Morphology and fragmentation of a massive star-forming filament

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OUTLINE

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- Targets
- Methodology
  - Observations
  - Analysis
- Results & Discussion
  - Observations
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Introduction

Juvela, M.; Mannfors, E. *Filaments in the OMC-3 cloud and uncertainties in estimates of filament profiles.* Accepted into A&A

arXiv:2301.06746

Mannfors, E.; Juvela, M; Liu,T; Pelkonen, V.-M. *Comparison of Herschel and ArTéMiS observations of massive filaments.* Submitted. 3 reminders to referee D:

All uncredited images are (adapted) from these papers

Dust properties: emission

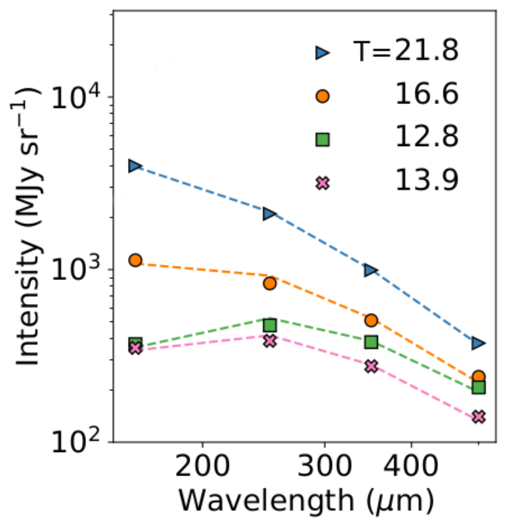
- Dust properties (temperature *T*, column density $N(H_2)$, optical depth τ) can be estimated by fitting a modified blackbody (MBB) function to *Herschel* 160-500 μm data

$$I_\nu = I_{\nu,0}\left(\frac{B_\nu(T)}{B_{\nu,0}(T)}\right)\left(\frac{\nu}{\nu_0}\right)^\beta$$

$$\tau_\nu = \frac{I_{\nu,0}}{B_\nu(T)}$$

$$N(H_2) = \frac{\tau_\nu}{\kappa_\nu \mu m_H}$$

I = Intensity
ν = frequency
ν_0 = reference frequency
$B_\nu(T)$ = Blackbody function at temperature *T*
β = opacity spectral index ~ 1.8-2.0
κ = dust opacity
$\mu\, m_H$ = total mass relative to the H_2 molecule



Dust properties: emission

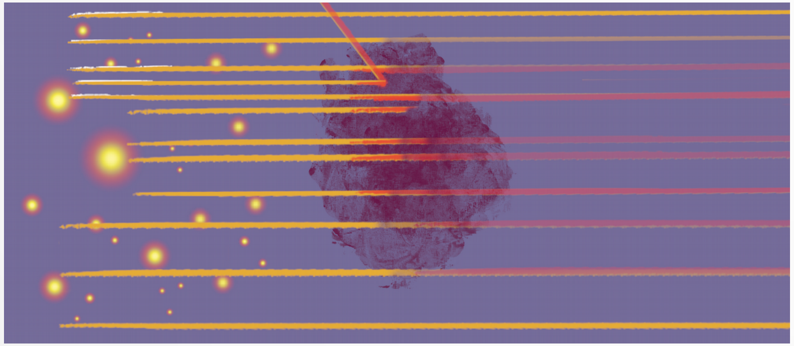
- *T*, *N*(H_2) maps are usually created at lowest resolution (~41”)
- Use Aniano et al. (2011) convolution kernels
- And Palmeirim et al. (2013) method for maps at ~20”

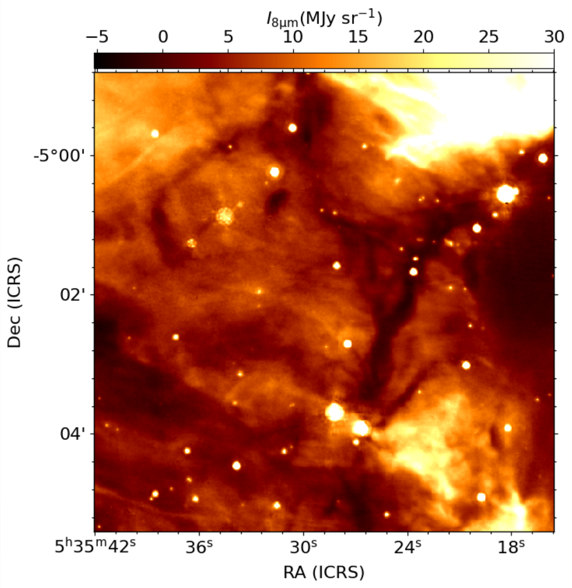
$$N(H_2)_P = N(H_2)_{500} + [N(H_2)_{350} - N(H_2)_{350\rightarrow 500}] + [N(H_2)_{250} - N(H_2)_{250\rightarrow 350}]$$

Dust properties: extinction

- Background light decreases due to absorption/scattering from the ISM
  - Can be used to estimate column densities
  - Independent from FIR estimates of dust emission

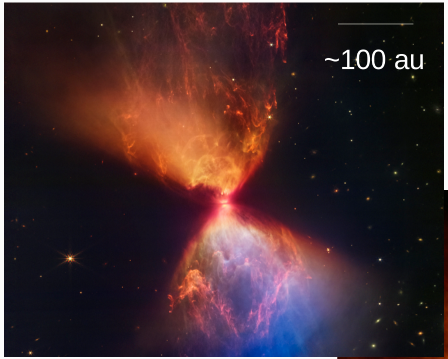
$$I_{obs} = I_{fg,true} + \left(I_{bg,true} \times e^{-\tau}\right) + \Delta I$$

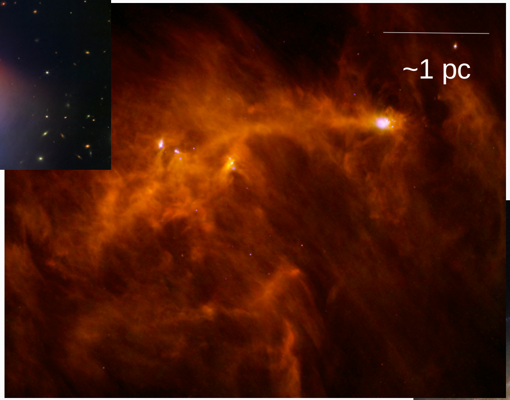


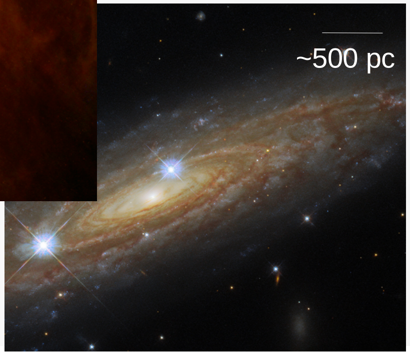


Filaments: basics

- Long, thin structures
- Ubiquitous in the ISM
    - In both observations and simulations
    - At multiple scales





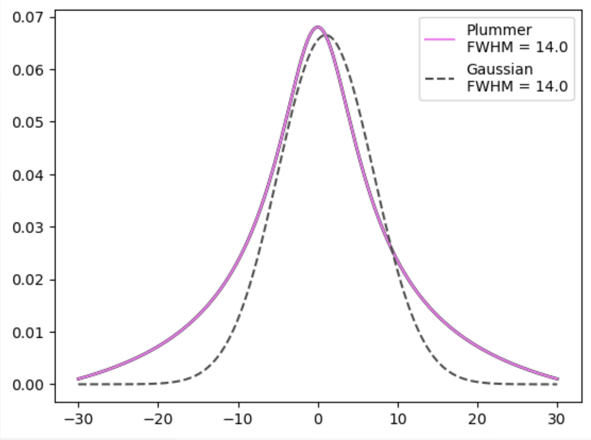


Images, top to bottom
L1527 (Taurus); JWST NIRCam

https://spaceref.com/science-and-exploration/webb-space-telescope-views-a-protostar-within-dark-cloud-l1527/
Chamaeleon I region, Herschel
ESA/Herschel; acknowledgement: Á. Ribas
UGC 11537; Hubble’s Wide Field Camera 3

Filaments: profile

- Profile can be fit with a Plummer function
- *R* and *p* are degenerate; *FWHM* is more robust



