A MULTI-PHASE AND MULTI-SCALE VIEW OF THE ISM IN THE CARINA NEBULA

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NRAO FELLOW AT JOINT ALMA OBSERVATORY

TRACING THE FLOW

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Outline

- **Large scale ISM in Carina**

➡ Molecular gas - Mopra

➡ Total gas - Herschel

➡ Atomic gas - ATCA

- **Small scale**

➡ Massive clump survey - Mopra

➡ Internal structure of massive clumps - ALMA

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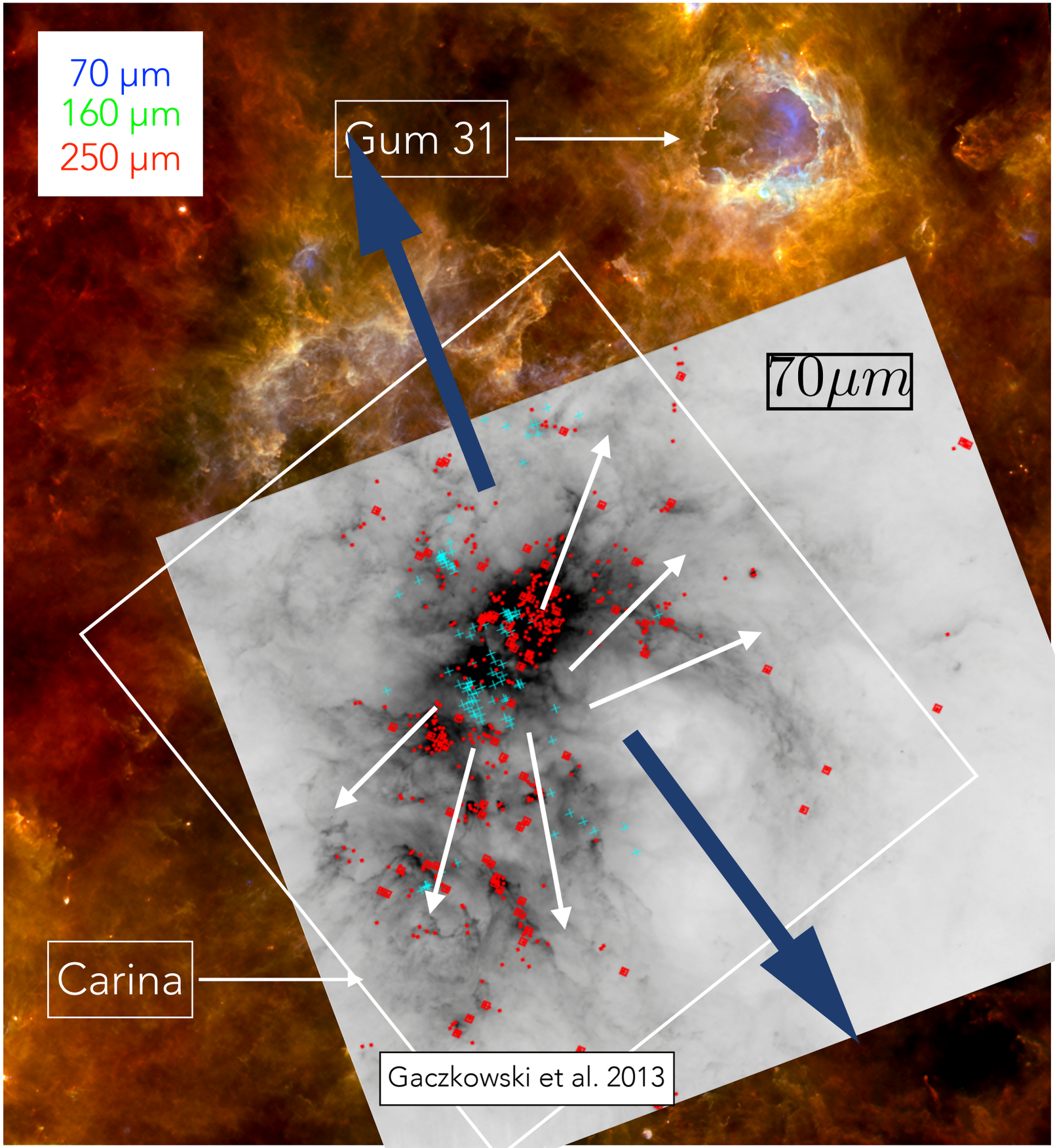
The Carina Nebula Complex

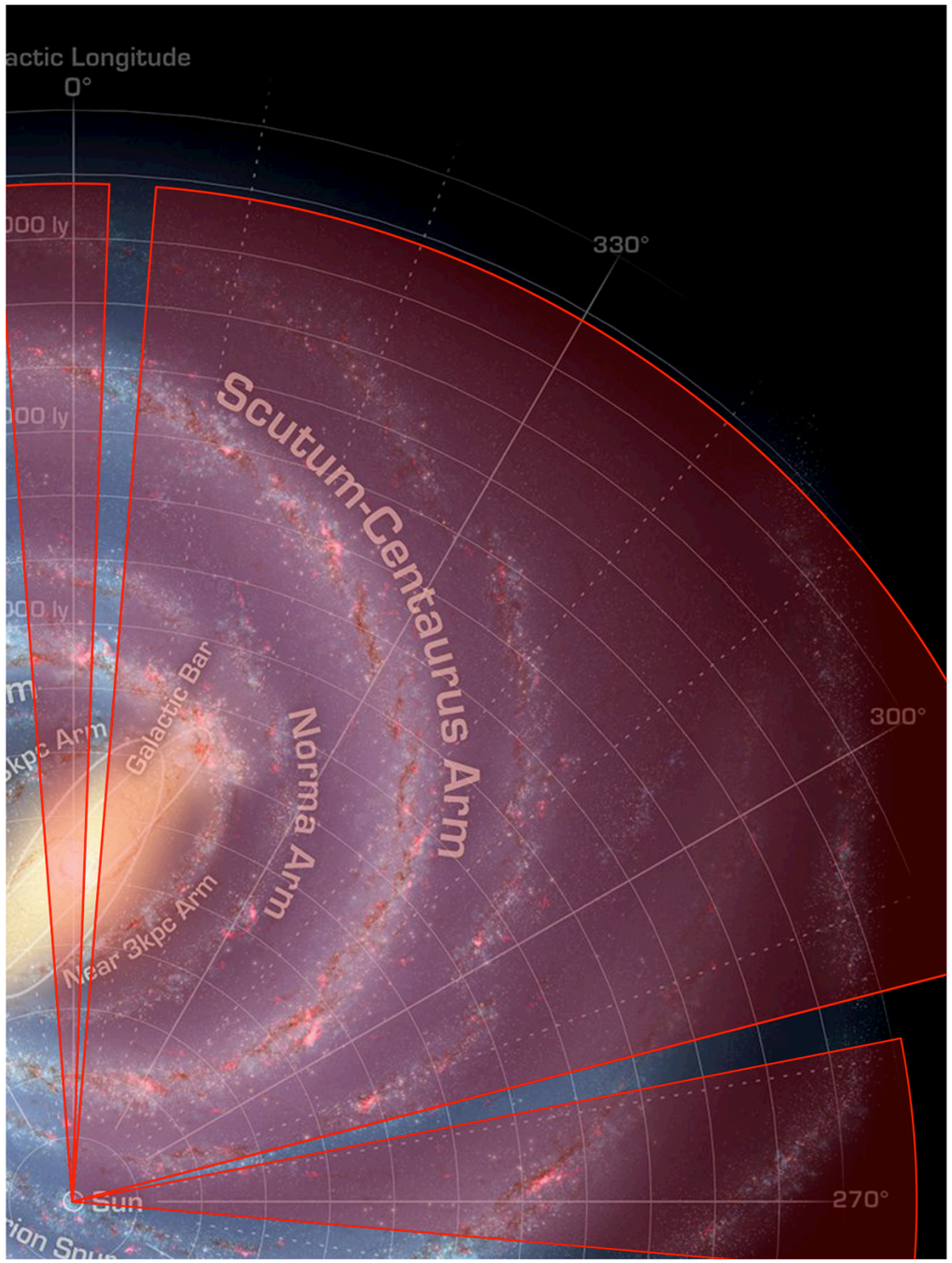
- **Located at 2.3 kpc, it is the nearest extreme star forming region.**
- **Excellent place for studying clustered star formation, stellar feedback and triggered star formation.**
- **Infrared observations revealed several candidates for sites of current star formation**
- **Those compact infrared sources are located at the heads of dust pillars or dark globules behind ionization fronts.**
- **Recent high resolution surveys at X-rays, optical and infrared wavelengths. However, millimetre and radio has been absent.**



Molecular Gas

THE MOPRA SOUTHERN GALACTIC PLANE CO SURVEY

- ^{12}CO, ^{13}CO, $C^{18}O$ and $C^{17}O$ J = 1-0
- l = 265 – 370°, $|b| < 0.5°$
- 0.6′ Beam @ 0.1 km/s resolution
- Fast mapping = 3 sq deg every 4 nights.
- Including: CMZ, Carina, and a few other (gamma ray) objects of interest.
- www.phys.unsw.edu.au/MopraCO/ (data publicly available as published.)



Dame, Hartmann & Thaddeus (2001)

50° 40° 30° 20° 10° 0° 350° 340° 330° 320° 310° 300° 290° 280° 270° 260

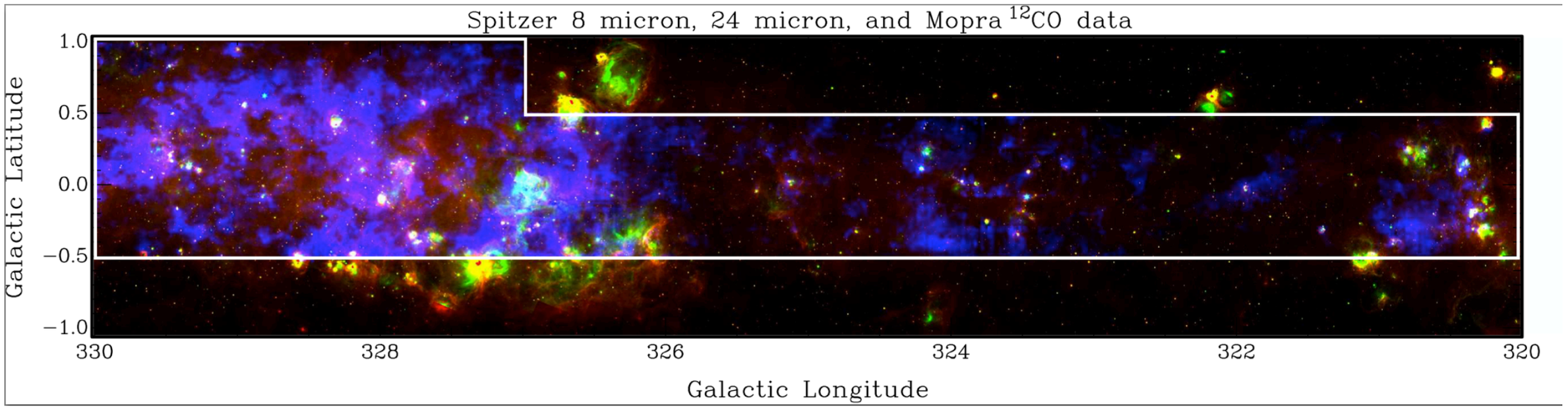
Galactic Latitude

+2°
+1°
+0°
-1°
-2°

0°

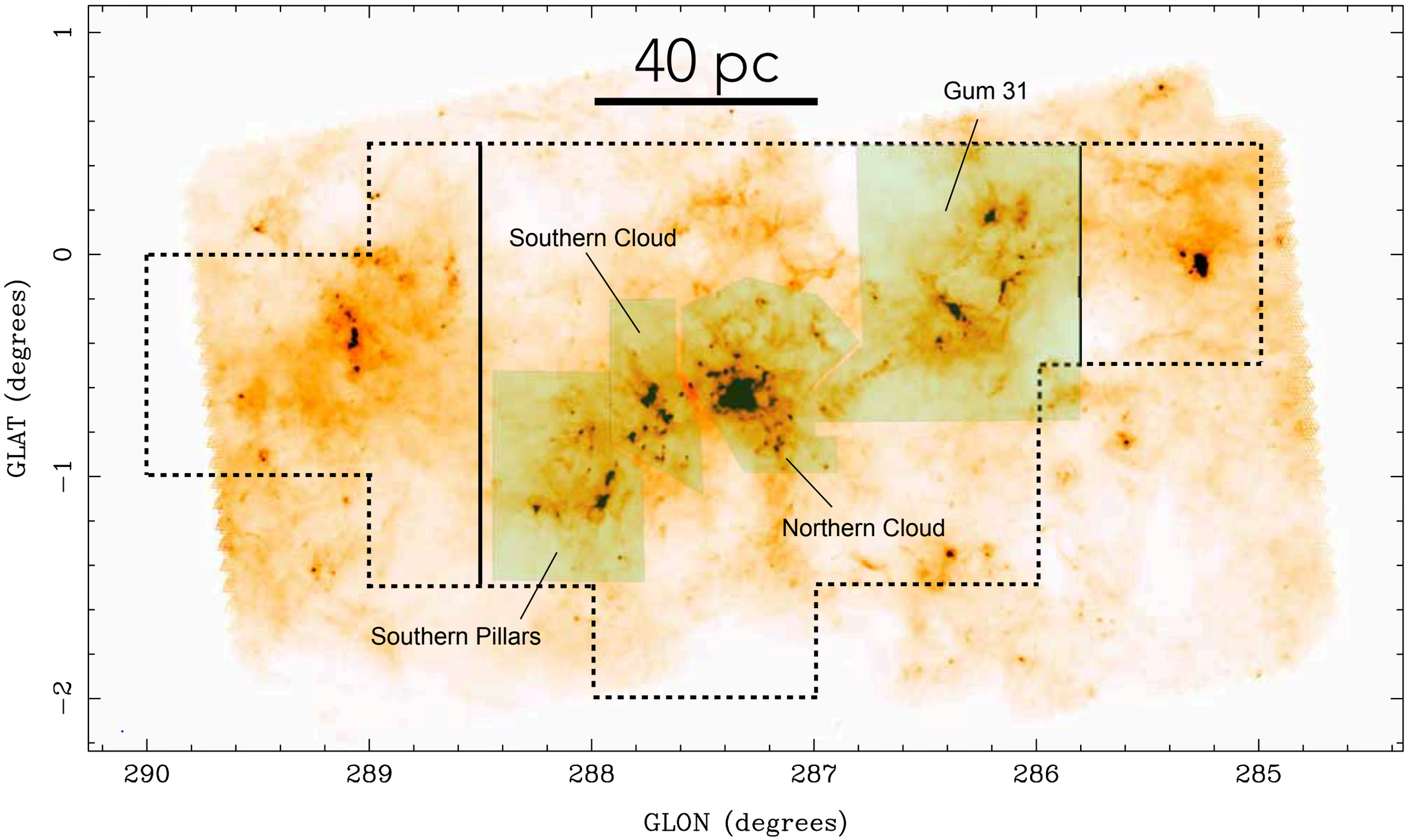
Data Release 1 (DR1)

- l = 320-330^o, |b| < 0.5^o; l = 327-330^o, 0.5^o < b < 1.0^o
- Clouds found with velocities -130 < v < +40 km/s
- Total mass in 10 square degrees ~ 4 x 10^7 M_{sun}
- **Paper: Braiding et al. 2015, PASA, 32, e20**



Data Release 2 (Carina)

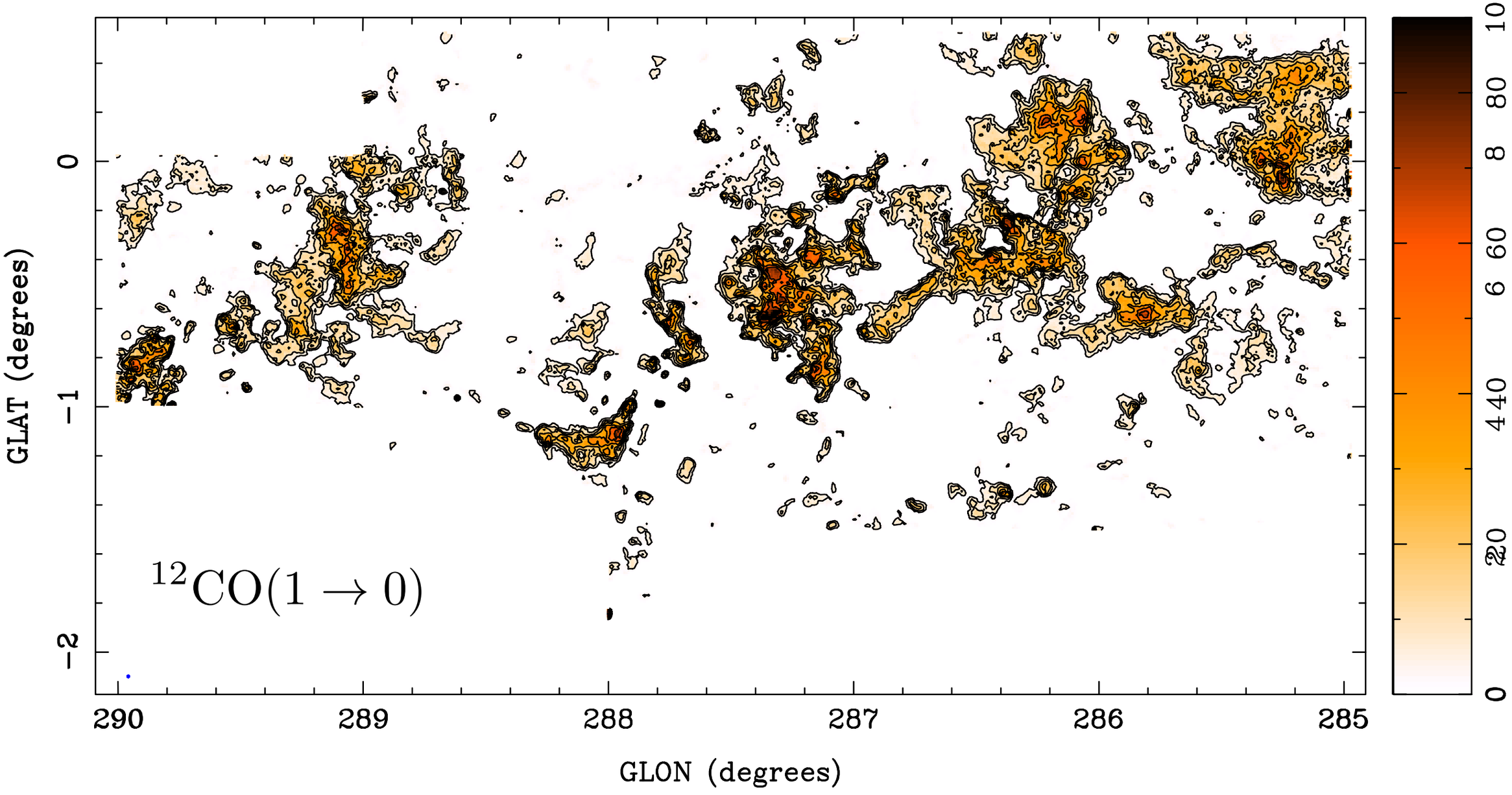
Rebolledo et al. 2016, MNRAS, 456, 2406



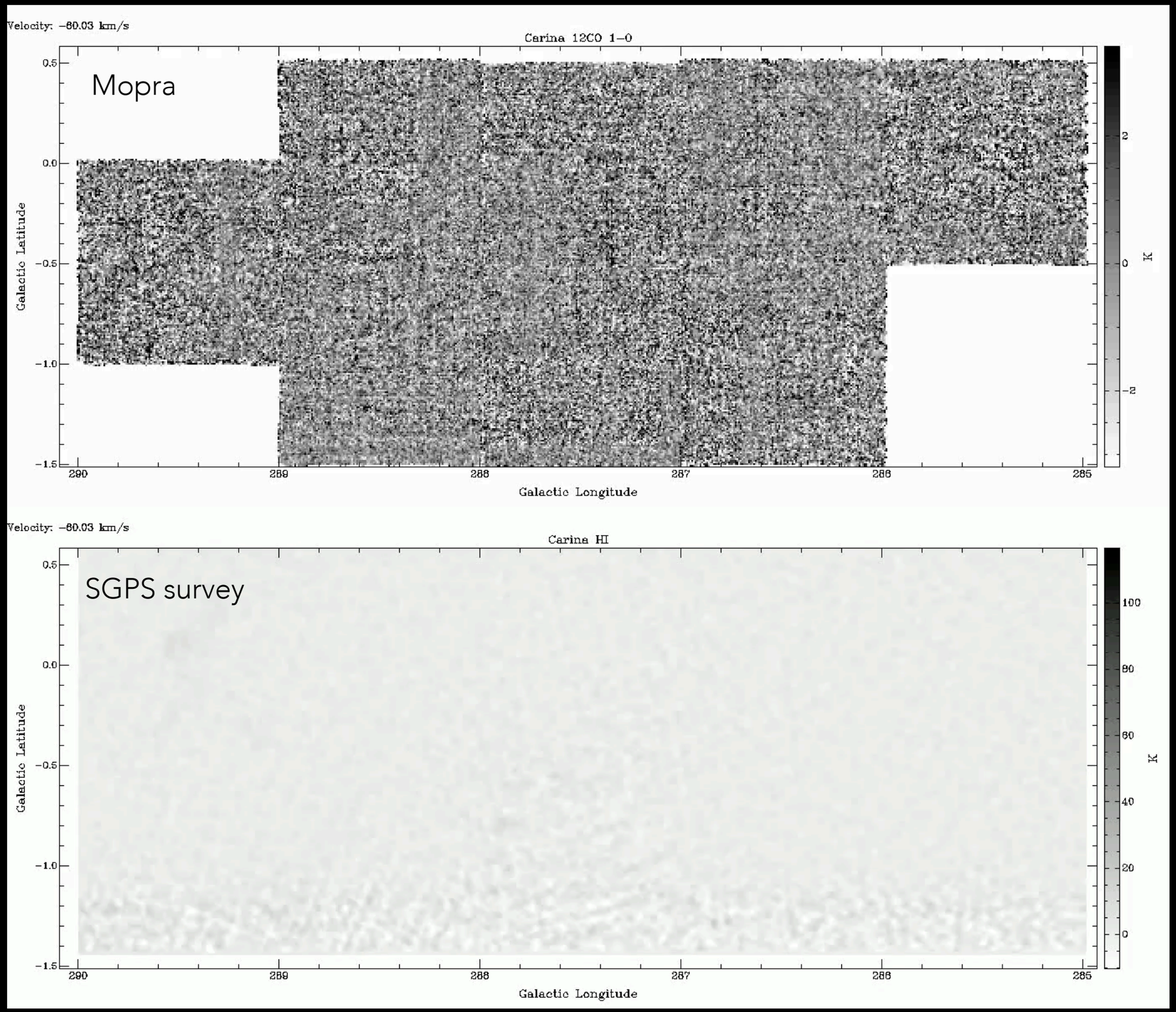
$\theta \sim$ 0.4 pc

40 pc

Coverage ~ 9.5 deg^2



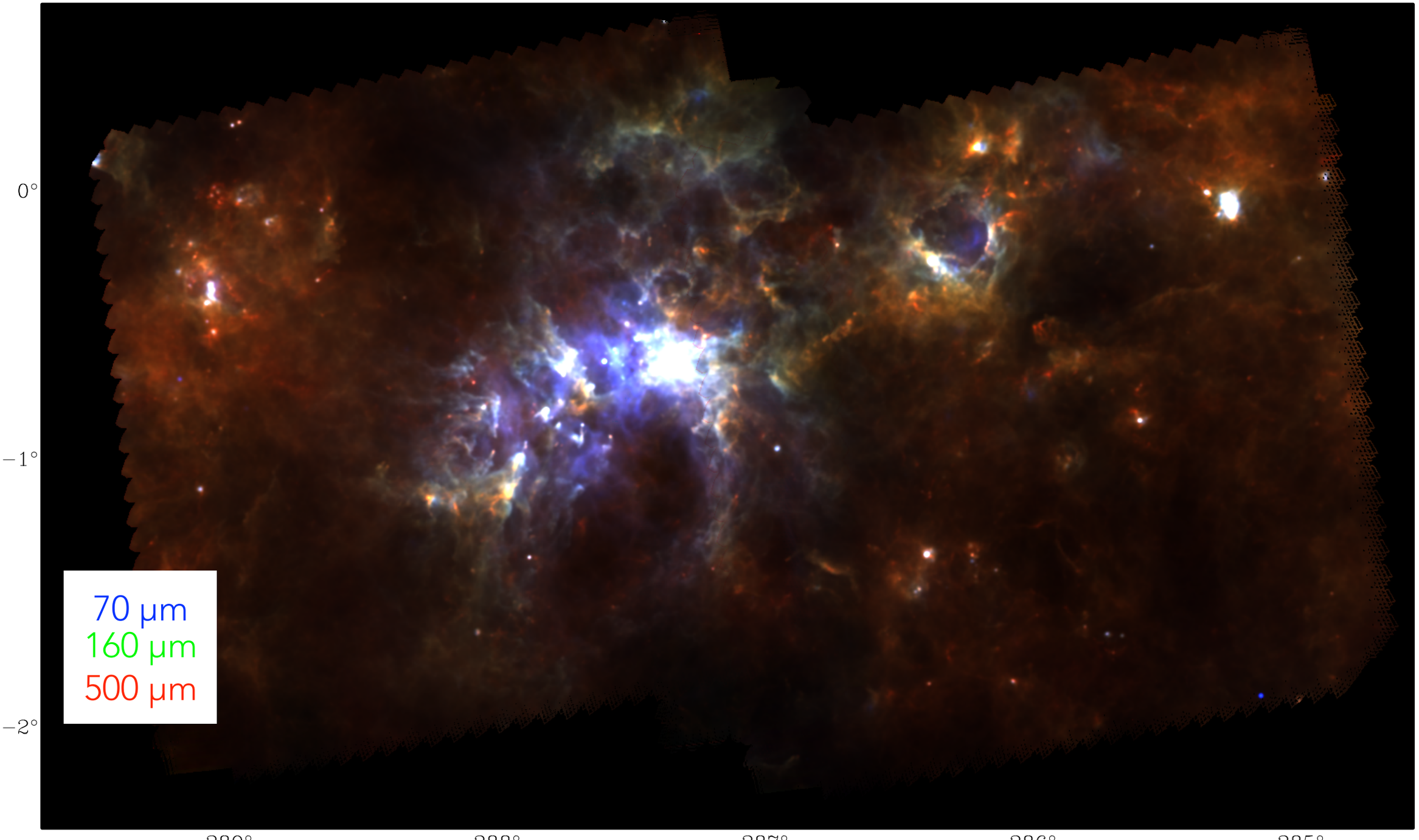
CARINA NEBULA: A FACTORY OF MASSIVE STARS



