Physical Characterization of Star-forming Cores as Mass Reservoirs for Protostars Using Numerical Passive Tracer Particles

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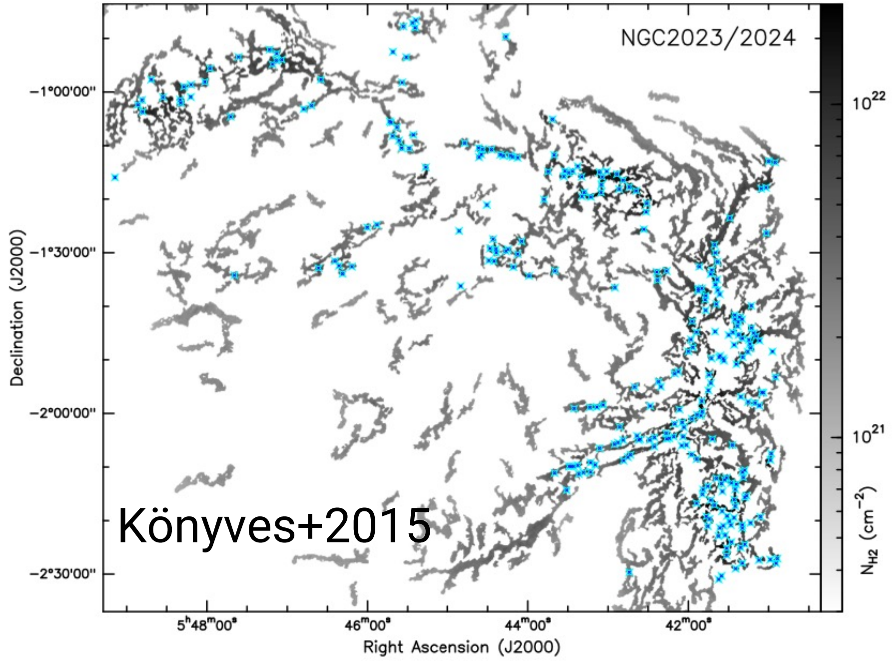
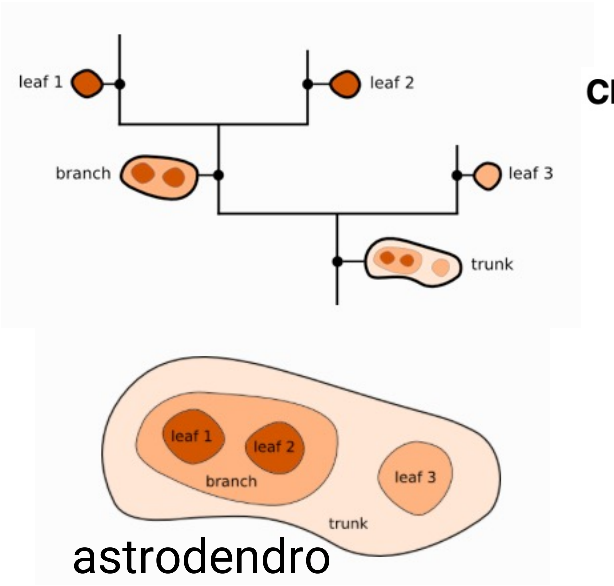
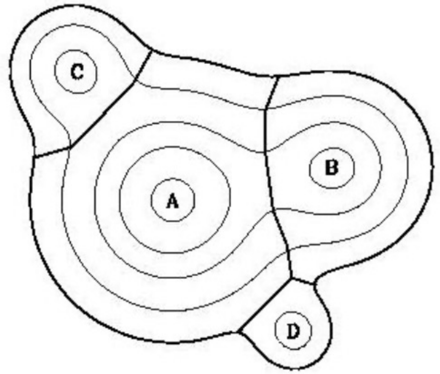
Nozaki et al. 2025; Nozaki et al. in prep.

Observations: Statistical Study of Molecular Cloud Cores

- Definition of cores: gravitationally bound, smallest units leading to stars
- A large number of cores are identified using intensity-based algorithms







Observed cores do not always trace the actual mass reservoirs for protostars

→ How far do mass reservoirs actually extend, and what are their properties?

