

Progress Report

Kotora Sasaki

1. Introduction

Massive star and molecular cloud

Massive stars ($> 8 M_{\odot}$)

Key drivers of ISM/Galaxy evolution (via UV, feedback)

Formation mechanism remains an open question.

Key observational environments

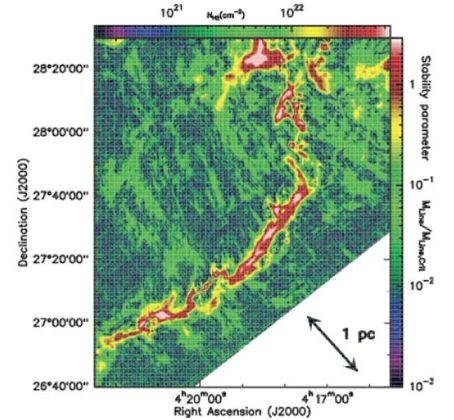
Filament structures

Hub-filament systems (HFSs):

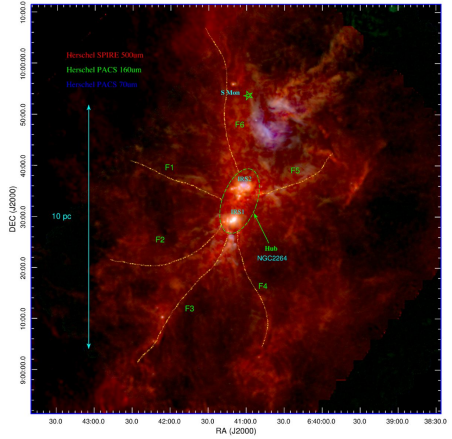
Mass convergence via filaments

Cloud-cloud collisions (CCCs):

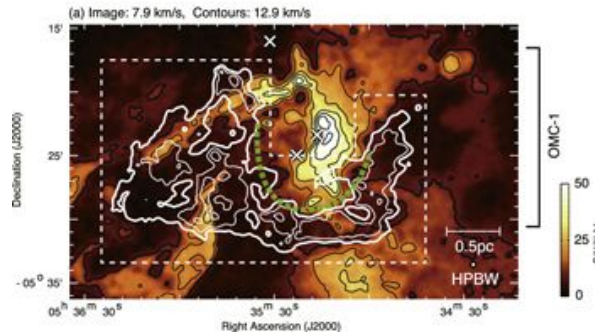
Rapid gas compression



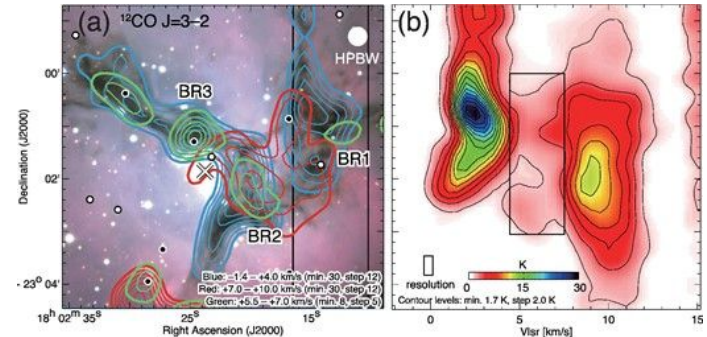
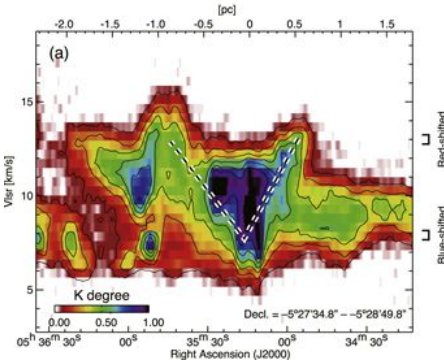
Taurus B211+L1495 (Palmeirim et al. 2013)



NGC2264 (based on Kumar et al. 2020)



OMC-1 (based on Fukui et al. 2018a)



M20 (Fukui et al. 2021)

1. Introduction

Pictures for the mass reservoir

Molecular clouds, and the star-forming regions within them, exhibit a pronounced hierarchical structure: Cloud / Clump / Core

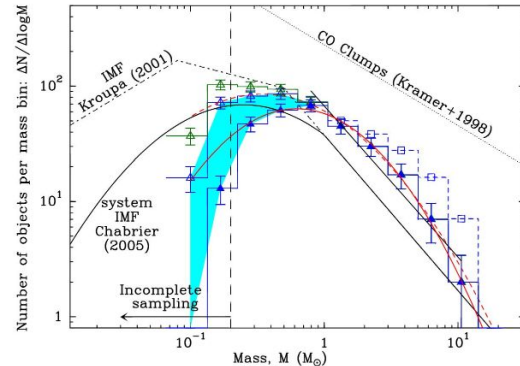
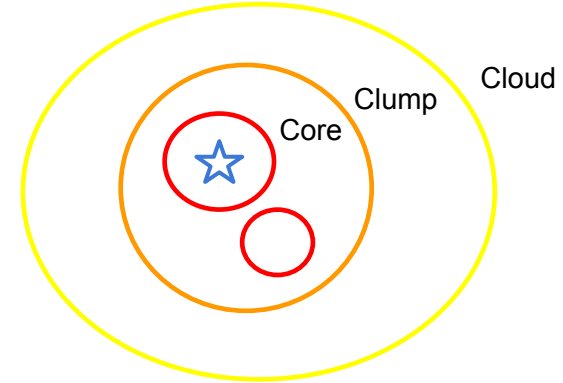
Where is the gas reservoir for their mass set?

In the core itself?

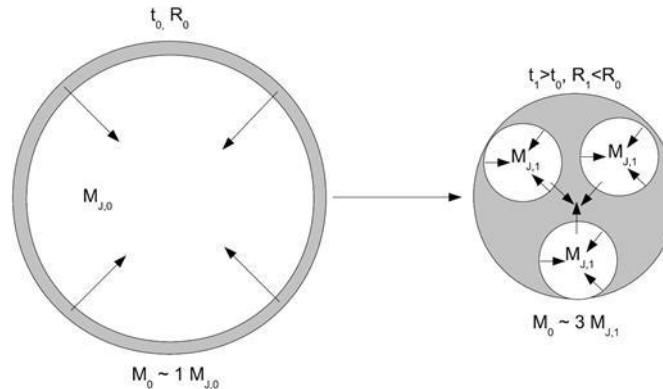
e.g., Turbulent core (McKee & Tan 2002, 2003)

In the structure hosting it?

