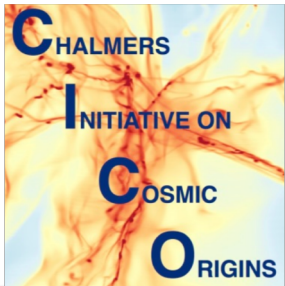


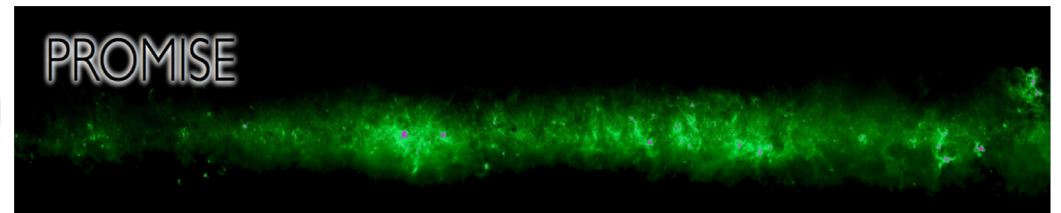
Are spiral filamentary structures ubiquitous in massive star-forming regions?

Sandra Patricia Treviño-Morales

J. Kainulainen, M. Zhang, M. Reiner, A. Fuente, J. R. Goicoechea, J. Cernicharo, Á. Sánchez-Monge, N. Schneider, P. Didelon, F. Motte, P. Tremblin, P. Hennebelle, S. Geen, J. Ballesteros, C. Kramer, T. Rayner, S. Suri



CHALMERS
UNIVERSITY OF TECHNOLOGY



PRobing the Origins of Masslve molecular cloud StructureE

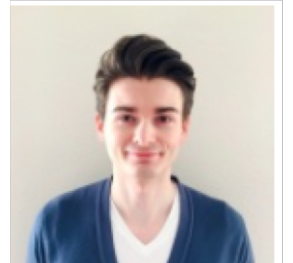


Jouni Kainulainen

Assistant profesor at Chalmers
Observational astronomer in the field of Galactic star formation and interstellar medium

Manuel Riener

PhD student at MPIA
Physical process controlling star formation in the Galactic molecular clouds; star formation in nerby galaxies



Andri Spilker

PhD student at Chalmers
Molecular cloud structure, star formation in the Milky Way



Miaomiao Zhang

Postdoc at MPIA
Young stellar objects; jets and outflows, Galactic star formation and interstellar medium



Sandra Treviño-Morales

Postdoc at Chalmers
Dynamics and fragmentation in Galactic molecular clouds from observational point of view; astrochemistry

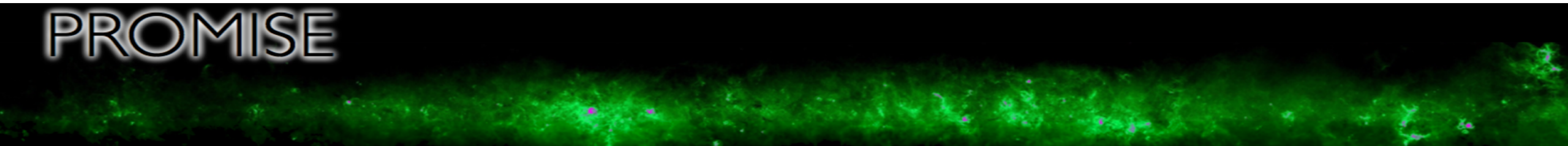


Jan Orkisz

Postdoc at Chalmers
Interstellar médium turbulence and magnetic fields, star formation



PROMISE



The birthplaces of the stars



Cepheus B



M16

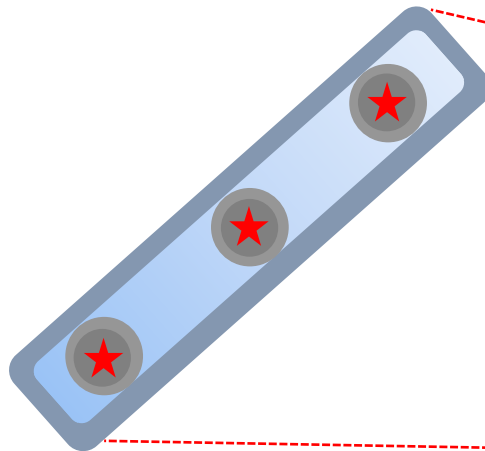


Barnard

The birthplaces of the stars

Molecular clouds formed by complex networks of filaments intersecting in high-density regions called hub

Star formation occurs along the filaments

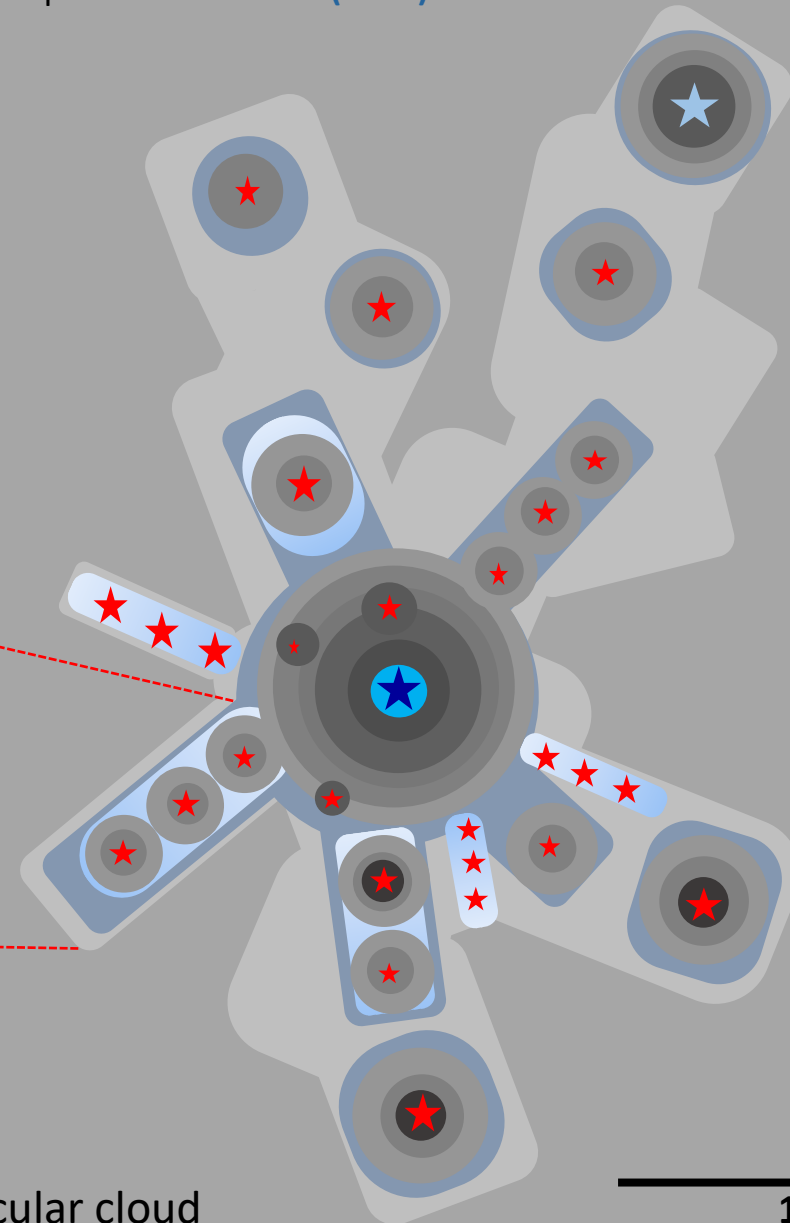


Andre et al. (2010), Molinari et al. (2010), Schneider et al. (2010), Csaengeri et al. (2011), Schneider et al. (2012), Hennemann et al. (2012), Busquet et al. (2013), Hacar et al. (2013), Peretto et al. (2014), Louvet et al. (2014), Tafalla & Hacar (2015), Smith et al. (2014), Henshaw et al. (2014), Tackenberg et al. (2014), Seifried & Walch (2015), Hacar et al. (2017)...

Figure adapted from [Baobab \(2010\)](#)

Molecular cloud

10 pc



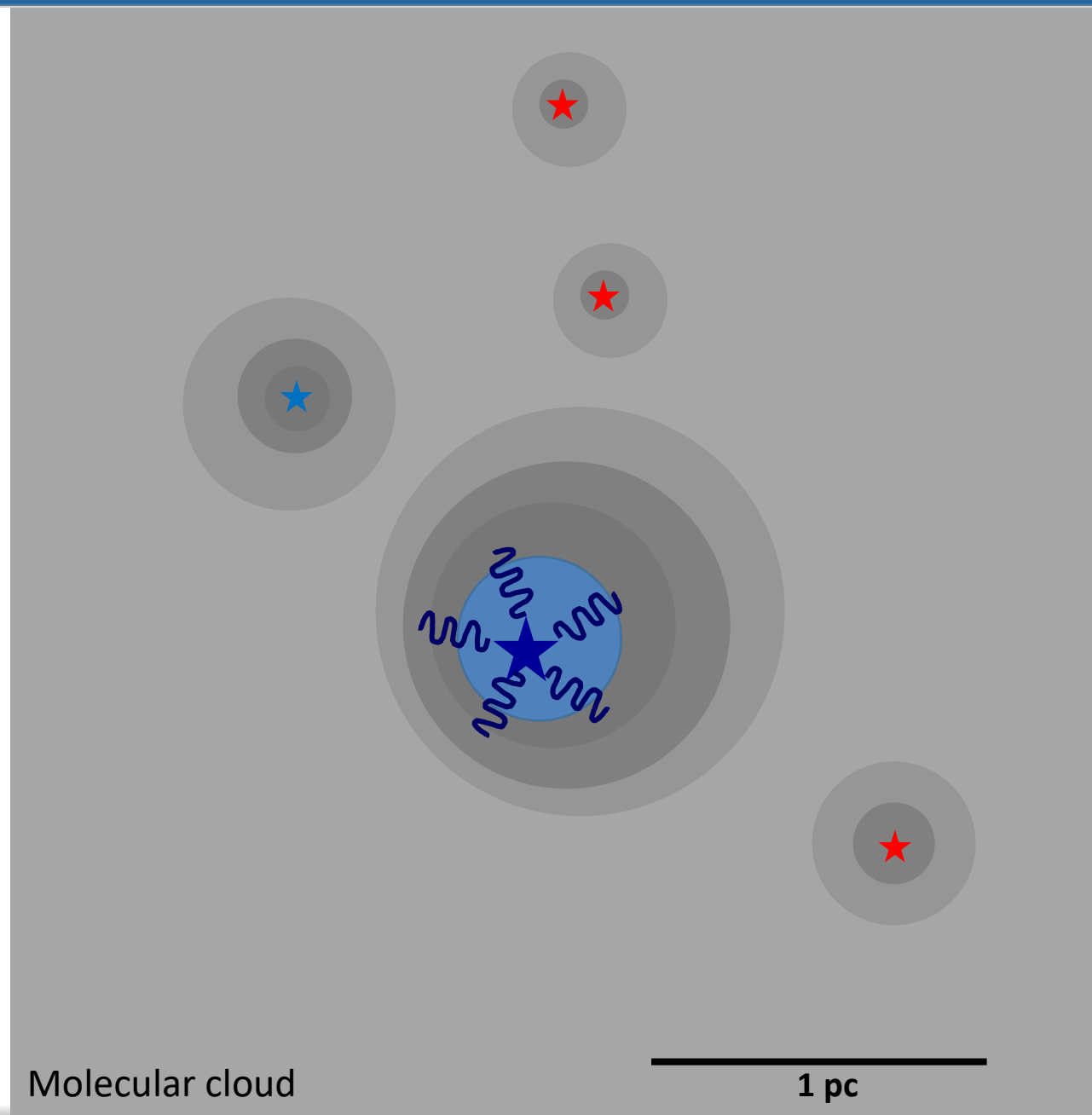
The birthplaces of the stars

Molecular clouds formed by complex networks of filaments intersecting in high-density regions called hub

Star formation occurs along the filaments
High-mass stars forming at the hubs

A massive star (O & B type) radiates enough **UV photons** with $E > 13.6 \text{ eV}$ that ionize the gas and generating an **HII region**... Photons with $6 < E < 13.6 \text{ eV}$ dissociate H_2 and CO molecules and generate a **photon-dominated region**.

Andre et al. (2010), Molinari et al. (2010), Schneider et al. (2010), Csaengeri et al. (2011), Schneider et al. (2012), Hennemann et al. (2012), Busquet et al. (2013), Hacar et al. (2013), Peretto et al. (2014), Louvet et al. (2014), Tafalla & Hacar (2015), Smith et al. (2014), Henshaw et al. (2014), Tackenberg et al. (2014), Seifried & Walch (2015), Hacar et al. (2017)...



