Line Profiles of Clustered Cores

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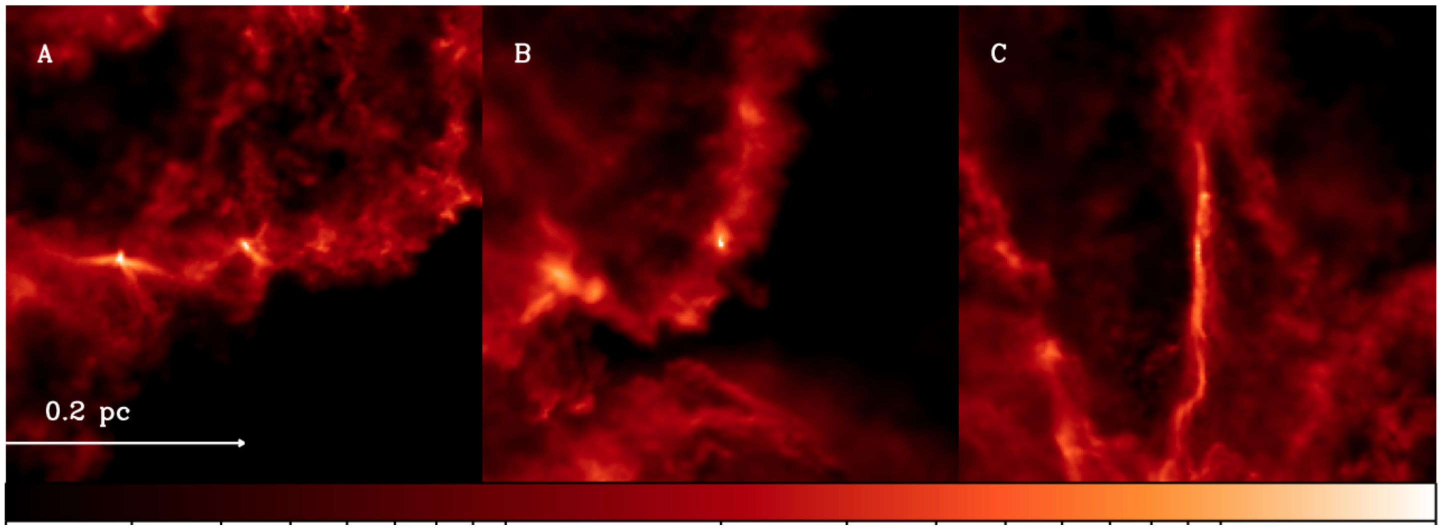

Motivation

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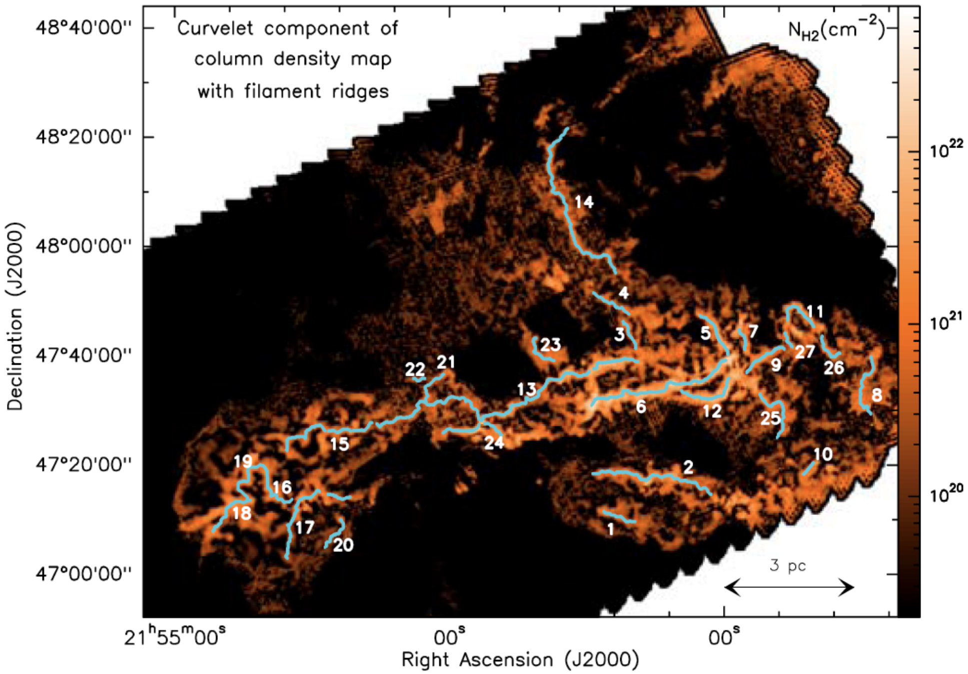
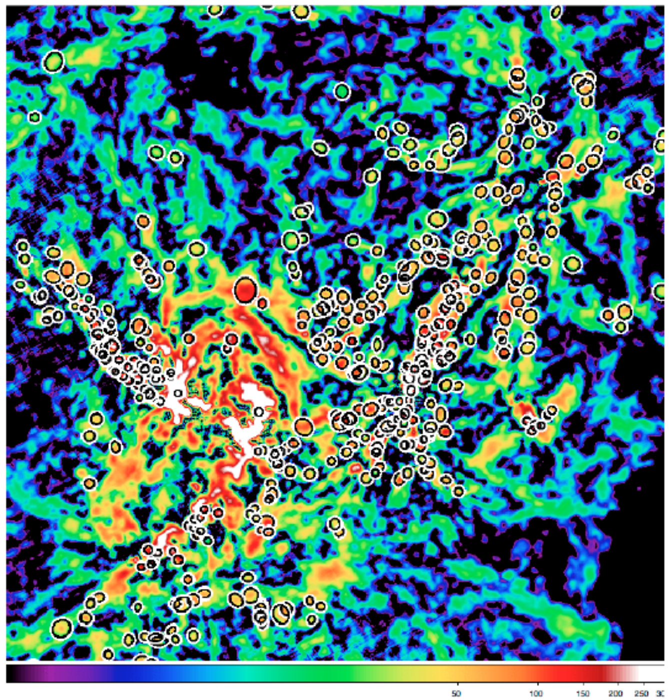
Herschel Observations



Azroumainian et. al. 2011

Herschel observations have shown molecular clouds are threaded with filaments.

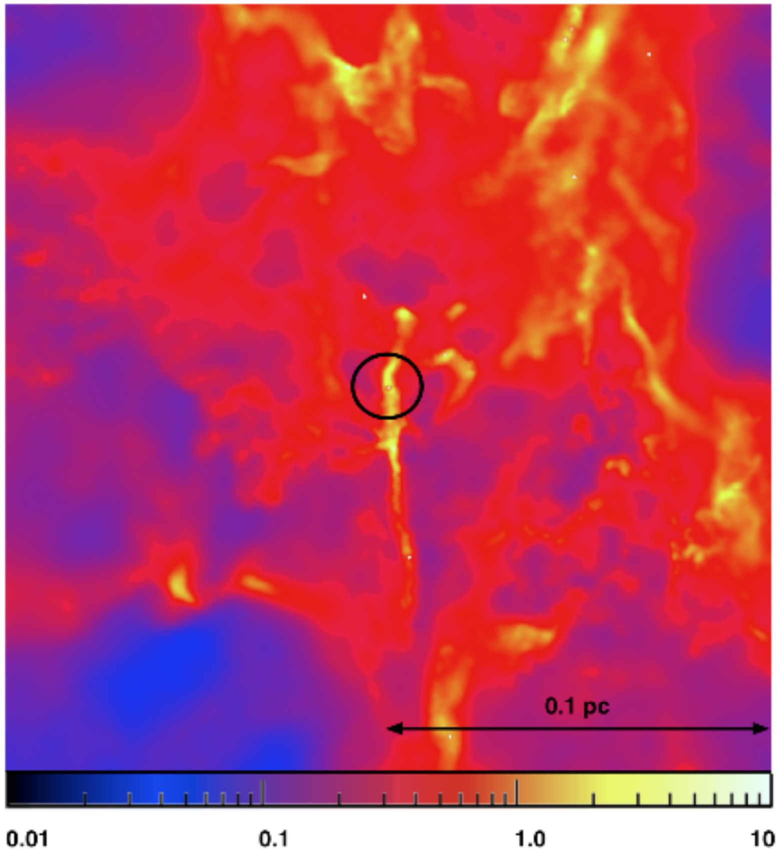


Men'shchikov et. al. 2011

Dense cores are embedded within the filaments.

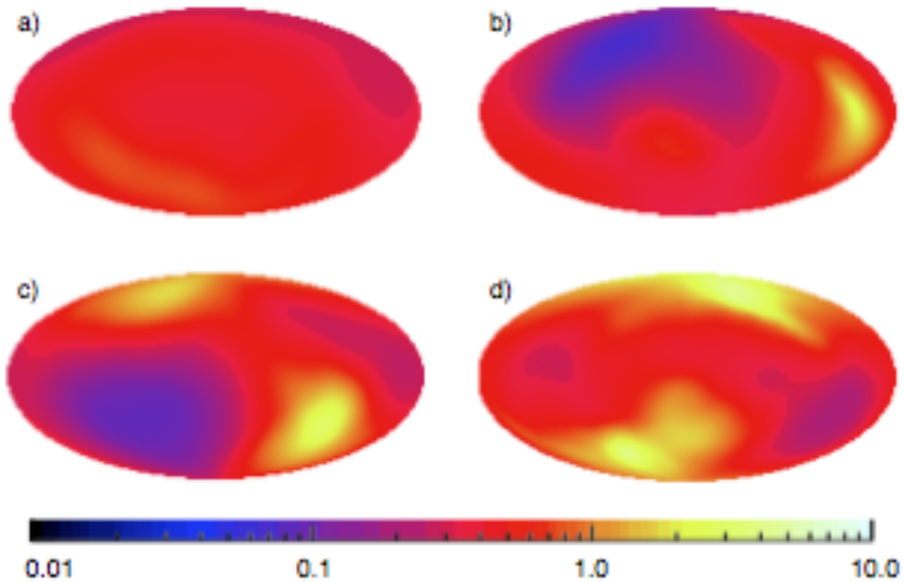
papers by: Andre, Peretto, Schisano, Polychroni, Zhang, Azromainian,Pineda, Hennebelle, Inutsuka and others...

Irregular Shapes



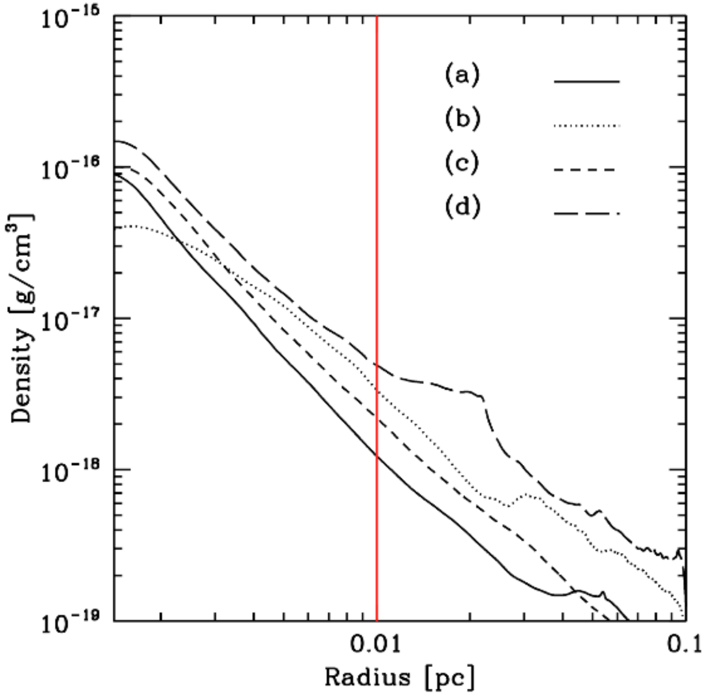
Column Density Projections

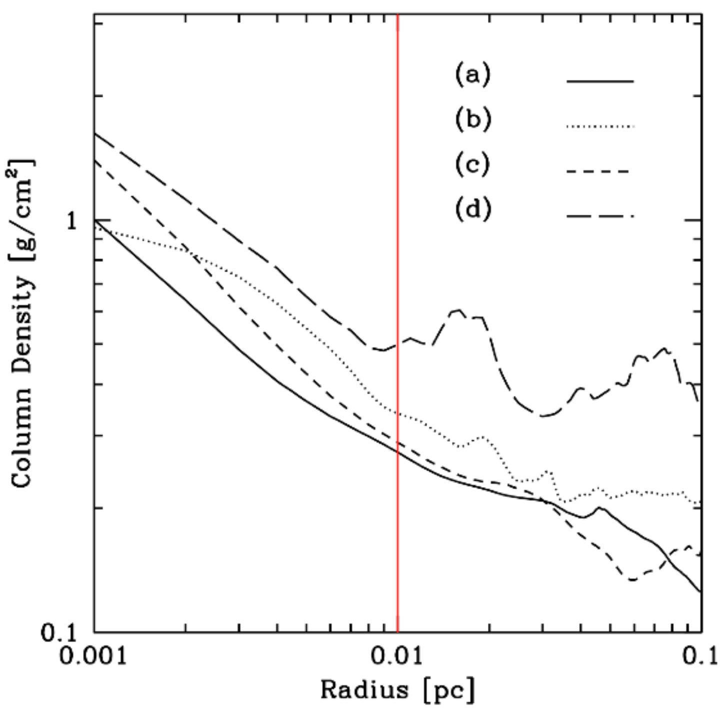
Smith et al 2011a



Cores in Simulations are non-spherical and **filamentary,** even on small scales.

