Ultrahigh-energy gamma-ray emissions associated with Black Hole-jet sysmtes

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for LHAASO Collaboration

LHAASO
高海拔宇宙线观测站

VGGRS V, 6-8 May 2025, Barcelona

Outline

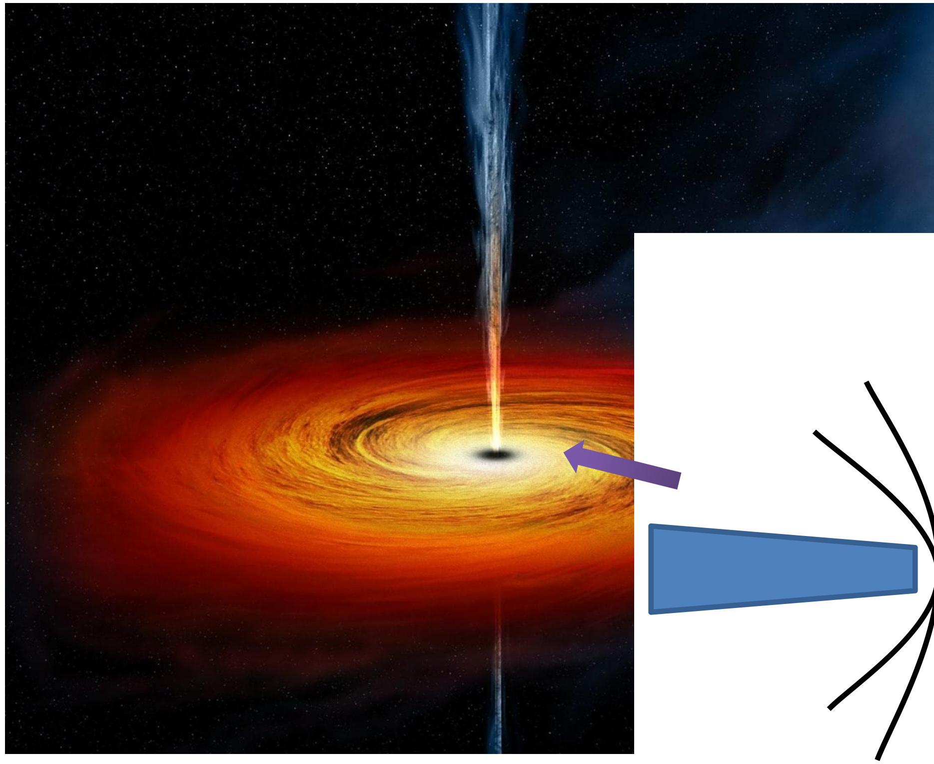
- A brief introduction of microquasars and LHAASO
- LHAASO's observations of microquasars
  - SS433
  - V4641 Sgr
  - GRS 1915+105
  - MAXI J1820+070
  - Cygnus X-1
- Discussion
- Summary

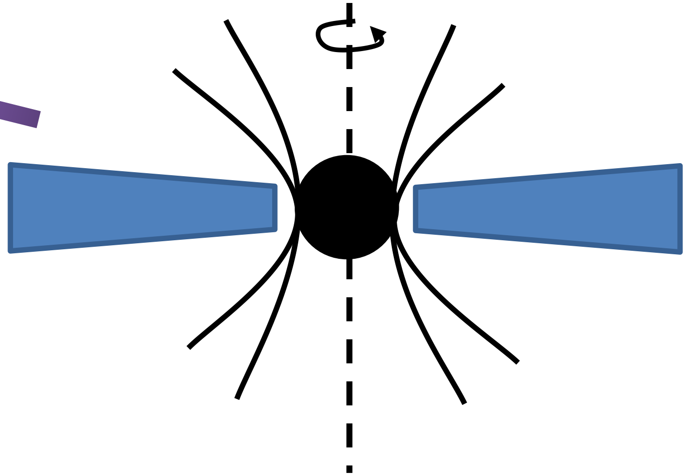
Microquasars

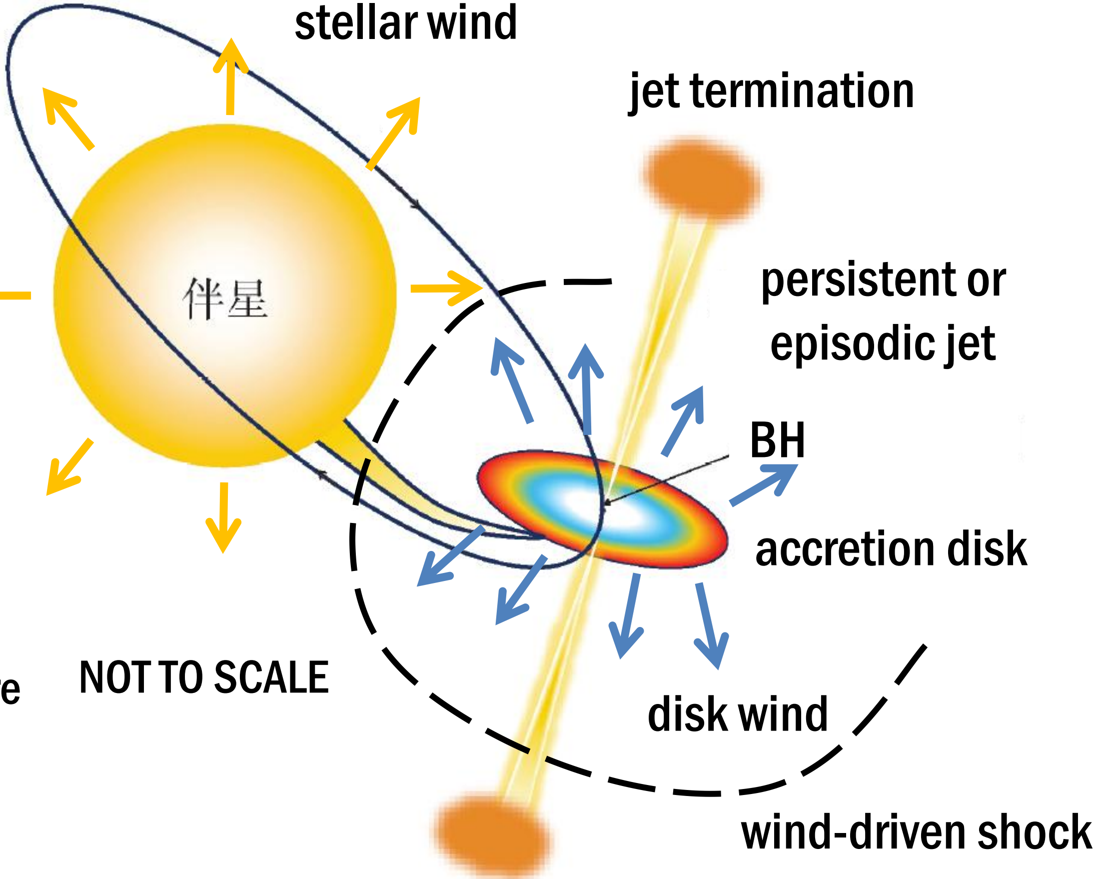
Binary + Mildly-relativistic Jets

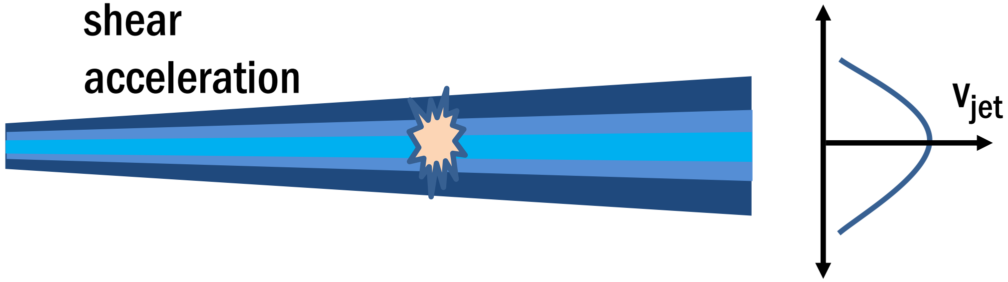
→ NS or stellar-mass BH + a donor star

Potential extreme particle accelerator where and how? maximum energy?









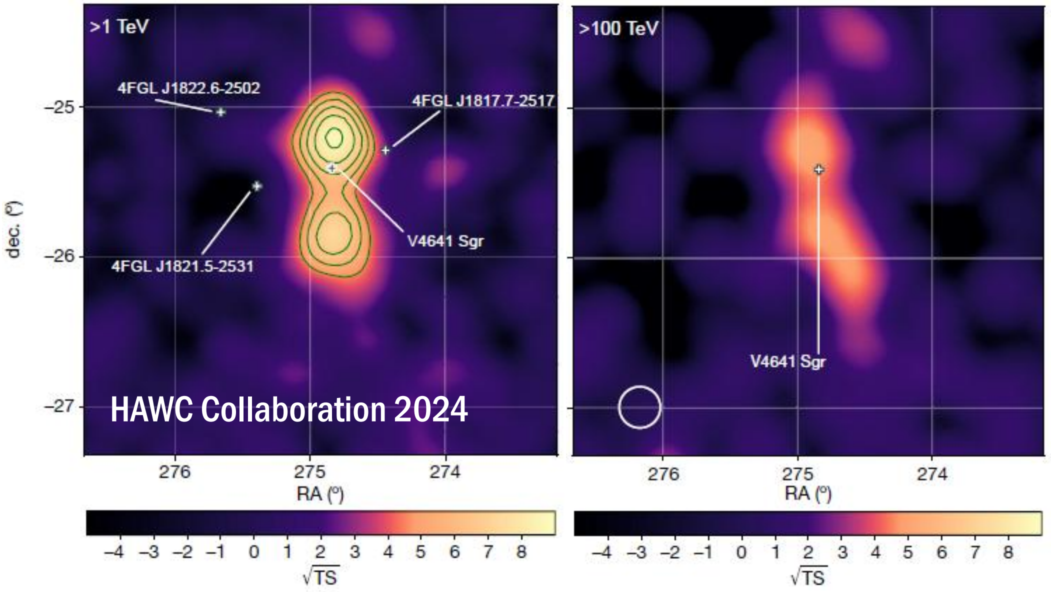
High-energy gamma rays as probes of efficient particle acceleration

