



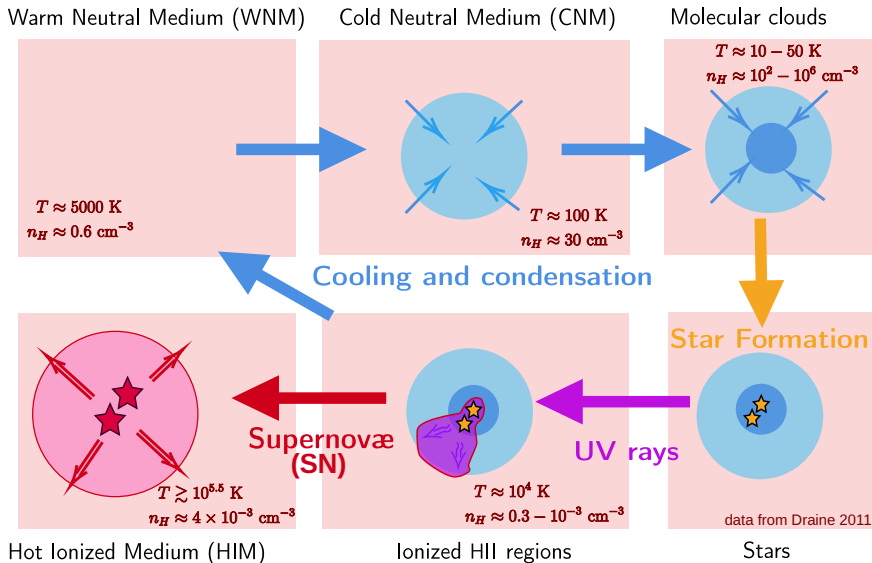
What is the contribution of gravity on the mass assembly of star-forming clouds?

Using tracers for time integrated force balance in Ramses

Noé Brucy, Enrique Vázquez-Semadeni, Tine Colman, Jérémy Fensch, Ralf Klessen

ASNUM - Grenoble, 12/2025

The matter cycle in the ISM



Key questions when studying star formation at the Galactic / ISM scale

How do the the warm diffuse gaz condense into cold dense clouds?
From there, how do these clouds further condense to form stars?

Several answers one can get:

- ▶ It's all (or mainly) due to [insert your favorite process here] (usually to pick among gravity, turbulence or magnetic field)
- ▶ It's a bit of everything
- ▶ It depends

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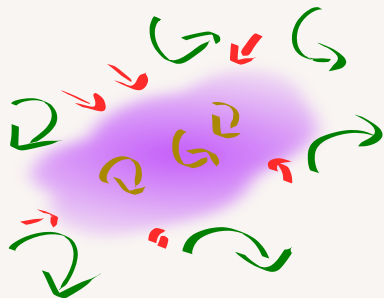
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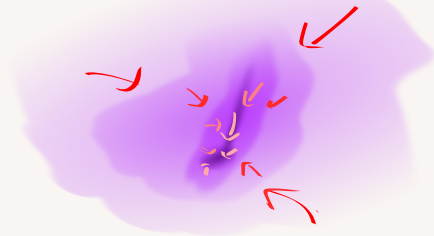
Mass assembly of molecular clouds and star formation

Turbulence-Driven



1. Turbulence shapes the density field
2. Small overdensities collapse because of gravity.

Gravity-driven (GHC)



- Gravity acts as a conveyor belt that drive gas accross density layers.

How to distinguish from the two paradigms?

In the Global Hierarchical Collapse scenario, the **contribution** of the gravitational pull needs to be large.

