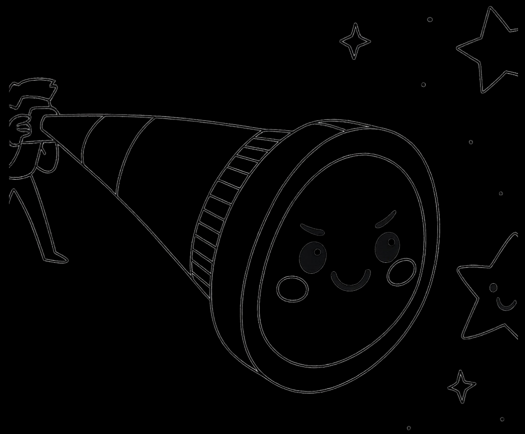

Zoom-in Numerical Simulations for Star Formation

Georges Abboudeh

2nd year PhD student

Supervisor : Patrick Hennebelle

Université Paris Cité

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RAMSES SNO - Paris

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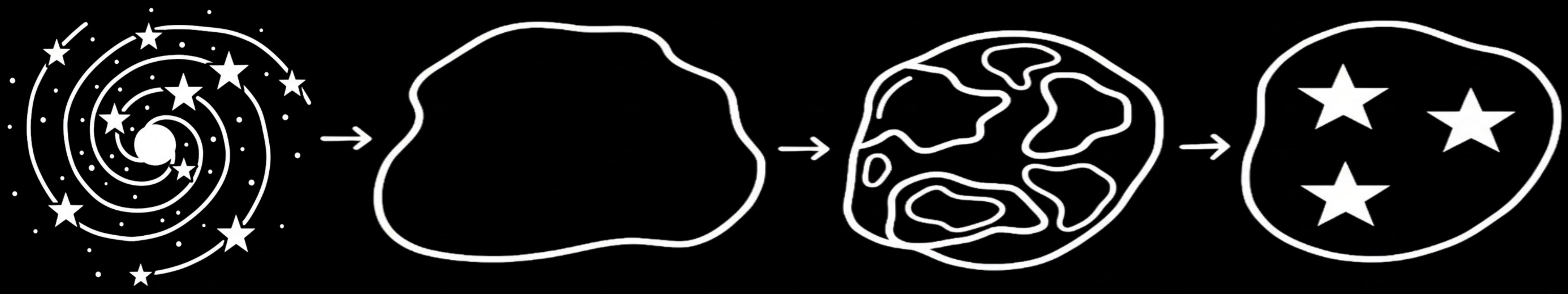
Goal: Connect the different scales, from the galaxy to the stars



Problem: One simulation with all these scales and physics is too computationally expensive

Compromise: Initial Conditions at 1kpc, then zoom up to 400 AU.

1) Are Supernovae driving turbulence in the galaxy ?

A comparison between Numerical Simulations and Observations

Turbulence in the Interstellar Medium

Origin

Large-Scales (gravitational instabilities, shear, accretion into the galaxy…)
Stellar Feedback (HII regions, jets, Supernovae…)

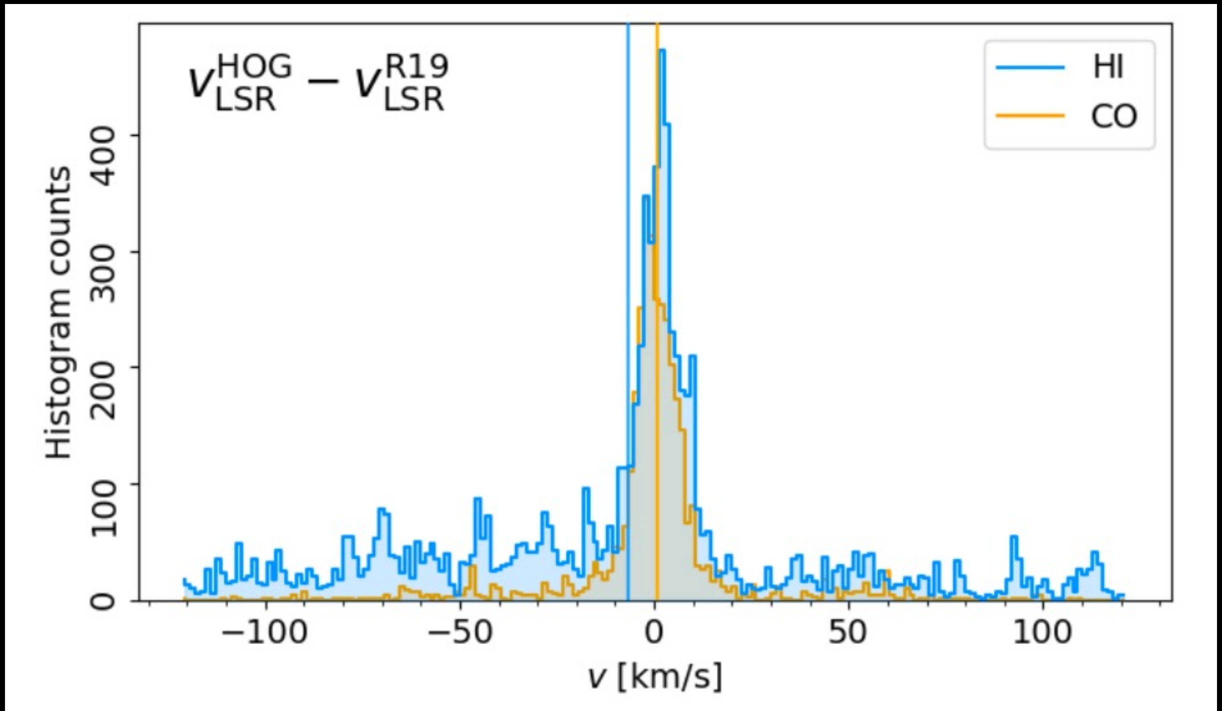
What dominates it?

