Search for molecular clouds in the dark ultra-high-energy gamma-ray source 1LHAASO J0007+5659u with the Nobeyama 45-m radio telescope

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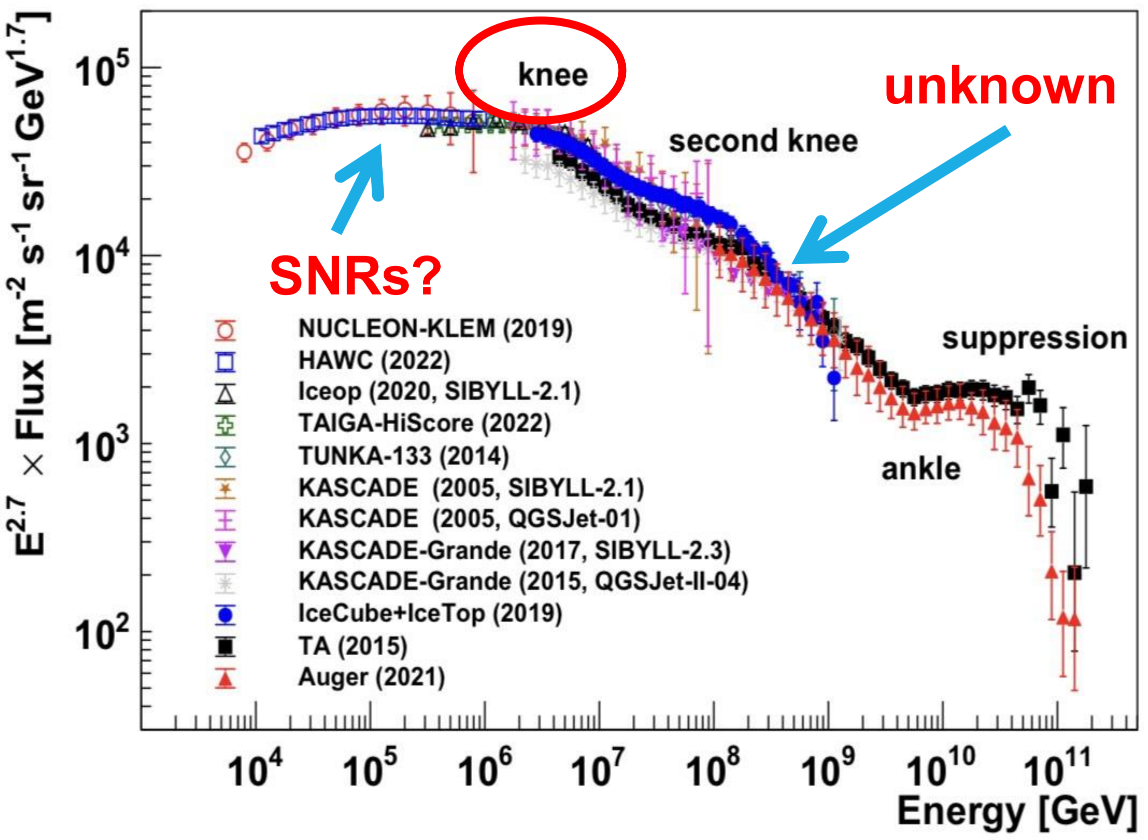
Cosmic Ray

- Cosmic-ray spectrum shows a *knee* at ~ 3 PeV.
- Sources that accelerate particles to PeV energies are referred to as PeVatrons.



Galactic cosmic-ray energy spectrum (Fahim et al. 2025).

< knee	→	Galactic SNRs?
knee – ankle	→	Unknown
> ankle	→	Extragalactic?

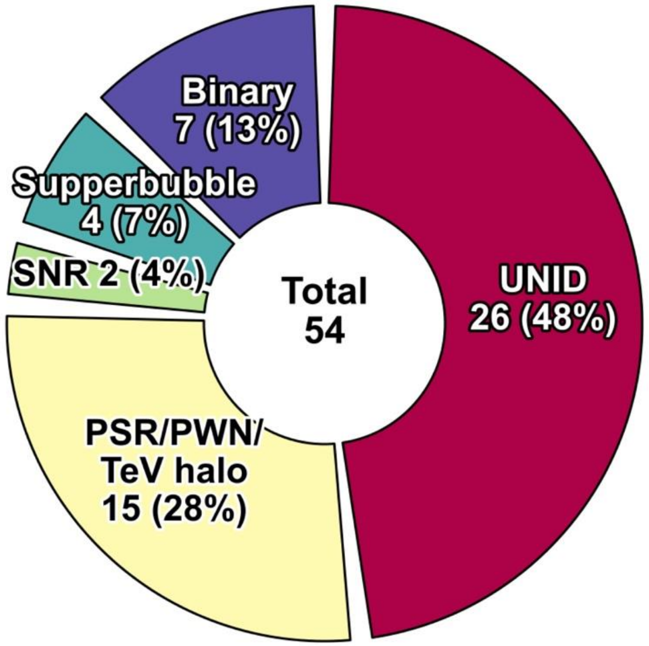
Ultra-high-energy (E > 100 TeV) gamma-ray sources are PeVatron candidates.

Gamma rays to find PeVatrons

LHAASO (Large High Altitude Air Shower Observatory)

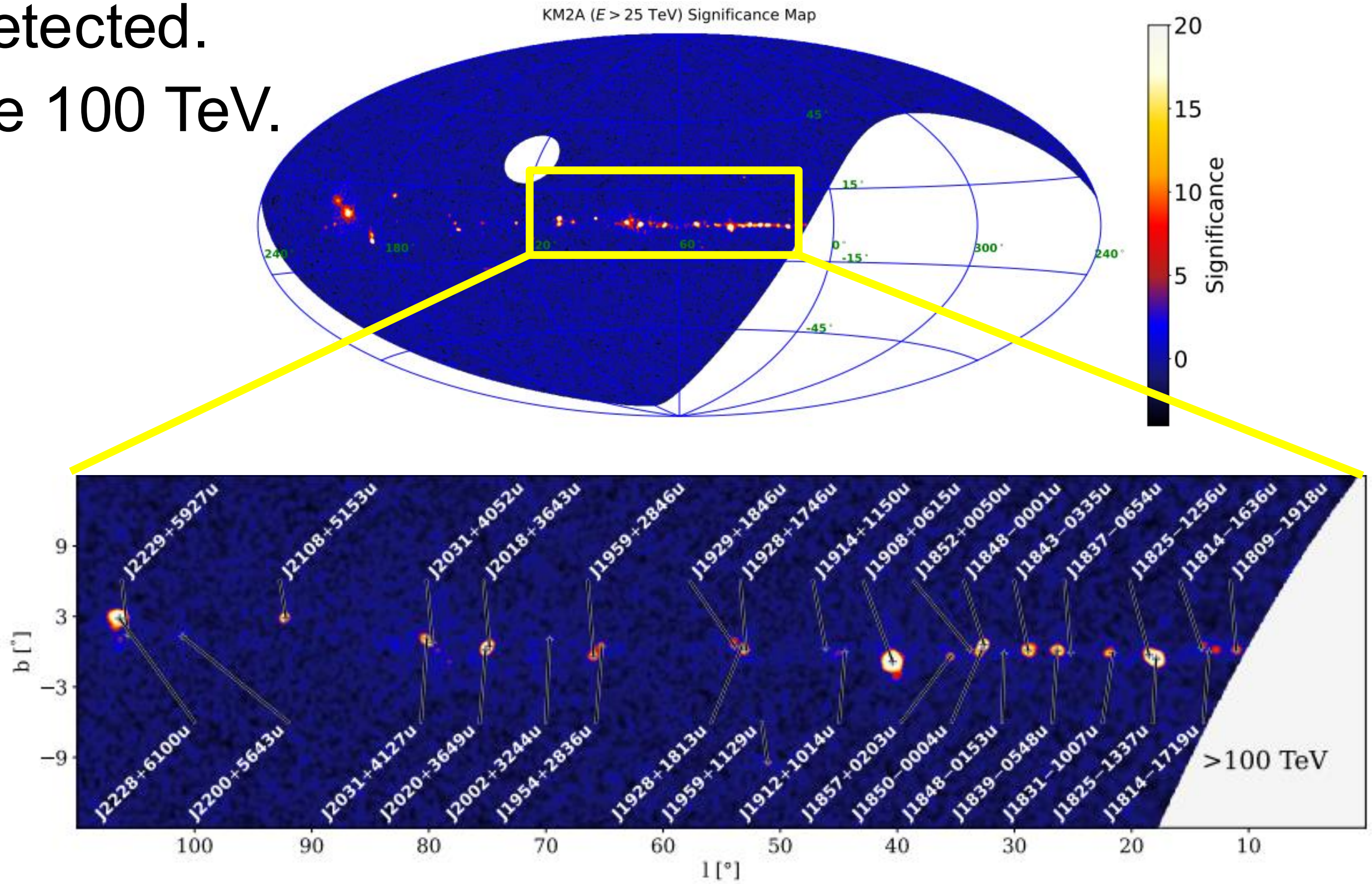
- Observes gamma rays from TeV to PeV energies.
- 90 gamma-ray sources have been detected.
- About 50 sources are detected above 100 TeV.

(Cao+ 2023)



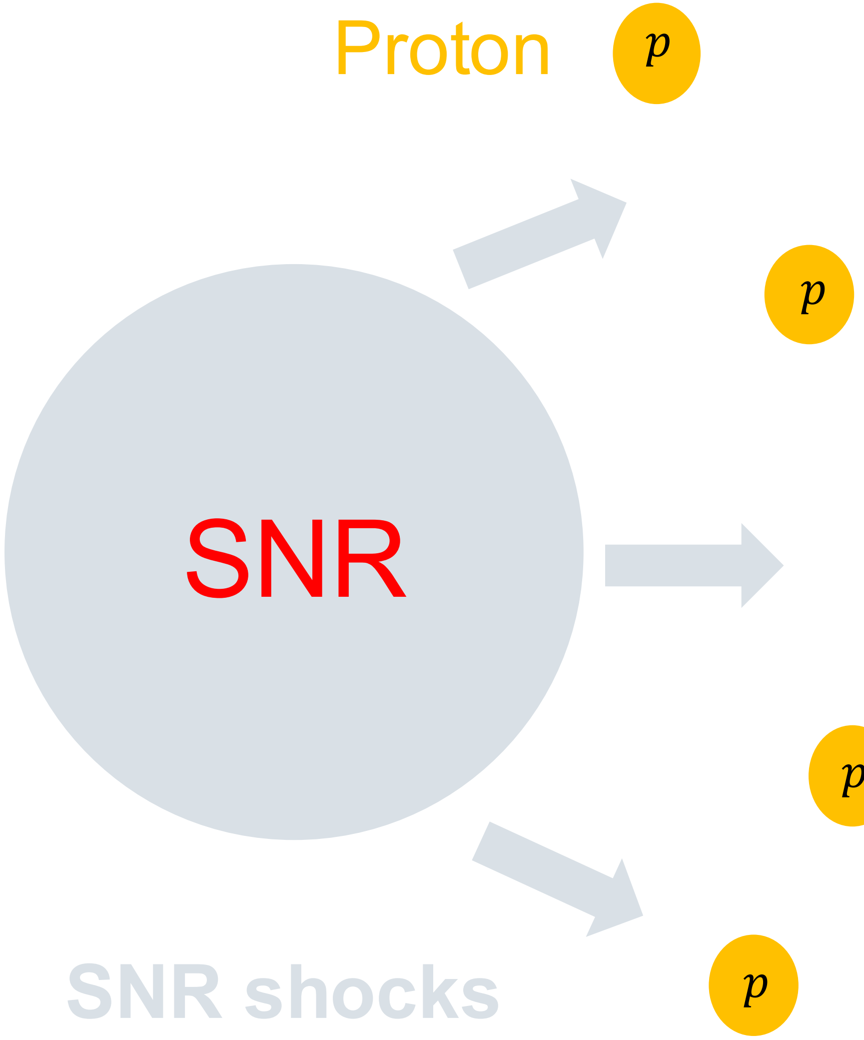
Breakdown of 50 UHE LHAASO sources

Courtesy of N. Tsuji

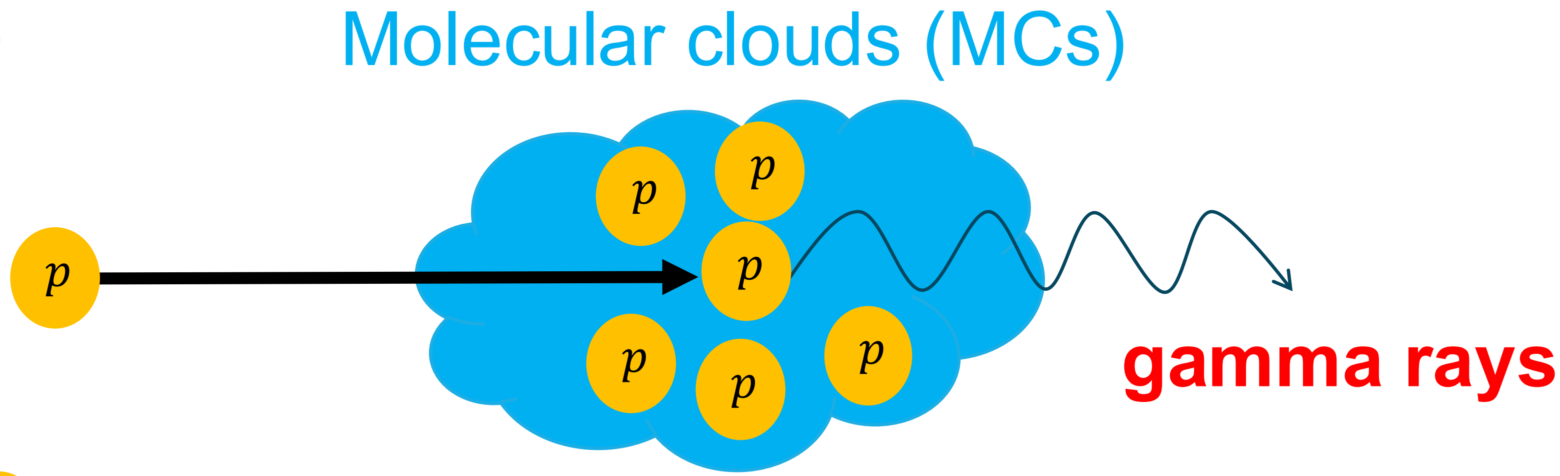


Hadronic scenario (proton origin)

Molecular cloud observations are key!



