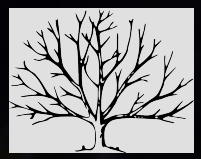


Dendrogram analysis of the first CARMA Large Area Star formation Survey regions

Shaye Storm
University of Maryland

June 8, 2013
CARMA Symposium

Co-authors: Lee Mundy (UMD), Peter Teuben (UMD),
Leslie Looney (UIUC), Katherine Lee (UIUC),
Manuel Fernandez-Lopez (UIUC), Erik Rosolowsky (UBC),
the CLASSy Collaboration

Dendrogram analysis of the first CARMA Large Area Star formation Survey regions

Big Picture

How do dense cores form and evolve to form stars?

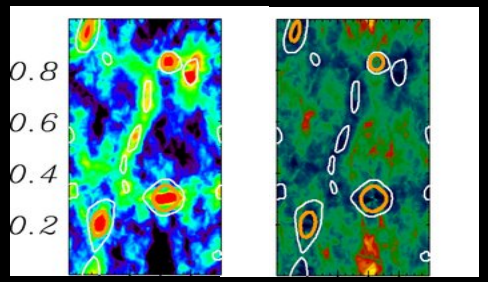
- Turbulence, magnetic fields, self-gravity, heating, chemistry

What We Know and Don't Know about Turbulence

- Observe supersonic gas in GMCs
- Observe turbulent scaling laws

- What are the turbulence drivers?
- Can we detect predicted signatures of turbulence driven core formation?

N-σ anti-correlation



Gong & Ostriker 2011

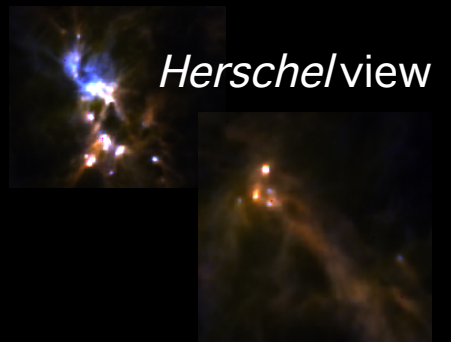
Observational Experiment for this Talk

- Identify dense gas structures
  $N_2H^+(1\text{-}0)$, $n > 10^5$ cm^{-3}
- Characterize their velocity field

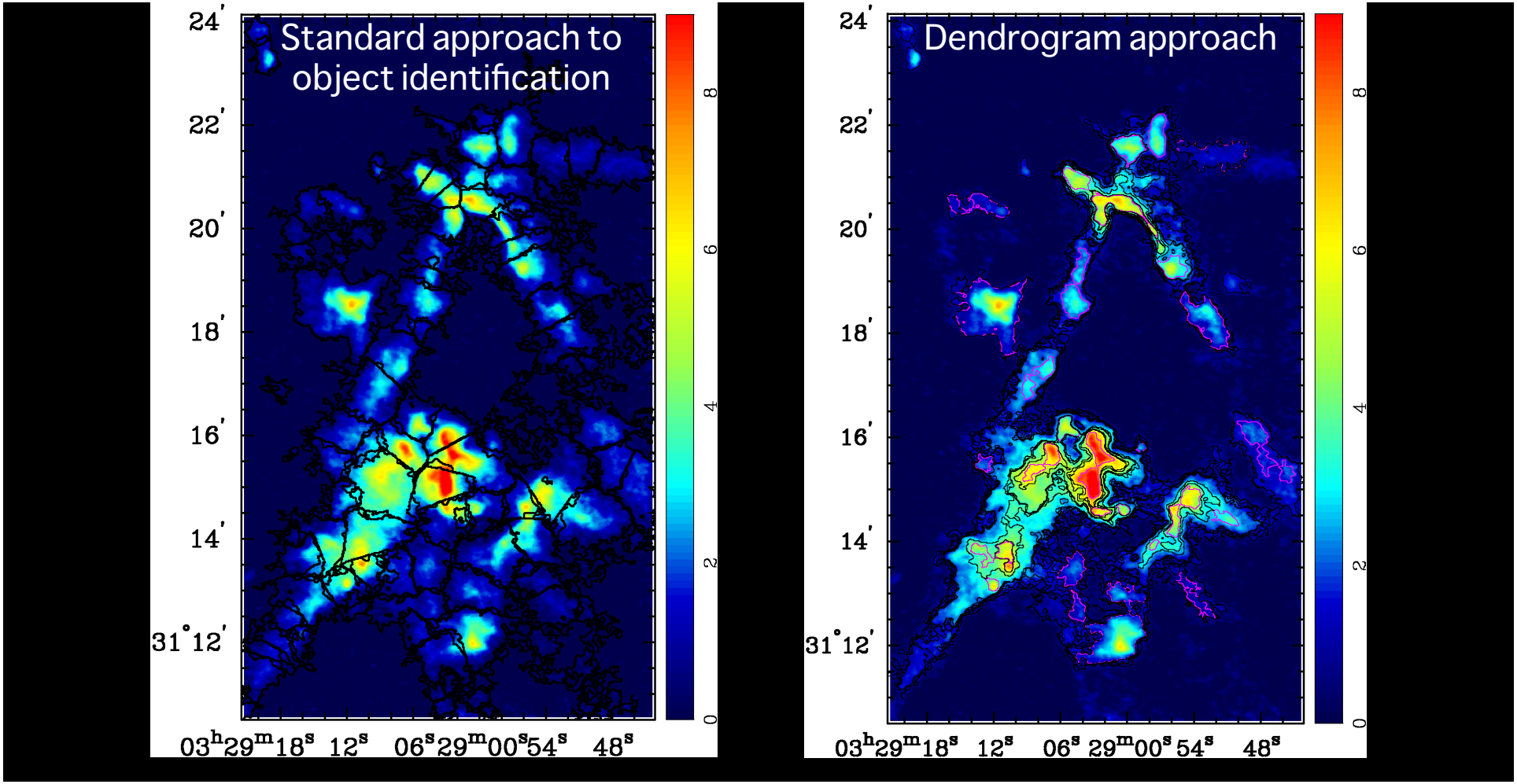
Hypothesis

Expect differences in turbulent properties

- NGC 1333: many young protostars driving outflows
- Barnard 1: mix; SW= filamentary without protostars



Herschel view



Observational Experiment for this Talk

- Identify dense gas structures ($n > 10^5$ cm^{-3})
- Characterize their velocity field

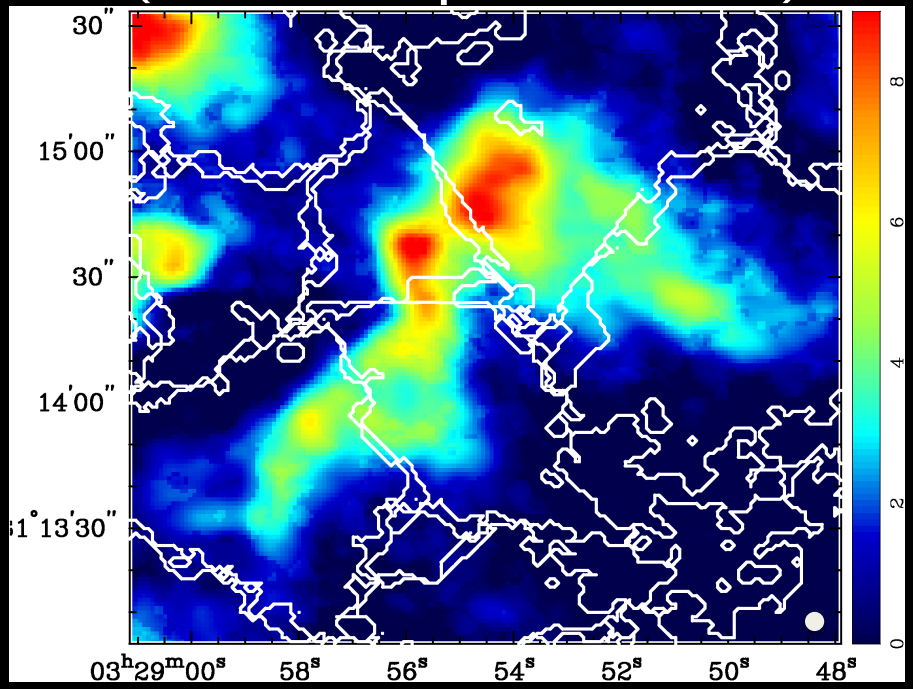
Not an issue of choosing the CORRECT object identification method, but choosing the MOST APPROPRIATE method

