The Pipe Nebula

A turbulent strongly magnetized young molecular cloud

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IPAG

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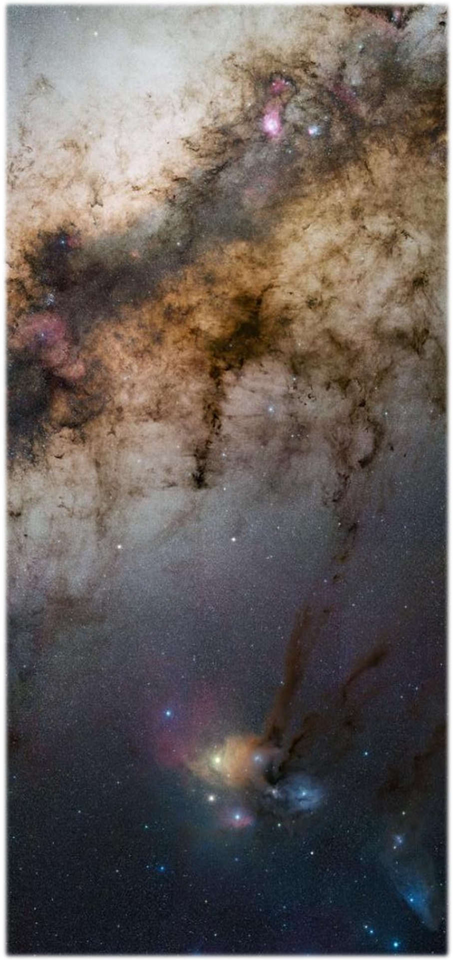
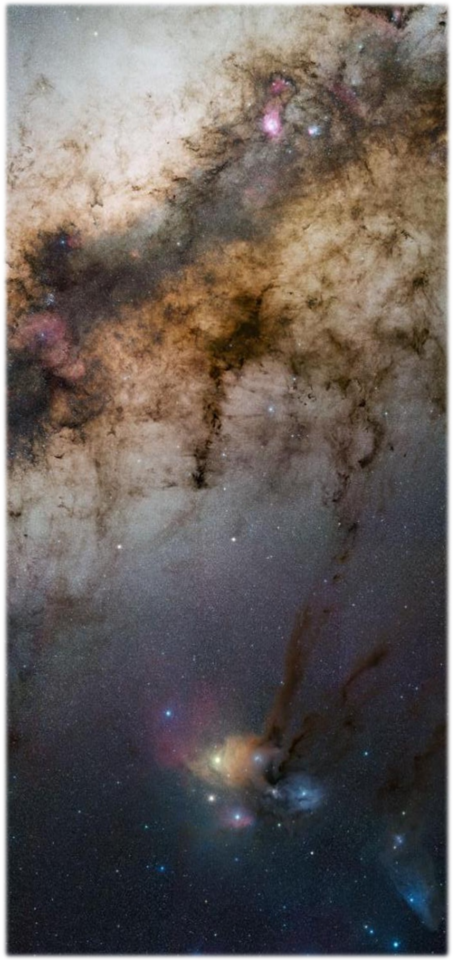


Outline of the talk

1. Presentation of the Pipe Nebula region
2. Objectives and presentation of the observations
3. The gas dynamic and filamentary structures characterization
4. Magnetic field intensity estimation
5. A study of the dense cores



Filamentary clouds which do not form stars everywhere

- In the Ophiucus region, $\sim 4°$ latitude,
  - 145 $\pm$ 16 pc (*Alves+07, Hipparcos)*
  - 163 $\pm$ 5 pc *(Dzib+18, Gaia DR2)*
- Filamentary shape, length $\sim$ 15-20pc
- Well studied cloud: multiple observations of gas, dust, and magnetic fields
- The Pipe is separated in 3 regions *(Alves+08)*
  - B59 : Forming stars
  - Stem : Tenuous filaments, few dense cores
  - Bowl : Tenuous or dense filaments, young dense cores
- What makes **star formation** efficiency so **different** across the Pipe ?
- Similarities with the Polaris molecular cloud
  - No star formation, a handful of dense cores *(Wagle+15)*; network of tenuous or dense filaments
  - BUT less ordered magnetic fields
- **Interplay between gas dynamics and magnetic fields**

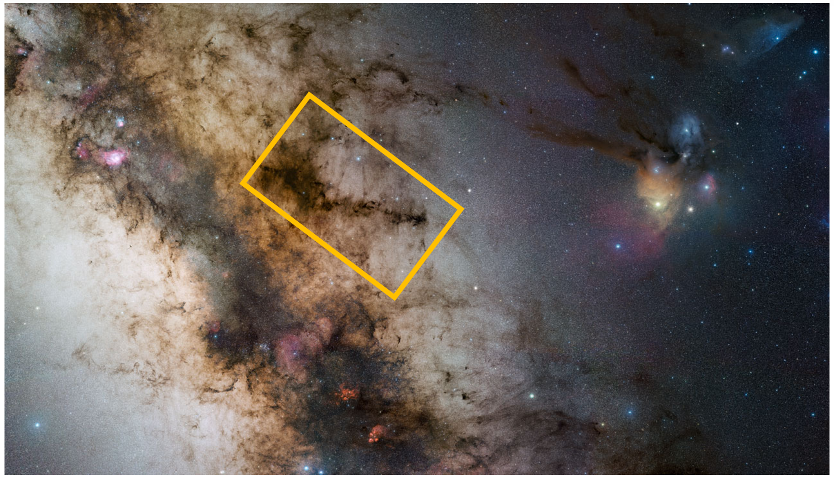
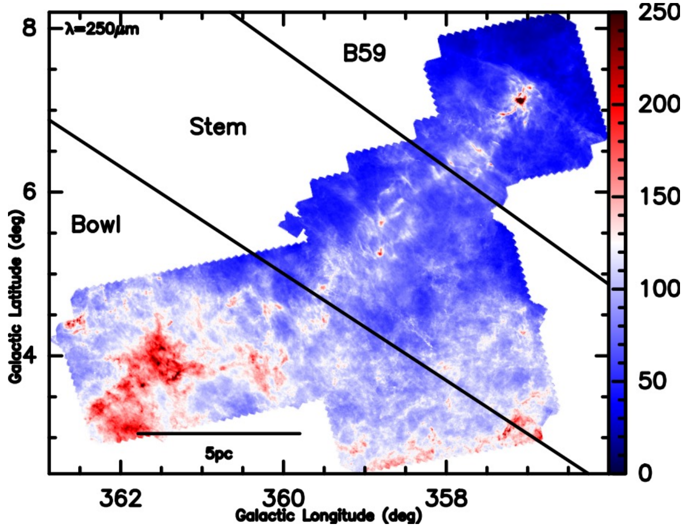


Image B,V,R S. Guisard (ESO)



Herschel-SPIRE view at 250μm

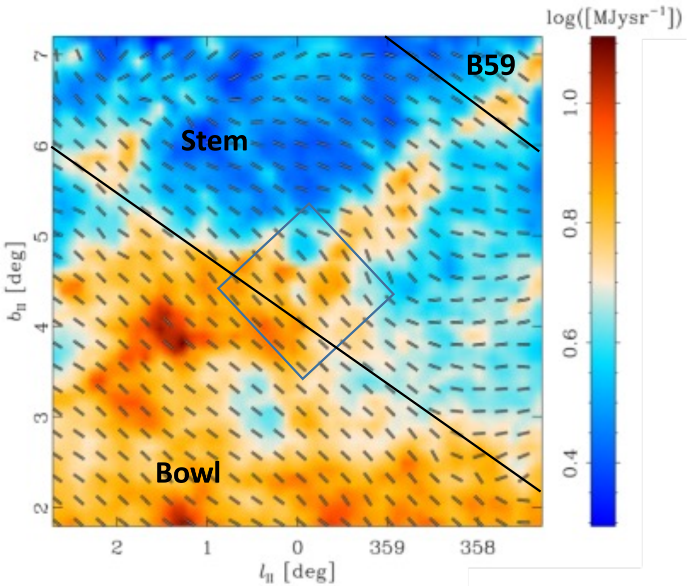
A well ordered magnetic field

- A highly ordered B on parsec scale at the Bowl/Stem limit
  - ➢ $\delta\varphi = 2.54°$
- Davis-Chandrasekhar-Fermi:

$$||B|| \approx 9.3\sqrt{n(H_2)}\frac{\Delta v}{\delta\varphi}$$

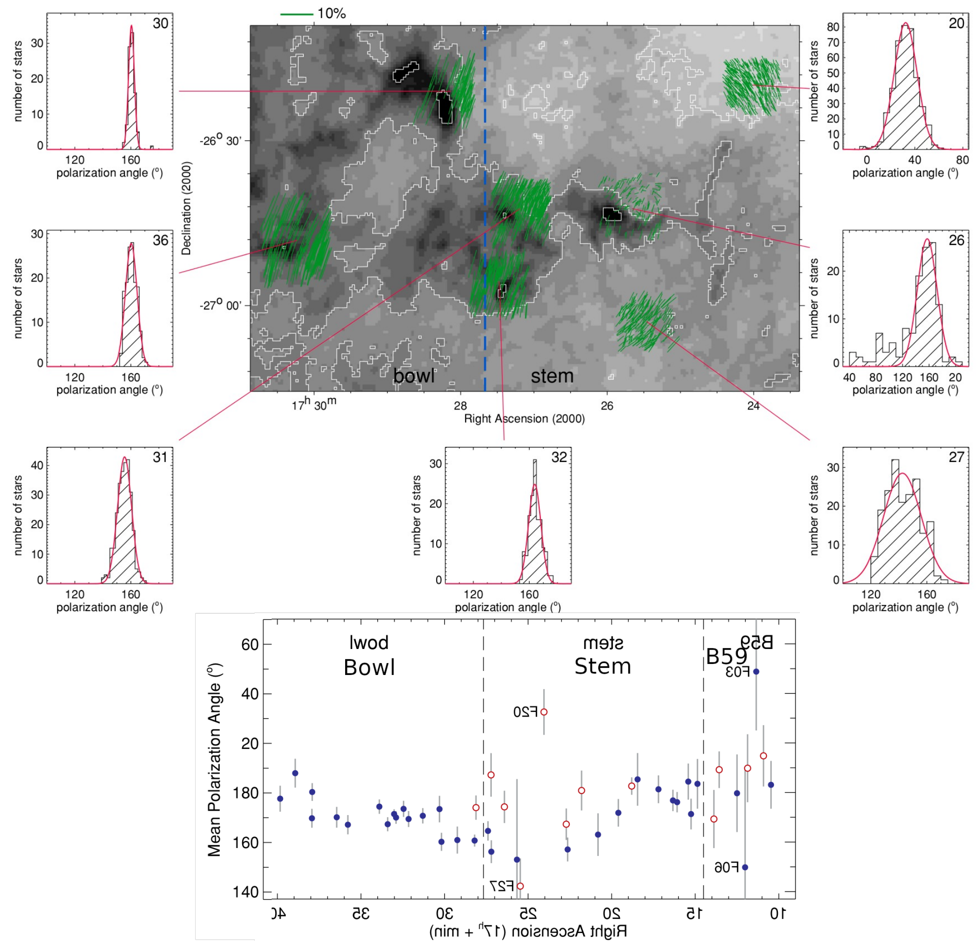
➢ High magnetic field intensity ?

- Alves+08 $\sim 65\mu G$



Polarization angle from Planck+15

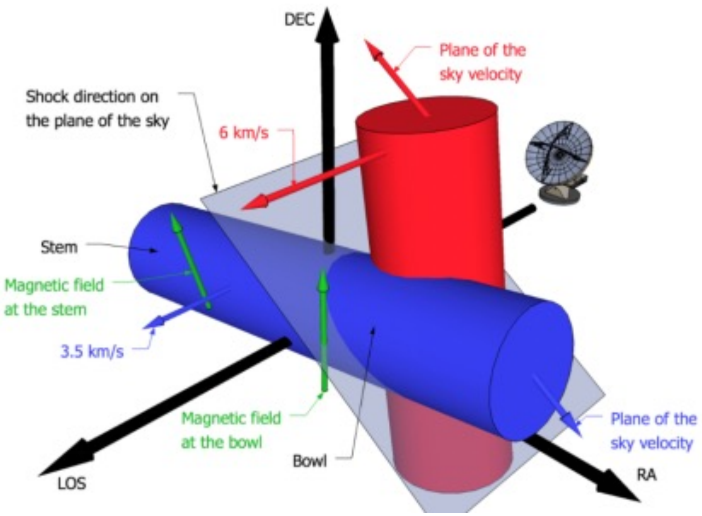
Top: Polarization angle from Franco+10 on a star density map from Lombardi+06
Bottom: Franco+10, Polarization angle across the Pipe



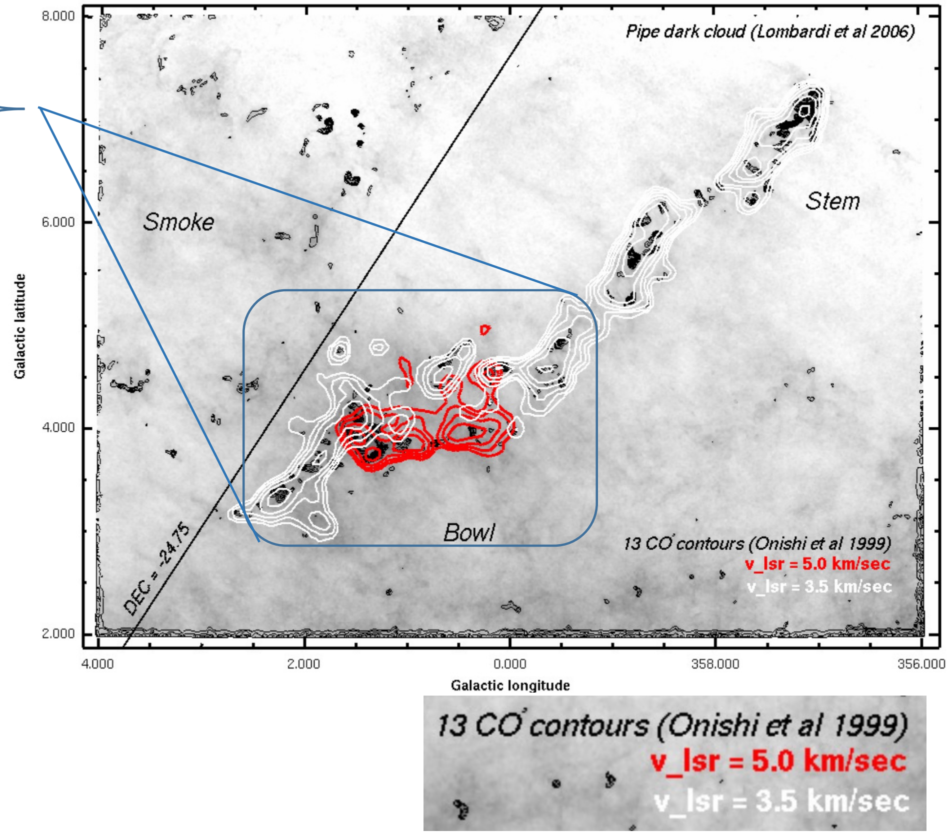
Large-scale structures shocking

- **Superposition** of 2 velocity structures on large scales
- Polaris: two components separated by 3.5 km/s, almost no overlap *(Falgarone+09)*
- Pipe nebula
  - two components separated by **2.5 km/s**, overlapping over a **broad area ~ 5.7pc**
  - Collision of filamentary molecular clouds *(Frau+15)*

Frau+15 Schematic view of the filaments collisions.



