Simulation and Observational Data Analysis for Understanding the Structural Evolution of Molucular Cloud

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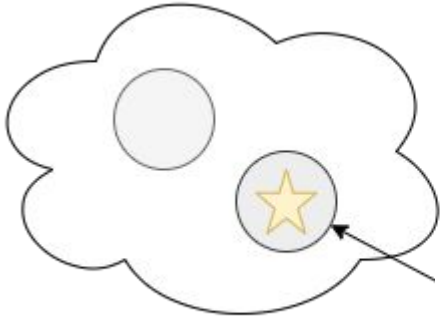
Agenda:

1. Introduction
2. Simulation data analysis
3. Observation data analysis
4. Discussion
5. Summary

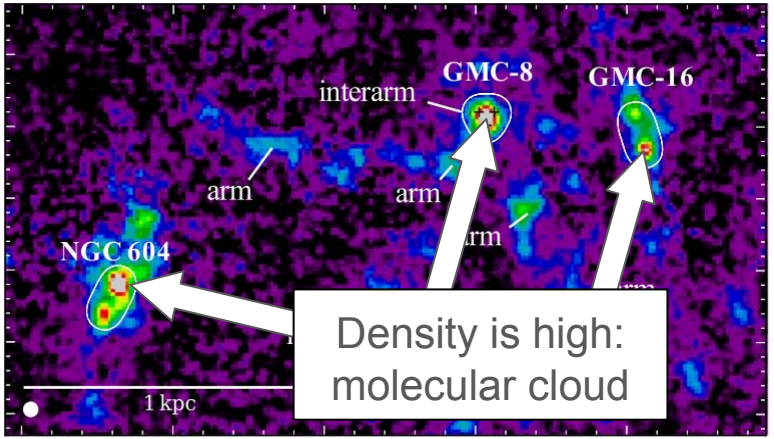
Introduction: molecular cloud and star formation

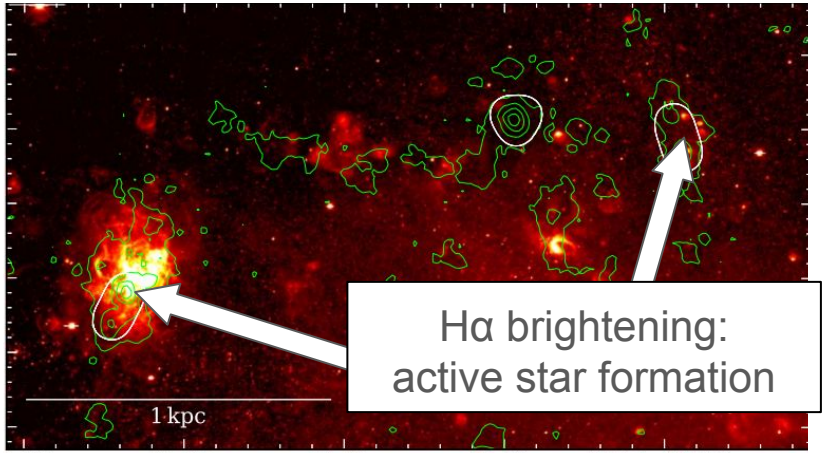
Star formation occurs in molecular clouds of dense interstellar gas, but evolutionary process of the structure of molecular clouds leading to star formation is unknown.



molecular cloud

core: unstable and star formation occurs





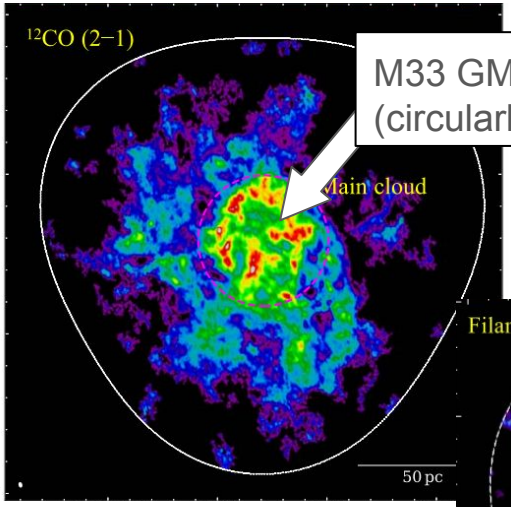
Based on Kondo+2021

Introduction: star formation research methods

- Observations: Comparison of multiple molecular cloud structures to assess relative evolutionary stages, but it is difficult to understand time evolution of structure from single molecular cloud data.

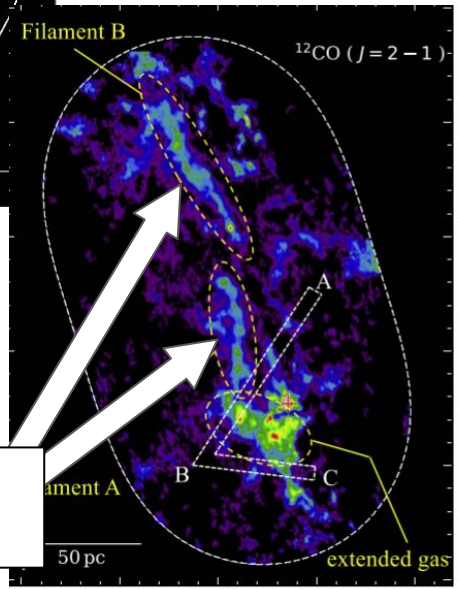
- Simulation: Various fluid models can be used to study star formation mechanisms to reproduce observational data.

→ **By analyzing the time evolution of self-gravity fluid in simulations that reproduce observations, it is easy to study the time evolution of structure of molecular clouds.**



M33 GMC-8
(circularly spread structure)

Based on Kondo+2021



M33 GMC-16
(filamented)

Based on Tokuda+2020

Introduction: aims

Analyze self-gravity hydrodynamic simulations and compare with observations for a detailed understanding of molecular cloud evolution

- Perform hydrodynamic simulations and focus on the structural changes of the fluid due to time evolution

- Apply structural analysis methods used in observations to simulations

→ **It is easy to compare simulation data with observation data**

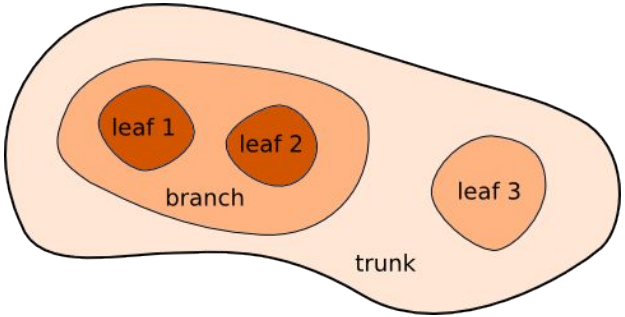
- Perform the same analysis on observed data and compare with simulation results

- Consider the evolutionary scenario of molecular clouds from the results obtained

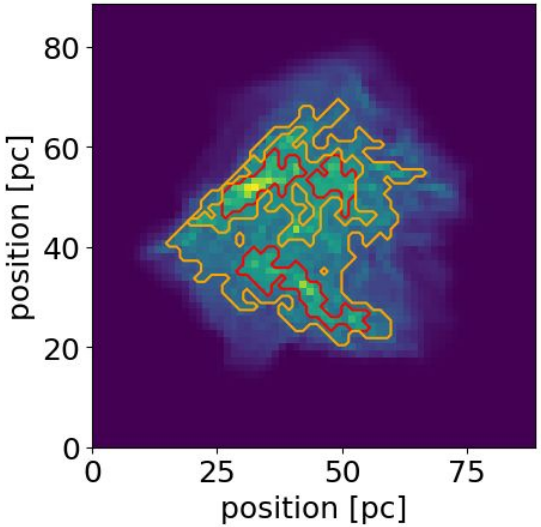
Introduction: analysis method

We use Dendrogram for my analysis: an algorithm for classifying hierarchical structures in multidimensional data sets.

