Ultrahigh-energy gamma-ray emissions associated with Black Hole-Jet Systems

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On behalf of the LHAASO Collaboration (arXiv: 2410.08988)
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LHAASO
高海拔宇宙线观测站

CDY Seminar, 27.11.2024 (Online)

Outline

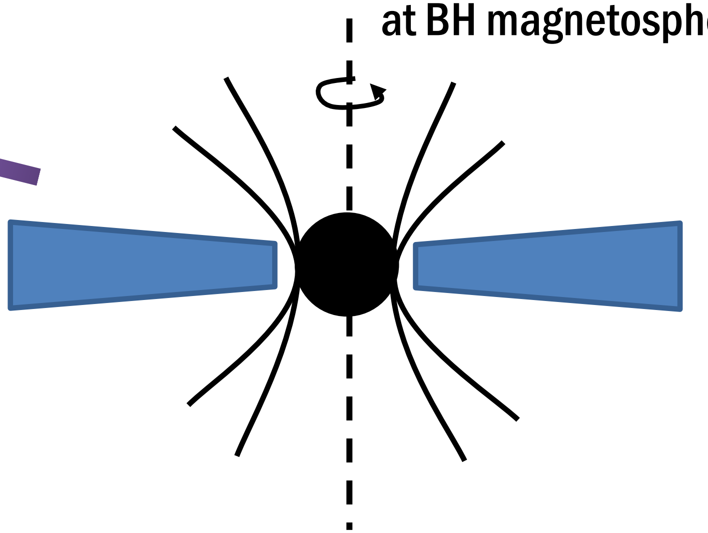
- A brief introduction of microquasars and LHAASO
- LHAASO's observations of microquasars
  - SS433
  - V4641 Sgr
  - GRS 1915+105
  - MAXI J1820+070
  - Cygnus X-1
- Discussion
- Summary

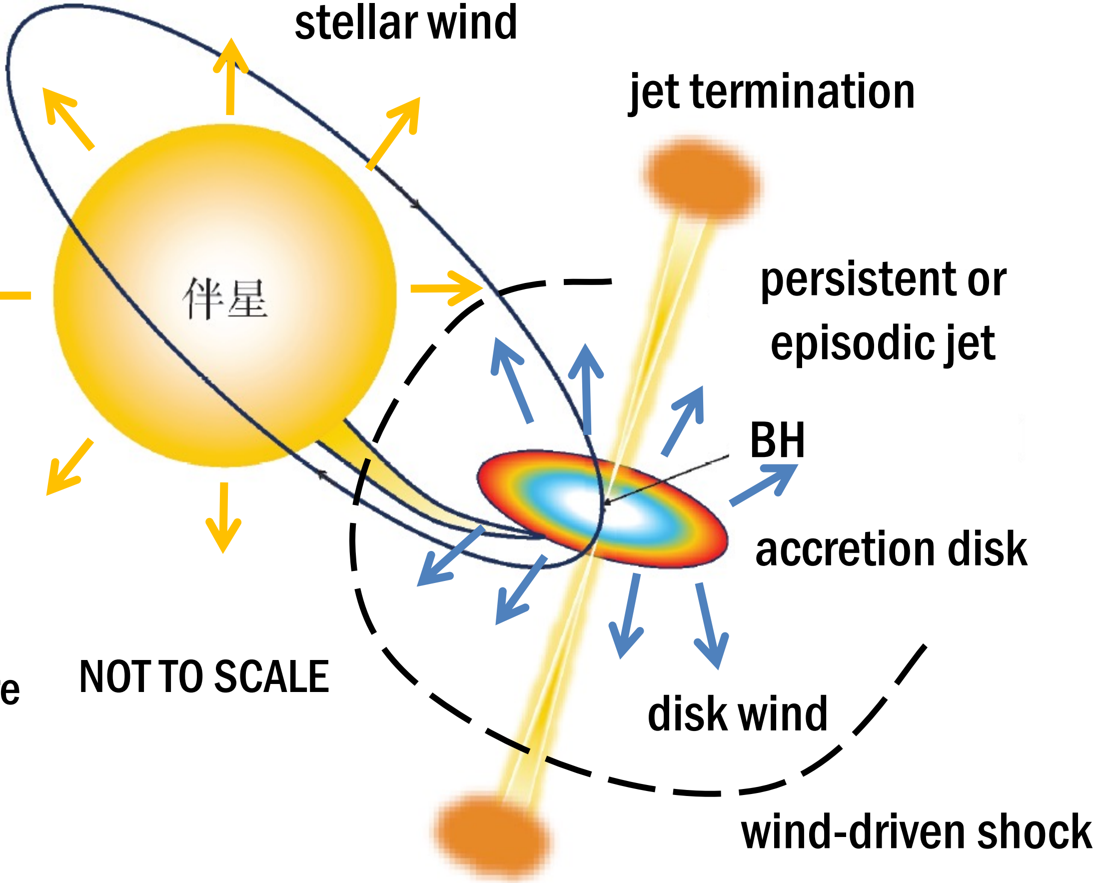
Microquasars

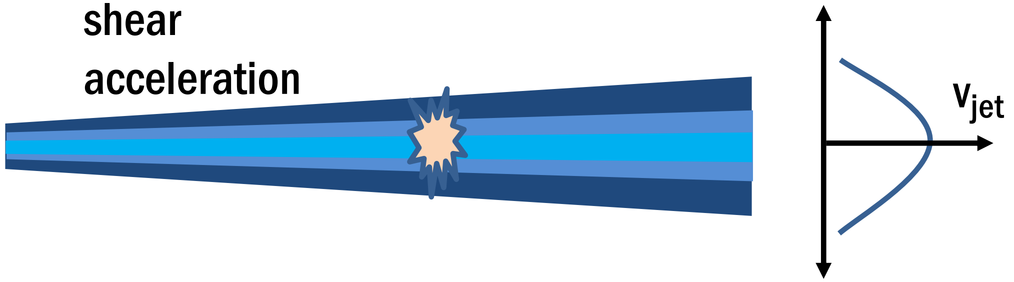
Binary + Mildly-relativistic Jets

→ **NS or stellar-mass BH + a donor star**

Potential extreme particle accelerator where and how? maximum energy?





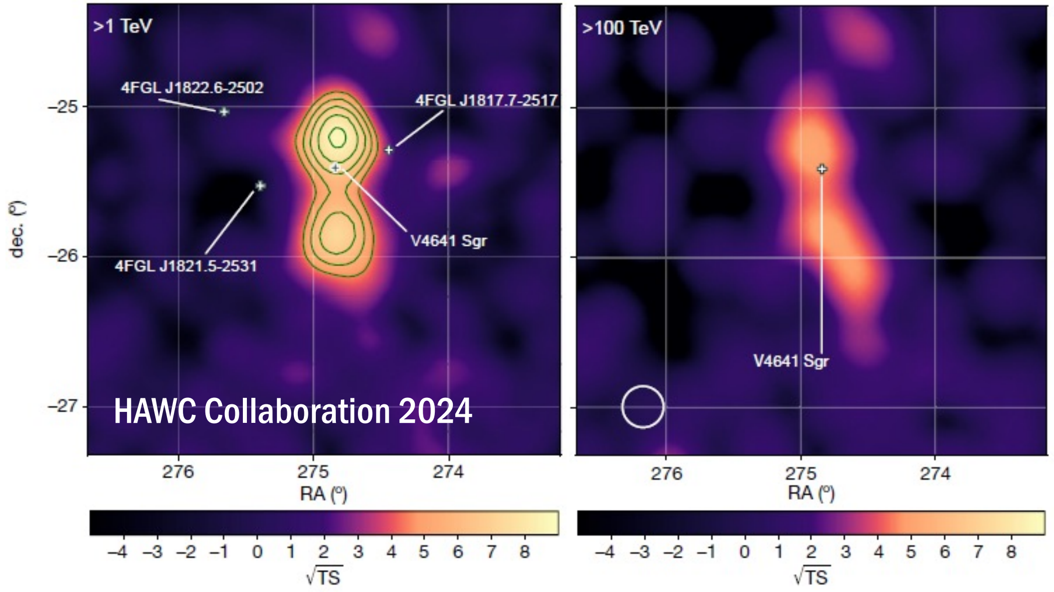


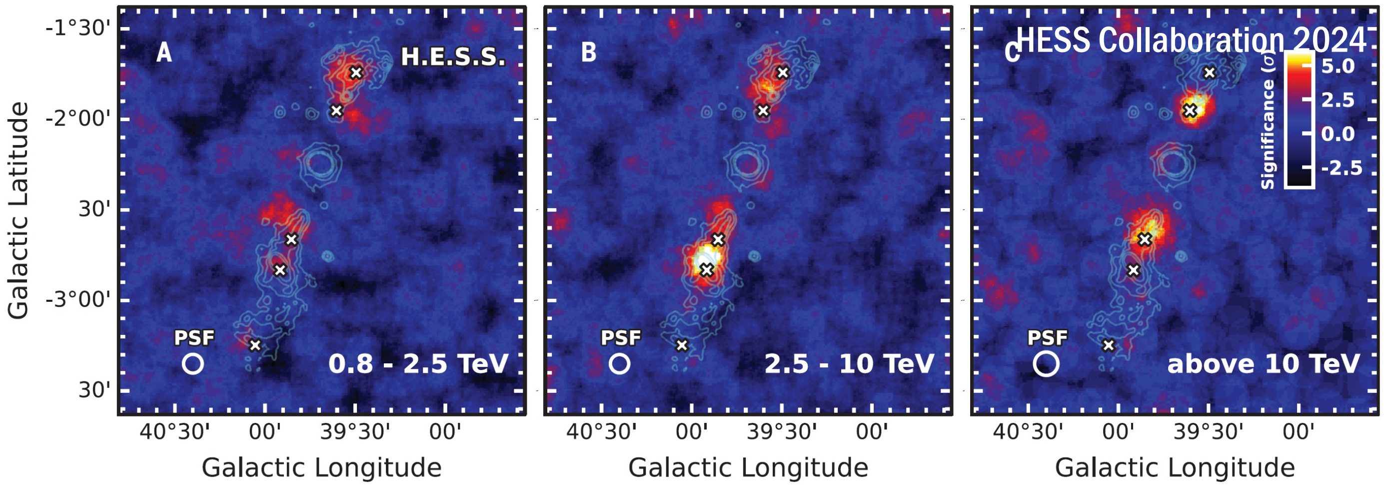
High-energy gamma rays as probes of efficient particle acceleration

Small Scale
intense radiation from corona, companion star;
dense matter in accretion flow, wind

Large Scale
CMB/ISRF, Molecular/Atomic Clouds

- Cygnus X-3 Fermi-LAT, AGILE: sporadic; 4.8h orbital modulation
  EAS at early 1980s, PeV emission with extraordinary flux?
- Cygnus X-1 Fermi-LAT: sporadic; correlated with hard state; hint of orbital modulation; AGILE: day-scale flare; MAGIC: hour-scale flare
- V404 Cygni? Fermi-LAT: GeV flare (controversial)
- GRS 1915+105? HEGRA: tentative detection of a flare
- SS 433 Fermi-LAT, HESS, HAWC: up to ~1<100 TeV, persistent emission, from two X-ray lobes (by HESS)
- V4641 Sgr, HAWC up to 200TeV



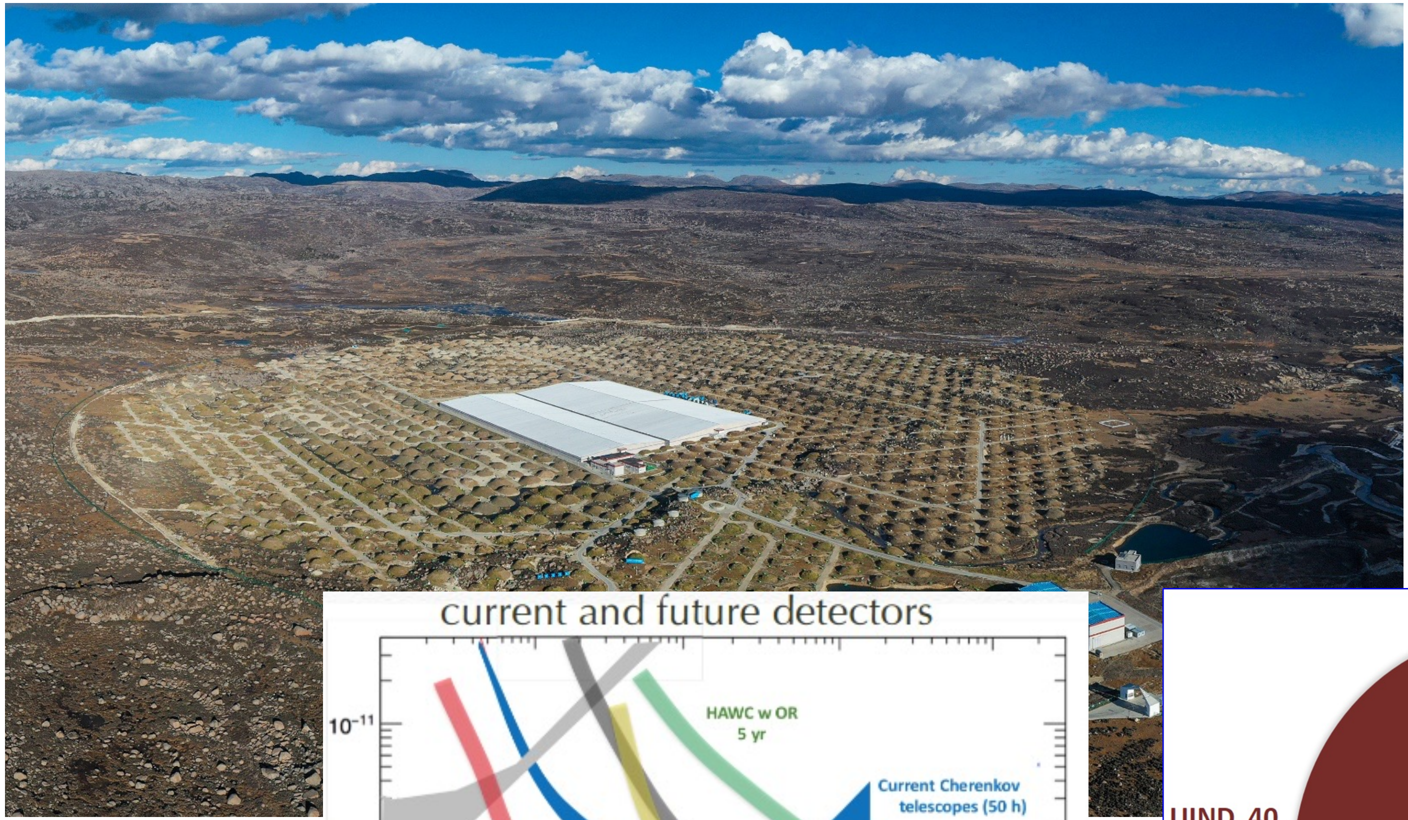


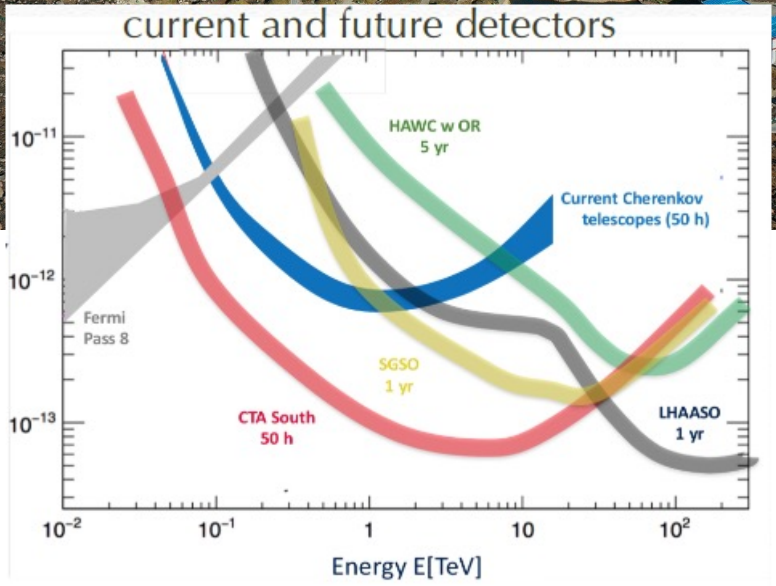
Energy-dependent morphology: leptonic, acceleration of 100TeV e-

