Revealing Galactic PeVatrons with LHAASO

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on behalf of the LHAASO collaboration

Purple Mountain Observatory

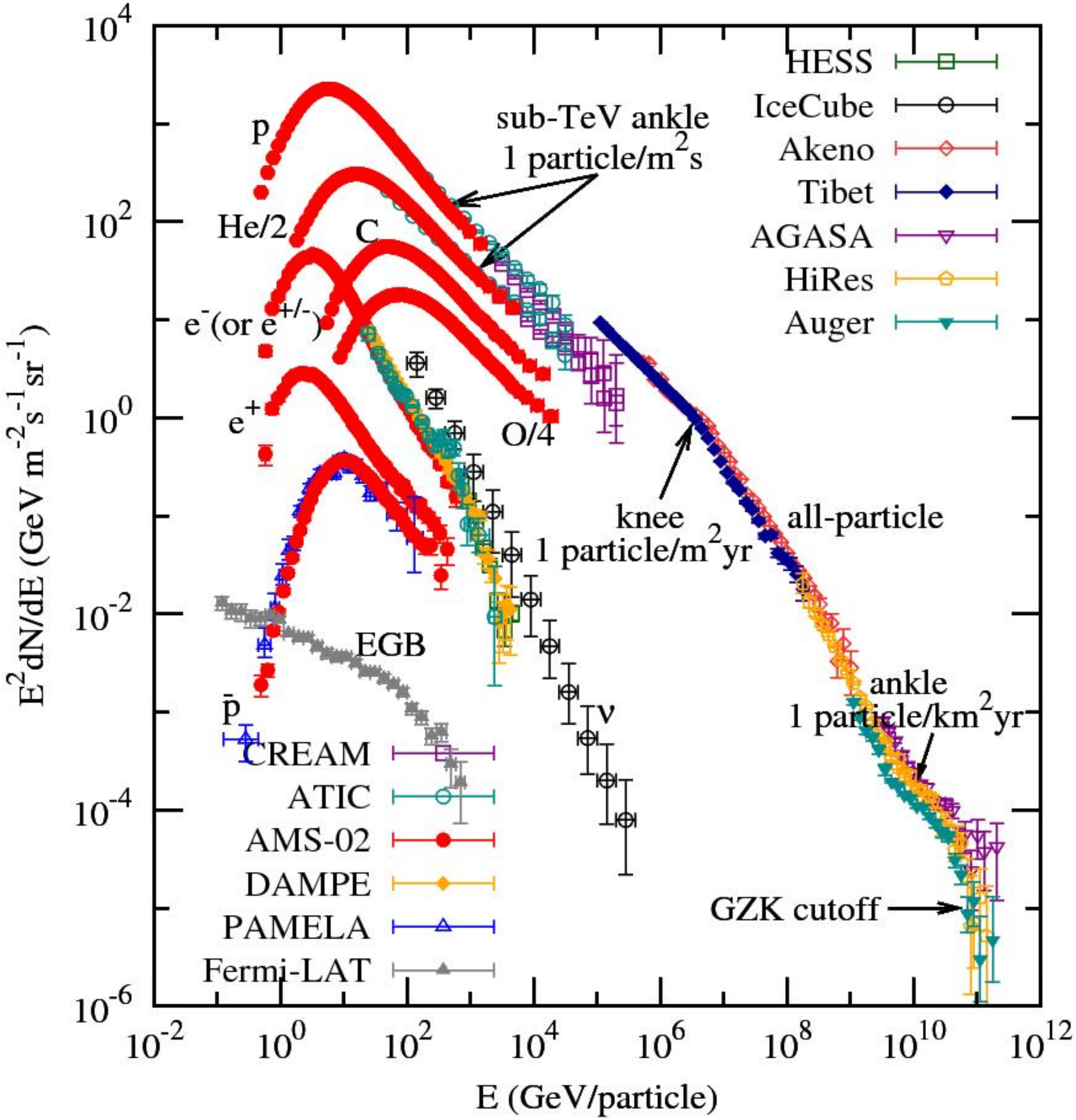
Dec. 5-7, 2021

Cosmic Rays in the Multi-Messenger Era, APC, Paris (online)

Outline

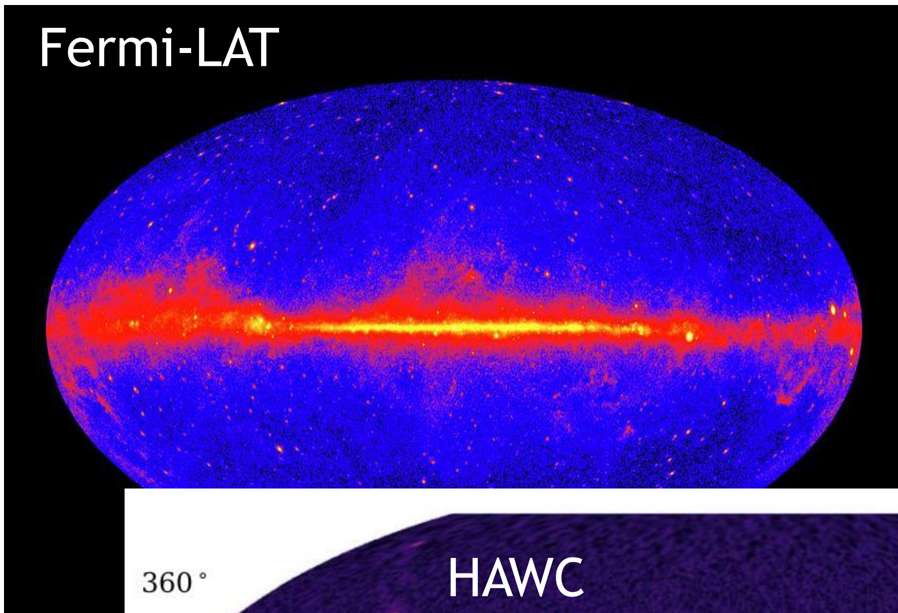
- Introduction of LHAASO
- LHAASO status and γ-ray performance
- LHAASO observations of Galactic γ-ray sources
- Summary

