The IMF of Pop. III stars: where do we stand?

Simon Glover
(ITA/ZAH, Heidelberg)

COOLING AND FRAGMENTATION OF PROTO-GLOBULAR CLUSTER CLOUDS

Francesco Palla

Astrophysical Observatory Arcetri

Hans Zinnecker

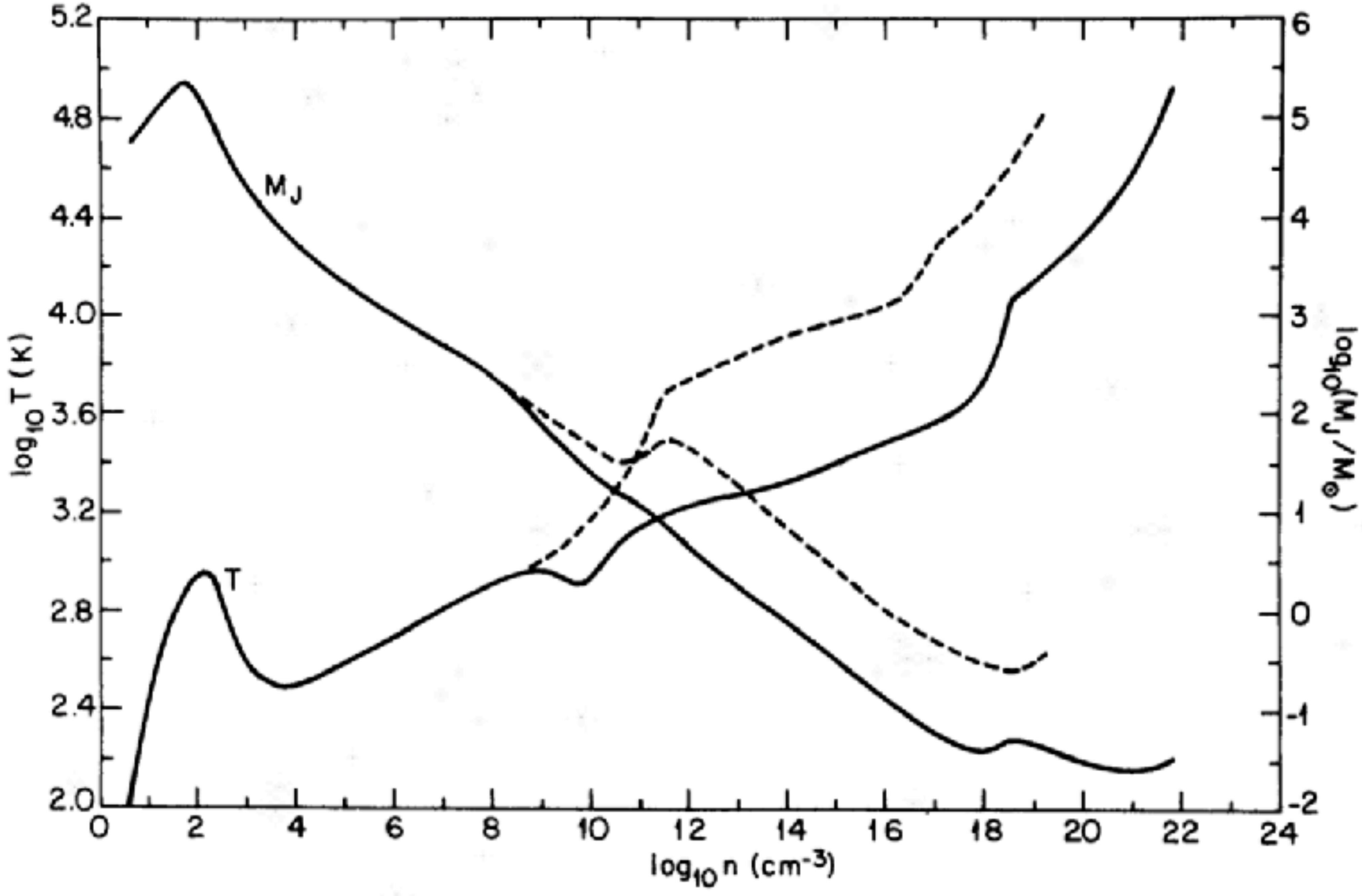
Royal Observatory, Edinburgh

Recently, Fall and Rees (1985) have proposed a theory for the origin of globular clusters forming from the largely primordial gas in the protogalaxy. These authors have explained the typical masses of proto-globular cluster clouds ($\sim 10^6\ M_\odot$) as gravitationally unstable condensations at temperature $T \sim 10^4$ in a hot protogalactic medium ($T \sim 10^6$ K) but they were not concerned with how these clouds would fragment into stellar masses ($\sim 1\ M_\odot$). In fact, their proto-globular cluster clouds are trapped at $T \sim 10^4$ K, and cannot cool to lower temperatures. However, substantial cooling must occur if these clouds are to form solar mass stars. It is known that under primordial conditions the only available cooling agent is molecular hydrogen, formed in the gas phase. Therefore, if sufficient molecular hydrogen is formed, it is possible to cool the gas well below $T \sim 10^4$ K. In the following we outline how non-equilibrium conditions lead to a larger H_2 abundance than derived by Fall and Rees, who assumed equilibrium conditions.

Early one-zone models

- Models focussed on predicting characteristic mass
- Assume hierarchical fragmentation, solve for evolution of Jeans mass with increasing density
- Minimum Jeans mass = characteristic mass
- Examples: Silk (1977), Palla et al (1983)
- Problem: results very sensitive to treatment of chemistry, cooling - predicted masses range from ~100 $M_\odot$ to very sub-solar