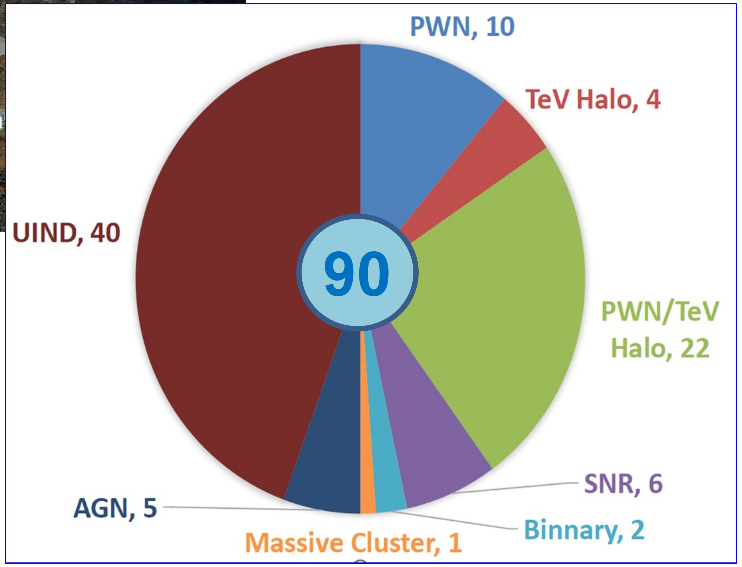
Large High Altitude Air Shower Observatory (LHAASO)

EAS type gamma-ray Detector @4410m

- 100% duty cycle
- Large FoV, θ ~ 50 deg (or larger for bright source)
- High rejection power of CR background
- WCDA : 1-30 TeV, 78000m^2
- KM2A: 20 TeV - a few PeV , km^2
- Angular resolution: 0.5 deg @ 1TeV
  0.2 deg @ 10TeV
  0.3 deg @ 25 TeV
  0.2 deg @ 100 TeV







1st LHAASO Catalog (LHAASO Coll. 2024, ApJS) based on data up to 31.07.2022

Data analysis of KM2A

Data including
1/2 array from 26/Dec/2019 – 30/Nov/2020 (with a live time of 302 days)
3/4 array from 01/Dec/2020 – 19/Jul/2021 (with a live time of 219 days)
full array from 20/Jul/2021 – 31/Jan/2024 (with a live time of 884 days)

Zenith angle <50 deg; extend to 60 deg for V4641 Sgr (dec ~ -25 deg, minimum zenith angle 55 deg)

Data analysis of WCDA

March 8, 2021 to May 31, 2024, with a total live time of 1092 days

12 dynamically confirmed BHs with persistent or episodic jets in FoV of LHAASO
(https://www.astro.puc.cl/BlackCAT)

12 BH microquasars in LHAASO's FoV, 5 associated with UHE gamma-ray sources

Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0457	9.7[c]	2.78 ± 0.19	$25 - 100$	$0.70°$	0.10
SS 433 W.	4.6 ± 1.3[32]	J1910+0509	8.6[c]	2.92 ± 0.21	$25 - 100$		0.082
SS 433 central		J1911+0513	9.8	4.03 ± 0.29	$100 - 400$	$0.32°$	0.32
V4641 Sgr	6.2 ± 0.7[33]	J1819-2541	8.1	2.67 ± 0.27	$40 - 1000$	$0.36°$	3.9
GRS 1915+105	9.4 ± 0.6[34]	J1914+1049	6.1	3.07 ± 0.15	$25 - 630$	$0.33°$	0.17
MAXI J1820+070	2.96 ± 0.33[35]	J1821+0726	5.9	3.19 ± 0.29	$25 - 630$	$< 0.28°$	0.13
Cygnus X-1	2.2 ± 0.2[36]	J1957+3517	4.0	4.07 ± 0.35	$25 - 100$	$< 0.22°$	< 0.01
XTE J1859+226	4.2 ± 0.5[37]	–	1.9	–	–	–	< 0.03
GS 2000+251	2.7 ± 0.7[38]	–	1.7	–	–	–	< 0.04
CI Cam	$4.1^{+0.3}_{-0.2}$[39]	–	1.4	–	–	–	< 0.03
GRO J0422+32	2.49 ± 0.3[40]	–	0.8	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14[41]	–	0.5	–	–	–	< 0.02
XTE J1118+480	1.7 ± 0.1[42]	–	0	–	–	–	< 0.01
V616 Mon	1.06 ± 0.1[43]	–	0	–	–	–	< 0.01

[a] separation between two point-like sources of SS 433 below 100 TeV; 39% containment radius for SS 433 central, V4641 Sgr and GRS 1915+105; one-tailed 95% confidence upper limit for the source size for MAXI J1820+070 and Cygnus X-1.

[b] at 100 TeV, 1 CrabUnit $\simeq 10^{-12}$ erg cm^{-2}s^{-1}

[c] the combined detection significance for the two point-like sources is 12.9σ.

All five detected microquasars show persistent or remarkable outbursts of BH activities in recent years

All seven undetected microquasars do not show notable BH activities in recent years

cooling time of particles responsible for UHE emission is > kyrs

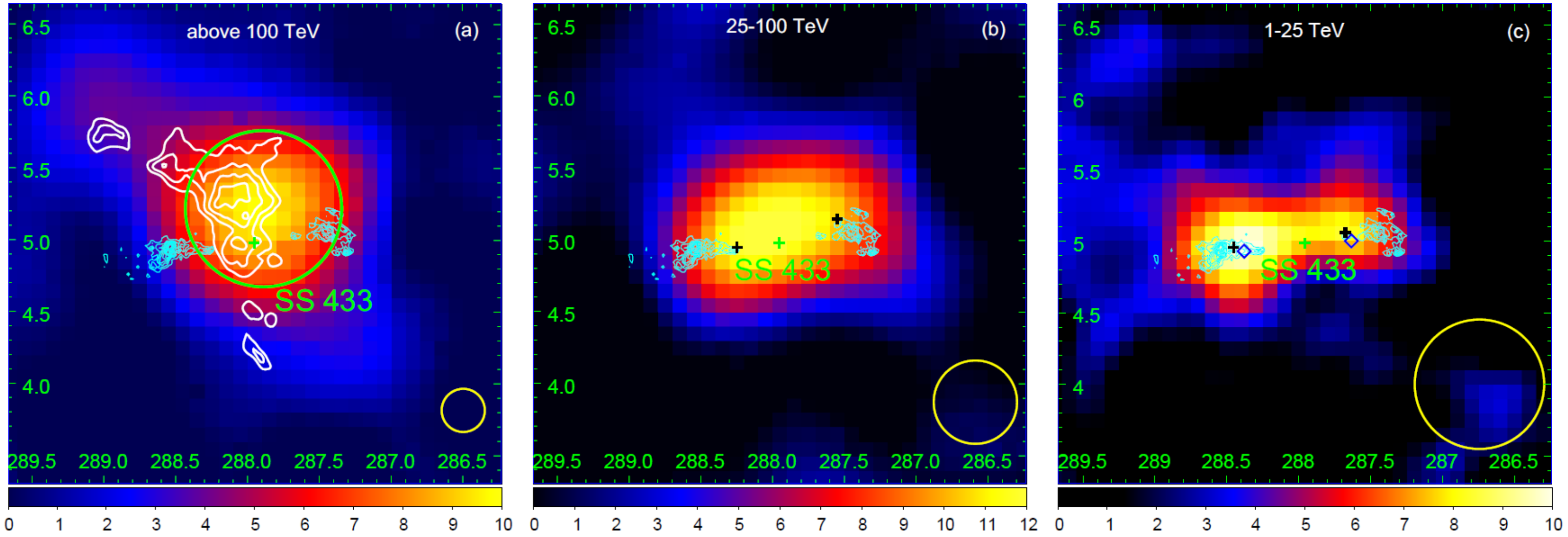
is it just coincidence?

Resolved: SS 433; V4641 Sgr; GRS 1915+105

Unresolved: MAXI J1820+070; Cygnus X-1

Is a BH's recent activity (over past decades) a proxy of UHE emission?

SS 433

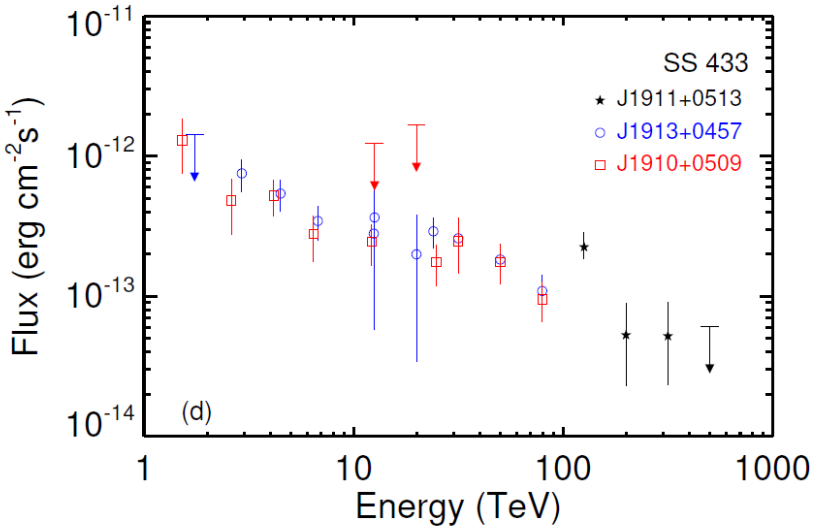


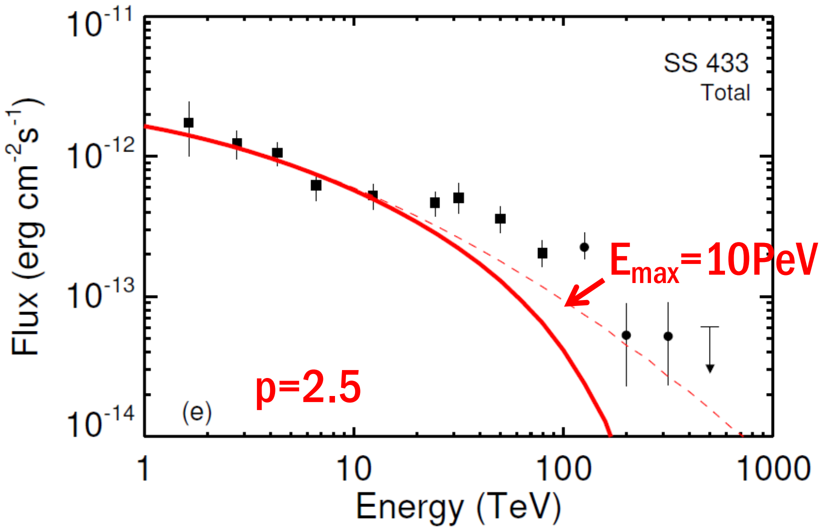
dramatic change of the morphology between low energy and high energy

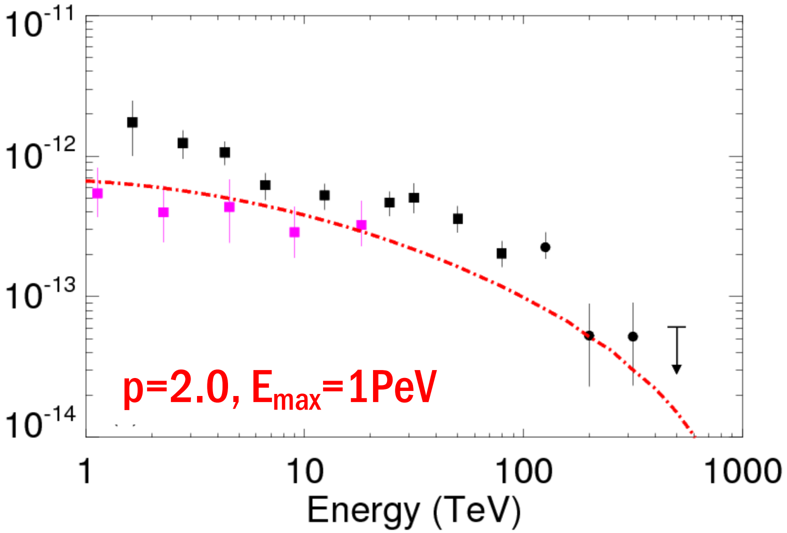
	1-25 TeV	25-100 TeV	above 100 TeV
ΔAIC	22.7	22.8	-12.5