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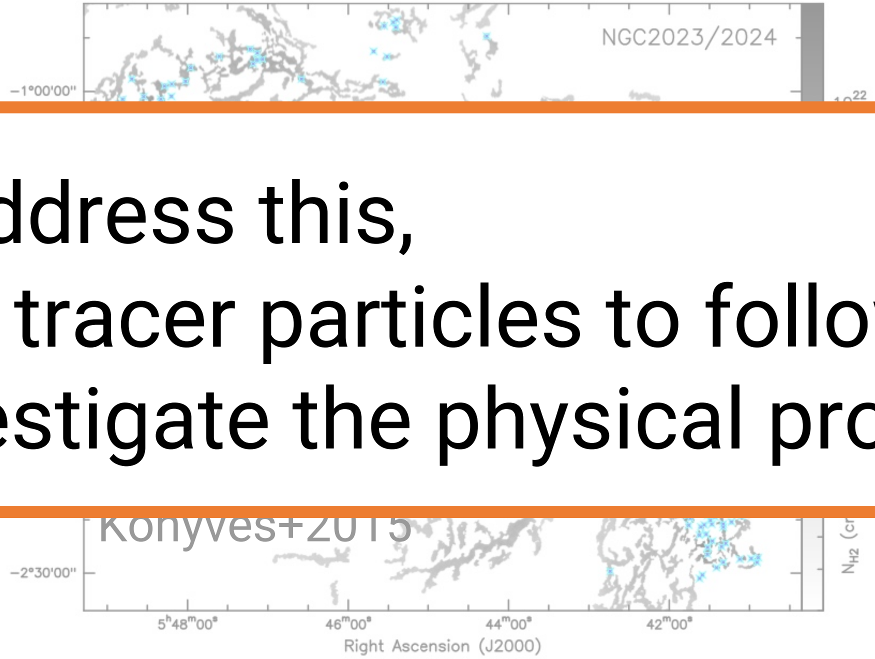
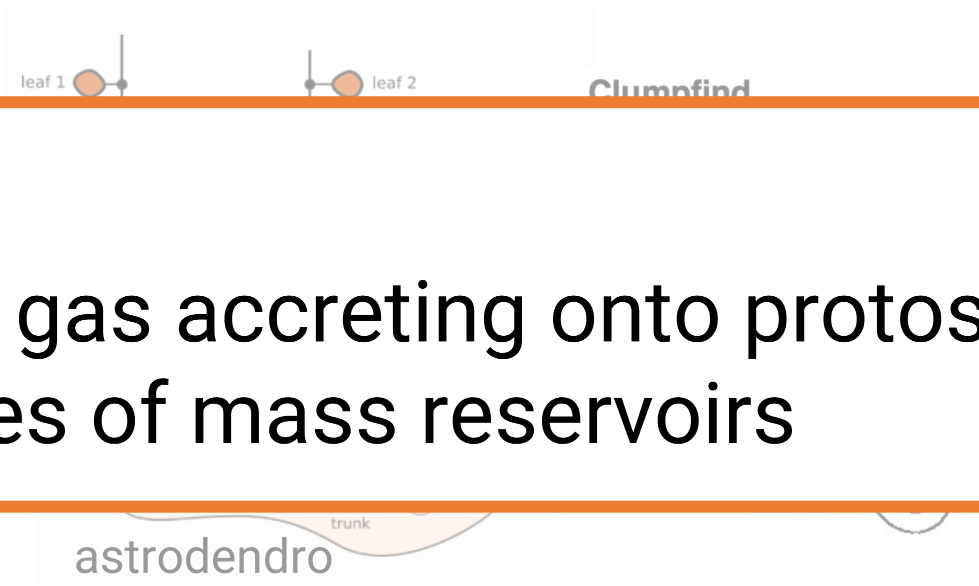




To address this,
- use tracer particles to follow the gas accreting onto protostars
- investigate the physical properties of mass reservoirs

Observed cores do not always trace the actual mass reservoirs for protostars
→ How far do mass reservoirs actually extend, and what are their properties?

Numerical Settings

3D HD / MHD Simulations (Code: SFUMATO)
(Matsumoto2007, Matsumoto+2015, Fukushima & Yajima 2021)

Initial Conditions:

✓ Uniform density field, $n_H \approx 1365\ cm^{-3}$

✓ Turbulence: observed scales $E(k) \propto k^{-2}$, M_{rms} = 2, 10

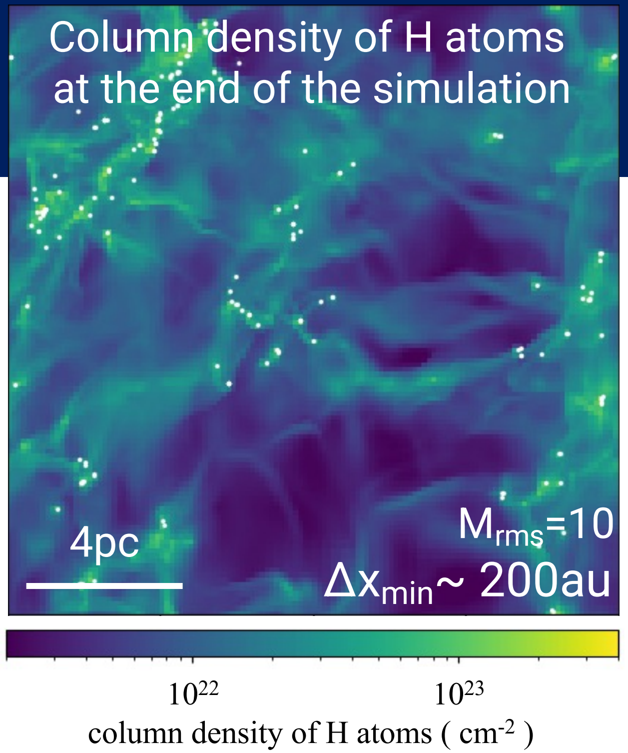
✓ Boundary : Periodic

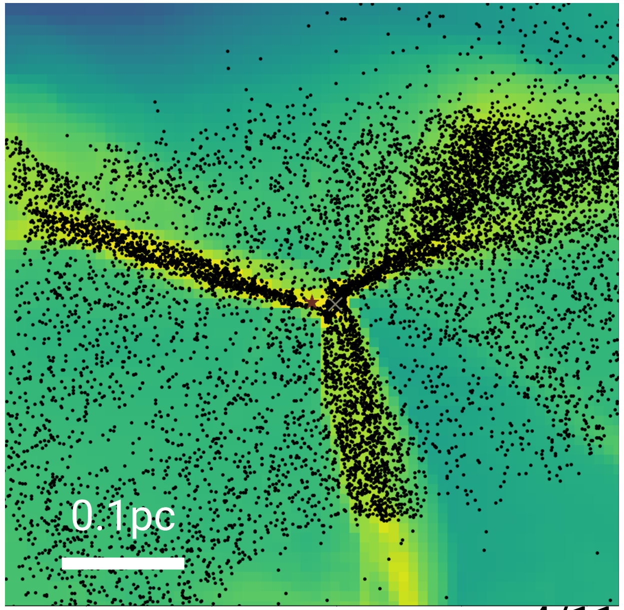
Sink particles: $n_{cri,H} > 9 \times 10^6\ cm^{-3}$

Passive Tracer Particles:

