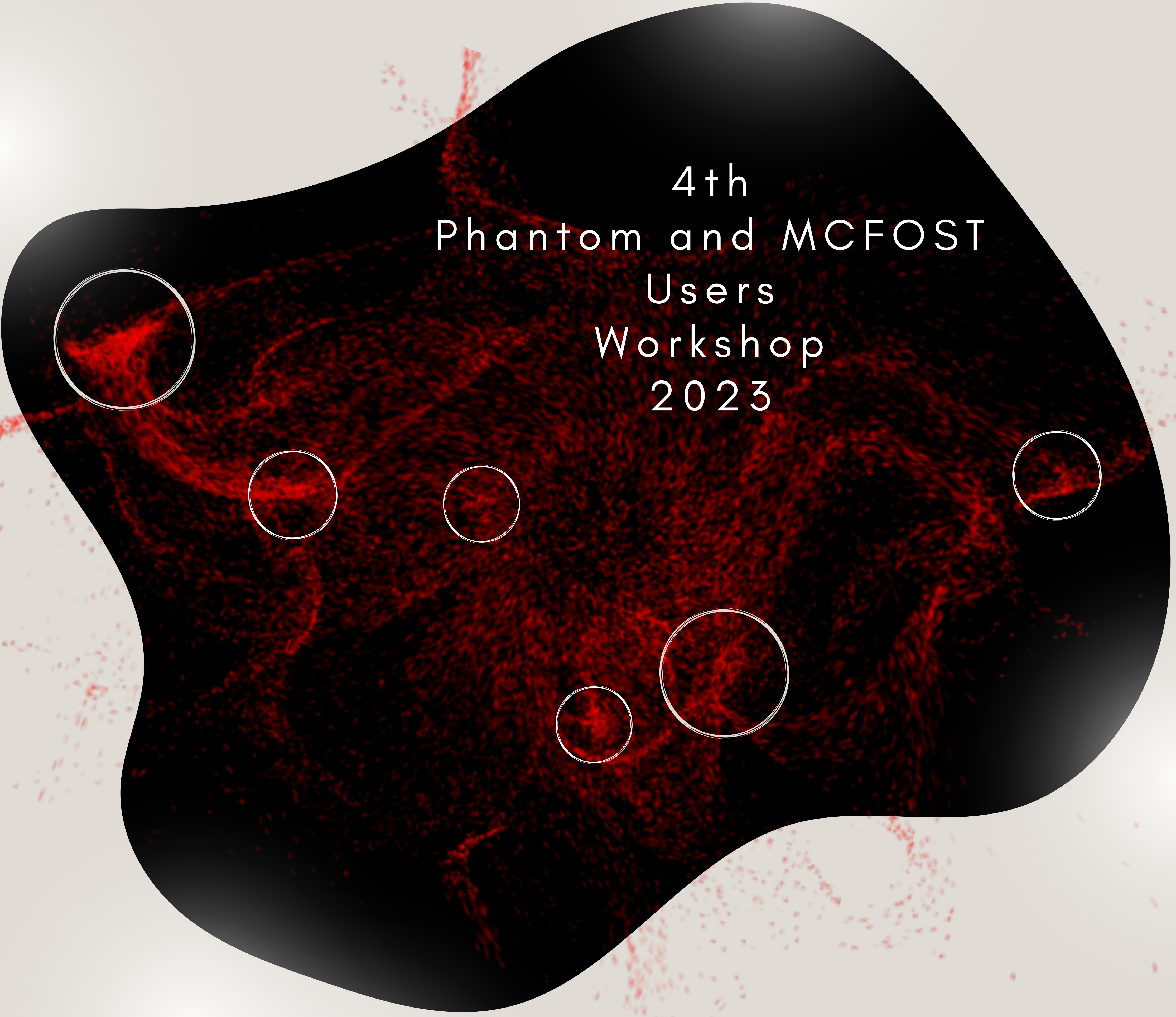


4th
Phantom and MCFOST
Users
Workshop
2023

Griselda Arroyo-Chávez
3rd year PhD

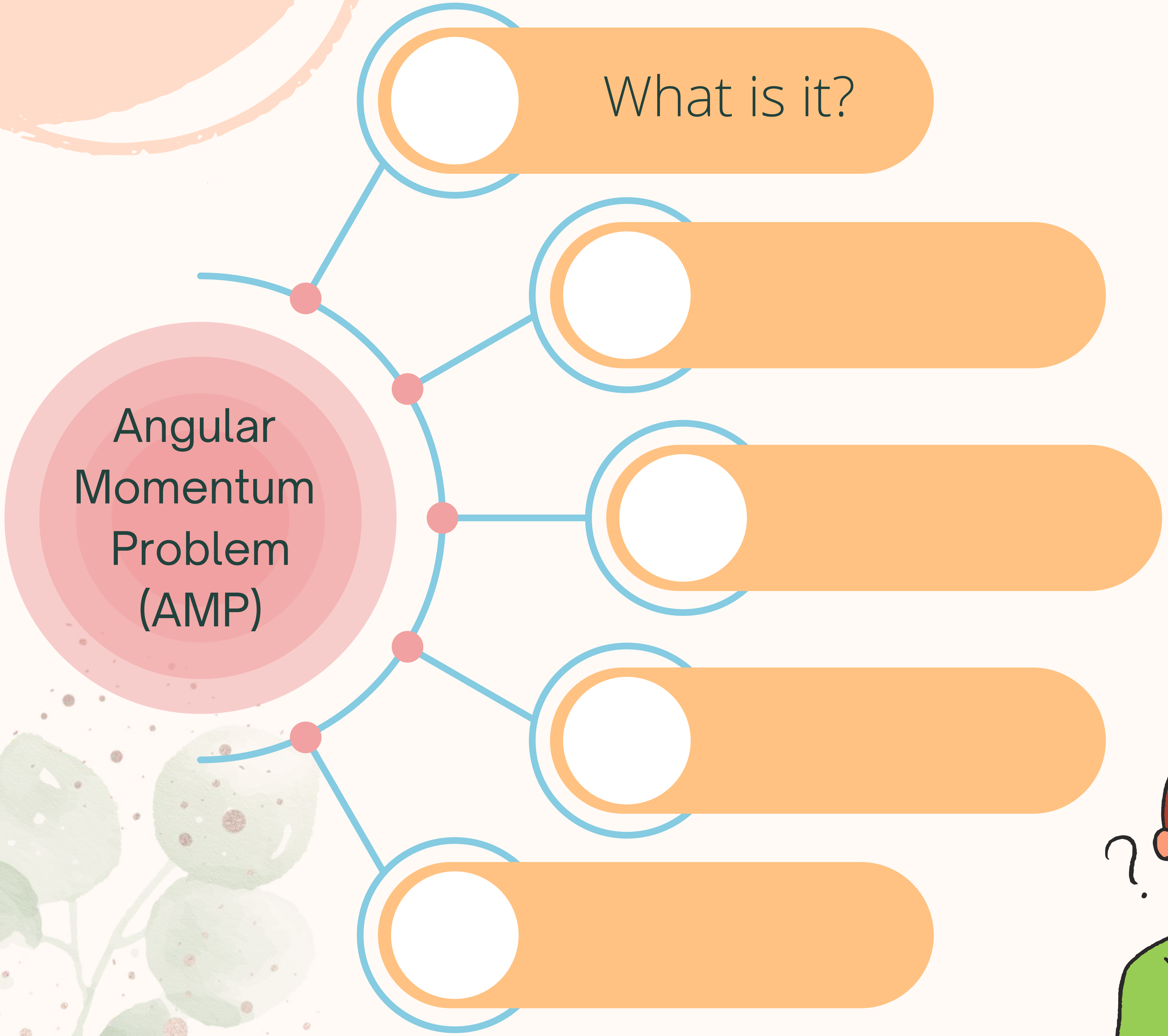
Supervisor:
Enrique Vázquez-Semadeni
Collaborators:
James Wurster

Institute of Radioastronomy and Astrophysics
UNAM- Mexico

Evolution of the specific angular momentum during gravitational fragmentation of simulated clumps in PHANTOM

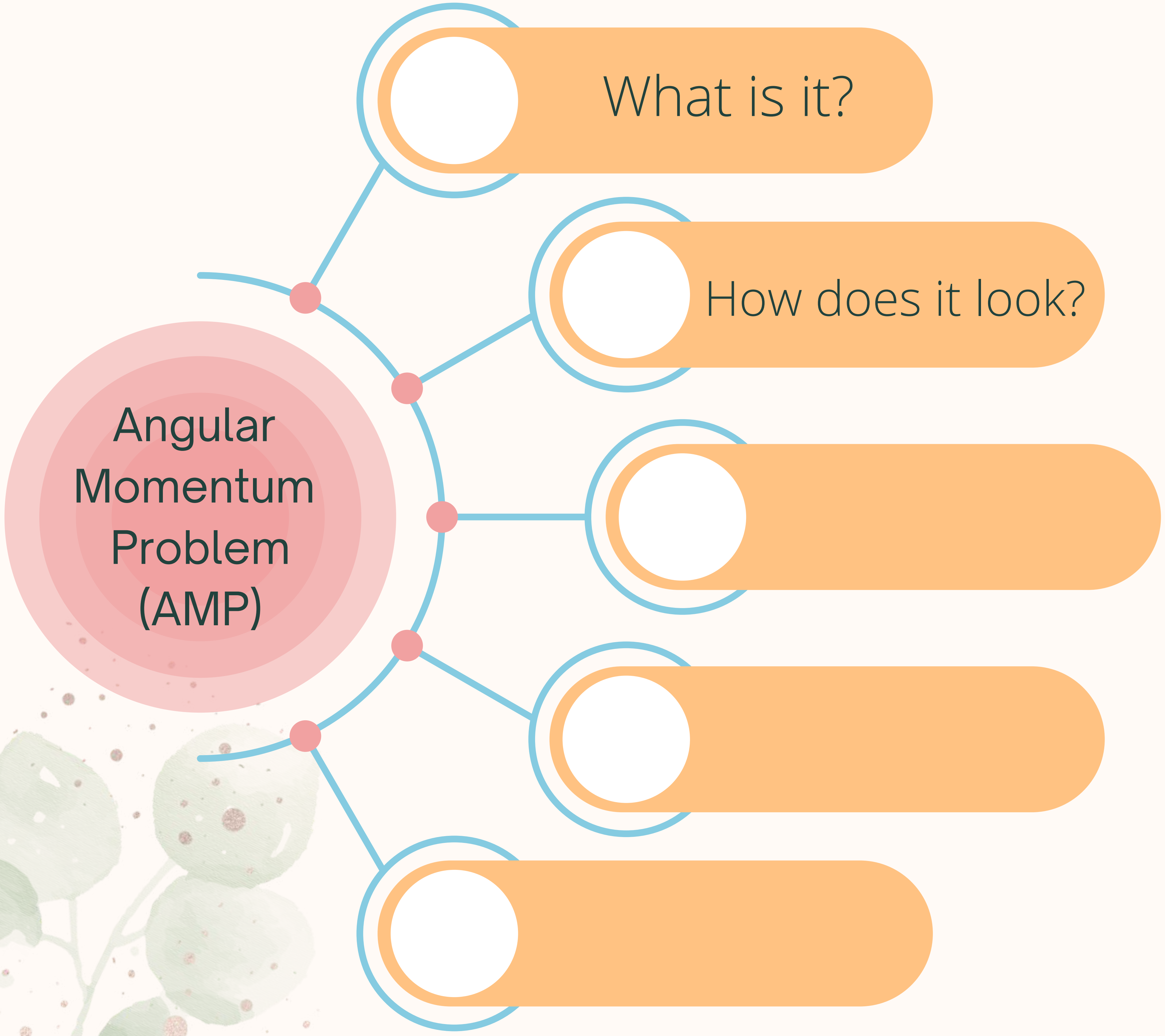
Feb. 13th, 2023

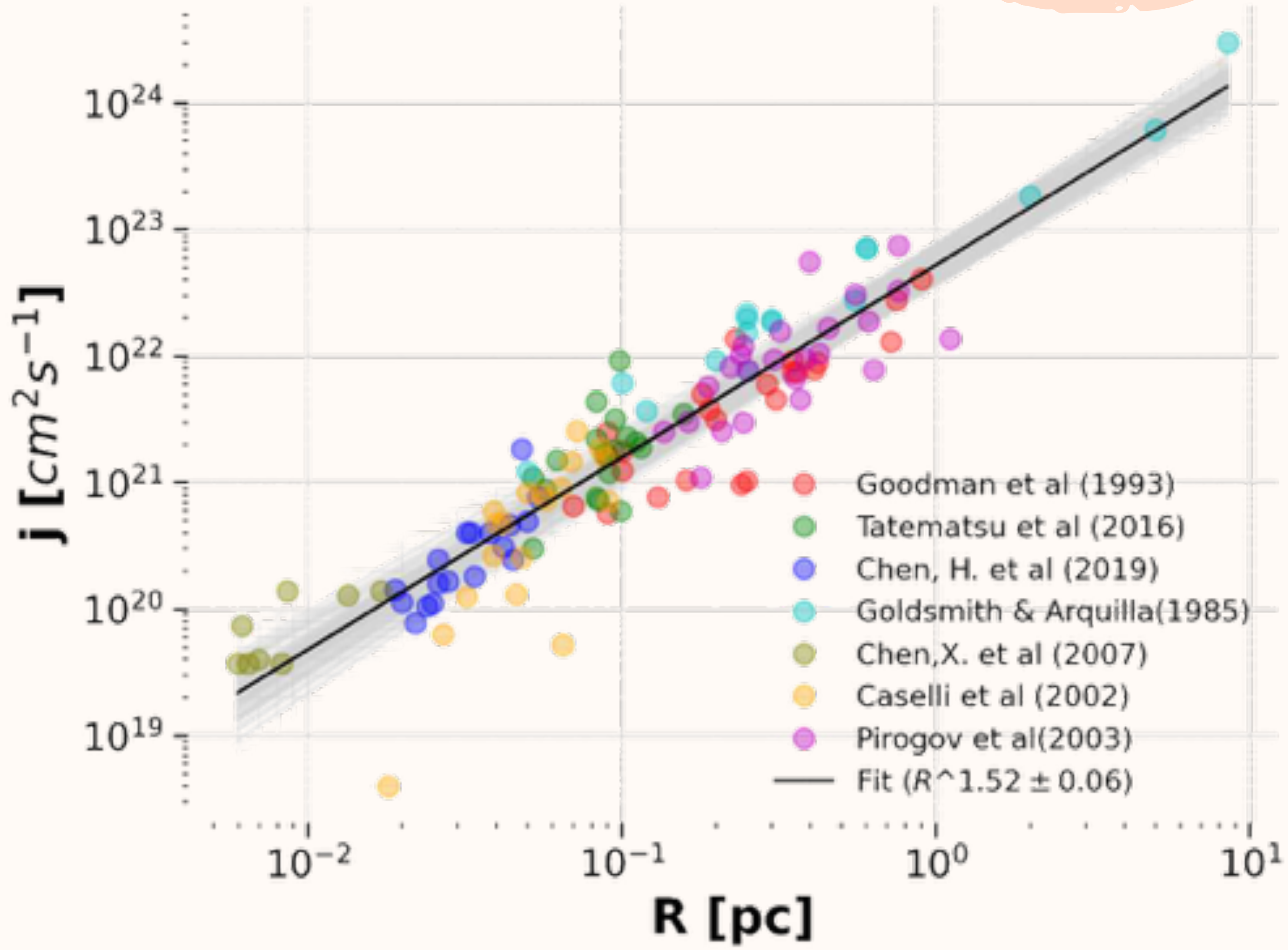
1. Introduction



Apparent loss of specific angular momentum (**j**) during the collapse of a molecular cloud, such that the resulting clumps and cores have **j** several orders of magnitude smaller than the parent cloud.

1. Introduction





Compilation by Arroyo-Chávez & Vázque-Semadeni 2022

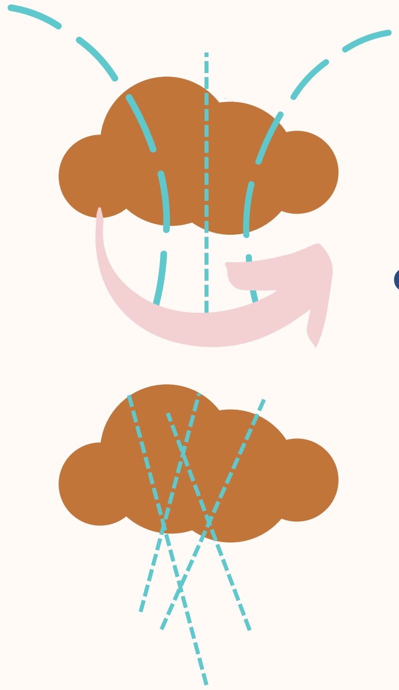
$$j = 10^{22.9\pm0.03}\left(\frac{R}{1\mathrm{pc}}\right)^{1.52\pm0.06} \mathrm{cm}^2\ \mathrm{s}^{-1}$$

1. Introduction

Angular Momentum Problem (AMP)

- What is it?
- How does it look?
- Are there solutions? **What are they?**

Magnetic braking



The torsion of the field lines due to the rotation of the cloud causes it to slow down.

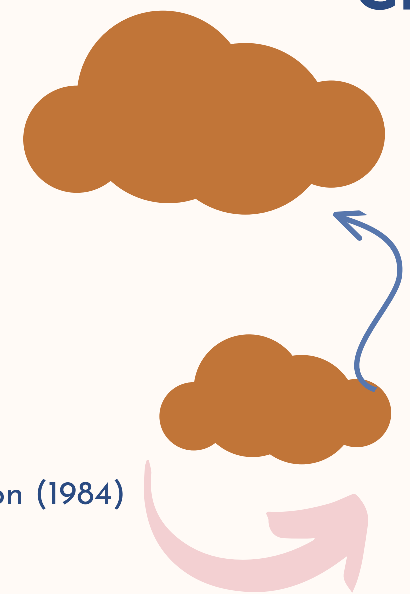
Gillis et al (1974,1979)
Mouschovias & Paleologou (1979,1980)

Turbulent viscosity

Momentum exchange among turbulent eddies

Larson (1984)

Gravitational torques



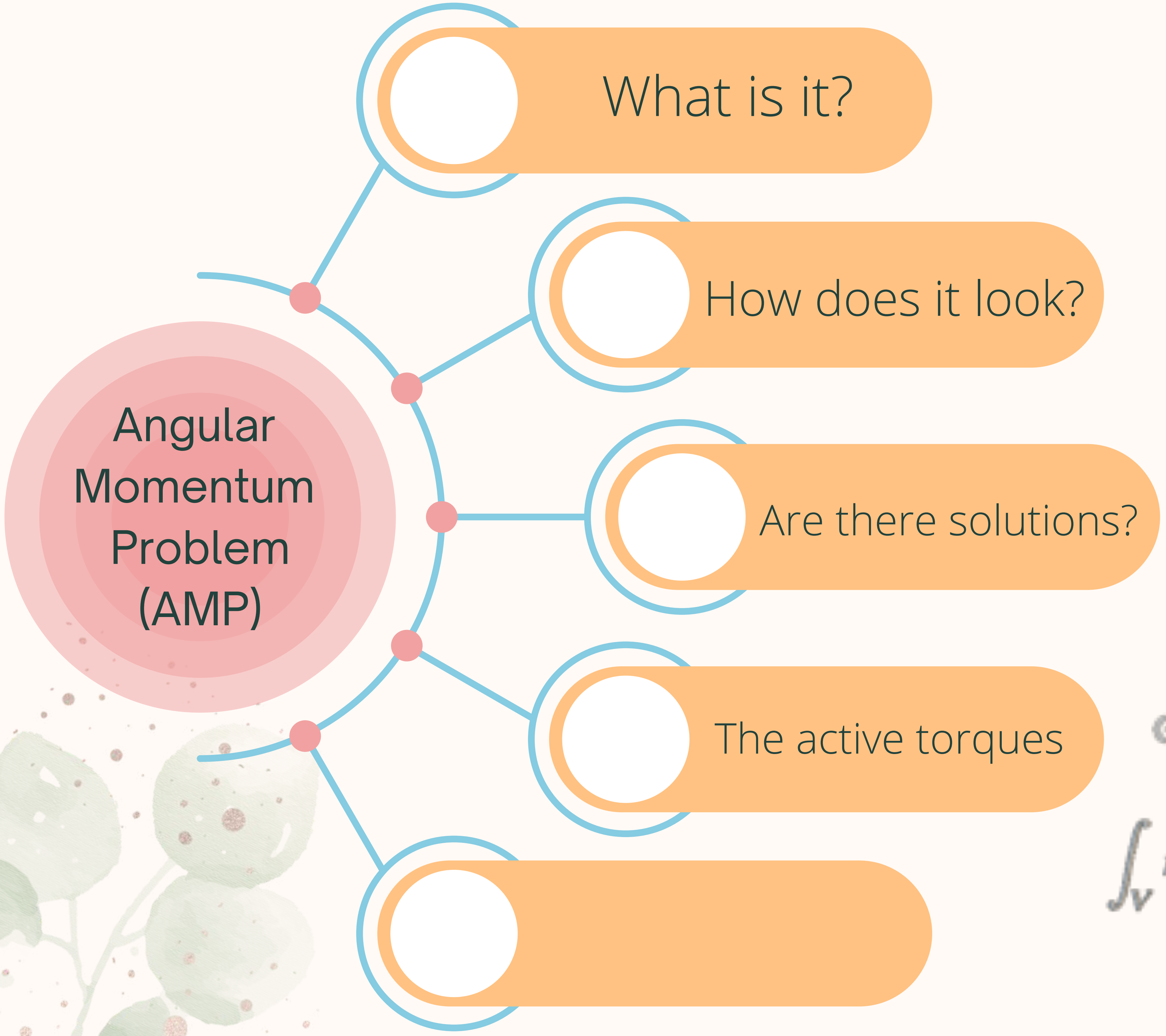
The cloud can be slowed down by the gravitational pull it experiences from another nearby object.

