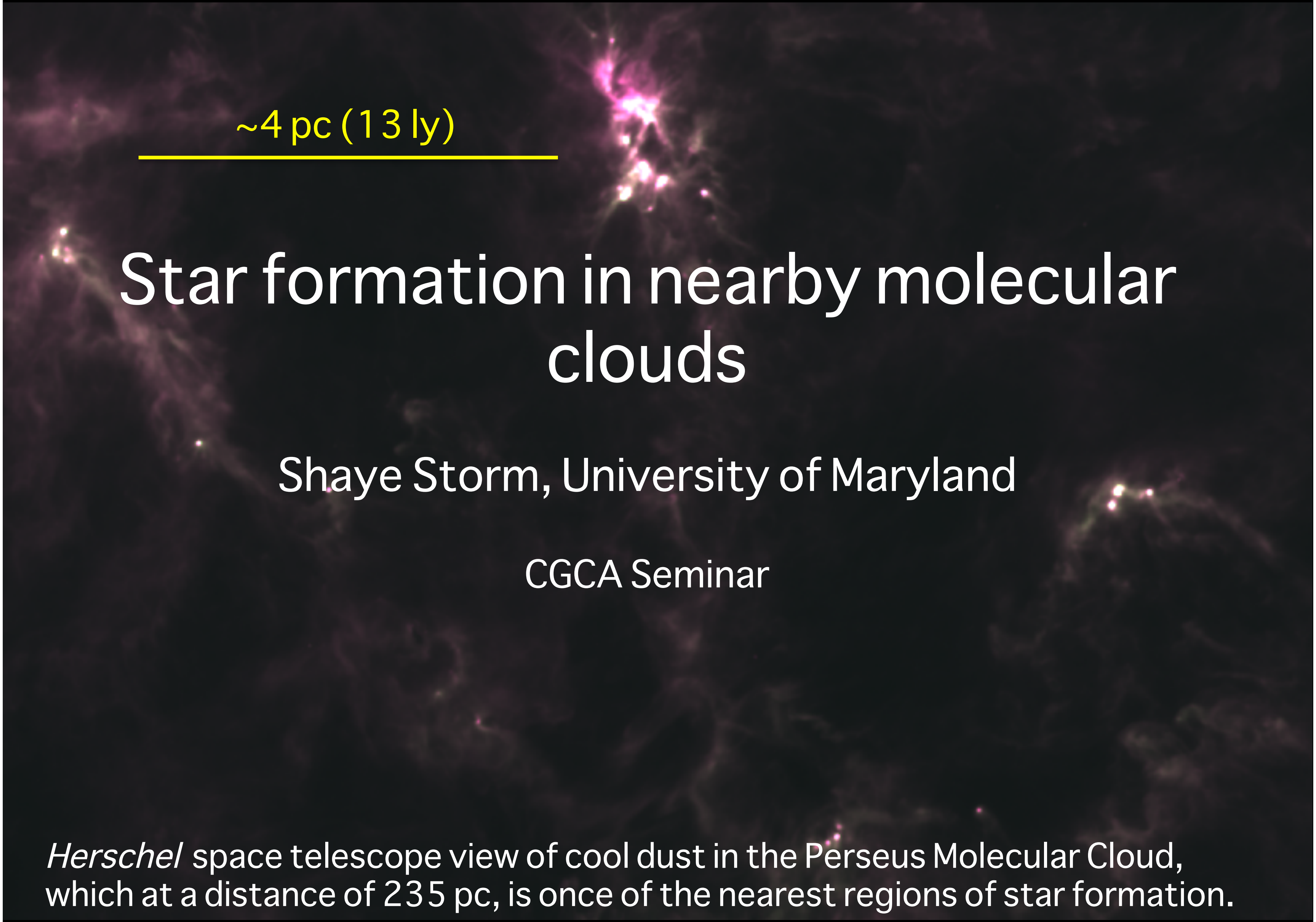
# Star formation in nearby molecular clouds

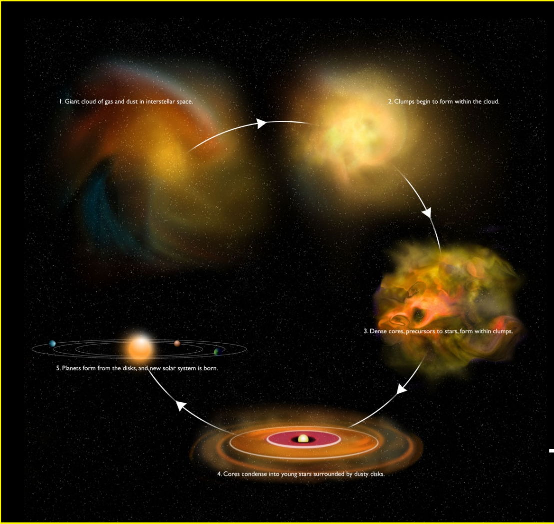
Shaye Storm, University of Maryland

CGCA Seminar

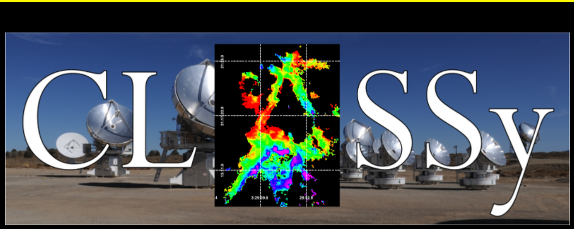


*Herschel* space telescope view of cool dust in the Perseus Molecular Cloud, which at a distance of 235 pc, is once of the nearest regions of star formation.

# Storyboard for Today's Talk

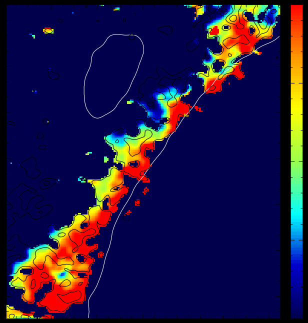


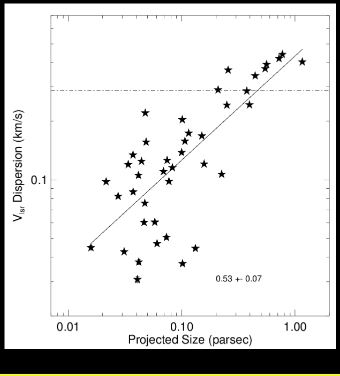
Star formation in Molecular Clouds: the Why, the Known, and the Unknown



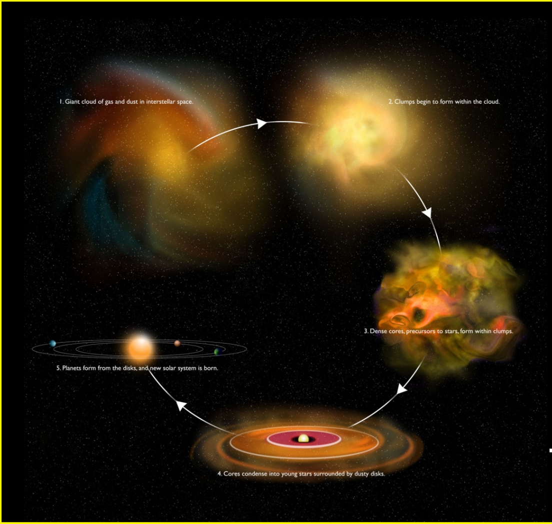
How we use CARMA to address the unknown

CLASSy reveals key signature of Molecular Cloud formation, and probes cloud turbulence



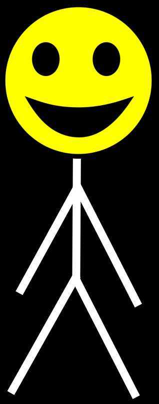


Summary

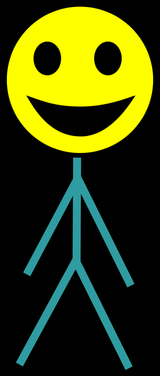


# Star formation in Molecular Clouds: the Why, the Known, and the Unknown

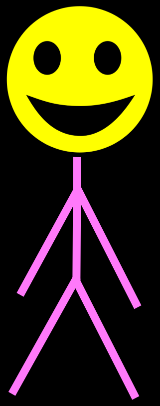
# Why do we care about star formation?



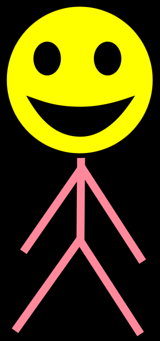
The average person
cares because …



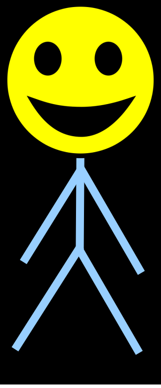
Jane, who studies
cosmology, cares
because …



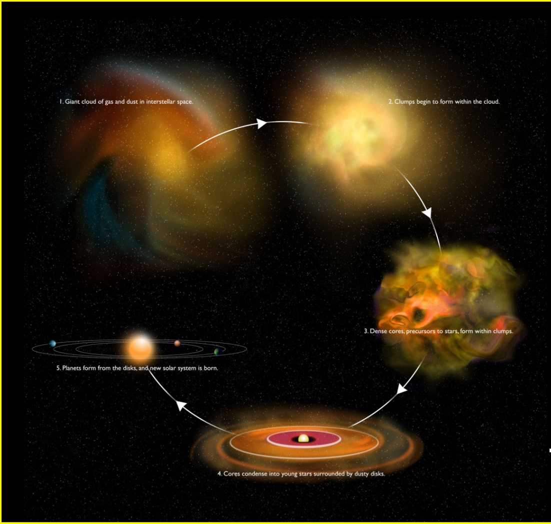
Jane, who studies
galaxy evolution,
cares because …



Joe, who studies
compact objects, cares
because …



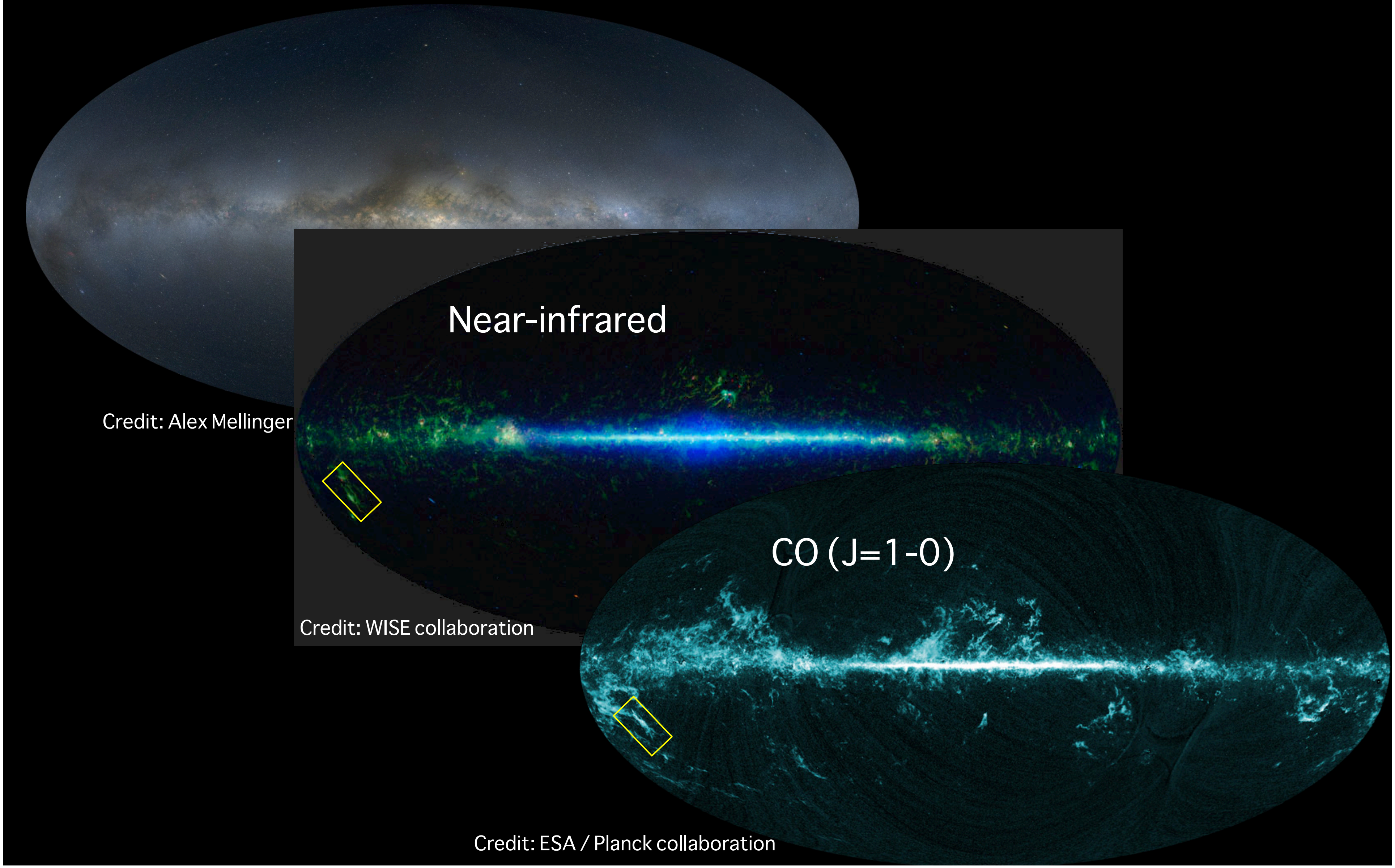
Joe, who studies star
formation, cares
because …



# Star formation in Molecular Clouds: the Why, the Known, and the Unknown

# Why the interest in Molecular Clouds?

## Molecular Clouds are where stars form!



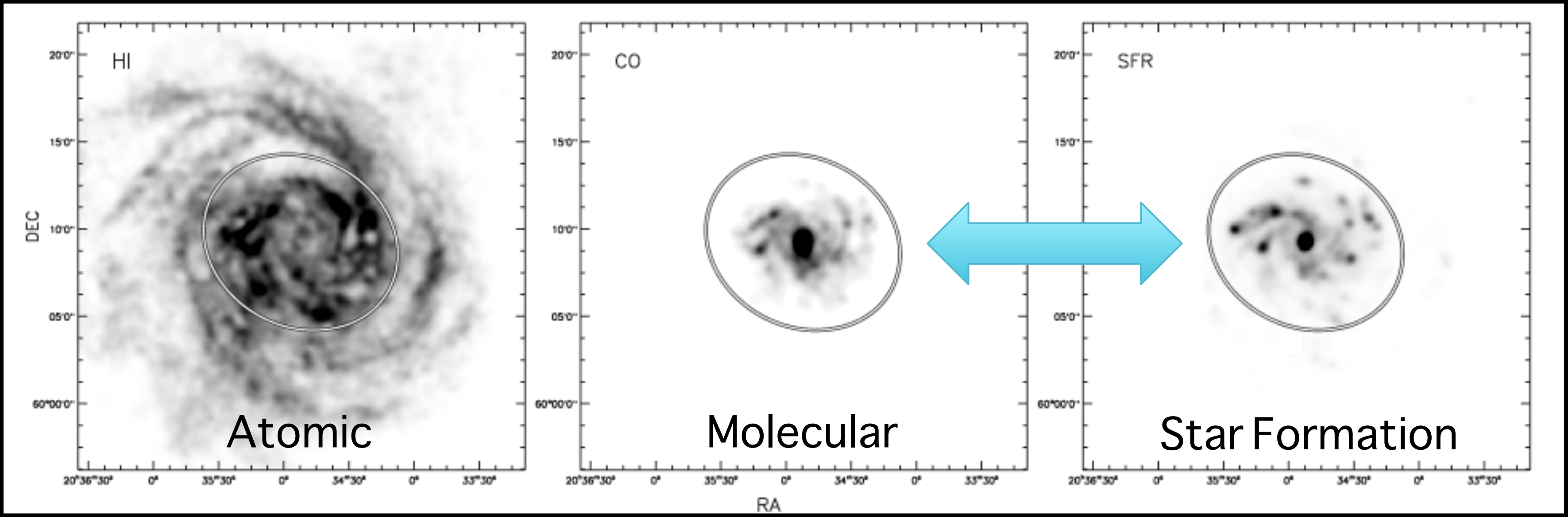
Credit: Alex Mellinger

Credit: WISE collaboration

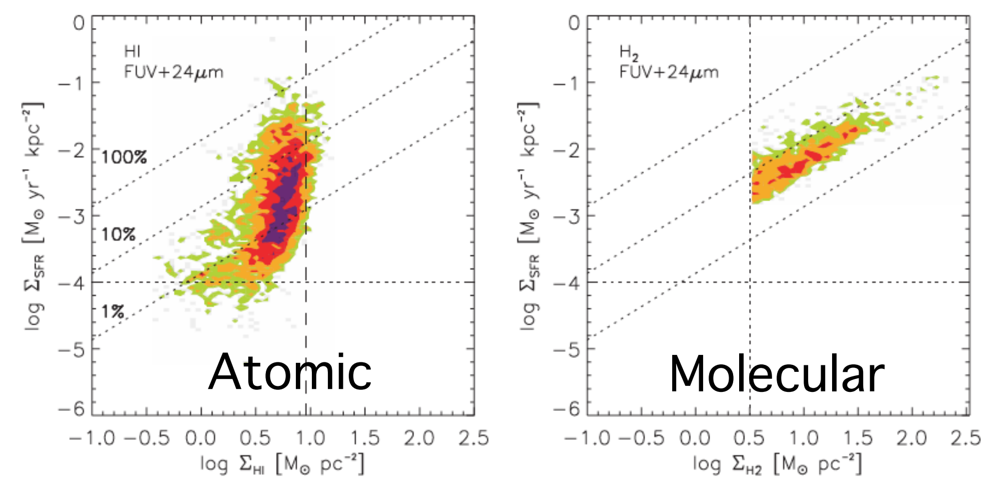
Credit: ESA / Planck collaboration

# Why the interest in Molecular Clouds?

## Molecular Clouds are where stars form!



Star formation linked with molecular gas, not atomic gas.



(Bigiel+ 2008)

# How Are Molecular Clouds observed?

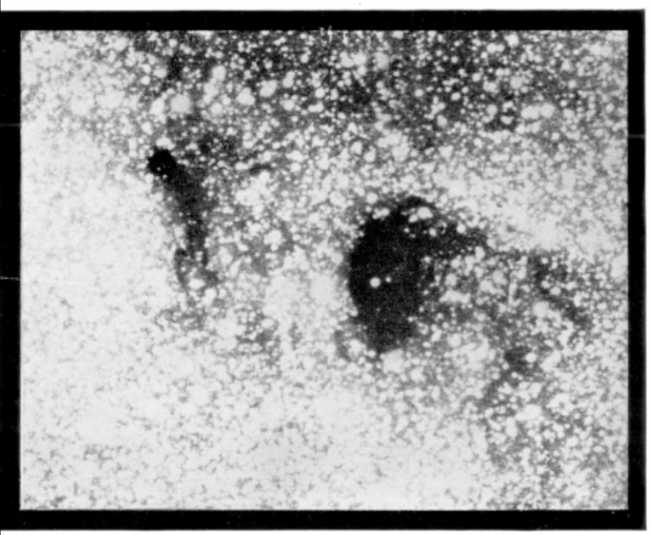
~1910s: Barnard started publishing dark obscuring regions in the Milky Way.

~1940s: First detections of interstellar molecule using stellar absorptions (Swings & Rosenfeld 1937, McKellar+ 1940, Adams+ 1941).

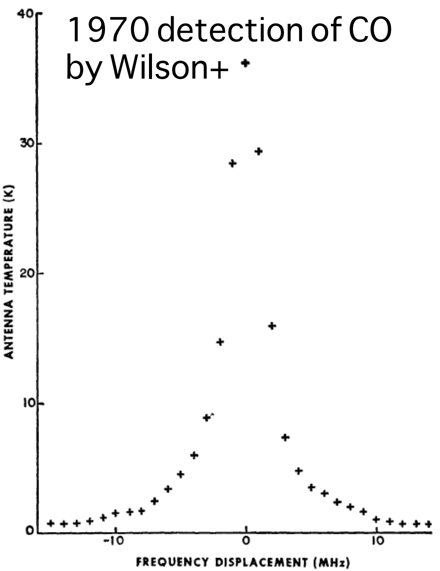
~1960s: First radio detections of molecular emission.

1970: First radio detection of CO, and first detection of $H_2$ using FUV absorption spectra (Wilson+ 1970, Carruthers+ 1970).

1980 – present: mapping of Milky Way MCs in many molecules, extragalactic GMCs.

