Characterisation of the mid-J CO emission towards an ATLASGAL-selected high-mass clumps in the inner Galaxy

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High-mass star formation at GHz/THz frequencies

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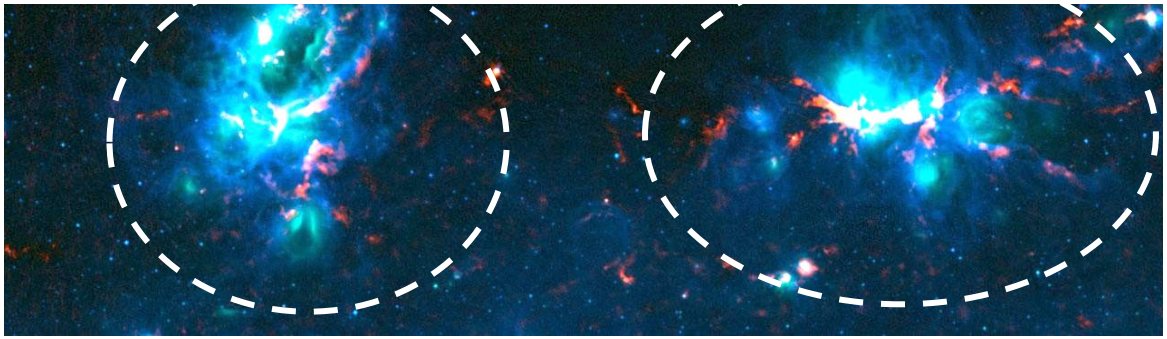
Outline

- High-mass star formation
- Ongoing works
  - mid-J CO observations at APEX
  - Molecular outflows
- Future works with LLAMA and other facilities

High-mass star formation

High-mass stars ($M > 8\ M_{Sun}$):

Important: heavy elements + evolution of the ISM + galaxies

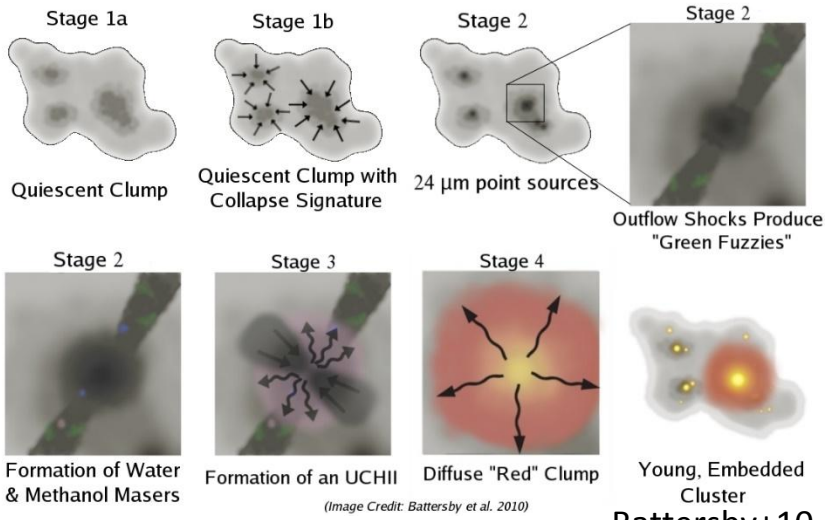


NGC 6357 (left) and NGC 6334 (right)
(ATLASGAL/MSX combined map)

Hard to detect: deeply embedded into parental clouds,
fast pre-MS evolution (~ Myr) and
rare (~1%, assuming a Salpeter IMF)

High-mass star forming regions (HMSFRs):
strongly correlated with **high column density**

Evolutionary sequence:
complex and still not completely understood
(e.g., Battersby+10)



Battersby+10

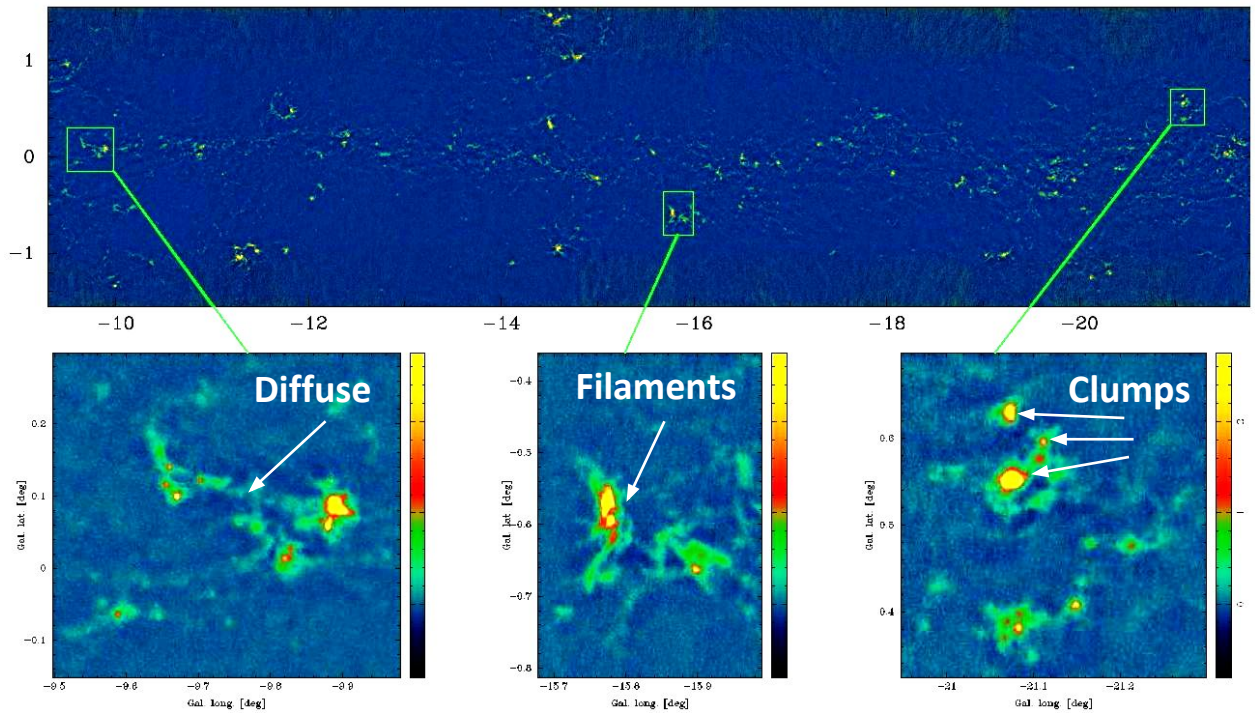
ATLASGAL: structure of the dust

SFRs ↔ **high-column density,** bright at **sub-millimeter** frequencies

ATLASGAL (Schuller+09)

observed the inner Galaxy (280º < l < 60º) at **870 μm** to provide an **unbiased** census of potentially **precursors of high-mass stars**.

