Simulations on a Moving Mesh: The Clustered Formation of Population III Protostars

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Outline

Collaborators:

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

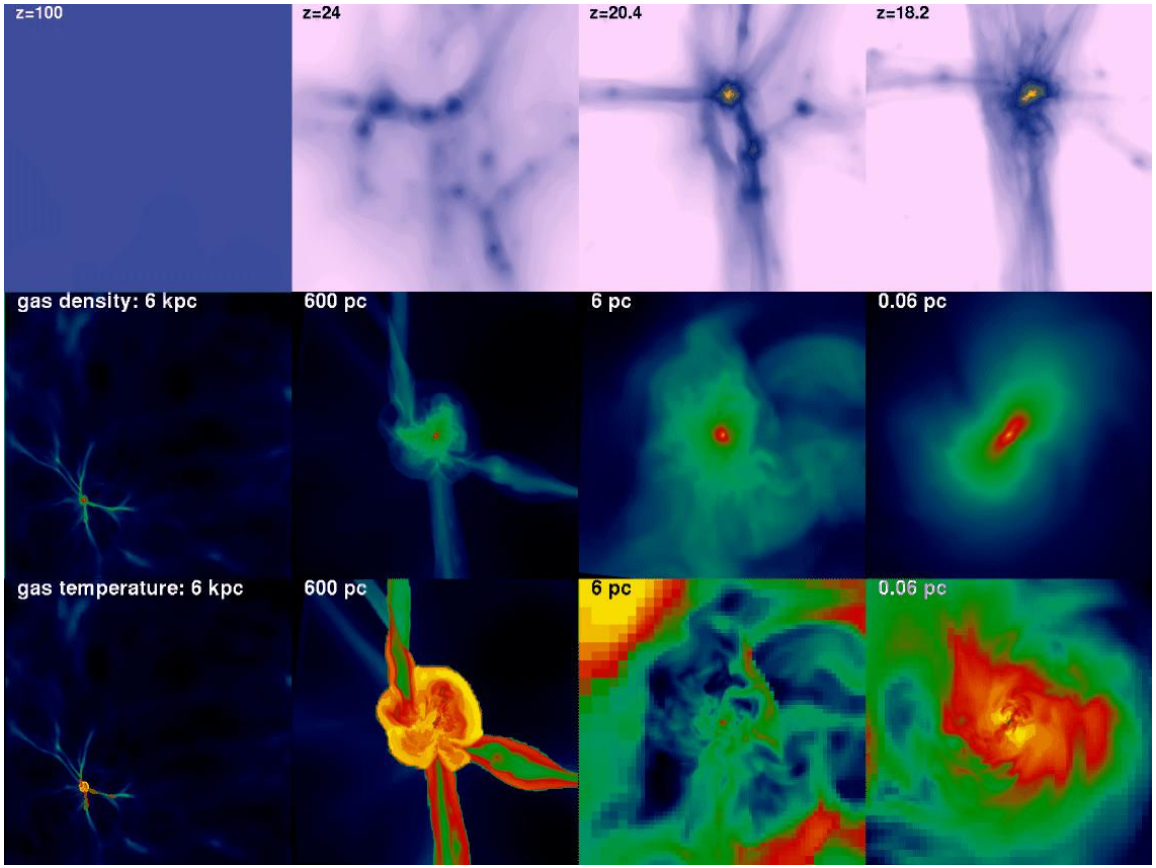
Outline:

- 'Status quo' of Population III Star Formation
- New Results obtained with Arepo
- Implications and Outlook

Review

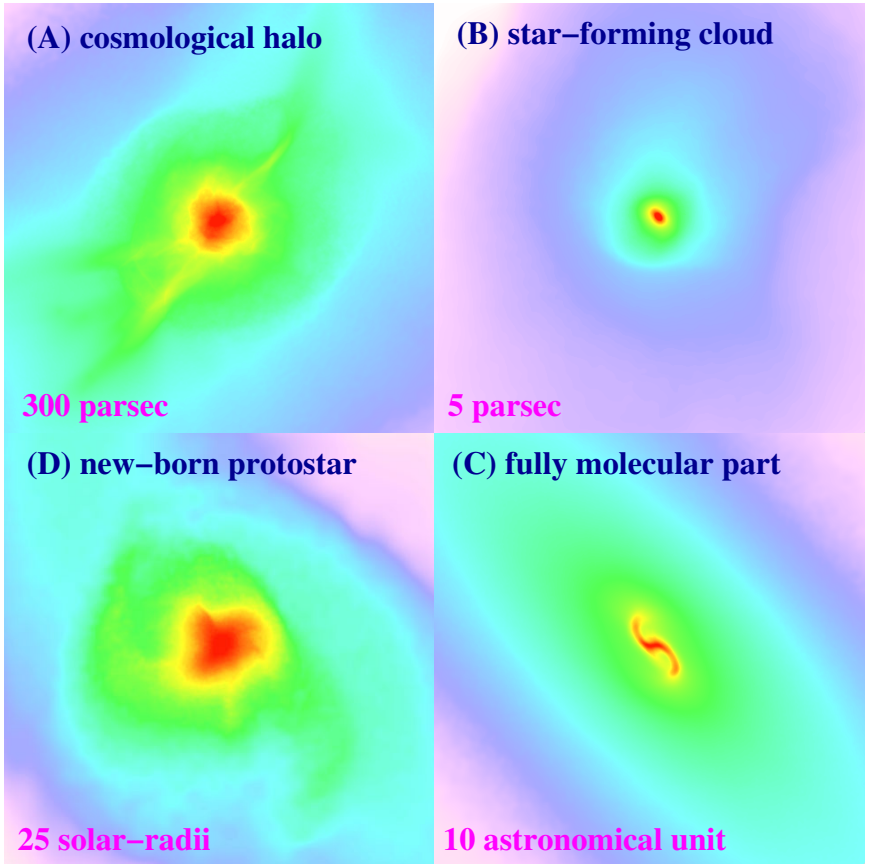
'Canonical' formation channel of Population III stars *(Abel et al. 02):*

