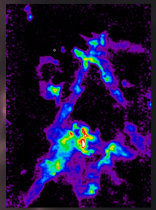
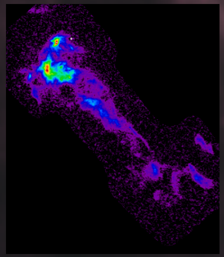
<u>Background</u>:
Herschel dust map with
CARMA N_2H^+ images overlaid

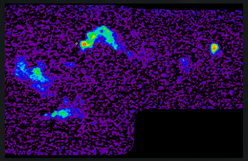
~4 pc



Large Area, High Resolution N_2H^+ studies of dense gas in the Perseus and Serpens Molecular Clouds

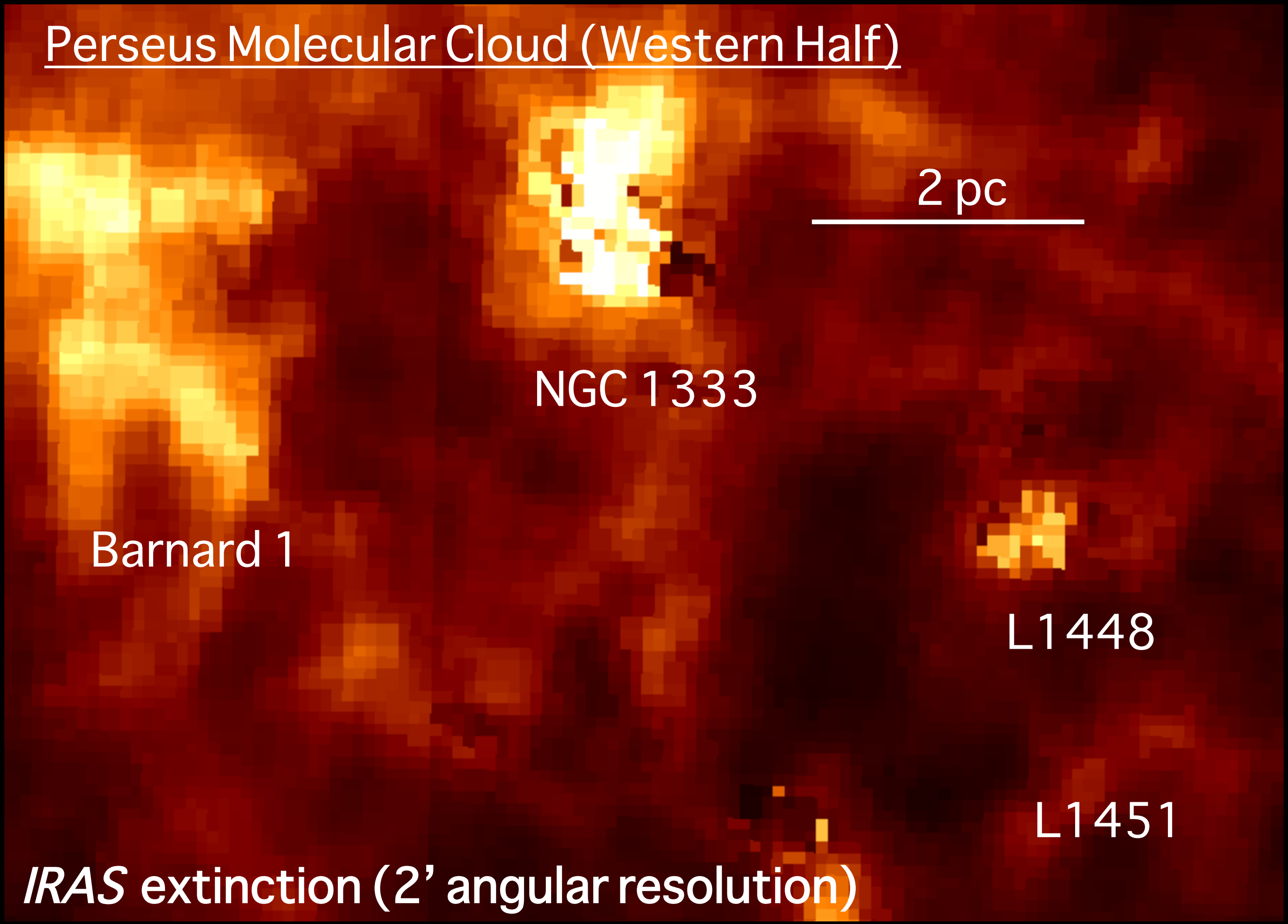


Shaye Storm
University of Maryland



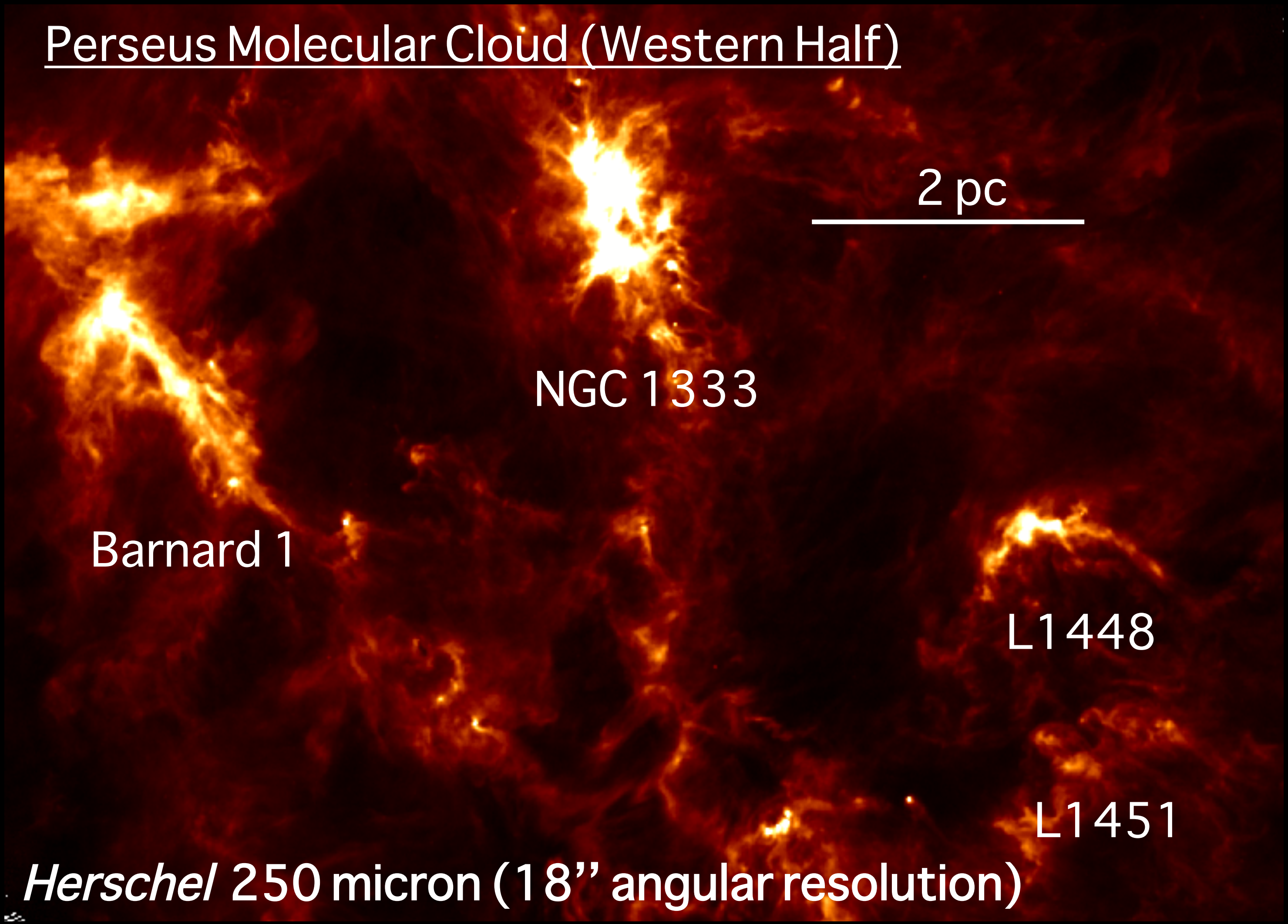
<u>Collaborators</u>: Lee Mundy, Eve Ostriker, Leslie Looney, Manuel Fernandez-Lopez, Katherine Lee, Hector Arce, Erik Rosolowsky, Che-Yu Chen, Peter Teuben, the CLASSy Collaboration

IRAS to *Herschel*: Large-Scale Structure Appears



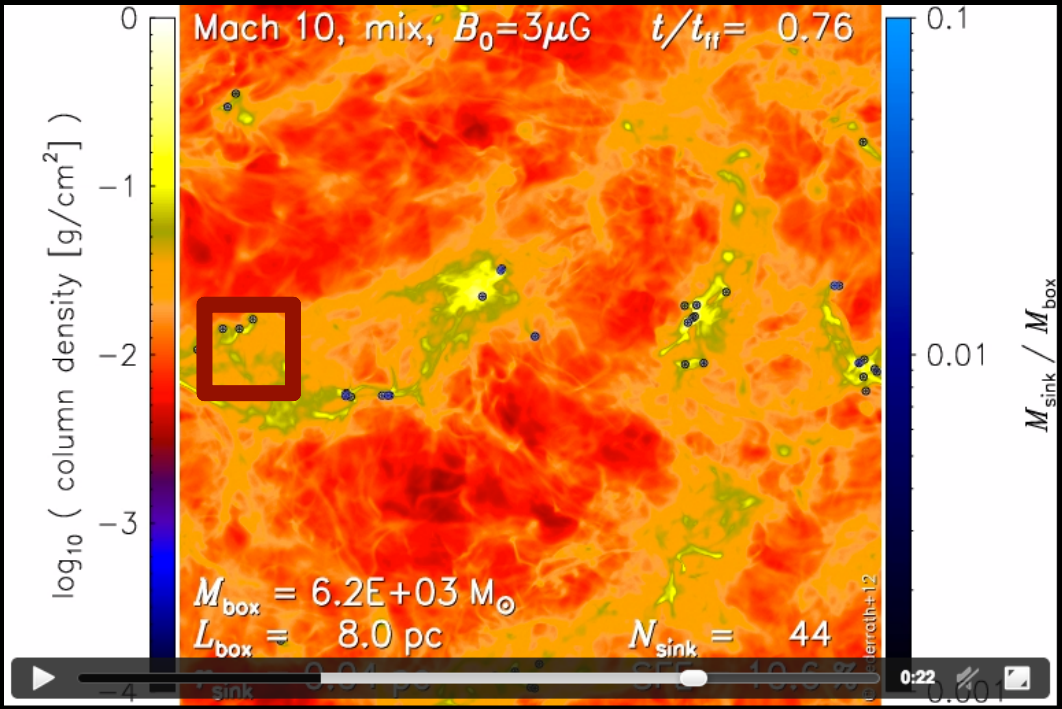
Schnee, Ridge, Goodman and Li (2005)

IRAS to *Herschel*: Large-Scale Structure Appears

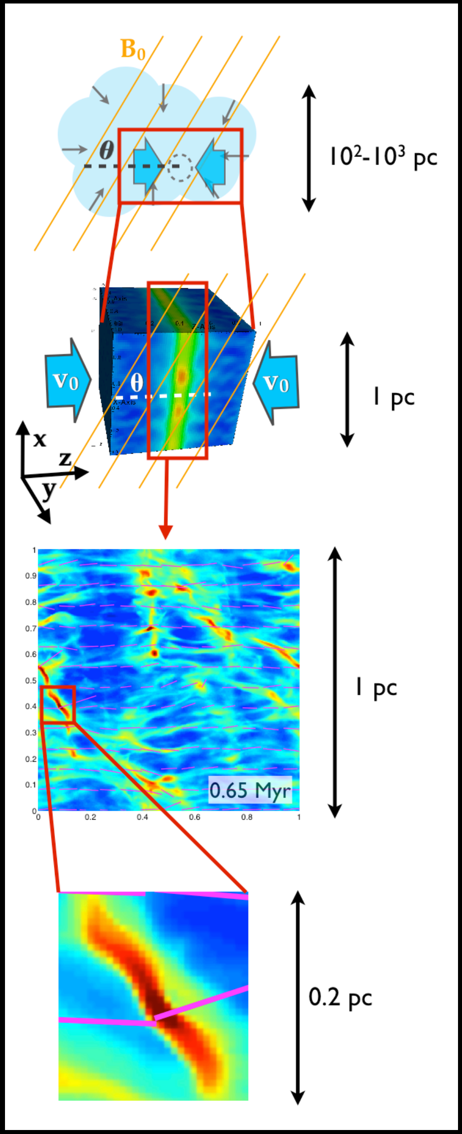


André et al. (2010)