Larson (1984)

1. Introduction

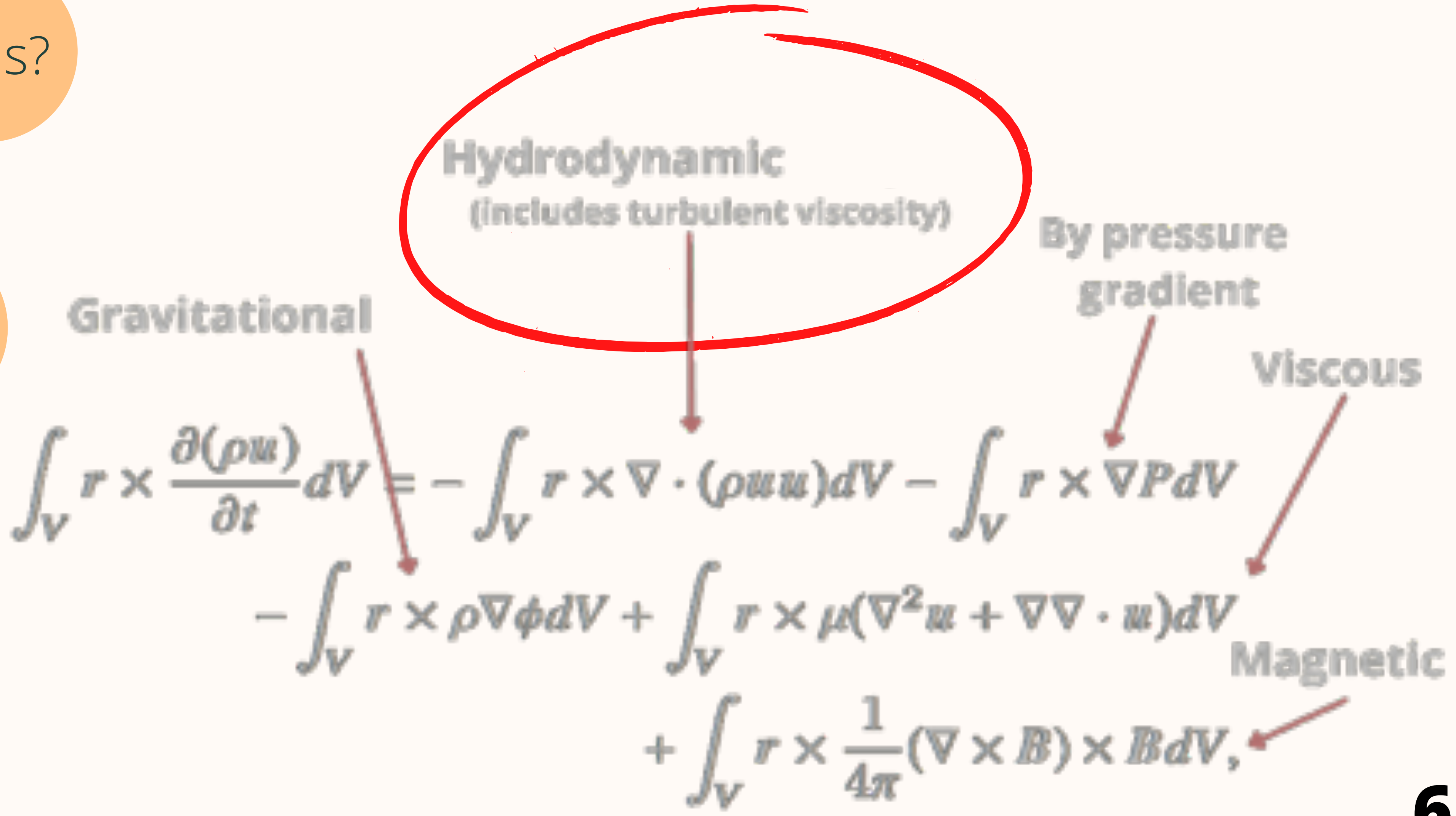
Angular Momentum Problem (AMP)

- What is it?
- How does it look?
- Are there solutions?
- The active torques



The "active torques" equation

The equation governing the evolution of the AM of a fluid parcel of volume V with respect to some coordinate origin :



$$\int_V r \times \frac{\partial(\rho u)}{\partial t} dV = -\int_V r \times \nabla \cdot (\rho u u) dV - \int_V r \times \nabla P dV - \int_V r \times \rho \nabla \phi dV + \int_V r \times \mu(\nabla^2 u + \nabla\nabla \cdot u) dV + \int_V r \times \frac{1}{4\pi}(\nabla \times B) \times B dV,$$

1. Introduction

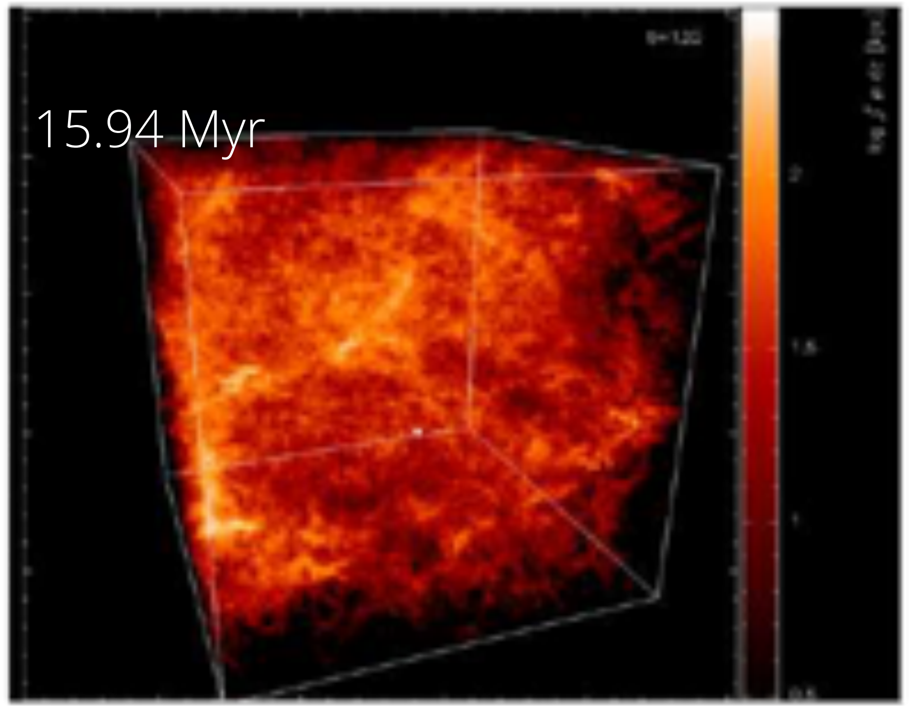
Angular Momentum Problem (AMP)

- What is it?
- How does it look?
- Are there solutions?
- The active torques
- Key question

What is the relative importance of these torques?

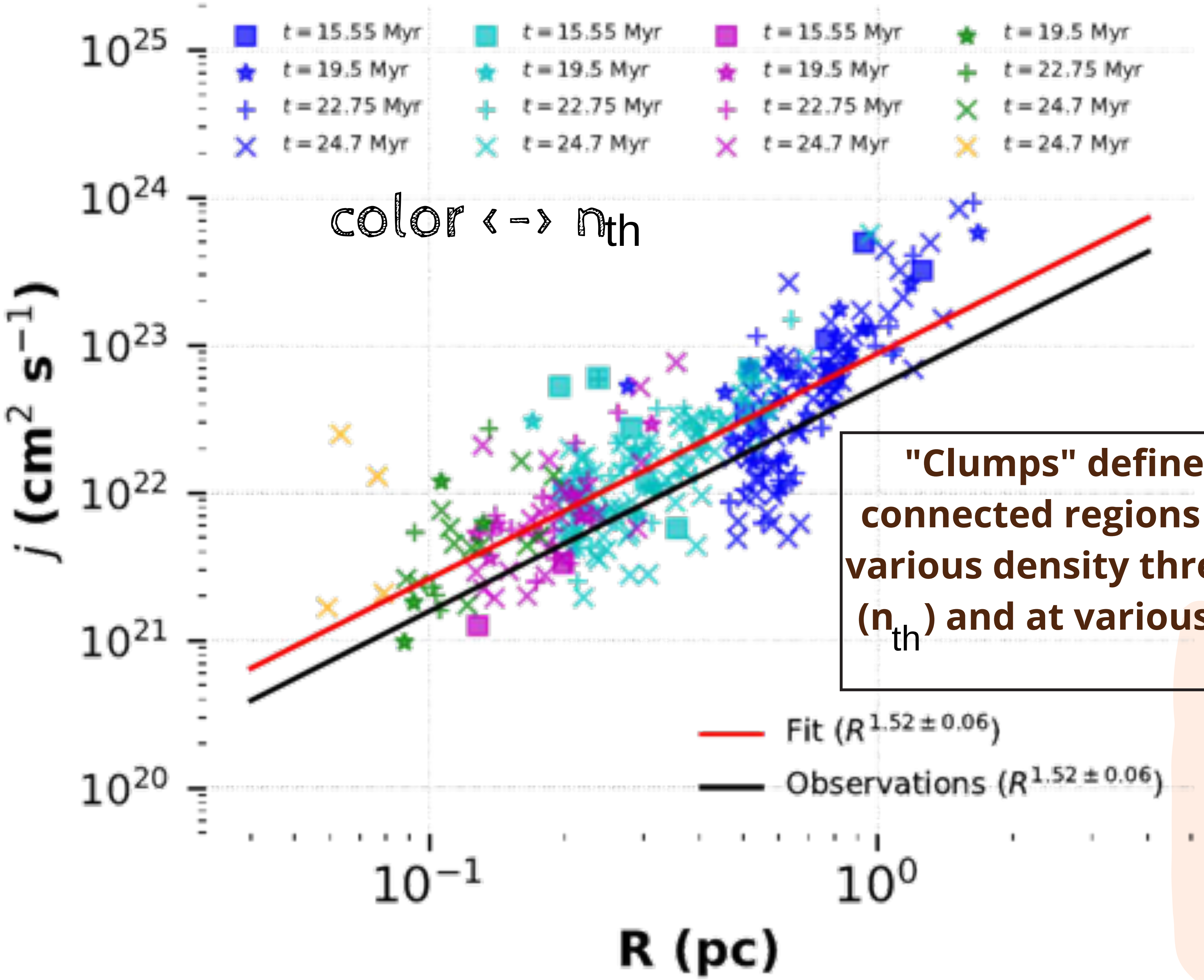
The simulation

Heiner et al. (2015)



- SPH simulation performed with GADGET-2
- $296^3 \approx 2.6\times10^7$ particles in a box of 256 pc per side.
- Particle mass set at 0.06 $M_\odot$. Total mass in the box: 1.58×10^6 $M_\odot$
- Initial density and temperature set at 3 cm^{-3} and 750 K [T_{eq} (n=3 cm^{-3})]. Thermally unstable warm atomic gas.
- Density threshold to form sinks: 3.2×10^6 cm^{-3}
- Includes selfgravity, cooling and diffuse heating processes (via adjusted functions)
- Does not include stellar feedback
- After 0.65 Myr: σ≈18 km/s

First result: a clump sample in the simulation reproduces the observed scaling

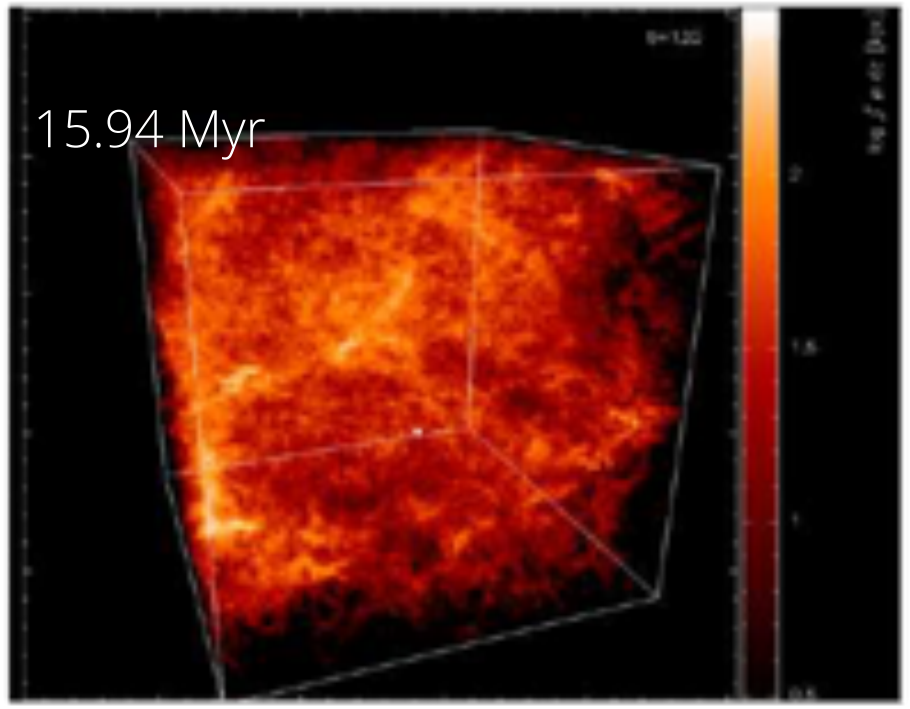


"Clumps" defined as connected regions above various density thresholds (n_{th}) and at various times

2. Our previous work

The simulation

Heiner et al. (2015)



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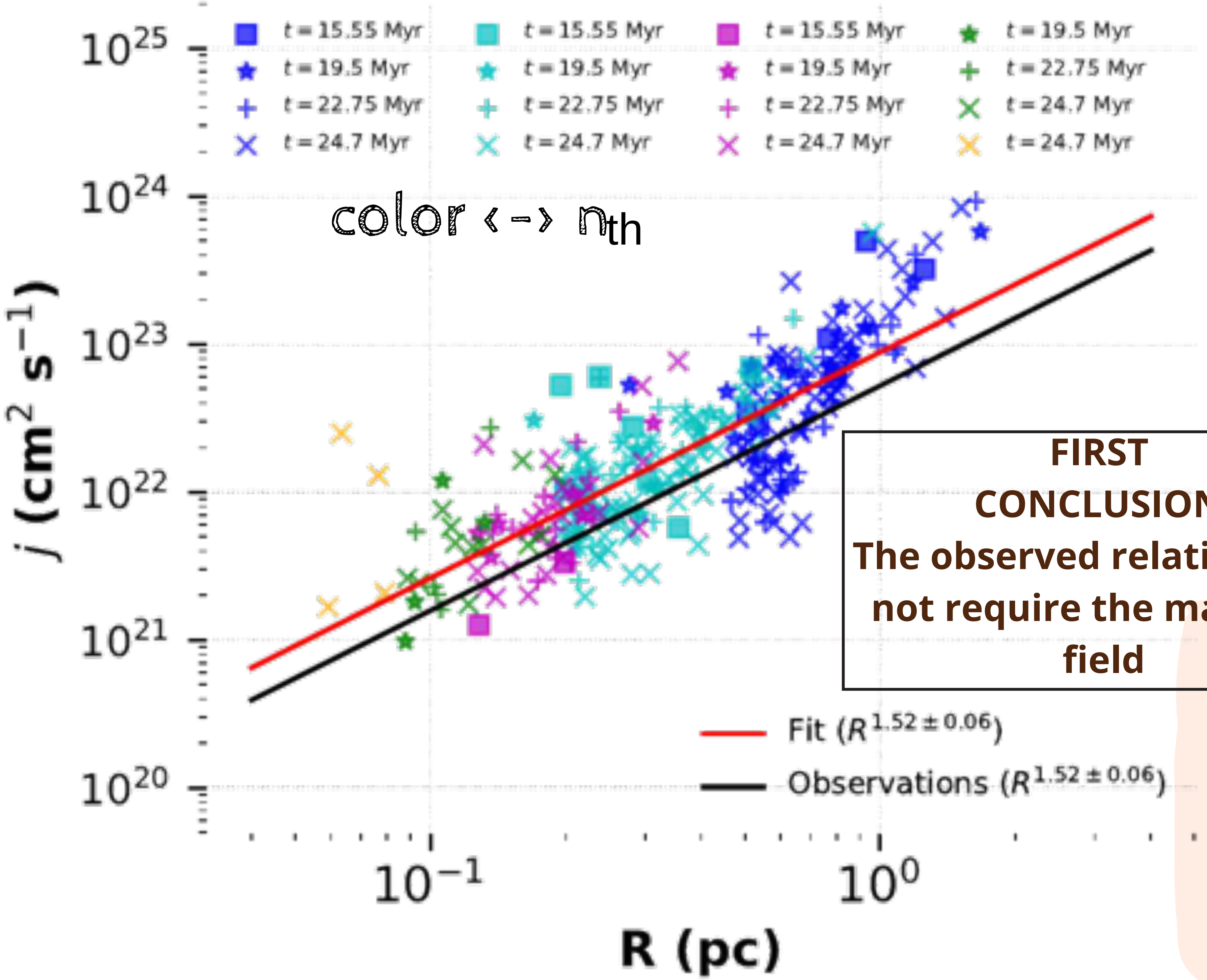
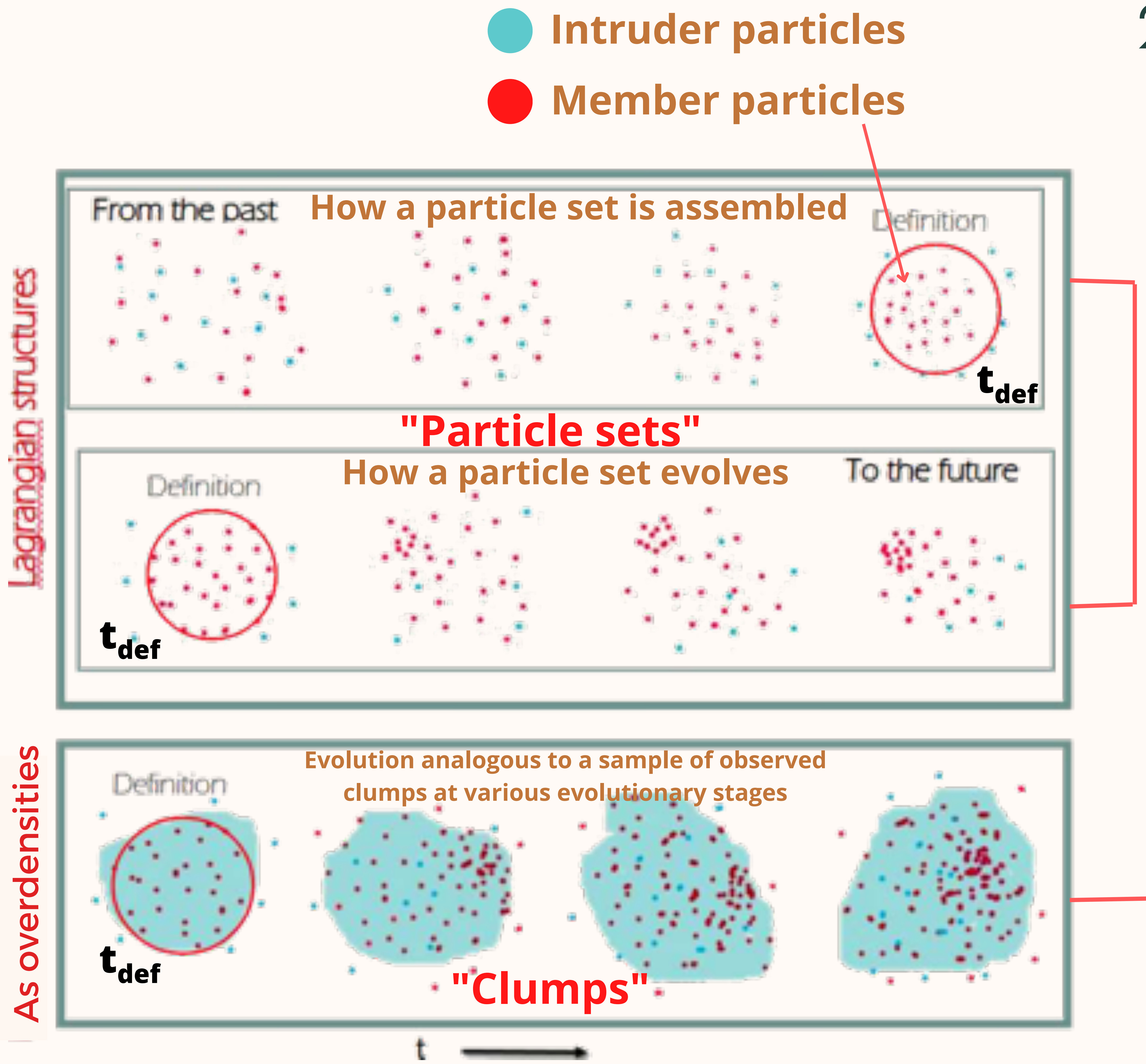


FIRST CONCLUSION: The observed relation does not require the magnetic field

Defining clumps

We use an SPH simulation because it allows us to track fixed sets of particles over time.

