The Stellar IMF in low metallicity gas

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Collaborators

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The Stellar Initial Mass Function

- Characterizes mass distribution of newly-formed stars
- **Not** the same as present-day mass function, as more massive stars have shorter lifetimes
- Appears to be universal; no widely accepted evidence for significant variation

- Main features:
  - Characteristic mass scale at ~ 1 $M_\odot$
  - Power law slope above this scale, with index α = 1.35 (Salpeter, 1955)
  - Possible high mass cutoff at ~ 150 $M_\odot$
- Question: does the IMF vary with metallicity?
- There's little evidence for evolution down to metallicities ~ 0.01 $Z_\odot$ (Globular clusters).

  But what about at lower Z?

Metal-free gas

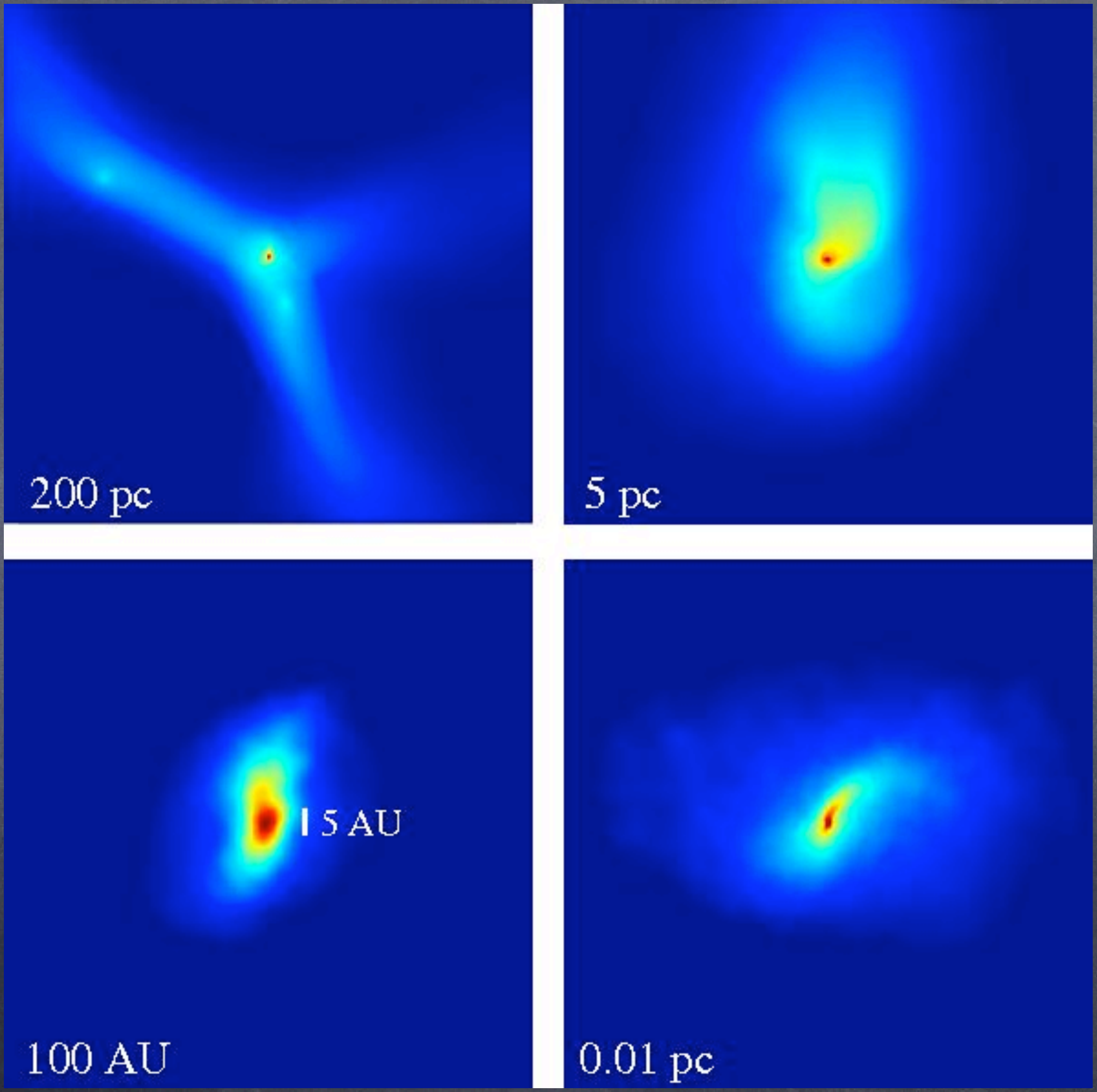
Inefficient cooling

$\Downarrow$

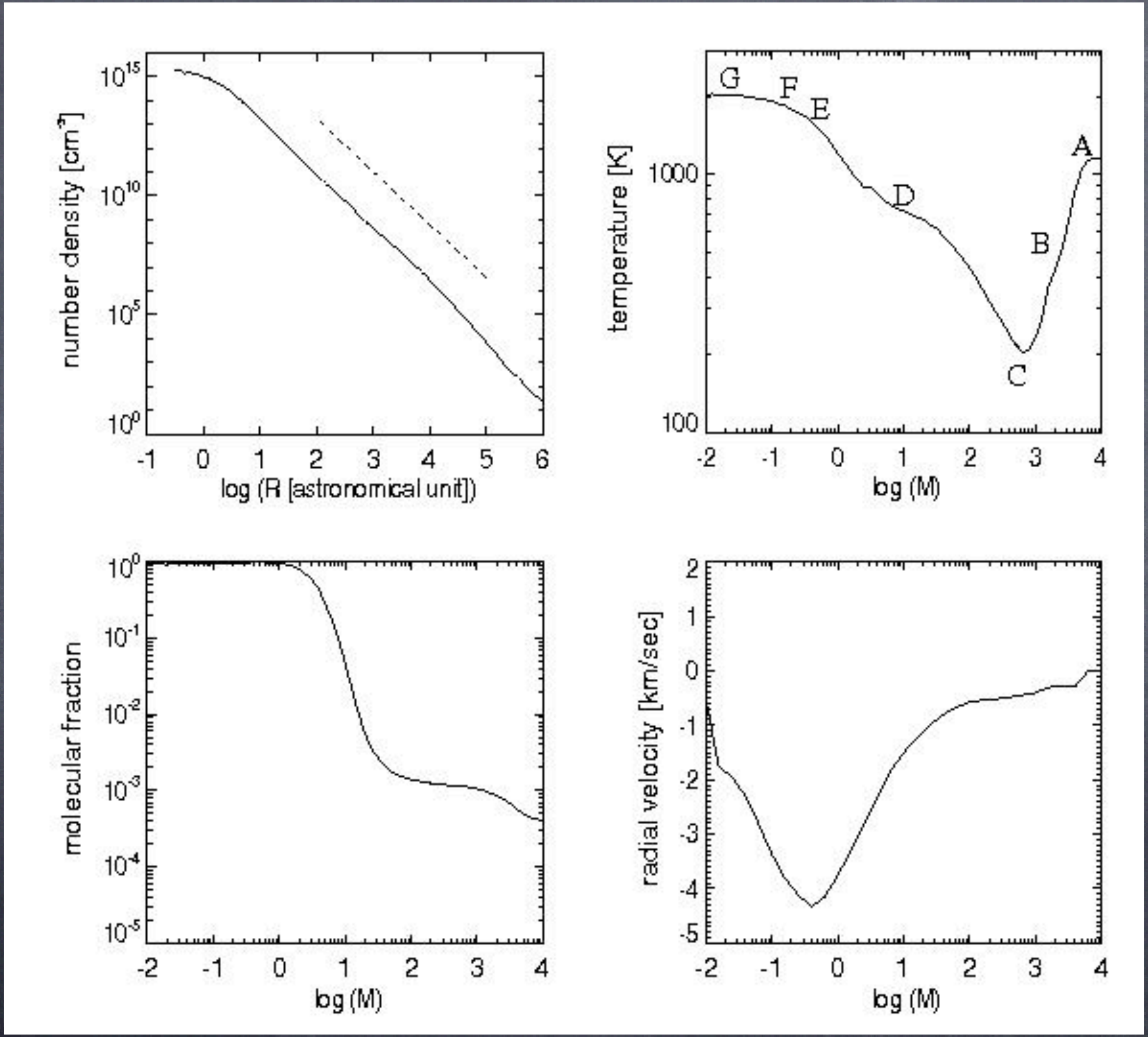
Collapse occurs on cooling timescale

$\Downarrow$

Gravitational fragmentation is ineffective



Yoshida et al, 2006



Yoshida et al, 2006

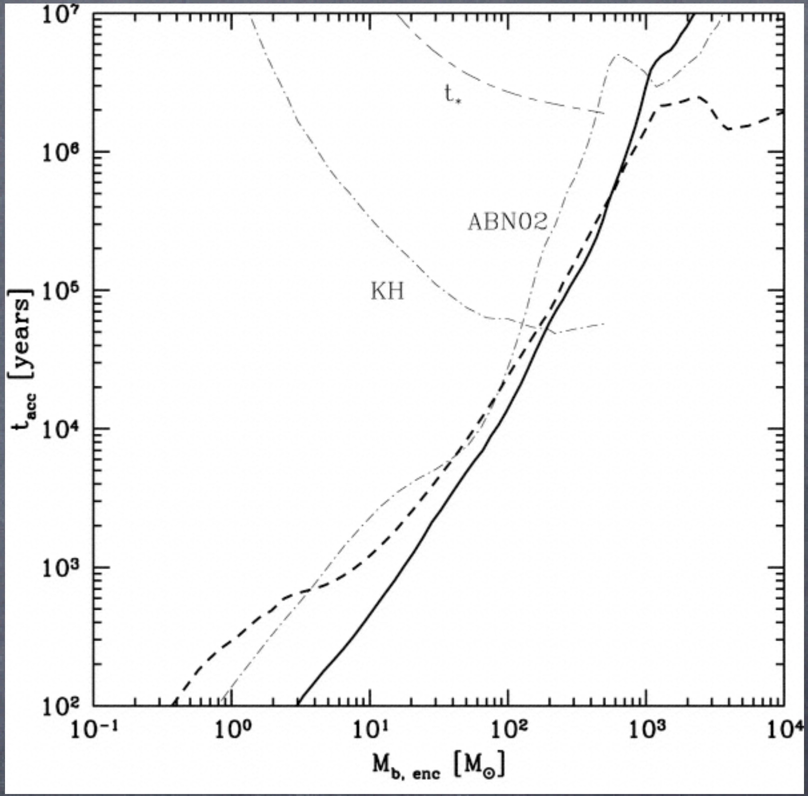