1. High-energy protons interact with the MCs.



2. π^0 mesons decay into gamma-rays.

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

$$\pi^0 \rightarrow \gamma + \gamma$$

Molecular clouds & CO observations

Molecular clouds

- H_2 is difficult to observe directly.
- CO emission is commonly used as a tracer of H_2.

Nobeyama 45-m radio telescope

- Observed lines: ^{12}CO, ^{13}CO and $C^{18}O$ (J=1-0)
- Angular resolution: ~ 20”

Nobeyama 45-m radio telescope

Research purpose

Search for molecular clouds associated with gamma rays.

Our targets observed with the Nobeyama 45-m radio telescope

Source name	l (deg)	b (deg)	Source type
1LHAASO J0007+5659u	116.9	-5.36	Dark source
1LHAASO J0216+4237u	139.2	-17.5	Dark source (MSP?)
1LHAASO J1959+1129u	51.1	-9.42	Dark source (LMXB)
1LHAASO J1740+0948u	33.8	+20.3	PWN

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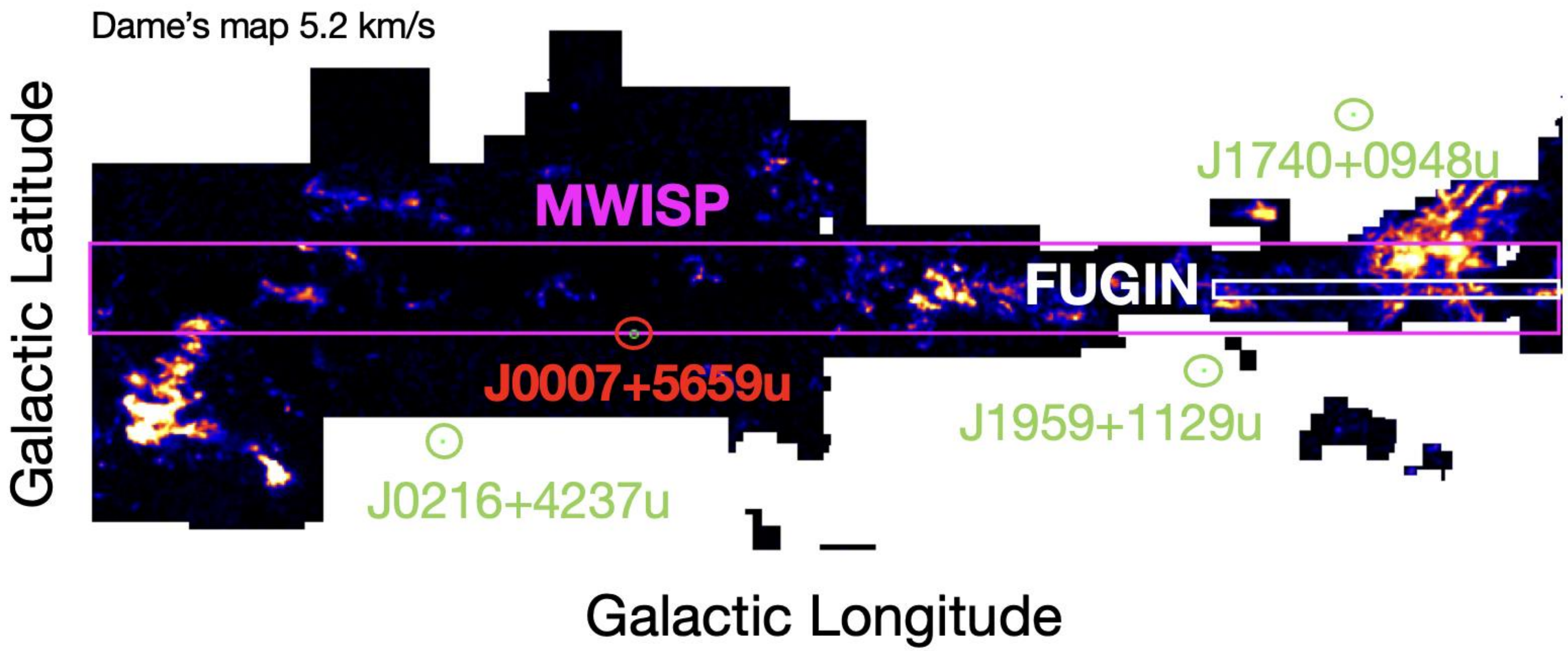
Off the Galactic plane targets



Dame et al. (2001).

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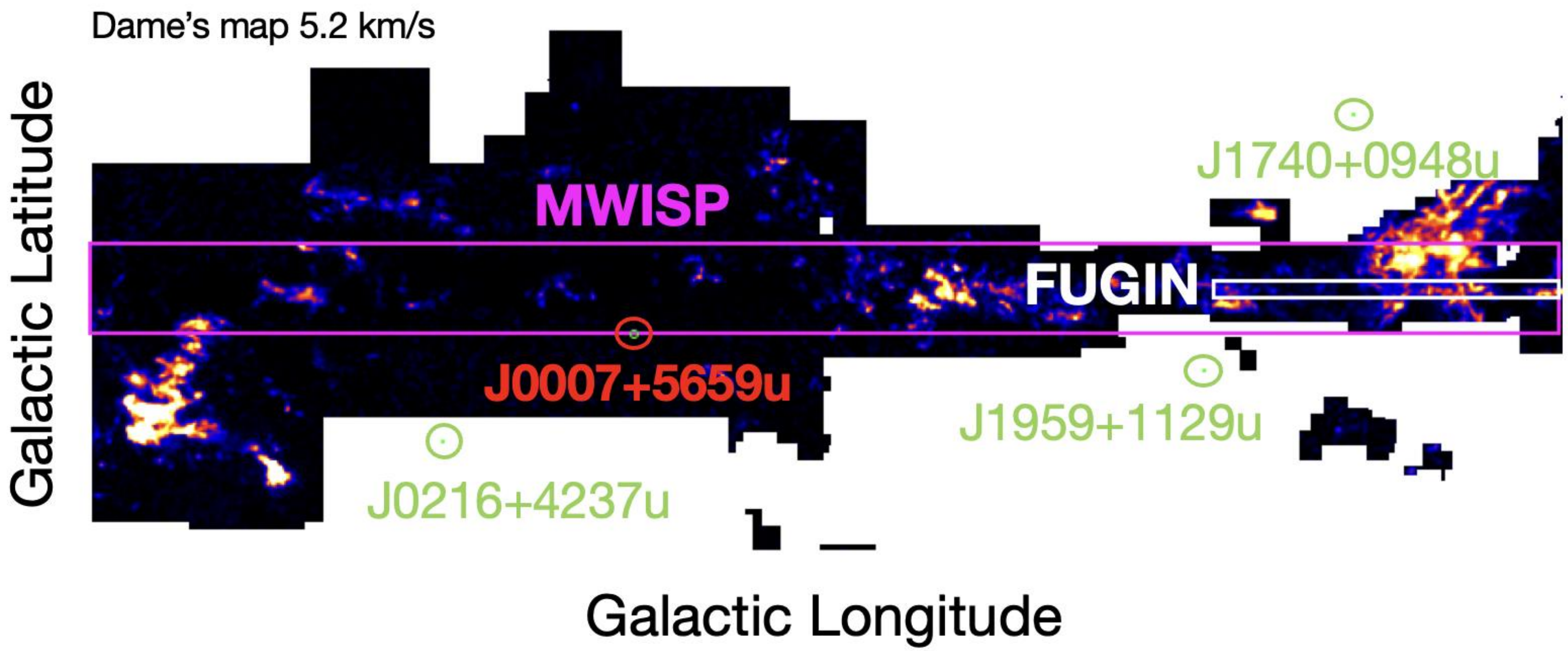


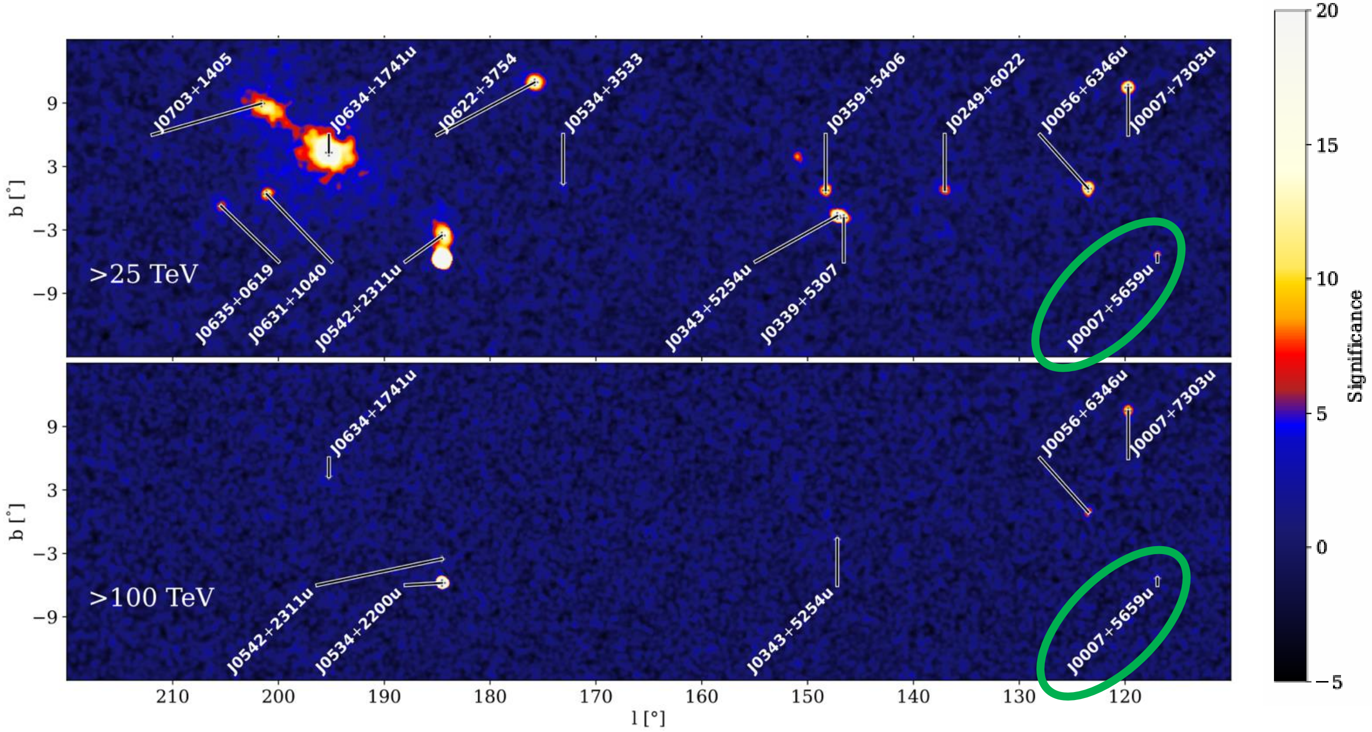
Dame et al. (2001).

