

The background of the slide is a cosmic scene. It features a dark blue to black background filled with numerous small white dots, representing stars or distant galaxies. Overlaid on this are intricate, filamentary structures in shades of purple, magenta, and bright orange. These filaments appear to be part of a larger, diffuse structure, possibly a molecular cloud or a galaxy's interstellar medium, with some regions being more densely packed and glowing brighter than others.

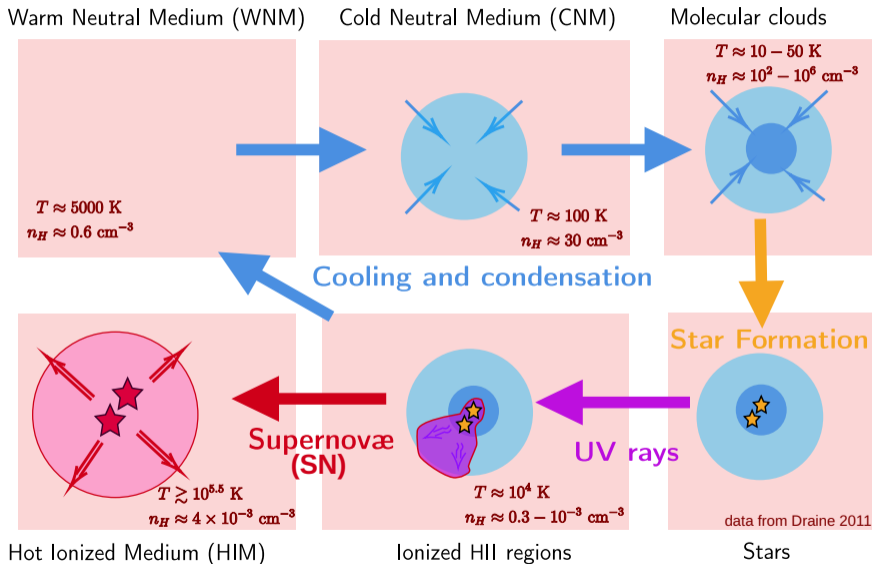
# What is the contribution of gravity on the mass assembly of star-forming clouds?

Using tracers for time integrated force balance in Ramses

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

SF2A - Grenoble, 06/2025

# 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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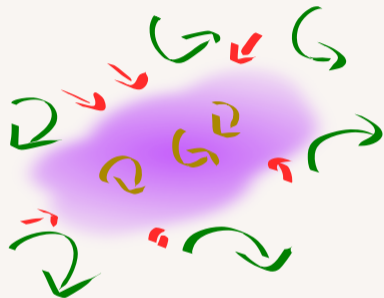
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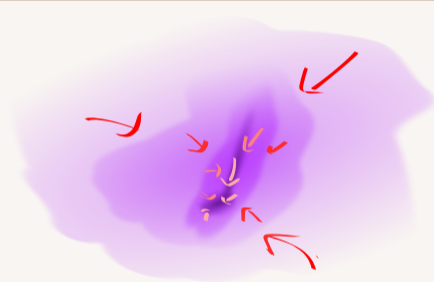
# Mass assembly of molecular clouds and star formation

## 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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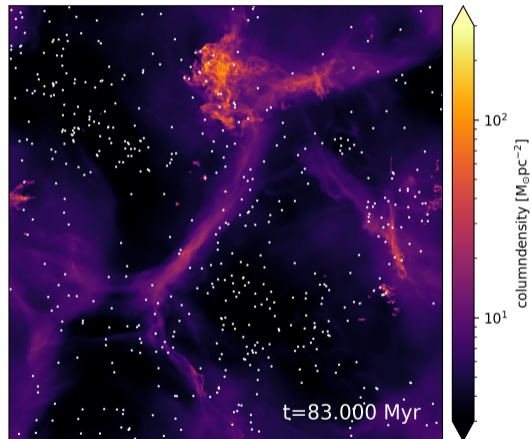
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# Application on a ISM simulation

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  $2.34 \cdot 10^{21} \text{ g}\cdot\text{cm}^{-3}$   
( $10^3 \text{ cm}^{-3}$ )

