Simulating the Formation of the First Stars

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Outline

Outline:

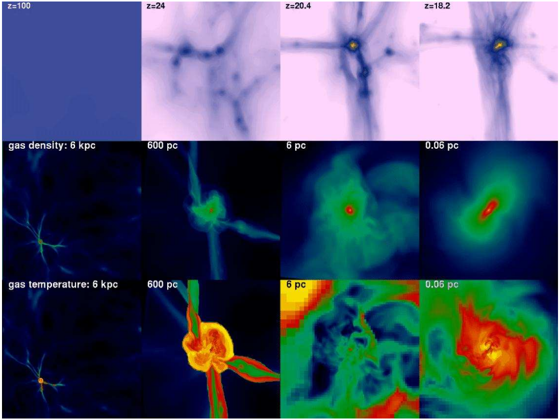
- (i) Previous work
- (ii) Recent simulations
- (iii) Disk fragmentation
- (iv) Protostellar migration and merging

Collaborators:

- Volker Springel, Simon White (HITS, MPA)
- Ralf Klessen, Simon Glover, Paul Clark, Rowan Smith (ITA Heidelberg)
- Volker Bromm (University of Texas)
- Jarrett Johnson, Athena Stacy (Goddard, LANL)
- Naoki Yoshida (IPMU)

From Cosmological to Protostellar Scales

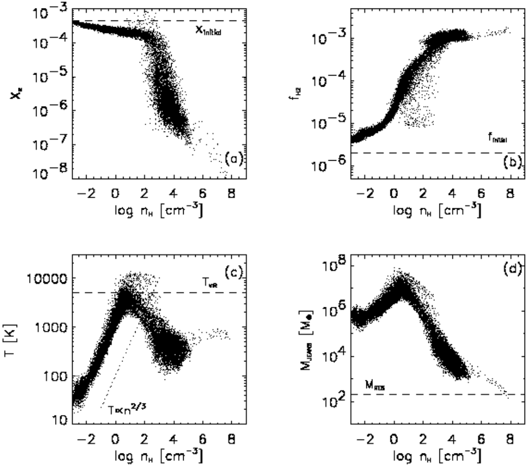
- Stage for Pop III SF: $\gtrsim 10^5\ \mathrm{M}_\odot$ DM 'minihalos' at $z > 20$
- Gas collapses and heats to $T_{\rm vir} \simeq 1000\,\mathrm{K}$



Abel et al. 02

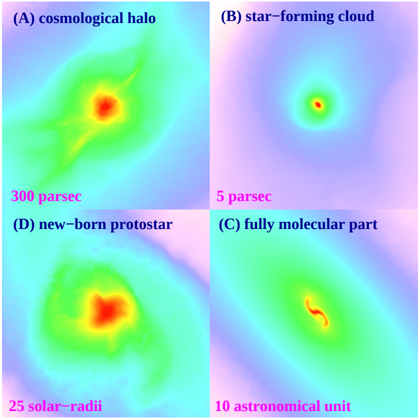
From Cosmological to Protostellar Scales

- Gas becomes dense enough for H_2 formation *(Bromm et al. 02)*
- Cooling by ro-vibrational transitions of H_2 to $\simeq 200\ \mathrm{K}$



From Cosmological to Protostellar Scales

- Central gas cloud becomes gravitationally unstable
- Nearly isothermal contraction to very high densities
- Protostar with $\simeq 5 \times 10^{-3}\,\mathrm{M}_\odot$ forms



Yoshida et al. 06, 08

From Cosmological to Protostellar Scales

Subsequent evolution?