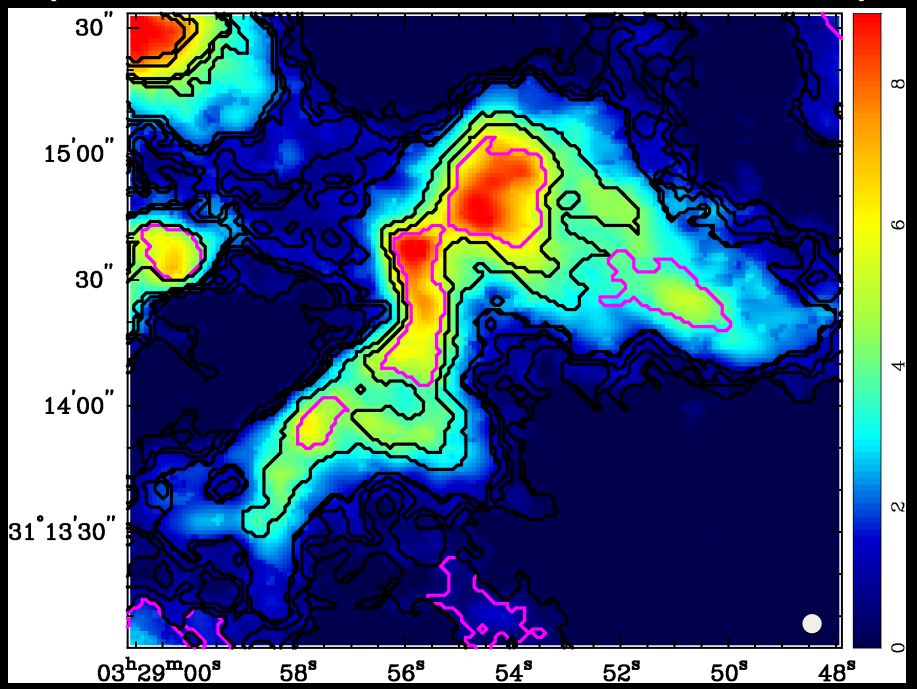
Object Identification Methods

Cloudprops
(best for sparse fields)

vs.

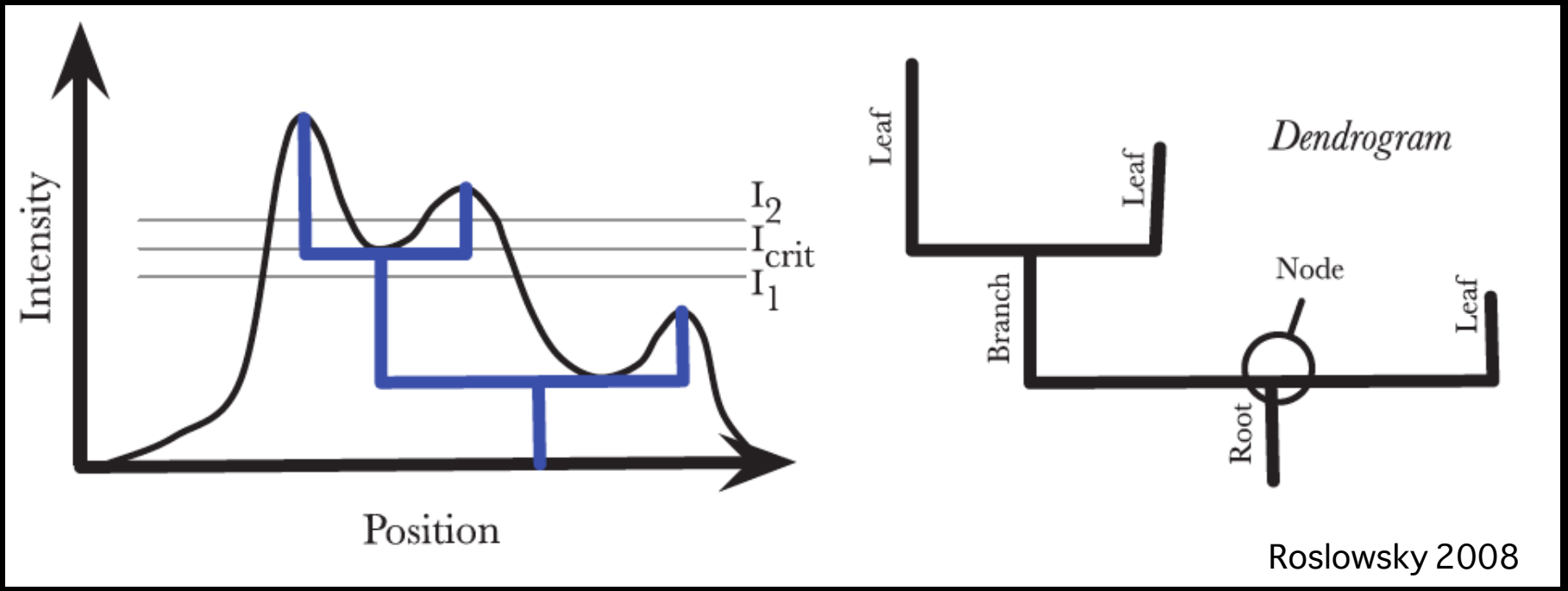
Dendrograms
(best for dense/blended fields)





Molecular Cloud structure is mostly hierarchical … dendrograms avoid small-scale segmentation and naturally capture large-scales in addition to the small-scales