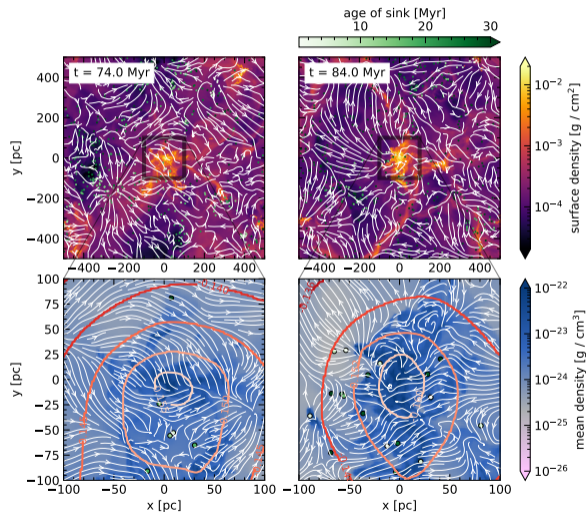


Setup: Iffrig+2015, Cooling+2018, Brucy+2020,2023, Colman+2022,2025

# Method

## Resimulation of the life of a molecular cloud

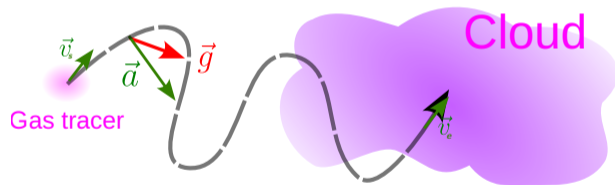
- ▶ From  $t_i = 74$  Myr to  $t_f = 84$  Myr
- ▶ At  $t_i$ , introduction of one tracer particle per cell
- ▶ Recording of the forces experienced by the tracer particles



# Method

Cloud-in-cell tracers particle

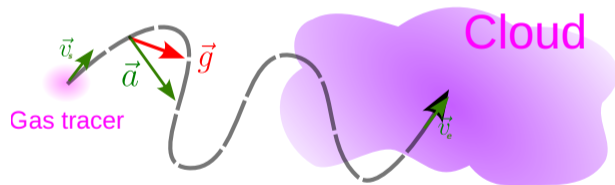
How do we recognize gravity-driven inflowing gas?



# Method

## Cloud-in-cell tracers particle

How do we recognize gravity-driven inflowing gas?



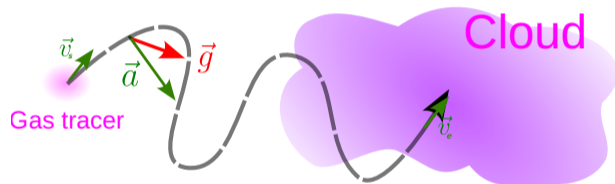
$$\vec{a}_{\text{grav}}(t_s, t_e) = \frac{\int_{t_s}^{t_e} \vec{g} dt}{t_e - t_s} \quad (1)$$