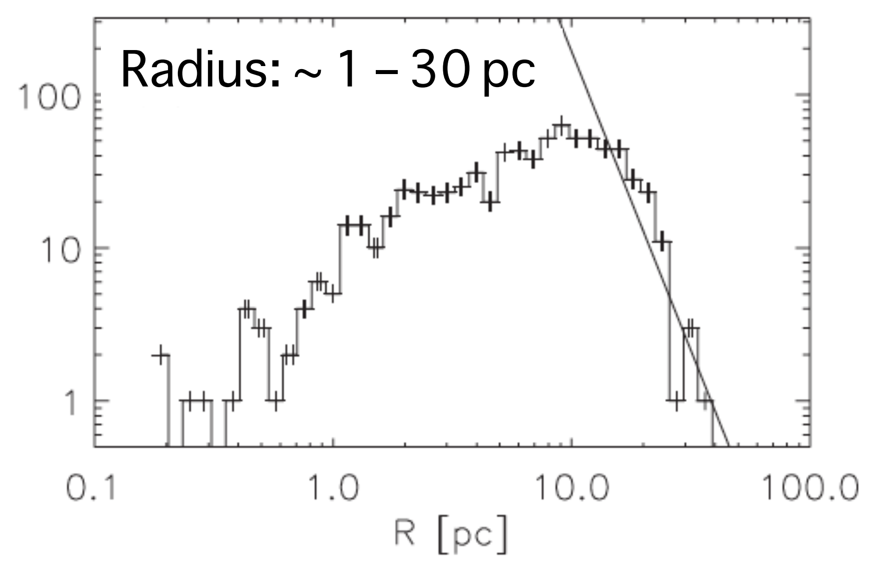


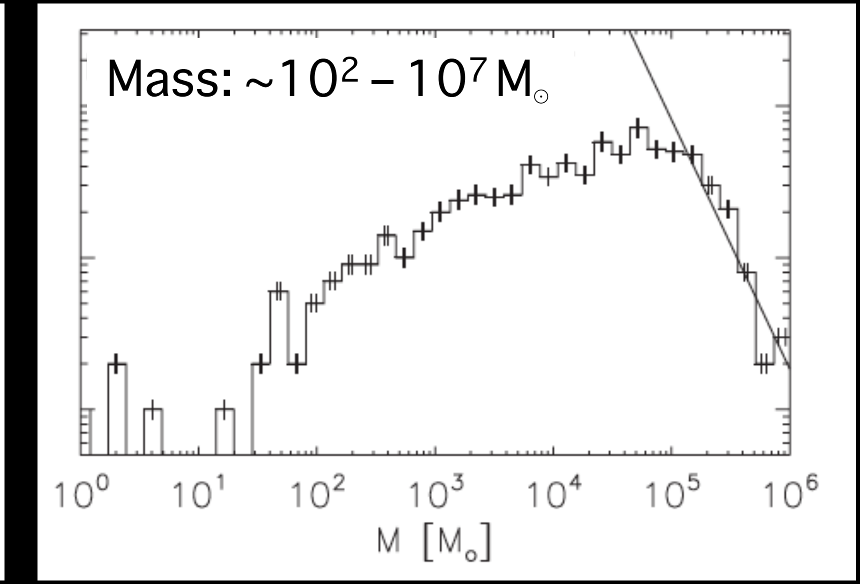
E. E. Barnard 1913 image of Sagittarius

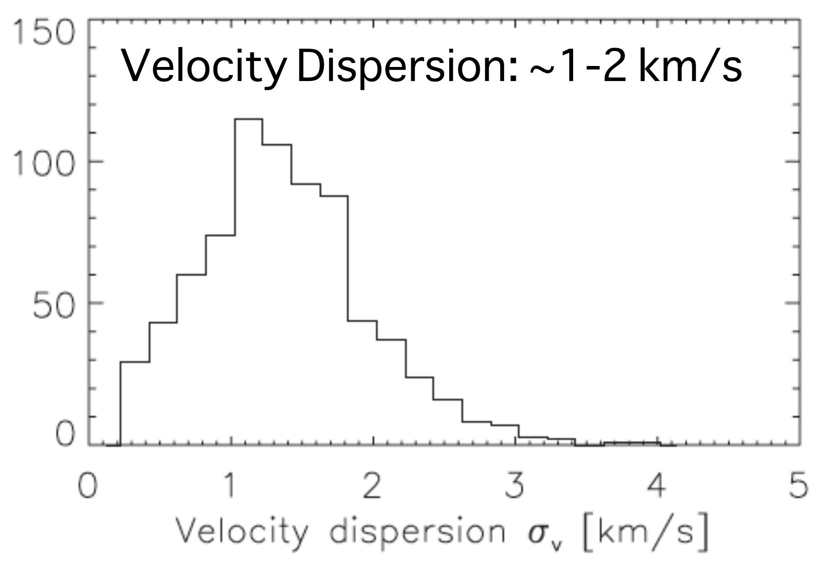


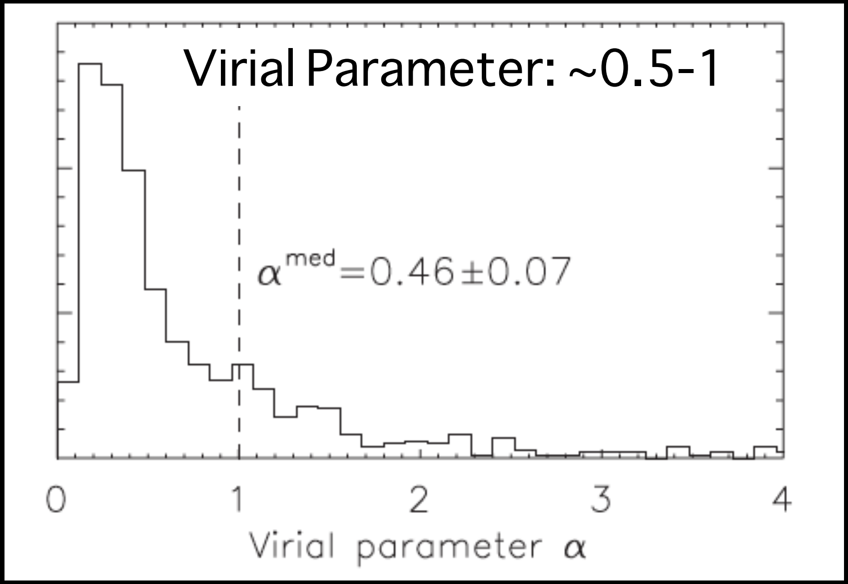
1970 detection of CO by Wilson+

# What are some basic Molecular Cloud properties?


Radius: ~ 1 – 30 pc

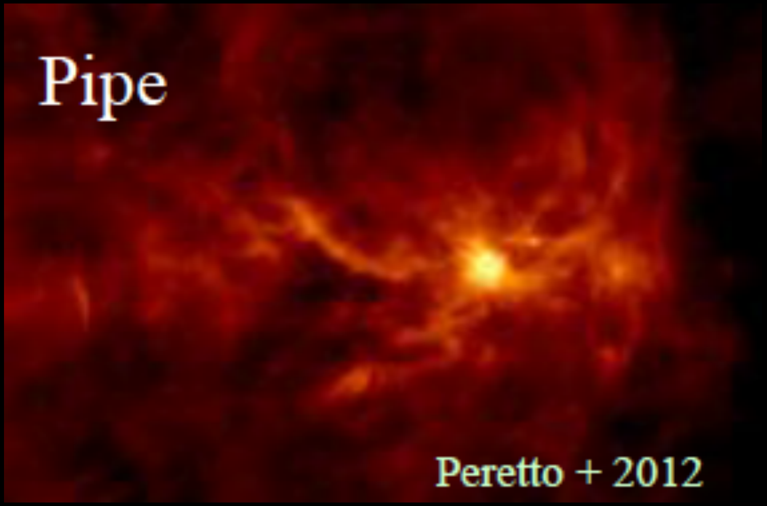

Mass: ~$10^2 – 10^7 M_\odot$


Velocity Dispersion: ~1-2 km/s

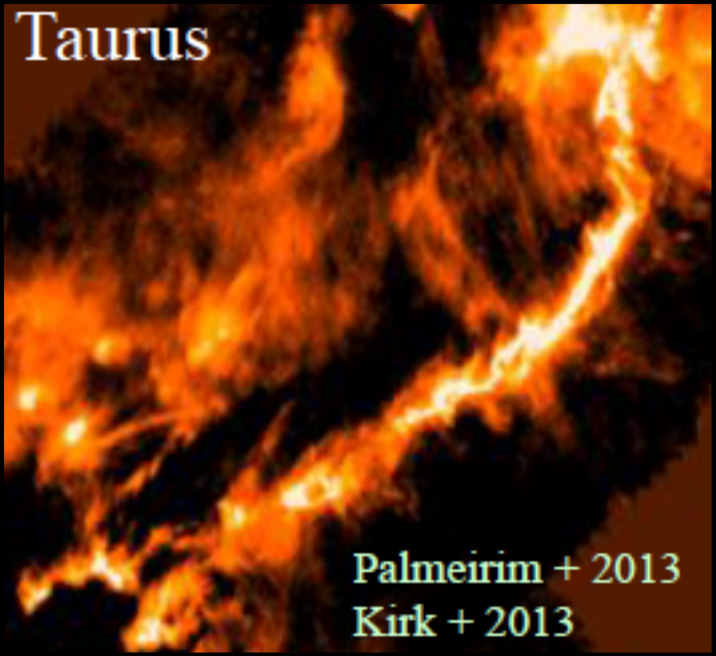

Virial Parameter: ~0.5-1

(Roman-Duval+ 2010)

# What are some basic Molecular Cloud properties?


Pipe

Peretto + 2012


Taurus

Palmeirim + 2013
Kirk + 2013


Aquila

Könyves + 2010

All appear filamentary …
star forming or not

(P. Andre PPVI Talk)

# What dynamic range of scales are we dealing with?

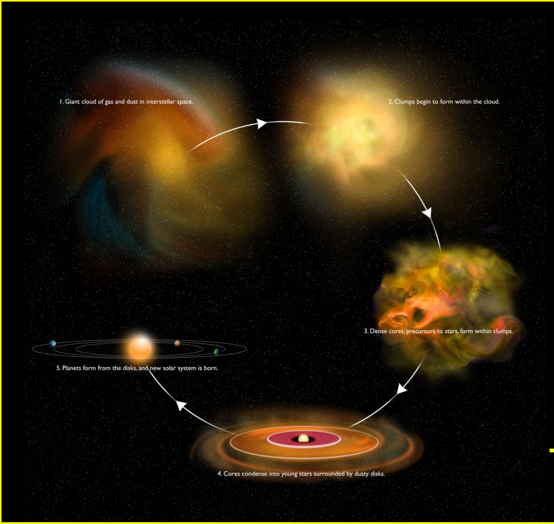
Galaxy
10 kpc

Molecular Cloud
10 pc

Cloud Core
0.1 pc

Protostellar Disk
0.001 pc

(S. Offner UMD Talk)



Star
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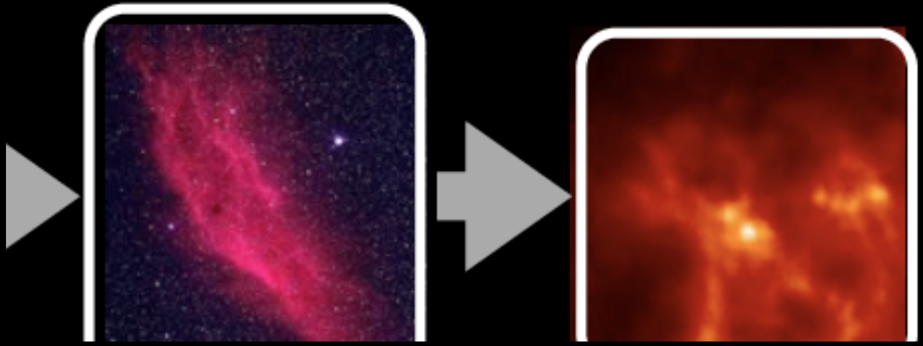
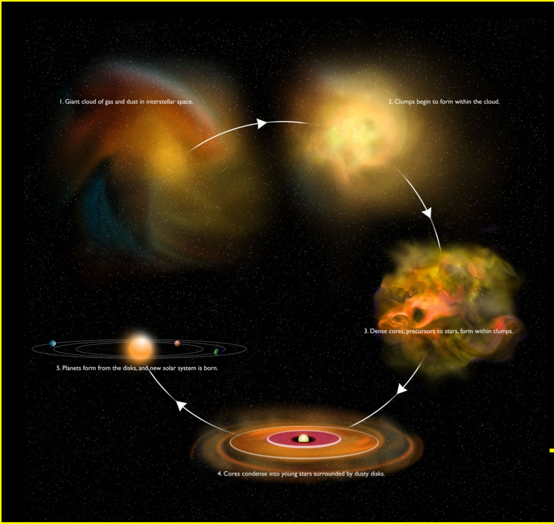


Molecular Cloud
10 pc

Cloud Core
0.1 pc

How do Molecular Clouds form and what determines their structure?

What is the nature of Molecular Cloud turbulence from cloud-scales down to core-scales?



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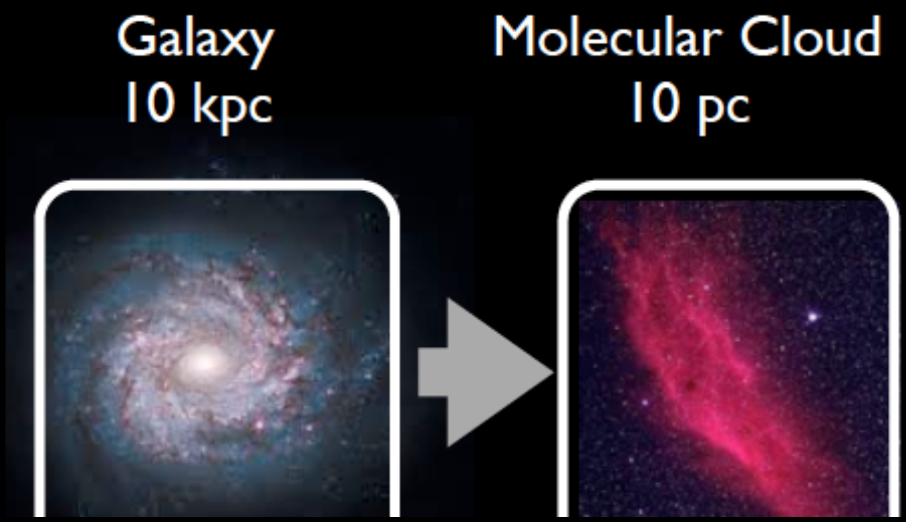

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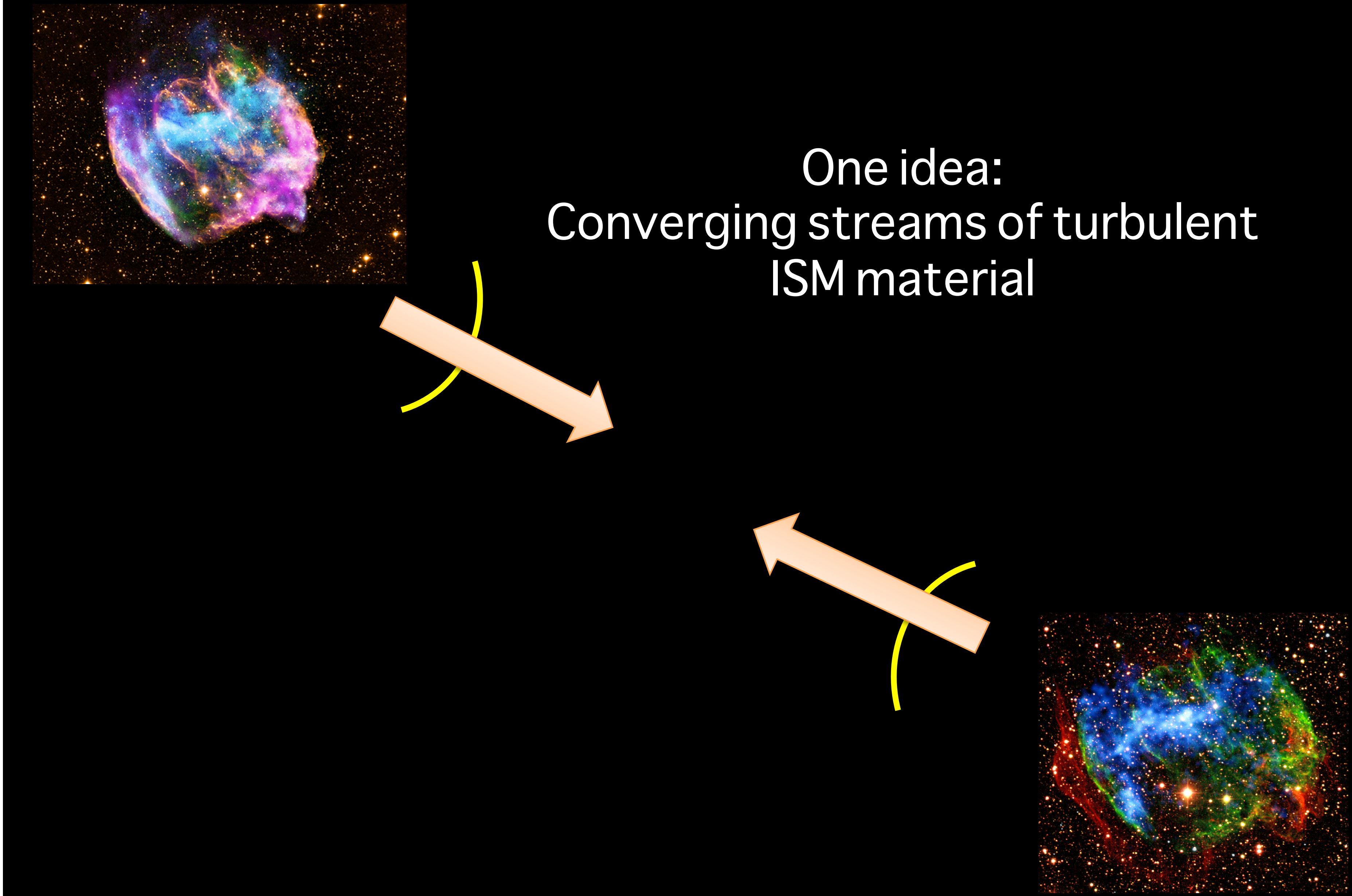
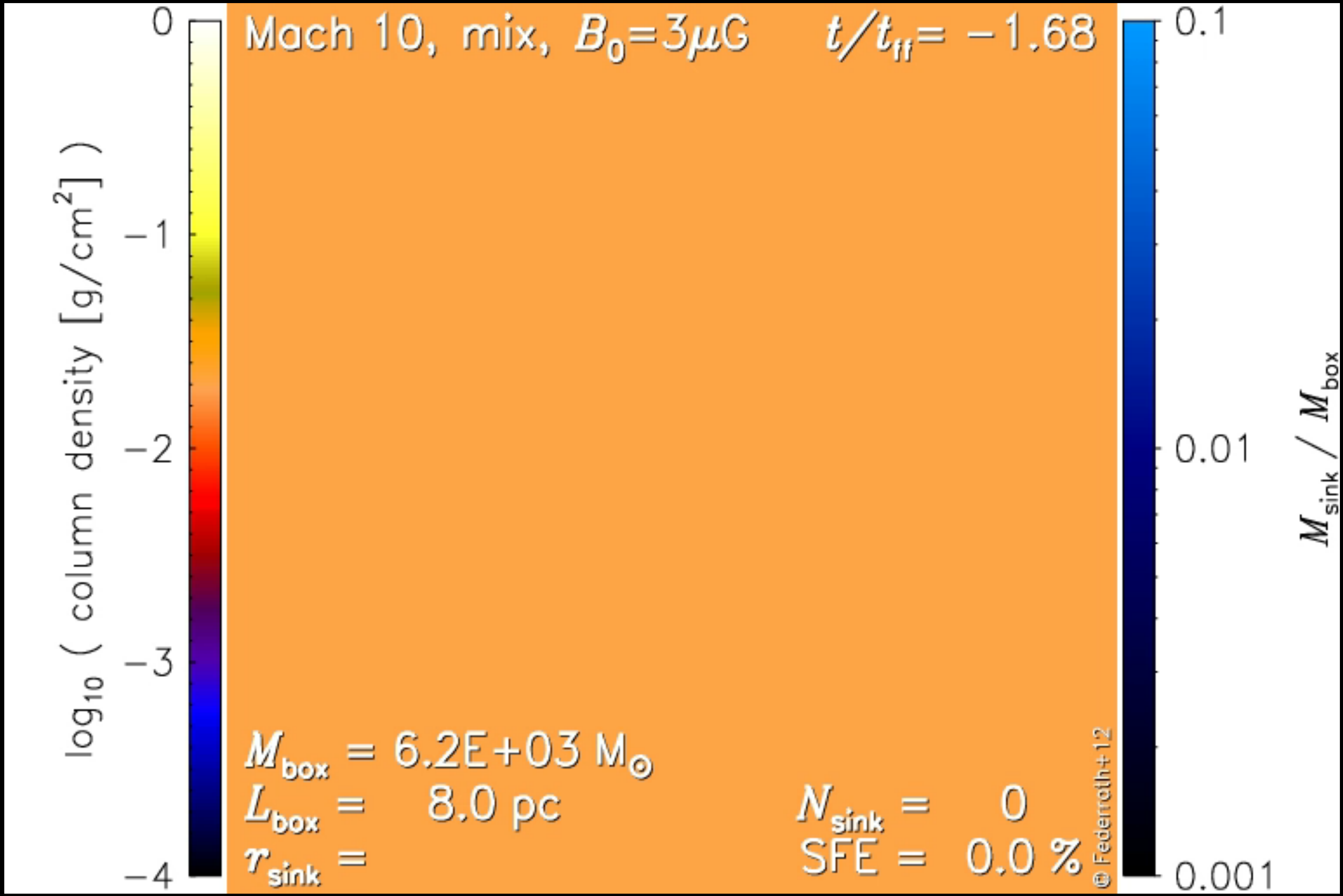
# How do Molecular Clouds form?



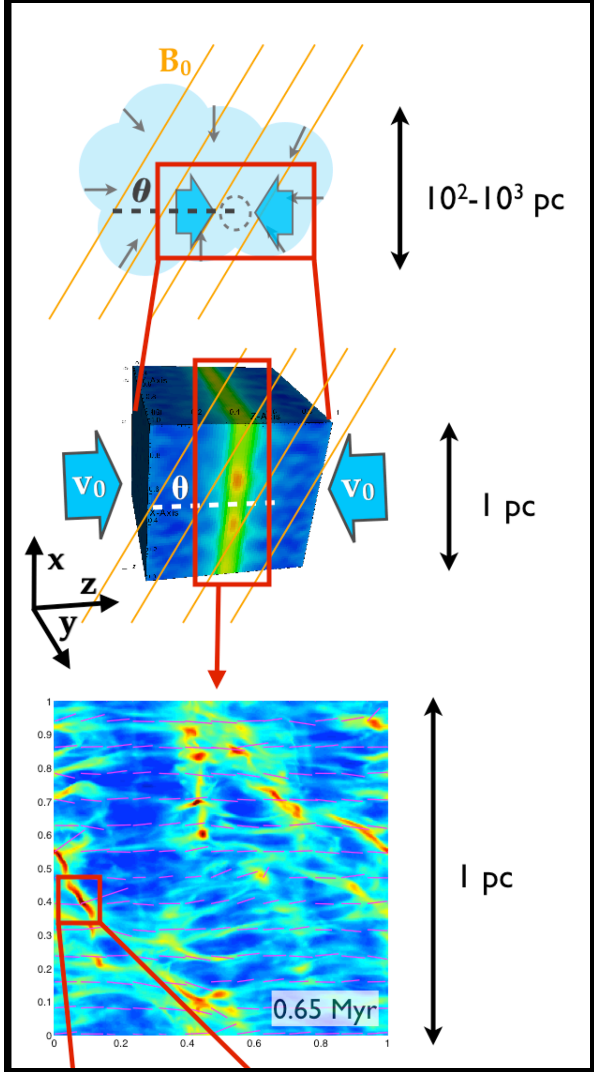
One idea:
Converging streams of turbulent
ISM material

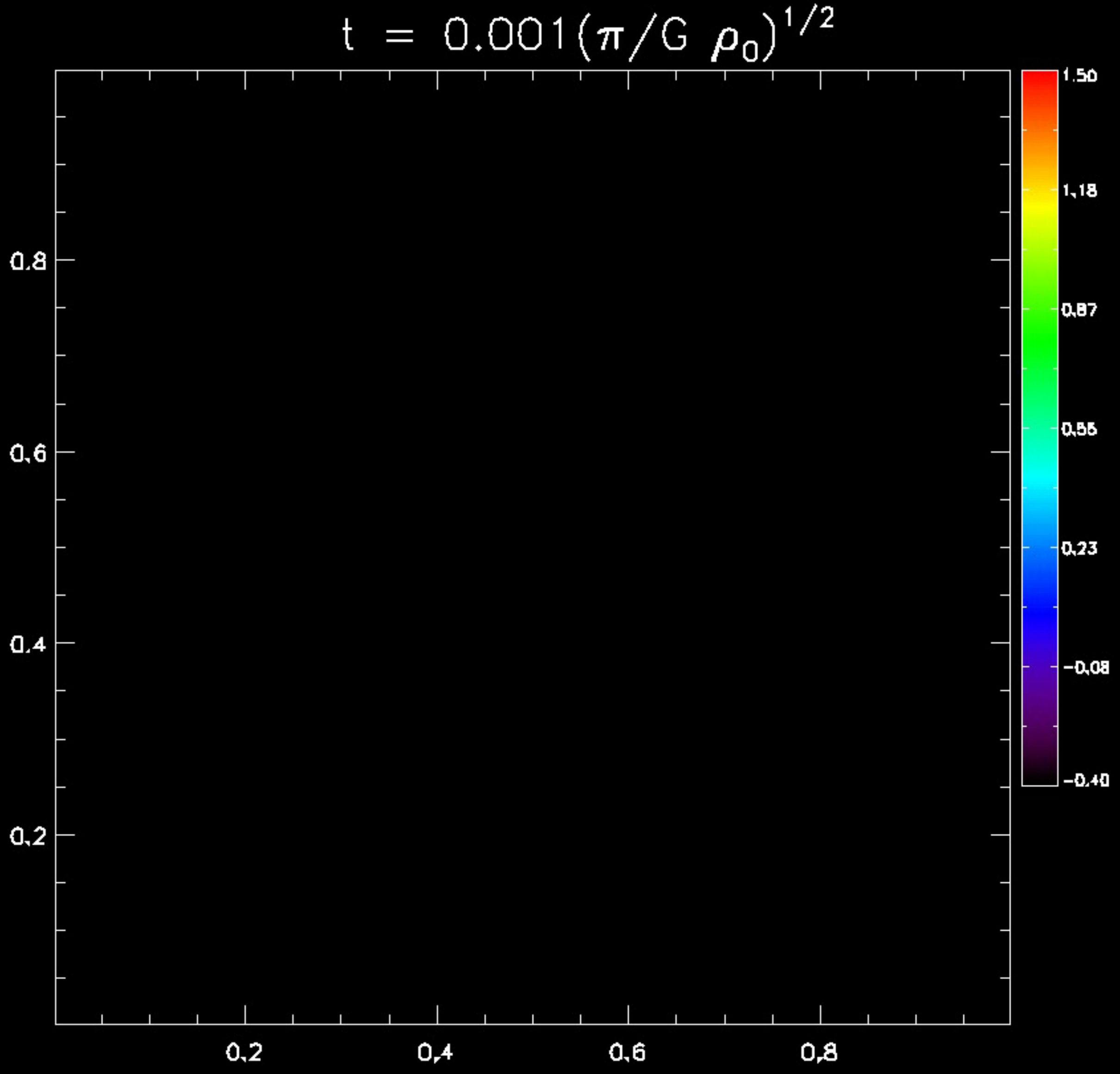
# How do Molecular Clouds form?



