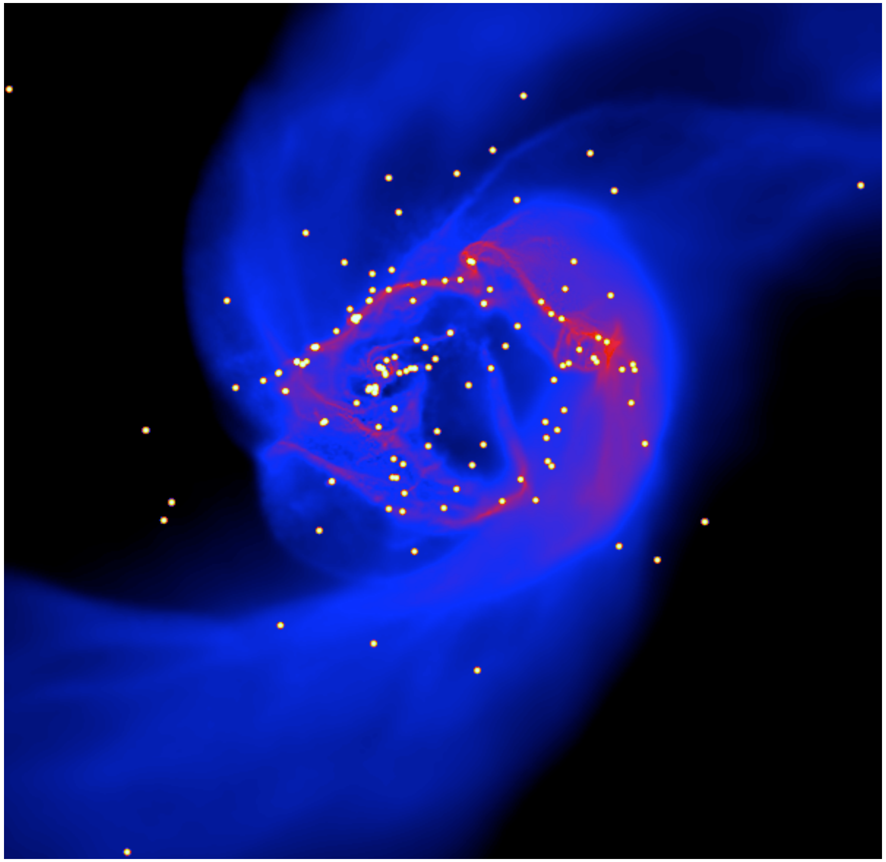
The IMF from primordial to present day star formation



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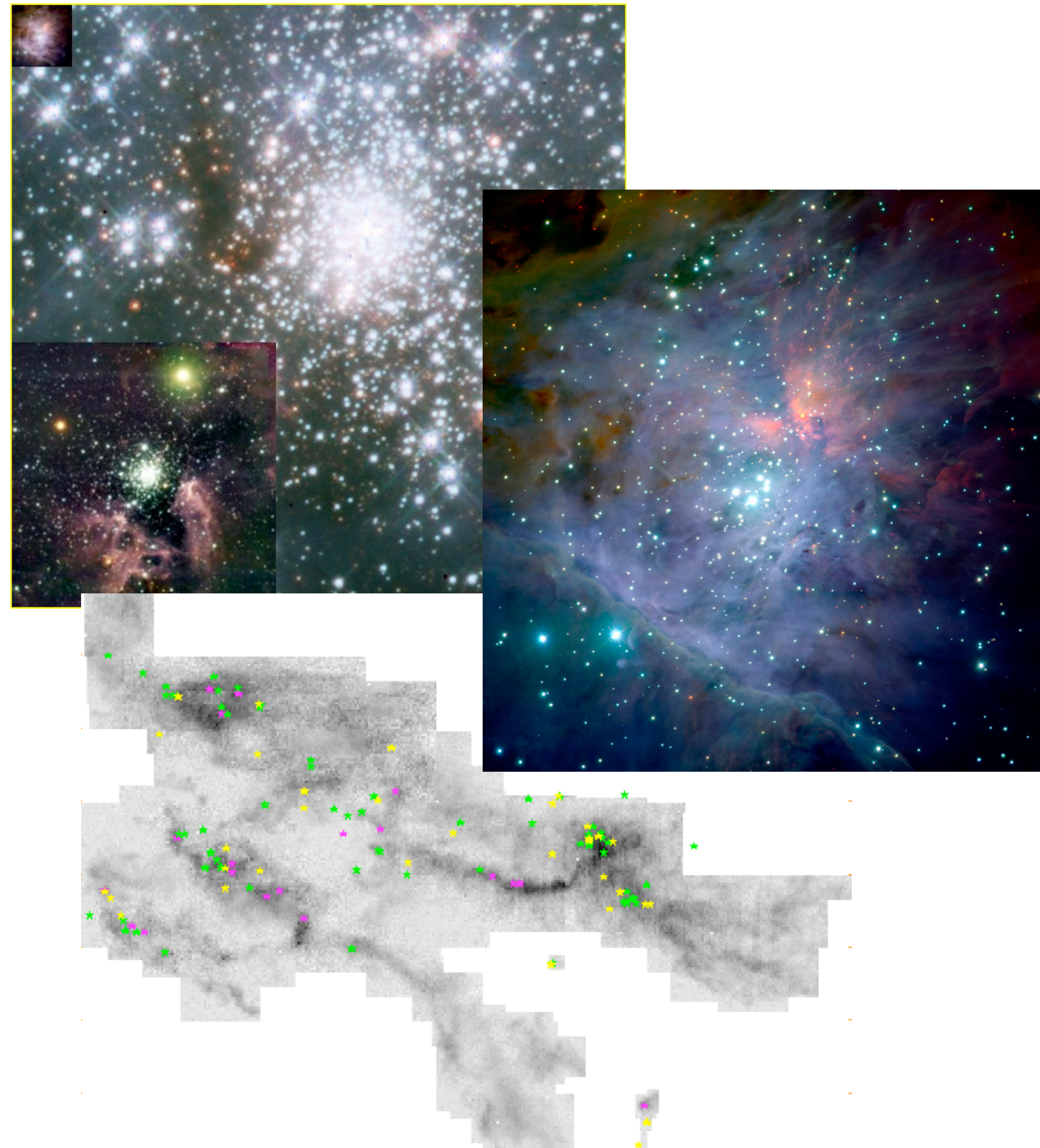
Volker Bromm

Thomas Greif

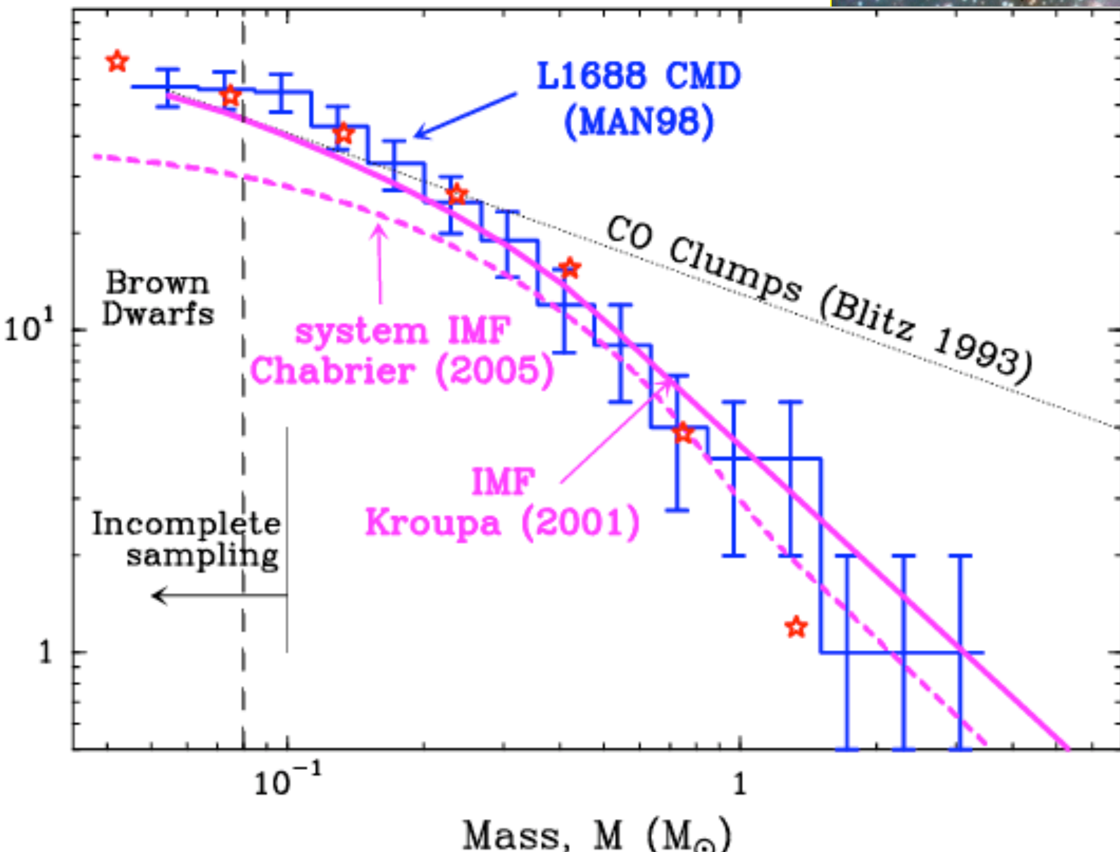
Present-day star formation

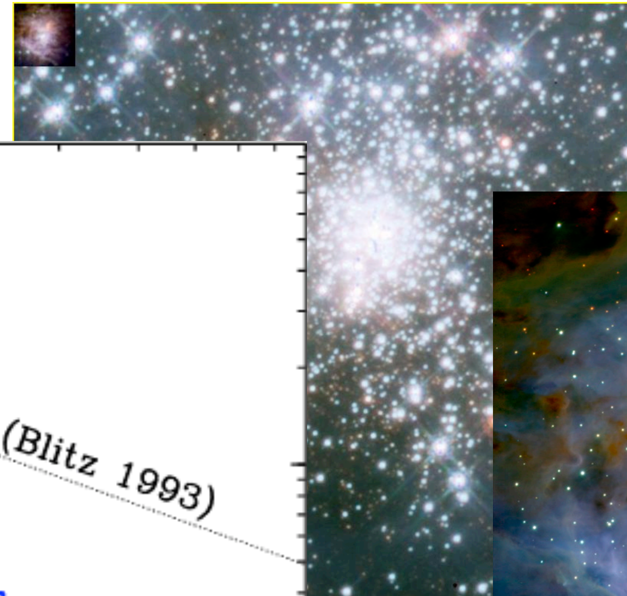


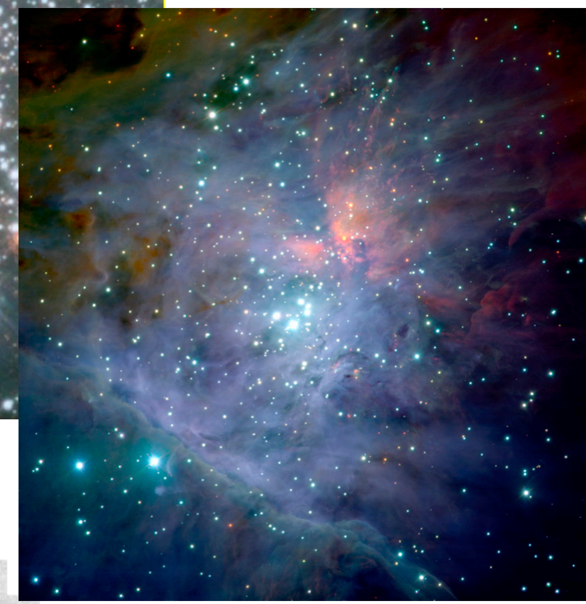
3 main features:

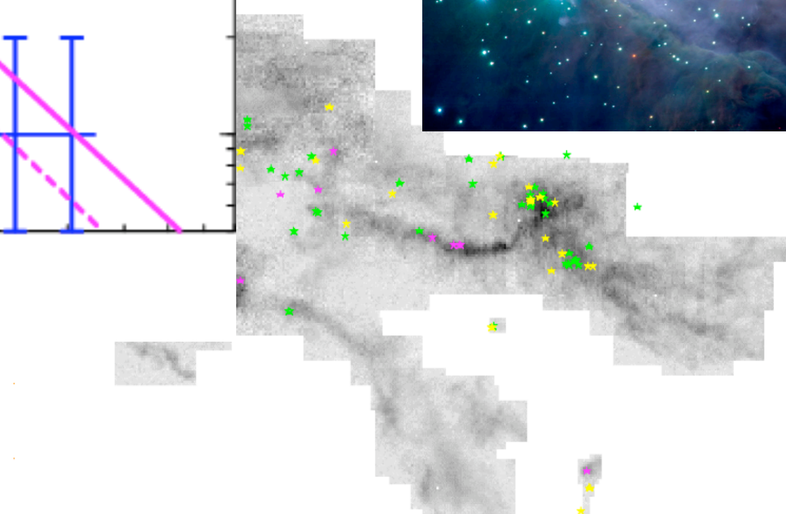
- Stars form in clusters/groups/ associtation, not in isolation (e.g. Lada & Lada).
- Stellar mass function seems to be independent of environment and cluster size (Kroupa 2002).
- Most stars have **low-masses**, between 0.1 and 0.5 $M_\odot$.

Present-day star formation



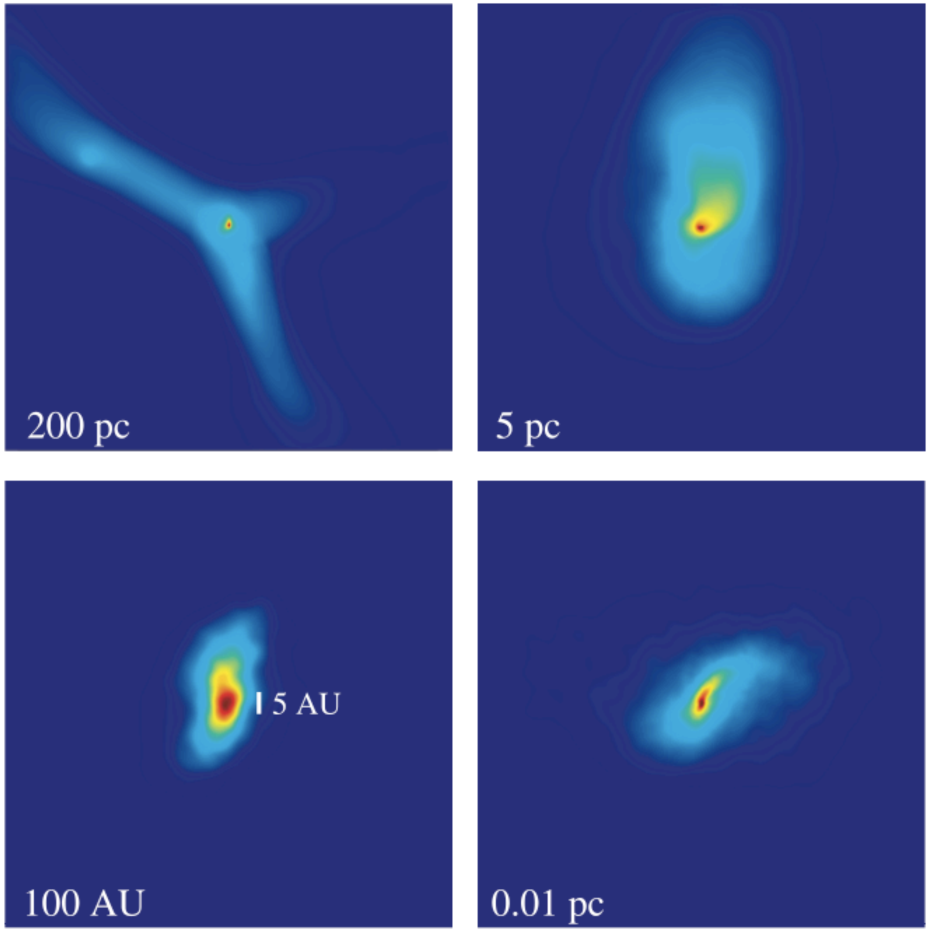






Primordial star formation

(Standard picture...)



Yoshida et al (2006)

Stars form in isolation

Stars are typically massive ($> 20M_{\odot}$)

(e.g. Abel et al 2002; Bromm et al 2002; Tan & McKee 2004; Yoshida et al 2006, 2008)

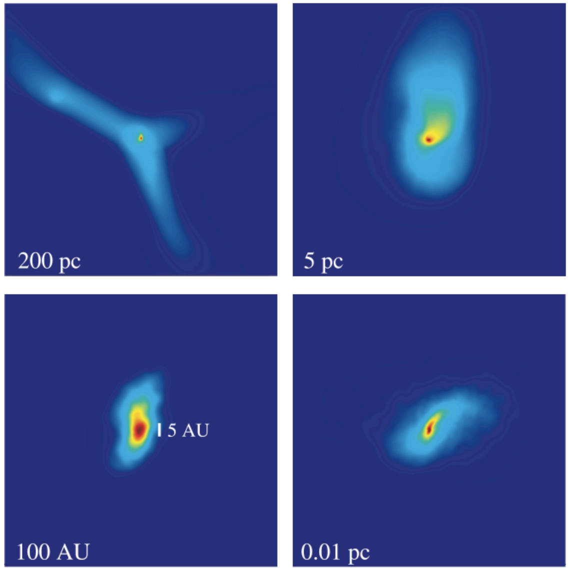
What causes the transition?

Jeans mass and length set the scales:

$$m_J = 1M_\odot \left[\frac{\rho}{10^{-19}\mathrm{gcm}^{-3}}\right]^{-1/2} \left[\frac{T}{10K}\right]^{3/2}$$

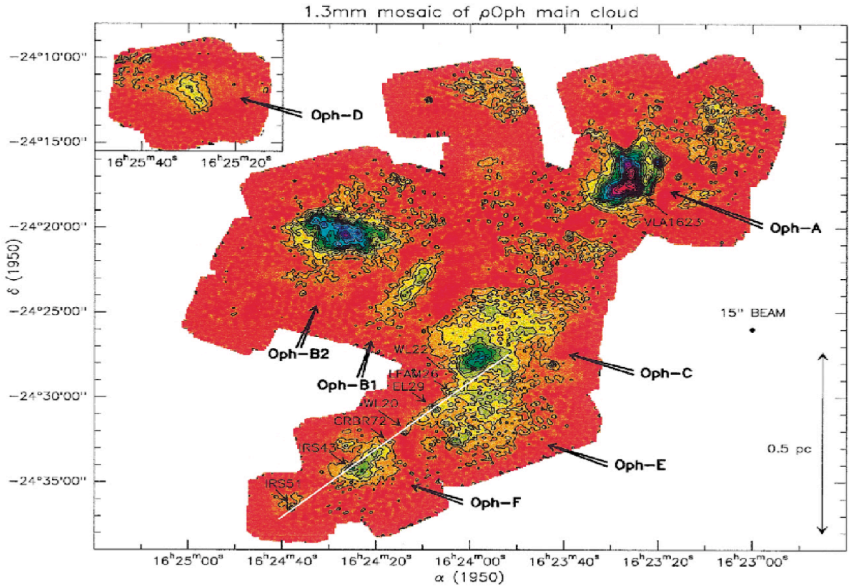
$$\lambda_J = 8500\mathrm{au} \left[\frac{\rho}{10^{-19}\mathrm{gcm}^{-3}}\right]^{-1/2} \left[\frac{T}{10K}\right]^{1/2}$$

T ~ 300 K



~1 Jeans mass

T ~ 15 K



> 10s of Jeans masses

Cooling causes transition

Two schools of thought:

1) C, O fine structure cooling? (e.g. Bromm et al 2001; Bromm & Loeb 2002; Santoro & Shull 2006; Frebel et al 2007; Smith & Sigurdsson 2007)

Occurs at low densities ($< 10^4$ cm^{-3})