High temperature

⇓

High accretion rate

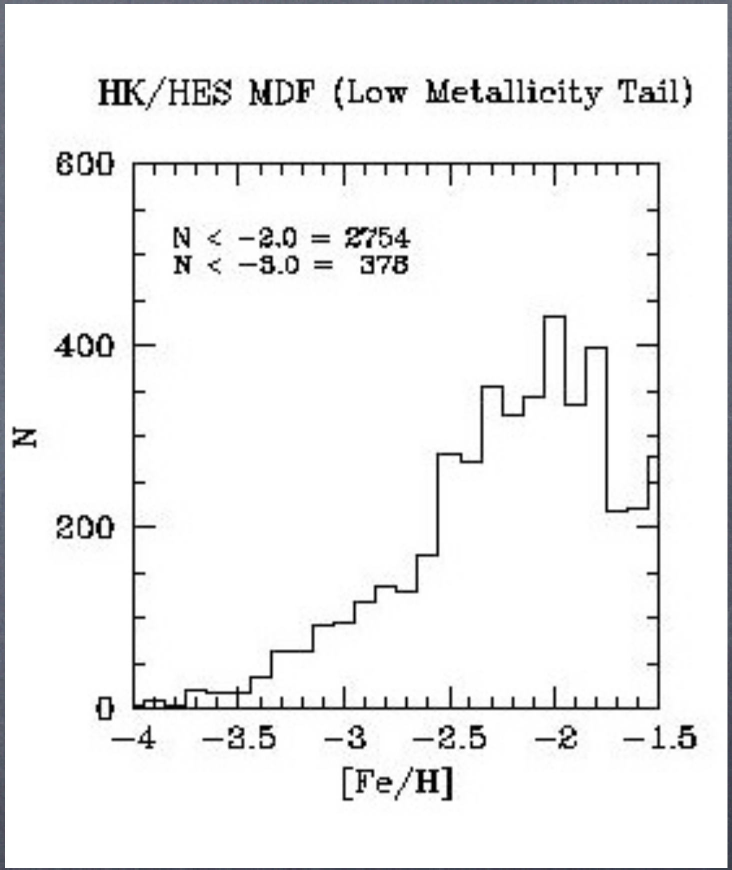
⇓

Large stellar mass



O'Shea & Norman, 2007

- No Z=0 star yet found
- Would expect to have found some if pop. III IMF were standard (Tumlinson, 2006)



Beers, 2005

- Population III IMF $\neq$ population II IMF
- But why does the IMF change?
- Perhaps because of the metals themselves

Metal-enriched gas

More efficient cooling

$\Downarrow$

Cooling is faster than collapse

$\Downarrow$

Gravitational fragmentation

- If the gas cools quickly, then we can build up many Jeans masses of cold gas before any can collapse
- Many Jeans masses => many fragments
- Fragments compete for available gas mass, in a process called **competitive accretion**
- Larger fragments accrete faster: "the rich get richer"
- Resulting IMF has a power-law slope that is close to the Salpeter value

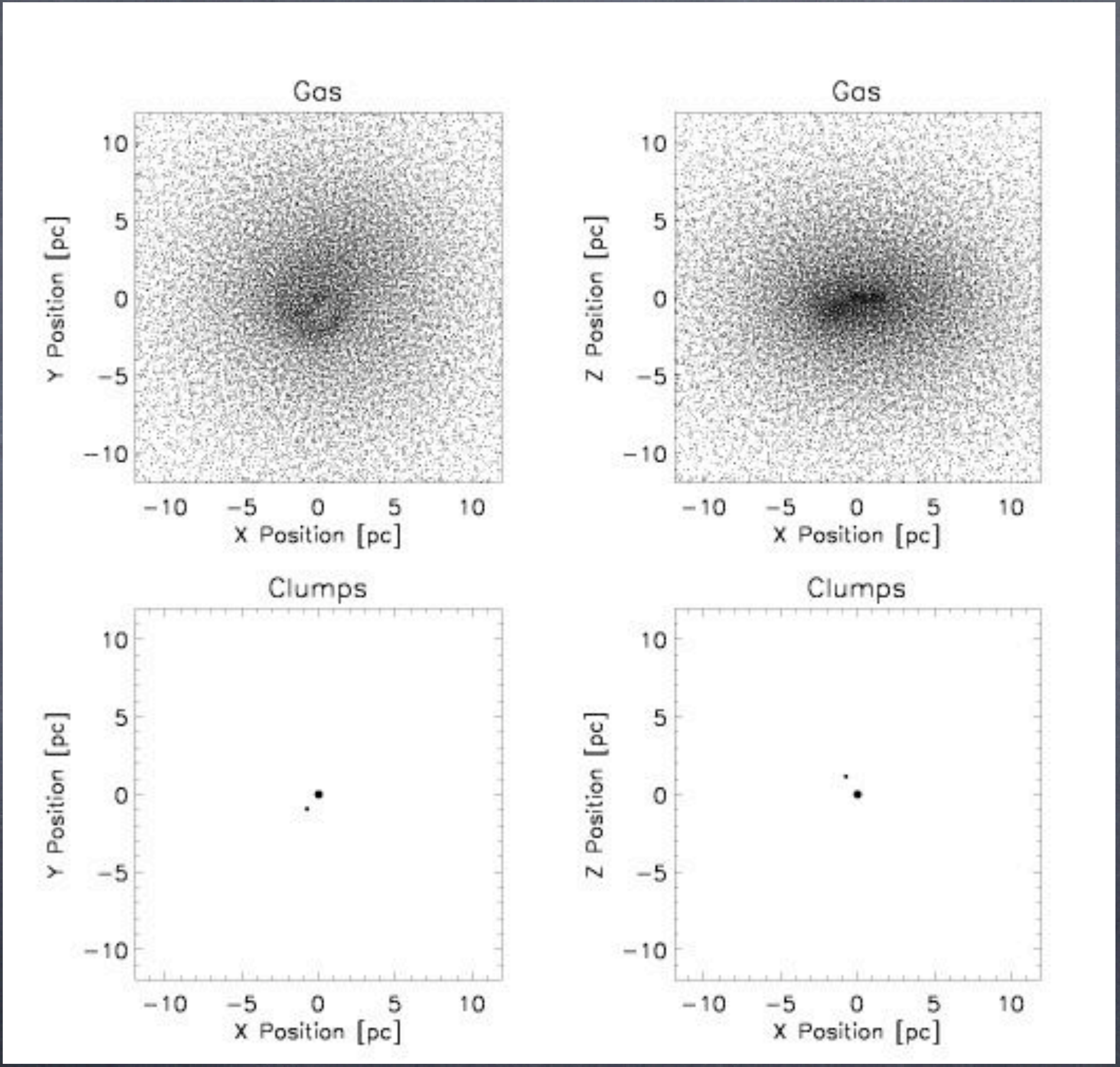
Rapid cooling at low metallicity

- Two main mechanisms:
  - H_2, HD and atomic fine structure lines at low densities
  - Dust at high densities
- So far, most studies have treated them separately

