LHAASO observations of UHE gamma-rays from Microquasars

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on behalf of LHAASO collaboration

«A Microquasar Odyssey: Unveiling the Complexities»
The 11th Microquasar Workshop, Cefalù, 15-19 September 2025

Outline

- Introduction of LHAASO
- Microquasars at ultra-high-energies
- The role of multi-wavelength on the origin of UHE
- Summary

LHAASO

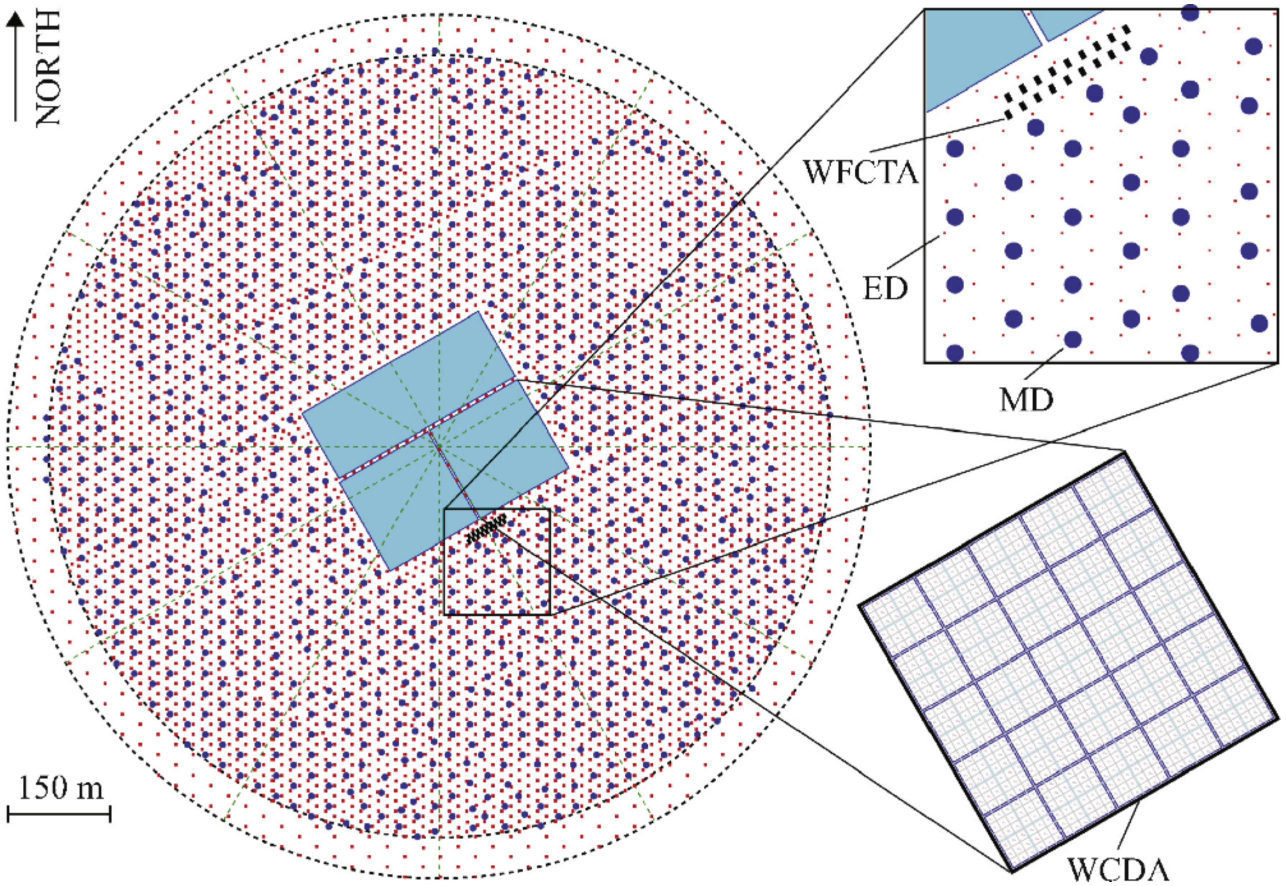
Large High Altitude Air Shower Observatory (LHAASO)

Location: 29°21′27.6” N   100°08′19.6"E

Altitude: 4410m a.s.l

Operation since 12.2019 with a half array, full array from 07.2021

Wide FoV

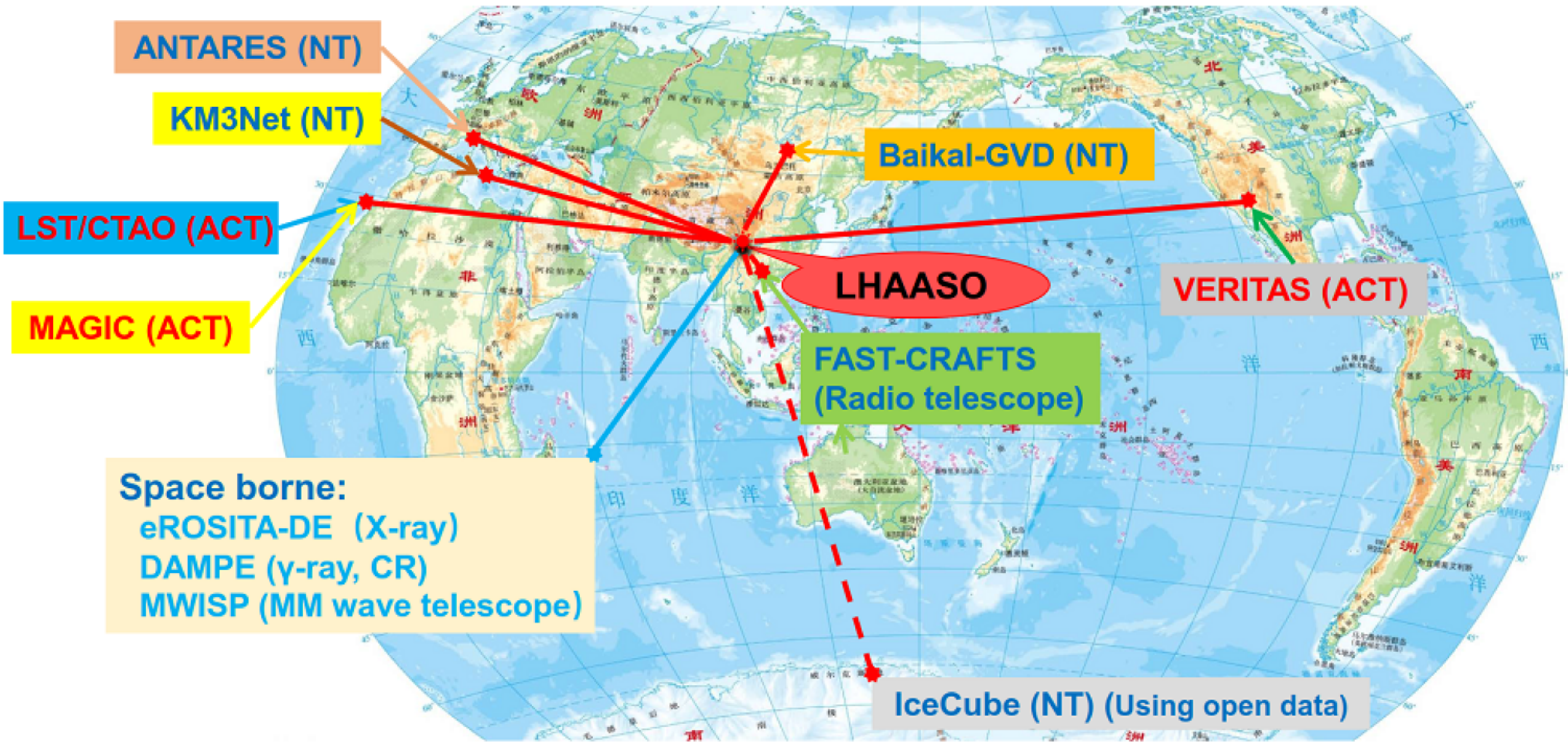


KM2A: 1.36 km^2, 10 TeV - 10 PeV (TeV= 10^{12}eV, PeV = 10^{15}eV)

Water Cherenkov Detector Array (WCDA): 78,000 m^2, 100 GeV - 30 TeV

Wide FoV Cherenkov Telescope Array: Cosmic ray detector >30 TeV

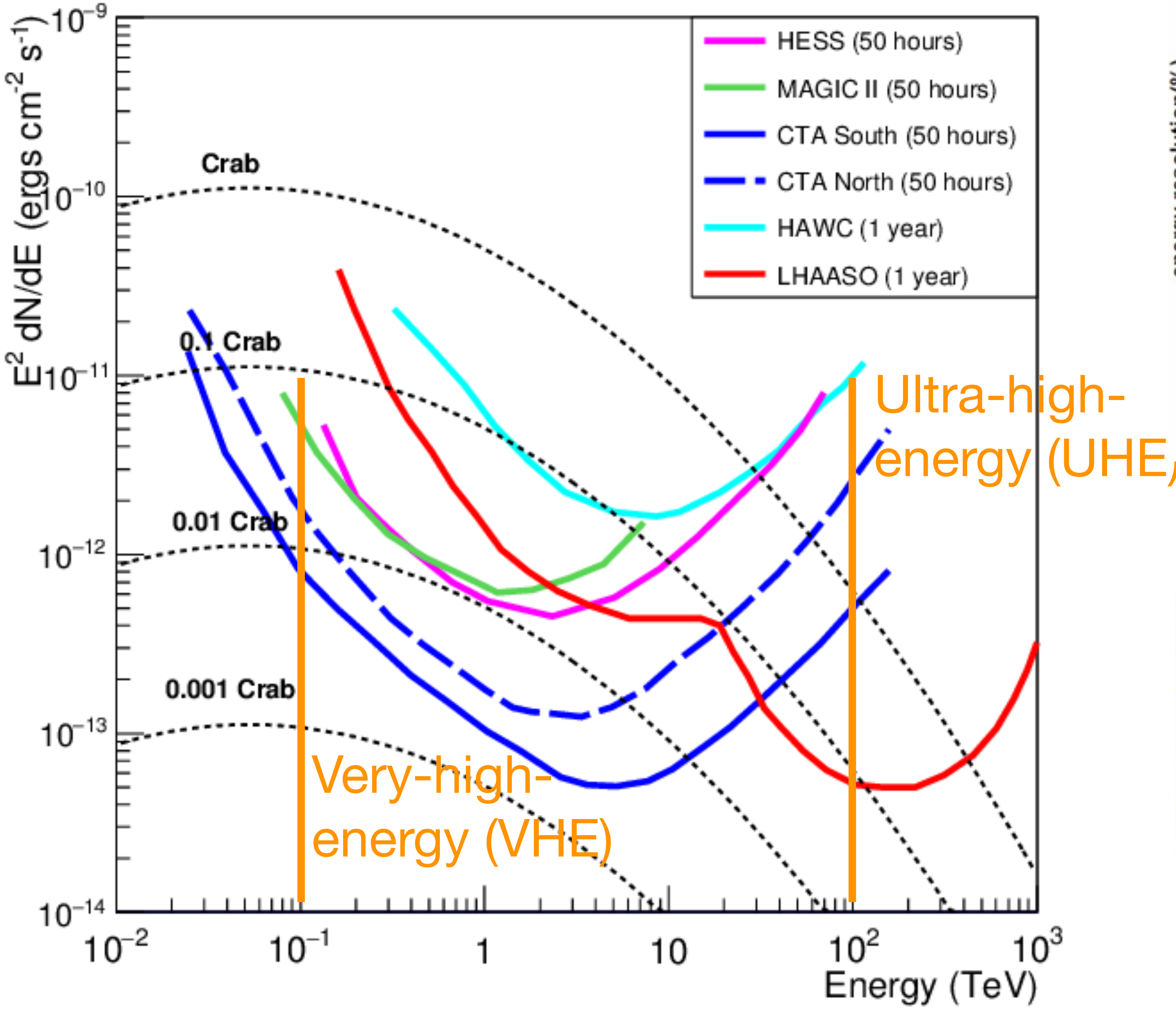
LHAASO and collaborations

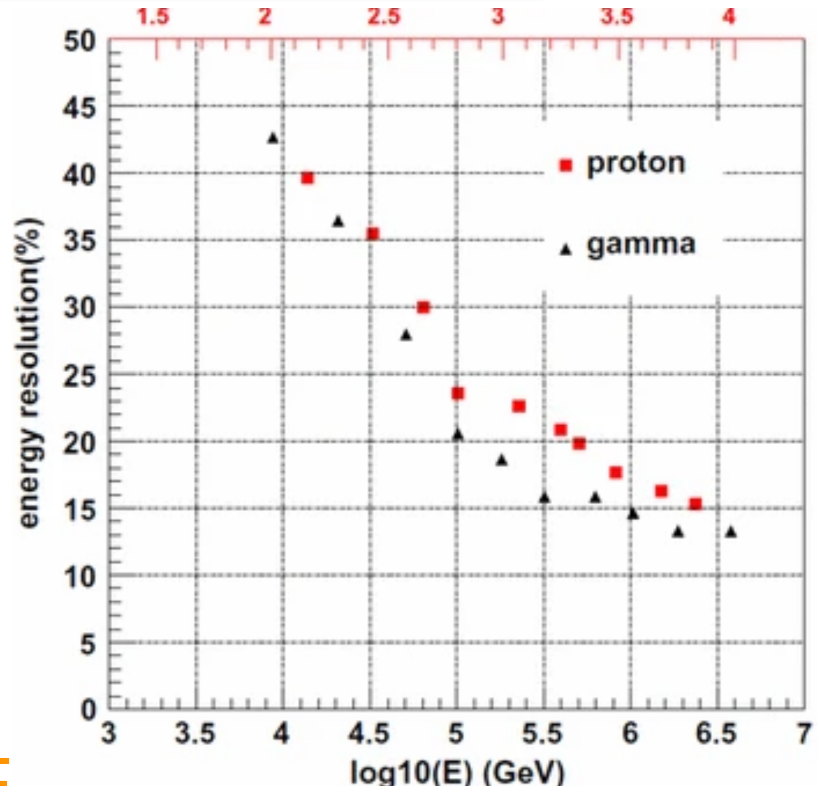


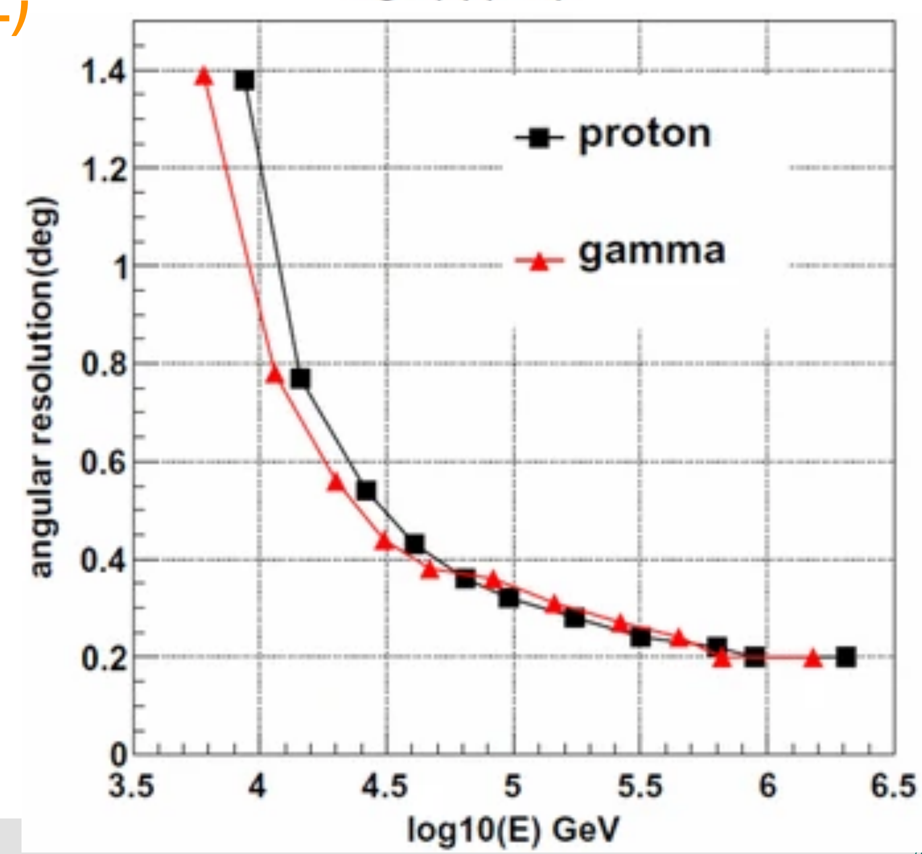
NT: neutrino telescope

ACT: Air Cherenkov telescope

LHAASO sensitivity (point-like sources)







