Recent results from the LHAASO experiment

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on behalf of the LHAASO collaboration

2025.1.7@ICRR, University of Tokyo

LHAASO 高海拔宇宙线观测站

中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

The extreme Universe viewed in very-high-energy gamma rays 2024

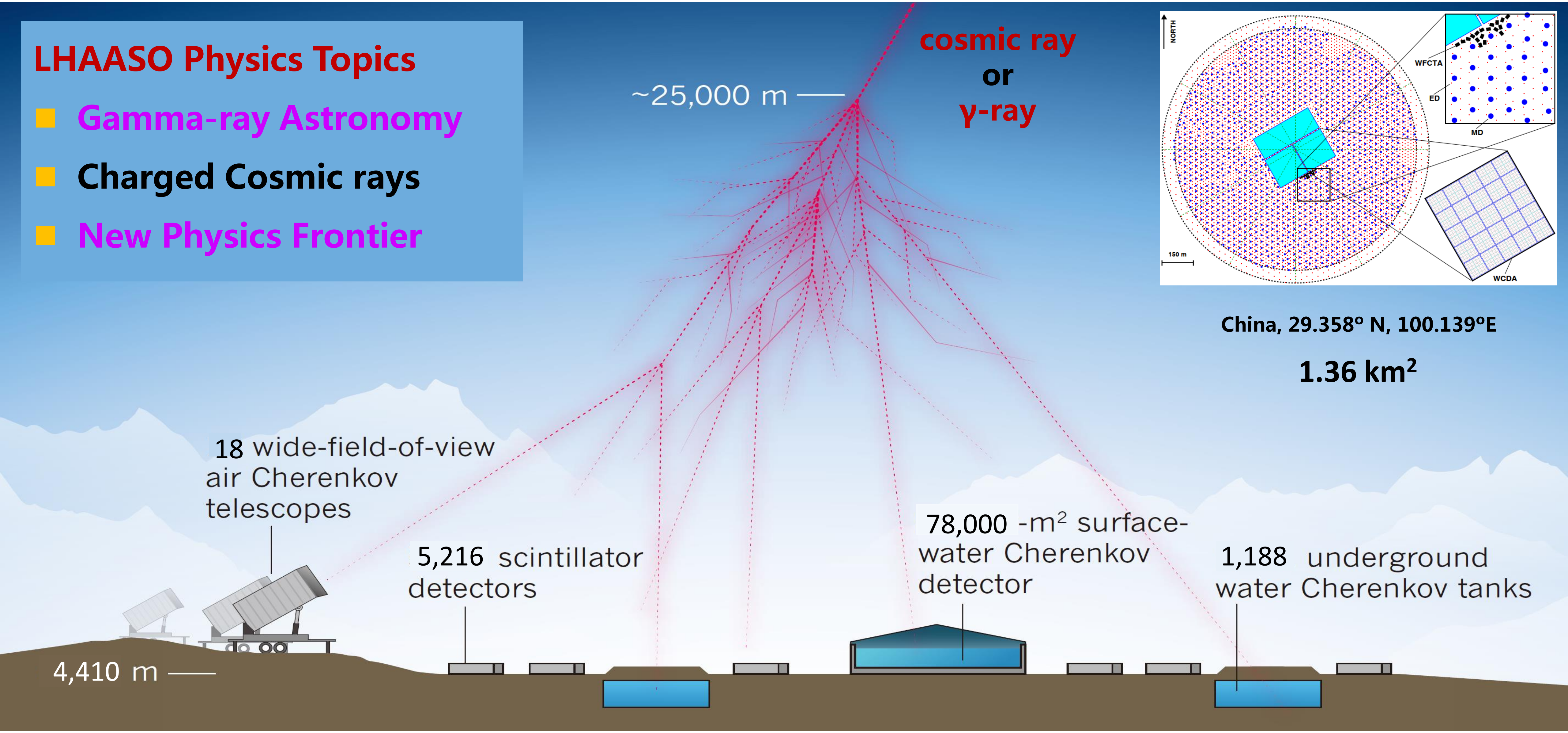
LHAASO collaboration

- 318 researchers from 30 institutes of 5 countries.

LHAASO detectors

LHAASO Physics Topics

- Gamma-ray Astronomy
- Charged Cosmic rays
- New Physics Frontier



China, 29.358° N, 100.139°E

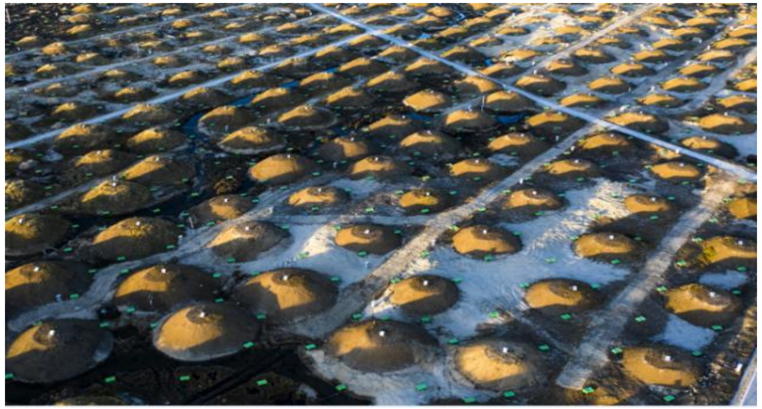
1.36 km^2

LHAASO arrays

The partial arrays since 2019

The full arrays since July 2021

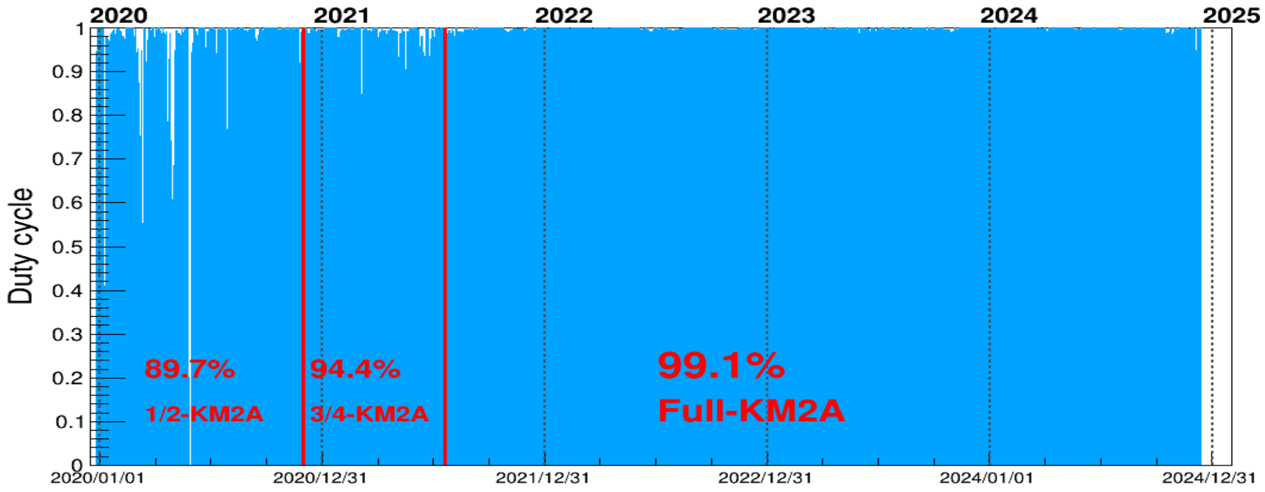
WCDA	KM2A	WFCTA+KM2A+WCDA
VHE γ-ray detector	UHE γ-ray detector	Cosmic ray detector
0.1 TeV-20 TeV	10 TeV-10 PeV	10 TeV-100 PeV



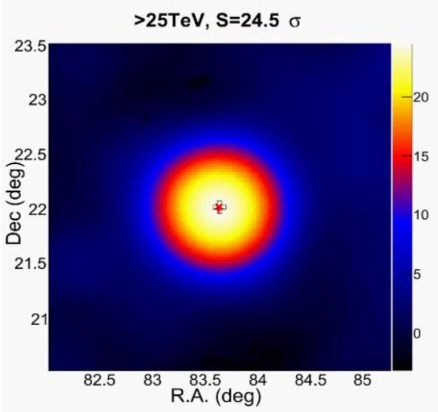
Status of LHAASO

Arrays	Running time per year	Duty cycle	Good Detector ratio
KM2A	8743 h	99.5%	99.6% (ED)
			99.6% (MD)
WCDA	8384 h	95.4%	97.4%
WFCTA	1418 h		99.8%

KM2A Duty cycle >99%, 5 years data

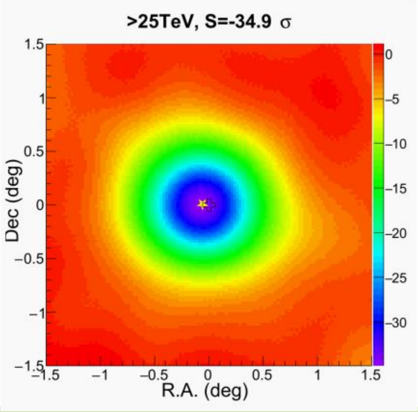


Crab Nebula

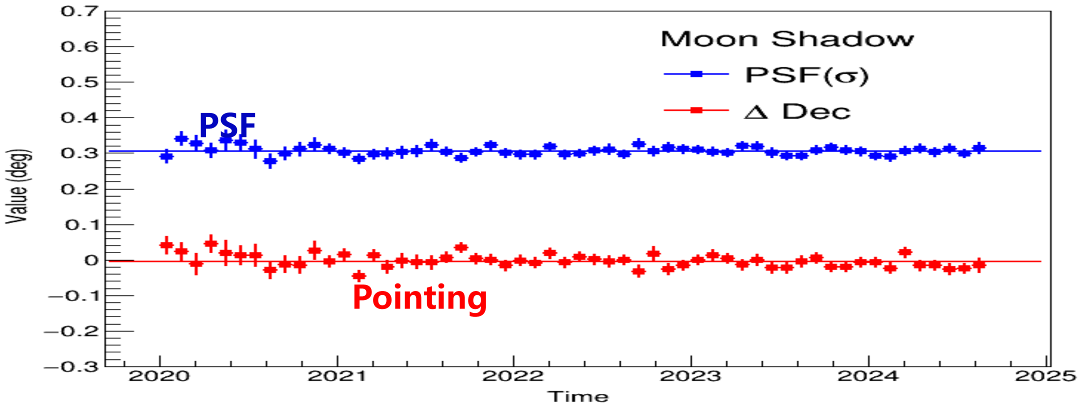


per Month

Moon shadow



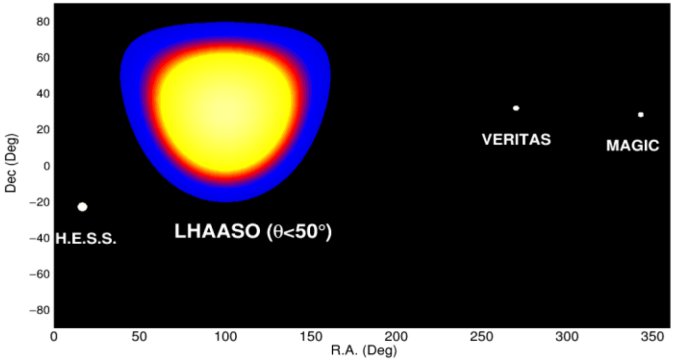
Stable pointing and angular resolution



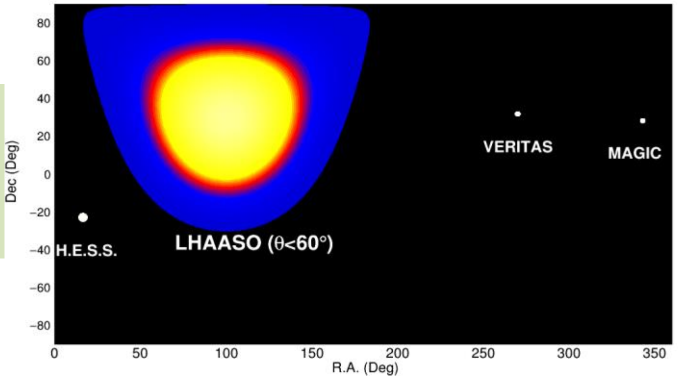
LHAASO coll. Astroparticle Physics, 164:103029 (2025)

LHAASO for γ-ray astronomy

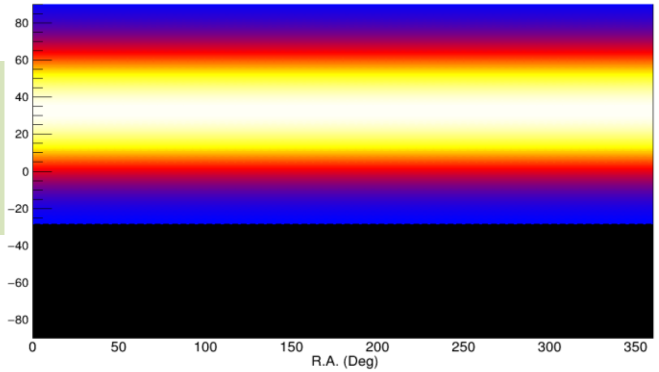
Every moment
(θ<50°, 18% sky)



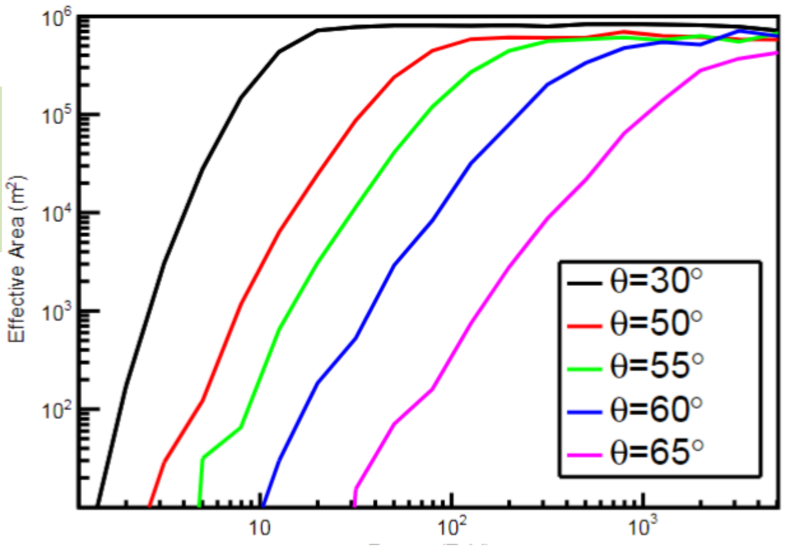
Every moment
(θ<60°, 25% sky)