Object Identification Methods: Dendrogram 1-D Example

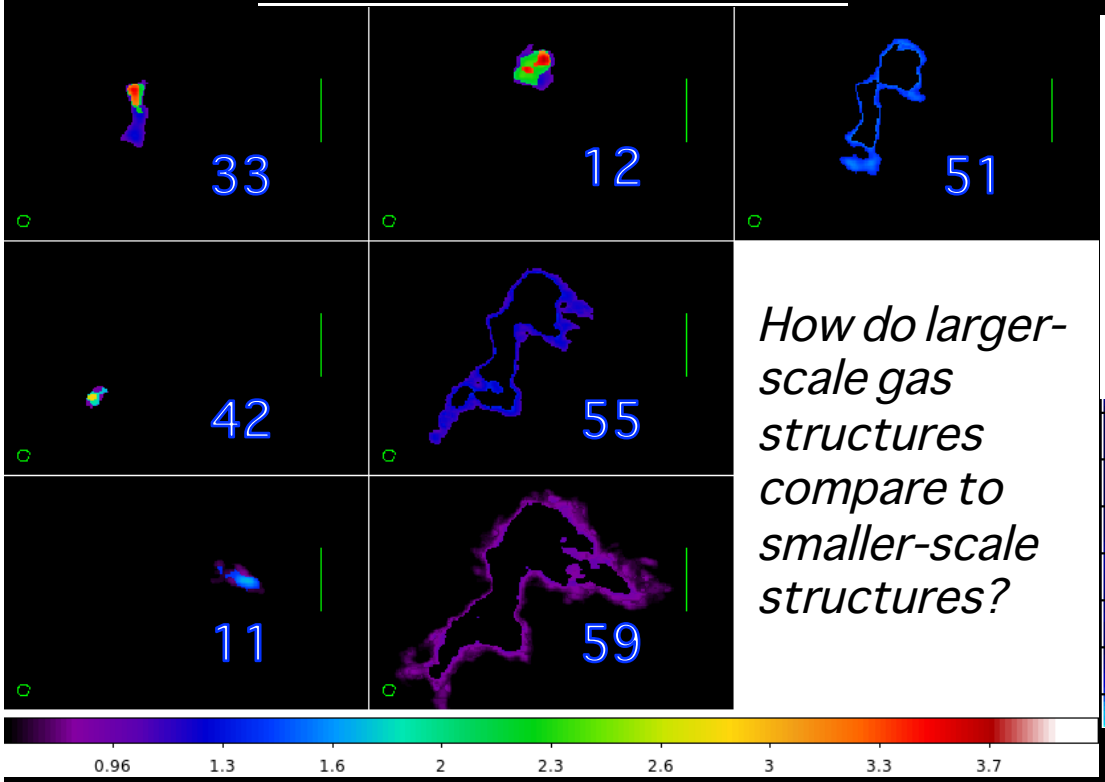


Roslowsky 2008

Molecular Cloud structure is mostly hierarchical … dendrograms avoid small-scale segmentation and naturally capture large-scales in addition to the small-scales

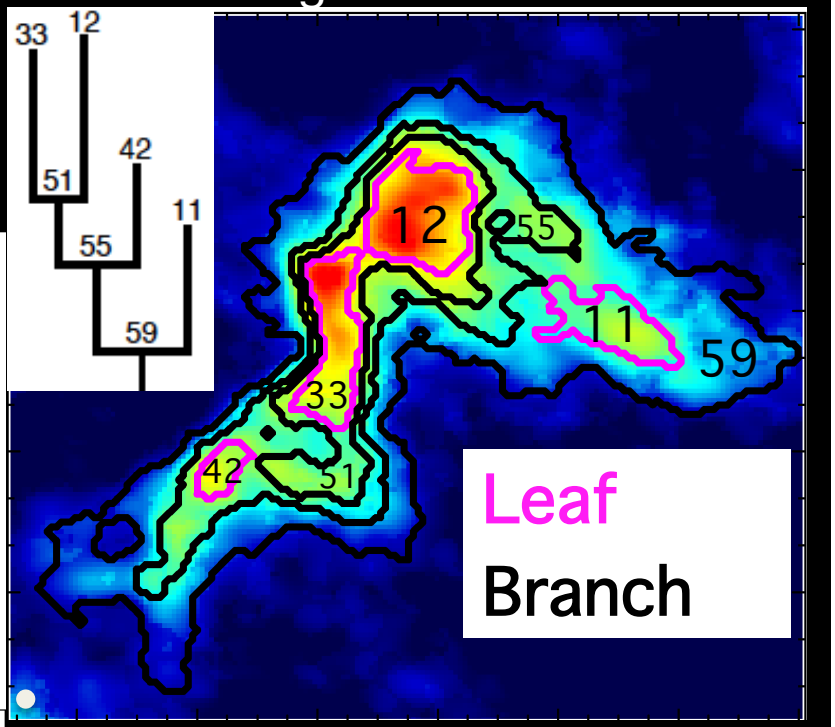
Capturing Large and Small Scales with Dendrogram Approach

Moment Zero Maps of Leaves and Branches



How do larger-scale gas structures compare to smaller-scale structures?

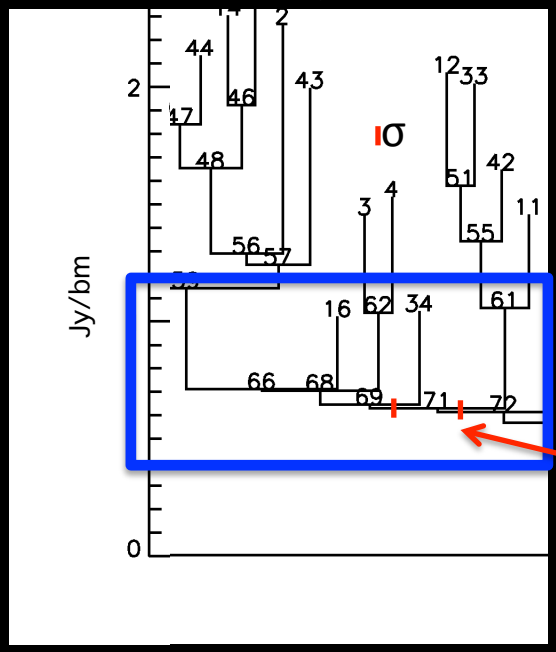
IRAS 2 region of NGC 1333



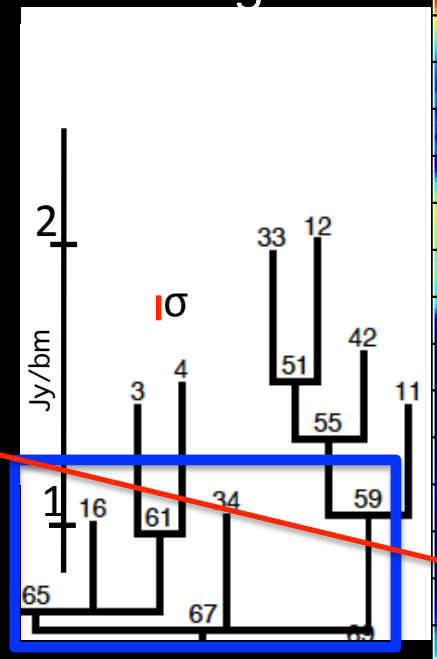
Facilitates an investigation of the turbulent properties of dense gas at different scales in a way that clumpfind-like segmentation would not allow

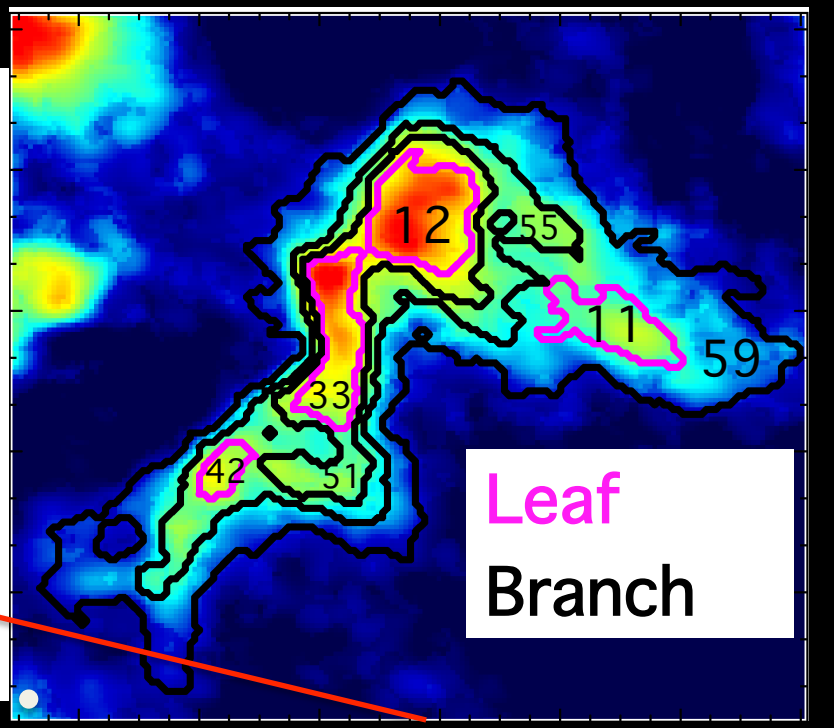
Dendrogram Implementation: A New Clustering Method