Energy frontier of the universe



- How cosmic rays are accelerated?
- Where are they originated from?
- How do they propagate in the space?
- How to form complicated spectral structures and abundance?

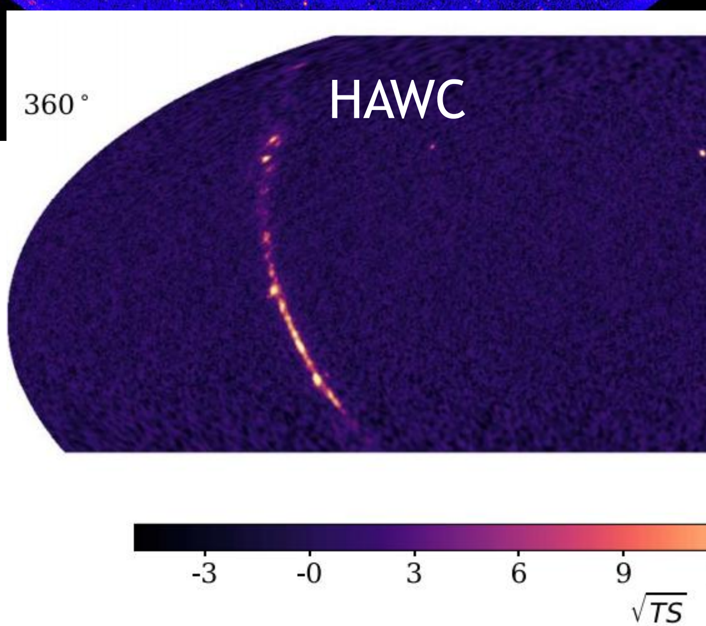
Probing CR acceleration and propagation with gamma rays

