Analysis of simulation and observation data for understanding the structural evolution of molecular clouds

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1. Background / Aims

Massive star formation and molecular cloud collisions

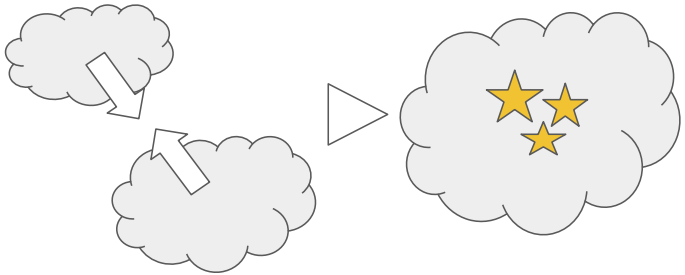
Massive stars: Formed as star clusters from only giant molecular clouds

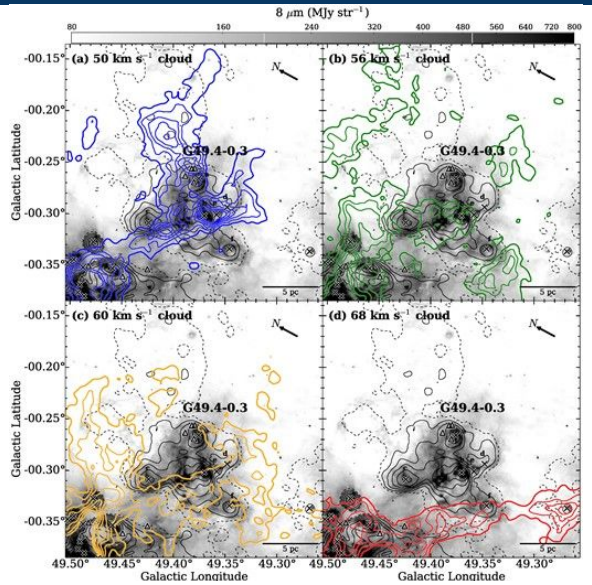
What process leads to star cluster formation from molecular clouds is a mystery

Molecular cloud collisions: a promising scenario for massive star formation

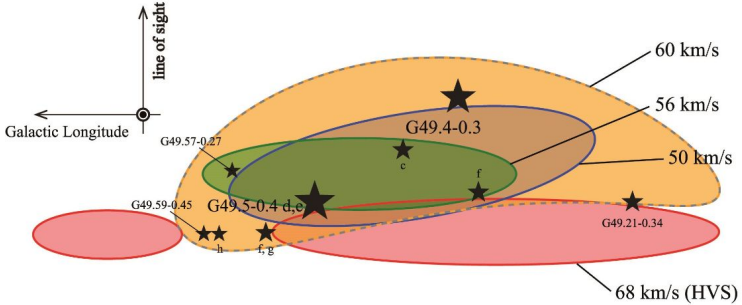
Numerous observations suggesting cloud collisions near massive stars (FUGIN: Fujita+2021, etc., ALMA: Sano+2013, etc.)

From the kinematic timescale, do molecular cloud collisions not occur at a dominant frequency? (Sun+2022)





Fujita+2021



1. Background / Aims

Hierarchical gravitational collapse

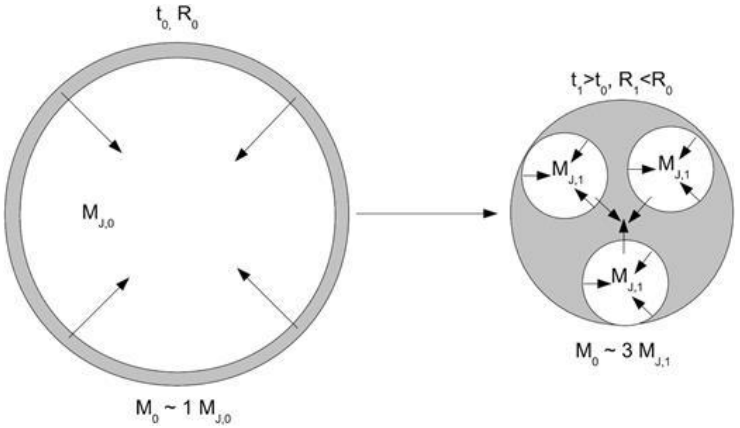
From previous research, hierarchical gravitational contraction is emerging as a likely scenario:

1. Giant molecular cloud shrinks globally
2. Hierarchically formed high-density areas inside
3. Internal structures collide with each other frequently

