The chemistry and thermodynamics of Pop III star formation

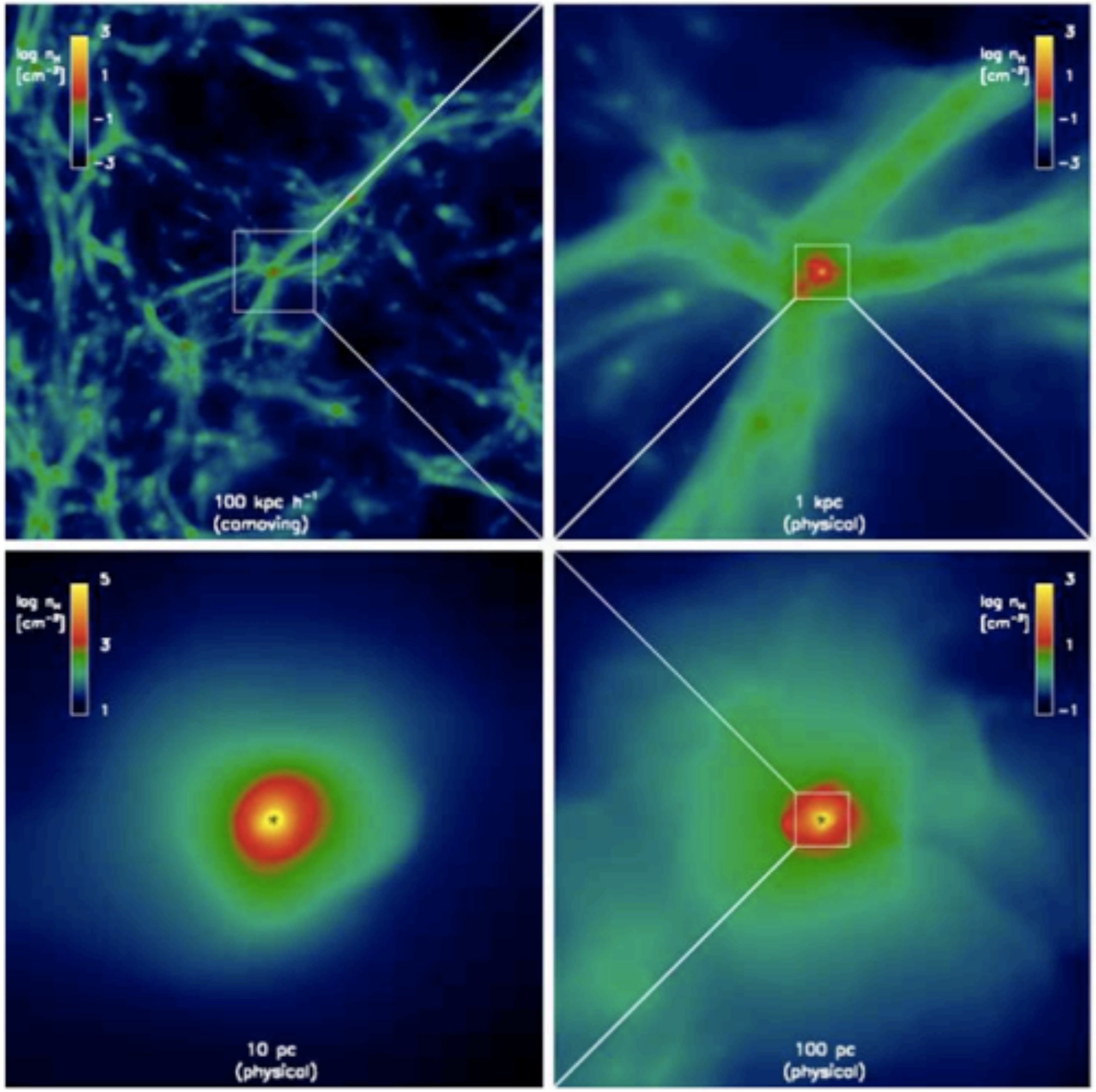
Where do the first stars form

- Form in dark matter minihalos with mass

  $M_{halo} \gtrsim 5 \times 10^5 M_\odot$

- Redshift $z = 16 - 20$
- $T_{vir} \sim 1000$ K
- Gas density is around

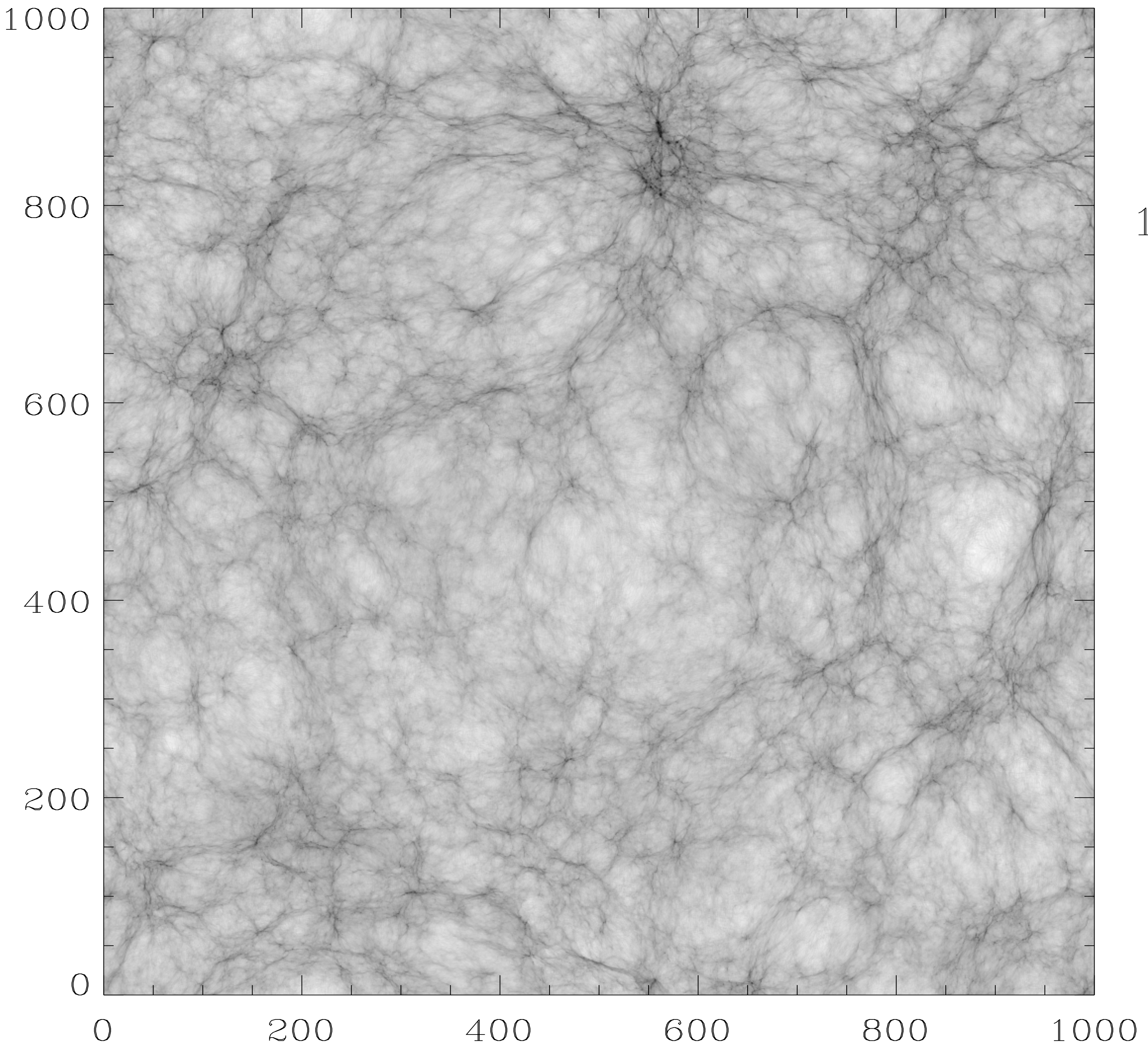
  1 cm^{-3}



Stacy, Greif and Bromm (2010)

Current state-of-the-art?

- 2048^3 DM particles
- 1 Mpc (co-moving)
- Particle mass ~ 9 $M_\odot$



Sasaki et al. (2013, in prep.)

The H_2 chemistry

- The ion-neutral reactions dominate in primordial gas

$$H + e^- \rightarrow H^- + \text{photon}$$

$$H^- + H \rightarrow H_2 + e^-$$

$$H^+ + H \rightarrow H_2^+ + \text{photon}$$

$$H_2^+ + H \rightarrow H_2 + H^+$$

- As we pointed out in lecture 2, these reactions depend on the ionisation state of the gas.
- Electrons and protons act as catalysts in these reactions.

Why do they form in these minihalos?

- Collapse occurs in minihalos with $t_{cool} < t_H$
- Below 7000 K, H_2 is the only useful coolant
- Collapse only occurs in minihalos that can form enough H_2 to permit them to cool
- Amount of H_2 produced is a strong function of temperature.
- Once T_{vir} reaches ~1000 K, enough H_2 can form to satisfy the above cooling time requirement.

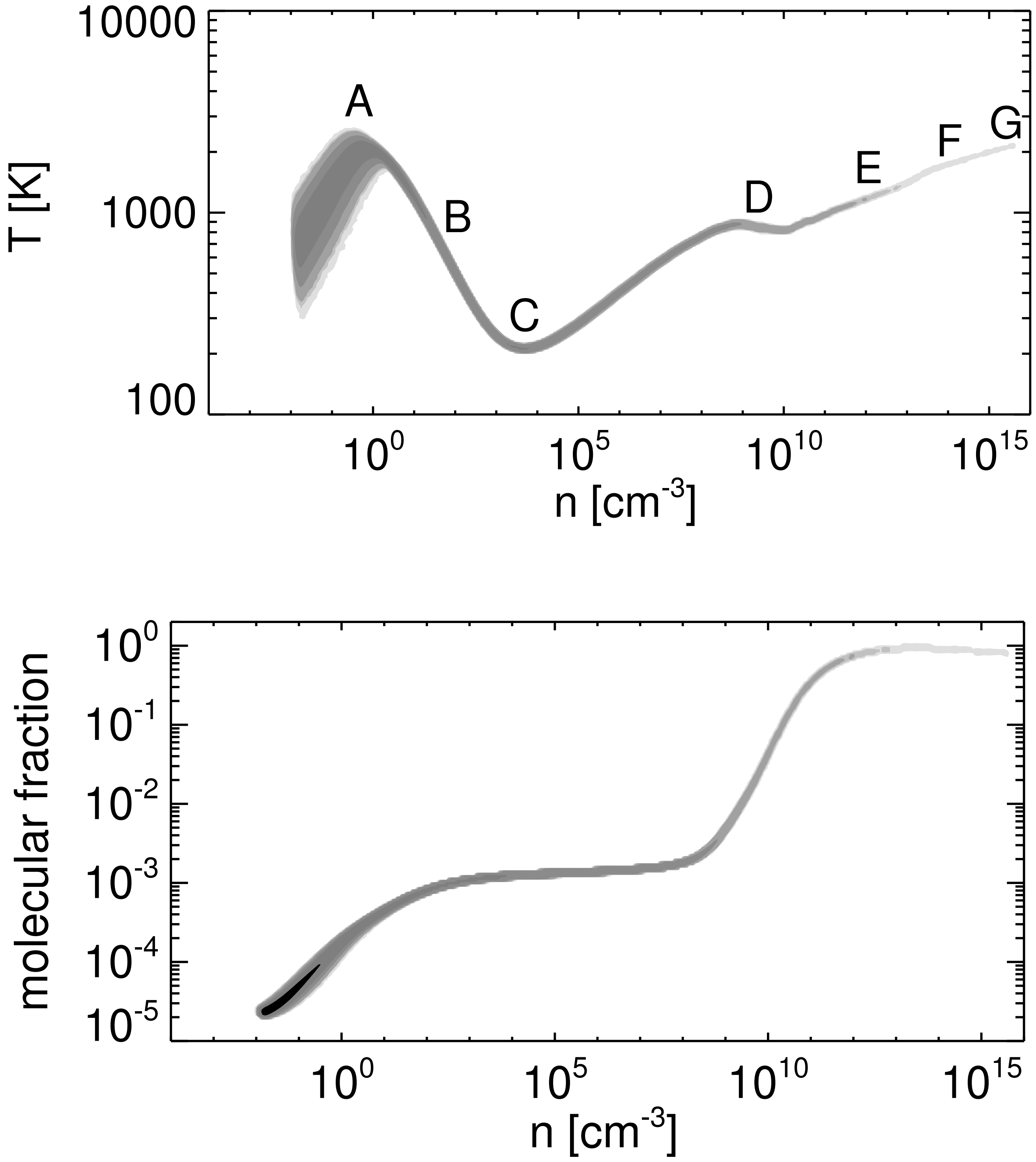
What sets the H_2 fraction?

- Rate of ion-neutral reactions depend on the ionisation fraction in the gas.
- Ionisation fraction is reduced by recombination.
- H_2 formation is a race against the recombination!
- Limits the amount of H_2 that a halo can form by this process to around $n_{H2} \sim 10^{-3}$ n
- Sets a limit to the cooling available in the halos as they collapse.

So what happens next?