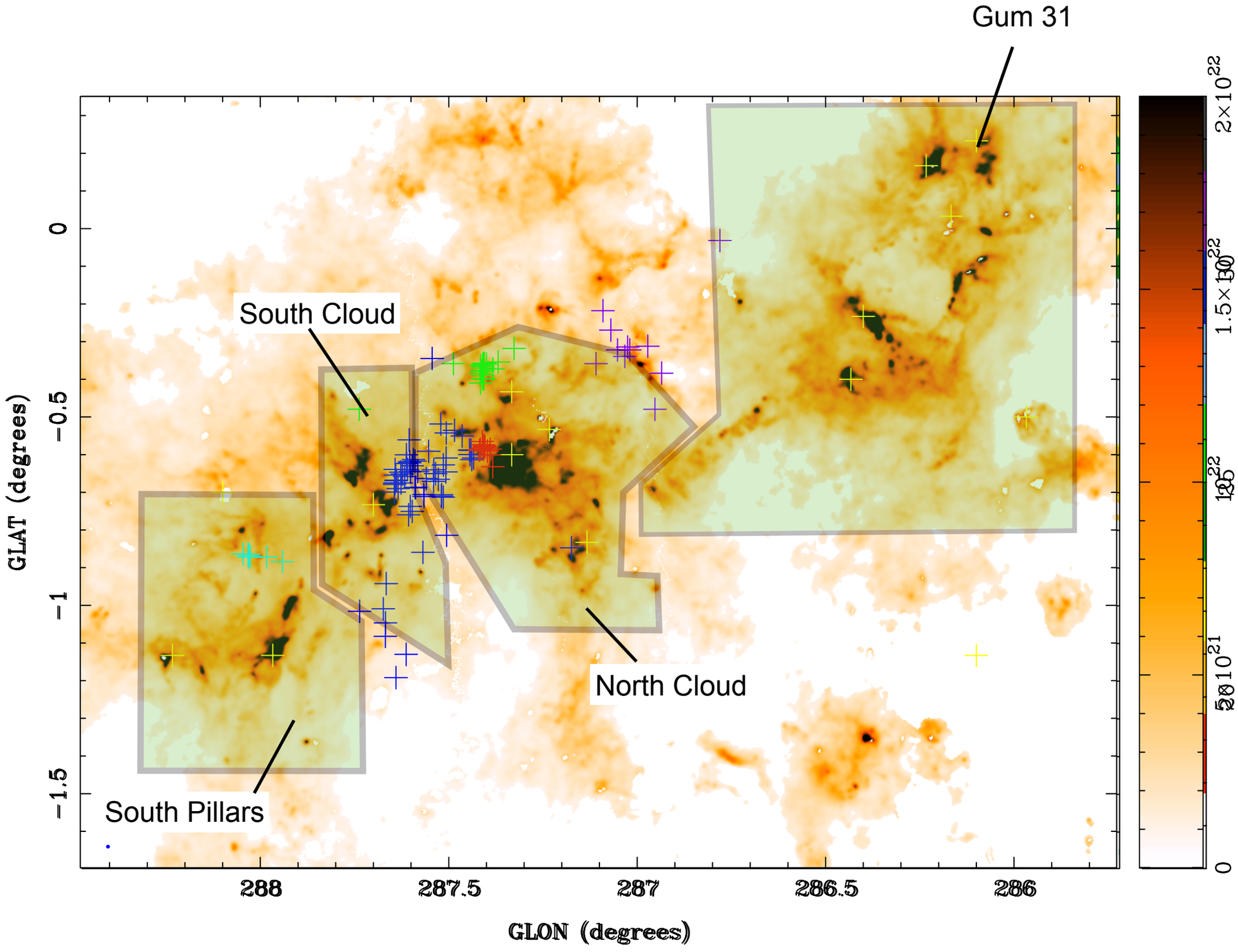
Total Gas from Dust

Herschel Infrared data

HiGal Survey, Molinari et al. (2010)

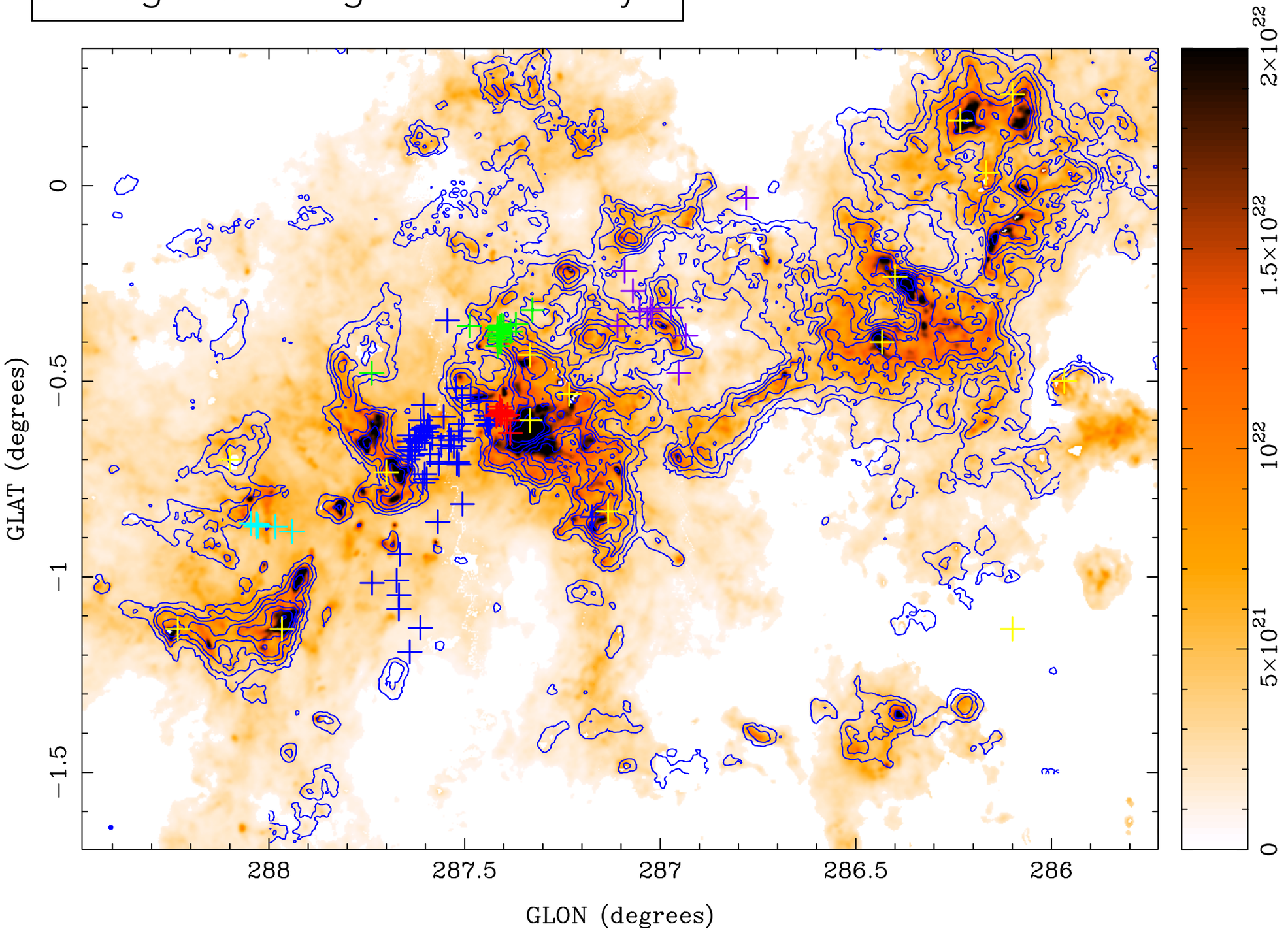


Dust temperature map



Gas column density map

Good spatial correlation between CO and regions with high column density



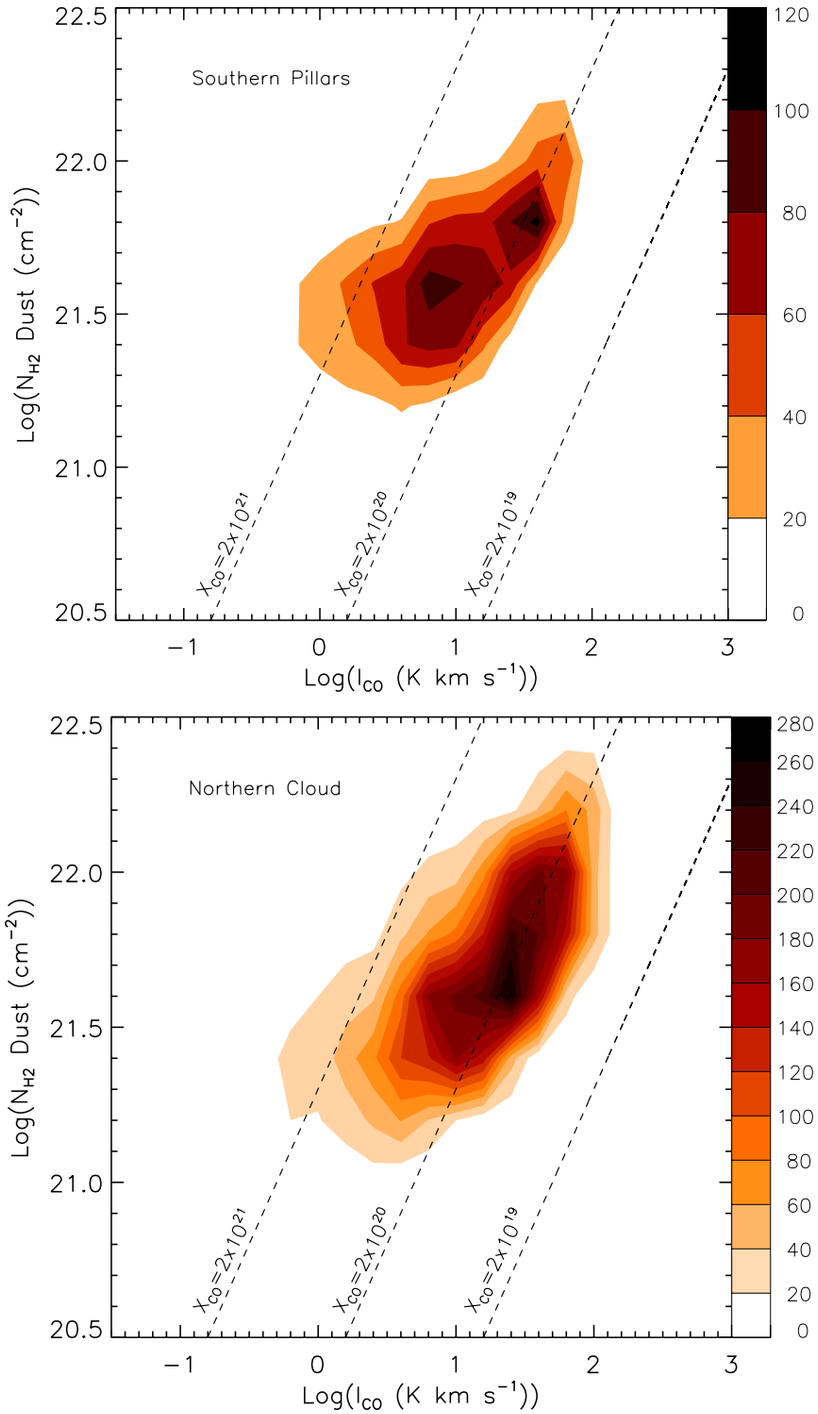
Gas vs ^{12}CO column density

$$X_{\rm CO} = 2.0 \times 10^{20}$$

Good approximation for North Cloud and Gum 31.

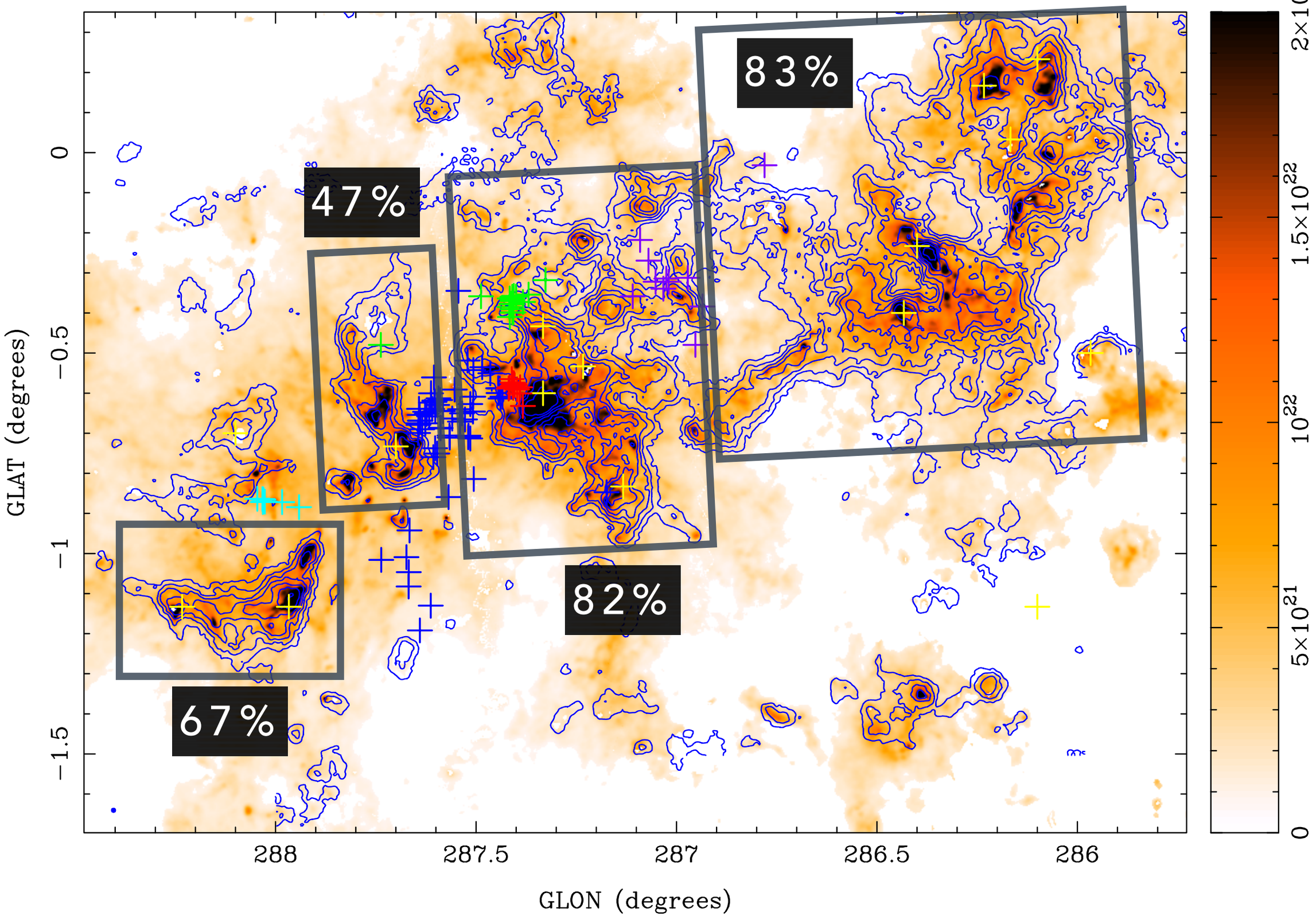
Larger Xco factor for South Pillars and the South Cloud.

Rebolledo et al. (2016)



Mass Budget

Rebolledo et al. (2016)



Atomic Gas

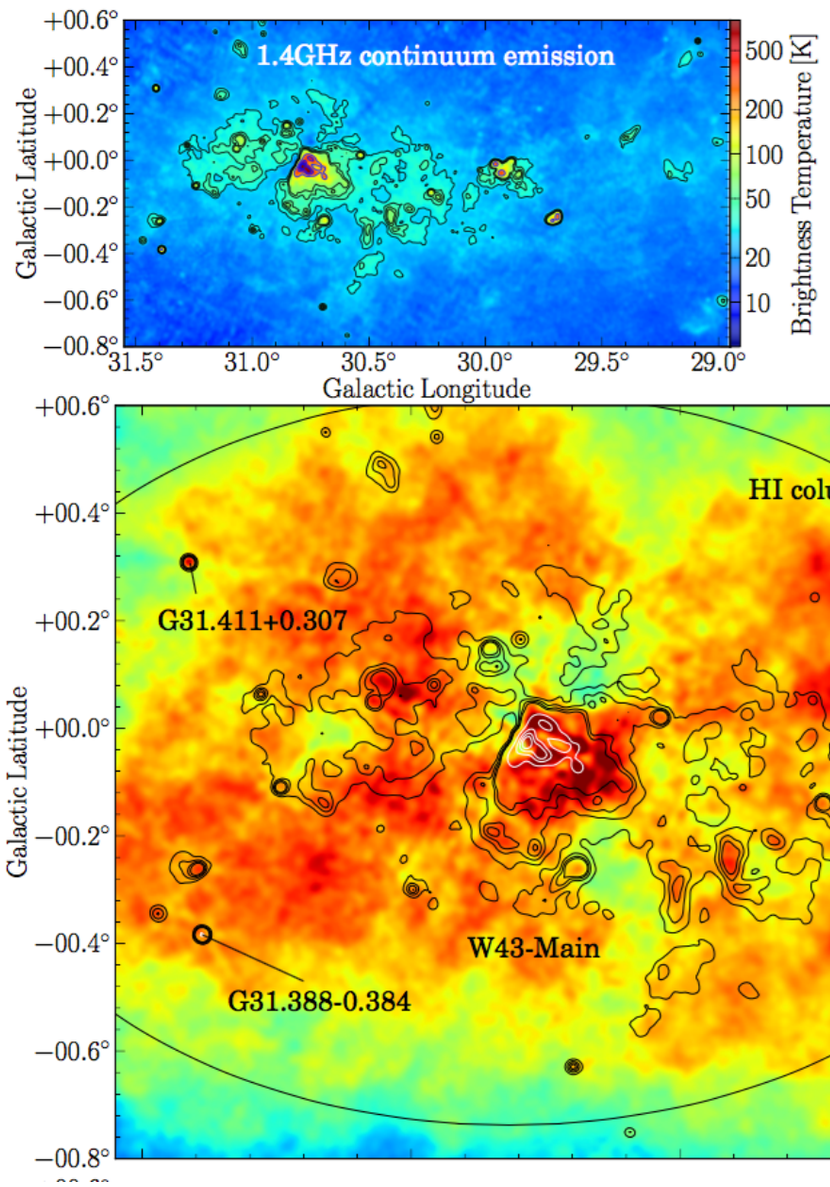
HI to H2 transition is also difficult

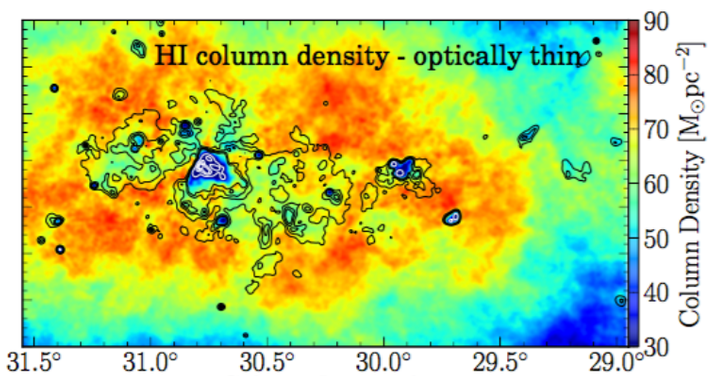
Correct for several observational effects:

- Optical depth of the 21 cm line.
- Effect of diffuse and weak continuum emission.

W43

Bihr+2015





HI mass is factor ~ 2.4 larger than optically thin mass

$$\Sigma_{\rm HI} \sim 140\ M_{\rm sol}/{\rm pc}^2$$

An order of magnitude larger than low mass star forming regions!

- Multi-wavelength study of the Carina Nebula: Full Stokes continuum, HI 21 cm, H158alpha recombination line, and OH-maser lines.

