Ionized regions & Star Formation

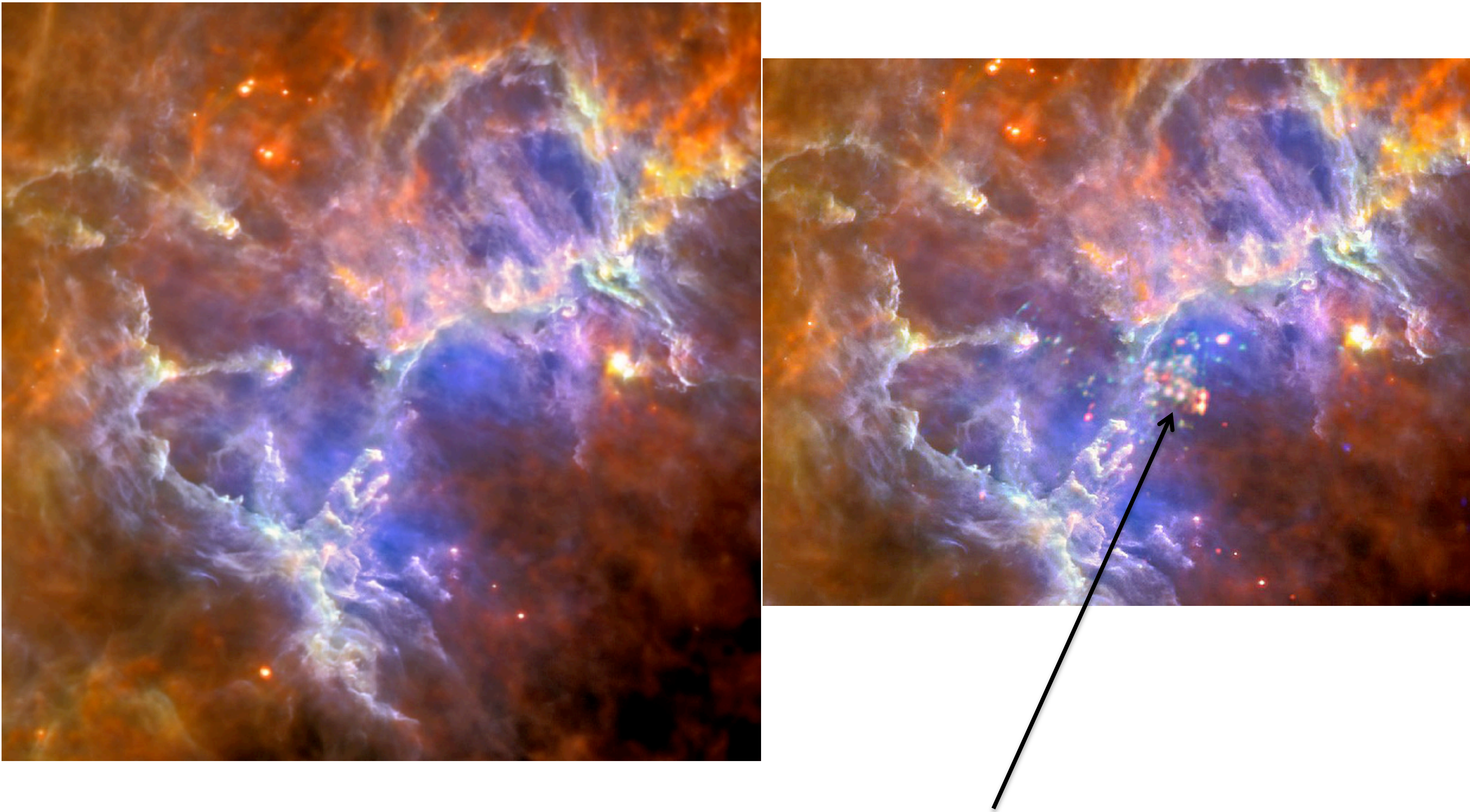
A. ZAVAGNO

Aix Marseille Université

This presentation has received *funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]*

CONTEXT

Interaction of high mass stars with the surrounding medium



Eagle Nebula: *Herschel* (70 160 250 μm) and *XMM Newton* (Xrays)
(Hill et al. 2012) HOBYS

HII regions & (high mass) Star formation

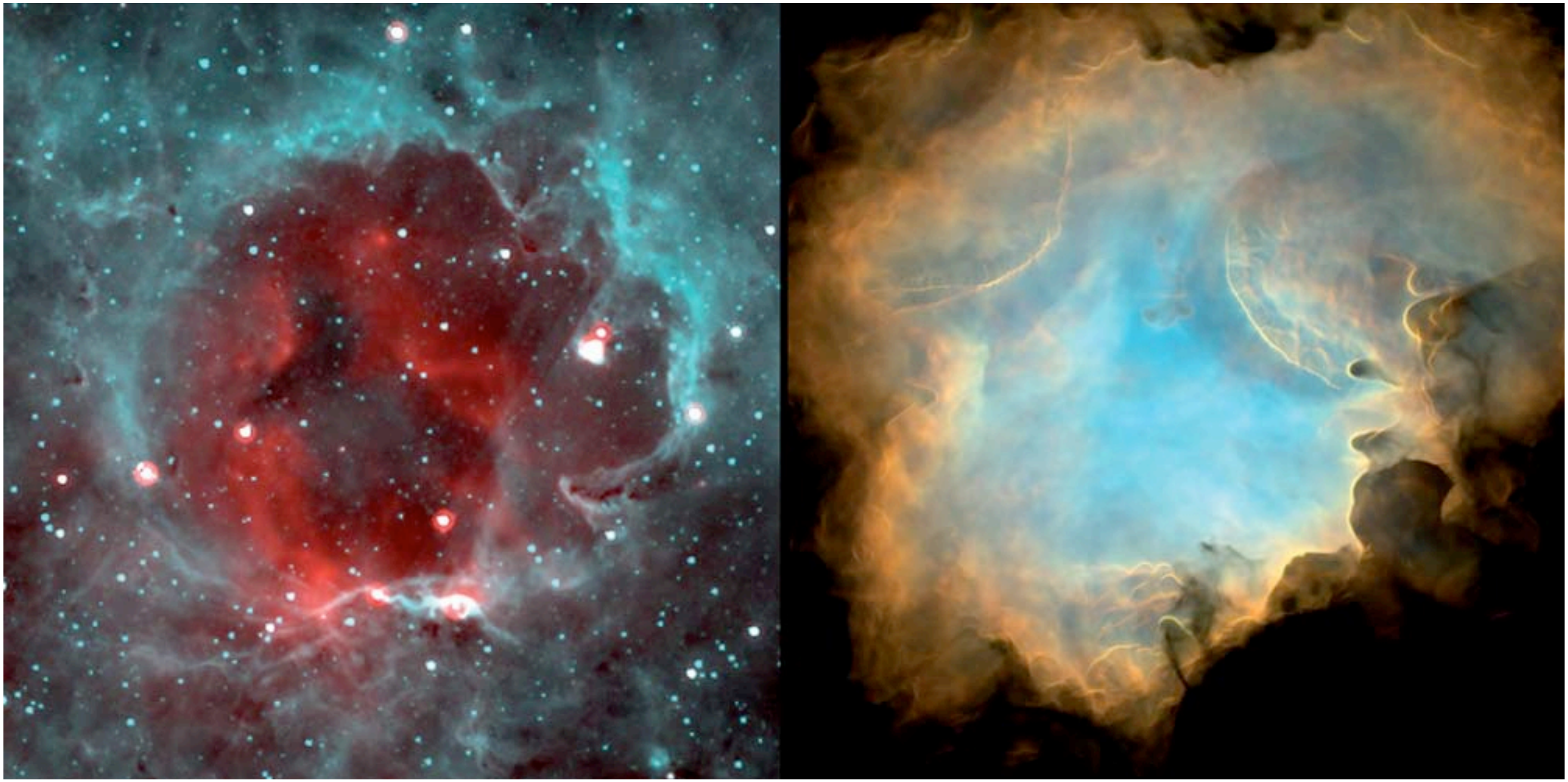
- Why care about ?
  - Key role of high mass stars in galaxies' evolution
  - Do HII regions promote the formation of high mass stars?

  - ~ 7 000 **ionized regions in the Galaxy** (Armentrout et al. 2019, L. Anderson's Web site: http://astro.phys.wvu.edu/wise/)

- Radiative feedback: positive or negative impact on star formation?
  - What models tell us ? *negative*

Radiation-MHD Simulations of HII Region and their associated PDRs in turbulent molecular clouds, 2011, MNRAS, 414, 1747

Arthur, S. J.; Henney, W. J.; Mellema, G.; de Colle, F.; Vázquez-Semadeni, E.

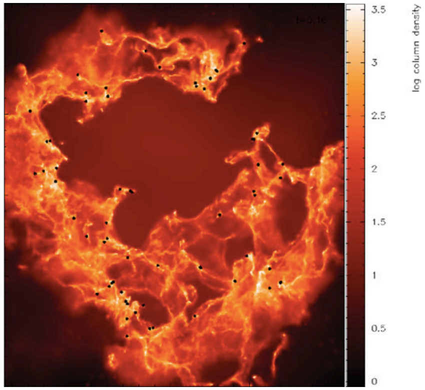


N12: *left*: colour image with the *Spitzer*-GLIMPSE image at 8 μm in turquoise and the *Spitzer*-MIPSGAL image at 24 μm in red.
Right : synthetic optical image of a simulated H II region evolving in a turbulent molecular cloud (Henney et al. 2010). The [NII] 6584 Å emission appears in red, the Hα 6563 Å emission in green, and the [OIII] 5007 Å emission in blue.

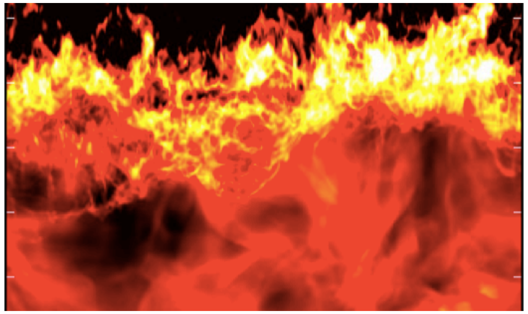
No self-gravity in the model → no star formation

Models

- Elmegreen & Lada (1977): Collect and collapse process
- Walch+ 2012, 2013, 2015: expansion of an HII region in a fractal medium

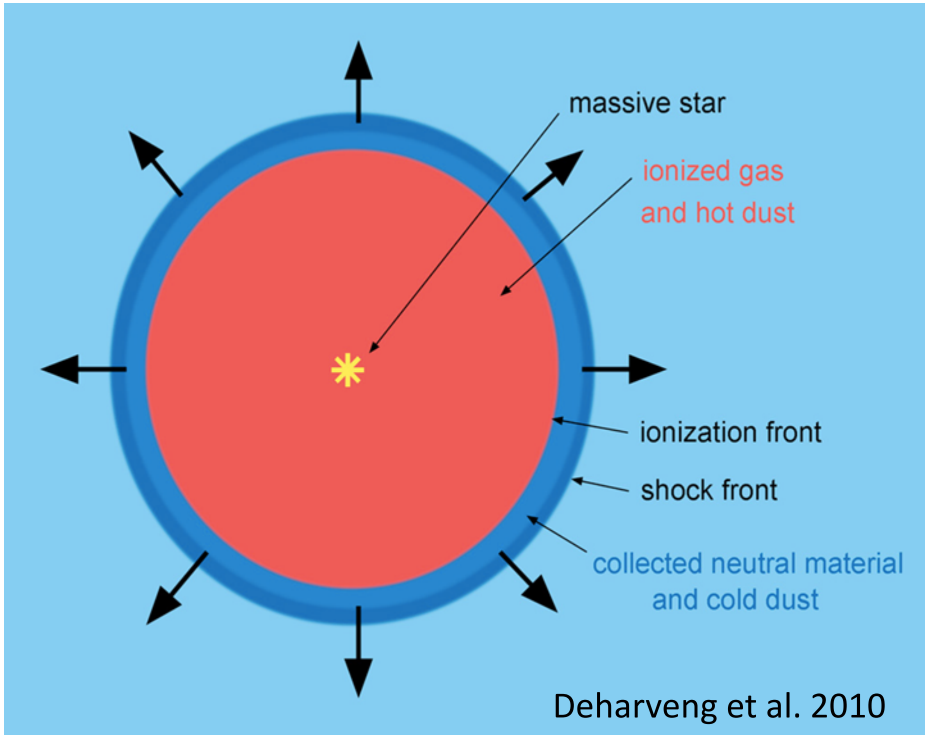


- Tremblin+ 2012, 2014: ionization in a turbulent medium



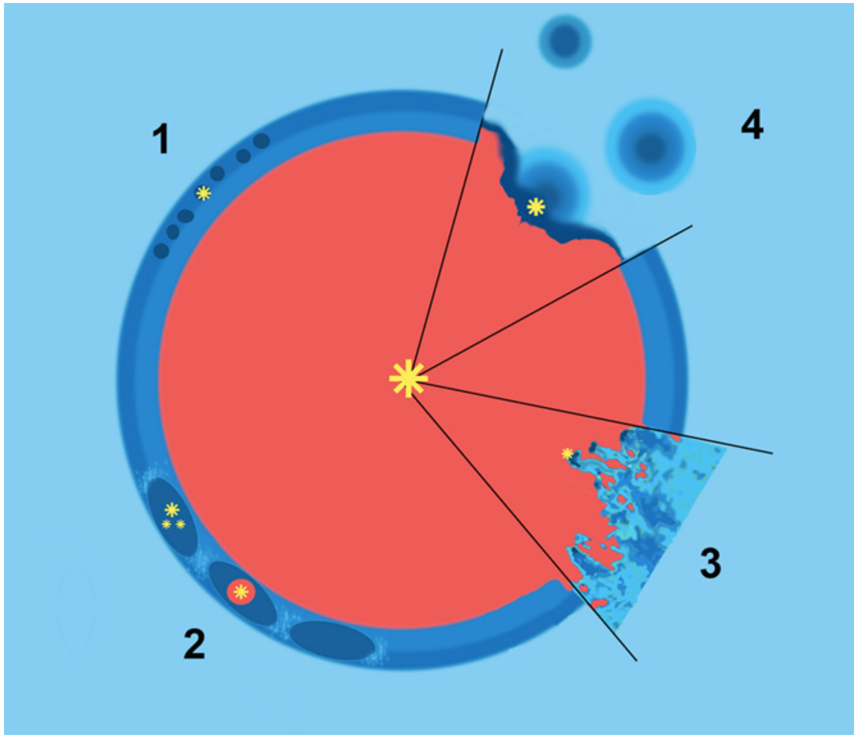
- Geen et al. 2015 (MNRAS, 454, 4484)
  - "We find that the mass in unstable gas can be explained by a model in which the clouds are evaporated by UV photons, suggesting that the net feedback on star formation should be negative. "
- Dale et al. 2015
  - Difficult to disentangle between spontaneous and triggered star formation (simulations and observations)

HII regions and star formation



Instabilities in the compressed shell:
Small-scale:
Low/intermediate mass
Star formation

