The IMF of primordial stars

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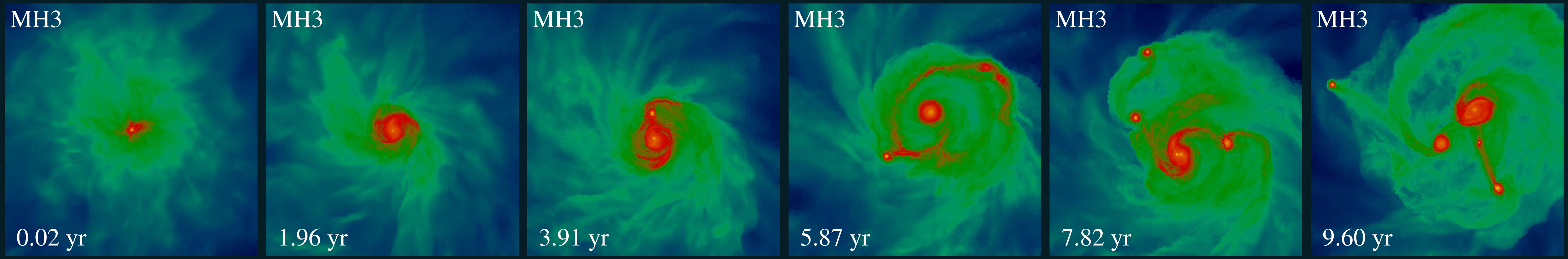
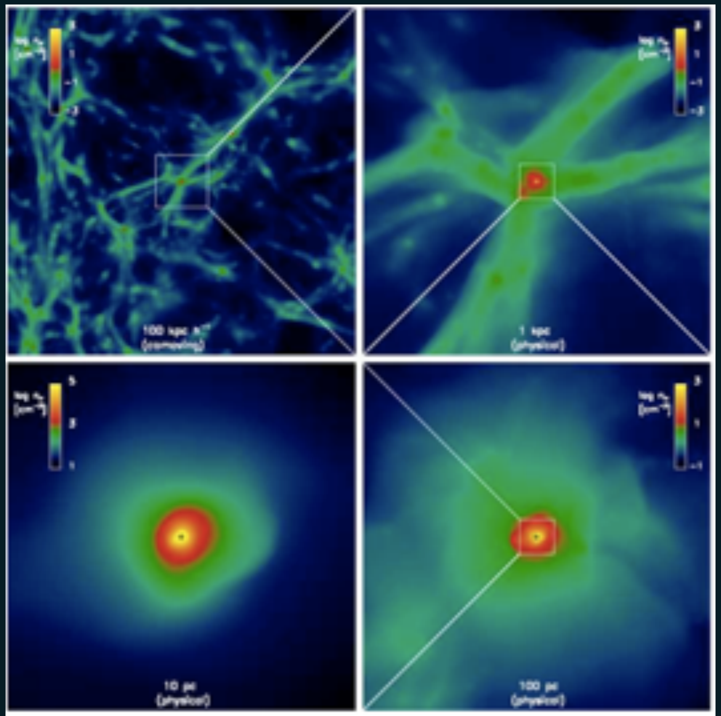


It was all so nice and simple...

Old picture:

- H_2 is a **poor** coolant.
- Gas is **hot** during the formation of the first stars ~ 1000K
- Gas collapses **quasi-statically**, and only has ~**1 Jeans mass**.
- Steep density gradient so no fragmentation + c_s^3/G is big!
- Forms a **single**, **massive** star (> 100 $M_\odot$?).

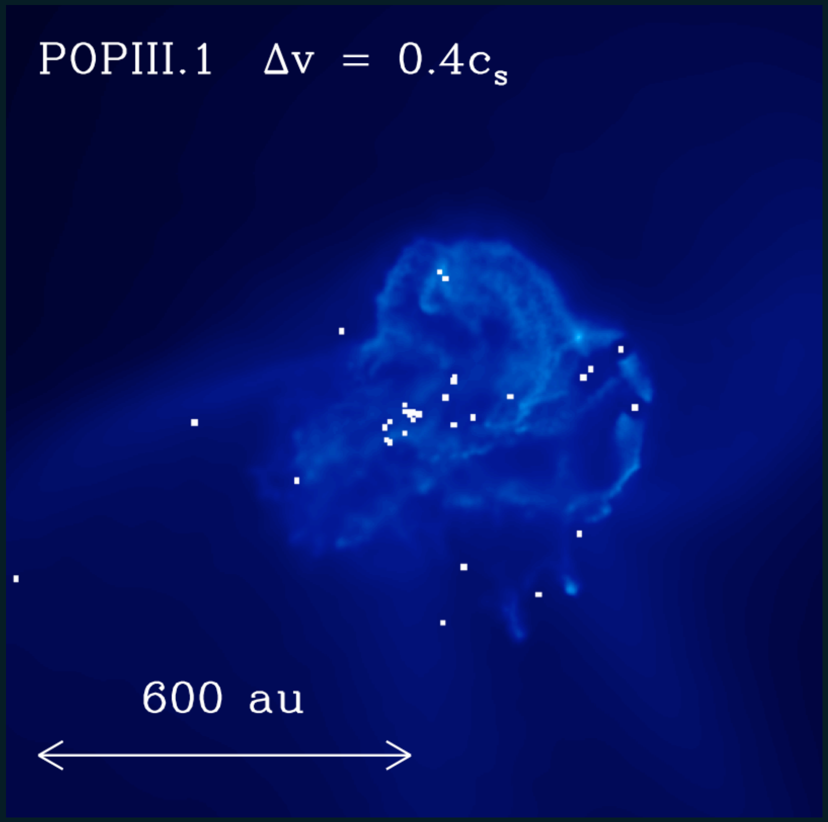
- Relatively simple prescription of star formation (compared to present-day star formation).
- Enabled a quasi-analytic treatment of the re-ionisation of the Universe and suppression of star formation in neighbouring halos.

