CARMA Large Area Star Formation Survey (CLASSy)

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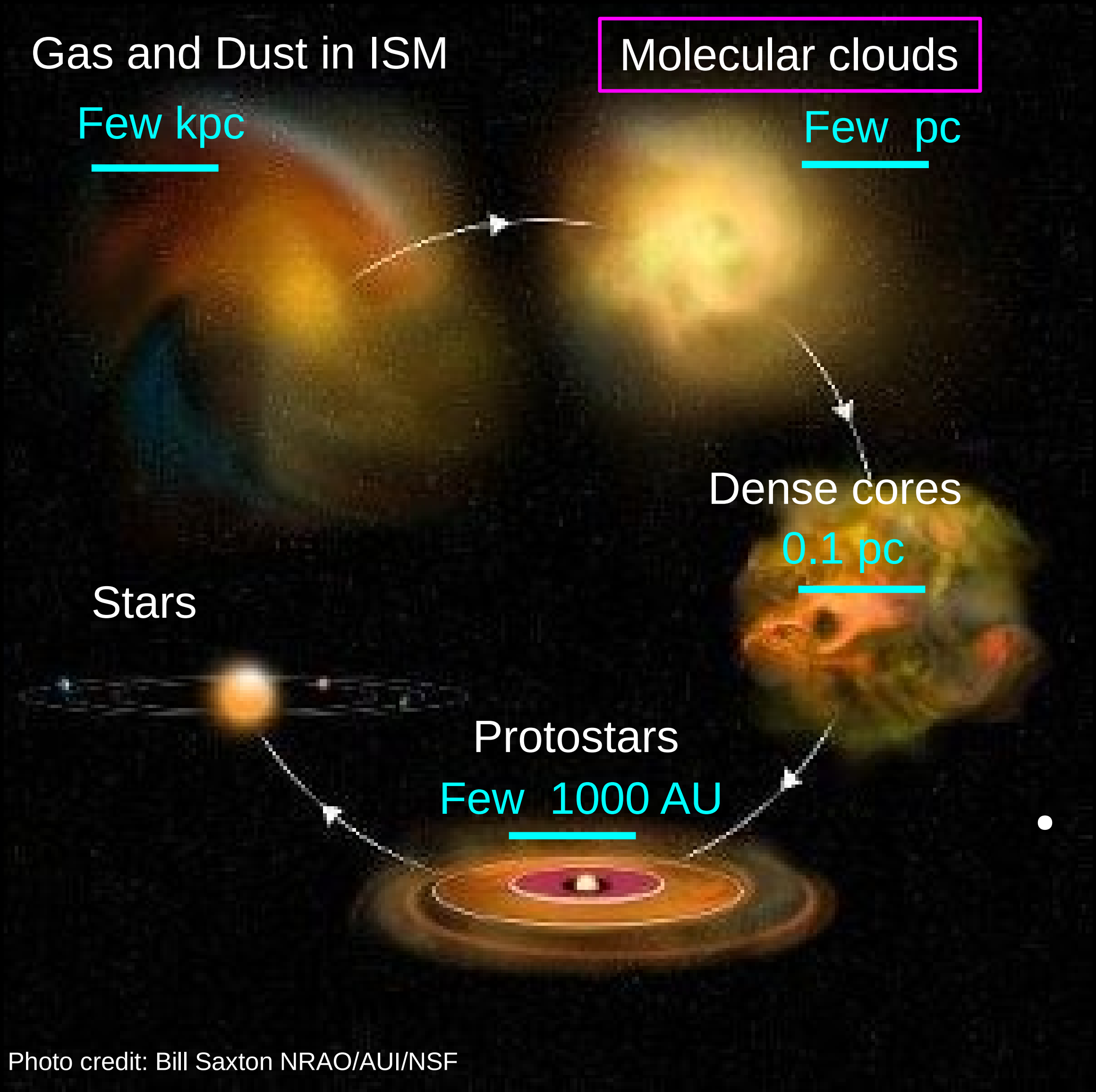
Outline

- Introduction: Star Formation from Large to Small Scales
- Observation: Serpens Main (Lee et al. 2014, ApJ submitted), Serpens South (Fernandez-Lopez et al. 2014, ApJL accepted), Barnard 1 (Storm et al. 2014, ApJ submitted), NGC 1333, L1451
- Results: Gas Structures and Kinematics
- Dendrogram Analysis: Characteristic Cloud Depth
- Filaments in Serpens: Widths, Two Types, YSOs
- Summary

Known and Unknown: Parsec-Scale

A simplified cartoon



Known

- Stars are formed in molecular clouds
- Molecular clouds are low-density (~ 100 cm^{-3})
- Dense gas (> 10^{4} cm^{-3}) is a small fraction but dominates star formation

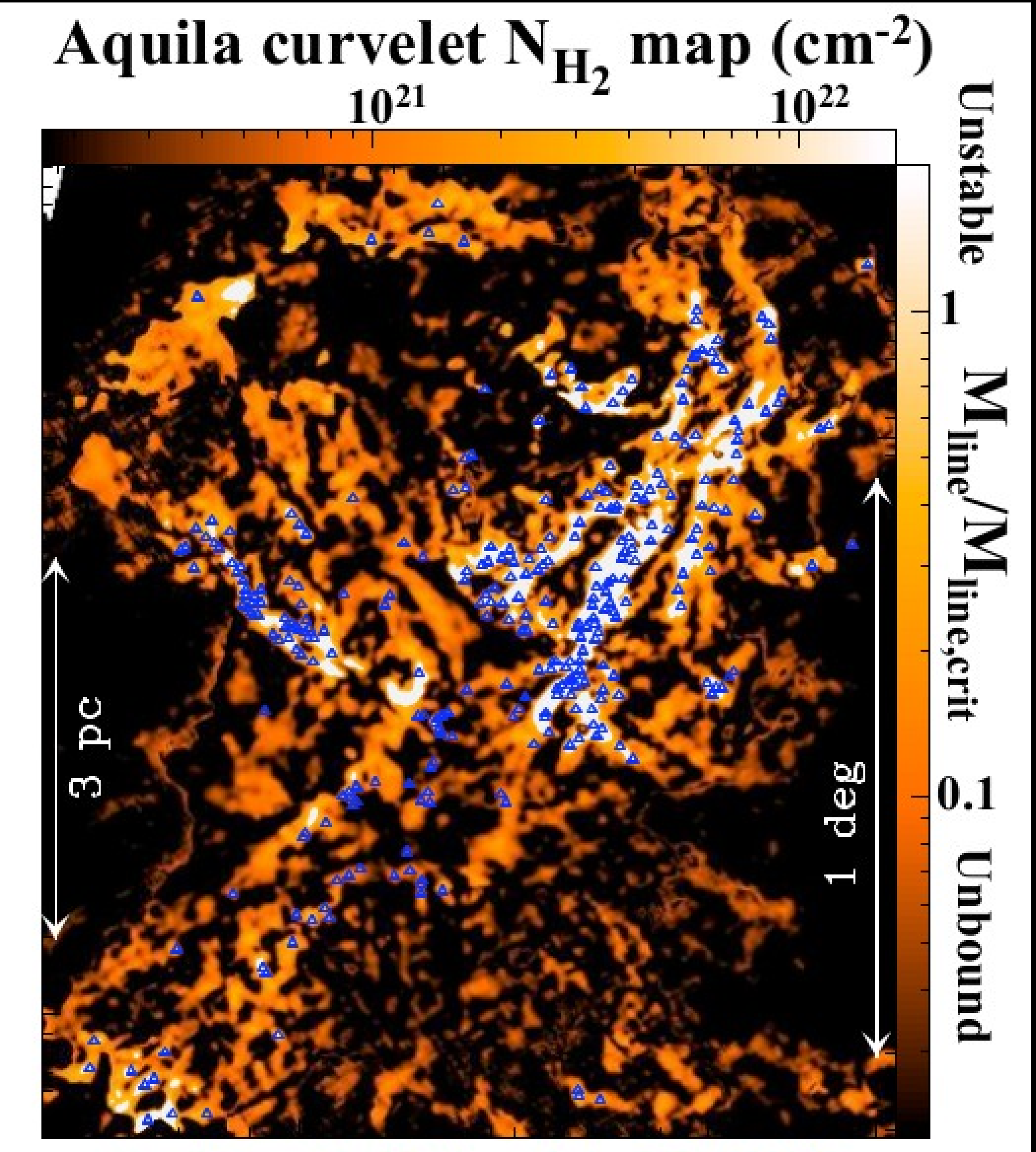
Unknown

- How does low-density gas reach threshold of star formation?

Known and Unknown: Parsec-Scale

Known

- Molecular clouds are filamentary by large
- Density threshold: N_{H_2} >= 7 x 10^{21} cm^{-2}
- 75% of prestellar cores form in filaments
- Characteristic width ~ 0.1 pc (Arzoumanian et al 2013)

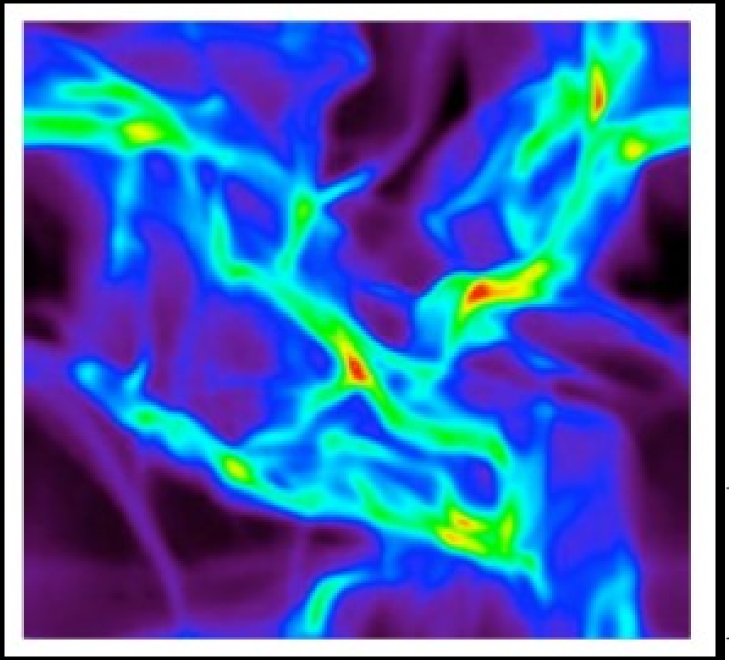


André et al. 2010, A&A, 518, L102

Unknown

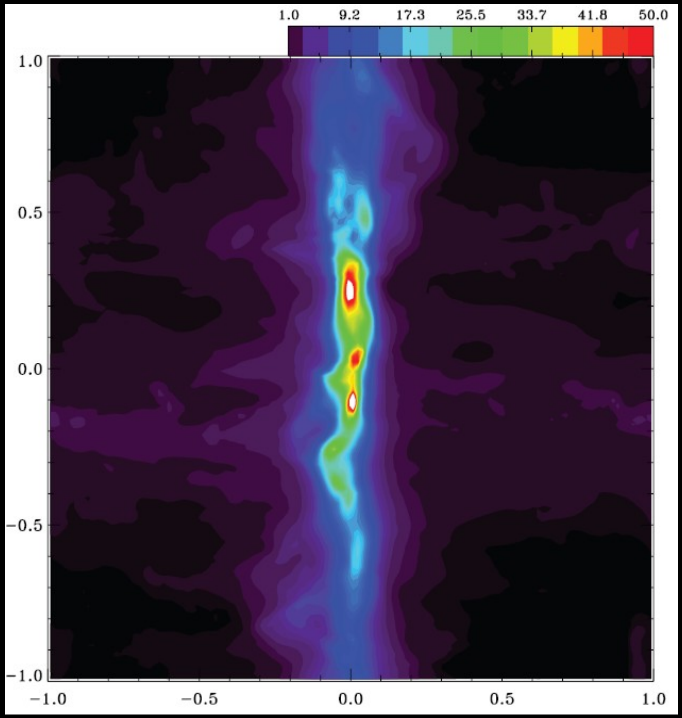
How do filaments form?

Supersonic turbulence



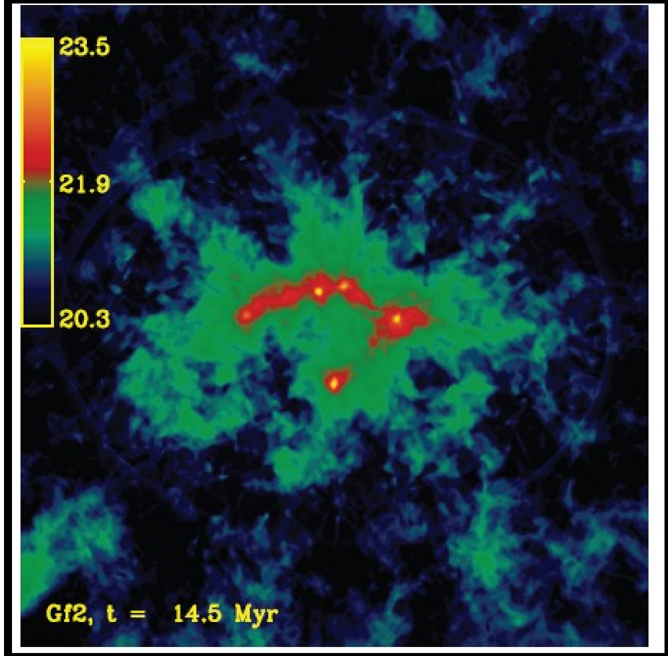
Padoan et al. 2001

More strongly magnetized



Nakamura & Li 2008

Gravity



Heitsch et al. 2008

Known and Unknown: Parsec → 0.1 pc

A simplified cartoon

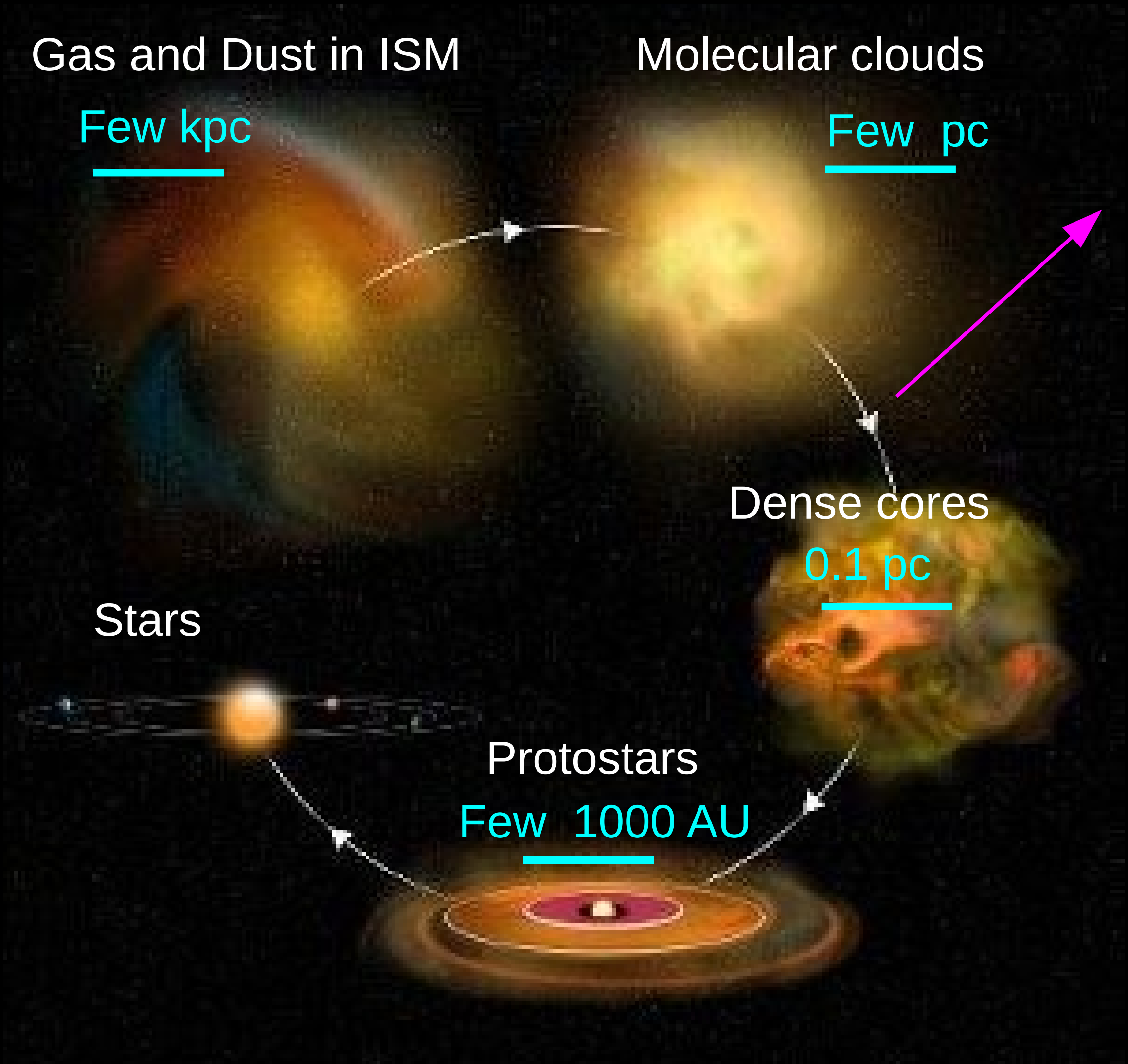
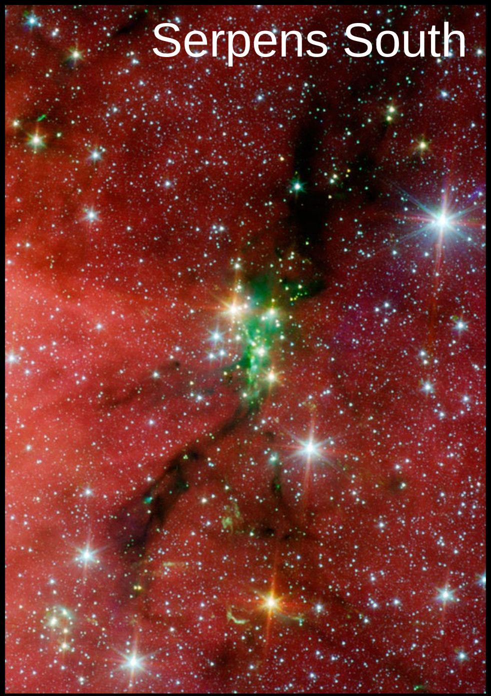


