PeVatrons as a Challenge in 21st Century Astronomy

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Detection of a new molecular cloud in the LHAASO J2108+5157 region supporting a hadronic PeVatron scenario†

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Astronomy & Astrophysics

LETTER TO THE EDITOR

Evidence for a gamma-ray molecular target in the enigmatic PeVatron candidate LHAASO J2108+5157★

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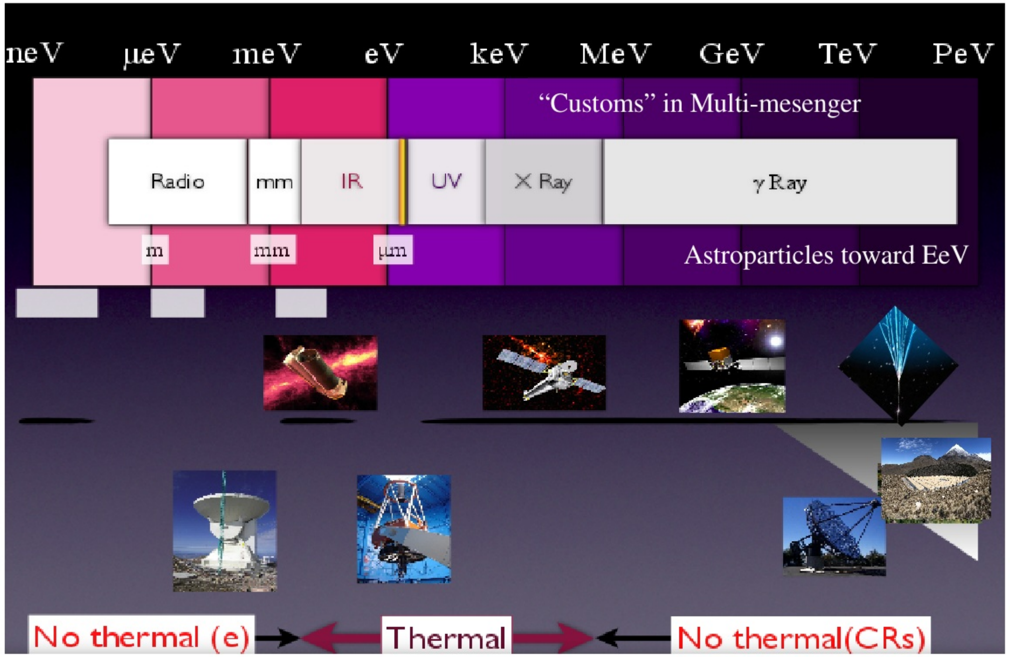
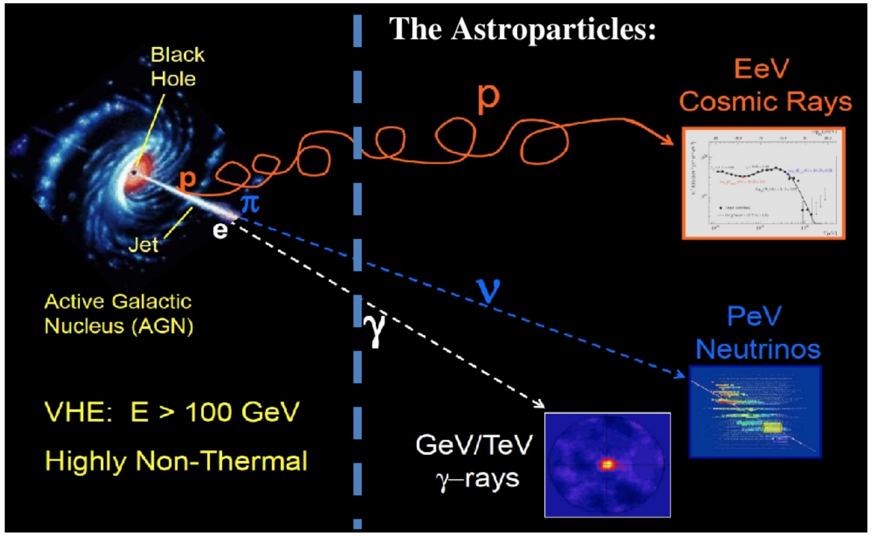
Gamma-Ray (GR) Astronomy: From GeV to (sub) PeV

Nature's Particle Accelerators are Gamma-Ray Sources





The Energy is the Key: LHC (~ 10TeV), Nature (to EeV)

Energy range:

LE or MeV	0.1—100 MeV
HE or GeV	0.1—100 GeV
VHE or TeV	0.1—100 TeV
UHE or PeV	0.1—100 PeV

Revolutions in the GRA (XXI Century):

1.- NASA-Fermi (GeV era)
2.- Maturity of the second generation of observatories in the XXI century: IACTs, WCDs, Scintillators (TeV era)
3.- UHE and PeVatrons (PeV era)

Gamma-Ray Astronomical + Man Made (e.g LHC) TeVatrons ⟺ Origin of cosmic rays

< 1 PeV ⇨ Galactic
> 1 Eev ⇨ X-Galactic
In between **Transition (?)**

What is the maximum energy that nature accelerates particles in the Galaxy?

Gamma-Ray nature (hadronic or leptonic)

⟺ **PeV Astronomy** ⟺ **Cosmic Rays**

- CR sources (what, where)
- How we can identify them?
- Acceleration mechanism?
- Effects on propagation?
- Isotropy (?)
- Chemical composition?

UHE γ -ray Astronomy:

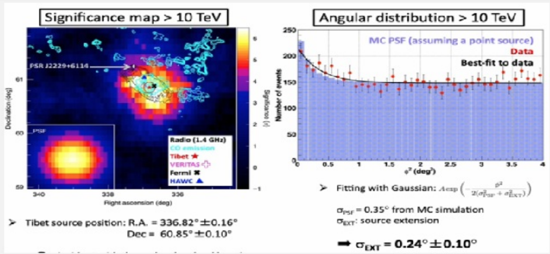
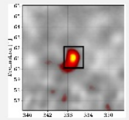
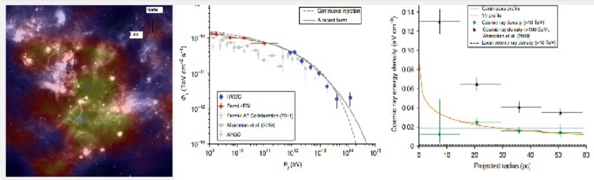
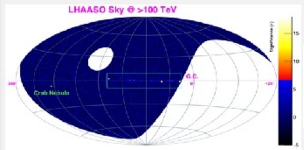
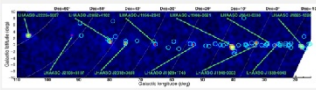
If we detect energies > 100 TeVs (gamma rays) from astronomical sources (*accelerator*), the expected particle acceleration is > 1 PeV (energy per beam).