Muench+07
Star density map (Lombardi+06)



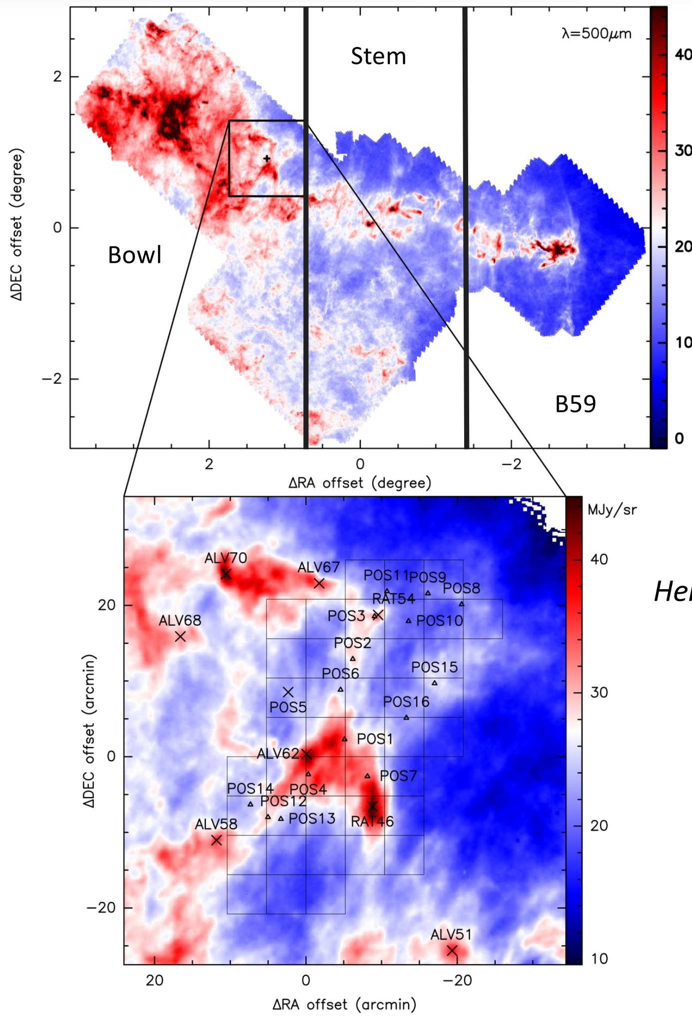
Our observations with the IRAM-30m

- In the region of overlapping velocity components, at the Bowl/Stem limit

- The largest $^{12}CO(1\text{-}0)$ map (~ 17.5deg^2) at this resolution (~ 32'' ~ 5000 au) of the Pipe Nebula
  - ➢ Dynamical analysis
  - ➢ Physical conditions
  - ➢ Tracers of turbulence
  - ➢ Quantitative constraints on the interplay between **B** and kinematics

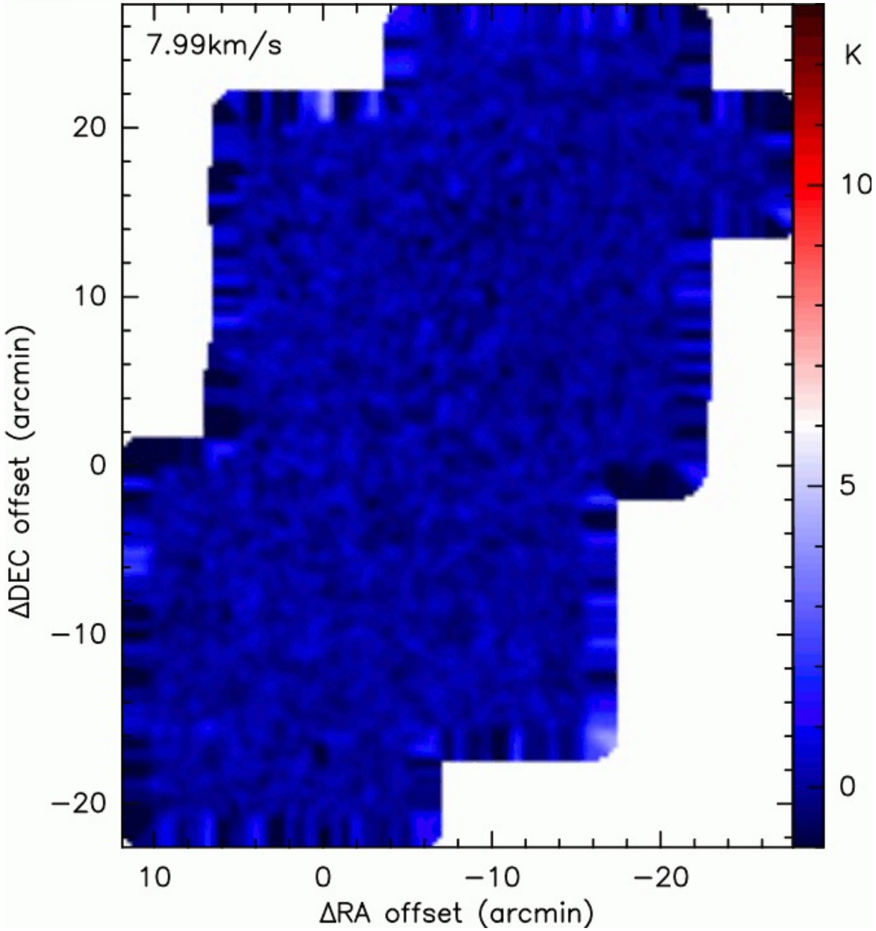
- Multi-line observations of 8 dense cores + 16 others positions ($^{12}CO(1\text{-}0)$, $^{12}CO(2\text{-}1)$, $^{13}CO(1\text{-}0)$, $C^{18}O(1\text{-}0)$,...)
  - ➢ Physical conditions

➢ **Objective: Studying the role of turbulence in filament and dense core formation**



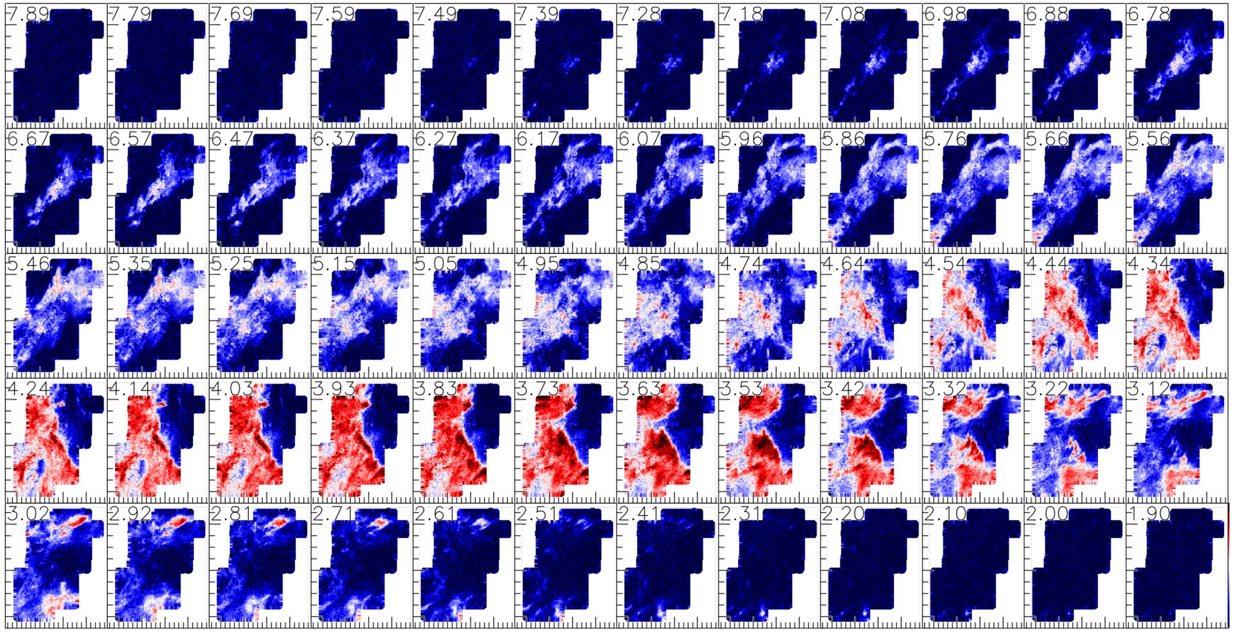
Herschel-SPIRE view at 500μm

A rich $^{12}CO(1\text{-}0)$ dynamic with numerous filamentary structures



Animated map smoothed at 20 mpc

- Large structure at v < 4 km/s and at v > 5km/s !
- Structures dynamically linked together
  - ➢ **Continous emission** between large-scales structures



Velocity tomography. Each plot represents the emission at a given velocity, indicated in the top left part

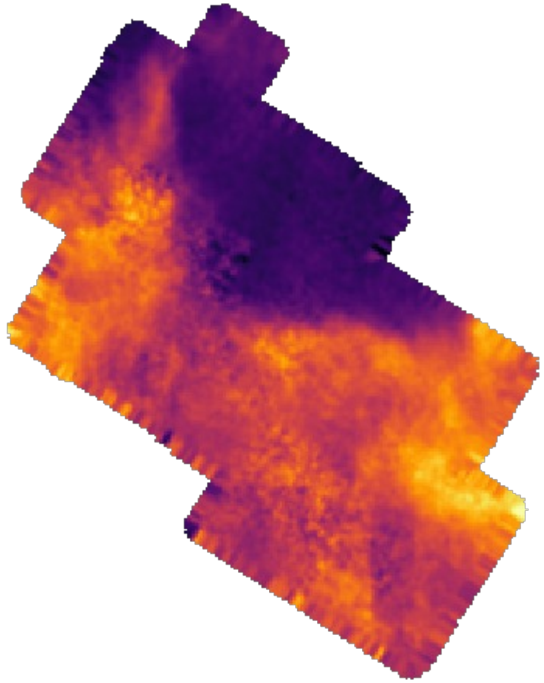
Dynamic of $^{12}CO(1-0)$ emission linked to large scale structure

Spectra averaged on 200x200''

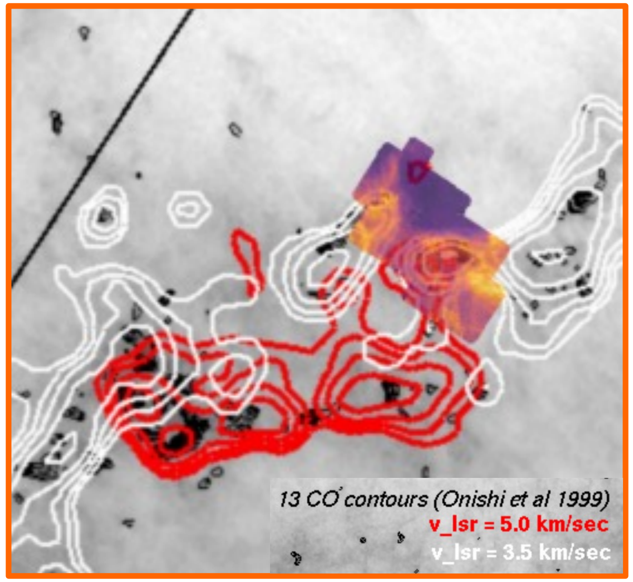
One velocity component at mainly v < 4 km/s

- $^{12}CO(1-0)$ dynamic coherent with large scale structures

Emission integrated at v < 4km/s



Emission integrated at v < 4km/s overlapped on $^{13}CO(1-0)$ contours from Onishi+99

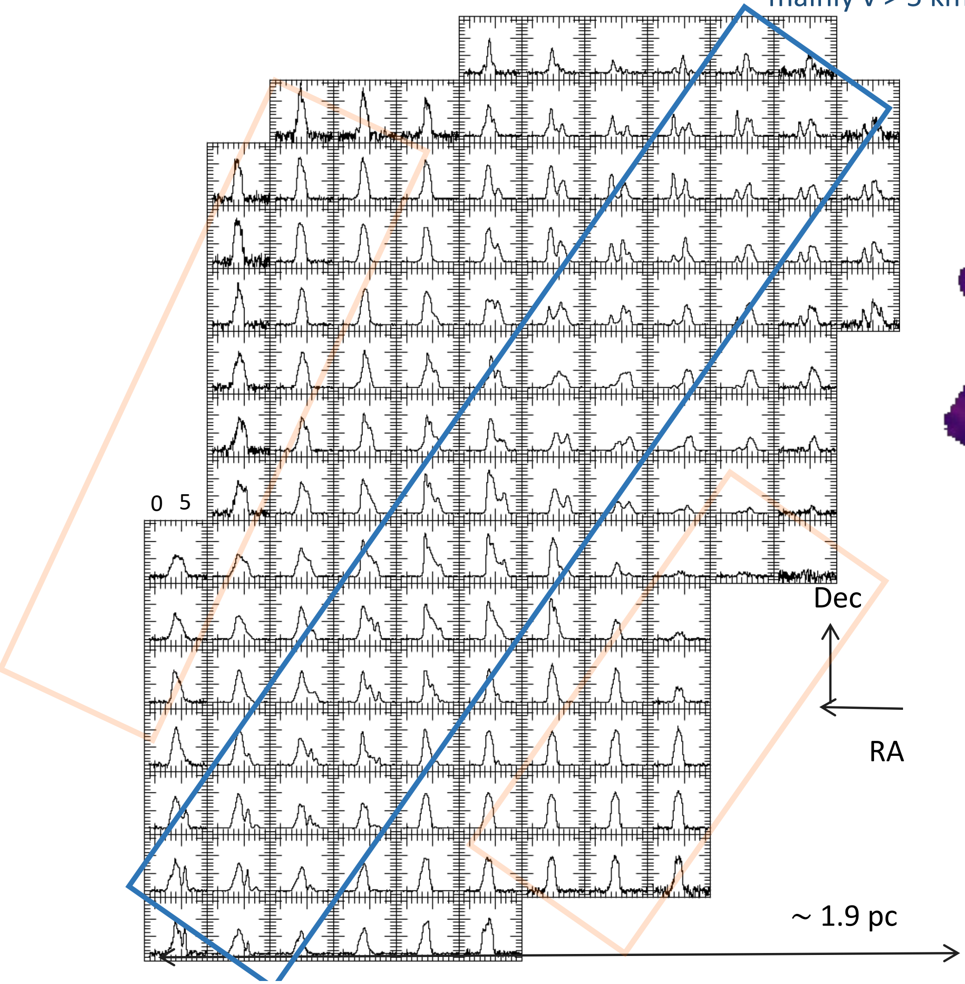


➢ **Spatial coherence with the 3.5 km/s structure**

Dynamic of $^{12}CO(1-0)$ emission linked to large scale structure

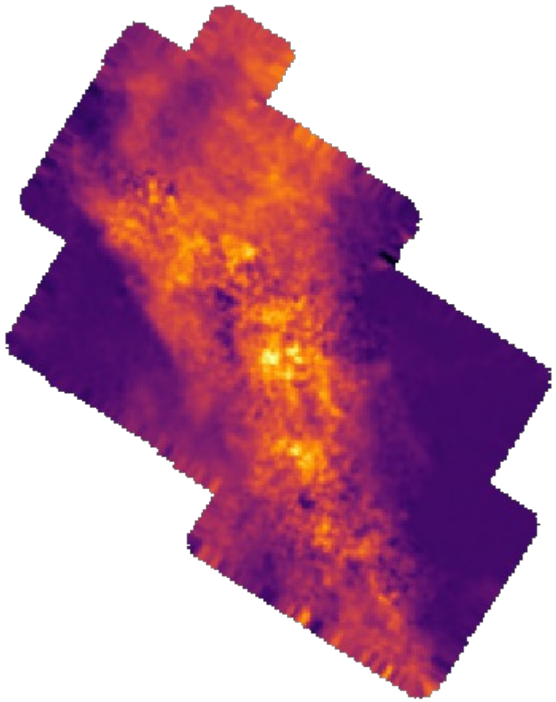
Spectra averaged on 200x200''

Velocity components at mainly v > 5 km/s

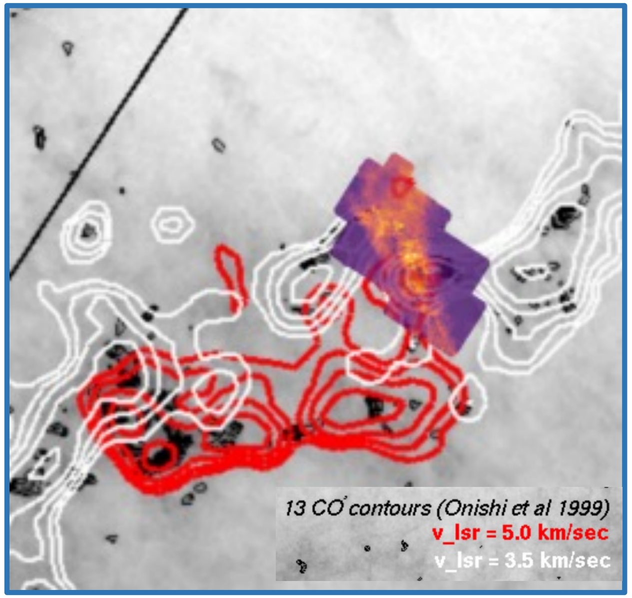


- $^{12}CO(1-0)$ dynamic coherent with large scale structures

Emission integrated at v >5km/s



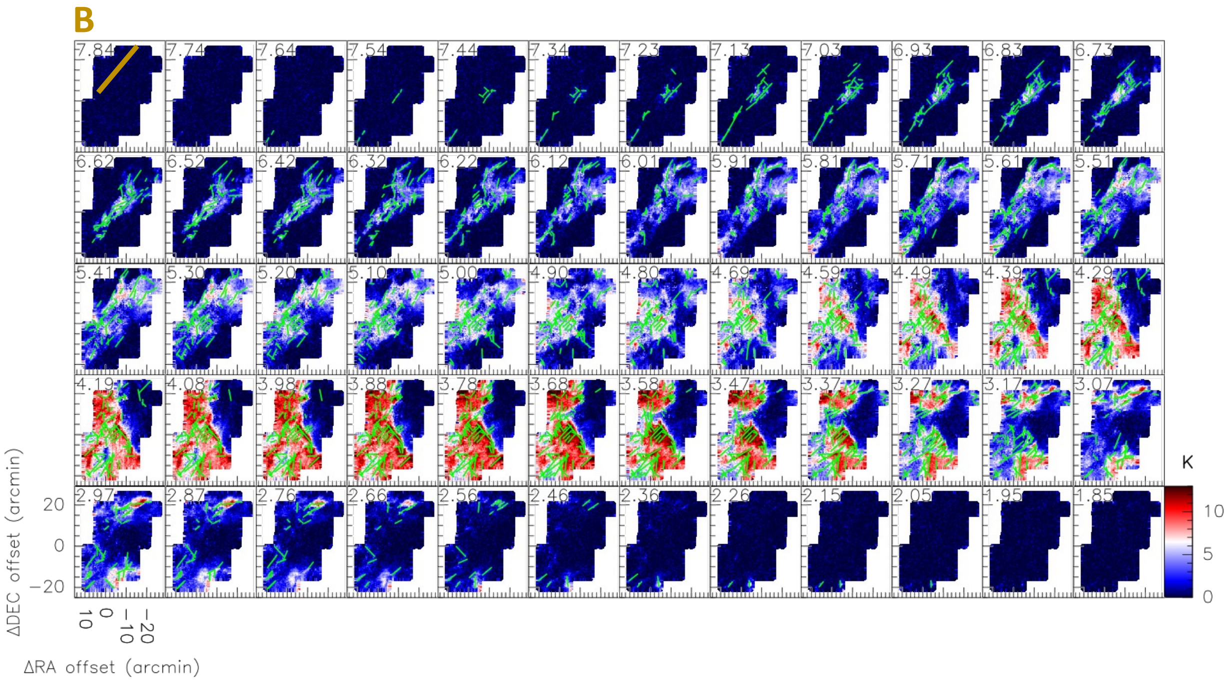
Emission integrated at v >5km/s overlapped on $^{13}CO(1-0)$ contours from Onishi+99