Photo credit: Bill Saxton NRAO/AUI/NSF

Known

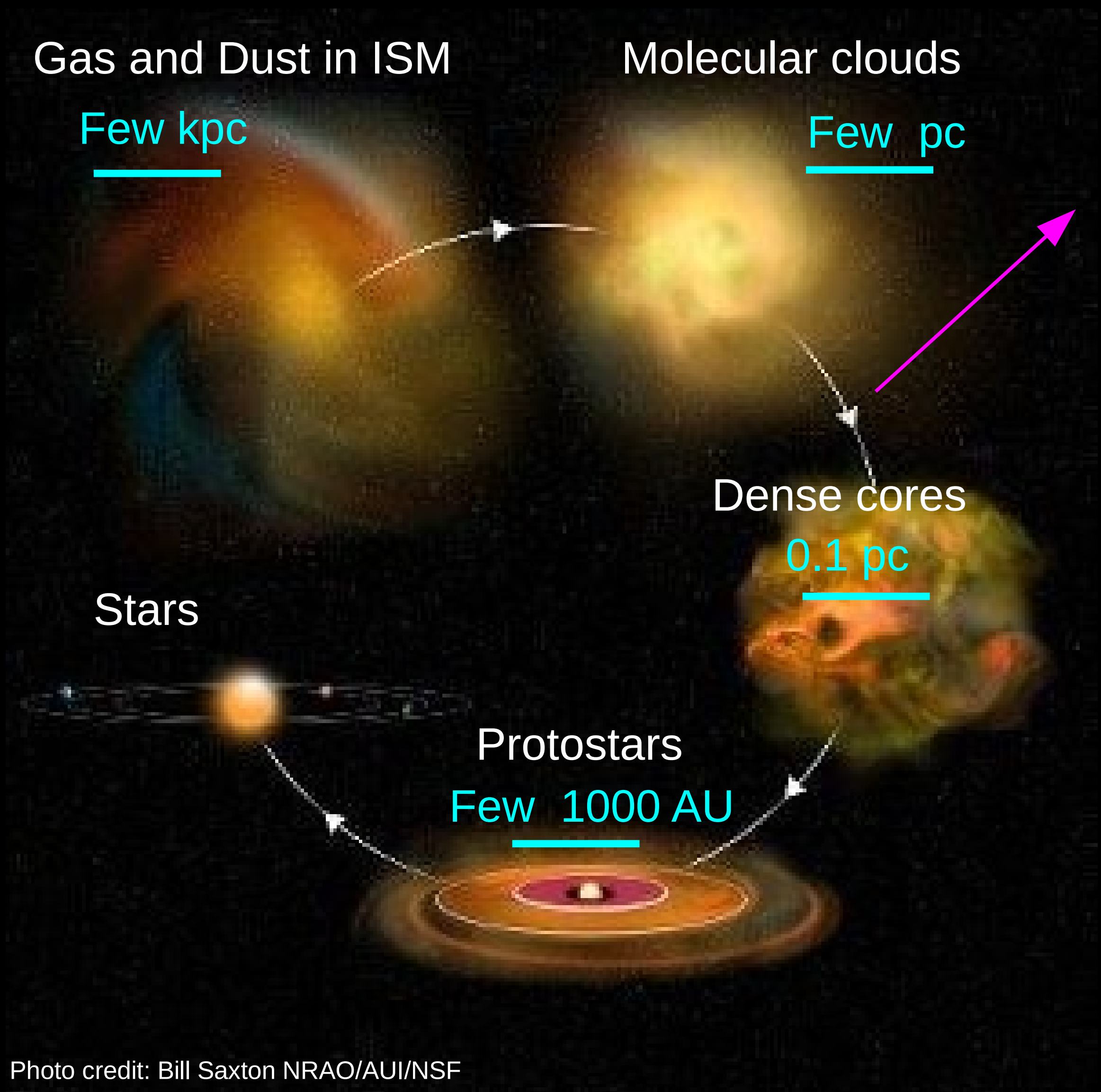
- Stars are formed in clusters
  (Lada & Lada 2003)
- Hub-Filament System (HFS)
  (Myers 2009)



Spitzer IRAC Gutermuth et al 2008

Known and Unknown: Parsec → 0.1 pc

A simplified cartoon



Known

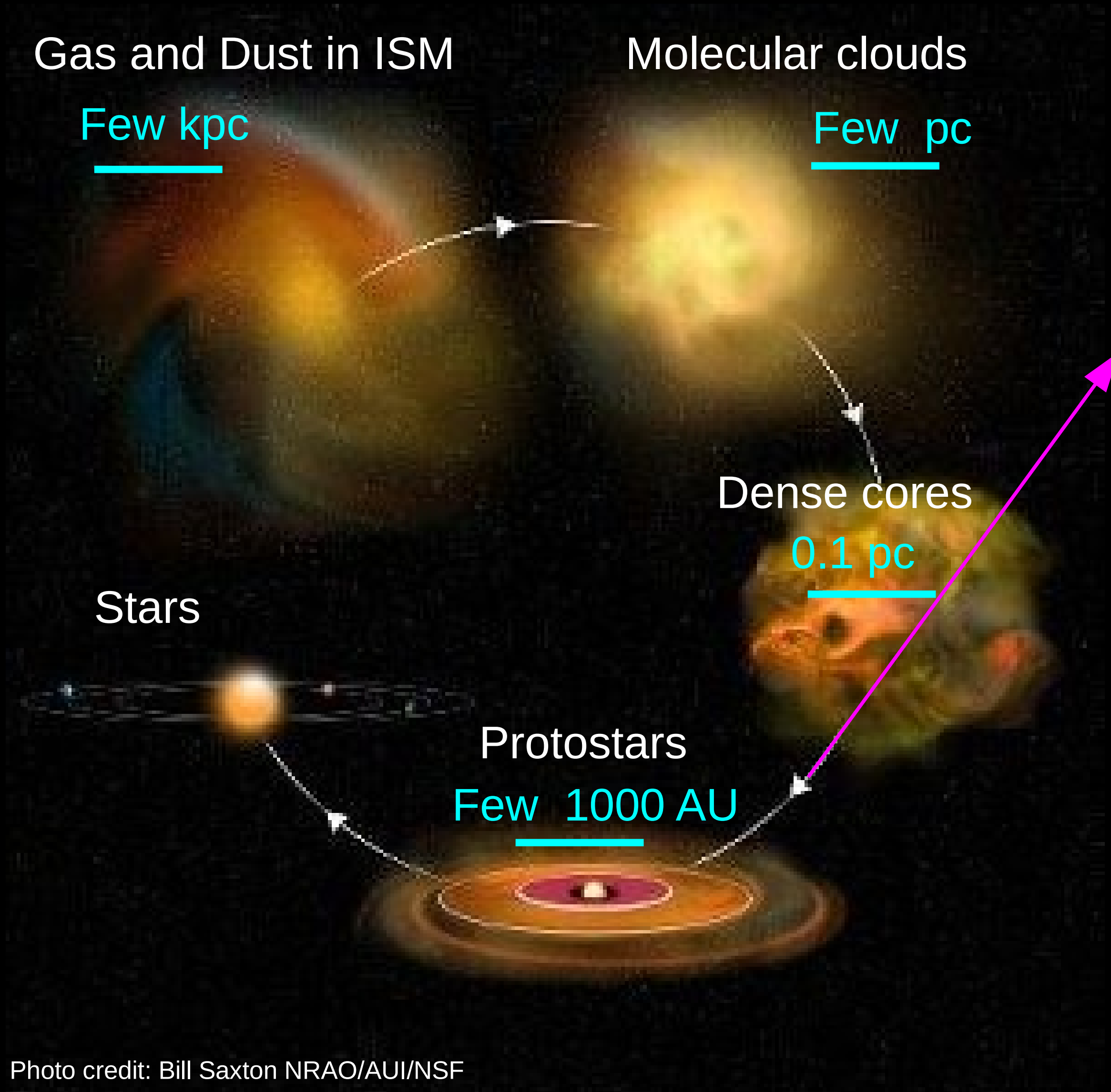
- Stars are formed in clusters
  (Lada & Lada 2003)
- Hub-Filament System (HFS)
  (Myers 2009)

Unknown

- What is the role of filaments in a hub-filament system?

Known and Unknown: 0.1 pc → 1000 AU

A simplified cartoon



Known

- Similarity between CMF and IMF in slope (e.g., Konyves et al 2010)
- Low-mass stars are often found in binary (Looney et al. 2000)

Unknown

- Is the stellar initial mass function imprinted in the structure of molecular clouds?

Motivation for CLASSy

- Cover areas of parsec scale with several thousand AU resolution
- Insights for star formation from dense gas structure and kinematics
- Span a wide range of activity levels from relatively quiescent regions to active cluster-forming regions

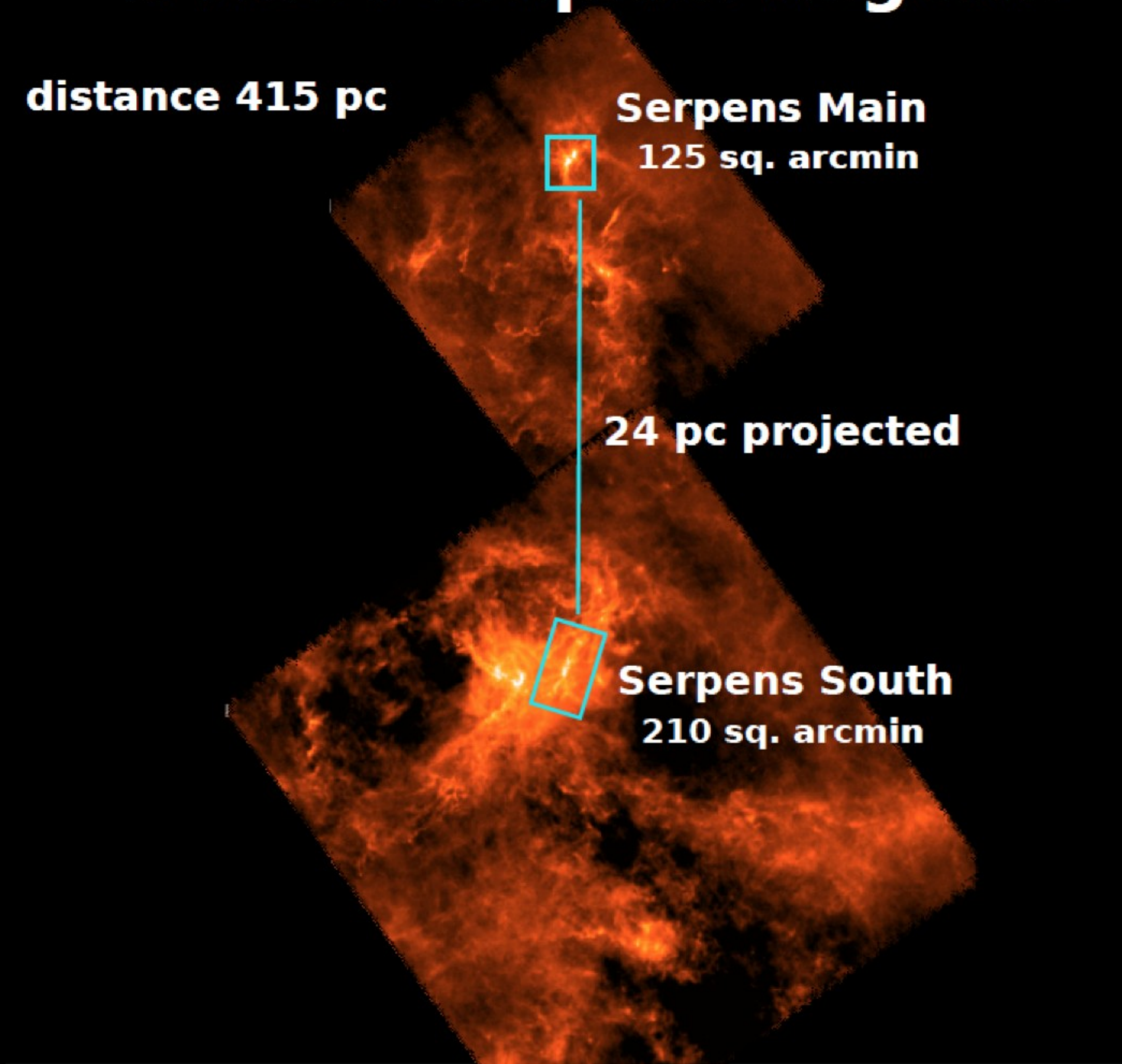
CLASSy Observations

- Observations cover 5 regions: Serpens Main, Serpens South, B1, NGC 1333, L1451
- Angular resolution: 7 arcsecs (3000 AU in Serpens). Spectral resolution: 0.16 km s^{-1}
- 120 to 200 square arcminutes each
- N_2H^+(1-0), HCO^+(1-0), HCN(1-0)
- CARMA-23 mode: combining interferometric and single-dish data to capture full emission

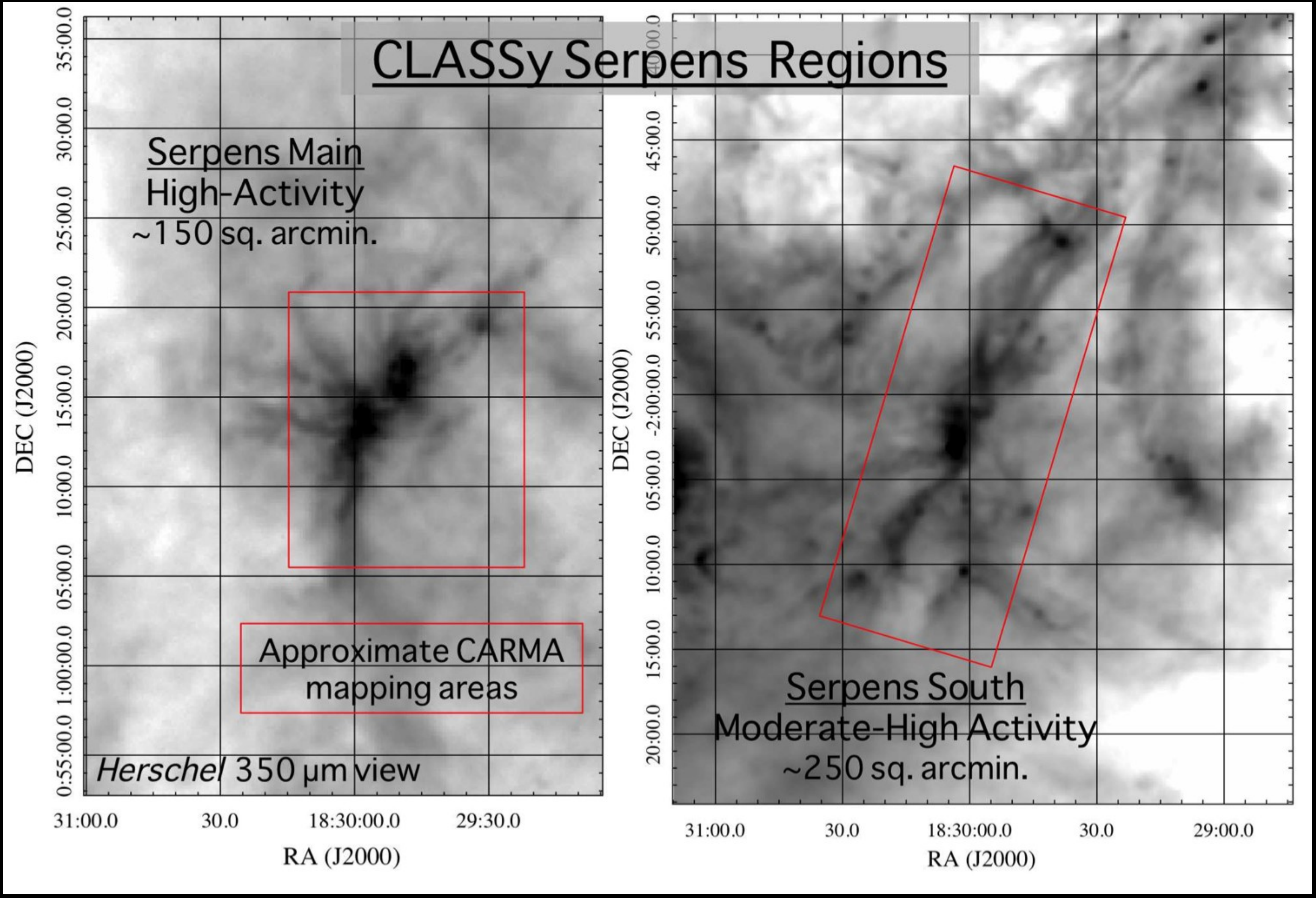
Why N_2H^+, HCO^+, HCN?

- They have high dipole moments so their emission dominantly arises in dense gas ($n > 10^5$ cm^{-3})
- N_2H^+ destroyed by CO, but stays in gas phase when CO goes into ices -> N_2H^+ prefers cold (< 20 K) places
- HCO^+ in regions of high ionization and CO abundance
- HCN is intermediate. It doesn’t like ionization but it doesn’t like cold places either

CLASSY Serpens Regions



Serpens Main and Serpens South



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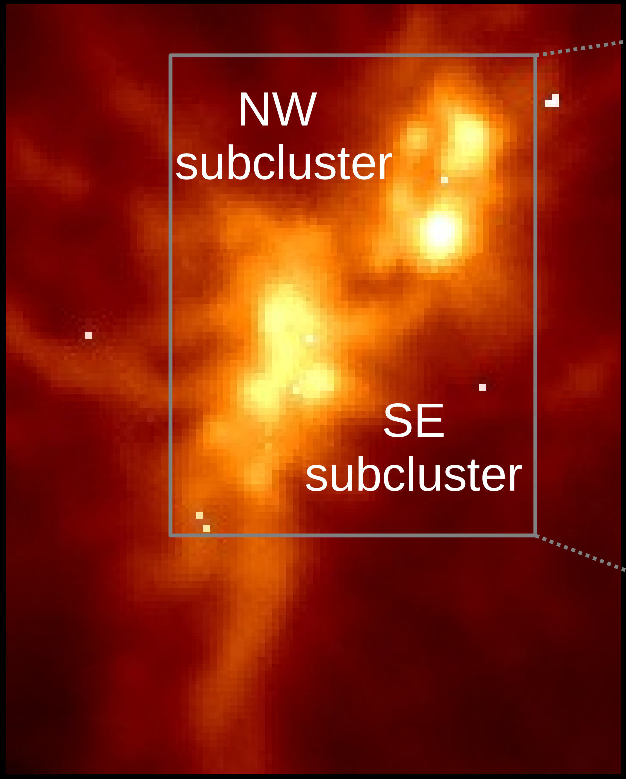
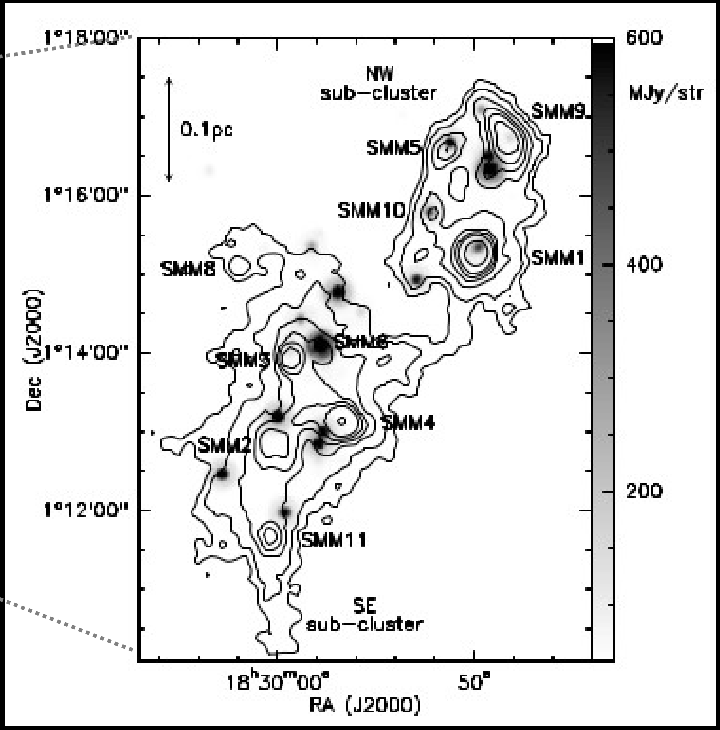
Serpens Main