✓ 3M particles, initially evenly spaced throughout the 3D box

✓ Can track gas that eventually accretes onto protostars





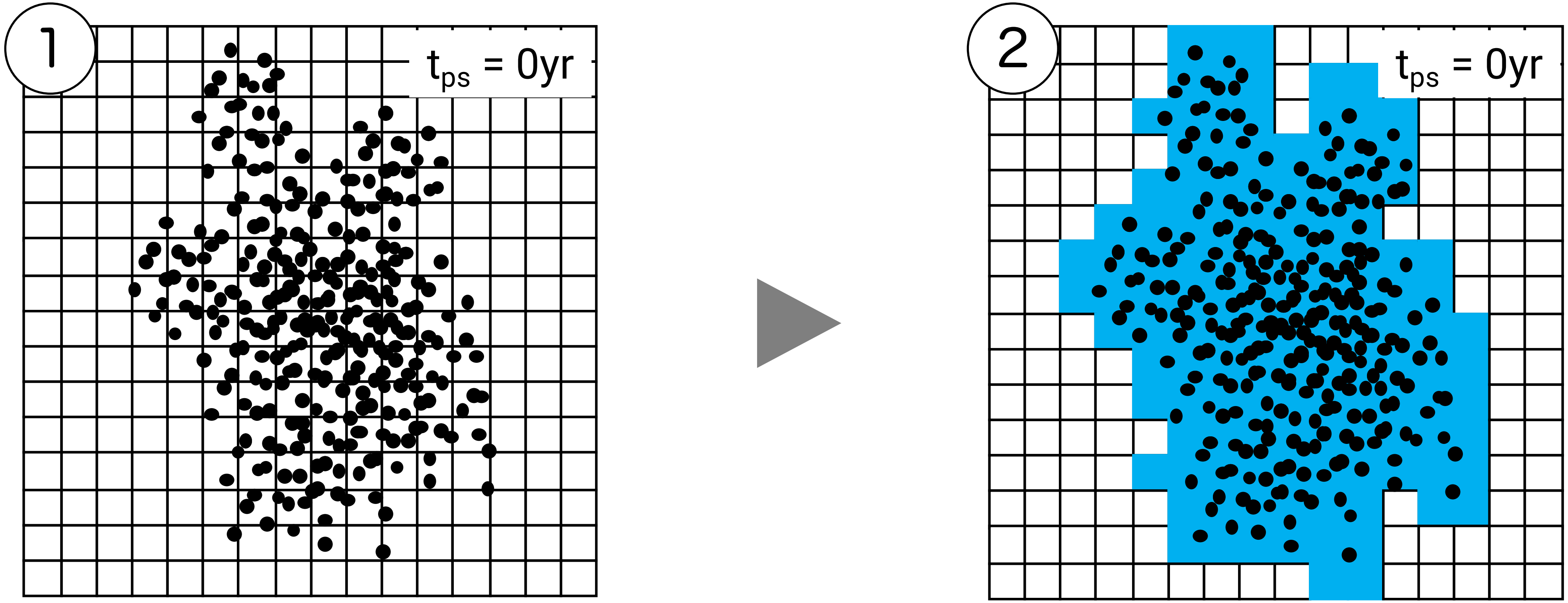
● tracer particle, ★Target protostars, X Nearby protostars

3D Mass Reservoir Identification Algorithm

1. Select the tracer particles that will accrete onto a protostar within 0.3 million years after protostar formation (corresponding to the Class 0/I phase)