Band	Centre Frequency	
Continuum	2100 MHz	1-3 GHz

Zoom Band	Centre Frequency (MHz)	# of zooms	Lines covered
z1	1420	4 zooms	HI
z2	1651	6 zooms	H158α recombination line
z3	1720.75	4 zooms	1720 MHz OH maser (satellite line)
z4	1666.25	6 zooms	1667/1667 MHz OH main-line masers

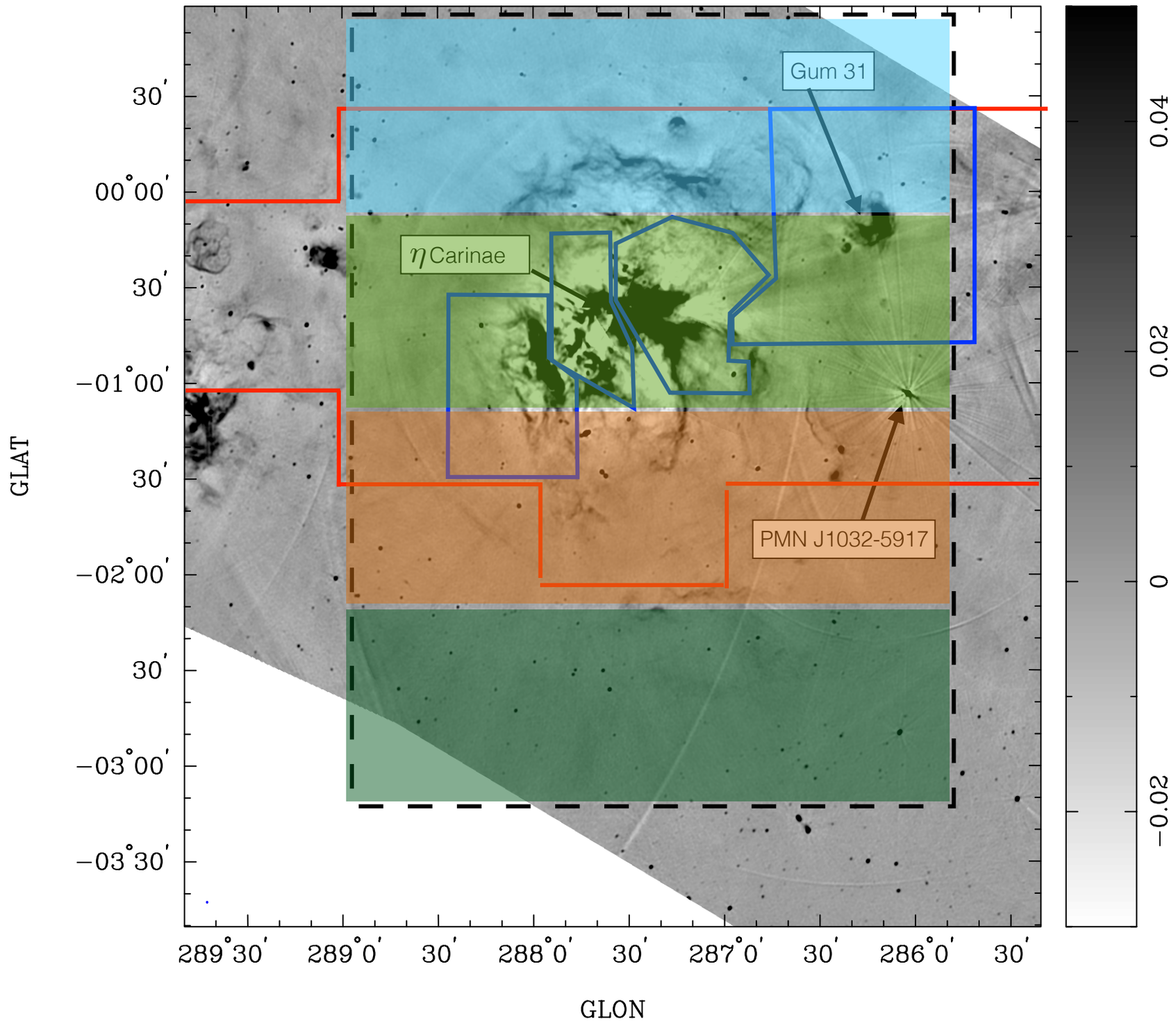
- 11 Array configurations
- 607 hours in total to complete project
- Carina has emission features from sub-arcsecond to degree scale. Imaging is challenging.
- Multi-frequency synthesis, wide field imaging.
- Test of CASA capabilities

Array	Mosaic 1	Mosaic 2	Mosaic 3	Mosaic 4
EW352				
750 A				
750 B				
750 C				
750 D				
1.5 A				
1.5 B				
1.5 D				
6 A				
6 B				
6 C				

Completed!

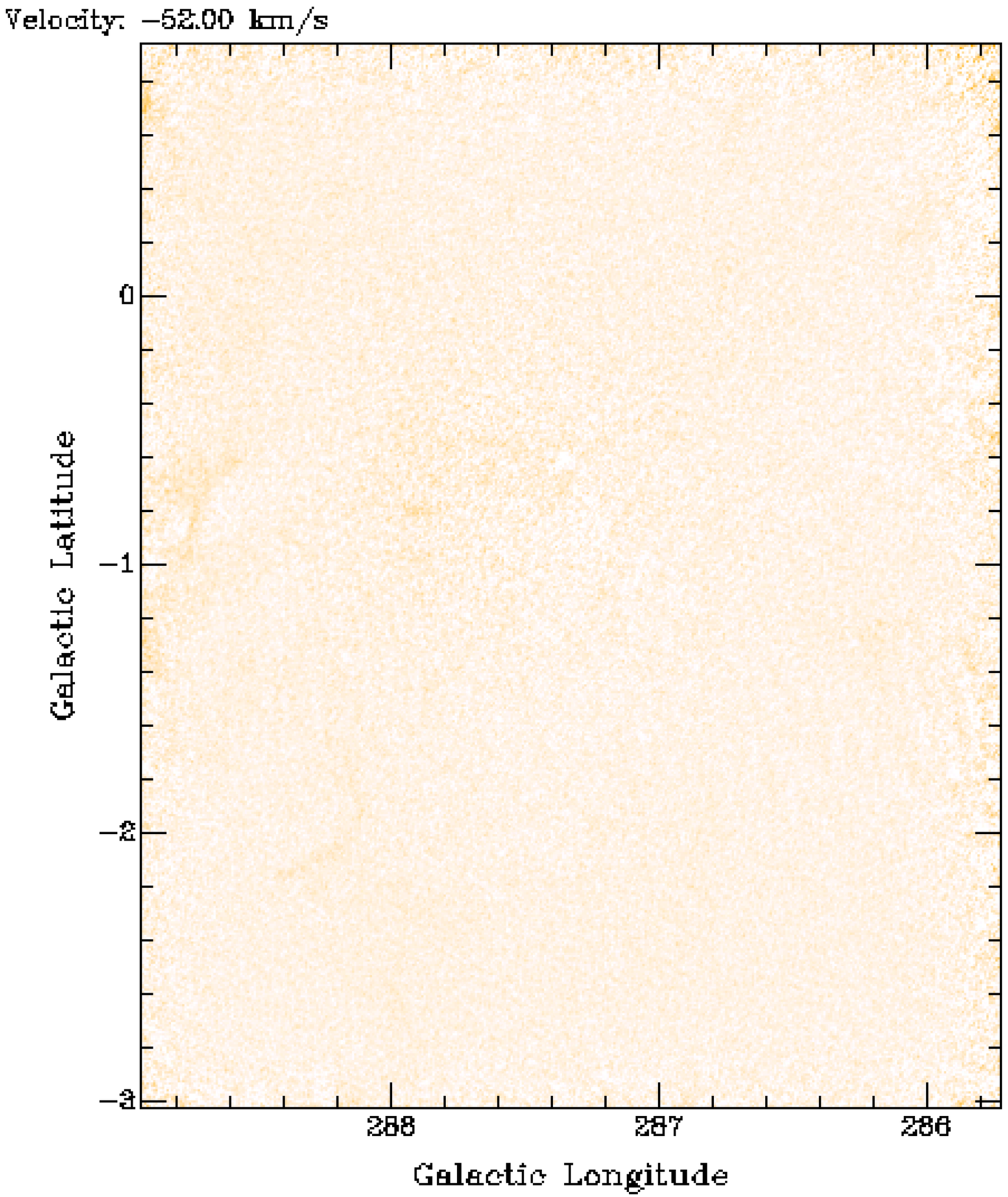
Observed

CARPARCS covers 3 x 4 deg2 on the sky in the 1-3 GHz continuum band with a total of 523 pointings.



$\theta \sim 0.4$ pc

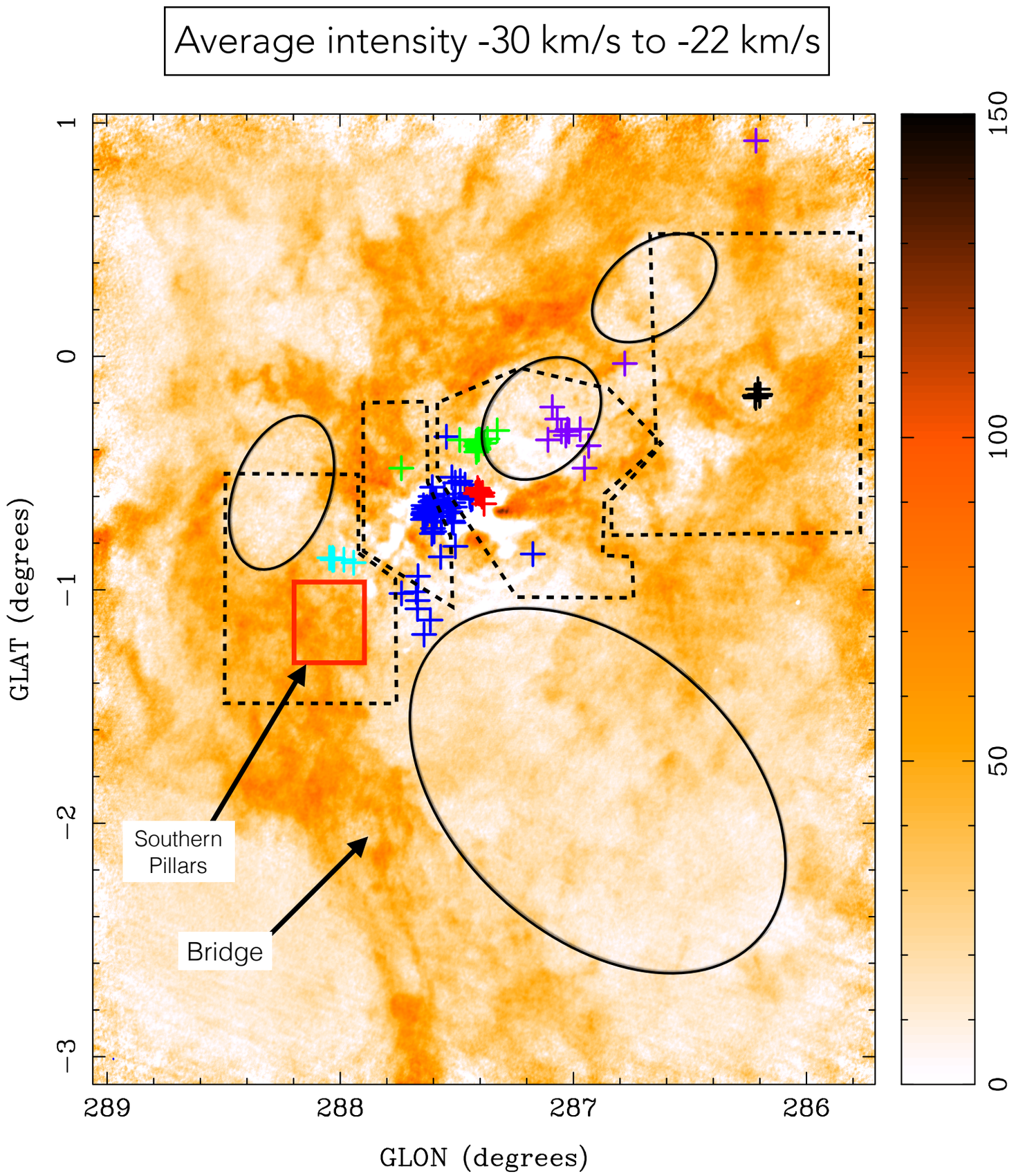
0.835GHz continuum emission of the CNC-Gum31 complex Molonglo Observatory Synthesis Telescope


Velocity: −52.00 km/s
0
−1
−2
−3
Galactic Latitude
288
287
286
Galactic Longitude

Several features in the CNC complex

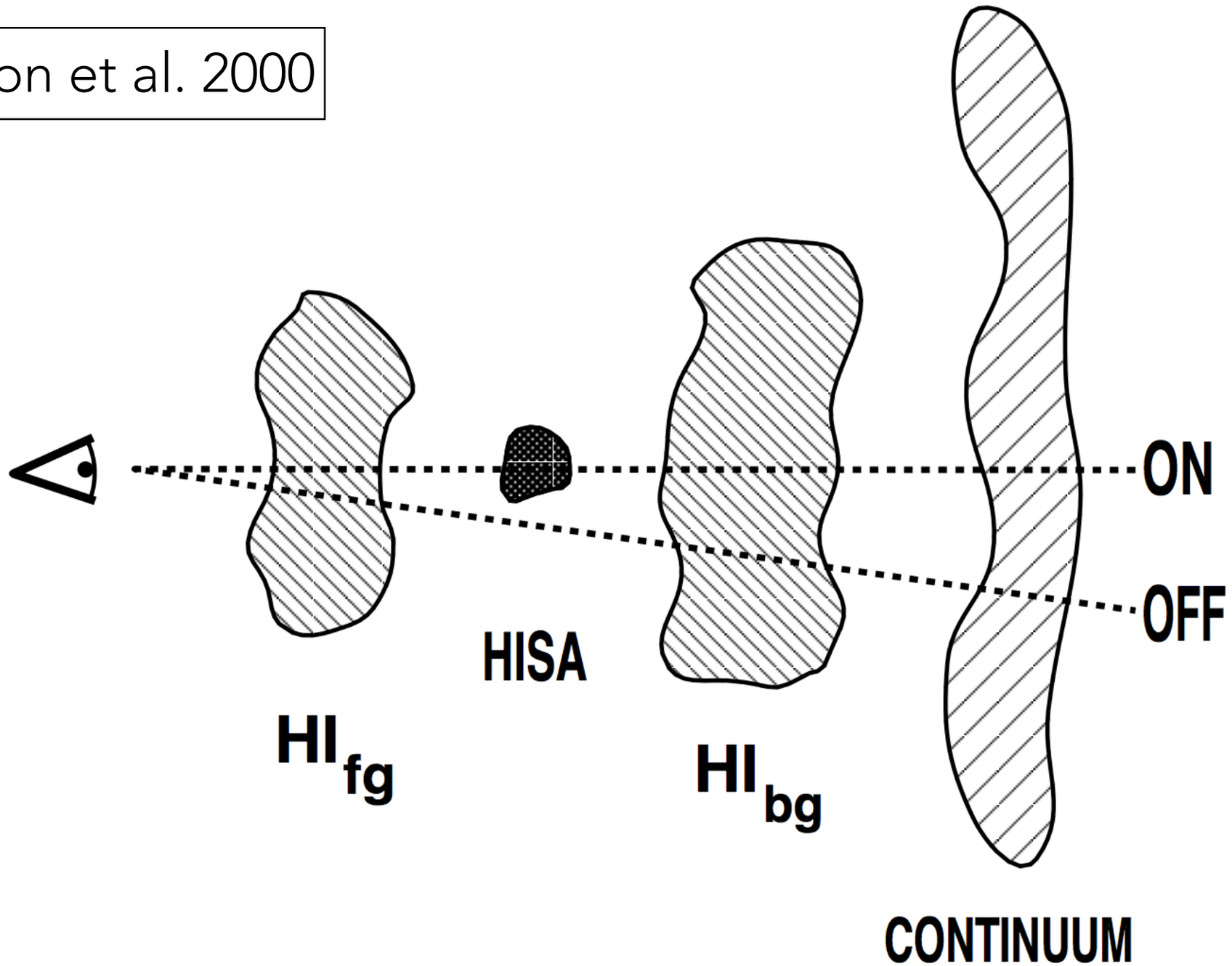
- Bubbles or cavities
- Massive star clusters not at the centre of the bubbles
- Bridge of gas toward the CNC
- Top of the bridge is located at the Southern Pillars

Rebolledo et al. (2017)