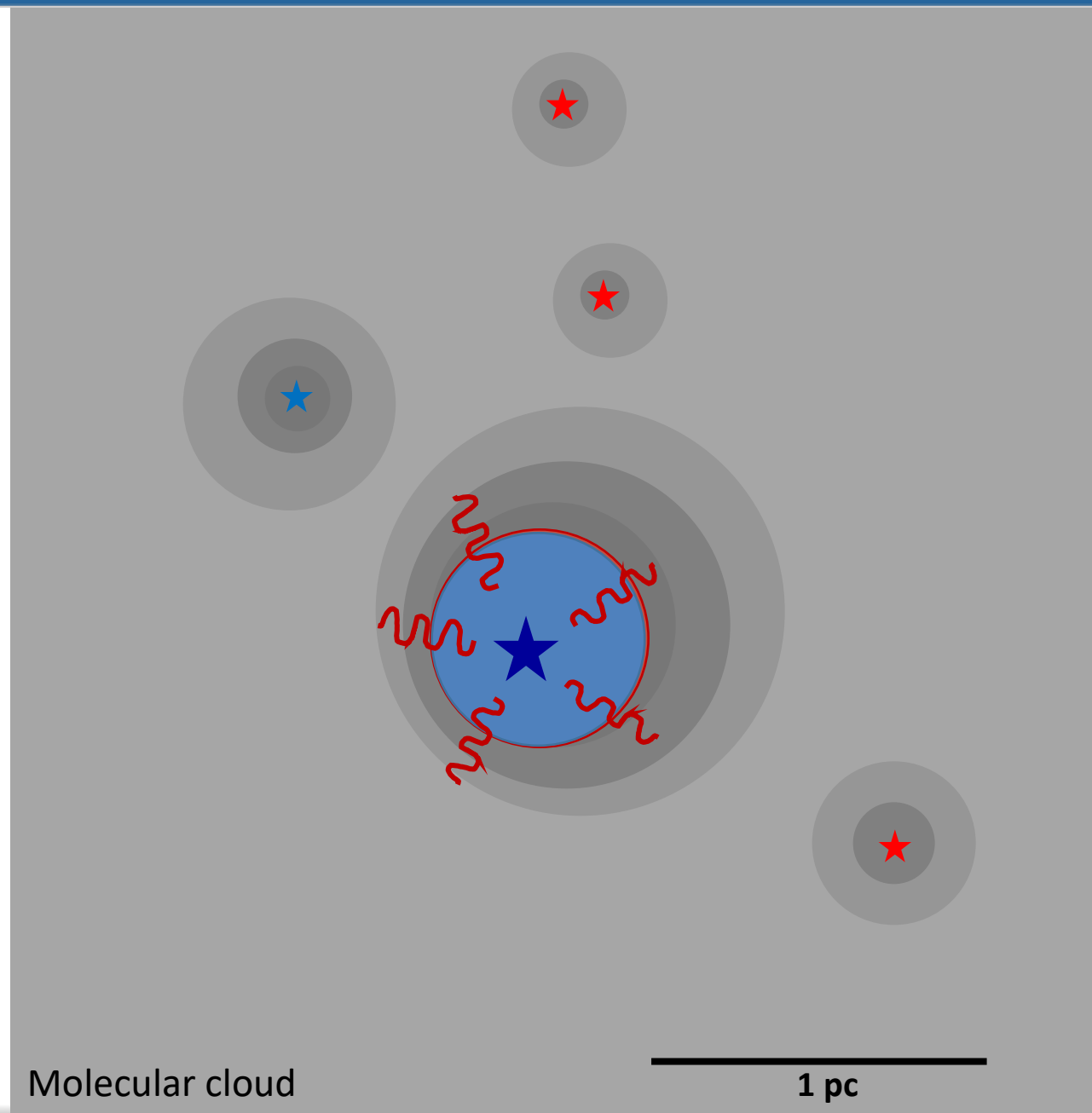
The birthplaces of the stars

Molecular clouds formed by complex networks of filaments intersecting in high-density regions called hub

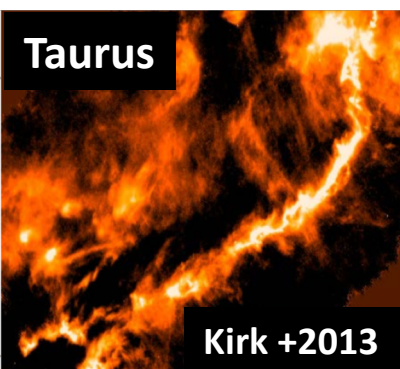
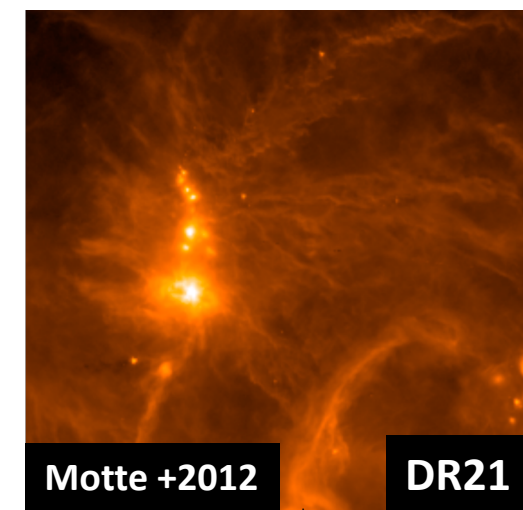
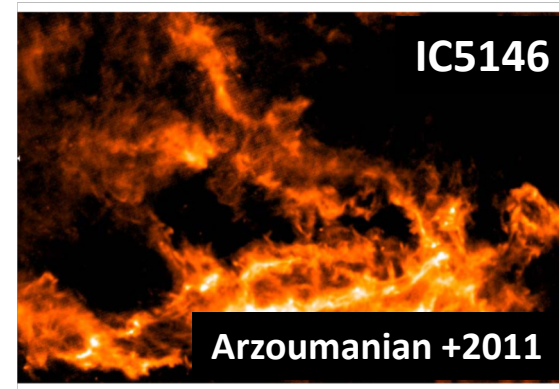
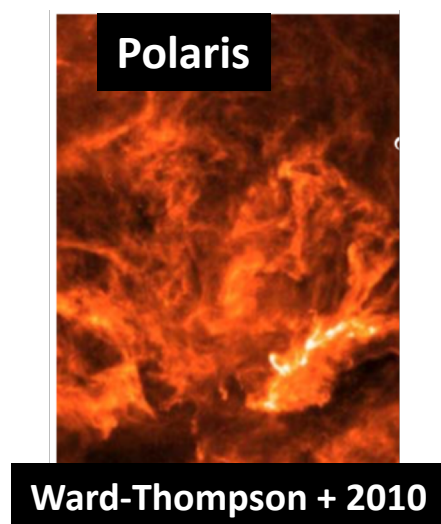
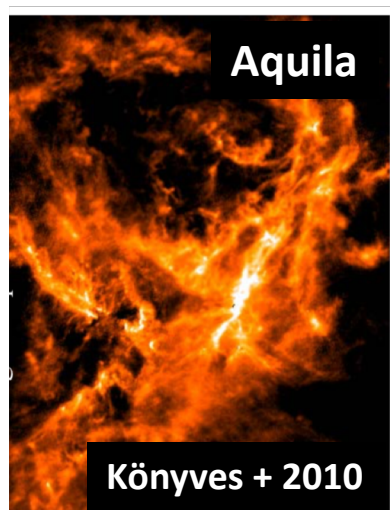
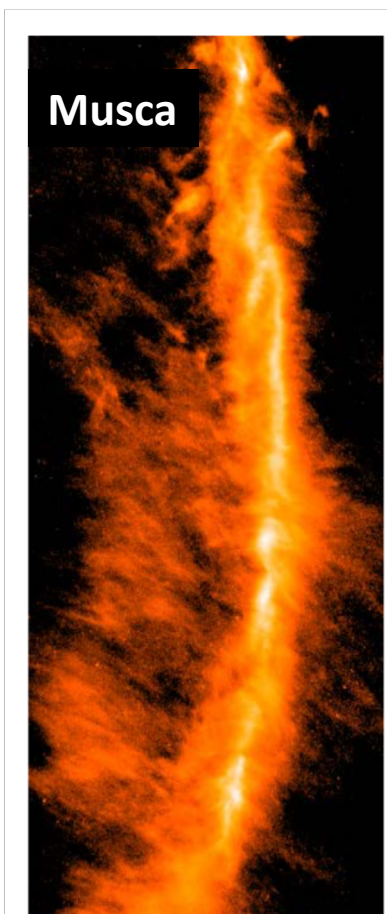
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The birthplaces of the stars

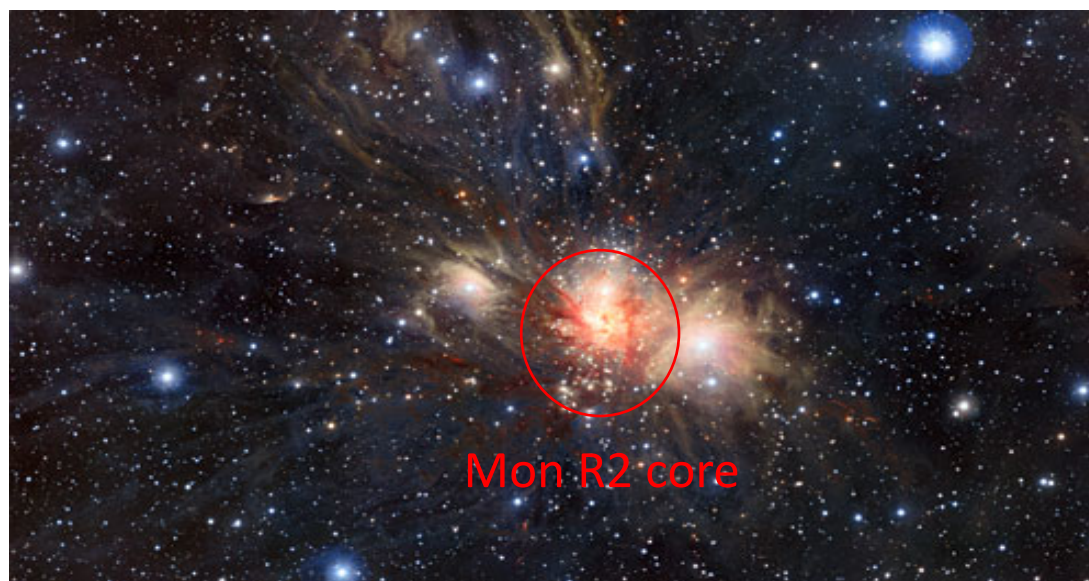


Filaments permeate the ISM on all scales

Andre et al. (2010), Molinari et al. (2010), Schneider et al. (2010), Csaengeri et al. (2011), Schneider et al. (2012), Hennemann et al. (2012), Busquet et al. (2013), Hacar et al. (2013), Peretto et al. (2014), Louvet et al. (2014), Tafalla & Hacar (2015), Smith et al. (2014), Henshaw et al. (2014), Tackenberg et al. (2014), Seifried & Walch (2015), Hacar et al. (2017)...