LHAASO sources

LHAASO
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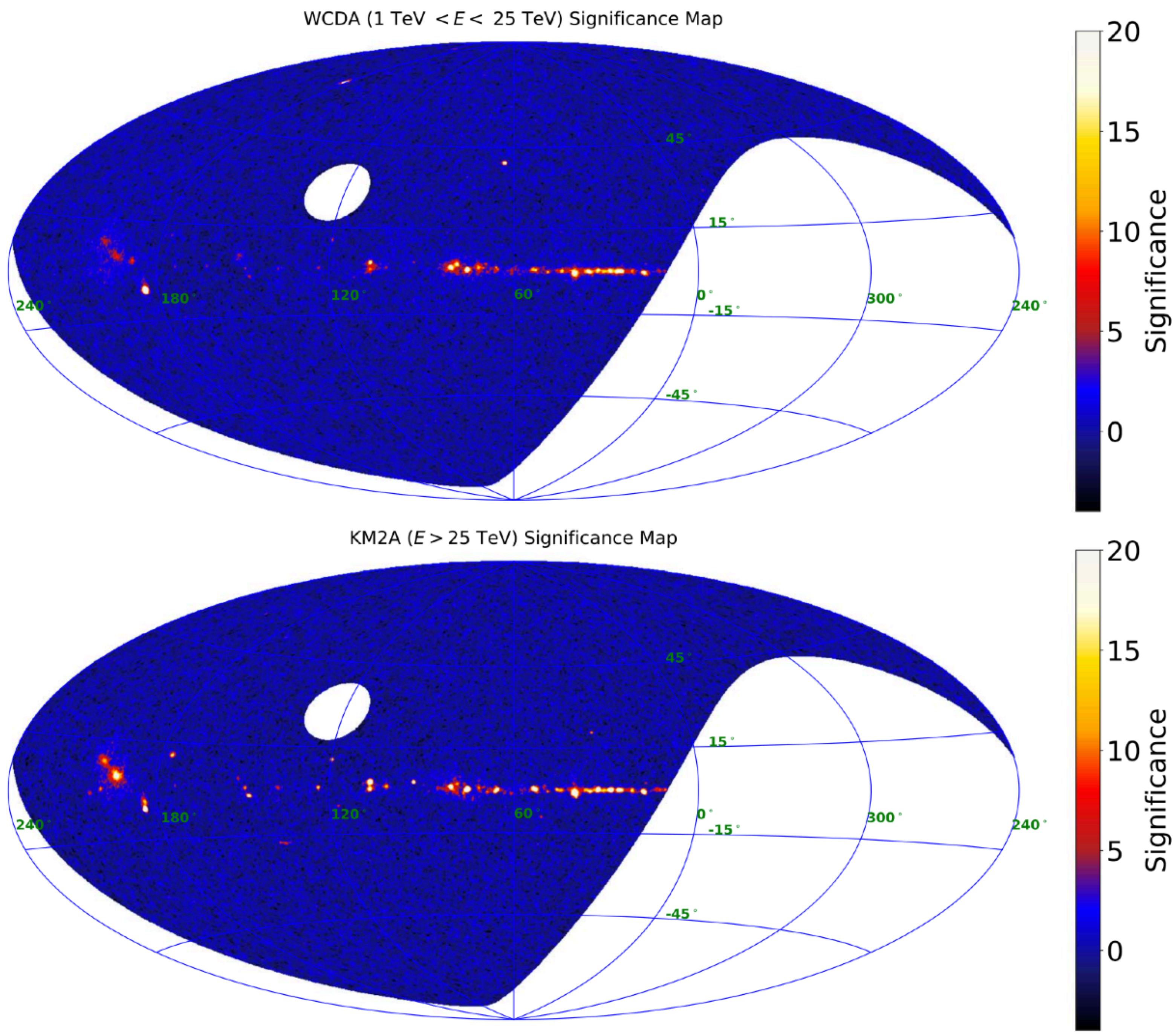


- 90 sources (galactic & EG):
- 32 new sources
- 43 sources with ultra-high energy (E > 100 TeV) emission at >4σ
- Gal: SNR, Pulsar (halo), microquasar (binaries), stellar clusters etc
- EG: AGN, GRB etc (ULX proposed)

LHAASO collaboration, 2021, Science; Nature, 2024, ApJS

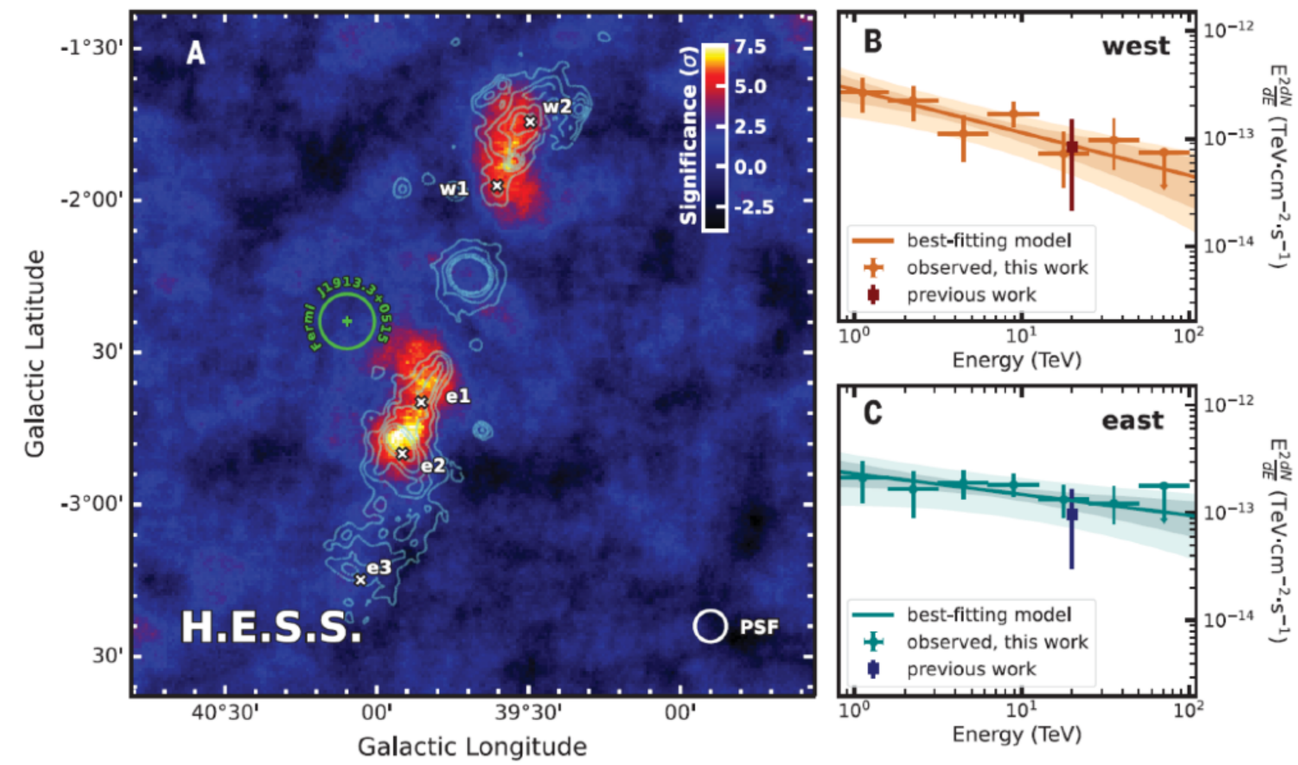
Microquasars by LHAASO

Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0455	9.9[c]	2.82 ± 0.16	$25 - 100$		0.10
SS 433 W.	4.6 ± 1.3[31]	J1910+0509	6.3[c]	2.94 ± 0.38	$25 - 100$	$0.73^\circ \pm 0.07^\circ$	0.082
SS 433 central		J1911+0510	8.0	3.96 ± 0.25	$100 - 630$	$0.32^\circ \pm 0.04^\circ$	0.32
V4641 Sgr	6.2 ± 0.7[32]	J1819-2541	10.5	2.84 ± 0.17	$40 - 1000$	$0.33^\circ \pm 0.08^\circ$	2.6
GRS 1915+105	9.4 ± 0.6[33]	J1915+1052	13.9	2.64 ± 0.14	$25 - 1000$	$0.25^\circ \pm 0.05^\circ$	0.11
MAXI J1820+070	2.96 ± 0.33[34]	J1821+0723	6.0	3.25 ± 0.26	$25 - 400$	$< 0.28^\circ$	0.02
Cygnus X-1	2.2 ± 0.2[35]	J1958+3522	4.4	3.98 ± 0.40	$25 - 100$	$< 0.22^\circ$	< 0.01
XTE J1859+226	4.2 ± 0.5[36]	–	2.7	–	–	–	< 0.02
GS 2000+251	2.7 ± 0.7[37]	–	2.3	–	–	–	< 0.04
CI Cam	$4.1^{+0.3}_{-0.2}$[38]	–	1.6	–	–	–	< 0.02
GRO J0422+32	2.49 ± 0.3[39]	–	0.7	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14[40]	–	1.5	–	–	–	< 0.03
XTE J1118+480	1.7 ± 0.1[41]	–	0.4	–	–	–	< 0.02
V616 Mon	1.06 ± 0.1[42]	–	0.4	–	–	–	< 0.01

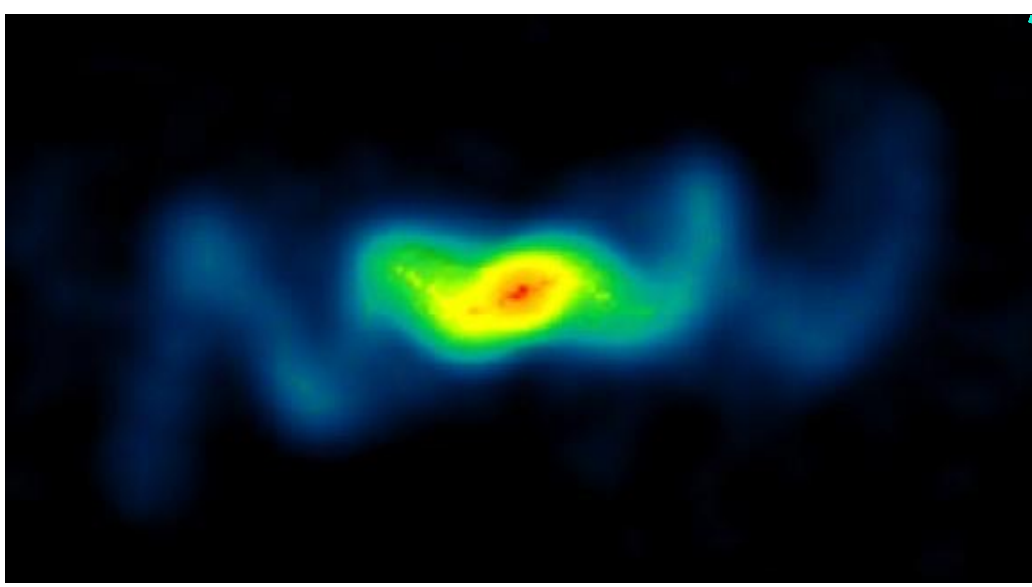
LHAASO collaboration, 2024, submitted, arXiv:2410.08988

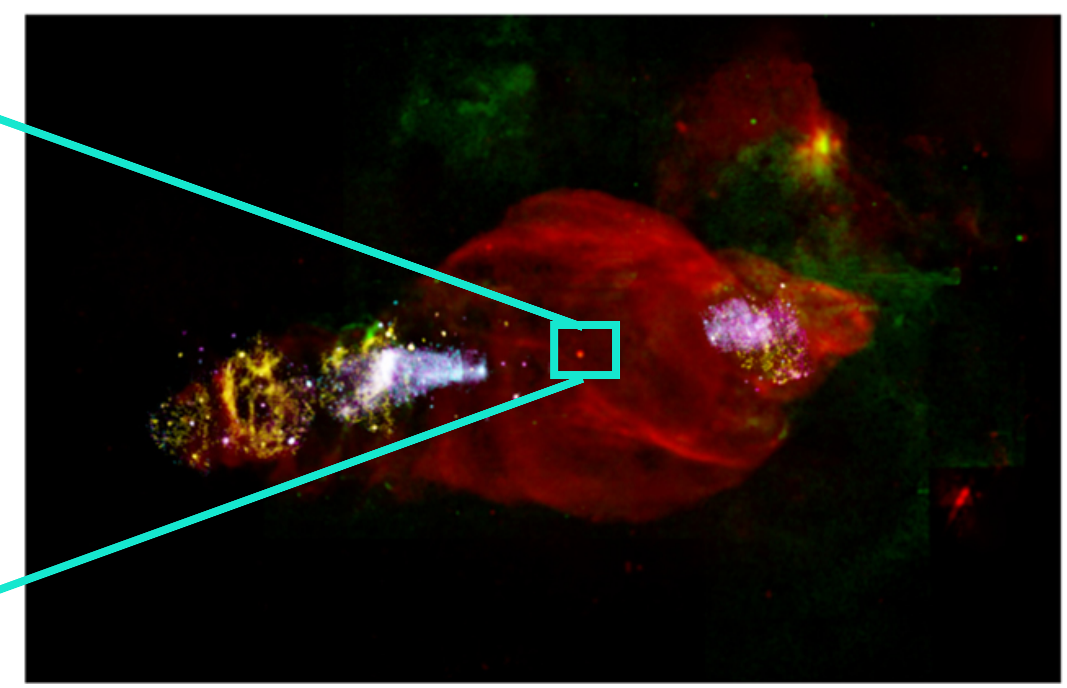
SS 433

- Intrinsically can be super-Eddington
- Two-sided jets, velocity: 0.26 c
- Orbital P=13.08 days, precessing inner jet: P=162.25 days
- Large-scale jet show non-thermal X-rays and TeV emission