- Minimal structure with no internal structure: leaf
- Structure encompassing the internal structure: branch
- Outermost structure: trunk



Apply structural analysis methods used in observations to simulations
→ **It is easy to compare simulation data with observation data**



For both simulated and observed data, the structure is obtained by performing a dendrogram on the integral intensity diagram.

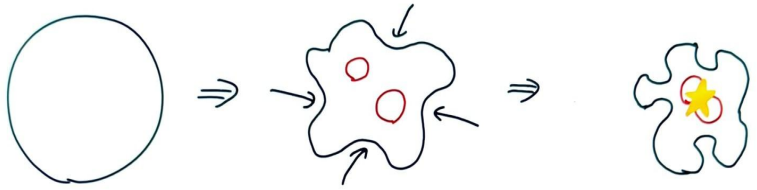
Find and discuss the size, mass, etc. of the structure.

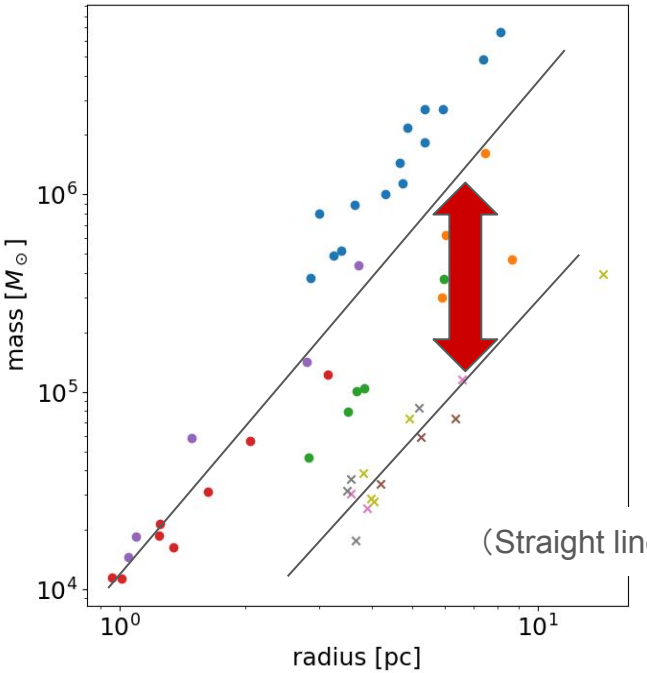
Introduction: progress so far

From the analysis of the simulations already done, the following scenario is inferred: the whole thing shrinks and grows by collision and coalescence of smaller gas masses inside it.

There was a discrepancy between the simulation and the observed data for the size and mass of the structure obtained by Dendrogram.

To bring the physical quantities of the structure closer to the observed data, **simulations should be performed under a variety of parameters and initial conditions.**





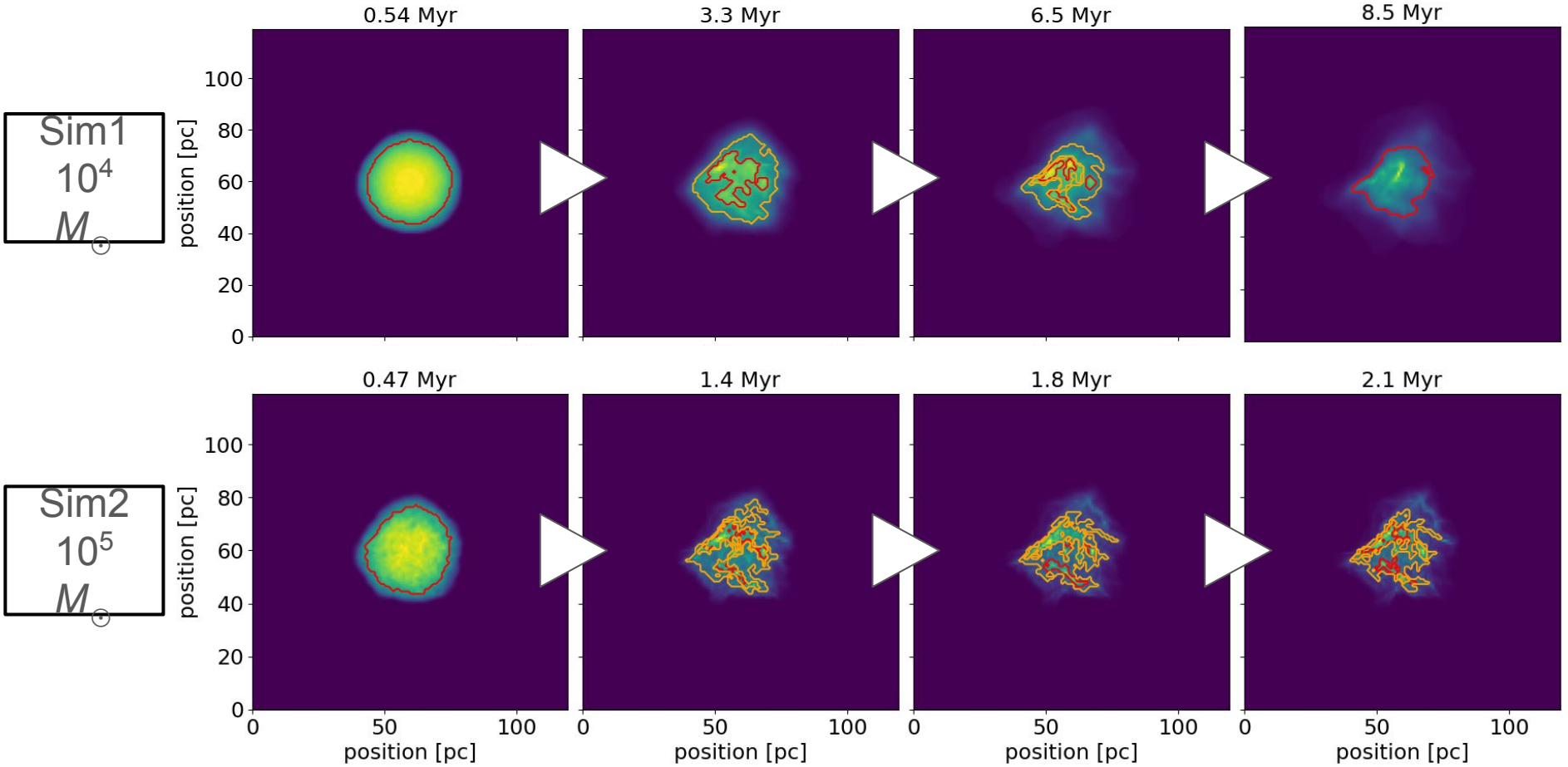
(Straight lines are images)