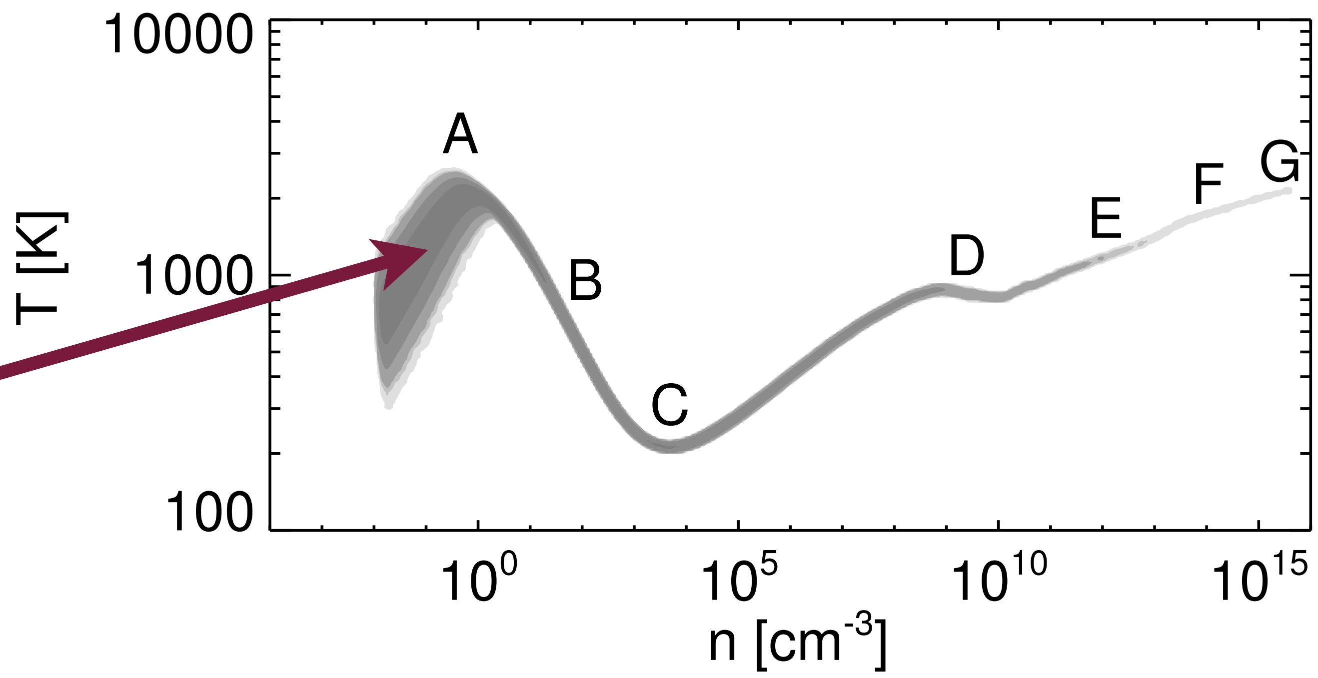
- The evolution of the temperature during the collapse is not well understood.
- Characterised by several key stages.
- Different H_2 physics (formation/heating/cooling) controls each stage.

Yoshida et al. (2006)

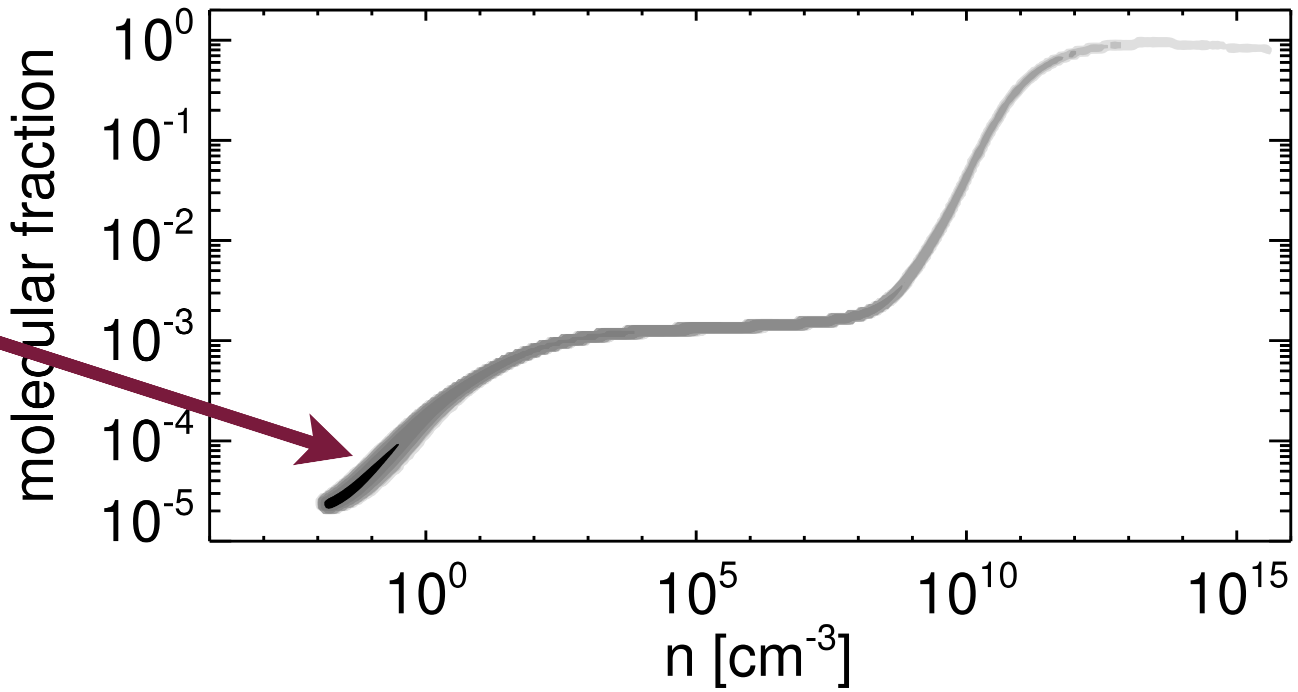


What's happening at each of these stages?

Yoshida et al. (2006)



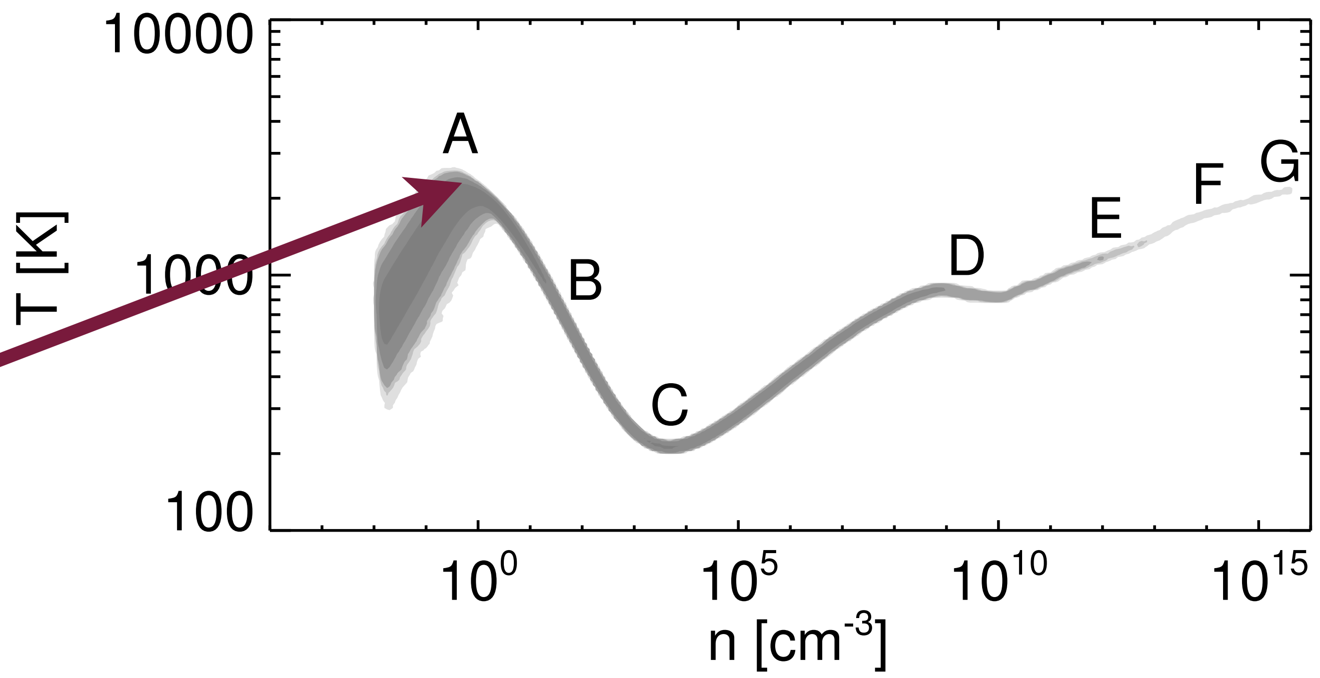
Gas falls into minihalo and shock heats to virial temperature



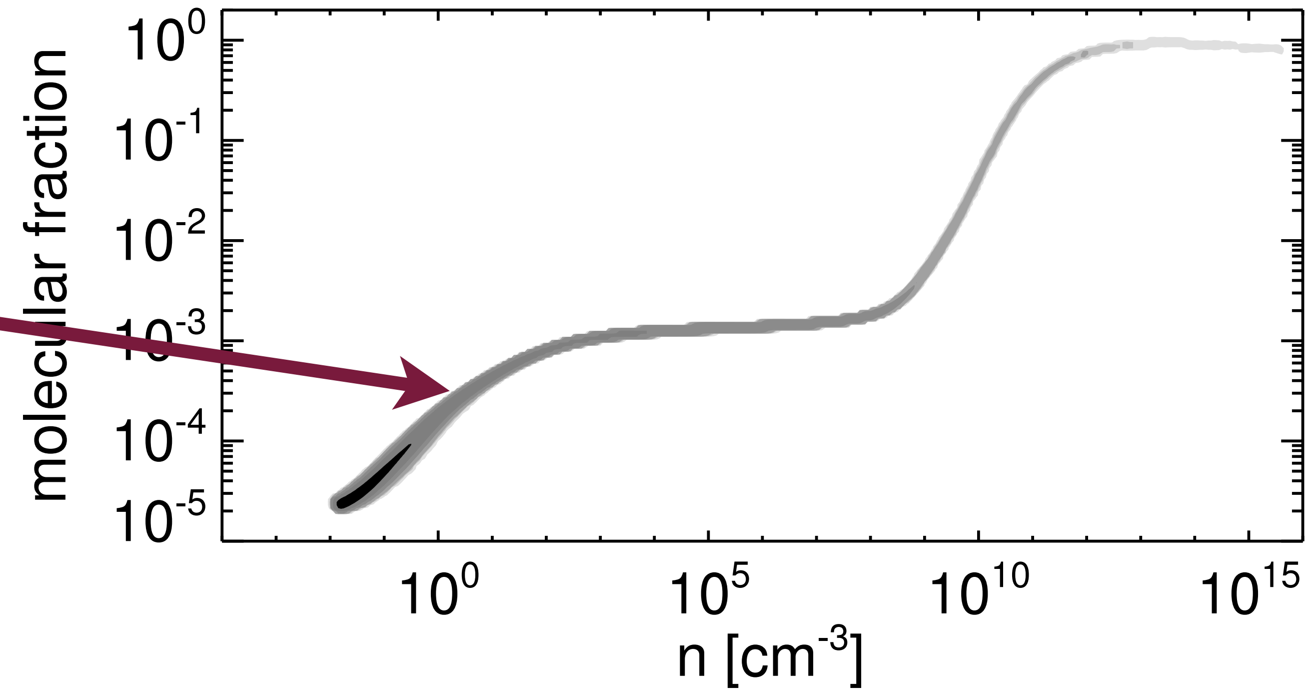
H_2 formation is enhanced by the temperature increase

What's happening at each of these stages?

Yoshida et al. (2006)



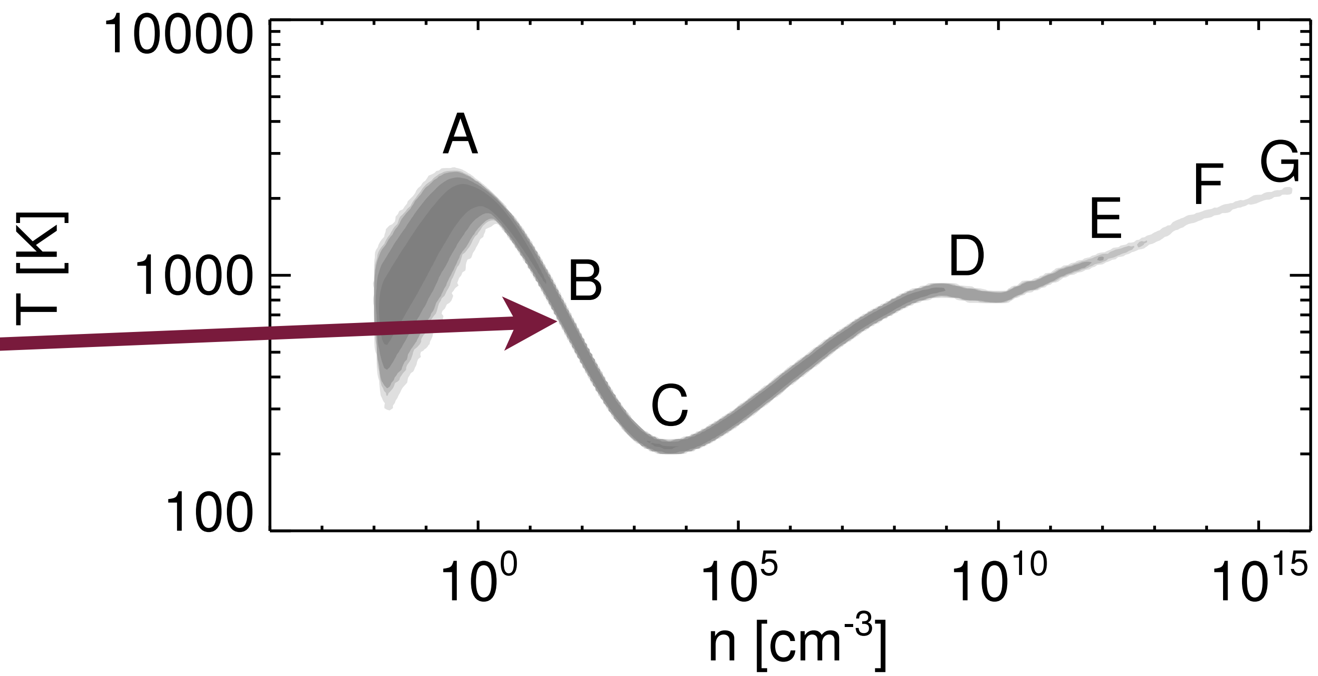
H_2 cooling counteracts the heating, and gas starts to cool down



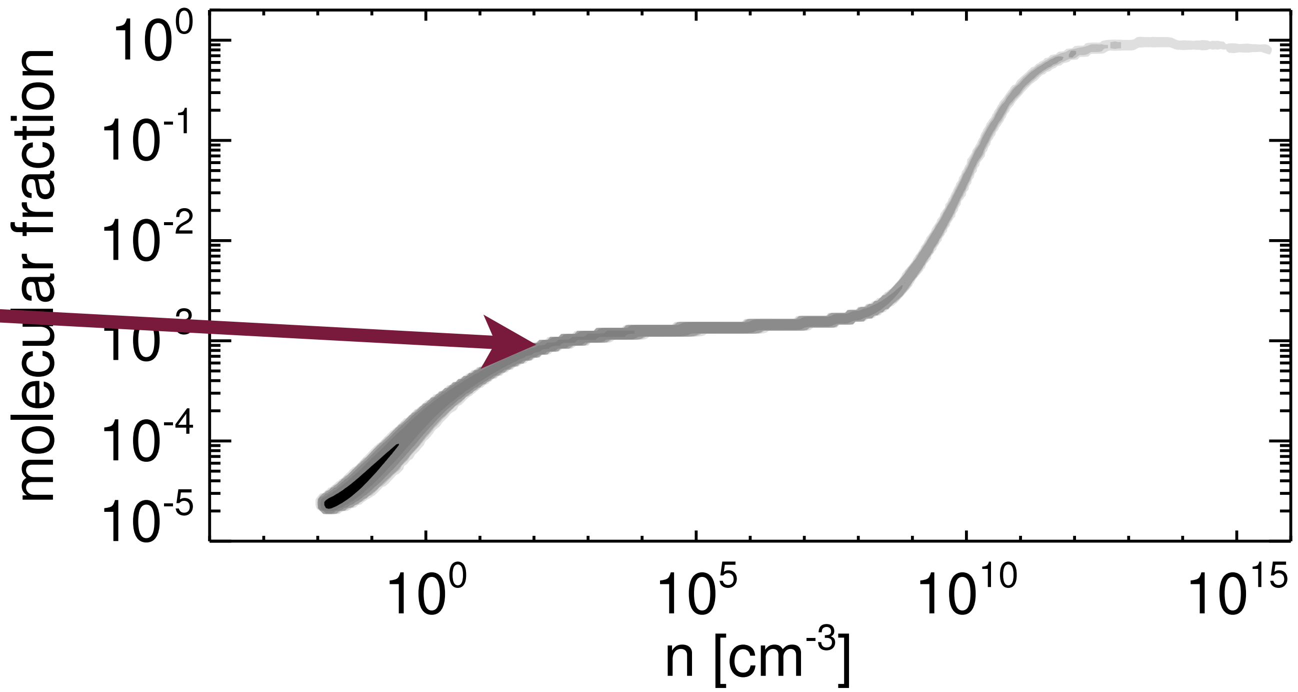
H_2 formation continues

What's happening at each of these stages?