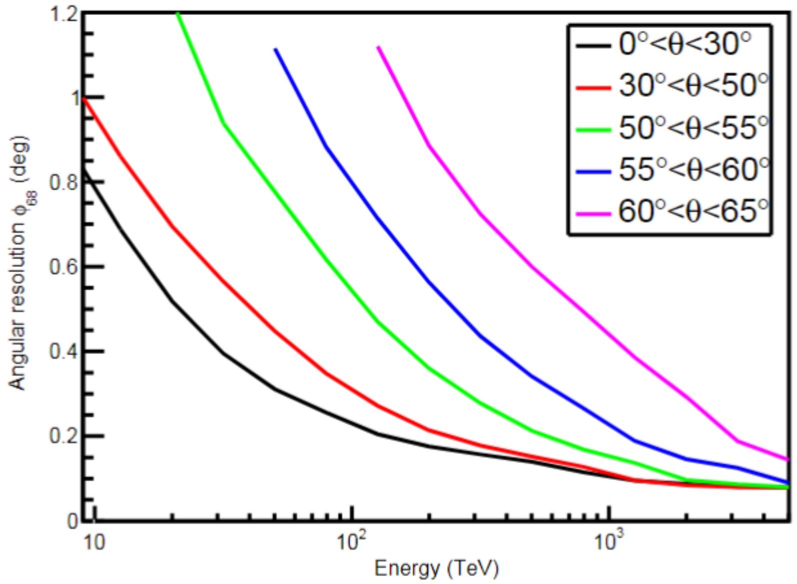
One day
(66% → 75% sky)



Effective Area
Of KM2A

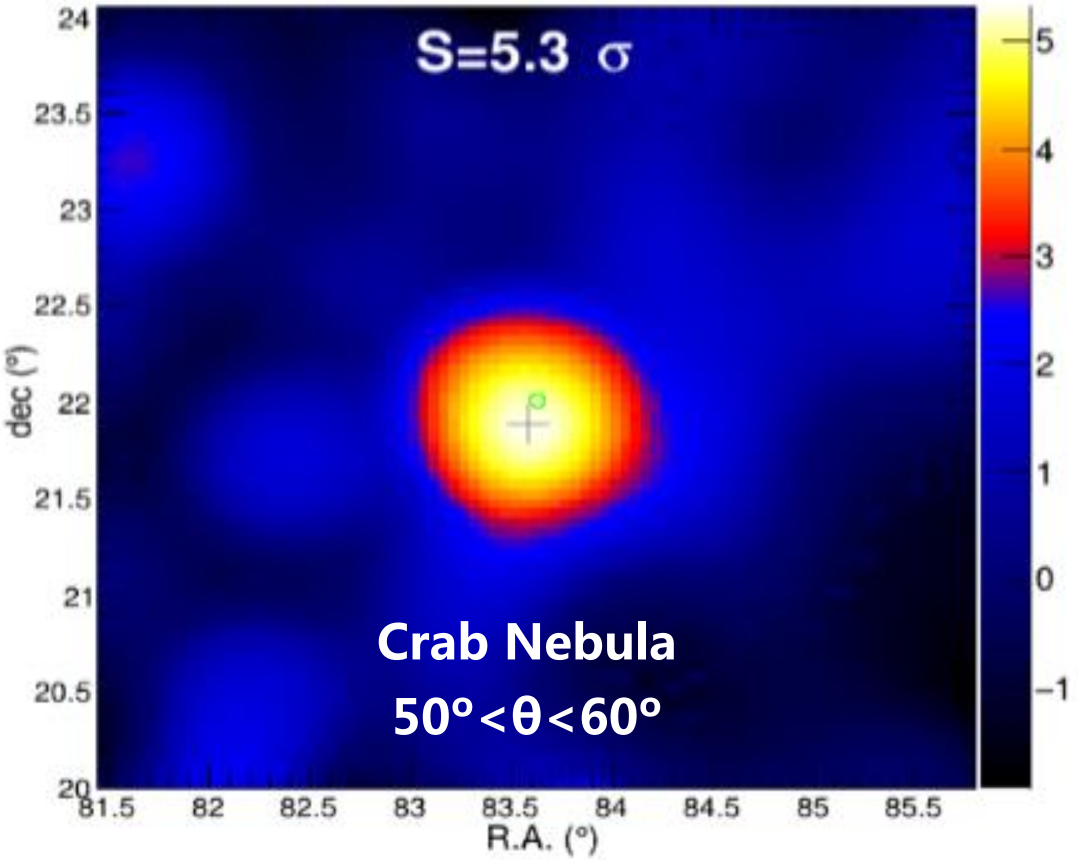


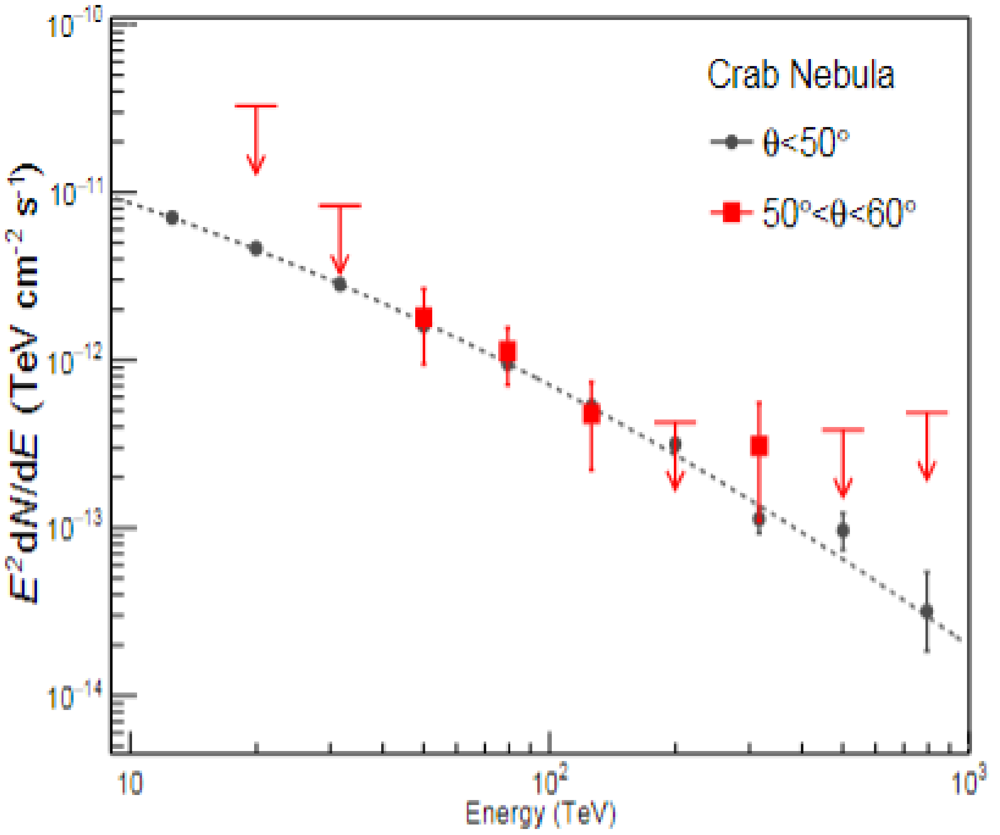
Angular resolution
Of KM2A



New update of LHAASO

The gamma-ray sources measurement using events with large zenith angles is also reliable according to checking using Crab Nebula.

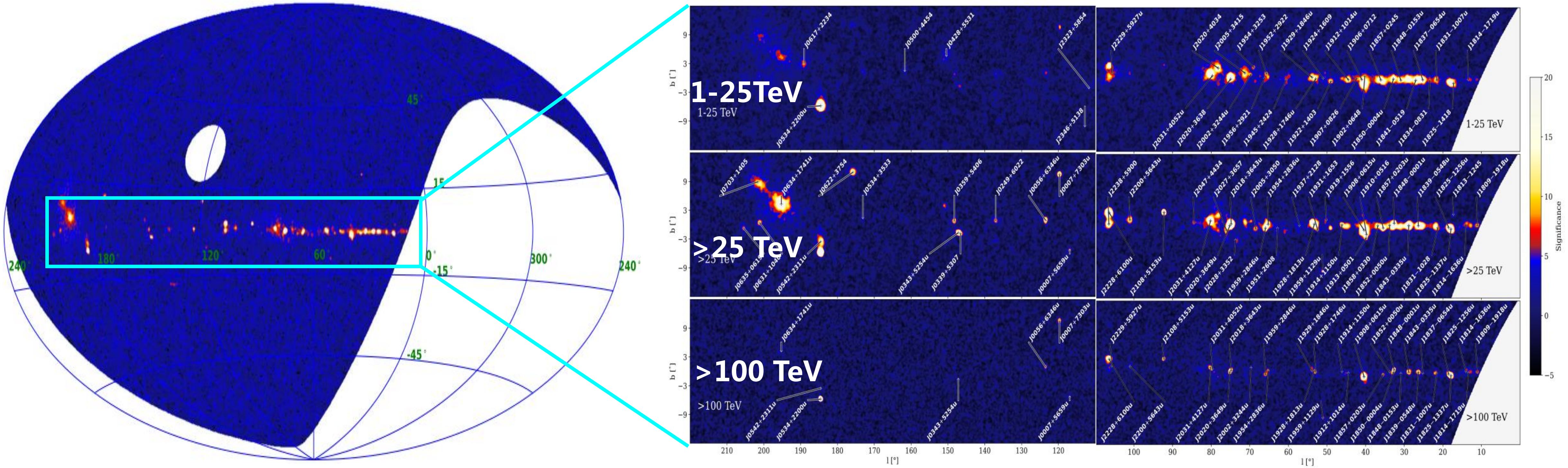




LHAASO recent highlight results
on Gamma-ray astronomy

The 1st LHAASO catalog

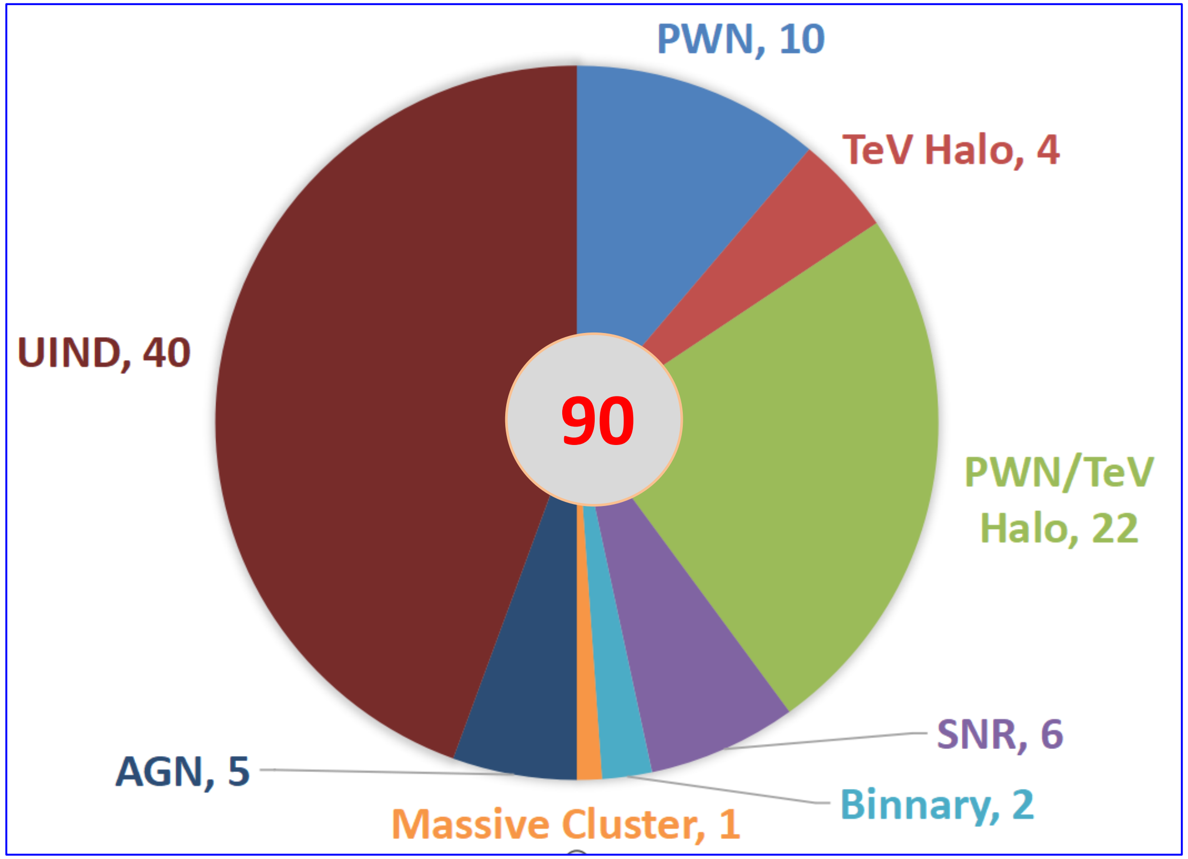
- **90 VHE sources with 32 new discoveries.**
- **43 UHE (>100 TeV) sources**



LHAASO coll. ApJS, 271:25 (2024)

LHAASO source types

- **Galactic sources**
  - Pulsar wind nebula/TeV halo
  - SNR
  - Binary (microquasar)
  - Massive cluster
- **Extra-galactic sources**
  - Active galactic nucleus
  - GRB

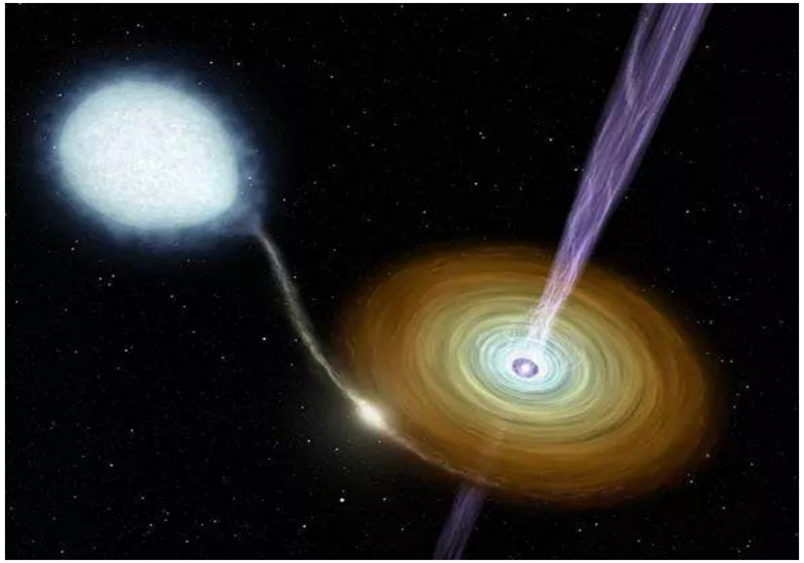


LHAASO coll. ApJS, 271:25 (2024)