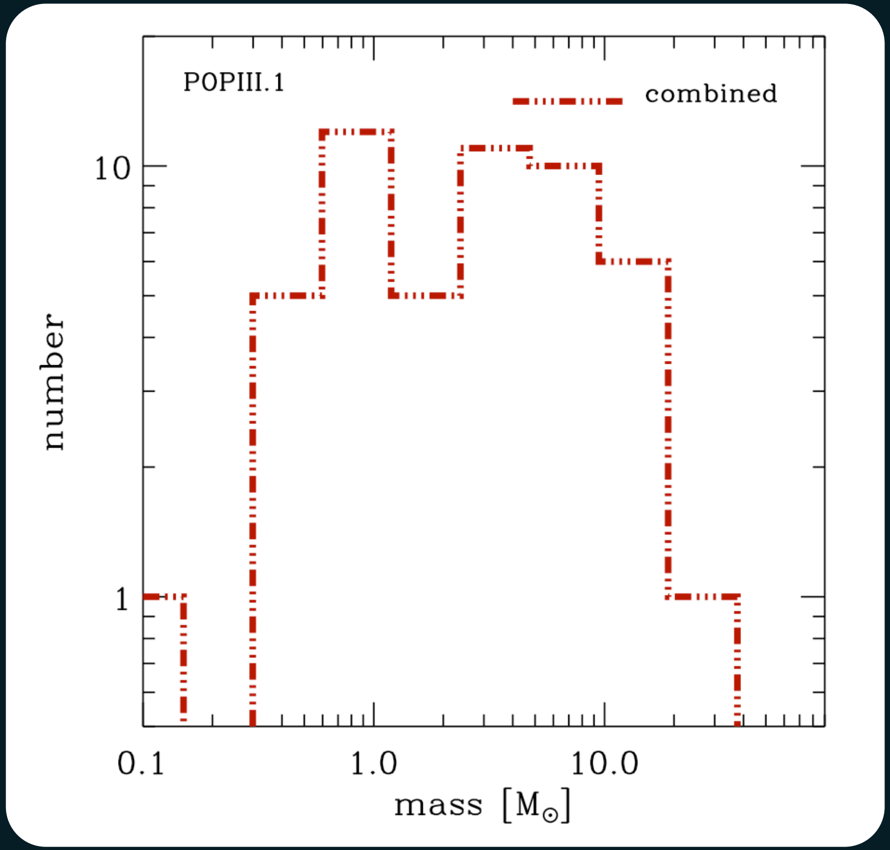


Stacy, Greif and Bromm (2010)

But then it got messy...

Clark et al. (2011a)





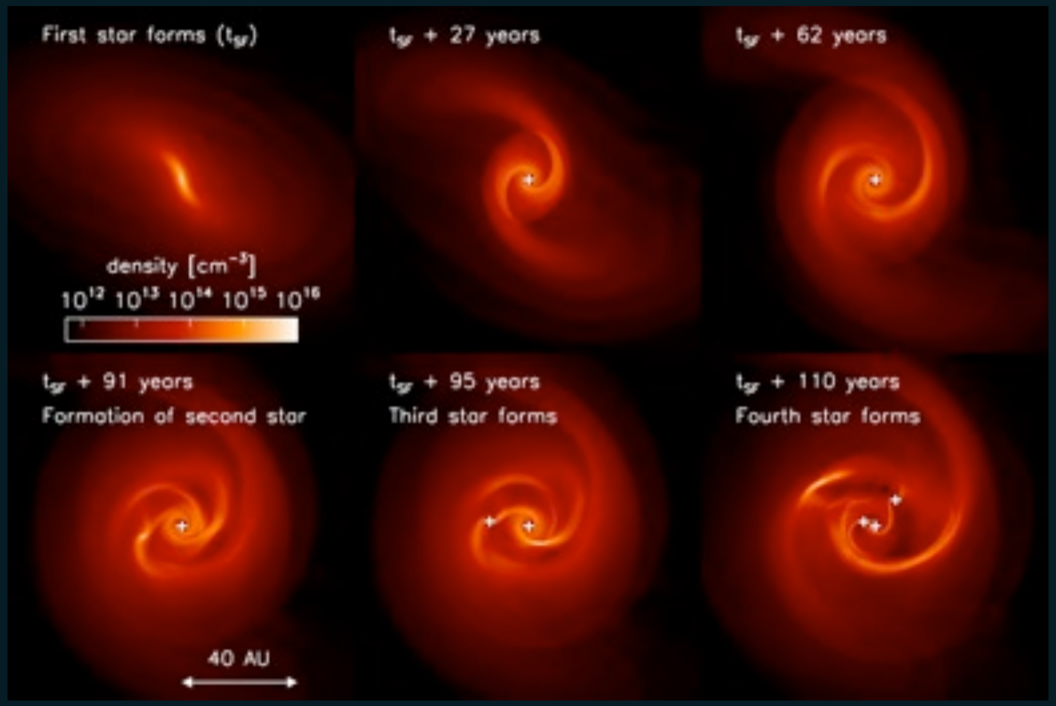
Primordial gas **IS** susceptible to fragmentation:

- H_2 cooling is sufficient at high densities to allow gas to fragment and collapse locally.
- Just needs a "window of opportunity" - disc, turbulence, etc.
- Fragmentation seems to very efficient once it gets going.
- Can form a cluster with a broad range of stellar masses.

SPH simulations - Cosmological ICs with Feedback?

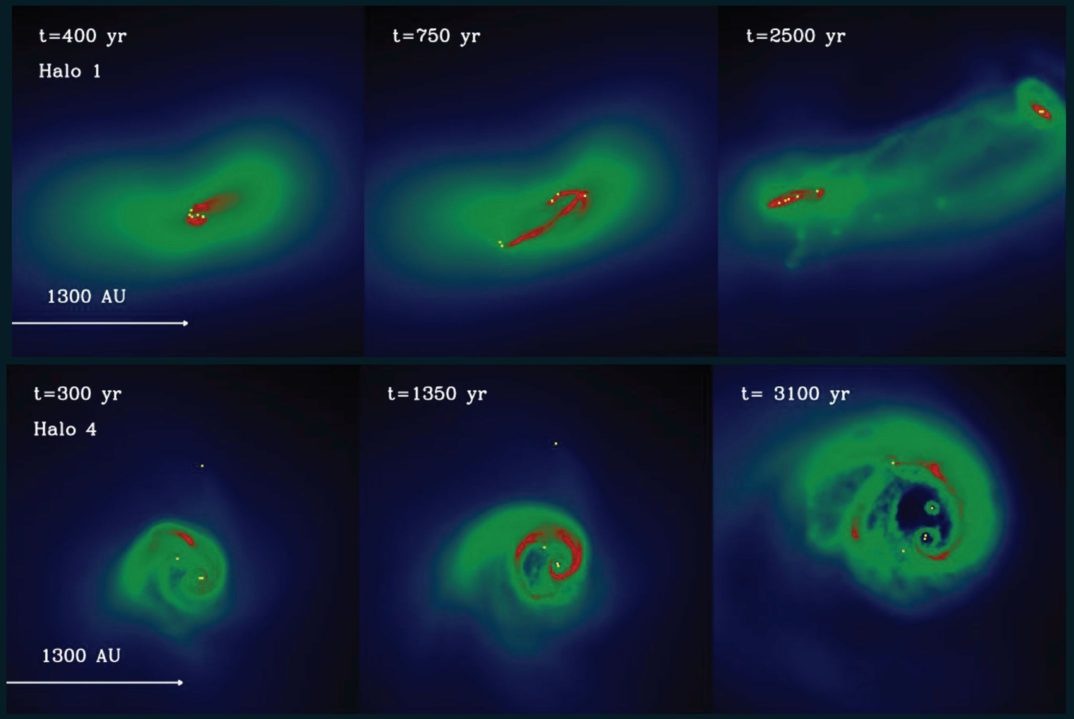
Clark et al (2011b):

- Found that discs that surround the first protostar are extremely gravitationally unstable.
- Accretion luminosity feedback from the new protostars was unable to suppress fragmentation in the disc.
- In 100 yr, we form 4 protostars!