Yoshida et al. (2006)



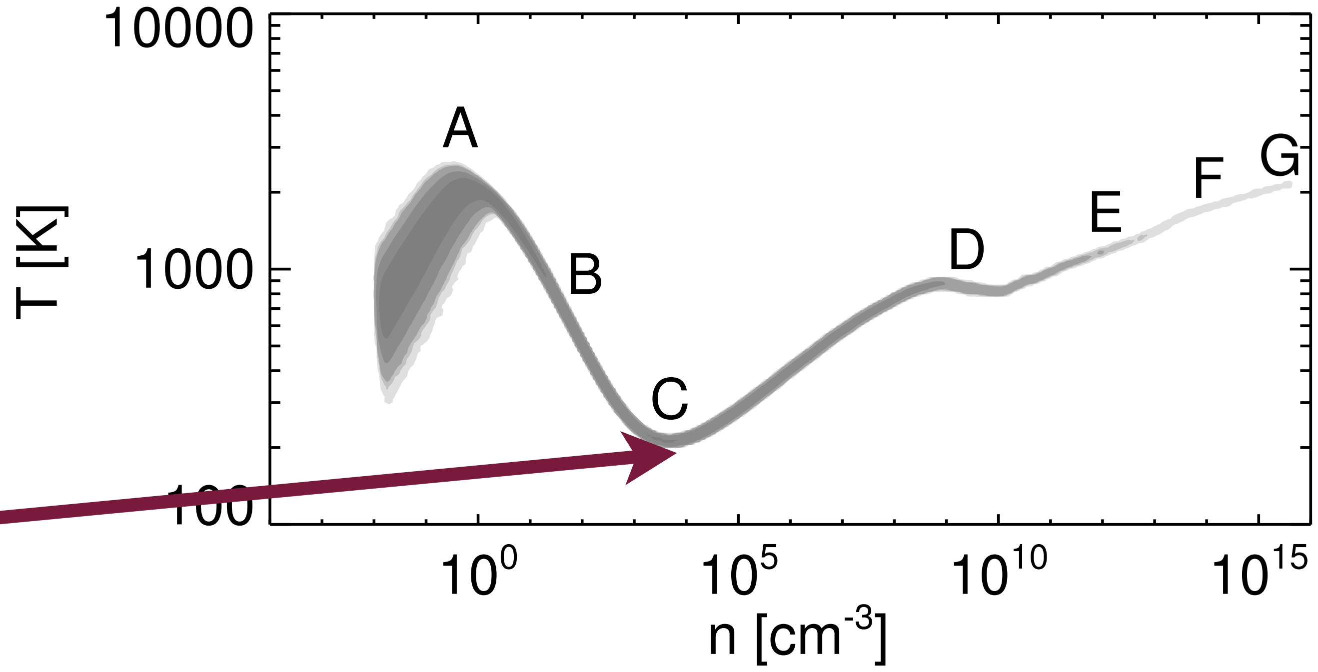
Cooling rate is faster than the heating rate (to do gravitational contraction). Density increases and T drops.



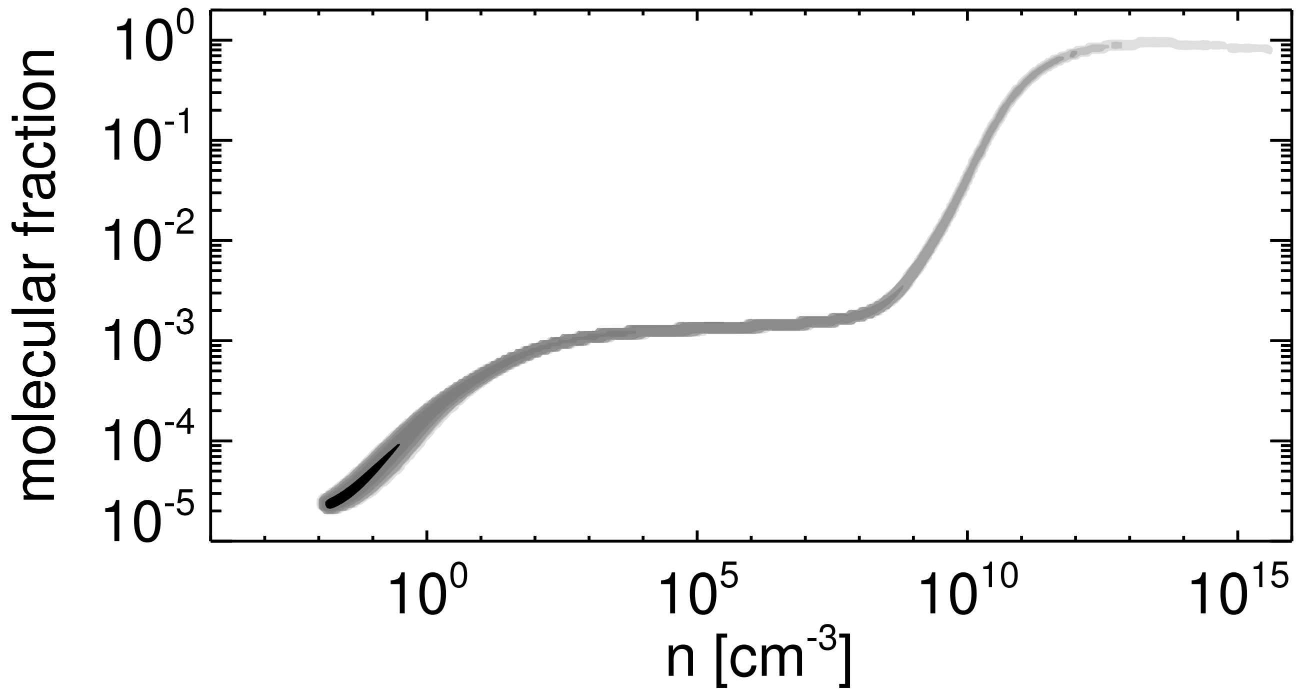
H_2 formation rate drops to around zero -- ionisation of gas is too low.

What's happening at each of these stages?

Yoshida et al. (2006)



H2 is ineffective below around 200 K!



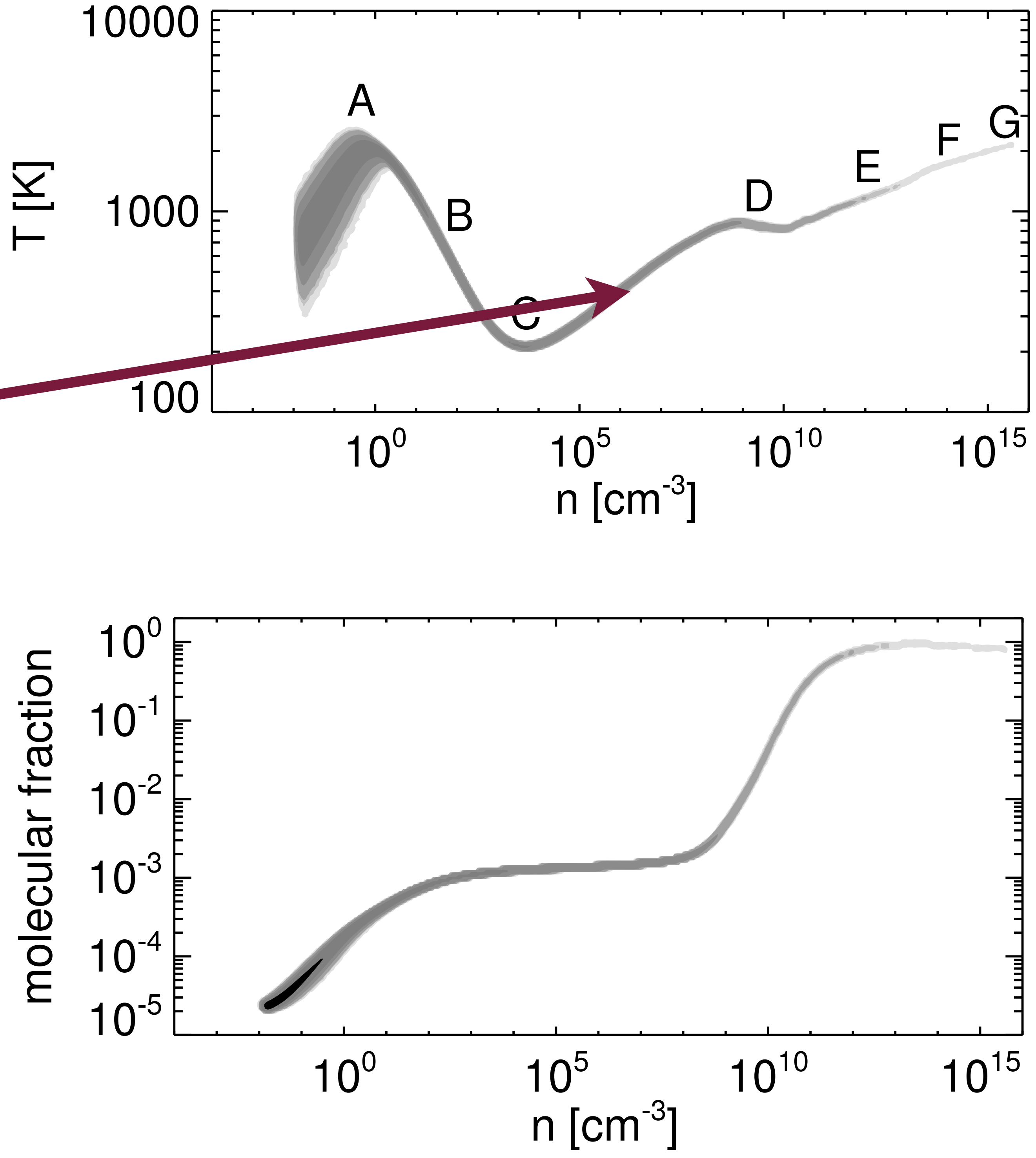
J = 2 rotational state sits at 512K

cooling rate drops as $e^{-T/512K}$

Limits minimum T to around few 100 K

What’s happening at each of these stages?

Yoshida et al. (2006)

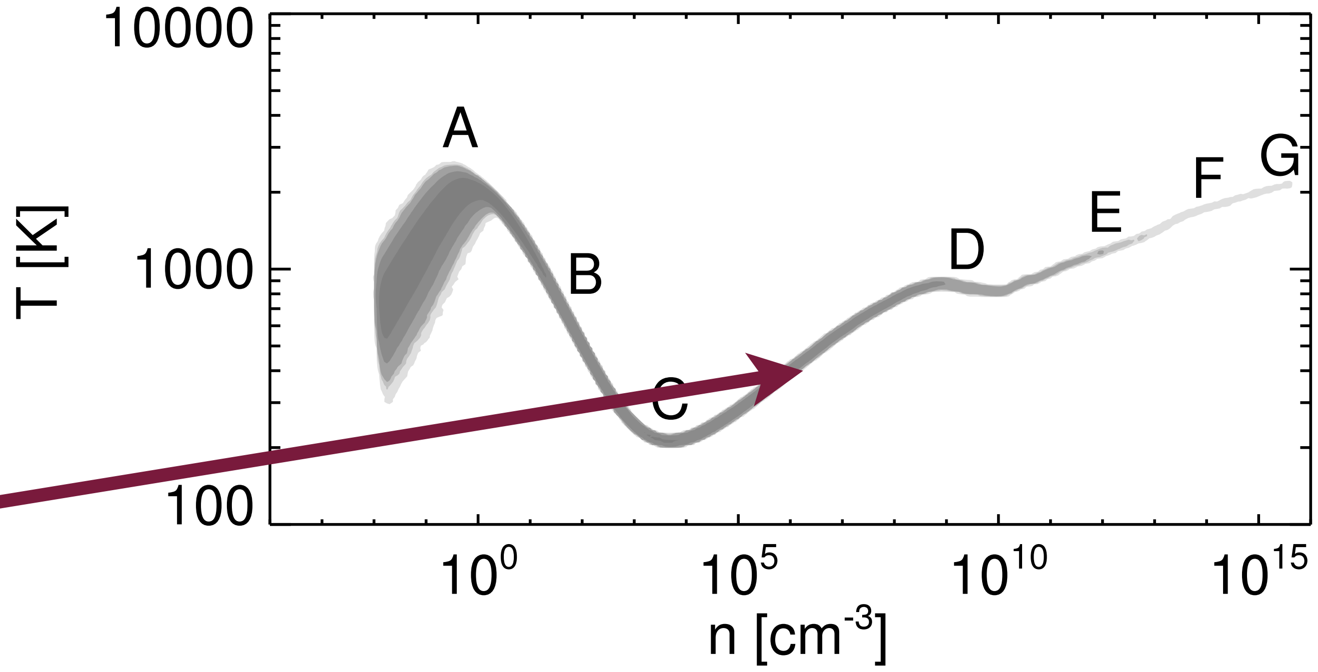


H2 reaches its critical density, and levels go into LTE

Cooling goes as n, rather than n^2

What's happening at each of these stages?

