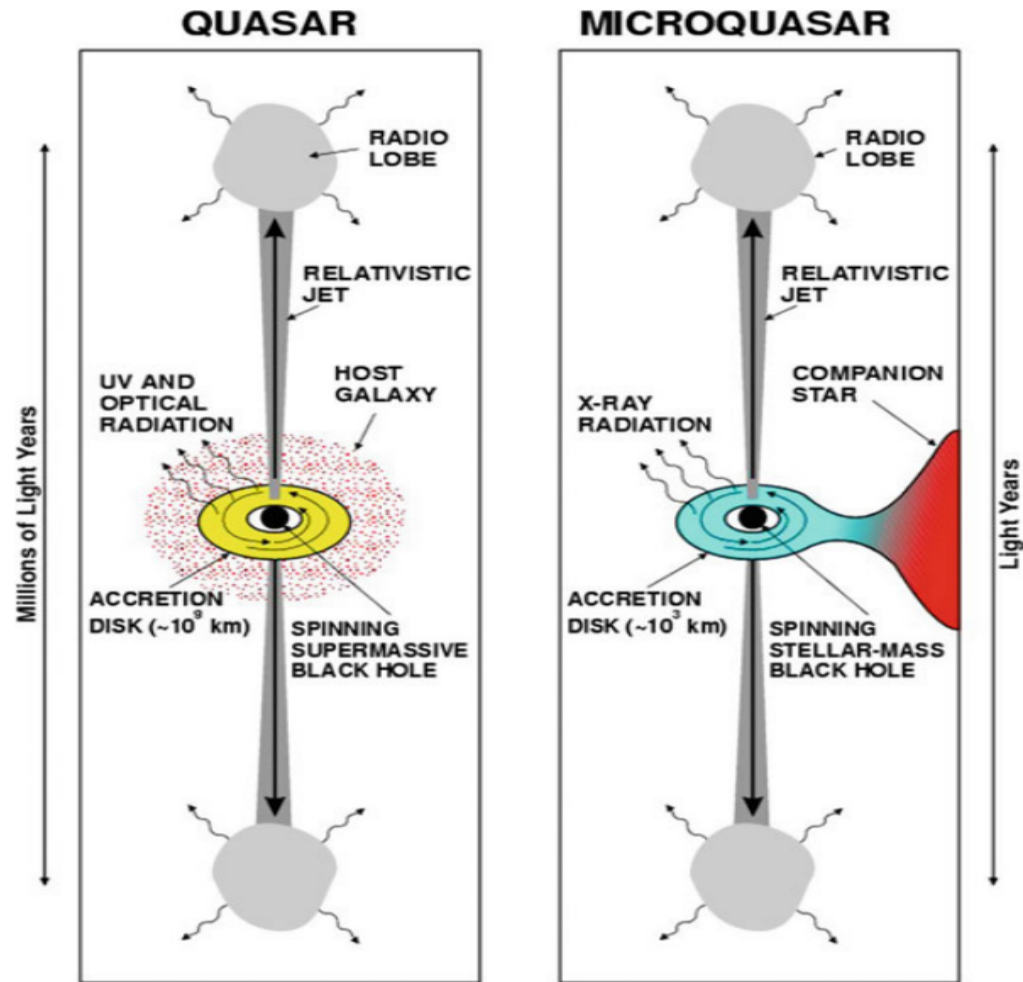


Detection of Microquasars at UHE by LHAASO

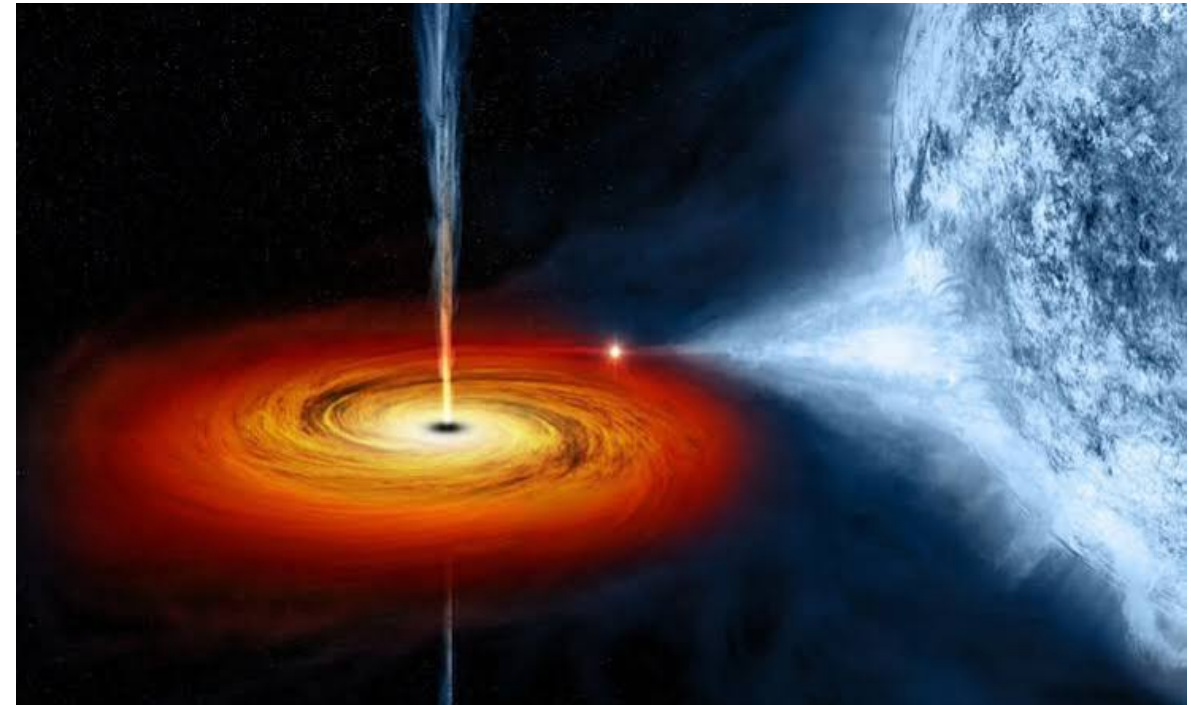
Cong Li (Institute of High Energy Physics)

On behalf of LHAASO Collaboration

Microquasar



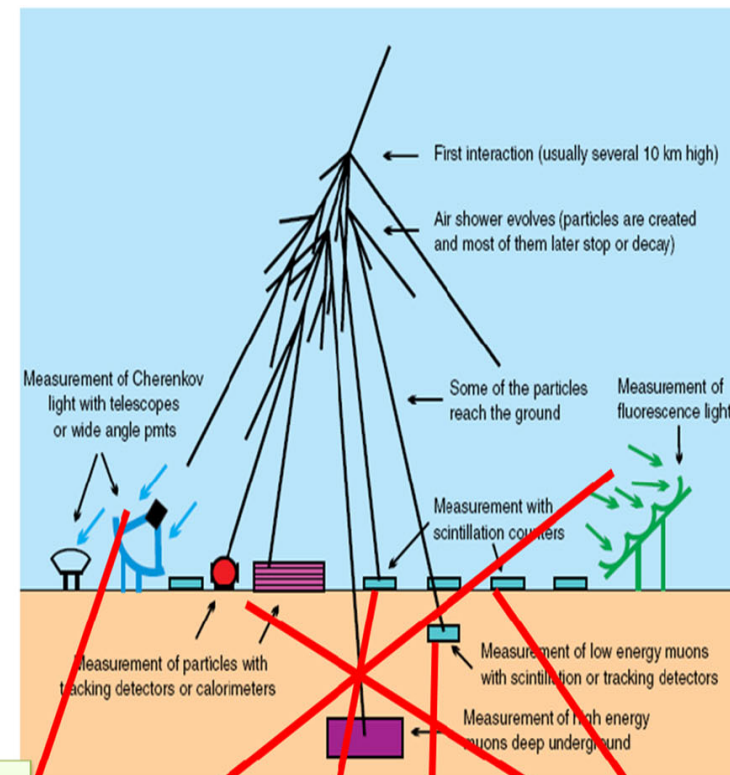
- Mini quasar in our galaxy, with unique features.