Plummer profile   Filament

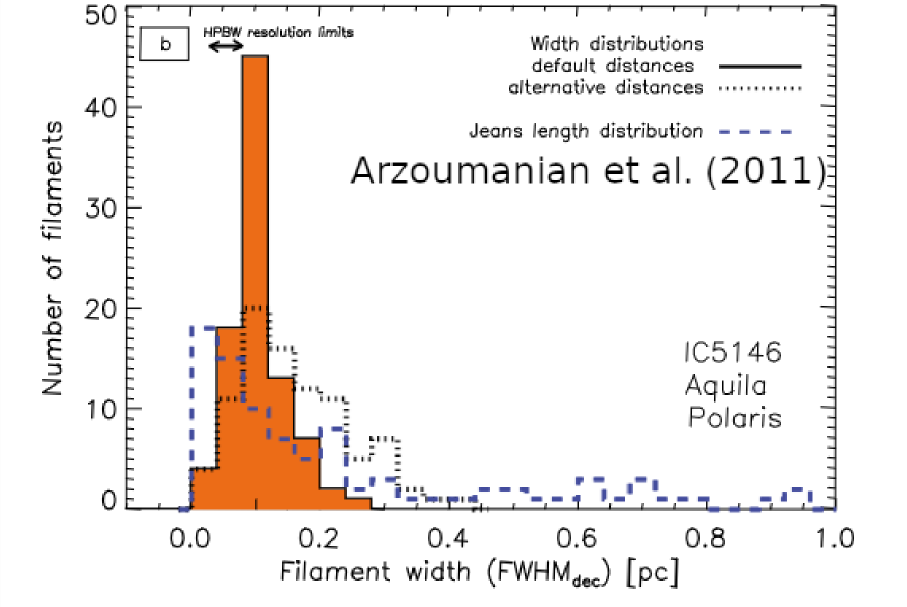
$$Y = \mathrm{Conv}\boxed{\left[N_0 \cdot \left(1.0 + \left(\frac{r + \Delta r}{R_{\mathrm{flat}}}\right)^2\right)^{0.5-0.5\cdot p}\right]} + \boxed{a + b \cdot r},$$

N_0 = maximum intensity
R_{flat} = width of filament
p = slope of filament
Δr = Offset from center

$$FWHM = 2 \times |R| \times \sqrt{2^{2/(p-1)} - 1}$$

Filaments: characteristic width?

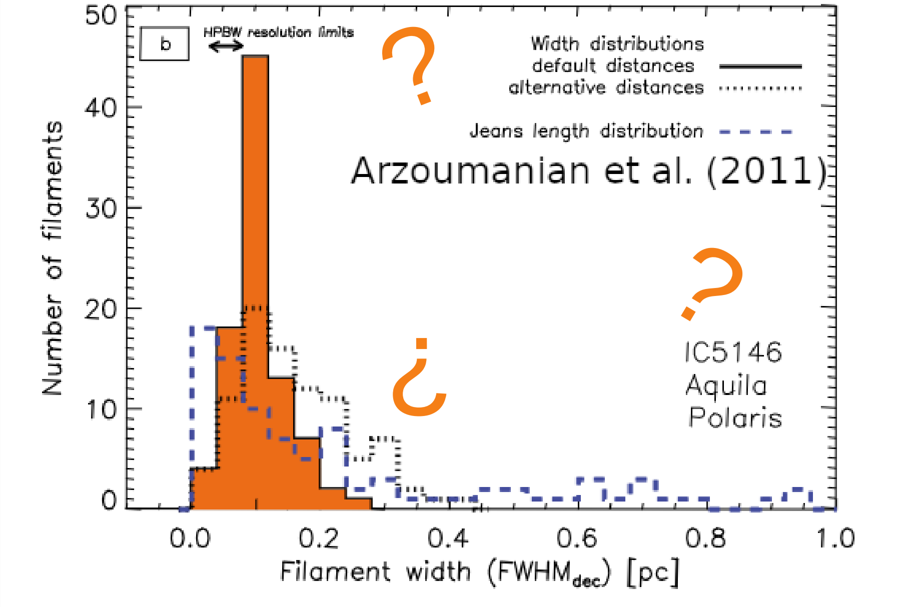
- Filaments in a wide range of environments all were observed to have a 0.1 pc width
- Possibly caused by the change between supersonic and subsonic turbulent gas motions (Padoan et al. 2001) or due to the dissipation mechanism of MHD waves (Hennebelle & André 2013)



Filaments: characteristic width?

- Later contested by e.g. Smith et al. (2014); Panopoulou et al. (2017, 2022)
→ Resolution, distance, etc. can affect derived widths

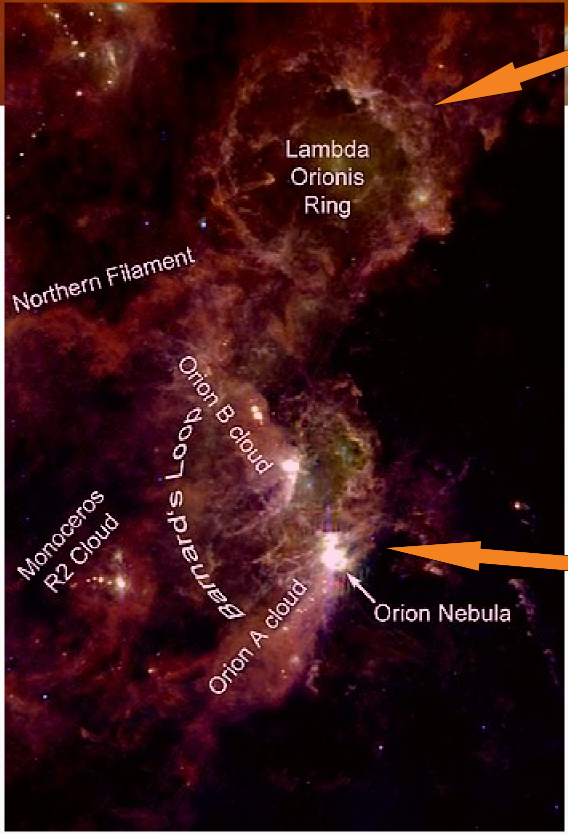
- Is this just the result of limited resolution? Caused by real physics?
  - Debate is ongoing (e.g. André et al. (2022)).

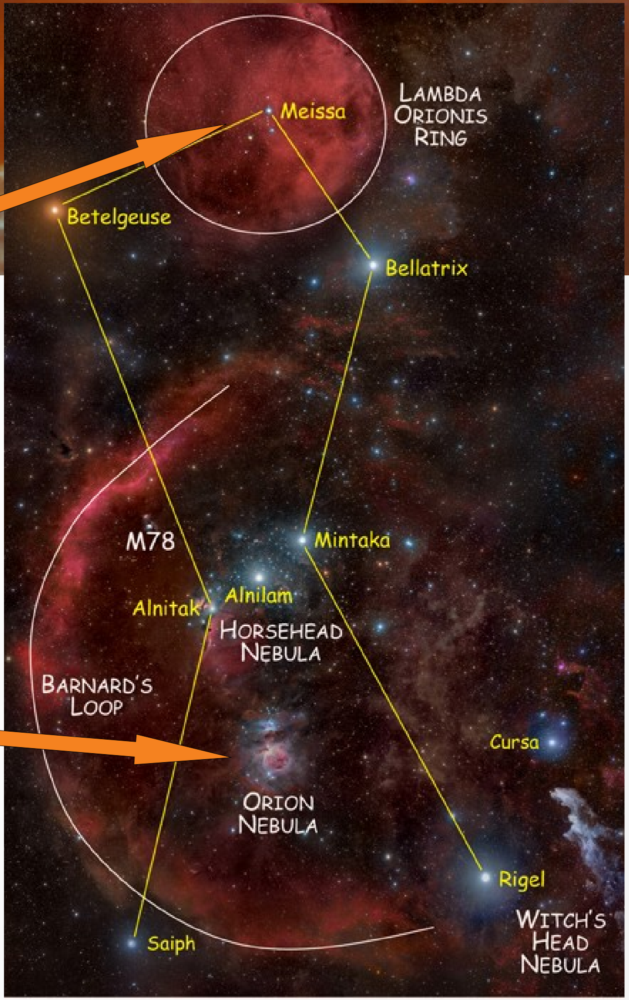


OMC-3

Orion Molecular Cloud (OMC)

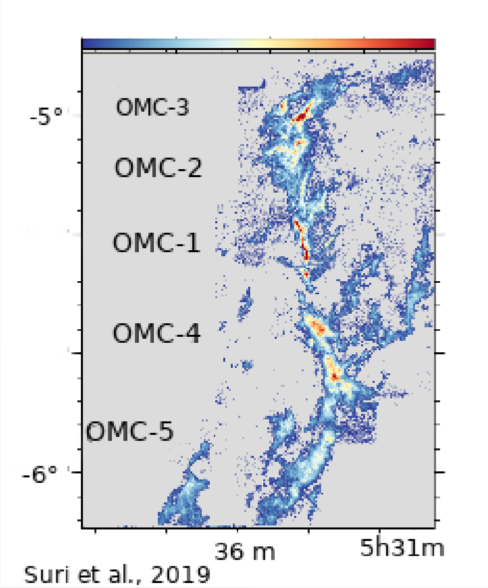
- *d* ~ 400 pc
  (Großschedl et al. 2018)
- High-mass SF region
- Ongoing SF, feedback from young massive stars