   Trace them back to their position after protostar formation

2. Define a mass reservoir as a group of cells including these tracer particles

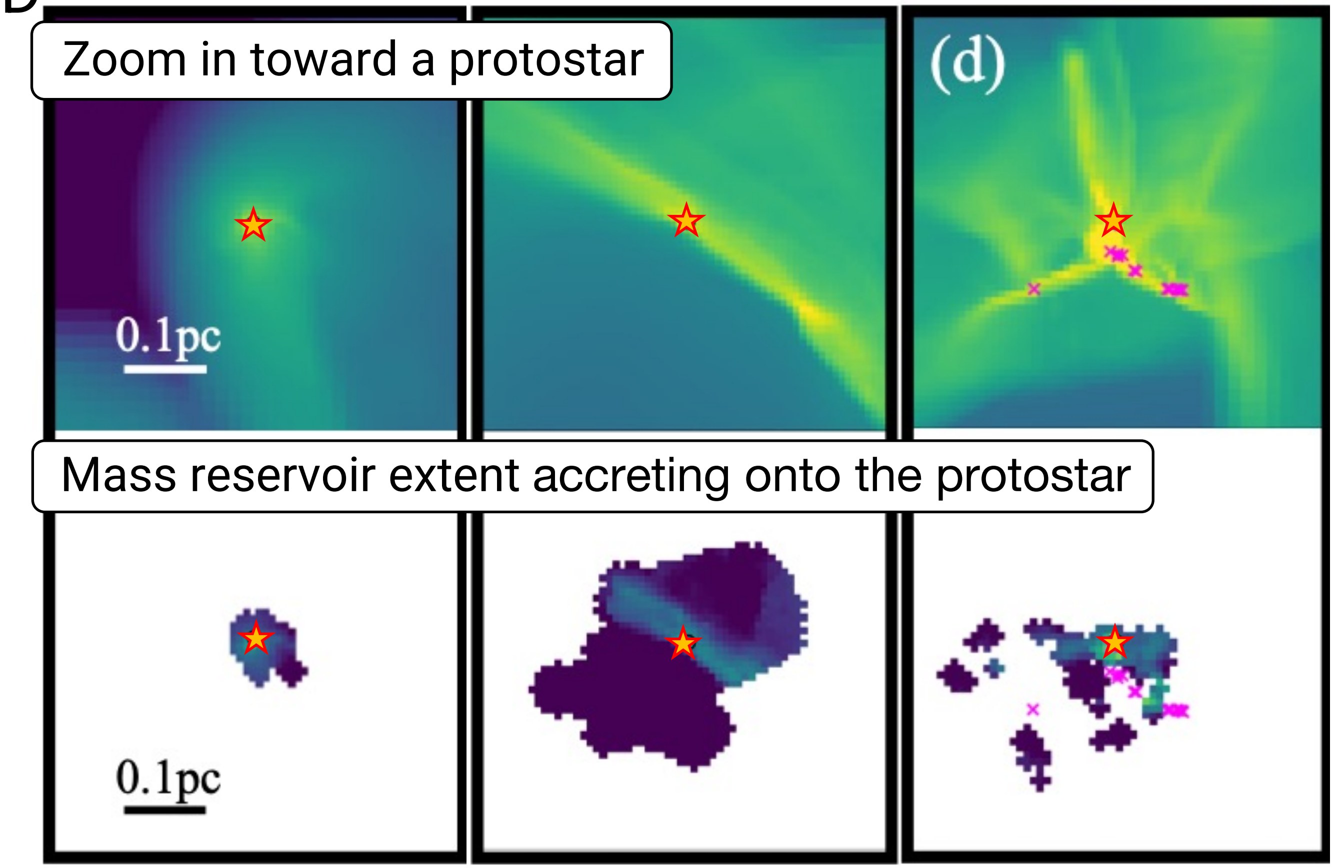


● : Tracer particle, ■ : Mass reservoir region (Star-forming core)

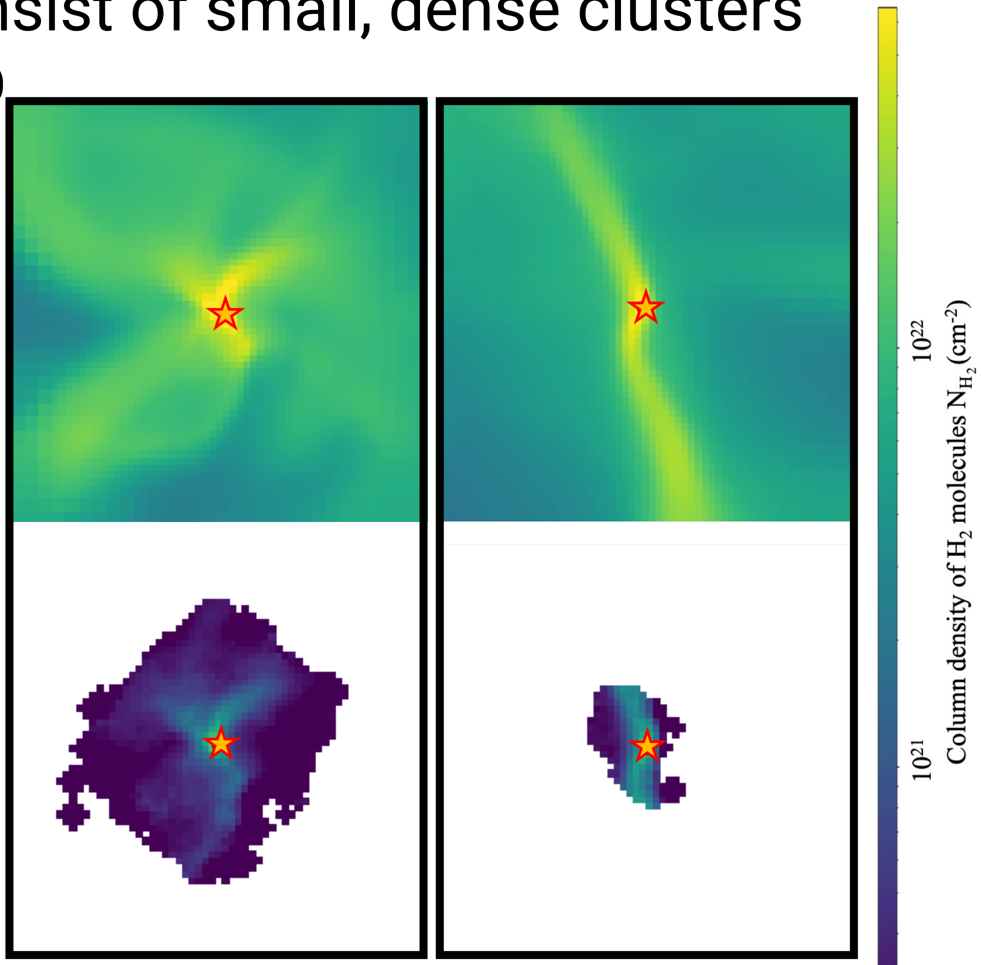
Mass Reservoirs at t_{ps}=0 in HD / MHD simulations

- ✓ Size of mass reservoirs accreting onto protostars: <0.1pc to ~0.4pc
- ✓ In clusters, mass reservoirs are clumped and consist of small, dense clusters

HD



MHD



Top：Column density around the protostar
Bottom：Column density of the identified mass reservoirs for protostars

☆ Target protostars
x Nearby protostars

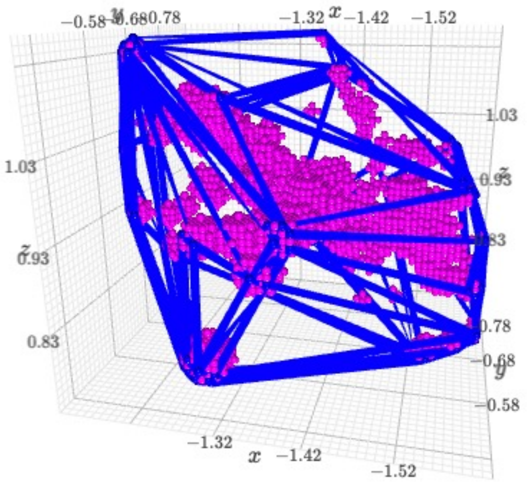
Filling Factor of Mass Reservoirs

To evaluate the overall core properties,
we define the convex hull core as region that encloses the mass reservoirs