Federrath, C. & Klessen, R. S., 2012

# How do Molecular Clouds form?





(Chen & Ostriker, 2014; Gong & Ostriker 2011)

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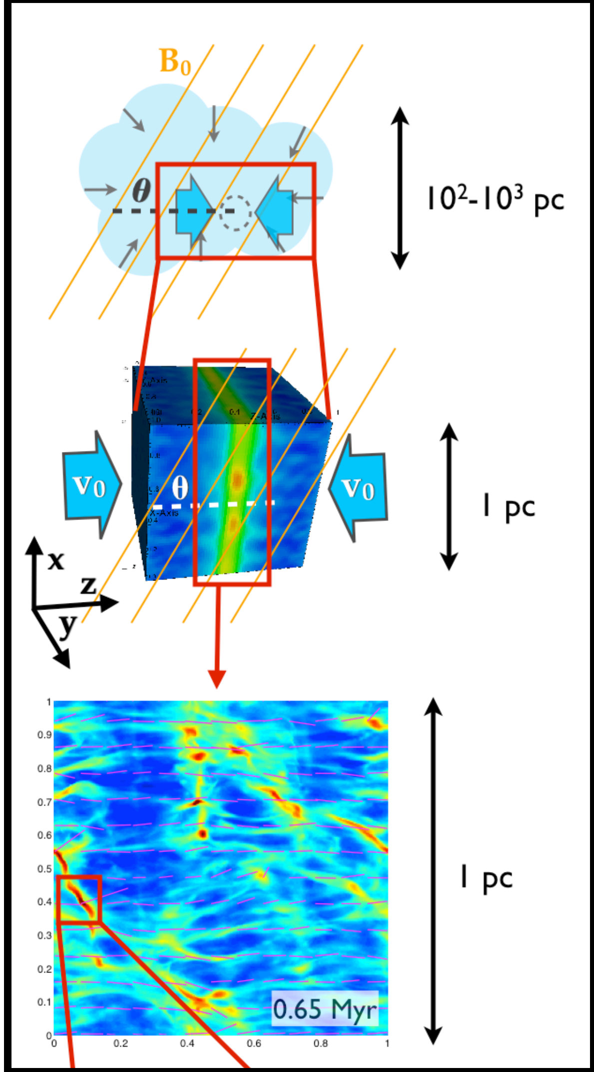

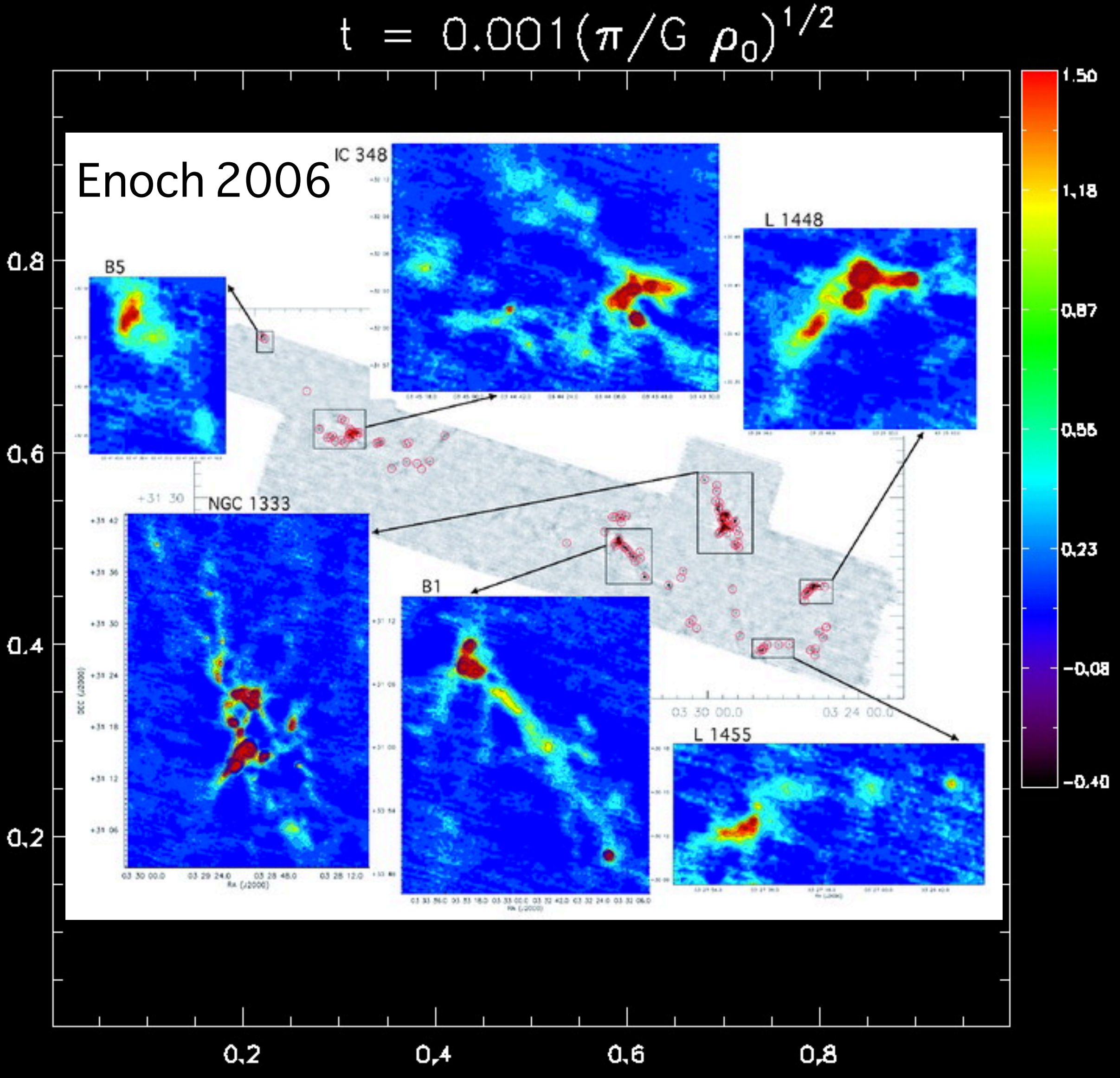

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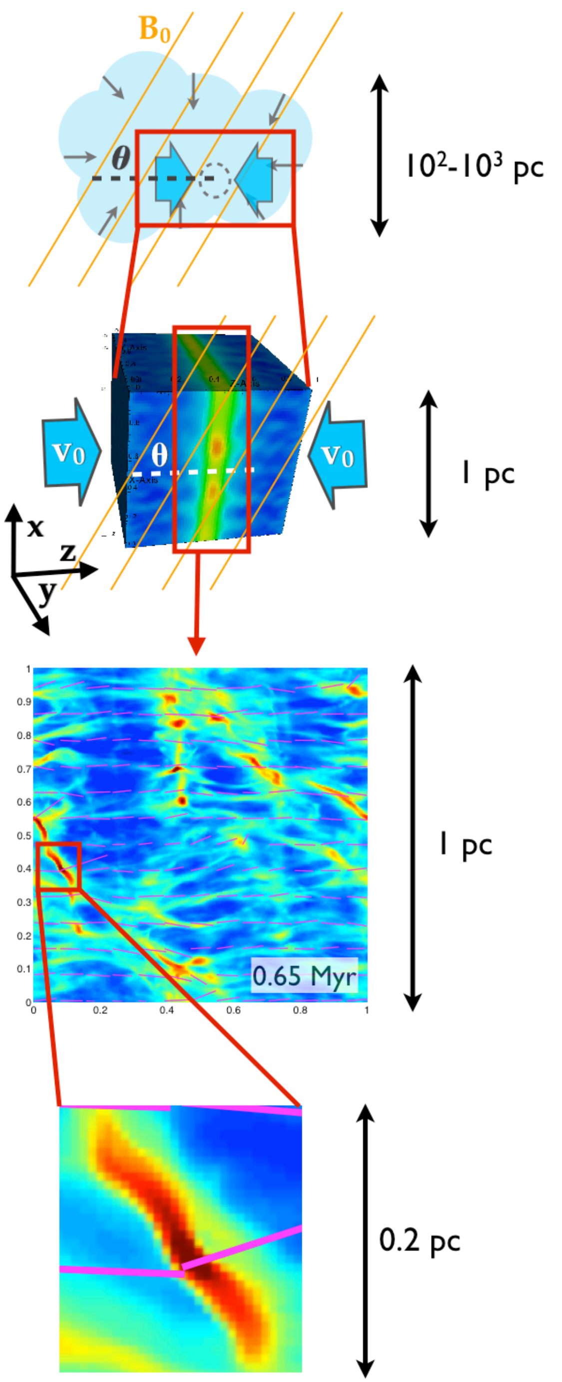
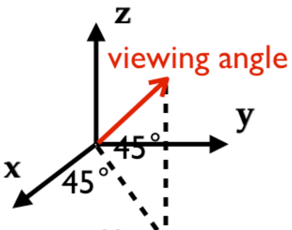
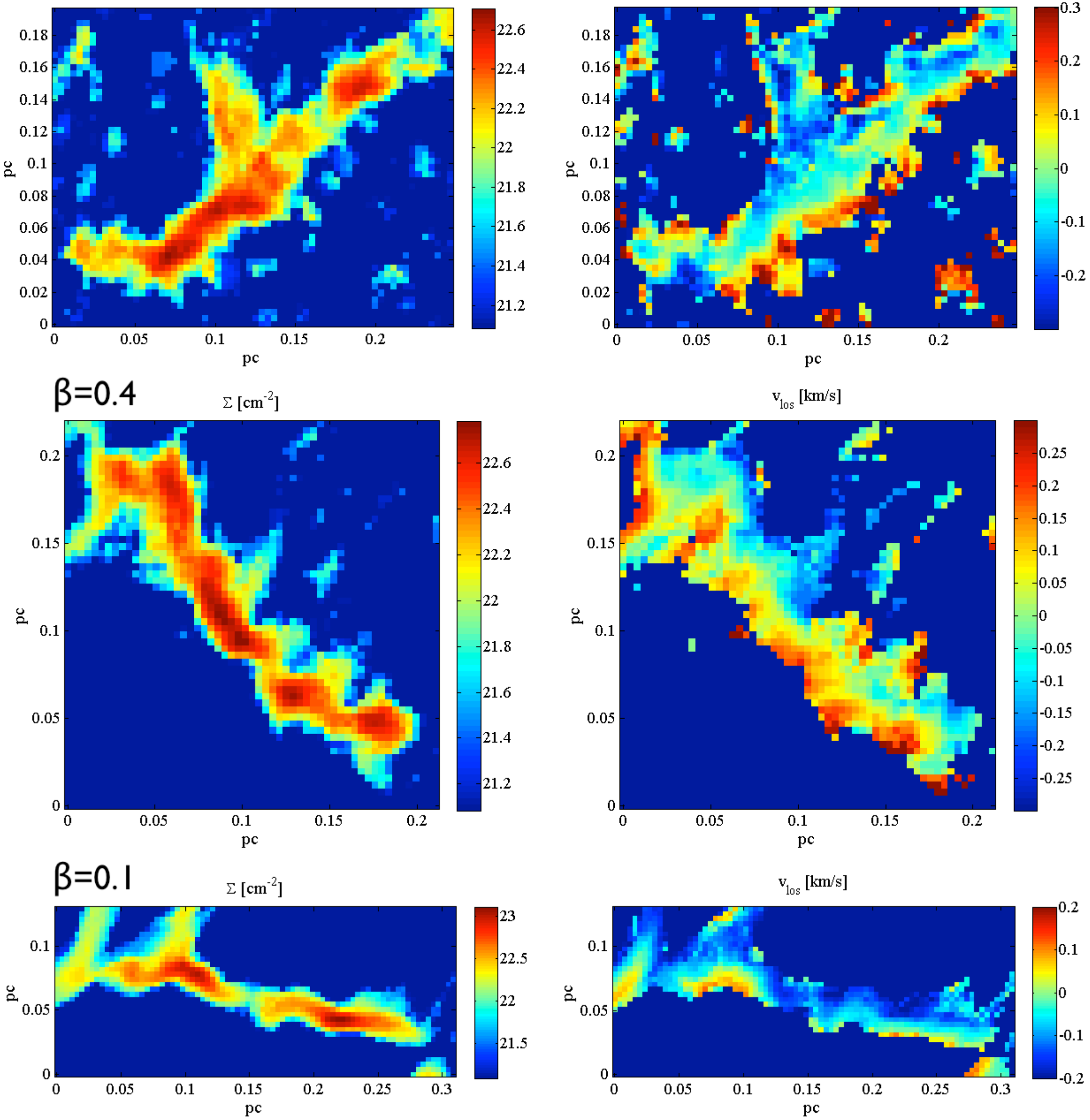


# example filaments (with n ≥ $10^5$ cm$^{-3}$)





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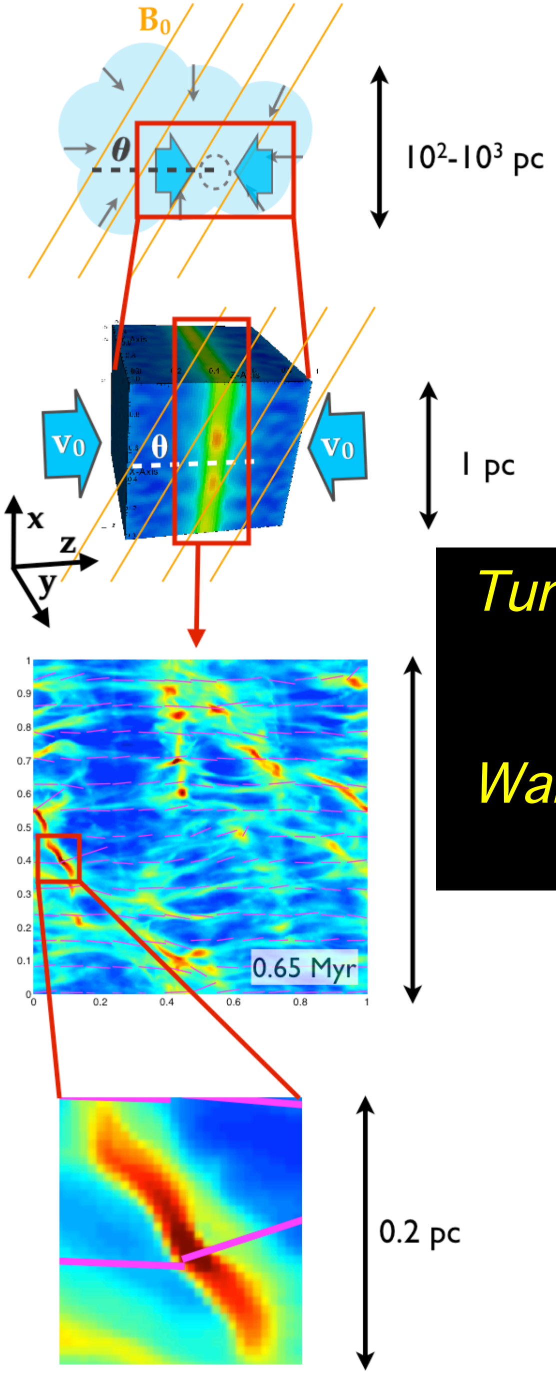

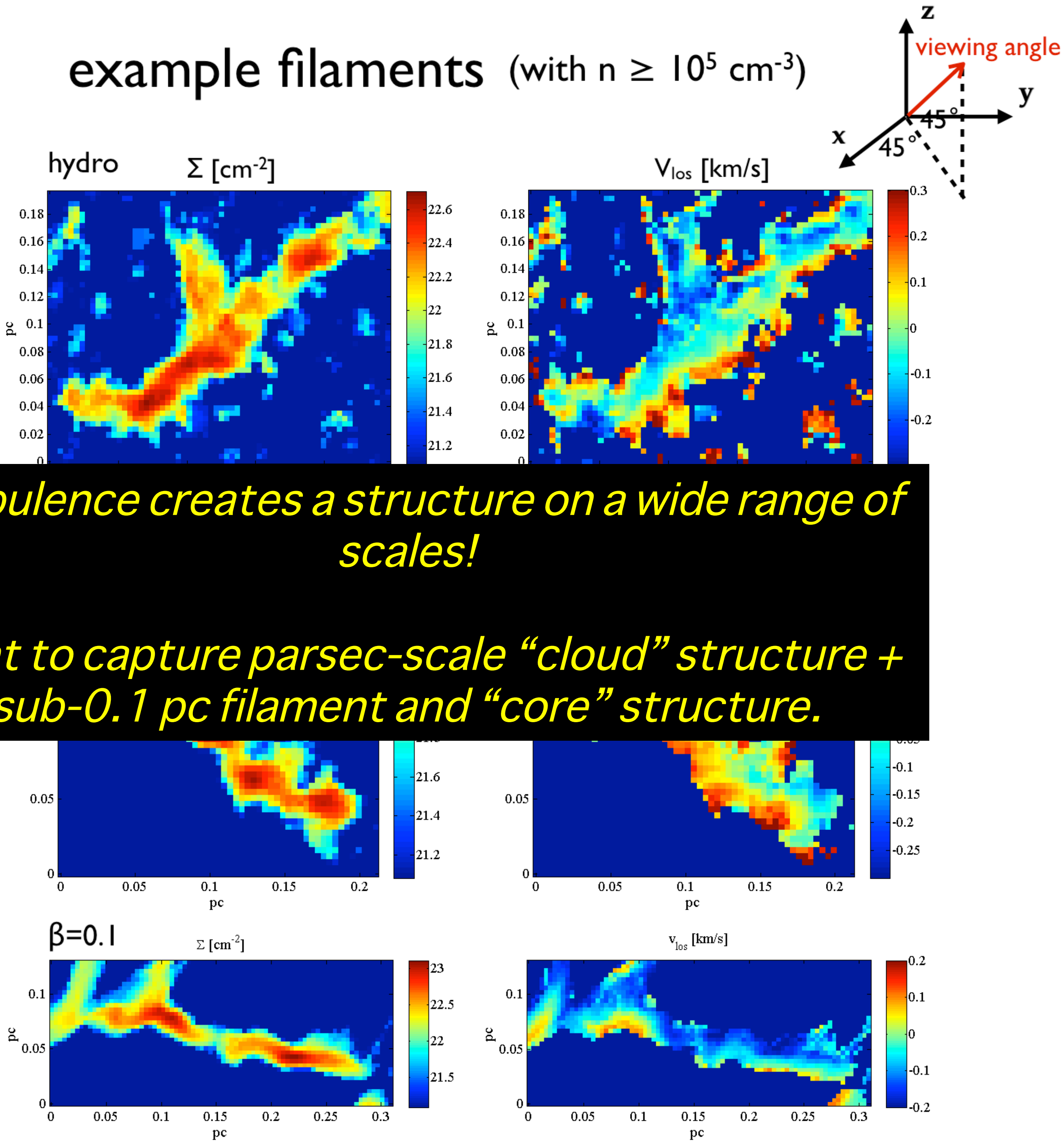

*Turbulence creates a structure on a wide range of scales!*

*Want to capture parsec-scale "cloud" structure + sub-0.1 pc filament and "core" structure.*

# Need a new way of looking at Molecular Clouds

Credit: National Geographic

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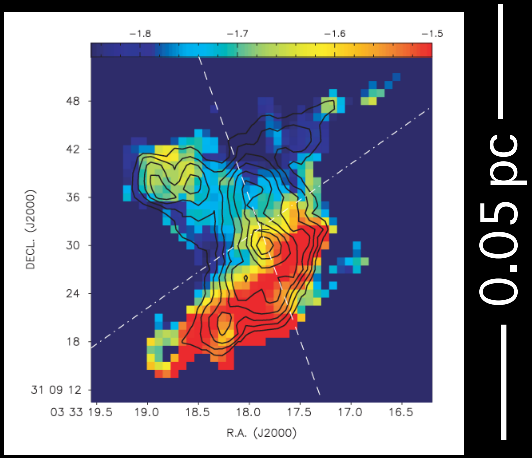
# Need a new way of looking at Molecular Clouds

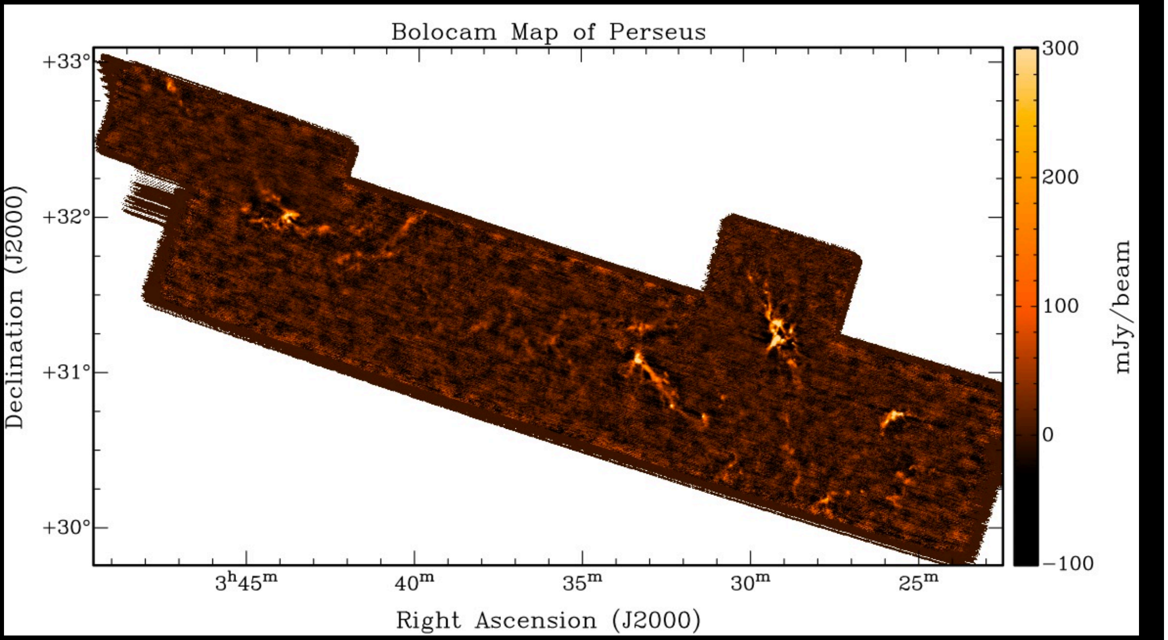
Existing interferometric surveys lack:
… cloud-scale information

Existing large area surveys lack:
… good enough spatial resolution
… and/or kinematic information



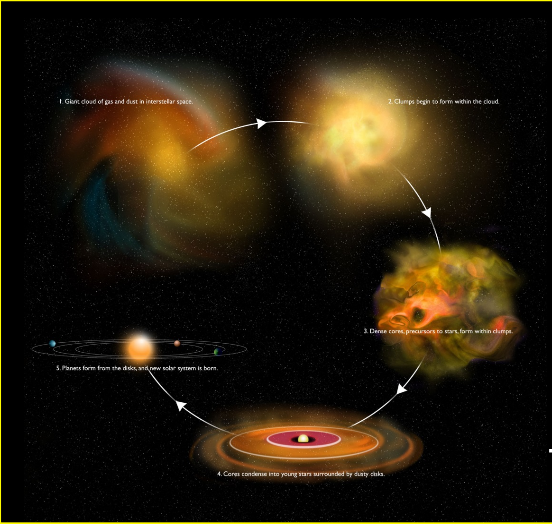
(Matthews+ 2006)

Need to connect
individual *core-scales
to cloud-scales*, and
need to capture
*structure and
kinematic*
information!



