Filaments, the Universal Nursery of Stars

Introduction on FUNS Survey and Physical Properties of L1478

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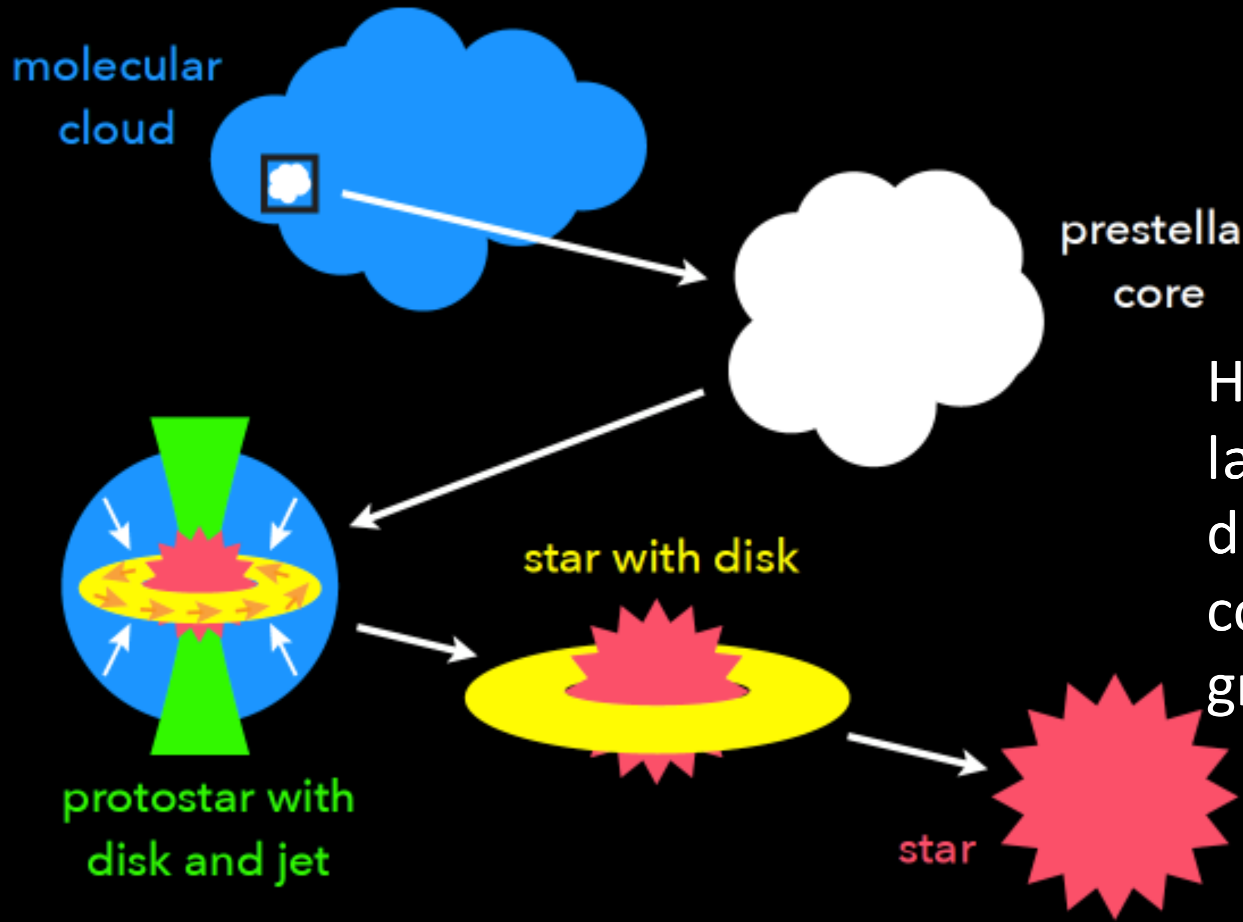
Classical Star Formation Model



Hierarchical fragmentation of the large "uniform and static" clouds due to their isothermal contraction in the beginning and gravitational collapse at the last

Recent IR and Radio Observations

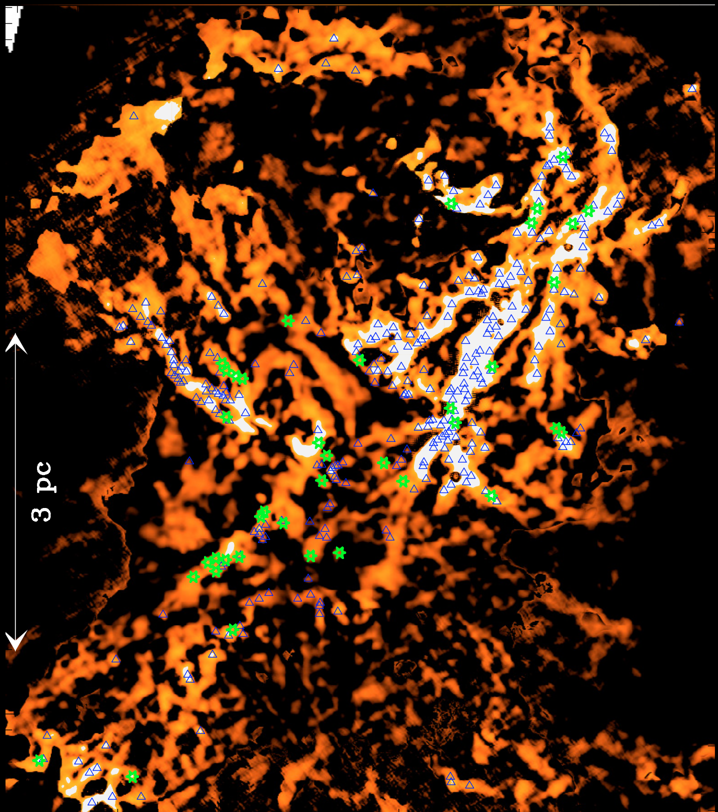
Filamentary and turbulent molecular clouds

Ubiquity of filamentary structure

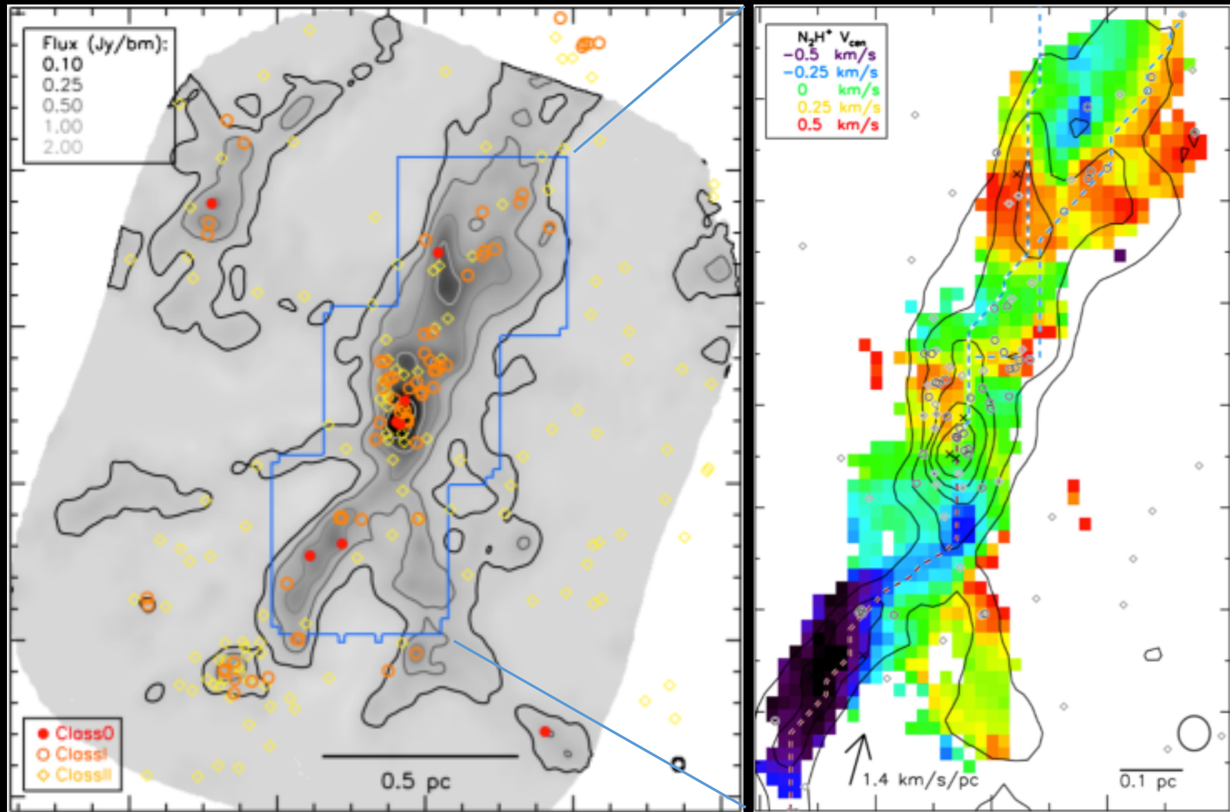
: preceding feature to any star formation activity in the clouds

(e.g., Arzoumanian et al. 2013)

From Filaments to Dense Cores



Column density map of Aquila from SPIRE/PACS data. The candidate Class 0 protostars and bound prestellar cores are shown as green stars and blue triangles, respectively. (e.g., Andre et al. 2010).



The centroid velocity measured for N2H+ across Serpens South showing Gas flow along the filament. The circles denote the YSOs. (Kirk. et al. 2013)

Questions

- How do the filaments, cores and stars form? In other words, do they form more by colliding flows or by self-gravity?
- Do their cores form at the same time as the filaments, or later by gravitational fragmentation?
- Do their cores gain mass more by axial flows along filaments, or by radial accretion onto the filaments?

Filaments studies

- are found from Legacy Survey of nearby Gould Belt's clouds Spitzer and Herschel Space Telescopes
- revolutionized the study of star formation process in molecular clouds
- most of the data are continuum emission and thus all physical properties on the filamentary structures are the integration of several different components to the line of sight, actually suffering from a lack of velocity information

We designed and proposed

TRAO Multi-beam Legacy Survey of
Nearby Filamentary Molecular Clouds.