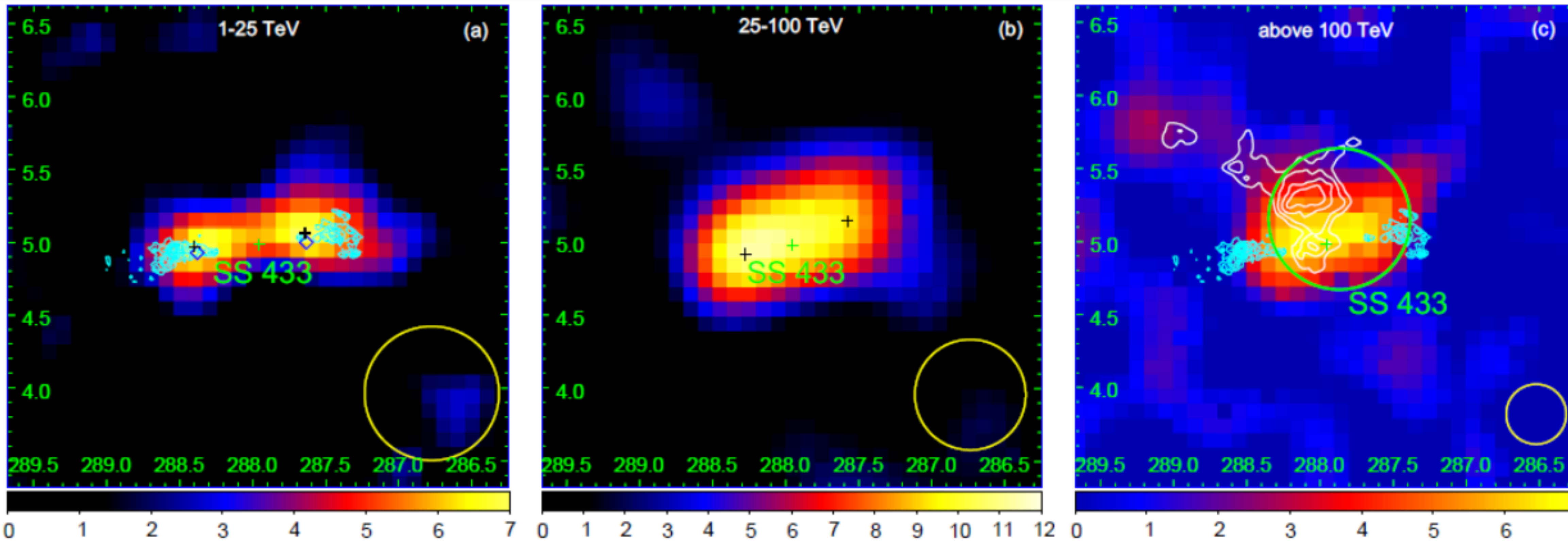
HESS collaboration, 2024, Science





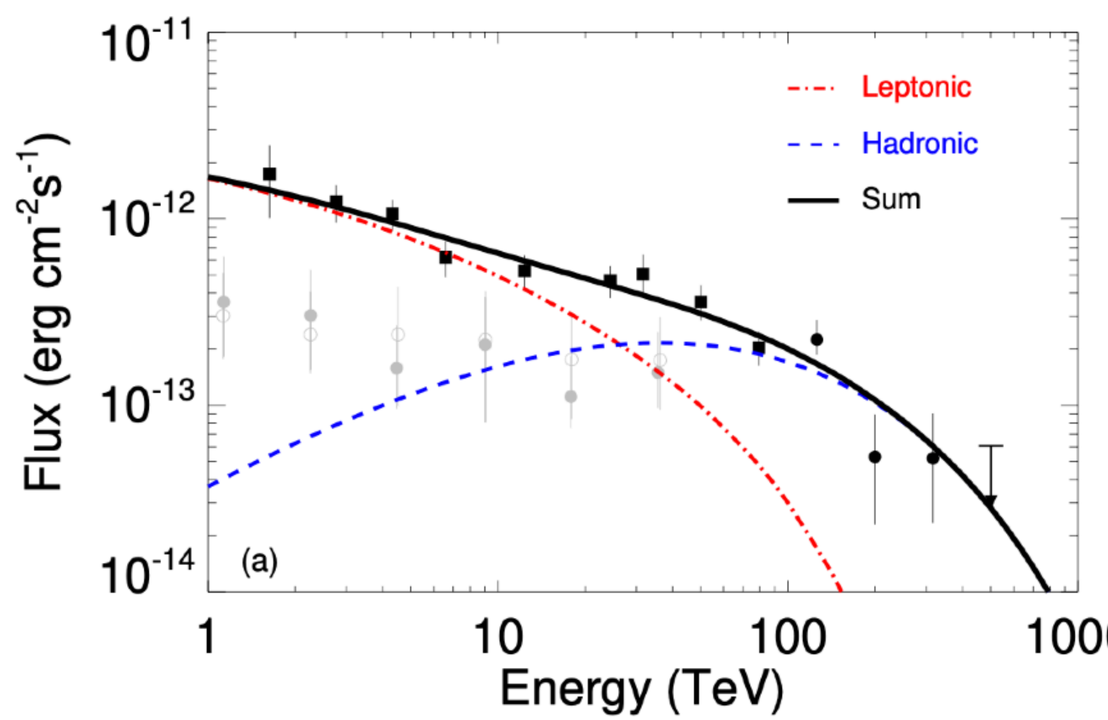
Safi-Harb et al. 2022, ApJ

SS 433 by LHAASO



- Detection of gamma-ray emission >100TeV with significance >5 sigma;

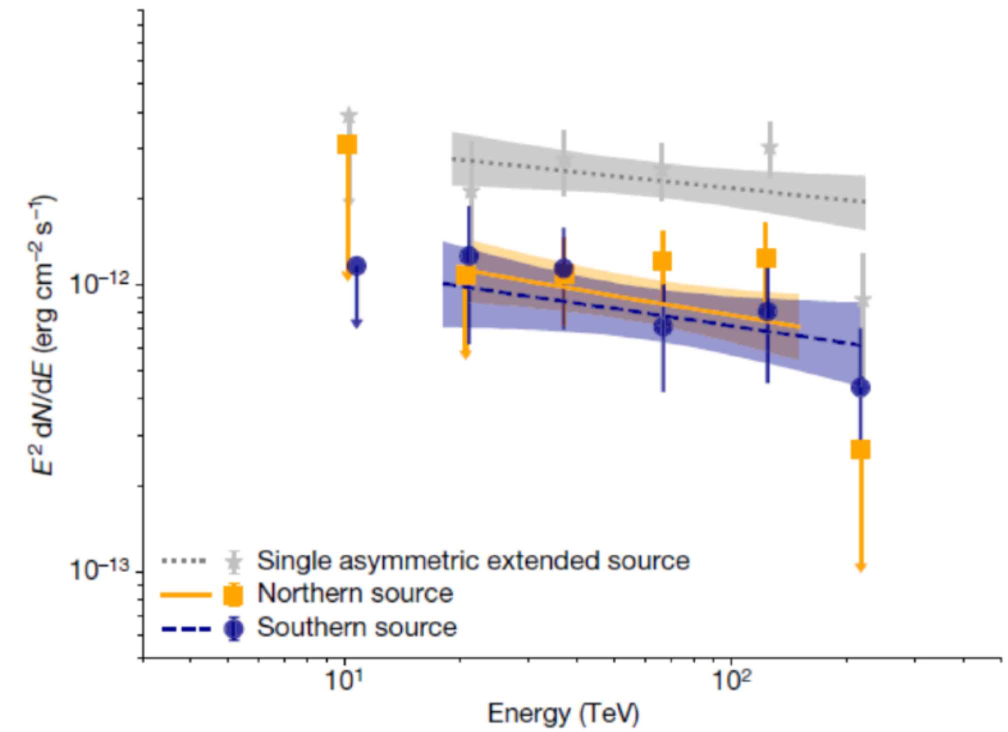
- The UHE emission is partly overlapped with HI cloud at the same distance of SS433, indicating contribution from hadronic process.

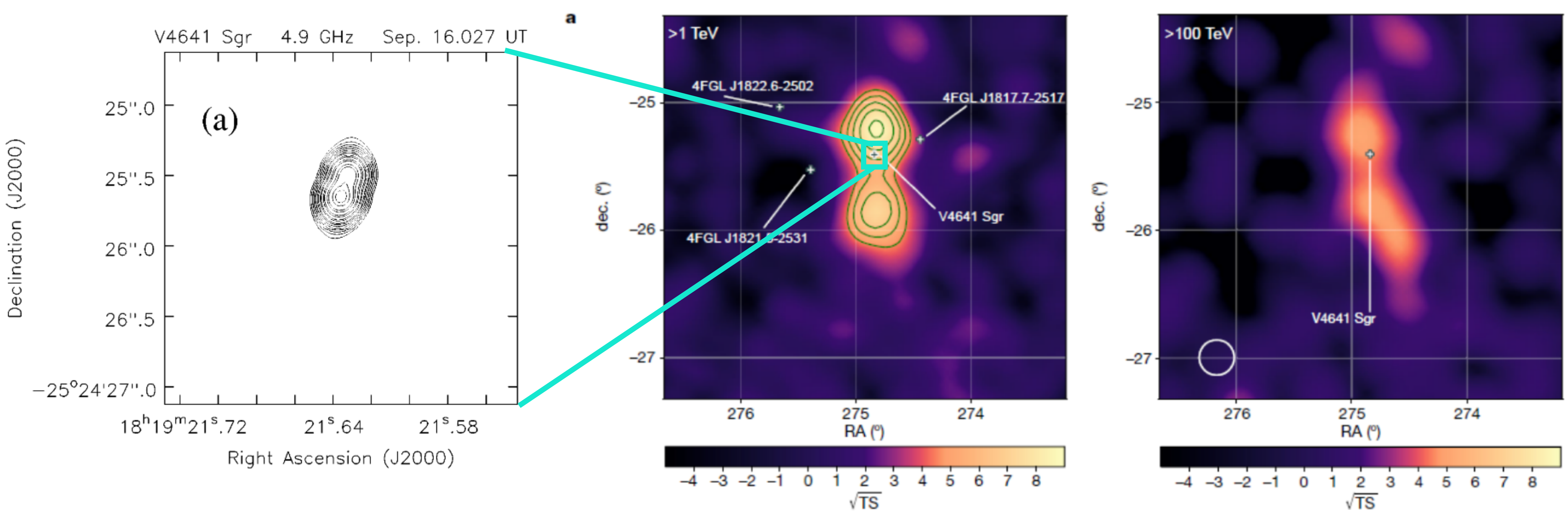


LHAASO collaboration, 2024, submitted, arXiv:2410.08988

V4641 Sgr

- P=2.82 days
- Mostly in quiescent state with strong outbursts, super-Eddington in 1999
- The inner radio jet has v=0.95c
- TeV emission seen in >10pc scale

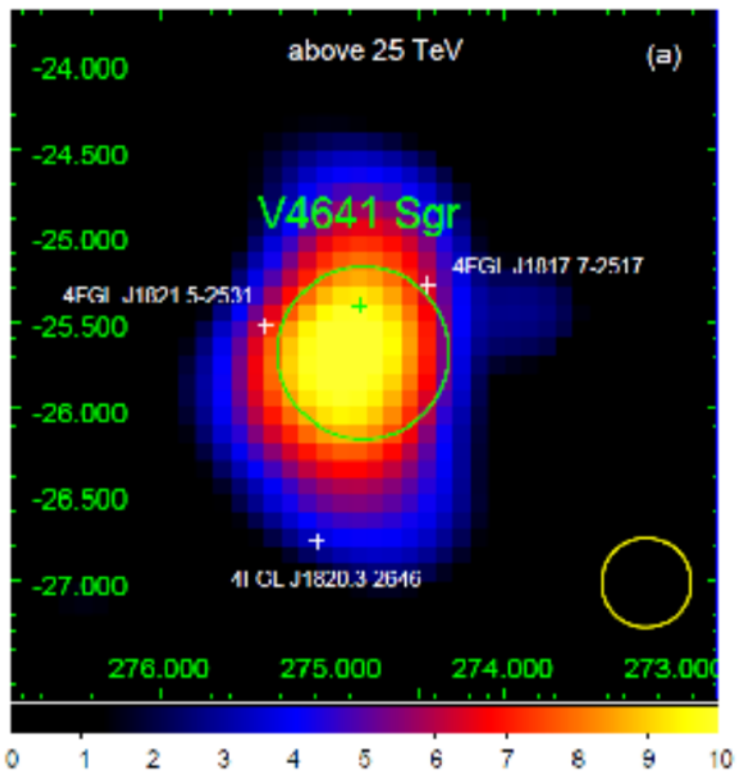


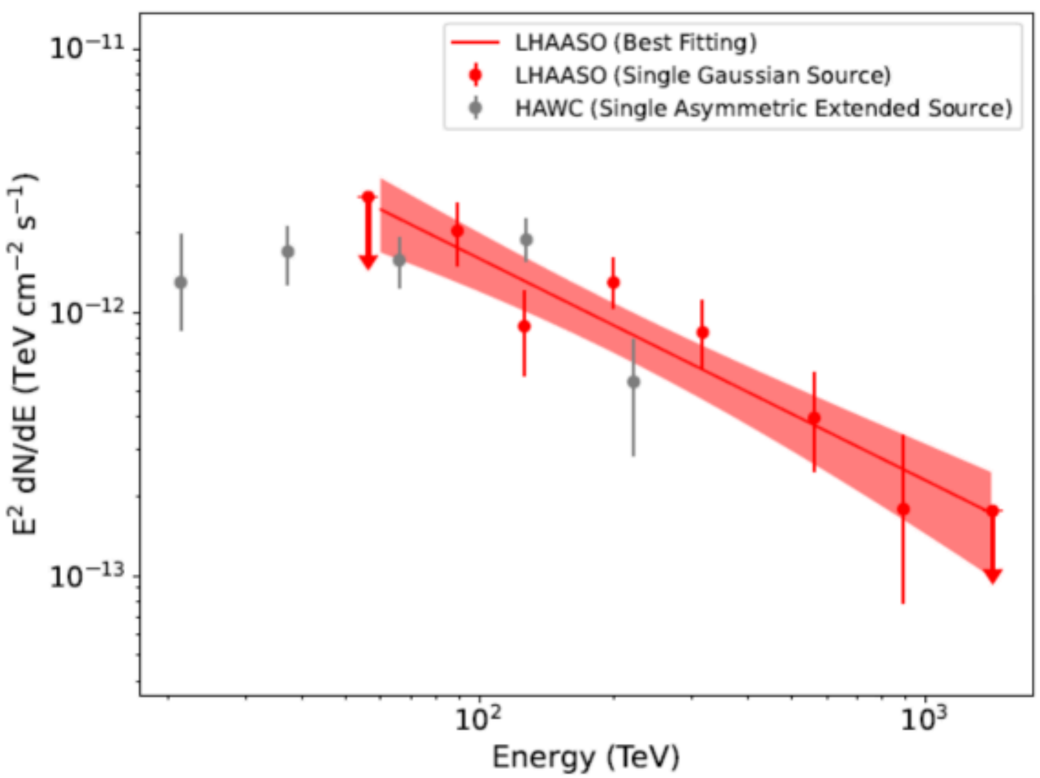


HAWC Collaboration, 2024, Nature

V4641 Sgr by LHAASO

- An extended source (0.33° ± 0.08°), but offset from V4641 Sgr by 0.19°
- Analysis favor an elliptical shape (asymmetric 2D Gaussian template)
- The flux is consistent with HAWC's result around 100TeV, but extends to ~1PeV.
- The hard spectrum up to PeV favors a hadronic contribution, and the apparent protons reaches energy of ~10PeV.