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

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

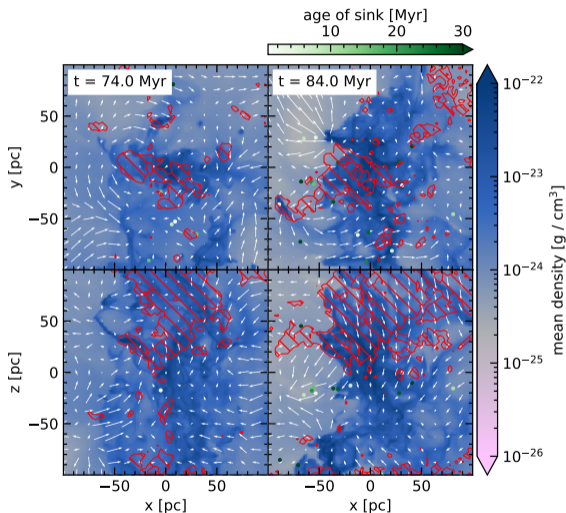
$$a_{\text{grav}} > a_{\text{other}}$$

# Gravity-driven accretion

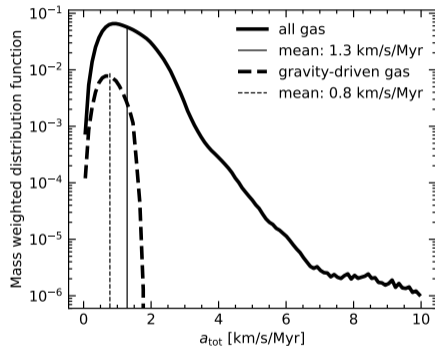
Where is the gravity-dominated gas coming from?

- ▶ 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.



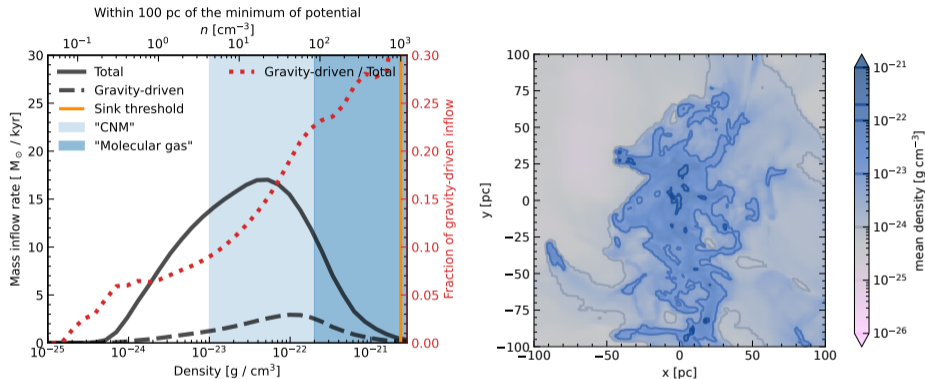
## But gravity-dominated gaz is slow



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

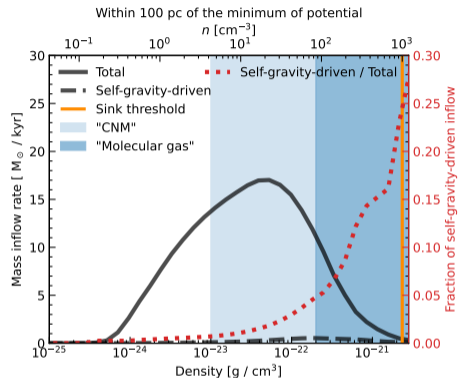
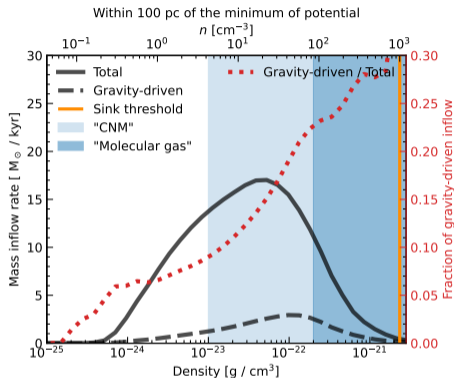
Can it has a significant contribution to the clouds' mass assembly?

# Mass flow towards across isodensity lines



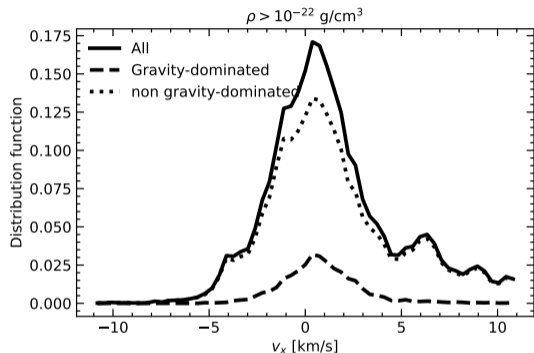
10 % of the gas inflowing onto the GMC is gravity-driven. This fraction rise to 30 % inside the clouds.