Filaments, the Universal Nursery of Stars

FUNS Survey

- Goals
  - Velocity distribution of low dense filaments and their dense cores
  - Inward motions toward dense cores from their surrounding filaments
  - Chemical differentiation of filaments and their dense cores

- Observing Strategy

Setup	Line	RMS [K]	ΔV [km/sec]
Filament kinematics	^{13}CO & $C^{18}O$ (1-0)	0.12	0.1 ~ 0.2
Core infall	N_2H^+ & HCO^+ (1-0)	0.07	0.06
Chemical evolution	SO (32-21) & NH_2D (1-0)	0.05	0.1

FUNS Target

	R.A.	Dec.	distance	SF property *	σ_{NT}/σ_T **	Classification ***
Polaris	01 55 00	+87 41 00	150 pc	Quiescent [A11]	0.98 [1]	1
IC 5146	02 48 00	+47 30 00	460 pc	quiescent LSF+active high mass SF [F09]	0.75 [1]	3+5
Perseus	03 37 00	+31 15 00	235 pc	Low and intermediate mass [B08]	2.80 [2]	3
Auriga	04 20 00	+38 05 00	450 pc	Relatively modest SF in GB, star-cluster-forming [H13]		4
Taurus	04 32 00	+26 10 00	140 pc	Low-mass SF [M13]	1.05 [2]	2,3
Orion B	05 40 00	-02 00 00	415 pc	Active, High mass [N98]	2.95 [3]	5
Scorpius	16 51 00	-25 20 00	145 pc	Active, High mass [B00]	2.01[9]	5
Serpens	18 23 00	-03 10 00	230 pc	Active, Low mass SF cloud [B13]	4.13 [8]	3
Aquila	18 32 00	-02 00 00	260 pc	Active [A11]	0.46 [1]	4
Cepheus	21 20 00	+72 30 00	~300 pc	L1251A - Low to intermediate mass SF [K08]	1.12 [9]	2,3

* star formation property (References: [A11] Arzoumanian+2011, [B00] Bhatt2000, [B08] Bally+2008, [B11] Belloche+2011, [B13] Burleigh+2013, [D12] Duarte-Cabral+2012, [F09] France+2009, [G15] Glenn+2015, [H13] Harvey+2013, [K08] Kun+2008, [L08] Luhman+M2008, [M02] Moreira+Y2002, [M13] Meng+2013, [N89] Nyman+1989, [N98] Nagahama+1998, [P11] Peterson+2011, [S08] Spezzi+2008, [T96] Tachihara+1996)

** ratio of non-thermal velocity dispersion to thermal velocity dispersion (using $C^{18}O$(1-0) linewidth and assuming 10 K)

References: [1] Arzoumanian+2013, [2] Meng+2013, [3] Shimajiri+2014, [4] Vilas-Boas+1994, [5] Hara+1999, [6] Glenn+2015, [7] Onishi+1999, [8] Graves+2010, [9] Vilas-Boas+2000

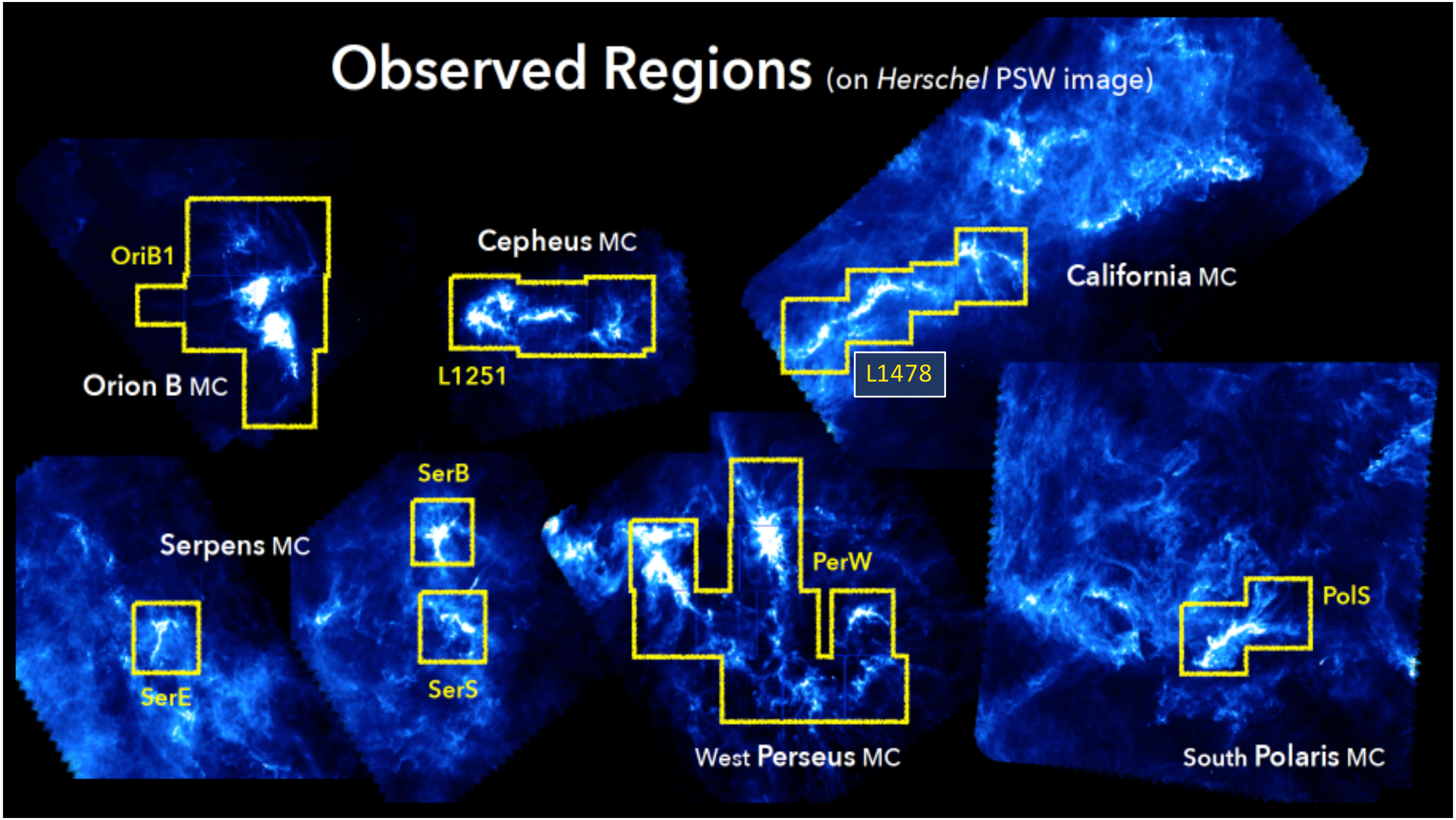
*** groups classified with their SF characteristics

1 : quiescent NSF, 2 : quiescent LSF, 3 : turbulent LSF, 4 : Star-cluster-forming, 5 : high-mass SF

Observation

TRAO 14m with SEQUOIA
Jan. 2016 –

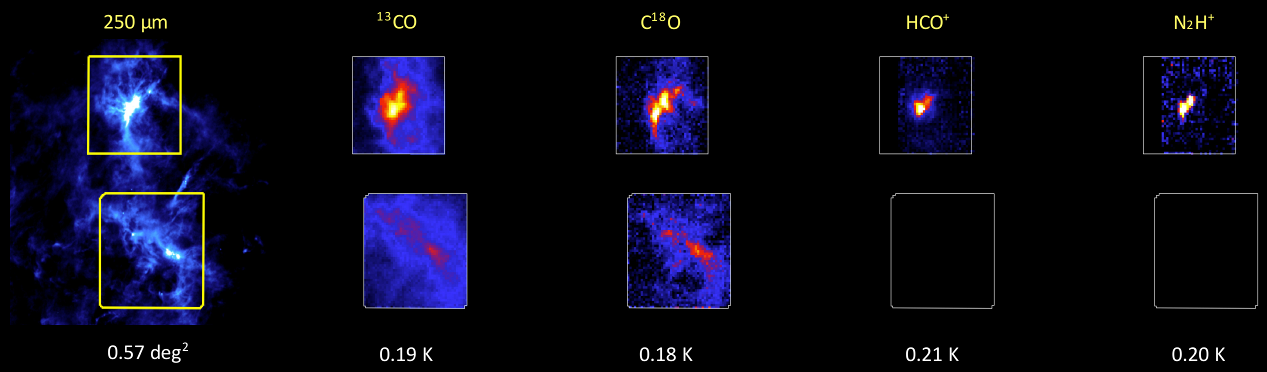
- 4x4 array receiver (SEQUOIA-TRAO) with $\Delta\theta$~47″ @ 110 GHz
- 2 lines simultaneous obs. (85-100 or 100-115 GHz)
- 4096x2 channels with Δv ~ 0.05 km/s @ 110GHz


Observed Regions (on *Herschel* PSW image)
OriB1
Orion B MC
Cepheus MC
L1251
California MC
L1478
Serpens MC
SerB
SerS
SerE
PerW
West Perseus MC
PolS
South Polaris MC