Traditional: binary dendrogram



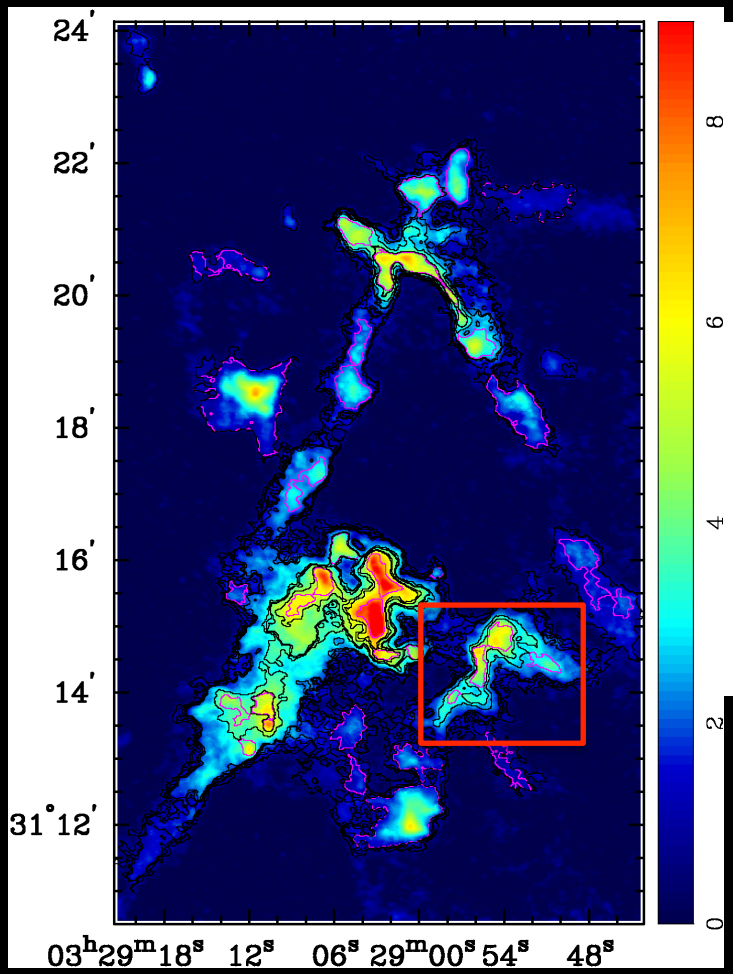
New: Non-binary dendrogram

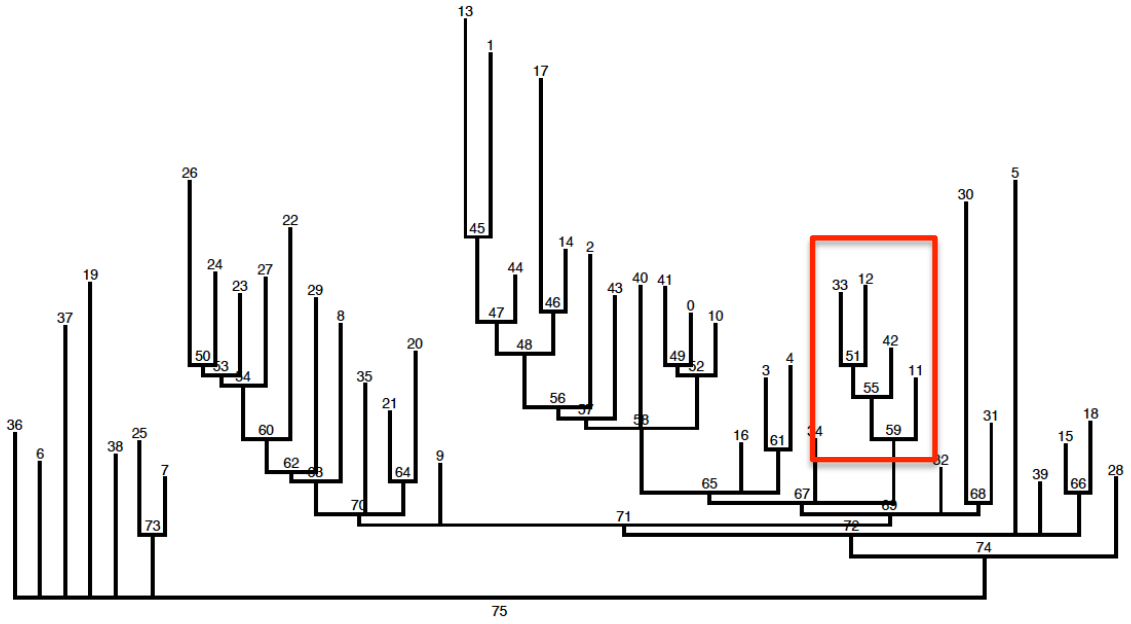




Forcing binary clustering results in "phantom" branching structure where > 2 structures should merge considering the noise limitations of real data

Results: Non-Binary Dendrogram of NGC 1333 N_2H^+ (1-0)

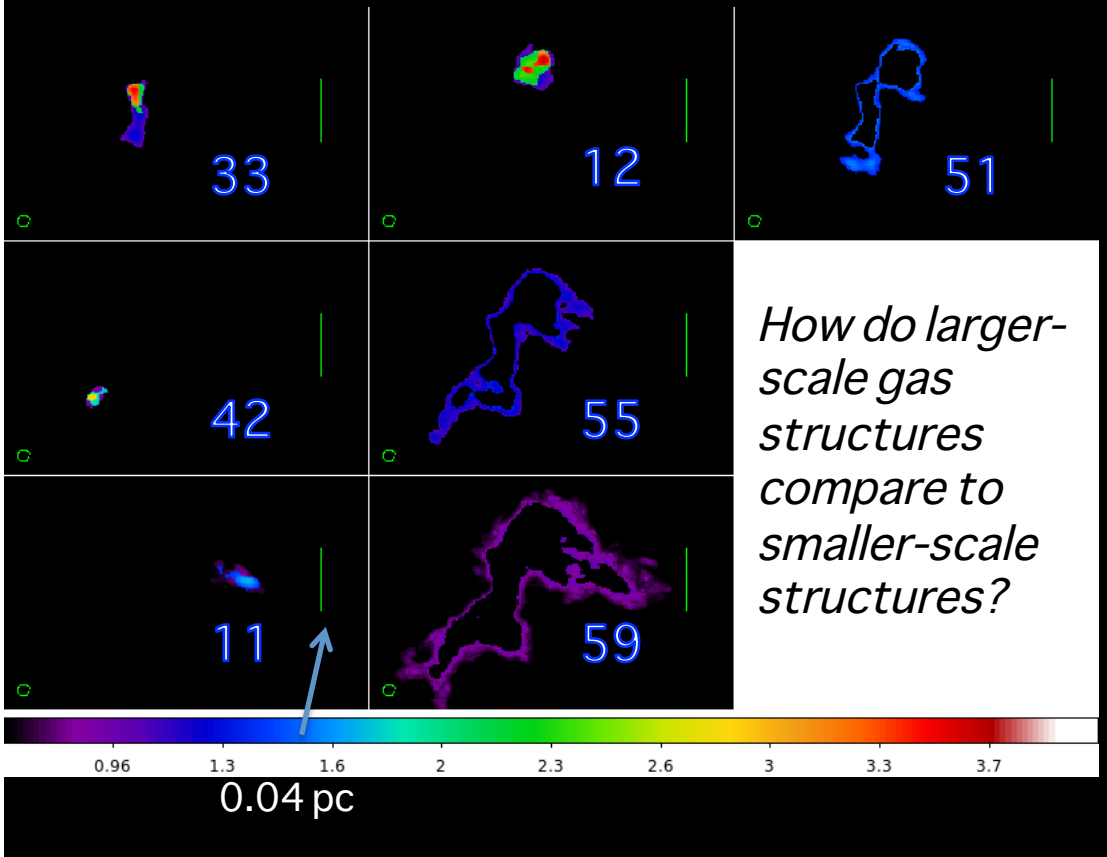




- Represents the observable hierarchy of emission within the limits of the noise
- Meaningful list of structures not polluted by phantom branching