Small Scale

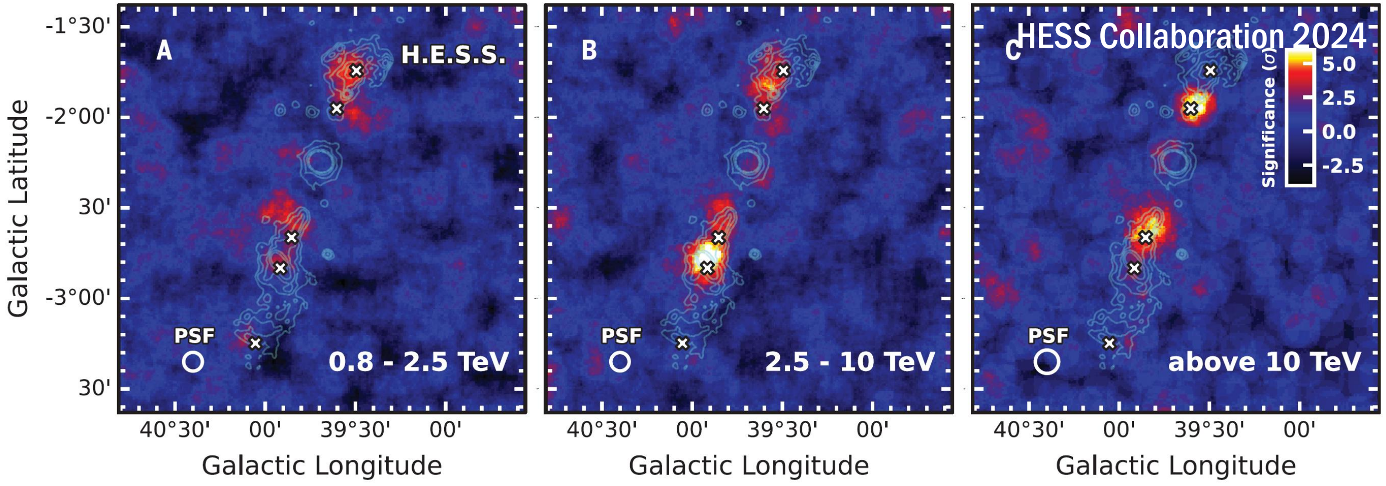
intense radiation from corona, companion star; dense matter in accretion flow, wind

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-

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	$25 - 100$		0.10
SS 433 W.	4.6 ± 1.3[32]	J1910+0509	8.6[c]	2.92 ± 0.21	$25 - 100$	0.70°	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

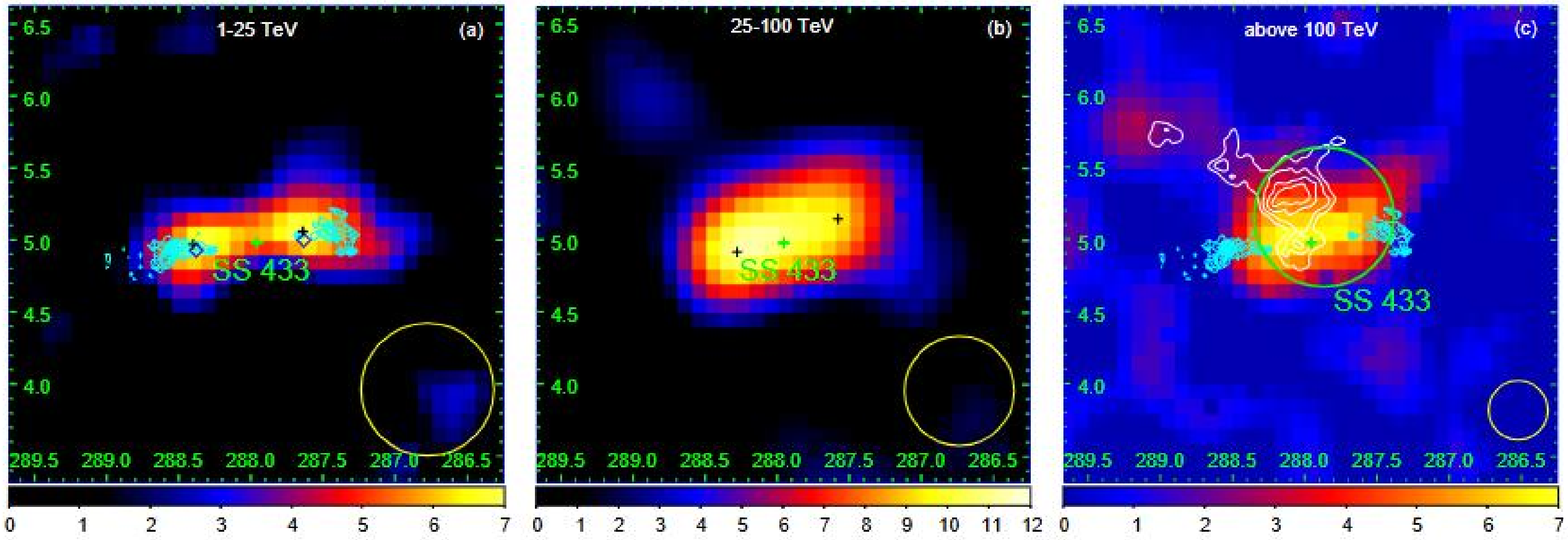
is it just coincidence?

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

Unresolved: MAXI J1820+070; Cygnus X-1

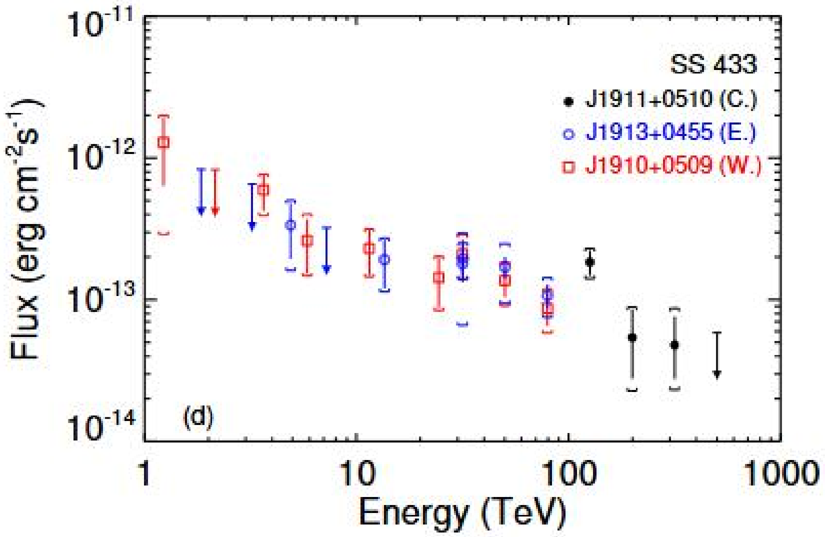
Is a BH's recent activity (over past decades) a proxy of UHE emission?

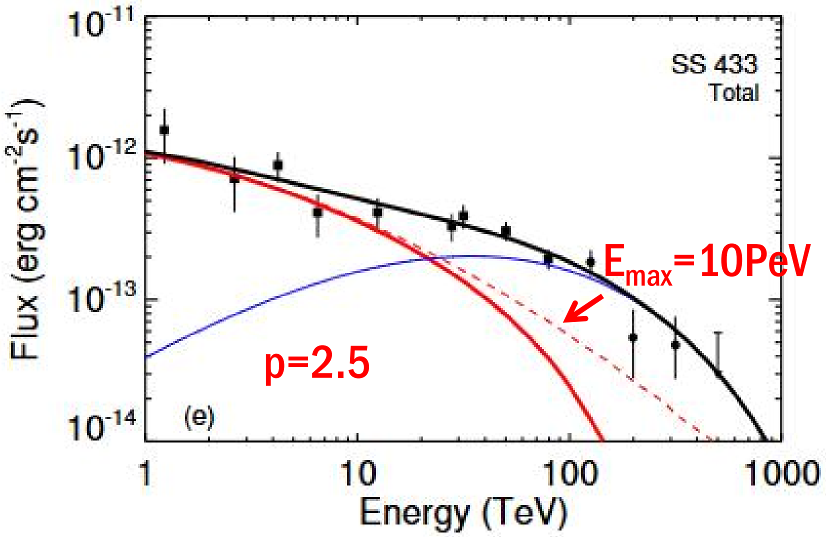
SS 433 (see Jian's talk)



energy dependent morphology, in particular above 100 TeV

Model of SS 433 above 100 TeV	Degree of Freedom	ΔTS	ΔAIC
2D Gaussian	5	0	0
two-point sources at H.E.S.S. emission above 10 TeV	4	-8.1	6.1
two-point sources at H.E.S.S. emission above 10 TeV + H I gas template	6	10.1	-8.1