Radial Averaged

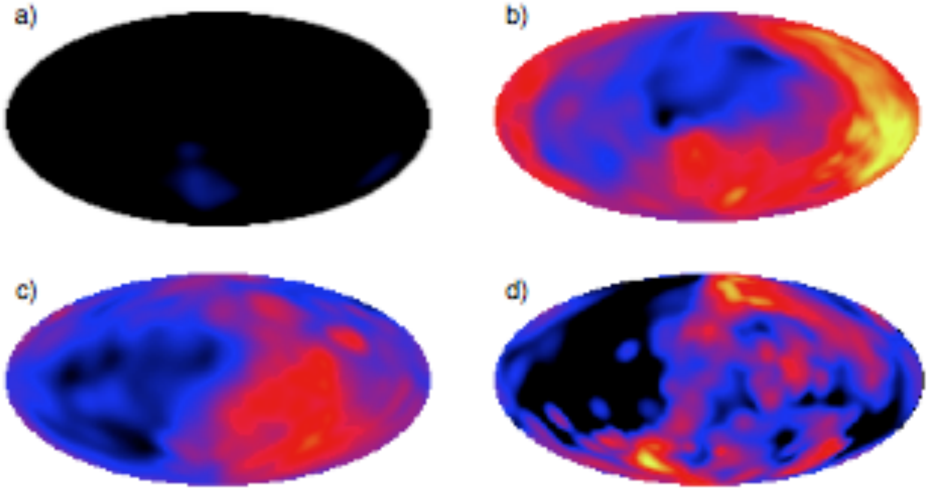




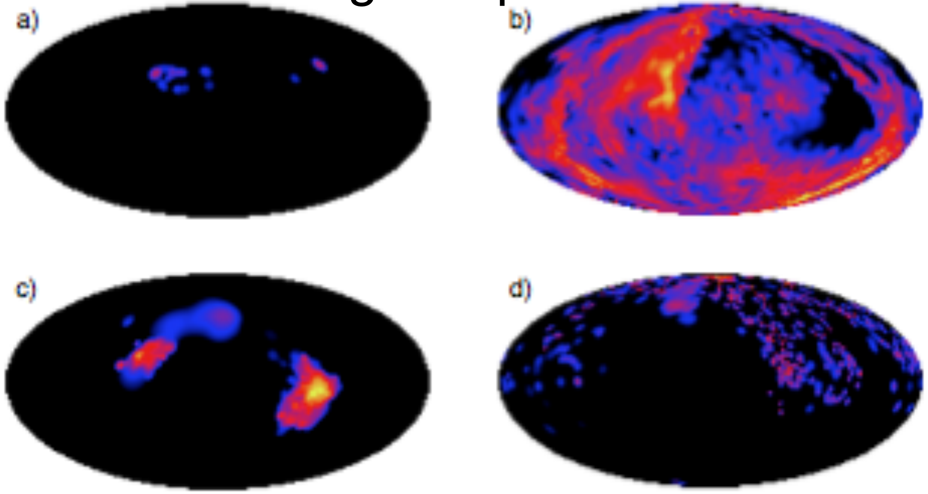
When averaged radially the cores are in good agreement with simpler spherical models.

Irregular Accretion

Flow through 0.01pc surface.



Flow through 0.1pc surface.



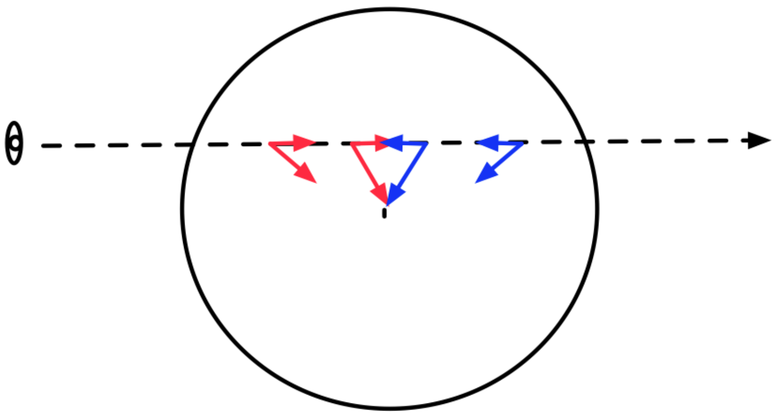
Accretion through the core boundary is also **irregular**.

Low mass stars have **no additional** accretion from outside the core.

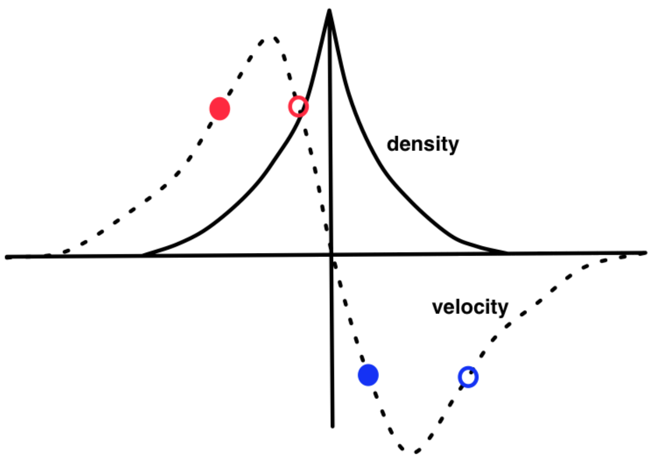
Massive stars have **substancial** accretion from outside the core.

Blue Asymmetry

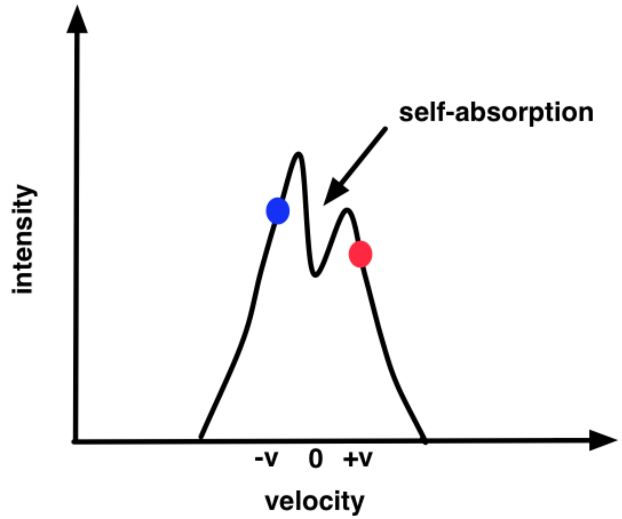
In a collapsing spherical core



The line-of-sight densities and velocities are...



In optically thick species only the nearest point at any velocity is seen.



Denser material emits at a greater intensity.

See also:

Zhou et. al. 1992,
Walker et. al. 1994,
Myers et. al. 1996

and others...

The Method

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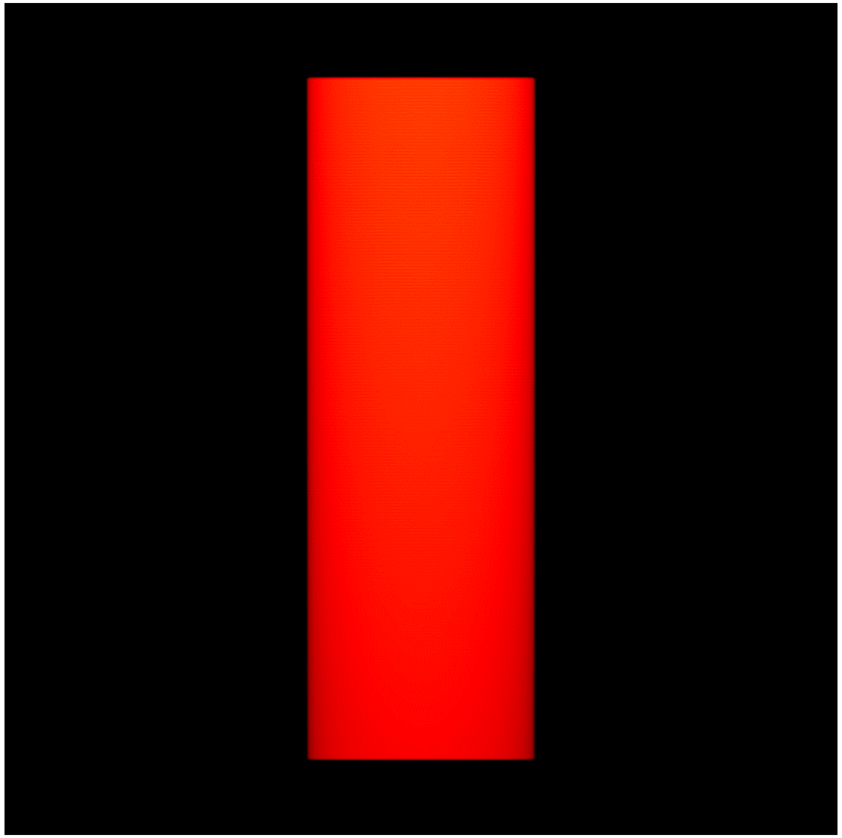
A GMC Simulation

Loosely based on Orion A

- 10 000 M_{sol}
- Smooth Particle Hydrodynamics
- 15.5 million particles
  - particle splitting
- Barytropic equation of state
- Sink particles for star formation
- Heating from sinks
- Self gravity
- Decaying turbulence
- No magnetic fields



Smith et. al. 2010, Bonnel et. al. 2010

Method

• Cores and embedded filaments from simulations shown in Smith et. al. 2009, Bonnell et. al. 2011

• Three collapsing cores embedded within filaments.

• Use 3D radiative transfer code RADMC-3D with LVG approximation for line transfer. Apply to three tracers.