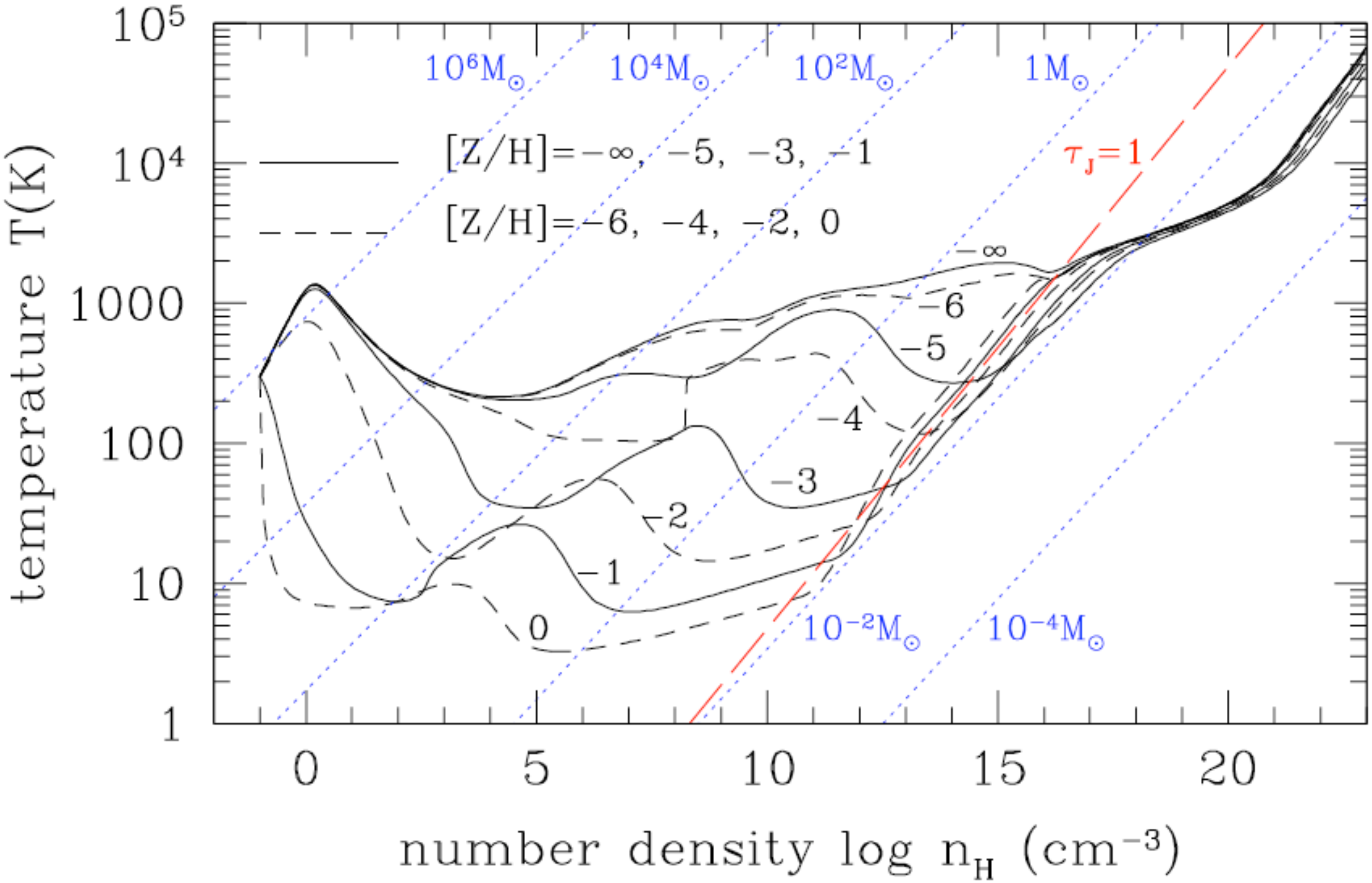
Sets a critical metallicity of $10^{-3.5}$ $Z_\odot$

2) Dust-cooling induced fragmentation? (e.g. Schneider et al 2002; Omukai et al 2005; Schneider et al 2006)

Occurs at very high densities ($> 10^8$ cm^{-3})

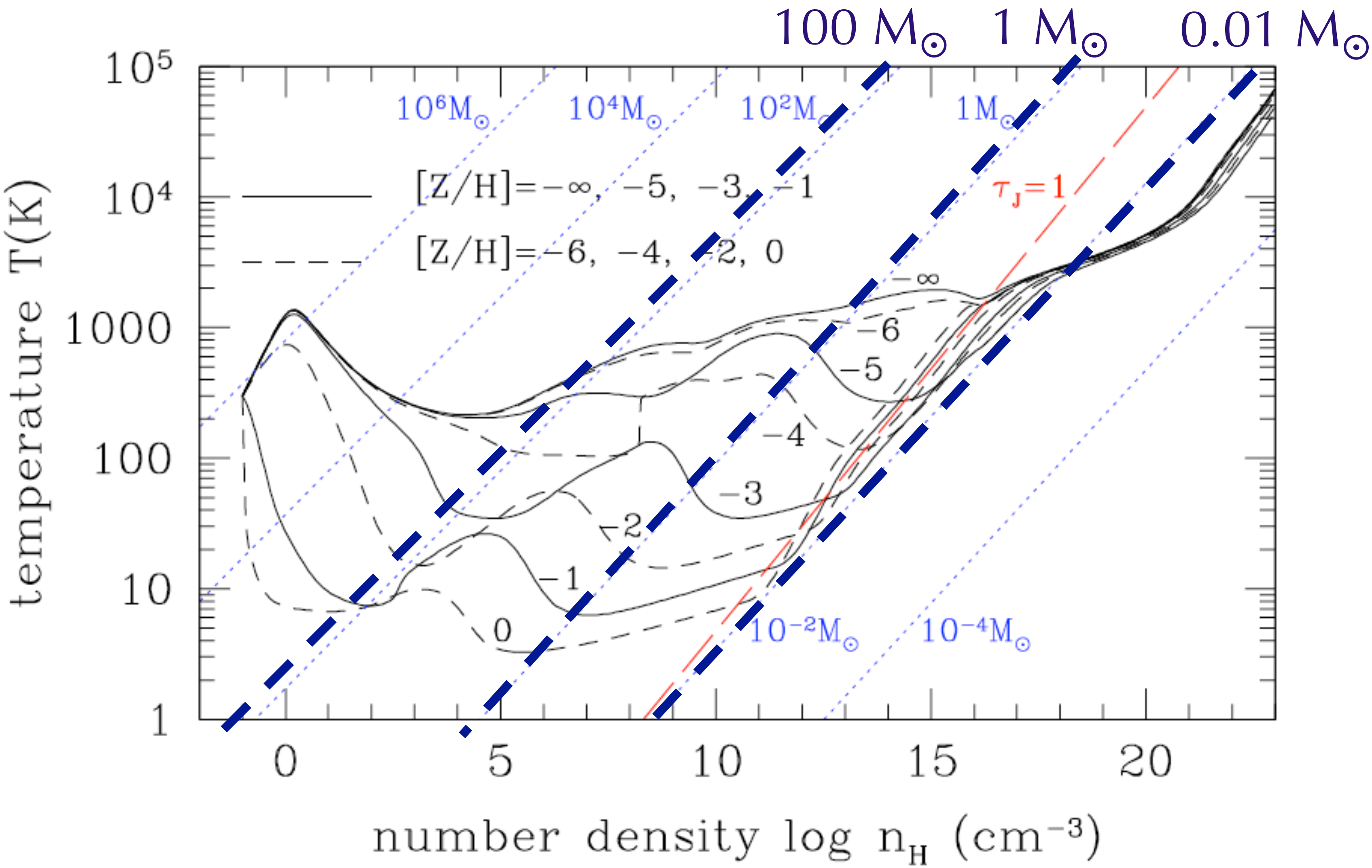
Possibly kicks in around 10^{-6} to 10^{-5} $Z_\odot$

Dust and line cooling



Omukai, Tsuribe, Schneider & Ferrara (2005)

Dust and line cooling



Omukai, Tsuribe, Schneider & Ferrara (2005)

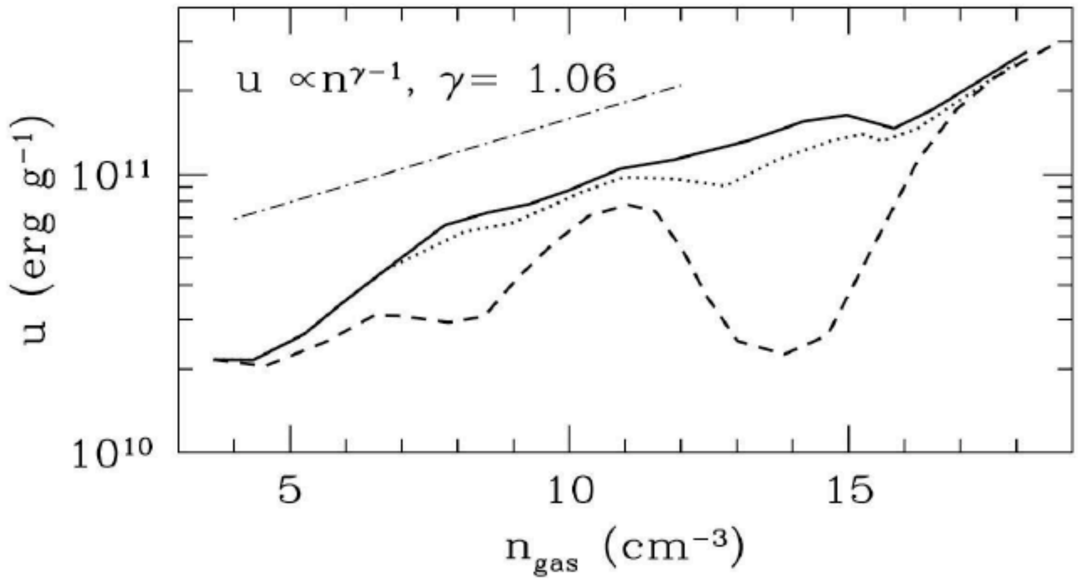
Initial conditions (I)

Gas clump parameters:

500 $M_\odot$ with 25 or 2 Million SPH particles.

Mass resolution ~$0.002 M_\odot$ or ~$0.02 M_\odot$.

Piece-wise polytropic fit to Omukai et al (2005) EOS.



Initial conditions (II)

Gas clump parameters:

Initial density = 5×10^5 cm^{-3}

Initial T = 200 ~ 250K (set by EOS)

$E_{therm} / |E_{grav}| = 0.39 - 0.32$ (depends on which EOS)

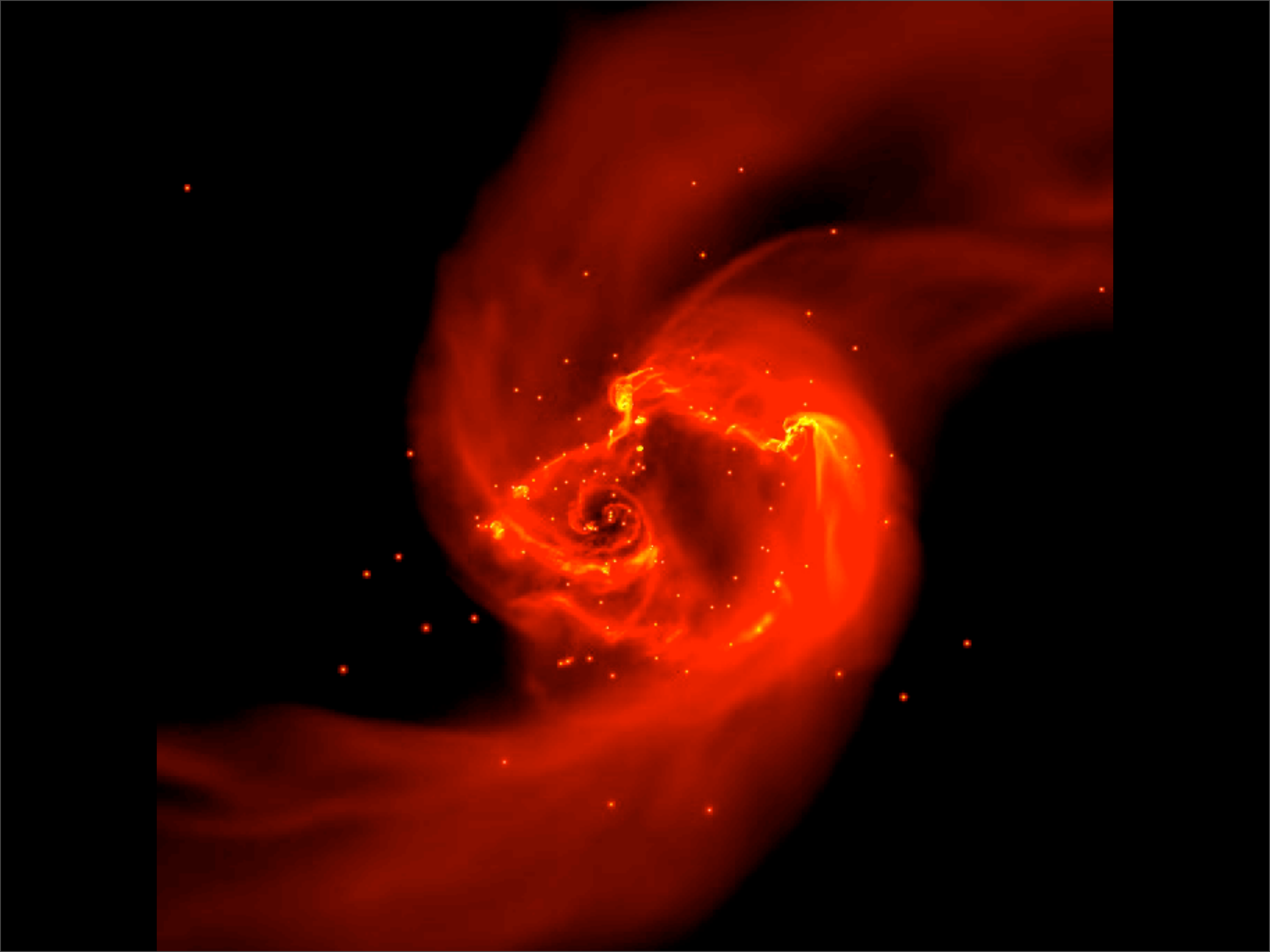
$E_{turb} / |E_{grav}| = 0.1$ (subsonic v_{rms})