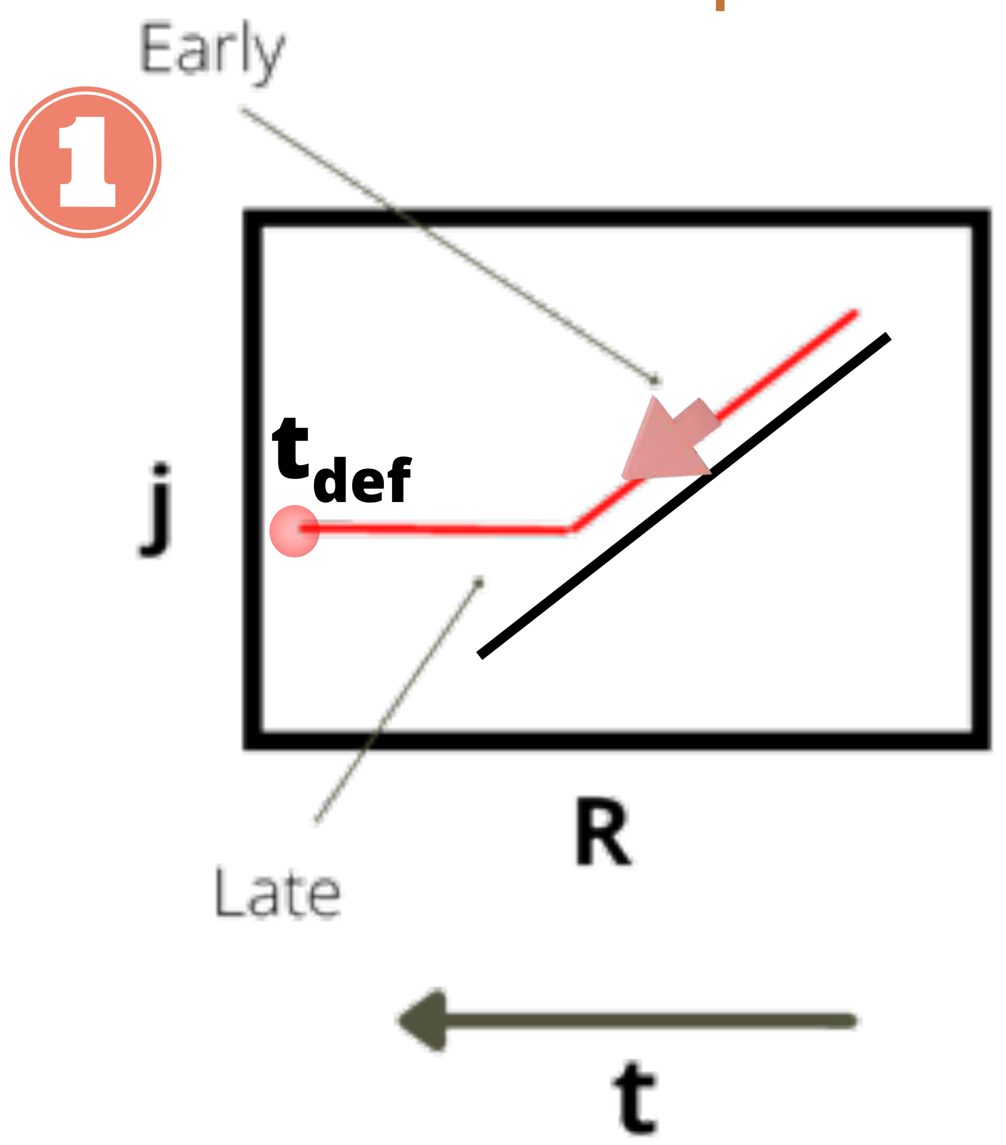


- Clumps defined in the "standard" way, as connected sets of particles above a density threshold at some time t_def.
- Then follow the same set of particles to the past or the future.

- Clumps followed as overdensities at all times.
- Do not consist of the same set of particles at different times.

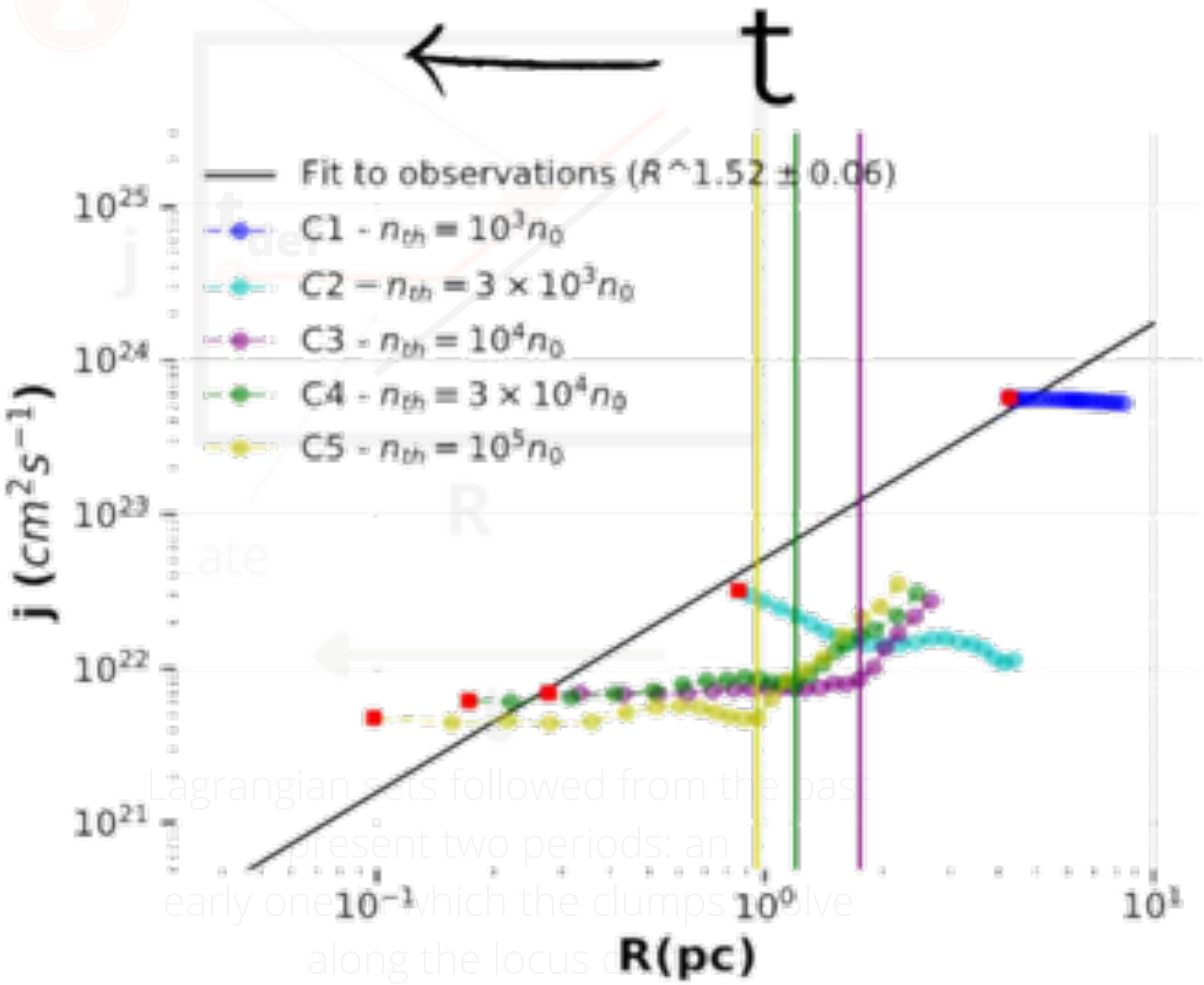
Results

Lagrangian particle sets tracked from the past



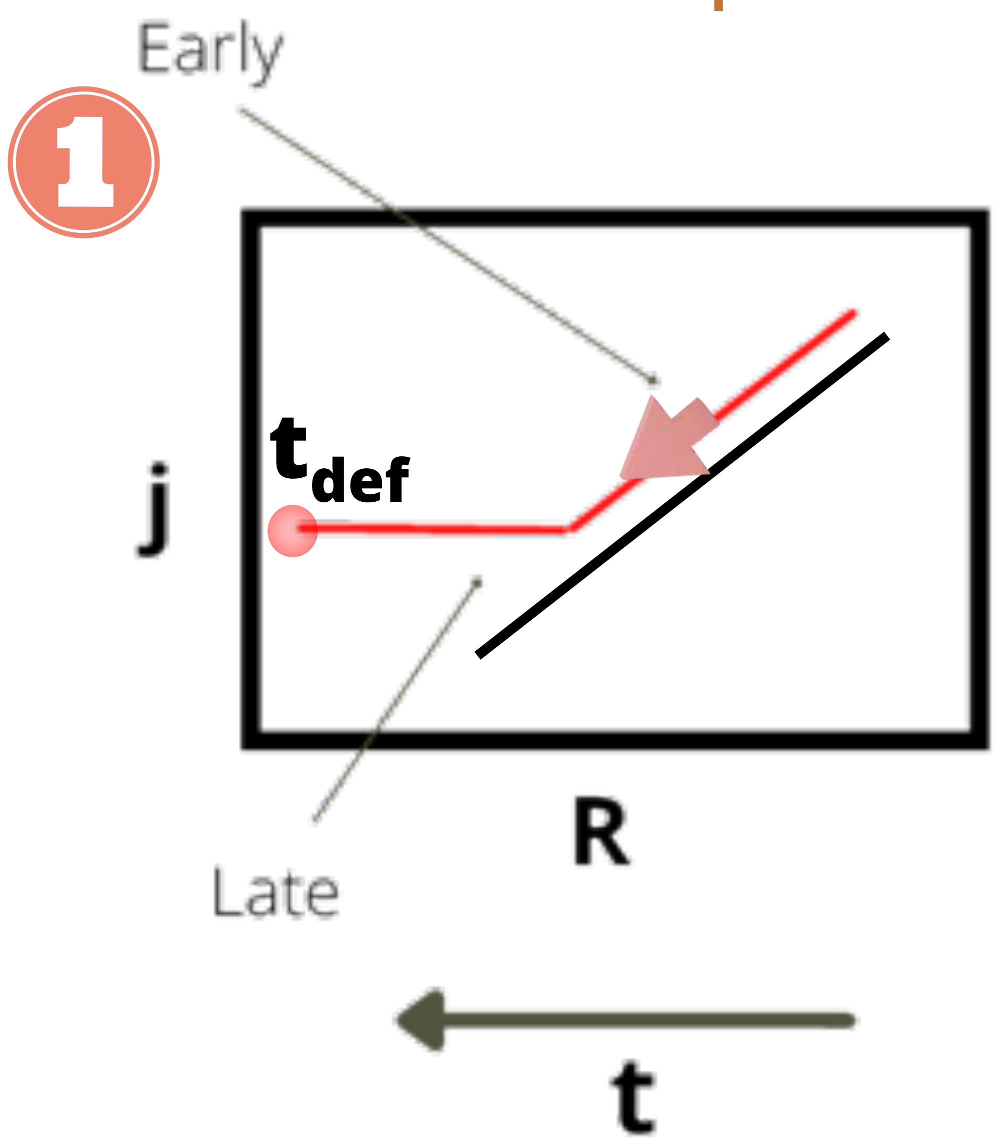
Lagrangian sets followed from the past present two periods: an early one, in which the clumps evolve along the locus of the observational j-R diagram and a late one, in which they evolve with j ~ cst. during the contraction.

Results


t
Fit to observations (R^1.52 ± 0.06)
C1 - $n_{th} = 10^3 n_0$
C2 − $n_{th} = 3 \times 10^3 n_0$
C3 - $n_{th} = 10^4 n_0$
C4 - $n_{th} = 3 \times 10^4 n_0$
C5 - $n_{th} = 10^5 n_0$
j ($cm^2 s^{-1}$)
R(pc)

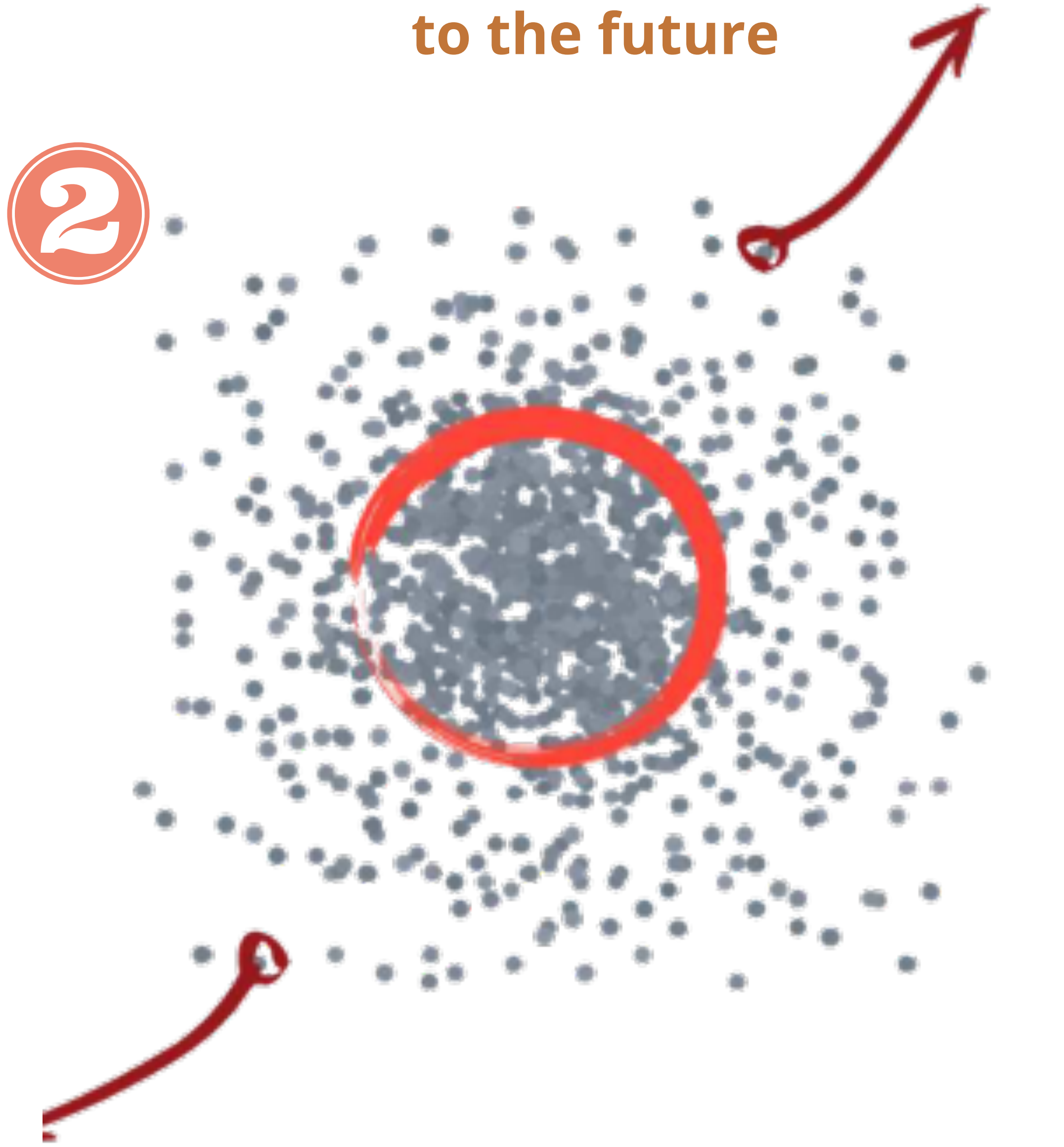
Results

Lagrangian particle sets tracked from the past



Lagrangian sets followed from the past present two periods: an early one, in which the clumps evolve along the locus of the observational j-R diagram and a late one, in which they evolve with j ~ cst. during the contraction.

Lagrangian particle sets tracked to the future



In Lagrangian clumps tracked to the future, the innermost regions collapse and form sinks (stellar particles), while the outer parts disperse

Similarly to accretion disks

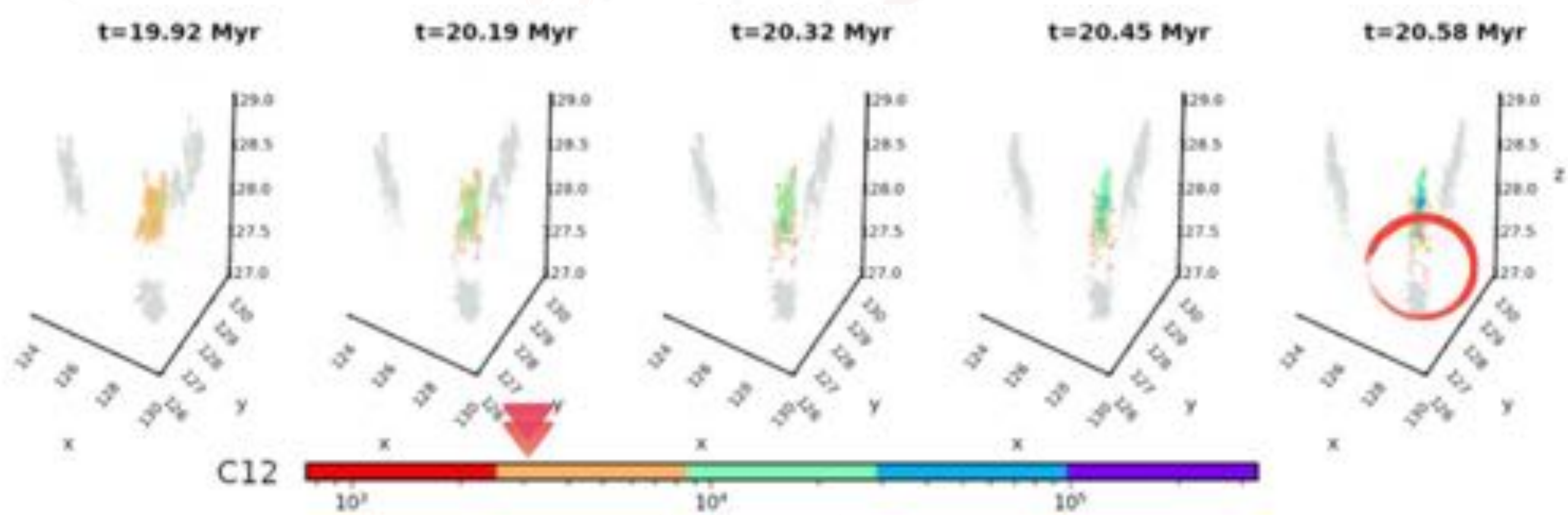
Results

2. Our previous work

Lagrangian particle sets tracked from the past

Lagrangian particle sets tracked to the future

Early



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Results

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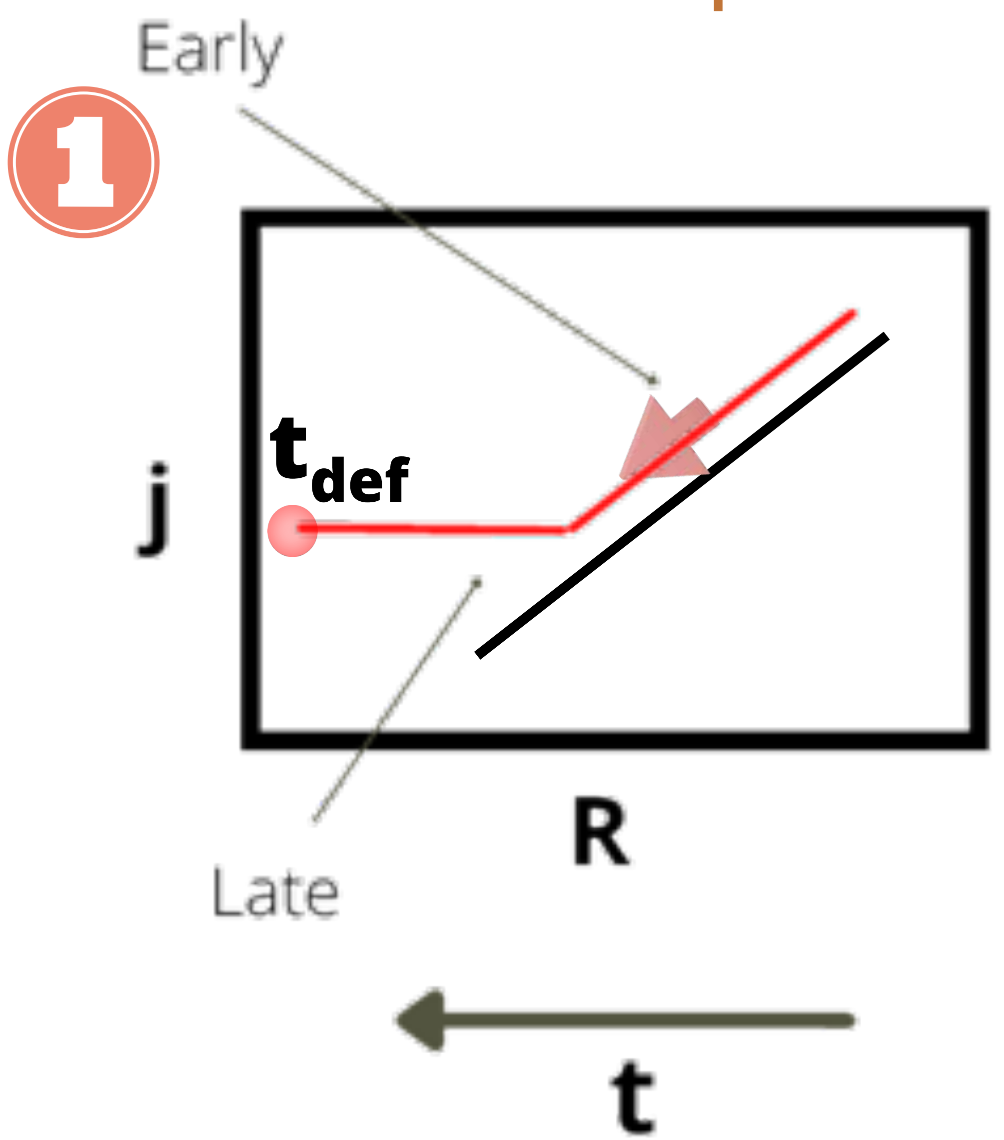