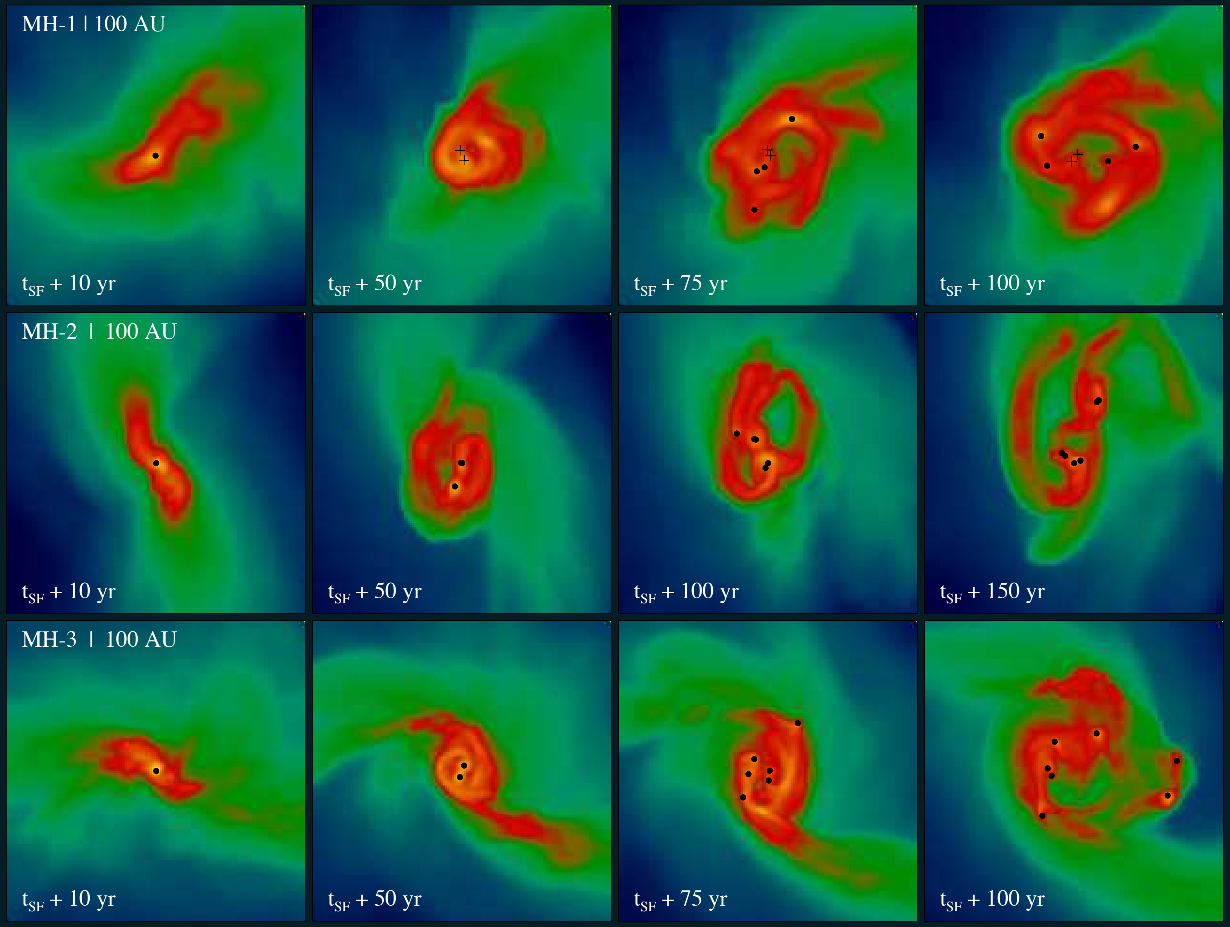
Smith et al (2011):

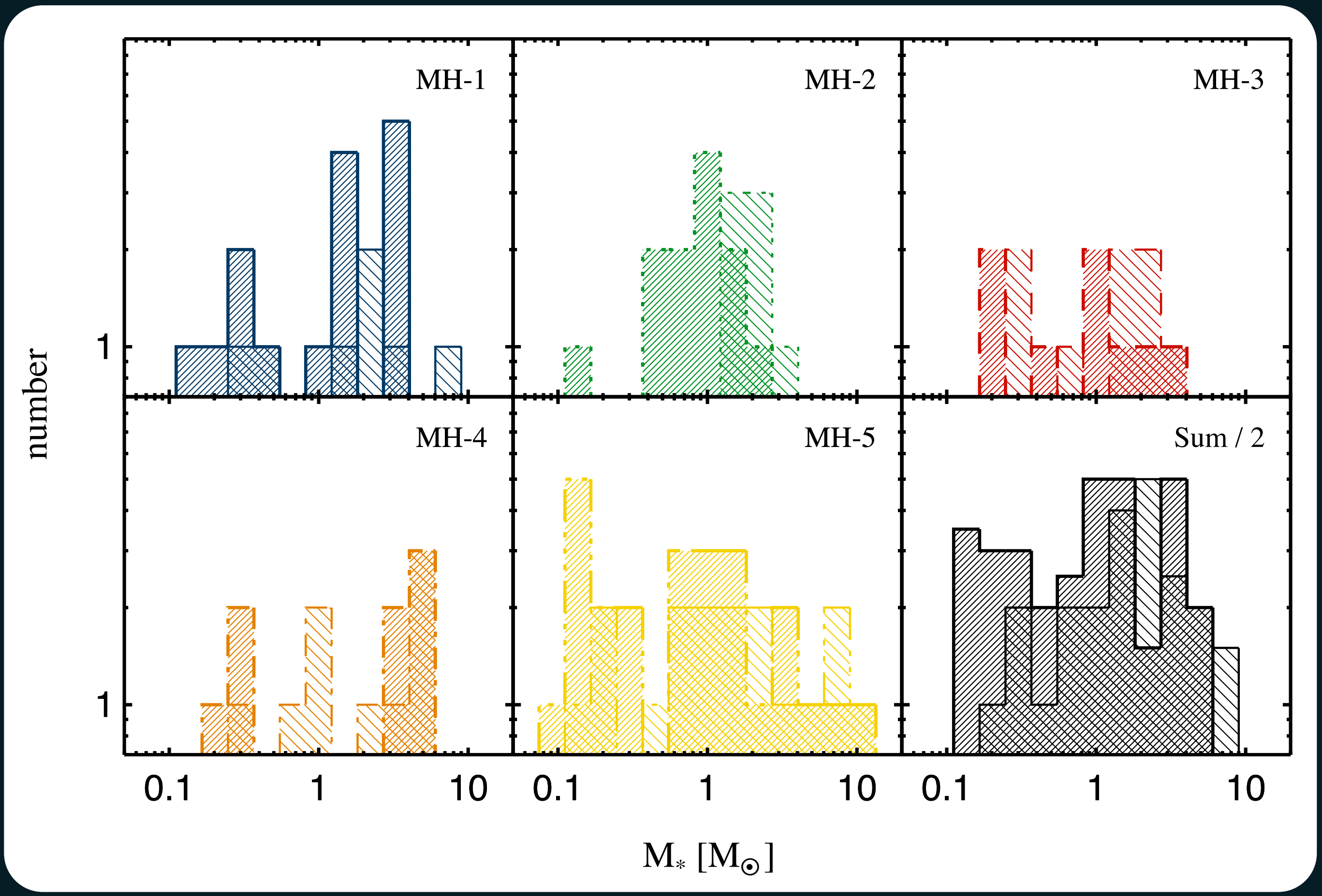
- Looked at larger scales, and longer timescales.
- Again found little influence of the feedback on the fragmentation properties.
- Simulations ran for 1000 - 10,000 yr



Different method of solving the fluid equations?