Highlight 1: Microquasar

Attractive features of microquasars

- Black hole
- Accretion disk
- Relativistic jet

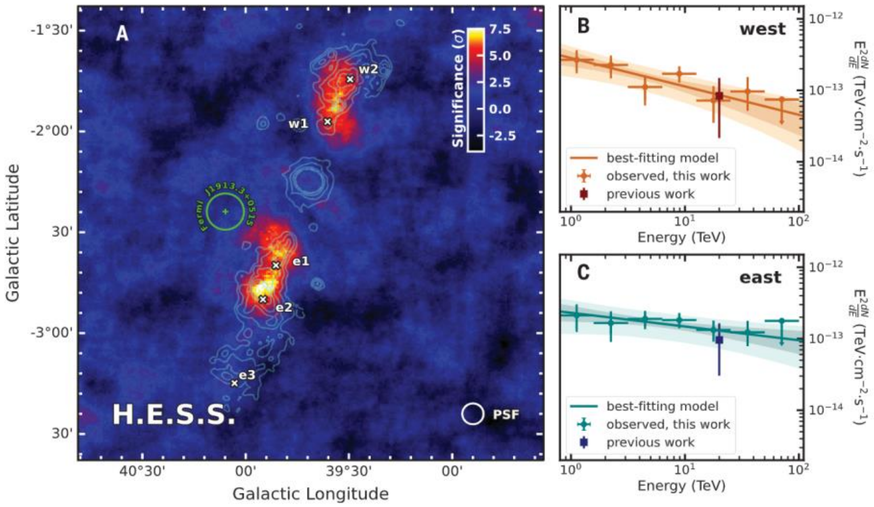


12 Galactic BH-jet systems within LHAASO FOV
5 systems with positive signals

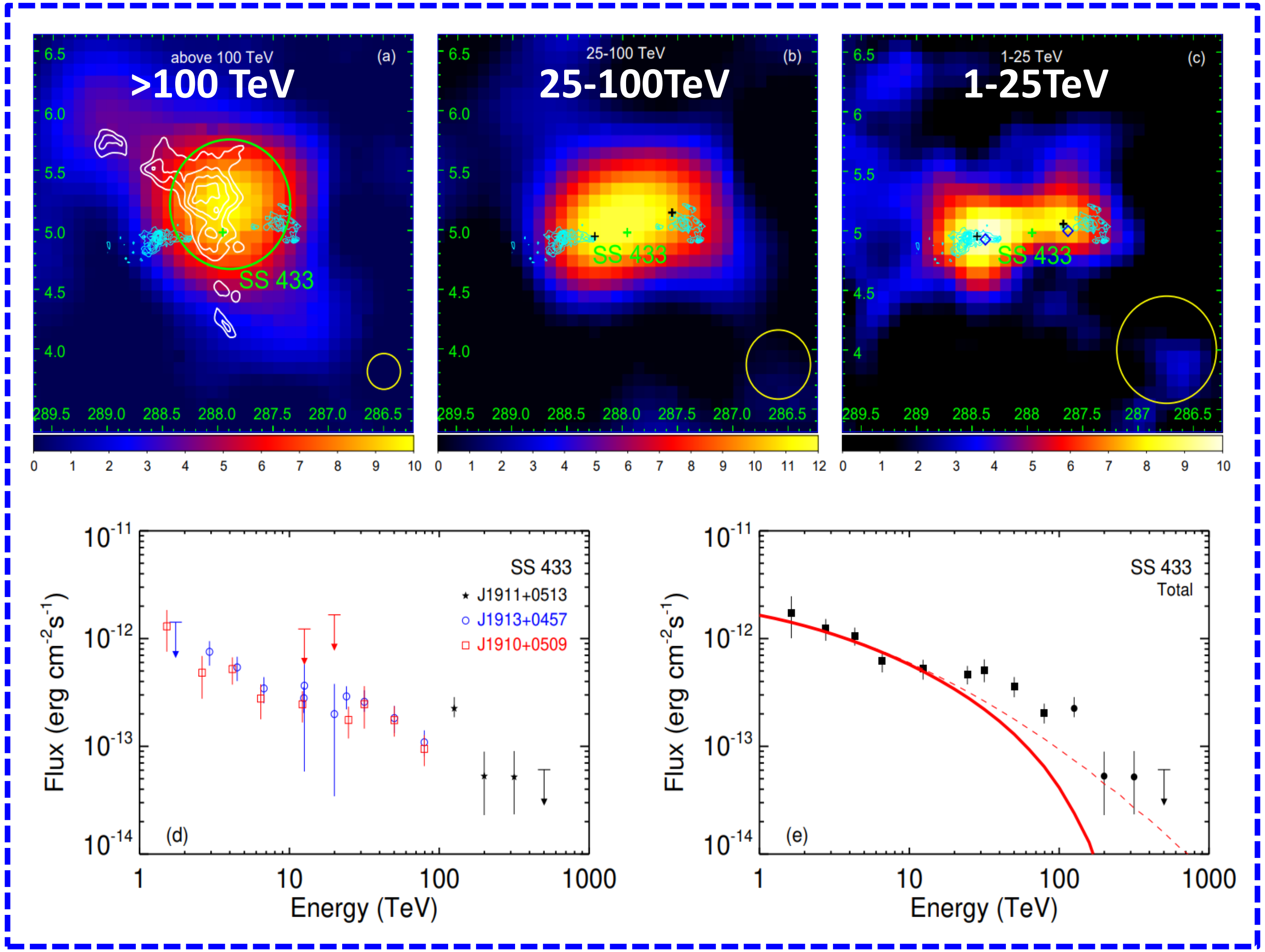
Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0457	9.7[c]	2.78 ± 0.19	25 – 100		0.10
SS 433 W.	4.6 ± 1.3 [32]	J1910+0509	8.6[c]	2.92 ± 0.21	25 – 100	0.70°	0.082
SS 433 central		J1911+0513	9.8	4.03 ± 0.29	100 – 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

Microquasar: SS 433

- ~4.6 kpc
- Morphology and SED is consistent with H.E.S.S. at <100 TeV
- New features at >100 TeV?



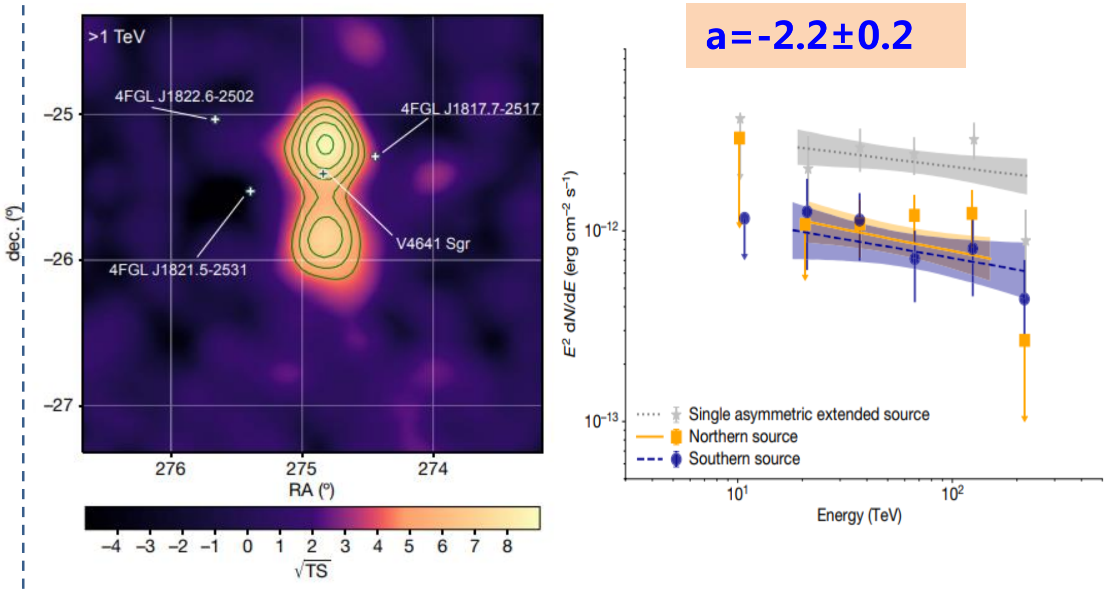
H.E.S.S. coll. 2024



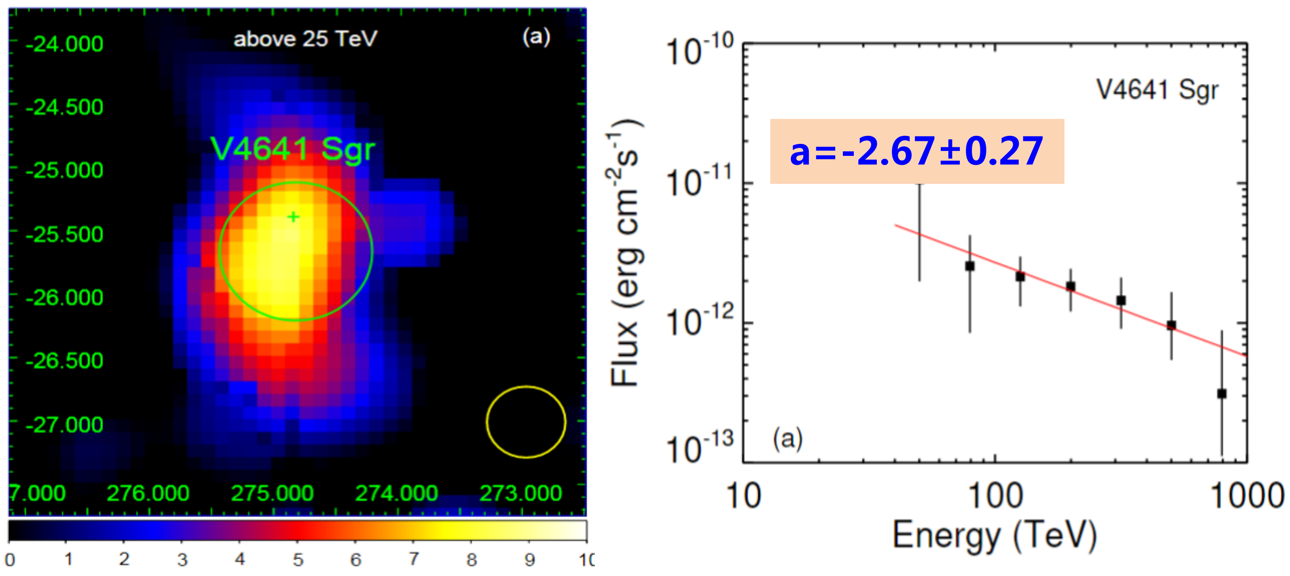
LHAASO coll. arXiv:2410.08988

Microquasar: V4641 Sgr

- ~6.2 kpc , large zenith angle (55°<θ) in LHAASO, >8σ detection
- Hard spectrum up to 1 PeV, a super-PeVatron?
- Jet-like morphology?



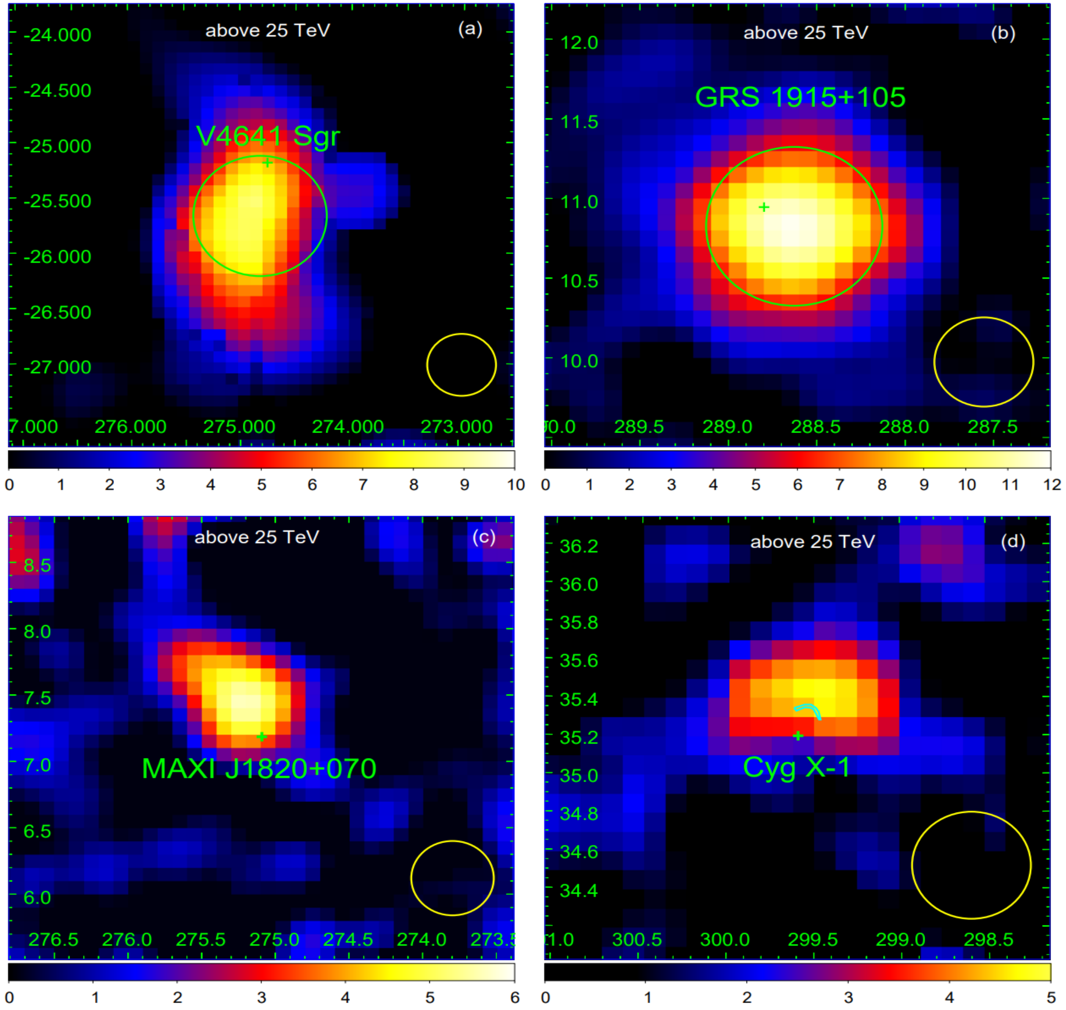
HAWC coll. 2024



LHAASO coll. arXiv:2410.08988

Other microquasars

- UHE gamma-ray detection demonstrates that accreting BH-jet system are extremely efficient accelerators.
- Questions:
- Where and how the particle is accelerated?
- Can it be the main factory for Galactic cosmic rays around knee?