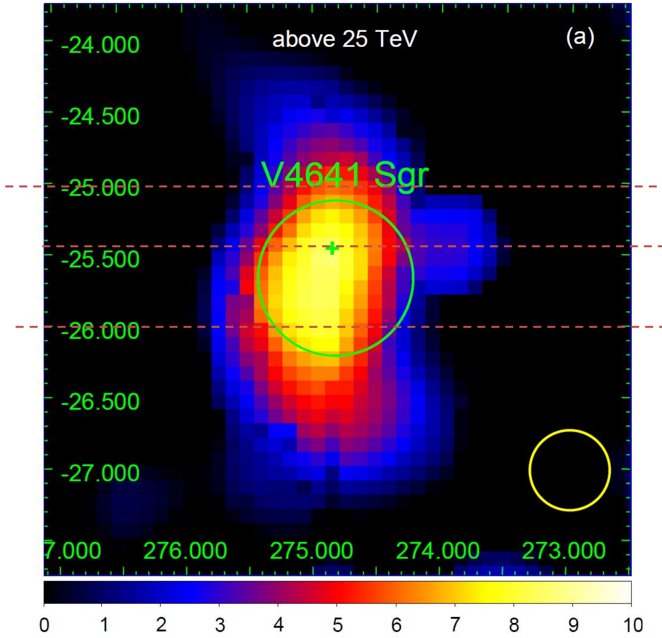


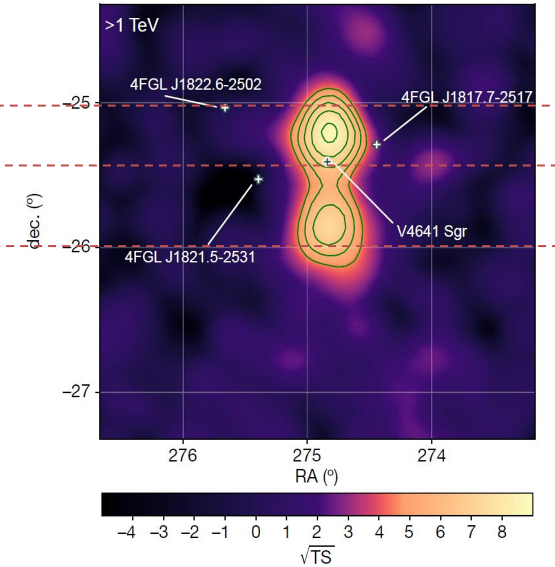
a second component is required to explain the UHE emission

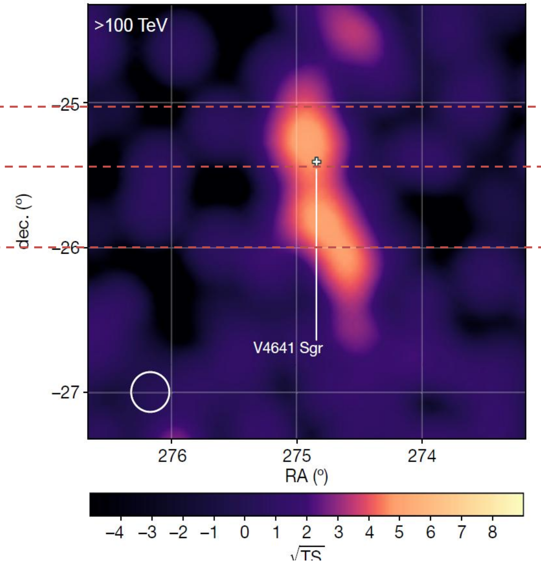
either leptonic or hadronic is Ok from the perspective of spectral fitting

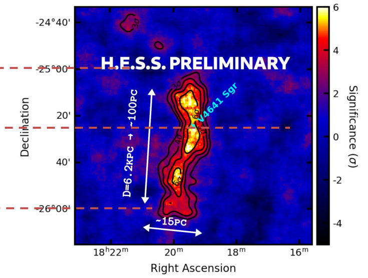
morphological study consistent witih hadronic origin