Still debated, but it depends on the scale, and the environment.
For example, SN-feedback dominates in low-gas density galactic disks, while large-scale drivers dominate in high density ones (Krumholz+2018, Brucy+2023)

Observations (Soler +2025 work)

What did they do?

- Combined 3D dust tomography with H I & CO emission
- Reconstructed ISM velocities between 70–1250 pc
- Applied |v| ≤ 25 km/s cut before rotation subtraction
- Find HI velocity dispersion: **σ ≈ 10.8 km/s**



Source : Soler+2025, Fig. A.13

Simulations (this work)

What did we do?

- Analyzed two suites of 1-kpc ISM simulations, each with a different turbulence driver:

  A) **Large-scale turbulent forcing** (Ornstein–Uhlenbeck) with different forcing amplitudes to mimic energy injection from galactic-scale processes
  B) **Supernova-driven simulations** (from Colman+25 and Kim & Ostriker 2017)

- Constructed sky maps that mimic the observational one
- Compared the obtained velocity dispersions

Simulations Series

Simulation Name	f_{rms}	n_0 [cm^{-3}]	B_0 [μG]	Resolution (pc)	$\sigma_{v,\mathrm{los}}$ [$\mathrm{km\,s^{-1}}$]
TURB-7	7000	1.5	3.5	0.5	9.76
TURB-10	10000	1.5	3.5	0.5	13.00
TURB-15	15000	1.5	3.5	0.5	13.33
TURB-20	20000	1.5	3.5	0.03	14.97
SN-0.66	0	0.66	2.1	1	5.72
SN-1.0	0	1.0	2.1	1	7.04
SN-1.5	0	1.5	2.1	1	6.78
TIGRESS-MHD4pc	0	2.85	2.6	4	7.41

Table 1: **Simulation parameters.** The `TURB` runs correspond to simulations with imposed large-scale turbulent forcing, the `SN` series to supernova–driven simulations (Colman et al. 2025), and `TIGRESS-MHD4pc` is also SN–driven (Kim & Ostriker 2017). f_{rms} sets the amplitude of the imposed large-scale turbulent forcing (zero for SN runs); n_0 is the initial mid-plane number density; B_0 is the initial magnetic-field strength. *Resolution* gives the finest grid spacing Δx_{min}. $\sigma_{v,\mathrm{los}}$ is the mean line–of–sight velocity dispersion computed from the different synthetic maps of each simulation after applying a LOS velocity threshold of $|v_{\mathrm{los}}| \leq 30\,\mathrm{km\,s^{-1}}$.

Constructing the sky maps

1) Place observers

• For each simulation snapshot, position multiple virtual observers across the x–y plane.

2) Compute LOS velocities

• Calculate v_{LOS} along every line of sight.

$$v_{\rm los}(\mathbf{r}) = \frac{x\,v_x + y\,v_y + z\,v_z}{\sqrt{x^2 + y^2 + z^2}}\,,$$

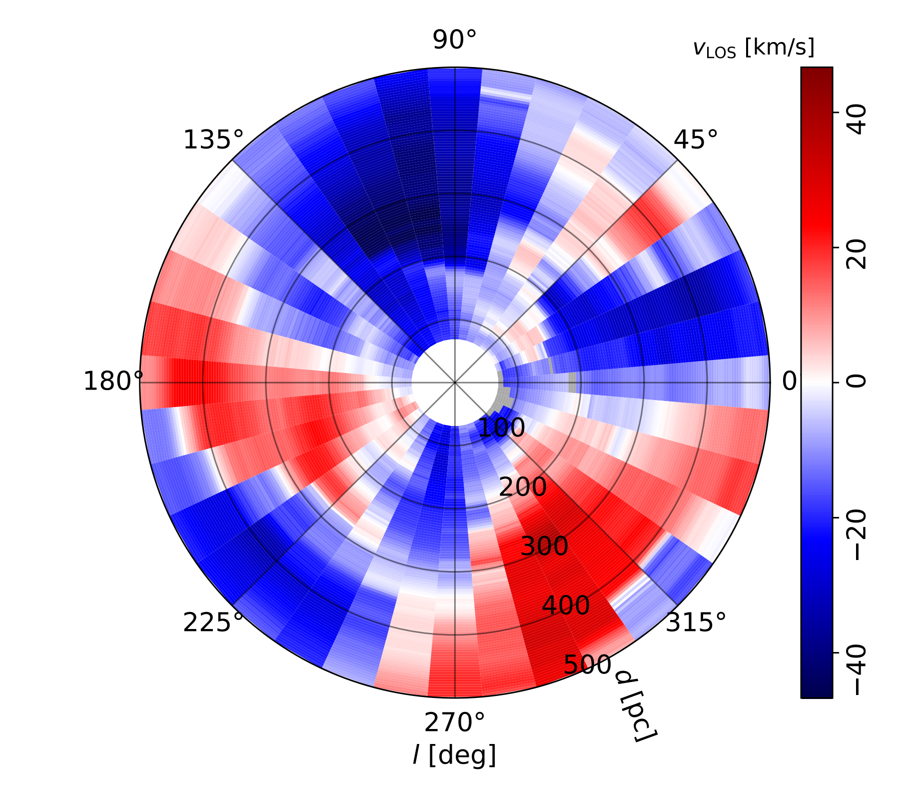
3) Apply observational cuts

• Density threshold for H I selection (> 0.1 cm^{-3})