Herschel 250 micron



HSA

Contour: SCUBA 850 micron
Grey scale: Spitzer 24 micron

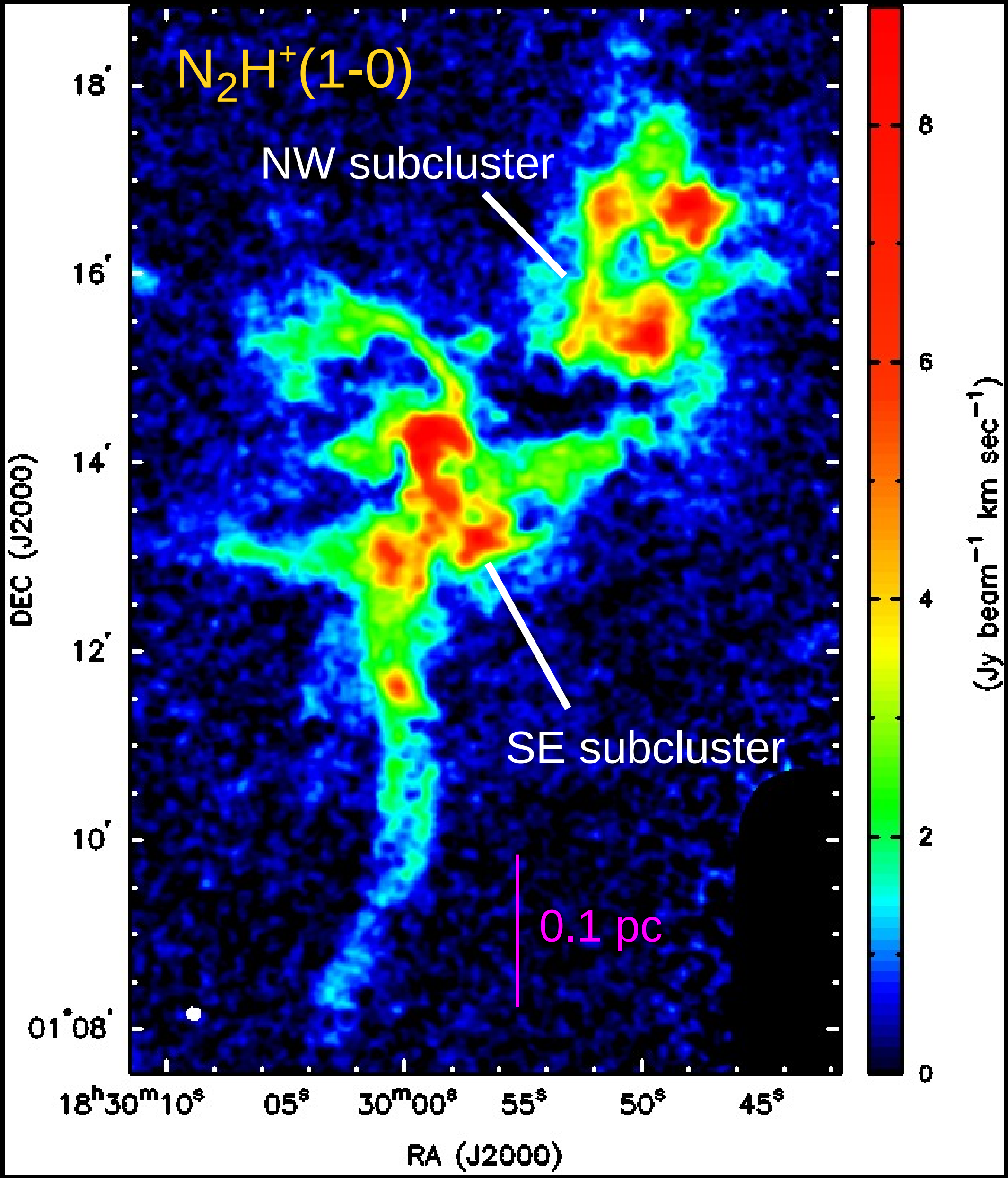


Davis et al. 1999; Harvey et al. 2007

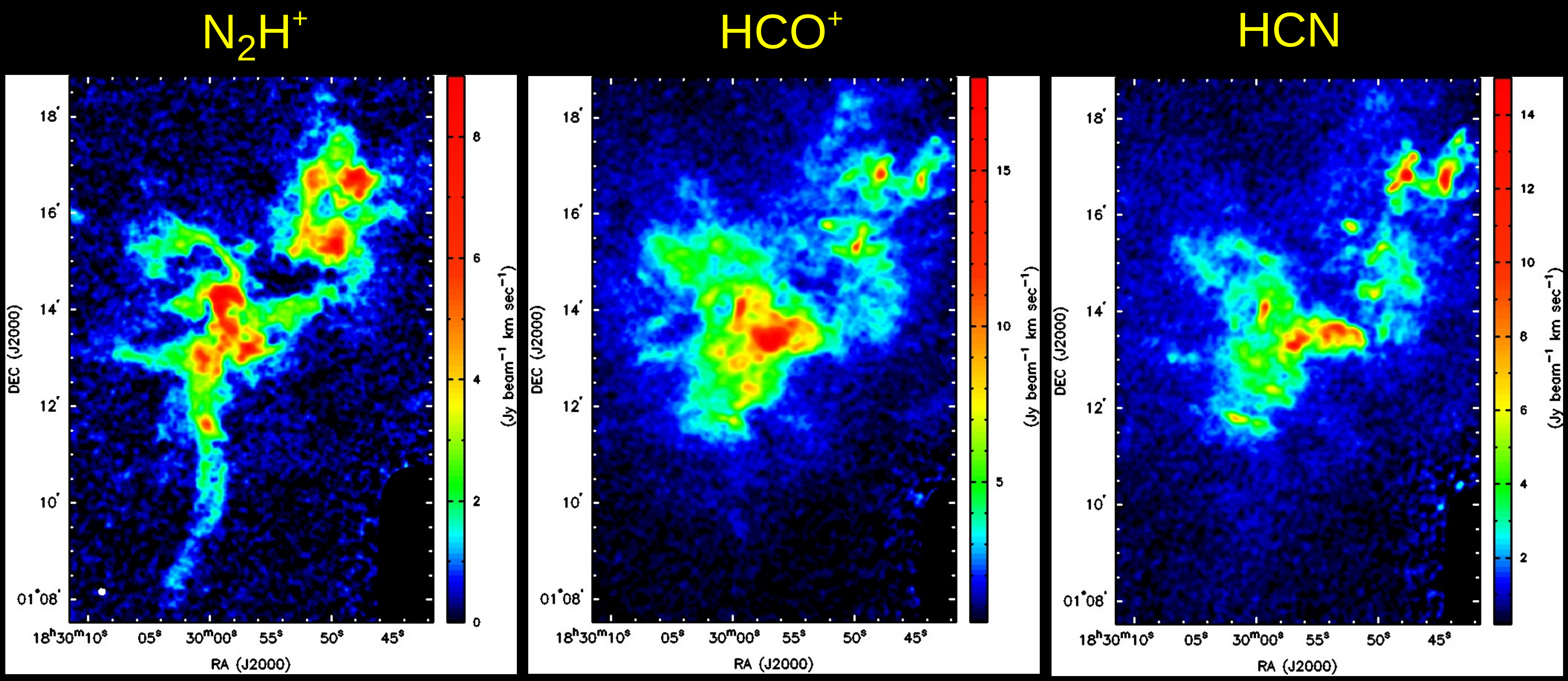
- Active star-forming region
- Distance of 415 pc
- A Hub-Filament System
- Dust concentrated in two subclusters
- Nearly hundred YSOs
- 11 SMM cores; outflows associated
- NW ~ 100 $M_{\odot}$
  SE ~ 150 $M_{\odot}$
  (Olmi & Testi 2002)

Gas Structures in Serpens Main

- Gas concentrated in NW and SE subclusters
- Filamentary structures in the SE subcluster
- Two resolved filaments in the south for the first time



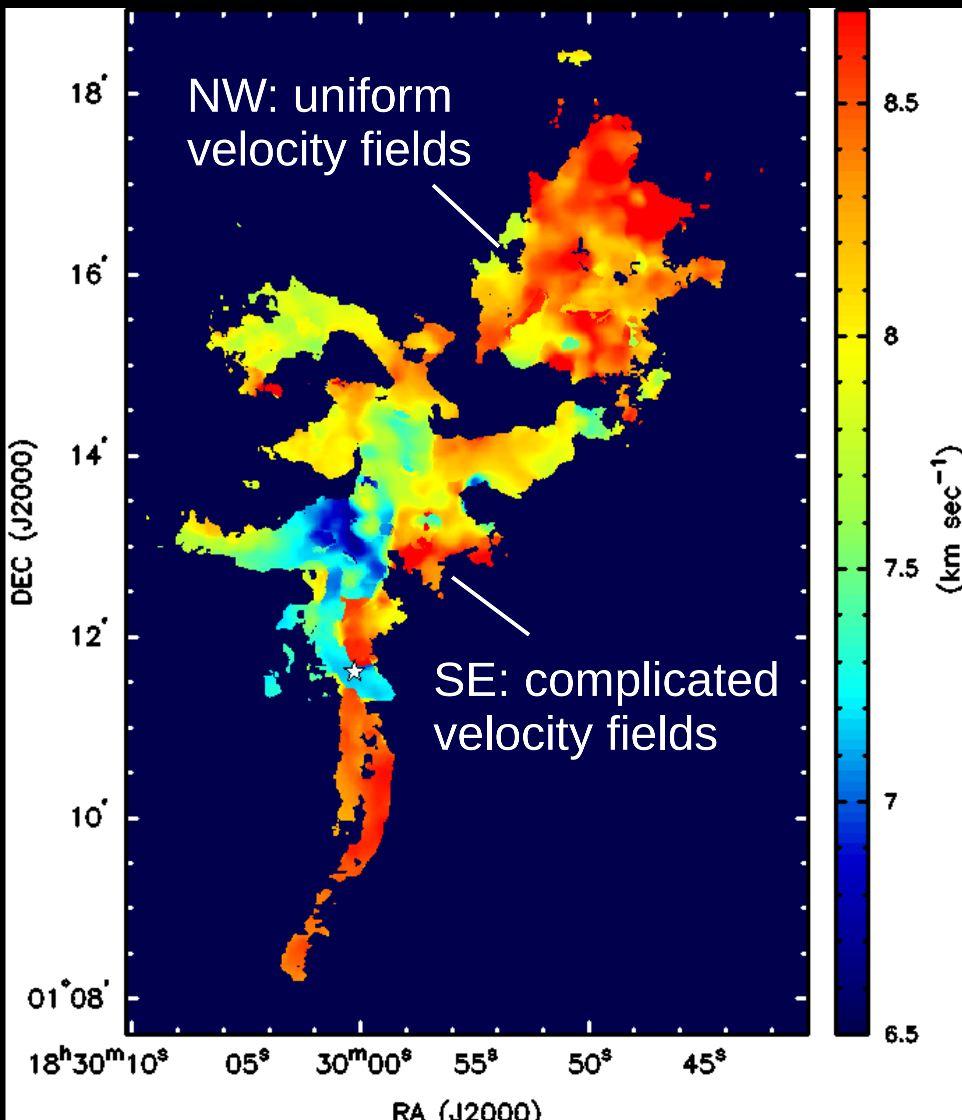
Gas Structures in Serpens Main



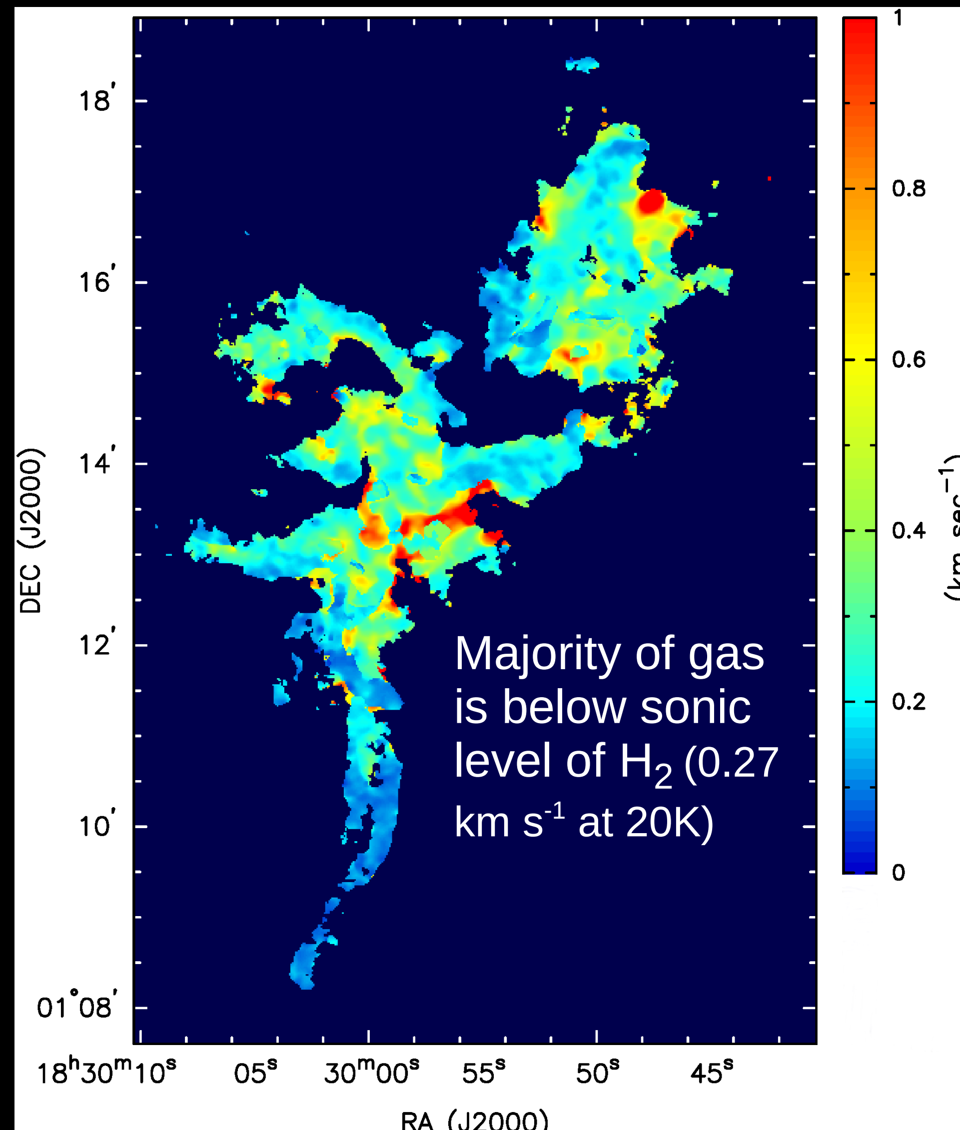
- N_2H^+ resembles dust emission the most, and shows the most obvious filamentary structures
- HCO^+ and HCN show more extended structures
- HCO^+ and HCN are likely to be affected by foreground, low-density gas