Early one-zone models

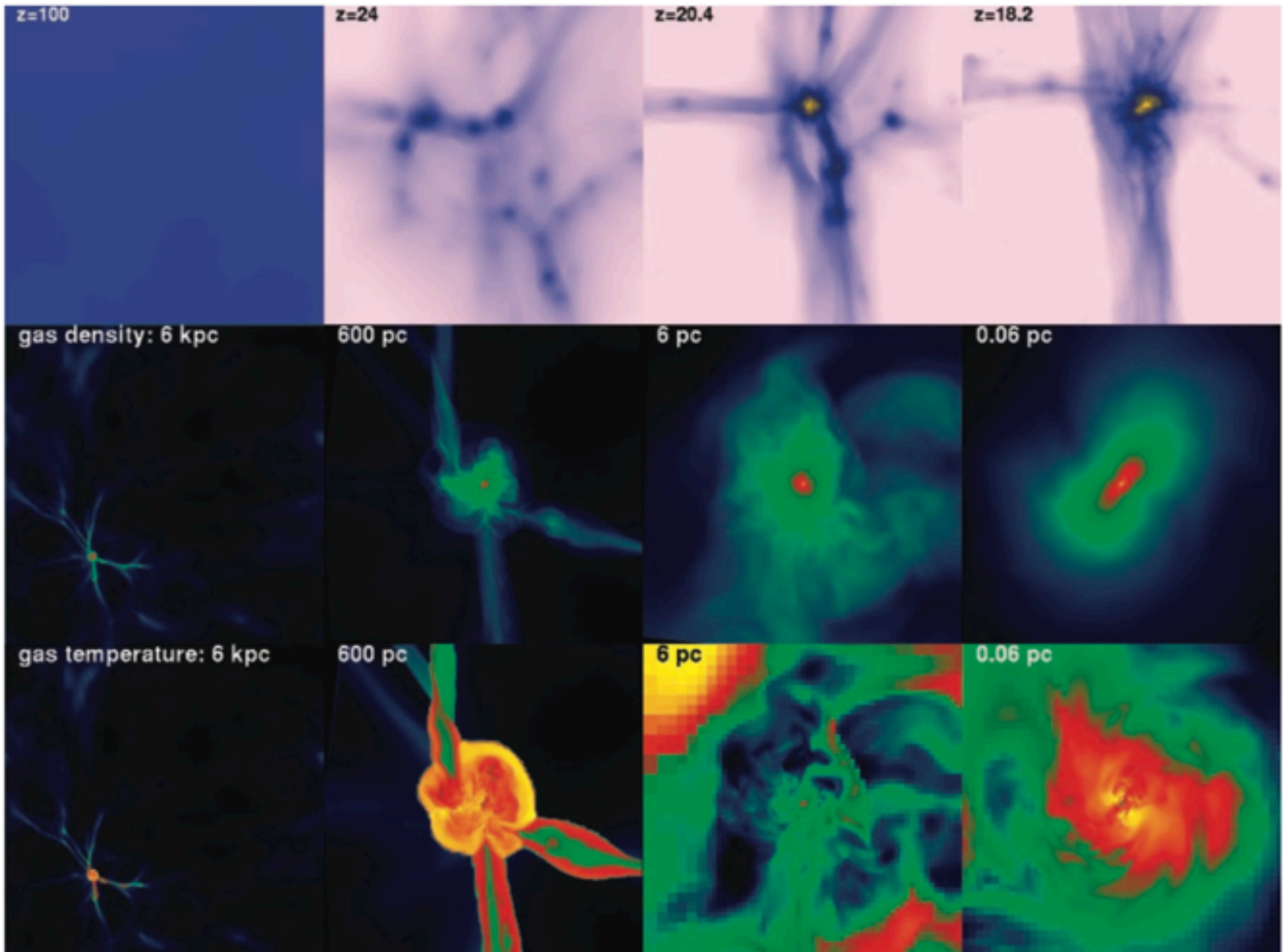


Palla et al (1983)

First 3D simulations

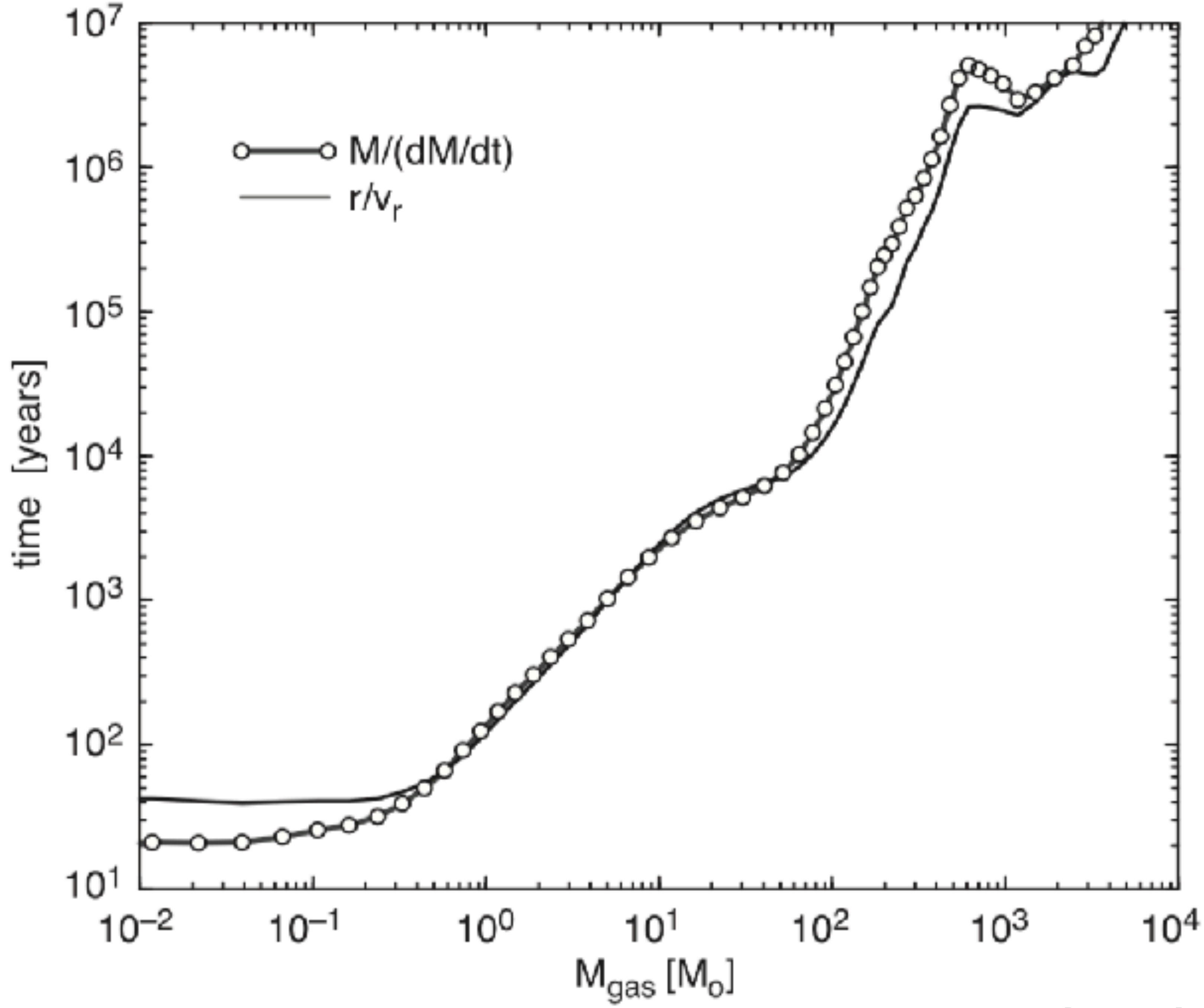
- Bromm et al (1999, 2002): SPH simulations of Pop. III star formation
- Abel et al (2002): AMR simulations of Pop. III star formation
- Both models included detailed chemical models, came to similar conclusions