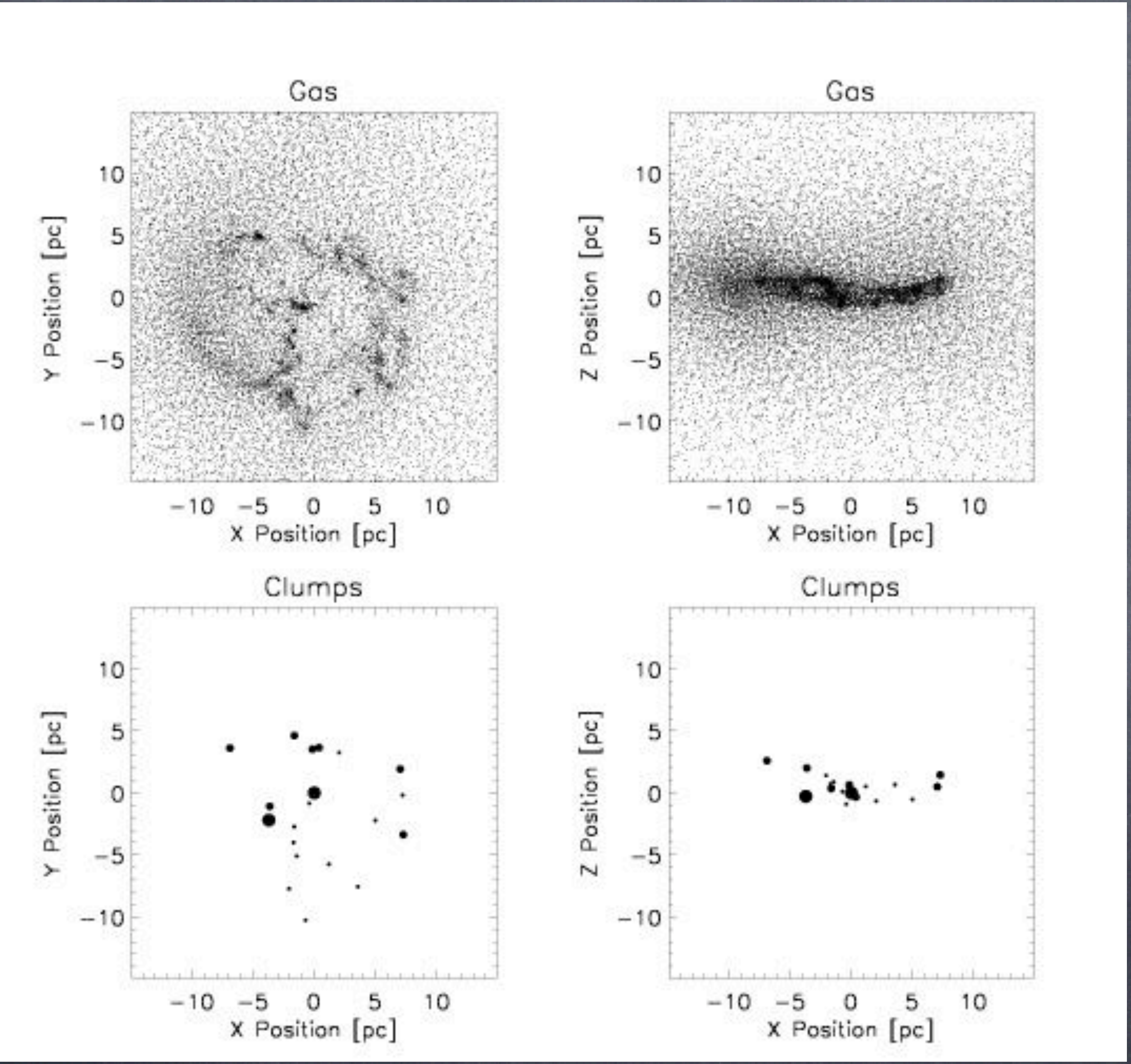
Cooling at low densities

- Bromm et al, 2001:
  - low-resolution SPH simulations
  - atomic fine structure cooling
  - no molecular hydrogen

- Gas with $Z = 10^{-4}\ Z_{sun}$ does not fragment
- Gas with $Z = 10^{-3}\ Z_{sun}$ **does** fragment

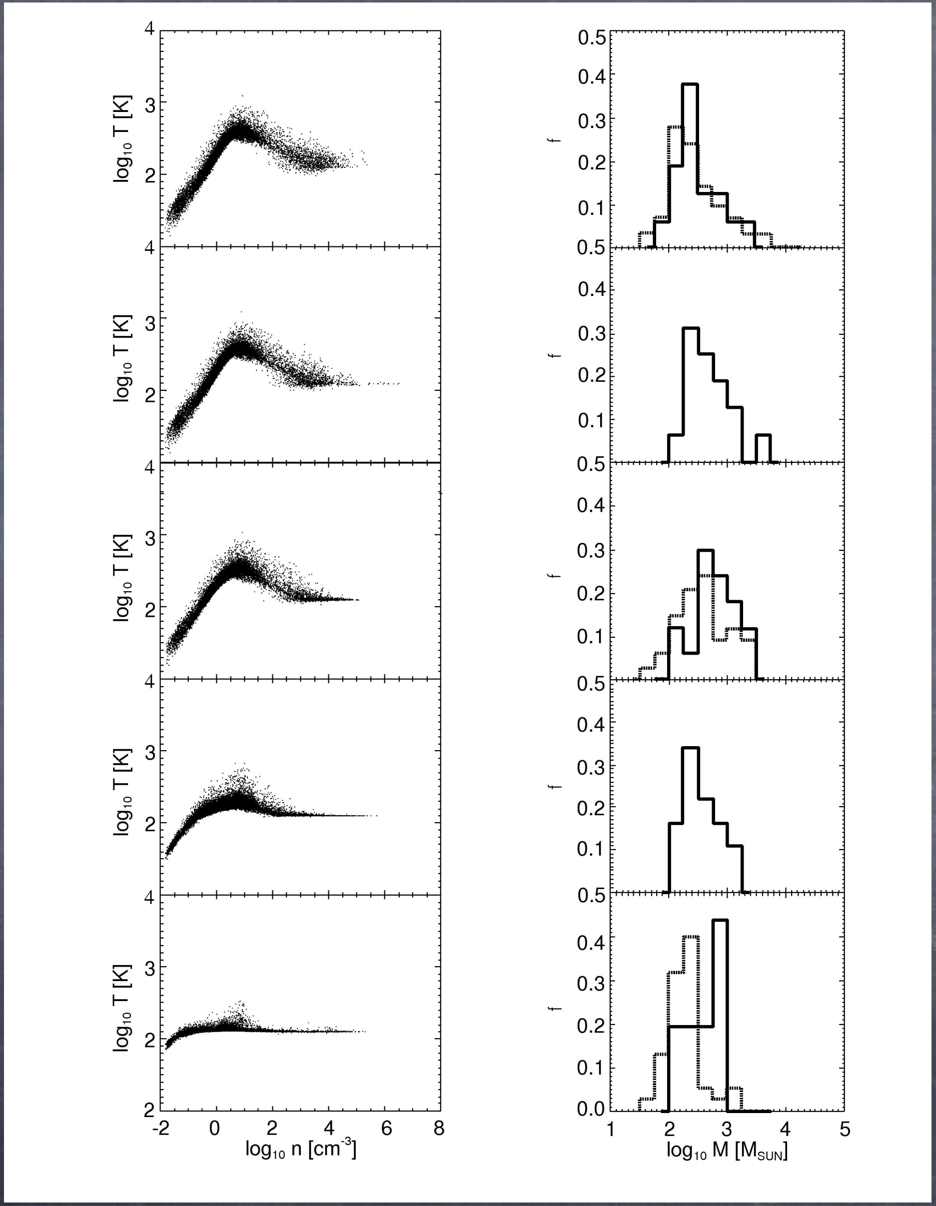


Bromm et al, 2001



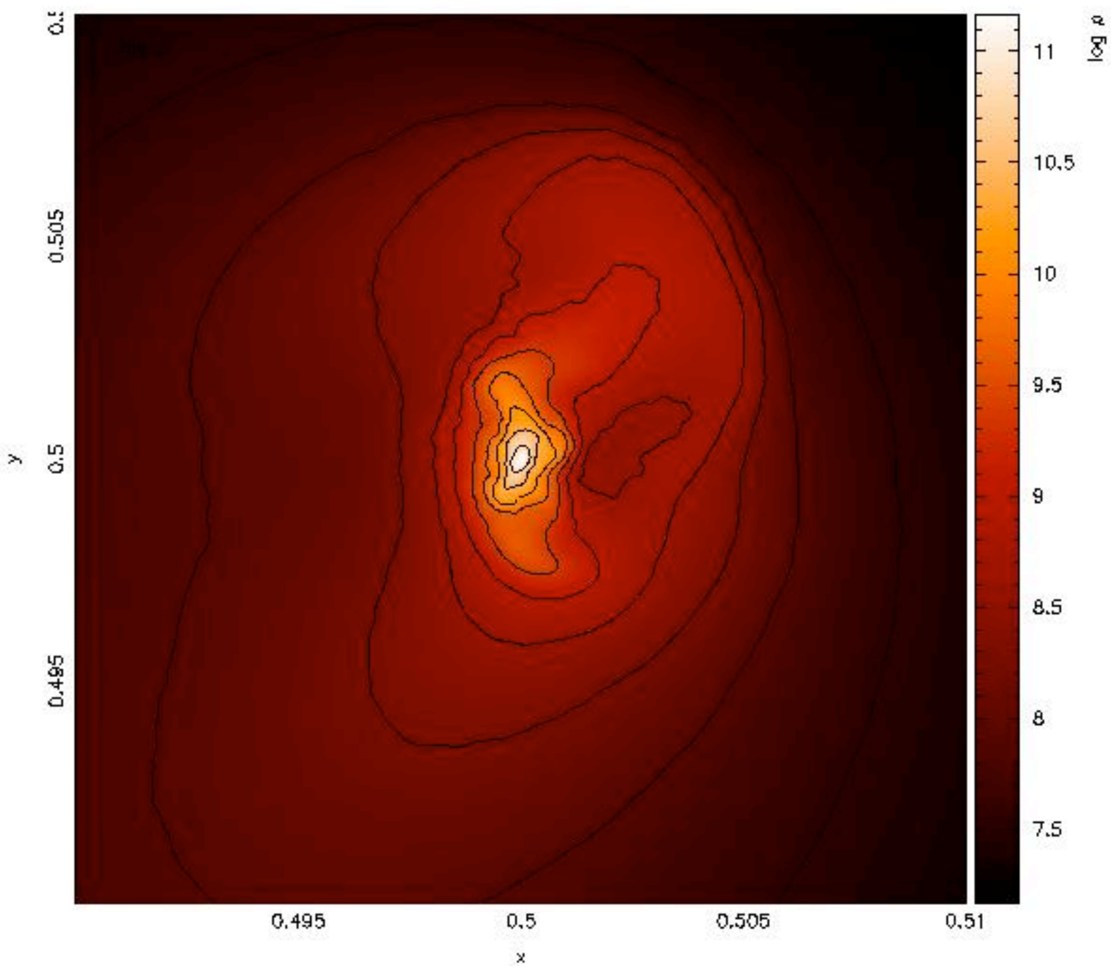
Bromm et al, 2001

- Jappsen et al, 2007: (arXiv: 0709.3530)
  - Similar SPH simulations
  - BUT: include H_2 cooling and chemistry
  - Fragmentation now occurs even in Z=0 case
  - Top-hat initial conditions lead to overly synchronized collapse