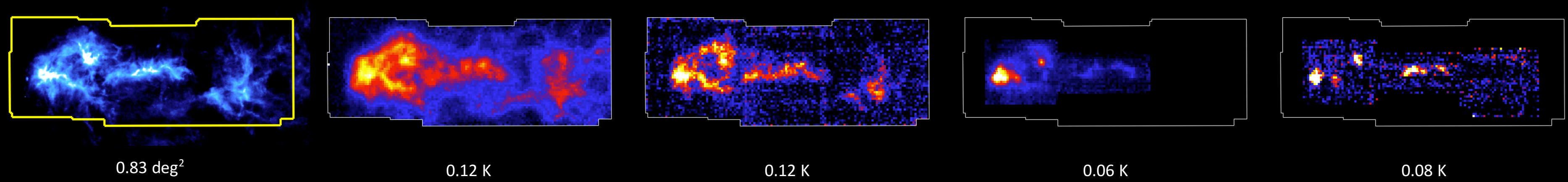
Observation Progress

6 targets
57 tiles
676 maps
7.1 deg^2

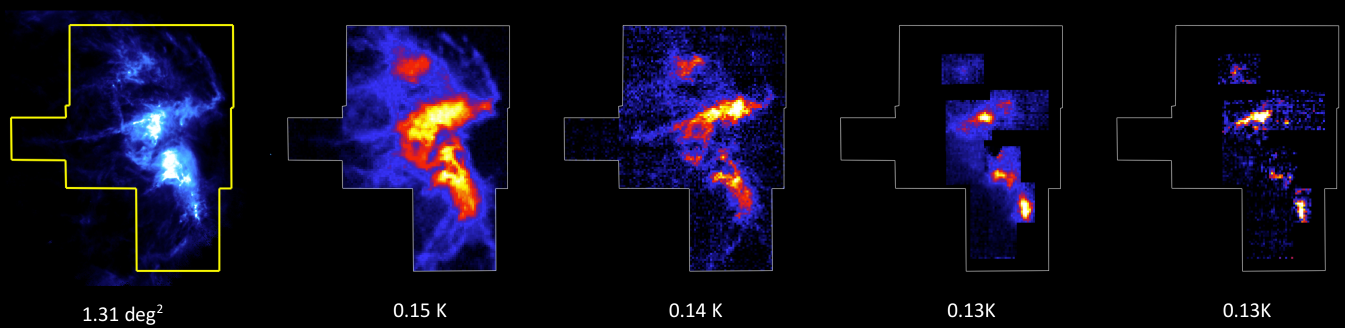
- Serpens

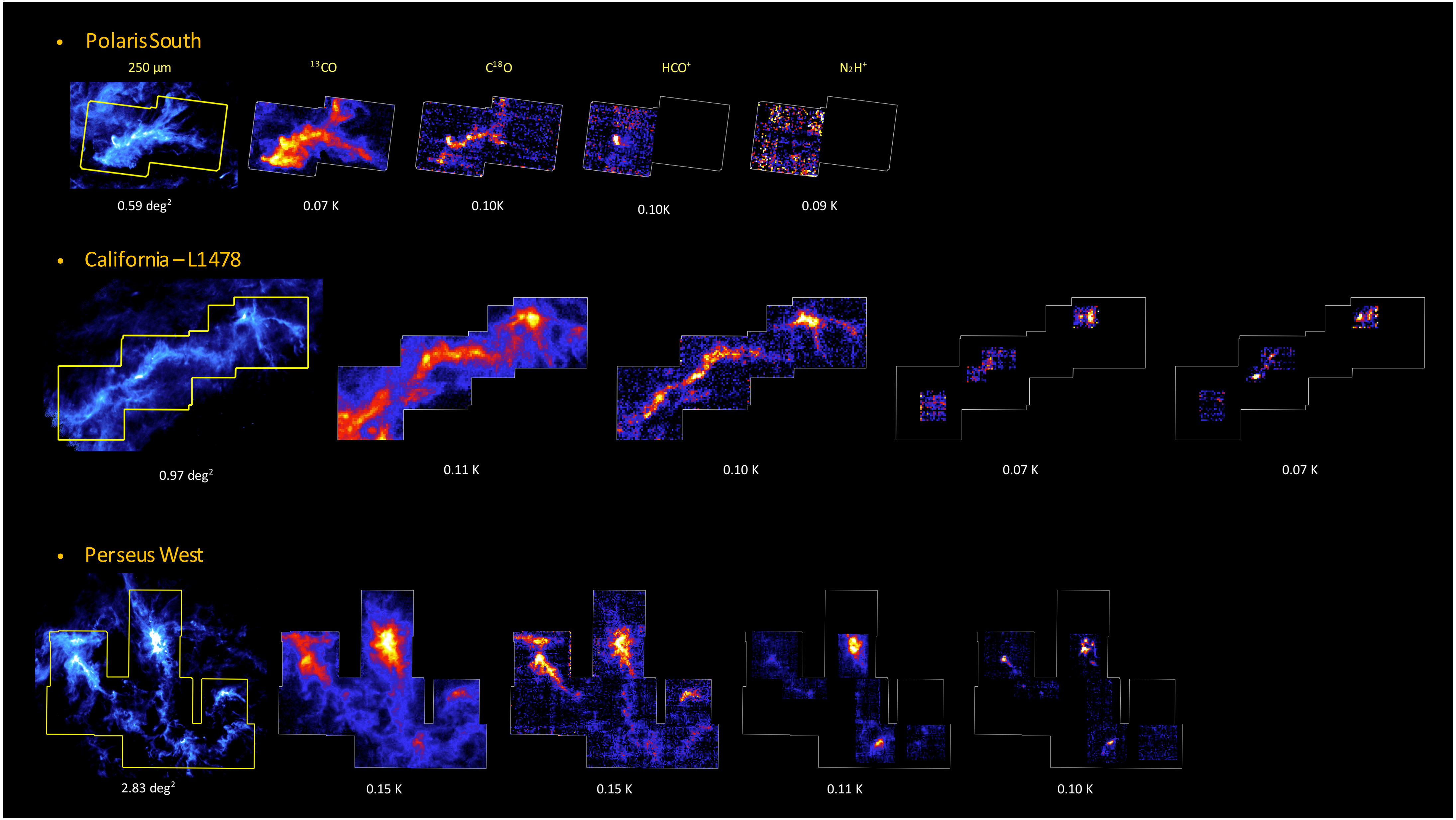


- L1251 (Cepheus)



- Orion B



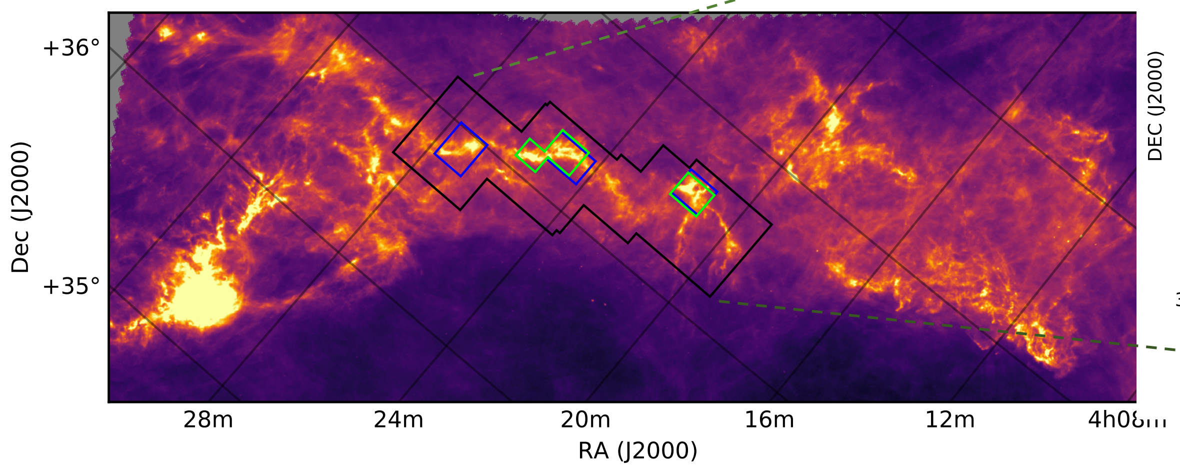


Polaris South
250 µm
13CO
C18O
HCO+
N2H+
0.59 deg2
0.07 K
0.10K
0.10K
0.09 K
California – L1478
0.97 deg2
0.11 K
0.10 K
0.07 K
0.07 K
Perseus West
2.83 deg2
0.15 K
0.15 K
0.11 K
0.10 K

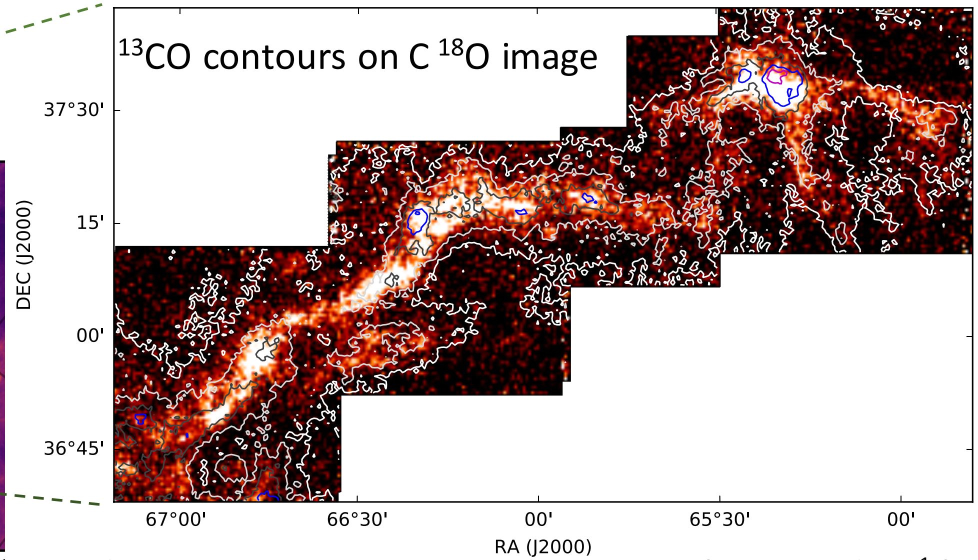
Filaments and Dense Cores of L1478 in CMC

California MC
- Distance ~ 450±23 pc (Lada+2009)
- Mass ~ 10^5 $M_{\odot}$ (Lada+2009)
- Modest star forming region (Harvey+2013)

$C^{18}O$ and ^{13}CO data cubes
- 1.1 square degree area
- rms level ~ 0.1 K (w/ $\Delta\theta_{cell}$~44″ and ΔV~0.1 km s^{-1})

