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

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NRAO FELLOW AT JOINT ALMA OBSERVATORY

NRAO POSTDOC SYMPOSIUM
SOCORRO
MARCH, 2018

Carina Project

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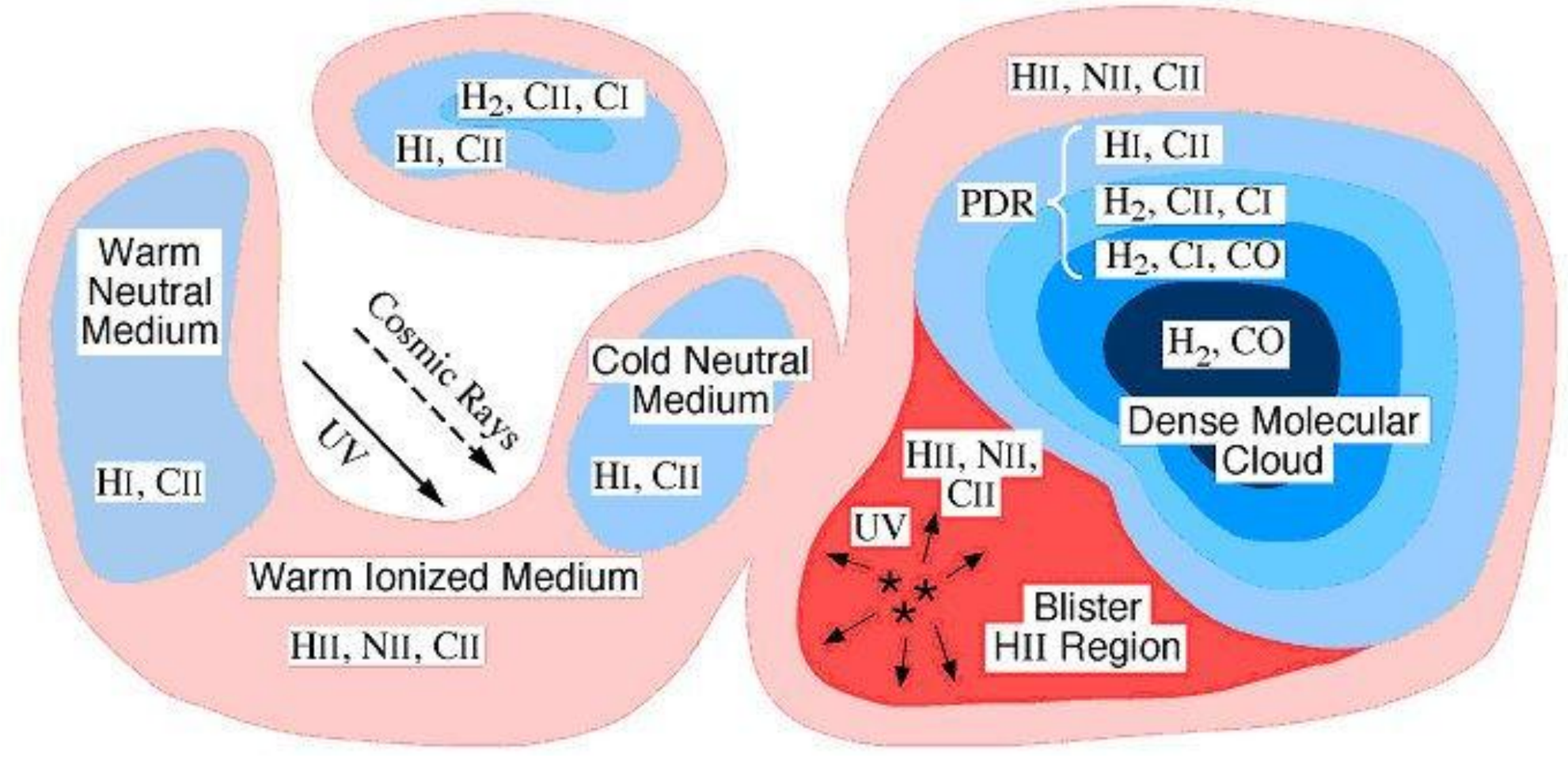
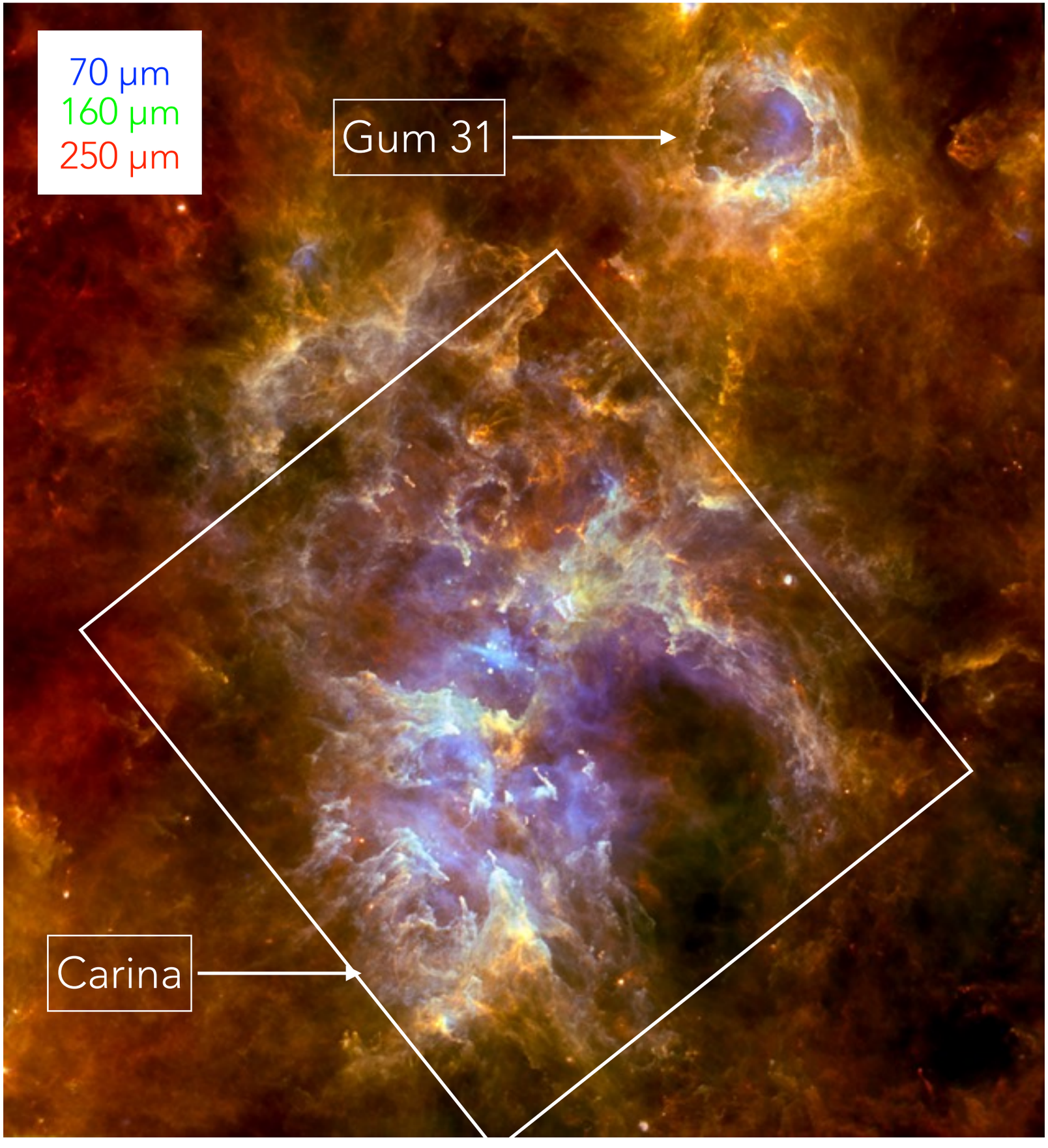
Shari Breen
Cormac Purcell
Yanett Contreras
B. M. Gaensler
Catherine Braiding
Guido Garay
Andres Guzman
and the Team Mopra!

Schematics of the multi-phase ISM and its diagnostic tracers



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.**



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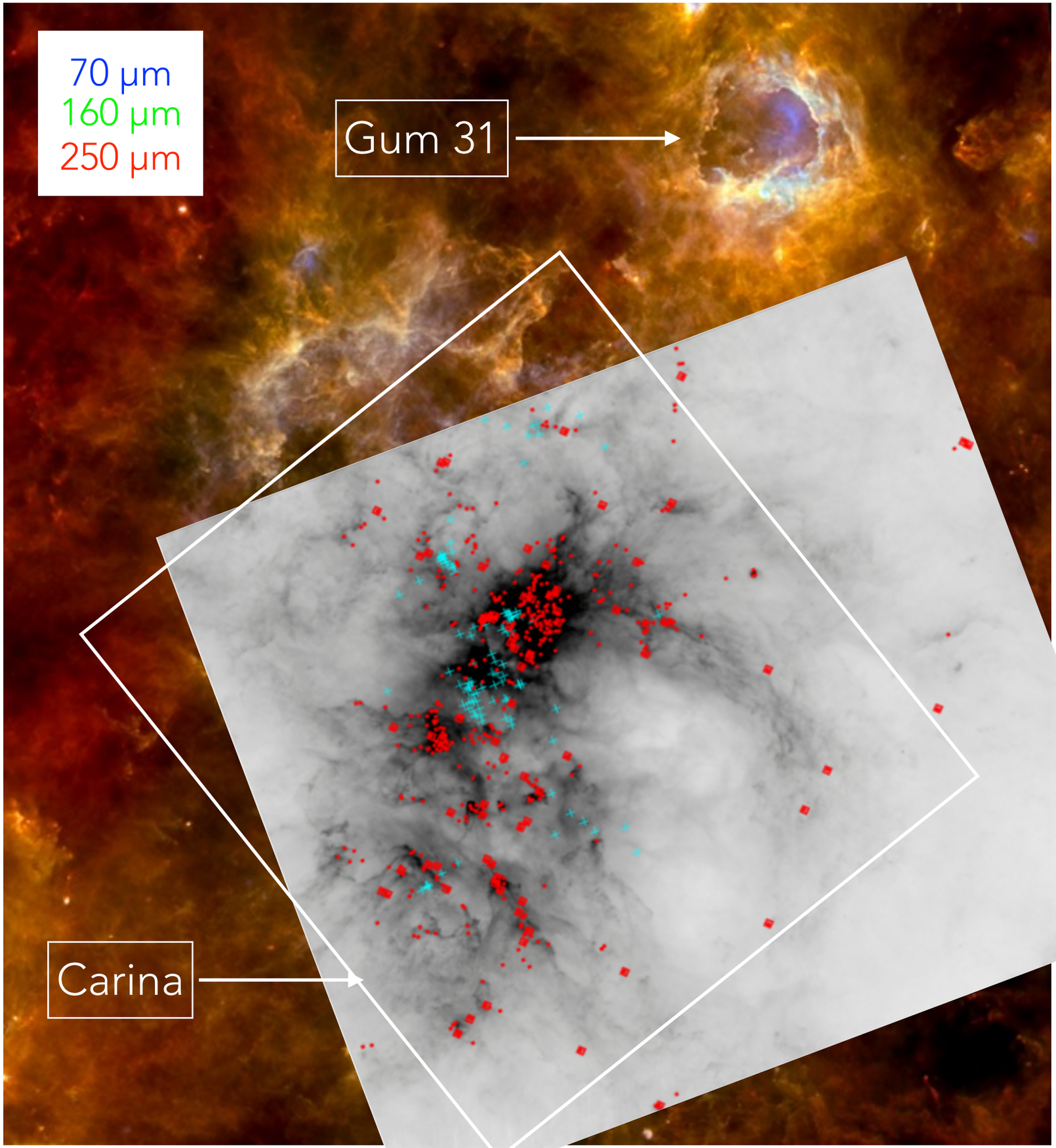

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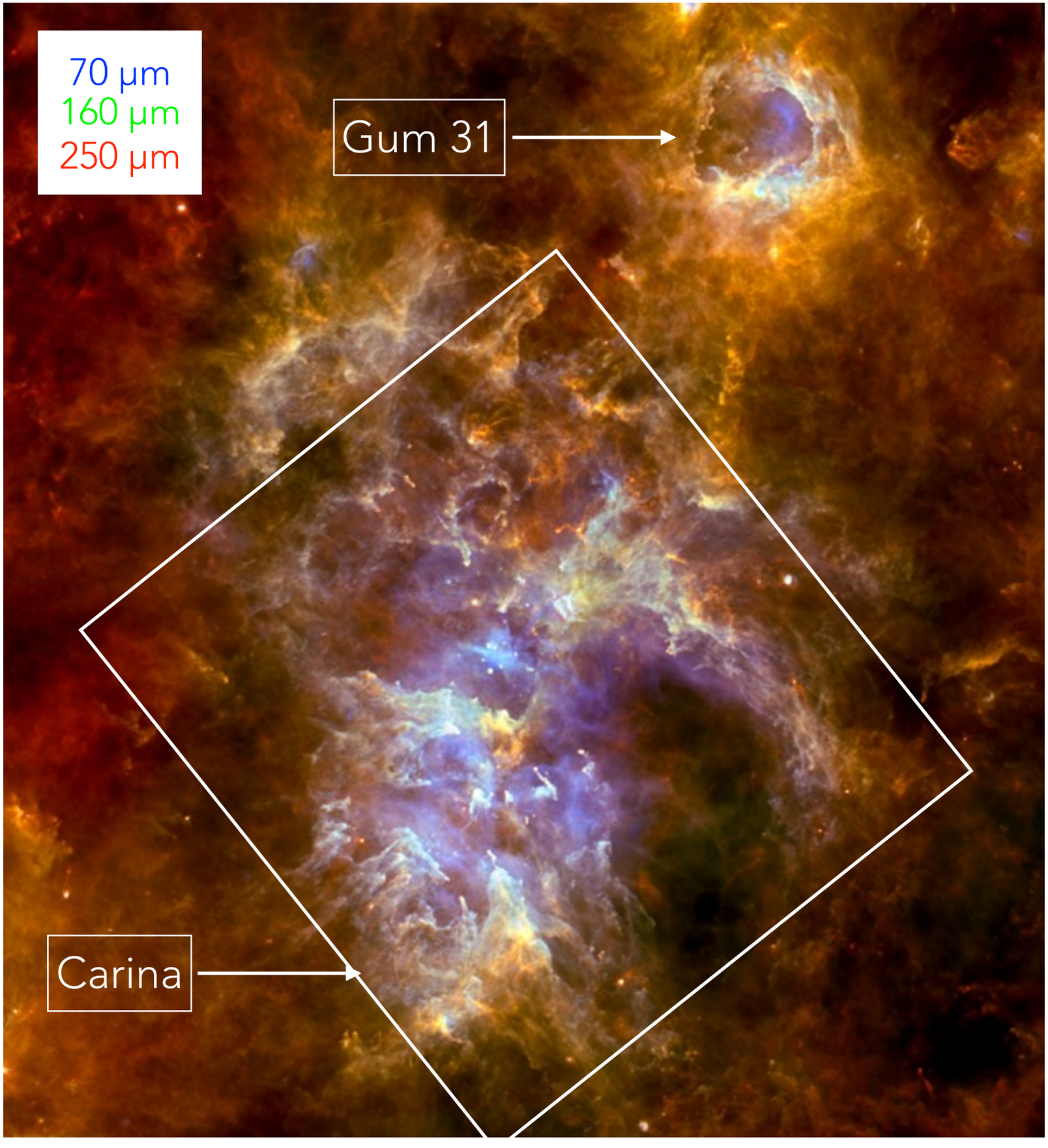

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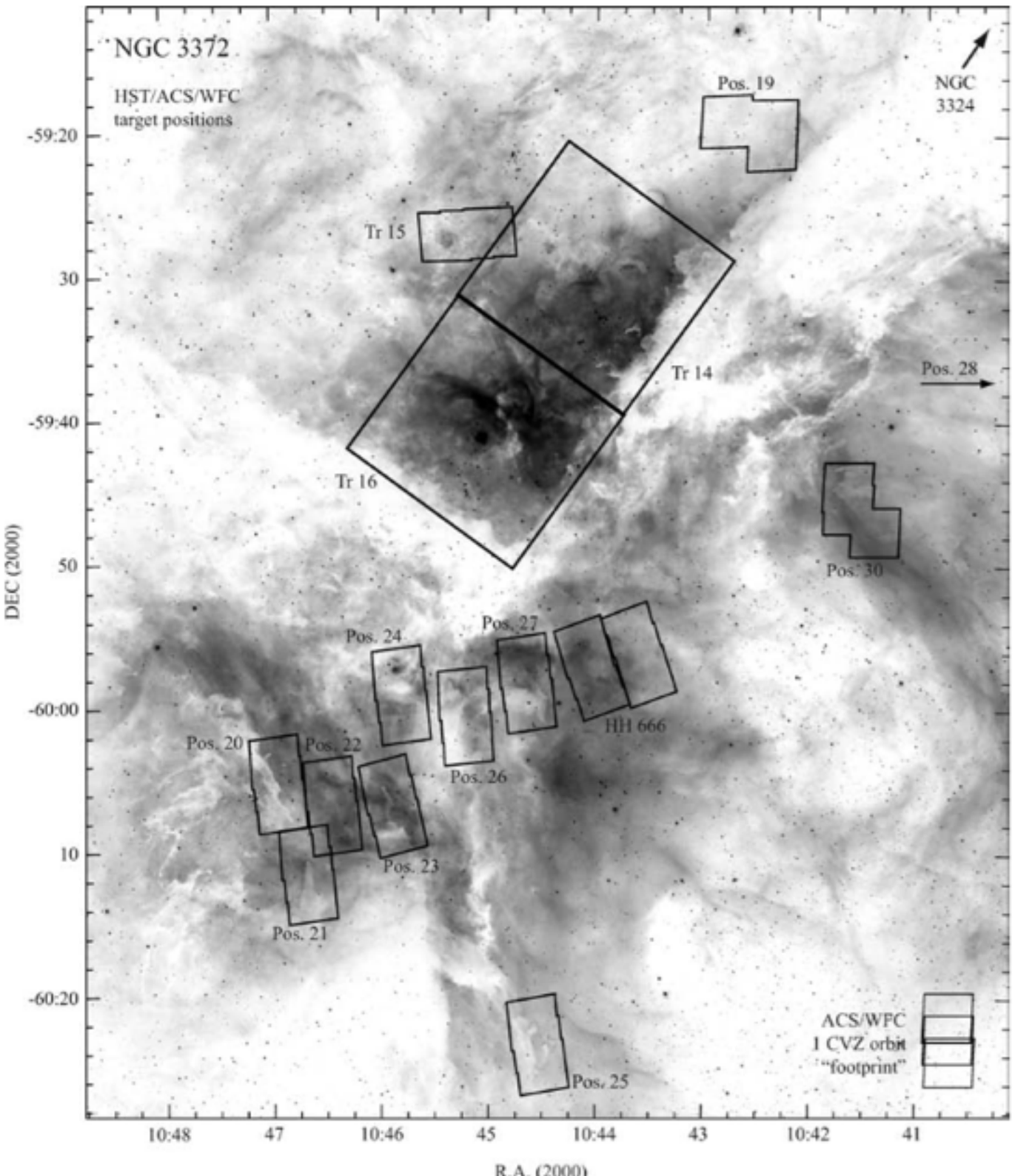

Smith et al., 2010

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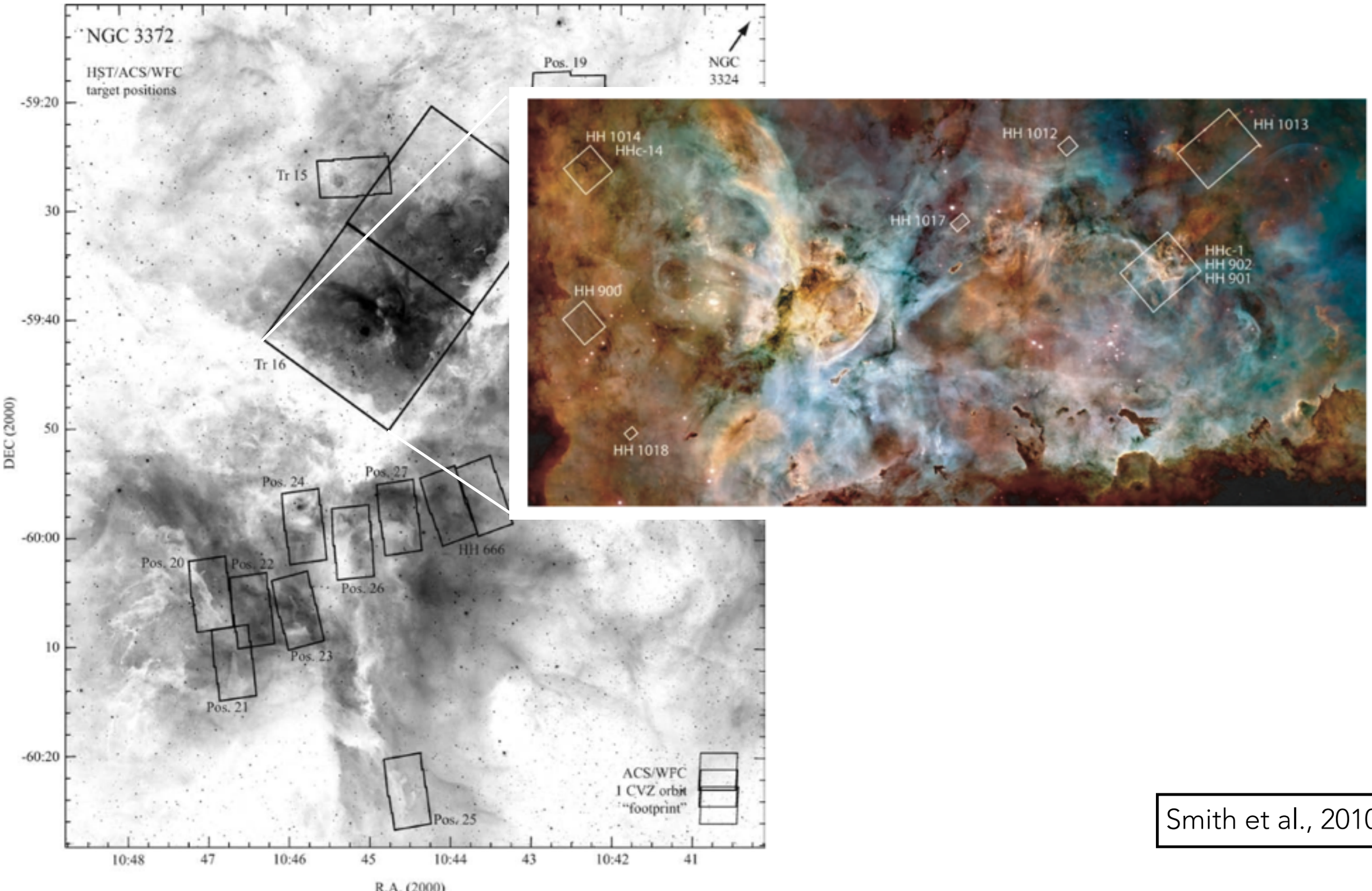