Numerical Simulations: Turbulence creates range of structure



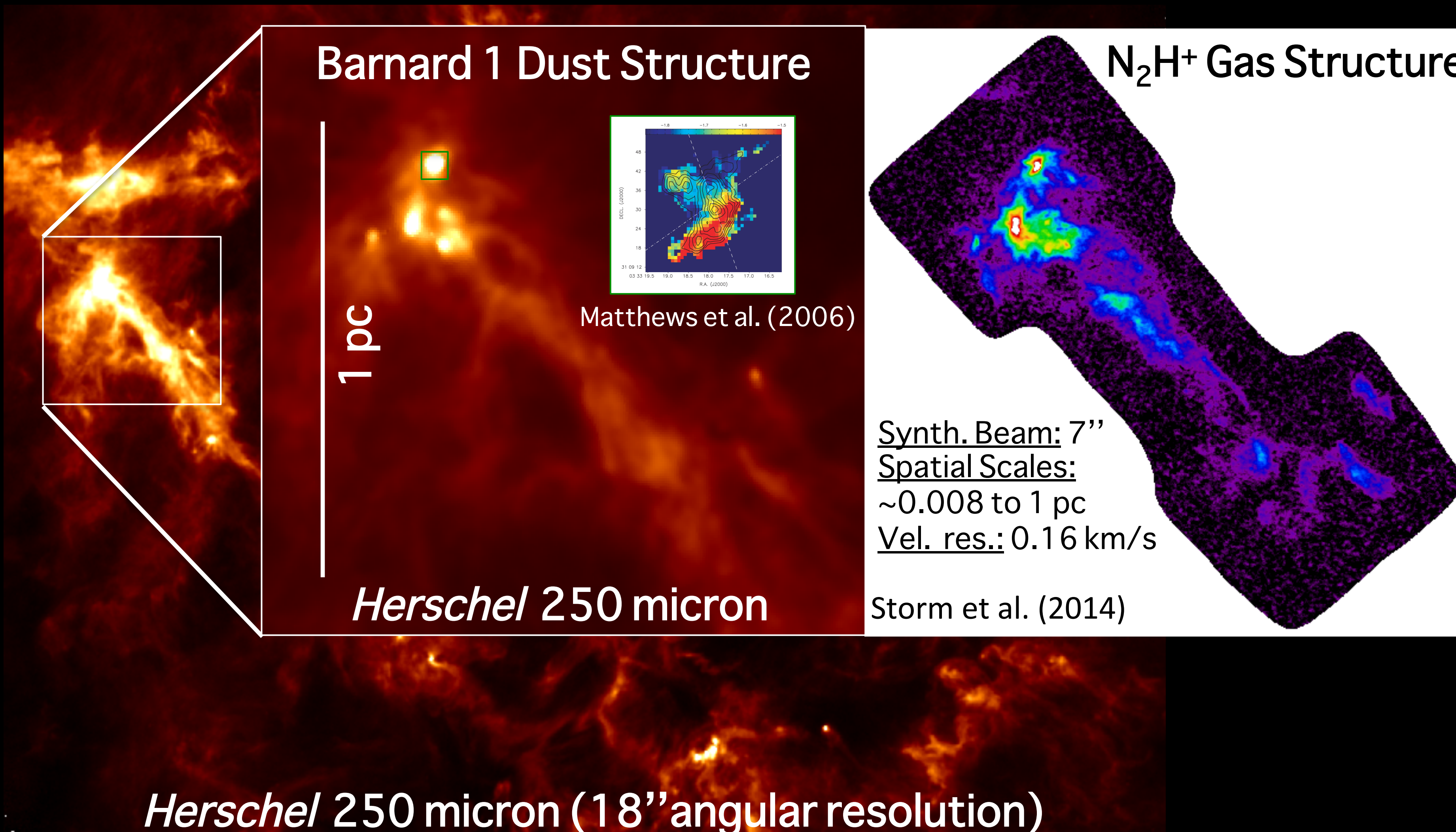
Federrath & Klessen (2012)



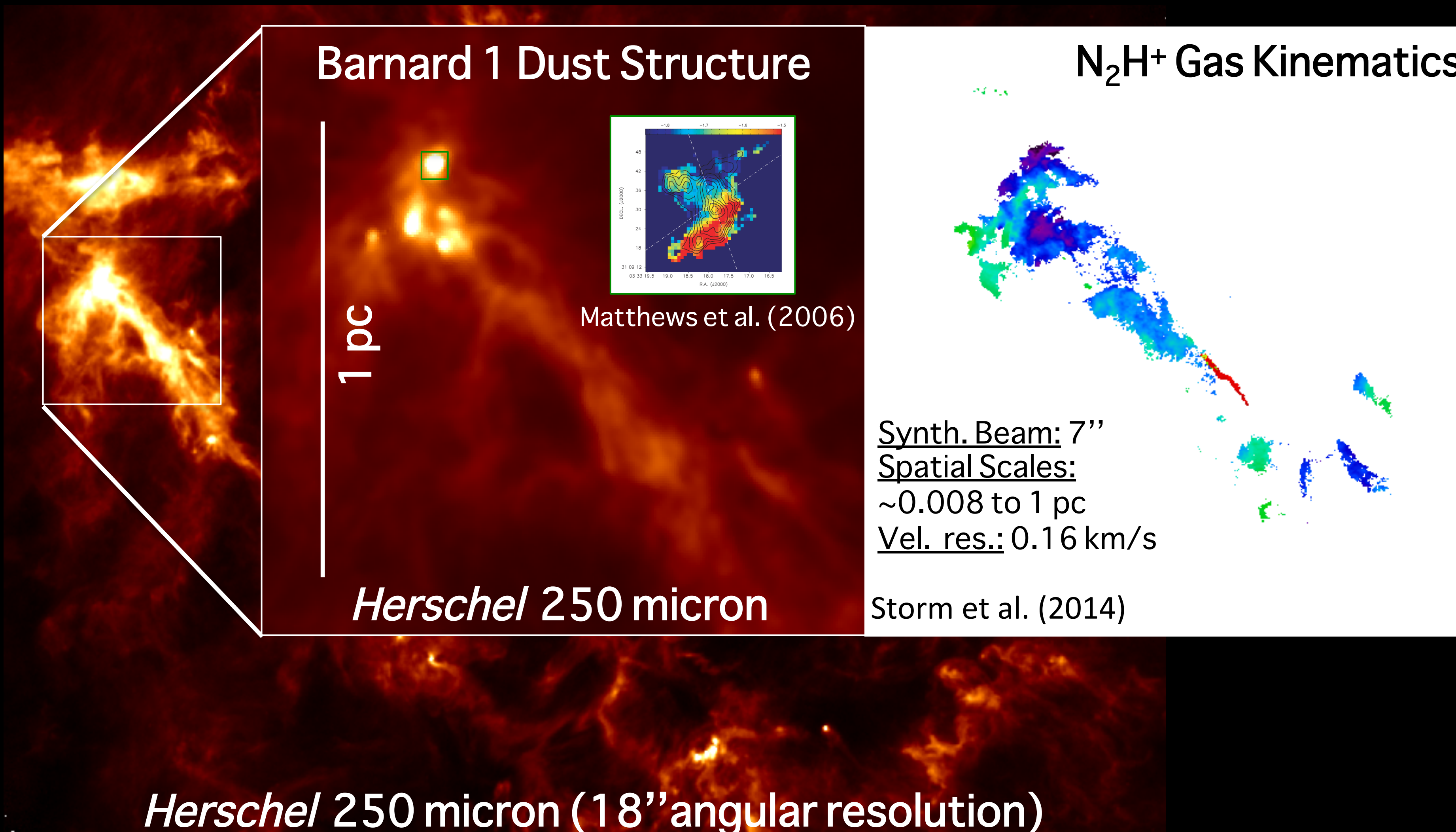
Chen & Ostriker (2014) and poster here today

- Turbulence and gravity create structure on a wide range of scales.
  - Want to observationally capture parsec-scale "cloud" structure + sub-0.1 pc filament and "core" structure … *as well as relationship with gas motions*.

Need more complete picture of Molecular Clouds



Need more complete picture of Molecular Clouds



CARMA Large Area Star formation Survey (CLASSy)

Team Members:

- Lee Mundy, Shaye Storm, Peter Teuben, Katherine Lee, Che-Yu Chen (U. Maryland)
- Leslie Looney, Manuel Fernandez-Lopez, Dominique Segura-Cox, Richard Crutcher (U. Illinois)
- Hector Arce, Adele Plunkett (Yale)
- Erik Rosolowsky (U. Alberta)
- Eve Ostriker (Princeton)
- John Tobin (NRAO)
- Yancy Shirley (U. Arizona)
- Andrea Isella (Caltech)

Three recent/upcoming publications:

- Fernandez-Lopez et al. 2014 ApJL
- Storm et al. 2014 ApJ
- Lee et al. 2014 ApJ

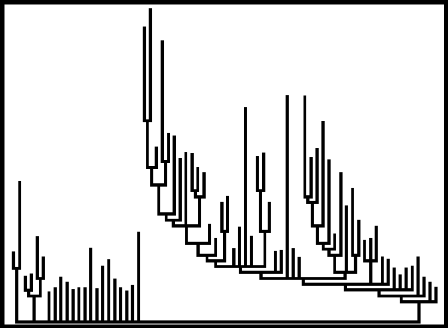
NGC 1333
Barnard 1
L1451

Serpens Main
Serpens South

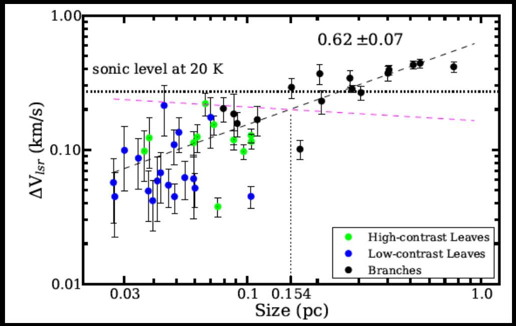
http://carma.astro.umd.edu/classy

... also Lee's poster

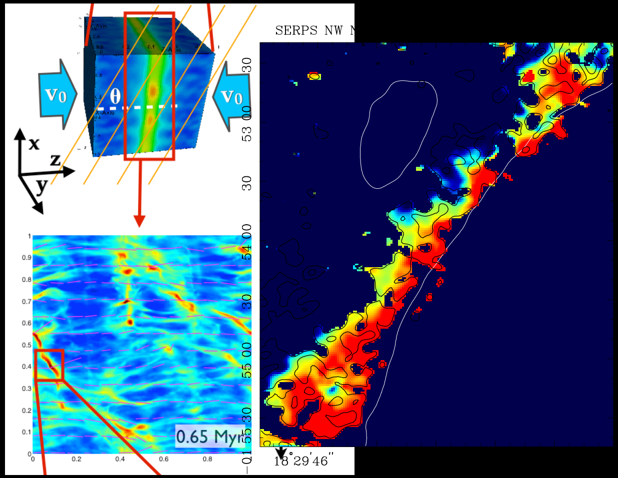
Science Issues for Understanding Pathway to SF



1. What is the connectivity of molecular cloud structures from parsec scales down to core scales?

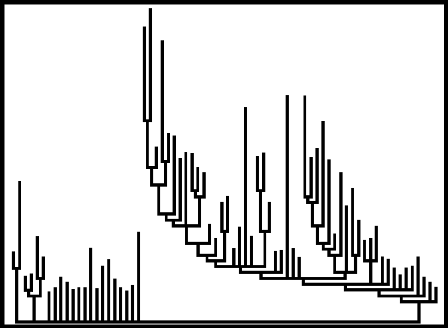


2. What can the kinematics of dense gas tell us about the formation of molecular cloud structures?



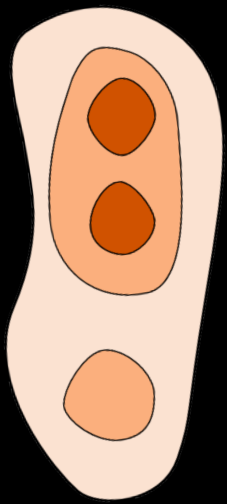
3. What is the origin of filaments, and what role do they play in core formation?

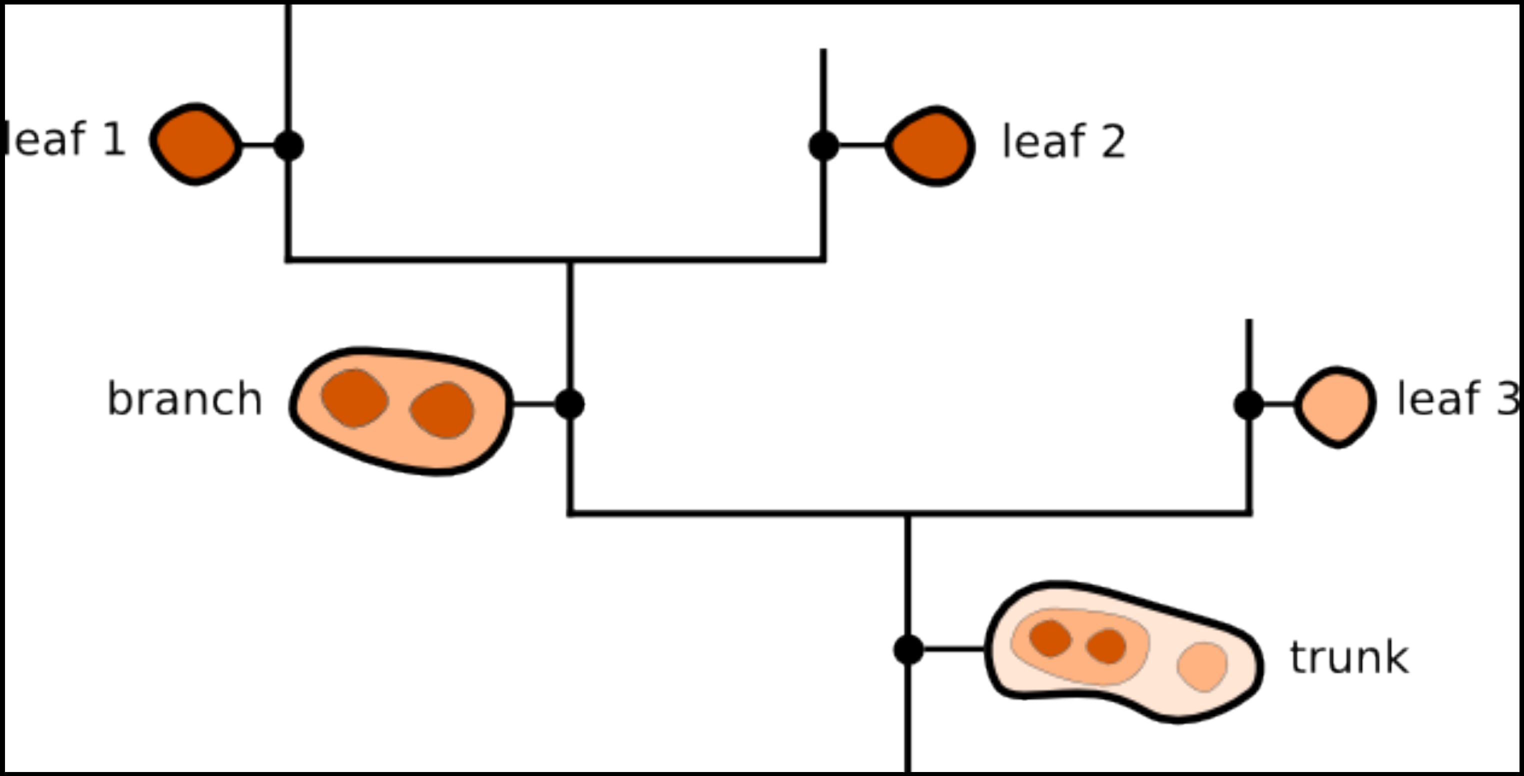
Science Issues for Understanding Pathway to SF