Tacer	Line	Critical density $[\mathrm{cm}^{-3}]$	Optically	Abundance $[\mathrm{n}/\mathrm{n}_{H_2}]$
N_2H^+	1-0	1.4×10^5	thin	10^{-10}
CS	2-1	3.2×10^5	thick	$4 \times 10^{-9} e^{-n(r)/n_d}$
HCN	1-0	2.6×10^6	thick	3×10^{-9}

Smith et. al. 2012

Cores embedded in filaments

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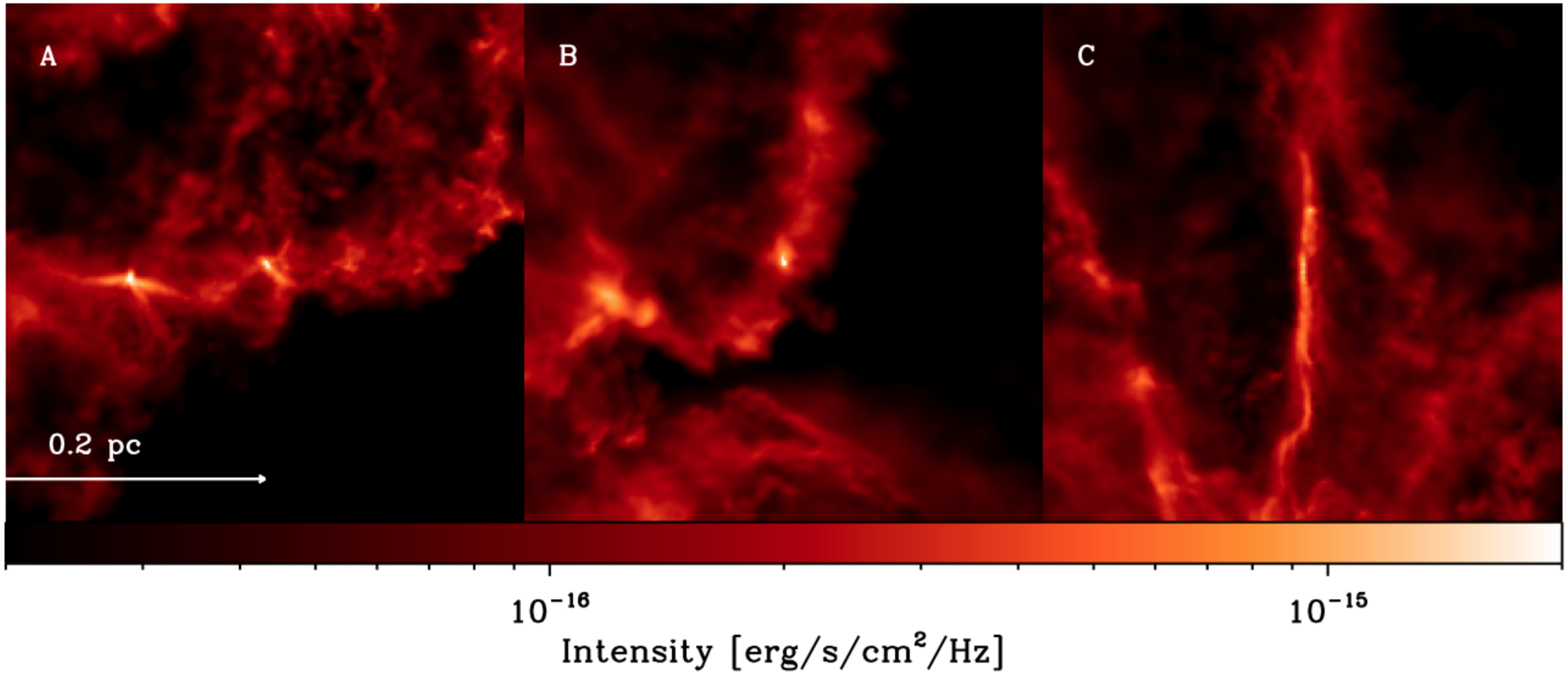
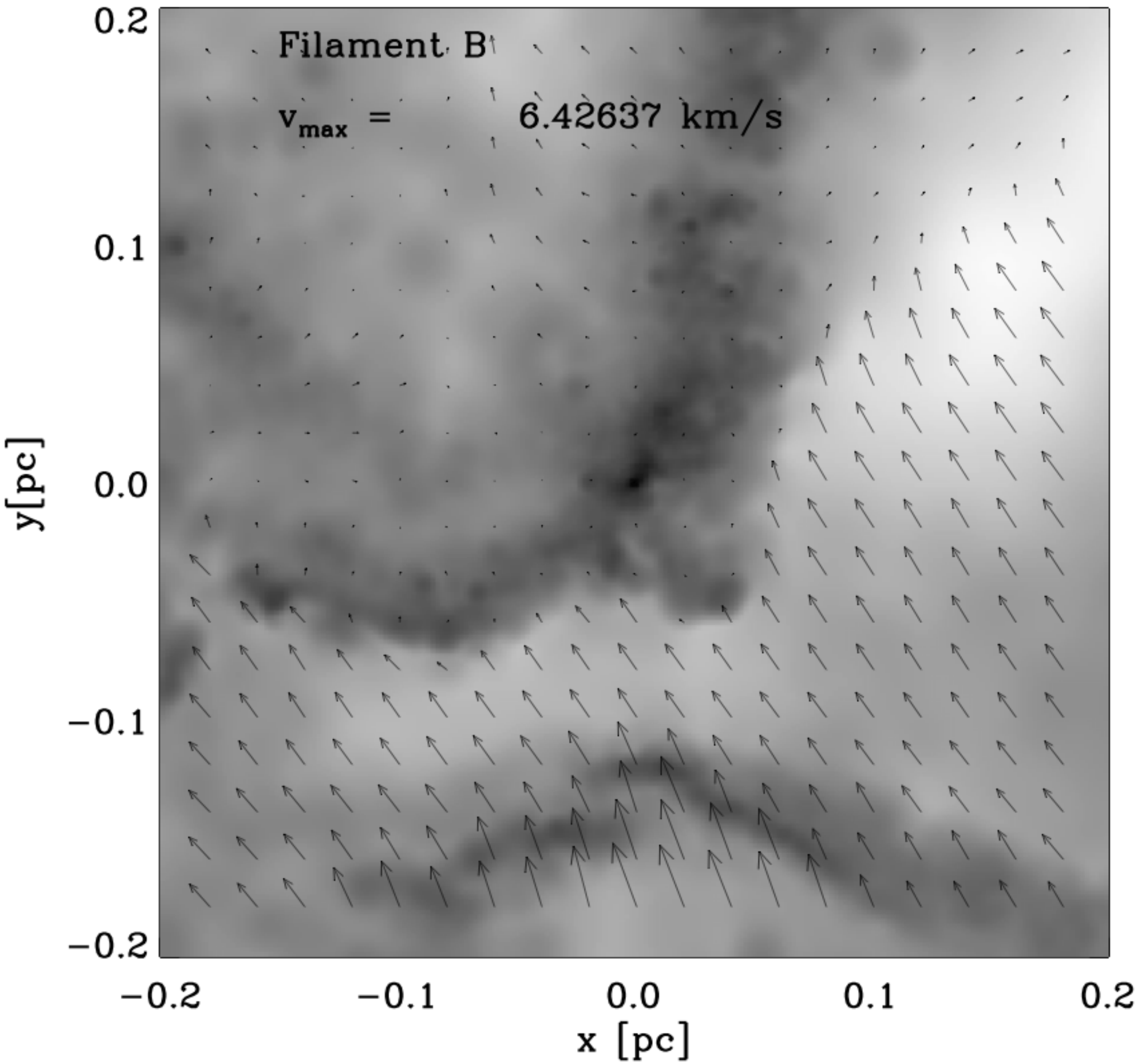
The Emission

Dust emission 850 μm.



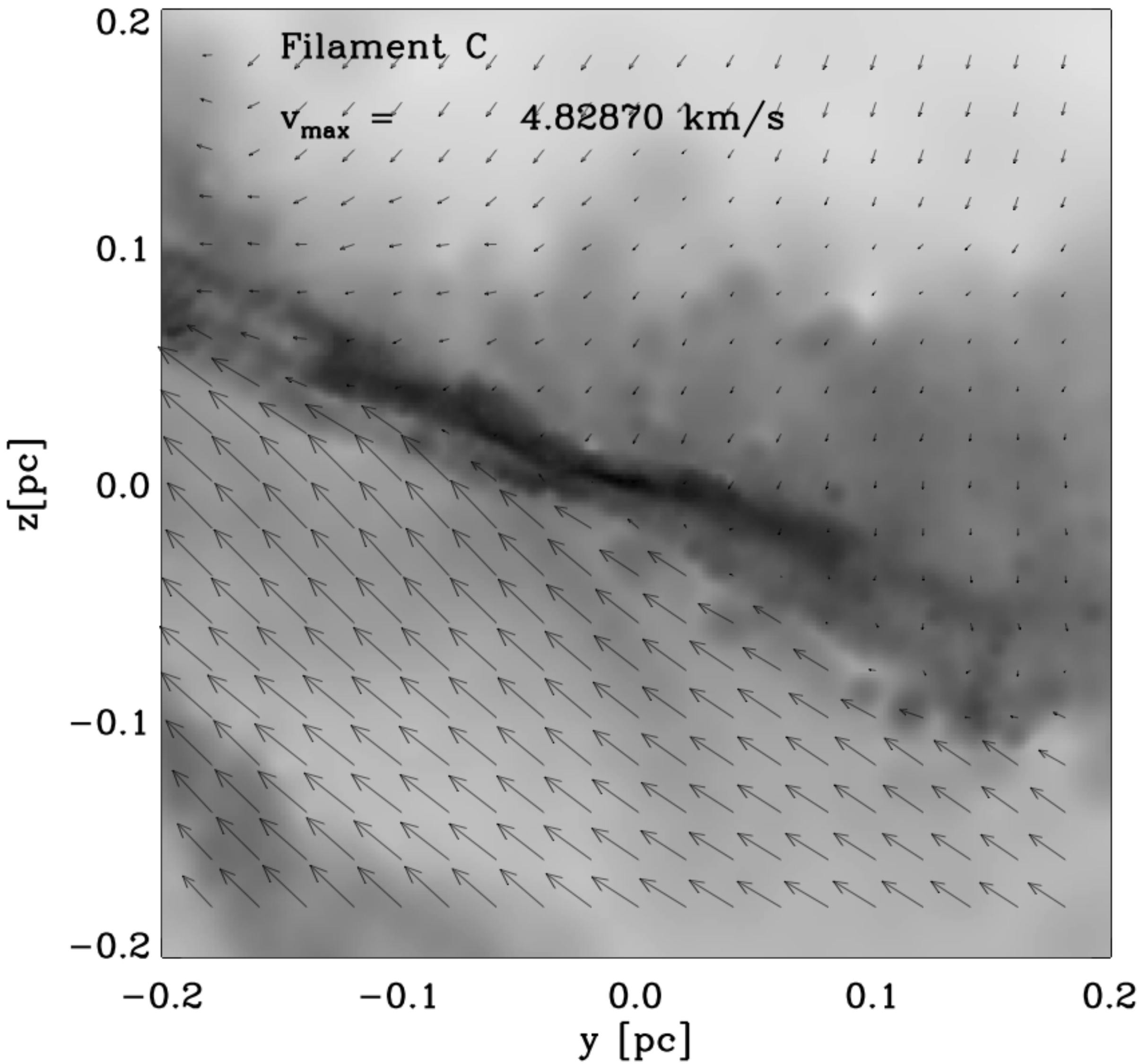
Velocities



Filaments formed through large scale **bulk flows and shocks and gravity**.

This drives **turbulence** within the filament.