Simulation analysis: outline

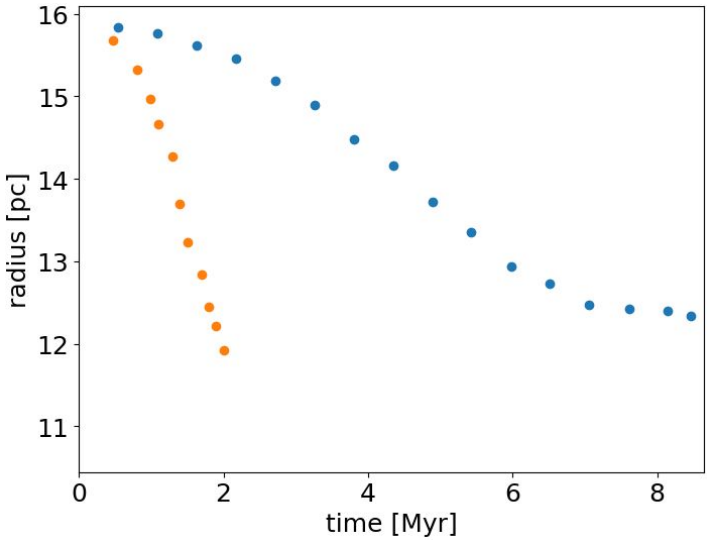
Simulations were performed using the XC50 supercomputer at the NAOJ.
Here we assume self-gravitational changes in a uniform single fluid sphere, and focus on how the properties of fluids change with differences in mass and with and without magnetic fields.

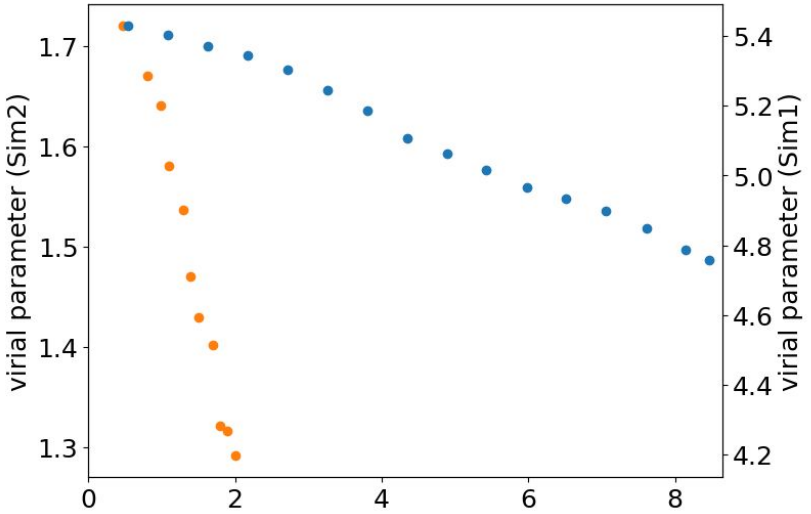
	radii [pc]	masses [$M_\odot$]	surface densities [$M_\odot$/pc^2]	virial parameter	magnetic field	feedback from sink particles
Sim1	20	10^4	8	1	No	No
Sim2	20	10^5	80	1	No	No
Sim3	20	10^5	80	1	Yes	Yes

Simulation analysis: results (Sim1 and Sim2)



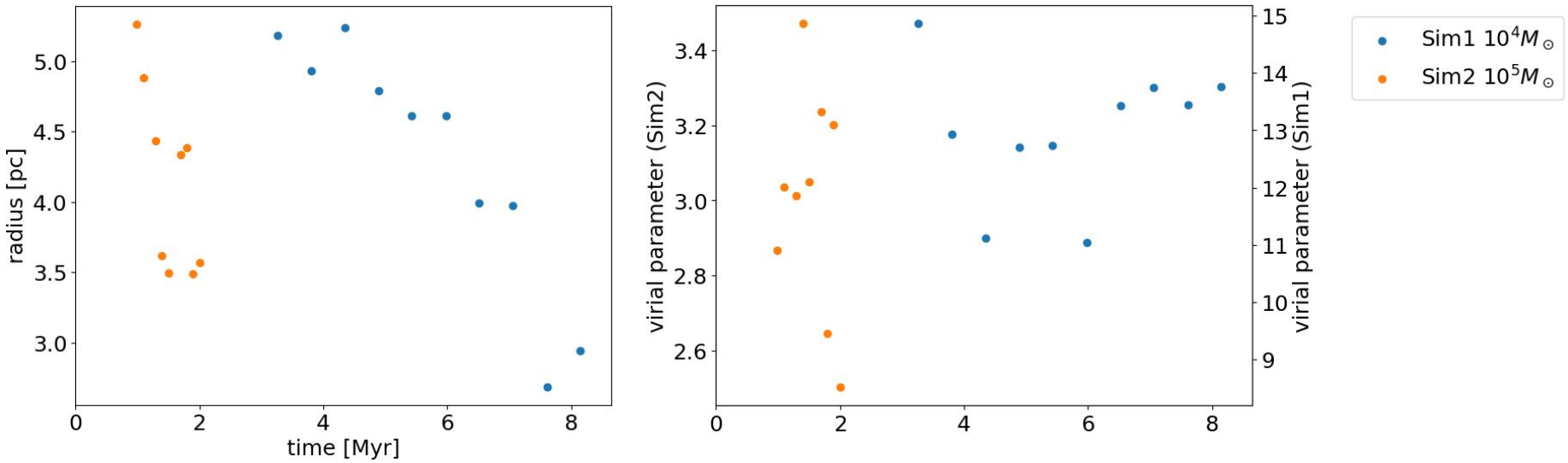
Simulation data analysis: time evolution (trunk)