$E_{rot} / |E_{grav}| = 0.02$ (added **on top** of turbulence)

Sinks Particles:

Form at ~10^{17} cm^{-3}

Accretion radii of 0.4 AU

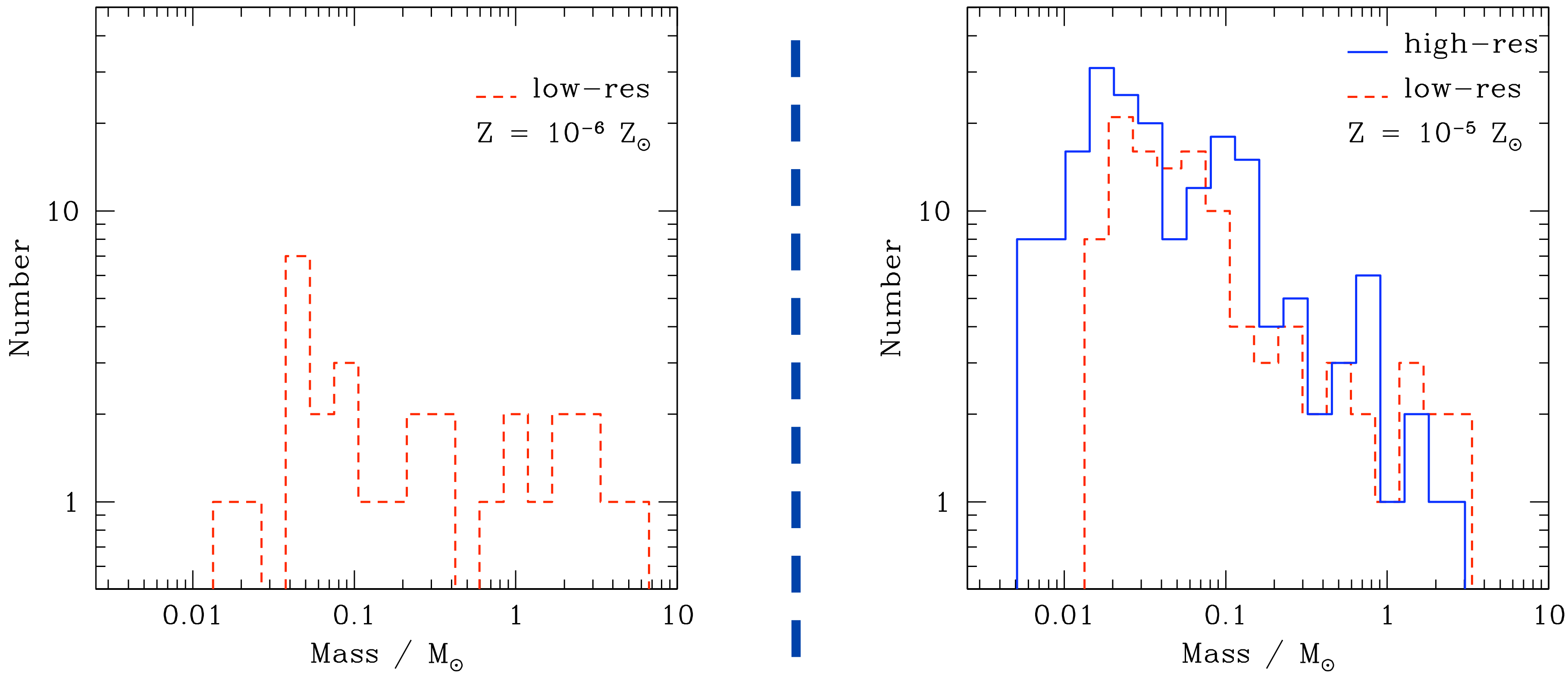


IMF?

IMFs are plotted when 19 $M_\odot$ is accreted:

Transition to present-day IMF?

Clark, Glover & Klessen (2008)



$Z = 10^{-6}\ Z_\odot$

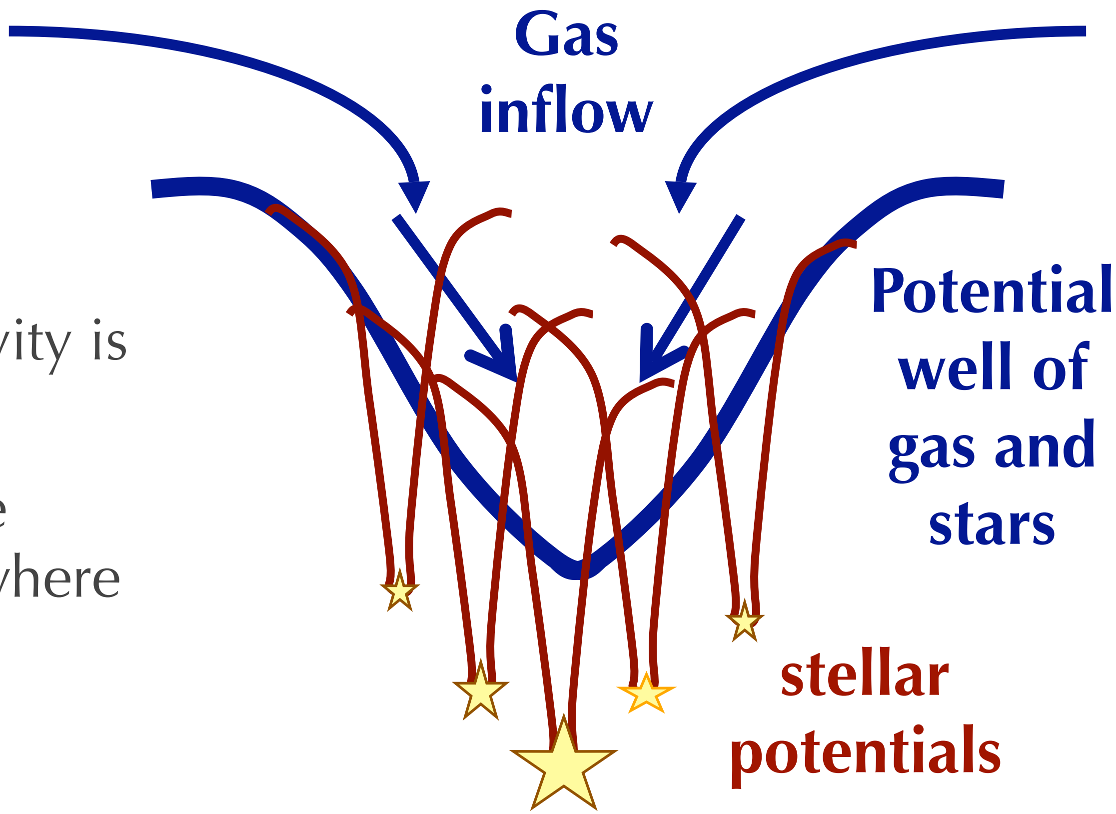
$Z = 10^{-5}\ Z_\odot$

Competitive accretion?

Bonnell & Bate (2006):

Need a situation where gravity is dominating the dynamics.

A collapsing, Jeans unstable region, creates a situation where competitive accretion is **unavoidable.**

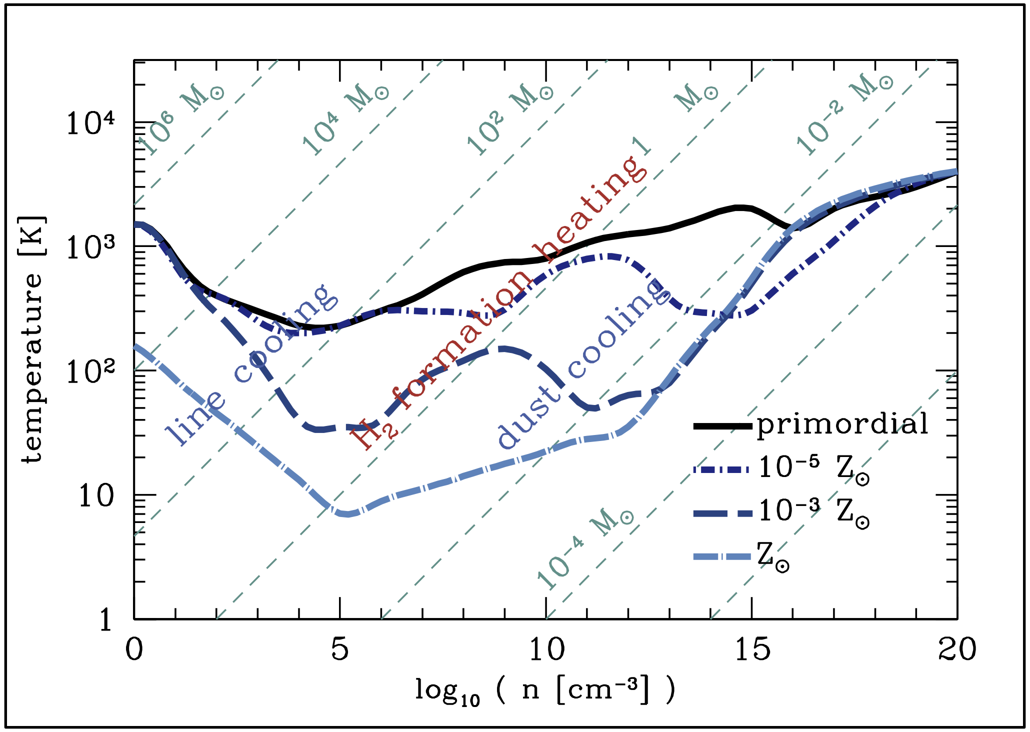


A universal slope for the IMF?

