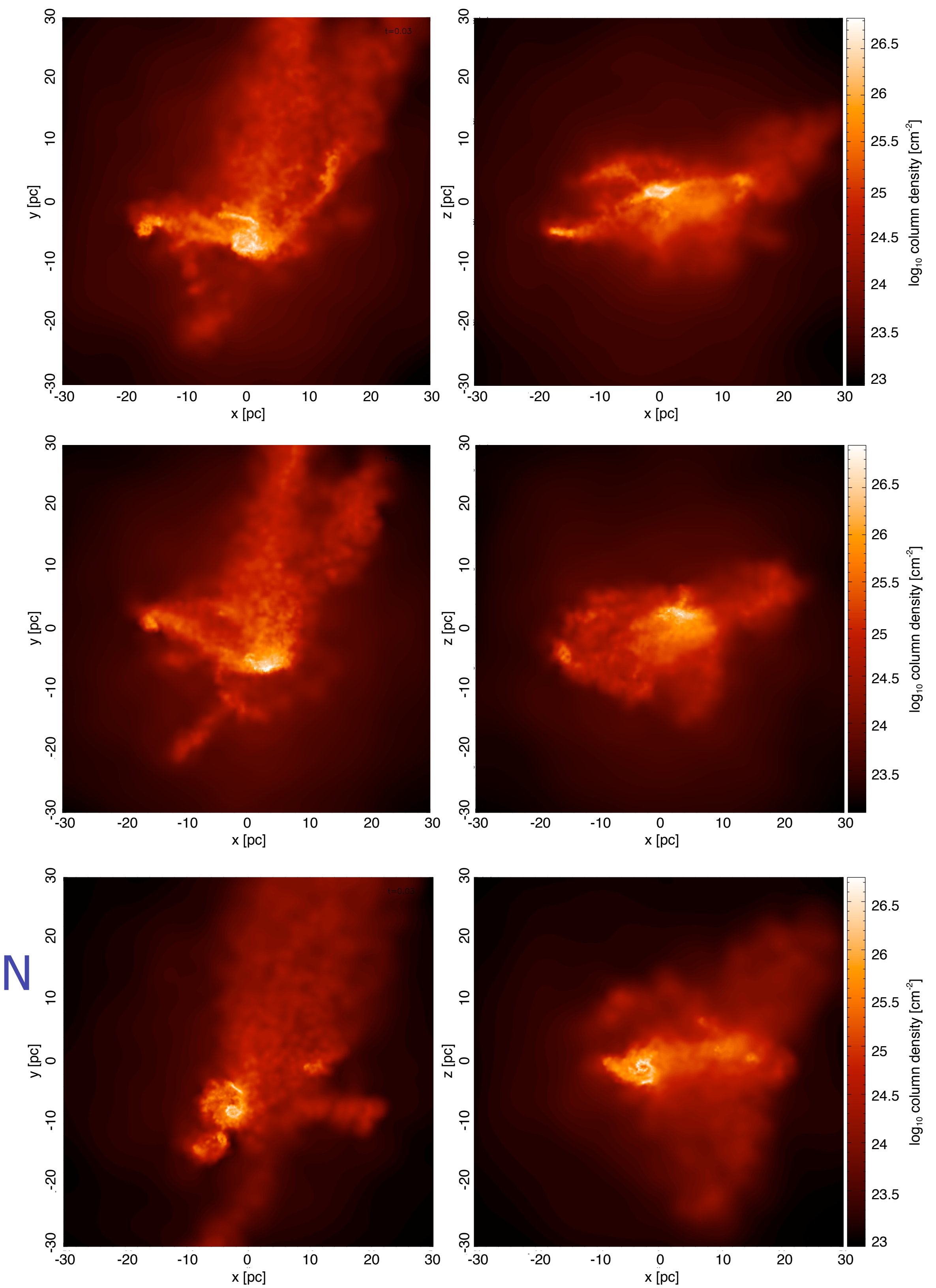
