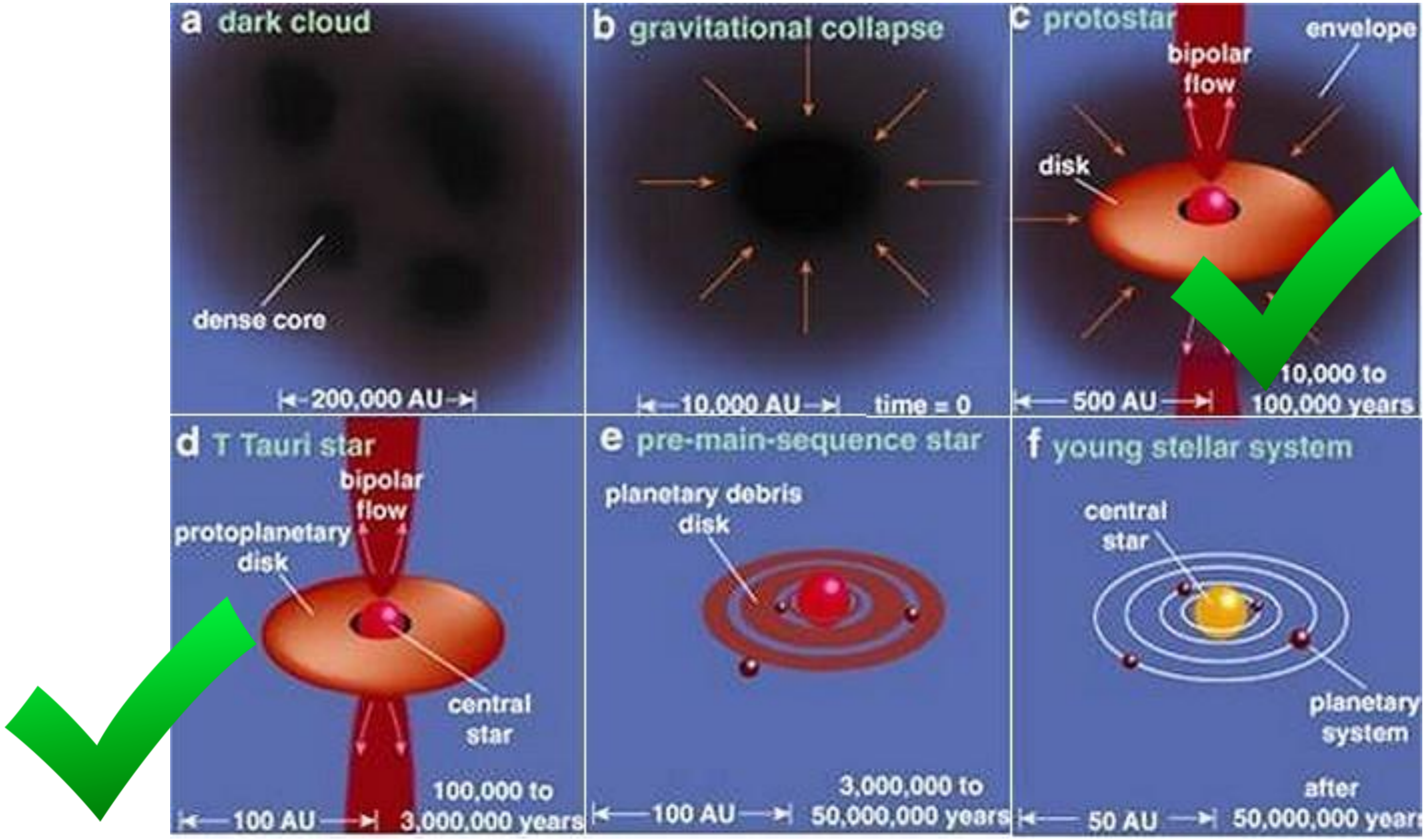
Gamma-ray detection consistent with a young stellar object

P. H. Thomas Tam (Sun Yat-sen University)

presenting the works of students: Sheng Tang, Li-Nuo Yang

Young stellar objects (YSOs)



During the process of star formation, collimated outflows are sometimes generated, and some works have found that these outflows can occasionally produce non-thermal radio lobes, such as refs [1],[2],[3].

The existence of these non-thermal radio lobes implies the occurrence of particle acceleration at the ends of these jets.

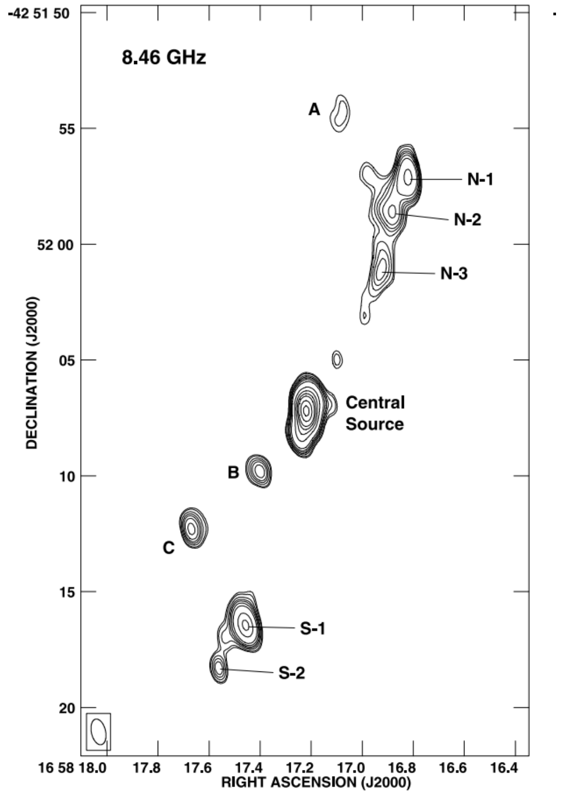
[1] G. Garay, K. J. Brooks, D. Mardones, and R. P. Norris, "A Triple Radio Continuum Source Associated with IRAS 16547–4247: A Collimated Stellar Wind Emanating from a Massive Protostar," ApJ, vol. 587, no. 2, pp. 739–747, Apr. 2003, doi: 10.1086/368310.