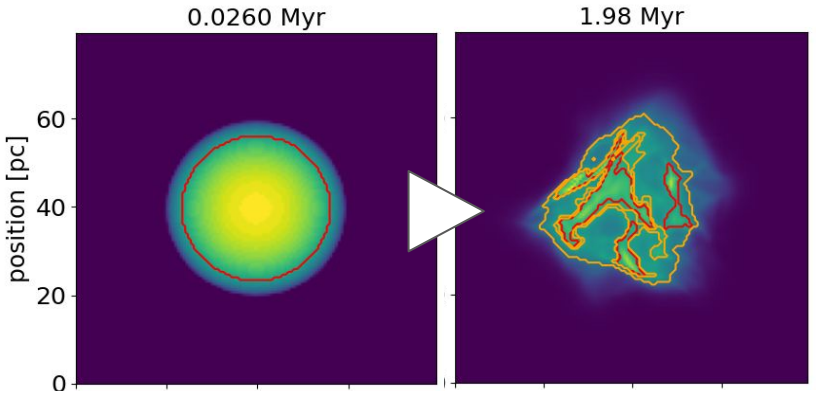
→ **It is possible to explain observational facts specific to massive star formation, such as massive star formation only in giant molecular clouds and molecular cloud collisions.**

Theoretical models incorporating hierarchical gravitational contraction have already been discussed (e.g. V´azquez-Semadeni+2019), but **there have been few attempts to verify them from both observation and simulation perspectives.**

Molecular cloud evolution scenarios can only be verified by analyzing simulations that can track temporal evolution using the same method as observational data.



V´azquez-Semadeni+2019



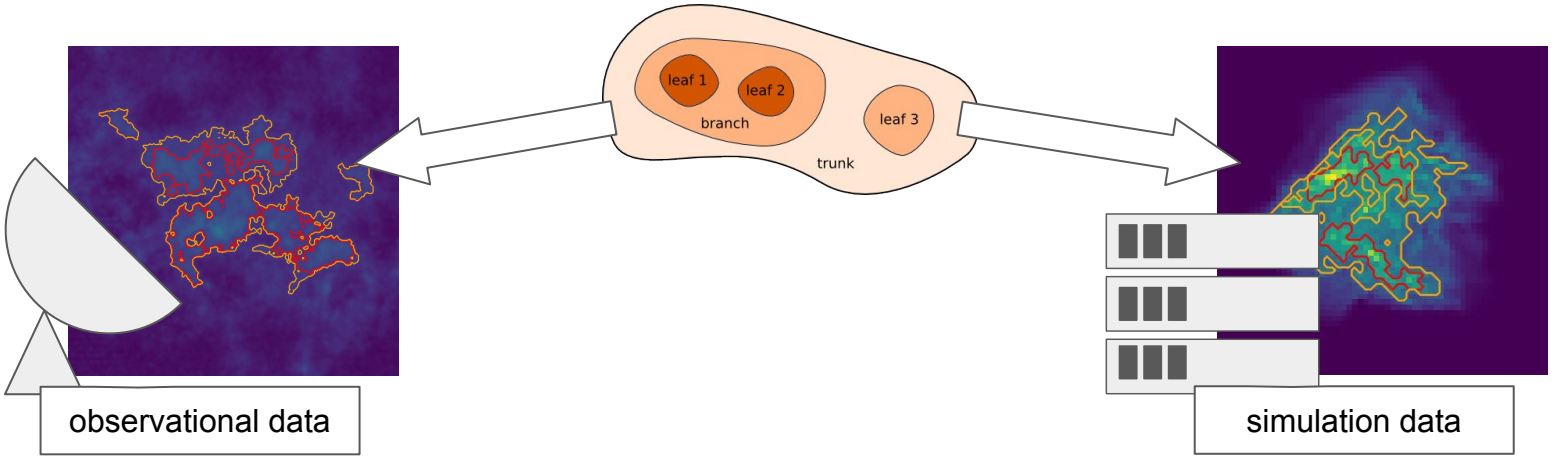
1. Background / Aims

Aims

Through observations and simulation analysis, we will investigate whether and how a new molecular cloud evolution scenario, involving hierarchical gravitational contraction and interactions of molecular clouds, is occurring, and elucidate the mechanism of high-mass star formation.

- Applying common structural analysis tools for both observation and simulation
→ **Easy comparison of observed data and simulation data**

- Compare the physical quantities of simulation data analysis and observation data analysis and consider molecular cloud evolution scenarios.



2. Method

Analysis tools

Analysis using astrodendro (Rosolowsky et al. 2008)

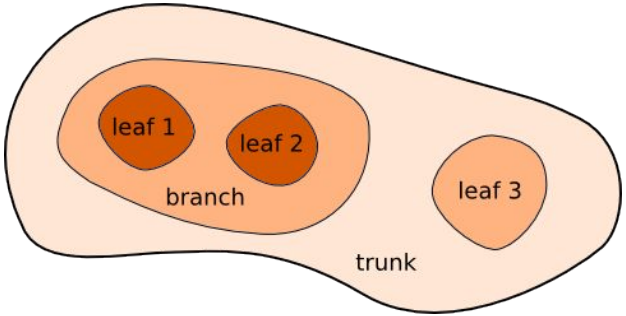
Dendrogram: an algorithm for classifying hierarchical structures in multidimensional datasets