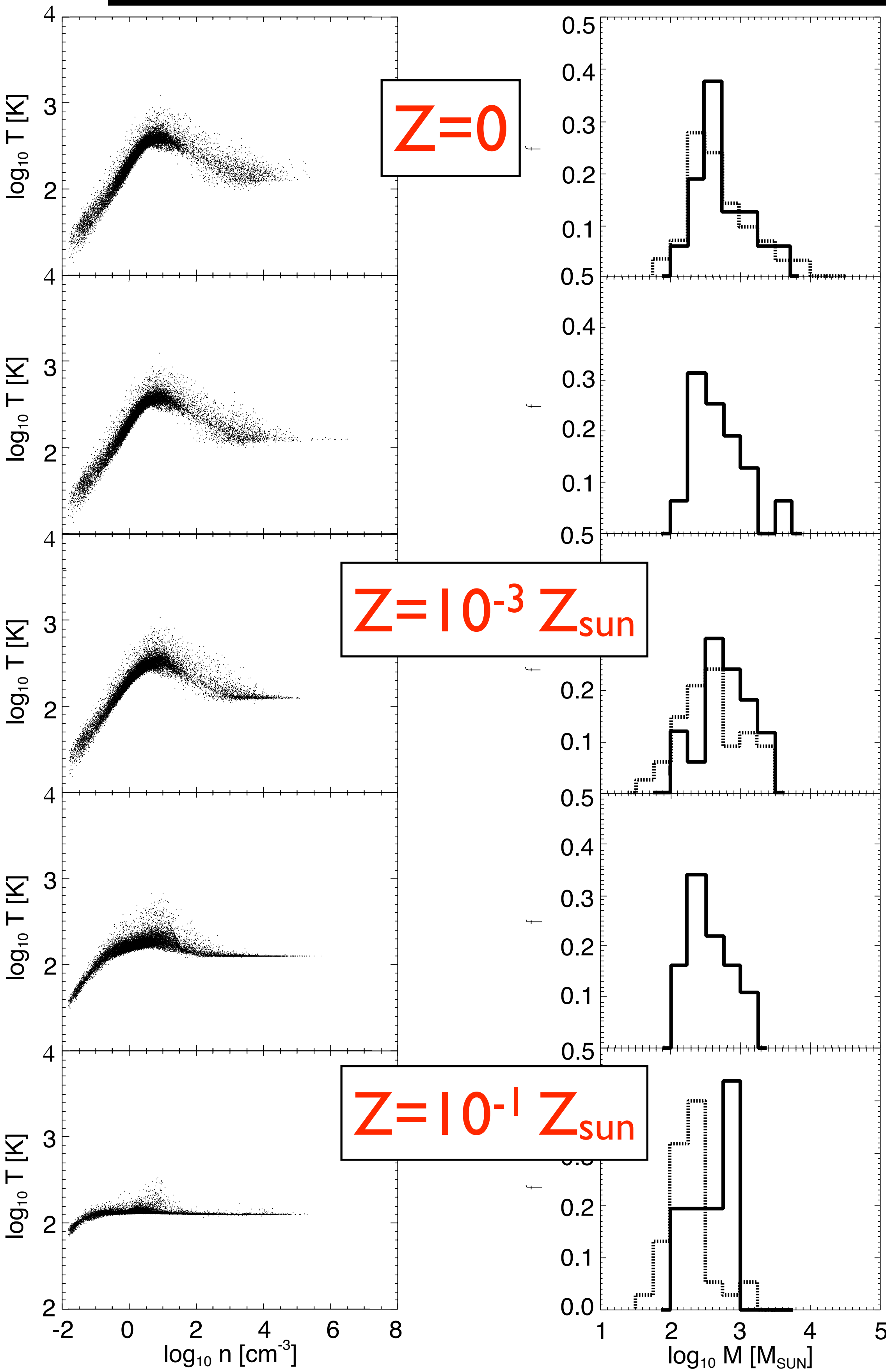