1LHAASO J0007+5659u

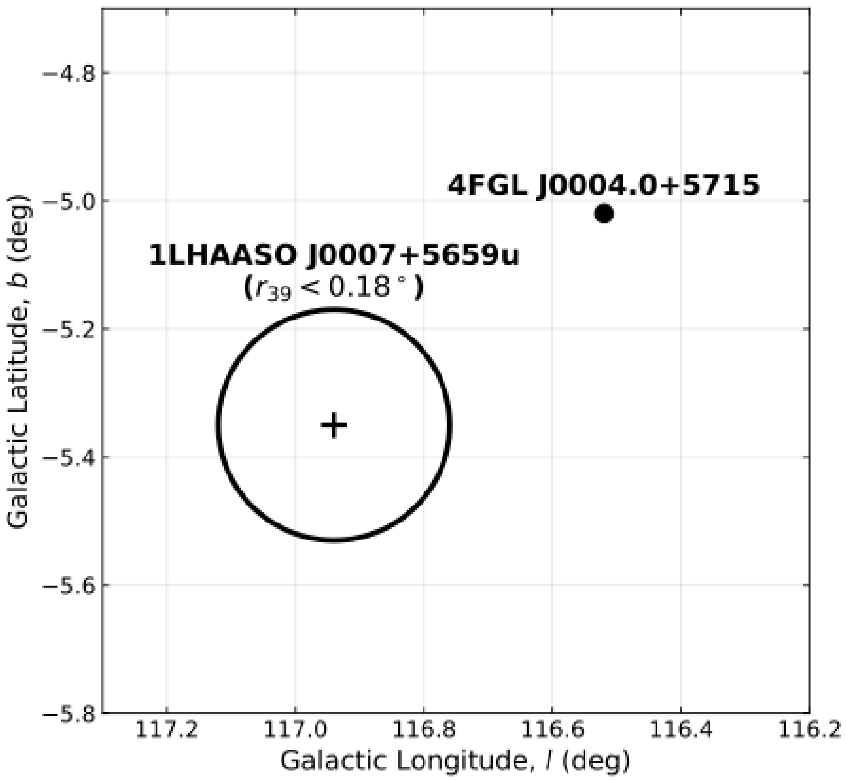
1LHAASO J0007+5659u

- r_{39} < 0.18 deg
- Γ = 3.10 ± 0.20
- Flux = 7.1×10^{-13} erg cm^{-2} s^{-1}

- Point-like gamma-ray source detected above 100 TeV.
- No firmly identified counterpart
- Dark source



(Cao+ 2023)

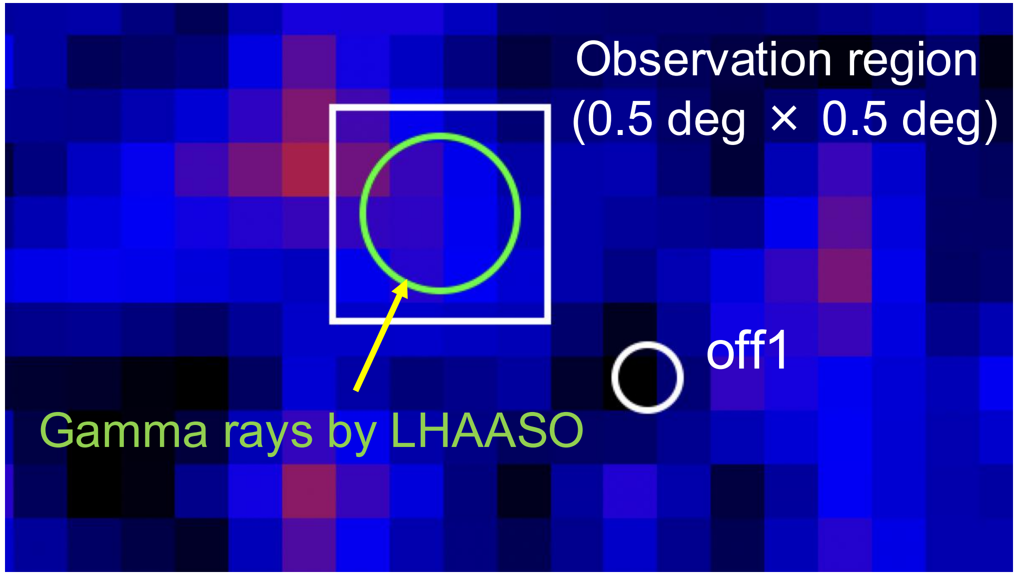


NRO (Nobeyama Radio Observatory) observation overview

- Observations of the ^{12}CO, ^{13}CO, and $C^{18}O$ lines (J=1-0), using the NRO 45-m telescope

- Overview
  - Observation dates (21 hours in total)
    - (Day1) 2025-12-08
    - (Day2) 2025-12-12
    - (Day3) 2025-12-14
    - (Day4) 2025-12-15
    - (Day5) 2026-04-01
  - Configuration: four-beam receiver FOREST and autocorrelation spectrometer SAM45
  - **Pointing source**: Y-cas (20-40 K)
  - **Calibration source**: J0007 cloud 1
  - Off position: off1

- Mapped area: 0.5 × 0.5 deg^2
- Velocity range: -150 to 150 km/s
- Velocity resolution: 0.2 km/s

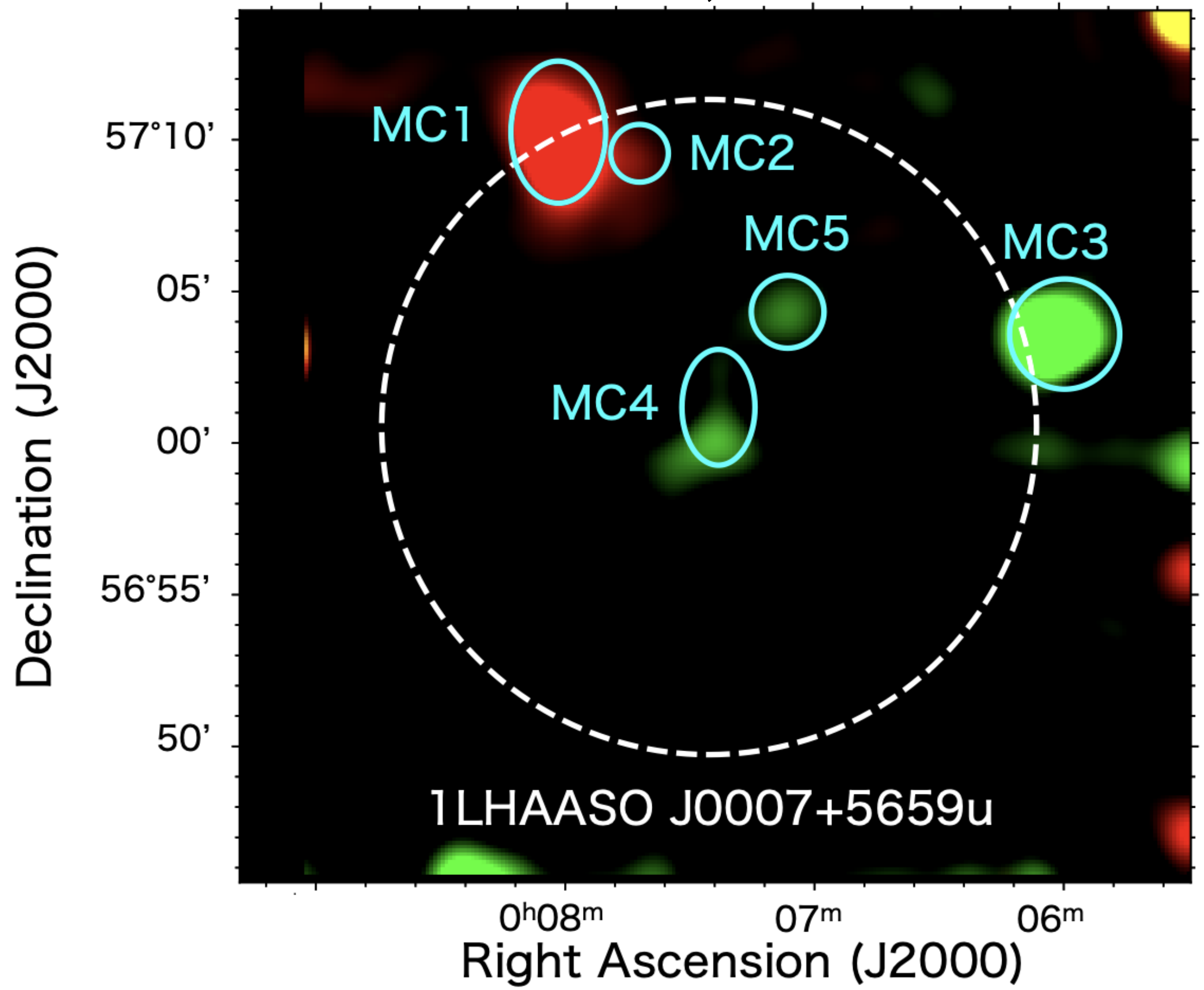


Galactic CO distribution from Dame et al. (2001).
(v=20 km/s)

Detection of molecular clouds

Detection of molecular clouds

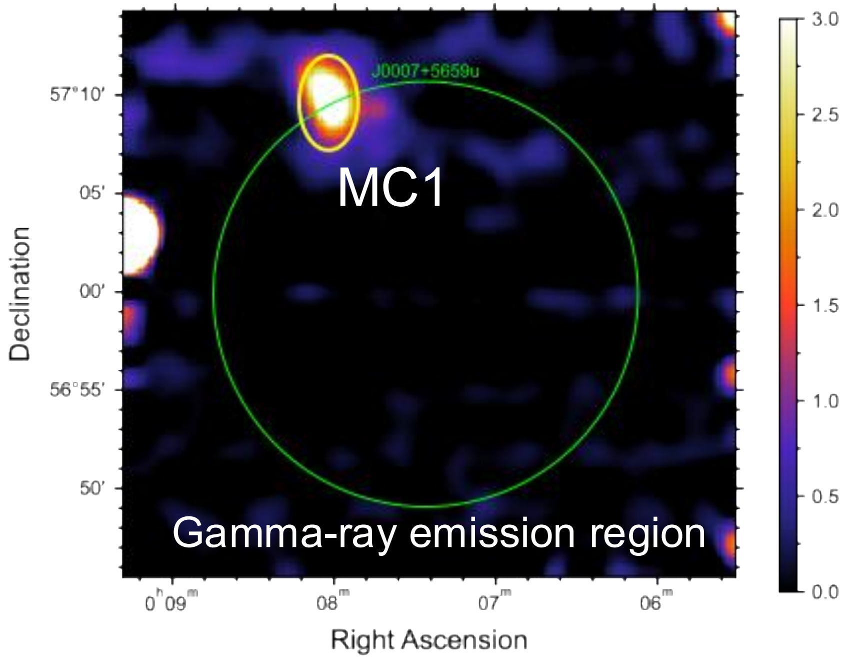
Red: -37.1 to -34.9 km/s, Green: -4.1 to -2.1 km/s

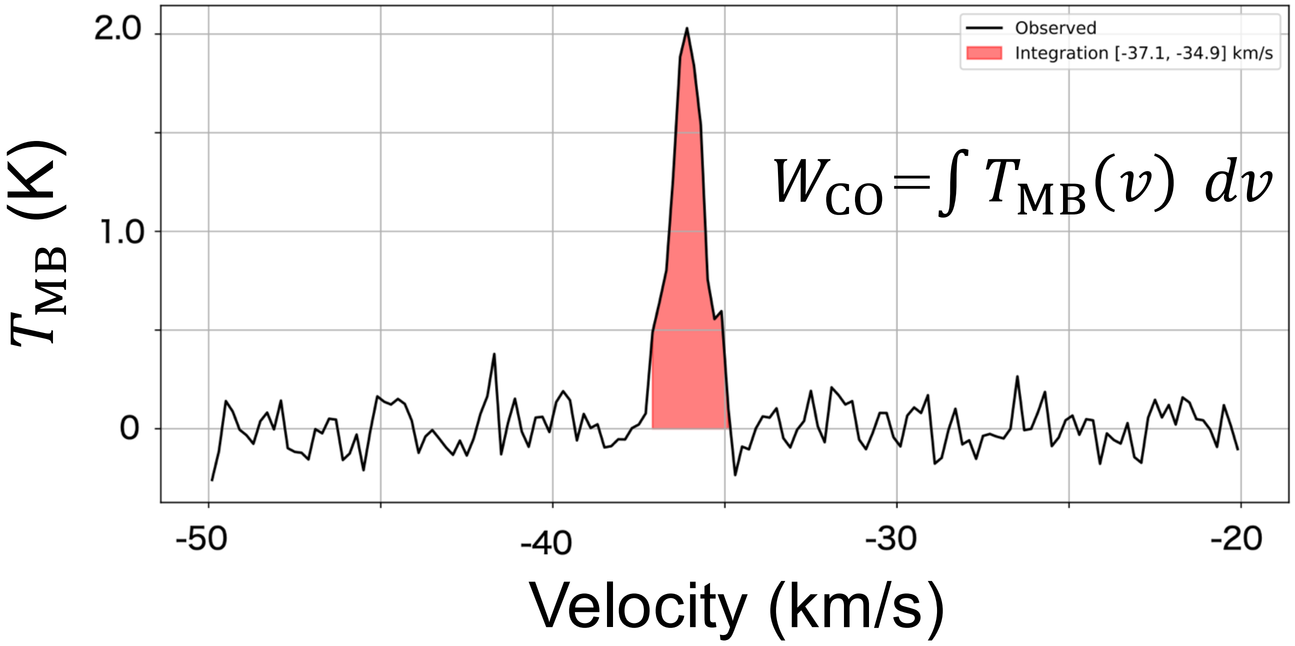


Five molecular clouds (MC1-MC5) were detected around 1LHAASO J0007+5659u.