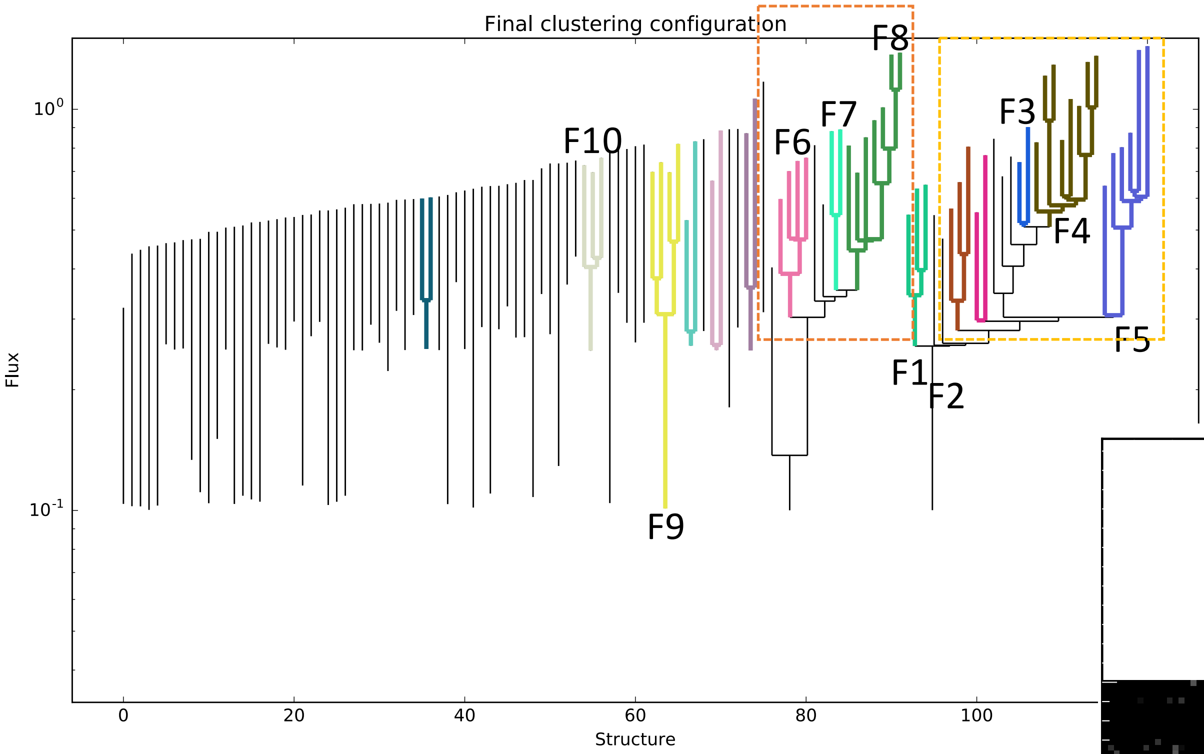


Herschel 250 μm image of California MC



The maps are integrated over a velocity range of -3.2 to 0.6 km s^{-1} for $C^{18}O$, and -3.8 to 2.3 km s^{-1} for ^{13}CO. The contour levels of ^{13}CO are 5, 9, 13, 17, and 21σ_{rms}.

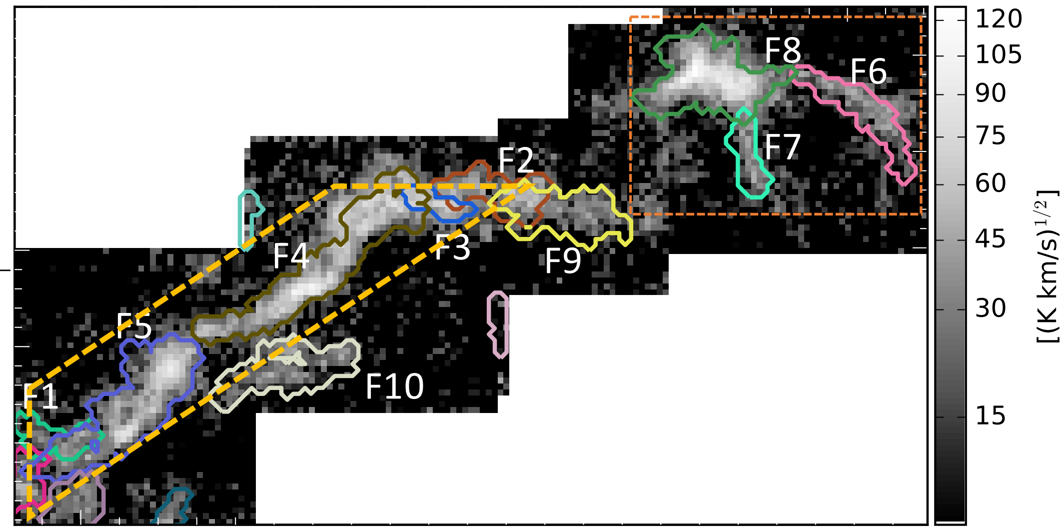
Filaments Identification with $C^{18}O$ Data Cube



d = Dendrogram.compute(data, min_value=1σ_{rms}, min_delta=2σ_{rms}, min_npix=4*ppb, verbose = 1)

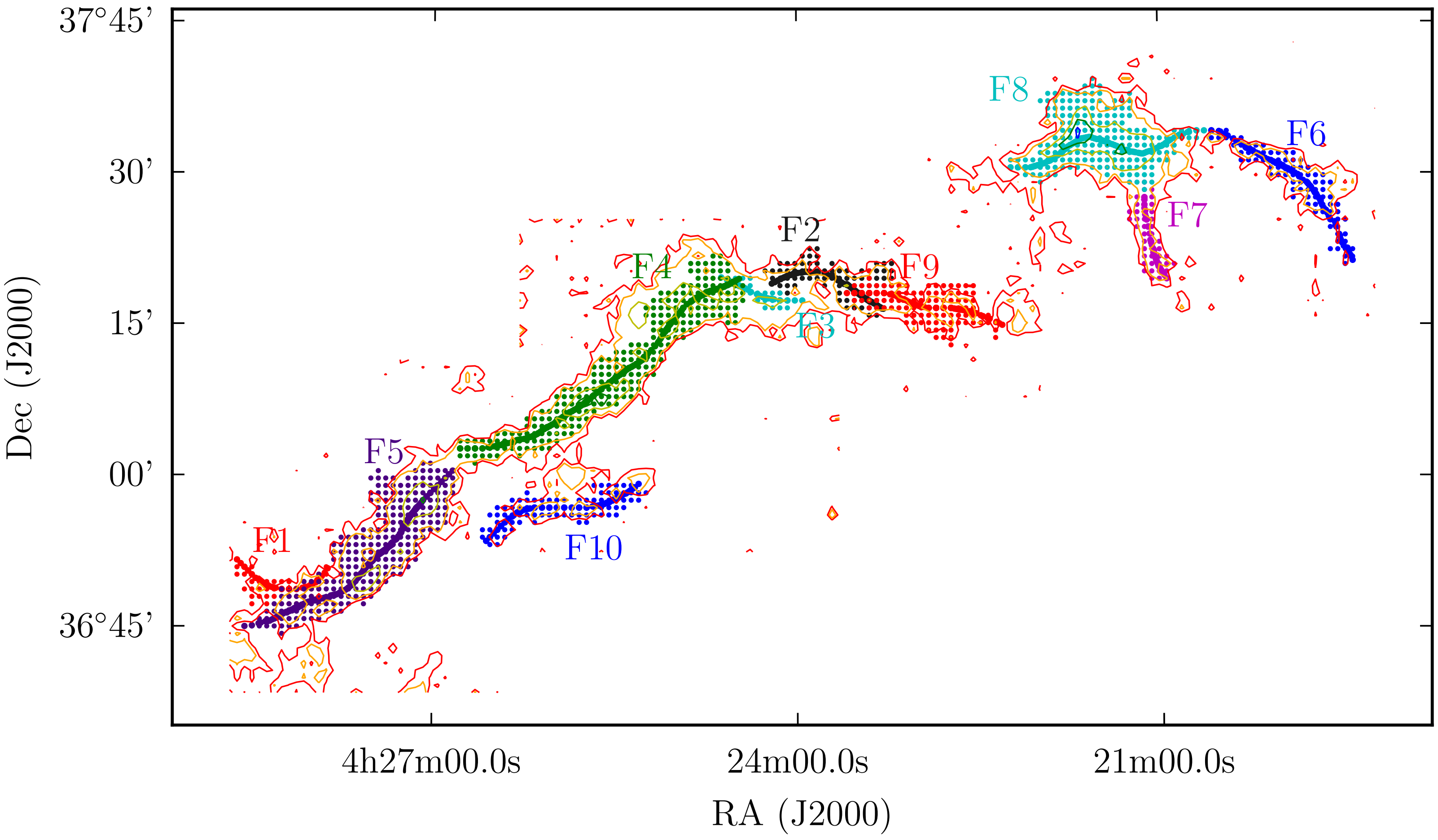
Final cluster number (after cleaning) 15

⇒ 10 clusters are selected.



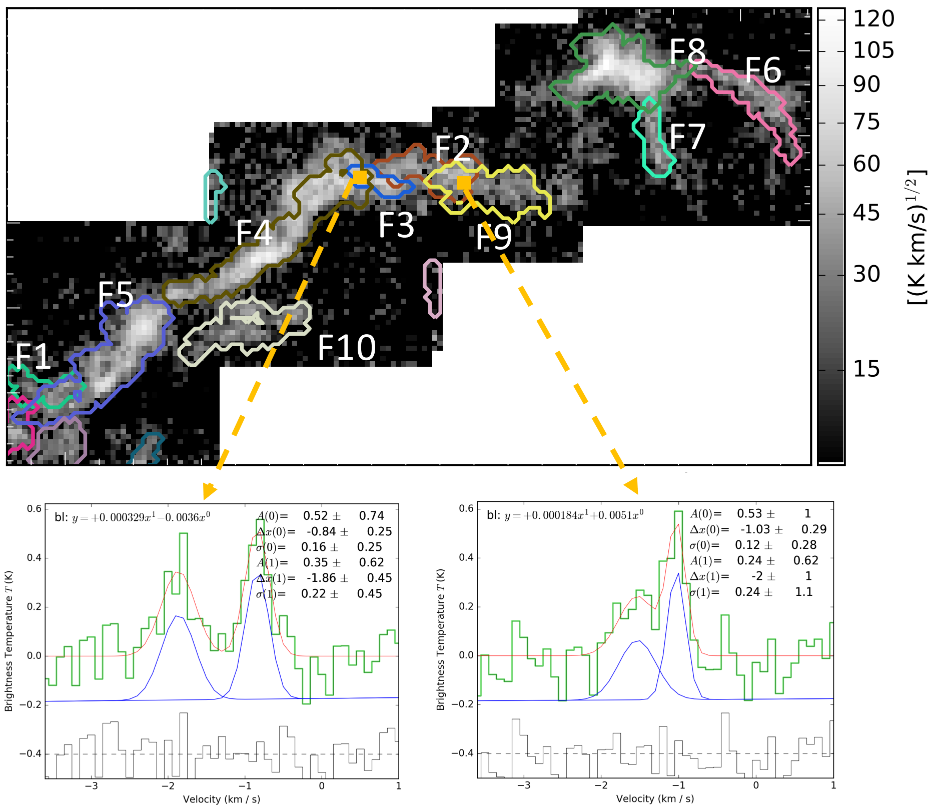
Skeletons : Find skeleton with FilFinder