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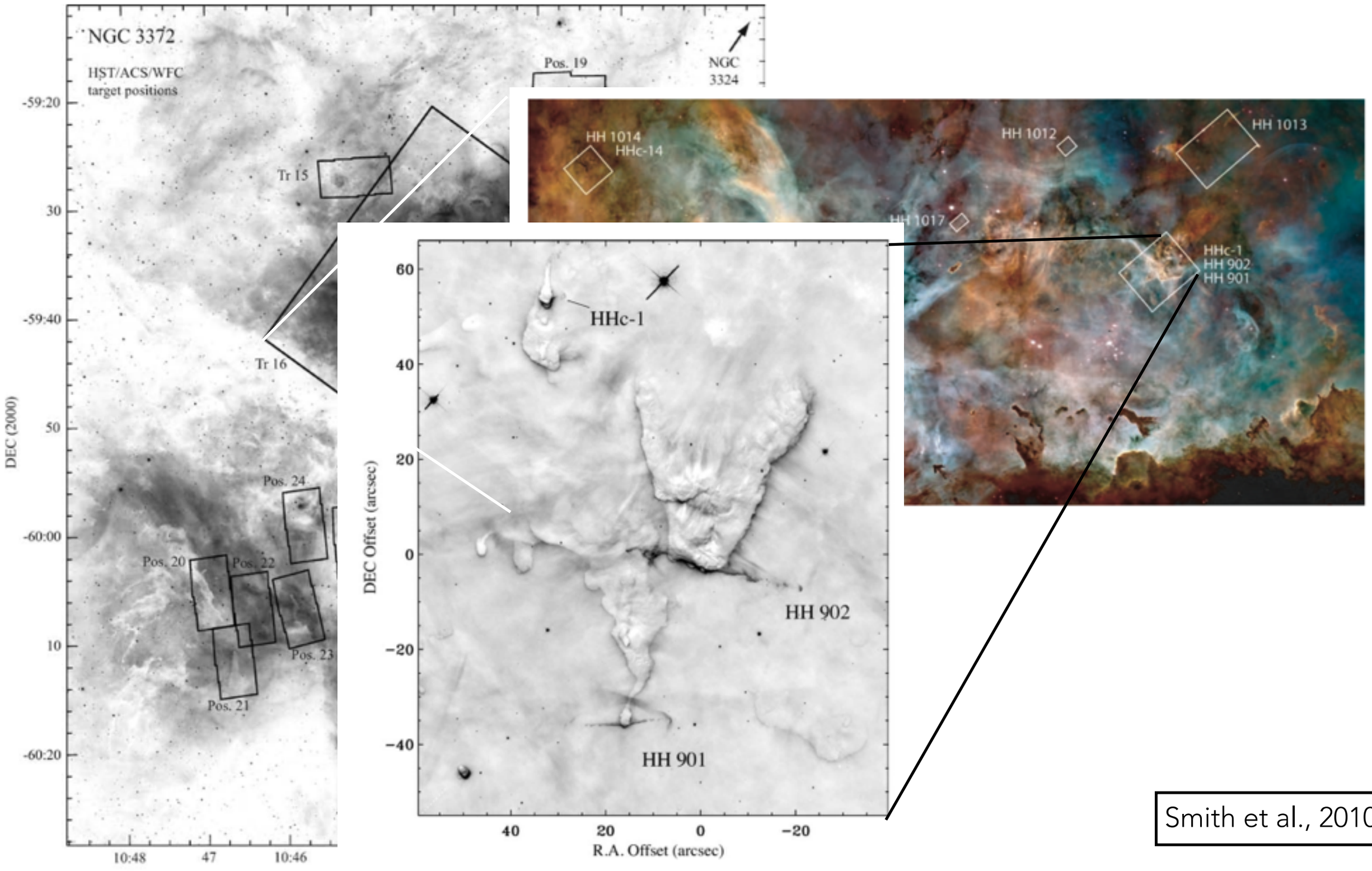
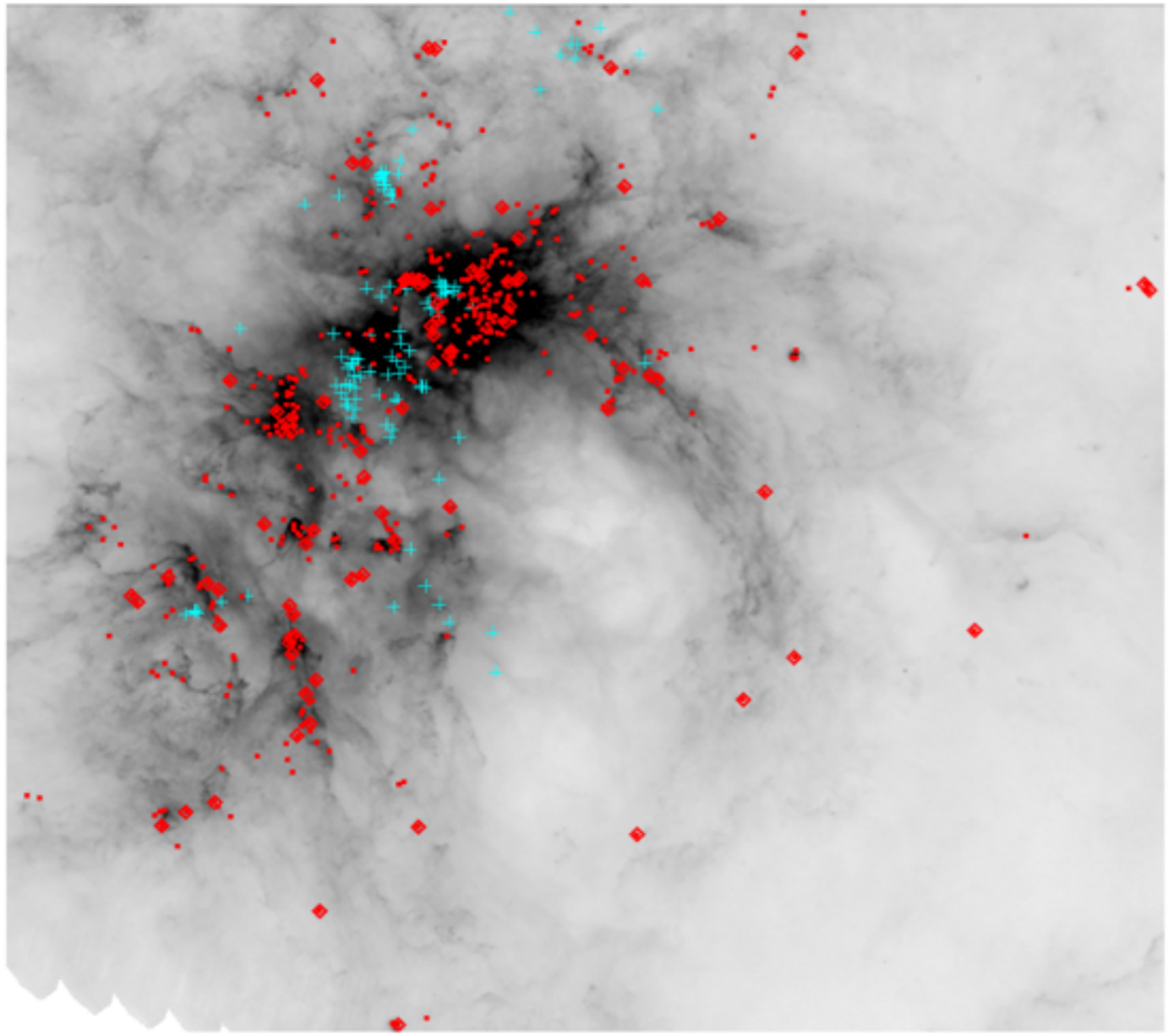


Smith et al., 2010

Gaczkowski et al. 2013

Several hundreds of young stellar object (YSO) candidates have been identify.



The YSOs are found predominantly just outside of the pillars head, suggesting that their formation was in fact triggered

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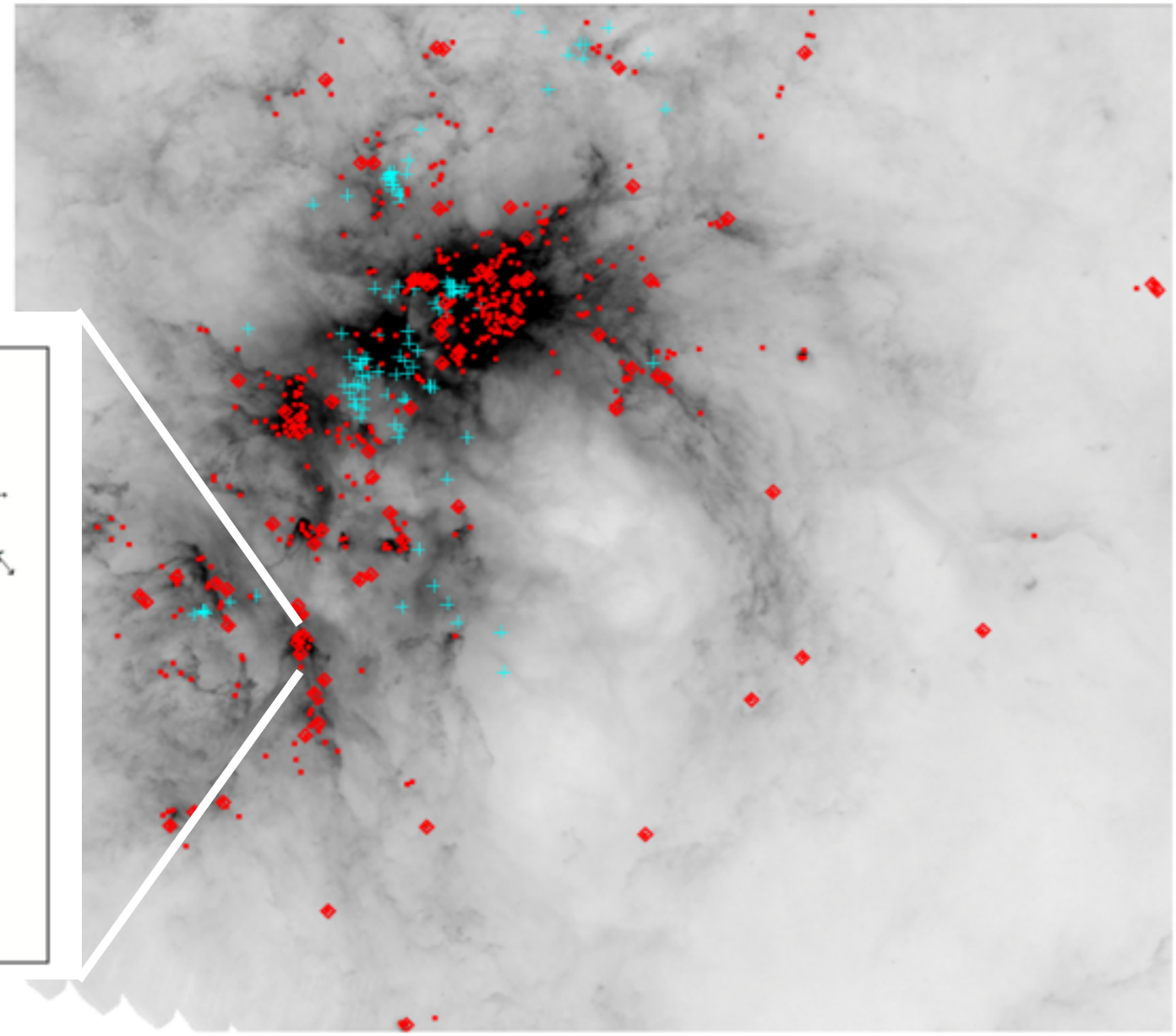
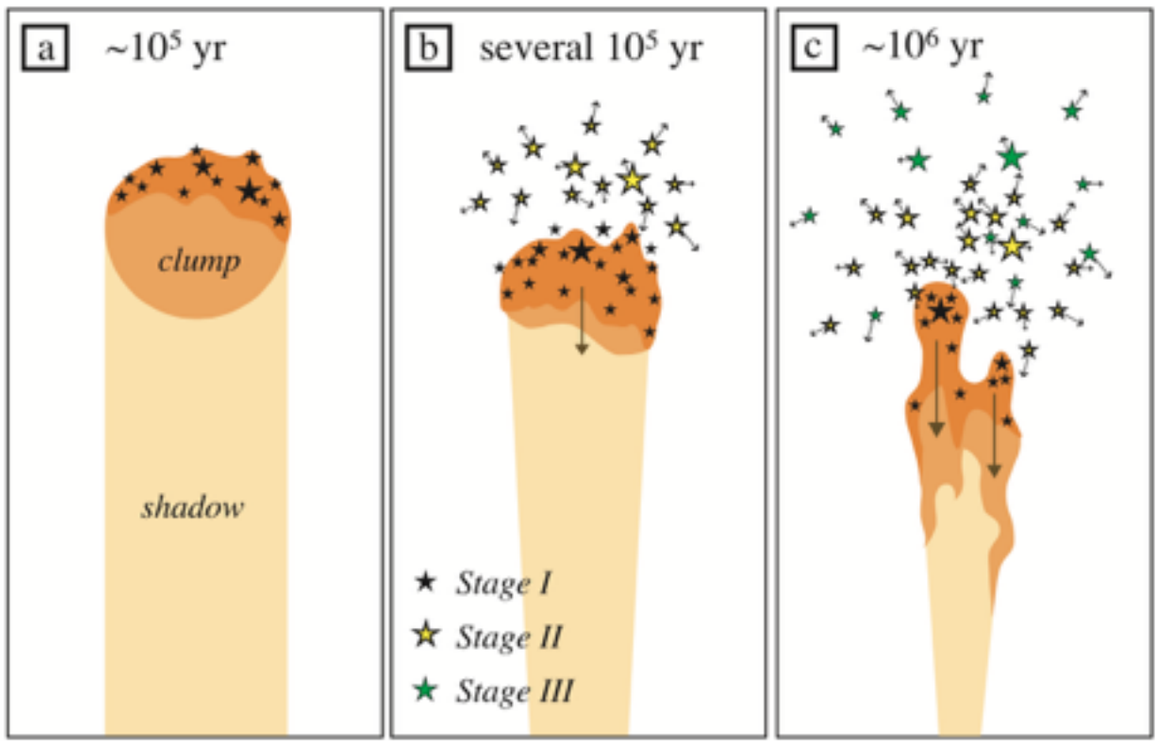
Gaczkowski et al. 2013





Smith et al. 2010

Still other open questions…

- **The total infrared luminosity detected from the region (re-radiated from ultraviolet heated dust) is only about half the energy input from the known stars.**

- **The measured free–free radio continuum emission only accounts for about three-quarters of the ionizing flux from these same stars.**

Molecular gas

$X_{\rm CO}$

Rebolledo et al. (2017)

CO

Rebolledo et al. (2016)

HI

Dust

τ, T_s

$\delta_{\rm GDR}$

Atomic gas

Total gas

The Carina Nebula Project

- CARPARCS
  - ATCA + Parkes
    - Ionised gas, B field
      atomic gas
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    - CO, C, and
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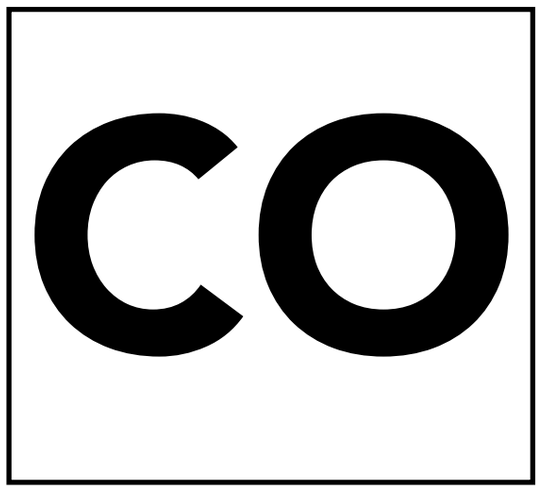
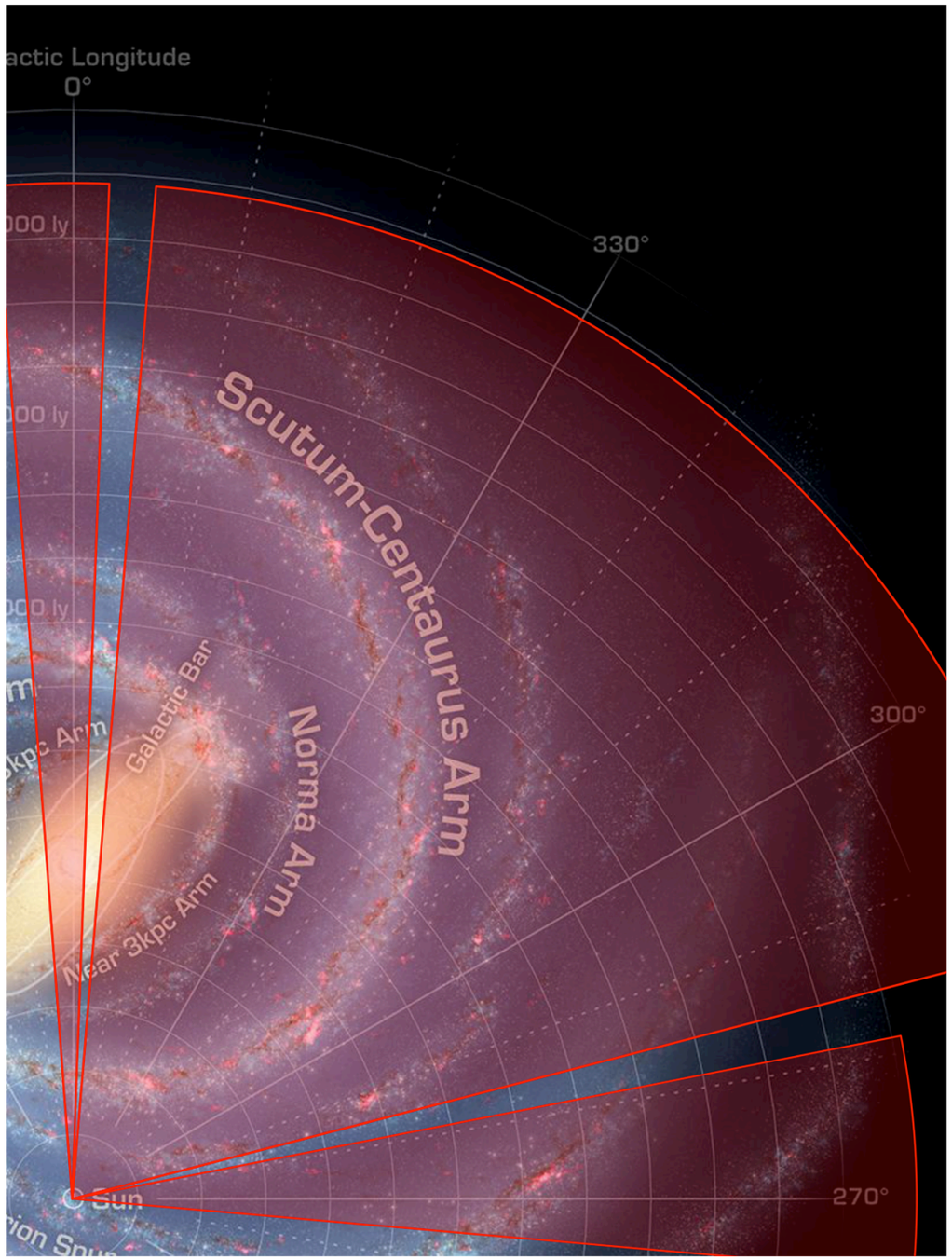

CO

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

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.)



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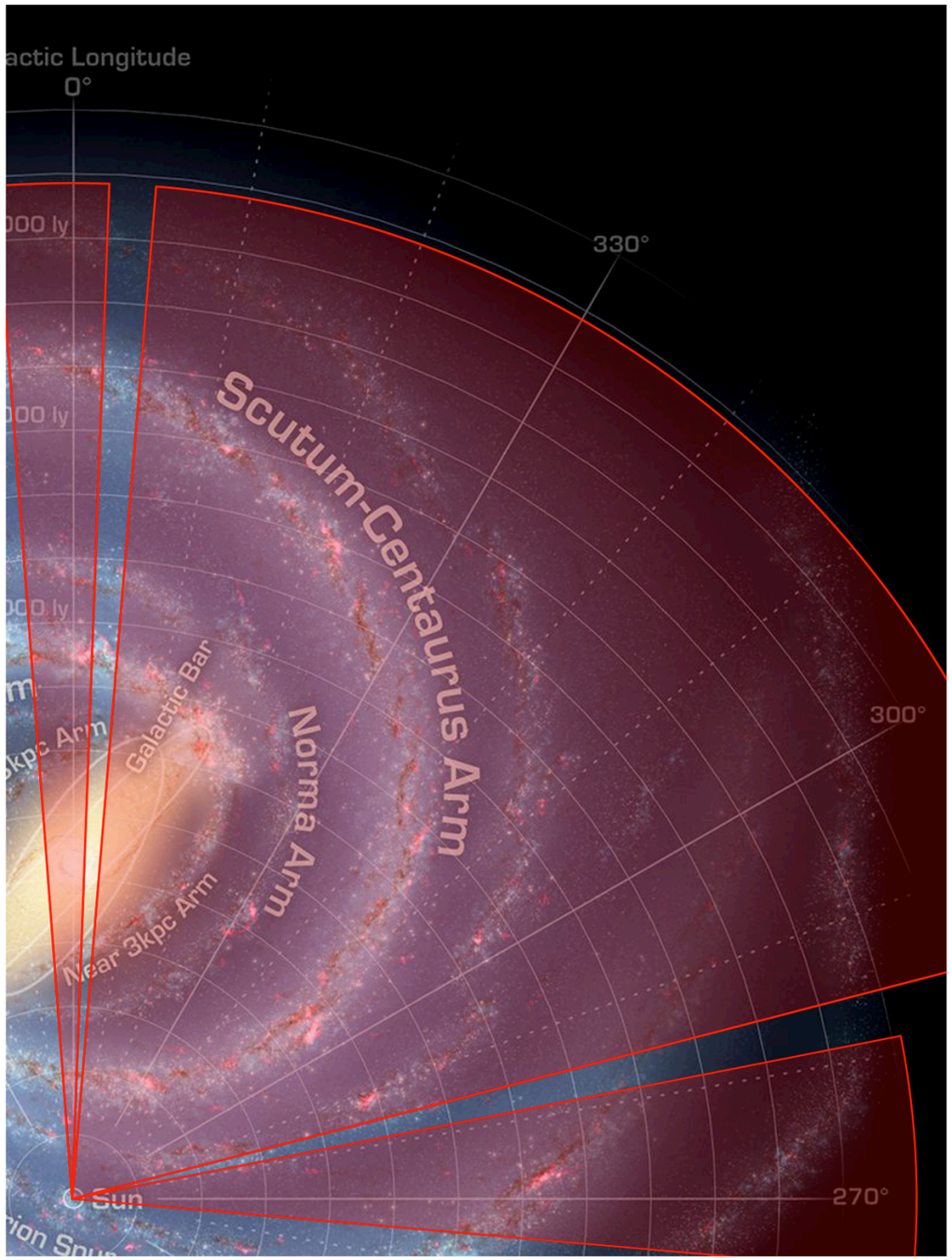
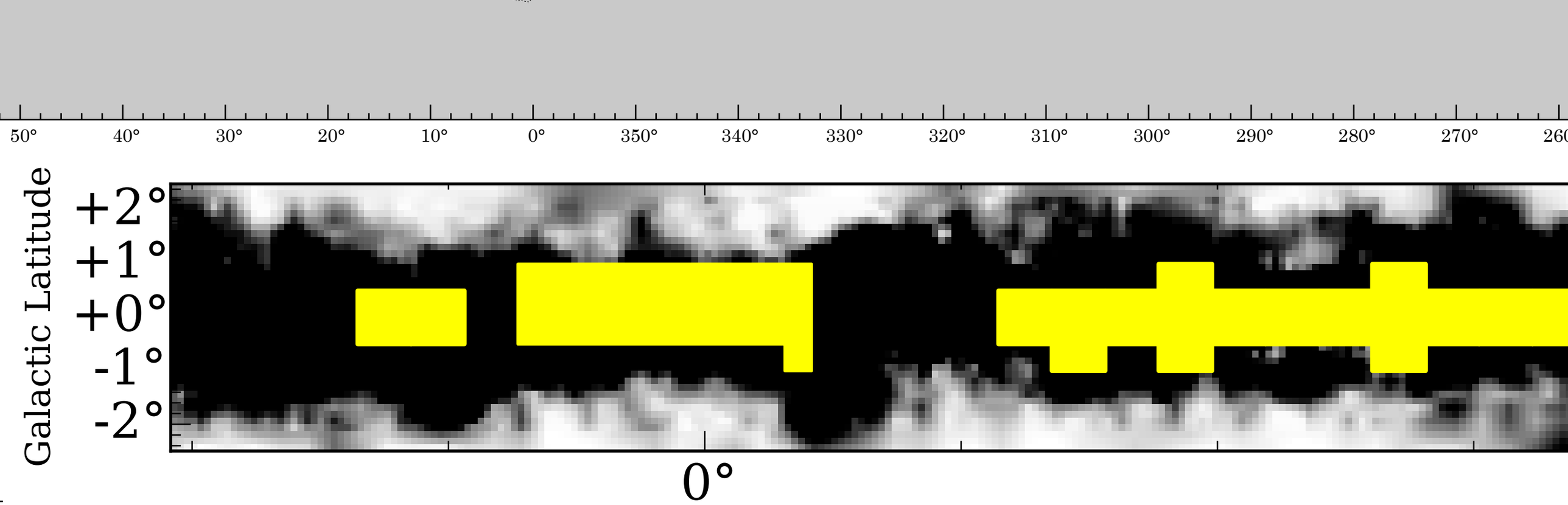