Yoshida et al. (2006)



H2 reaches its critical density, and levels go into LTE

Cooling goes as n, rather than n^2

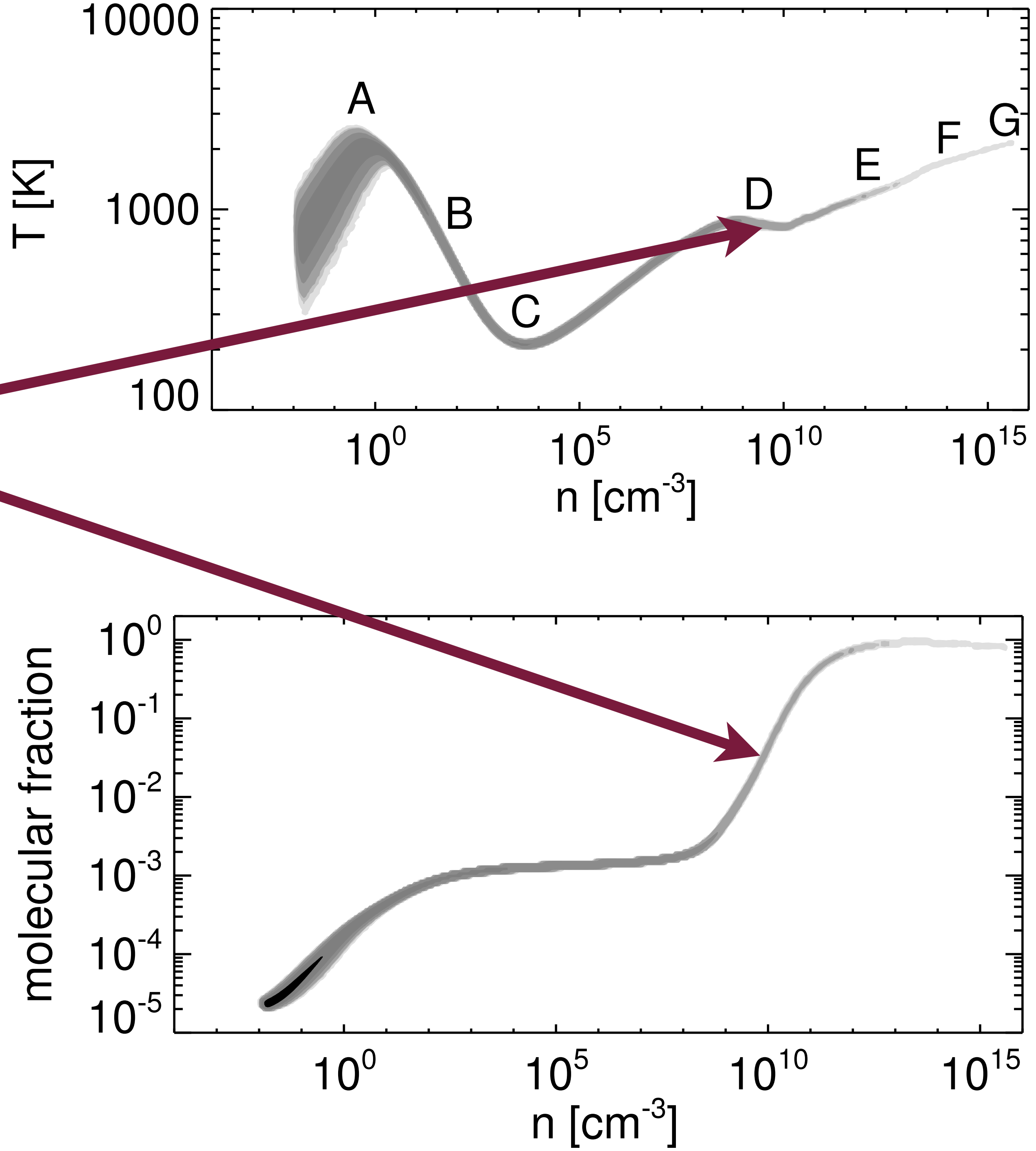
Compressional heating from gravitational collapse

$$\frac{\mathrm{d}e}{\mathrm{d}t} = \frac{kT}{\mu m_{\mathrm{p}}} \left[\frac{32\mathrm{G}}{3\pi} \right]^{1/2} \rho^{3/2} - \Lambda_V + \Gamma_V$$

Gas has to heat up as it collapses

What's happening at each of these stages?

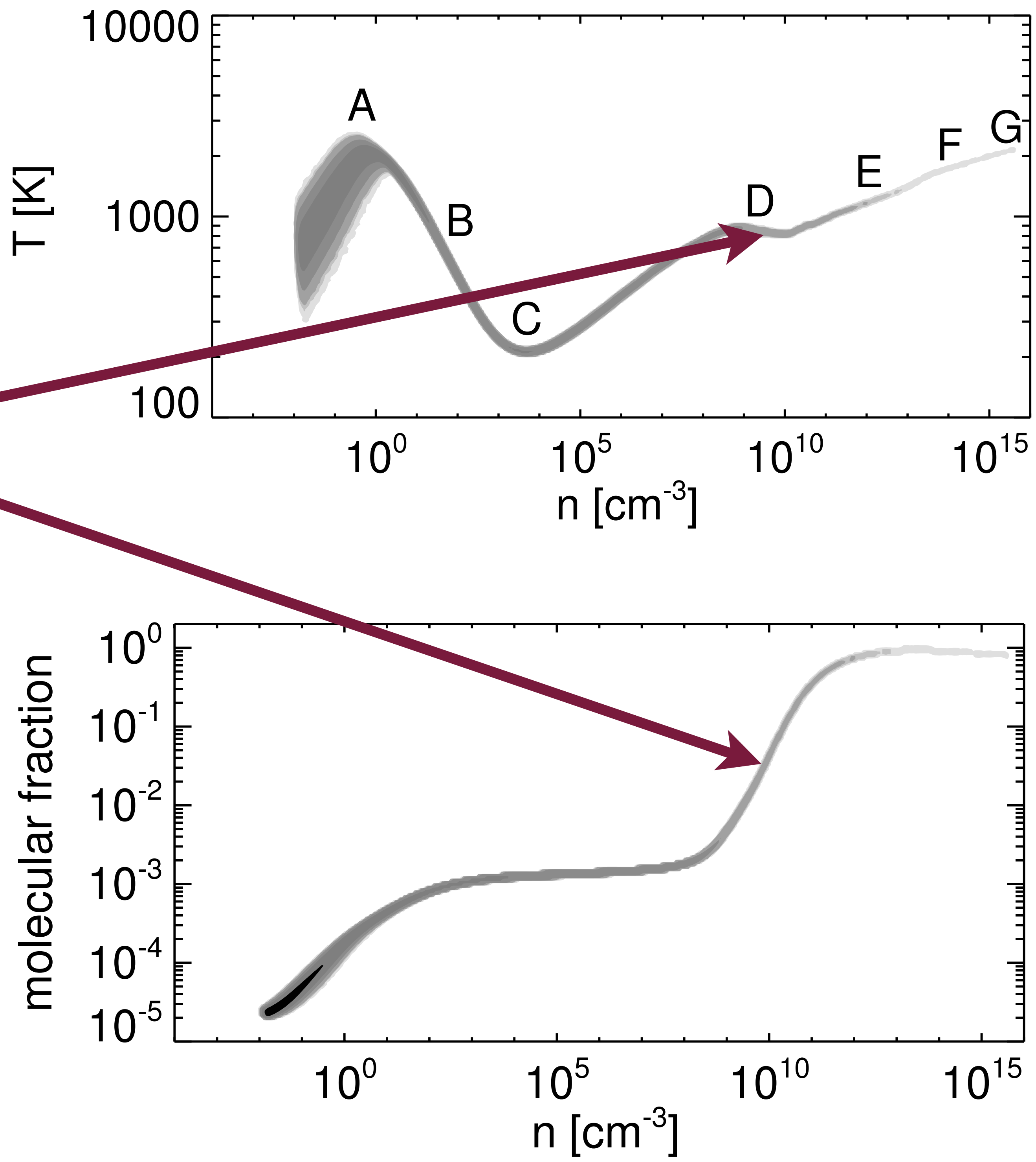
Yoshida et al. (2006)



Rapid rise in the H2 fraction due to 3-body reactions. Results in cooling once H_2 fraction is high

H_2 becomes optically thick!

Yoshida et al. (2006)



Rapid rise in the H2 fraction due to 3-body reactions. Results in cooling once H_2 fraction is high

The 3-body formation regime

- Two path ways:

$$H + H + H \rightarrow H_2 + H$$

$$H_2 + H + H \rightarrow H_2 + H_2$$

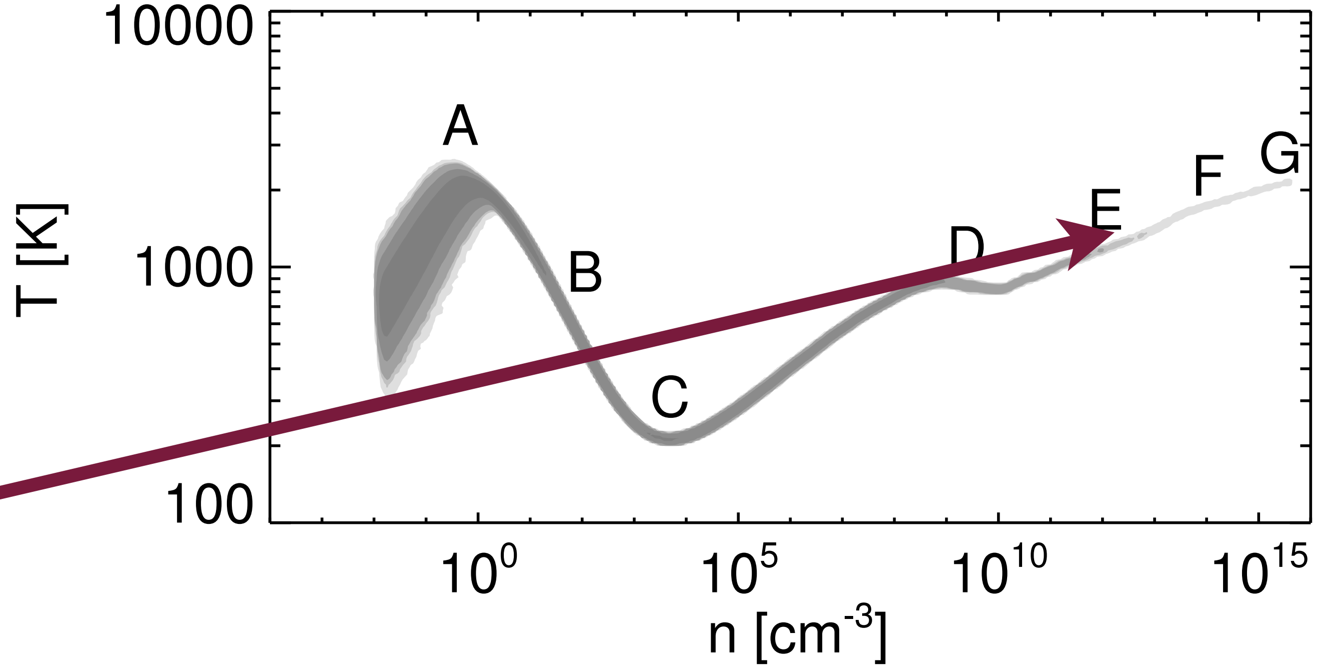
- Consider the first. Using the rate from Glover (2008):

$$\frac{\mathrm{d}n_{\mathrm{H}_2}}{\mathrm{d}t} = k_{3\mathrm{b}} n_{\mathrm{H}}^3 \qquad k_{3\mathrm{b}} = 7.7 \times 10^{-31} T^{-0.464}\ \mathrm{cm}^6\ \mathrm{s}^{-1}$$

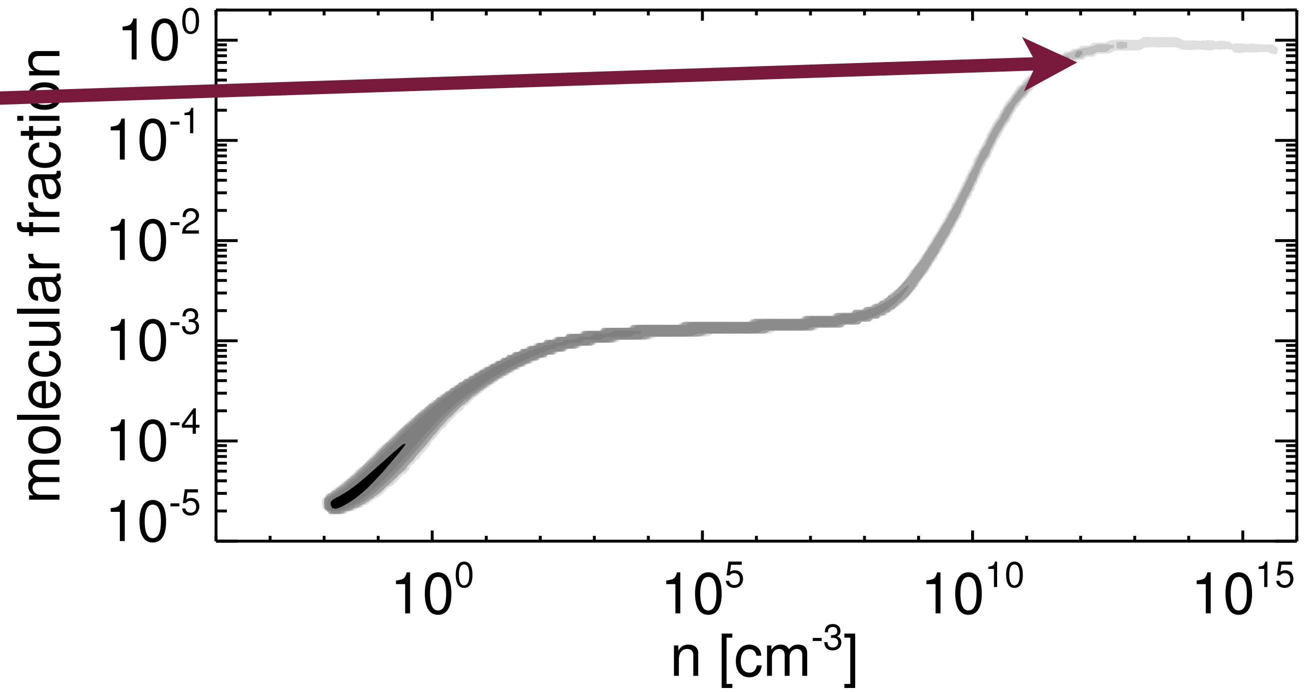
$$\Gamma_{3\mathrm{b}} = 4.4\,\mathrm{eV}\,\frac{\mathrm{d}n_{\mathrm{H}_2}}{\mathrm{d}t} \qquad t_{\mathrm{H}_2} \sim \frac{n_{\mathrm{H}_2}}{k_{3\mathrm{b}} n_{\mathrm{H}}^3}$$

H_2 becomes optically thick!