Velocities



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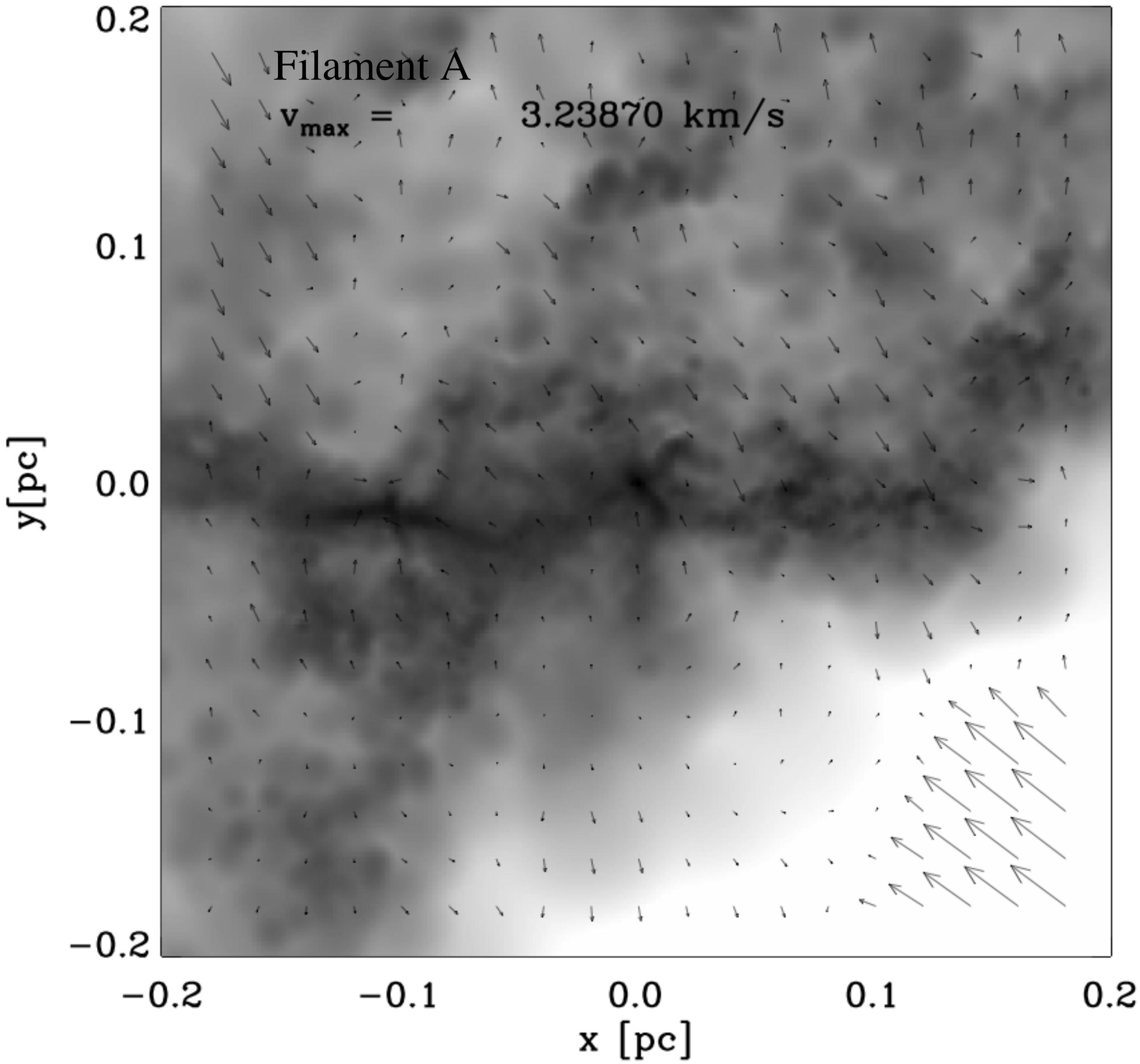
Velocities



Filament is a **turbulent sheet**.

There are **multiple sites of collapse** within the filament.

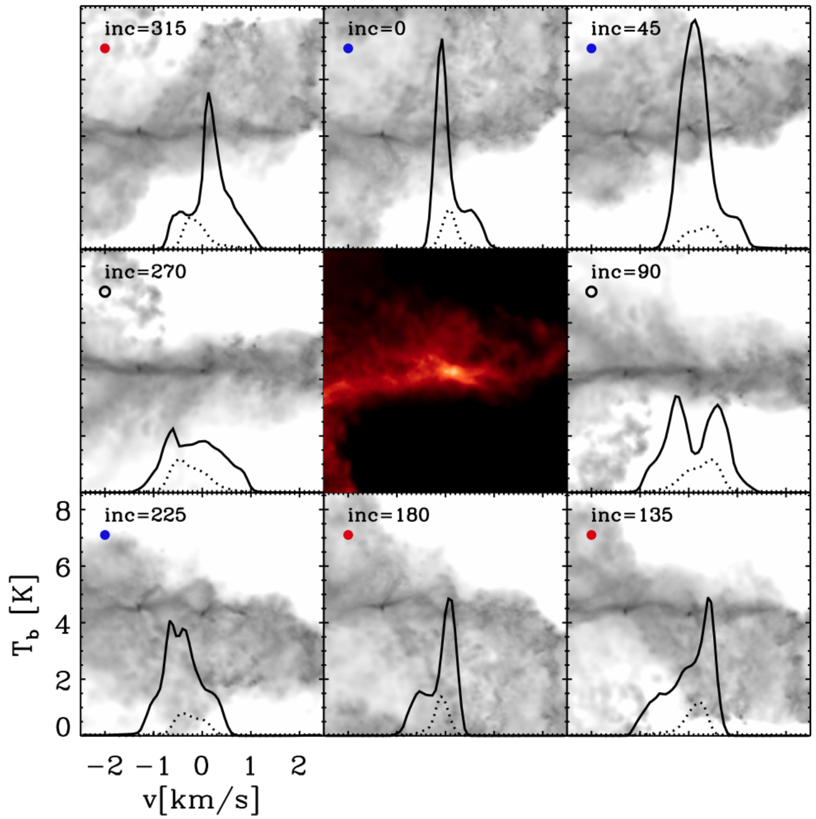
The filament velocities show **no universal systematic motion**.

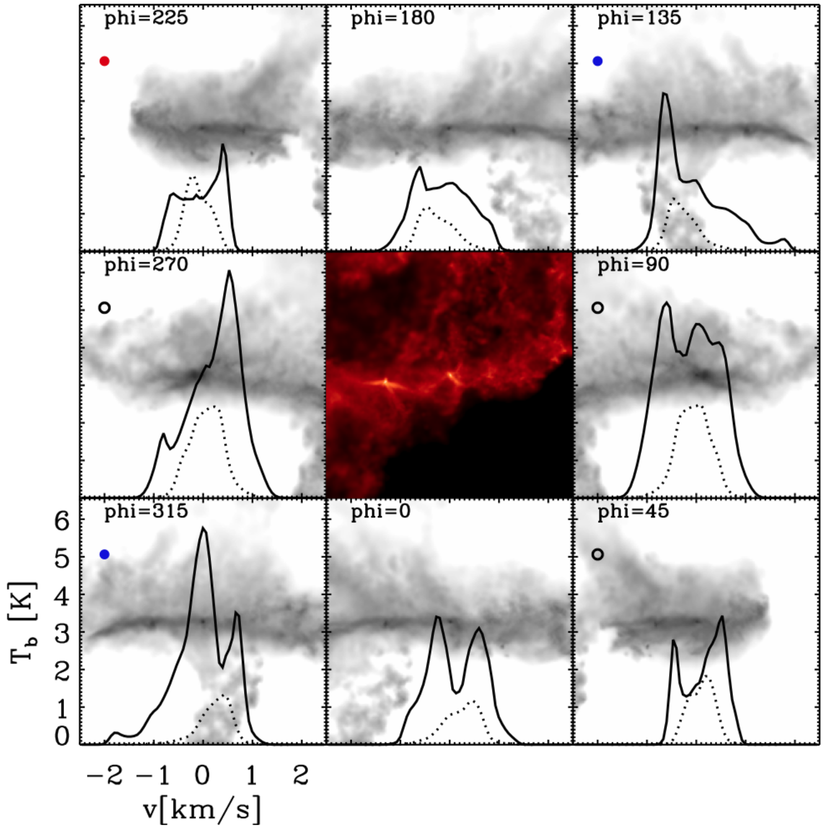
but see Hacar & Tafalla 2011

HCN line profiles

Line profiles are highly dependent on **viewing angle**.

Profiles, contain **blue, red** and **ambiguous** asymmetries.

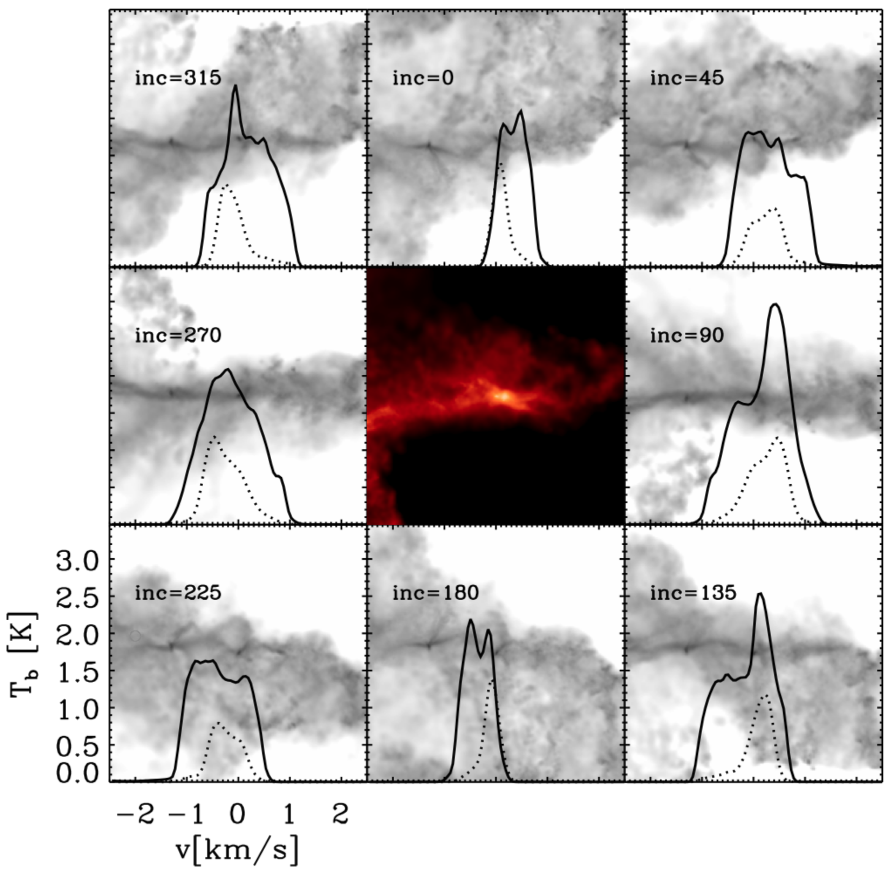


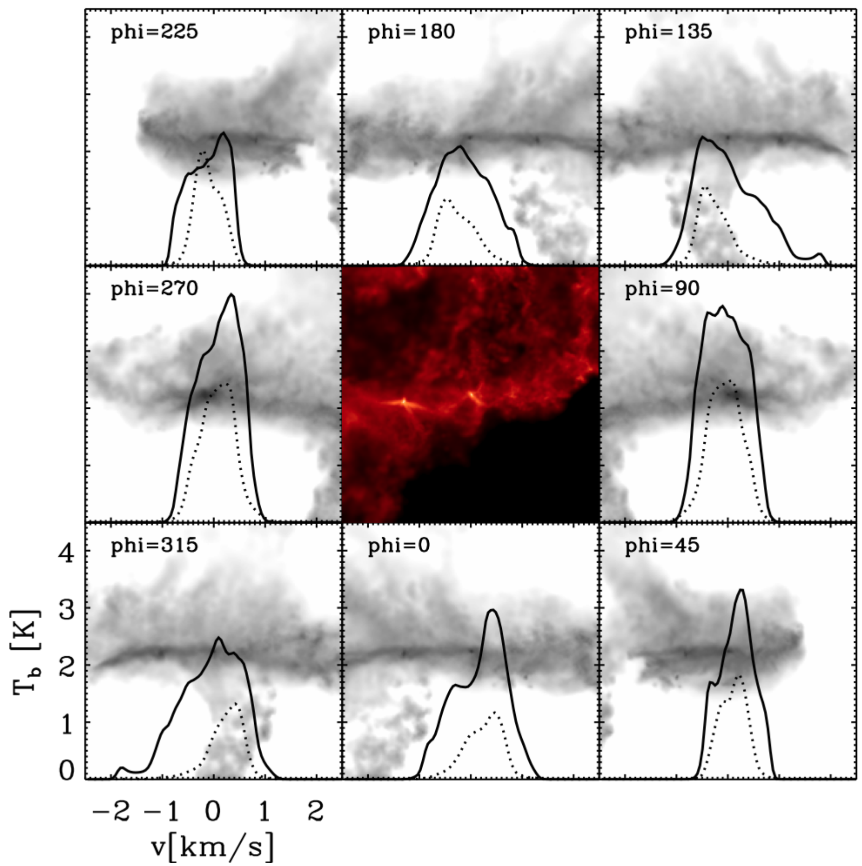


see also Mardones & Myers 97, Gregersen et. al. 97, Lee et. al. 99, Wu et. al. 03 & more