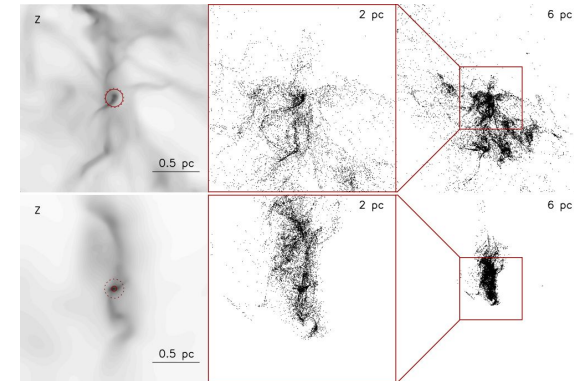
e.g., Competitive accretion (Bonnell et al. 2001, 2004),
Global hierarchical collapse (Vázquez-Semadeni et al. 2009, 2019)
Conveyor belt (Padoan et al. 2020)



Könyves et al. 2015



Vázquez-Semadeni et al. 2019



Padoan et al. 2020

1. Introduction

Observational constraint on the reservoir

The frameworks are not mutually exclusive — they differ in boundedness at each scale and flow connectivity between scales.

→ **Measuring virial state + internal kinematics vs. scale, over a large sample constrains their relative roles, not a single winner.**

Apply a dendrogram to FUGIN ^{13}CO cubes of 13 Galactic star-forming regions, smoothed to a common ~ 1 pc resolution (Sasaki et al. submitted).

Trunk — parent structure (yellow)

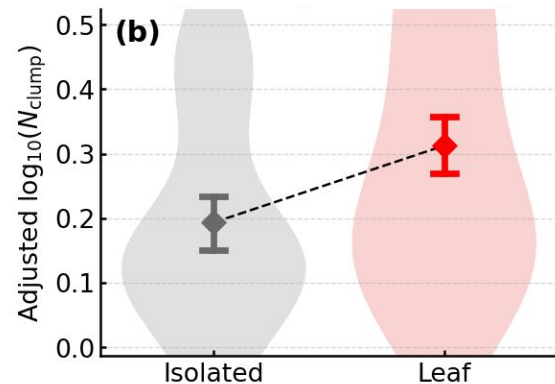
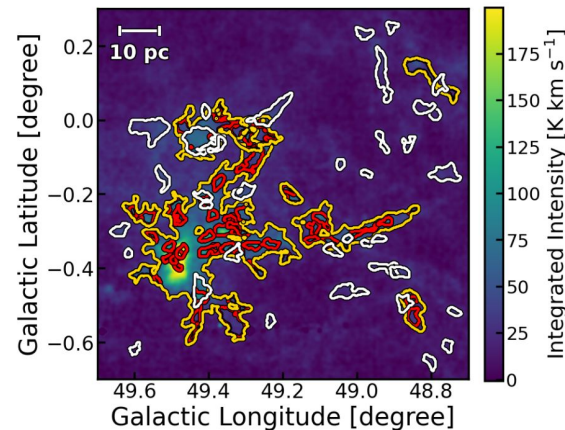
Leaf — densest, inside a trunk (red)

Isolated — no hierarchy (white)

**The trunk acts as a massive, bound gas reservoir.
Its deep potential sustains accretion onto the leaves and drives
interactions among them, raising the characteristic fragmentation mass
— channeling gas into massive clumps rather than low-mass YSOs.**

The reservoir is set by where a structure sits in the hierarchy, not by a local, core-scale property

→ **consistent with large-scale-reservoir models, not the turbulent-core picture**



1. Introduction

Aims

Causality — does accretion actually raise the fragmentation mass?

Continuous mass transport raises fragmentation mass and suppresses small-scale fragmentation (Li et al. 2024)

The rate that sets the size of this effect cannot be measured from a single epoch

Do the dendrogram structures trace real gas?

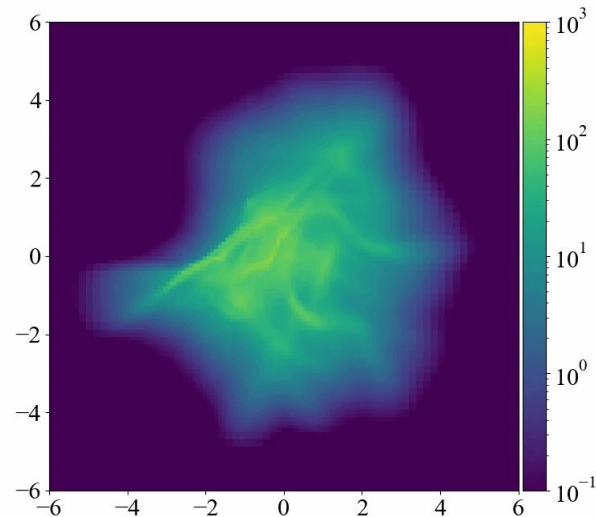
PPV structures need not correspond to PPP density structures (Shetty et al. 2010; Beaumont et al. 2013; Clarke et al. 2018)

^{13}CO makes structures appear more extended than they are (Priestley et al. 2023)

A simulation has both axes the observations lack

It evolves in time, and its true 3D density and velocity fields are known
Degrading it to FUGIN resolution therefore puts the same analysis on a system whose physics is already known.

Run cloud-scale collapse simulations (spheres of radius $\lesssim 100$ pc), post-process them into FUGIN-like cubes, and apply the same dendrogram pipeline — recovering the time evolution the observations cannot access, while calibrating the derived properties against the true 3D gas.



2. SFUMATO#

Advection equation

Both space and time are discretized

The gas is divided into cells; each cell stores the amount of mass, momentum and energy it holds