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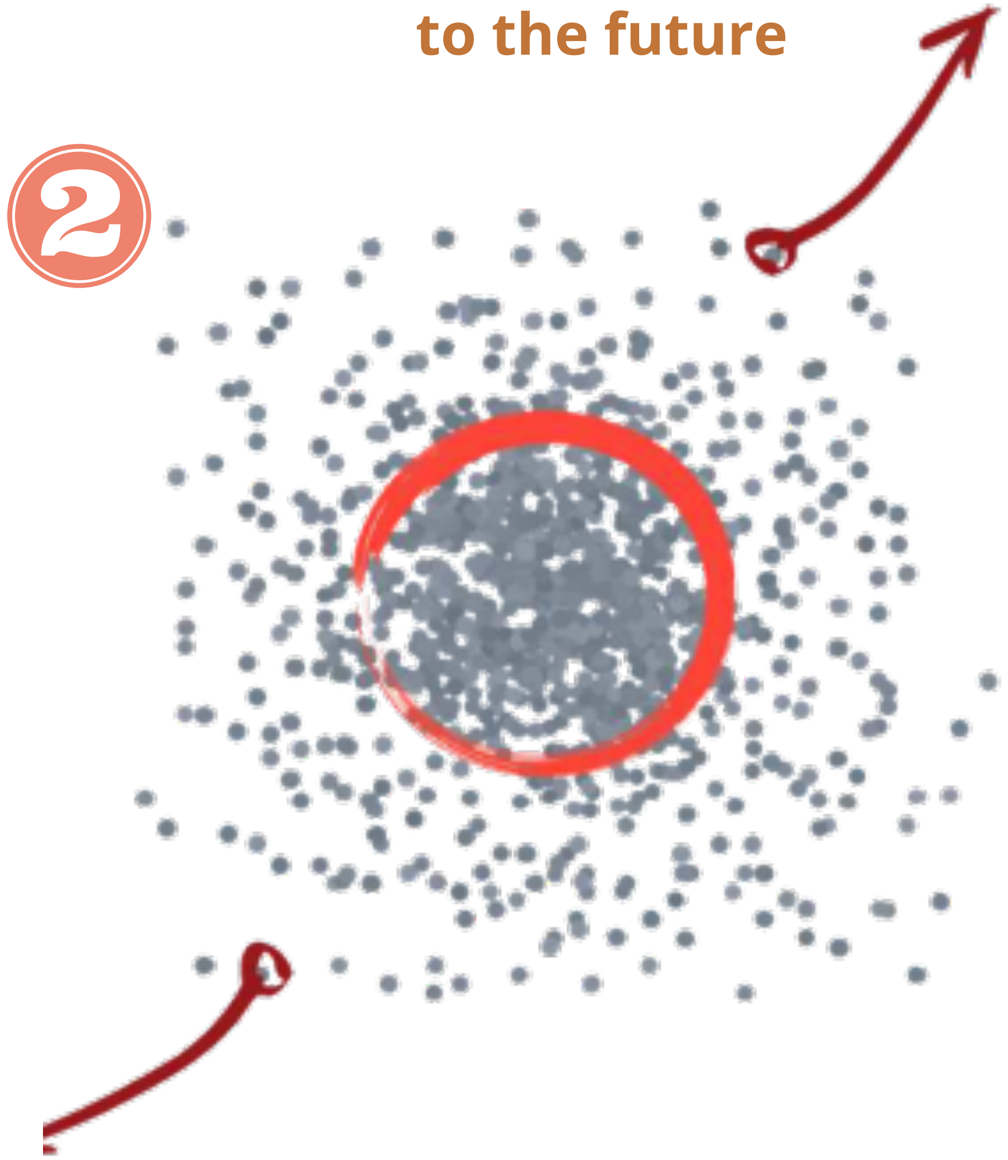
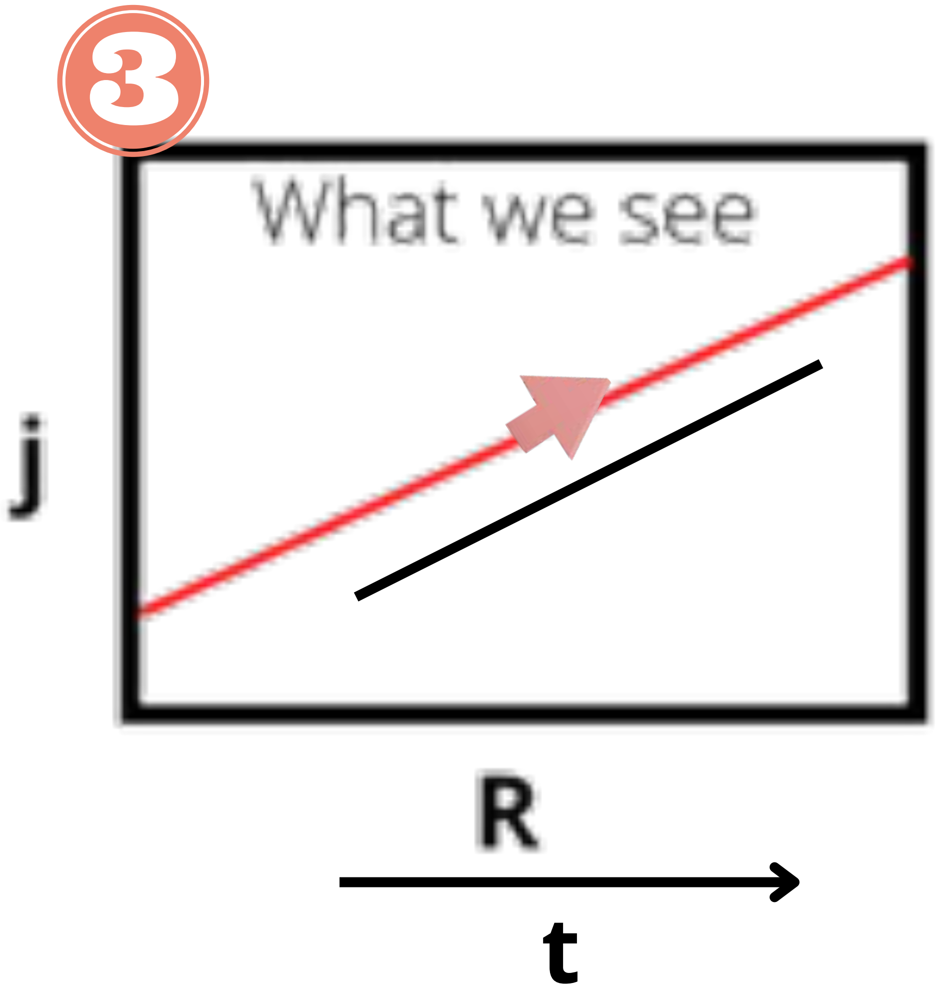


In Lagrangian clumps tracked to the future, the innermost regions collapse and form sinks (stellar particles), while the outer parts disperse

Similarly to accretion disks

Clumps as overdensities tracked to the future



The evolution in both radius and SAM occurs along evolutionary tracks close to the locus of the observational sample in this diagram.

Clumps increase their radius and mass even though they are collapsing!

(See also Camacho+20, ApJ, 903, 46)

Results

Lagrangian particle sets tracked from the past

Early

Late

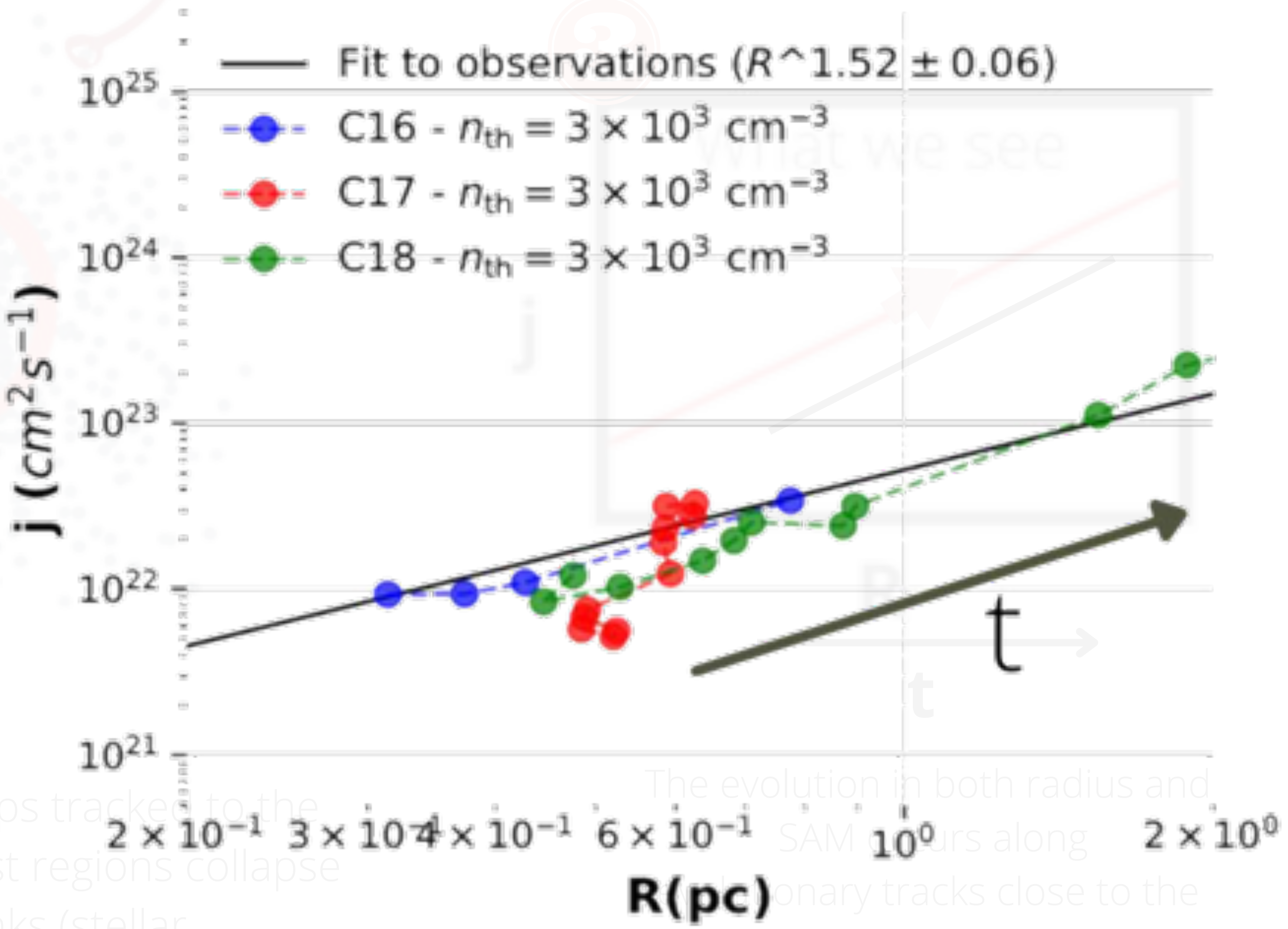
Lagrangian sets followed from the past present two periods: an early one, in which the clumps evolve along the locus of the observational j-R diagram and a late one, in which they evolve with j ~ cst. during the contraction.

Lagrangian particle sets tracked to the future

In Lagrangian clumps tracked to the future, the innermost regions collapse and form sinks (stellar particles), while the outer parts disperse

Similarly to accretion disks

Clumps as overdensities tracked to the future



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THE ASTROPHYSICAL JOURNAL

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Evolution of the Angular Momentum during Gravitational Fragmentation of Molecular Clouds*

Griselda Arroyo-Chávez[1] and Enrique Vázquez-Semadeni[1]

Published 2022 January 26 •

The Astrophysical Journal, Volume 925, Number 1

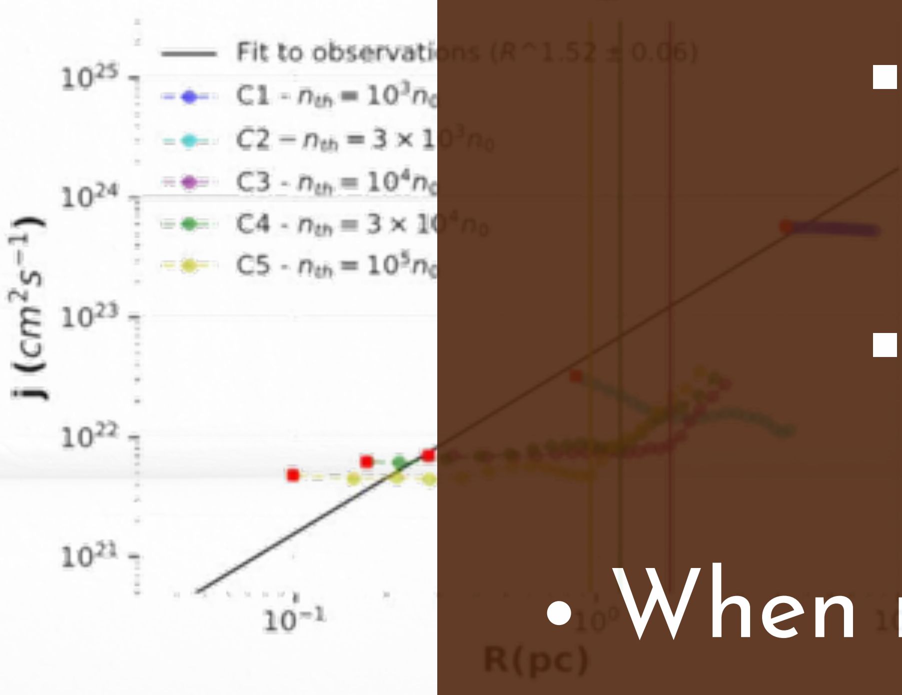
Citation Griselda Arroyo-Chávez and Enrique Vázquez-Semadeni 2022 *ApJ* **925** 78

2 Lagrangian clumps tracked to the future

Conclusions:

- No magnetic field is needed to closely reproduce the observed j-R scaling.
- The AM transfer mechanism is essentially one of fragmentation:
  - A subregion contracts by transferring AM to another. Observed while tracking to the future.
  - The transfer is performed through "intruder particles". Observed while tracking from the past.
- When not enough intruder particles are present, evolution proceeds at nearly constant AM. Observed while tracking from the past.

1 Lagrangian clumps tracked from the past



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future, the innermost regions collapse
particles), while the outer parts disperse
Similar to accretion disks

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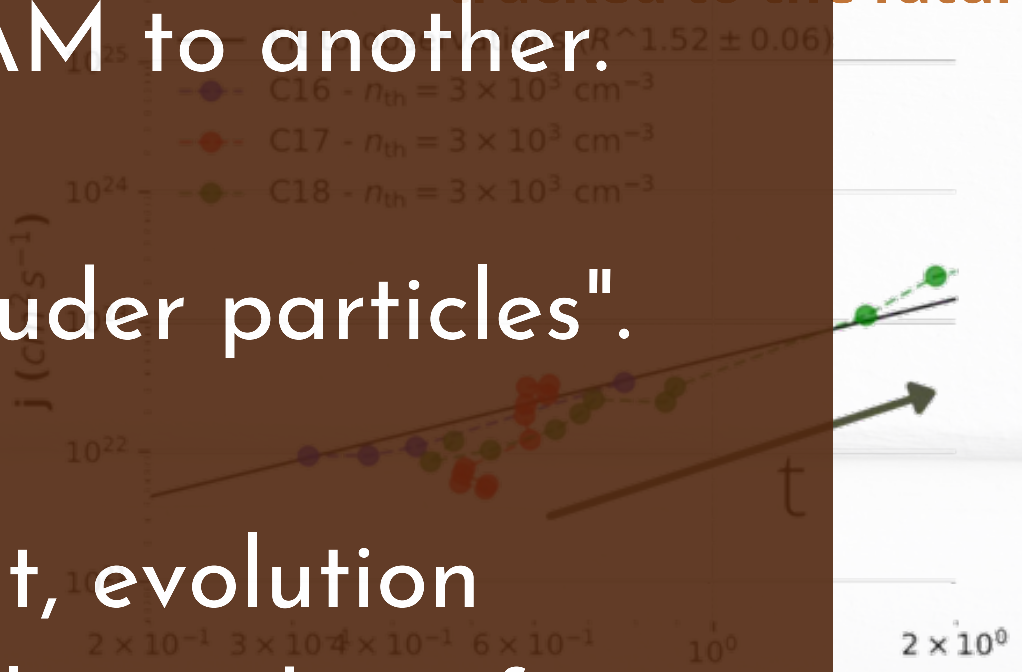
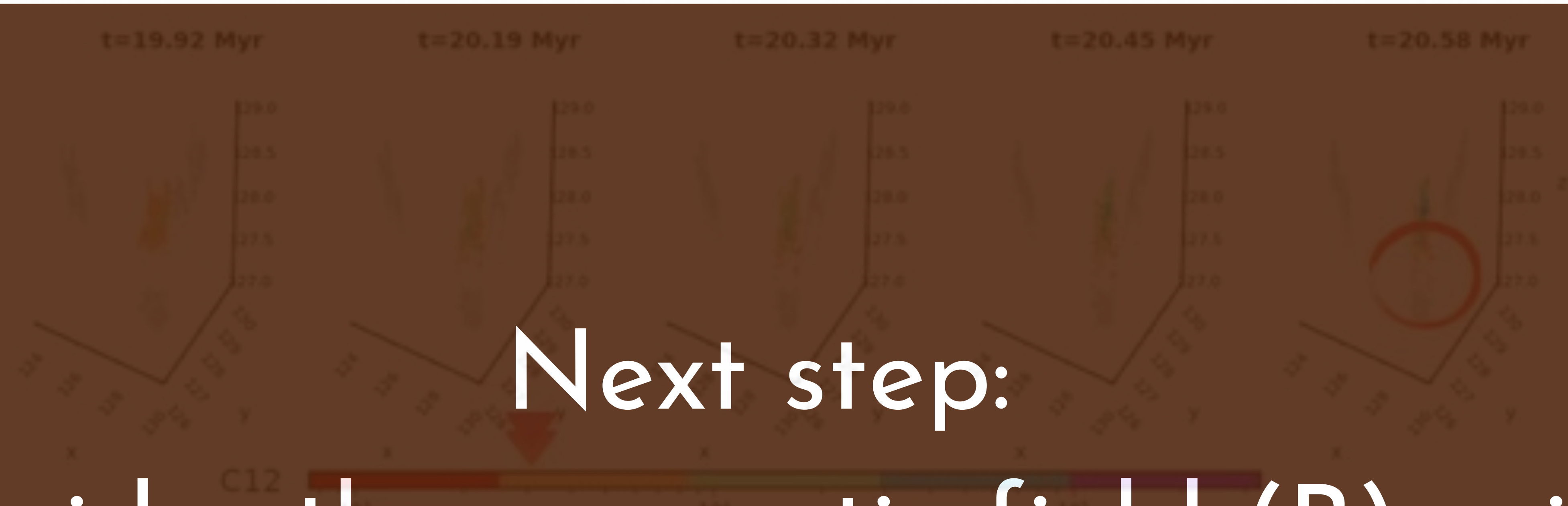
3 ...verdensities tracked to the future