Yoshida et al. (2006)



H2 cooling becomes optically thick.

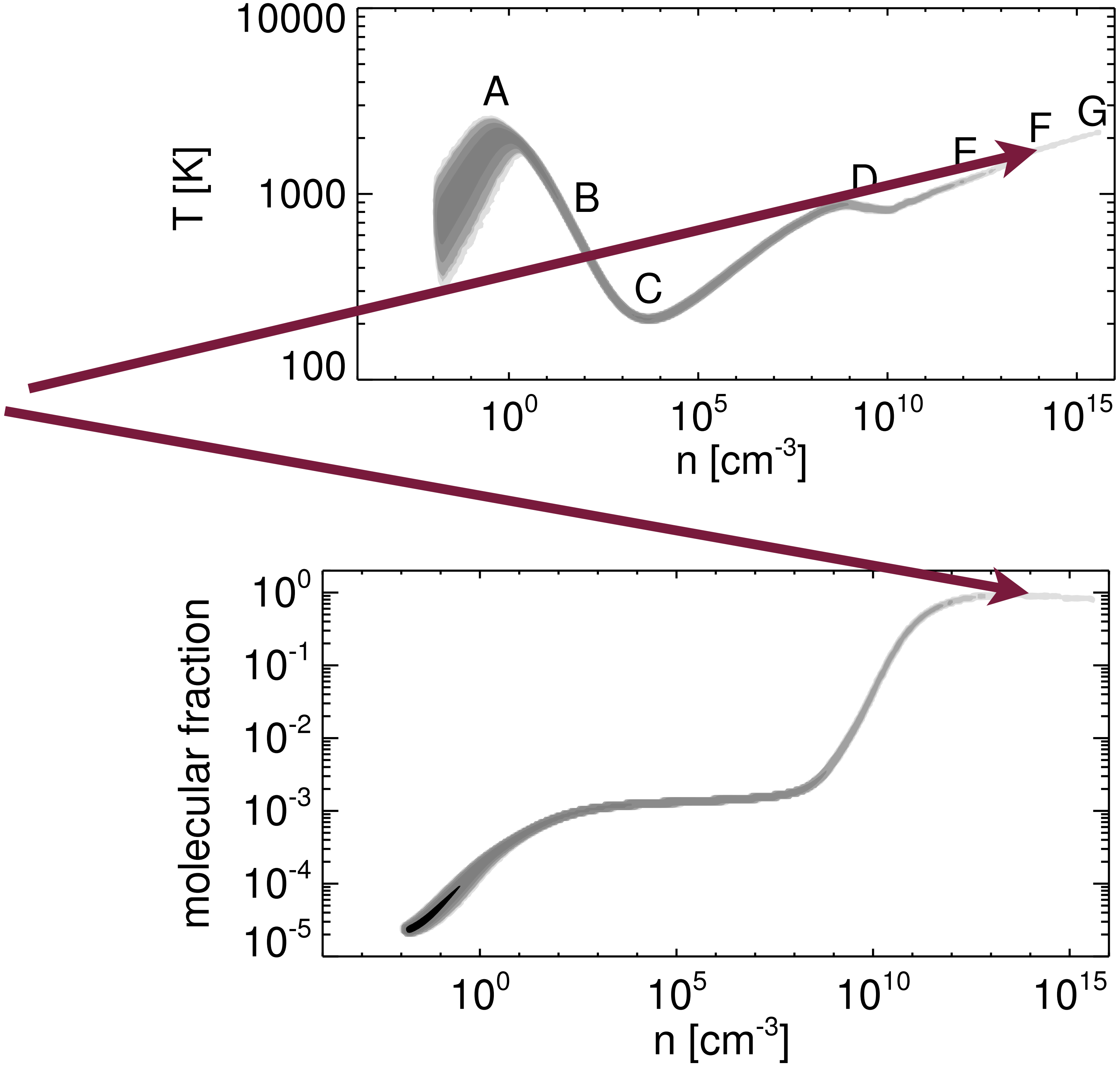


Reason: n_{H2} is very high!

H_2 becomes optically thick!

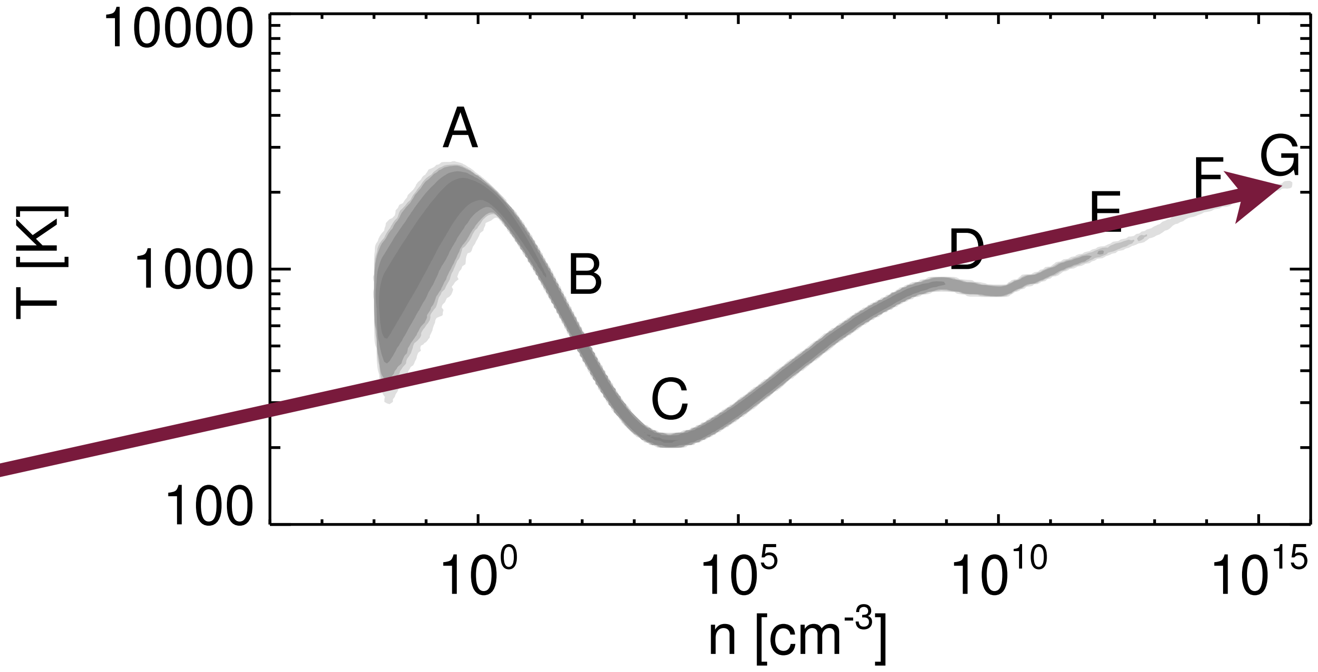
Yoshida et al. (2006)

Collision induced emission (CIE) cooling takes over



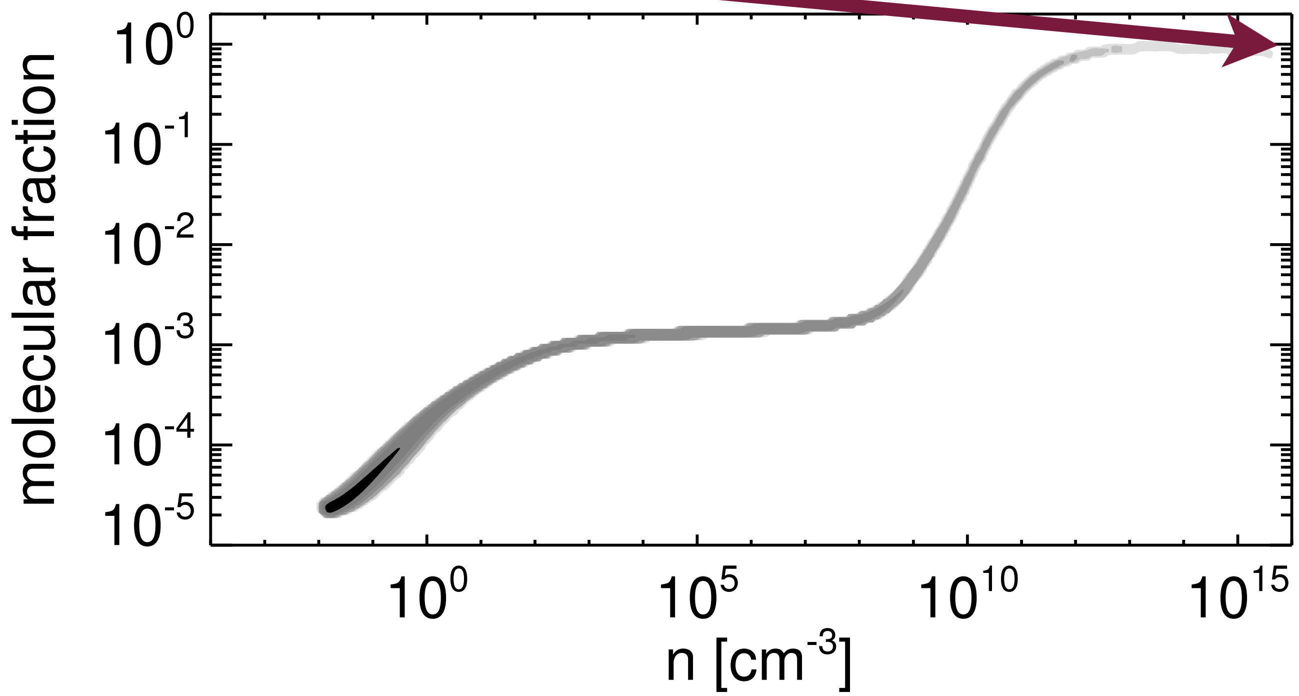
H_2 becomes optically thick!

Yoshida et al. (2006)



CIE cooling becomes optically thick

Gas cools via collisional dissociation (recover 4.4eV per molecule)



Different path to Pop III?

HD cooling:

- Formed and destroyed via the reactions,

$$H_2 + D^+ \rightarrow HD + H^+$$ (exothermic)

$$HD + H^+ \rightarrow H_2 + D^+$$ (endothermic)

- Below 462K, reaction 1 is favoured over reaction 2.
- Results in chemical fractionation

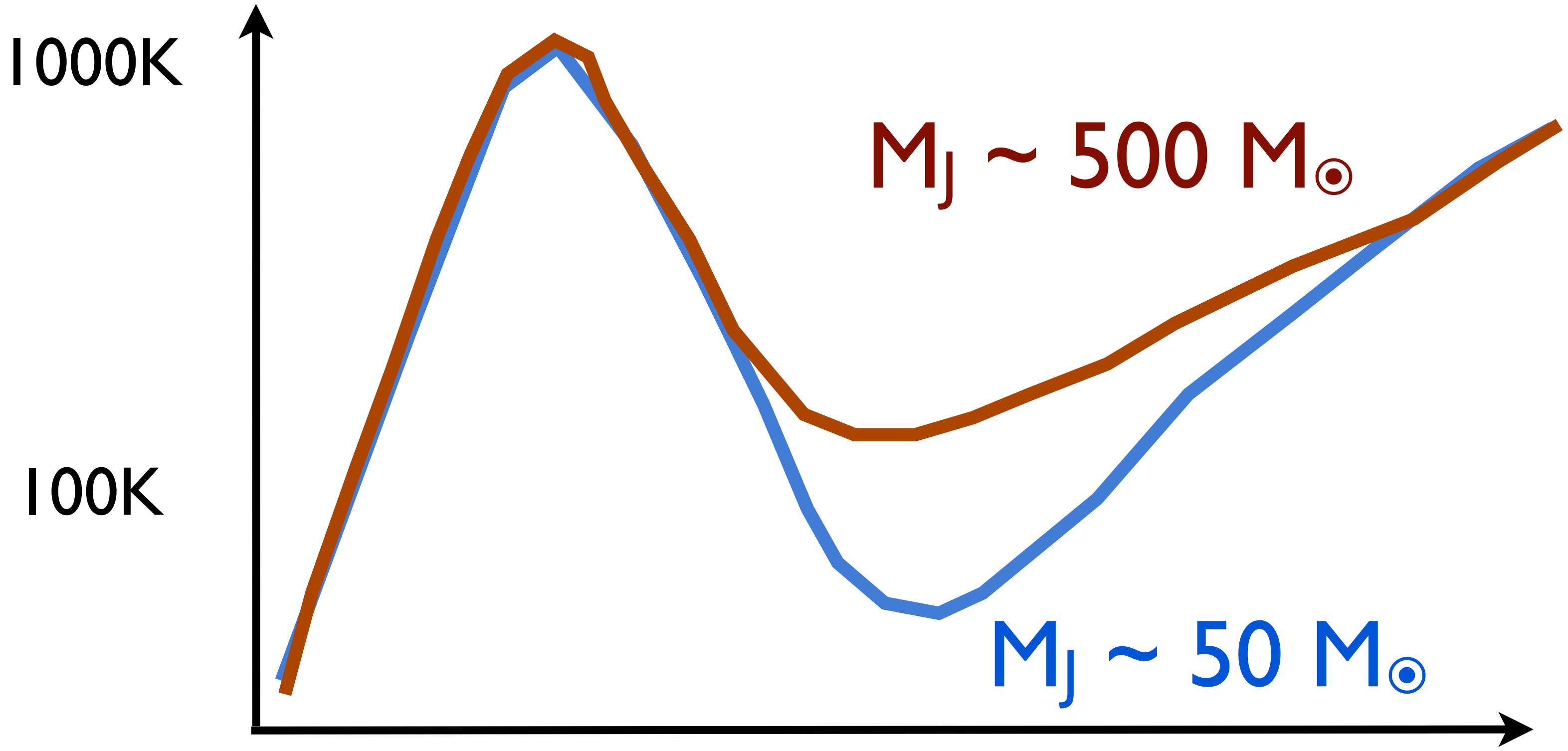
$$\frac{x_{\mathrm{HD}}}{x_{\mathrm{H_2}}} > \frac{x_{\mathrm{D}}}{x_{\mathrm{H}}} \qquad (x_{\mathrm{D}} = 2.6 \times 10^{-5})$$

Different path to Pop III?