First 3D simulations



Abel et al (2002)

First 3D simulations



Abel et al (2002)

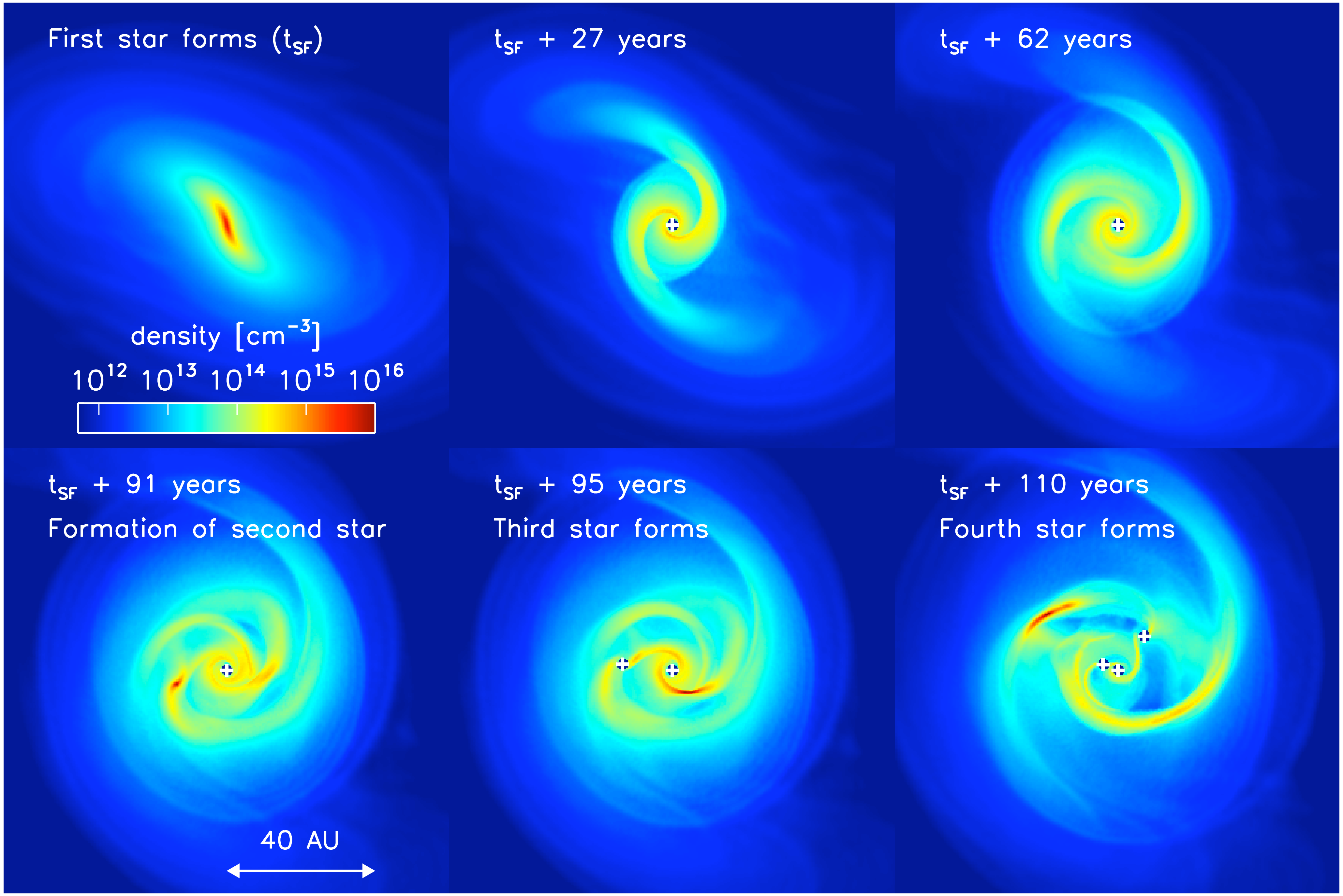
First 3D simulations

- Little fragmentation during initial collapse
- No attempt to follow gas dynamics after protostar formation - material simply assumed to be accreted
- Comparison of accretion time, stellar lifetime yields predicted mass ~ 100 $M_{\odot}$ (with large scatter)
- Problem: same logic applied to studies of present day star formation would predict one star / GMC

Disk fragmentation

- Stacy et al (2010), Clark et al (2011), Greif et al (2011): first attempts to model gas dynamics after protostar formation
- Massive protostellar accretion disk forms, quickly becomes unstable and fragments
- Dense protostellar cluster: encounters, mergers, ejections common
- Flat IMF, most mass in high-mass stars