(MST method – with inscribed circle and decide its skeleton)

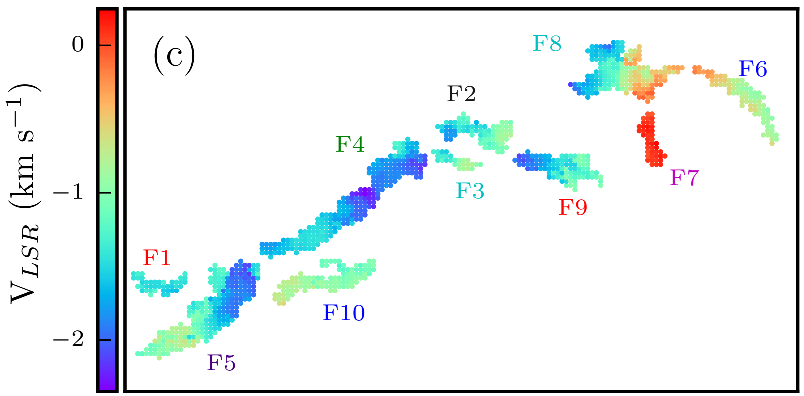


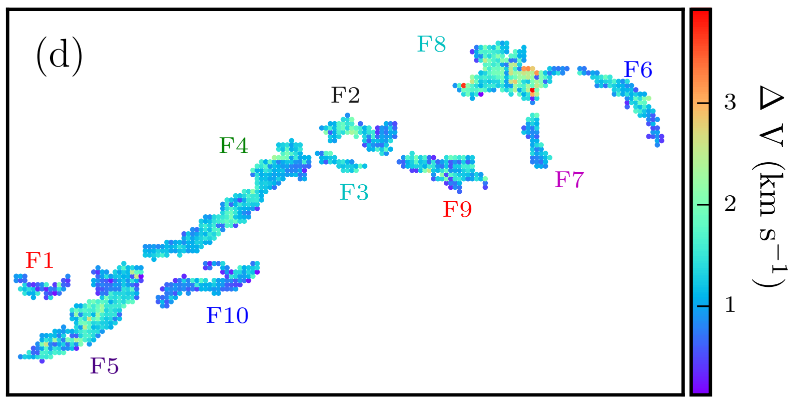
V_{lsr} and Line Widths of $C^{18}O$

Gaussian fitting for $C^{18}O$ spectra (> $3\boldsymbol{\sigma}_{rms}$) with PYTHON code based on the Dendrogram results



Gaussian Peak Velocity maps of Filaments





Line Widths maps of Filaments

H_2 Column Density from $C^{18}O(1\text{-}0)$

following Pattle+2015

Column density N (Garden+1991) :

$$N = \frac{3k_B}{8\pi^3 B\mu_D^2} \frac{e^{hBJ(J+1)/k_B T_{ex}}}{J+1} \frac{T_{ex} + \frac{hB}{3k_B}}{1 - e^{-h\nu/k_B T_{ex}}} \int \tau dv$$

B : rotational constant

μ : permanent dipole moment of the molecule

J : lower rotational level

T_{ex} : excitation temperature (Pineda+2008)

$$T_{ex} = \frac{T_0}{\ln\left(1 + T_0\left(\frac{T_R}{1-e^{-\tau}} + \frac{T_0}{e^{T_0/T_{bg}}-1}\right)^{-1}\right)}$$

$T_0 = h\nu / k_B$

T_{bg} : CMB temperature (2.73 K)

T_R : radiation temperature – T_R of ^{13}CO

$$\int \tau(v)dv = \frac{1}{J(T_{ex}) - J(T_{bg})} \int \frac{\tau(v)}{1-e^{-\tau(v)}} T_{MB} dv$$

$$\approx \frac{1}{J(T_{ex}) - J(T_{bg})} \frac{\tau(v_0)}{1-e^{-\tau(v_0)}} \int T_{MB} dv$$

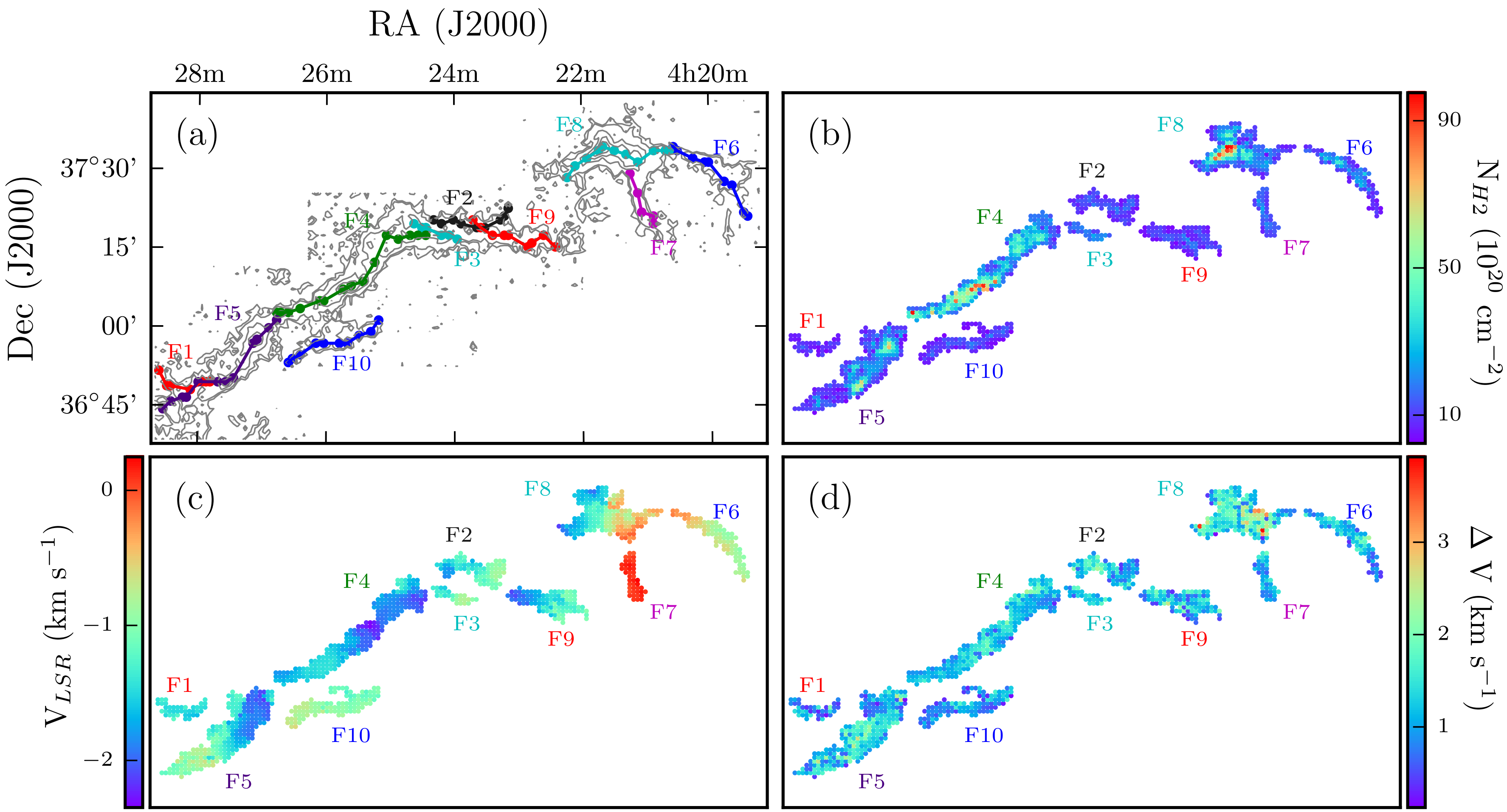
$$J(T) = \frac{T_0}{e^{T_0/T} - 1}$$

$$\frac{T_{max,C^{18}O}}{T_{max,^{13}CO}} = \frac{1-e^{-\tau_{C^{18}O}}}{1-e^{-\tau_{^{13}CO}}}$$

with $\tau_{13CO} = 5.5\tau_{C18O}$

Conversion factor of $X(C^{18}O) = 2.635 \times 10^{-7}$

(Pineda+2010, Frerking+1982, Wilson 1999)



(a) Locations of ten identied filaments (ridges) on top of the integrated intensity map of $C^{18}O$ (contours are 3, 6, 9, and 12×σ in K km s^{-1}. **(b)** - **(d)** H_2 column density, velocity field, and linewidths maps of each filament. V_{LSR} and ΔV (linewidth) are derived quantities by gaussian fitting method. Small offset is given to the original position of each filament to avoid spatial overlaps of filaments.