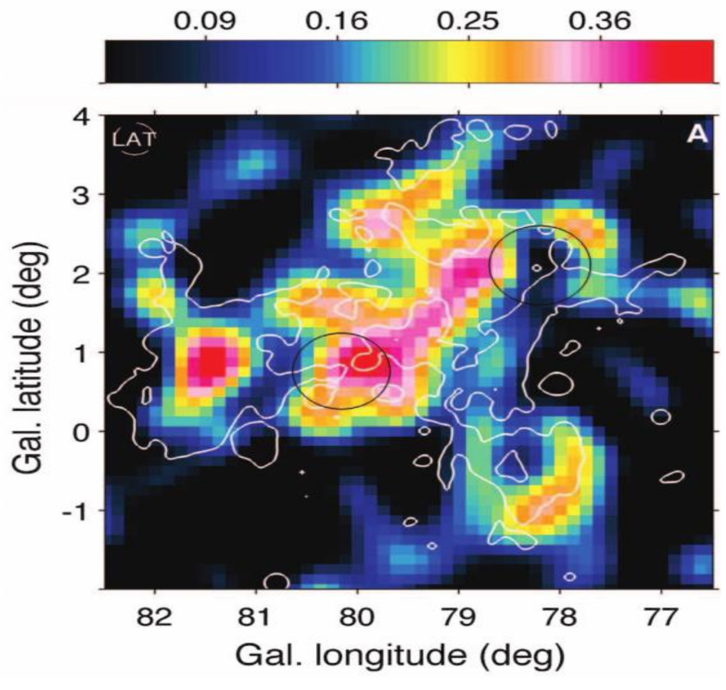
LHAASO coll. arXiv:2410.08988

Highlight 2: Cygnus region

Cygnus X region (~1.4 kpc) is rich with potential particle accelerators.

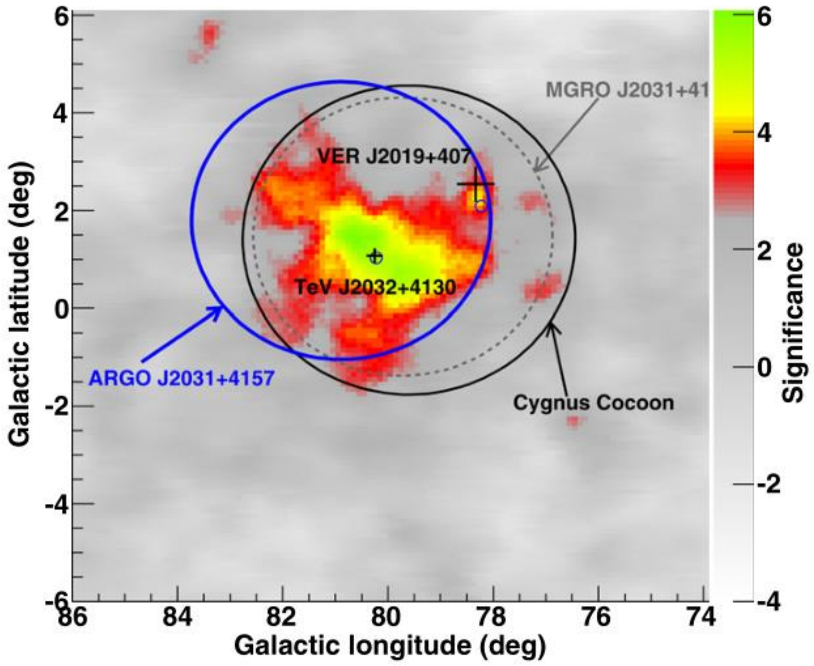
Extended (σ~ 2°) gamma-ray emission revealed in GeV-TeV

Fermi-LAT: 10~100 GeV



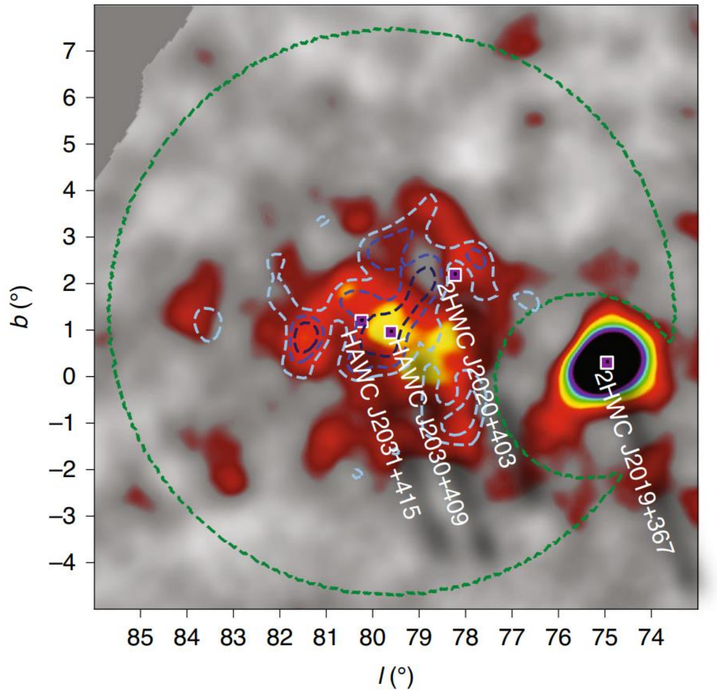
Fermi-LAT coll. 2011

ARGO-YBJ: 0.2-10 TeV



ARGO-YBJ coll. 2014

HAWC: 1-100 TeV



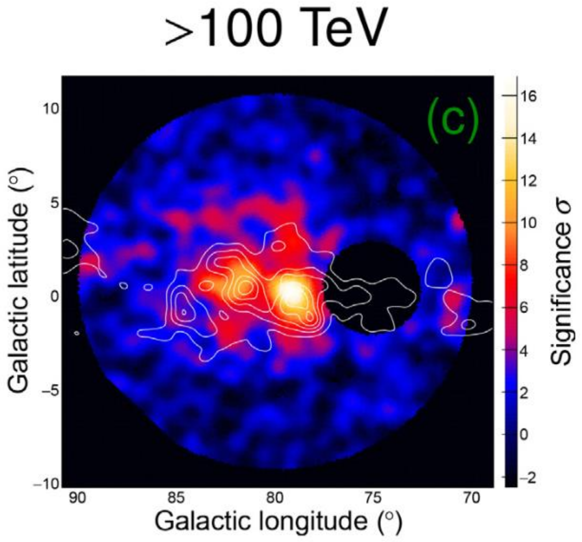
HAWC coll. 2021

LHAASO identify a super PeVatron

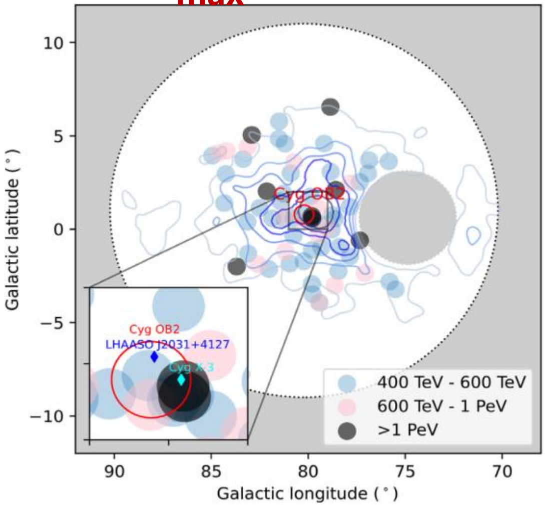
- Large UHE γ-ray bubble with a radius of 6° (~150pc)
  - Larger than the Cygnus Cocoon(2°)
  - SED is connected with Fermi-LAT for core region
- Associated with Molecular Clouds
- 8 photons >1 PeV
- 10 PeV cosmic ray super-PeVatron

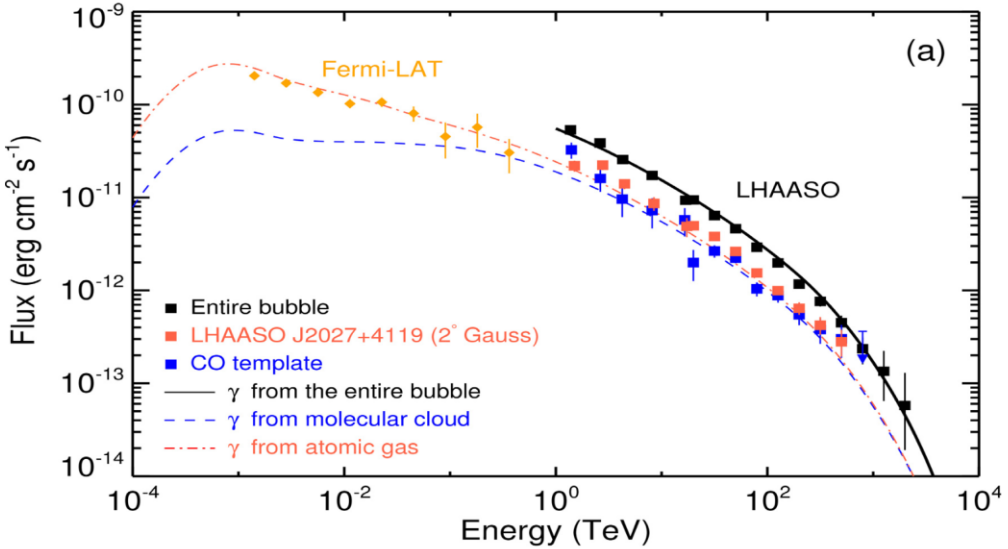
Question:
Which source accelerate particles to such high energy?

LHAASO coll. Science Bulletin 69:449–457(2024)



E_{max}=2.5 PeV





Highlight 3: SNR as cosmic ray sources

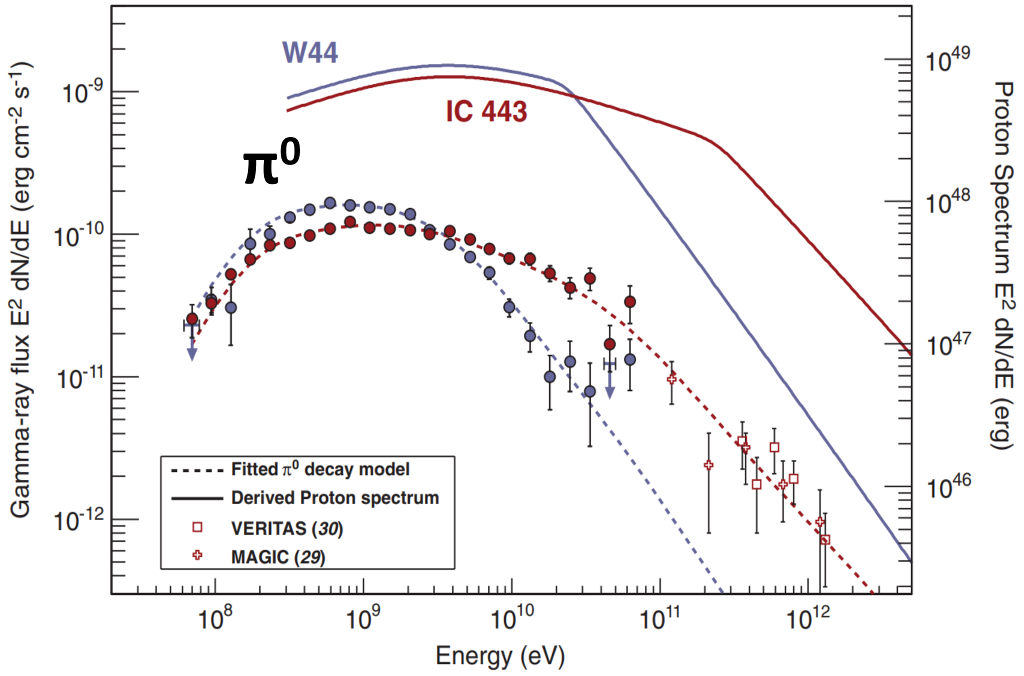
SNRs are very important CR accelerators!

What is the maximum energy that SNR can accelerate?

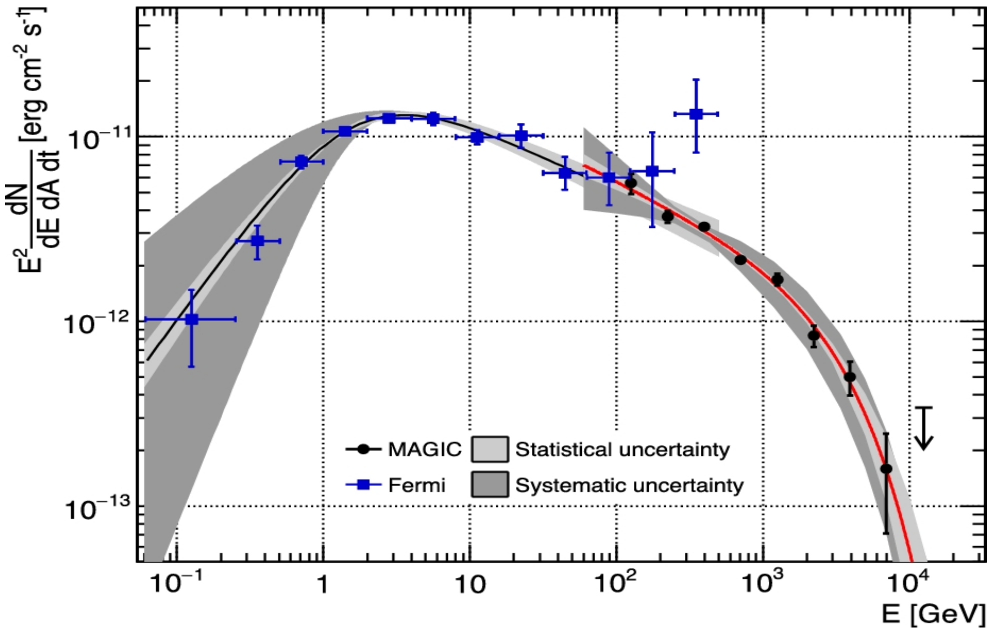
~10 kyr

Only up to 10 TeV?