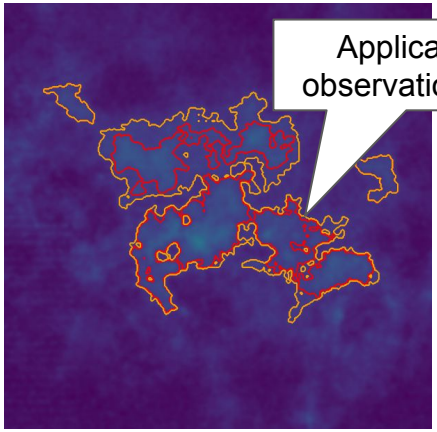
- Minimal structure without internal structure: leaf
- Structure containing internal structure: branch
- Outermost structure: trunk

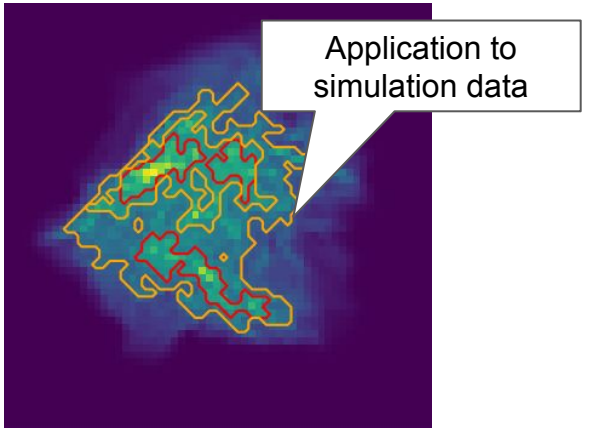
Hierarchical classification algorithm
→ **Ideal for verifying hierarchical gravitational contraction**

Applies to both observational data and simulation data
→ **Easy comparison of simulation data and observation data**

Obtain and discuss physical quantities for each structure obtained.







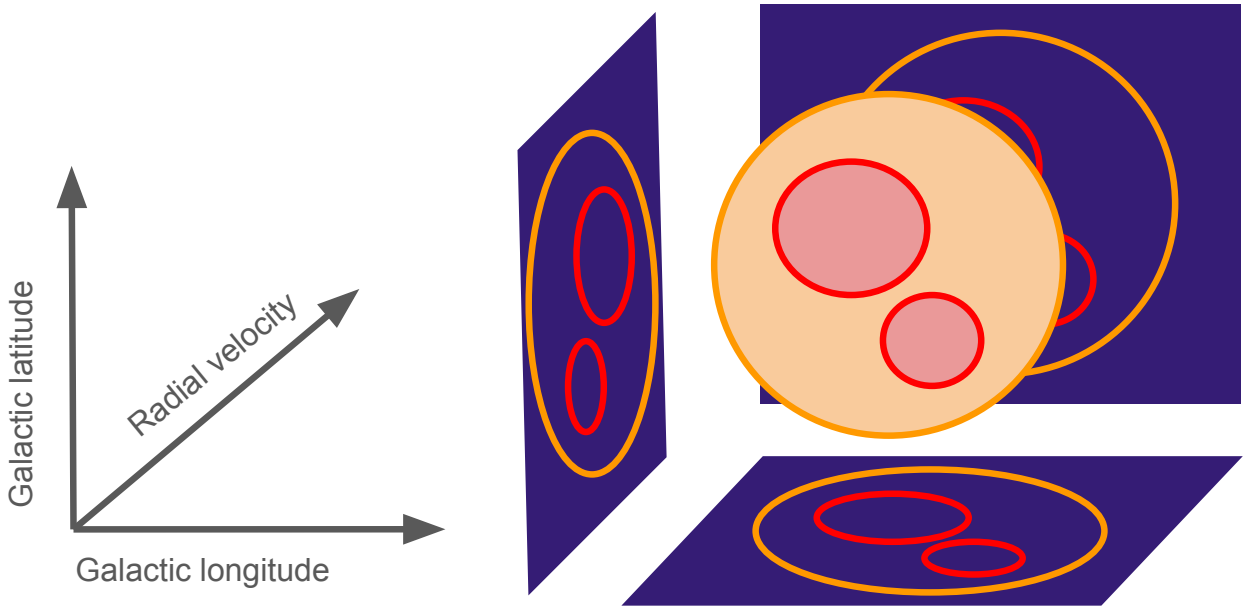
2. Method

Observation data

・FUGIN (Umemoto et al. 2017): Simultaneous CO multi-line survey observation using Nobeyama 45m radio telescope

・Analysis of PPV 13CO (J = 1-0) emission line intensity maps for 17 types of molecular clouds

・Smoothed to match W49, the most distant object (11.11 kpc)



3. Result

Velocity-resolved column density

Density decreases toward the outermost structure (main layer).

Low-density leaves with a density similar to that of isolated leaves branch off from the main layer and exist outside the high-density region in terms of position and velocity.