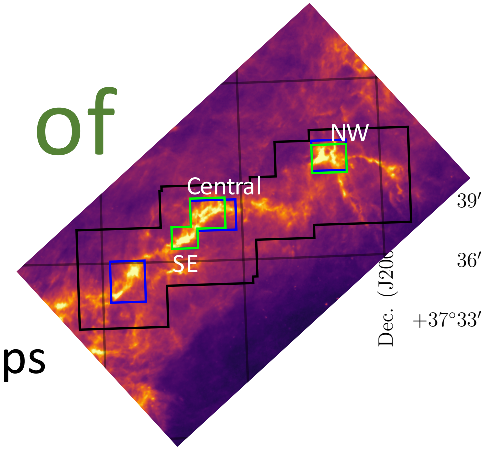
Physical Properties of Filaments

Table 2. Physical Properties of Filaments

Fil. ID	V_{lsr} range (km s^{-1})	L (pc)	$\bar{W}$ (pc)	M ($M_\odot$)	$\bar{M}_{lin}$ ($M_\odot$ pc^{-1})	ΔV_{lsr} (km s^{-1})	$\lvert\nabla \bar{V}_{lsr}\rvert$ (km s^{-1} pc^{-1})	YSOs [a]
1	-1.7 to -1.2	0.45	0.10	6.9±	15.3	0.5	1.12	
2	-1.9 to -0.8	0.51	0.12	17.8±	30.8	1.1	1.90	
3	-1.6 to -0.8	0.35	0.07	9.4±	30.7	0.8	2.61	
4	-2.3 to -1.3	1.40	0.08	216.1±	149.0	1.0	0.69	2
5	-2.2 to -0.6	1.12	0.19	85.6±	68.7	1.6	1.28	
6	-1.0 to -0.2	0.83	0.10	25.7±	28.6	0.8	0.89	
7	0.0 to 0.3	0.35	0.13	12.3±	25.9	0.3	0.63	
8	-2.1 to -0.1	0.87		127.8±	144.5	2.0	2.26	2
9	-2.1 to -1.0	0.66	0.14	20.0±	28.5	1.1	1.57	
10	-1.3 to -0.6	0.70	0.08	19.3±	23.5	0.7	0.85	

[a] YSOs identified with *Spitzer* and *Herschel* (Broekhoven-Fiene et al. 2014)

Identification of Dense Cores

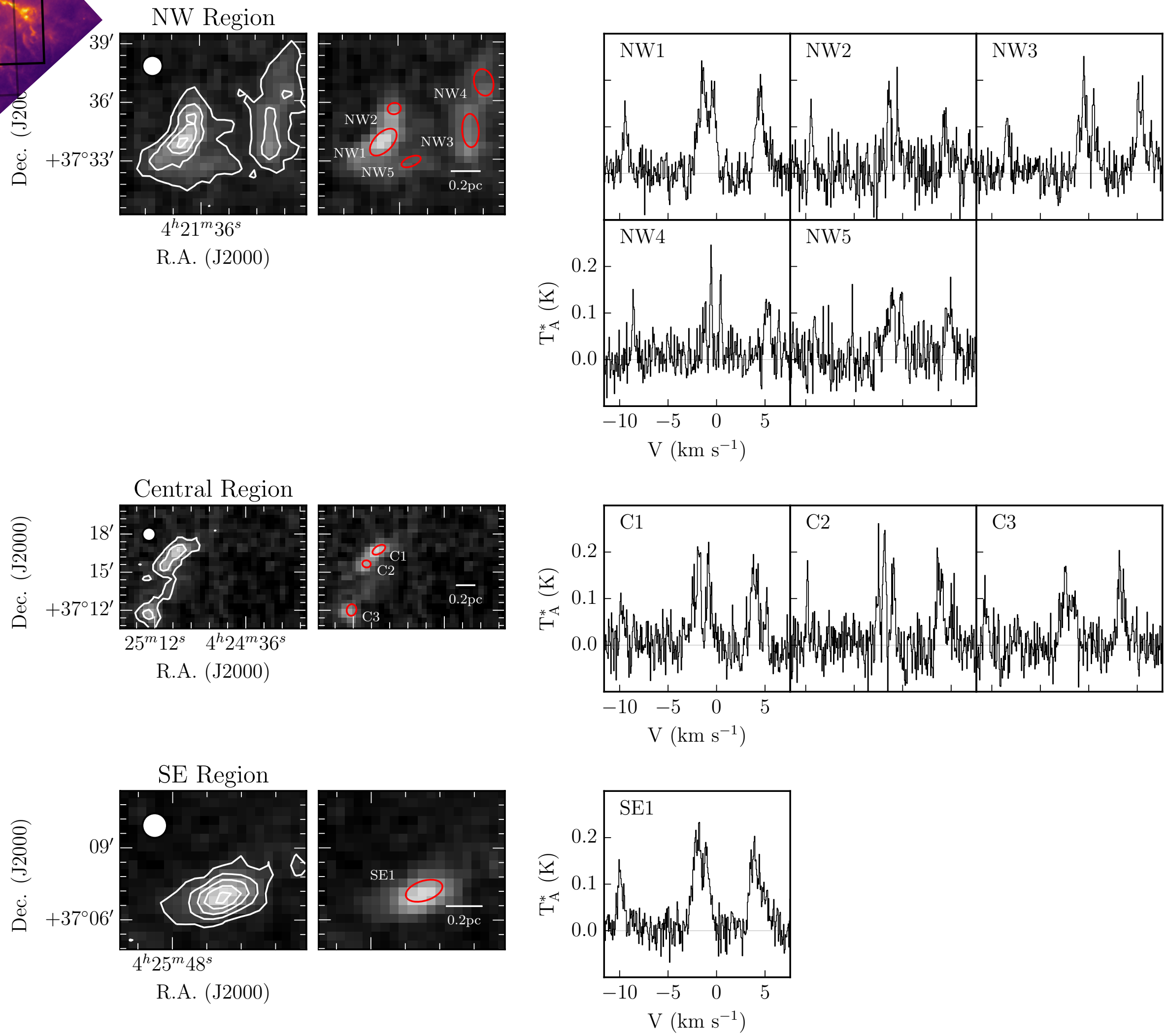


- N2H+(1-0) moment 0 maps
- FellWalker algorithm

Physical Properties of Cores

Core ID	Position		Size		PA
	RA (h:m:s)	Dec (° :′:″)	Major (pc)	Minor (pc)	(deg.)
NW1[a]	4:21:40.1	37:33:55.9	0.223	0.123	135
NW2[a]	4:21:37.1	37:35:38.8	0.090	0.076	102
NW3	4:21:17.5	37:34:29.2	0.225	0.112	3
NW4	4:21:13.9	37:36:56.6	0.182	0.128	15
NW5	4:21:32.9	37:32:55.8	0.137	0.063	112
C1	4:25:01.9	37:16:46.3	0.146	0.079	122
C2[b]	4:25:06.8	37:15:39.2	0.087	0.073	79
C3	4:25:12.7	37:12:01.5	0.121	0.099	168
SE1[a]	4:25:36.9	37:07:13.2	0.207	0.108	107

[a, b] Reported by Broekhoven-Fiene+2014 and Harvey+2013

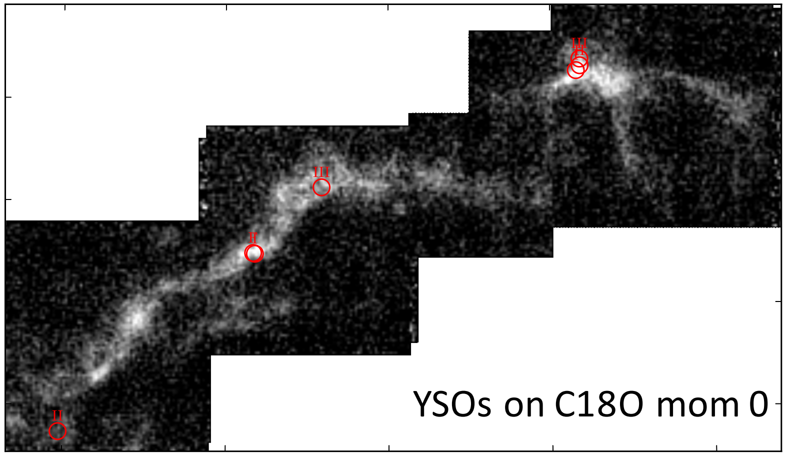


Are the filaments in L1478 gravitationally bound?

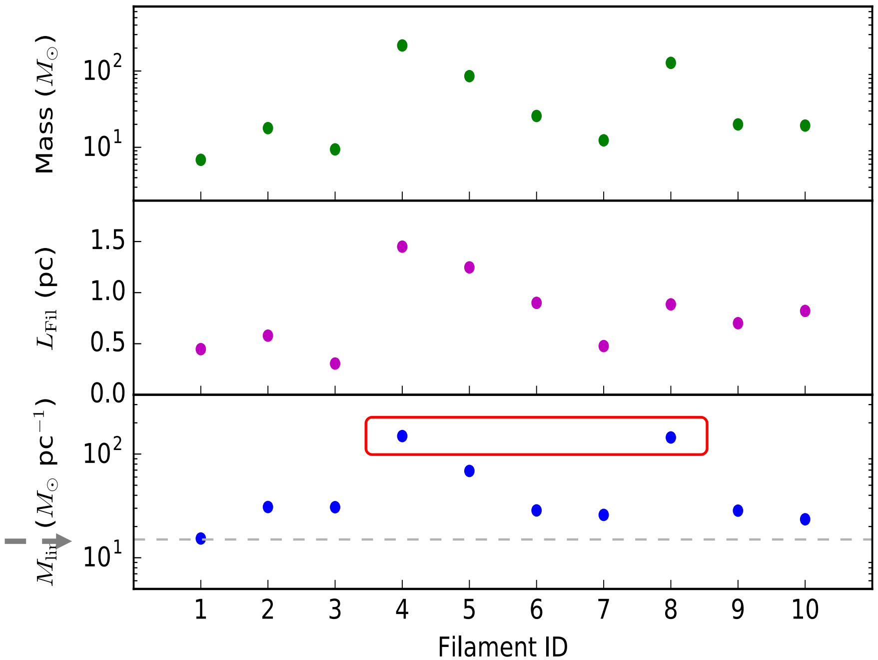
The critical line mass or mass per unit length for isothermal cylinder in pressure equilibrium

$M_{\mathrm{line,crit}} = 2c_s^2/G$ (Ostriker 1964), where c_s is the isothermal sound speed.

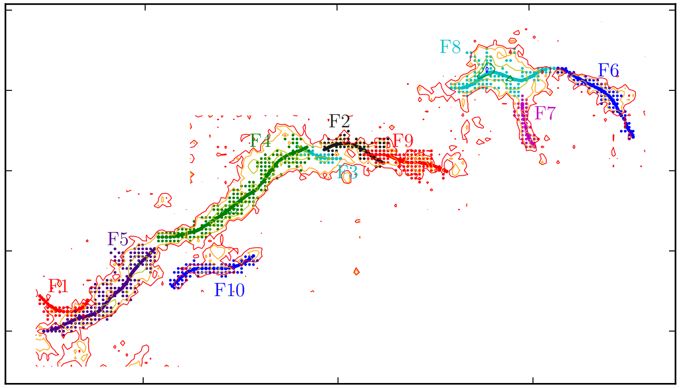
Inutsuka & Miyama (1992), (1997) showed that an unmagnetized isothermal filament is unstable to axisymmetric perturbations if $M_{\mathrm{line}} > M_{\mathrm{line,crit}}$.