Time advances in finite steps Δt

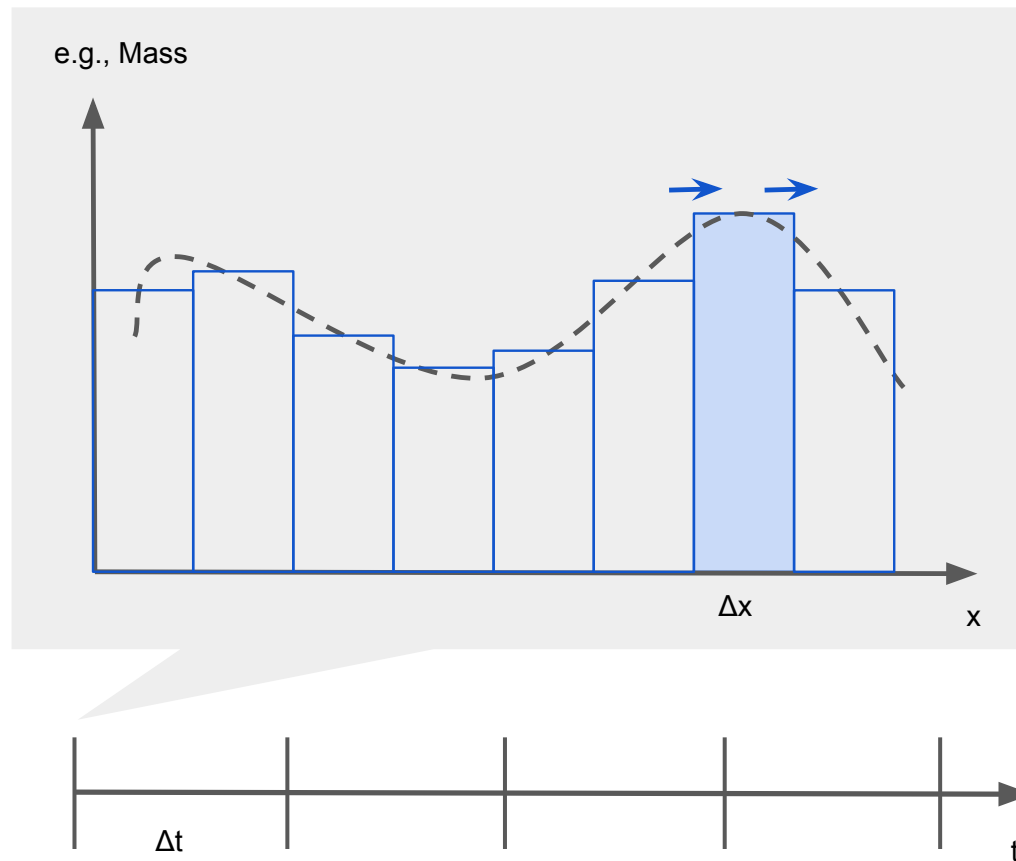
A cell can only change through its faces

$$\rho_i^{n+1} \Delta x = \rho_i^n \Delta x + (F_{i-1/2}^n - F_{i+1/2}^n) \Delta t$$

$$F = \rho v$$

One step propagates information by exactly one cell

→ $v \Delta t < \Delta x$ (the CFL condition)



2. SFUMATO# AMR

A uniform grid at the required resolution is not affordable

e.g., 256 pc box, base $\Delta x = 2$ pc, 6 levels of refinement $\rightarrow$ finest $\Delta x \approx 0.03$ pc
 $\rightarrow$ uniform equivalent: $8192^3 \approx 5.5 \times 10^{11}$ cells — tens of TB of memory

Dense gas occupies $< 10^{-4}$ of the volume $\rightarrow$ refine only where it is needed

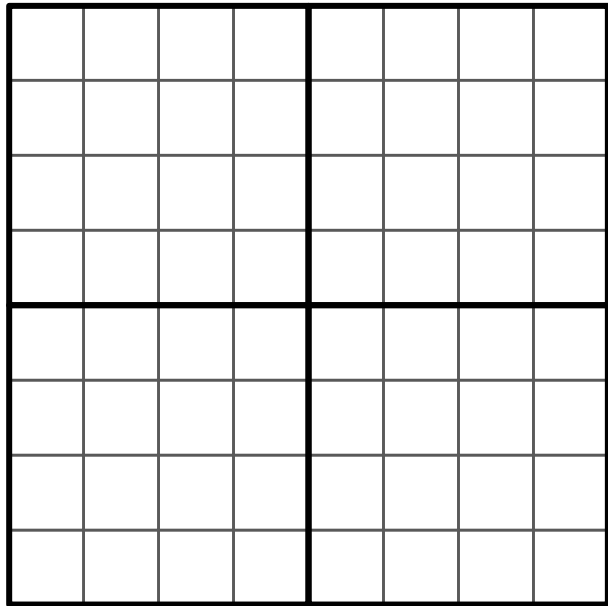
1. The domain is covered by blocks. One block = 8^3 cells, all sharing the same Δx (= its level)

2. Each cell computes its own Jeans length: $\lambda_J = (\pi c_s^2 / G \rho)^{1/2}$

3. A cell is flagged if its Jeans length is no longer resolved by enough cells:

$$\lambda_J / \Delta x < N_J$$

4. If any cell in a block is flagged, the whole block splits into 8 children



Collapse raises ρ and $\lambda_J \propto \rho^{-1/2}$ keeps shrinking, so the mesh follows the dense gas on its own

Below ~ 4 cells per λ_J the gas fragments artificially (Truelove et al. 1997); $N_J = 8-16$ is common

Since $\Delta t \propto \Delta x$, finer levels can advance at their own smaller Δt

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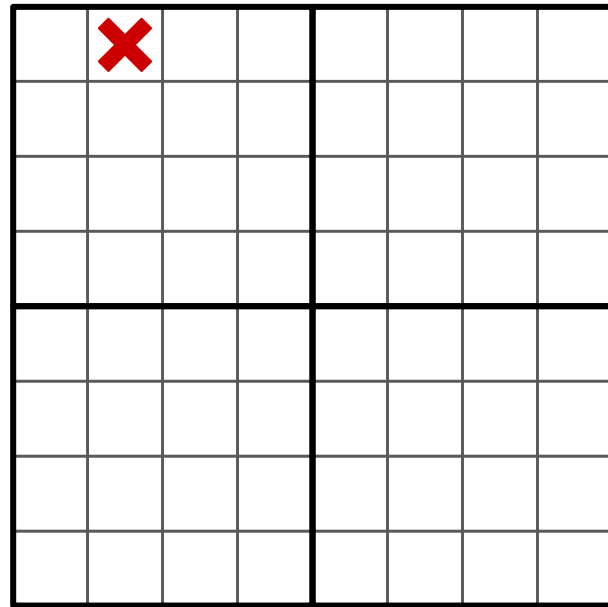
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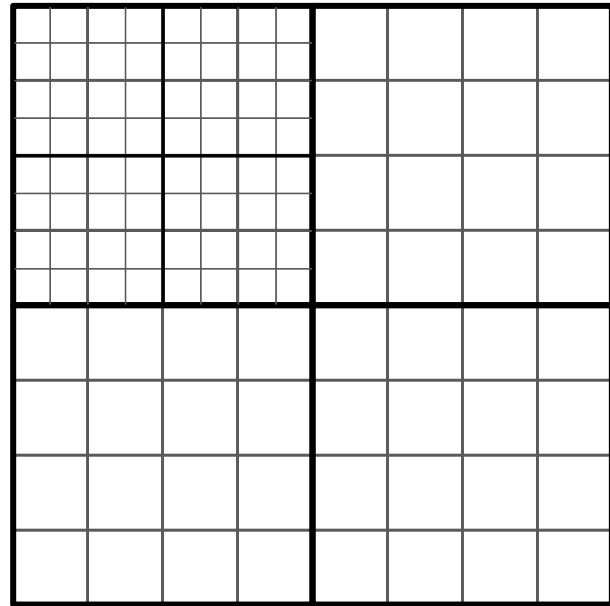
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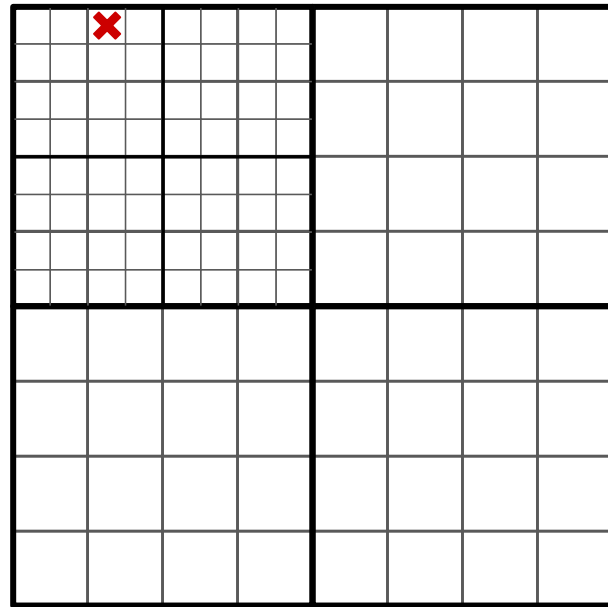
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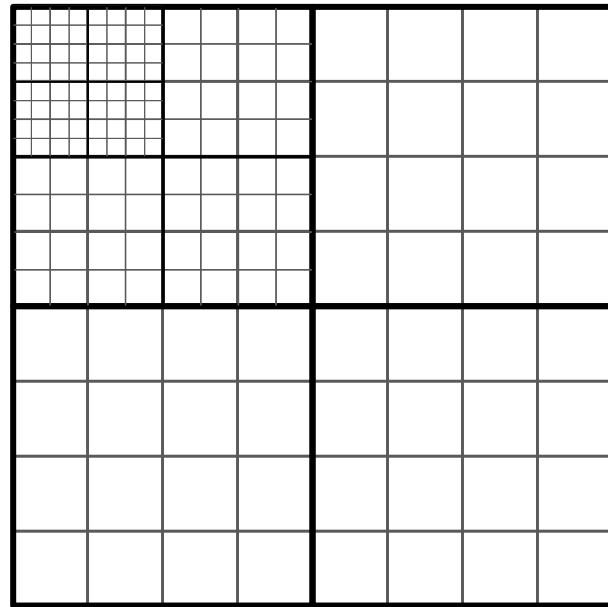
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2. SFUMATO#