V4641 Sgr

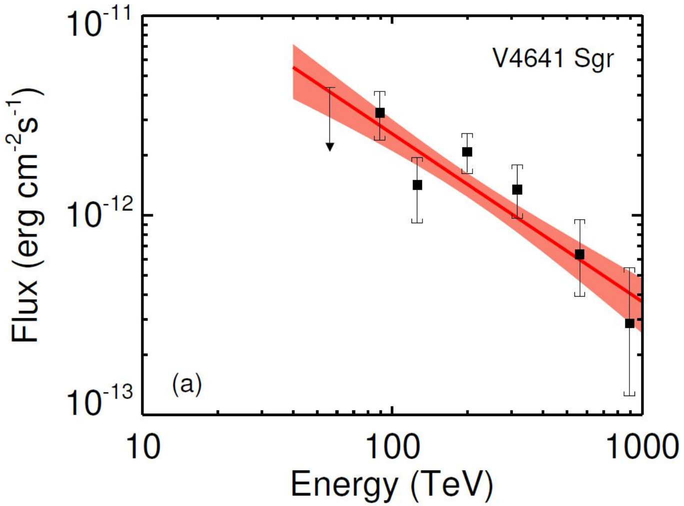


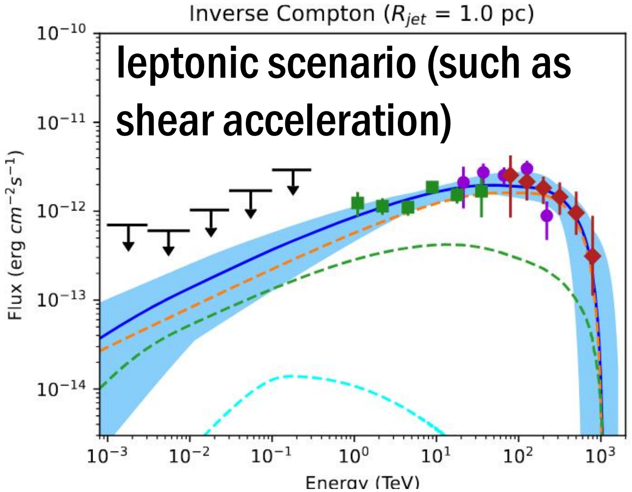


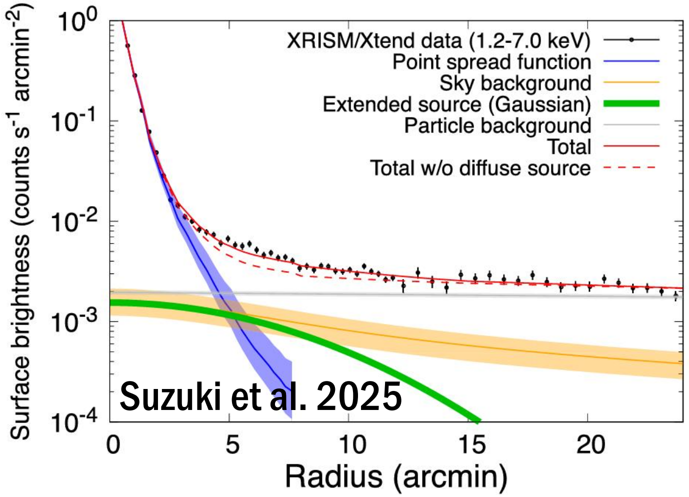




courtesy of L. Olivera-Nieto

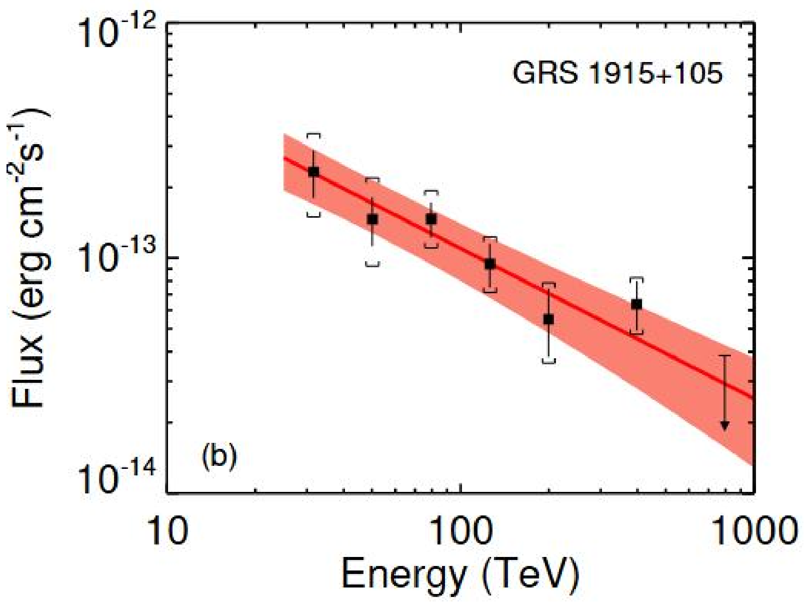


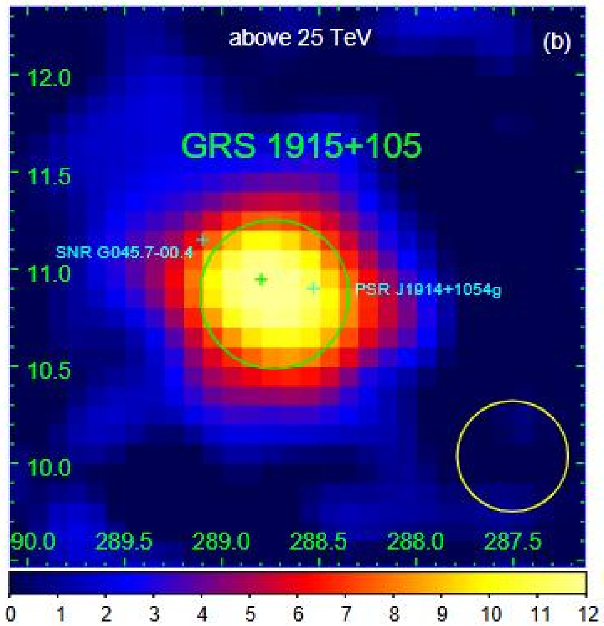


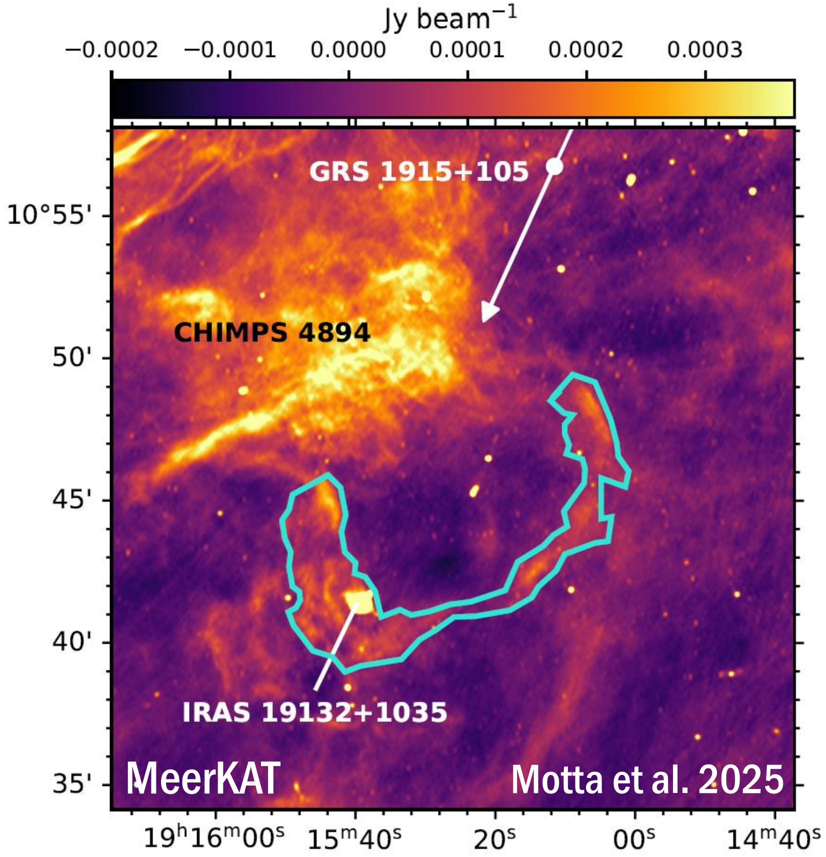


X-ray observation can impose strong constraints

GRS 1915+105

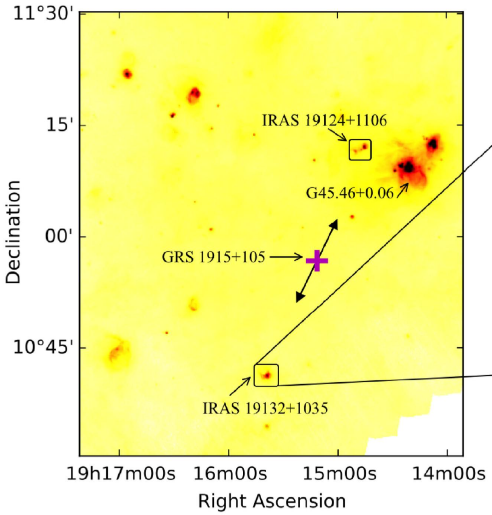


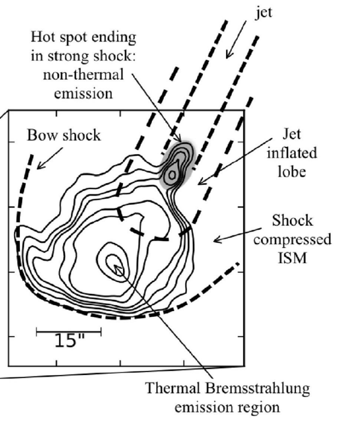




ALMA found two radio hotspots at 0.28 deg in both sides of the BH

two unresolved lobes or diffuse emission?





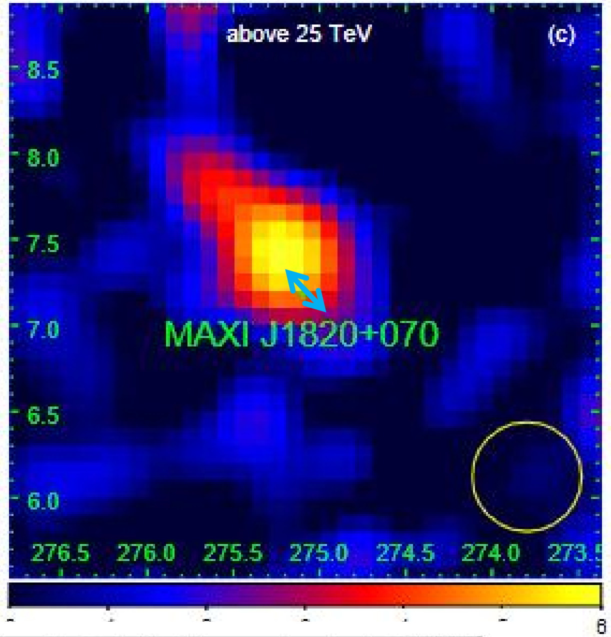
Jet-ISM Interaction Model Proposed by Kaiser et al. (2004)

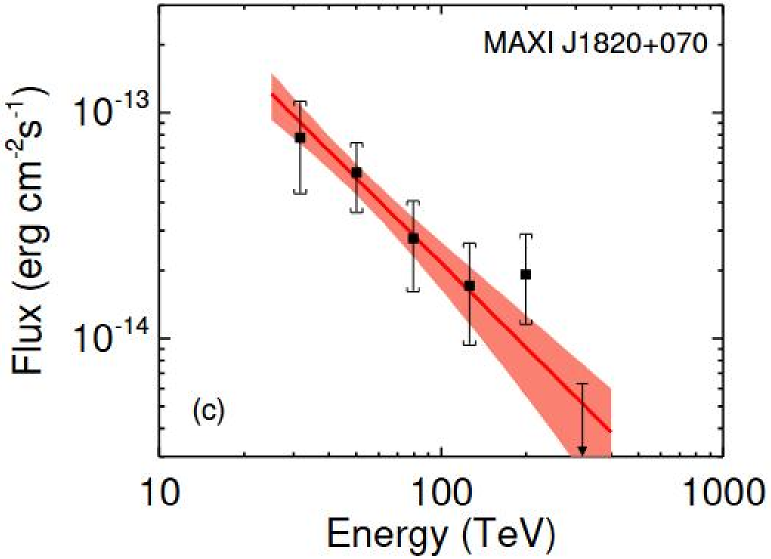
Observations with better angular resolution in gamma-ray or X-ray bands will be crucial to understand the origin

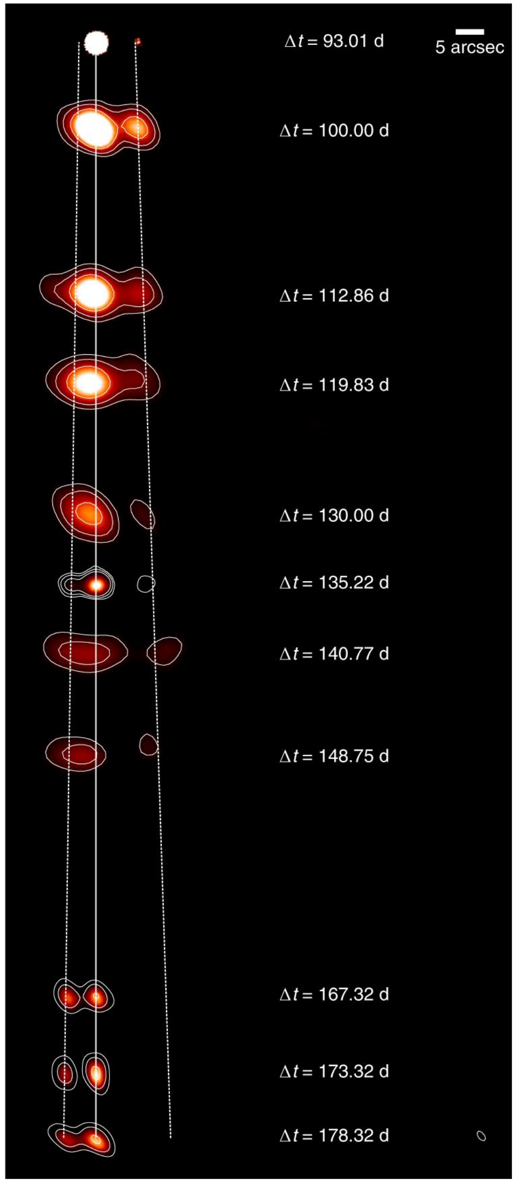
MAXI J1820+070 & Cygnus X-1

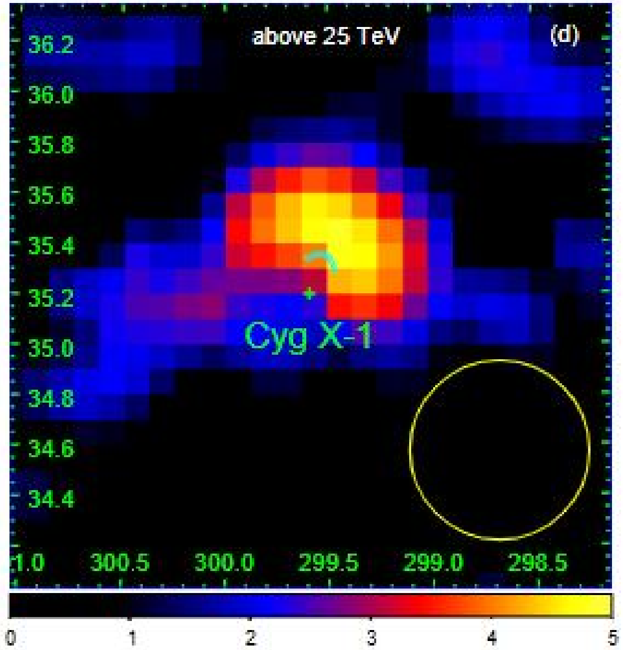
"new" BH discovered in 2018
(Tucker et al. 2018, Kawamuro et al. 2018)