• 69–500 pc distance range, $|\,b\,| \leq 5°$

4) **Project onto the sky**

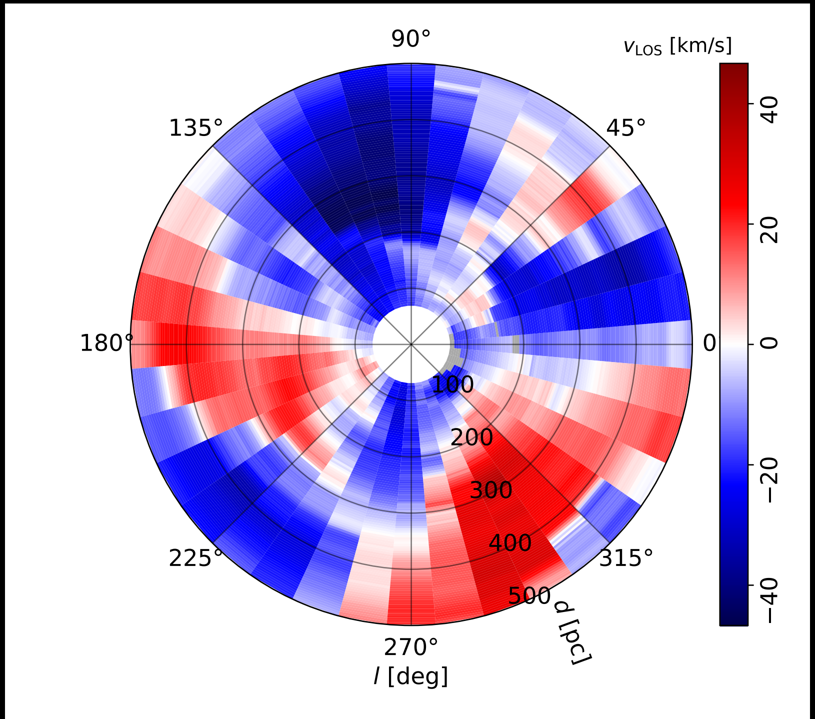
• Convert to Galactic longitude–latitude and build synthetic maps. Resolution (4 pc per radial bin x 10 degrees per longitude)