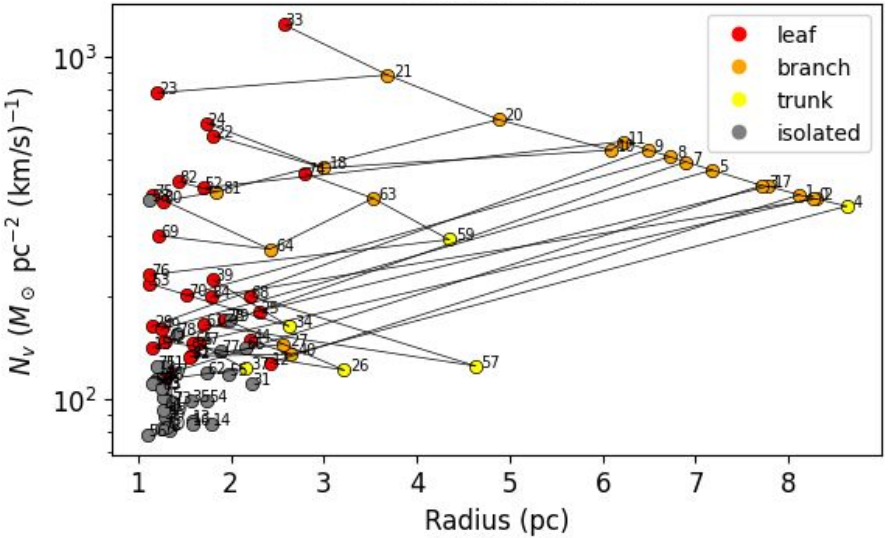
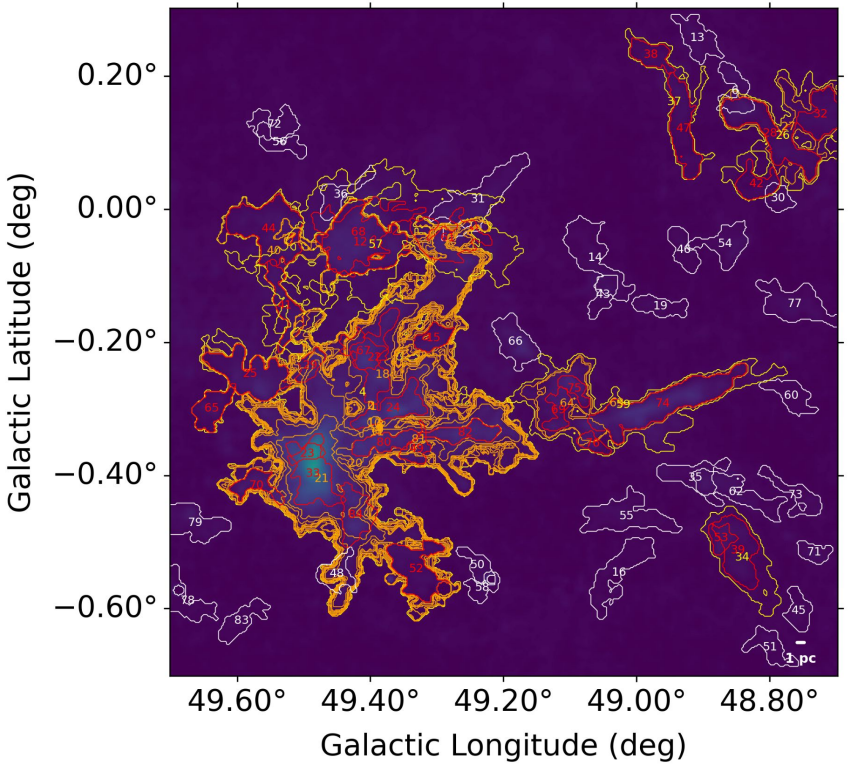


Figure: result of W51



3. Result

Virial parameter

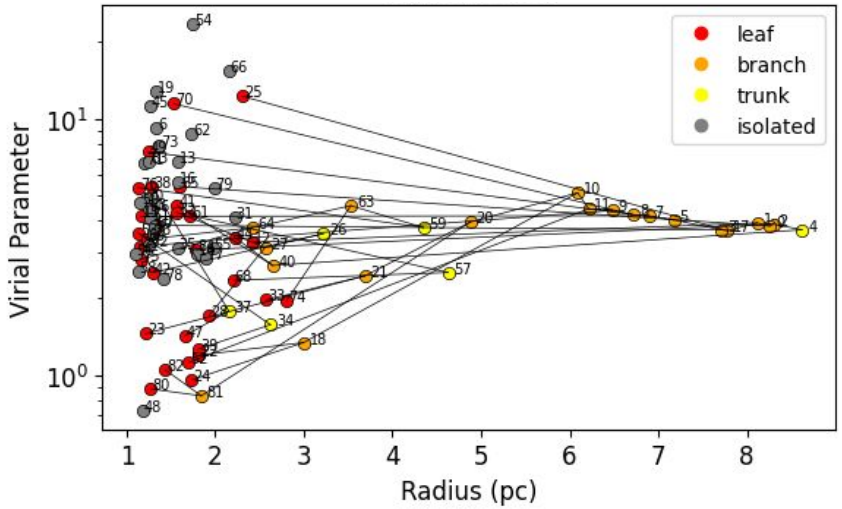
Hierarchical structures have higher column density and lower virial parameters than isolated structures.