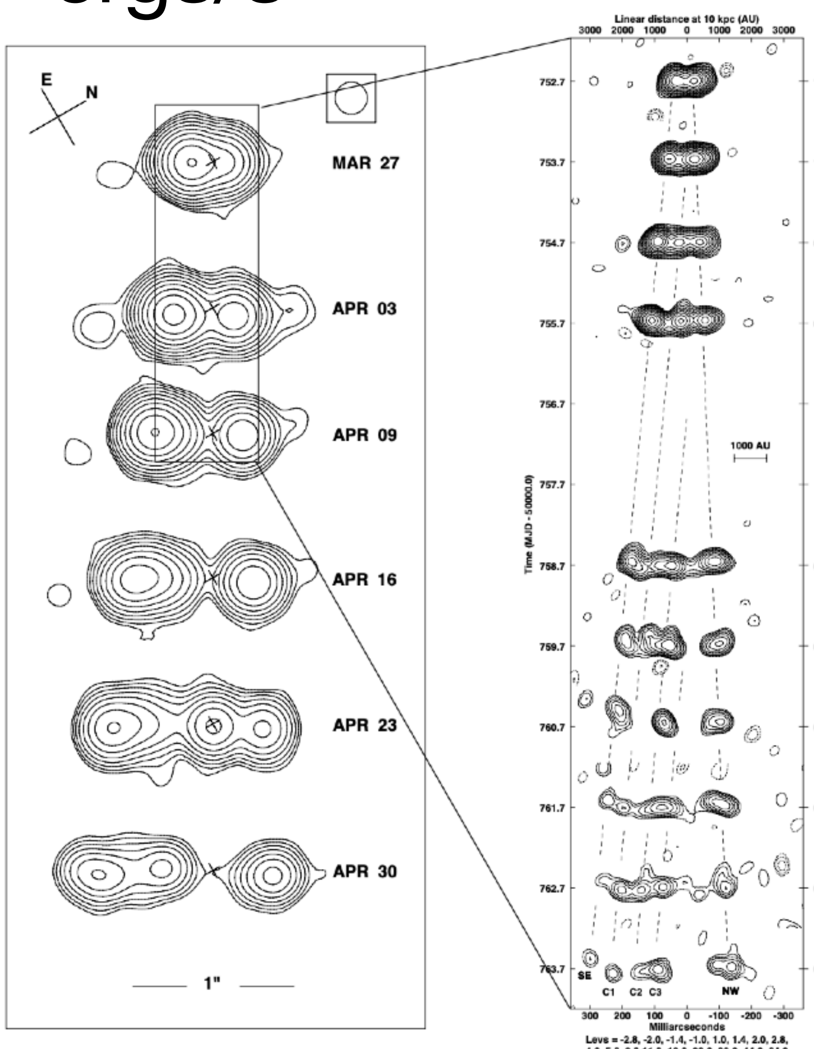




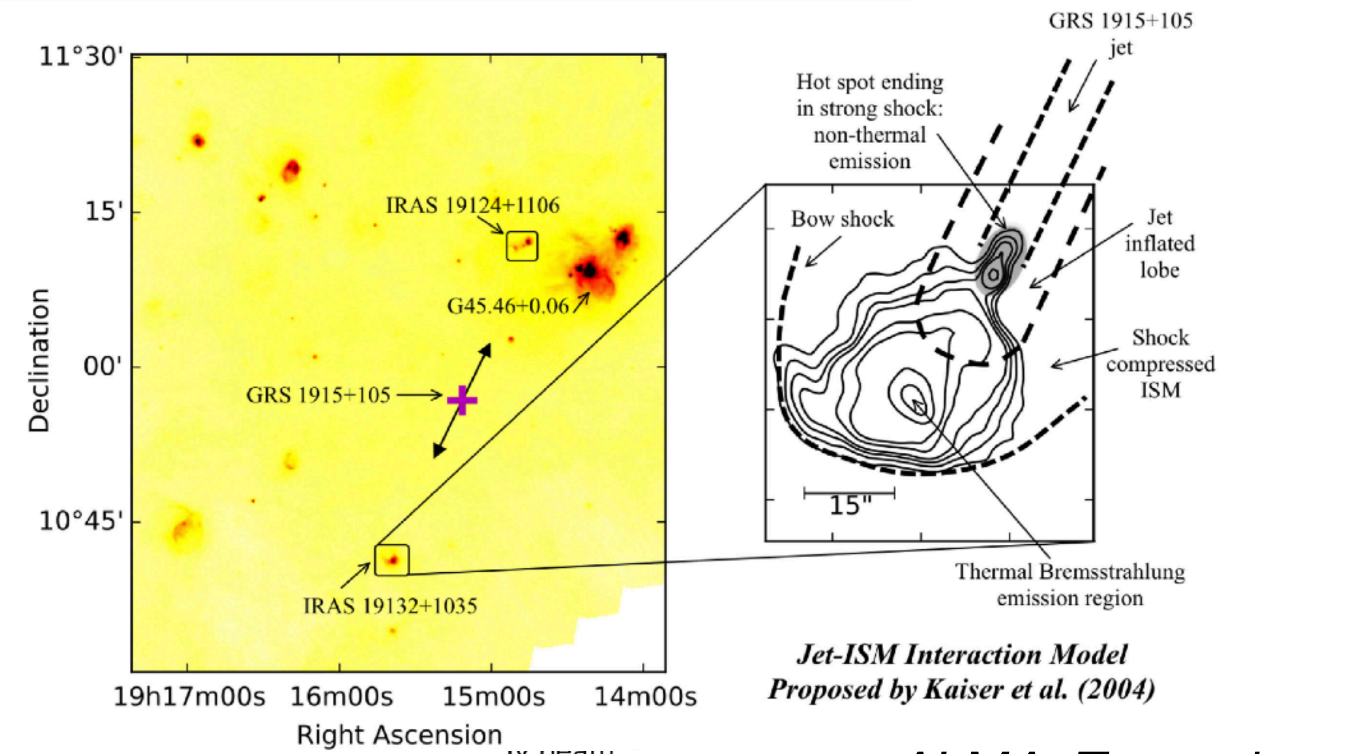
LHAASO collaboration, 2024, submitted, arXiv:2410.08988

GRS 1915+105

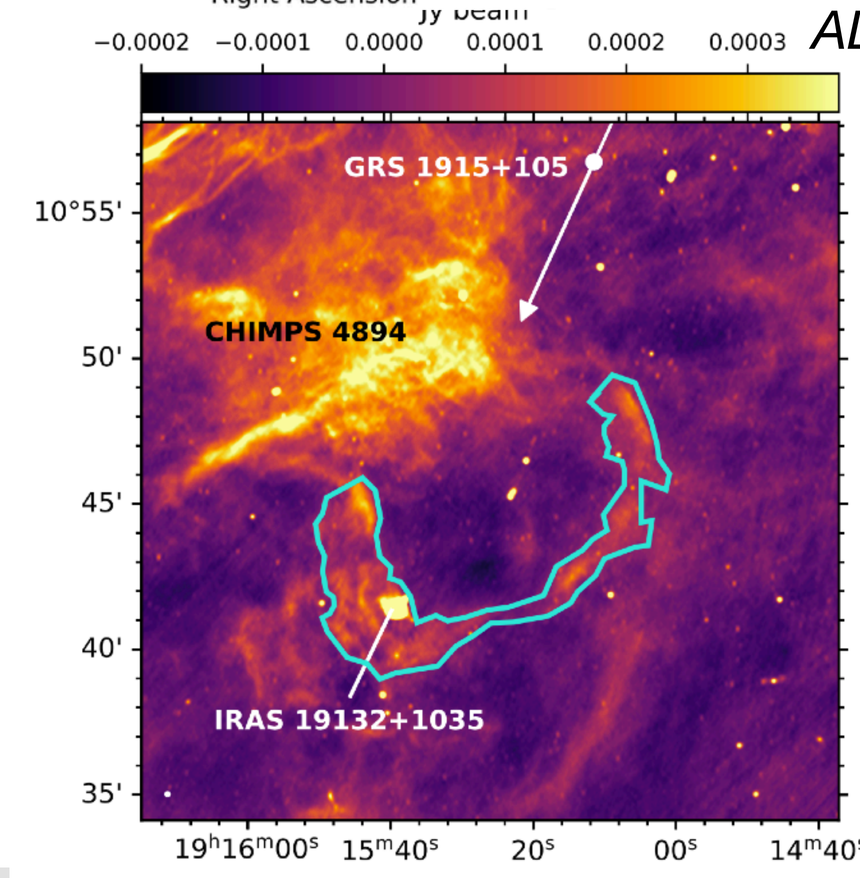
- (Near)-Eddington accretion, Jet v>0.9c
- Large-scale Jet-ISM interactions, jet power: 10^{37}-10^{39} ergs/s



Mirabel & Rodriguez 1994; Fender+ 1999



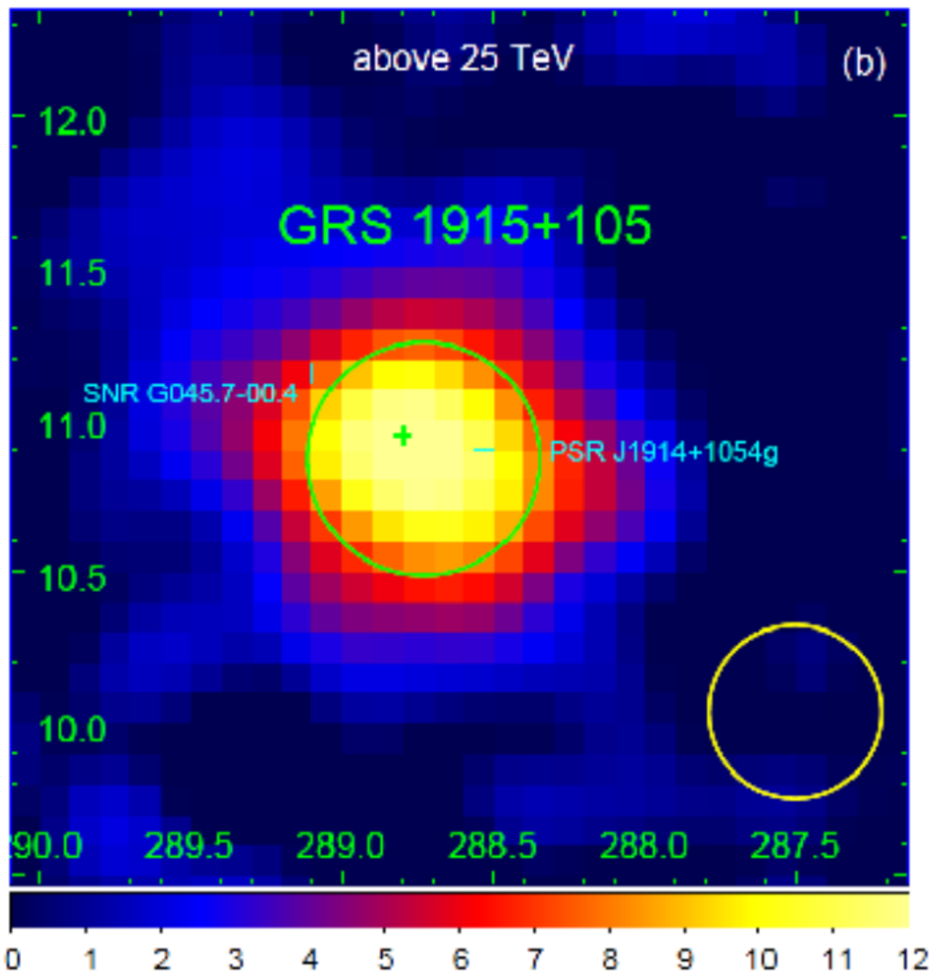
ALMA: Tetarenko et al. 2018

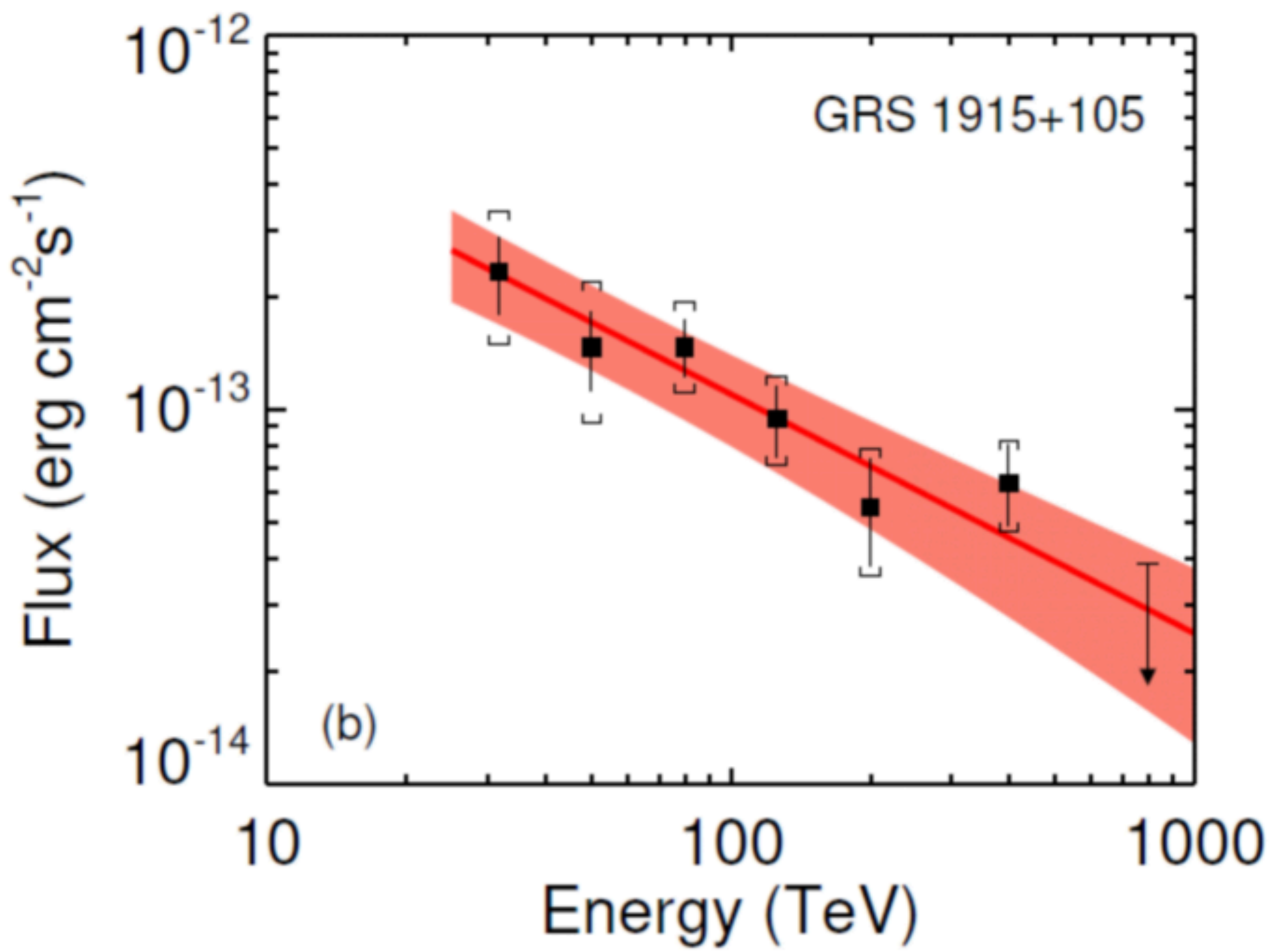


MeerKAT: Motta et al. 2025

GRS 1915 by LHAASO

- LHAASO J1915+1052: An extended source: 0.25°±0.05°, offset by 0.1°
- Nearby sources:
  - Radio pulsar PSR J1914+1054g (Spindown luminosity: 4×10^{35} ergs/s; Age: 82kyr), but larger offset, 0.26deg
  - Supernova remnant (SNR) G045.7-00.4, No clear association between UHE emission and CO at G045.7-00.4's distance.