- Virialization of $\gtrsim 10^5\ \mathrm{M}_\odot$ DM halos at $z \sim 20$ (3σ)
- Activation of H_2 cooling



Review

- Central gas cloud becomes Jeans unstable
- Runaway collapse to extremely high densities
- Formation of a protostar with $10^{-3}\,M_{\odot}$



Yoshida et al. 06, 08

Review

Predicted mass scale of Population III stars:

- Accretion onto central protostar: $\dot{M} \propto c_s^3 \propto T^{3/2}$
  - Primordial gas cloud: $\simeq 200\,\mathrm{K}$
  - Present-day molecular clouds: $\simeq 10\,\mathrm{K}$
  - $\rightarrow$ Pop III stars accrete ~ 100 times more aggressively

- Accreted mass within Kelvin-Helmholtz time $\rightarrow M_* \sim 100\,\mathrm{M}_\odot$
  (Bromm et al. 04, O'Shea et al. 07)

- More detailed semianalytical model $\rightarrow M_* \sim 100\,\mathrm{M}_\odot$
  (Tan & McKee 04, McKee & Tan 08)

Review

What about fragmentation?

- No fragmentation: *Abel et al. 02, O'Shea et al. 05, Gao et al. 07, Yoshida et al. 06, 08*
- Fragmentation in one out of five minihalos: *Turk et al. 09*

However:

Courant-Friedrichs-Lewy (CFL) criterion prevents simulations from probing beyond the initial collapse, where simulations of present-day star formation show fragmentation

$\rightarrow$ Usage of sink particles to avoid CFL constraint:

- Low densities: *Stacy et al. 10*
- Idealized initial conditions: *Clark et al. 08, 11a*
- Cosmological IC's and high densities: *Clark et al. 11b, Greif et al. 11*

Simulations

The moving-mesh code AREPO *(Springel 10)*:

- Maintains adaptivity of SPH with the hydrodynamical accuracy of AMR
- No preferred directions, Galilean-invariant
- Simple implementation of additional physics (chemistry, sink particles)

