Dawn : The childhood of stellar clusters

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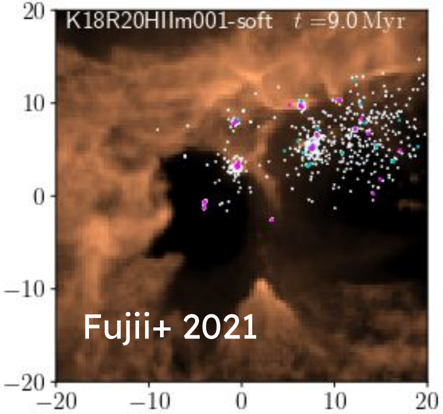
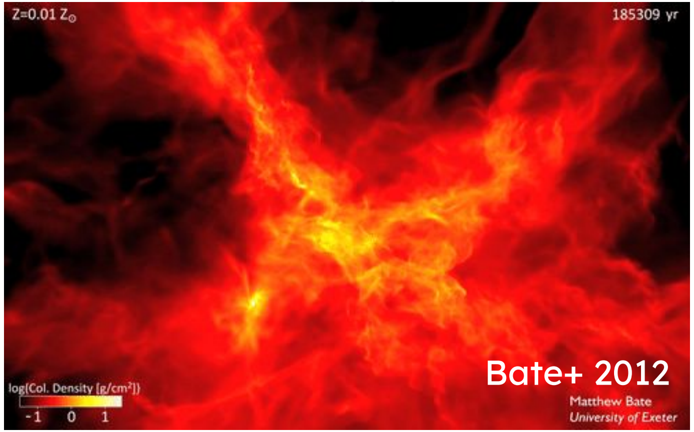
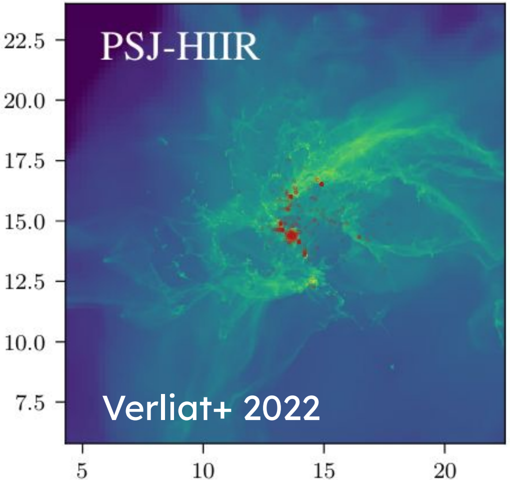
DAWN I : Simulating the formation and early evolution of stellar clusters with Phantom N-Body submitted to A&A