[2] Anglada G, Rodríguez L F and Carrasco-González C 2018 Radio jets from young stellar objects Astron Astrophys Rev 26 3

[3]W O Obonyo, S L Lumsden, M G Hoare, S J D Purser, S E Kurtz, K G Johnston, A search for non-thermal radio emission from jets of massive young stellar objects, Monthly Notices of the Royal Astronomical Society, Volume 486, Issue 3, July 2019, Pages 3664–3684, https://doi.org/10.1093/mnras/stz1091

Araudo et al. (2007) developed a multi-wavelength radiative model for IRAS 16547-4247 based on non-thermal radio observations.

VLA image of
IRAS 16547–4247



Rodríguez+ (2005)

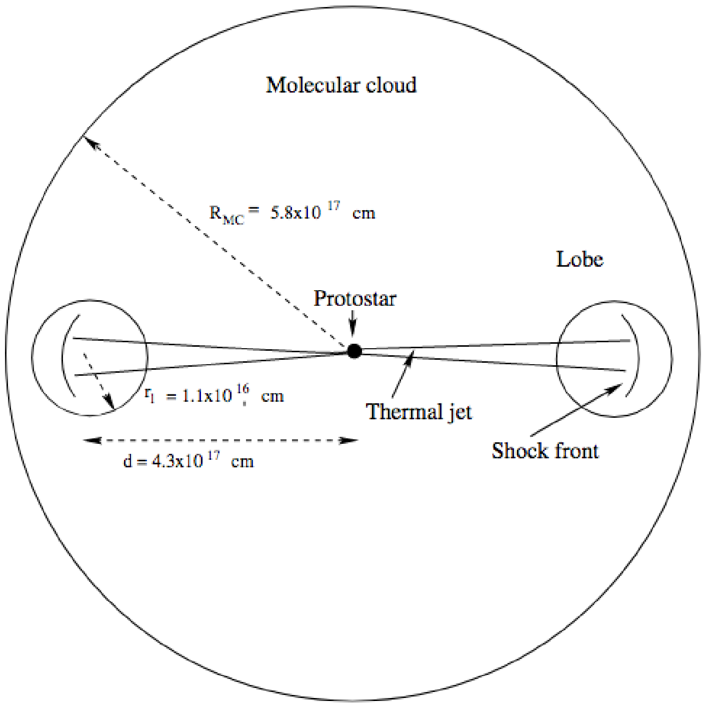
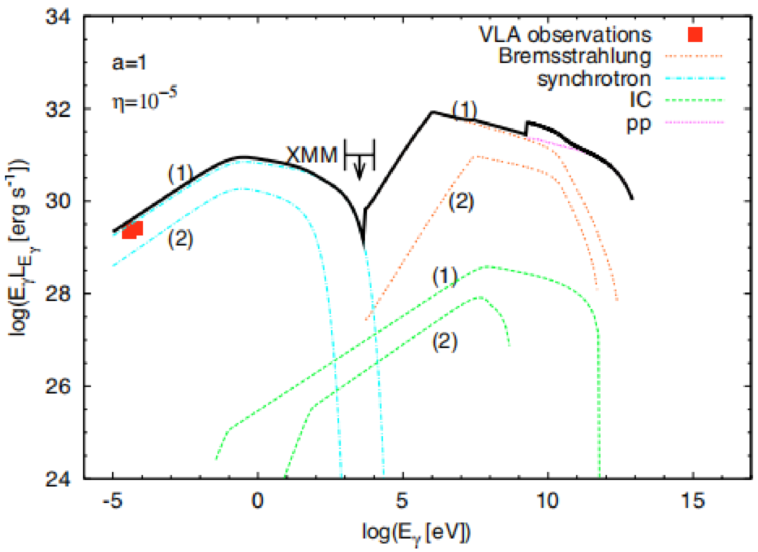


Fig. 1. Sketch of the scenario discussed in this work.

This model suggests that particles accelerated by YSO jets can also produce gamma radiation.



V. Bosch-Ramon et.al(2010) explored the conditions for particle acceleration in Young Stellar Objects (YSOs) and pointed out that under appropriate conditions, particles accelerated by YSO jets can emit gamma radiation detectable by Fermi-LAT and the new generation of Cherenkov telescopes.