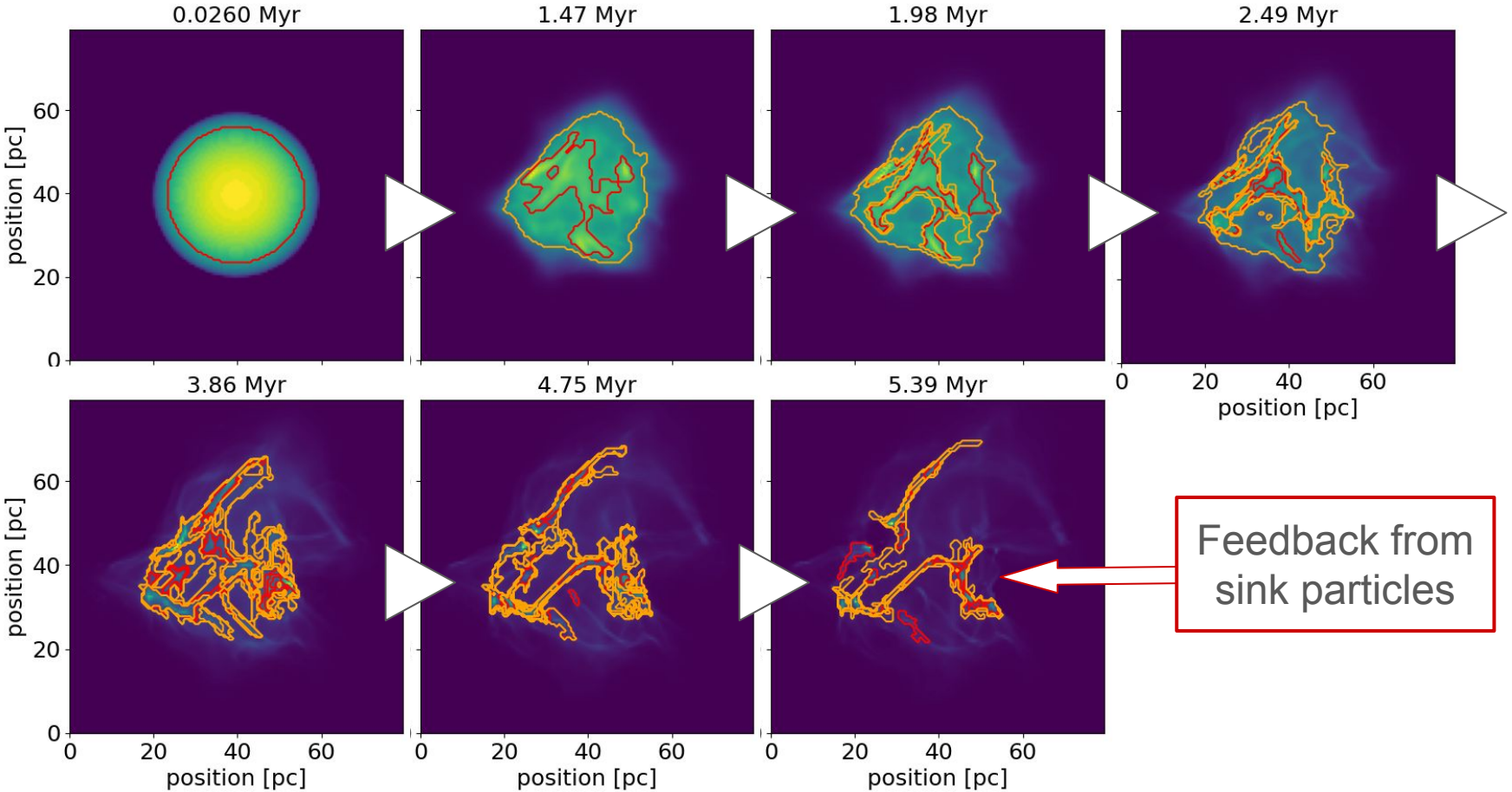
Size, mass, velocity dispersion, virial parameters are all decreasing.
The larger the initial mass, the faster the physical quantity decreases.

Simulation data analysis: time evolution (inner)

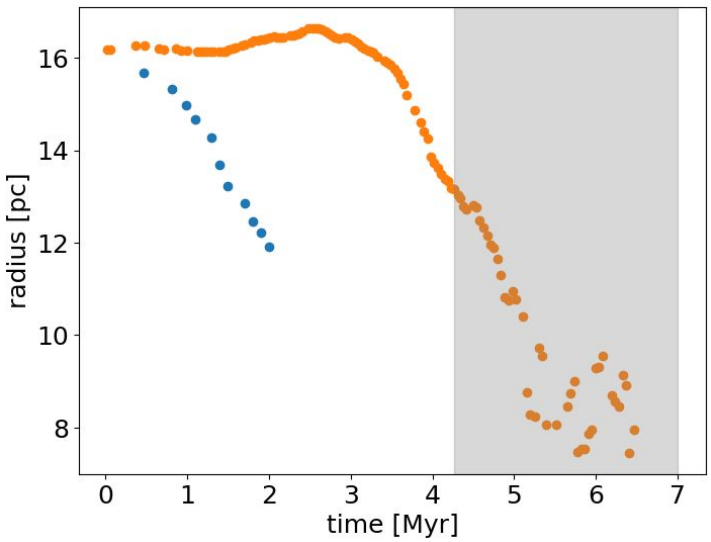


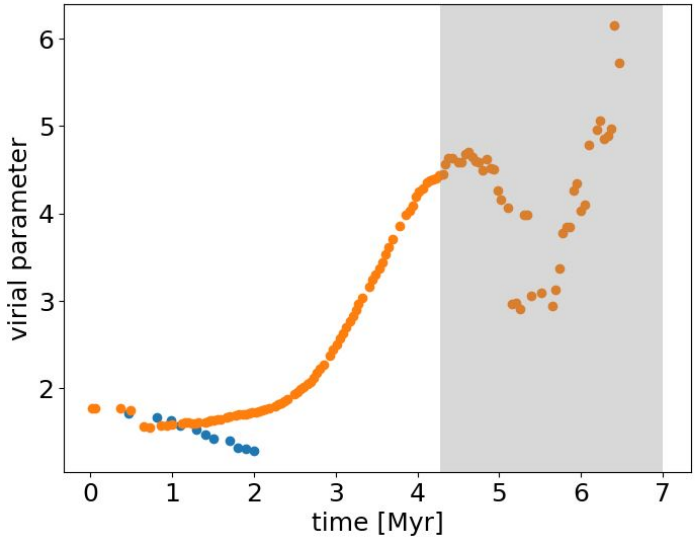
Size, mass are decreasing and the larger the initial mass, the faster the size and mass decrease.
Velocity dispersion and virial parameters fluctuate widely and are difficult to interpret, but the larger initial mass has the smaller overall value of virial parameters.

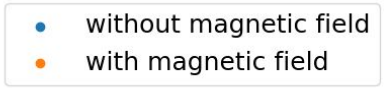
Simulation analysis: results (Sim3)



Simulation data analysis: time evolution (trunk)