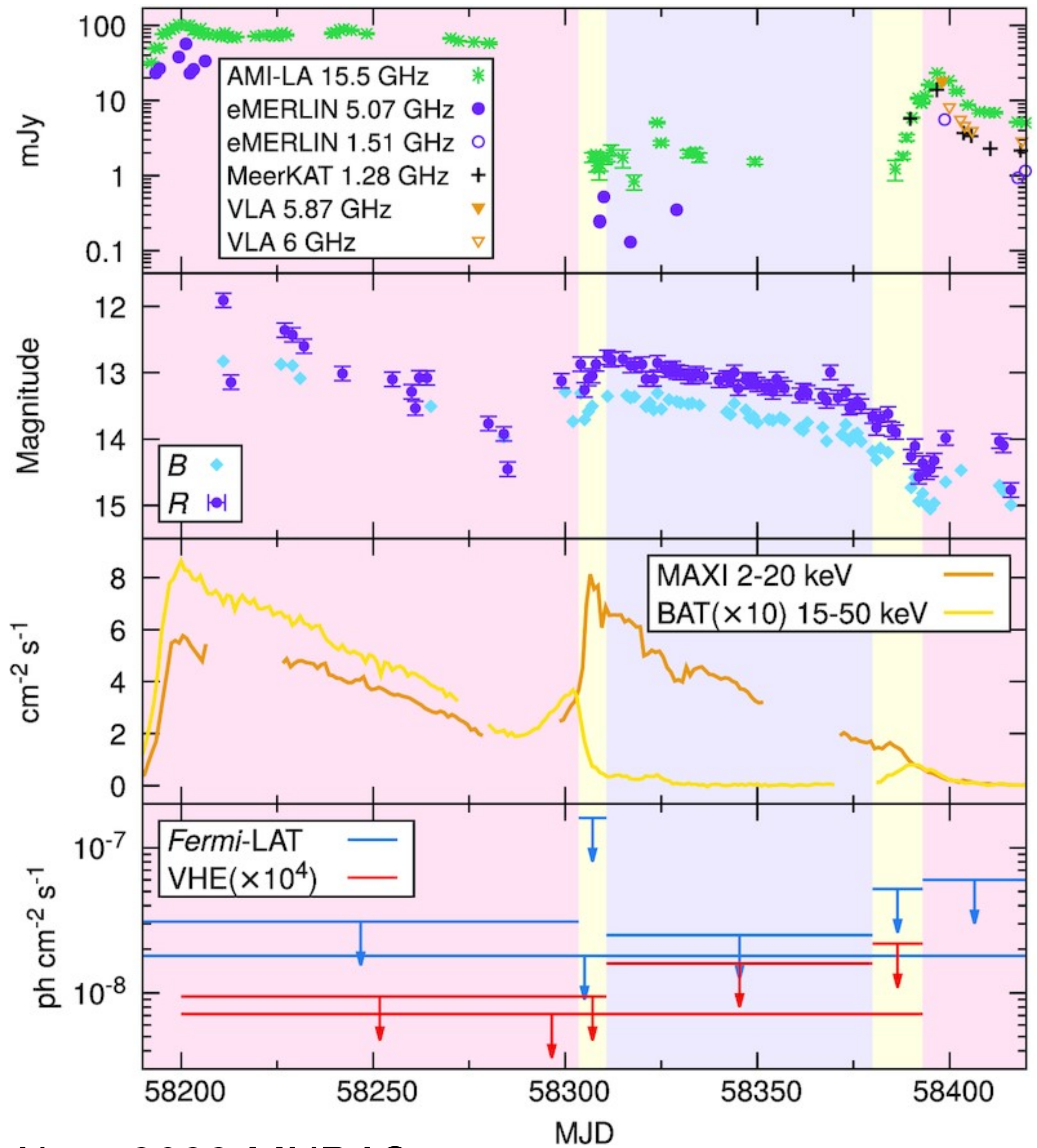




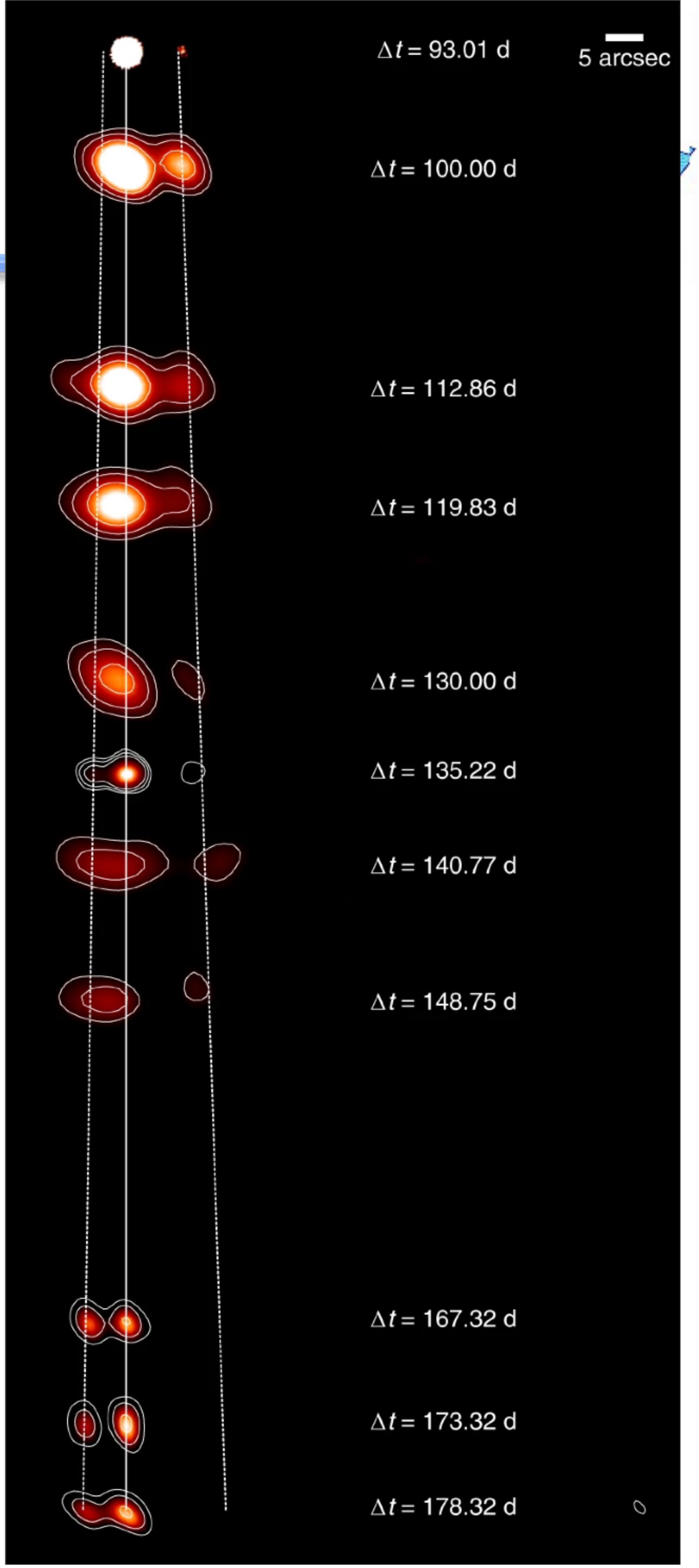
LHAASO collaboration, 2024, submitted, arXiv:2410.08988