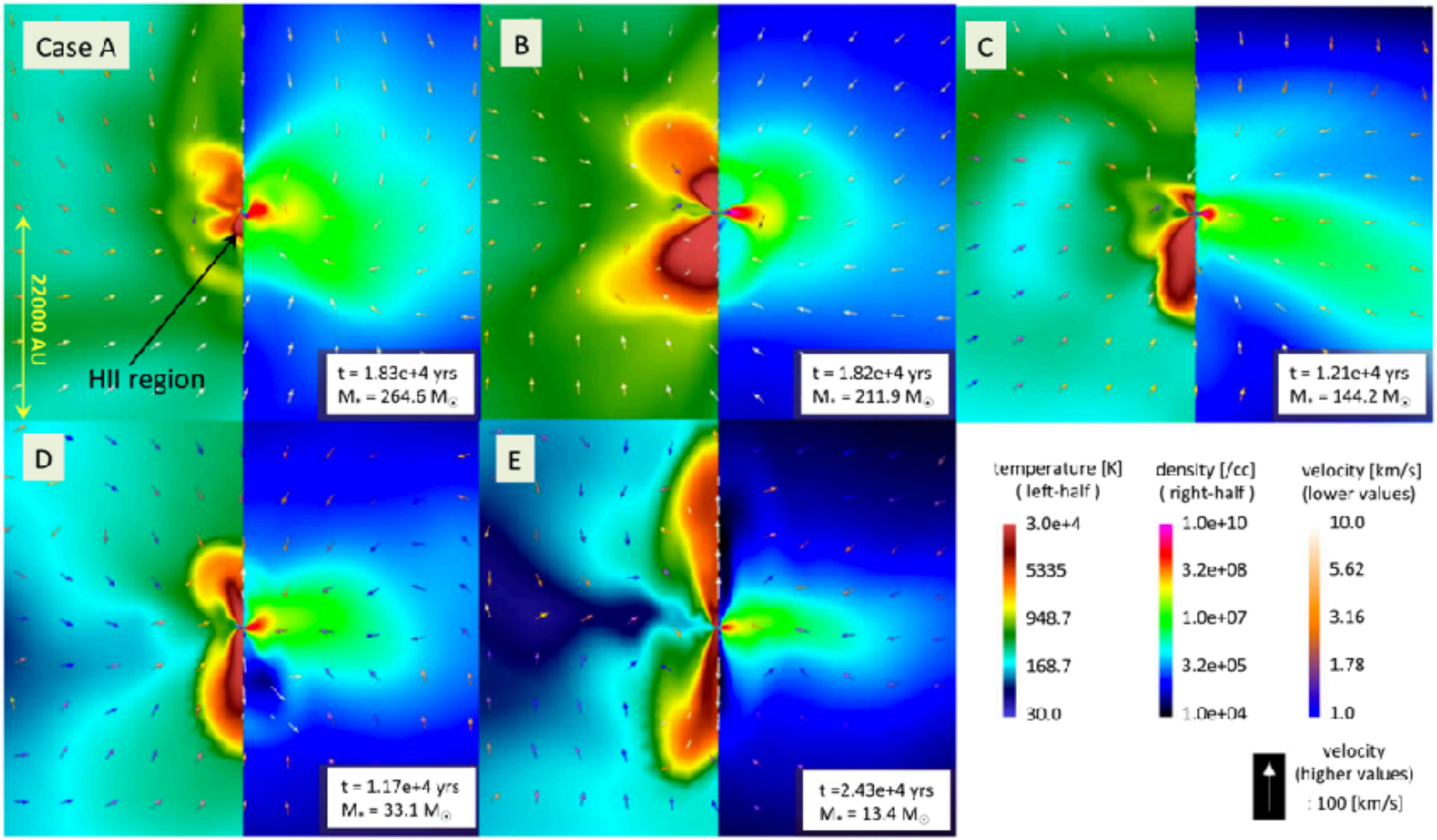
Disk fragmentation



Clark et al (2011)