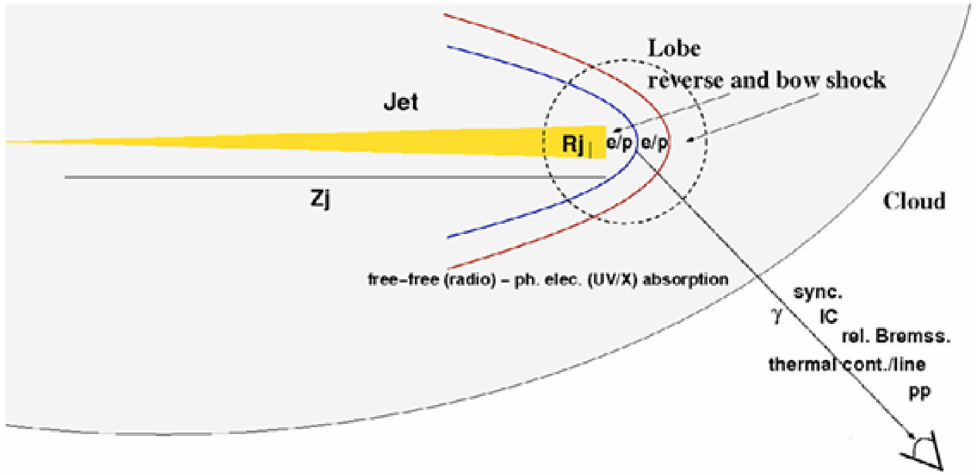


Fig. 1. Sketch of the termination region of the jet of a massive YSO. Two shocks of different strengths and velocities will form depending on the jet-medium properties. Electrons and protons can be accelerated in the shocks, and generate nonthermal emission via interaction with the ambient matter, magnetic, and radiation fields. The shocked material will also produce thermal radiation.

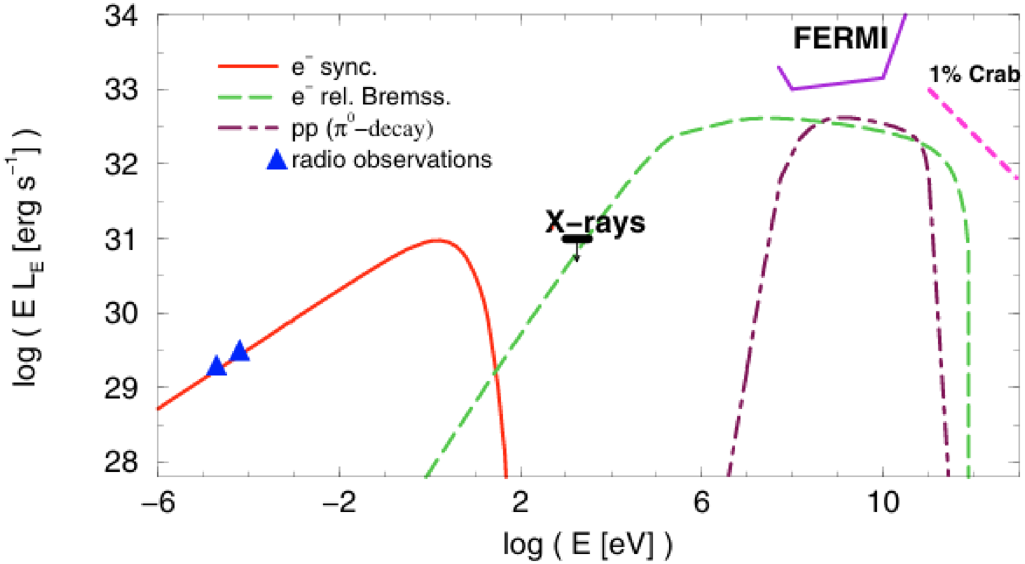


Fig. 2. Spectral energy distribution of the nonthermal emission for IRAS-N in the primary electron scenario. The IC contribution is negligible and not shown here. Observational points are from IRAS 16547−4247 (radio, Rodríguez et al. 2005; X-rays, ARA07). The 1 yr/5 σ sensitivity of *Fermi* in the direction of the galactic plane is shown. A curve above 100 GeV showing a luminosity corresponding to 0.01 Crab, typical sensitivity of a Cerenkov telescope for exposures of ~50 h, is also presented.

The association between Fermi sources and MYSOs

1.Munar-Adrover et al. (2011) first studied the association of YSOs with gamma-ray sources on a statistical basis.

· Data source: The First Fermi Catalog was used, which contains 1,451 gamma-ray sources detected in the energy range from 100 MeV to 100 GeV. The authors excluded known gamma-ray sources, leaving 1,392 unidentified gamma-ray sources.

· Cross-matching: The unidentified gamma-ray sources were cross-matched with the following catalog of young galactic objects:

Massive Young Stellar Objects (MYSOs): Using the Red MSX Source (RMS) survey catalog, which contains 637 confirmed MYSOs (Lumsden+, 2013).

They obtained a list of 12 massive MYSOs that are spatially coincident with 1FGL sources. Our results indicate that ~70% of these candidates should be gamma-ray sources with a confidence of ~5σ (estimated by MC simulation).

[1]. Munar-Adrover P, Paredes J M, Romero G E, et al. A study of the association of Fermi sources with massive young galactic objects[J]. Astronomy & Astrophysics, 2011, 530: A72.