1. What is the connectivity of molecular cloud structures from parsec scales down to core scales?

Connectivity captured with dendrograms

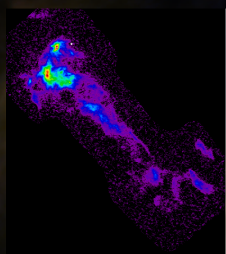


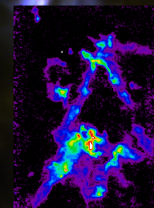


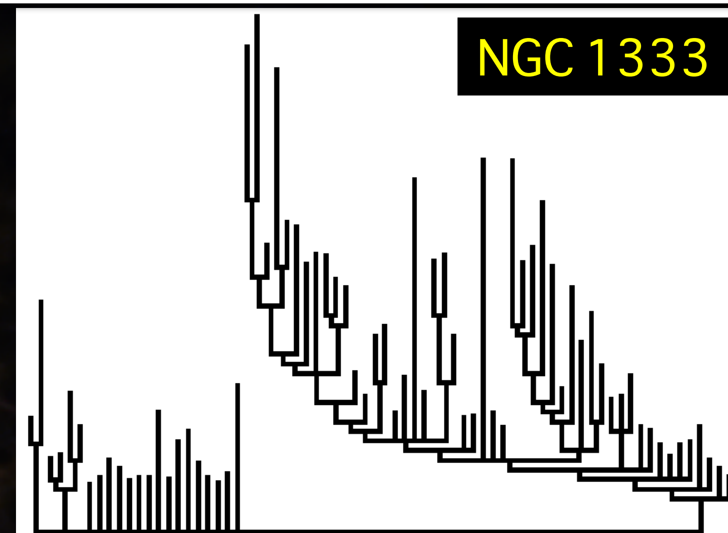
A dendrogram is a useful quantization of 1D, 2D, or 3D structures. (Our CARMA images are 3D PPV cubes.) This dendrogram shows a 2-level hierarchy.

Image Credit: dendrograms.org

N_2H^+ Non-binary Dendrograms Across Perseus



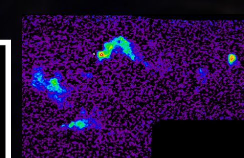




16-Level Hierarchy

4-Level Hierarchy

Dense gas cores are more complexly nested in NGC 1333 compared to Barnard 1; L1451 dense gas shows no hierarchical structure.

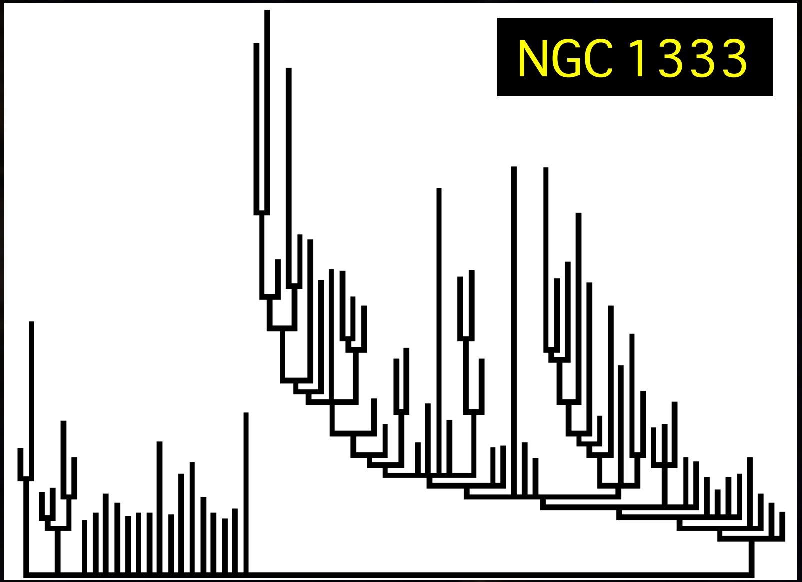


0-Level Hierarchy

Star Formation Activity and Hierarchical Complexity

NGC 1333

Spitzer YSOs	70
Herschel 70 micron sources	25
CARMA 3 mm continuum sources	17
SFE_{cloud} (Jørgensen 2008)	14%



The amount of star formation activity correlates with the hierarchical complexity of dense gas structures.

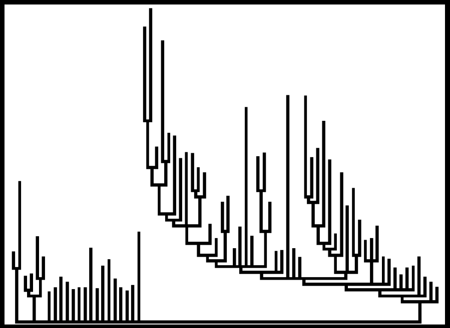
Star Formation Activity and Hierarchical Complexity

L1451

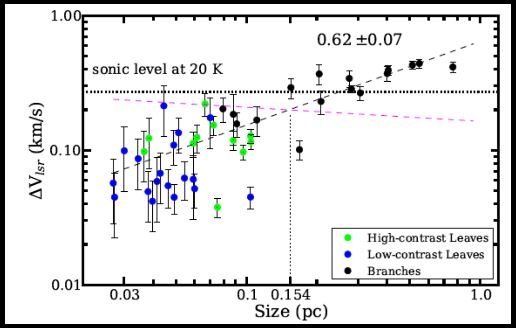
Spitzer YSOs	0
Herschel 70 micron sources	0
CARMA 3 mm continuum sources	1
SFE_{cloud}	0%

The amount of star formation activity correlates with the hierarchical complexity of dense gas structures.

Science Issues for Understanding Pathway to SF

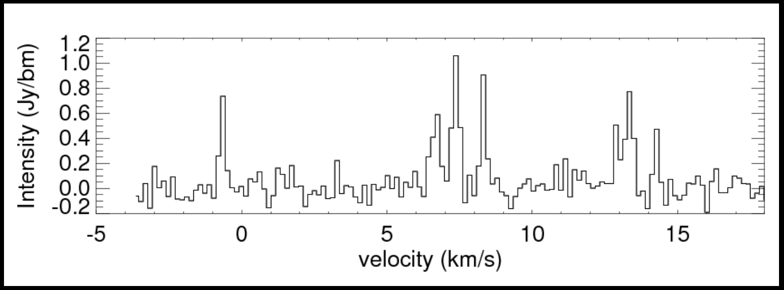


Dense regions with evolved SF and many cores are highly hierarchical relative to regions just beginning to form cores

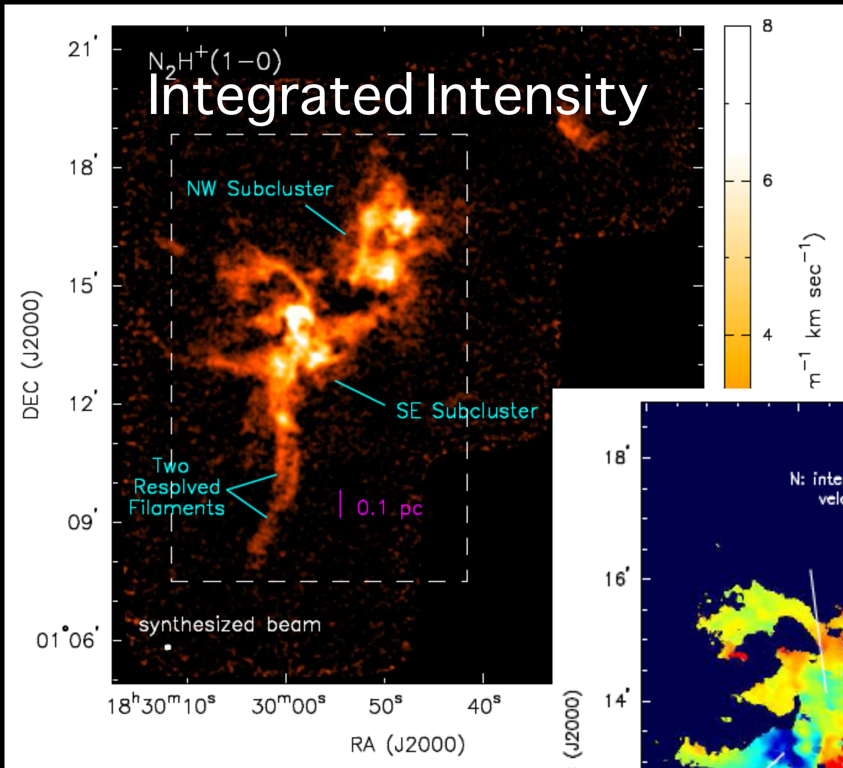


2. What can the kinematics of dense gas tell us about the formation of molecular cloud structures?

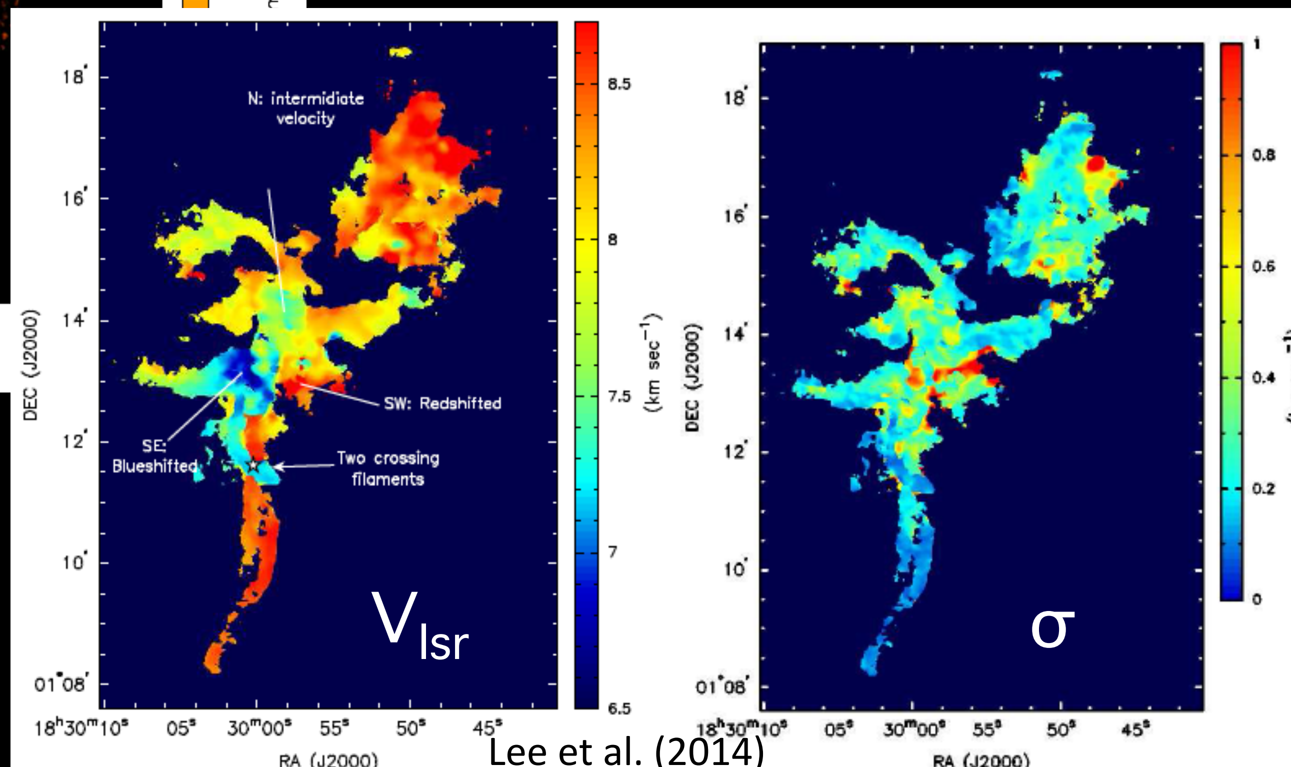
Example N_2H^+ (J=1-0) spectrum in very narrow line region



Science Issue #2. Kinematics of dense gas revealing MC formation processes

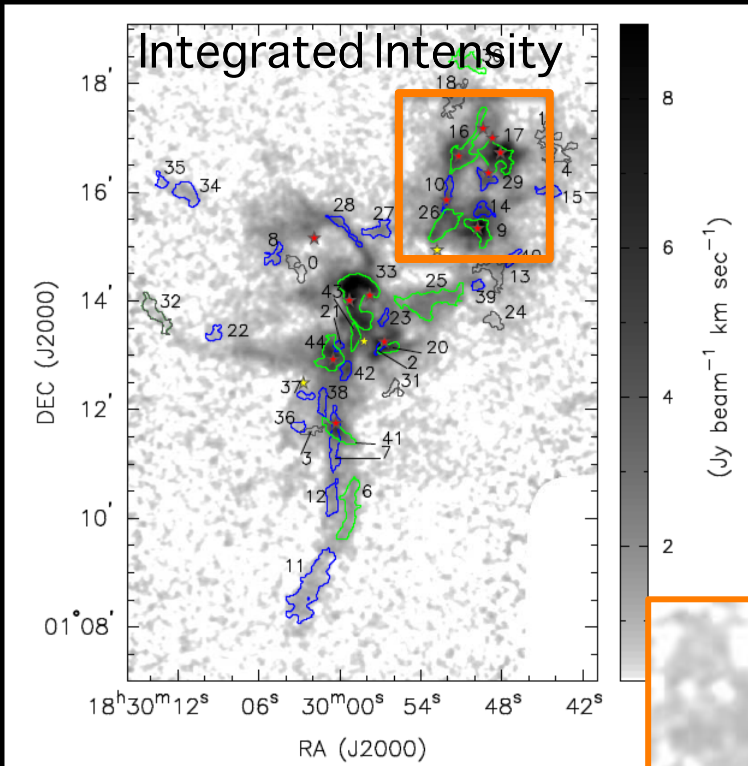


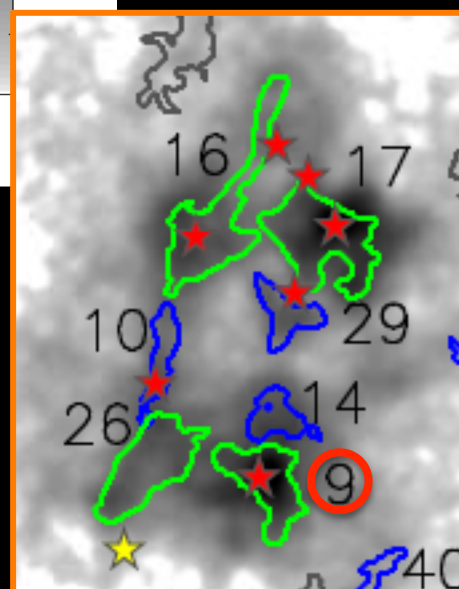
Lee et al. (2014)