For a given molecular cloud we need to quantify how much gas is:

- ▶ gravity-driven
- ▶ inflowing into the cloud

We can do it in simulations of the interstellar medium, by tracking the gas

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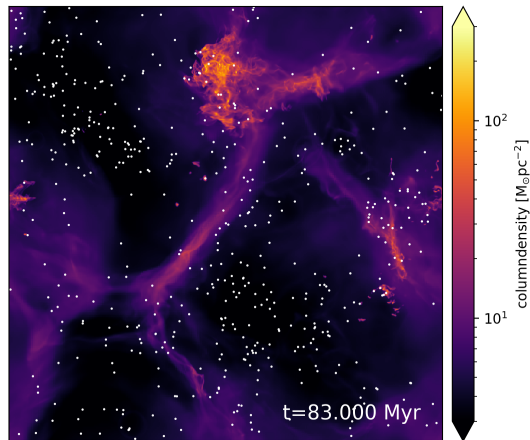
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Application on a ISM simulation

Introduced in Colman+2025

Stratified ISM box simulation

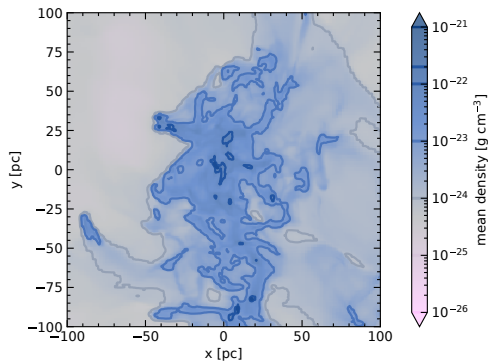
- ▶ Stratified kpc box
- ▶ ISM cooling/heating
- ▶ Supernova and HII radiation
- ▶ Resolution 4 pc - 1 pc
- ▶ Sinks form at $2.34 \cdot 10^{21} \text{ g}\cdot\text{cm}^{-3}$
(10^3 cm^{-3})



Setup: Iffrig+2015, Cooling+2018, Brucy+2020,2023, Colman+2022,2025

What are we looking at

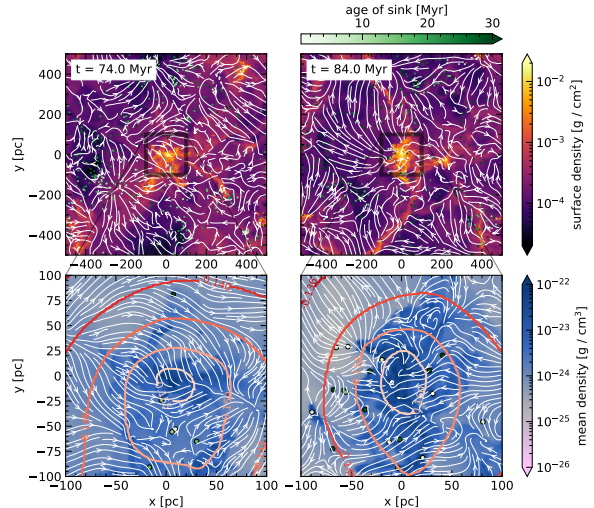
- ▶ A giant overdensity of gas
- ▶ Lifetime ≈ 15 Myr
- ▶ Density: from 10^{-23} to $4 \cdot 10^{-21} \text{ g}\cdot\text{cm}^{-3}$
- ▶ CNM mass: $2 \cdot 10^5 M_{\odot}$
- ▶ Size: ≈ 200 pc
- ▶ Velocity dispersion: $9 \text{ km}\cdot\text{s}^{-1}$



Method

Resimulation of the life of a molecular cloud

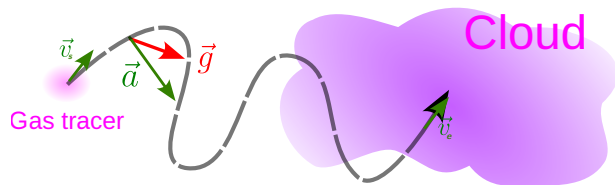
- ▶ From $t_i = 74$ Myr to $t_f = 84$ Myr
- ▶ At t_i , introduction of one tracer particle per cell
- ▶ Recording of the forces experienced by the tracer particles



Method

Cloud-in-cell tracers particle

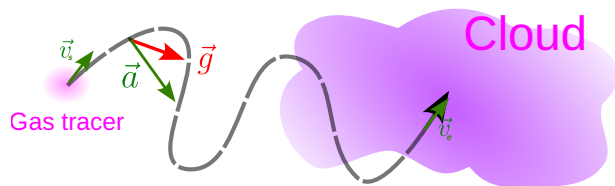
How do we recognize gravity-driven inflowing gas?