Clark, Glover, Bonnell & Klessen (2009):

Any regime in which $t_{cool} < t_{ff}$ during collapse gives you these conditions.

Could be line and/or dust cooling.



Caveats...

We‘re using an equation of state, so no self-consistent heating-cooling and dynamics.

Assumptions about the dust: are scaled down solar properties valid?

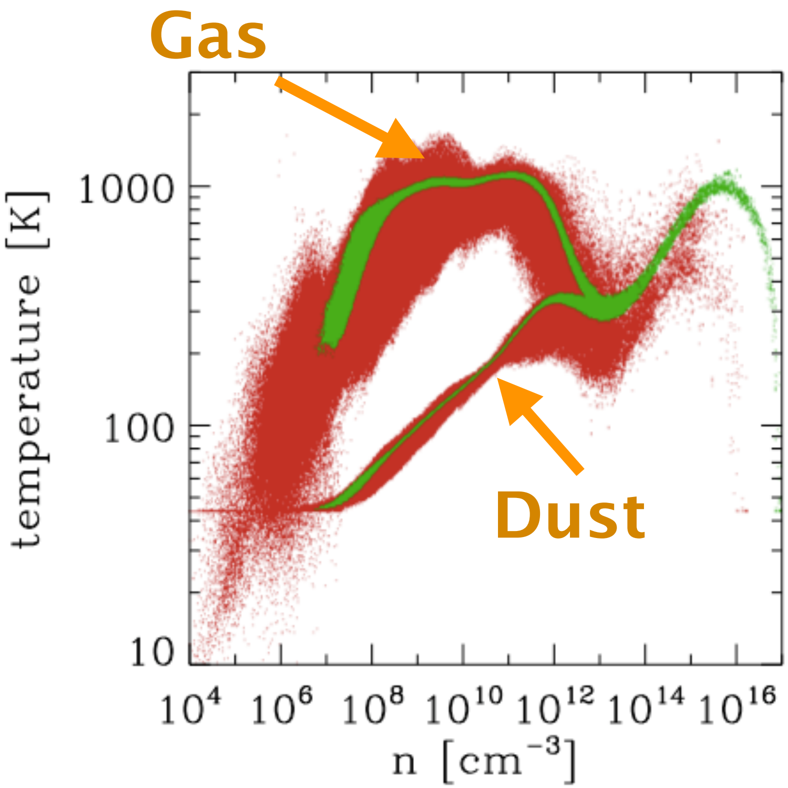
Uncertainties in the chemical reaction rates will affect the temperature - density relationship.

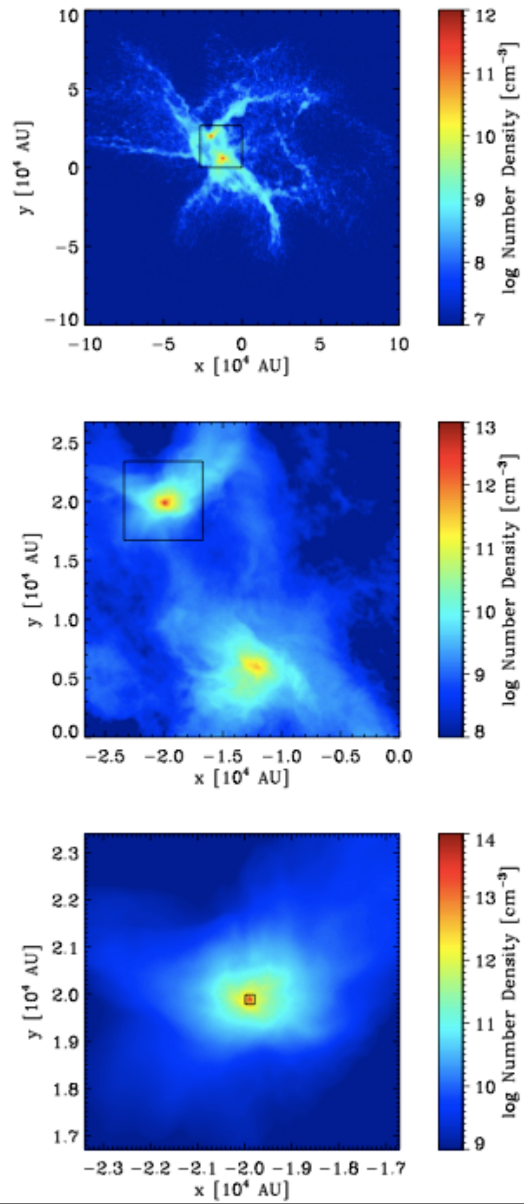
No feed-back from the stars: assuming that dust can cope with the accretion luminosity.

Assumes that chemical enrichment allows $10^{-5}\ Z_{\odot}$ gas: may always overshoot to higher values.

Caveat i) Self-consistent thermodynamics

Gustavo Dopcke's PhD:





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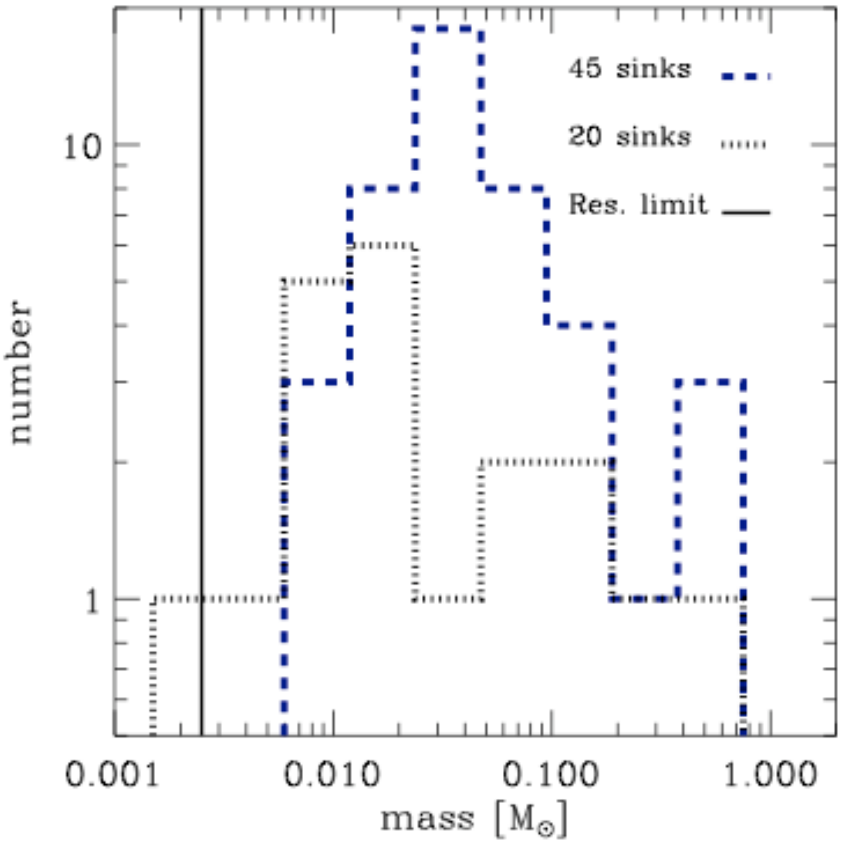
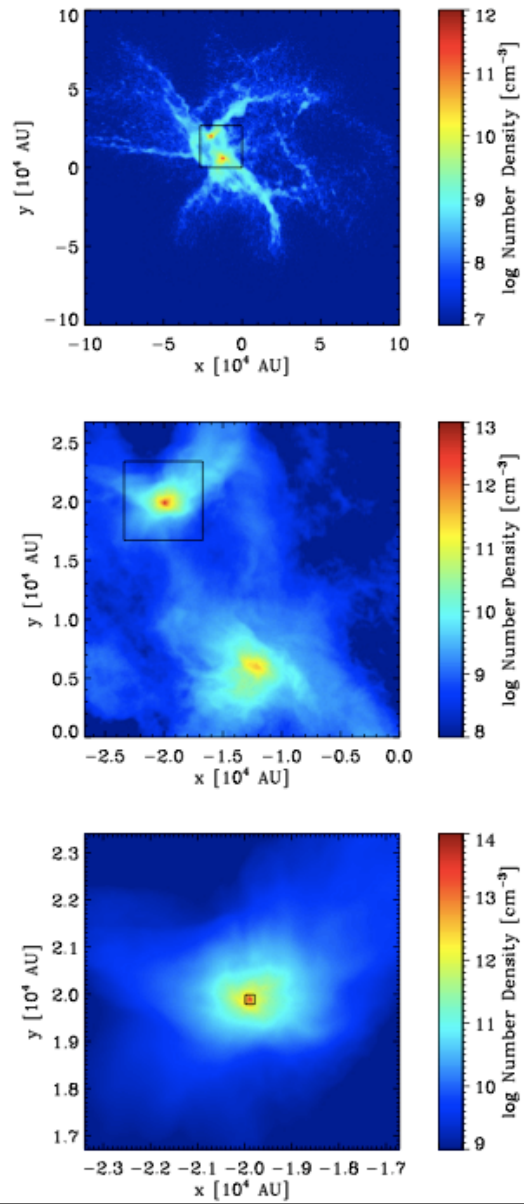
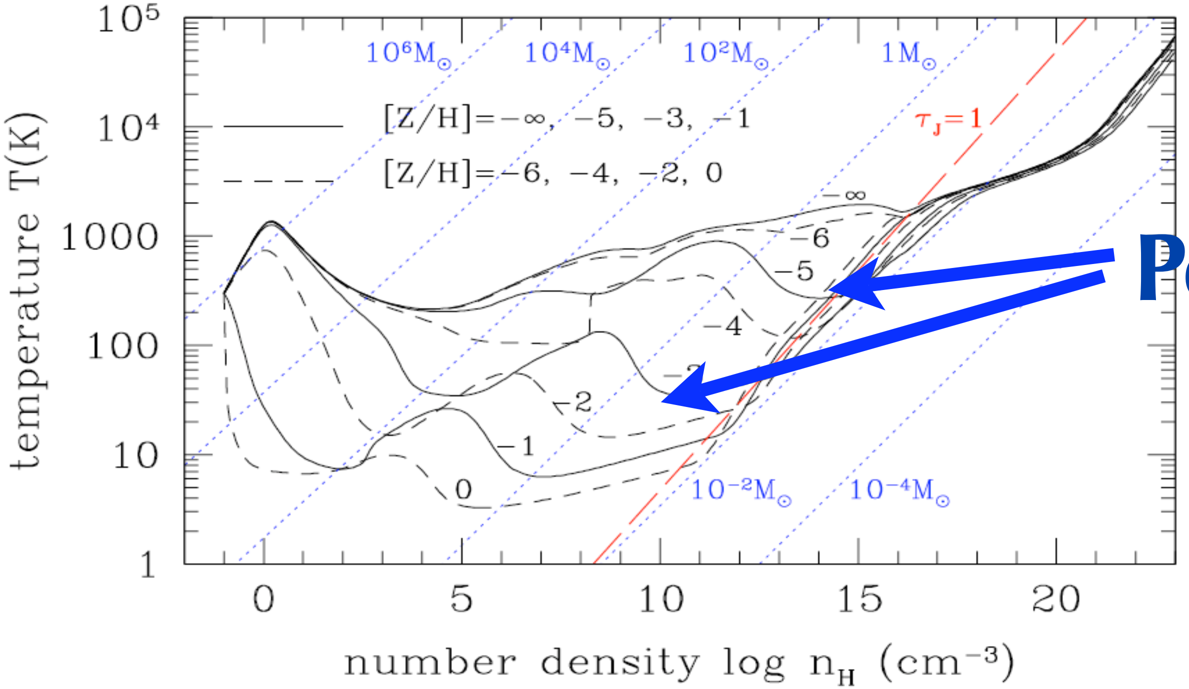




Conclusions from these models

- The peak in the mass function is closely related to the Jeans mass at the trough of the cooling curve.
- The upper mass function is roughly Salpeter-like.