Study of dynamics & fragmentation

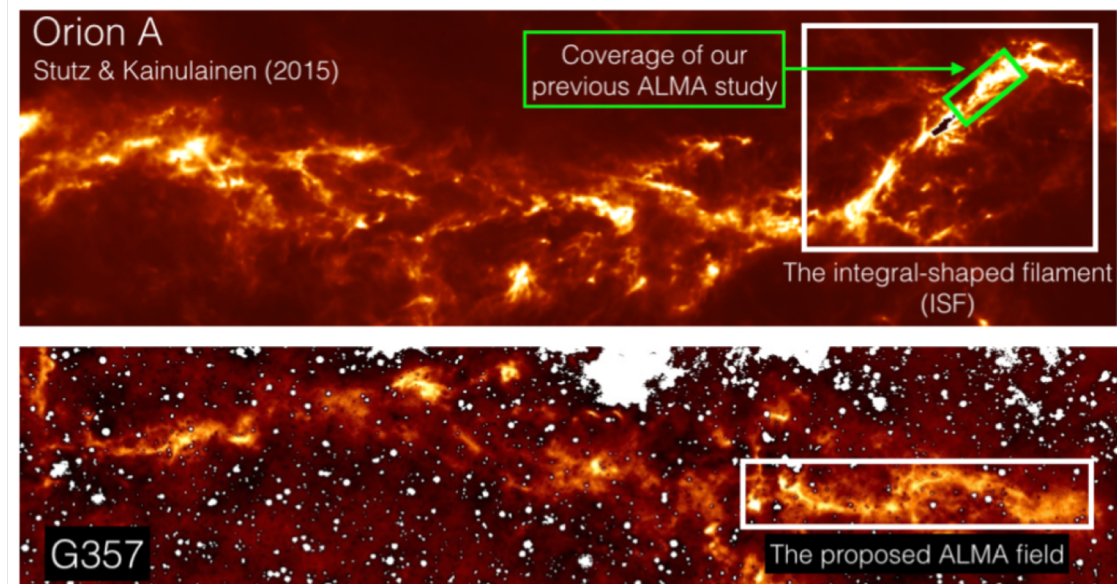
Monoceros R2



- At **830 pc** of distance
- Contains several sites of active star formation
- **Mon R2** is the most massive and cluster:
 - ... rich cluster with **B-type** stars
 - ... large mass reservoir, with a mass of **$10^4 M_{\odot}$**

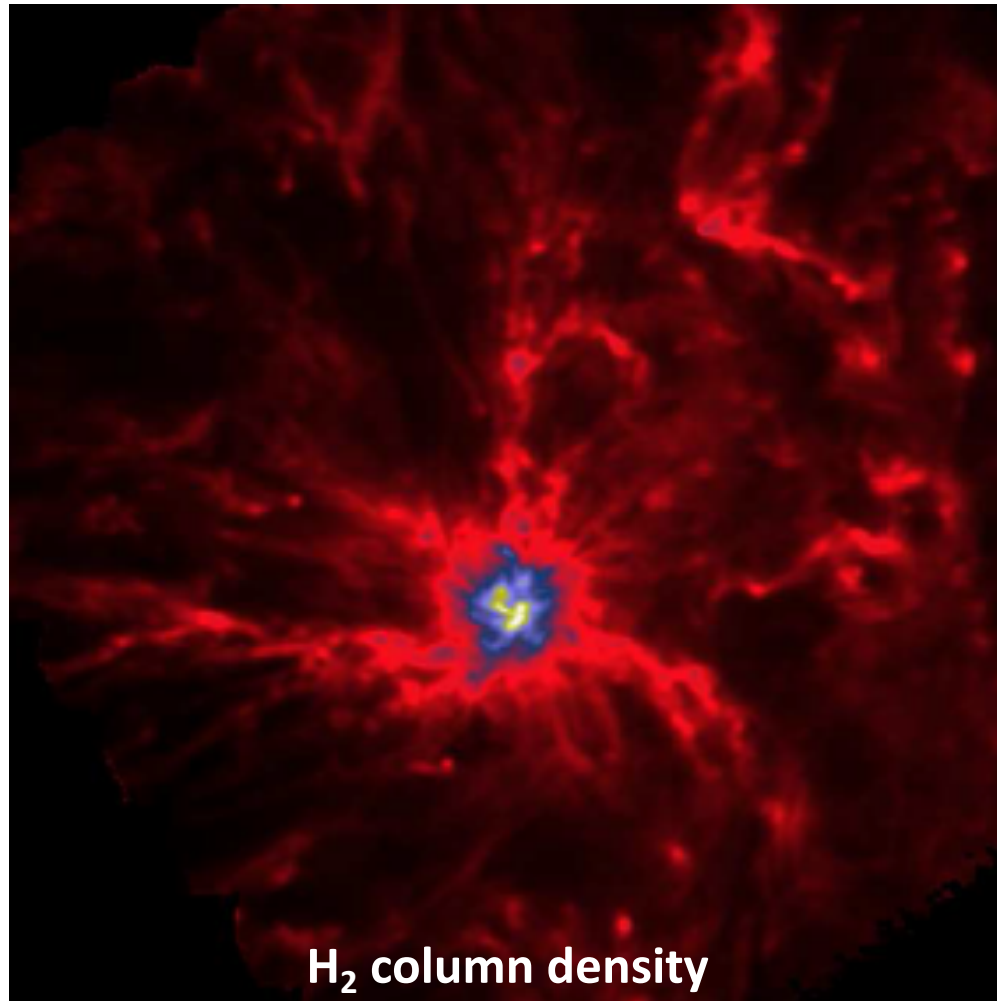
Carpenter (2000); Carpenter & Hodapp (2008)

G357



- At **3 Kpc** of distance
- Morphology and mass similar to Orion A
- Dense cloud (**$M_L \sim 300 M_{\odot} / pc$**)
- Younger evolutionary state... It is expected to actively form stars in the future.

Monoceros R2



Mon R2 contains:

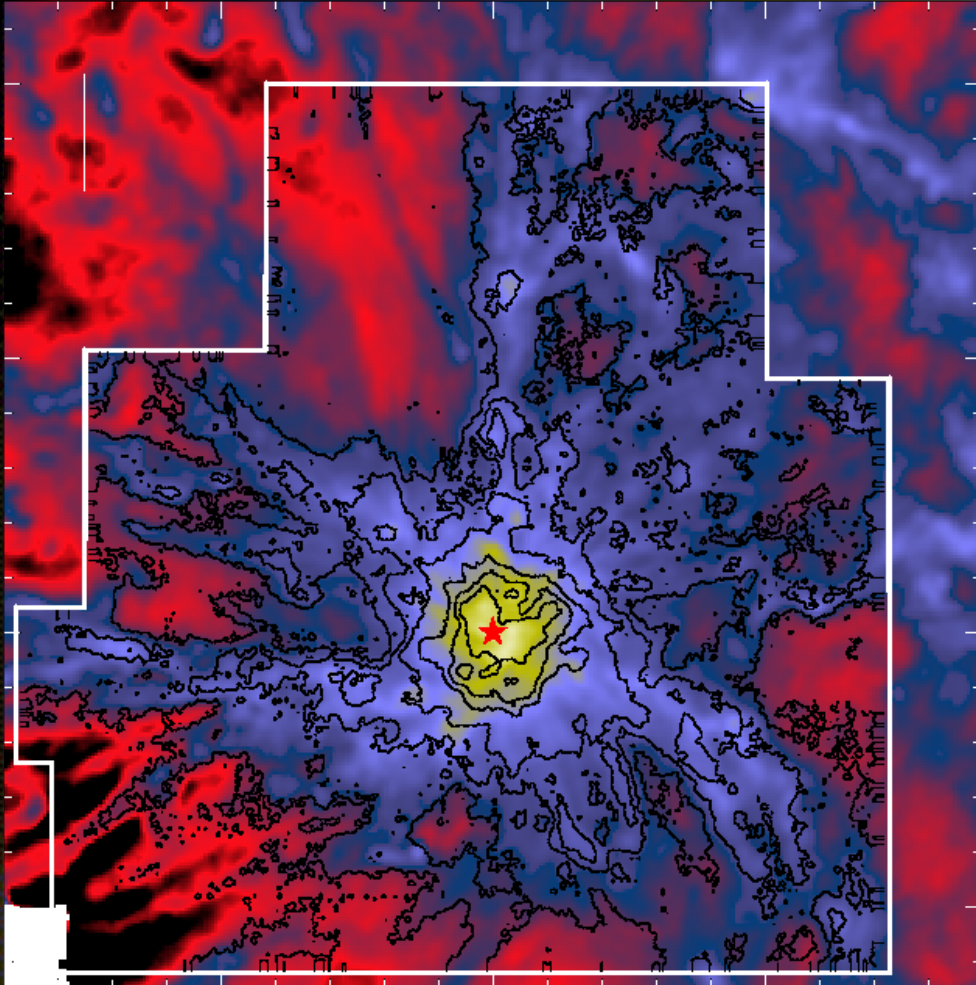
- filamentary structure converging into a hub
- massive star formation is ongoing
- UC HII region
- PDRs

Mon R2 is an excellent target to study

- kinematics
- dynamics
- feedback
- chemistry

Kinematical study towards Monoceros R2 On basis of IRAM-30m observations

Didelon et al (2015); Treviño-Morales et al (2018)



Large scale observations

- *IRAM-30m telescope* (Pico Veleta, Granada)
- 2014 -- 2016 (> 100 hours) at **3 mm band**
- **> 600 arcmin²**

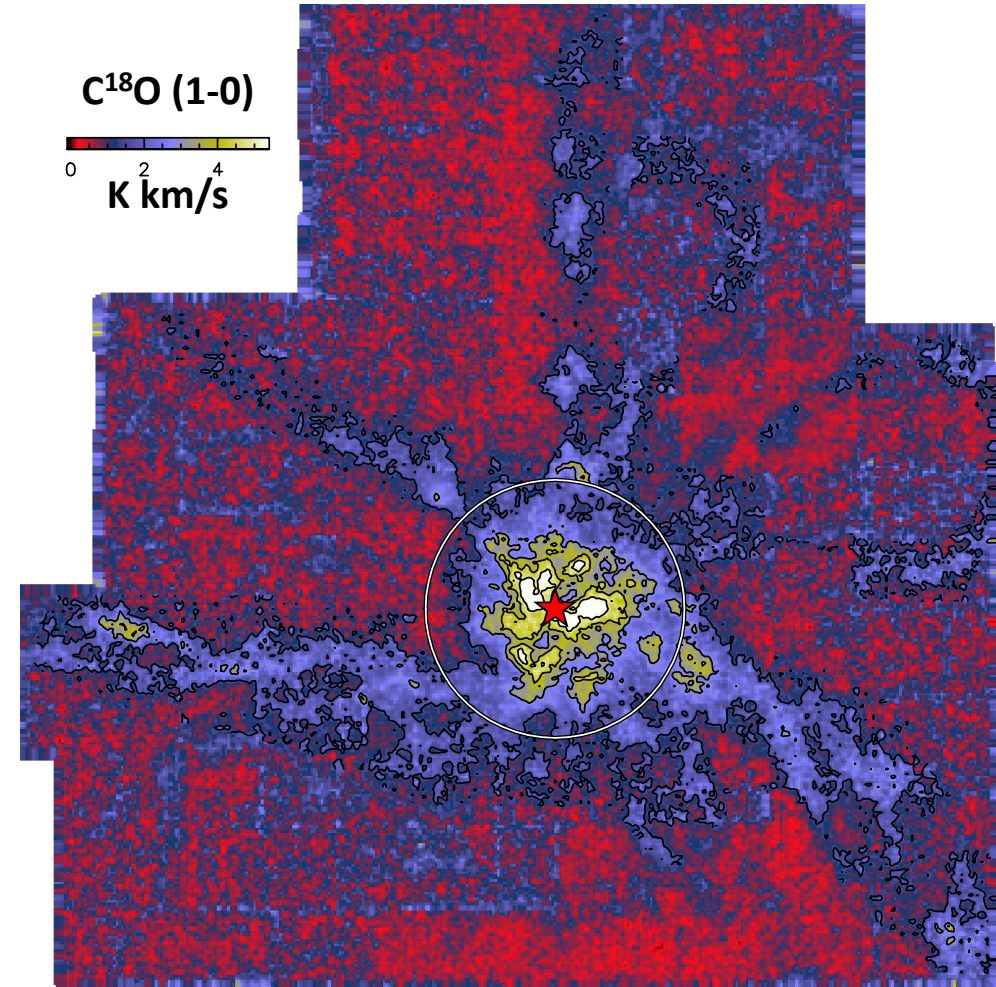
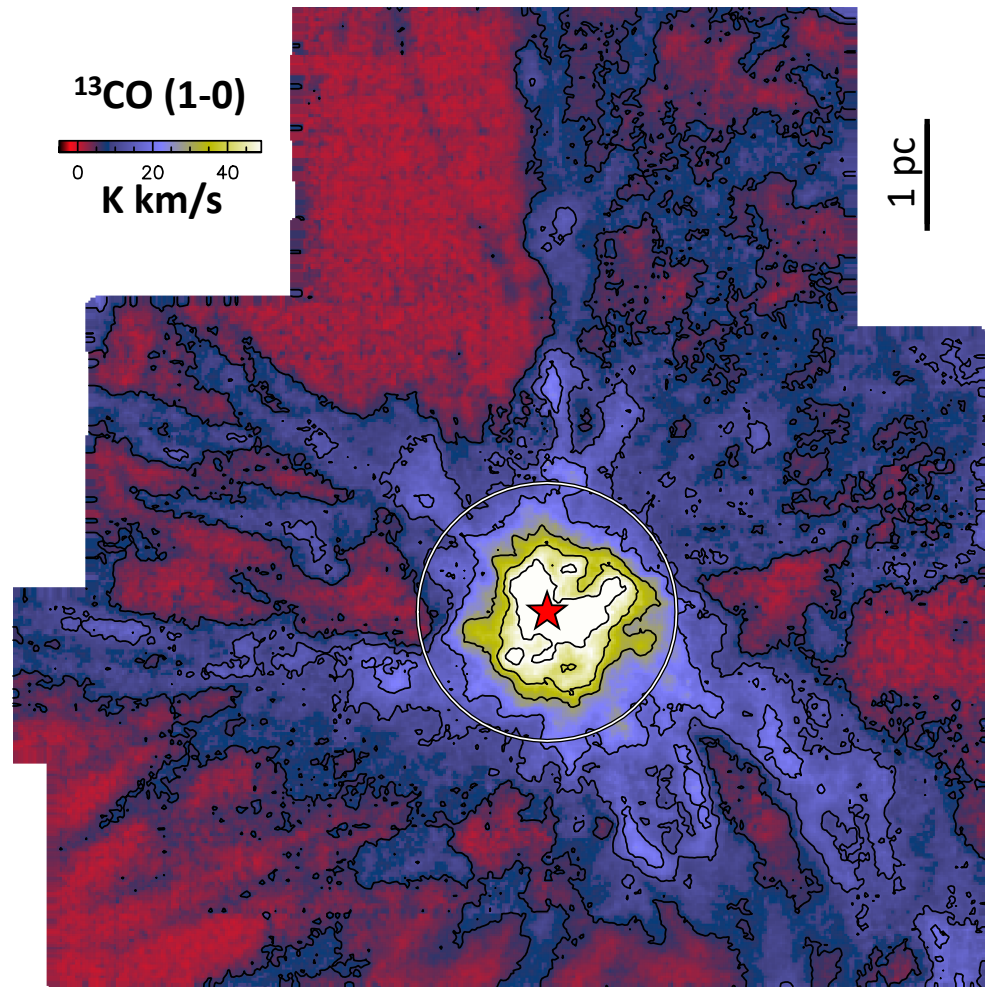
Surveyed species