2021: A new window in Astronomy: A transition from Tevatrons to PeVatrons:

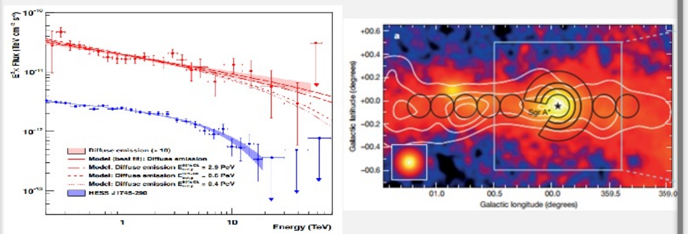
The rise of the PeV era (Pevatrons)

Gamma-Ray Ultra-High Energy (E >100 TeV).

Time-line Observationally speaking (high energy sensitivity):

High sensitivity observatory (By year pub.)	Remarkably Contribution Object: reference and year	Results	Comments and Remarks
Tibet AS γ  **Energy range: Beyond 100 TeV**	SNR G106.3+2.7 Nature Astronomy, 5, 460 (2021) Published: 2021/03/06 Confirmation as PeVatron		HAWC Coll. ApJL, 896, L20 (2020):  Crab Nebula paper: PRL, 123, 051101 (2019)
HAWC High Altitude Water Cherenkov Gamma-Ray Observatory  **Energy range: 100 GeV to 100 TeV**	Cygnus Cocoon (FERMI-LAT) Nature Astronomy, 5, 465 (2021) Published: 2021/04/06 Star-Clusters as PeVatron		Star forming región at Cygnus-X: Cyg-OB2 Association Crab Nebula paper: ApJ, 881, 134 (2019)
 **Energy range: 0.1 TeV to 0.1 EeV**	North Sky (> 1.4 PeV) Nature, 594, 33 (2021) Published: 2021/05/17 Sky map and 12 PeV candidates (galactic)	 First PeV sky map 	Crab Nebula as PeVatron: **Science, 373, 425** **(2021/07/08)**

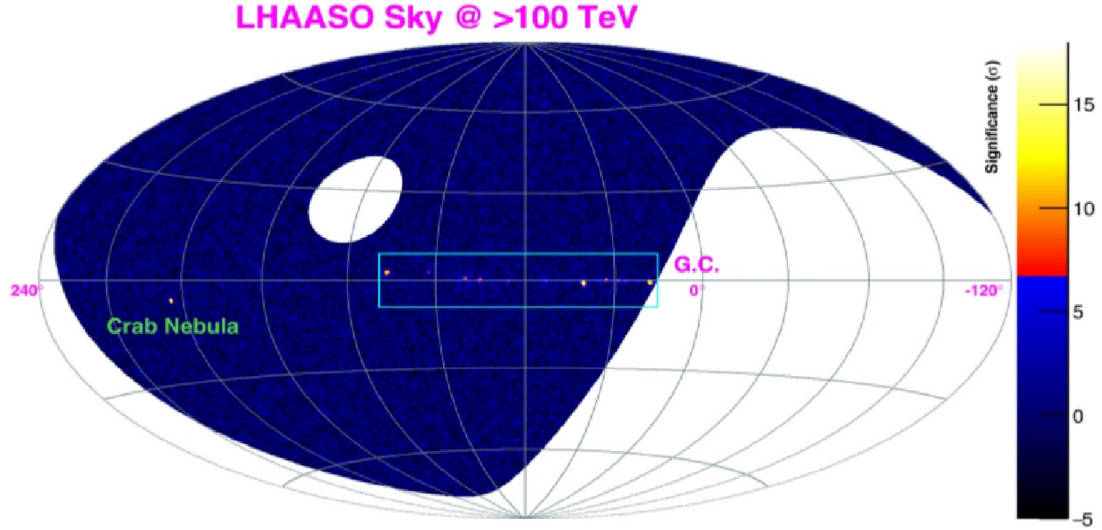
Reference work where the term "PeVatron" was coined by first time in 2016 (Obs+predictions):

Energy range:10s of GeV to 10s of TeV. H.E.S.S. 	Galactic Center Study Nature, 531, 476 (2016) Published: 2016/03/16 Suggesting Sag. A* black hole could be the PeVatron		This work is the first robust detection of a VHE cosmic hadronic accelerator As PeVatron, HESS refer to hadrons Previous GC observations by IACTs HESS: 2004, 2066 MAGIC: 2006, 2016 VERITAS: 2011

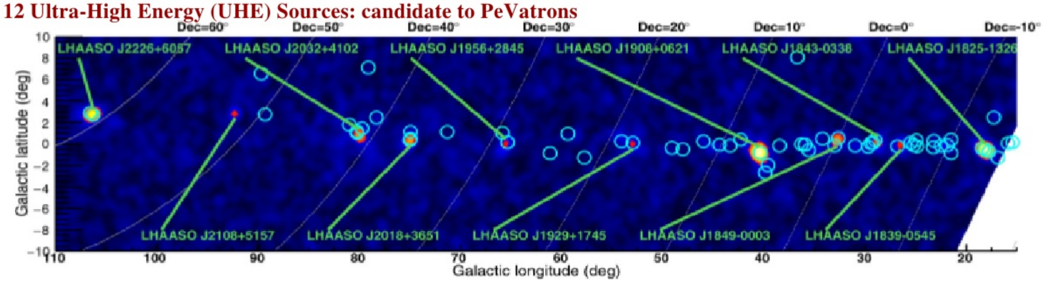
PeVatron: (2021)

Particle accelerators boosting energy of protons to the PeV domain without a sharp cutoff up to 1 PeV

An astronomical object that can produce particles upto the knee (3 PeV) without a visible cut-off



12 Ultra-High Energy (UHE) Sources: candidate to PeVatrons



Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

"I think leptonic and hadronic accelerators are equally interesting and equally important. And in fact, it s virtually certain that all hadronic accelerators are also leptonic accelerators. Understand co-acceleration is of crucial importance"
Paolo Lipari (ICRC 2021 at GR-Indirect discussion session)

- No consensus on the definition yet (2021): An astronomical object that can accelerate particles at PeV energies.

2022: An astronomical object (accelerator) able to accelerate particles at energies > 1 PeV

- The main conflict point is: Only hadrons?. (ICRC 2021 discussion at GR-indirect).

LPeV for PWNe, and HPeV for individual SNR and stellar winds (v > 0.01; B > 0.01 G)?

To date, there is a high debate about hadronic PeVatrons associated with SNR.

- Three conditions to confirm a PeVatron: (Discussion between conveners and the rapporteur of session 55: UHE gamma rays and *PeVatron in ICRC 2021*)

a) An acceleration at PeV (emission > 100 TeV is not enough to claim a Pevatron; e.g. Crab and some leptonic sources)
b) Molecular Gas Environment,
c) Neutrino detection--coincidence (true)

2023: X-Ray Observations covering all PeVatrons candidates are crucial (to constrain leptonic emission)

First PeVatron Catalogue by LHAASO in 2023 (90 sources; significance of 5 σ; extended size < 0.2 deg)

https://arxiv.org/pdf/2305.17030.pdf

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, Q. An, Axikegu, L. X. Bai, Y. X. Bai, Y. W. Bao, D. Bastieri, X. J. Bi, Y. J. Bi, H.

