Pillars, PDRs and Triggered Star Formation: New Insights from the [CII] 158μm line with SOFIA GREAT

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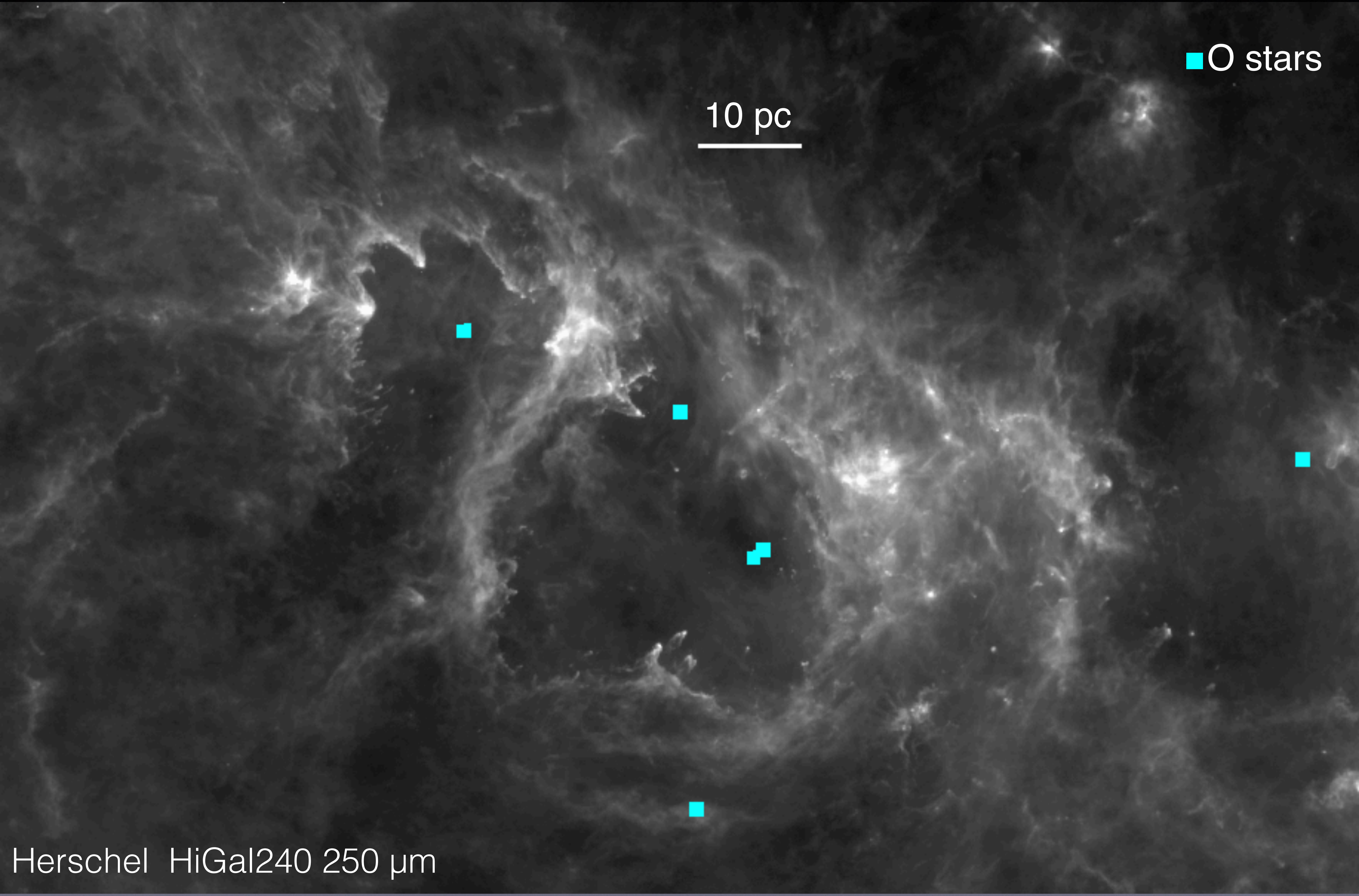
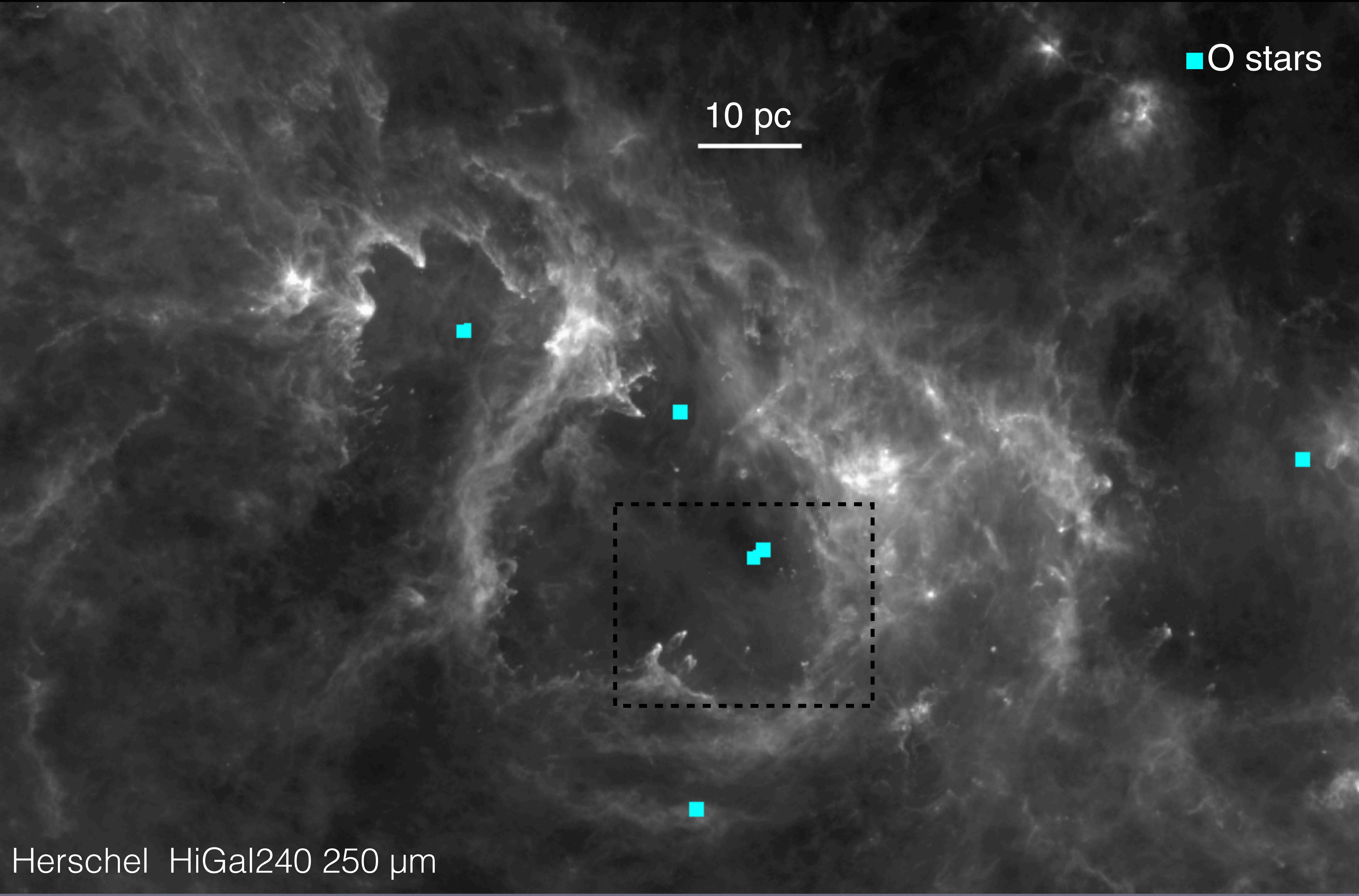
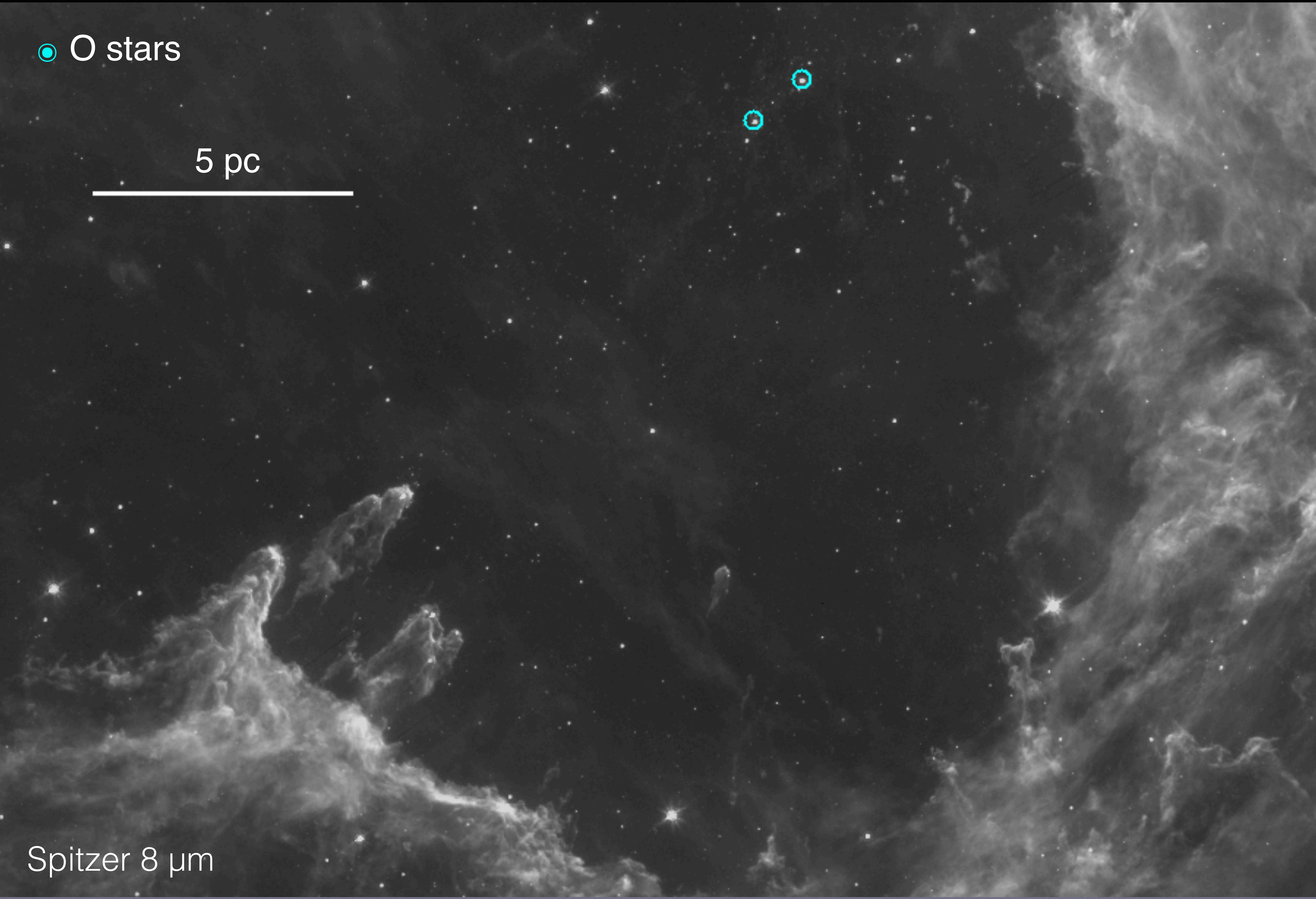
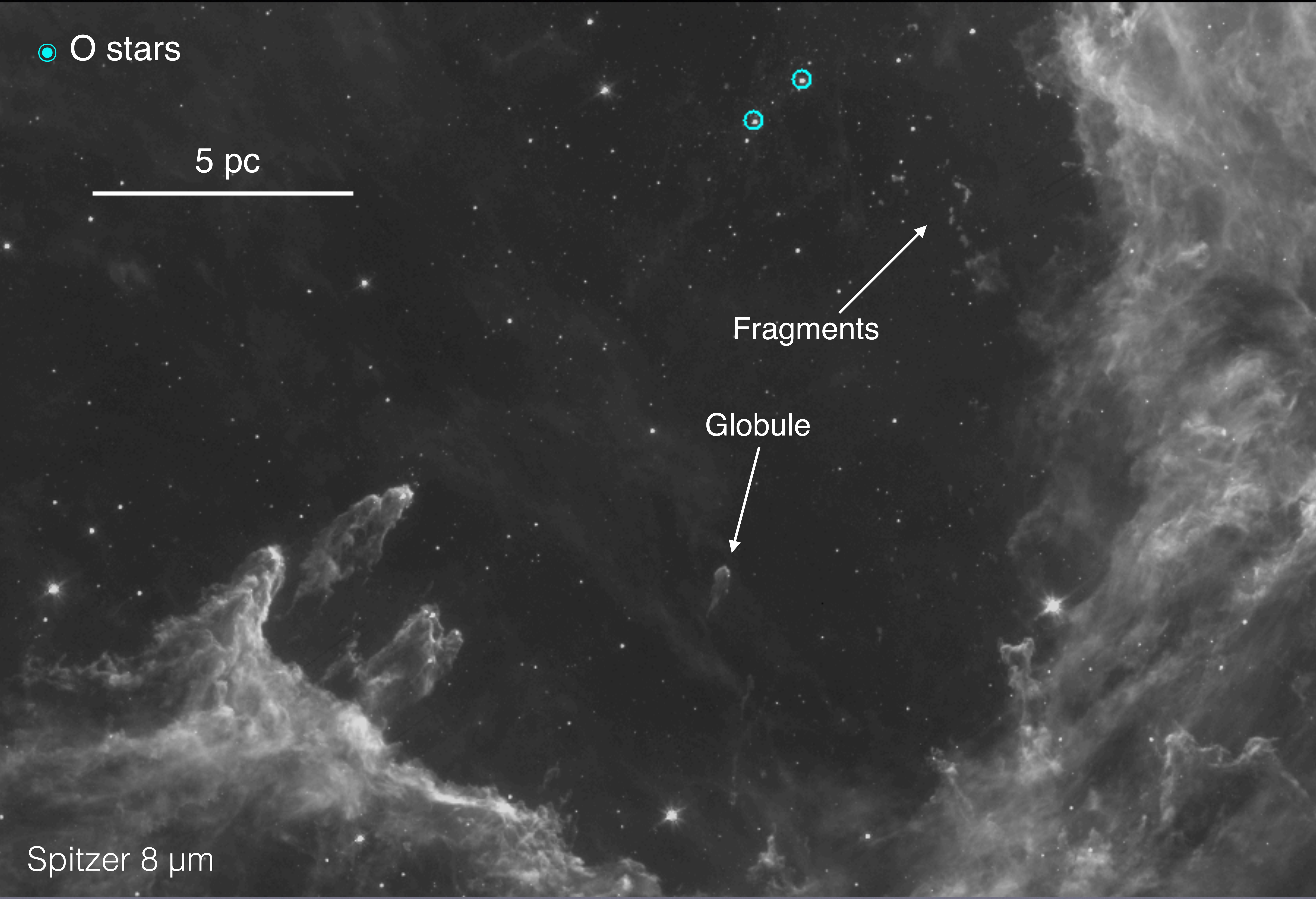
A profound and dramatic effect…