Peak + Salpeter

So what about the Pop III IMF?

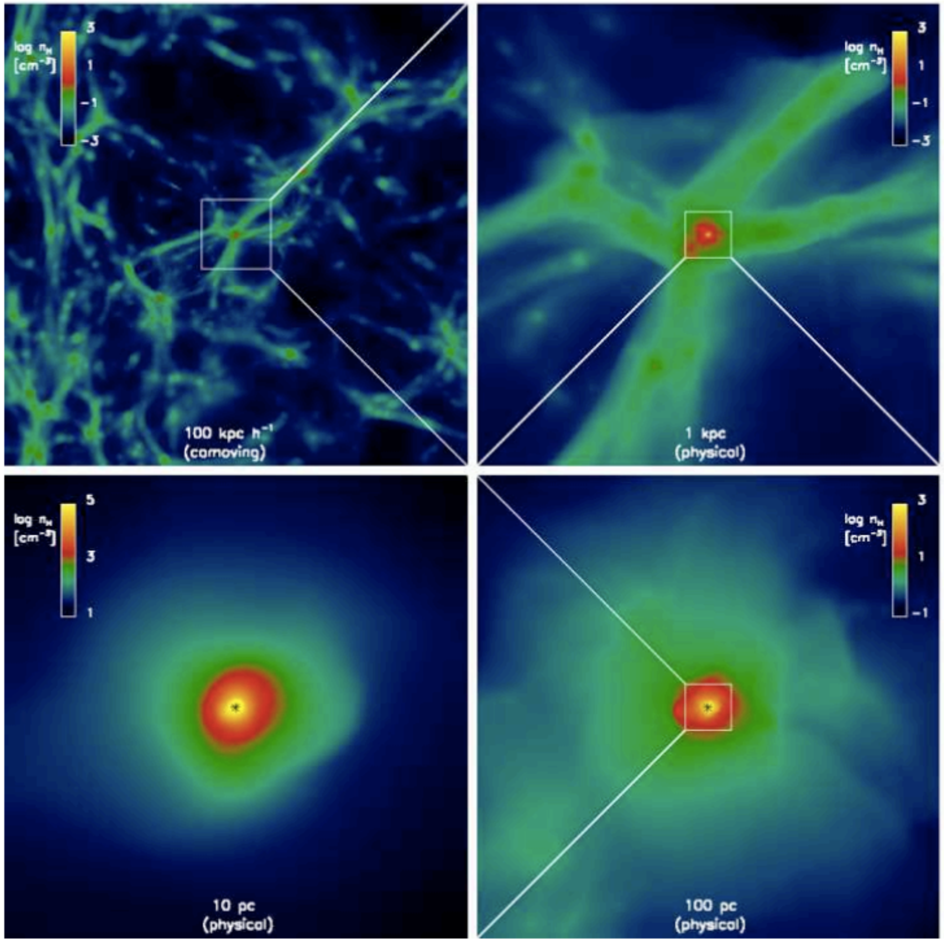
Cosmological initial conditions

Initial conditions from a cosmological GADGET2 simulation (performed by T. H. Greif, similar to that in Stacy et al 2010):

- 200 kpc (co-moving) cosmological box
- Λ-CDM: $\Omega_m = 1 - \Omega_\Lambda = 0.3$; $\Omega_b = 0.04$; $h = H_0/100\ \mathrm{km\ s^{-1} Mpc^{-1}} = 0.7$; $\sigma_8 = 0.9$
- Evolved from $z = 99$ to 22, when baryons first become self-gravitating

Then re-zoom the simulation:

- Go from Thomas' 5 M_{sun} SPH resolution to 0.05 M_{sun} , and run collapse to $n = 10^{13}$ cm^{-3}.
- Refine final stages of collapse to 0.001 M_{sun} resolution --> 200,000 SPH particles in disc



Stacy, Greif & Bromm (2010)

Additional components

Chemical processes:

- 3-body H_2 formation heating.
- Rotational + vibrational line-emission from H_2 (Glover & Abel 2008).
- At high densities, H_2 energy levels are computed accounting for the escape-probability for the photons (Yoshida et al 2006).
- Collision induced emission (CIE; Ripamonti & Abel 2004) + reduction by continuum absorption (see Matt Turk).

Luminosity feedback:

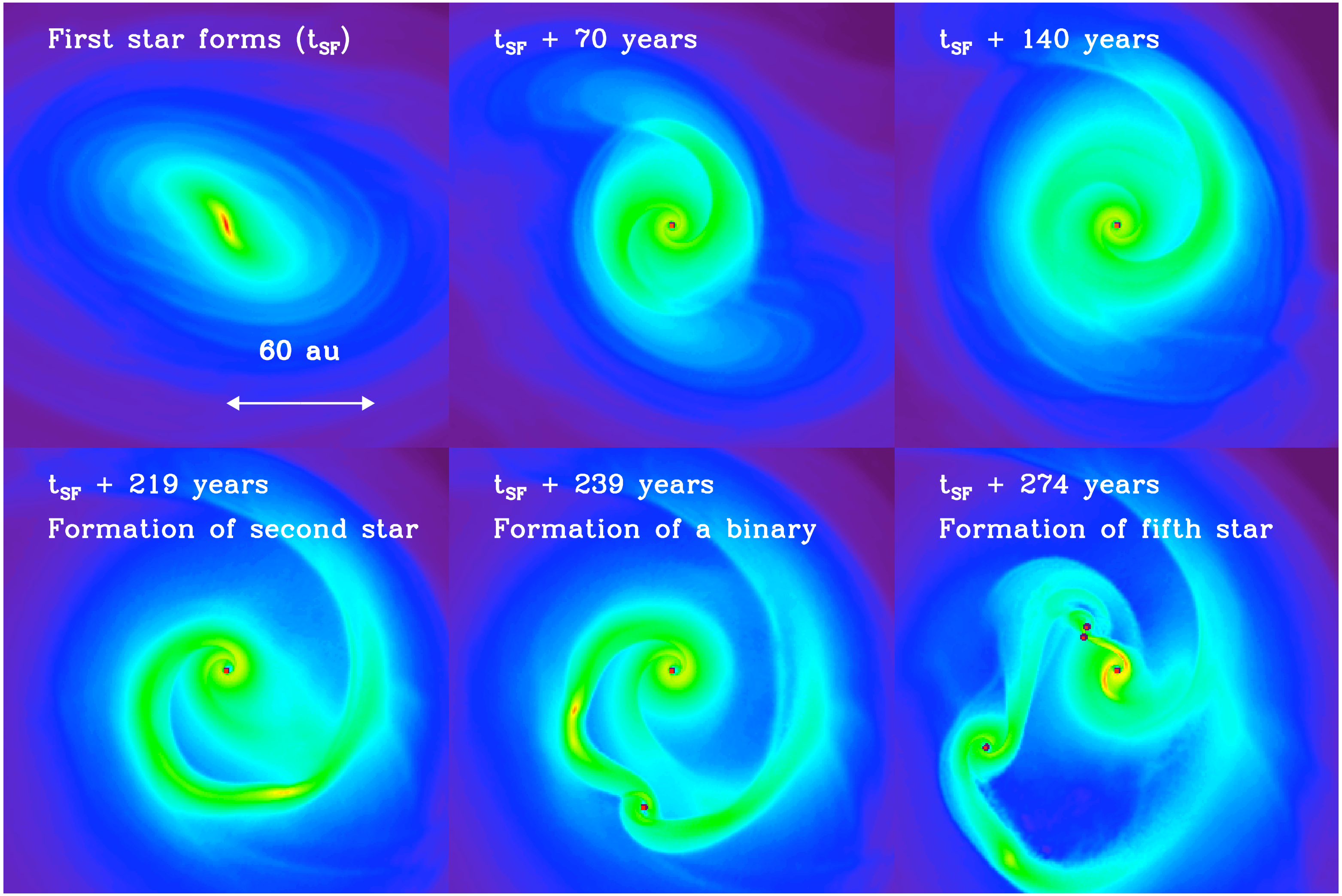
$$R_* = 26 M_*^{0.27} (\dot{M}/10^{-3})^{0.41}$$