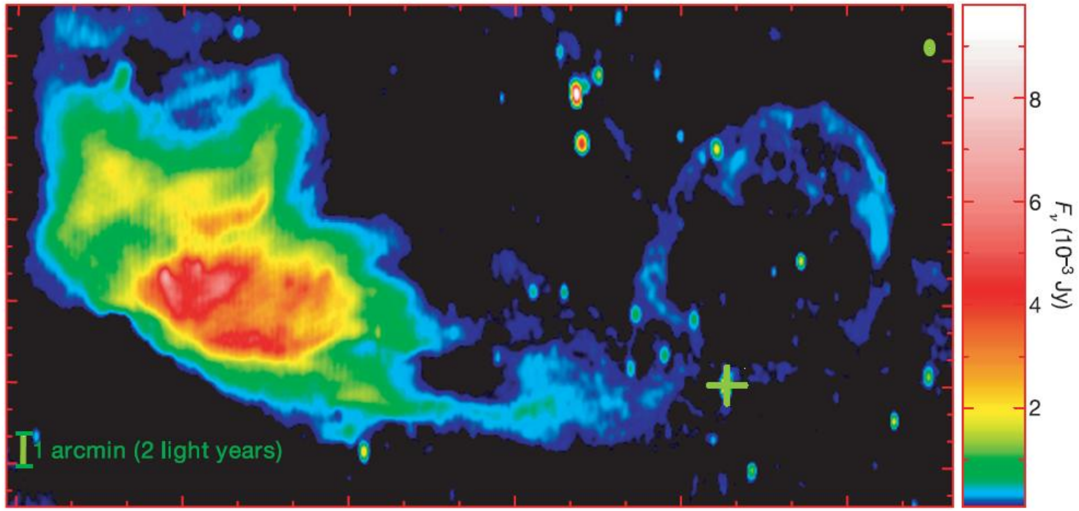
r<0.28 deg











first identified BH in 1960s

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

r<0.22 deg

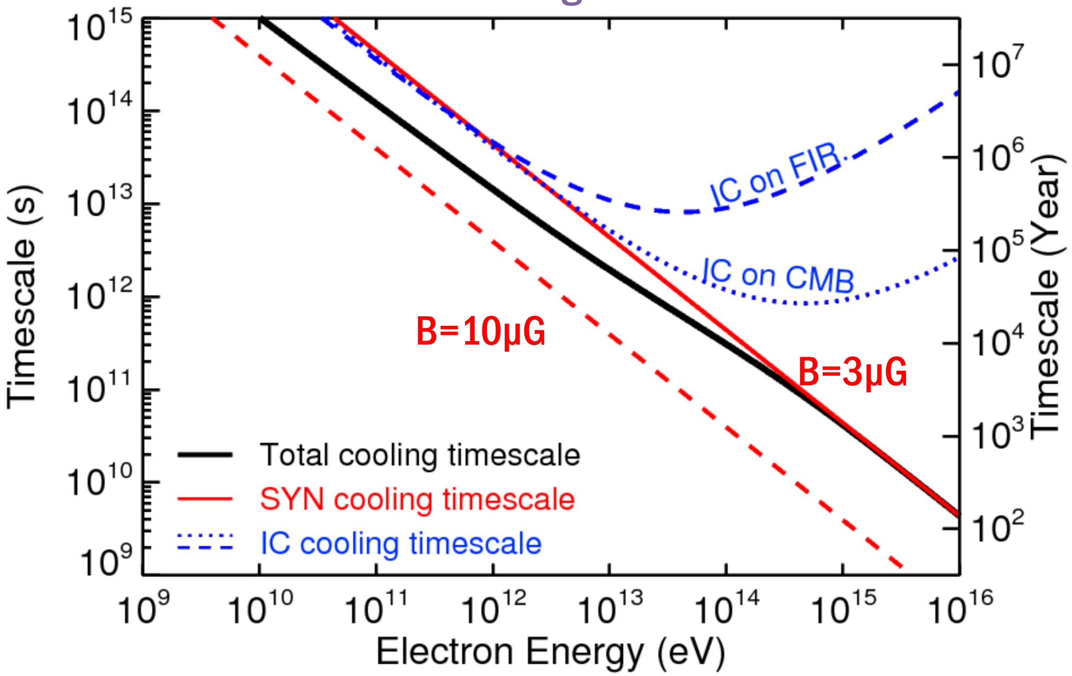
Connection between BH activity and UHE emission

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 $(n/10cm^{-3})^{-1}$

Electron Cooling Timescale



- 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? frequent perturbation to surrounding B field to confine injected CRs?
- If coincidence: expection of UHE emission from other quiescent BHXRBs, or even undiscovered systems; can be tested in the future

Contribution to the measured CR flux

active BHs and their environments can be PeV proton factories

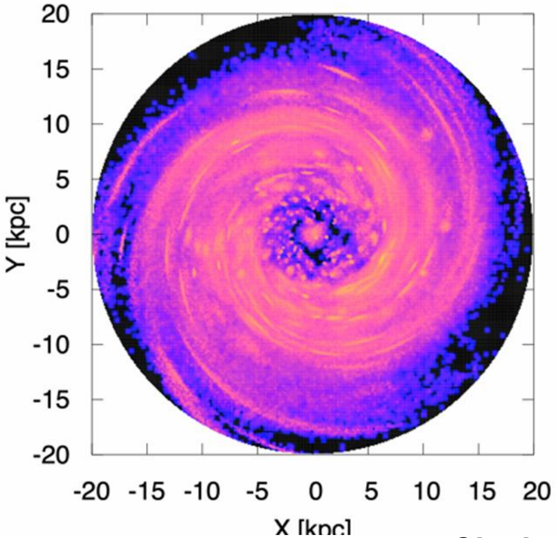
$L_p(1\mathrm{PeV}) \sim 10^{38}$ erg/s from the lepto-hadronic model for SS433's SED

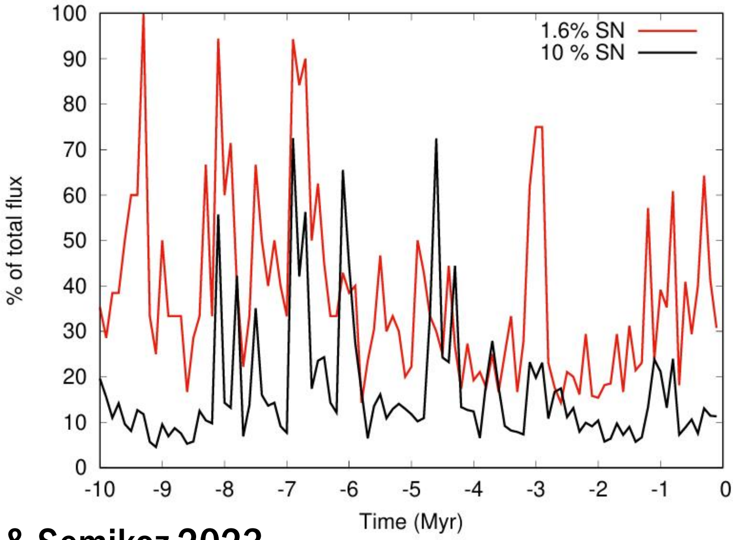
$$F(E_\mathrm{p} = 1\,\mathrm{PeV}) = \frac{c}{4\pi}\frac{L_\mathrm{p} f_{\mu\mathrm{Q}} t_\mathrm{res}}{2\pi R_\mathrm{Gal}^2 H_\mathrm{CR}}$$

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

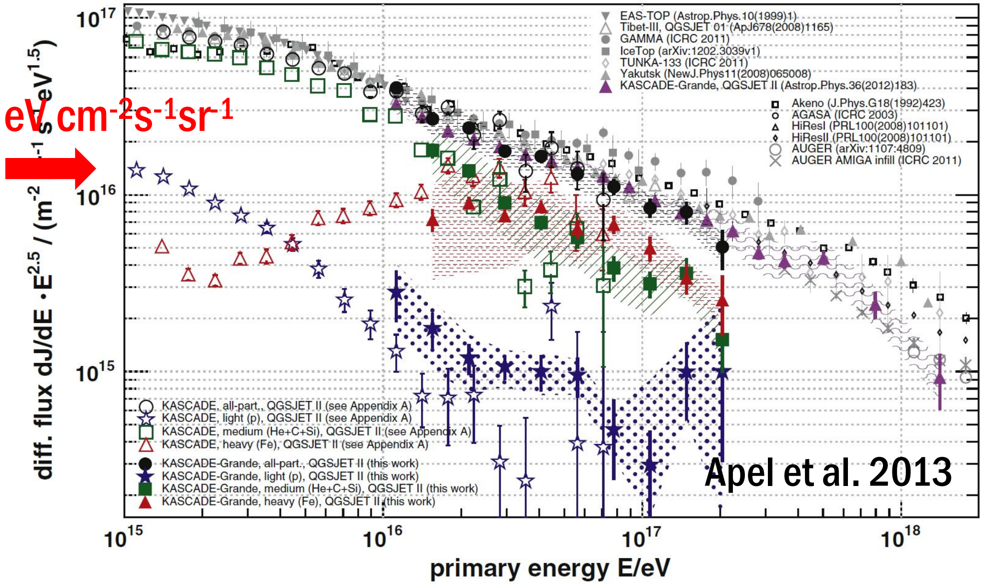
$$\approx 3\times 10^4 \left(\frac{f_{\mu\mathrm{Q}} L_\mathrm{p}}{10^{39}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{D_\mathrm{ISM}}{10^{31}\,\mathrm{cm^2 s^{-1}}}\right)^{-1}\left(\frac{H_\mathrm{CR}}{4\,\mathrm{kpc}}\right)\left(\frac{R_\mathrm{Gal}}{15\,\mathrm{kpc}}\right)^{-2}\ \mathrm{eV\,cm^{-2}s^{-1}sr^{-1}}$$

