Interaction of the massive OB stars with ISM in the Monoceros star-forming field:

The Rosette Nebula and Monoceros Loop Region

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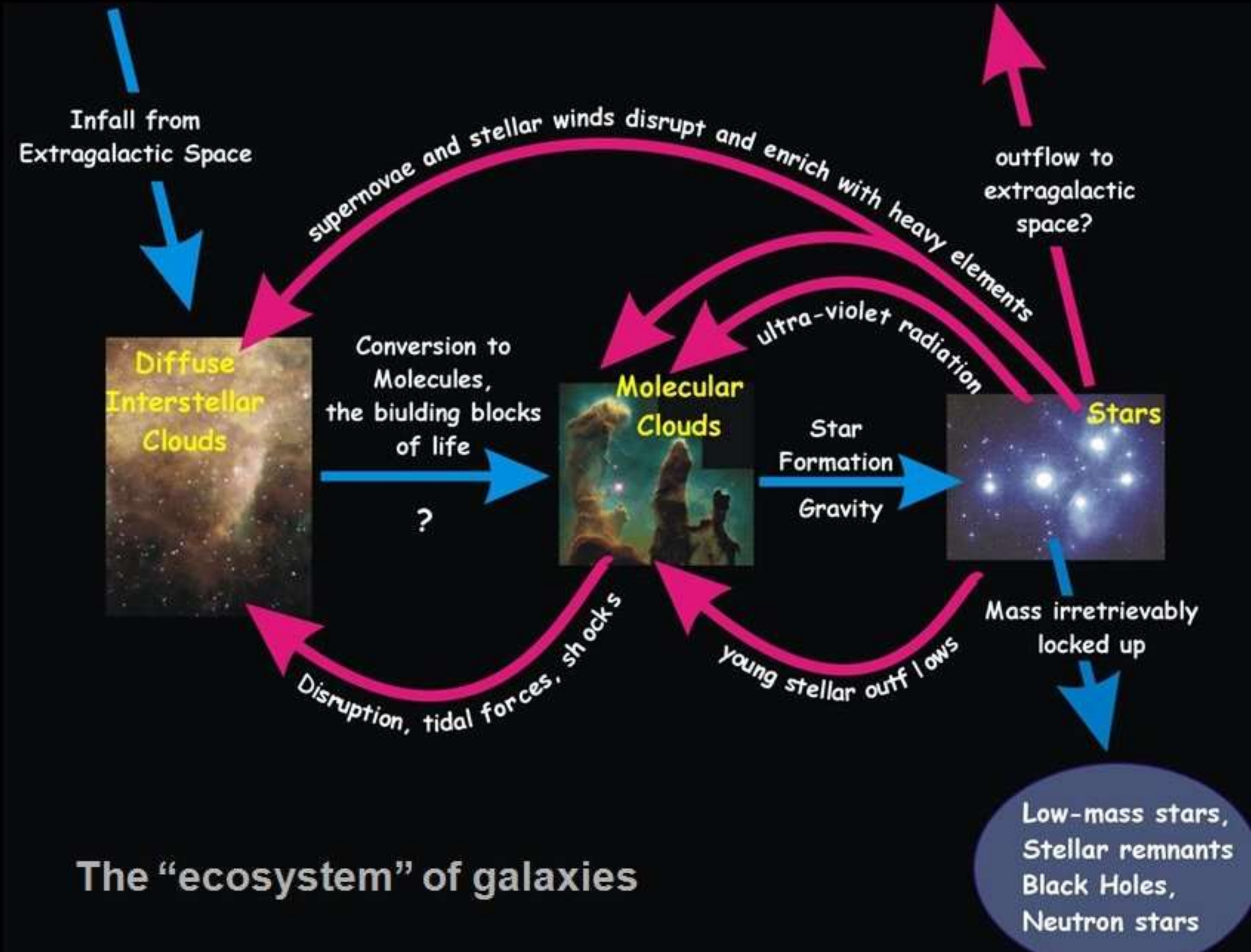
The Global Picture

Massive O and early B-type stars inject huge amounts of energy into the ISM through stellar winds, UV radiation, and during the SN phase at the end of their evolution. Their presence largely modifies the morphology and radiation at various wavelengths of their interstellar environment. In the case of OB associations, their collective effect has a huge impact in the surrounding ISM, creating large structures of about hundred parsecs. Winds and Supernova explosions transfer to the ISM vast amounts of mechanical energy, generating a compression of nearby molecular clouds.

We analyse the interaction between the ISM and massive OB stars in the field of Northern Monoceros. The region is the most complex star-forming region in the Perseus section of the Milky Way. The area harbors a huge collection of OB stars, both found in compact clusters or loose unbound groups, and also some of the most spectacular features of ISM known to date. The field provides an excellent opportunity to investigate the connection between the young stellar population and its associated ISM.

The Evolution of Matter



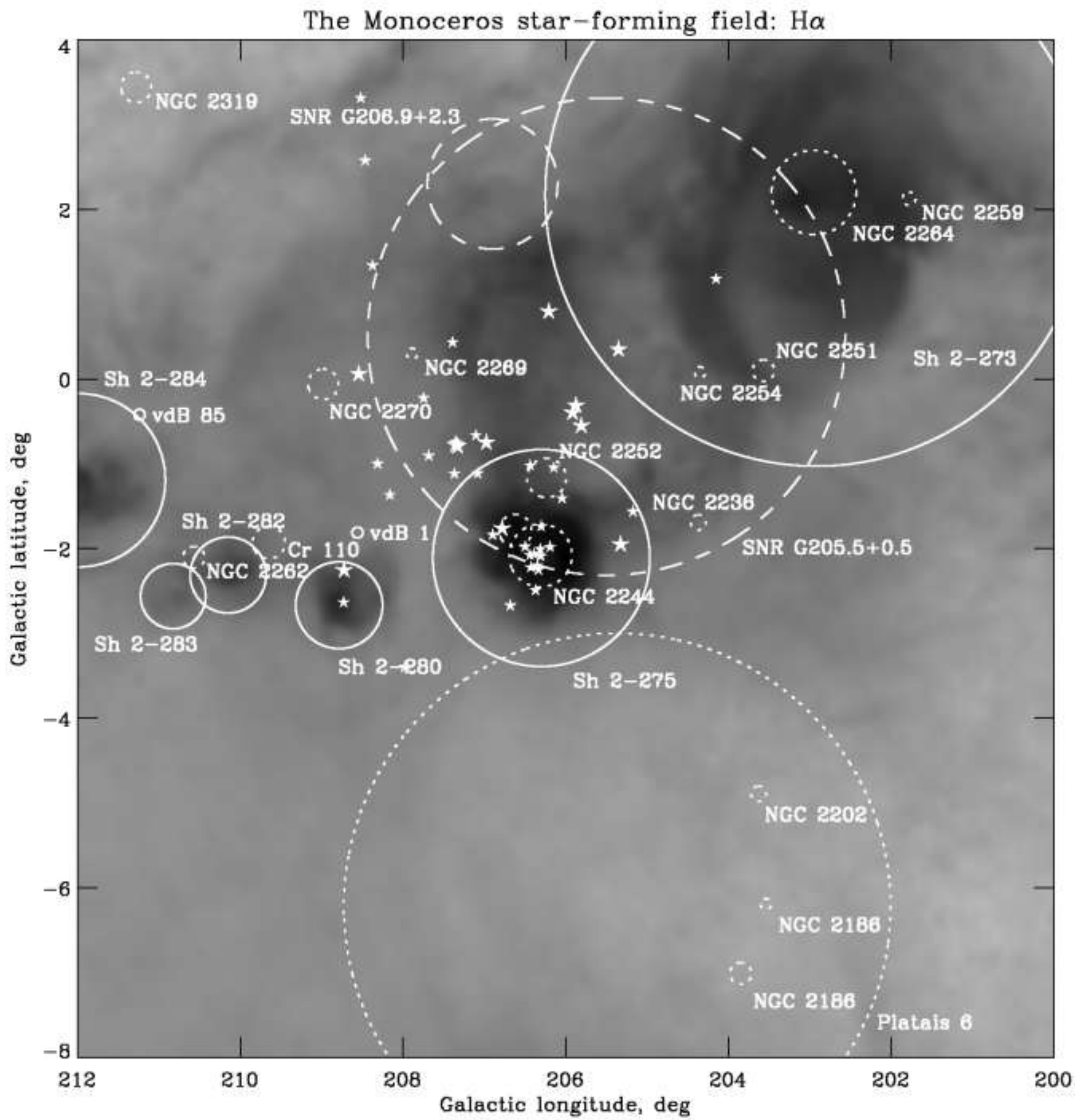
Astroinformatics context

The goal of this work is to achieve a better understanding of the phenomena associated with the interaction between young massive stars in the region and their surrounding ISM. We investigate the Monoceros star-forming field, located in the Perseus section of the Milky Way, by analyzing the distribution of the massive OB stars, ionized and neutral material, and that of the interstellar dust. To carry out this study, **a multi-wavelength approach is essential** in order to obtain a complete picture of the massive stellar population, the different components of the ISM, and the interactions among them.

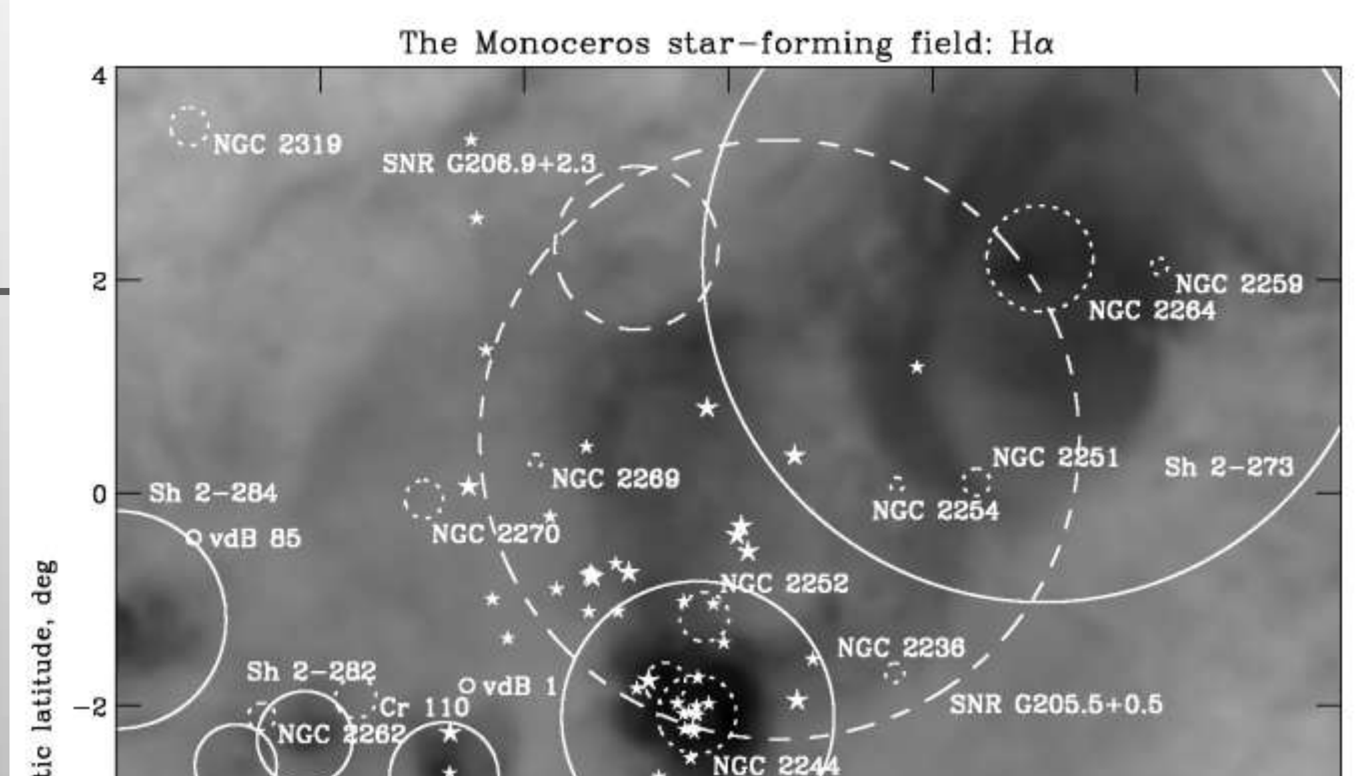
Radio continuum (RC) images at 408 and 1420 MHz, HI 21cm line 3D data, molecular 3D observations of the $_{12}$CO(1-0) line at 115 GHz, IRAS and DIRBE/COBE mid IR and FIR observations, Hα images, the 2MASS catalog, uvbyβ and UBV photometric data were used. ***SkyView*** Virtual Observatory generating images of any part of the sky at wavelengths in all regimes from Radio to Gamma-Ray was extensively involved.