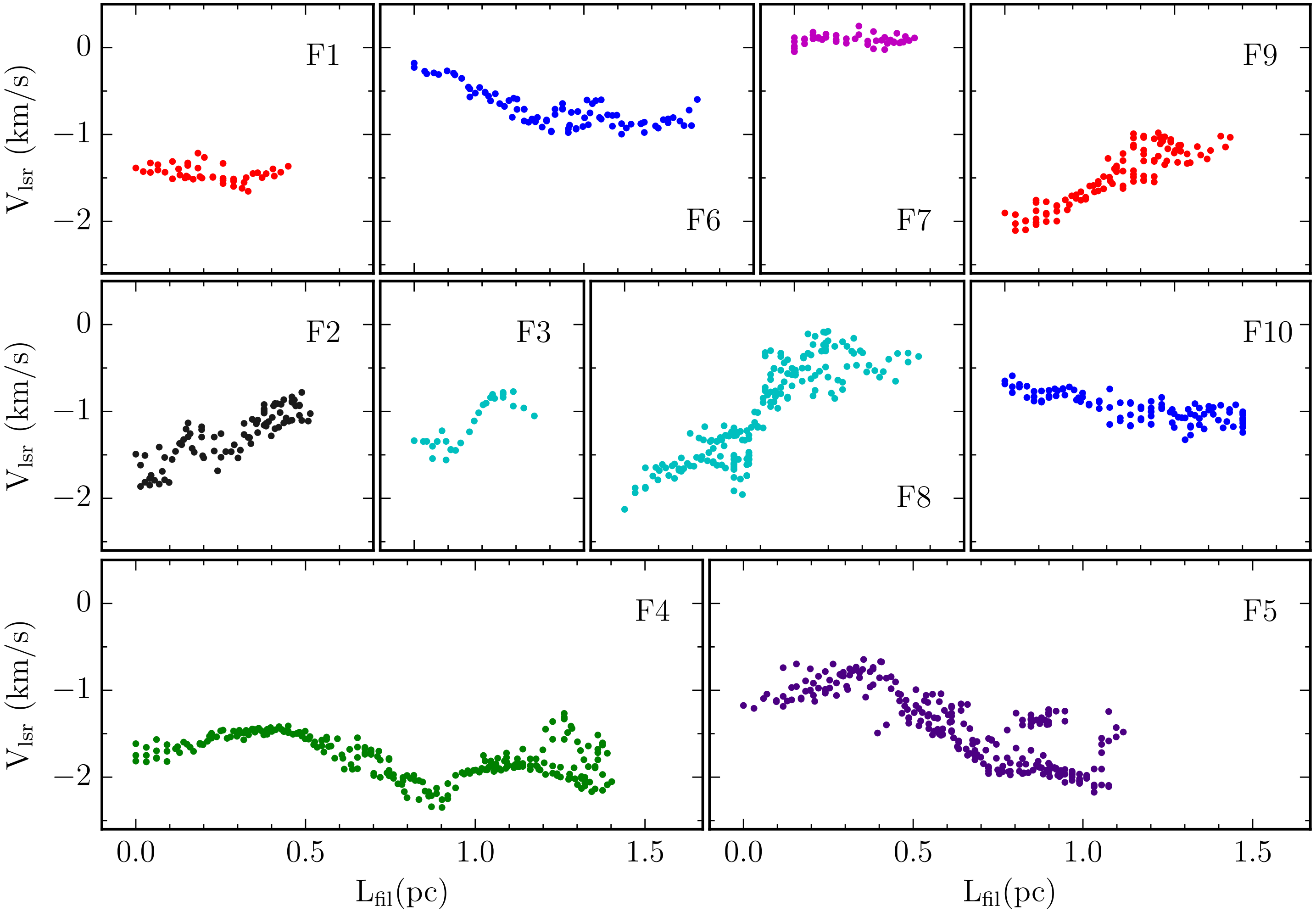
Equilibrium value (~15$M_{\odot}$ pc^{-1}) for isothermal cylinder in pressure equilibrium at 10K



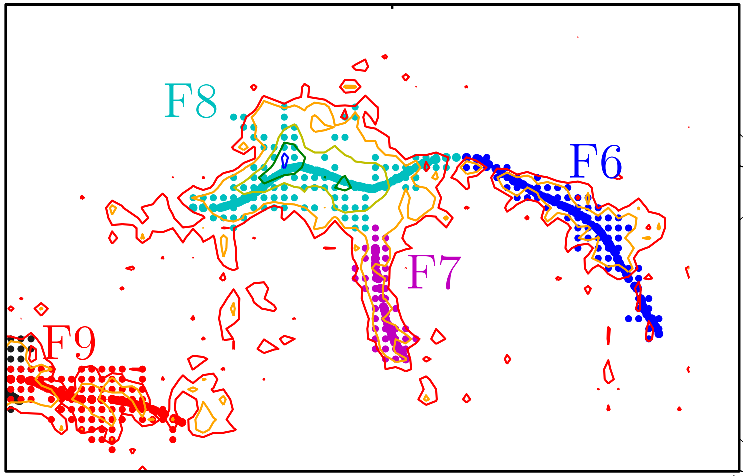
Is there any mass flow along the filaments?

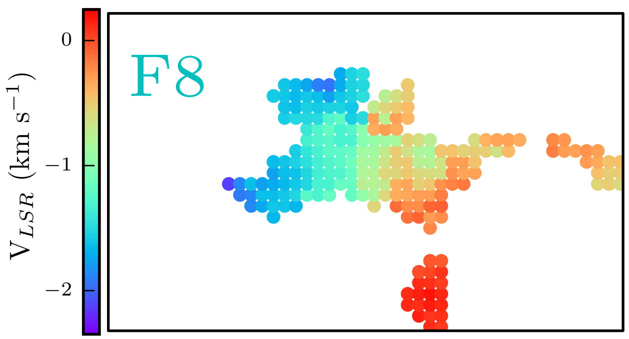


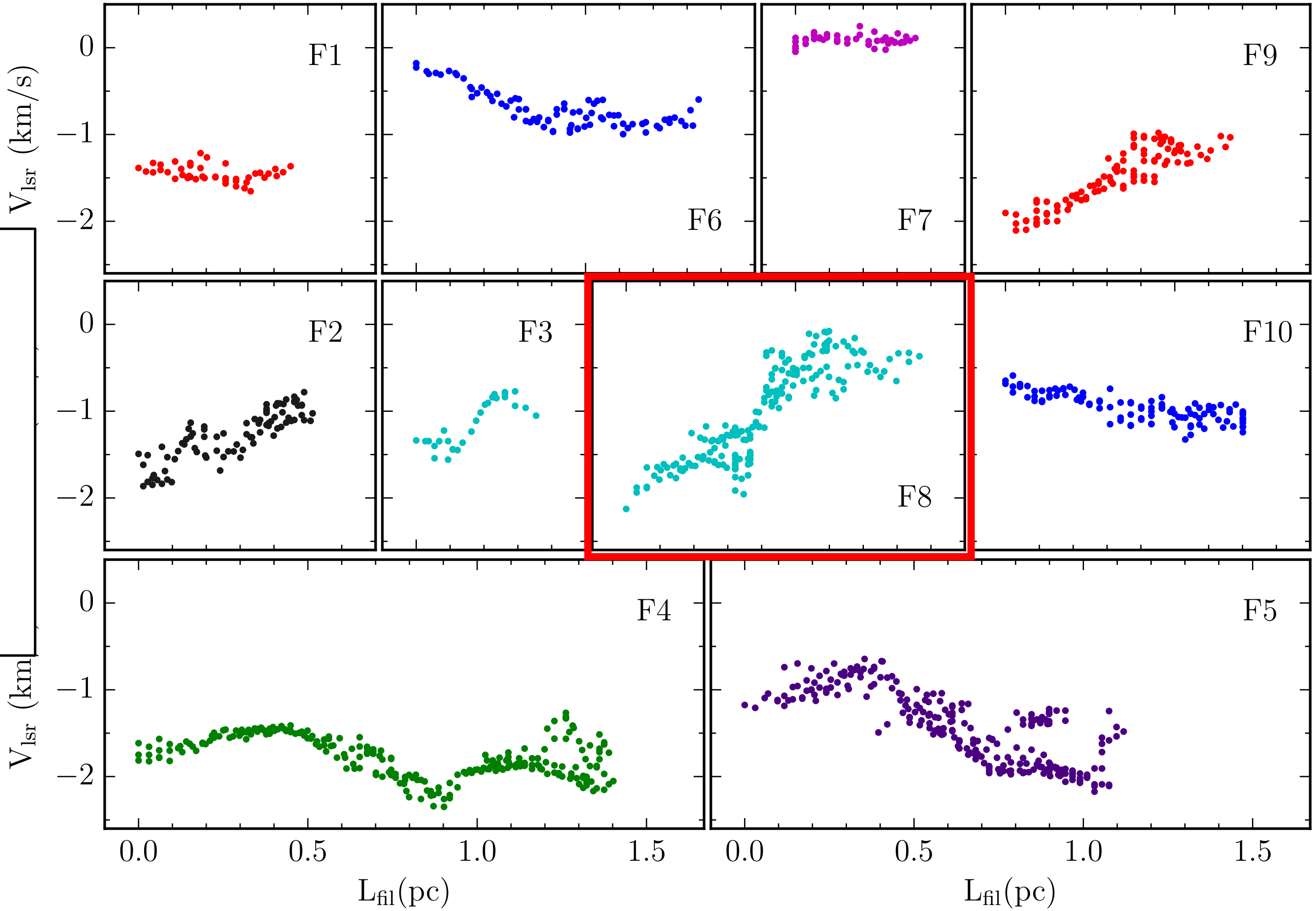
Fil. ID	V_{lsr} range (km s^{-1})	ΔV_{lsr} (km s^{-1})	$\lvert\nabla \bar{V}_{lsr}\rvert$ (km s^{-1} pc^{-1})
1	-1.7 to -1.2	0.5	1.12
2	-1.9 to -0.8	1.1	1.90
3	-1.6 to -0.8	0.8	2.61
4	-2.3 to -1.3	1.0	0.69
5	-2.2 to -0.6	1.6	1.28
6	-1.0 to -0.2	0.8	0.89
7	0.0 to 0.3	0.3	0.63
8	-2.1 to -0.1	2.0	2.26
9	-2.1 to -1.0	1.1	1.57
10	-1.3 to -0.6	0.7	0.85