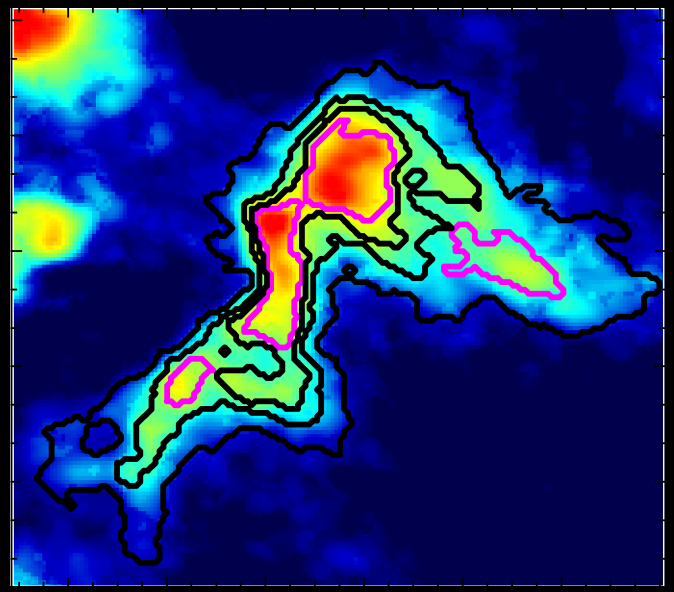
Results: Non-Binary Dendrogram of NGC 1333 N_2H^+ (1-0)

Integrated Intensity Maps



How do larger-scale gas structures compare to smaller-scale structures?

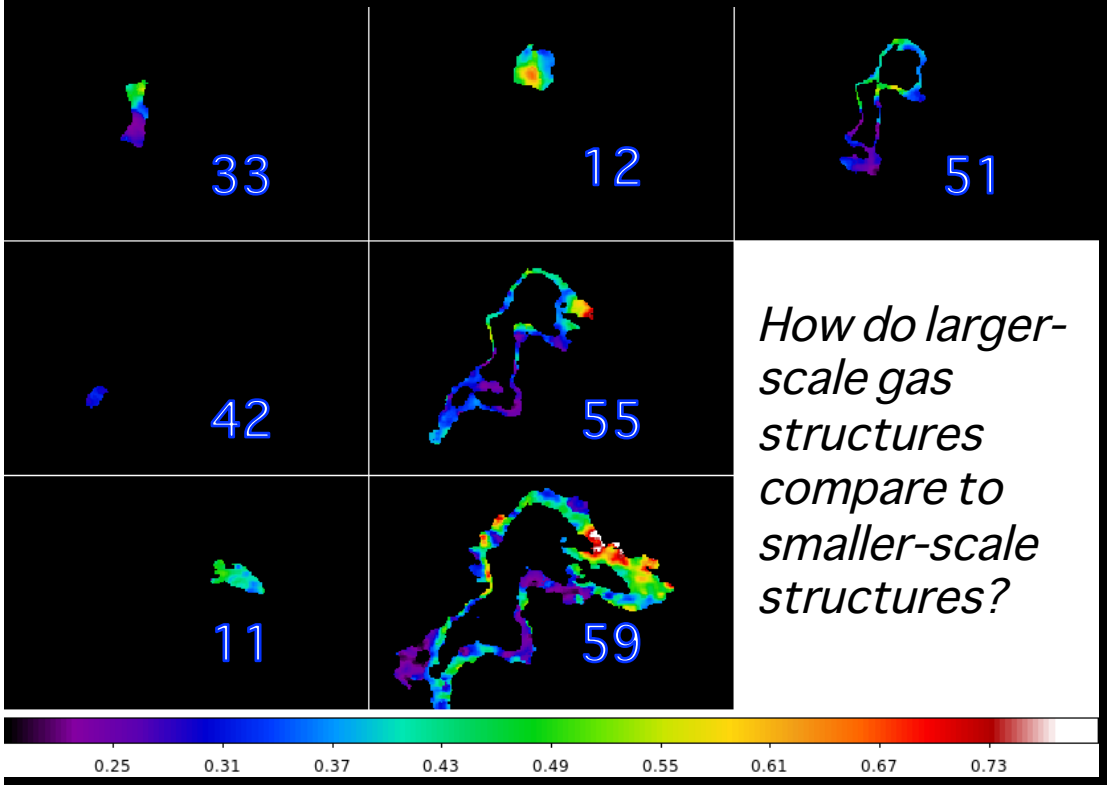
We evaluated the size and kinematics of each identified gas structure



Turbulence … across different spatial scales within a single cloud
… across different clouds at different stages of evolution?

Results: Non-Binary Dendrogram of NGC 1333 N_2H^+ (1-0)

Fitted Line Dispersion Maps



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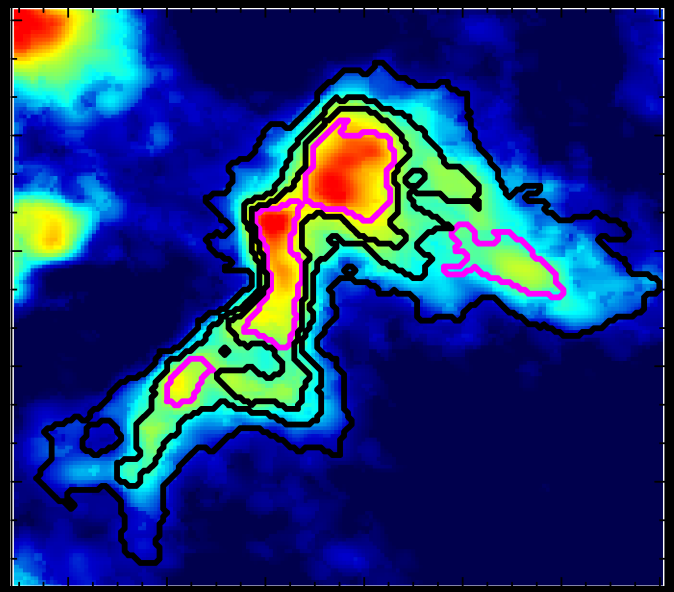
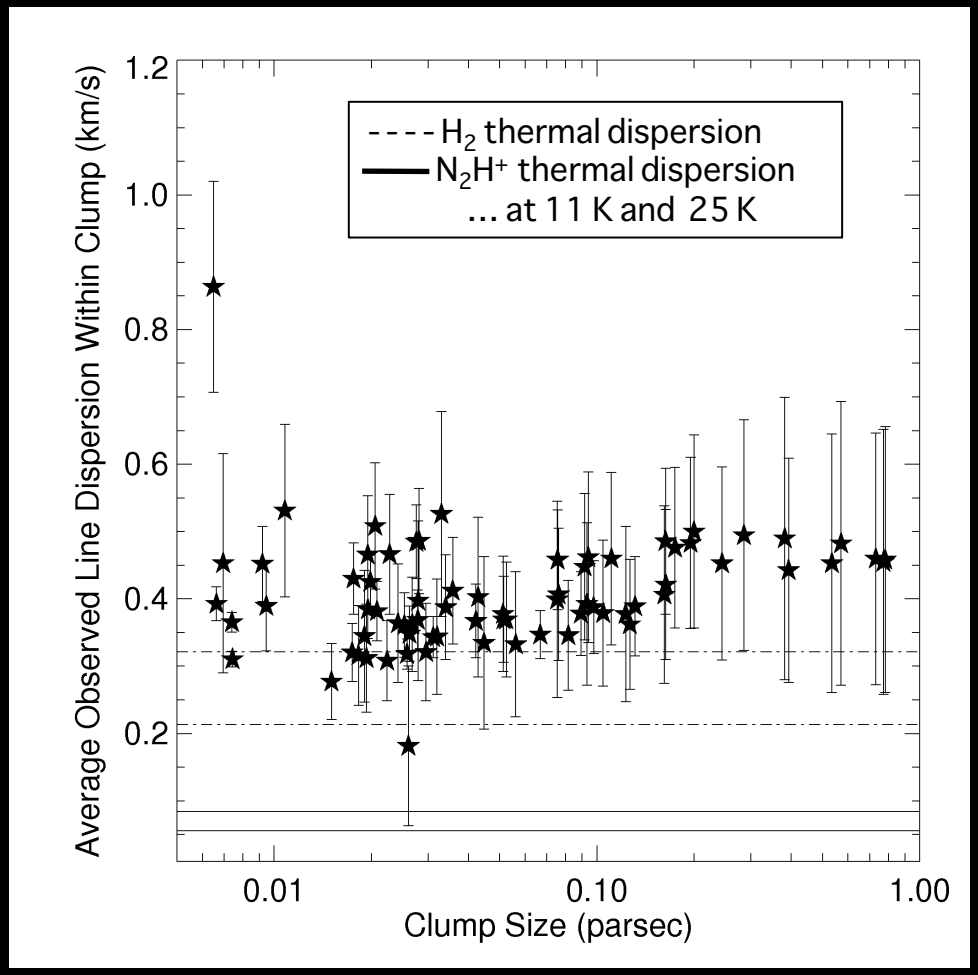