Method

Cloud-in-cell tracers particle

How do we recognize gravity-driven inflowing gas?



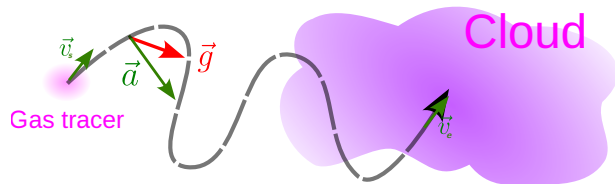
$$\vec{a}_{\text{grav}}(t_s, t_e) = \frac{\int_{t_s}^{t_e} \vec{g} \, dt}{t_e - t_s} \quad (1)$$

$$\vec{a}_{\text{other}}(t_s, t_e) = \frac{\int_{t_s}^{t_e} \vec{a} \, dt}{t_e - t_s} - \vec{a}_{\text{grav}}(t_s, t_e) \quad (2)$$

Method

Cloud-in-cell tracers particle

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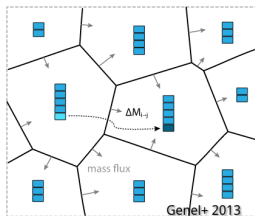
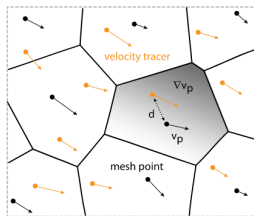
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Gravity-driven: gravity contributed to more than 50 % of the resulting integrated acceleration

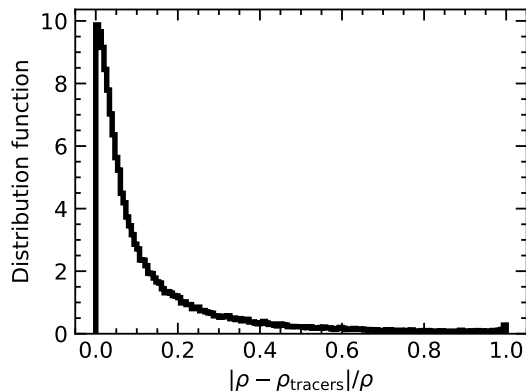
$$a_{\text{grav}} > a_{\text{other}}$$

Tracers in Ramses?



- ▶ We use velocity-advected tracers (Pichon+2011, Dubois+2012)
- ▶ Known for their lack of accuracy (Genel+2013)
- ▶ Other technique: Monte-Carlo tracers (Cadiou+2018) → not suited for force recording
- ▶ We quantify the error on the density

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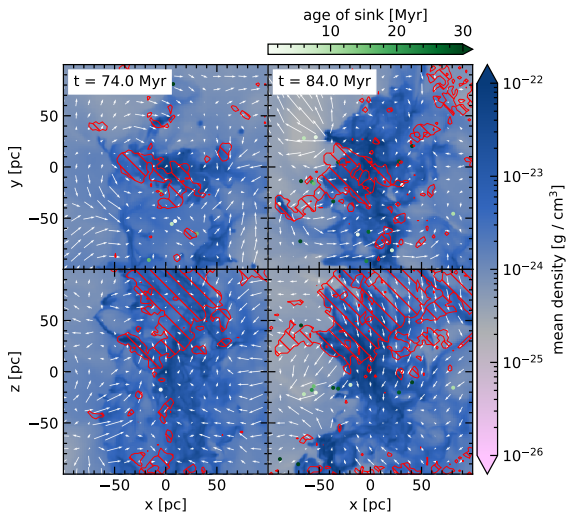
Error < 15 % for 70 % of the tracers' mass.