LHAASO

Location: $29^{\circ}21'27.6''N$ $100^{\circ}08'19.6''E$

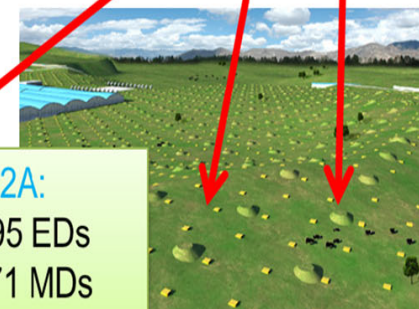
Altitude: 4410m a.s.l



WFCTA:
12 telescopes
1024 pixels each

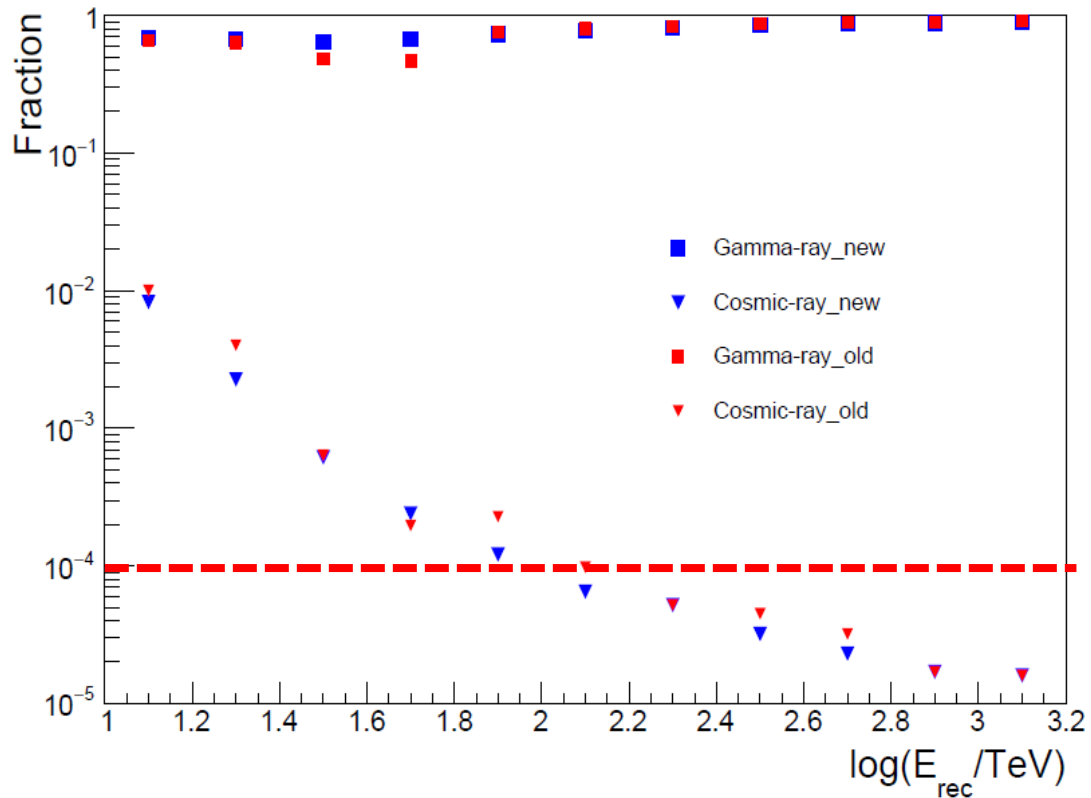
KM2A:
5195 EDs
1171 MDs

WCDA:
3000 cells



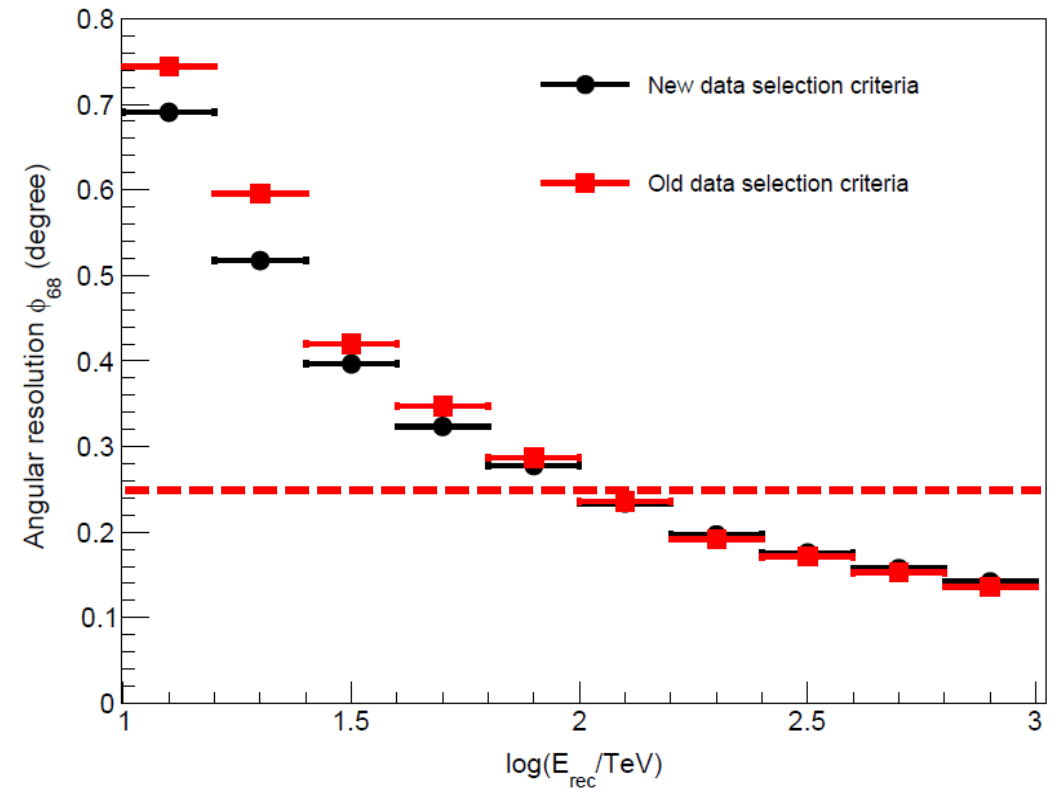
Performance at UHE

Rejection power: $1.e-4@100\text{TeV}$

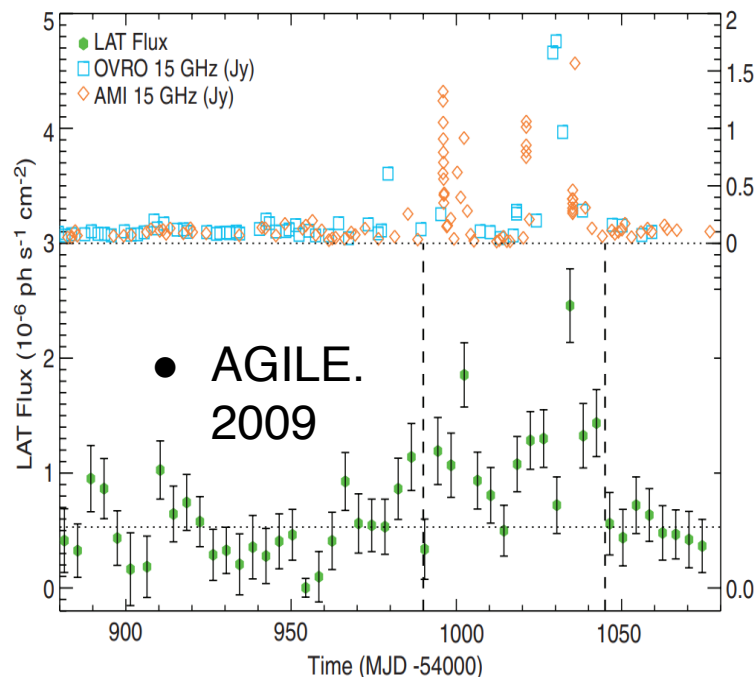


• LHAASO CPC 2024

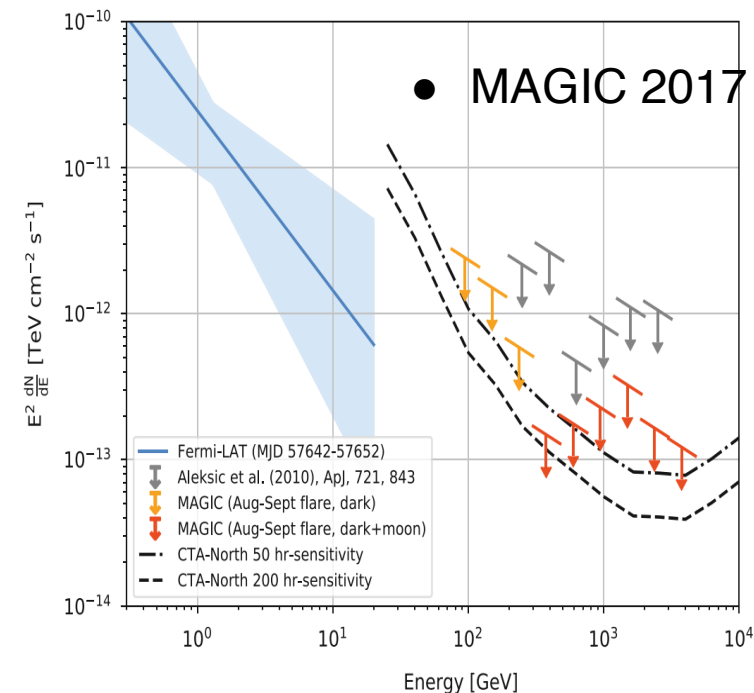
Psf: $0.25^{\circ}@100\text{TeV}$



Historical puzzle: Cygnus X-3



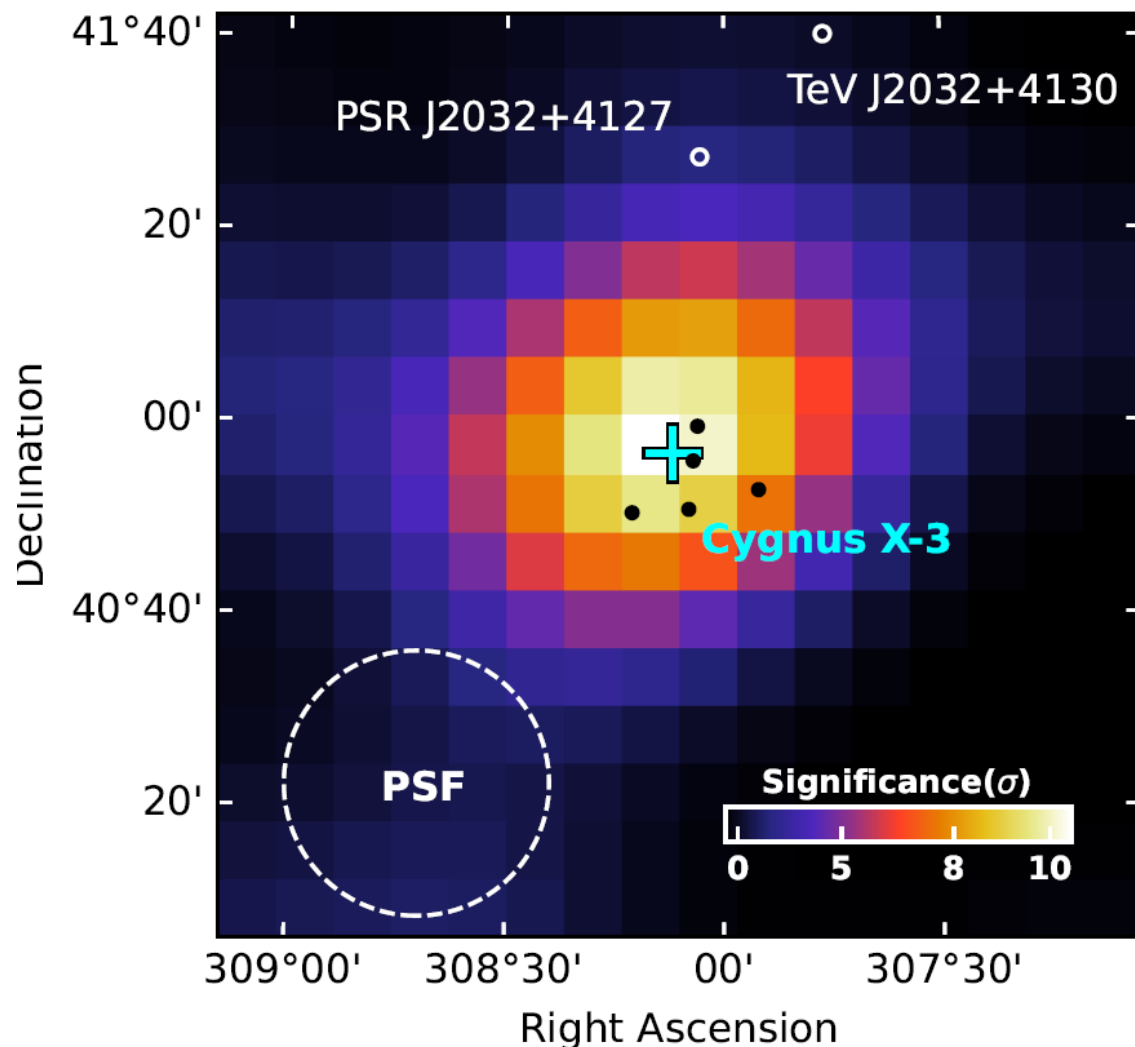
- Correlation between GeV and radio flux;
- Detection of orbital modulation with high significance.