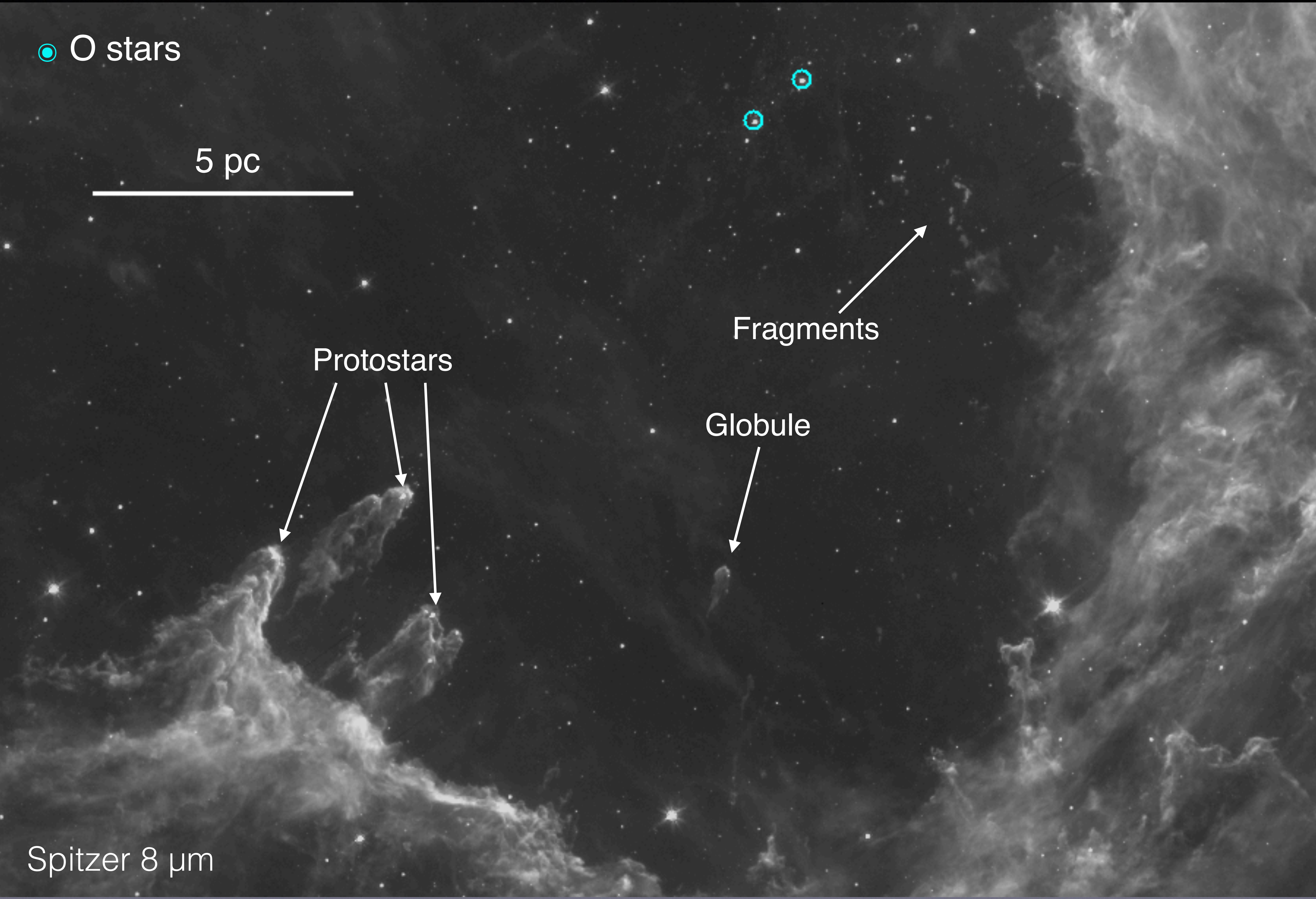


A profound and dramatic effect…



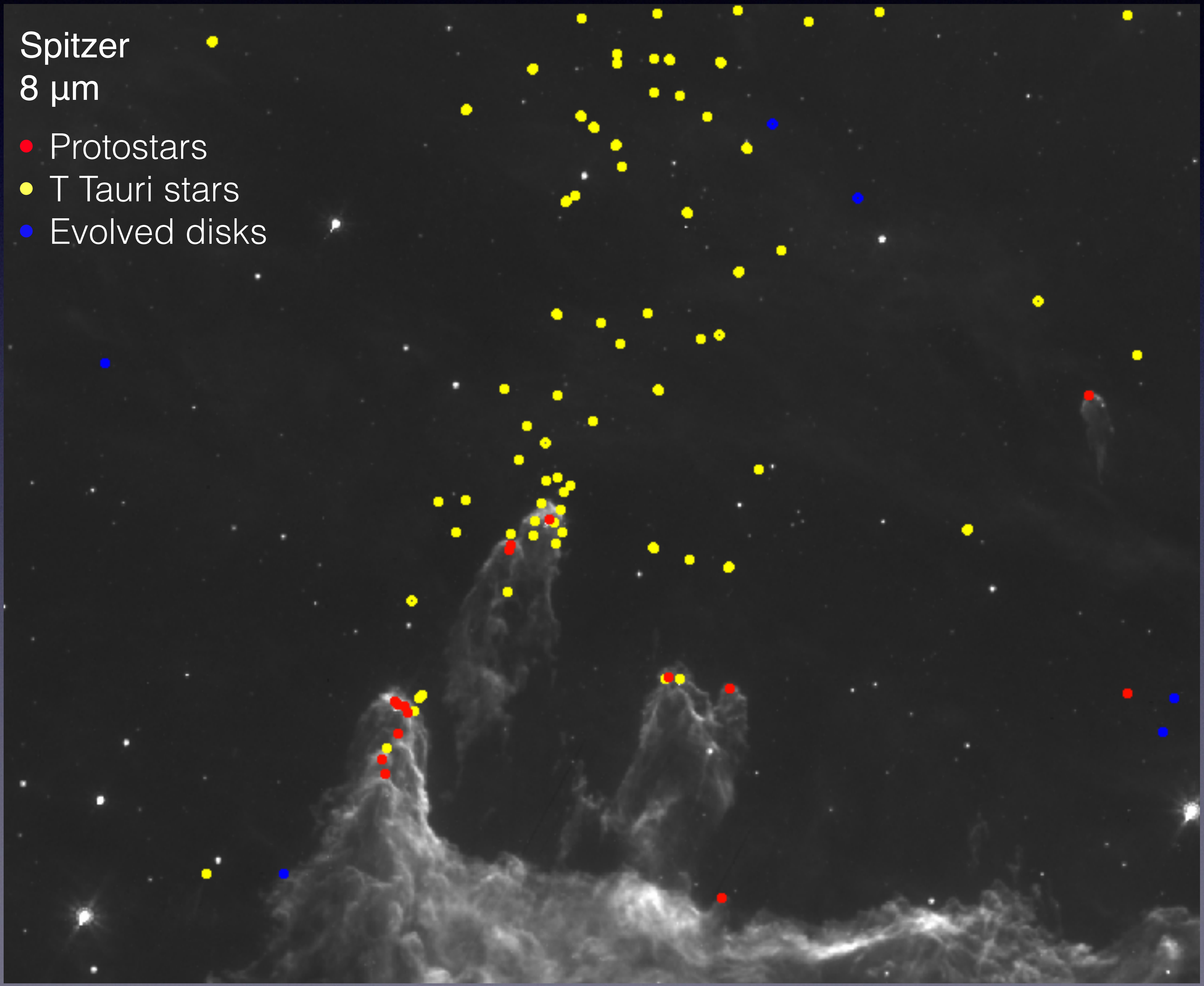

O stars
5 pc
Spitzer 8 µm


O stars
5 pc
Fragments
Globule
Spitzer 8 µm


O stars
5 pc
Fragments
Protostars
Globule
Spitzer 8 µm

- Massive star forming regions are the dominant producers of stars in spiral galaxies (e.g. Lada & Lada 2003, Koenig & Leisawitz 2014)
- Pillars and globules are ubiquitous and are the sites of secondary star formation
- What is the origin, nature and star forming role of pillars in massive star forming regions?

Star formation in pillars



- Distribution of recently formed stars suggest pillars may be part of larger, eroded, dense structure (Koenig et al. 2012).
- Filamentary, continuous distribution of YSOs, comparable to filamentary structure seen in Herschel dust maps.

Triggering?

- O stars are clearly responsible for the formation of pillars and globules but how?
- … and do they trigger the formation of stars?
- Theoretical arguments center on the properties of pre-existing structure in the molecular gas

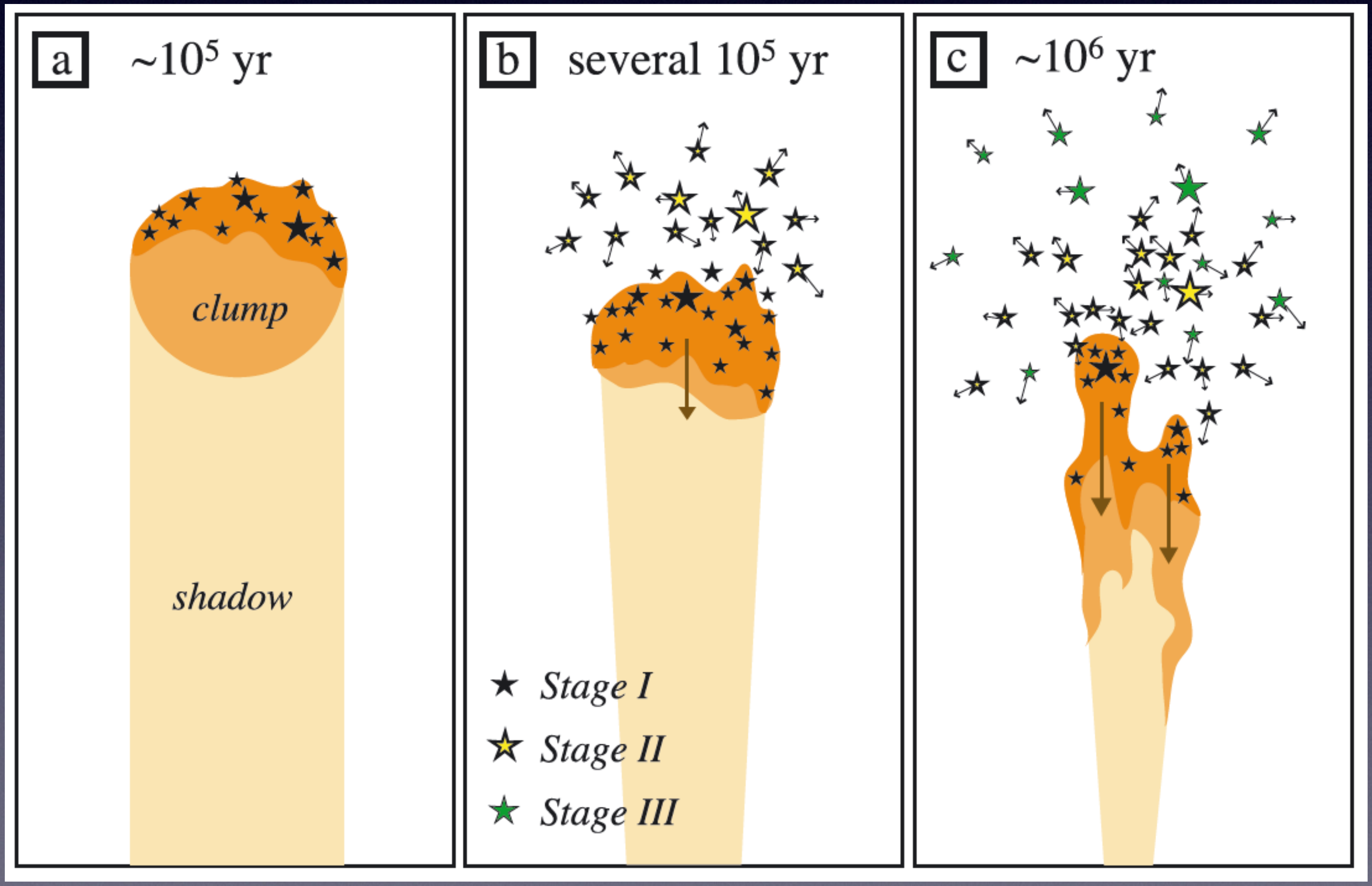
Pre-existing structure is dense

- Radiatively Driven Implosion of pre-existing dense clumps
- Originated in the work of Oort (1954) and Oort & Spitzer (1955) on expanding HII regions and the rocket effect: neutral gas clouds propelled by expansion of ionized surface layers