$$L_{acc} = G M_* \dot{M} / R_*$$

$$\Gamma_{acc} = \rho_g \kappa_P \left(\frac{L_{acc}}{4\pi r^2} \right)$$

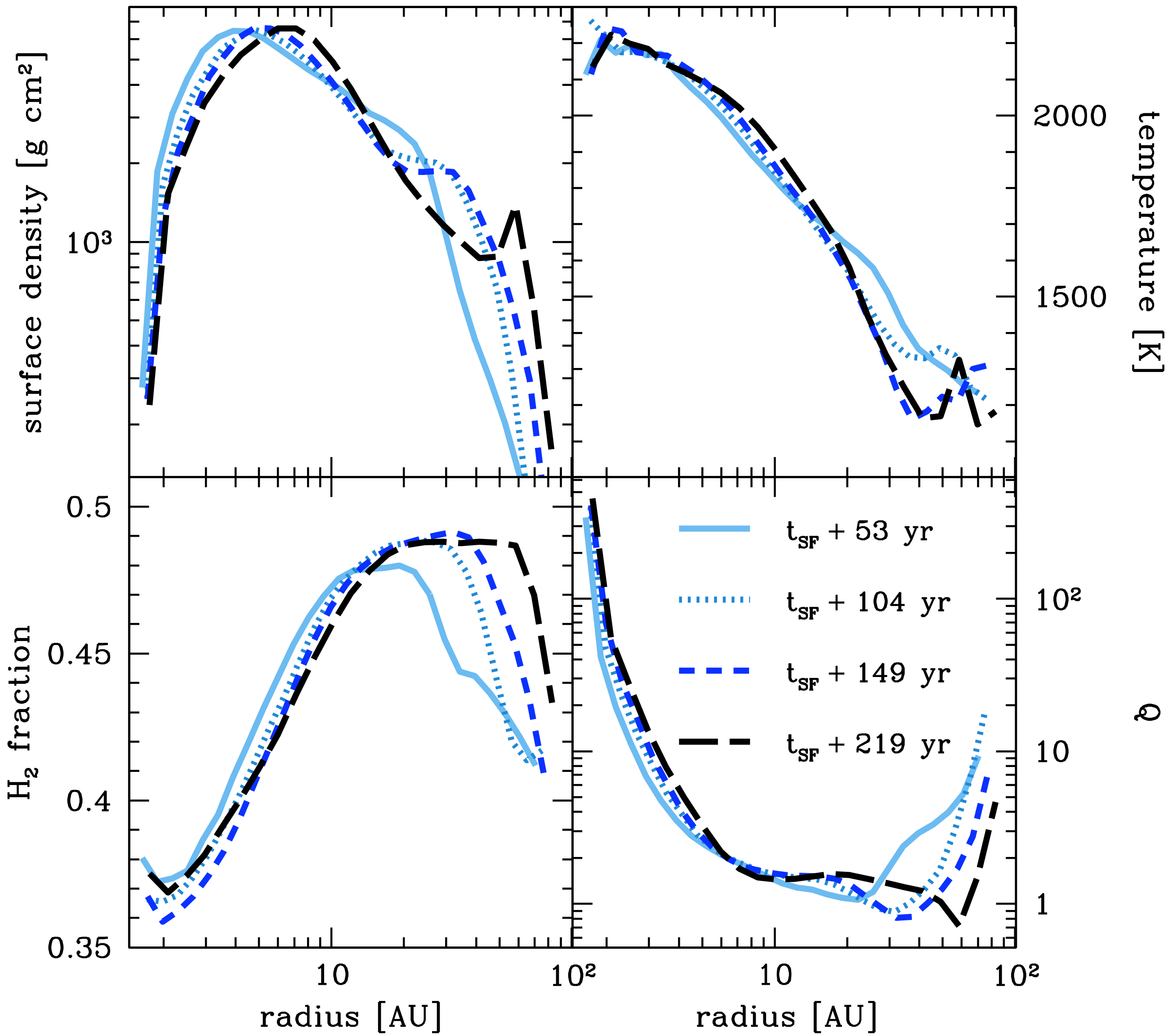
- Mass-radius relationship from Stahler, Palla & Salpeter (1986).
- Plank mean opacities from Mayer & Duschl (2005).
- We fix L_{acc} at 10^{-2} M_{sun} yr^{-1} in our current simulations.

Fragmentation around Pop III protostellar discs?



Clark et al (2010, *submitted*)

So why does the disc form stars?



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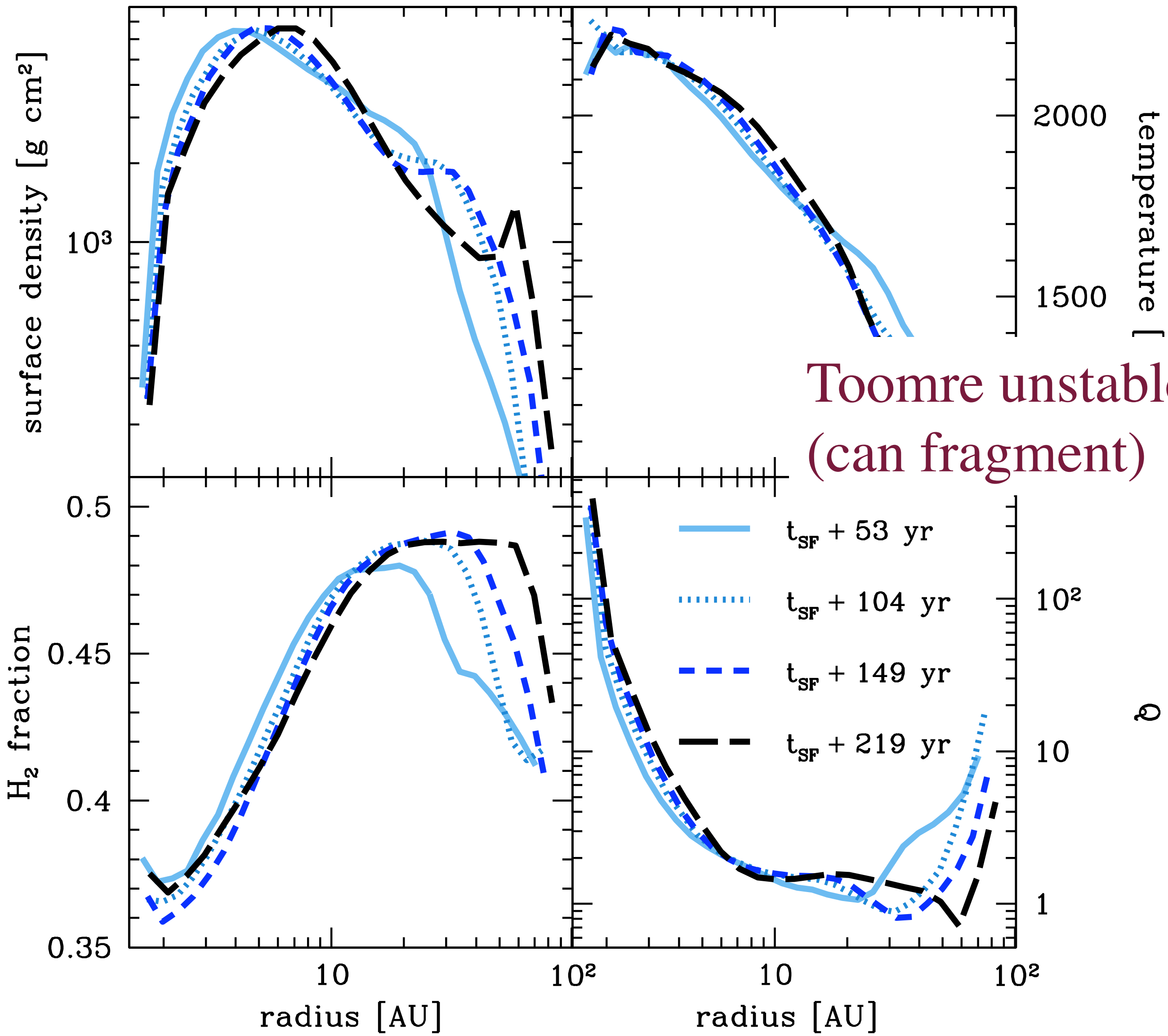
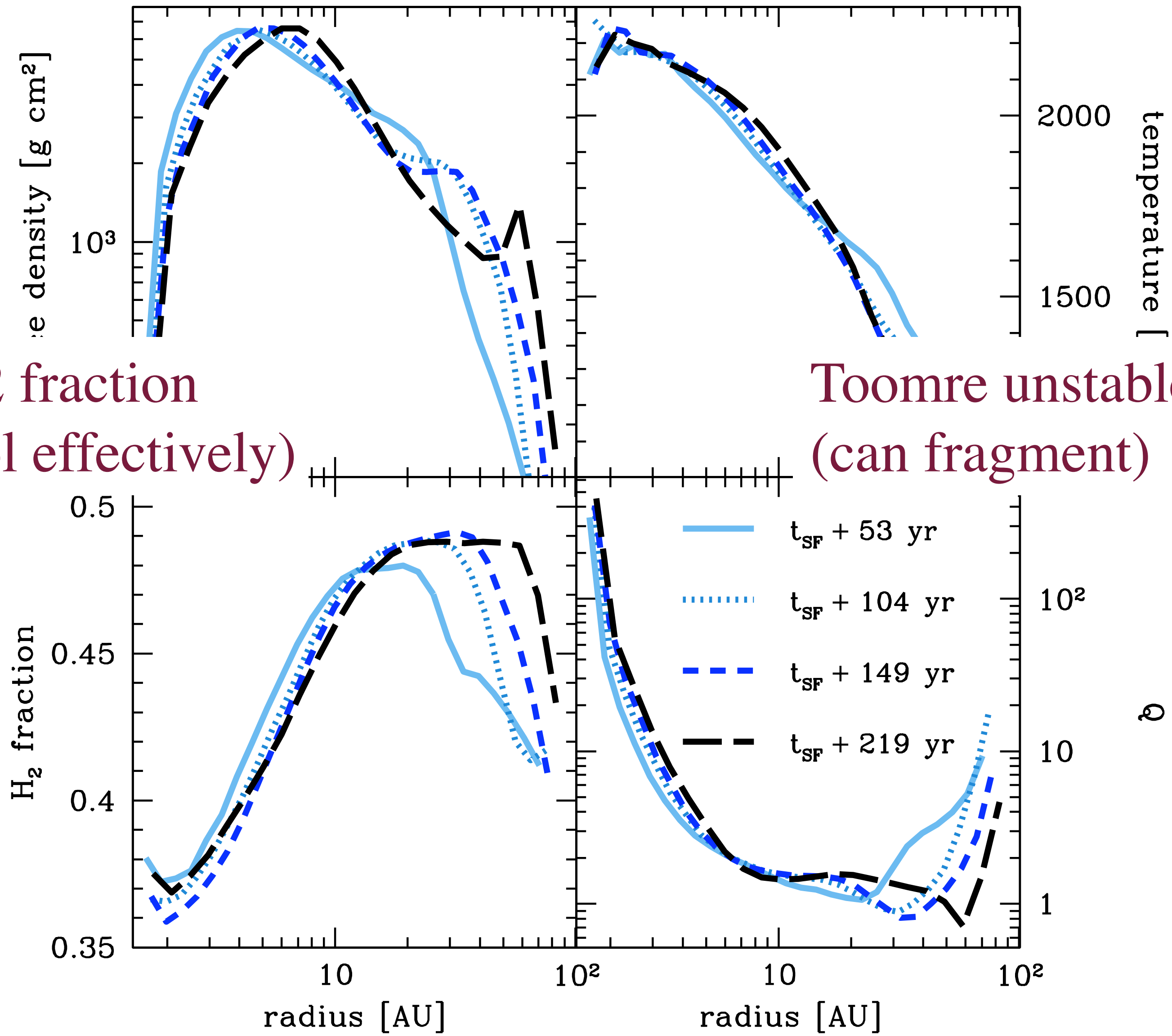


Toomre unstable
(can fragment)

So why does the disc form stars?



High H2 fraction
(can cool effectively)

Toomre unstable
(can fragment)

IMF of Pop III stars?

Too early to tell at these scales.