MAXI J1820+070

- Jet activity (v>0.7c) in 2018 outburst
- Non-detection at HE and VHE



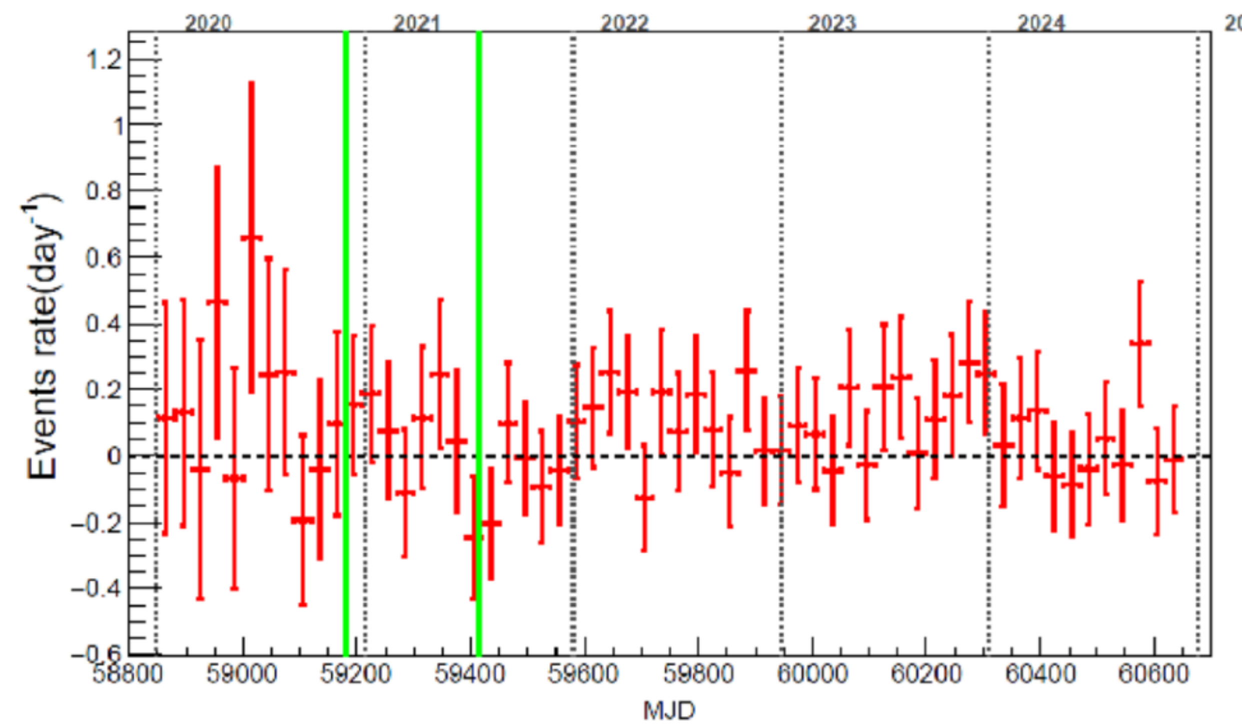
Abe+ 2022 MNRAS

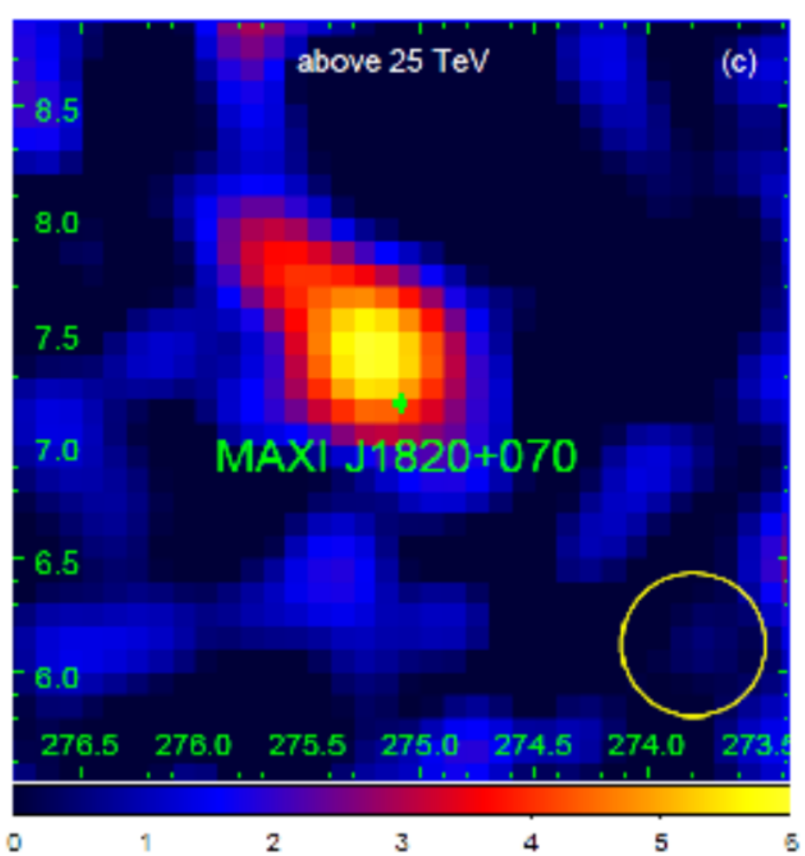


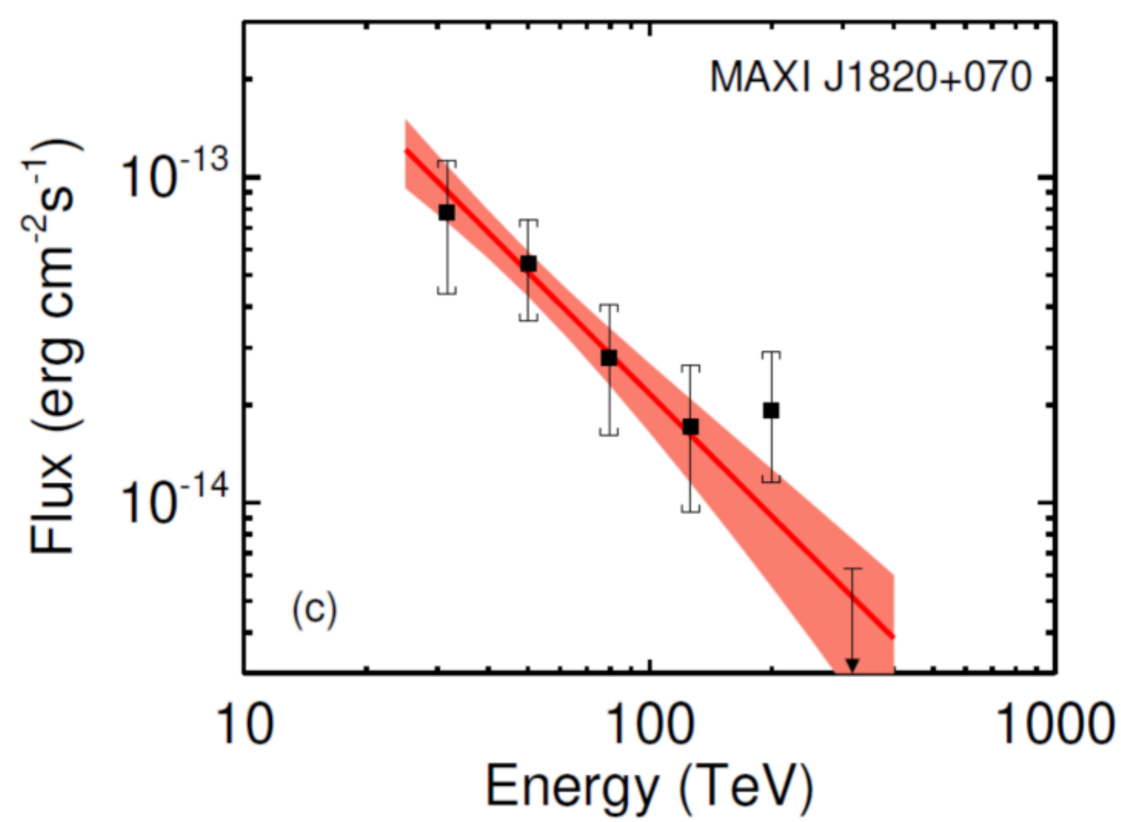
Bright+ 2020, NatAs

MAXI J1820 by LHAASO

- A point-like source (6 sigma) with an offset of 0.27° from MAXI J1820
- No significant variability
- The large-scale jet?



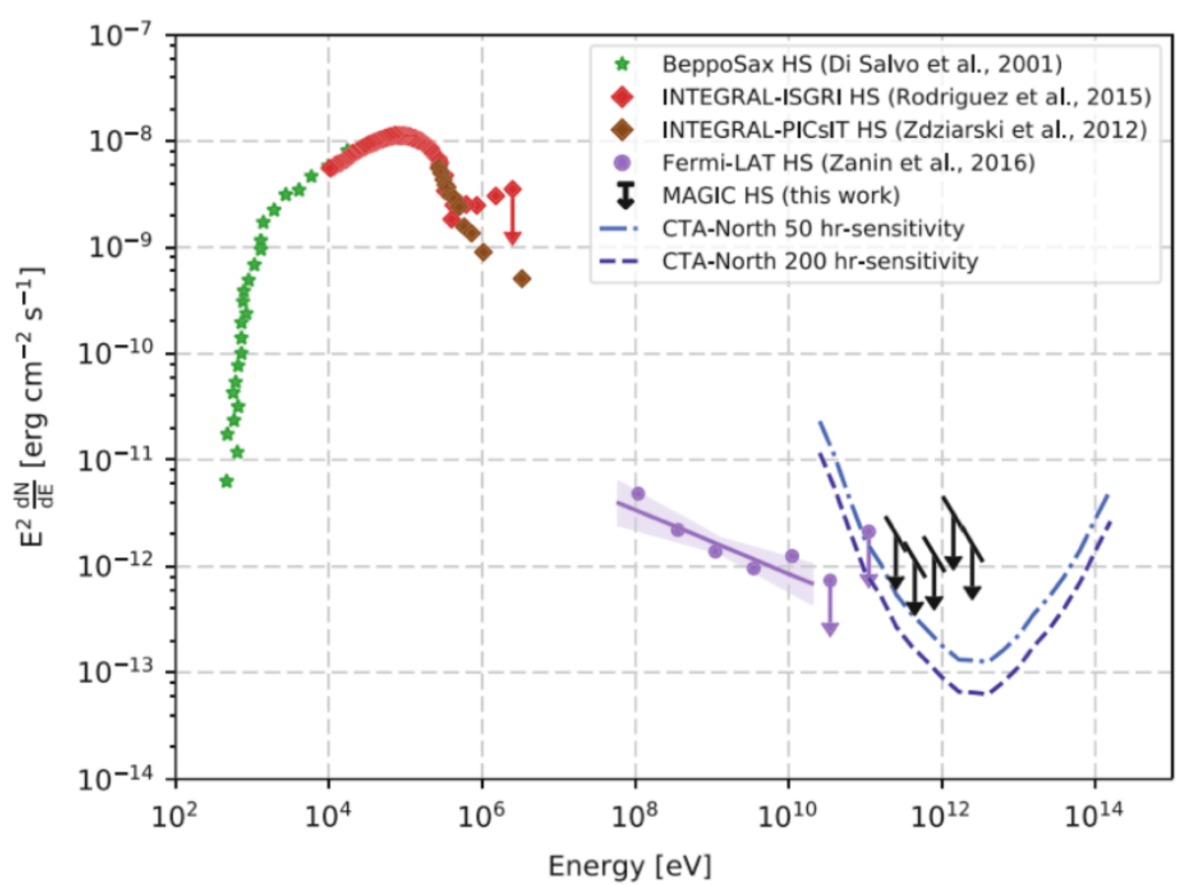


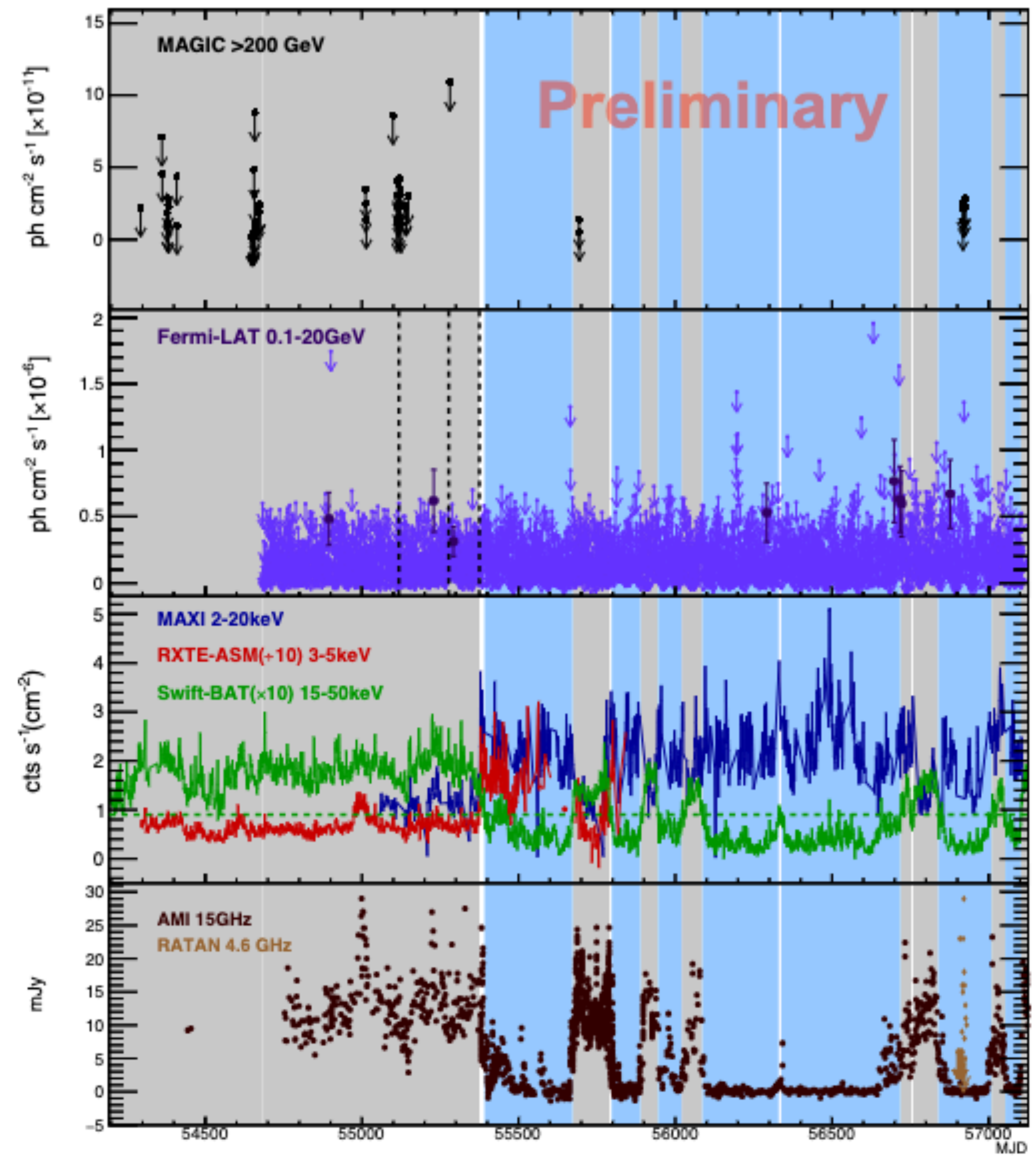


LHAASO collaboration, 2024, submitted, arXiv:2410.08988

Cygnus X-1

- Large-scale Jet-ISM interaction, persistent radio-jet (> 0.6*c*)
- Fermi LAT detected flaring GeV emission (hard state only) -> inner jet
- No obvious VHE (TeV) emission