- PeV signals were reported by early ground-based experiments at 1980s;
- Not confirmed by future more sensitive detector.

First PeV gamma-ray source

• LHAASO NSR 2026

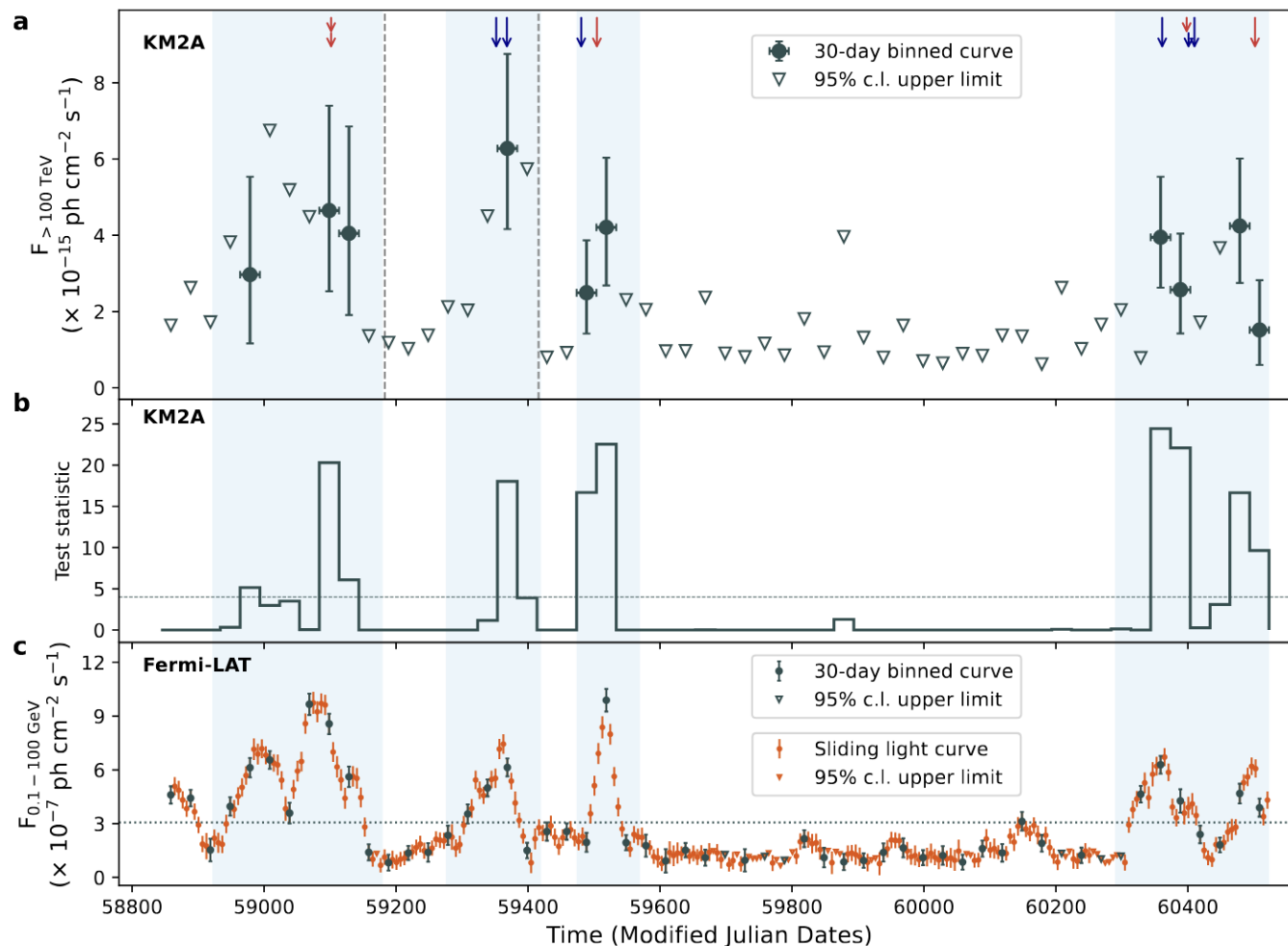


- A point source is detected positionally coincident with Cygnus X-3 at a significance of **11.58** (GeV active state);

$$RA = 308.10 \pm 0.03_{stat} \pm 0.03_{syst};$$
$$DEC = 40.92 \pm 0.02_{stat} \pm 0.03_{syst};$$

- ◆ UHE Photons:
5 photons are detected with $E > 1\text{PeV}$;
- ◆ Background:
~0.008 from residual cosmic rays;
~0.051 from gamma ray background.

UHE Flares



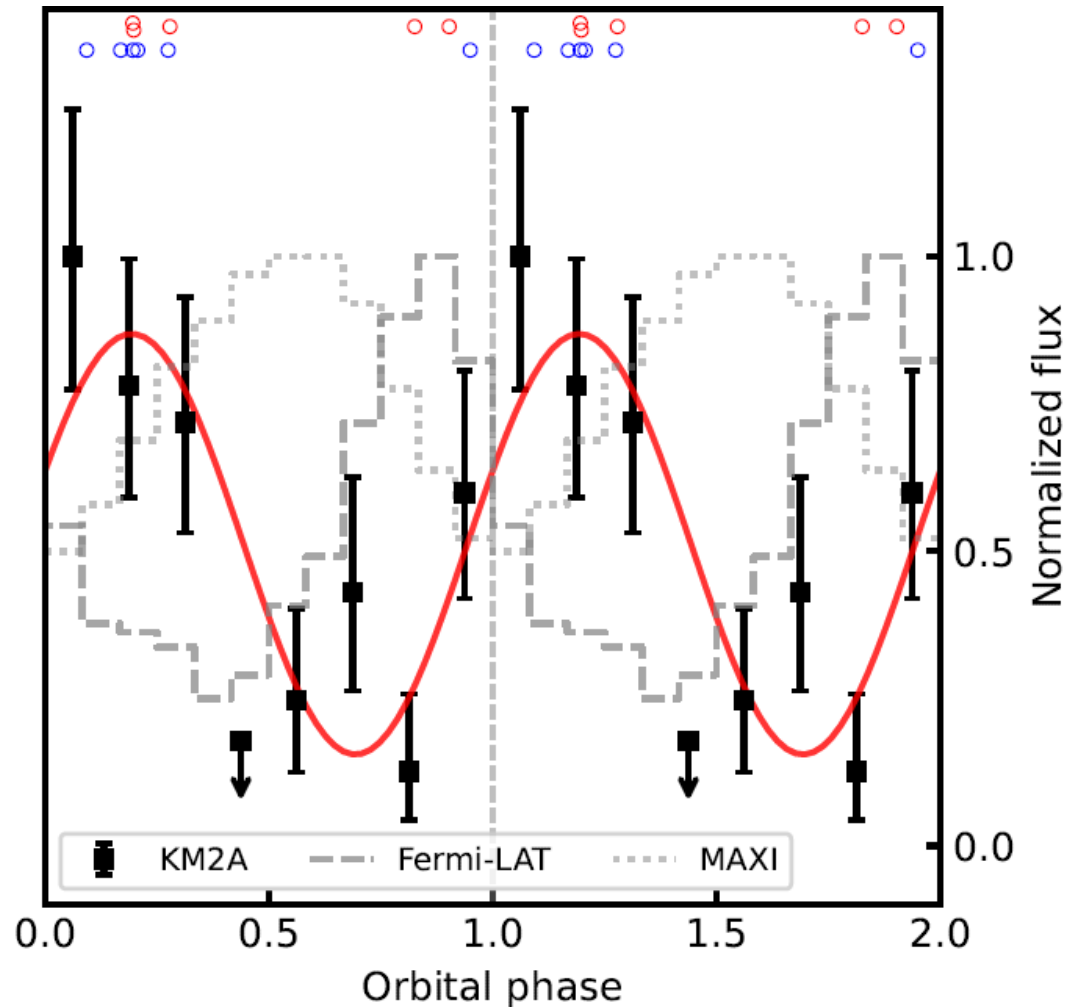
- Divide the data into two parts according to GeV states. Ratio of exposure time: 1:1.6.

➤ Variability test:

- **H0: Constant flux;** $\Delta TS = 75 \sim 8.6 \sigma$
- **H1: Change of flux at two states.**

◆ It is confirmed that the UHE flux is variable with time with a pre-defined GeV time window.