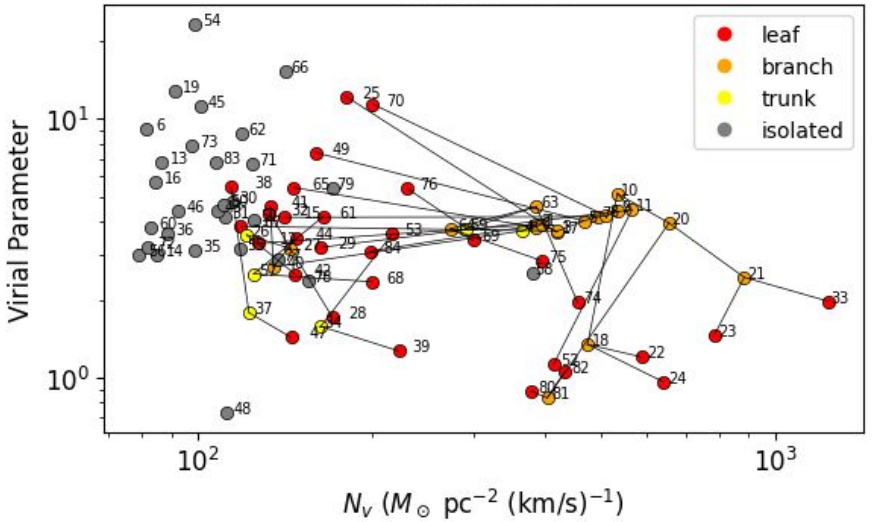
→ **GMCs that can form massive stars have a hierarchical structure?**

Virial parameter:
The ratio of the gravitational potential of a structure to its kinetic energy, which evaluates how gravitationally bound it is.

$$\alpha_{\mathrm{Gvir}} = \frac{5\sigma^2 R}{3GM}$$

σ: velocity dispersion / R: cloud radius / M: cloud mass





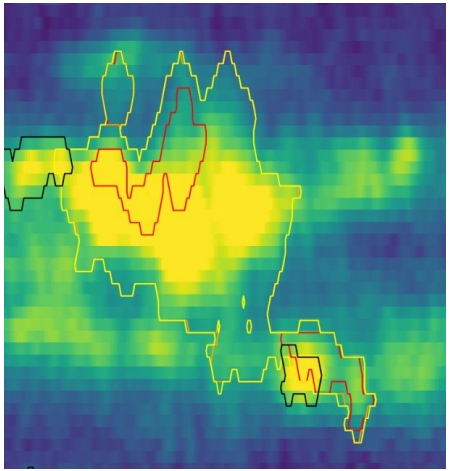
3. Result

Hierarchy across multiple velocity structures

The PV diagram shows that **there are leaves on top of multiple velocity structures, and branches and trunks exist across the velocity range, covering them.**

→ **indicates that internal interactions (CCC) occur in a hierarchical manner?**

Figure: result of G18



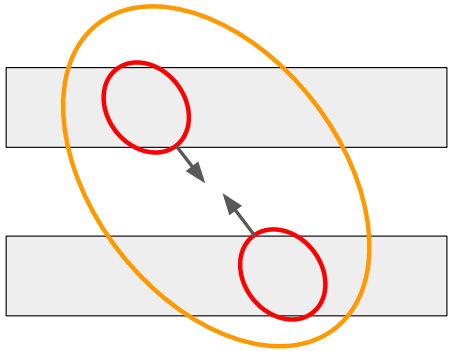
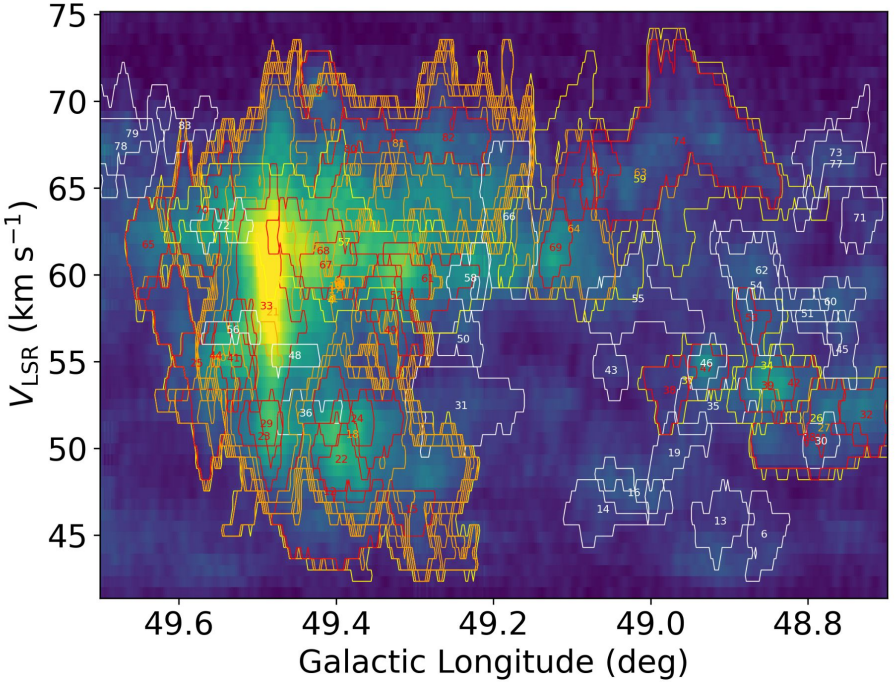