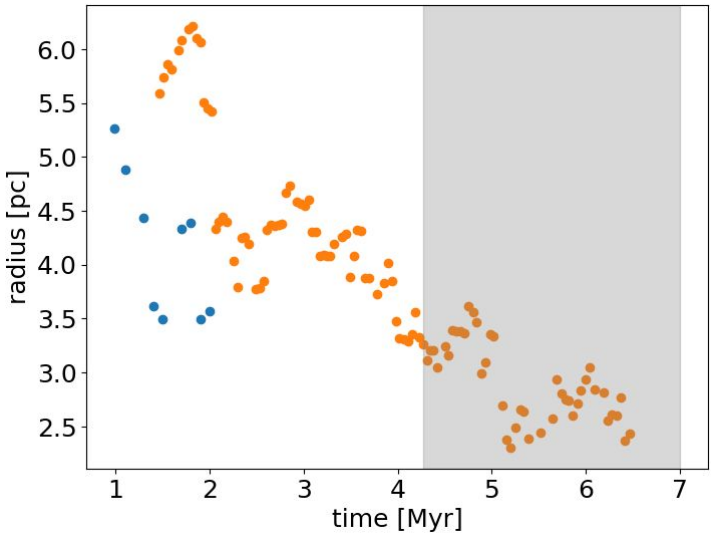


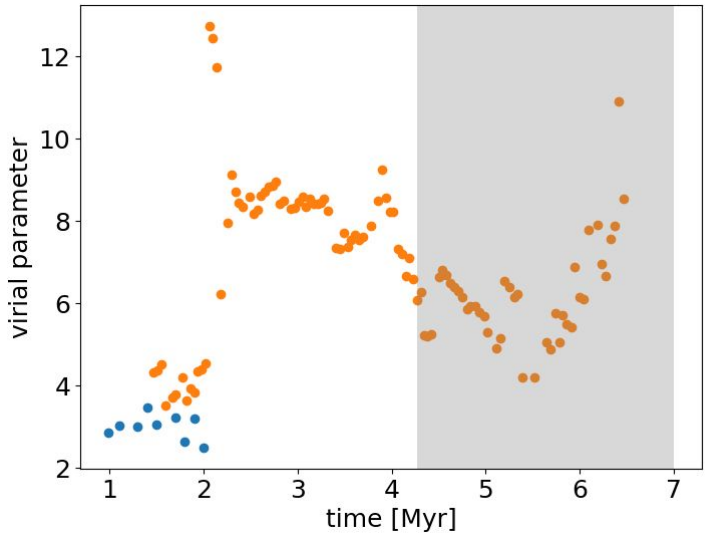


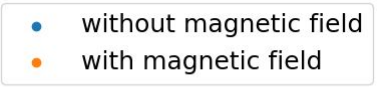
grey area:
with sink particle

Size and mass are decreasing, but the magnetic field slows the rate of decrease. Feedback also causes fluctuations in the changes.
Velocity dispersion and virial parameters are decreasing without magnetic field but increasing with magnetic field. There are also other steep increases that are due to feedback.

Simulation data analysis: time evolution (inner)







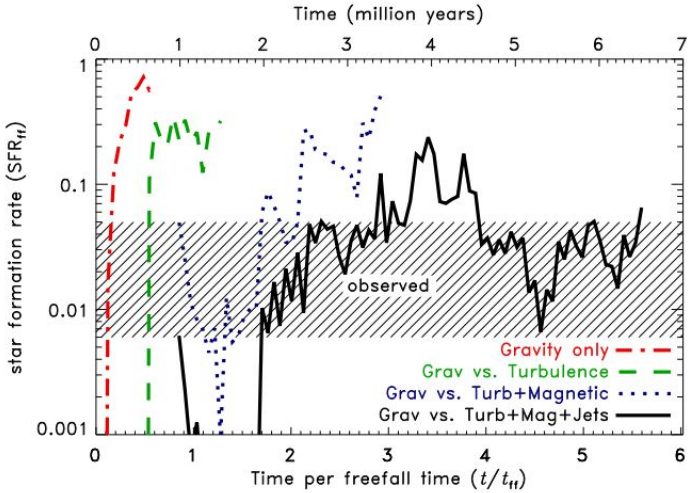
grey area:
with sink particle

Size and mass are decreasing, but the magnetic field slows the rate of decrease.
Velocity dispersion and virial parameters can be seen to be increasing or decreasing. The virial parameter is larger with magnetic field.
Compared to trunk, the impact of feedback appears to be small.

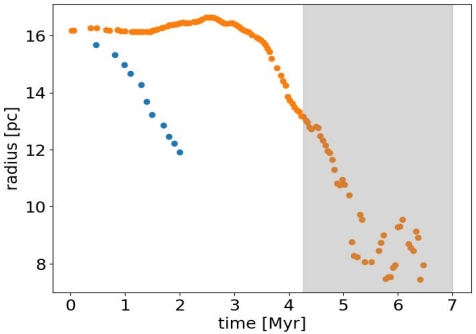
Simulation data analysis: effect of magnetic field and feedback

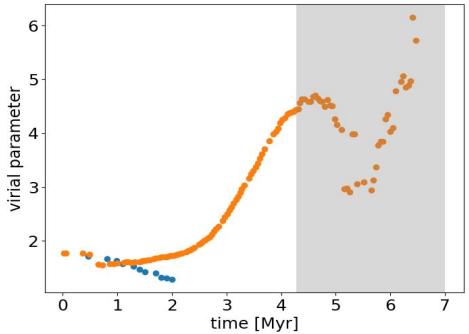
There have been many fluid simulations involving turbulence, magnetic fields, and stellar feedback on scales from 0.1 pc to several pc (e.g. Wang+2010, Padoan+2011, Federrath+2012, Myers+2014, Federrath2015), and all of these effects have reduced the SFR.

Simulations on scales of tens of pc to 100 pc (this work) show trends such as **the blocking of gravitational collapse and the increased contribution of turbulence by the magnetic field and feedbacks, which would lead to a decrease in SFR.**



Federrath2015





Observation data analysis: outline

FUGIN Project: CO emission line intensity mapping project using Nobeyama 45m telescope

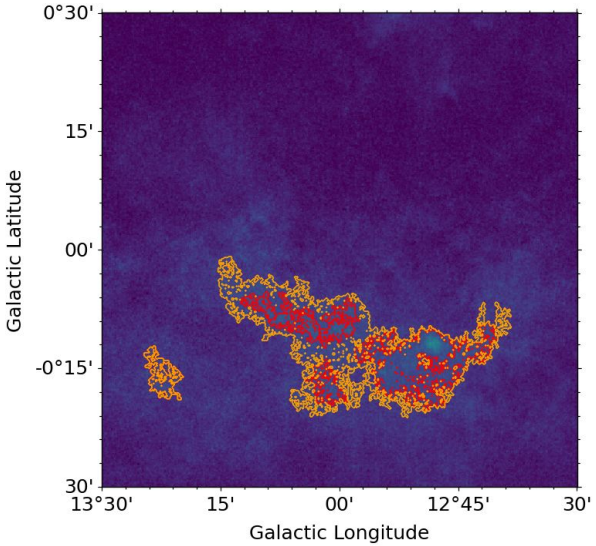
Produce an integral intensity diagram from the FITS file of 13CO emission line intensities, solve it with a astrodendro, and compare it with the integral intensity diagram of the simulation.