Modulation with orbital phases

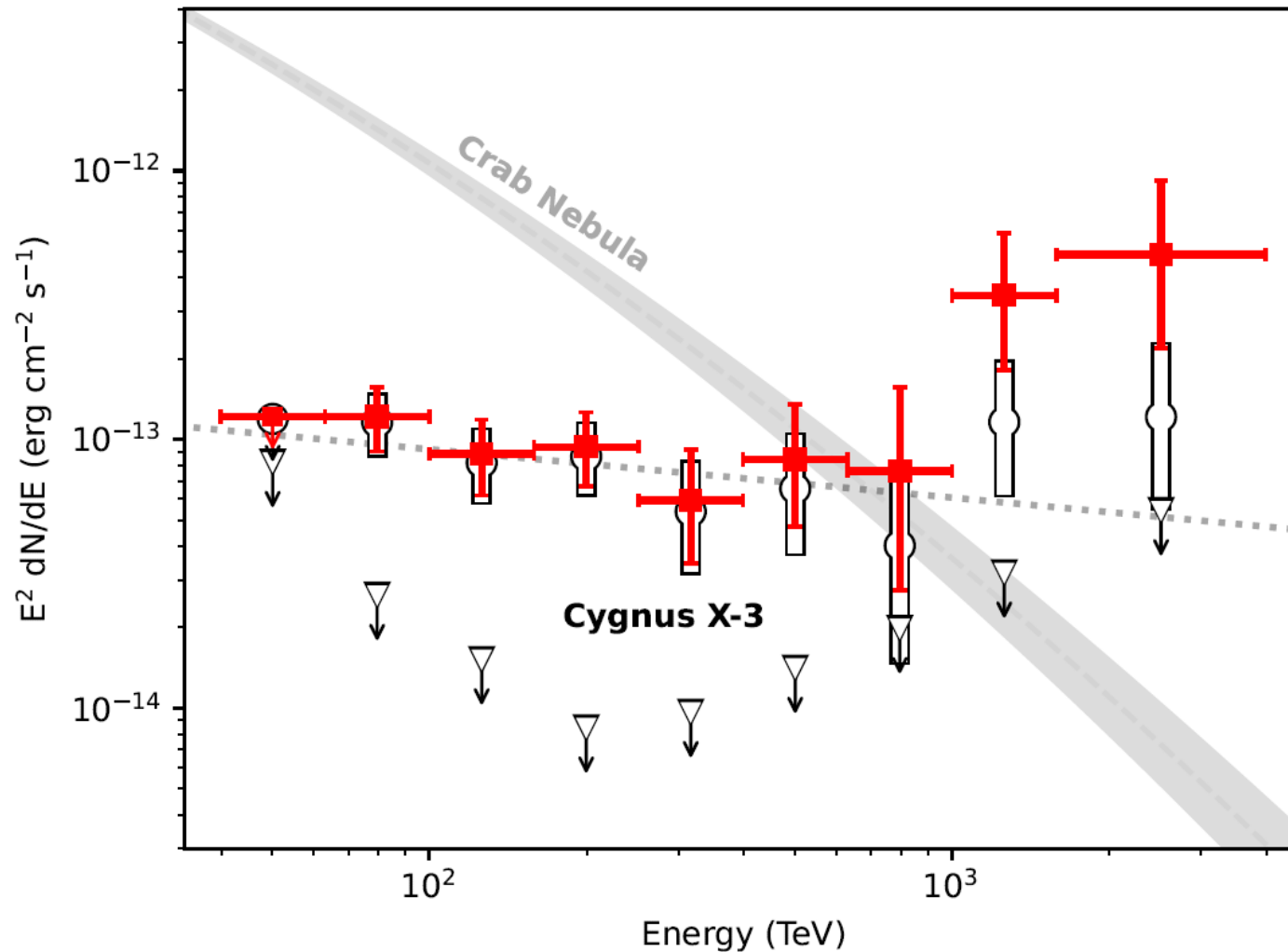


- The significance for variability:
 $3.5\sigma \sim 3.2\sigma$ (post trials).
- Comparison between cosine function and constant function:

$$\Delta TS = 15.24\sigma \sim 3.3\sigma.$$

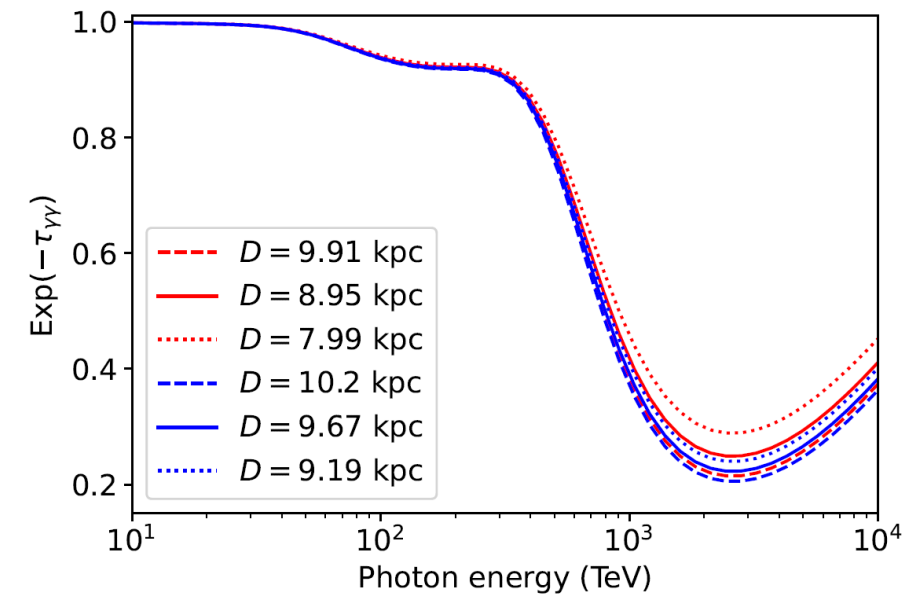
□ Constrain the emission region $< 3 \times 10^{11} \text{ cm}$

Spectrum

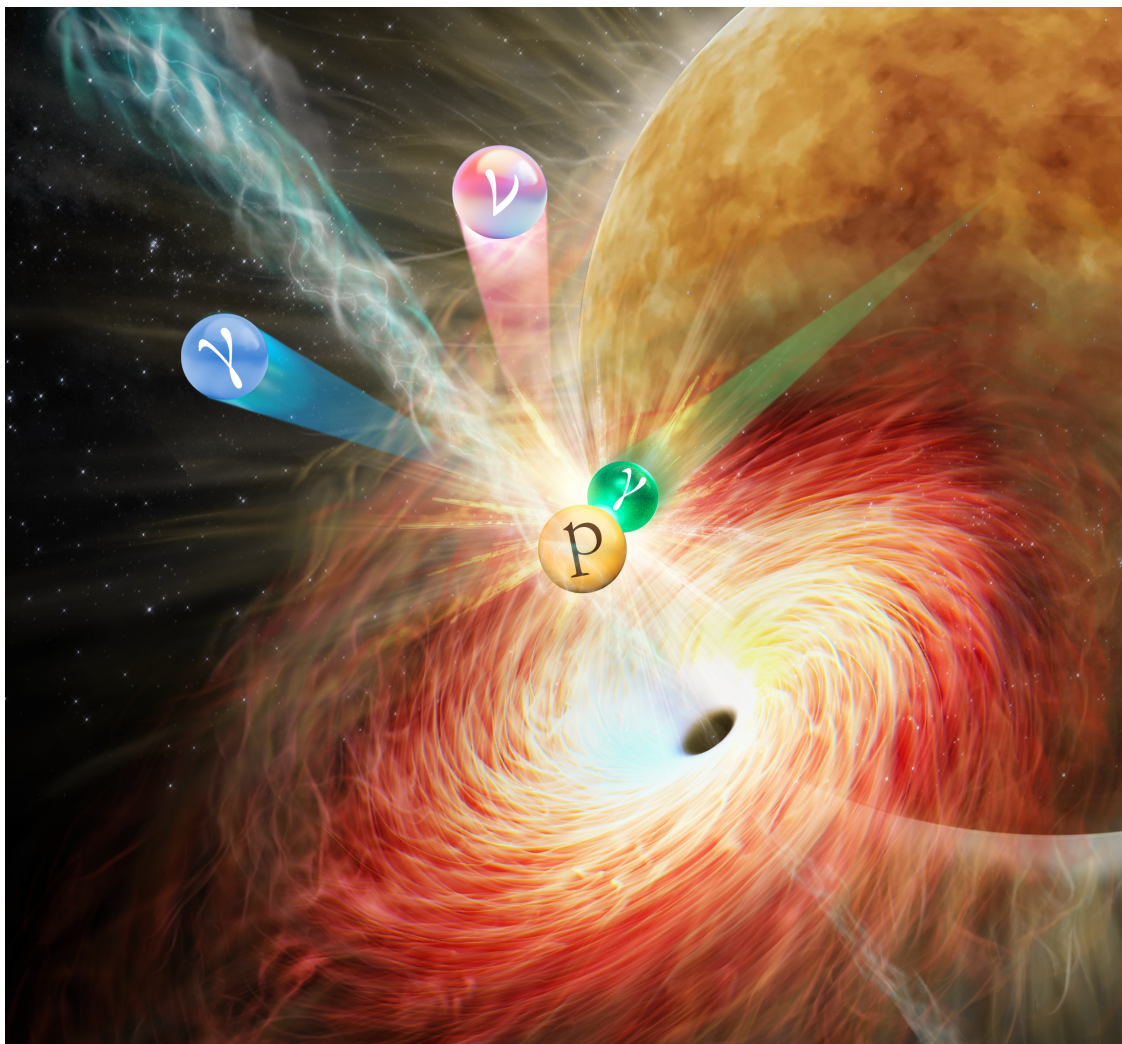


◆ Hardest SED ever at UHE energy range:

$$\Gamma = 2.18 \pm 0.14 \text{ (before correction)}$$



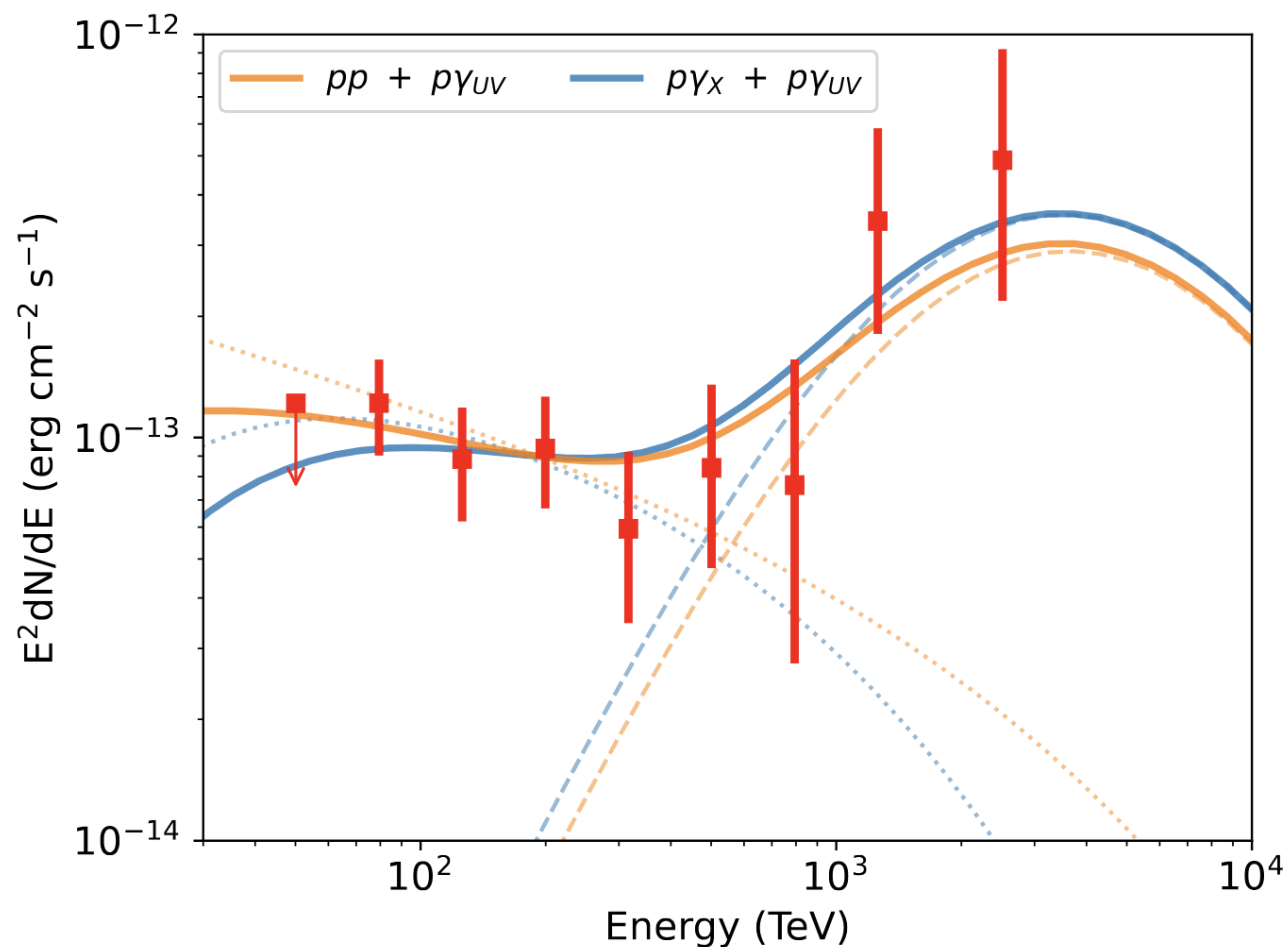
Physical Scenario



The high density of material (photons or gas) makes it natural for hadronic process.