# Stratified potential vs Self-gravity



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

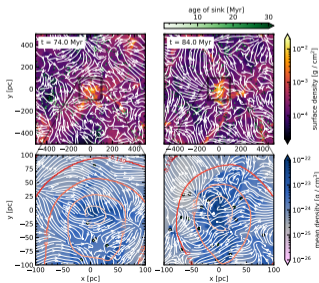
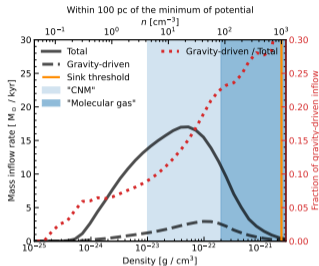
# Conclusions

Brucy+2025 (Open Journal of Astrophysics!)

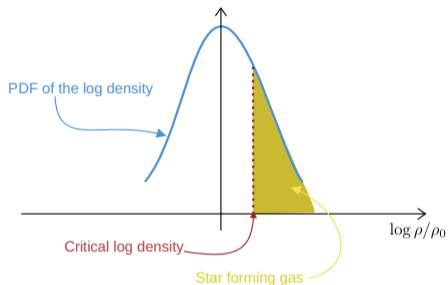
- ▶ Tracers particles allows for Lagrangian tracking of gas flow in Eulerian simulations, with some caveats.
- ▶ About 20 % on the inflowing gas is gravity-dominated → **not the main driver of cloud mass assembly.**
- ▶ The fraction of gravity-driven inflowing gas progressively increases with density.

## Perspectives

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

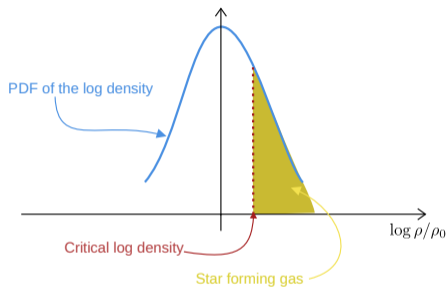


## A bit more on Gravo-turbulent models



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

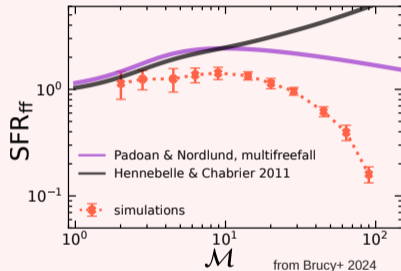
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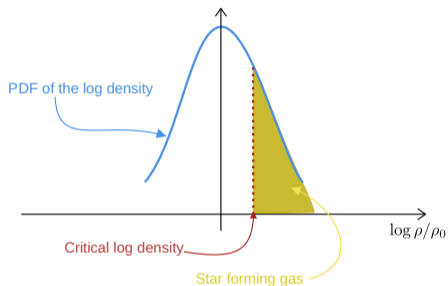
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These models don't work at high Mach