ΔAIC<-10 favors Gaussian model

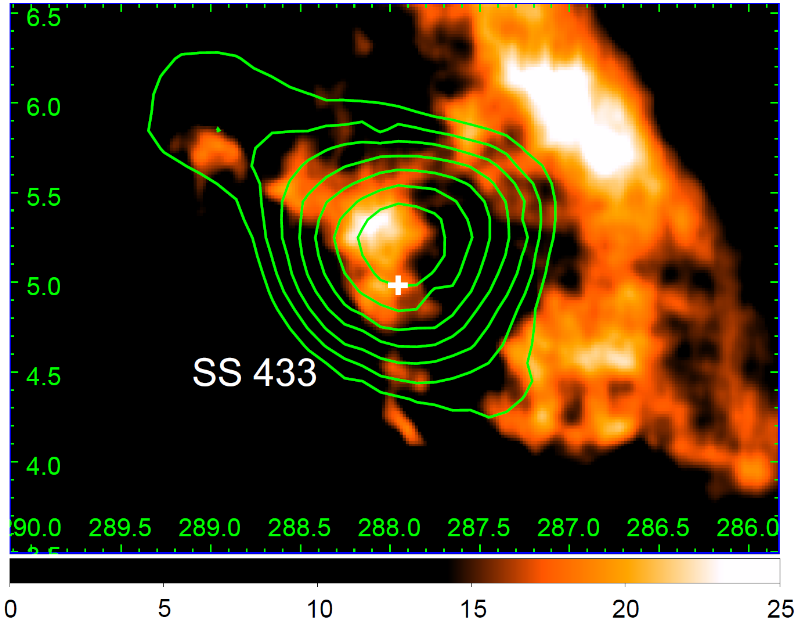
ΔAIC>-10 favors 2PS model

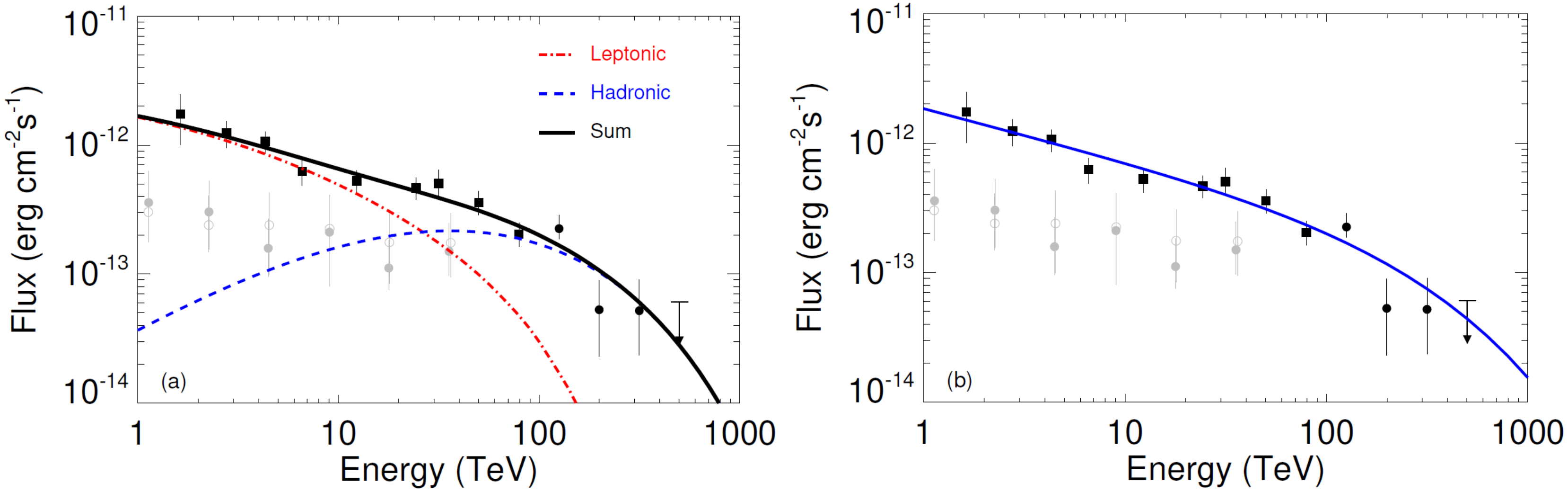


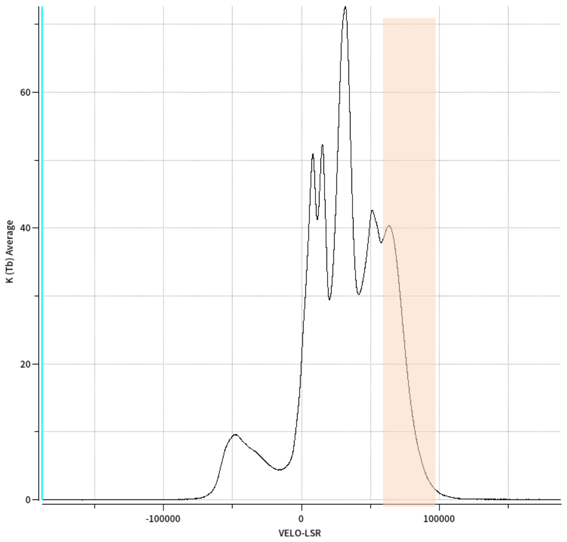




Hadronic origin of UHE emission







d=4.1±0.7kpc,
M_H=2.5e4$M_\odot$,
R_c=20pc,
n=30cm^{-3}

$$Q_{\rm p}(E_{\rm p}) = Q_{0,\rm p} E_{\rm p}^{-s_{\rm p}} \exp(-E_{\rm p}/E_{\rm p,max})$$

$$s_{\rm p} = 1.8,\ E_{\rm p,max} = 1\,{\rm PeV}.$$

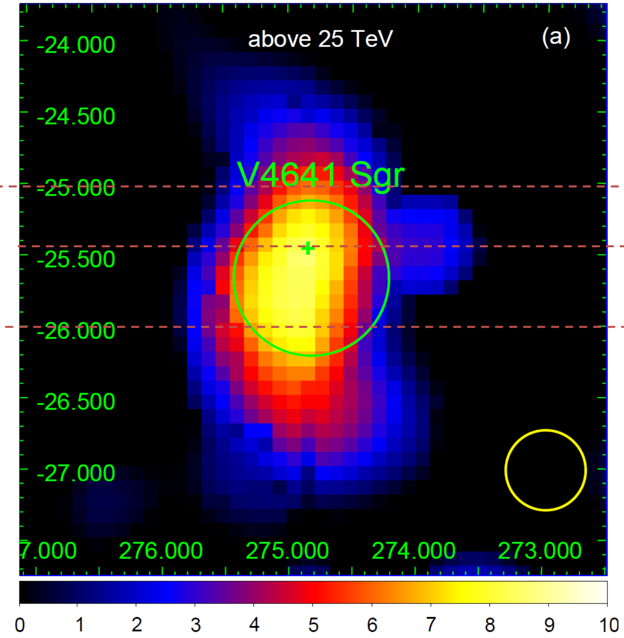
$$s_p = 2.5 \text{ and } E_{\rm p,max} = 3\,{\rm PeV}$$

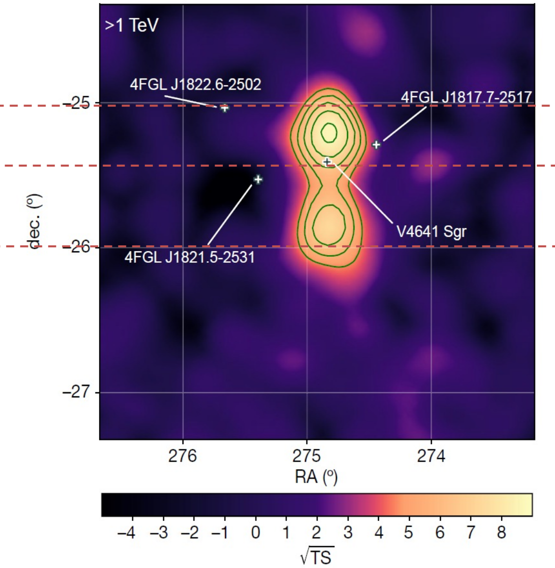
$$W_{\rm p} = 5\times 10^{50}(n_{\rm H}/10{\rm cm}^{-3})^{-1}\ {\rm erg}$$

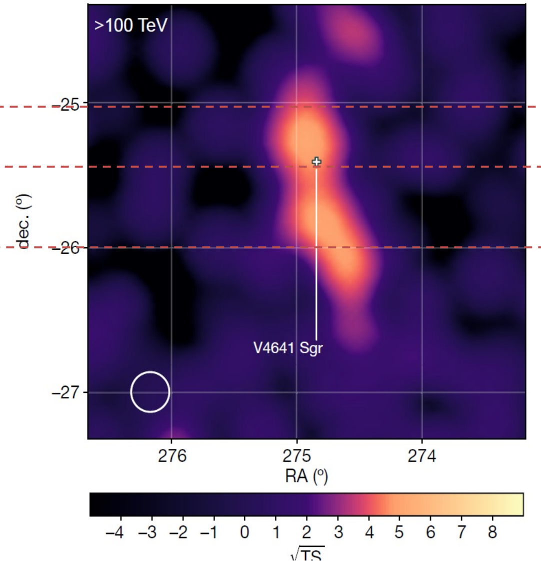
L_p=10^{39} erg/s L_p(>1PeV)=10^{38} erg/s

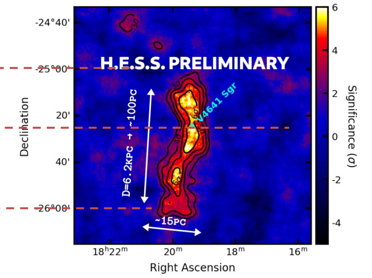
see, for example, Peretti et al. 2024 for a detailed model of particle acceleration

V4641 Sgr

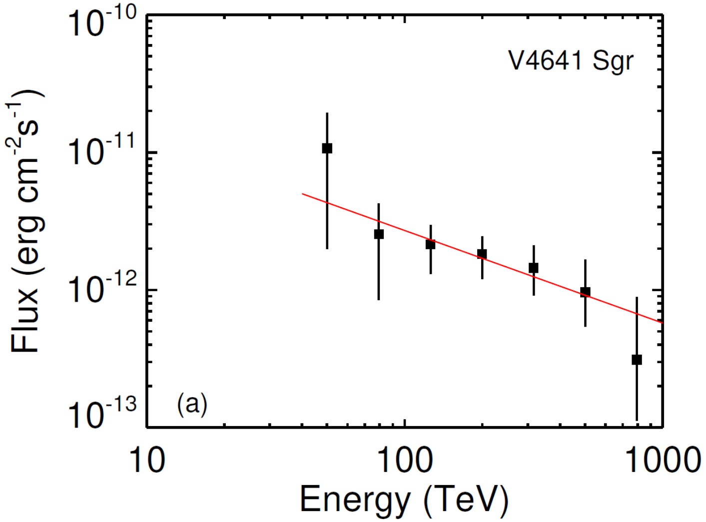






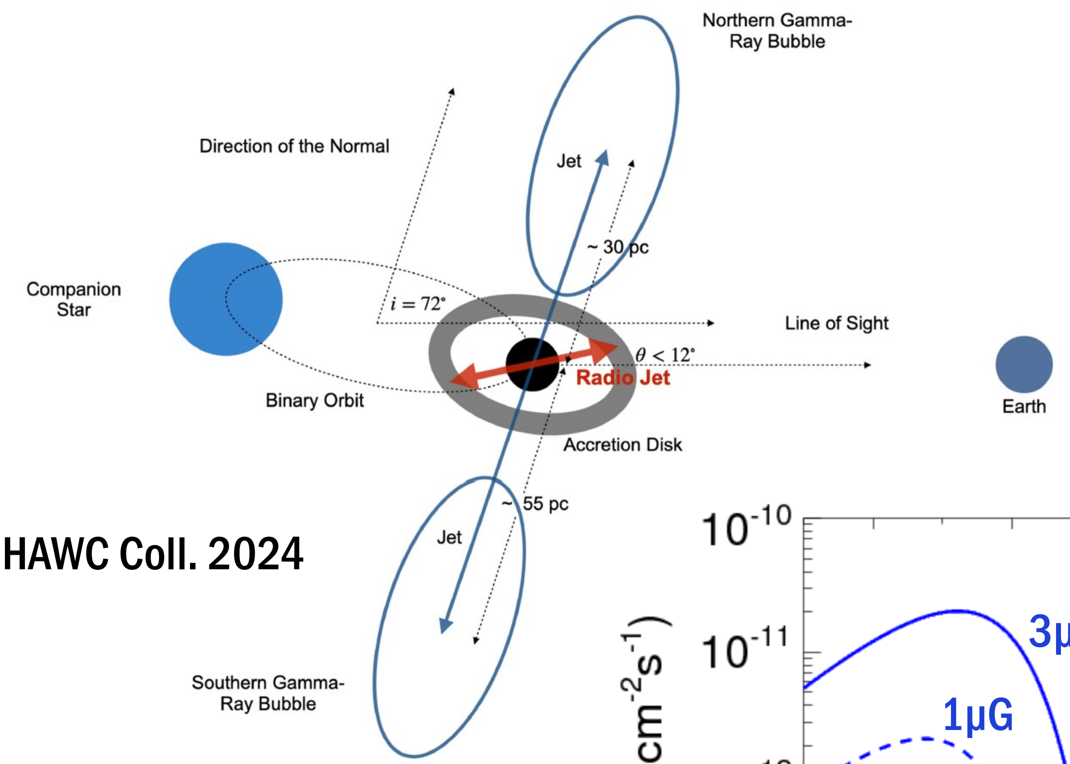


courtesy of L. Olivera-Nieto



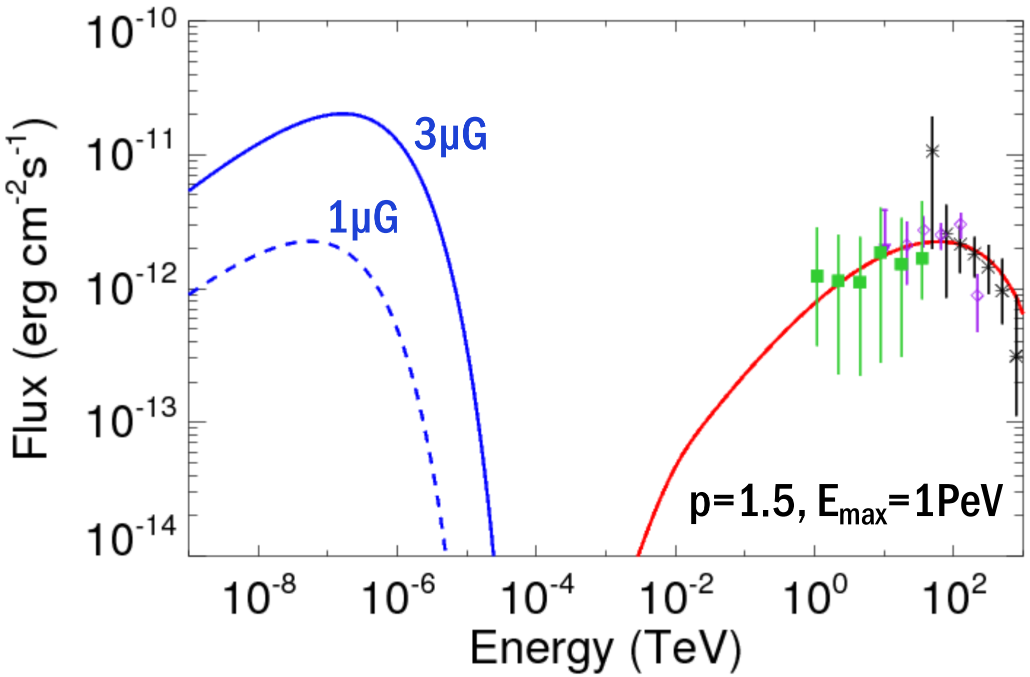
Model	Ra	Dec	L./a	W./b	N of W angle	TS
2PS	274.94±0.08 274.94±0.08	-25.97±0.09 -25.11±0.12	N/A	N/A	N/A	130.1
Rect.	274.87±0.05	-25.72±0.09	1.78±0.24	0.18±0.30	84.8 ±6	133.7
eGauss	274.87±0.05	-25.72±0.09	0.52±0.10	0.1±0.2	86 ±6	132.9