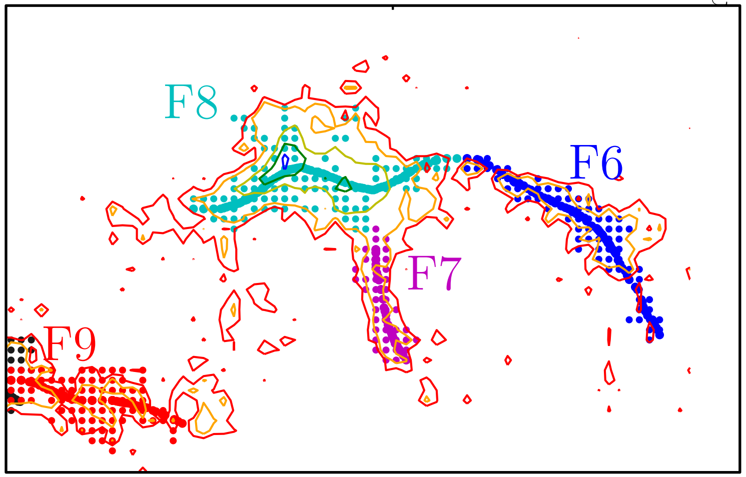
Hub-Filament structure of F8 :
morphology
and
velocity field

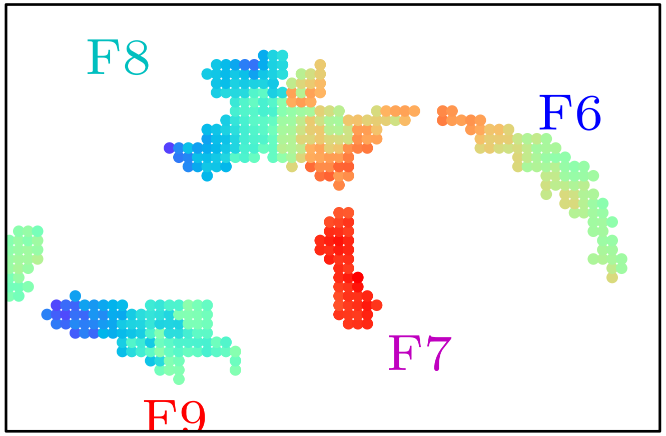


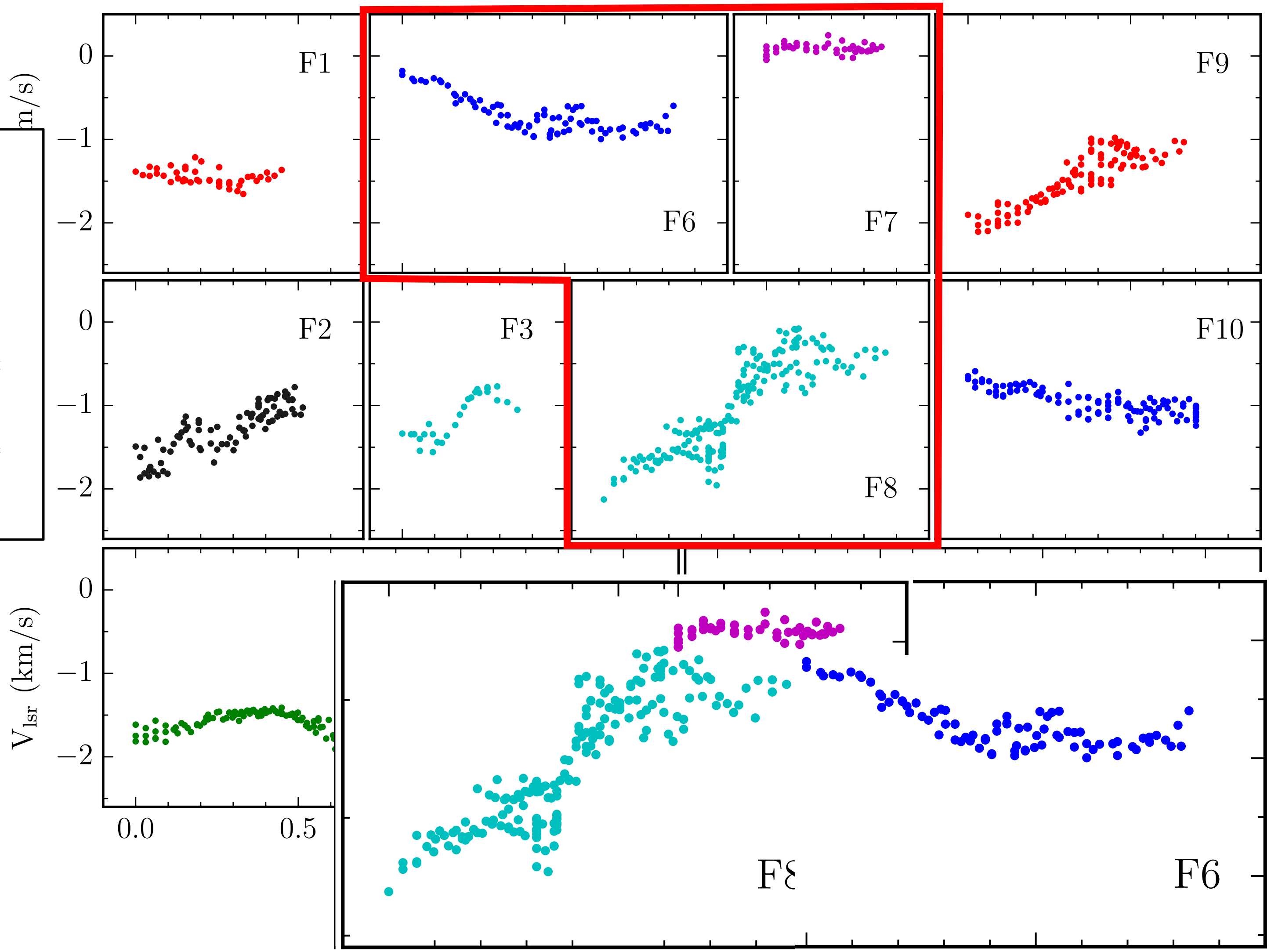




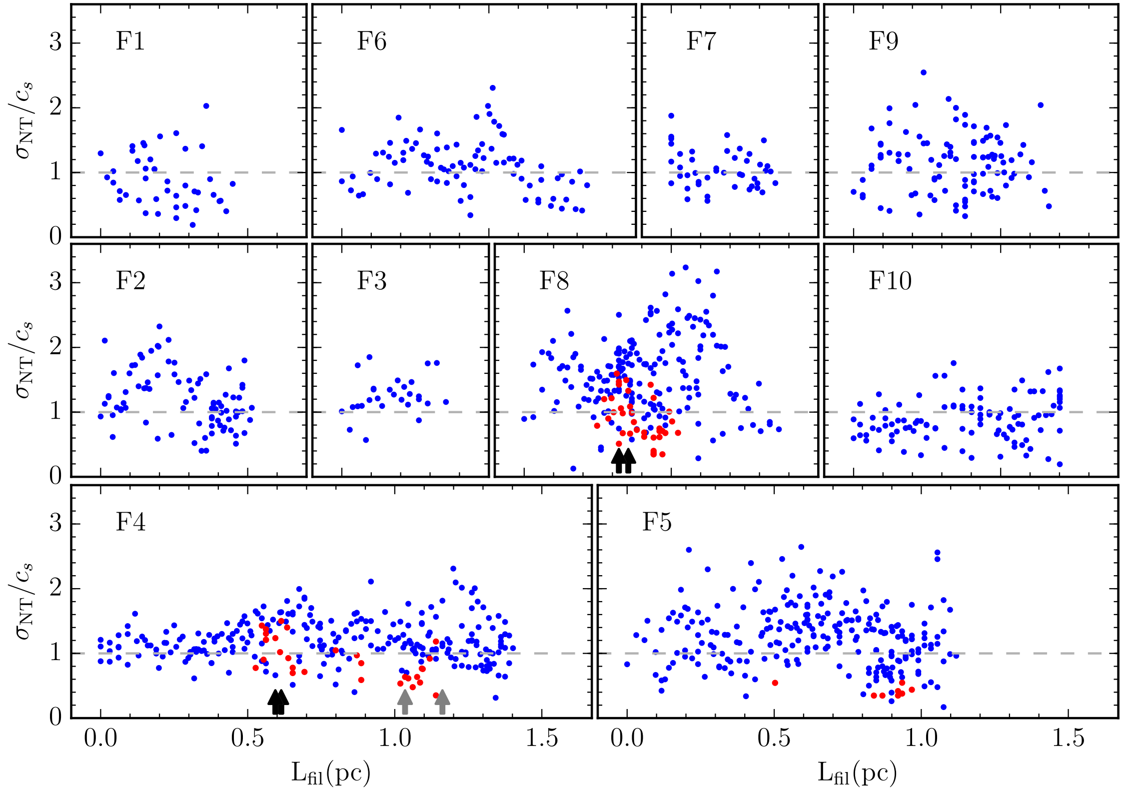
Hub-Filament structure :
F8 +F6+F7?







Do cores form by collisions of turbulent flows?



Colliding model (e.g., Padoan et al. 2001) :
large scale turbulent flows collide together
-> dense cores form due to turbulent dissipation
-> subsonic dense cores + turbulent filaments

- Nonthermal and thermal velocity dispersions :

$$\boldsymbol{\sigma}_{NT} = (\boldsymbol{\sigma}_{C18O}{}^2 - k\ T_{kin}/m_{C18O}\ )^{1/2}$$
$$\boldsymbol{\sigma}_{T} = (k\ T_{kin}/m_H\ \mu)^{1/2}$$

$\boldsymbol{\sigma}_{C18O}$ – vel. dispersion from $C^{18}O$ FWHM
k – Boltzmann constant
T_{kin} – dust temperature (assumed as 10 K)
m_{18CO} – mass of a C18O molecule
m_H – an atomic hydrogen mass
μ - mean molecular weight of a H_2 (=2.72) (Myers 1983)

Summary and Conclusions

- FUNS (Filaments, the Universal Nursery of Stars) survey with TRAO
- Filament identification of L1478 with C18O 1-0
- Core identification with N2H+ 1-0
- CMC is similar to Orion with the mass and size but its star formation property seems to be quite different, i.e., low mass SF
- Filaments with coherent velocity components,

  and hub-filaments structure
- Core evolutionary stages and mass flow along the filaments