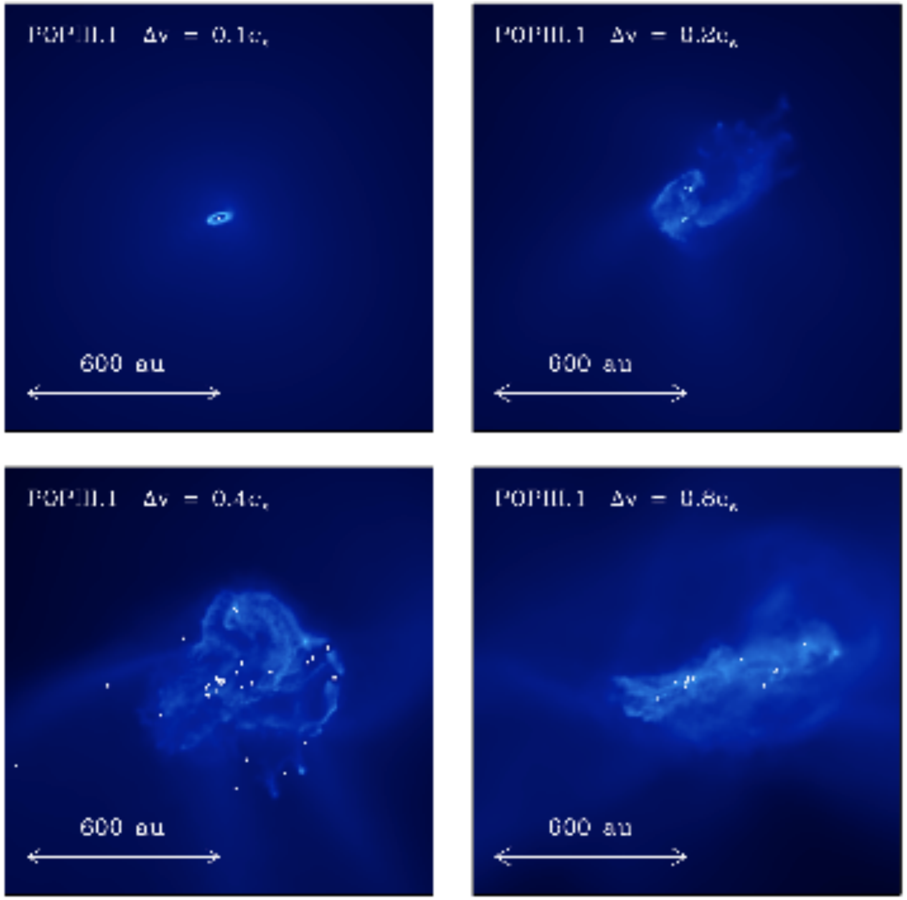
But binary (and small N) systems seem unavoidable

What about larger scales?

BE spheres injected with subsonic turbulence:

- Primordial gas Pop III.1 and Pop III.2 channels.
- Find significant fragmentation in the Pop III.1 but **VERY** little in the Pop III.2 case.
- If baryonic component of mini-halos has significant turbulent component (e.g. Turk, Abel & O'Shea 2009), fragmentation may be common.

Pop III.1

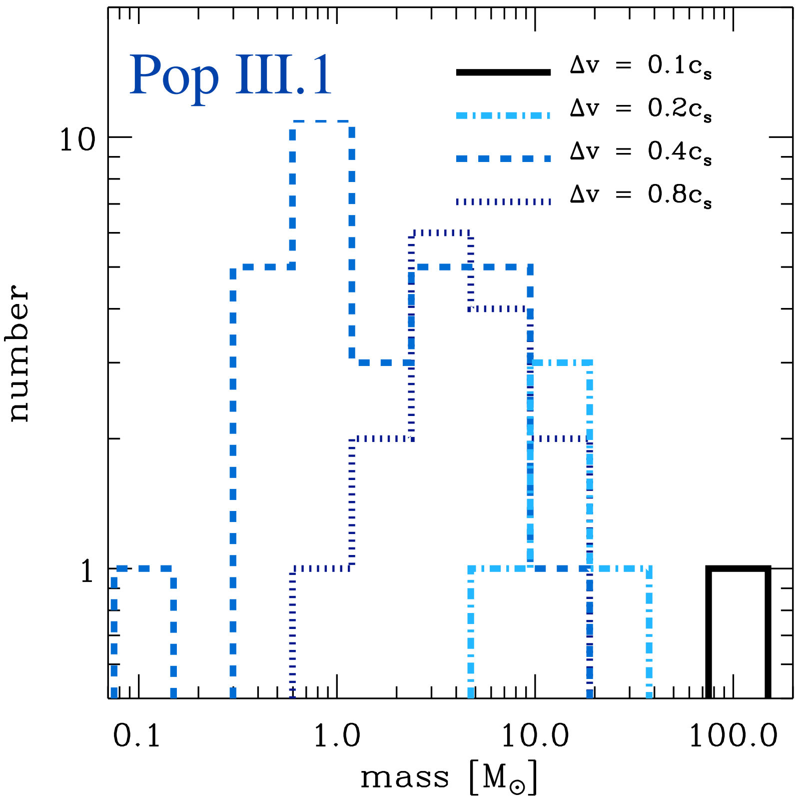


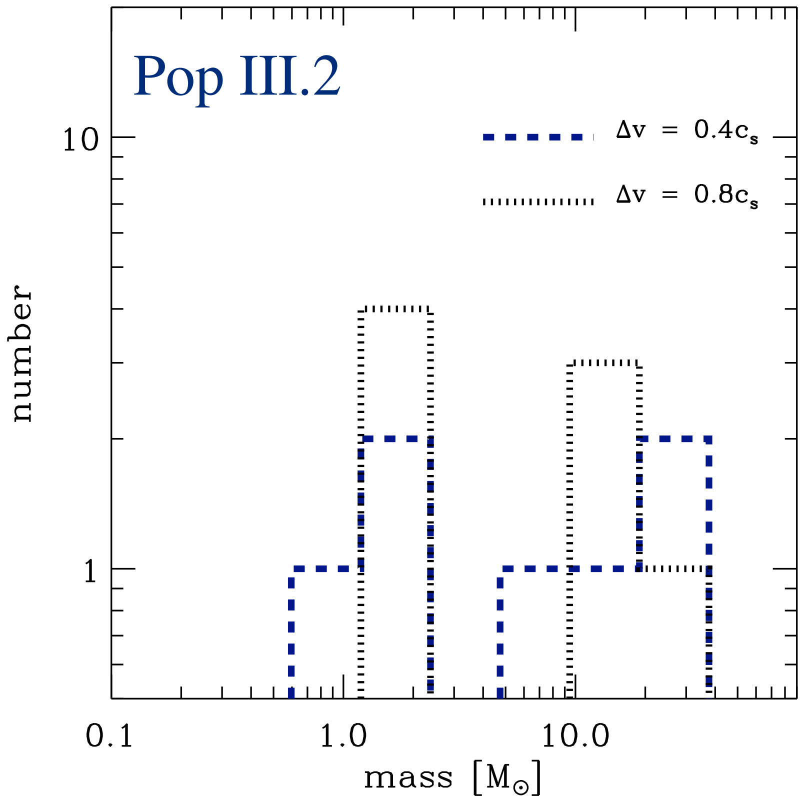
Clark, Glover, Klessen & Bromm (2010)

Pop III.1/III.2 IMF?

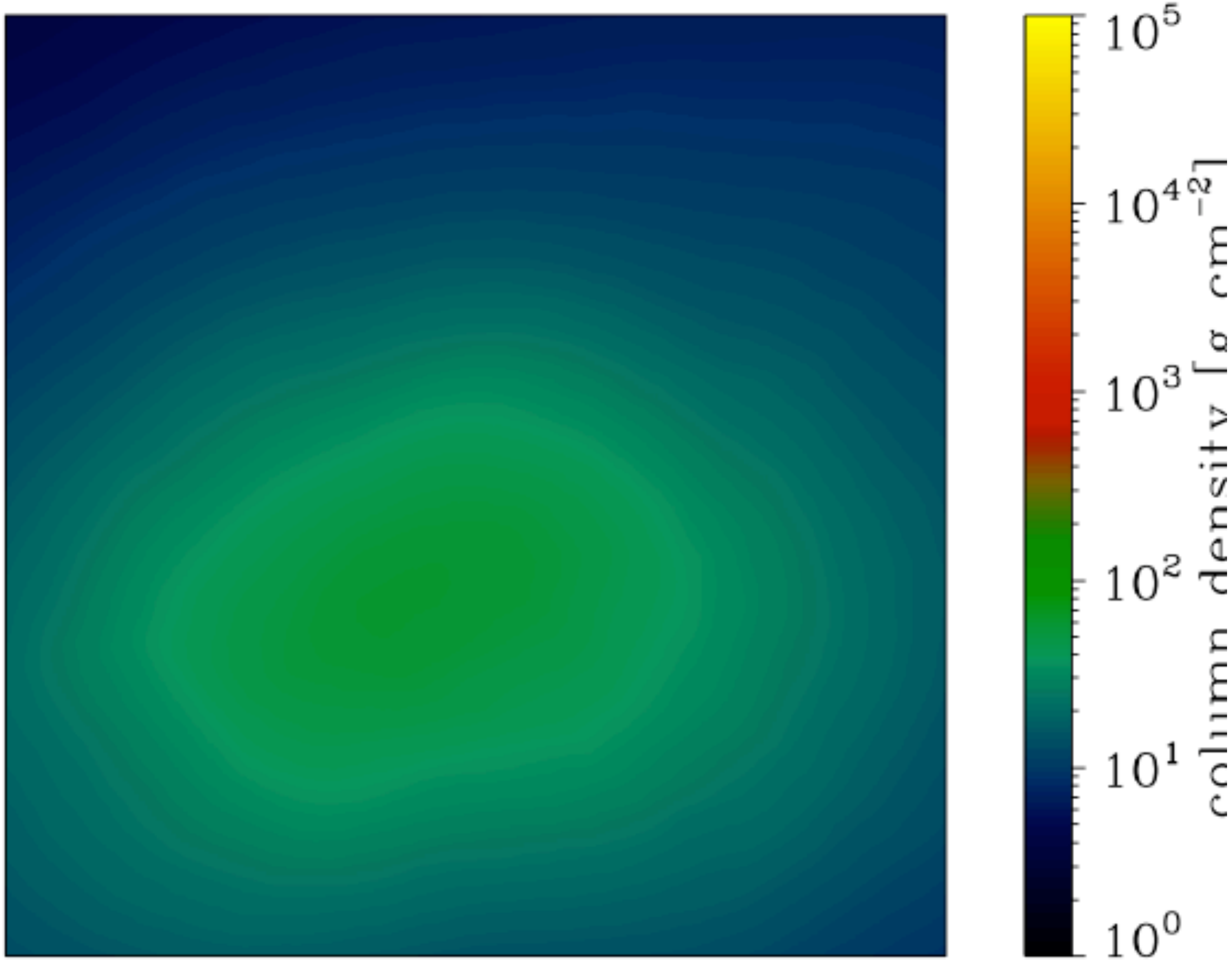
So if our little experiment is related to reality (!):

Clark, Glover, Klessen & Bromm (2010)





Clearly full cosmological simulations are necessary to test how likely these initial conditions are.



10^5
10^4
10^3
10^2
10^1
10^0
column density [g cm^{-2}]

Summary

- Dust cooling can provide an efficient transition to the type of low-mass star formation that we see today.
- The upper mass function is roughly Salpeter-like due to competitive accretion.
- The turnover in the IMF (or characteristic mass) appears to be connected to the T-rho space at which dust cooling is most effective.
- The Pop III IMF is more uncertain, however fragmentation is inevitable, and a broad IMF seems likely.
- If Pop III stars do form in clusters, then Salpeter slope is possible with a turnover $> 1 M_\odot$