> It seems indicated to seek the answer in the expansional motions that, as we have just considered, must be set up in the cold regions surrounding the ionized nebula around a newly born O star (or group of O stars). We do not know how these primary O stars were formed; we have to accept this as a fact of observation. But it is tempting to think that, subsequently, the strong compression in the surrounding cool clouds will lead to the formation of new early-type stars that then would share the outward motions that the HII region has imposed upon these clouds. The expansion of the associations of early-type stars would in this way become understandable [6]).

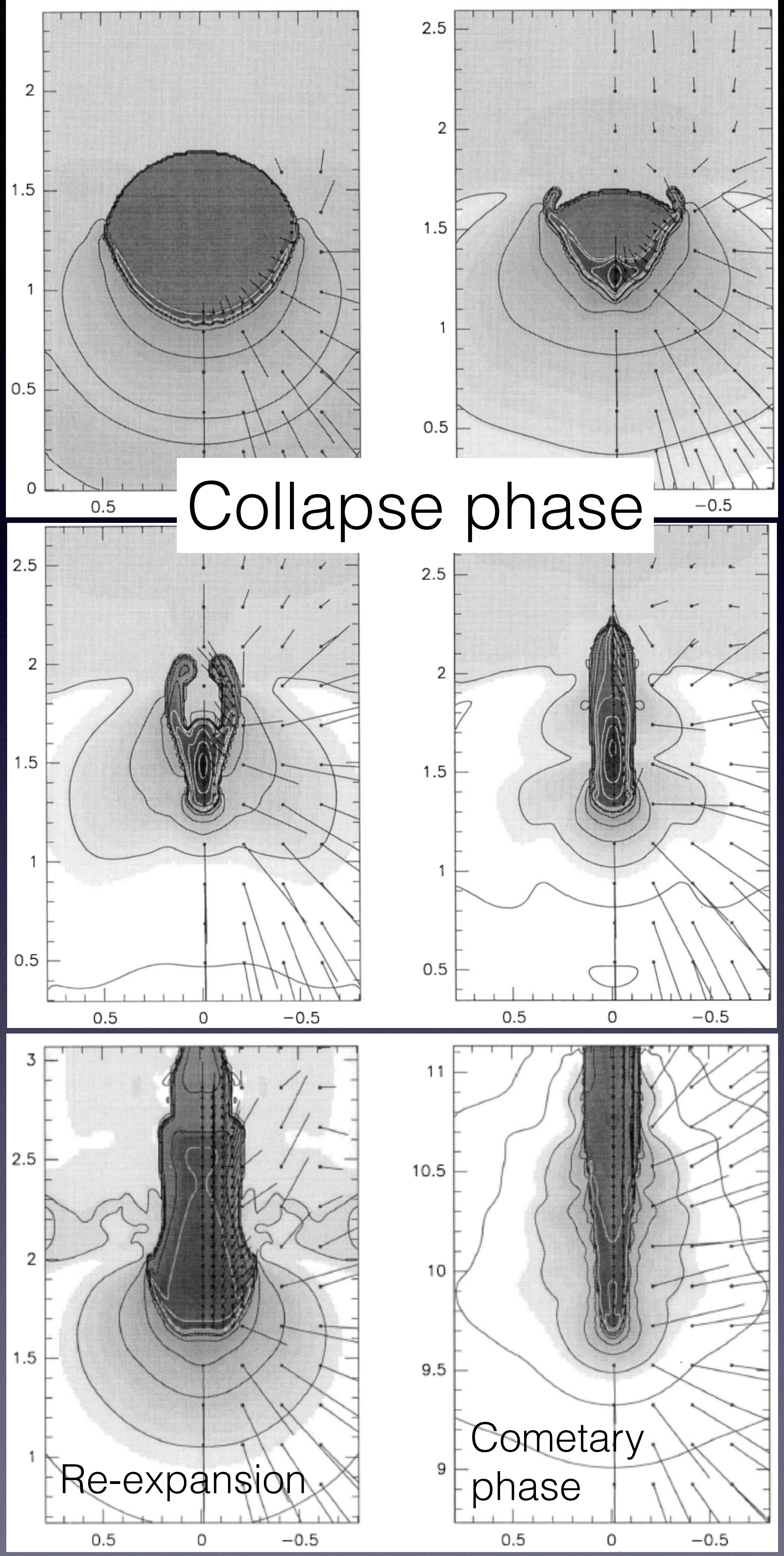
Oort (1954)

- Radiatively Driven Implosion
- Theoretical work by Sandford et al. (1982), Bertoldi (1989), Lefloch & Lazareff (1994) and others



Nathan Smith et al. (2010)

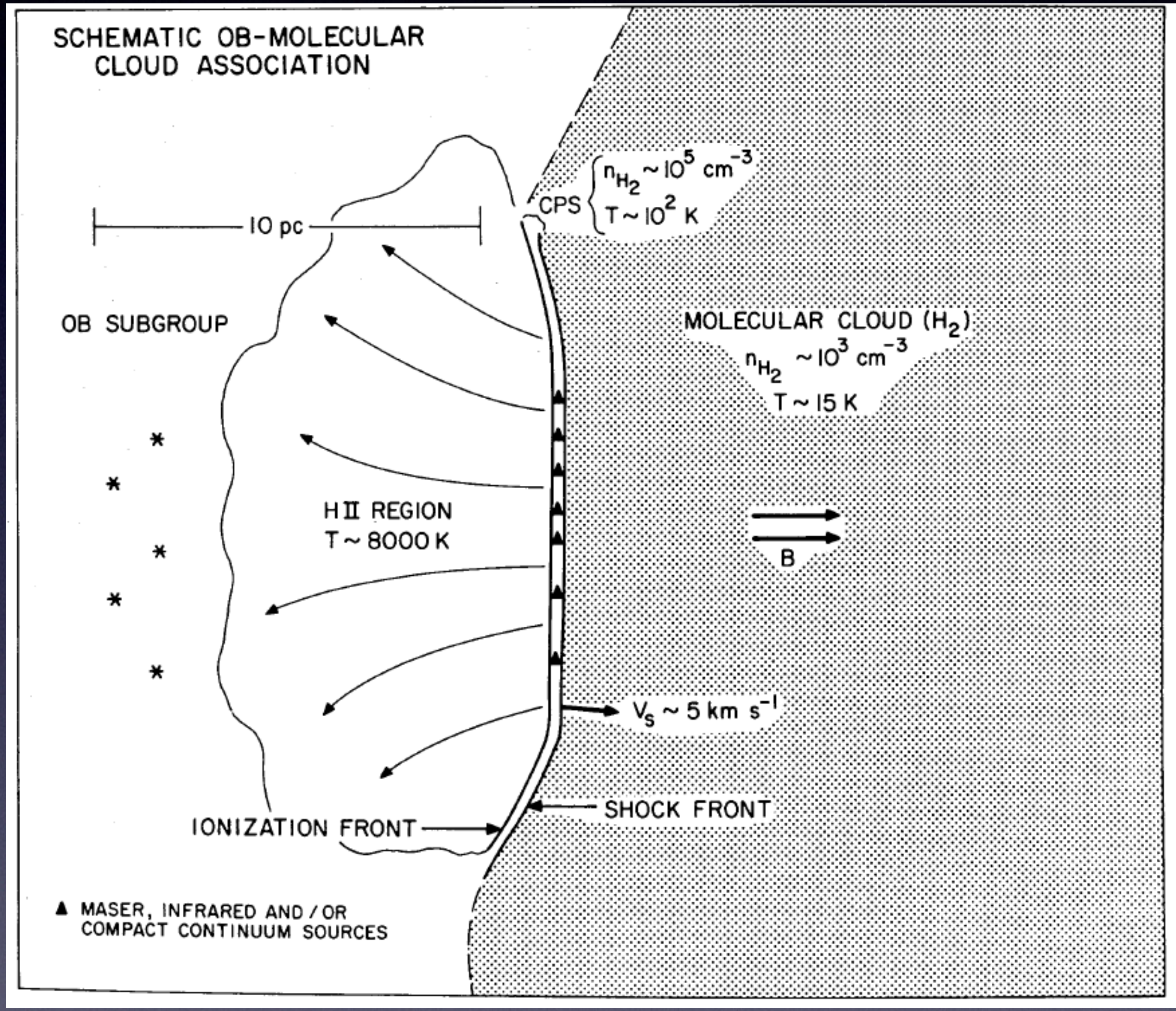
- Detailed theoretical picture put together by Lefloch & Lazareff (1994)
- Globule undergoes an initial collapse phase for ~10^5 yr
- Then oscillates, expanding and re-contracting
- Finally, in cometary phase cloud loses mass until it disappears at ~3 Myr



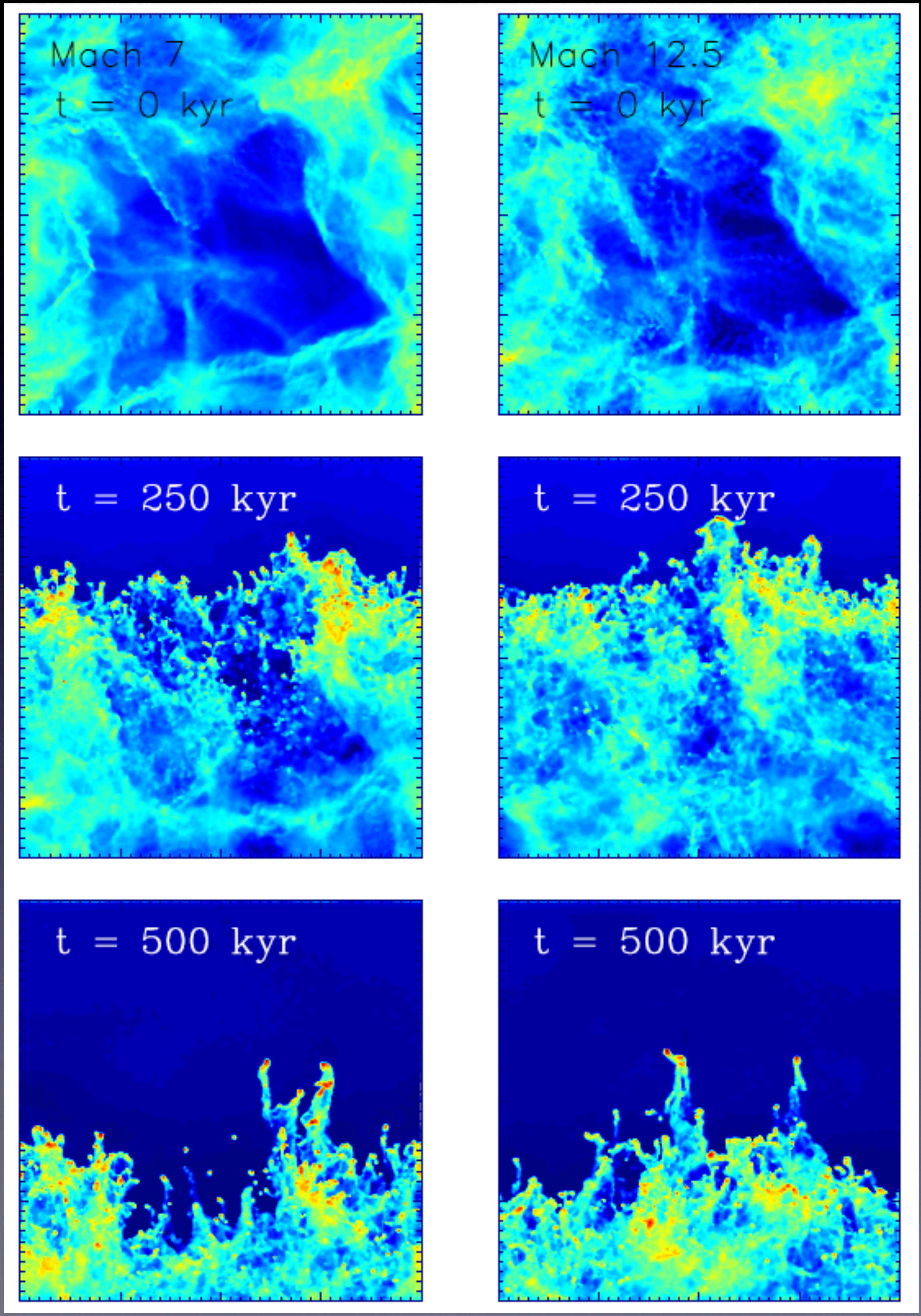
Theoretical simulations: Lefloch & Lazareff (1994)