- ^{13}CO (1-0)
- C^{18}O (1-0)
- HNC (1-0)
- N_2H^+ (1-0)
- ... and others HC_3N , SO , CCS , $\text{H40}\alpha$

Large-scale emission

Molecular emission is extended and *well correlated with the dust emission*

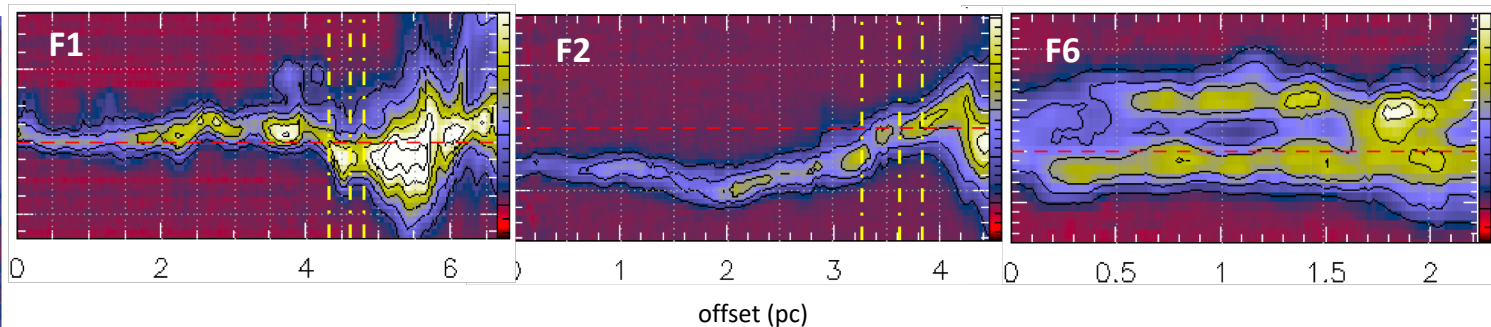
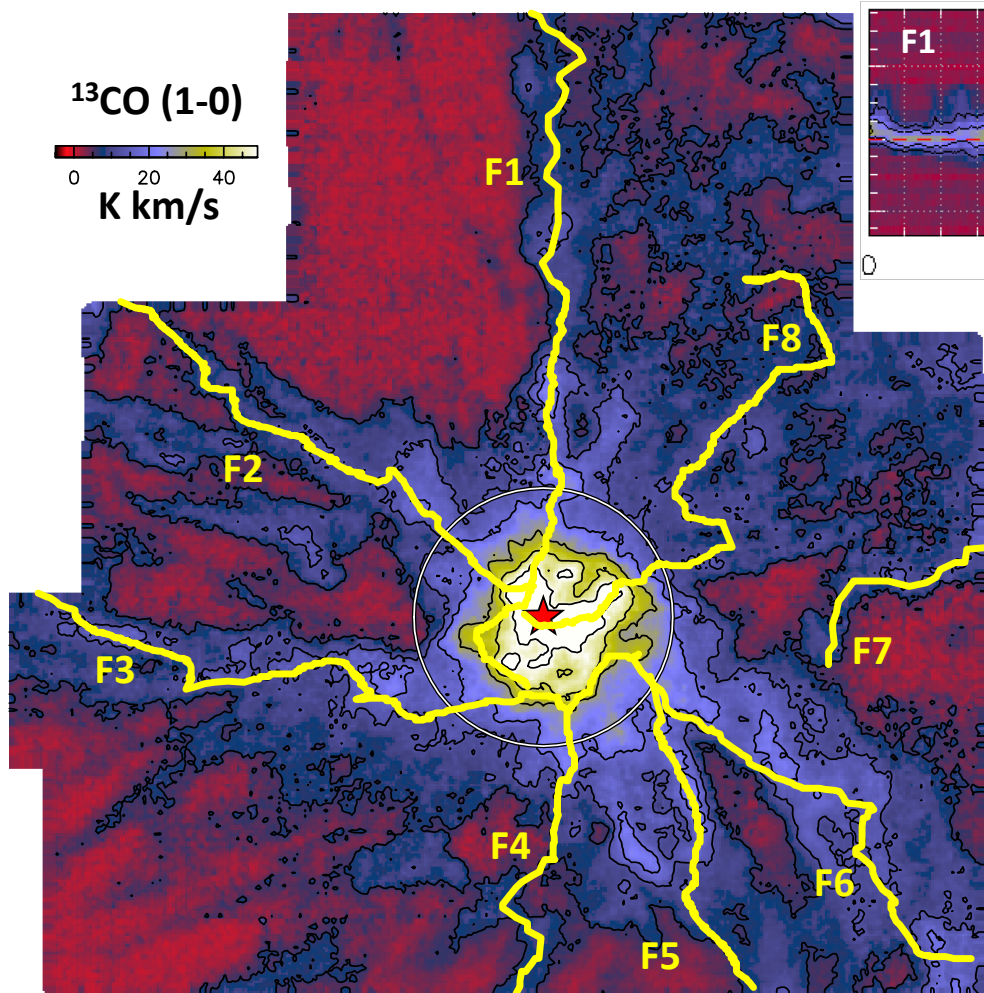
Treviño-Morales et al (2018)



Filaments: stability and kinematics

$$M_{\text{total}} = 8300 M_{\odot}; M_{\text{hub}} = 2800 M_{\odot} \text{ (inner 250''); } M_{\text{fil}} = 2800 M_{\odot}$$

Treviño-Morales et al (2018)



$$M = \frac{N}{X} A (2.8 m_{\text{H}}).$$

$$(M/L)_{\text{crit}} = \frac{2\sigma_{\text{ther}}^2}{G} = 16.7 \left(\frac{T}{10\text{K}} \right) M_{\odot} \text{ pc}^{-1}$$

with $T \sim 28 \text{ K}$

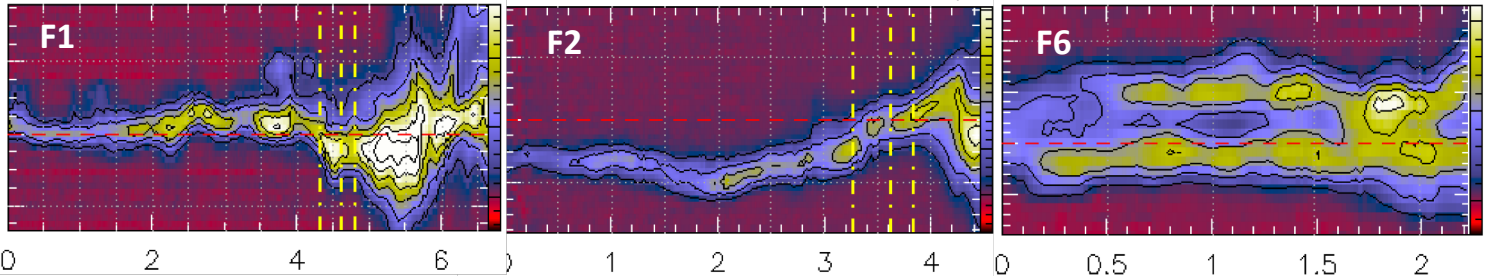
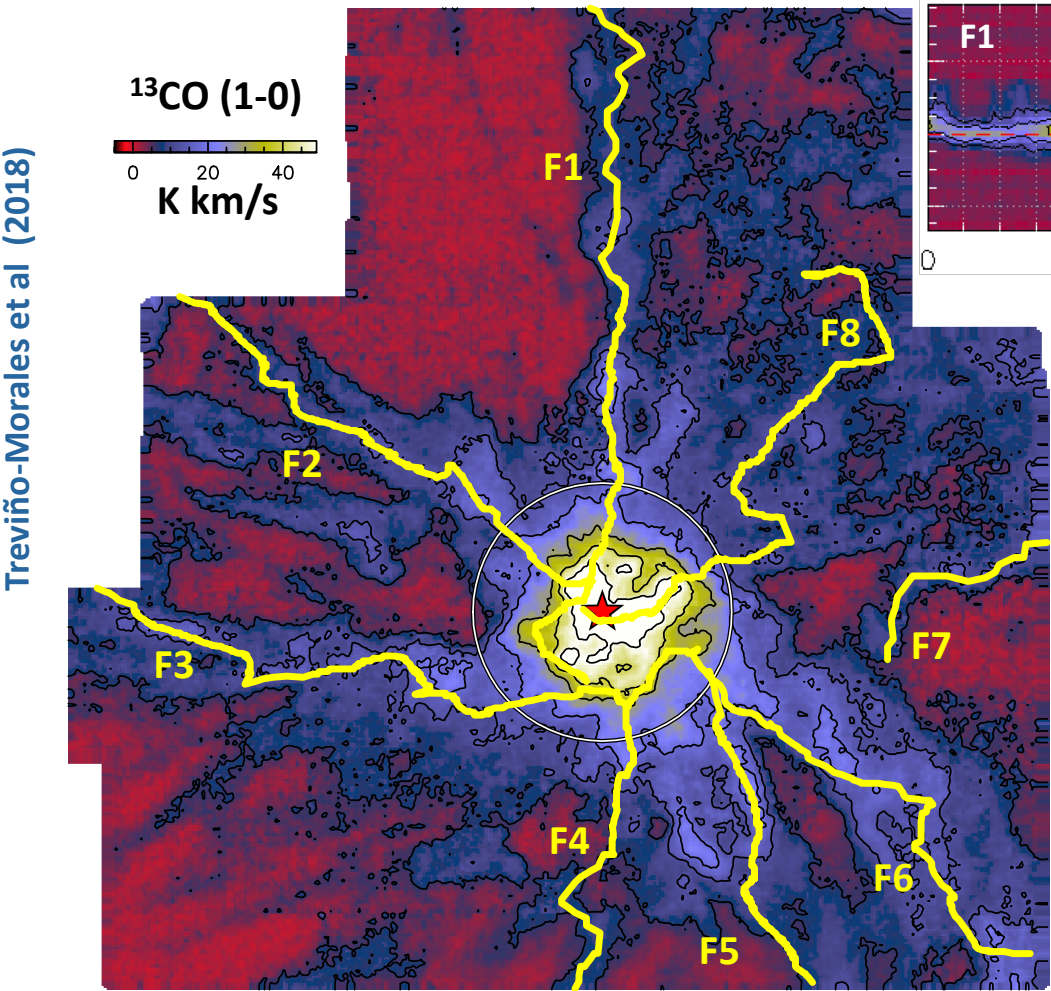
Kirk et al (2013); Nagasawa 1987; Wang et al 2014

	L^a (pc)	Area ^b (pc ²)	T^c (K)	σ_{ther}^d (km s ⁻¹)	$N(\text{H}_2)^e$ ($\times 10^{21} \text{ cm}^{-2}$)	M^f ($M_{\odot}$)	M/L ($M_{\odot}/\text{pc}$)	$(M/L)_{\text{crit}}^g$ ($M_{\odot}/\text{pc}$)	λ_{cl}^h (pc)	M_{cl}^i ($M_{\odot}$)
F1	4.8	1.55	28.04	0.40	10.43	365.61	76.17	46.83	1.35–0.43	100–32
F2	3.9	1.05	29.34	0.41	8.10	190.91	48.95	49.00	1.44–0.45	113–36
F3	4.1	1.48	27.24	0.39	11.60	386.82	94.35	45.49	1.32–0.41	94–30
F4	2.0	0.52	27.20	0.39	14.37	167.23	83.62	45.42	1.01–0.32	71–23
F5	2.8	0.79	28.70	0.40	6.40	95.11	25.10	47.76	1.51–0.47	113–36
F6	3.0	0.60	28.44	0.40	7.91	105.30	35.10	47.50	1.23–0.39	92–29
F7	4.6	1.42	27.13	0.39	11.77	375.07	81.54	45.31	1.22–0.39	86–27
F8	2.1	0.70	26.90	0.39	6.34	98.46	46.89	44.92	1.73–0.54	122–39
F9	4.7	1.37	27.95	0.40	8.10	248.59	52.90	46.70	1.46–0.46	109–35

