Search for New Stellar Sources of Gamma-Rays

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different aspects of this work in collaboration with:

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CONSEJERÍA DE ECONOMÍA, INNOVACIÓN Y CIENCIA

Outline of the talk

1. Introduction.

2. Search for new gamma-ray binaries using archival data.

3. Search for new kinds of gamma-ray sources in star forming regions: the *ρ-Ophiuchi* and *Monoceros R2* cases.

4. Conclusions and future perspectives.

1. Introduction

Astron. Astrophys. 338, L71–L74 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

The system LS 5039: a new massive radio emitting X-ray binary

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The non-thermal radio counterpart of **LS 5039** was first noticed after inspection of archival survey data (NVSS).

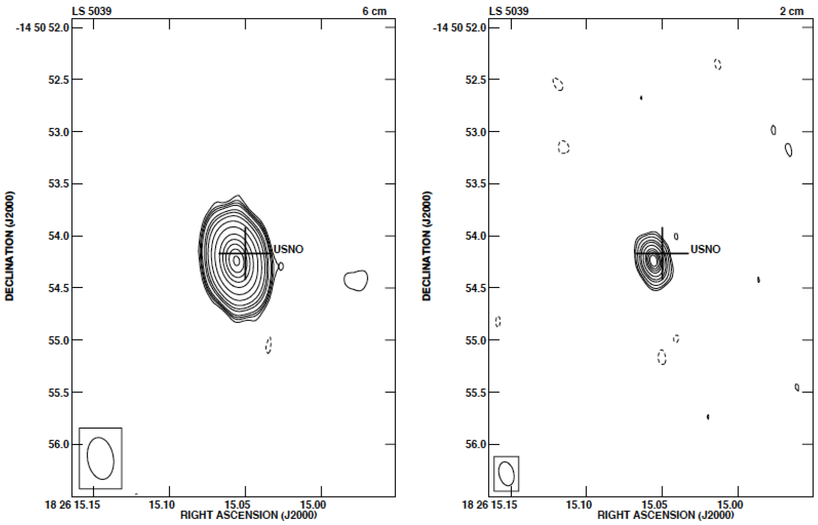

Fig. 1. Left. Self-calibrated map of LS 5039 at the 3.5 cm wavelength obtained from the concatenation of all our VLA data in the A configuration. Natural weight of the visibilities was used. The thick cross indicates the optical position of LS 5039 as listed in the USNO-A1.0 catalogue. Contours are −3, 3, 5, 7, 10, 20, 30, 50, 100, 200, 400, 600, 800, 1000 and 1200 times 0.015 mJy beam^{-1}, the rms noise. The synthesized beam is shown at the bottom left corner and corresponds to 0.″40×0.″25, with position angle of 9.°1. **Right.** The same at the 2.0 cm wavelength. Contours are −3, 3, 5, 10, 20, 30, 50, 80, 100, 120 and 140 times 0.082 mJy beam $^{-1}$, the rms noise. The 2.0 cm synthesized beam is 0.″23×0.″14, with position angle of 13.°4.

Currently known gamma-ray binaries include:

LS I +61303, PSR B1259-63, LS 5039, HESS J0632+057, 1FGL J1018.6-5856, AGL J2241+4454 + …. ?

In addition, microquasar systems detected at gamma-rays include:

Cygnus X-3, Cygnus X-1 + …. ?

Interestingly, some of the currently known gamma-ray binaries and new additions to this class correspond to objects already present in **ancient catalogues** of peculiar stars. For example:

- Catalogue of Luminous Stars in the Northern Milky Way (Hardorp + 1959-1965): LS I+61303, HESS J0632+057 (LS VI+05 11), …
- Catalogue of Luminous Stars in the Southern Milky Way (Stephenson & Sanduleak 1971): LS 5039, PSR B1259-63 (LS 2883) …
- Catalogue of Early-Type Stars Whose Spectra Have Shown Emission Lines (Wackerling 1970): HESS J0632+057 (MWC 656), AGL J2241+4454 (MWC 656) …

Are there any more similar systems waiting for discovery in the archives?

Systematic searches could still provide interesting results here in parallel to serendipitous discoveries.

Cross-Id techniques have been historically developed in our group (e.g.):

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DOI 10.1007/s10509-010-0438-3

ORIGINAL ARTICLE

A systematic cross-search for radio/infrared counterparts of XMM-*Newton* sources

J.A. Combi · J.F. Albacete Colombo · L. Pellizza · J. López-Santiago · G.E. Romero · J. Martí · A.J. Muñoz-Arjonilla · E. Sánchez-Ayaso · P.L. Luque-Escamilla · J.R. Sánchez-Sutil

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First sample of possible coincidences

We constructed our sample of X-radio source coincidences in three steps. First, we computed for each pair of sources (one in the 2XMM catalog and the other in the corresponding radio catalog) the R statistic defined as

$$R = \left[\frac{(\alpha_X - \alpha_R)^2}{\sigma^2_{\alpha,X} + \sigma^2_{\alpha,R}} + \frac{(\delta_X - \delta_R)^2}{\sigma^2_{\delta,X} + \sigma^2_{\delta,R}} \right]^{1/2}, \qquad (1)$$

where $(\alpha_{X/R}, \delta_{X/R})$ are the equatorial coordinates of the X-ray/radio source, and $(\sigma_{\alpha,X/R}, \sigma_{\delta,X/R})$ their corresponding standard deviations. Clearly, R increases with the increase of the source differential position, in such a way that the uncertainties in the coordinates of each source are fully taken into account. Low R values point to a possible coincidence, while high R values suggest no relationship between the sources. Under the assumption that the positions of both sources do coincide, R has a Rayleigh distribution (e.g. Allington-Smith et al. 1982), i.e. the probability that R is greater than any given non-negative value R_0 is

$$P(R > R_0) = \exp(-R^2/2). \qquad (2)$$

Accounting for unrelated coincidences

$$P_u(R \le R_0) = \int_0^\infty \int_0^\infty P_u(R \le R_0 \mid \sigma_\alpha, \sigma_\delta) \times f(\sigma_\alpha, \sigma_\delta) d\sigma_\alpha d\sigma_\delta, \qquad (3)$$

where $\sigma_\alpha = (\sigma^2_{\alpha,X} + \sigma^2_{\alpha,R})^{1/2}$, $\sigma_\delta = (\sigma^2_{\delta,X} + \sigma^2_{\delta,R})^{1/2}$, $P_u(R \le R_0|\sigma_\alpha, \sigma_\delta)$ is the conditional probability that an unrelated pair has $R < R_0$, given the values of σ_α and σ_δ, and $f(\sigma_\alpha, \sigma_\delta)$ the joint probability density function of these two variables. It can be seen, from the definition of R, that $P_u(R \le R_0 \mid \sigma_\alpha, \sigma_\delta)$ is the probability of finding at least one radio source inside an ellipse of semiaxes σ_α and σ_δ centered at the position of the 2XMM source. If the local density of radio sources is n, this is simply

$$P_u(R \le R_0 \mid \sigma_\alpha, \sigma_\delta) = 1 - e^{-\pi n R_0^2 \sigma_\alpha \sigma_\delta}. \qquad (4)$$

Combi et al. 2011

2. Search for new gamma-ray binaries using archival data

The ideal gamma-ray binary/microquasar candidate would be an **early-type** star found to be consistent in position with:

1) A gamma-ray source (unassociated)

2) An X-ray source.

3) A non-thermal radio source.

4) With correlated multi-λ variability.

In practice not all requirements are easily fullfilled. The cross-Id process is still going one. Some interesting objects found so far are listed in the next Table.