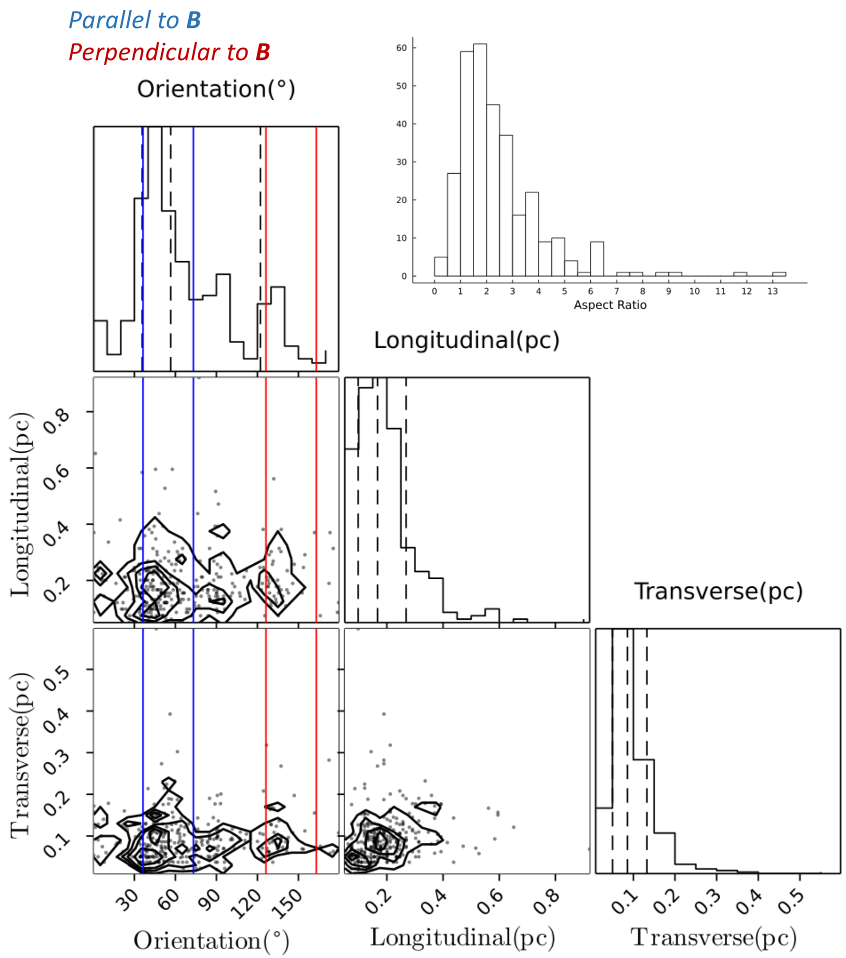
➢ **Second structure extended to higher velocity > 5km/s!**

Filamentary structures well aligned with B

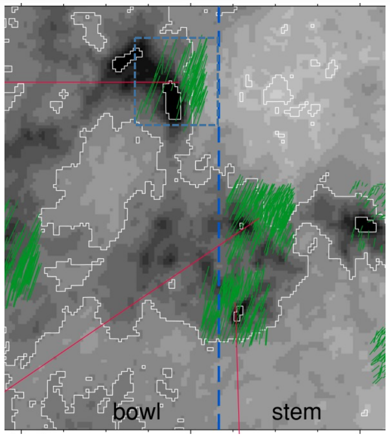
- High number ~314 of structures at small scales, with **~ 284 filaments**
- Filaments mainly parallel to **B,** others perpendicular.
- One of the smallest **transverse size: (0.06 ± 0.02) pc** *(dist=163pc)*
- Two to three distributions in orientation
  - Parallel and perpendicular to **B**



Distributions of the filaments characteristics

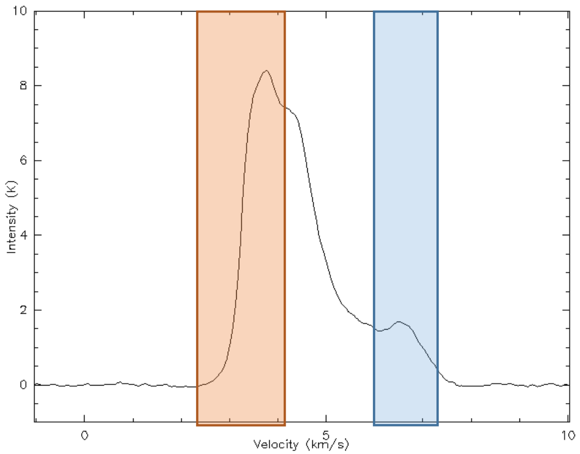


Magnetic field intensity estimation



Polarization angle from Franco+10

Average of the [12]CO(1-0) emission at the same coordinates as polarimetric measurement from Franco+10

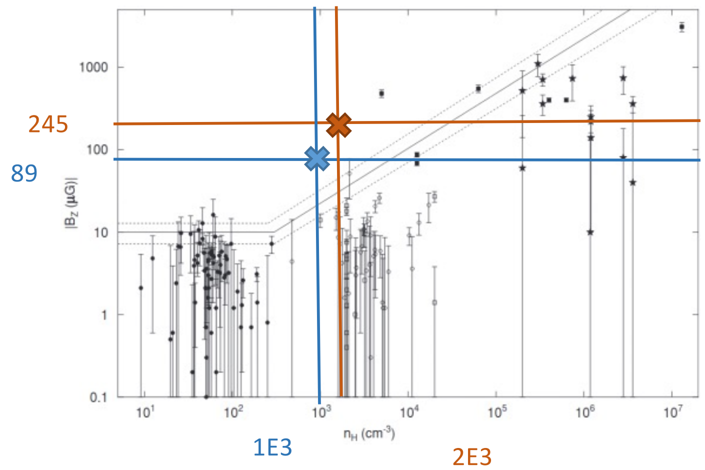


Large scale structure
< 4km/s
$\Delta v \sim 1\ km/s$
$I_{co} \sim 6.92\ K.km/s$

Large scale structure
> 5 km/s
$\Delta v \sim 0.5\ km/s$
$I_{co} \sim 3.64\ K.km/s$

- $\|B\| \approx 9.3\sqrt{n(H_2)}\frac{\Delta v}{\delta\varphi}$ *(Ostriker+01)*
  - $89 \leq \|B\|\ (\mu G) \leq 245$
- **High magnetic field intensity**

Crutcher+10: $|\boldsymbol{B}|$ versus n_H from Zeeman measurements.



- $\mathcal{M} = \frac{\sigma_v}{c_s}$: $\boldsymbol{\mathcal{M} \sim 14}$ *(Ostriker+01)*
- $\beta = \left(\frac{B_0}{1.4\mu G}\right)^{-2}\left(\frac{T}{10K}\right)^{1/2}\left(\frac{n_{H2}}{100cm^{-3}}\right)^{1/2}$: $\boldsymbol{\beta \sim 3E(-4)}$ | $\boldsymbol{2E(-3)}$
  - ***β<<1 : Strong field***

Projection effects or dense cores ?

- Detection of ^{12}CO(1-0), ^{12}CO(2-1), ^{13}CO(1-0), $C^{18}O$(1-0), some HCO+
- Not detected
  - HCN ($\sigma = 0.025\ K$)
  - N_2H^+ ($\sigma = 0.019\ K$)
  - ^{13}CN(1-0) ($\sigma = 0.03$K)
  - ^{13}CS(2-1) ($\sigma = 0.021\ K$)

  Usually associated to high-density tracers BUT need **more transitions** to be compared with
- Multi-components fitting : 4 to 5 gaussian components
- Gaussian fitting for each velocity component and using radiative transfert equations:

$$1\text{E}20 \leq \text{N}(H)\ [cm^{-2}] \leq 1E21$$
$$0.31 \leq A_v\ [mag] \leq 2.18$$

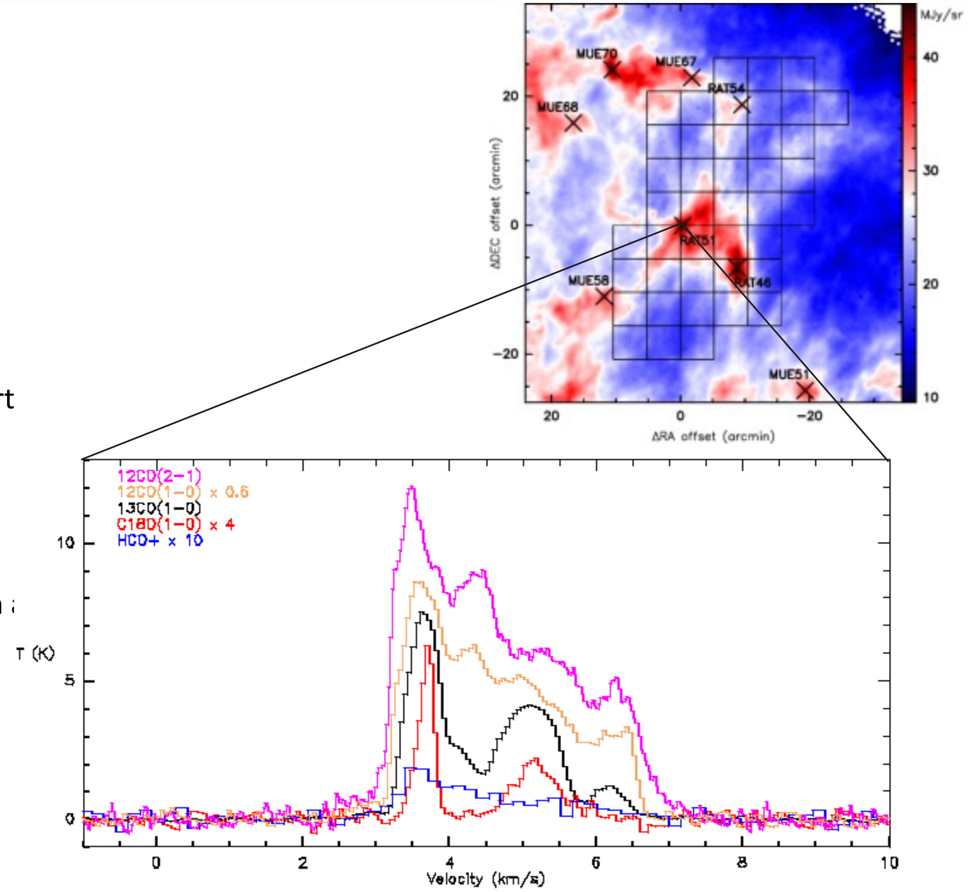
- From Rathborne+09, based on infrared measurements of dust extinction automatic core identification:

$$1\text{E}21 \leq \text{N}(H_2)\ [cm^{-2}] \leq 1E22$$
$$2.0 \leq A_v\ [mag] \leq 7.4$$

- A_v of a dense core ~ 2.8 mag

➢ Rat51, a **false positive** dense core

➢ Dense cores, or **projected superposition**?



Spectra of core #51 (numbered from Rathborne+09)

Summary, and more results to come...

- Large-scale map at **32''-resolution** of **highly dynamic, non star-forming** region in the Pipe molecular cloud

- A test case for **strongly magnetized turbulence**
  - Colliding clouds caught in the act? **Turbulent energy injection** at the Bowl/Stem limit ?
  - Two $^{12}CO(1-0)$ velocity components consistent with **large scale filamentary structures** in $^{13}CO(1-0)$
  - A **Mach** number of **14**, and **beta plasma** of **3E-4, 2E-3**

- Formation of filaments and dense core in such conditions
  - Network of tenuous filaments in the vicinity of a dense core: **Projection effects?** False positivie ? **General in this higly dynamic region!**
  - **Work in Progress:** Further studies of dense cores in the vicinity

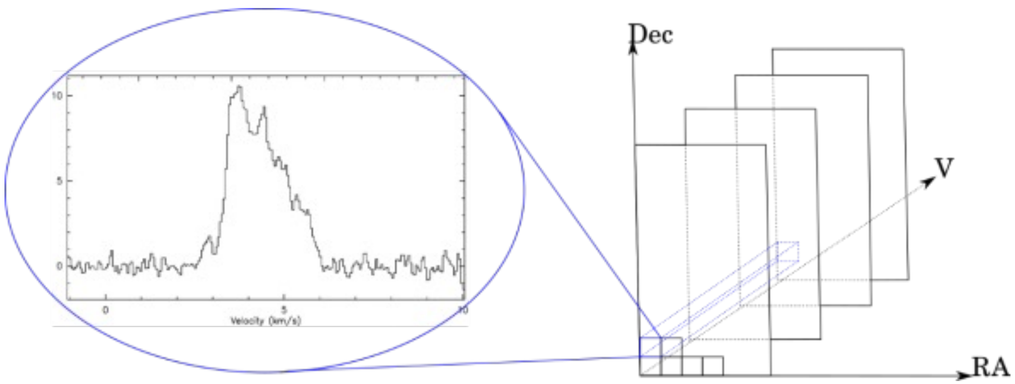
- **A case study to compare with numerical simulations !**
- **Probe the role of turbulence in filament and dense core formation !**

Thank you for your attention

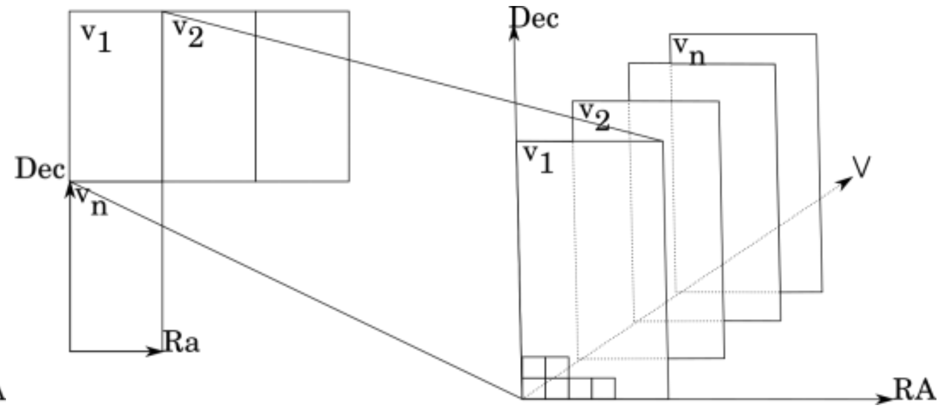
Dissecting a Position-Position-Velocity cube

- Cube with 187x149 pixels, with one spectrum per pixel
  - 3 dimensions: 2 in spatial and 1 in velocity space