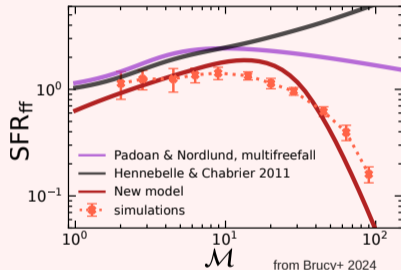
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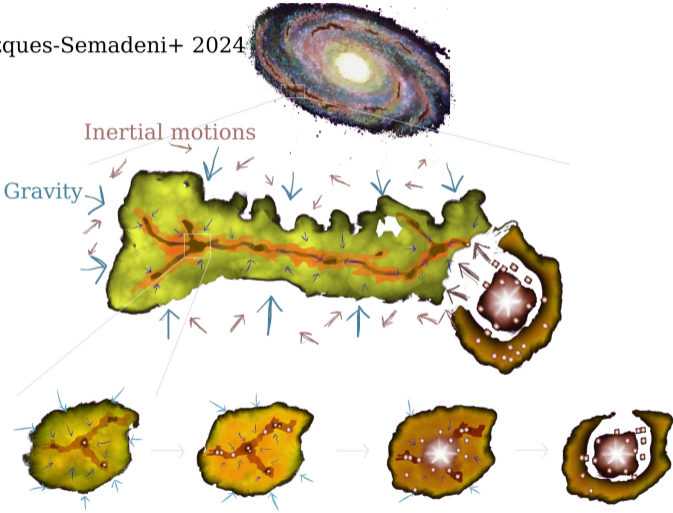
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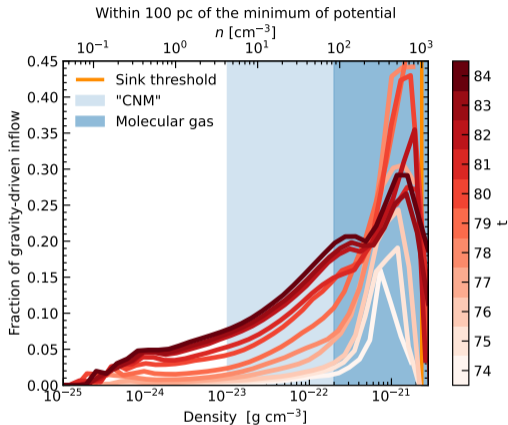
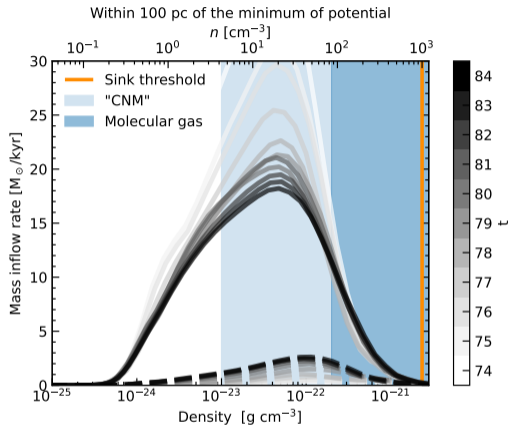
Check new **Turbulent support** model:  
Hennebelle+2024, Brucy+ 2024.

# A bit more on GHC

Vázquez-Semadeni+ 2024



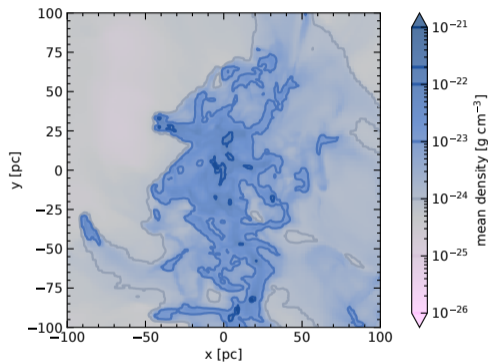
# Time evolution



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

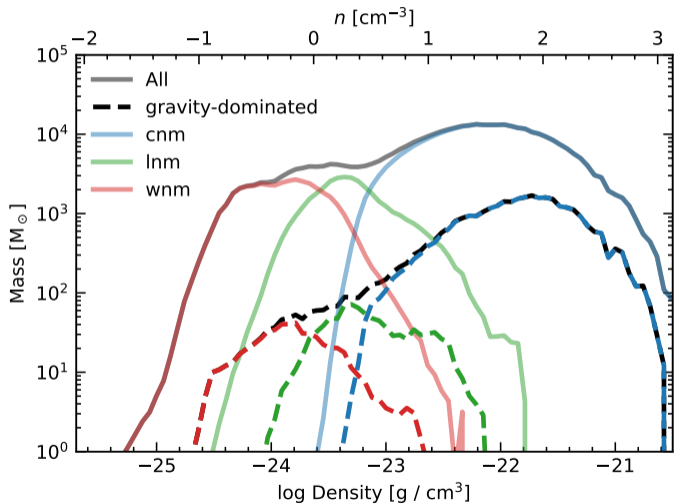
# What are we looking at

- ▶ A giant overdensity of gas
- ▶ Lifetime  $\approx 15$  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:  $\approx 200$  pc
- ▶ Velocity dispersion:  $9 \text{ km}\cdot\text{s}^{-1}$