Giant Molecular Cloud collapse simulations

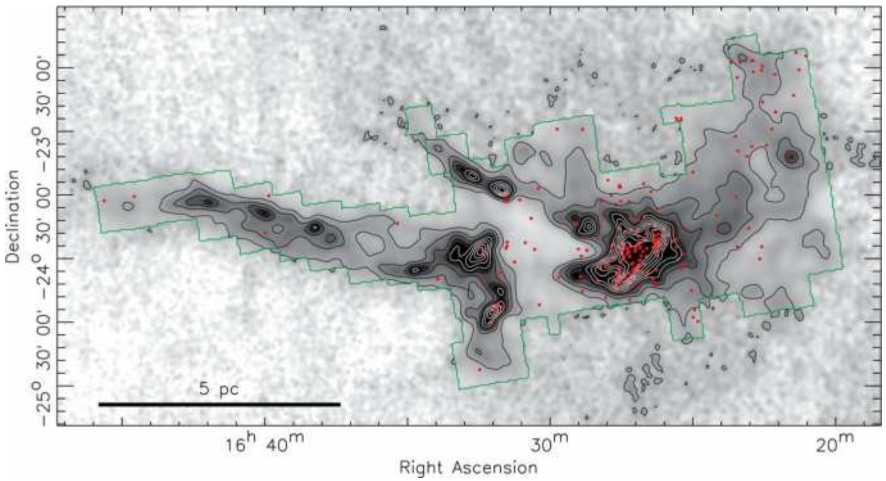




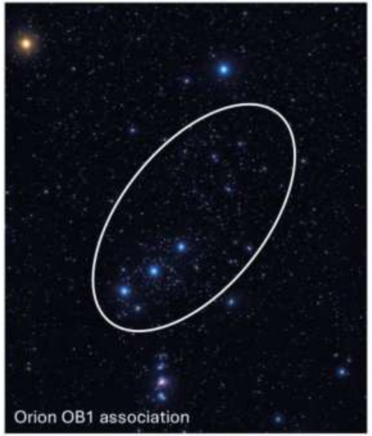


Dynamical evolution of young clusters

Gutermuth + 2011



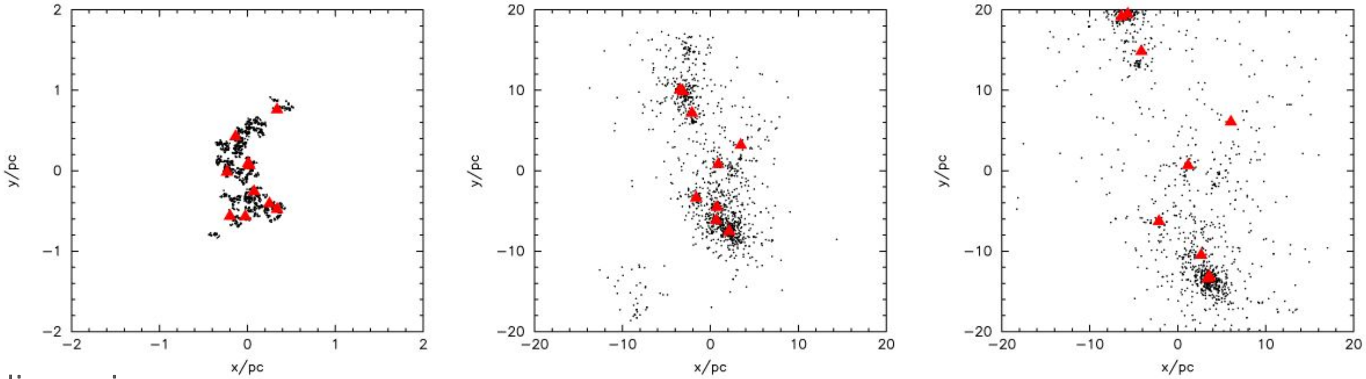
Extinction map of the Ophiuchus cloud overlaid in red
with the spatial distribution of *Spitzer*-identified YSOs.



Time

Dynamical evolution of young clusters

Pure N-body dynamics : Integration for 10 Myr



Output:
- Velocity dispersion
- Mass segregation
- Expansion rate

Input:
- Fractal dimension
- Virial parameter

Parker + 2014

Time

Dawn : Definitions and Objectives

GMC collapse up to **gas removal**

- Hydro/N-Body solvers
- Star formation
- Precise stellar dynamics
- Stellar feedback

x10~100

Statistics

Evolutionary tracks

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Initial conditions of formation

Observations

Methods : N-body integration

RESPA: Two levels Leapfrog integrator

1st level:

- Slow forces
- Hydro forces
- Large timesteps
- individual time stepping

$$\left\{\begin{array}{l} \mathbf{v} = \mathbf{v} + \frac{1}{2}\Delta t_{\mathrm{sph}}\mathbf{a}_{\mathrm{sph}} \\ \text{N substeps} \left\{\begin{array}{l} \mathbf{v} = \mathbf{v} + \frac{1}{2}\Delta t_{\mathrm{fast}}\mathbf{a}_{\mathrm{fast}} \\ \mathbf{r} = \mathbf{r} + \Delta t_{\mathrm{fast}}\mathbf{v} \\ \mathbf{a}_{\mathrm{fast}} = \mathbf{a}_{\mathrm{fast}}(\mathbf{r}) \\ \mathbf{v} = \mathbf{v} + \frac{1}{2}\Delta t_{\mathrm{fast}}\mathbf{a}_{\mathrm{fast}} \end{array}\right\} \\ \mathbf{a}_{\mathrm{sph}} = \mathbf{a}_{\mathrm{sph}}(\mathbf{r}) \\ \mathbf{v} = \mathbf{v} + \frac{1}{2}\Delta t_{\mathrm{sph}}\mathbf{a}_{\mathrm{sph}}, \end{array}\right.$$

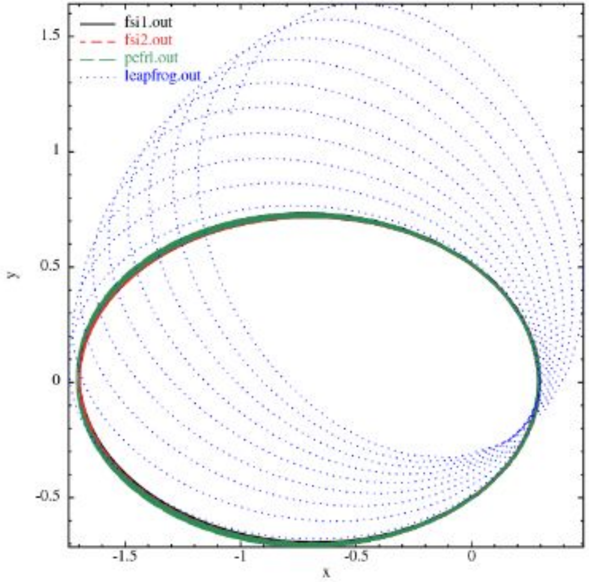
2nd level:

- Fast forces
- sink interactions/cooling...
- Small sub timesteps

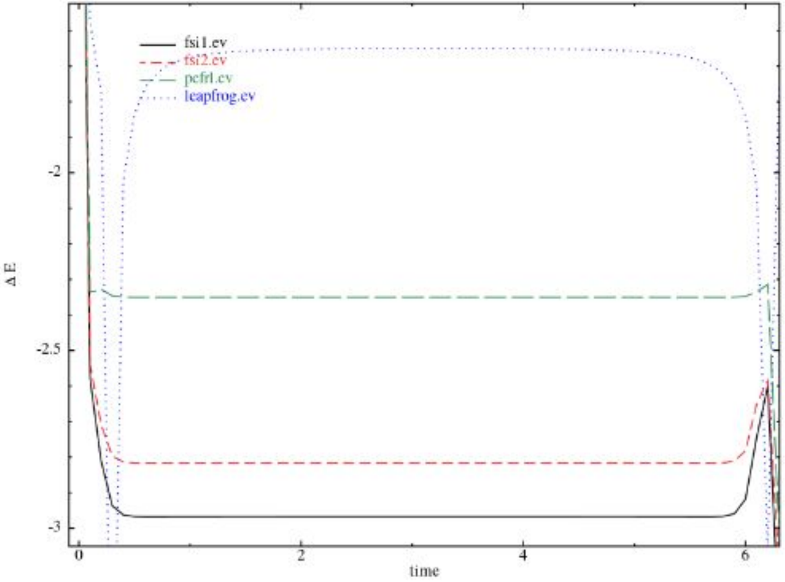
Methods : N-body integration

2nd order vs **4th** order

Leapfrog: 2nd order
PEFRL: 4th order
FSI: Forward 4th order



(a) 10 orbits of a point mass around a fixed potential. Initial eccentricity is set to 0.7 and the semi-major axis is 1. The amount of (spurious) orbital precession can be seen to inversely correlate with integrator precision.



(b) Logarithm of the relative energy of the particle on 1 orbit.

Methods : N-body integration

Dynamical collisions are essential in the evolution of a star cluster:

- Collisional gravitational interactions are expensive to integrate
  - Close encounters and highly eccentric binaries

adaptive or individual time stepping

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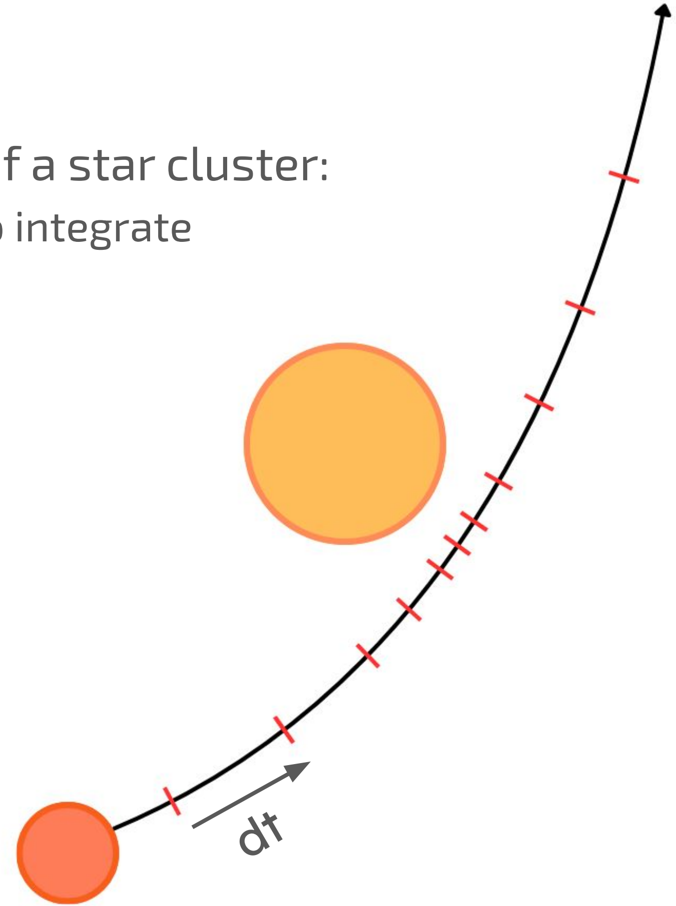
accumulation of errors