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
Cygnus region	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
Cygnus region	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	— Cygnus region	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

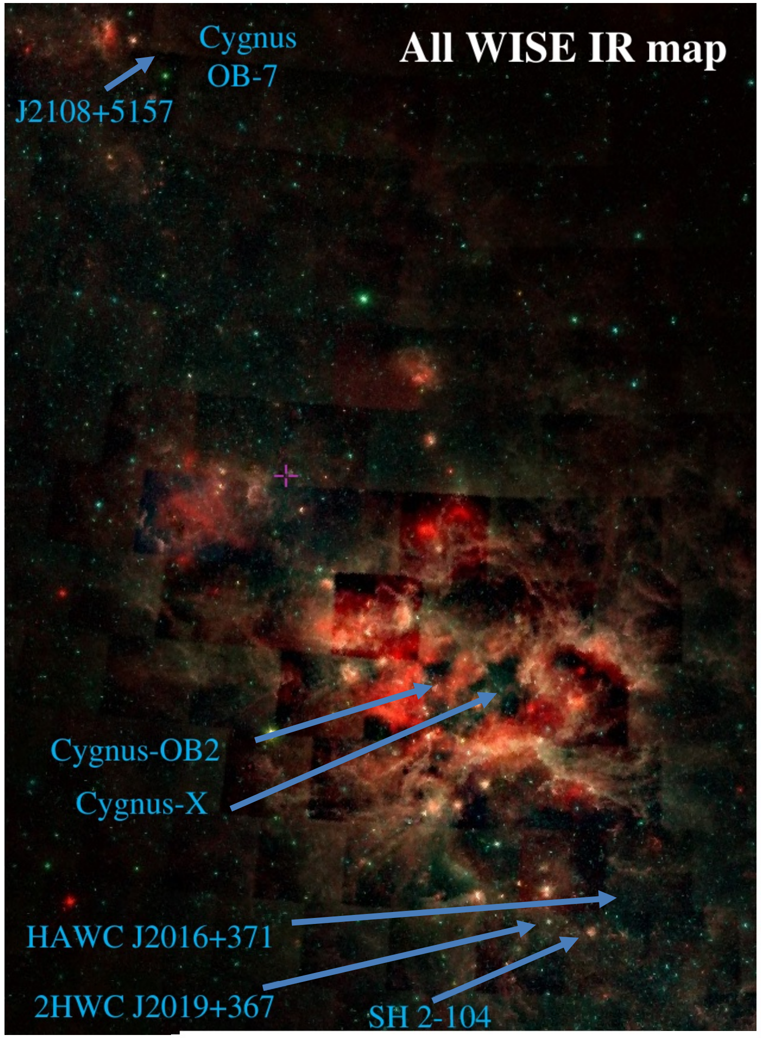
Nature 594, 33–36 (2021)

LHASSO J2108+5157

The Astrophysical Journal Letters, 919:L22 (9pp), 2021 October 1 https://doi.org/10.3847/2041-8213/ac2579

Discovery of the Ultrahigh-energy Gamma-Ray Source LHAASO J2108+5157

Zhen Cao[1,2,3], F. Aharonian[4,5], Q. An[6,7], Axikegu[8], L. X. Bai[9], Y. X. Bai[1,3], Y. W. Bao[10], D. Bastieri[11], X. J. Bi[1,2,3], Y. J. Bi[1,3], H. Cai[12], J. T. Cai[11], Zhe Cao[6,7], J. Chang[13], J. F. Chang[1,3,6], B. M. Chen[14], E. S. Chen[1,2,3], J. Chen[9],



Parameter	10 GeV−1 TeV	1 GeV−1 TeV	Unit
R.A.	317.33 ± 0.18	317.01 ± 0.02	deg
Decl.	51.82 ± 0.15	51.92 ± 0.02	deg
Extension (σ)	$0.50^{+0.10}_{-0.09}$	$0.48^{+0.06}_{-0.06}$	deg
Flux	1.73 ± 0.40	49.1 ± 3.6	$\times 10^{-10}$ ph cm^{-2} s^{-1}
Index	2.05 ± 0.24	2.34 ± 0.08	
TS	25.3	318.0	
TS_{ext}	15.5	63.8	

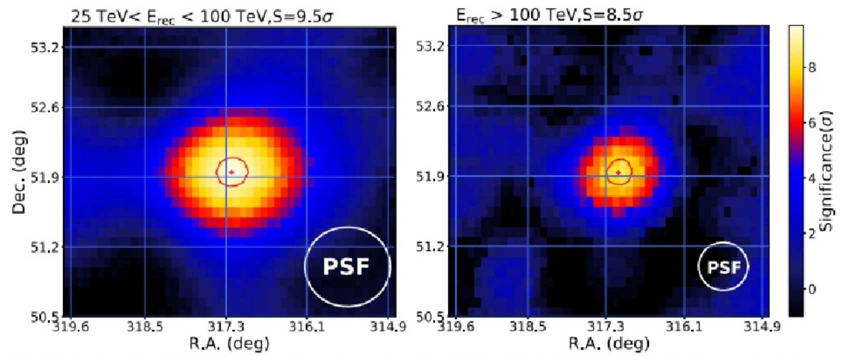
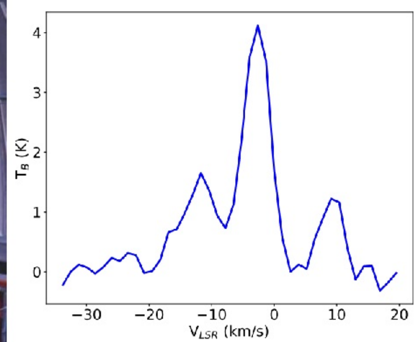
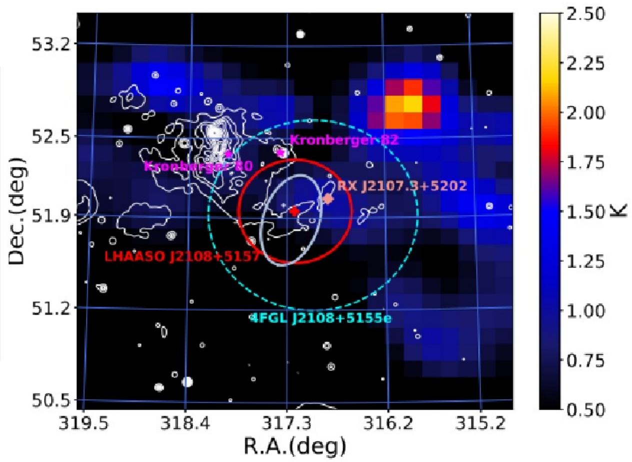


Figure 1. Left: significance map around LHAASO J2108+5157 as observed by KM2A for reconstructed energies from 25 to 100 TeV. Right: significance map for energies above 100 TeV. The red plus sign and circle denote the best-fit position and 95% position uncertainty of the LHAASO source. The white circle in the bottom right corner shows the size of the PSF (containing 68% of the events).