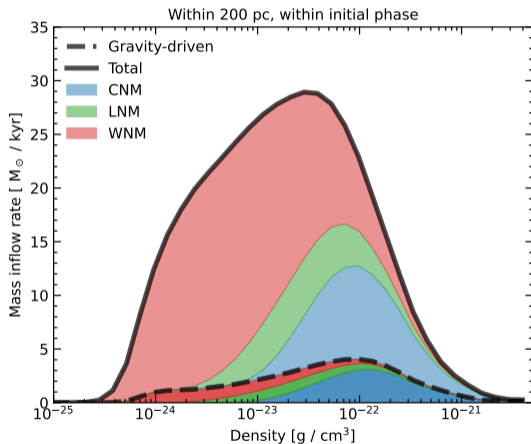
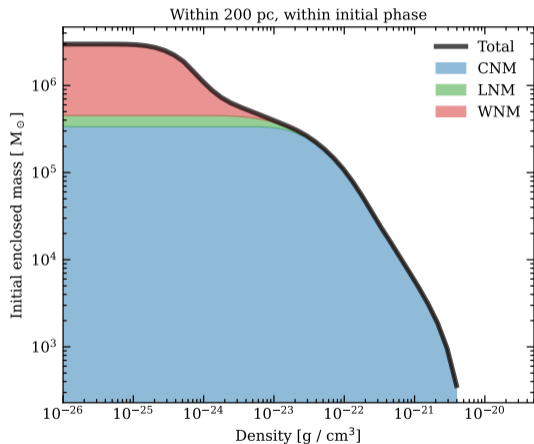
# Phase decomposition

based on temperature

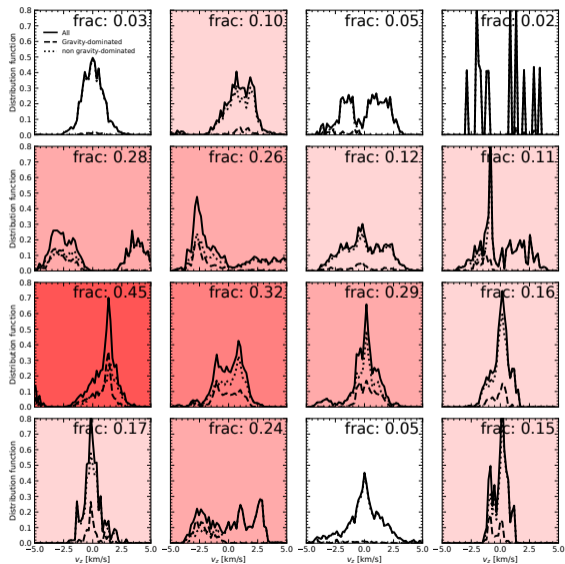
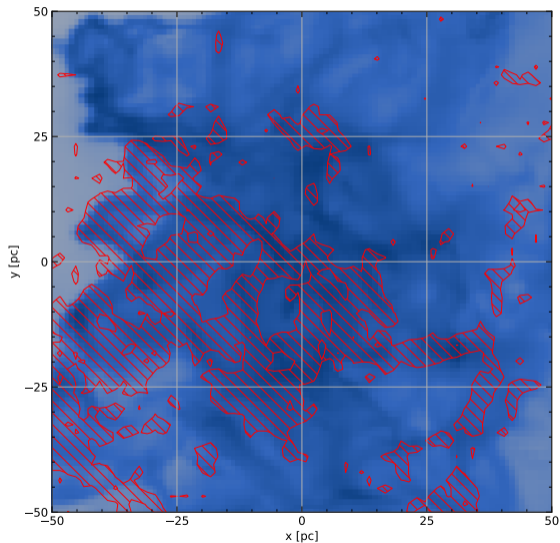