Cas A(330 yr)



Fermi-LAT coll. 2013

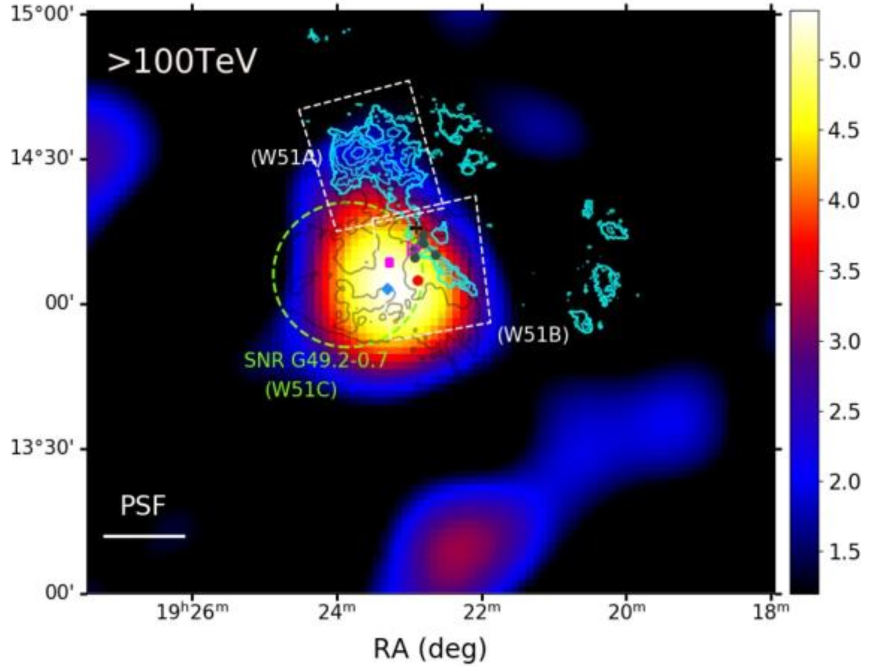


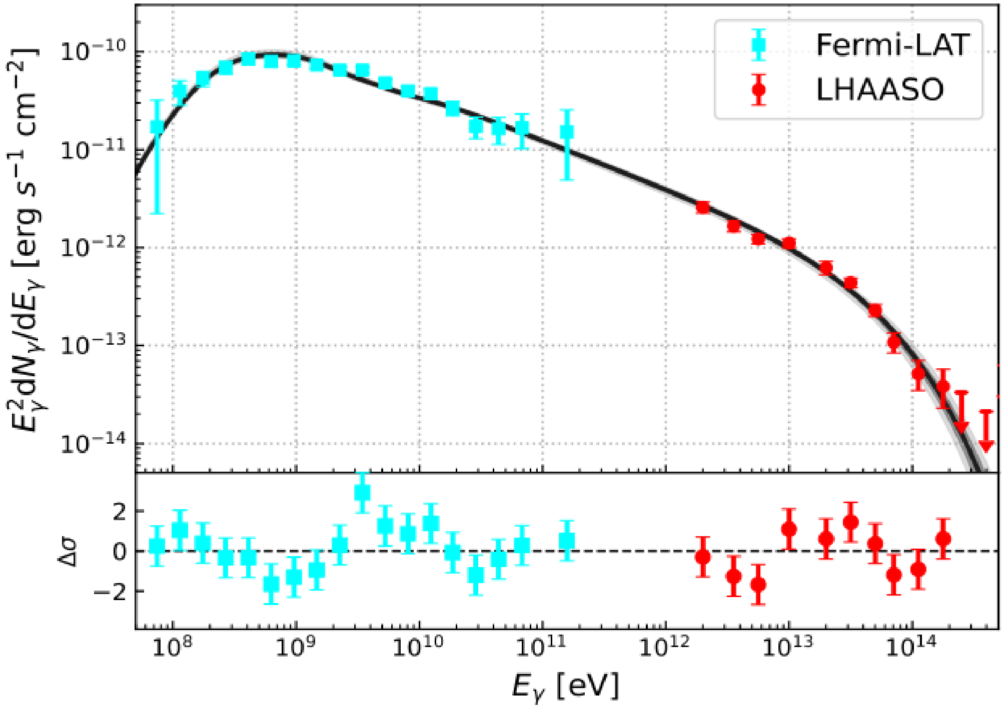
MAGIC coll. 2017

LHAASO reveal SNR approaching PeV

- **SNR W51C：An interaction region between the cosmic rays and the dense molecular clouds.**
- **Underline cutoff energy of proton up to** $E_{p,\mathrm{cut}} = 385^{+65}_{-55}\ \mathrm{TeV}$

W51C:~30 kyr, 5.5 kpc

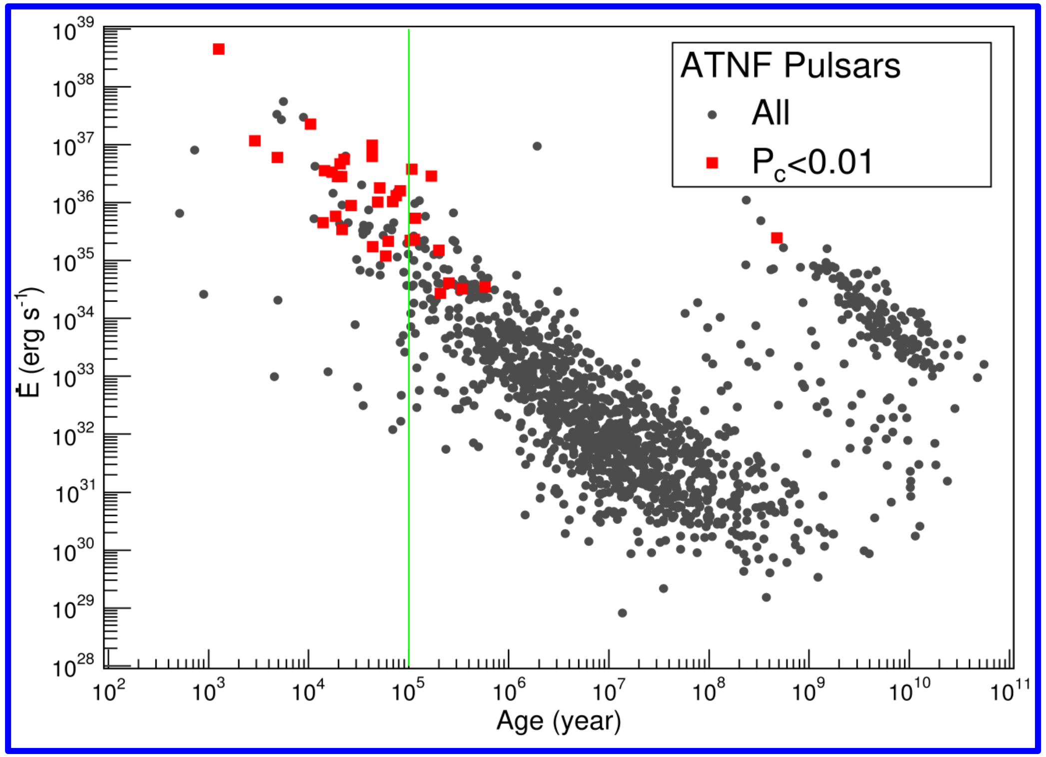




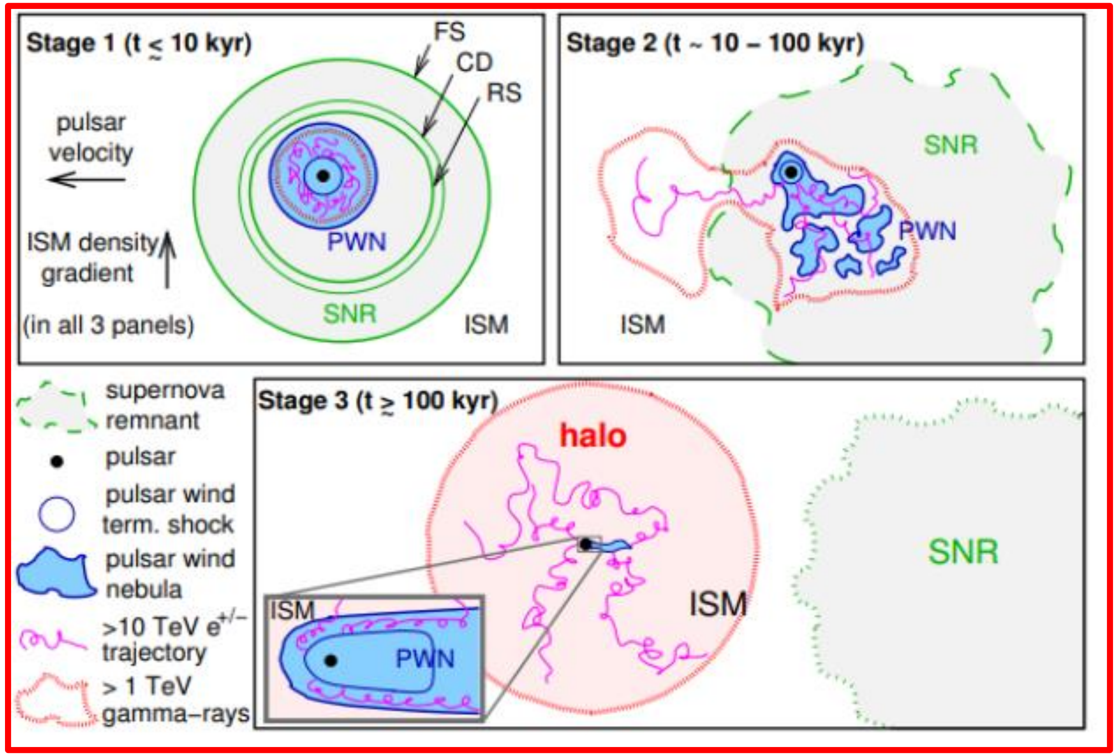
LHAASO coll. Science Bulletin, 69:2833-2841 (2024)

Highlight 4: evolution of PWNs

- Most of the energetic pulsars >10^{36} erg s^{-1} within the FOV of LHAASO are associated with 1LHAASO sources.
- The PWNe of energetic pulsars are effective VHE gamma-ray emitters.



LHAASO coll. ApJS, 271:25 (2024)

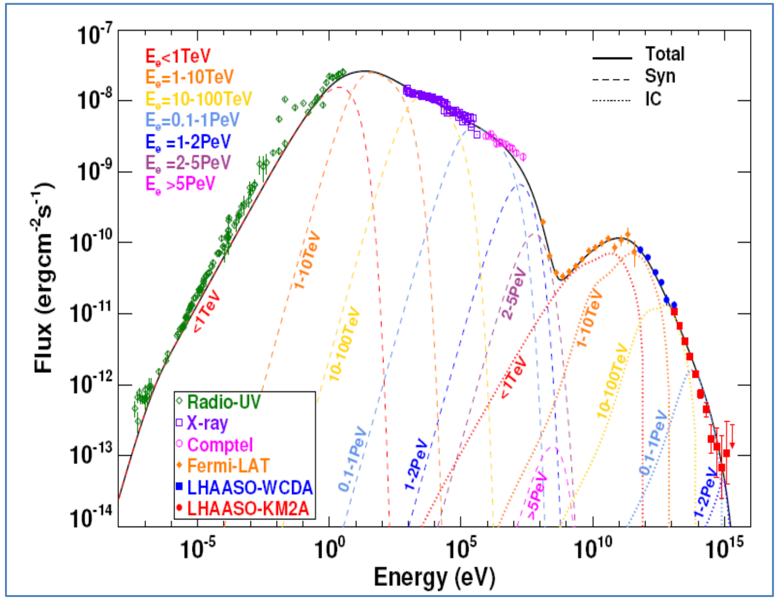


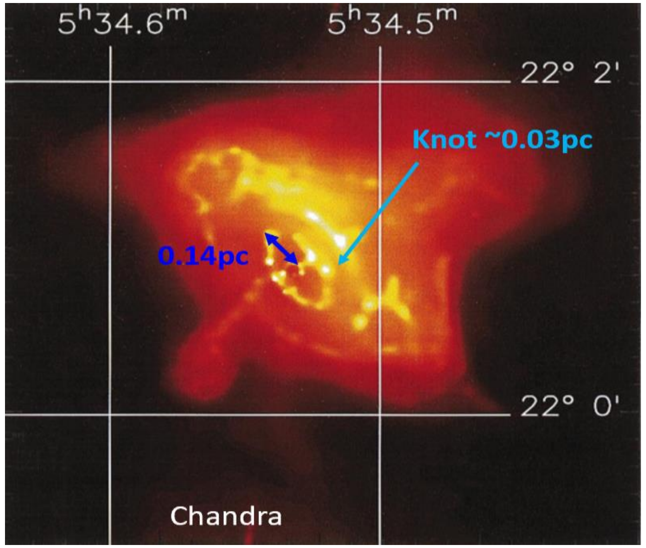
Giacinti et al.(2020)

Young PWN Crab Nebula

- Photon maximum energy
  1.1PeV→1.4 PeV
- Primary electron energy
  2.3 PeV→2.8 PeV
- Acceleration rate
  $\eta \approx 0.16 \rightarrow 0.26$
- Accelerator size l >
  R_g=0.025 pc→0.032 pc

Crab Nebula: 1 kyr, ~2kpc



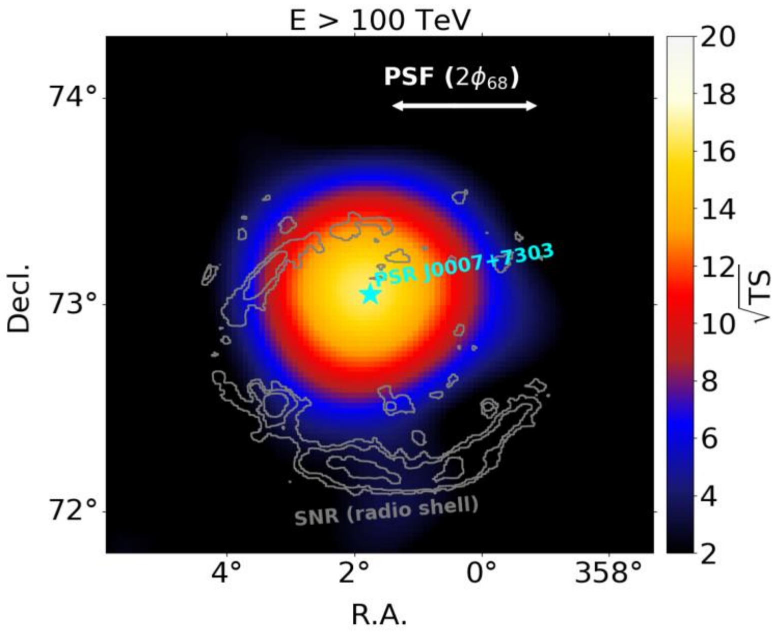


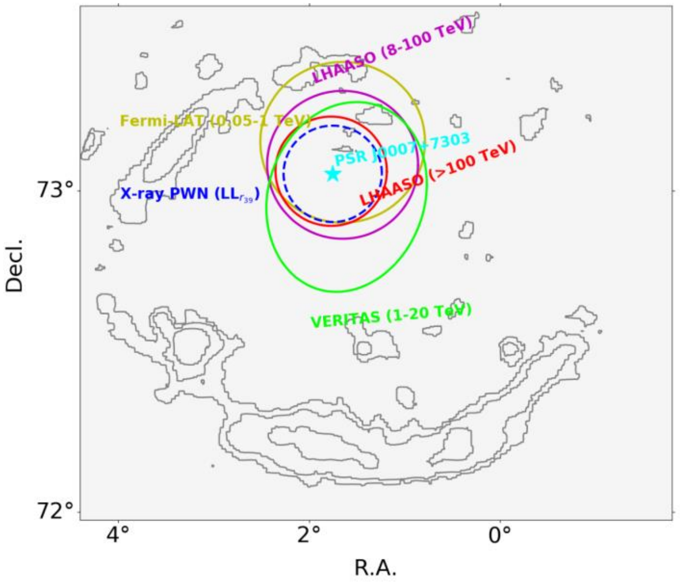
LHAASO coll. Science,373:425 (2021)