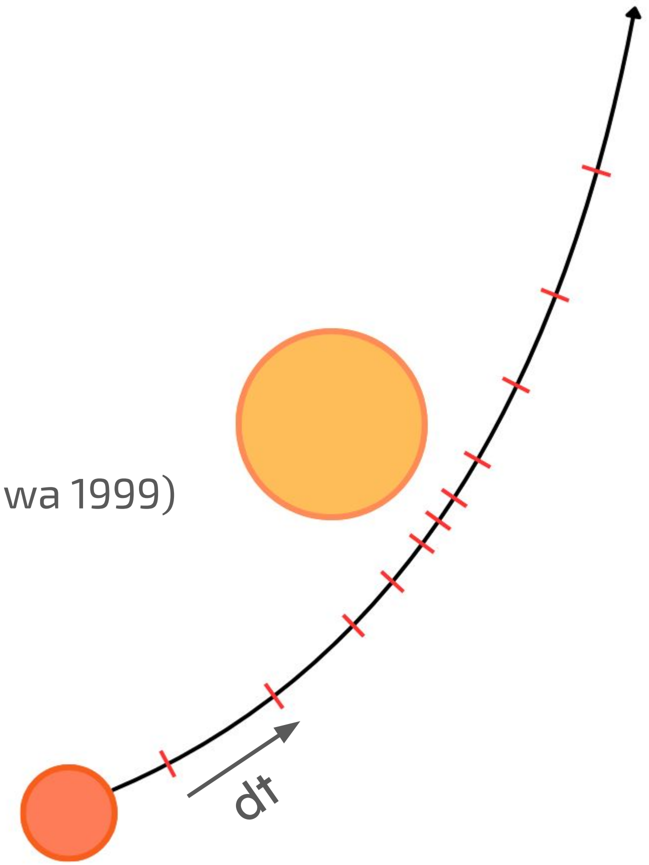


Methods : N-body integration

Regularisation of equations of motion

- Kustaanheimo and Stiefel (1965)
  - Spatio-temporal transformation
- **Algorithmic regularisation** (Mikkola et Tanikawa 1999)
  - time transformation

$$ds = \Omega(\mathbf{r})dt, \qquad \Omega(\mathbf{r}) = \sum_{i=1}^{N}\sum_{i\neq j}^{N}\frac{m_i m_j}{r_{ij}}.$$



Methods : N-body integration

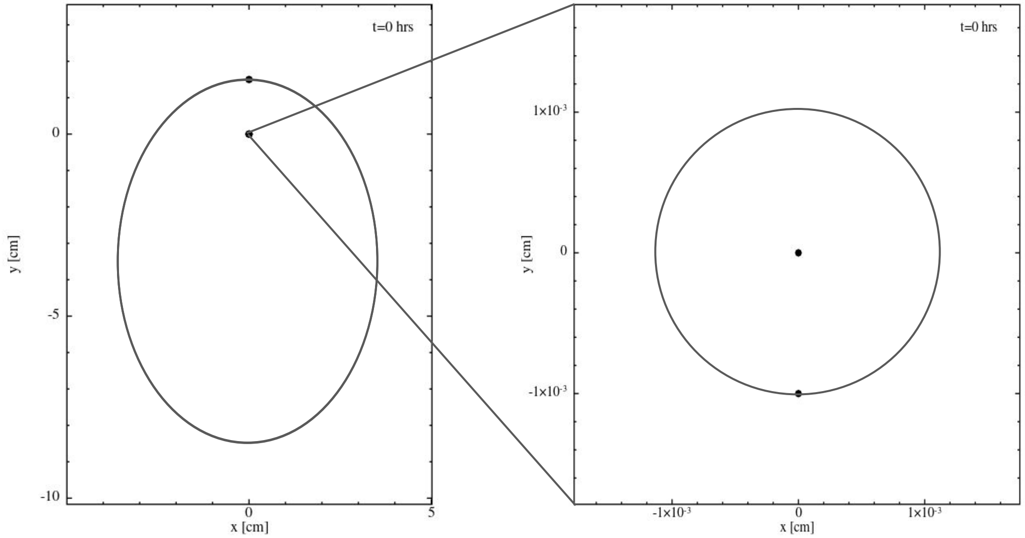
(Mikkola et Aarseth 1996)

Hard binaries and stable hierarchical systems:
- Strong time step constraint
- Stable on the cluster crossing time (~Myr)

Slow Down binaries

Outer:
e= 0.7
a= 5.0
m1= 1.0
m2= 2.0

Inner:
e= 0.
a= 0.001
m1= 0.9
m2= 0.1



$$H = \frac{1}{\kappa} H_b + (H - H_b),$$

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\frac{G m_c (\mathbf{r}_i - \mathbf{r}_c)}{\kappa \|\mathbf{r}_i - \mathbf{r}_c\|^3} - \frac{\partial U(\mathbf{r}_i)}{\partial \mathbf{r}_i},$$

$$\frac{\mathrm{d}\mathbf{r}_i}{\mathrm{d}t} = \frac{\mathbf{v}_i}{\kappa},$$

Methods : N-body integration

$$\mathbf{v} = \mathbf{v} + \tfrac{1}{2}\Delta t_{\mathrm{sph}}\mathbf{a}_{\mathrm{sph}}$$