Dame, Hartmann & Thaddeus (2001)



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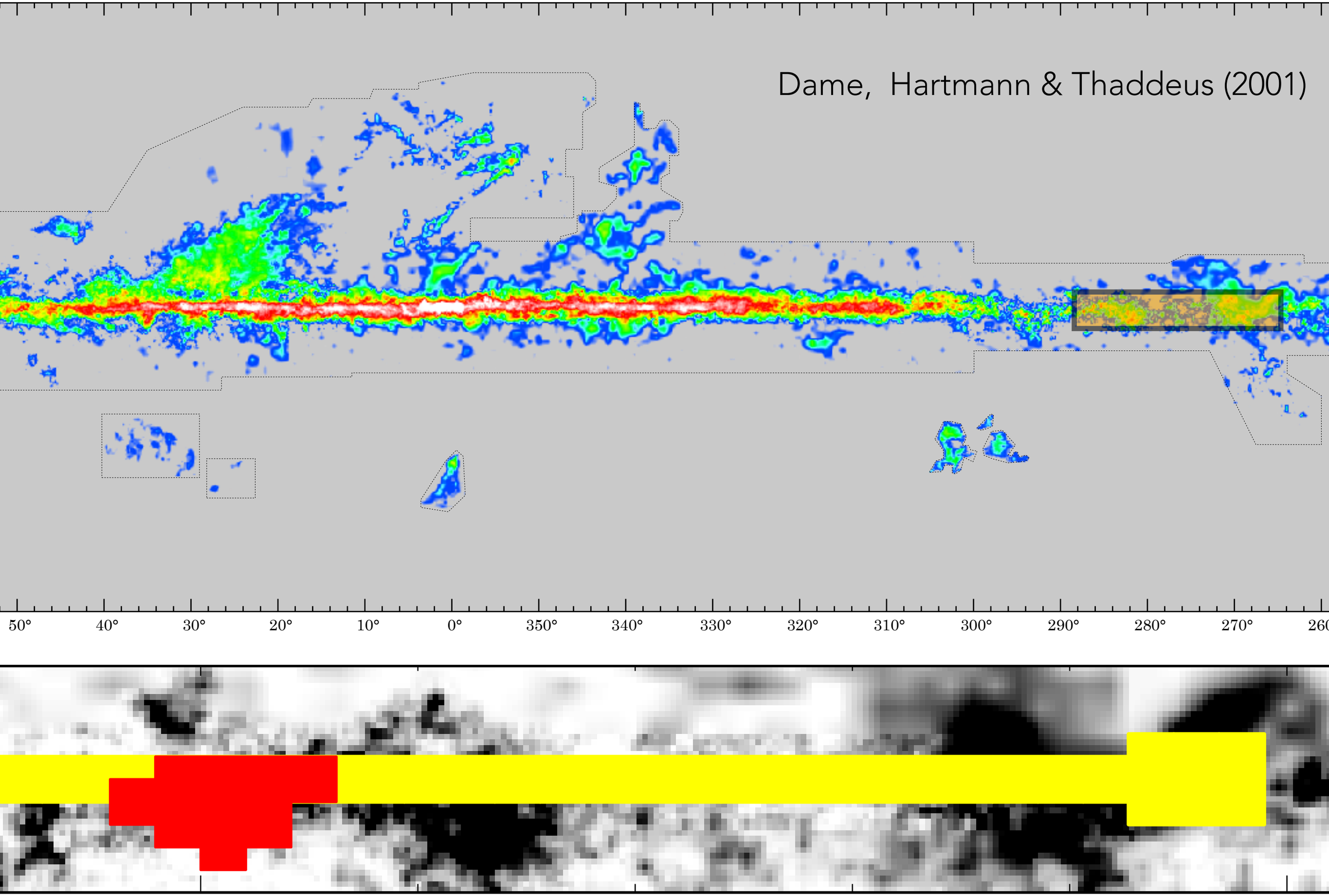
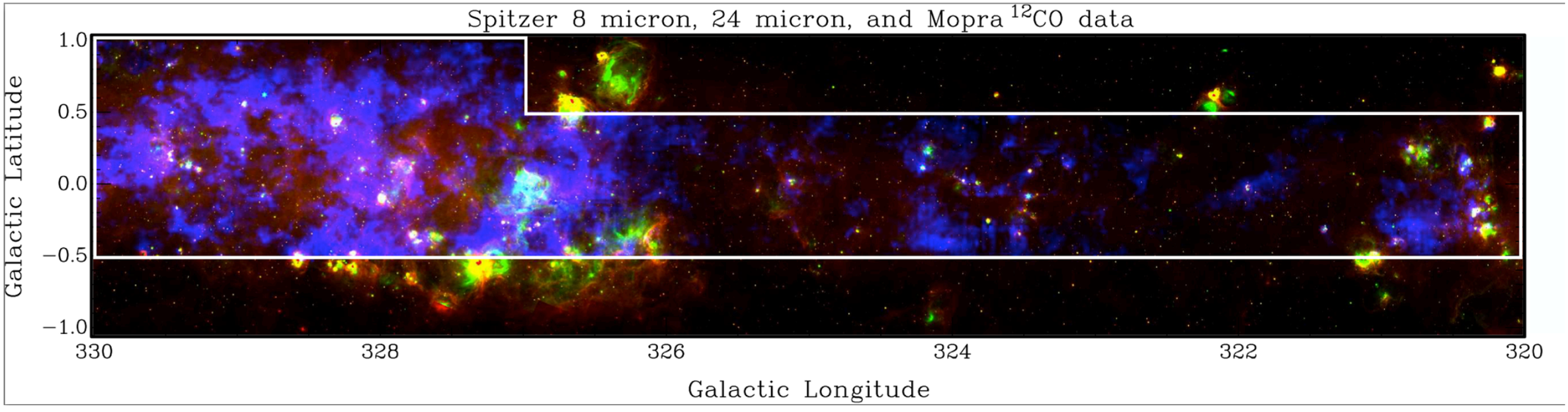


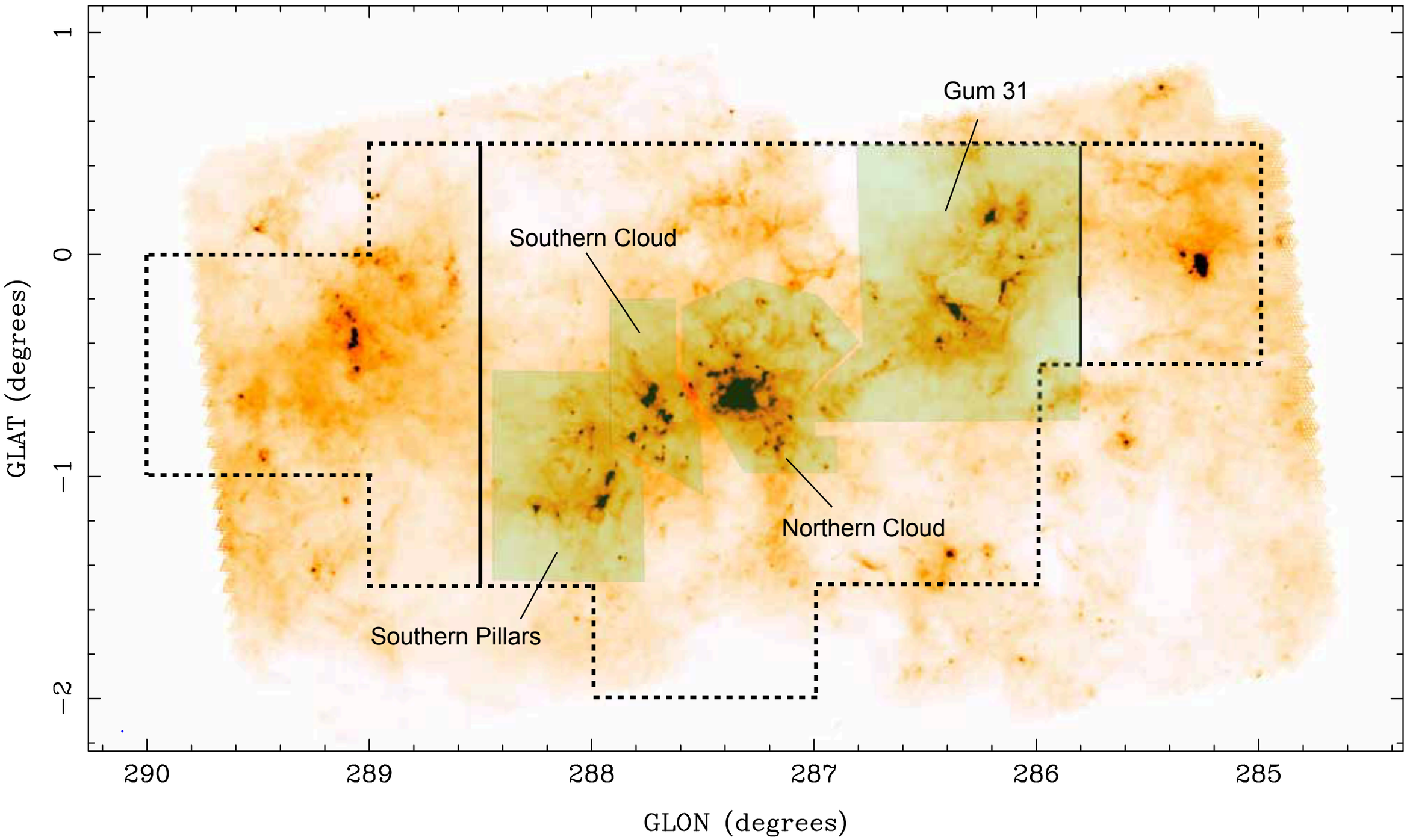
Data Release 1! (DR1)

- 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

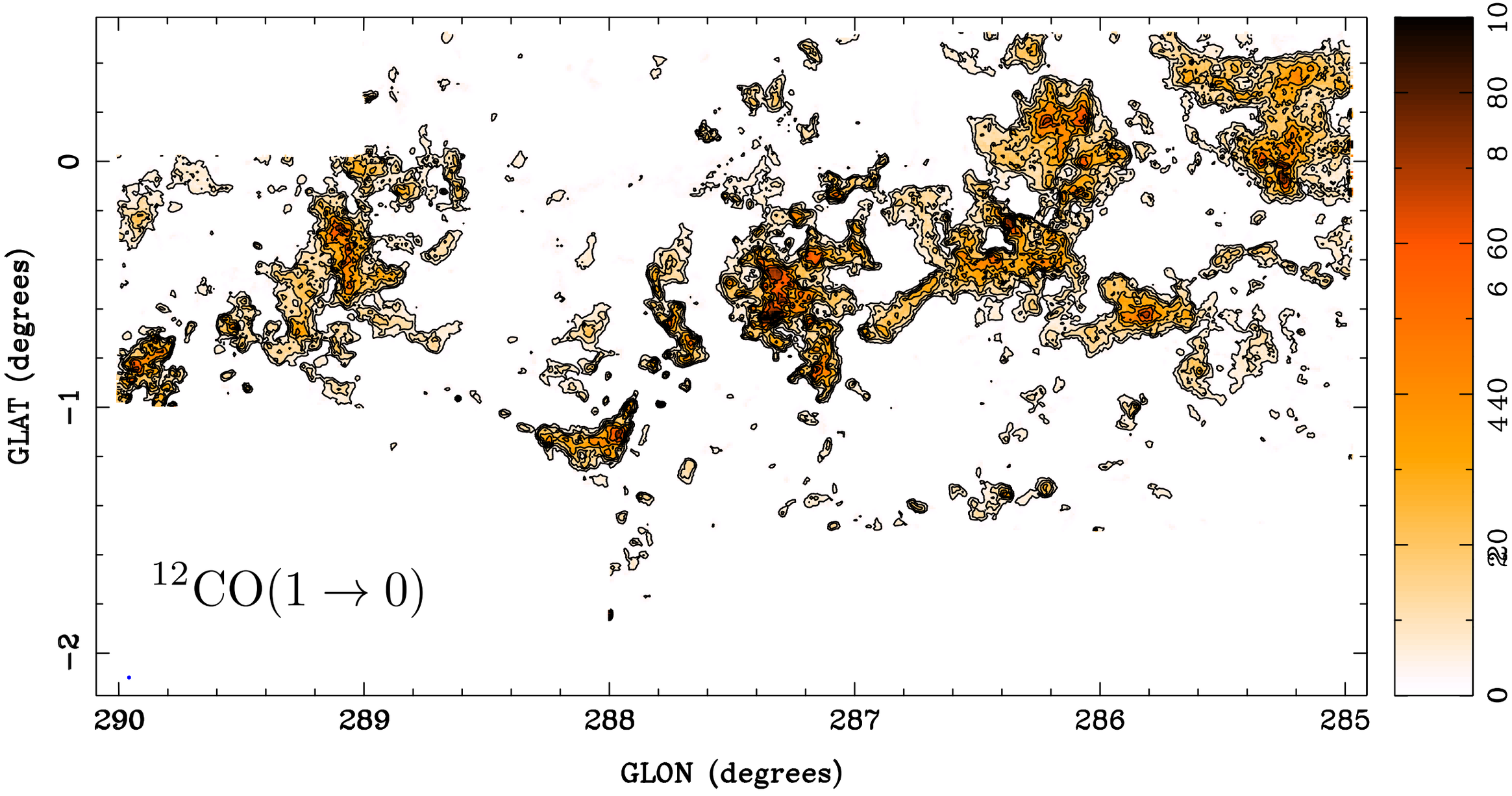


Data Release 2! (Carina)

Rebolledo et al. 2016, MNRAS, 456, 2406



Coverage ~ 9.5 deg^2



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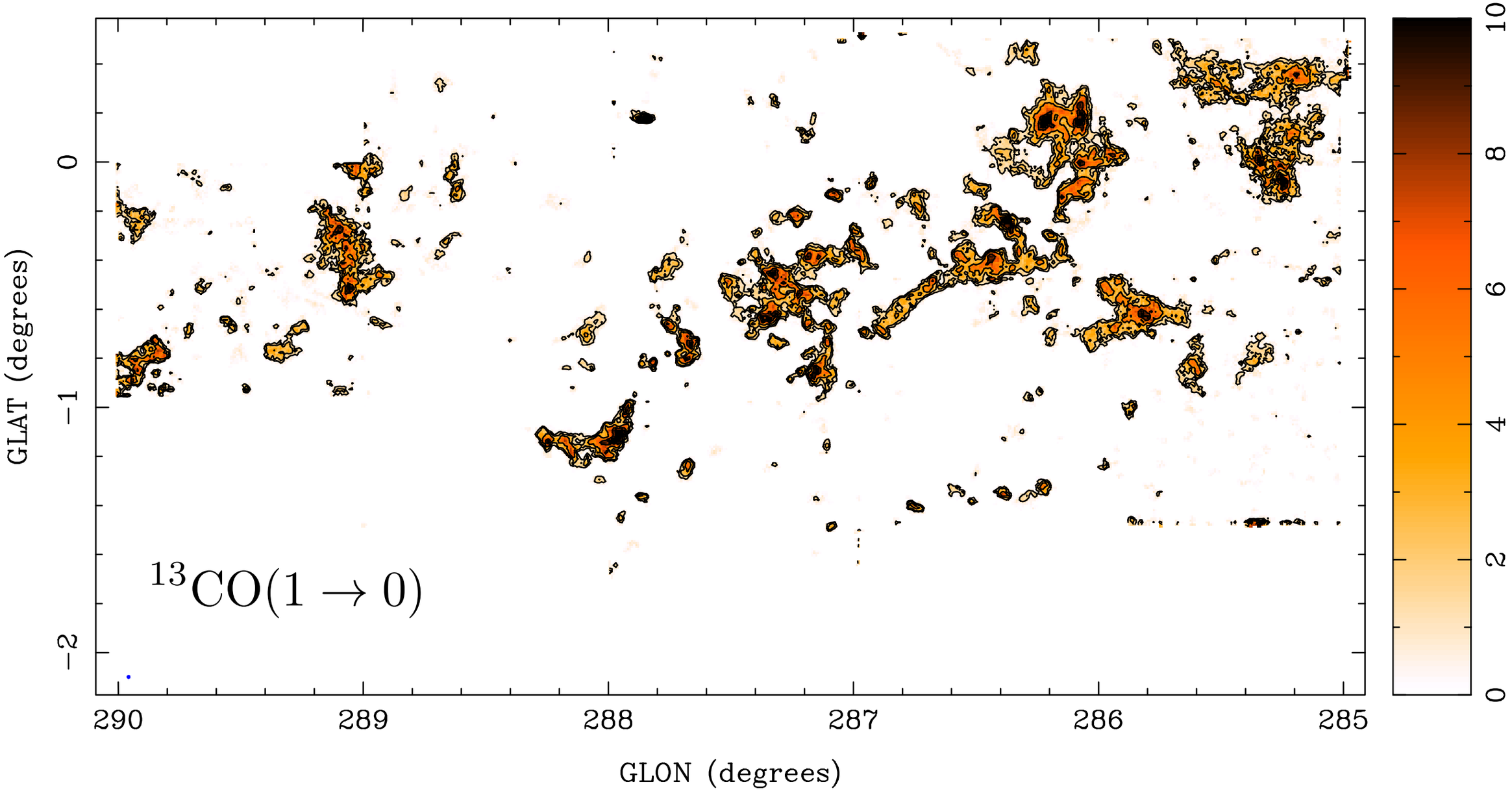
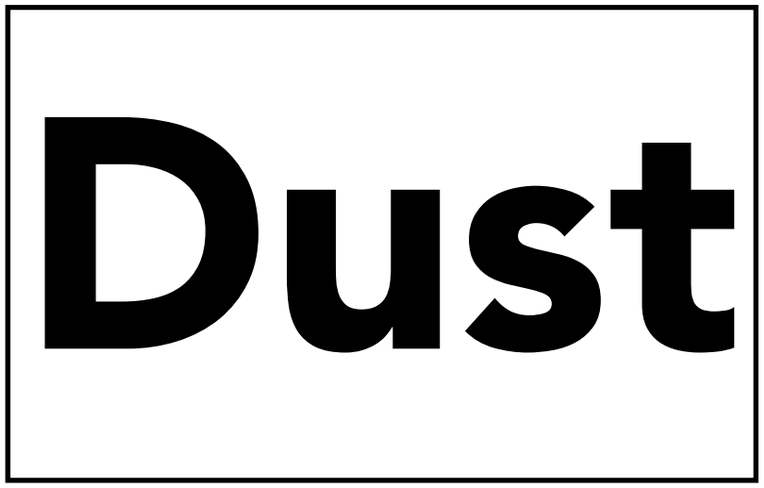
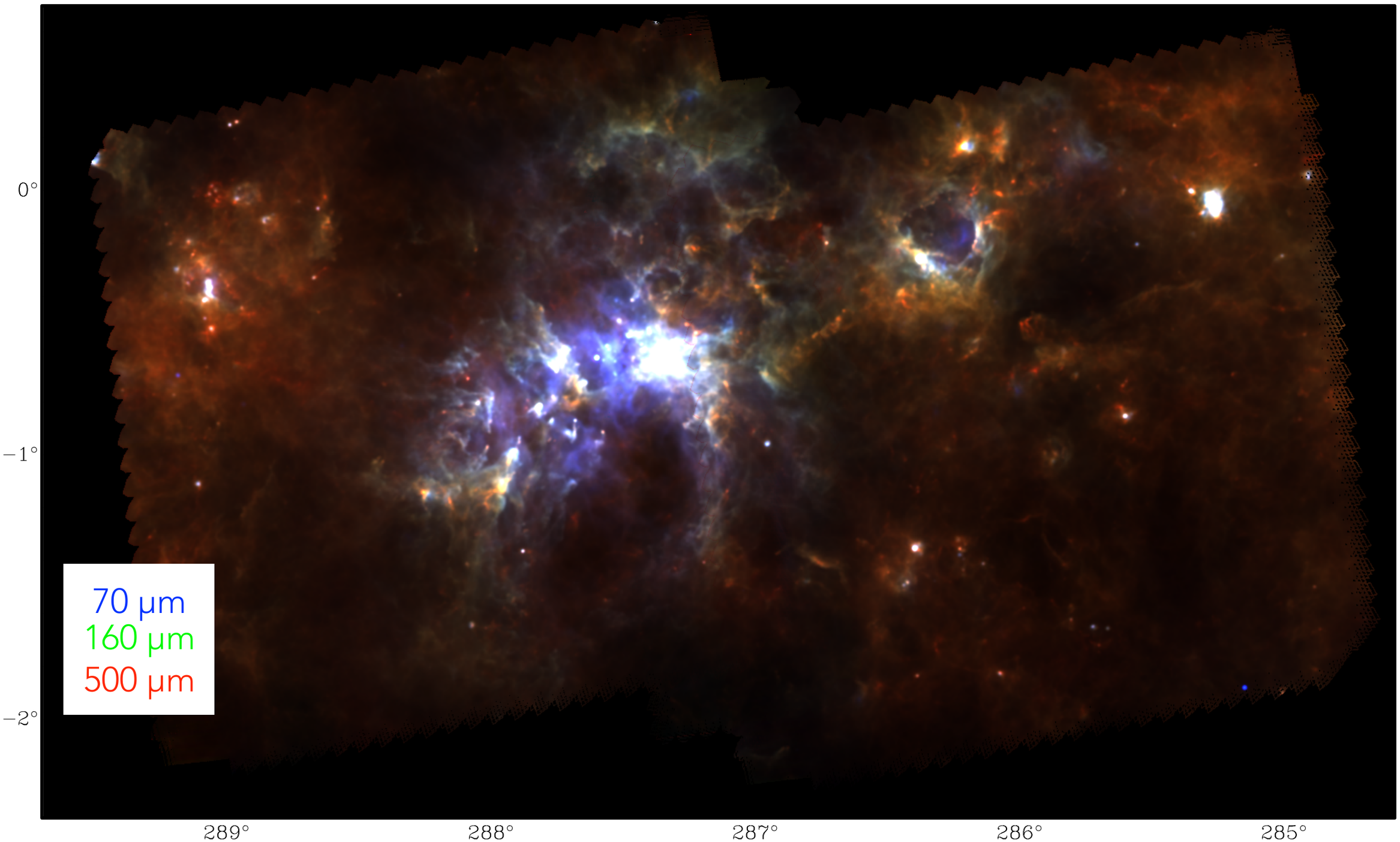