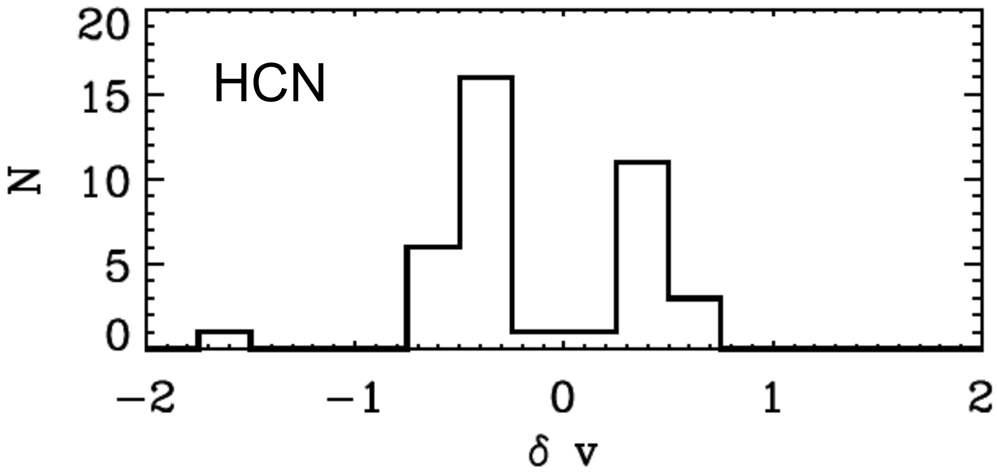
CS line profiles

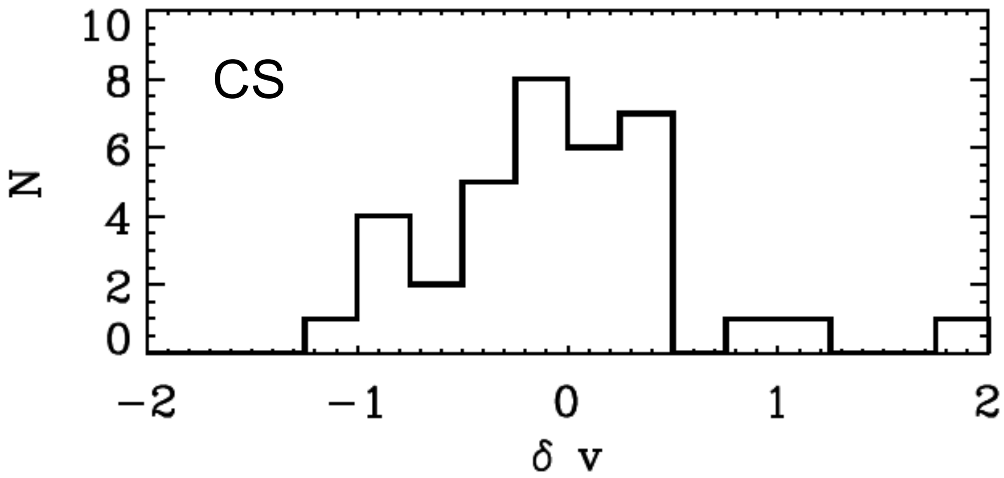
CS line profiles are particularly hard to interpret.





Normalised velocity difference





$$\delta V = (V_{\rm thick} - V_{\rm thin})/\Delta V_{\rm thin}$$

An alternative way of searching for infall is to calculate the **normalised velocity difference**.

Both our samples are **skewed** towards the blue side.

Filaments Hiding Collapse

For the three filaments considered, a blue asymmetric profile indicating the collapse of the central core was observed in **less than 50% of cases**.

By Shape:

HCN	36% blue	17% red

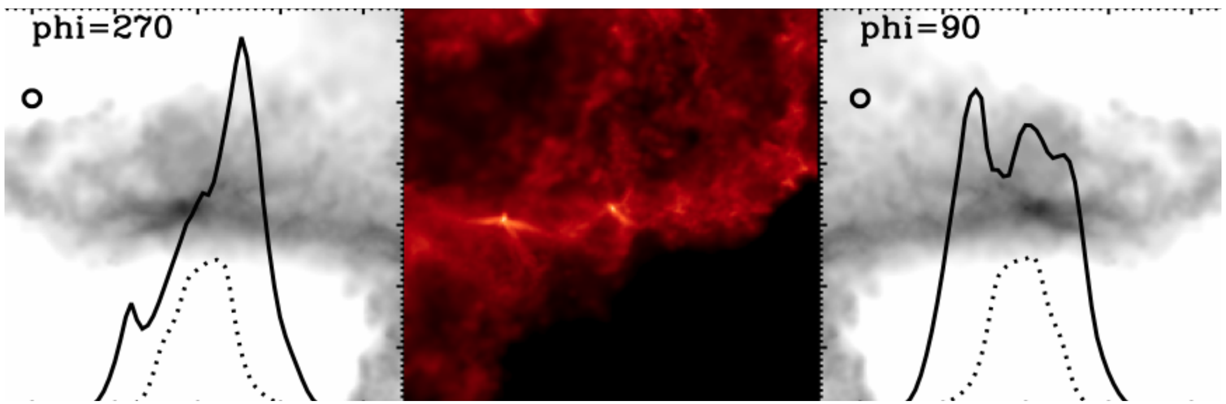
By dV:

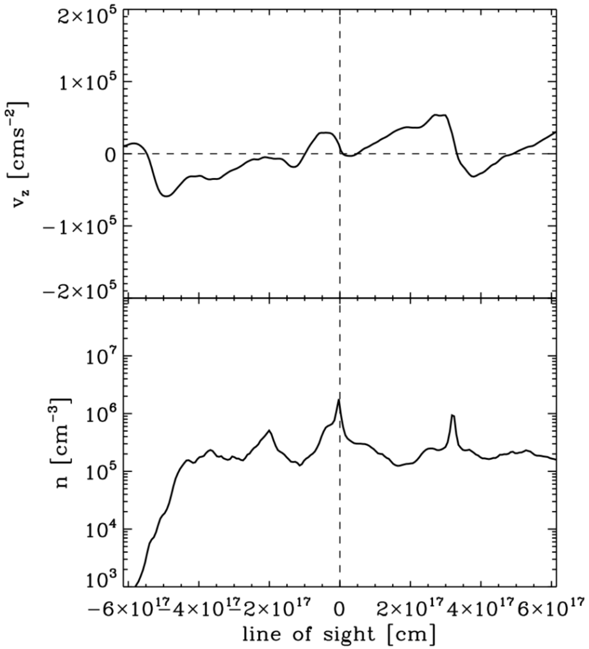
HCN	48% blue	17% red
CS	38% blue	33% red

Filaments can obscure the velocities of their embedded cores.

Interference from turbulence

If a large component of the filament is included in the line of sight, the optically thick emission is **no longer coming from the embedded core**.

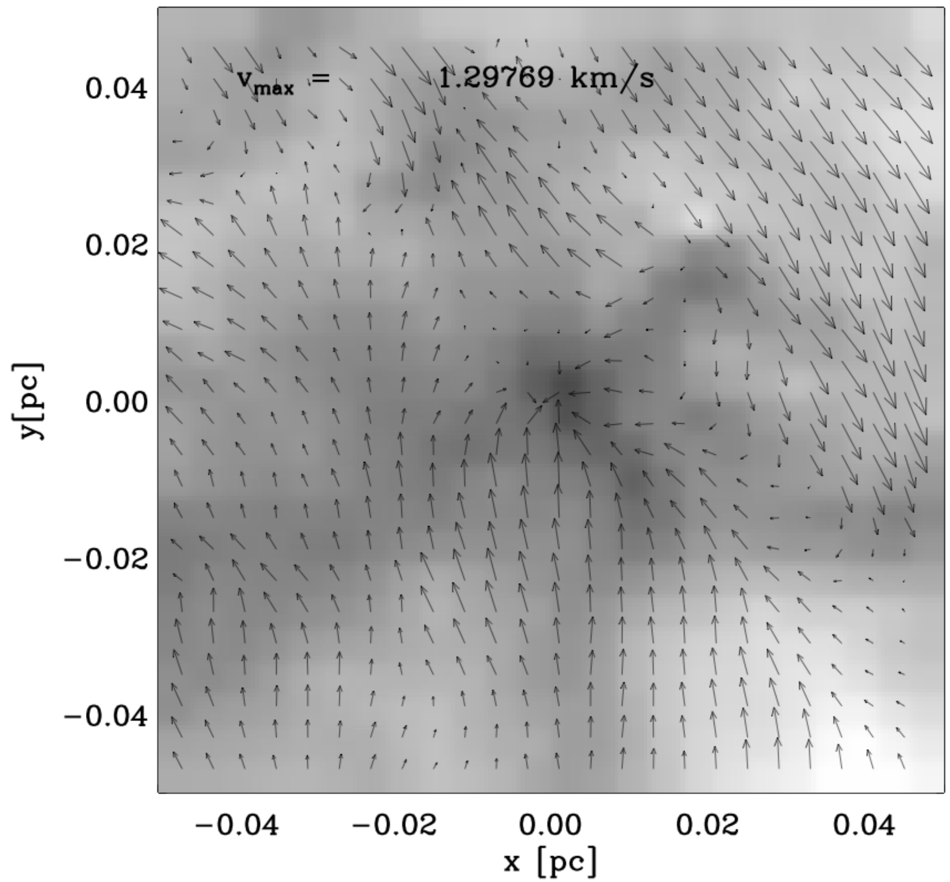


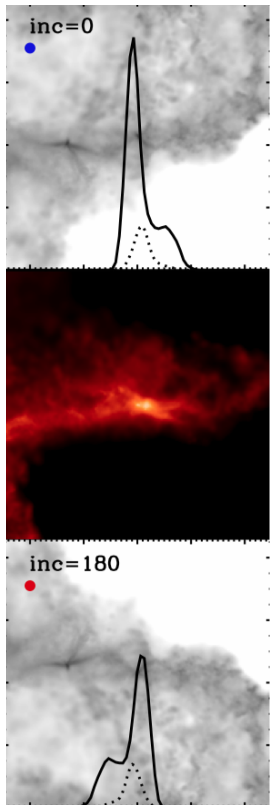


Velocities at core

Flow of gass on to the core is not purely radial. It **twists and curves** onto the core.

There is **not always** a substantial mass flow from all directions.





A red profile from a collapsing core!

Comparison to Observations

Survey	Species	No. Cores	Blue	Red
Gregersen et al. (1997)	HCO^+	23	39%	13%
Gregersen & Evans (2000)	HCO^+	17	35%	0%
Lee et al. (1999)	CS	69	29%	4%
Mardones et al. (1997)	H_2CO,CS	47	32%	*
André et al. (2007)	CS, HCO^+	25	24-64%	*
Sohn et al. (2007)	HCN	64	43%	22%
This Work				
By shape	HCN	42	36%	17%
By δV	HCN	42	48%	31%
By δV	CS	42	38%	33%

Dense tracer line widths

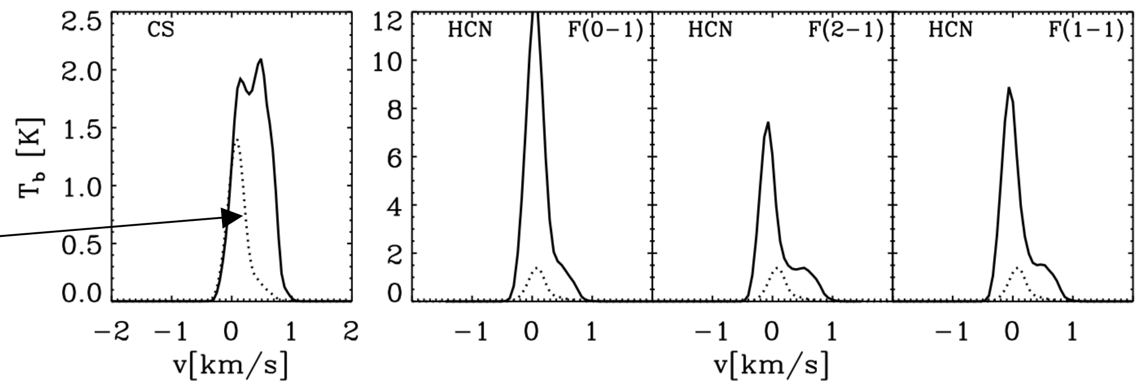
N_2H^+ lines widths are **sonic**.

(see Pineda et. al. 2011)

Line widths of the three filaments studied averaged over viewing angle.

Mean $\sigma(v)=0.28\ kms^{-1}$	Mean $\sigma(v)=0.20\ kms^{-1}$	Mean $\sigma(v)=0.20\ kms^{-1}$
Max $\sigma(v)=0.36$	Max $\sigma(v)=0.21$	Max $\sigma(v)=0.30$
Min $\sigma(v)=0.15$	Min $\sigma(v)=0.16$	Min $\sigma(v)=0.14$

N^2H^+ is coherent, but envelope tracers are not.