Gravity-driven accretion

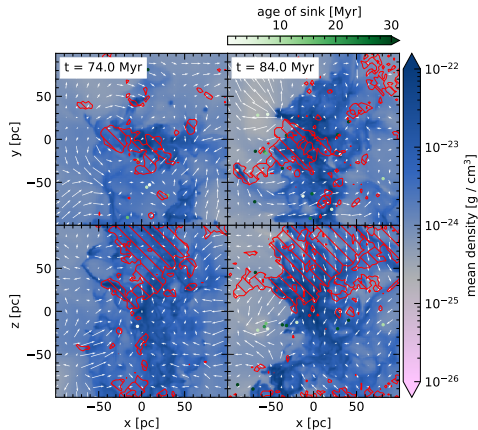
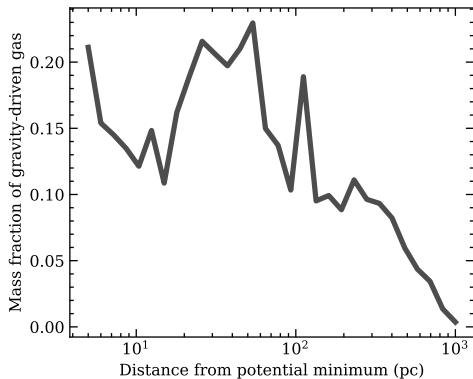
Where is the gravity-dominated gas coming from?

- Density slices
- Red = $> 20\%$ of gravity-dominated tracers
- White dots = new stars

Answer: A bit from everywhere, with self-gravity dominated gas in the midplane and a significant contribution from the Galactic fountain.

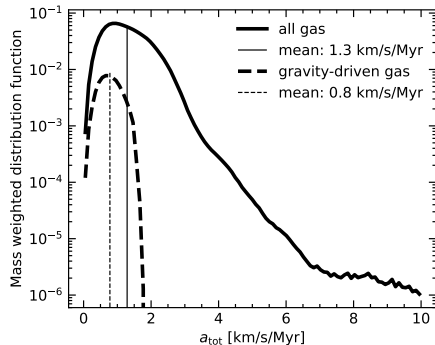


Mass fraction of gravity-driven gas



A fraction of 10-20 % of the gas is gravity-driven up to 100 pc from the center of the cloud

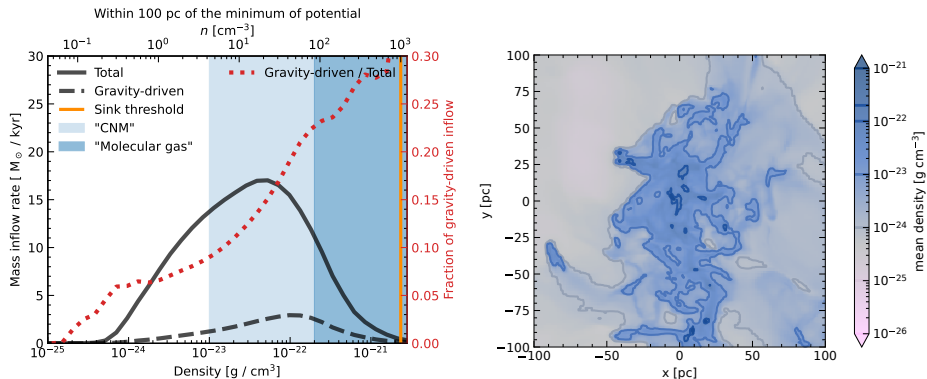
But gravity-dominated gas is slow



Supernova driven gas can reach several hundreds of km/s while gravity infall is limited to 8 to 10 km/s.

Can it has a significant contribution to the clouds' mass assembly?