- Photon from companion star(~ 10 eV): $p\gamma_{uv}$;
- Photon from accretion disk, jet or outflow($\sim$ keV): $p\gamma_x$;
- Gas from jet of companion star: pp ;

$P - \gamma$ Process

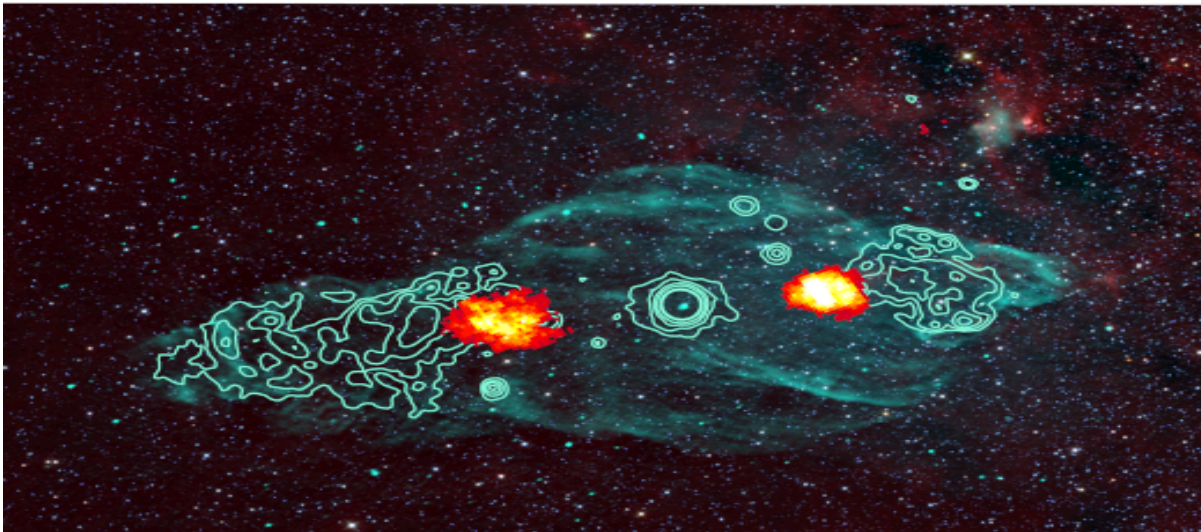


- ◆ $E_t \sim 10 \text{ eV}$, interaction angle $\theta = 90^\circ$;
- ◆ $E_p \sim 10 \text{ PeV}$, $E_\gamma \sim 1 \text{ PeV}$

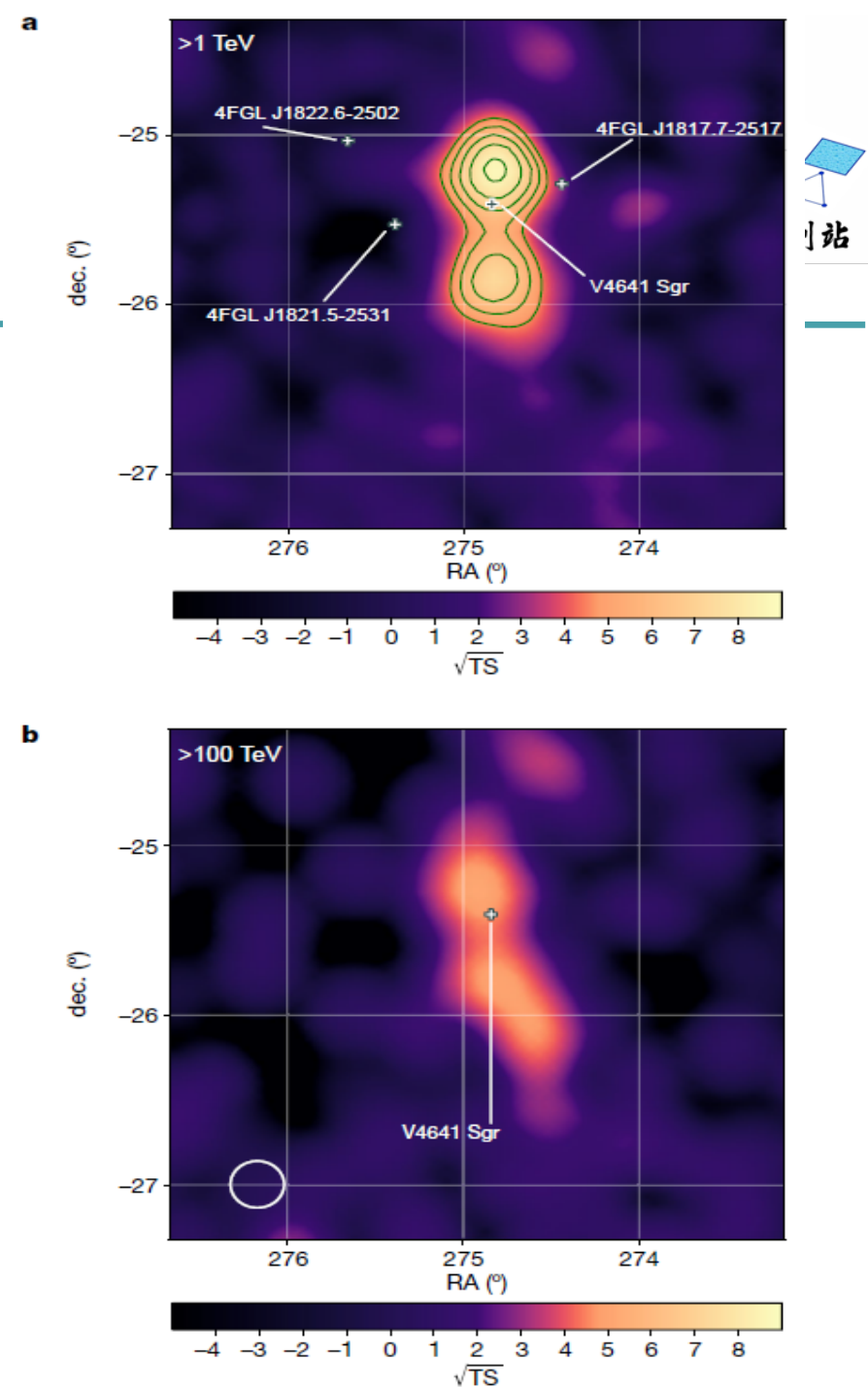
- Proton needs to be accelerated at least to 10 PeV.
- It is a unique feature that distinguishes from other processes.

Microquasar Remnants

- UHE($>100\text{TeV}$) emission associated with microquasars were detected recently.
(LHAASO, HAWC, HESS)



GSSI 2026



Search for UHE emission around microquasars

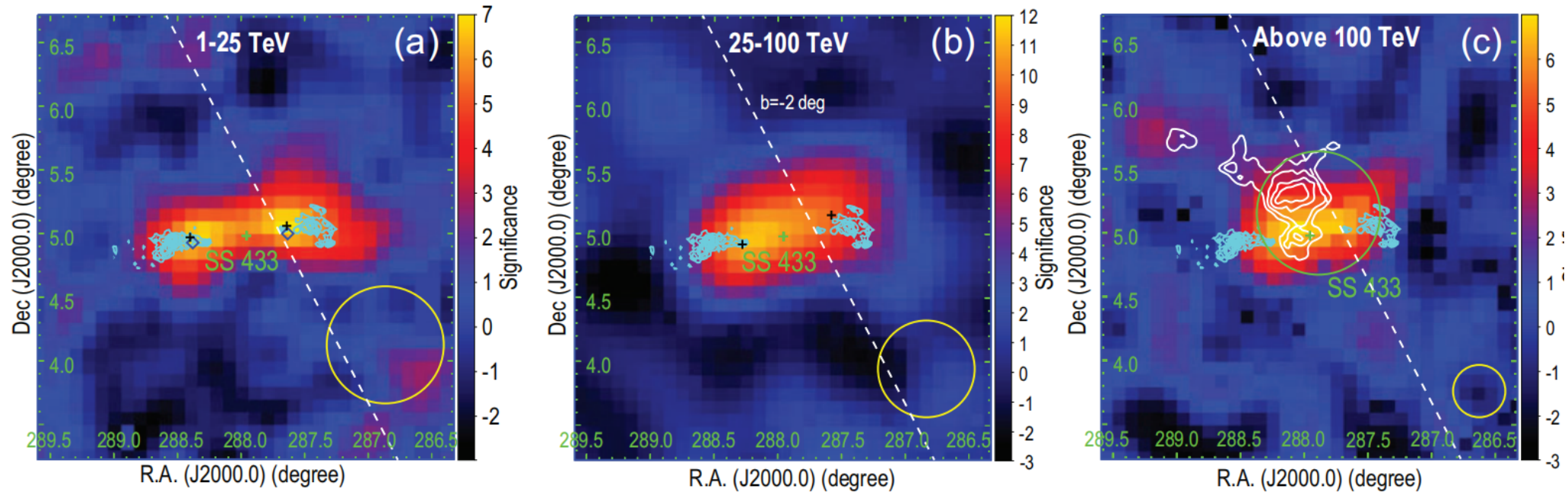
• LHAASO NSR 2025

Table 1. LHAASO's measurement of galactic BH-jet systems in the field of view.

Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon index	Energy range (TeV)	Extension ^a	Flux ^b (Crab unit)
SS 433 E.	4.9 ± 0.4 [31]	J1913+0455	9.9 ^c	2.82 ± 0.16	25-100	$0.73^\circ \pm 0.07^\circ$	0.10
SS 433 W.		J1910+0509	6.3 ^c	2.94 ± 0.38	25-100		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+1053	15.1	2.68 ± 0.13	25-1000	$0.28^\circ \pm 0.05^\circ$	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 [25]	J1958+3522	4.4	3.98 ± 0.40	25-100	$< 0.22^\circ$	< 0.01
XTE J1859+226	4.2 ± 0.5 [35]	–	2.7	–	–	–	< 0.02
GS 2000+251	2.7 ± 0.7 [36]	–	2.3	–	–	–	< 0.04
Swift J1727.8-1613	2.7 ± 0.3 [37]	–	0.7	–	–	–	< 0.04
GRO J0422+32	2.49 ± 0.3 [38]	–	0.7	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14 [39]	–	1.5	–	–	–	< 0.03
XTE J1118+480	1.7 ± 0.1 [40]	–	0.4	–	–	–	< 0.02
V616 Mon	1.06 ± 0.1 [41]	–	0.4	–	–	–	< 0.01

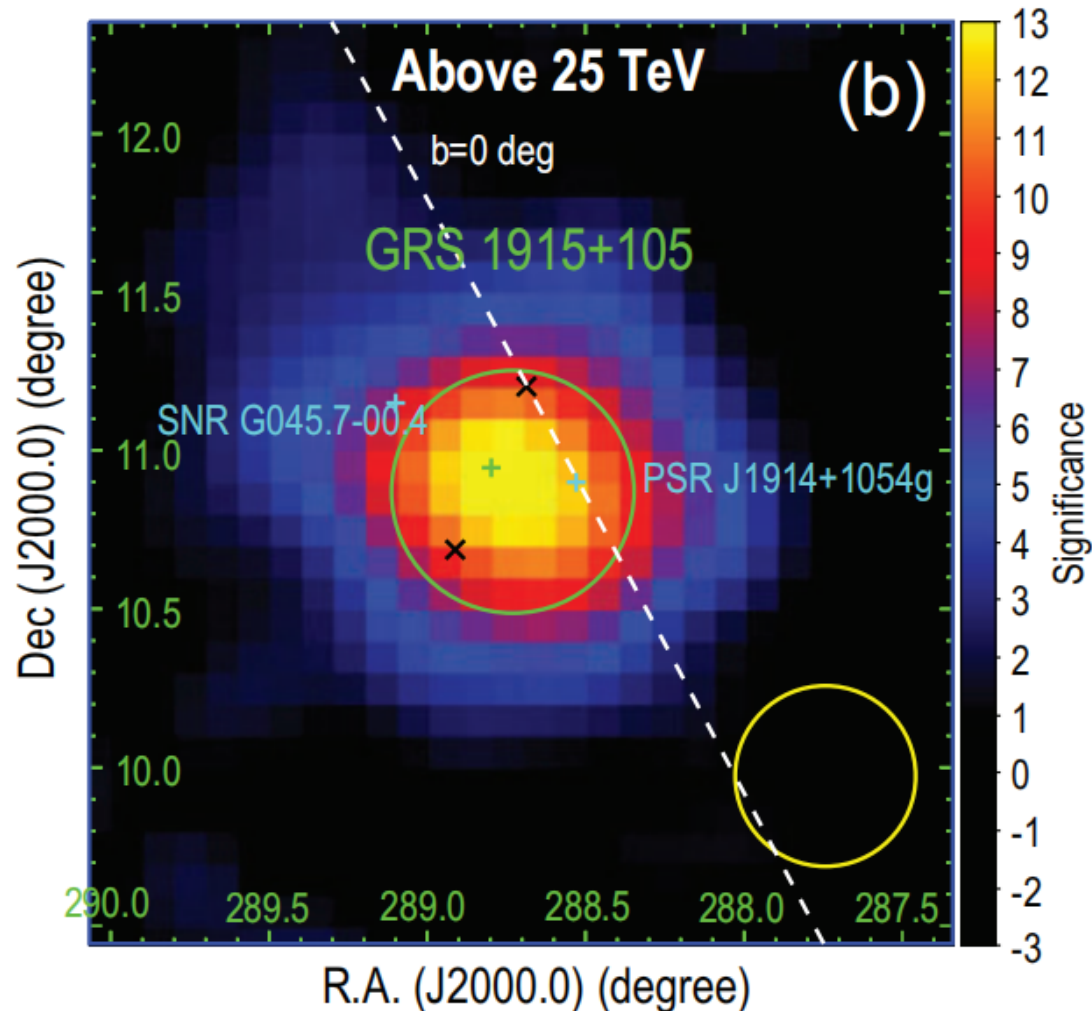
□ It may common for microquasar to accelerate particles to very/ultra high energy

SS433



- ◆ Detection of gamma-ray emission >100 TeV with significance >5 sigma;
- ◆ The position is shifted closer to the center with energy increase.

GRS 1915+105



A new extended source, with an extension of $0.25^\circ \pm 0.05^\circ$, was detected at an offset of 0.1° southwest of GRS 1915+105.

Other possible candidates:

➤ Radio pulsar PSR J1914+1054g

Spindown luminosity: 4×10^{35} ergs/s;

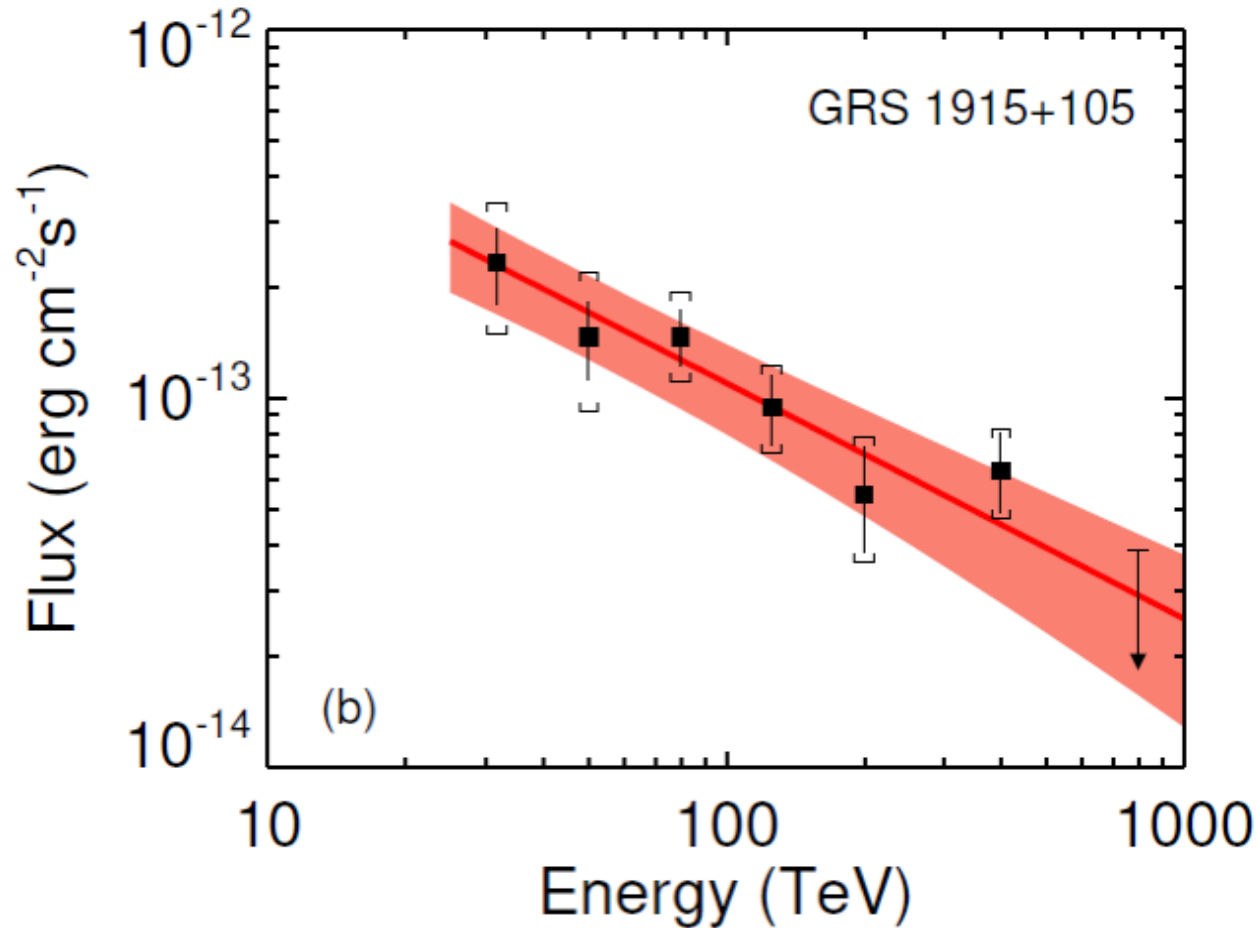
Age: 82kyr;

The larger offset, 0.26deg, making it unlikely the main contribution to LHAASO J1915+1052.

➤ Supernova remnant (SNR) G045.7-00.4

No clear association between LHAASO J1915+1052 and CO at G045.7-00.4 distance.