Absorption features depends on the complex structure of the ISM

Gibson et al. 2000

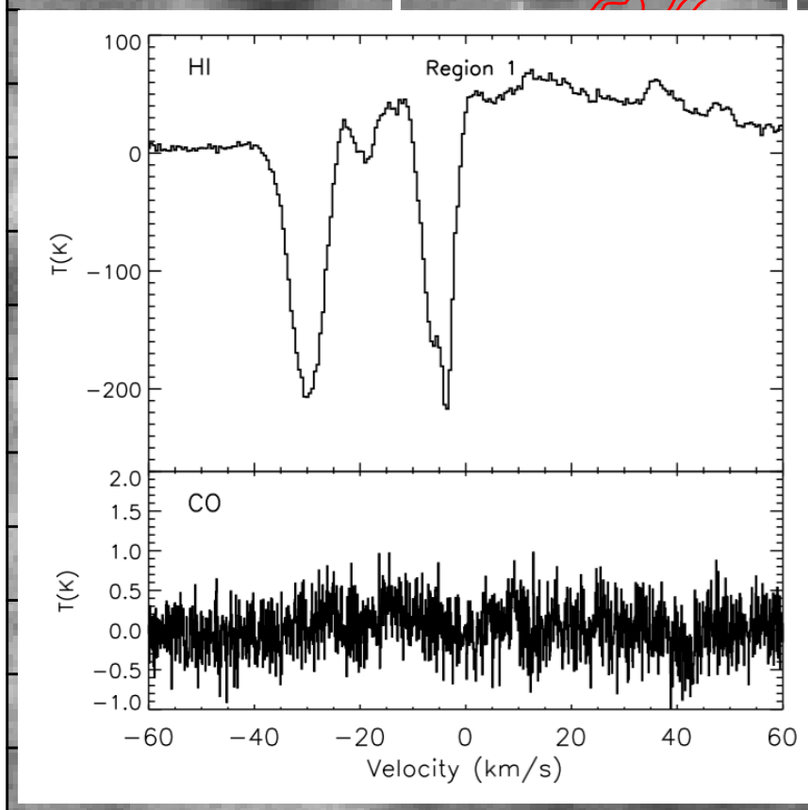


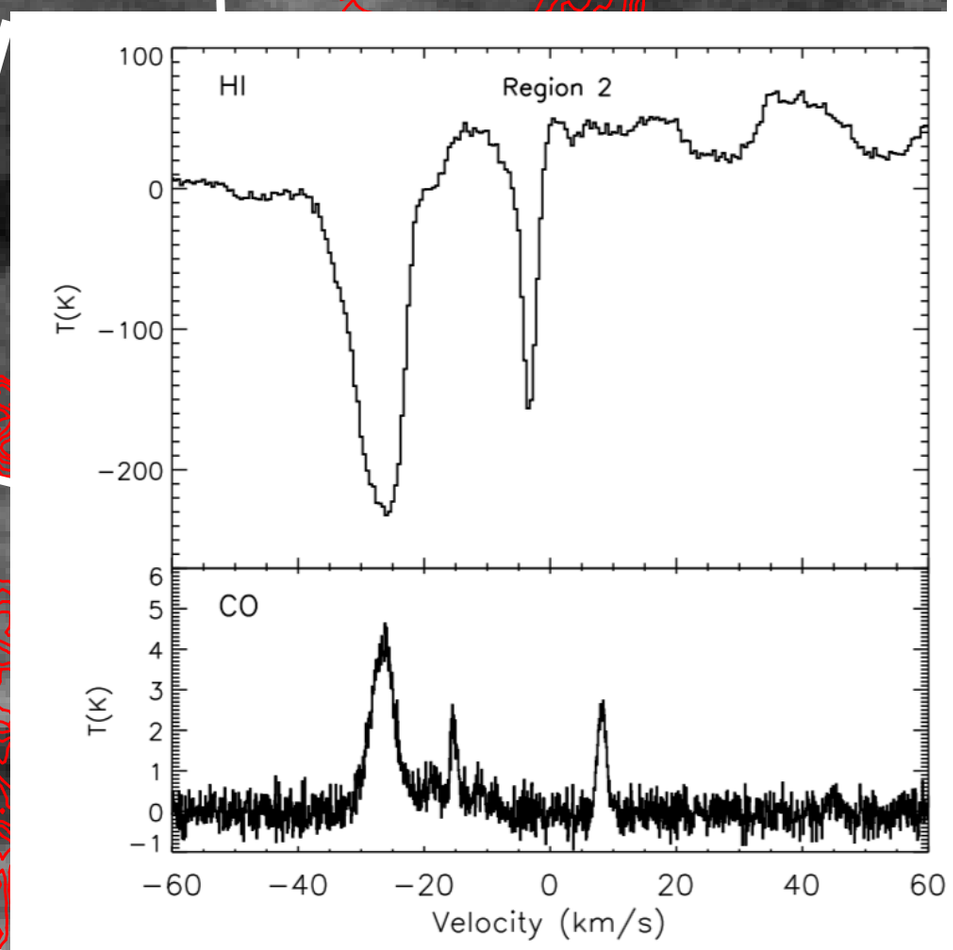
Cold HI

Region 1

Region 2

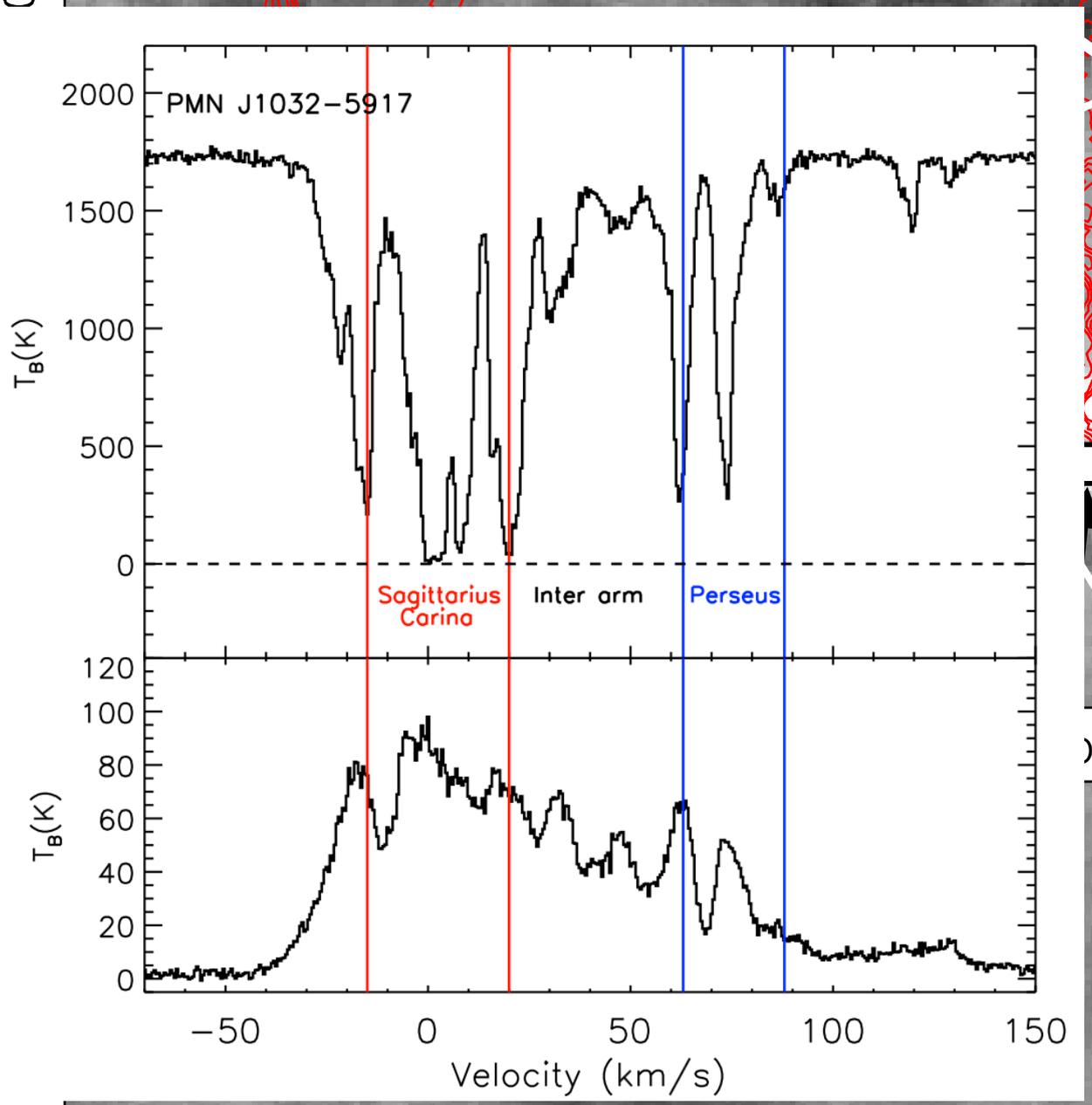
PMN J1032-5917

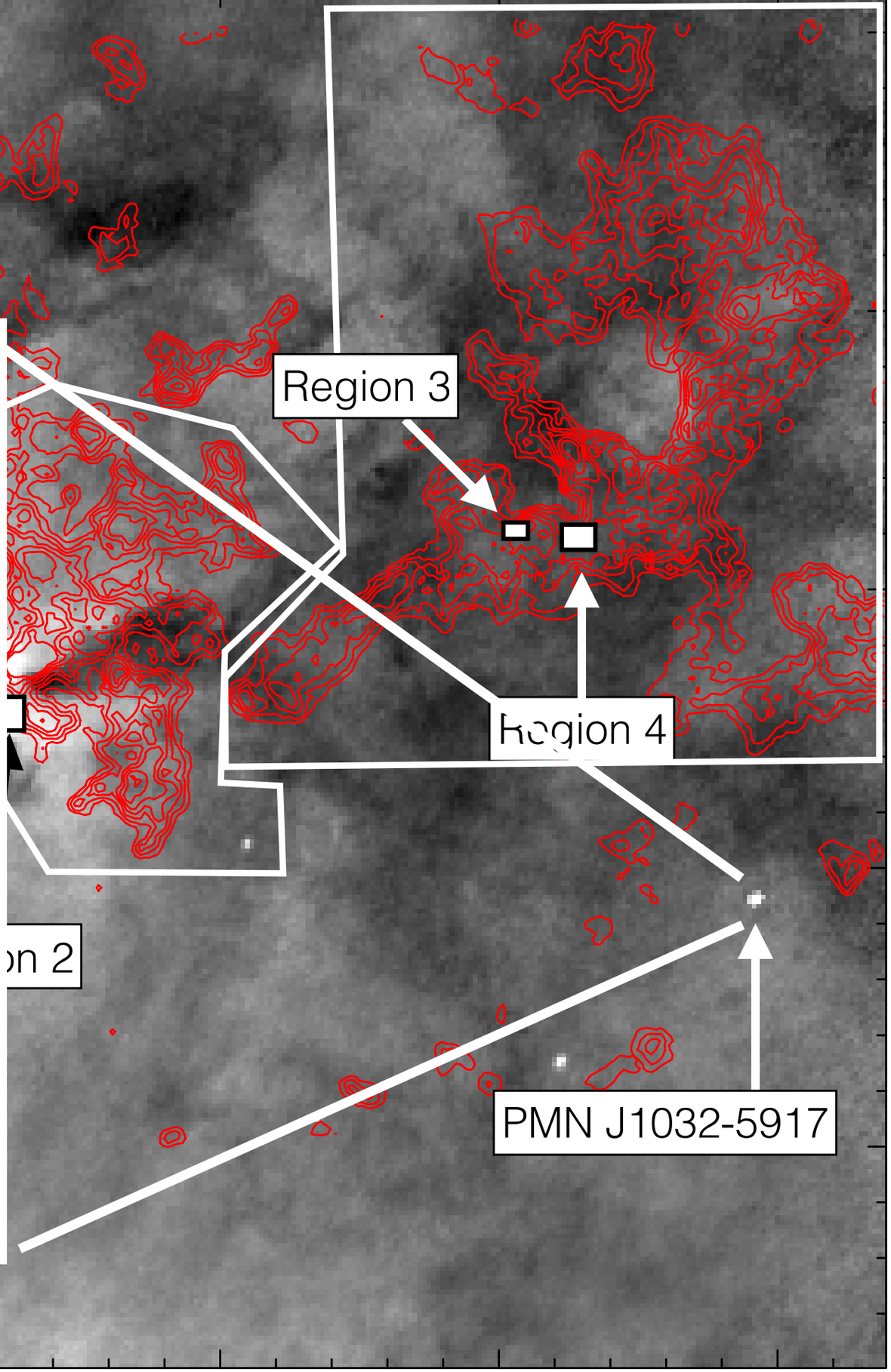


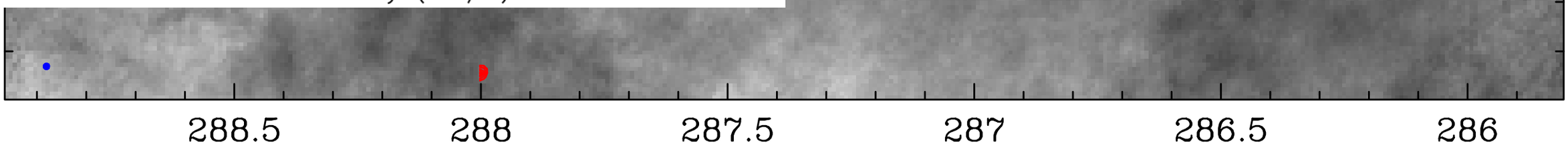


0.5
0
−0.5
−1
−1.5
288.5
288
287.5
287
286.5
286

Cold HI


PMN J1032−5917
2000
1500
1000
500
0
T_B(K)
Sagittarius Carina
Inter arm
Perseus
120
100
80
60
40
20
0
T_B(K)
−50
0
50
100
150
Velocity (km/s)


Region 3
Region 4
on 2
PMN J1032-5917


288.5
288
287.5
287
286.5
286

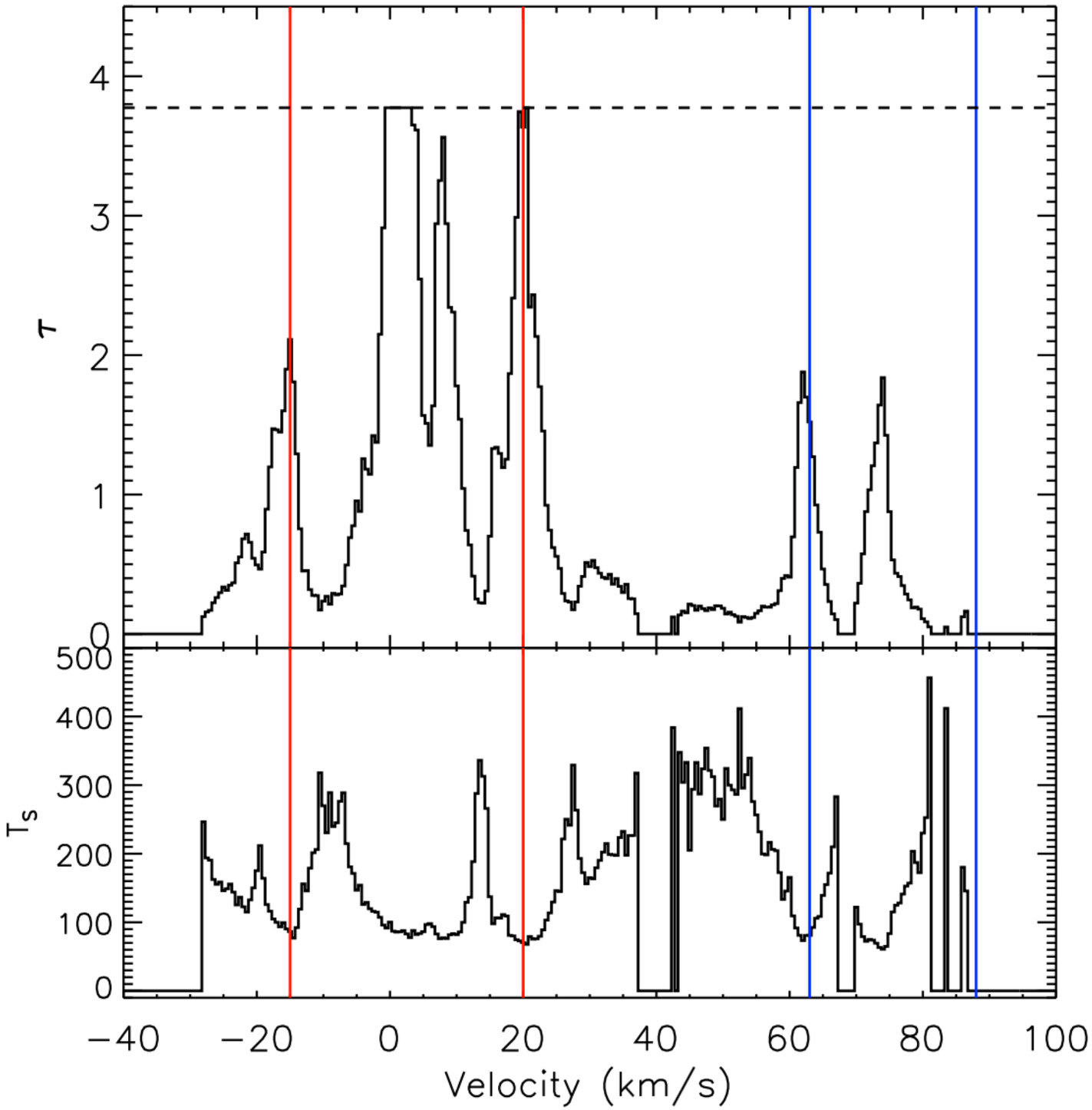
Optical depth and spin temperature of the HI

$$\frac{N_{\rm H}}{\rm cm^{-2}} = 1.8224 \times 10^{18} \frac{T_{\rm S}}{\rm K} \int_{-\infty}^{\infty} \tau(v)\, d\left(\frac{v}{\rm km\,s^{-1}}\right)$$

$$T_{\rm B,HI} = (T_{\rm S} - T_{\rm C})(1 - e^{-\tau}).$$

$$\tau = -\ln\left(\frac{T_{\rm ON} - T_{\rm OFF}}{T_{\rm C}}\right)$$

$$T_{\rm S} = \frac{T_{\rm OFF}}{(1 - e^{-\tau})}.$$



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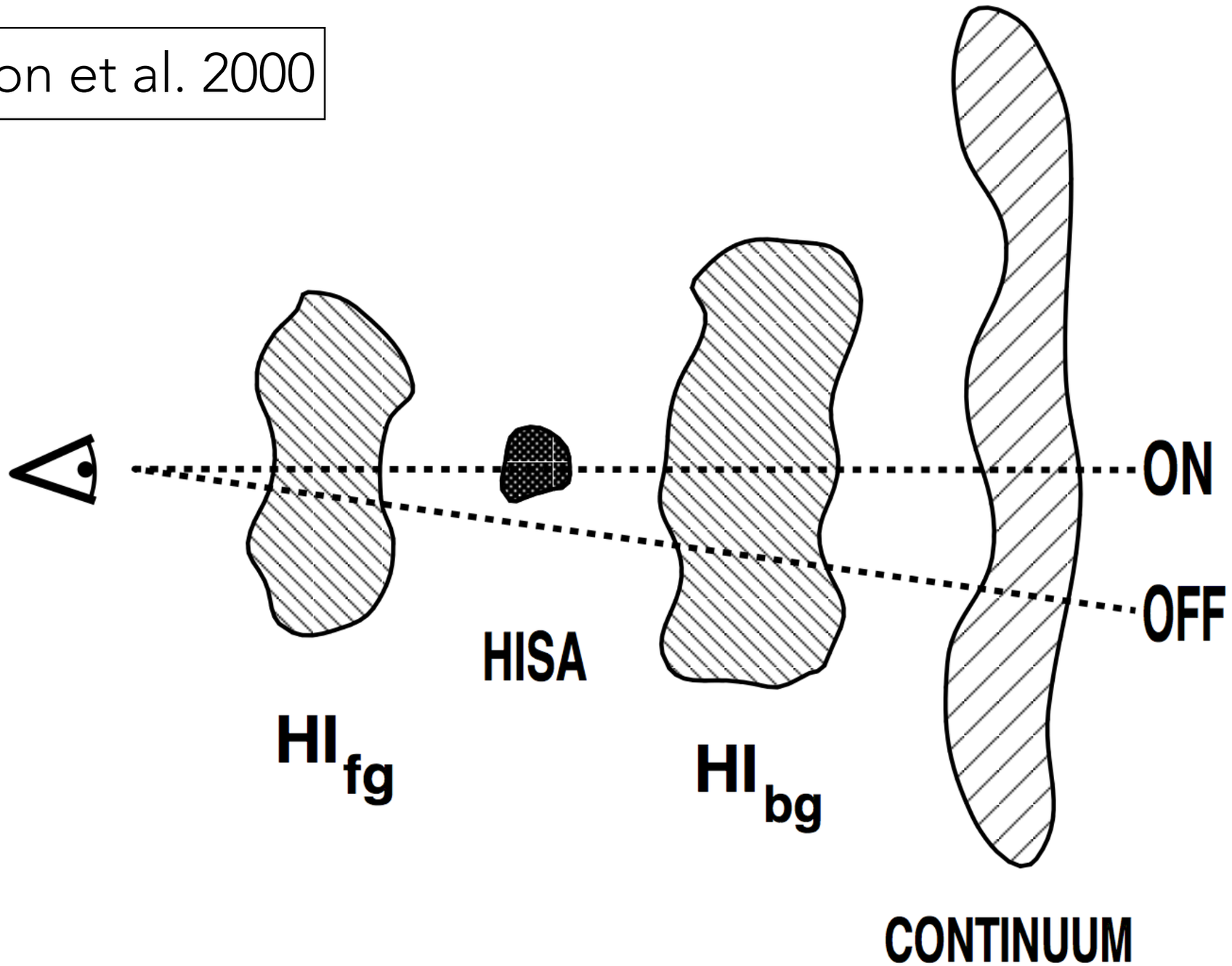
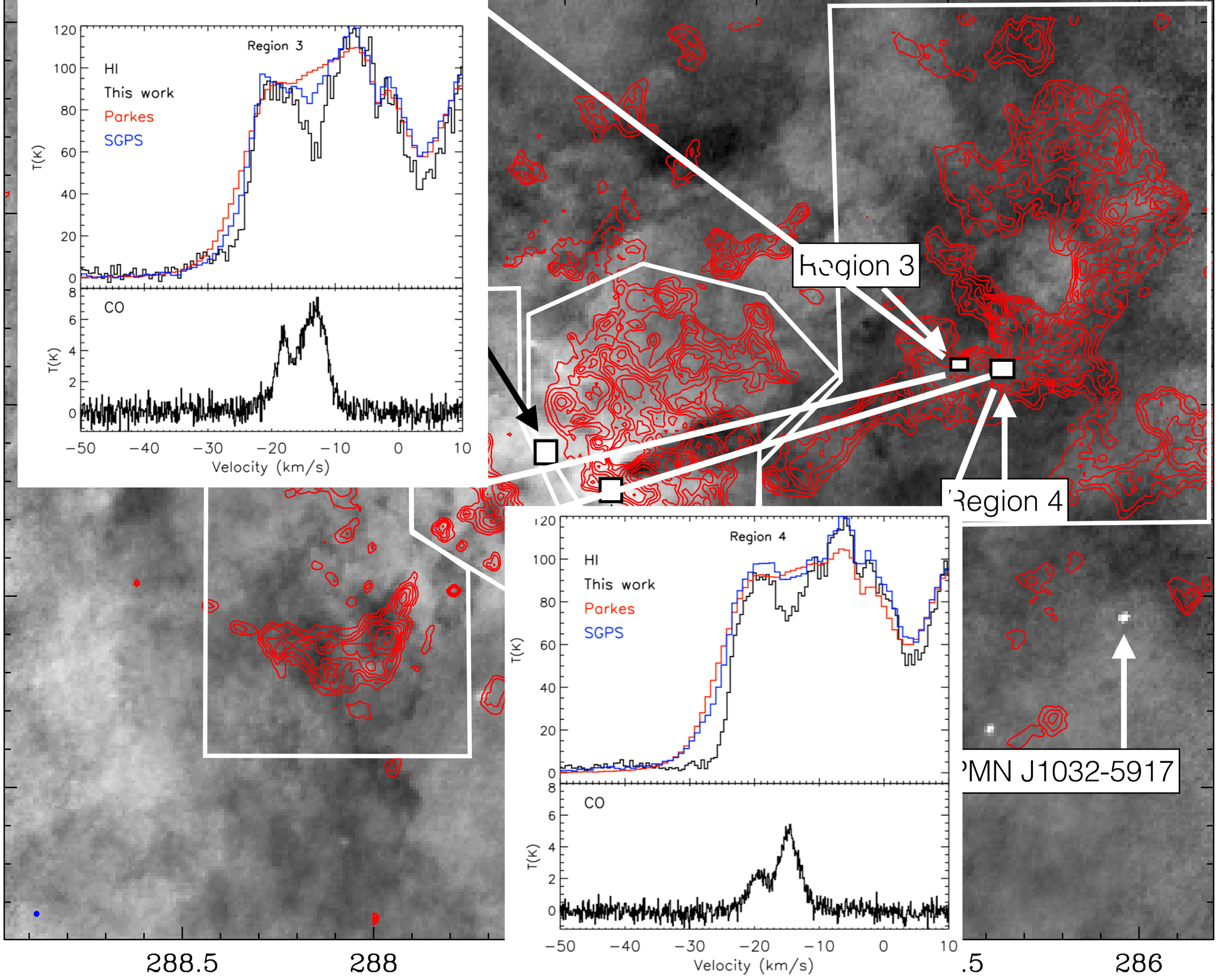
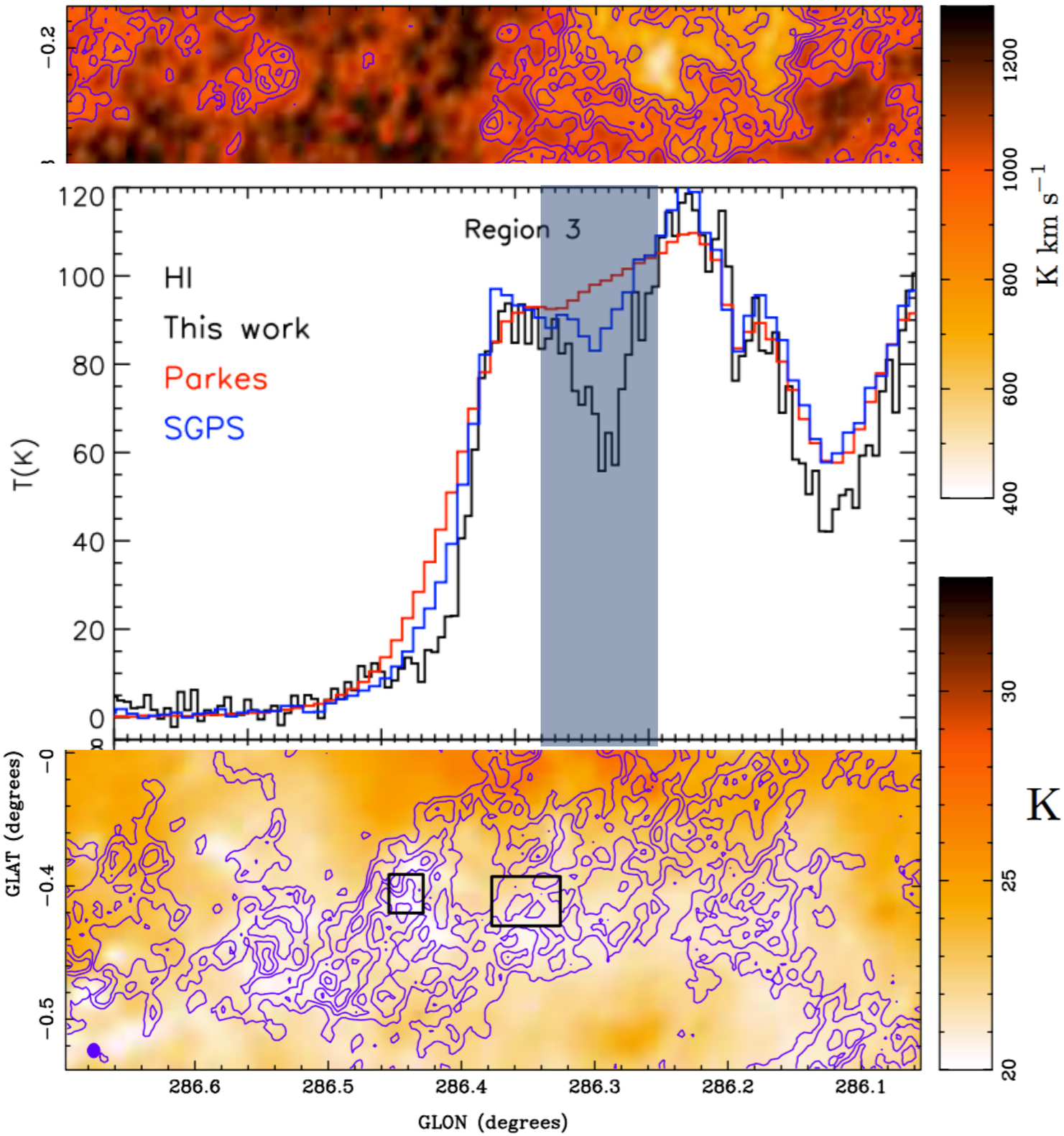



Region 3
HI
This work
Parkes
SGPS
T(K)
CO
Velocity (km/s)
Region 4
MN J1032-5917
0.5
0
−0.5
−1
−1.5
288.5
288
.5
286

HI integrated intensity over the HISA feature

Rebolledo et al. (2017)



Good correlation between HISA features and cold gas

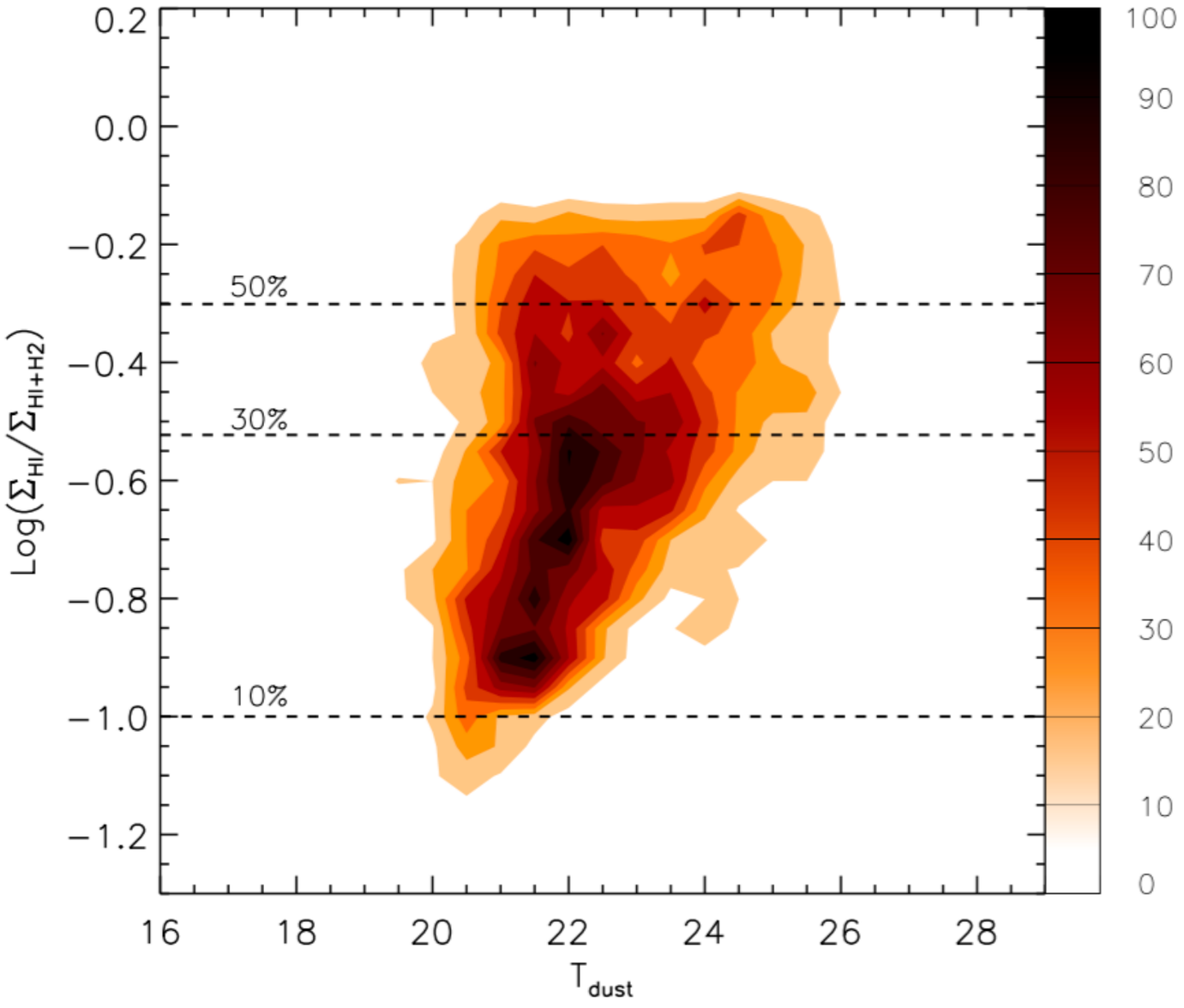
Dust temperature

Atomic gas fraction

Gum 31 region

The fraction of atomic gas gradually decreases as the dust temperature gets colder.

Transition from atomic to molecular gas is likely to be happening in this region.