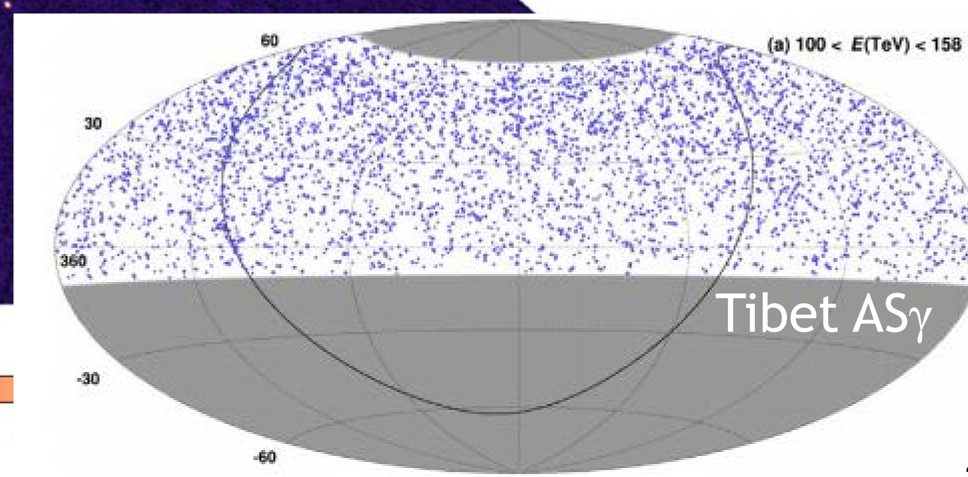


p,α + gas → π^0 → 2γ

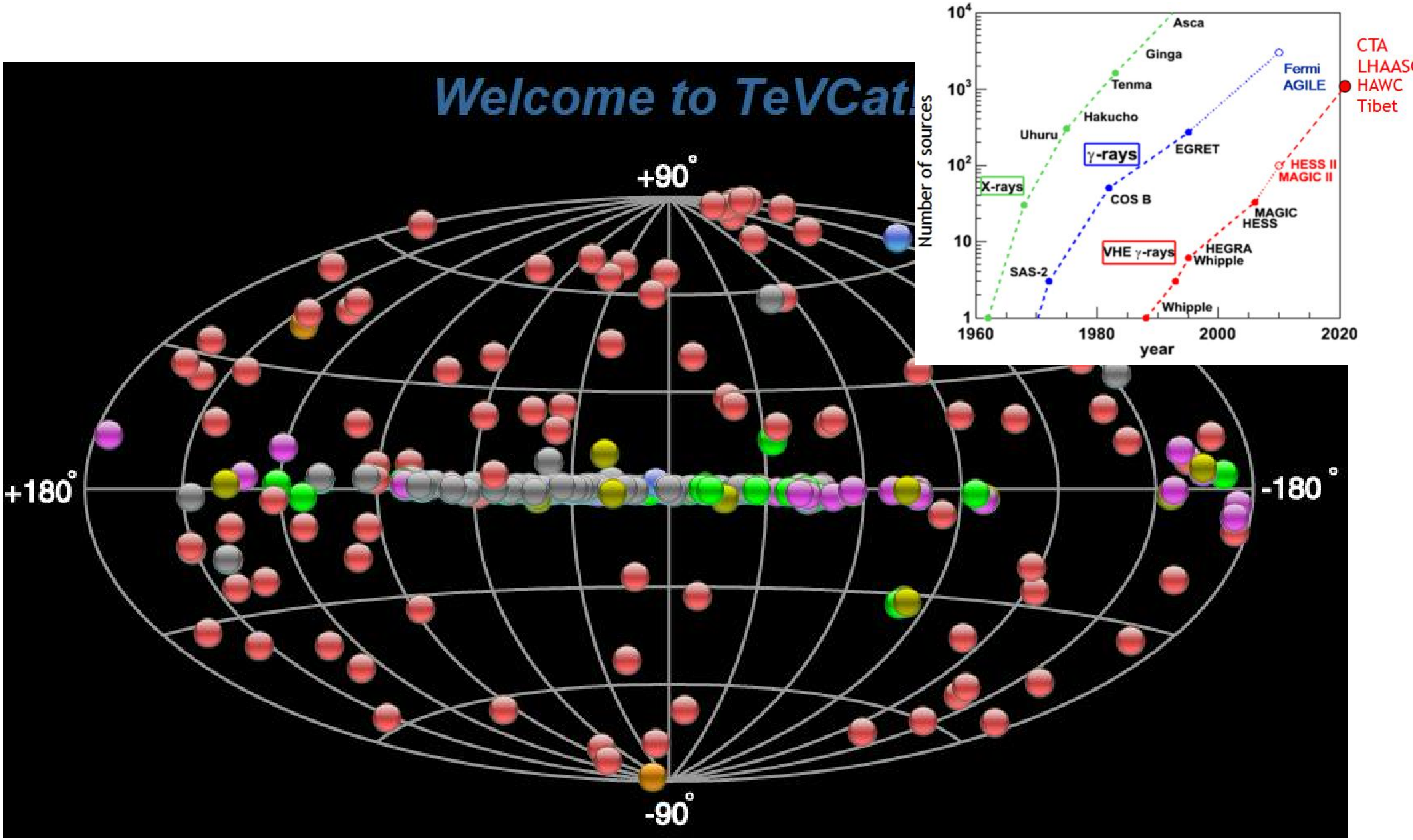
$e^{+/-}$ + gas → γ (bremsstrahlung)

$e^{+/-}$ + ISRF → γ (inverse Compton scattering)