Dust

Herschel Infrared data

HiGal Survey, Molinari et al. (2010)



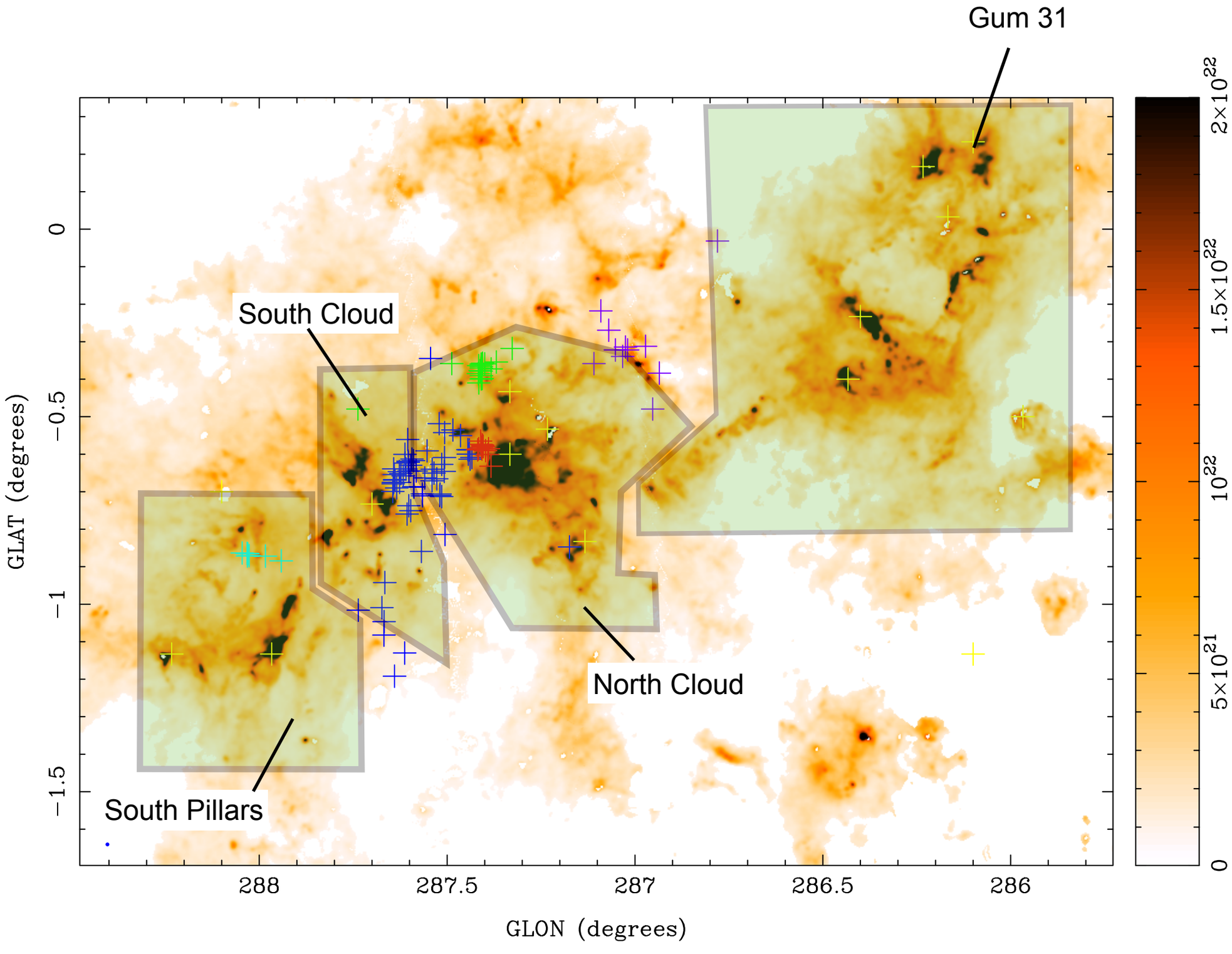
SED FITTING TO INFRARED DATA

$$F_\nu = \Omega \; B_\nu(T_{\rm dust}) \; \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta \; n_{\rm dust} \qquad\qquad N_{\rm H} = 2\frac{n_{\rm dust}}{\mu_{\rm H2} \; m_{\rm H} \; R_{\rm dg}}$$

Pixel by Pixel robust non-linear least squares curve fitting

- $T_{\rm cold}$ Cold dust temperature
- $N_{\rm H}$ Gas column density

Dust temperature map



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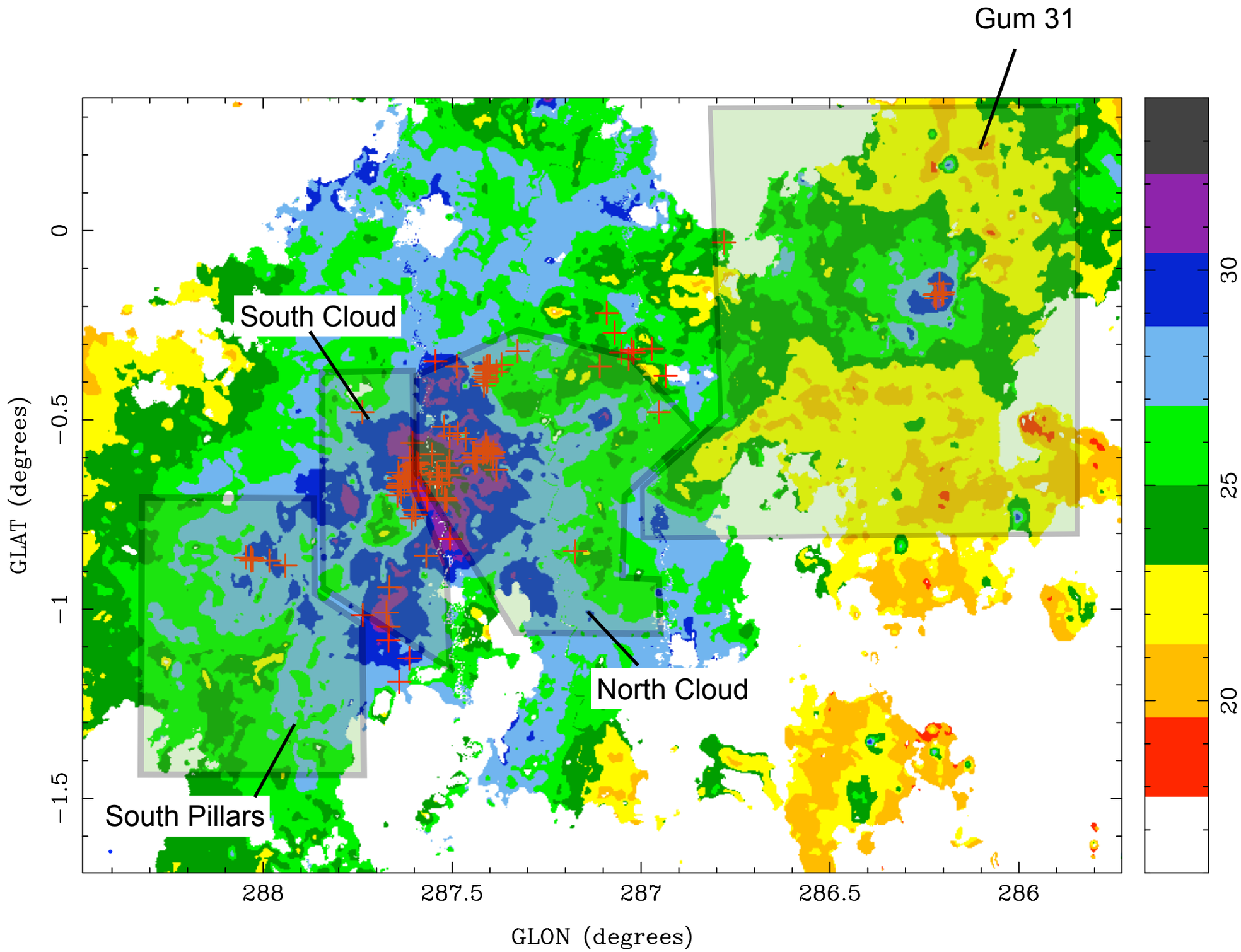
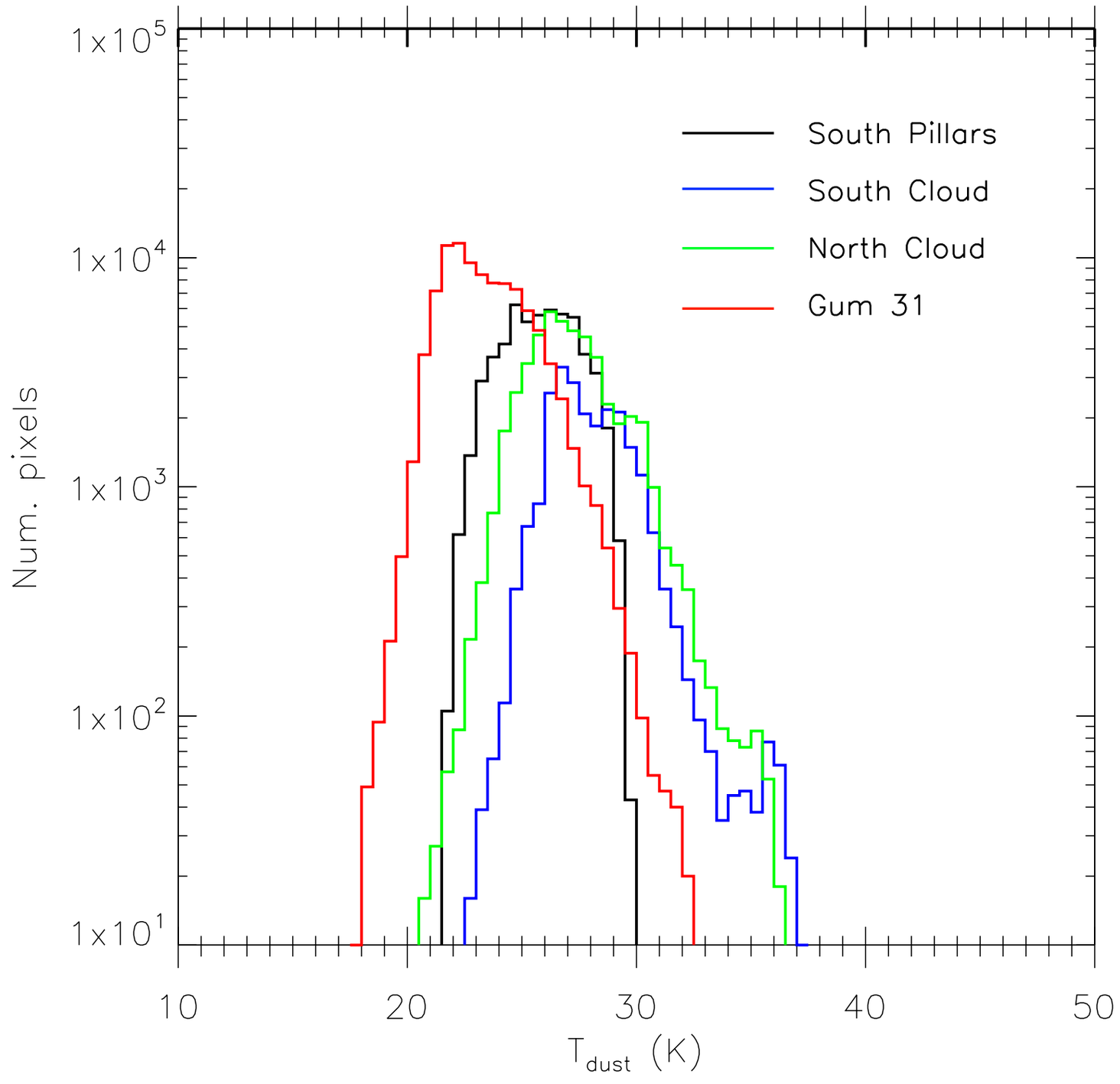


Dust temperature map

Rebolledo et al. (2016)

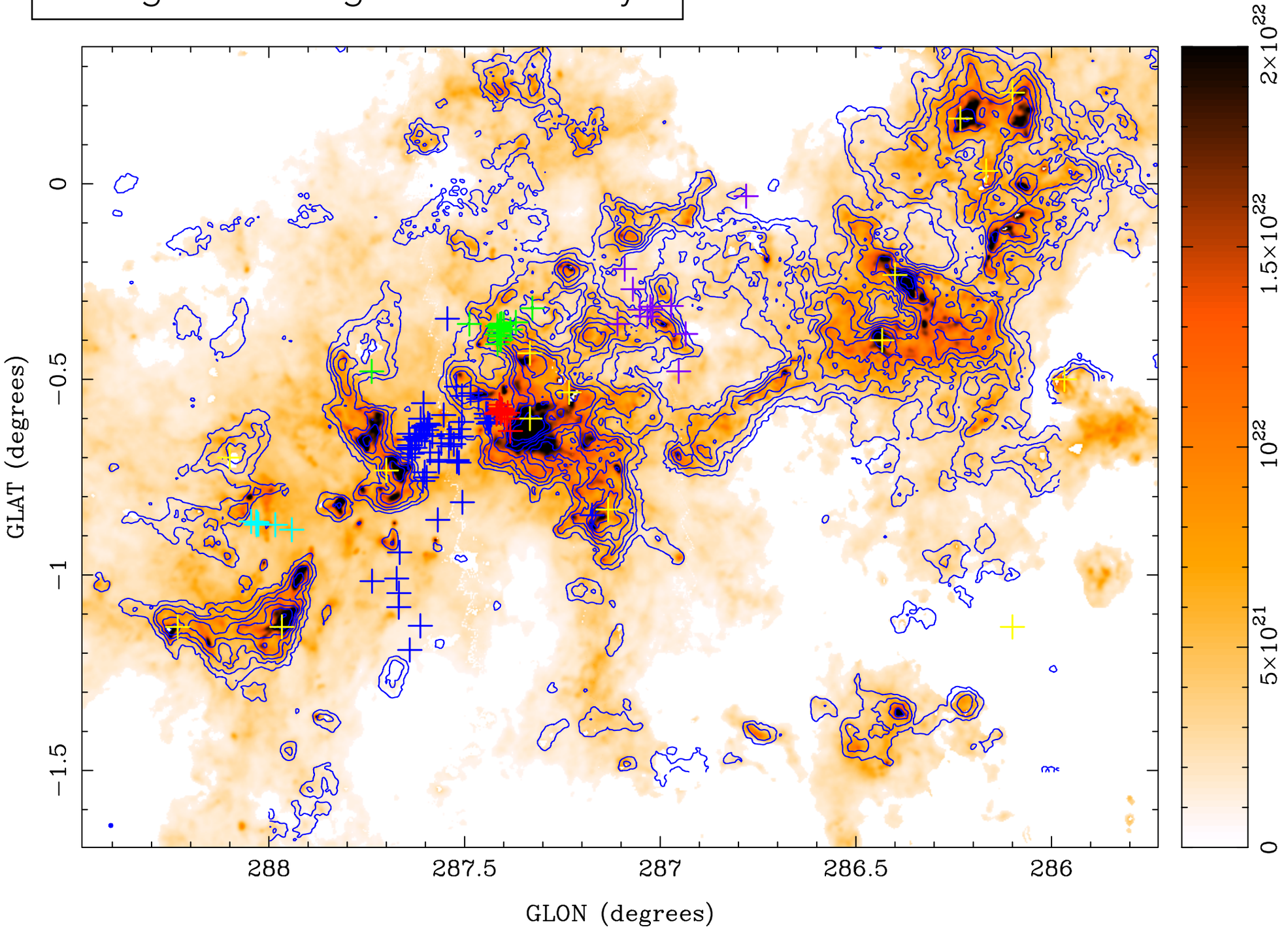
Southern Cloud and Norther Cloud more affected by massive stars.

Gum 31 is further way from the centre of the star clusters so the region has cooler gas.



Gas column density map

Good spatial correlation between CO and regions with high column density



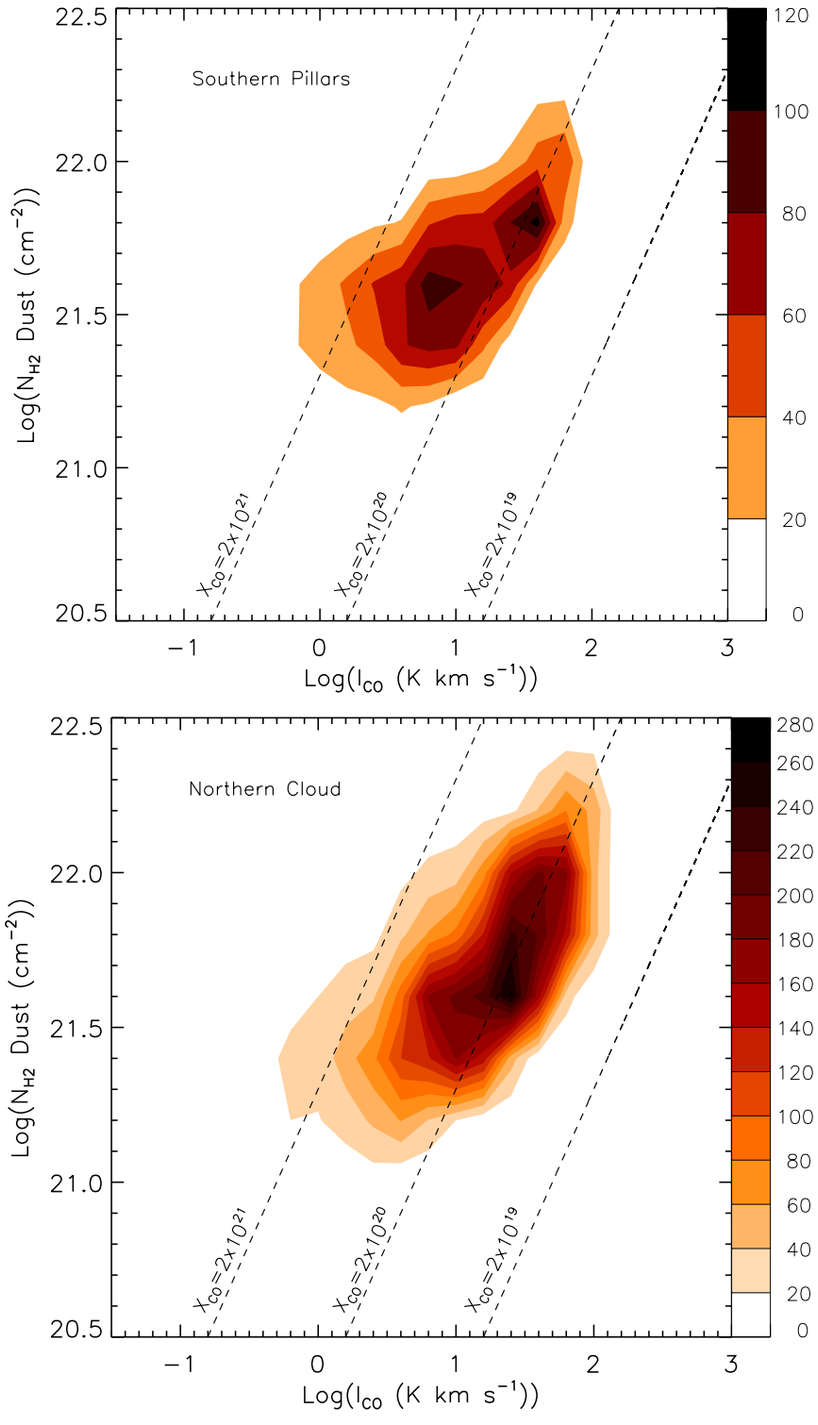
Gas vs ^{12}CO column density

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

Good approximation for North Cloud and Gum 31.

Larger Xco factor for South Pillars and the South Cloud.

Rebolledo et al. (2016)

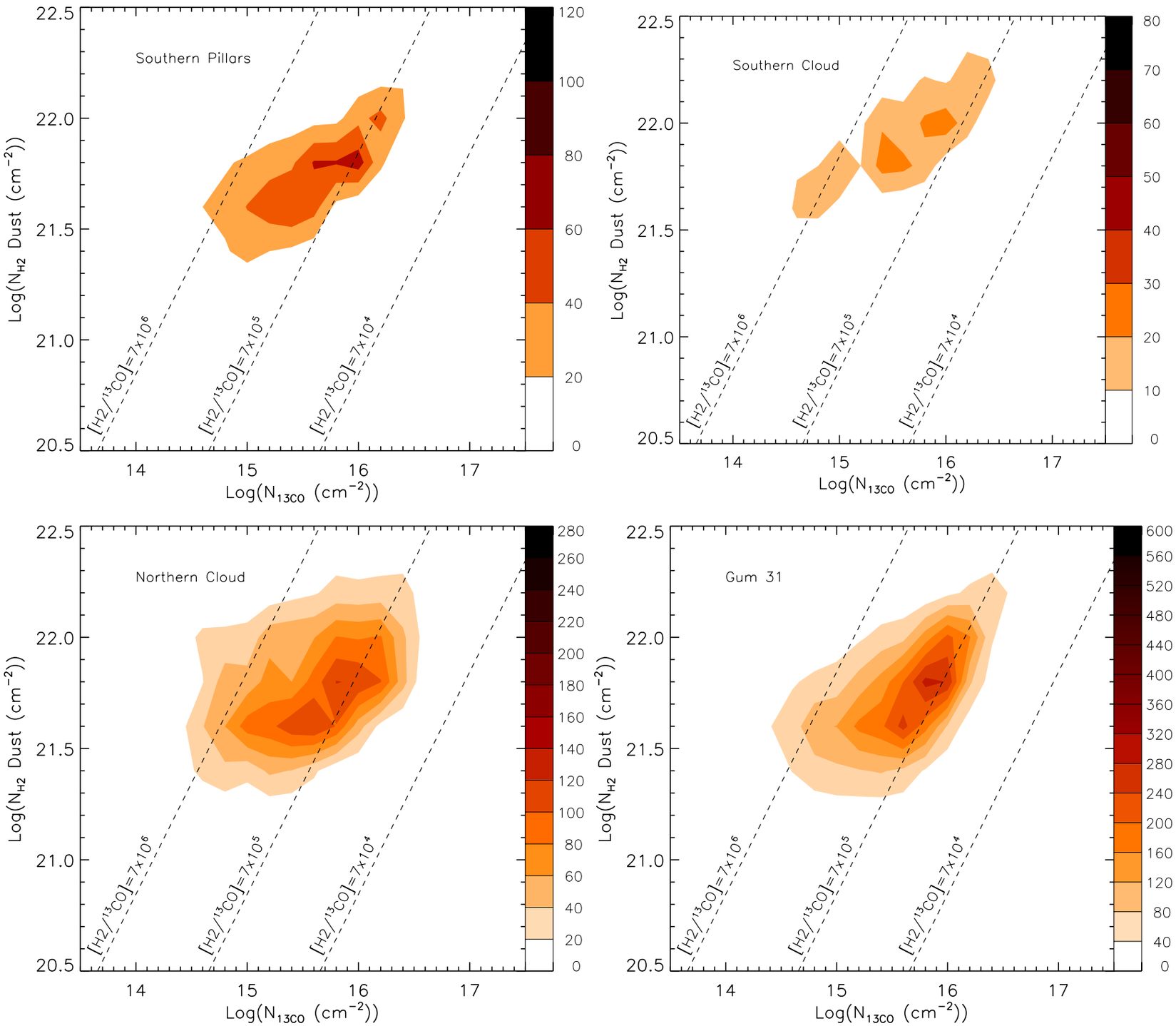


Gas vs ^{13}CO column density

Good approximation for North Cloud and Gum 31.