$$\text{N substeps}\begin{cases}
\mathbf{v} = \mathbf{v} + \tfrac{1}{6}\Delta t_{\mathrm{fast}}\mathbf{a}_{\mathrm{fast}} \\
\mathbf{r} = \mathbf{r} + \tfrac{1}{2}\Delta t_{\mathrm{fast}}\mathbf{v} \\
\mathbf{r}_{\mathrm{sub}} = \mathrm{SDAR}(\mathbf{r}_{\mathrm{sub}}, \mathbf{v}_{\mathrm{sub}}) \\
\tilde{\mathbf{a}}_{\mathrm{fast}} = \mathbf{a}_{\mathrm{fast}}(\mathbf{r}_*); \qquad \mathbf{r}_* = \mathbf{r} + \frac{\Delta t_{\mathrm{fast}}^2}{24}\mathbf{a}_{\mathrm{fast}}(\mathbf{r}) \\
\mathbf{v} = \mathbf{v} + \tfrac{2}{3}\Delta t_{\mathrm{fast}}\tilde{\mathbf{a}}_{\mathrm{fast}} \\
\mathbf{r}_{\mathrm{sub}} = \mathrm{SDAR}(\mathbf{r}_{\mathrm{sub}}, \mathbf{v}_{\mathrm{sub}}) \\
\mathbf{r} = \mathbf{r} + \tfrac{1}{2}\Delta t_{\mathrm{fast}}\mathbf{v} \\
\mathbf{a}_{\mathrm{fast}} = \mathbf{a}_{\mathrm{fast}}(\mathbf{r}) \\
\mathbf{v} = \mathbf{v} + \tfrac{1}{6}\Delta t_{\mathrm{fast}}\mathbf{a}_{\mathrm{fast}}
\end{cases}$$

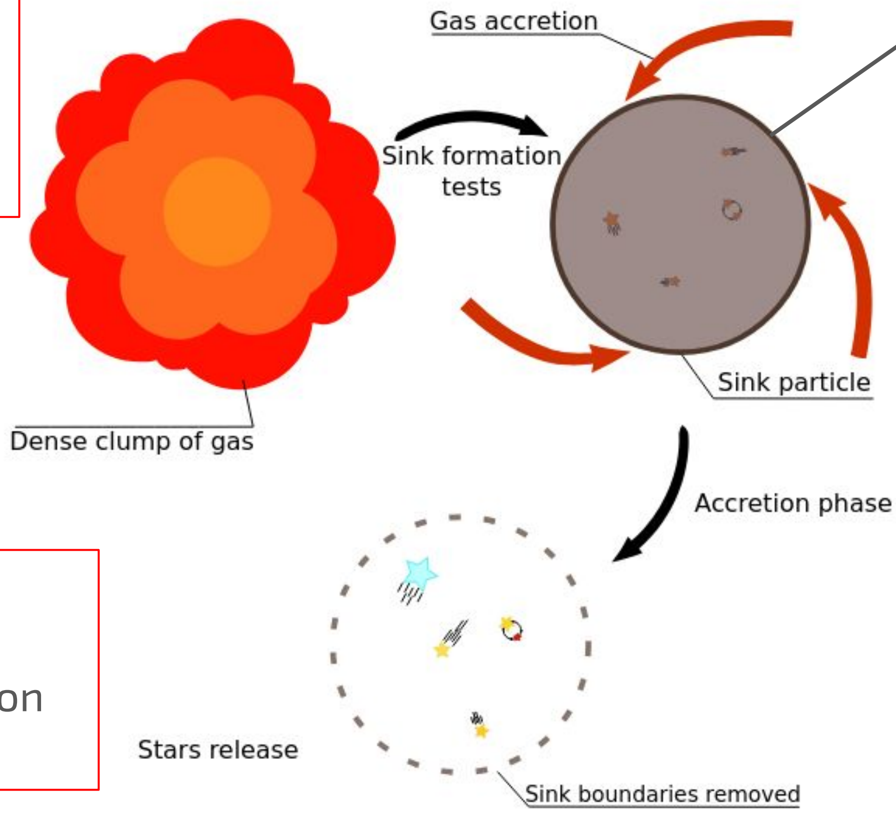
$$\mathbf{a}_{\mathrm{sph}} = \mathbf{a}_{\mathrm{sph}}(\mathbf{r})$$

$$\mathbf{v} = \mathbf{v} + \tfrac{1}{2}\Delta t_{\mathrm{sph}}\mathbf{a}_{\mathrm{sph}},$$

Methods : Star formation prescription

Sink formation tests:
Central density > ρ_{crit}
Collapsing
Local minimum potential

Bate 1995



8000 au

Star seeds living in the sink during the accretion phase

N_{seed} = random{1,5}

0.5 Myr

Star release:
Random mass sharing
Plummer spatial distribution
Virial equilibrium