Gas Kinematics with N_2H^+

Velocity centroid map



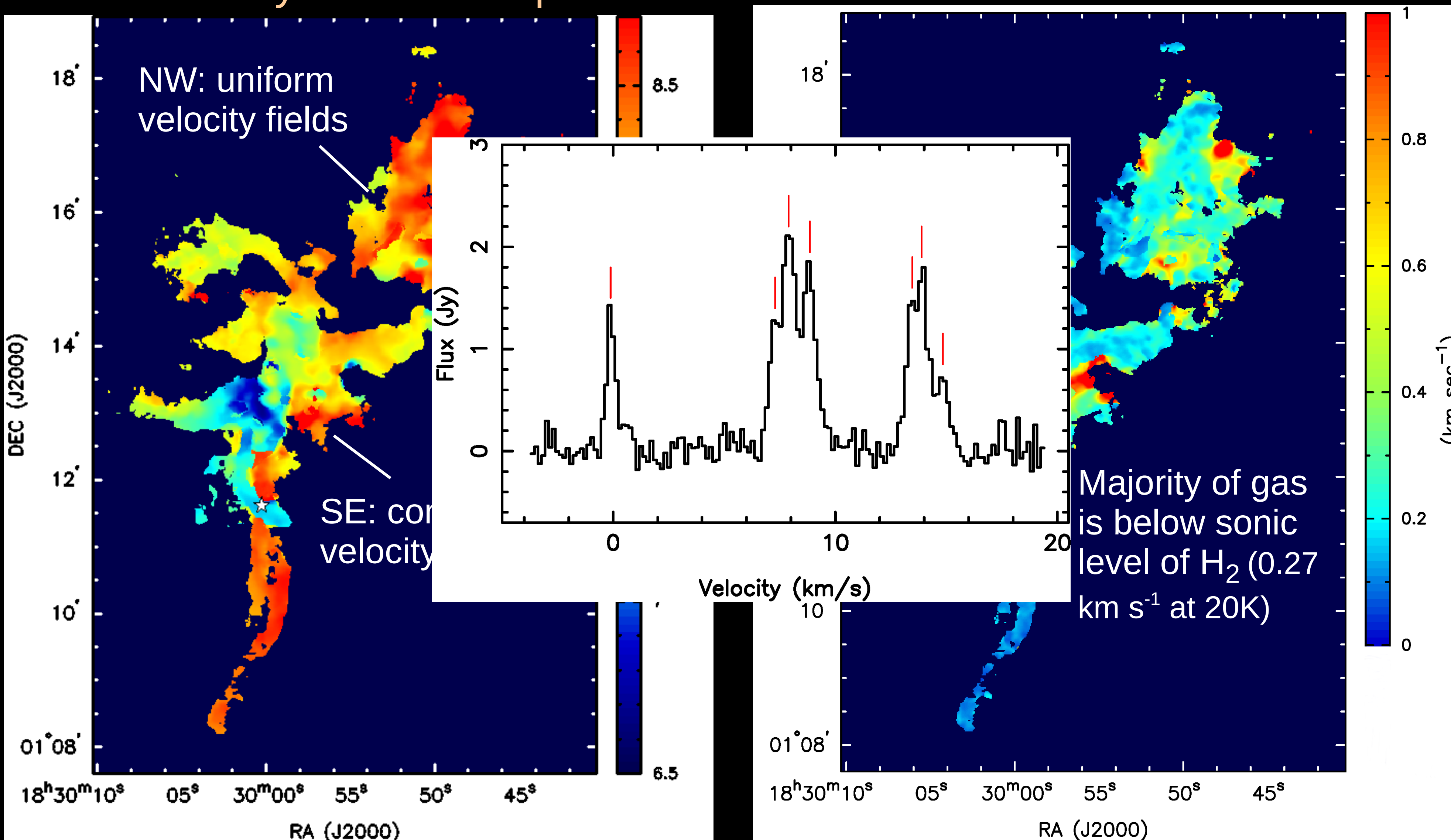
Velocity dispersion map



Gas Kinematics with N_2H^+

Velocity centroid map

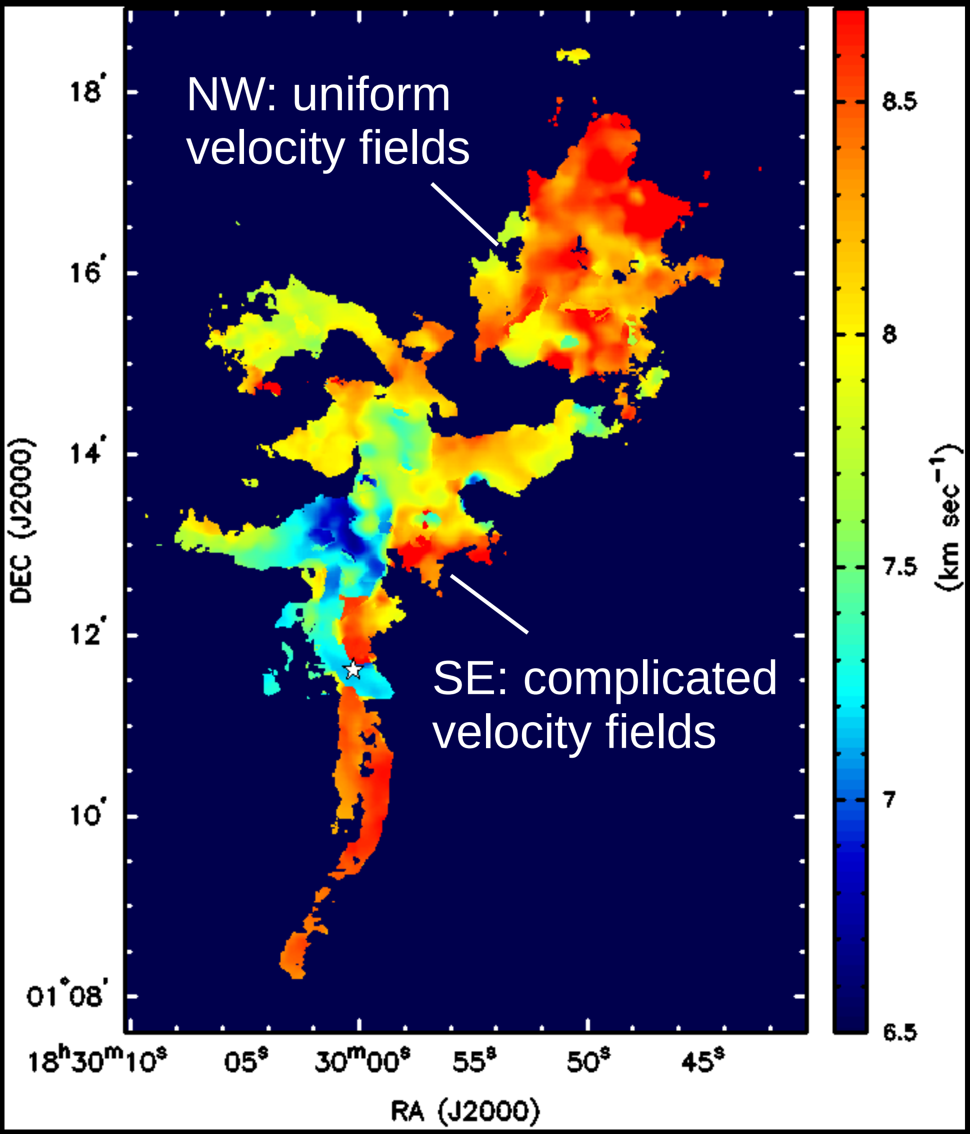
Velocity dispersion map



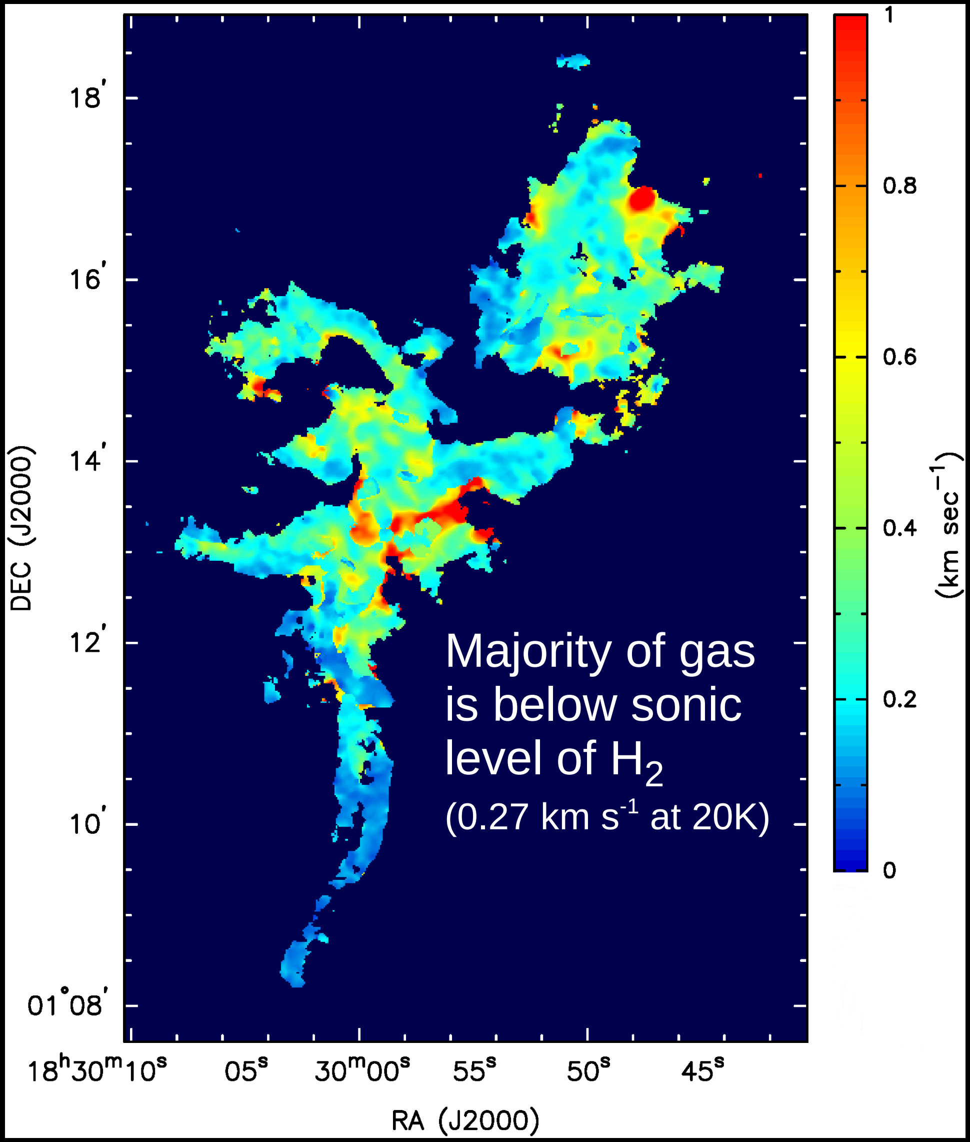
Majority of gas is below sonic level of H_2 (0.27 km s^{-1} at 20K)

Gas Kinematics with N_2H^+

Velocity centroid map

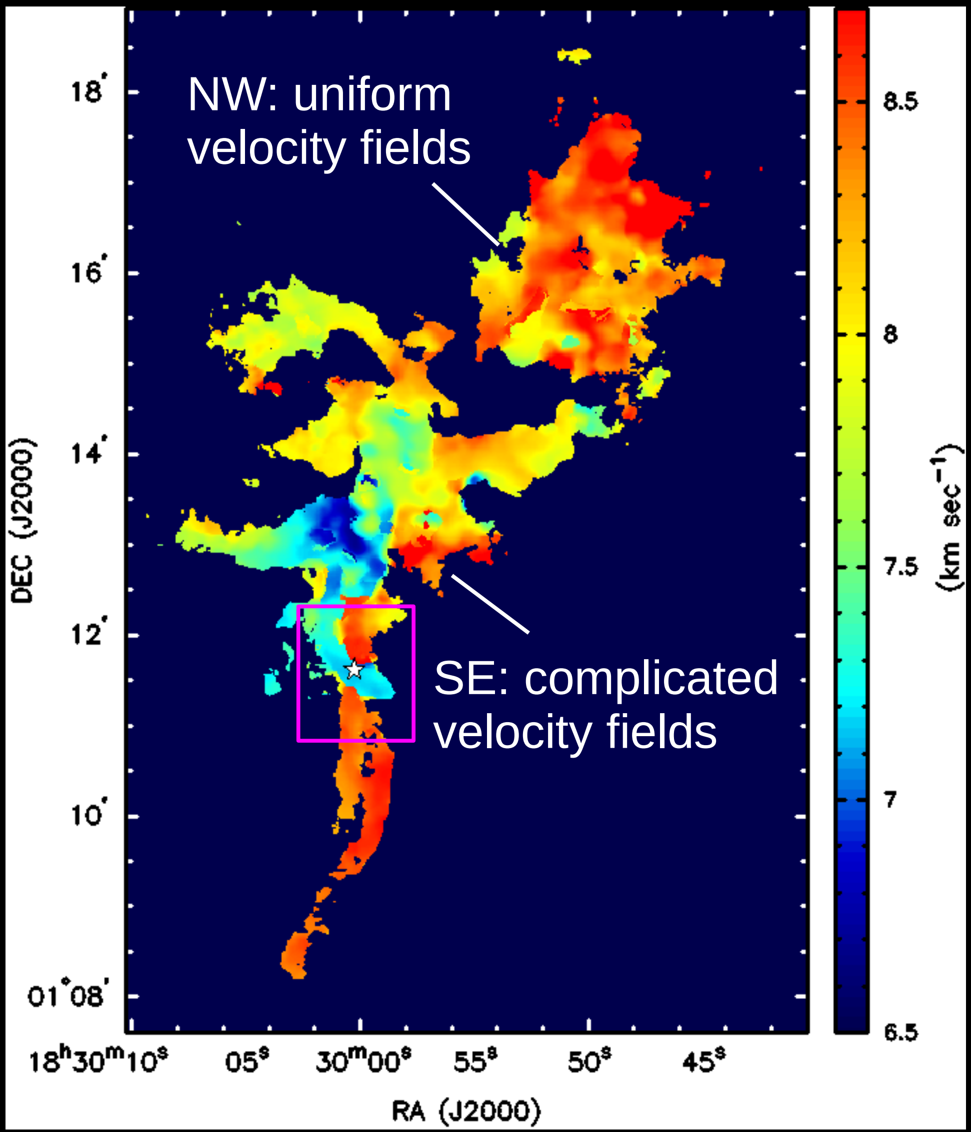


Velocity dispersion map

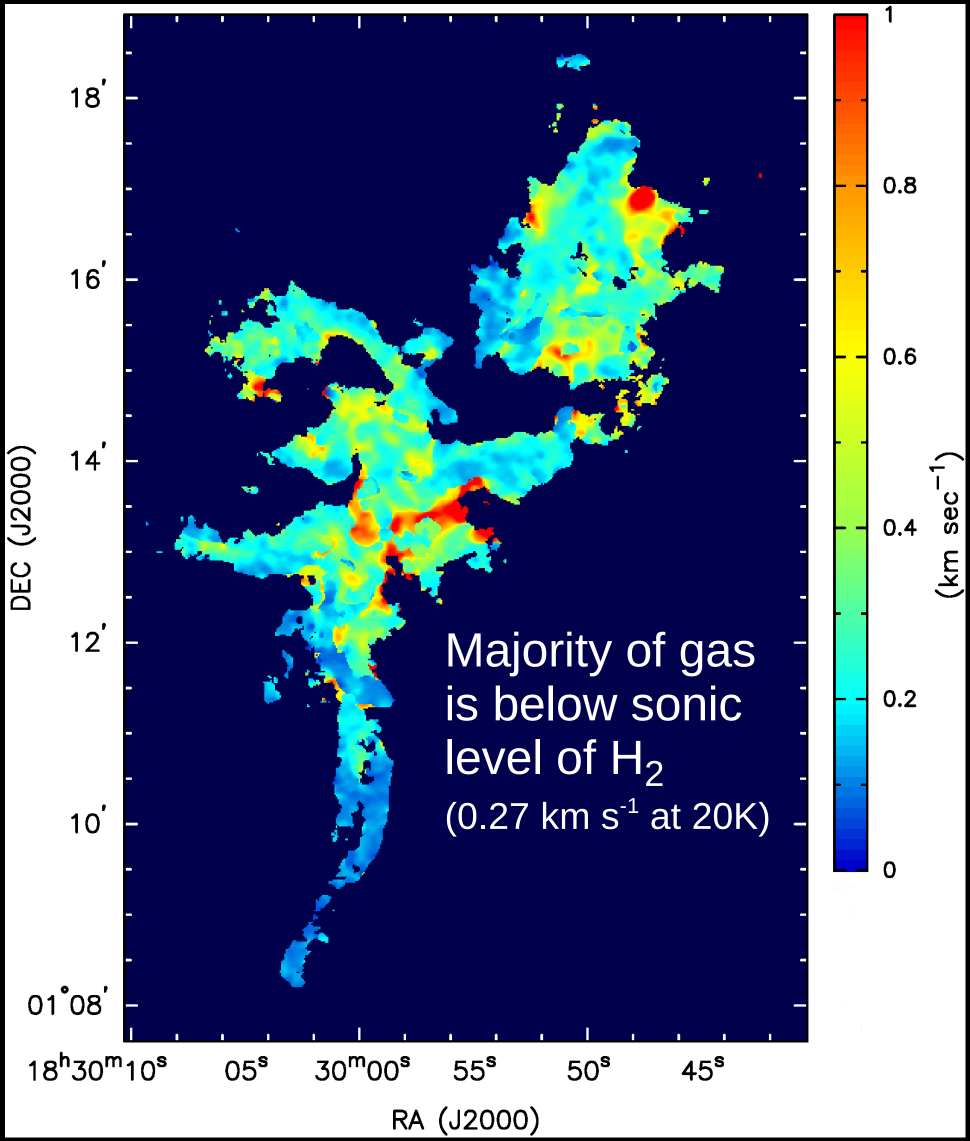


Gas Kinematics with N_2H^+

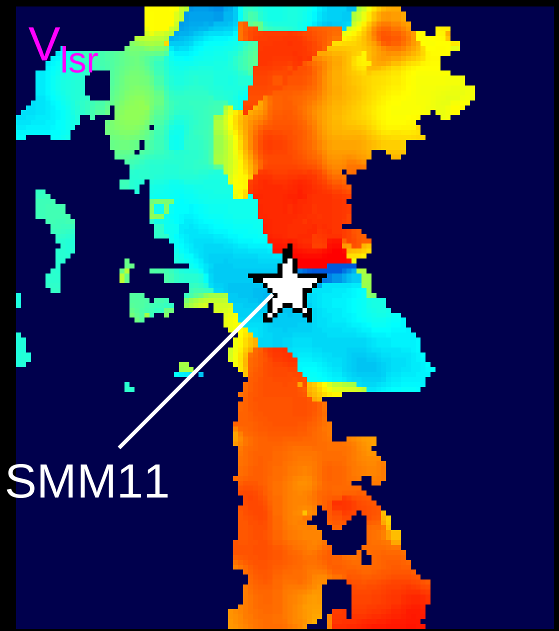
Velocity centroid map

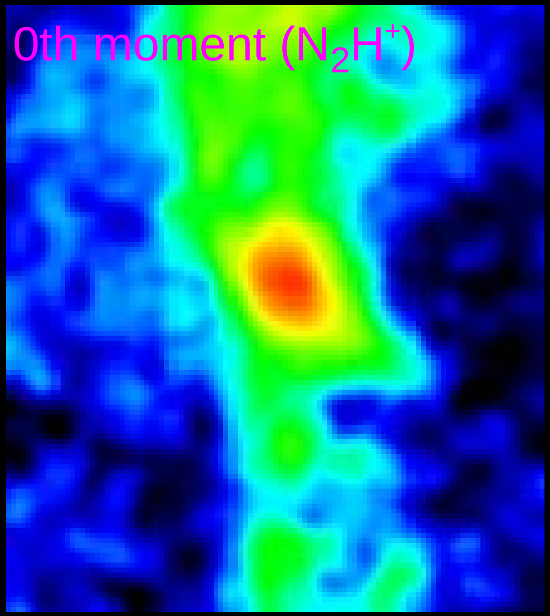


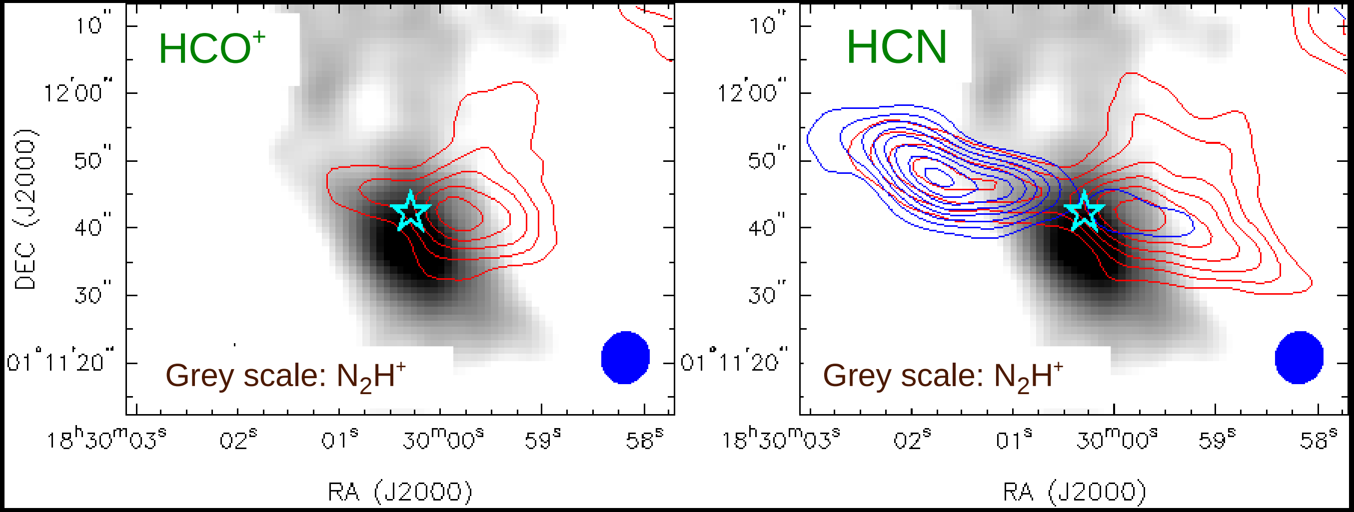
Velocity dispersion map



Gas Kinematics near SMM11







- Two overlapping filaments with different velocities
- N_2H^+ enhancement in the overlapped position
- Outflow detection with HCN and HCO^+
- Follow-up with SMA