n(H2) = 30 cm^-3 @3 Kpc

The 1.2 Meter Millimeter-Wave Telescope (MWT) at the CfA| Harvard & Smithsonian





12CO(1–0) line survey integrated over a velocity interval between -14.3 and -9.1 km/seg

Dame 2001, ApJ, 547, 792

The PeVatron Candidate LHASSO J2108+5157 (II)

PeVatrons as challenge in 21st century astronomy

A&A 673, A75 (2023)
https://doi.org/10.1051/0004-6361/202245086

Astronomy & Astrophysics

Multiwavelength study of the galactic PeVatron candidate LHAASO J2108+5157

S. Abe[1], A. Aguasca-Cabot[2], I. Agudo[3], N. Alvarez Crespo[4], L. A. Antonelli[5], C. Aramo[6], A. Arbet-Engels[7],

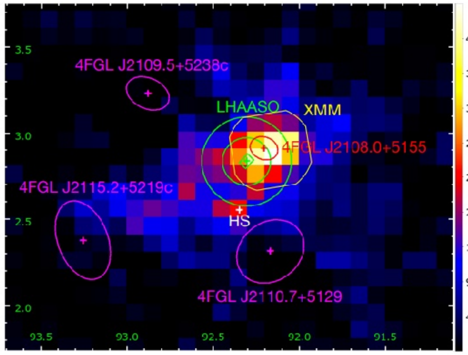
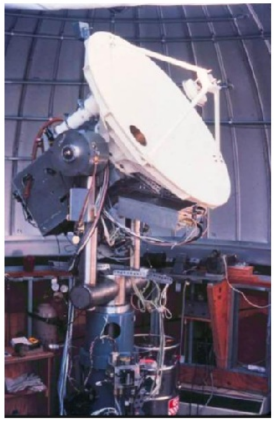


Fig. 3. *Fermi*-LAT TS map in Galactic coordinate above 2 GeV, which shows the sources present in the 4FGL-DR3 catalog with their 95% positional errors (magenta and red ellipses). The small green rectan-



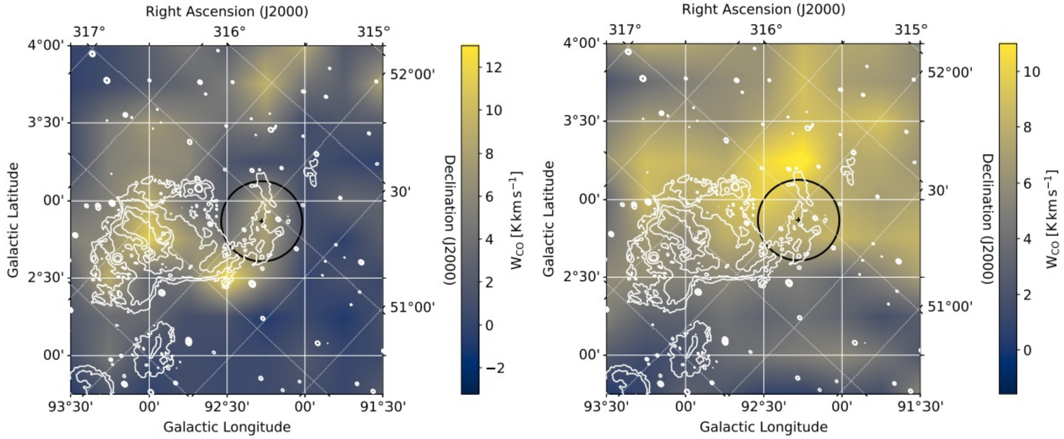
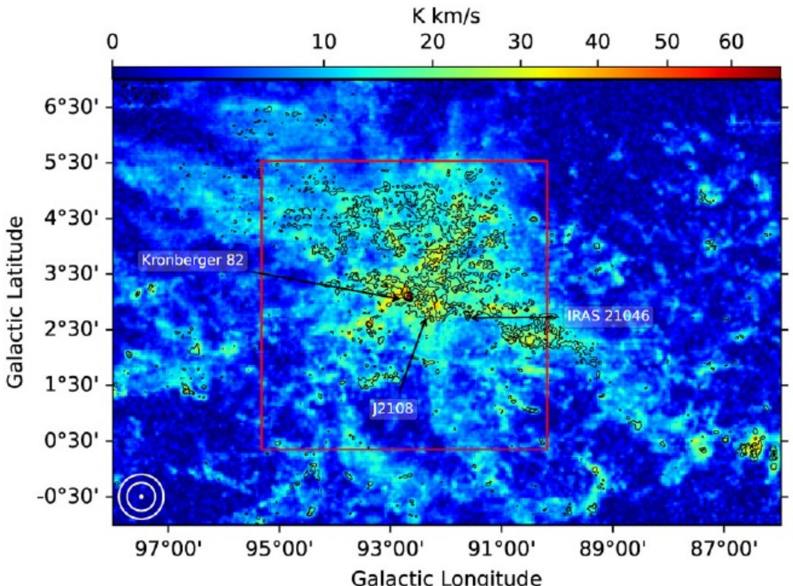
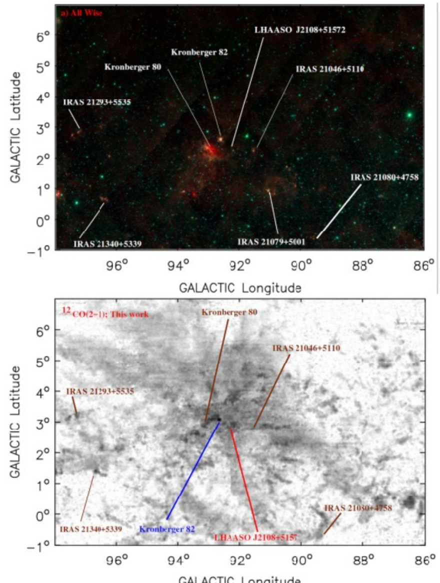