GRS 1915+105

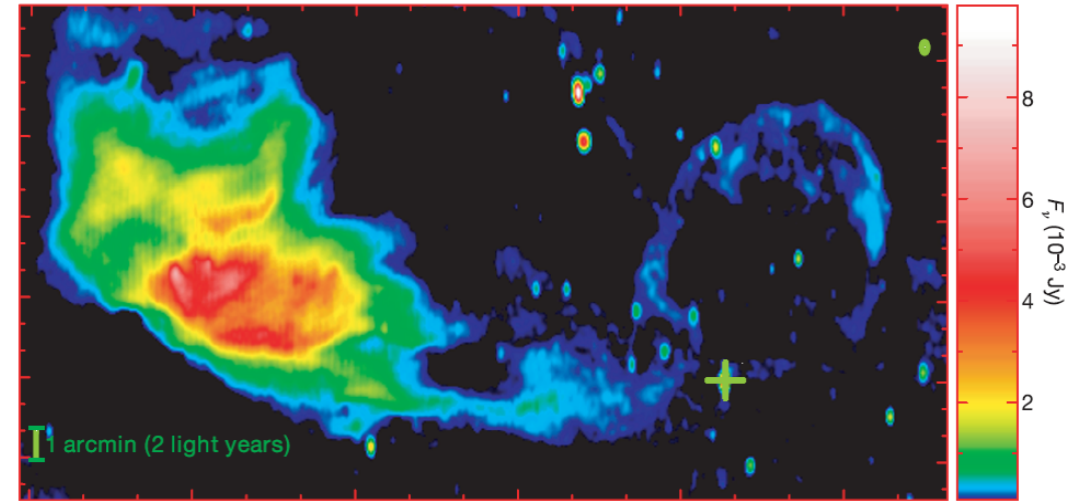
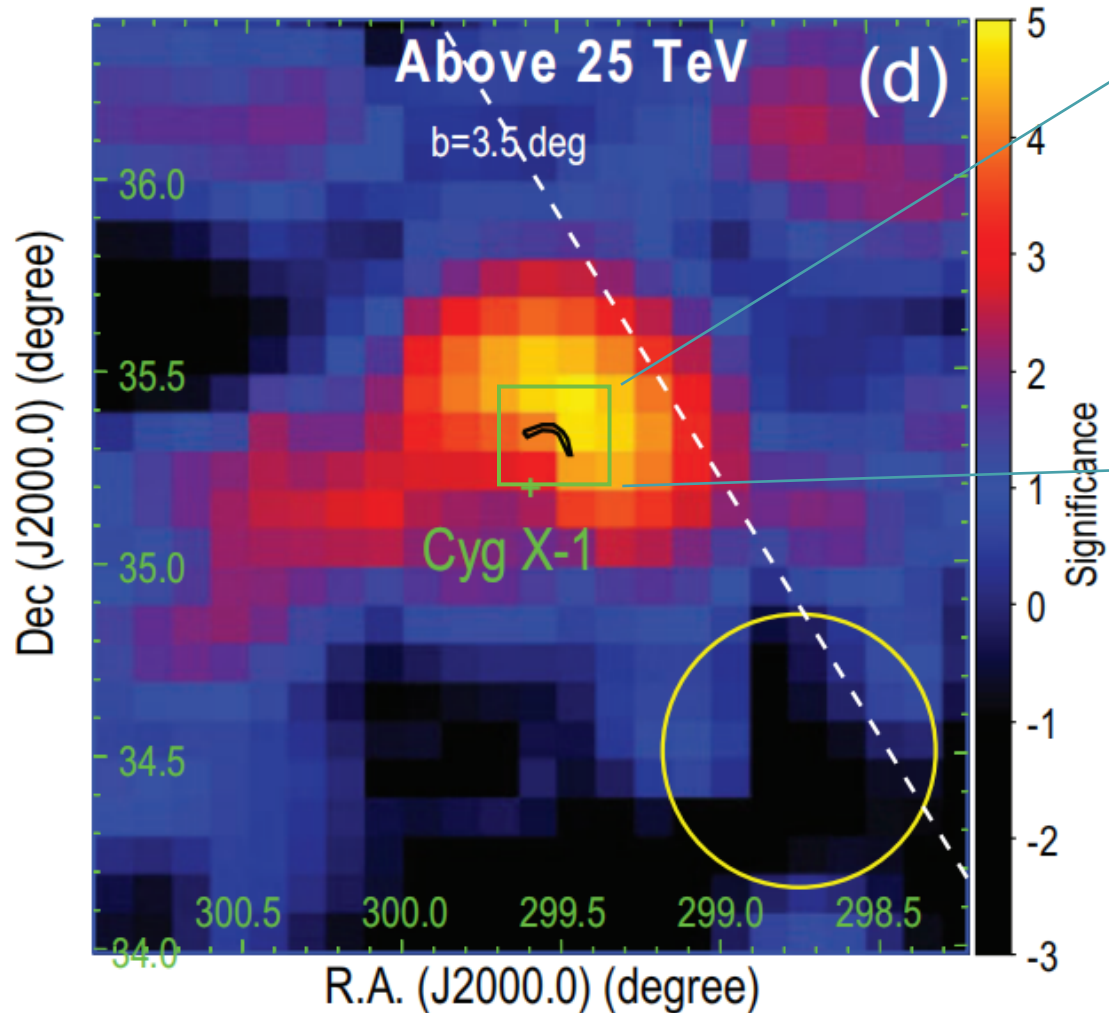


Best fitted by pure power-law:

$$\frac{dN}{dE} = (0.43 \pm 0.11) \times 10^{-16} \left(\frac{E}{50 \text{ TeV}} \right)^{-2.64 \pm 0.14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

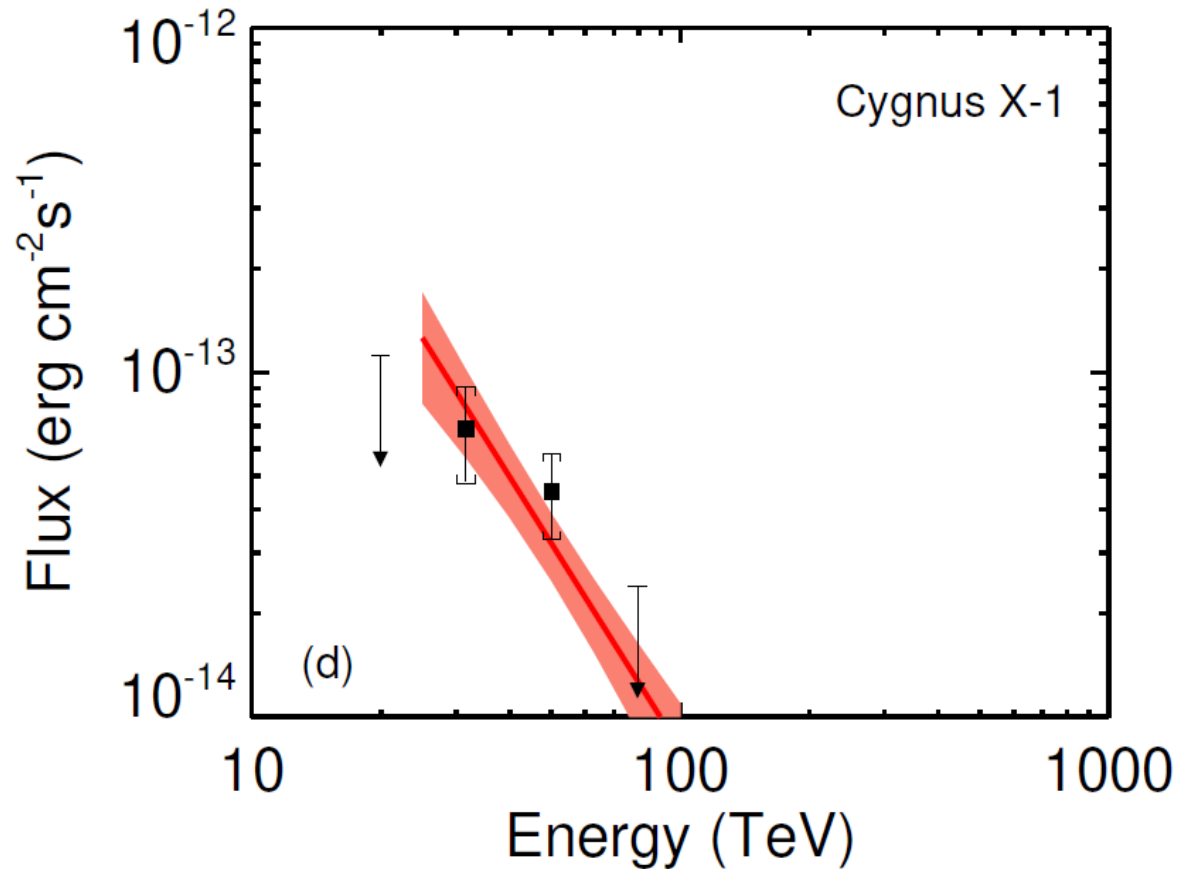
- ◆ A hard spectrum extends to ~400 TeV.
- ◆ It is unlikely from a PWN and most likely related to GRS 1915+105.

Cygnus X-1



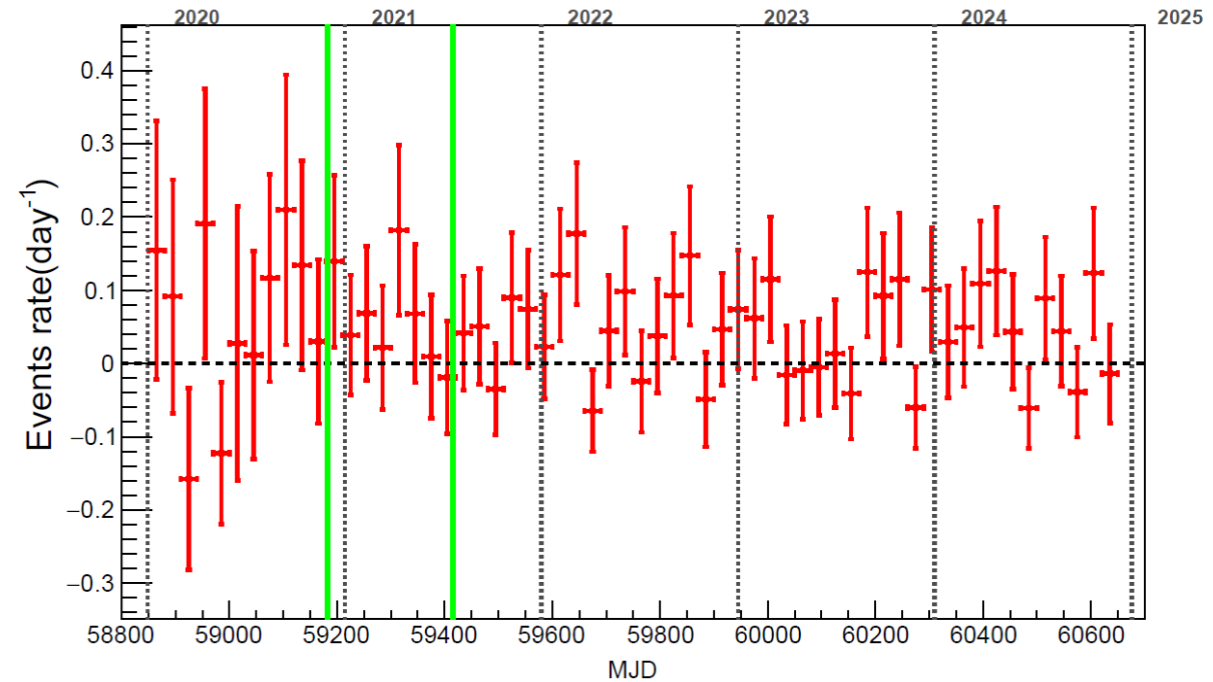
- ◆ A point-like source is detected with significance of 4.4σ above 25 TeV.
- ◆ The position is at the direction of nebula probably inflated by the jet of BH.