HD cooling:

- HD can cool the gas down to the CMB temperature,

$$T_{\rm CMB} = 2.728\,{\rm K}\,(1+z)$$

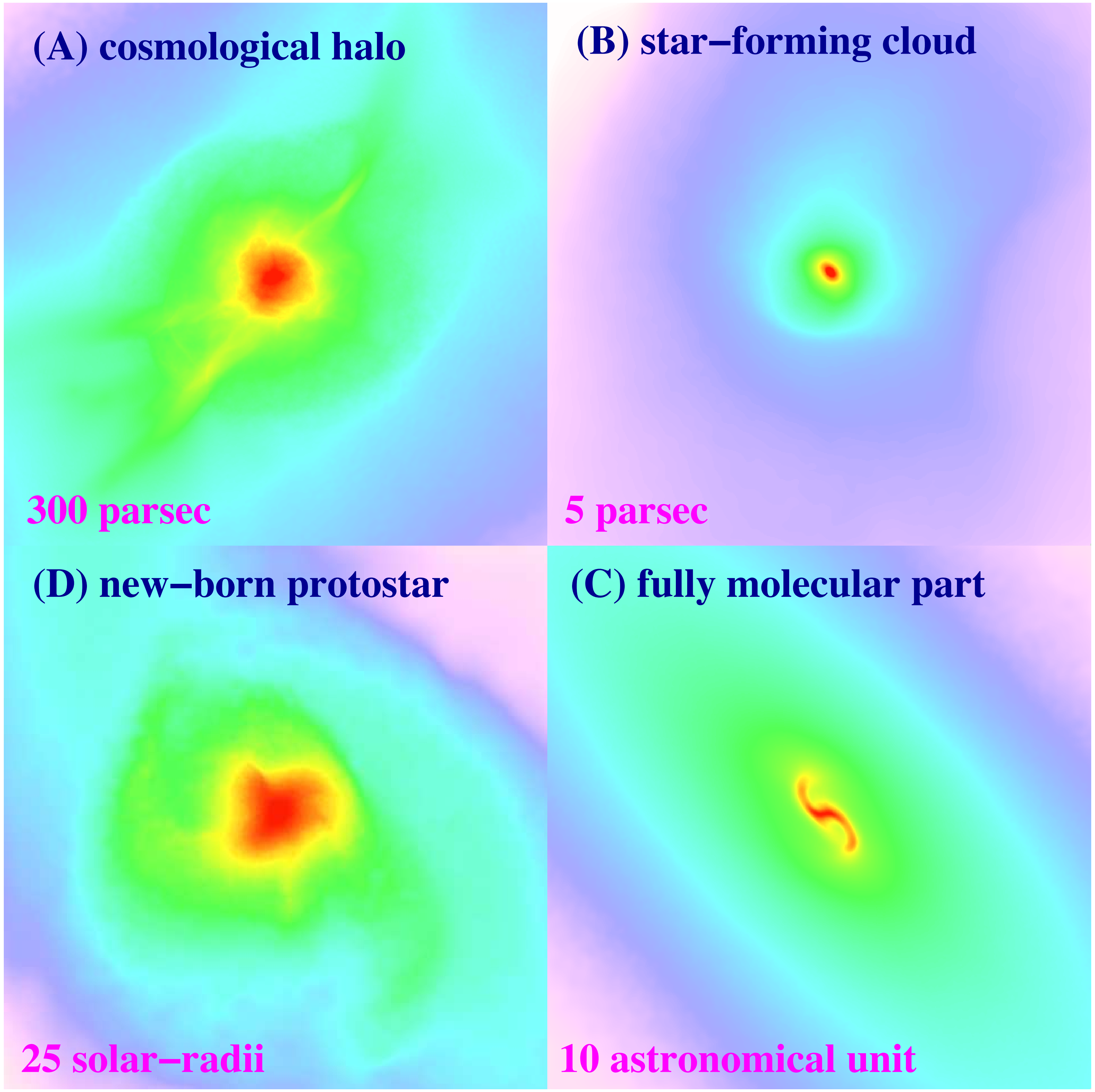


Different path to Pop III?

How to excite the HD cooling channel?

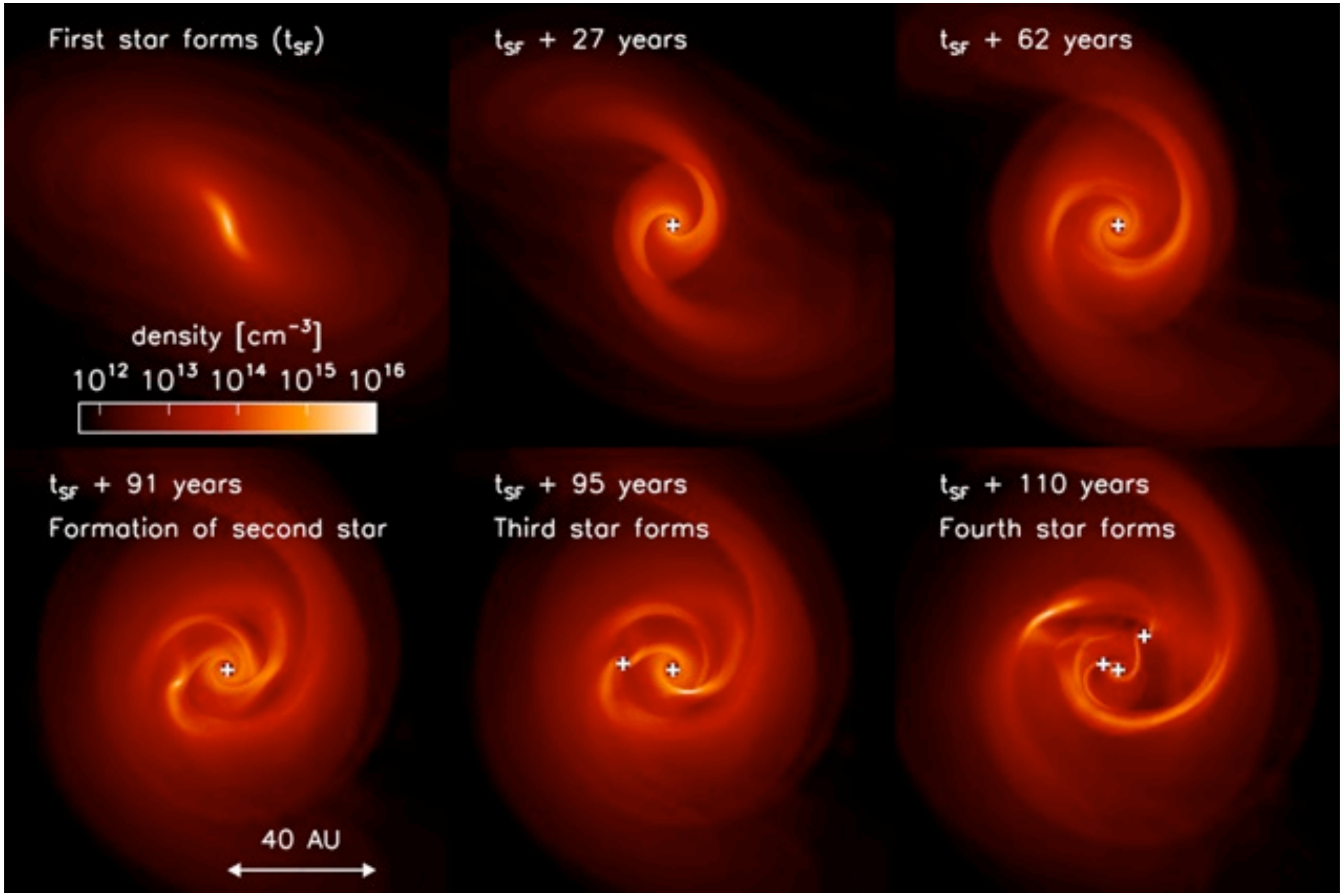
- Recall that the H2 fraction depends on the ionisation fraction in the minihalo.
- Halos with higher ionisation fractions can form more H2, and cool to slightly lower temperatures.
- Can then produce the HD fractionation, and the HD cooling.
- Can be triggered by nearby star formation or via collisional ionisation is slightly more massive halos.

What happens next?



Yoshida, Omukai, Hernquist (2008)

What happens at high densities?

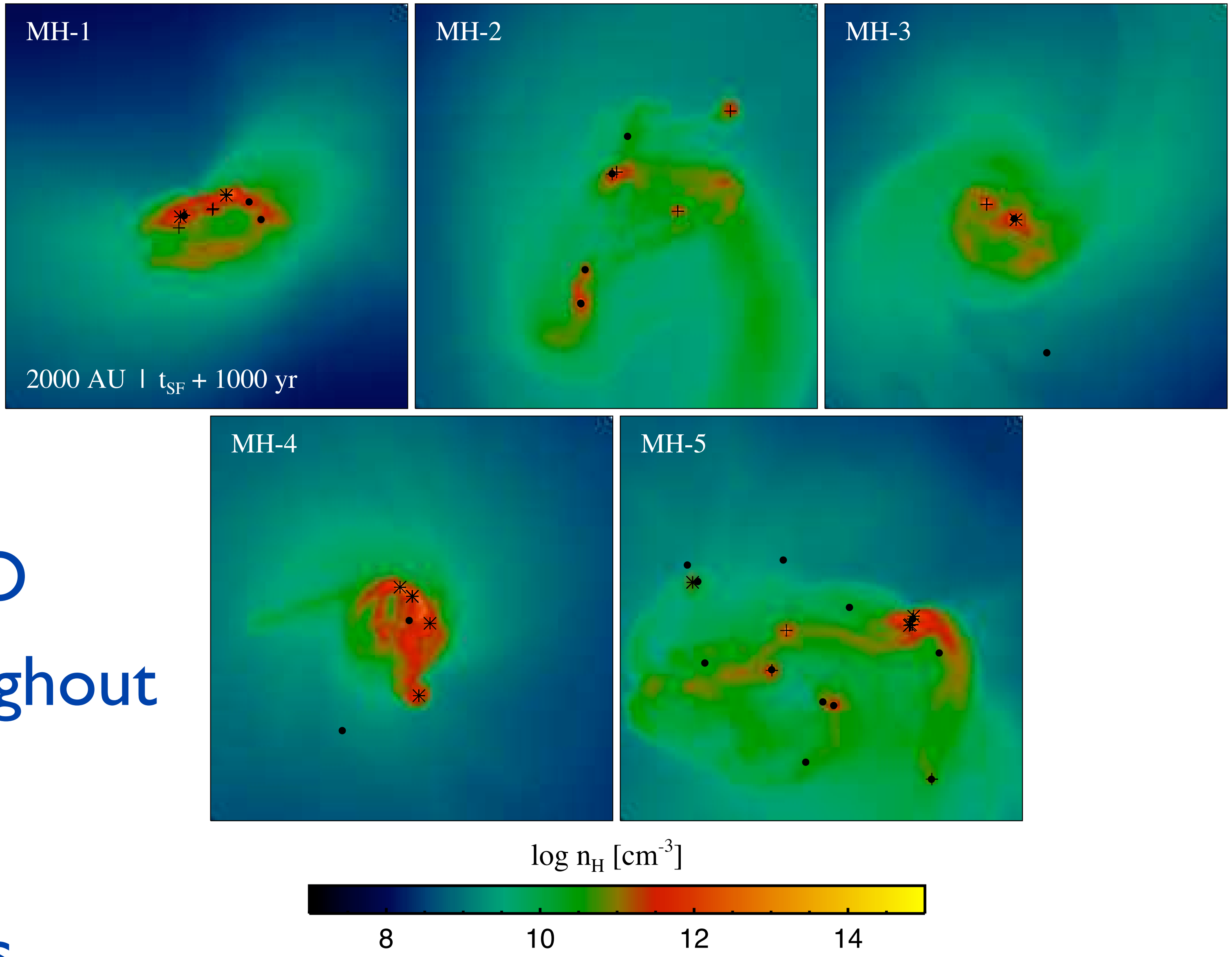


Clark et al. (2011b)

- Disc builds up which fragments to form a small N system
- Central protostar mass ~ 0.5 $M_\odot$
- Fragmentation timescale ~ 100 yr

Complimentary study

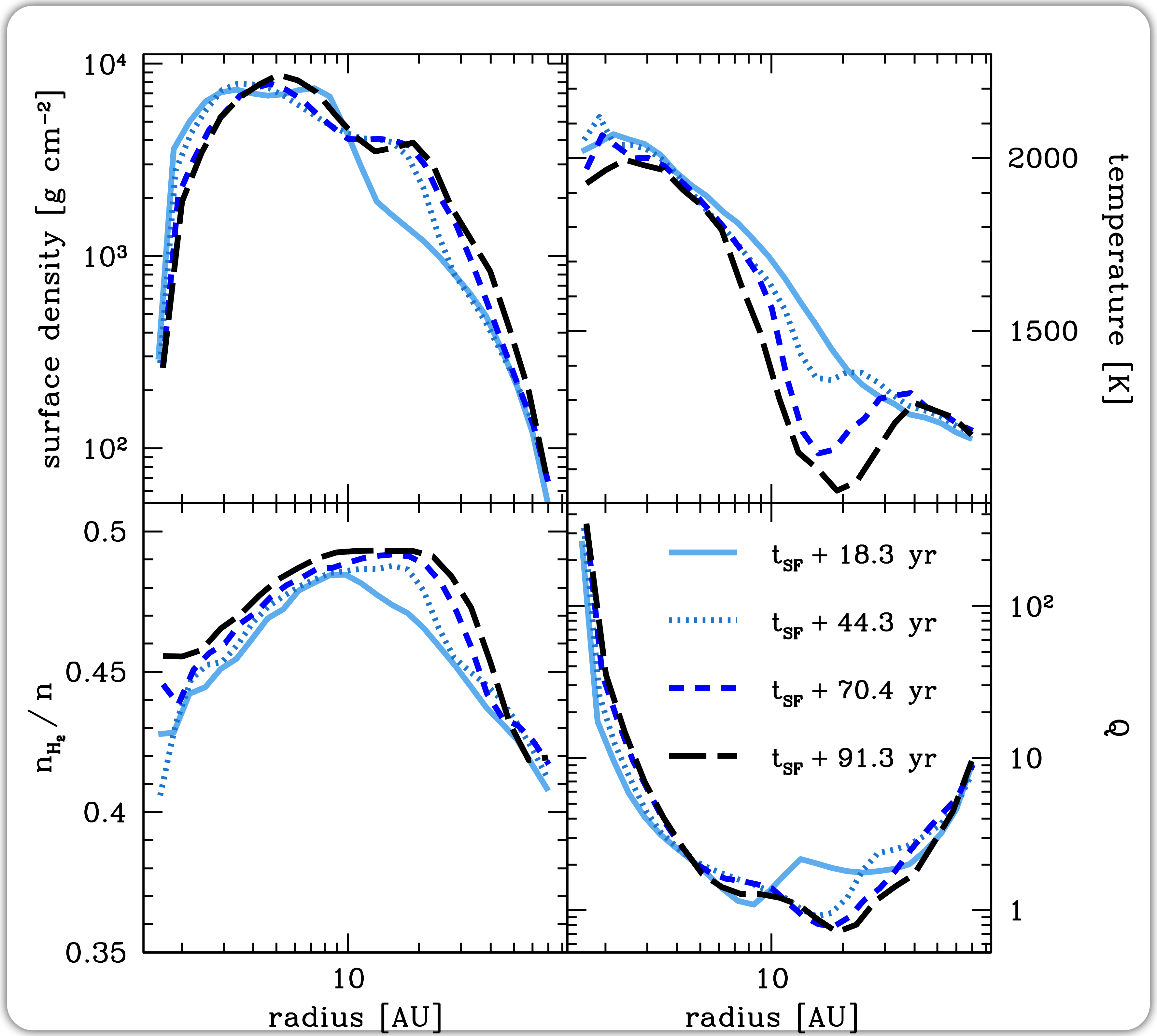
Always good to use a different code!