The association between Fermi sources and MYSOs

2. Detection of S255 NIRS 3

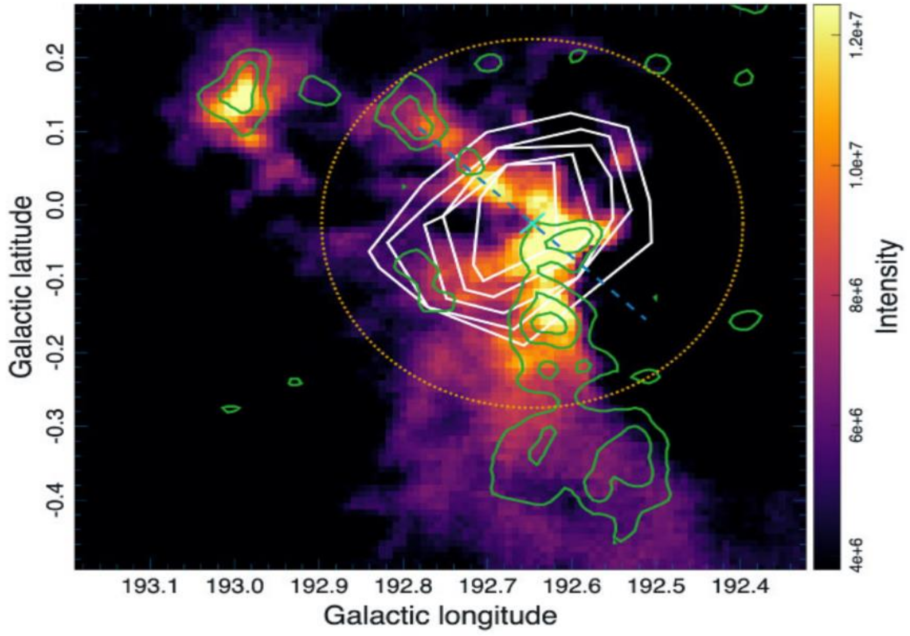


Figure 3. Integrated ^{13}CO intensity map of the S255 NIRS 3 region obtained from the MWISP survey. The green contours are obtained from the $C^{18}O$ intensity map, tracing the two extense filamentary structures emerging from the core of the emission. The contours above 12 TS (in steps of 2 TS) obtained from the LAT Test-Statistic skymap above an energy threshold of 1 GeV are overlaid in white and the best-fitting position in cyan. The direction of the 1 arcmin molecular bipolar outflow is shown with a blue dashed line. The orange circle marks the 95 per cent CL on the source extension.

· S255 NIRS 3 (also known as G192.60–00.04) is a well-studied high-mass young stellar object (HMYSO) with a mass approximately 20 times that of the Sun, located in the S255IR massive star-forming region at a distance of about 1.8 kpc from Earth.

· A GeV source named 4FGL J0613.1+1749c was discovered, coinciding with the position of S255 NIRS 3. This source exhibits two filamentary CO structures, each approximately 10 pc in length, aligned with the direction of the radio jet.

[1]. de Oña Wilhelmi E, López-Coto R, Su Y, et al. High-energy gamma-ray emission powered by a young protostar: the case of S255 NIRS 3[J]. Monthly Notices of the Royal Astronomical Society, 2023, 523(1): 105-110.