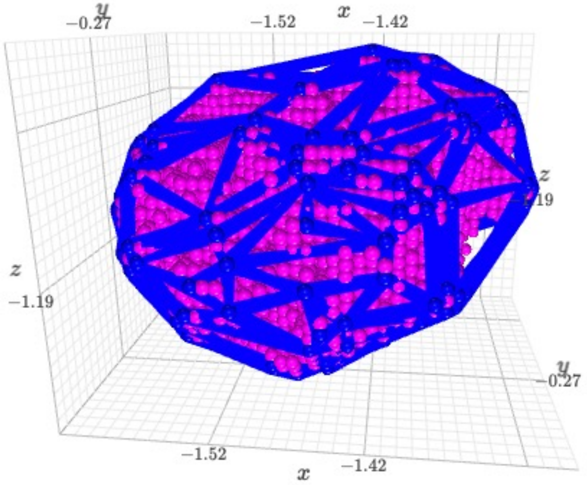
The ratio of mass reservoir volume V_{core} to convex hull core volume V_{hull}
= filling factor of cores Φ_{core}

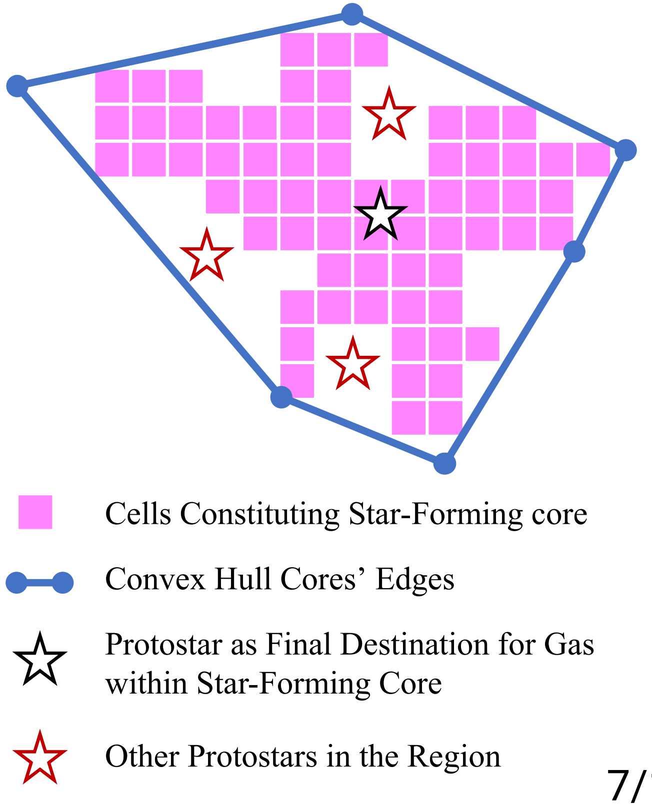
$$\phi_{\text{core}}(\%) = \frac{V_{\text{core}}}{V_{\text{hull}}} \times 100.$$

$\Phi_{\text{core}} = 11.3\%$



$\Phi_{\text{core}} = 63.3\%$



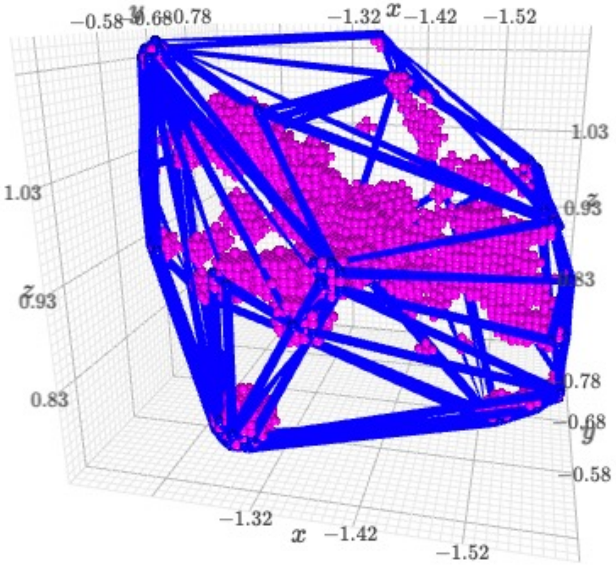


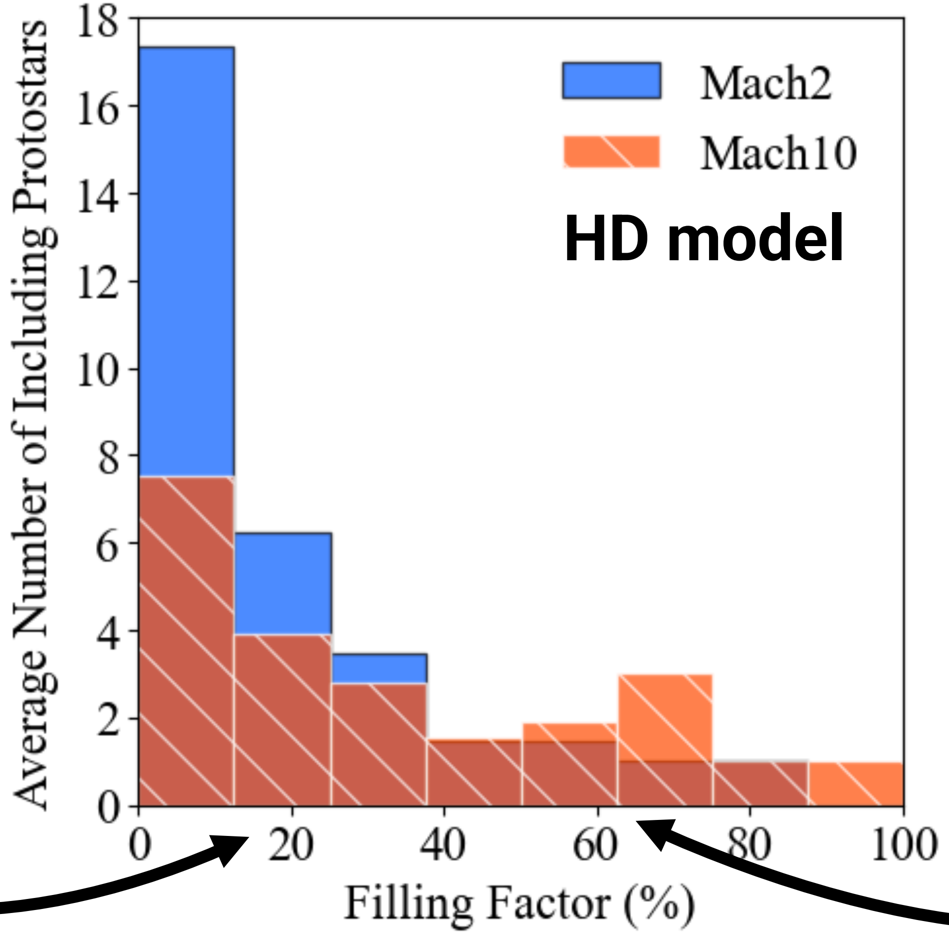
→Smaller Φ_{core} indicates a more loosely packed core