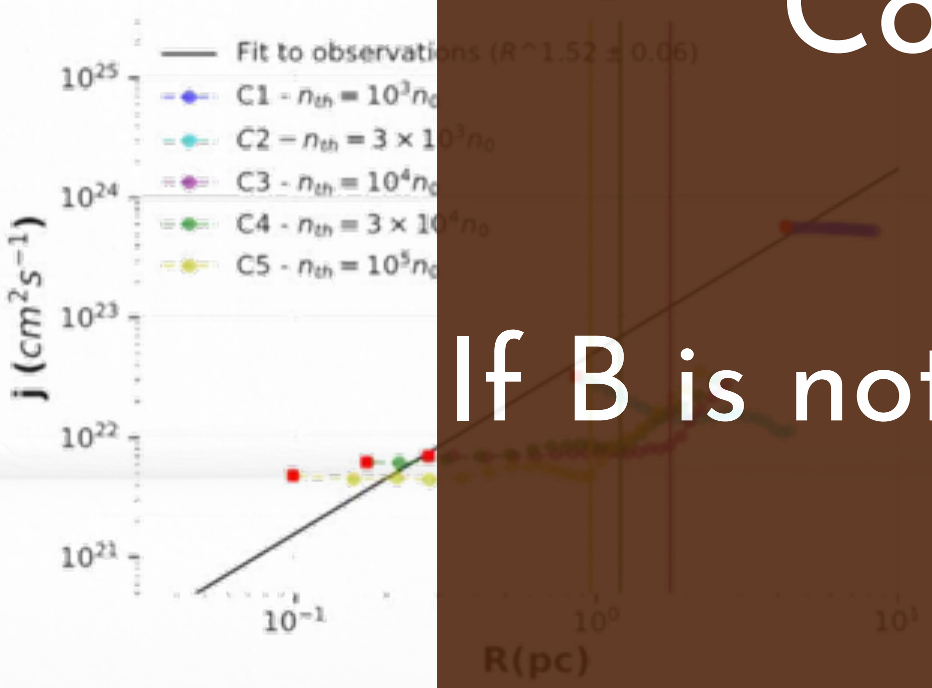
The evolution in both radius and SAM occurs along evolutionary tracks close to the locus of the observational sample in this diagram.

Increase its radius and mass even though it's collapsing!

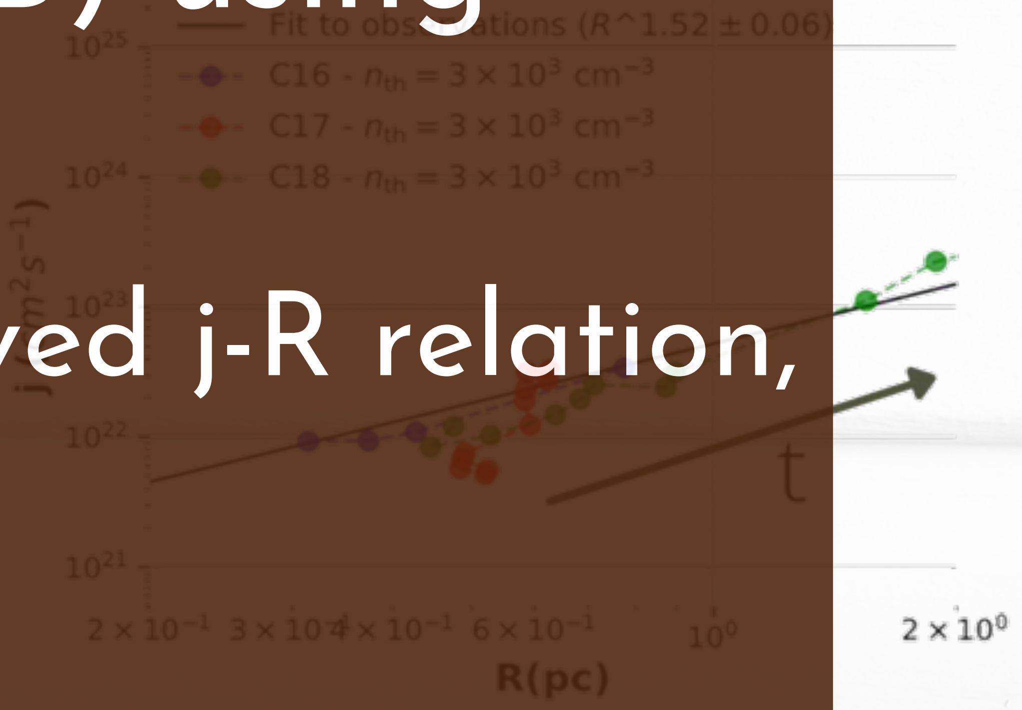
2 Lagrangian clumps tracked to the future



1 Lagrangian clumps tracked from the past



3 Clumps as overdensities tracked to the future



Next step:

Consider the magnetic field (B) using PHANTOM

If B is not necessary to recover the observed j-R relation, what is its role?

Lagrangian sets followed from the past present two periods: an early one, in which the clumps evolve along the locus of the observational j-R diagram and a late one, in which they evolve with j ~ cst. during the contraction.

OPEN ACCESS

Evolution of the Angular Momentum during Gravitational Fragmentation of Molecular Clouds

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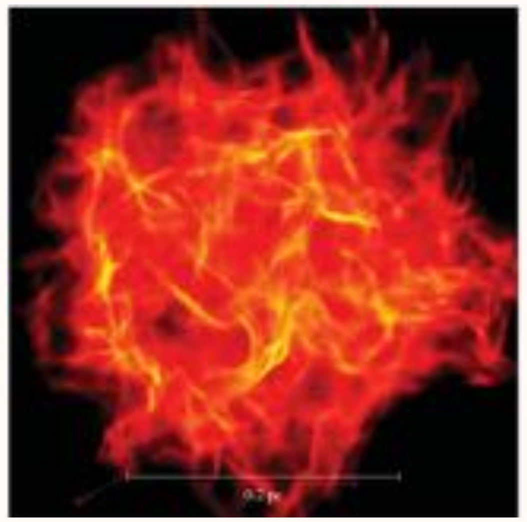
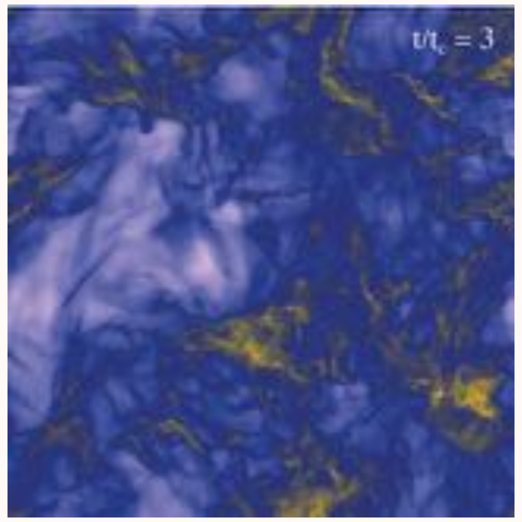
The evolution in both radius and SAM occurs along evolutionary tracks close to the locus of the observational sample in this diagram.
Increase its radius and mass even though it's collapsing!

We combine setups

Cluster formation

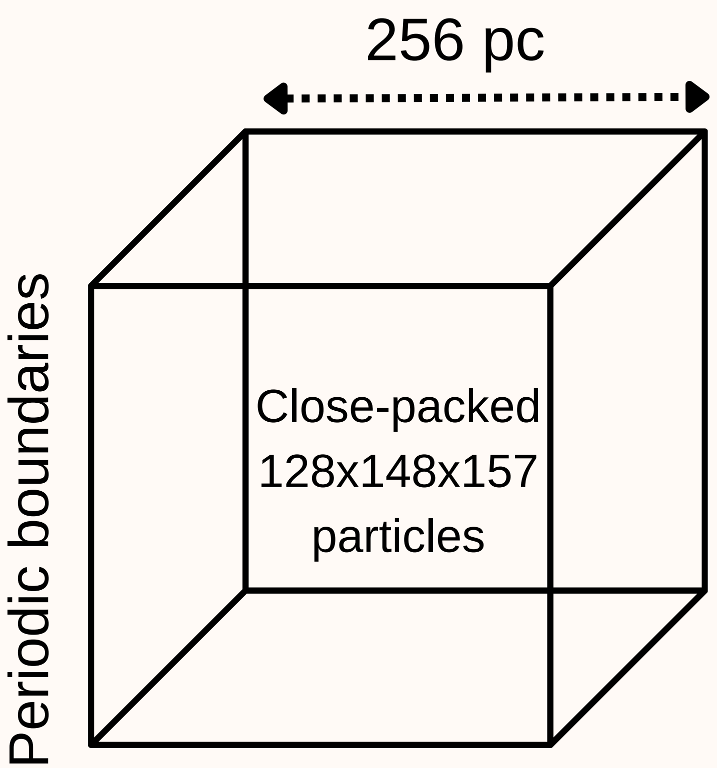


Turbulence



(Price et al., 2018)

To create two simulations with the following features:

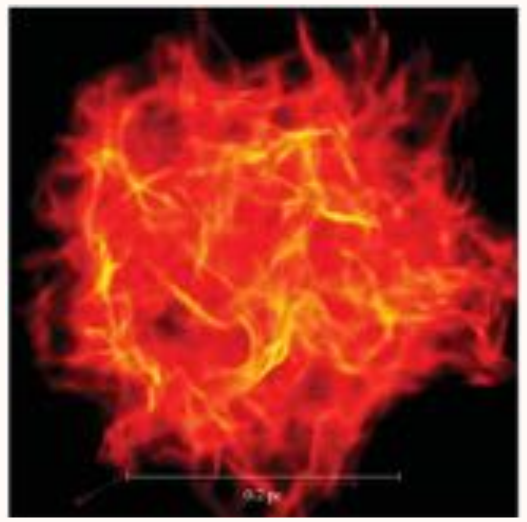


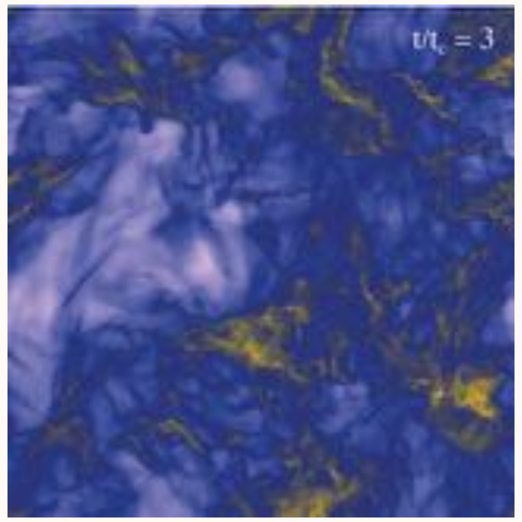
- Initial density and temperature set a 2 cm^{-3} and 1450 K [T_{eq} (n = 2 cm^{-3})]
- Density threshold to form sinks: 4.7x10^{5} cm^{-3}
- Includes selfgravity, cooling and difusse heating processes (Implicit Koyama & Inutsuka 2002)
- Initial default forcing of the *cluster formation* setup with σ ≈ 12 km/s at t=0
- With and without uniform magnetic field of 3 μG

3. Simulations with PHANTOM

We combine setups

Cluster formation | *Turbulence*





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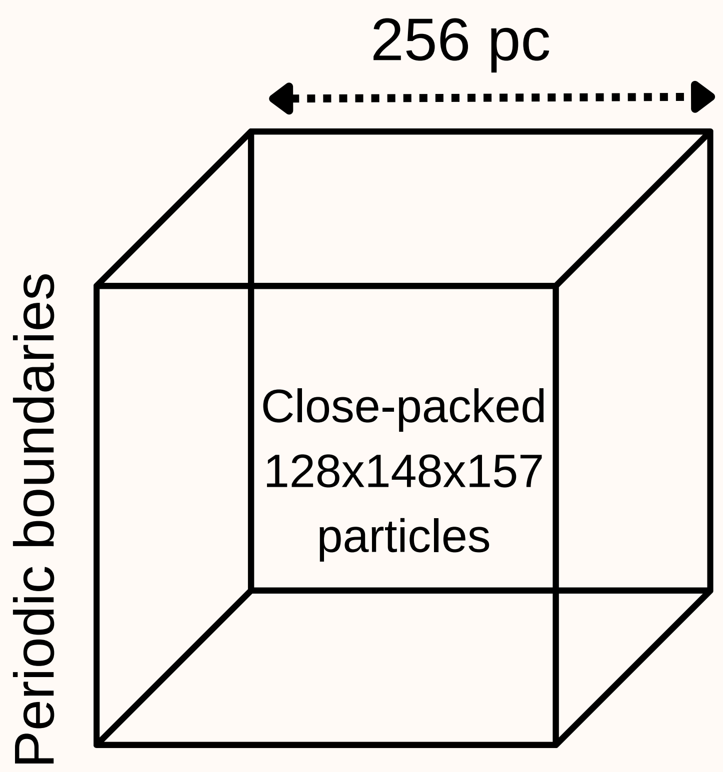

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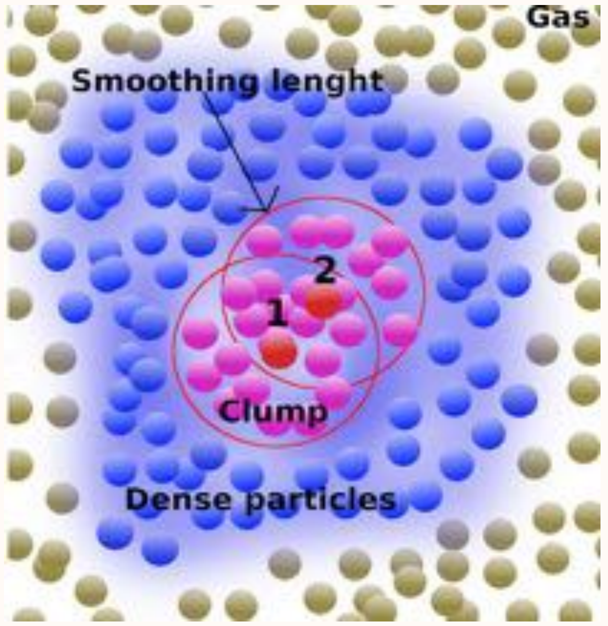
For the analysis of the outputs we use

PLONK

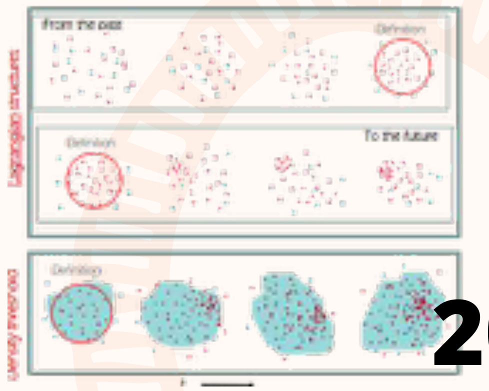
To generate a sample of simulated clumps



External SPH clump finding algorithm

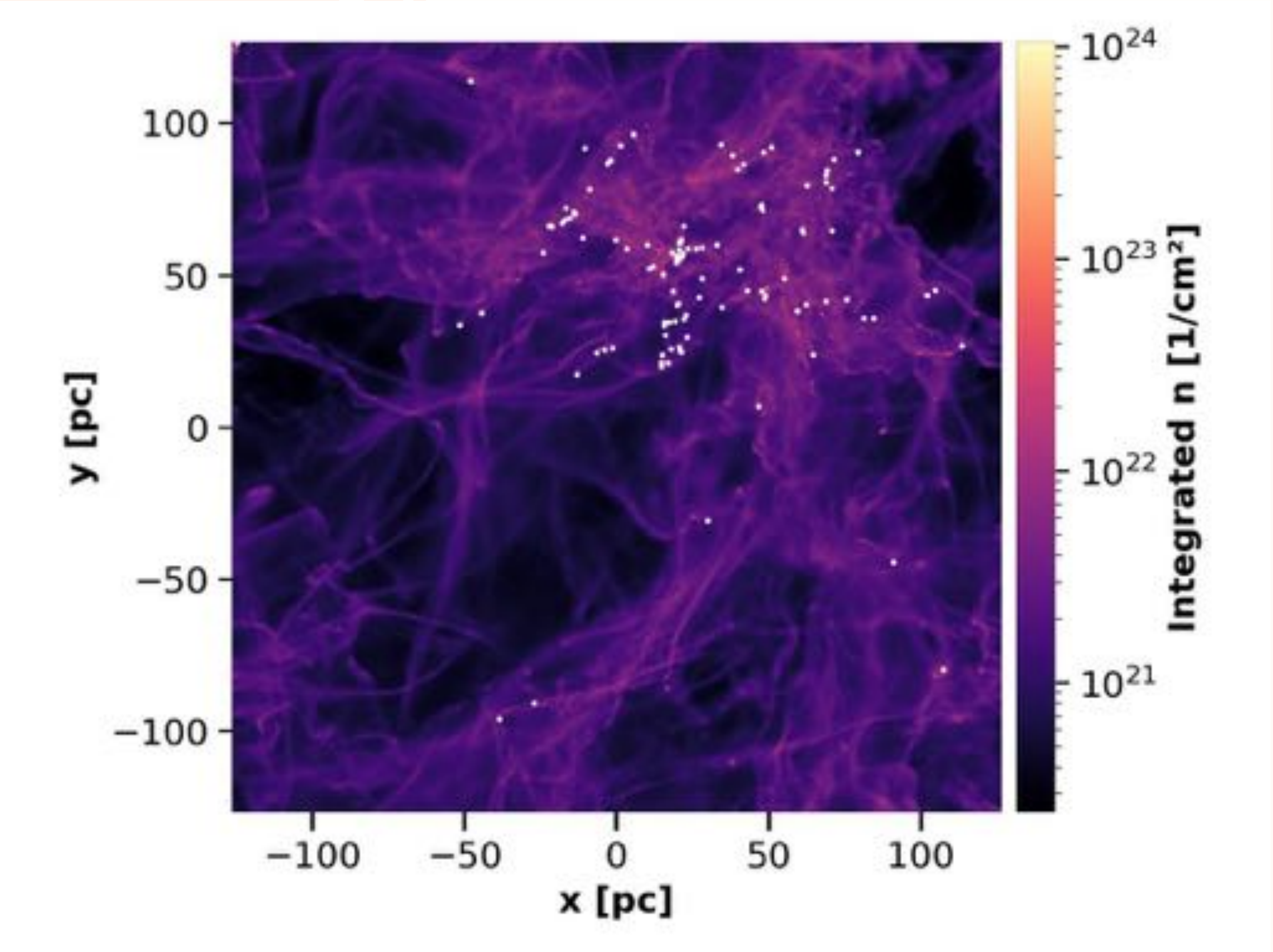
(Camacho+16)