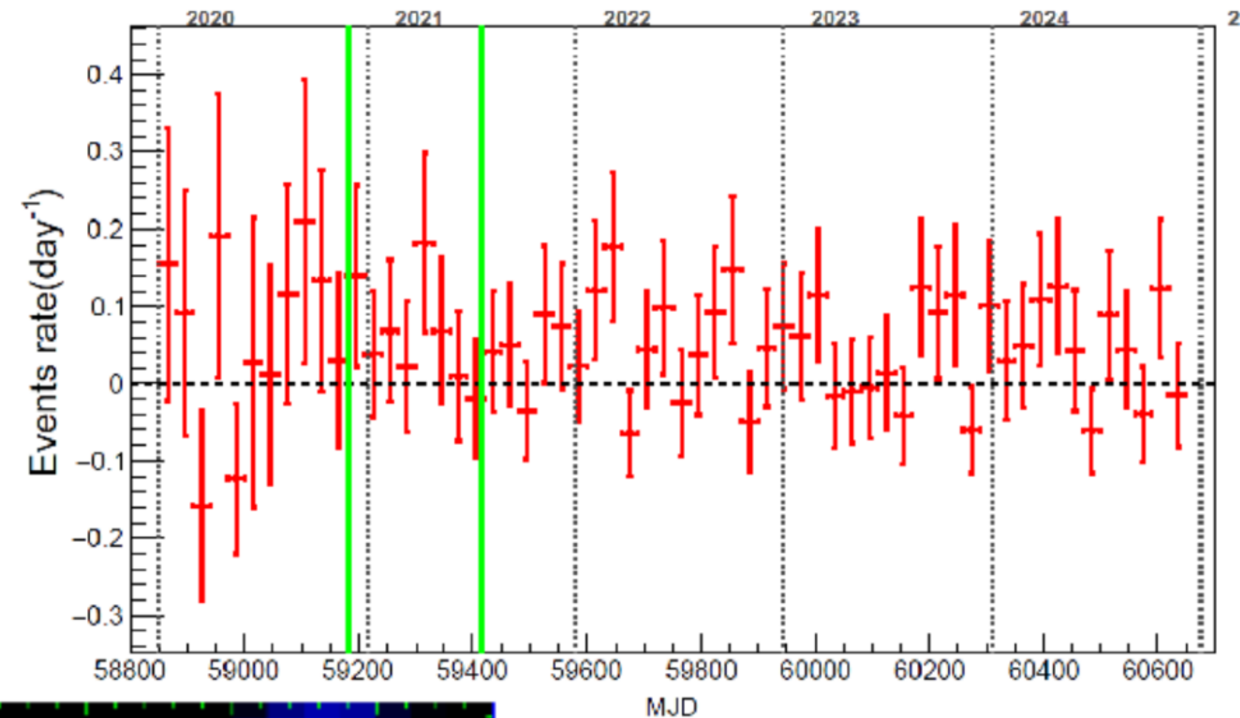


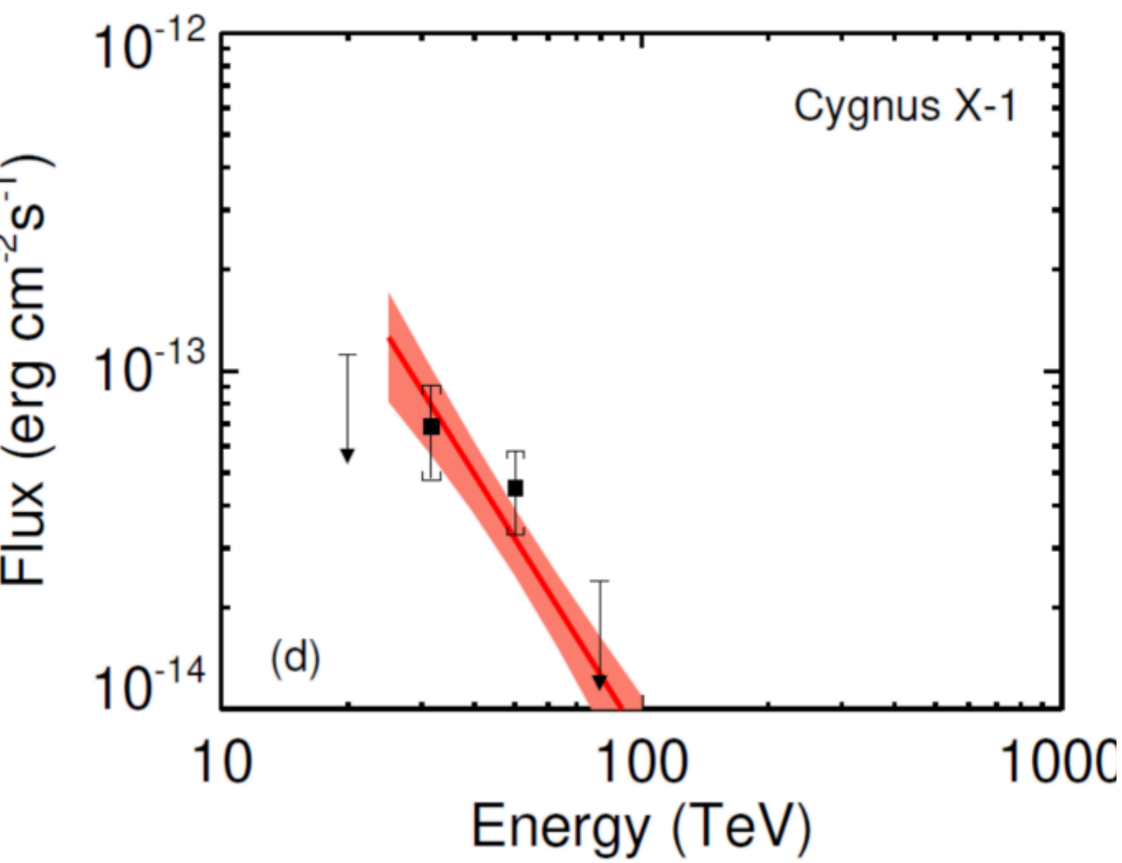


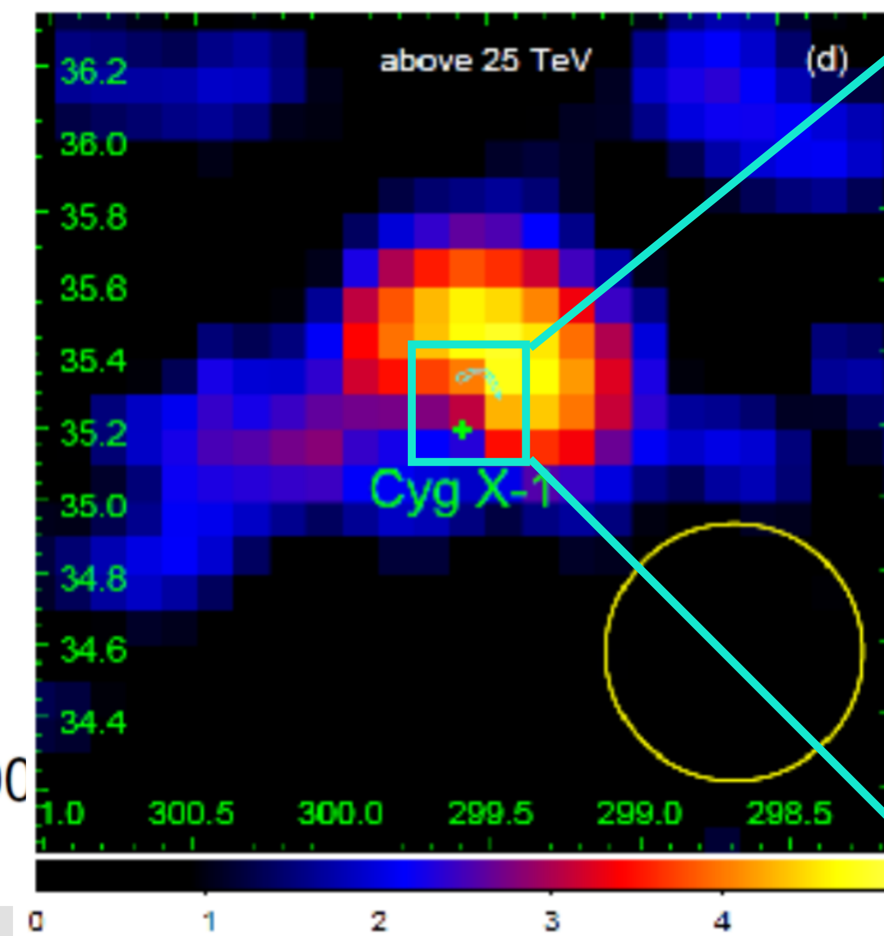
Fernández-Barral+, ICRC 2017

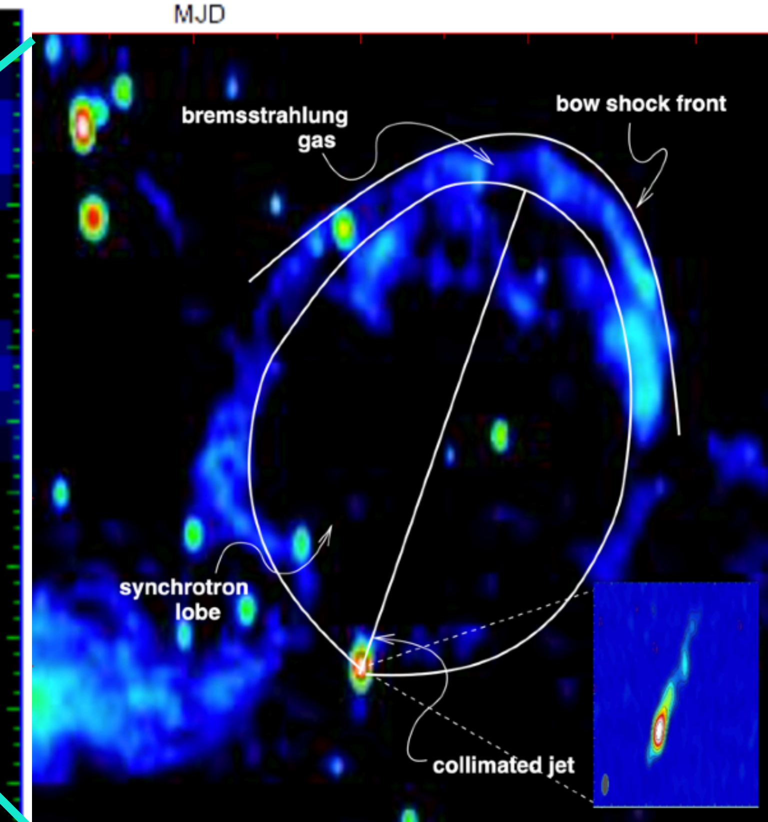
Cygnus X-1 by LHAASO

- A point-like source is detected with significance of 4.4 sigma above 25 TeV.
- No evidence of variability (caveat: 4.4 sigma only)







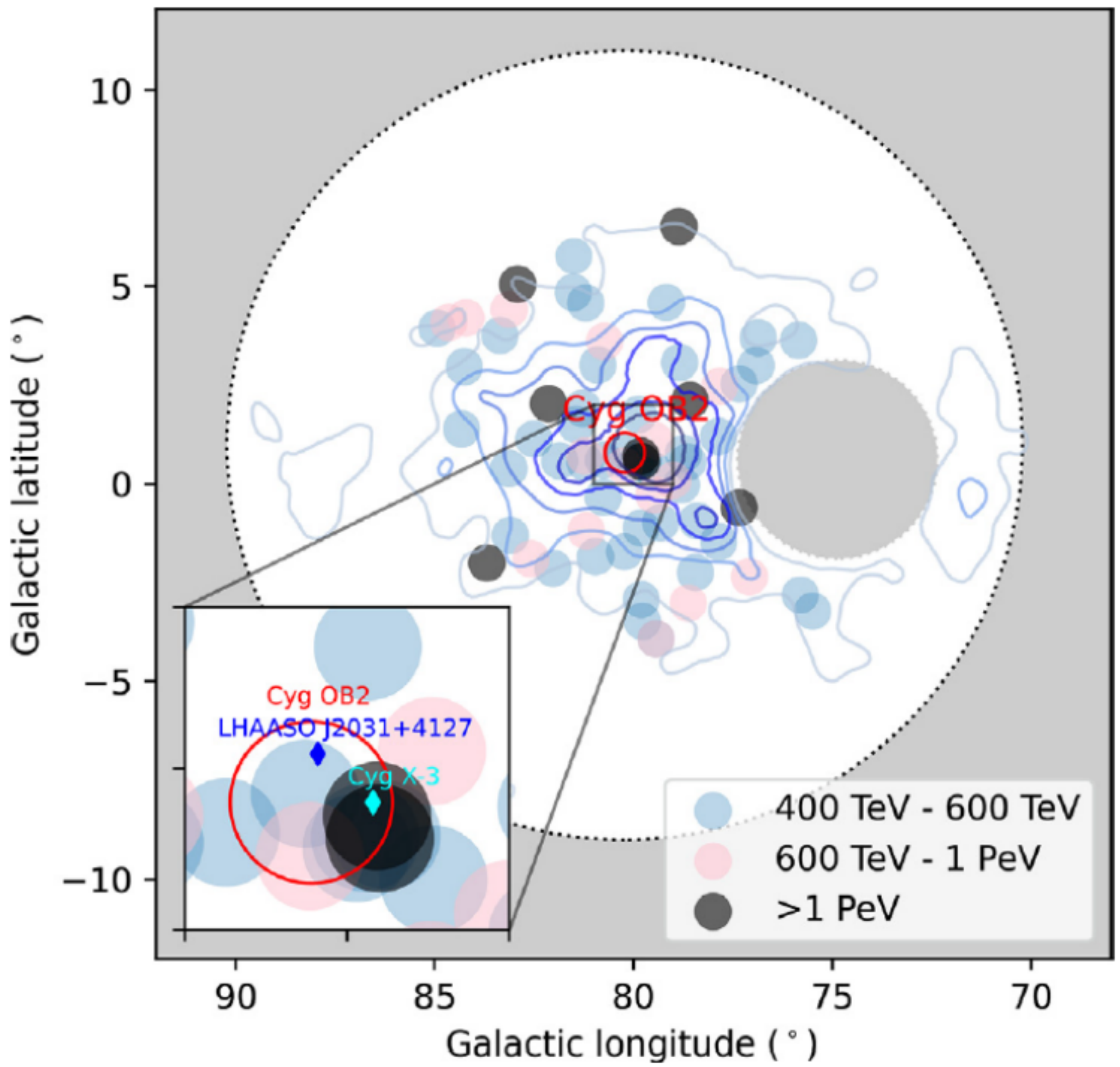


Gallo+ 2005, Nature

LHAASO collaboration, 2024, submitted, arXiv:2410.08988

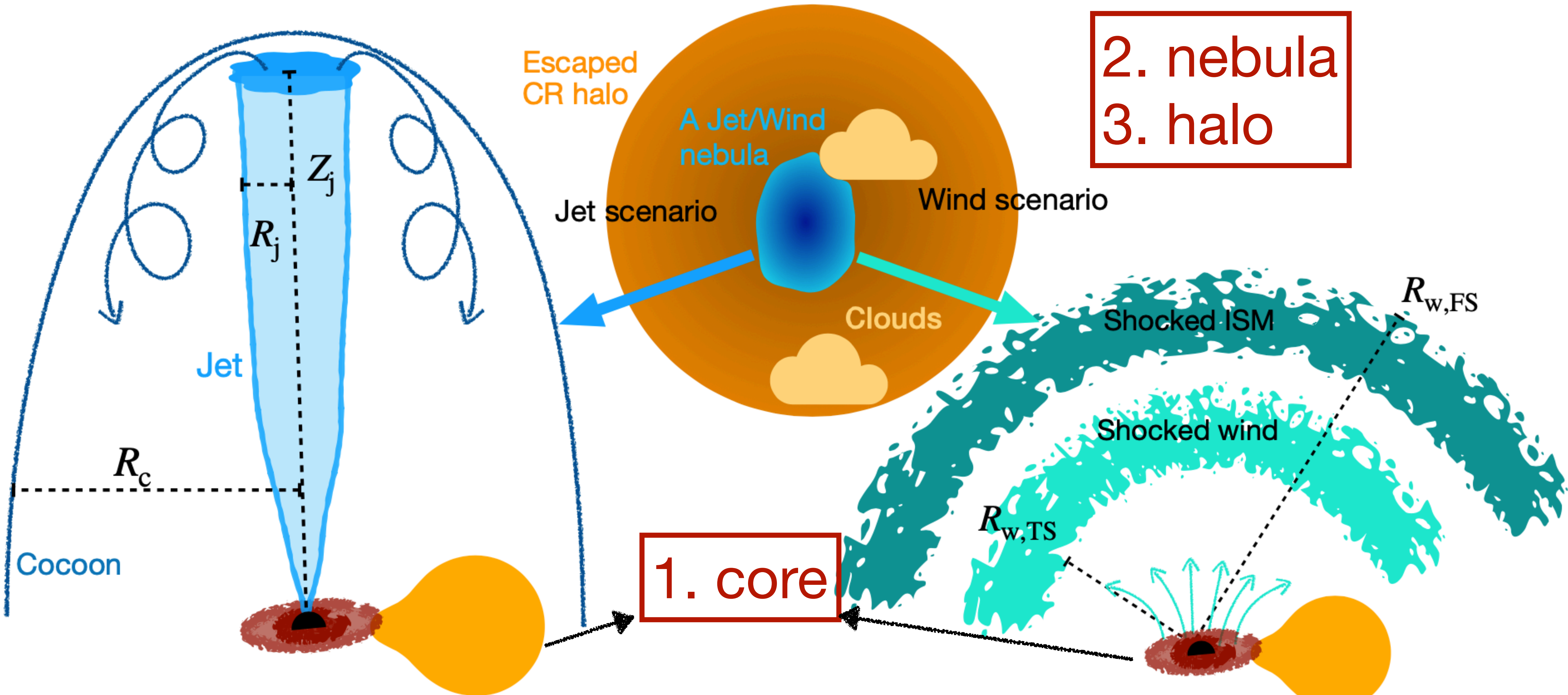
Possible UHE from Cygnus X-3

- In the Cygnus bubble, 7 out of the 66 photons with energy >400 TeV and 2 out of 8 with energy > 1PeV are concentrated within 0.5 degree, 5–10 times higher than expectation of bubble
- Extra contribution from Cygnus X-3 (stay tuned!!)