Φ_{core} v.s. Average Number of Protostars within Cores

Lower Φ_{core} corresponds to a higher number of protostars – i.e., clustered regions.
→ Filling factor can be regarded as an indicator of how clustered a core is.

$\Phi_{core} = 11.3\%$





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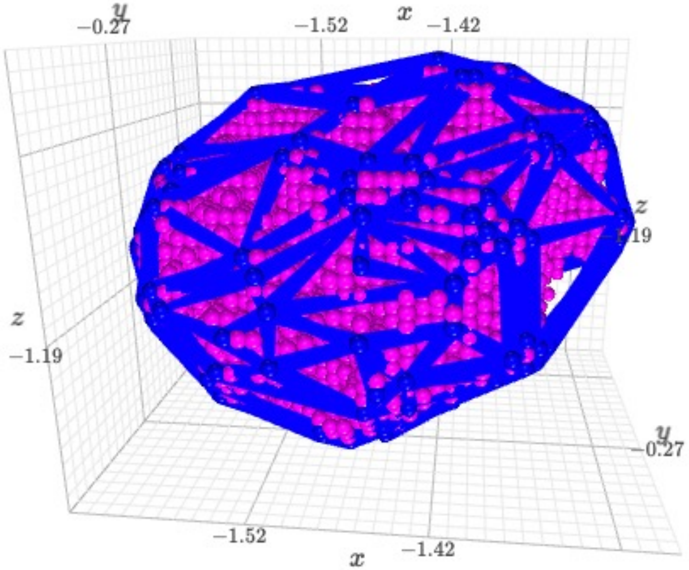
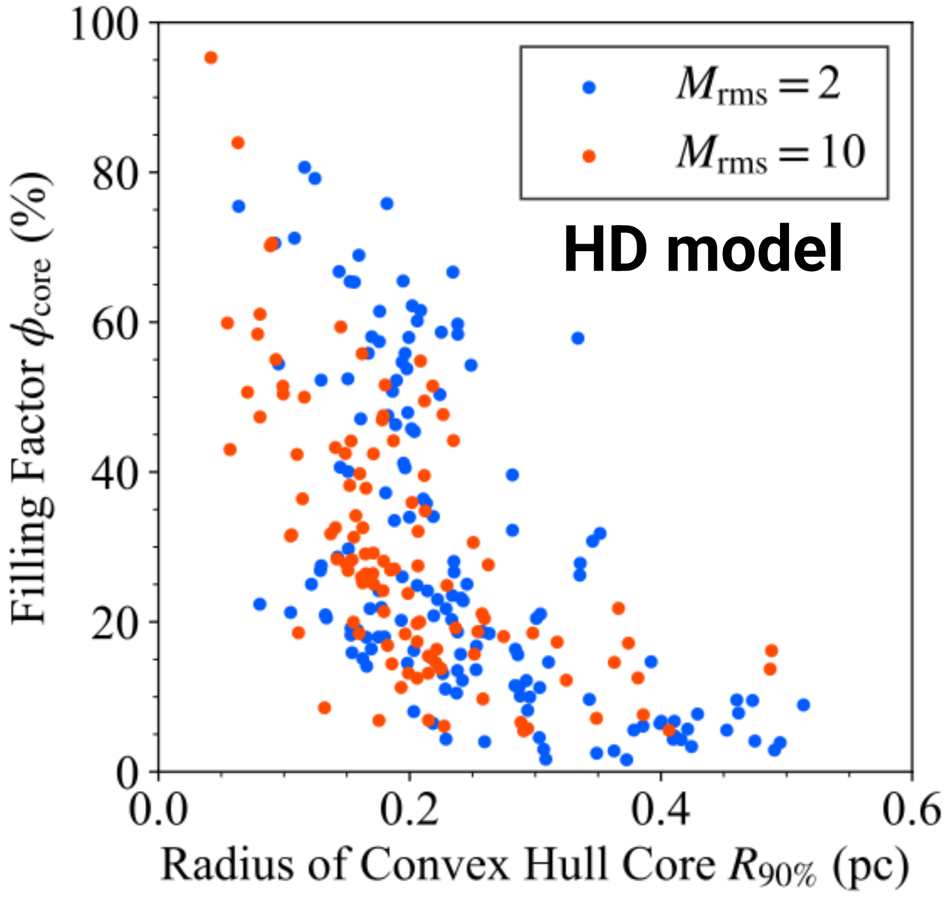