Pre-existing structure is weak

- Collect and Collapse
- Described by Elmegreen & Lada (1977)
- Expanding HII region bubble creates an ionization front, preceded by a shock front
- Neutral gas accumulates and at some point collapses

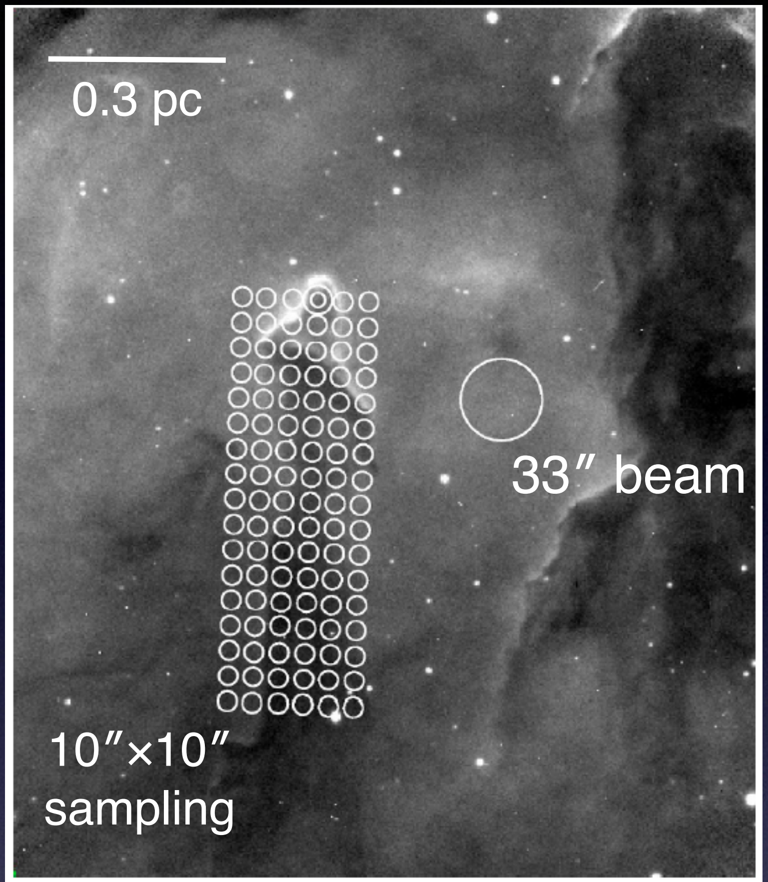


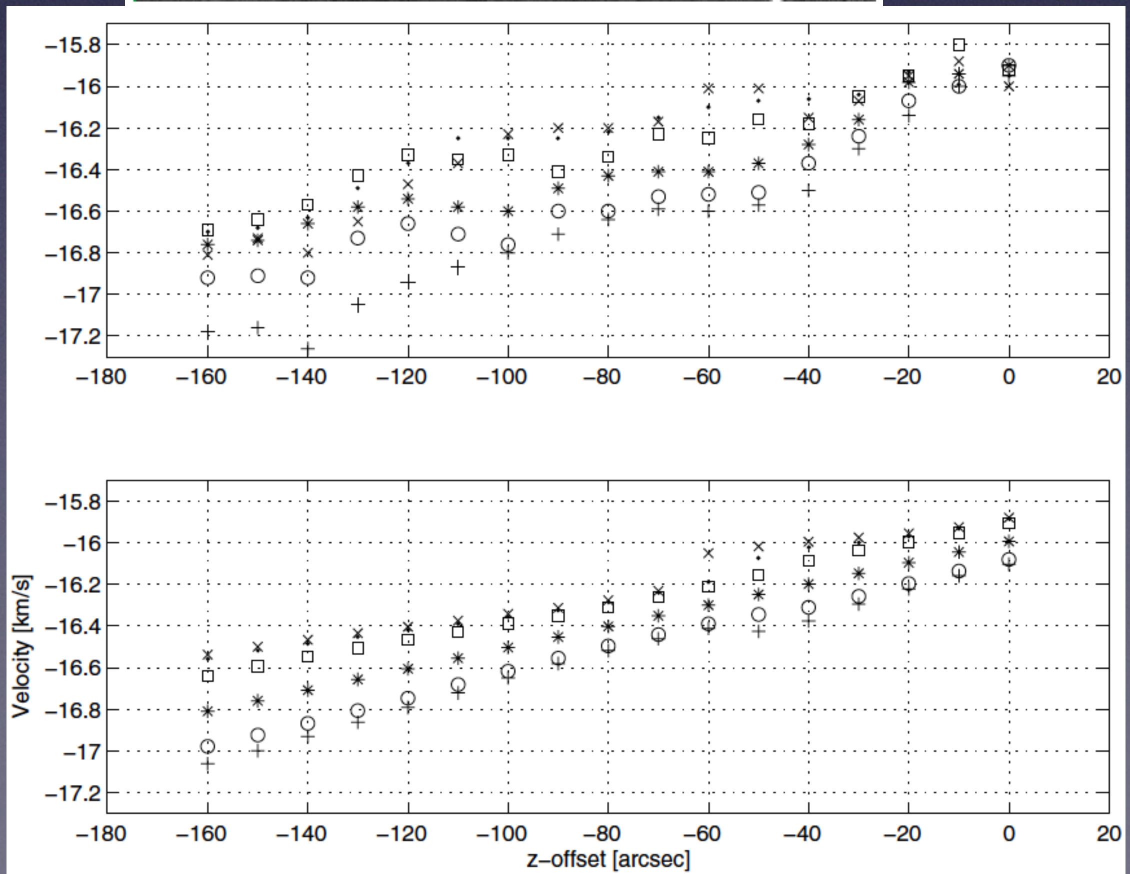
- Given some turbulent structure, Collect and Collapse can produce pillars
- Gritschneder et al. (2009, 2010) ‘collect and collapse with turbulent seeds’ or ‘radiative round-up’
- Ionized low density regions compress denser surroundings
- Pillars are corkscrew-like, torqued and show rotation



CO observations

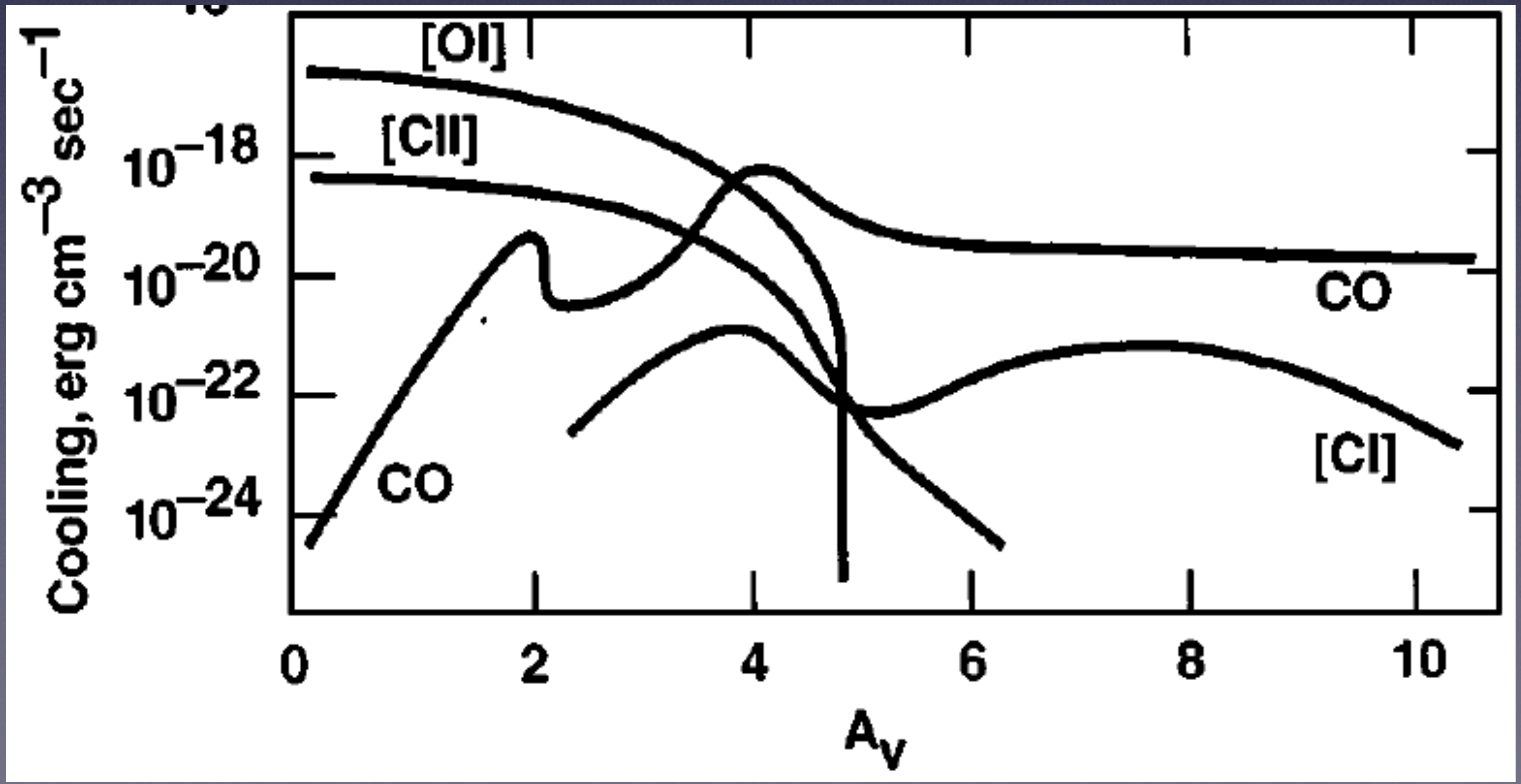
- Gahm et al. (2006) find a signature of rotation in a sample of 4 pillars observed with ^{12}CO
- Lines are single peaked, widths ~1.1 to 3 km s^{-1}
- Appears inconsistent with RDI predictions of broad or double peaked line profiles
- Can we confirm these results with a surface gas tracer?





The [CII] 158 μm line

- Stratified Photo-Dissociation Region (PDR) models predict that forbidden line C^+ emission at 158μm is produced in surface layers, typically where $A_V < 2$ (Wolfire et al. 1989)
- Provides complementary information to any molecular line tracers of dense gas.