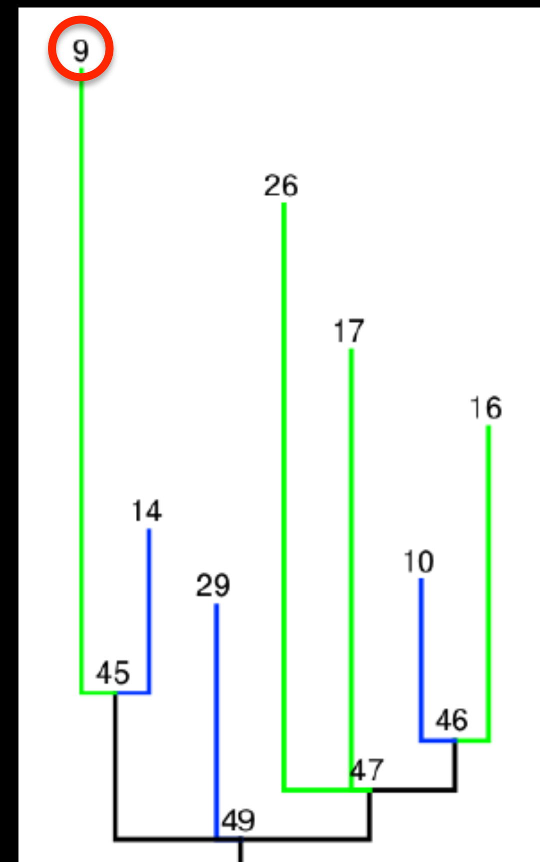


Lee et al. (2014)

Science Issue #2. Kinematics of dense gas revealing MC formation processes







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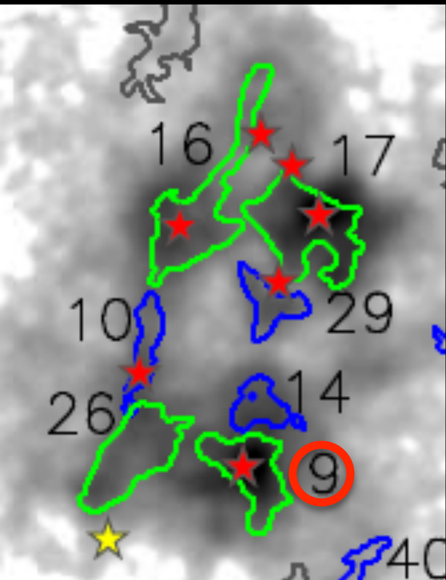
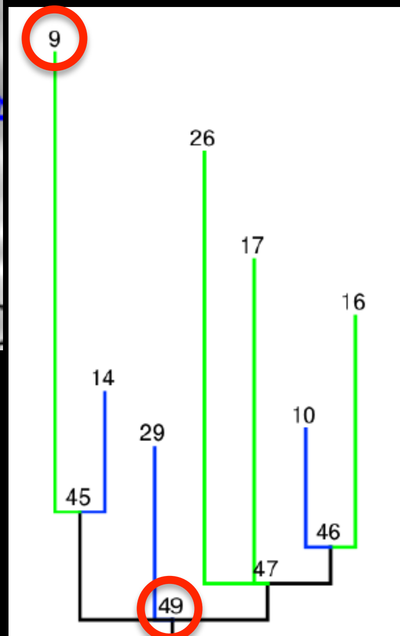
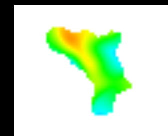
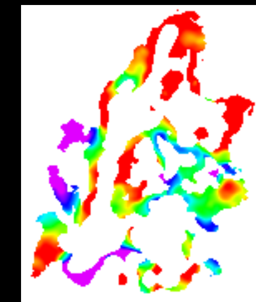




Smaller Scale Leaf | Larger Scale Branch



V_{lsr} Map



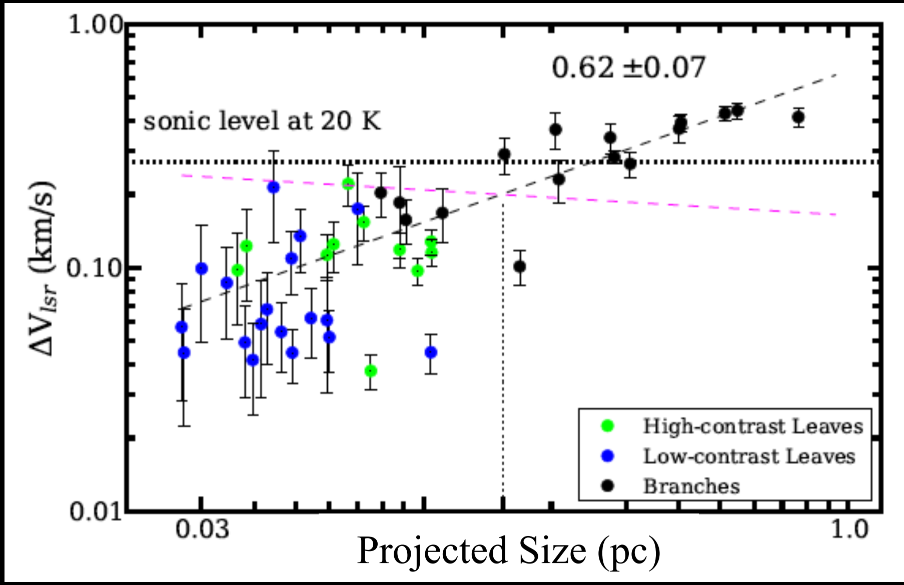
σ_{nt} Map

Two types of "linewidths" from this high-resolution data:

1. Variation of V_{lsr} within each object (ΔV_{lsr})
2. Mean non-thermal velocity dispersion within each object ($<\sigma>_{nt}$)

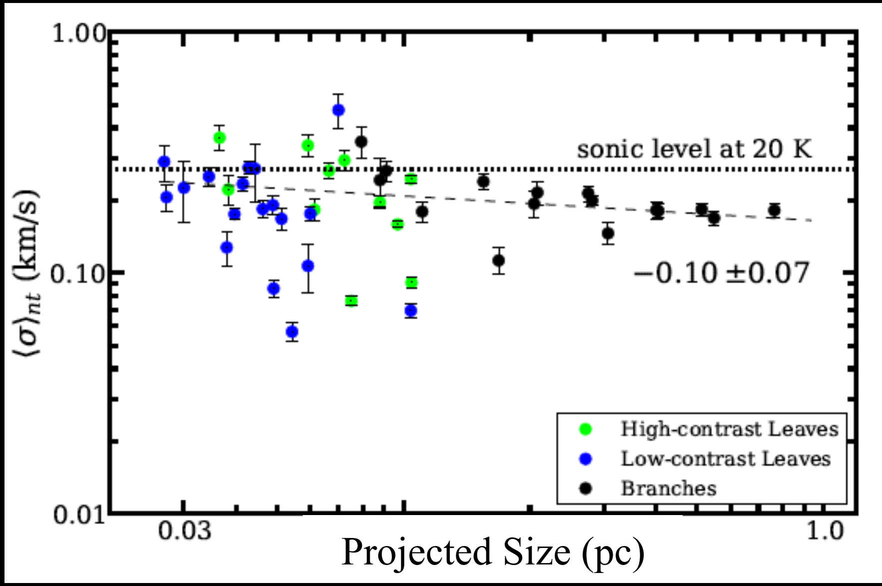
Two Size-Linewidth Relations

ΔV_{lsr} vs. Projected Size



Larger objects have more V_{lsr} variation than than smaller objects

$<\sigma>_{nt}$ vs. Projected Size



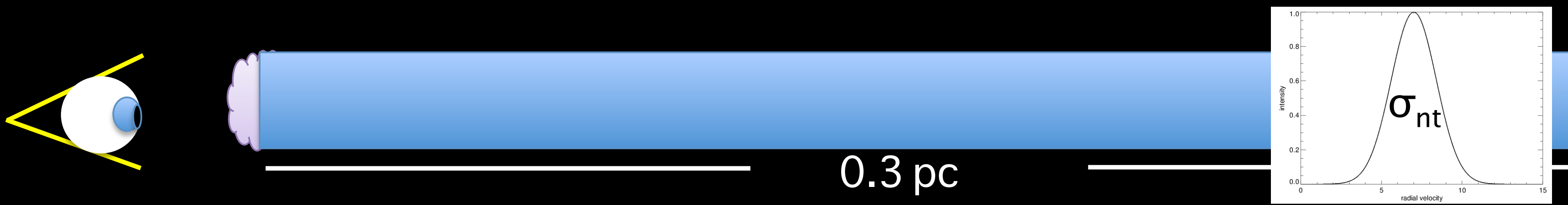
All objects have similar $<\sigma>_{nt}$, independent of projected size

Why the difference?

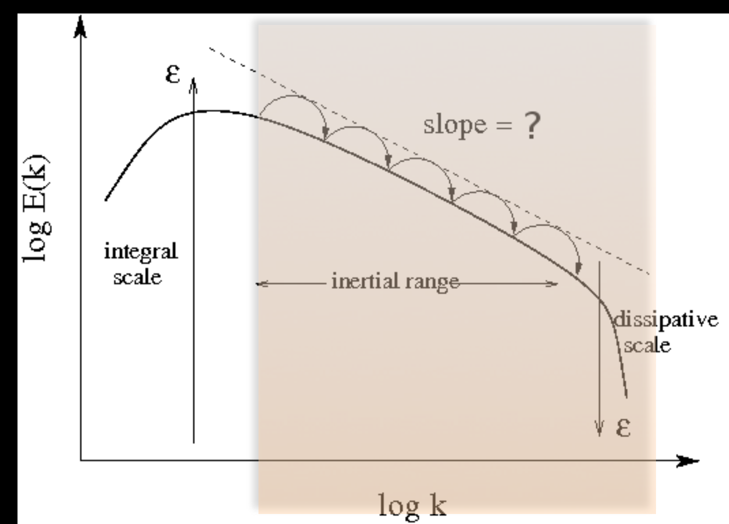
… differences between an object's projected size and depth into the plane of the sky.

Linewidth influenced by largest scale

$$v_{nt}^2(L) \propto L^{2q} \rightarrow \sigma_{nt}(L) \propto L^q$$



Angular resolution element



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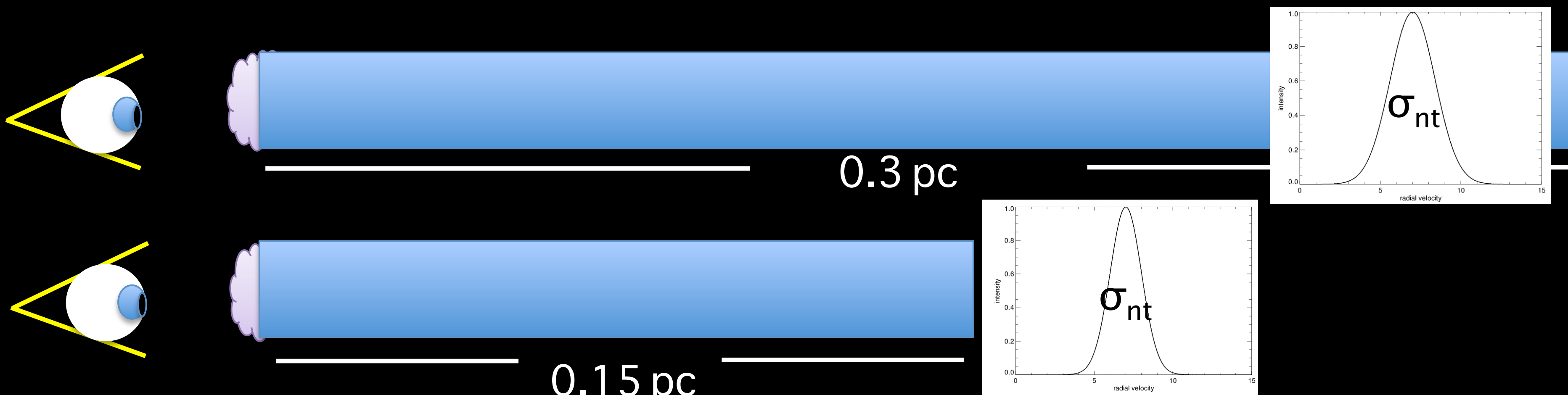

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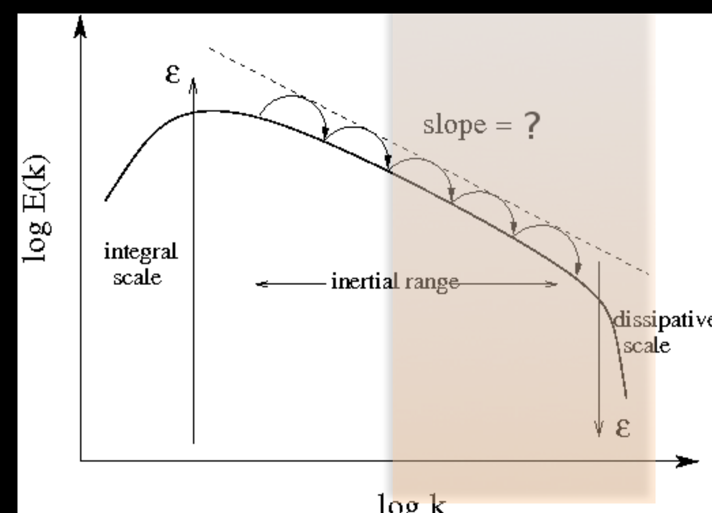