The field:

Only
the major
stellar
and
nonstellar
objects
are
shown

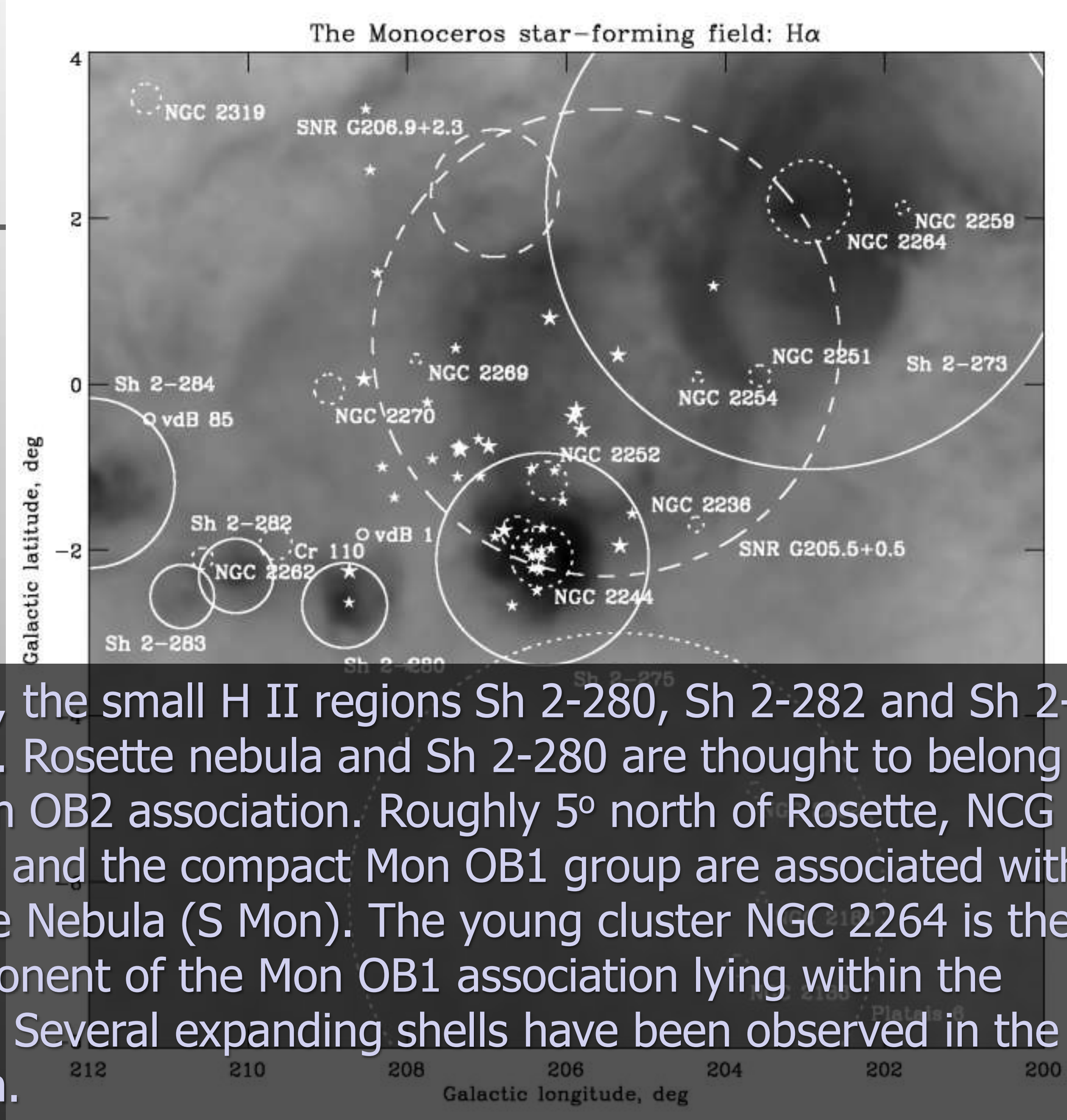


The field:



The Rosette Molecular Cloud (RMC) is known as one of the most massive molecular complexes in the Galaxy. The area is dominated by the Rosette Nebula (M 16 = Sh 2-275 = NGC 2237–2239, NGC 2244, and NGC 2246) - a large HII region at the tip of the RMC. Beside NGC 2244, the RMC contains a number of embedded clusters with diverse properties. RMC is among the most prominent sites for the exploration of active star formation. The still ongoing star-formation activities in this field have initiated extensive optical, IR, and X-ray studies.

The field:



Next to Rosette, the small H II regions Sh 2-280, Sh 2-282 and Sh 2-284 are located. Rosette nebula and Sh 2-280 are thought to belong to the large Mon OB2 association. Roughly 5º north of Rosette, NCG 2264 (Sh2-273) and the compact Mon OB1 group are associated with the diffuse Cone Nebula (S Mon). The young cluster NGC 2264 is the dominant component of the Mon OB1 association lying within the local spiral arm. Several expanding shells have been observed in the Mon OB1 region.

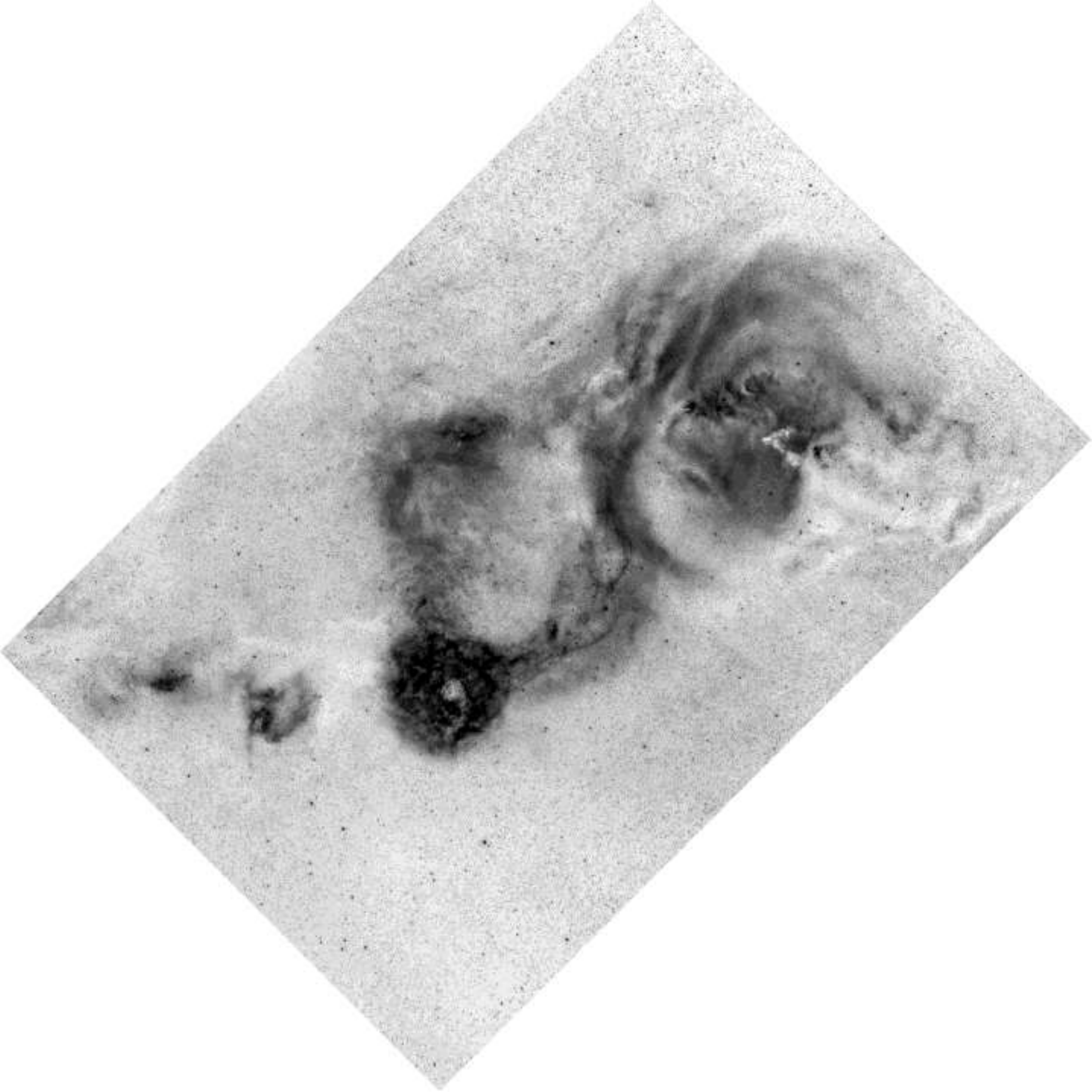
Herschel

The *Herschel* has recently observed the RMC, providing an unprecedented view of its star formation activity. The far-IR data reveal a population of compact young stellar objects, several clusters are distinguished including the cloud centre, the embedded clusters in the vicinity of luminous IR sources, and the interaction region. The protostellar population in RMC ranges from 0.1 to ~ 15 $M_{\odot}$ with luminosities between 1 and 150 $L_{\odot}$. Some sources lack counterparts at near- to mid-IR wavelengths, indicating extreme youth.

Hα deep

The field of interest

galactic coordinates



OB-stars in Northern Monoceros

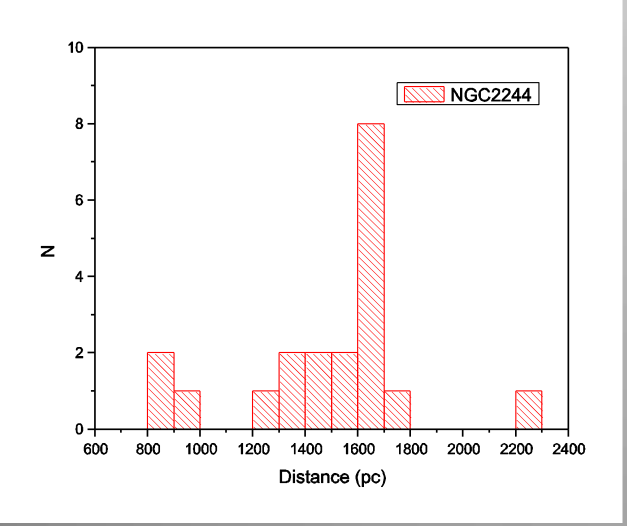
In light of the growing importance of Northern Monoceros in the study of star-formation, precise distance estimates to the apparent structures of young stars in the field are most important for a variety of reasons.

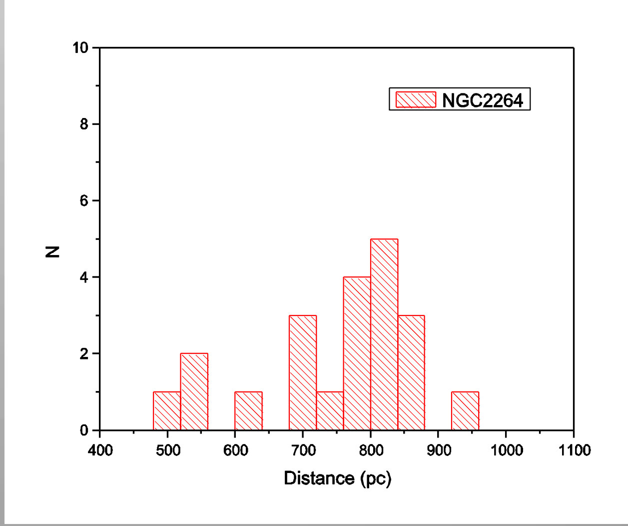
The area harbors a huge collection of recently born massive stars:

Mon OB1, Mon OB2, NGC 2244, NGC 2264, and more ...

OB-stars in Northern Monoceros

Despite the extensive studies, the existing distance estimates to both Mon OB1 and Mon OB2 associations and the major open clusters in the field are still controversial:





Distances to NGC 2244 and NGC 2264 found in the literature (1950-present)

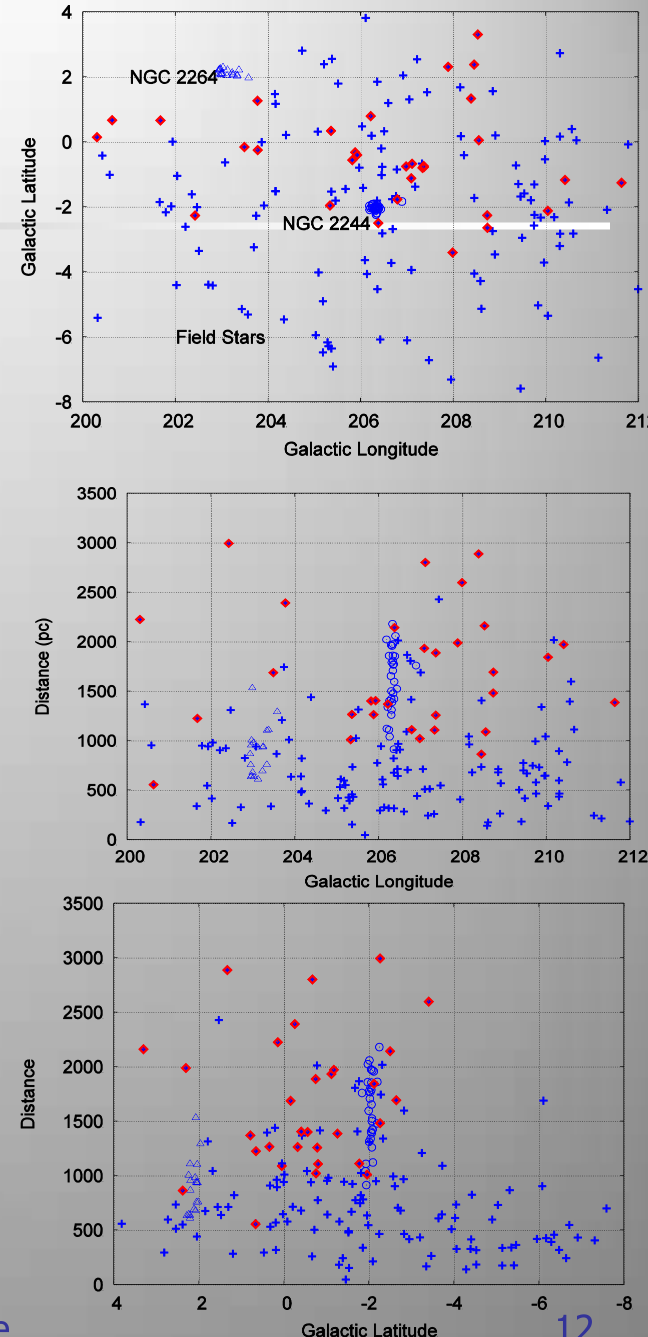
OB-stars in Northern Monoceros

Resent study of the structure of the field based uvbyβ photometric distances – see Kaltcheva, Kuchera, & Hathaway 2010, Astronomische Nachrichten, vol. 331, p.384

Red diamonts – stars with Mv < –3 (should belong to the classical Mon OB2 at 1.6 kpc – see Turner 1976)