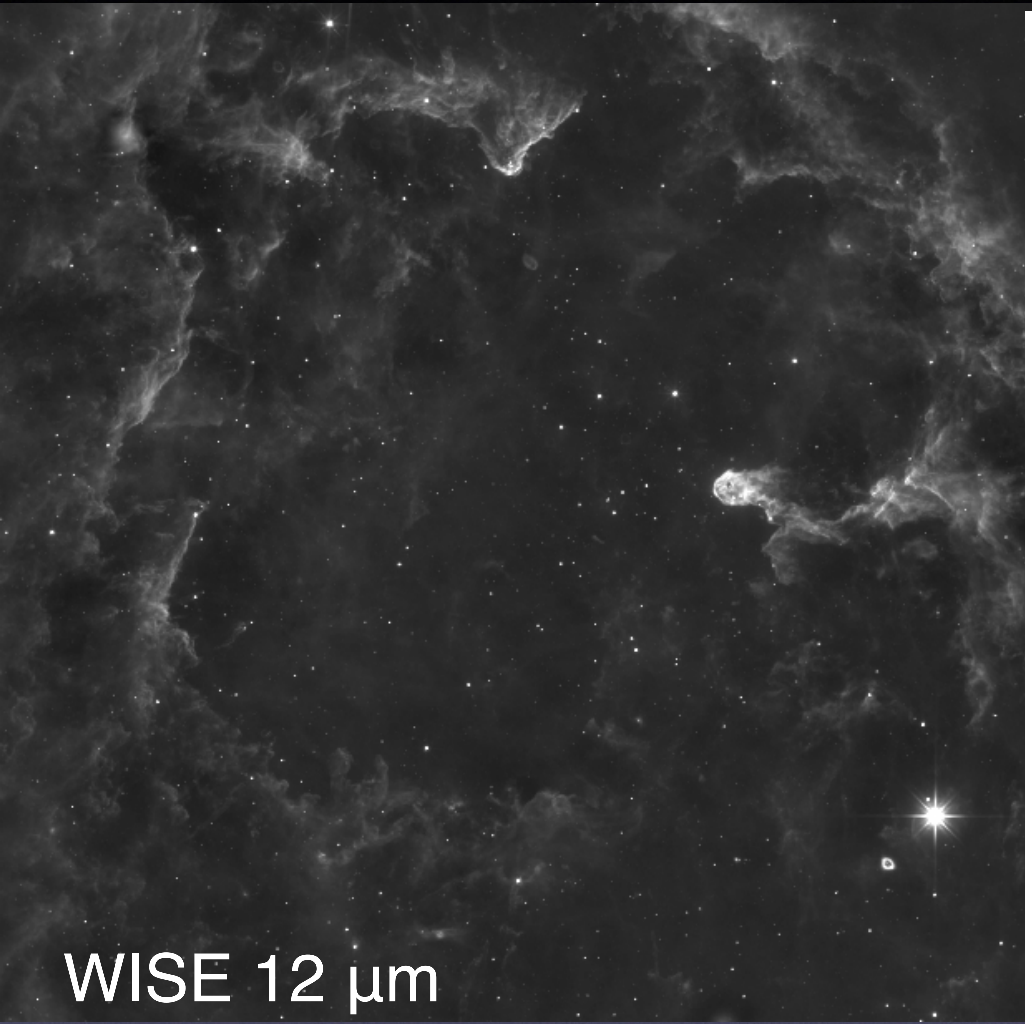


Orion PDR model: Hollenbach & Tielens (1997)

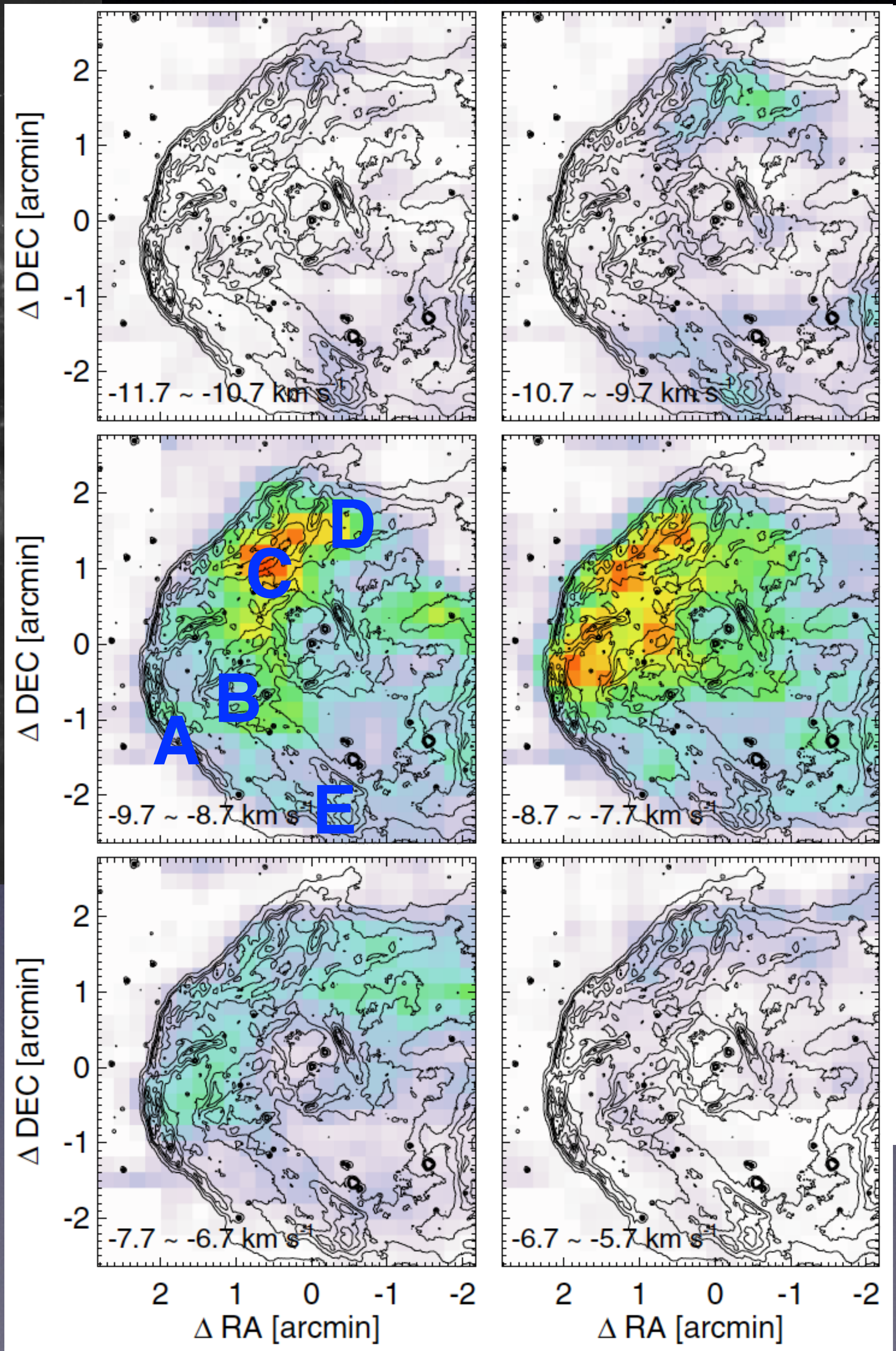
[CII] with SOFIA GREAT

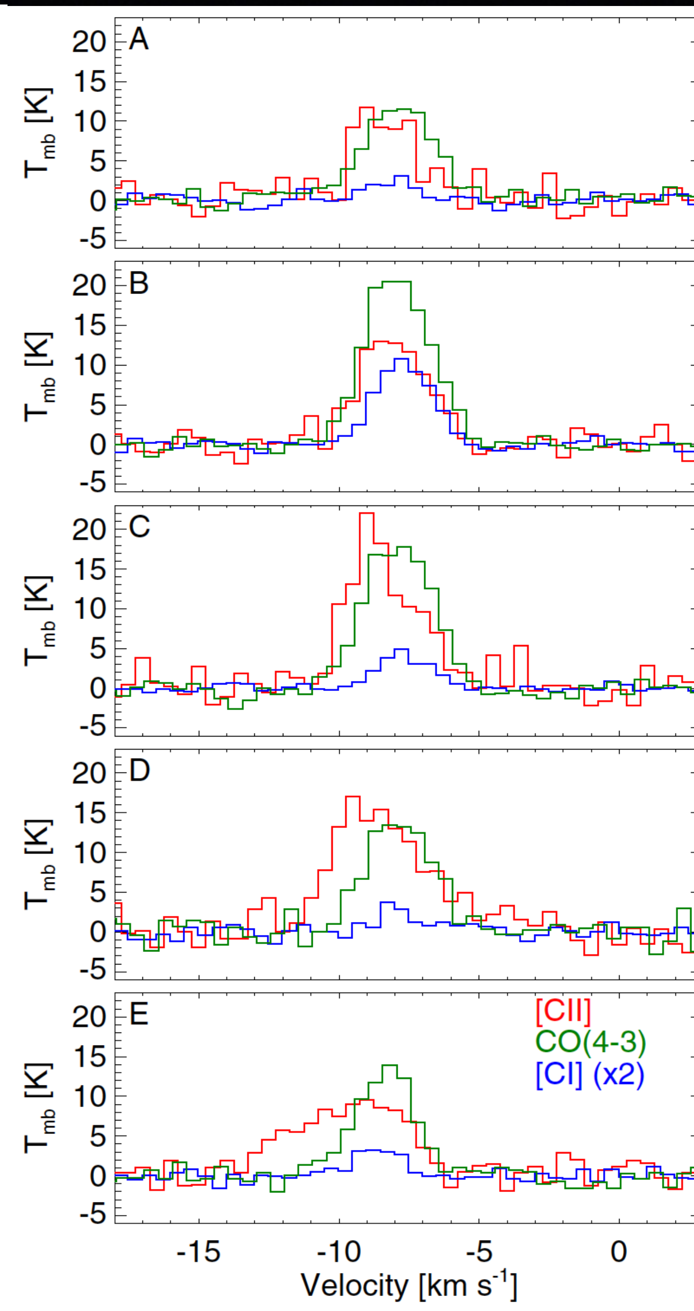
- GREAT: modular dual-color heterodyne instrument for high-resolution far-infrared spectroscopy
- The L2 receiver channel covers 1.8 to 1.9 THz, encompasses the [CII] 158 μm line
- Resolution after resampling: 0.5 km s^{-1}
- Pixel size in OTF map mode: ~8″, resolution 15.6″
- Two studies have already used GREAT to map [CII] across star forming pillars

IC 1396



WISE 12 µm
(Koenig et al. 2012)



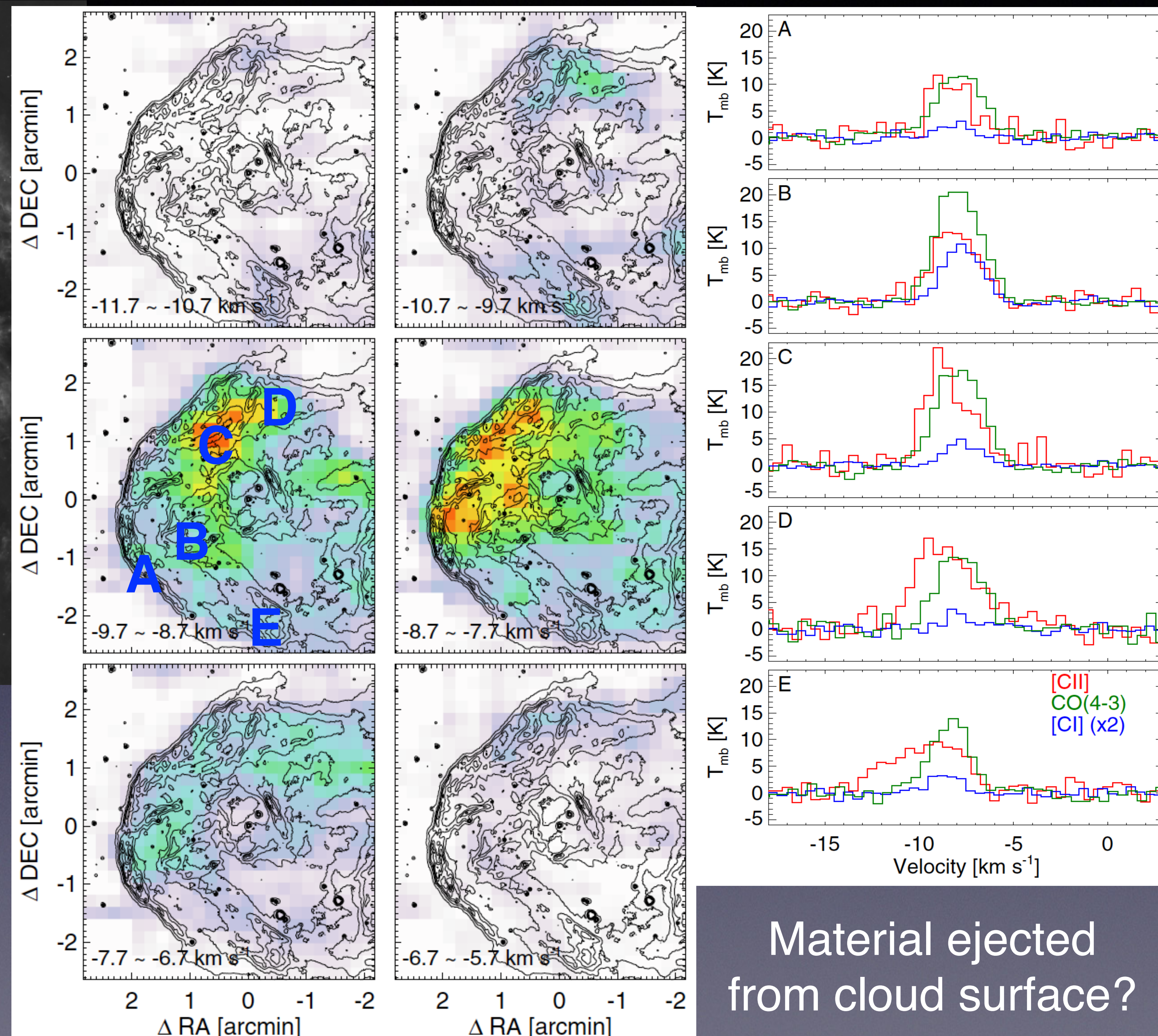


Material ejected from cloud surface?