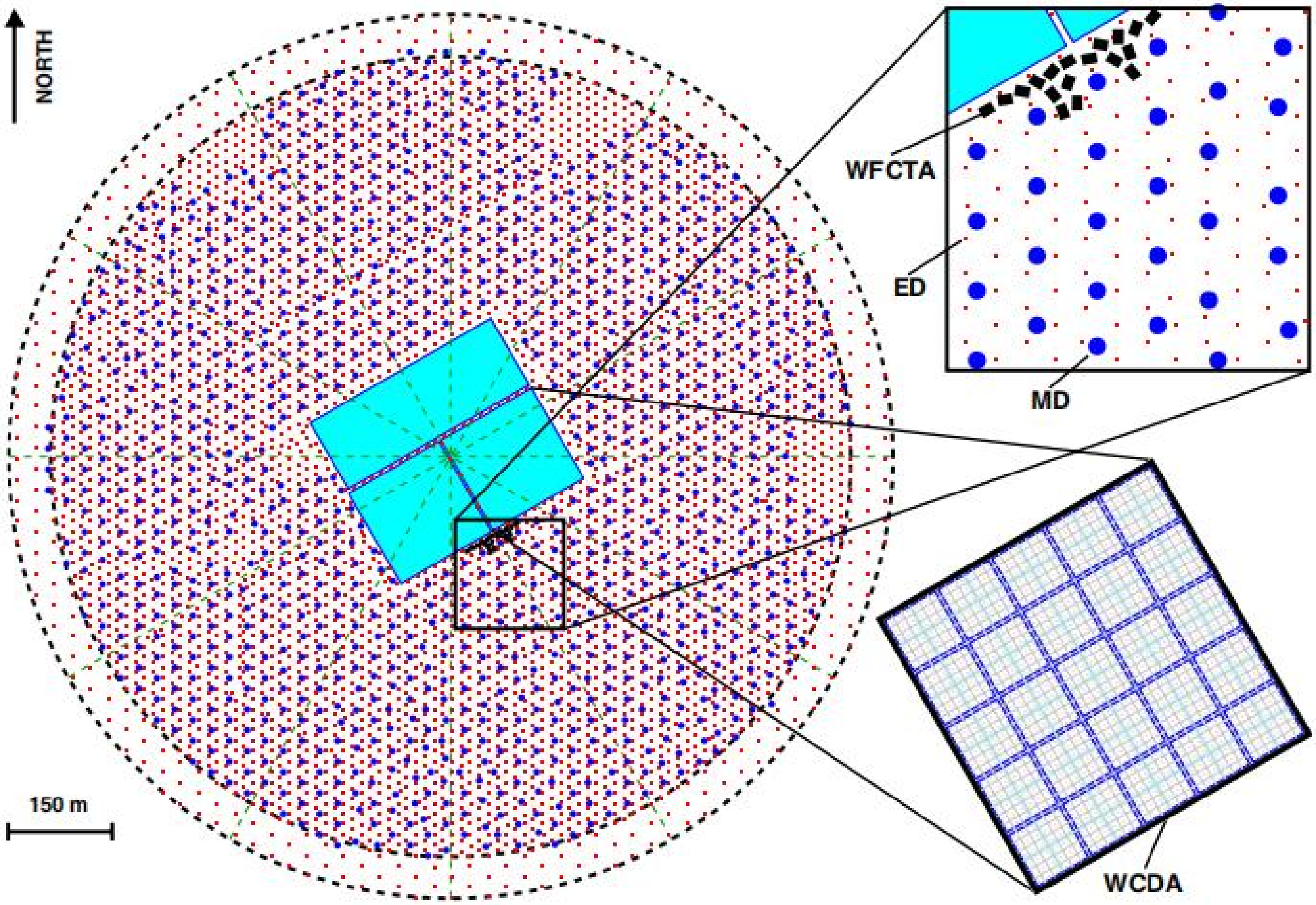


Very-high-energy gamma ray sources



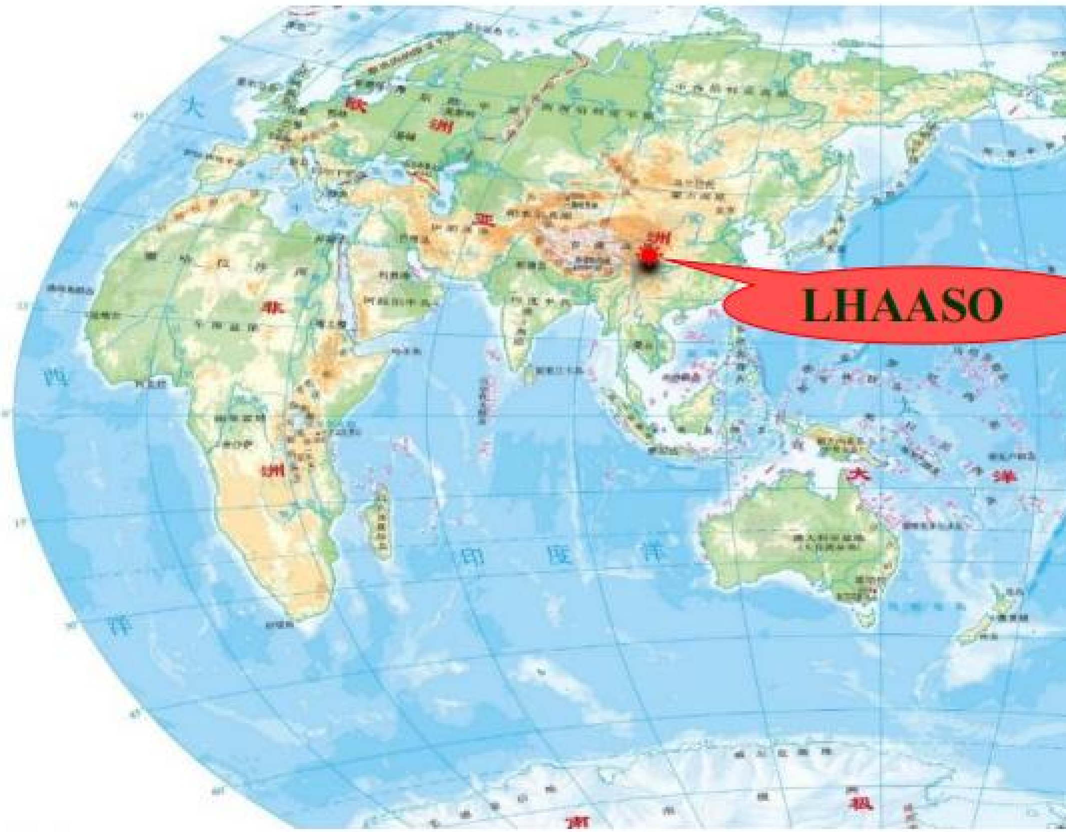
http://tevcat.uchicago.edu/

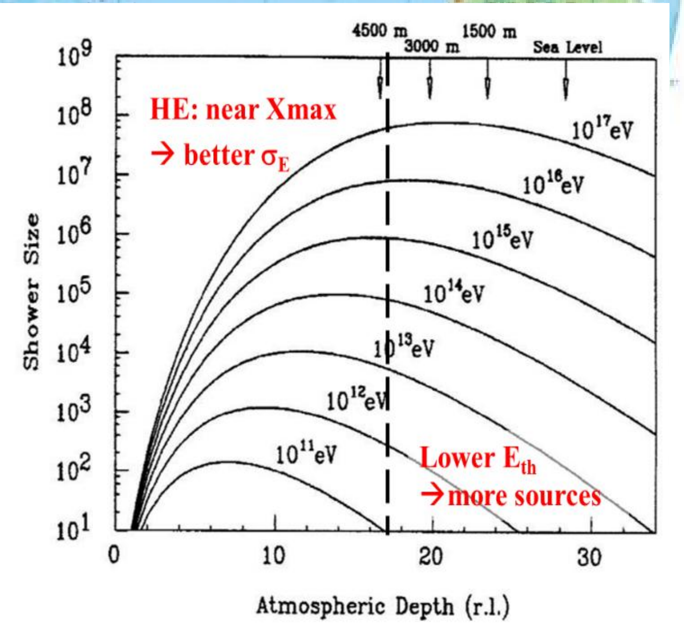
Large High Altitude Air Shower Observatory (LHAASO)



Detecting air showers produced by cosmic rays (and gamma rays) with ~km² area and hybrid techniques