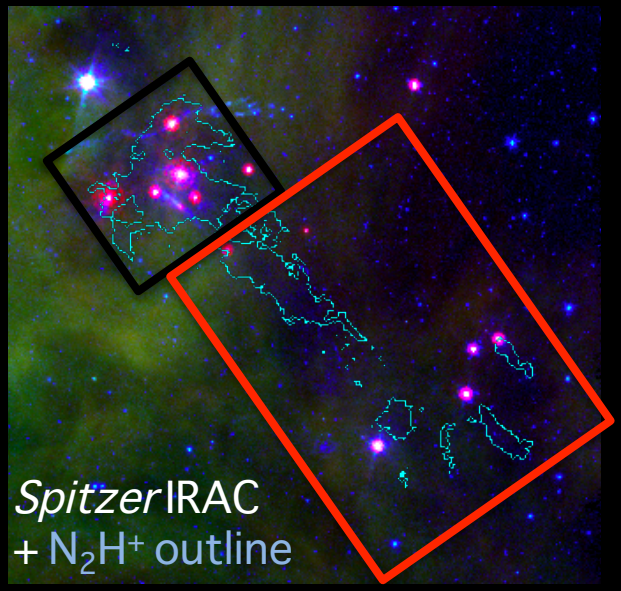
Turbulence … across different spatial scales within a single cloud
… across different clouds at different stages of evolution?

Results: Line Dispersion vs. Size in NGC 1333 Gas Structures

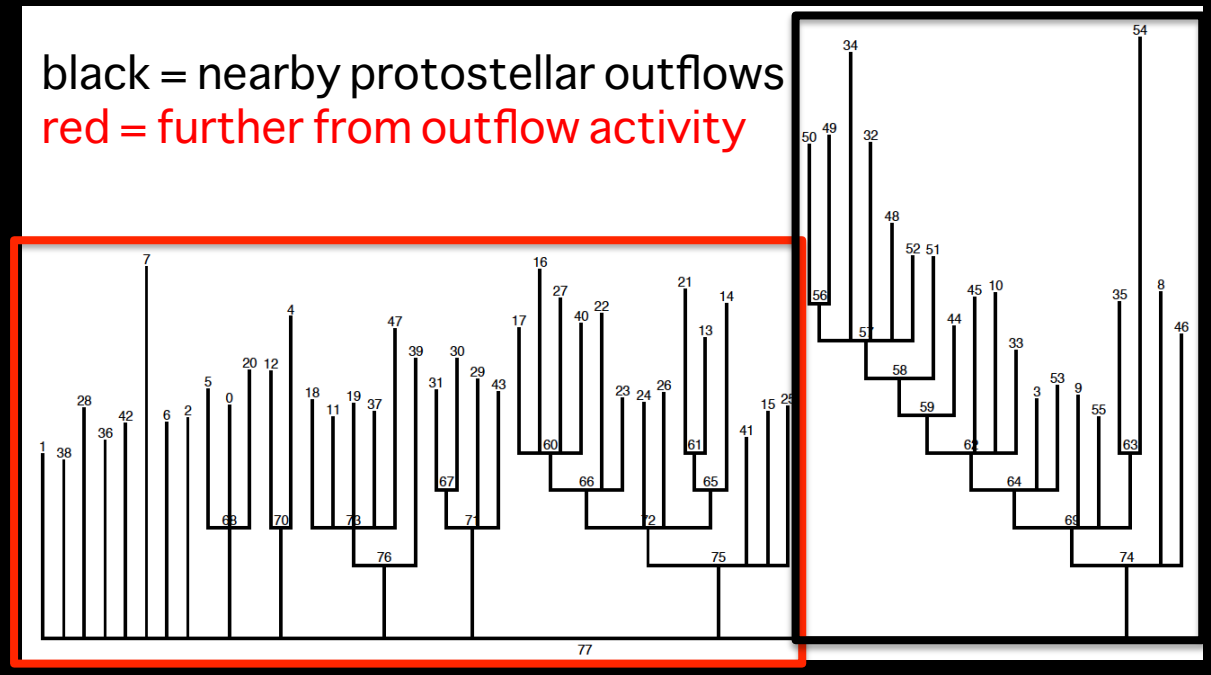


Capturing mean internal turbulence

Results: Non-Binary Dendrogram Structure of Barnard 1 N_2H^+ (1-0)