(Enoch+ 2006)

# Storyboard for Today’s Talk



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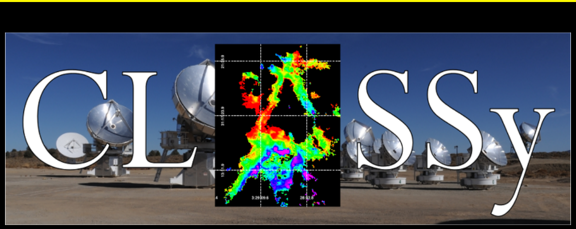
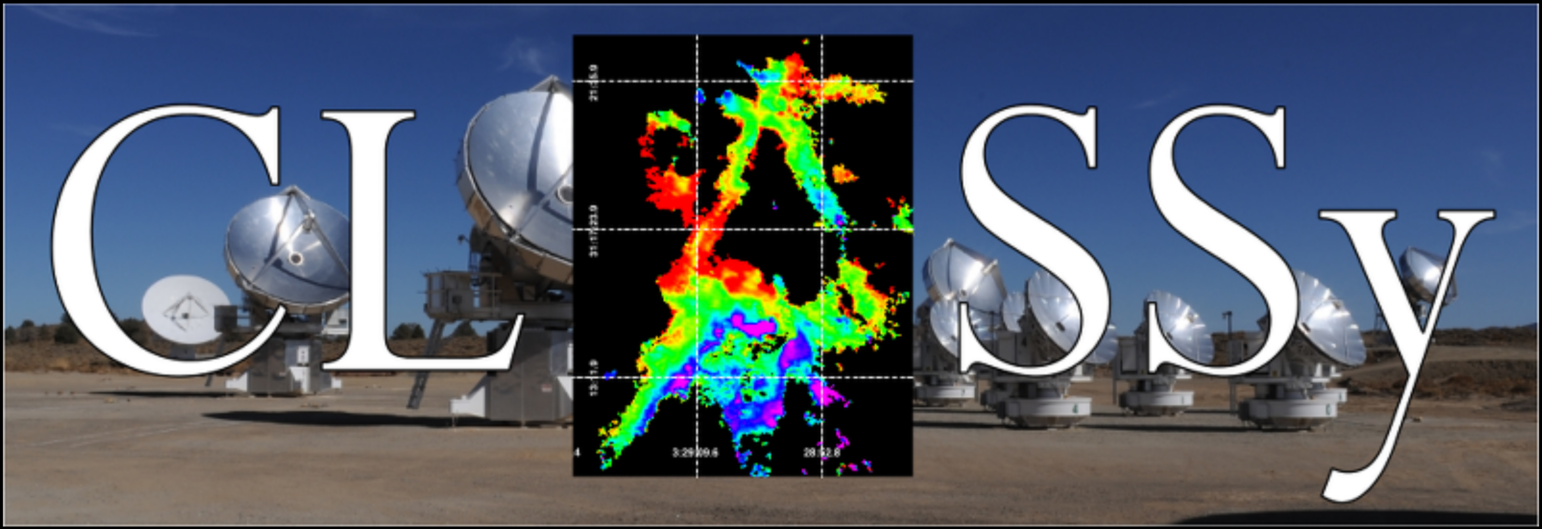


How we use CARMA to address the unknown

# CARMA Large Area Star formation Survey (CLASSy)

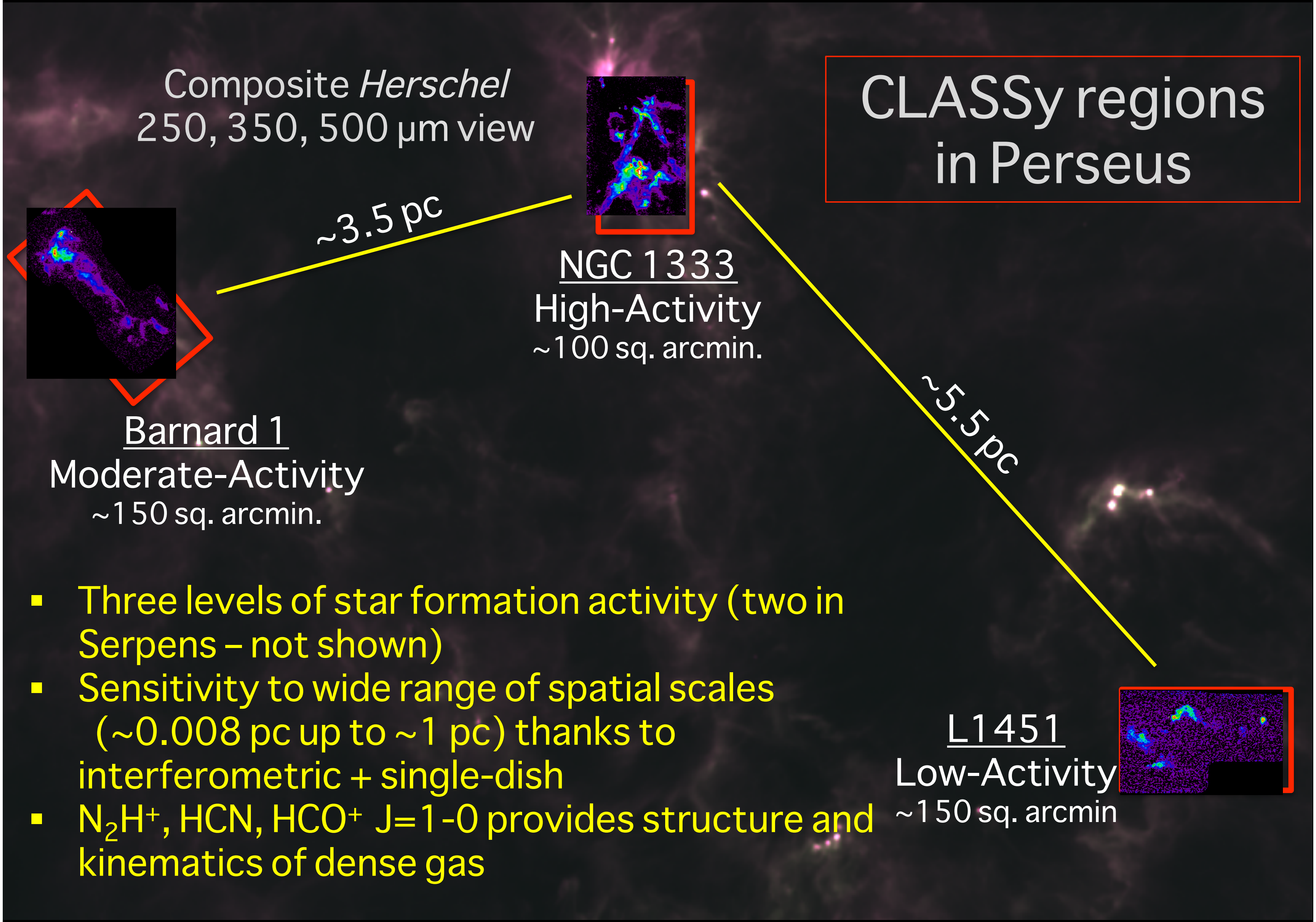
Team Members:

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



http://www.astro.umd.edu/~sstorm/CLASSy/

# CLASSy regions in Perseus



Composite *Herschel* 250, 350, 500 μm view

~3.5 pc

~5.5 pc

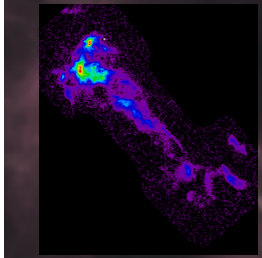
NGC 1333
High-Activity
~100 sq. arcmin.

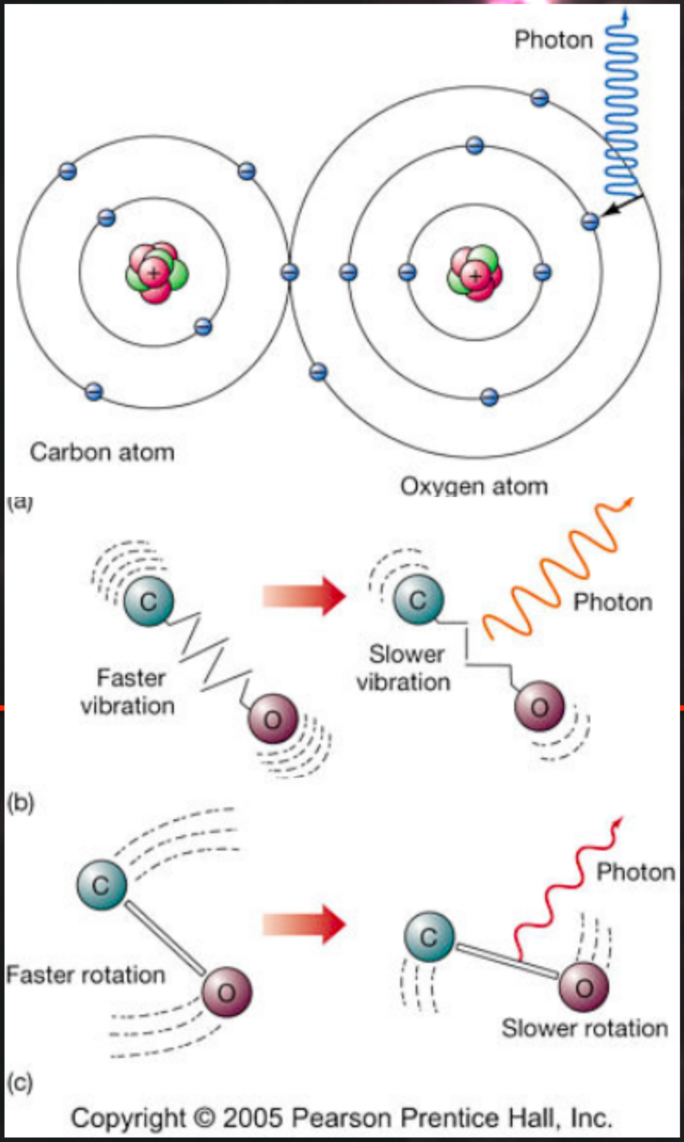
Barnard 1
Moderate-Activity
~150 sq. arcmin.

L1451
Low-Activity
~150 sq. arcmin

- Three levels of star formation activity (two in Serpens – not shown)
- Sensitivity to wide range of spatial scales (~0.008 pc up to ~1 pc) thanks to interferometric + single-dish
- $N_2H^+$, HCN, $HCO^+$ J=1-0 provides structure and kinematics of dense gas

# How do Molecules Emit Photons?





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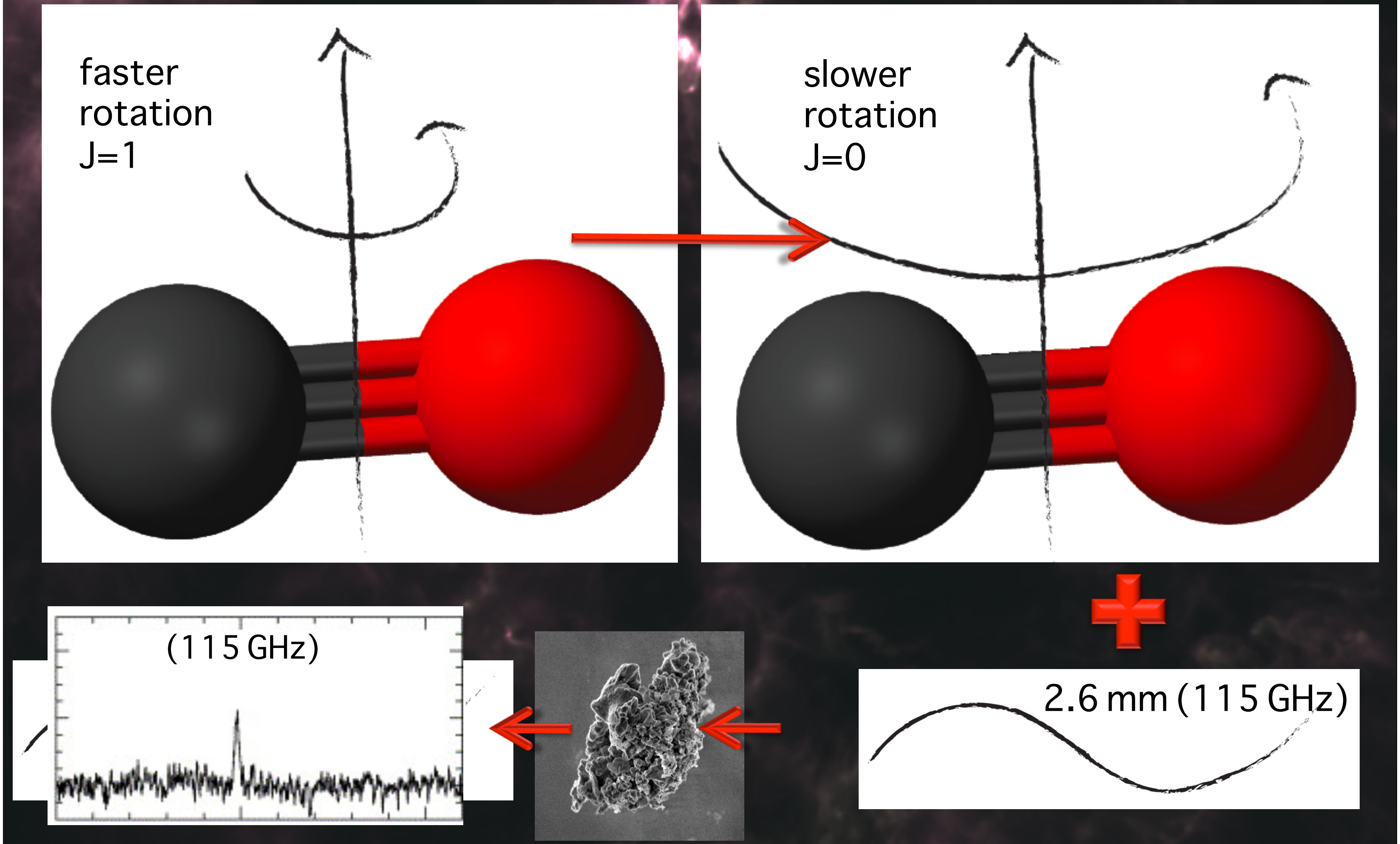
Electronic transitions require:
few 1000s K

Vibration transitions require:
few 100s K → few 1000s K

Rotation transitions require:
few K → few 10s K

*Molecular clouds are ~10-30 K*

# How do Molecules Emit mm Photons?



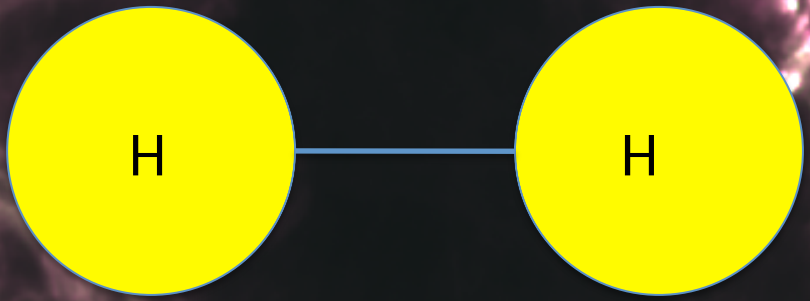
faster
rotation
J=1

slower
rotation
J=0

2.6 mm (115 GHz)

(115 GHz)

# How do Molecules Emit mm Photons?



What about the most abundant molecule out there?

No permanent dipole → No rotational emission!

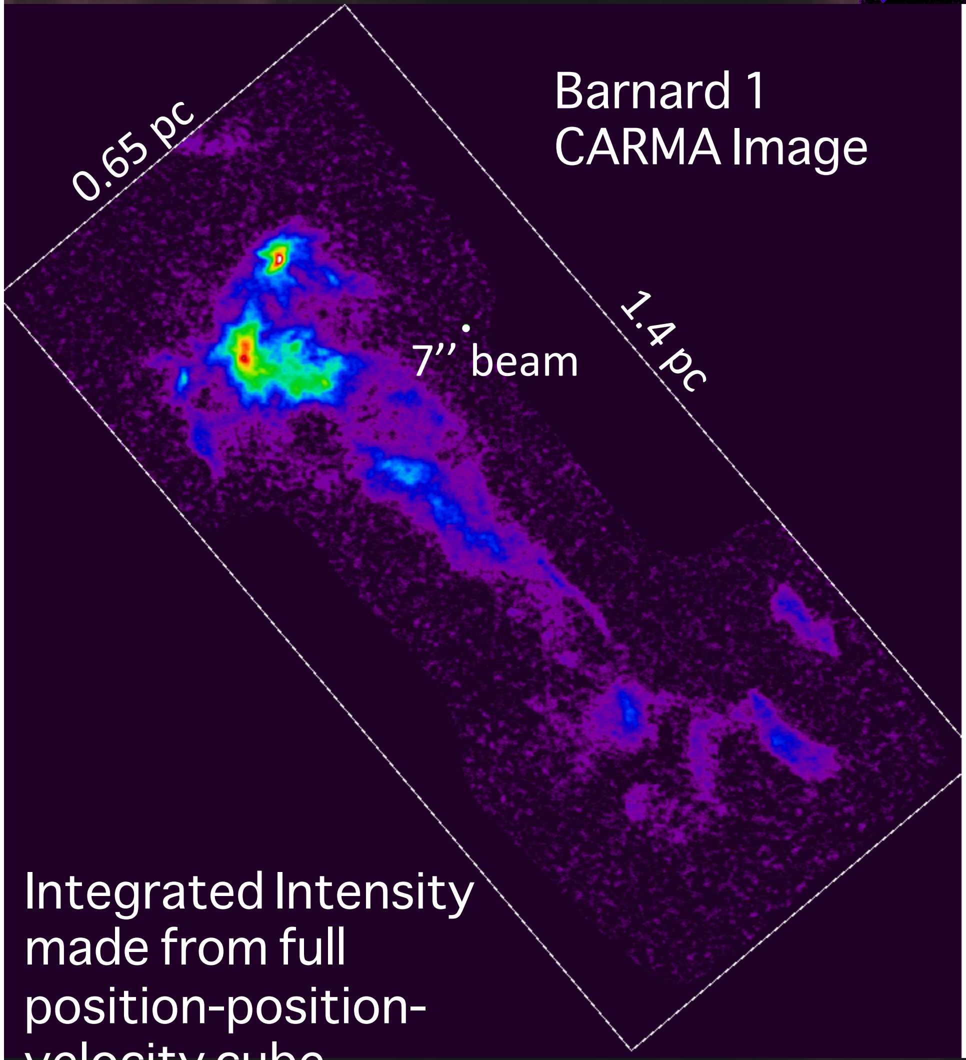
Rate of photon emission due to a transition from a higher to a lower energy mode, is proportional to the electric dipole of molecule