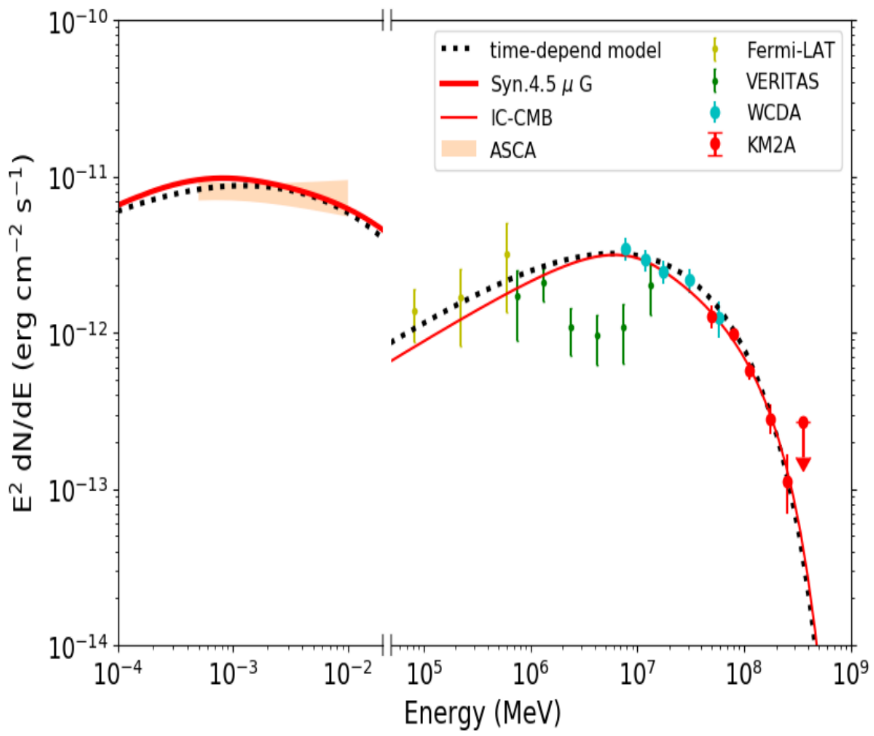
UHE emission from CTA 1

CTA 1: 13.9 kyr, 1.4 kpc, 4.5× 10^{35} erg s^{-1}

- **PWN and SNR composite region**
- **The morphology shows the PWN scenario.**
- **The magnetic field is ~ 4.5 μG.**



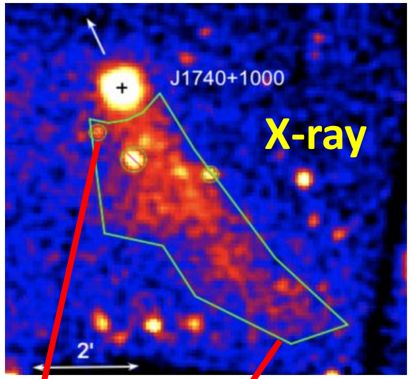




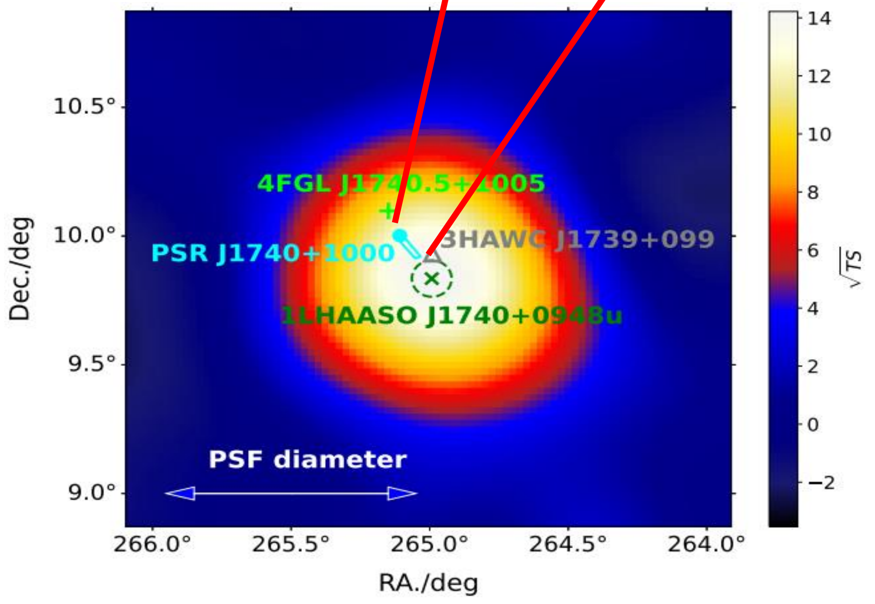
LHAASO coll. SCIENCE CHINA: Physics, Mechanics & Astronomy (in press)

UHE emission from bow shock pulsar tail

J1740+1000: 114 kyr, ~1.4 kpc, 2.32×10^{35} erg s^{-1}



- The small morphology disfavors TeV halo scenario.
- Precise measurements offset from the pulsar and is located in the direction of its tail.
- Particle acceleration in pulsar tails ?



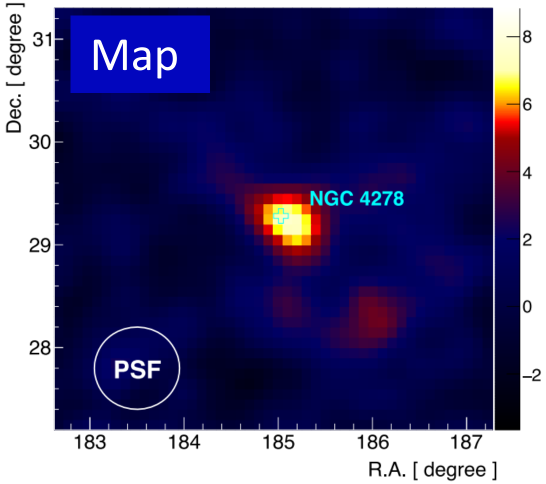
LHAASO coll. The innovation (in press)

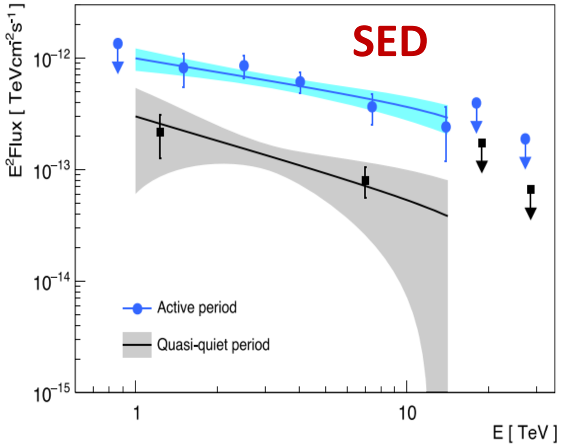
Highlight 5: LHAASO extragalactic sources

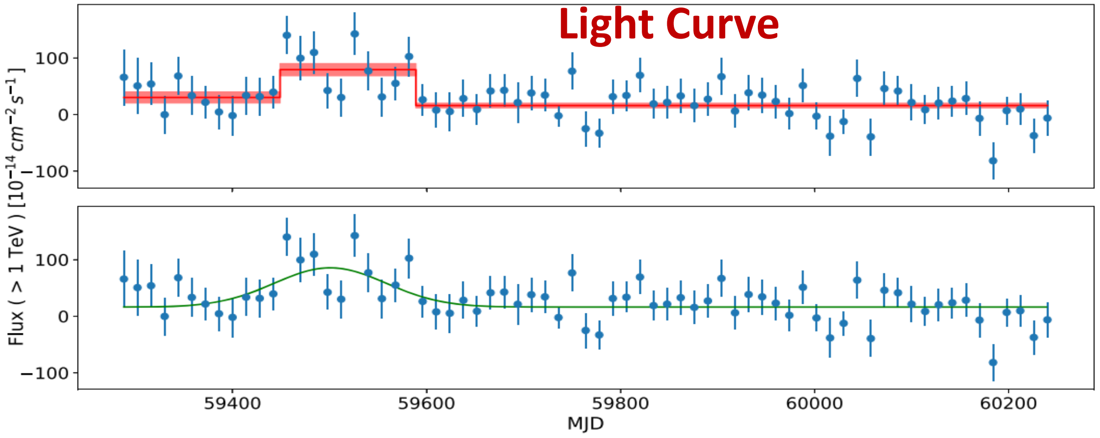
Name	Note	Arrays	z	Type
GRB 221009A	Science, Science Advances	WCDA+KM2A	0.151	GRB
Mrk 421	1st catalog	WCDA+KM2A	0.031	Blazar(H)
Mrk 501	1st catalog, Atel#16625	WCDA+KM2A	0.034	Blazar(H)
1ES 2344+514	1st catalog	WCDA	0.044	Blazar(H)
1ES 1727+502	1st catalog, Atel#16881	WCDA	0.055	Blazar(H)
1ES 1959+650	Atel#16437	WCDA	0.048	Blazar(H)
BL Lacertae	Atel#16850	WCDA	0.069	Blazar(I)
NGC 1275	MNRAS	WCDA	0.0176	FRI
M87	ApJL	WCDA	0.0044	FRI
NGC 4278	1st catalog, ApJL	WCDA	0.002 (16.4Mpc)	Low luminosity AGN
IC 310	Atel#16513, Atel#16540	WCDA+KM2A	0.0189	AGN(unknown type)

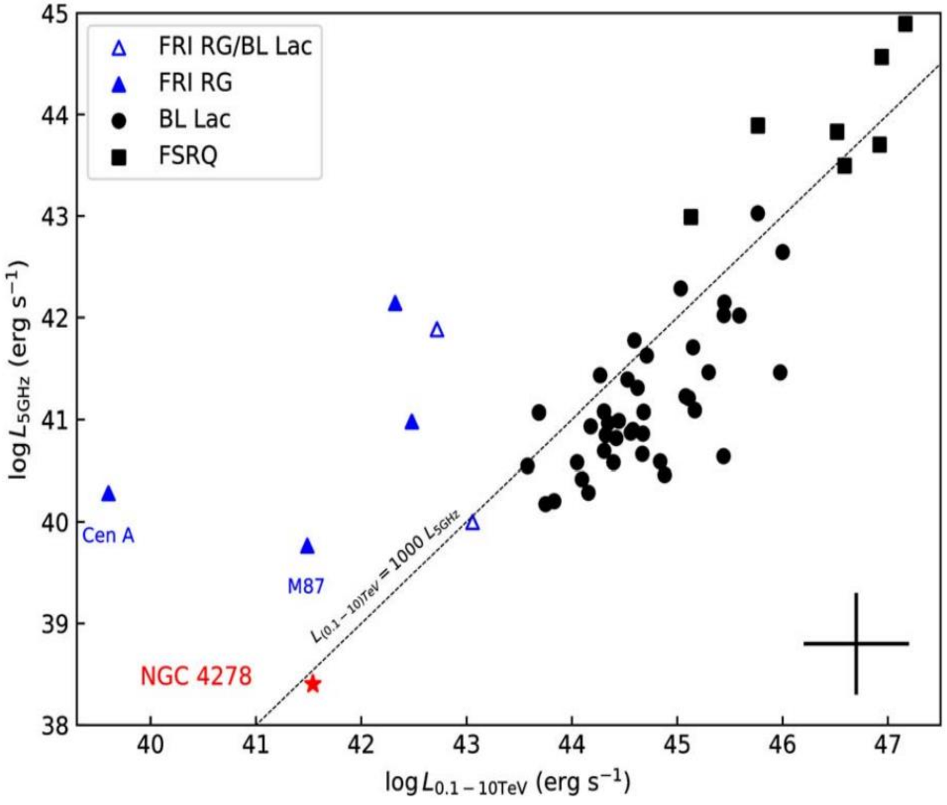
LLAGN NGC 4278

First evidence for the Low-luminosity AGN with VHE γ-ray!





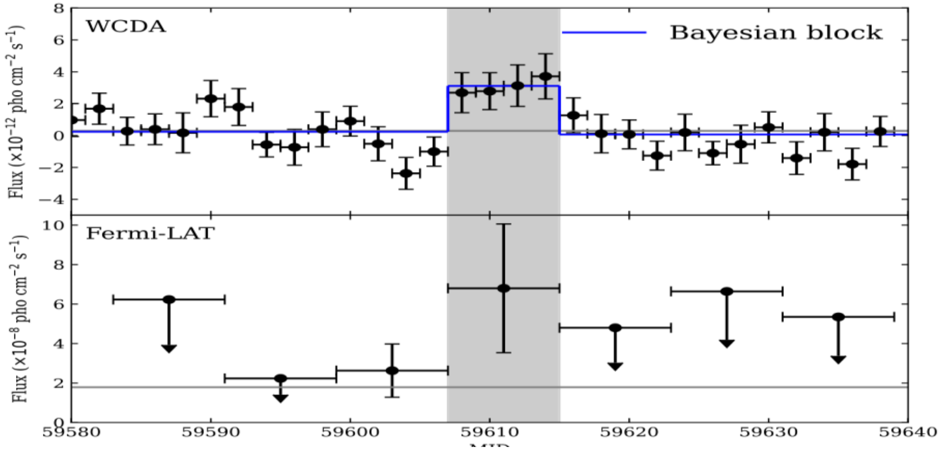


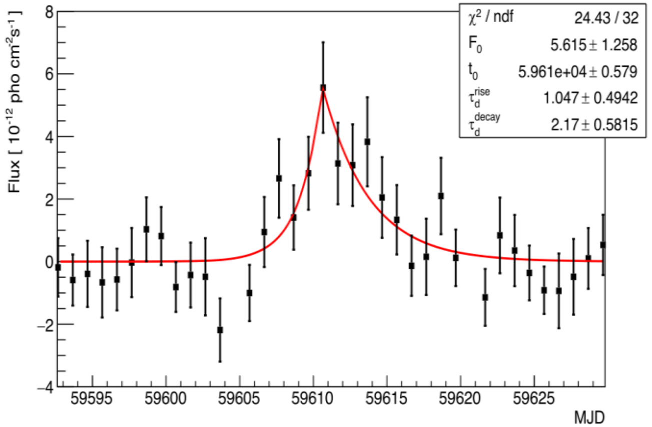


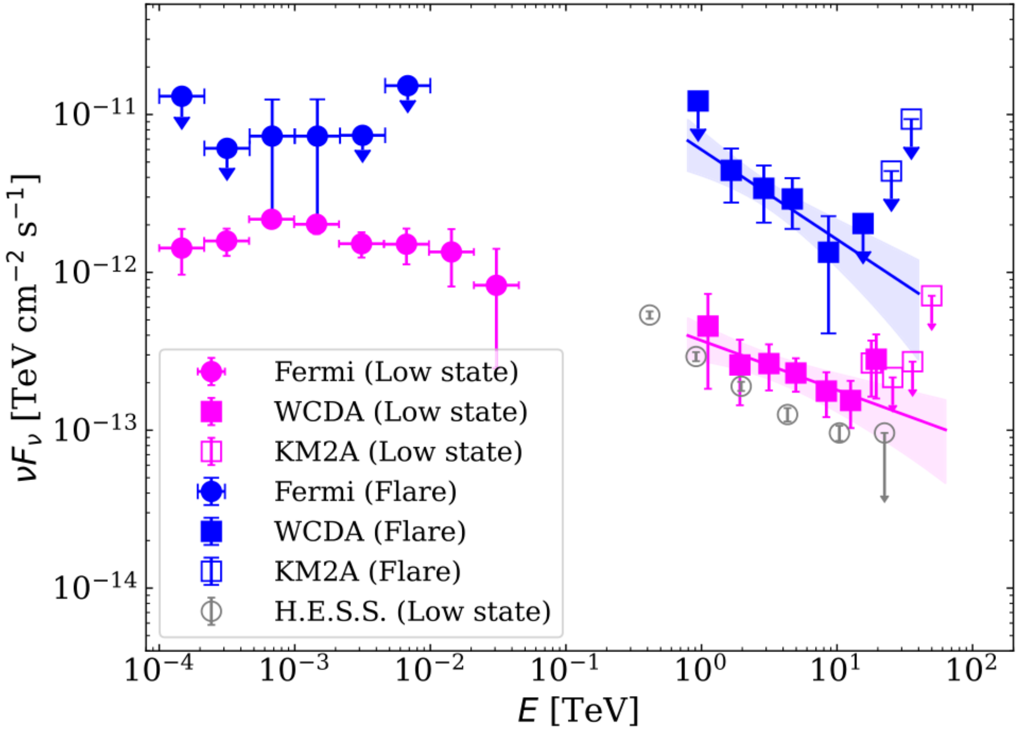
LHAASO coll. ApJL, 971:L45 (2024)

Radio Galaxy M87

The variability time ~1 day, a few Schwarzschild radii of BH in M87
The continuous monitoring reveals a duty cycle of ~1% for VHE flares







LHAASO coll. ApJL, 975:L44 (2024)

The BOAT GRB 221009A

LHAASO detect onset of the TeV afterglow for the first time !
Precise LC provides a unique opportunity to study the early afterglow physics !