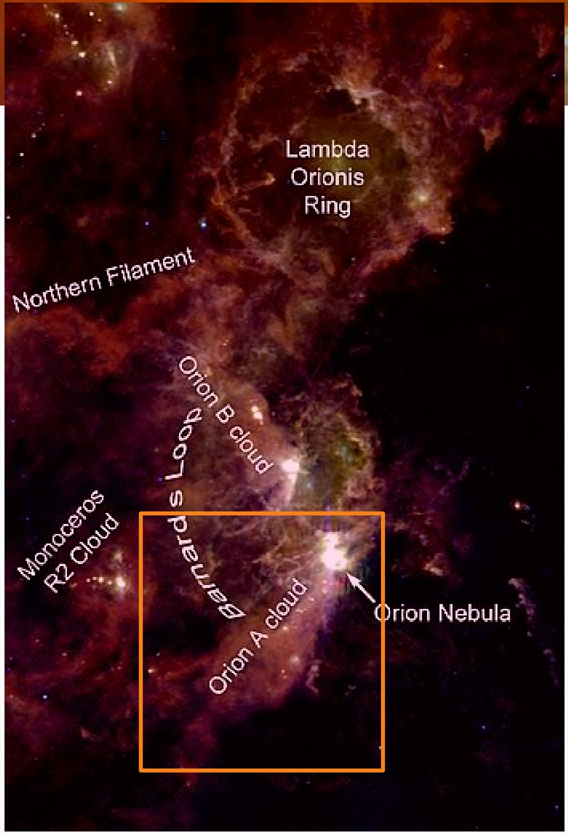


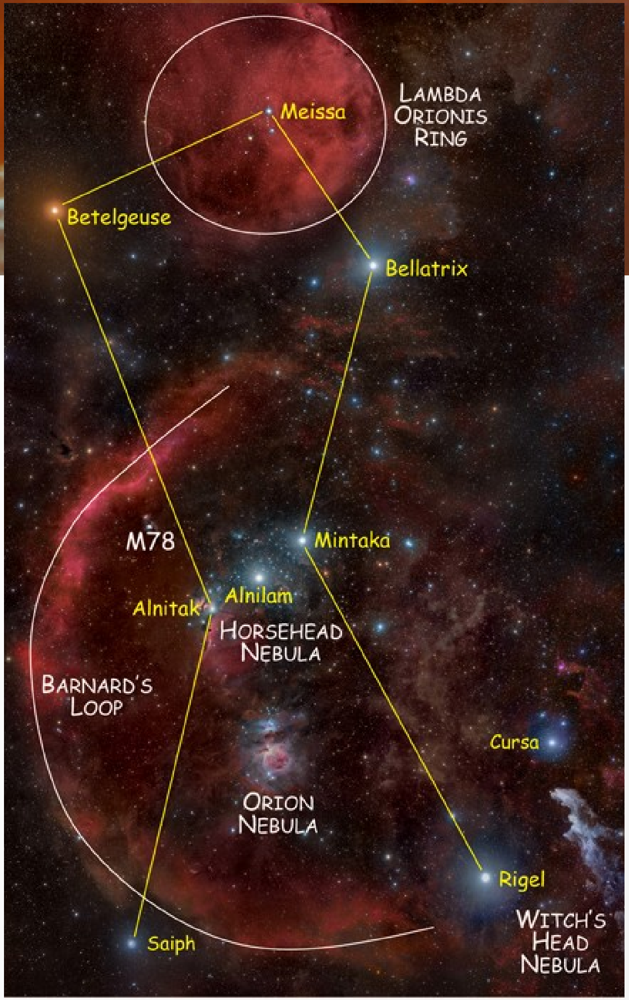


Images:
https://en.wikipedia.org/wiki/Orion_molecular_cloud_complex
https://www.adirondackdailyenterprise.com/opinion/columns/2020/02/the-orion-molecular-cloud-complex/

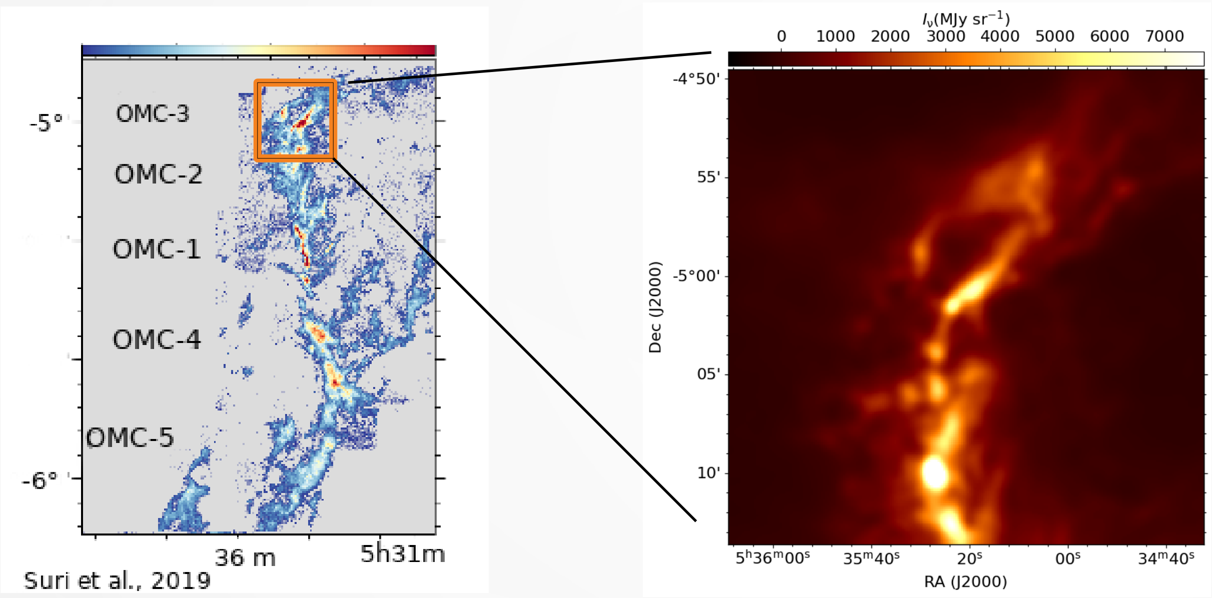
Orion Molecular Cloud (OMC)