Line Brightness

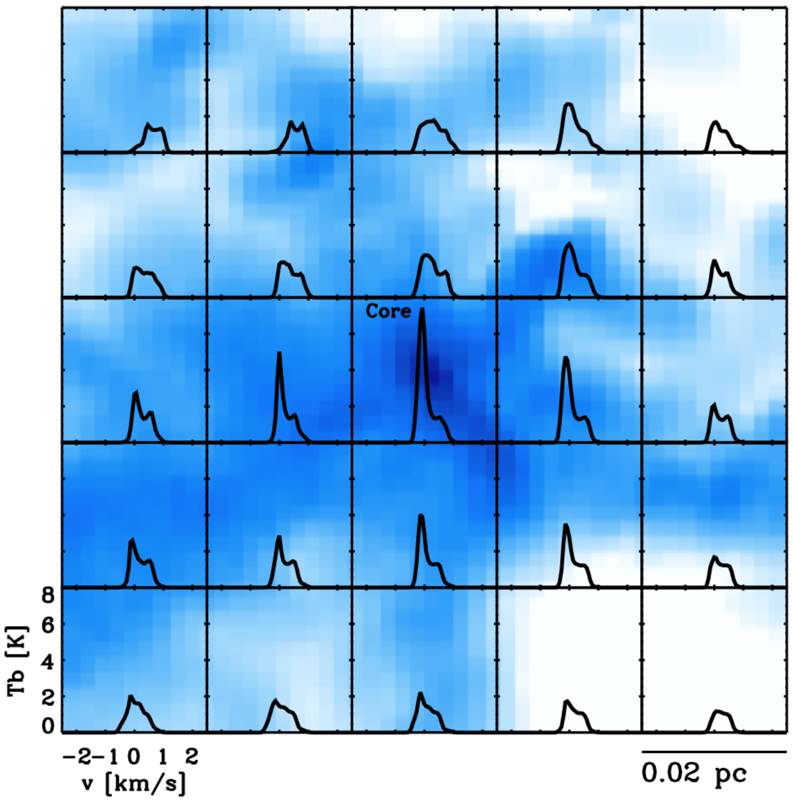
Filament	Species	Blue	Red	Ambiguous
A	HCN	5.92 ± 1.84	4.54 ± 1.16	4.07 ± 1.53
A	N_2H^+	1.14 ± 0.32	1.42 ± 0.41	1.82 ± 0.64
B	HCN	4.22 ± 1.07	2.32 ± 0.51	2.48 ± 1.07
B	N_2H^+	1.09 ± 0.22	1.14 ± 0.05	1.22 ± 0.20
C	HCN	5.51 ± 0.89	2.85	3.44 ± 1.63
C	N_2H^+	1.20 ± 0.36	1.94	1.25 ± 0.40

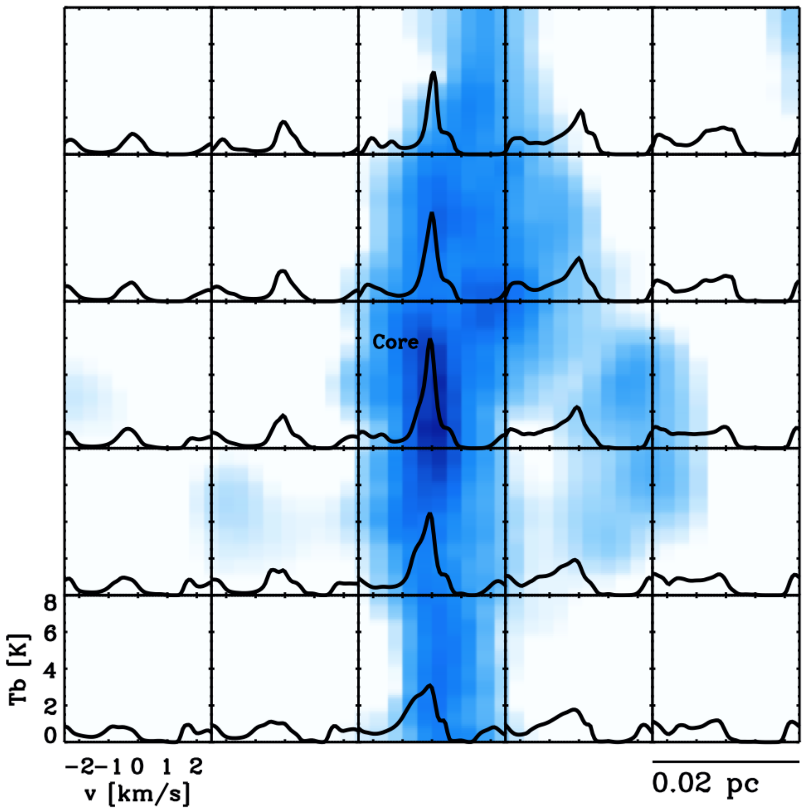
Optically thick emission from the core is systematically **brighter** when a blue asymmetry is observed.

This trend is not present in the optically thin species.

Use as an **indicator** of where the **filament is obscuring core velocities**.

Filament environment





Massive-star forming regions

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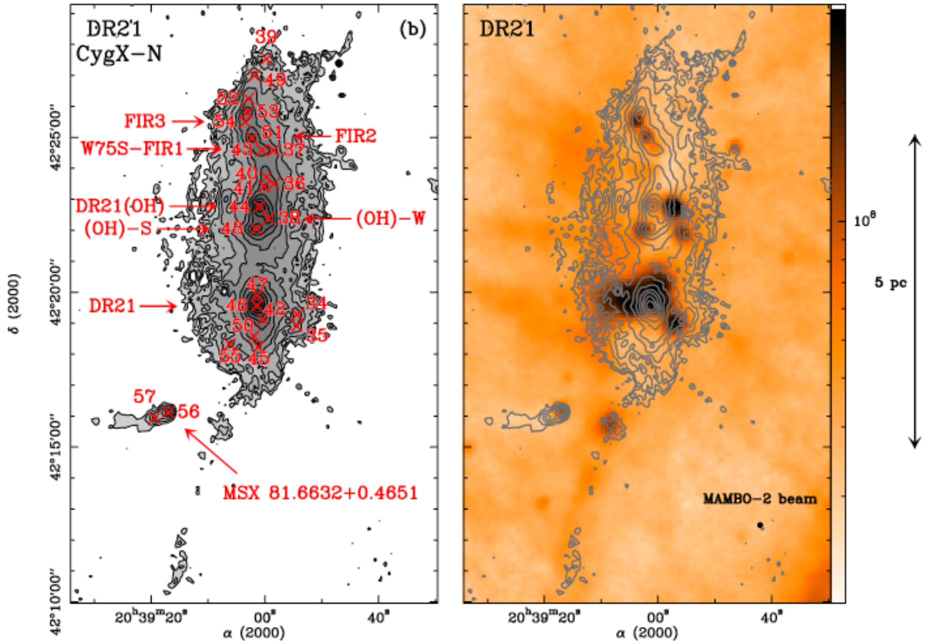
Massive Star Observations



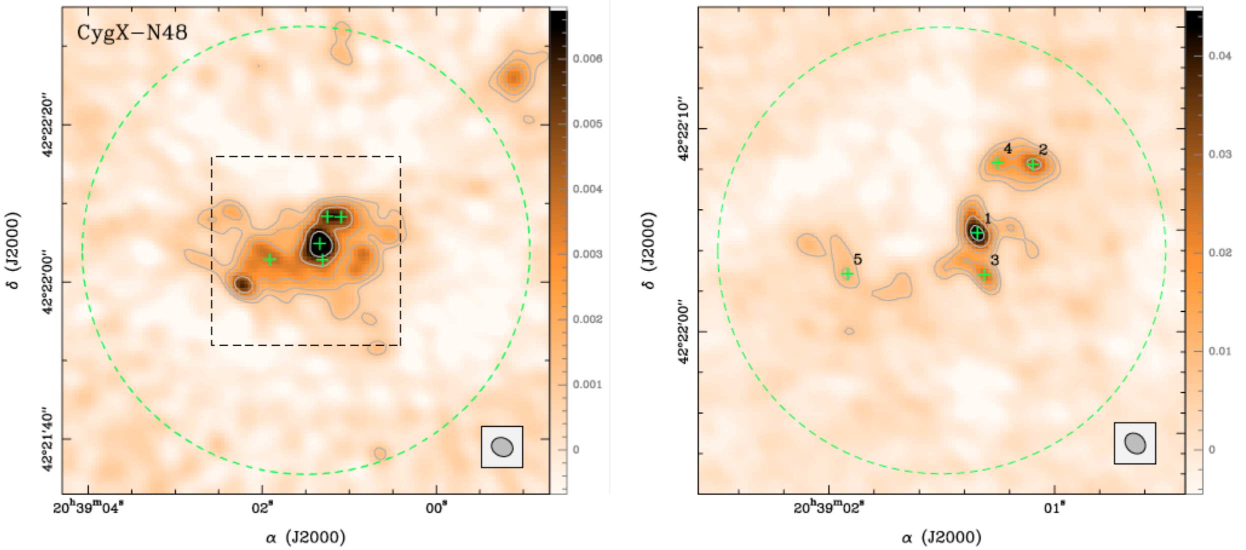
Massive stars usually form at the centre of dense star forming clumps.

Pre-stellar massive cores either extremely short lived or don't exist

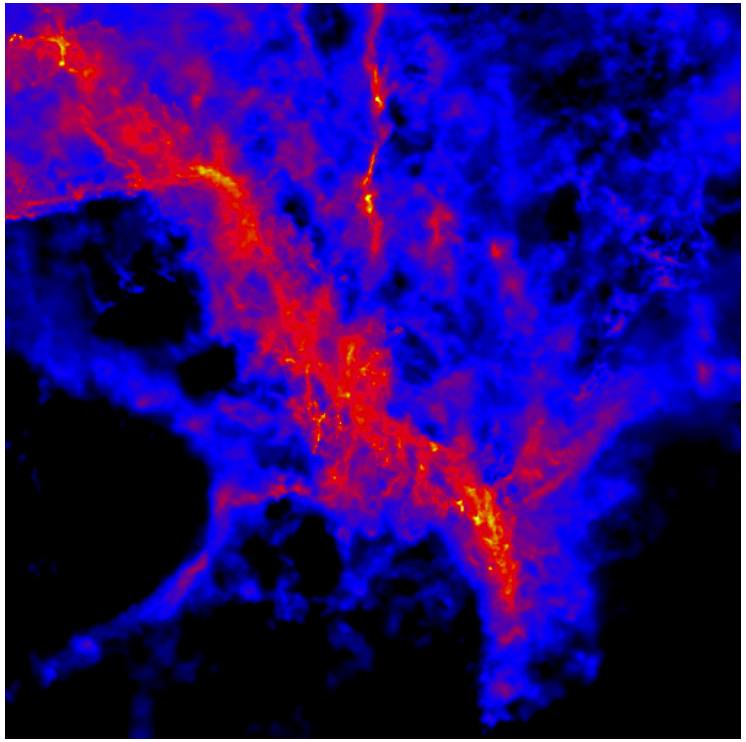
Motte et. al. 2007

Interferometry observations of such regions usually reveal substructure.