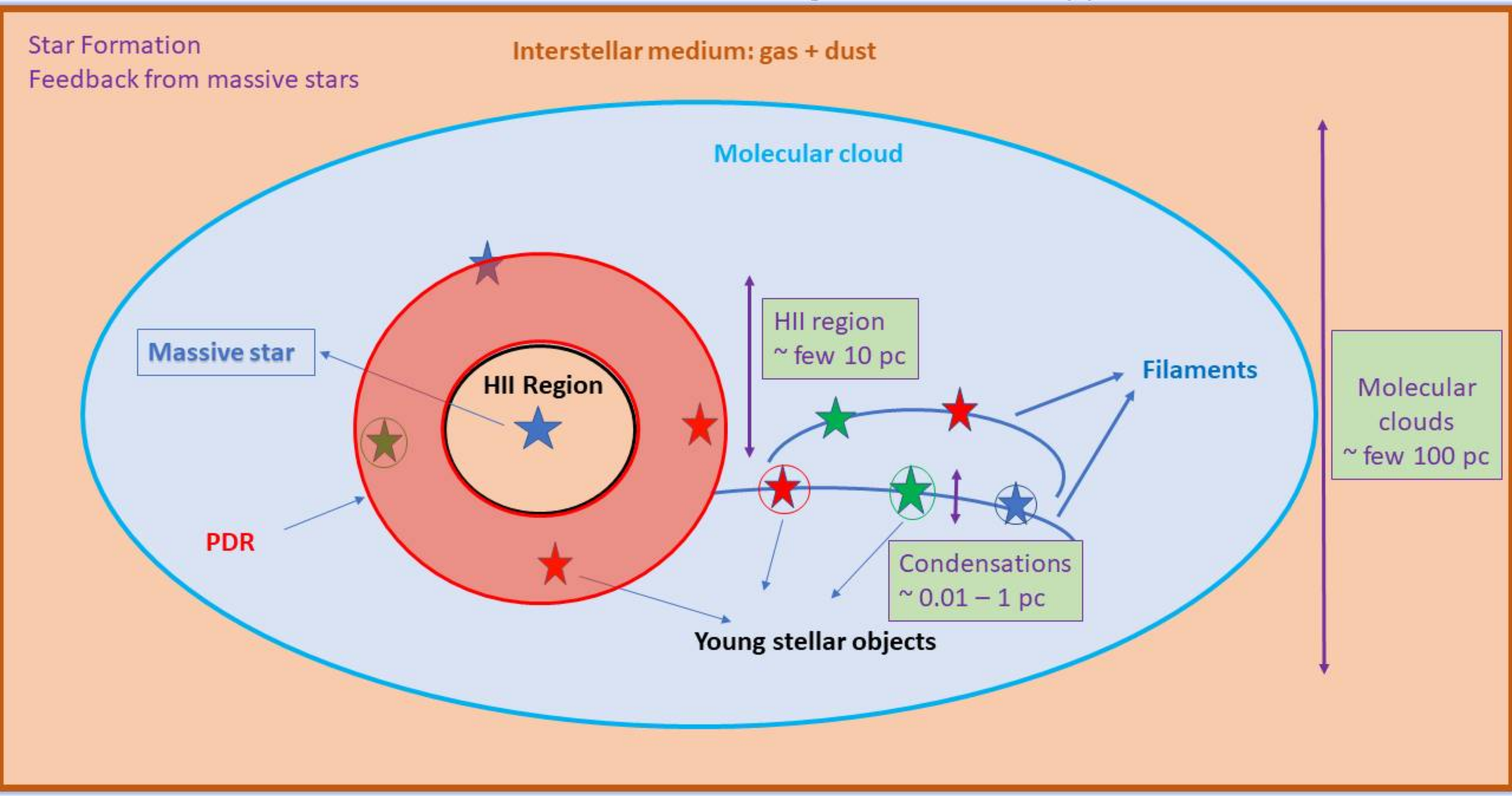
Radiation-driven compression of pre-existing dense clumps



Instabilities in the compressed shell:
Large-scale: Massive Star formation
2nd generation HII regions
Clusters formation

Ionizing radiation acting on a turbulent medium:
Pillar formation

Star formation: A multi wavelength, multi scale approach



OBSERVATIONS: KEY INFORMATION

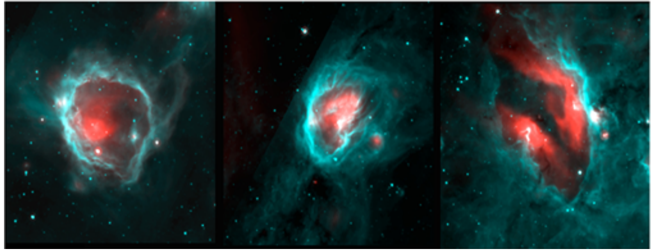
Observations

- Detect HII regions (IR, radio, 24 μm emission)
- Study the young stellar population
  - *Near IR, mid-IR, far-IR: 2MASS, Spitzer, Herschel* Hi-GAL, HOBYS, ….
- Study the associated molecular material
- Dynamics
  - Association of YSOs with the HII regions (velocities, distances)
  - Properties of the molecular material

STATISTICAL STUDIES

Deharveng+ 2010

Kendrew+ 2012, 2016 The Milky Way Project



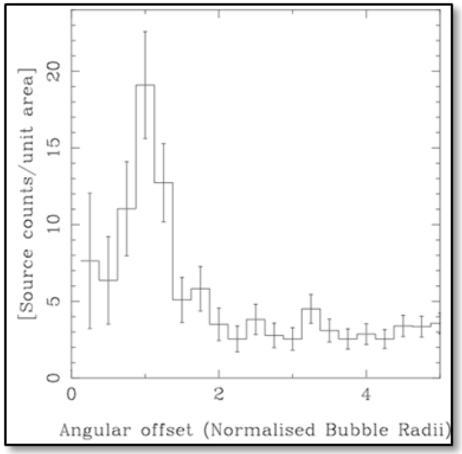
Spitzer (GLIMPSE, MIPSGAL), ATLASGAL

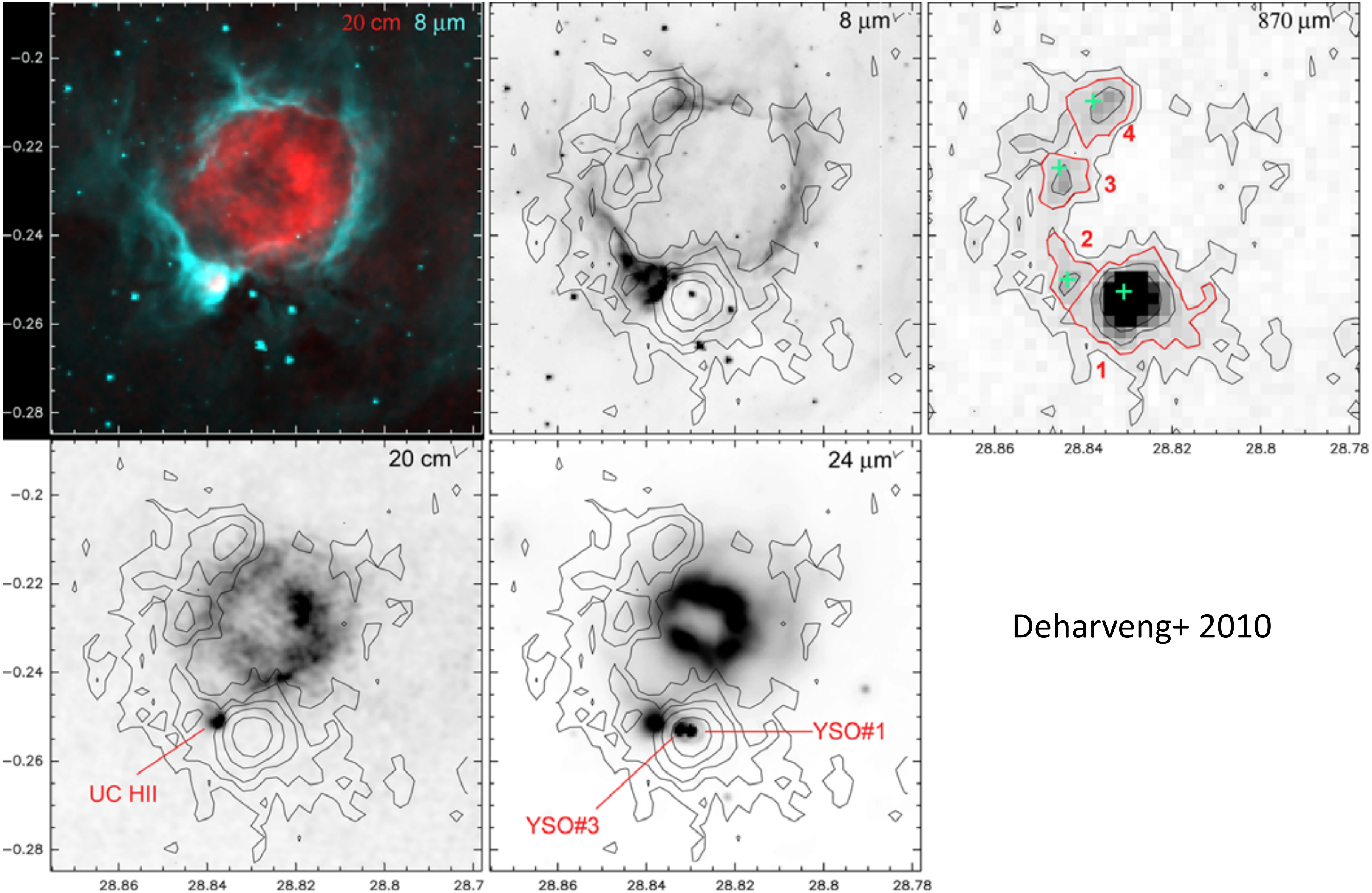
- Overdensity of bright ATLASGAL (870 μm) clumps
- 50% in close proximity to an HII region
- 25% appear directly projected toward the HII region PDR (rim)
- Strong correlation of massive cold clumps with HII regions

Thompson+ 2012: overdensity of YSOs at the edges of HII regions

RMS Massive Young stellar Objects

(Red MSX sources)



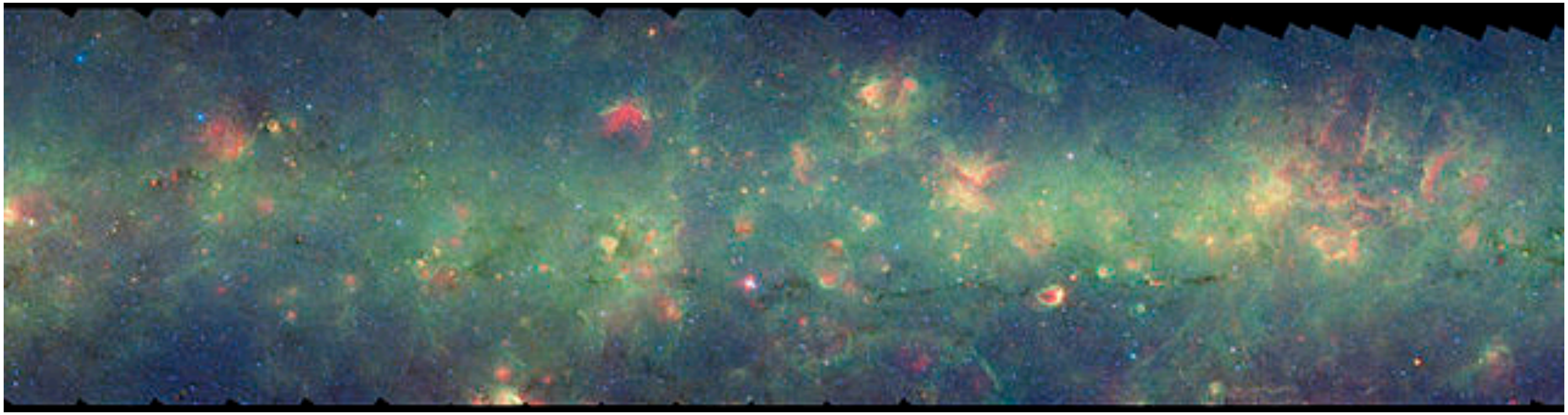


Deharveng+ 2010

N49. *Top left*: *Spitzer*-GLIMPSE 8.0 μm emission in turquoise and 24 μm emission in red. *Others*: contours of 870 μm emission superimposed to greyscale images at 8.0 μm, 870 μm, 20-cm, and 24 μm; the 870 μm contour levels are 0.08 Jy/beam, 0.25, 0.5, 1.0, and 2.0 Jy/beam. The green crosses indicate the NH_3 positions measured by Wyrowski & Wienen . The massive stage I YSOs found by Watson et al. (2008) are indicated.