Methods : HII region expansion feedback

$$R_{\rm St} = \left(\frac{3Q}{4\pi\alpha_{\rm B} n_{\rm H}^2} \right)^{1/3},$$

Strömgren radius

Q: the ionizing photon rate of the star

$$\delta N_i = \frac{m_i}{\mu m_p} \alpha_\beta n_i,$$

Cycling on nearest neighbors and subtract to Q δN_i

Q = 0

HII region fully sampled

Ionisation front

T = 10 K

T = 10000 K

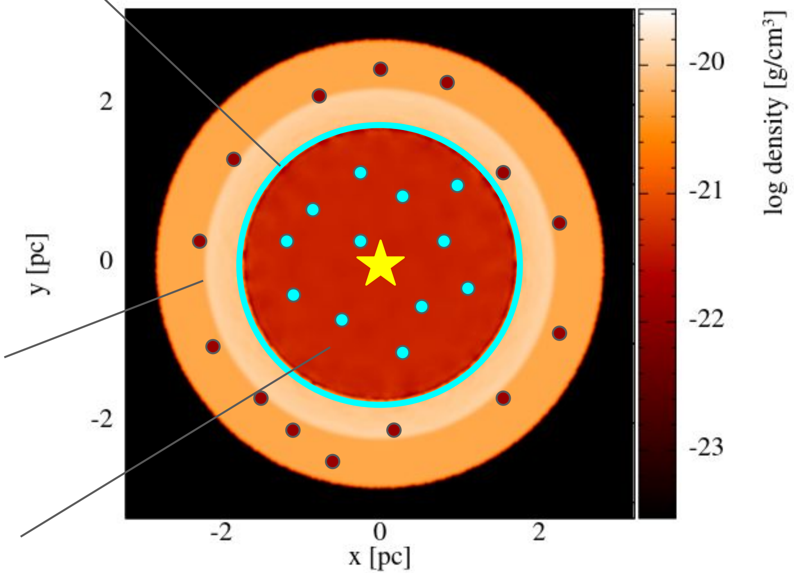


Fig. B.2: Density slice of a uniform density sphere where a HII region expands from its center. A central stellar object produces many ionizing photons that heat the gas around it. Two media (hot and cold) are separated by a front shock that propagates inside the cold sphere sweeping up the gas. A denser shell of material forms just next to the ionization front.

Methods : HII region expansion feedback

$$R_{\rm St} = \left(\frac{3Q}{4\pi\alpha_{\rm B} n_{\rm H}^2}\right)^{1/3},$$

Strömgren radius

$$\frac{I(r)}{4\pi} = \sum_{i=1}^{N_{\rm LOS}} r_i^2 \langle n(r_i)\rangle^2 \alpha_B \Delta r_i . \quad \times N_{\rm gas}$$

$$4\pi r^2 F(r) = Q_{\rm H} - I(r)$$ > 0 is ionised

HII region fully sampled

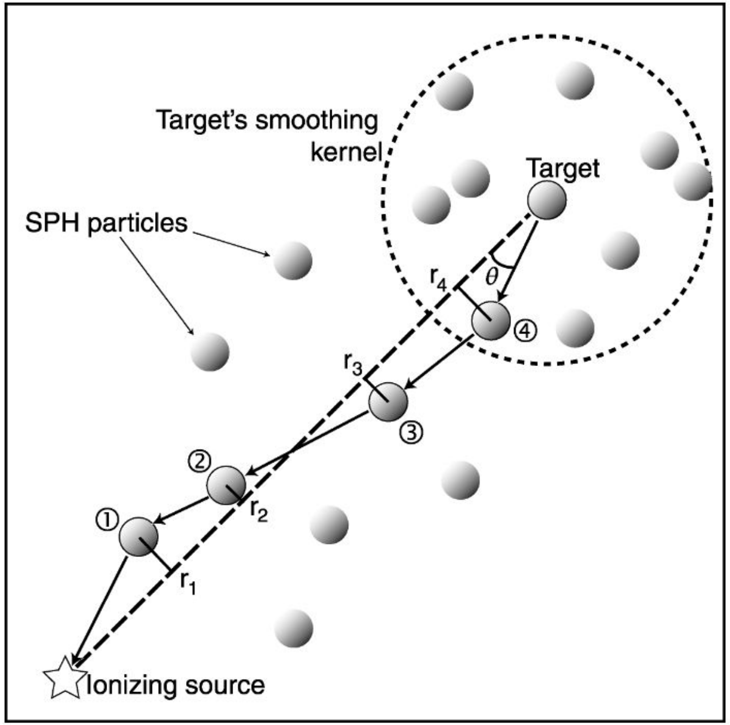


Figure 1. Illustration of the method used to select particles whose densities are to be used to derive the density profile along the line-of-sight between the radiation source and a given target particle, denoted by the thick dashed line.