Gamma-ray source	Candidate γ-ray binary	Remarks
1FGL J2056.7+4938/ 2FGLJ2056.7+4939	LS III +49 13	Star already proposed as possible microquasar by Paredes et al. (2002); Haakonsen et. (2009) suggest 47% chance coincidence with *ROSAT* source; *Fermi*-LAT source could be an AGN.
1FGL J0608.1-0630c/ 2FGLJ0607.5-0618c	LS IV -06 1	Unassociated *Ferm*i-LAT source; Star in nebula; Possible NVSS radio counterpart; no X-ray detection.
1FGL J1823.2-1336c/ 2FGLJ1823.1-1338c	LS 4995	Unassociated *Fermi*-LAT source; candidate star is an early-type supergiant; no X-ray nor radio detection in archives.
1FGL J0220.0+6257/ 2FGLJ0221.4+6257c	VES 737	Fermi-LAT could be associated with SNR but this is not clear; VES 737 is an emission line star with a possible X-ray detection by *EINSTEIN.*

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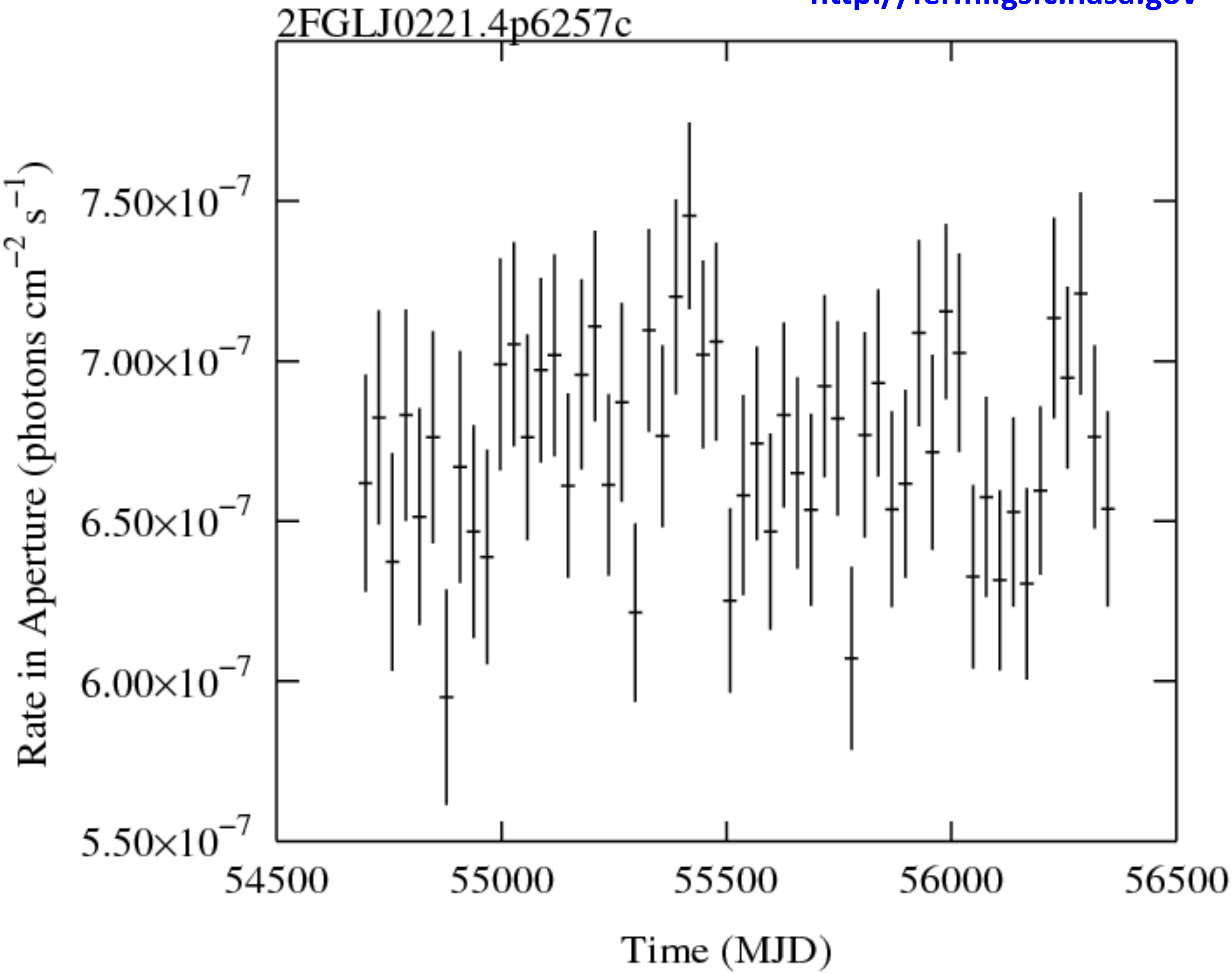
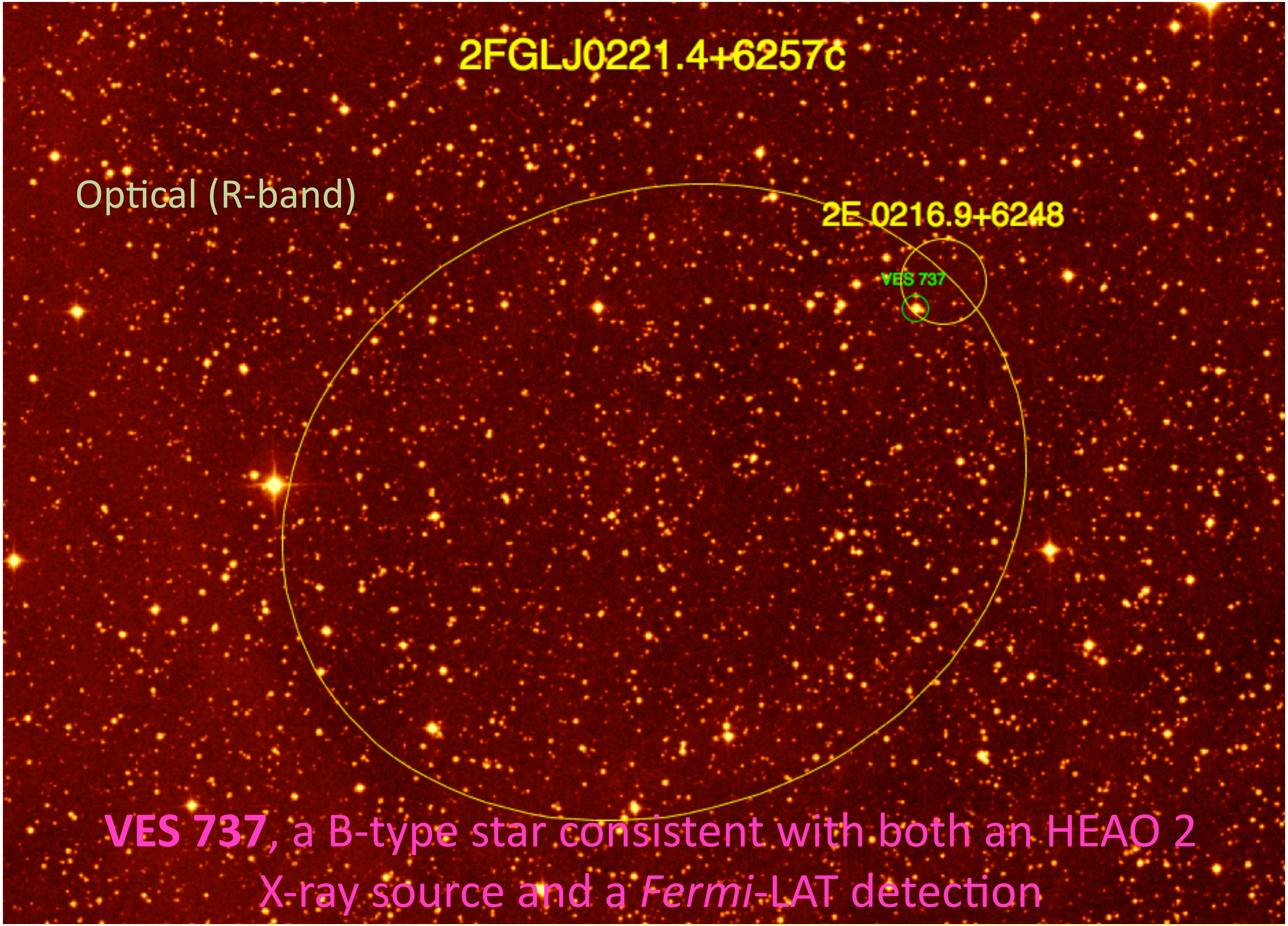
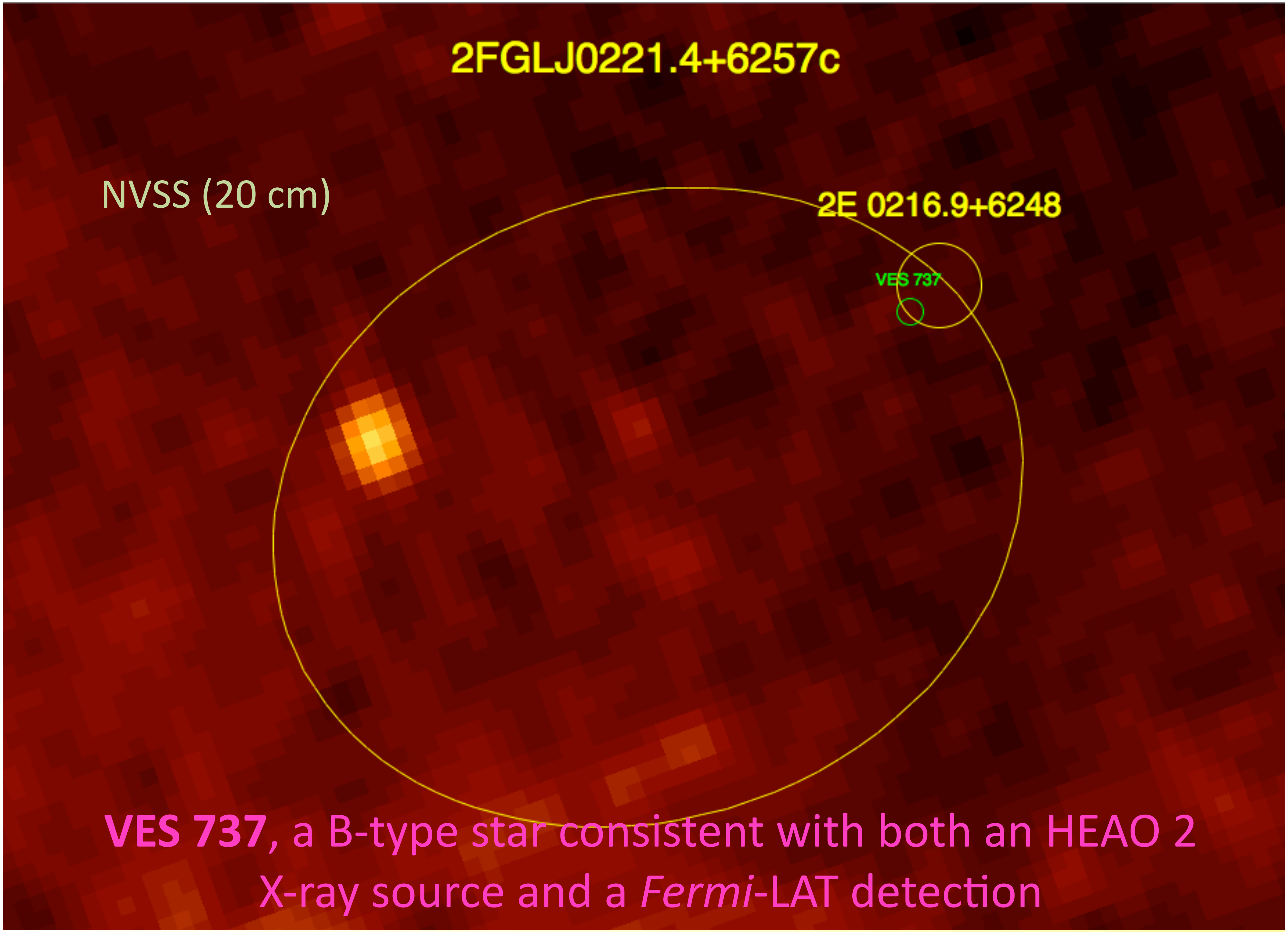
http://fermi.gsfc.nasa.gov