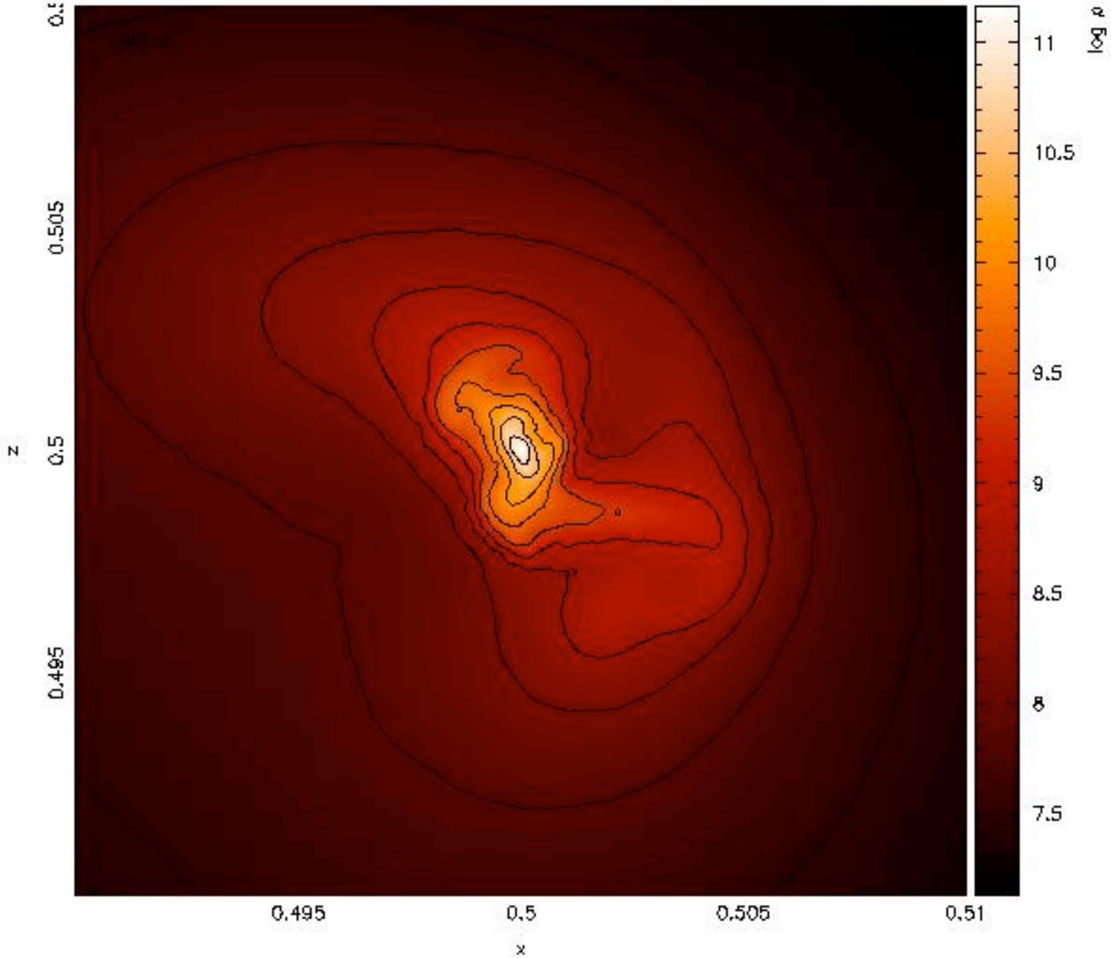


Jappsen et al 2007

- Jappsen et al, 2008: (arXiv:0810.1867)
  - High-resolution SPH simulations with particle splitting
  - Detailed molecular chemistry model & cooling function (including CO and H_2O)
  - **Hot** initial conditions ($T = 10^4$ K, ionized gas)
  - Find no fragmentation at $n < 10^8$ cm^{-3}



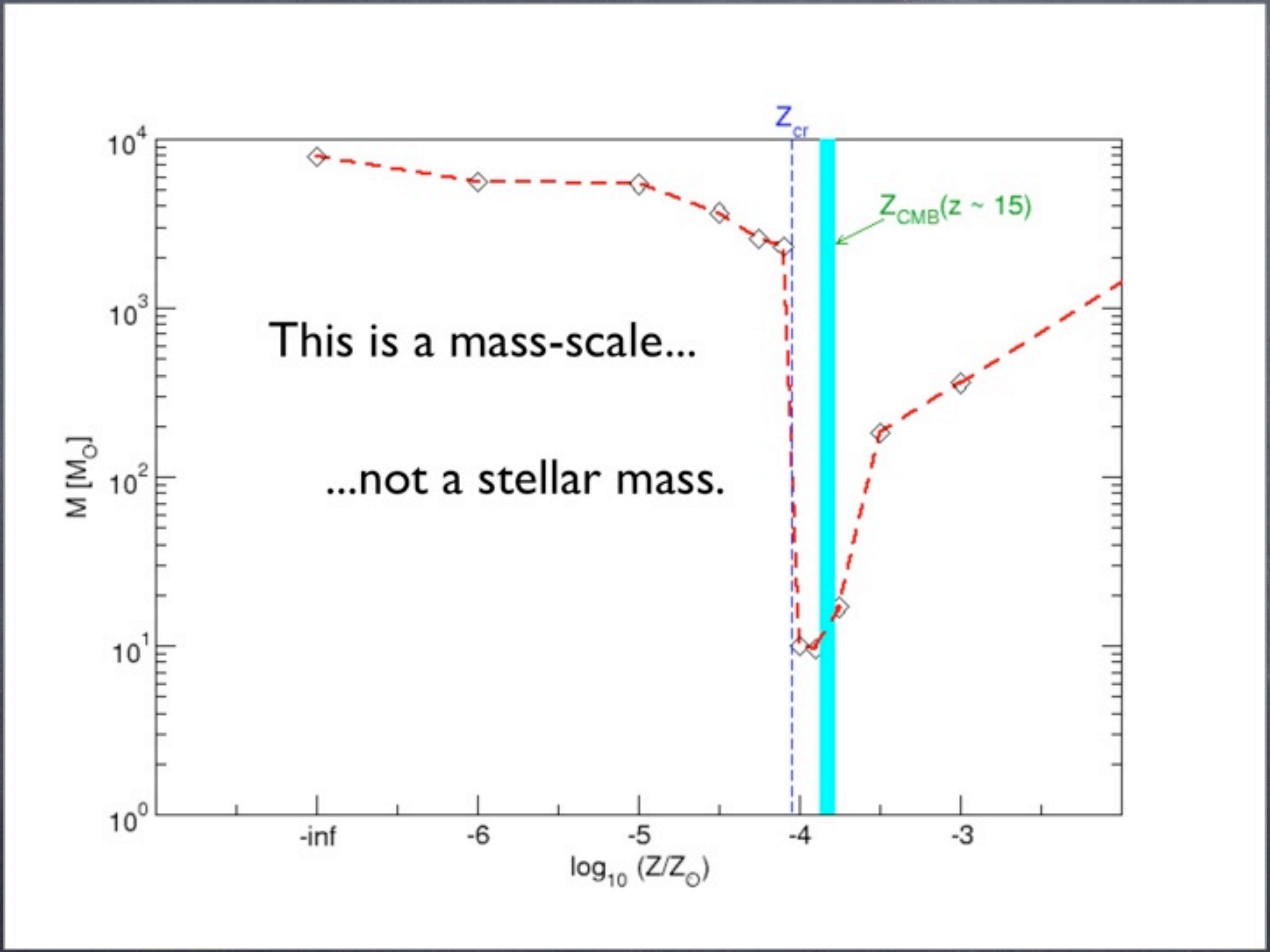
Jappsen et al, 2008 (JMGKS08)



JMGKS08

- Why don't we get fragmentation in this case?
- Gas cools **too** quickly - reaches CMB temperature while still at low density
- Low density => large Jeans mass even at T_{CMB}
- Gas at T_{CMB} can't cool further - no opportunity for further fragmentation while it remains there