Physical parameters of MCs derived from CO observations

^{12}CO integrated intensity map
(-37.1 to -34.9 km/s)





Mean velocity spectrum of MC1

Main-beam temperature T_{MB}[K]: CO line intensity

Molecular hydrogen column density

$$\boxed{N(\mathrm{H_2}) = X_{\mathrm{CO}} \cdot W_{\mathrm{CO}}}$$

X_{CO}: CO-to-H_2 conversion factor 2.0×10^{20} $\mathrm{cm^{-2}}$ (K・km/s)$^{-1}$
(Bolatto et al. 2013)

Physical parameters of MCs derived from CO observations

Distance

- Traditional kinematic distance using the Galactic rotation curves

(e.g., Brand & Blitz 1993; Reid et al 2014; Wenger et al. 2018)

Mass

$$M = \mu m_{\mathrm{H}} d^2 \Omega\, N(\mathrm{H}_2)$$

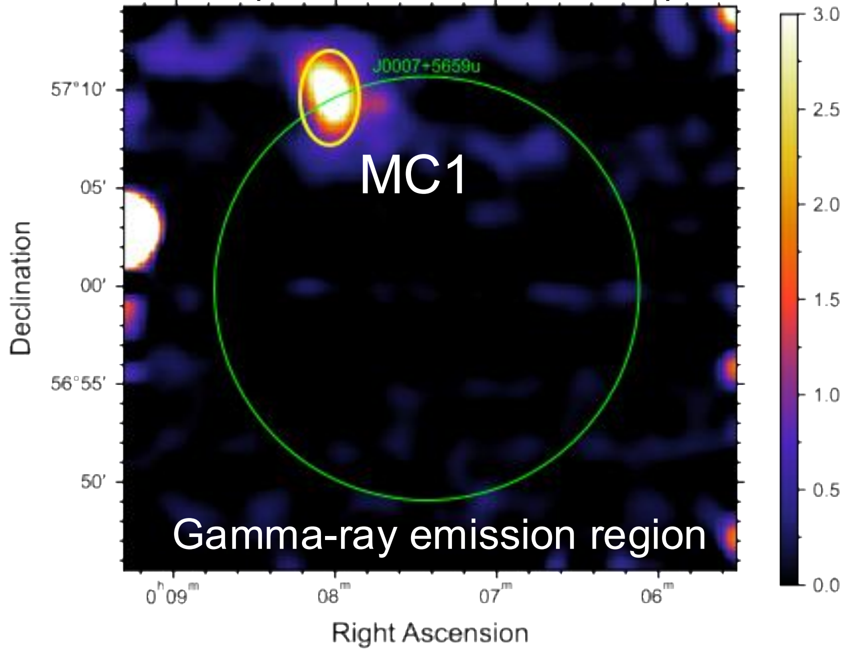
- Ω: angular area of a grid space (7.5 × 7.5 arcsec^2)
- μ: mean molecular weight: 2.8

Number Density

$$n(\mathrm{H}_2) = \frac{M}{\mu m_{\mathrm{H}} V}$$

- V: Volume of the MC
- The cloud geometry approximated by a sphere or an ellipsoid

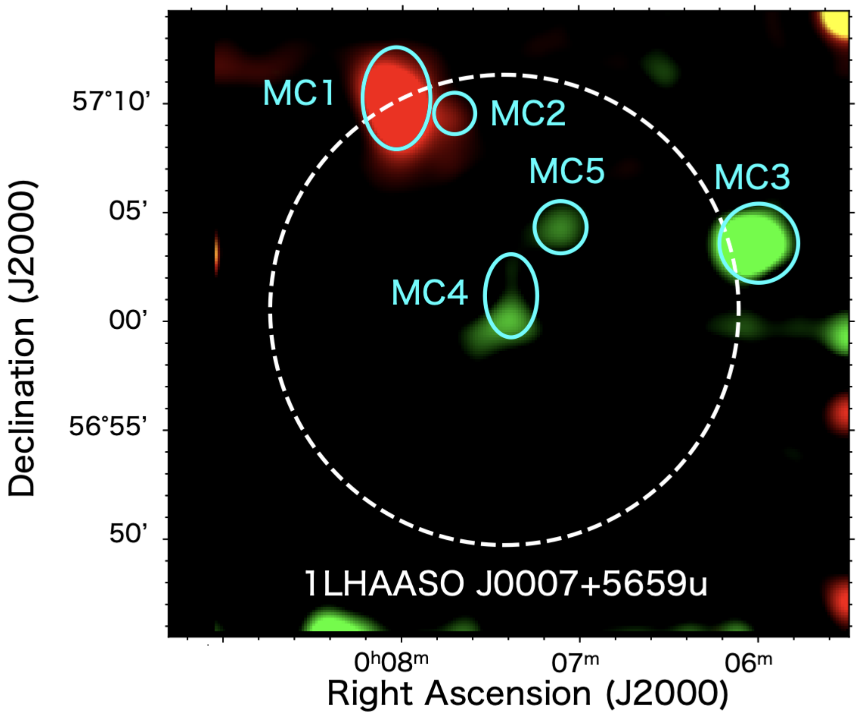
^{12}CO integrated intensity map (-37.1 to -34.9 km/s)

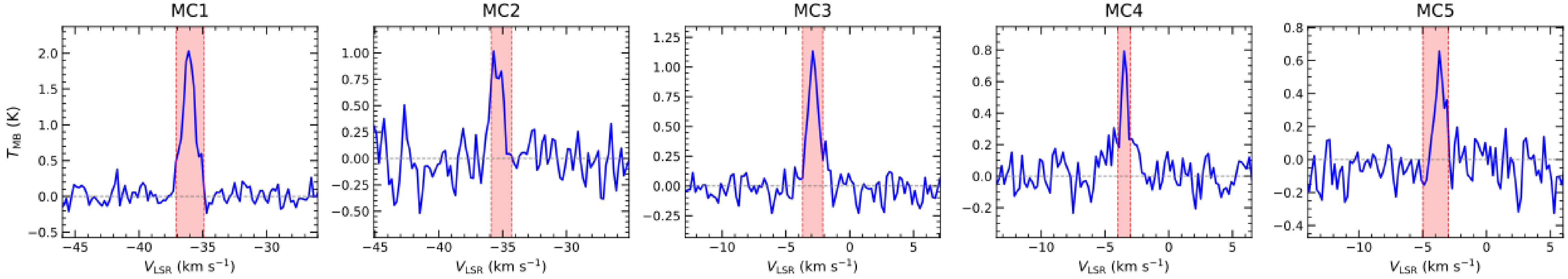


Parameters of clouds

cloud	V_{LSR} (km/s)	d (kpc)	M (M_{sun})	n (cm^{-3})	W_p (erg)
1	-36.1	2.85	90	192	6.6×10^{45}
2	-35.5	2.87	9.66	138	9.4×10^{45}
3	-2.85	0.42	0.95	609	4.5×10^{43}
4	-3.67	0.72	1.13	308	2.6×10^{44}
5	-3.64	0.42	0.25	546	5.1×10^{43}

Red: -37.1 to -34.9 km/s
Green: -4.1 to -2.1 km/s





Hadronic modeling using the physical properties of MC4

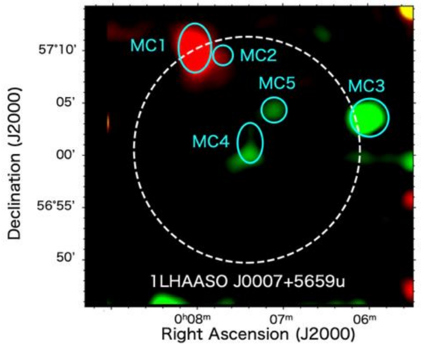
Assumed proton distribution

$$N(E_\mathrm{p}) = KE^{-s}\exp\left(-\frac{E_\mathrm{p}}{E_\mathrm{c}}\right)$$

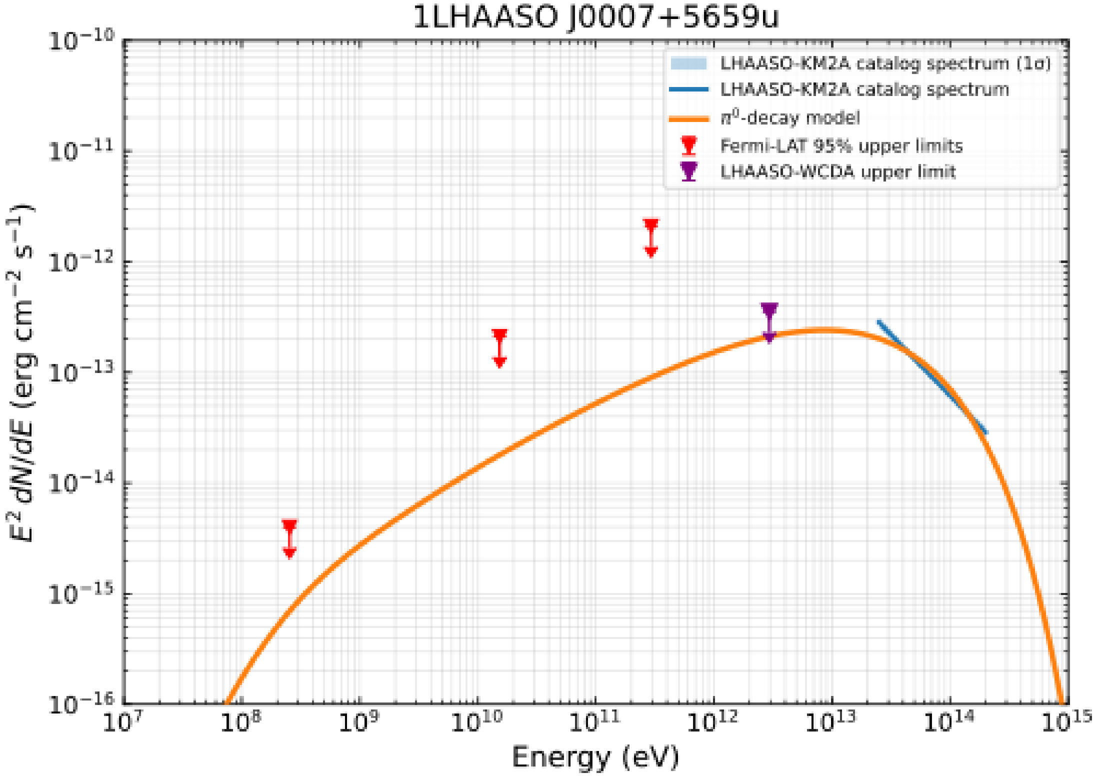
K: normalization s: proton spectral index
E_c: proton cutoff energy

Fixed parameters (MC4)

- d = 0.72 kpc
- $n(\mathrm{H_2})$ = 308 cm^{-3}



The Fermi-LAT 95% C.L. upper limits and LHAASO-WCDA upper limits from Xie et al. (2025) were used as constraints.