The association between Fermi sources and MYSOs

2.Detection of S255 NIRS 3

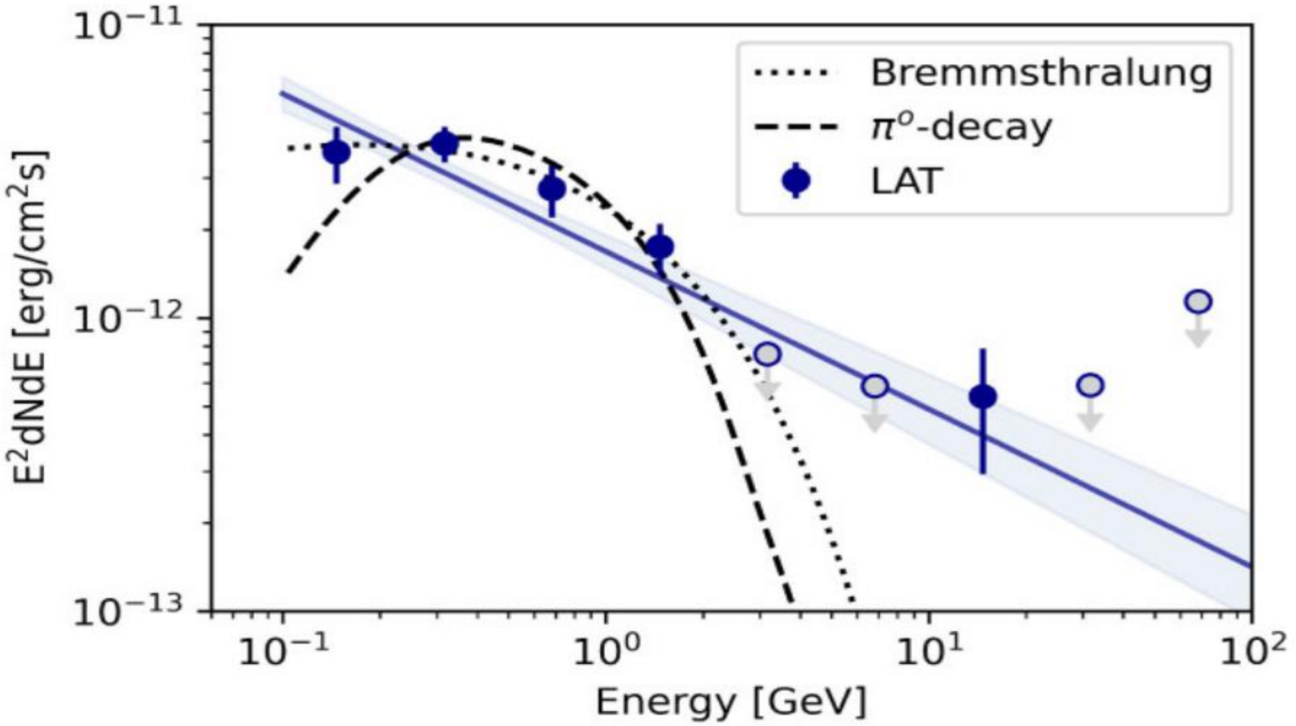
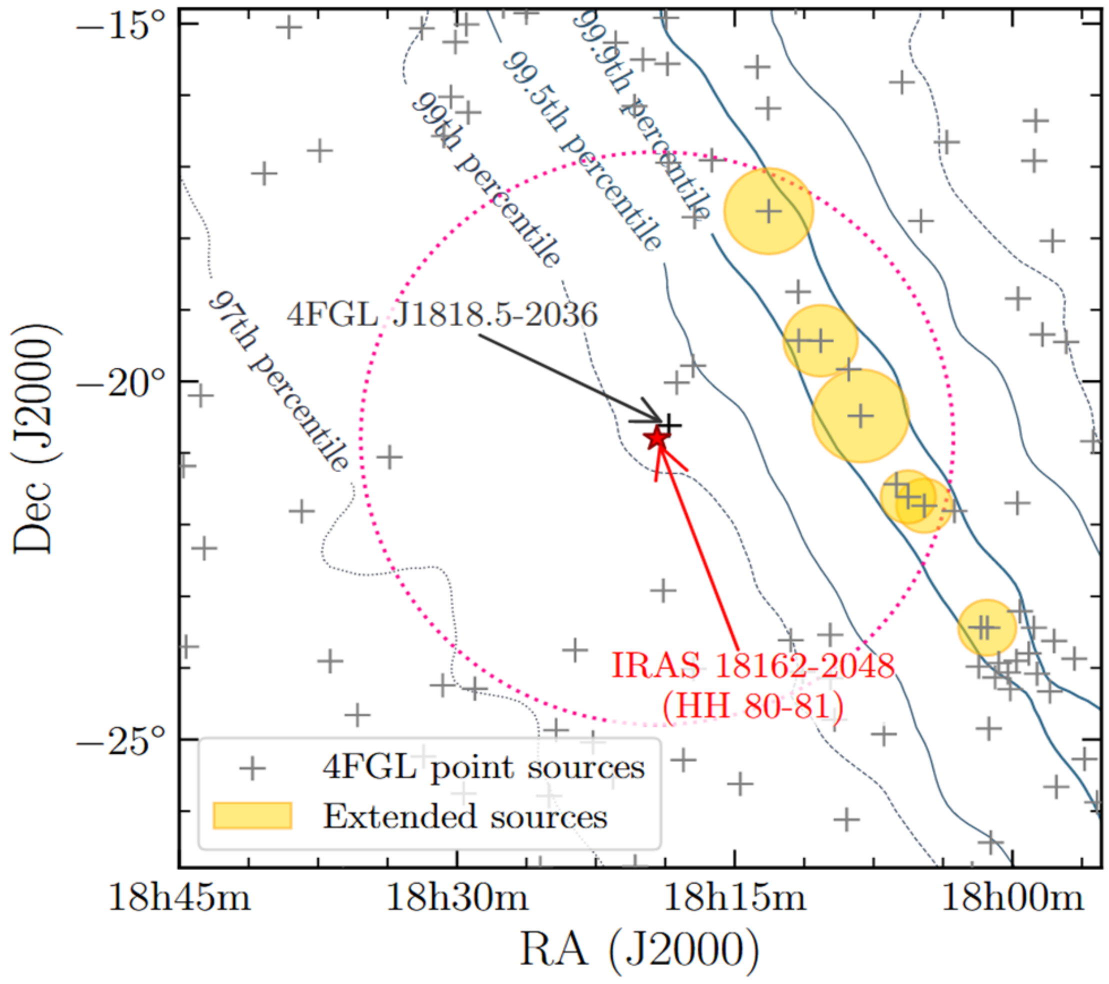


Figure 1. Spectral energy distribution derived from 4FGL J0613.1+1749c. The 1σ error in the best-fitting parameters is shown with a shaded blue area. The dashed and dotted lines show the best-fitting models obtained for hadronic and leptonic emission mechanisms.

[1]. de Oña Wilhelmi E, López-Coto R, Su Y, et al. High-energy gamma-ray emission powered by a young protostar: the case of S255 NIRS 3[J]. Monthly Notices of the Royal Astronomical Society, 2023, 523(1): 105-110.

The association between Fermi sources and MYSOs

3.The case of HH 80-81 protostellar jet .



· HH 80-81 is one of the most powerful collimated protostellar jet systems in our Galaxy, and has been detected in non-thermal radio, X-ray, and gamma-ray emissions.

· 4FGL J1818.5-2036:
A 4σ unassociated point source, located 0.2° away from IRAS 18162-2048.