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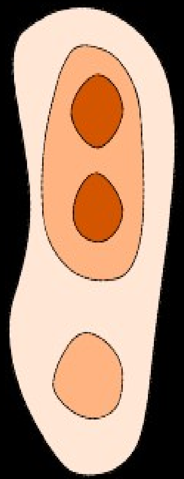
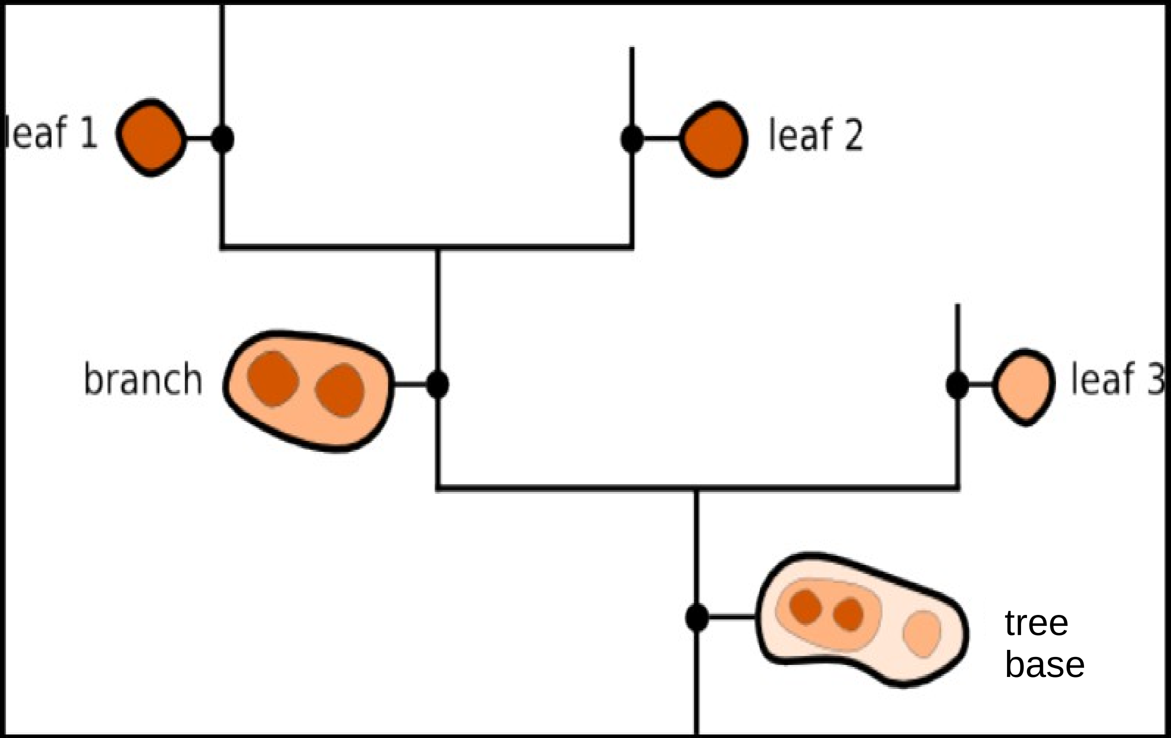
Dendrogram Analysis with N_2H^+

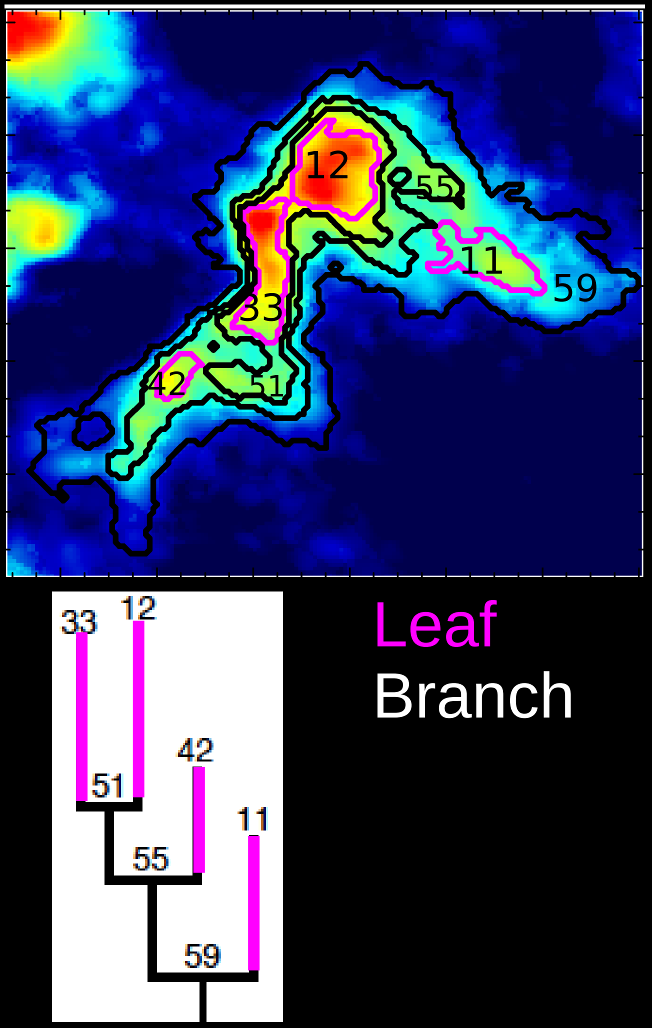
Identifying hierarchical structures in the gas

Dendrogram



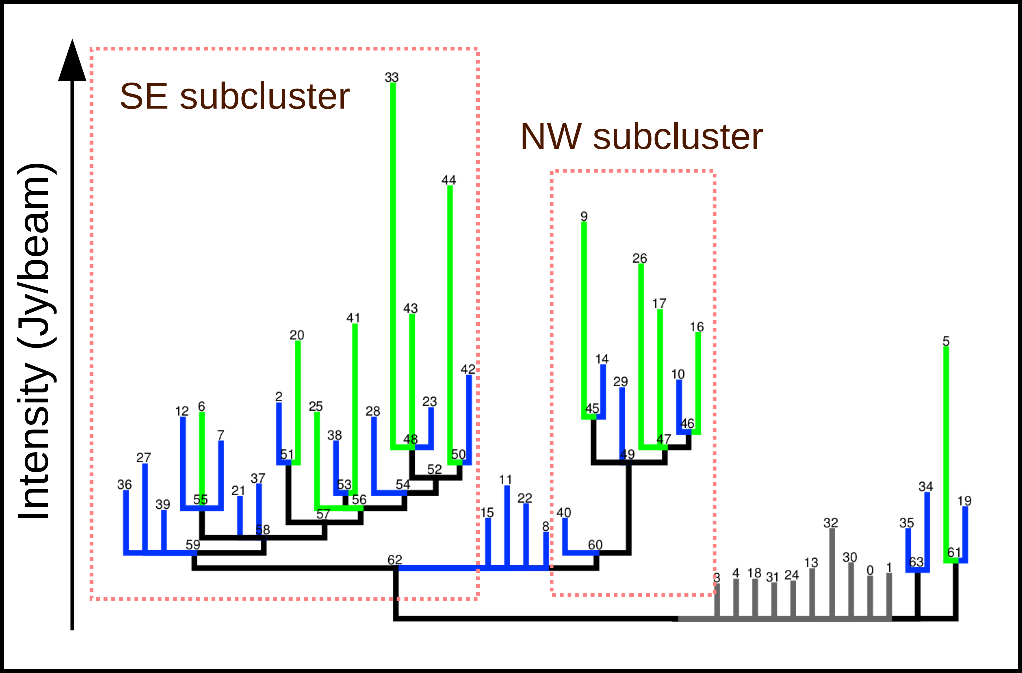


IRAS 2 region of NGC 1333



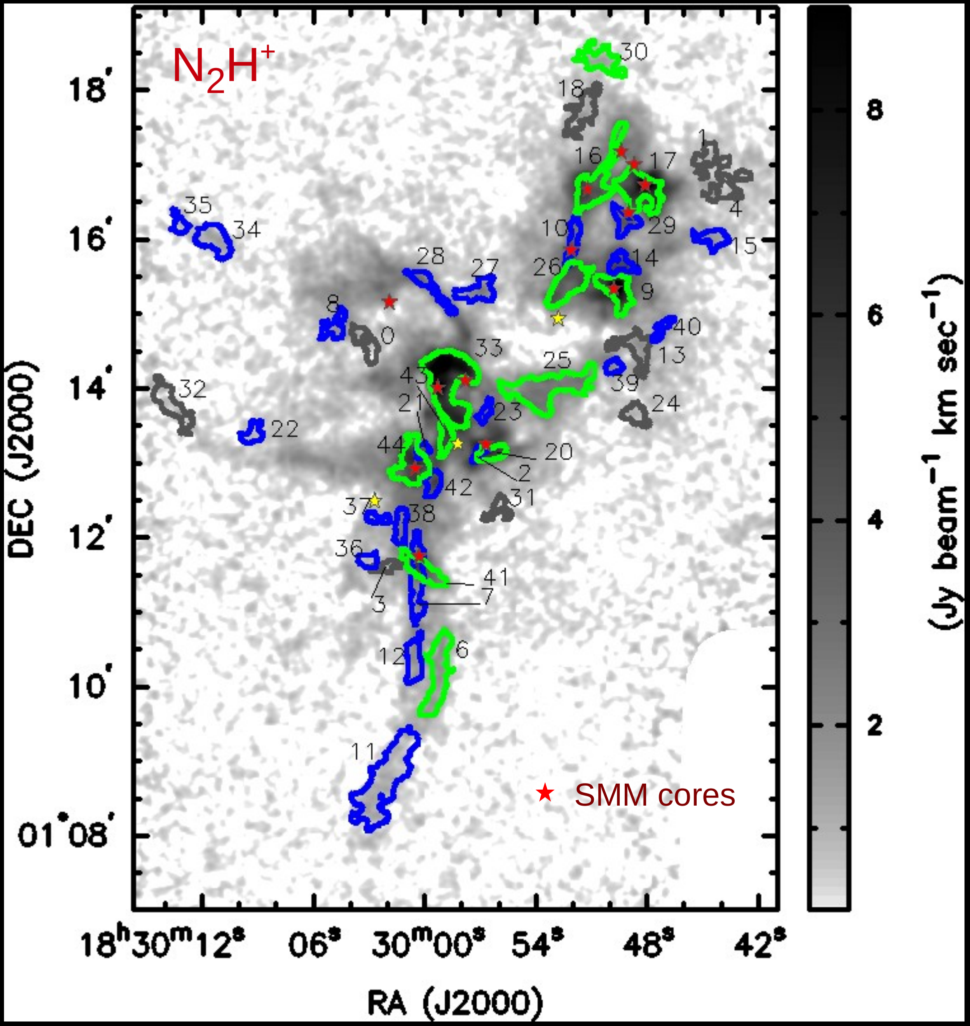
Dendrograms avoid small-scale segmentation and naturally captures structures at large scales.
3D (PPV) identification.

Dendrogram in Serpens Main



Green: High-contrast leaves
Blue: Low-contrast leaves

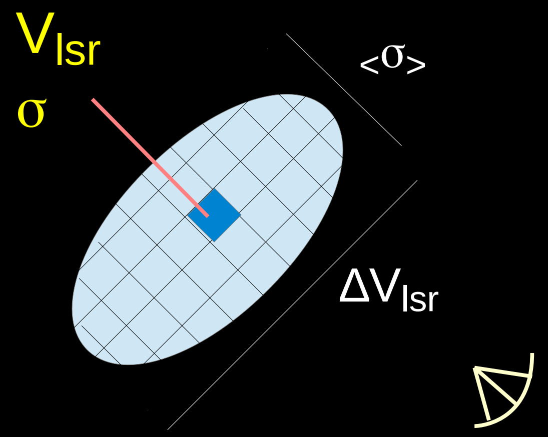
SE subcluster exhibits more complicated hierarchical structure compared to NW



- Correlation with SMM cores: High-contrast leaves may be linked with forming dense cores

Kinematic Properties of Dendrogram

Every pixel has fitted centroid velocity (V_{lsr})
Velocity dispersion (σ)



ΔV_{lsr}: how V_{lsr} vary across the object; standard deviation of V_{lsr}

Radial gas motions across the plane of sky

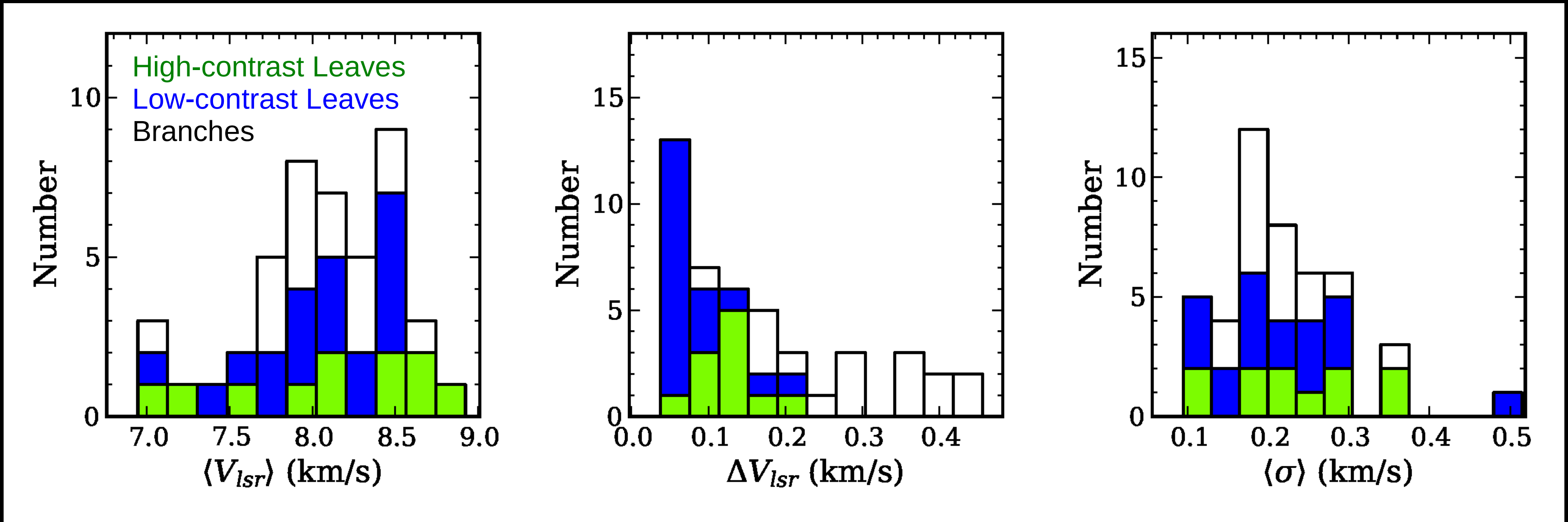
$<\sigma>$: mean velocity dispersion in an object

Gas motions along the line of sight

Serpens Main

Branches have larger ΔV_{lsr} than leaves

No difference between leaves and branches



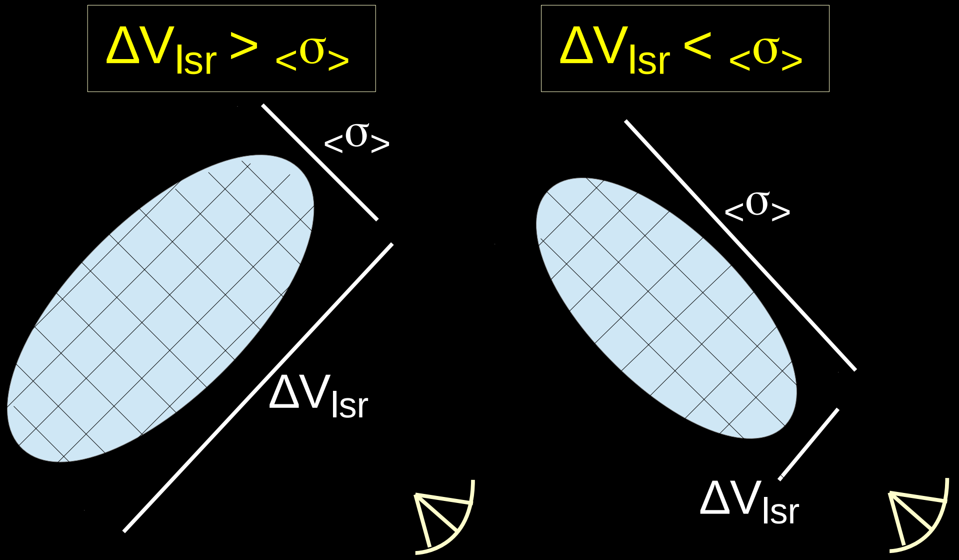
The Characteristic Cloud Depth

Assumption: Gas motions are characterized by isotropic 3D turbulence

$$\sigma_v(\ell) \propto \ell^q$$

$\langle\sigma\rangle$: mean gas motions along line of sight

ΔV_{lsr}: radial gas motions on the plane of the sky



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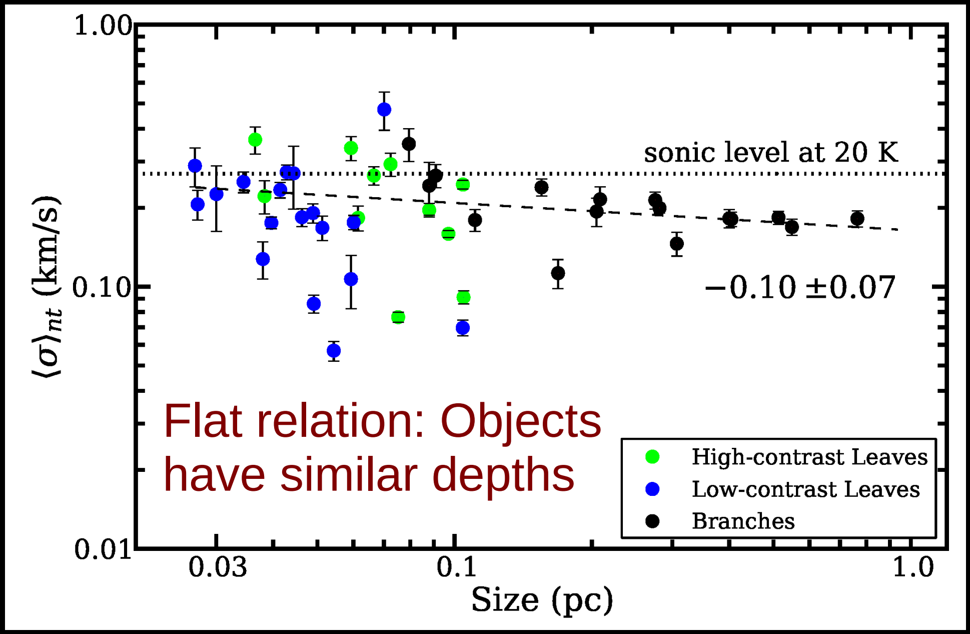