Fitted and derived parameters

- Proton spectral index: s ~ 1.4
- Proton cutoff energy: E_c ~ 250 TeV
- Total proton energy: W_p ~ 6.0 × 10^{44} erg

Discussion

Required proton energy: W_p (> 1 TeV) : 10^{43} – 10^{45} erg

Typical SNR cosmic-ray budget

$E_{\mathrm{SN}} \sim 10^{51}$ erg $\quad W_{\mathrm{CR}} \sim \eta_{\mathrm{CR}} E_{\mathrm{SN}} \sim 10^{49}$ erg $\quad$ ($\eta_{\mathrm{CR}} = 0.01 \sim 0.1$)

The origin of the high-energy protons remains unclear

Possible particle accelerators

- Escaped cosmic rays from an undiscovered SNR
- Proton acceleration by an isolated black hole

Kimura et al. (2025)

Isolated Black Hole Scenario for 1LHAASO J0007+5659u

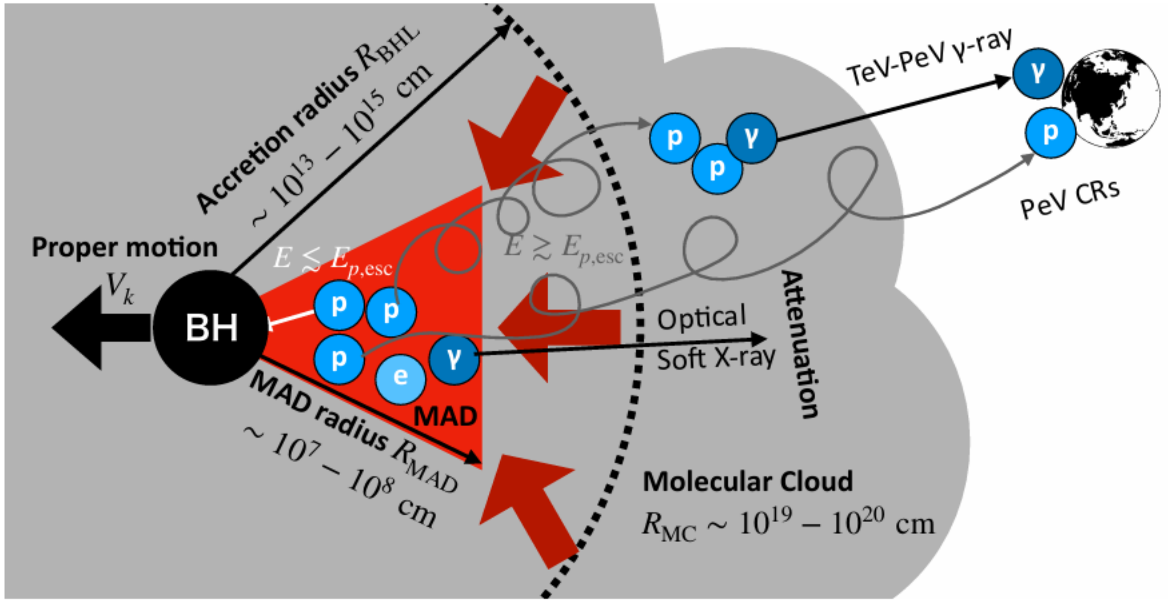
An isolated black hole accretes gas in a molecular cloud and forms a magnetically arrested disk (MAD).

Protons are accelerated around the black hole.

Escaping PeV protons interact with molecular gas (pp → π⁰ → γγ).

X-rays are emitted near the black hole.

Kimura's talk in this session



Isolated Black Hole PeVatron Scenario
From Kimura et al. (2025)

This scenario will be tested with XMM-Newton and NuSTAR observations in 2026-2027 (approved in NuSTAR AO-12).

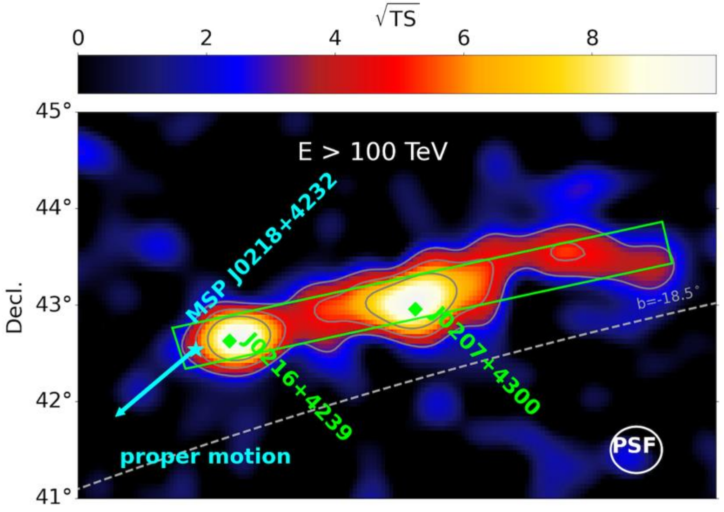
1LHAASO J0216+4237u

- **1LHAASO J0216+4237u**
  - r_{39} < 0.13 deg
  - Γ = 2.58 ± 0.17
  - Flux = 3.2×10^{-13} erg cm^{-2} s^{-1}
- **Nobeyama observations**
  - 1.4 × 0.9 deg^2
  - 21 hours in total
- **No clear CO emission**
- **Possible associated source: MSP PSR J0218+4232**
  - E_dot = 2.4×10^{35} erg/s
  - ***d* = 3.2 kpc**

W_{CO} (K・km/s)	$N(H_2)$ (cm^{-2})	n (cm^{-3})	V_{LSR} range (km/s)	d (kpc)
< 0.47	< 1.7×10^{19}	< 0.36	-40 to -30	3.2

1LHAASO J0216+4237u

LHAASO Collab.



Peanut region

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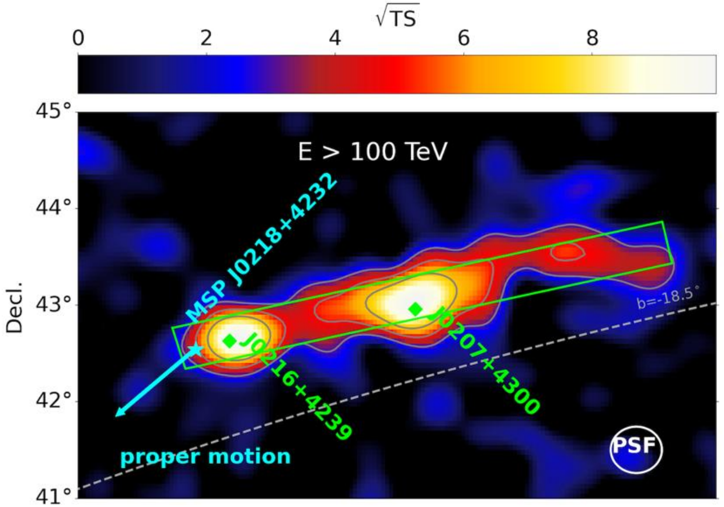
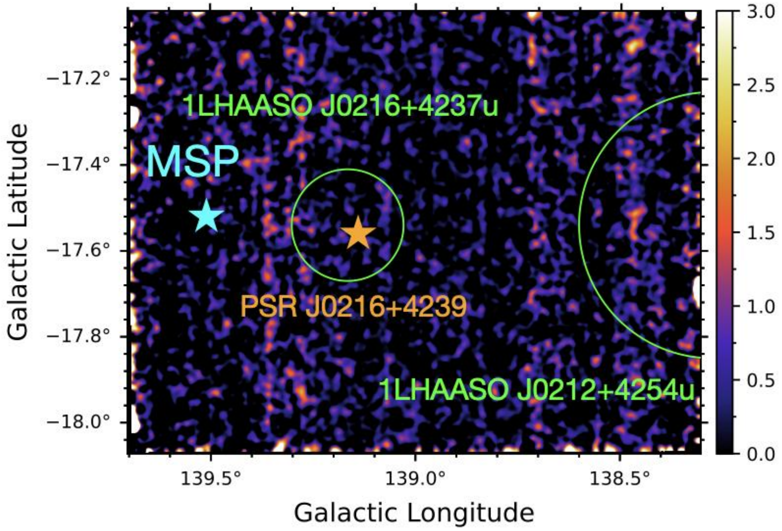


Peanut region

^{12}CO Map (v = -40 to -30 km/s)



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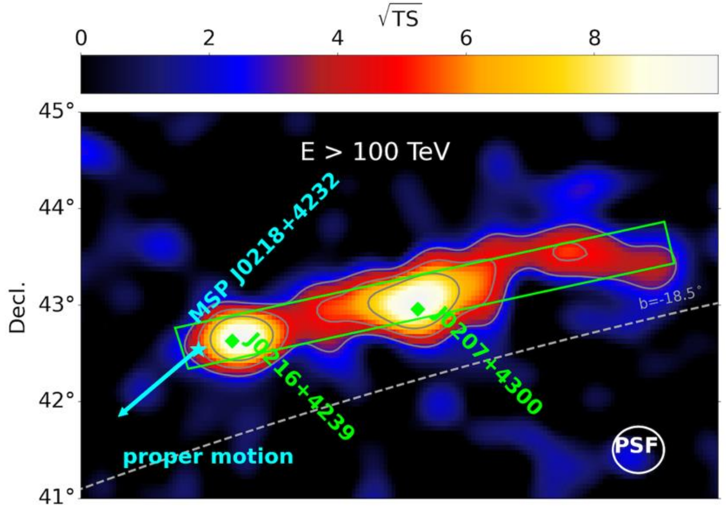

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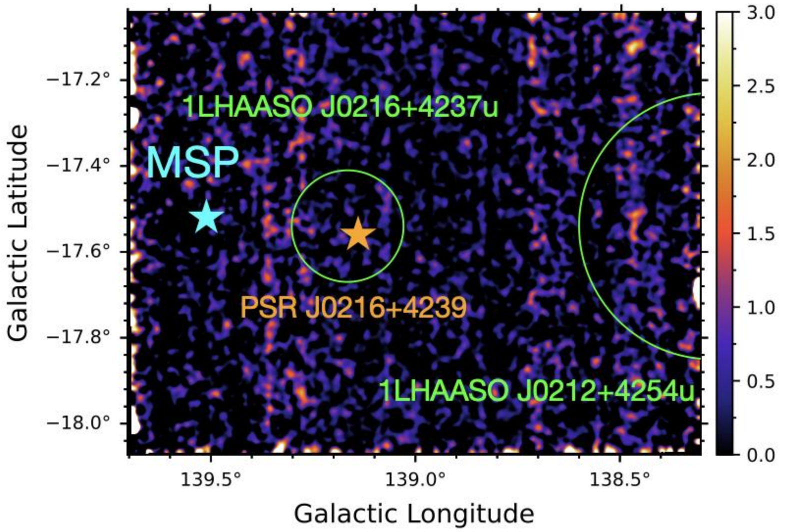
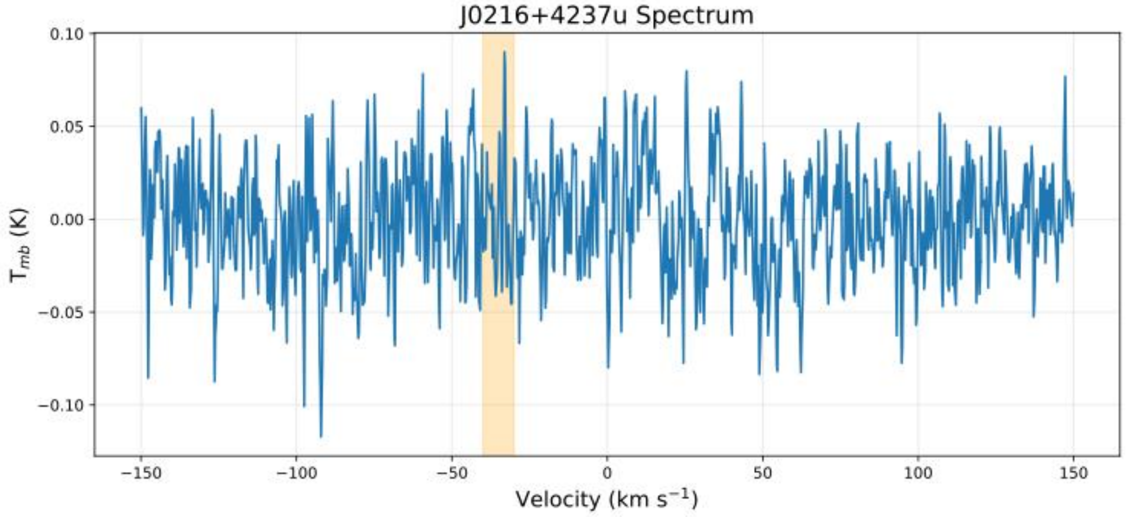


Velocity spectrum from the green circle (*r*=0.13°)



1LHAASO J1959+1129u

- **1LHAASO J1959+1129u**
  - r_{39} < 0.21 deg
  - Γ = 2.69 ± 0.17
  - Flux = 4.8×10^{-13} erg cm^{-2} s^{-1}
- **Nobeyama observation**
  - 0.6 × 0.6 deg^2
  - 7 hours in total
- **No clear CO emission**
- **Possible associated source: LMXB 4U 1957+11**
  - Low-mass X-ray binary
  - ***d* = 6 - 10 kpc**