VES 737, a B-type star consistent with both an HEAO 2 X-ray source and a *Fermi*-LAT detection



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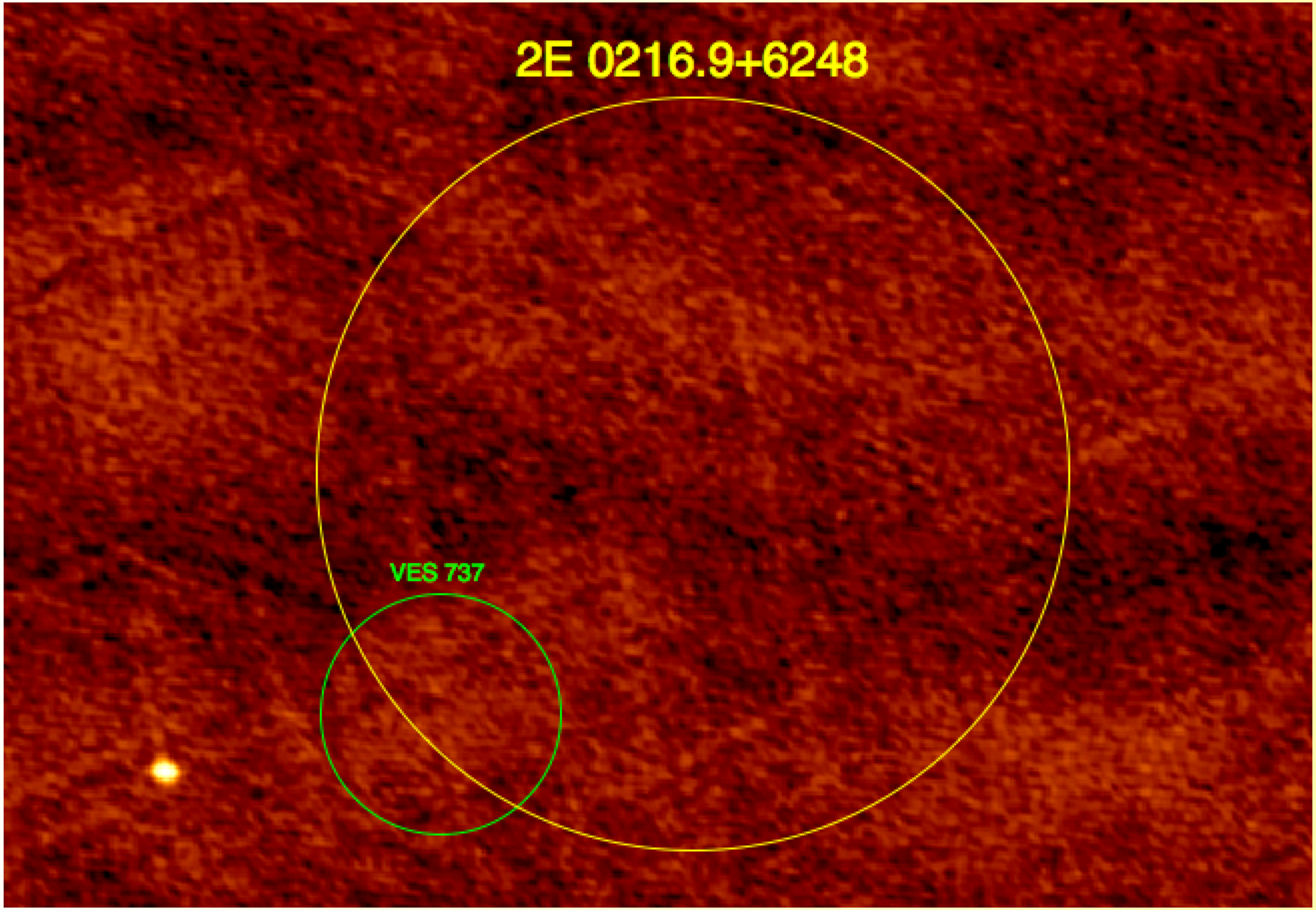
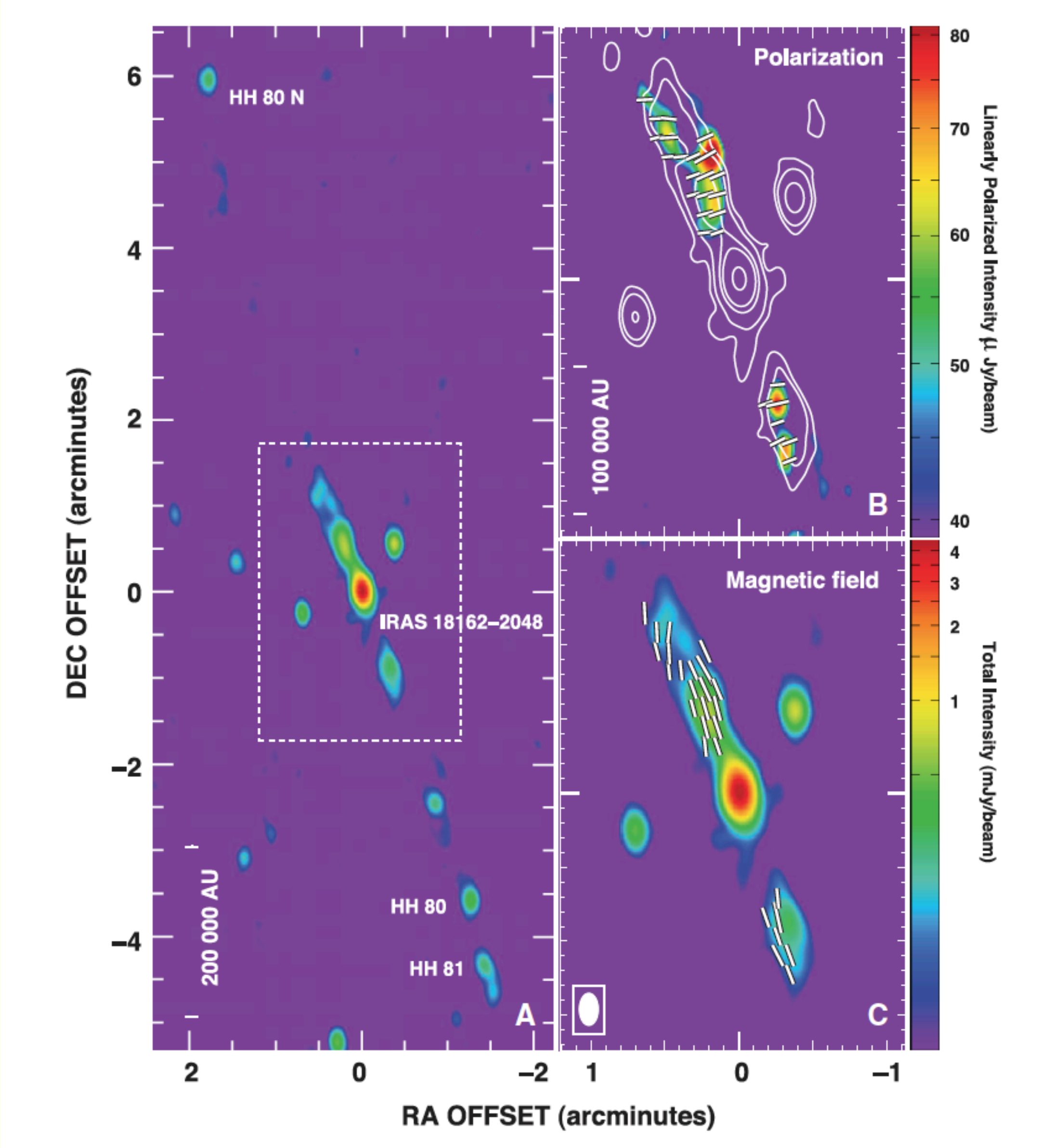
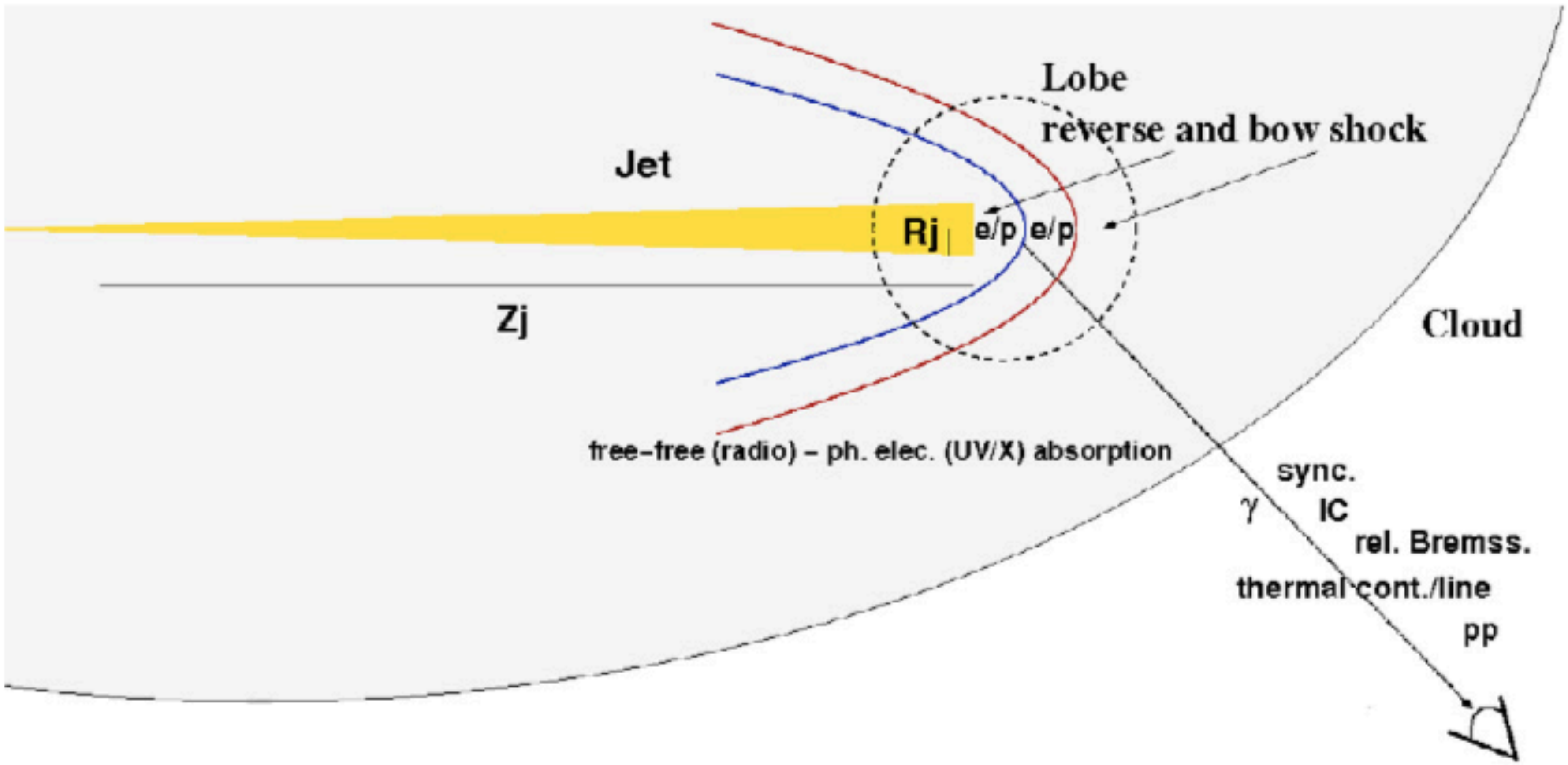