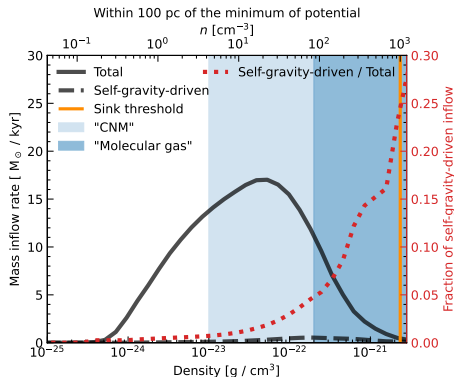
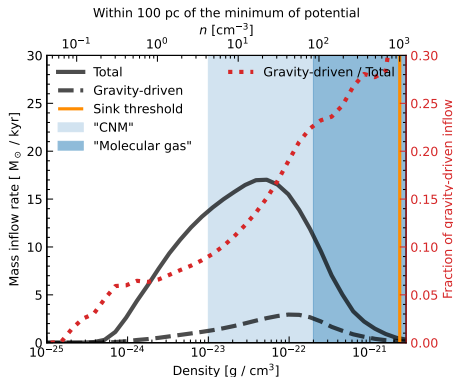
Mass flow towards across isodensity lines



10 % of the gas inflowing onto the GMC is gravity-driven. This fraction rise to 30 % inside the clouds.

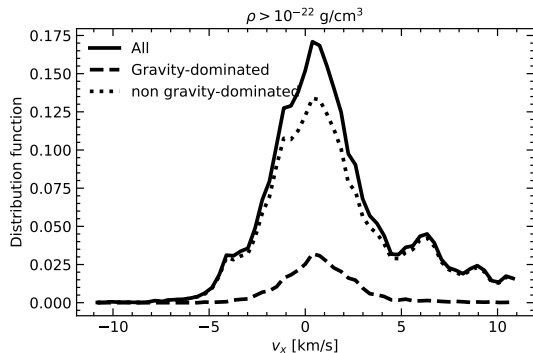
Stratified potential vs Self-gravity

Proxy: looks at gas for which the movement parallel to the plane is gravity-driven



Stratified potential dominates the gravity-driven gas at large scales while self-gravity is stronger in dense regions

Contribution of the gravity-driven gas to the linewidth



- ▶ Linewidth over a 100 pc wide area
- ▶ Gravity-driven gas: 10 % of the variance of the velocity
- ▶ No change of the FWHM

At 100pc scale, the contribution of gravity-driven gas to the linewidth is negligible

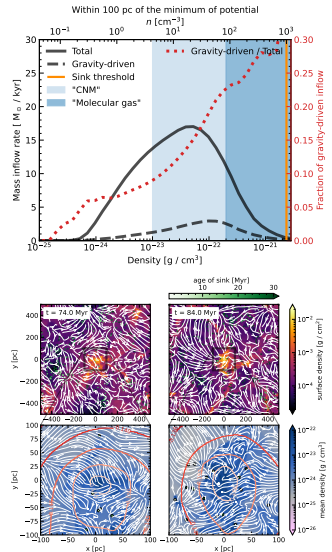
Conclusions

Brucy+2025 (accepted today in Open Journal of Astrophysics!)

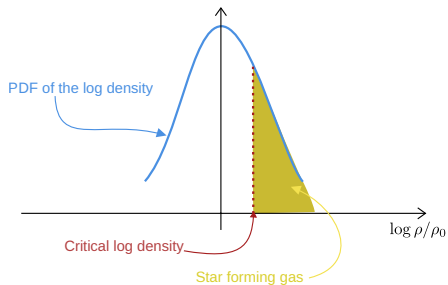
- ▶ Tracers particles allows for Lagrangian tracking of gas flow in Eulerian simulations, with some caveats.
- ▶ Only 10 % on the inflowing gas is gravity-dominated → **not the main driver of cloud mass assembly.**
- ▶ The fraction of density inflowing gas progressively increases with density.

Perspectives

- ▶ Do a statistical study, look at larger and small scales
- ▶ Derive a criterion that can be used in observations

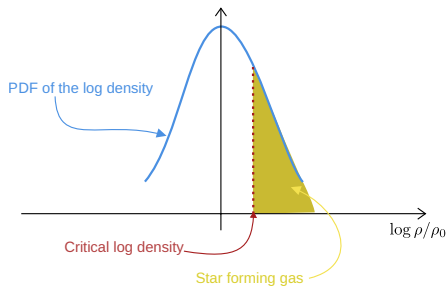


A bit more on Gravo-turbulent models



Krumholz & McKee 2005, Padoan & Nordlund 2008, Hennebelle & Chabrier 2011, Federrath and Klessen 2012.