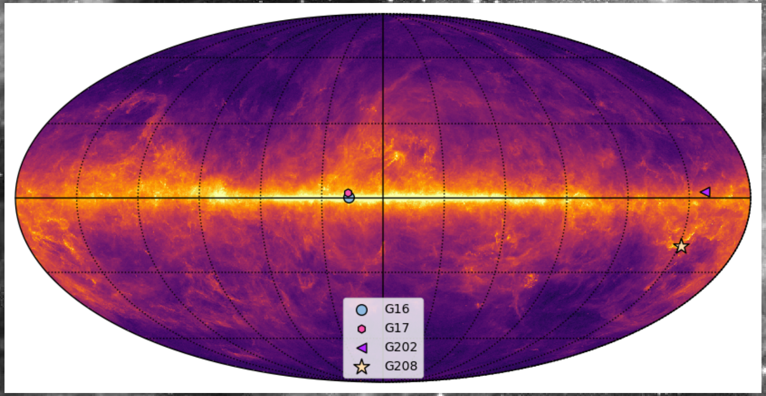




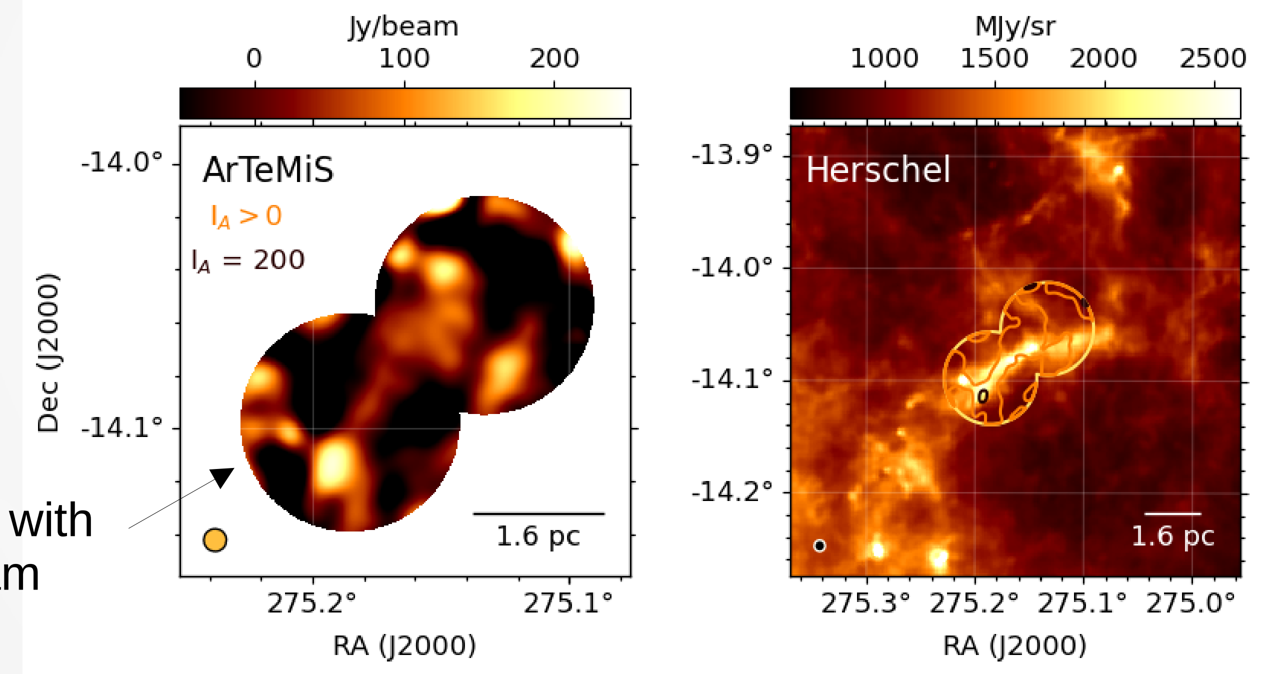
OMC-3


OMC-3
OMC-2
OMC-1
OMC-4
OMC-5
-5°
-6°
36 m
5h31m
Suri et al., 2019
I_ν(MJy sr^{-1})
0 1000 2000 3000 4000 5000 6000 7000
-4°50'
55'
-5°00'
05'
10'
Dec (J2000)
$5^h36^m00^s$
35^m40^s
20^s
00^s
34^m40^s
RA (J2000)

Other targets



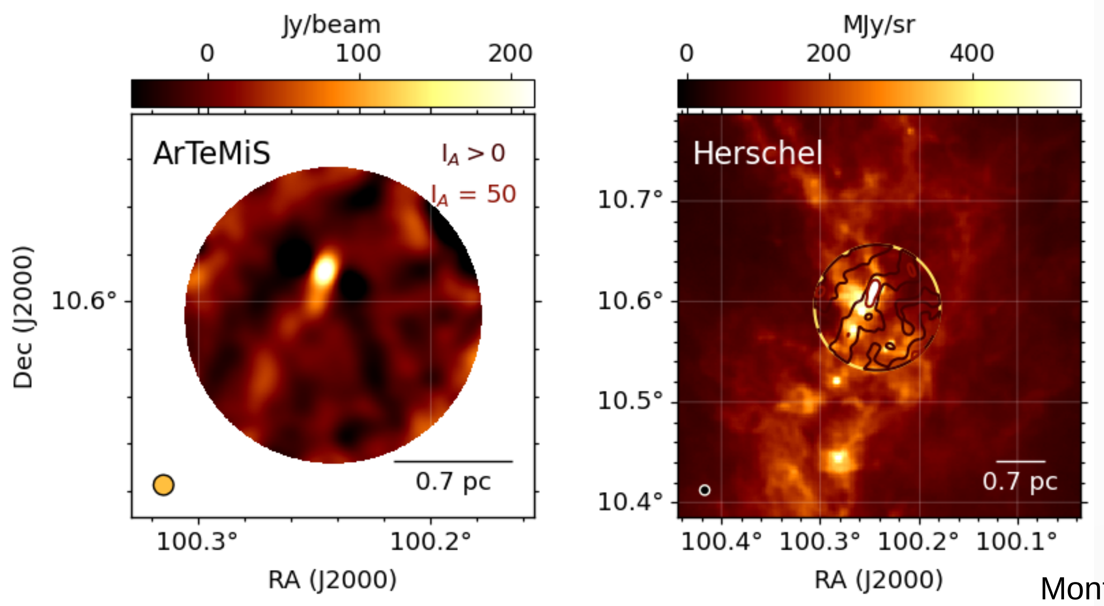
G17



Convolved with a wide beam (~40 pix)

In Galactic plane
d ~ 1850 pc

G202



- Monoceros OB 1 association
- *d* ~760 pc
- Multiple colliding filaments feeding SF

Montillaud, J., Juvela, M., Vastel, C., et al. 2019a, A&A, 631, L1
Montillaud, J., Juvela, M., Vastel, C., et al. 2019b, A&A, 631, A3

Methods

MIR
FIR

Observations

Herschel

- 160, 250, 350, 500 μm
- Lower resolution *(FWHM*$_{\text{beam}}$ ~20-40” ~ 0.04-0.08 pc**)*
- Space based → sees extended emission

APEX** ArTeMis***

- 350 & 450 μm
- Higher resolution *(FWHM*$_{\text{beam}}$ ~9” ~0.02 pc*)*
- Does not see extended emission due to filtering of the atmosphere

Spitzer

- MIR extinction, 3.6 μm-8 μm
- Highest resolution *(FWHM*$_{\text{beam}}$ ~2” ~0.004 pc*)*

*Assuming *d* = 400 pc

** *Atacama Pathfinder EXperiment*
*** *Architectures de bolometres pour des Telescopes a grand champ de vue dans le domaine sub-Millimetrique au Sol*

Combining data

- One dataset with high resolution but no large-scale structure
- One with lower resolution

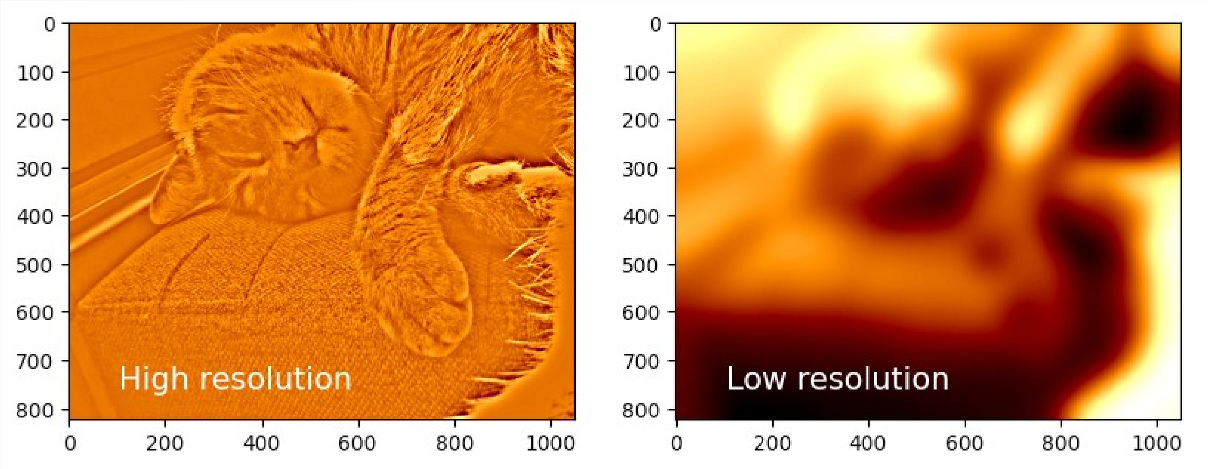


Image: E. Mannfors, Luna "Meow" Mannfors

MIR
FIR

Combining (feathering) data

Feathering (uvcombine)*
Resulting map has high resolution but also extended emission