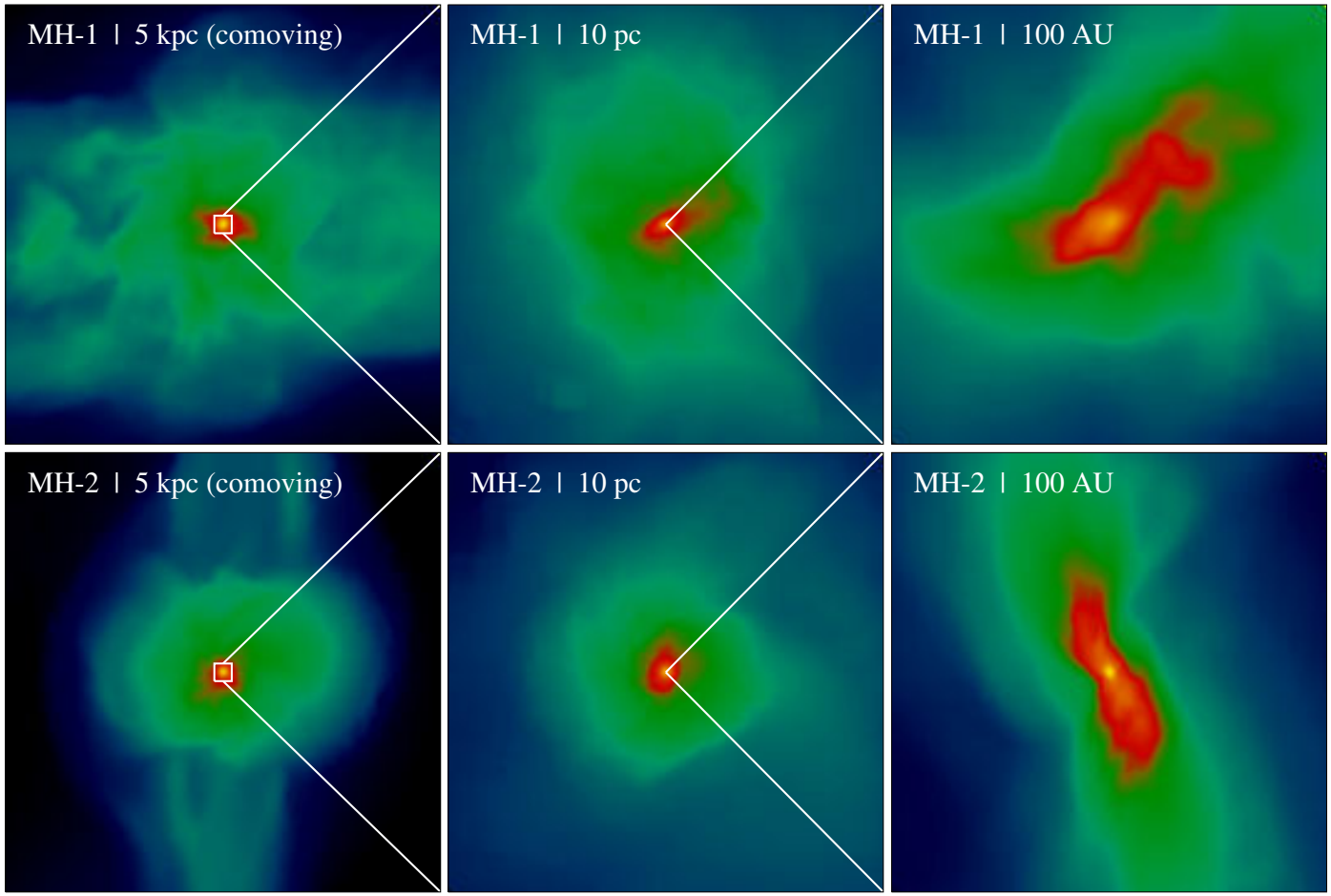
Setup:

- Cosmological zoom simulations initialized at $z = 99$
- Five different box sizes ranging from 250 to 1000 kpc
- Initial DM and gas particle masses: $\simeq 3.53$ and $0.72\,\mathrm{M}_\odot$

Additional physics:

- Complete primordial chemistry and cooling network
- Additional runtime refinement to ensure 128 cells per Jeans length
- Sink particles inserted at a density of $n_\mathrm{H} \simeq 10^{17}\,\mathrm{cm}^{-3}$