- Smith et al 2008:
  - AMR simulations using Enzo
  - H_2 chemistry, cooling
  - C, O, Si etc. cooling assuming chemical equilibrium (CLOUDY)
  - cosmological initial conditions
  - find fragmentation for $Z > 10^{-4}\ Z_{sun}$; but if Z is too large, we cool to T_{CMB} too quickly and get no fragmentation
  - reducing T_{CMB} allows fragmentation for wider range of Z



B. Smith, private communication

- CMB temperature floor also affects characteristic mass
- Competitive accretion gives Salpeter slope for masses > initial Jeans mass
- Initial Jeans mass set by T, n at point when gas stops cooling quickly
- If $T = T_{cmb}$, then:

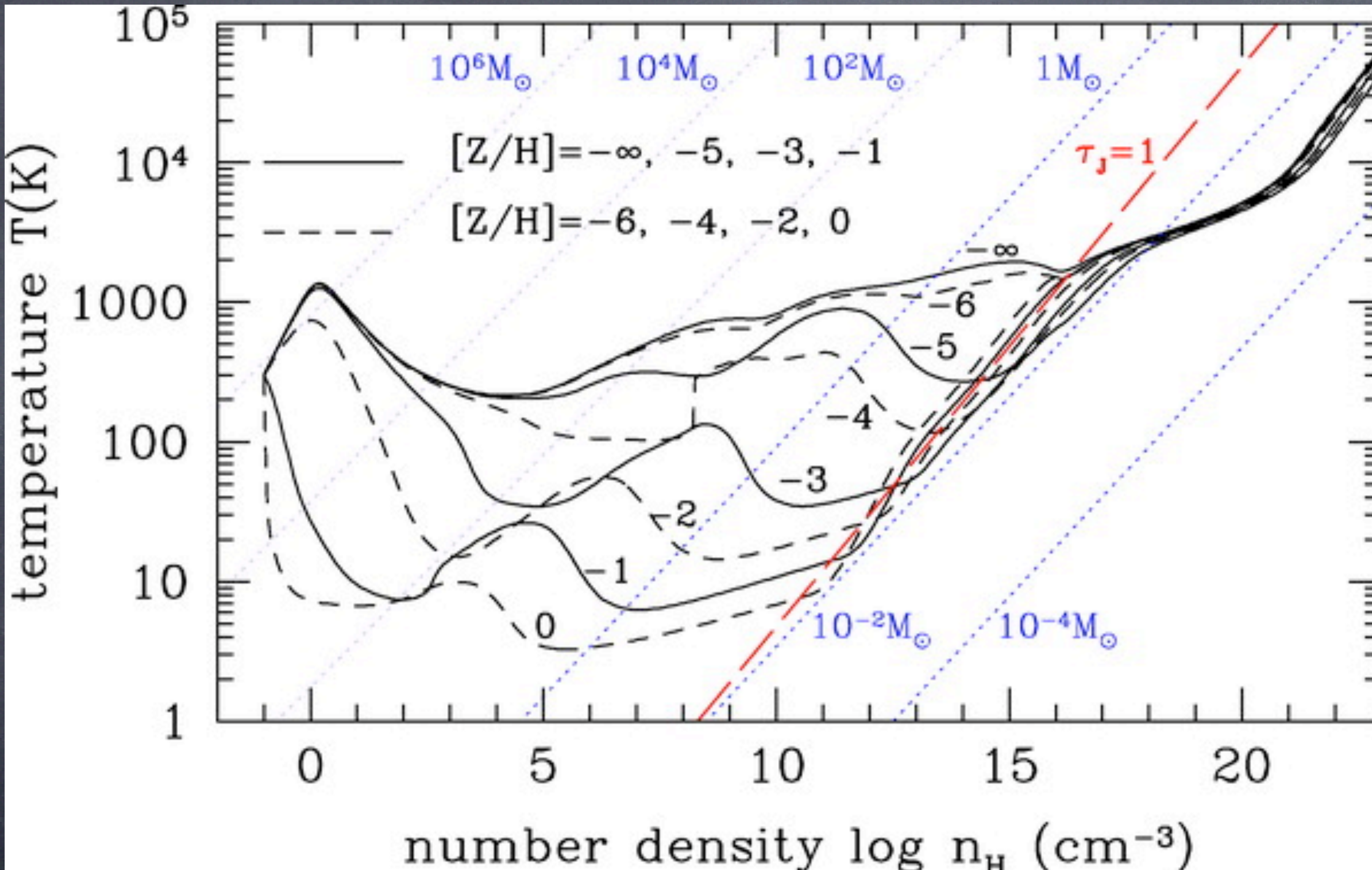
$$M_{char} \approx 10 \, (n/10^6 \, cm^{-3})^{-1/2} \, (z/20)^{3/2} \, M_{sun}$$

- For $n < 10^6$ cm^{-3} and $z = 20$, this gives:

$$M_{char} \gtrsim 10 \, M_{sun}$$

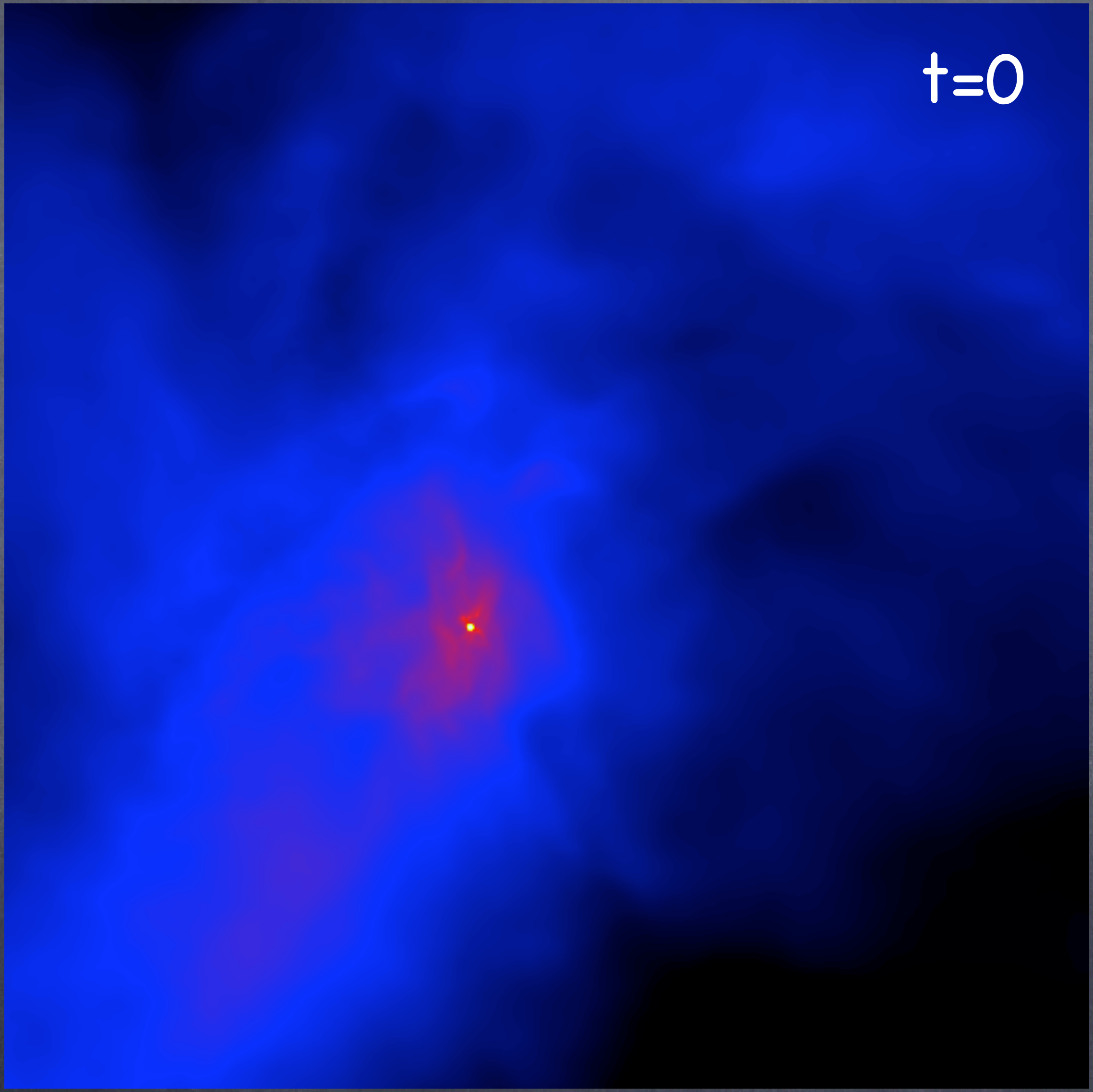
Cooling at high densities

- Omukai, 2000:
  - one-zone models with detailed chemical model and cooling function
  - predicts sharp drop in temperature at densities above 10^{10} cm^{-3} in $Z < 10^{-4} Z_{sol}$ gas, resulting from the onset of efficient dust cooling
- Schneider et al, 2002 pointed out that this may lead to gravitational fragmentation at this point
- Critical metallicity required: $Z_{cr} \approx 10^{-5} F_{dust}^{-1} Z_{sun}$