Dale+ 2007

Performance bottleneck

Sinks-gas interactions:

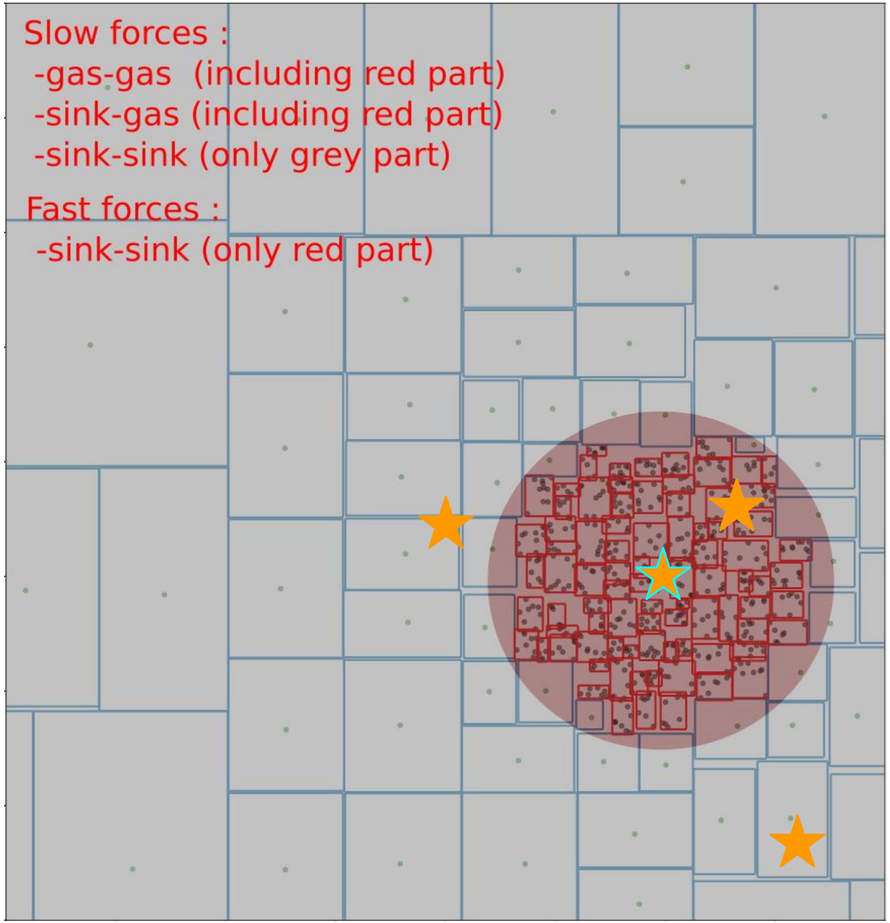
- direct N^2 into Phantom
- always at the lowest bin

Hit the perf when N_{sinks} > ~1000

Waste of computations:

- Softened interactions
- Long range interactions

Push sinks in the KD tree



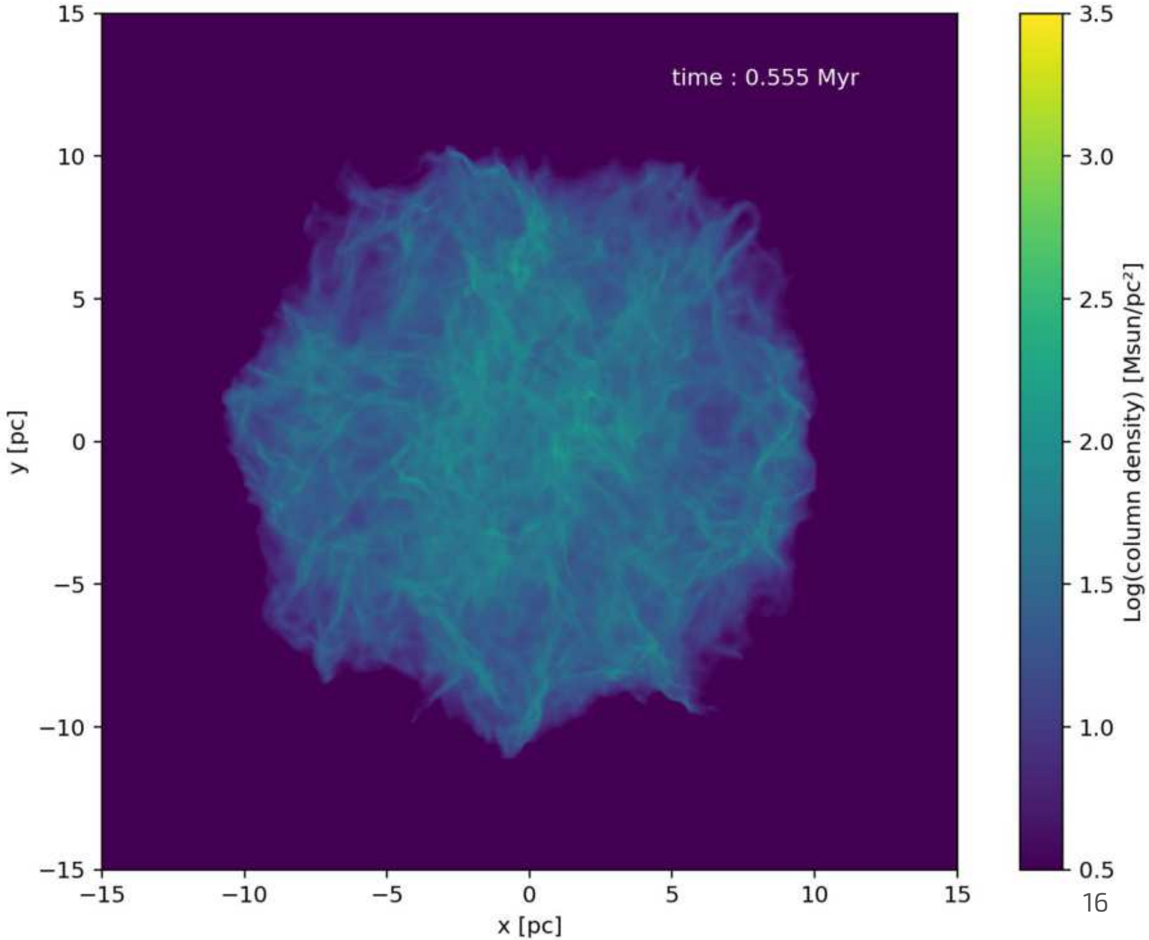
Simulation setup

Initial GMC:

- $R = 10$ pc
- $M = 10\,000$ Msun
- $T = 10$ K
- $\mu = 2.35$
- $\alpha = 2$
- 2 500 000 SPH particles
- $\tau_{ff} = 5.7$ Myr

Turbulent velocity field:

- $E_k \propto k^{-2}$



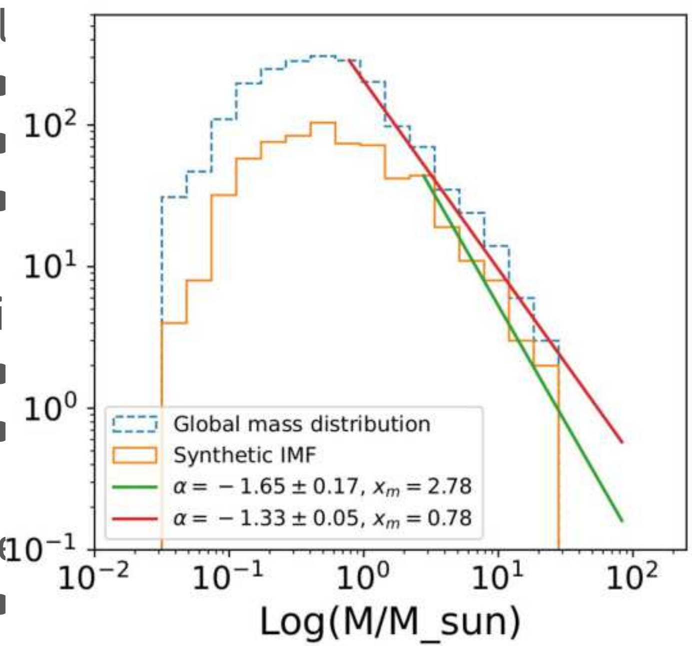

time : 0.010 Myr

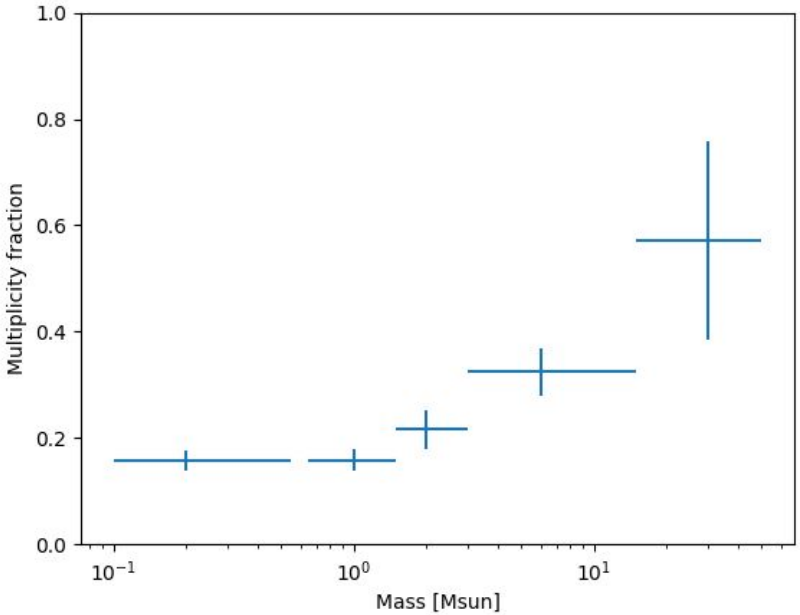
Conclusions and perspectives

Al

Si

Re





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formation of **massive stars**

- The need for a **statistical study**