$H_2$ = 0 Debye; CO ~ 0.1 Debye; HCN ~ 3.0 Debye

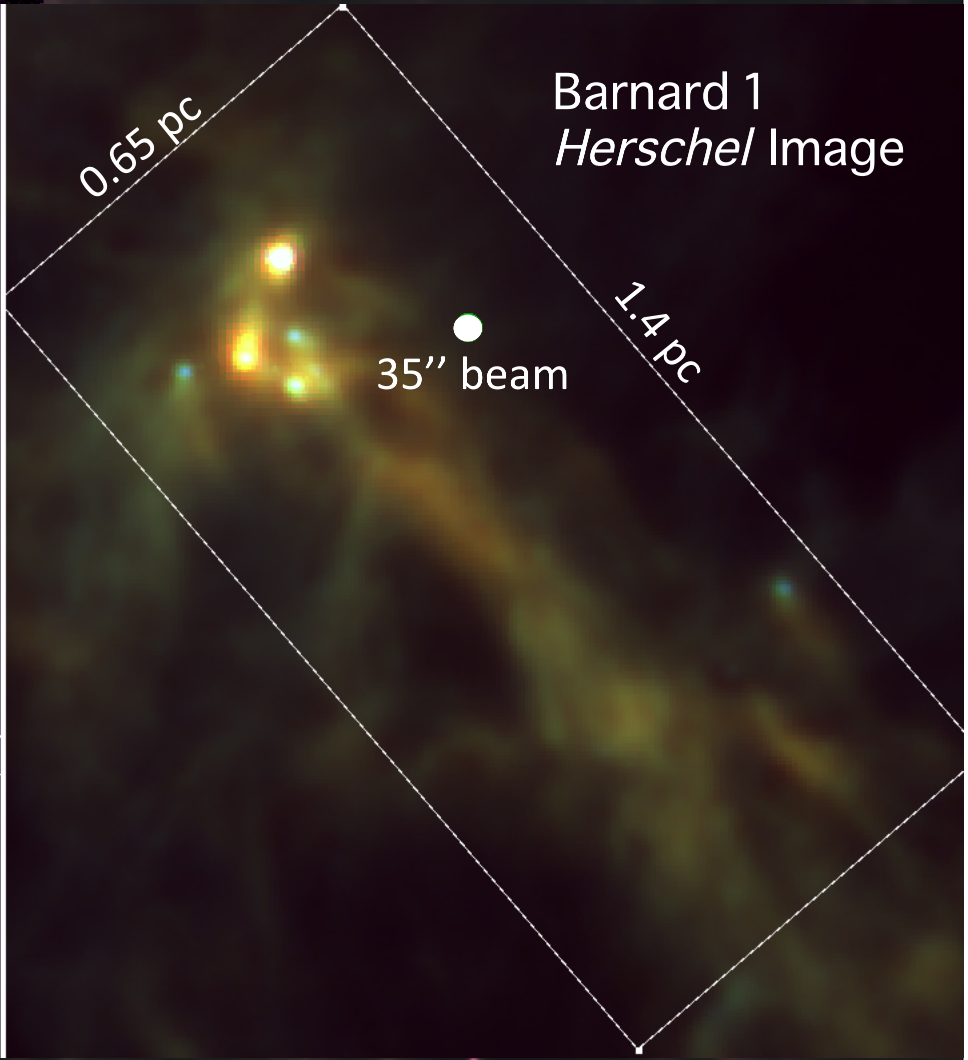
# Motivating the CLASSy molecules

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

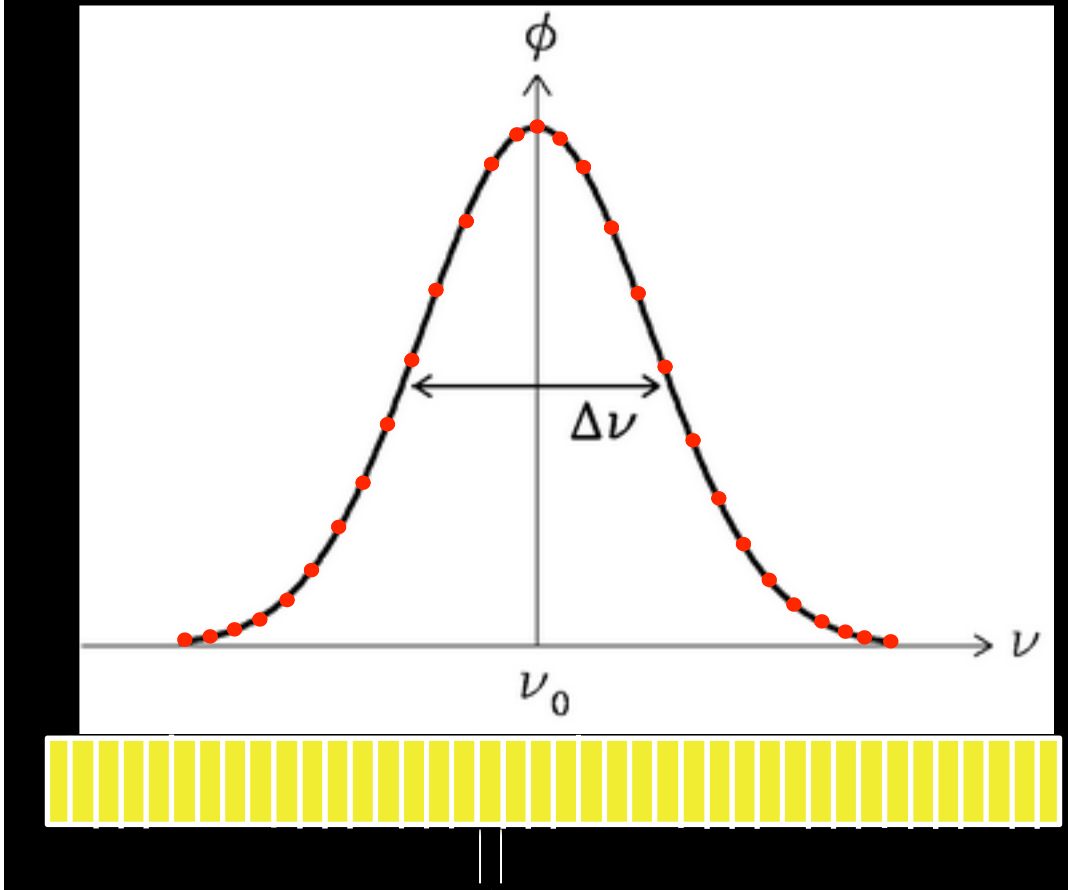
# $N_2H^+$ - Dust Comparison


Barnard 1
CARMA Image

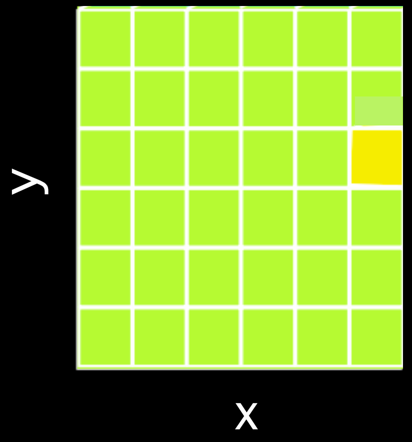
Integrated Intensity made from full position-position-velocity cube


Barnard 1
*Herschel* Image

# How do we observe molecular emission?



ν resolution
of observations



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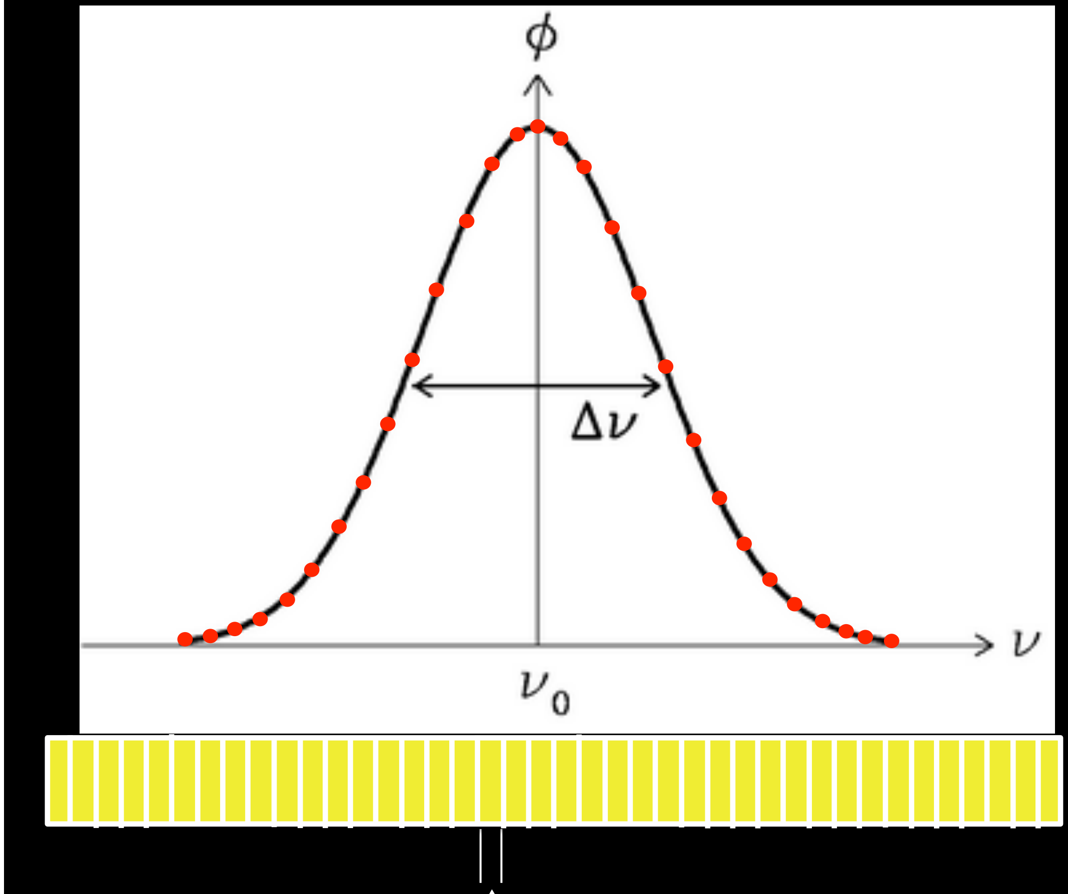

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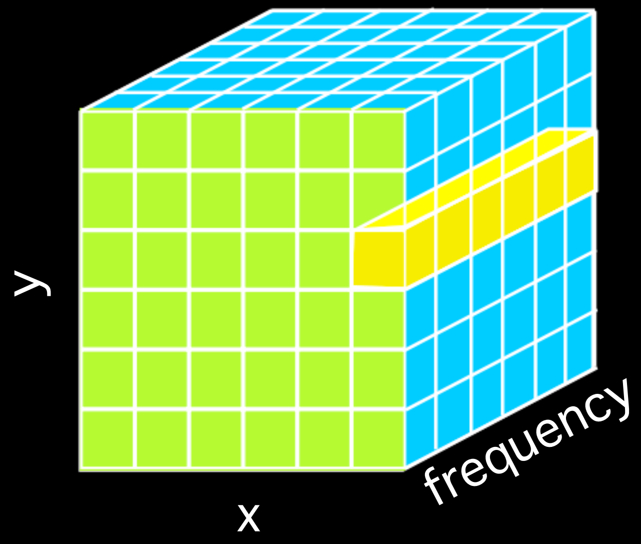

$$v = c(1 - \frac{\nu}{\nu_0})$$

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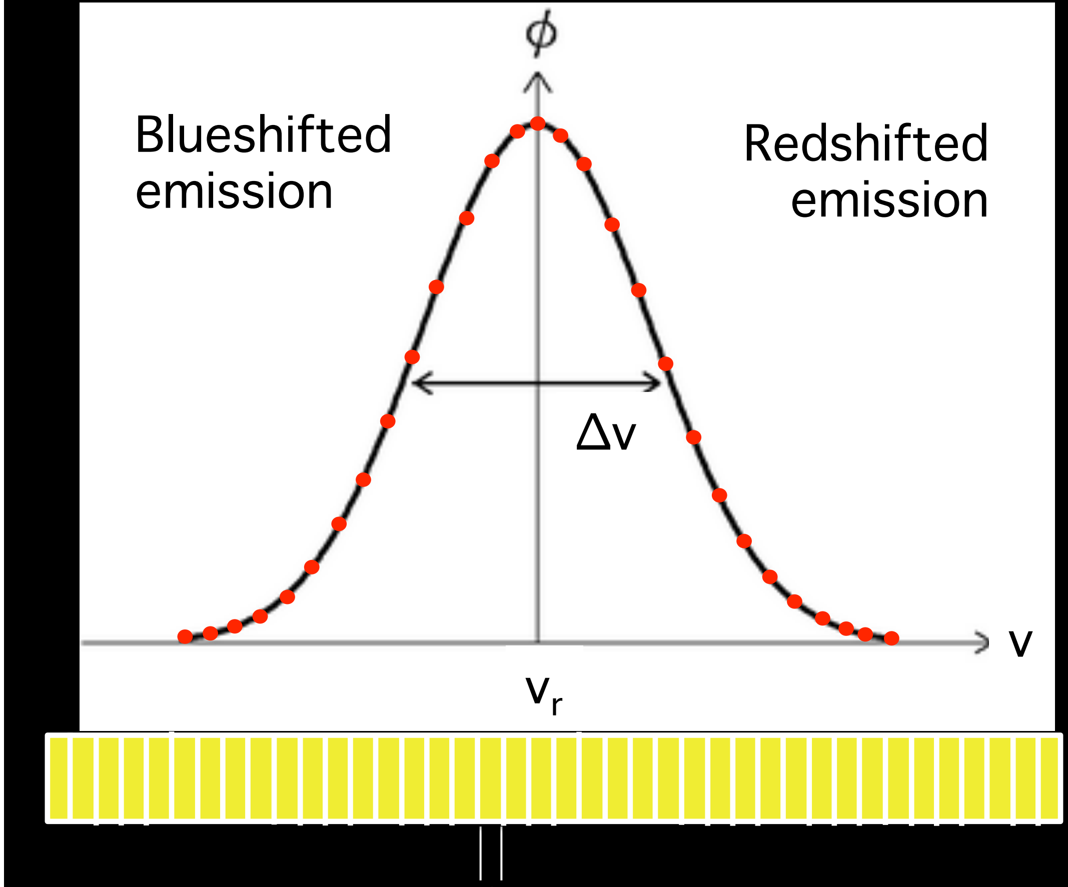

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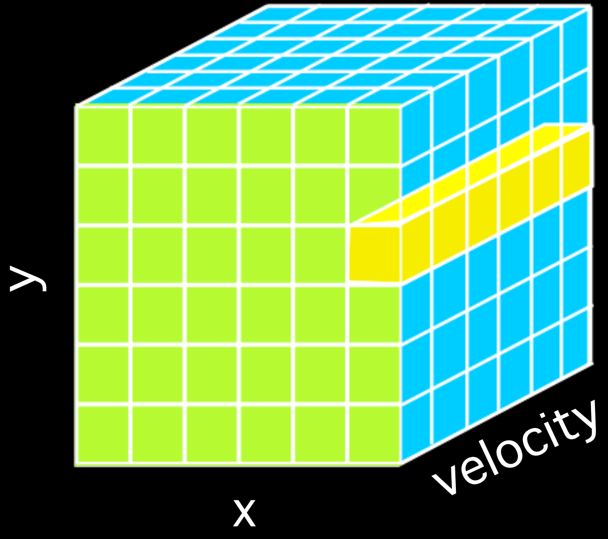

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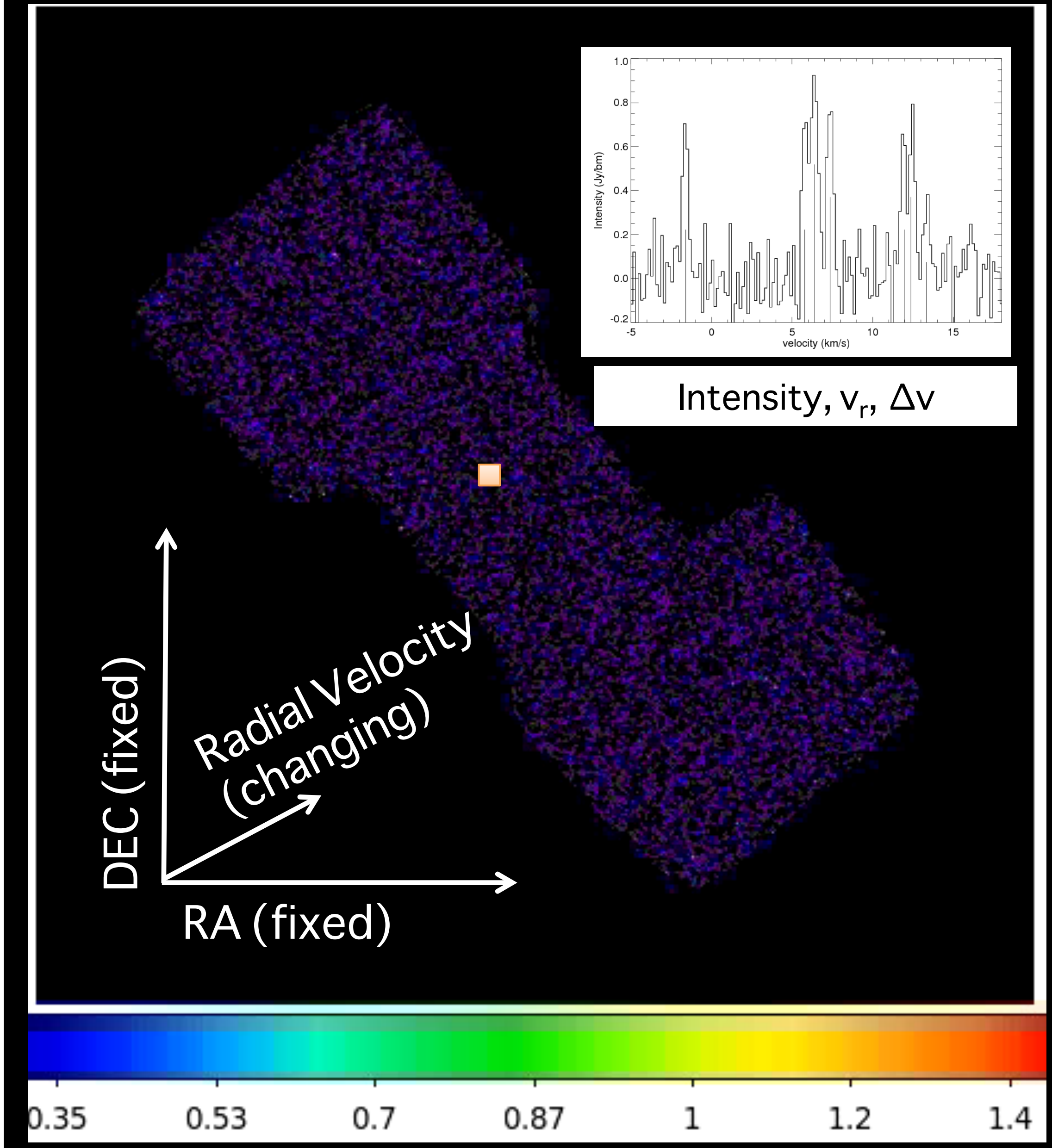
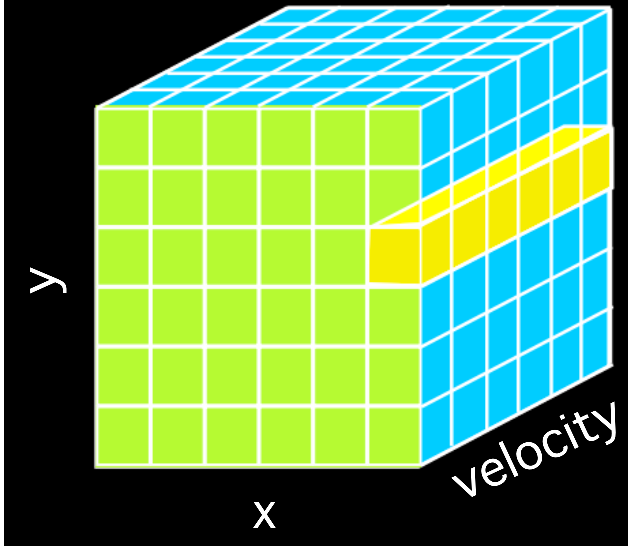
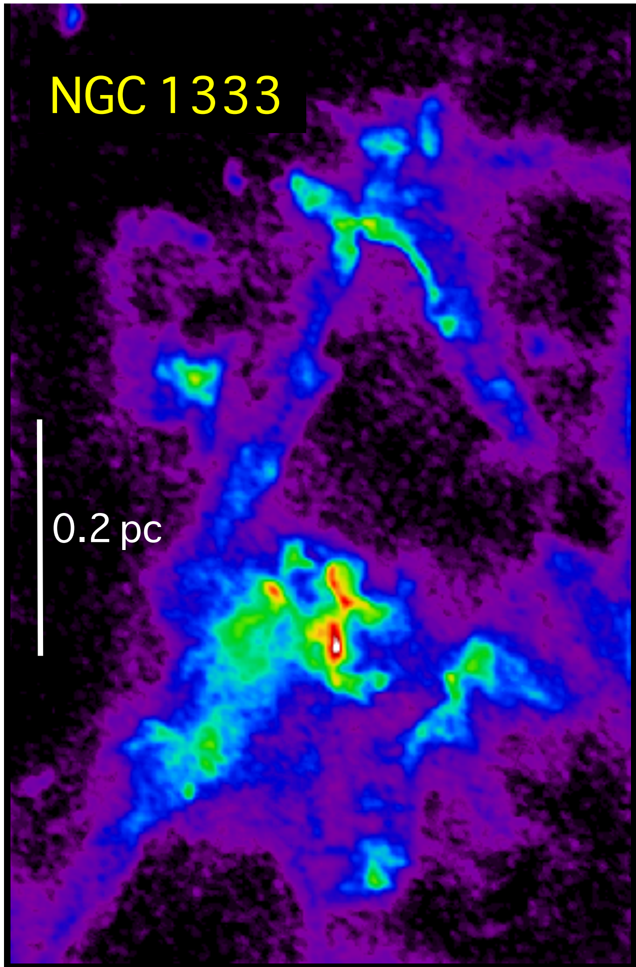
# How do we observe molecular emission?