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

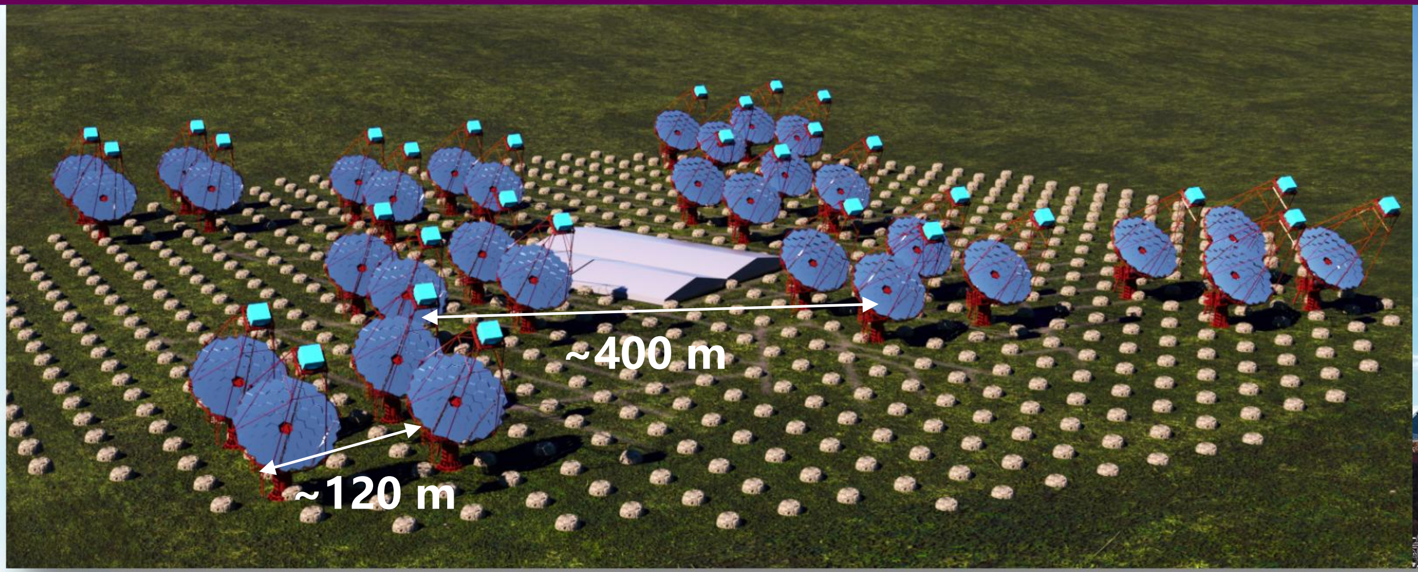




Giacinti & Semikoz 2023



Large Array of Cherenkov Telescopes



- **Funded**
- **32 telescopes：8×4 array at LHAASO site**
- **6-m telescopes**
- **Angular resolution: < 0.05° @ > 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**

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 is consistent with 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;

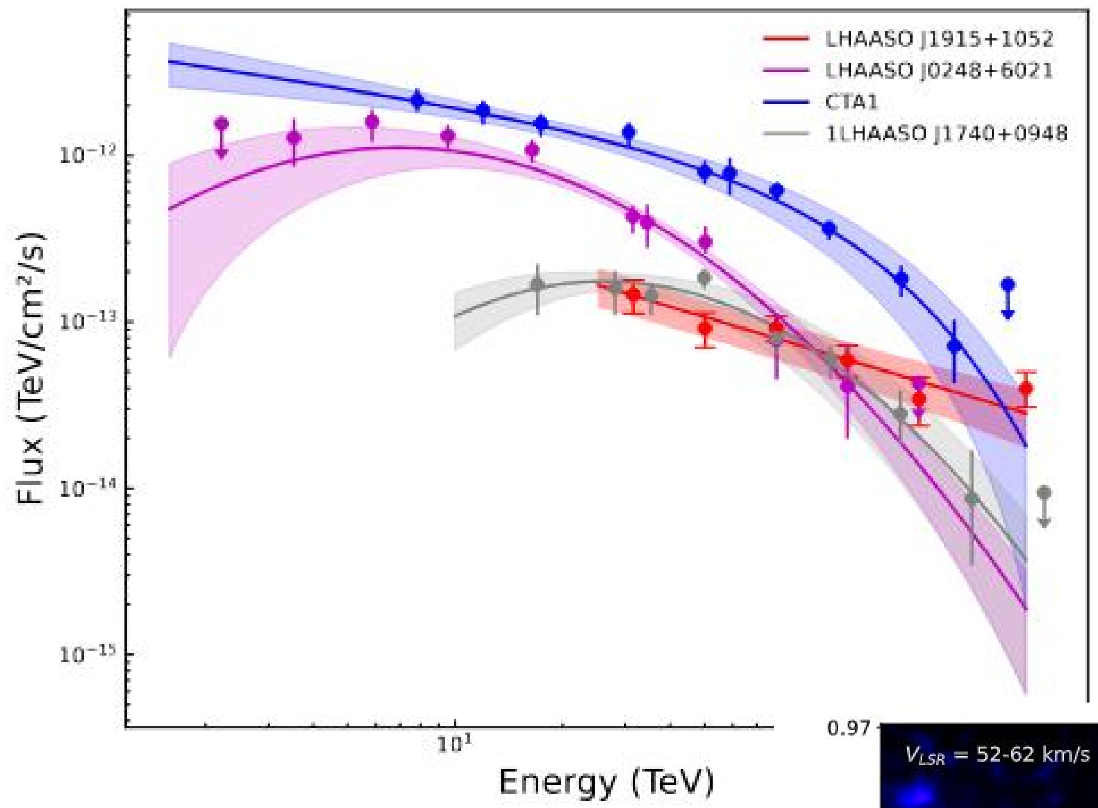
- Our results indicate active BH and their environment are a new class of PeVatron/Super-PeVatron

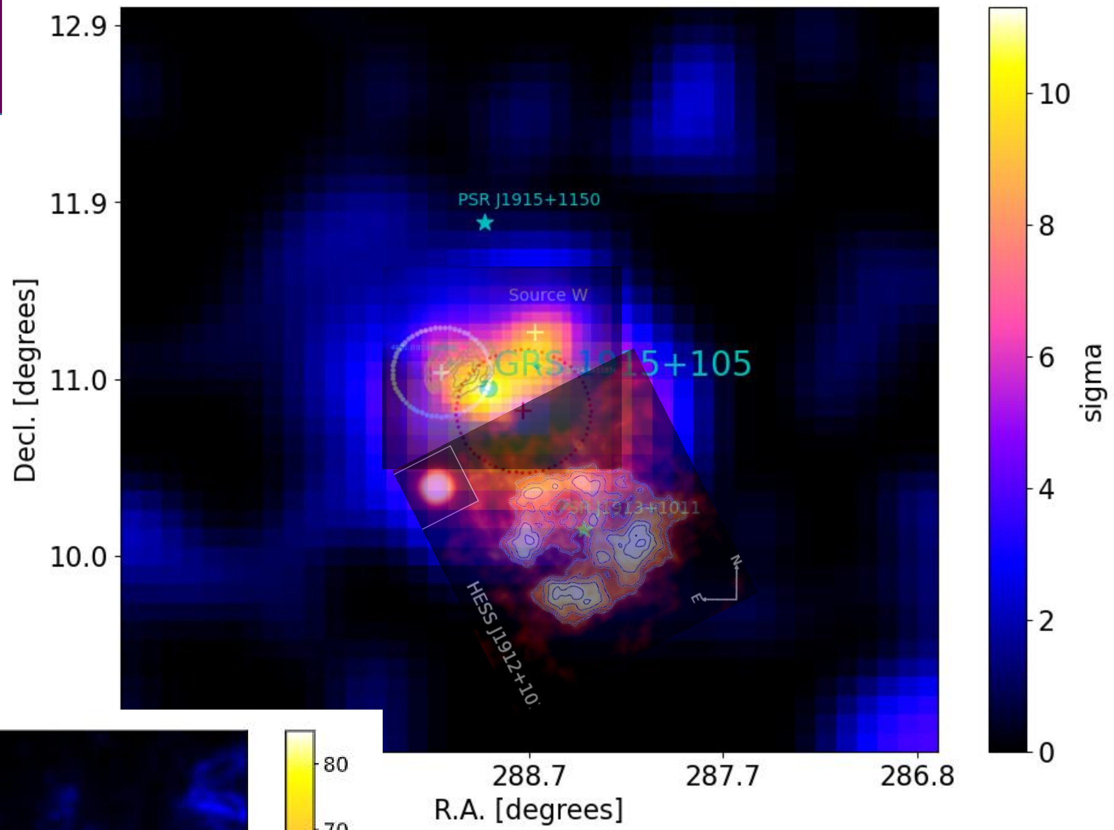
\- implication for particle acceleration in more powerful SMBH-jet systems (blazar, radio galaxies) and origin of UHECRs. Hints of other relevant processes: jet formation, jet dynamics...

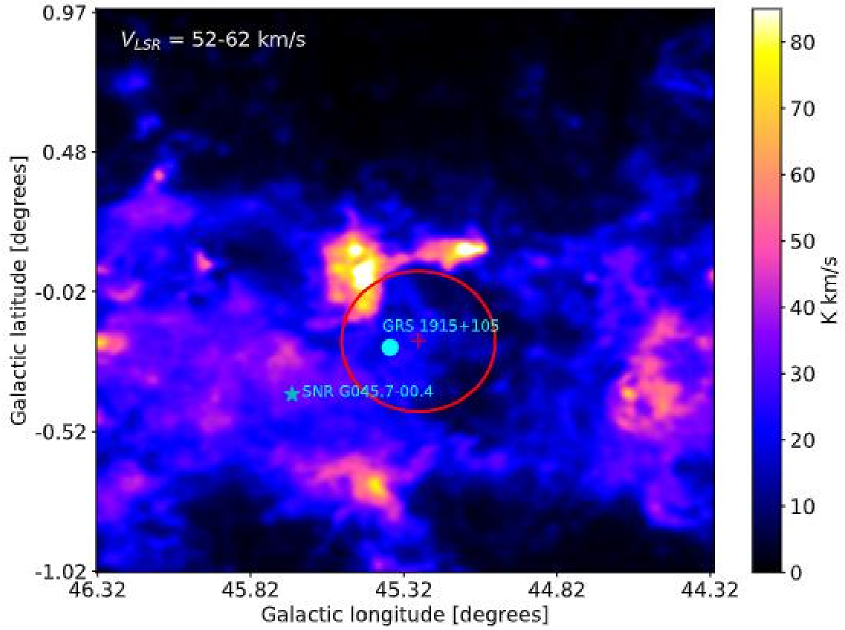
- A connection between UHE emission and BH activities. More samples are needed to answer the possible association between recent BH activities and UHE emission.

Thank you very much for your attention!