Greif et al. (2011, 2012):



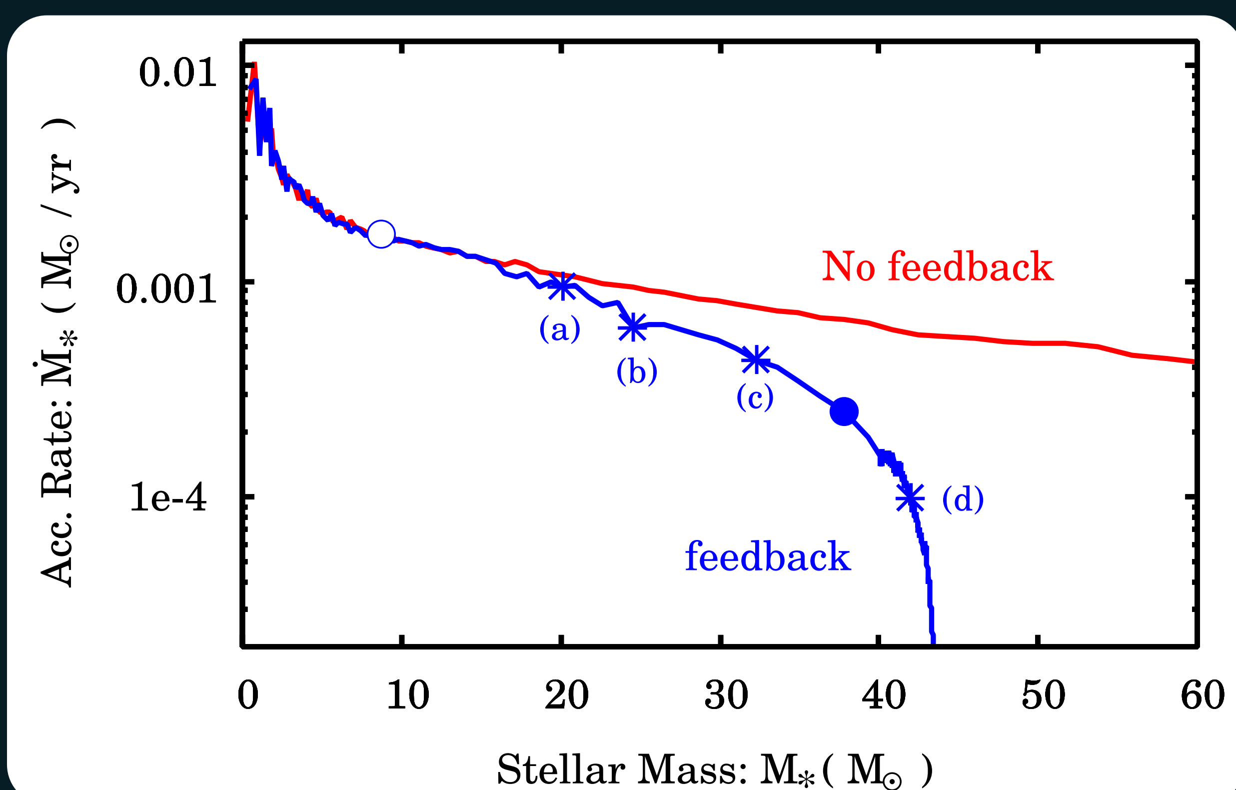


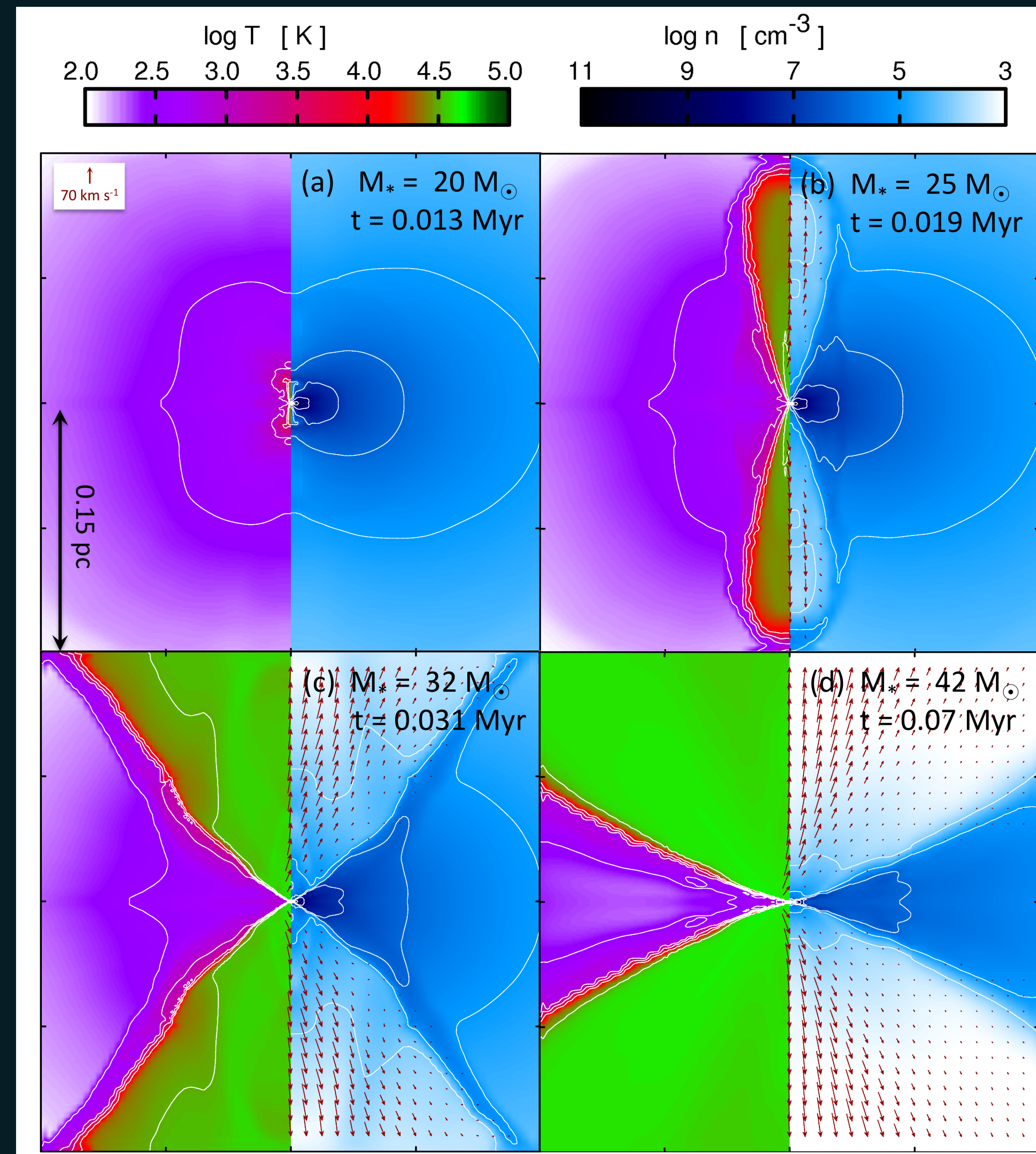
- Used *Arepo* (Springel 2010).
- Found the same behaviour in the fragmentation properties of primordial gas.
- Note that the sink particles are also slightly different in this code.
- General IMF from all simulations is 'flat', from $0.1 M_\odot$ up (same as Clark/Smith et...).