Spectra



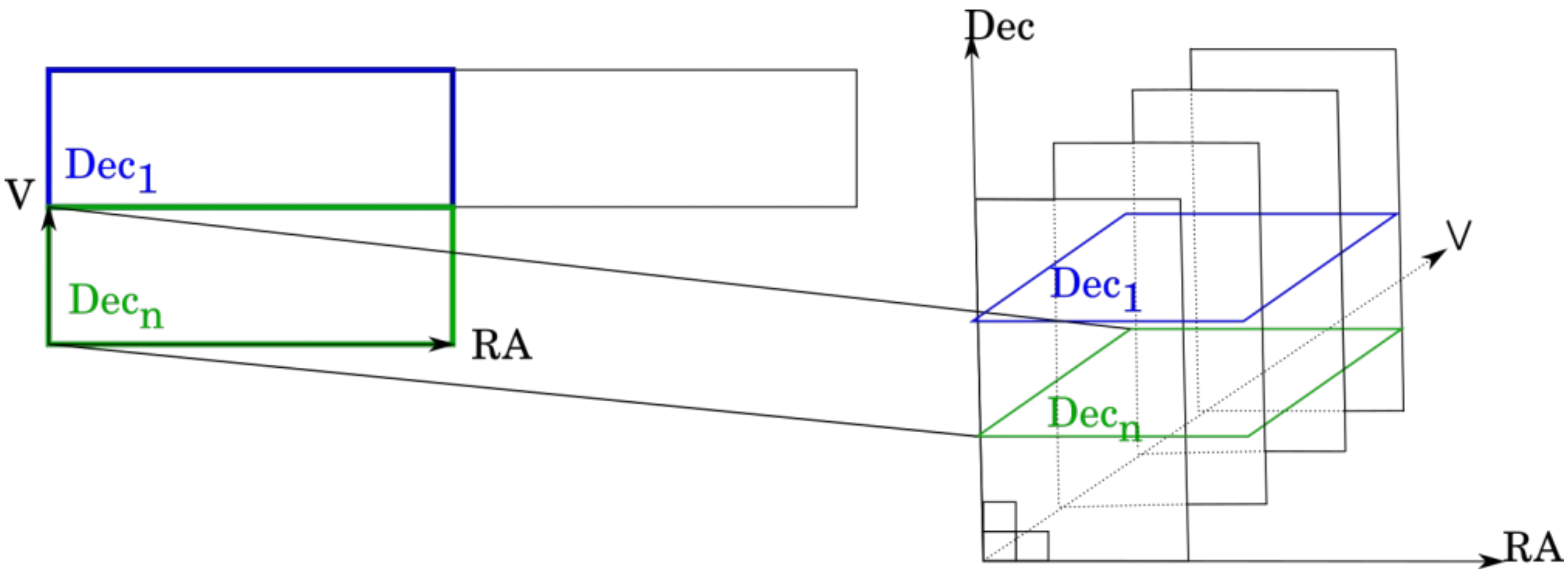
Velocity Channel map



Annexe PV-cut: representing the observations

Position-Velocity cut

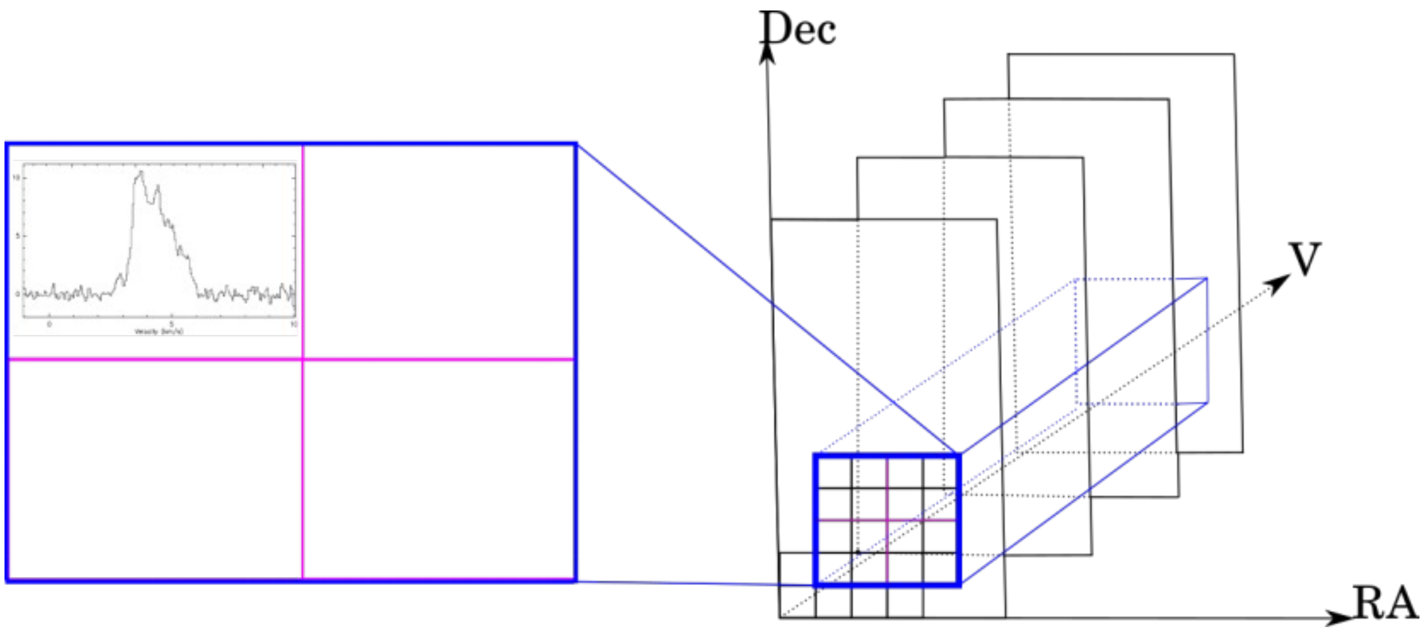
- Spectra of one row/column stacked
  - ➢ Velocity gradient



Annexe: Representing the observations

Spectra averaged

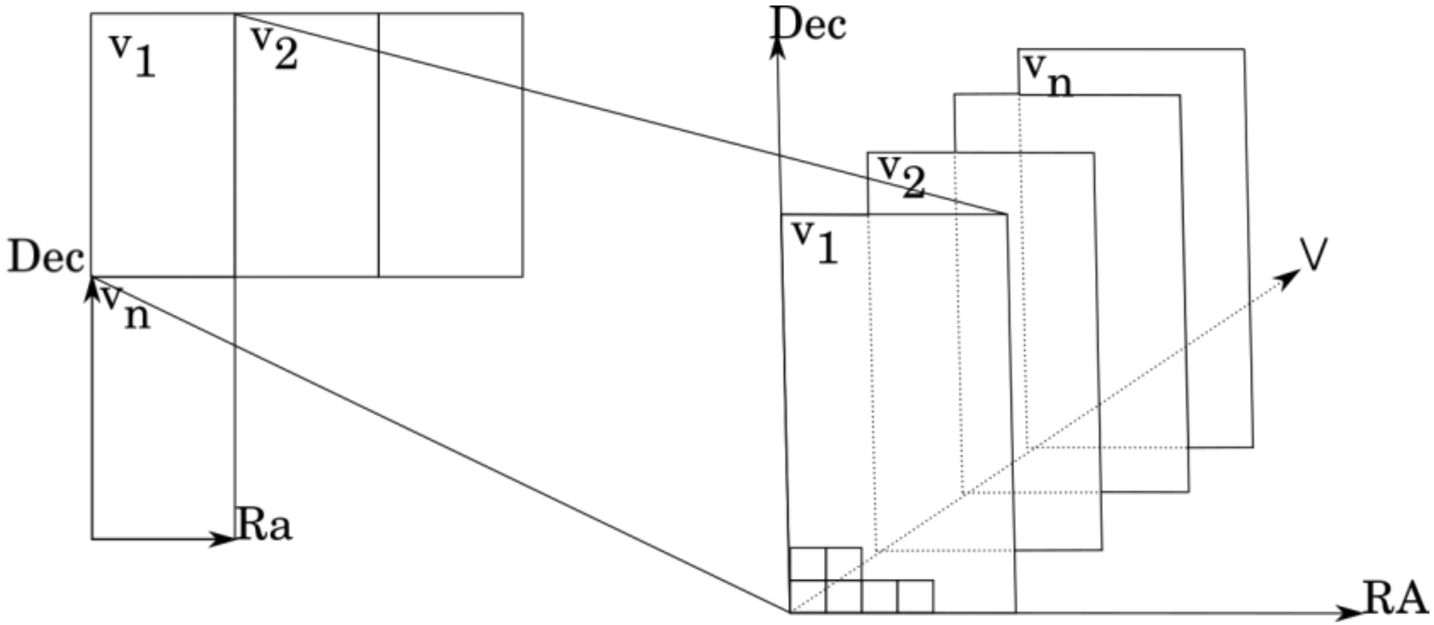
- Spectra of a region, averaged by proximity
    - ➢ Spectra evolution in 2D



Annexe: Representing the observations

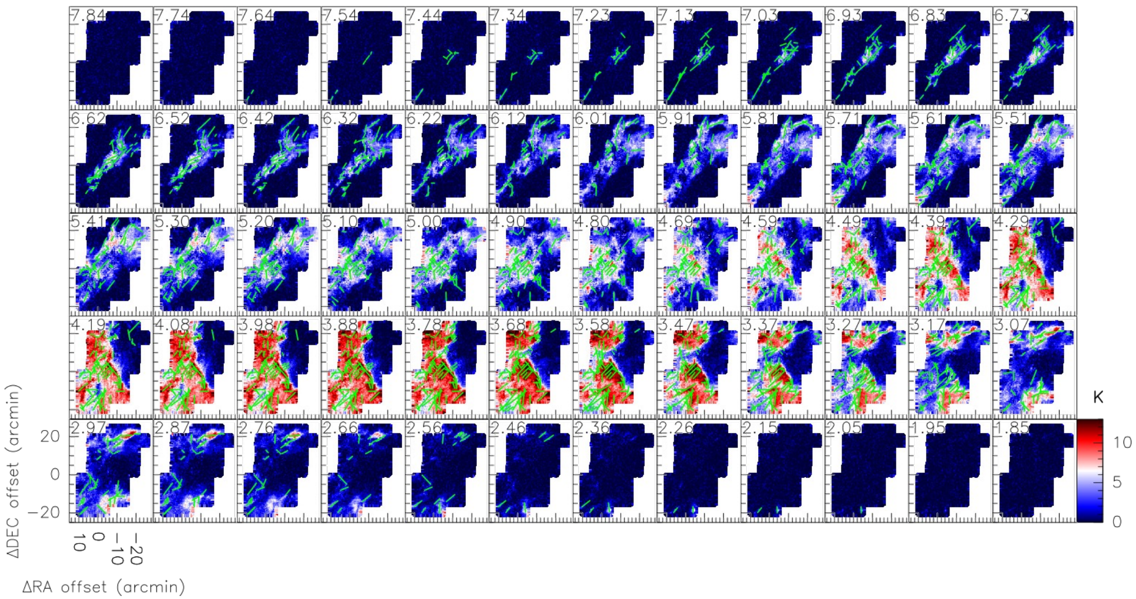
Velocity channel map

- Velocity channel plotted one by one
  - ➢ Velocity structure

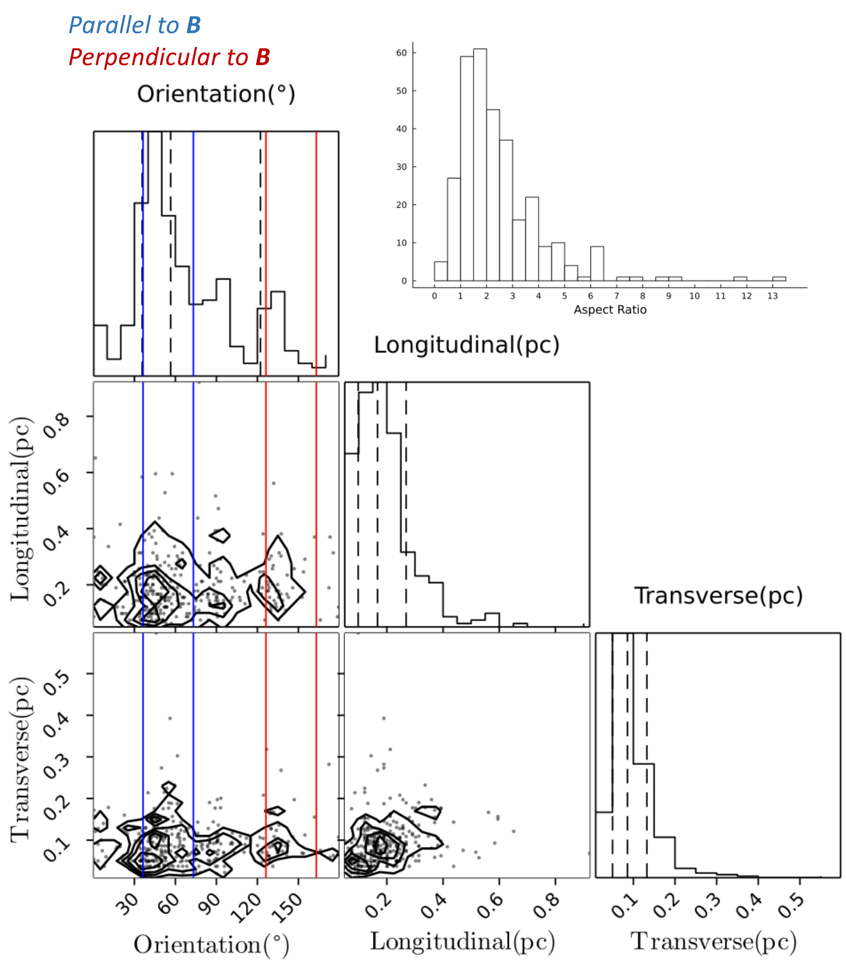


Filamentary structures characterization

- 314 filaments detected
    - ➢ **High number of filaments**
- Two to three distributions in orientation
    - Parallel and perpendicular to **B**
- Longitudinal size mainly lower than 0.4 pc
- One of the smallest **transverse size: (0.06 ± 0.02) pc** *(dist=163pc)*



Distributions of the filaments characteristics



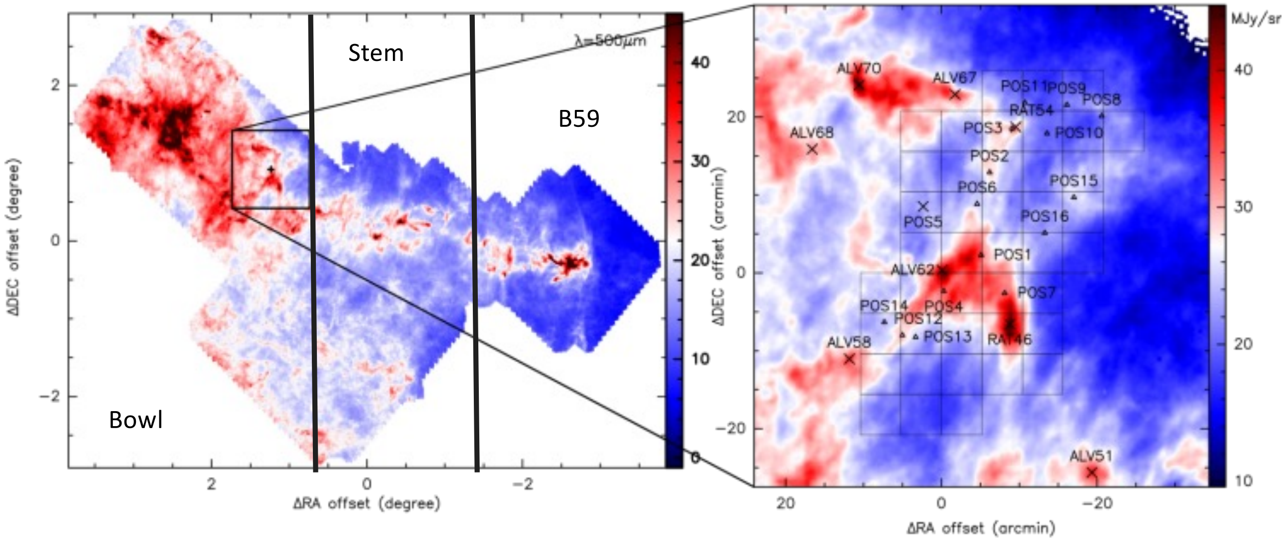
Our observations with the IRAM-30m

- In the region of overlapping velocity components, at the Bowl/stem limit

- The largest $^{12}CO(1\text{-}0)$ map at this resolution of the Pipe Nebula *(Onishi+99 observations)*
  - 42 fields of 5'x5' ≤17.5 deg^2 | *27 deg^2*
  - HPBW 32'' = 22 mpc = 4538 au | *4' = 35065 au*
  - Spectral resolution: 0.1 km/s | *0.1 km/s*
  - Number of spectra: 27863
  - Typical rms: 0.5 K | *0.08 K*

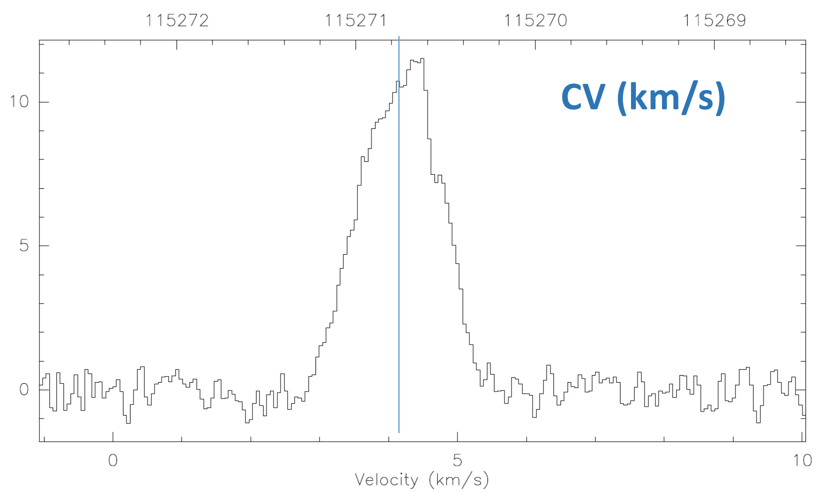
- Multi-line observations of 8 dense cores + 16 others positions
  - **$^{12}CO(1\text{-}0)$, $^{12}CO(2\text{-}1)$, $^{13}CO(1\text{-}0)$, $C^{18}O(1\text{-}0)$**
  - bonus lines: HCN, ***HCO^+***, N_2H^+