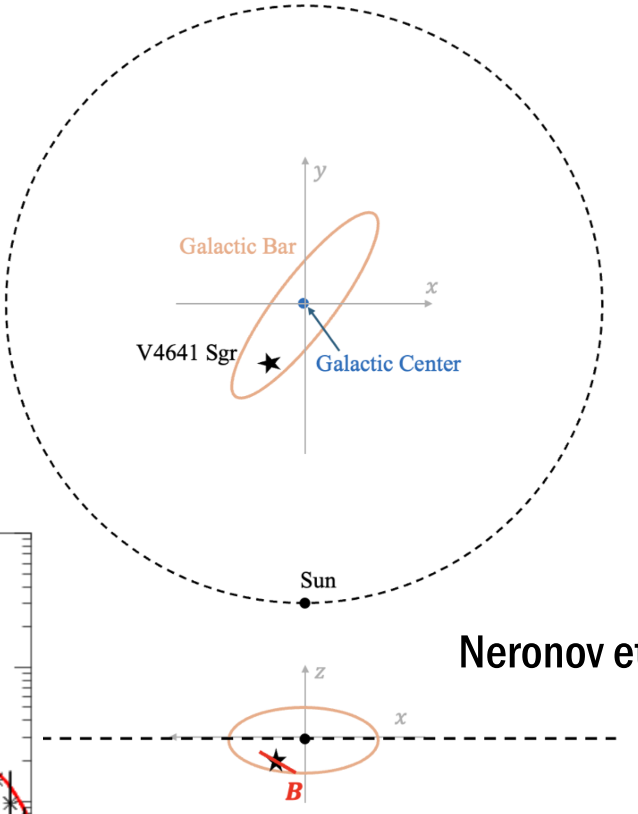
Possible interpretation of the V4641's emission



HAWC Coll. 2024

b=-4.8 deg
z=- 500pc

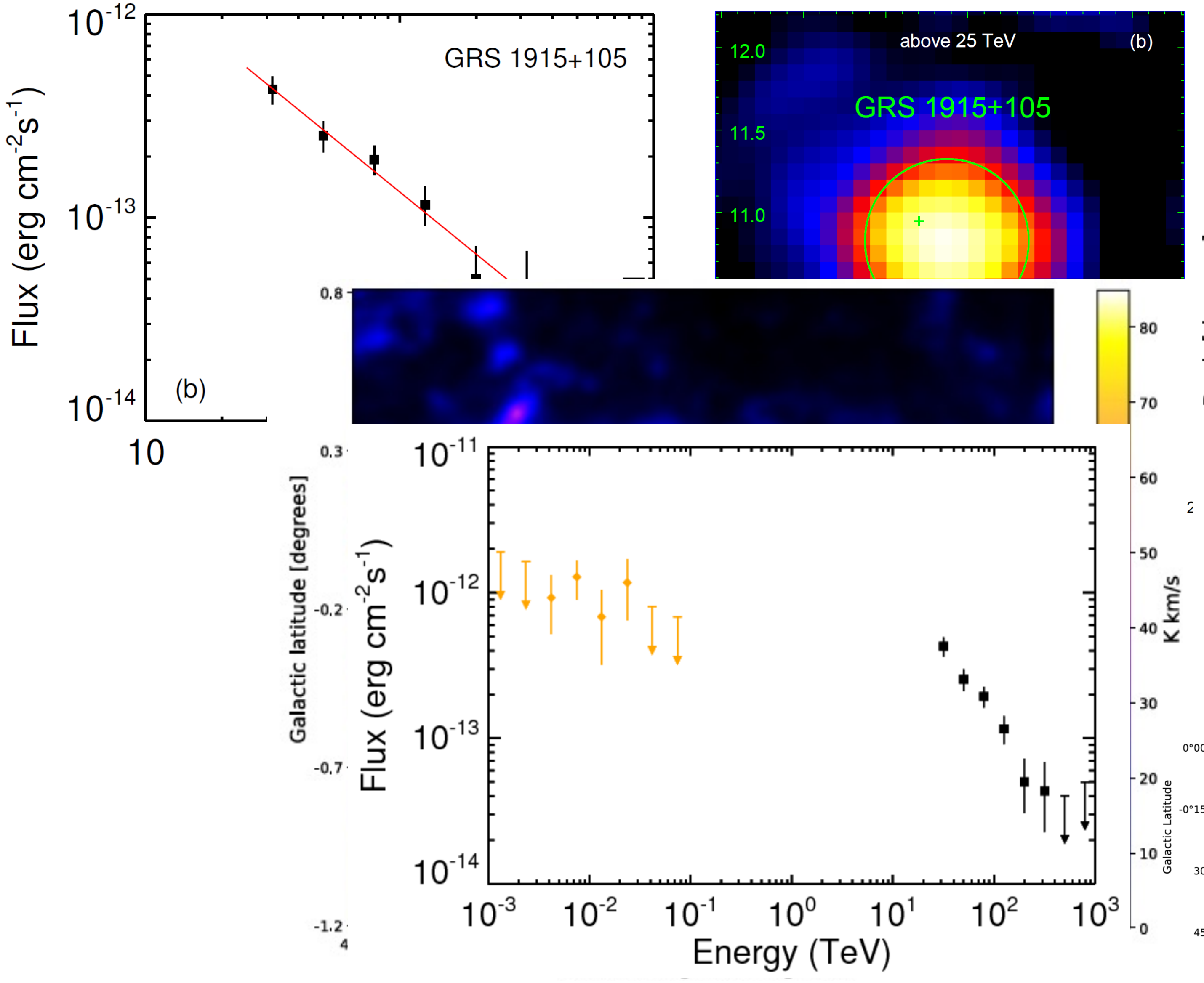


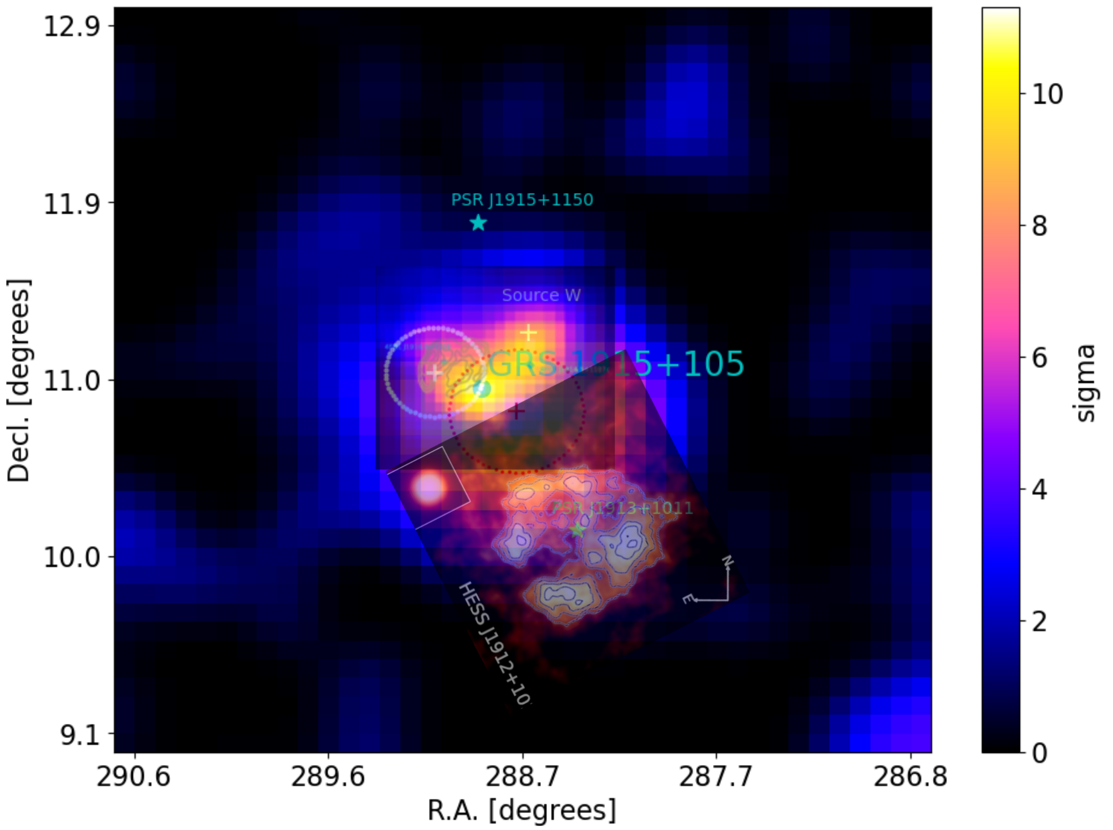


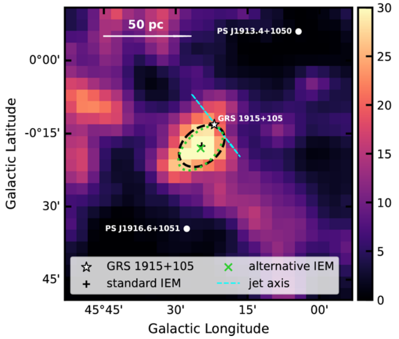
Neronov et al. 2024

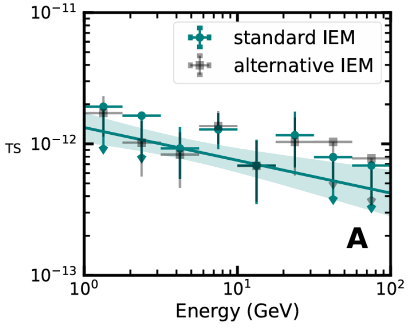
deep X-ray and atomic/molecular line observations will be crucial to understand the origin of the UHE emission

GRS 1915+105



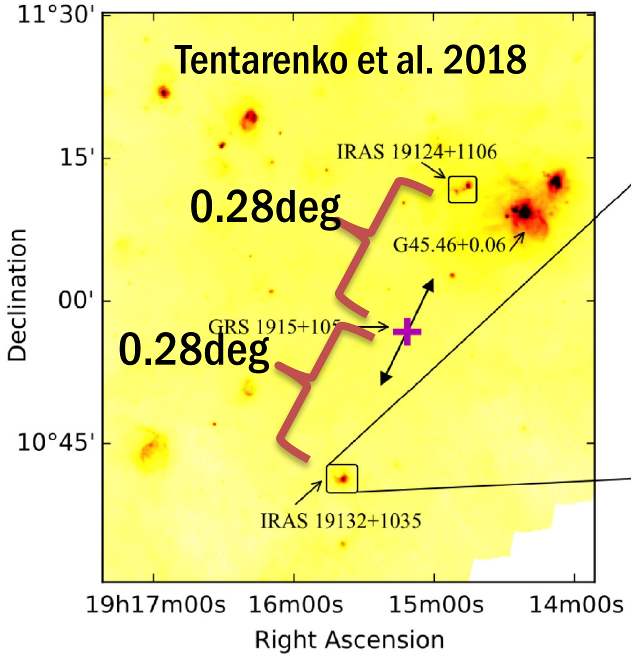


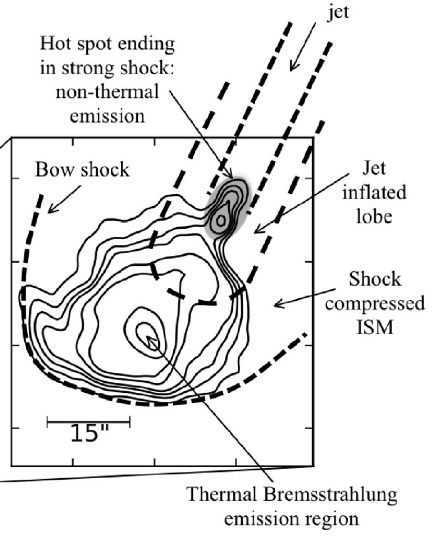




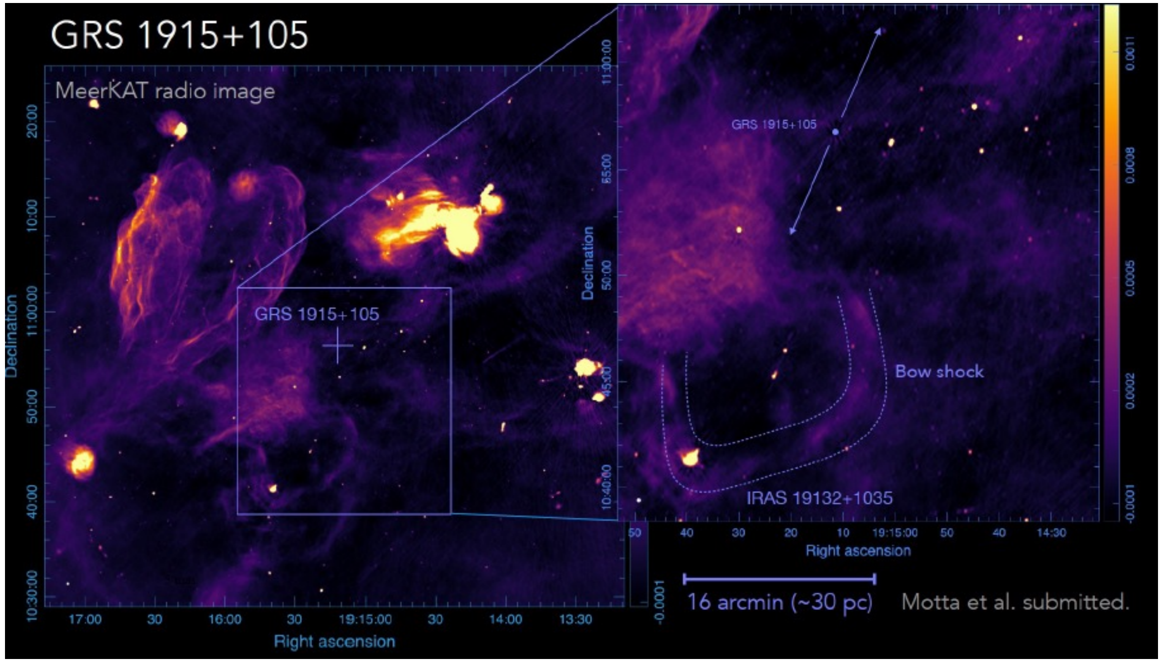
a GeV counterpart?
(Marti-Devesa & Olivera-Nieto 2024)