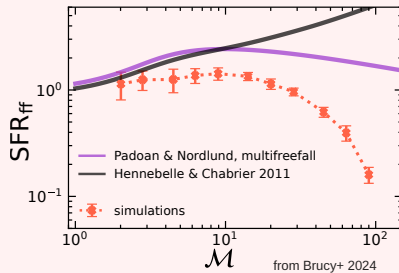
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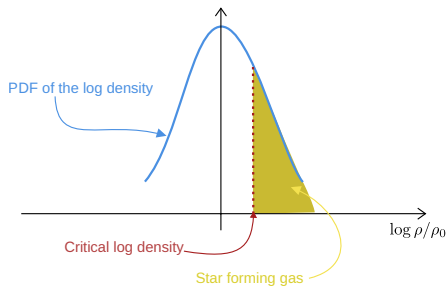
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These models don't work at high Mach



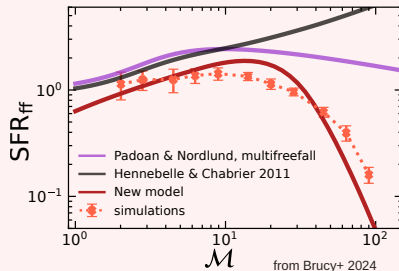
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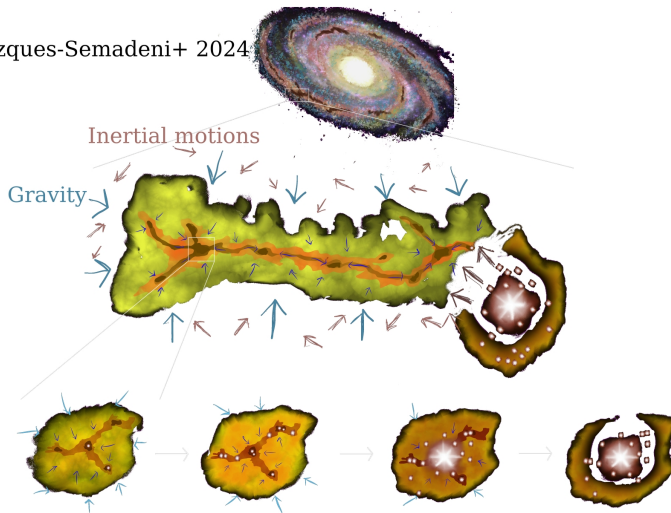
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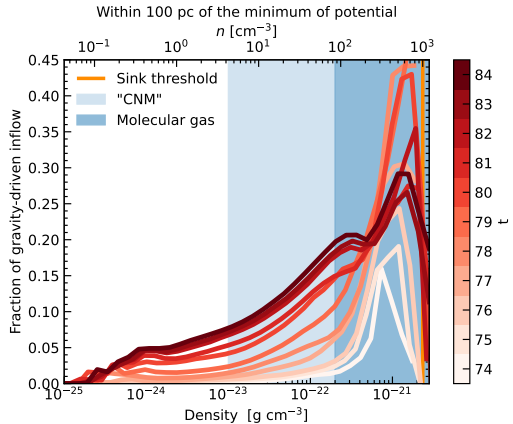
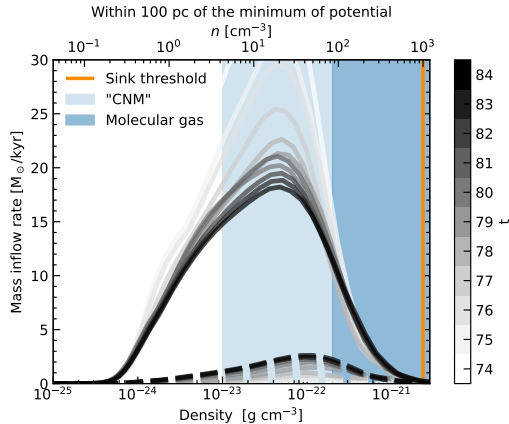
Check new **Turbulent support** model:
Hennebelle+2024, Brucy+ 2024.