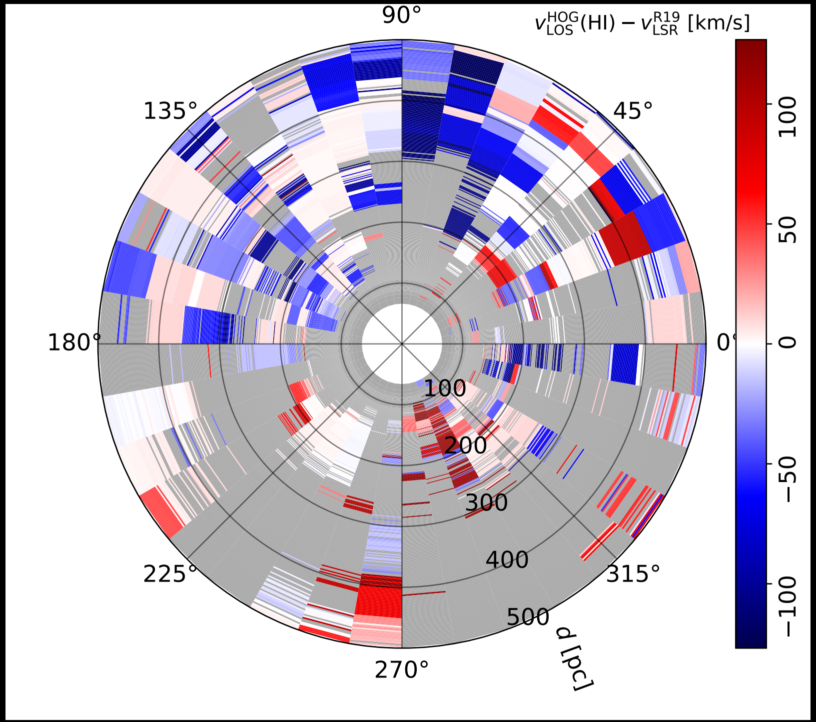
Example of a sky from simulation

Comparing the sky maps

Simulation map

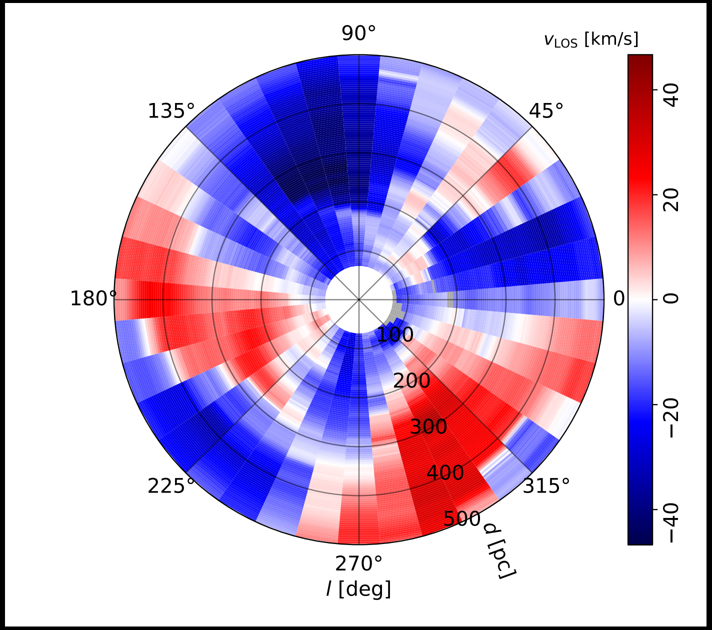


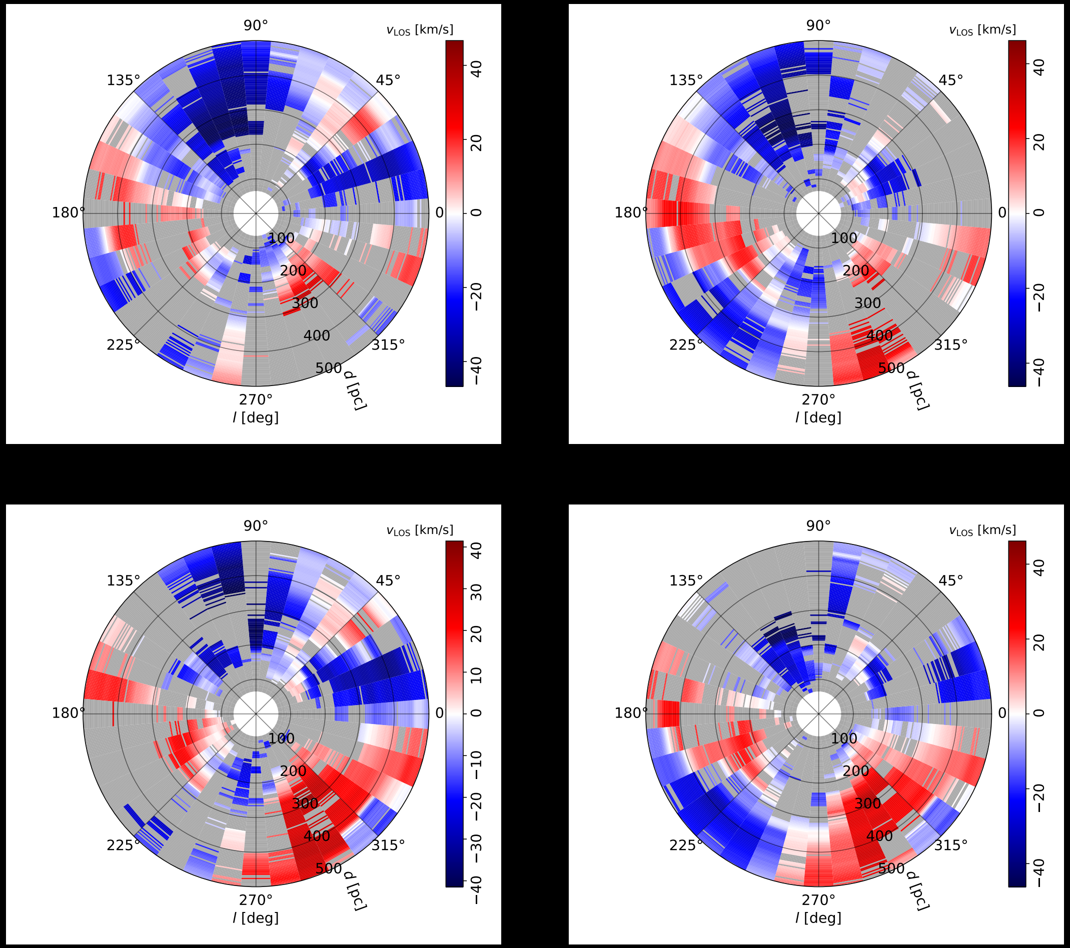
Observation map



The observation map is ‘emptier’