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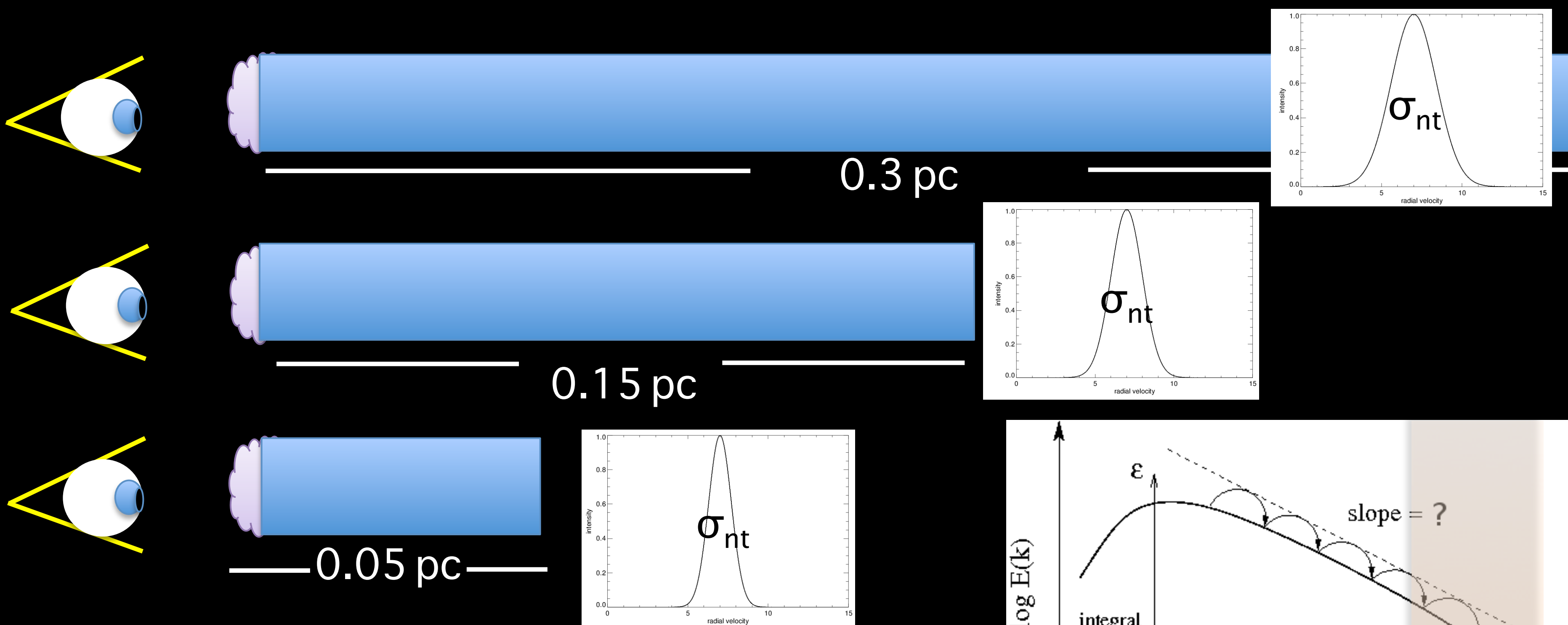
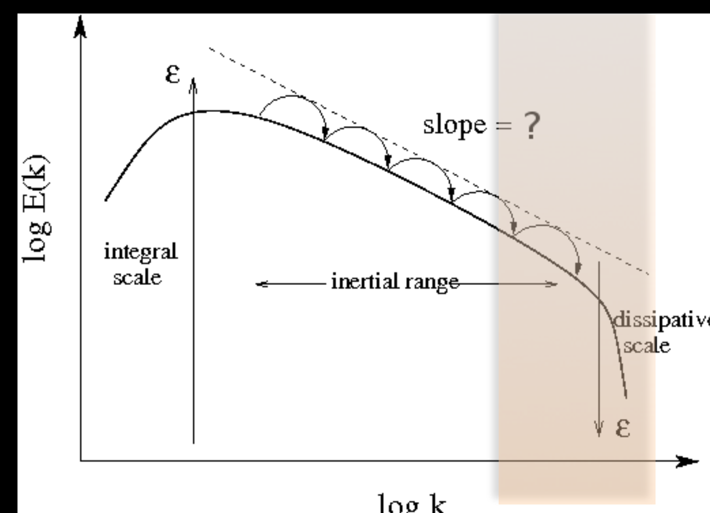
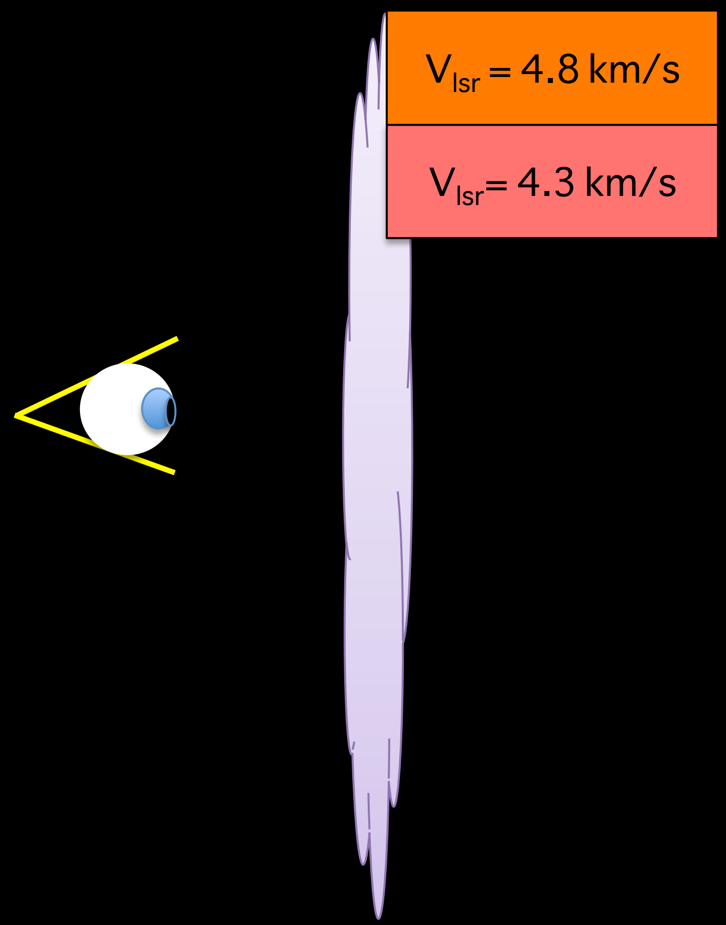


Angular resolution element

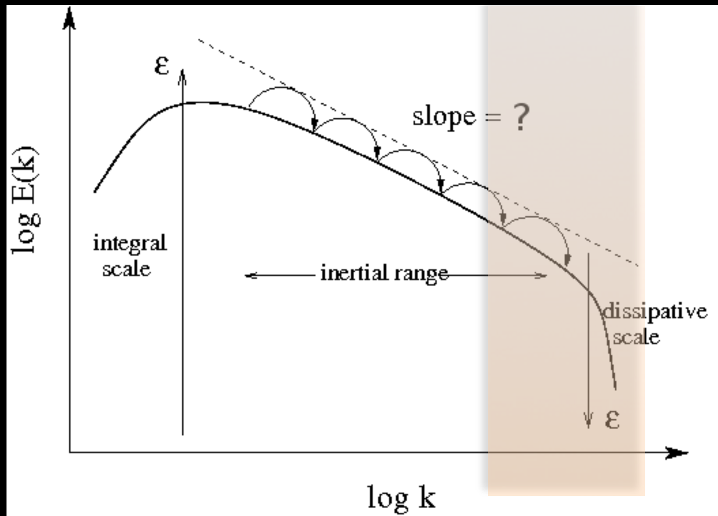


Linewidth influenced by largest scale

$$v_{nt}^2(L) \propto L^{2q} \rightarrow \Delta V_{lsr}(L) \propto L^q$$



Angular resolution element



Linewidth influenced by largest scale

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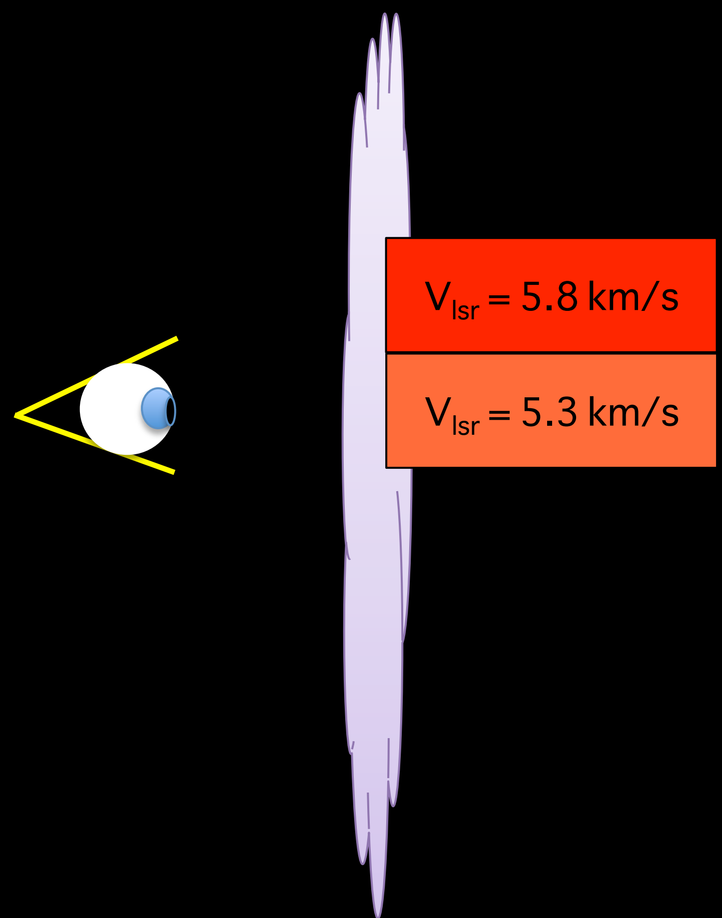
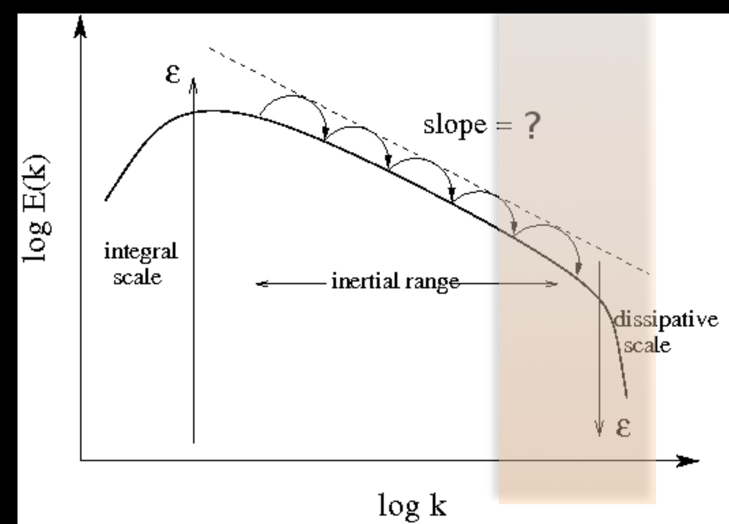



Angular resolution element



Linewidth influenced by largest scale

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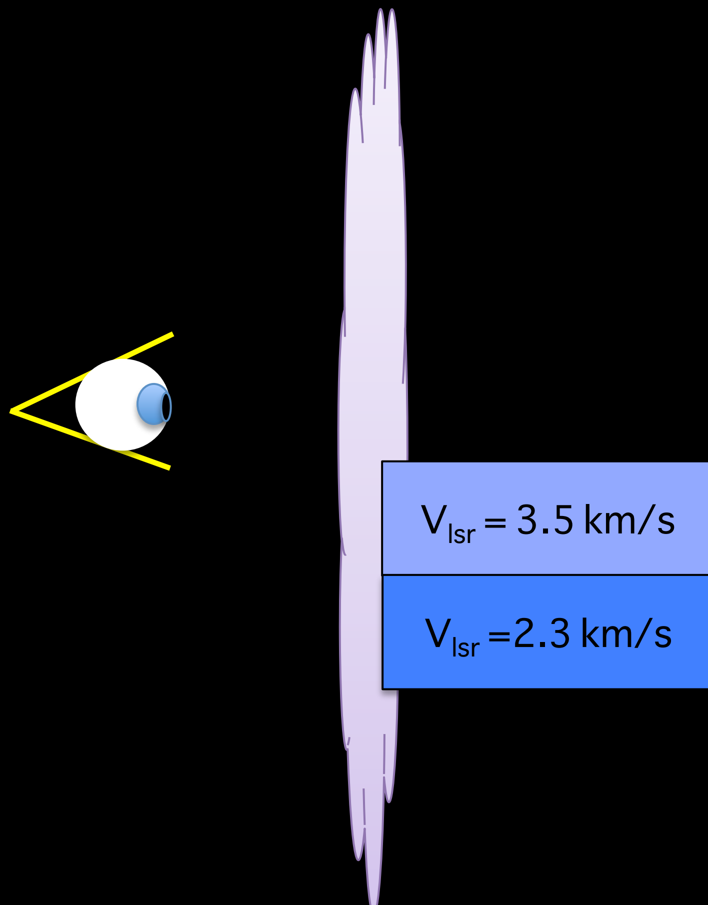