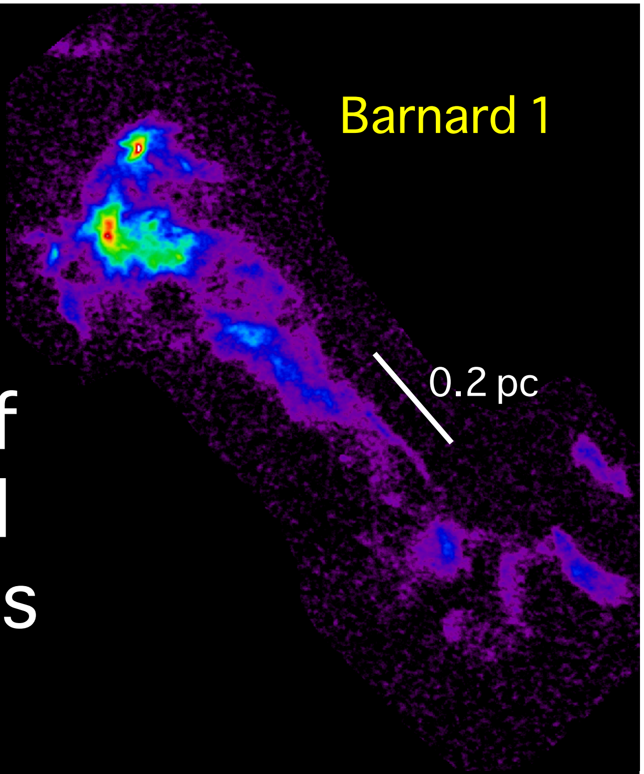


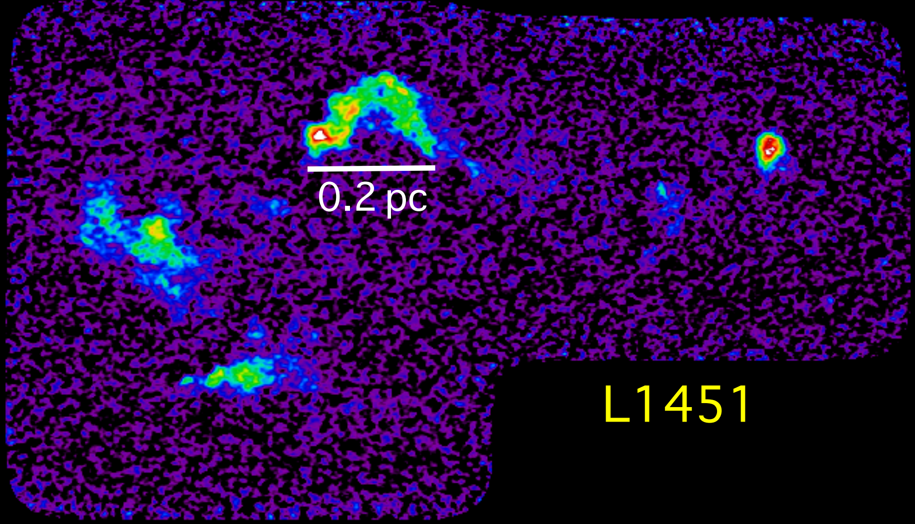


$$v = c(1 - \frac{\nu}{\nu_0})$$

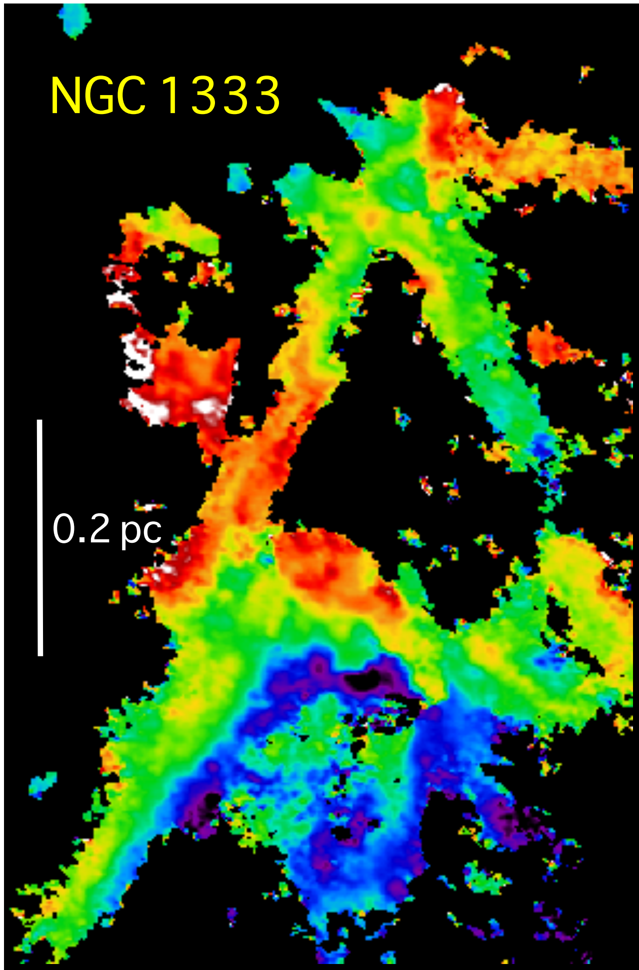
# CLASSy maps of $N_2H^+$ integrated intensity towards Perseus

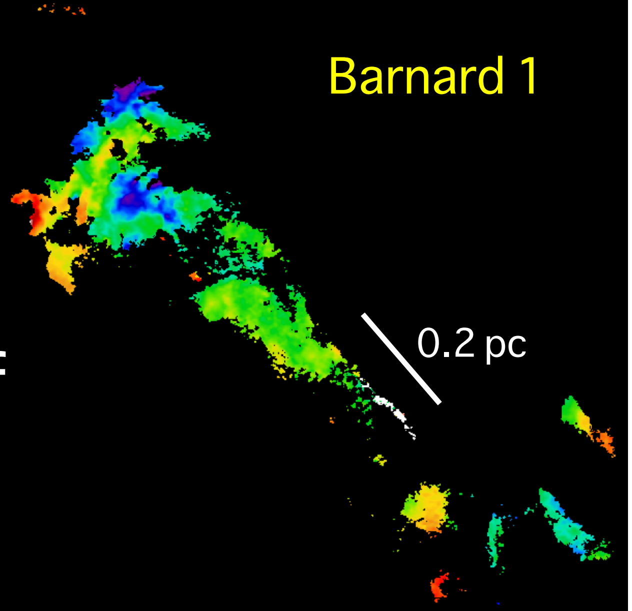


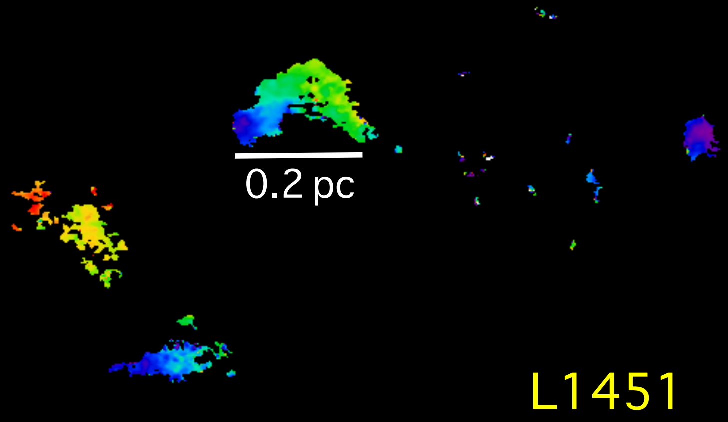




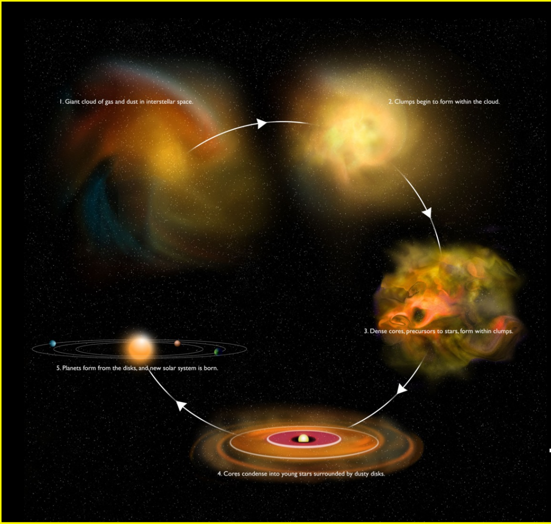
# CLASSy maps of $N_2H^+$ radial velocity field towards Perseus



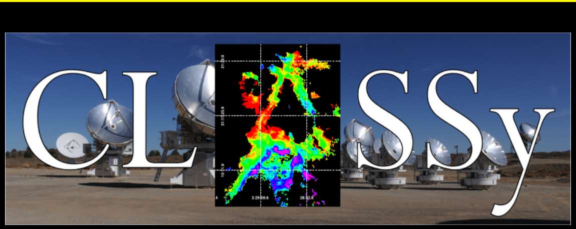




# Storyboard for Today’s Talk

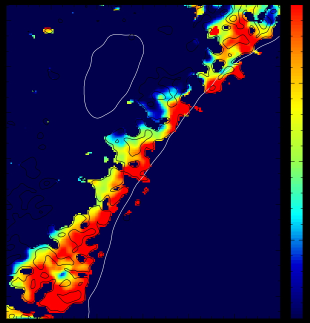


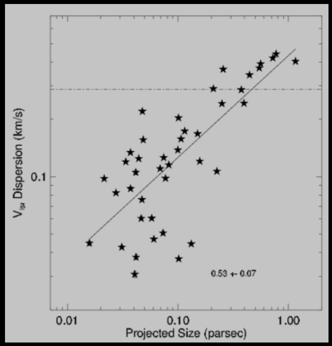
Star formation in Molecular Clouds: the Why, the Known, and the Unknown

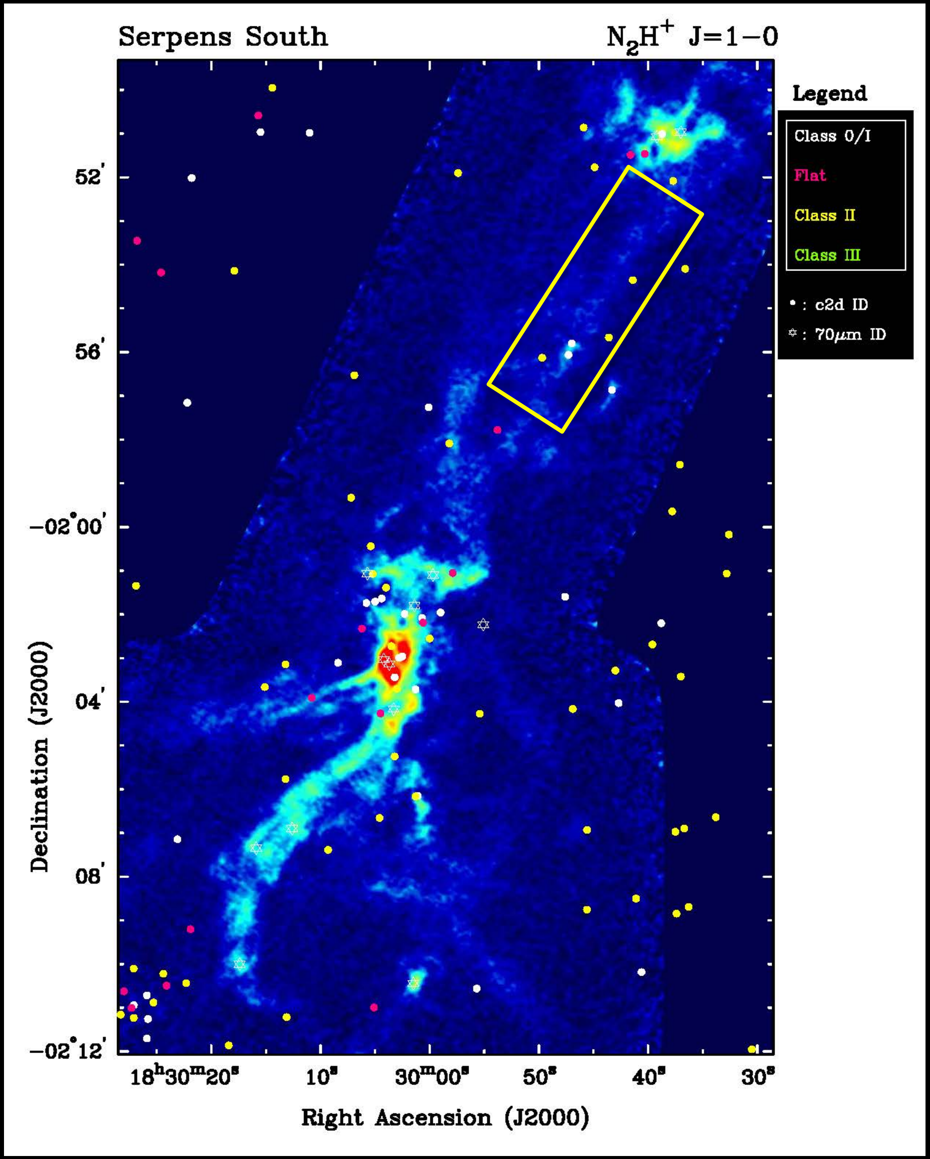


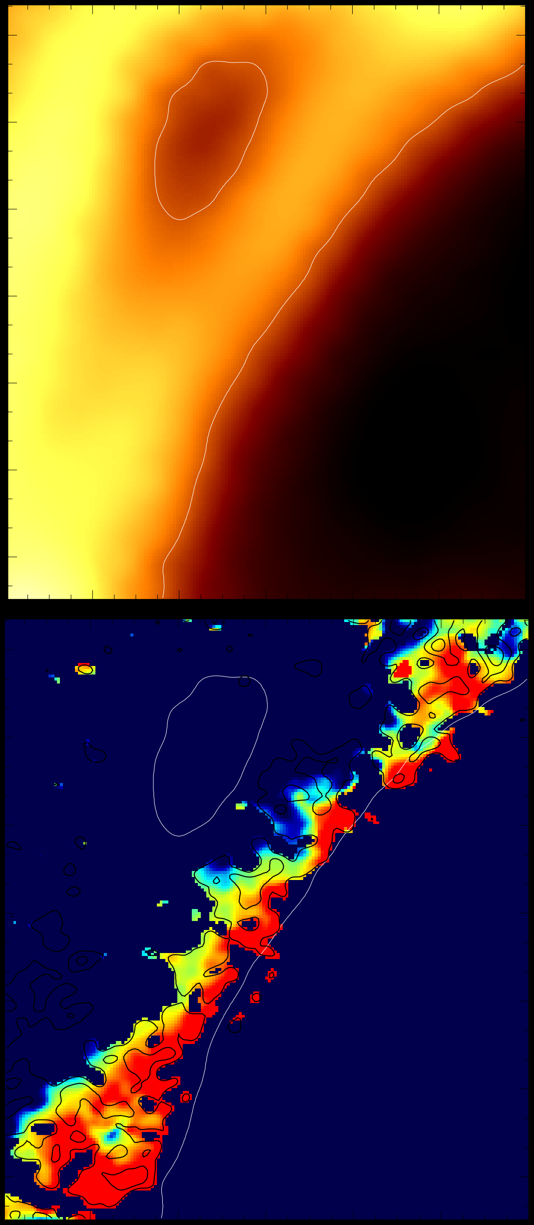
How we use CARMA to address the unknown

CLASSy reveals key signature of Molecular Cloud formation, and probes cloud turbulence

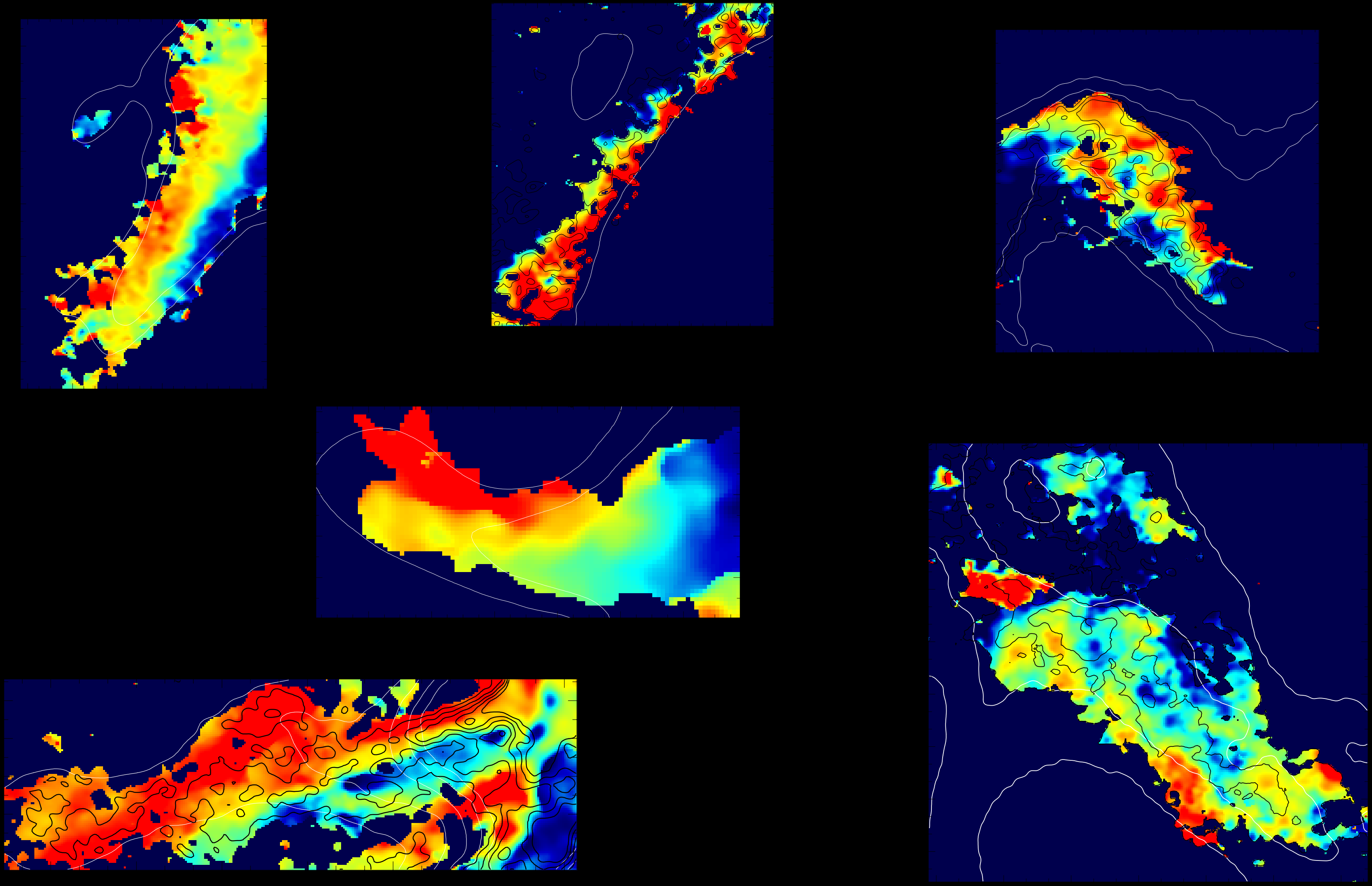




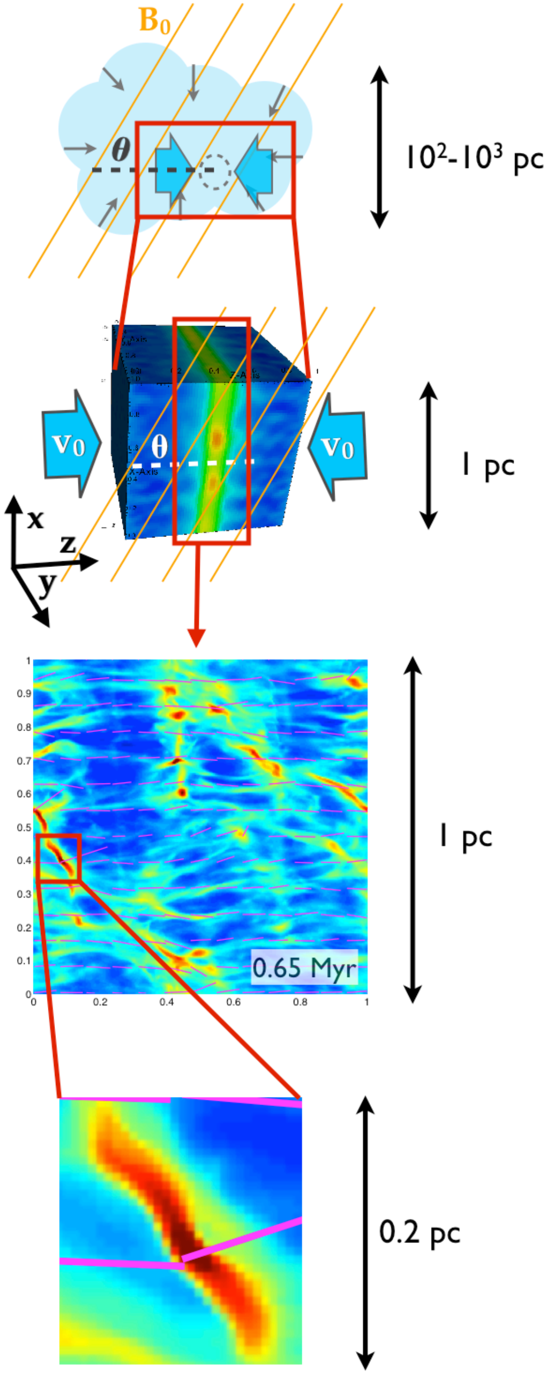

Serpens South
N2H+ J=1−0
Legend
Class 0/I
Flat
Class II
Class III
• : c2d ID
✡ : 70μm ID
52′
56′
−02°00′
04′
08′
−02°12′
Declination (J2000)
18h30m20s
10s
30m00s
50s
40s
30s
Right Ascension (J2000)