So when does the star formation end?

Hosokawa et al. (2012):

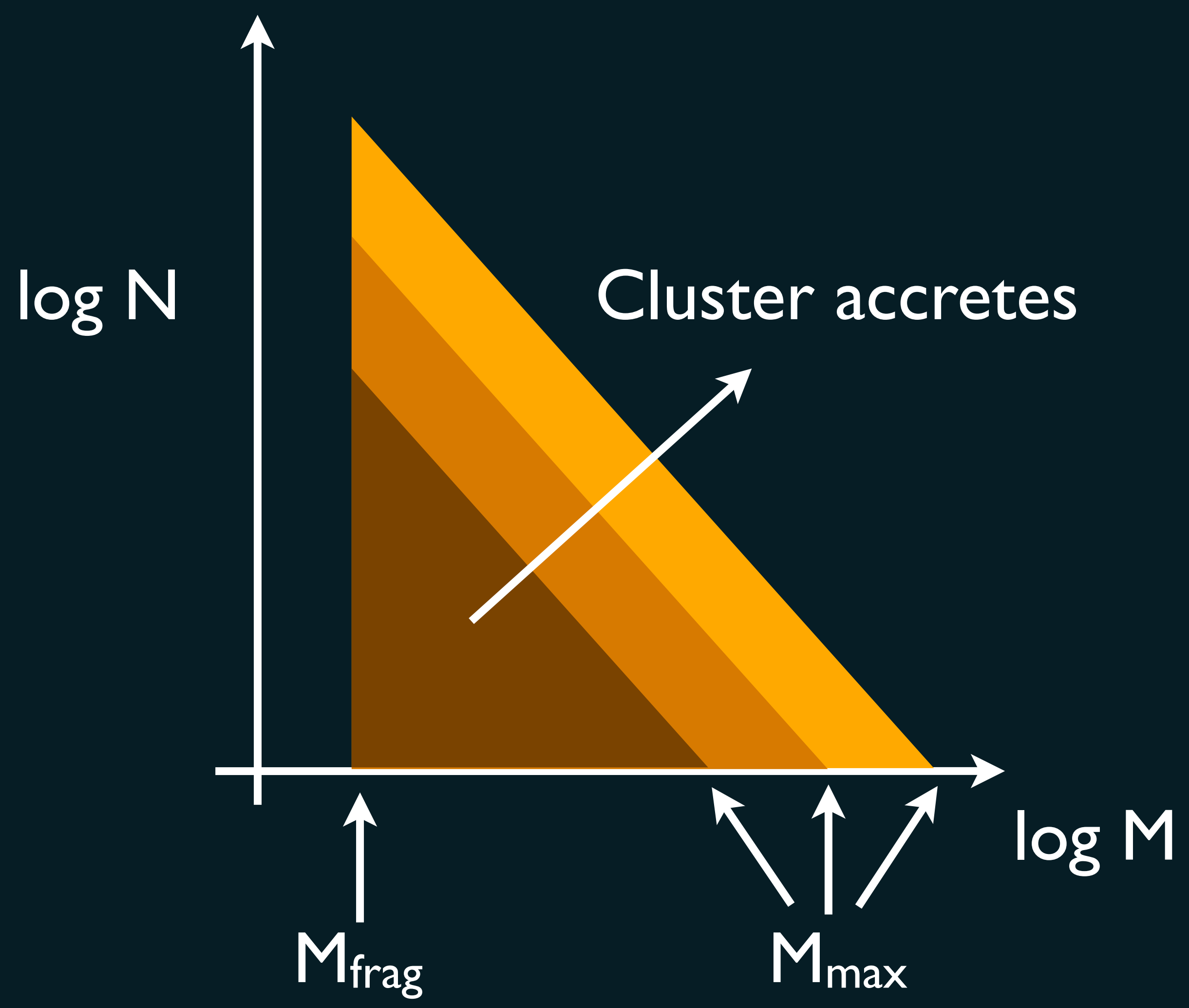
- 2D simulations show that radiative feedback can halt growth of central object once it reaches ~ 45 $M_\odot$.
- Is this when star formation ends?
- Can we use this together with the IMF to get a final cluster mass (halo SFE)?