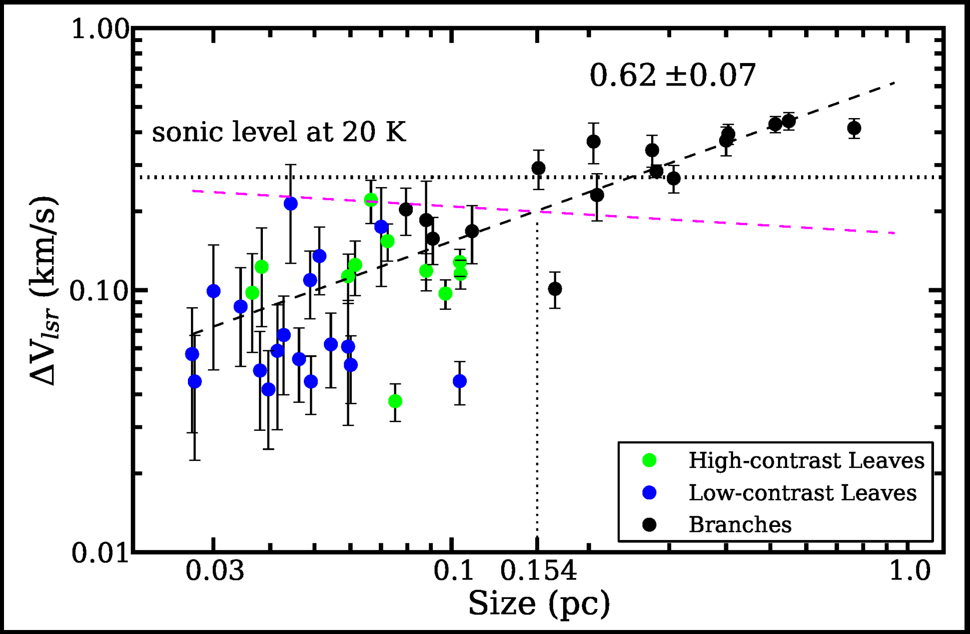

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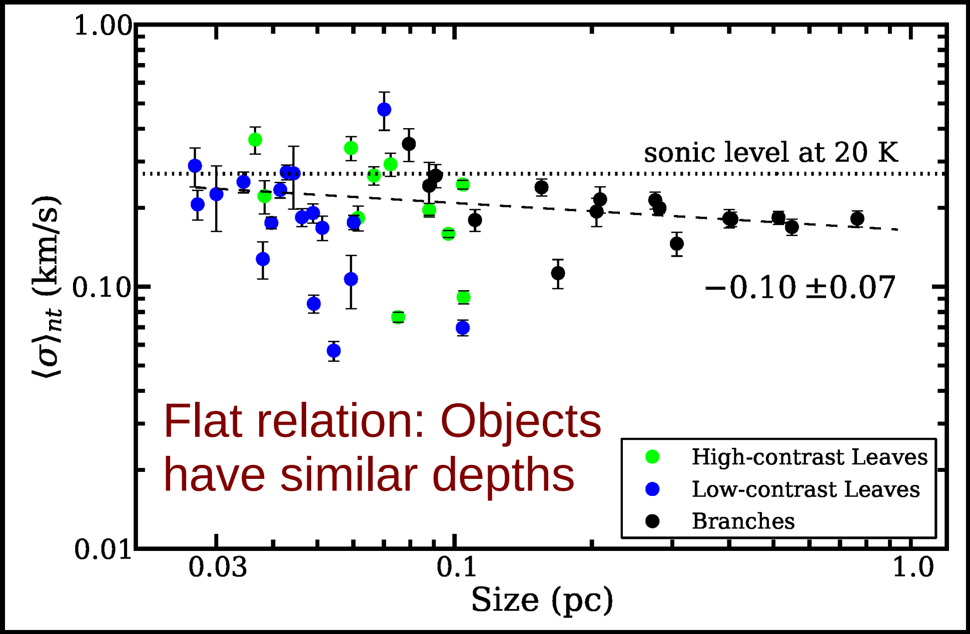
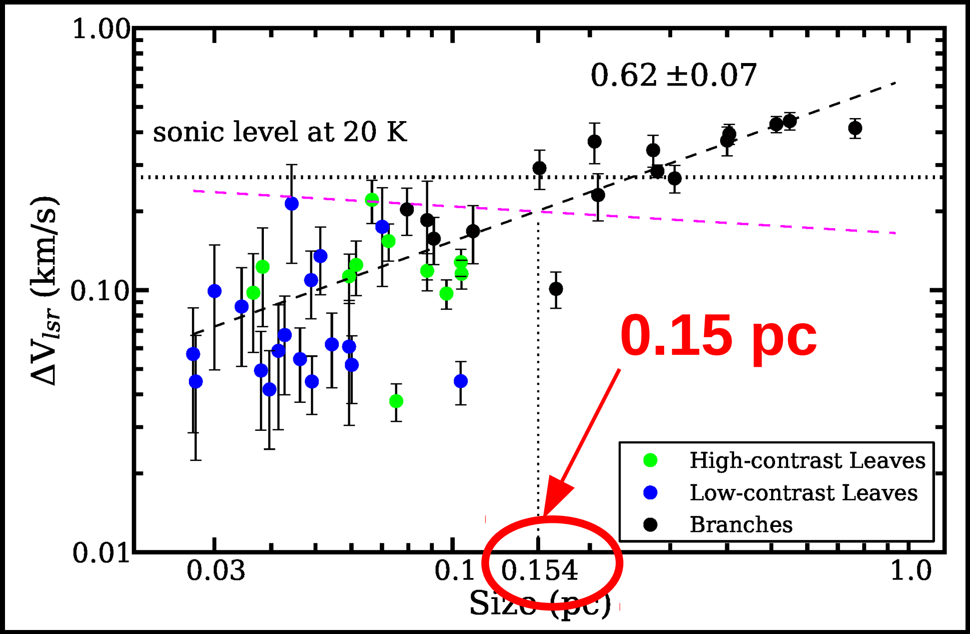


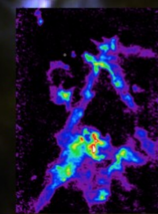


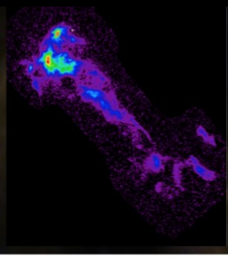
Dendrograms Across Perseus

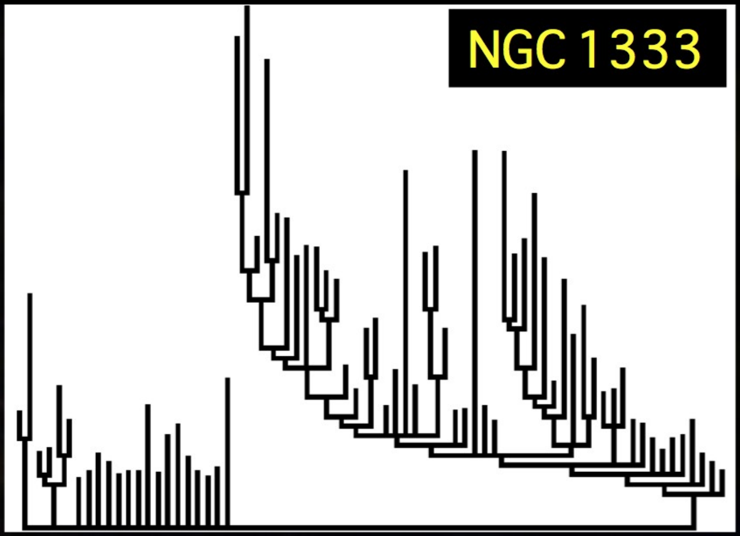
Hierarchical complexity

↕

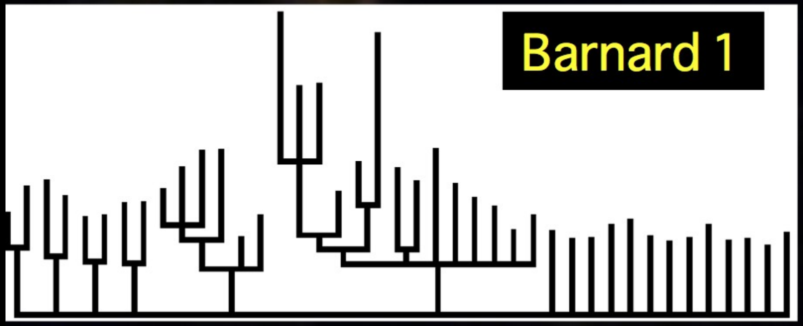
Star formation activity





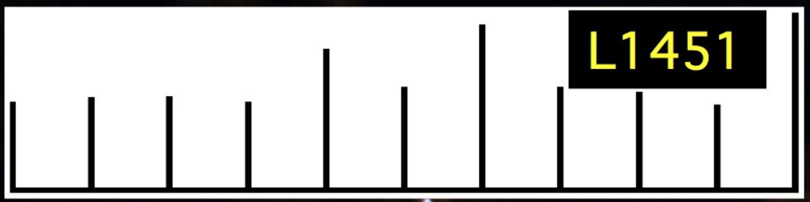


16-Level Hierarchy

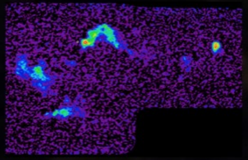


4-Level Hierarchy

Dense gas in NGC 1333 has more hierarchical complexity than in Barnard 1; L1451 dense gas shows no hierarchical structure.



0-Level Hierarchy



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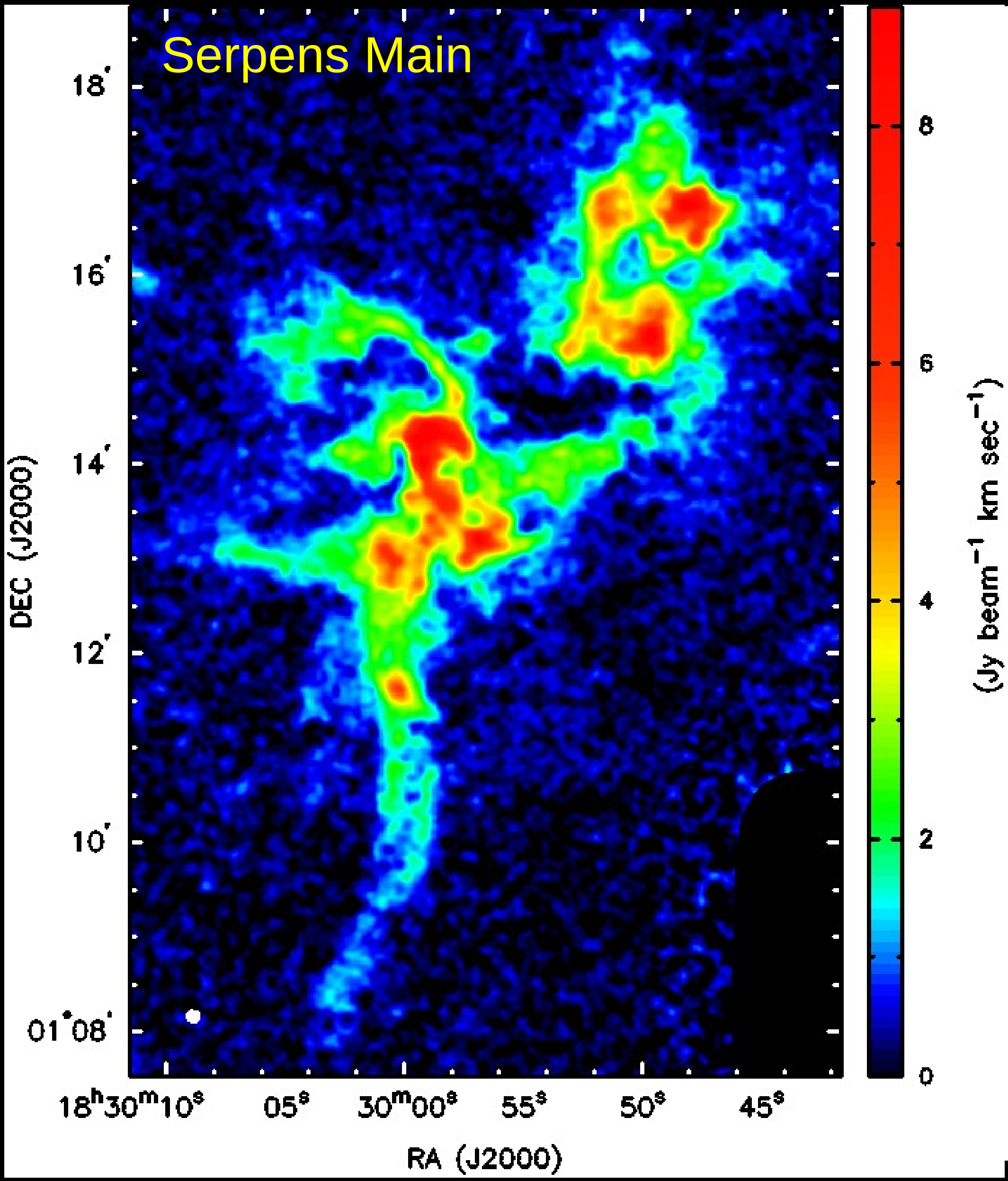
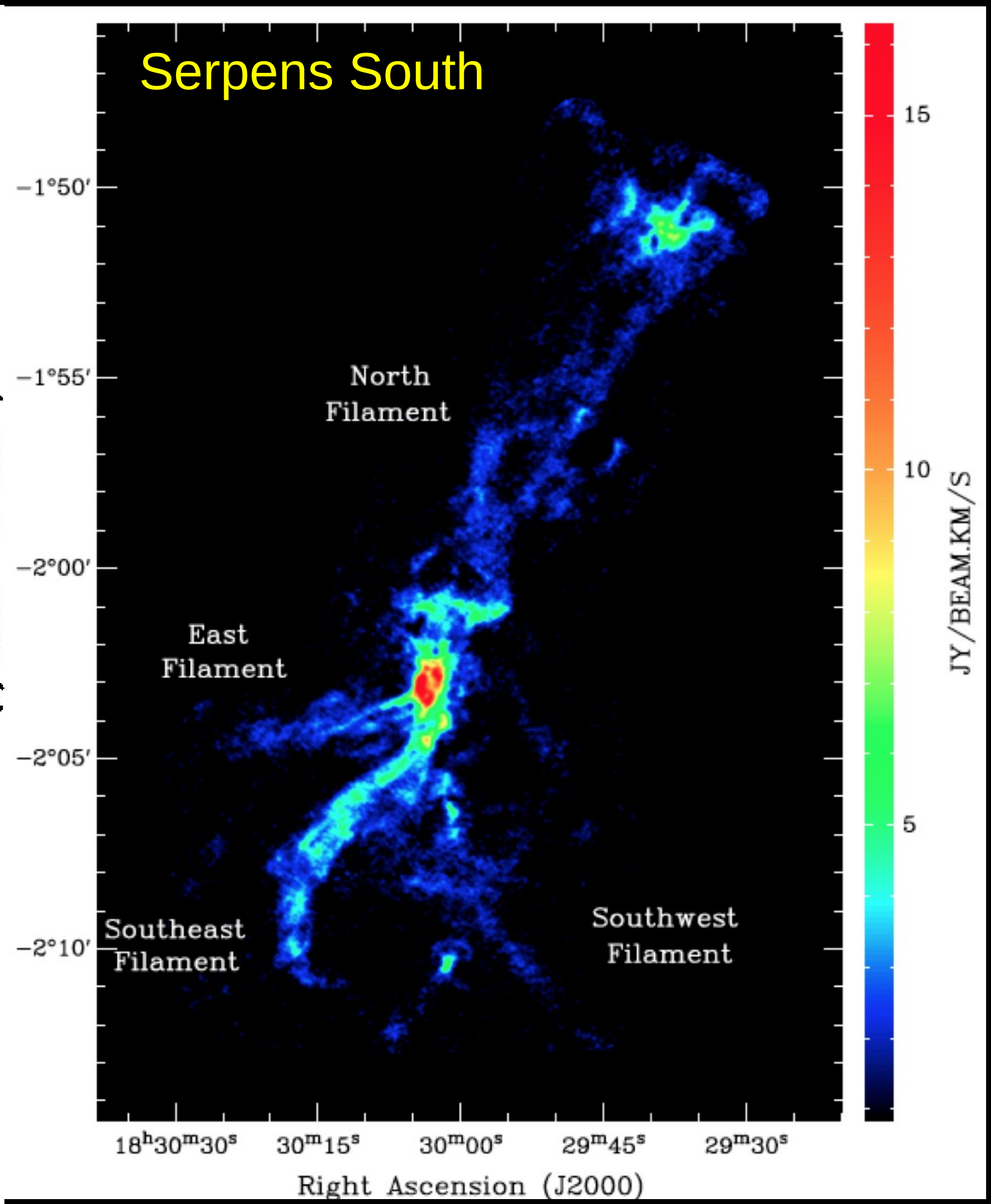
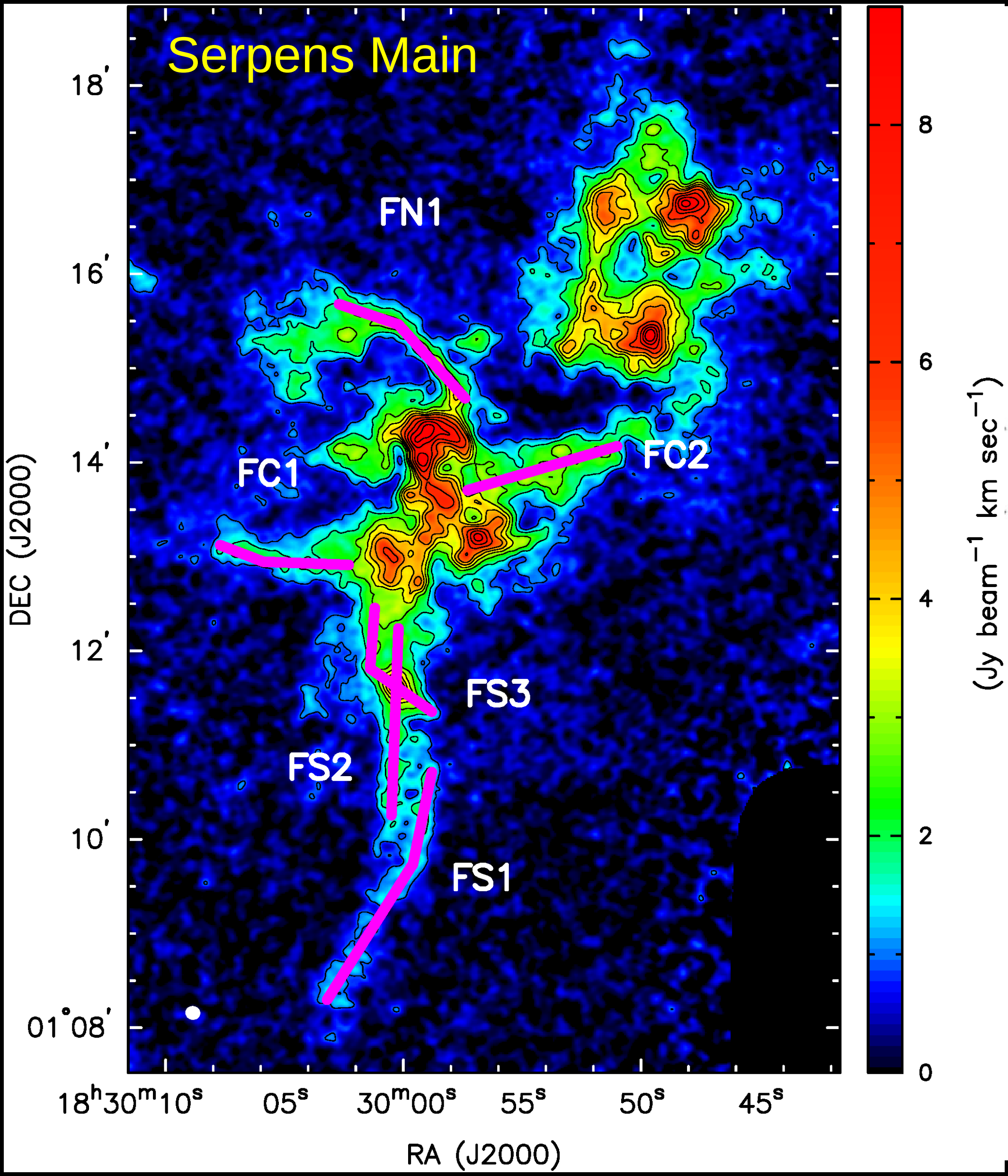
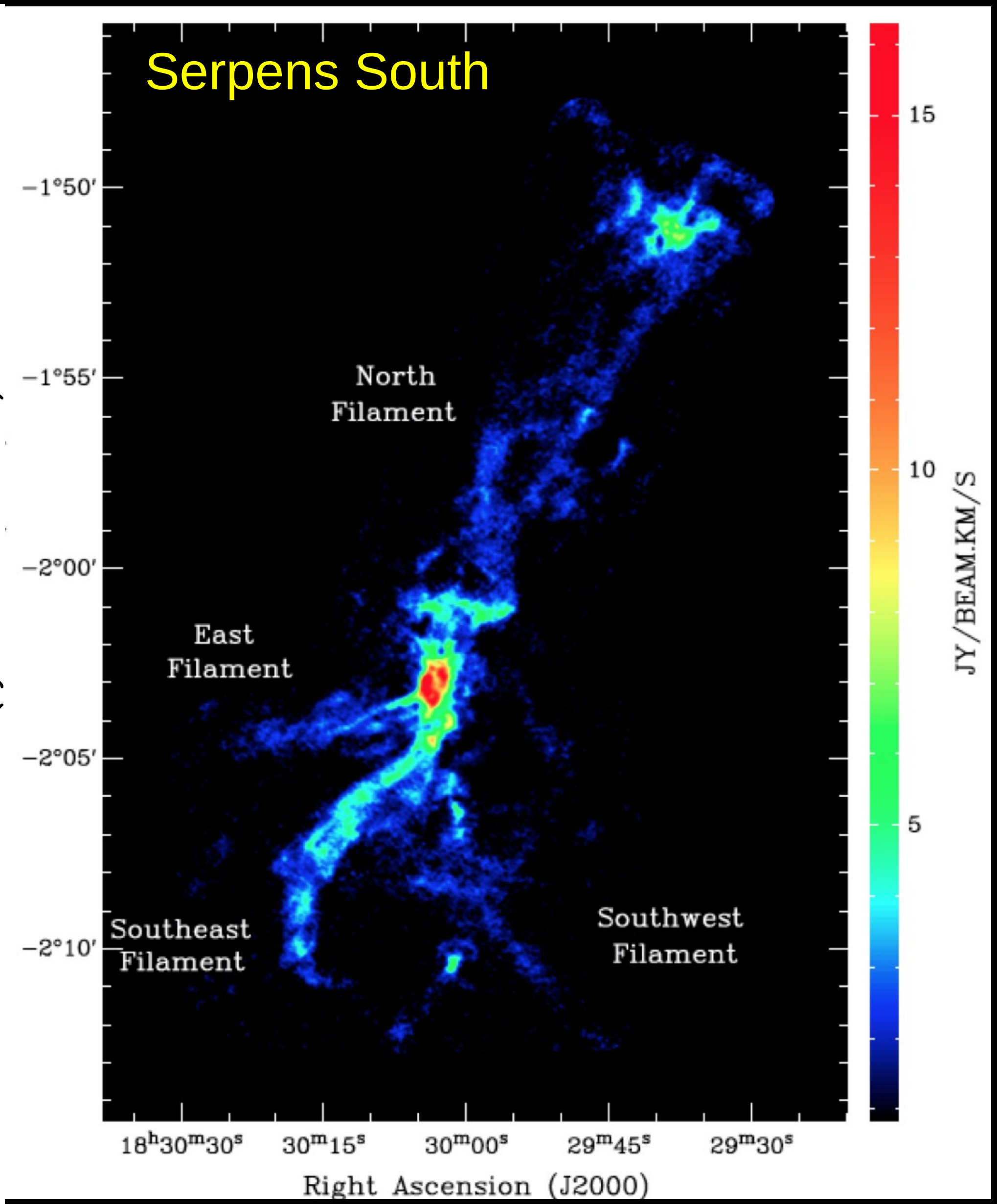
Filaments in Serpens