LABOCA/APEX: Observations at 870 μm, angular resolution of ~19”, sensitivity ~60 mJy/beam



ATLASGAL Top 100 Sample

Initial catalog: ~10,000 sources (Contreras+13, Csengeri+14)

ATLASGAL Top100 sample: the **100 brightest** ATLASGAL clumps, selected through **additional IR criteria.**

→ **unbiased** study of clumps at different evolutionary stages (König+17)

Identify a solid **evolutionary sequence** for **high-mass star formation**.

Additional follow-up studies:

1) CO depletion (Giannetti+14)
2) Association with RRLs and ionized gas (Kim+17)
3) Warming-up of the gas as a feedback process from the central sources (Giannetti+17)
4) Characterisation of the ^{12}CO emission (Navarete+, *subm.*)
5) Association with mid-J CO outflows (Navarete+, *in prep.*)

Observations: CHAMP$^+$/APEX

mid-J CO transitions observed using the **CHAMP$^+$** heterodyne array at the **APEX** 12-m telescope

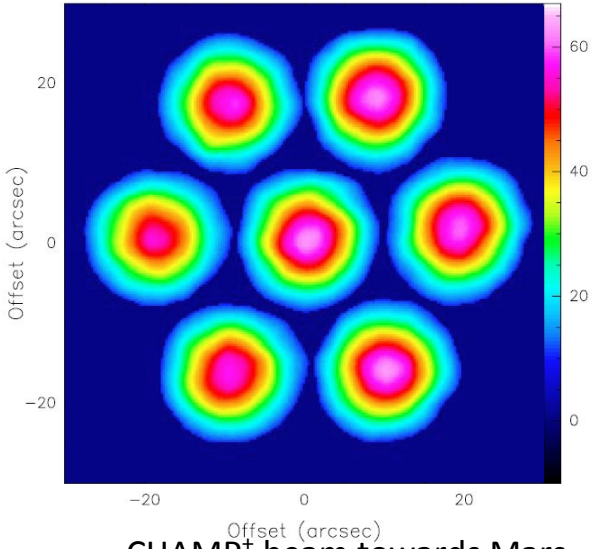
CHAMP$^+$ has two 7-pixel arrays, observing simultaneously two different spectral ranges:

LFA: 620-720 GHz; HFA: 780-950 GHz; Δv~0.3 km/s

CO (6-5) – 691 GHz – beam size 9.5”, rms~200 mK

CO (7-6) – 812 GHz – beam size 8.2”, rms~900 mK

CO (6-5) is the only CO transition available during LLAMA first-light! (Band 9)