- Total of 113hr (August 2021, January 2022) + 16hr planned 18 to 21 of June 2022

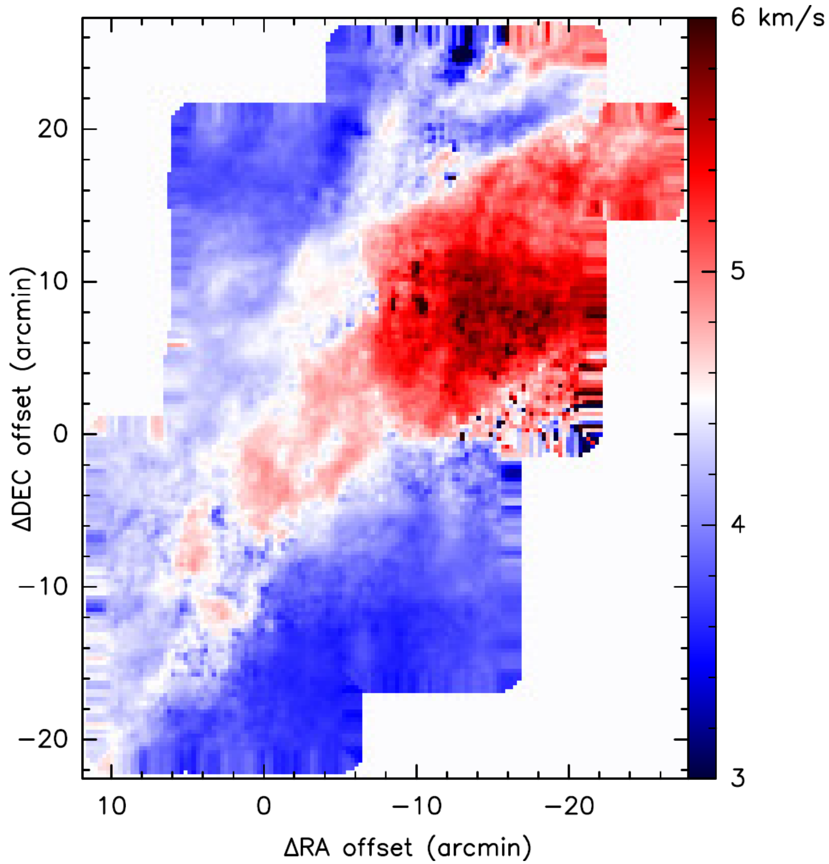


Herschel-SPIRE view at 500µm

Annexe - CV: Large centroid velocity differences

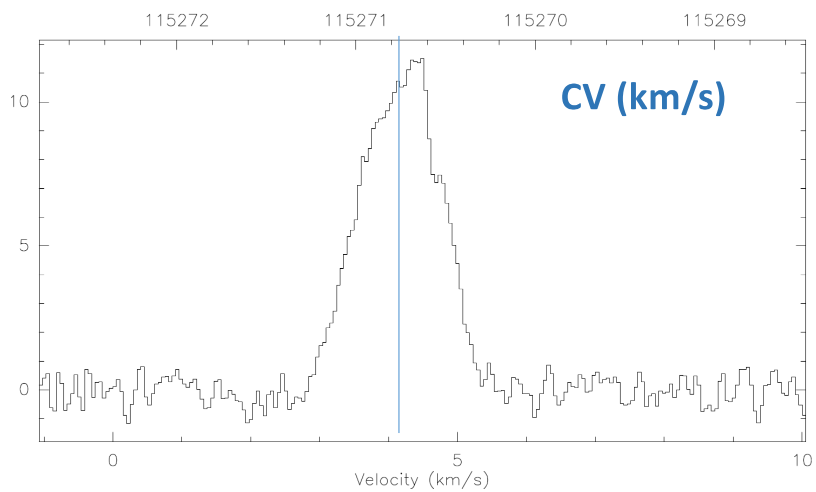


- Gradient of CV values ~3 km/s
- Spatial correlation with high velocity structure ?



Centroid Velocity map

Annexe - CV: Large centroid velocity differences



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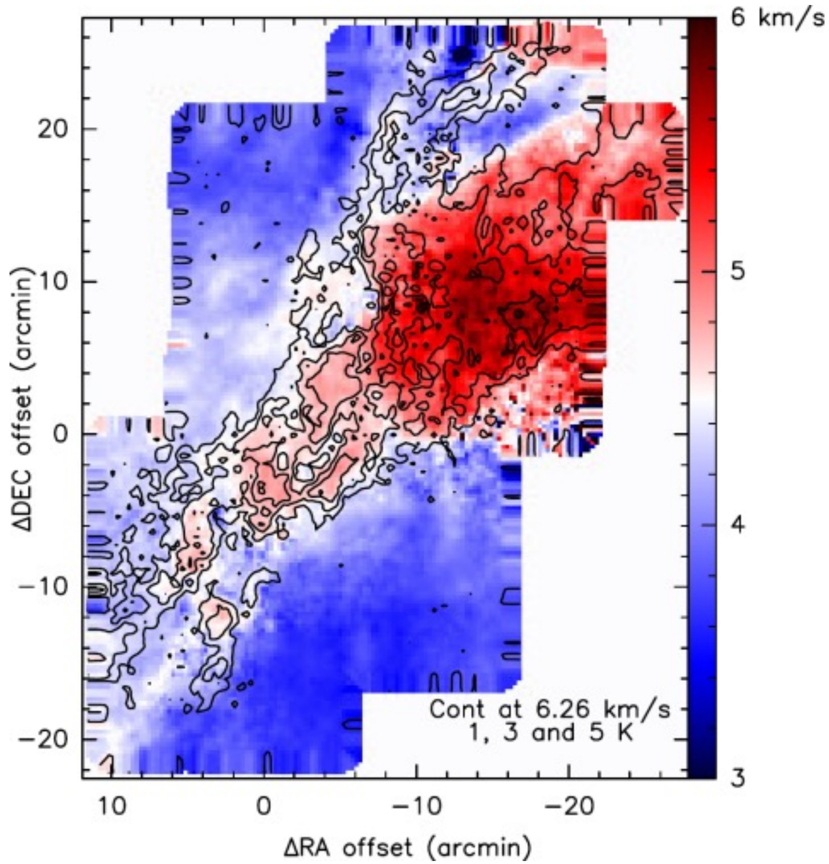
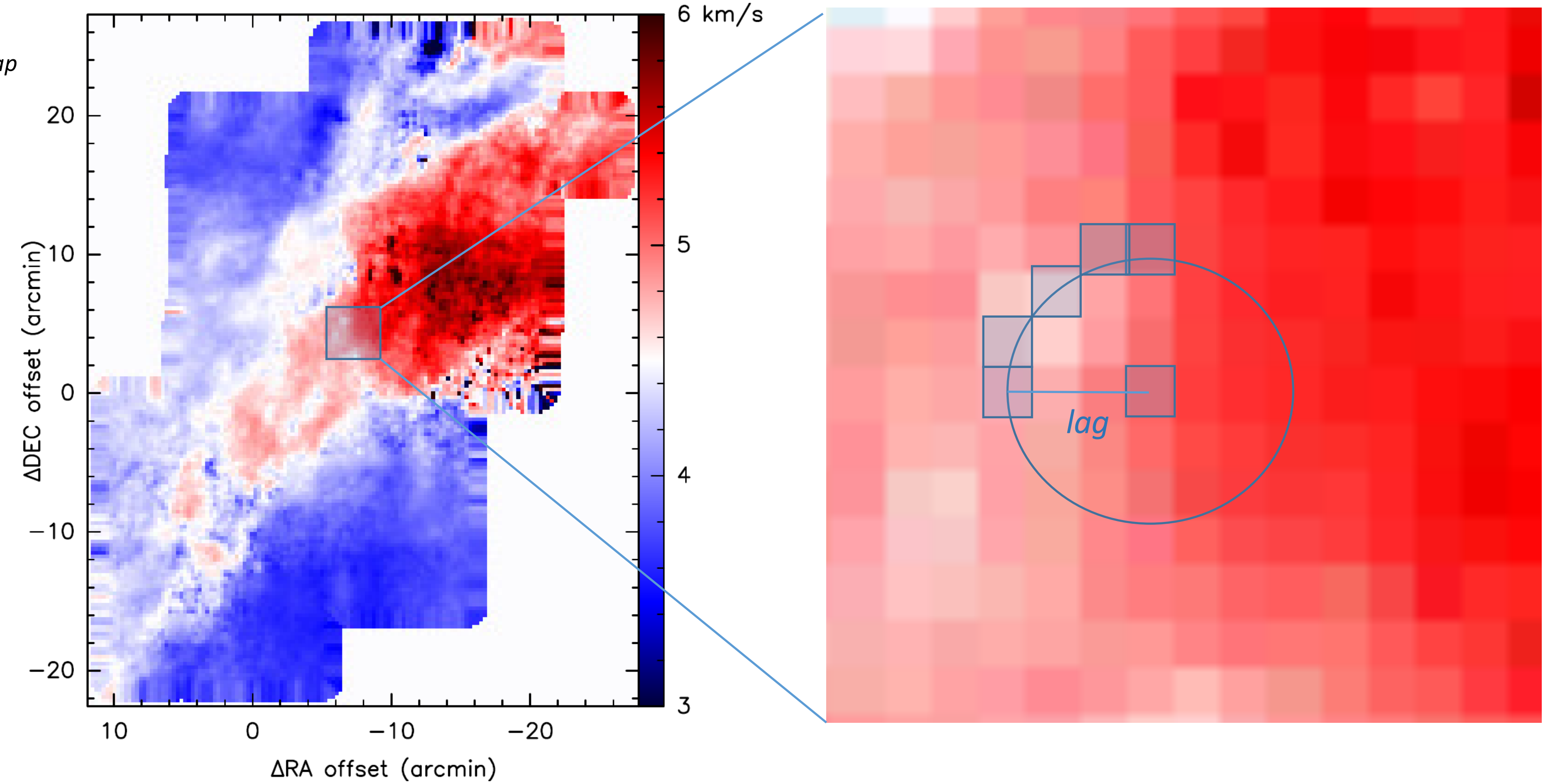


Centroid Velocity map

Annexe: Gradient of the centroid velocity

- Centroid velocity gradient trace intense velocity shear in a turbulent gas *(Hily-Blant+2009)*
  - ➢ Differences pixel per pixel of the centroid velocity at a given distance

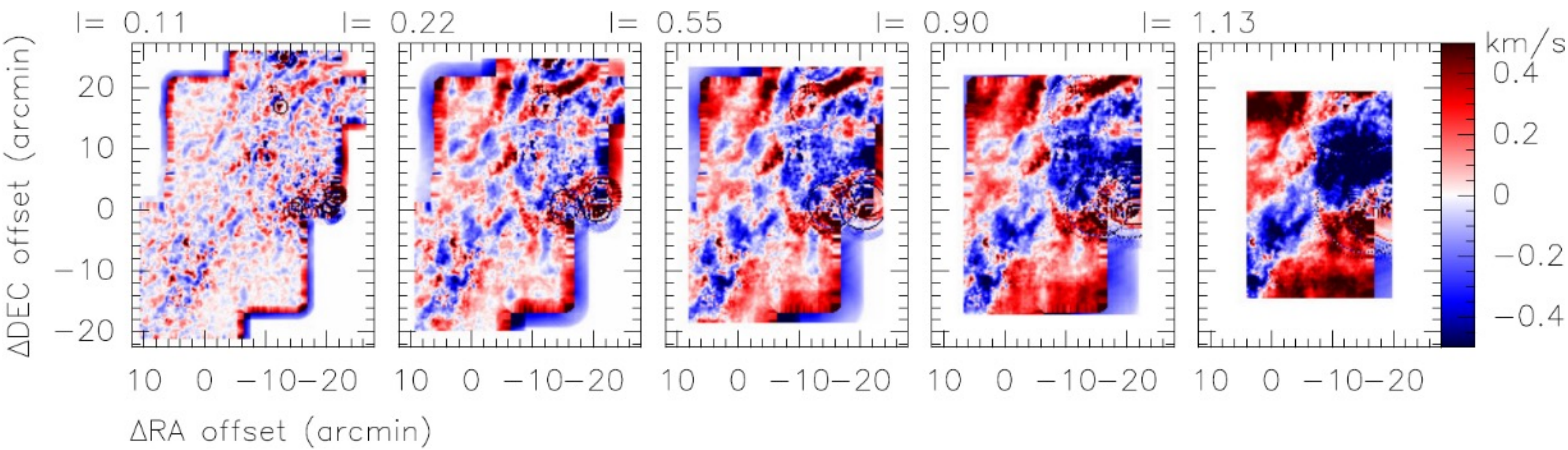
Centroid Velocity map



Annexe: Gradient of the centroid velocity

- Centroid velocity gradient trace intense velocity shear in a turbulent gas

- Structure with high velocity gradient
  - ➢ Velocity shear from small (0.1pc) to large scale (1pc)

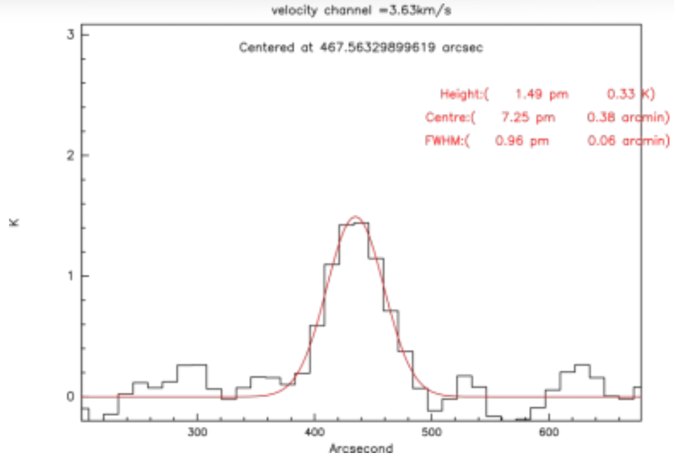


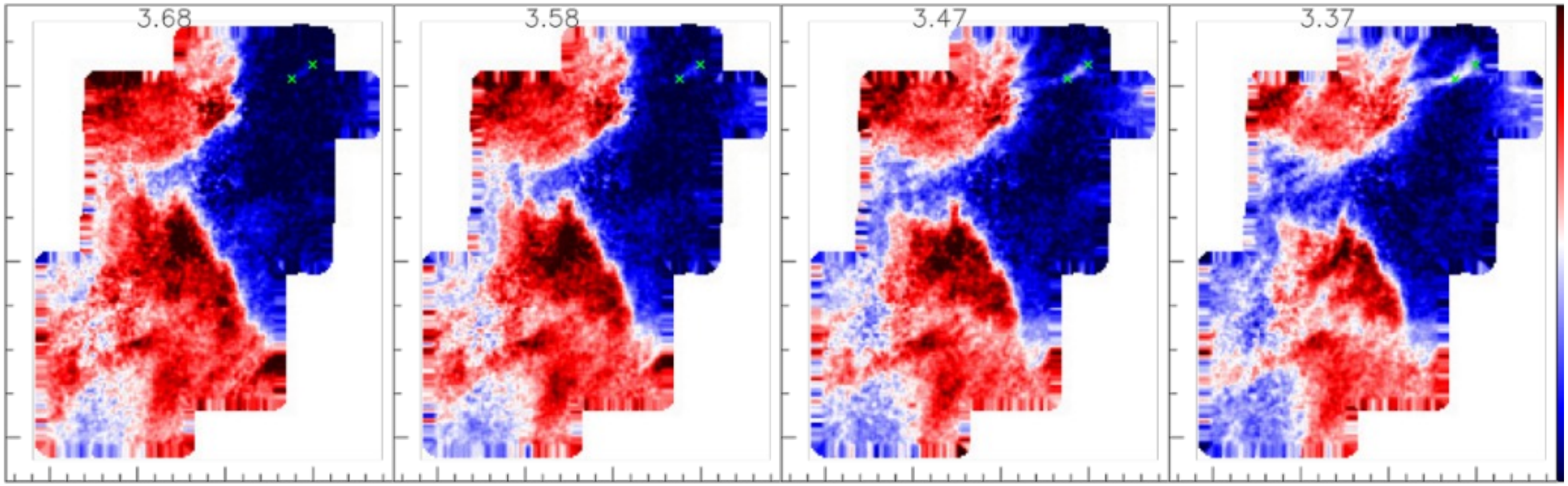
Centroid Velocity Increment map. Lag is given by l in parsec.