Same methodology as in our previous work

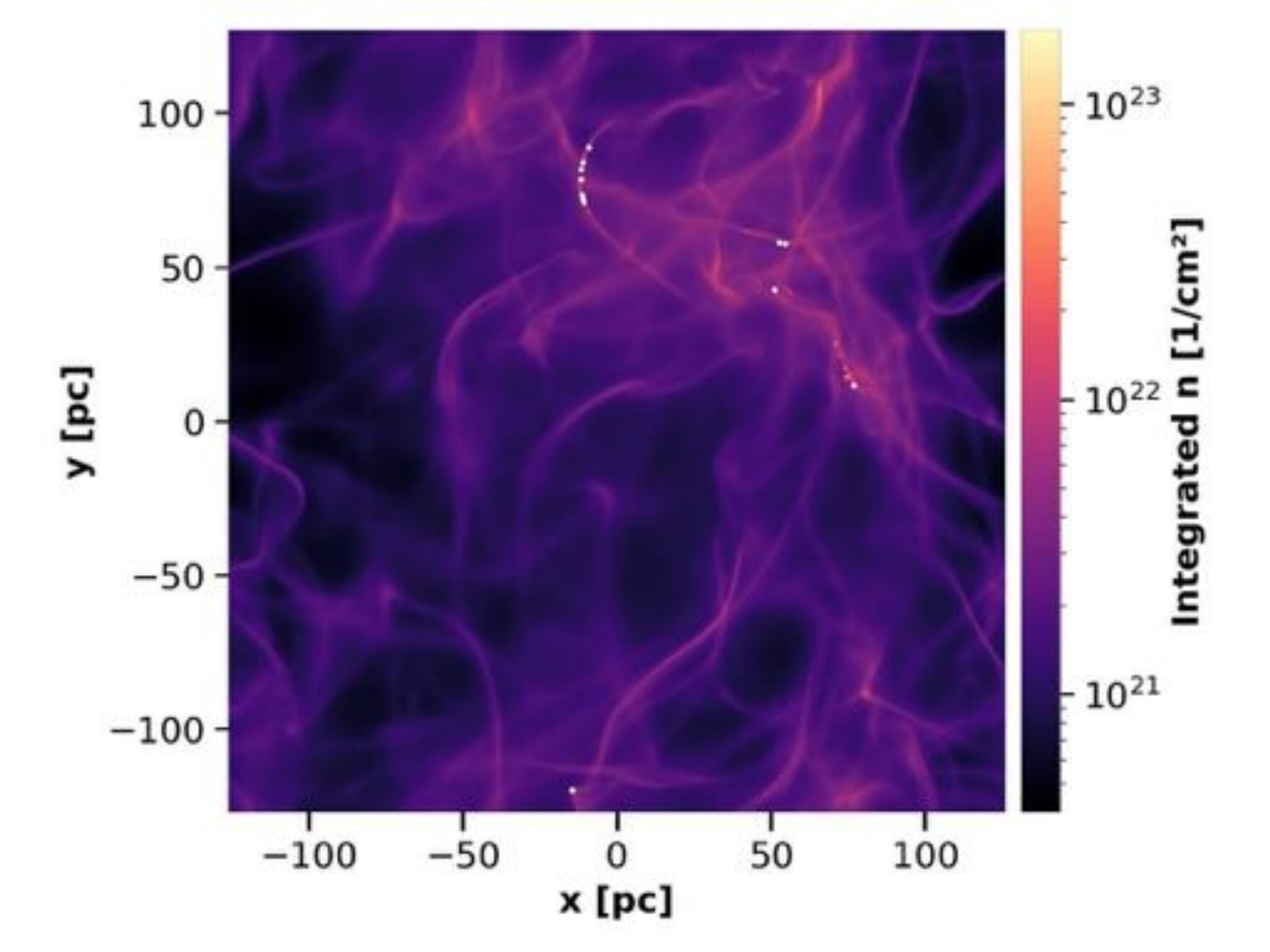


3. Simulations with PHANTOM

Hydro



Magnetic

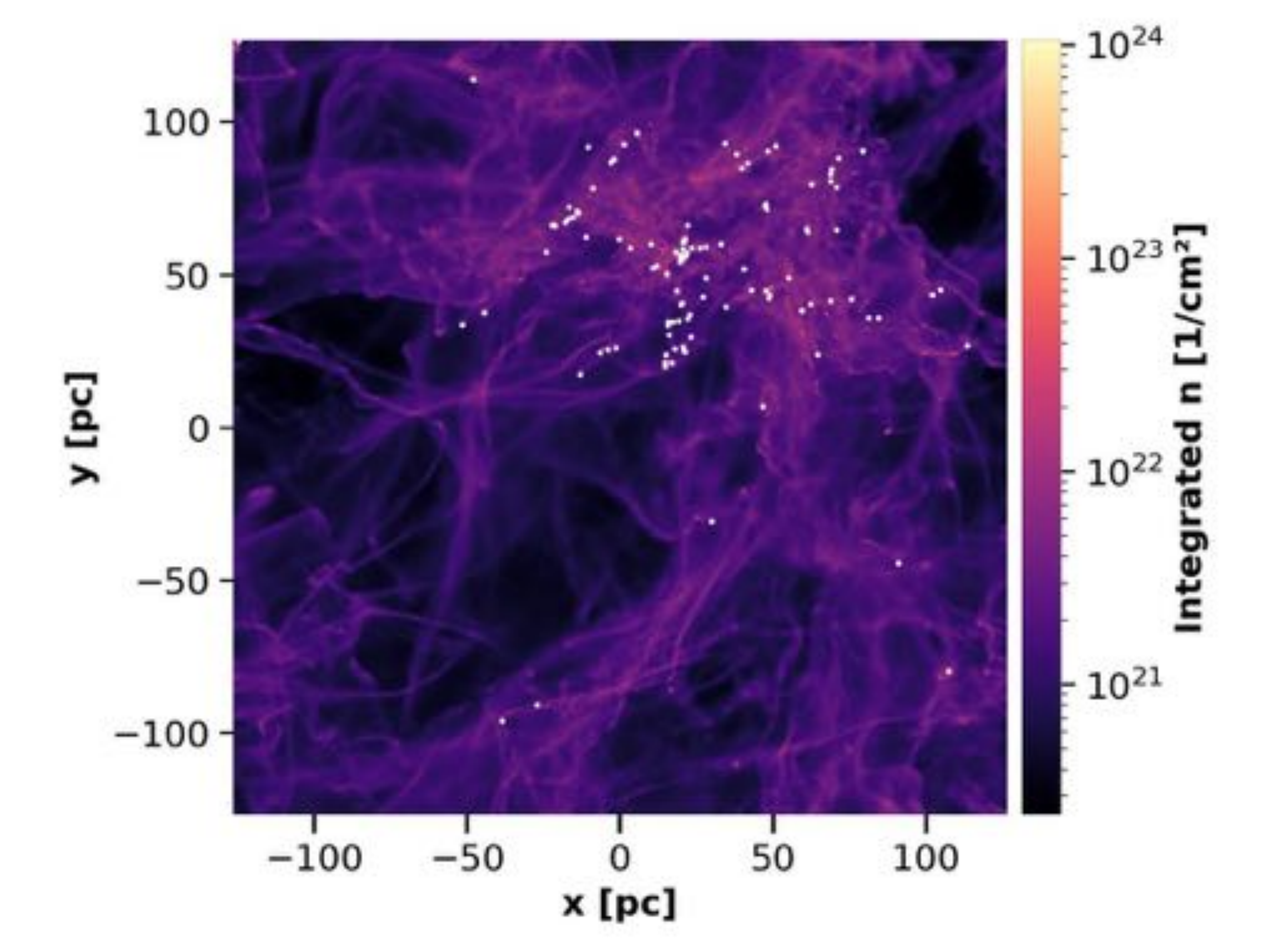


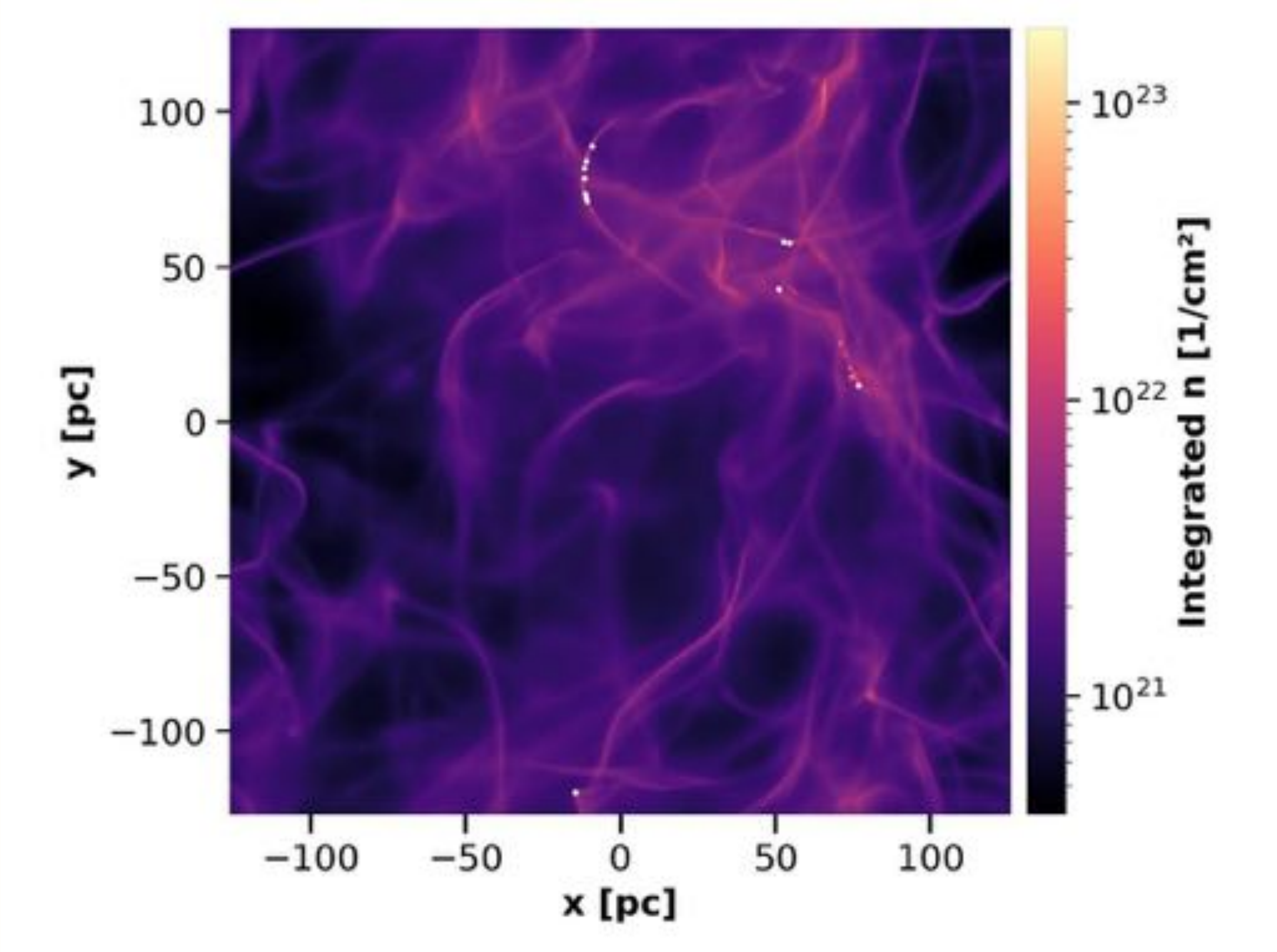
t ~ 10 Myr

4. Preliminary results with PHANTOM

Hydro

Magnetic





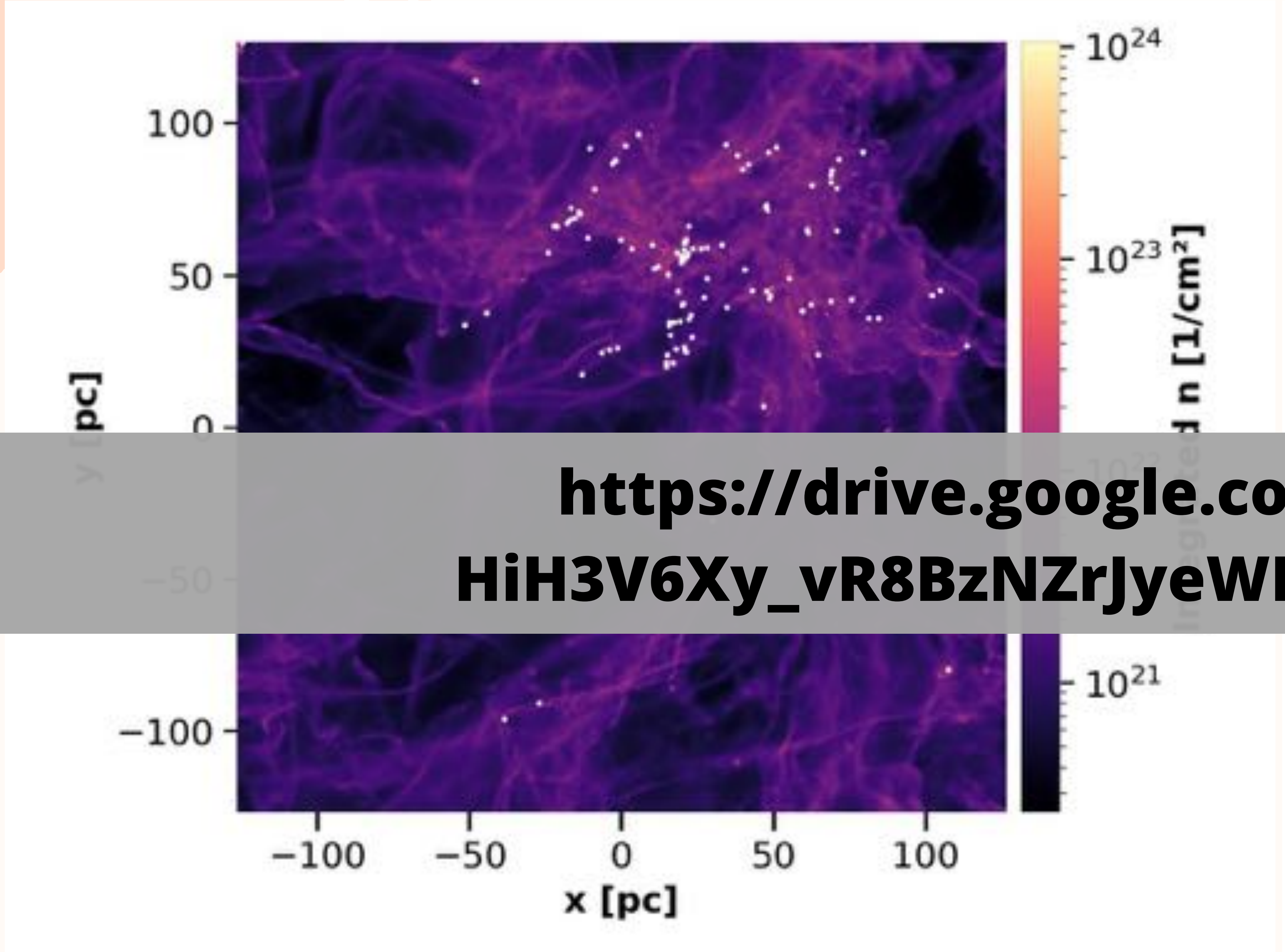
t ~ 10 Myr

- **More fragmented**
- **Large sink formation rate**

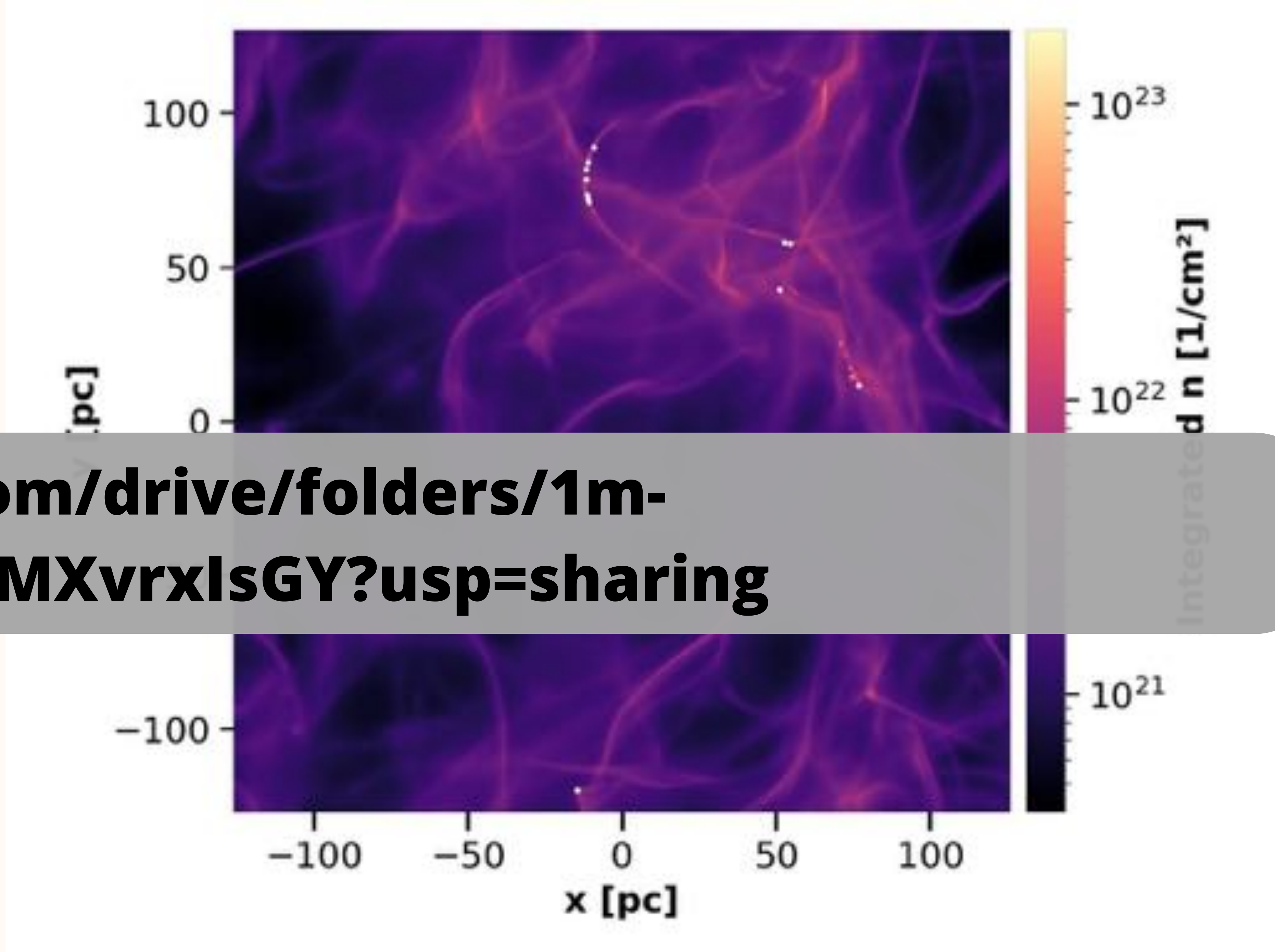
- **More filamentary structures**
- **Low sink formation rate**

4. Preliminary results with PHANTOM

Hydro



Magnetic



https://drive.google.com/drive/folders/1m-HiH3V6Xy_vR8BzNZrJyeWMXvrxIsGY?usp=sharing