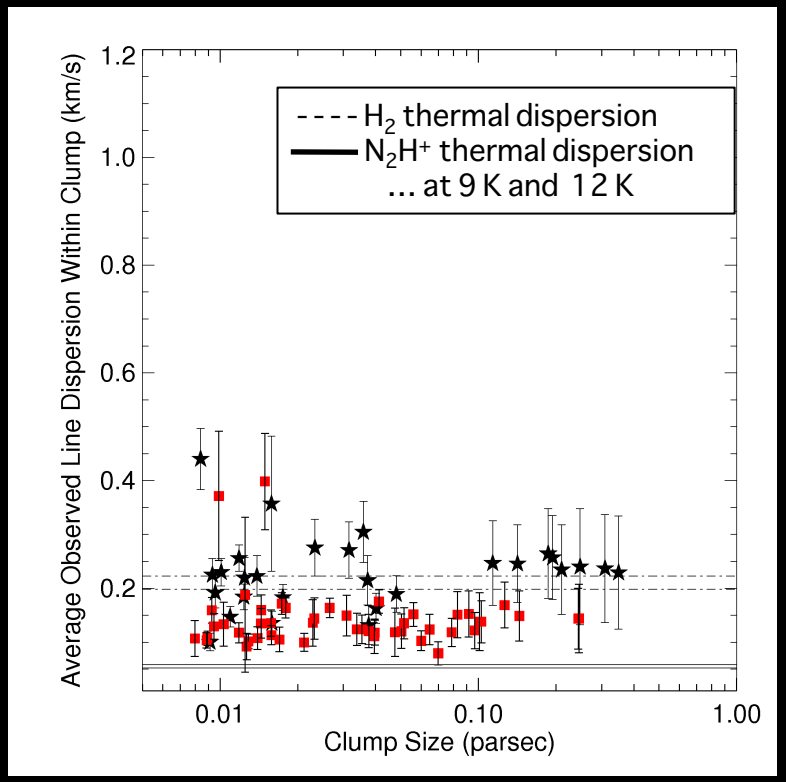


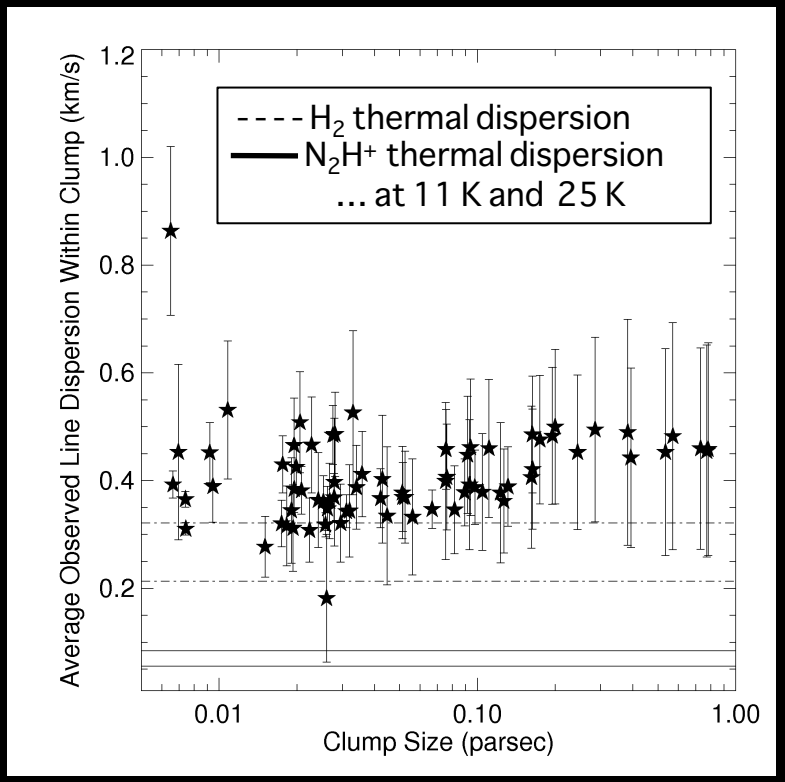
black = nearby protostellar outflows
red = further from outflow activity



Results: Cross-Cloud Comparison

Barnard 1 vs. NGC 1333





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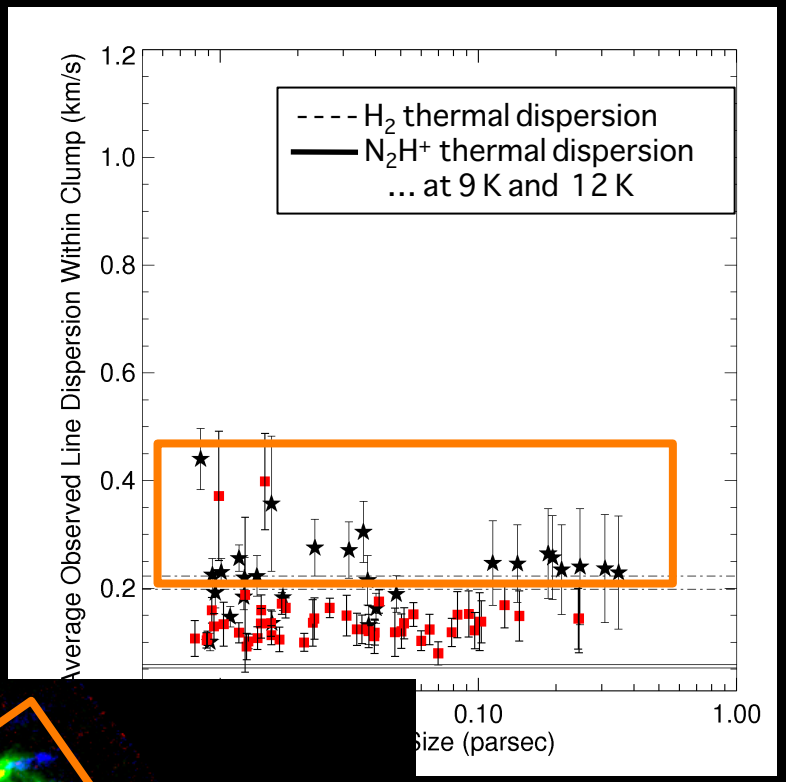
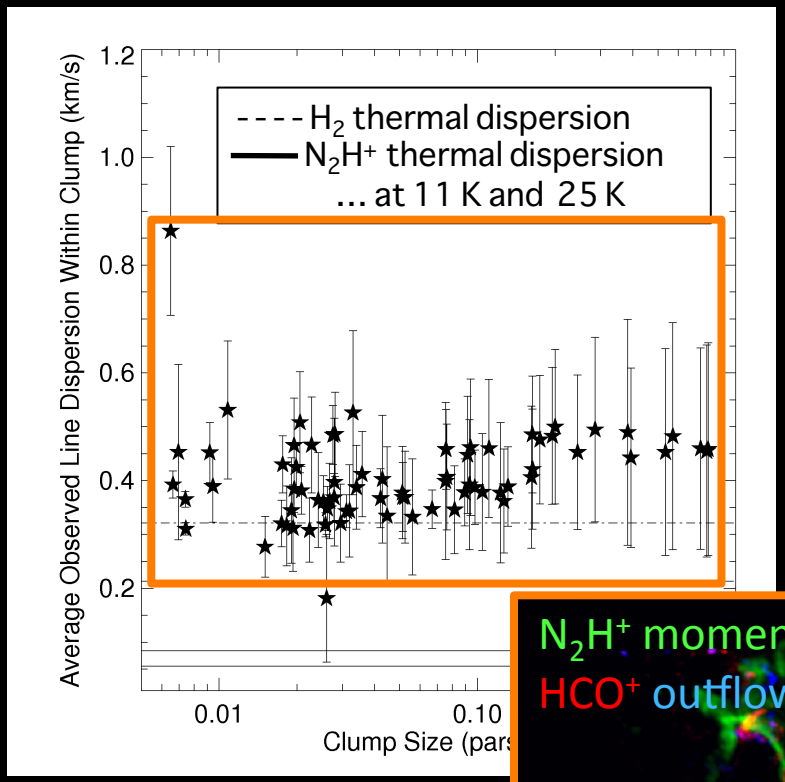
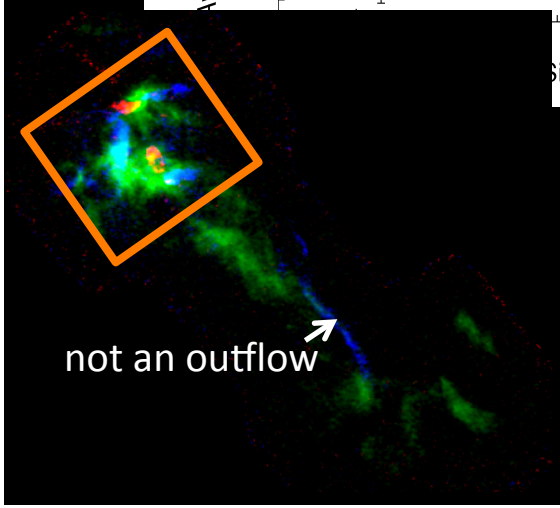
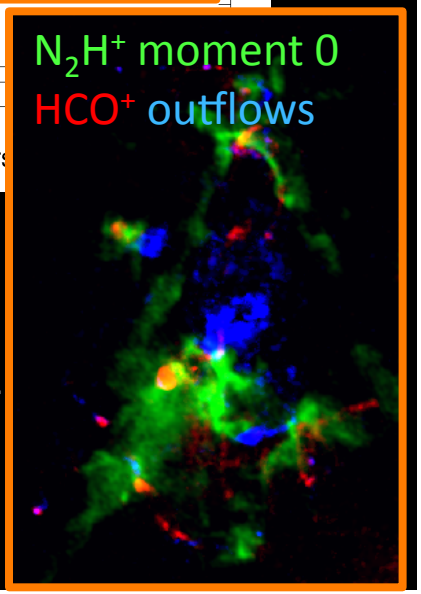