Class II / I ratio, Class II III / 0 I ratio: an indicator of the star formation stage of a star cluster (molecular cloud)

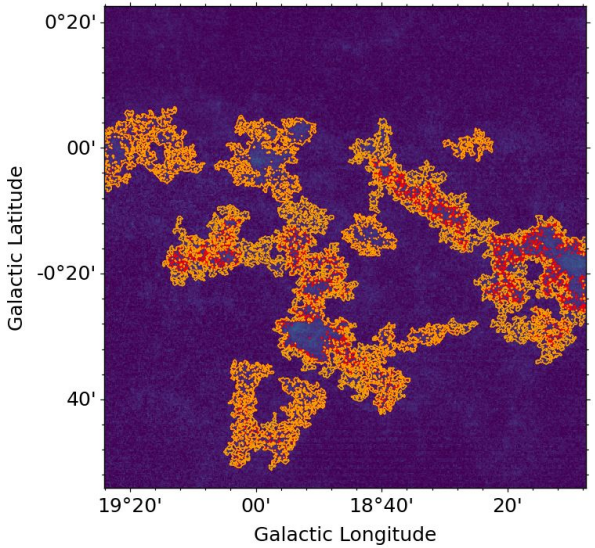
	distance [kpc]	Class II / I ratio	Class II III / 0 I ratio
W43 Main	5.5	4.58	
W49	11	2.1	
W51A, B	5.4	2.50	
M16	1.7		1.7
M17	2.0		1.4
W33	2.4	1.54	
W39	4.5	2.86	
W42	3.8	2.26	
G45	8.0	2	

Observation data analysis: results

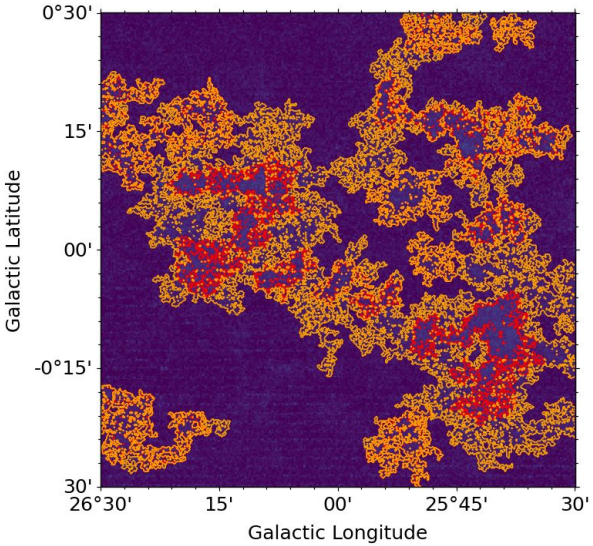
around W33
(42 pc × 42 pc)



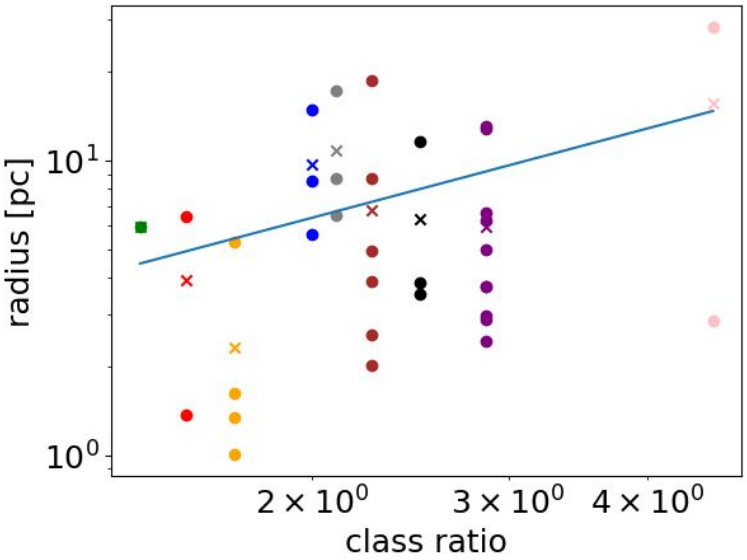
around W39
(100 pc × 100 pc)

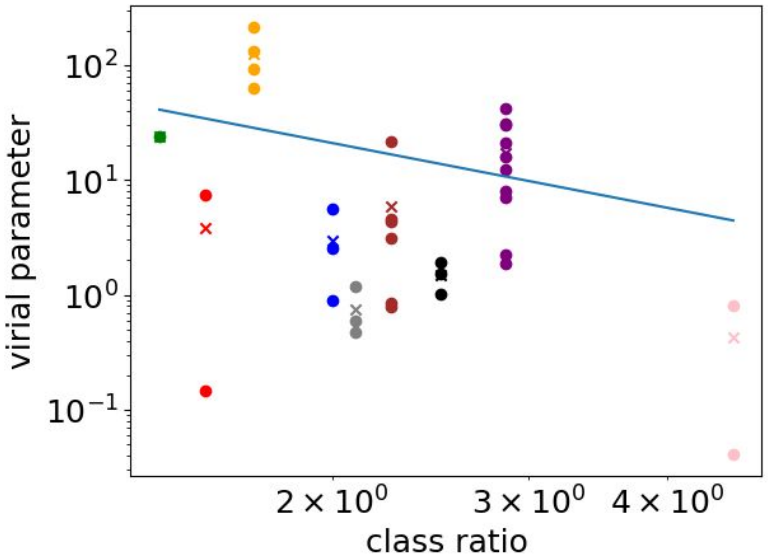


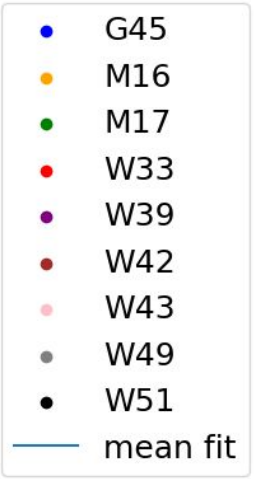
around W42
(66 pc × 66 pc)



Observation data analysis: time evolution (trunk)