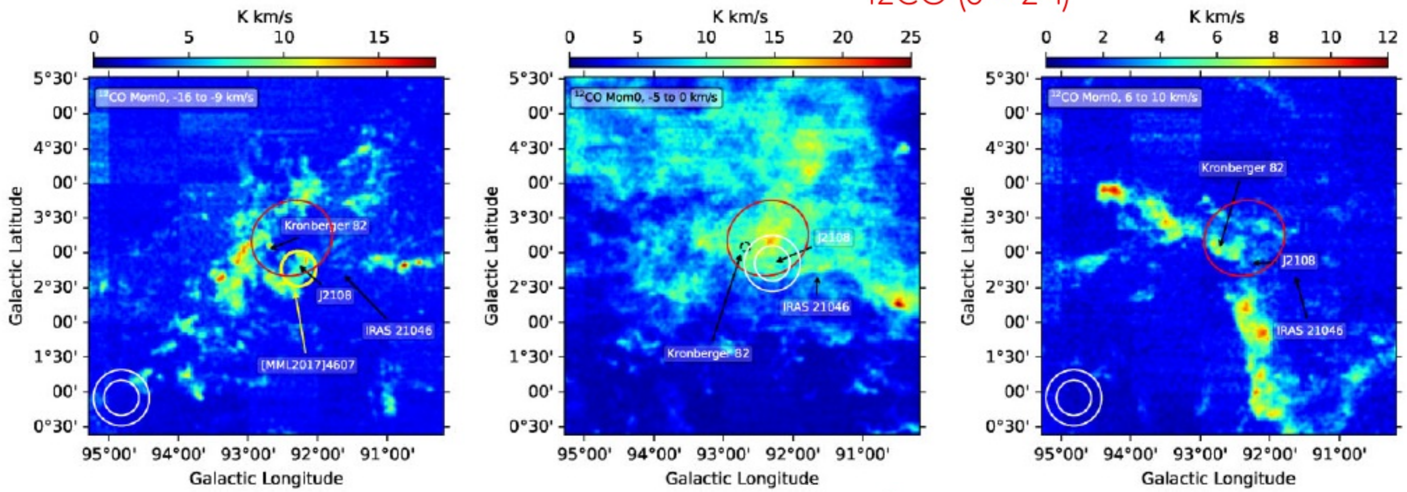
Fig. 6. Velocity-integrated ^{12}CO intensity (W_{CO}) of two molecular clouds spatially coincident with the direction of LHAASO J2108+5157. Left: Integrated velocity of the first Gaussian component peaking at $v_1 \approx -11.8\,\mathrm{km\,s^{-1}}$, with corresponding distance of $d_1 \approx 3.1$ kpc. Right: Integral of the second Gaussian component at $v_2 \approx -2.7\,\mathrm{km\,s^{-1}}$ and $d_1 \approx 2.0$ kpc. The white contour represents 1420 MHz continuum emission from the Canadian Galactic Plane Survey (Taylor et al. 2003). The position of LHAASO J2108+5157 is marked with a black cross, and 95% UL on its extension (0.26°) is indicated with a black circle (Cao et al. 2021a). Bilinear interpolation is used to smooth out the contributions from individual pixels.

The 1.85m mm/sub-mm telescope (Osaka Prefecture University). 12CO, 13CO, and C18O (J = 2-1); 230 GHz; 3 arcmin; −100 to 80 kms−1 rms ~0.3K at a 0.3 kms−1.

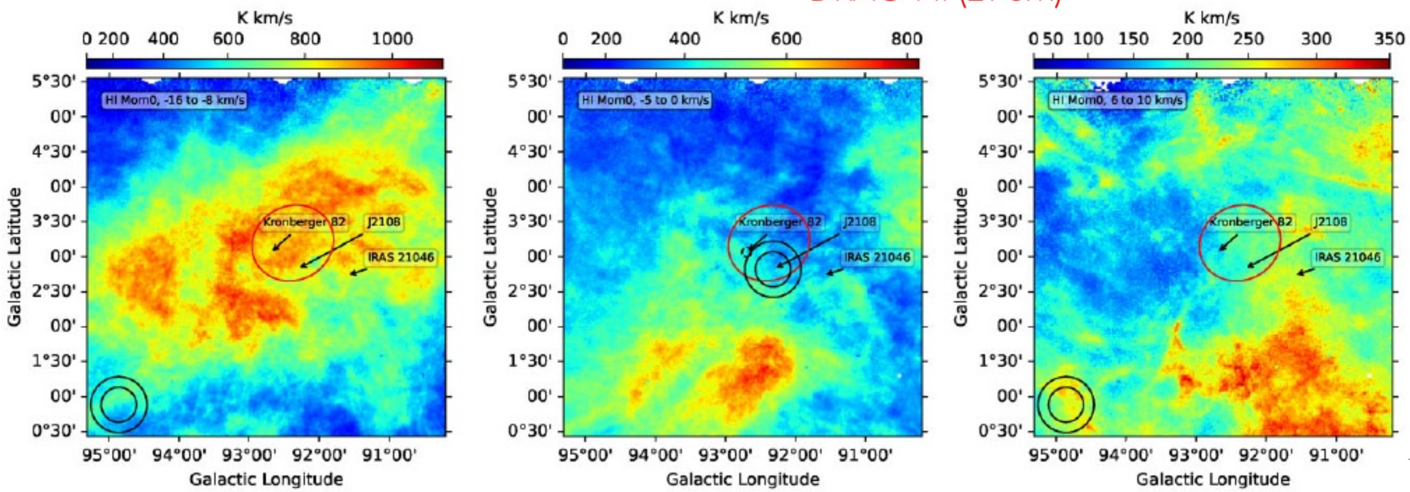


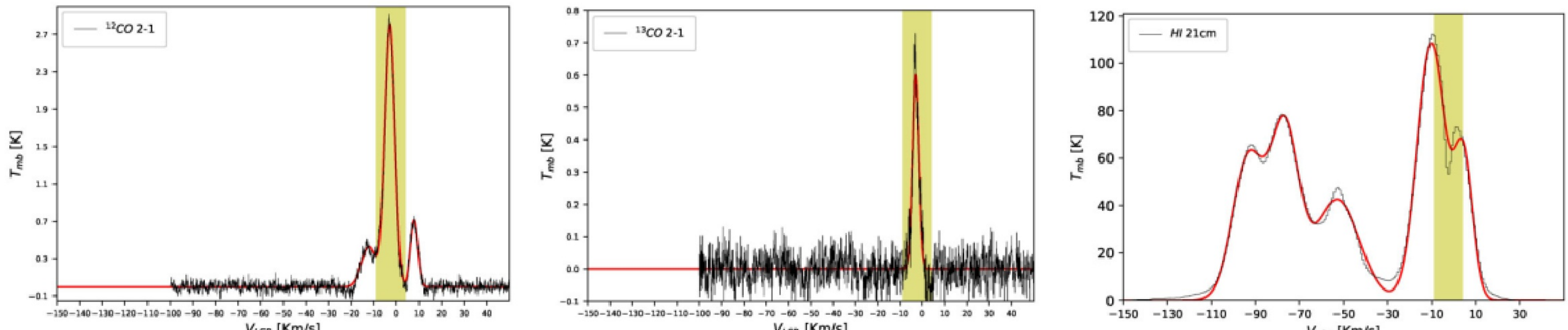


12CO (J = 2-1)