[1]. Méndez-Gallego J, López-Coto R, de Oña Wilhelmi E, et al. Exploring the capability of the HH 80-81 protostellar jet to accelerate relativistic particles[J]. Astronomy & Astrophysics, 2025, 695: A11.

The association between Fermi sources and MYSOs

3.Detection of HH 80-81 protostellar jet .

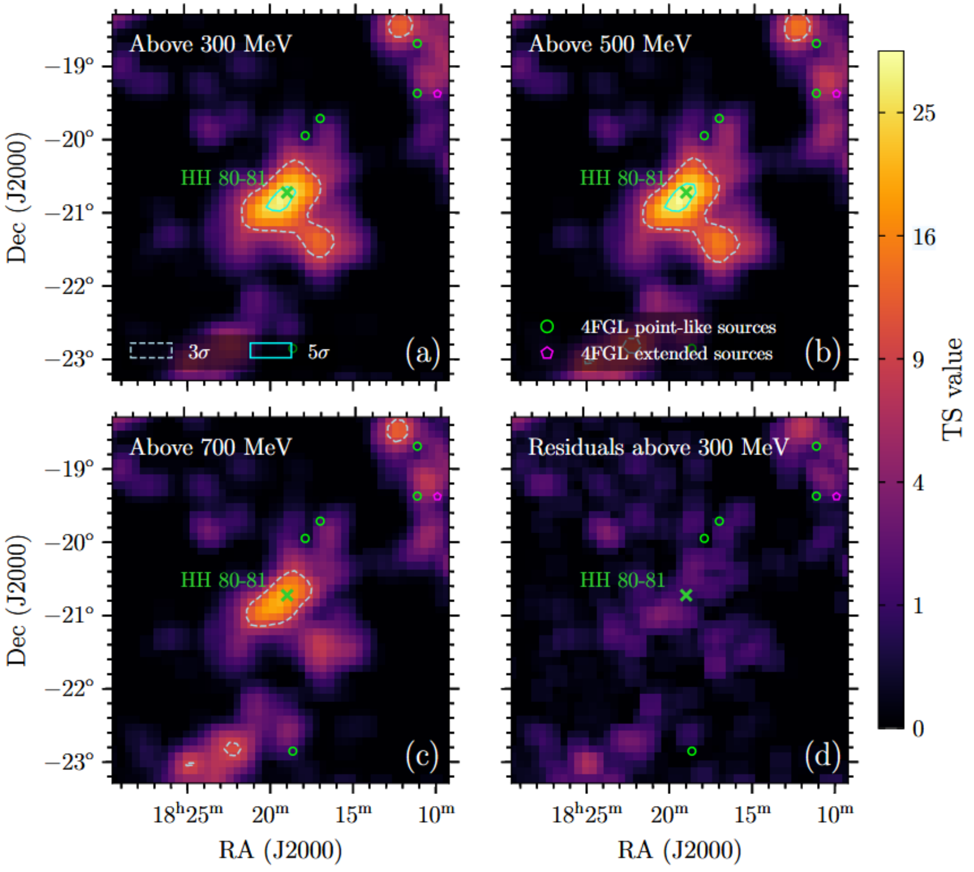


Fig. 2. TS maps for a 5° × 5° region centered in IRAS 18162-2048. Contour maps show the detection significance while color maps indicate the TS value of each spatial bin. Green cross indicates the position of the protostar driving the HH 80-81 system. Panels (a), (b), and (c) show the significance map for HH 80-81 above 300 MeV, 500 MeV, and 700 MeV respectively. Panel (d) shows the residual TS map above 300 MeV as a proof of the reliability of our fitted model.