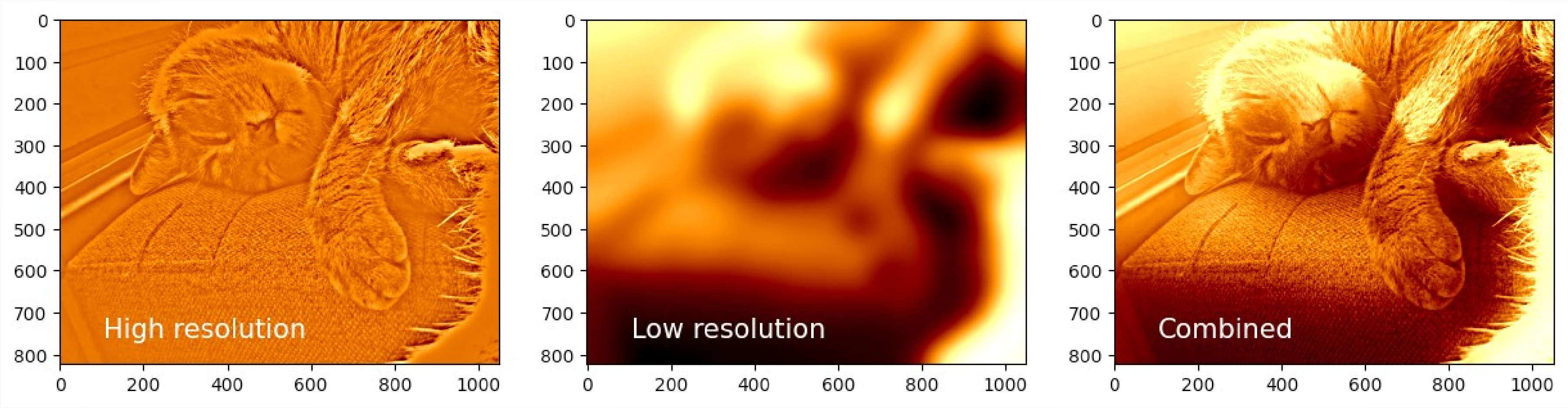
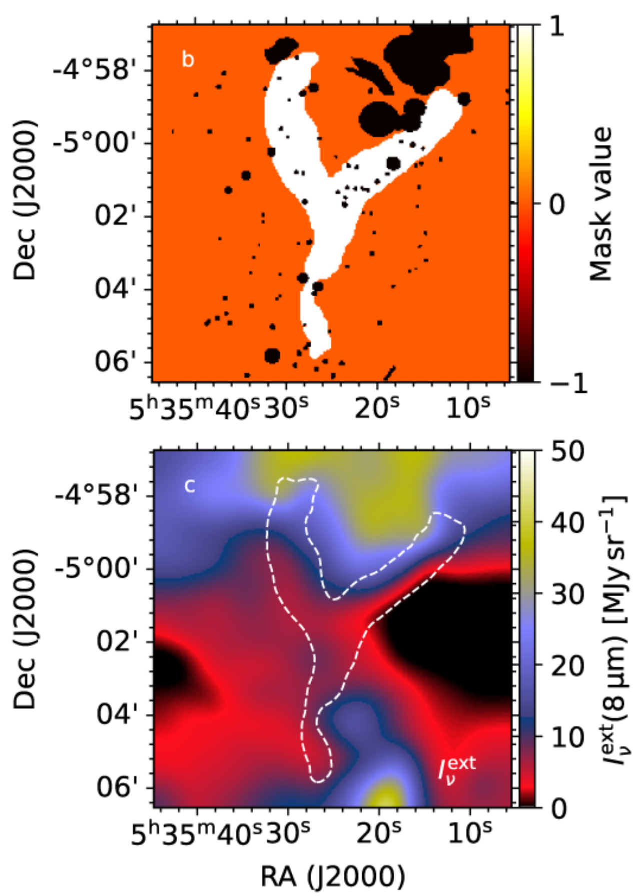


Image: E. Mannfors, Luna “Meow” Mannfors

*https://github.com/radio-astro-tools/uvcombine

Estimating absorption

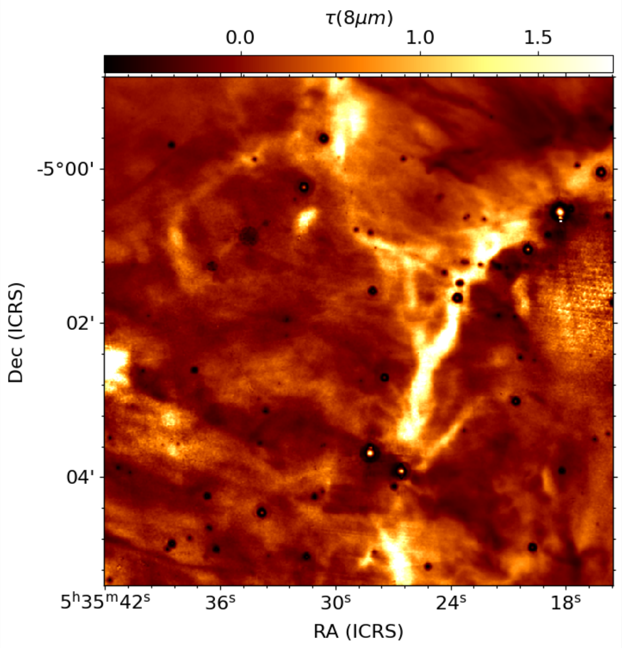
- Estimate extended emission by masking filament and point sources, and convolve by a large beam
- Assume foreground emission = minimum observed surface brightness



Estimating absorption

- Estimate foreground emission by masking filament and point sources, and convolve by a large beam
- Assume foreground emission = minimum observed surface brightness

→ Optical depth map at *FWHM* ~ 2”



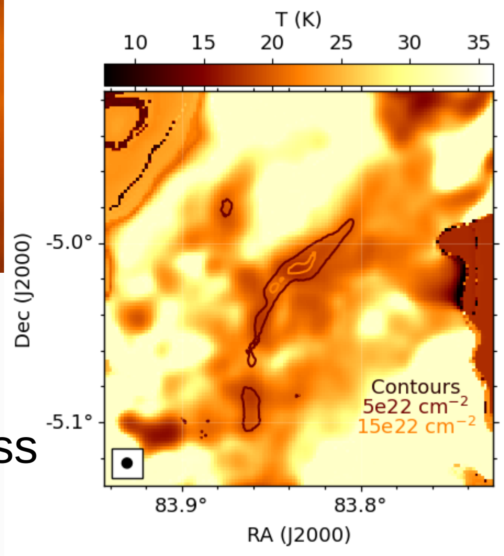
Column densities

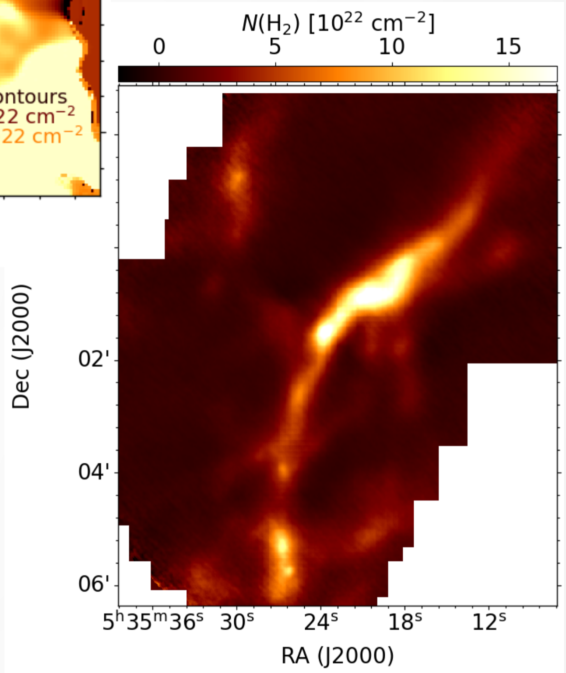
MIR
FIR

- *Herschel N*(H_2) using MBB (*FWHM* ~ 20")

- ArTeMiS *N*(H_2) using 350 um surface brightness *(FWHM ~ 9")* and *Herschel* temperature

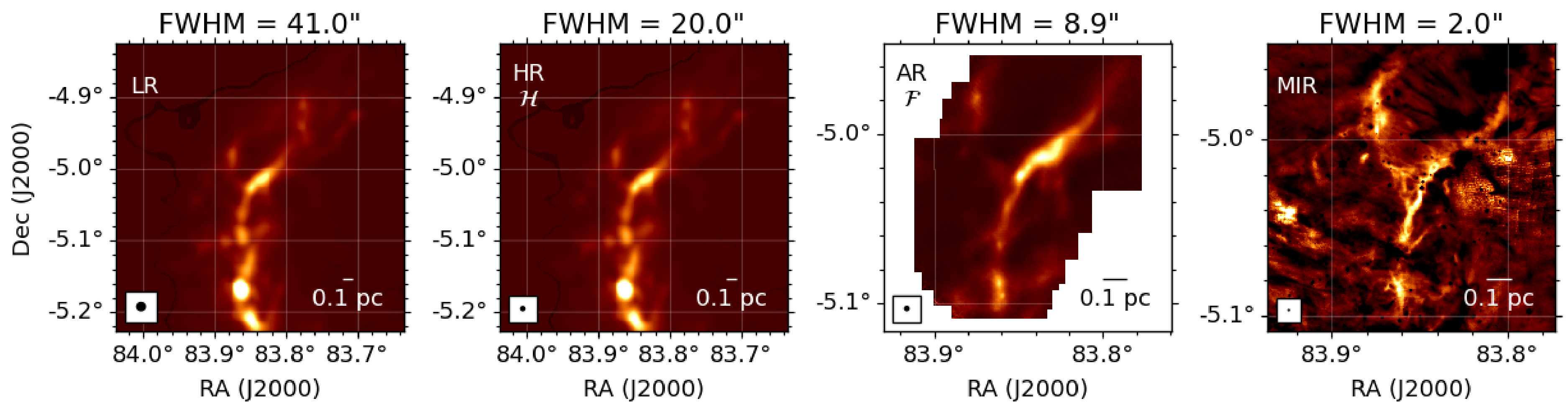
- *Spitzer* N(H2) using the τ map and 8 um dust opacity of 7.5 $cm^2\ g^{-1}$