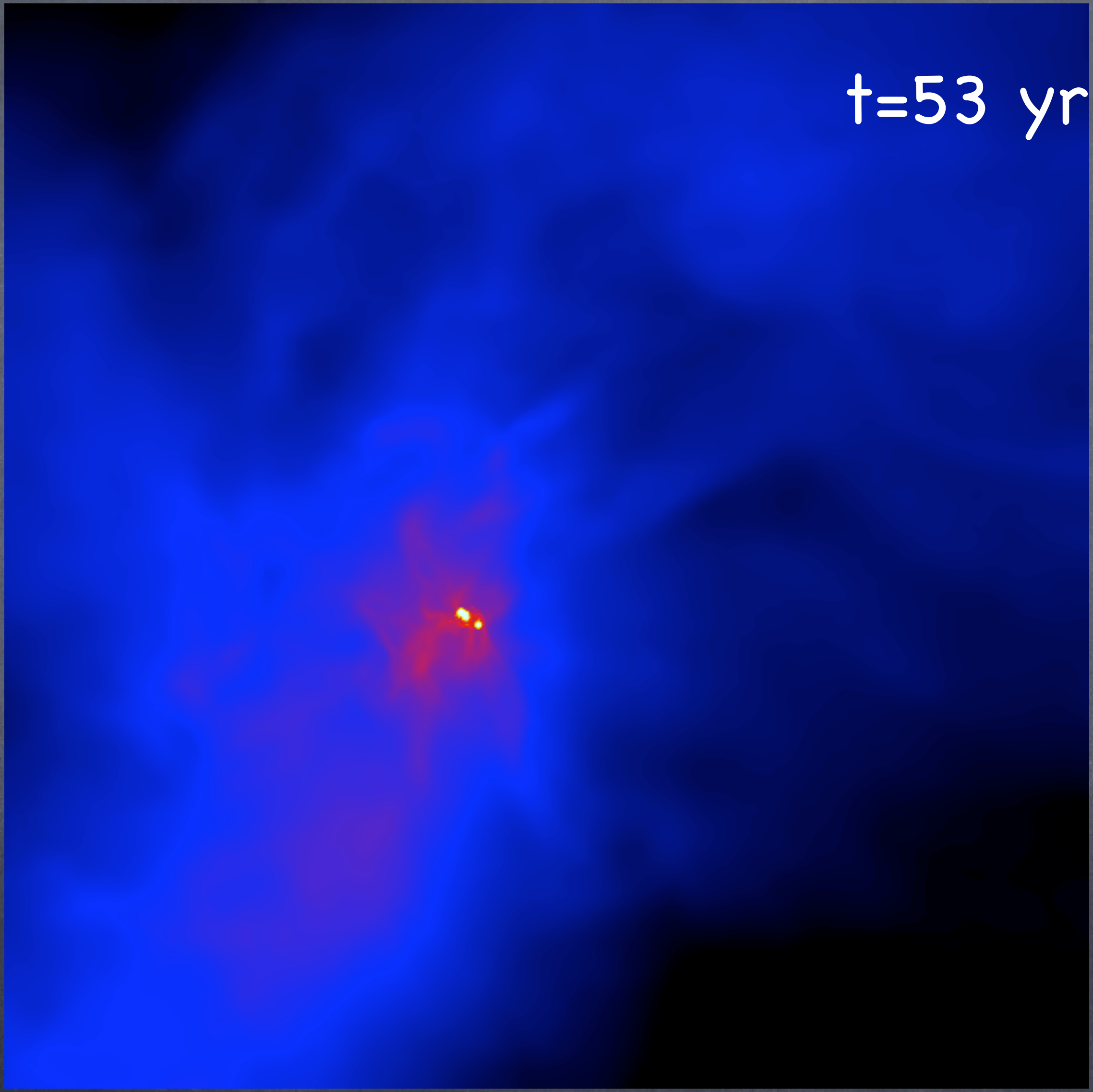


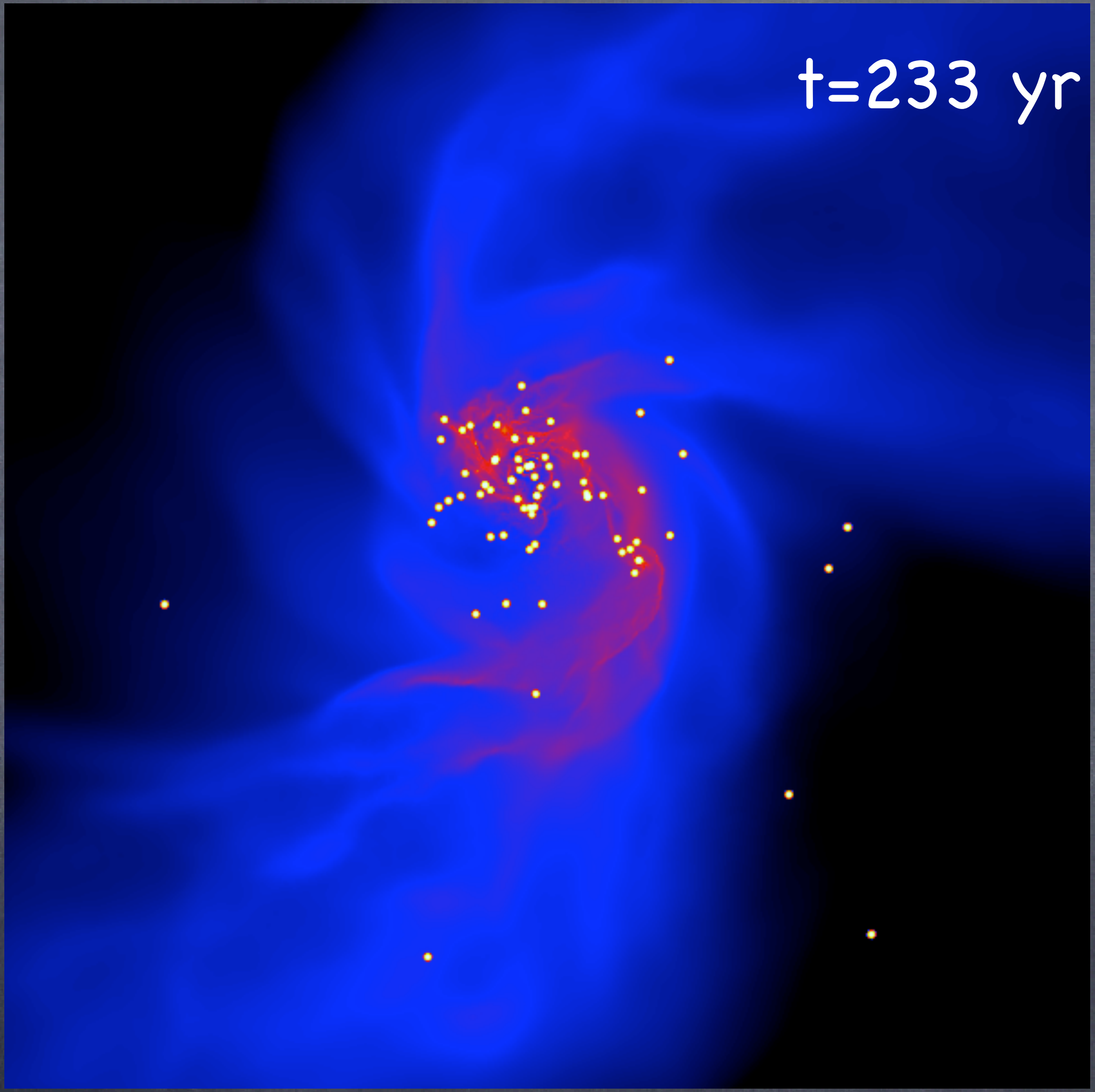
Omukai et al, 2005

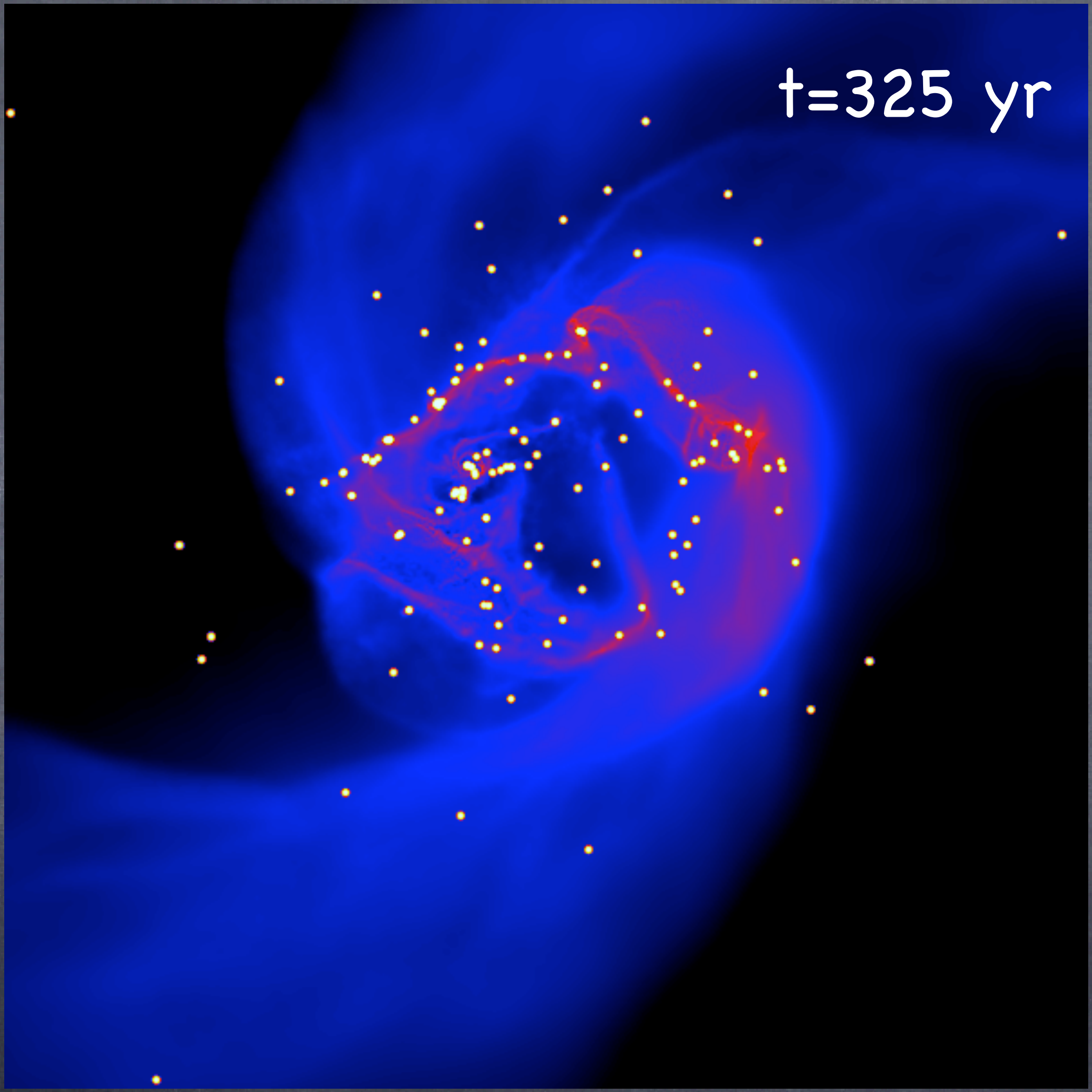
- Clark, Glover & Klessen 2008:
  - Tabulated equation of state
  - Large particle number: $N = 2.5 \times 10^7$