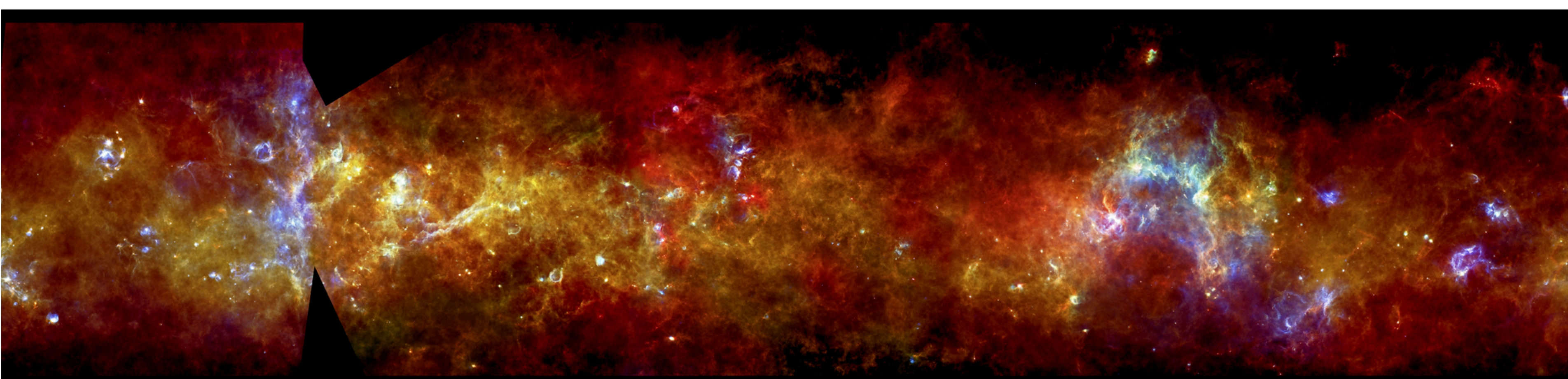
GLIMPSE Survey

- Identify HII region
- YSO population



Hi-GAL Survey

- Probe cold neutral medium
- Reveal the early stages of Star Formation

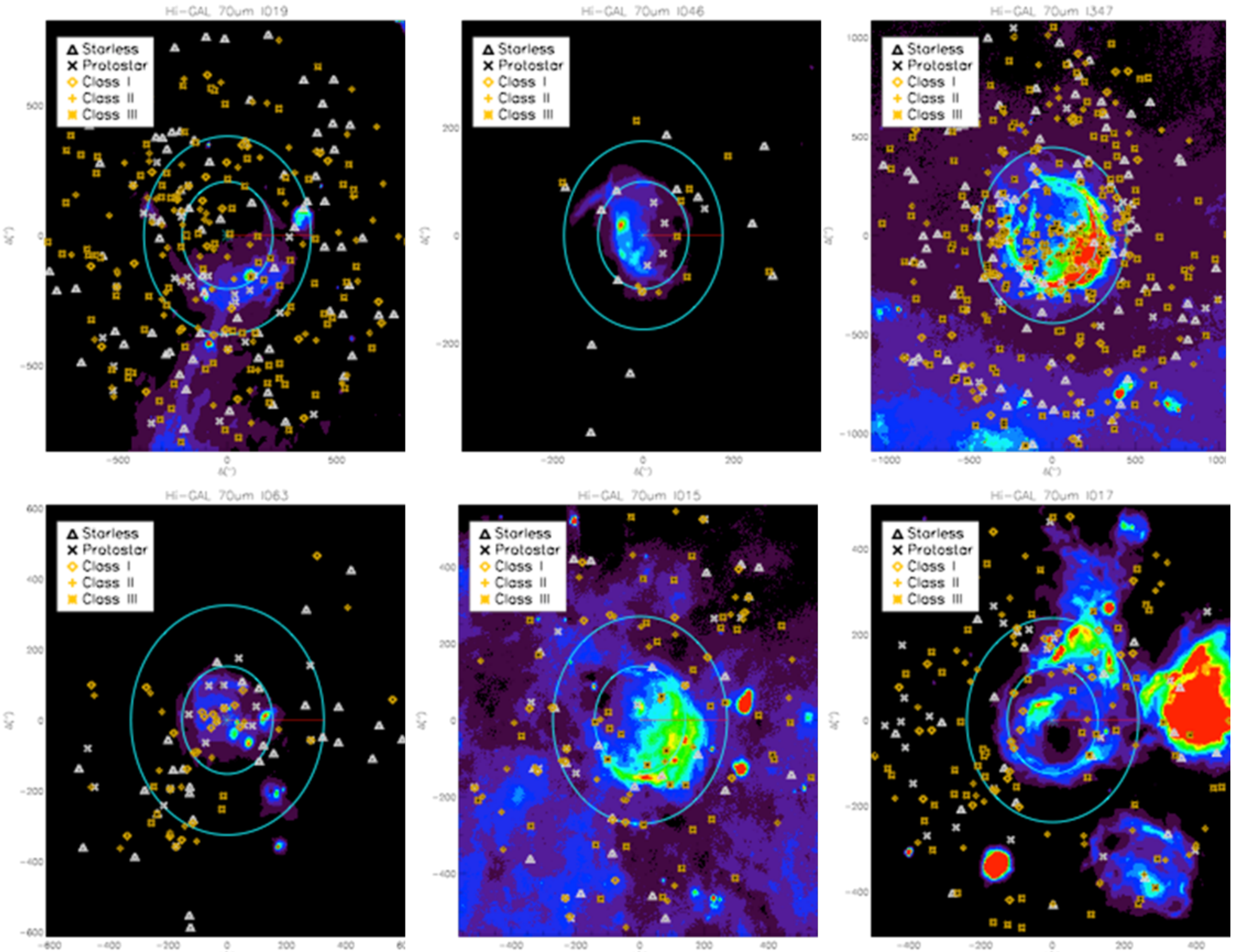


Palmeirim+ 2017

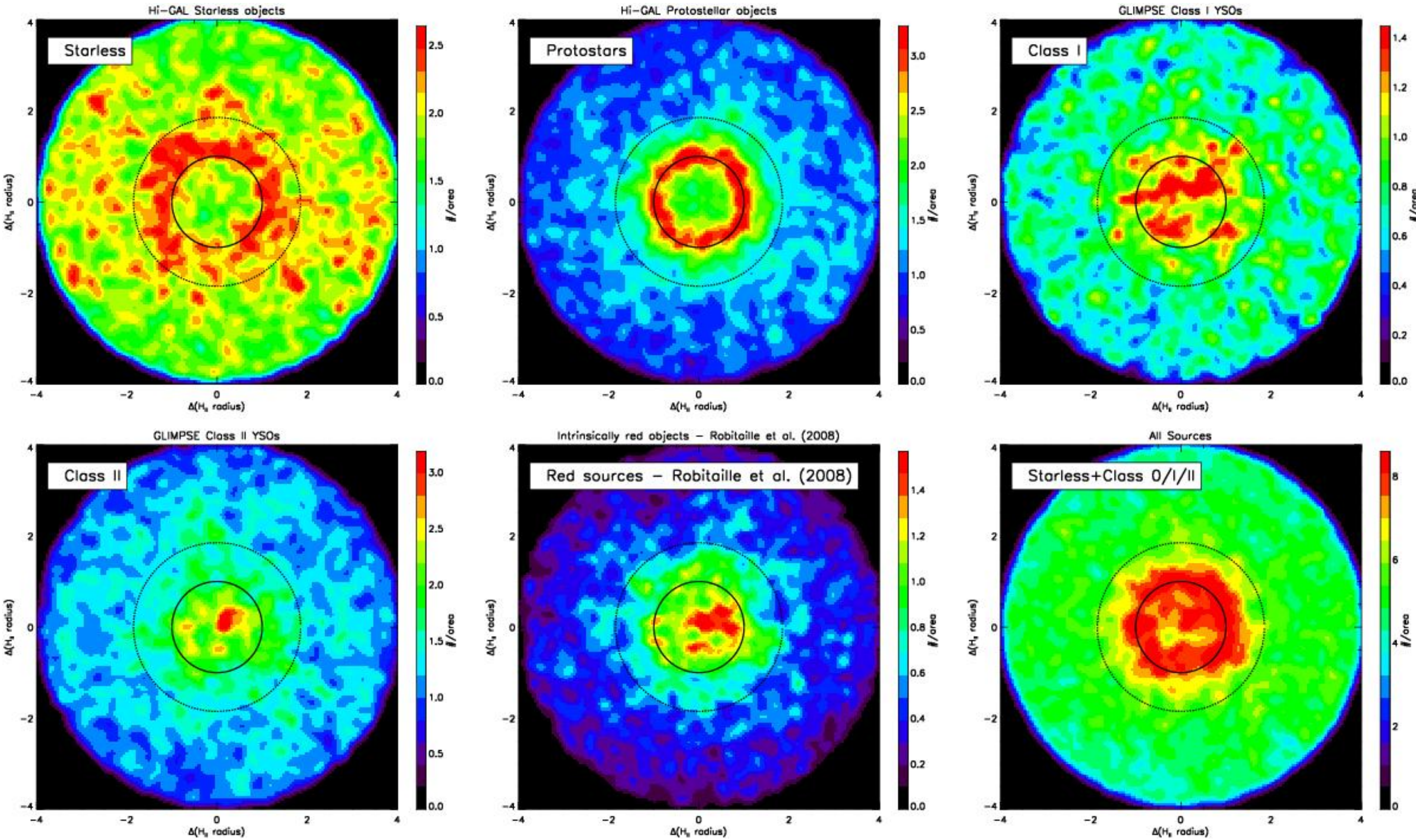
Spitzer, *Herschel* Hi-GAL

1360 HII regions

~ 60 000 star-forming objects



Surface density maps (Palmeirim+ 2017)



Ongoing study

- Bias the search towards very young massive sources associated with HII regions (Zhang+ 2019, in prep.)

→High Mass Starless Clumps (HMSCs) (Yuan+2017: ATLASGAL clumps)

Massive, dense, no star formation activity

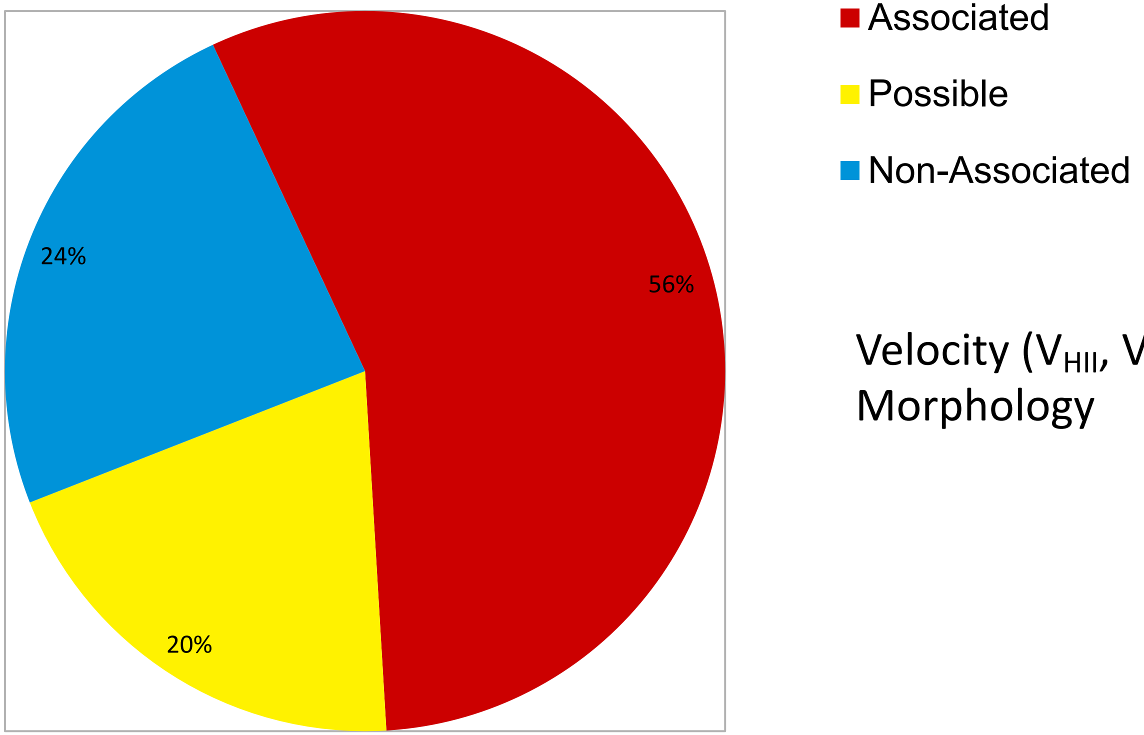
Association with HII regions

Comparisons with non-associated ones

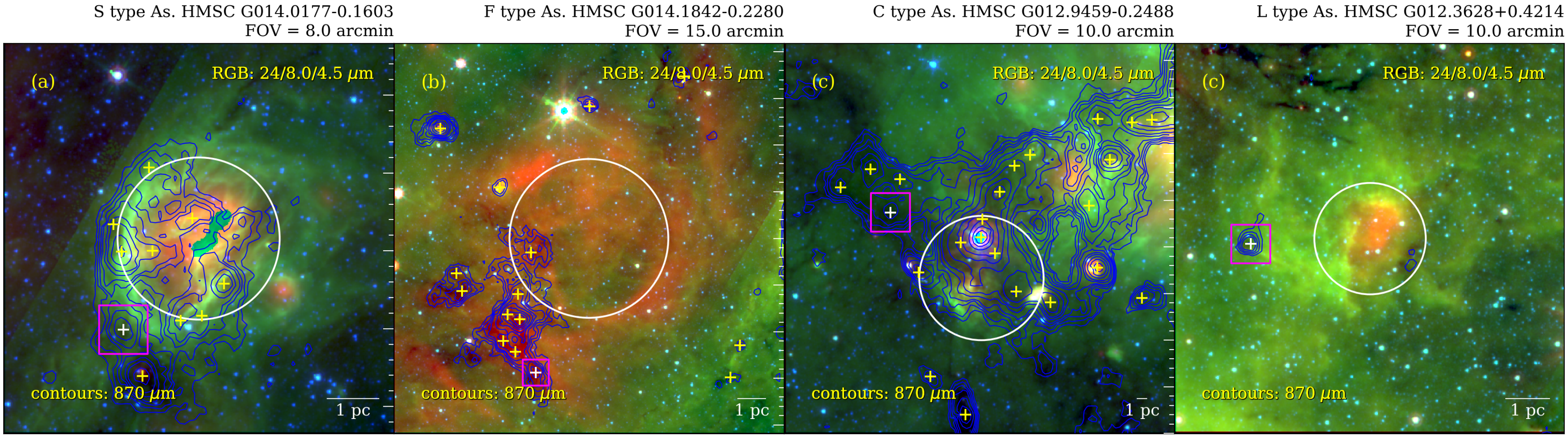
Properties of the whole sample

338 HMSCs in the inner galactic plane (3°<|l|<60°, |b|<1°)

Zhang + in prep.



Velocity (V_{HII}, V_{clump})
Morphology



Highlight the impacts of HII regions

- HMSCs associated with HII regions: hotter, more compact, more luminous, more turbulent than the non-associated ones
- **L/M ratio** may not be a **reliable** evolutionary probe for massive clumps → environment to take into account
- Many HMSCs found nearby (< 1pc) denser and more massive clump. Filamentary structures connect the HMSCs and higher density peaks: interaction ?