3.5 1.05 28 0.40 9.44 225 60 47 0.80 50

Filaments: stability and kinematics

$M_{\text{total}} = 8300 M_{\odot}$; $M_{\text{hub}} = 2800 M_{\odot}$ (inner 250"); $M_{\text{fil}} = 2800 M_{\odot}$



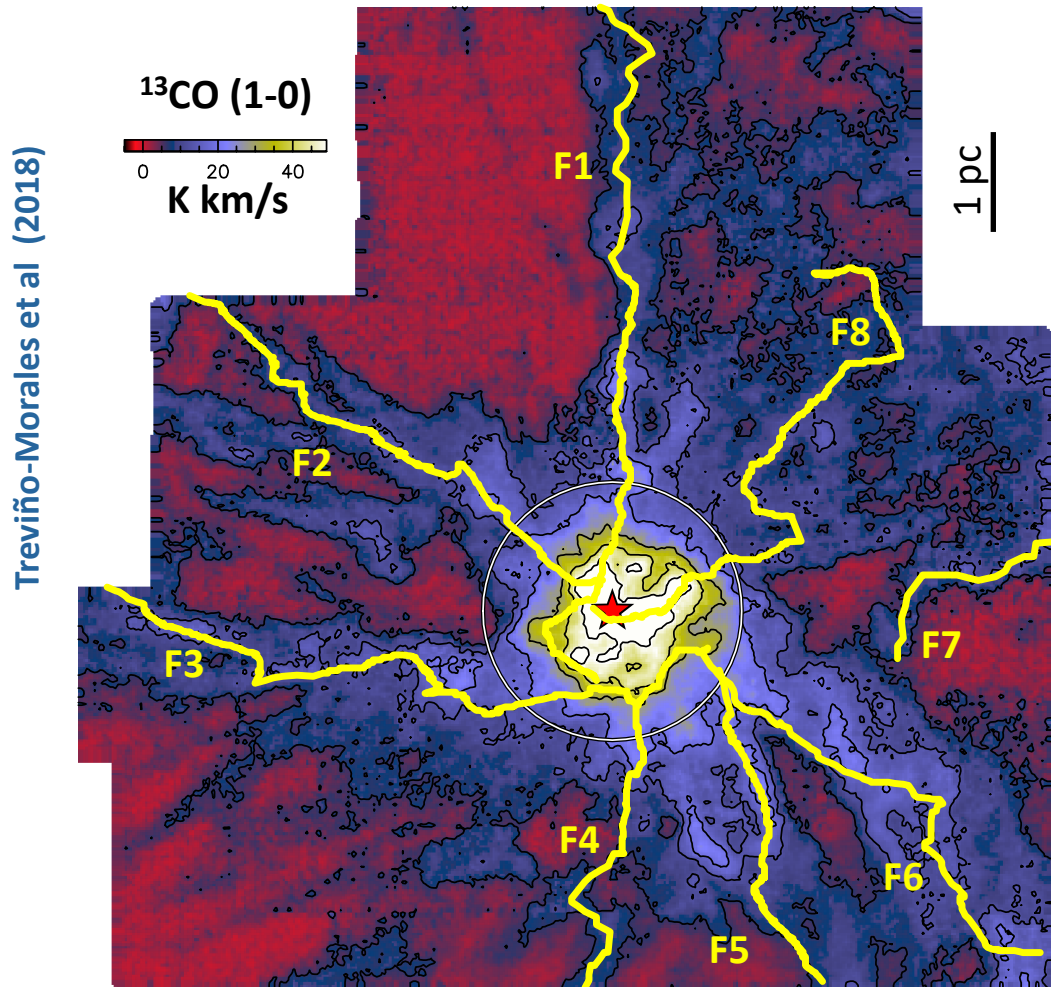
Musca :	M/L = 30 ($M_{\odot} \text{ pc}^{-1}$)	Cox + (2015)
Taurus (B211)	M/L = 50 ($M_{\odot} \text{ pc}^{-1}$)	Palmeirim +(2013)
DR21	M/L = 100-700 ($M_{\odot} \text{ pc}^{-1}$)	Hennemann + (2012)

	L^a (pc)	Area ^b (pc ²)	T^c (K)	σ_{ther}^d (km s ⁻¹)	$N(\text{H}_2)^e$ ($\times 10^{21} \text{ cm}^{-2}$)	M^f ($M_{\odot}$)	M/L ($M_{\odot}/\text{pc}$)	$(M/L)_{\text{crit}}^g$ ($M_{\odot}/\text{pc}$)	λ_{cl}^h (pc)	M_{cl}^i ($M_{\odot}$)
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Filaments: stability and kinematics

$M_{\text{total}} = 8300 M_{\odot}$; $M_{\text{hub}} = 2800 M_{\odot}$ (inner 250"); $M_{\text{fil}} = 2800 M_{\odot}$



Filament	L (pc)	M ($M_{\odot}$)	V_{Hub} (km s $^{-1}$)	V_{Far} (km s $^{-1}$)	V_{obs} (km s $^{-1}$)	∇V_{obs}^a (km s $^{-1}$ /pc)	M_{accr}^b ($10^{-4} M_{\odot} \text{ yr}^{-1}$)	α^c (degrees)	$M_{\text{accr}}^{\text{corr},d}$ ($10^{-4} M_{\odot} \text{ yr}^{-1}$)
F1	4.8	365.61	9.0	10.3	-1.3	-0.27	1.00	-37	1.32
F2	3.9	190.91	10.5	8.5	+2.0	+0.52	1.00	+56	0.67
F3	4.1	386.82	11.5	8.0	+2..5	+0.61	2.40	+60	1.38
F4	2.0	167.23	10.5	9.8	+0.7	+0.35	0.60	+44	0.62
F5	2.8	233.10	10.5	10.7	-0.2	-0.07	0.15	-11	0.77
F6	2.6	77.75	10.6	11.2	-0.6	-0.23	0.20	-31	0.33
F7	4.6	375.07	10.5	11.2	-0.7	-0.15	0.60	-19	1.74
F8	2.1	98.46	12.5	13.3	-0.8	-0.38	0.40	-41	0.46
F9	4.7	248.59	9.5	11.0	-1.5	-0.32	0.80	-42	0.88

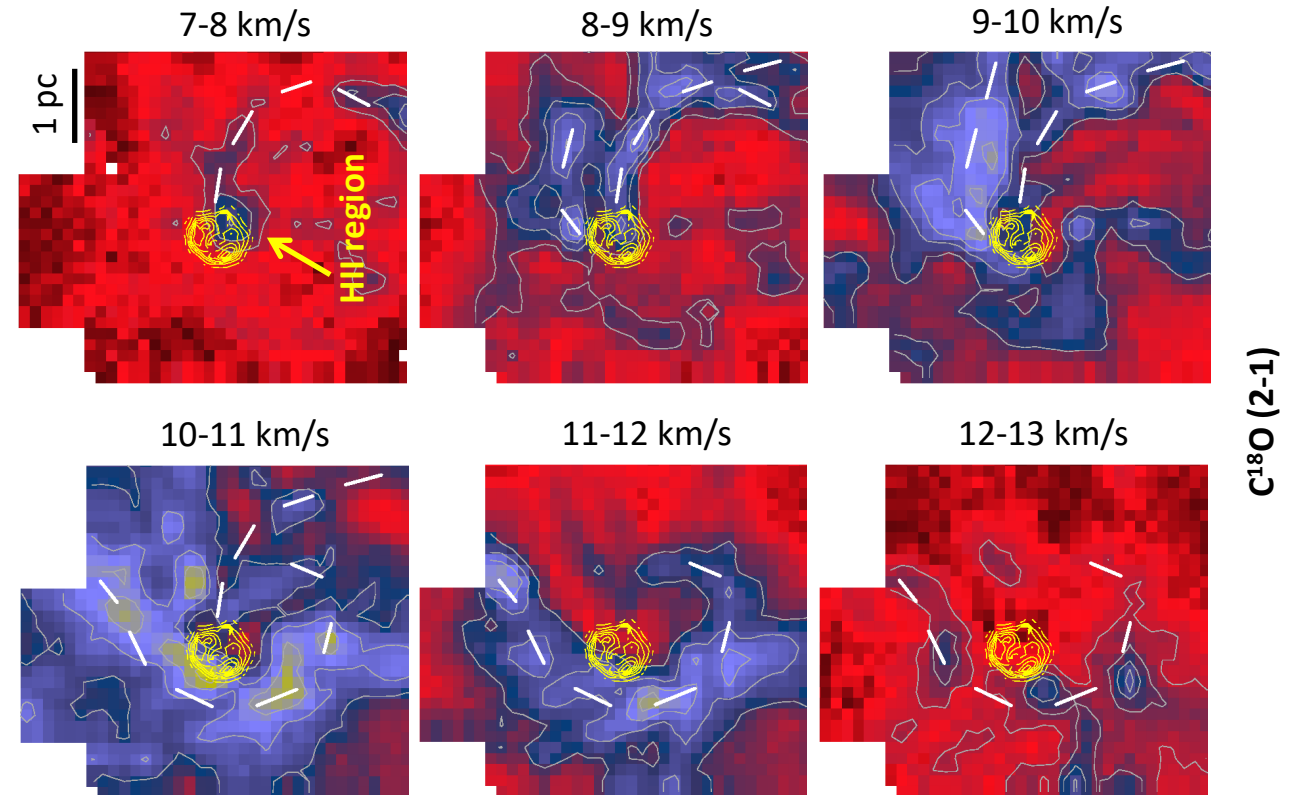
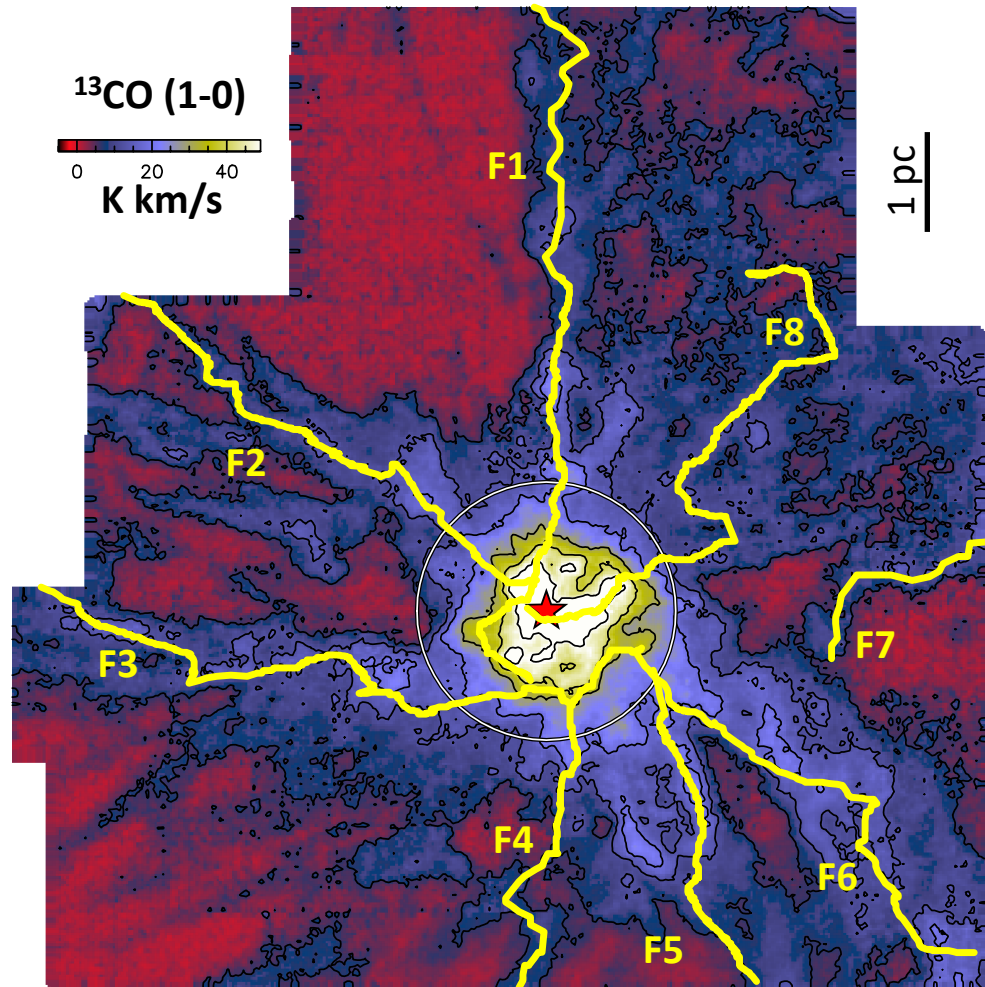
3.5 225 10 10.5 1.5 0.35 1.5