Jansky EVLA observations of the 2E 0216.9+6248/VES 737 field of view,
carried out in 2011 at the 20 cm wavelength. No radio counterpart detected (so far).

3. Search for new kinds of gamma-ray sources in star forming regions



Evidence of relativistic particles in stellar jets from massive protostars have been reported (e.g. HH 80-81, **Carrasco-González et al. 2010, Science, 330, 1209**).



Bipolar outflows of massive protostars also produce strong shocks that have been proposed as acceleration sites of gamma-ray emitting particles (**Bosch-Ramon et al. 2010, A&A, 511, A8**).

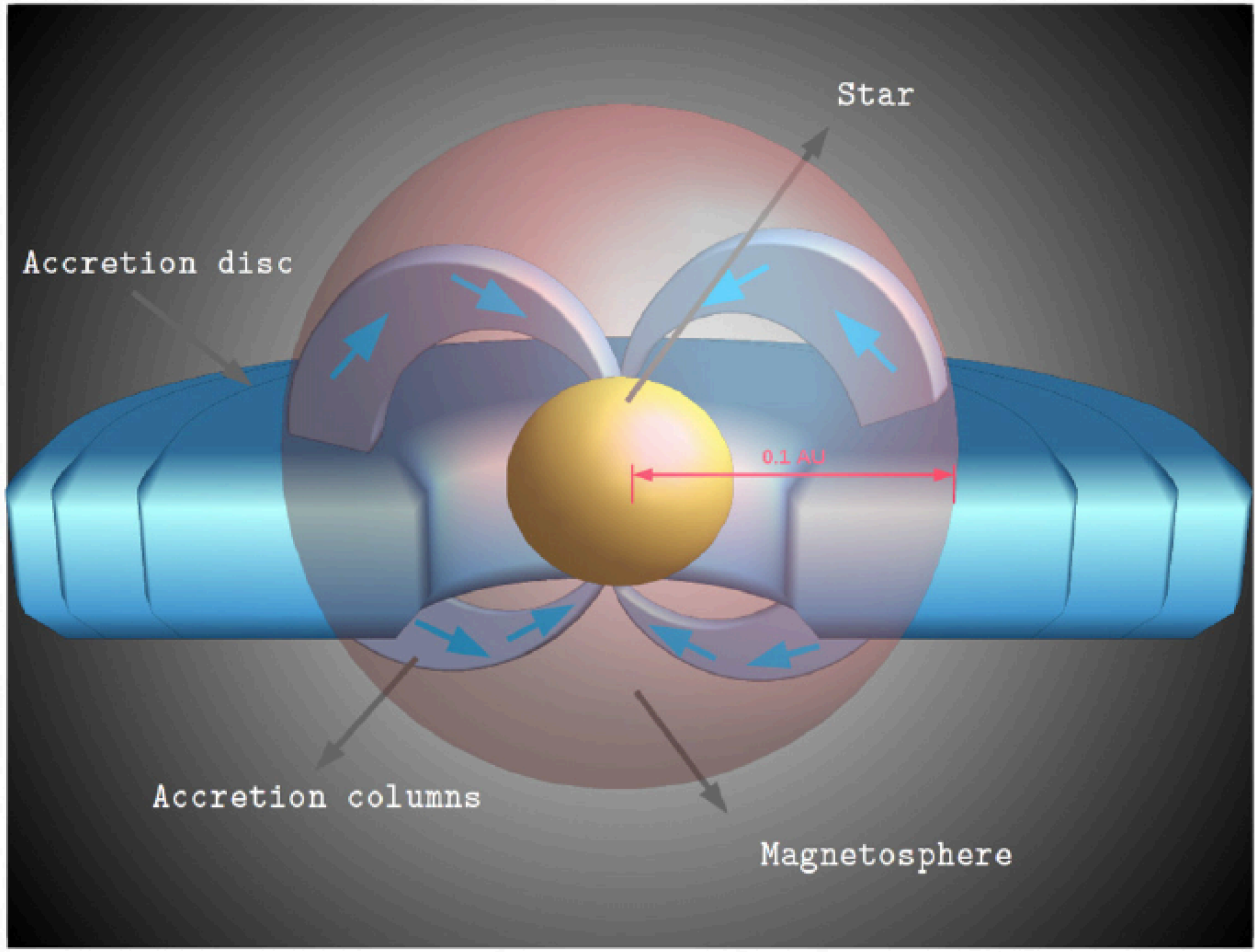


Figure 1. Sketch of a T Tauri star adapted from Feigelson & Montmerle (1999).