Possible origin of the UHE emission

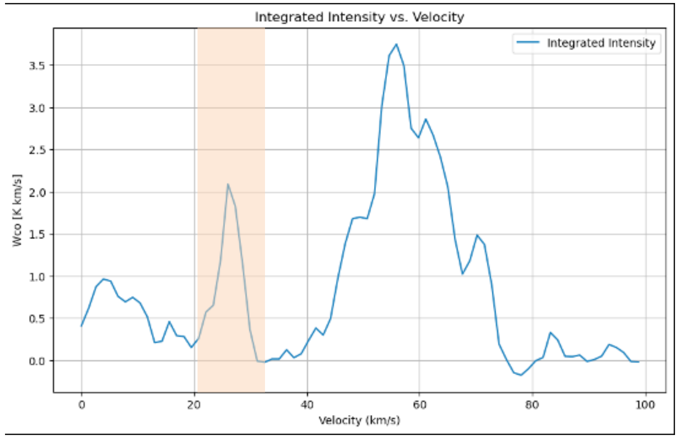


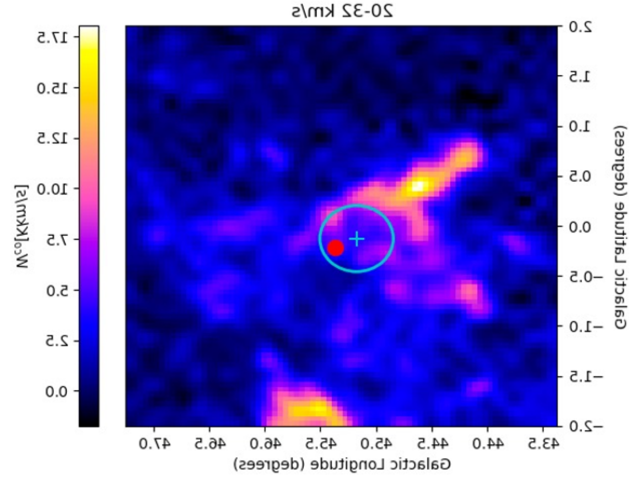


Jet-ISM Interaction Model
Proposed by Kaiser et al. (2004)



from the talk by Melania Del Santo in Leonardo meeting





within LHAASO source
M=1.6e5 $M_\odot$
n=5 cm^{-3}

W_p(>200TeV)~4e48erg

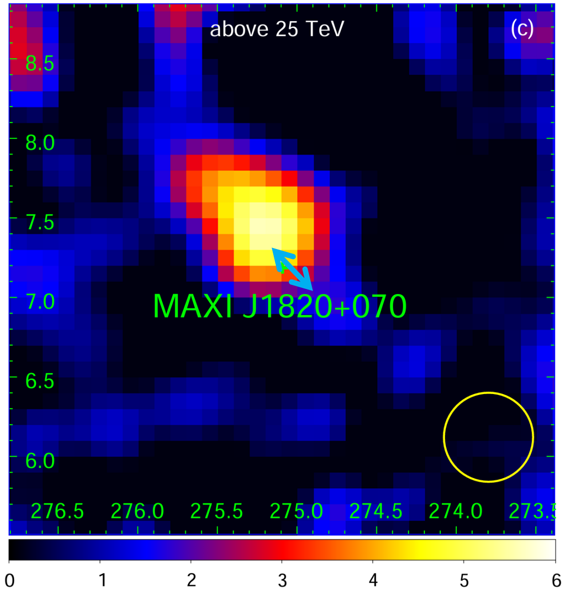
two unresolved lobes or diffuse emission?

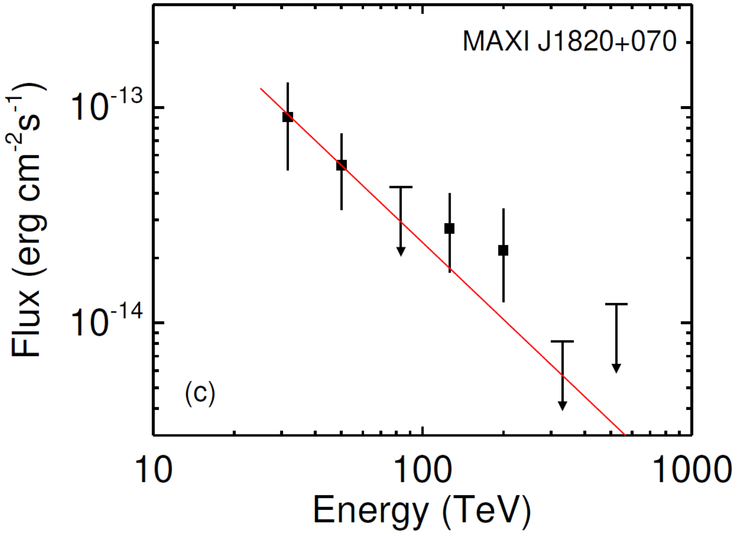
Khangulyan et al. 2024, JHEAP

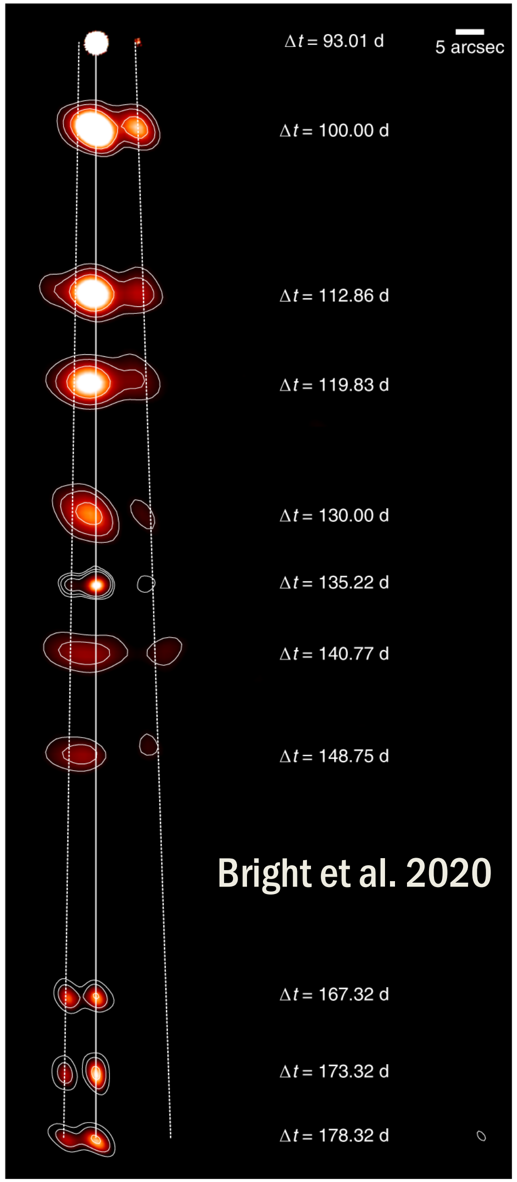
MAXI J1820+070 & Cygnus X-1

“new” BH discovered in 2018 (Tucker et al. 2018, Kawamuro et al. 2018)

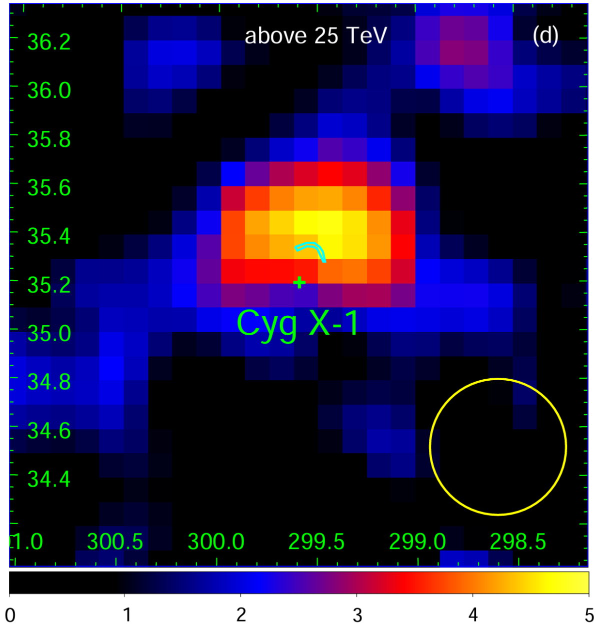
r<0.28 deg

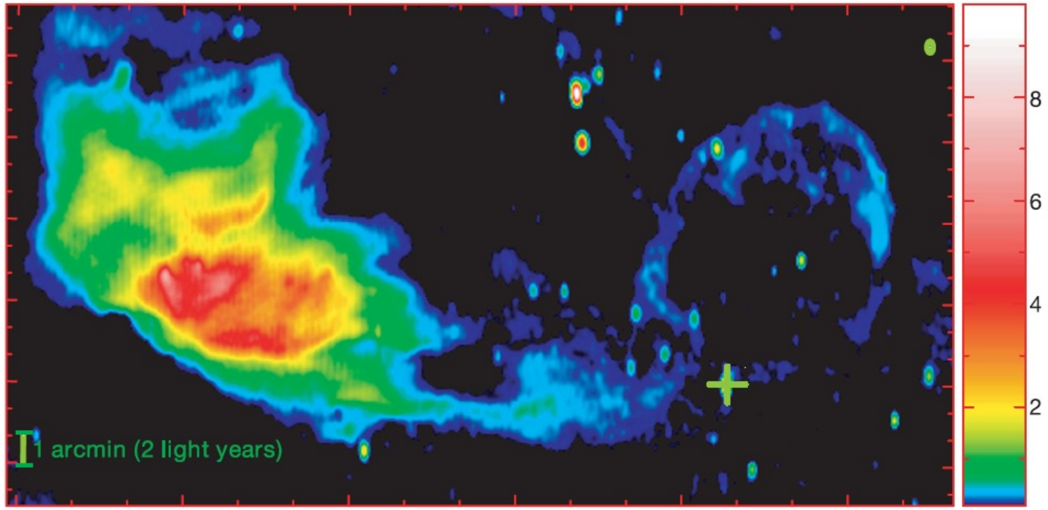






Bright et al. 2020

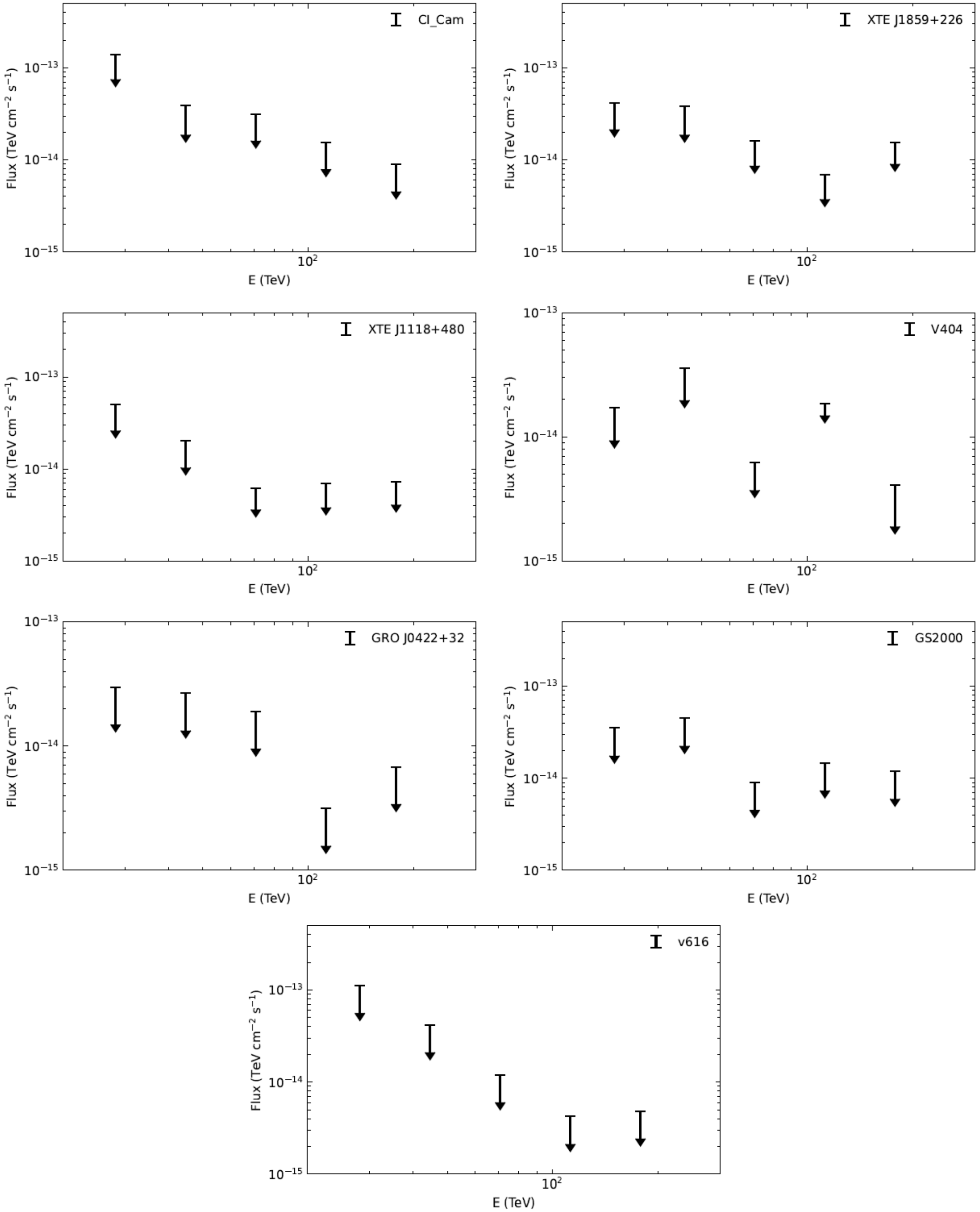


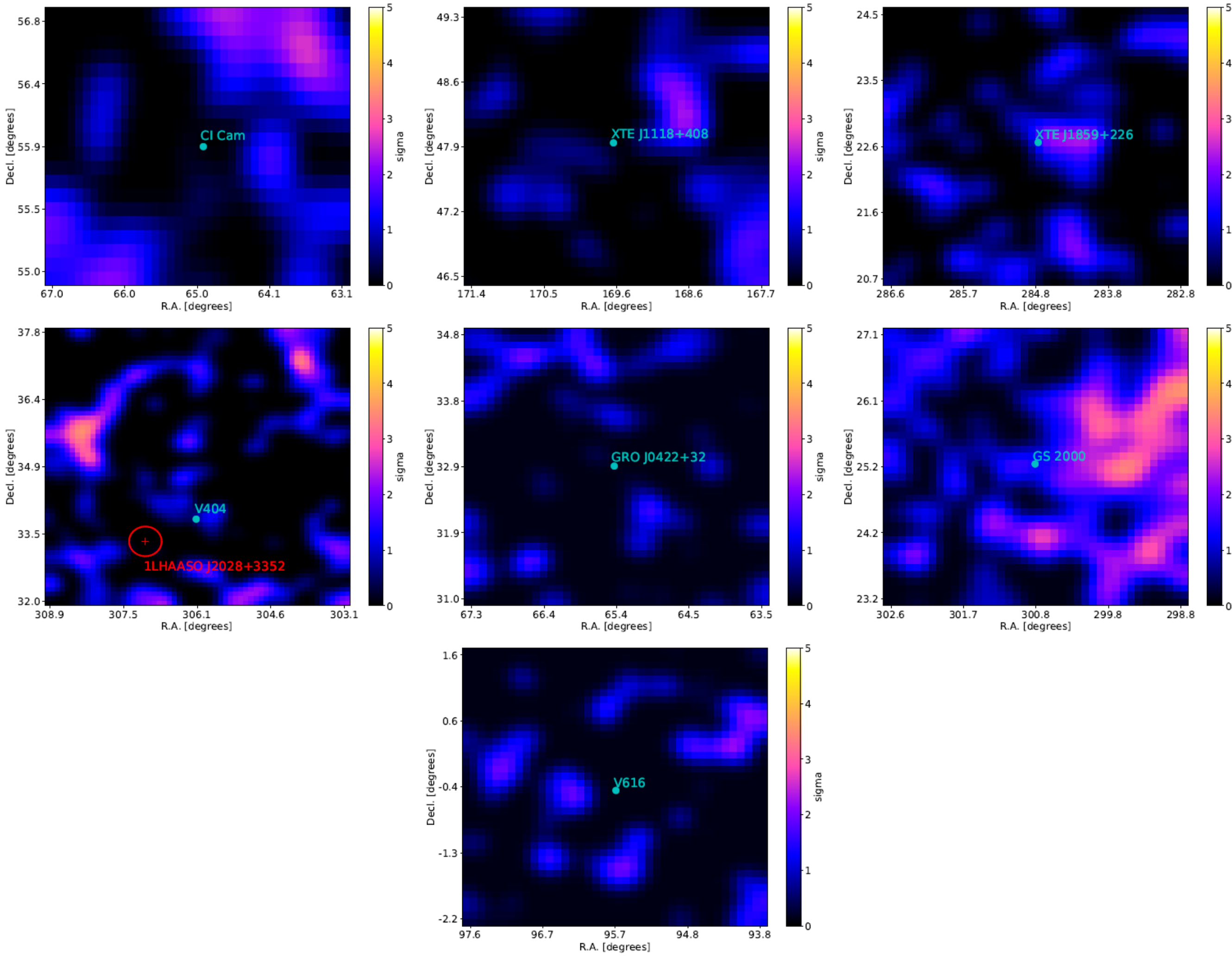


first identified BH in 1960s

bubble inflated by a dark jet? (Gallo et al. 2005)