Rebolledo et al. (2017)

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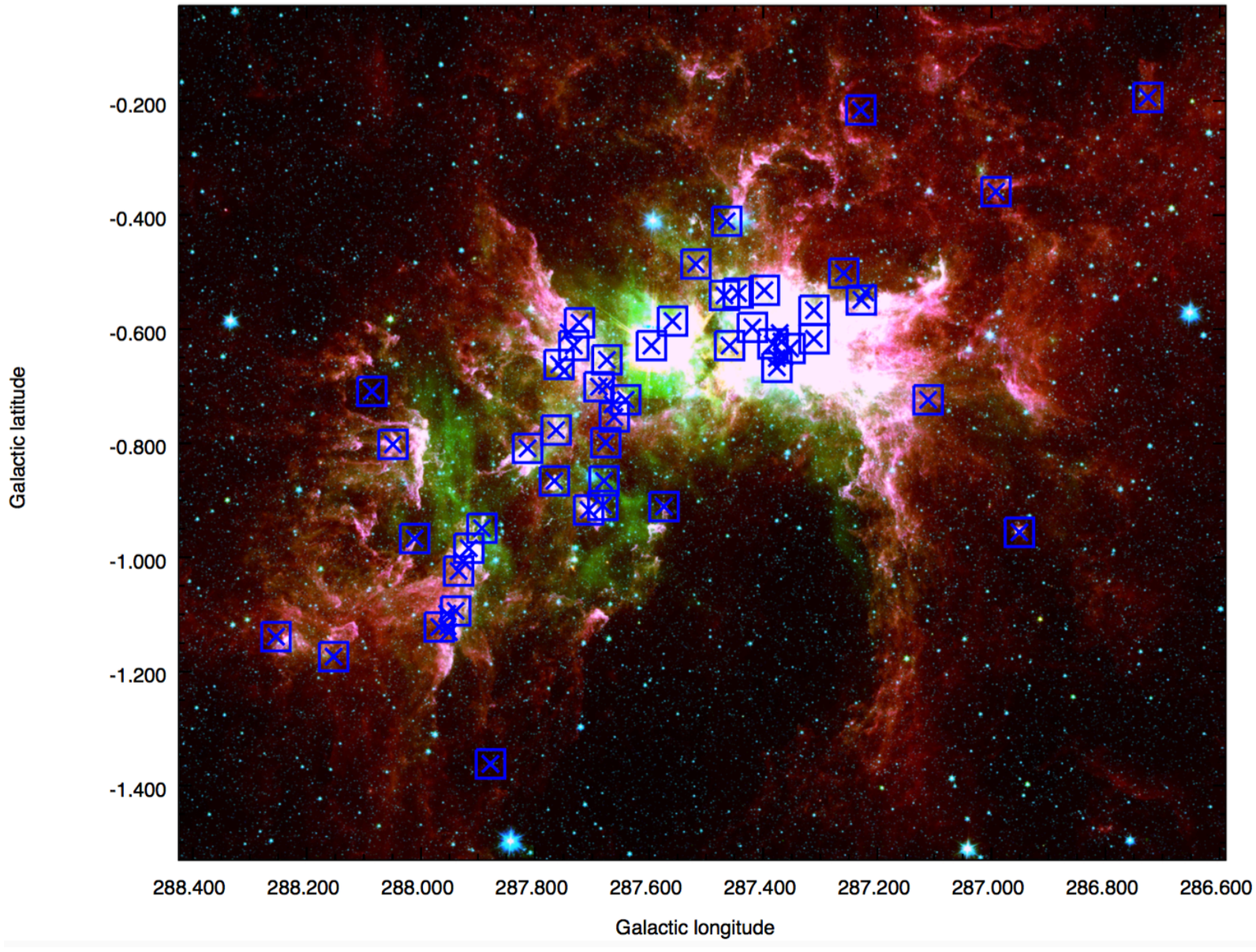
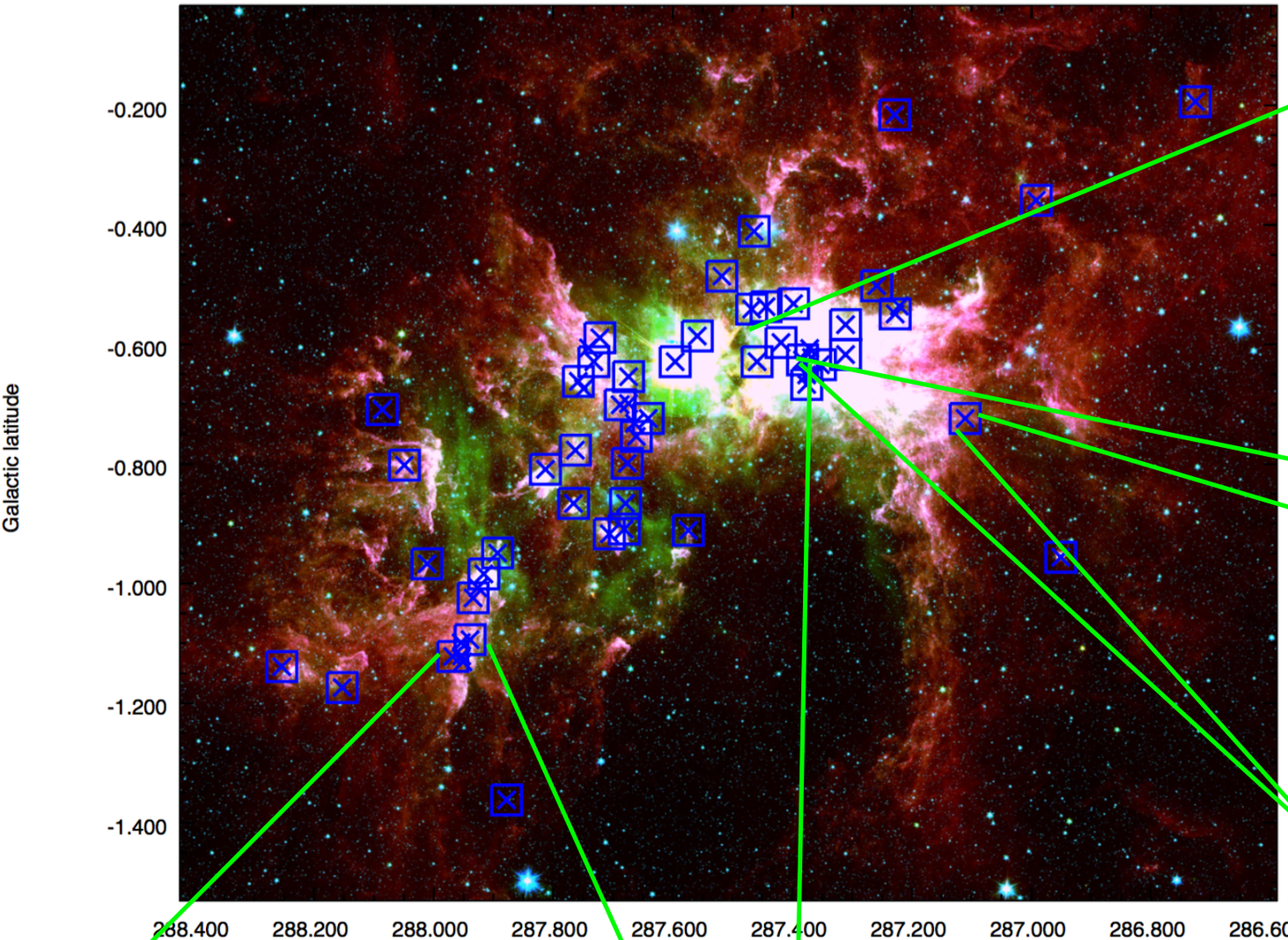
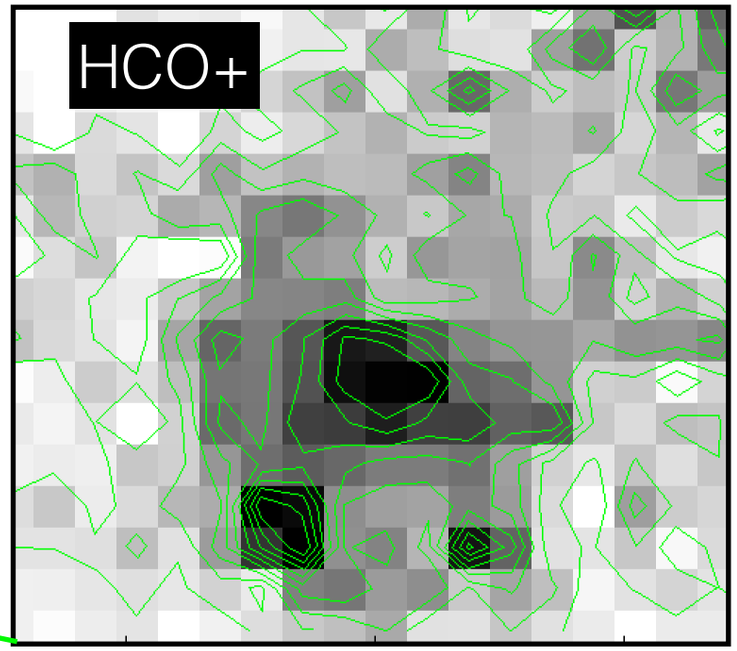
High-mass star forming clumps in the Carina Nebula

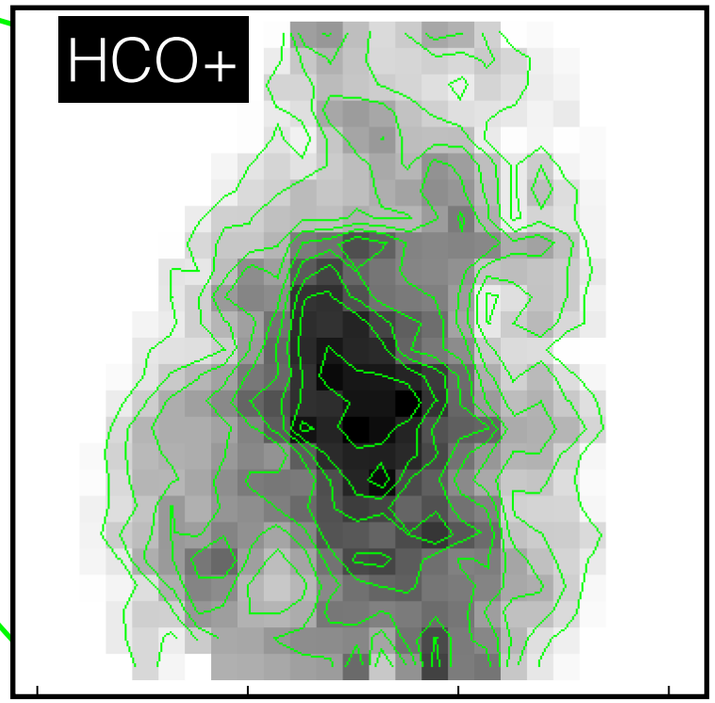
PI: Yanett Contreras

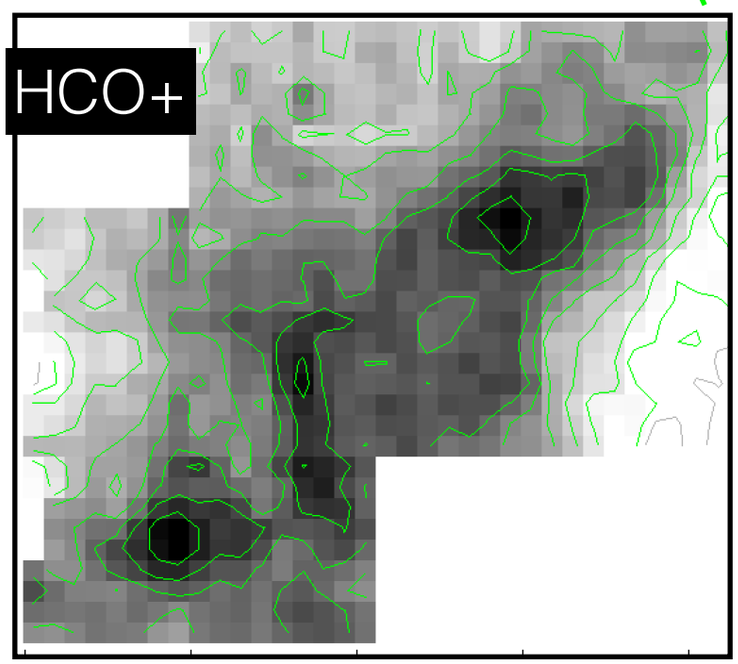
- Observations toward 60 high mass star forming clumps selected from ATLASGAL
- Combination of dense gas, shock and ionisation tracers
- Observing 16 spectral lines at ~ 90 GHz, including HCN, HCO+, HNCO, and SiO.

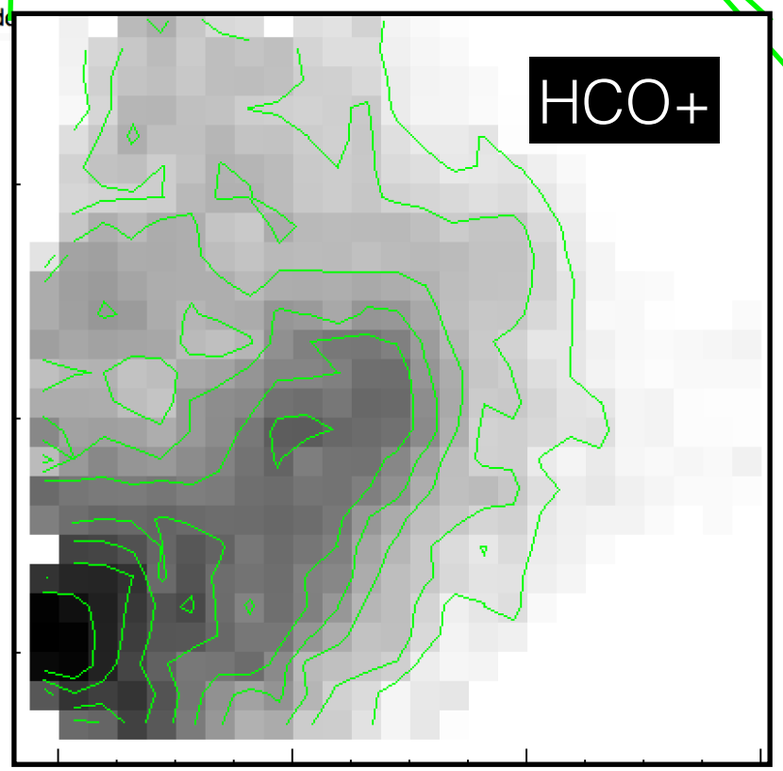



-0.200
-0.400
-0.600
-0.800
-1.000
-1.200
-1.400
Galactic latitude
288.400
288.200
288.000
287.800
287.600
287.400
287.200
287.000
286.800
286.600
Galactic longitude