Del Valle et al. (2011)

ρ-Ophiuchi

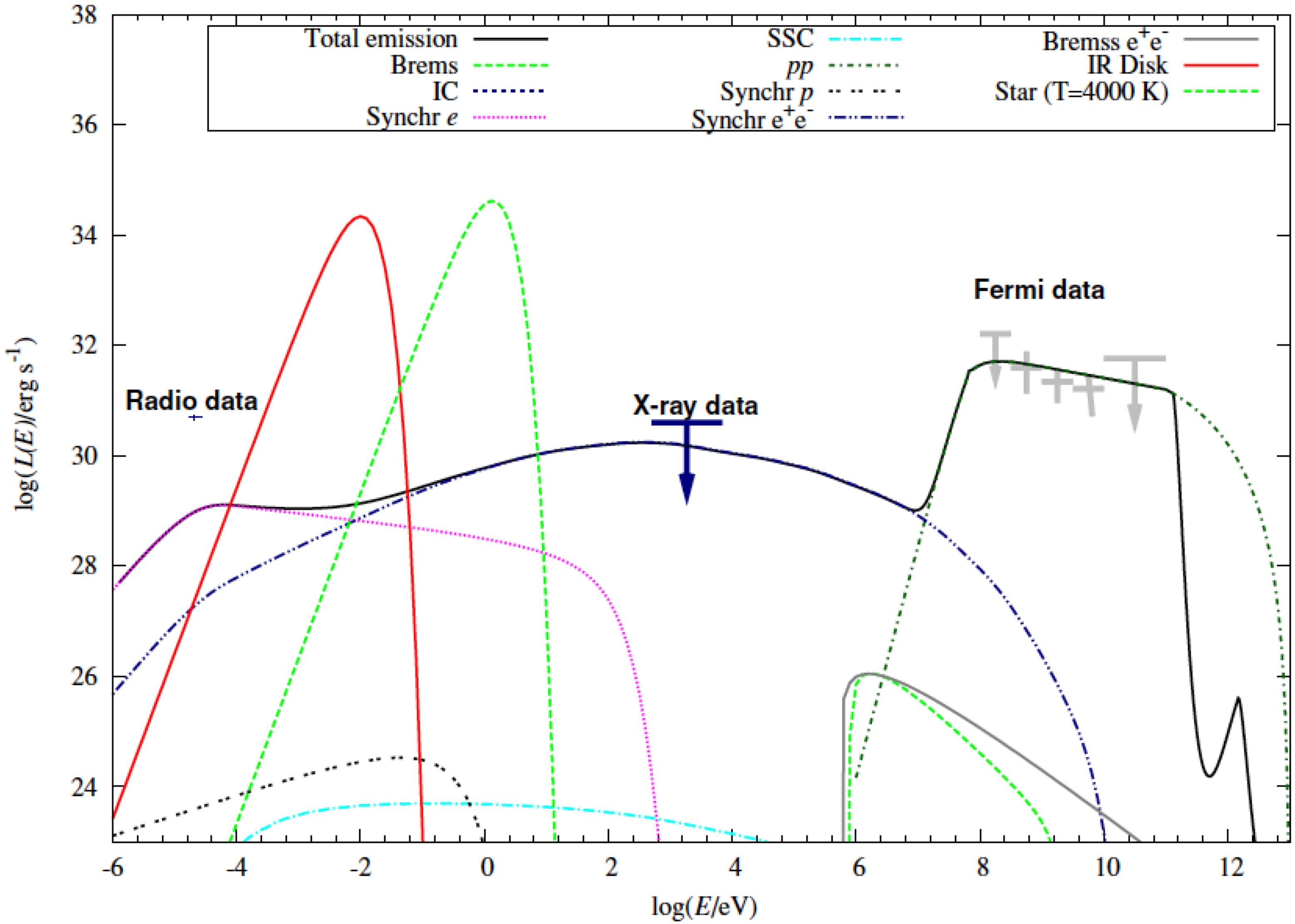


Figure 10. Computed non-thermal luminosity and *Fermi* upper bounds for the four T Tauri stars, assuming a distance of 120 pc. The spectral energy distribution is corrected by photon absorption. Model parameters as in Table 1.

Del Valle et al. (2011)

ρ-Ophiuchi

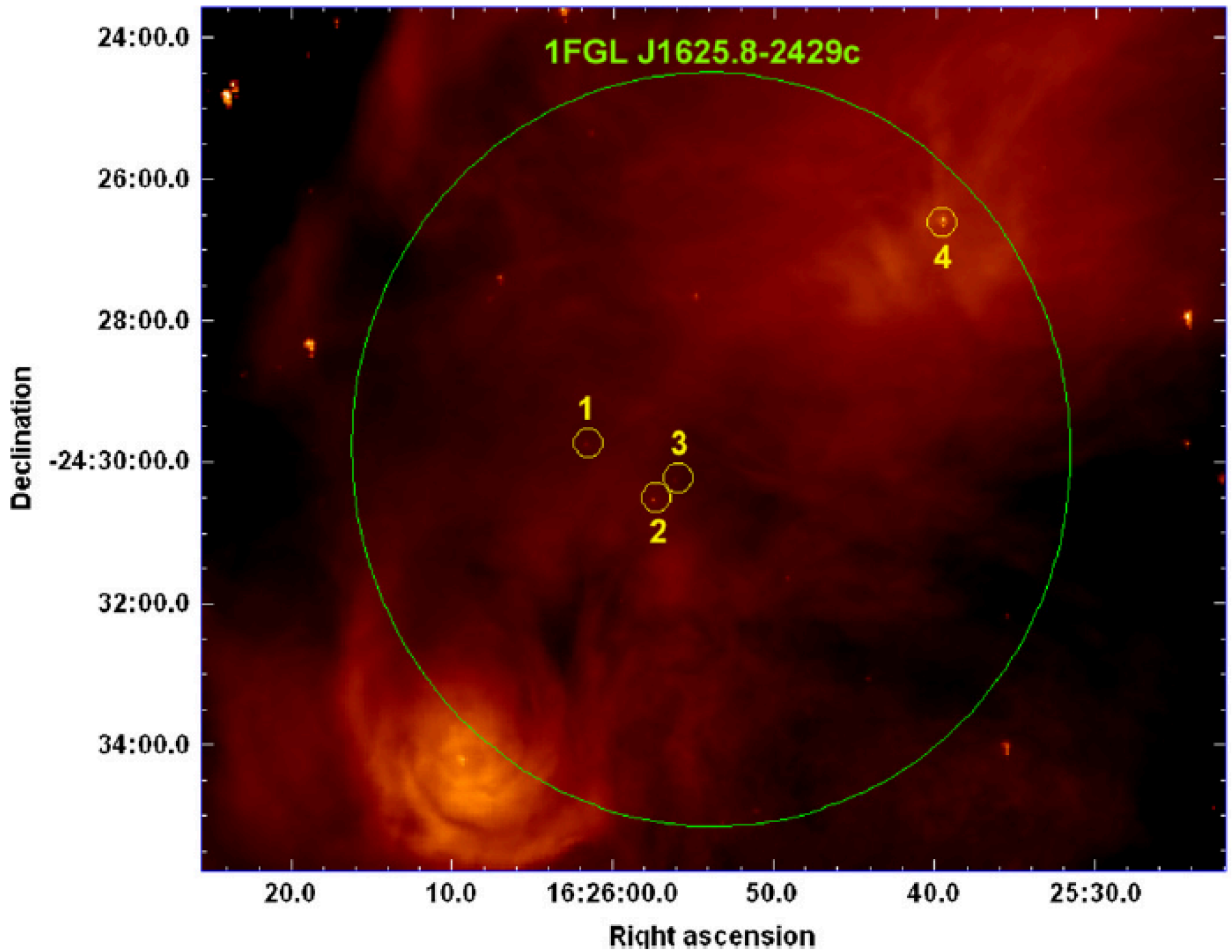


Figure 7. GLIMPSE infrared image in the 8.0 μm band showing the contents of the 1FGL J1625.8−2429c error circle toward the ρ Ophiuchi cloud. Several T Tauri stars are consistent with the *Fermi* γ-ray source position. They are labeled from 1 to 4 in decreasing order or right ascension. Axis coordinates are of equatorial J2000.0-type.