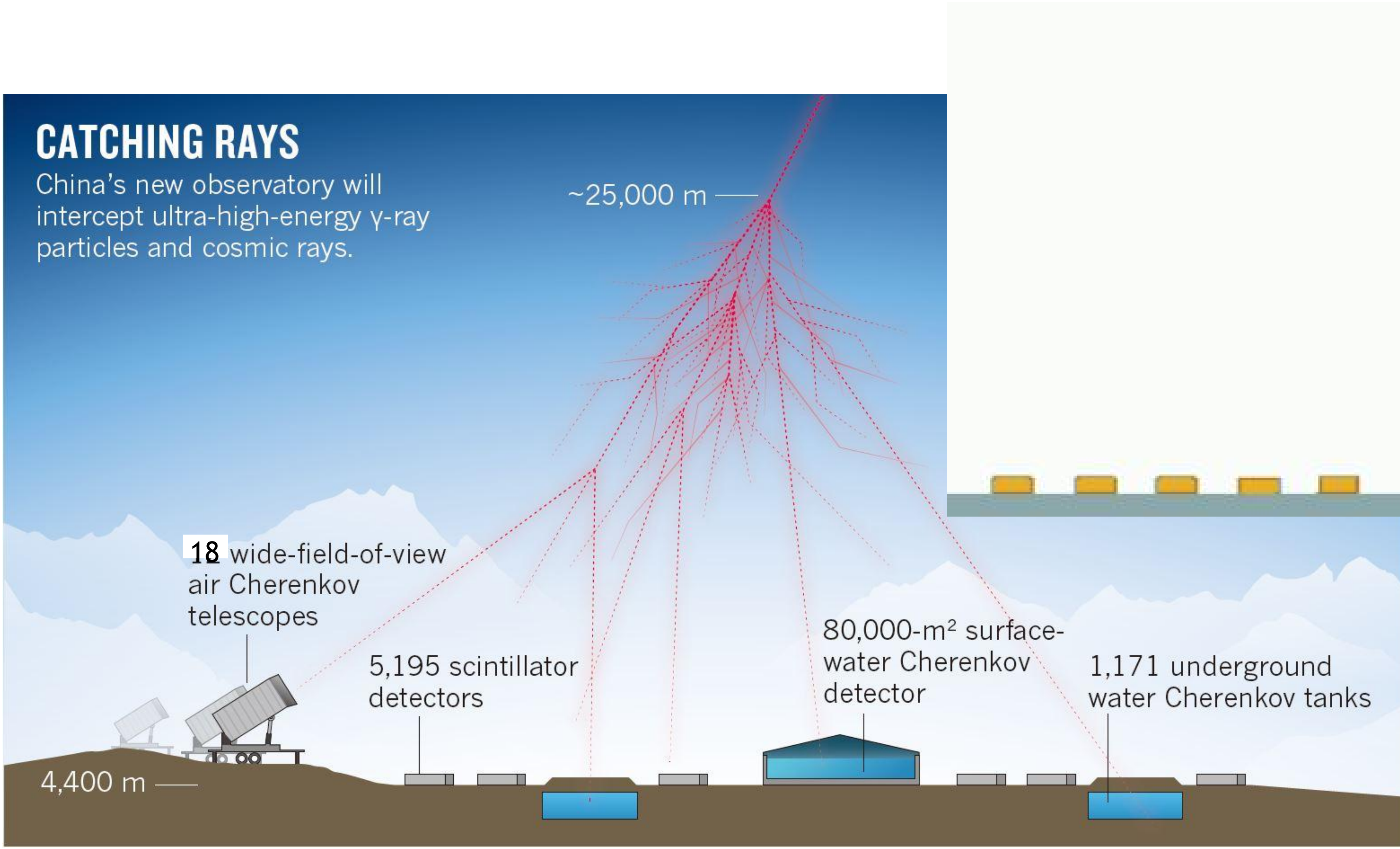
LHAASO site



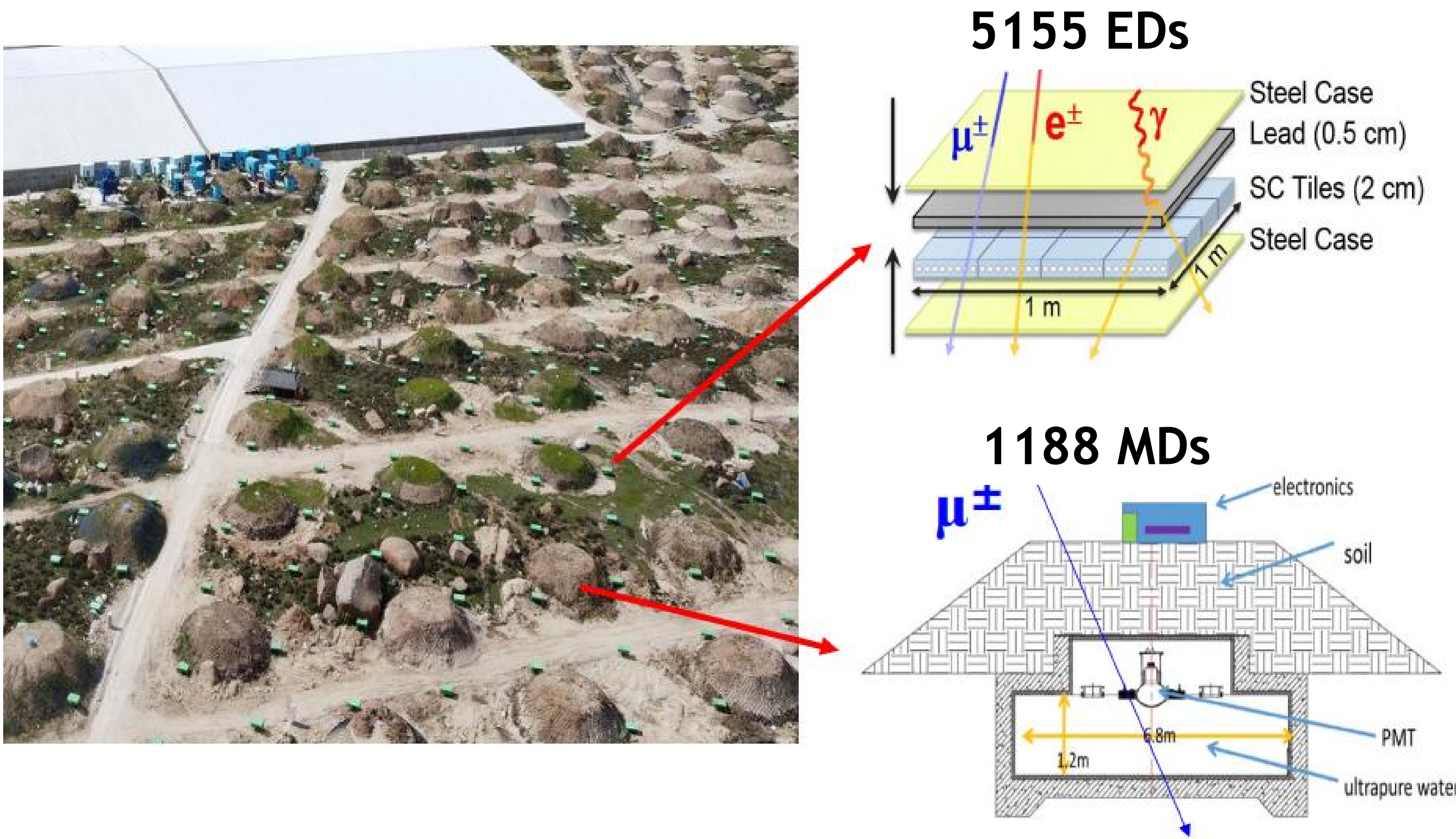


- Haizi mountain, Sichuan, China
- 4410 m above the sea level

Air shower detection

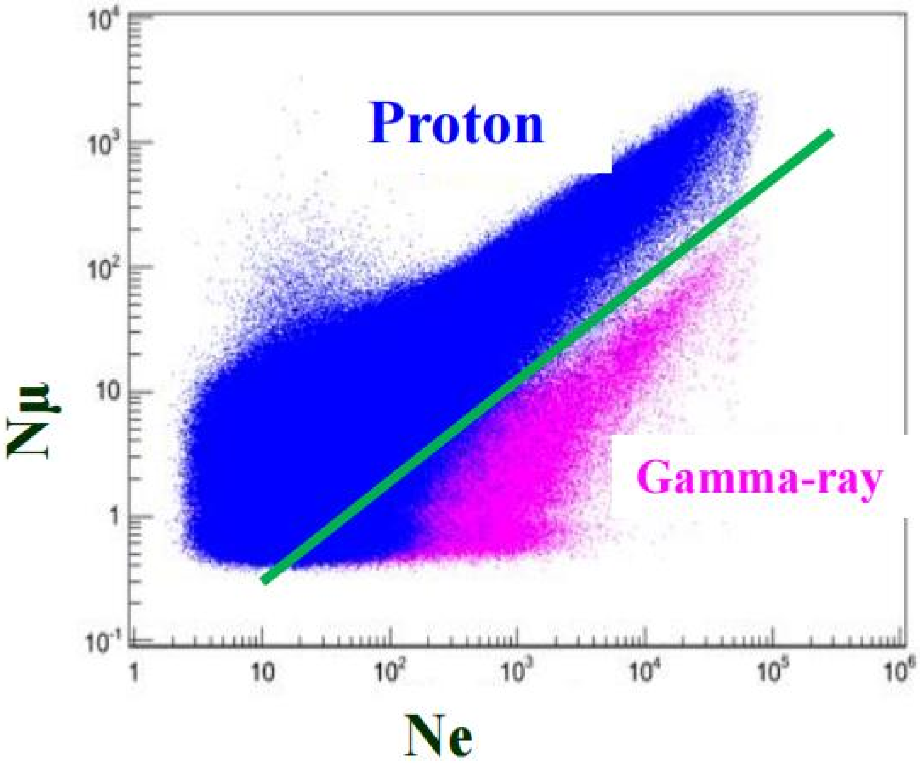