- Greif et al. 2011 used AREPO
- Had higher resolution throughout collapse.
- Better able to resolve the turbulence in the infalling gas.
- Same basic picture, but much more messy.

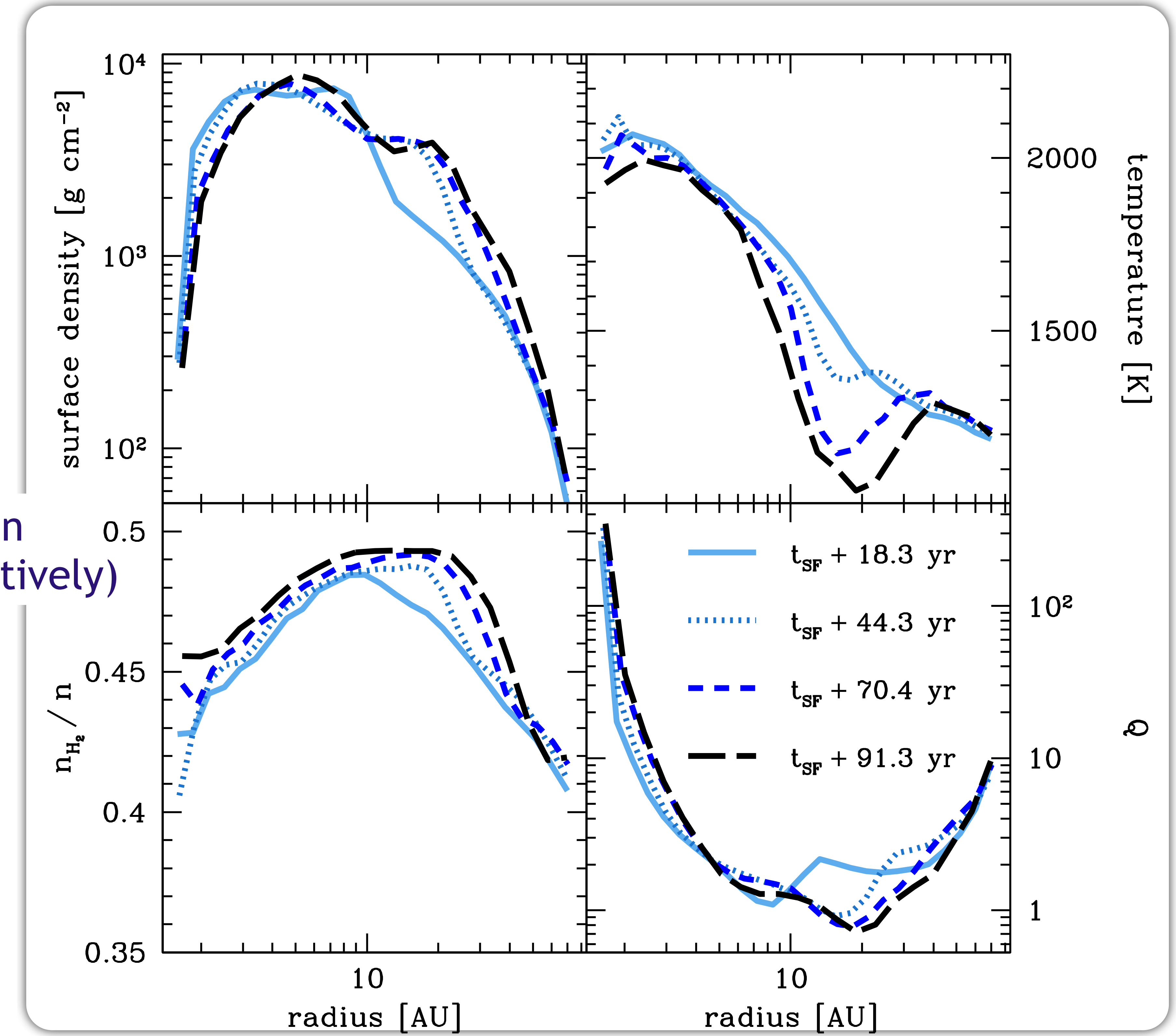
Greif et al. (2011) + Smith et al. (2011)

Why does the gas fragment?



Clark et al. (2011b)

Why does the gas fragment?

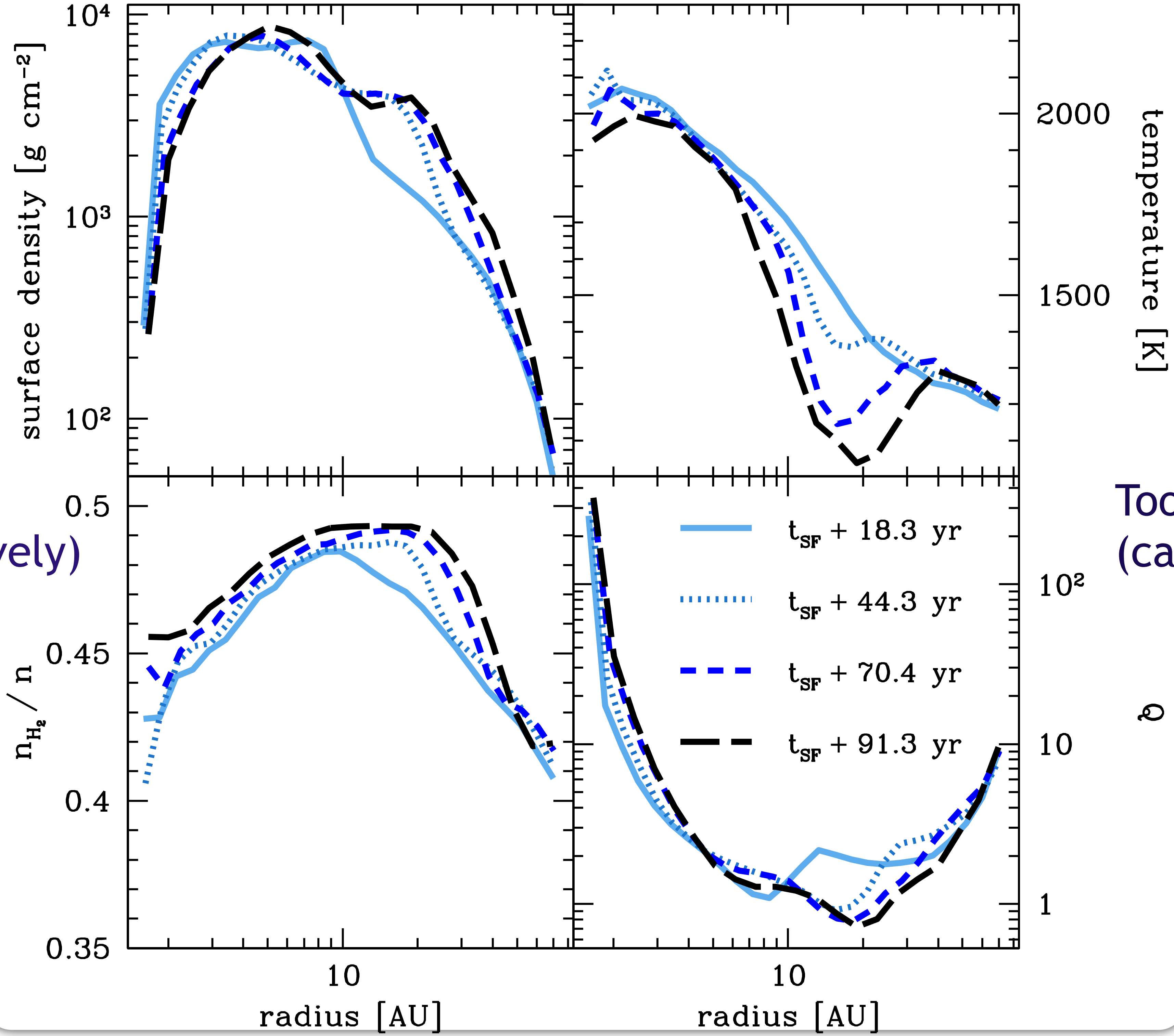


High H2 fraction
(can cool effectively)

Clark et al. (2011b)

Why does the gas fragment?

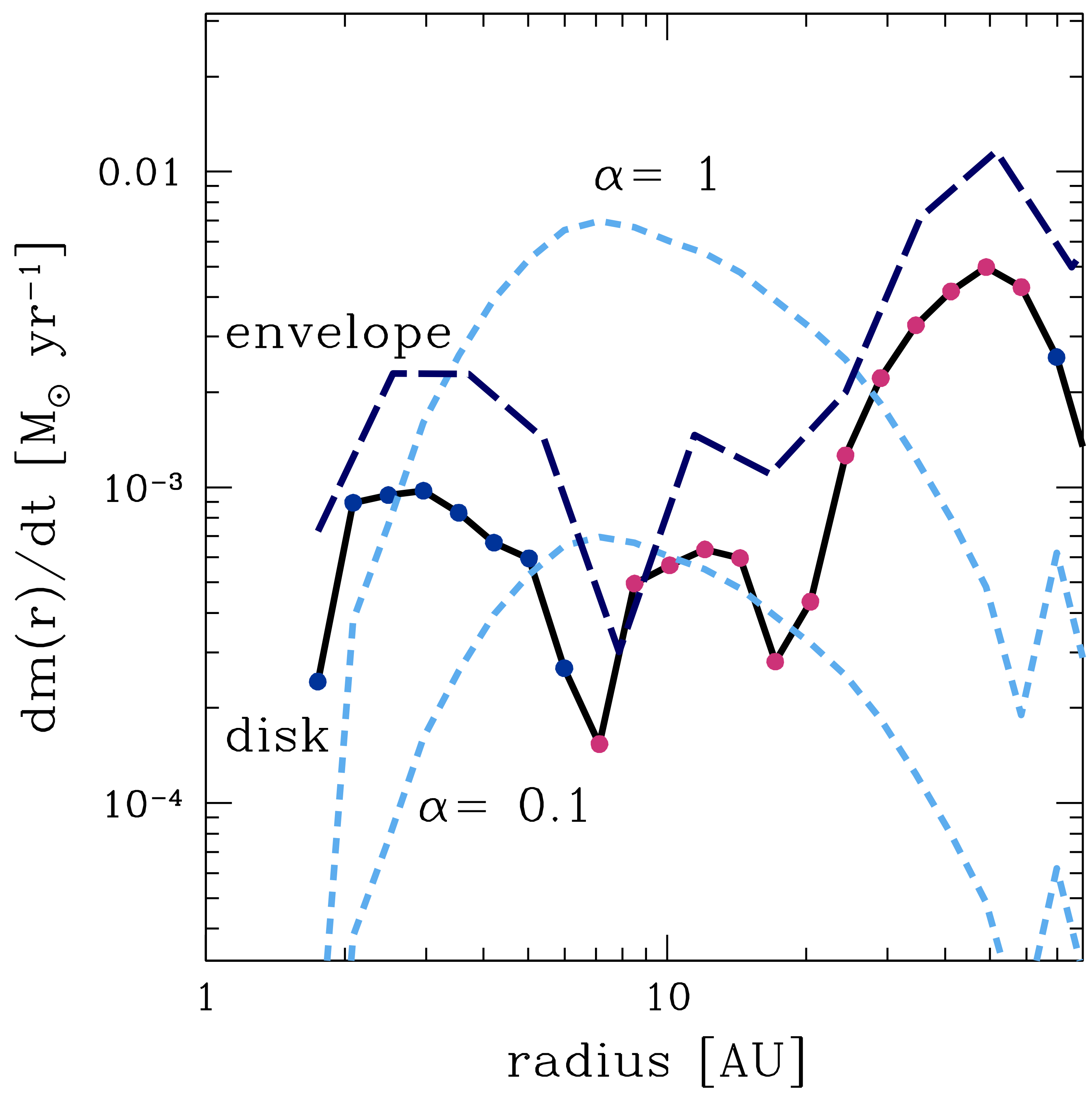
High H2 fraction
(can cool effectively)



Toomré unstable
(can fragment)

Clark et al. (2011b)