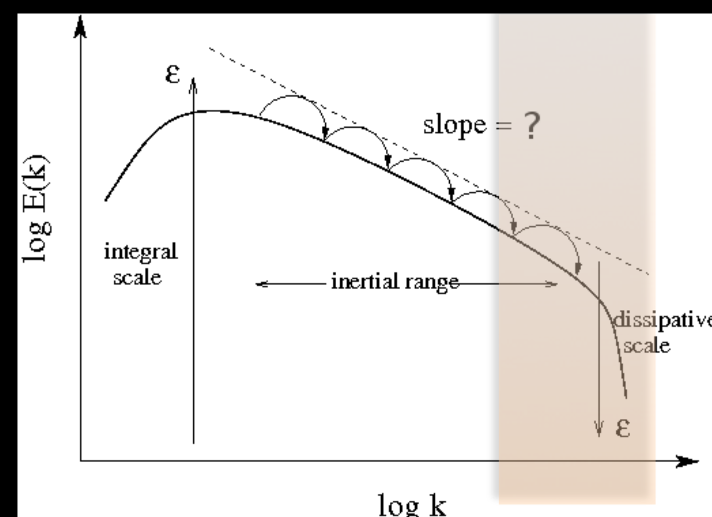

Angular resolution element

Linewidth influenced by largest scale

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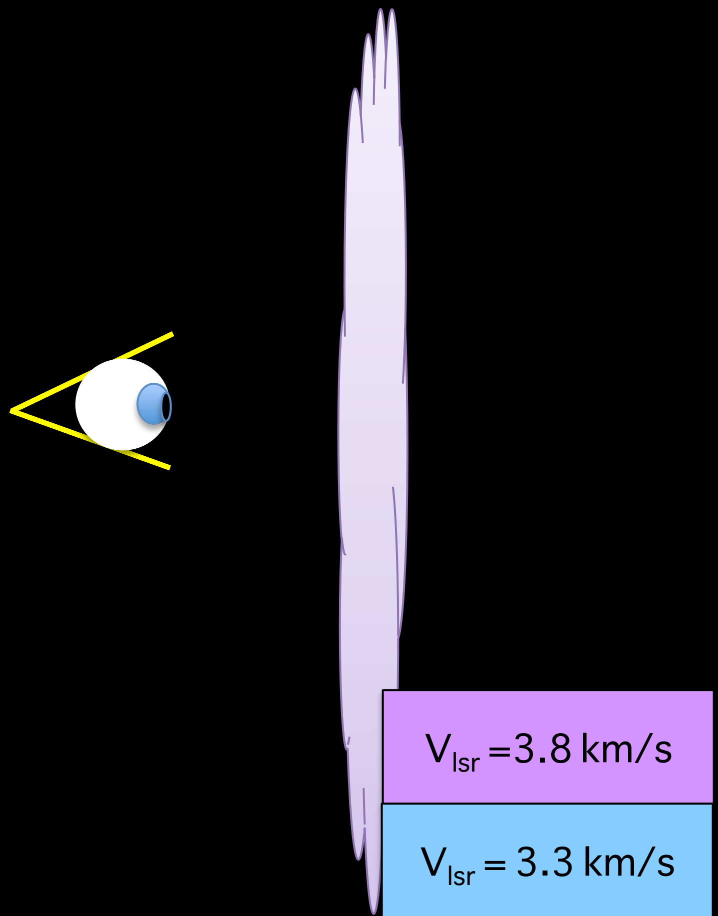

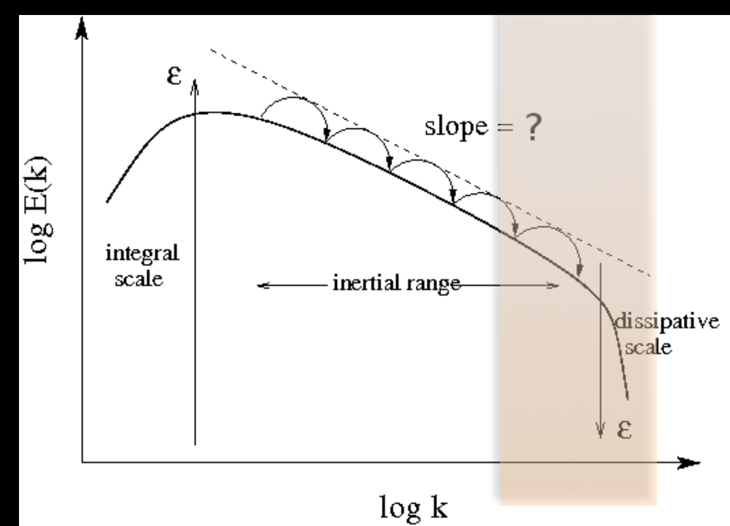

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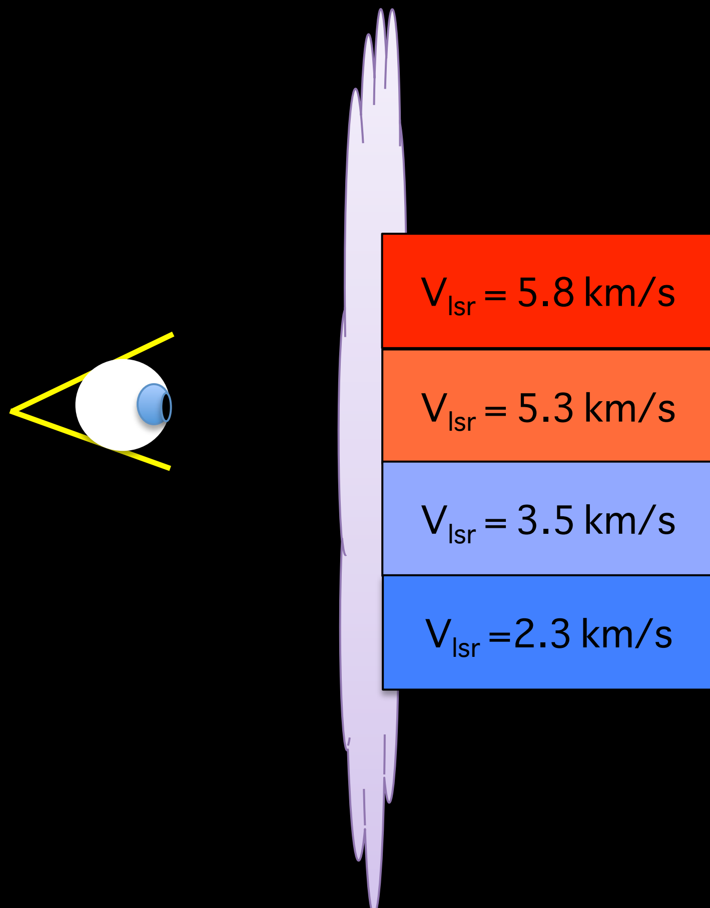

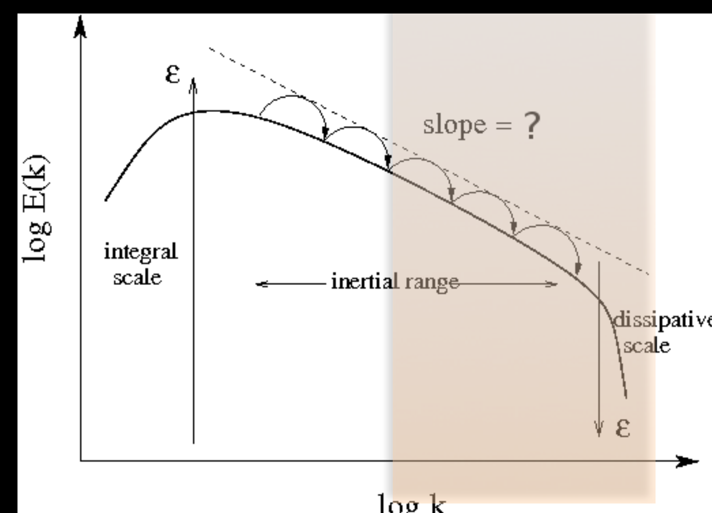


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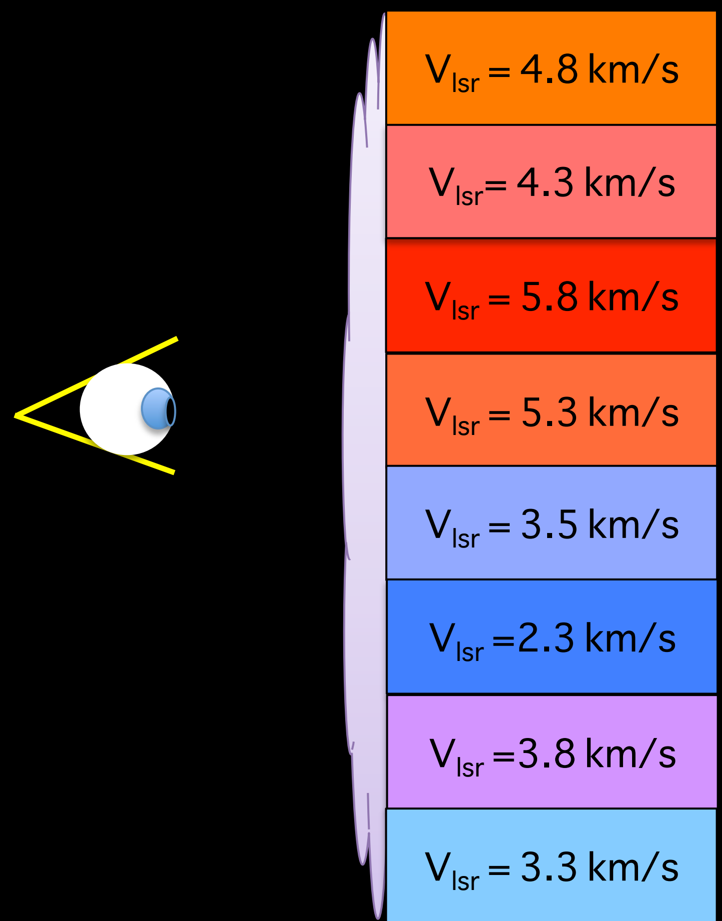
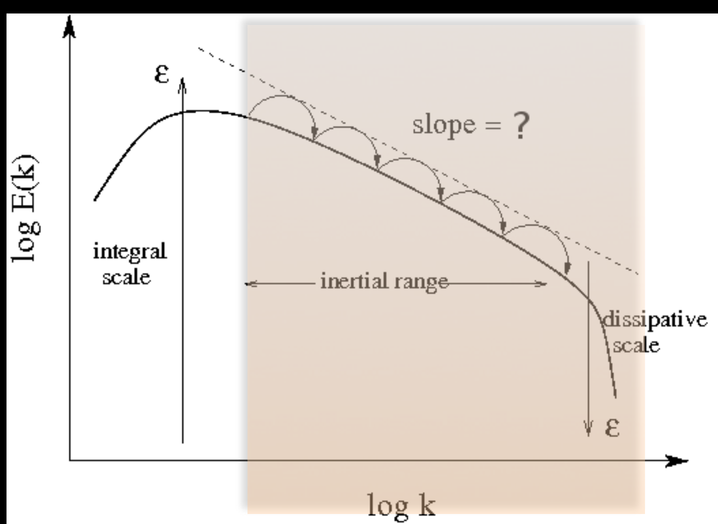
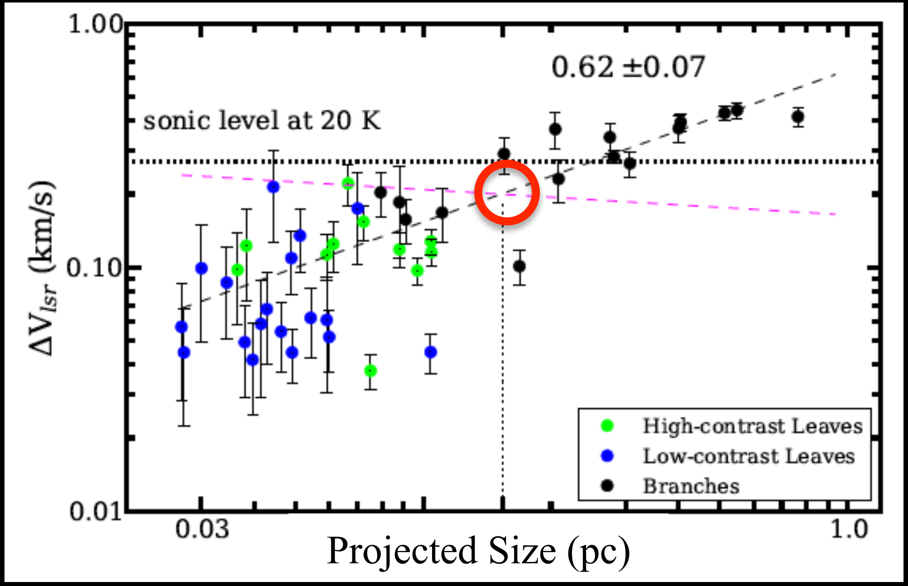



Angular resolution element

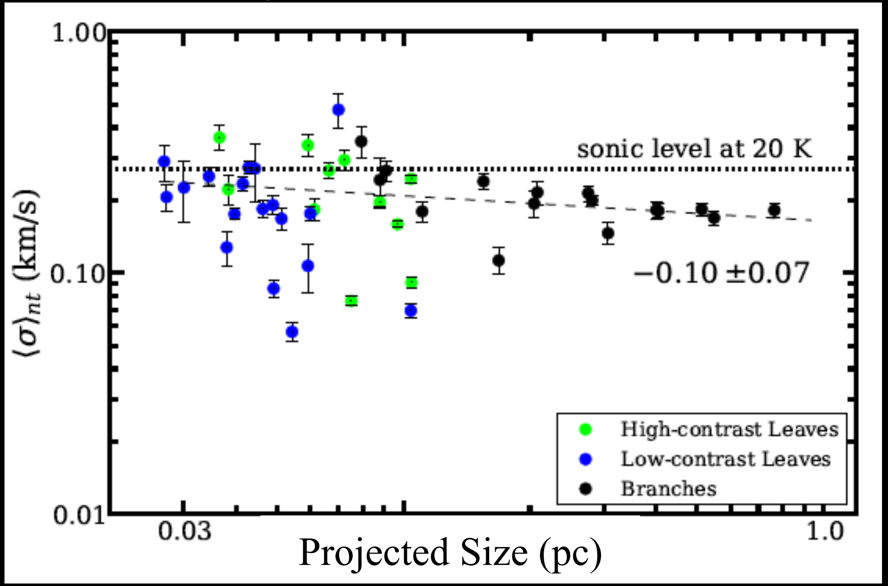


Size-Linewidth Relations Reveal Cloud Depth

ΔV_{lsr} vs. Projected Size

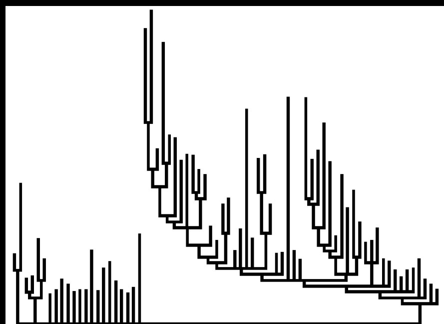


$<\sigma>_{nt}$ vs. Projected Size

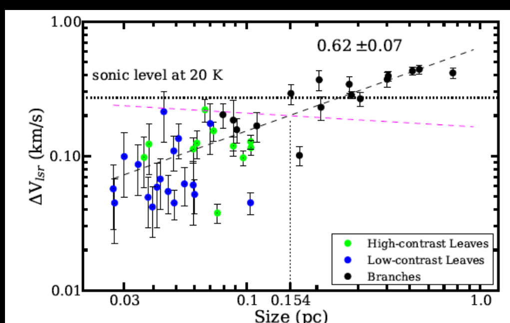


- Typical depth of Serpens Main is ~0.15 pc.
- CLASSy data reveals that depth of the structures into the sky is relatively small compared to the largest scale we see.
- Flattened large-scale structures are consistent with overdensities formed at intersection of turbulent flows.