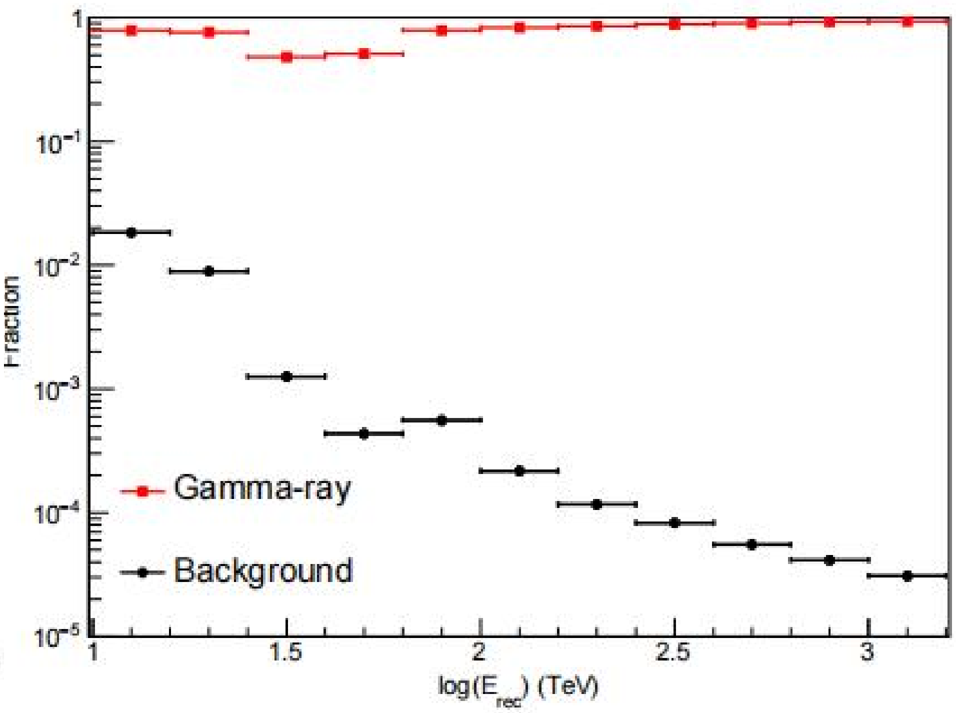
LHAASO detector - KM2A



- ➢ Electromagnetic particles to reconstruct energy and direction
- ➢ Muons to distinguish different particles (especially γ rays)
- ➢ Covering energies from 10 TeV to 10 PeV