Slow rise: Favor ISM environment ?

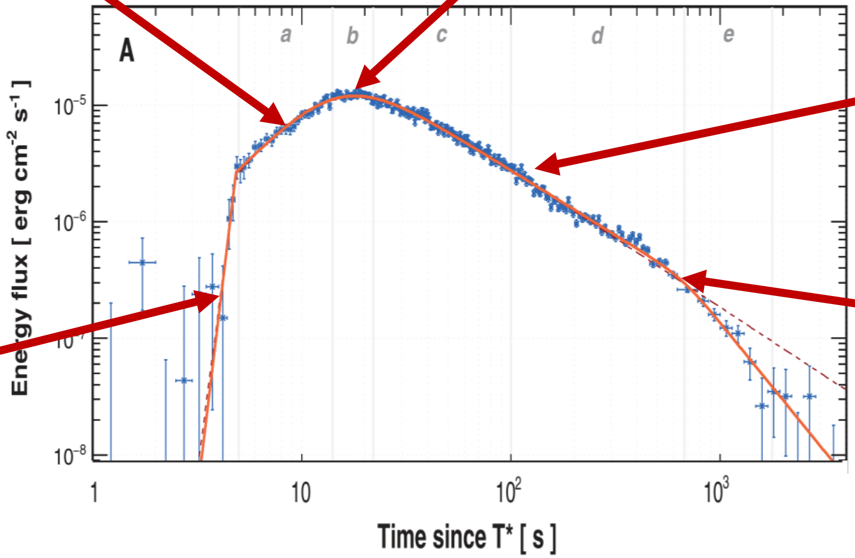
$\alpha_1 = 1.82^{+0.21}_{-0.18}$

Peak time : The bulk Lorentz factor of ~**500.**

$$\Gamma_0 = \left(\frac{3E_k}{32\pi n m_p c^5 t_{\rm peak}^3}\right)^{1/8} = 440 E_{k,55}^{1/8} n_0^{-1/8} \left(\frac{t_{\rm peak}}{18\,{\rm s}}\right)^{-3/8}$$

Slow decay: Electron SED index -2.1

$\alpha_2 = -1.115^{+0.012}_{-0.012}$



Unusual Fast rise:
energy injection ?

$\alpha_0 = 14.9^{+5.7}_{-4.0}$

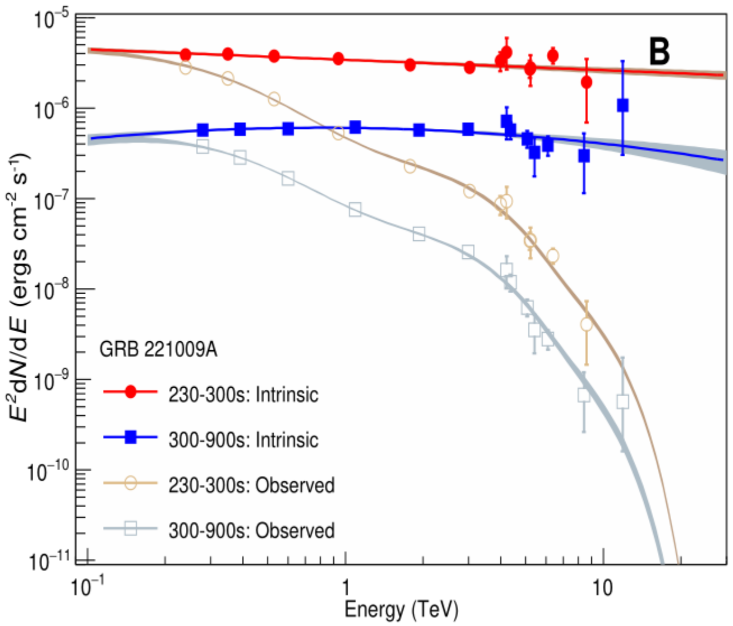
- **Fast decay:** A **jet break** at the earliest time! Jet half opening angle of **0.8º**. $\alpha_3 = -2.21^{+0.30}_{-0.83}$

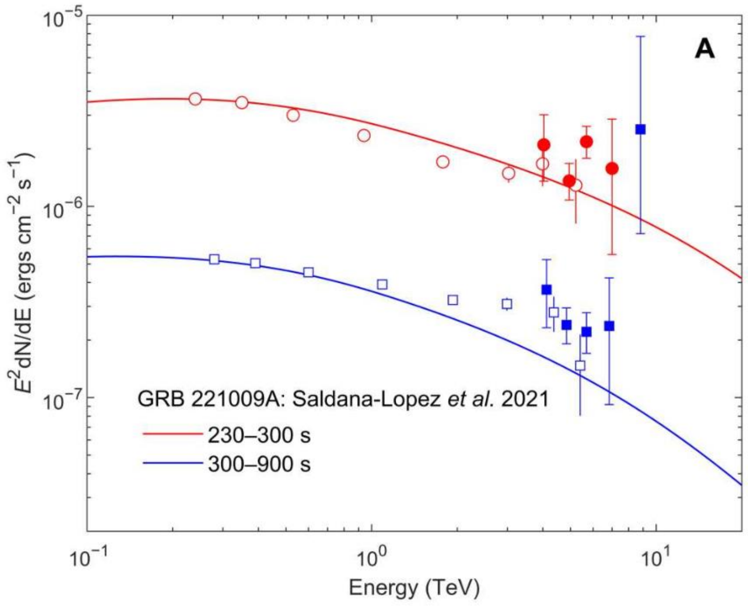
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{b,2}}{670\,{\rm s}}\right)^{3/8}$$

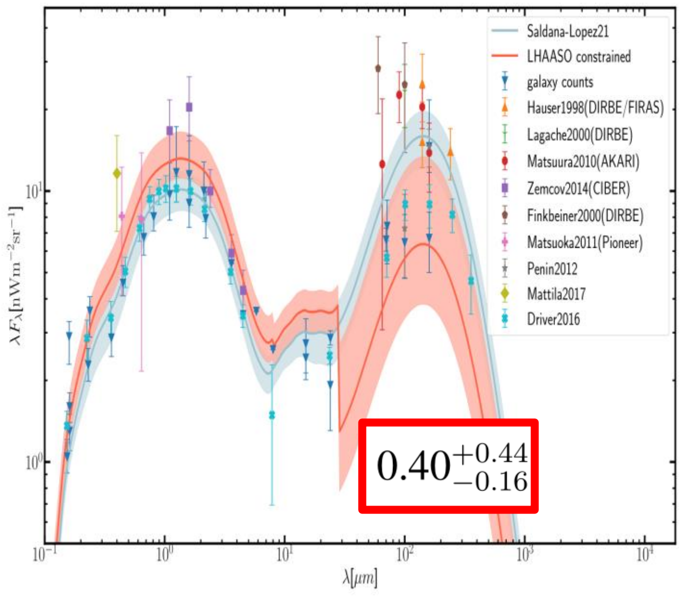
LHAASO coll. Science,380:1390 (2023)

The highest energy photon of GRB

- The maximum energy photon from GRB ~12.5TeV
- Hard SED challenge to GRB afterglow model SSC
- Low EBL density (~40%) at $\lambda > 28\mu m$







LHAASO coll. Science Advances,9: eadj2778 (2023)

LHAASO recent highlight results
on New Physics Frontier

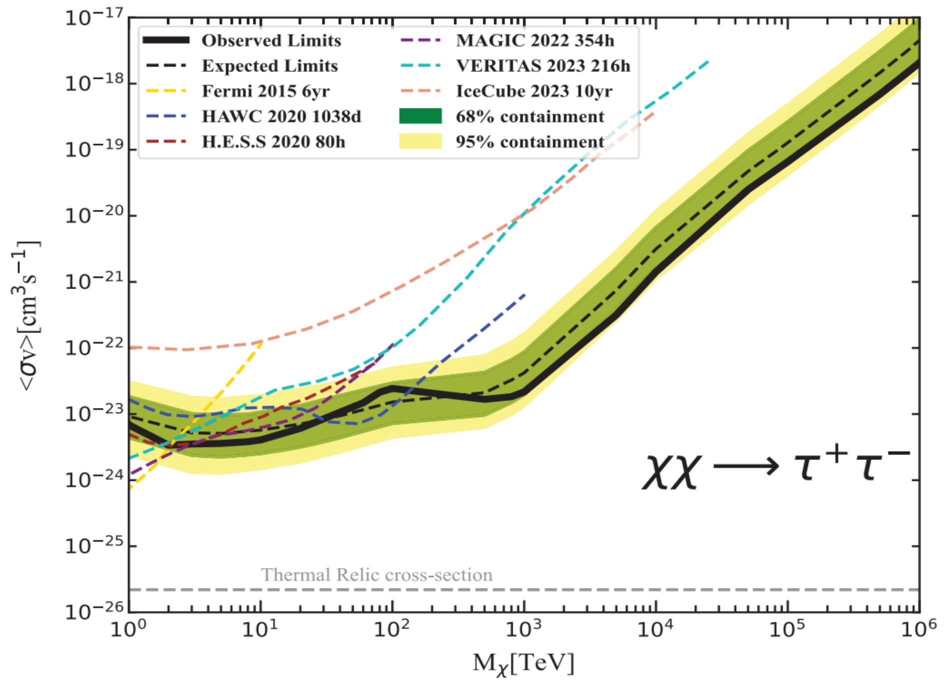
LHAASO constraints on dark matter

16 dwarf spheroidal galaxies

The strongest constraints on dark matter annihilation cross section

Name	$\log_{10}(J_\theta/\mathrm{GeV}^2\,\mathrm{cm}^{-5})$	θ_{anni} (deg)	$\log_{10}(D_\theta/\mathrm{GeV}\,\mathrm{cm}^{-2})$	θ_{decay} (deg)
Draco	$18.96^{+0.16}_{-0.15}$	1.0	$19.38^{+0.24}_{-0.32}$	2.3
Ursa Minor	$18.79^{+0.12}_{-0.11}$	1.0	$18.68^{+0.33}_{-0.15}$	2.1
Ursa Major I	$18.40^{+0.28}_{-0.27}$	0.9	$18.64^{+0.50}_{-0.48}$	1.8
Ursa Major II	$19.70^{+0.43}_{-0.43}$	1.0	$19.41^{+0.43}_{-0.57}$	2.0
Bootes 1	$18.39^{+0.36}_{-0.37}$	0.9	$18.77^{+0.40}_{-0.54}$	1.8
Canes Venatici I	$17.43^{+0.16}_{-0.15}$	0.8	$18.19^{+0.40}_{-0.39}$	1.3
Coma Berenices	$19.26^{+0.35}_{-0.43}$	0.9	$19.12^{+0.46}_{-0.73}$	1.8
Leo I	$17.58^{+0.10}_{-0.10}$	0.8	$18.44^{+0.33}_{-0.42}$	1.4
Segue 1	$19.25^{+0.60}_{-0.69}$	0.8	$18.33^{+0.69}_{-0.63}$	0.8
Sextans	$17.80^{+0.10}_{-0.10}$	1.0	$18.49^{+0.28}_{-0.21}$	1.8
Canes Venatici II	$17.82^{+0.38}_{-0.37}$	0.8	$18.45^{+0.50}_{-0.74}$	1.4
Hercules	$17.60^{+0.53}_{-0.69}$	0.8	$17.79^{+0.62}_{-0.61}$	1.0
Leo II	$17.72^{+0.18}_{-0.17}$	0.8	$17.85^{+0.62}_{-0.40}$	1.0
Willman I	$19.80^{+0.50}_{-0.52}$	0.9	$19.00^{+0.71}_{-0.93}$	1.5
Aquarius 2	$18.57^{+0.50}_{-0.57}$	1.1	$18.53^{+0.61}_{-0.68}$	1.3
Leo T	$17.66^{+0.55}_{-0.52}$	0.8	$17.88^{+0.65}_{-0.69}$	1.0