- Velocity gradients** measured as the velocity difference between the extremes of the filament
- Mass accretion rates**, assuming 45° of orientation

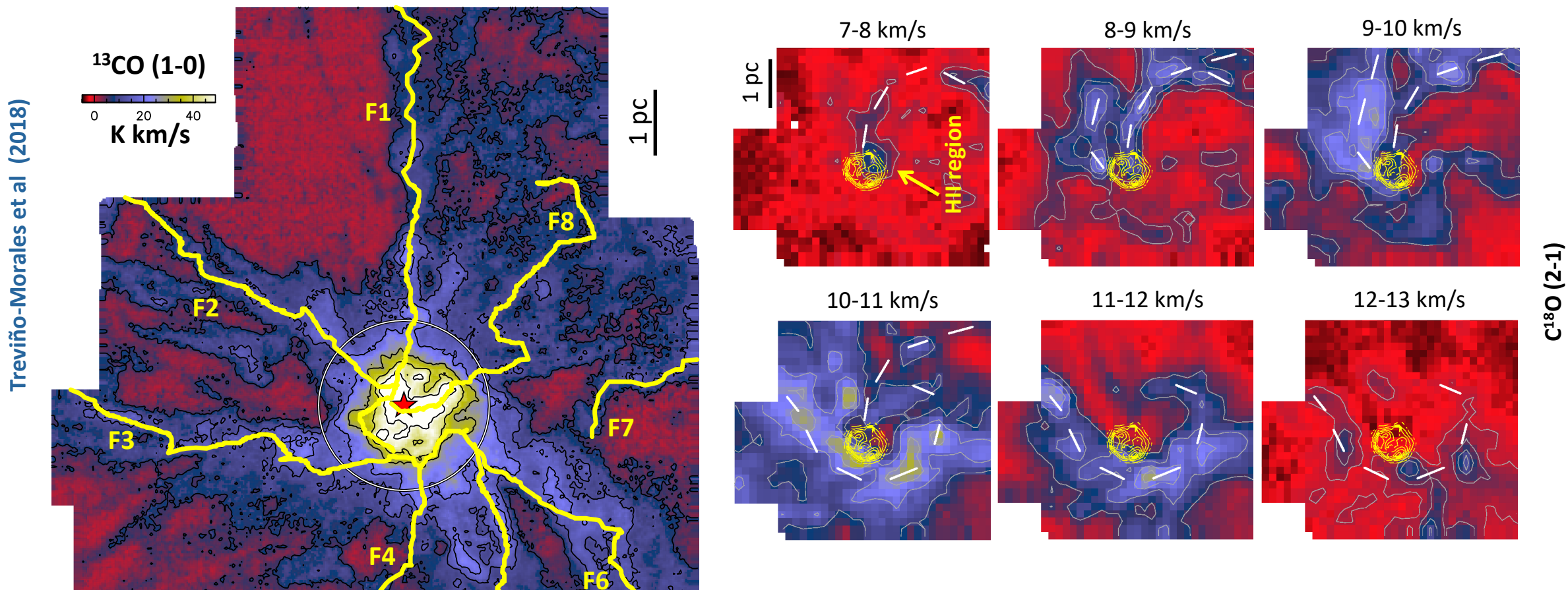
$$M_{\text{accr}} = \frac{\left(\frac{M}{L_{\text{obs}}} V_{\parallel \text{obs}} \right)}{\tan \alpha} = \frac{M \nabla V_{\parallel \text{obs}}}{\tan \alpha}$$

Filaments: stability and kinematics

Treviño-Morales et al (2018)

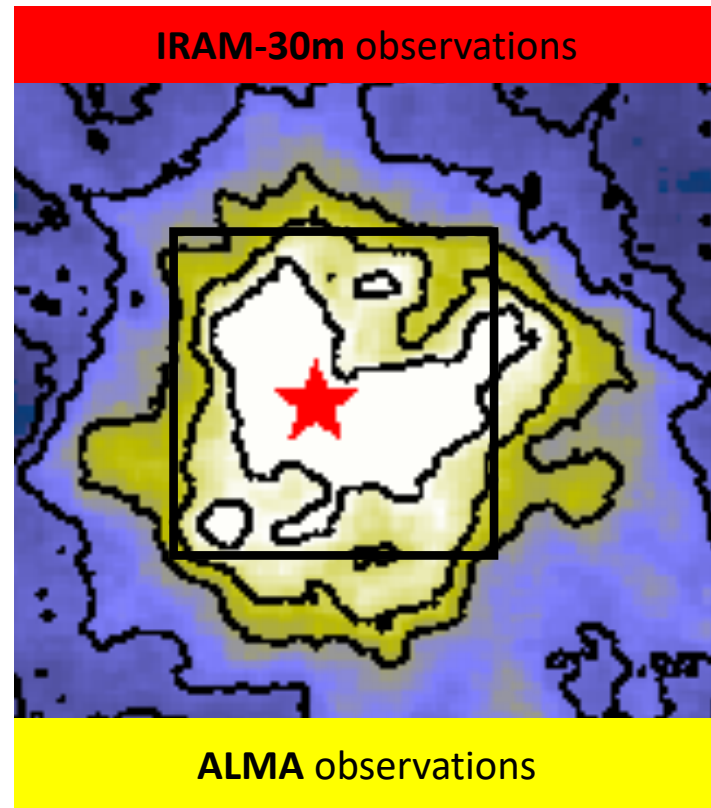


Filaments: stability and kinematics



A young HII region breaking out of the dense filamentary hub where it was formed, with material still flowing inward along the filaments.

ALMA observations to study the **fragmentation** and the **substructure**



ALMA:

- Kinematics
- Fragmentation
- Substructures

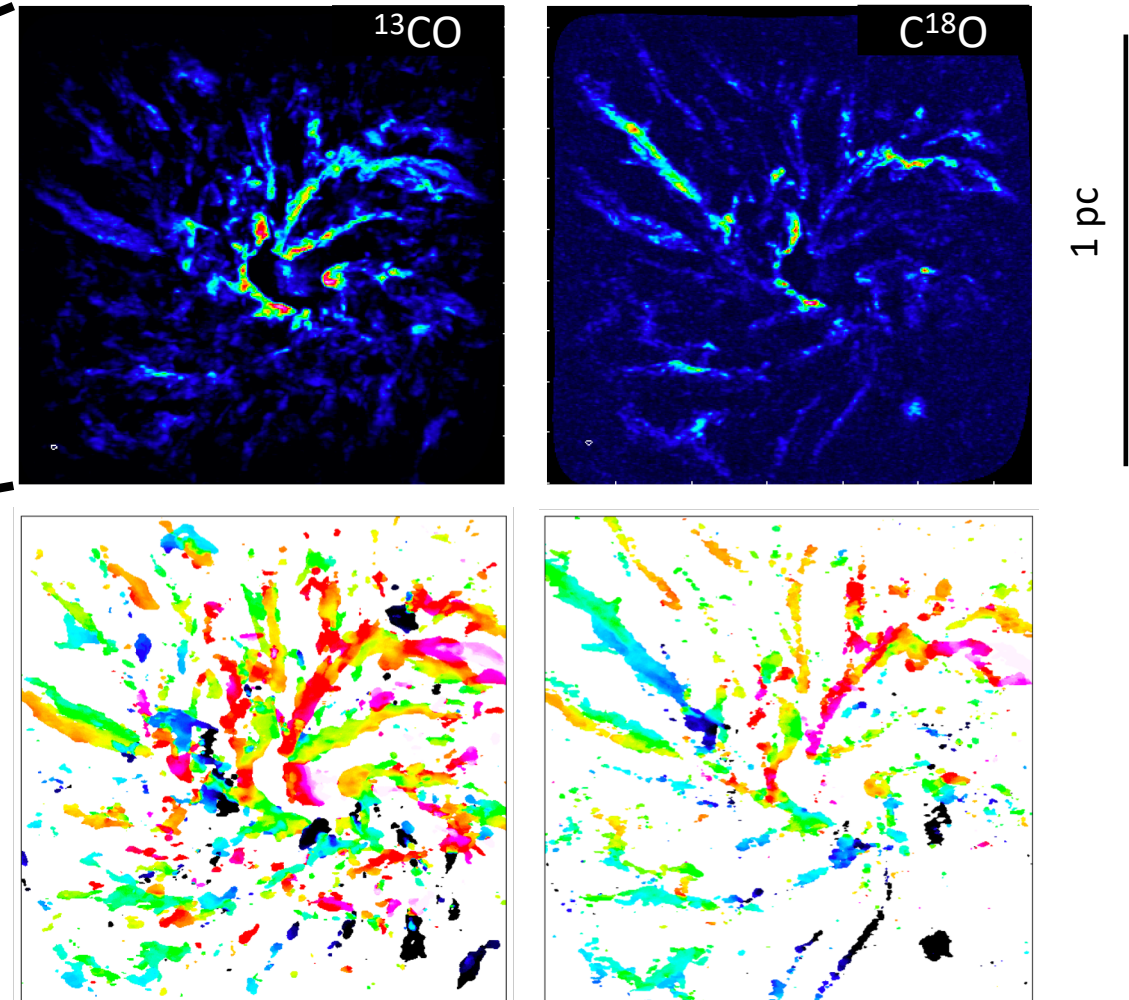
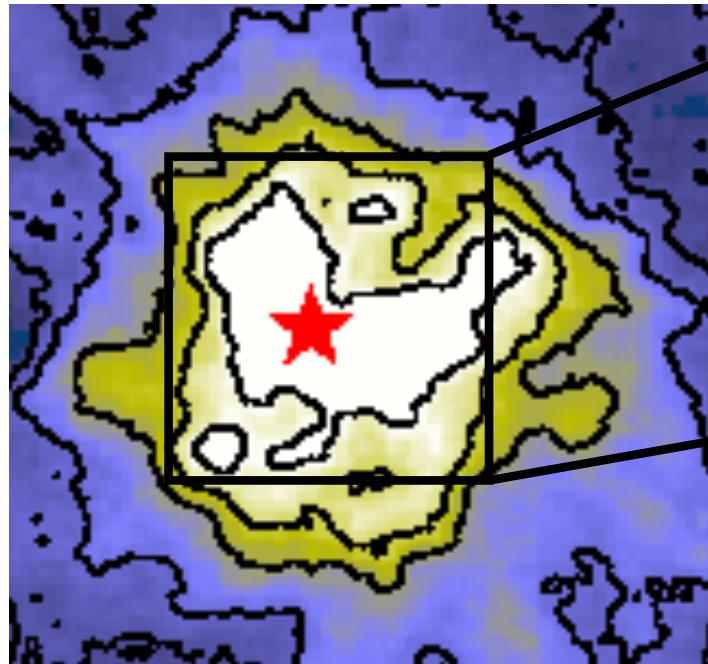
IRAM-30m + ALMA:

- Variation in the velocity
- Variation in the accretion

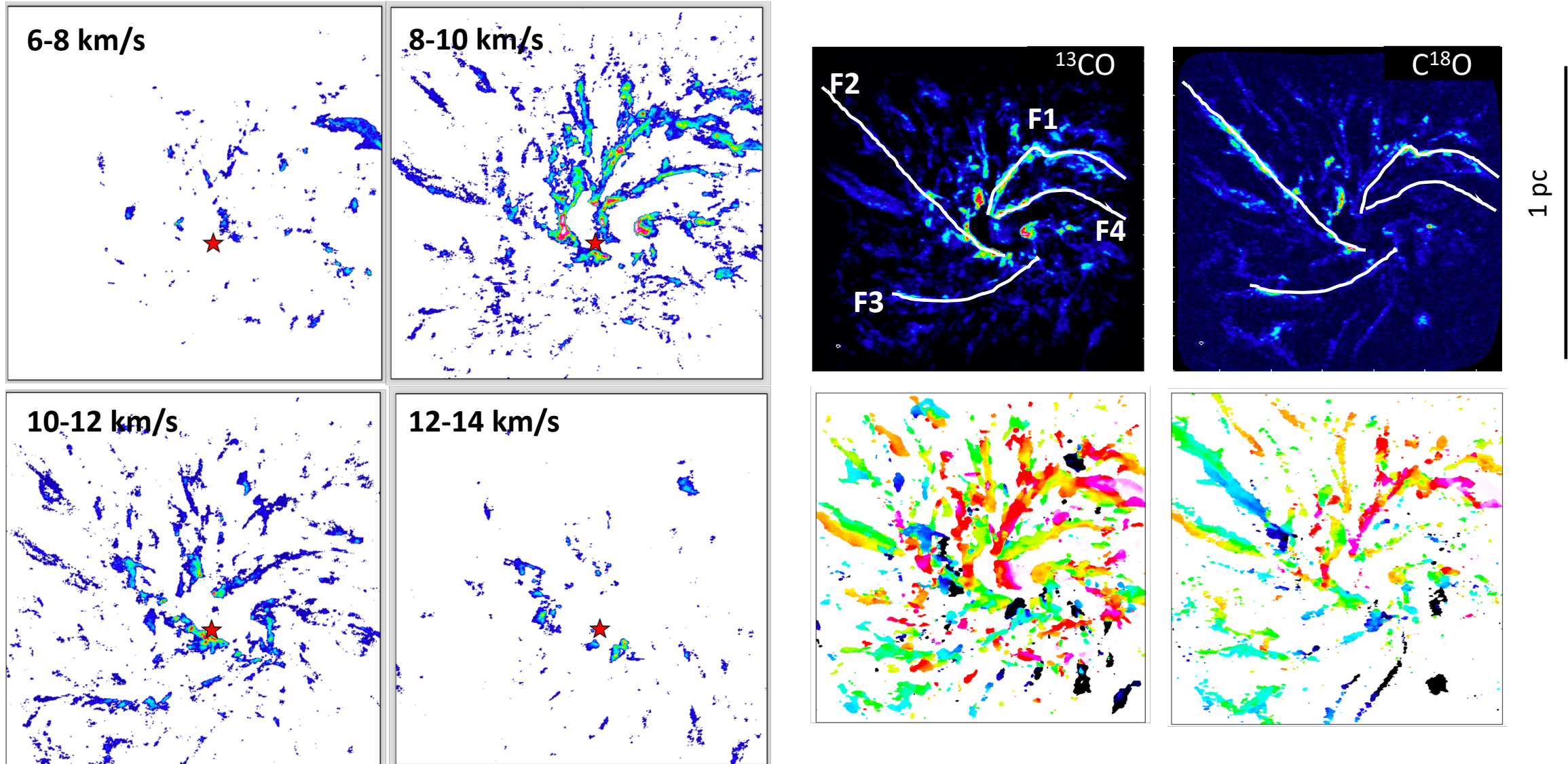


IRAM-30m observations

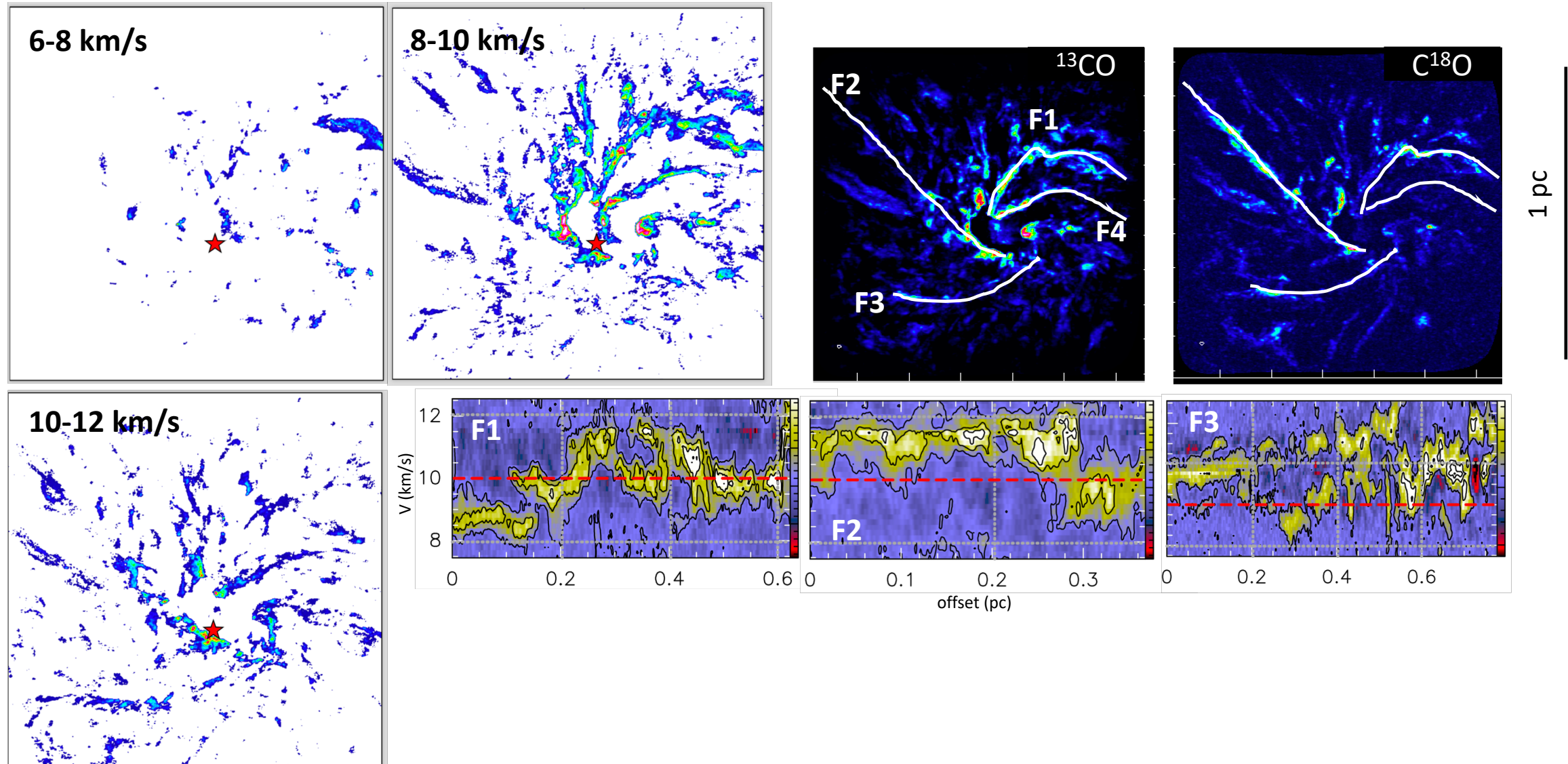
ALMA observations



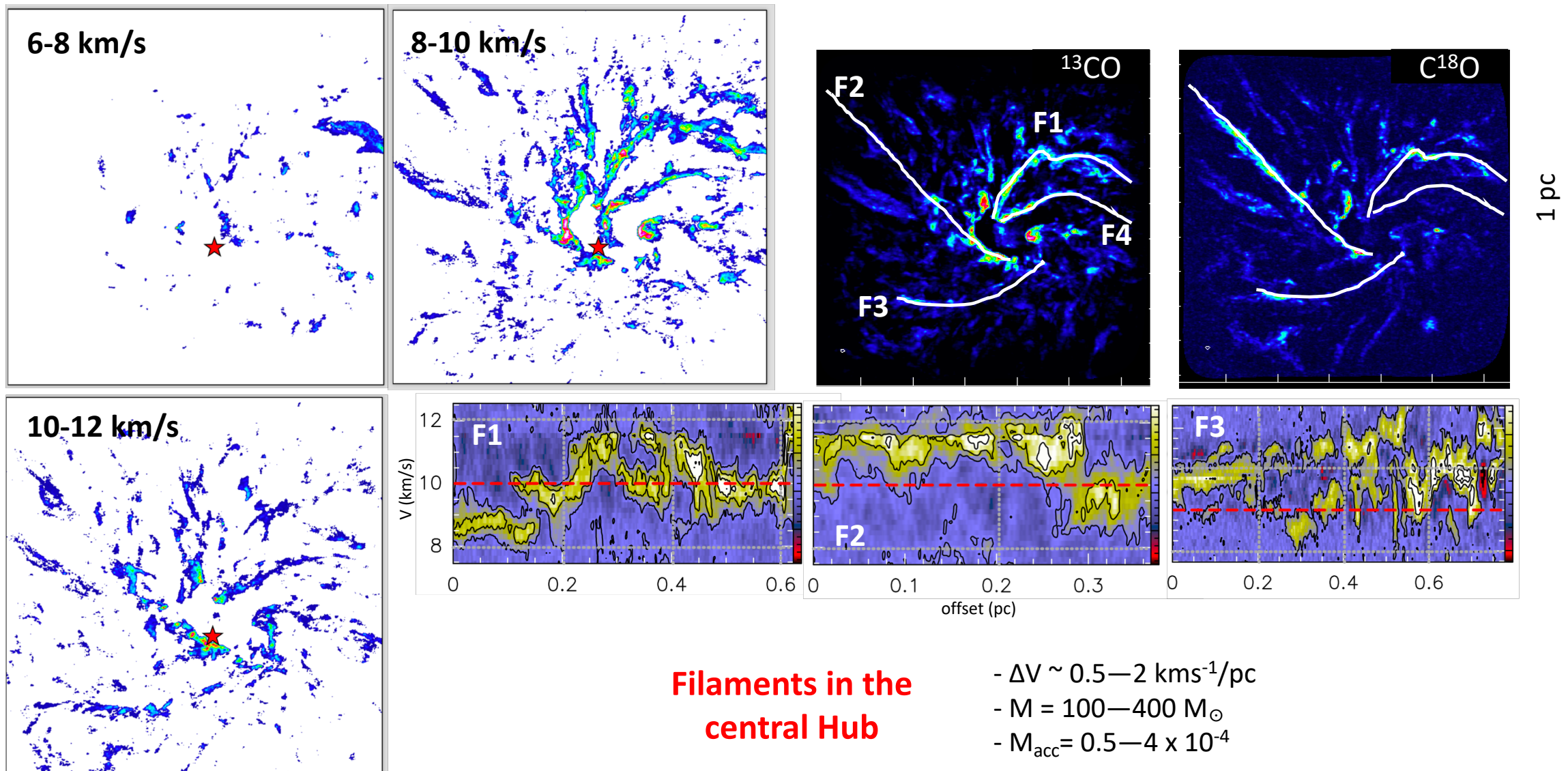
ALMA observations



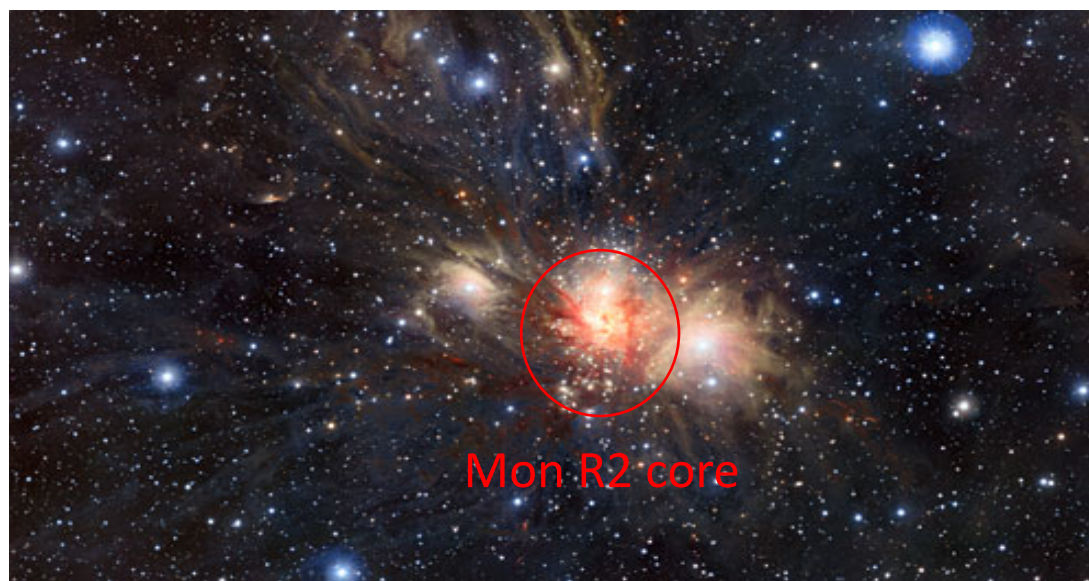
ALMA observations



ALMA observations



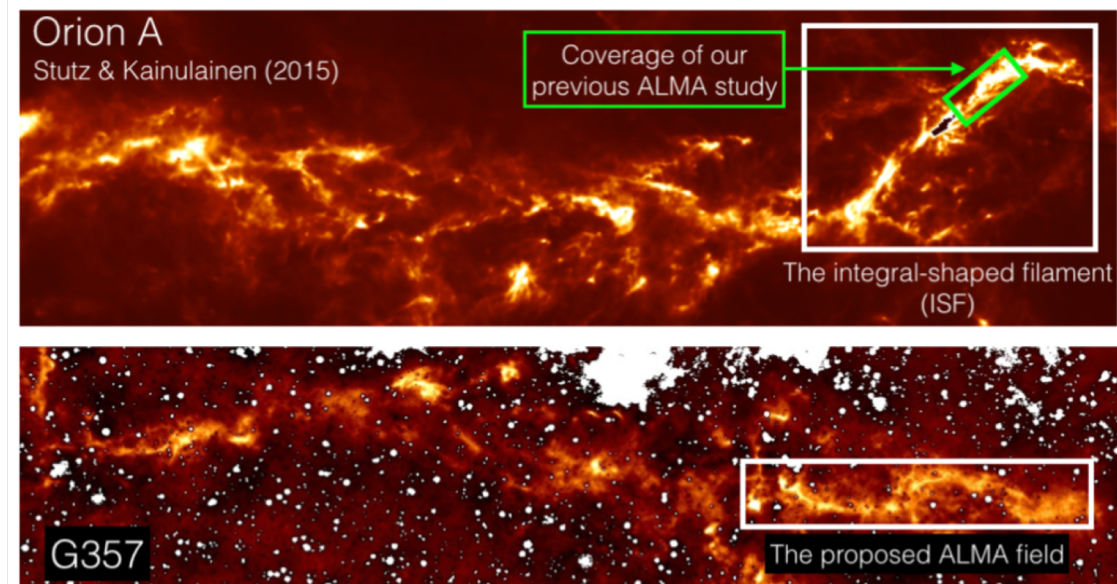
Monoceros R2



- At **830 pc** of distance
- Contains several sites of active star formation
- **Mon R2** is the most massive and cluster:
 - ... rich cluster with **B-type** stars
 - ... large mass reservoir, with a mass of **$10^4 M_{\odot}$**