HCO+


HCO+

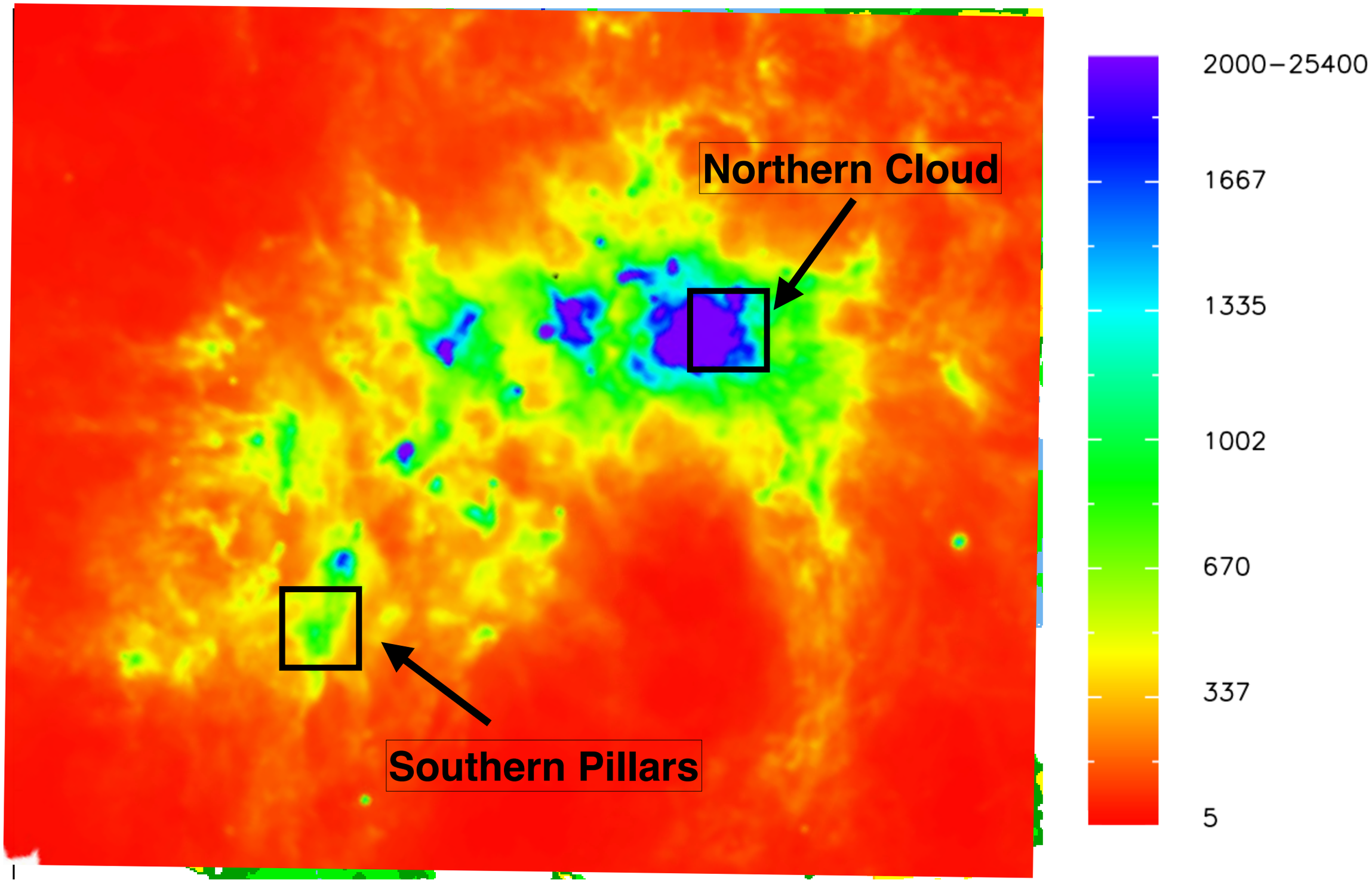

HCO+

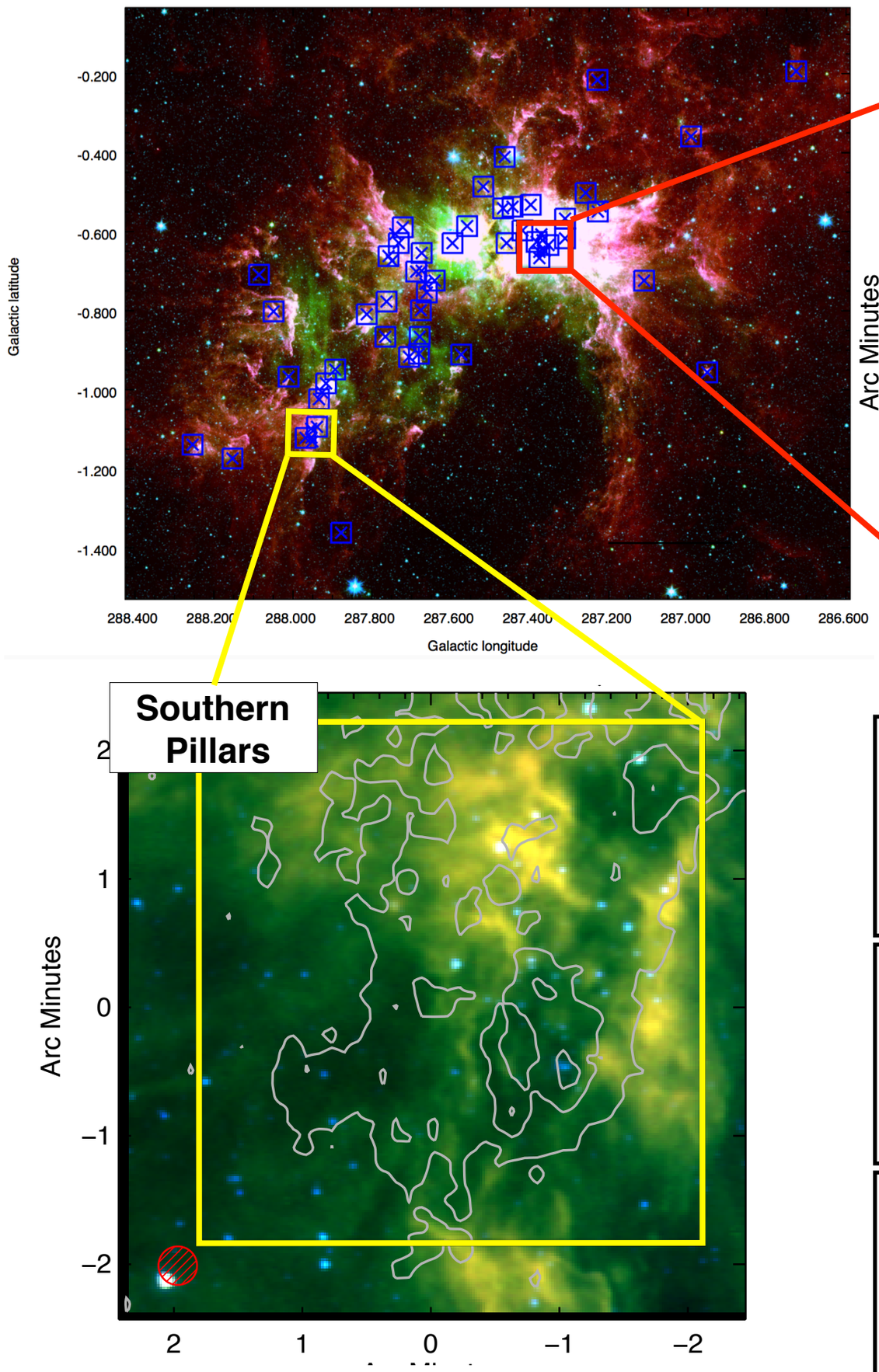

HCO+

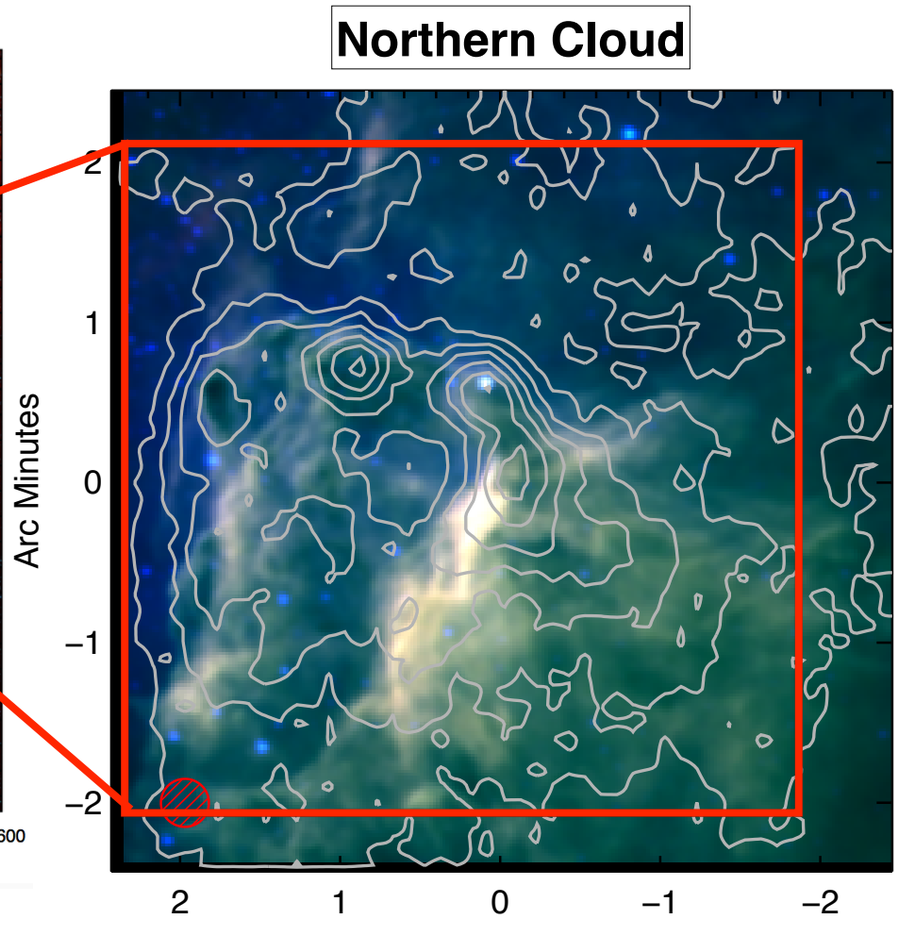
3 pc

Mopra

Two distinct regions to study feedback effects on star formation







2.7 pc

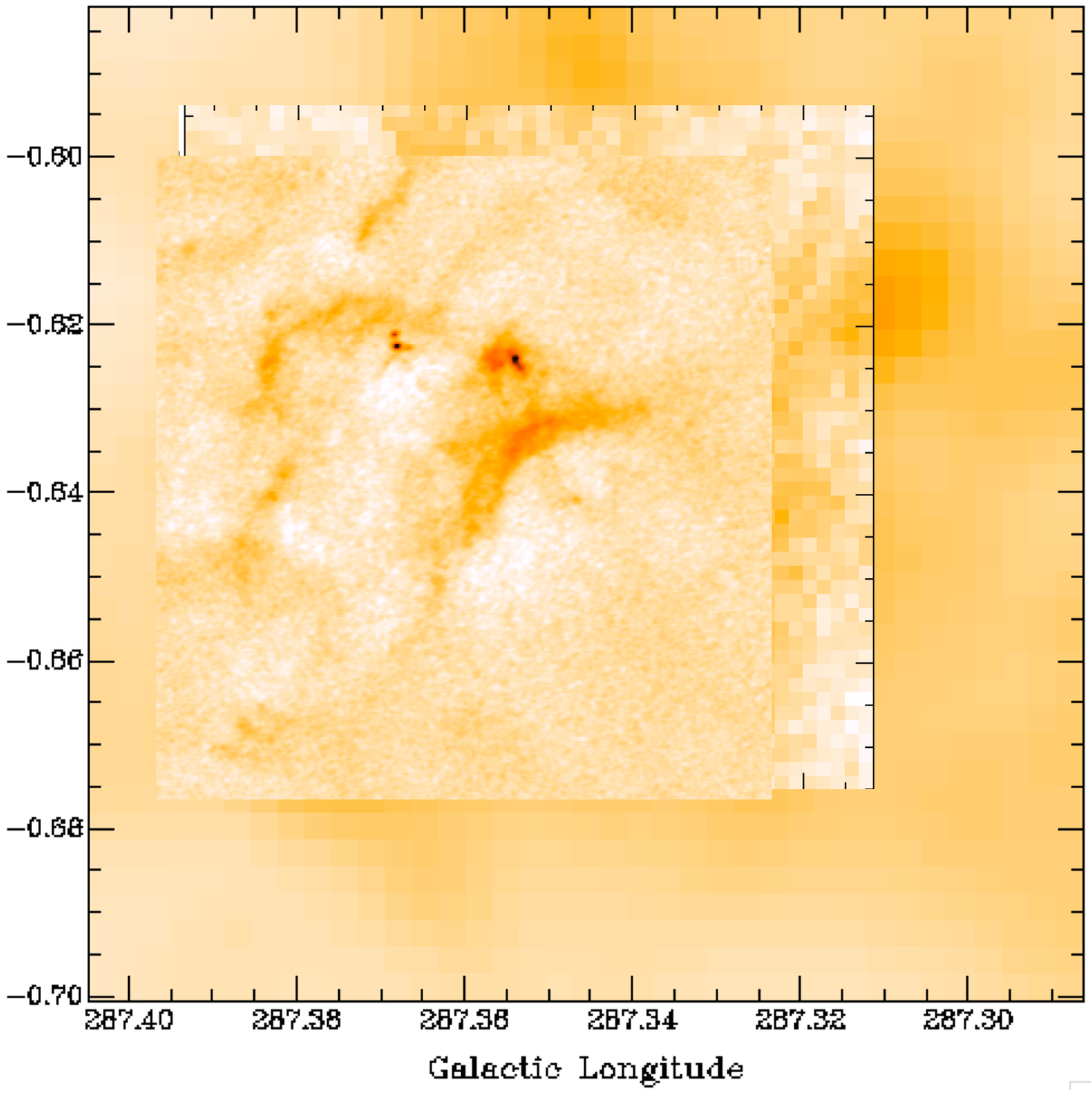
Cycle 4 - Band 3 (3mm)
HCO+, HCN and other molecules + dust continuum at 3 mm

Cycle 5 - Band 6 (1mm)
Higher transitions of HCO+ and HCN+ dust continuum at 1mm

Cycle 6 - Band 3 (3mm)
N_2H+, ^{13}CO, $C^{18}O$, CH_3CN, CN and others

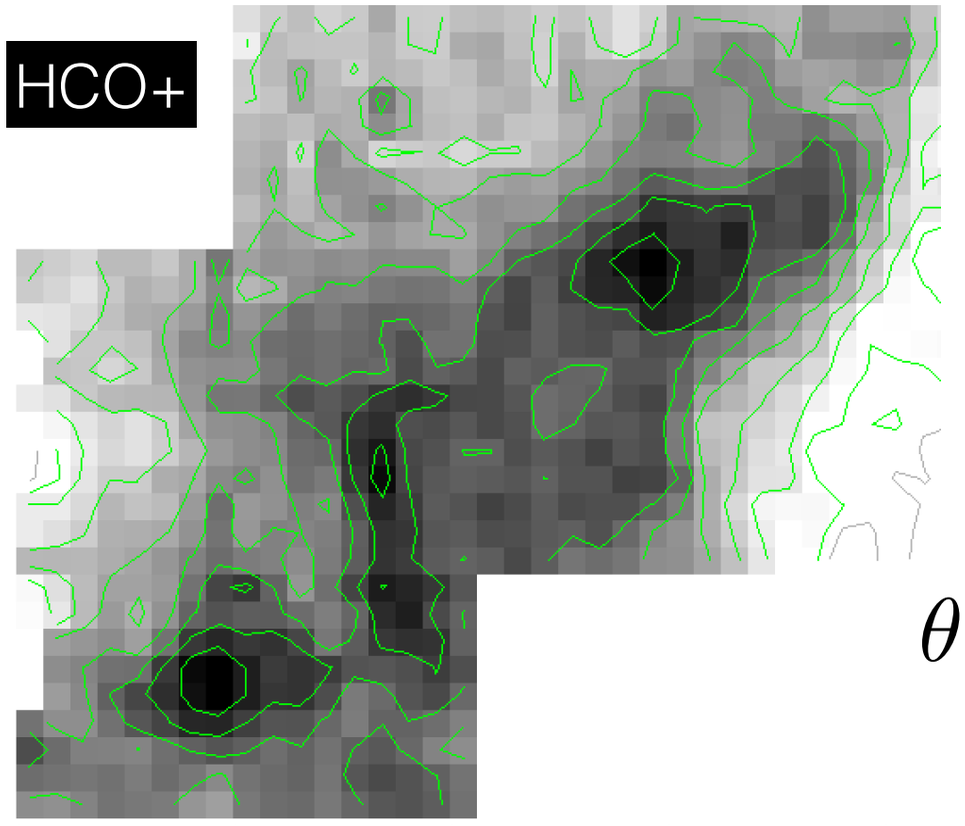
Northern Cloud

ATALMAAL



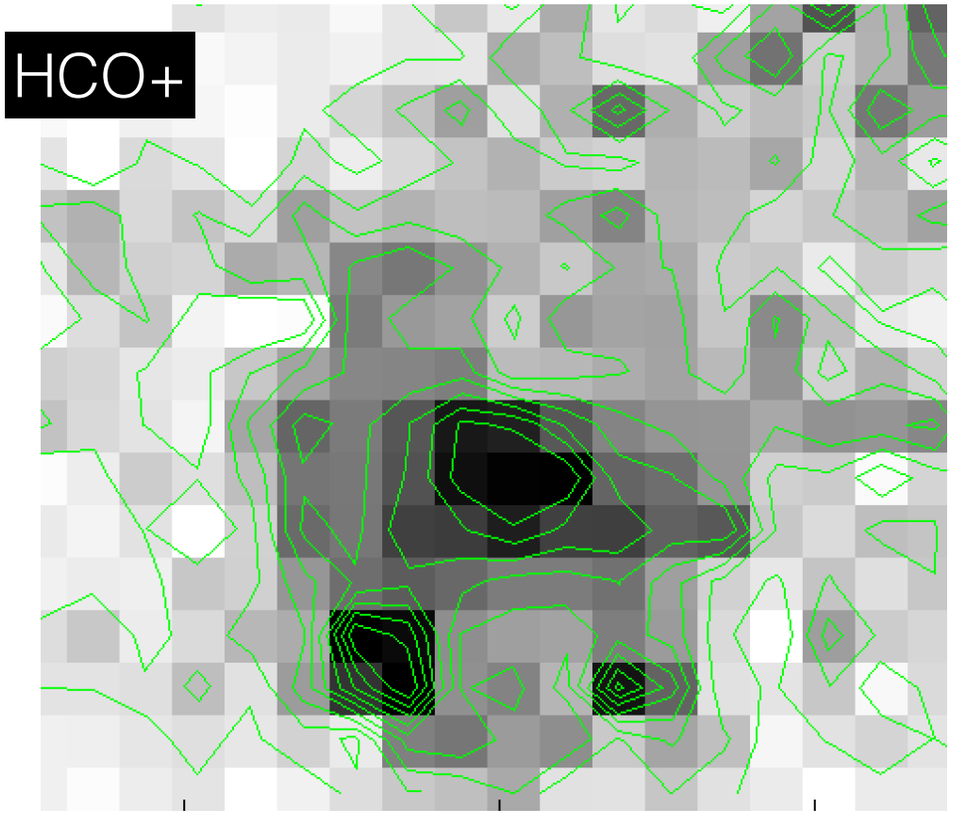
$\theta \sim 0.42$ pc

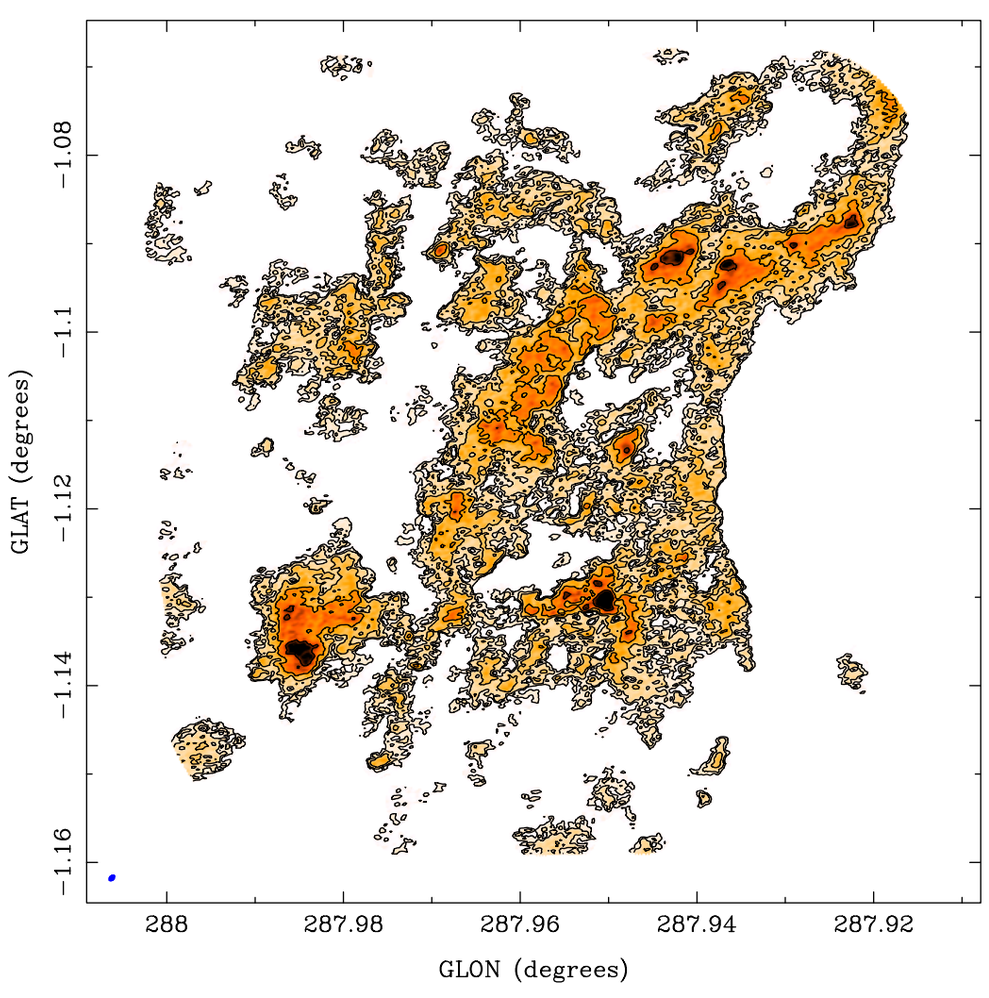
2.7 pc



Mopra

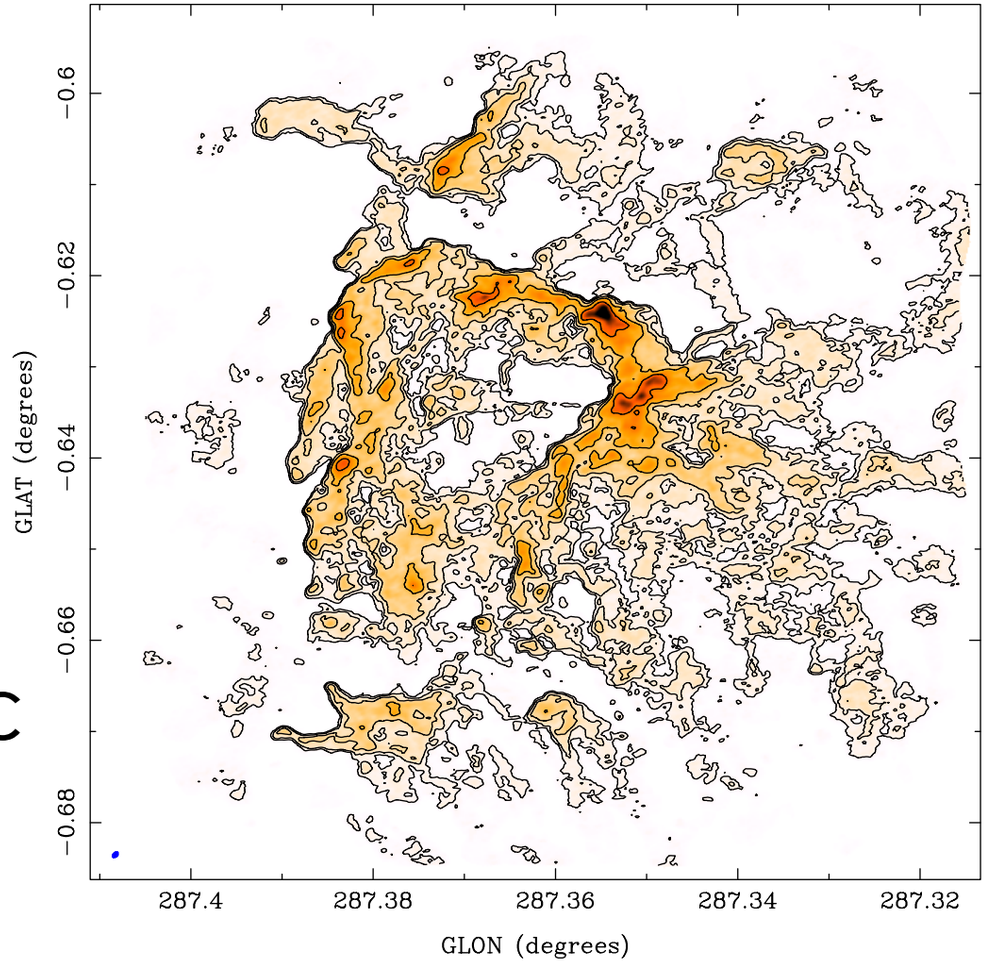
$\theta \sim$ 0.4 pc

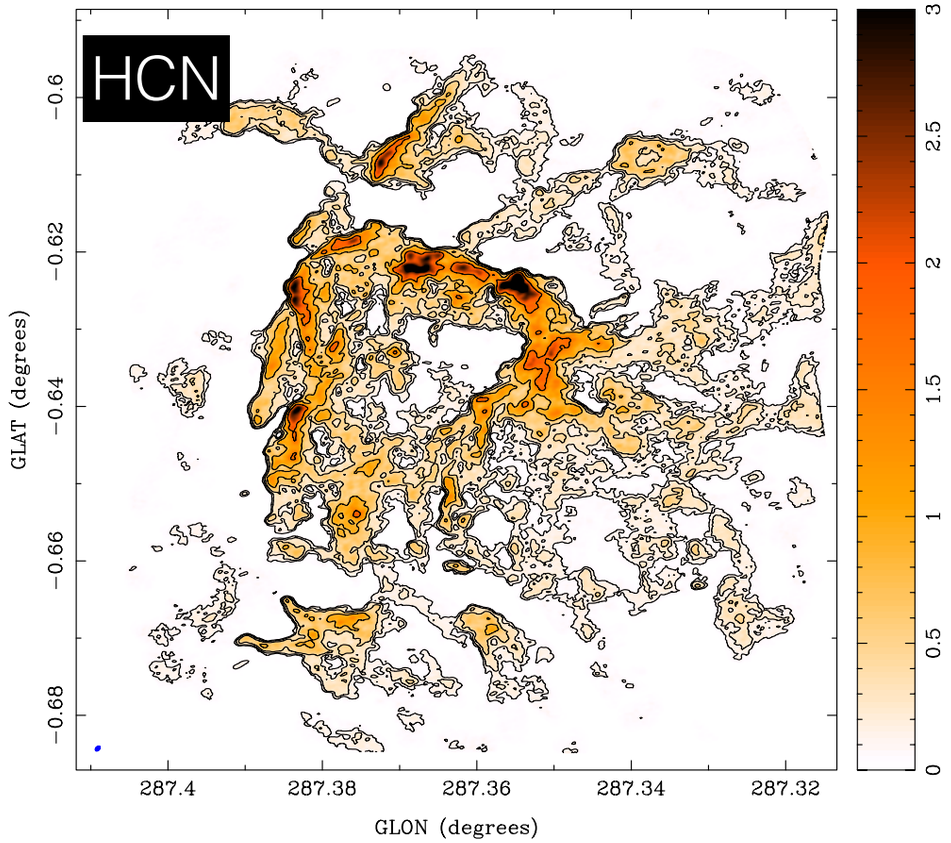


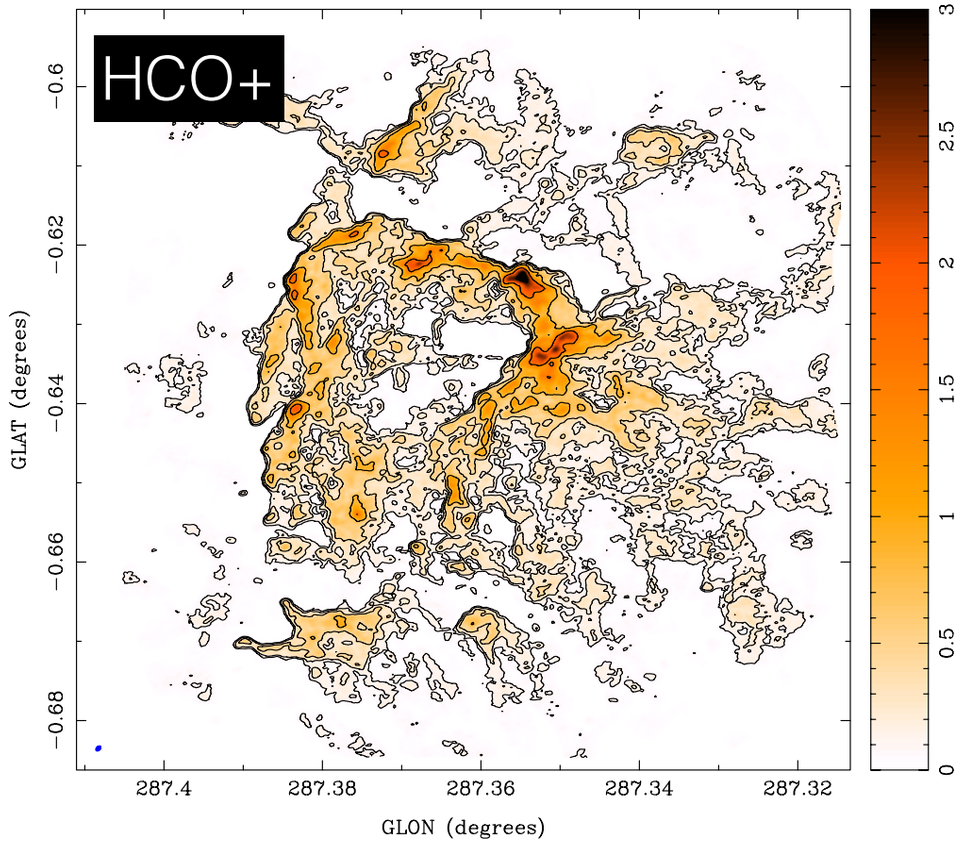


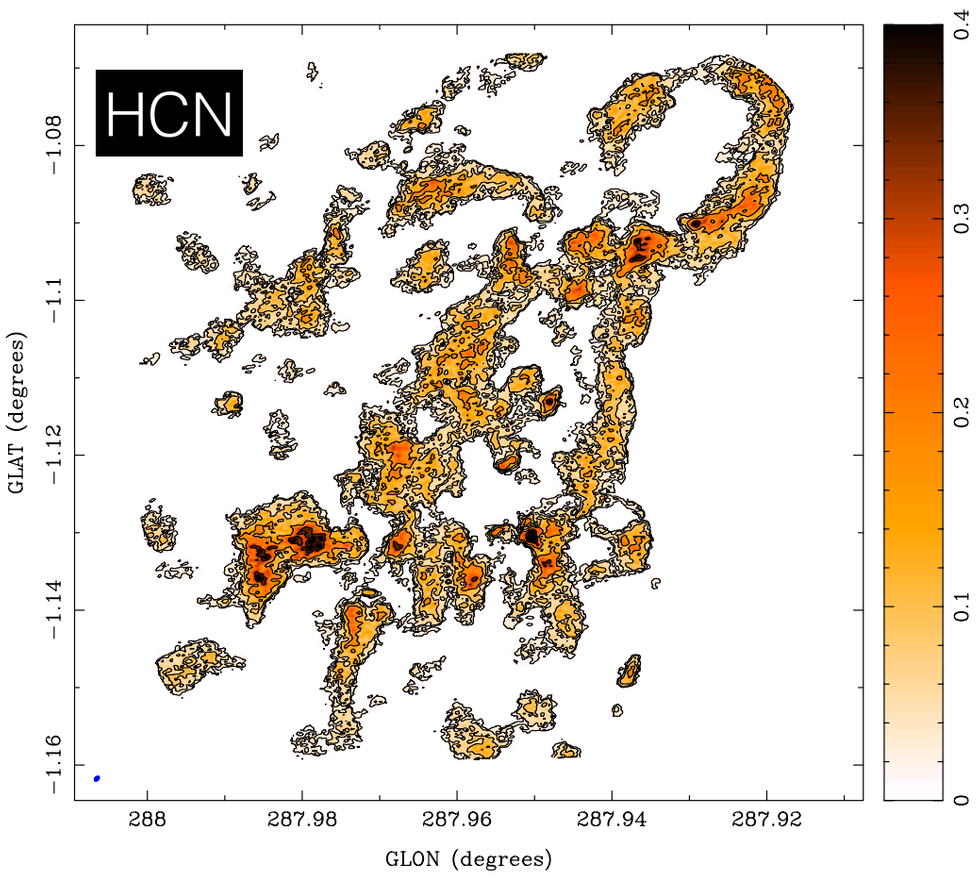
ALMA

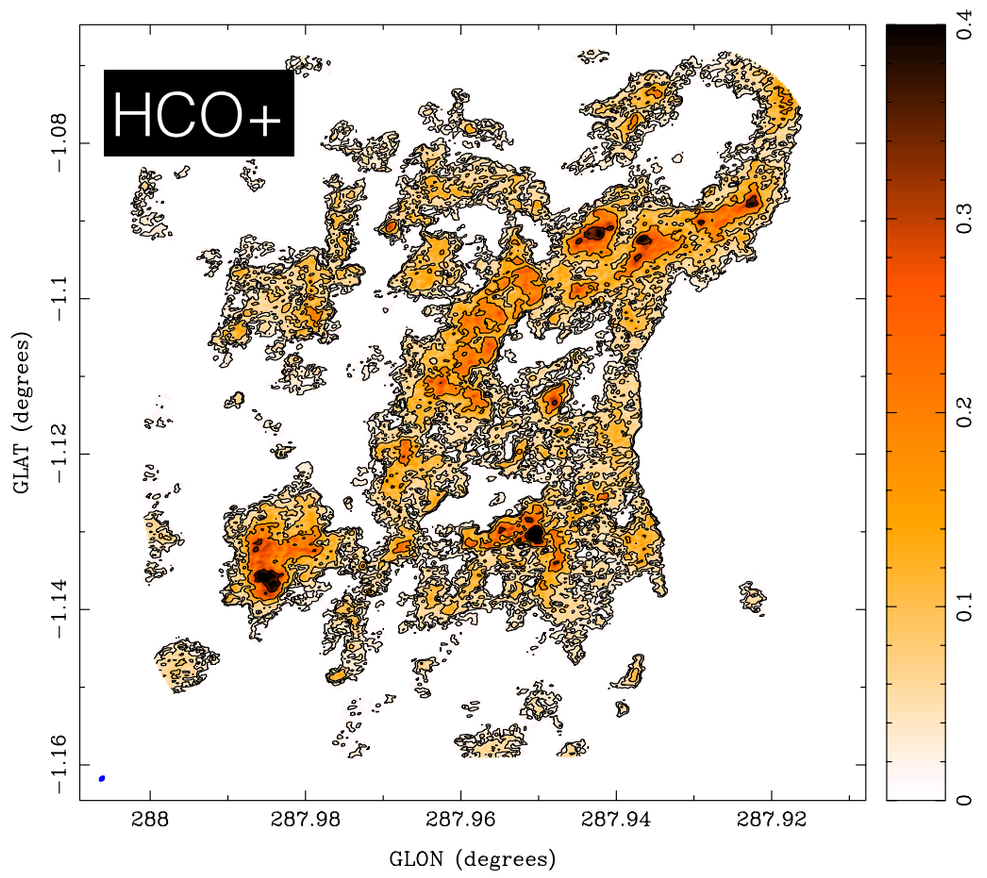
$\theta \sim$0.02 pc



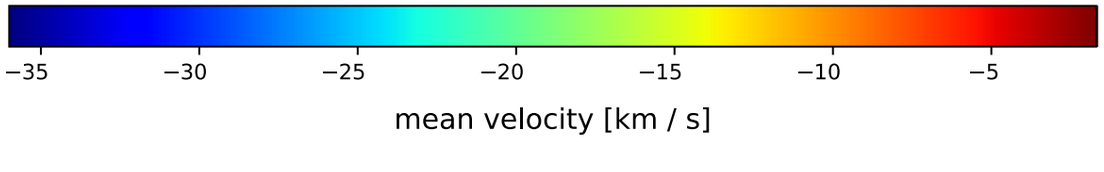

HCN
GLAT (degrees)
−0.6
−0.62
−0.64
−0.66
−0.68
287.4
287.38
287.36
287.34
287.32
GLON (degrees)
0
0.5
1
1.5
2
2.5
3