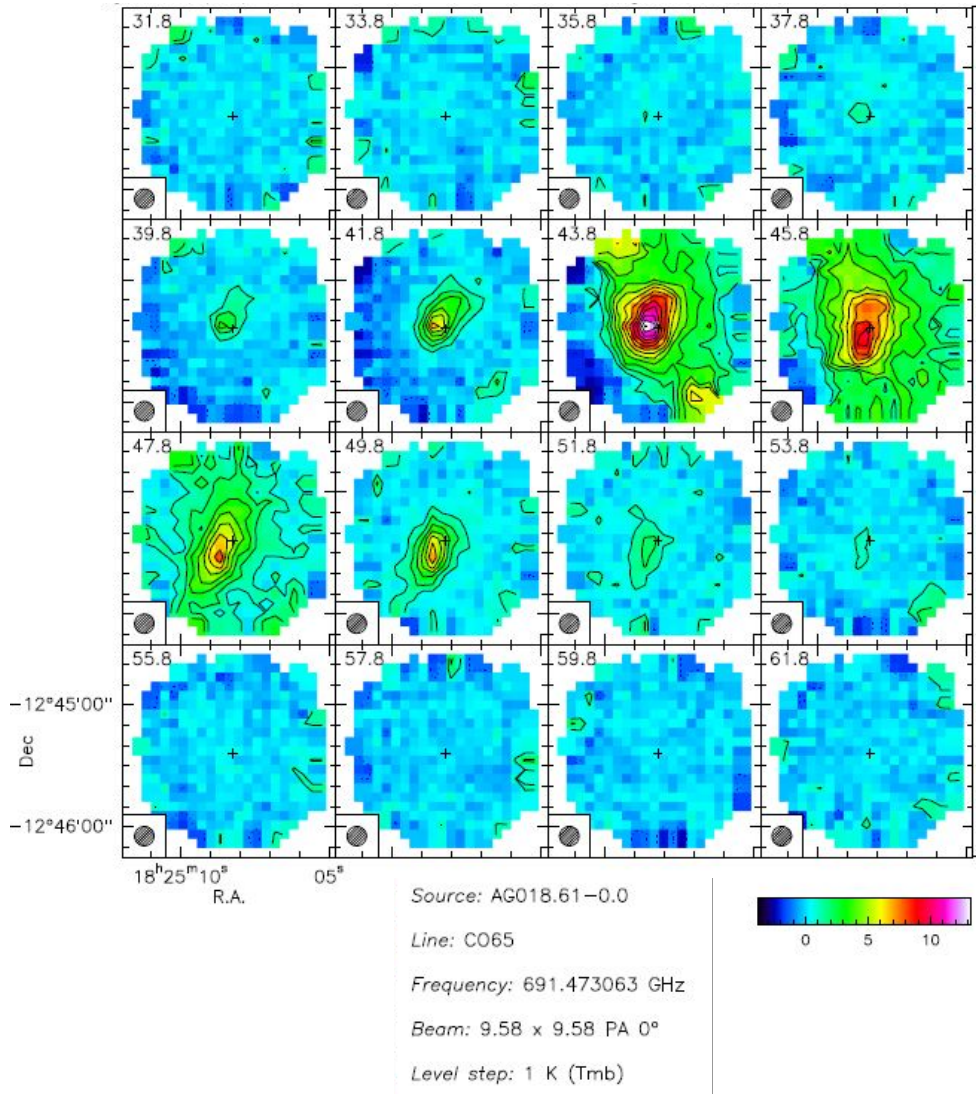


CHAMP$^+$ beam towards Mars (Kasemann+08)

Observations: CHAMP$^+$/APEX

- On-the-fly (OTF) observations:

  maps of 80 x 80 arcsec^2



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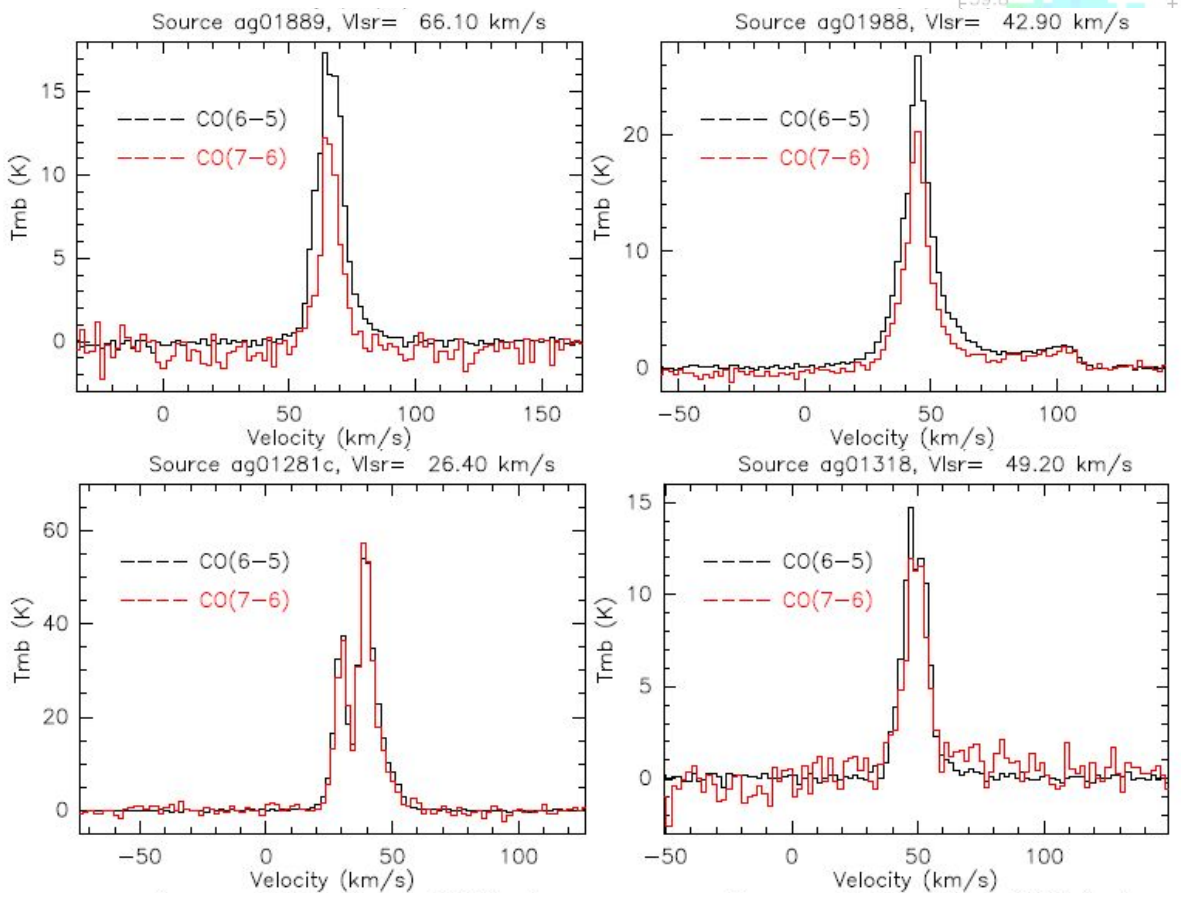
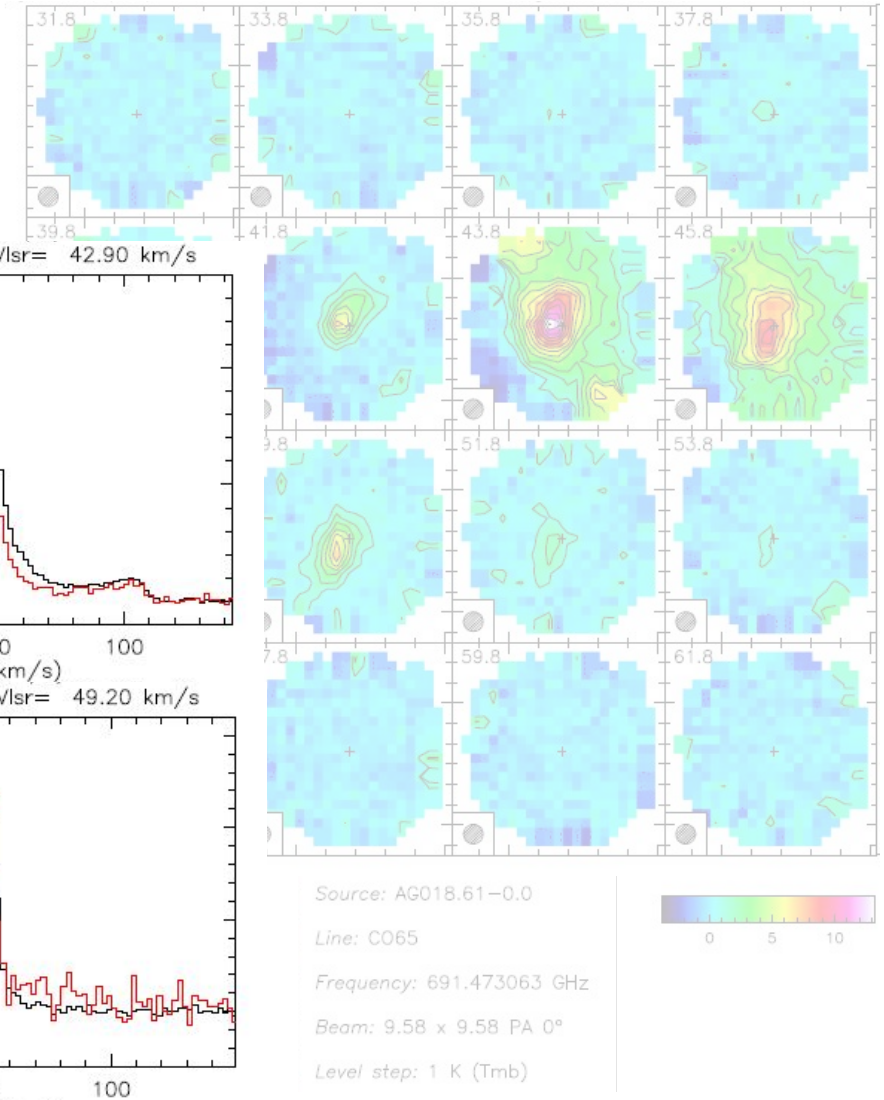
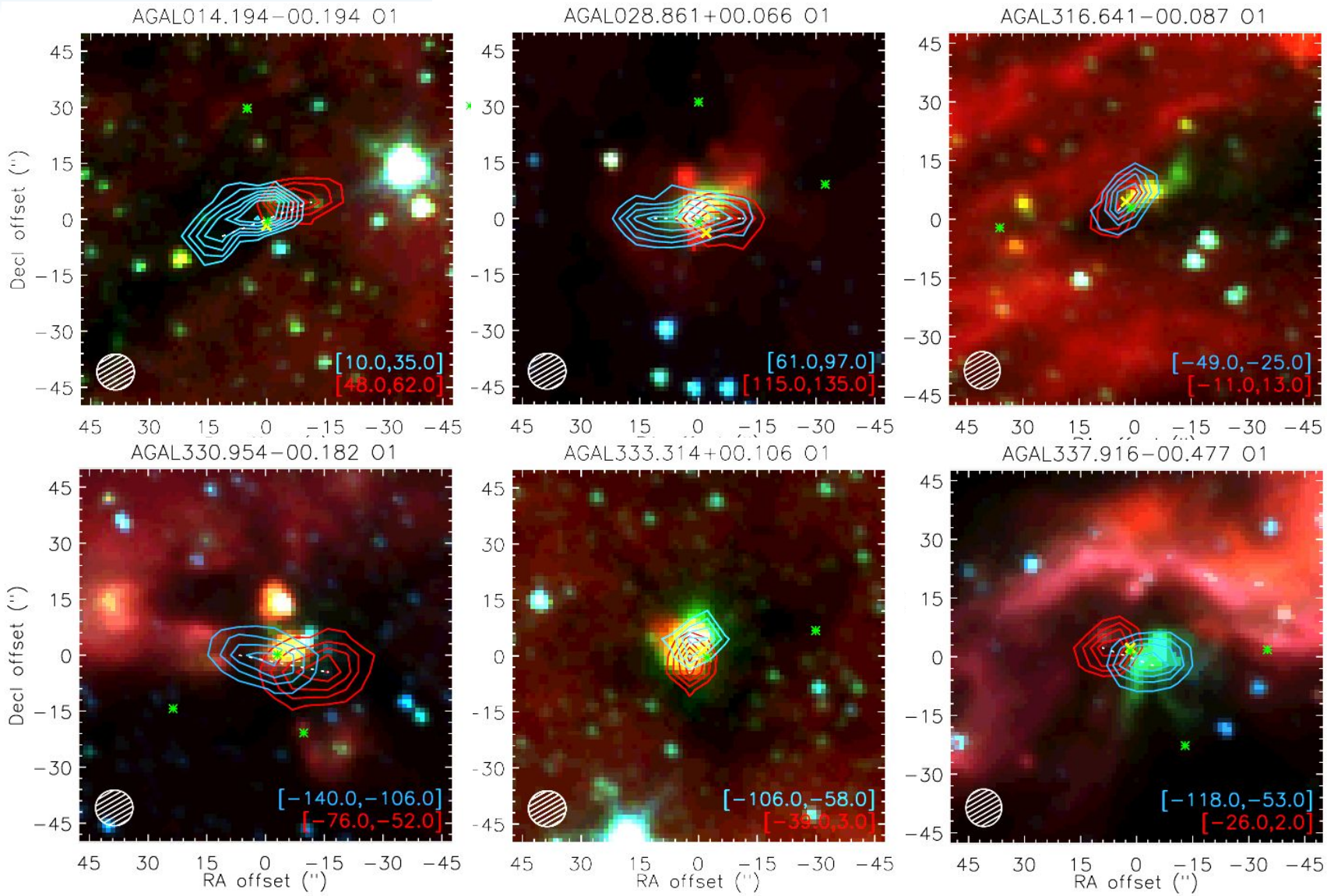