  - Good mass resolution: $M_{res} = 0.002\ M_{sun}$
  - Sink particles
  - Simulated clouds with $Z = 0, 10^{-6}, 10^{-5}\ Z_{sun}$

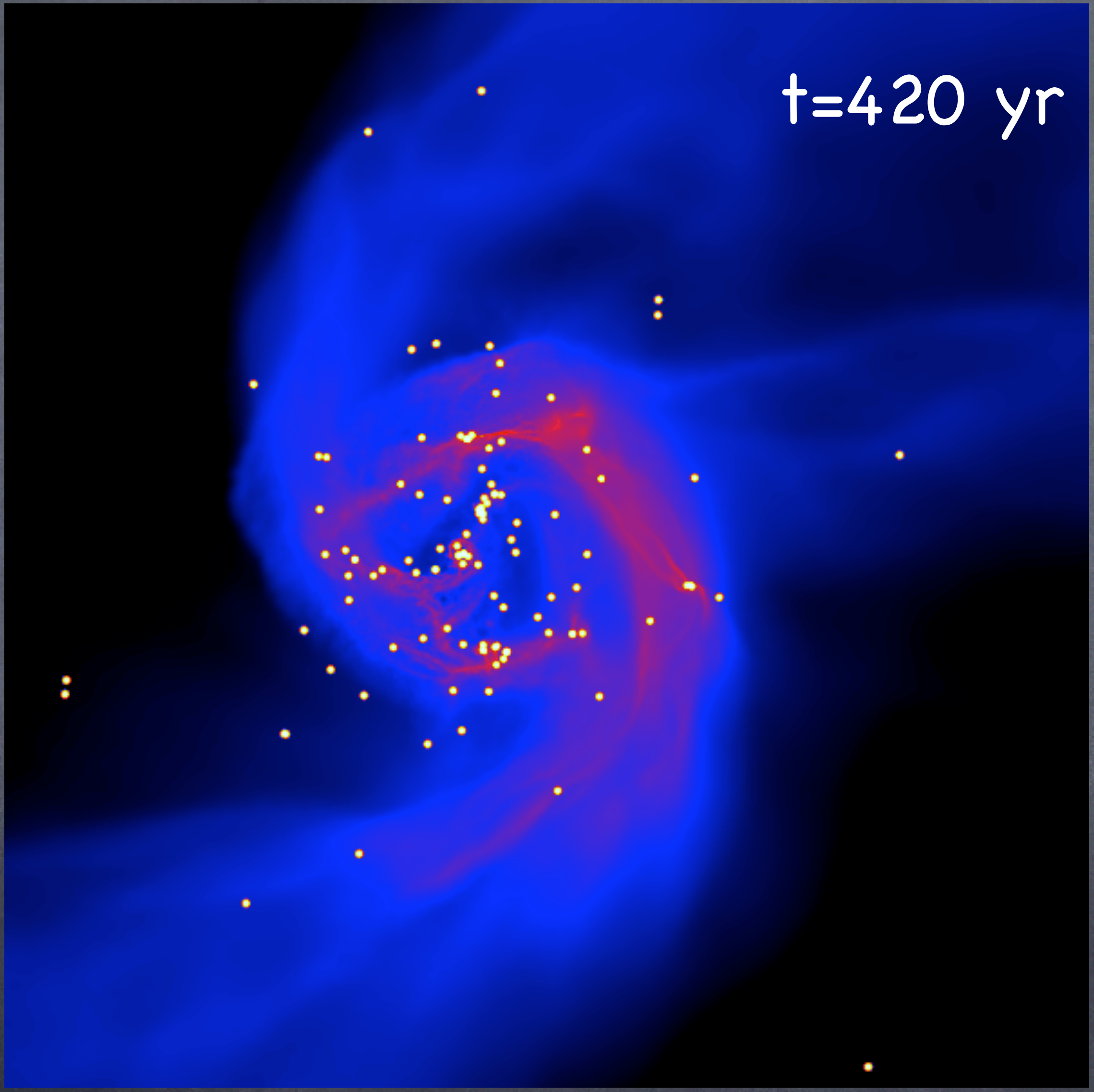


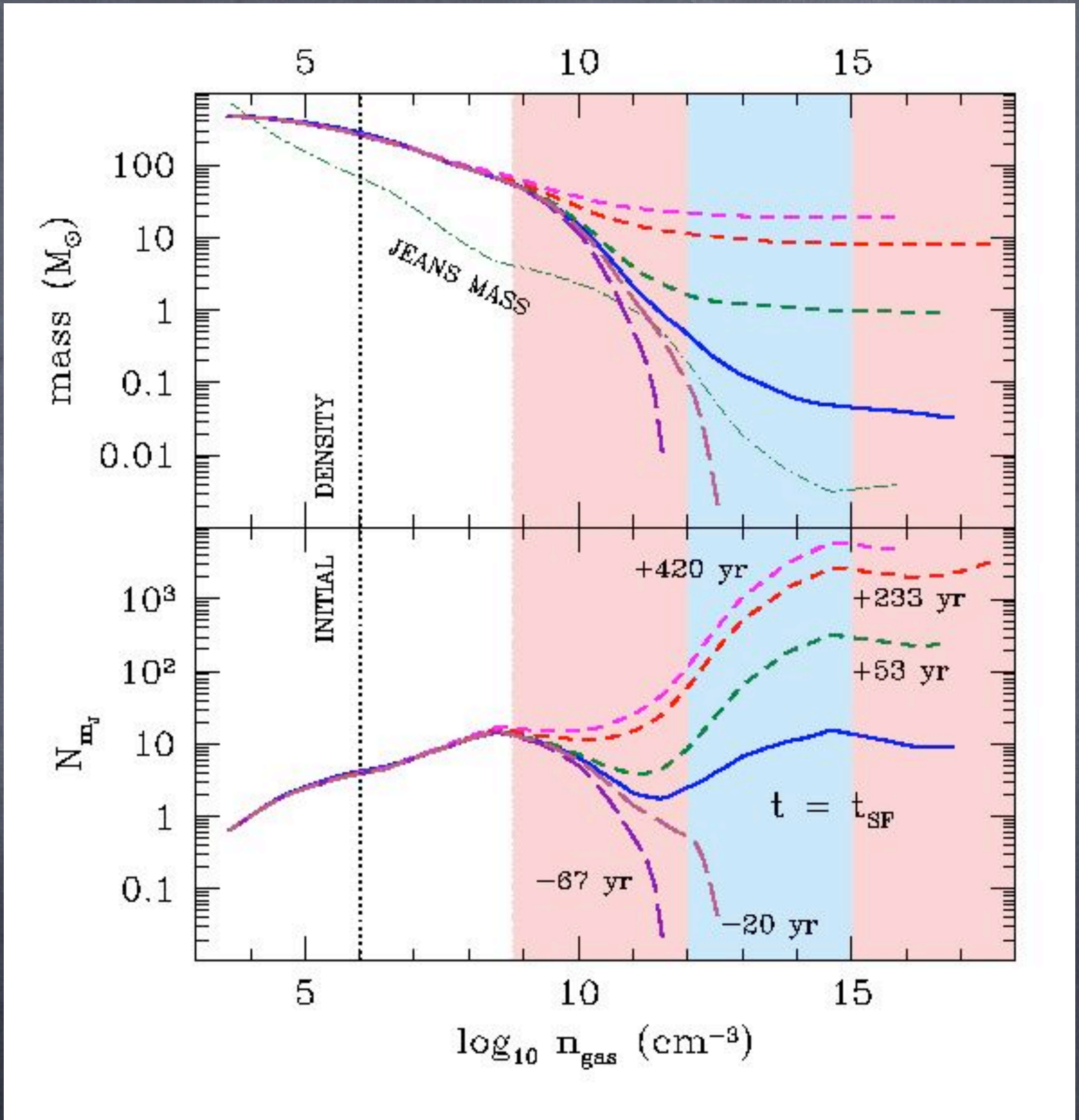
Clark, Glover & Klessen, 2008 (CGK08)