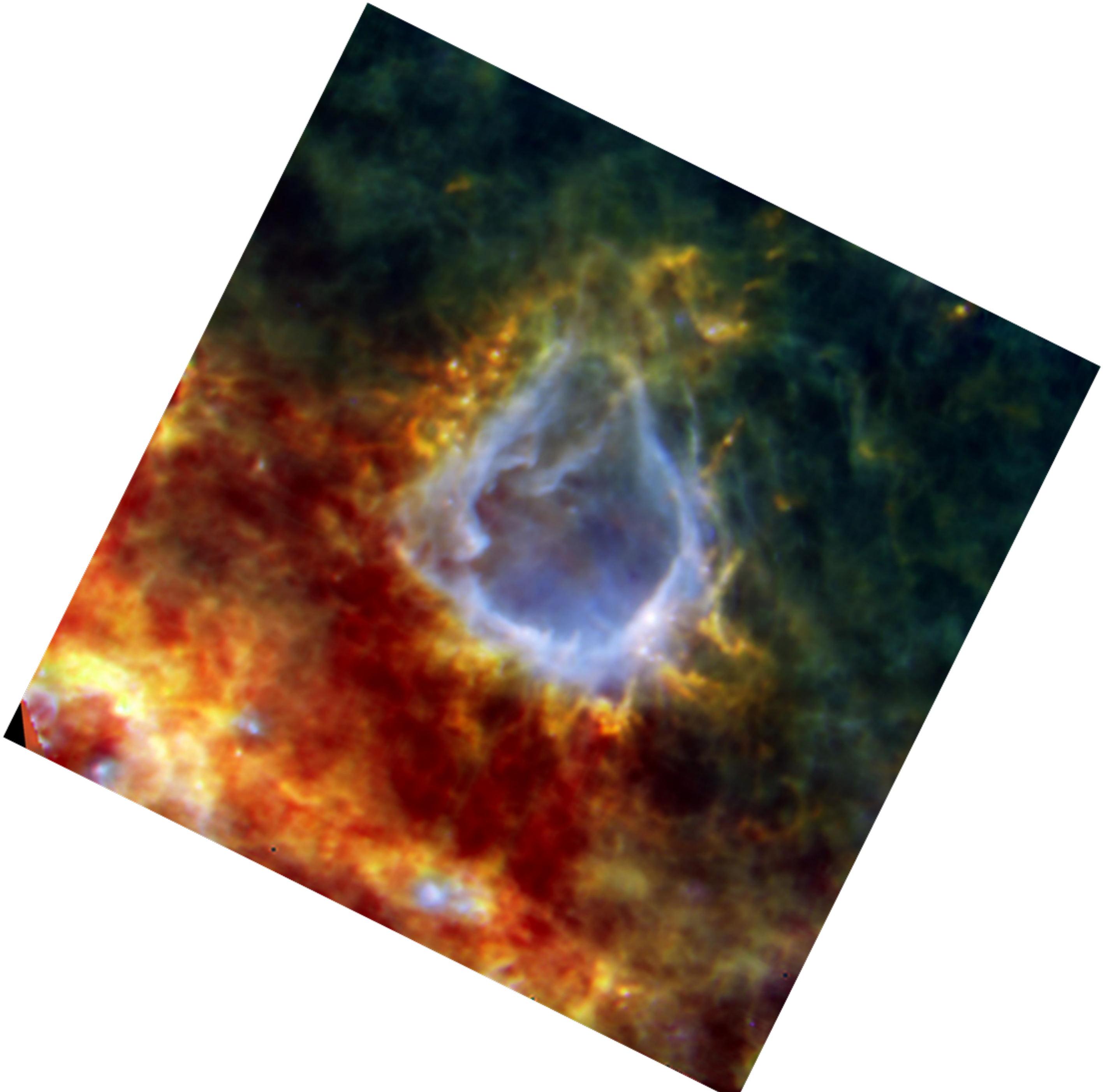
Main results from statistical studies

- Overdensity of massive young stellar objects at the edges of HII regions

- Specific properties for HMSCs associated with HII regions

- Highly dynamical environment

INDIVIDUAL STUDIES



RCW 120
Herschel HOBYS
Zavagno + 2010

100 μm
160 μm
250 μm

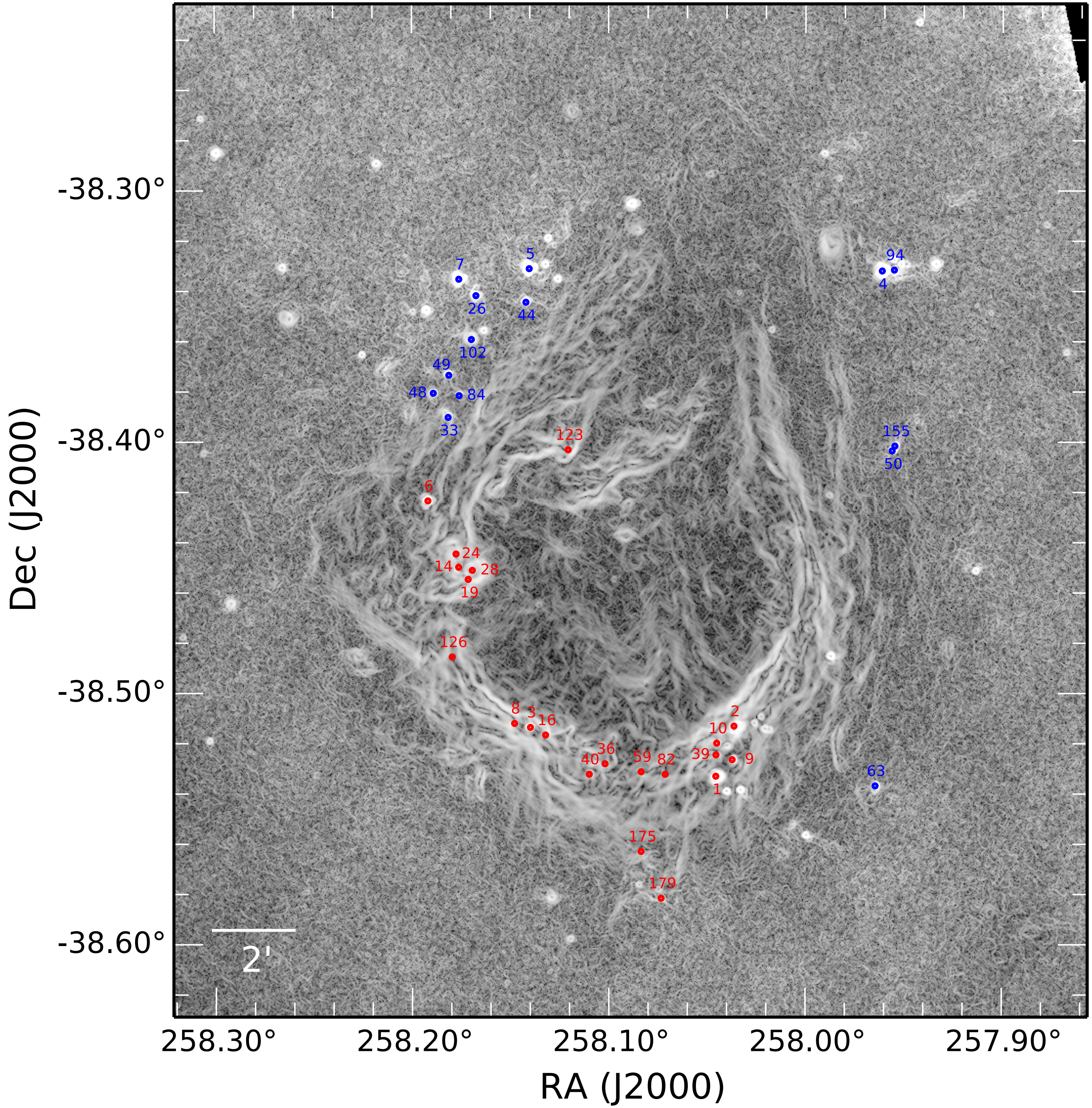
RCW 120

70 µm gradient image

35 Compact sources

Inside outside the PDR

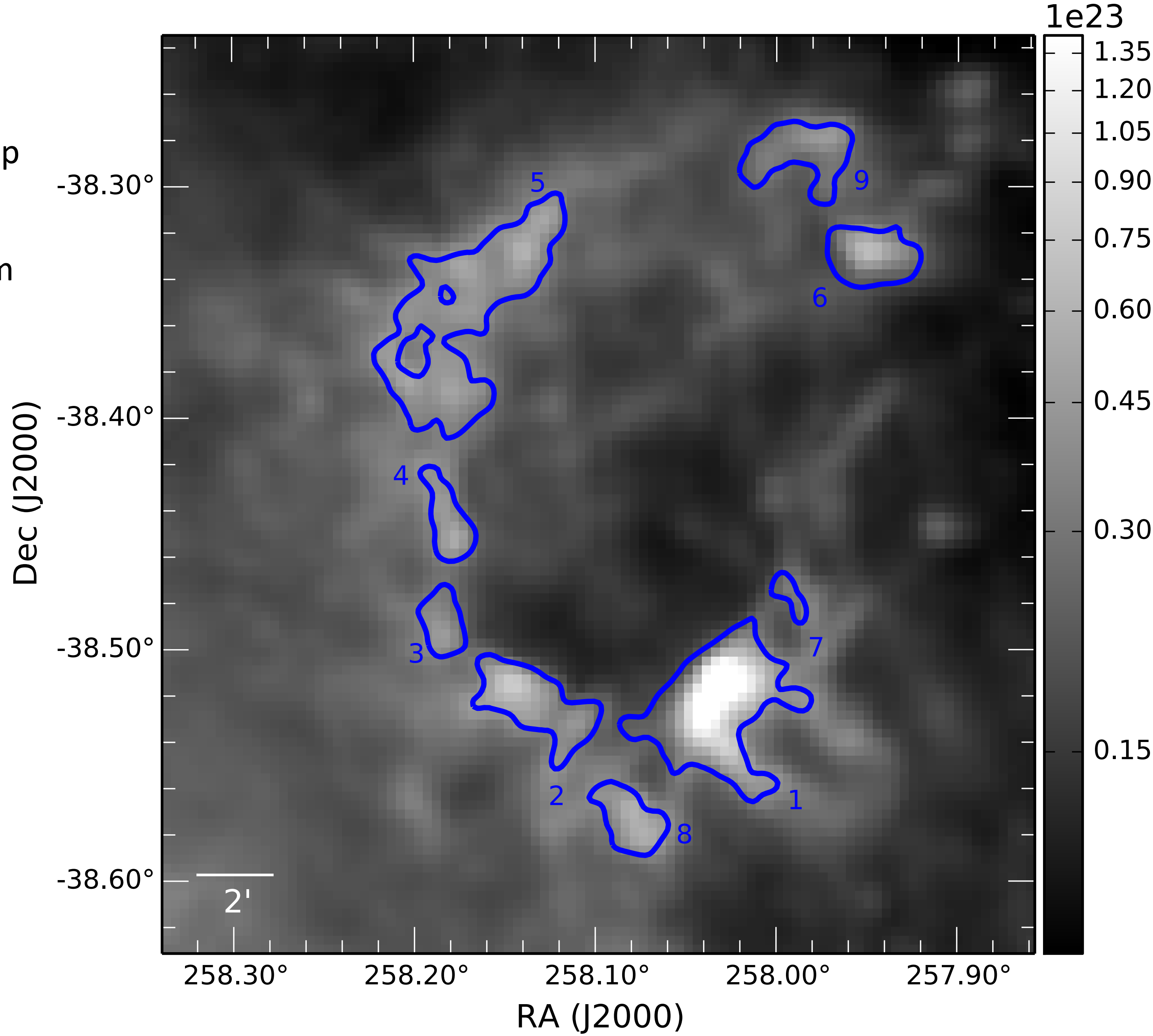
Figueira + 2017



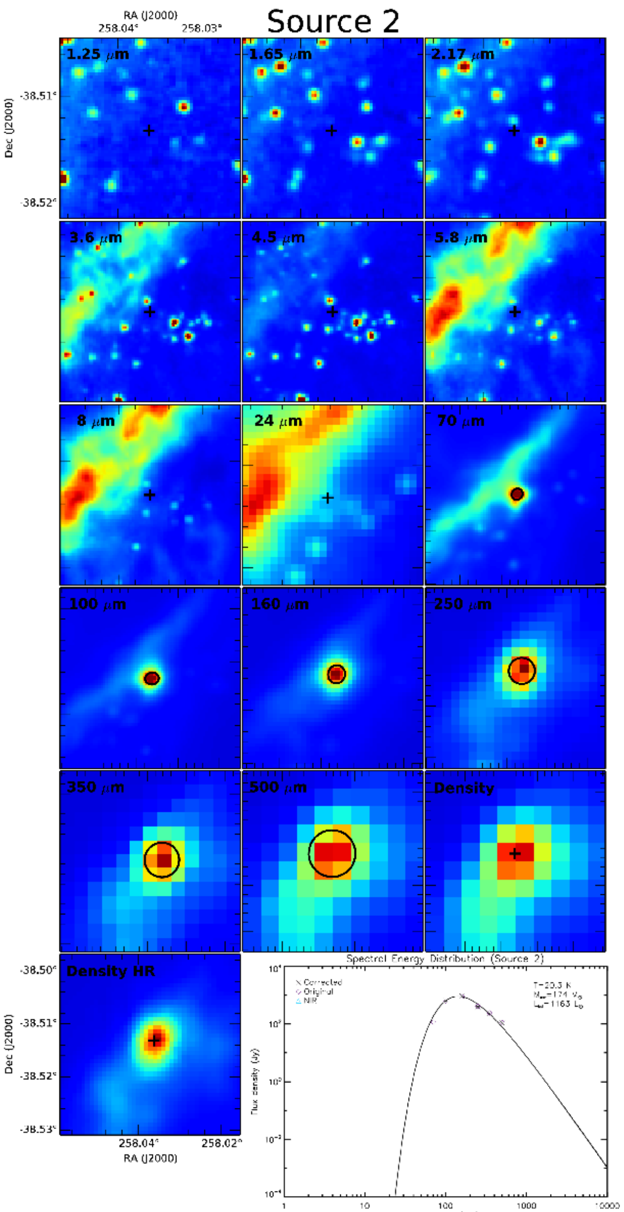
RCW 120

Column density map
N(H2) cm^{-2}

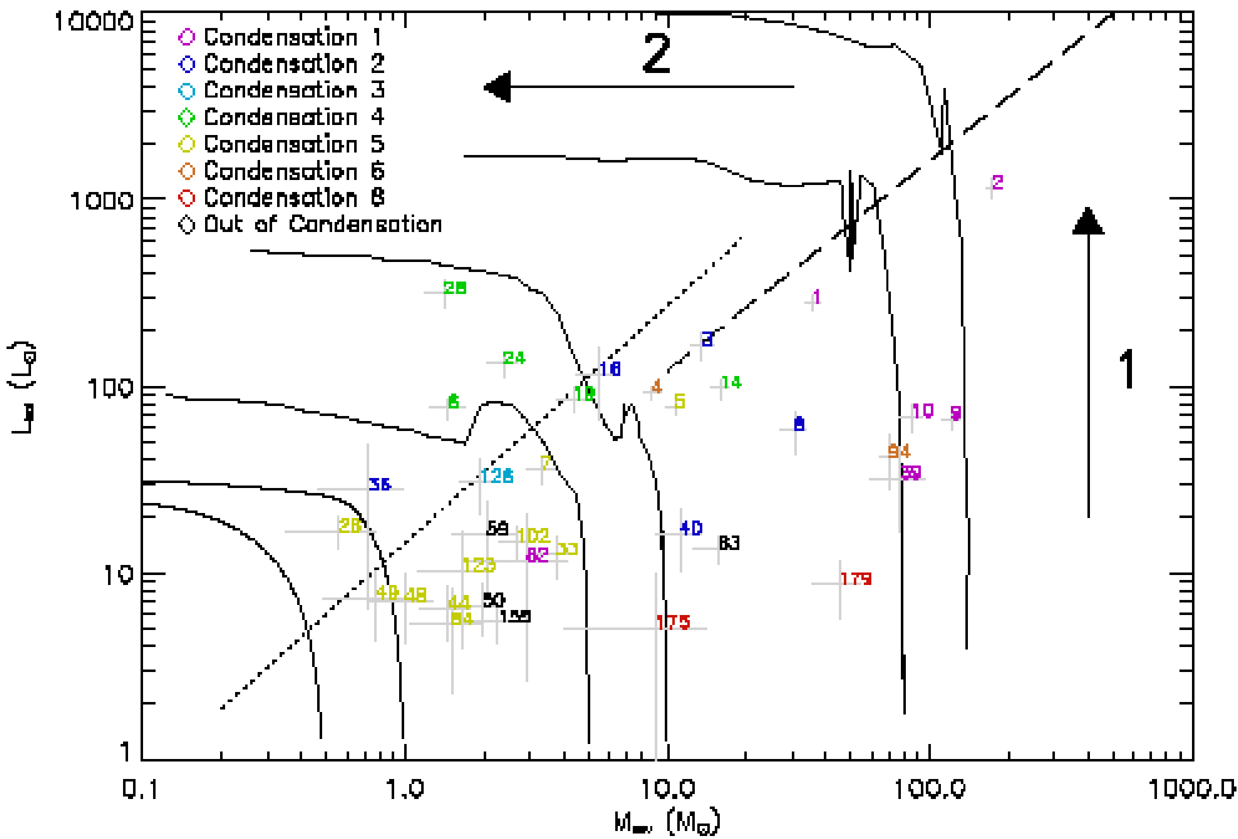
Condensations from
1.3 mm continuum
emission
(Zavagno+ 2007)