Bontemps et. al. 2010



Time Evolution



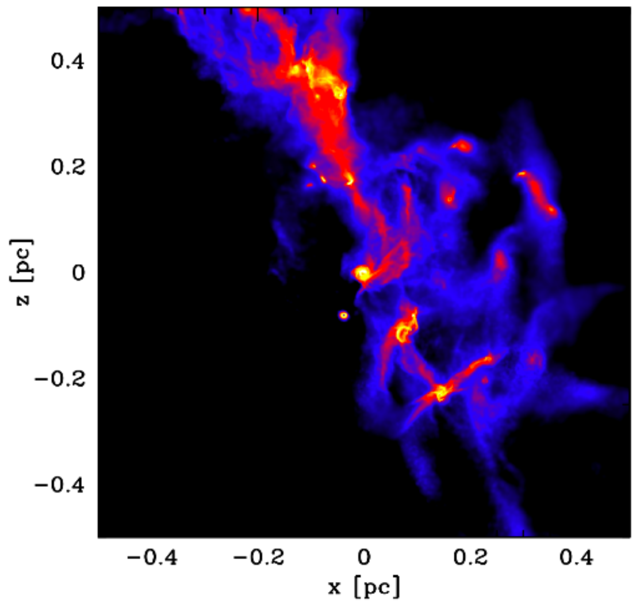
column density

blue: 0.05 gcm^{-2} yellow: 5 gcm^{-2}

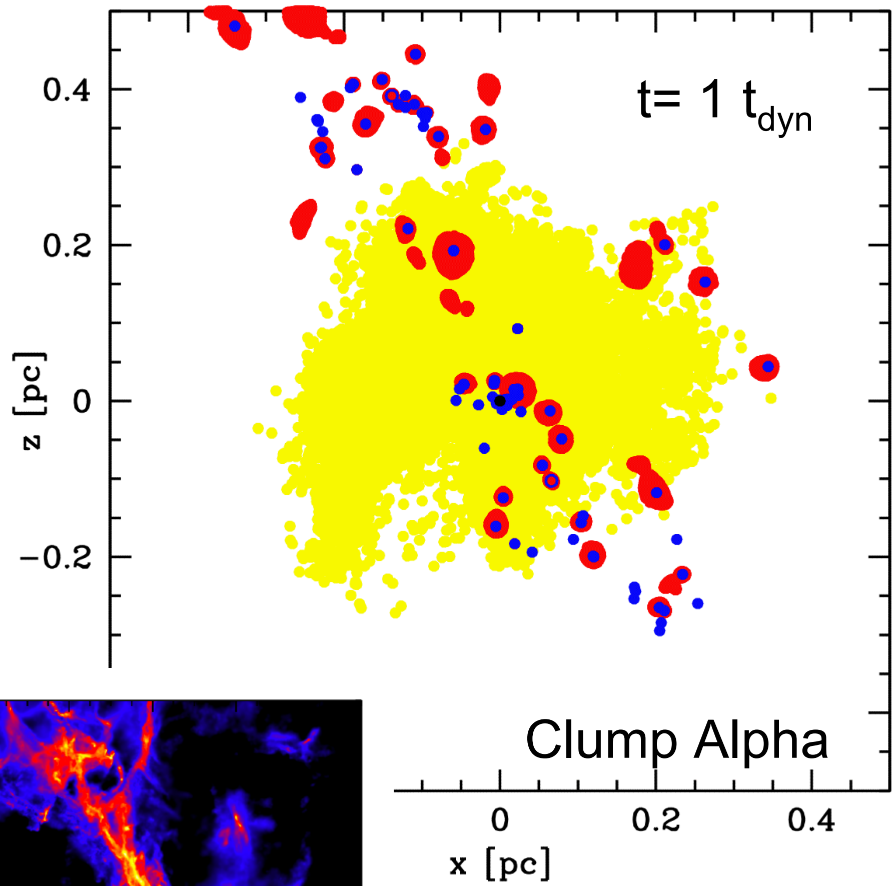
Filament collapsing along its axis

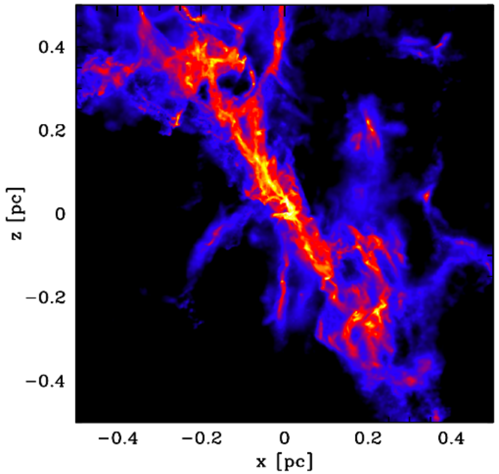
- evolves to a more compact state with less sub-structure

2.4 x 10^5 yrs



Fate





Smith et. al. 2009b

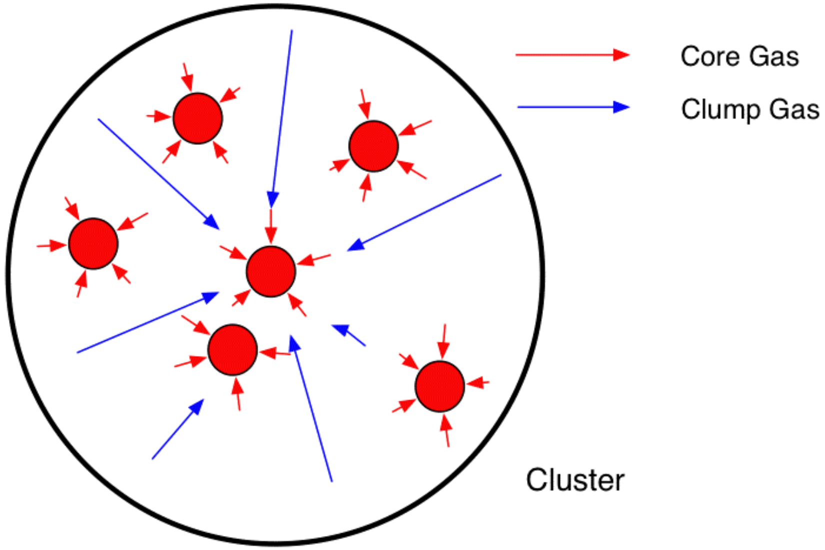
Red = p-cores

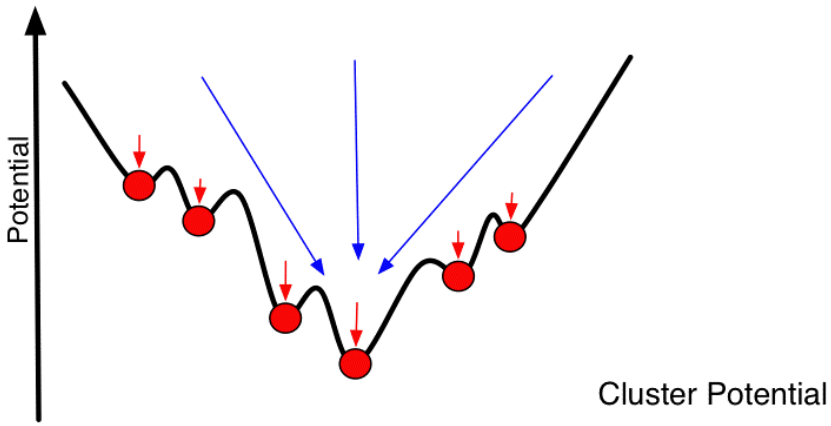
Solid blue = sinks

Hollow blue= pre-stellar

Yellow = mass which will be accreted by the most massive sink within 0.25 t_{dyn}

A simple picture





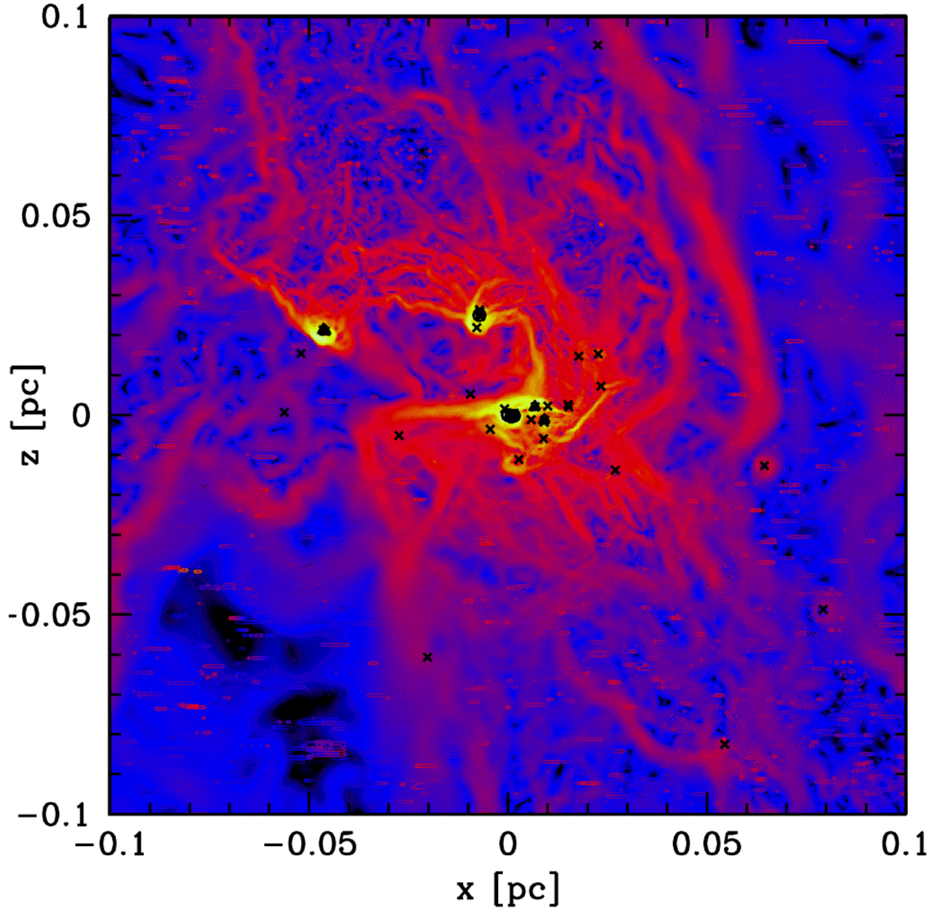
Two regimes of collapse:

- **local** collapse forms low mass stars

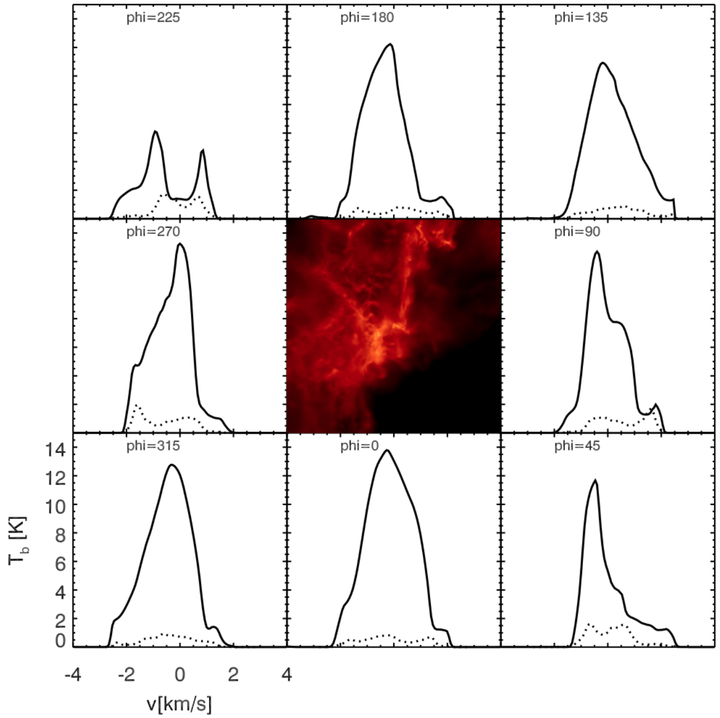
- **global** collapse turns low mass cores into massive stars

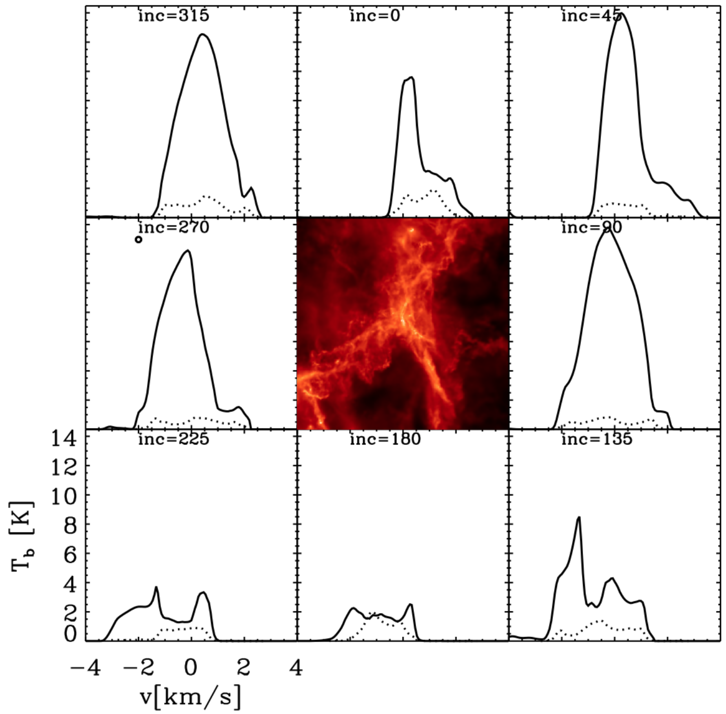
This is a **universal** process, it will work in all dense collapsing clumps with pre-existing substructure *(e.g. Clark et. al. 2009)*