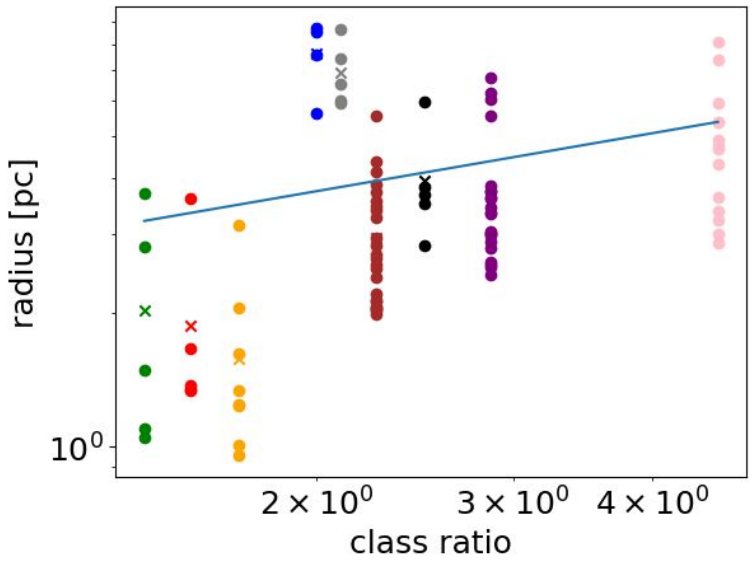


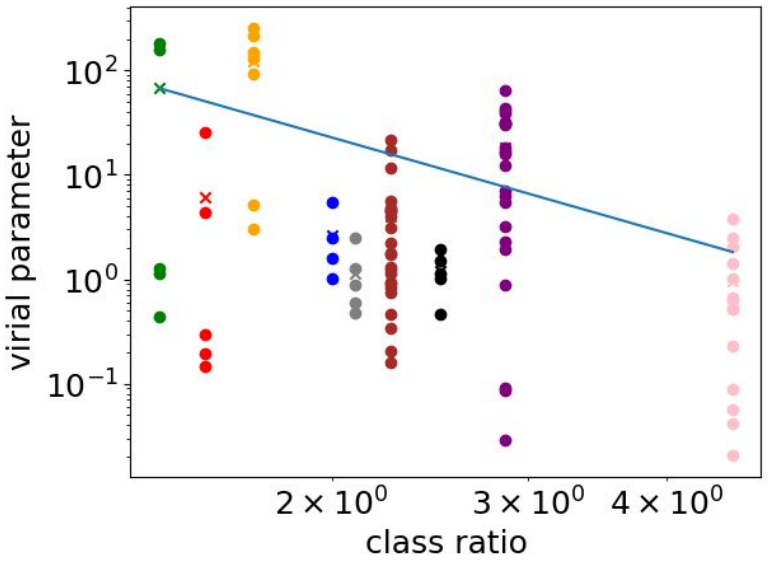




Size and mass tend to increase through the ages, which is different from simulation (tend to decrease).
Velocity dispersion and virial parameters show a decreasing trend, which is consistent with the simulation without magnetic field.

Observation data analysis: time evolution (inner)





Size and mass tend to increase through the ages, which is different from simulation (tend to decrease).
Velocity dispersion and virial parameters show a decreasing trend.

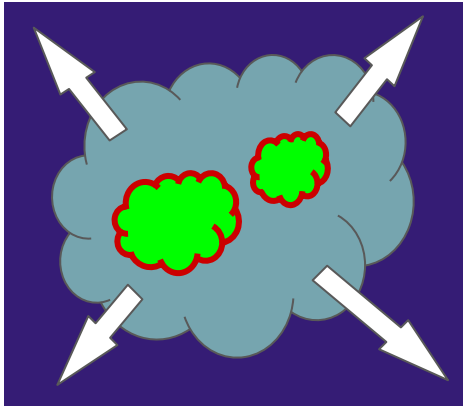
Observation data analysis: simulation closer to observation

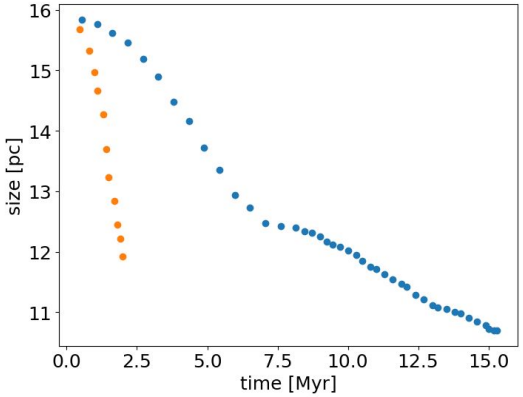
Given the observational data, the natural scenario seems to be for small molecular clouds or gases to come together and increase in size and mass while becoming gravitationally bound.

If molecular clouds are gathering from outside the observation area, simulations should be performed to reproduce such an environment.

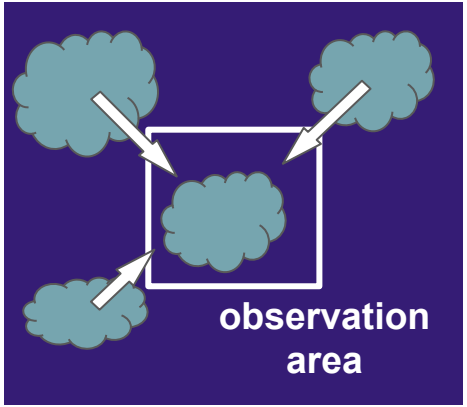
We plan to attempt to reproduce an environment more similar to an actual molecular cloud, starting with fluid sphere collisions.

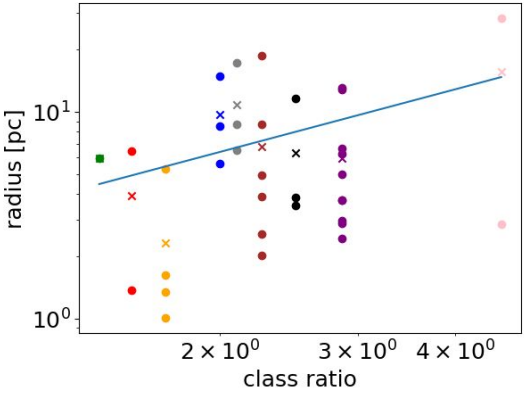
simulation





observation





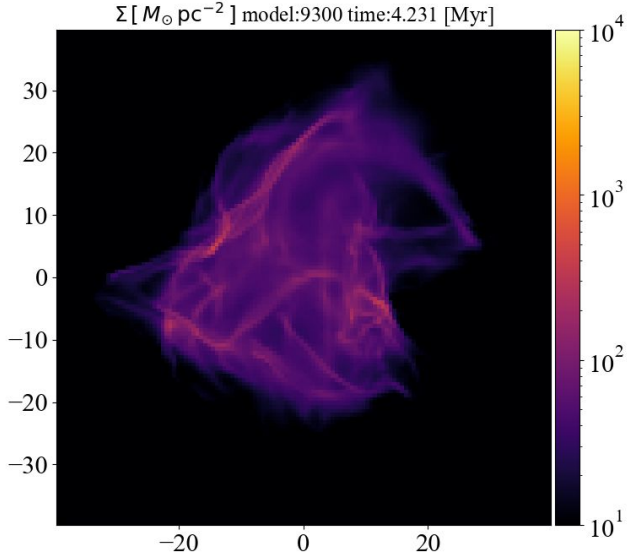
Summary

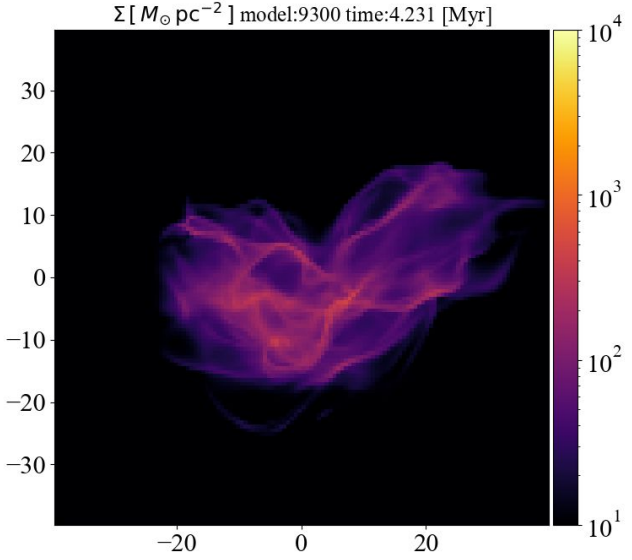
・We performed self-gravity hydrodynamics simulations assuming molecular clouds under various conditions and analyzed with astrodendro.
  ・The larger the initial mass of the fluid sphere, **the stronger the gravitational contraction** and the faster the decrease in size/mass.
  ・The magnetic field and stellar feedback **prevented gravitational contraction and increased the contribution of turbulence,** resulting in a slower decrease in size/mass, and an increase or decrease in velocity dispersion/virial parameters.