Figure: result of W51



4. Discussion

Compare with Spitzer 8 μm

The region with high density of gas and bright 8μm, that is, the region with active star formation overlaps.

The hierarchical structure is more dense and has a higher intensity of 8 μm, meaning that star formation activity is more active.

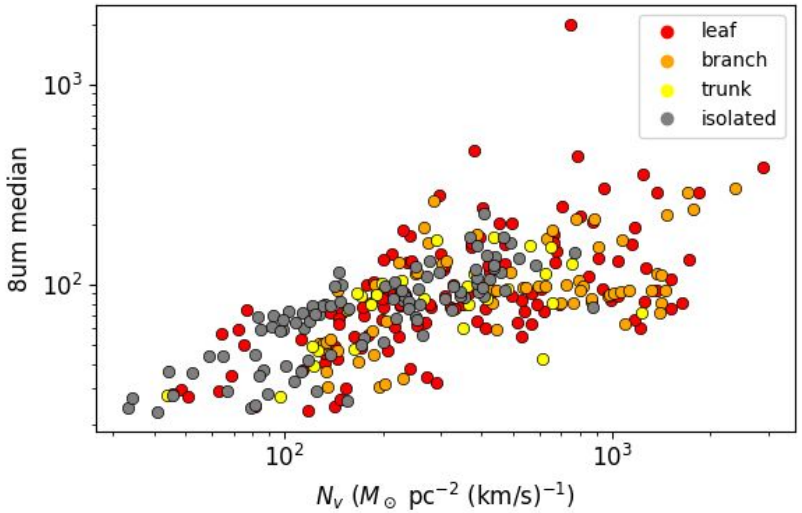
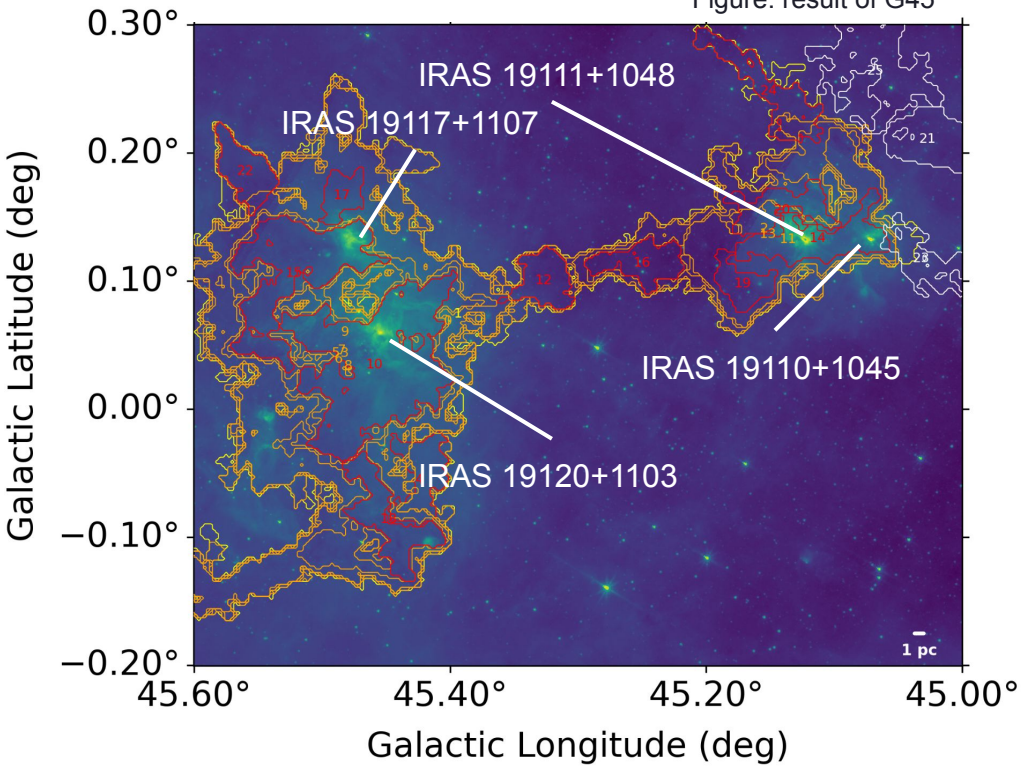