W_{CO} (K・km/s)	$N(H_2)$ (cm^{-2})	n (cm^{-3})	V_{LSR} range (km/s)	d (kpc)
< 0.09	< 3.2×10^{18}	< 0.11	27 to 37	8.0

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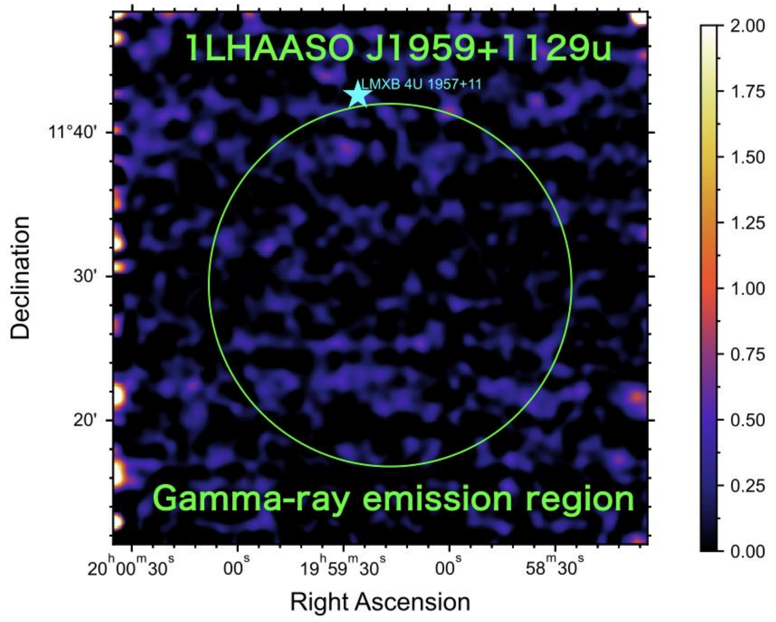
^{12}CO Map (v = 27 to 37 km/s)



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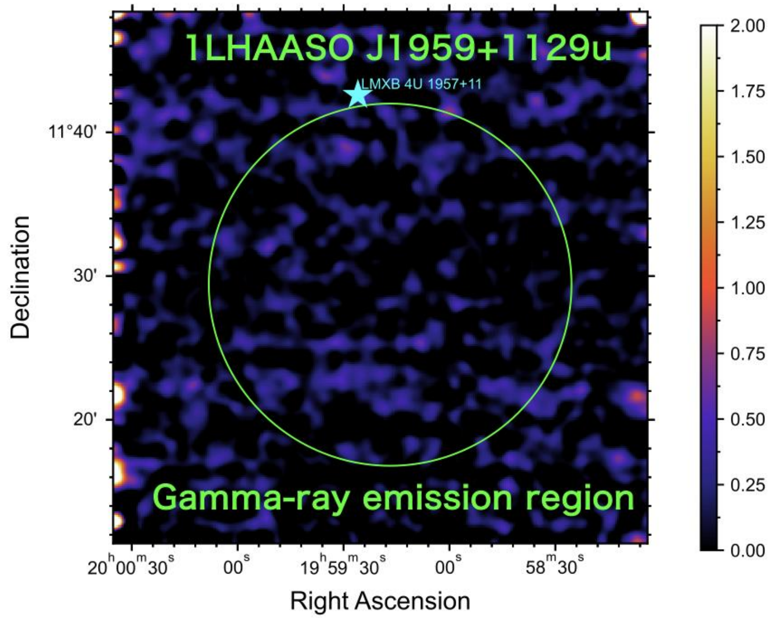
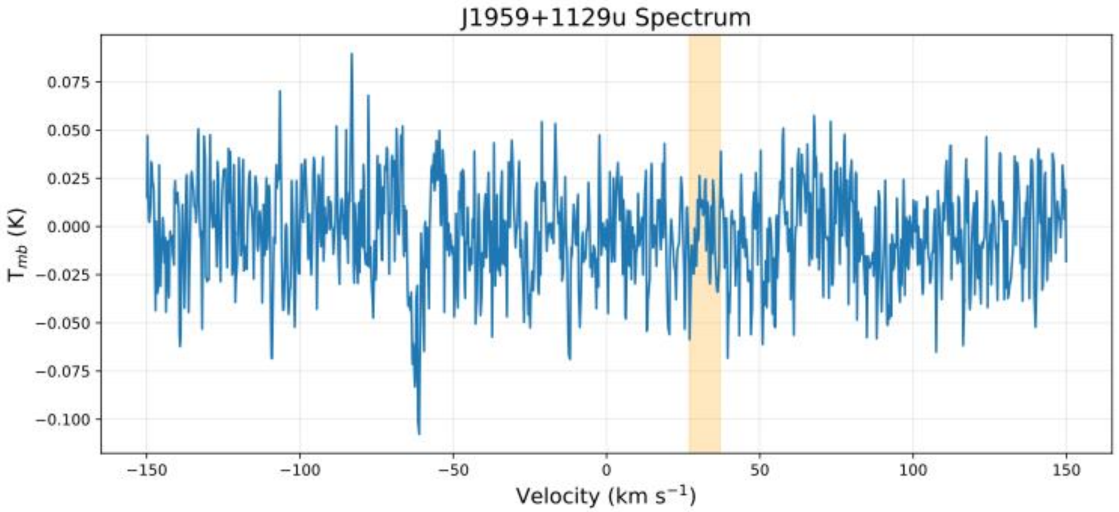


Velocity spectrum from the green circle (r=0.21°)



1LHAASO J1740+0948u

- **1LHAASO J1740+0948u**
  - r_{39} < 0.11 deg
  - Γ = 3.13 ± 0.15
  - Flux = 9.0×10^{-13} erg cm^{-2} s^{-1}
- **Nobeyama observation**
  - 1 × 0.8 deg^2
  - 14 hours in total
- **No clear CO emission**
- **Possible associated source: PSR J1740+1000**
  - E_dot = 2.3×10^{35} erg/s
  - ***d* = 1.2 kpc**

W_{CO} (K・km/s)	$N(H_2)$ (cm^{-2})	n (cm^{-3})	V_{LSR} range (km/s)	d (kpc)
< 1.6	< 5.7×10^{19}	< 4.0	12 to 22	1.2

1LHAASO J1740+0948u

LHAASO Collab.

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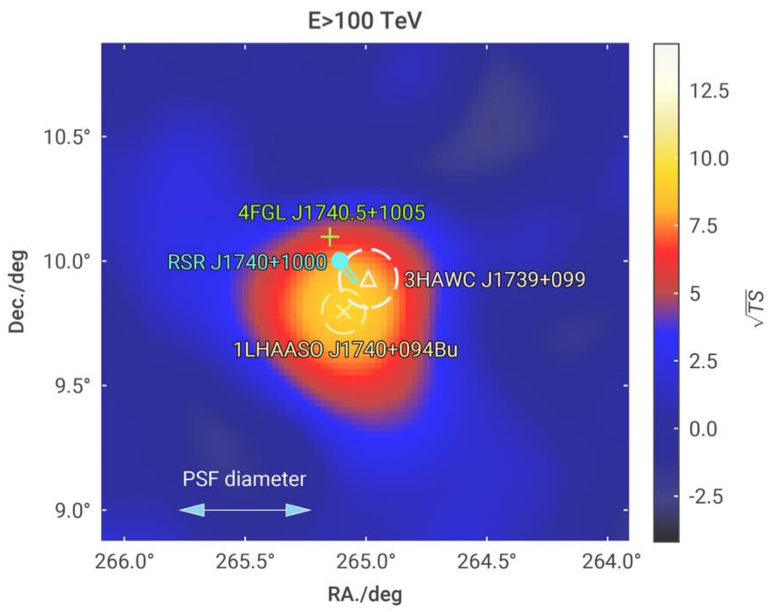

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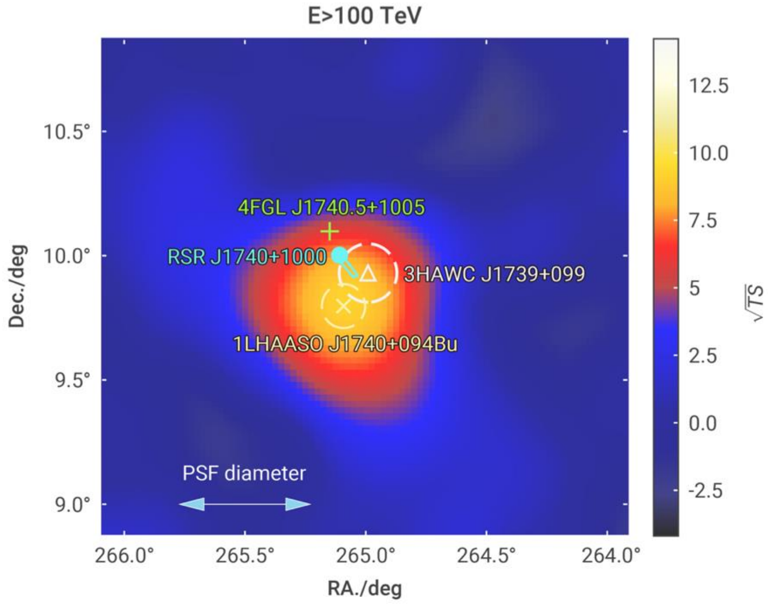
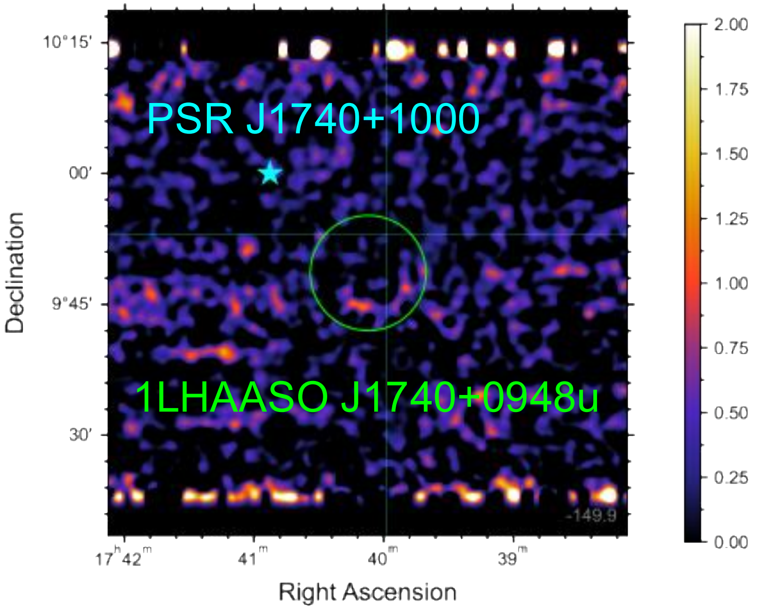


^{12}CO Map (v = 12 to 22 km/s)



- **1LHAASO J1740+0948u**
  - r_{39} < 0.11 deg
  - Γ = 3.13 ± 0.15
  - Flux = 9.0×10^{-13} erg cm^{-2} s^{-1}
- **Nobeyama observation**
  - 1 × 0.8 deg^2
  - 14 hours in total
- **No clear CO emission**
- **Possible associated source: PSR J1740+1000**
  - E_dot = 2.3×10^{35} erg/s
  - ***d* = 1.2 kpc**

W_{CO} (K・km/s)	$N(H_2)$ (cm^{-2})	n (cm^{-3})	V_{LSR} range (km/s)	d (kpc)
< 1.6	< 5.7×10^{19}	< 4.0	12 to 22	1.2

1LHAASO J1740+0948u

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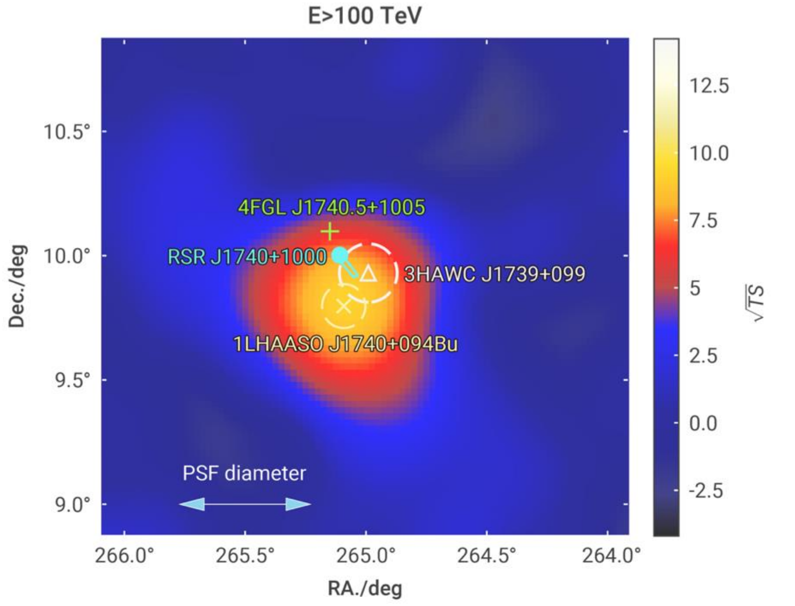
LHAASO Collab.