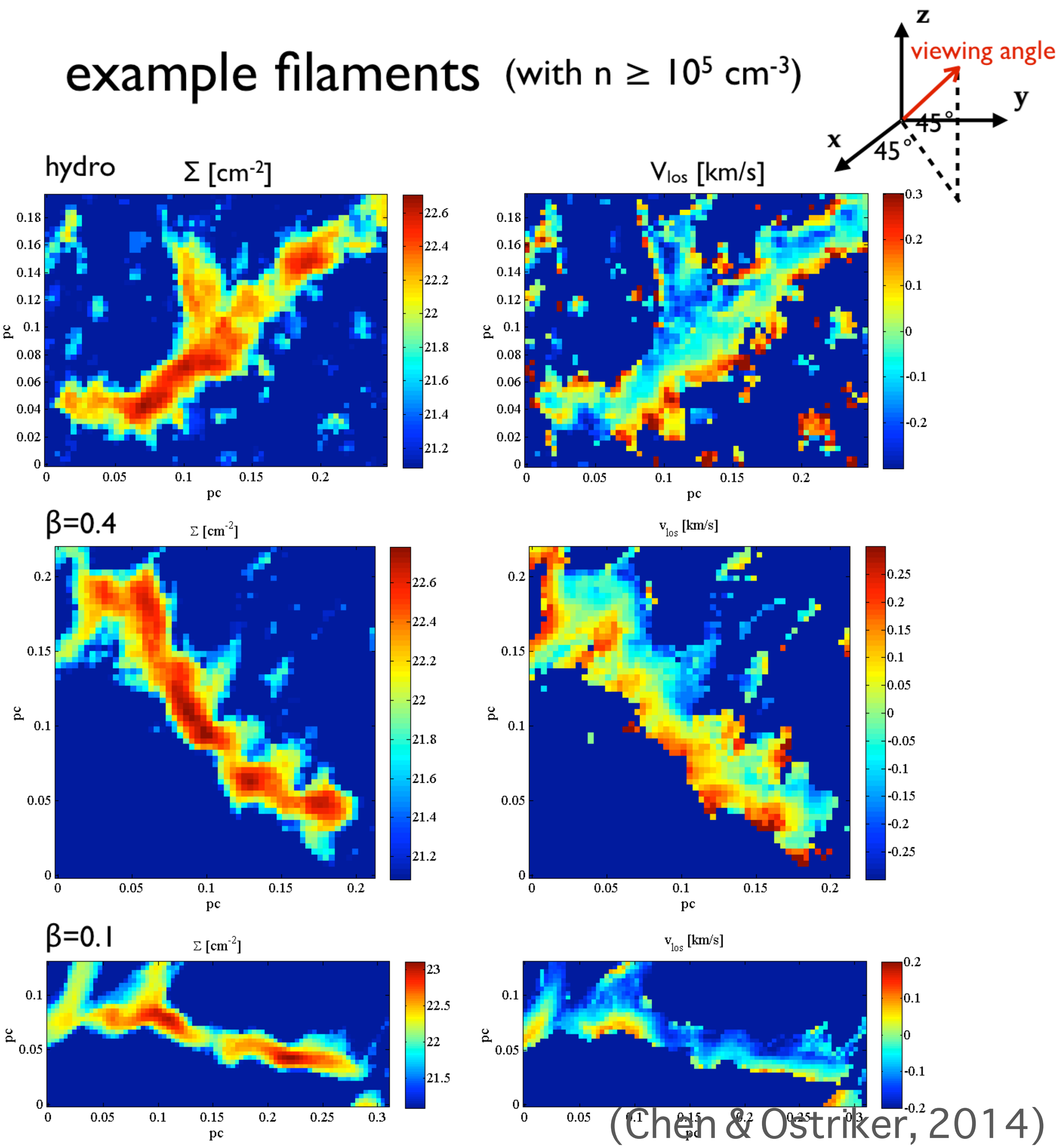


# CLASSy has discovered a zoo of filaments with similar kinematic signature



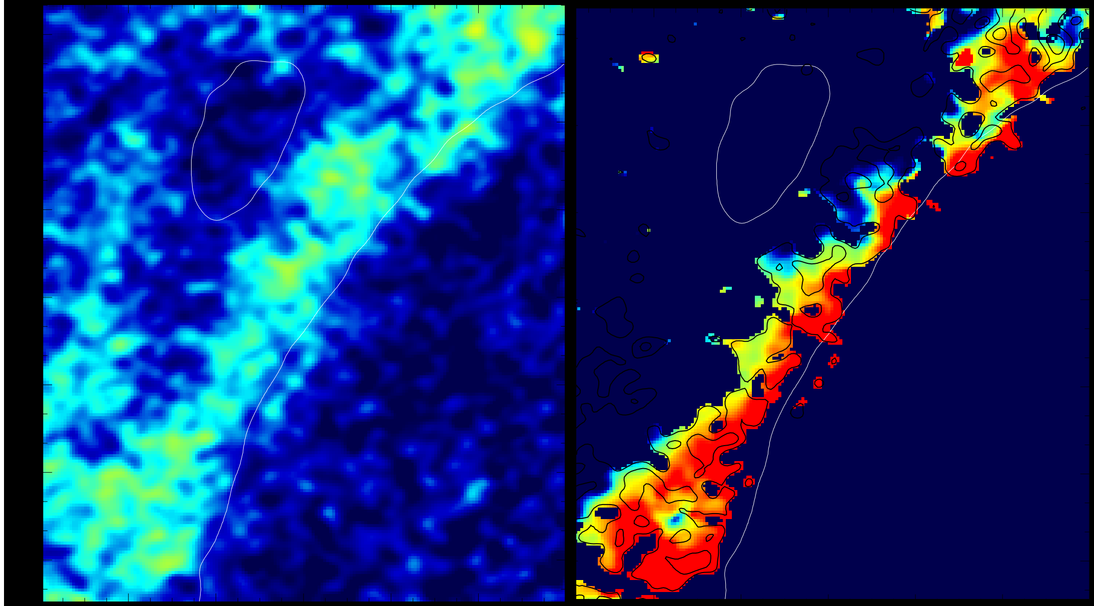
# example filaments (with $n \geq 10^5$ cm$^{-3}$)





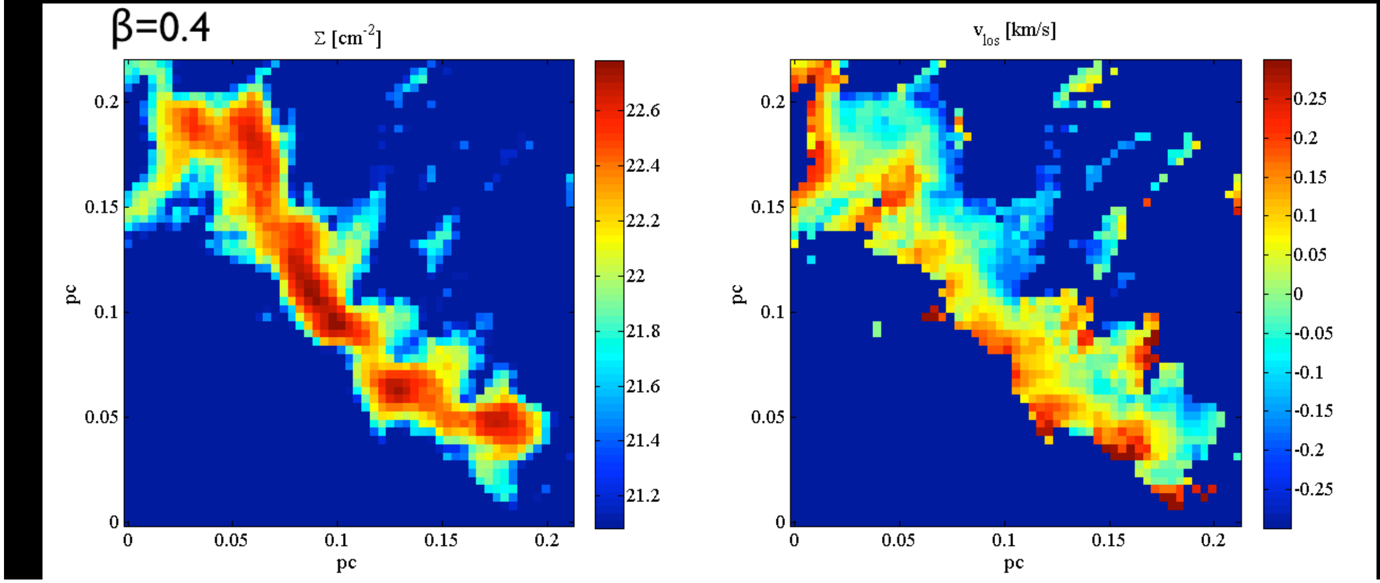
(Chen & Ostriker, 2014)

# Comparing CLASSy and simulated filaments

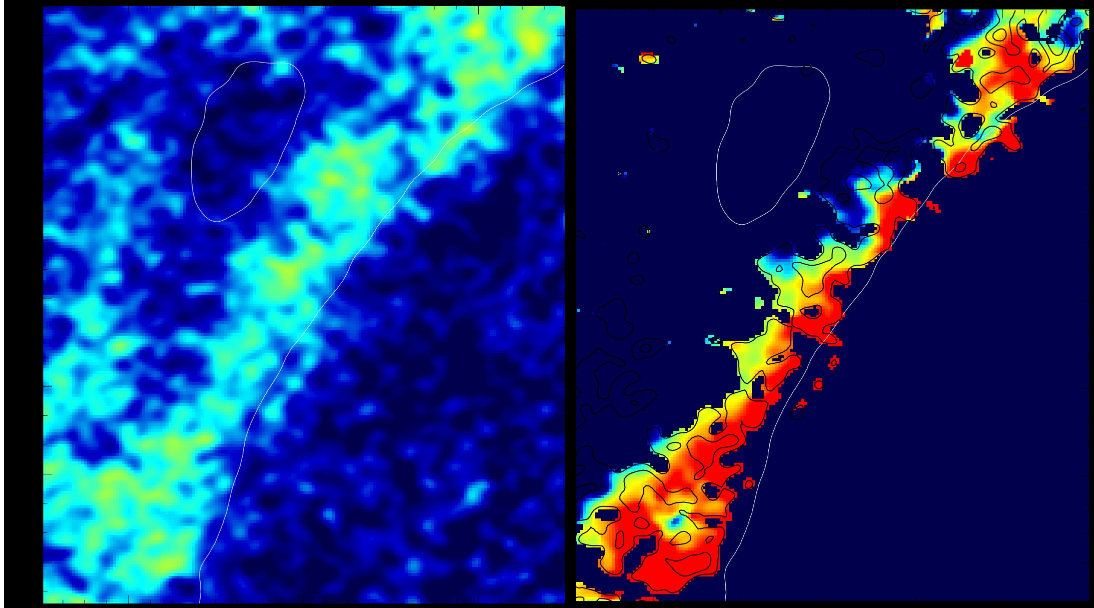


- Compare the kinetic energy to the gravitational energy:

$(v_{r,1} - v_{r,2})^2 / (GM/L)$



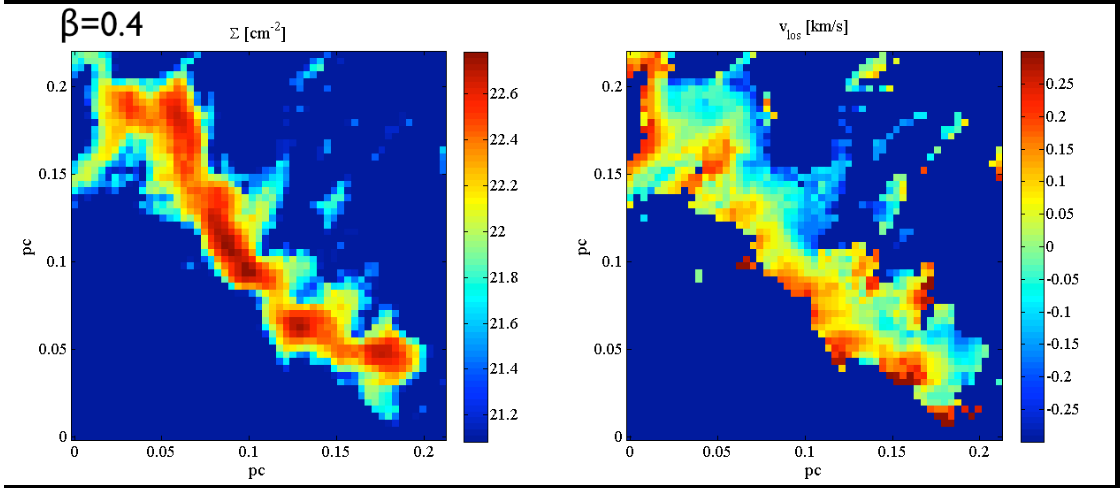
# Comparing CLASSy and simulated filaments



- Compare the kinetic energy to the gravitational energy: $(v_{r,1} - v_{r,2})^2 / (GM/L)$

- Used $N_2H^+$ (1-0)/(3-2) and *Herschel* dust maps to estimate filament density → $M/L \sim 10\ M_\odot/pc$
- Used CLASSy $N_2H^+$ (1-0) velocity maps to estimate $\Delta v^2$ → $(v_{r,1} - v_{r,2})^2 \sim 0.2$ km/s

# Comparing CLASSy and simulated filaments

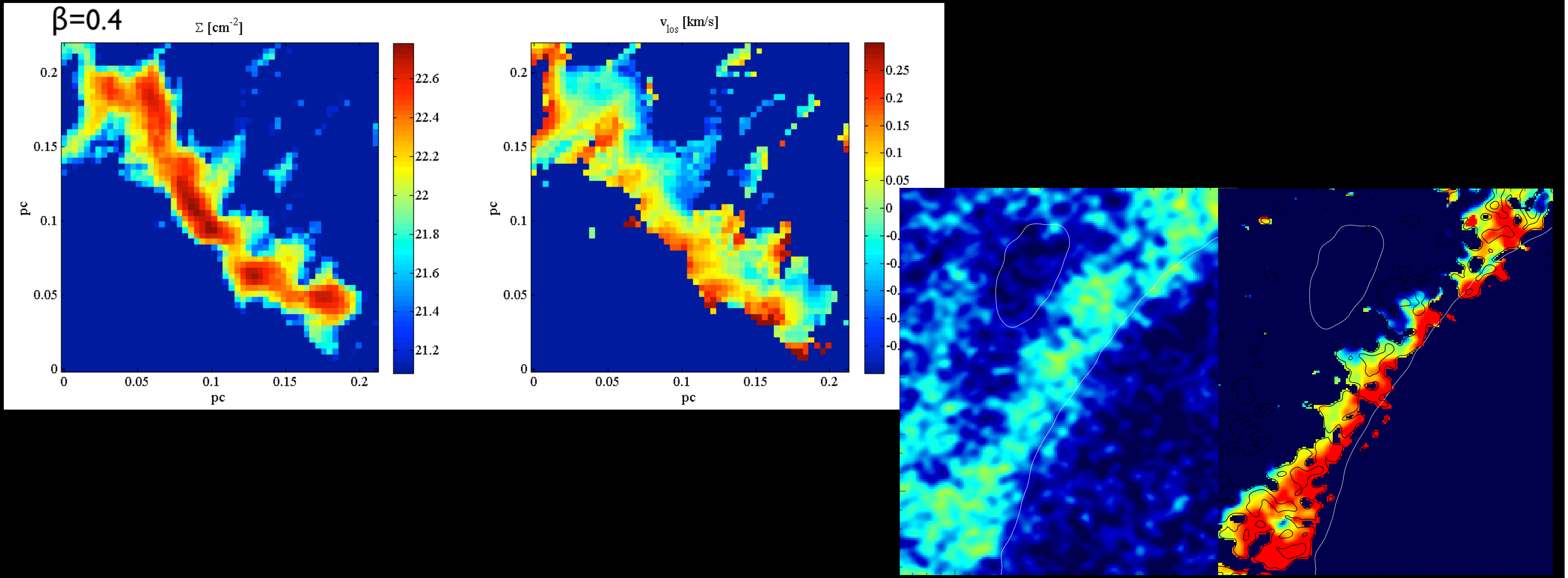


- Compare the kinetic energy to the gravitational energy: $(v_{r,1} - v_{r,2})^2 / (GM/L)$

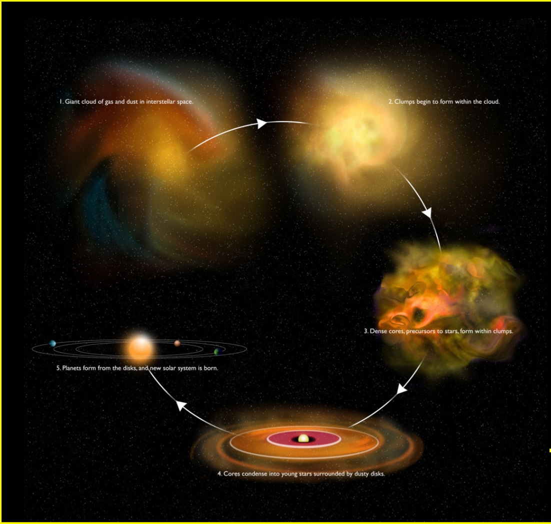
- Used 3D simulations to calculate M/L ~ 10-40 $M_\odot$/pc
- Used 3D simulations to calculate $(v_{r,1} - v_{r,2})^2$ ~ 0.2 km/s

→ Observations and simulations agree to within a factor of 2 that filaments are nearly balanced in kinetic and gravitational energy.

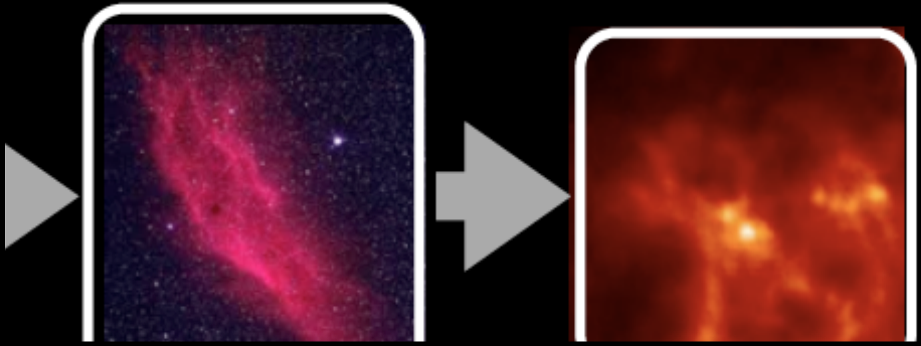
# Preliminary result … being drafted for ApJL



- CLASSy provides first kinematic evidence that filamentary cloud structure is driven by turbulent converging flows.



Star formation in Molecular Clouds: the Why, the Known, and the Unknown



Molecular Cloud
10 pc

Cloud Core
0.1 pc

How do Molecular Clouds form and what determines their structure?

What is the nature of Molecular Cloud turbulence from cloud-scales down to core - scales?

# Turbulence

“Turbulence is defined by the Oxford English Dictionary as a state of ‘violent commotion, agitation, or disturbance,’ with a turbulent fluid further defined as one ‘in which the velocity at any point fluctuates irregularly.’ Although turbulence is, by definition, an irregular state of motion, a central concept is that order nevertheless persists as scale-dependent spatial correlations among the flow variables.”

- *McKee and Ostriker (2007),*
  *Theory of Star Formation*

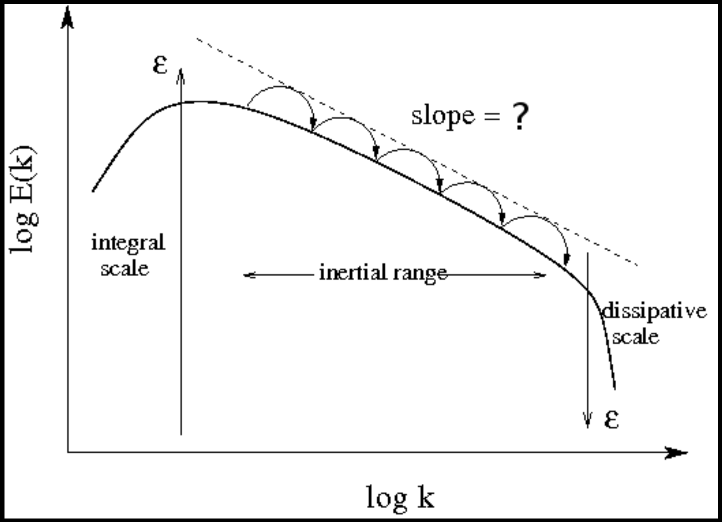
# Turbulence

When there is a large range of spatial scales with consistent physics, like a turbulence energy cascade from pc to AU scales, <u>spatial correlations take on power-law form.</u>

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

"[…] scaling relations reflect the basic physics governing the flow."

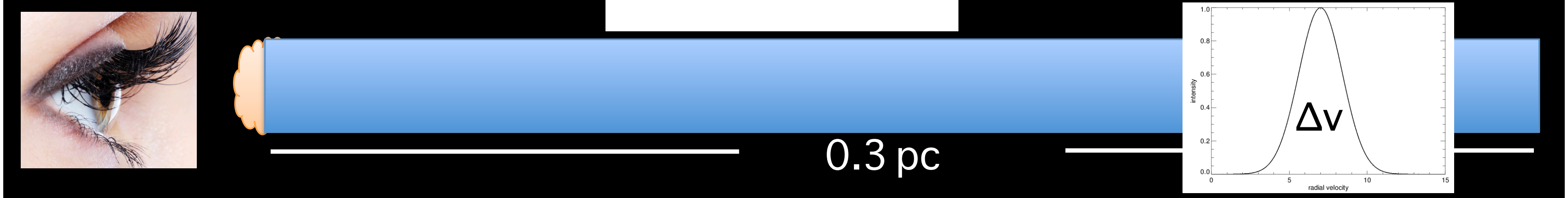
*- McKee and Ostriker (2007), Theory of Star Formation*

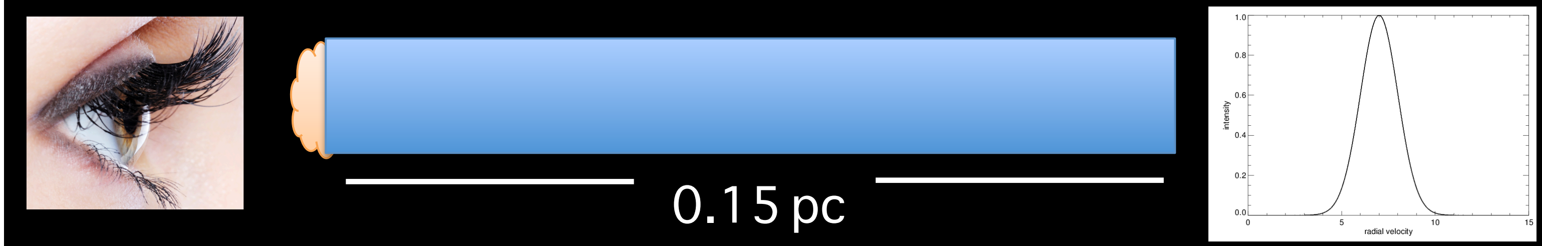


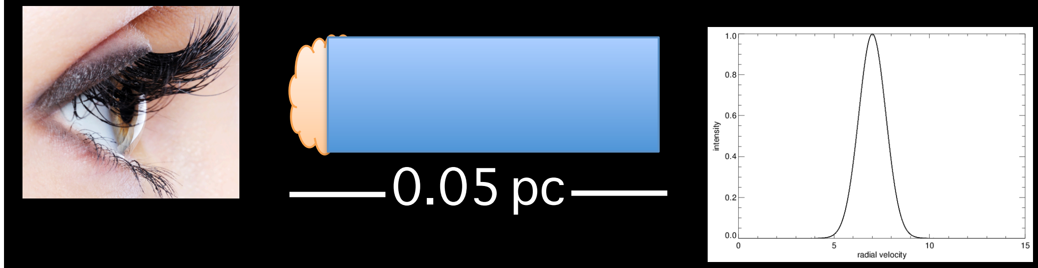
# Turbulence measured along single resolution element – variation in Δv

Angular resolution element

$$\Delta v(\ell) \propto \ell^q$$



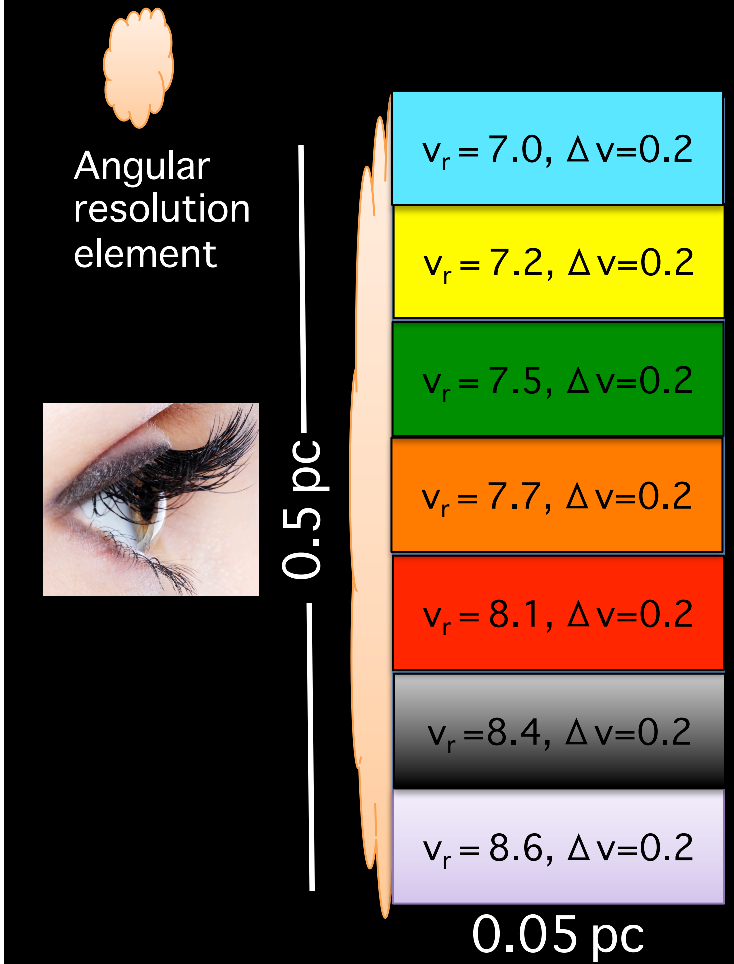




- Assuming we can see along the entire line of sight, and that gas motions are isotropically turbulent, deeper clouds will have larger linewidths compared to shallower cloud.
- Relation set by turbulent cascade properties.