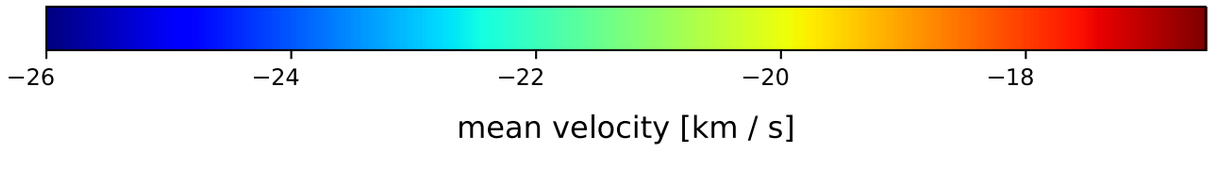

HCO+
GLAT (degrees)
−0.6
−0.62
−0.64
−0.66
−0.68
287.4
287.38
287.36
287.34
287.32
GLON (degrees)
0
0.5
1
1.5
2
2.5
3

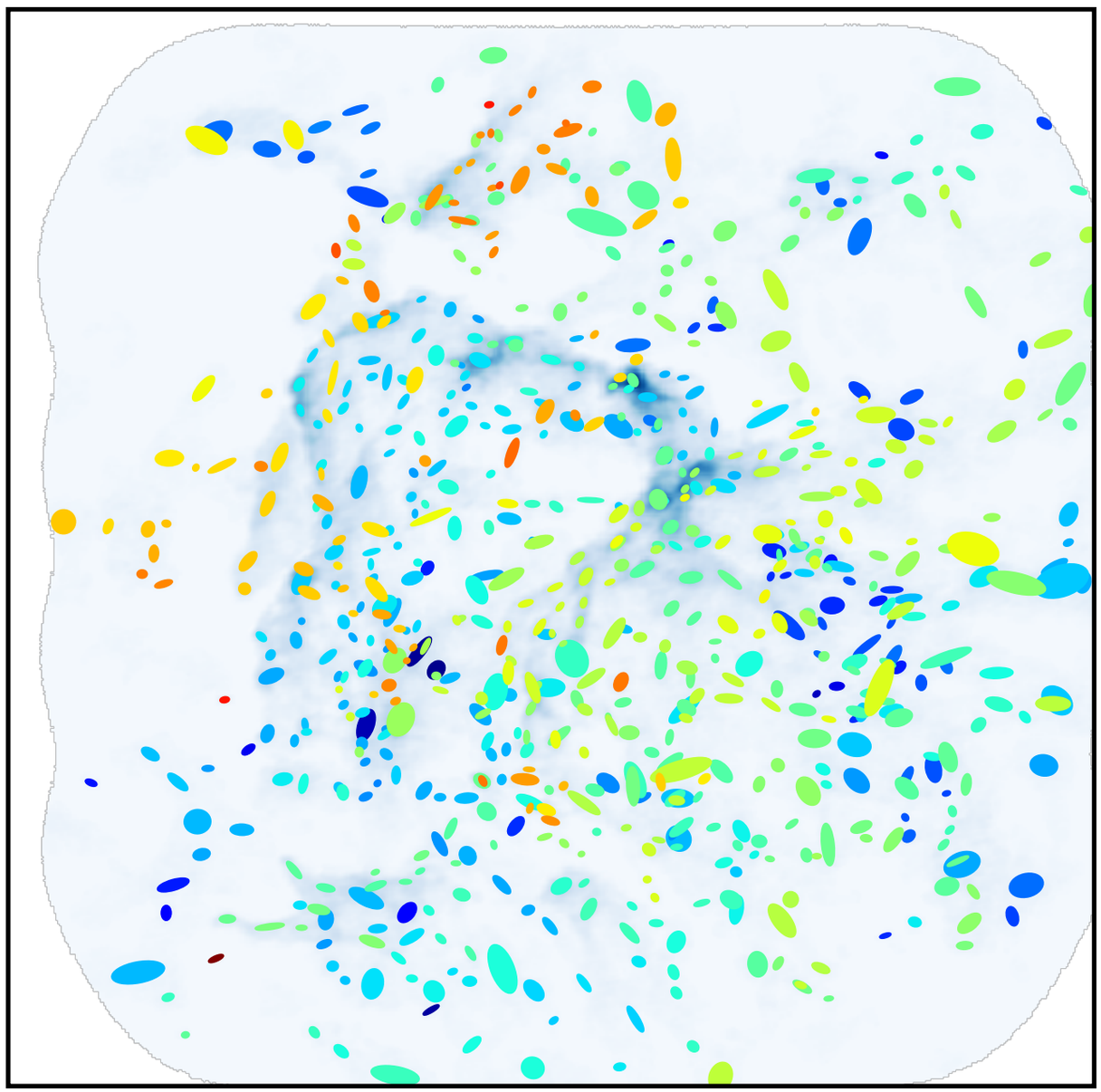

HCN
GLAT (degrees)
−1.08
−1.1
−1.12
−1.14
−1.16
288
287.98
287.96
287.94
287.92
GLON (degrees)
0
0.1
0.2
0.3
0.4

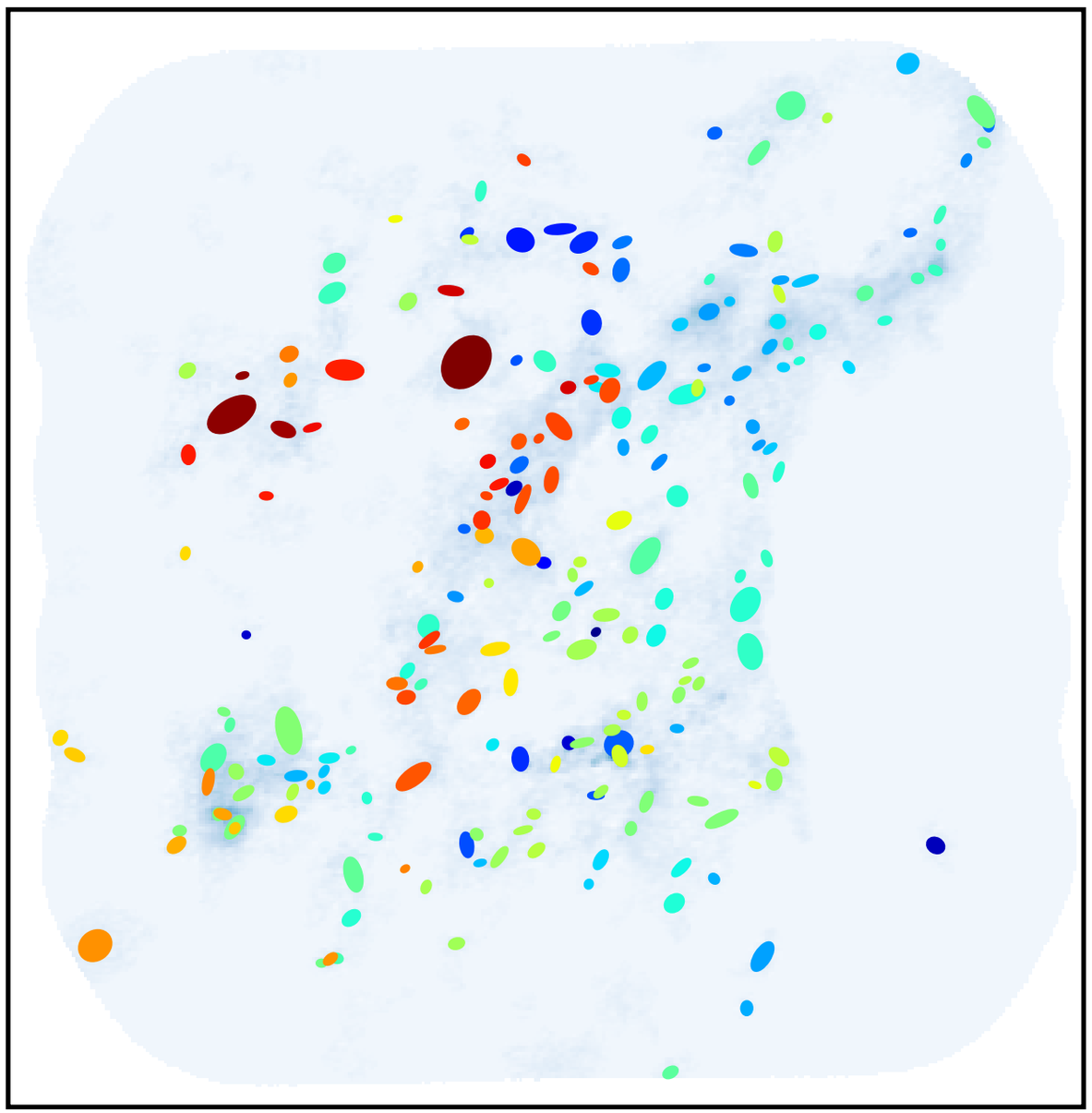

HCO+
GLAT (degrees)
−1.08
−1.1
−1.12
−1.14
−1.16
288
287.98
287.96
287.94
287.92
GLON (degrees)
0
0.1
0.2
0.3
0.4