Emptying the simulations sky maps



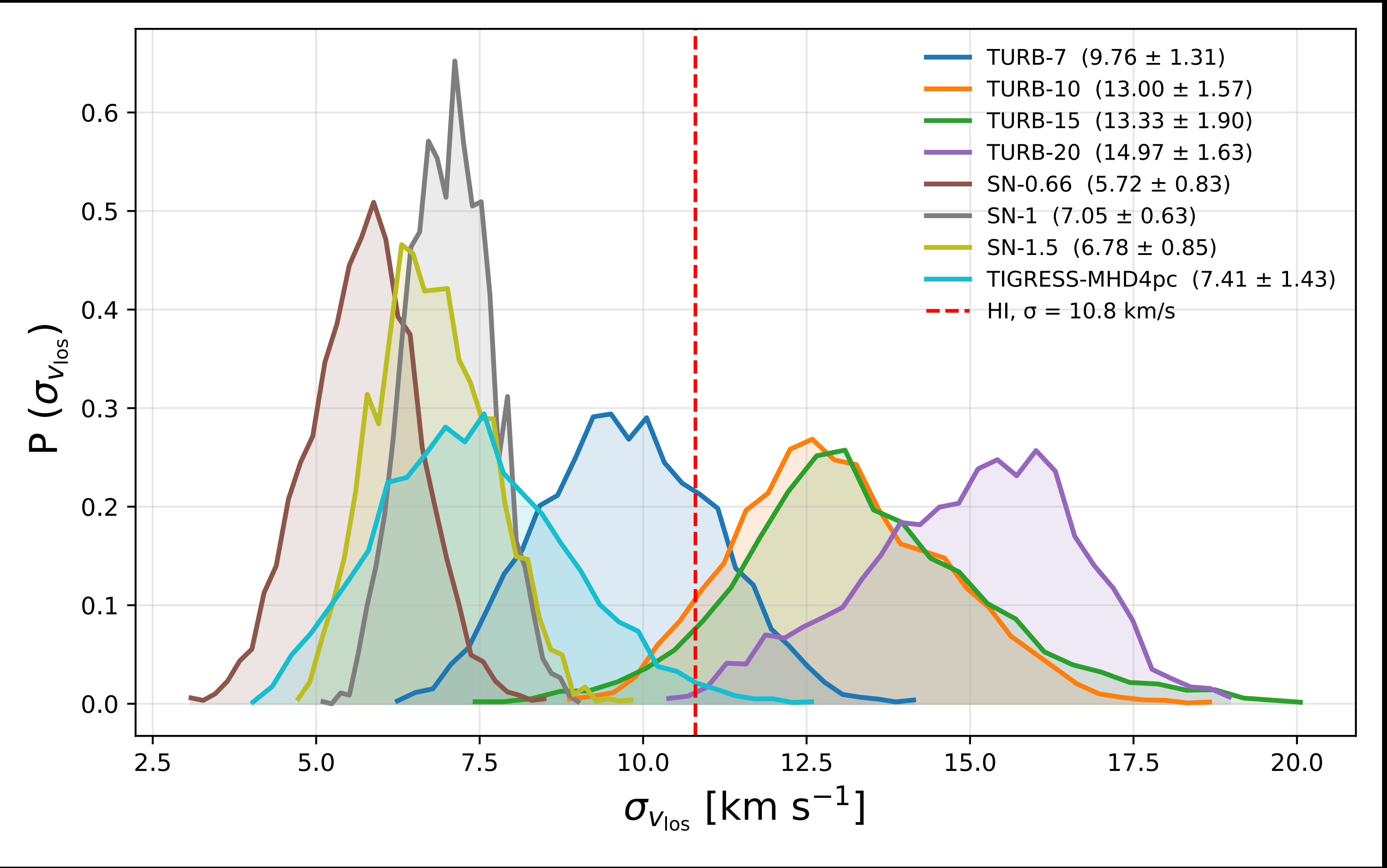


- We built an observational mask to remove regions from simulations where no observational data exist, ending up with a close number of cells.
- Because simulations have no preferred viewing direction, we rotated the mask four times.
- This produces four independent masked sky maps from each full simulation map.

Comparing velocity dispersions

- We only take $|v| \leq 30$ km/s (this value correspond to the maximum velocity in observations in the 69-500 pc range after subtracting the galactic rotation model)
- For each simulation map, we compute the mass-weighted line of sight velocity dispersion.

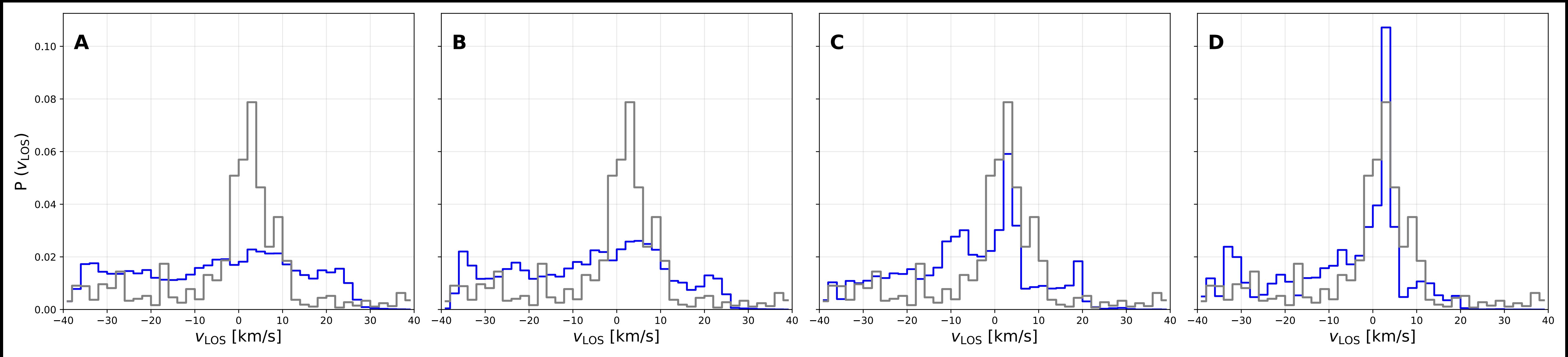
SN driven simulations present lower velocity dispersion than the observations



Distribution of velocity dispersion values from the different simulations

Are velocities > 30 km/s just noise?

The high peak, and large tails can be recovered in simulations and may be a result of the resolution and the non-full map



In grey: observational H I v_{LOS} PDF within [-40,40] km/s

In blue: simulated v_{LOS} PDF from **TURB-15**, shown after successive processing steps:

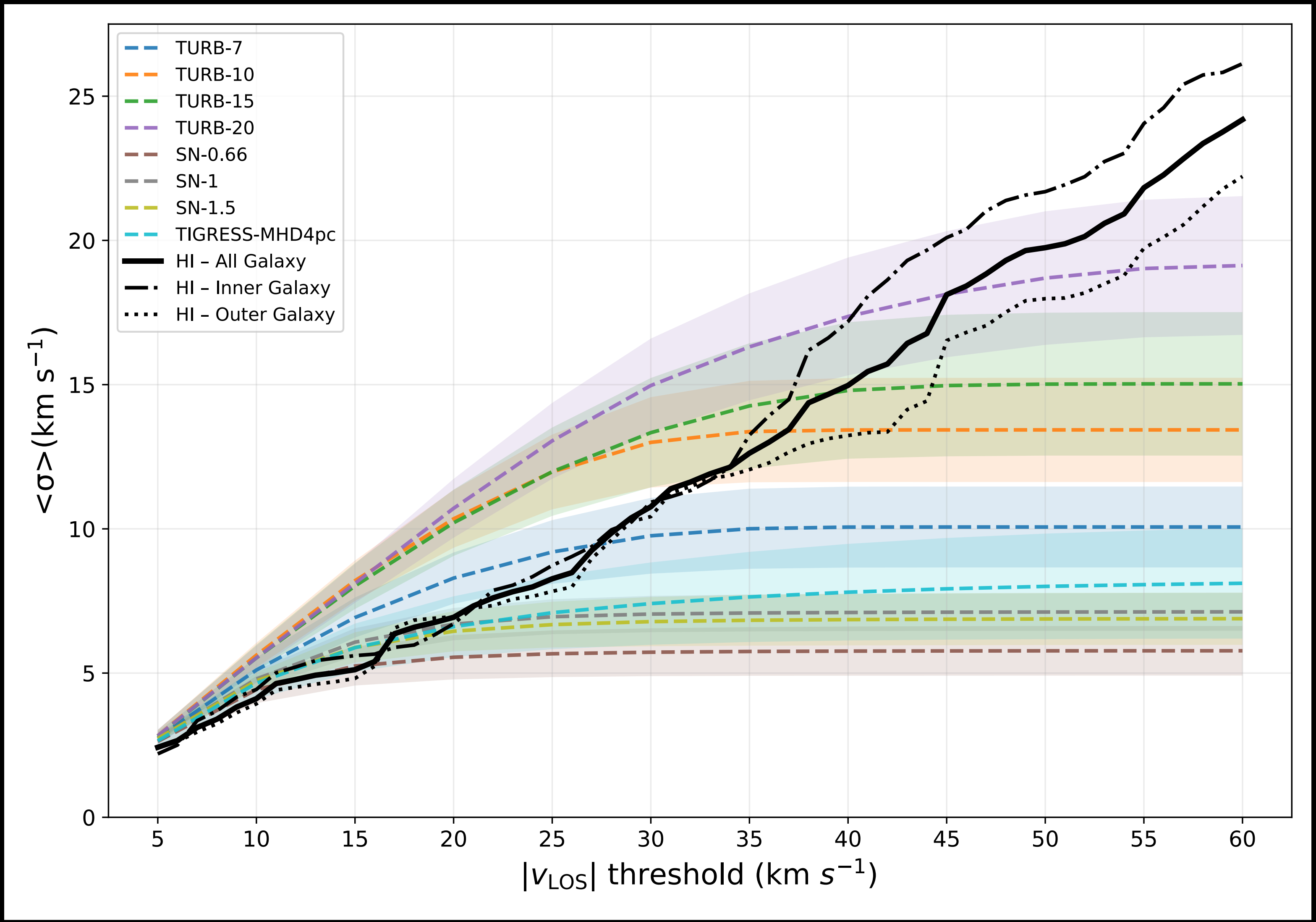
- A: 3D v_{los} data (~600000 cells)
- B: after averaging into a 2D x-y map
- C : after projecting into the sky
- D : after applying the observational mask (~1200 cells)

Changing velocity thresholds

- We explore how the results vary when changing the maximum velocity threshold

SN–driven simulations yield systematically lower velocity dispersions once $| v_{LOS} | > 20$ km/s are included.

The best TURB Model depends on the velocity threshold, to determine it we need more confident observational measurements at high-velocities, separating noise from real data.



Average velocity dispersion (per simulation) at different velocity threshold

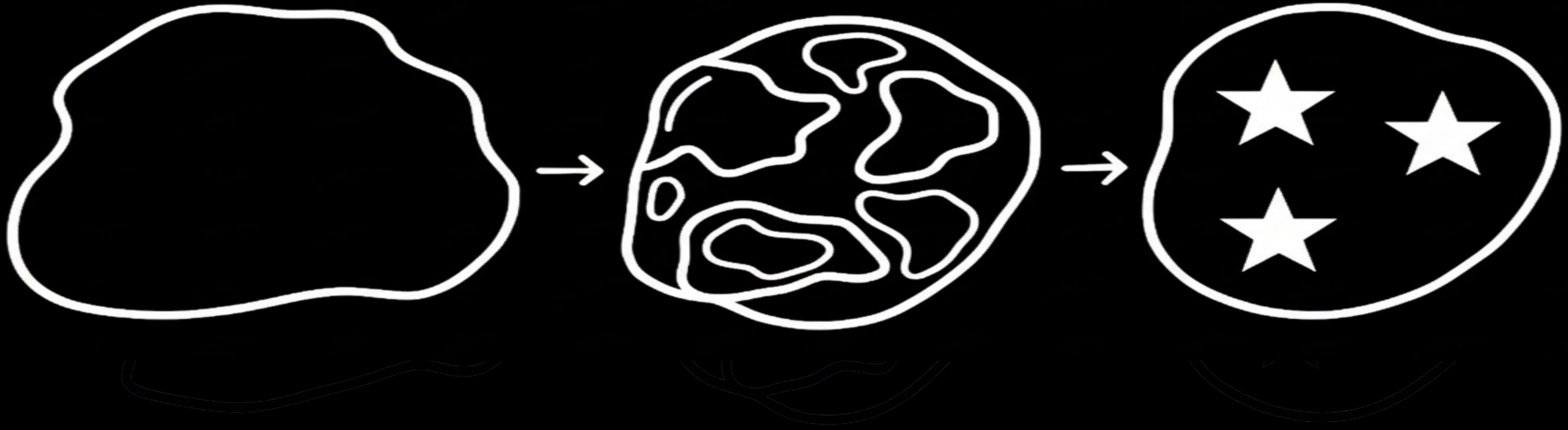
Summary

- We compared recent HI line-of-sight velocity observational data with a series of 1 kpc numerical simulations that include two distinct turbulent drivers: (i) supernova (SN) feedback and (ii) imposed large–scale turbulent forcing.
- For each simulation, we construct synthetic sky maps that closely mimic the observational one, allowing a consistent comparison between the simulations and the observational data.
- SN-driven simulations underpredict the observed velocity dispersions, whereas the large-scale forcing ones can reach and even exceed the measured turbulent amplitudes.
- In the explored 69−500 pc range, SN feedback cannot by itself drive the turbulence in the WNM, and large-scale drivers are needed.