Sink particles

Collapse never stops raising ρ , so λ_J keeps shrinking and refinement never terminates — with $\Delta t \propto \Delta x$, the run grinds to a halt
→ above a threshold density, **the region is replaced by a point particle** that carries mass, momentum and angular momentum

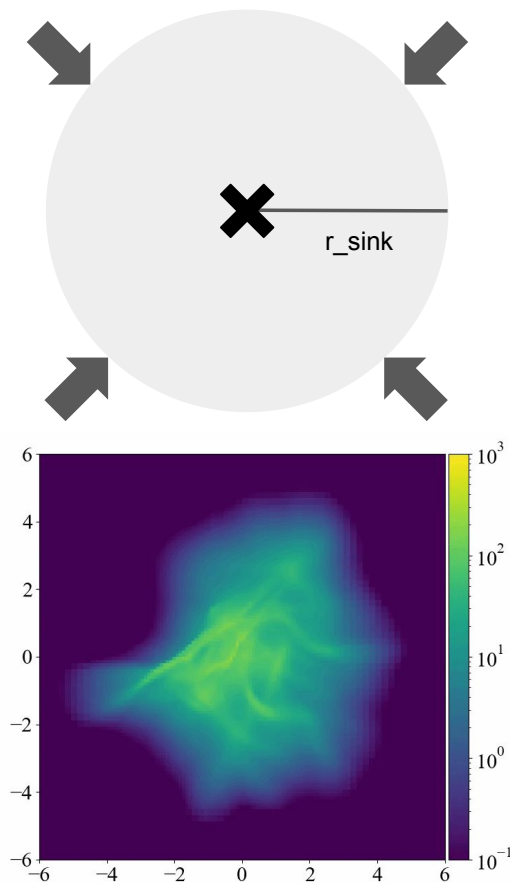
The particle moves off-grid, contributes to the gravitational potential, accretes surrounding gas, and radiates

A transient shock must not leave a permanent particle behind, so the site is also required to be **a potential minimum / converging ($\nabla \cdot \mathbf{v} < 0$) / contracting along all three axes (all eigenvalues of the symmetric part of $\nabla \mathbf{v}$ negative) / gravitationally bound ($E_{\text{th}} + E_{\text{kin}} + E_{\text{grav}} < 0$), and no creation within $2 r_{\text{sink}}$ of an existing sink**

Inside r_{sink} , density in excess of ρ_{thr} is removed and added to the sink; the removed momentum goes with it, and this caps the local density and stops the refinement cascade

A sink is not one star.

At $\Delta x \sim 0.03$ pc, $r_{\text{sink}} \sim 0.1$ pc represents a core or a small group — relevant when comparing to observed YSO / clump counts



2. SFUMATO#

Radiative transfer

Sink particles radiate, so the transport of those photons has to be solved.

EUV ionizes H, FUV heats dust, IR is dust re-emission;
Lyman–Werner (H₂ dissociation) is scaled from FUV at a fixed ratio.

The radiative transfer equation:

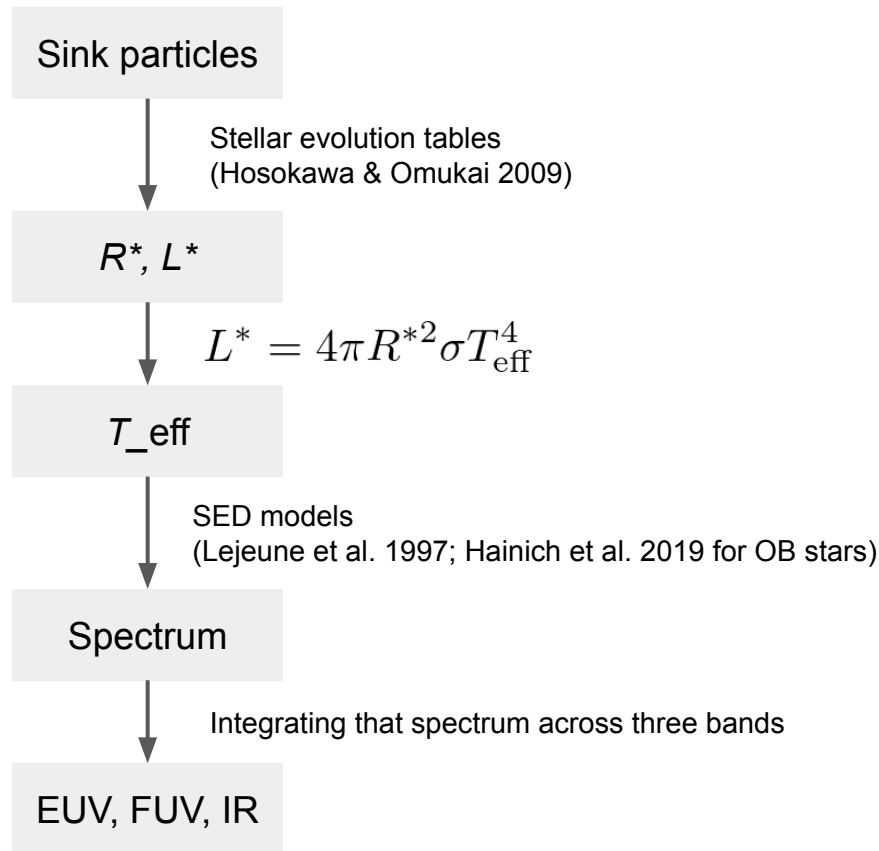
$$\frac{1}{c} \frac{\partial I(\mathbf{x}, \mathbf{n}, \nu)}{\partial t} + \mathbf{n} \cdot \nabla I = \eta - \chi I$$