Data types

Emission | Extinction



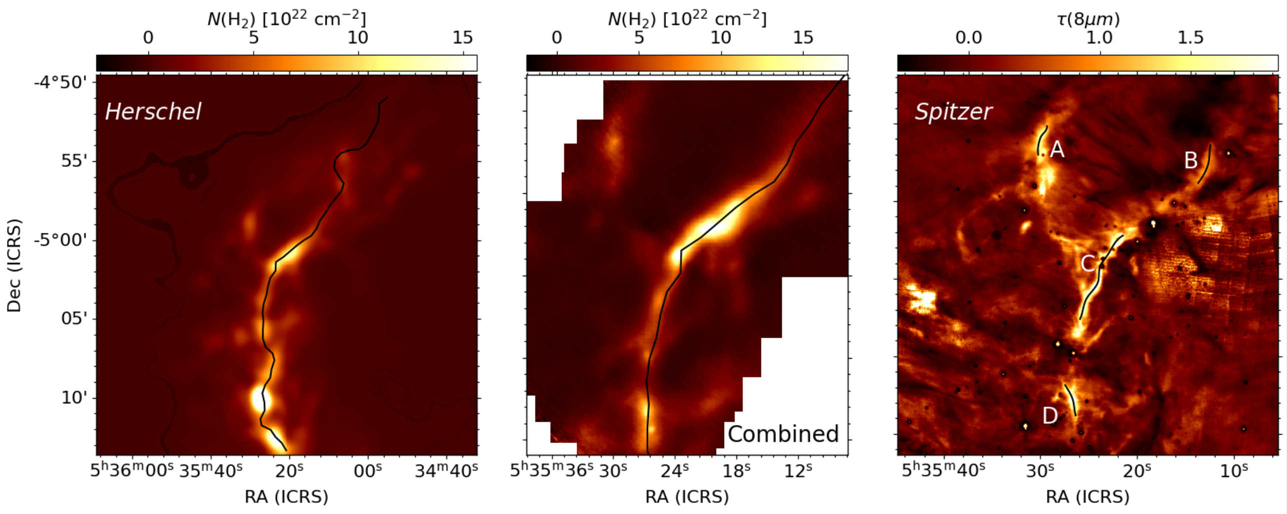
Herschel
250, 350, 500 um

ArTeMis
350 um

Spitzer
8 um

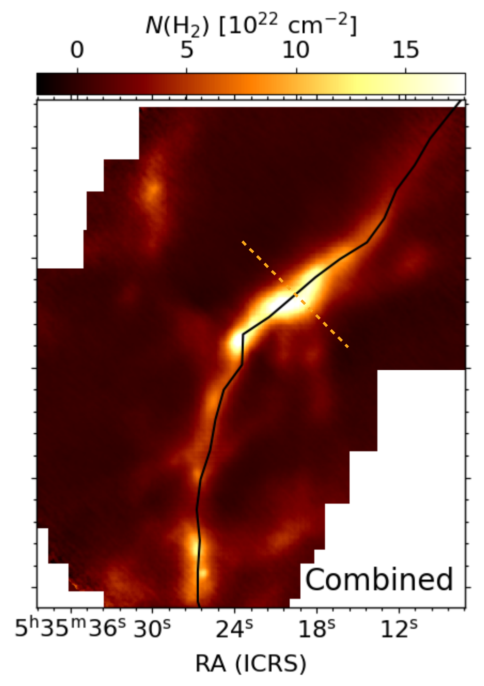
Filament extraction

- Filaments were found from the data
    - Main filament from FIR *(Herschel* and combined*)* data
    - Four brightest segments from MIR *(Spitzer)* data

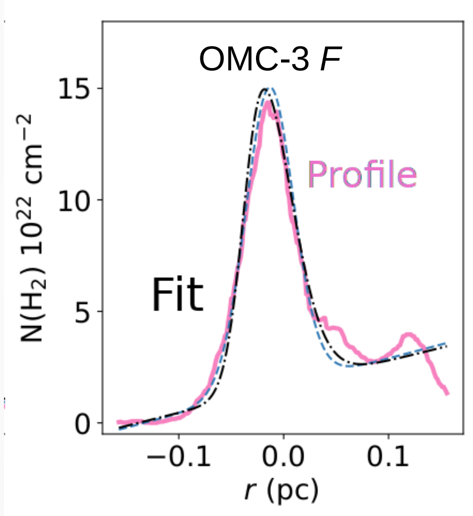


Profile fitting

MIR
FIR



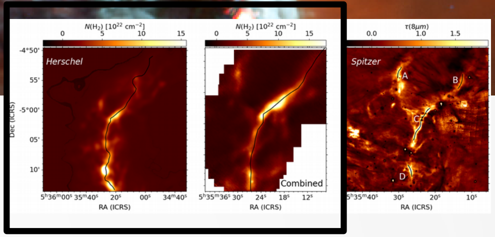
- Extracted profiles perpendicular to filament path
- Fit profile with Plummer function
- Full-width at half-maximum (*FWHM*) describes filament width

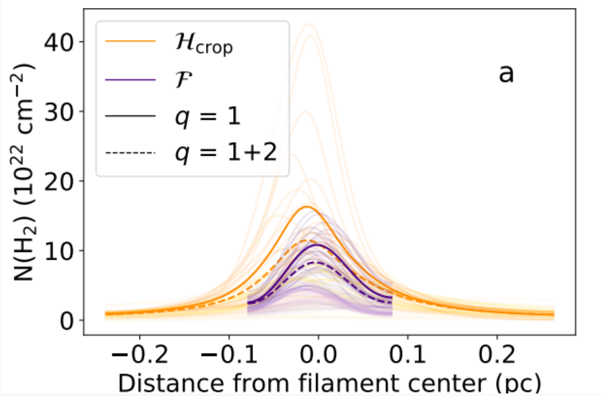


Results

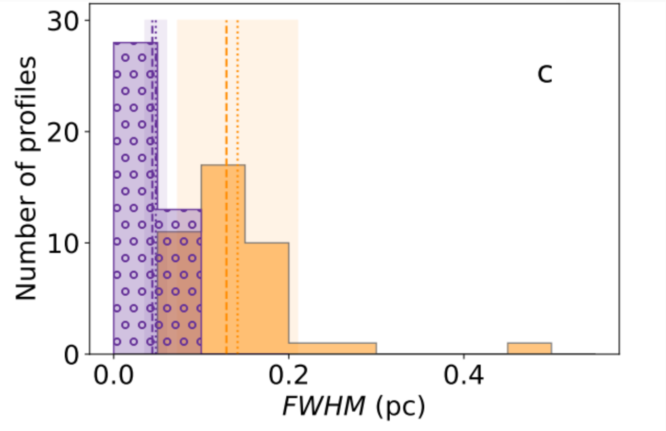
MIR
FIR

Significant differences between characteristics in *Herschel* vs. combined data: filament shape



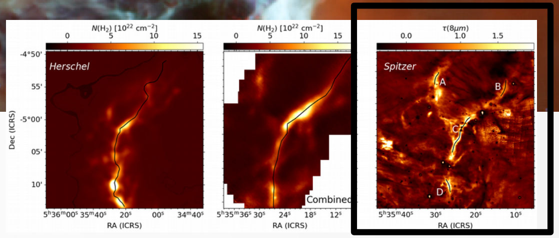


Using the full filament:
- Widths are significantly larger in *H* data

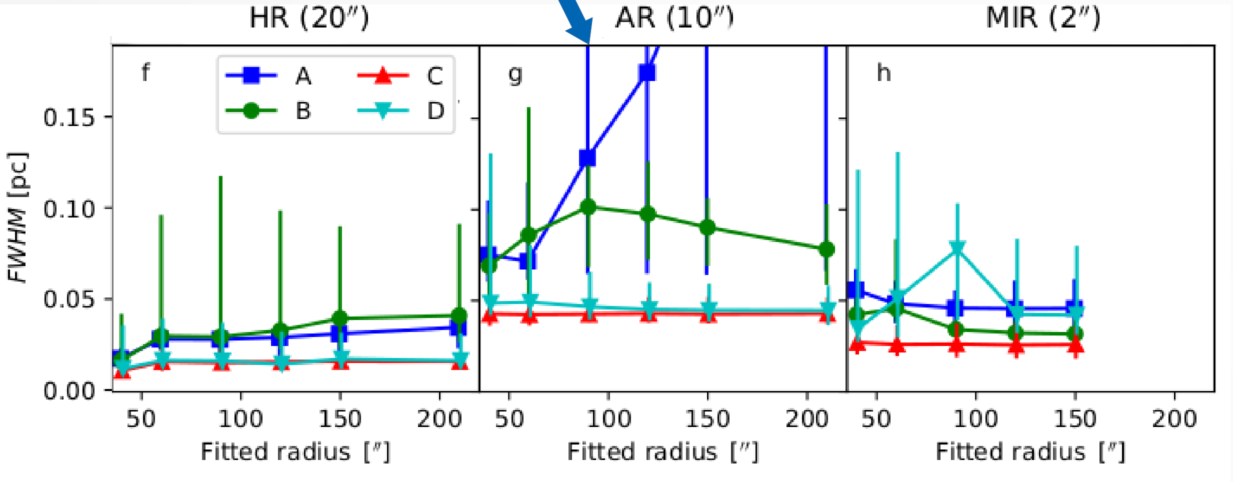


MIR
FIR

But no significant difference with filament segments:



Segment A is close to map edge in AR map



- No change in (mean) width
- (Not due to fitting routine)
-Why don’t densest filament segments show change in widths?