# Turbulence measured across multiple resolution elements – variation in $v_r$

$$\sigma_{v_r}(\ell) \propto \ell^q$$



Angular resolution element

0.5 pc

$v_r = 7.0$, $\Delta v = 0.2$

$v_r = 7.2$, $\Delta v = 0.2$

$v_r = 7.5$, $\Delta v = 0.2$

$v_r = 7.7$, $\Delta v = 0.2$

$v_r = 8.1$, $\Delta v = 0.2$

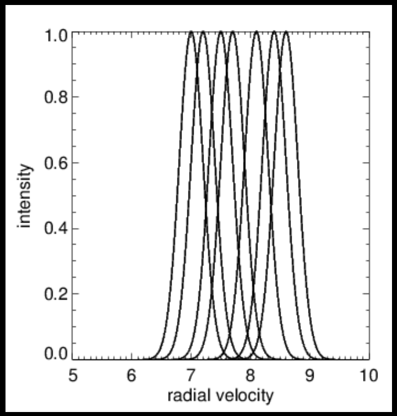
$v_r = 8.4$, $\Delta v = 0.2$

$v_r = 8.6$, $\Delta v = 0.2$

0.05 pc

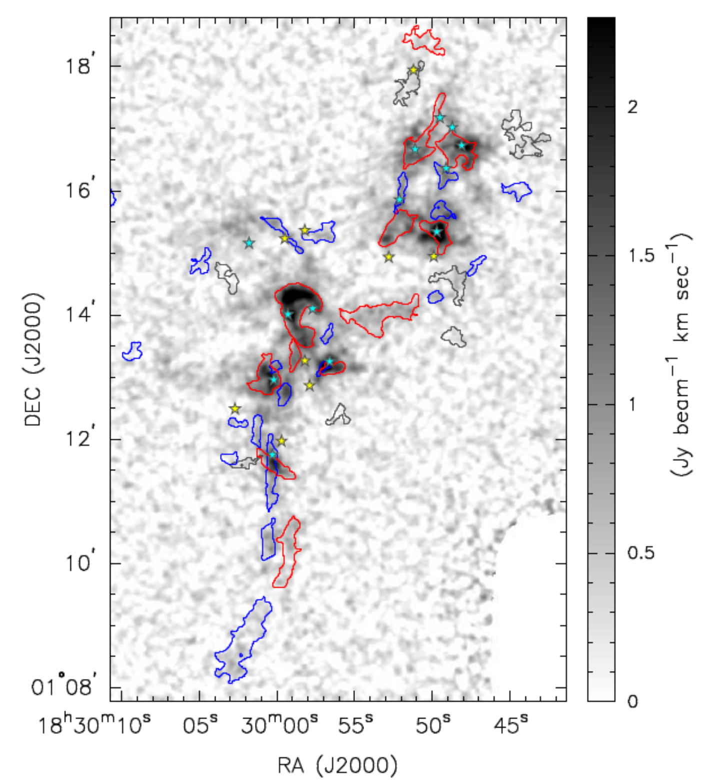
*Cartoon not to scale

- Each line of sight has same linewidth, due to the same length along the line of sight, but a different centroid radial velocity.
- Variation of centroid radial velocity along the face of the cloud will be set according to the turbulence cascade just like before – assuming the gas motions are isotropically turbulent.



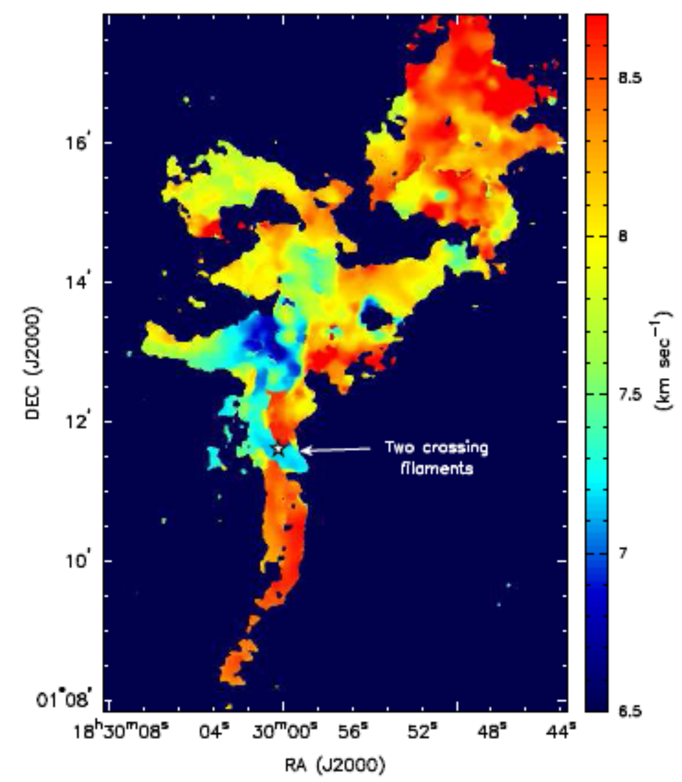
# Size-Linewidth Relation of Clumps within Serpens Main

## Map of identified clumps



"Size" = Projected size (pc) of each clump measured across plane of sky

## Map of radial velocity ($v_r$)

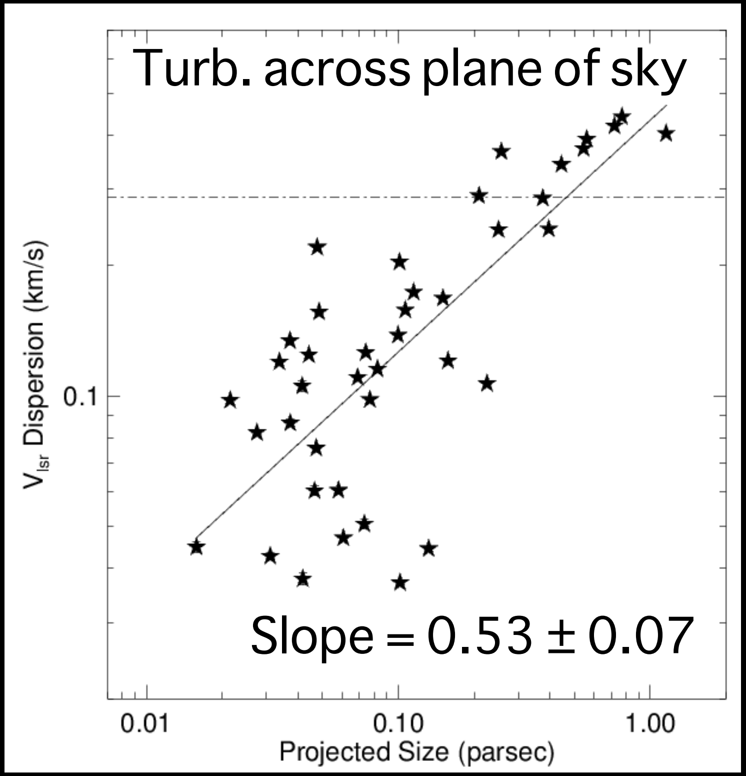


Two crossing filaments

"Linewidth" 1 = Dispersion of $v_r$ (km/s) measured within area of each clump – measure of turbulence *across* the plane of sky on that size scale

# Size-Linewidth Relation of Clumps within Serpens Main

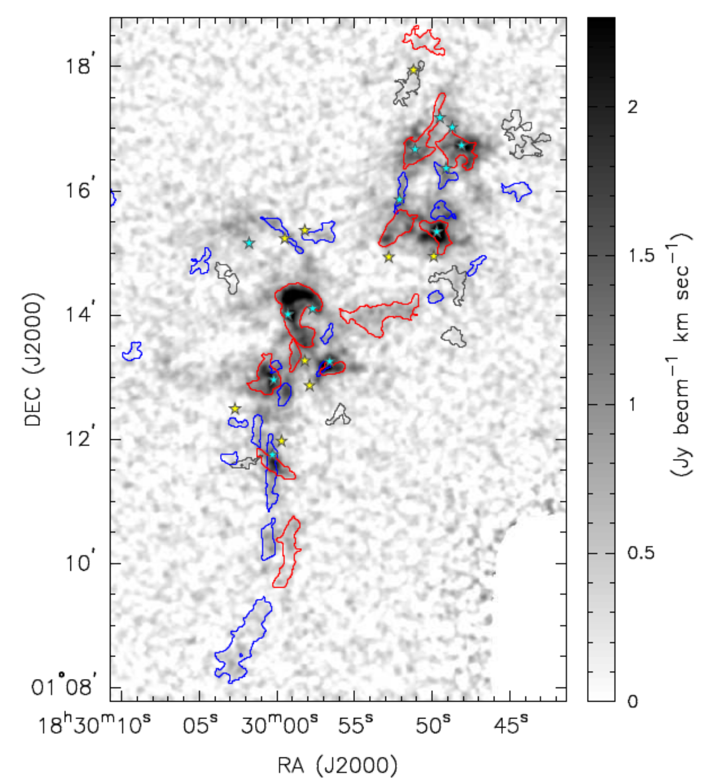
Linewidth 1



**Larger objects have more variation of $v_r$ than than smaller objects – power law slope ~0.5, consistent with a shock-dominated turbulent cascade throughout the cloud.**

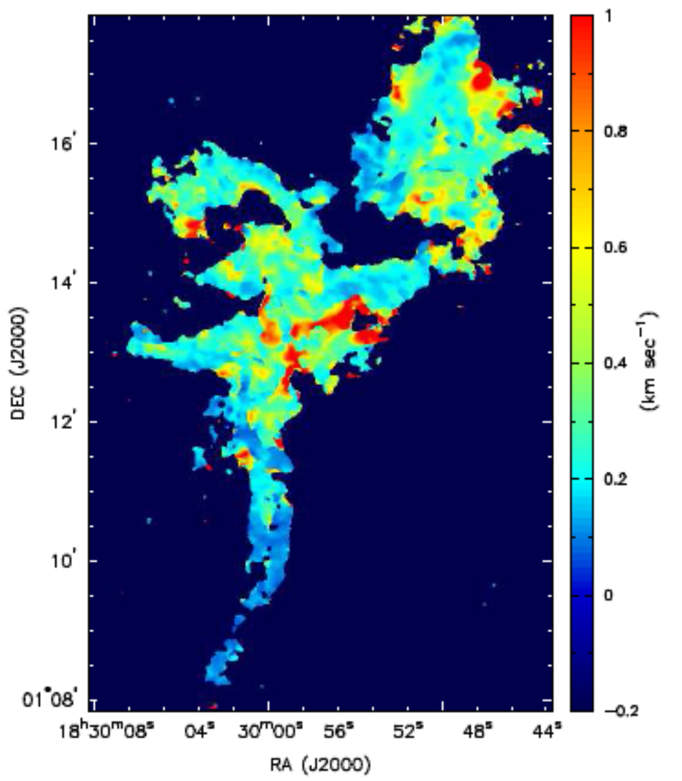
# Size-Linewidth Relation of Clumps within Serpens Main

Map of identified clumps



“Size” = Projected size (pc) of each clump measured across plane of sky

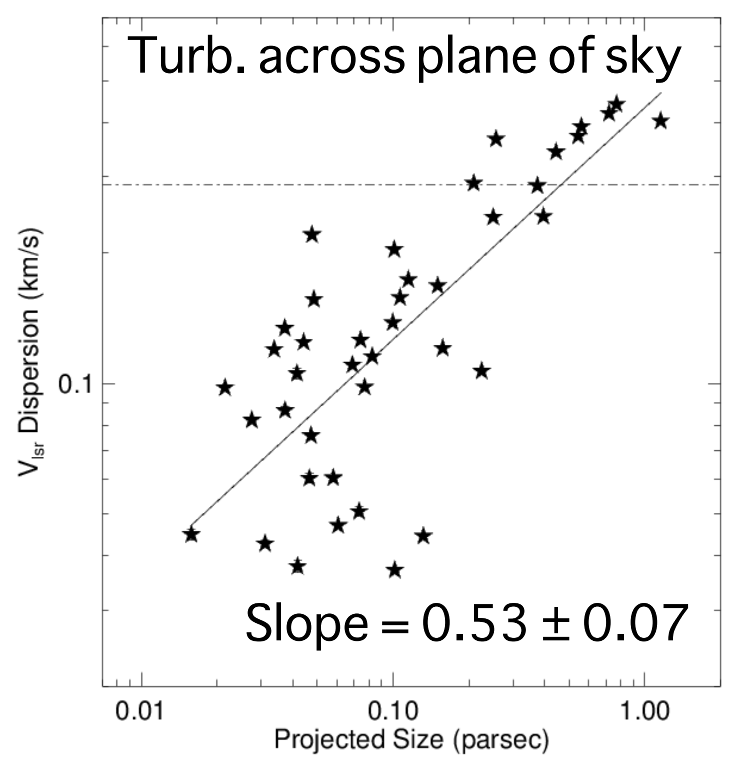
Map of linewidth (Δv)



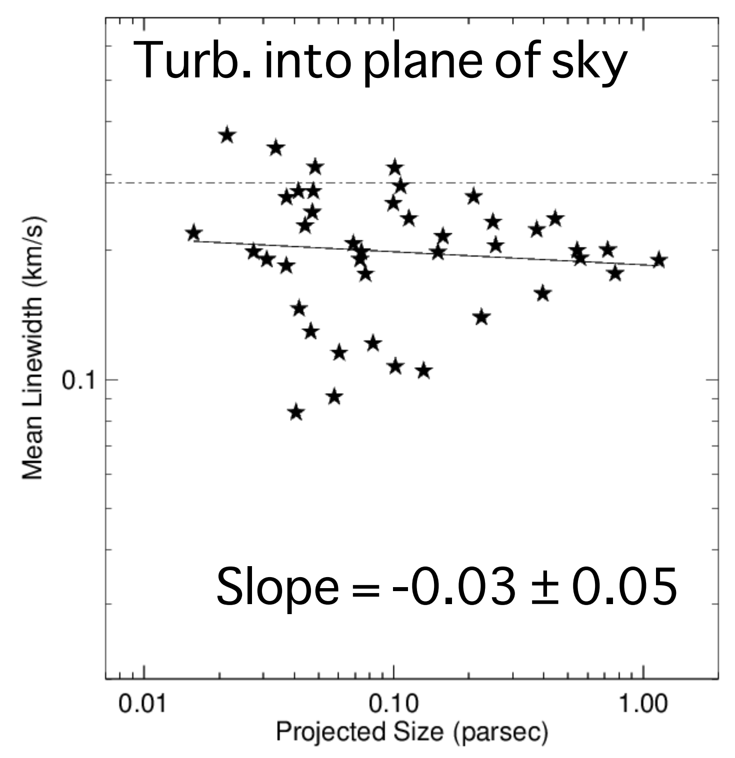
“Linewidth” 2 = Mean Δv (km/s) measured within area of each clump – measure of turbulence into the plane of sky on that size scale

# Size-Linewidth Relation of Clumps within Serpens Main

Linewidth 1

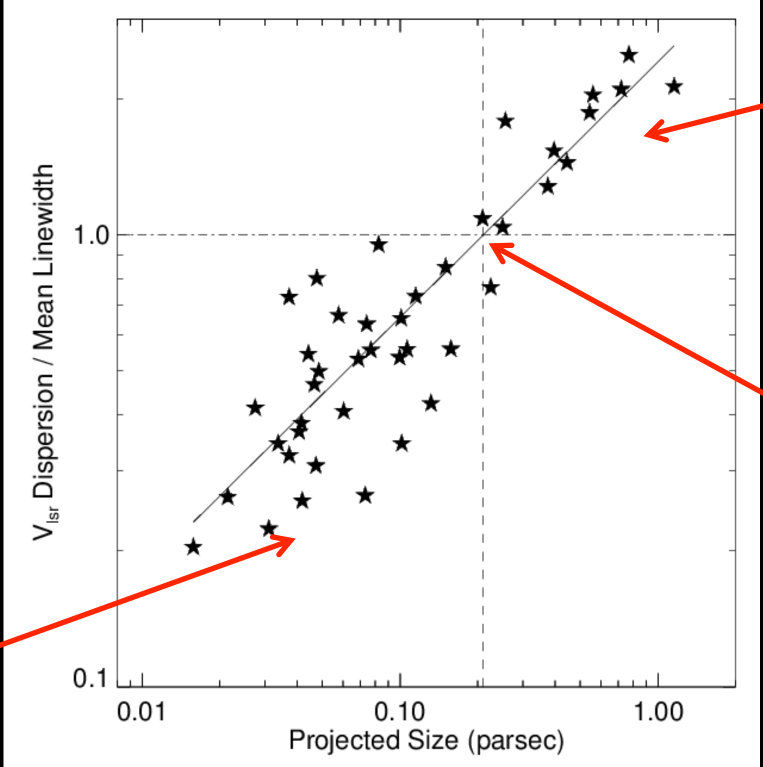


Linewidth 2



No variation of mean Δv with size – indication that these objects, no matter what their size across the plane of the sky, are all similar depth into the plane of the sky. What is that depth?

# Size-Linewidth Relation of Clumps within Serpens Main

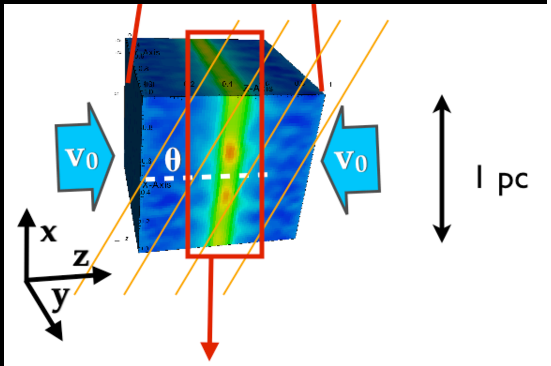


Variation of centroid velocity across sky is greater than linewidth from motions into the plane of the sky

Turbulent motions across and into the plane of the sky are comparable ~0.2 pc.

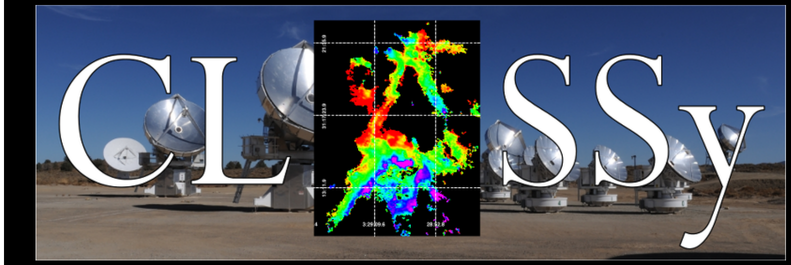
Linewidth from motions into plane of sky are greater than variation of centroid velocity across sky

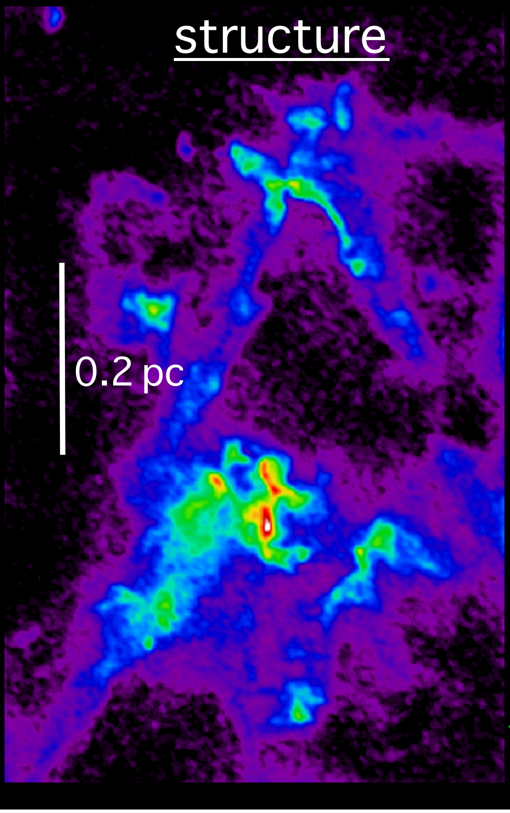
- CLASSy data reveals that molecular clouds are more planar than spherical at largest scales!
- Thickness of Serpens Main is no more than ~0.2 pc.
- Supports the idea that molecular clouds are formed at intersections of converging, turbulent flows.

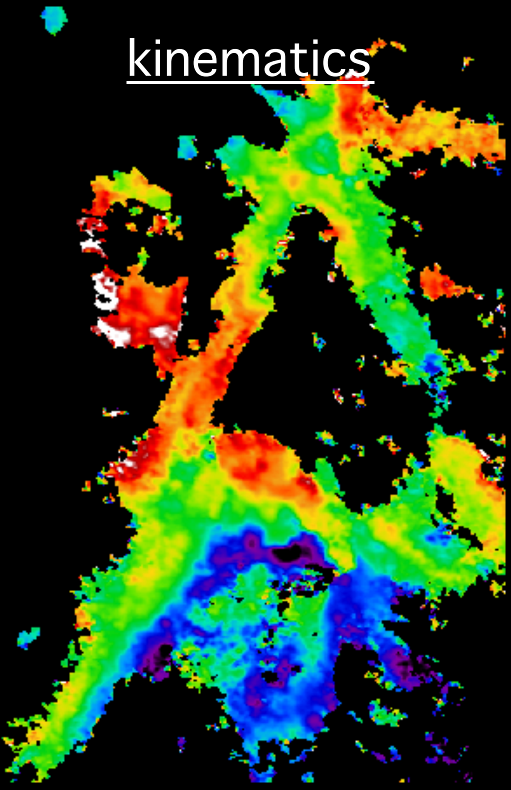


# Summary

- CARMA has connected the cloud-to-core scales in several nearby molecular clouds with high angular resolution, large-area mosaics.
- Observed dense gas to understand the structure and kinematics of the cloud material that is currently forming stars.




structure


kinematics

# Summary

- Identified a collection filaments with velocity gradients perpendicular to their major axes – first observational support of this predicted signature of cloud formation from converging, turbulent flows.

- Characterized turbulence in Serpens Main across and into the plane of the sky, and found that largest scale structure are more planar than spherical. Suggests that clouds are sheet-like structures at the largest scales that formed at intersection of converging flows.