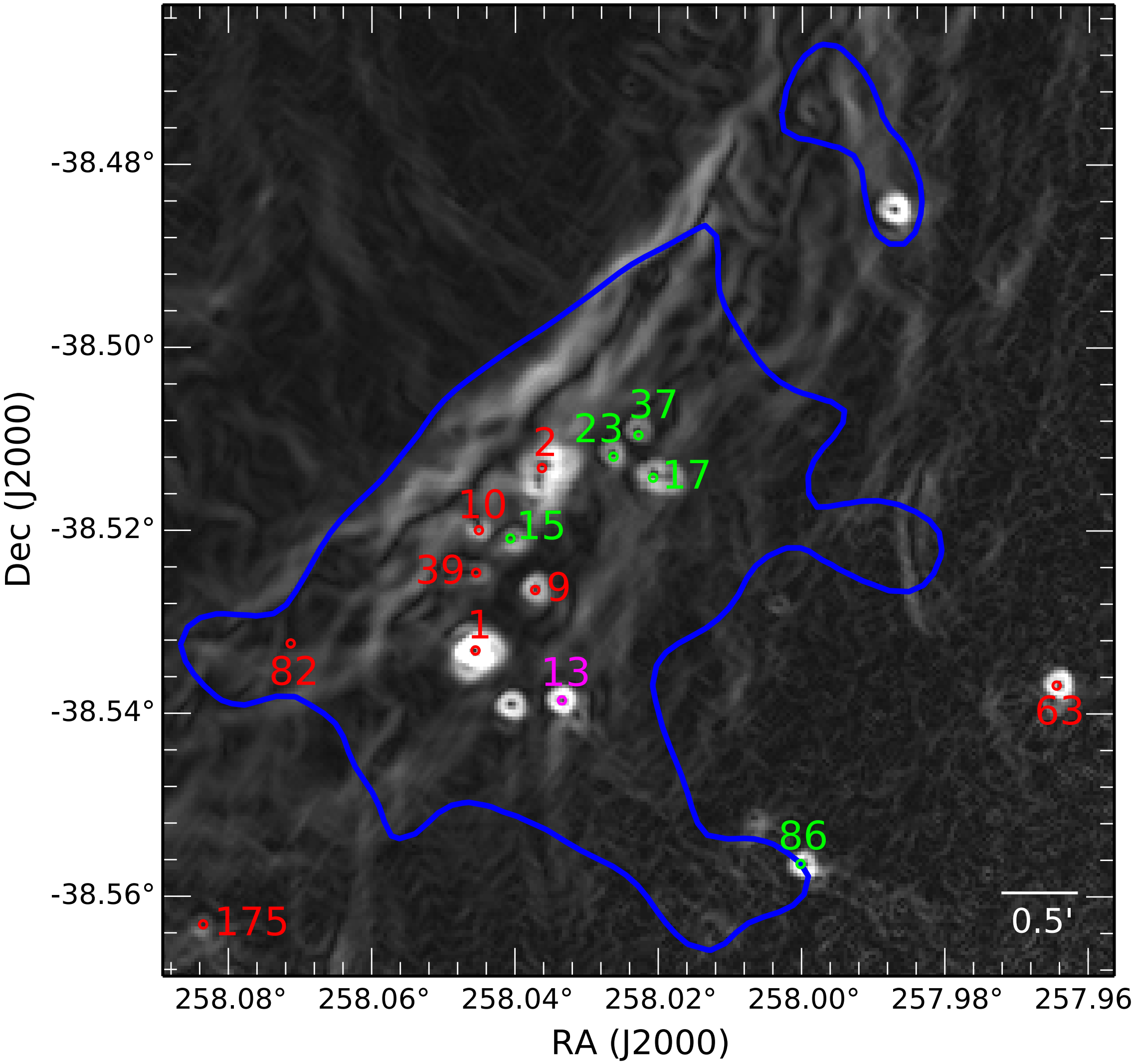
RCW 120 with *Herschel* HOBYS

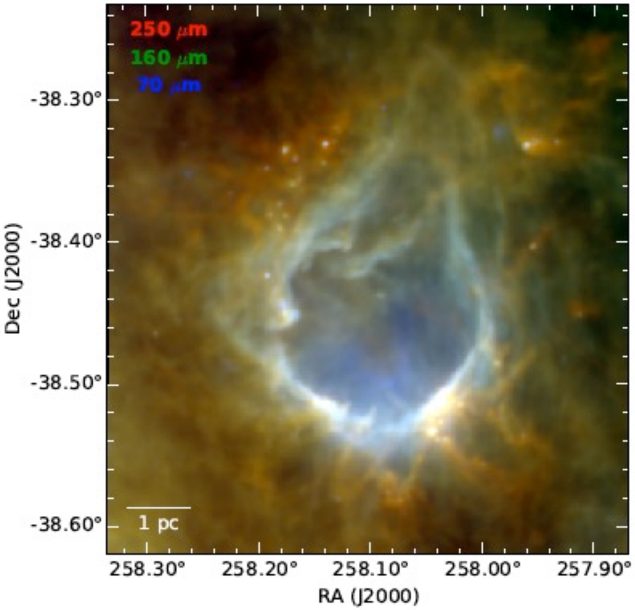


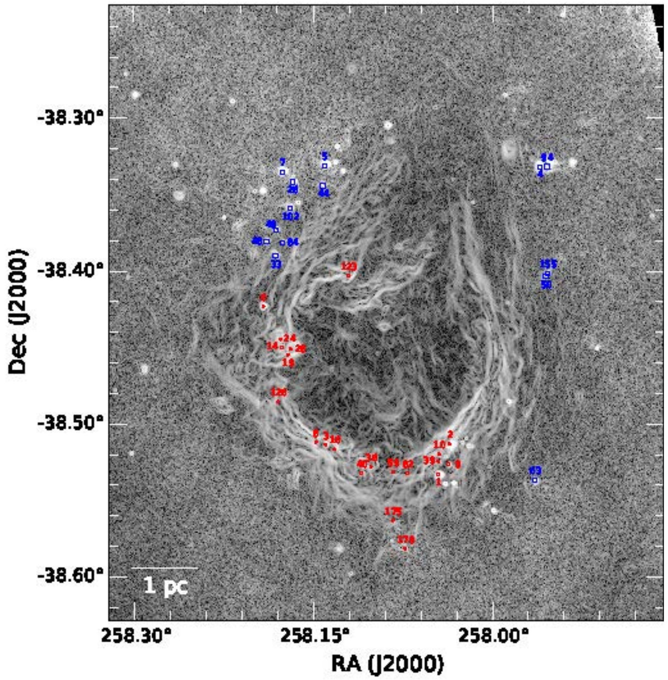
Figueira+ 2017

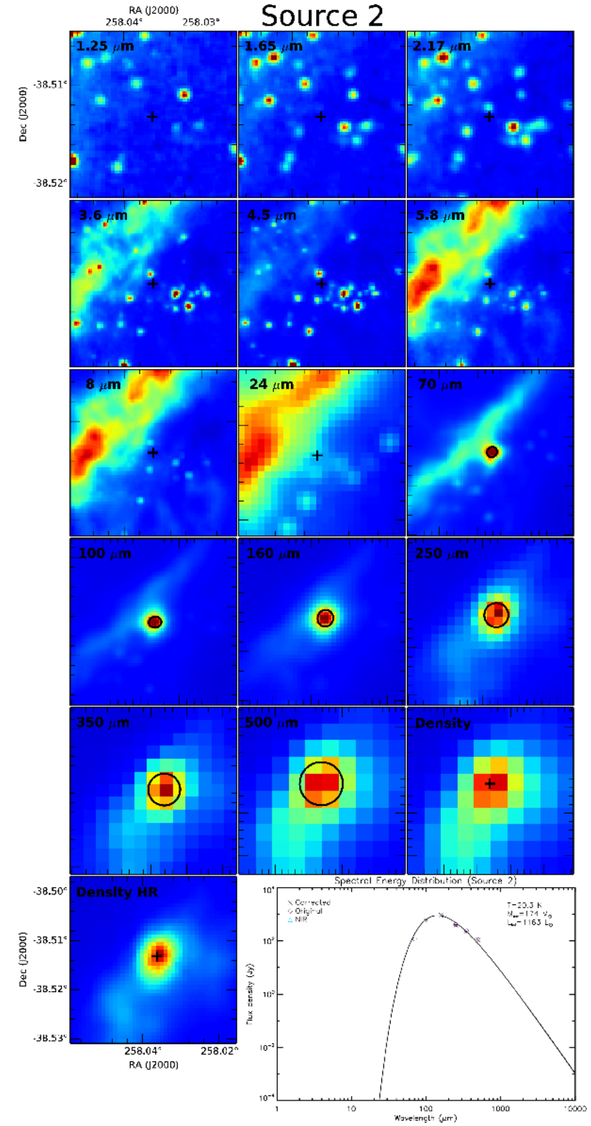


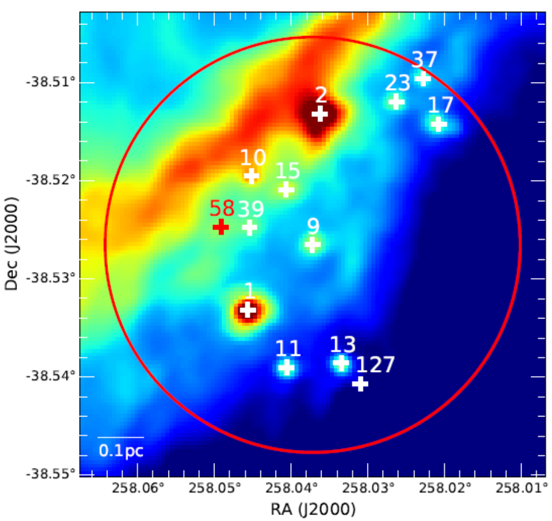
RCW120: Condensation 1: high mass star formation



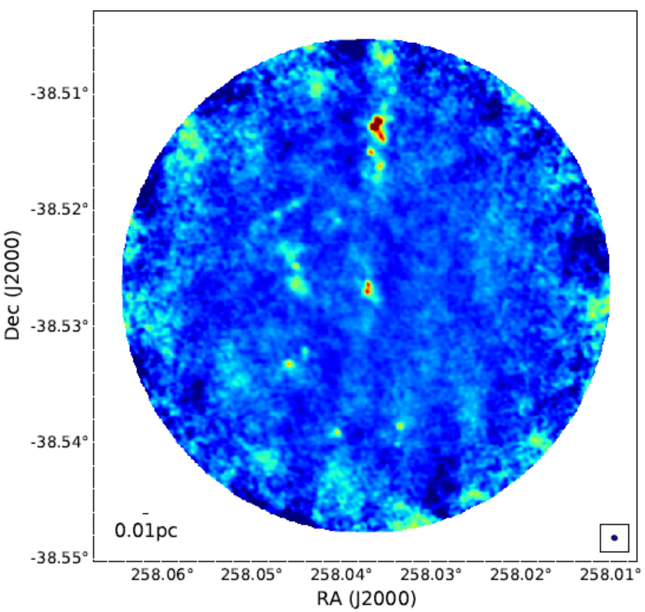






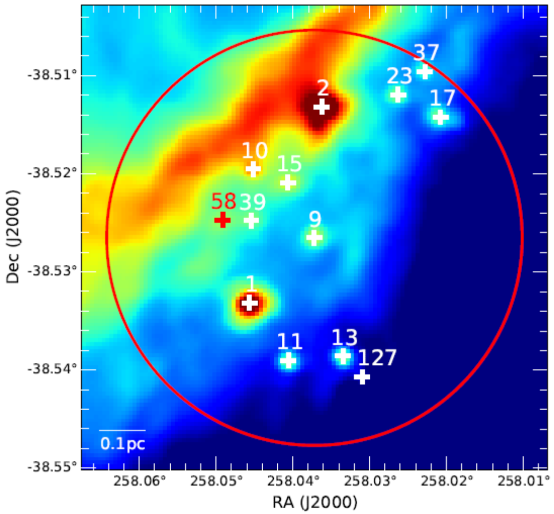


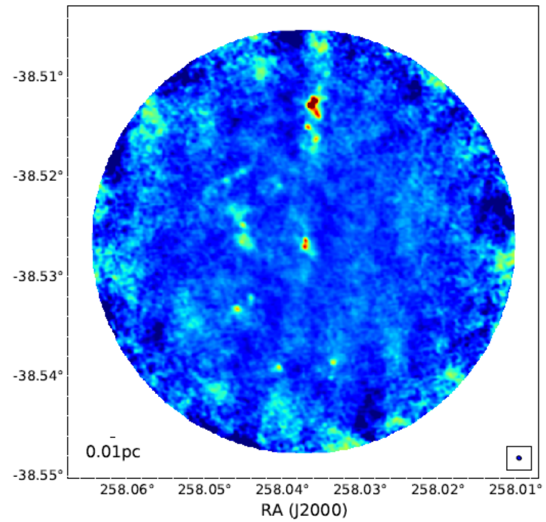
Herschel 70 μm



ALMA 3 mm continuum

Multi scale, multi wavelength – several orders of magnitude





Herschel **& ALMA data**
(pc to milli-pc scale)
Figueira+ 2018

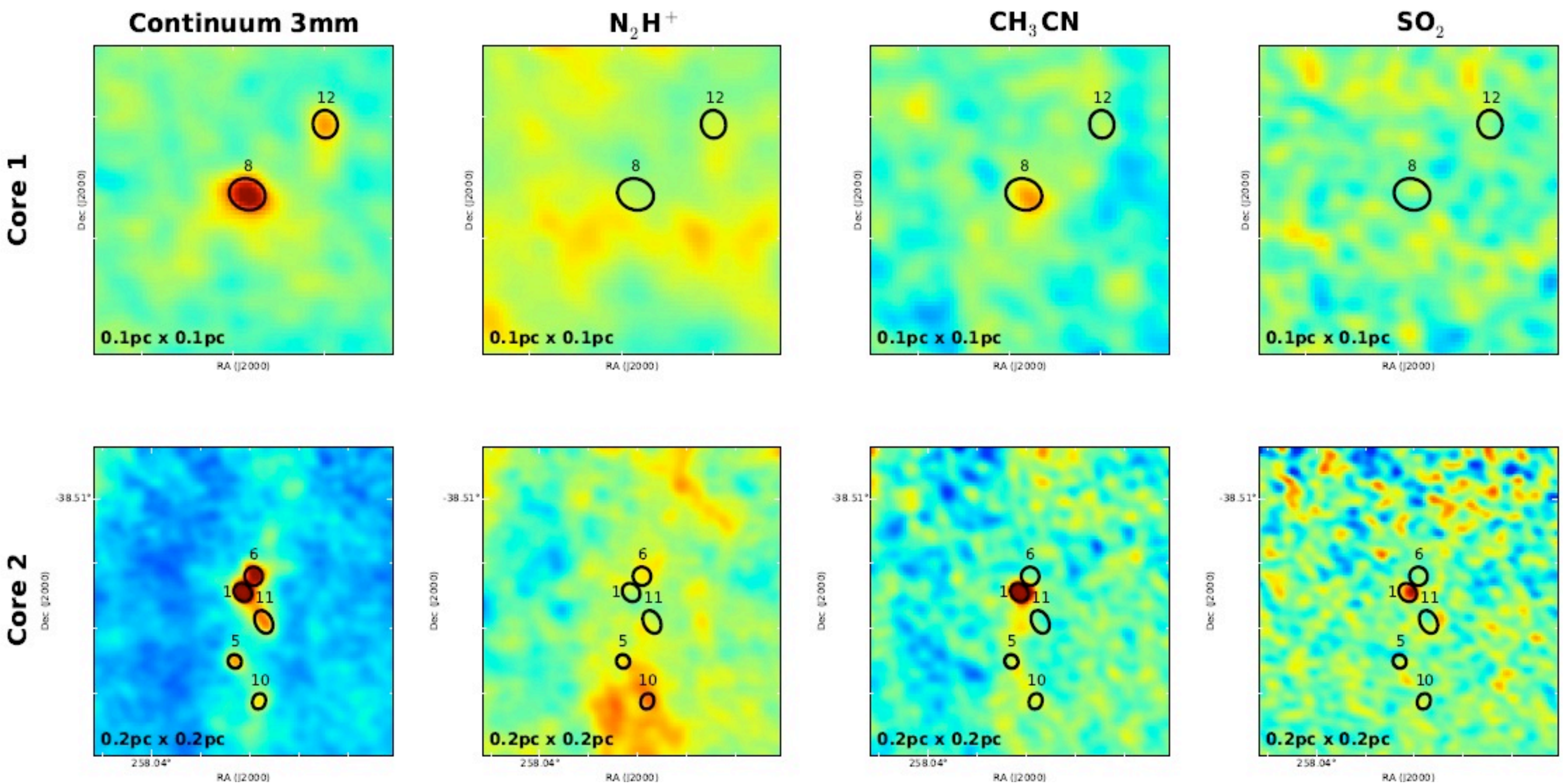
Source 2: 5 fragments (Core 2)