- BACKUP SLIDES


LHAASO J1915+1052
LHAASO J0248+6021
CTA1
1LHAASO J1740+0948
10^{-12}
10^{-13}
10^{-14}
10^{-15}
Flux (TeV/cm²/s)
10^{1}
Energy (TeV)

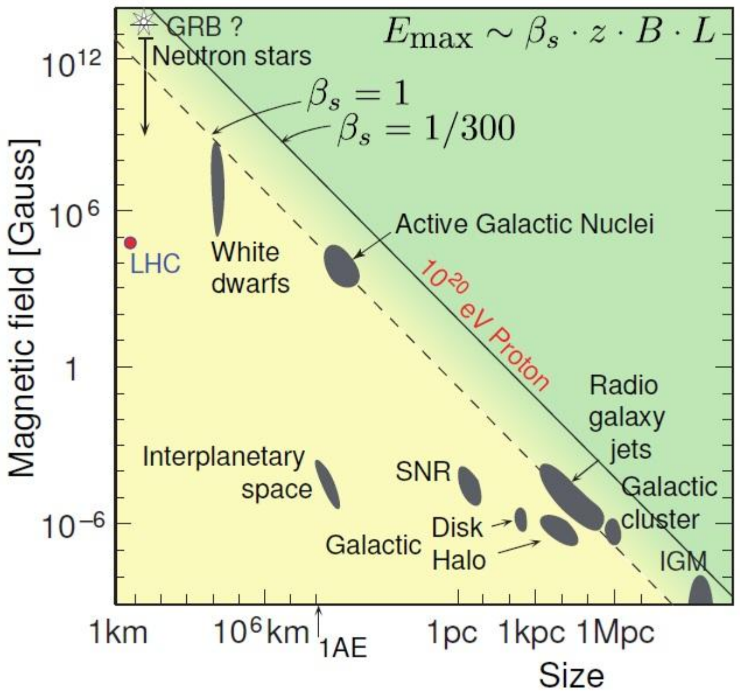

12.9
11.9
11.0
10.0
Decl. [degrees]
PSR J1915+1150
Source W
HESS J1912+10
288.7
287.7
286.8
R.A. [degrees]
10
8
6
4
2
0
sigma

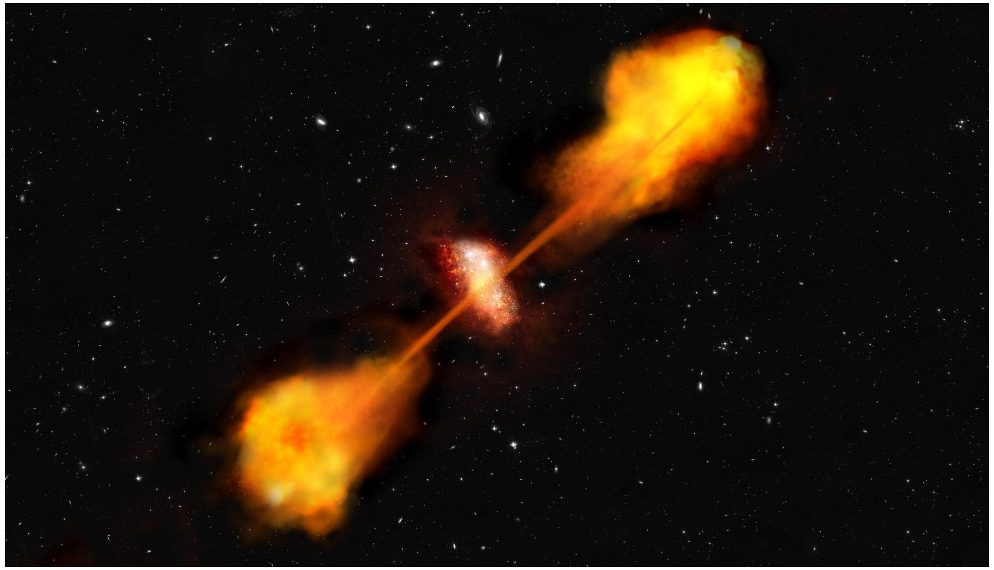

V_{LSR} = 52-62 km/s
GRS 1915+105
SNR G045.7-00.4
0.97
0.48
-0.02
-0.52
-1.02
Galactic latitude [degrees]
46.32
45.82
45.32
44.82
44.32
Galactic longitude [degrees]
80
70
60
50
40
30
20
10
0
K km/s

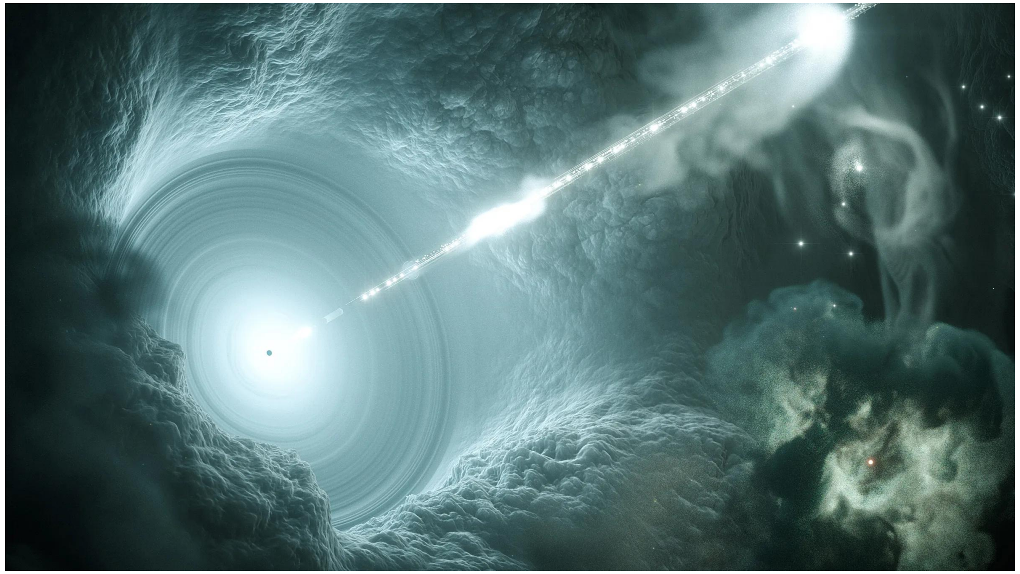
Implications for particle acceleration at AGN

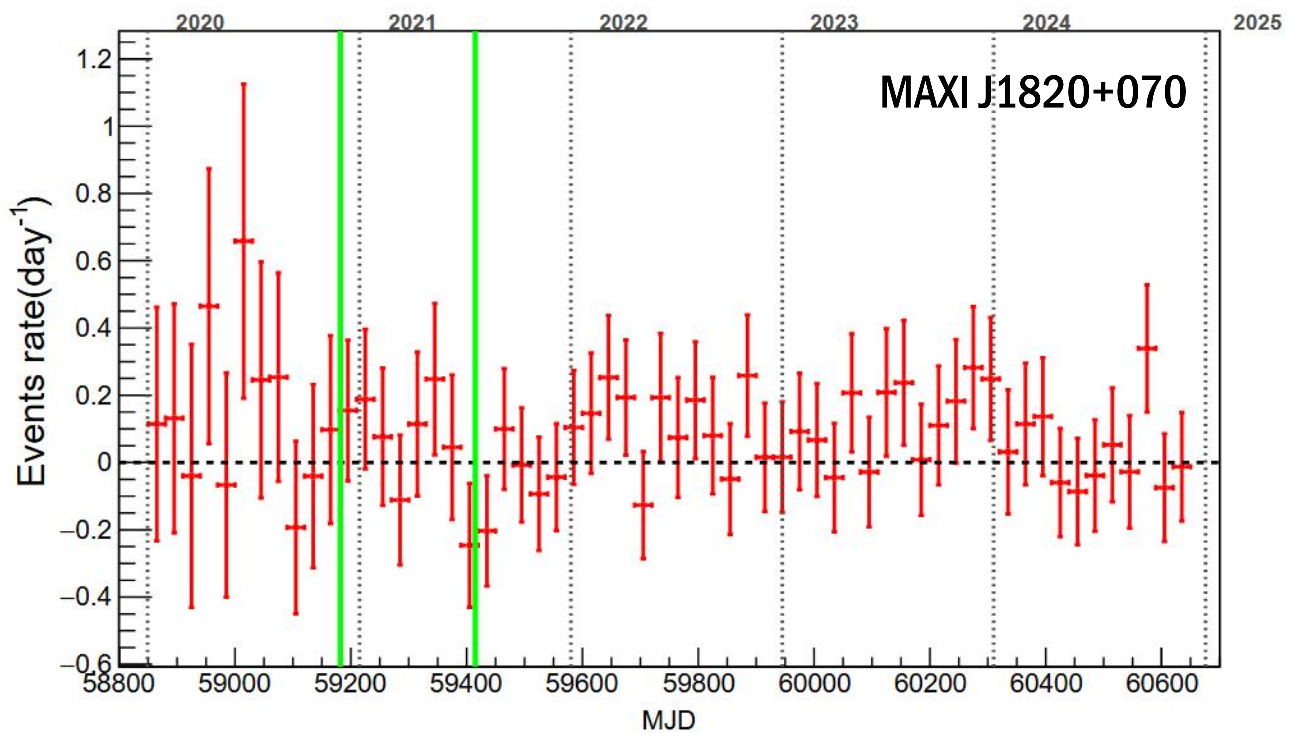
stellar-mass BH-Jet systems
-> accelerators of >~10 PeV at different locations of the system