The uvbyβ distances suggest that Mon OB2 can be broken down into two parts:

- a loose extended group averaging a distance of ~2250 pc, and
- a compact group ~1250 pc located toward Rosette and Mon Loop

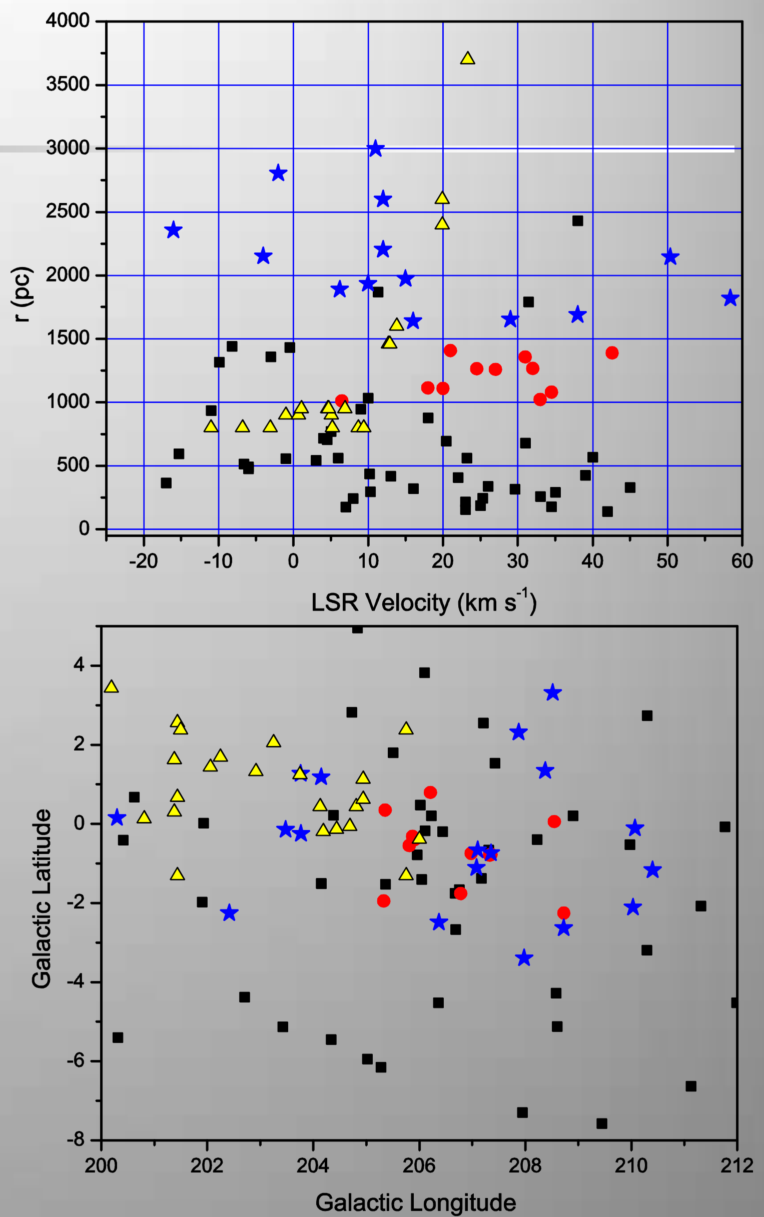


All OB stars with radial velocities and uvbyβ photometric distances

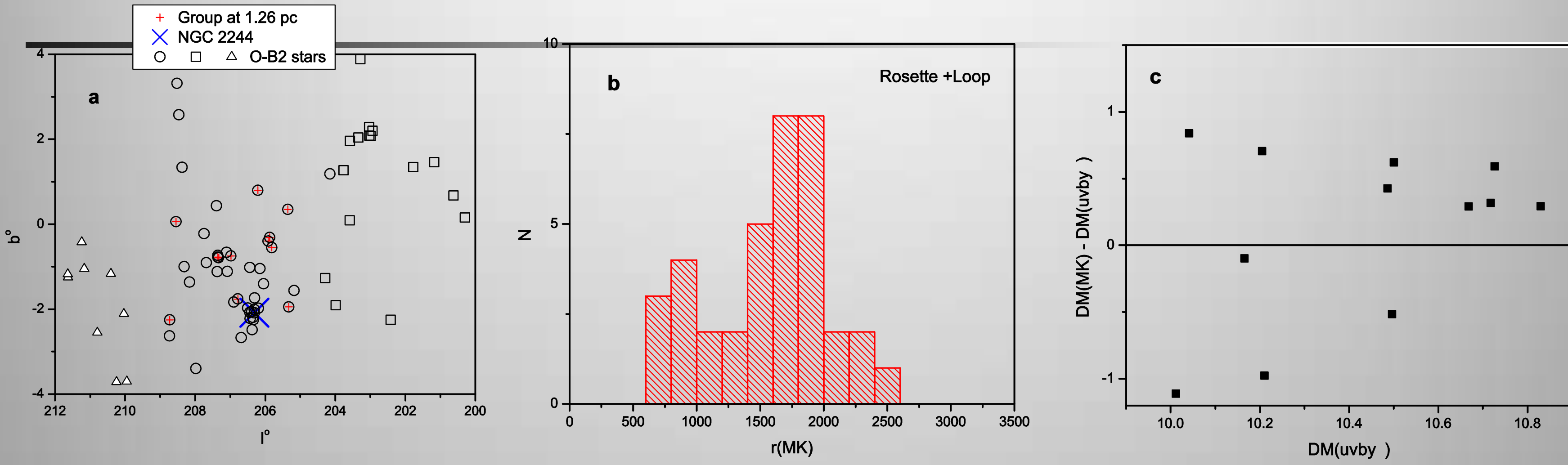
Red symbols: group of massive stars ($M_V < -3$ mag) at an average distance 1260 pc.

Blue asterisks: layer of massive stars at average distance 2150 pc.

Filled squares: stars with $M_V > -3$ mag, most of them located closer than 1000 pc.



Expanding the sample: all O-B2 stars in the field



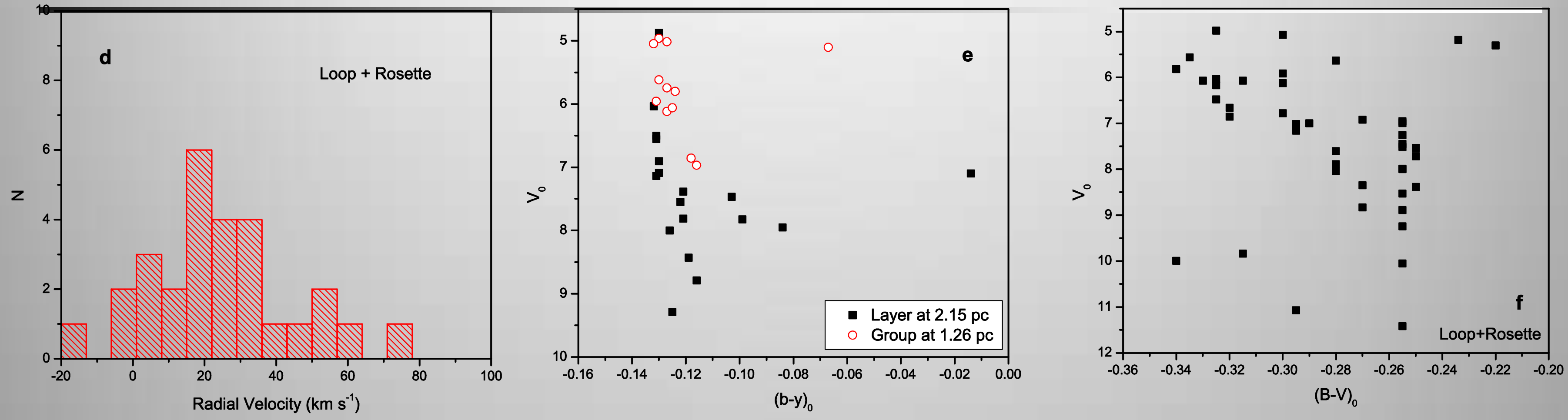
(a) All O-B2 stars included in SIMBAD (different symbols - an arbitrary division according to galactic longitude, stars with uvbyβ distances - red symbols).

(b) Distribution of distances (spectroscopic calibration of Deutschman et al. 1976): maximum at 1710±365 (s.d.) – corresponds to the classical estimate for Mon OB2 – ***we argue that this distance is overestimated.***

(c) Comparison between the spectroscopic and uvbyβ distances: spectroscopic distance moduli are overestimated by ~0.5 mag - leads to a distance larger by a factor of 1.25.

An uvbyβ distance of 1.26 kpc corresponds to a spectroscopic distance of 1.58 kpc.

Expanding the sample: all O-B2 stars in the field



(d) Radial velocities available for 80% of the O-B2 stars toward the Loop and Rosette (open circles in plot (a)): maximum at ~26 km/s agrees well with the radial velocity estimate for the Loop and the group of 12 stars at 1.26 kpc.

(e,f) Color-Magnitude diagrams for the O-B2 stars in the vicinity of the Loop and Rosette based on uvbyβ photometry and on the calibration of Deutschman et al. (1976).

Individual distances based on MK types are of low precision and can not be used to select additional members of the 1.26 kpc group.

OB-stars: main findings

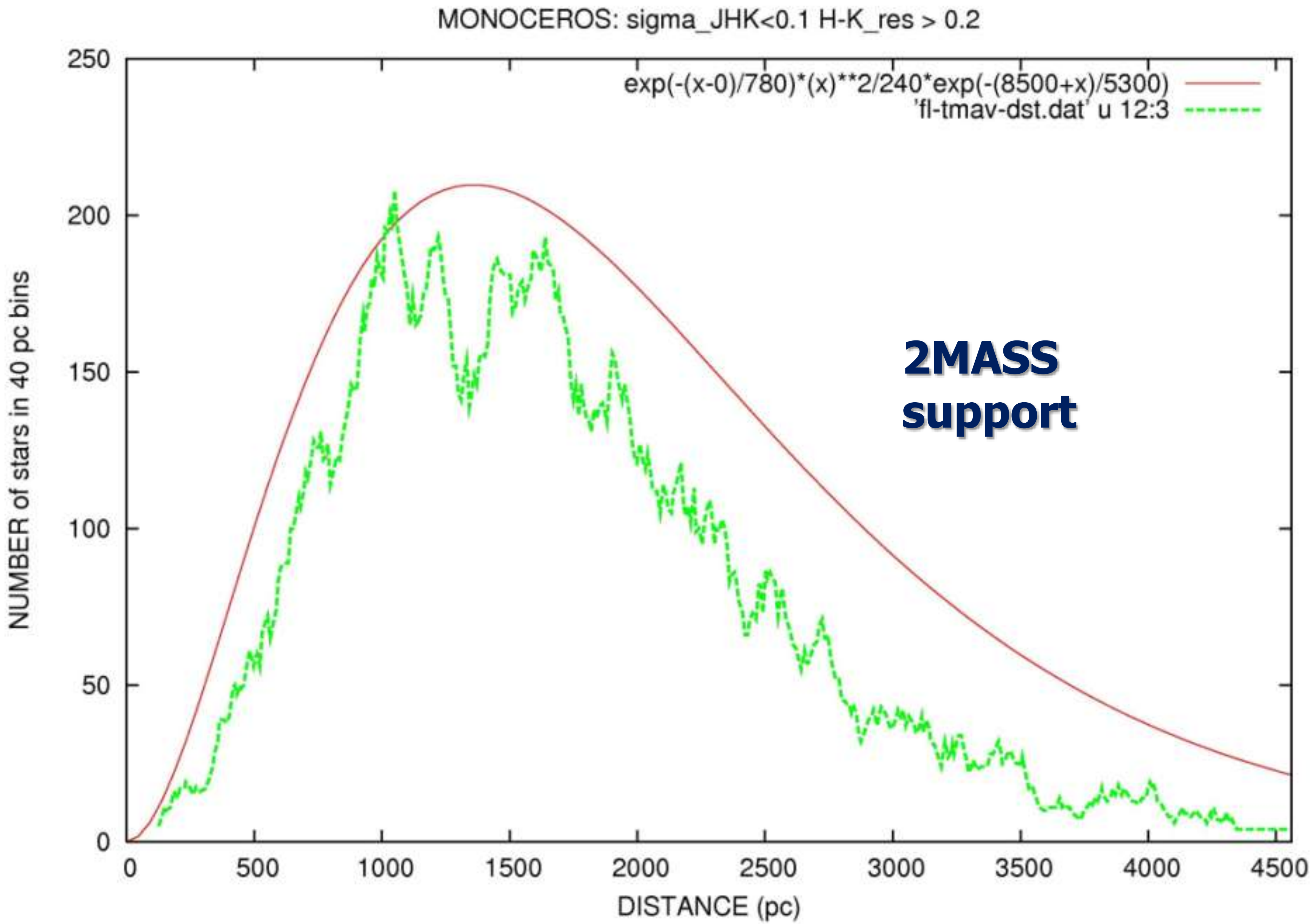
- We present arguments that the distance of 1.6-1.7 kpc to the OB stars toward Rosette and the Mon Loop is overestimated

- A close inspection of the uvbyβ photometric distances, radial velocities, and an analysis of the discrepancy between the photometric and spectroscopic distances justifies a conclusion that probably most of the O-B2 stars located toward Rosette and the Loop belong to a structure at about 1.26 kpc.