r<0.22 deg





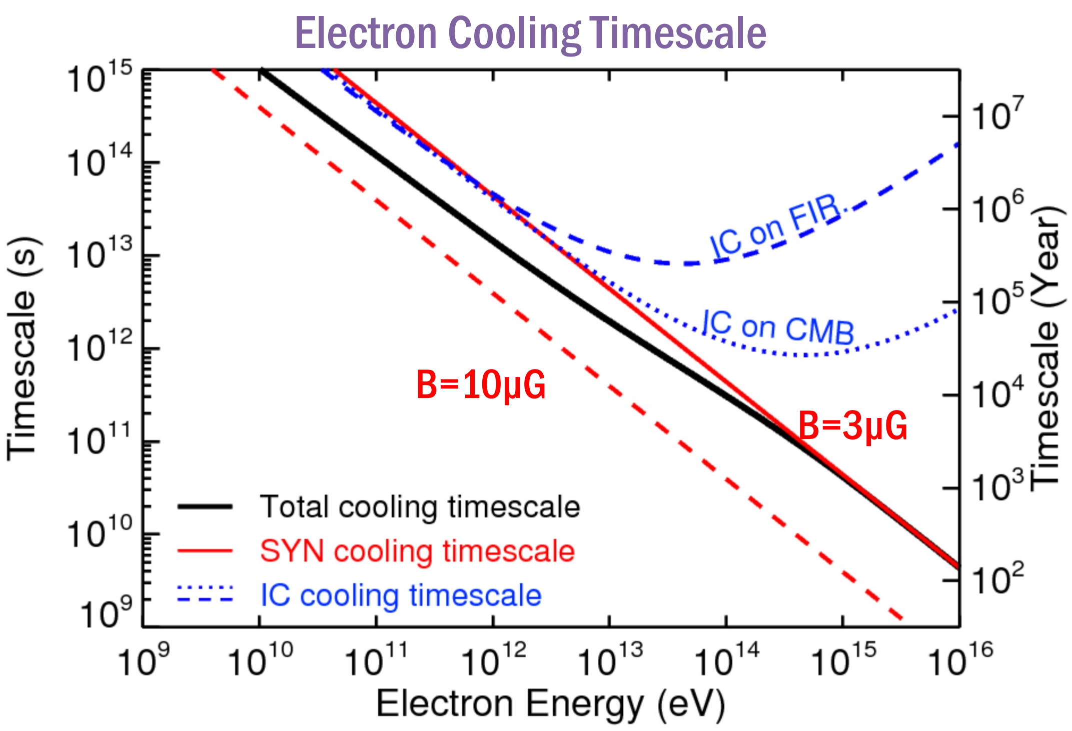
other seven undetected microquasars, longer exposure is needed

Connection between BH activity and UHE emission

SS 433: persistent
Cyg X-1: persistent
GRS 1915: active for decades before entering a "dim state" in X-ray band since 2018, but still exhibits frequent, bright radio flares
V4641 Sgr: highest frequency of outburst among transient BHXRBs
MAXI J1820: major outburst in 2018

V616 Mon: no outburst since 1975
GS 2000+251: no outburst since 1988
GRO J0422+32: no outburst since 1992
CI Cam: no outburst since 1998
XTE J1859+226: no outburst since 1999
XTE J1118+480: no outburst since 2000
V404 Cygni: no outburst since 2015

Proton Cooling Timescale: t_{pp}=4 Myr $(n/10cm^{-3})^{-1}$



- If not coincidence: duty cycle of BHXRBs inferred from observations of recent decades could reflect the energy release of the binary system in past thousands of years?
- If coincidence: expection of UHE emission from other quiescent BHXRBs, or even undiscovered systems
- other factors: fractional energy in nonthermal particles; disk instabilities; radiation efficiency

Contribution to the measured CR flux

active BHs and their environments can be PeV proton factories

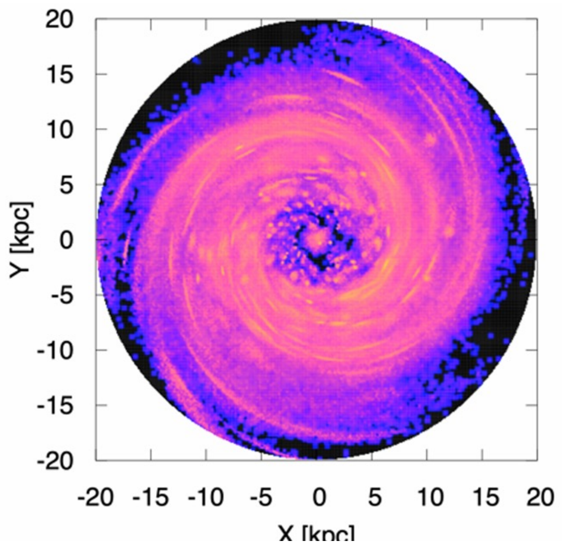
$L_p(1\mathrm{PeV}) \sim 10^{38}$erg/s from the lepto-hadronic model for SS433's SED

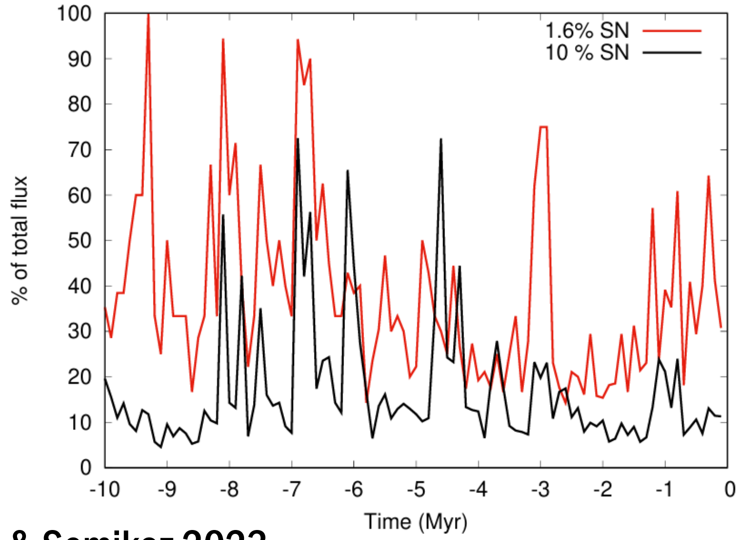
the total number of BH X-ray binaries in Milky Way is expected to be about 1000, with a dozen of them probably boasting X-ray luminosity exceeding 10^{39}erg/s

$$F(E_p = 1\,\mathrm{PeV}) = \frac{c}{4\pi}\frac{L_p f_{\mu Q} t_{res}}{2\pi R_{Gal}^2 H_{CR}}$$

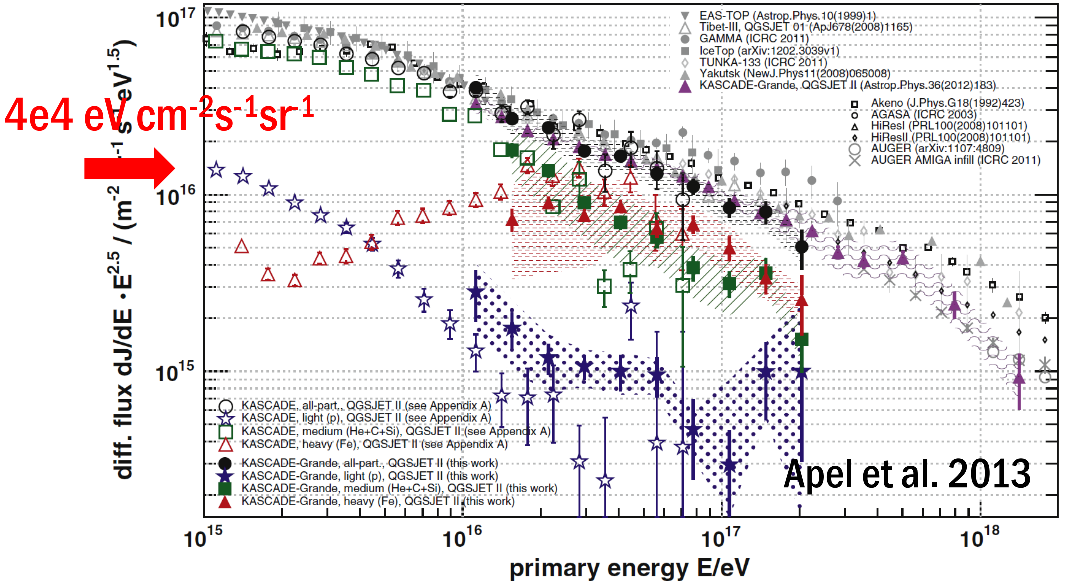
$$f_{\mu Q} = 10 - 100$$

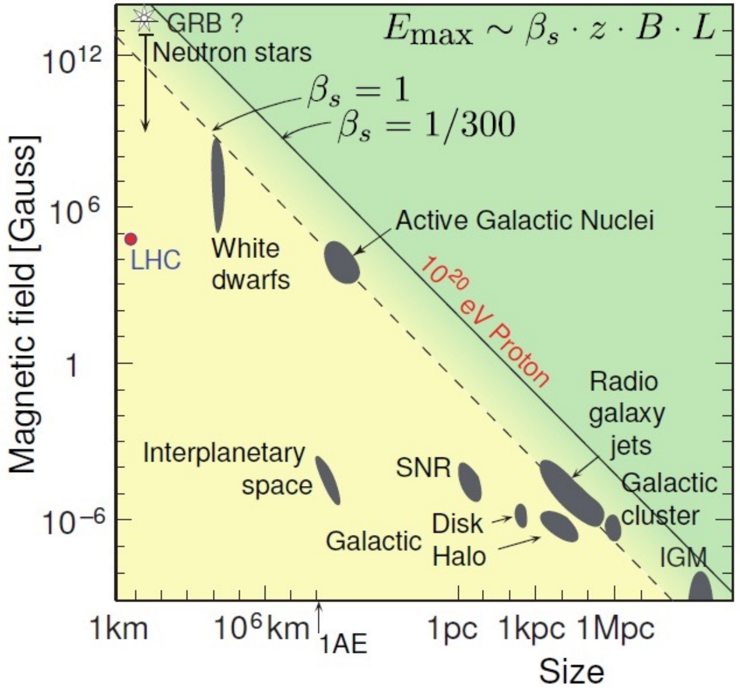
$$\approx 3\times10^4 \left(\frac{f_{\mu Q} L_p}{10^{39}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{D_{ISM}}{10^{31}\,\mathrm{cm^2 s^{-1}}}\right)^{-1}\left(\frac{H_{CR}}{4\,\mathrm{kpc}}\right)\left(\frac{R_{Gal}}{15\,\mathrm{kpc}}\right)^{-2}\ \mathrm{eV\ cm^{-2}s^{-1}sr^{-1}}$$