2) Zoom-in numerical Simulations for star formation

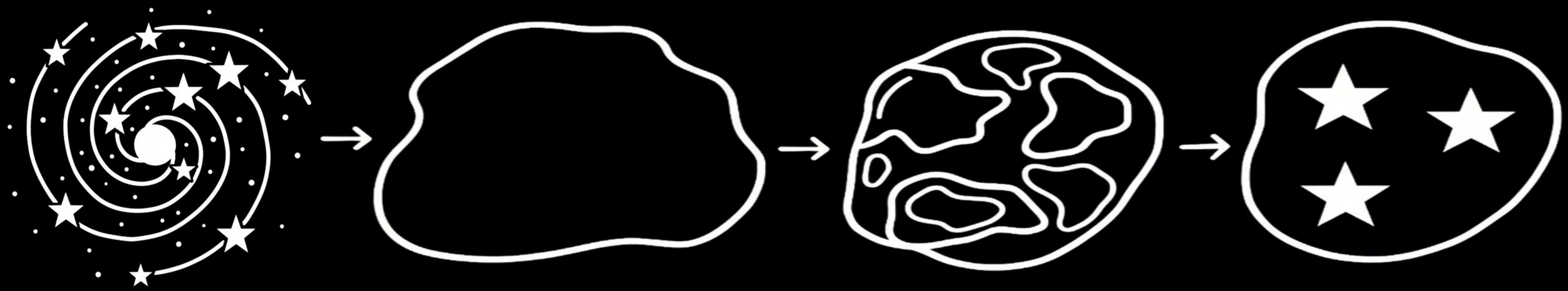
A brief introduction

Where do stars come from?



- Dense regions within molecular clouds begin to collapse gravitationally when self-gravity exceeds turbulent, magnetic, and thermal support.
- As the cloud contracts, it fragments into smaller clumps and prestellar cores.
- Once a core becomes sufficiently dense and hot, hydrogen fusion begins and a new star forms.
- Clouds themselves are a result of physical processes happening at the galactic scale

<u>Goal:</u> Connect the different scales, from the galaxy to the stars



<u>Problem:</u> One simulation with all these scales and physics is too computationally expensive

Strategy: Adaptive Zoom-In from 1kpc box up to 400 AU (check Hennebelle 2018)

Initialize ISM Patches

Realize 1 kpc^3 ISM MHD simulations with RAMSES (Teyssier 2002).

Turbulence Development

Allow the 1 kpc^3 boxes to evolve, enabling turbulent cascades and self-gravity to naturally develop and shape the medium.

Identify & Zoom

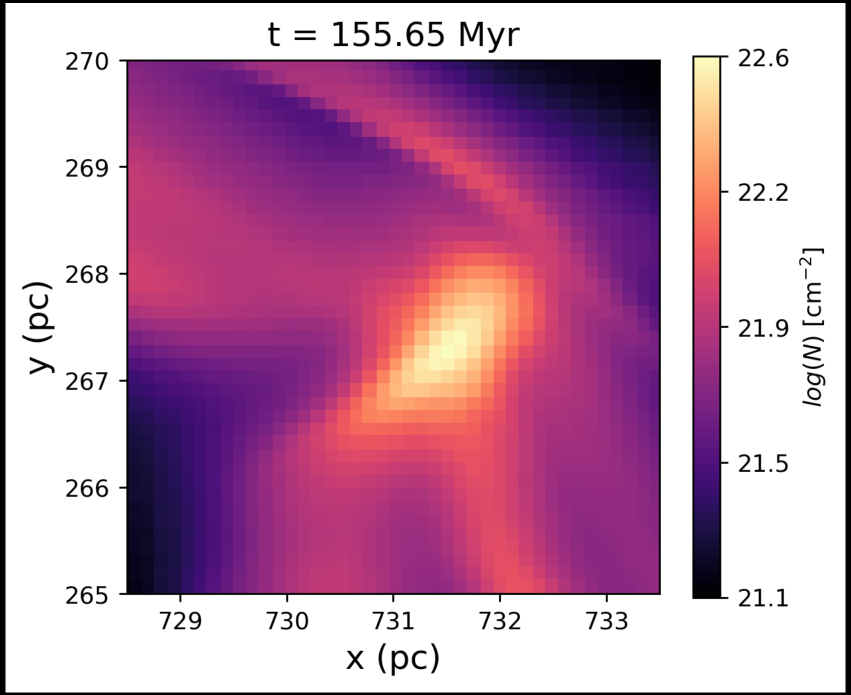
Target regions of interest (collapsing clumps and dense structures) then go back in time, and apply adaptive mesh refinement down to 400 AU resolution.

Statistical Analysis

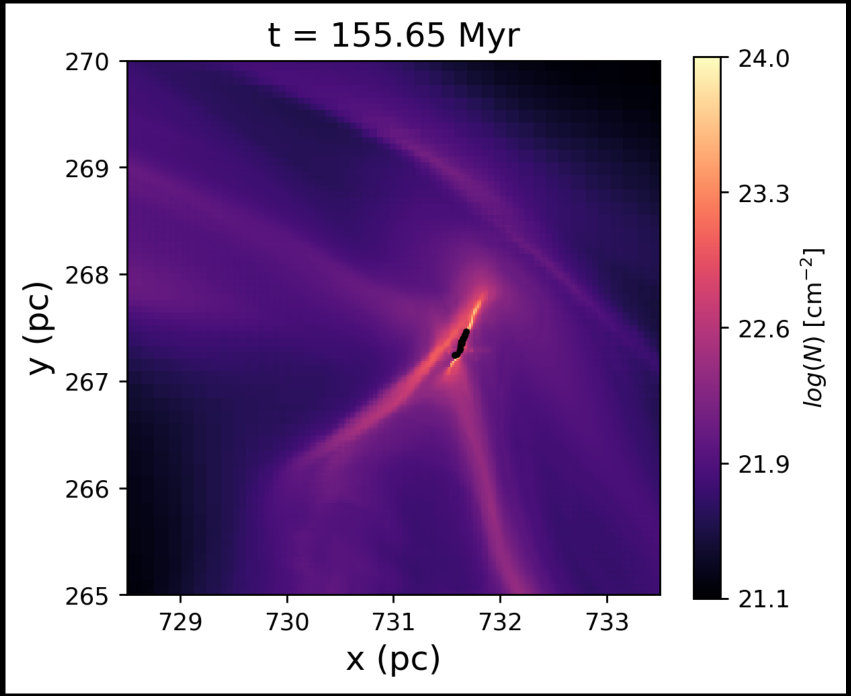
Extract statistics from different regions (e.g. core masses, fragmentation patterns, and accretion rates across multiple zoom-in realizations)