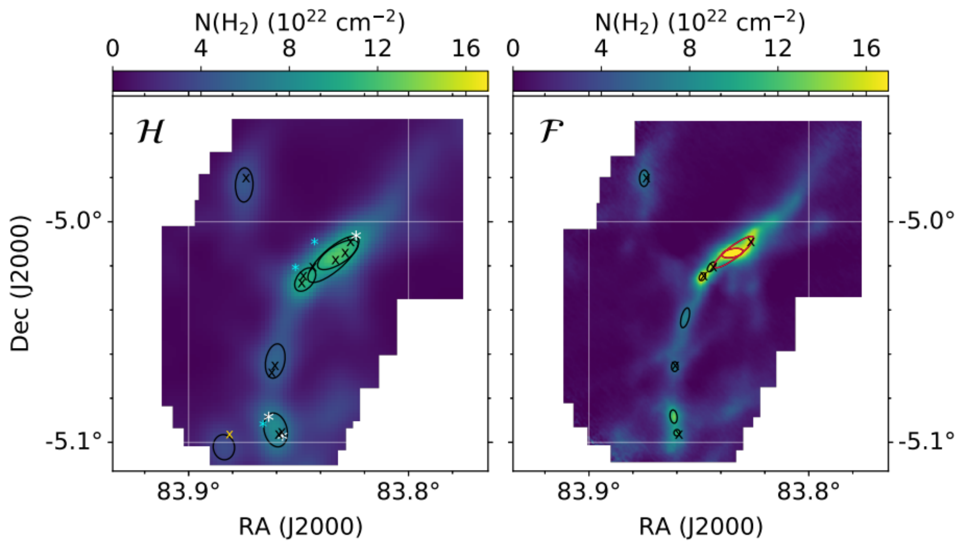
Filament widths

Spread in widths caused by hierarchial structure in the ISM?

Method	Full filament *Herschel*	Full filament *F*	MIR absorption	FIR emission	FIR emission
Resolution	20”	10”	2”	20”	10”
FWHM (pc)	0.11±0.03	0.05±0.01	0.04	0.02-0.04	~0.05

Significant differences between characteristics in *Herschel* vs. combined data: fragmentation

- Clumps in *H* are larger, but have lower mass and density
- Median separation between *H* structures is > Jeans length
- All clumps are stable against gravity → not collapsing
- *F* clumps have separation = Jeans lengths
- Two *F* clumps are potentially collapsing
    - No associated protostars with these clumps



Protostars (crosses and asterisks) from Megeath et al. (2012)

Synthetic filament observations

- Used RT simulations to study possible sources of error in filament fitting
    - Single linear filament, with density profile:
      R = 0.0696 pc, p = 3 → $FWHM$ = 0.14 pc = 72″
    - Isotropic background, and sometimes a point source (B5V star)
    - FIR emission calculated with core-mantle-mantle (CMM) dust
    - MIR emission calculated with Compiègne et al. (2011; COM) dust model
    - Dust scattering with CMM dust
    - RT using SOC (Juvela 2019) program
    - Column density of filament was varied from ~10^{21} – 10^{23} cm^{-2}
- “Observed” with a Gaussian beam of 24”

Bias in MIR observations

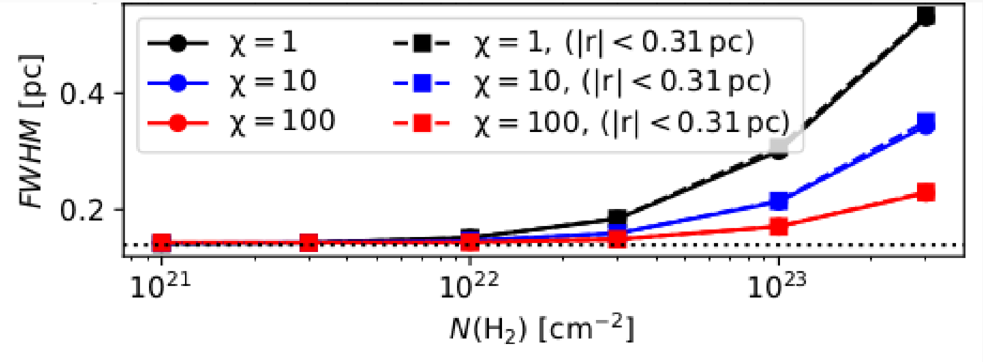
Scattered light
- High τ or strong point sources increase bias due to scattered light *but* don't generally have a strong effect
- Only significant if $N(H_2) \geq 10^{24}$ cm^{-2}

→ Not significant error source in OMC-3

Thermal dust emission
- *p* and *FWHM* are overestimated near bright point sources
- This effect is worse if the source is along the LOS
- Bias worsens with increasing $N(H_2)$

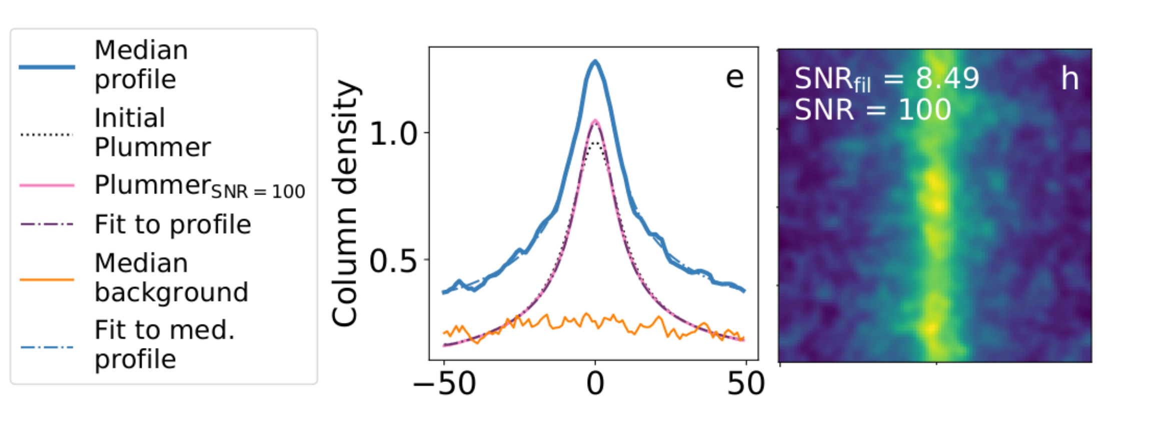
Bias in FIR observations

- Often caused by line-of-sight temperature variations
- Increasing $N(H_2)$ → τ is underestimated, *p* and *FWHM* overestimated
- A stronger radiation field can compensate for these biases
- Change in dust properties can also affect parameters
- Single-temperature MBB model can cause biases

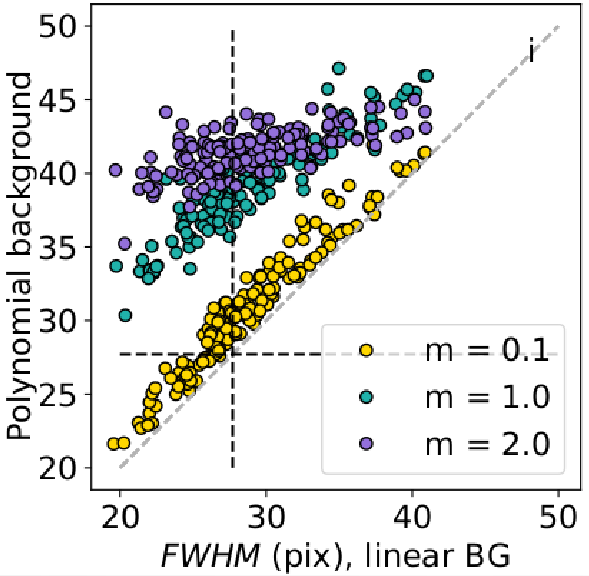


Uncertainties in fitting routines

- Performed Plummer fits using different methods to test changes in parameters
- Using both observed data and a simulated filament