Giacinti & Semikoz 2023

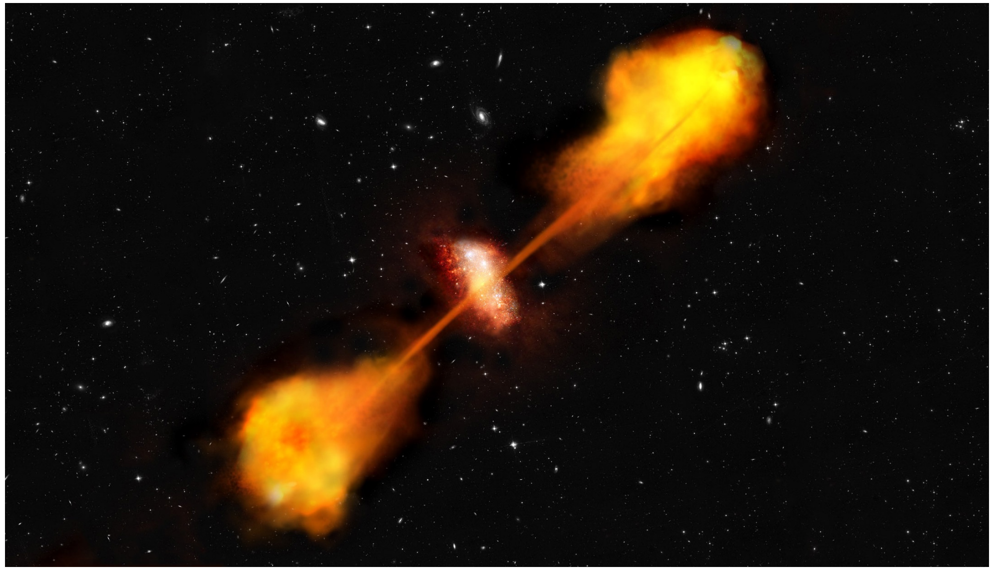


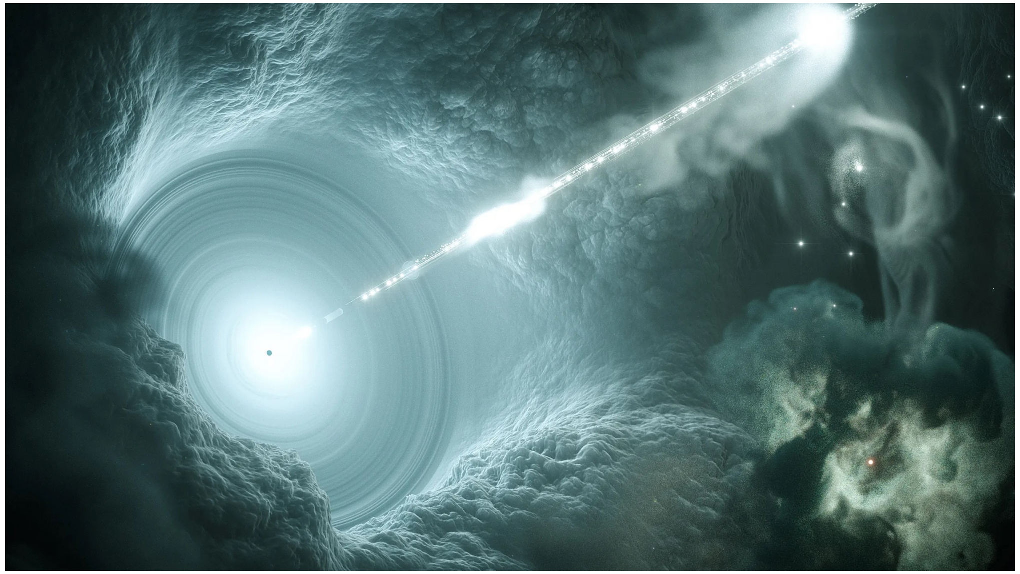


Implications for particle acceleration at AGN

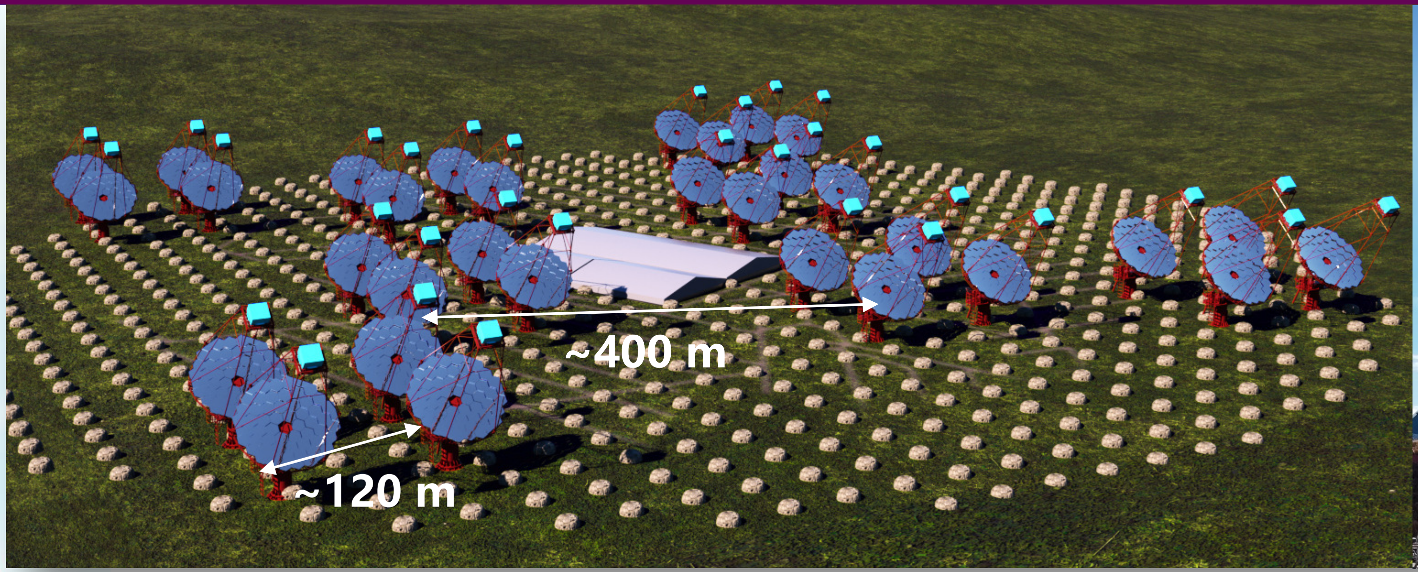
stellar-mass BH-Jet systems
-> accelerators of >~10 PeV at different locations of the system

Insights into particle acceleration of supermassive BH-Jet systems
(more powerful, more gigantic)



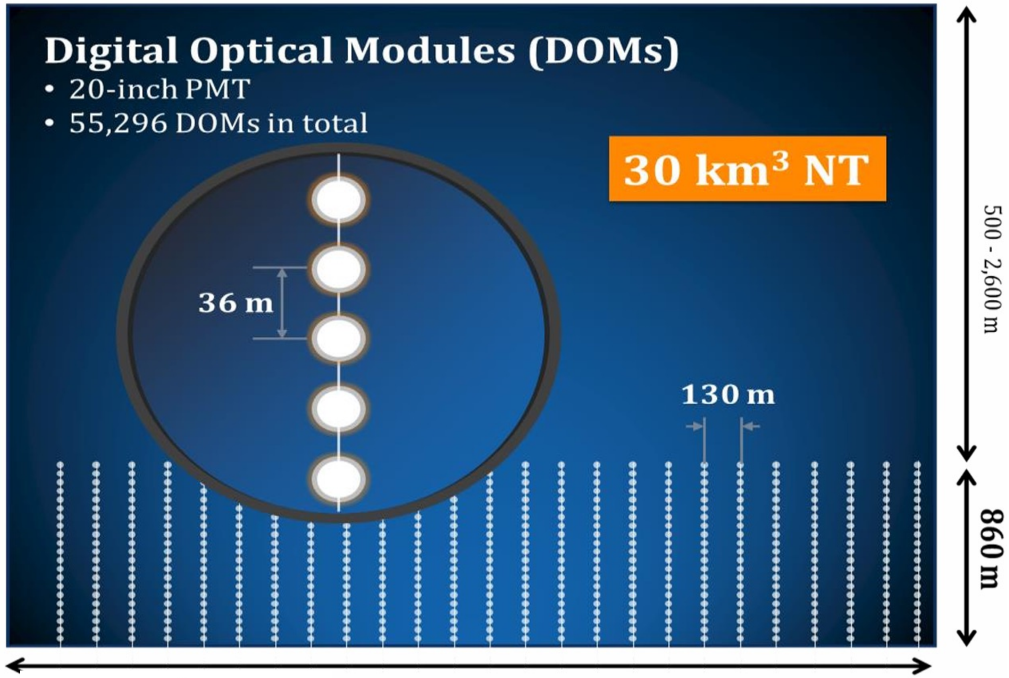


Large Array of Cherenkov Telescopes



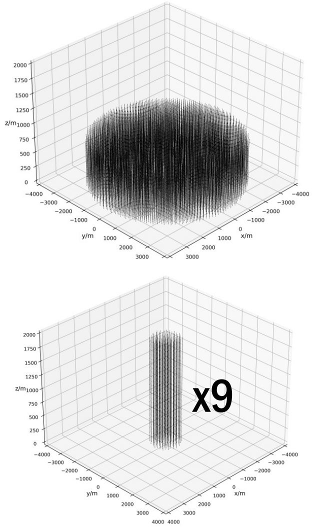
- Funded
- 32 telescopes： 8×4 array at LHAASO site
- 6-m telescopes
- Angular resolution: $< 0.05^{\circ}$ @ > 10 TeV
- LHAASO MD array provides excellent γ/p discrimination
- two proto type telescopes
- First light soon in next year!
- The full array will be completed by 2028

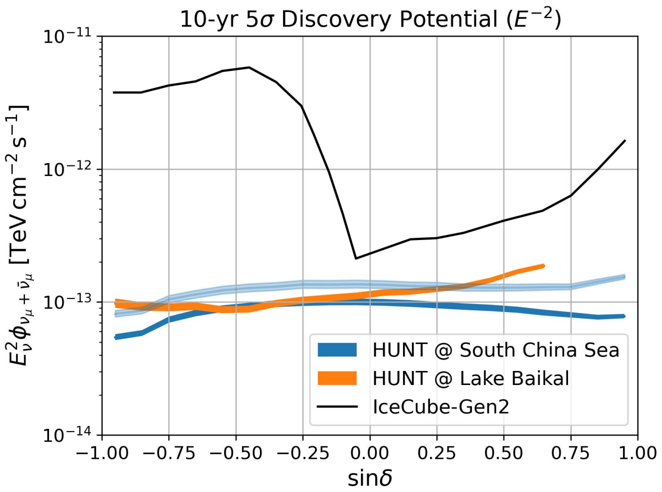
High-energy Underwater Neutrino Telescope



Candidate sites

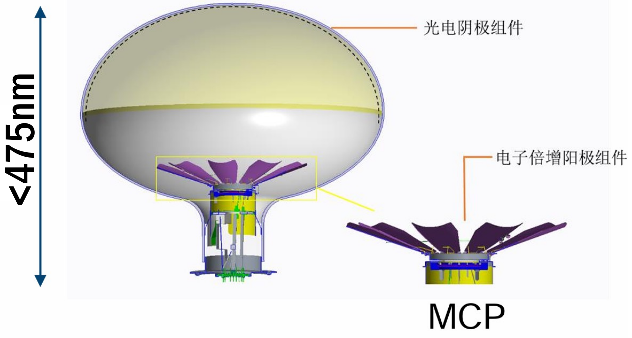
	Lake Baikal	South China Sea
Absorption length	~20 m	**~25 m**
Depth	~1366 m	**~2500 m (better atmospheric muon background rejection)**
Deployment Cost	**~K$ /string**	High
Reparability	**Work on the ice (low cost)**	Difficult to be repaired
Power Supply cable	**~10 km cable**	~100 km cable or battery
Construction and Deployment	**~5 years (Feb. to Apr. every year)**	Rely on deep-ocean facilities





Prototype Test

New 20-inch PMT with short neck



Summary

- LHAASO has detected 5 out 12 BH microquasars in FoV associated with UHE emission.
  - SS433, V4641 Sgr, GRS 1915+105, MAXI J1820+070, Cygnus X-1 present gamma-ray emission around and above 100TeV
  - energy-dependent morphology of SS 433 indicate different origin of emission above 100TeV and that <<100TeV, association of >100TeV source with atomic cloud support a hadronic origin

- Among 5 sources, there are both extended and point-like morphology -> radiation/particle acceleration from different scales of the BH-jet system;

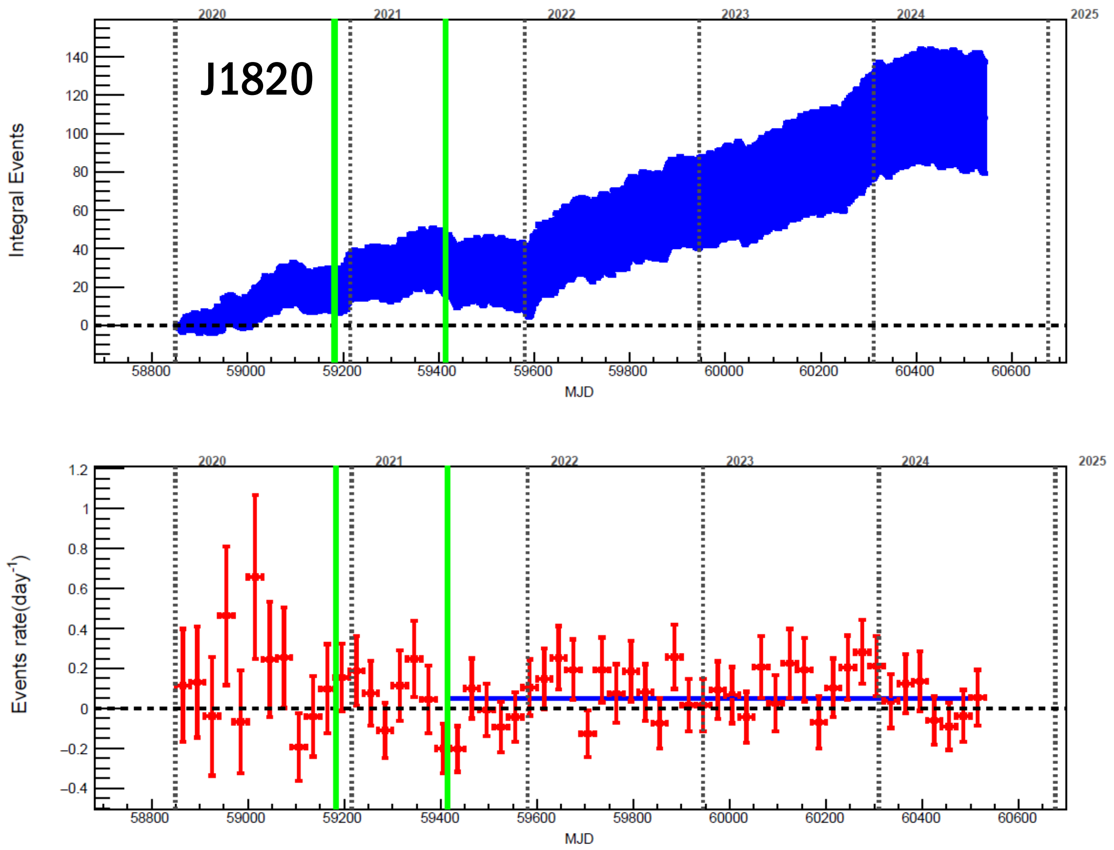
- Our results indicate active BH and their environment are a new class of PeVatron/Super-PeVatron

- implication for particle acceleration in more powerful SMBH-jet systems (blazar, radio galaxies) and origin of UHECRs. Hints of other relevant processes: jet formation, jet dynamics...

- A connection between UHE emission and BH activities. More samples are needed to answer the possible association between recent BH activities and UHE emission.

Thank you very much for your attention!