Each cell stores 4 values per band:

$$E_r \propto \int d\Omega I, \quad \mathbf{F}_r \propto \int d\Omega \mathbf{n} I$$

and is updated by the same finite-volume machinery.
The system is closed with the M1 approximation
(Levermore 1984)

CFL with $v = c \rightarrow$ reduced speed of light, $\tilde{c} = 10^{-4} c$



2. SFUMATO#

Code overview and computing platform

SFUMATO#: a GPU implementation of the SFUMATO AMR code (Fukushima & Matsumoto 2026)

What it solves, in one step

Hydrodynamics — finite-volume update through cell faces, limited by the CFL condition

AMR — blocks refined where the Jeans length is no longer resolved

Self-gravity — Poisson's equation solved across all levels by a multigrid solver

Sink particles — collapsing regions above ρ_{thr} replaced by point particles

Radiative transfer — E_r and F_r per band, M1 closure, reduced speed of light

Non-equilibrium chemistry — H, H₂, H⁺, e (CO is not included)

Thermal evolution — gas and dust temperatures evolved separately

Runs on Miyabi (JCAHPC — U. Tokyo + U. Tsukuba)

Miyabi-G: 1,120 nodes, one NVIDIA GH200 Grace Hopper Superchip
per node → **one node = one GPU = one MPI process**

80.1 PFLOPS peak in double precision, of which Miyabi-G supplies
78.8 PFLOPS

Grace CPU and Hopper GPU share memory over NVLink-C2C, so
AMR block management (CPU-like) and the numerics (GPU-like) can
be interleaved cheaply

11.3 PB all-NVMe parallel file system

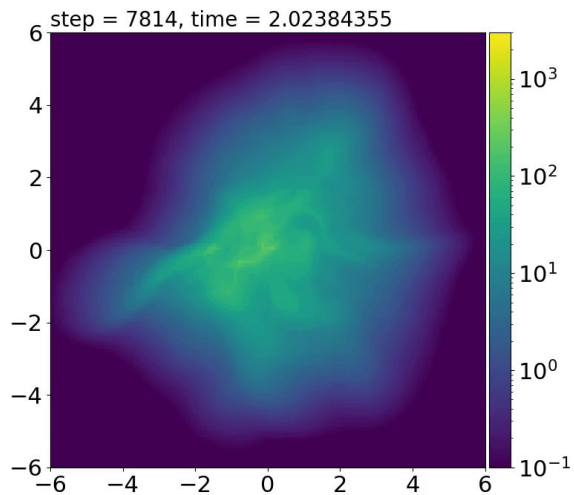


Credit: CCS

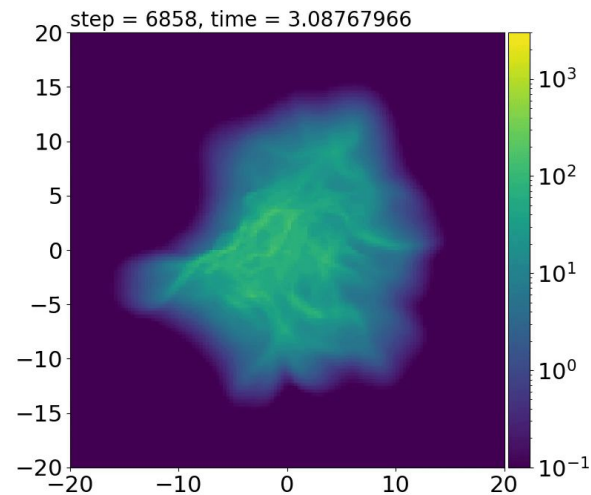
2. SFUMATO#

Test runs

	Radius	Box size	Resolution	Mass	Virial parameter	Gas temperature
Test 1	3 pc	12^3 pc	~ 0.094 pc	$10^3 M_{\text{sun}}$	1	10 K
Test 2	10 pc	40^3 pc	~ 0.31 pc	$10^4 M_{\text{sun}}$	1	10 K



Test 1



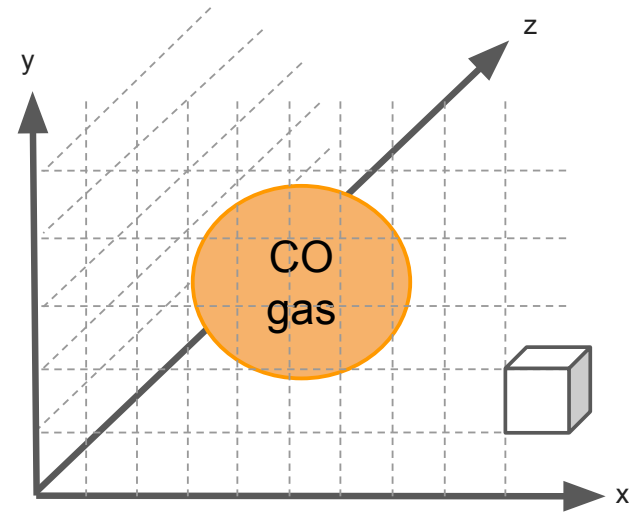
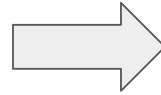
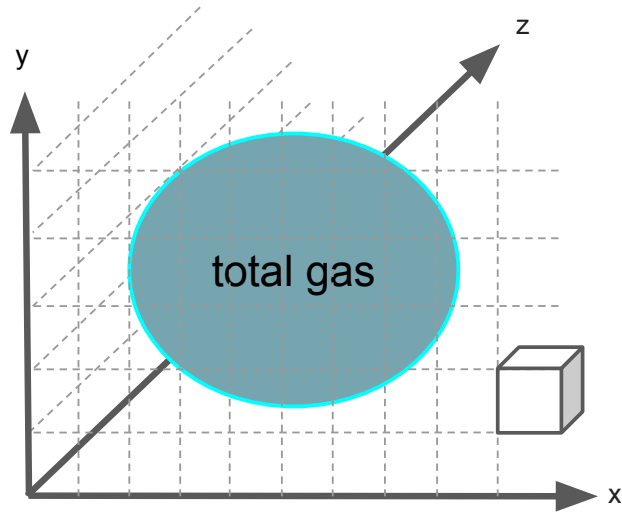
Test 2