Del Valle et al. (2011)

ρ-Ophiuchi

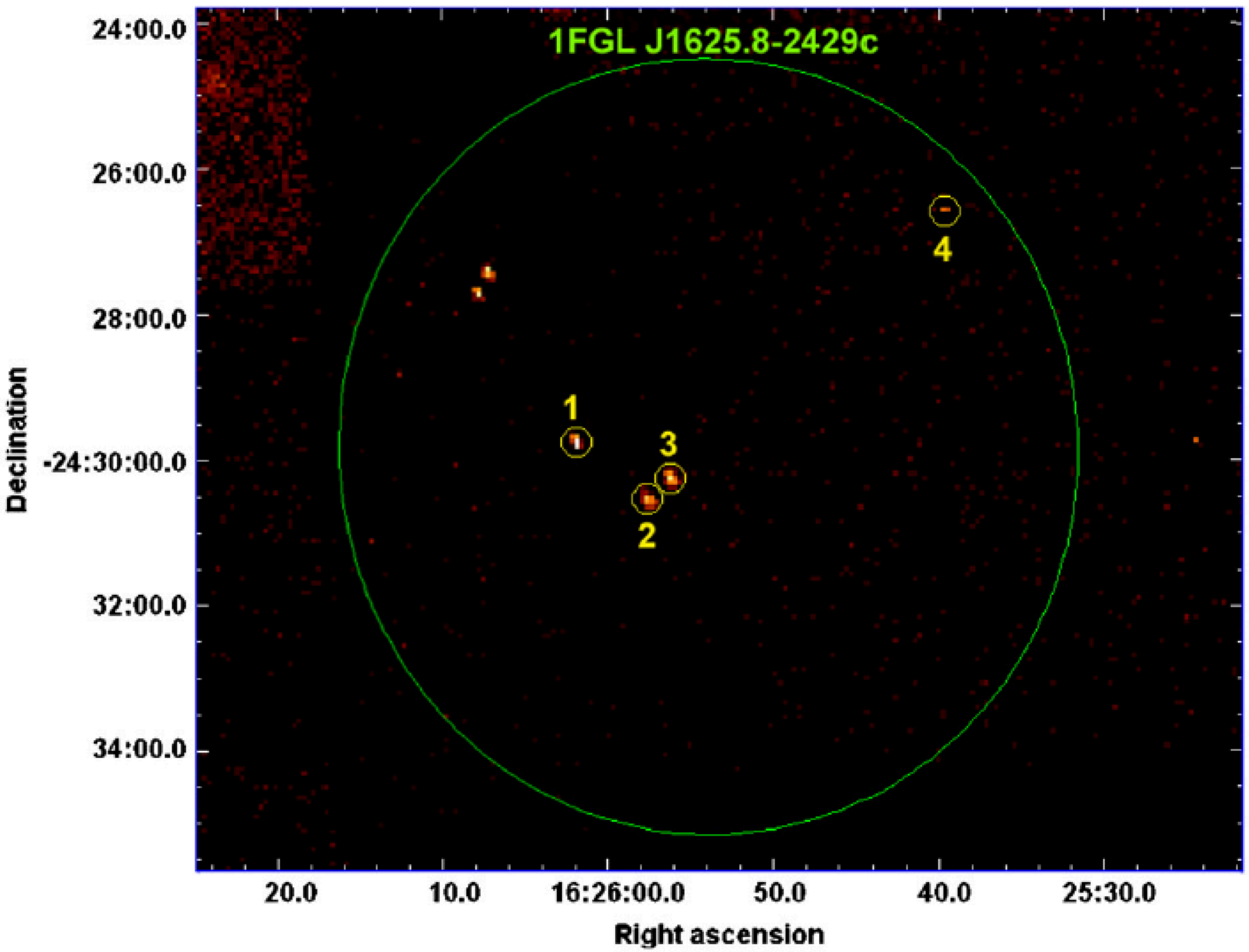


Figure 8. Composite X-ray image of the 1FGL J1625.8−2429c error circle obtained with the *Chandra* ACIS camera in the energy range 0.1–10 keV (data set identifier: ADS/Sa.CXO#obs/00618). Numbers indicate the T Tauri stars consistent with this *Fermi* source in decreasing order of right ascension. All of these stars are X-ray emitters.

Del Valle et al. (2011)

Monoceros R2

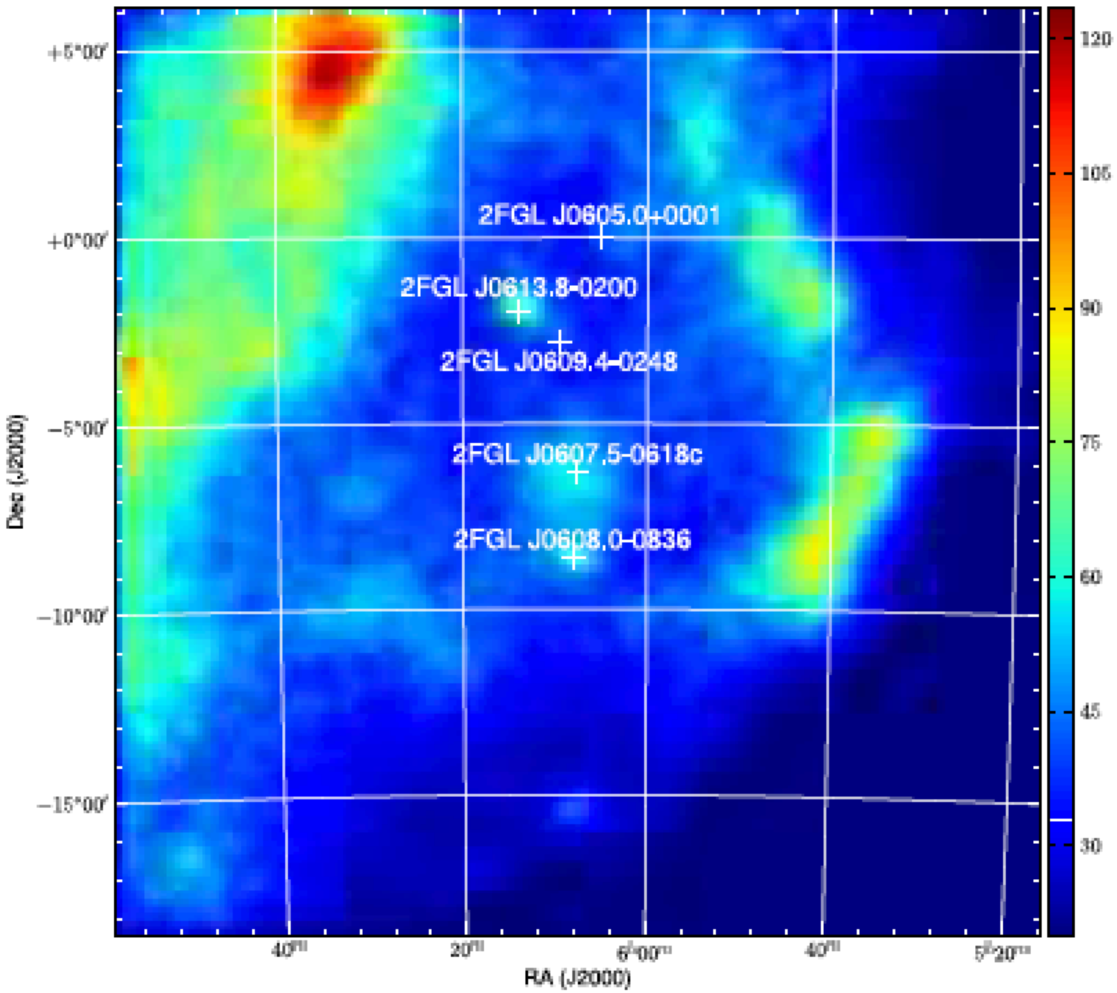


Fig. 4. Image of the 2FGL J0607.5−0618c field resulting from the *Fermi* LAT data processed in this work. The image has been smoothed with a 2-pixel Gaussian kernel. The target centroid position is marked at the center as a green cross. Other sources from the 2FGL catalog are also marked for image completeness.