- Observe supersonic turbulence at ~0.01 – 0.5 pc scales near active young stars
- Indication that outflows are an important turbulent driver of the dense gas at these scales



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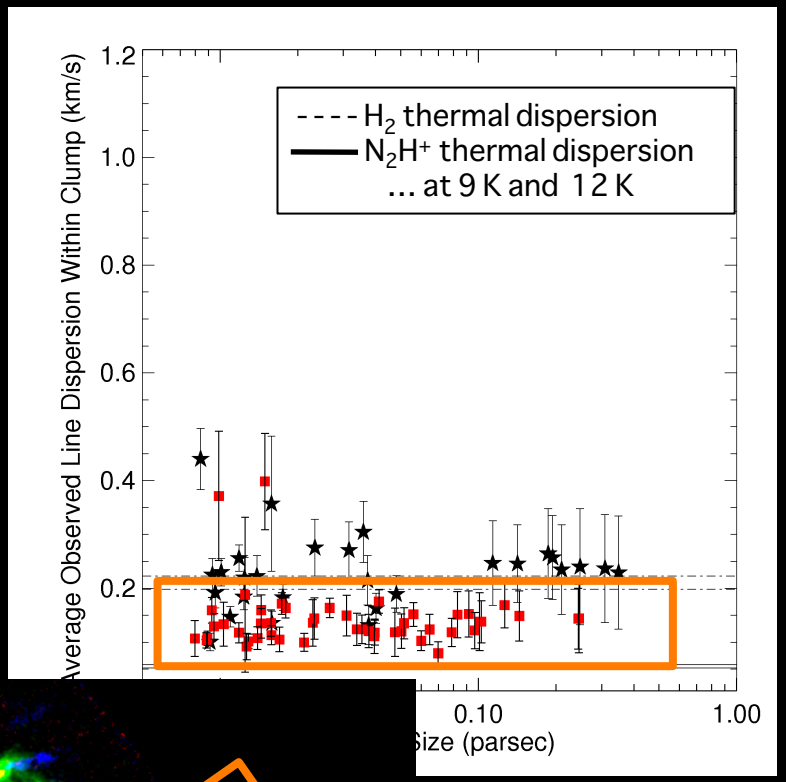
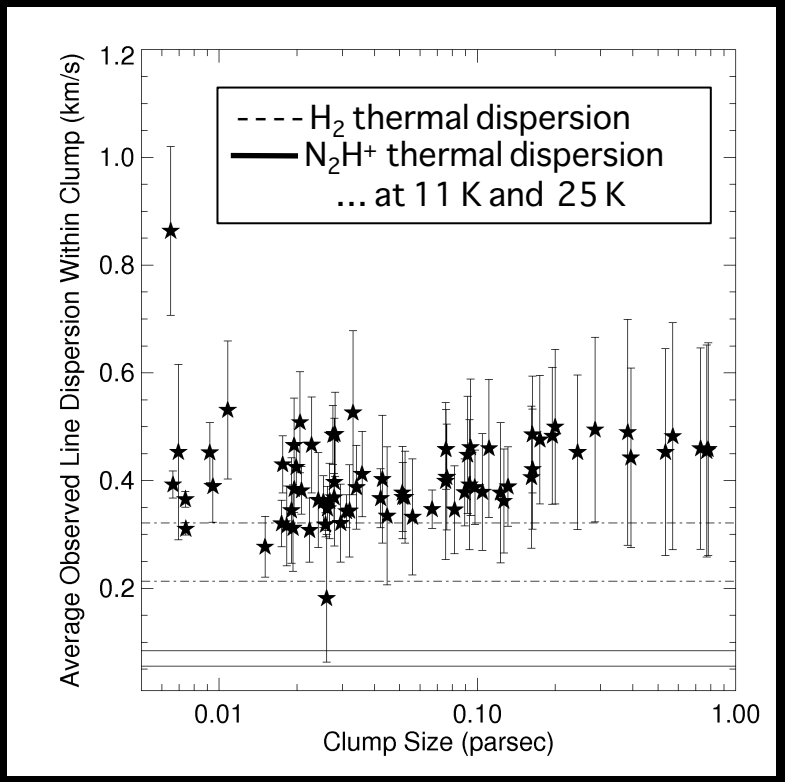
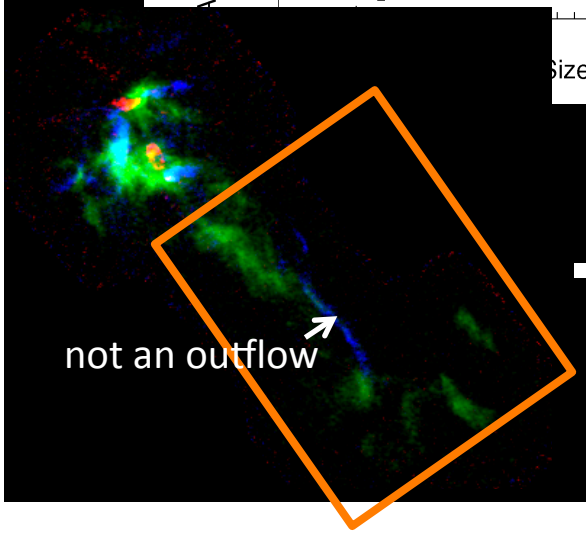






- Observe subsonic turbulence in filamentary regions yet to form young, active stars
- … expected if these dense gas filaments formed from supersonic turbulence
- Next step to probe even larger scales and make connection to lower density gas

Summary

- Dendrograms used to decompose dense gas emission and explore kinematics of structures in CLASSy clouds

- Created statistically meaningful sample of gas structures with new non-binary clustering version of dendrograms

- Compared turbulent linewidths of NGC 1333 and B1 gas structures:
  - Star formation feedback correlates with supersonic turbulence at the ~0.01 – 0.5 pc scale
  - B1 filament is a great region to probe turbulence driven star formation theories

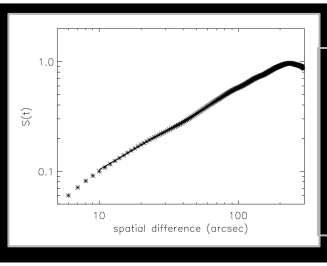
Sampling of Future and Ongoing CLASSy Work

Extend to other CLASSy regions, molecules

Complete L1451 and Serpens South observations/mapping (Fall), and do same analysis for a complete Perseus picture and Perseus-Serpens comparison

Complementary approaches to turbulence

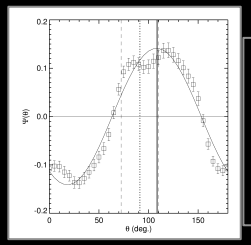
Explore turbulent energy cascade with statistical analysis of velocity fields:
- Two-point correlations statistics (e.g., structure function), PCA



Structure function for HCO^+ in NGC 1333

Connection to Magnetic Fields?

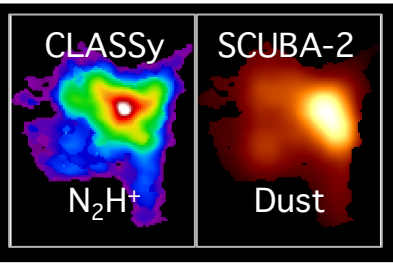
Explore effects of magnetic fields on turbulent energy cascade
- Observable anisotropies in velocity field scaling laws?



Anisotropy in structure function in B1 main core

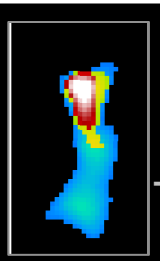
Connection to Dust

Tie gas together with dust to explore virial boundedness of identified gas structures



Morphology and Connection to YSOs

Use dendrogram decomposition for:
- Characterizing morphology of dense gas from ~0.01 – 1 pc
- Connecting with existing young stellar content



~0.04 pc