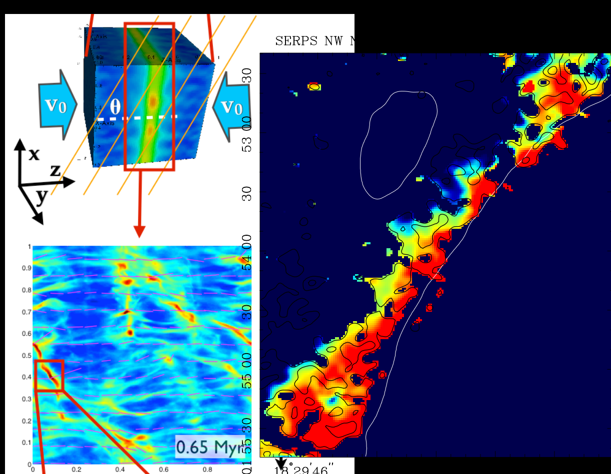
Science Issues for Understanding Pathway to SF



Dense regions with evolved SF and many cores are highly hierarchical relative to regions just beginning to form cores

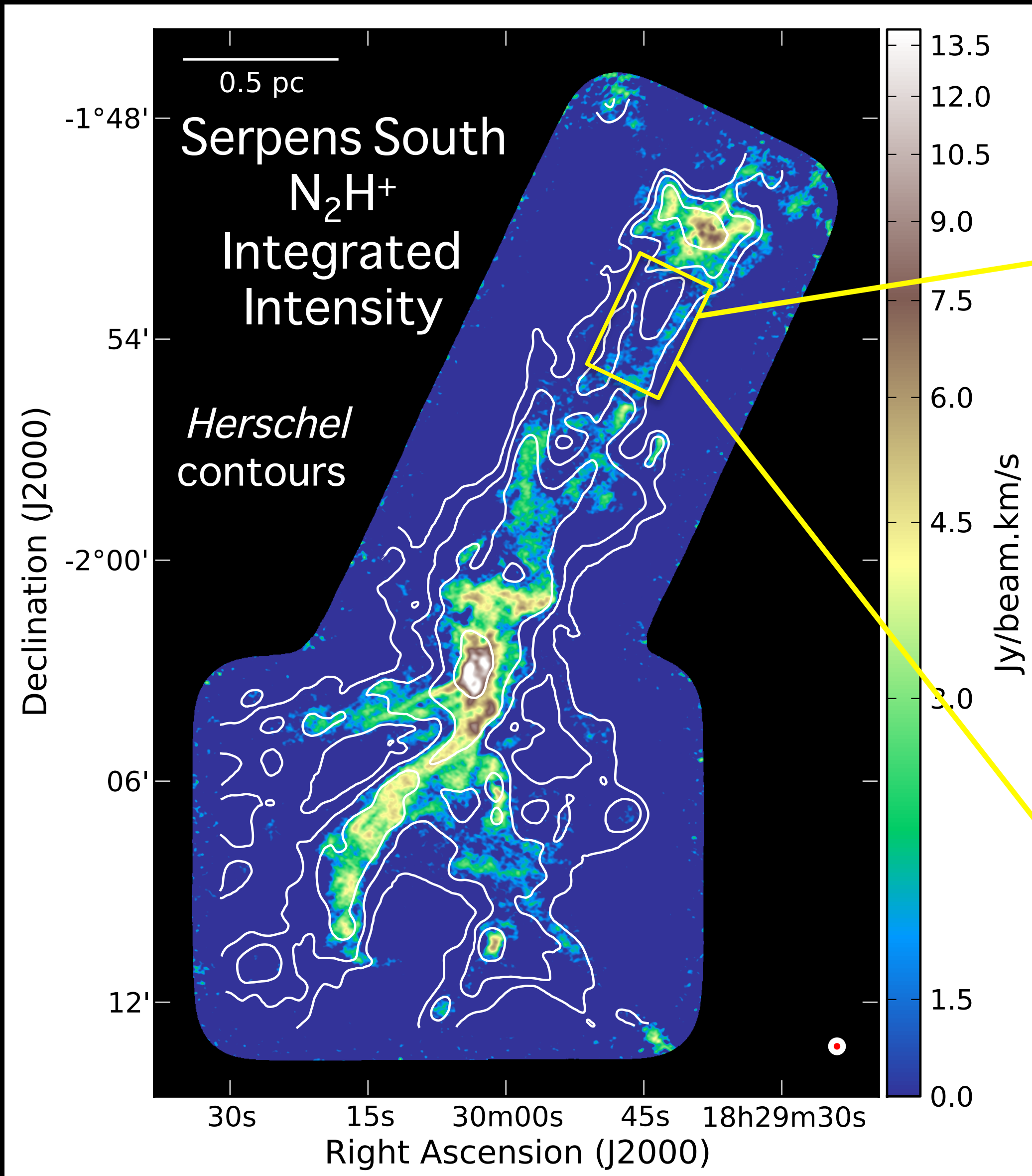


High resolution structure+kinematics reveals that the dense gas in CLASSy regions is flattened at largest scales



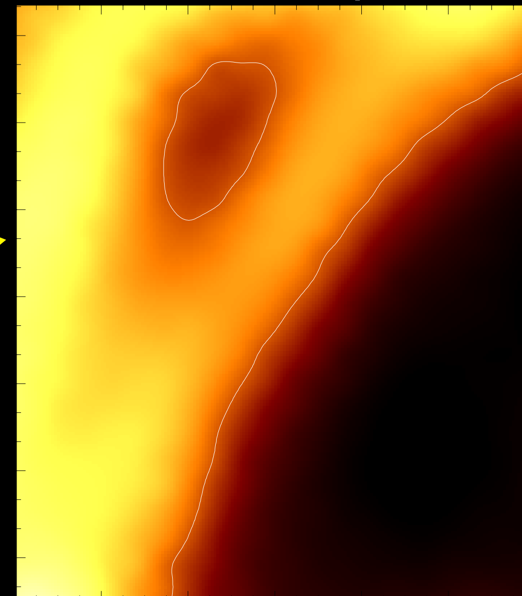
3. What is the origin of filaments, and what role do they play in core formation? (quick summary!)

Science Issue #3. Origin of filaments and their role in core formation

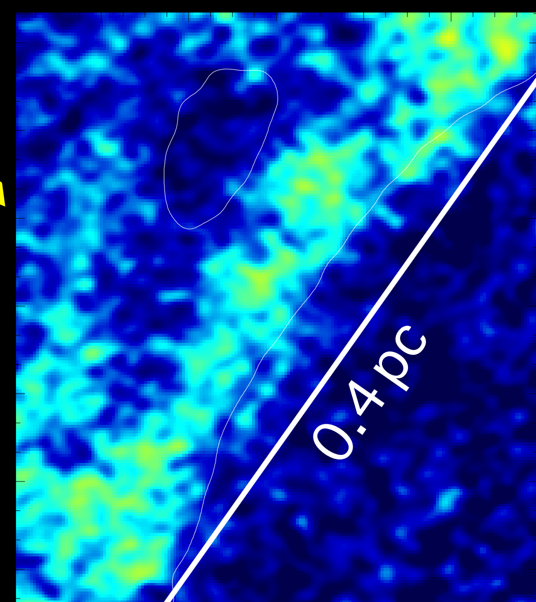


Fernandez-Lopez et al. (2014)

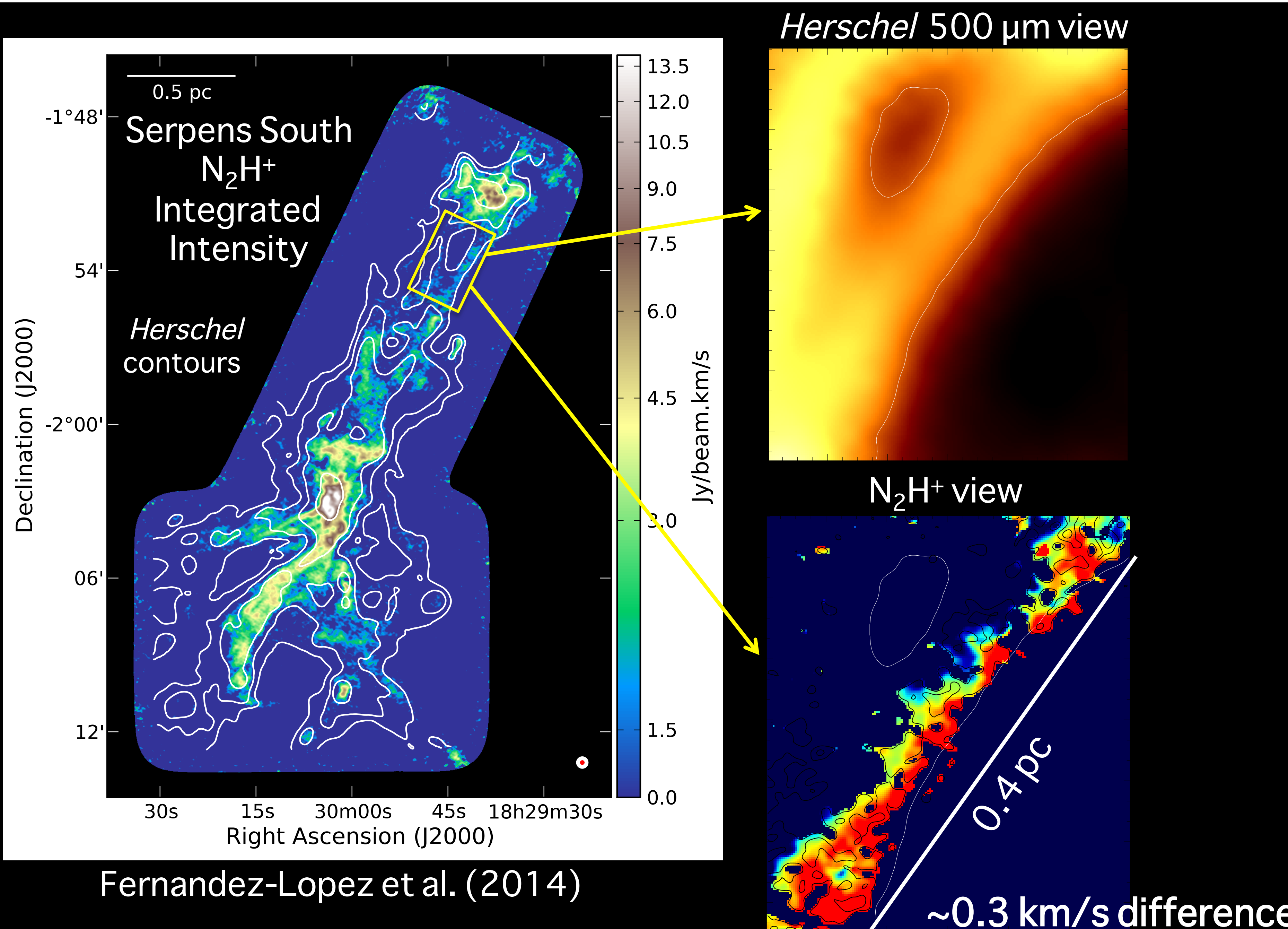
Herschel 500 μm view



N_2H^+ view



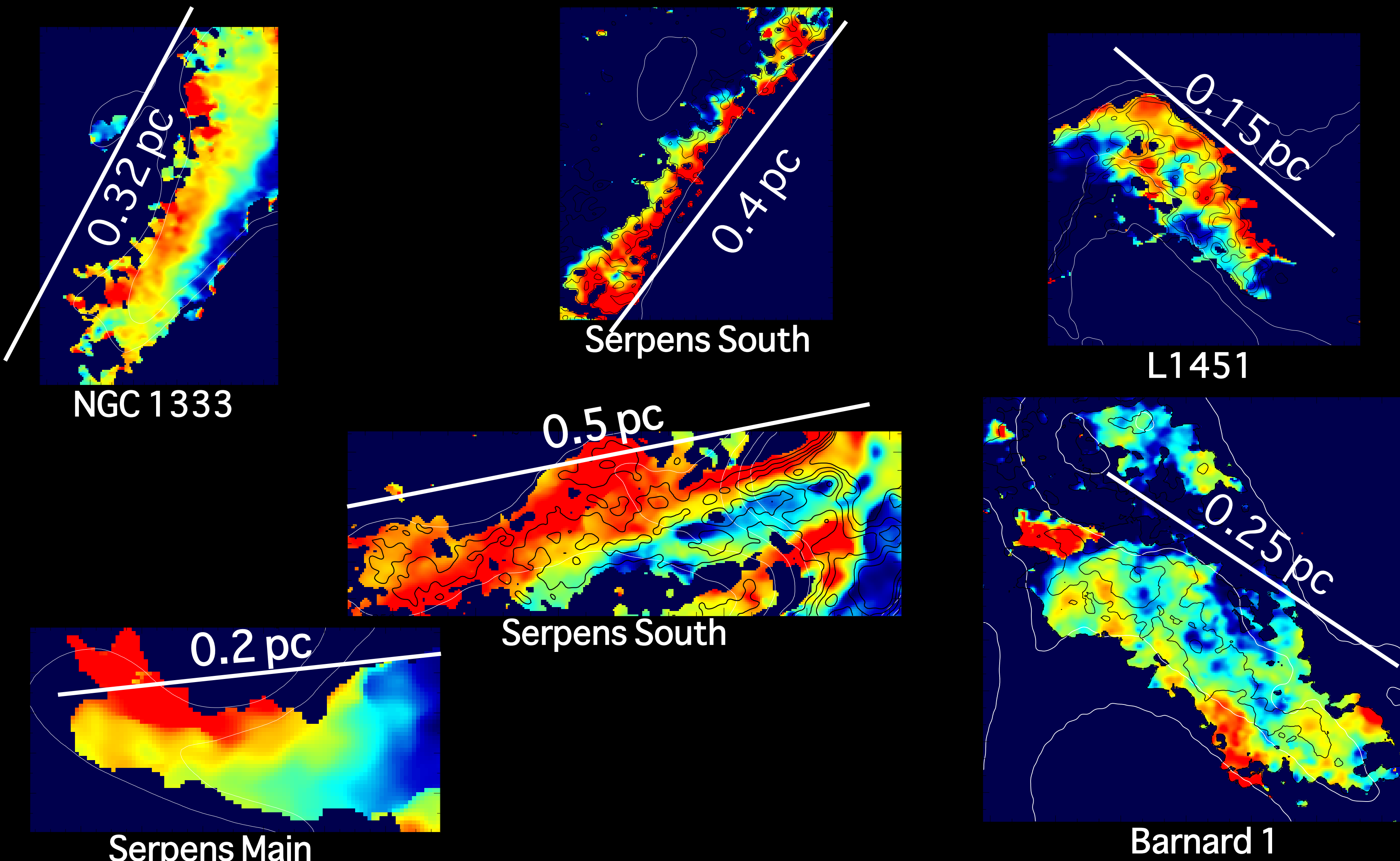
Science Issue #3. Origin of filaments and their role in core formation