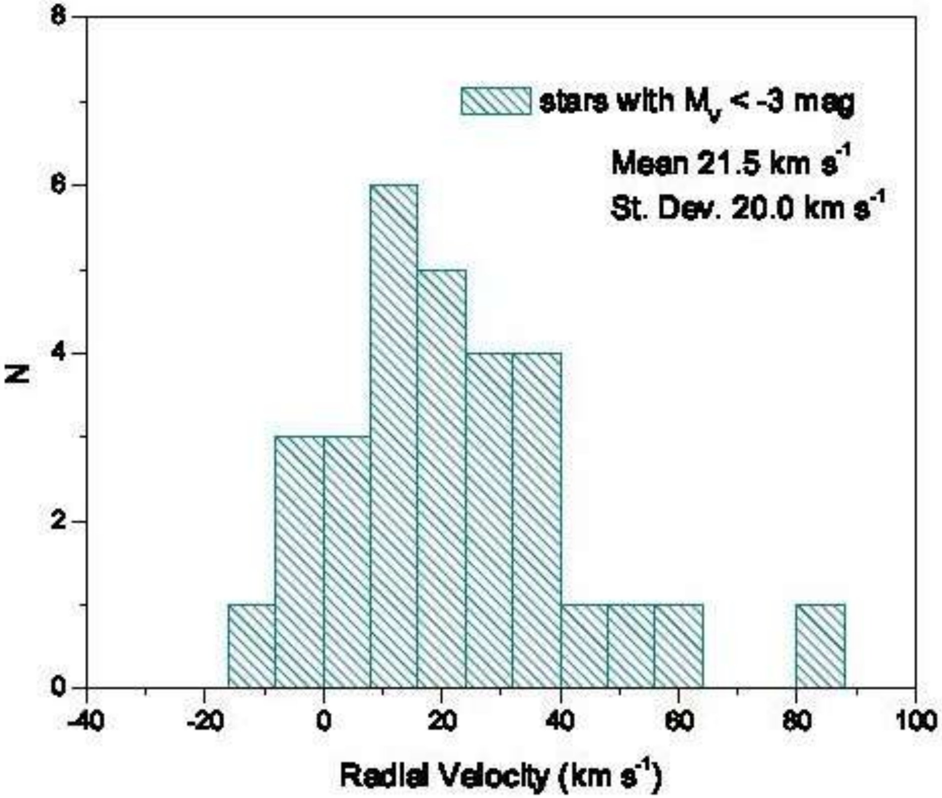
(Excellent agreement with a recent distance estimate of 1.25±0.19 kpc to the Monoceros Loop; Borka Jovanovic and Urosevic, 2009.)

Suggested OB-star distribution in Northern Monoceros:

- Compact OB group toward Rosette and the Loop at 1.26 kpc.
- Layer of OB stars between 1.5 and 3 kpc (2.15 kpc average).

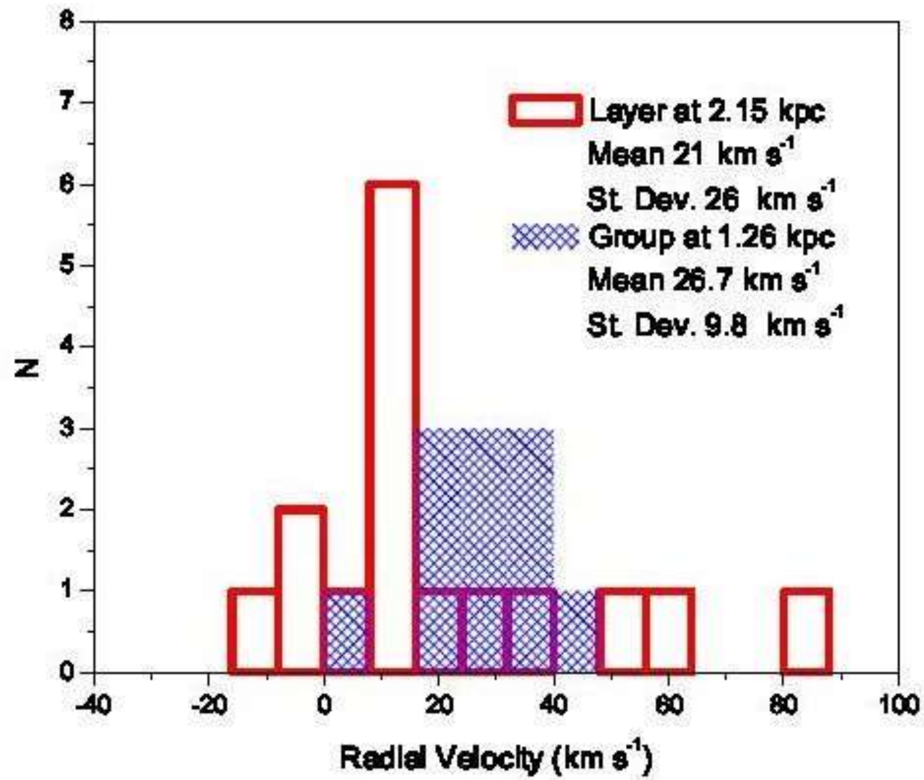

MONOCEROS: sigma_JHK<0.1 H-K_res > 0.2
exp(-(x-0)/780)*(x)**2/240*exp(-(8500+x)/5300)
'fl-tmav-dst.dat' u 12:3
NUMBER of stars in 40 pc bins
DISTANCE (pc)
0
50
100
150
200
250
500
1000
1500
2000
2500
3000
3500
4000
4500
2MASS support

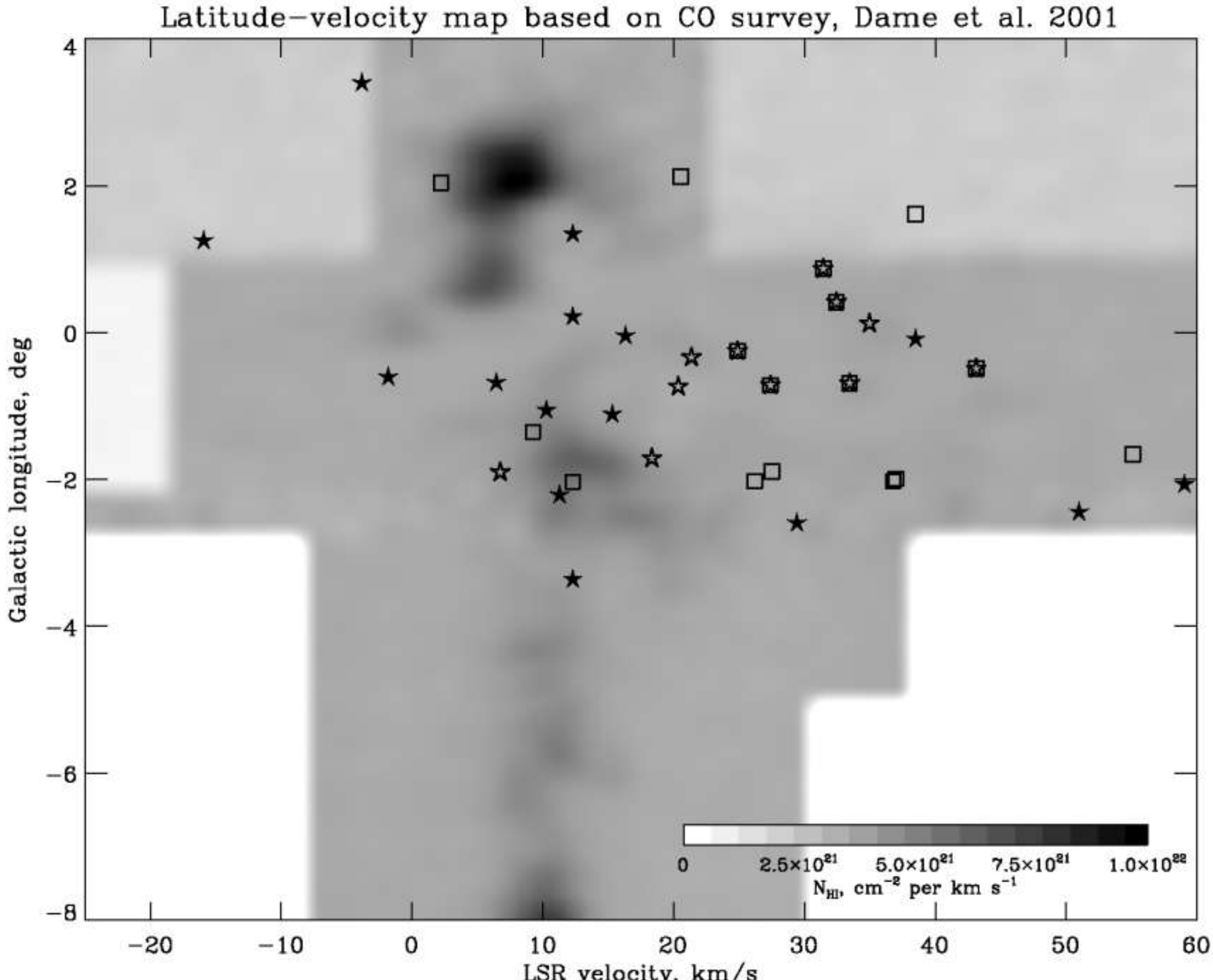
Histograms of radial velocities



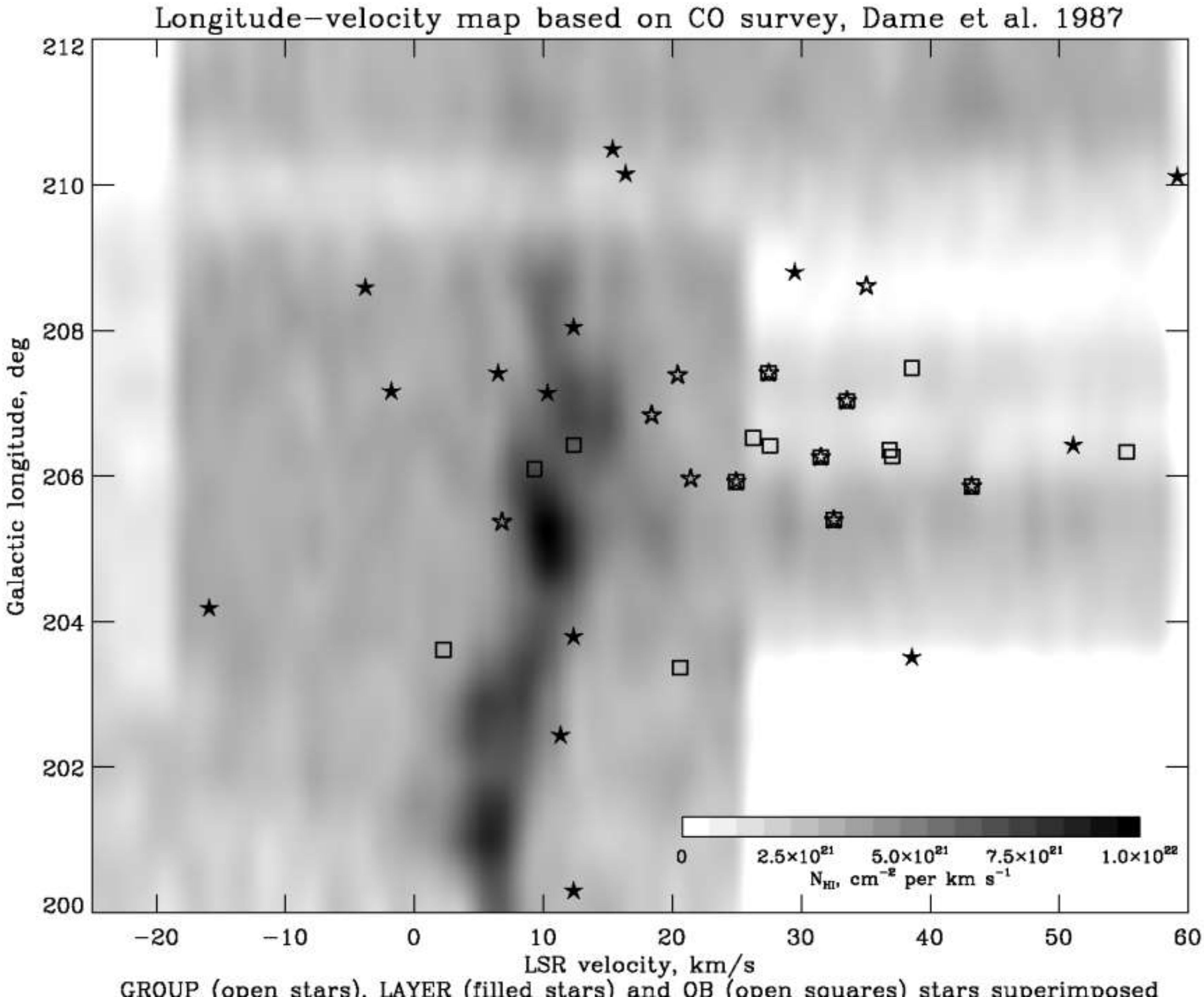
← all stars with $M_V < -3^m$.