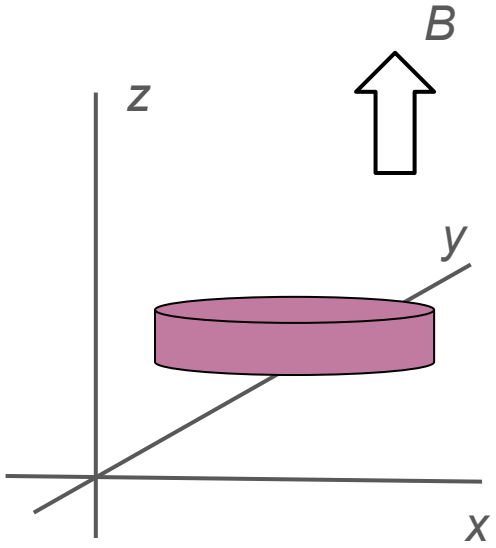
・We performed the same analysis on observed data and compared with simulations.
  ・Unlike the simulation with magnetic field, **the size/mass were increased, while the velocity dispersion and virial parameters were decreased.**
  ・In order to approximate the trend of physical quantities, **the simulation should consider multiple molecular clouds rather than a single fluid sphere.**

Future work:
Running simulations with multiple fluid spheres, such as collisions
Further observational data analysis

Appendix: Sim3







Appendix: trend of each physical quantity

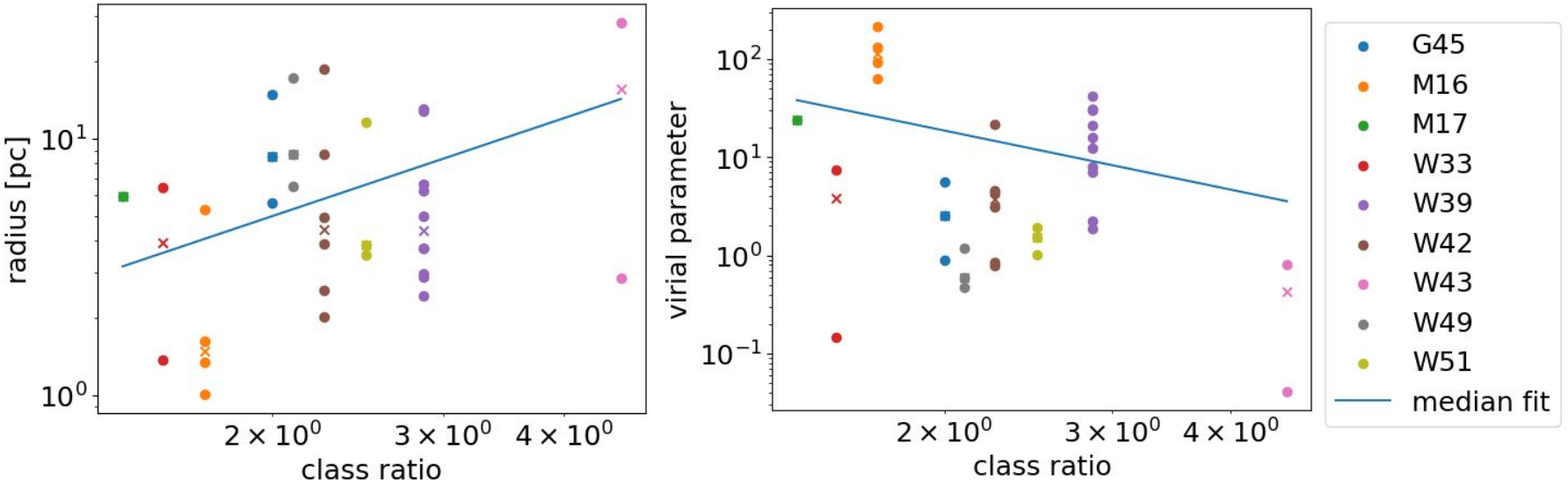
size / mass

	trunk	inner
simulation (without magnetic field)	**decrease**	**decrease**
simulation (with magnetic field and feedback)	**decrease**	**decrease**
observation	**increase**	**increase**

velocity dispersion / virial parameter

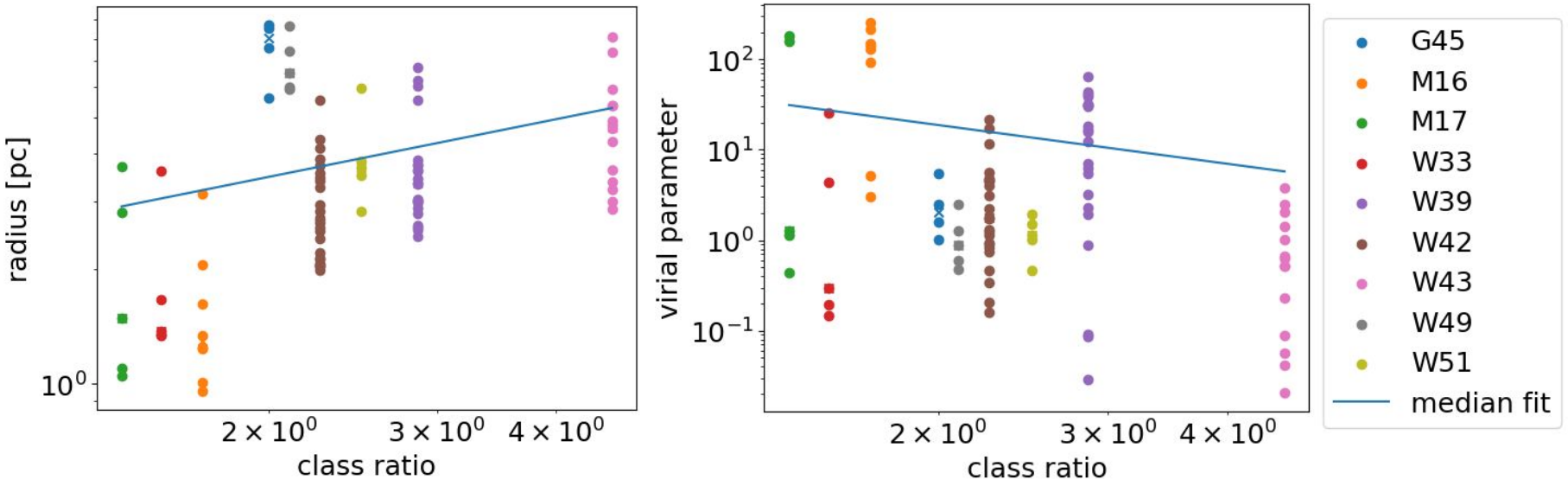
	trunk	inner
simulation (without magnetic field)	**decrease**	increase and decrease
simulation (with magnetic field and feedback)	increase and decrease	increase and decrease
observation	**decrease**	**decrease**

Appendix: observational time evolution with median fit (trunk)



Size and mass tend to increase through the ages, which is different from simulation (tend to decrease).
Velocity dispersion and virial parameters show a decreasing trend, which is consistent with the simulation without magnetic field.

Appendix: observational time evolution with median fit (inner)



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