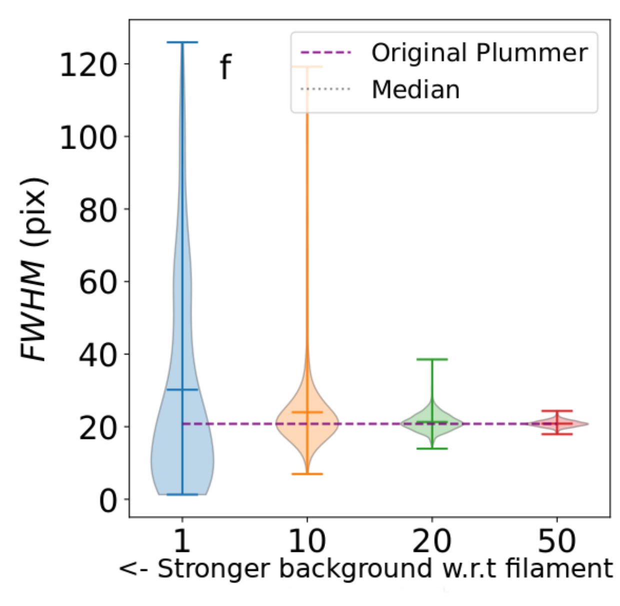


Uncertainties in fitting routines

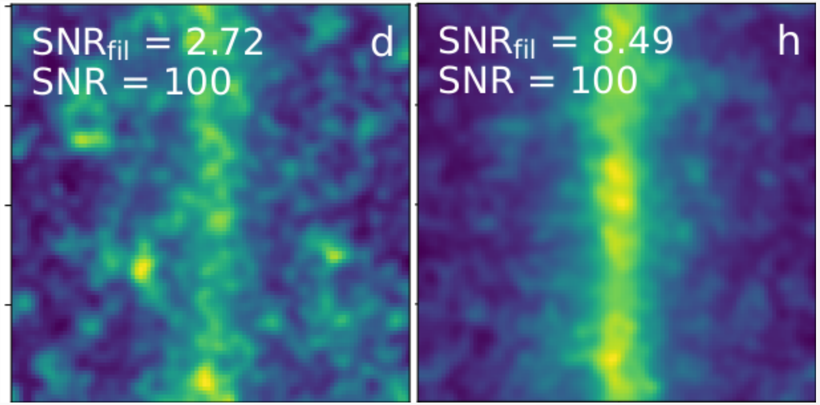


- Assumed background shape changes derived parameters
- A stronger polynomial background raises *FWHM*

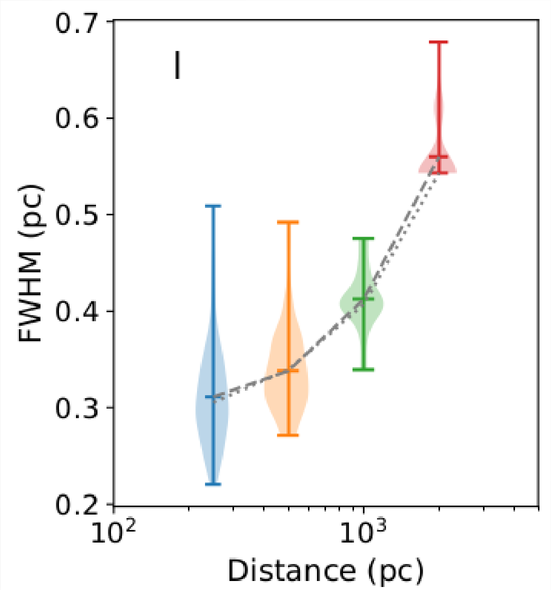
Uncertainties in fitting routines



- A stronger background sky increases uncertainty in *FWHM*



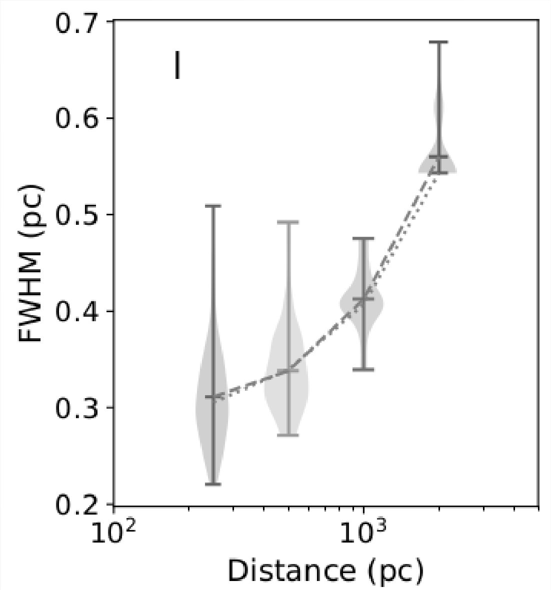
Uncertainties in fitting routines



Increased distance to filament increases *FWHM...*

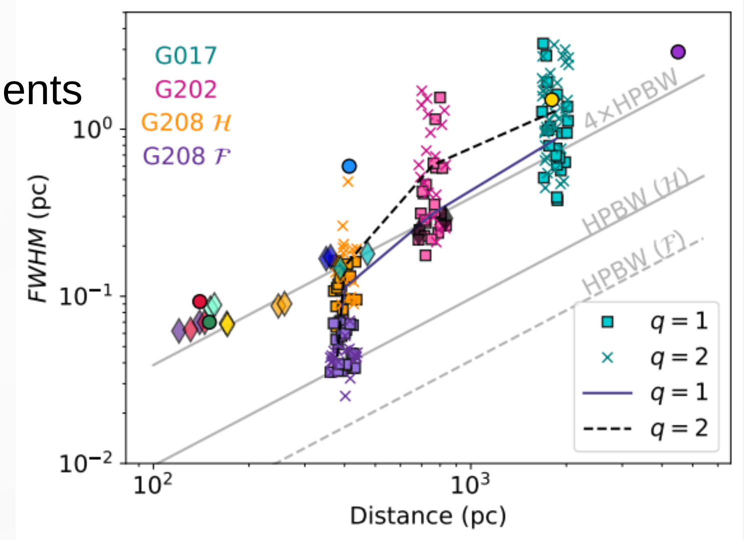
Uncertainties in fitting routines

MIR
FIR

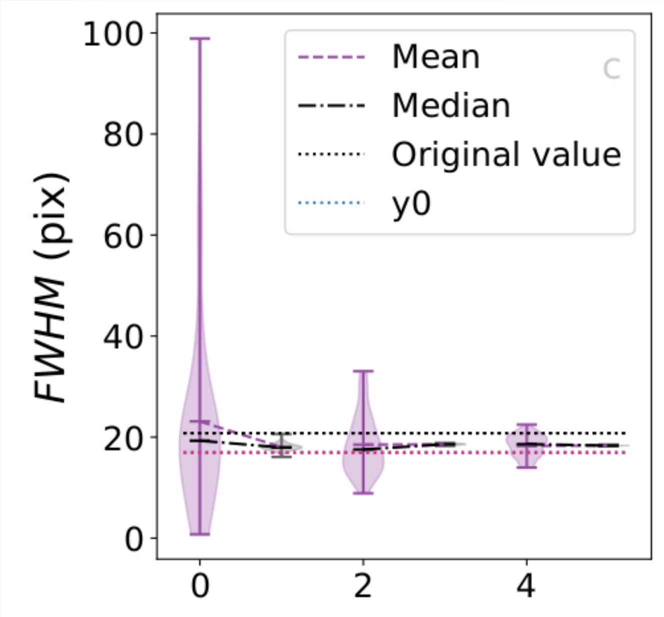


Increased distance to filament increases *FWHM*...

… also in observed filaments



Uncertainties in fitting routines



← stronger BG

- Convolving the Plummer with a 1-D convolution means subsequent rows are not correlated → more uncertainty
- Even moderately strong filaments ($Max_{filament}$ = 8.5 x σ_{BG}) have little error in mean values

Main conclusions

- The ISM shows structure on many scales
0.1 pc may be an important scale
- Importance of high-resolution data to study fragmentation in more detail

- OMC-3 shows evidence of possible future SF

- Bias in filament fitting increases with higher column density
- But with a 10x higher radiation field (= higher *T*), bias decreases
- In our simulations, thermal MIR emission is more significant than MIR scattering
- All depend on e.g. dust models used

- Filament fitting routines are subject to uncertainty & must be taken into account when comparing results

Future projects

LOri BFROST observations
- See talks on Friday (Job, Julien)

Circumplanar gas in nearby galaxies (ALMA)

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