Larger [H2/13CO] abundance ratio for South Pillars and the South Cloud.

Rebolledo et al. (2016)



Mass Budget

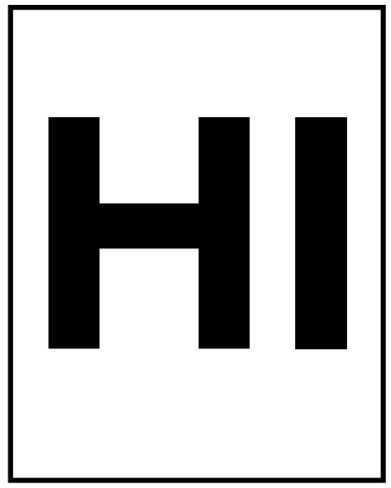
Rebolledo et al. (2016)

Region	$M(\mathrm{dust})^{a}$ $M_\odot$	$M_{12}{}^{a}$ $M_\odot$	$M(\mathrm{dust})^{b}$ $M_\odot$	$M_{13}{}^{b}$ $M_\odot$	$M_{12}{}^{a}/M(\mathrm{dust})^{a}$	$M_{13}{}^{b}/M(\mathrm{dust})^{b}$
SP	32056	21482	20665	15793	0.67	0.76
SC	21198	10031	12227	5368	0.47	0.44
NC	86568	71070	59467	36431	0.82	0.61
Gum 31	122451	102095	82212	57911	0.83	0.70
Total	262273	204678	174571	115503	0.78	0.66

Notes.

[a] Mass is calculated summing over the pixels defined by the ^{12}CO mask.

[b] Mass is calculated summing over the pixels defined by the ^{13}CO mask.


HI

The Carina Nebula Project

- CARPARCS
  - ATCA + Parkes
    - Ionised gas, B field
      atomic gas
- Molecular
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THE CARINA NEBULA PROJECT

- The Carina Parkes-ATCA Radio Cm-wavelength Survey (CARPARCS)

- Multi-wavelength study of the 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

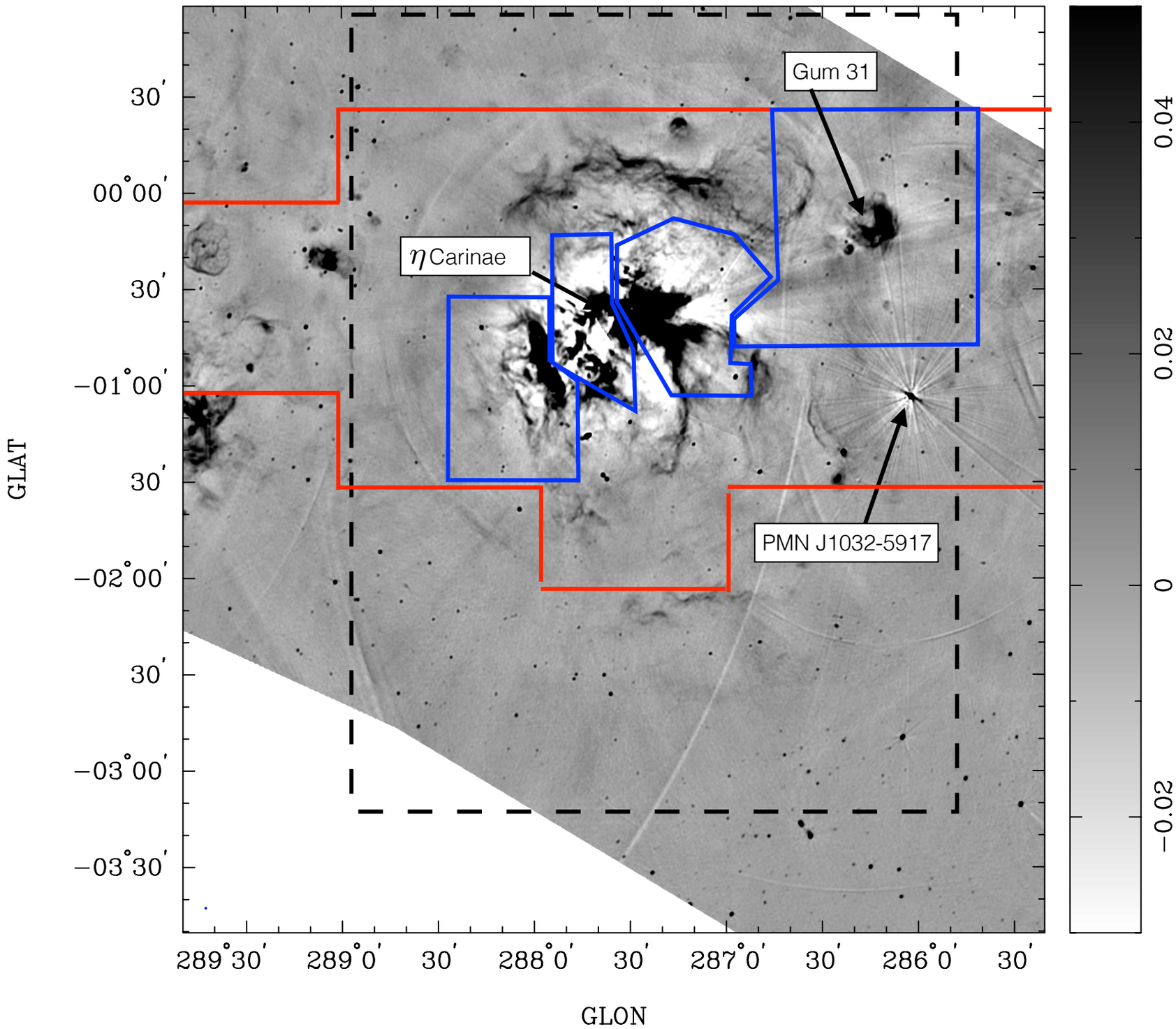
- 11 Array configurations
- 607 hours in total to complete project
- Carina has emission features from sub-arcsecond to degree scale. Imaging is challenging.
- Multi-frequency synthesis, wide field imaging.
- Test of CASA capabilities

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.



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

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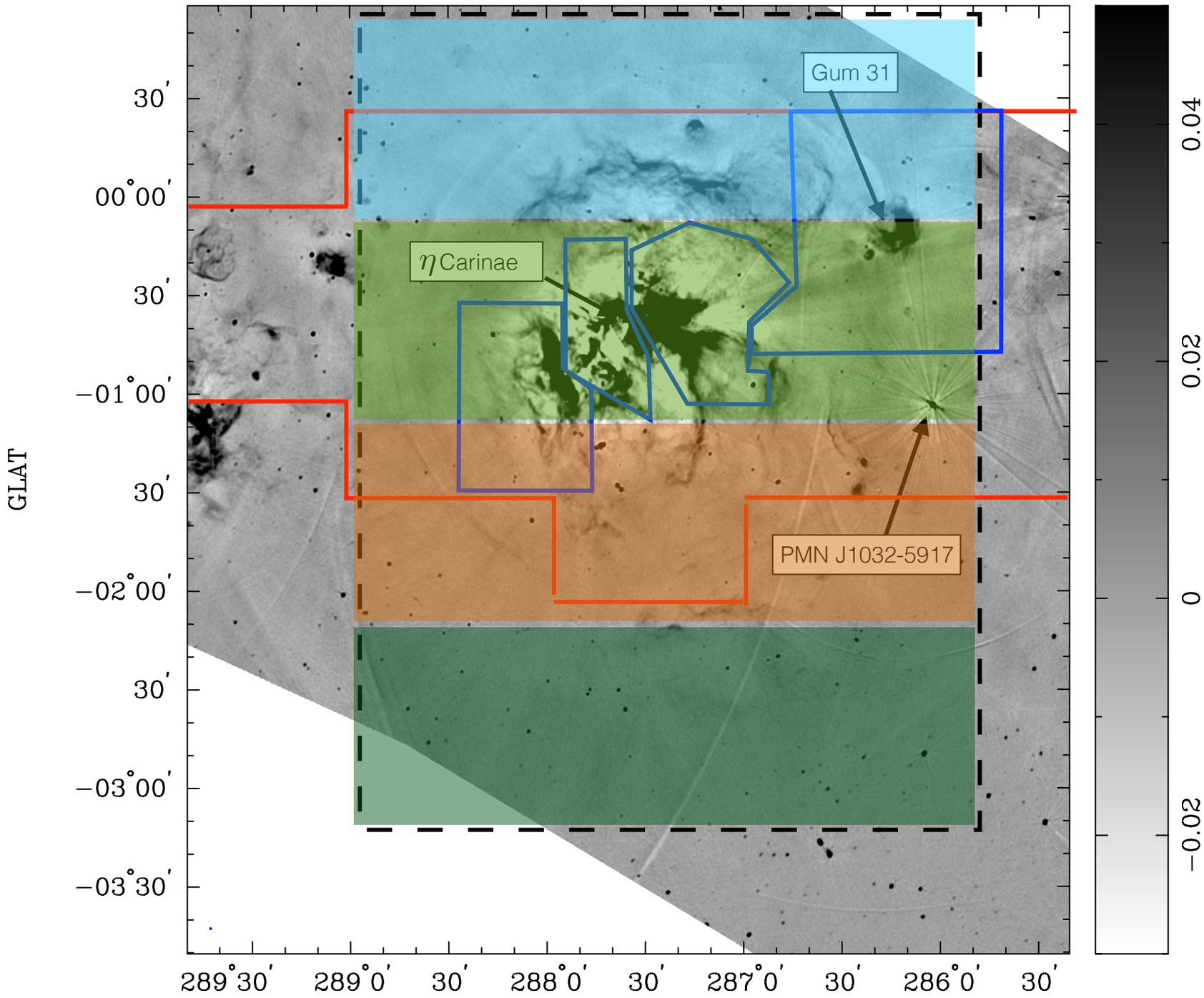
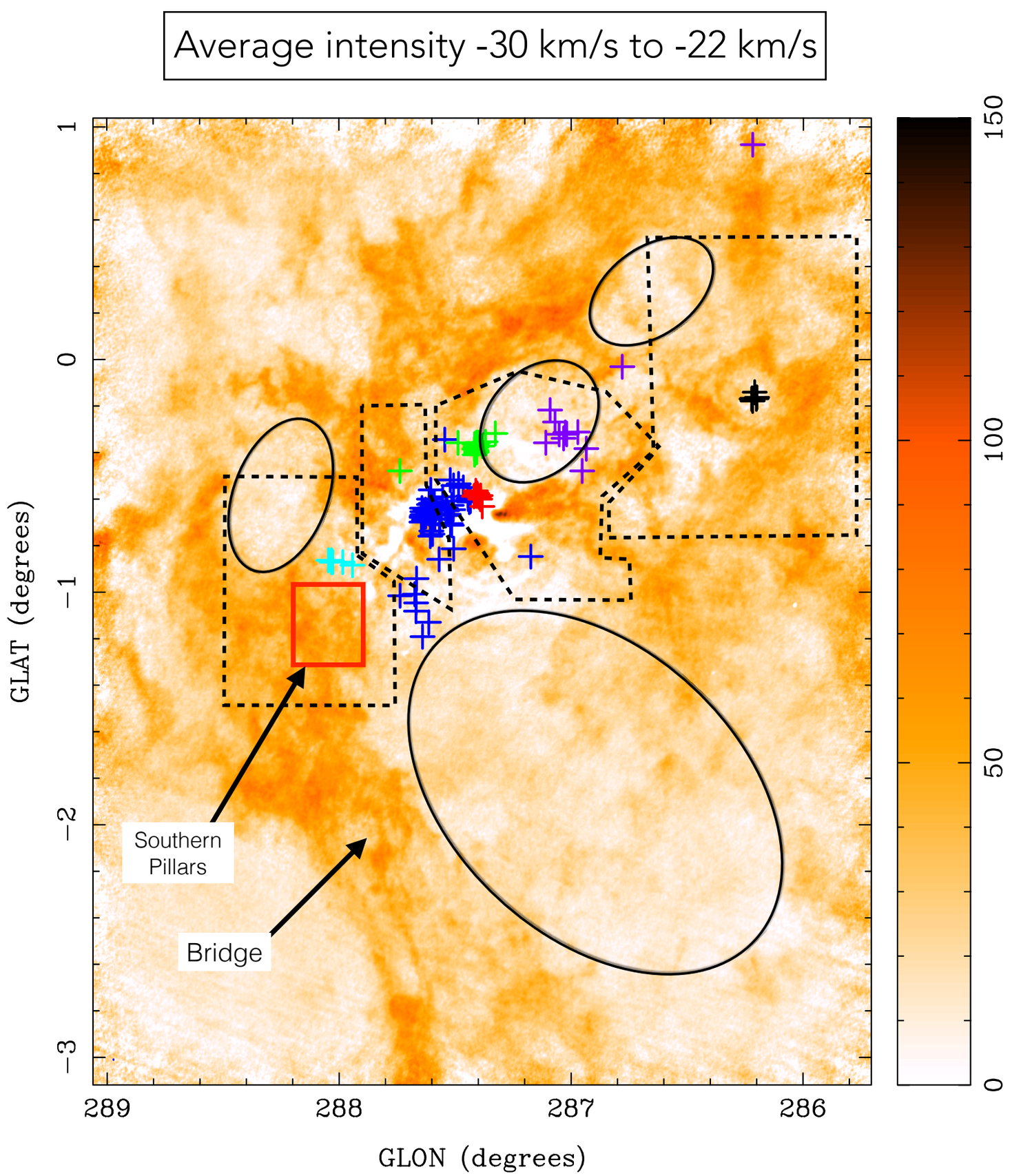


0.835GHz continuum emission of the CNC-Gum31 complex Molonglo Observatory Synthesis Telescope

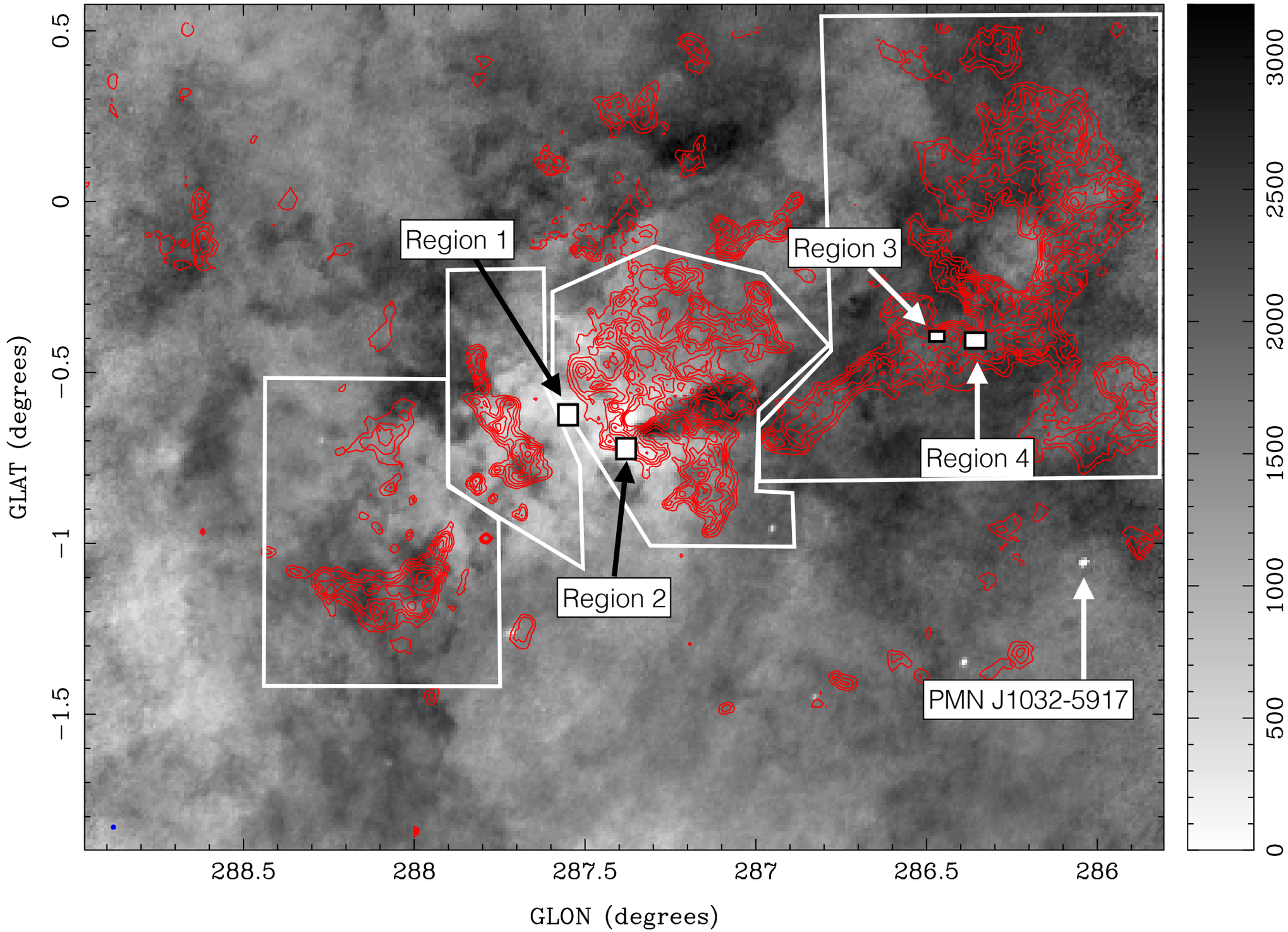
Several features in the CNC complex

- 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)