Results

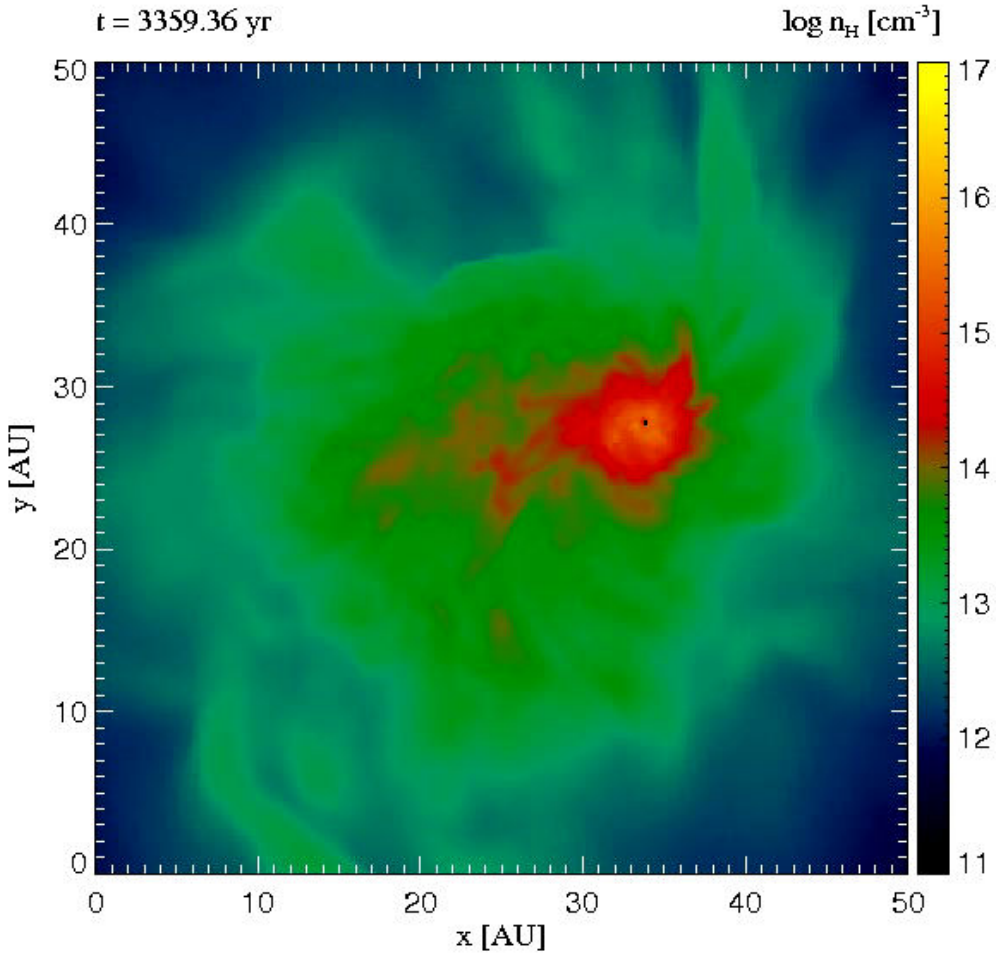


- Representative sample of minihalos with $M_{\rm vir} \simeq 1 - 5 \times 10^5\,{\rm M}_\odot$
- Dynamical range of more than 20 orders of magnitude in density

Results

Initial fragmentation phase:

- Formation of a circumstellar disk
- Fragmentation and formation of a secondary protostar



Results

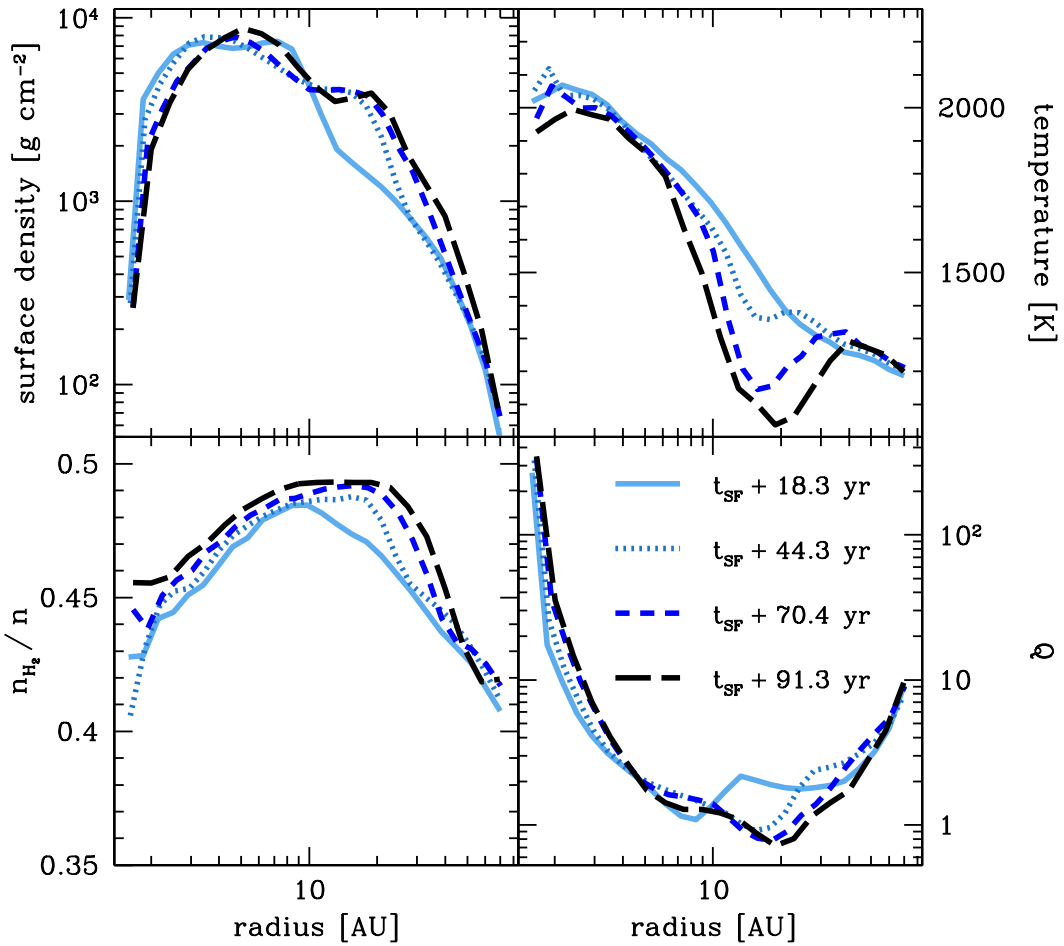
Fragmentation can be understood in terms of a Toomre analysis:

- $Q = c_s \omega / \pi G \Sigma$

Governed by:

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

For $Q < 1$: disk becomes Toomre-unstable

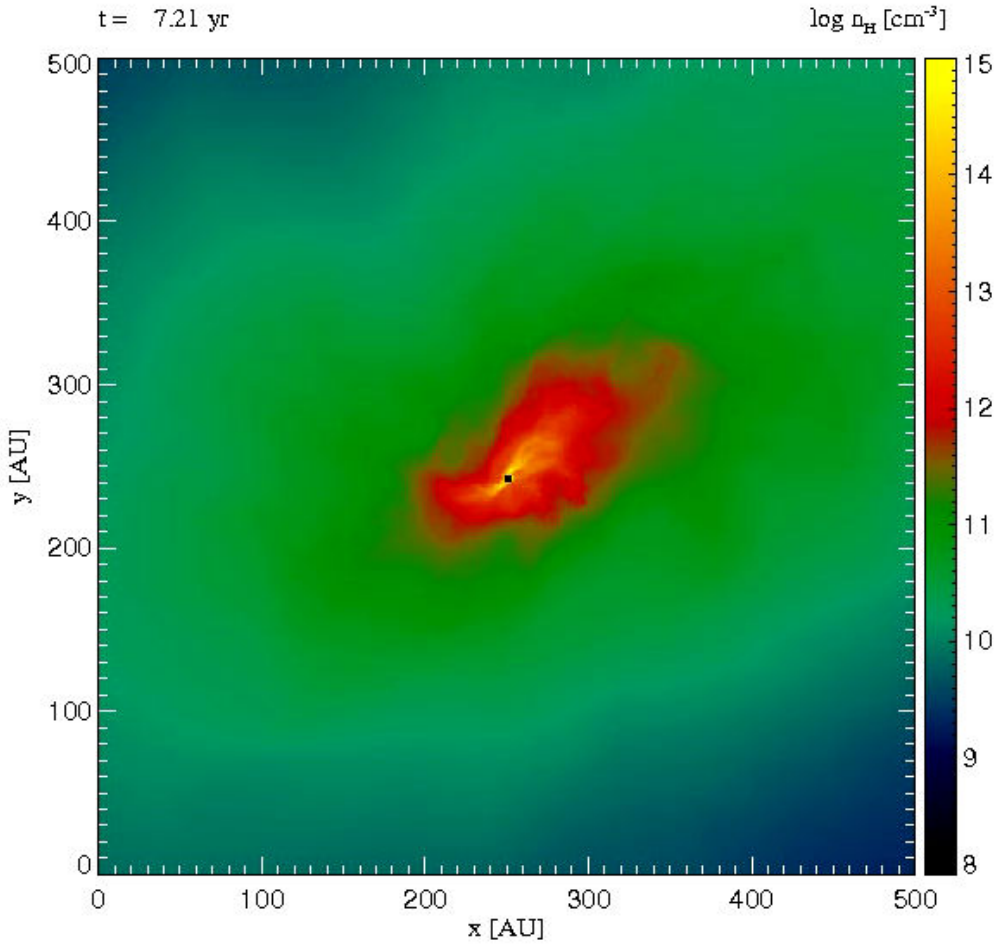


Clark et al. 11b

Results

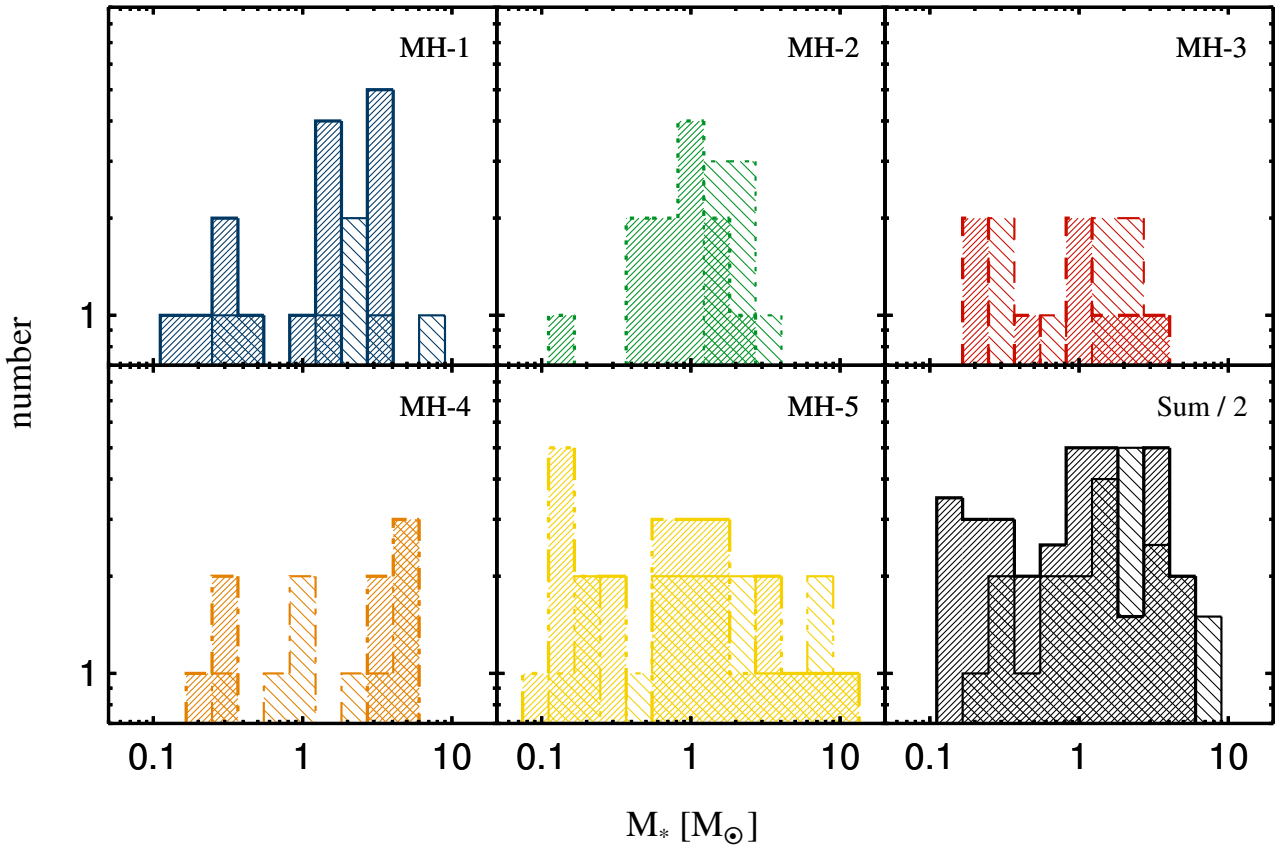
Full evolution:

- 1000 yr of continued fragmentation and accretion
- Formation of a protostellar cluster consisting of both low and high-mass stars



Results

Protostellar mass function



- Formation of a cluster with of order 10 protostars in every minihalo
- Relatively flat mass function $\rightarrow$ most of the mass in high-mass stars

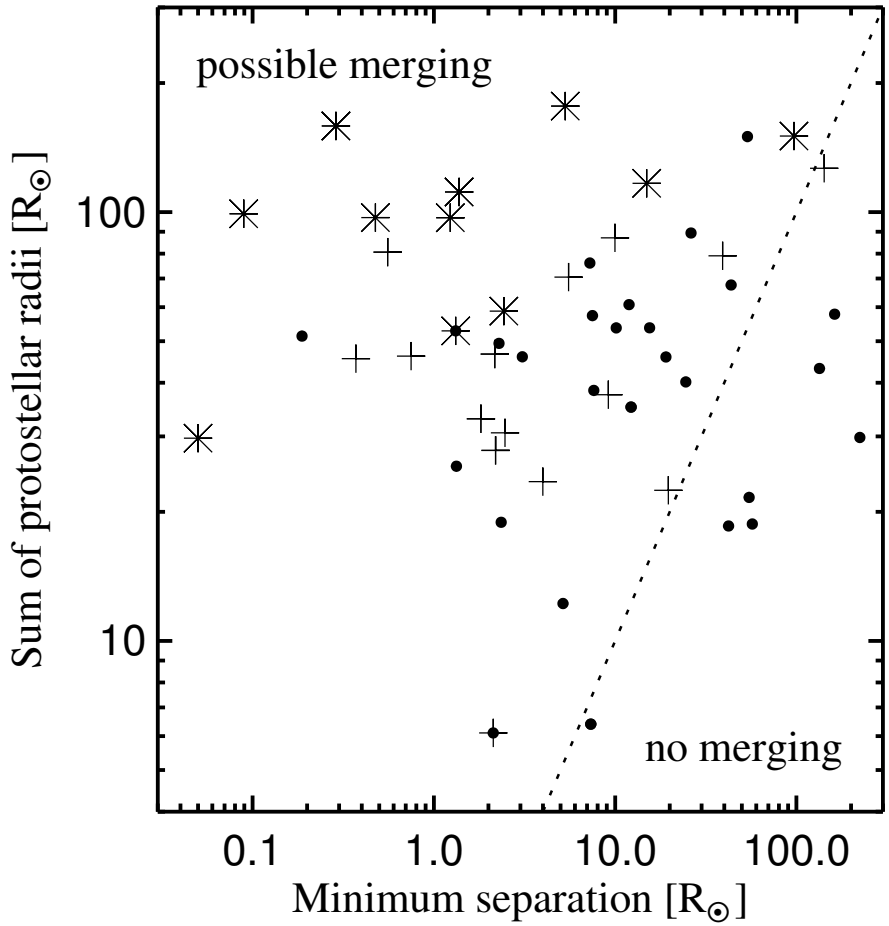
Results

Chaotic N-body interactions:

- Ejection of low-mass protostars
- Survival to the present day?

Cautionary note:

- Interactions often occur on the scale of the accretion radius!