Okada et al. (2012)

IC 1396

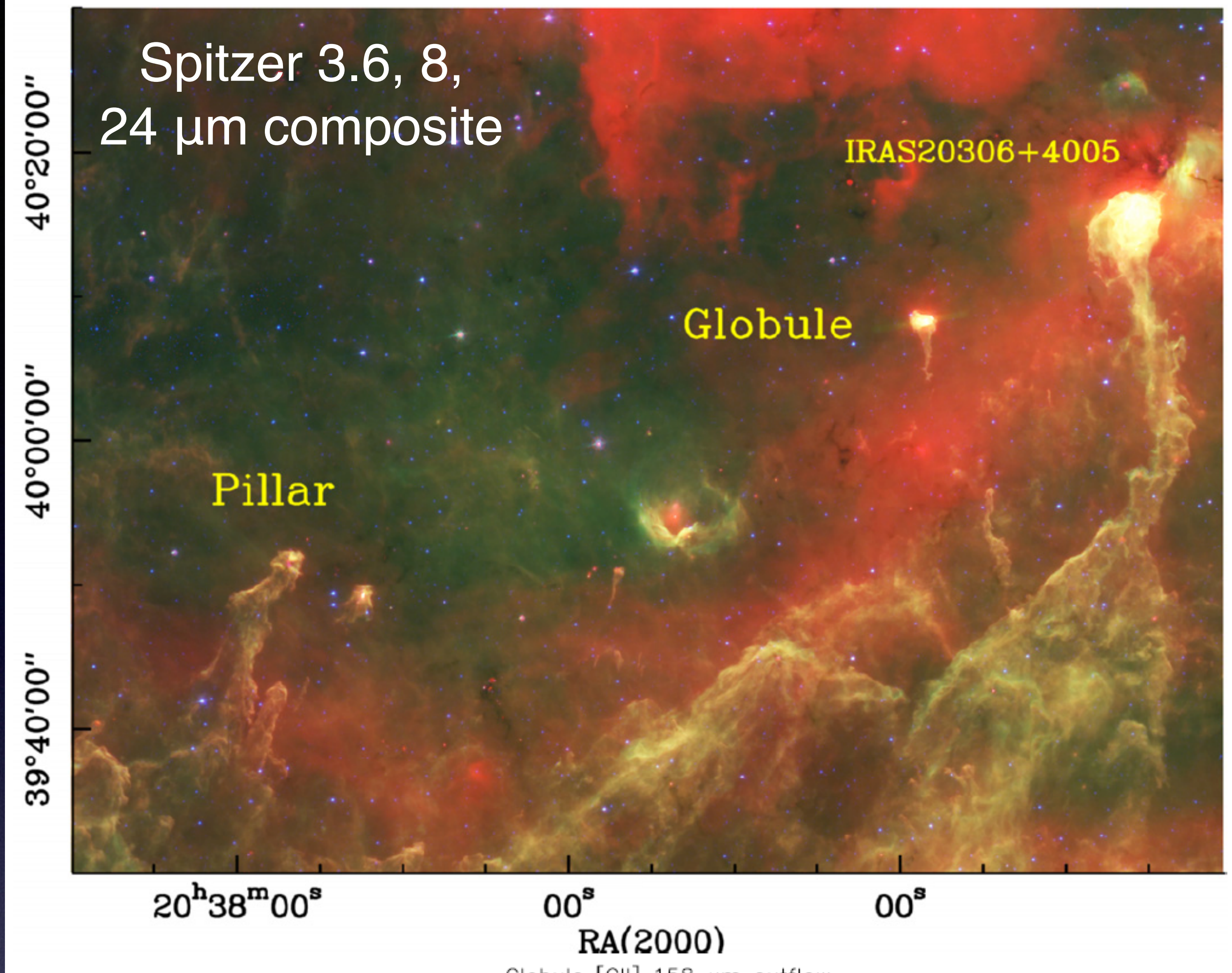
WISE 12 µm
(Koenig et al. 2012)

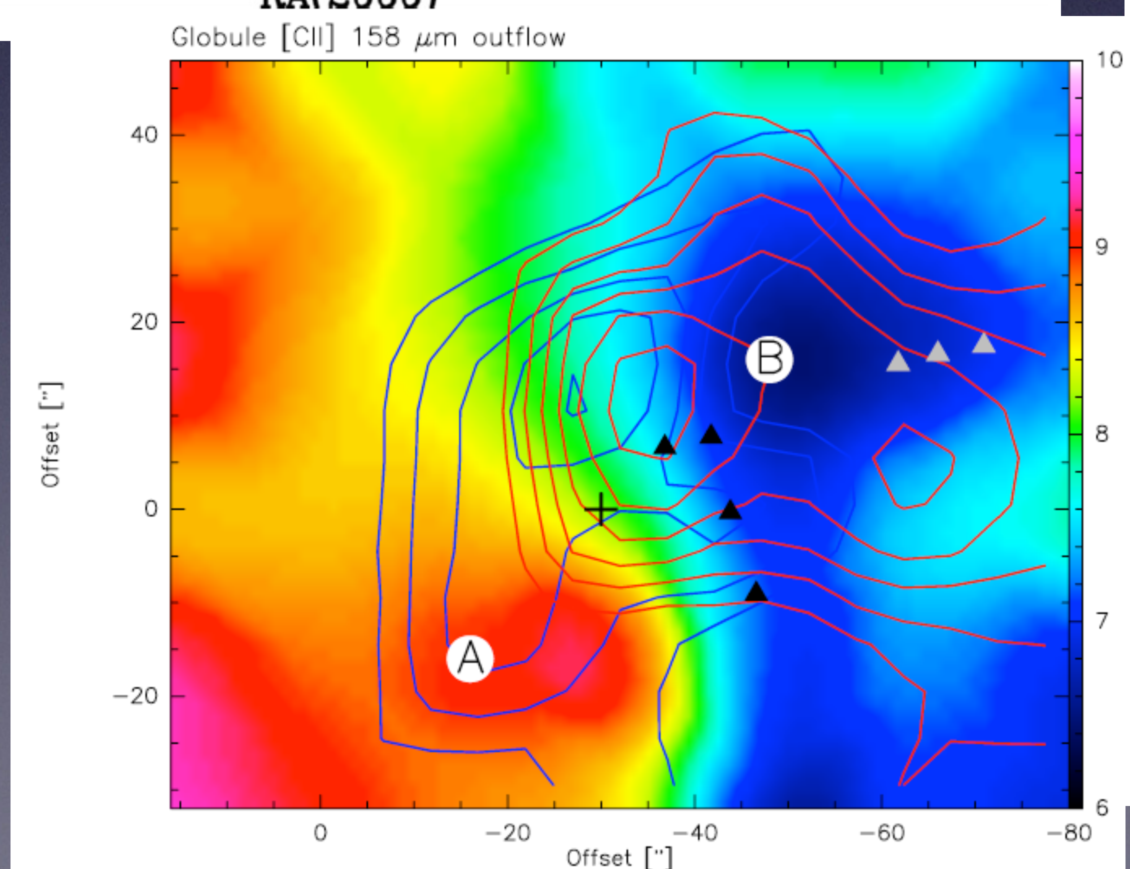


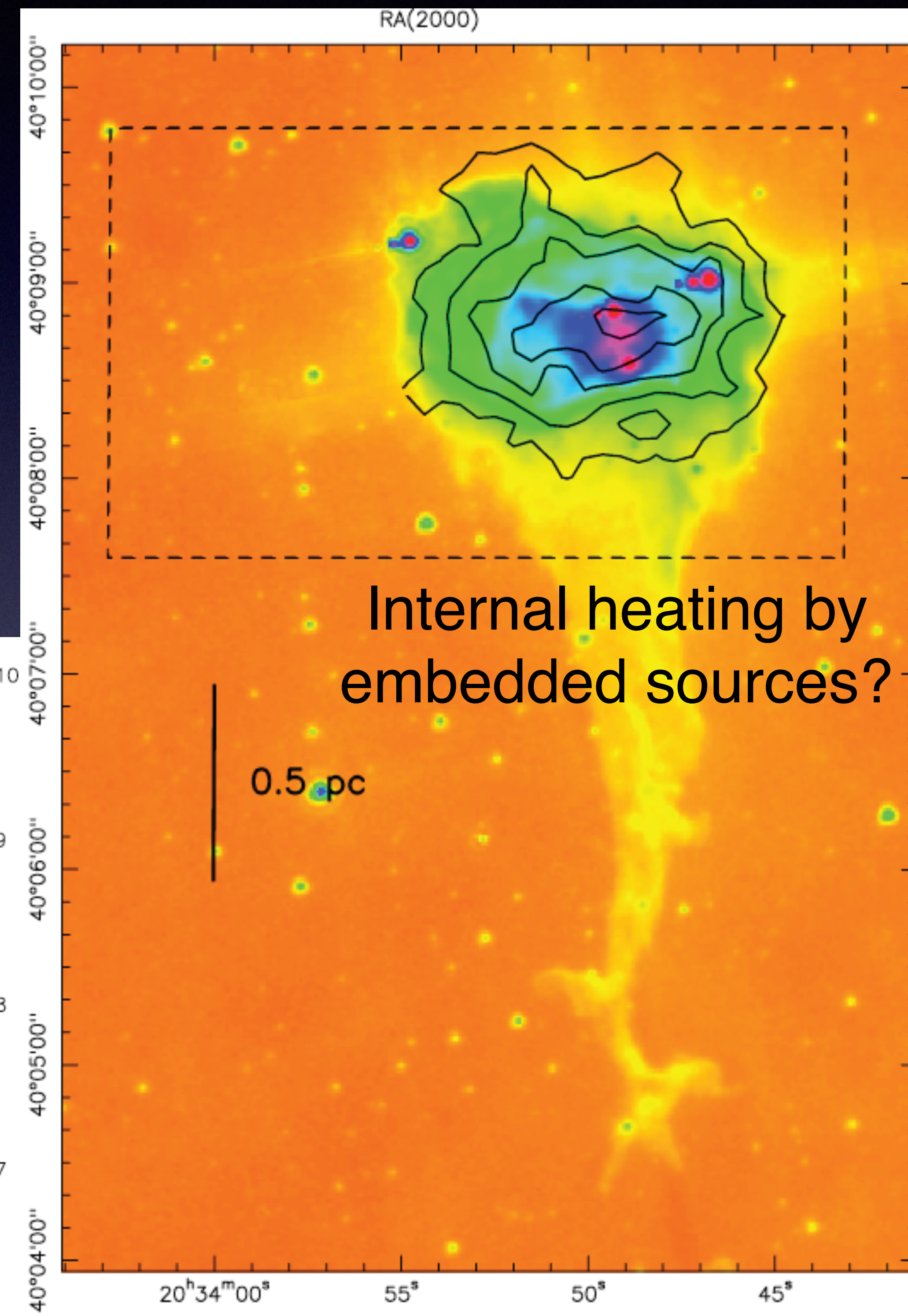
Material ejected from cloud surface?

Okada et al. (2012)

Cygnus X





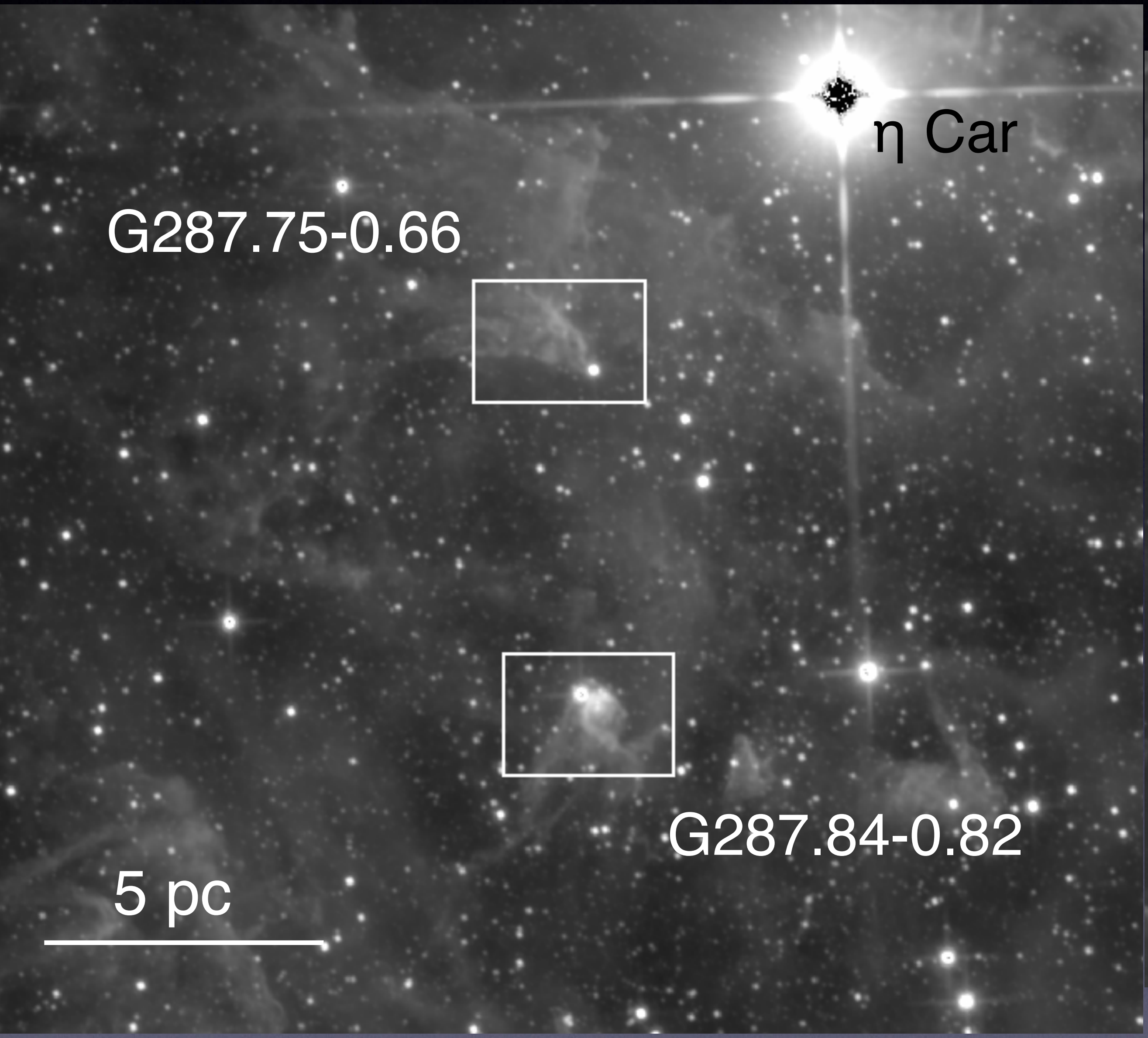


Internal heating by embedded sources?