Annexe: One of the smallest filament

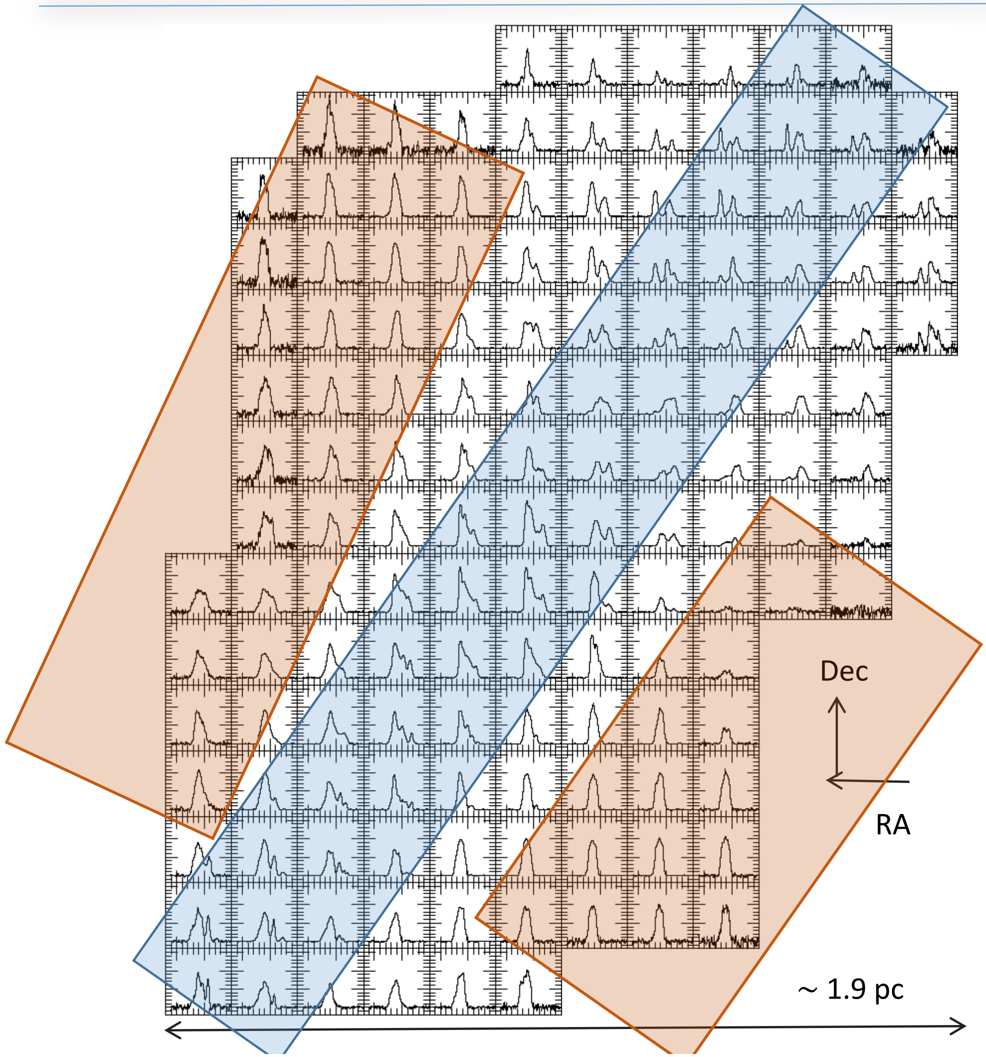
- Transverse size: (0.06 ± 0.02) pc

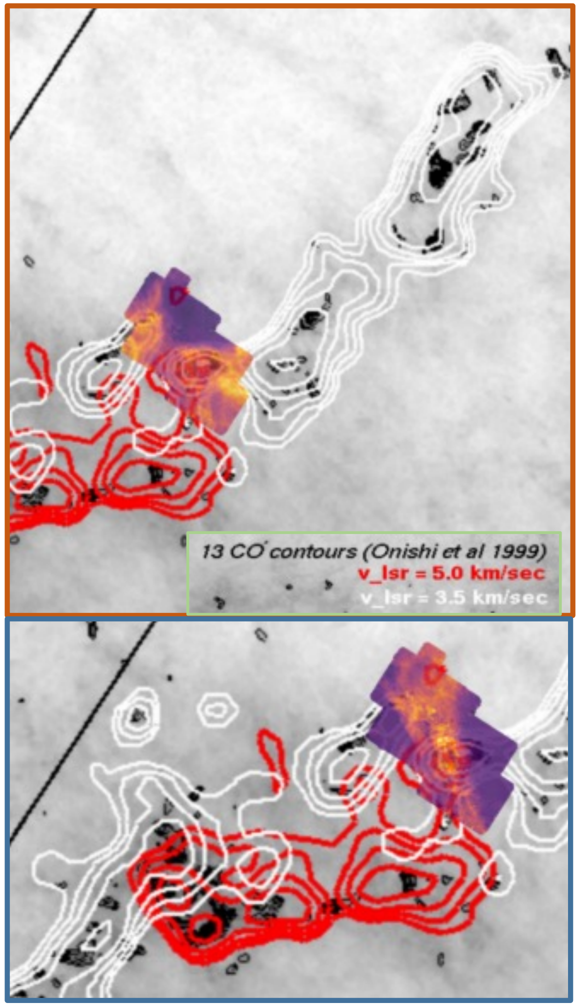
- Uncertainty equals the angular resolution of our data !





Annexe: Spectra overview of the $^{12}CO(1-0)$ map





Annexe: Column density calculations

- Two unknowns are opacity profile and excitation temperature, but can be estimated with multi-line analysis. Need to assume that the excitation temperature is identical for the three CO isotopologs. For every emission T_{mb}:

$$T_{mb} = [J_\nu(T_{ex}) - J_\nu(T_{bg})](1 - e^{-\tau_\nu})$$

where T_{bg} is the temperature of background emission assumed to be a black-body, τ_ν the line center optical depth at frequency ν.

- For an optically thick transition ($\tau_\nu \gg 1$), we have $J_\nu(T_{ex}) = T_{mb} + J_\nu(T_{bg})$, then

$$T_{ex} = \frac{h\nu}{k}\left[\ln\left(1 + \frac{h\nu}{k}\frac{1}{T_{mb} + J_\nu(T_{bg})}\right)\right]^{-1}$$

- Using T_{ex} we can calculate $J_\nu(T_{ex})$:

$$J_\nu(T_{ex}) = \frac{h\nu}{k_B}\frac{1}{\exp(h\nu/k_B T_{ex}) - 1}$$

- The opacity can be calculated with:

$$\tau_{18} = -\ln\left[1 - \frac{T_{18}}{J_\nu(T_{ex}) - J_\nu(T_{bg})}\right]$$

- Or using :

$$\frac{T_{12}}{T_{18}} = \frac{1 - e^{-\tau_{12}}}{1 - e^{-\tau_{18}}} = \frac{1 - e^{-\tau_{12}}}{1 - e^{-\tau_{12}/500}}$$

- Then, using the opacity profile of an optically thin transition (which will be better approximated by a Gaussian), we can use :

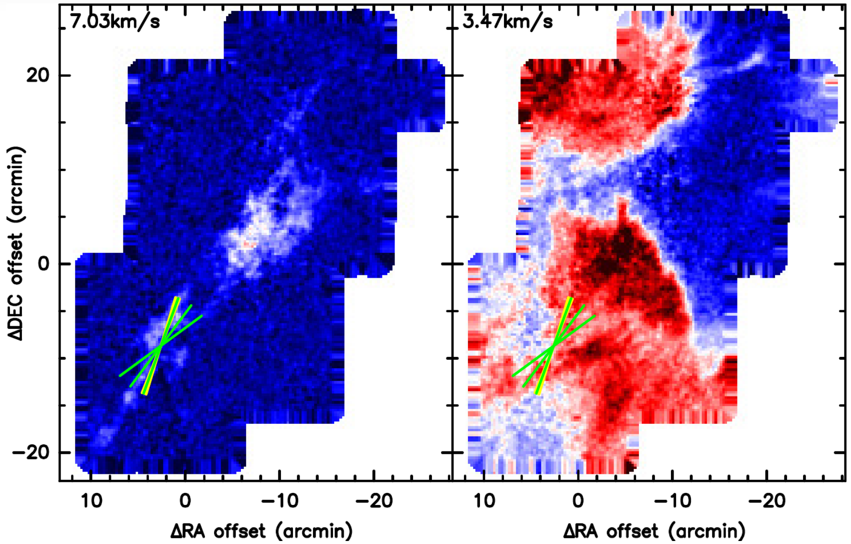
$$N_{18} = \frac{8\pi\nu^3}{c^3}\frac{Q}{A_{ul}g_u}\frac{e^{E_l/kT_{ex}^{ul}}}{1 - e^{-h\nu_{ul}/kT_{ex}^{ul}}}\int \tau_\nu^{ul} dv \approx \frac{8\pi\nu^3}{c^3}\frac{Q}{A_{ul}g_u}\frac{e^{E_l/kT_{ex}^{ul}}}{1 - e^{-h\nu_{ul}/kT_{ex}^{ul}}} 1.064\Delta v\tau_0$$

with Q the particition function, A_{ul} the Einstein coefficient for spontaneous radiative decay, g_u the upper level multiplicity and Δv the FWHM.

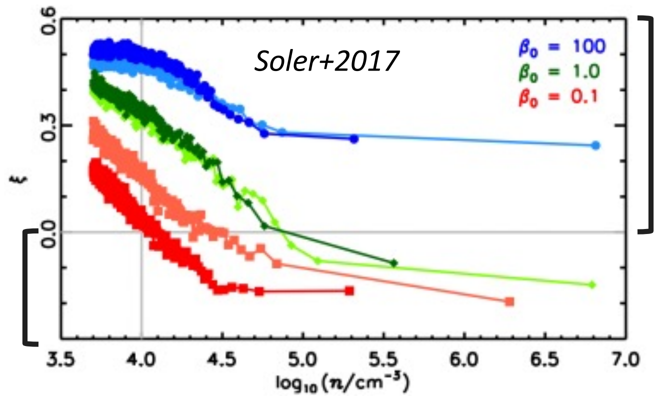
Annexe: Orientation of filamentary structures

- Filamentary structures in channel maps
  - Parallel to **B**
  - Others neither parallel nor perpendicular to **B**
  - Green: **B** from dust extinction *(Franco+2010)*
  - Yellow: **B** from thermal dust emission *(Planck Collaboration+ 2015)*
- Theoretical predictions from ideal MHD
  - Low density: mostly parallel
  - High-density: mostly perpendicular
  - Consistent with Planck (*Planck Coll. XXXV 2016)*

➢ In a transition from tenuous to dense filaments ?



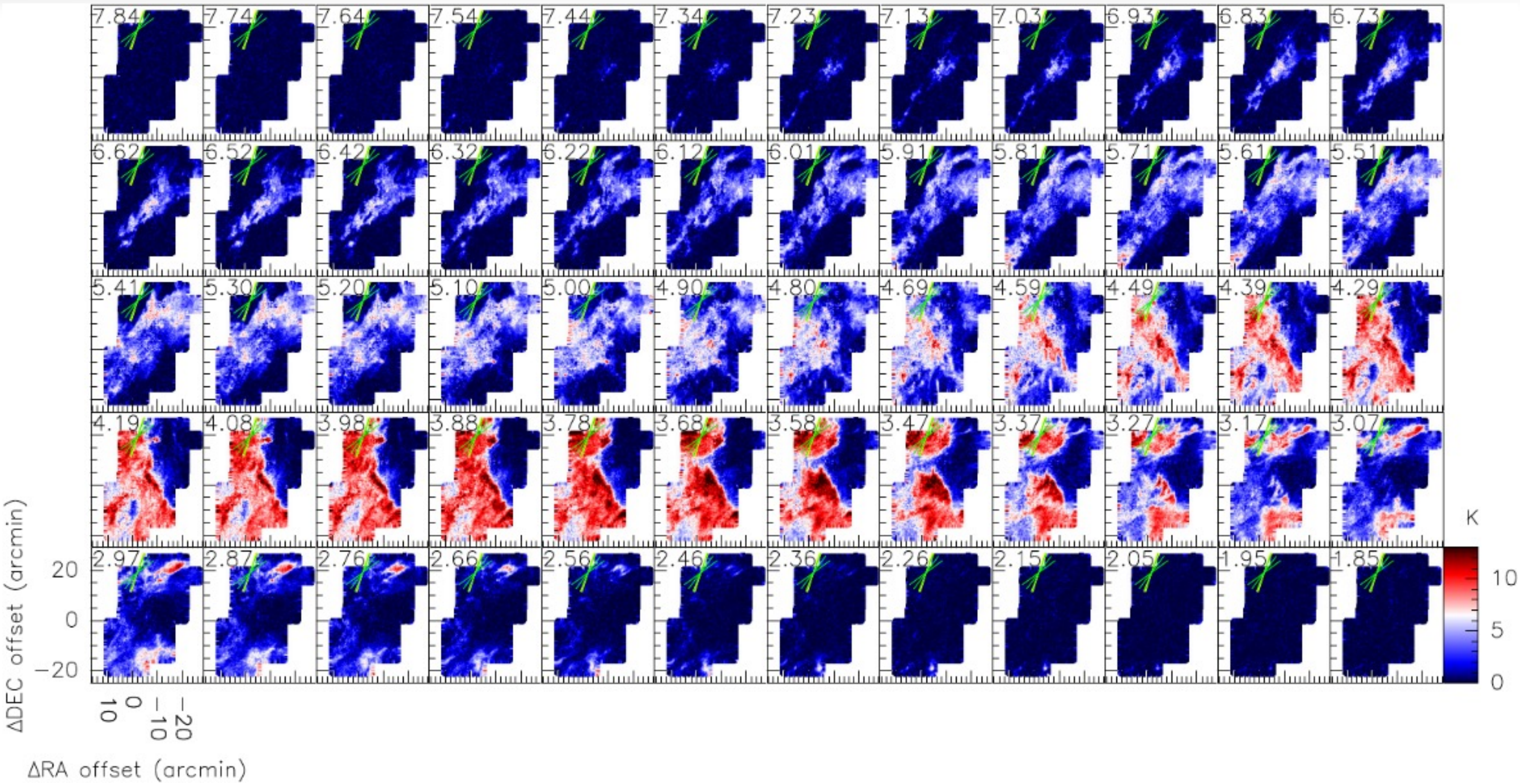
$\xi > 0$: Dust filaments parallel to **B**



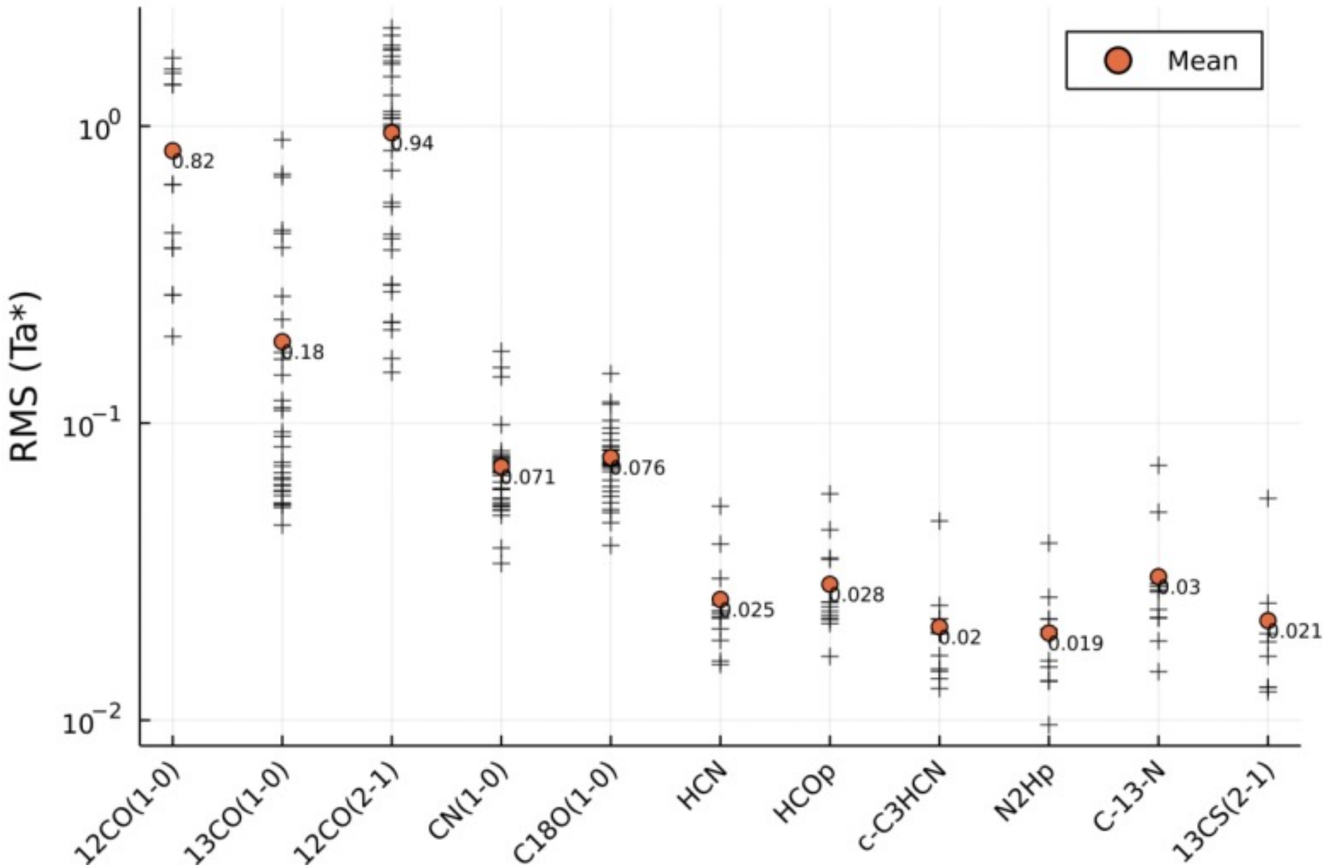
$\xi < 0$: Dust filaments perpendicular to **B**