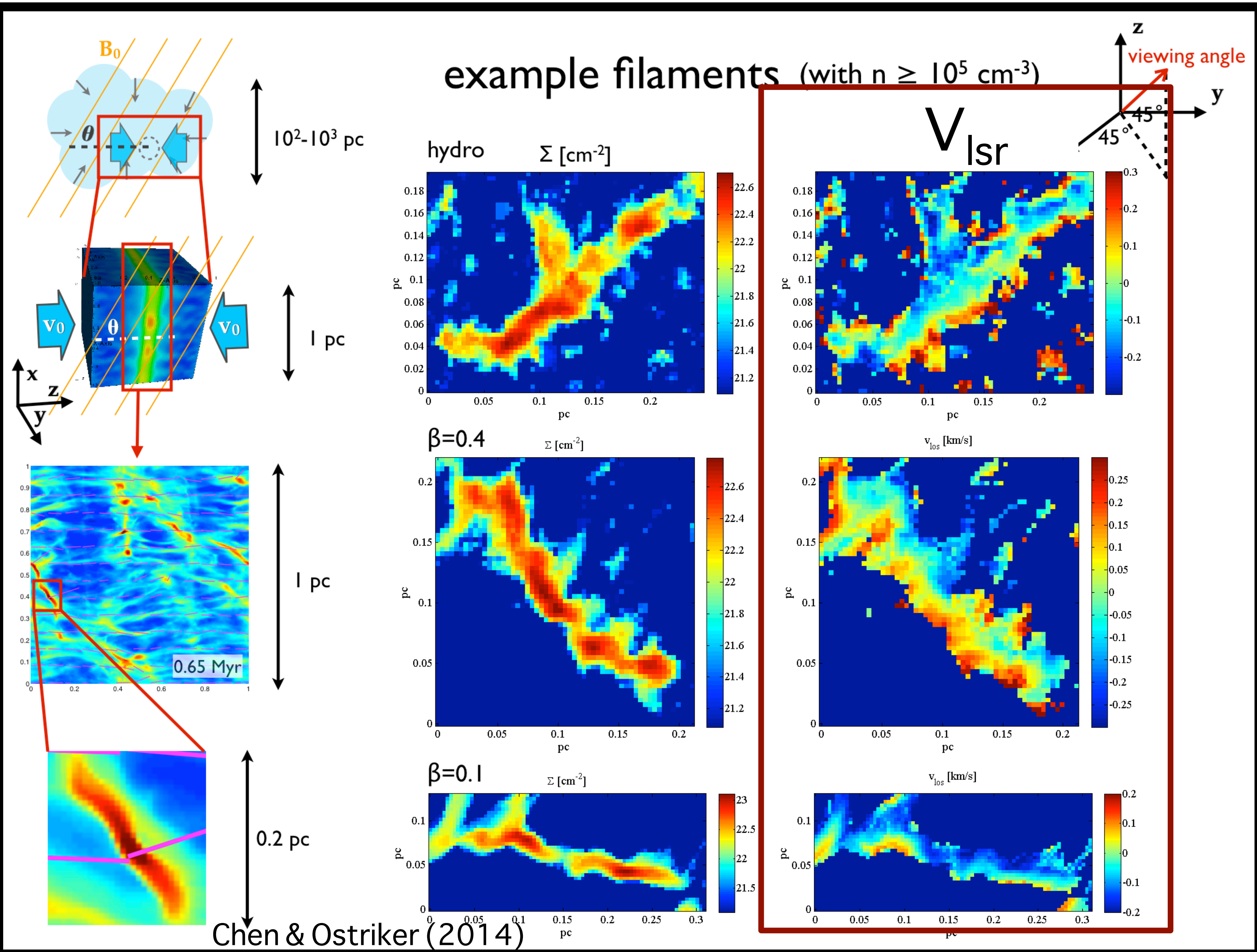
Fernandez-Lopez et al. (2014)

Science Issue #3. Origin of filaments and their role in core formation

CLASSy has discovered many filaments with similar kinematic signature

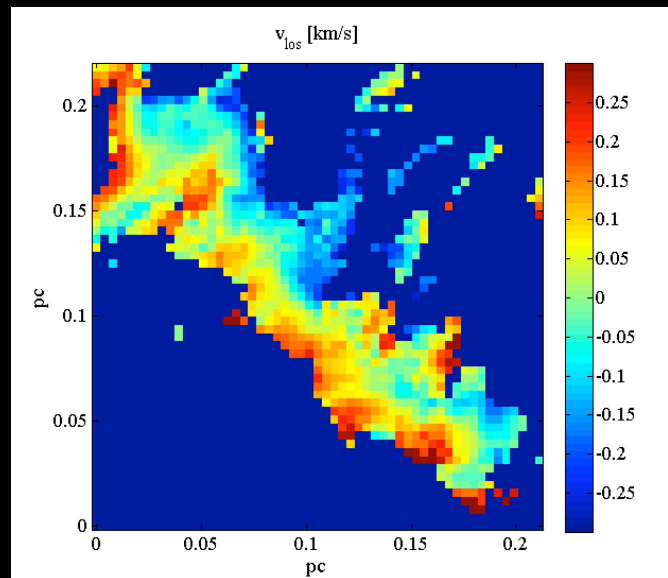


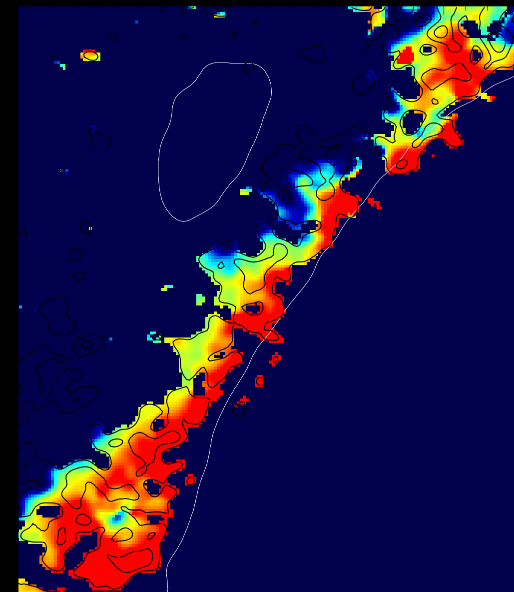
Science Issue #3. Origin of filaments and their role in core formation

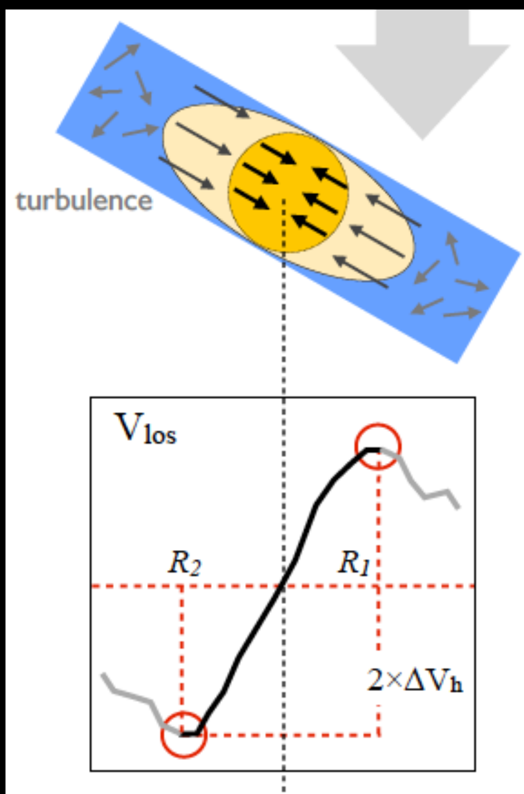


Comparing CLASSy and simulated filaments

See poster 108.06 for more details.







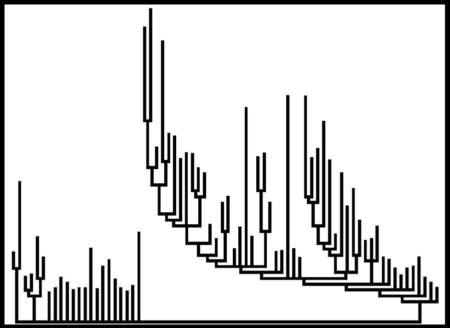
Can calculate the dimensionless coefficient:

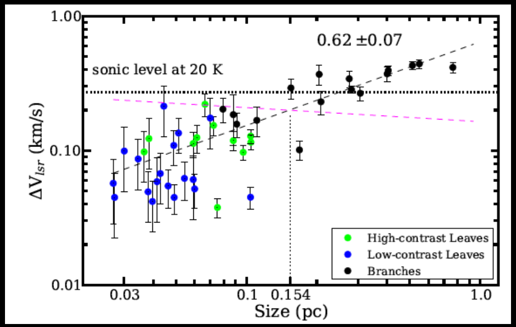
$$C = \frac{{\Delta v_h}^2}{G\overline{M_R/L}}$$

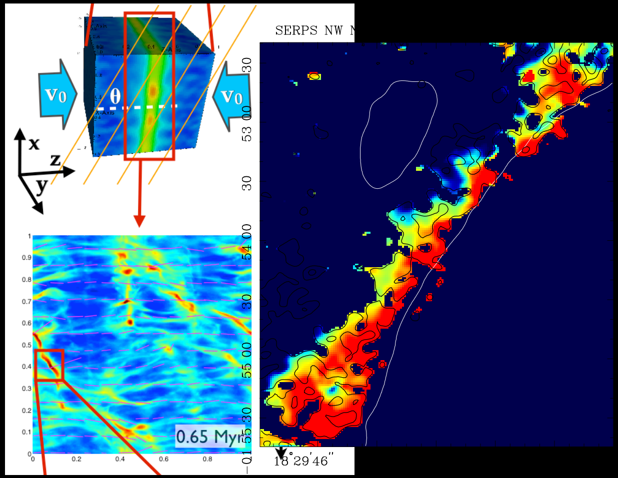
$C \sim 1$ gravity-induced velocity gradient

$C \gg 1$ turbulence-dominated structure

Science Issues for Understanding Pathway to SF







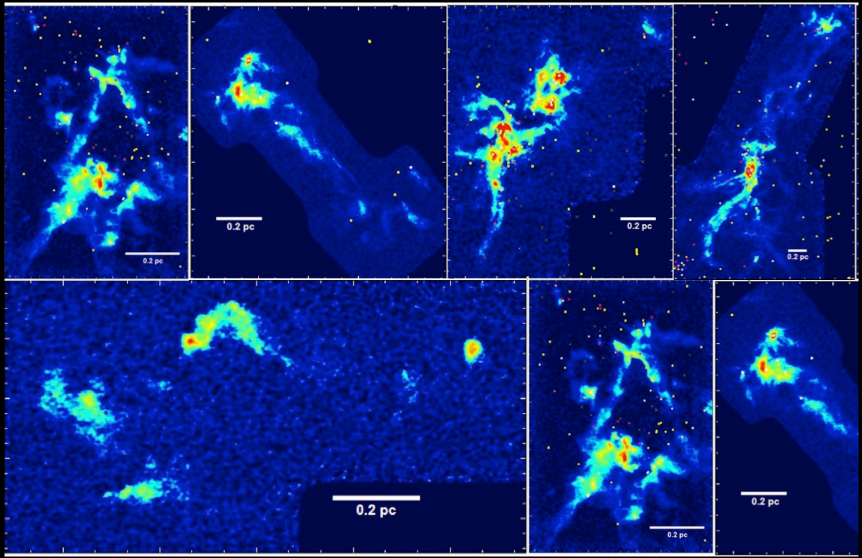
Dense regions with evolved SF and many cores are highly hierarchical relative to regions just beginning to form cores

High resolution structure+kinematics reveals that the dense gas in CLASSy regions is flattened at largest scales

CLASSy reveals filaments with structure and kinematics that suggest formation in flattened structures

Summary

- *<u>Observing Campaign</u>:* **CARMA** has connected the cloud-to-cores scales in several nearby molecular clouds with high angular resolution, large-area mosaics. We observed cold, dense gas to understand the structure and kinematics of the cloud material that is currently forming stars.
- *<u>Initial Science Results:</u>* Over-dense, sheet-like regions in molecular clouds fragment into filaments, and build up hierarchical structures on the pathway to forming dense cores.



Data becoming public:
http://carma.astro.umd.edu/classy

Stop by Lee's poster for more details and discussion!