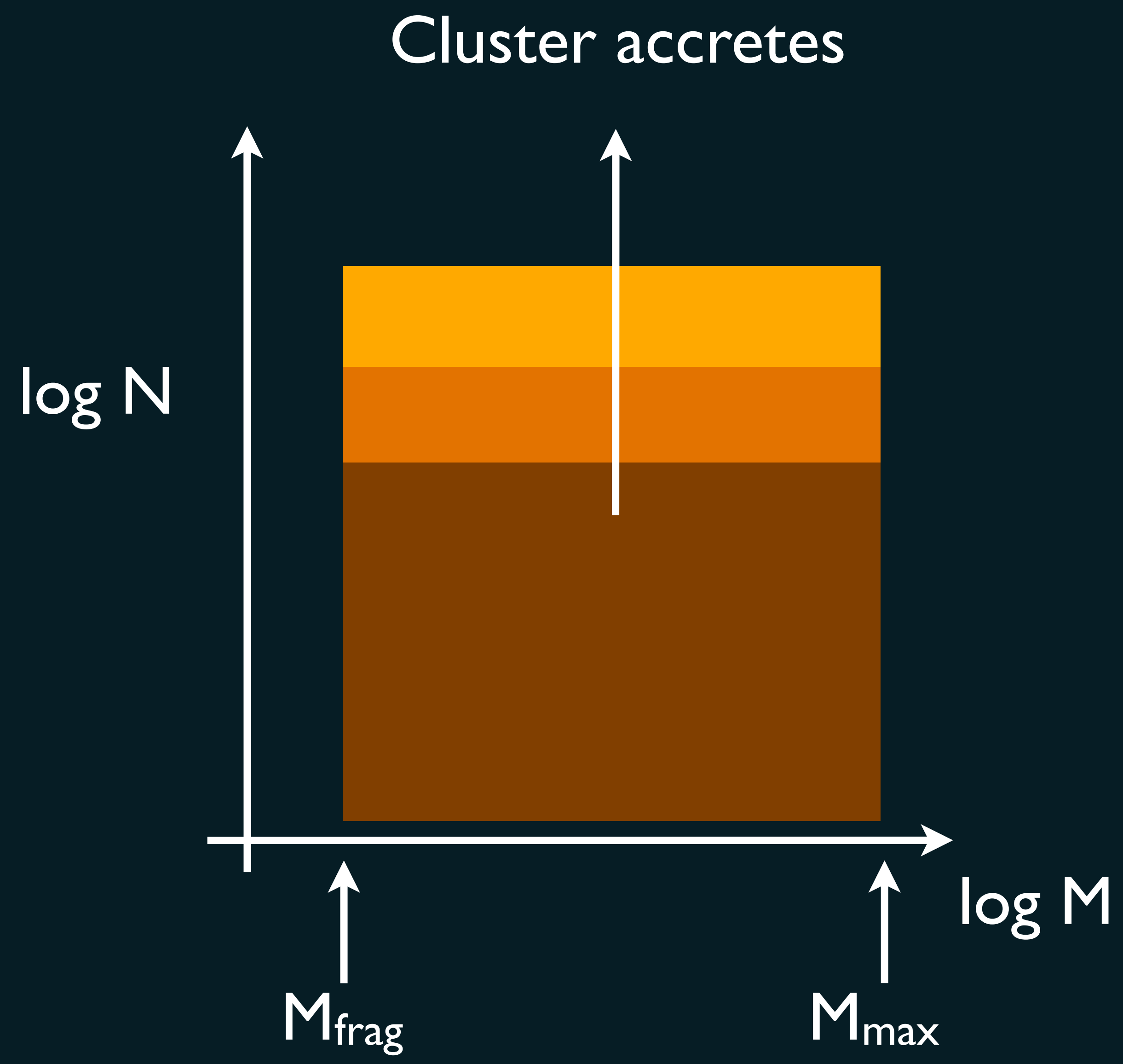


The problem with flat mass functions...

Imagine we have a standard power-law mass function:

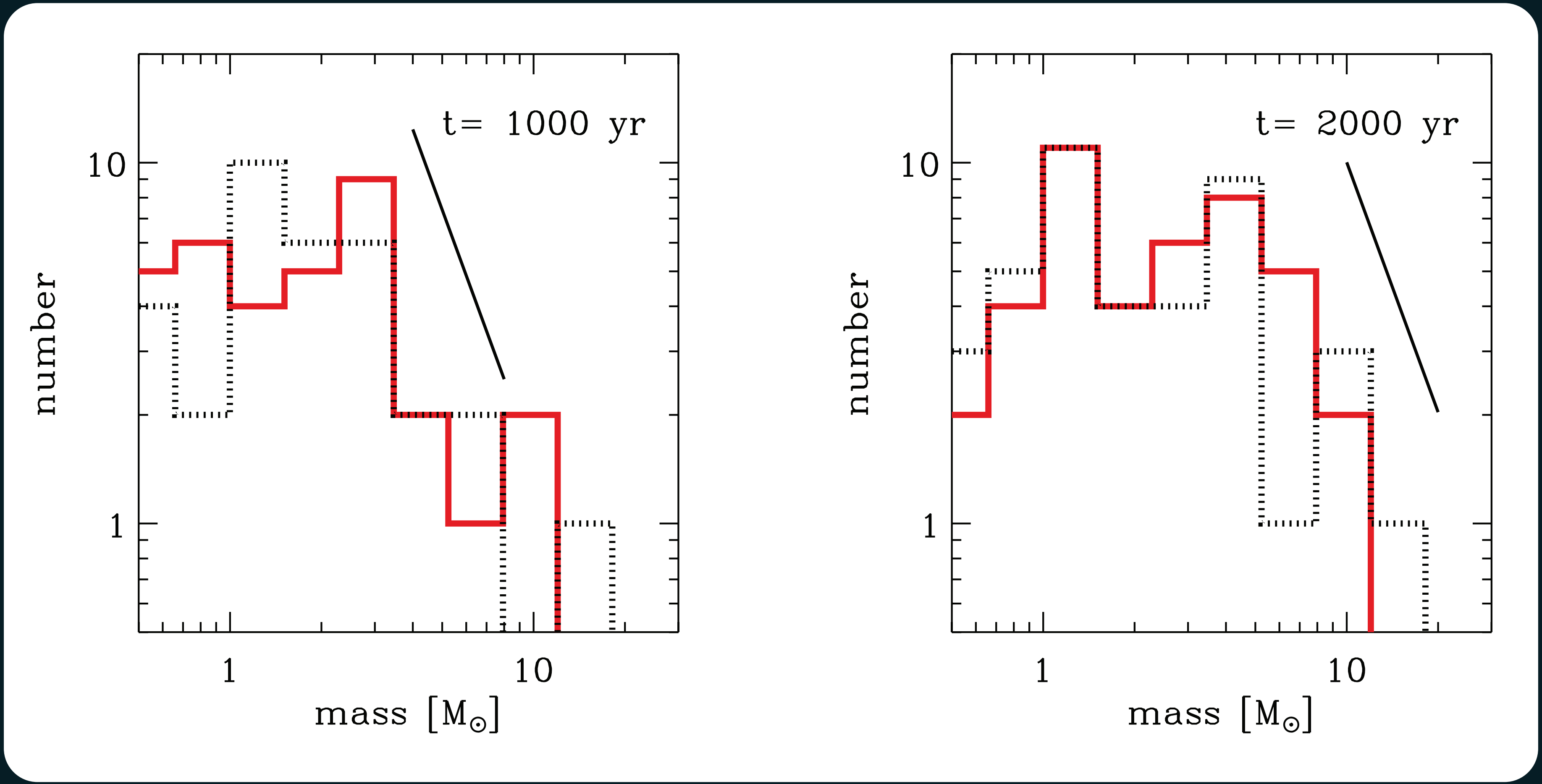


Now imagine a flat mass function:



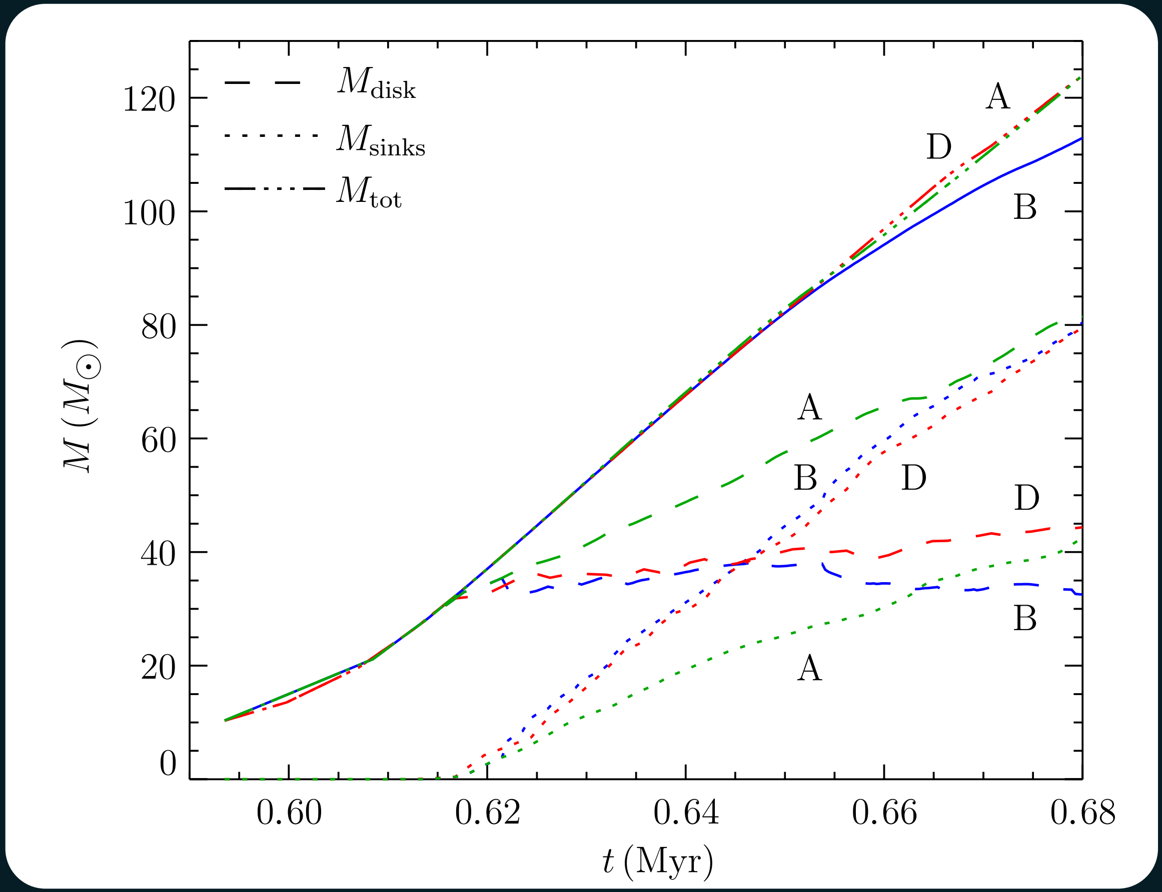
What do the simulations show....

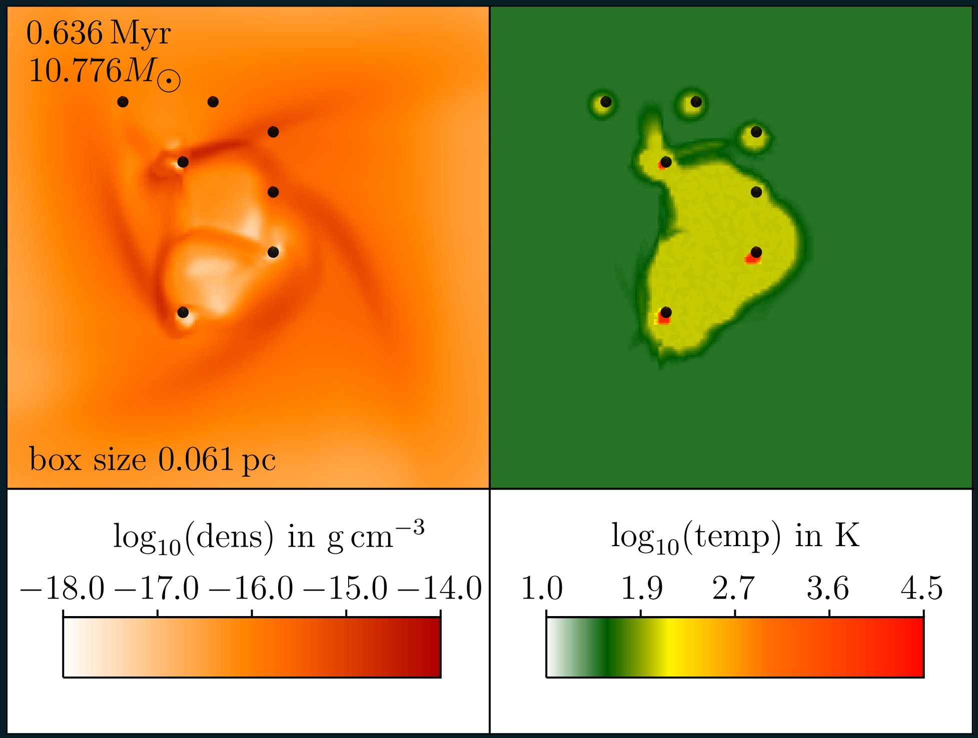
Smith et al. (2011)



- Ran simulations until a star of ~ 10 $M_\odot$ was formed.
- Chaotic: time taken can vary by factors of 5 or more.
- M_{max} is a **weak** function of the cluster mass.
- IMF seems to be controlled by “fragmentation induced starvation” (Peters et al. 2010)

Can we grow the central object?





Peters et al. (2010)

- Simulations of present-day massive star formation by Peters et al. (2010) find no evidence that ionisation terminates the accretion process?
- Fragmentation induced starvation prevents M_{max} growing beyond 25 $M_\odot$.
- How can we reconcile this with the 2D Hosokawa et al. (2012) results?

Caveats

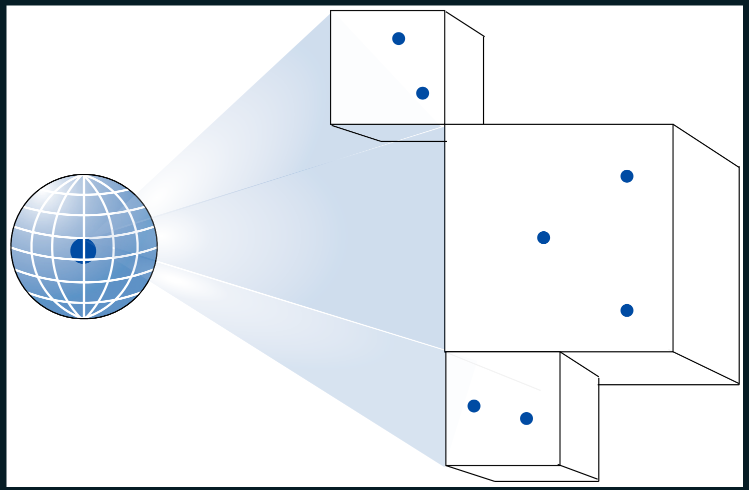
- Treatment of the radiation?
- Are we numerically resolved?
- Is our current treatment of the sink particles adequate?