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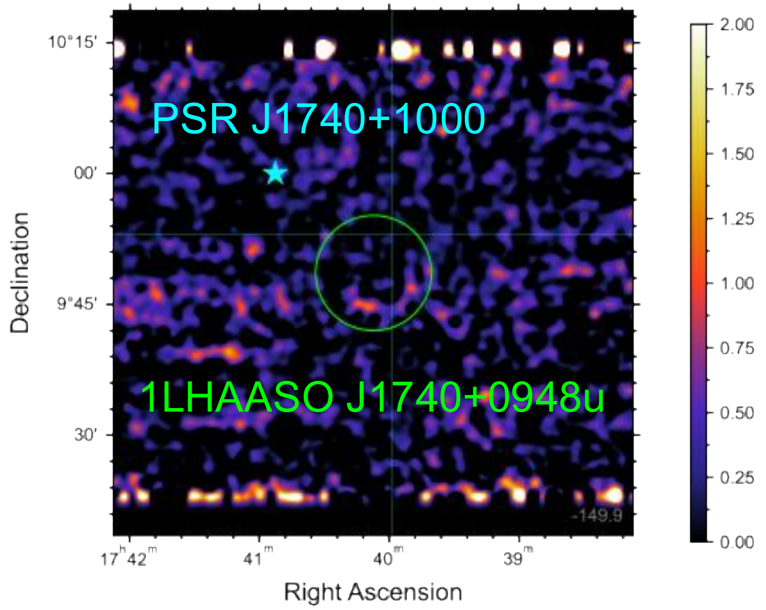
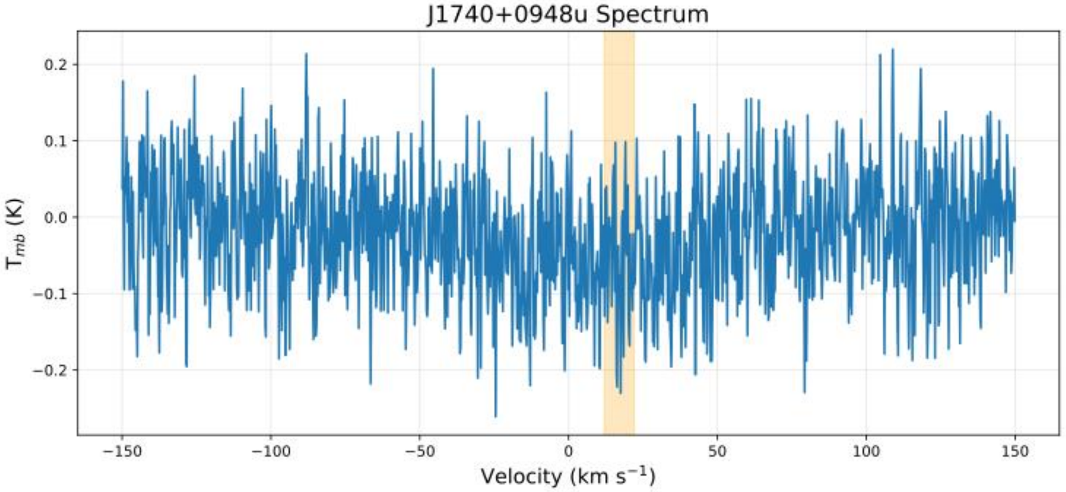


Velocity spectrum from the green circle (r=0.11°)



Future Work

We will continue CO observations of high-Galactic-latitude LHAASO sources that have not been sufficiently covered by previous CO surveys.

Target list for observations in 2026

Source name	l(deg)	b(deg)	r_{39} (deg)	Source type
1LHAASO J0206+4302u (Peanut region)	137.3	-17.71	< 0.27	Dark source
1LHAASO J0212+4254u (Peanut region)	138.3	-17.55	< 0.31	Dark source
1LHAASO J0622+3754	175.8	+10.96	0.46 ± 0.03	PWN (PSR J0622+3749)
1LHAASO J0007+7303u	119.7	+10.47	< 0.18	PWN + SNR (CTA 1)

Summary

Research objective

To investigate the hadronic origin of LHAASO UHE gamma-ray sources through molecular cloud observations.

1. 1LHAASO J0007+5659u

・Molecular clouds were detected in two velocity ranges.

・A hadronic origin is possible if a suitable proton accelerator is present.

2. Other observed LHAASO sources

・No clear CO emission was detected around 1LHAASO J0216+4237u, 1LHAASO J1740+0948u and 1LHAASO J1959+1129u.

・Hadronic scenarios involving dense molecular clouds are unlikely for these sources.

Thank you for your attention.

Uncertainty in the CO-to-H_2 conversion factor

$$N(\mathrm{H_2}) = X_{\mathrm{CO}} \cdot W_{\mathrm{CO}}$$

Typical uncertainty in X_{CO}: ~ $\pm 30\%$ (for the Milky Way disk; Bolatto et al. 2013)

Why does X_{CO} vary?

X_{CO} depends on the physical and chemical conditions of molecular gas.

- Metallicity: CO abundance
- UV radiation / shielding: CO-dark H_2
- Gas temperature and density: CO excitation

Therefore, the same amount of H_2 does not always produce the same CO intensity.

Kinematic distance and near-far ambiguity

$$v = R_0\, v_r \left(\frac{1}{R} - \frac{1}{R_0}\right) \sin l$$

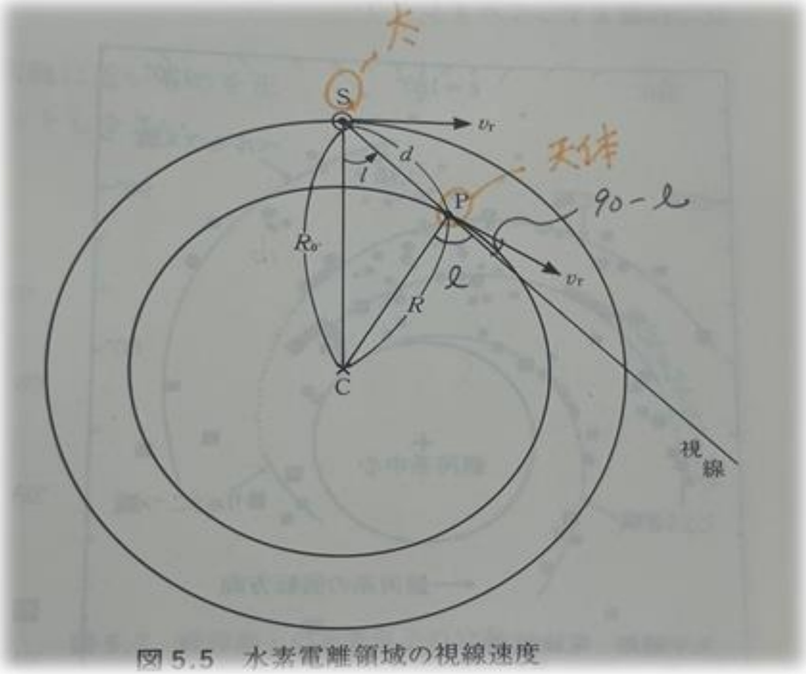
v：line-of-sight velocity of the MC

R_0：Solar galactocentric distance （8.5 kpc)

R: galactocentric distance

$$R^2 = d^2 - 2R_0 d \cos l + R_0^2$$

Inner Galaxy ($|l| < 90°$):
near and far solutions exist



Adapted from Seminar on Astrophysics (T.Ebisuzaki)

Distance

・ Coordinate and velocity
・ Traditional kinematic distance using the Galactic rotation curves

(e.g., Brand & Blitz 1993; Reid et al. 2014; Wenger et al. 2018)

Gas physical parameters from CO observations

Gamma-ray energy flux F_γ

$$F_\gamma = \int E \frac{\mathrm{dN}}{\mathrm{dE}} \mathrm{d}E$$

(Cao+ (2023))

The gamma-ray energy flux was calculated using the spectral parameters reported in the LHAASO catalog

Total energy of cosmic-ray protons W_p

$$W_\mathrm{p} = \frac{4\pi d^2 F_\gamma}{n_\mathrm{H} \kappa \sigma_\mathrm{PP} c}$$

(Gabici et al. (2006))

This gives the minimum proton energy required to explain the observed gamma-ray emission

Need spectral modeling

Spectral Modeling

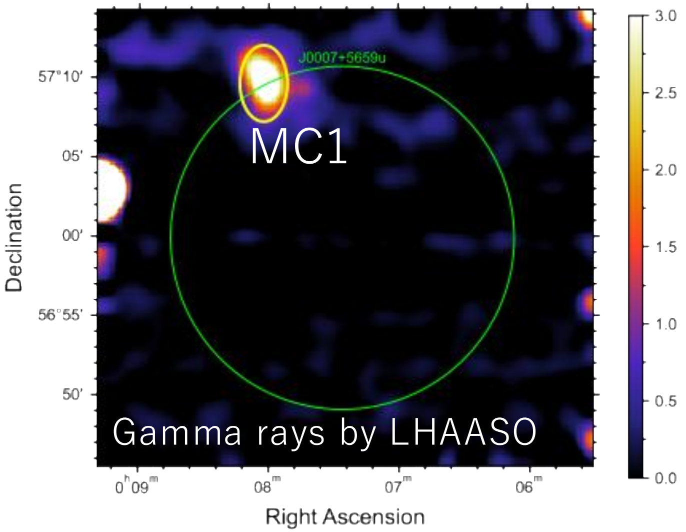
- Proton spectrum assumed (power-law with cutoff)
- Target density from CO observation
- Gamma-ray emission via pp interaction
- We model the gamma-ray spectrum using Naima

1LHAASO J0007+5659u ^{12}CO Map

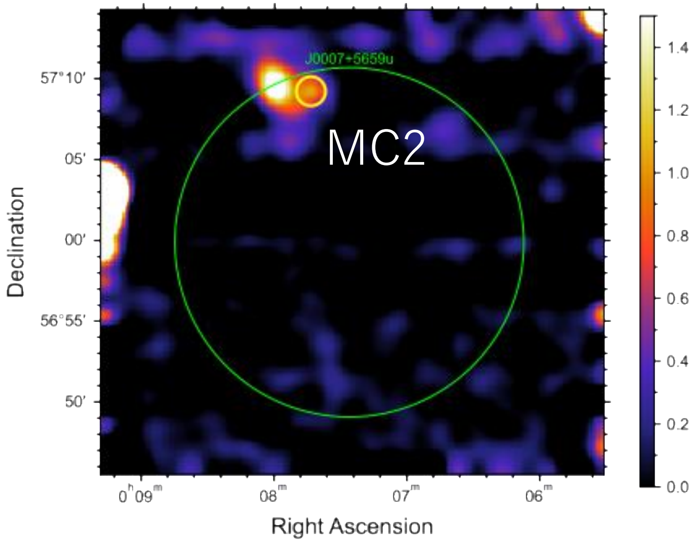
r: Radius
d: Distance
M: Mass

r_{major} = 1.9 pc
r_{minor} = 1.3 pc
d = 2.9 kpc
M = 90 M_{sun}

(-37.1 to -34.9 km/s)



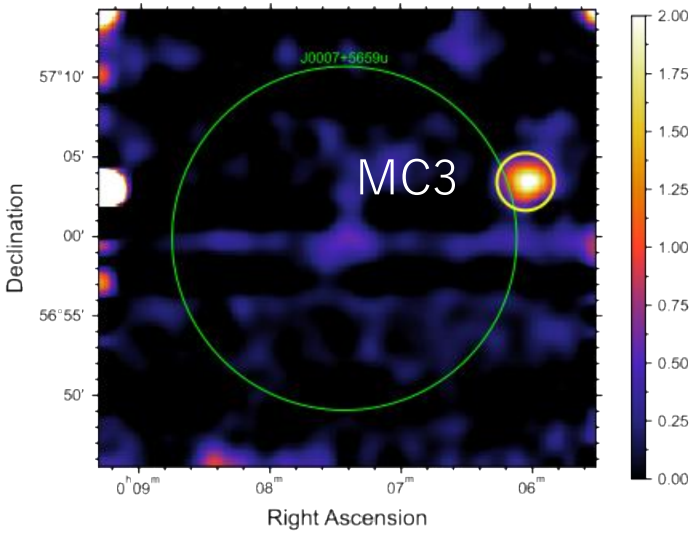
(-35.9 to -34.3 km/s)