t=53 yr


t=233 yr

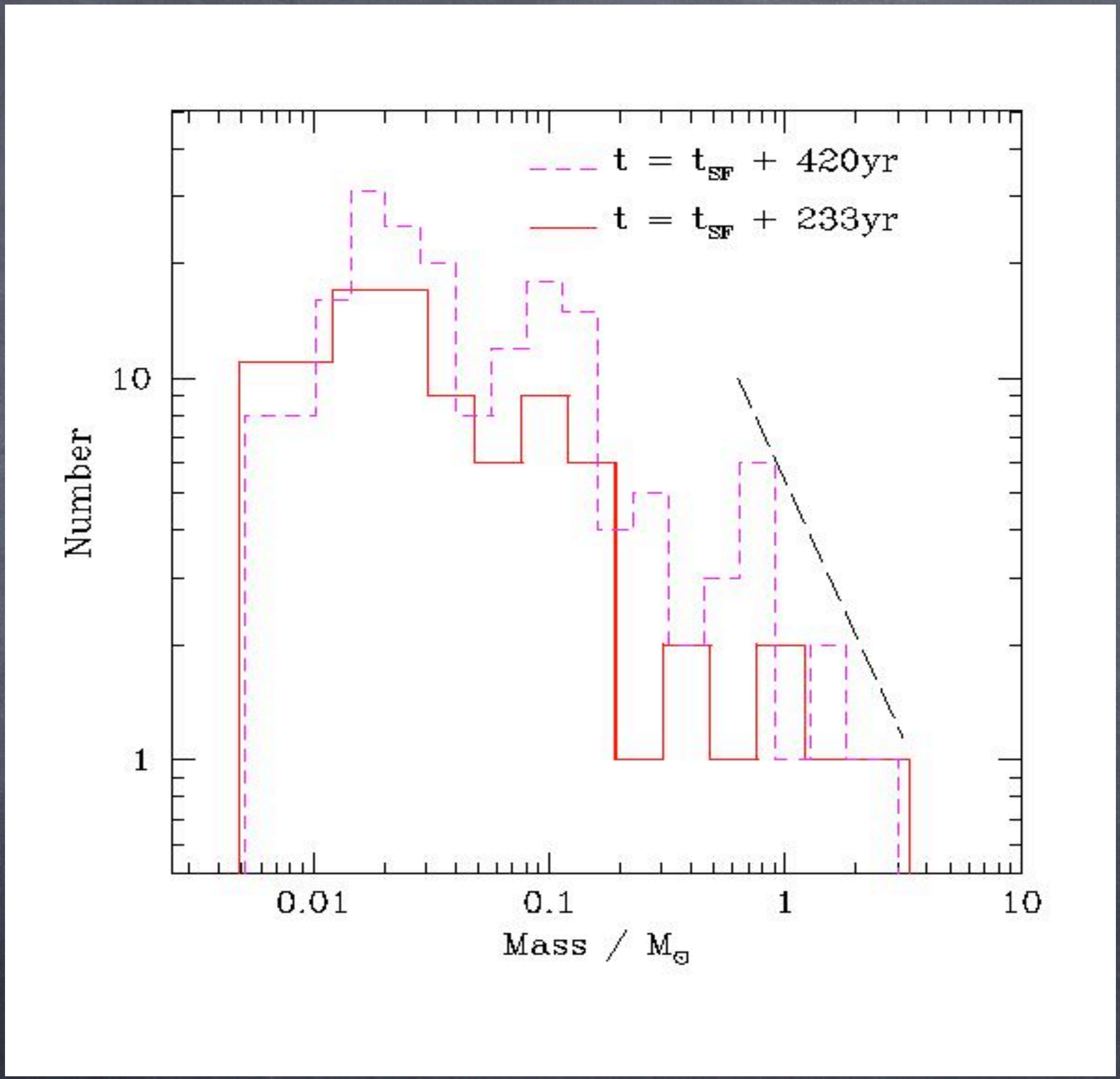

t=325 yr


t=420 yr



5
10
15
100
10
1
0.1
0.01
mass ($M_\odot$)
JEANS MASS
INITIAL DENSITY
10^3
10^2
10
1
0.1
N_{m_J}
+420 yr
+233 yr
+53 yr
$t = t_{SF}$
−67 yr
−20 yr
$\log_{10} n_{gas}$ (cm^{-3})

CGK08

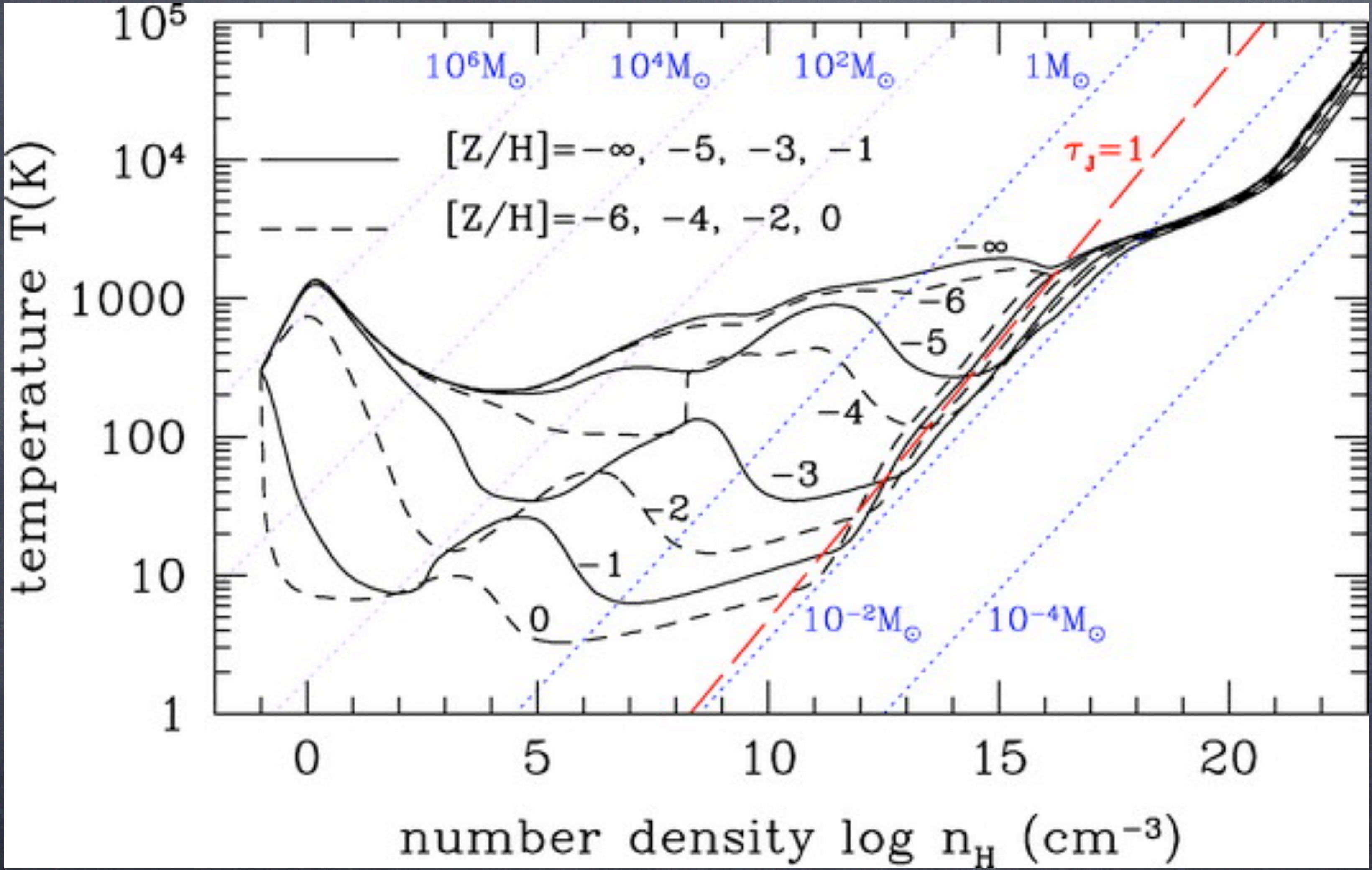


t = t_SF + 420yr
t = t_SF + 233yr
10
1
Number
0.01
0.1
1
10
Mass / M_⊙

Caveats

- Single EOS not really appropriate
- Amount of heating prior to dust cooling quite uncertain (dynamics, chemistry)
- No protostellar feedback
- Dust model uncertain
- No magnetic fields

Can the low and high density modes coexist?



Omukai et al, 2005

- In principle, yes!

- But will depend on details of thermal evolution, value of F_{dust}, etc.

- There's still a lot of work to do here...

Conclusions

- Competitive accretion yields a power-law IMF even at very low metallicity, provided that gas can cool quickly enough
- Two cooling mechanisms => two fragmentation regimes; these may or may not coexist in practice
- CMB a big problem for producing low mass stars at high redshift by low density cooling