Monoceros R2

Martí, J. et al.: The star forming region Monoceros R2 as a gamma-ray source

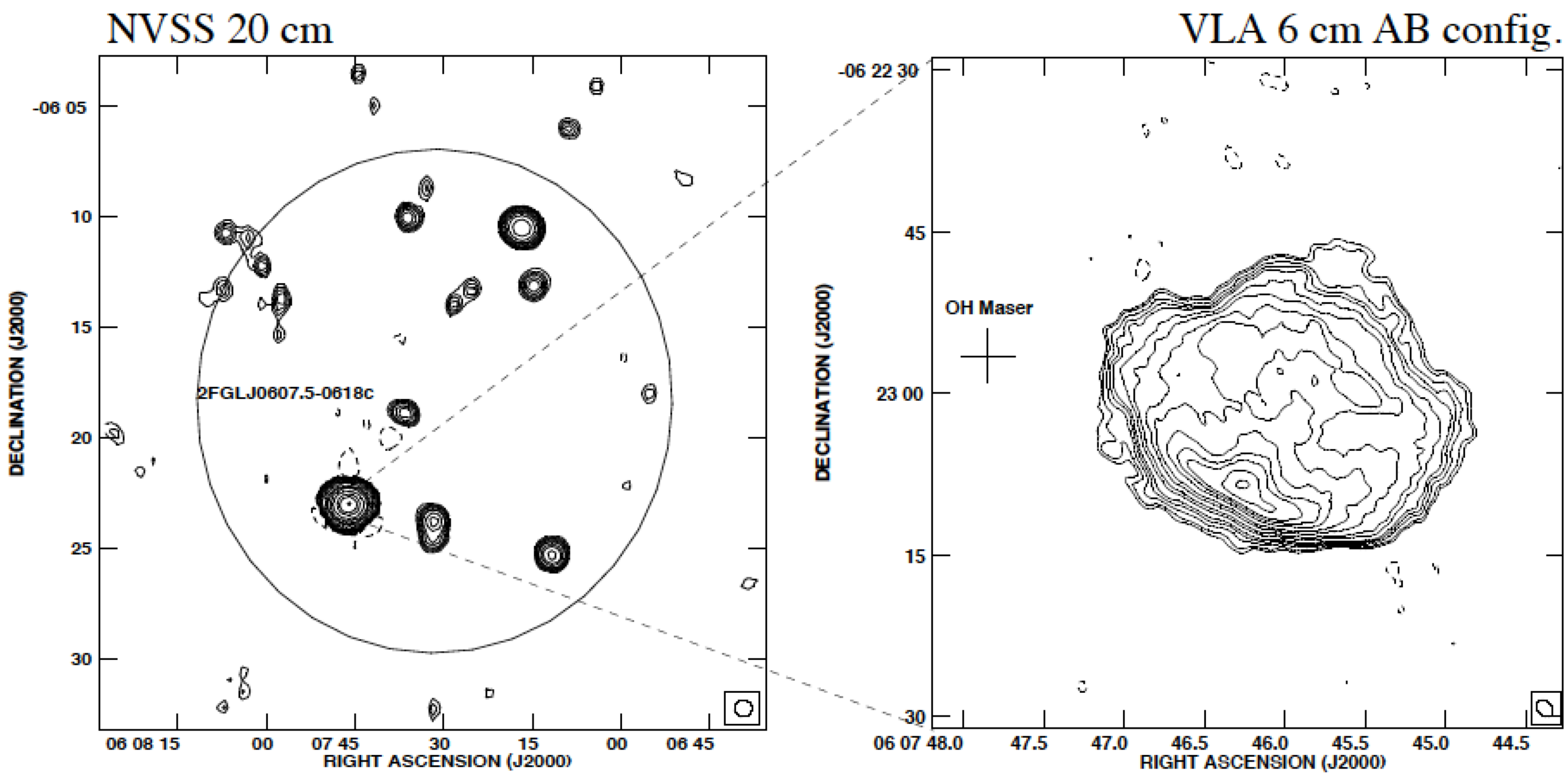


Fig. 1. Left. Radio map of the Mon R2 region from the NRAO VLA Sky Survey at the 20 cm wavelength. The restoring beam is a circular 45″ Gaussian. Contours shown correspond to −3, 3, 5, 6, 8, 10, 15, 20, 30, 50, 100, 200, 300, 500, 1000, 2000, 3000 and 5000 times 0.7 mJy beam^{-1}, the rms noise. The 95% confidence ellipse for the gamma-ray source detected in the Mon R2 direction is plotted as provided by two year *Fermi* LAT catalog. Mon R2 is the brightest and most relevant radio source consistent with it. **Right.** Zoom of the Mon R2 central region as observed with the VLA at the 6 cm wavelength. This high resolution map has been selfcalibrated using the OH maser in the field (cross) and computed with pure uniform weight. Contours shown correspond to −3, 3, 4, 6, 8, 10, 15, 20, 30, 40, 60, 80, 100, 140 and 180 times 0.7 mJy beam^{-1}, the rms noise. The restoring beam is shown at the panel bottom right corner as 1.″80 × 1.″25 ellipse, with position angle 41°.

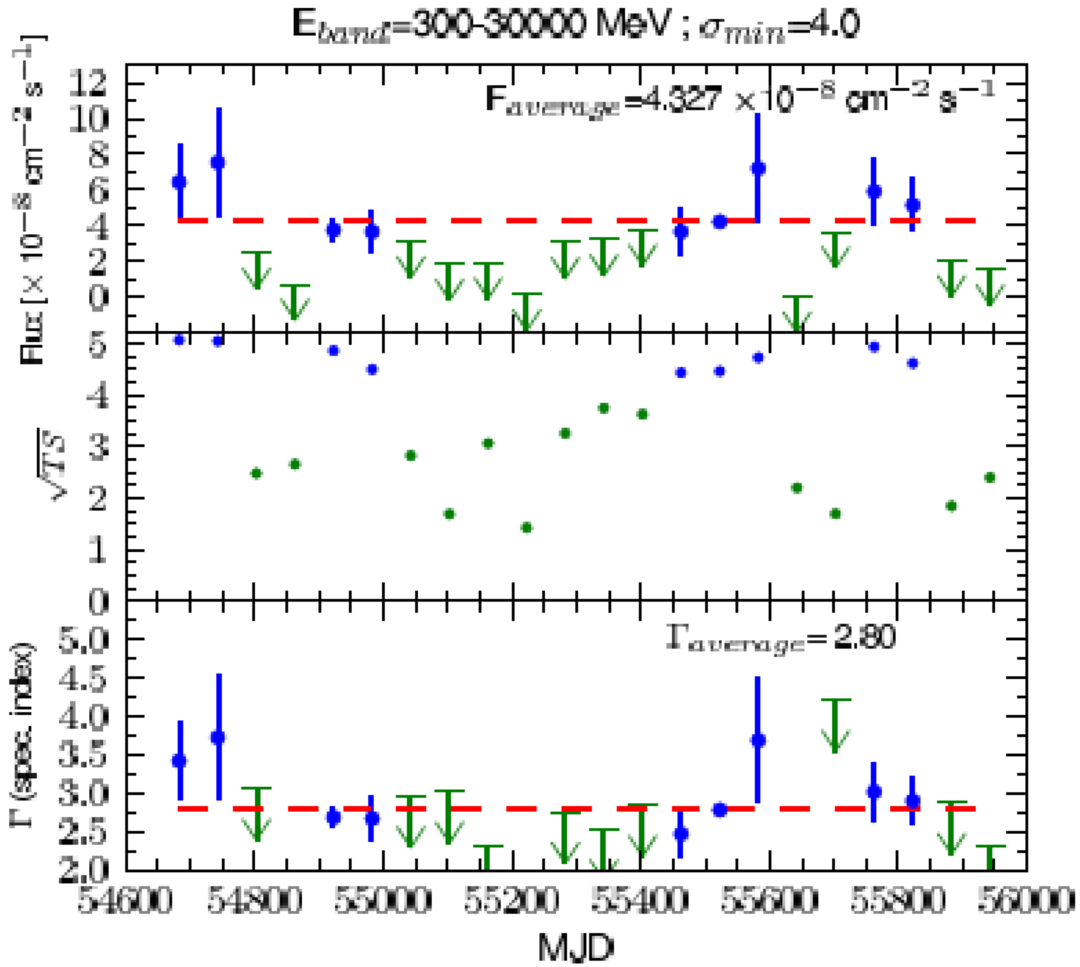


Fig. 2. Light-curve study of the source 2FGL J0607.5–0618c in the 0.3–300GeV energy range. Upper pannel: *Fermi* LAT light curve of 2FGL J0607.5–0618c sampled with 60 day bin intervals. Middle pannel: value of $\sqrt{TS}$ value for each light-curve bin. Lower pannel: fitted spectral index Γ for each light-curve bin. Bins with $\sqrt{TS}$ < 4.0 (σ_{min}) show their flux value and spectral index as arrow upper limits. Horizontal dashed lines represent average values.