3. Creating observational data mocks

Conversion to CO



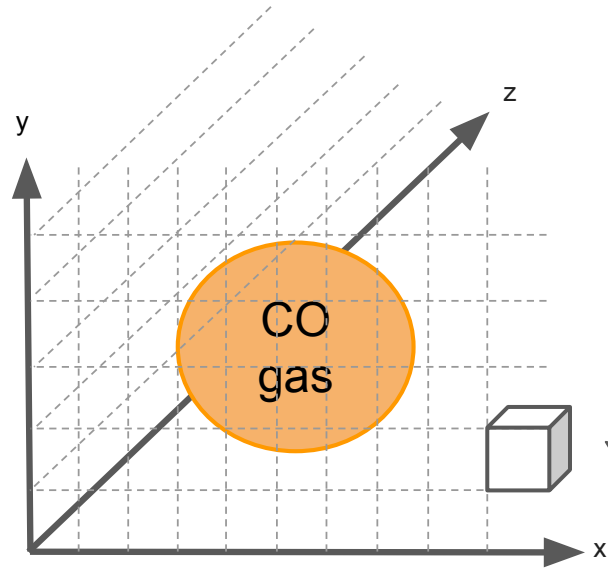
(Dullemond et al. 2012)



$$\left| \begin{array}{l} n_{\text{H}_2} = \left(\frac{\rho_{\text{total}} \times X_{\text{H}}}{\mu_{\text{H}} \times m_{\text{amu}}} \right) \times f_{\text{H}_2}, \quad n_{\text{CO}} = n_{\text{H}_2} \times X_{\text{CO}} \\ v_z, \quad T \end{array} \right.$$

3. Creating observational data mocks

Emission and absorption per cell



$$\nu_{\text{shift}} = \nu_0 \left(1 - \frac{v_z}{c}\right)$$

$$\Delta\nu_D = \frac{\nu_0}{c} \sqrt{\frac{2k_B T}{m_{\text{CO}}} + v_{\text{turb}}^2}$$

$$\rightarrow \phi(\nu) = \frac{1}{\sqrt{\pi} \Delta\nu_D} \exp\left(-\left(\frac{\nu - \nu_{\text{shift}}}{\Delta\nu_D}\right)^2\right)$$

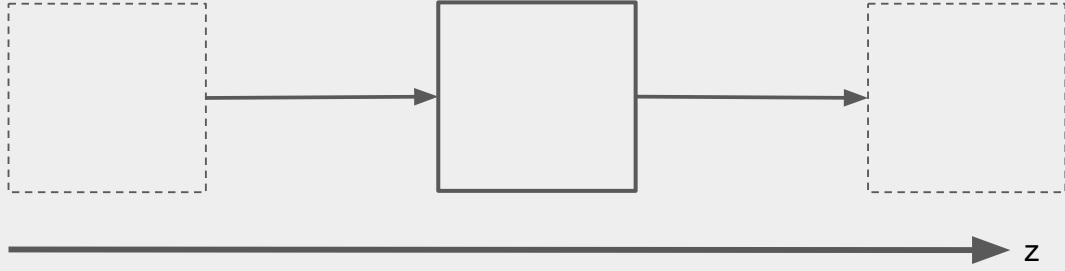
$$\rightarrow \alpha_\nu = \frac{h\nu}{4\pi} (n_l B_{lu} - n_u B_{ul}) \phi(\nu)$$

$$\rightarrow j_\nu = \alpha_\nu B_\nu(T)$$

$$\rightarrow \Delta\tau_\nu = \alpha_\nu \Delta z$$

3. Creating observational data mocks

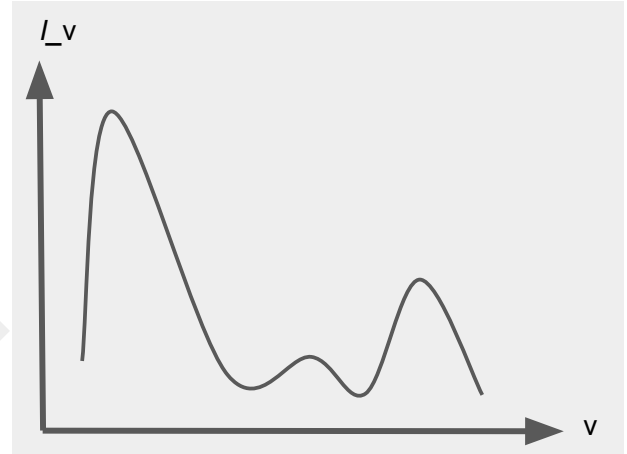
Integration along the line of sight



$$\frac{dI_\nu}{dz} = j_\nu - \alpha_\nu I_\nu$$

$$\Rightarrow I_{\nu,\text{out}} = I_{\nu,\text{in}}e^{-\Delta\tau_\nu} + B_\nu(T)(1 - e^{-\Delta\tau_\nu})$$

Solve recursively and derive the nearest I_ν
Repeat for all ν



3. Creating observational data mocks

Matching the FUGIN observation

RADMC-3D returns I_ν [Jy/pixel] on a bare grid.

To compare with FUGIN, we reproduce the observational effects:

Sky coordinates

$$\Delta\theta = \frac{1}{D} \frac{L_{\text{box}}}{N_{\text{box}}}$$

Galactic frame (GLON/GLAT-SFL)

Beam convolution

Gaussian beam,
 $\theta_{\text{FWHM}} = 20.7''$ (NRO 45 m)