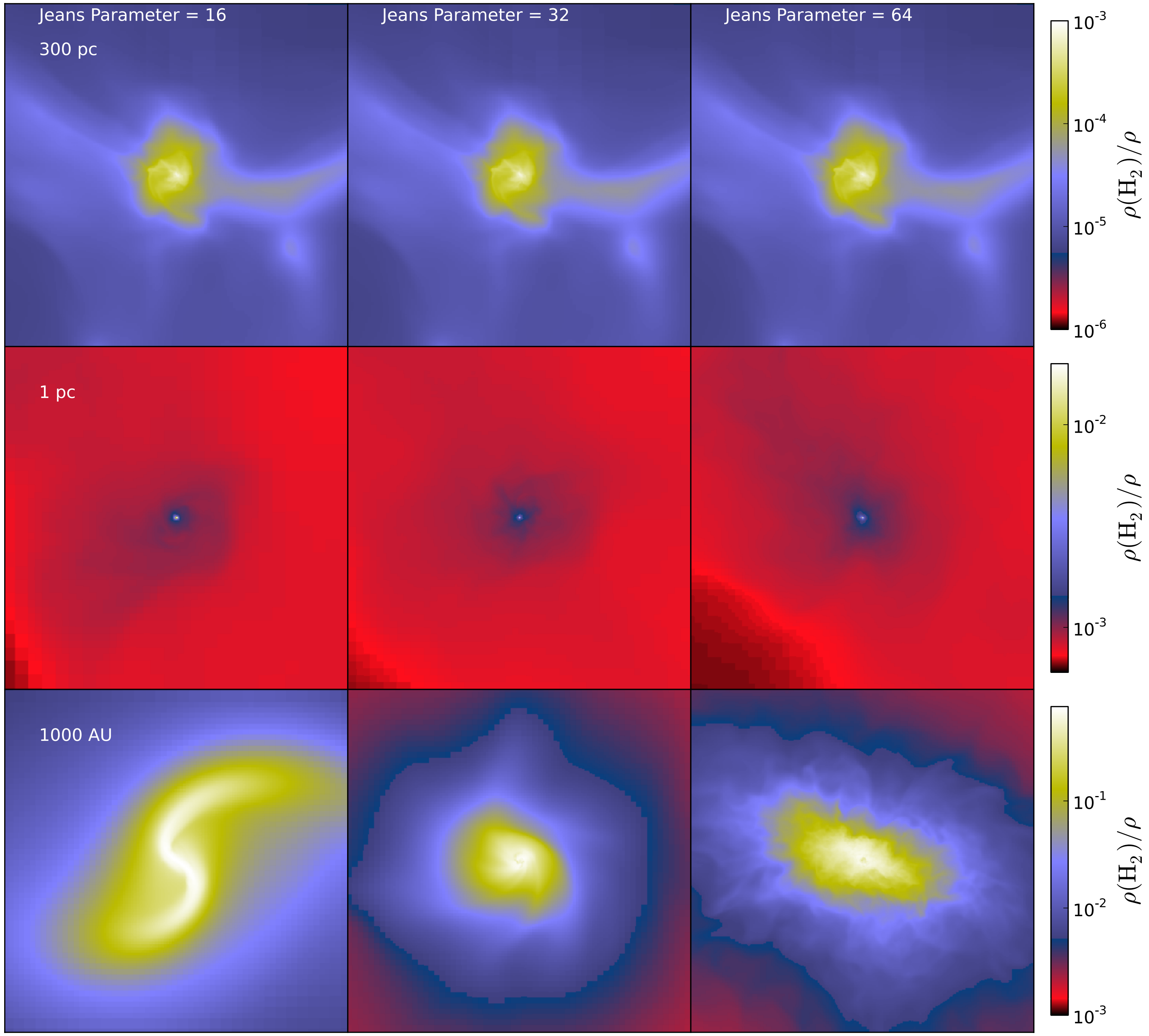
Why does the gas fragment?



Clark et al. (2011b)

Problems with convergence?

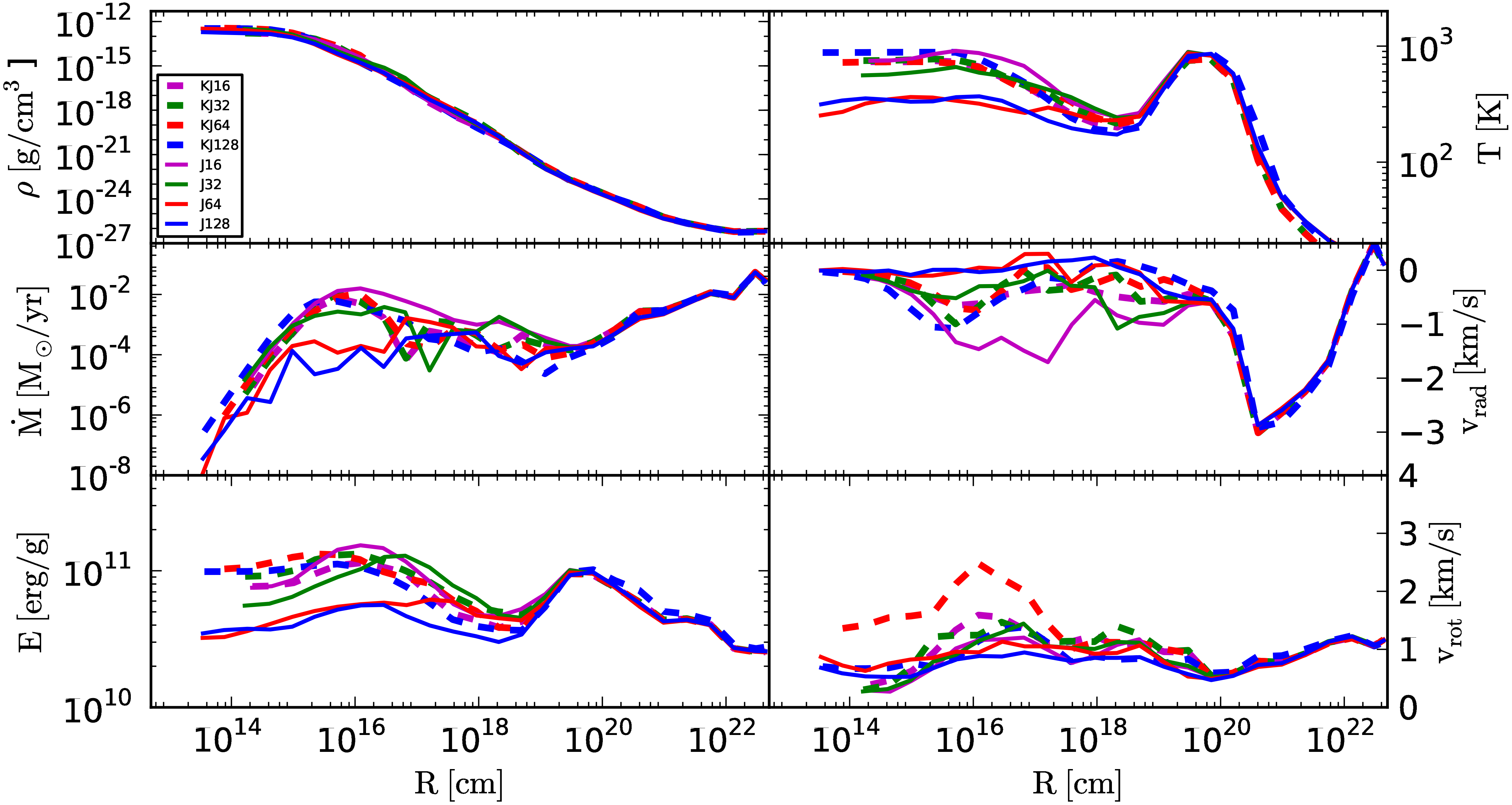
- Should we form a large, gravitationally unstable disc?



Turk et al. (2012)

Problems with convergence

- Need to be careful of how the chemistry/cooling is solved!

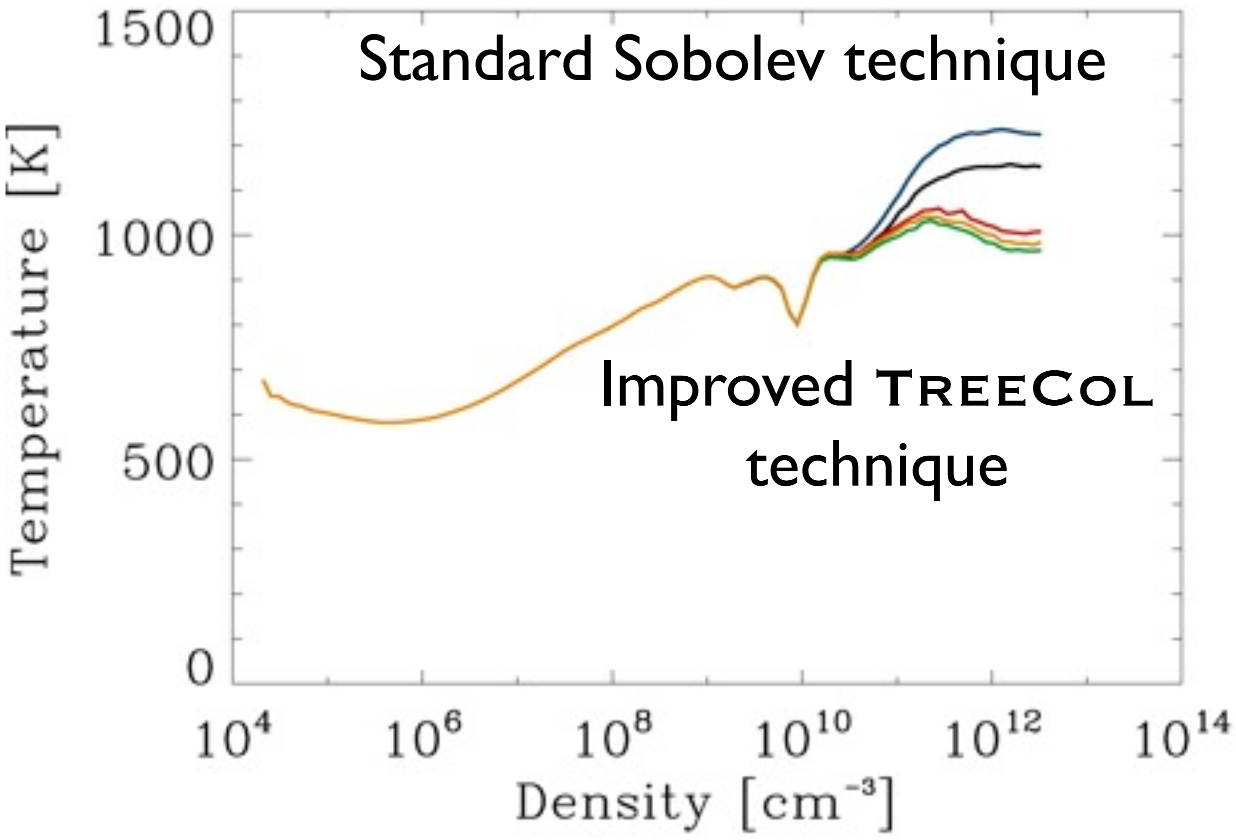


Bovino et al. (2013)

Clearly H_2 line-cooling is important

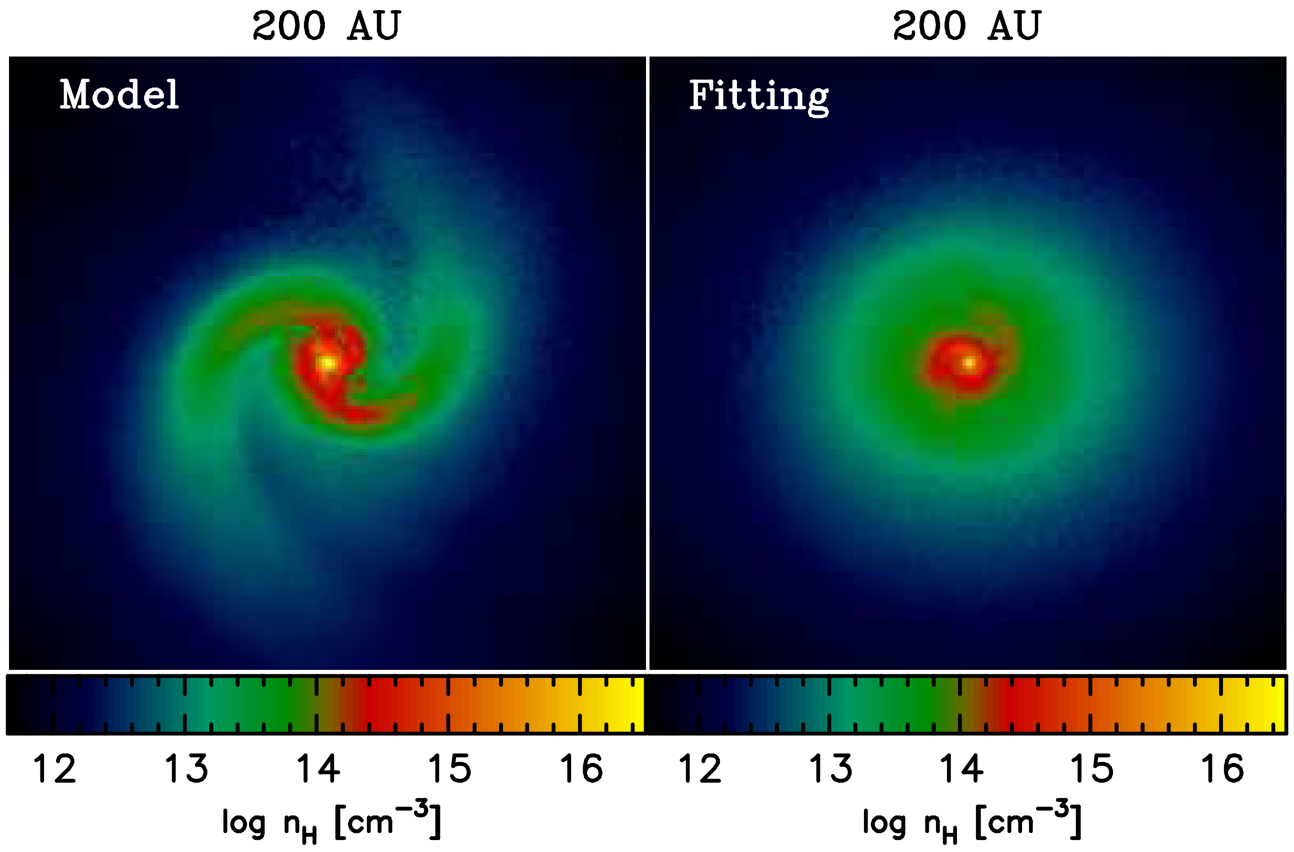
Tilman Hartwig's Masters Thesis:

- Working to improve H2 line cooling using TreeCol.
- Finds that we have been significantly underestimating the amount of cooling that occurs in the 'optically thick' regime.
- TreeCol allows us to better estimate the effective optical depth of the line.



What about CIE cooling?

- Shingo Hirano has shown the how you treat the CIE cooling can affect the cooling and dynamics.



Hirano et al. (2013)