Mean Velocity

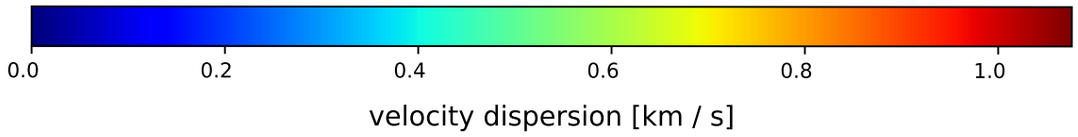


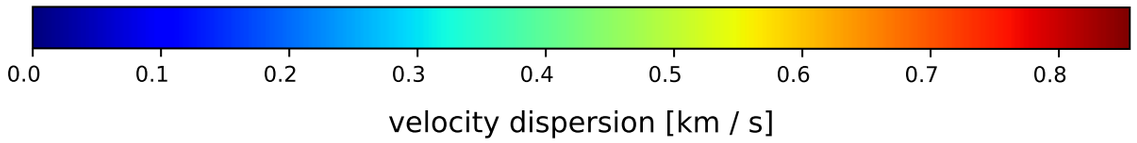


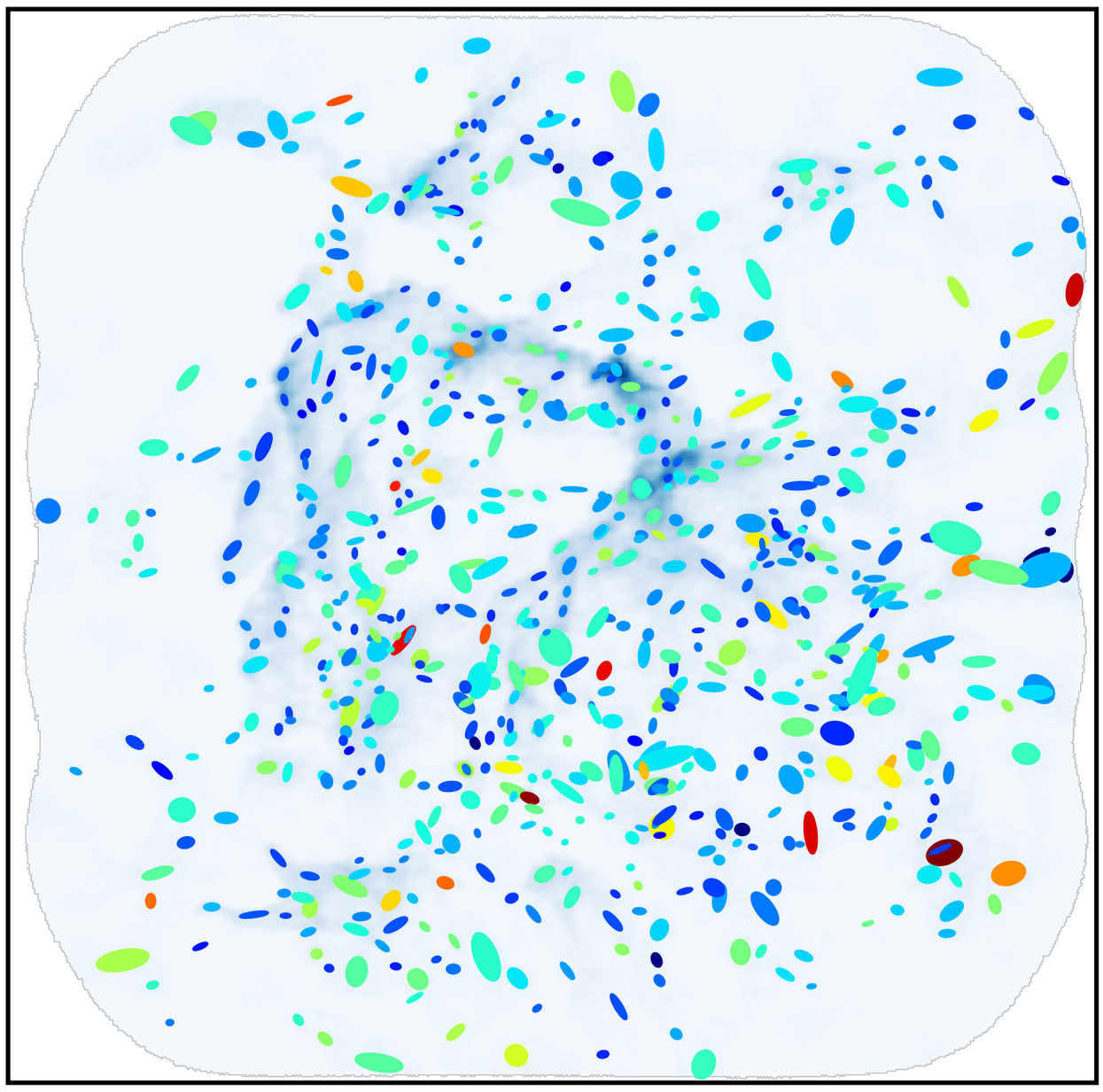


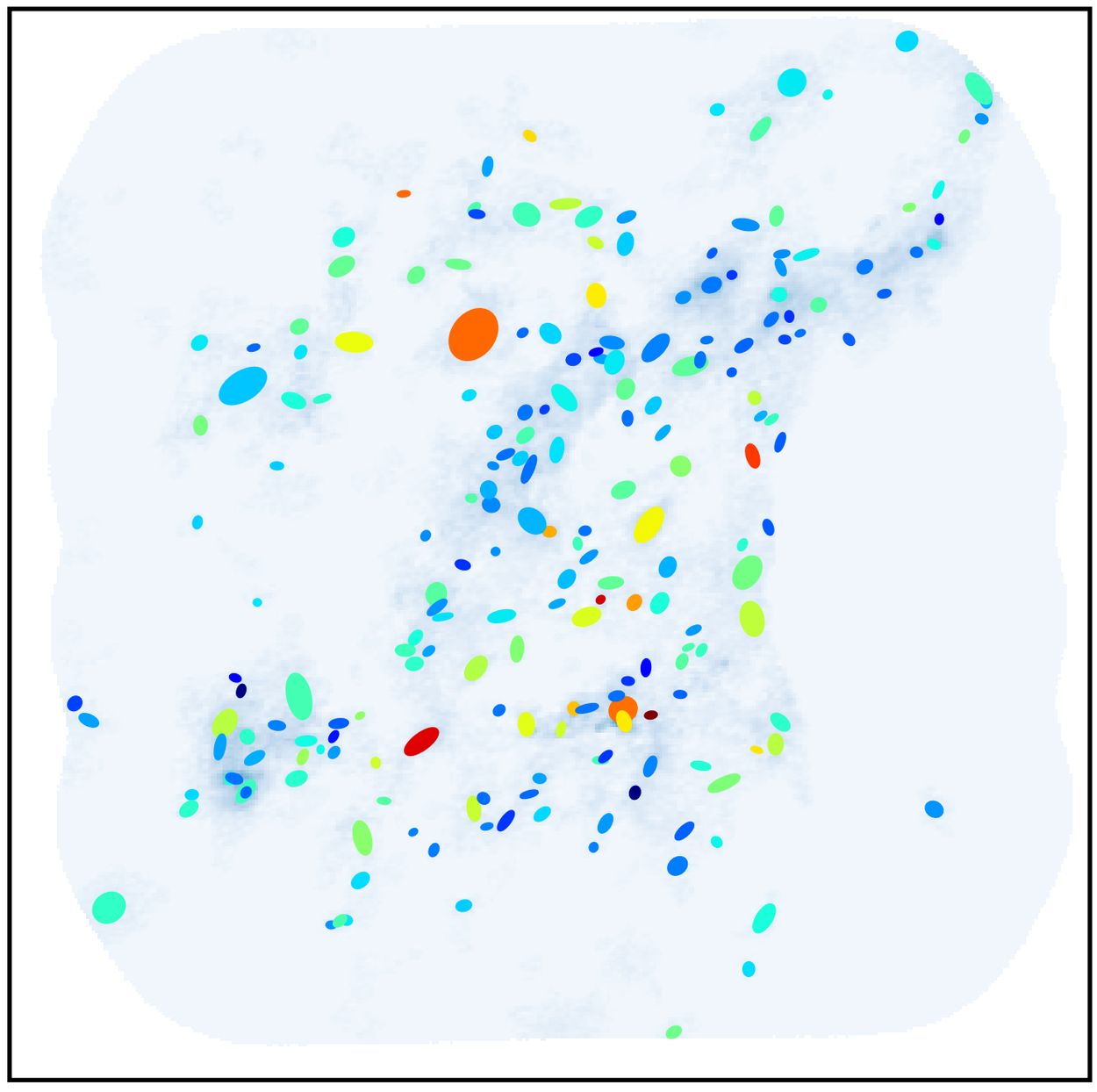


Velocity dispersion

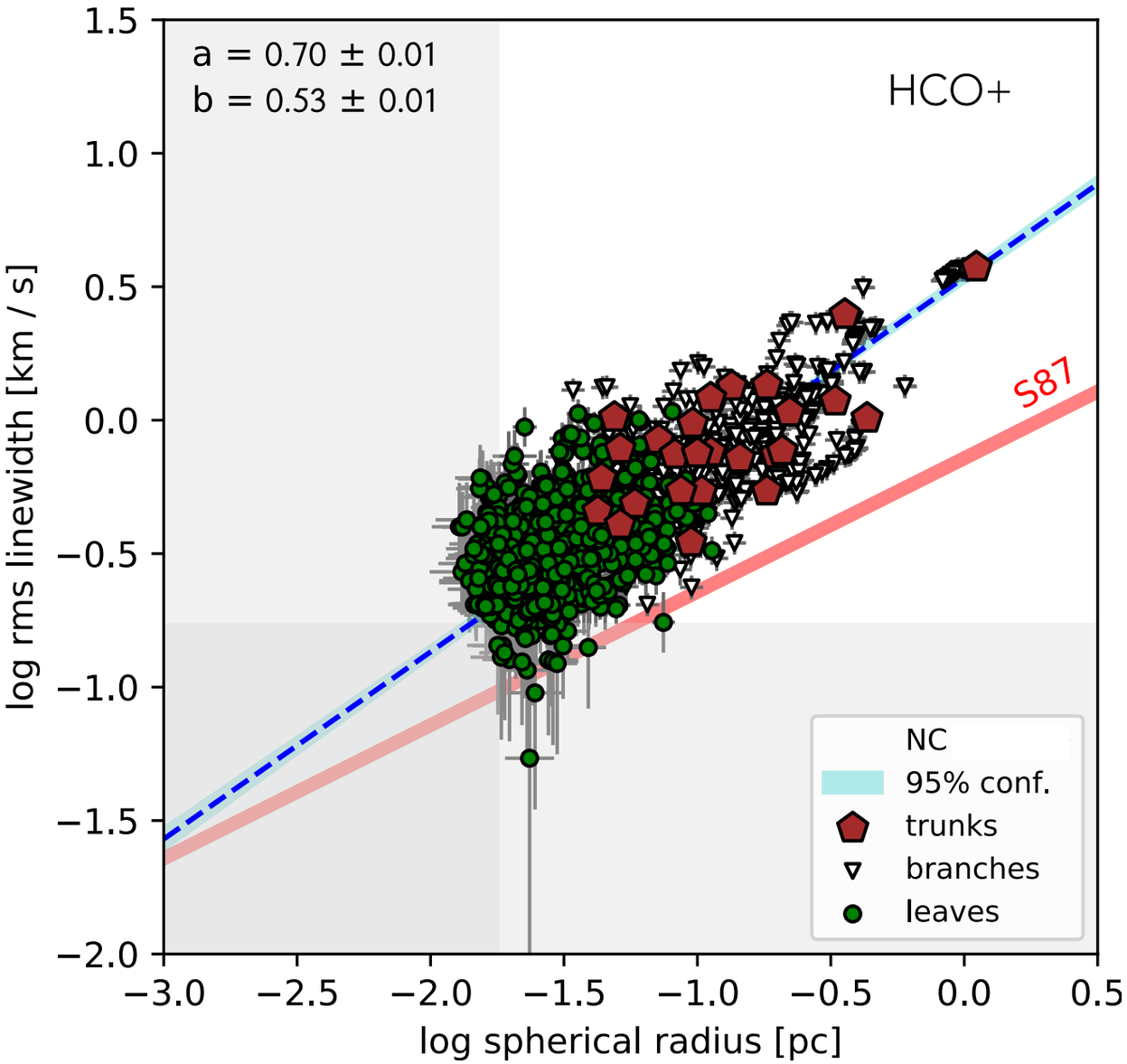




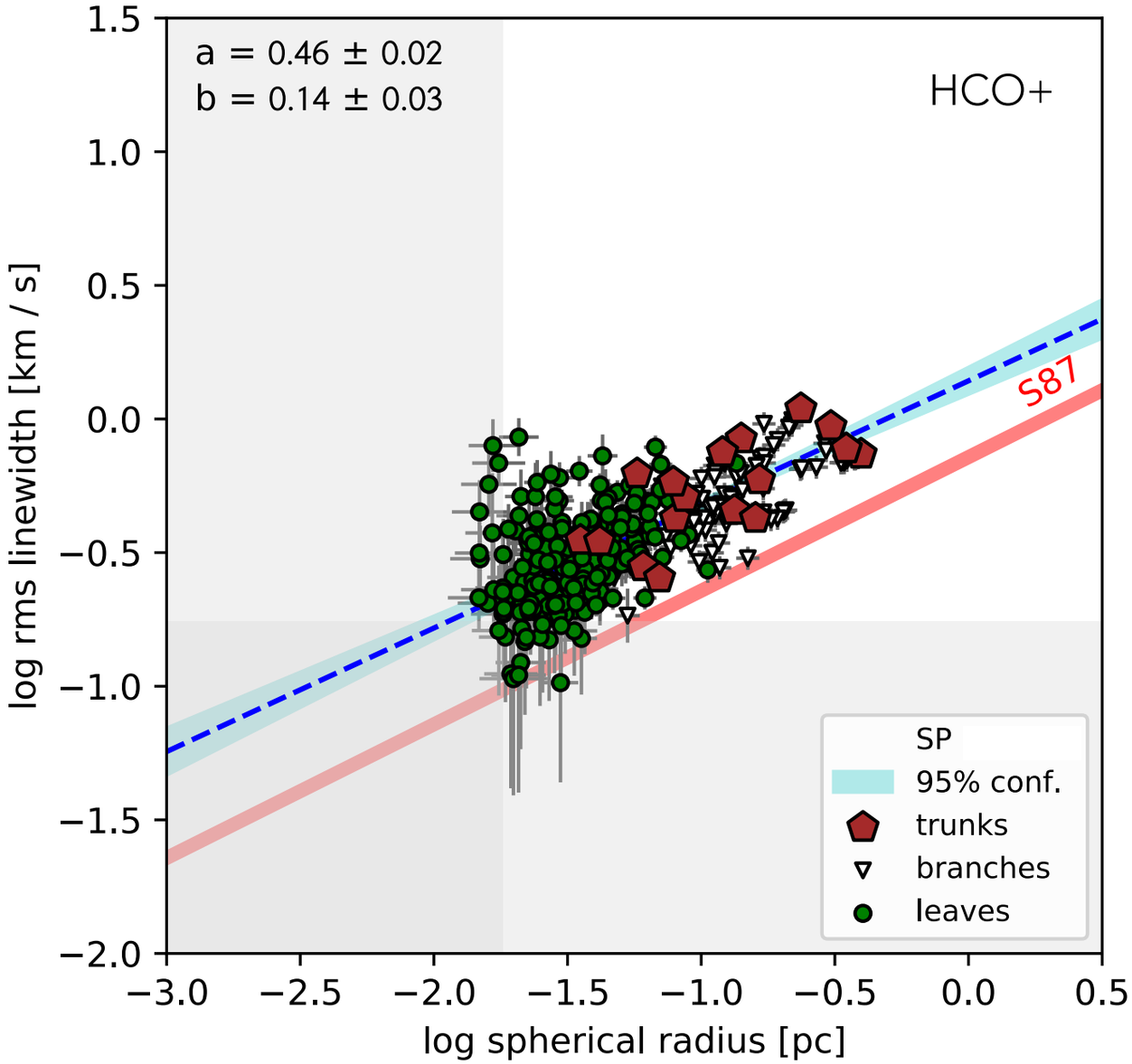




Northern Cloud



Southern Pillars



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WHAT IS NEXT?

- Detail model of the atomic gas (Cold+Warm component), and correction of the diffuse continuum effect.

- Characterization of the properties of the 60 massive clumps observed with Mopra

- Robust comparison between Northern Cloud and Southern Pillars using high resolution ALMA data

SUMMARY

- We have created a high resolution maps of the the molecular and atomic phases of the ISM in the Carina Nebula-Gum 31 complex, with a factor of 4 improvement in beam size compared to previous surveys.

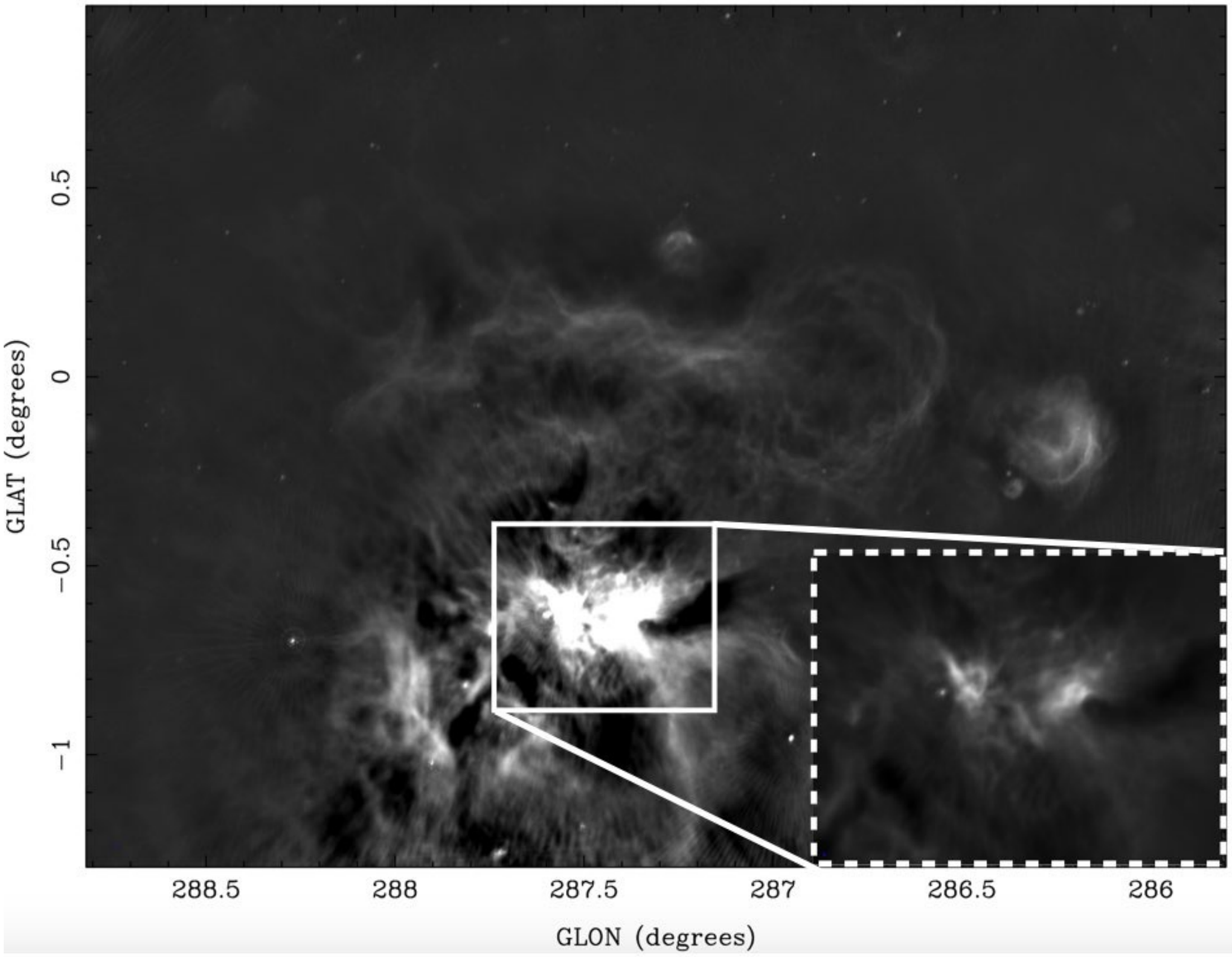
- The ISM in the Carina Nebula - Gum 31 complex is molecular dominated, despite the strong feedback effect exert by the massive stellar clusters.

- The high resolution map of the atomic gas has allowed us to find regions of cold HI where the phase transition from atomic to molecular is likely to be occurring.

- ALMA has provided detailed maps of the internal properties of two massive clumps at very different environments.

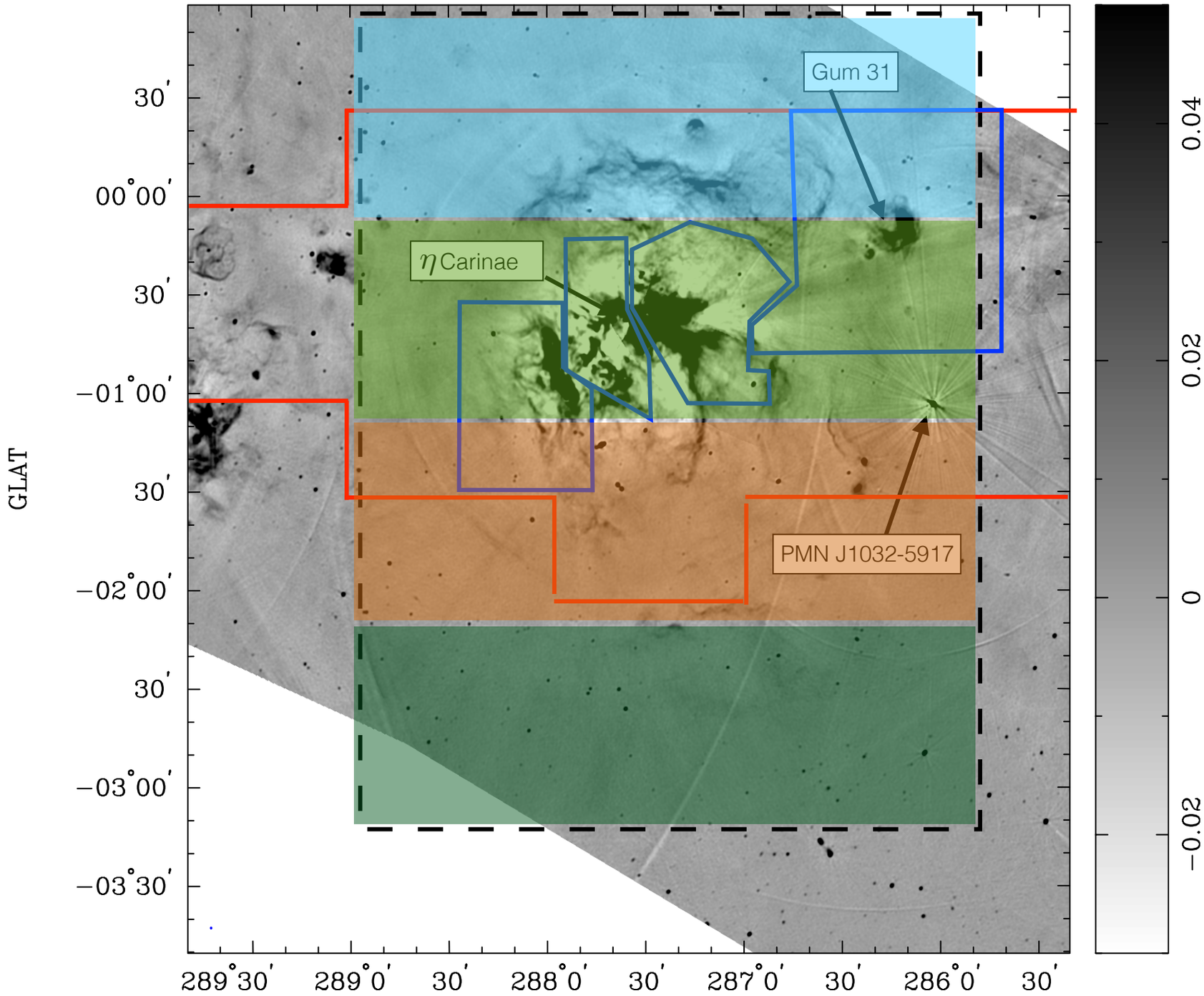
In progress… stay tuned

Continuum 1.8 GHz



Ionized Gas

CARPARCS covers 3 x 4 deg2 on the sky in the 1-3 GHz continuum band with a total of 523 pointings.



0.835GHz continuum emission of the CNC-Gum31 complex Molonglo Observatory Synthesis Telescope

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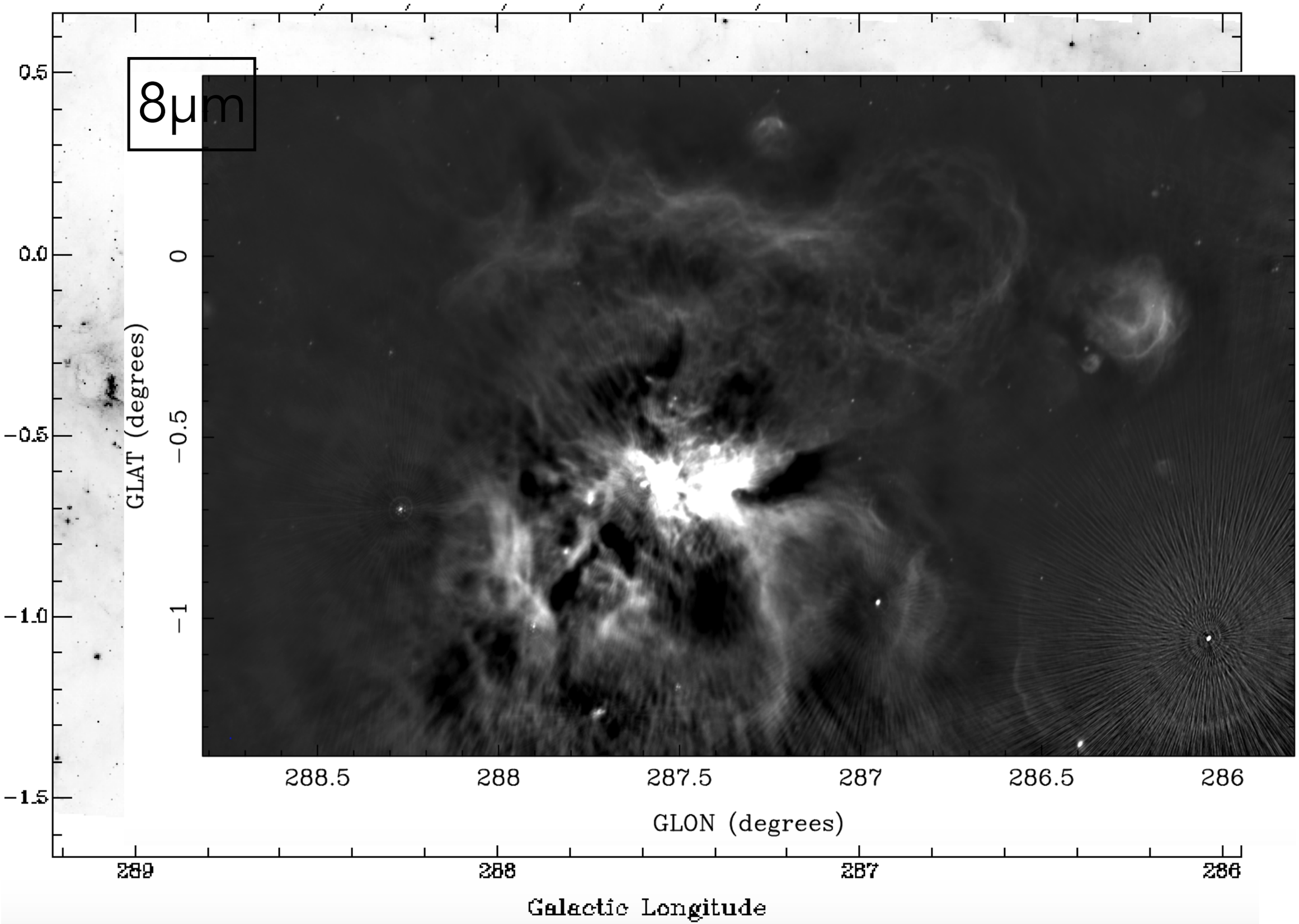
Continuum 1.8 GHz



Gas vs ^{12}CO + HI

Gum 31 region

Optically thin

$$N_H = 1.8 \times 10^{18} T_{MB} \Delta V \quad \mathrm{cm}^{-2}$$

$$X_{\mathrm{CO}} = 2.0 \times 10^{20}$$

$$R_{\mathrm{dg}} = 0.01$$

Overall consistency between the different mass tracers

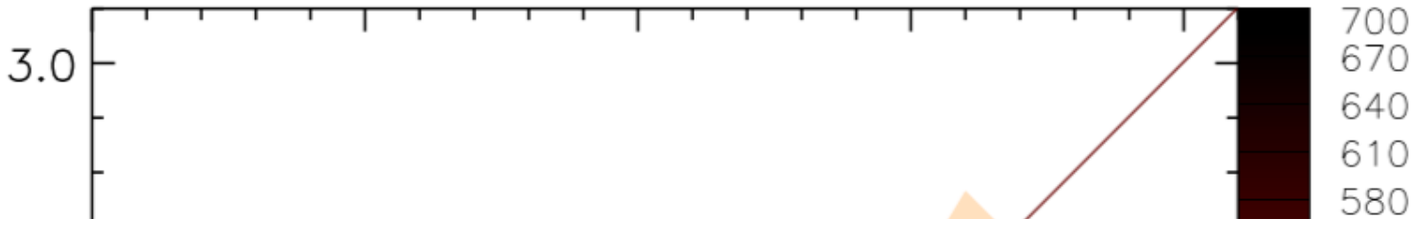


Table 1. Gas mass budget for Gum 31.

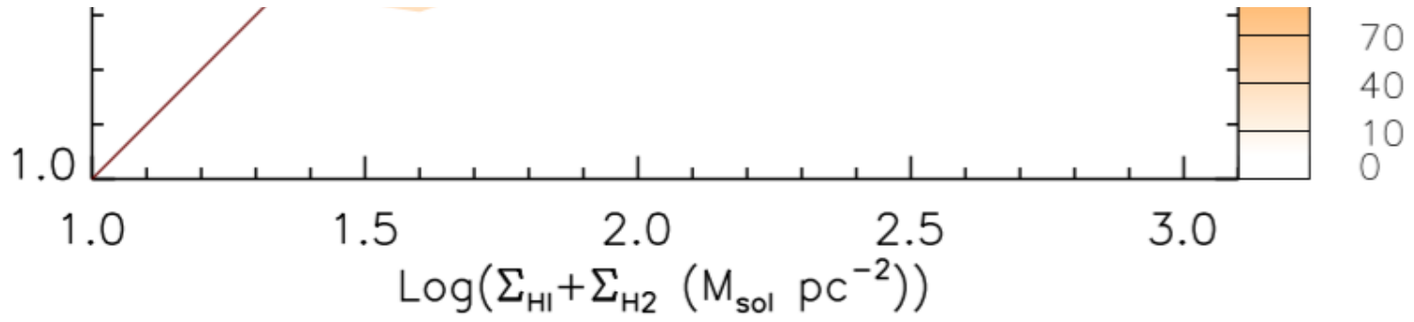
M(dust)[a] $M_\odot \times 10^5$	M_{H2}[b] $M_\odot \times 10^5$	M_{HI}[c] $M_\odot \times 10^5$	$M_{\mathrm{H2}}+M_{\mathrm{HI}}$ $M_\odot \times 10^5$
(1.5 ± 0.1)	(1.1 ± 0.1)	(0.6 ± 0.1)	(1.7 ± 0.1)

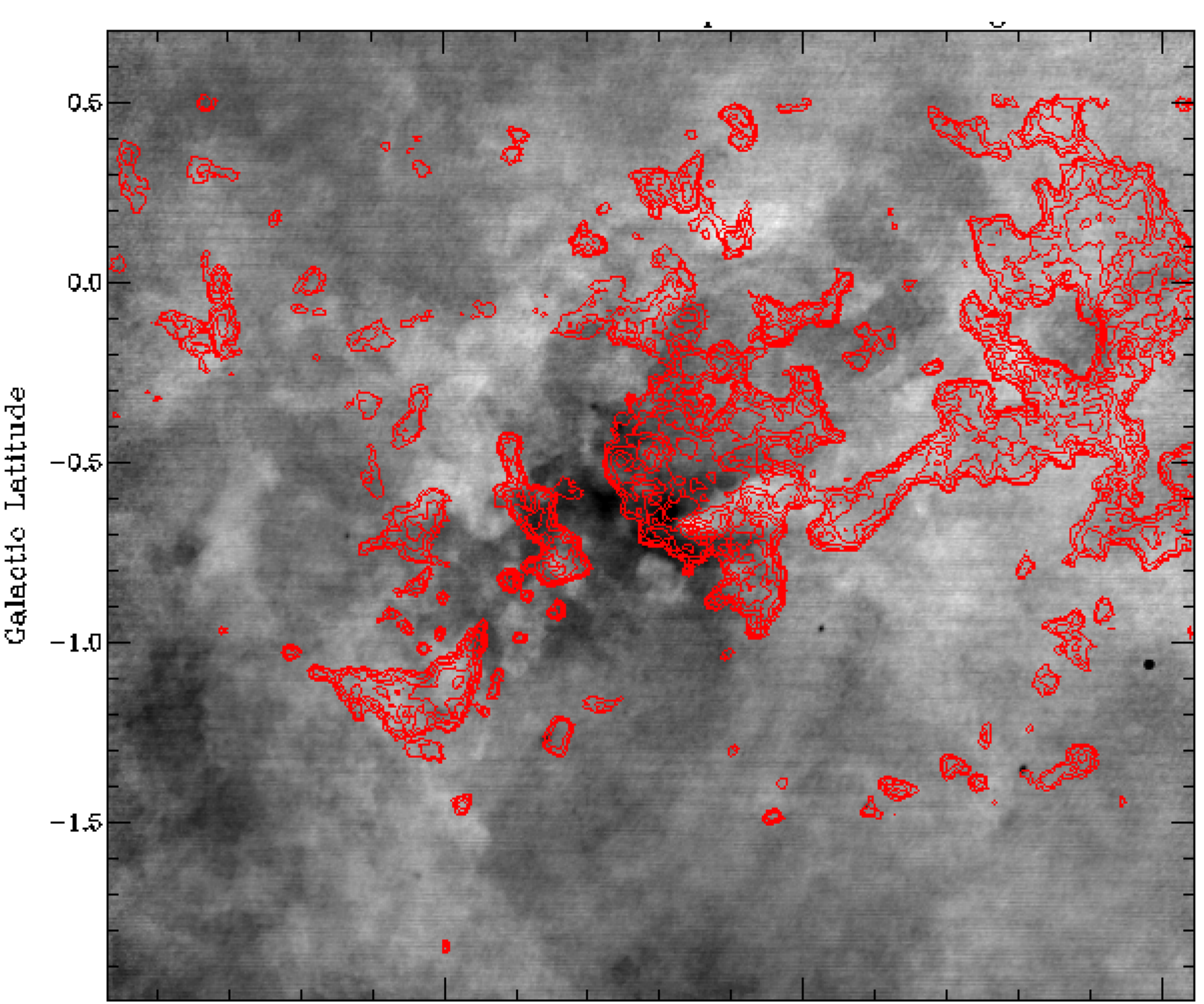
Notes.

[a] M(dust) is the total gas mass derived from dust emission.

[b] M_{H2} is the molecular gas mass derived from ^{12}CO.

[c] M_{HI} is the atomic gas mass derived from H I 21 cm line.




0.5
0.0
−0.5
−1.0
−1.5
Galactic Latitude

THE MOPRA SOUTHERN GALACTIC PLANE CO SURVEY

- Mopra telescope is a 22-m single dish telescope
- Warrumbungle Mountains, about 450 km north-west of Sydney.
- Elevation of 866 m
- Primarily for 3-mm spectroscopy