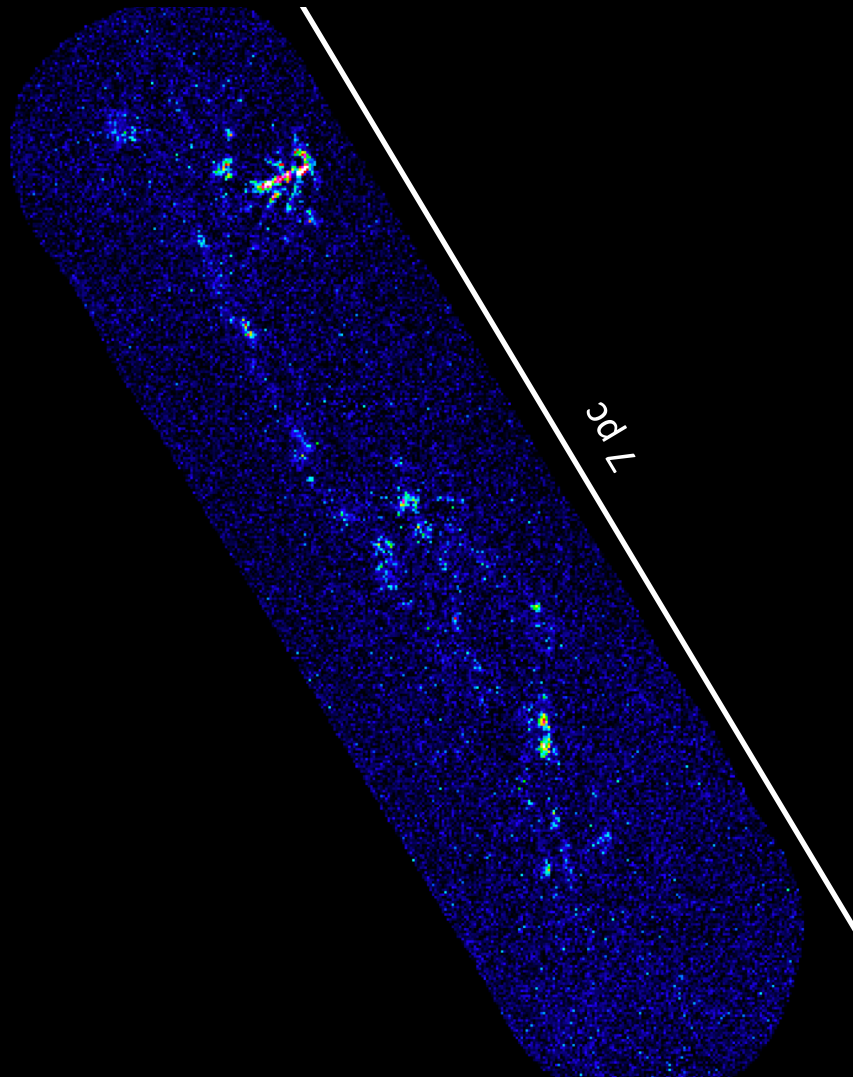
Carpenter (2000); Carpenter & Hodapp (2008)

G357

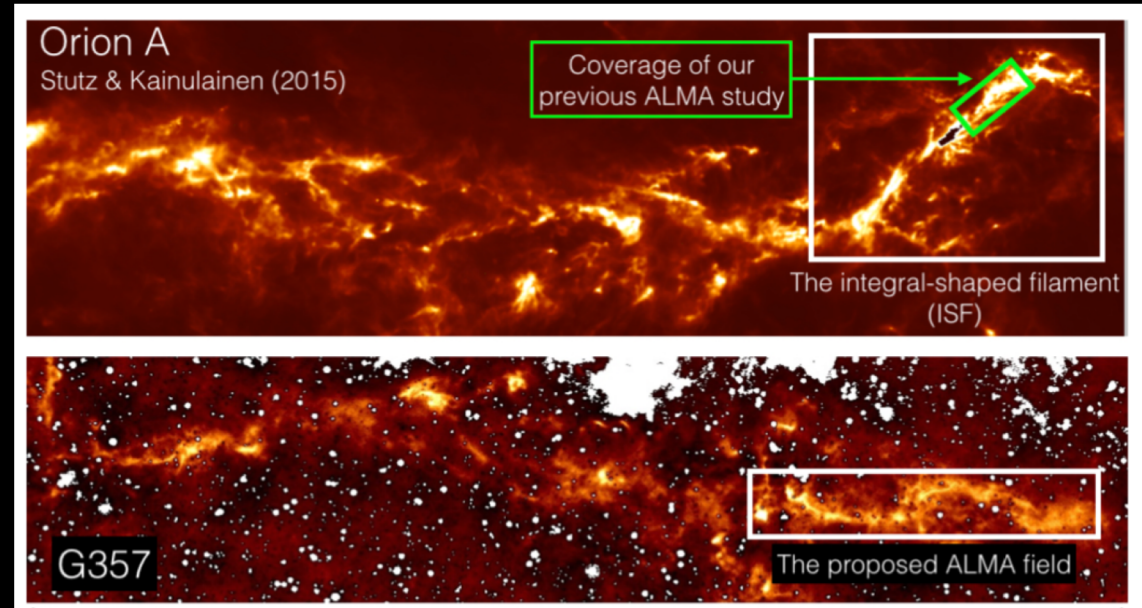


- At **3 Kpc** of distance
- Morphology and mass similar to Orion A
- Dense cloud (**$M_L \sim 300 M_{\odot} / pc$**)
- Younger evolutionary state... It is expected to actively form stars in the future.

ALMA observations

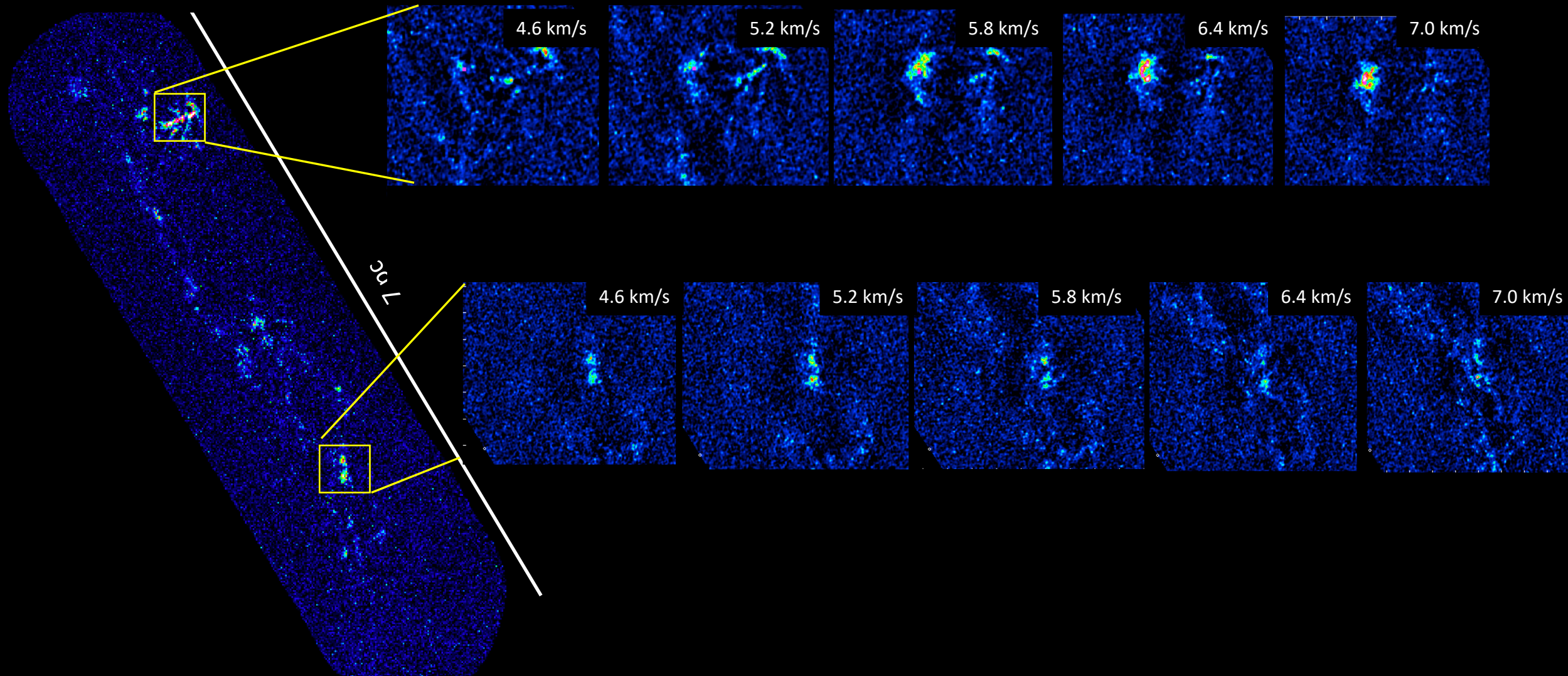


G357



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ALMA observations



THE ASTROPHYSICAL JOURNAL, 779:121 (28pp), 2013 December 20

doi:[10.1088/0004-637X/779/2/121](https://doi.org/10.1088/0004-637X/779/2/121)

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MUSCLE W49: A MULTI-SCALE CONTINUUM AND LINE EXPLORATION OF THE MOST LUMINOUS
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R. GALVÁN-MADRID¹, H. B. LIU², Z.-Y. ZHANG^{3,4}, J. E. PINEDA^{1,5,6}, T.-C. PENG¹, Q. ZHANG⁷, E. R. KETO⁷,
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Roberto Galvan-Madrid and Adam Ginsburg talks

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**ALMA RESOLVES THE SPIRALING ACCRETION FLOW IN THE LUMINOUS OB CLUSTER-FORMING
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Roberto Galvan-Madrid and Adam Ginsburg talks

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II. Continuum millimeter emission of Sgr B2(M) and Sgr B2(N) with ALMA

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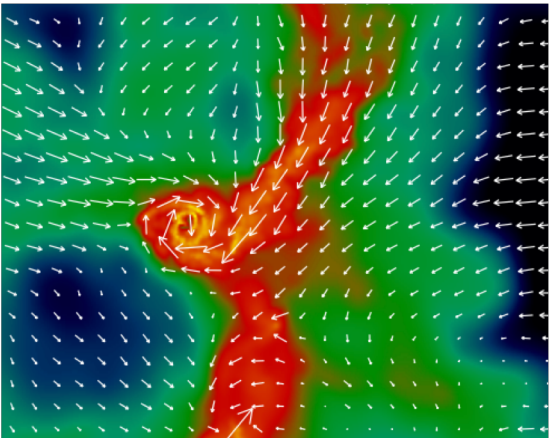
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FILAMENTS IN SIMULATIONS OF MOLECULAR CLOUD FORMATION

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Summary

MonR2, IRAM-30m:

Fragmentation

Mass flux along the filaments

An expanding HII region braking out the filaments

MonR2, ALMA:

Spiral structure within the central hub

Strong velocity gradients

Similar structures have been found, although with lower spatial resolution, **in other massive star-forming regions** and even seen in simulations, posing the question **whether these structures are required in the formation of massive stars or are an outcome of the accretion process.**

Thanks for your attention!