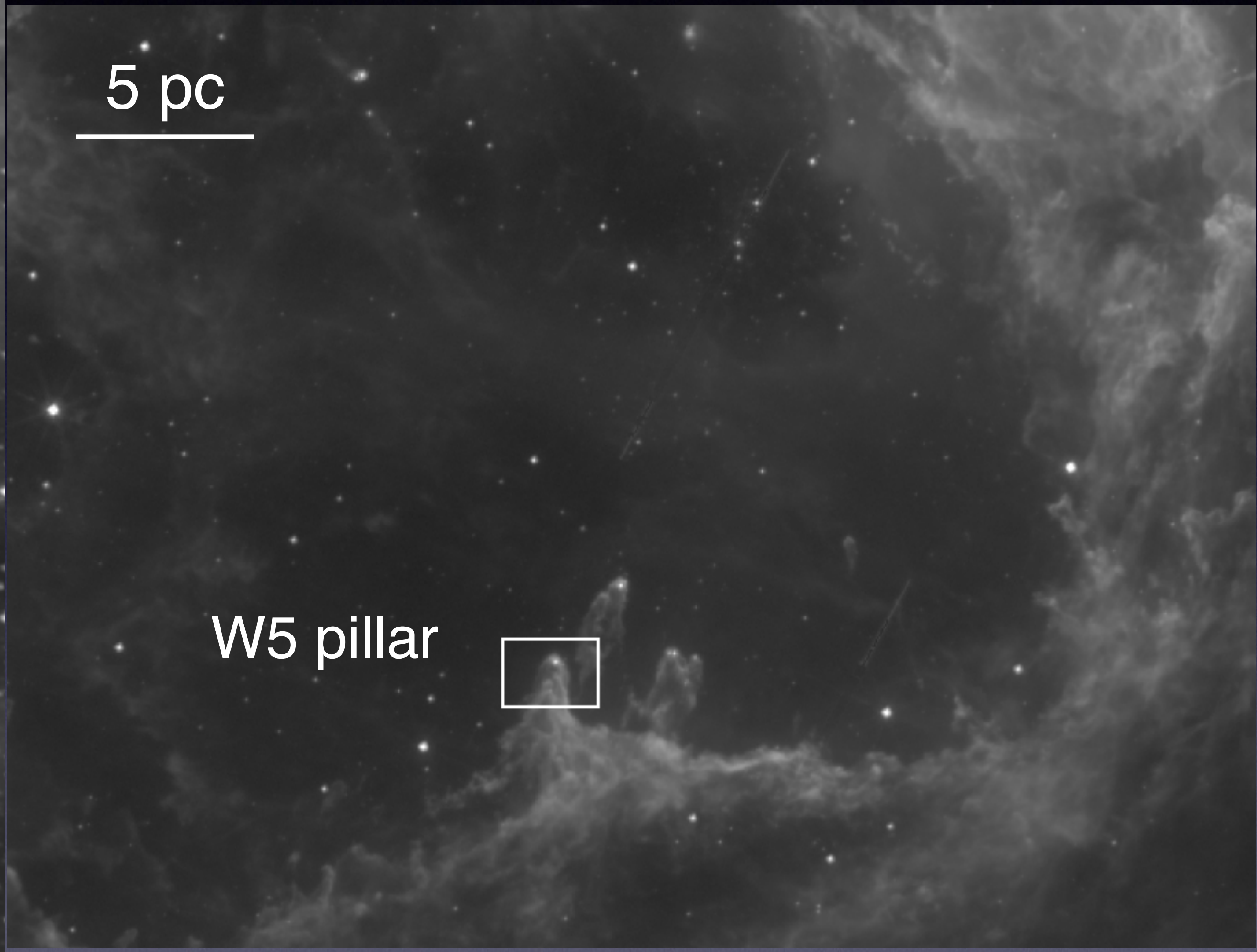
Rotation?

- Schneider et al. (2012)