Cygnus X-1

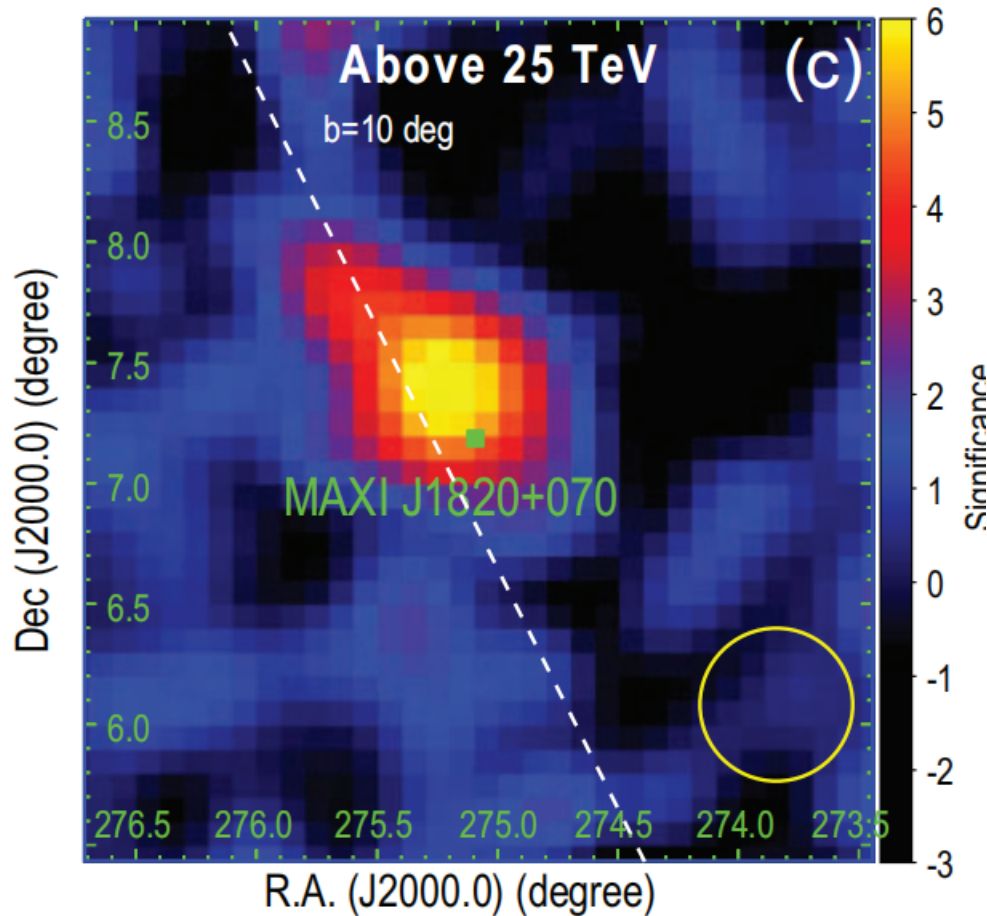


◆ Soft spectrum with a hint of cut-off.

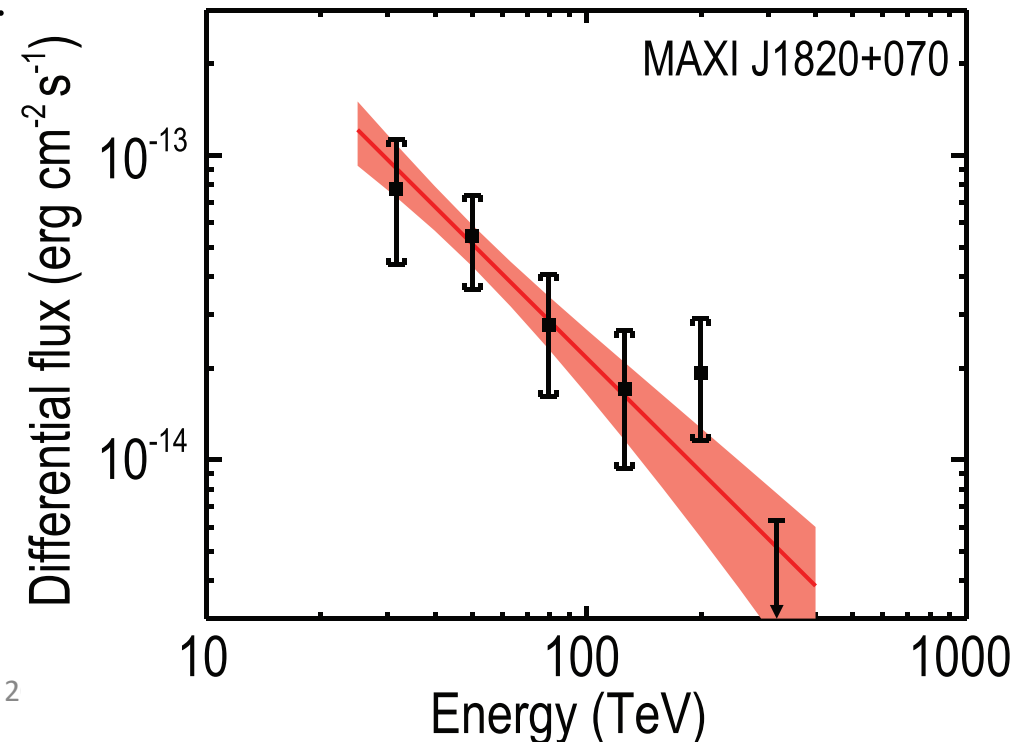
◆ No variability is observed.



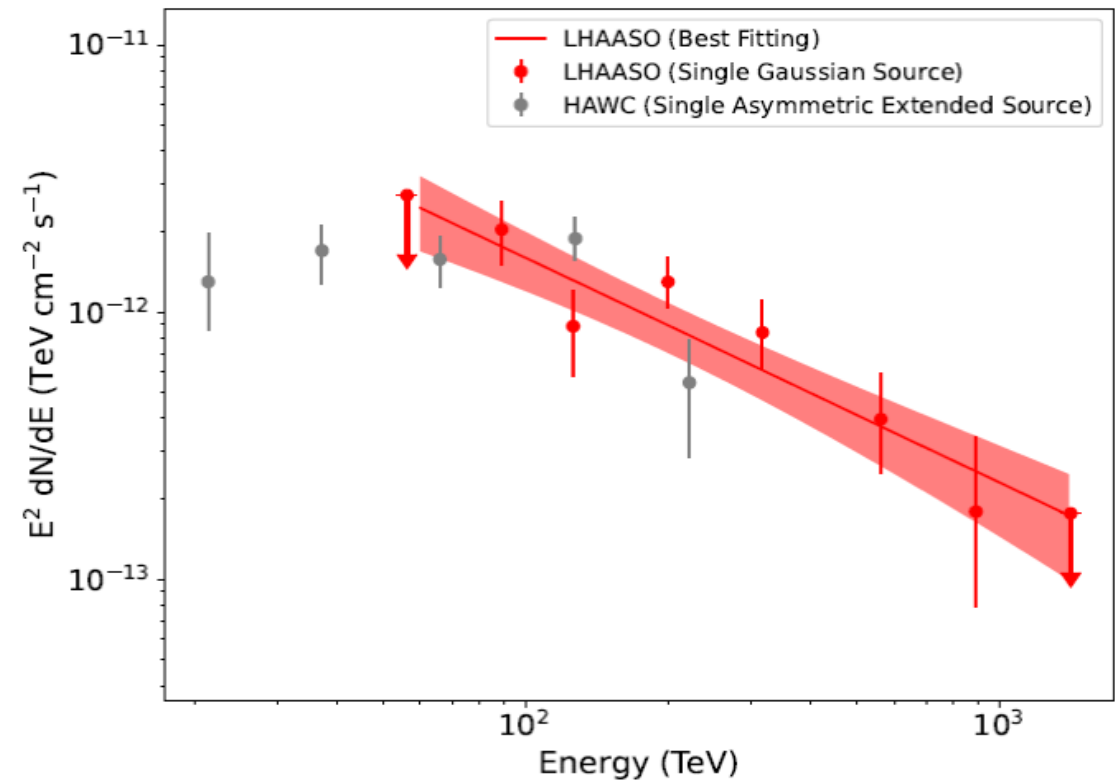
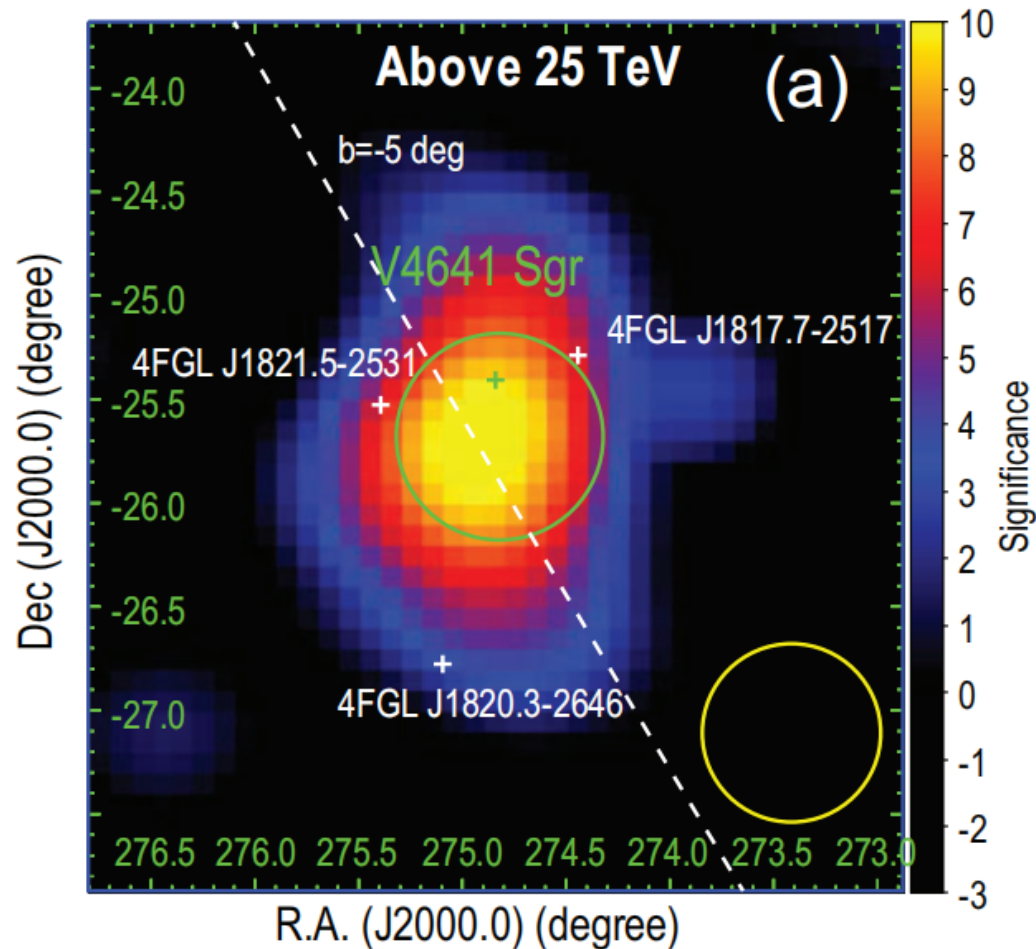
MAXI J1820+070



- 0.27° northeast of the BH, in alignment with the propagation direction of the receding ejecta .
- The spectrum is characterized with a PL up to hundreds of TeV.



V4641 Sgr



- ◆ An extended source was detected around V4641 Sgr at an offset of 0.19deg. The extension is $0.33^\circ \pm 0.08^\circ$.
- ◆ The Spectrum extends to $\sim \text{PeV}$.

Conclusion

- Cygnus X-3 is firmly detected at UHE with amazing characteristics: flares, orbital modulation, highest energy photon ...
- It demonstrates that protons could be accelerated to at least tens of PeV in microquasar binary system.
- Efficient acceleration could also happen at the outflow from microquasars.