Initial Conditions II

- gas partially ionized: $x_e = 10^{-4}$
- initial temperature: 200 K
- DM halo mass: $2 \times 10^6\ M_{SUN}$
- top-hat approximation, r = 150 pc
- number of gas particles: 10^5 - 10^6
- resolution limit: $12\ M_{SUN} - 100\ M_{SUN}$
- metallicities: $0 < Z < 0.1\ Z_{SUN}$



Initial Conditions II: Results



- Bromm et al. 01: critical metallicity due to metal-line cooling in absence of H_2
- our simulations with H_2: no critical metallicity
- H_2 dominant coolant, destroys threshold for fragmentation (Jappsen et al. 07, submitted, arxiv: 0709.3530)

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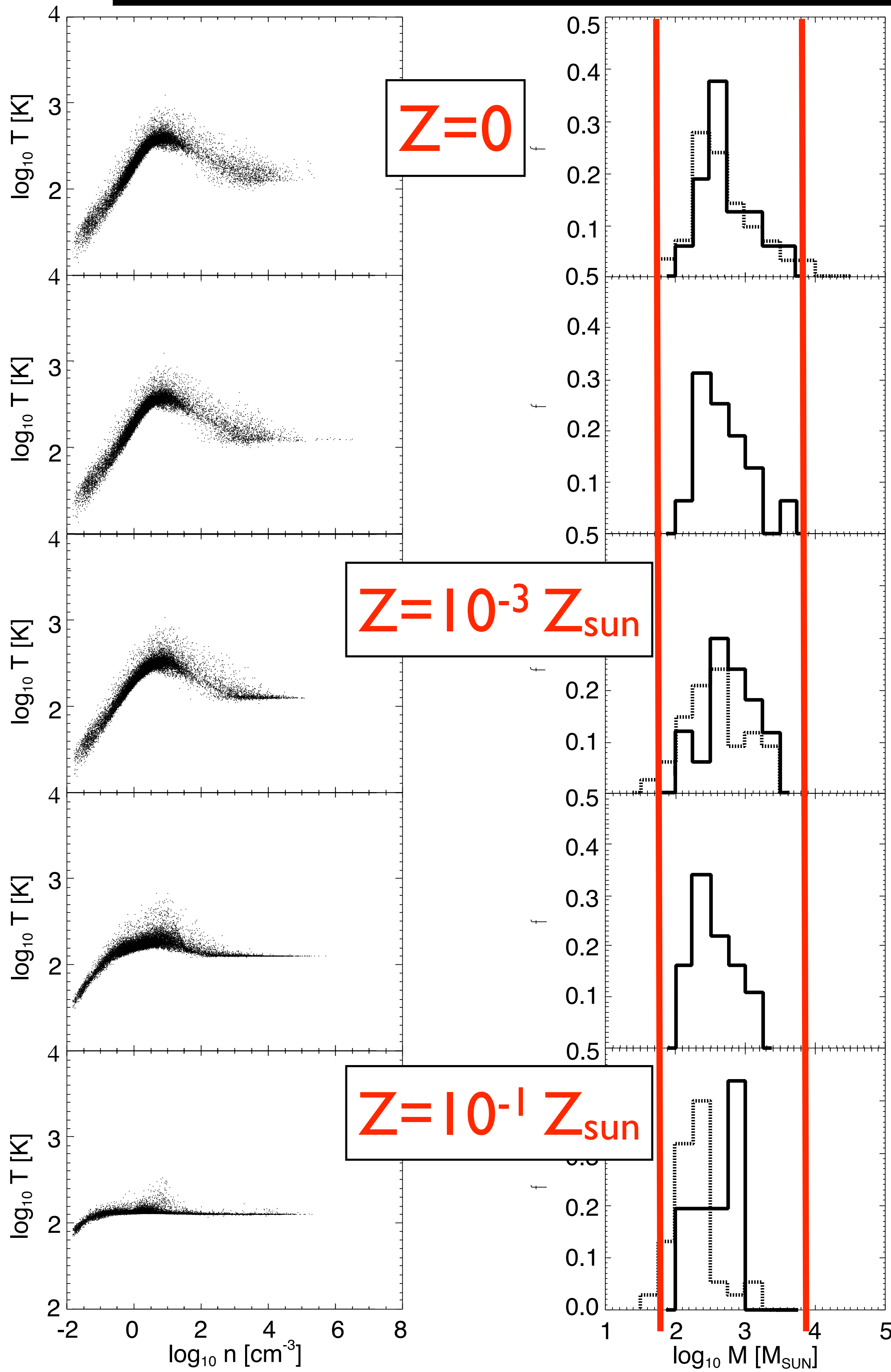

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Results and Outlook

- H_2 dominant & most effective coolant, destroys threshold for fragmentation
- For $n < 10^4$ cm^{-3}: evolution of n and T not changed by metallicity below 10% solar
- We find no metallicity threshold for the two different initial conditions
- Fragmentation due to dust cooling at higher densities?
  (Omukai et al. 05, Clark et al. 07)
- What are most appropriate initial conditions?