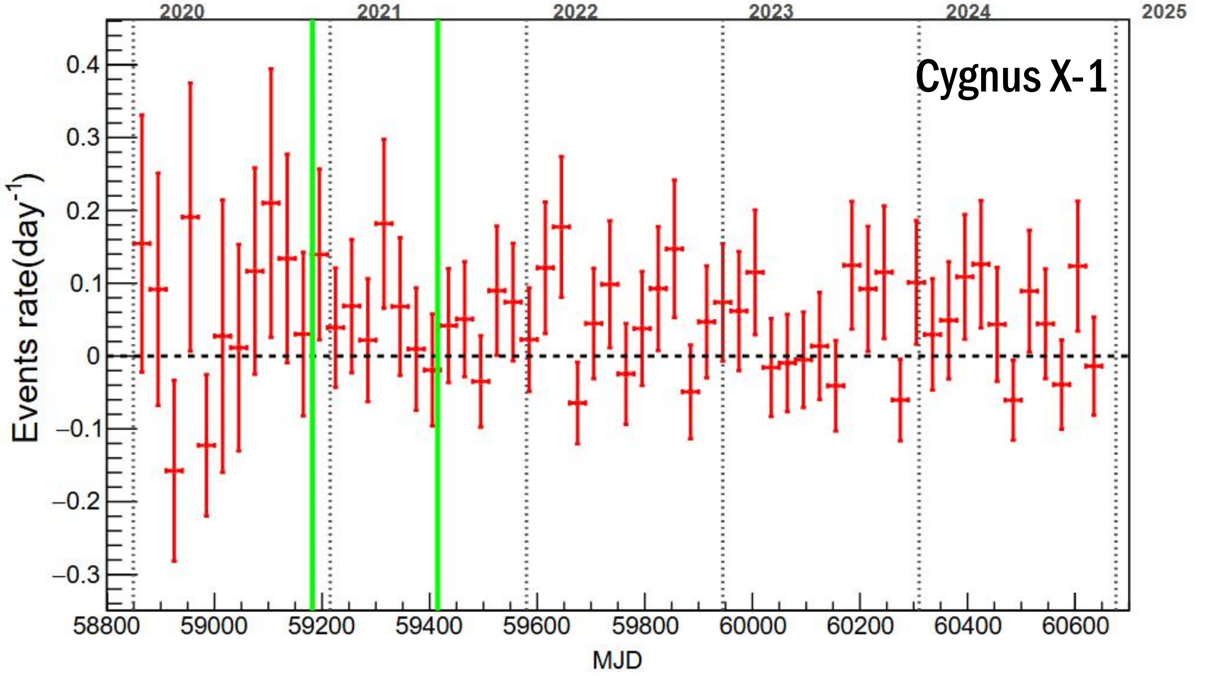
Insights into particle acceleration of supermassive BH-Jet systems (more powerful, more gigantic)

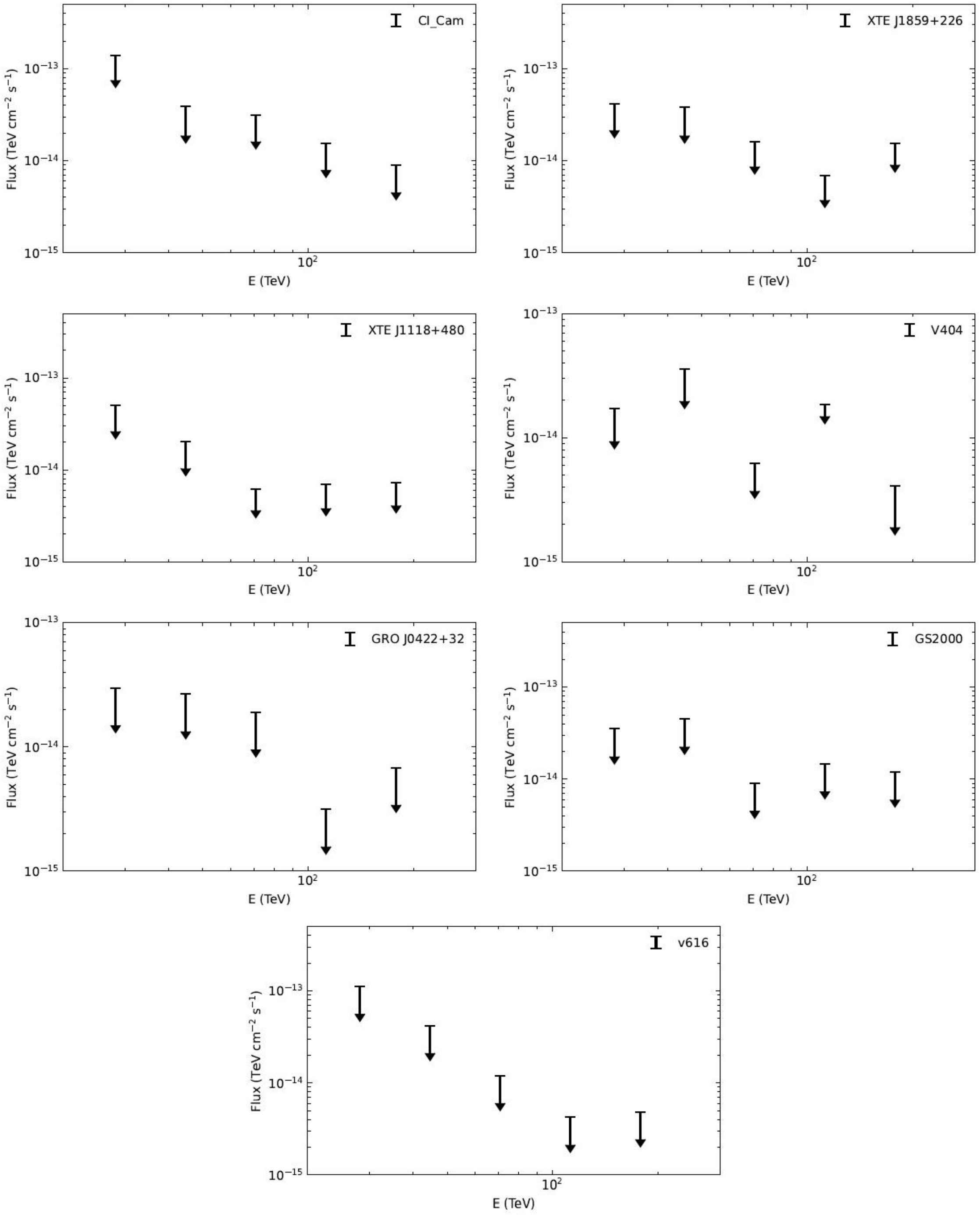


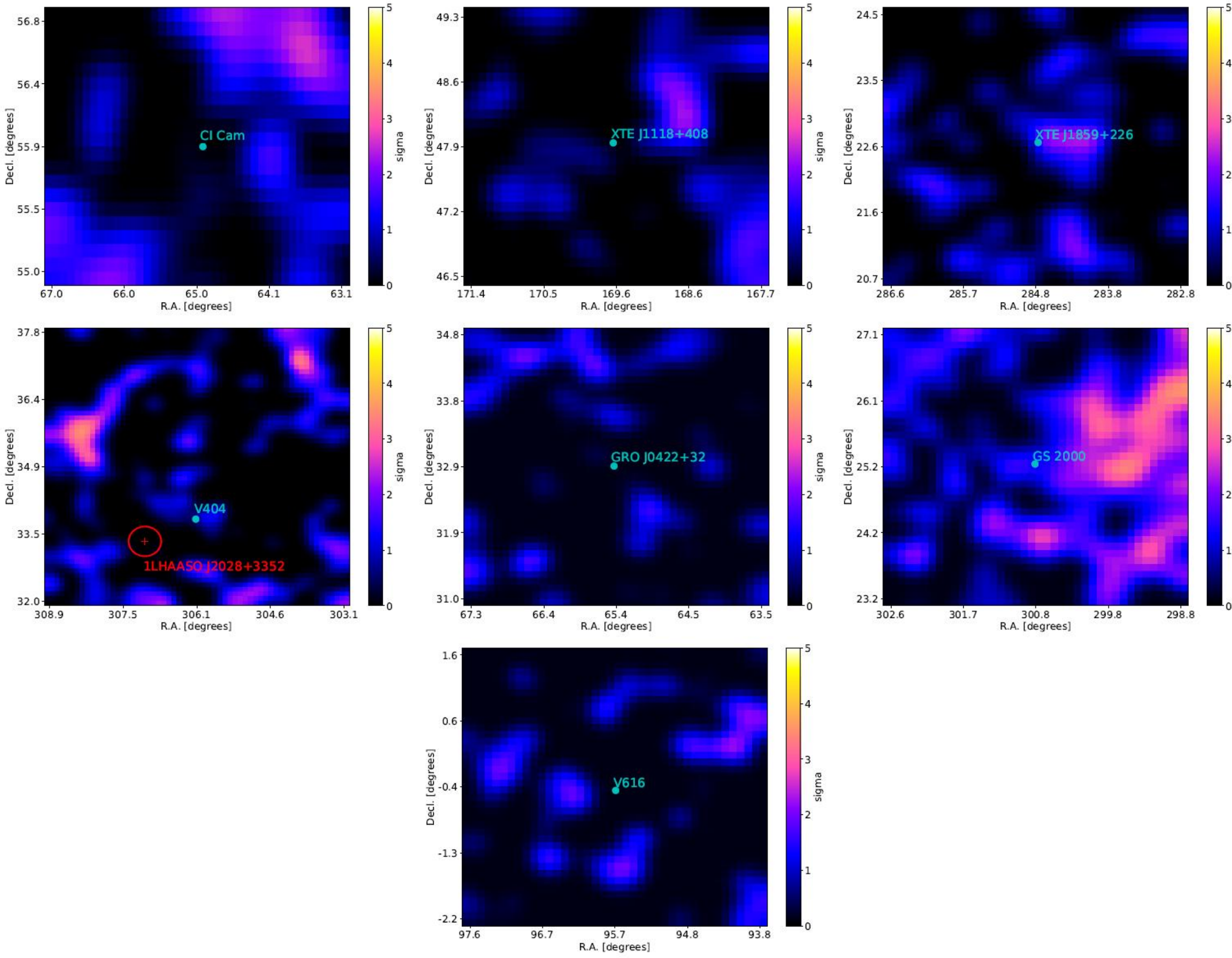





MAXI J1820+070
Events rate(day^{-1})
MJD
2020
2021
2022
2023
2024
2025


Cygnus X-1
Events rate(day^{-1})
MJD
2020
2021
2022
2023
2024
2025





other seven undetected microquasars, longer exposure is needed

Model	RA	DEC	Extension (σ_{ext})	TS
		One source scenario		
Gaussian	$274.88° \pm 0.09°$	$-25.69° \pm 0.11°$	$0.33° \pm 0.08°$	126.8
Ellipse Gaussian	$274.87° \pm 0.06°$	$-25.72° \pm 0.09°$	$0.49° \pm 0.08°/0.1° \pm 0.18°$	140.7
		Two sources scenario		
Point source	$274.95° \pm 0.08°$	$-25.83° \pm 0.09°$	-	134.8
Point Source	$274.77° \pm 0.09°$	$-25.07° \pm 0.11°$	-