Our sample

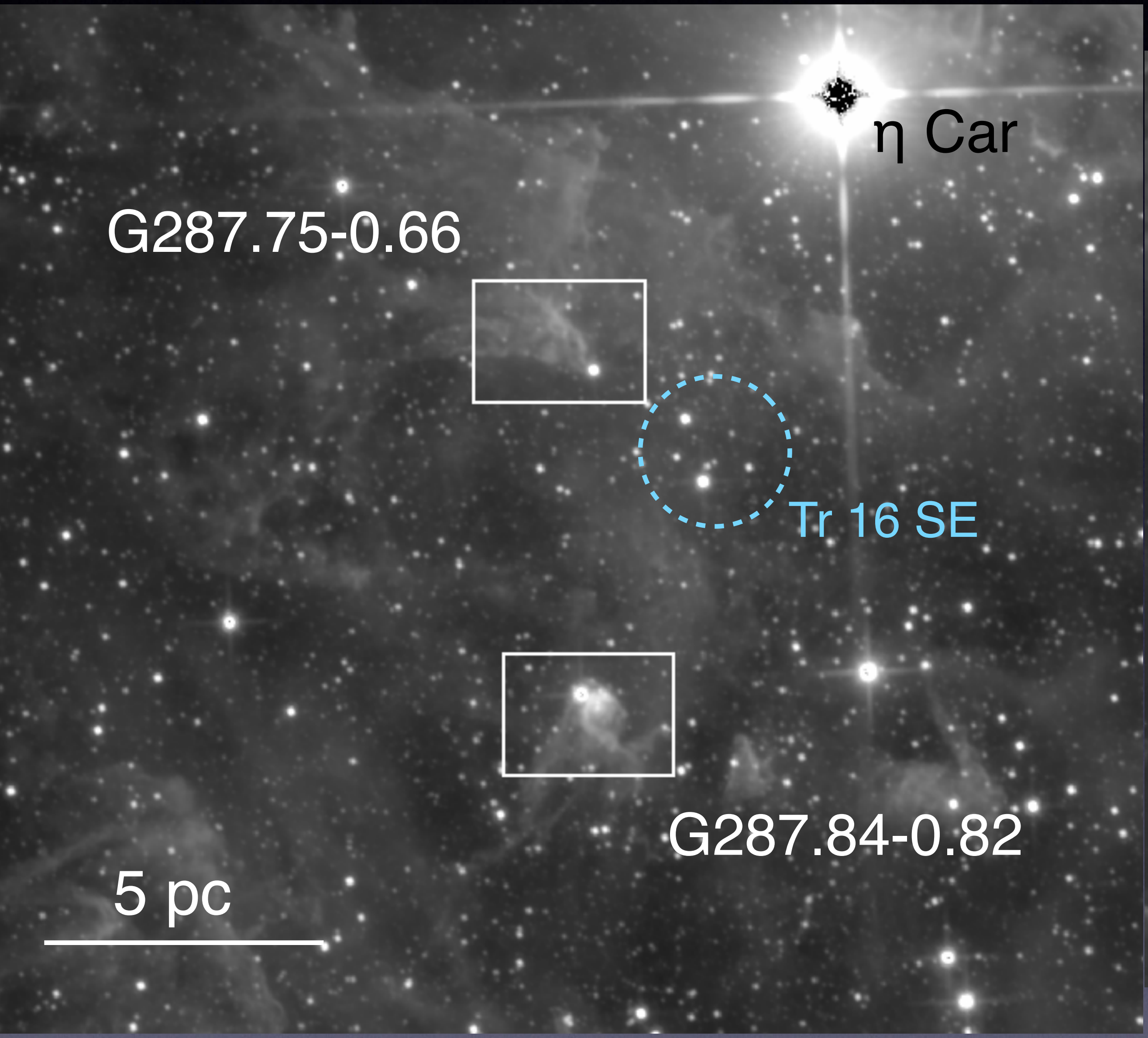


Carina WISE 12 μm

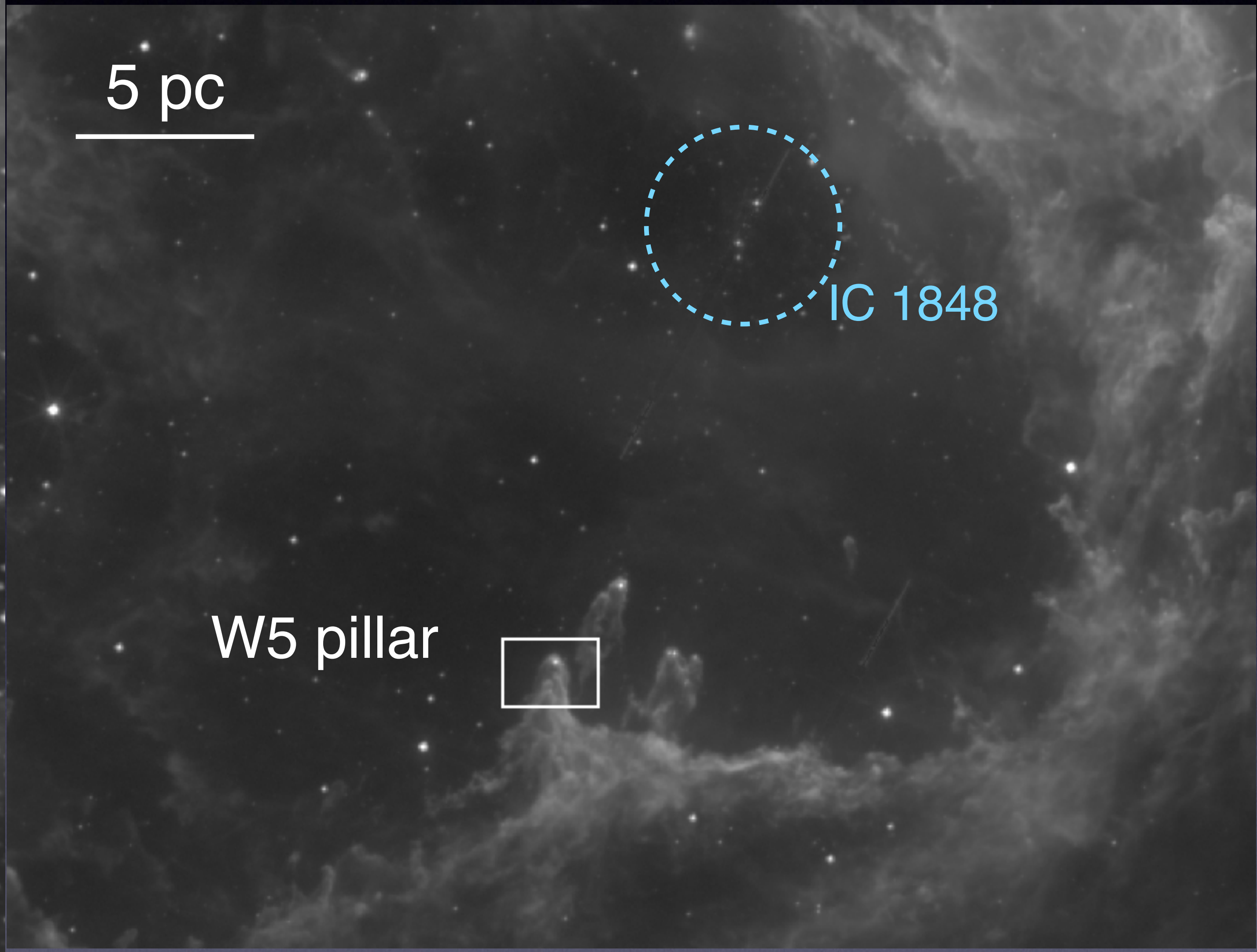


W5 WISE 12 μm

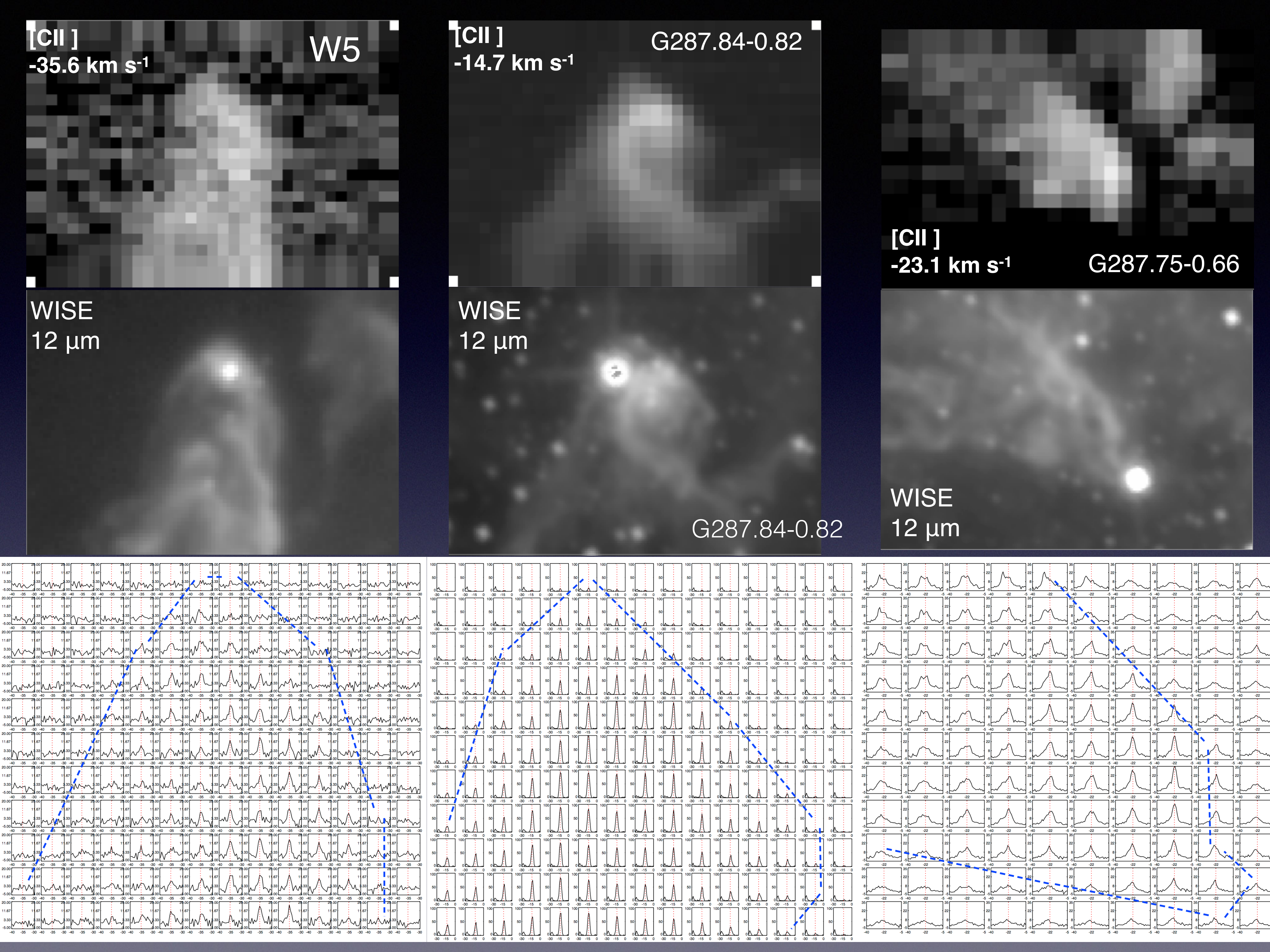
Our sample

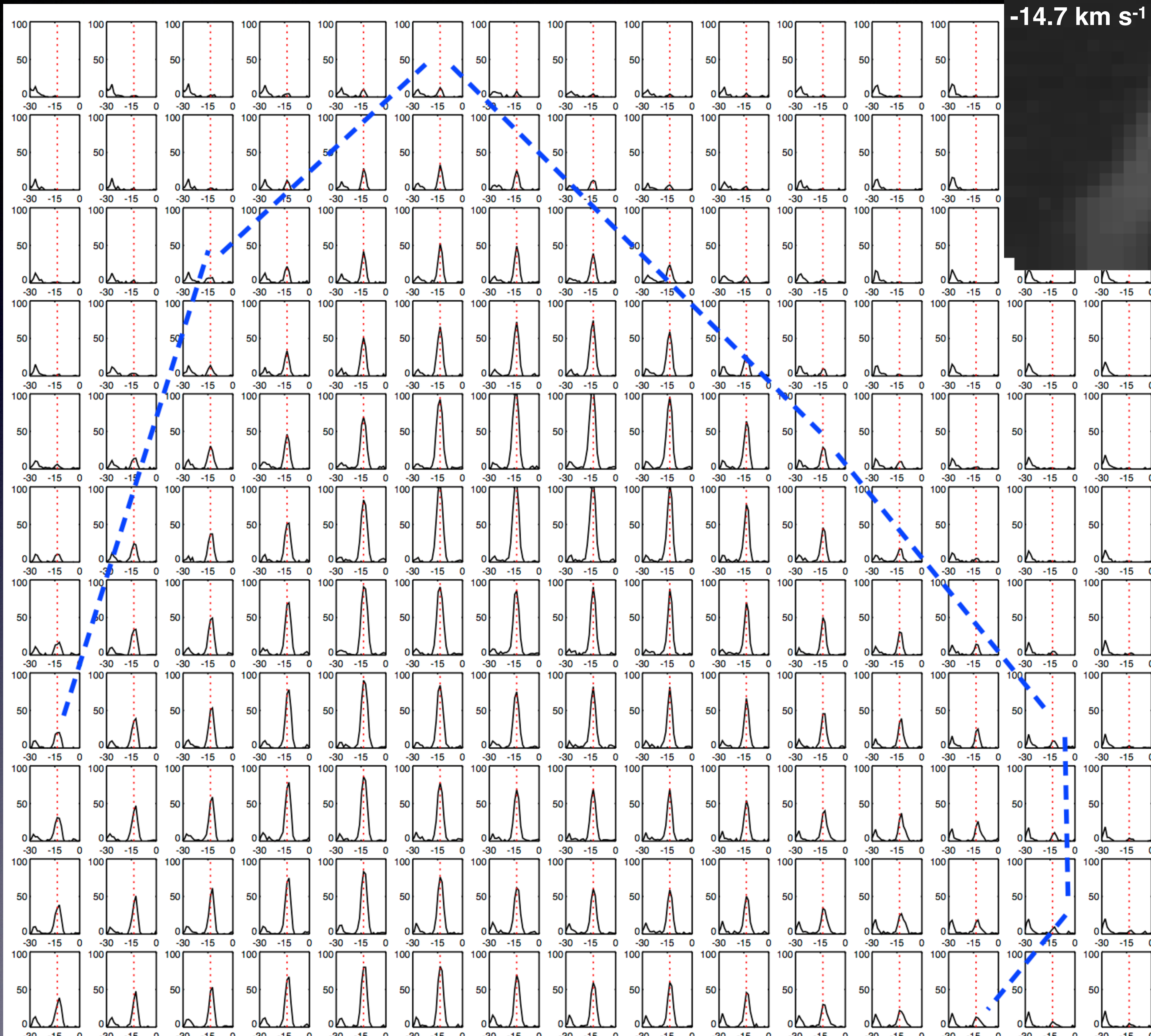


Carina WISE 12 μm



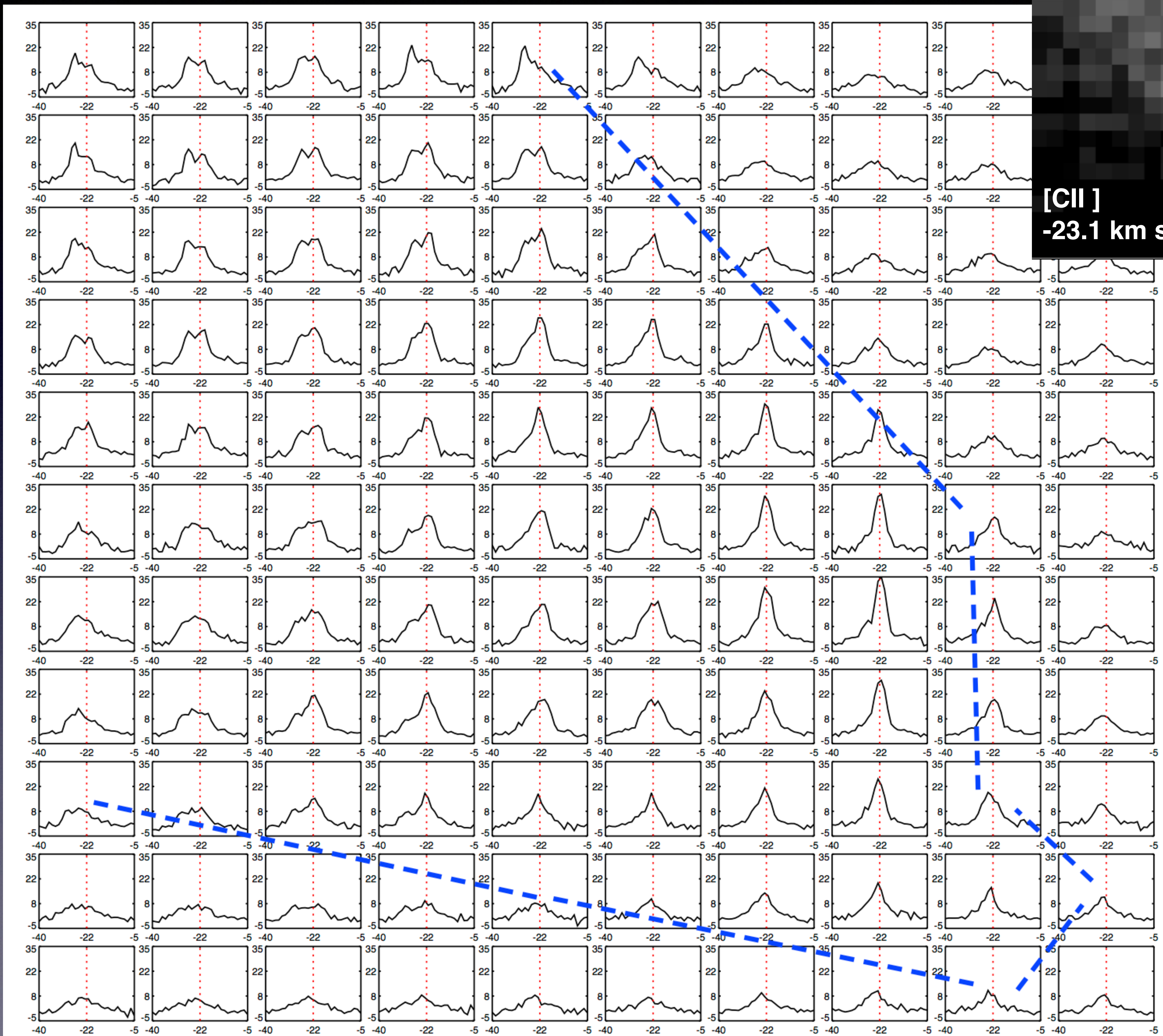
W5 WISE 12 μm

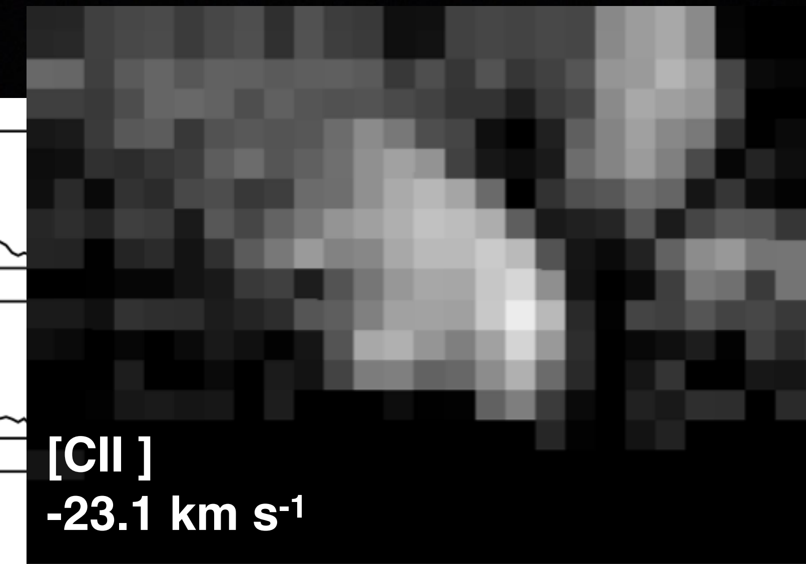

[CII]
-35.6 km s-1
W5
WISE
12 µm
[CII]
-14.7 km s-1
G287.84-0.82
WISE
12 µm
G287.84-0.82
[CII]
-23.1 km s-1
G287.75-0.66
WISE
12 µm



G287.84-0.82

Boxes
30 km s^{-1}
wide





G287.75-0.66

Boxes
35 km s^{-1}
wide

- Typical velocities:
    - -14.7 km s^{-1} G287.84-0.82, $v_{FWHM} \sim 4.5$ km s^{-1}
    - -23.1 km s^{-1} G287.75-0.66, $v_{FWHM} \sim 3.7$ km s^{-1}
    - -35.6 km s^{-1} W5 pillar (SFO 11E, Sugitani et al. 1991), $v_{FWHM} \sim 1.6$ km s^{-1}
- Collapse or rotational motions small if any
- No sign of large velocity gradient along pillars
- Work in progress!