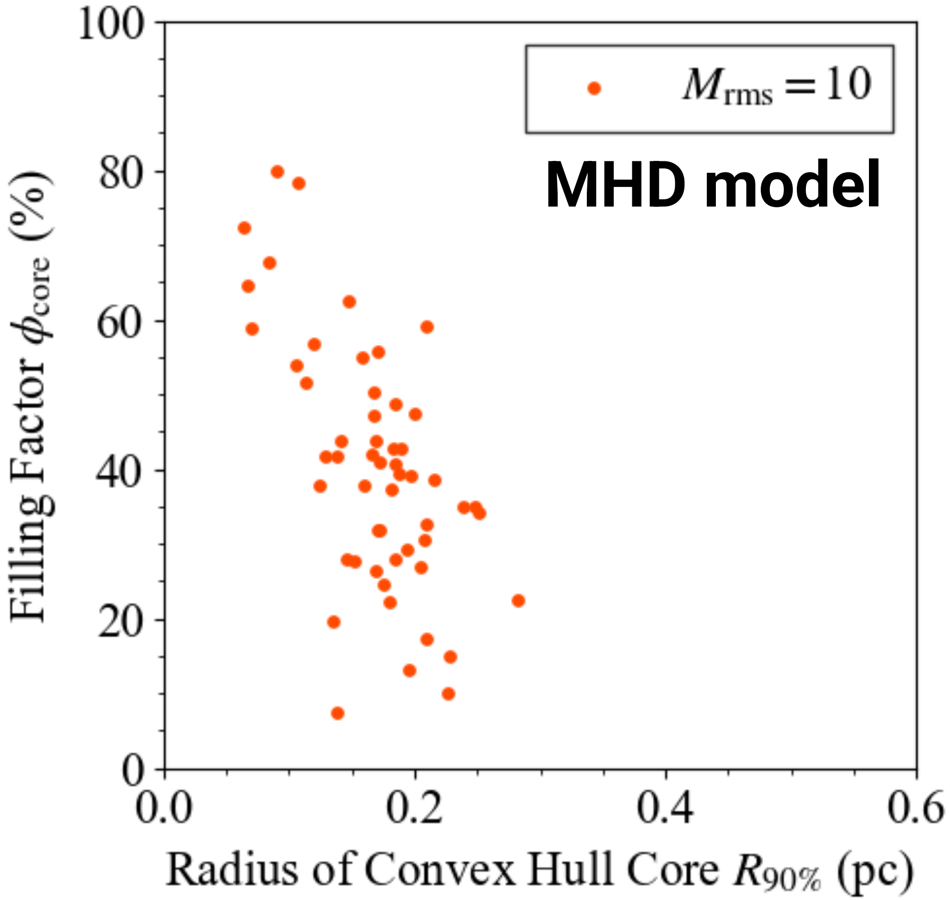
Φ_{core} vs. Spatial Extent of Convex Hull Cores

HD: larger filling factors are associated with convex hull cores of larger radii

MHD: radius remains abount 0.1-0.2pc, regardless of the filling factor

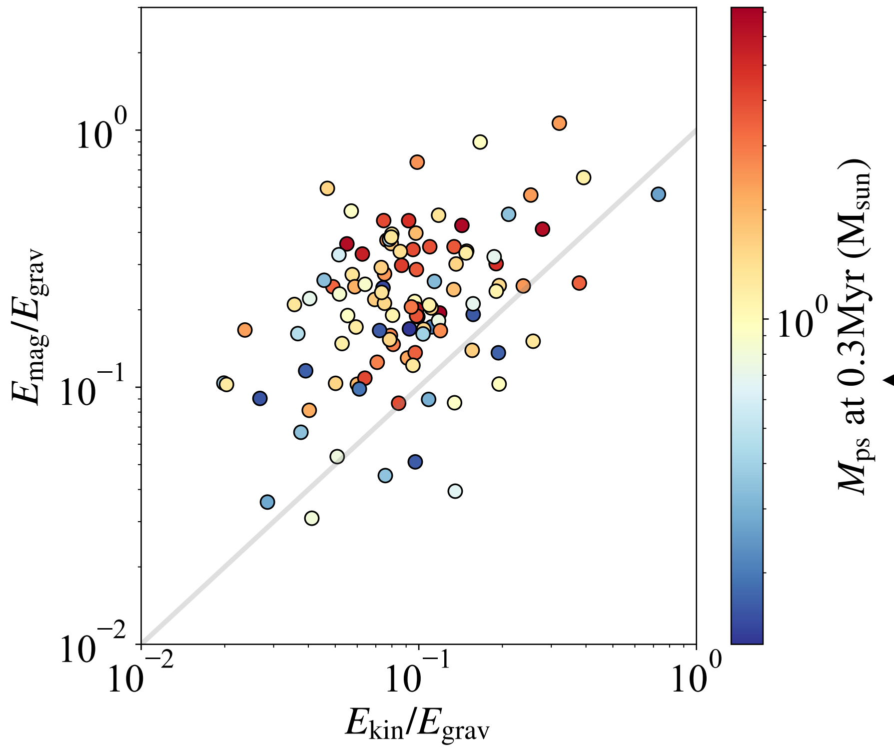
→Within 0.3 Myr after formation, mass-supplying regions extend ~0.2 pc in radius