Potential Gradient



Sight-lines

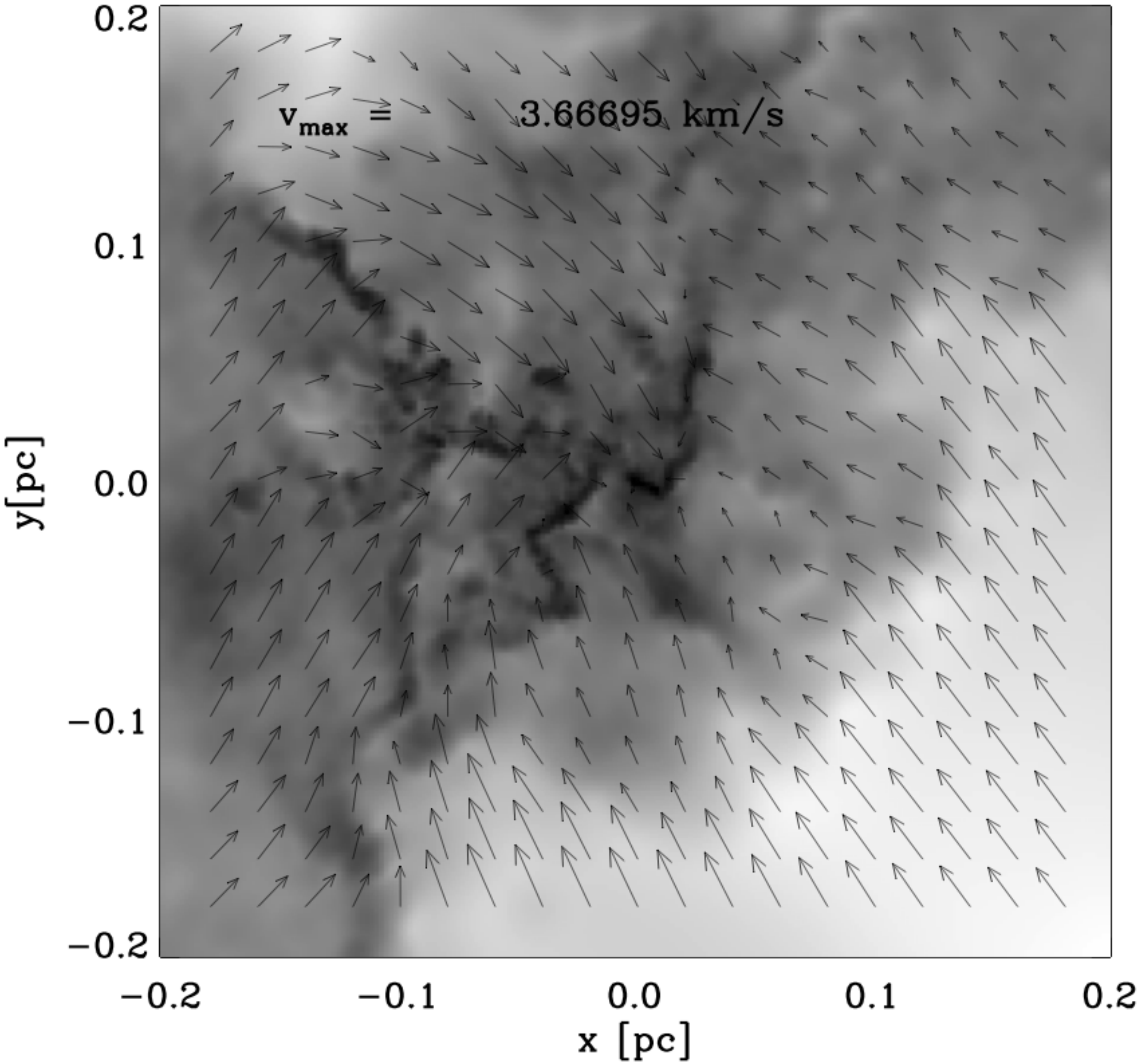




Less variation in the line profile than low mass cases.

Optically thick line profiles often show a characteristic **broad peak with a small red shouder**.

Velocity Map



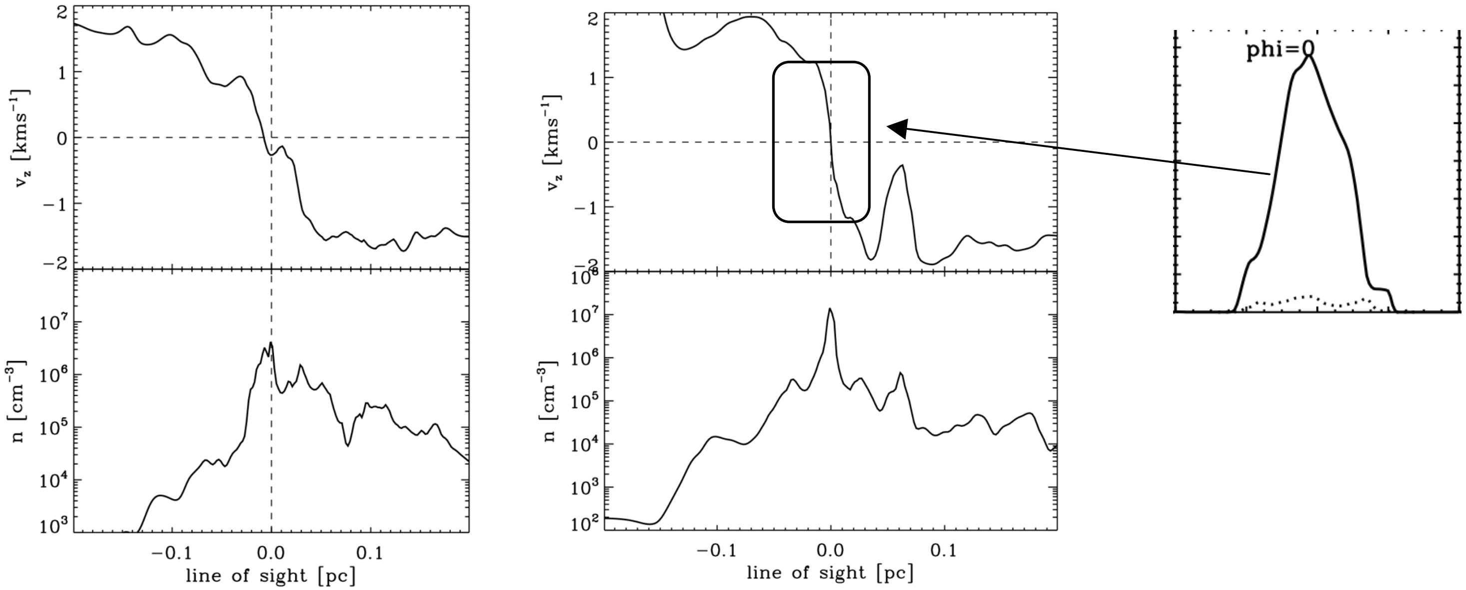
A **larger scale** collapse than in the filament.

Once again flow is **not** purely radial.

Multiple filamets form a hub.

(see Myers 2011, Smith et. al. 2010)

Line of sight

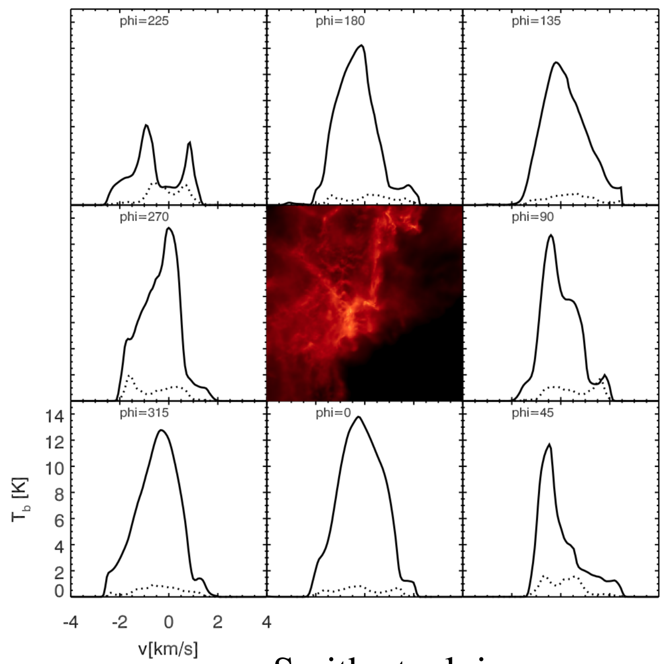


Superposition of large scale collapse motion, with smaller scale local core collapse within the massive star forming region.

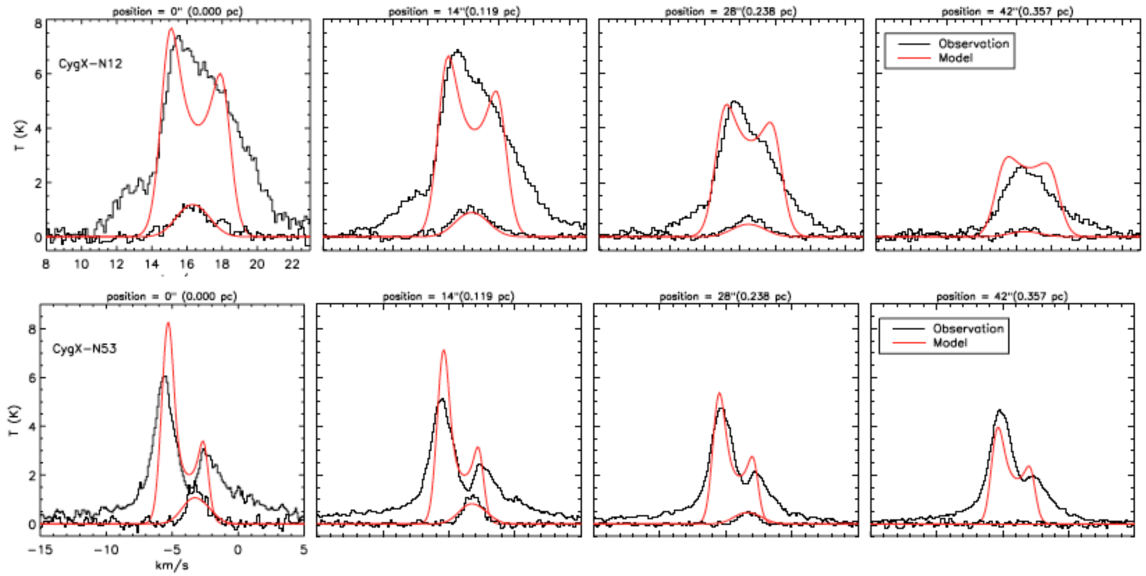
Supersonic infall as proposed by Motte et. al. 2007 from observations of Cygnus X. See also Schneider et. al. 2010

Linewidths due to **collapse** not supportive turbulence or rotation.

Observations



Smith et. al. in prep



Csengeri et. al. 2011

Red fit from their model.

Conclusions

5

Conclusions

Filaments

1. The filaments in our simulations are turbulent and disordered.
2. The line widths of the high density tracer are roughly sonic.
3. Optically thick line profiles are highly variable with viewing angle.
4. In more than 50% of cases filaments hide the collapse of their embedded cores.
5. A red asymmetric profile can be observed from a collapsing core.

Massive star formation *(in preparatation)*

1. The massive star forming region has a large velocity gradient due to large scale (>0.4 pc) supersonic collapse motions.
2. A massive star is formed at centre of the cluster potential where filaments intersect to form a hub.
3. The linewidth is broad and due to collapse.

Outlook

There is still lots of work to do....

• A study of which line transitions are the most reliable in different regimes.

• Detailed kinematic comparison of the velocities in the filaments.

• A fuller study of the massive star forming regions, looking at how the line profiles evolve over time.

Aim: To find the physically most informative observable variables.

If you have suggestions or data you would like to compare, please let me know.