Noise

Gaussian noise is added to every voxel

Its level is set by the peak S/N measured on the real FUGIN W49 cubes

^{12}CO : S/N = 34, ^{13}CO : S/N = 35

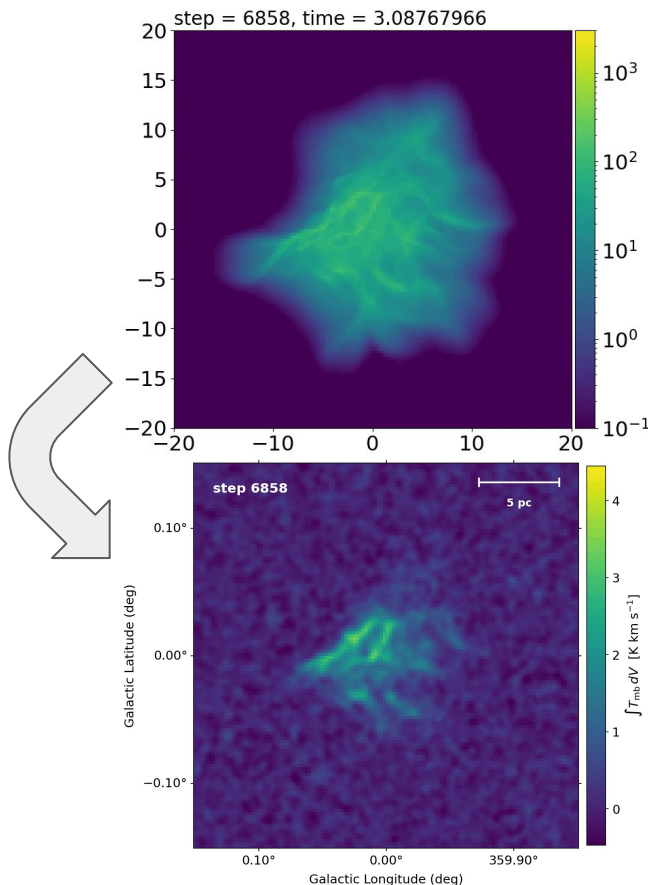
Velocity axis

$$v = c \left(1 - \frac{\nu}{\nu_0} \right)$$

$\nu_0 = 110.20 \text{ GHz}$ ($^{13}\text{CO } J=1-0$),
 115.27 GHz ($^{12}\text{CO } J=1-0$)

Brightness temperature

$$T_{\text{mb}} = \frac{c^2 I_\nu}{2k\nu^2 \Omega_{\text{pix}}}$$



4. Tracking the time evolution of dendrogram structures

Tracking structures between snapshots

Dendrogram algorithm (Rosolowsky et al. 2008)

Identifies hierarchical structures in 3D data cubes based on emission intensity

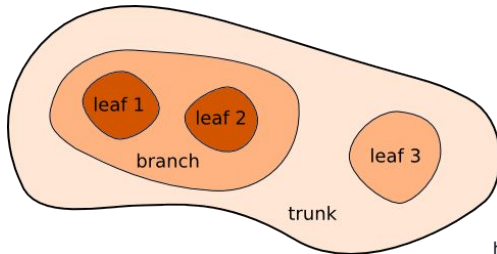
Leaf: smallest unit with no substructure

Branch: structure containing substructures

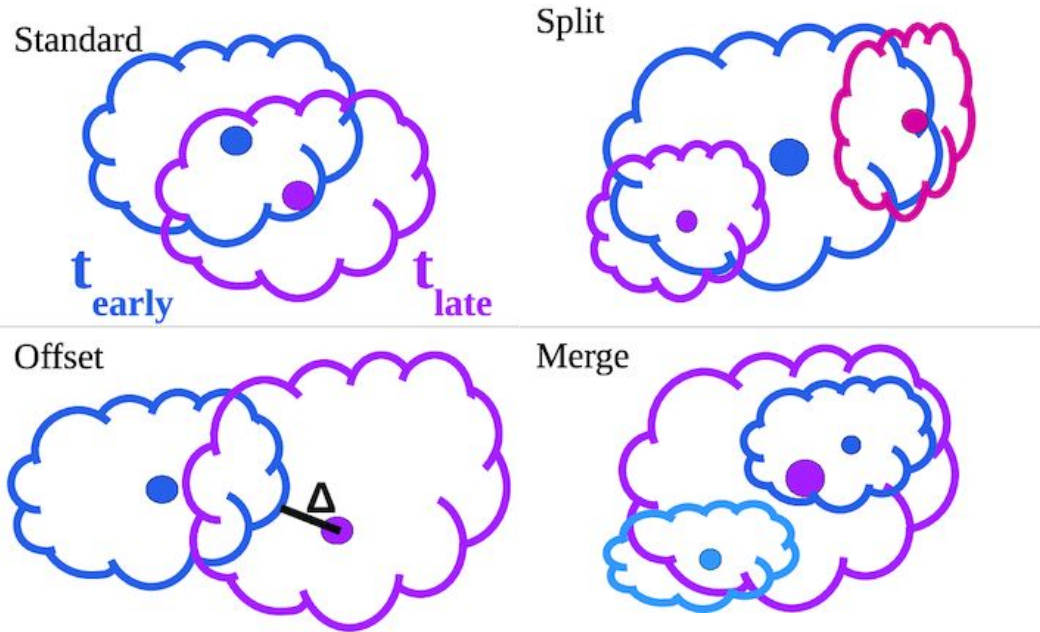
Trunk: top-level structure (largest scale)

To track the temporal changes in the dendrogram structure, we adopted a tracking pipeline similar to that used in Smullen et al. 2020:

For each leaf at time t_{early} , find all leaves at time t_{late} whose surface contains the centroid, and require the match to hold in both time directions