DRAO HI (21 cm)





$$N_\gamma^{had} = N_\gamma^{obs} - N_\gamma^{lep} \propto c\,n(\mathrm{H})\,N_p(\mathrm{CR}),$$

$$N(\mathrm{H}) = 2N(\mathrm{H_2}) + N(\mathrm{H\,I}),$$

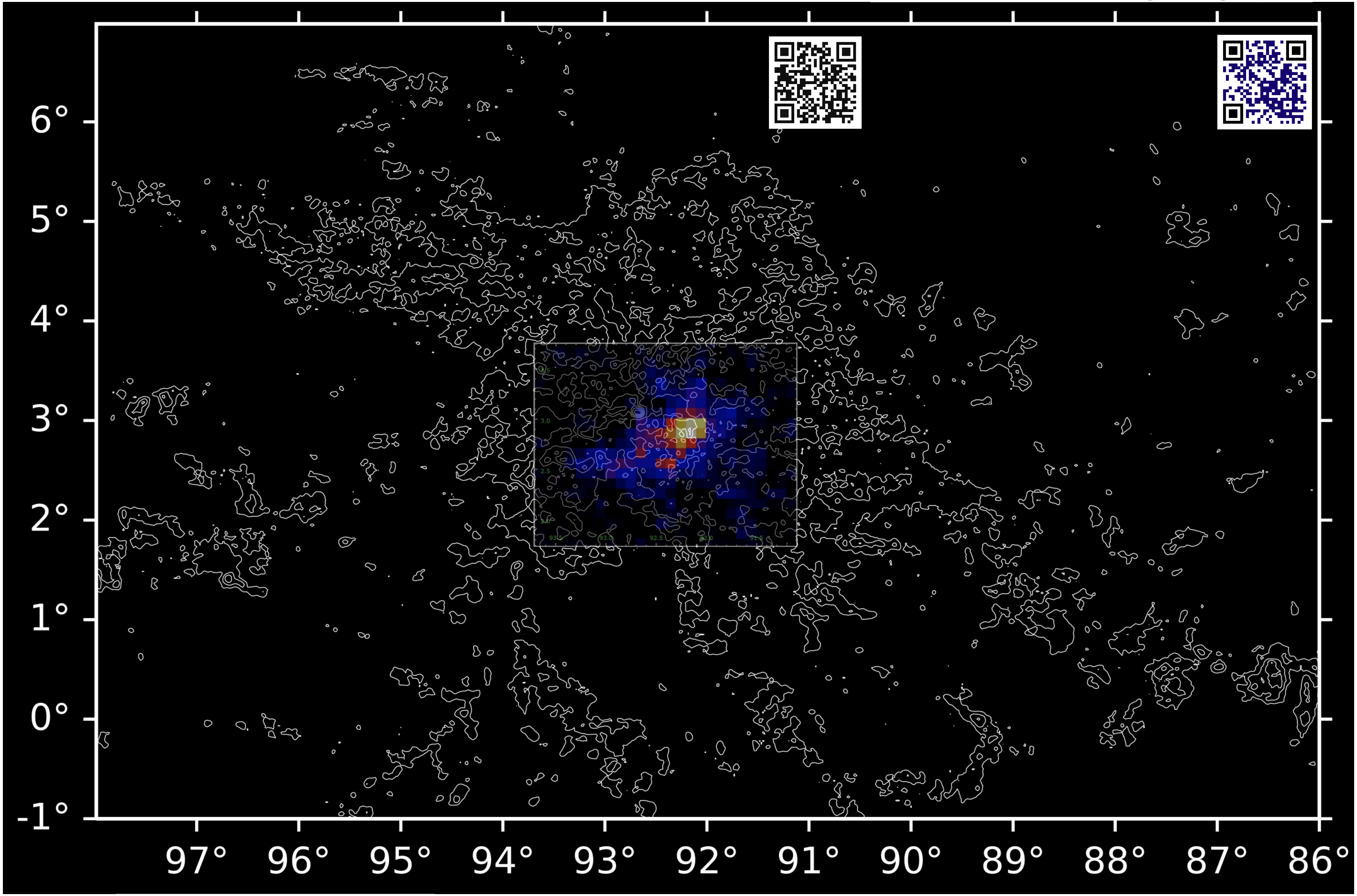
[FKT-MC]2022 is situated at a distance of 1.7 ± 0.6 kpc. It is $\sim 1°1$ in size and has nucleon densities ($\mathrm{H\,I} + \mathrm{H_2}$) of ~80 and 37 $\mathrm{cm^{-3}}$ for ^{12}CO (optically thick) and ^{13}CO (optically thin) emission, respectively. These values correspond to $M(\mathrm{H\,I} + \mathrm{H_2})$ of $\sim 4 \times 10^4\, M_\odot$ and $2 \times 10^4\, M_\odot$, respectively.

Miville-Deschênes, Murray, & Lee (2017)
https://ui.adsabs.harvard.edu/abs/2017ApJ...834...57M/

1.2 m telescopes; angular resolution of ~8 5 armin at 115 GHz OPTICALLY THICK OBSERVATIONS 12CO(1--0)

ANSWER: Accurate determination of the nucleons density (Hydrogen; H_2 + HI)

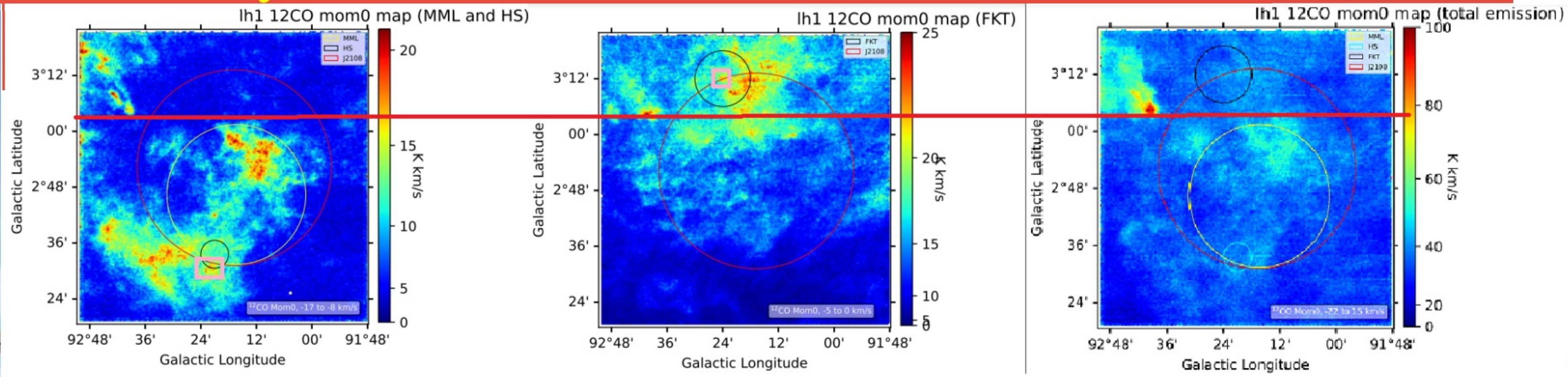
Source	V_{LSR} [km s^{-1}]	D [°]	Distance [kpc]	$n(\mathrm{H_2})$ [cm^{-3}]	$M_{vir}(\mathrm{H_2})$ [$10^4\,M_\odot$]	$M(\mathrm{H_2})$ [$10^4\,M_\odot$]	$M(\mathrm{H\,I}+\mathrm{H_2})$ [$10^4\,M_\odot$]	Projected size [°]
MML	−13.71	0.5	3.3	12.26	—	0.84	—	0.5 at 3.3 kpc
FKT-MC (^{12}CO)	-3.0 ± 0.1	1.1 ± 0.2	1.7 ± 0.6	31 ± 14	9.5 ± 0.1	3.0 ± 1.4	3.6 ± 1.6	1.1 at1.7 kpc
FKT-MC (^{13}CO)	-2.9 ± 0.1	1.1 ± 0.2	1.7 ± 0.6	9 ± 4	3.8 ± 0.2	0.9 ± 0.4	1.5 ± 0.6	1.1 at 1.7 kpc