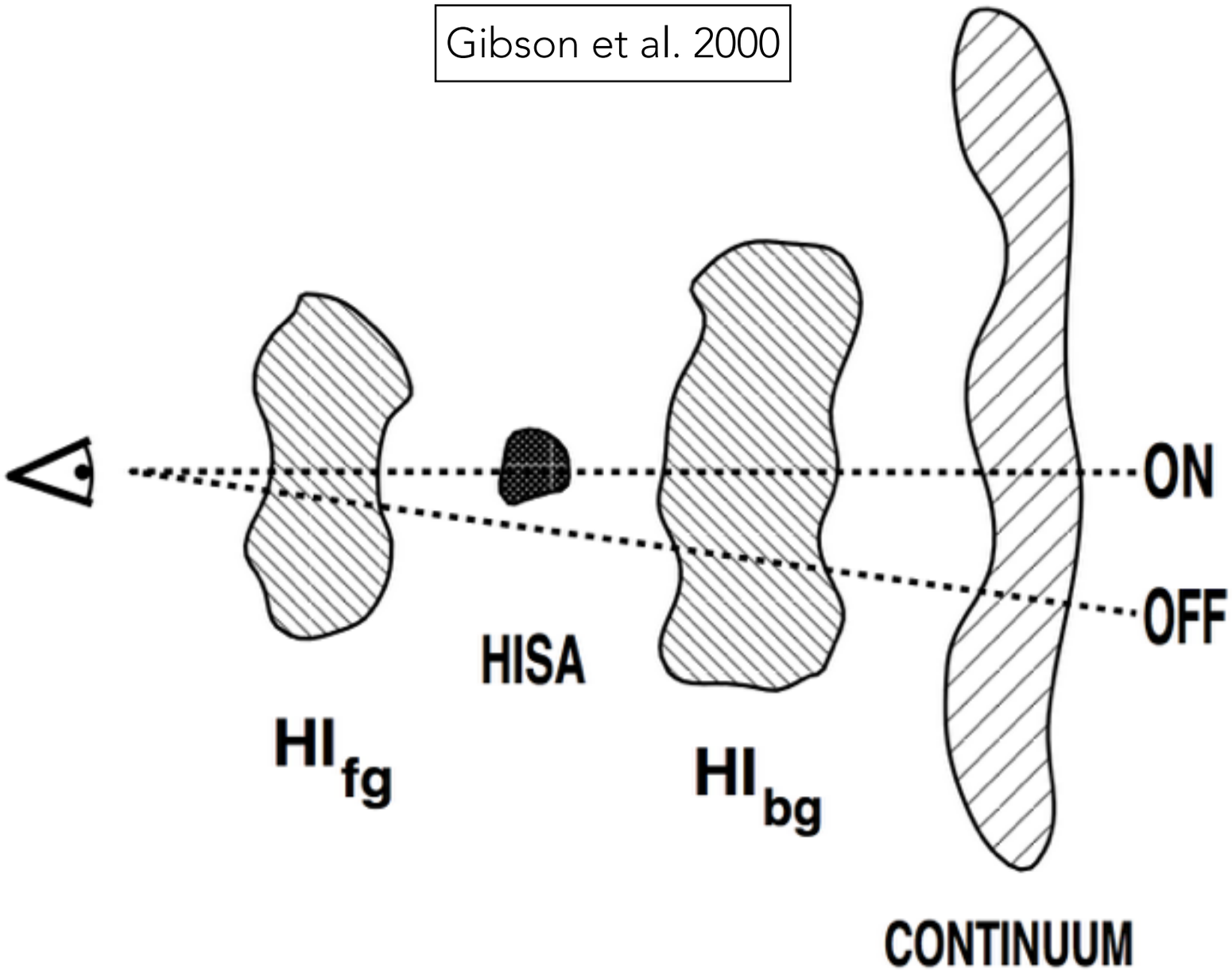


Absorption features

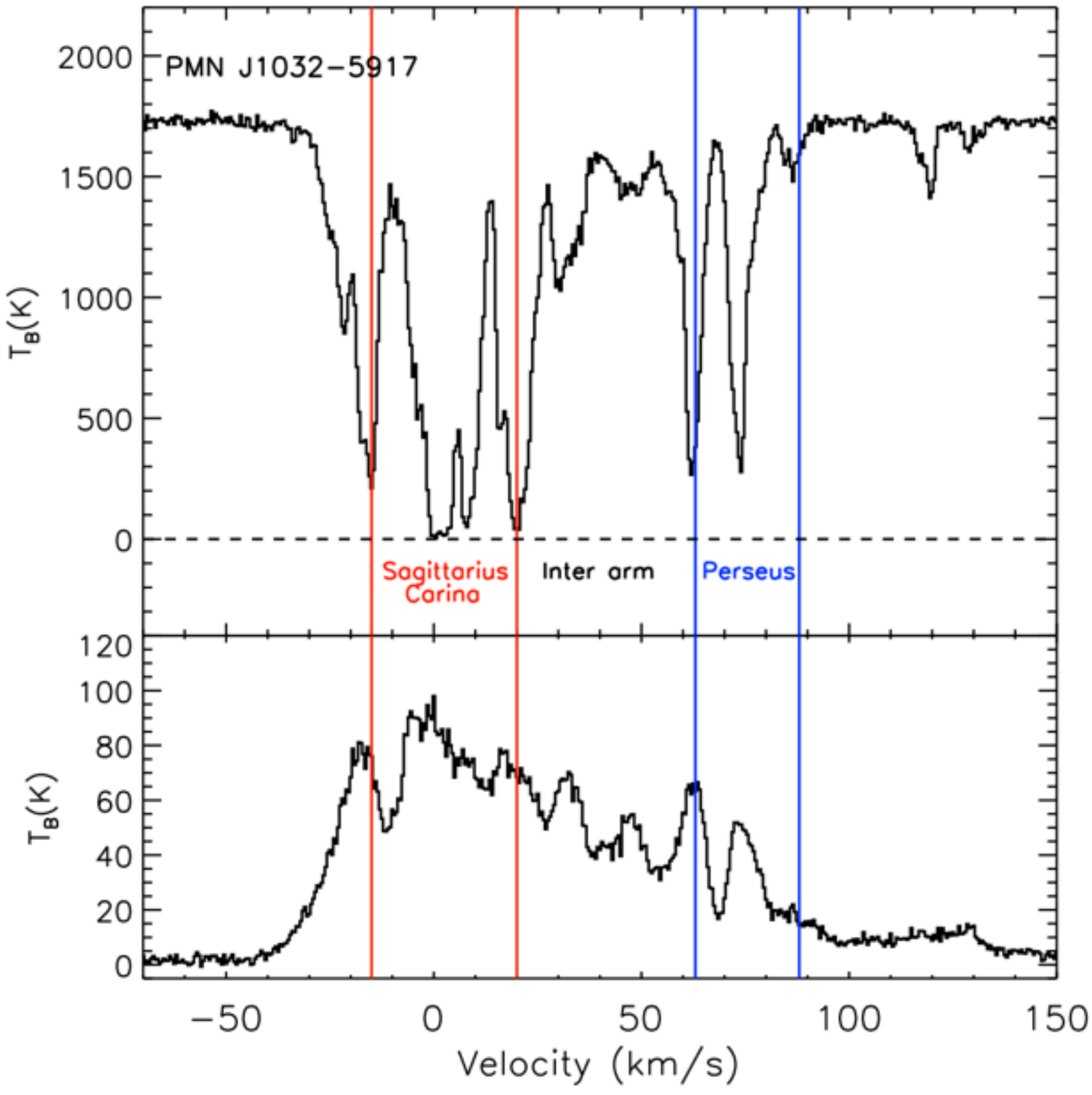


Depends on the complex structure of the ISM

Gibson et al. 2000



Absorption of background continuum point source

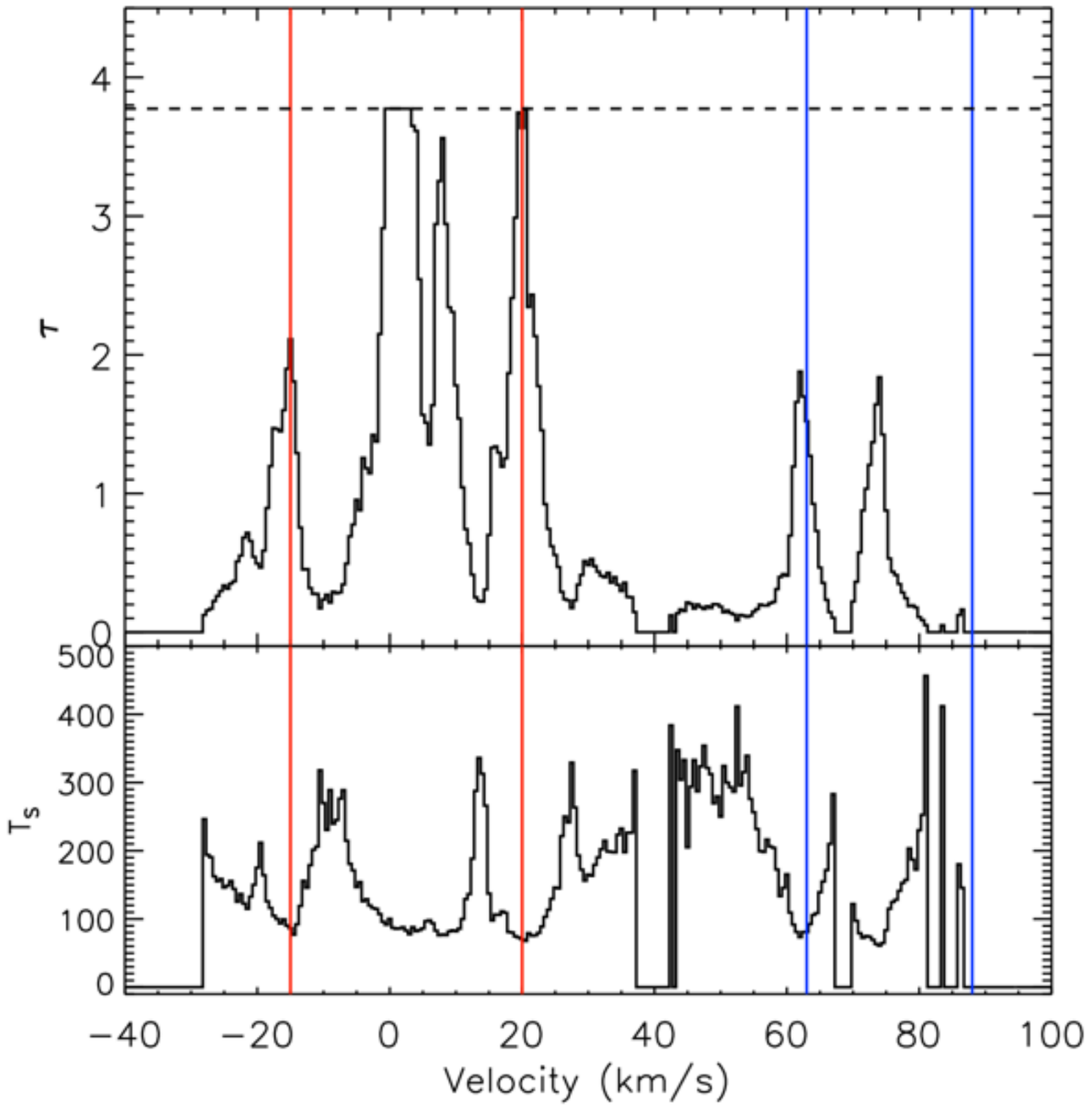


Optical depth and spin temperature of the HI

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

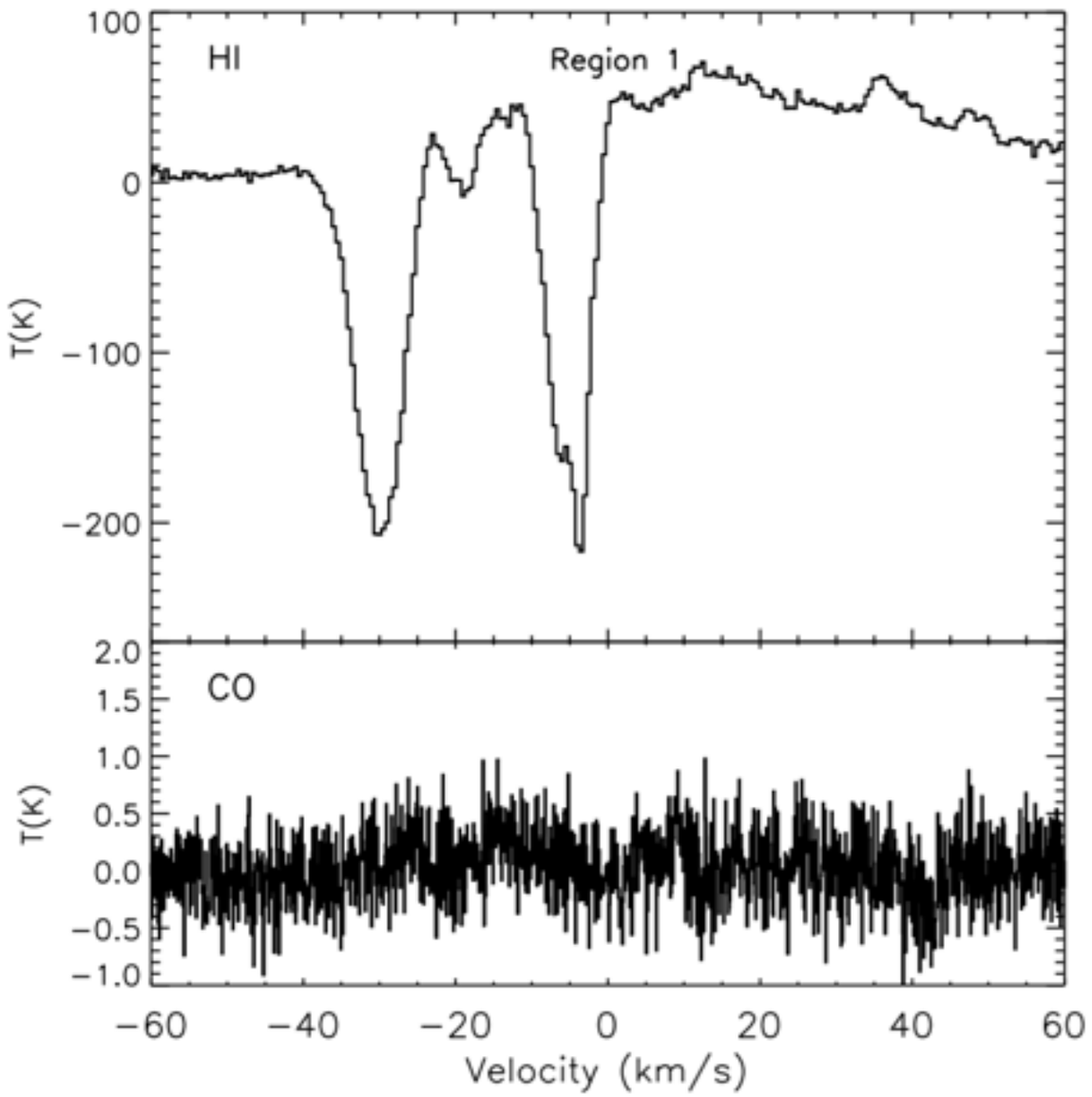
$$\tau = -\ln\left(\frac{T_{\mathrm{ON}} - T_{\mathrm{OFF}}}{T_{\mathrm{C}}}\right)$$

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



Background strong continuum sources can be used as tools to detect the cold components

No CO counterpart



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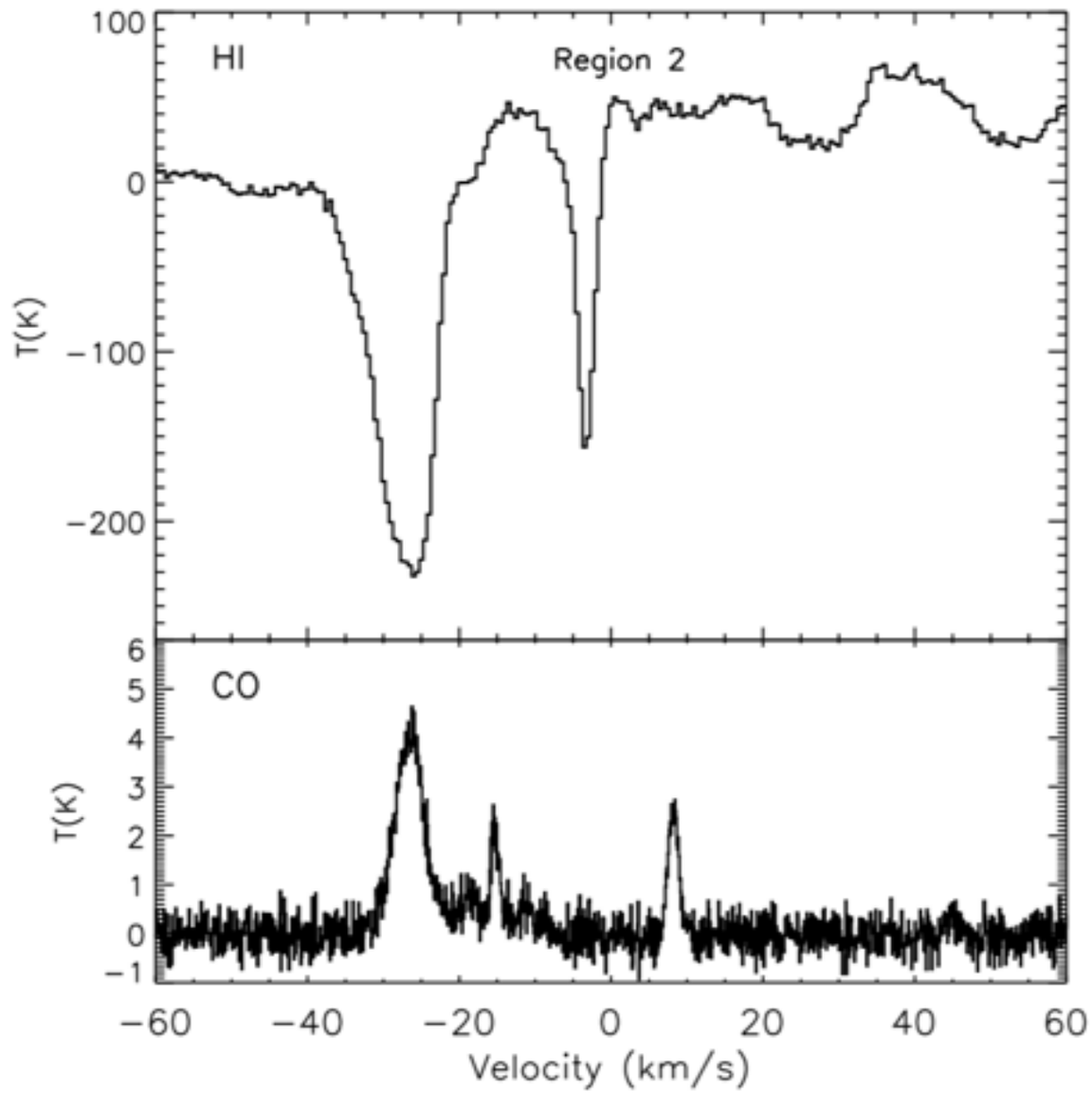
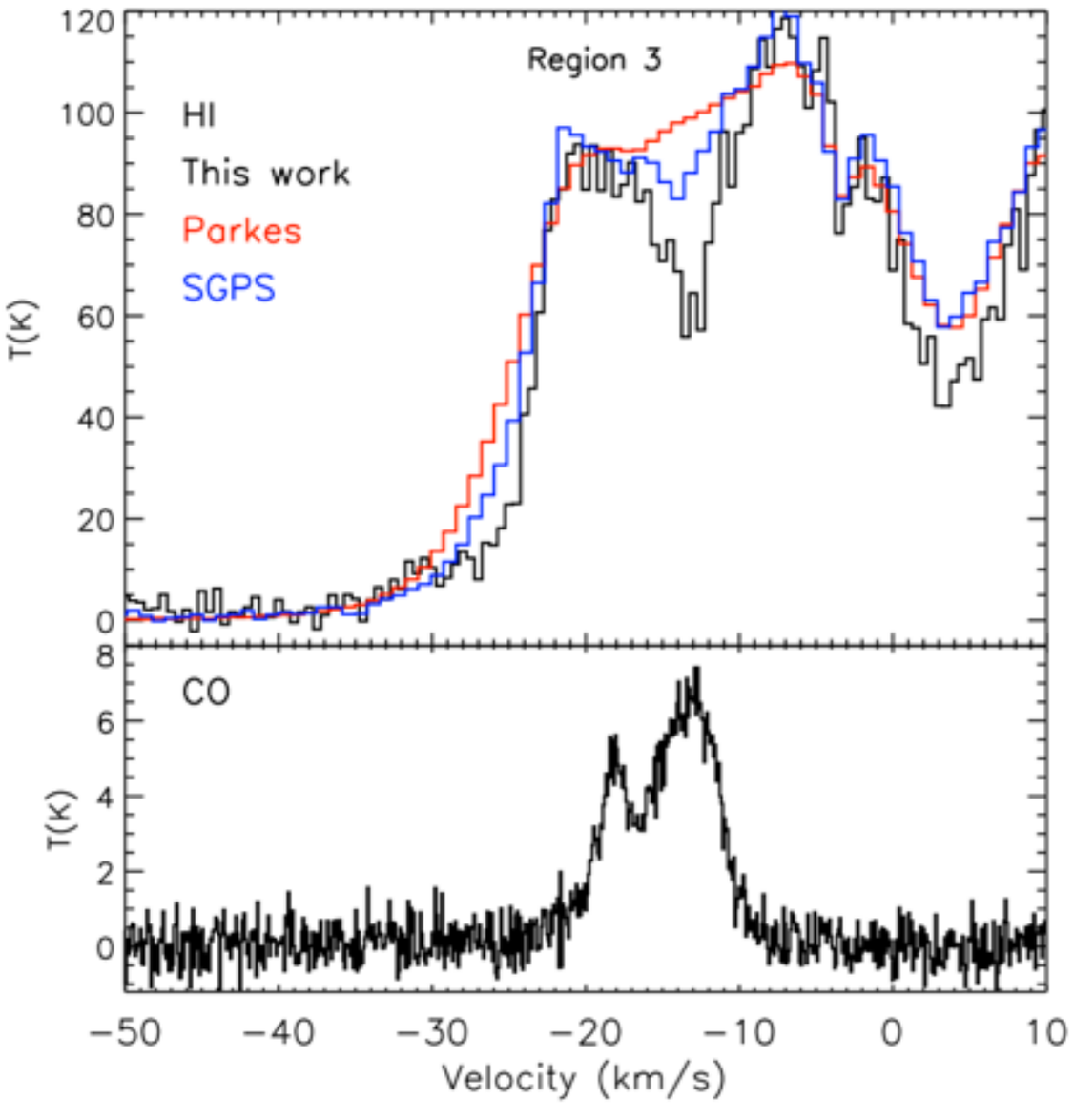
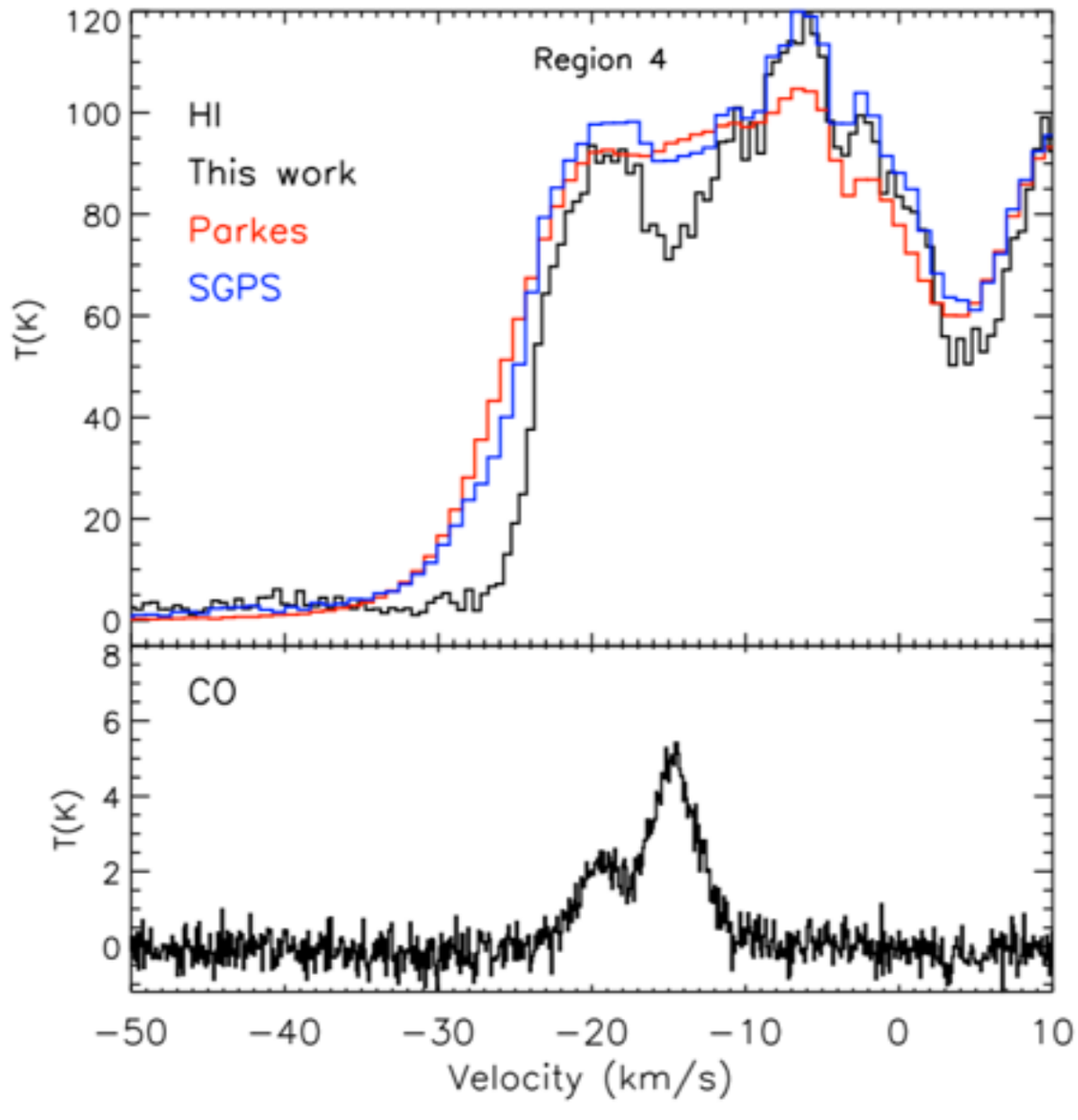