95% C.L. upper limits



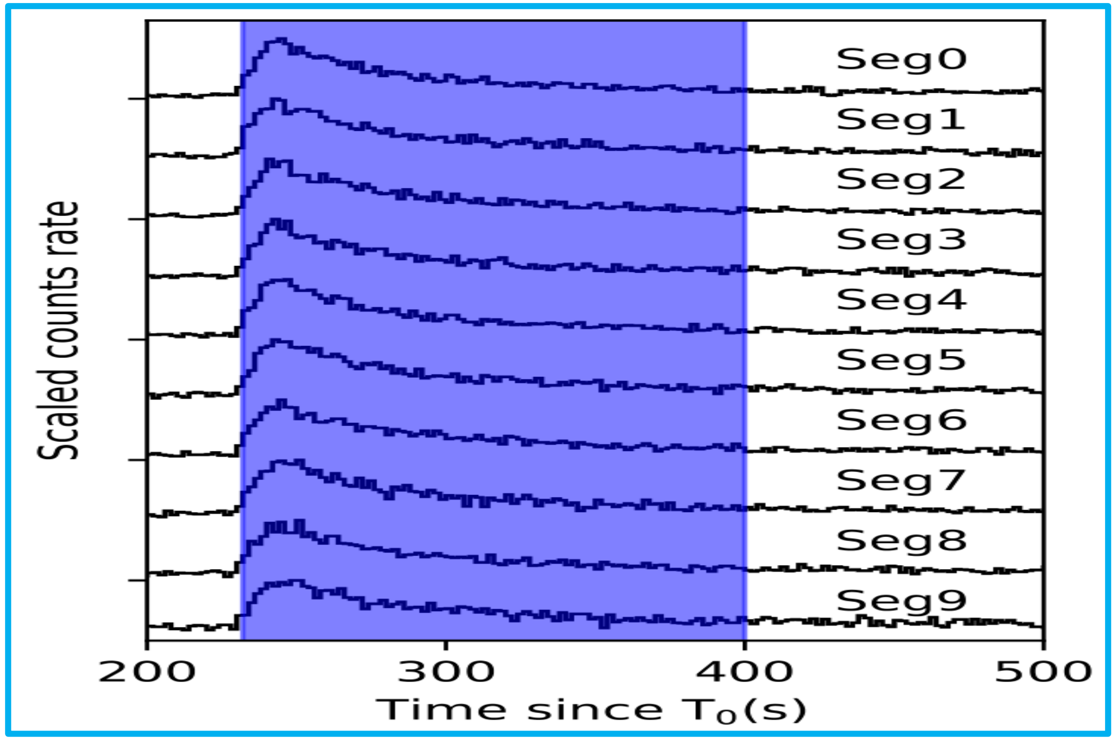
LHAASO coll. PRL 133:061001 (2024)

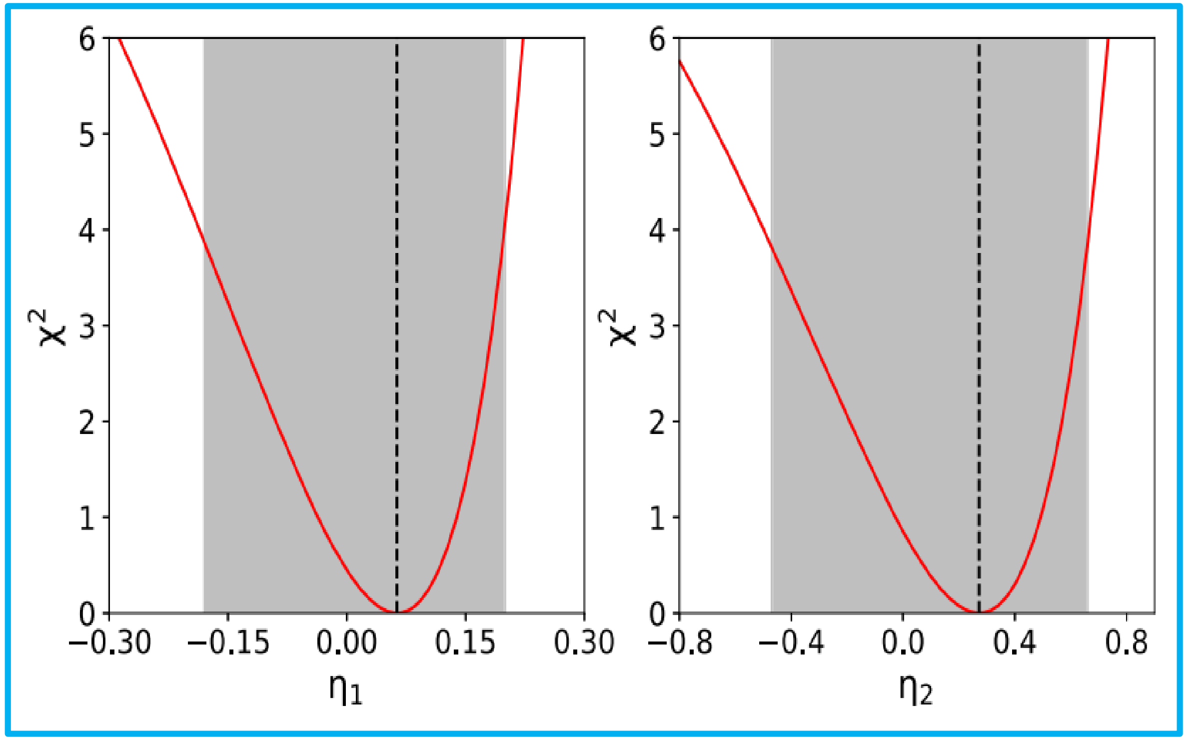
Stringent Tests of Lorentz Invariance Violation

Using time lag of different energy from GRB 221009A.

Improved by factors of 5–7 for both subluminal or superluminal

$$\Delta t_{\mathrm{LIV}} = s\frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{\mathrm{QG},n}^n}\int_0^z \frac{(1+z')^n}{H(z')}dz'$$





LHAASO coll. PRL 133, 071501(2024)

Summary

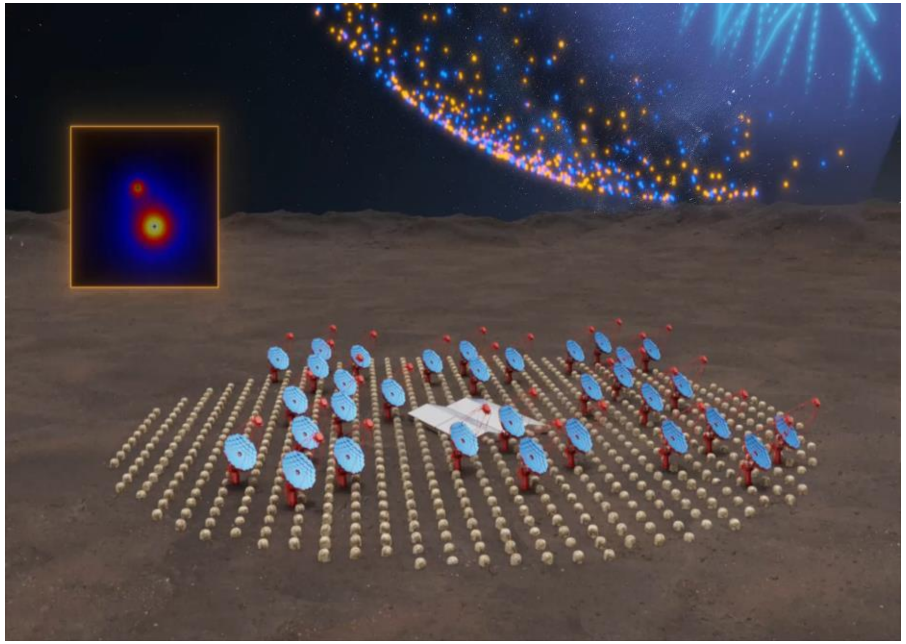
- LHAASO is operated very stable with full duty cycle since July 2021.
- LHAASO open-up a new UHE era with many new discoveries about Massive star, SNR, PWN, AGN, GRB and so on.
- LHAASO also throw light on the new physics frontier.
- There are still much more new interesting phenomena ahead!

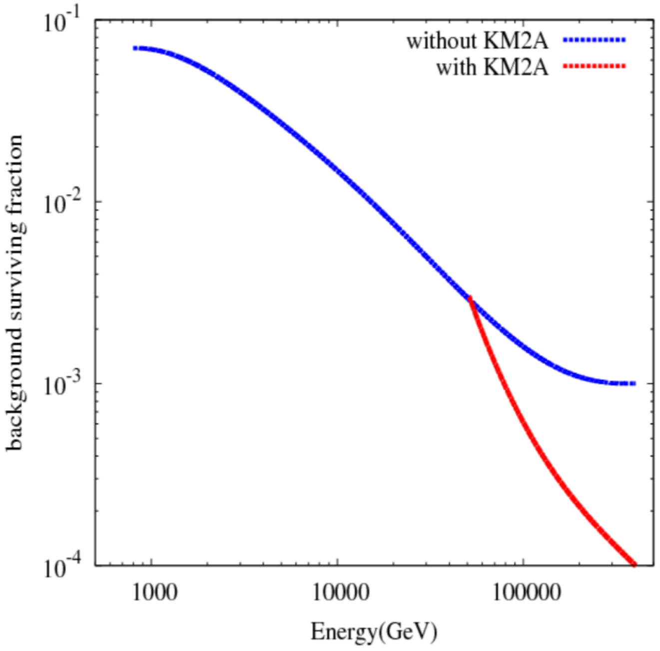
LHAASO: 0.3TeV-10000TeV

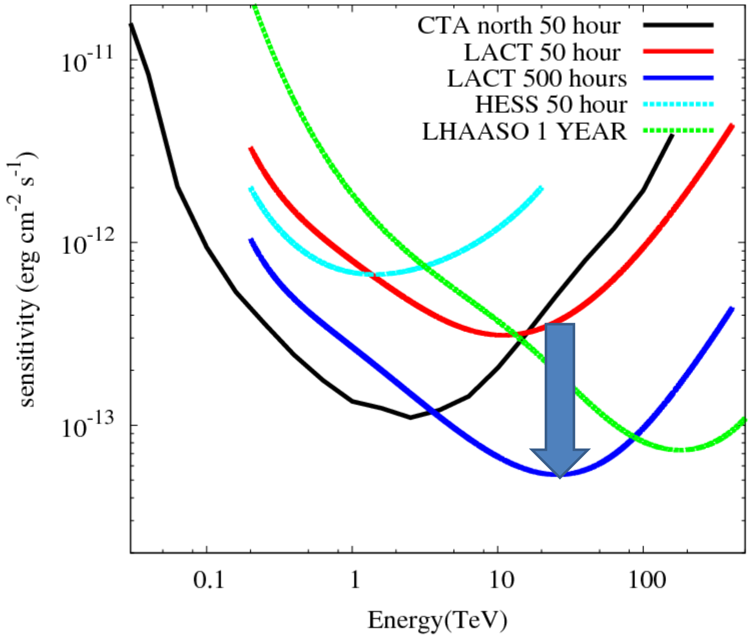
(2019-2021-now- 2040?)

Outlook: LHAASO upgrade plan LACT

- LACT improve the angular resolution <0.05°
- LACT + KM2A muon detectors
  → Better gamma-ray selection
- Construction: 2024.10 – 2028.9



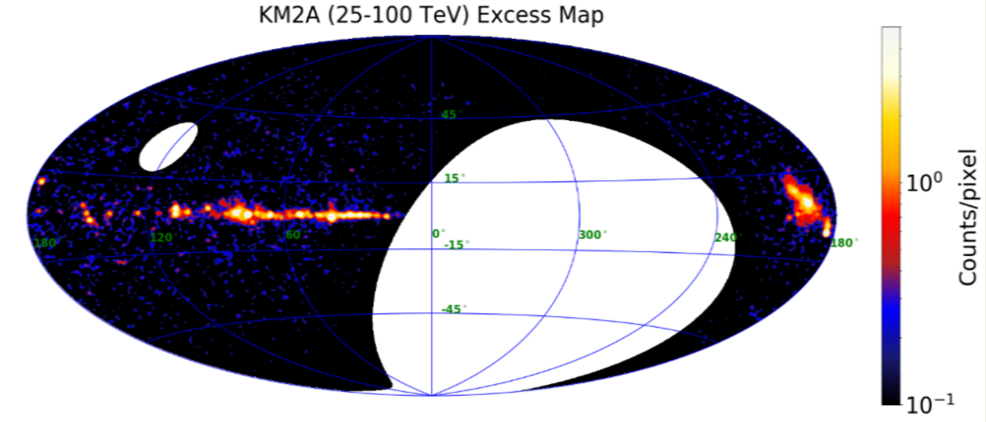


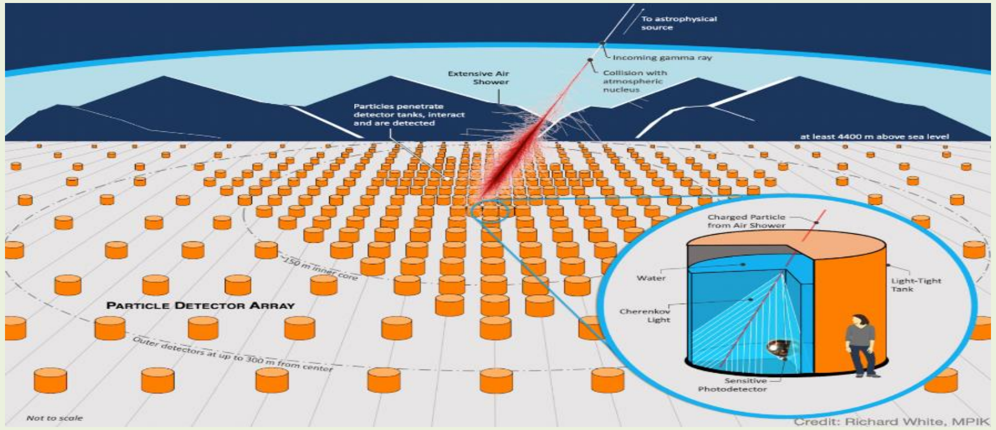


Outlook：Future plans

SWGO

(Southern Wide-field Gamma-ray Observatory)



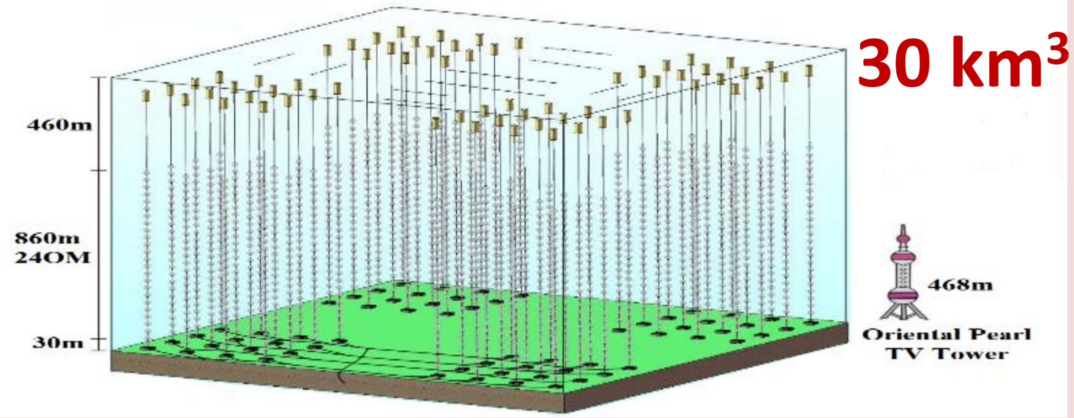


HUNT

(High-energy Underwater Neutrino Telescope)

2023.02@South China Sea

2024.02@Baikal




More LHAASO results can be found from :
http://english.ihep.cas.cn/lhaaso/
Thank you!