β_0: ratio of thermal to magnetic pressure

Annexe: $^{12}CO(1\text{-}0)$ velocity channel map

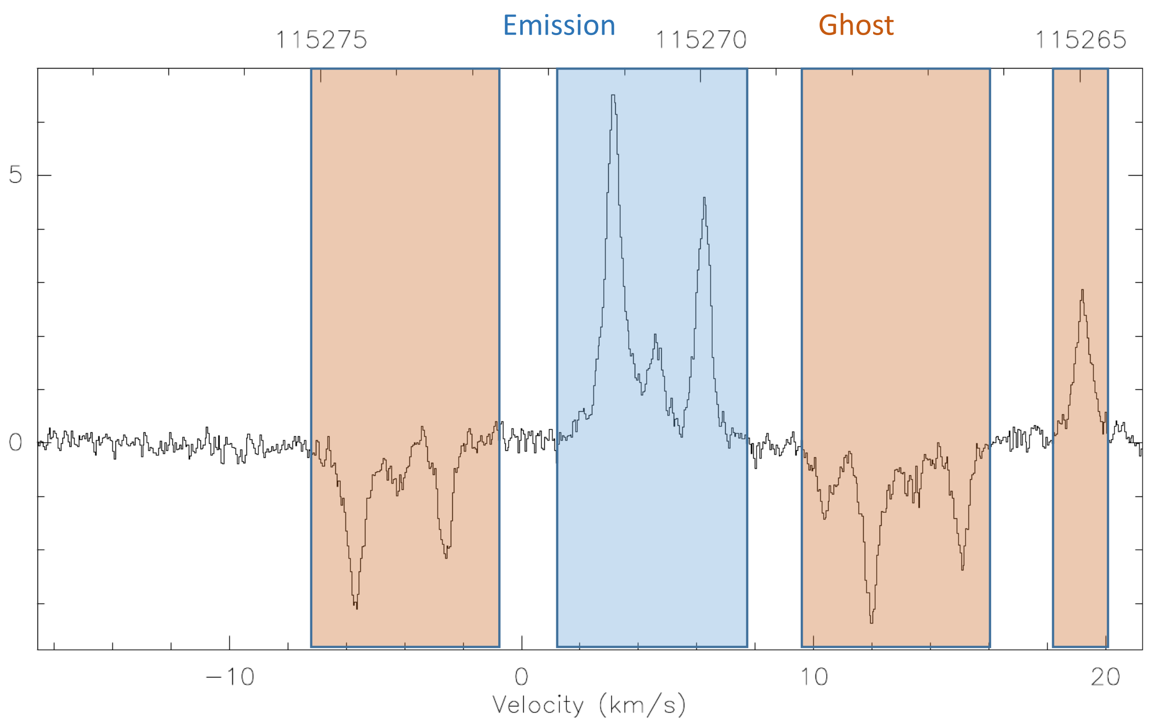


Annexe: RMS of the integrated positions



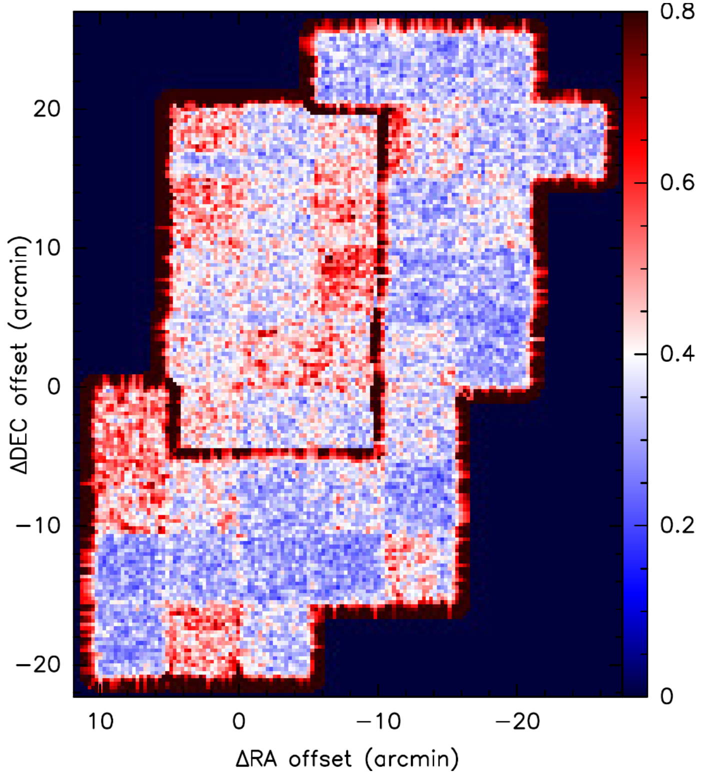
Annexe - Data reduction: The complexity of reducing a 17.5 deg^2 PPV cube

- A technical problem during winter observation run
  - Ghosts at 1 km/s from the signal
  - Need to be very careful in the window definition



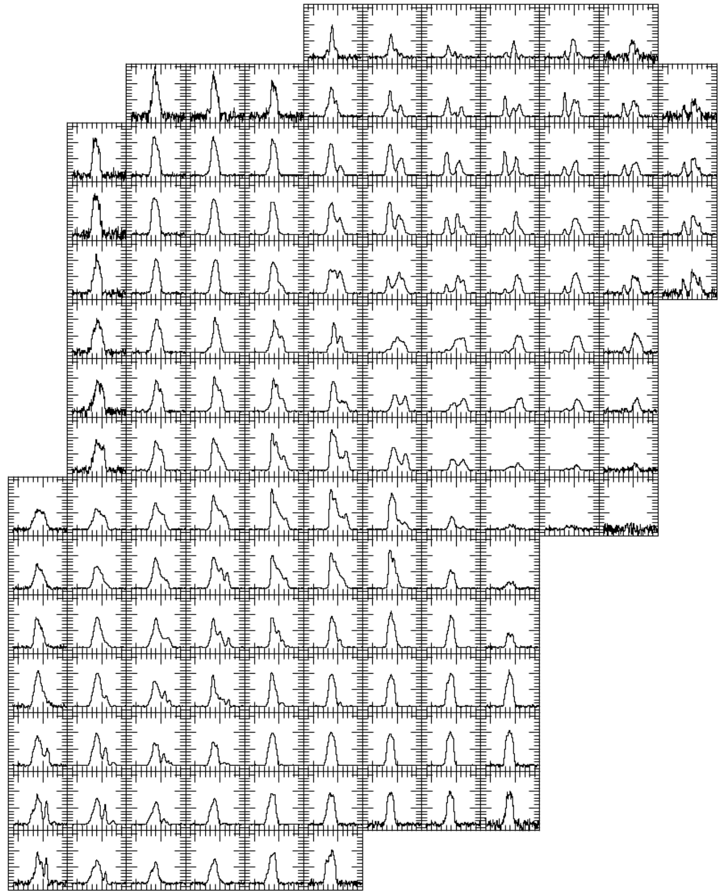
Annexe - Data reduction: The complexity of reducing a 17.5 deg^2 PPV cube

- Main concerns are about baseline reduction
  - ➢ Consequences at submap borders



RMS map of our $^{12}CO(1\text{-}0)$ cube, before baseline reduction. Colorscale in K. First observing run is easily seen as the almost centered red rectangle.

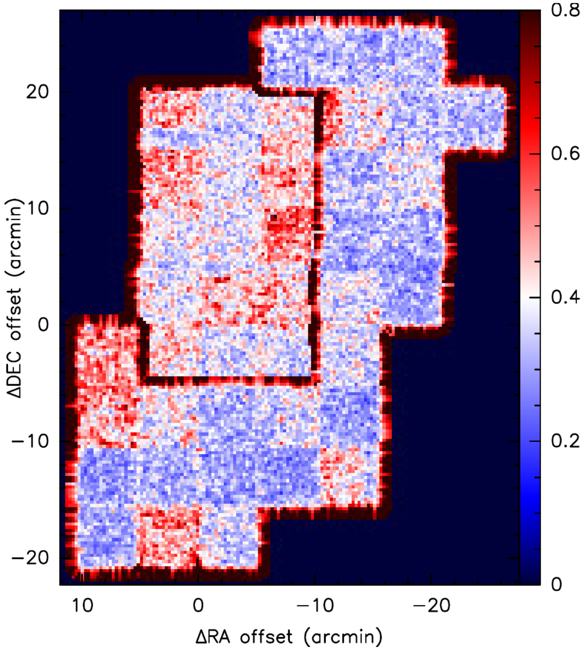
- How to deal with spectra so differents ?



Annexe - Data reduction: Resolving the data reduction problem

- Working on a first cube with all the spectra not reduced
  - ➢ Do not distinguish data between the two observing run

- Took around 10 weeks to conclude on the data reduction



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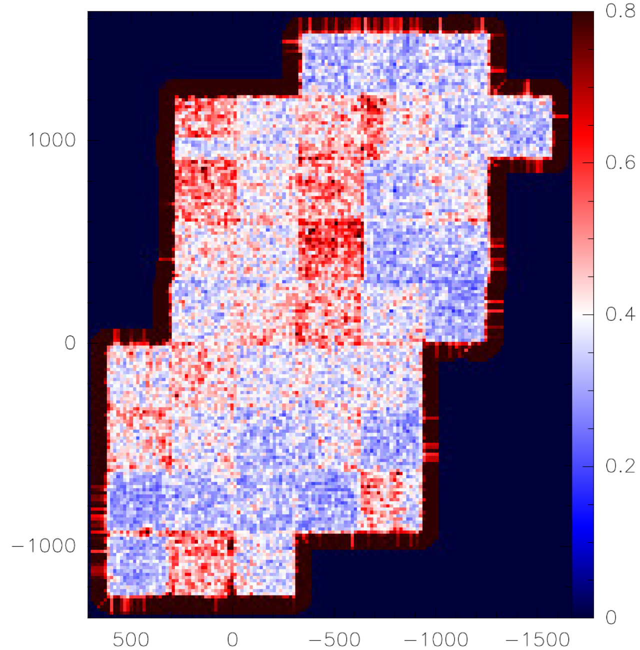


RMS map of our $^{12}CO(1\text{-}0)$ cube, after baseline reduction. Colorscale in K. First observing run is easily seen as the almost centered red rectangle.

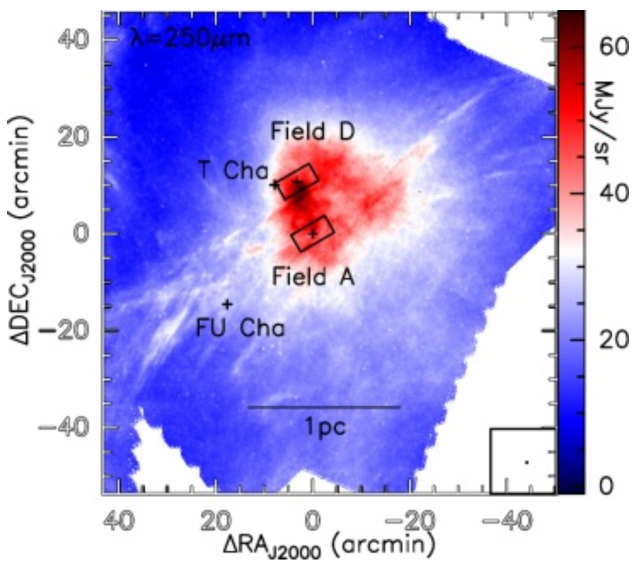
Annexe: Study of the dissipation of turbulence intermittency in molecular clouds

- Turbulent pressure is the dominant support of the gas against self-gravity.
  - ➢ Turbulent dissipation : key in formation of dense cores and stars

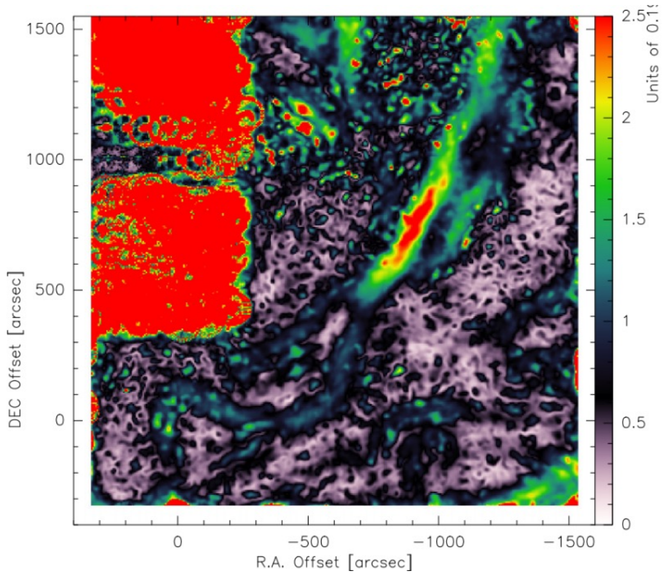
- Study of turbulent dissipation combine **structural** and **statistical** analysis

^{12}CO(1-0) ALMA-ACA observations of Dcl300.2-16.9 in the Chamaeleontis region.

Herschel-SPIRE view at 250μm



Conception of a code in Julia to statistically pinpoints site of dissipation of turbulence intermittency using Principal Component Analysis



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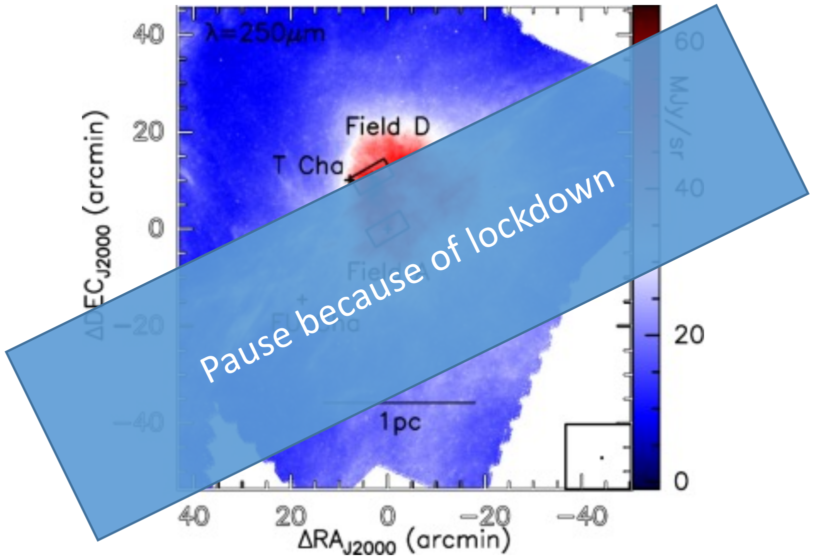