Examples of CO(6-5) outflows



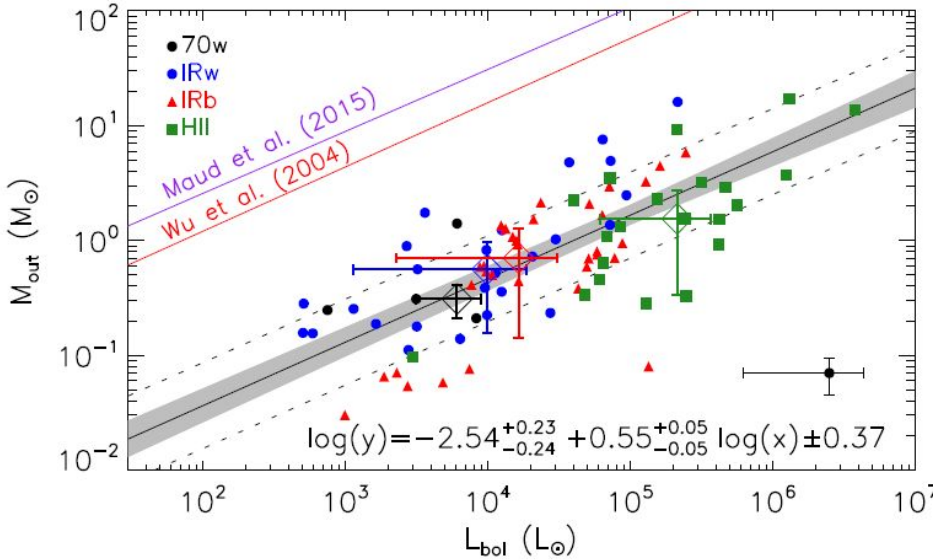
Outflows: correlation with clump properties

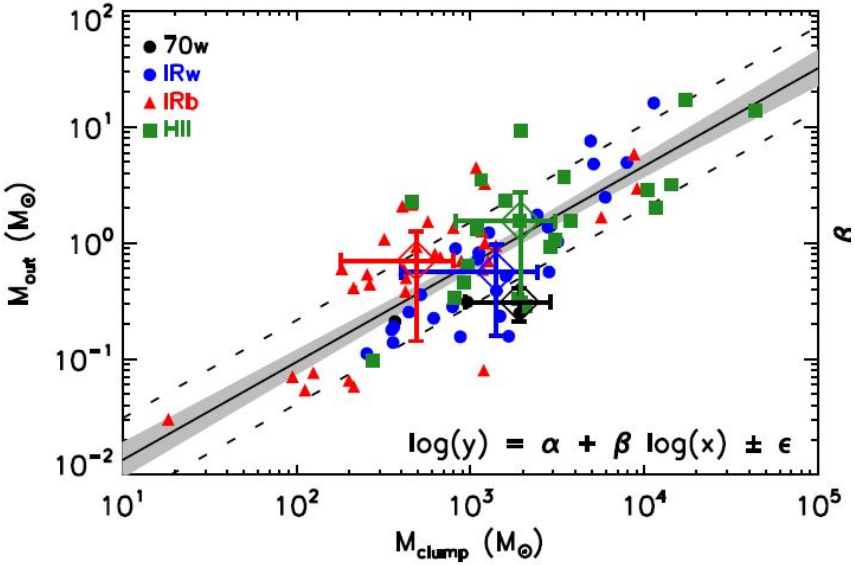
Outflow masses (and energetics):

$$M_{out} = \mu_{H2}\, m_H\, A_{pix}\, [H_2/CO]\, N_{total}$$

$$N_{total} \propto \int T_{mb}\, dV$$

- **Inclination-free** parameter → correlation with clump properties is crucial





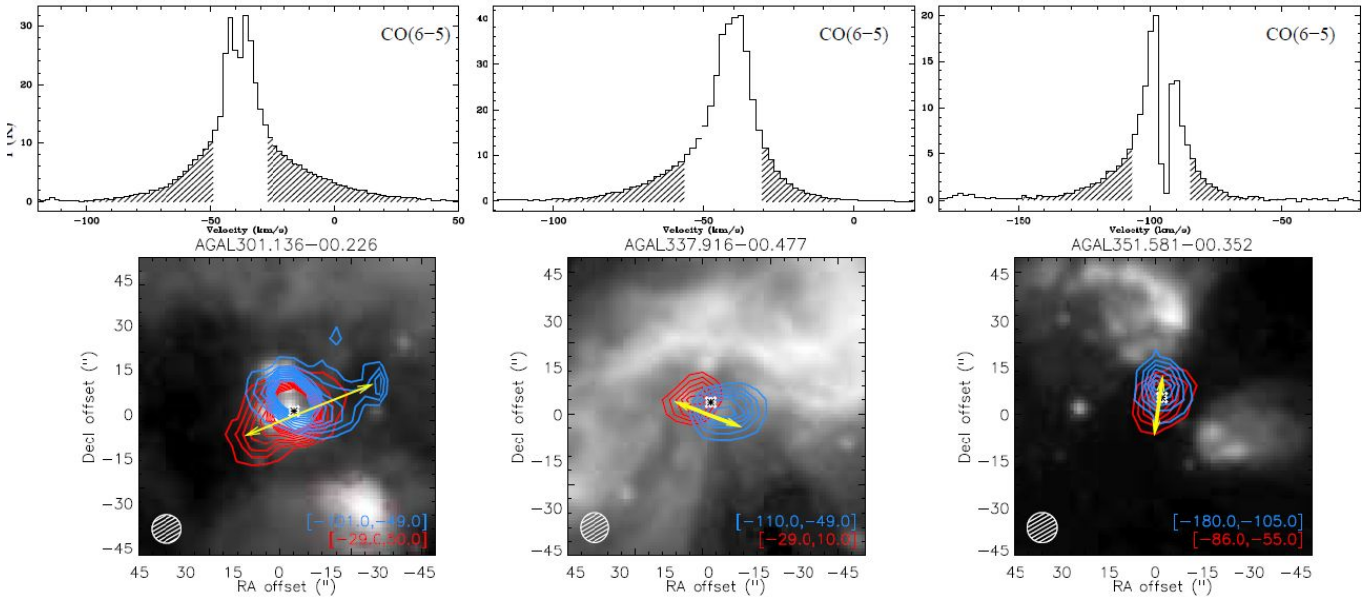
The **outflow mass** is correlated with L_{bol} and M_{clump}