H_2 line cooling

- Currently, calculate a Sobolev length to find the opacity of the line.

$$\tau_{ul} = \alpha_{ul} L_{sob} \qquad\qquad L_{sob} = v_{th} / |\nabla \cdot v|$$

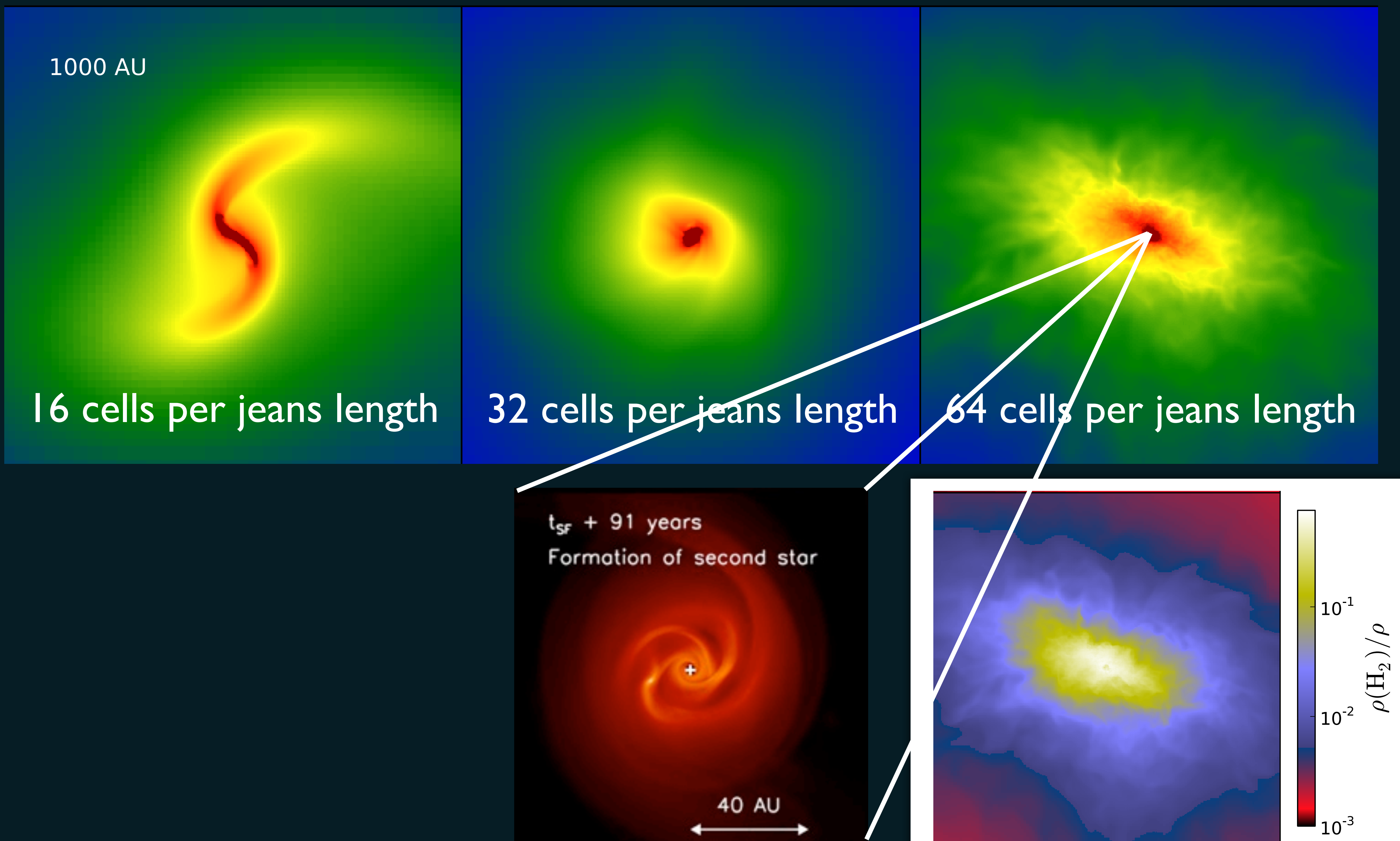
- Only really a good approximation in supersonic flows.
- The disc around Pop III stars have transonic motions.
- Currently working on a better approach using the new TreeCol alogorithm (Clark, Glover & Klessen 2012).



- Obtains column densities during the gravitational treewalk.
- Can calculate τ directly, by considering the column of material close to the line.
- See also work by Shingo Hirano on the treatment of the CIE opacities.

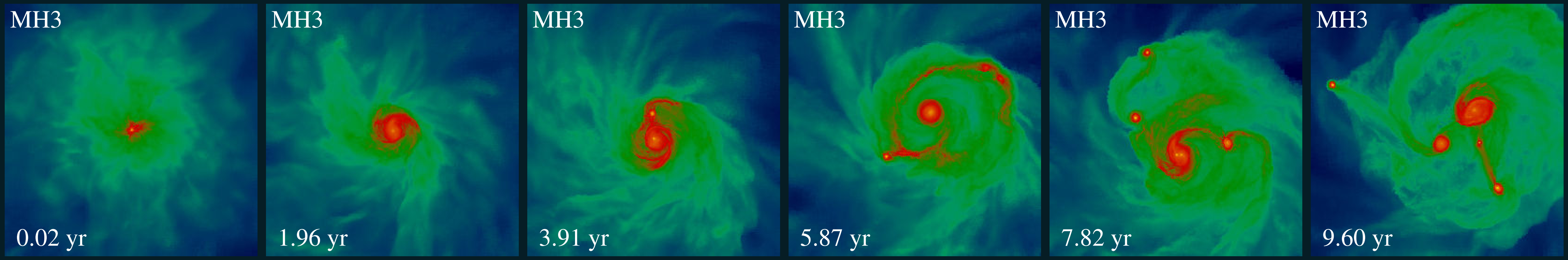
Is our fragmentation a result of poor resolution?

Turk et al. (2012)



Can we rely on sink particles?

- Inclusion of sink particle breaks the fluid equations at the scale at which they accrete.
- However without them, cluster growth/dynamics is essentially intractable.



Greif et al. (2012)

- Managed ~10 yr of evolution... Took about 3 months to run each sim!
- See the same basic fragmentation behaviour.
- Ejections and violent encounters are still common.
- Roughly 50 % of fragments merge.
- Picture is more complicated than the sink particle simulations suggest.

Summary:

- Fragmentation seems to be an unavoidable consequence of the collapse of purely primordial gas (but see Rowan Smith's talk).
- The emerging mass spectrum of Pop III stars appears to be flat - but halo to halo differences are large. Will this persists as the cluster grows?
- Evidence that the accretion stops once the central source reaches ~ 45 $M_\odot$. Is that when star formation stops?
- Do we need smarter sink particles?