Most massive one: 30 M_{sun}

Massive star (CH_3CN and SO_2)

Size: 8.6 10^{-3} pc

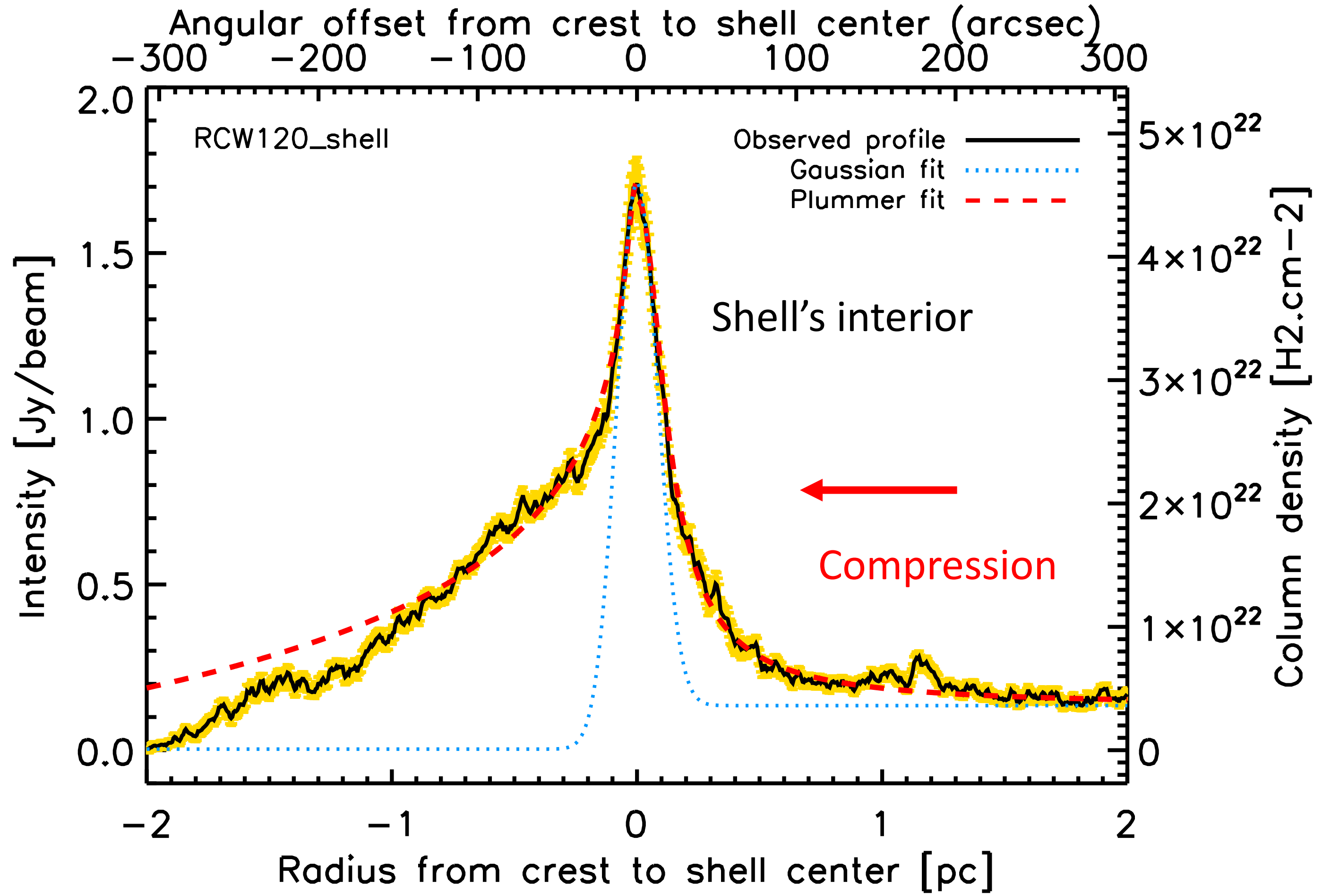
Limited fragmentation



Radiative compression

RCW 120: APEX-ArTéMis and *Herschel* data

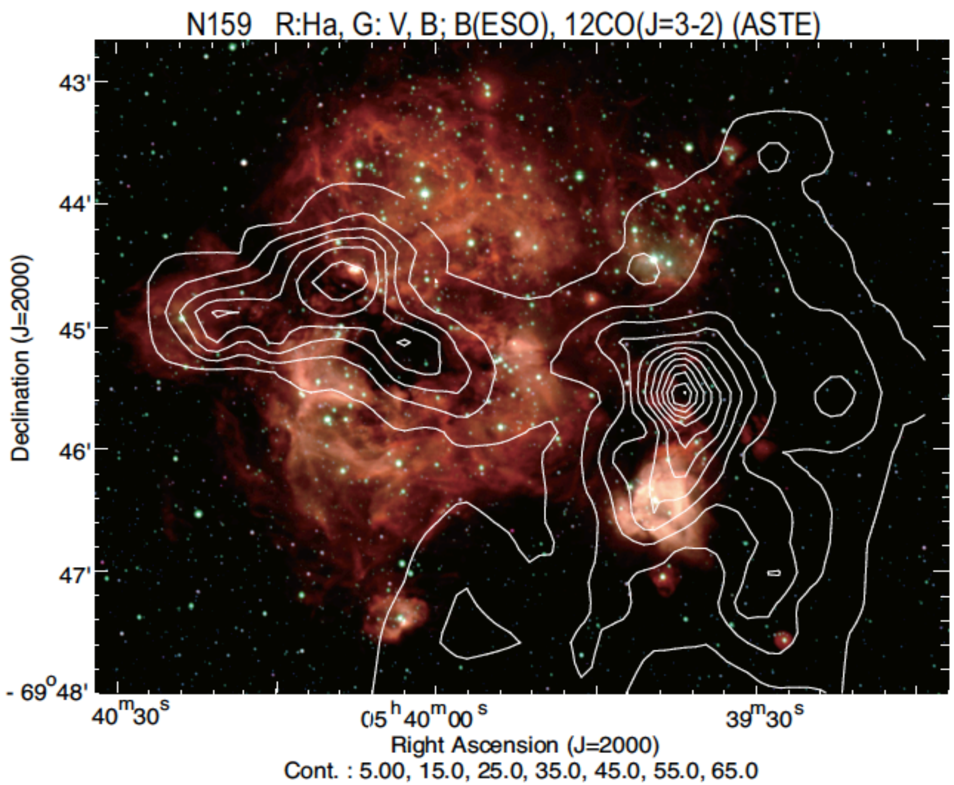
Asymmetric intensity profile

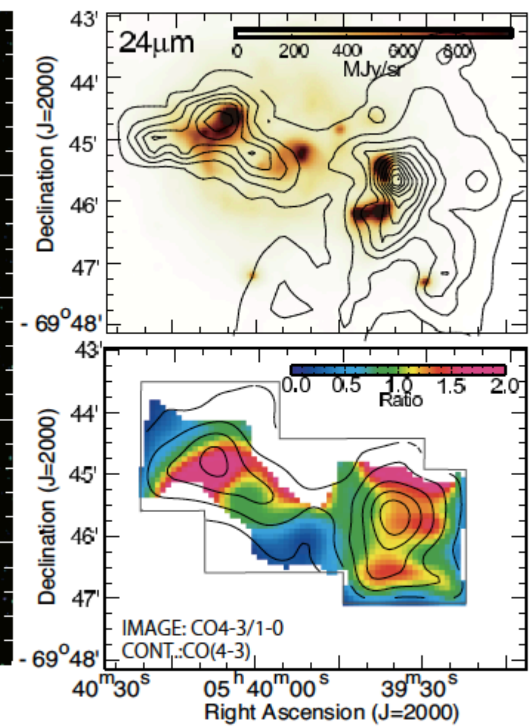


EXTRAGALACTIC STUDY

HII regions and Star formation in the Large Magelanic Cloud

- Why ? Lower metallicity $Z=1/3\ Z_{\odot}$ D=49.97 kpc
- *Herschel* results (Galametz+ 2013)
- N159: on-going high mass star formation in the Local Group (Mizuno + 2010)

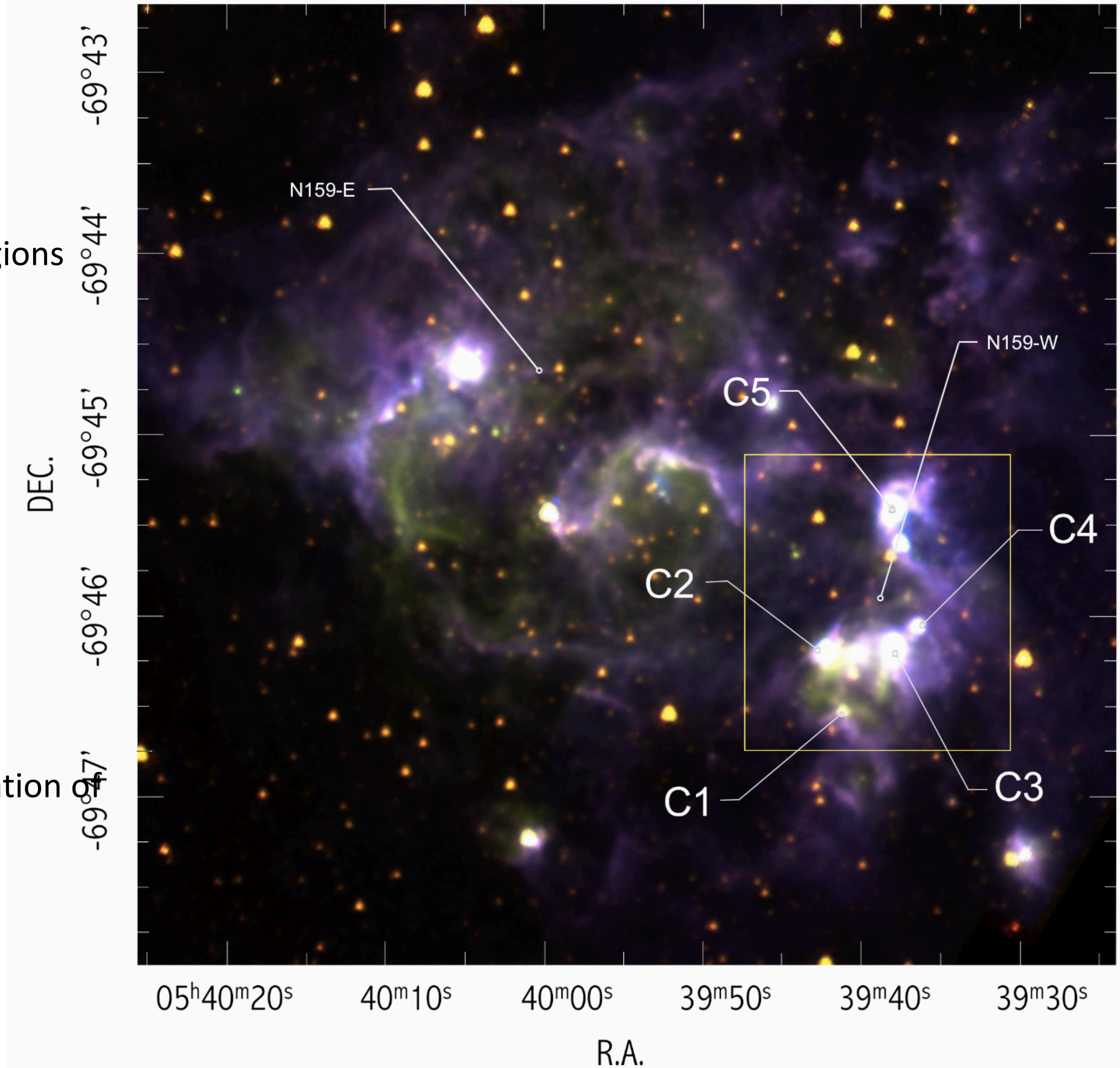




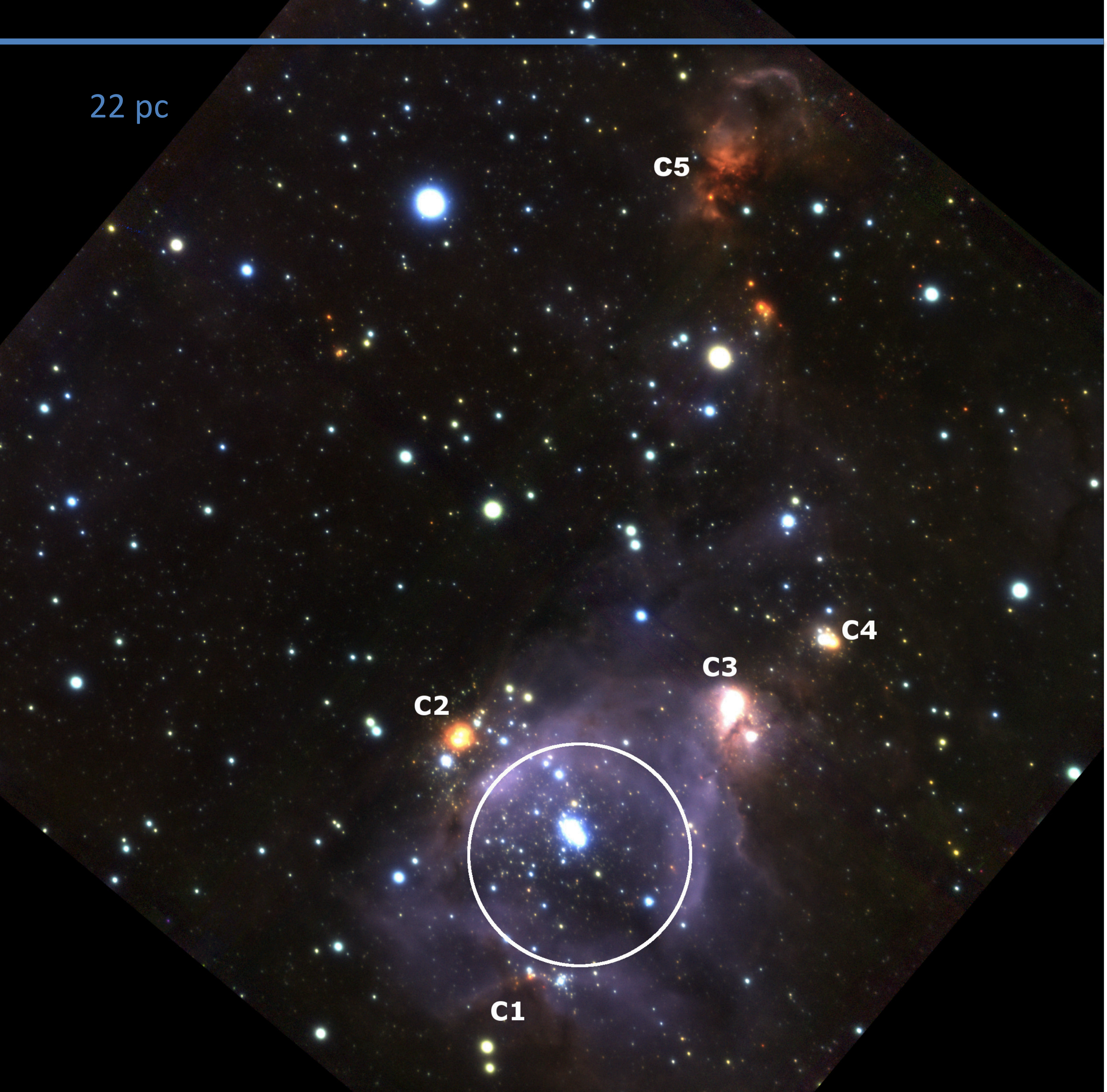
N159E and N159W regions
Spitzer
3.6 µm 4.5 µm
8 µm