- BACKUP SLIDES


J1820
Integral Events
Events rate(day^{-1})
MJD
2020
2021
2022
2023
2024
2025
58800
59000
59200
59400
59600
59800
60000
60200
60400
60600

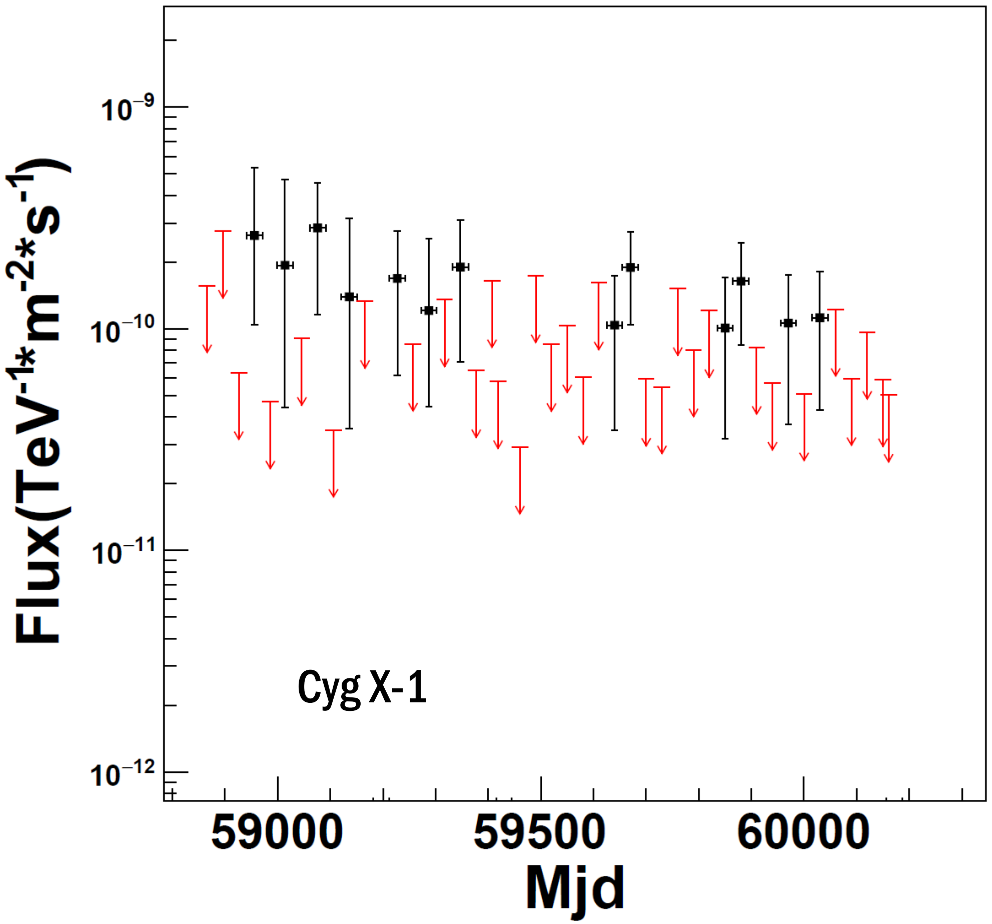
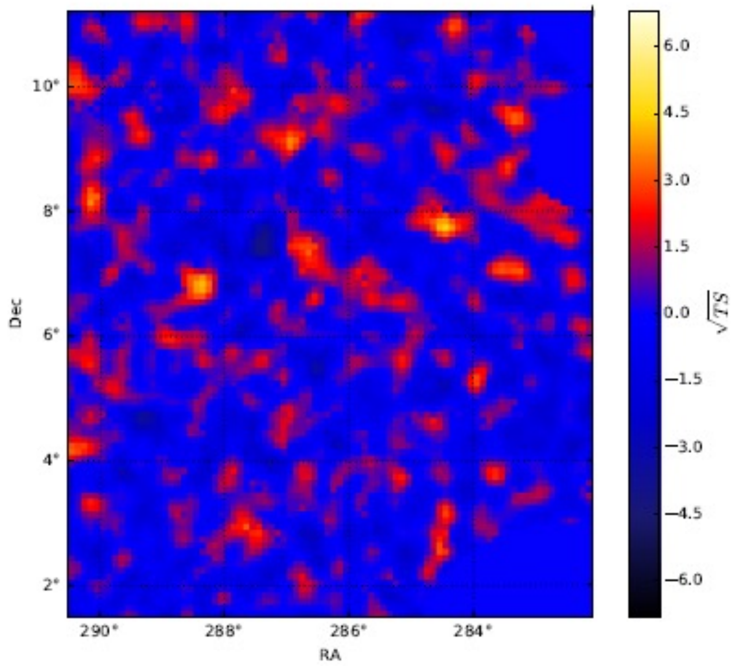
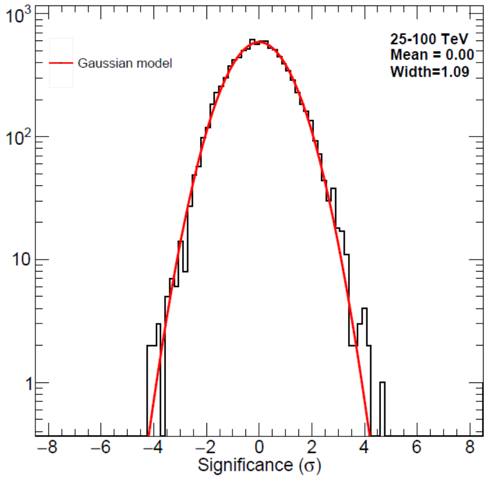
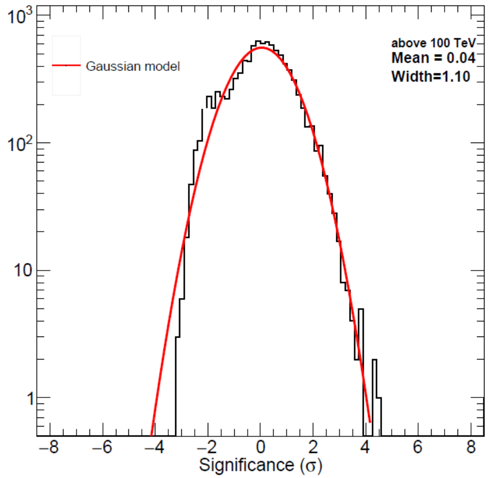

Flux(TeV^{-1}*m^{-2}*s^{-1})
Mjd
Cyg X-1
10^{-9}
10^{-10}
10^{-11}
10^{-12}
59000
59500
60000

Table 1: Best-fit model parameters of SS 433 region at 25-1000 TeV.

Name LHAASO	R.A. degree	Dec degree	σ degree	Possible Association
J1908+0614	287.06±0.01	6.23±0.01	0.36±0.01	1LHAASO J1908+0615u MRGO J1908+06
J1907+0613	286.79±0.10	6.22±0.10	1.31±0.07	new source
J1912+0500	288.17±0.04	5.01±0.03	ps	1LHAASO J1913+0501 SS 433 E.
J1910+0506	287.55±0.07	5.11±0.06	ps	1LHAASO J1910+0516 SS 433 W.
J1908+0818	287.03±0.06	8.31±0.06	0.03±0.05	1LHAASO J1907+0826 2HWC J1907+084
J1857+0201	284.42±0.02	2.02±0.02	0.25±0.02	1LHAASO J1857+0203u HESS J1858+020
J1858+0322	284.58±0.03	3.38±0.04	0.43±0.02	1LHAASO J1858+0330
J1913+1033	288.44±0.03	10.55±0.03	0.45±0.02	1LHAASO J1912+1014u HESS J1912+101
J1914+1148	288.72±0.03	11.81±0.03	0.13±0.02	1LHAASO J1914+1150u 2HWC J1914+117

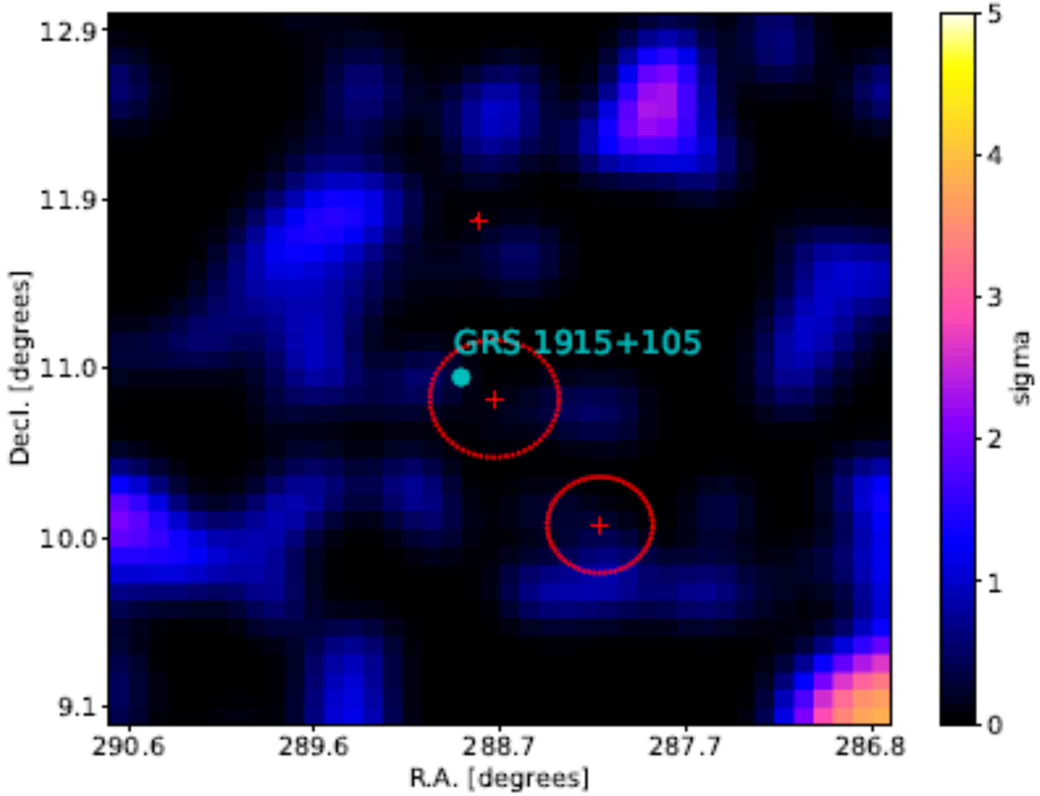






Model	R.A.°	Dec.°	σ	TS
One source scenario				
Gaussian	288.60 ± 0.04	11.07 ± 0.07	0.55 ± 0.04	1832.6
Two sources scenario				
Gaussian	288.71 ± 0.02	11.81 ± 0.03	0.10 ± 0.04	2029.2
Gaussian	288.44 ± 0.04	11.57 ± 0.05	0.41 ± 0.03	
Three sources scenario				
Gaussian	288.71 ± 0.02	11.83 ± 0.03	0.09 ± 0.04	2065.8
Gaussian	288.08 ± 0.08	10.12 ± 0.11	0.28 ± 0.08	
Gaussian	288.63 ± 0.07	10.81 ± 0.06	0.33 ± 0.04	
Gaussian	288.71 ± 0.02	11.80 ± 0.02	0.11 ± 0.04	2047.8
Gaussian	288.30 ± 0.06	10.43 ± 0.07	0.39 ± 0.04	
Point source	288.85 ± 0.09	10.92 ± 0.05	-	
Point source	288.71 ± 0.02	11.83 ± 0.03	-	2064.4
Gaussian	288.0 ± 0.08	10.12 ± 0.10	0.27 ± 0.08	
Gaussian	288.63 ± 0.06	10.83 ± 0.06	0.33 ± 0.04	

Table 2: Morphology test for TeV emisson near GRS 1915+101



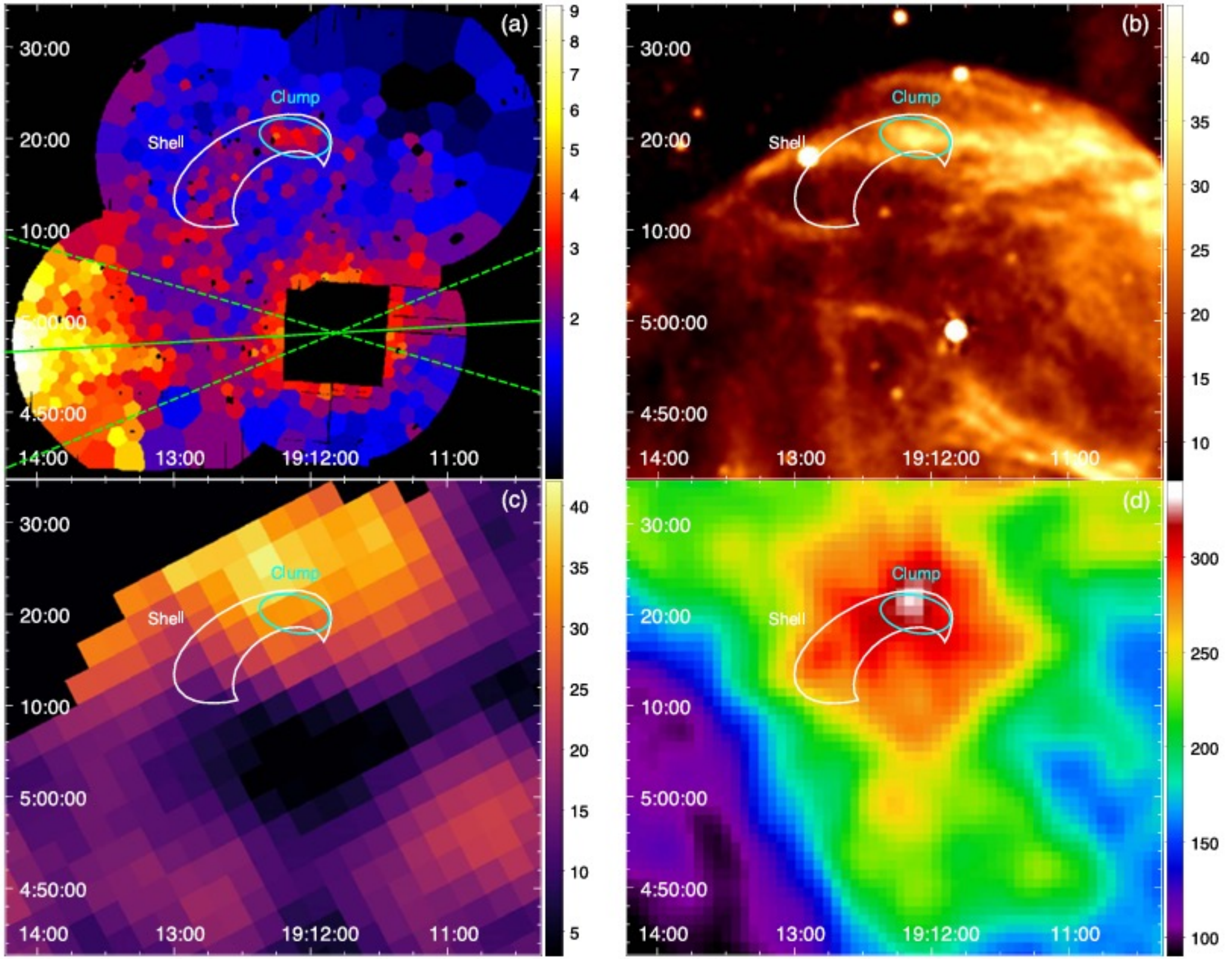


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Figure 2. Zoom-in multiband images of our region of interest. (a) XMM-Newton EPIC 0.4–1.2 keV mosaic in units of counts deg^{-2} s^{-1}. Each bin has a signal-to-noise ratio of ~10. The X-ray shell and clump are labeled in white and cyan, respectively. The green solid and dashed lines mark the jet axis and cone of the jet precession and nod, respectively (S. Fabrika 2004). (b) VLA 1.4 GHz intensity map in units of mJy beam^{-1} (G. M. Dubner et al. 1998). (c) Sino-German 6 cm polarized fraction map in units of percentage (X. Y. Gao et al. 2011). (d) Arecibo H I intensity in 68–75 km s^{-1} in units of K (J. E. G. Peek et al. 2018; Y. Su et al. 2018).