HI self absorption features - HISA

High resolution observations are needed to detect HISA features

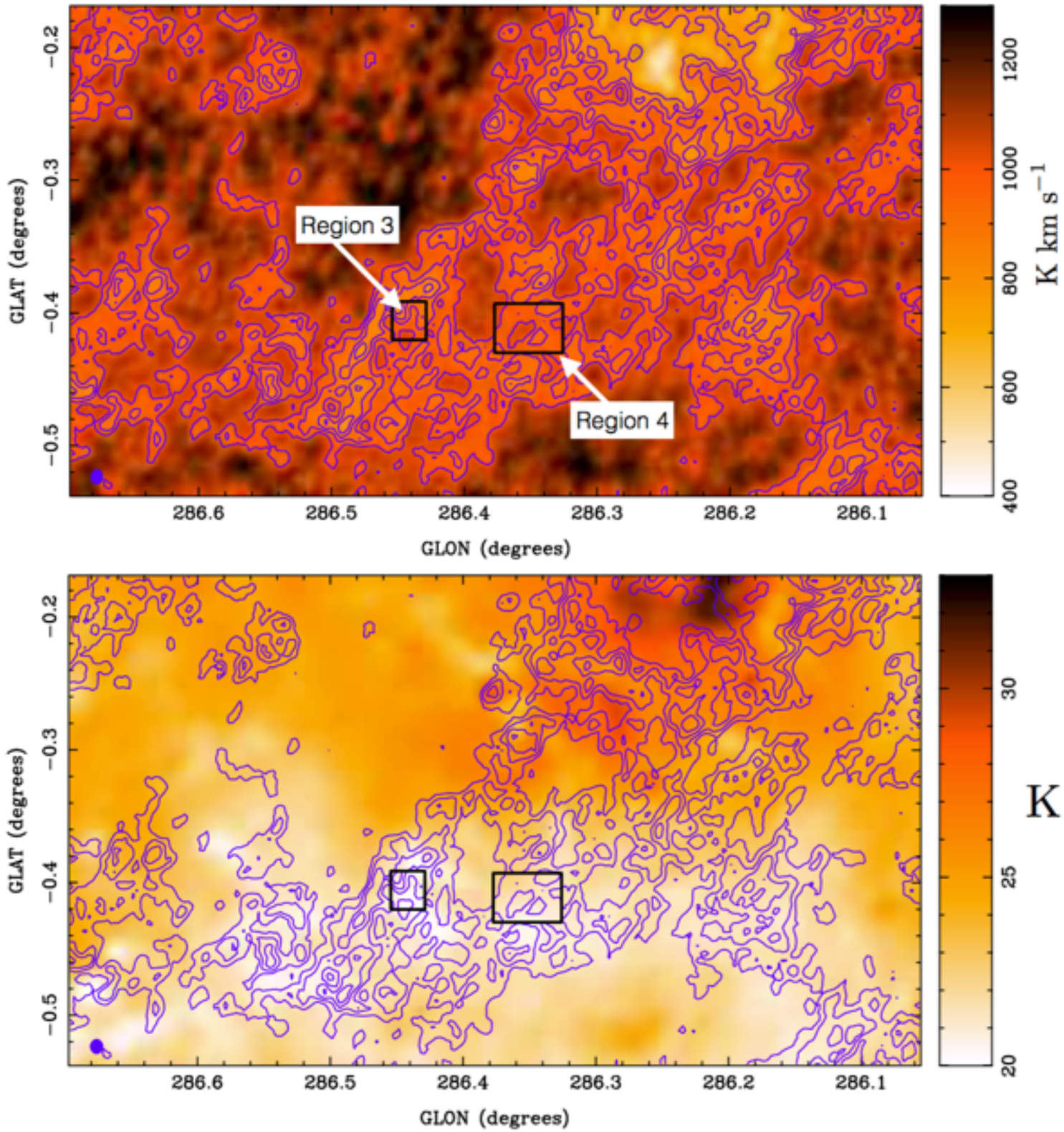
Rebolledo et al. (2017)





Rebolledo et al. (2017)

HI integrated intensity over the HISA feature



Good correlation between HISA features and cold gas

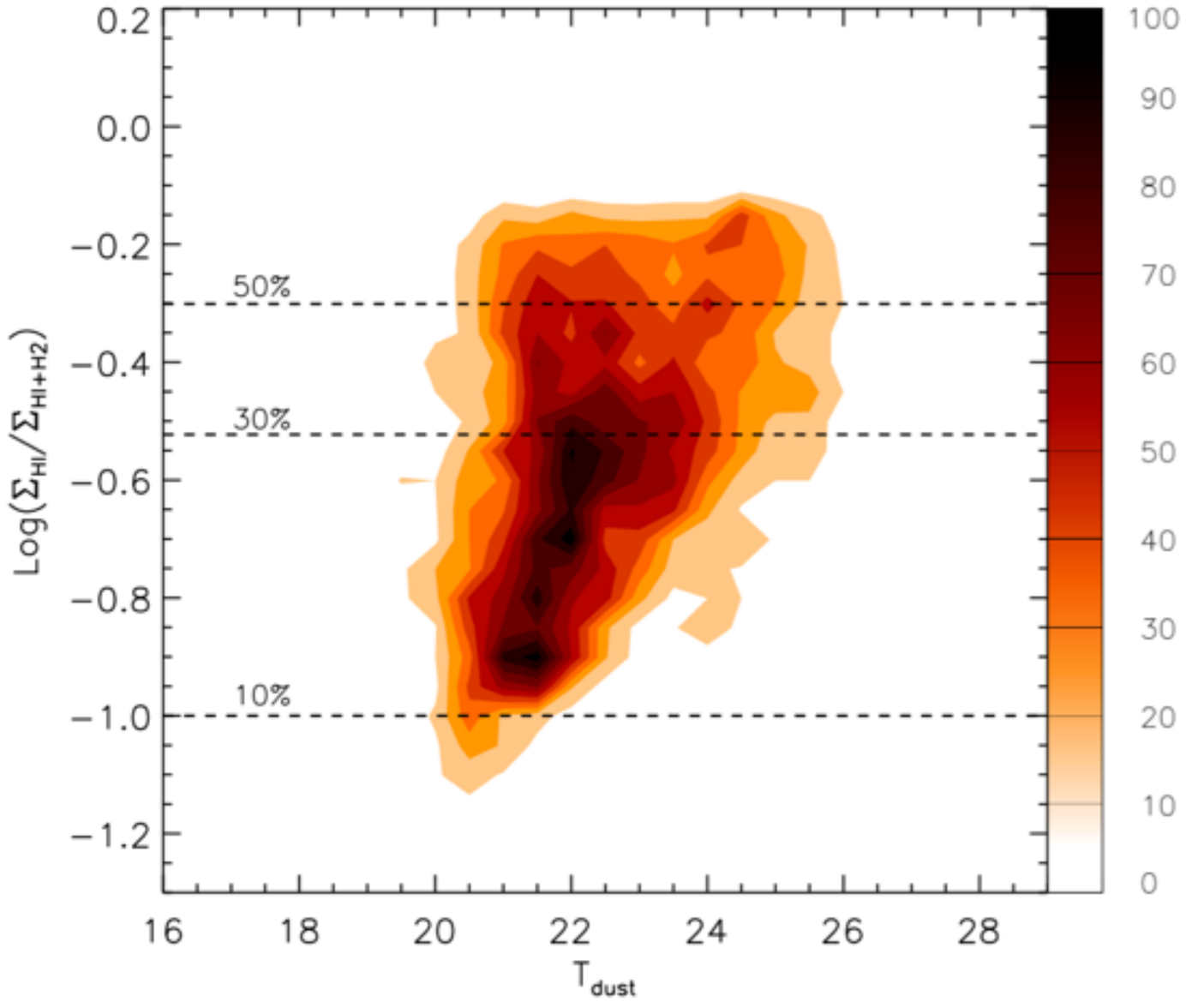
Dust temperature

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)

Gas vs ^{12}CO + HI

Optically thin

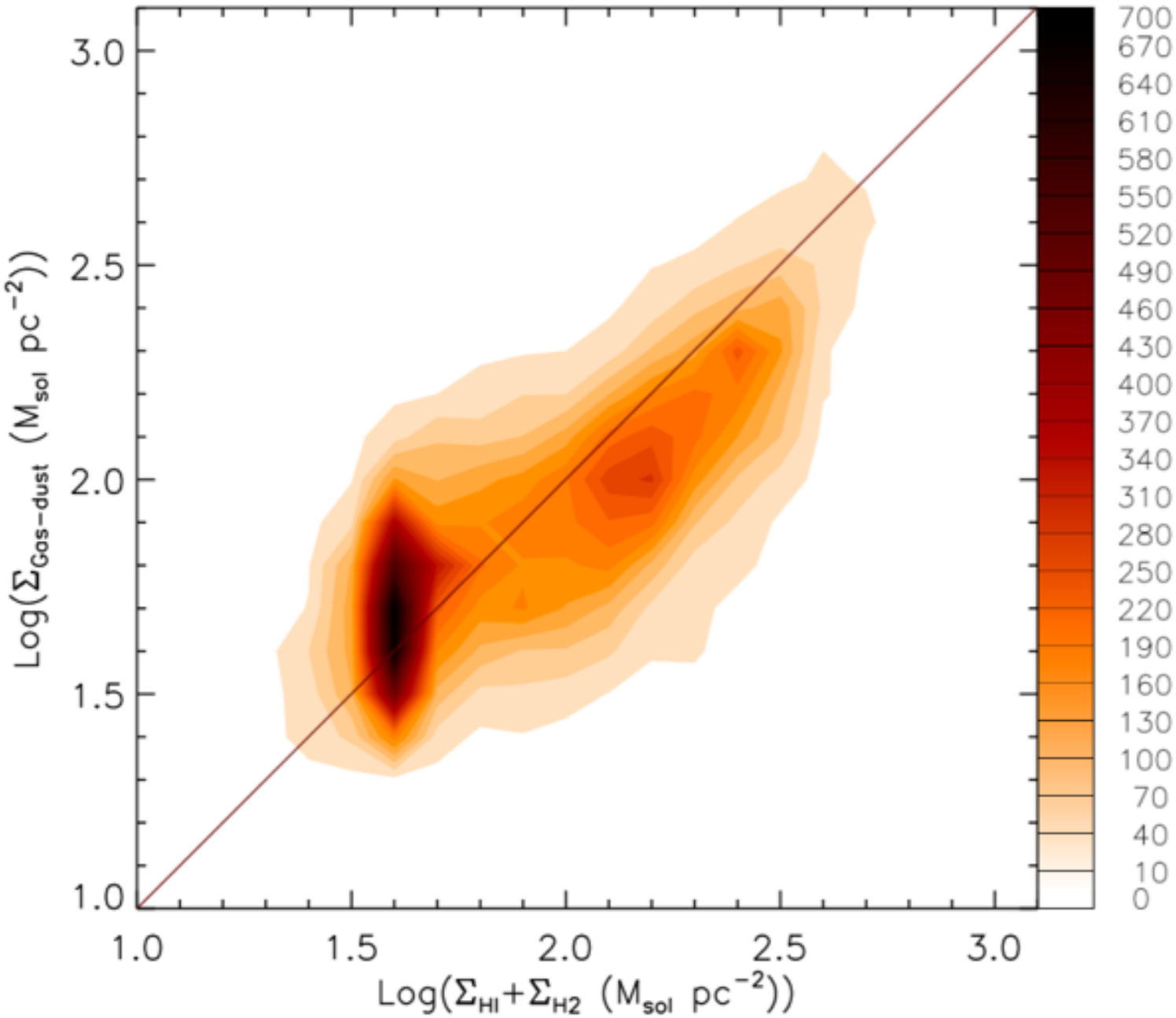
$$N_H = 1.8 \times 10^{18} T_{MB} \Delta V \ \ \mathrm{cm}^{-2}$$

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

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

Overall consistency between the different mass tracers

Gum 31 region



Gas vs ^{12}CO + HI

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Optically thin

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Overall consistency between the different mass tracers

Table 1. Gas mass budget for Gum 31.

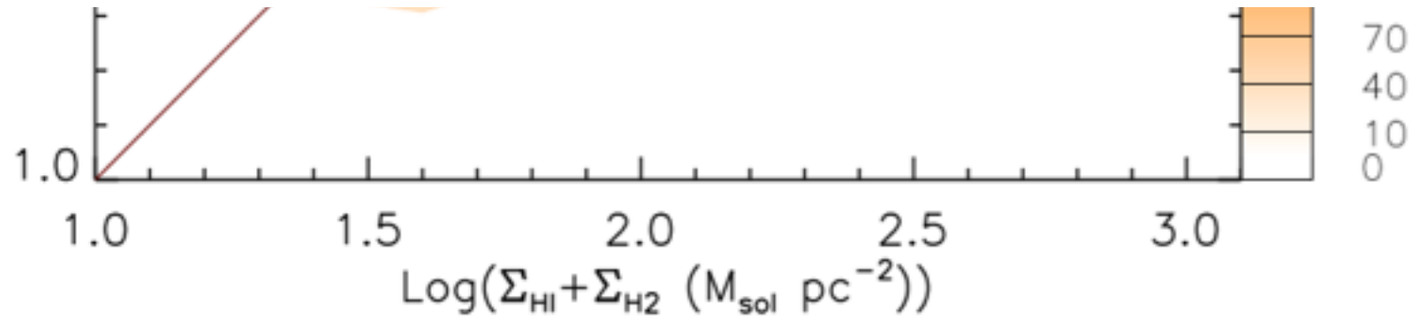
M(dust)[a] $M_\odot \times 10^5$	M_{H2}[b] $M_\odot \times 10^5$	M_{HI}[c] $M_\odot \times 10^5$	$M_{\mathrm{H2}}+M_{\mathrm{HI}}$ $M_\odot \times 10^5$
(1.5 ± 0.1)	(1.1 ± 0.1)	(0.6 ± 0.1)	(1.7 ± 0.1)

Notes.

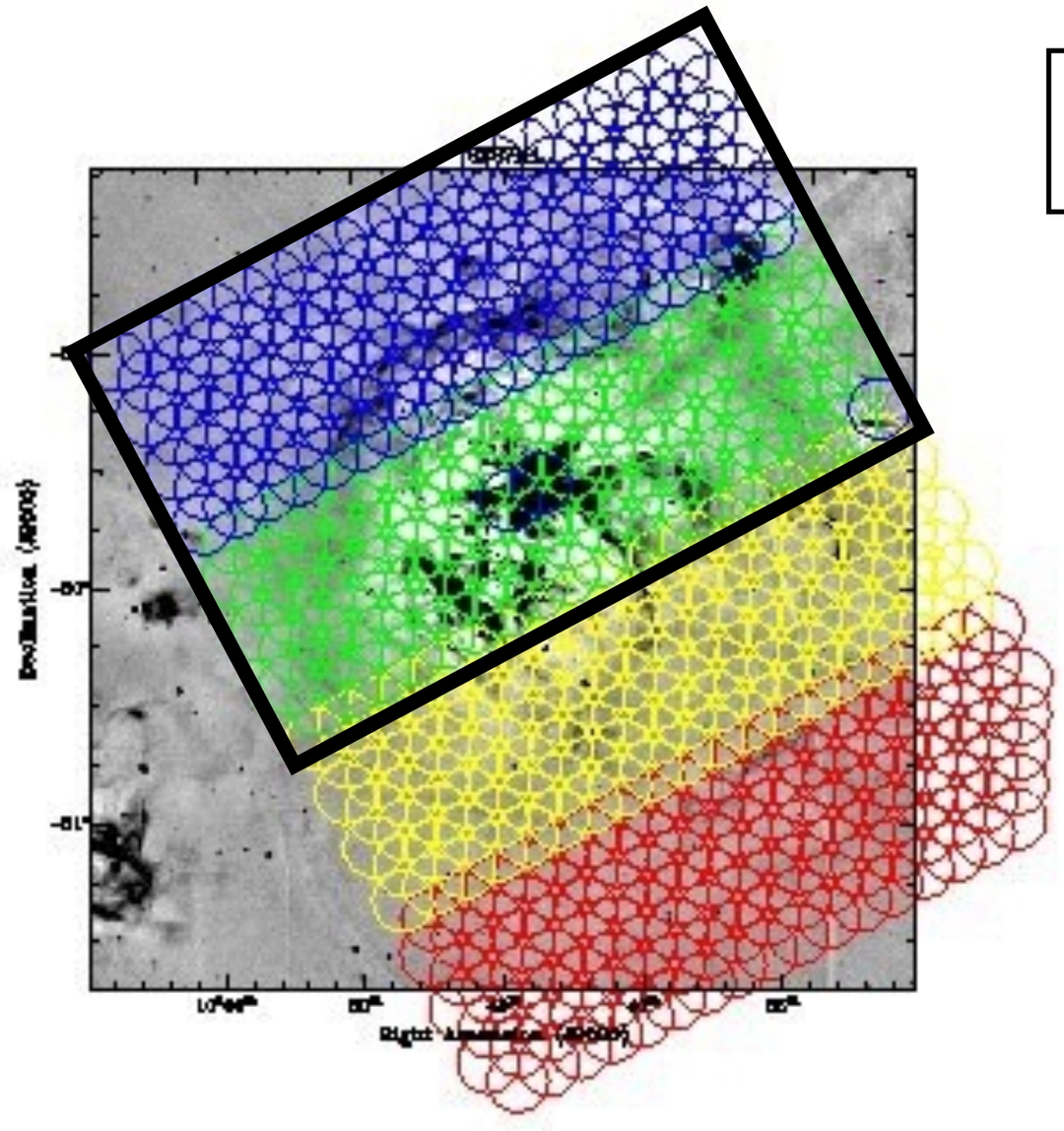
[a] M(dust) is the total gas mass derived from dust emission.

[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.



CARPARCS covers a 2.3 x 2.1 degree region on the sky in the 1-3 GHz continuum band with a total of 523 pointings.



Continuum

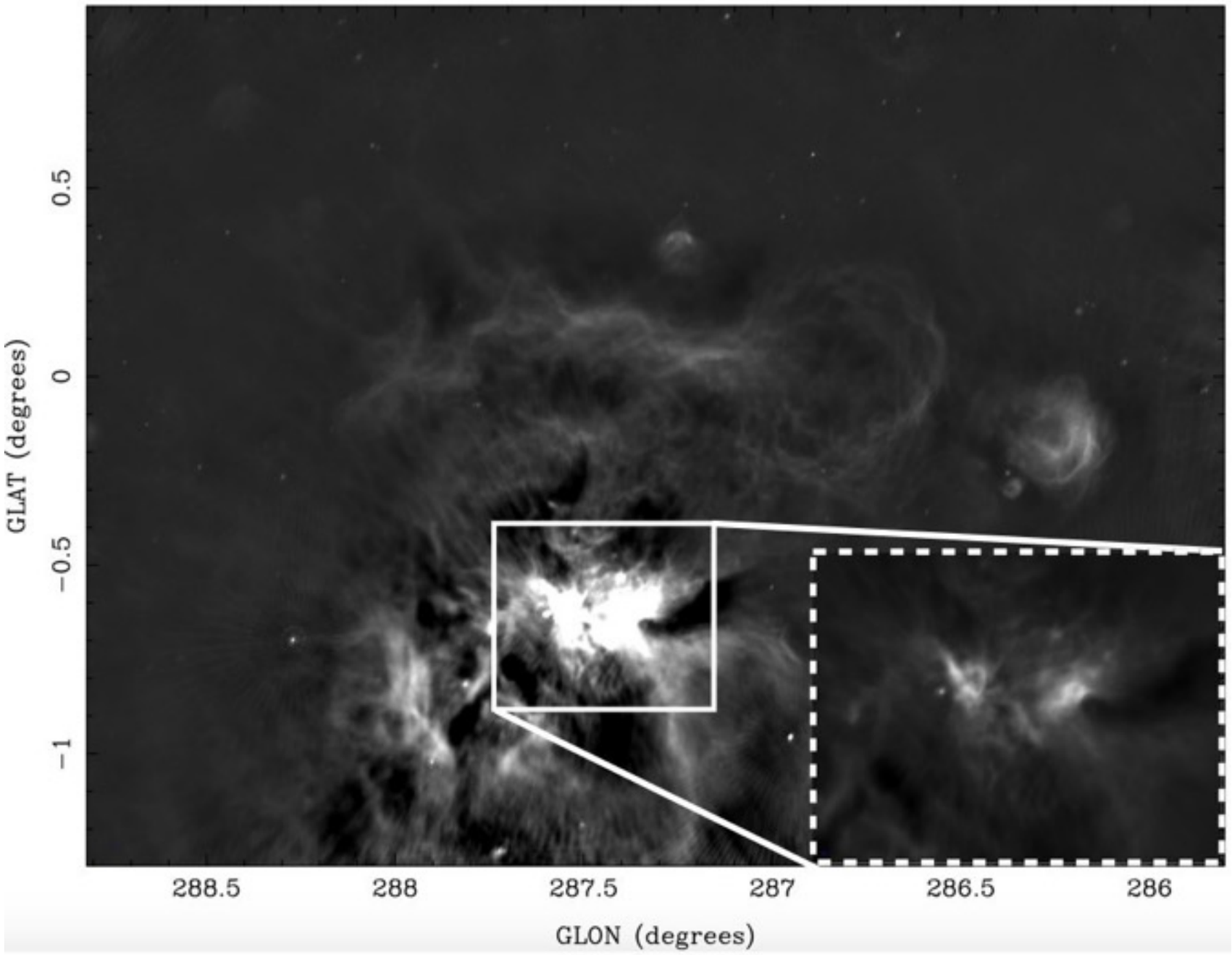
http://www.physics.usyd.edu.au/sifa/carparcs