The origin of UHE emission

- Multiple acceleration and emission site from different scales, multi-wavelength would greatly help to resolve
- Particles need to be efficiently accelerated to > PeV energies (super-PeVatrons)



JW, Reville & Aharonian, 2025, ApJL, arXiv:2507.21048

General requirements on Accerlation

- Maximum particle energy (Hillas limit)
  $E_{\max} = Ze\bar{\mathscr{E}}R$
  $\bar{\mathscr{E}} \sim \beta B$ in ideal MHD

- Source Poynting flux
  $$L_B = \frac{B^2}{4\pi}\beta c\,\omega\pi R^2$$
  $\omega = 1,4$ is the geometric factor

- Source kinetic flux
  $L_{\mathrm{K}} = (\Gamma - 1)\rho c^2 \beta c\,\omega\pi R^2 \equiv L_{\mathrm{B}}/\sigma$
  magnetization
  $\sigma = B^2/[4\pi(\Gamma - 1)\rho c^2]$

General constraints on Super-PeVatrons

- Maximum particle energy (Hillas limit)
  $E_{\rm max} = Ze\bar{\mathscr{E}}R$
  $\bar{\mathscr{E}} \sim \beta B$ in ideal MHD
- Source Poynting flux
  $$L_B = \frac{B^2}{4\pi}\beta c\,\omega\pi R^2$$
  $\omega = 1,4$ is the geometric factor
- Source kinetic flux
  $L_{\rm K} = (\Gamma - 1)\rho c^2 \beta c\,\omega\pi R^2 \equiv L_{\rm B}/\sigma$
  magnetization
  $\sigma = B^2/[4\pi(\Gamma - 1)\rho c^2]$

- Maximum particle energy (Hillas limit)
  $E_{\rm max} = 35Z\sigma_{-1}^{1/2}(L_{\rm K,39}\beta)^{1/2}\omega^{-1/2}$ PeV
- For 10 PeV protons:
  $$L_{\rm K} \geq 10^{38}\left(\frac{E_{\rm max}}{10\,{\rm PeV}}\right)^2 \omega\,\beta^{-1}\sigma_{-1}^{-1}\ {\rm erg/s}$$
  - If $v = \beta c = 0.1c$ or Hillas limit cannot be reached, a flux of $\gtrsim 10^{39}{\rm erg/s}$ is needed.
- Jet/Wind power is essential: X-ray (intrinsic) luminosities, the nebula dynamics

Microquasars as Super-PeVatrons

LHAASO
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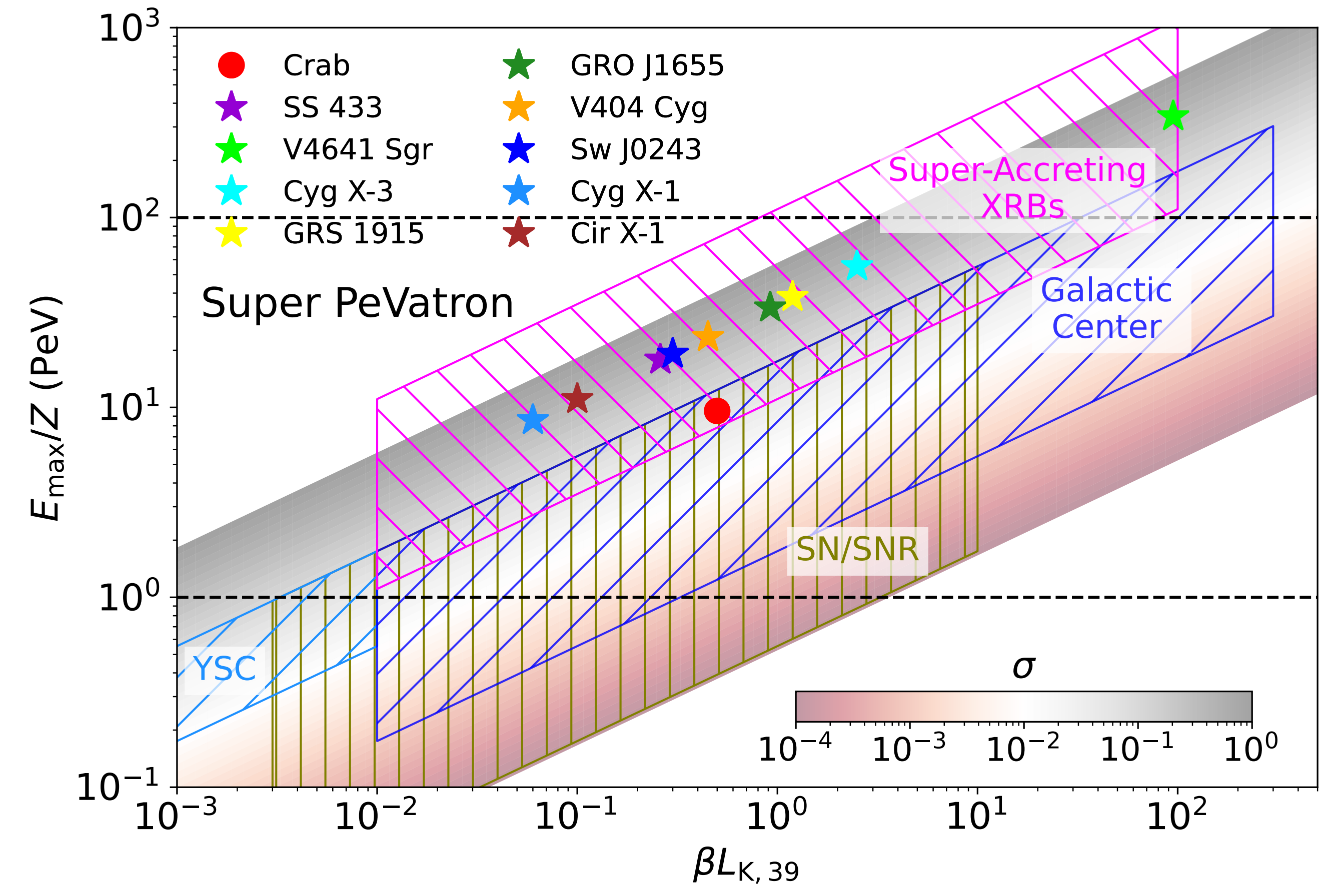
- Microquasars at near/super-Eddington states are perfect candidates for cosmic rays (CRs) above PeV energies (super-PeVatrons)
- The number of sources is essential to constrain their contribution to CRs

Sources	Power (10^{39} erg/s)	Velocity (c)	Magnetization
YSC[a]	$0.1-1$	$0.003-0.01$	$10^{-4}-0.1$
SN/SNR[b]	$0.1-10^3$	$0.03-0.1$	$10^{-4}-0.1$
GC* [c]	$10-3\times10^3$	$10^{-3}-0.1$	$10^{-3}-0.1$
XRB[d]	$0.1-10^2$	$0.1-1$	$0.01-1$
Crab[e]	0.5	1	0.06
SS 433[f]	1	0.26	$0.1\sigma_{-1}$
V4641 Sgr[g]	10^2	0.95	$0.1\sigma_{-1}$
Cyg X-3[h]	5	0.5	$0.1\sigma_{-1}$
GRS 1915+105[i]	1.7	0.95	$0.1\sigma_{-1}$
GRO J1655-40[j]	1	0.92	$0.1\sigma_{-1}$
V404 Cyg[k]	0.9	0.5	$0.1\sigma_{-1}$
Swift J0243.6+6124[l]	1.5	0.2	$0.1\sigma_{-1}$
Cyg X-1[m]	0.1	0.6	$0.1\sigma_{-1}$
Cir X-1[n]	0.2	0.5	$0.1\sigma_{-1}$

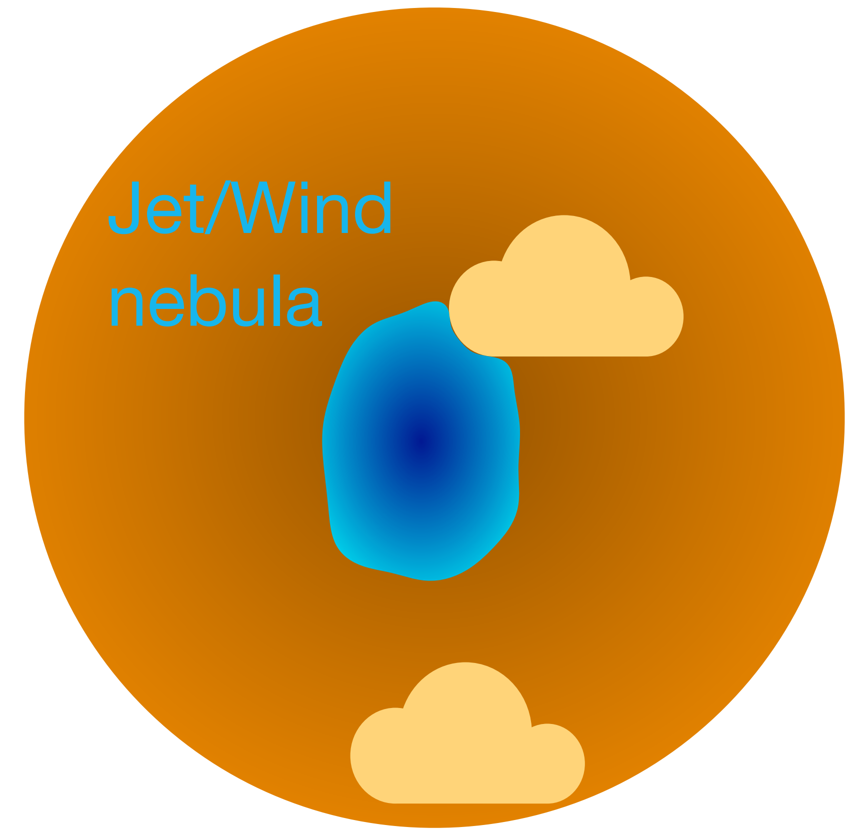


Caveat for flaring sources

JW, Reville & Aharonian, 2025, ApJL, arXiv:2507.21048

Nebula emission

- Leptonic (Inverse Compton) emission from the jet/wind-driven nebulae
- Due to cooling, sources size is limited
  - $c\tau_{\mathrm{c}} \approx 100(E_e/1\ \mathrm{PeV})^{-1}(B/6\mu\mathrm{G})^{-2}\ \mathrm{pc}$
- Age estimation can differ by a factor of 10



Jet nebula

$$Z_{\mathrm{j}} = \int \beta_{\mathrm{h}} c \mathrm{d}t \approx 10^3 \beta_{\mathrm{j}} t_{\mathrm{dec},0}^{1/3} t_5^{2/3}\ \mathrm{pc};$$

$$R_{\mathrm{c}} = \int \dot{R}_{\mathrm{c}} \mathrm{d}t \approx 20 \frac{L_{\mathrm{j},39}^{1/4} \epsilon_{\mathrm{c}}^{1/4} t_5^{7/12}}{t_{\mathrm{dec},0}^{1/12} n_a^{1/4} \beta_{\mathrm{j}}^{1/4}}\ \mathrm{pc}.$$

Wind nebula

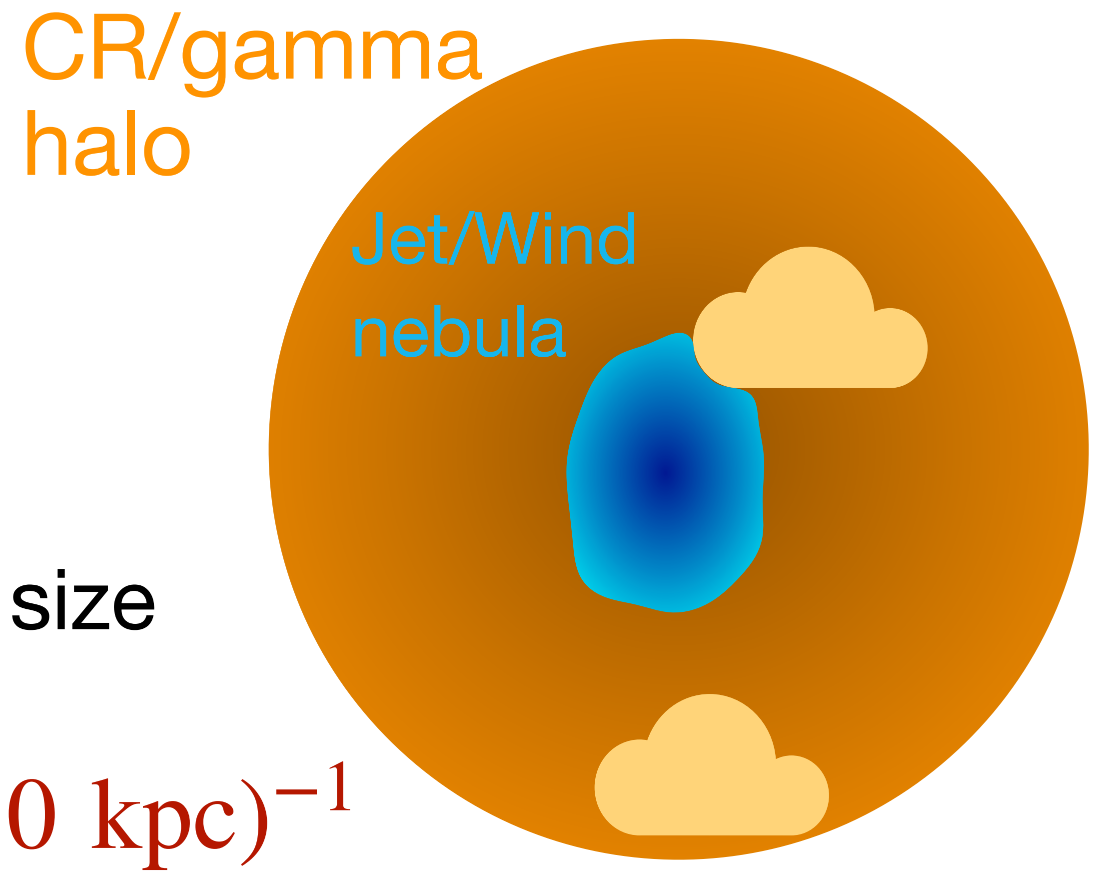
$$R_{\mathrm{w,TS}} = 0.9 \left(\frac{L_{\mathrm{w}} t^{4/3}}{\rho_{\mathrm{a}} \beta_{\mathrm{w}}^{5/3} c^{5/3}}\right)^{\frac{3}{10}} = 1.1 \frac{L_{\mathrm{w},39}^{3/10} t_5^{2/5}}{n_{\mathrm{a}}^{3/10} \beta_{\mathrm{w}}^{1/2}}\ \mathrm{pc}$$

$$R_{\mathrm{w,FS}} = 0.76 \left(\frac{L_{\mathrm{w}} t^3}{\rho_{\mathrm{a}}}\right)^{\frac{1}{5}} = 28 \frac{L_{\mathrm{w},39}^{1/5} t_5^{3/5}}{n_{\mathrm{a}}^{1/5}}\ \mathrm{pc},$$

JW, Reville & Aharonian, 2025, ApJL, arXiv:2507.21048

Halo emission

- Hadronic emission from cosmic rays escaped from the nebulae
- A fraction of kinetic power into CRs:
  $\dot{Q}_p = \epsilon_{\rm CR} L_{\rm K} (E/3\,{\rm GeV})^{2-s}$
- Making a CR halo in ISM with angular size (diffusion dominated escape):
  $\theta_h = R_{\rm Halo}/d = 0.7^{\circ} D_{30}^{1/2} E_{\rm PeV}^{\delta/2} t_3^{1/2} (d/10\ {\rm kpc})^{-1}$
- Gamma-ray flux with s=2.2:
  $$F_\gamma(E_\gamma = 100\ {\rm TeV}) \approx 10^{-13} \epsilon_{\rm CR,-1} L_{\rm K,39} (\theta/1^{\circ})^2 n_{\rm t} D_{30}^{-1}\ {\rm erg\ cm^{-2} s^{-1}}$$
- Nearby over density (e.g., cloud) would lead to localized structures



JW, Reville & Aharonian, 2025, ApJL, arXiv:2507.21048

Summary

- VHE/UHE γ-rays provide a new window to study microquasars
- LHAASO detected UHE emission associated with 4 + 1 candidate (4.4 sigma), but most-likely from large-scale jets
  - What drives the large-scale jets?
- Super-accreting microquasars ($\gtrsim 10^{39}$ erg/s) can be super-PeVatrons and galactic CR sources above PeV energies
  - High jet power means high maximum CR energy, high CR flux and high gamma-ray flux
- MWL observation will be greatly appreciated
  - To resolve the acceleration/emission site and mechanisms
  - To find out the number of super-accreting XRBs and their variabilities, metallicities (origin of cosmic rays)