A bit more on GHC

Vázquez-Semadeni+ 2024



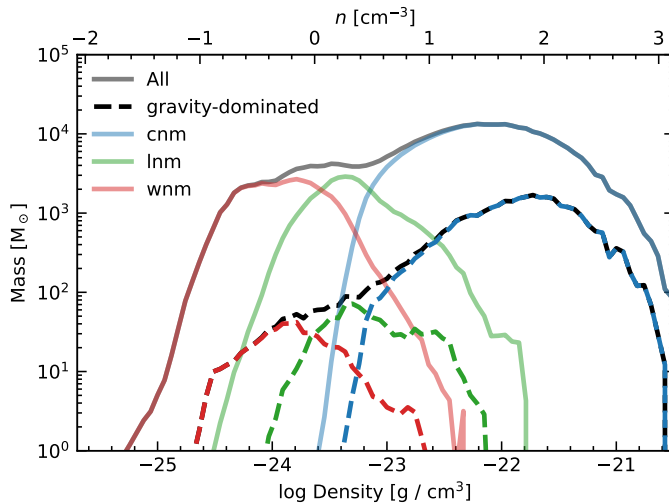
Time evolution



The fraction of gravity-driven increases as the integration time increase

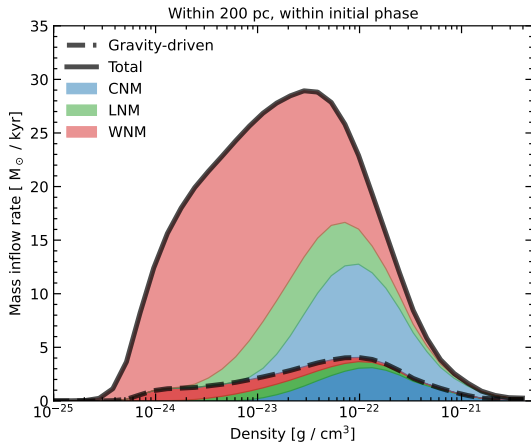
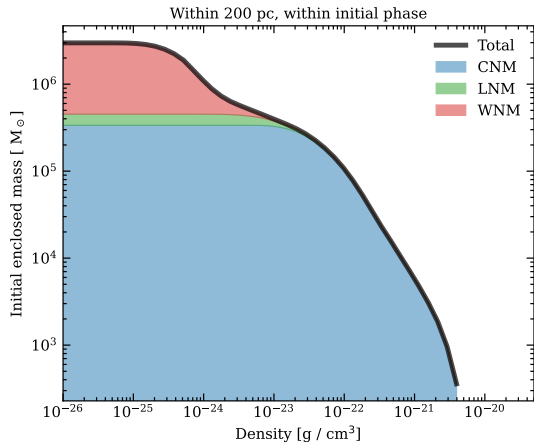
Phase decomposition