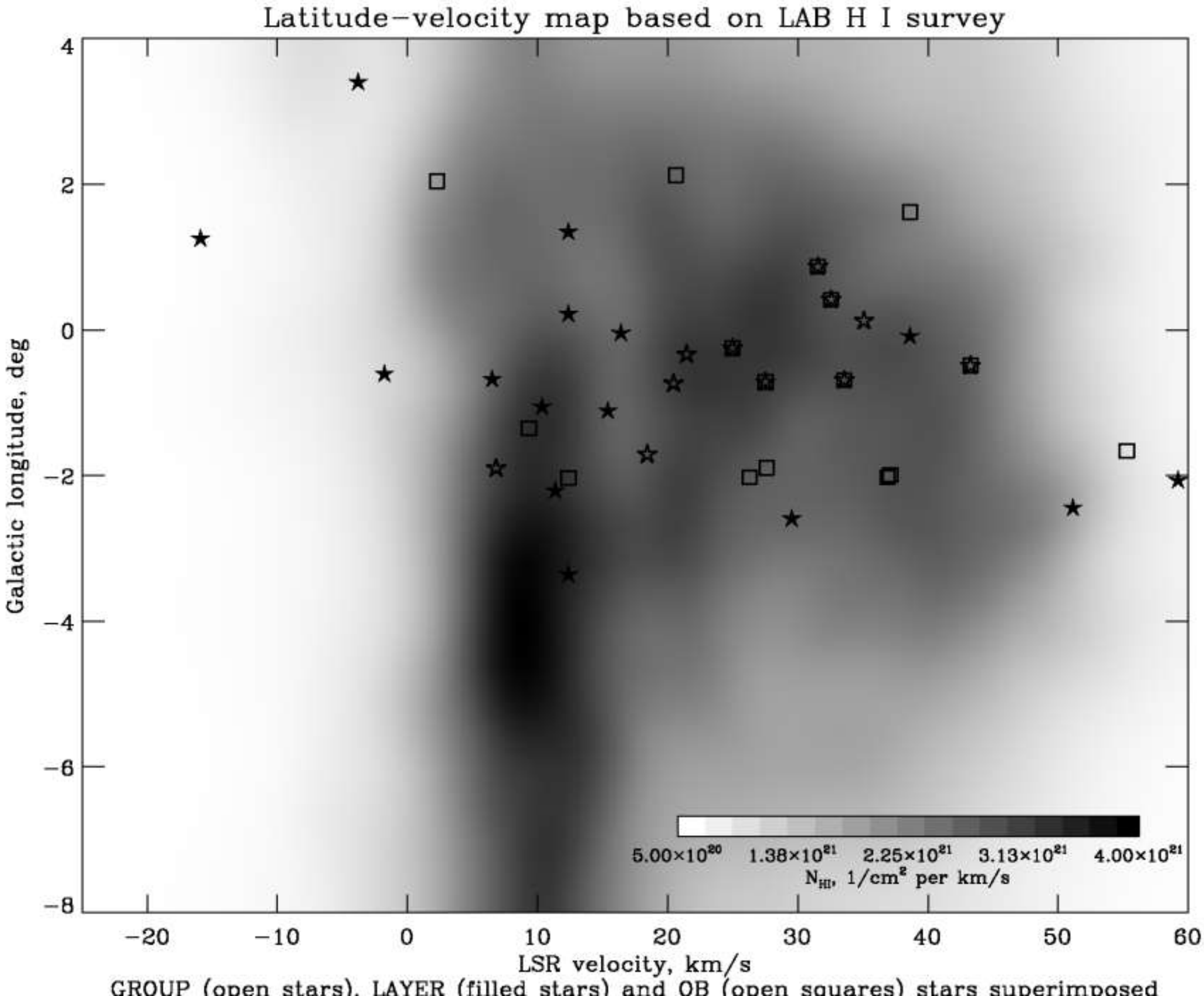
stars associated with the layer between 1.5 - 3 kpc (solid red line) and stars associated with the group at 1.26 pc. →



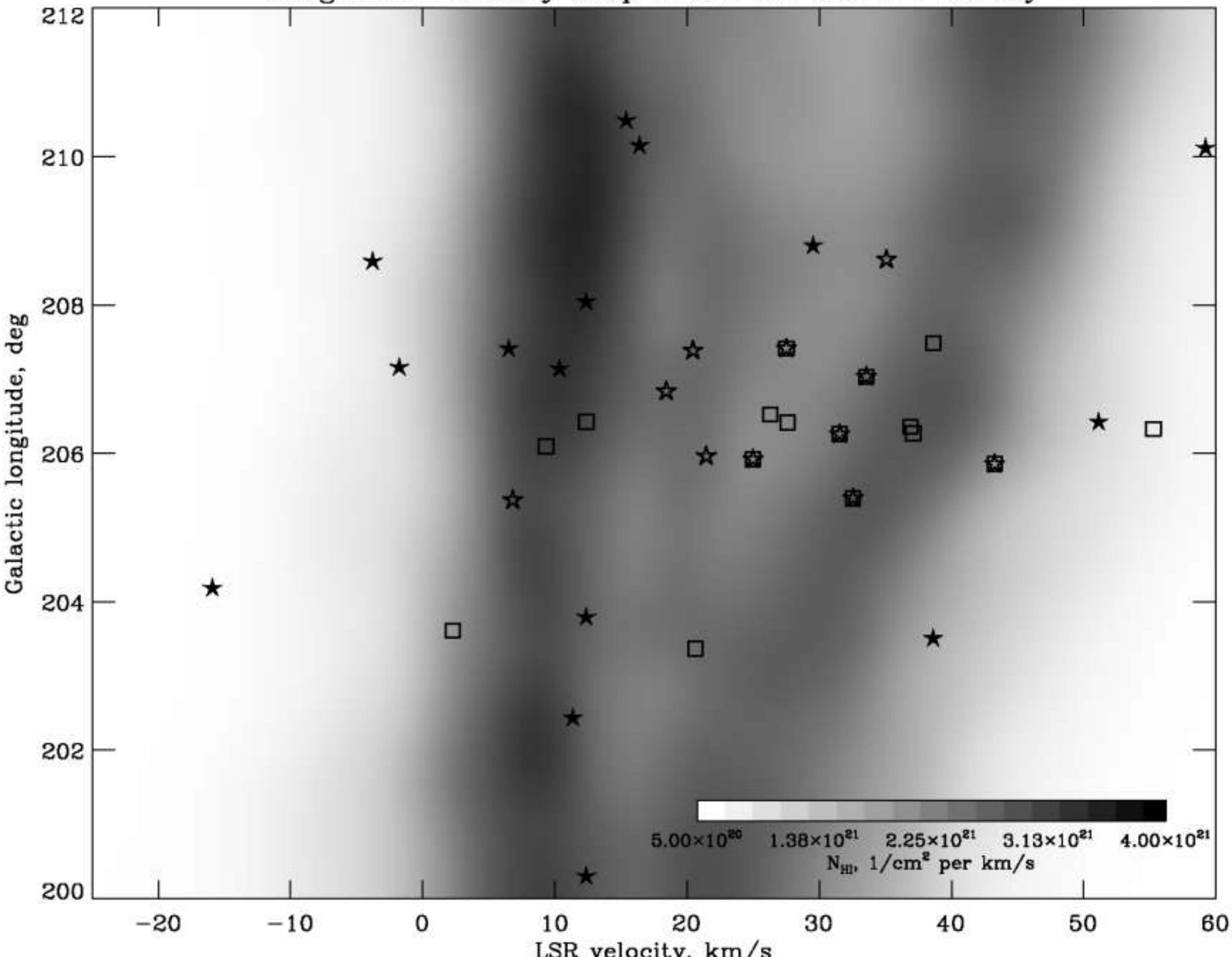


GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed


Longitude−velocity map based on CO survey, Dame et al. 1987
Galactic longitude, deg
212
210
208
206
204
202
200
−20
−10
0
10
20
30
40
50
60
0
2.5×10^21
5.0×10^21
7.5×10^21
1.0×10^22
N_HI, cm^-2 per km s^-1
LSR velocity, km/s
GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed

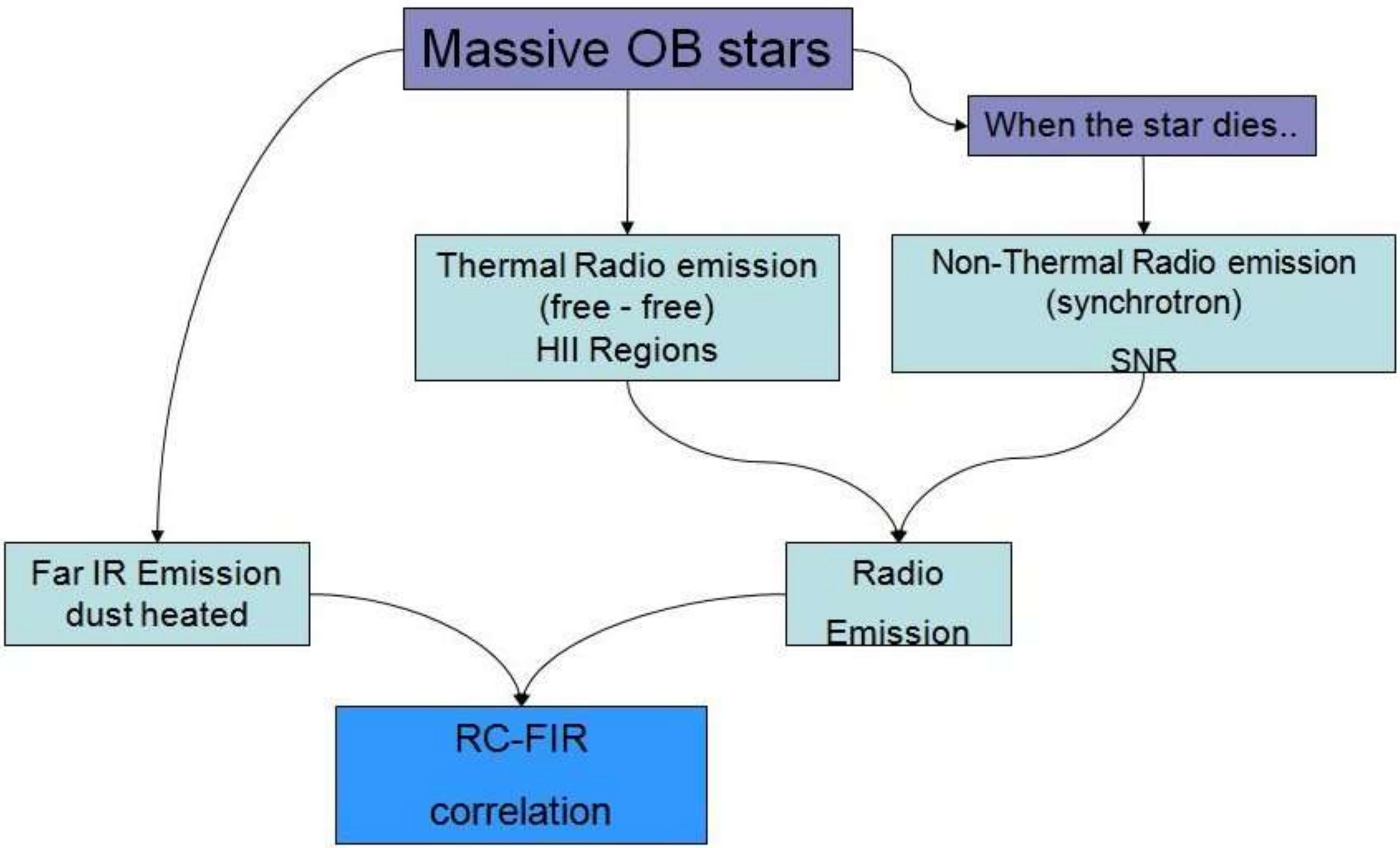

Latitude−velocity map based on LAB H I survey
Galactic longitude, deg
LSR velocity, km/s
5.00×10^20 1.38×10^21 2.25×10^21 3.13×10^21 4.00×10^21
N_HI, 1/cm^2 per km/s
GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed

Longitude−velocity map based on LAB H I survey



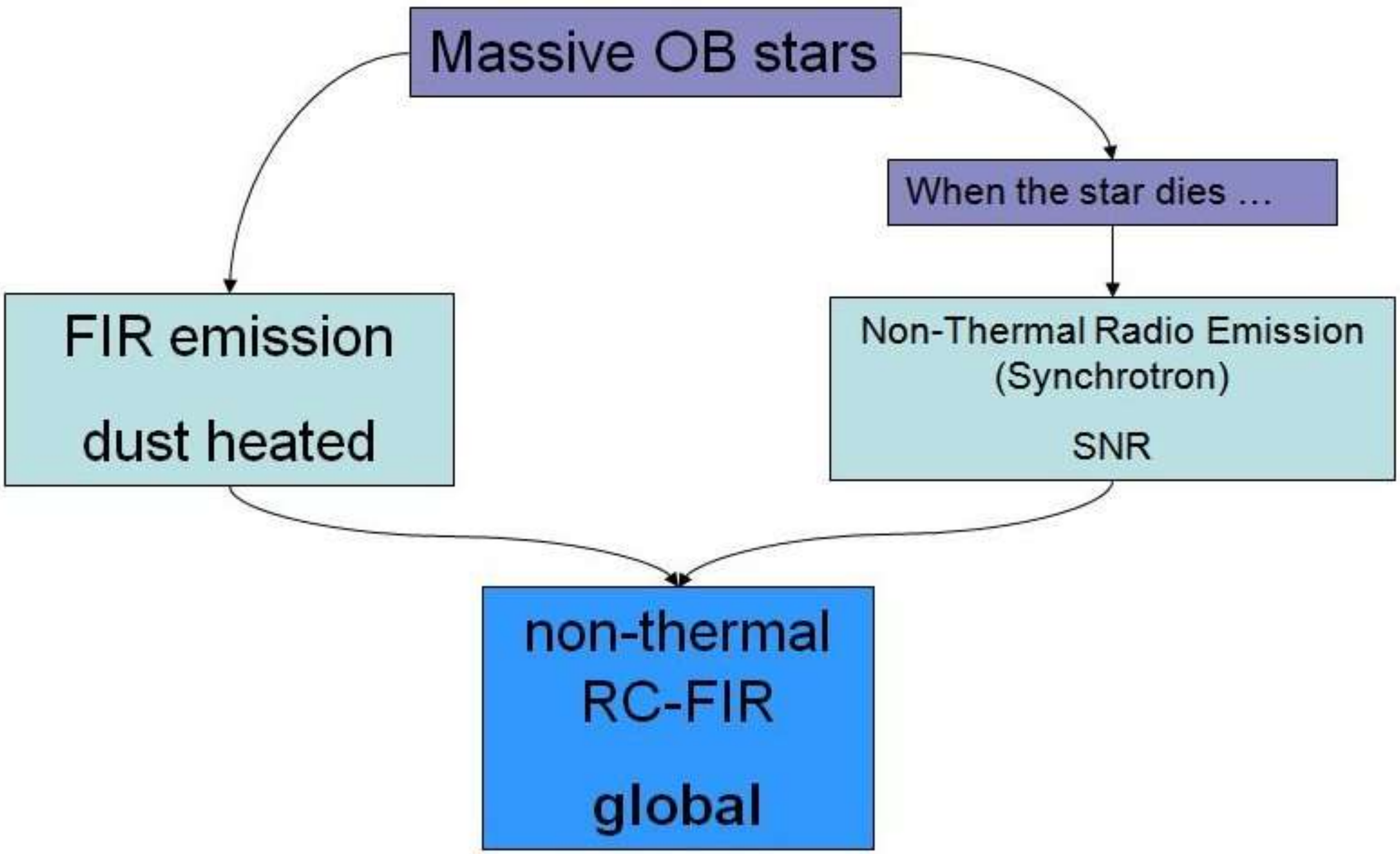
GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed

RC-FIR Correlation



RC-FIR correlation "Global"

The relation between the infrared and the non-thermal radio emission is expected to be only global. It breaks down at scales below about 1kpc



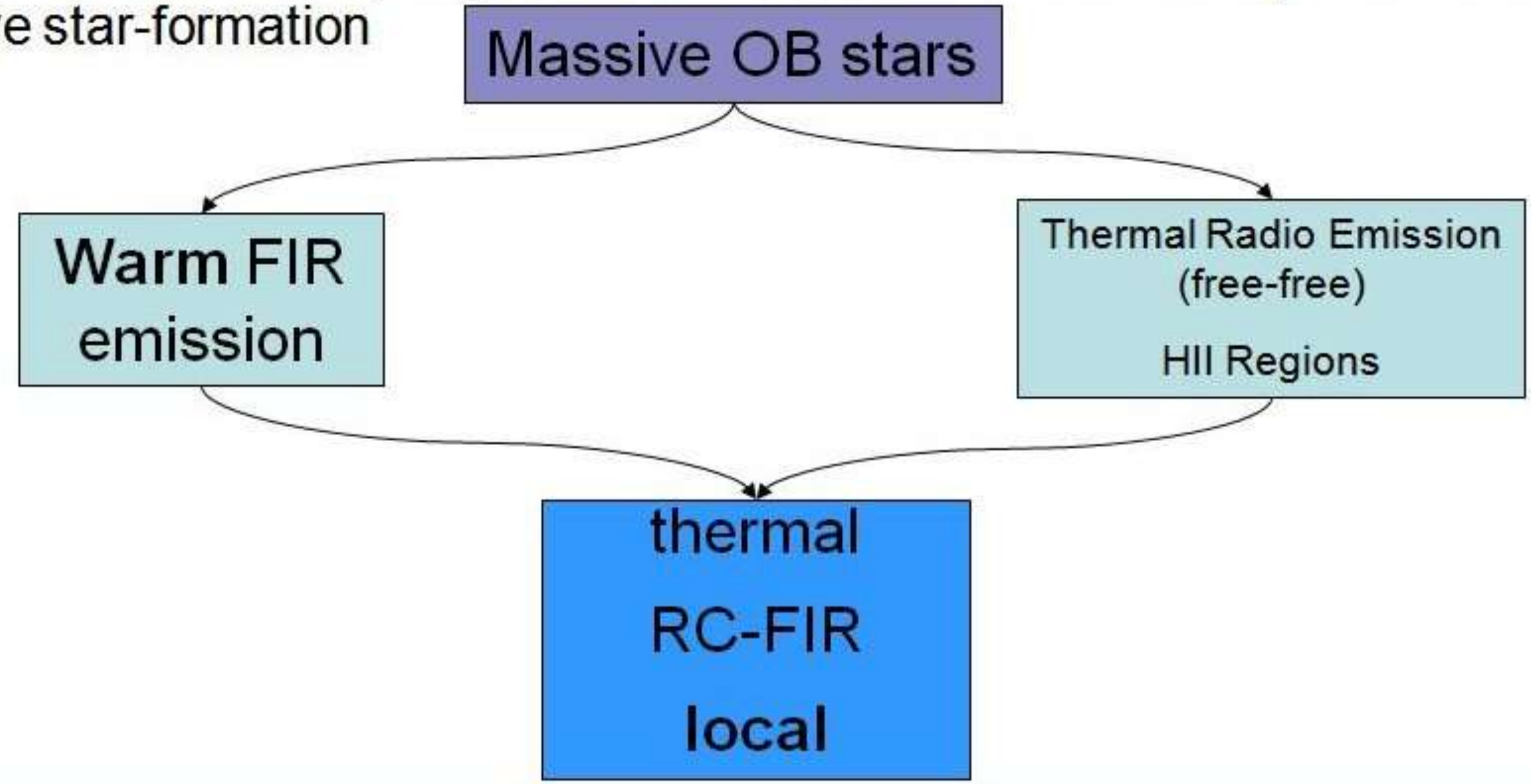
RC-FIR correlation "Local"

The dust has 2 components :

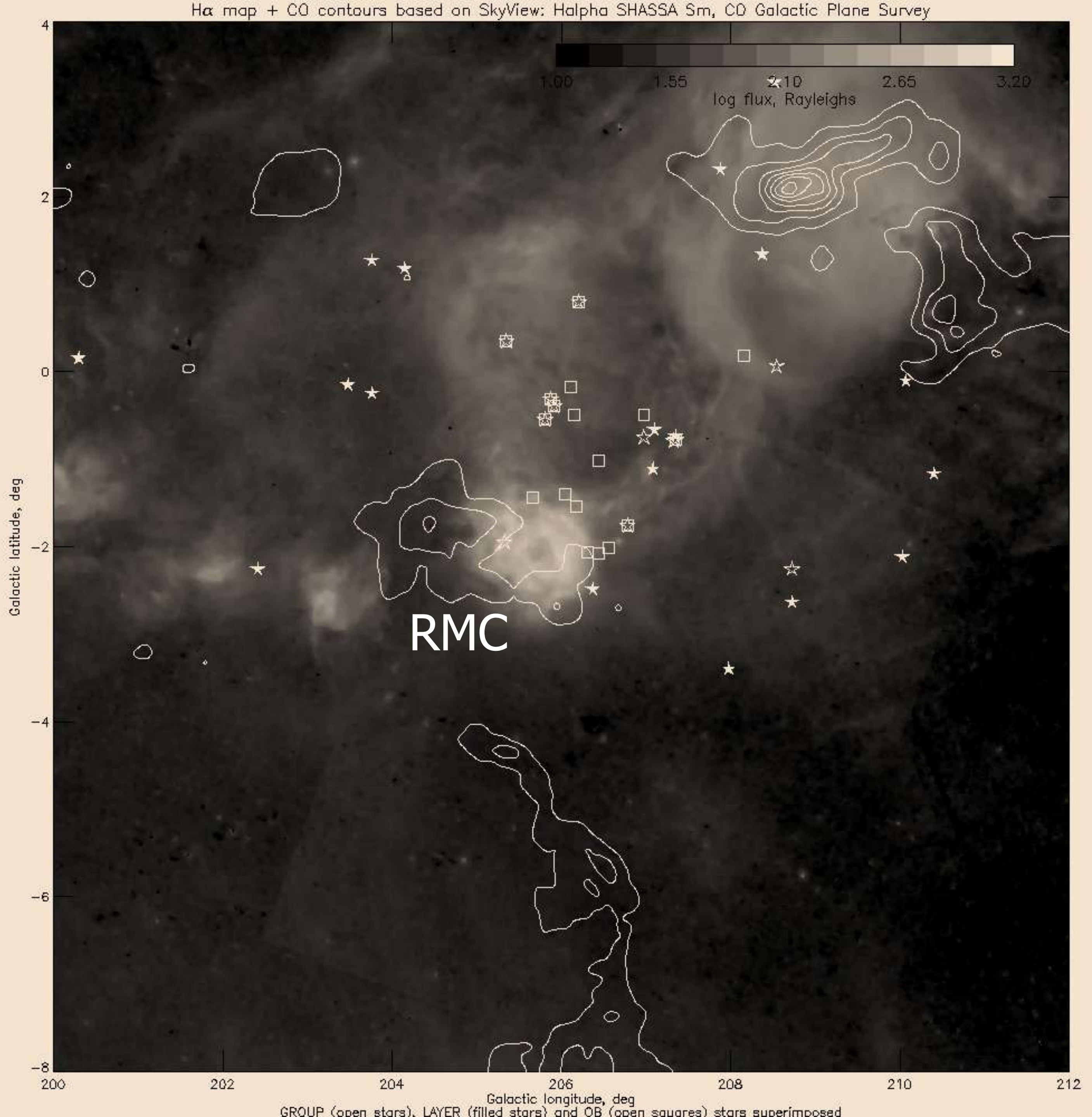
Warm : T ~ 45 K (dust heated by nearby stars)

Cold : T ~ 20 K (dust in the diffuse general interstellar medium)

Then correlation between the warm dust component and the thermal radio emission is clearly expected local, since both are directly related to massive star-formation