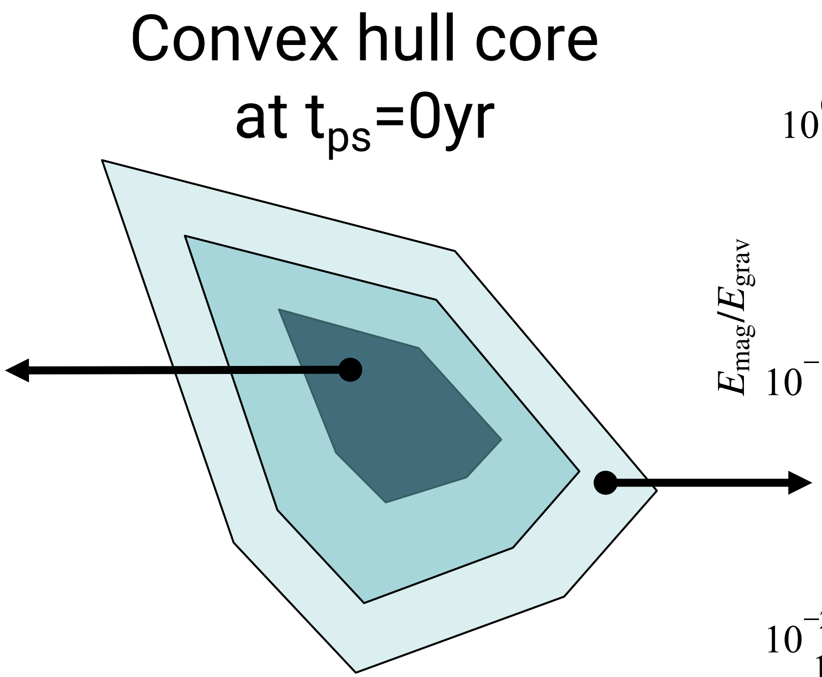




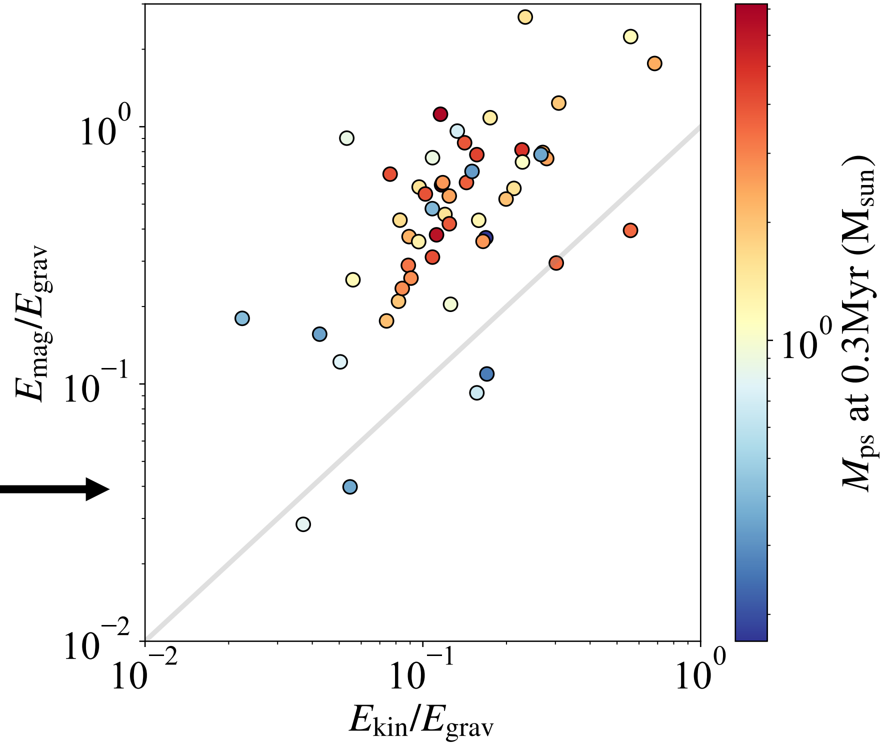
Energy Ratio $E_{kin}/|E_{grav}|$ vs. $E_{mag}/|E_{grav}|$

Convex hull core enclosing gas accreting within **0.1Myr**





Convex hull core enclosing gas accreting within **0.3Myr**



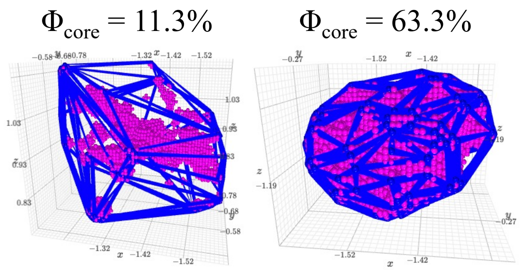
- ✓ Most cores just after protostar formation exhibit E_{mag}> E_{kin} from all region to the center
- ✓ No clear or only weak correlation is found with the stellar mass

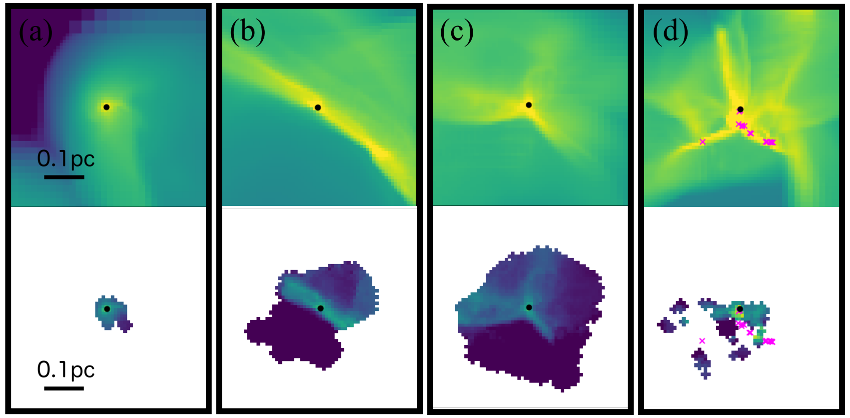
Summary

Numerical simulations of multiple star formation with tracer particles
→ Track gas accreted onto protostars and identify cores as mass reservoirs

<u>Identified star-forming cores (i.e., mass reservoirs):</u>
✓ Spherical, filamentary, and hub-filamentary morphologies
✓ Cores containing multiple protostars are not well bundled
→ Each protostar selectively acquires gas

<u>Core filling factor = Indicator of clustering degree</u>
Low filling factor cores:
✓ Contain more protostars
✓ Have larger radius ~0.2pc





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