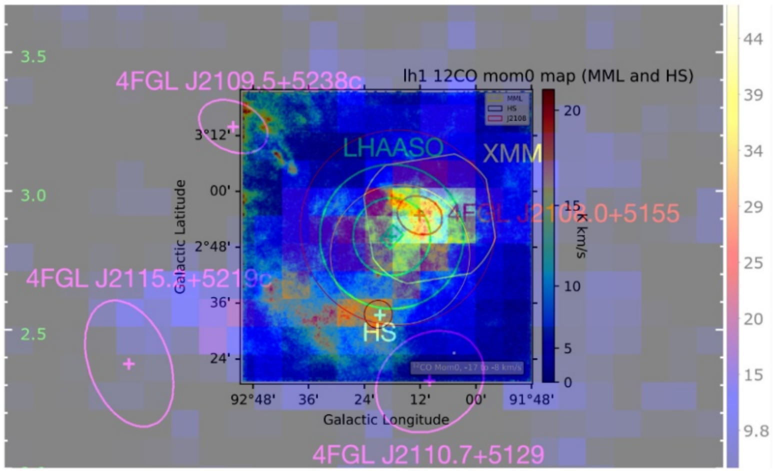


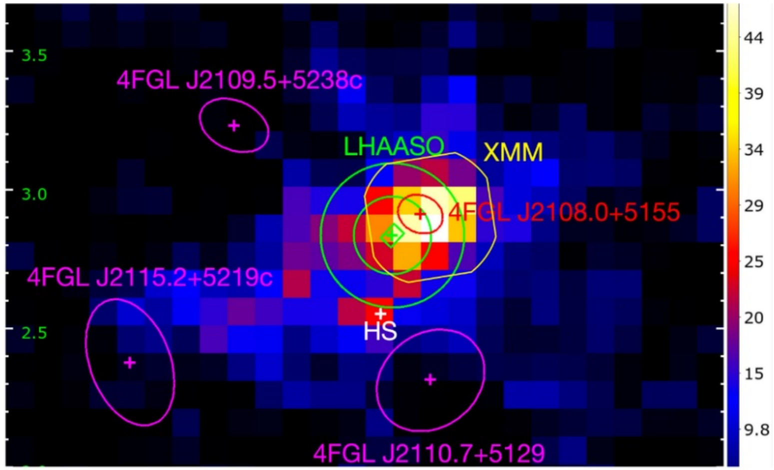
Contours: Osaka Prefecture University (OPU) Observations at 12CO(2-1)
Colour bar scale: NASA-FERMI (GeV Gamma-Ray Astronomy)

The PeVatron Candidate LHASSO J2108+5157 (I)

Nobeyama 45m meet PeVatrons







Nobeyama 45 m radio-telescope

12,13 CO(1-0), C18O (1-0)

OPTICALLY THIN GAS

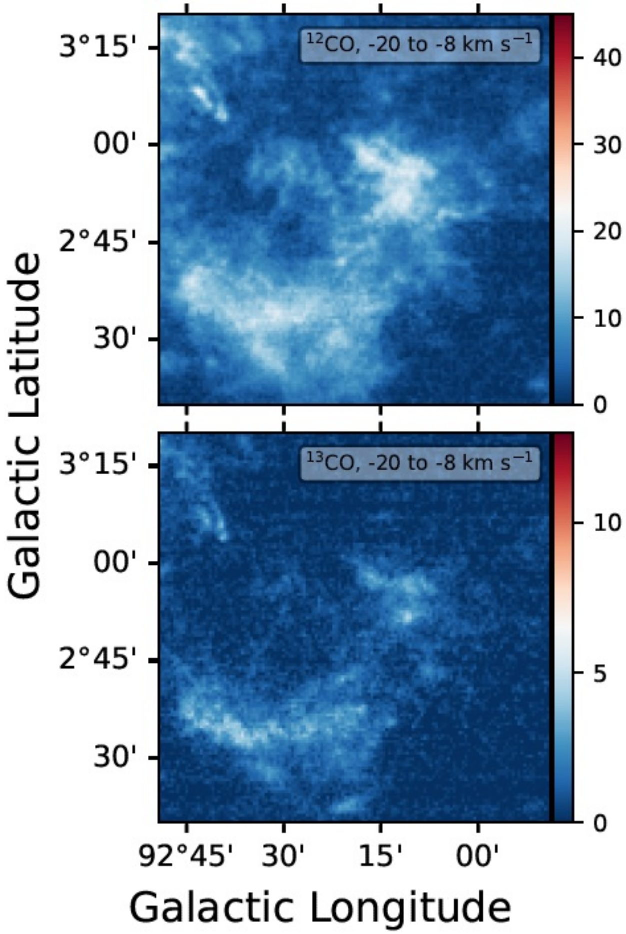
velocity range: –80 and 80 km s–1
spectral resolution of ~0.5 km s–1.
The effective spatial resolution is 17''

FKT (PASJ) and FTK (A&AL)

The PeVatron Candidate LHASSO J2108+5157 (II)

PeVatrons as challenge in 21st century astronomy

Ivan Toledano-Juarez, Ph. D. Thesis, CUCEI, Universidad of Guadalajara.