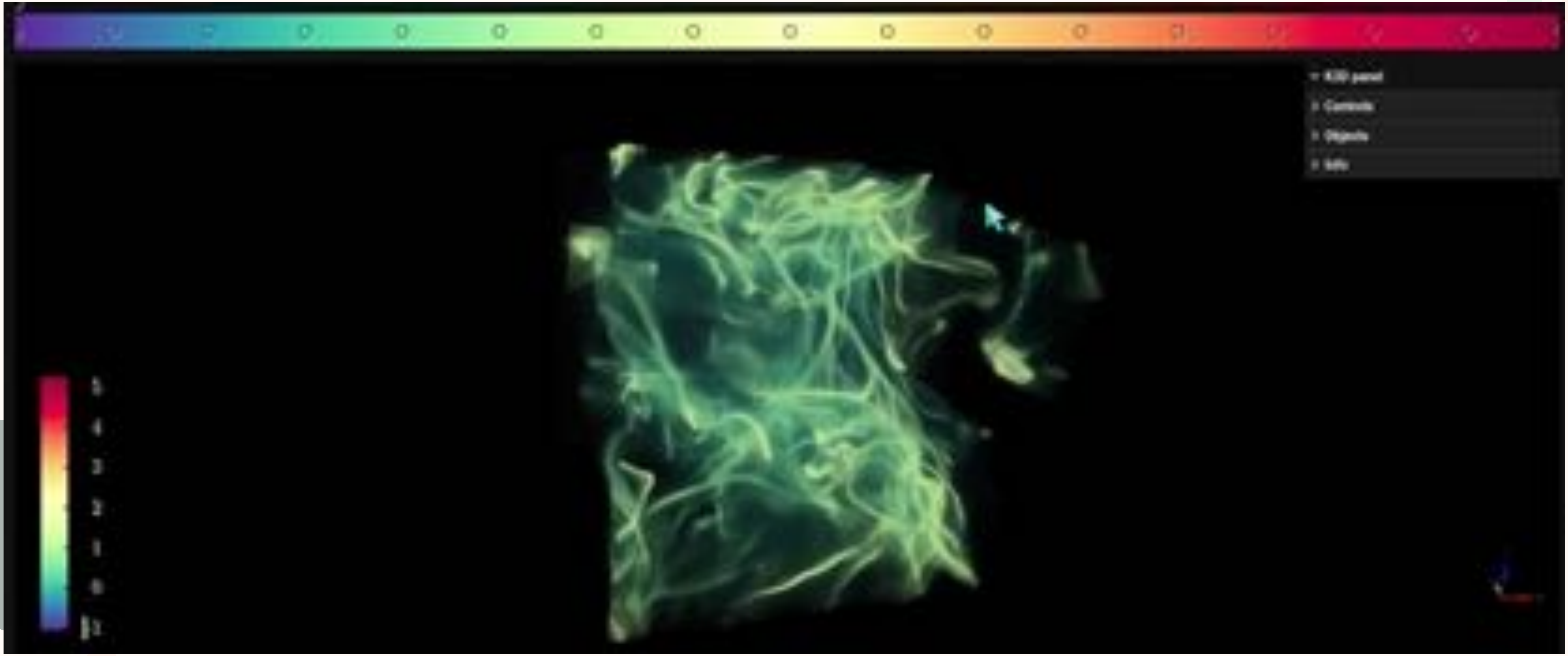
t ~ 10 Myr

- More fragmented
- Large sink formation rate

- More filamentary structures
- Low sink formation rate

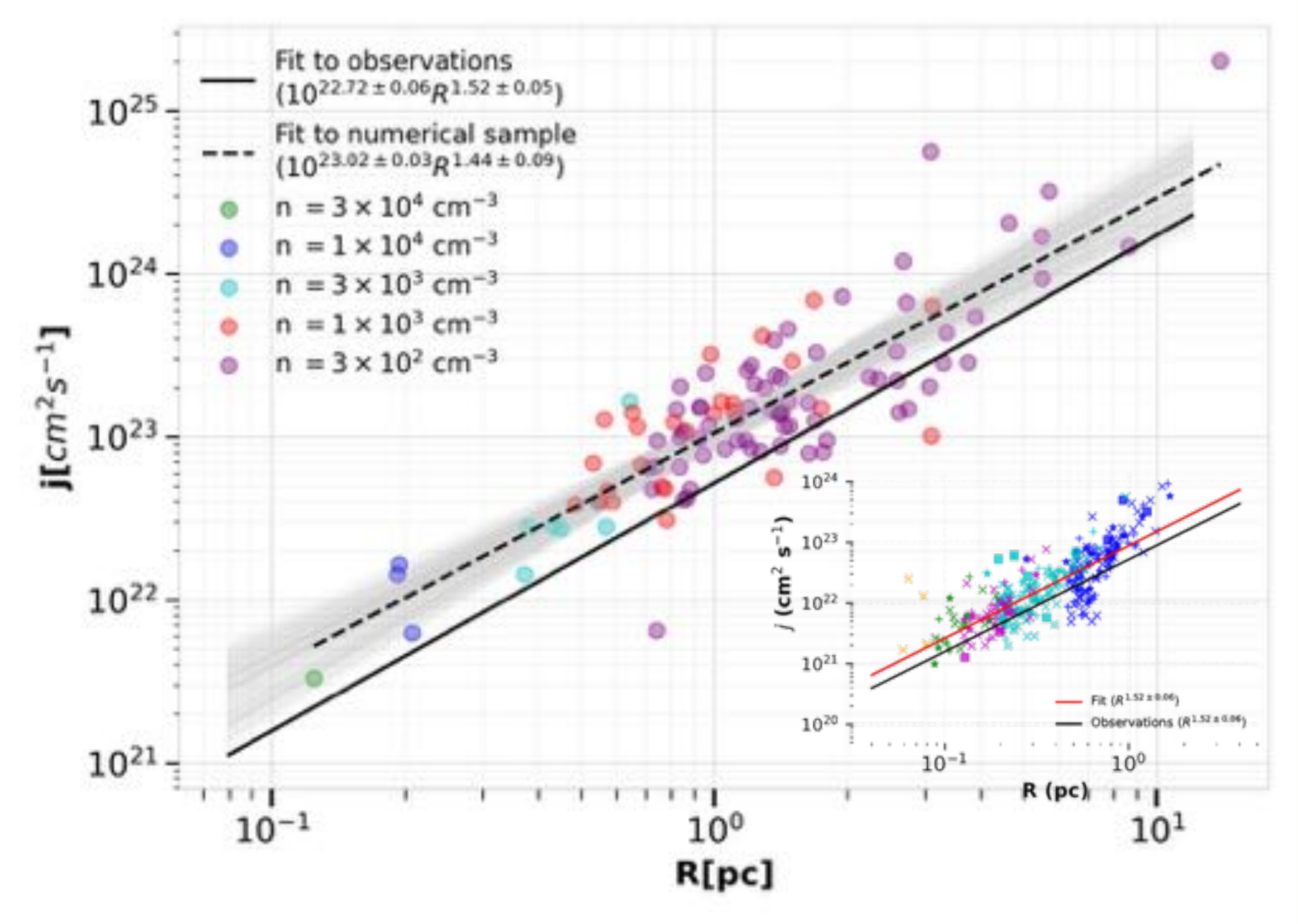
4. Preliminary results with PHANTOM

3D visualization with K3D

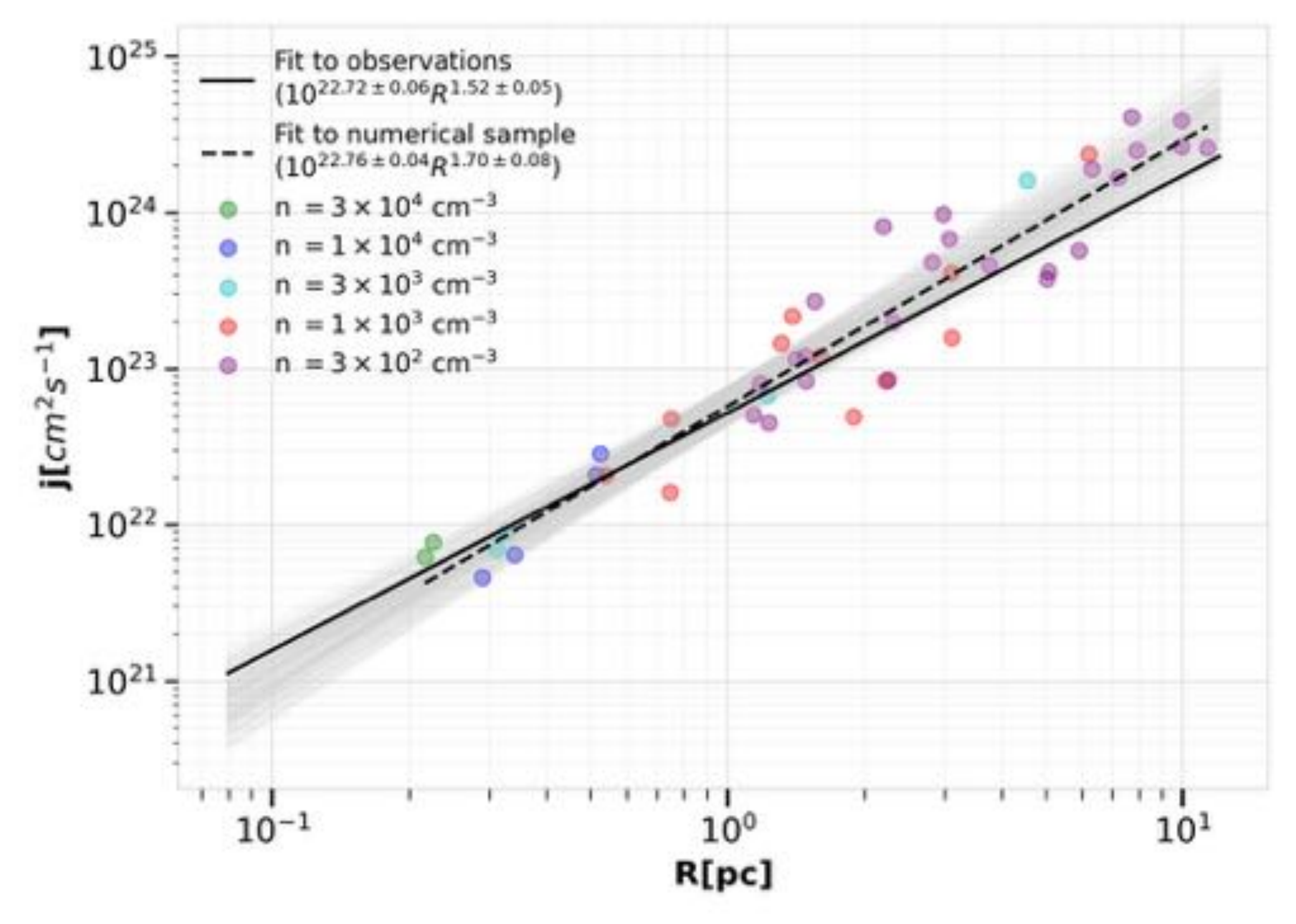


Video at https://drive.google.com/drive/folders/1m-HiH3V6Xy_vR8BzNZrJyeWMXvrxIsGY?usp=sharing

The j-R relation



Hydro

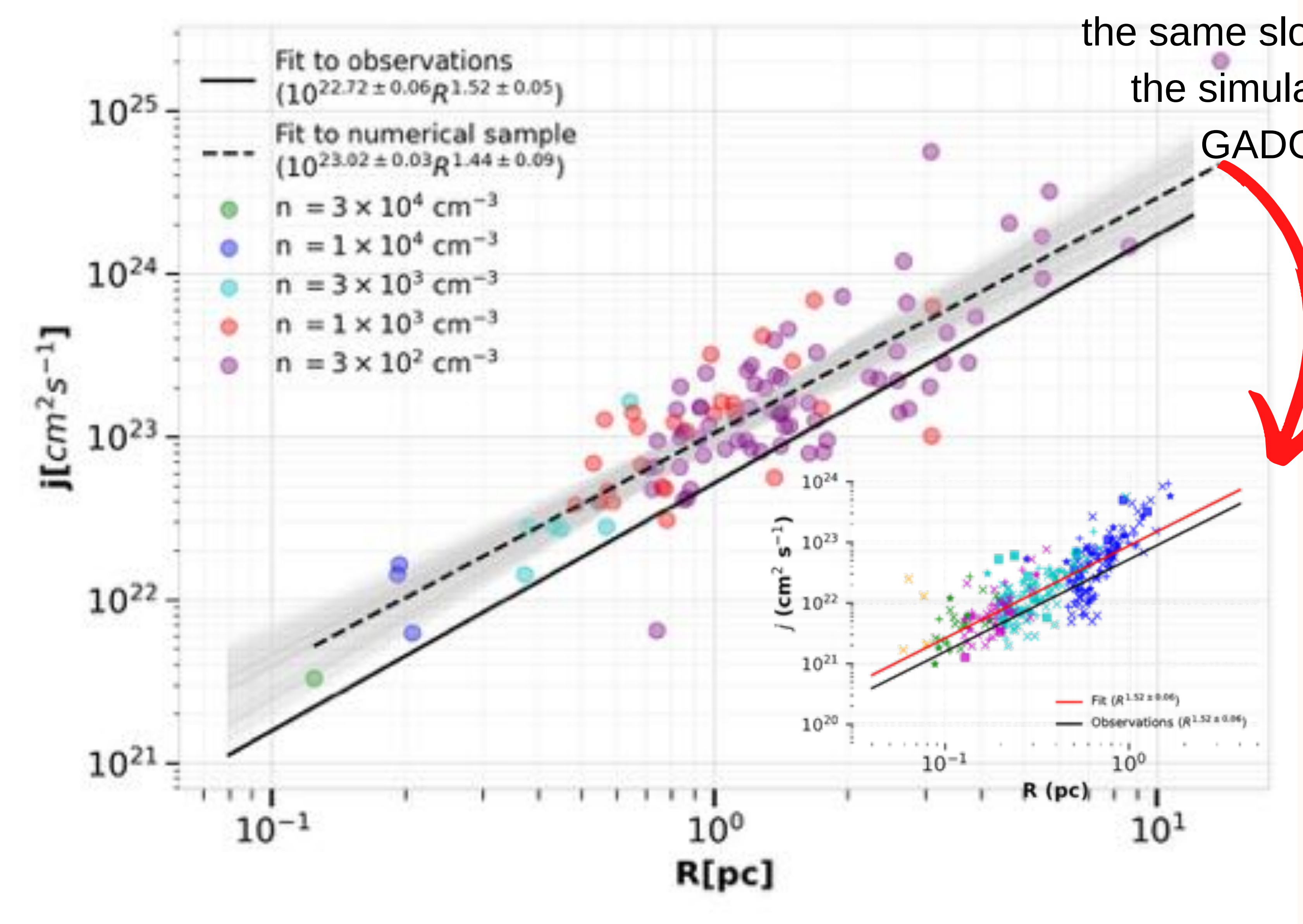


Magnetic

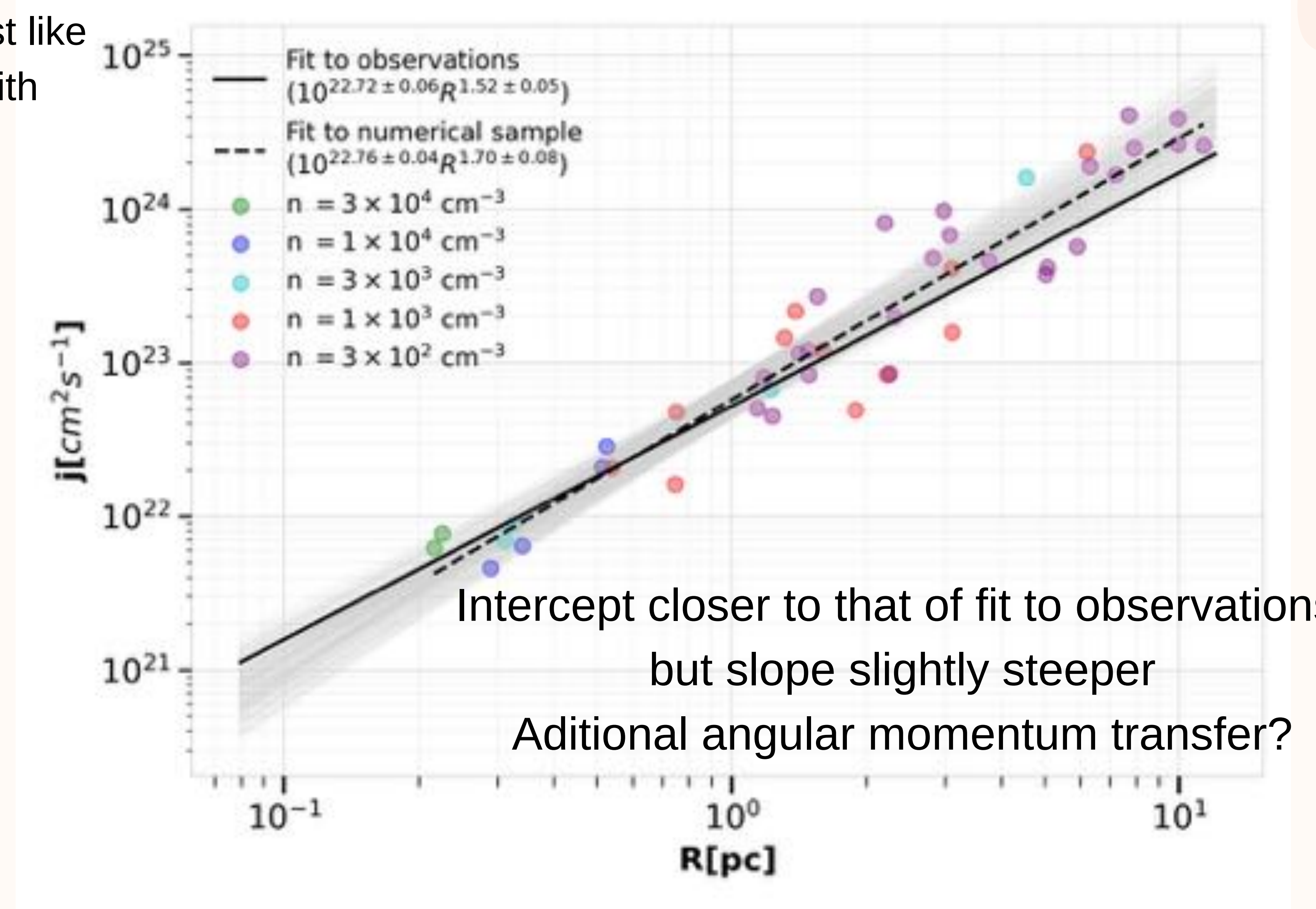
4. Preliminary results with PHANTOM

The j-R relation

Hydro simulation tends to be slightly above the observed relation but with the same slope, just like the simulation with GADGET2



Hydro



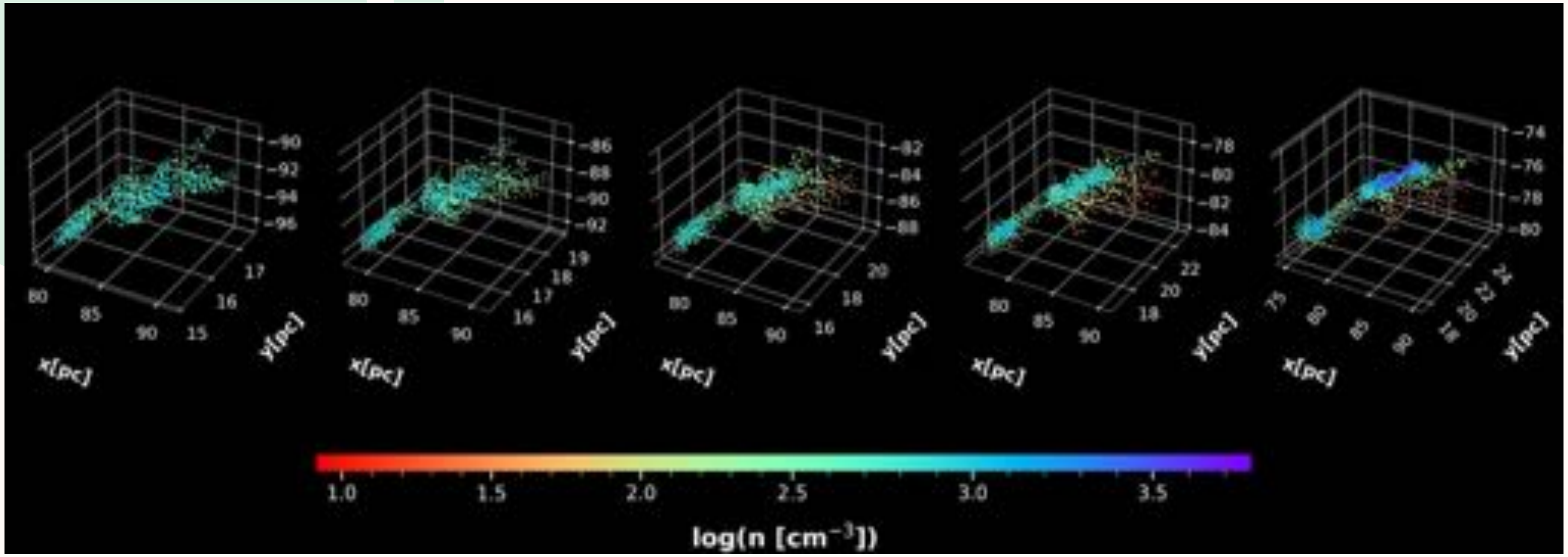
Intercept closer to that of fit to observations, but slope slightly steeper
Aditional angular momentum transfer?