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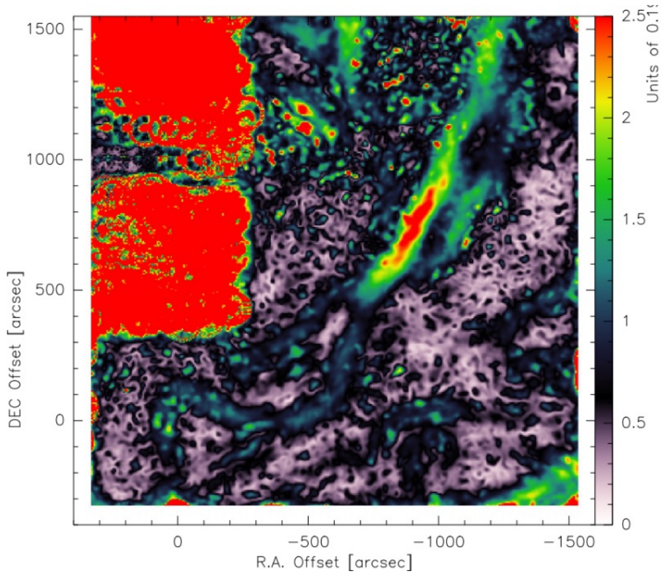
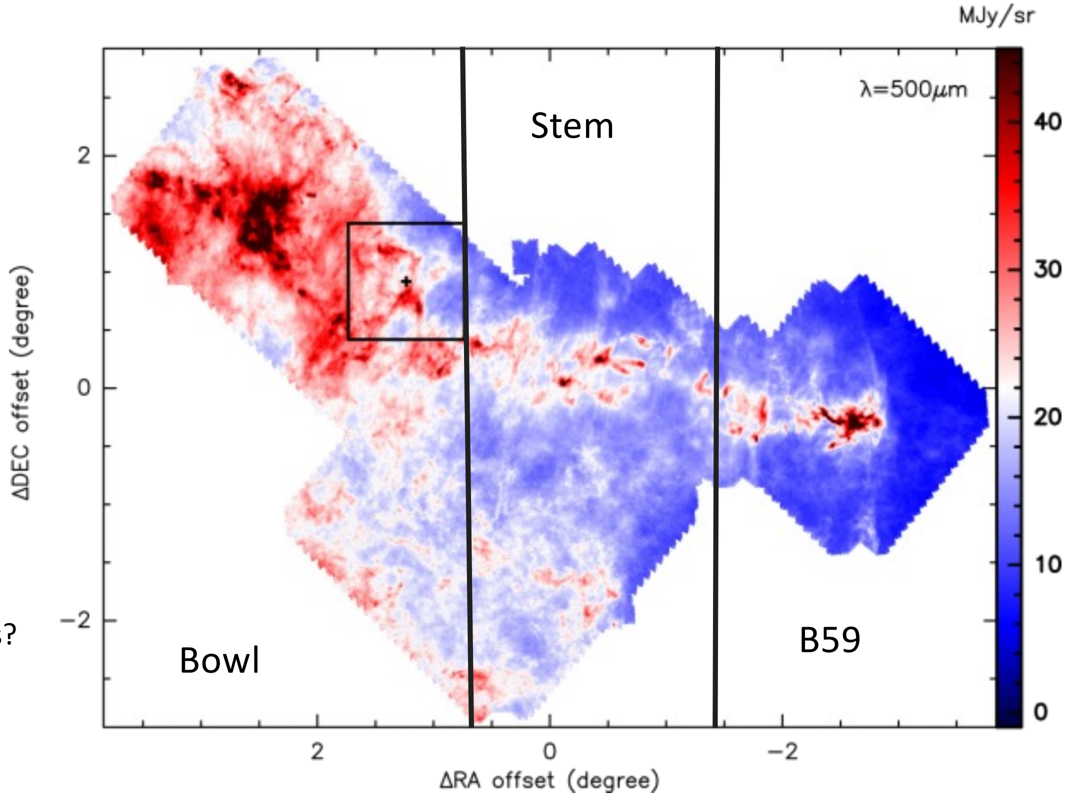


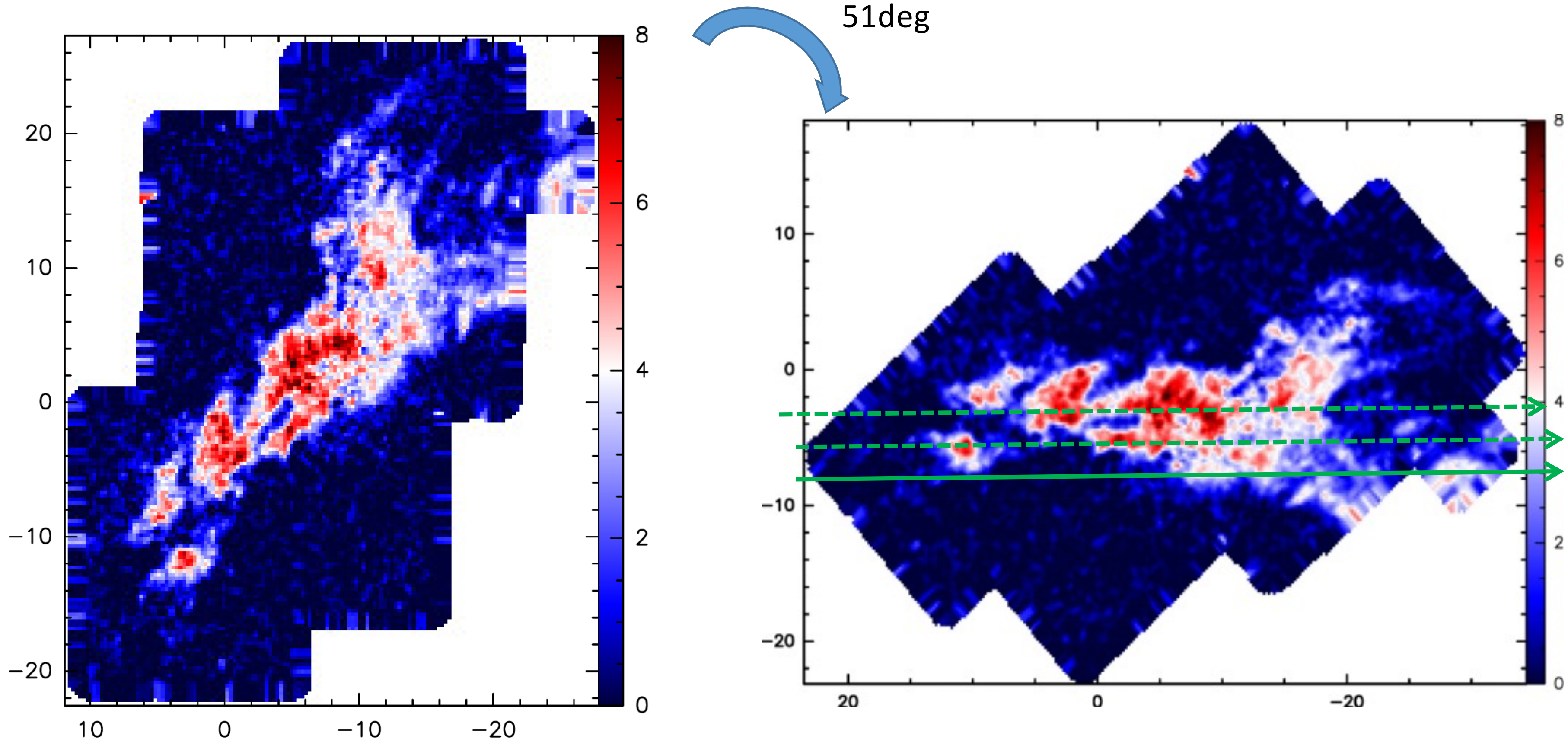
What we want to do...

- Determine the physical conditions in both structures, and dense cores
  - Temperature, column density, extinction...
- Provide quantitative constraints on the interplay between kinematics and magnetic fields
  - Magnetic to turbulent energy ratio
  - Gaz structures orientations with **B**
- Examine the dynamic repercussion of the colliding filaments
  - Markers of intermittency?
  - Constraints on the evolutionary state of dense cores?

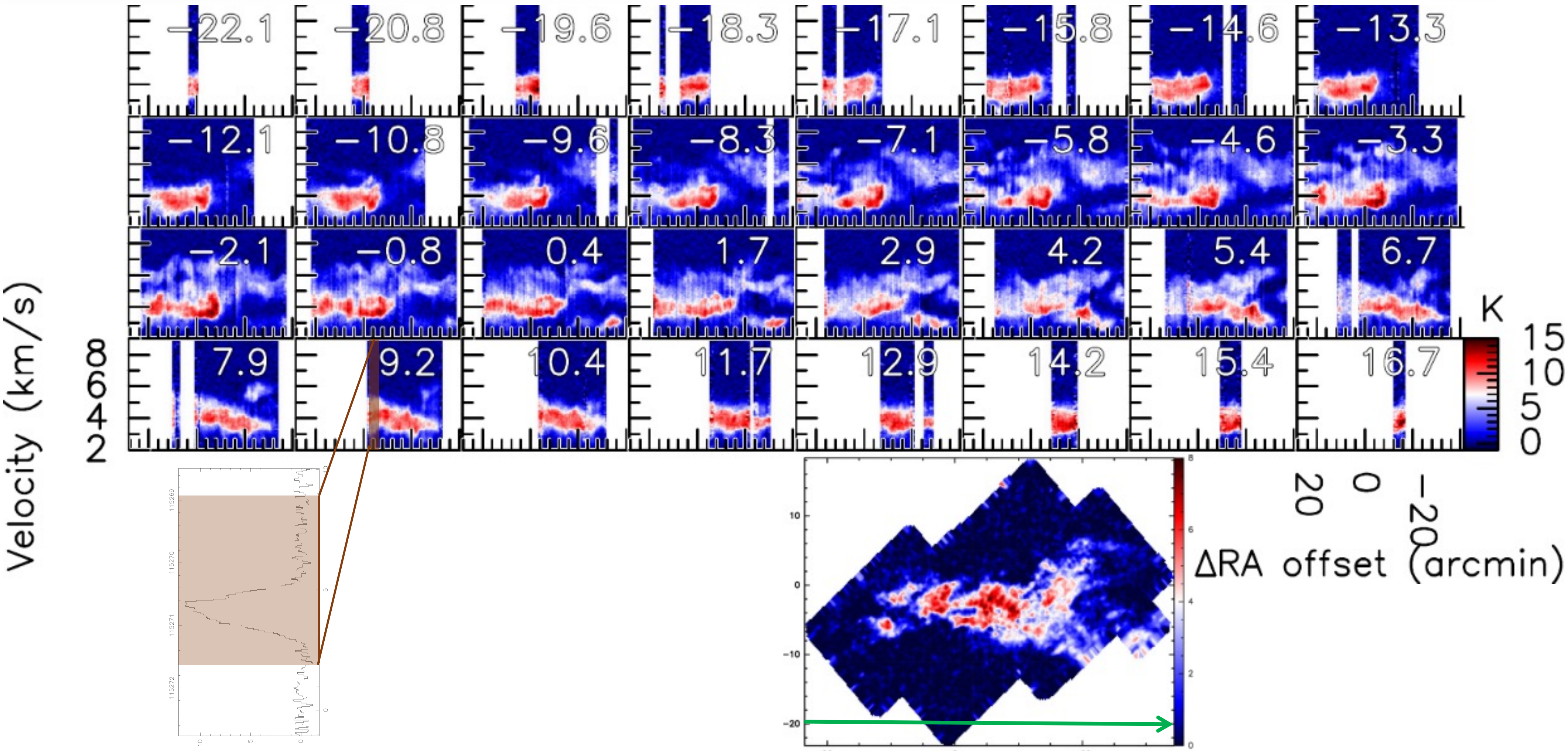


Herschel-SPIRE view at 500μm

Annexe PV-cut: preparing Position-Velocity cut

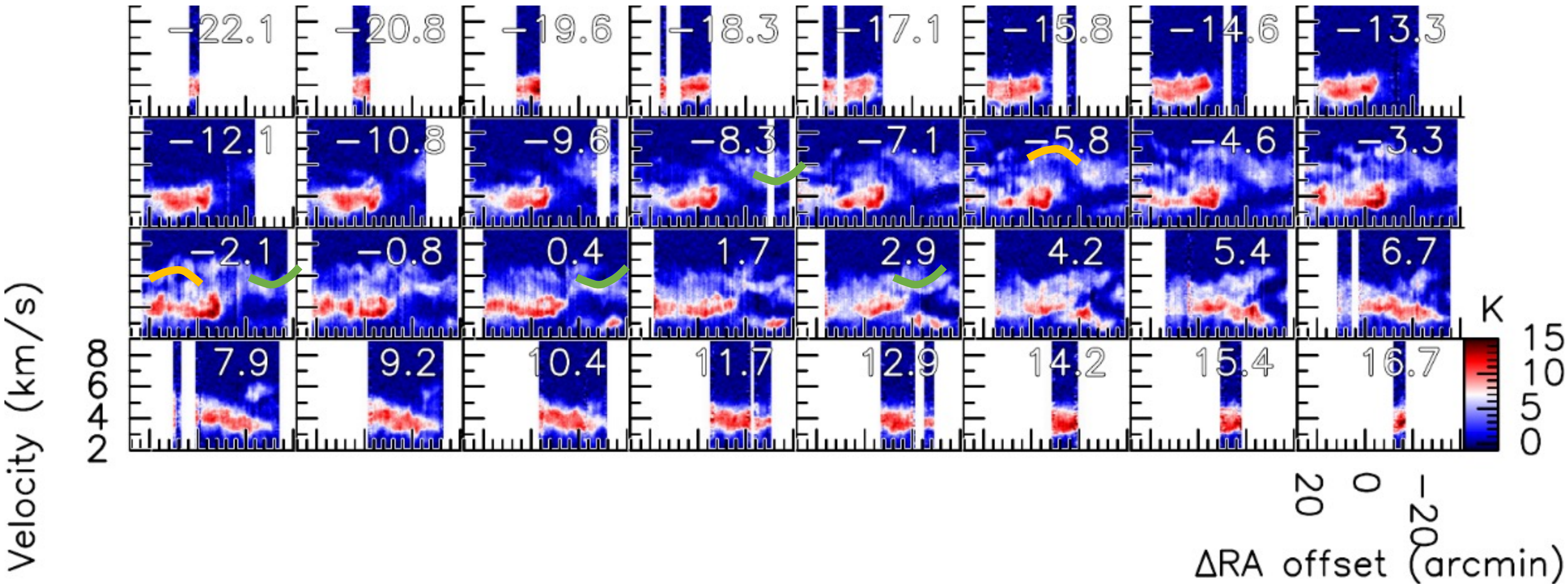


Annexe PV-cut: oscillation visible in velocity space



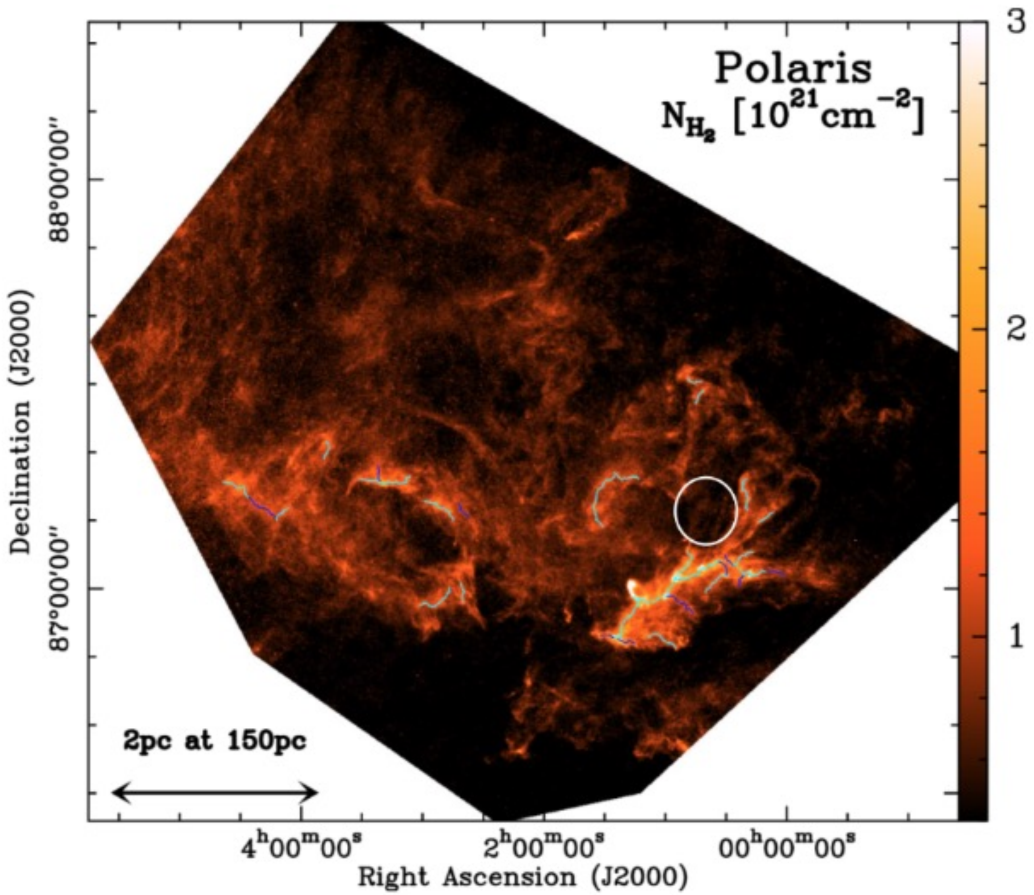
Annexe PV-cut: oscillation visible in velocity space

- Sinewave velocity profiles, with phase shifting
    - ➢ Helical flows aligned with **B** ?



Comparisons with the Polaris flare molecular cloud

Herschel column density, from Arzoumanian+20019.



- Network of tenuous and dense filaments
- Located in a low star formation rate
- Superposition of 2 velocity structures coherent on parsec scale
- Vicinity of dense cores located at the velocity overlap
- BUT a magnetic field **less ordonate**
- Nearby cloud $\sim 150\ pc$