GEMINI
GeMS/GSAOI field

C1 to C4 show the location of the YSOs identified by Chen+ 2010



Bernard + 2016



TGeMS/GSAOI image of N159W J (blue), H (green), and Ks (red

Compact clusters (C1-C5)

HII region and central star cluster

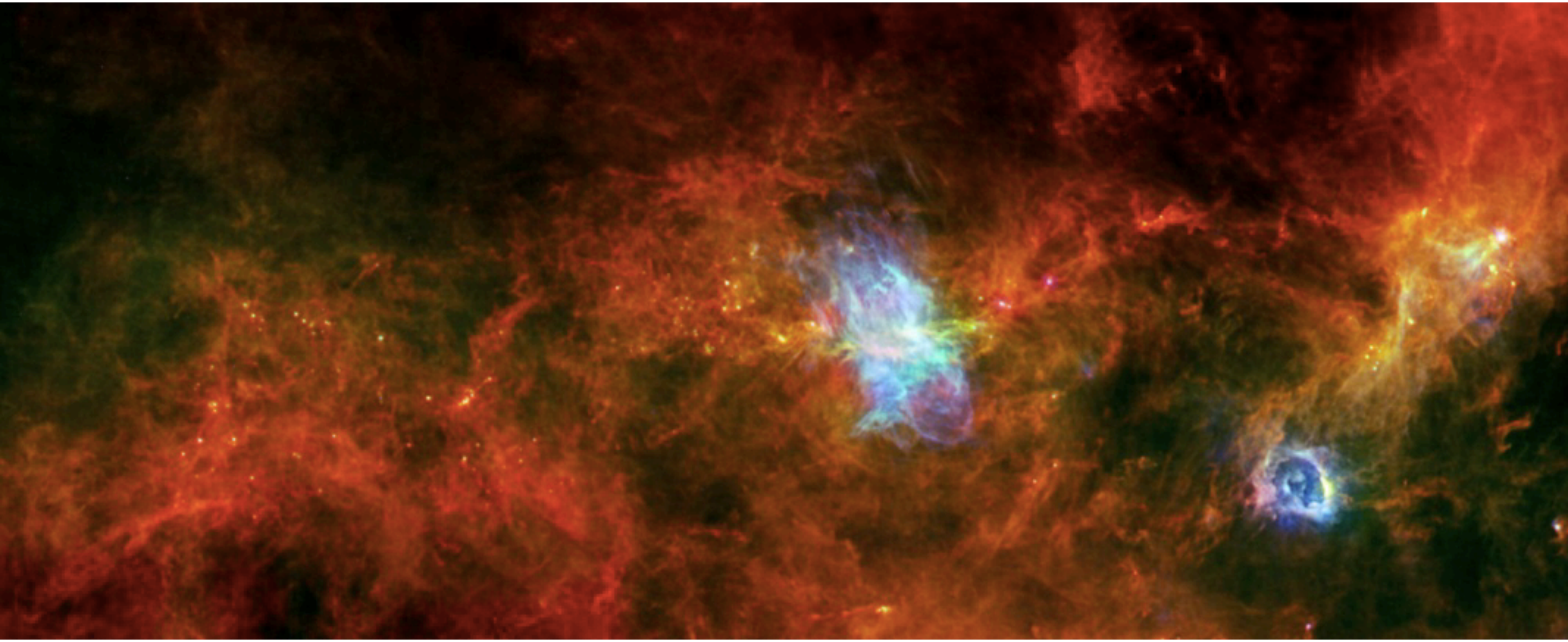
Summary

- Many individual studies
- High mass stars in *different* evolutionary stages
- HII regions limit the fragmentation ?
- Evidence for radiative compression
- Extragalactic studies

BIPOLAR HII REGIONS

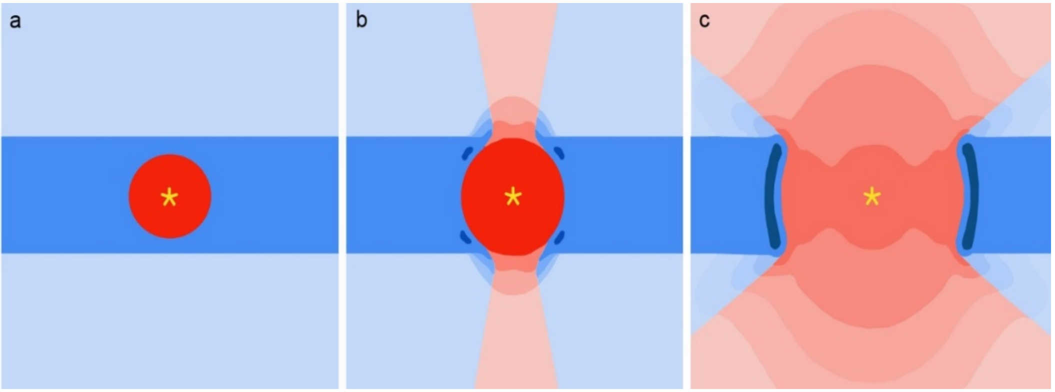
Vela C cloud and the RCW 36 bipolar region

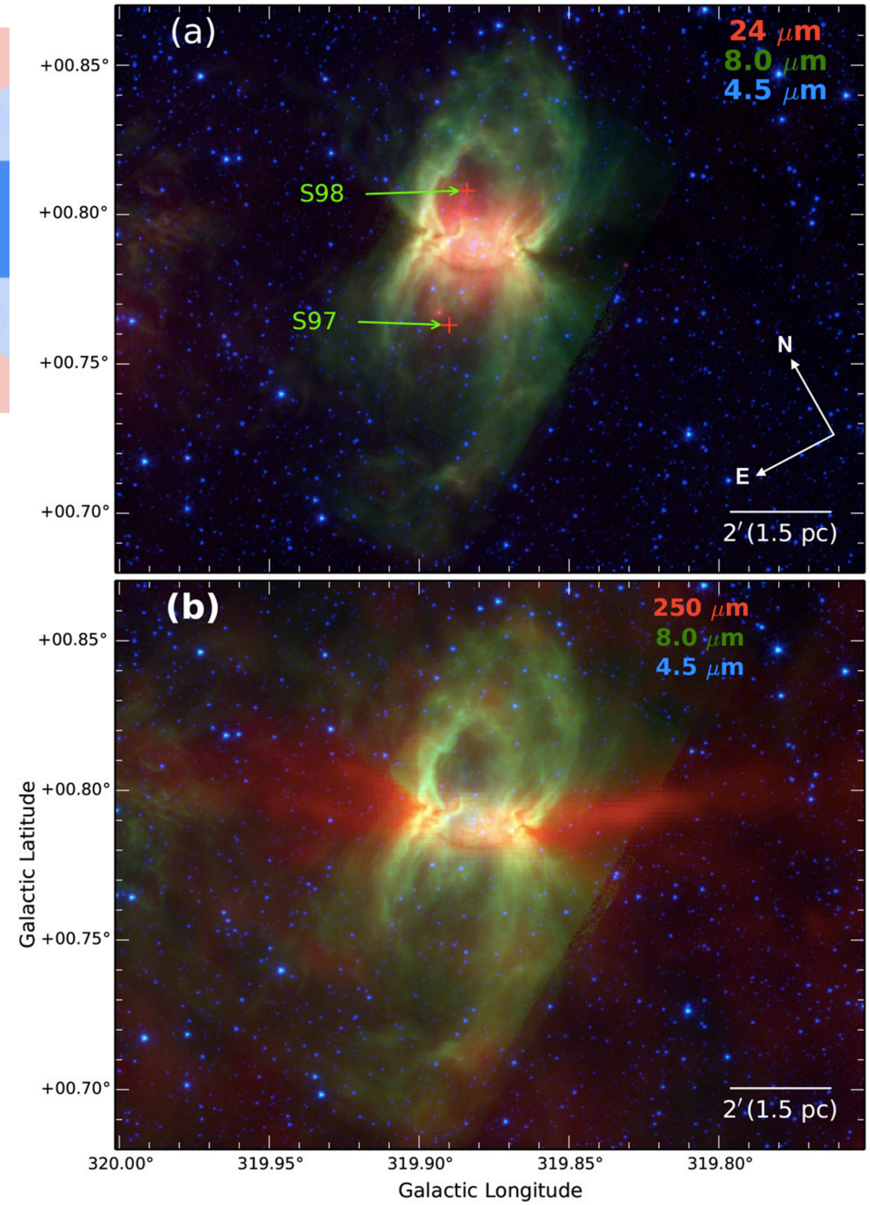
70 160 250 μm (Minier et al. 2013)



Importance of bipolar HII regions (Deharveng et al. 2015, Samal et al. 2018, Schneider et al. 2018, Dewangan et al. 2019, ….)

co-evolution of the high mass star formation process





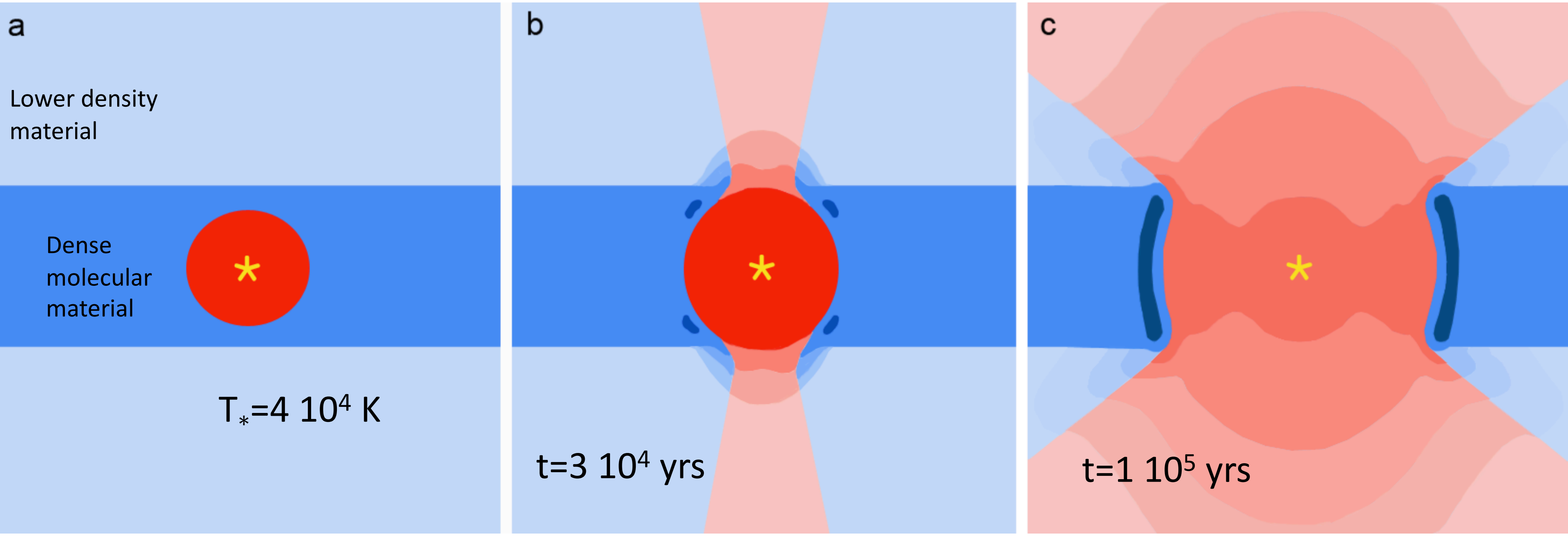
Bipolar HII regions

(Deharveng + 2015, Samal +2018)

Bipolar HII regions

High density compressed molecular material at the waist
Formation of a **taurus**

(Deharveng+ 2015)

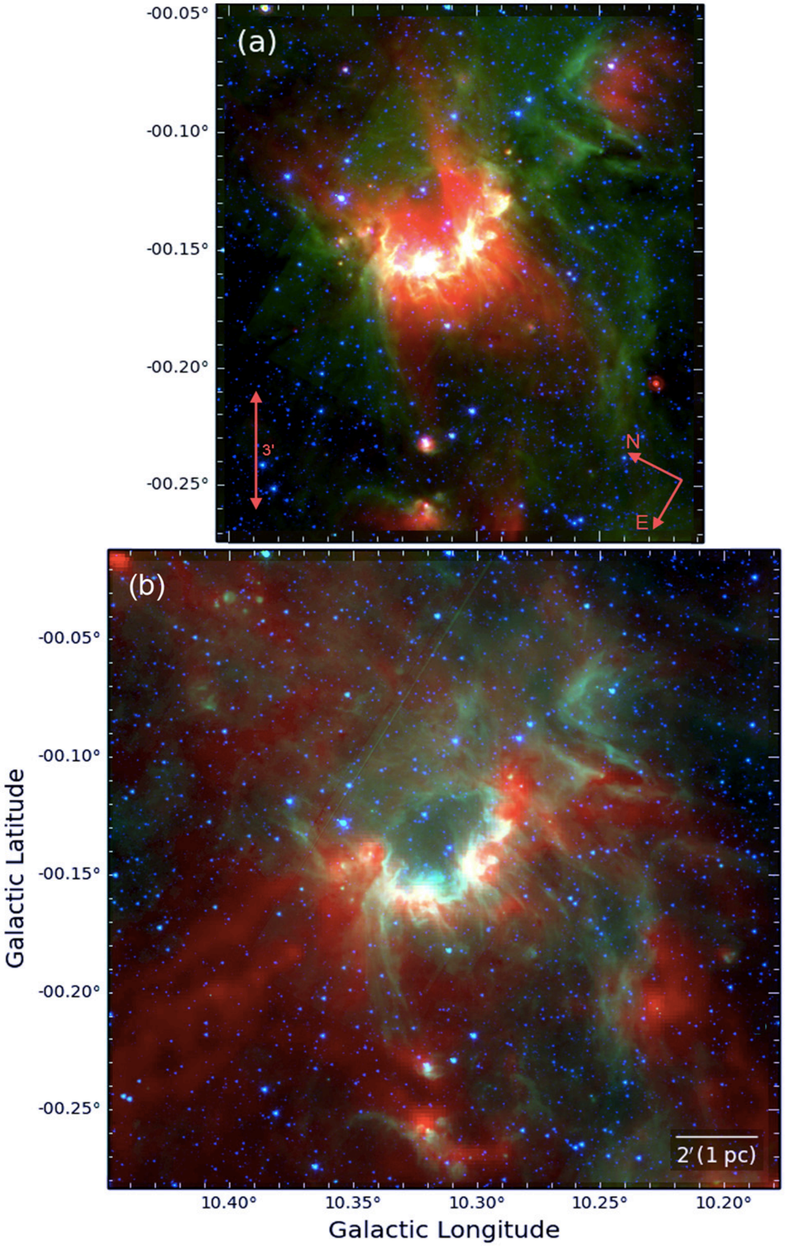


Formation of a bipolar HII region (simulation of Bodenheimer et al. 1979).