Filaments in Serpens

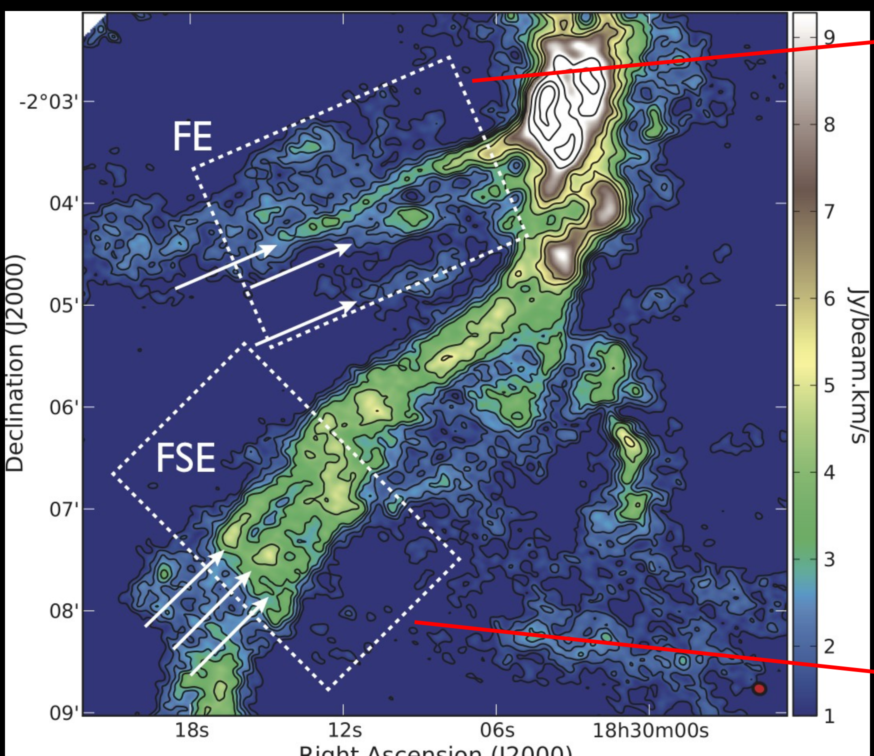


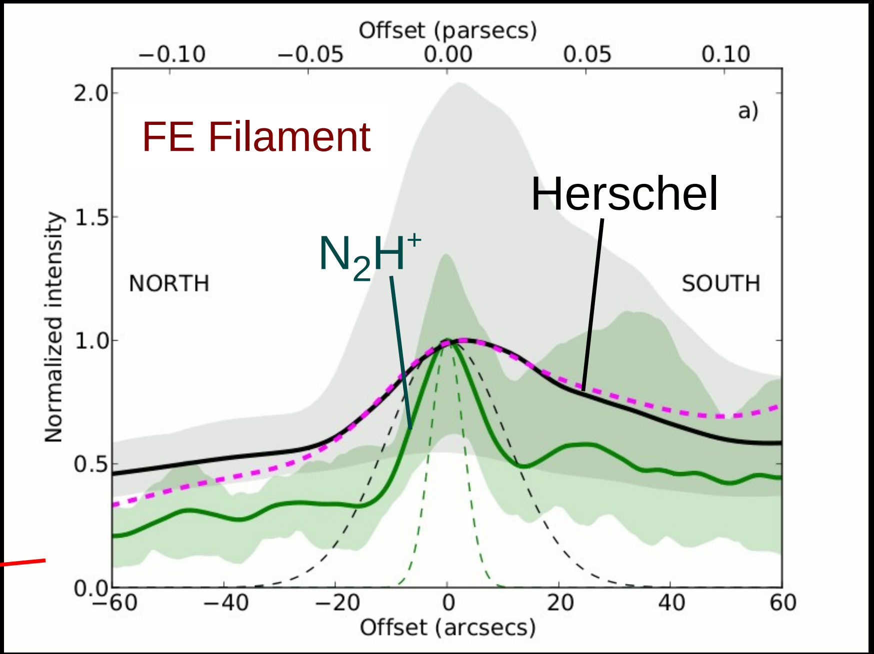


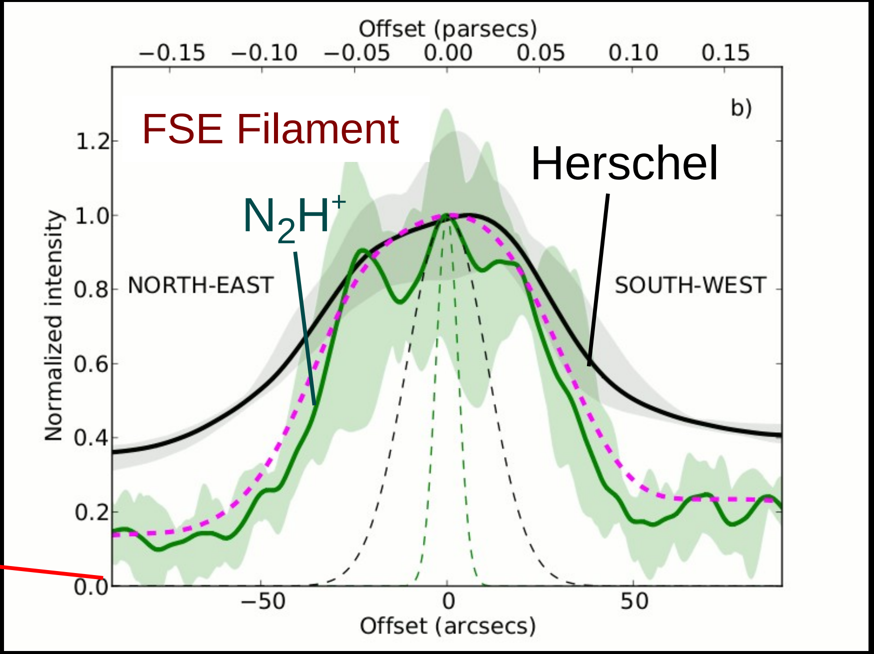
N_2H^+ Filament Widths ~ 0.03 pc

- Filaments in Serpens Main and Serpens South show an average width of 0.035 pc
- One-third of the Herschel width of 0.1 pc
- Combination effect from excitation conditions and chemical reactions
- Quasi-parallel filaments in one Herschel filament

Filaments do not always present uniform structures

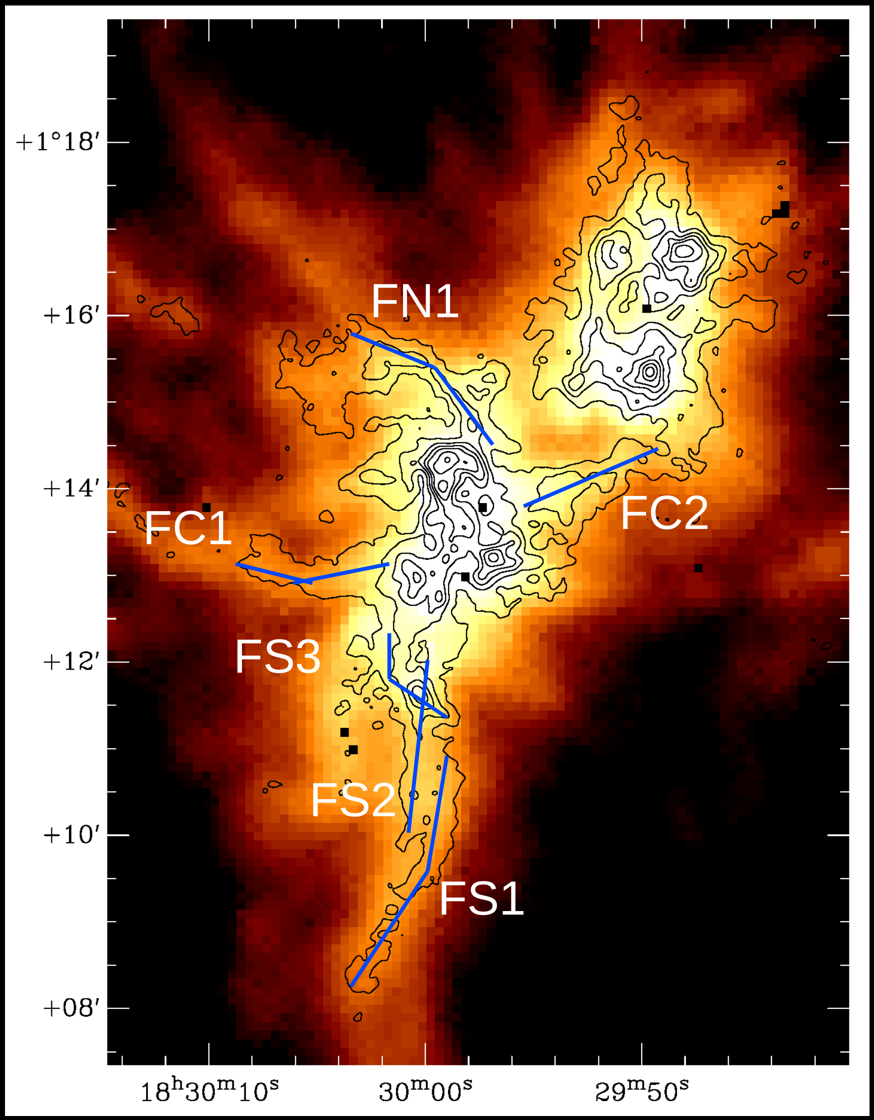






Properties of Filaments in Serpens Main

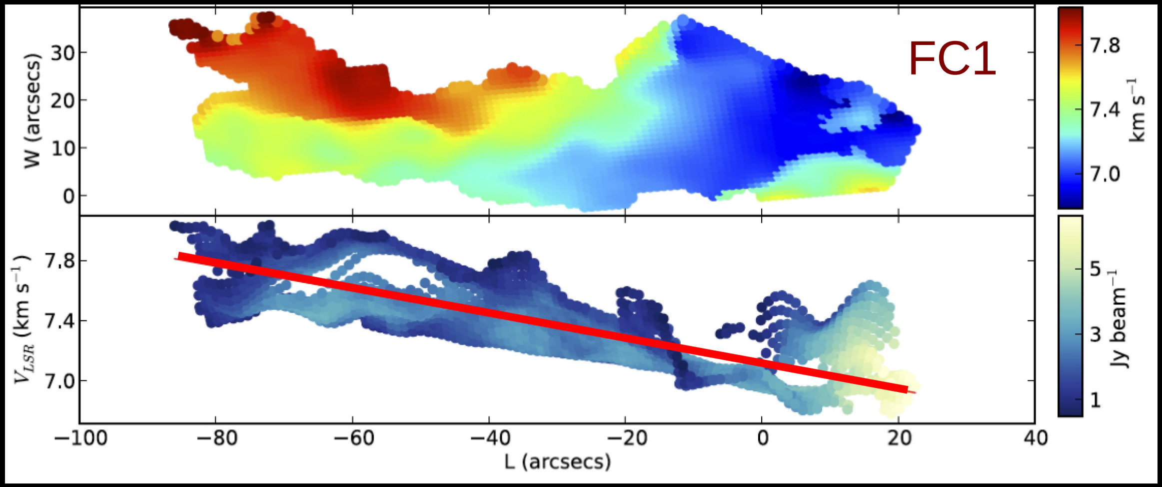
N_2H^+ superposed on Herschel 250 micron



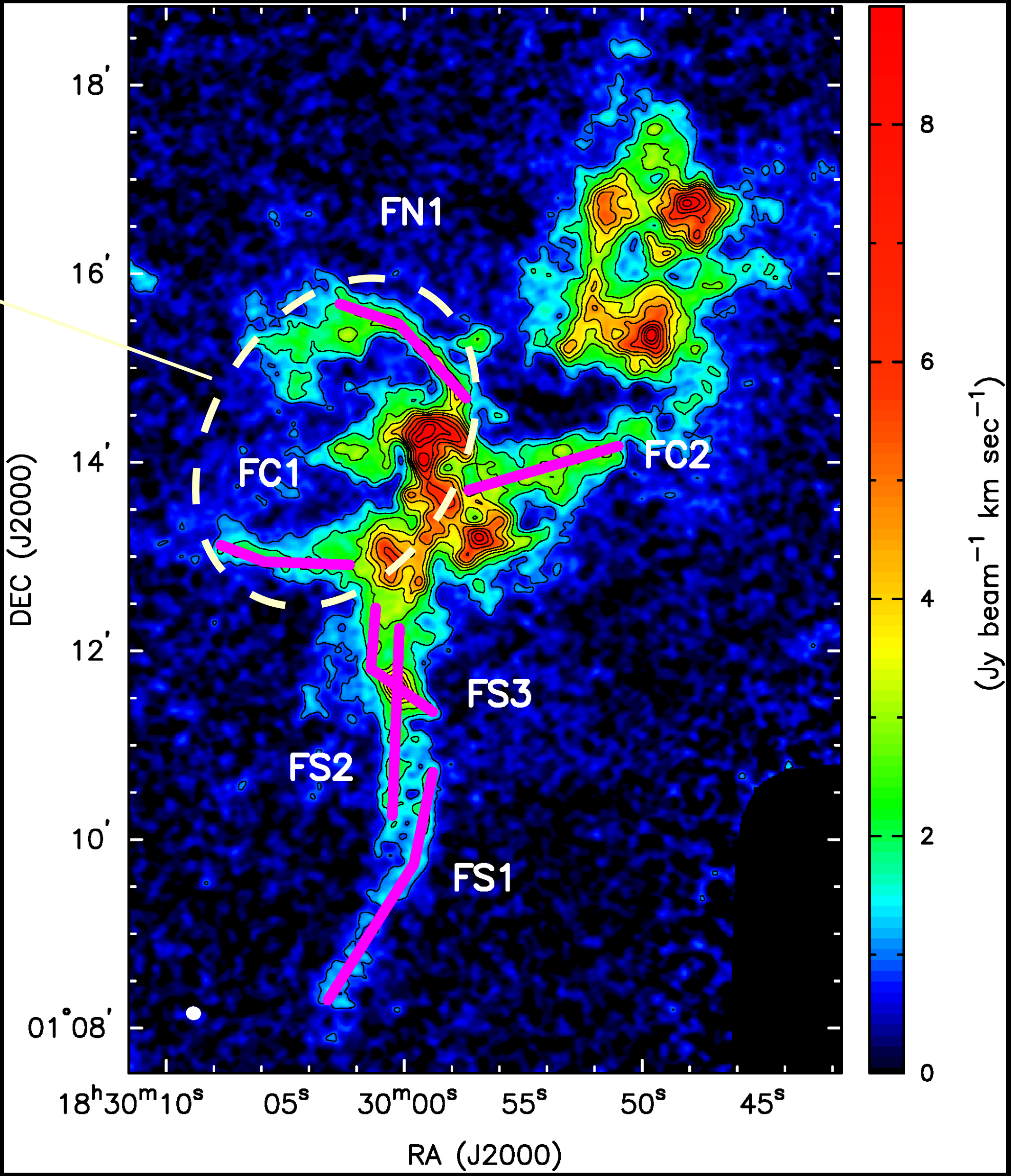
- All the N_2H^+ filaments have Herschel counterparts
- SED fitting (pixel-by-pixel) using 160, 250, and 350 μm
- Column density: 4 x 10^{22} to 9 x 10^{22} cm^{-2}
  Temperature: 11.5 K to 14 K
- Compare mass-per-unit-length with critical value:

$$M_{L,crit} = 2c_s^2/G = 16.7\ (\frac{T}{10K})\ M_\odot\ pc^{-1}$$

- Velocity gradients along filaments: linear fitting



Two Types of Filaments



First Type

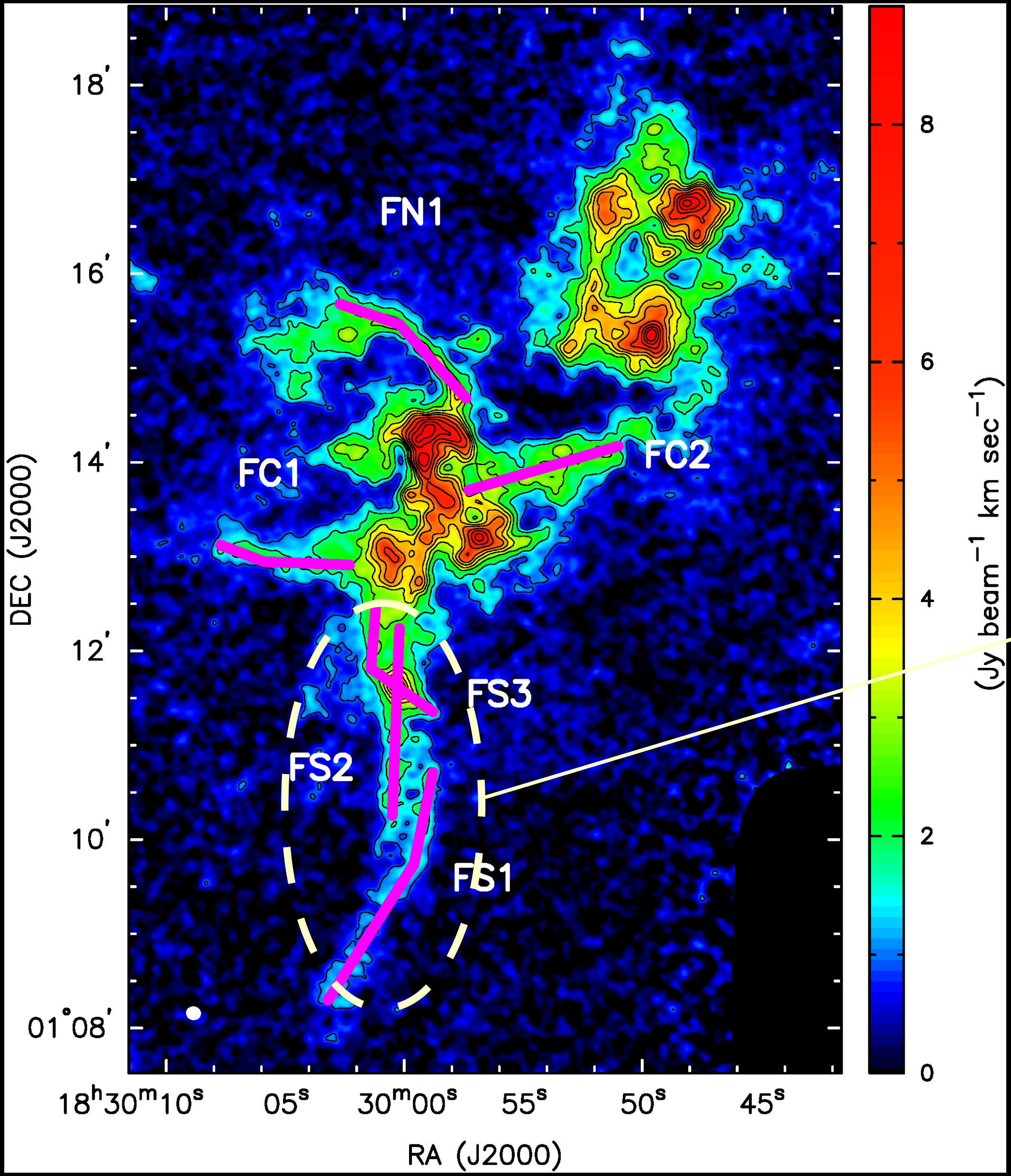
- Large velocity gradients (along filaments): > 3 km s^{-1} pc^{-1}
- Small masses: 4 $M_\odot$
- Nearly critical mass per unit length: $M_L \approx M_{L,crit}$

FC2: closer to 2nd type

Second Type

- Small velocity (along filaments): < 2 km s^{-1} pc^{-1}
- Large masses: 15 $M_\odot$
- Supercritical mass per unit length: $M_L \approx 3.5 \times M_{L,crit}$

Two Types of Filaments



First Type

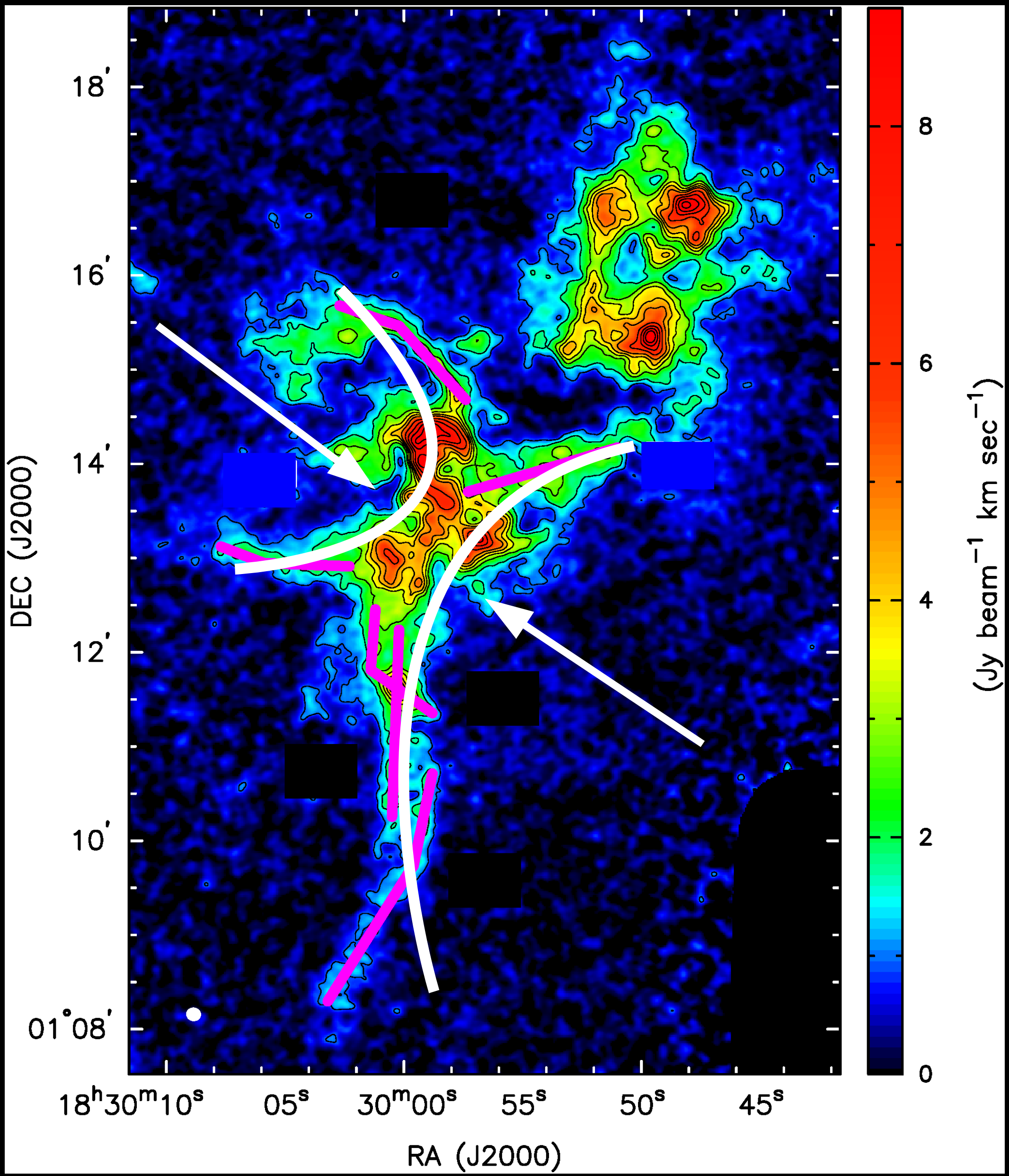
- Large velocity gradients (along filaments): > 3 $km\ s^{-1}\ pc^{-1}$
- Small masses: 4 $M_{\odot}$
- Nearly critical mass per unit length: $M_L \approx M_{L,crit}$

FC2: closer to 2nd type

Second Type

- Small velocity gradients (along filaments): < 2 $km\ s^{-1}\ pc^{-1}$
- Large masses: 15 $M_{\odot}$
- Supercritical mass per unit length: $M_L \approx 3.5 \times M_{L,crit}$

Colliding Flows (work-in-progress)



- The similarity in filaments in each type may suggest that they are originated from the same large-scale structure.
- Central cluster could be linked with piled-up gas from two colliding large-scale structures

N_2H^+, Filaments, and YSOs

N2H+ correlates with early stage of star formation

- Younger sources are more closely related to N2H+ ; evolved sources are distributed more widely

SE subcluster is more evolved than NW subcluster

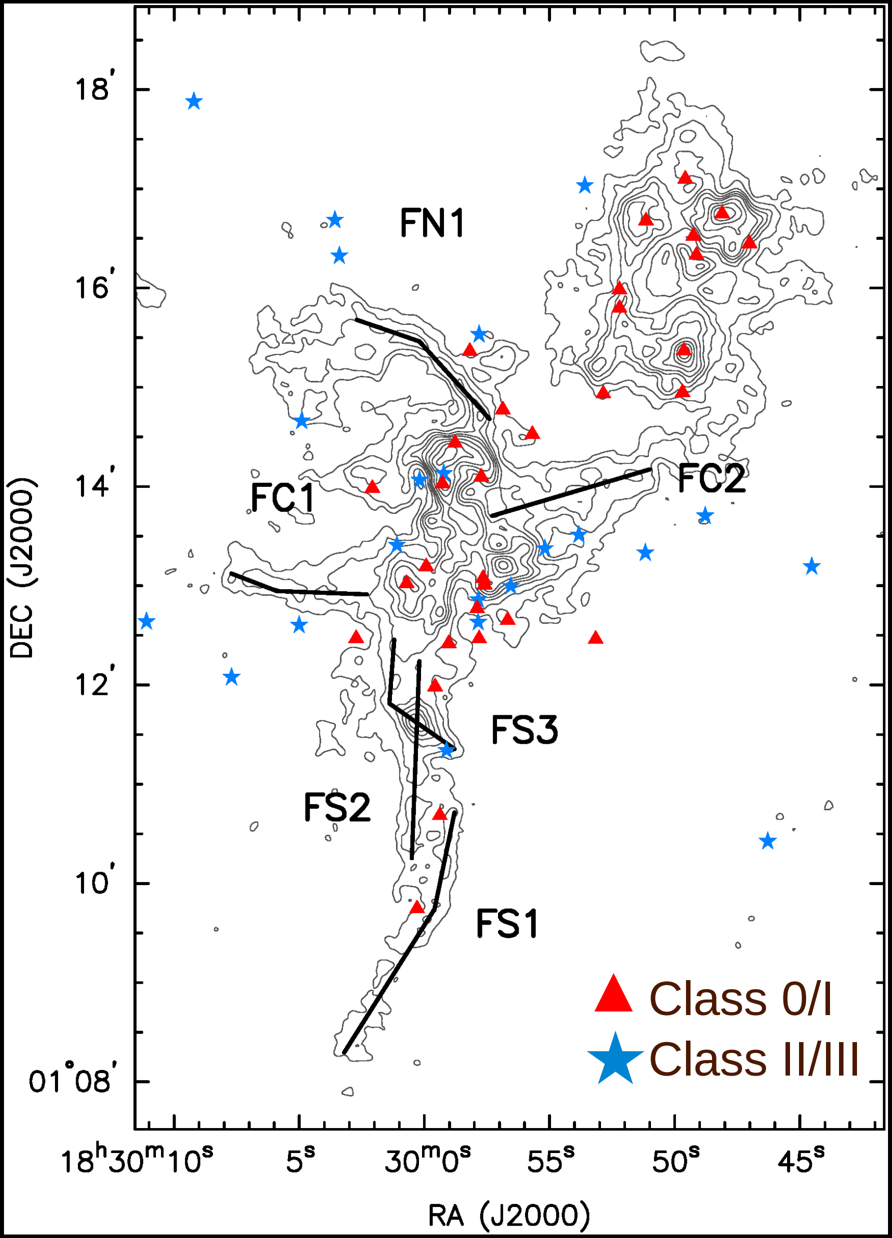
- SE subcluster: Class 0/I + Class II/III
  NW subcluster: Class 0/I only; no Class II/III

YSOs formed on gravitationally unstable filaments

- Five YSOs are formed on FS1 ($M_L \approx 2.6\ M_{L,crit}$) and FS2 ($M_L \approx 3.7\ M_{L,crit}$)
- Nearly critical filaments don't have YSOs

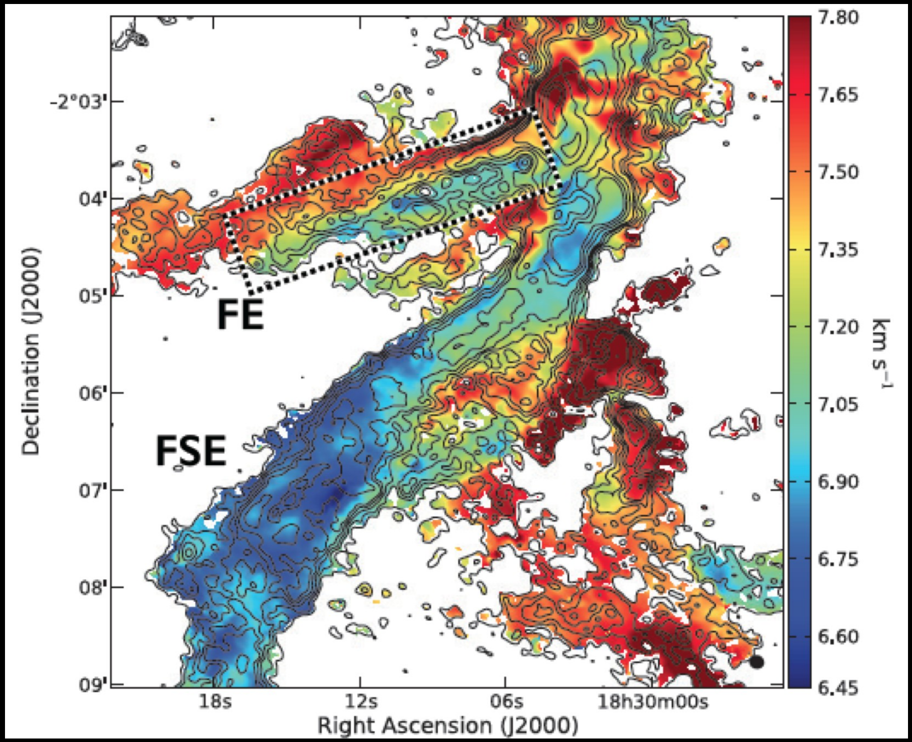
SE subcluster vs. NW subcluster

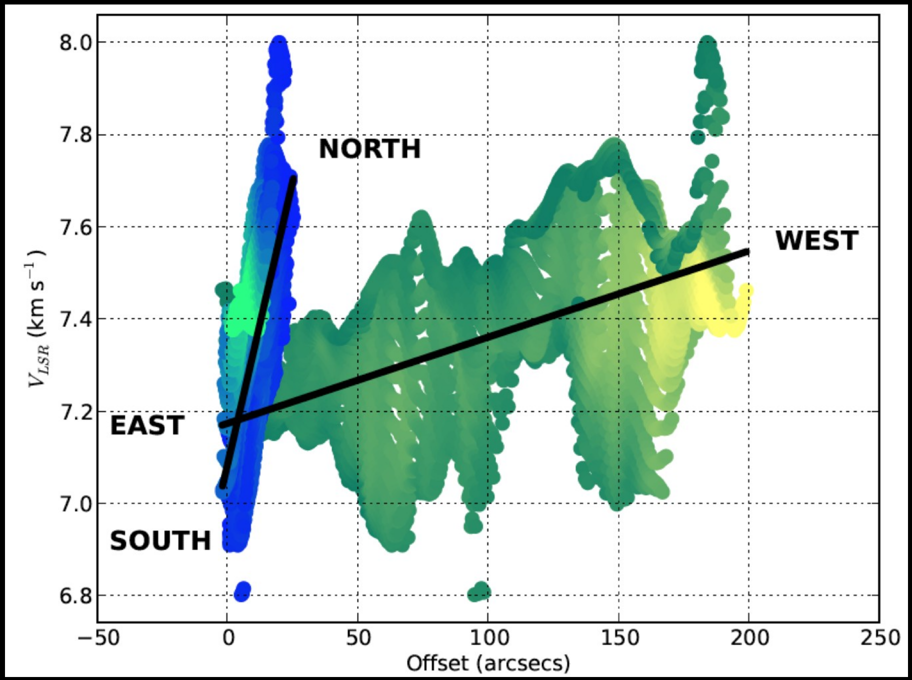
- More complicated velocity fields
- More hierarchical
- More filamentary
- Consistent with SE subcluster being more evolved



Velocity Gradients Across Filaments

CLASSy is the first observation to see velocity gradients across filaments at 0.03 pc scale!





- Several filaments in CLASSy regions show velocity gradients across filaments
- Gradient perpendicular an order of magnitude greater than along the filament (12 km/s/pc vs. 1 km/s/pc)
- Gas flow along filament (Kirk et al 2013) is not the whole story
- Perpendicular gradient could be natural consequence of filament formation through supersonic converging flows (e.g., Chen & Ostriker 2014)

Some insights from CLASSy

- How does low-density gas reach the threshold of star formation ?

  Not simple spherical collapse. They build hierarchical structure to higher column densities and densities. Stars form in the context of this structure. Strongly suggest turbulence is the driving force.

- Can we observationally test theoretical scenarios for filament formation?

  Velocity gradients across filaments provide an observational comparison with numerical simulations involving supersonic turbulence. Dendrogram technique identifies the structures into the sky, which will help constraining numerical simulations

- What is the role of filaments in a hub-filament system?

  Accretion flow into the central hub in Serpens South is not the whole story.
  Our Serpens Main data shows that the HFS could arise from collisions of directed flows.
  The central cluster could arise from compression associated with large-scale flow.

- Is the stellar mass initial mass function imprinted in the structure of molecular clouds?

  The definition of a core mass is problematic in clouds with hierarchical structure.
  Simple comparisons should be viewed with caution.

Summary

- In Serpens Main, gas is concentrated in two subclusters. The SE subcluster is more evolved, more hierarchical, more complicated in velocity structures, and more filamentary compared to the NW subcluster
- Hierarchical gas emission can be characterized by dendrogram. Star formation activity is linked with the level of hierarchy
- A characteristic width of 0.15 pc can be inferred by ΔV_{lsr} vs. size and $_{<\sigma>}$ vs. size relations in Serpens Main
- N2H+ shows 0.035 pc for filament widths, one-third of 0.1 pc as suggested by Herschel. This can be due to excitation conditions and chemical effects, or Herschel may not resolve well
- Two types of filaments have very different properties in Serpens Main; this could indicate that the SE subcluster is formed by two colliding large-scale structures
- Five YSOs are formed on supercritical filaments, while no YSOs are associated with nearly critical filaments, suggesting that YSOs are formed on gravitationally unstable filaments.