Optically THIN Gas!!!
Tau = 0.2 in average

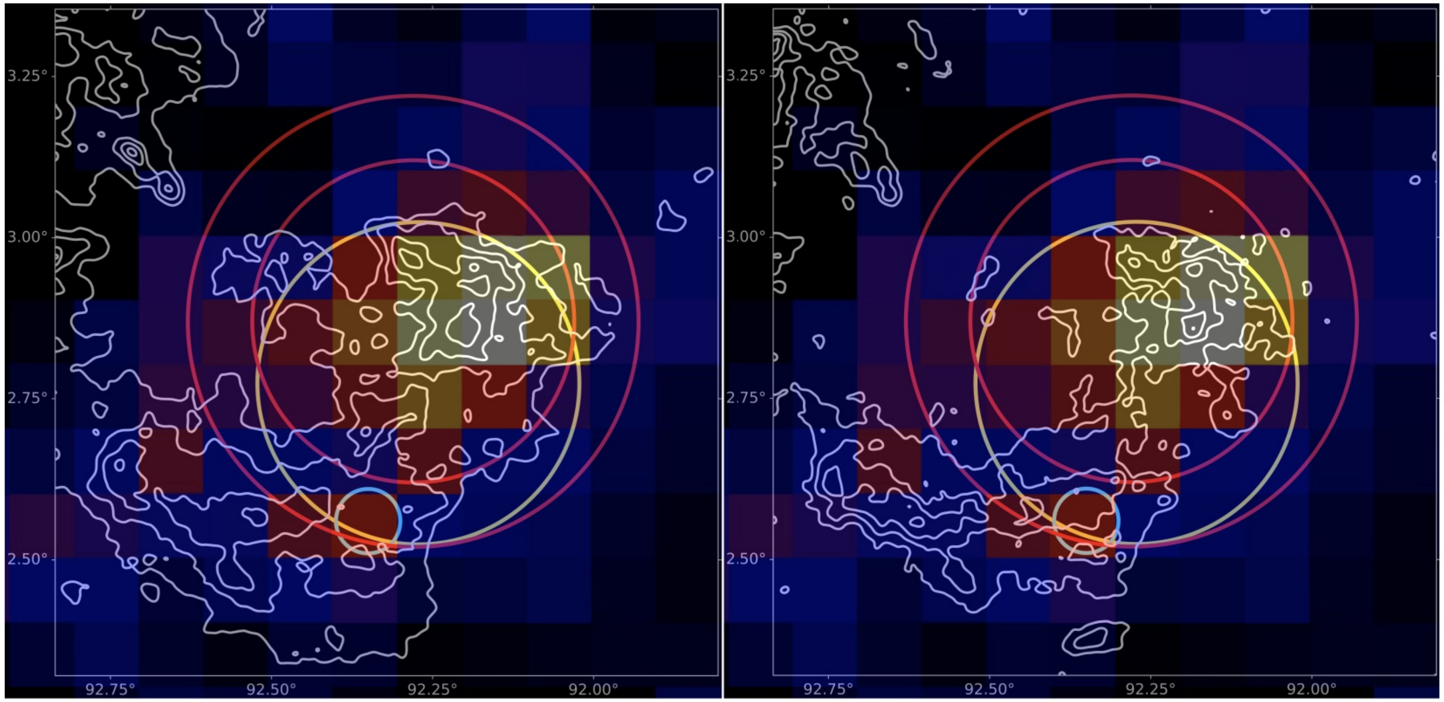


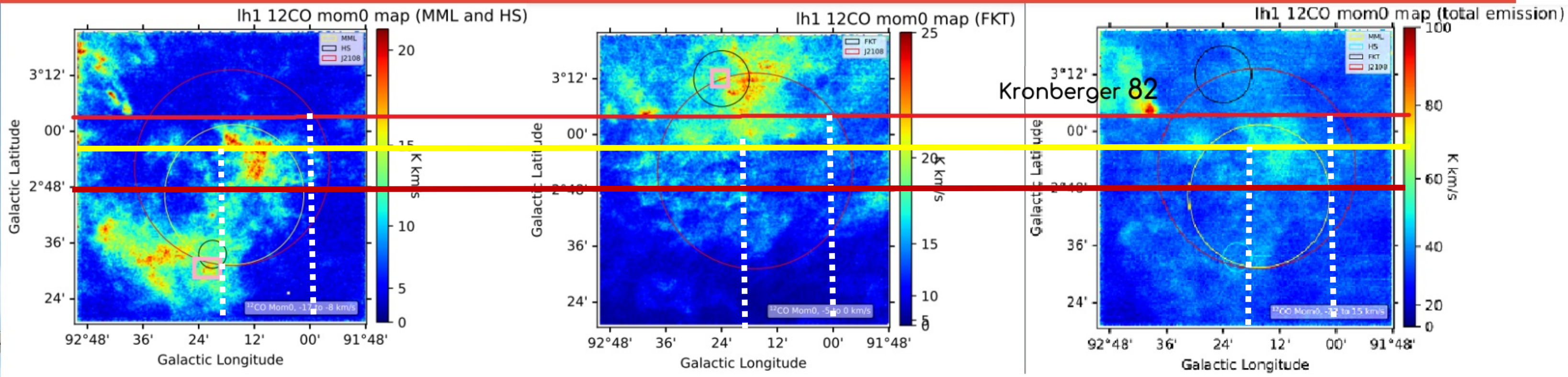
Table 4. Parameters and results of the hadronic model of Naima for the FTK molecular cloud

Distance [kpc]	$N(H)^a$ [10^{21} cm^{-2}]	n(H)^a [cm^{-3}]	Size [degree]	W_p [10^{46}erg]	Cutoff [TeV]
1.6±0.1	6.2±2.1	133±45	0.55±0.02	$4.3^{+2.0}_{-1.1}$	700^{+400}_{-300}

[a] The column and number density of nucleons is calculated as $N(H) = 2N(H_2) + N(HI)$ and $n(H) = 2n(H_2) + n(HI)$, respectively.

The PeVatron Candidate LHASSO J2108+5157 (III)

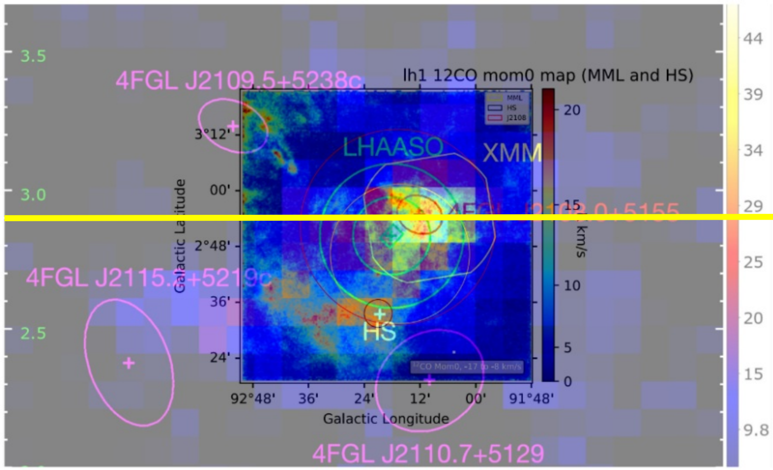
PeVatrons as challenge in 21st century astronomy

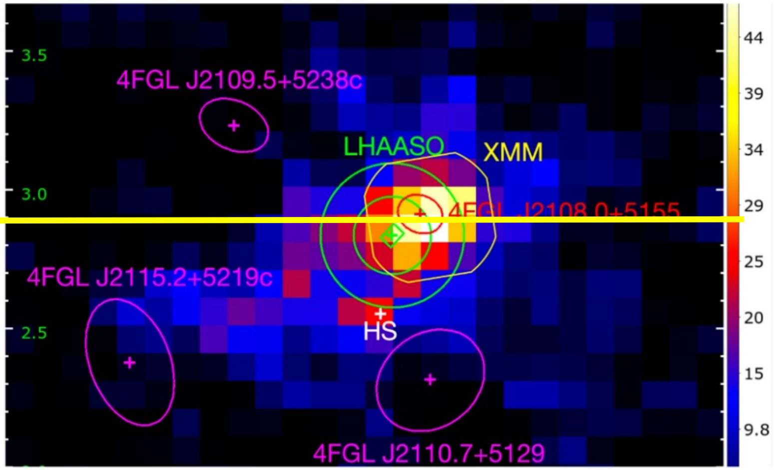


Nobeyama 45 m radio-telescope

12,13CO(1-0), C18O (1-0)

OPTICALLY THIN GAS





FKT (PASJ) and FTK (A&AL) SAME CLOUD!?

Ongoing work......

THANK YOU!...