- Avoid CFL constraint by using sink particles
  (Bromm et al. 04, Stacy et al. 10, Clark et al. 08, 11, Greif et al. 11)

Recently:

- Direct simulation without sink particles
- Very limited timescales: $\sim 10\,\mathrm{yr}$ (however: $\gtrsim 100\,\mathrm{yr}$ now possible)

Simulations

Moving-mesh code AREPO *(Springel 10)*:

- Hybrid Lagrangian / Eulerian code
- Voronoi tesselation of space based on a distribution of points
- Hydrodynamic fluxes computed across cell faces
- Mesh-generating points advected with flow
- Galilean-invariant, low diffusivity

Simulation Setup:

- Cosmological initial conditions
- Four realizations in boxes of size 250 and 500 kpc
- Four-step process to arrive at final simulations on AU scales

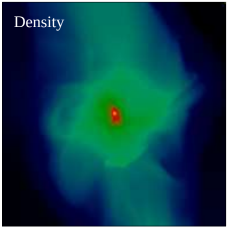
Simulations

First step:

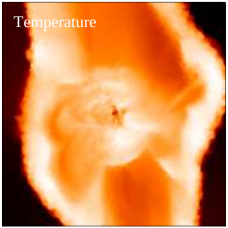
- Low-resolution DM-only simulations
- Initialized at $z = 99$ with ΛCDM/WMAP 7
- First halo with mass $> 5 \times 10^5\,\mathrm{M}_\odot$ located

Second step:

- Reinitialization with DM and gas
- Zoom-in on target minihalo ($\times 8^3$) $\rightarrow \simeq 1\,\mathrm{M}_\odot$ gas resolution
- Non-equilibrium primordial chemistry and cooling network
- On-the-fly refinement ensures resolution of Jeans length ($128 \rightarrow 32$)
- Run until $n_\mathrm{H} = 10^9\,\mathrm{cm}^{-3}$



Width: $5\,\mathrm{kpc}$ (comoving)



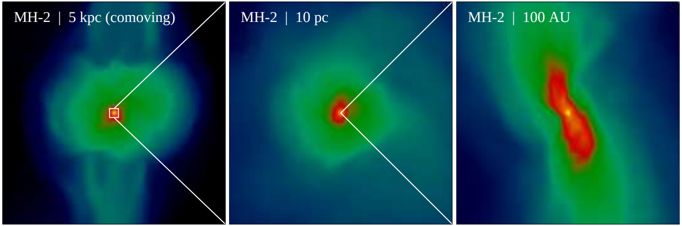
Simulations

Third step:

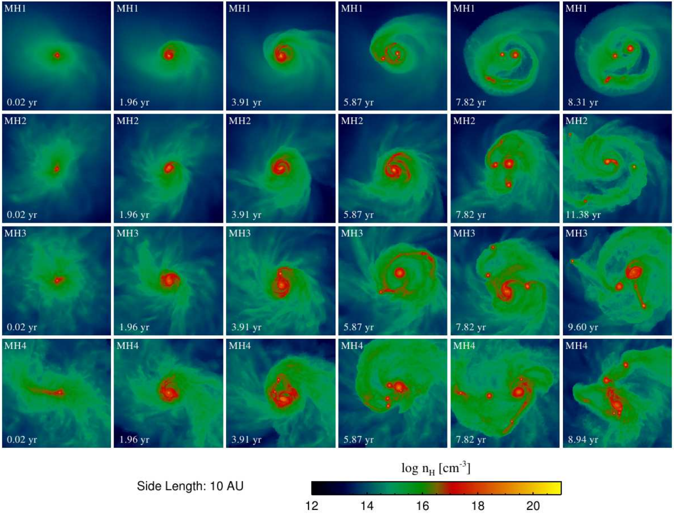
- Central 1 pc cut out (only gas, DM mass fraction $\simeq$ 10 %)
- Resimulation with reflective boundary conditions
- Additional equilibrium chemistry solver for $n_{\mathrm{H}} > 10^{14}\,\mathrm{cm}^{-3}$
- Run until $n_{\mathrm{H}} = 10^{19}\,\mathrm{cm}^{-3}$

Fourth step:

- Central 2000 AU cut out
- Run for $\simeq$ 10 yr (1 month on 32 cores)



Time sequence:



Disk evolution:

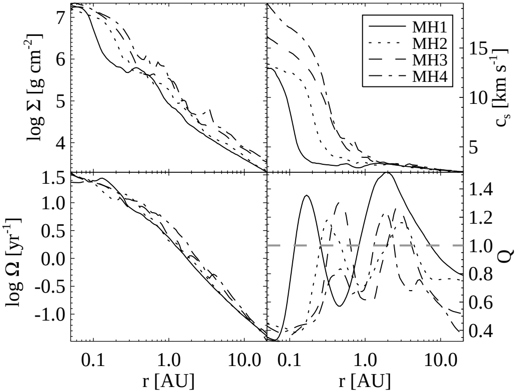
- Stability governed by Toomre parameter
- $Q = c_s\Omega/\pi G\Sigma$

Set by:

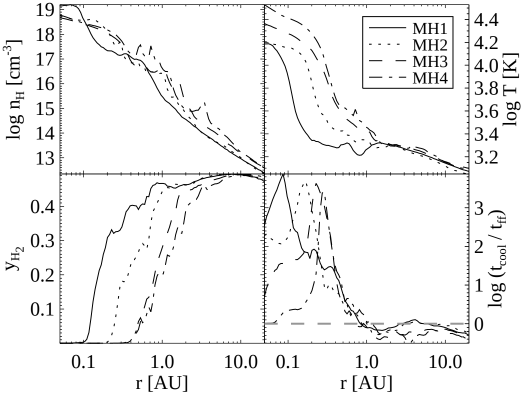
- Σ: surface density
- c_s: sound speed
- Ω: orbital frequency

For $Q < 1$:

- perturbations grow



$Q < 1$ at $\lesssim 0.2$ AU and $\simeq 1$ AU



In addition:

- Gammie criterion:
- $t_{\mathrm{cool}} \lesssim t_{\mathrm{ff}}$

Fragmentation:

- Occurs at $\simeq 1\,\mathrm{AU}$
- Innermost regions stable
- Below $1\,\mathrm{AU}$: temperature rises rapidly to $\simeq 10^4\,\mathrm{K}$
- H_2 fraction drops

$\rightarrow$ Relevant cooling mechanisms?

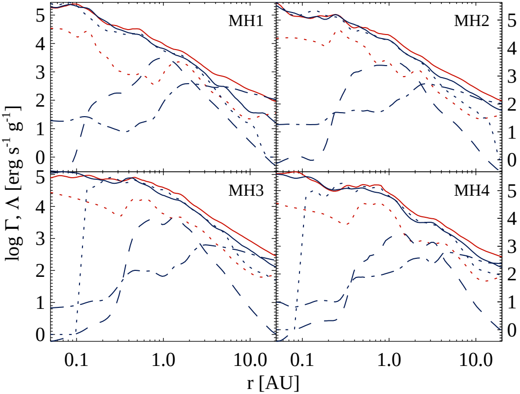
Disk Fragmentation

Heating:

- Compressional heating *(solid line)*
- H_2 formation heating *(dotted line)*

Cooling:

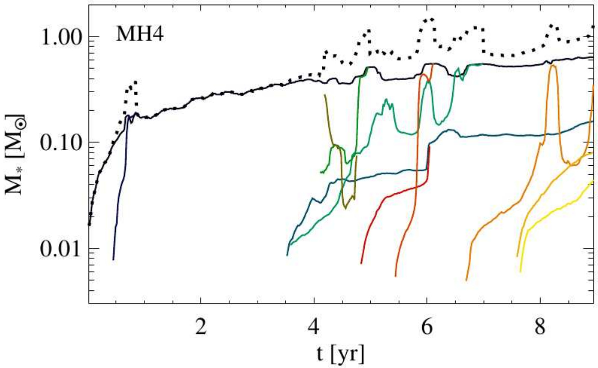
- Expansion cooling *(solid line)*
- H_2 dissociation cooling *(dotted line)*
- Collision-induced emission *(dashed line)*
- H_2 line cooling *(dot-dashed line)*



Most important ‘coolant’: H_2 dissociation cooling

Subsequent evolution:

- Secondary protostars migrate to center and merge with primary
- Mergers rarely occur between secondary protostars
- Primary protostar dominates mass budget



Torques:

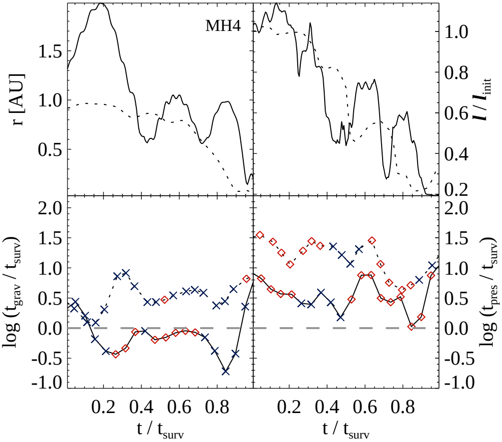
- Decomposition into:
- Gravitational torques
- ∇P torques
- Timescales:

$$t_{\rm grav,pres} = \mathbf{L}/\tau$$

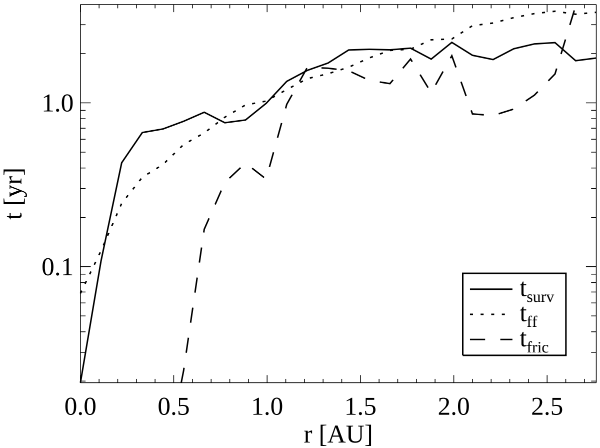
$$\tau = \mathbf{r} \times \mathbf{F}_{\rm grav,pres}$$

Overall:

- Gravitational torques dominate
- Directed inward
- Torquing time agrees with merging time

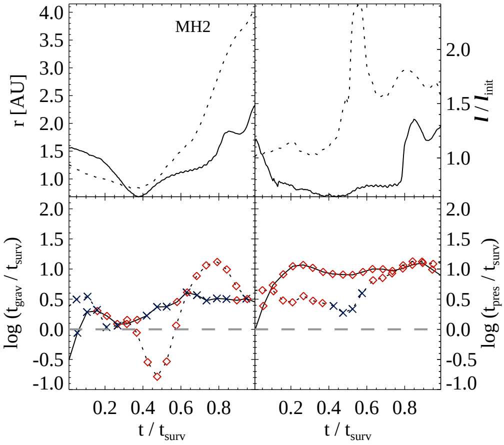


Merging timescales:



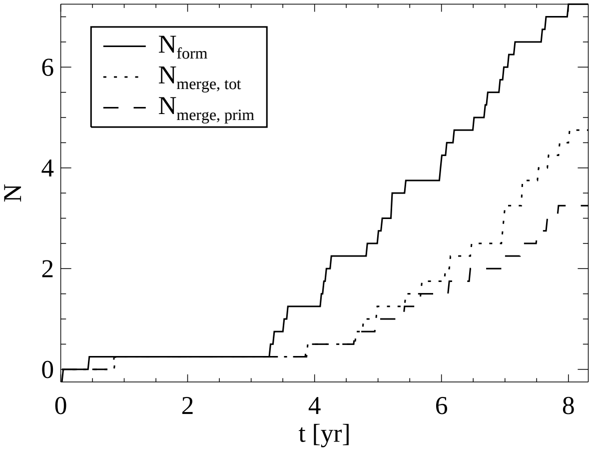
Merging occurs in a free-fall time!

Similar analysis for protostars that survive:



Slingshot effect: Migration to higher orbits via N-body interactions

Evolution of multiplicity:



50% of all secondary protostars merge with primary!

Summary

- Gas in minihalos becomes rotationally supported and fragments
- Very efficient merging (free-fall time)
- Predominant growth of primary protostar
- Slingshot migration of low-mass protostars
- Final mass function unclear, but most likely top-heavy ($\lesssim 50\,\mathrm{M}_\odot$)
- Caveats: magnetic fields / radiative transfer / limited timespan