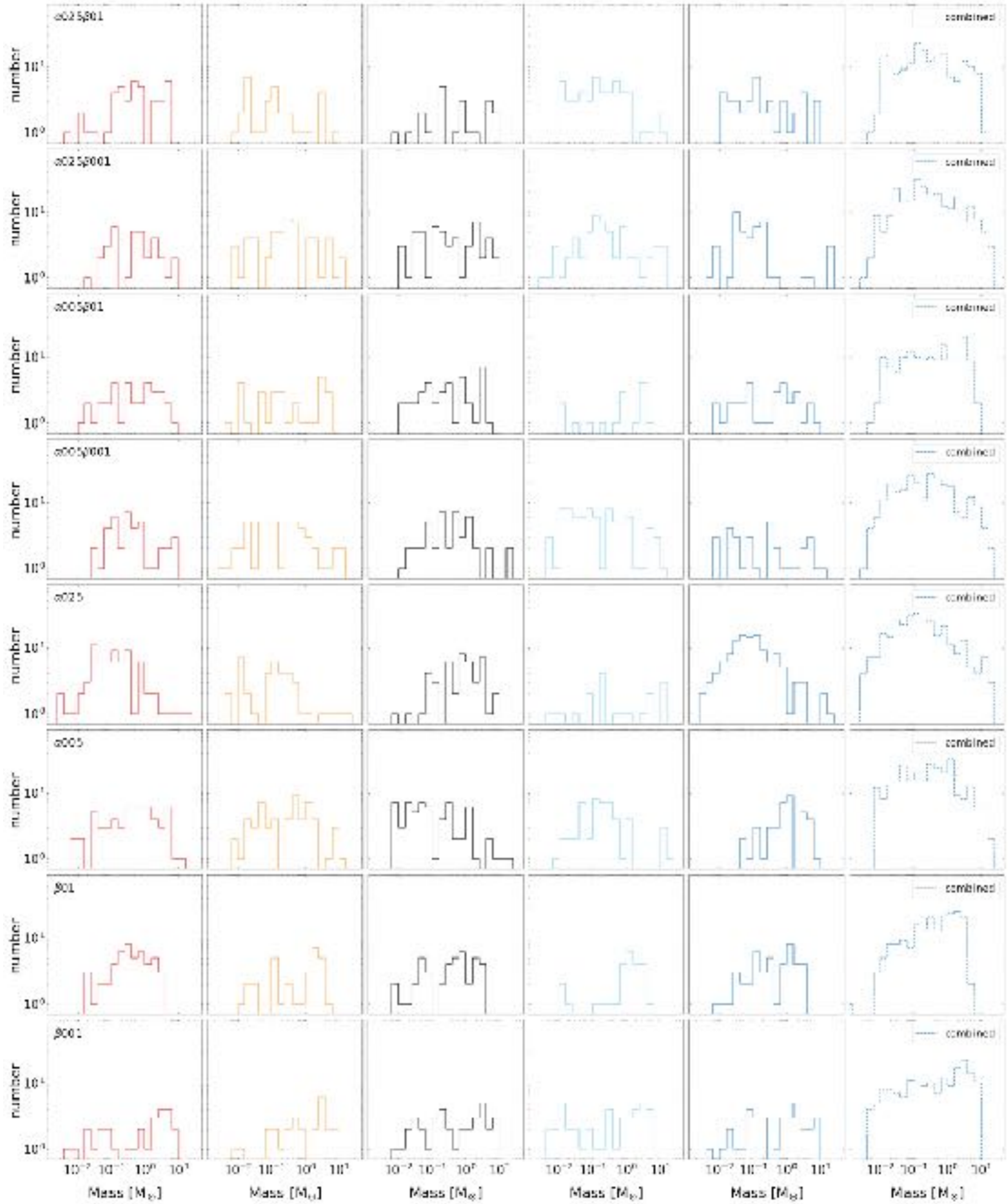
Disk fragmentation

- Problems:
  - Missing physics (photoionization, magnetic field)
  - How well do sink particles represent behaviour of "fluffy" protostars?
  - Timescale and resolution
  - Robustness of results to changes in initial conditions?
- Lots of work on these over the past few years



Hosokawa et al (2016)

Wollenberg et al, in prep.



What do we think we know?

- Broad consensus on basic features of chemical, thermal evolution
- Formation of massive unstable disks v. difficult to avoid
- Very high total accretion rates (scales as $T^{3/2}$, and T much higher than in local GMCs)
- Gas will be magnetized (turbulent dynamo), although dynamical significance unclear
- Disk fragmentation is highly stochastic
- Many studies recover flat IMFs

The big open questions

- Do the fragments survive as independent protostars? Or do they simply migrate inward and merge?
  - Simulation results on this depend on choice of numerical method
- What terminates accretion? Radiative or mechanical feedback?
- What does the magnetic field do?
- What is the IMF after ~ 1 Myr?
  - Simulations that are fast enough to follow gas evolution for this long have too little resolution to follow small-scale fragmentation