based on temperature

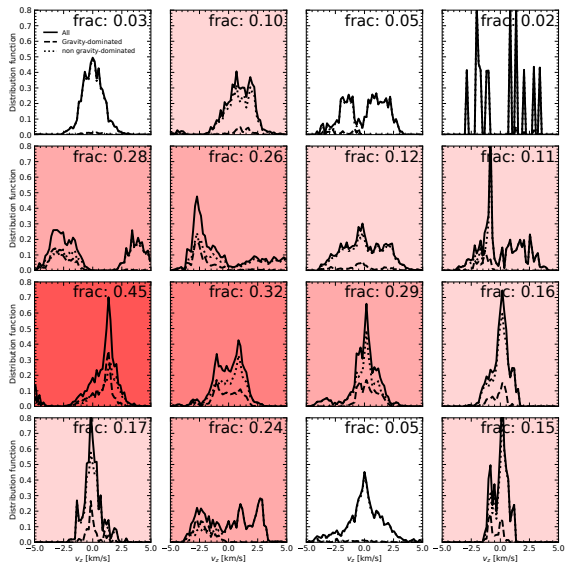
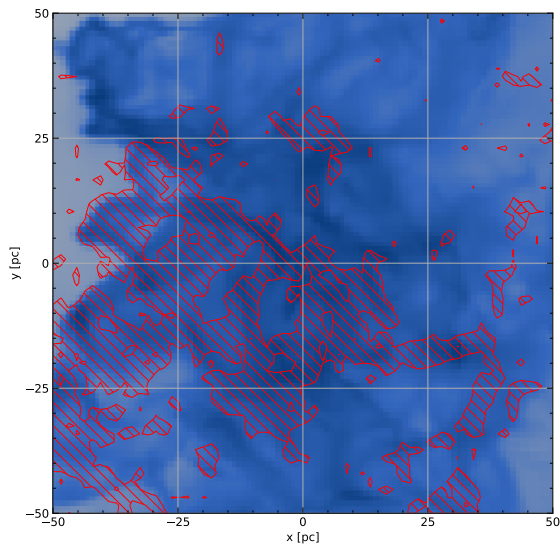


Phase decomposition

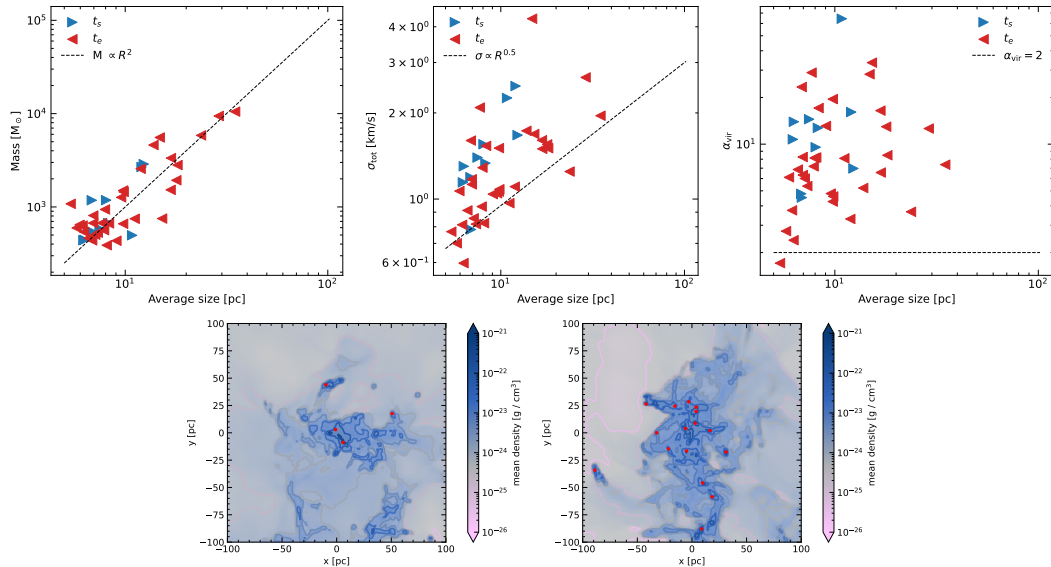
based on temperature



Perspective: towards an observational criterion



Cloud properties



Tracers in Ramses?

Changes in the code: `tracers_memory` branch

Goal: Gravitational contribution to the acceleration

- ▶ Make it possible to initialize "classical" tracers (again)
- ▶ Add new particle arrays (`vp_grav`, `vp_prev`, `ap_grav`)
 - ▶ Declaration
 - ▶ Allocation
 - ▶ Communication
 - ▶ I/O (dump & re-read)
- ▶ Update the new arrays with grav contribution (`move_fine` and `synchro_fine`)
- ▶ Repair and adapt `amr2cube` and `part2cube`

Thanks to the headers, the new arrays are directly read by Osyris.

In green: Useful fixes that were ported in Ramses Vanilla.