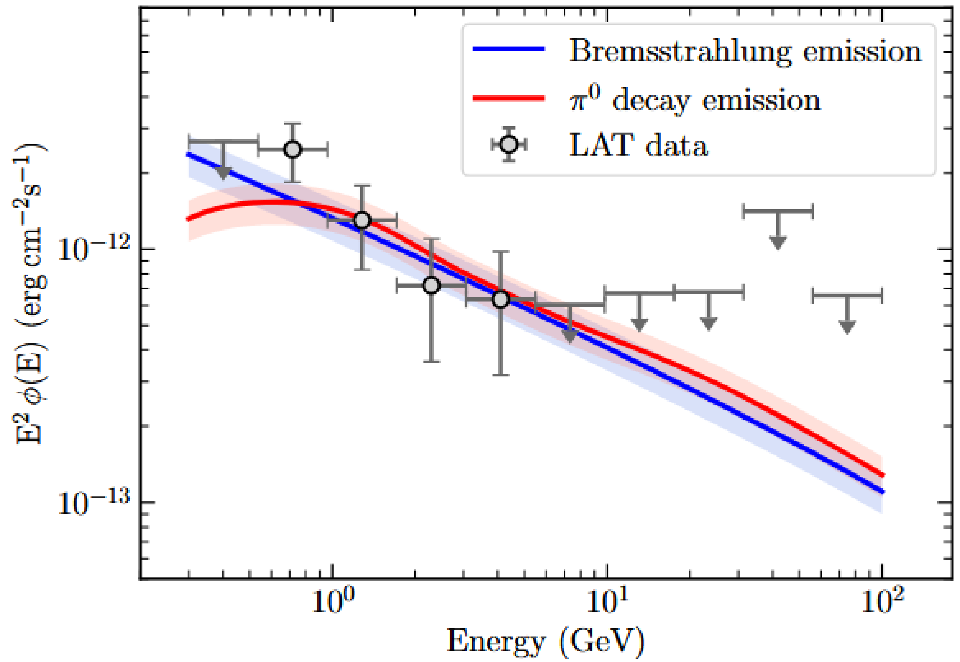
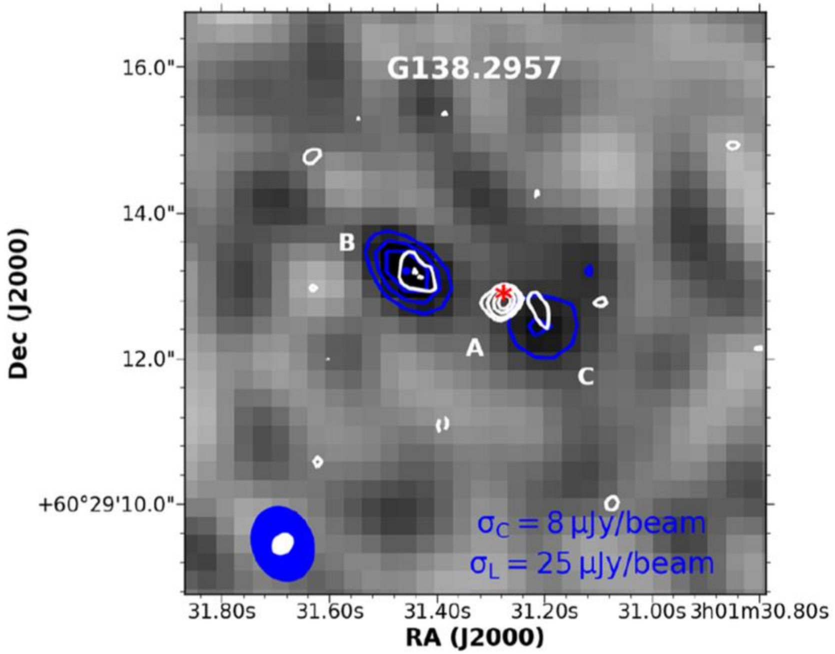


Fig. 7. SED fitting for leptonic and hadronic models of γ-ray production. Grey points represent the *Fermi*-LAT emission from Fig. 3 obtained in this work. Shaded areas show the 1σ error for both fittings.

[1]. Méndez-Gallego J, López-Coto R, de Oña Wilhelmi E, et al. Exploring the capability of the HH 80-81 protostellar jet to accelerate relativistic particles[J]. Astronomy & Astrophysics, 2025, 695: A11.

The search of gamma-rays from MYSOs

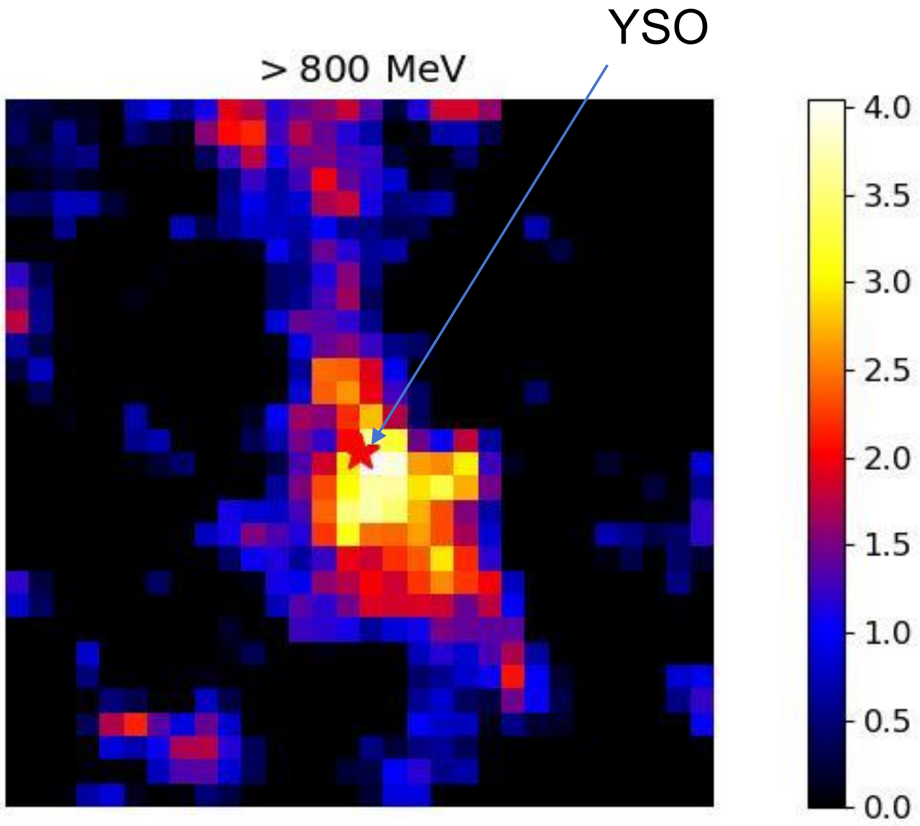
- Obonyo et al. (2019) list 15 MYSOs with non-thermal radio jets