Figure: result of G45



4. Discussion

Spitzer 8 μm and velocity-resolved column density

High-density leaf - bright region at 8 μm

Low-density leaf - dark region at 8 μm

→ **indicates that star formation is active in the hierarchically generated high-density regions?**

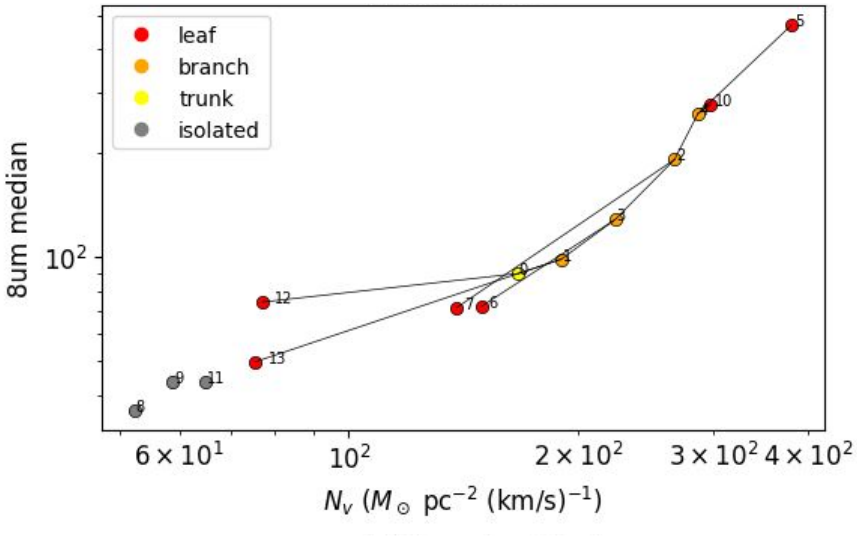
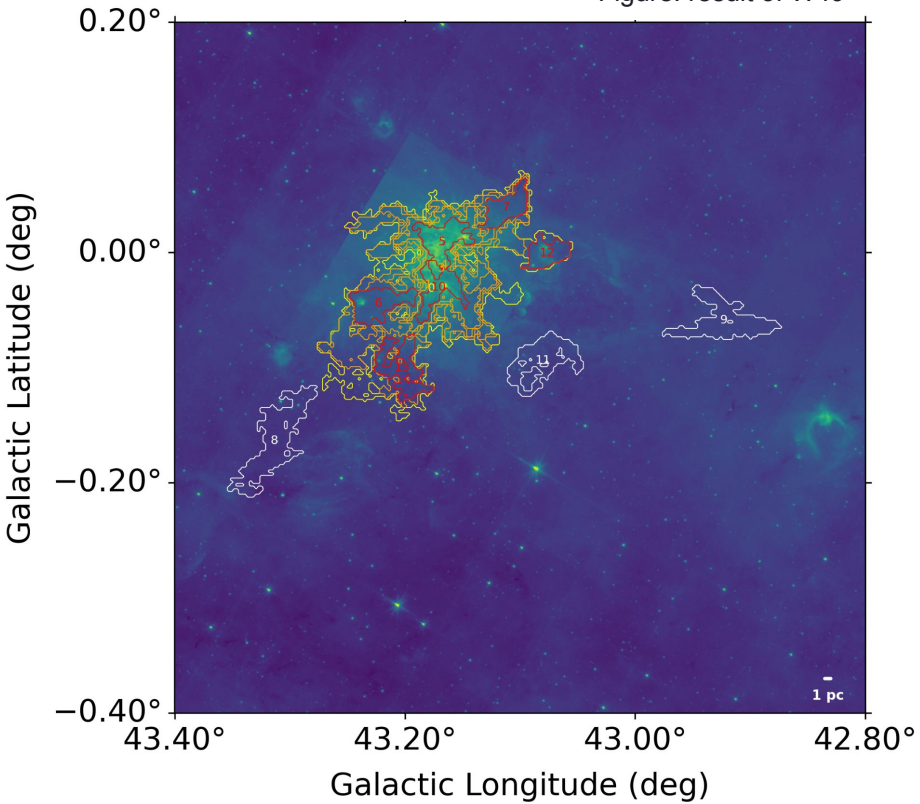
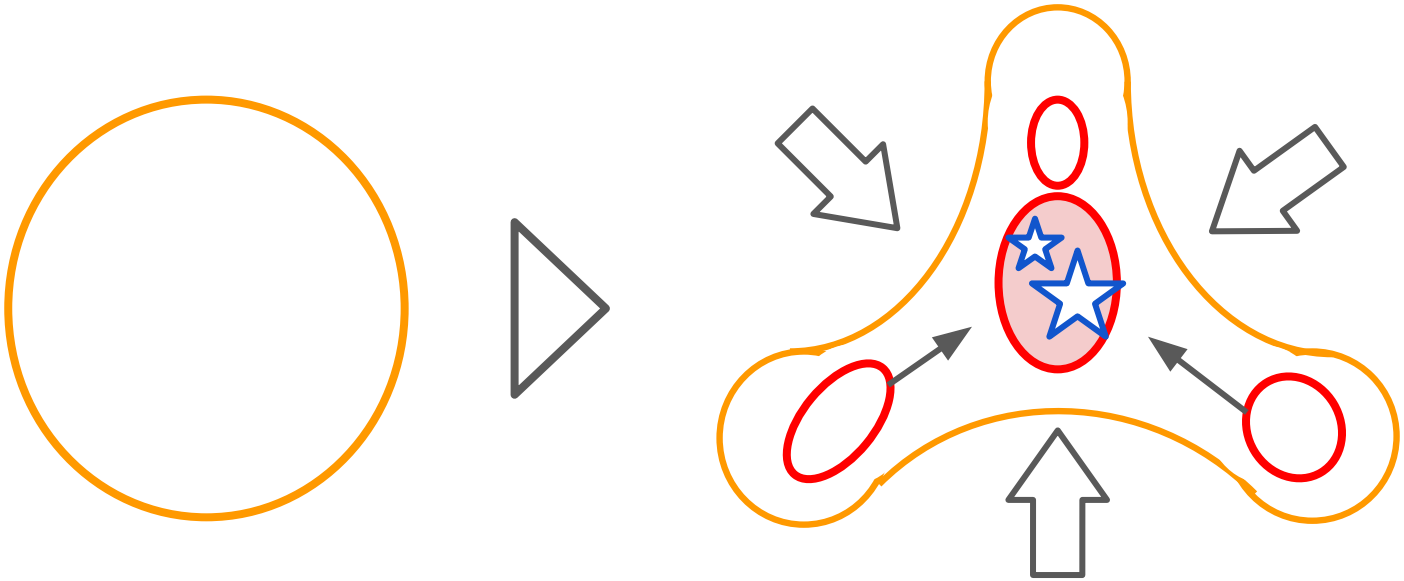