Results

Speculative Implications:

- Typical mass reduced to $\sim 10\,\mathrm{M}_{\odot}$
- Less ionizing photons per stellar baryon
- Different nucleosynthetic signature
- Less pair-instability supernovae
- More core-collapse supernovae, GRB's

Apache Point Observatory

If dynamical ejections are real:

- Possibility for low-mass Population III stars
- High concentration in Galactic bulge *(Diemand et al. 05, Gao et al. 10)*
- Near-IR spectroscopy of bulge stars with APOGEE *(Majewski et al. 07)*

Outlook

Advantages of sink particles:

- Avoid CFL constraint
- Computationally inexpensive

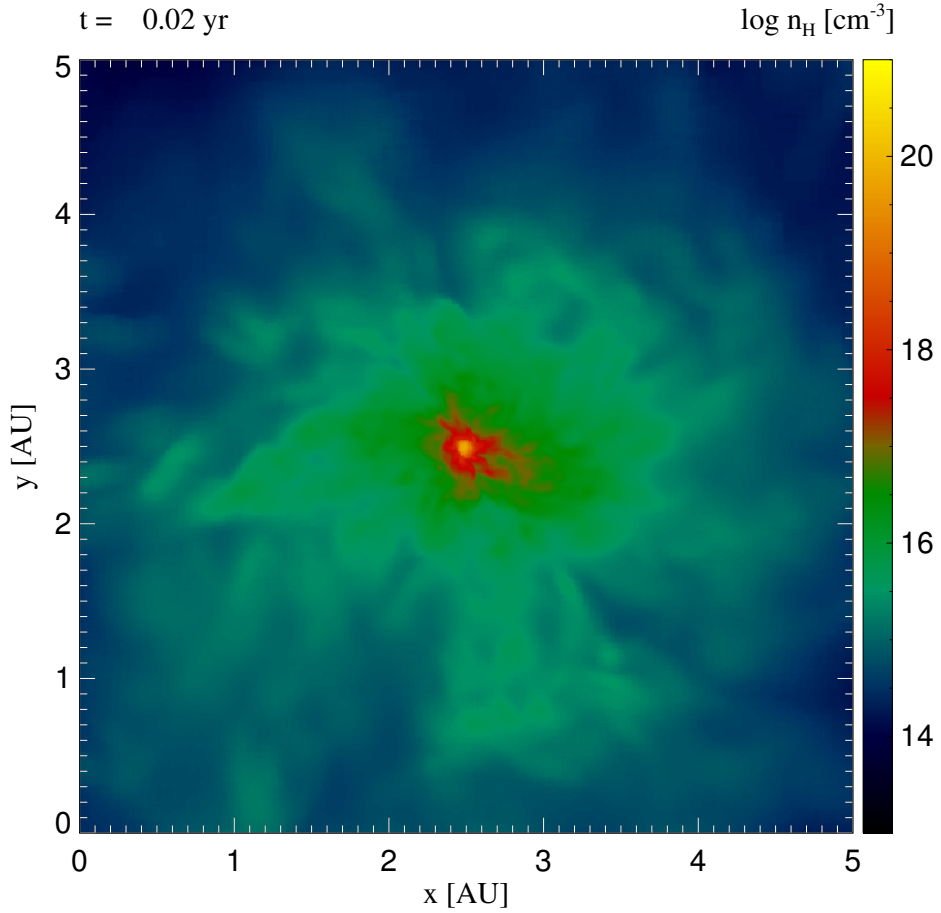
Disadvantages:

- Unreliable accretion rates
- Questionable small-scale interactions

→ Replace sink particles

Restrictions:

- Slow and expensive
- Feasible: 10 – 100 yr



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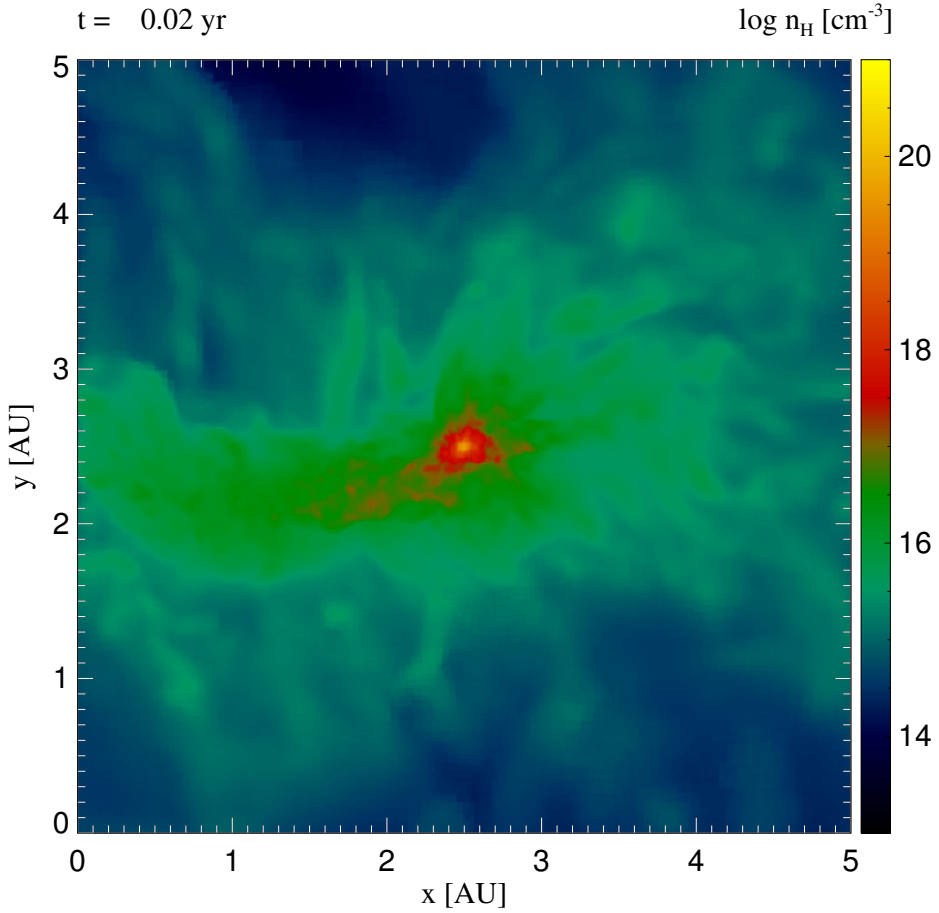
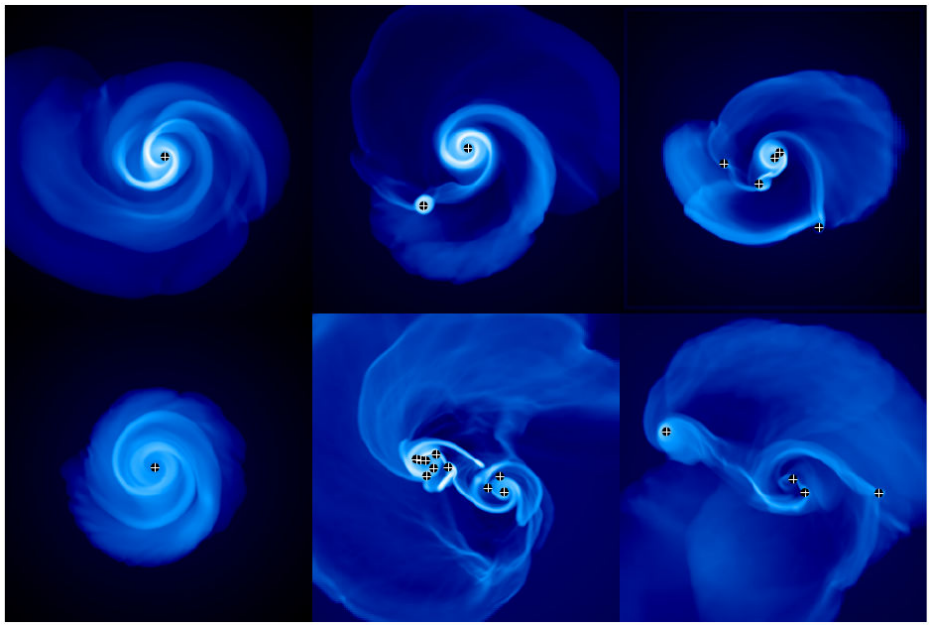
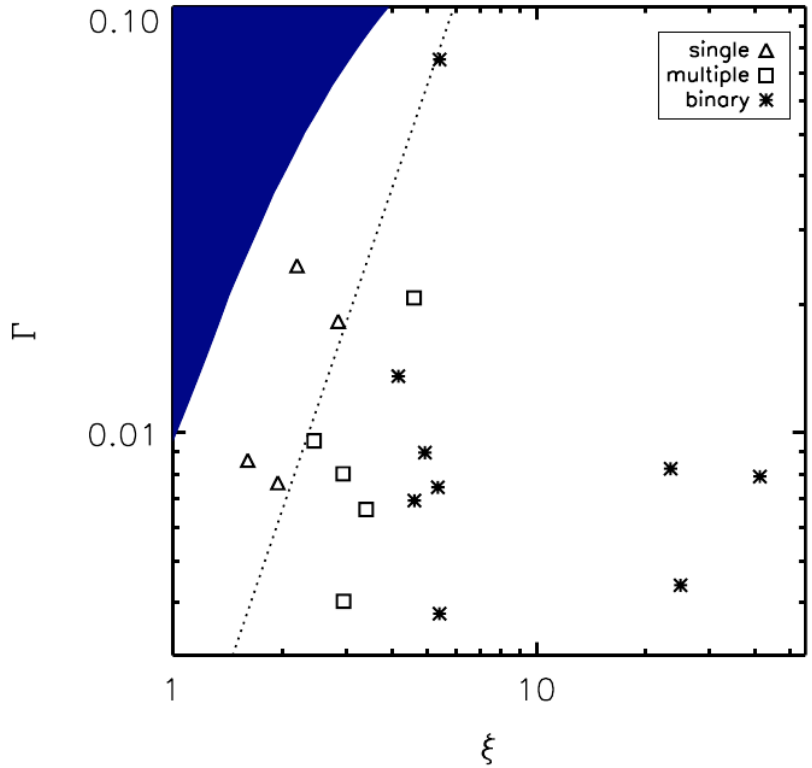


Outlook

Fragmentation in the present-day universe





Kratter et al. 10