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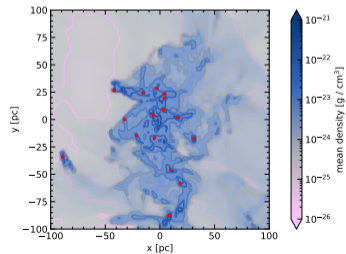
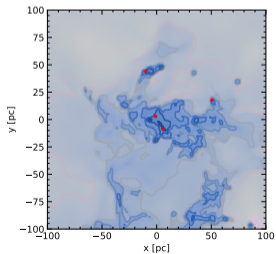
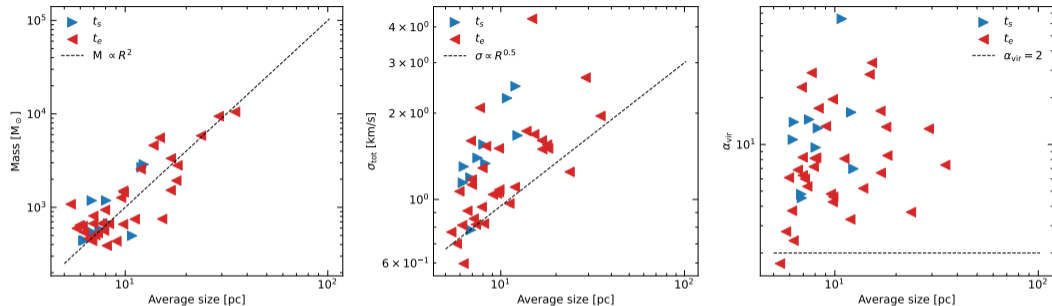
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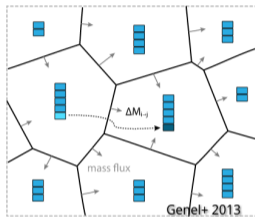
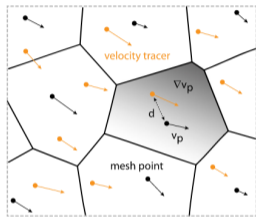
# Perspective: towards an observational criterion



# Cloud properties

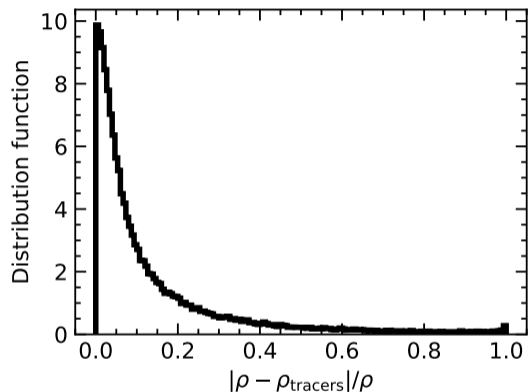


# Tracers in Ramses?



- ▶ 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.

# Tracers in Ramses?

Changes in the code: `tracers_memory` branch

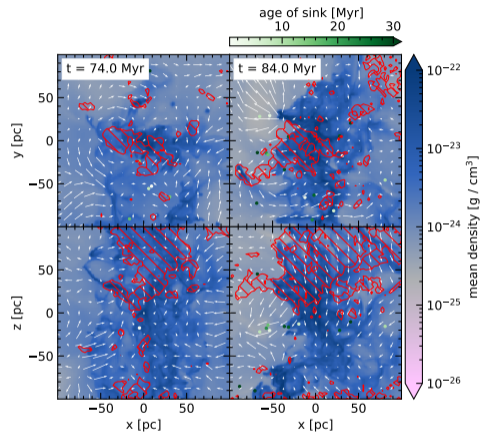
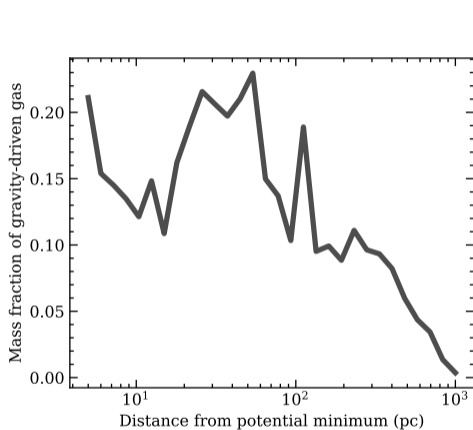
*Goal: Gravitational contribution to the acceleration*

- ▶ 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.

# 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