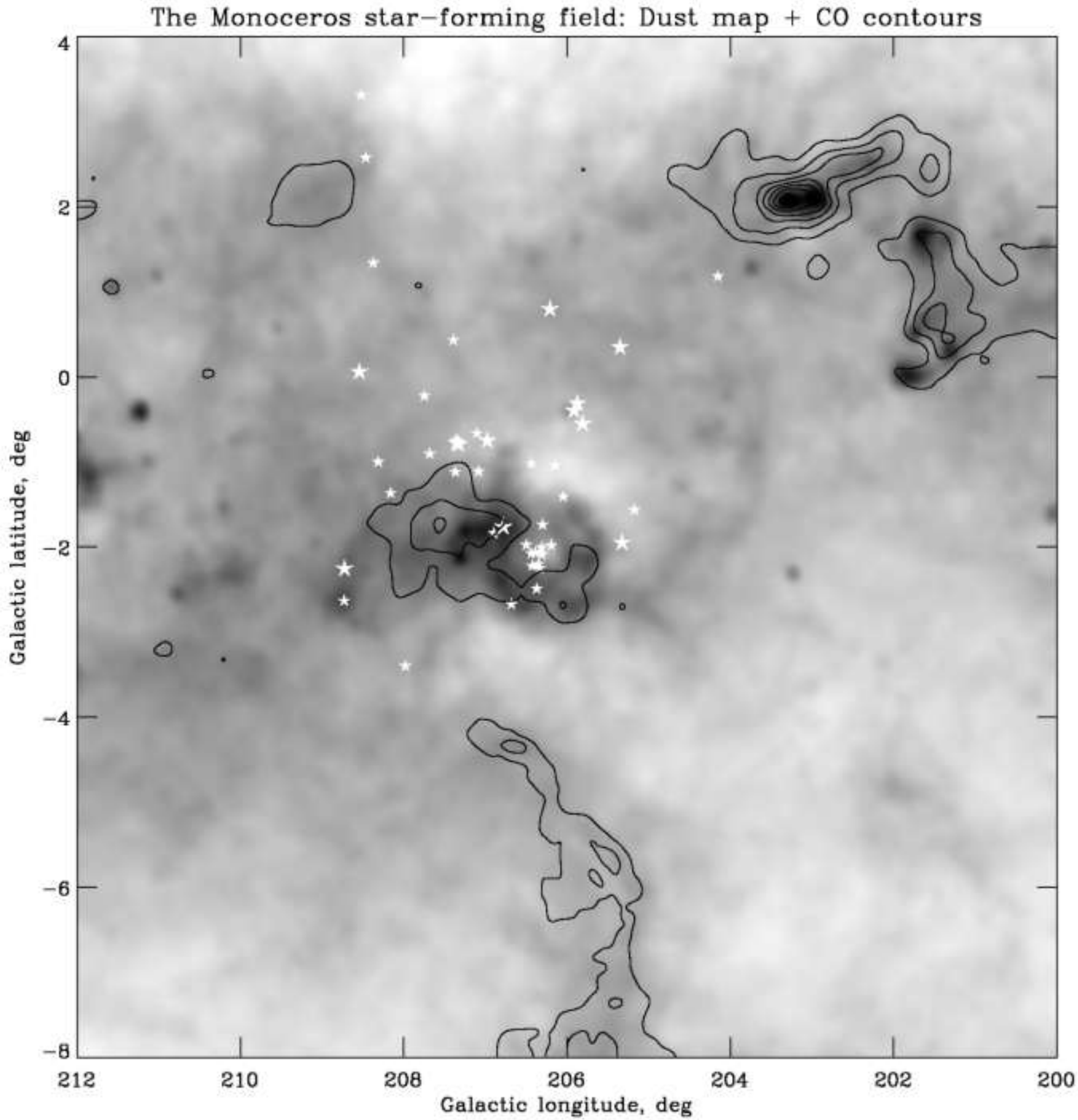
Hα + CO



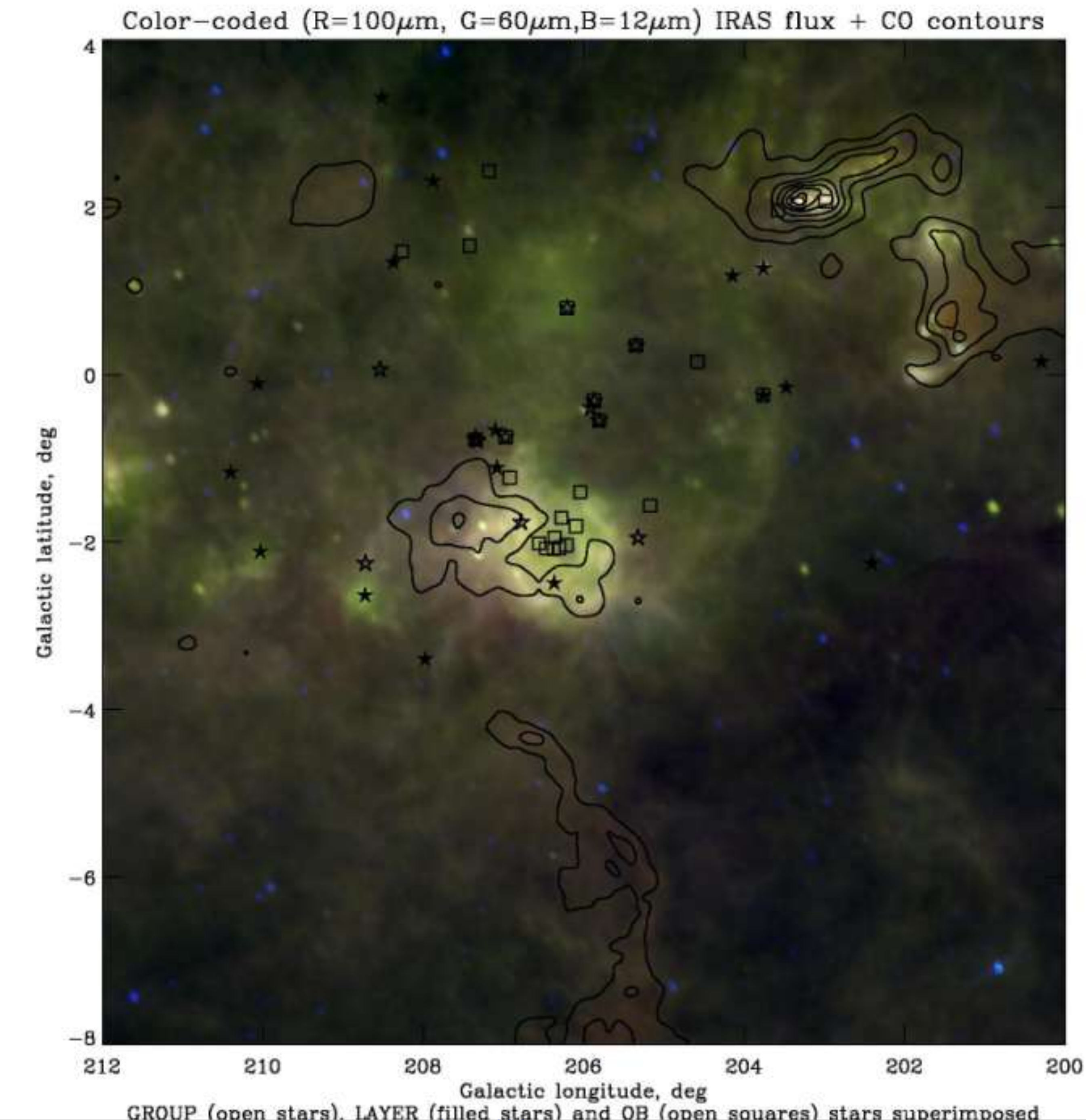
Hα map + CO contours based on SkyView: Halpha SHASSA Sm, CO Galactic Plane Survey
1.00
1.55
2.10
2.65
3.20
log flux, Rayleighs
Galactic latitude, deg
4
2
0
−2
−4
−6
−8
RMC
200
202
204
206
208
210
212
Galactic longitude, deg
GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed

E(B-V) reddening

COBE/ DIRBE + CO



IRAS+CO

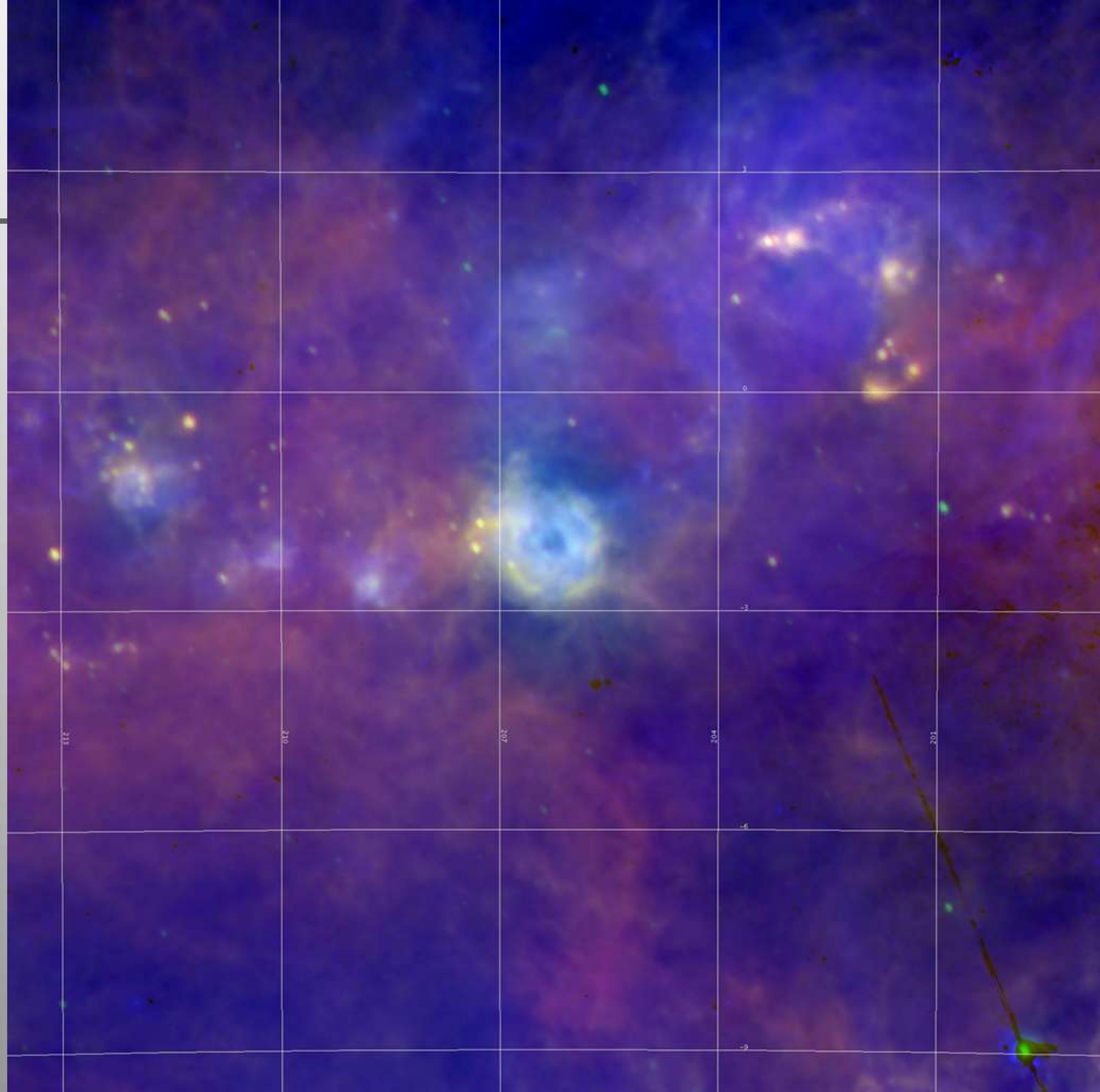


Color−coded (R=100μm, G=60μm,B=12μm) IRAS flux + CO contours
Galactic latitude, deg
4
2
0
−2
−4
−6
−8
212
210
208
206
204
202
200
Galactic longitude, deg
GROUP (open stars), LAYER (filled stars) and OB (open squares) stars superimposed

COBE
+IRAS
+Hα

RGB channels:

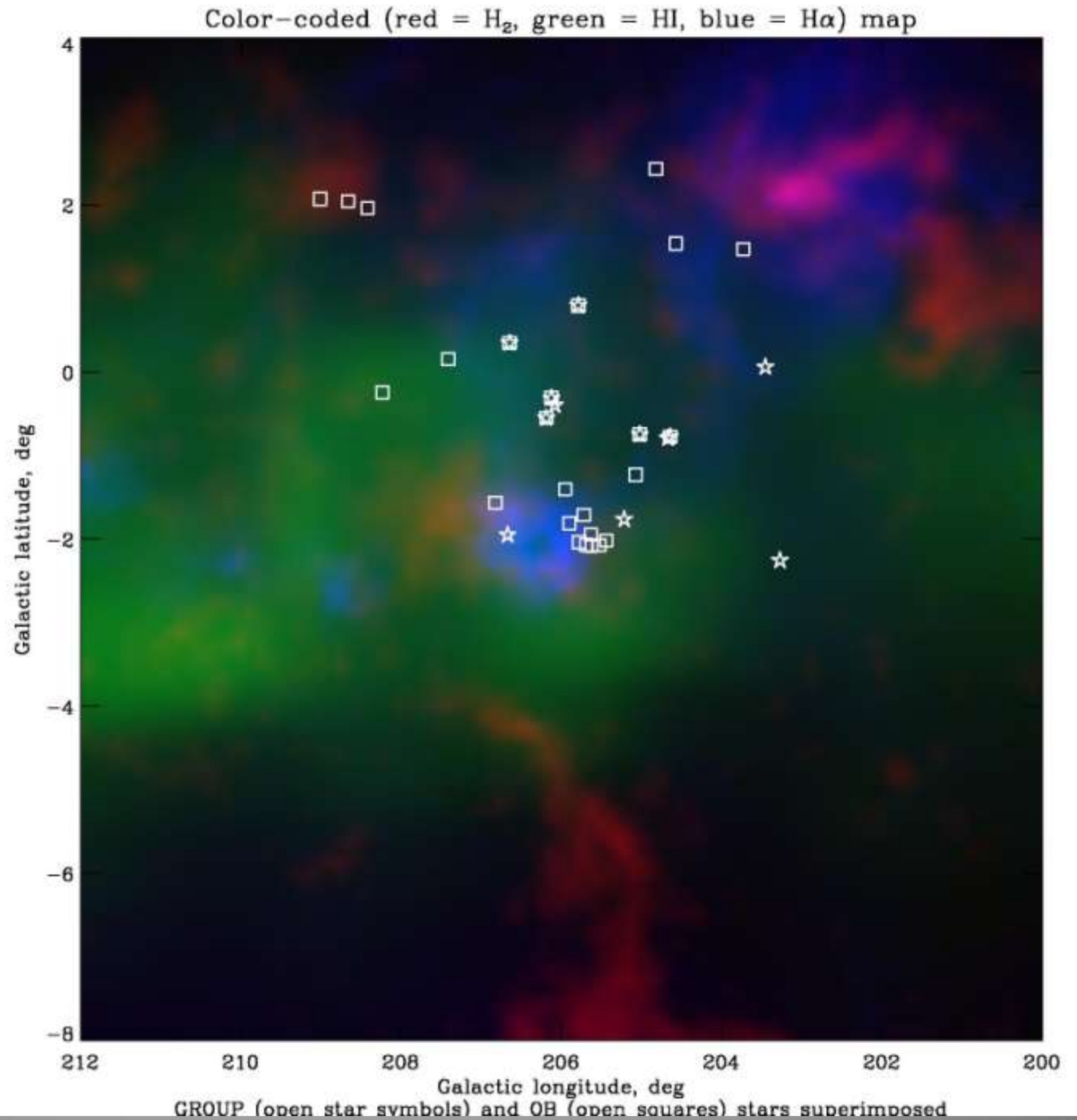
R = dust
G = 60 μm
B = Hα



"Hydrogen map"

RGB channels:

R = H_2
G = H I
B = Hα



Spectral Index

The temperature spectral index β is defined as :

$$T_b \propto \nu^{-\beta}$$

$$\beta = \frac{\log \frac{T_b(408)}{T_b(1420)}}{\log \frac{1420\text{MHz}}{408\text{MHz}}}$$

Rayleigh-Jeans Approximation :