Momentum, Energy and on… are also correlated with L_{bol} and M_{clump}

Future works: ALMA

- Ongoing **ALMA Band-6** observations (210-270 GHz):

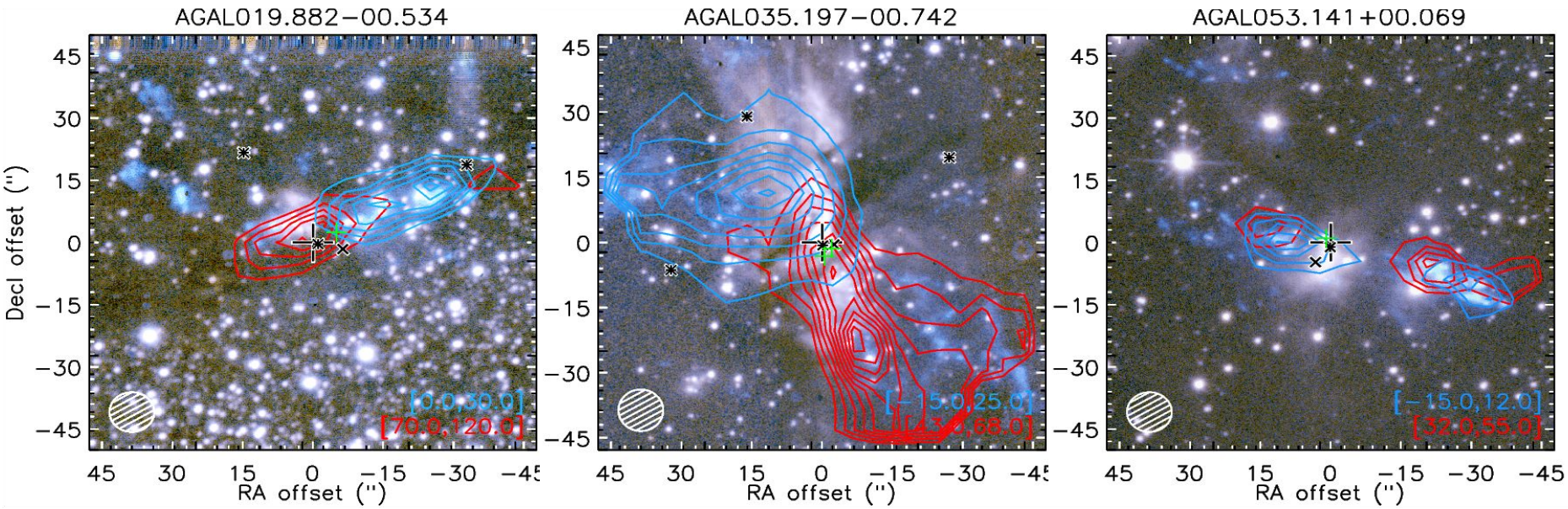
  investigate the **launching point** of the large-scale **CO outflows** identified at CO(6-5)
  (PI: S. Leurini, granted 7 hours in cycle 5)



Future work: Astrochemistry of Outflows

Comparison between the structure of **near-infrared molecular jets** at 2.12 um (Navarete+15) and **molecular outflows** at CO (6-5) (Navarete+, *subm.*).
⟶ Who comes first: the jet or the outflow? (cf. Sanna+16)

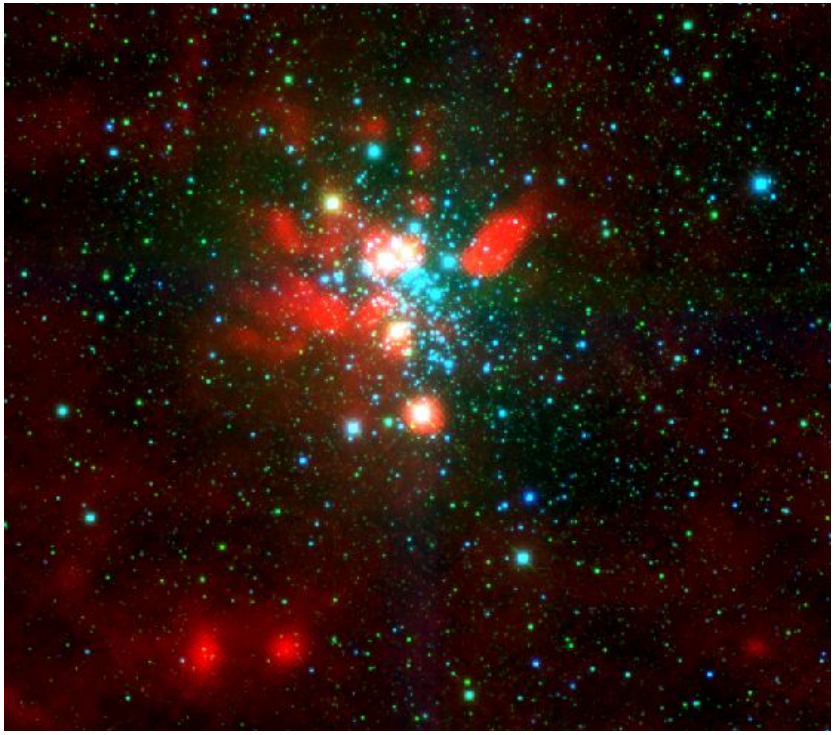
Study the **astrochemistry of the outflows** as a function of the evolution of the clumps
⟶ broadband spectra of many molecular features (SiO, CS, HCO+) using **LLAMA** telescope



Triggered star formation in Westerlund 1

While studying the reddening of the massive stellar cluster Westerlund 1 (Damineli+16), we identified **FIR clumps** in the vicinity of Wd1 ⟶ good **star-forming clumps** candidates.

map: J (~1.6 μm) + K (~2 μm) ⟶ stellar content
Herschel-PACS 70 μm ⟶ warm dust (~40 K)