<http://www.dendrograms.org/>



based on Smullen et al. 2020

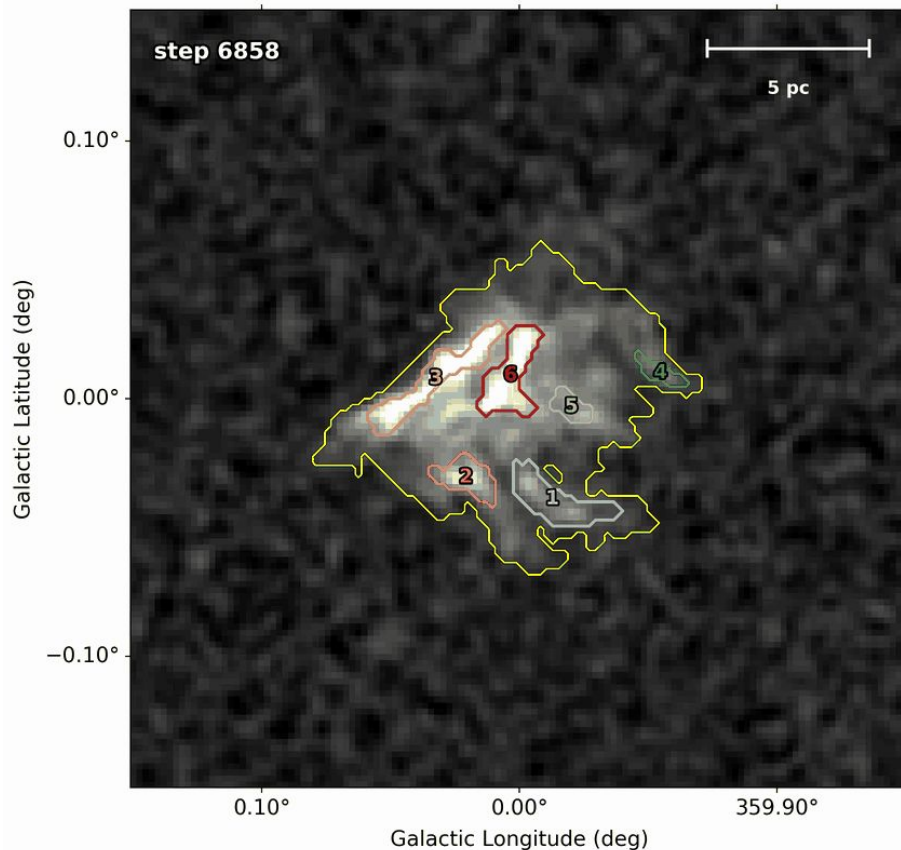
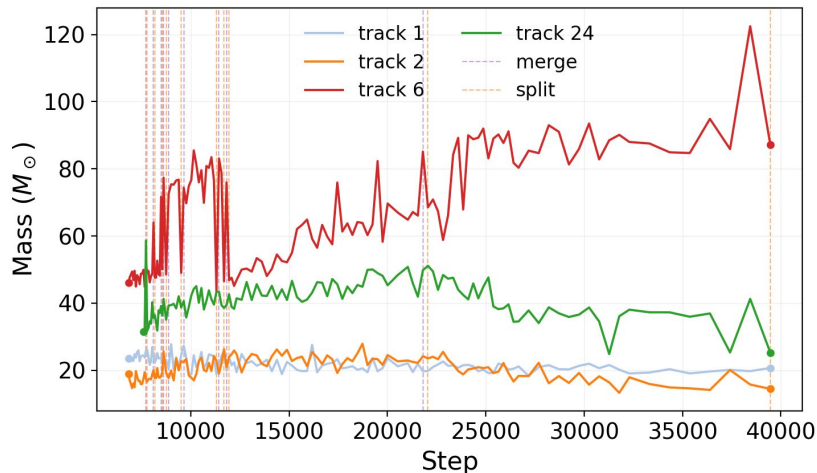
4. Tracking the time evolution of dendrogram structures

First look at the tracked structures

Masses fluctuate step-to-step by tens of per cent — the same behaviour Smullen et al. (2020) report, **arising from the dendrogram redrawing its contours rather than from physical evolution**

Even so, **individual tracks differ: some stay flat, some rise steadily once the fluctuations settle**

Whether that rise is continuous accretion or discrete capture at merger events is left for the production run



5. Summary

The reservoir that sets stellar mass — core-scale or larger-scale — is still open. FUGIN ^{13}CO dendrogram analysis favours the trunk as a bound, massive reservoir (Sasaki et al. submitted)

What is needed is a simulation that carries the two axes the observations lack: time, and the true 3D field — one that can be degraded to FUGIN resolution and put through the same analysis

SFUMATO#

GPU AMR code on Miyabi, solving self-gravity, radiative transfer, non-equilibrium chemistry and sink particles.
Test runs of $3 \text{ pc} / 10^3 M_{\odot}$ and $10 \text{ pc} / 10^4 M_{\odot}$ clouds are complete

RADMC-3D

the 3D field is converted to CO, integrated along the line of sight, and matched to FUGIN in beam, velocity axis and noise, giving $^{12}\text{CO} / ^{13}\text{CO}$ cubes

Dendrogram tracking

the same pipeline as the observation, extended to link leaves between snapshots by containment of the centroid (after Smullen et al. 2020)

Next

Whether accretion and mergers actually occur, and how they change the masses and fragmentation-related quantities

Compare the derived properties against the true 3D field

Appendix

Column Density Calculation (Excitation Temperature)

$$\begin{aligned}\Delta I_{12} &= (1 - e^{-\tau_{12}})(B_{\nu}(T_{\text{ex}}) - B_{\nu}(T_{\text{bg}})) \\ &= (B_{\nu}(T_{\text{ex}}) - B_{\nu}(T_{\text{bg}})) \quad \because \tau_{12} \gg 1\end{aligned}$$

$$\Delta I_{12} = \frac{2k\nu_{12}^2}{c^2} T_{\text{peak}} \quad B_{\nu}(T) = \frac{2h\nu_{12}^3}{c^2} \frac{1}{e^{h\nu_{12}/kT} - 1}$$

$$\begin{aligned}\therefore T_{\text{peak}} &= \frac{h\nu_{12}}{k} \frac{1}{e^{h\nu_{12}/kT_{\text{ex}}} - 1} - \frac{h\nu_{12}}{k} \frac{1}{e^{h\nu_{12}/kT_{\text{bg}}} - 1} \\ &= \frac{5.53}{e^{5.53/T_{\text{ex}}} - 1} - 0.819\end{aligned}$$

$$\Rightarrow T_{\text{ex}} = \frac{5.53}{\ln \left(1 + \frac{5.53}{T_{\text{peak}} + 0.819} \right)}$$

Column Density Calculation (Optical Thickness)

$$\Delta I_{13} = (1 - e^{-\tau_{13}})(B_{\nu}(T_{\text{ex}}) - B_{\nu}(T_{\text{bg}}))$$

$$\Rightarrow \tau_{13} = -\ln \left(1 - \frac{\Delta I_{13}}{B_{\nu}(T_{\text{ex}}) - B_{\nu}(T_{\text{bg}})} \right)$$

$$\Delta I_{13} = \frac{2k\nu_{13}}{c^2} T_{\text{b}}$$

$$\tau_{13} = -\ln \left(1 - \frac{T_{\text{b}}}{\frac{h\nu_{13}}{k} \frac{1}{e^{h\nu_{13}/kT_{\text{ex}}} - 1} - \frac{h\nu_{13}}{k} \frac{1}{e^{h\nu_{13}/kT_{\text{bg}}} - 1}} \right)$$

$$= -\ln \left(1 - \frac{T_{\text{b}}}{5.29(J - 0.164)} \right), \quad J = \frac{1}{e^{5.29/T_{\text{ex}}} - 1}$$

Column Density Calculation (Column Density)

$$N_{13} = \frac{3k}{8\pi^3 \mu^2 B} \frac{T_{\text{ex}} + 0.88}{1 - e^{-h\nu_{13}/kT_{\text{ex}}}} \int \tau_{13} dv$$

$$= 2.42 \times 10^{14} \frac{T_{\text{ex}} + 0.88}{1 - e^{-5.29/T_{\text{ex}}}} \int \tau_{13} dv$$

Here, partition function is $Q = \sum_J (2J + 1) e^{-\frac{E_J}{kT_{\text{ex}}}} \sim \frac{kT_{\text{ex}}}{hB} + \frac{1}{3} \sim T_{\text{ex}} + 0.88$

$$N_{\text{H}_2} = 5.0 \times 10^5 N_{13} \quad (\text{Dickman 1978})$$