Example

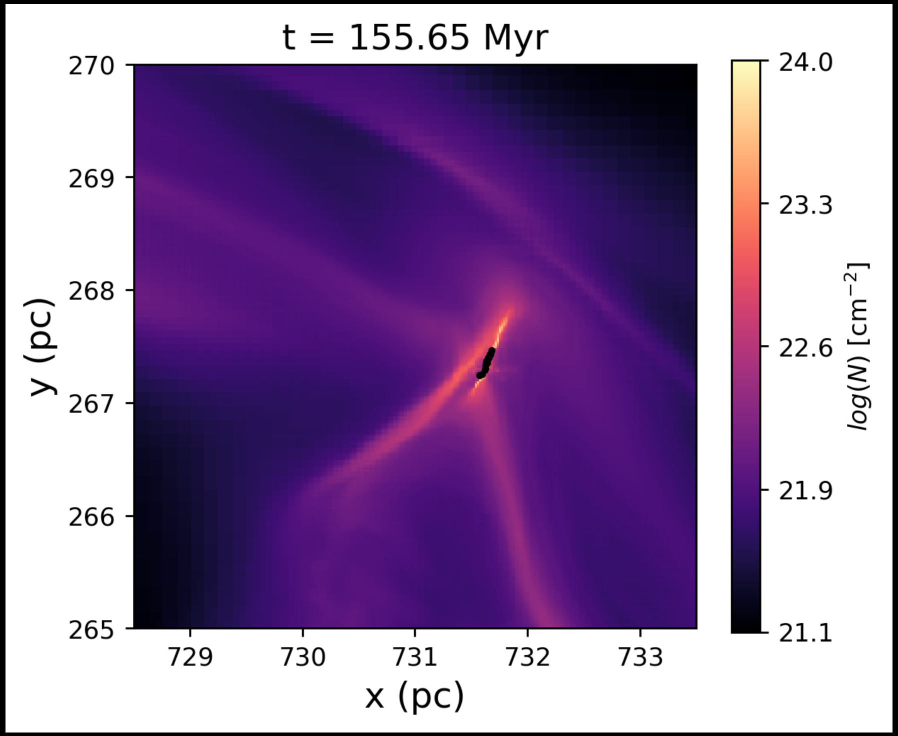
Identified clump at large scale

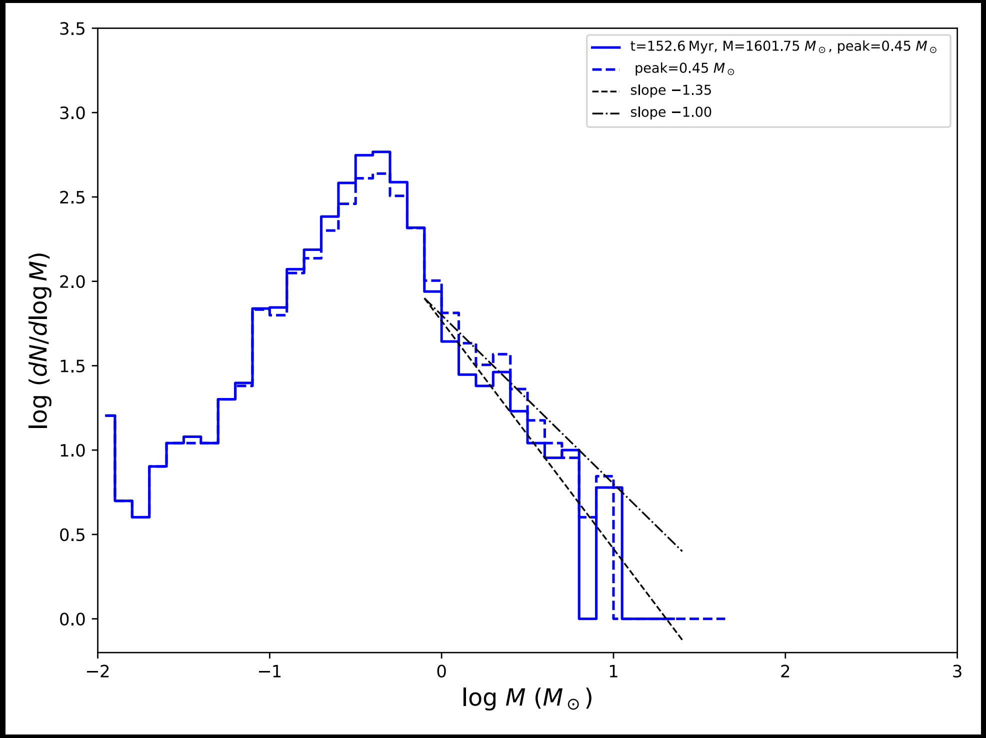


Same clump after going back in time and refining



Sink Particles





- Sink particles are only allowed to form after zooming in
- Sink parameters are chosen that the sink mass distribution resembles a realistic IMF (peak ~0.3 solar mass and power law slope at high mass) –
- Sinks particles form when a 10^7 cm^{-3} density is reached.
- No sink merging is allowed.
- Sinks emit outflows, and massive ones UV .

What Next?

- Zoom-in on different regions
- Evolve for 0.5-2 Myr (from the birth of the first sinks)
- See how statistics change between different regions and compare with observations.