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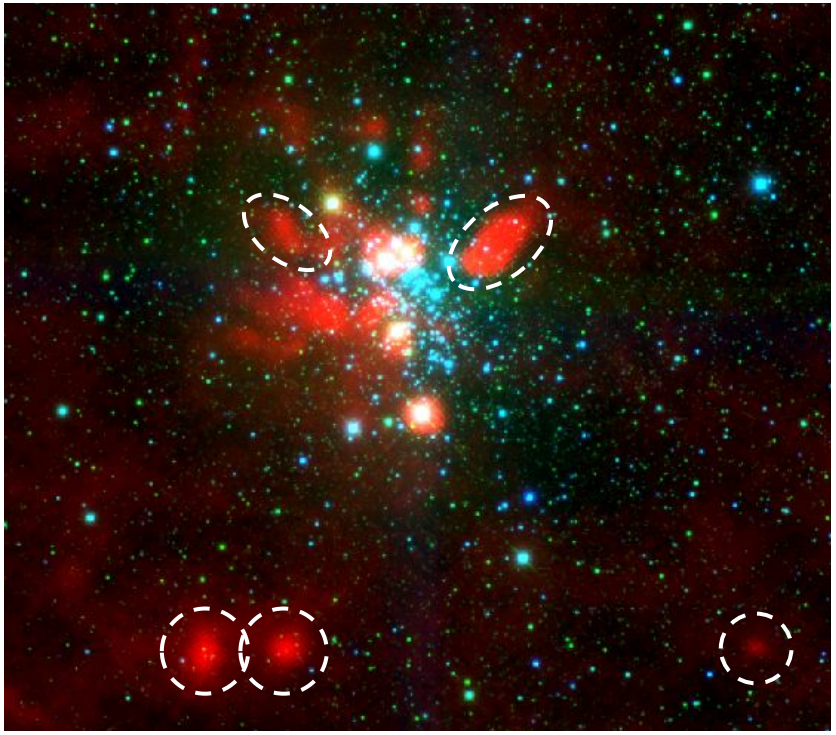

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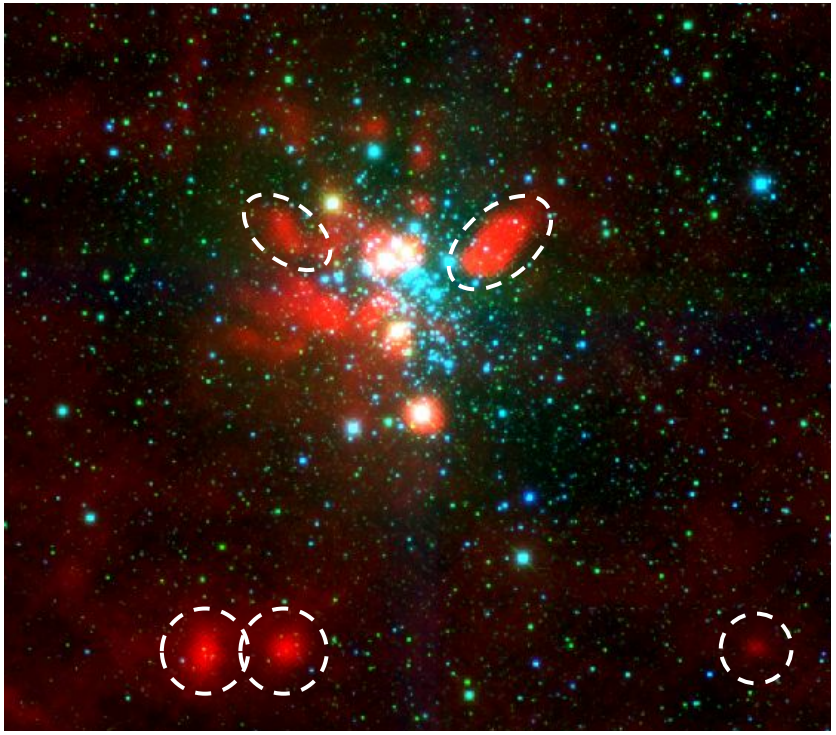


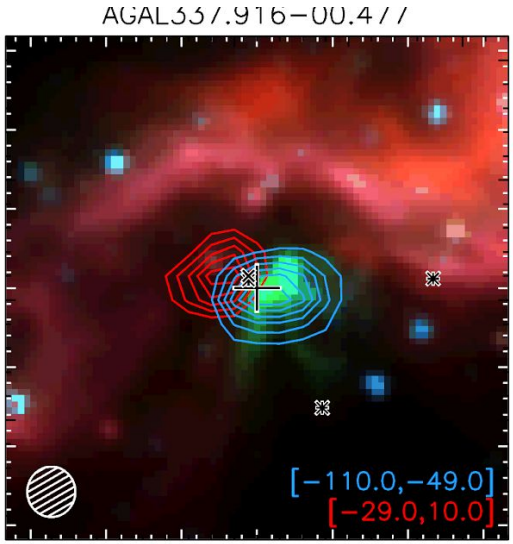
Strategy:

1) Derive the **physical properties** of these clumps through **single-pointing Band-9** observations of **CO (6-5)** and its main isotopologues (^{13}CO, $C^{18}O$)

2) Follow-up **on-the-fly maps** of interesting sources to detail **kinematic structures** (e.g. outflows or infalling gas)

Summary

- **High-mass star formation** is a hot topic in Astrophysics.
- **ATLASGAL** offers a large catalogue to explore **potential high-mass clumps** in the Galaxy
- **Synergy** between **IR** and **sub-mm/mm** observations (e.g. LLAMA, APEX)
- Sources are located at **larger distances** → **interferometry** is required! (ALMA)



Obrigado!

Thank you!