Figure: result of W49



4. Discussion

Possible Hierarchical CCC Scenarios



It is possible that **the hierarchical gravitational contraction of a uniform molecular cloud results in the creation of a high-density internal structure, and that the accretion of a low-density internal structure onto this structure leads to collision and merging, leading to the formation of a large mass.**

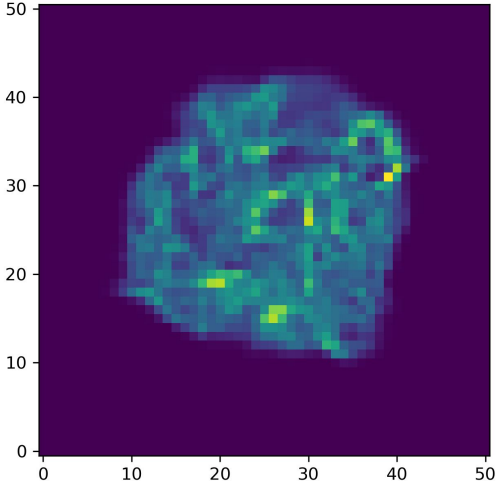
5. Future work

Simulation using GPU

Hydrodynamics simulations are being performed and analyzed using the Miyabi supercomputer.

Analysis code: An improved version of SFUMATO (Matsumoto+2007) that enables calculations on GPUs (Fukushima-san)

GPU-based simulations are more than 10 times faster and offer higher resolution than conventional CPU-based calculations, a first in the field of star formation.



test plot
Radius: 20 pc
Mass: 10^5 Msun
9.8×10^5 yr

6. Summary

We analyzed the molecular baseline data from FUGIN using Dendrogram to investigate whether and how hierarchical evolution is occurring.

・The GMCs formed a hierarchical structure in which density increased toward the interior.

　　・There were (relatively) low-density regions within them.

　　・The structure outside the hierarchy spanned multiple velocity components.

・The hierarchical structure was found to have higher density and lower virial parameter than the isolated structure.

・The high-density regions within the hierarchical structure have a large intensity at 8 μm, indicating that more active star formation is occurring in these regions.

→ **A molecular cloud can undergo hierarchical gravitational contraction, producing a dense core inside it; subsequent accretion and merging of surrounding lower-density substructures onto that core can then build up a massive structure.**

Future work:

・Computing simulation

・Estimating the SFR of molecular clouds and comparing it with their structures

・Estimating the volume density of structures using Radex

・Writing thesis