The association between Fermi sources and MYSOs

4. A new discovery?

·The following shows Fermi sky map in the vicinity of a massive protostar with a non-thermal jet (among the 15 shown previously).
We used 16 years of Fermi-LAT data (from August 4, 2008 to August 6, 2024) to generate a TS map after subtracting all sources from the 4FGL DR4 catalog.



model	loglike
4FGL	1054472
4FGL+Src1	1054488

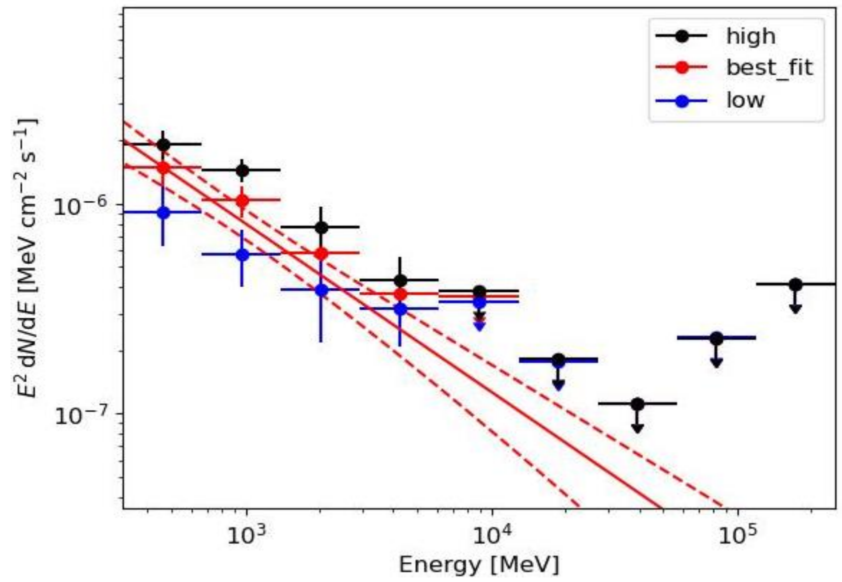
Model	Loglike	TS	ΔAIC
Model1 (PS1)	6015509	136	0
Model2 (PS2)	6015518	161	-18
Model3 (PS1+PS2)	6015531	PS1(40),PS2(77)	-40

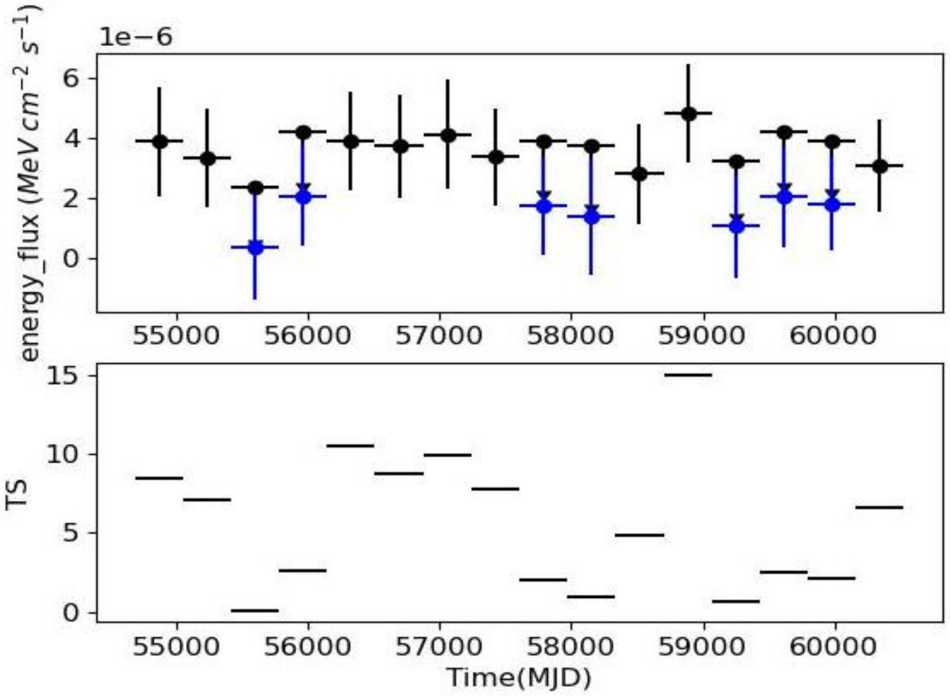
Tang, Yang, Tam (in prep.)

The association between Fermi sources and MYSOs

4. A new discovery?

Based on the new spatial model, we extracted the energy spectrum of Src1 using data above 300 MeV and conducted its light curve analysis.





SED

Note: Since this source is located near the Galactic disk, we manually varied the norm of the best-fit result of the GDE by 6% to obtain the high and low energy spectra of Src1 respectively.

lightcurve:The top panel shows the energy flux, while the bottom panel displays the Test Statistic (TS) values. For bins with TS < 5, we calculated the 95% confidence level upper limits on the energy flux.

Tang, Yang, Tam (in prep.)

Summary

- YSOs are embedded deeply in, or surrounded by **molecular clouds**
  -> Molecular clouds provide natural targets for p-p interaction
- YSOs with non-thermal radio jets provide natural **particle acceleration** sites, protons and electrons alike
- Several YSOs have been detected to be **gamma-ray sources** using Fermi-LAT
- A new probe of YSO environment using high-energy observations