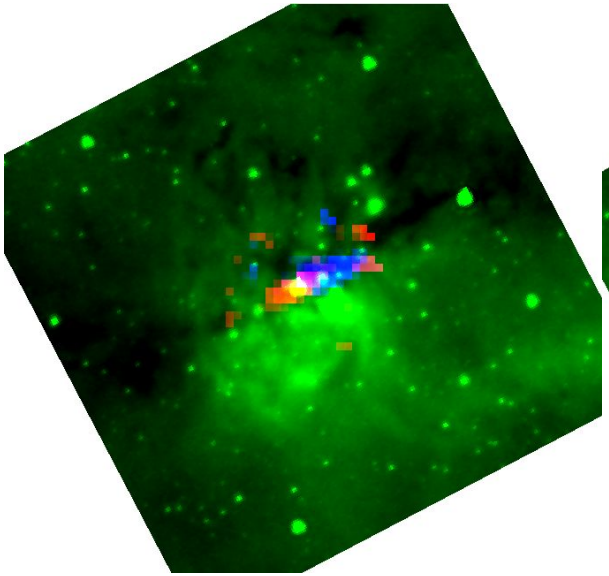
Future work: Inflow and Outflow alignment

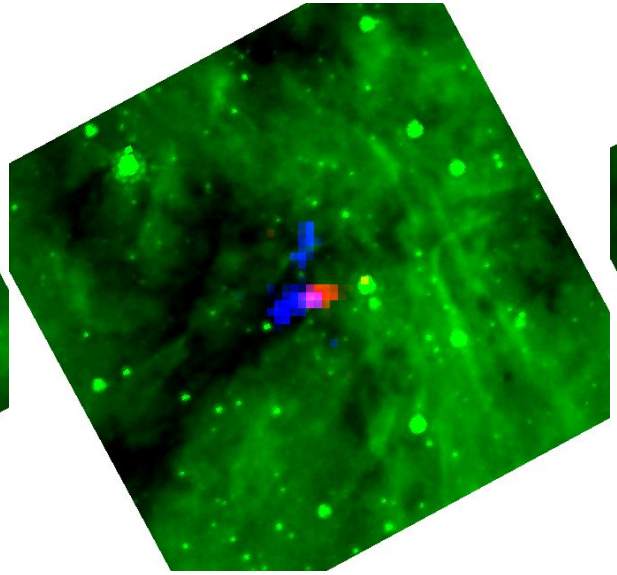
Compare the orientation of inflowing and outflowing material

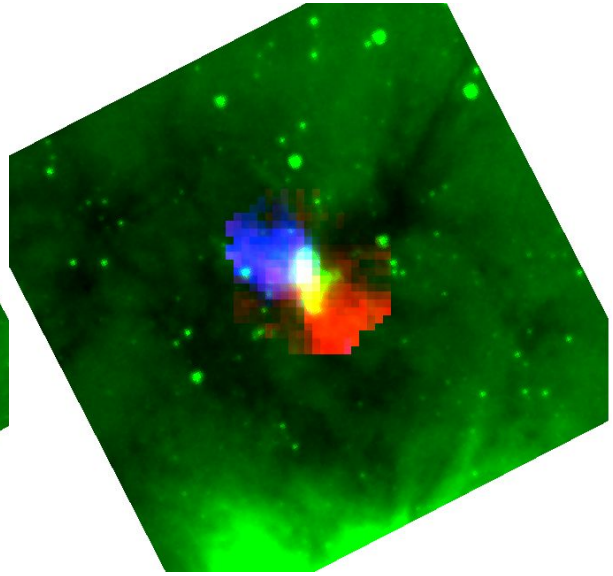
- **IRAC/Spitzer maps at 8 μm** trace **high-density filaments** as absorption features.
- **APEX CO(6-5) maps** trace the structure of the **outflows**.

Proposition: inflowing motions are aligned with the large-scale filaments.

Expectation: outflowing gas should be perpendicularly oriented to the filaments.







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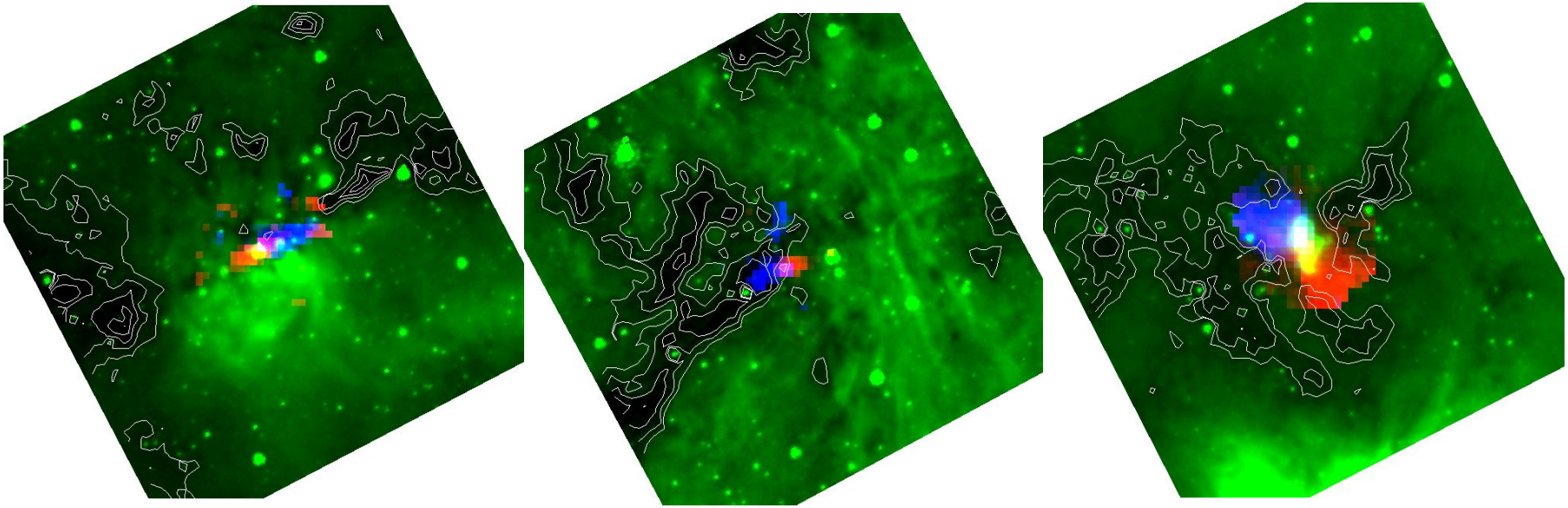

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