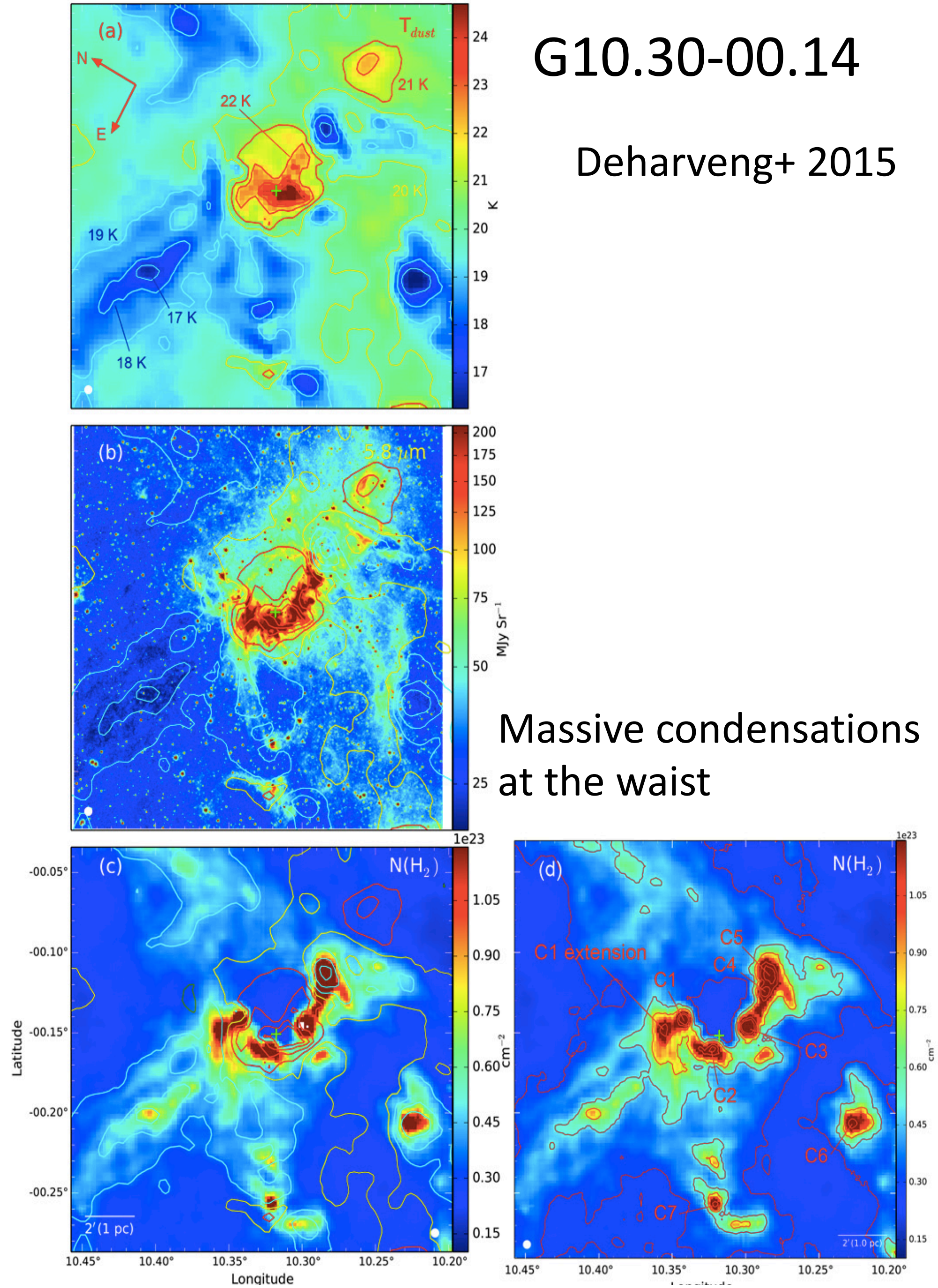
Thickness of the parental plane is 1.3 pc - density 300 H_2 cm^{-3}

ionized material neutral material

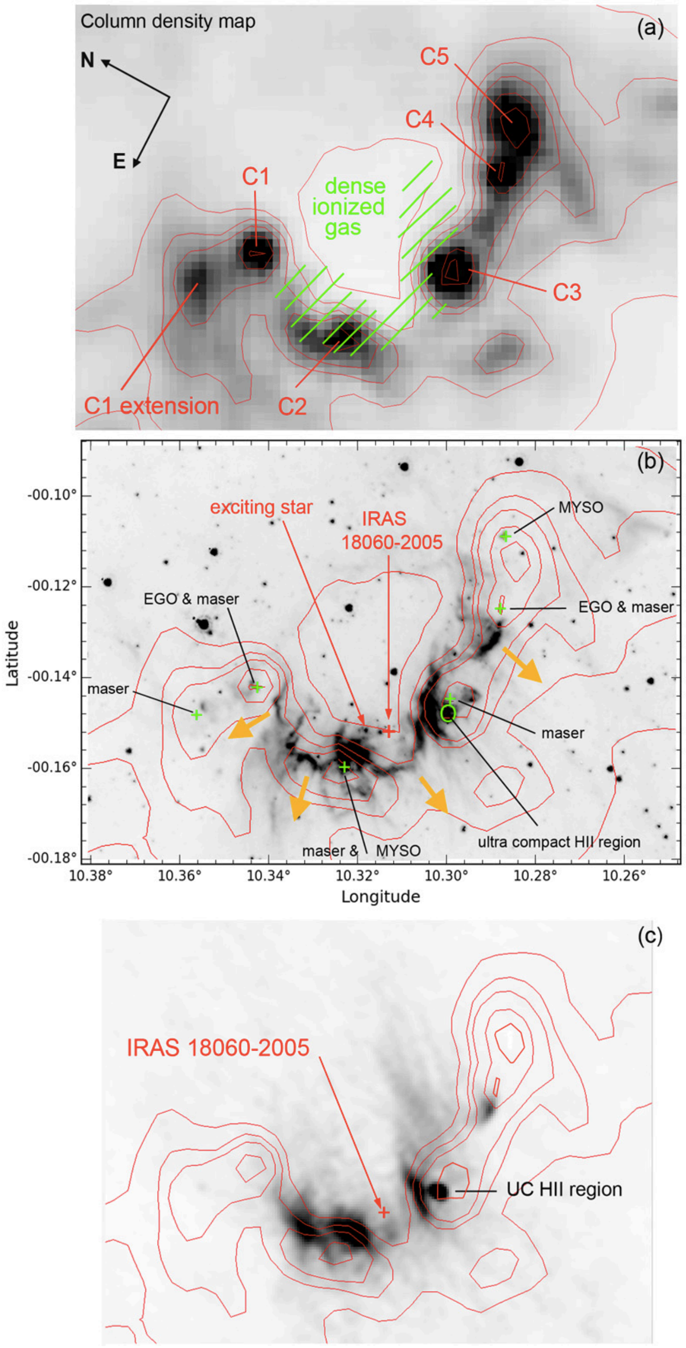
G10.30-00.14



Deharveng+ 2015

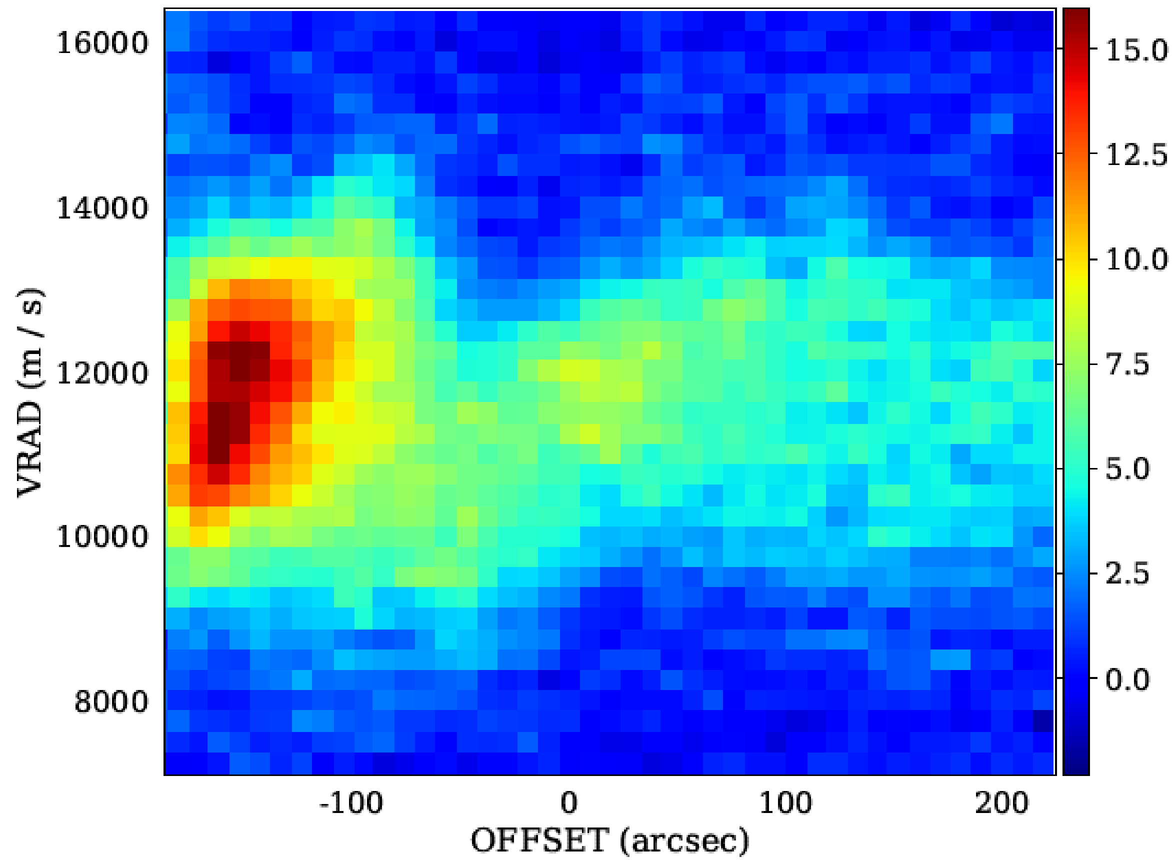


Massive condensations at the waist



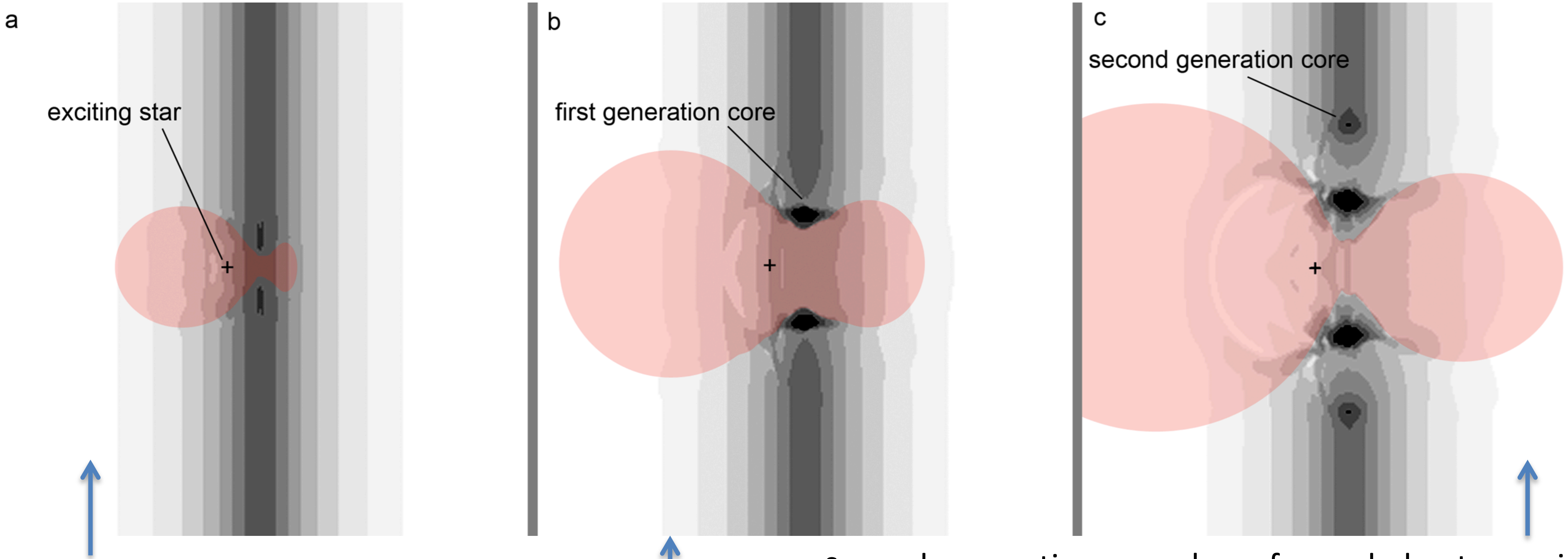
Condensations: *pre-existing* origin ?

Position- Velocity diagram observed towards G010.32−00.15 using ^{13}CO SEDIGISM data (Zhang et al., in prep.), for Condensation 1 and the parental filament, suggesting an ongoing accretion flow (see also the case of S106, Schneider et al. 2018).



Bipolar HII regions

Star formation triggered by the expansion of an HII region close to a filament (simulation of Fukuda & Hanawa 2000) neutral sound speed 0.3 km s^{-1}, Maximum density on the axis of the filament 2 10^6 cm^{-3} exciting star at 0.025 pc of the filament's axis.



The expanding HII region (age 8.5 10^4 yr) pinches the molecular filament

Second-generation cores have formed, due to gravity (age 3 10^5 yr). The first- and second-generation cores are separated by 0.1 pc.

First-generation cores have formed by compression of the neutral material by the ionized gas (age 2.1 10^5 yr)

FUTURE PROSPECTS

Quantification of HII regions' impacts

- Star formation timescales, SFR, SFE

- Fragmentation, compression
  - Chemistry → Goicoechea+ 2017 *Compression and ablation of the photo-irradiated molecular cloud the Orion Bar* (Nature)
  - Dynamics → Orkiz+ 2017 (Orion B): *Nature of turbulence (compressive, solenoidal): variations and effects on the star formation*

- GAIA: evidence for TSF by HII regions: Star ages spread

Prisinzano+ 2019: *In particular, members with accretion and/or disk, formed in the last 1Myr, show evidence of subclustering around the cluster center, in the Hourglass Nebula and in the M8-E region, suggesting a possible triggering of star formation events by the O-type star ionization fronts.*

Summary

- HII regions' impact on high mass star formation: models: no, observations: yes
- Need for dedicated models

- Evidence for radiative compression → Density increase → promote the formation of high mass cores?

- HII regions limit the fragmentation at early stages? Promote the formation of high mass stars?

Thanks