Continuum 1.8 GHz

Extremely complex flux distribution

Strong point sources and diffuse emission makes difficult imaging

In progress…

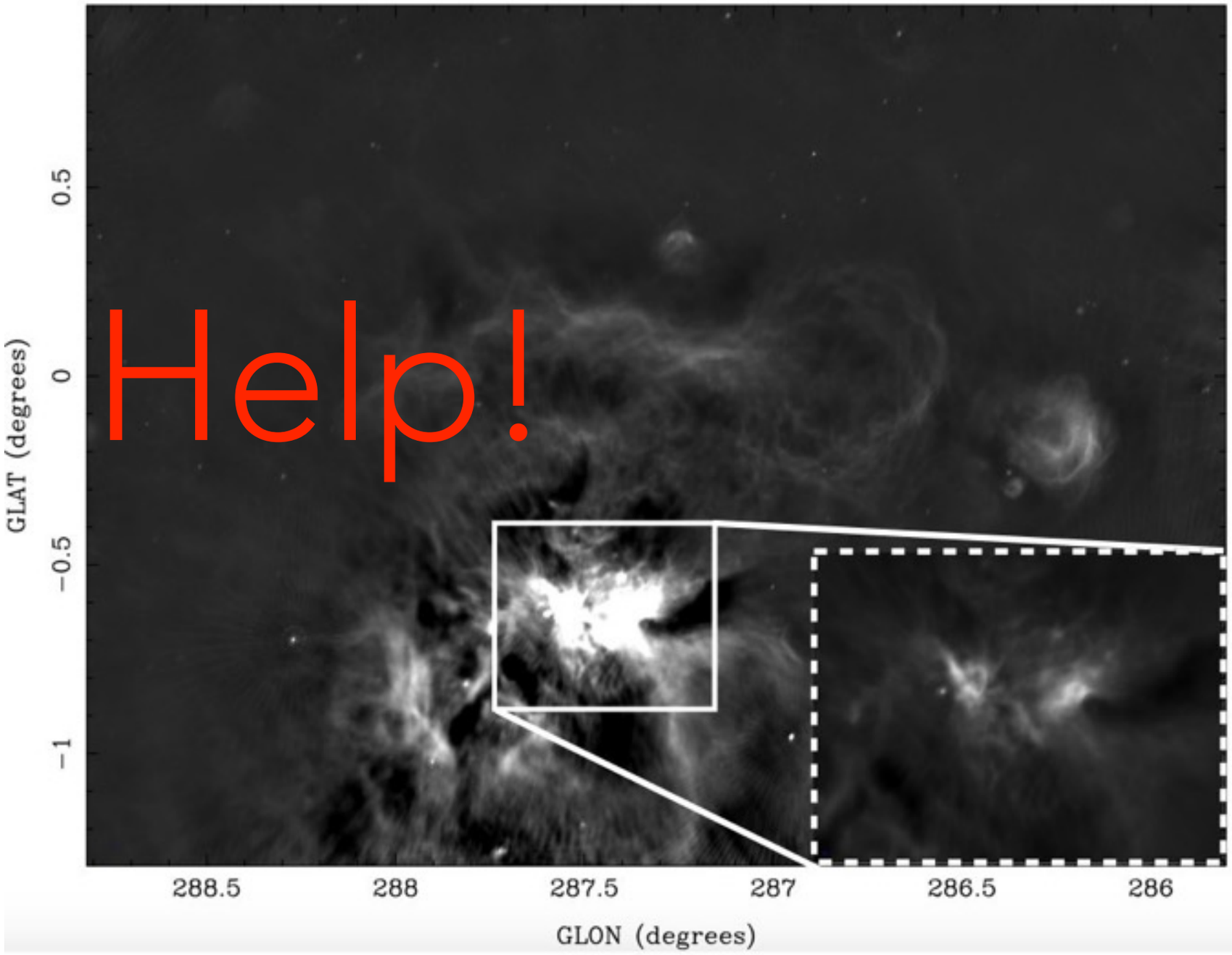


Continuum 1.8 GHz

Extremely complex flux distribution

Strong point sources and diffuse emission makes difficult imaging

In progress…

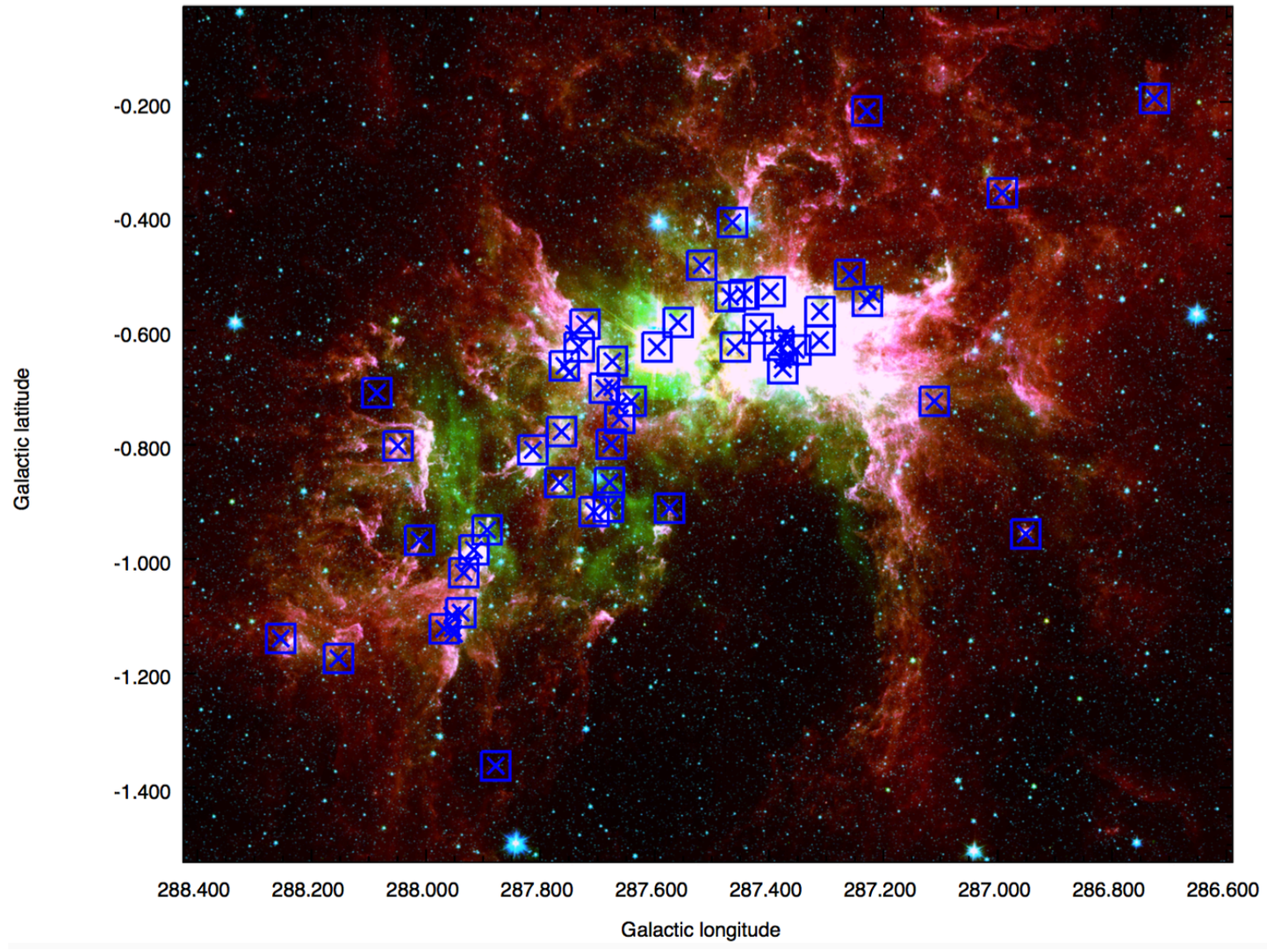


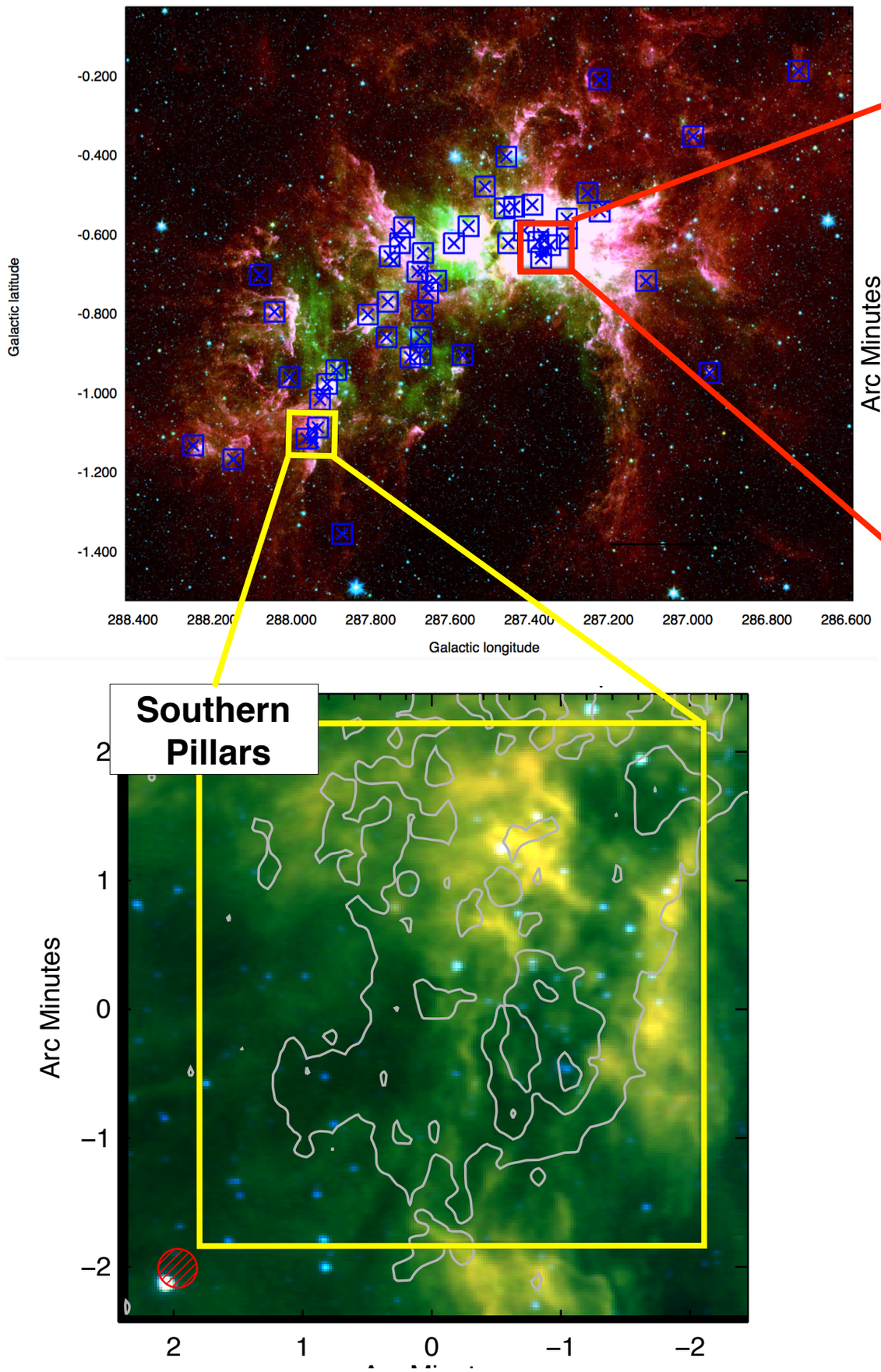
ALMA

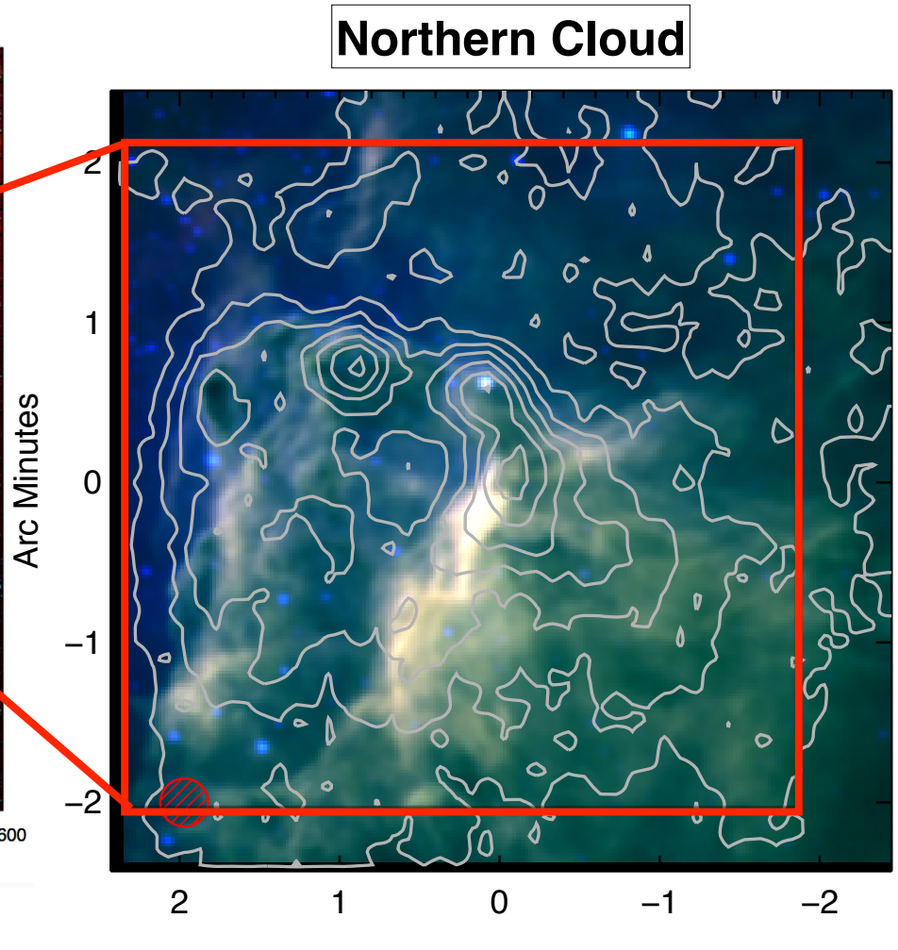
High-mass star forming clumps in the Carina Nebula

PI: Yanett Contreras

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

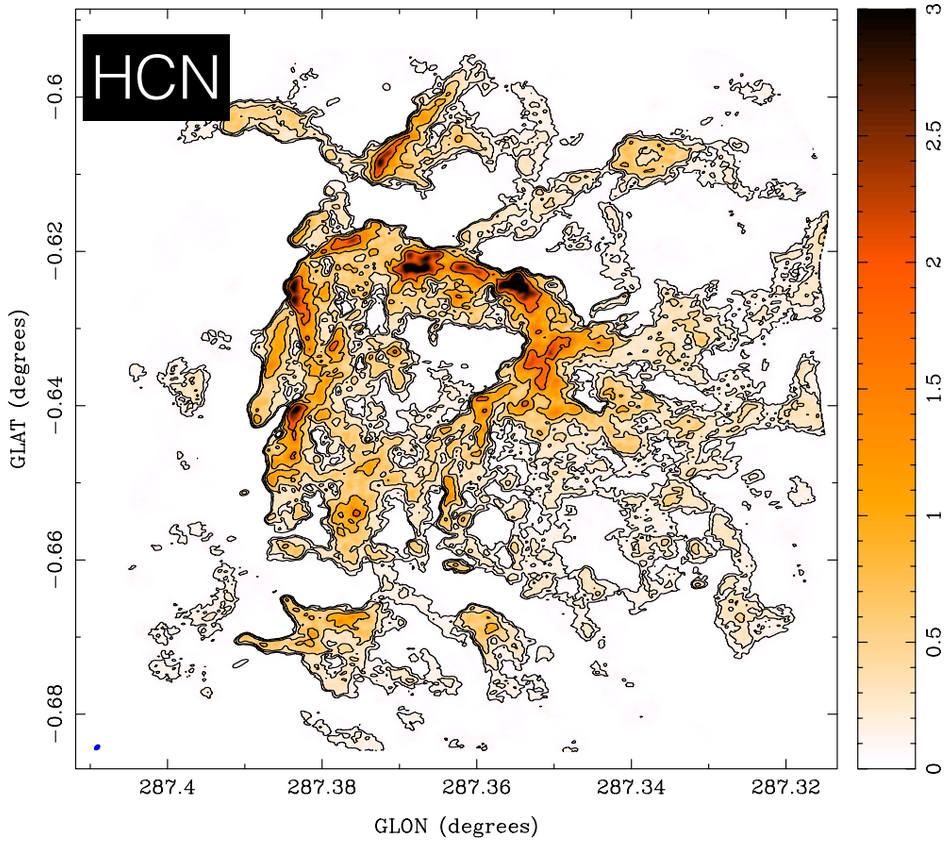


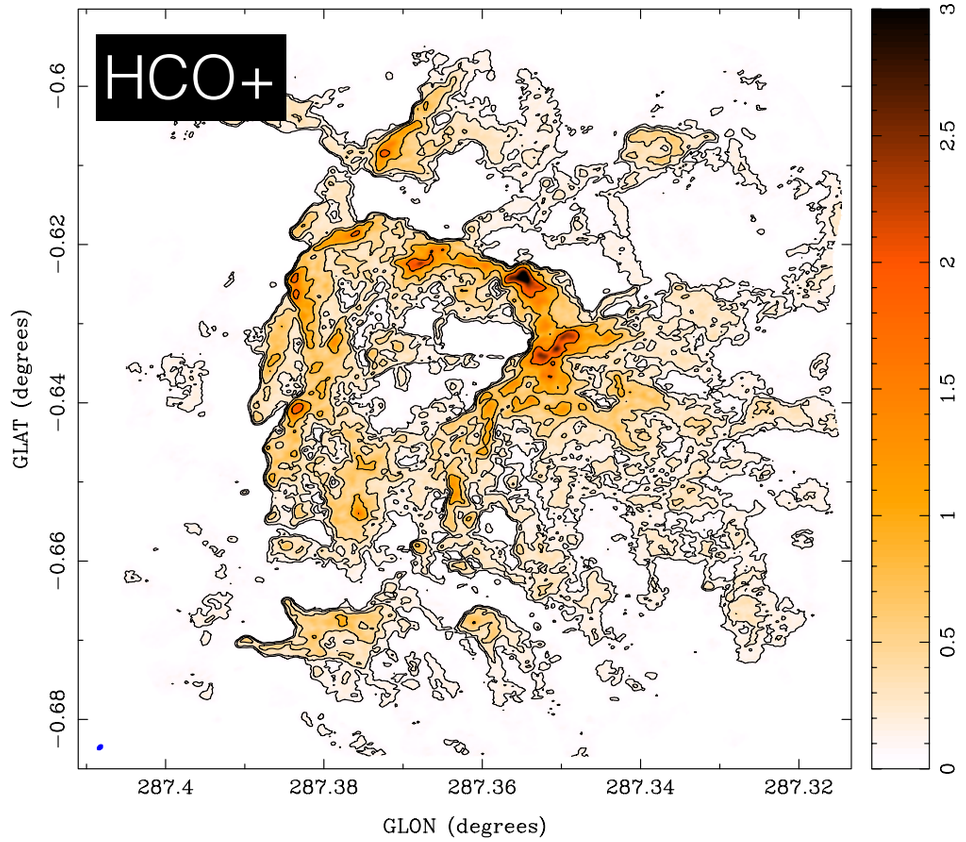


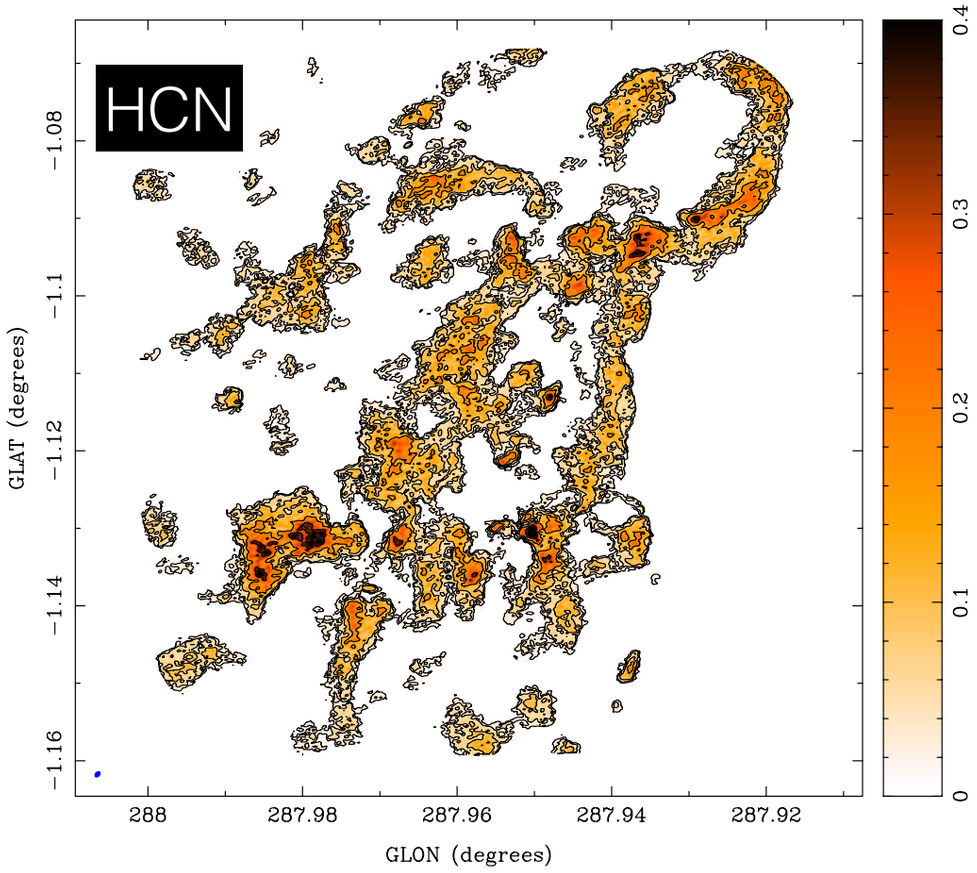


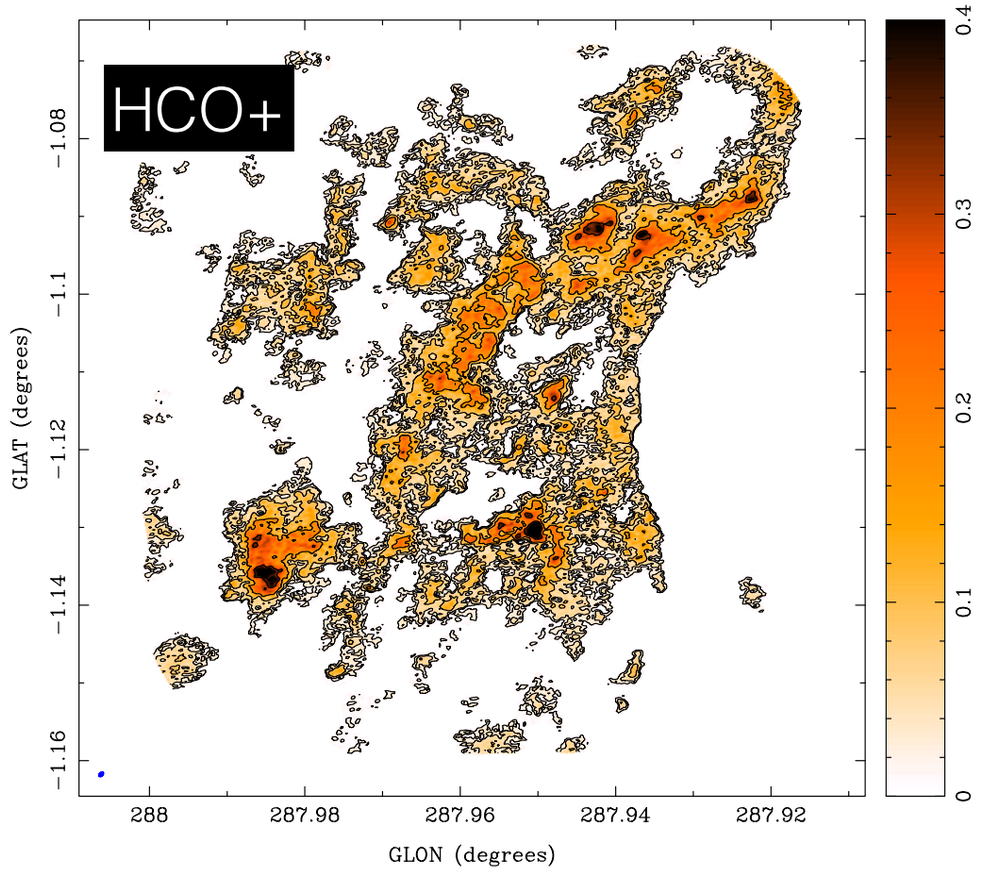
Cycle 4 - Band 3 (3mm)
HCO+, HCN and other molecules +
dust continuum at 3 mm

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


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+
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287.94
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0
0.1
0.2
0.3
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WHAT IS NEXT?

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

- Better comparison between different components of the ISM

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

SUMMARY

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

- High resolution maps have allowed us to find compact regions of cold HI where the phase transition is likely to be occurring.

- Imaging continuum is difficult…