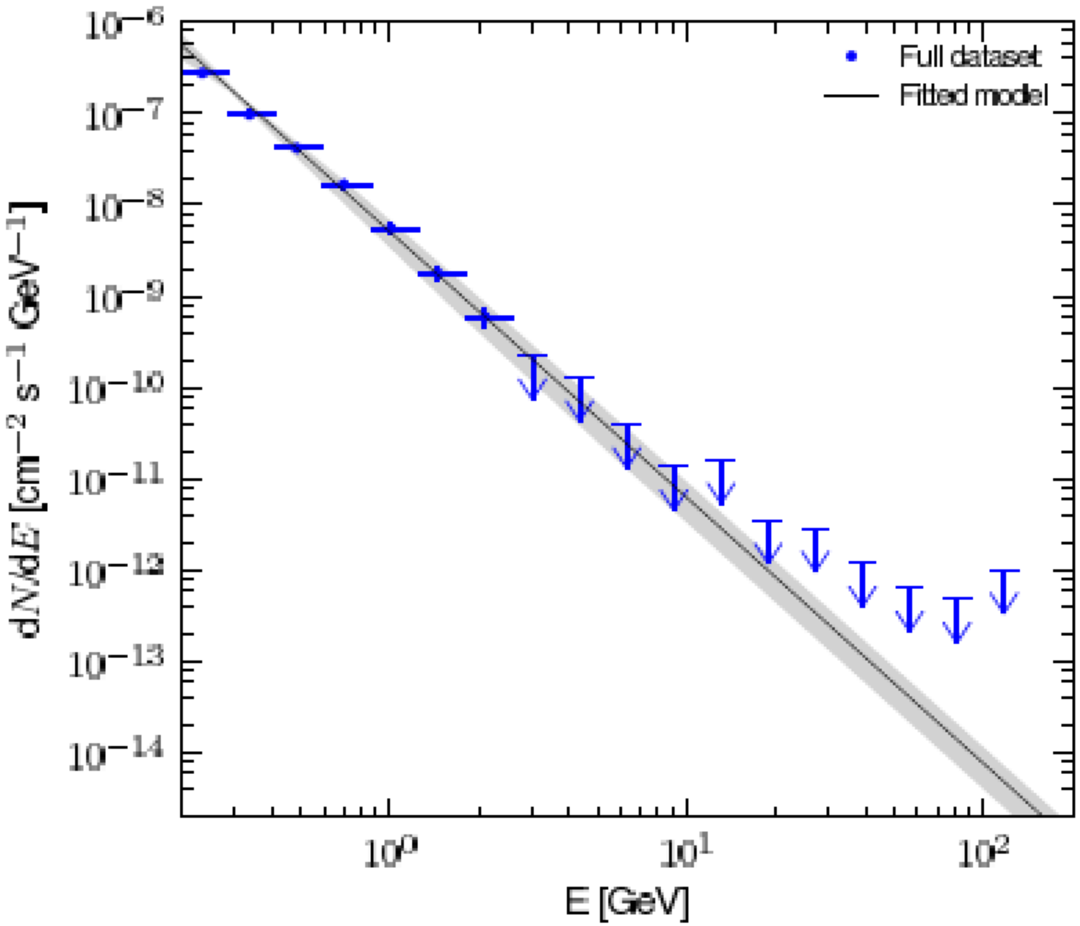


Fig. 3. *Fermi* LAT spectrum of 2FGL J0607.5−0618c resulting from our binned likelyhood analysis. **Shaded region represents the final power-law fit and its uncertainty** resulting from this work.

Monoceros R2

Martí, J. et al.: The star forming region Monoceros R2 as a gamma-ray source

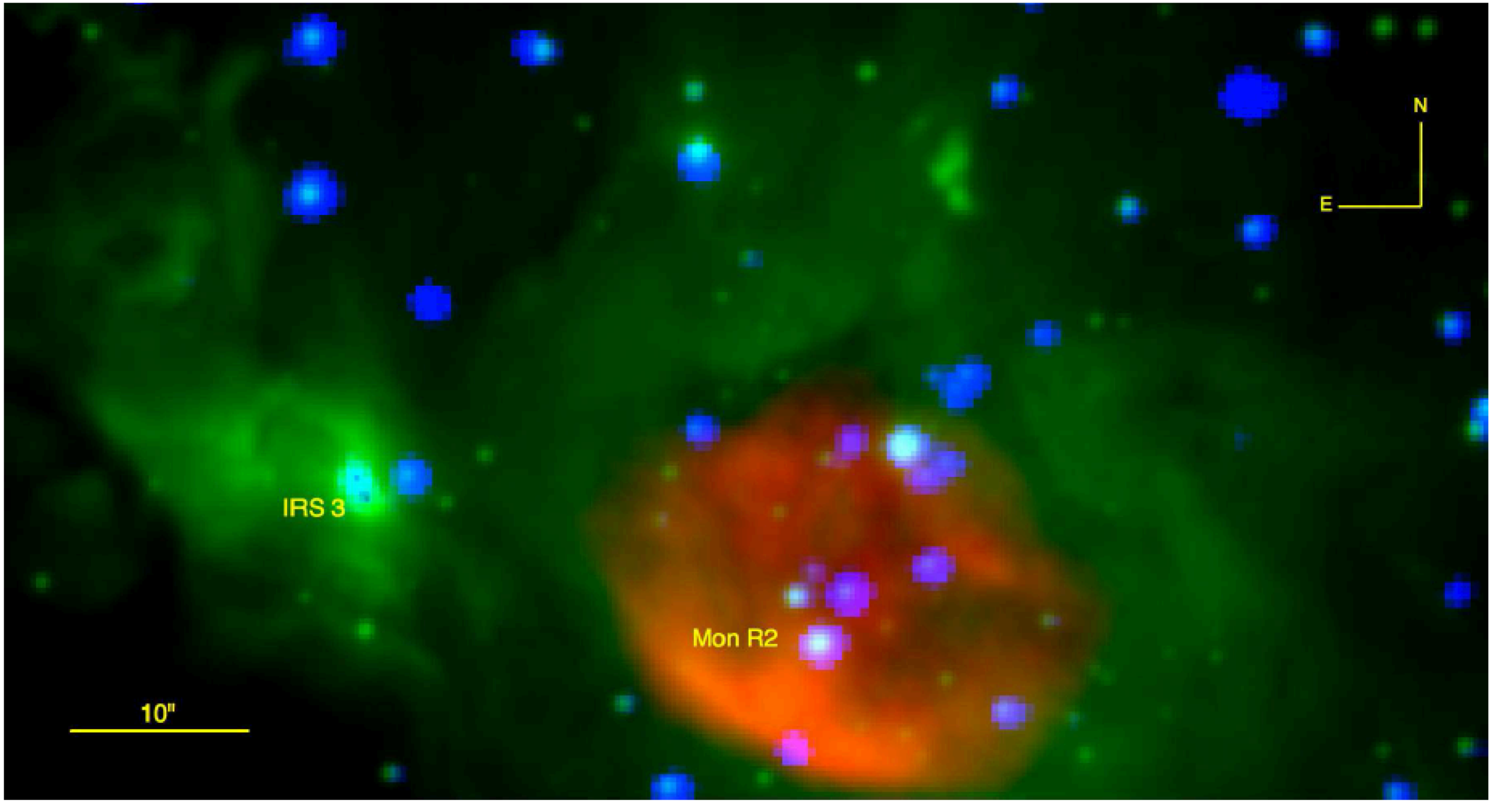


Fig. 6. Trichromatic image of the Mon R2 central cluster region. Red, green and blue colors correspond to VLA 6 cm radio, ESO NTT *Ks*-band infrared and *Chandra* X-ray emission, respectively. The brightest infrared and maser source in the field (IRS3) is also indicated. The field of view shown is fully inside the 95% confidence ellipse for 2FGL J0607.5−0618c. It corresponds to 0.75×1.40 $arcmin^2$ with North up and East left.

4. Conclusions and future perspectives

- Old **catalogs of luminous/peculiar stars** could still hide very relevant sources for high-energy astrophysics.

- When combined with modern surveys, cross-Id work has revealed a few luminous stars worth to follow-up as possible **gamma-ray binary candidates**.

- New kinds of stellar gamma-ray sources are likely to exist (and be detectable) in **nearby star-forming regions** (e.g. ρ-Ophiuchi, Monoceros R2).

- ***Fermi*-LAT data** accumulated over the years will play a major role to test the proposed associations.

Thank you!