Magnetic

Both reproduce the observed j-R relation

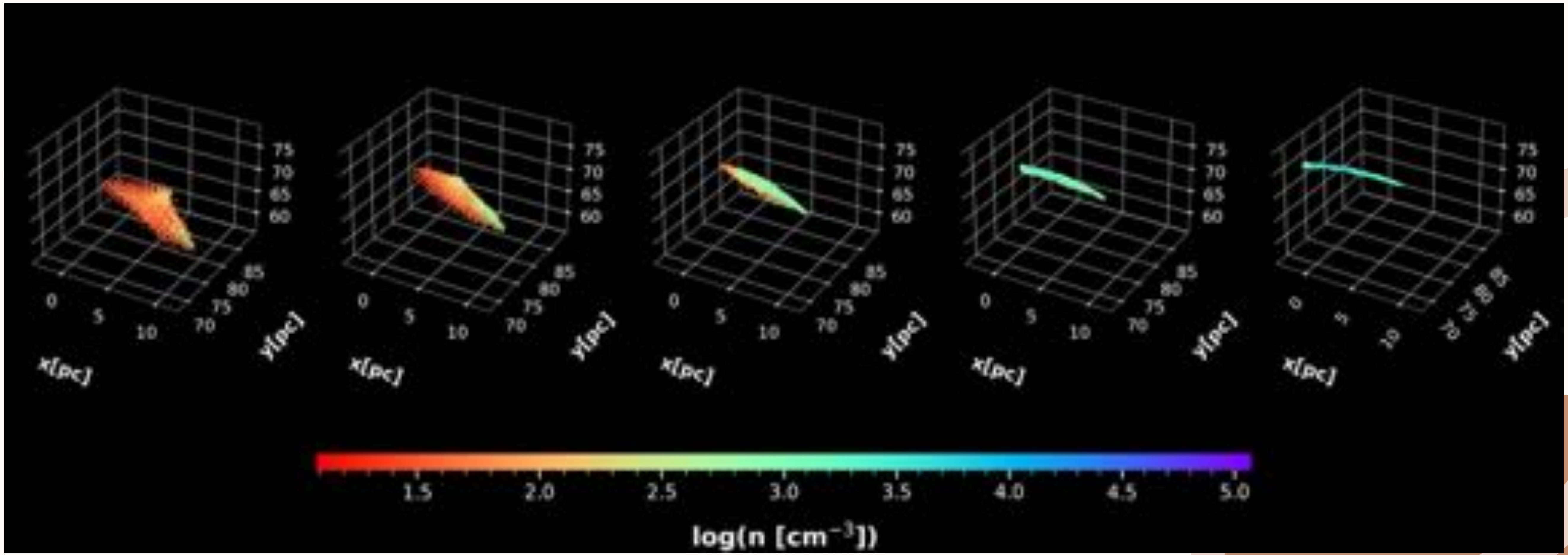
4. Preliminary results with PHANTOM

Tracking to the future



In Lagrangian particle sets tracked **to the future** we recover the same behavior in both simulations: the innermost regions collapse and form sinks while the outer parts disperse

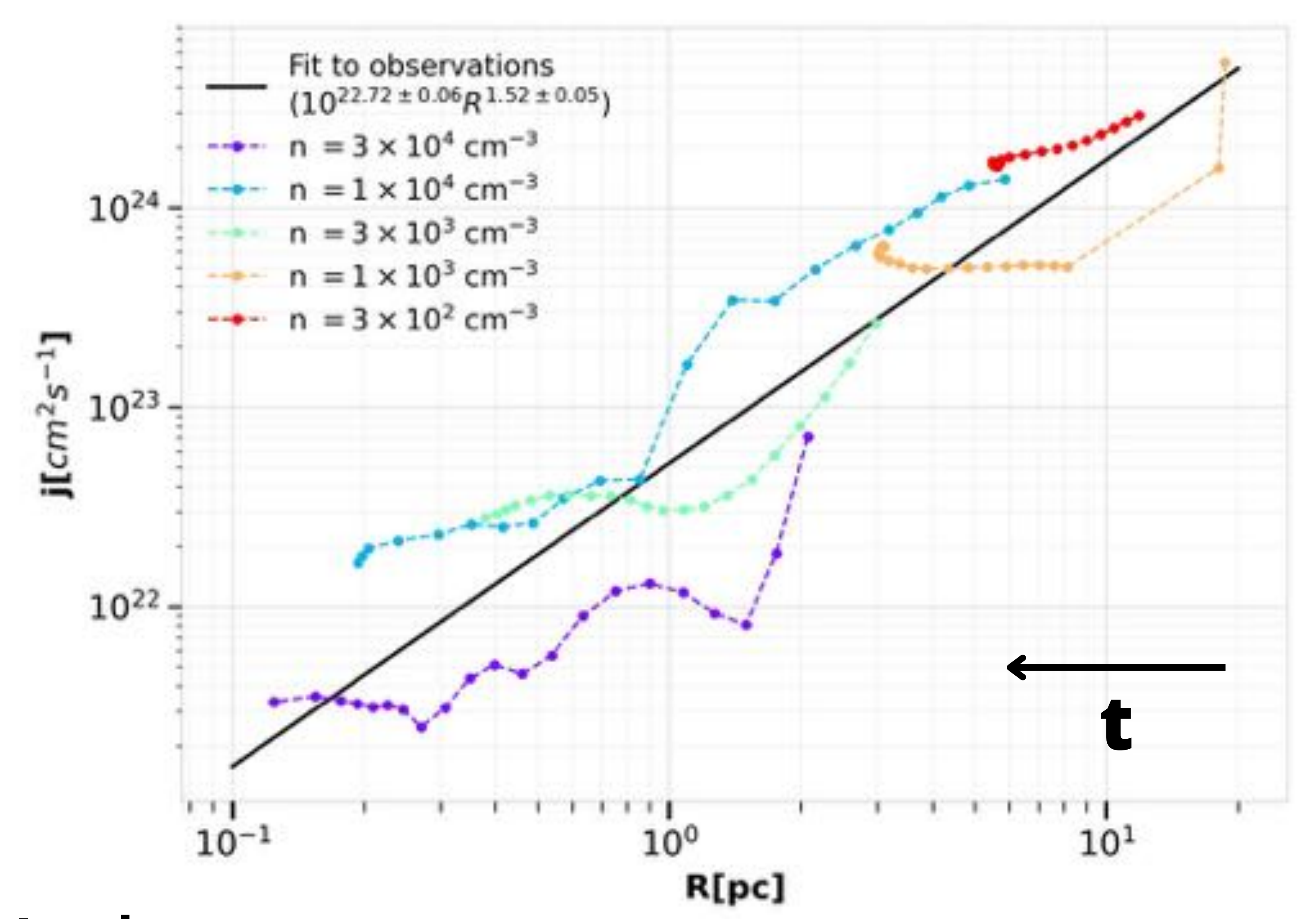
Tracking from the past



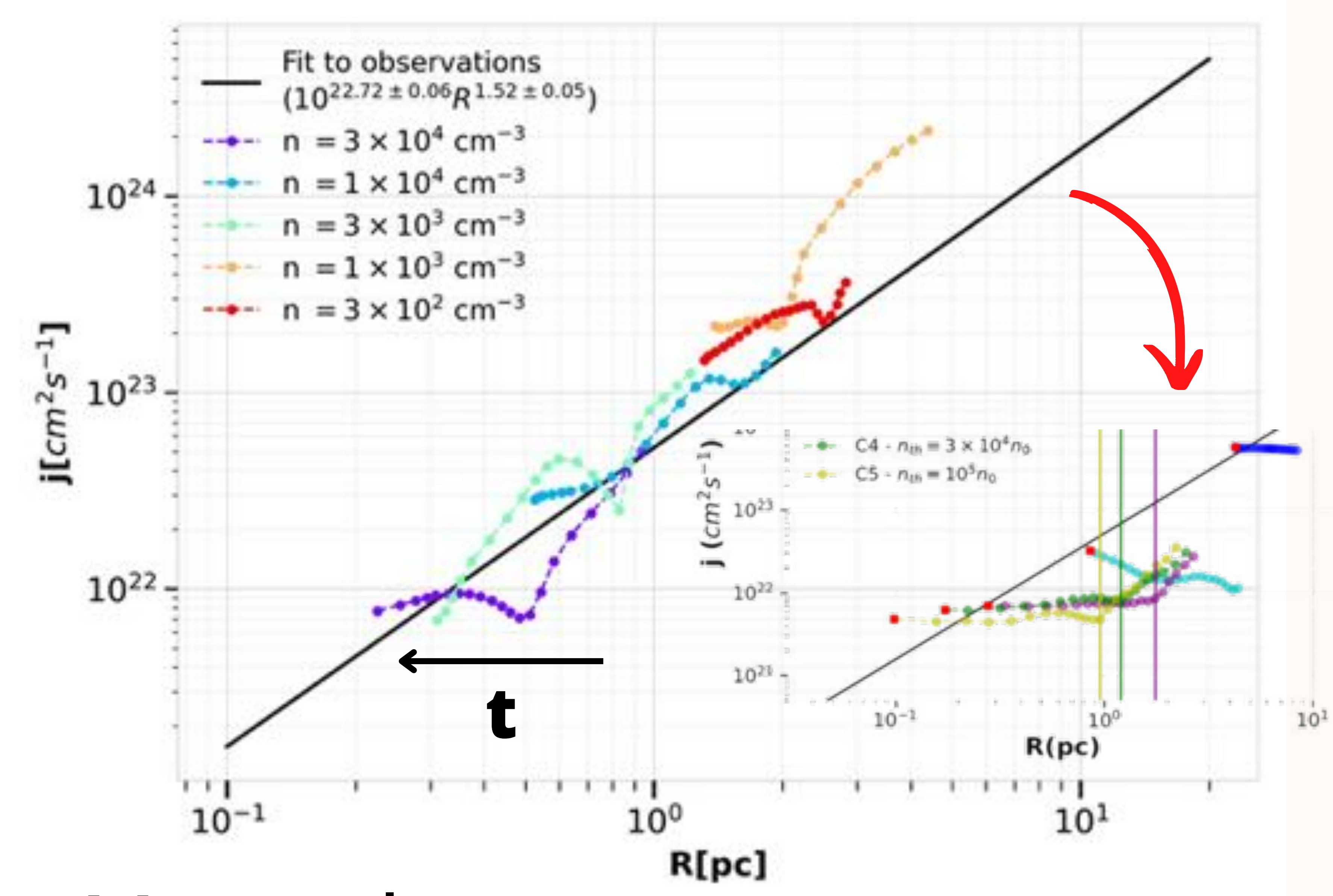
In Lagrangian particle sets tracked **from the past** we see how the clump is assembled. Clumps become much more filamentary in the magnetic simulation

4. Preliminary results with PHANTOM

Tracking from the past in the j-R plot



Hydro

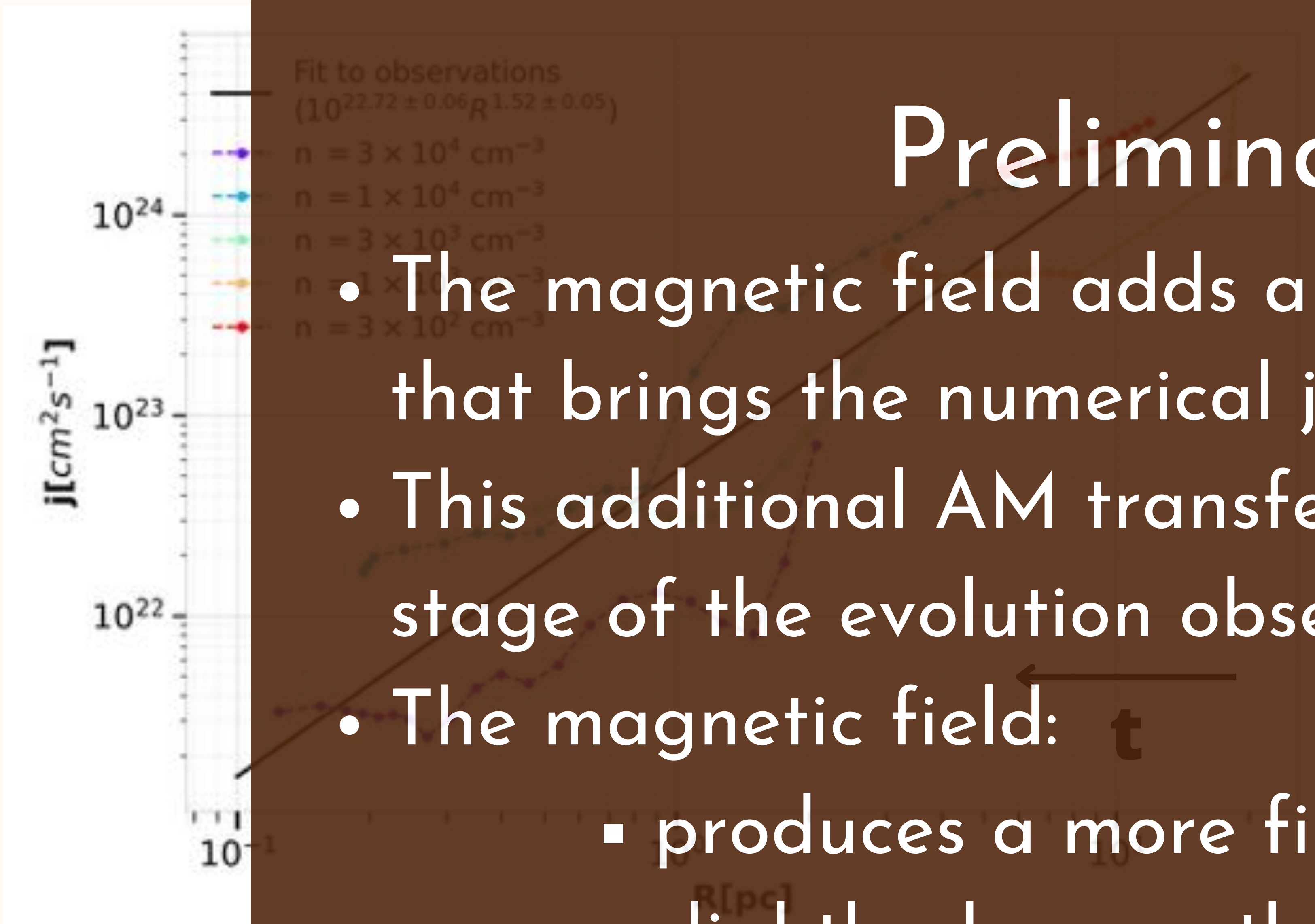


Magnetic

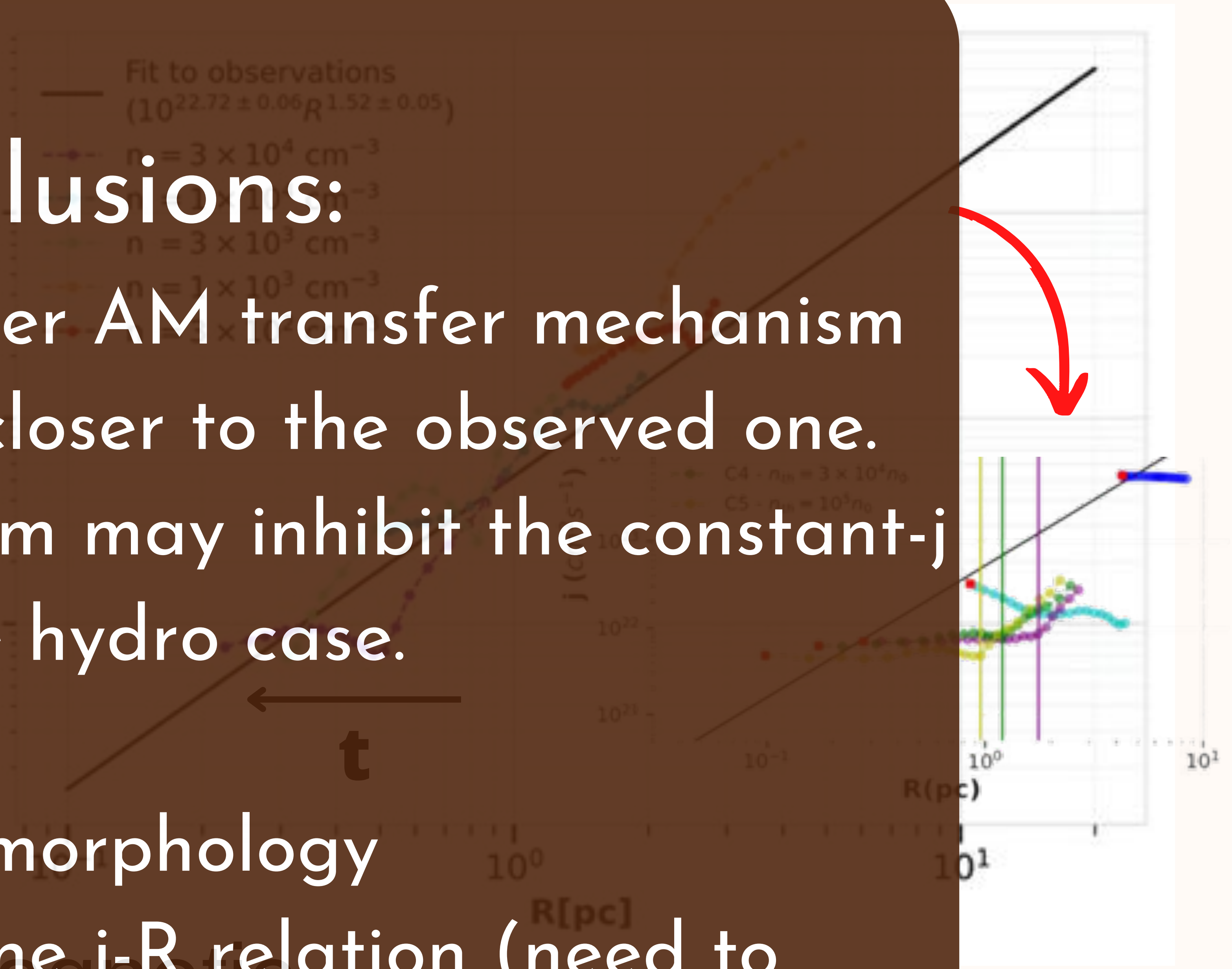
- **The behavior of the clumps in the hydro simulation is not entirely clear, so we will carry out a statistical study to study the general trend.**

- **The densest fragments seem to reproduce the break in the j-R plot**
- **But the trend is a continued loss of j in contrast to our previous study without magnetic field.**

Tracking from the past in the j-R plot



Hydro



Magnetic

Preliminary conclusions:

- The magnetic field adds a second-order AM transfer mechanism that brings the numerical j-R scaling closer to the observed one.
- This additional AM transfer mechanism may inhibit the constant-j stage of the evolution observed in the hydro case.
- The magnetic field:
  - produces a more filamentary morphology
  - slightly changes the slope of the j-R relation (need to verify)

- The behavior of the clumps in the hydro simulation is not entirely clear, so we will carry out a statistical study to study the general trend.

- The densest fragments seem to reproduce the break in the j-R plot
- But the trend is a continued loss of j in contrast to our previous study without magnetic field.

What's next?

Measure torques directly in the simulation.
Are turbulent viscosity torques important?

Thanks!

Radiative HII region-like feedback and synthetic observations

What I would like to learn here

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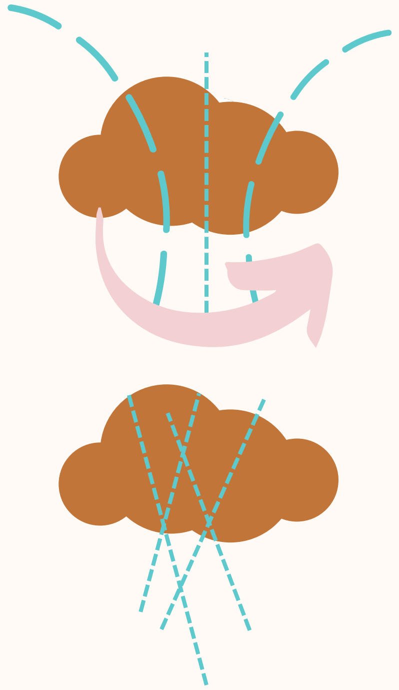
Angular Momentum Problem (AMP)

- What is it?
- How does it look?
- Are there solutions?

Problems

Magnetic braking



- May be excessive (Magnetic braking catastrophe; Allen et al. 2003b)
- j-R scaling appears also in non-magnetic simulations (Jappsen & Klessen 2004)

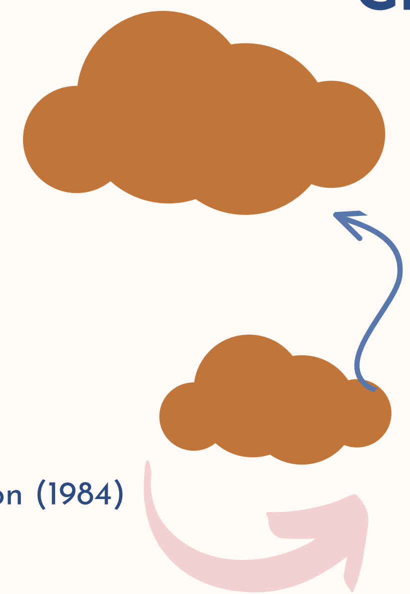
Gillis et al (1974,1979) Mouschovias & Paleologou (1979,1980)

Turbulent viscosity

- Larson (1984) argued that no known sources of turbulence for MCs exist.

Larson (1984)

Gravitational torques



Larson (1984)

- Conclusion generally reached by ***eliminating other possibilities***, not by direct measurements. [Larson(1984),Kuznetsova et al.(2019)]
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