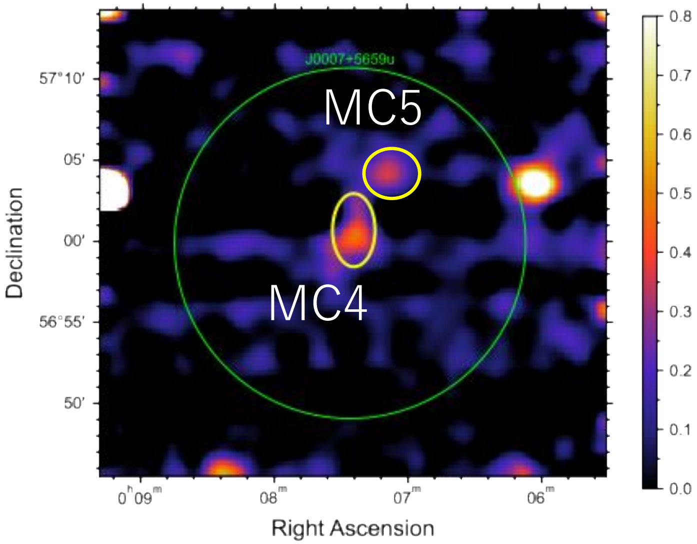
r = 0.79 pc
d = 2.9 kpc
M= 9.7 M_{sun}

r = 0.22 pc
d = 0.42 kpc
M= 0.95 M_{sun}

(-3.7 to -2.1 km/s)



(-3.7 to -2.9 km/s)



MC4
r_{major} = 0.40 pc
r_{minor} = 0.25 pc
d = 0.72 kpc
M = 1.13 M_{sun}

MC5
r = 0.15 pc
d = 0.42 kpc
M = 0.25 M_{sun}

Hadronic modeling using the physical properties of MC4

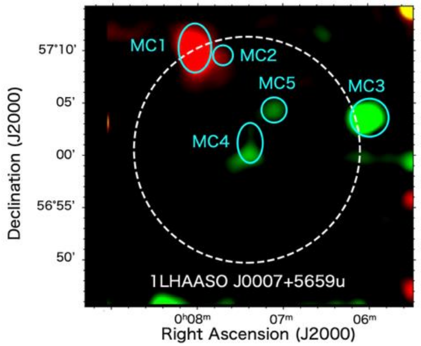
Assumed proton distribution

$$N(E_\mathrm{p}) = KE^{-s}\exp\left(-\frac{E_\mathrm{p}}{E_\mathrm{c}}\right)$$

K: normalization s: proton spectral index
E_c: proton cutoff energy

Fixed parameters (MC4)

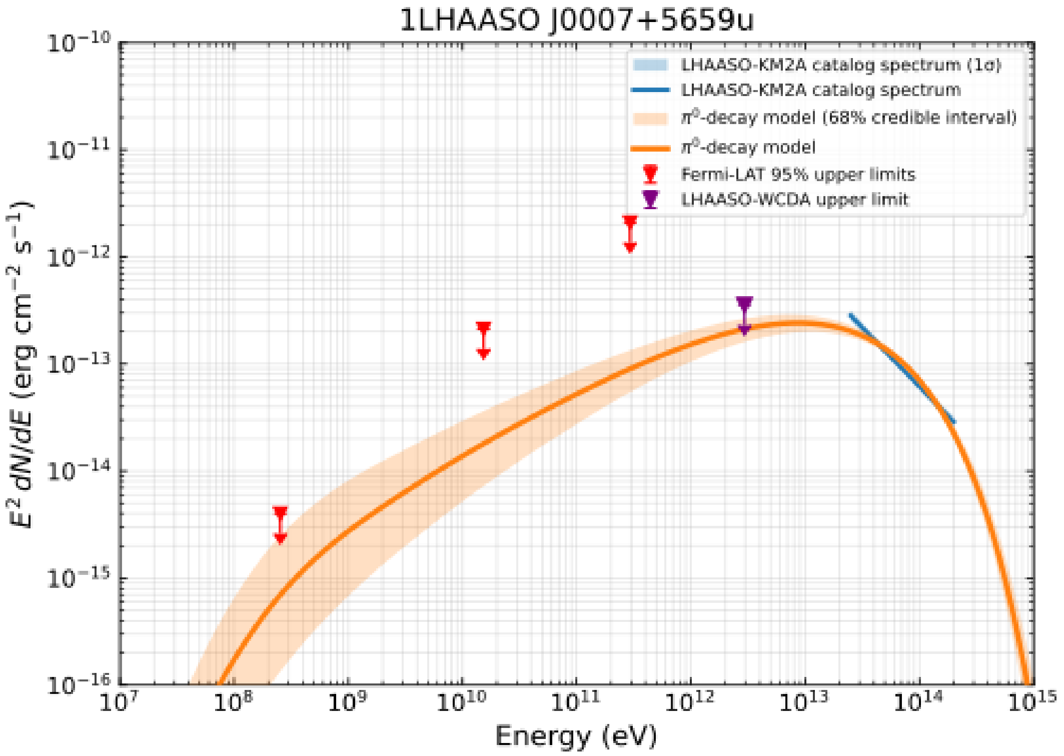
- d = 0.72 kpc
- $n(H_2)$ = 308 cm^{-3}



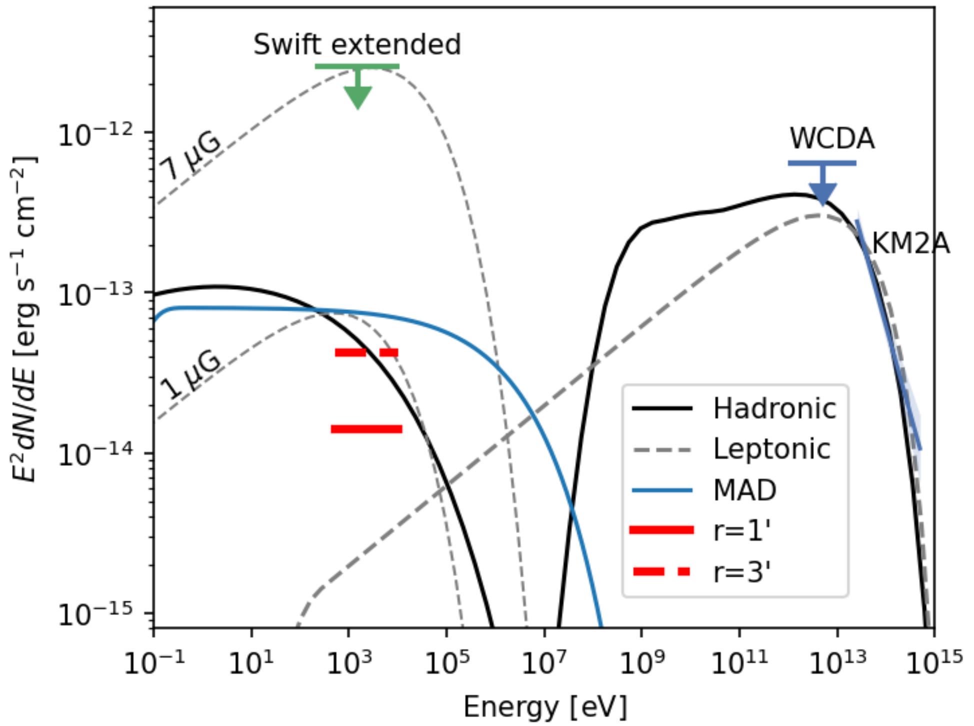
The Fermi-LAT 95% C.L. upper limits and LHAASO-WCDA upper limits from Xie et al. (2025) were used as constraints.

Fitted and derived parameters

- Proton spectral index: $s = 1.42^{+0.15}_{-0.24}$
- Proton cutoff energy: $E_\mathrm{c} = 253^{+56}_{-44}$ TeV
- Total proton energy: $W_p = (6.0^{+1.6}_{-1.3}) \times 10^{44}$ erg



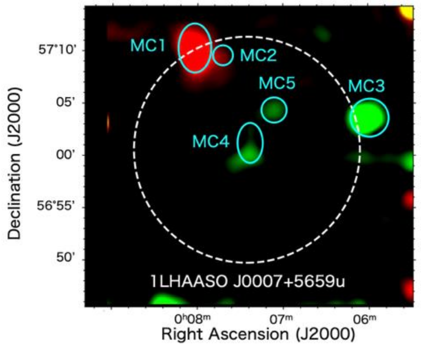
Leptonic modeling using the physical properties of MC4

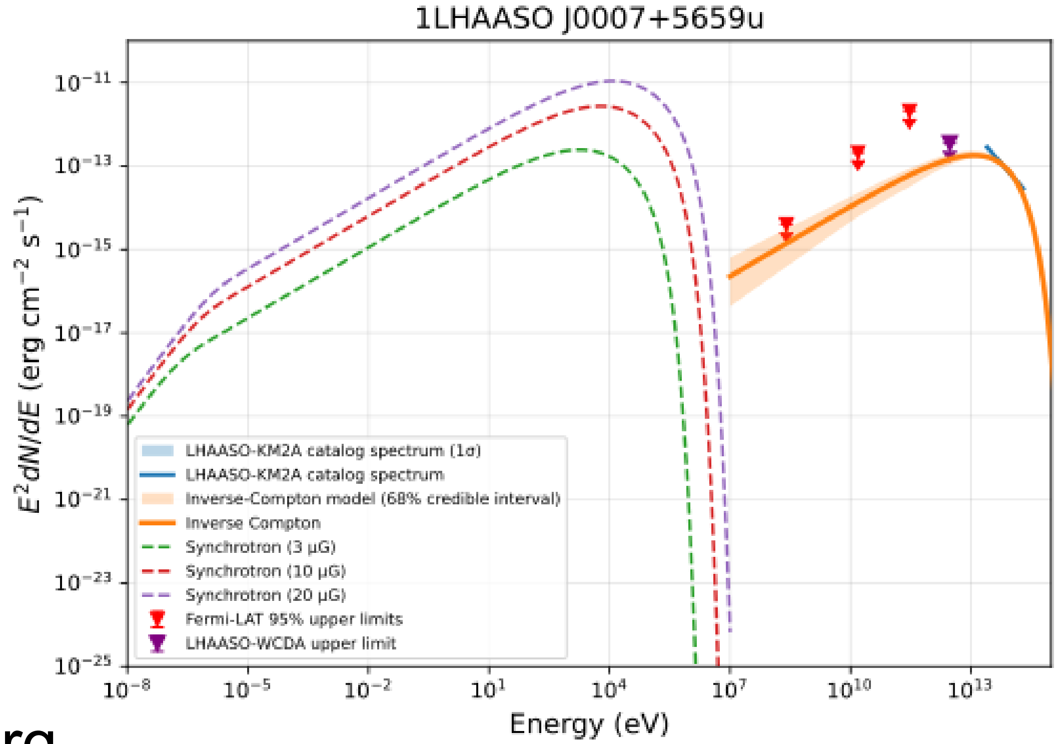


Courtesy of N. Tsuji

Fixed parameters (MC4)

- d = 0.72 kpc





Fitted and derived parameters

- Electron spectral index: $s = 1.87^{+0.13}_{-0.26}$
- Electron cutoff energy: $E_c = 102^{+24}_{-17}$ TeV
- Total electron energy: $W_e = (1.3^{+0.41}_{-0.51}) \times 10^{44}$ erg

Estimation of upper limits for non-detected CO emission

RMS noise

- Mean RMS noise within the LHAASO r_{39} region.
- ΔT_{MB}: RMS noise
- $\Delta V = 0.2\ \mathrm{km/s}$

3σ upper limit on CO integrated intensity

Assuming a CO line width of 10 km/s

$$W_{\mathrm{CO}}^{3\sigma} = 3\Delta V\sqrt{N}\Delta T_{\mathrm{MB}}$$

H_2 column density

$$N(\mathrm{H_2})^{3\sigma} = X_{\mathrm{CO}} W_{\mathrm{CO}}^{3\sigma}$$

$X_{\mathrm{CO}} = 3.5 \times 10^{19}\ \mathrm{cm^{-2}}\ (\mathrm{K} \cdot \mathrm{km/s})^{-1}$

Number density

L: assumed line-of-sight size of the gamma-ray emission region.

$$n(\mathrm{H_2})^{3\sigma} = \frac{N(\mathrm{H_2})^{3\sigma}}{L}$$

The X_{CO} value for high Galactic latitudes was adopted from Acharyya et al. (2025).