$$S_\nu = \frac{2\nu^2}{c^2} k T_b$$

$$S_\nu \propto \nu^{-\alpha}$$

$$\alpha = \beta - 2$$

Spectral Index

$$S_\nu \propto \nu^{-\alpha}$$

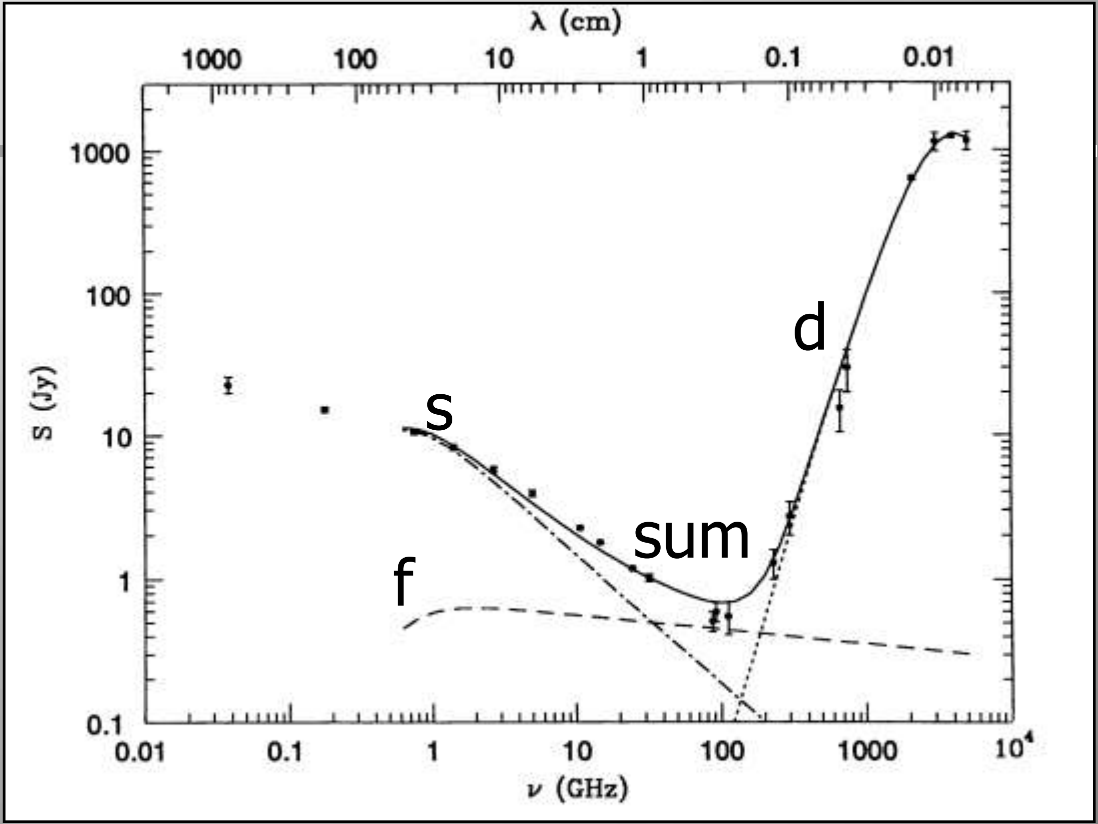
s: synchrotron $\alpha \sim 0.7$

f: free-free

- optically thin $\alpha \sim 0.1$
- optically thick $\alpha \sim -2.0$

d: dust $\alpha \sim 1.5$

Spectral Energy Distribution



Spectral index map

green: synchrotron

α ~ 0.5

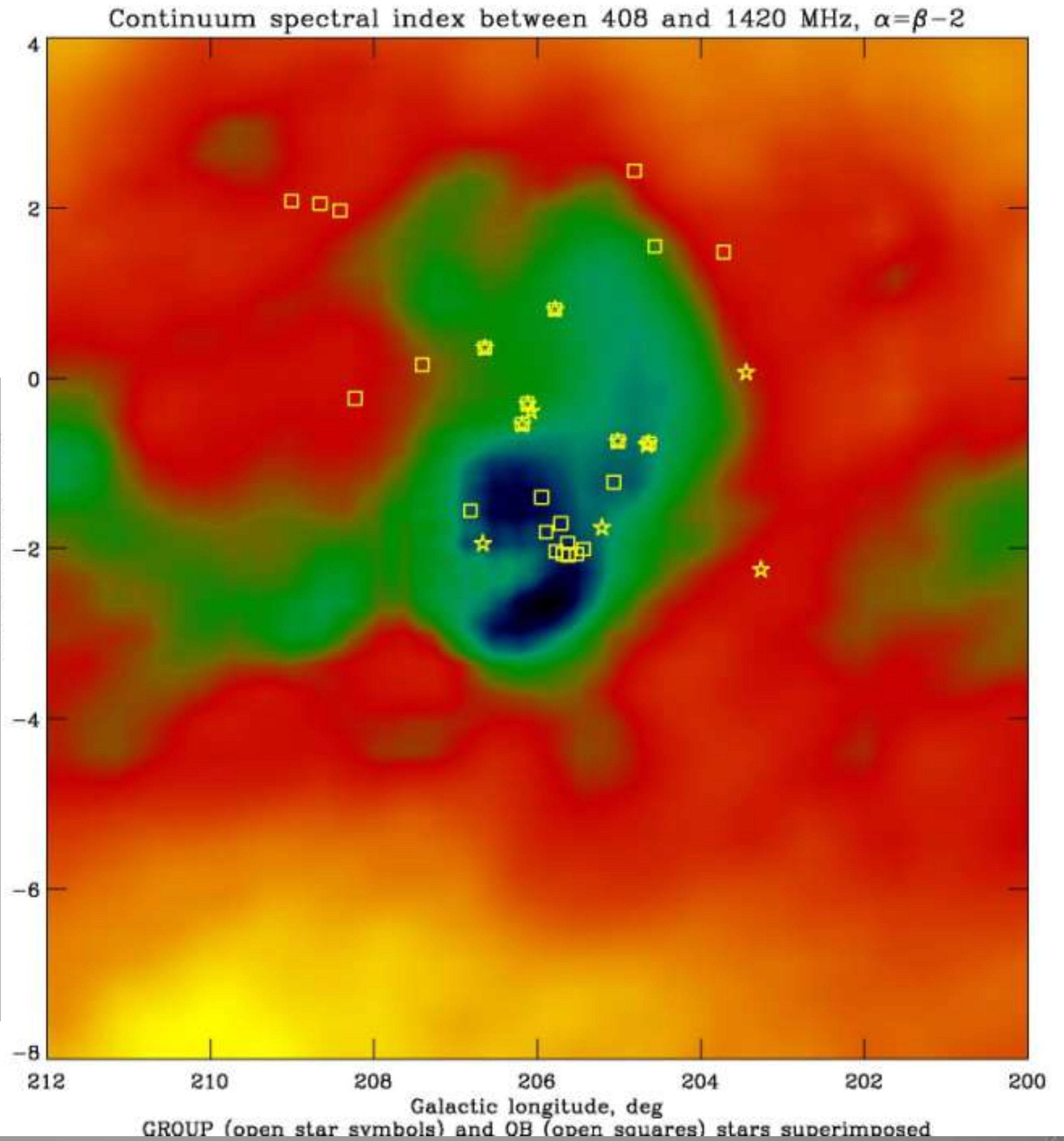
blue: free-free

- optically thin

α ~ 0.1

red: dust

α ~ 1.5



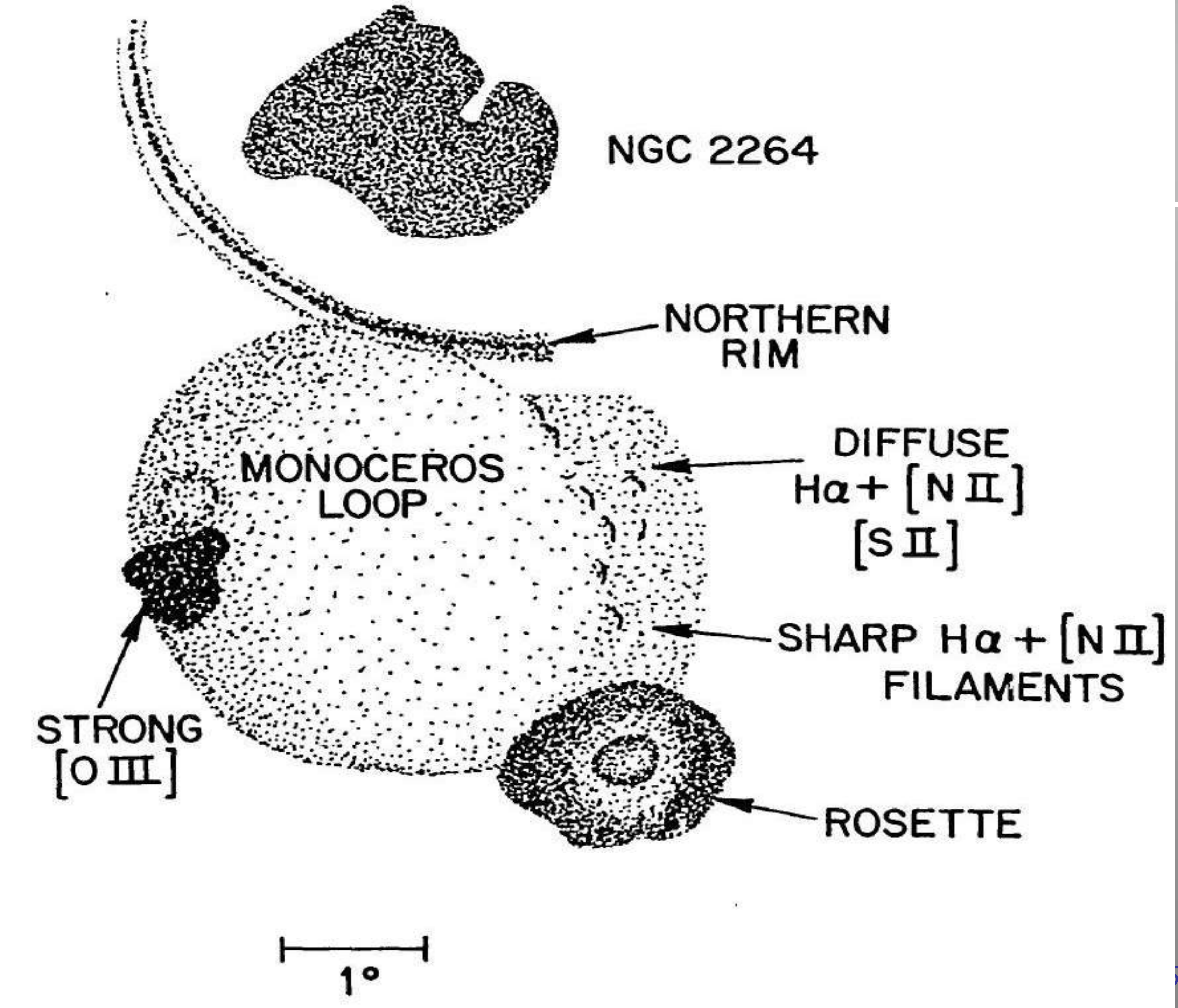
The SNR and OB stars

The Monoceros Loop (SNR G205.5+0.5 = Monoceros Loop/Nebula) was recognized as SNR from radio observations in 1963. Detailed structure of the this SNR (< 500 000 yr old) and its relationship to the two adjacent H II regions Sh2-273 and Sh2-275 is shown schematically in the figures below.

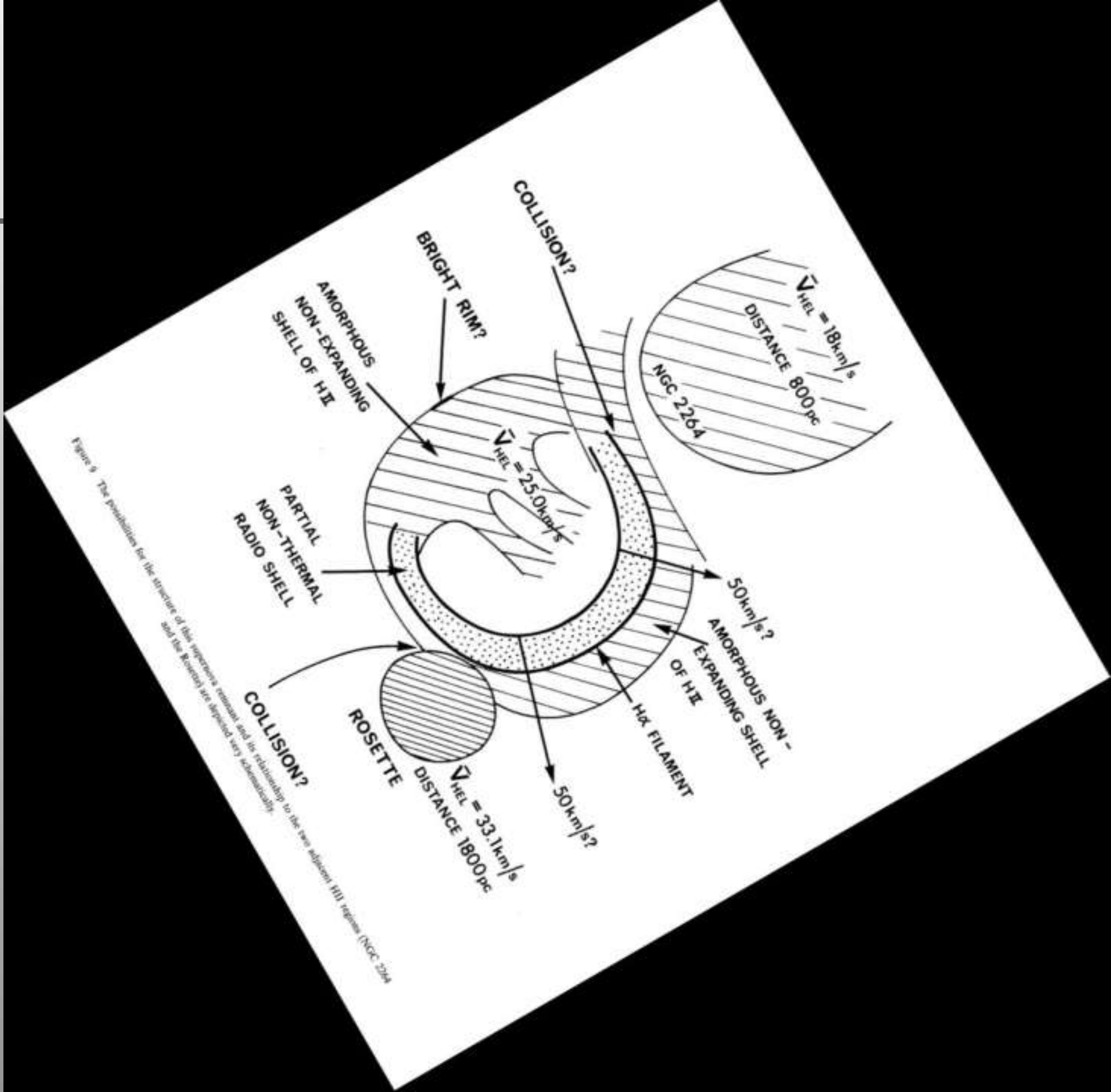
Recently[⋆] it was noted again the influence of molecular clouds on Monoceros Loop. If that influence constantly existed during the loop's evolution, then for distance it is better to adopt the value 1250 ± 190 pc (if not, it is more suitable to adopt the value 1630 ± 250 pc as to the NGC 2244). The CO at 115 GHz traced the presence of molecular clouds at distances 0.8-0.95 kpc interacting with expanding SNR shells.

Thus, the location of this SNR in such a dense region is in accordance with a distance of 1250 ± 190 pc.

(⋆) **see Borka Jovanović & Urošević 2009, Astronomische Nachrichten, vol.330, p.741 and references therein for details**


NGC 2264
NORTHERN RIM
MONOCEROS LOOP
DIFFUSE Hα + [N II] [S II]
SHARP Hα + [N II] FILAMENTS
STRONG [O III]
ROSETTE
1°

SNR structure



Conclusions

We establish reliable homogeneous distances to the massive OB stars toward the Monoceros Loop and Rosette Nebula and spatially correlates the stars to the features of the ISM.

The environment of the OB stars is then studied via various multi-wavelength surveys of the ISM in order to provide more insights on the star-formation history of the region.

The RC and CO data confirm the influence of molecular clouds interacting with expanding shells of Monoceros Loop and support the distance estimation of 1.26 kpc to the group of majority of O-B2 stars.

Thank you for your attention!

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