LHAASO detector - KM2A

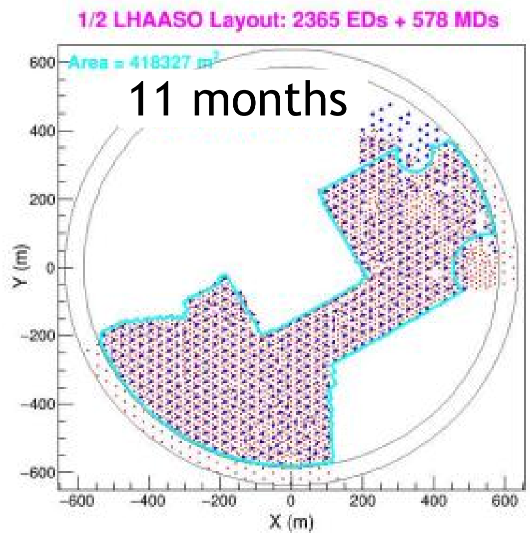


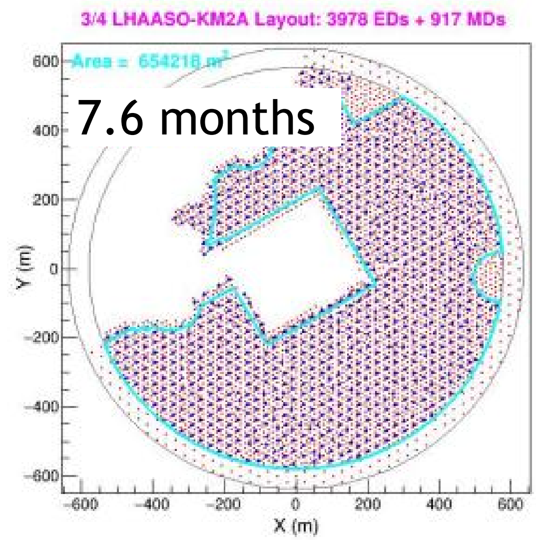


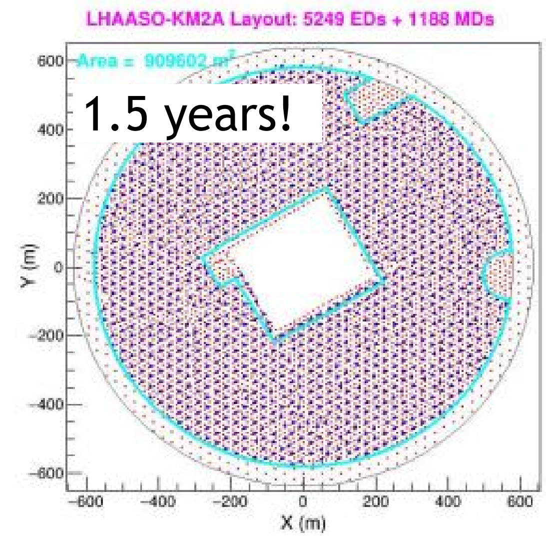
$$R = \log\left(\frac{N_\mu + 0.0001}{N_e}\right)$$

Chin. Phys. C, 45, 025002 (2021)

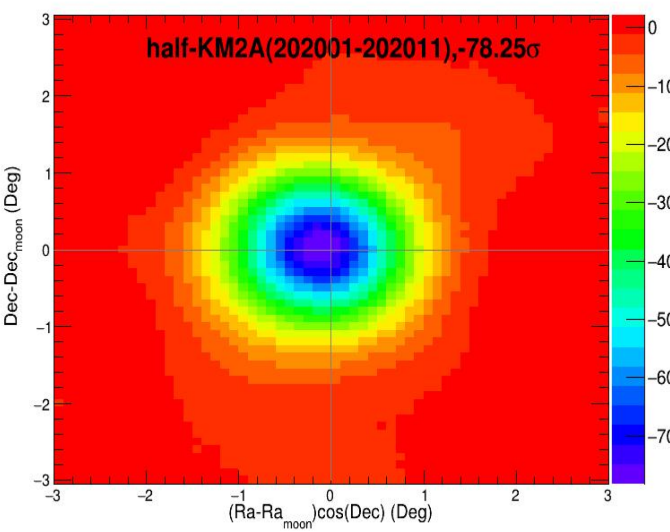
LHAASO detector - KM2A

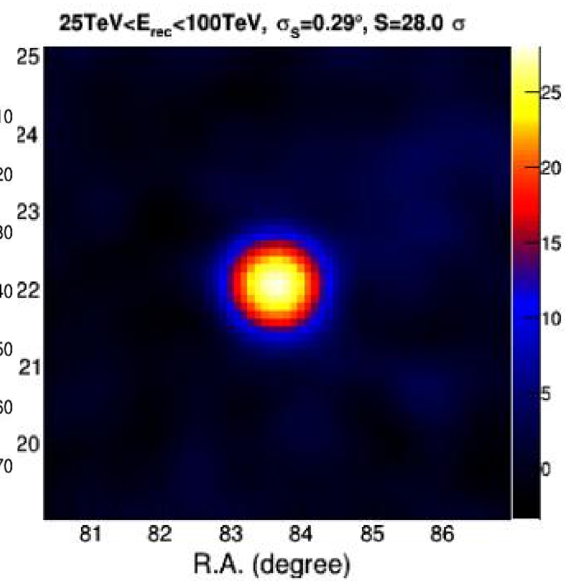


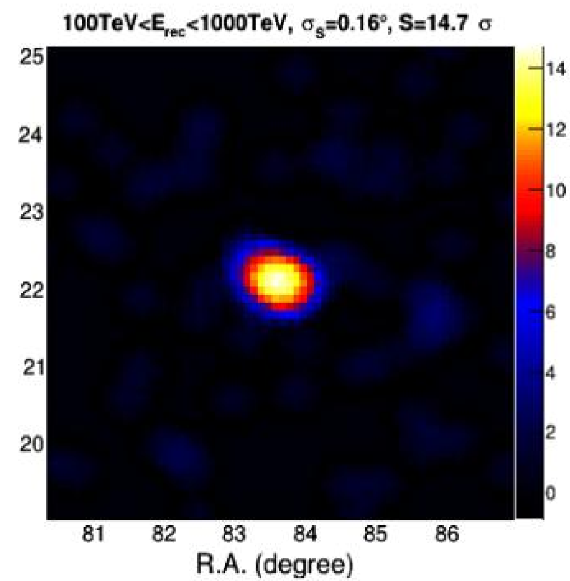




1/2: 20191217->20201130 3/4: 20201201->20210719 Full: 20210720->







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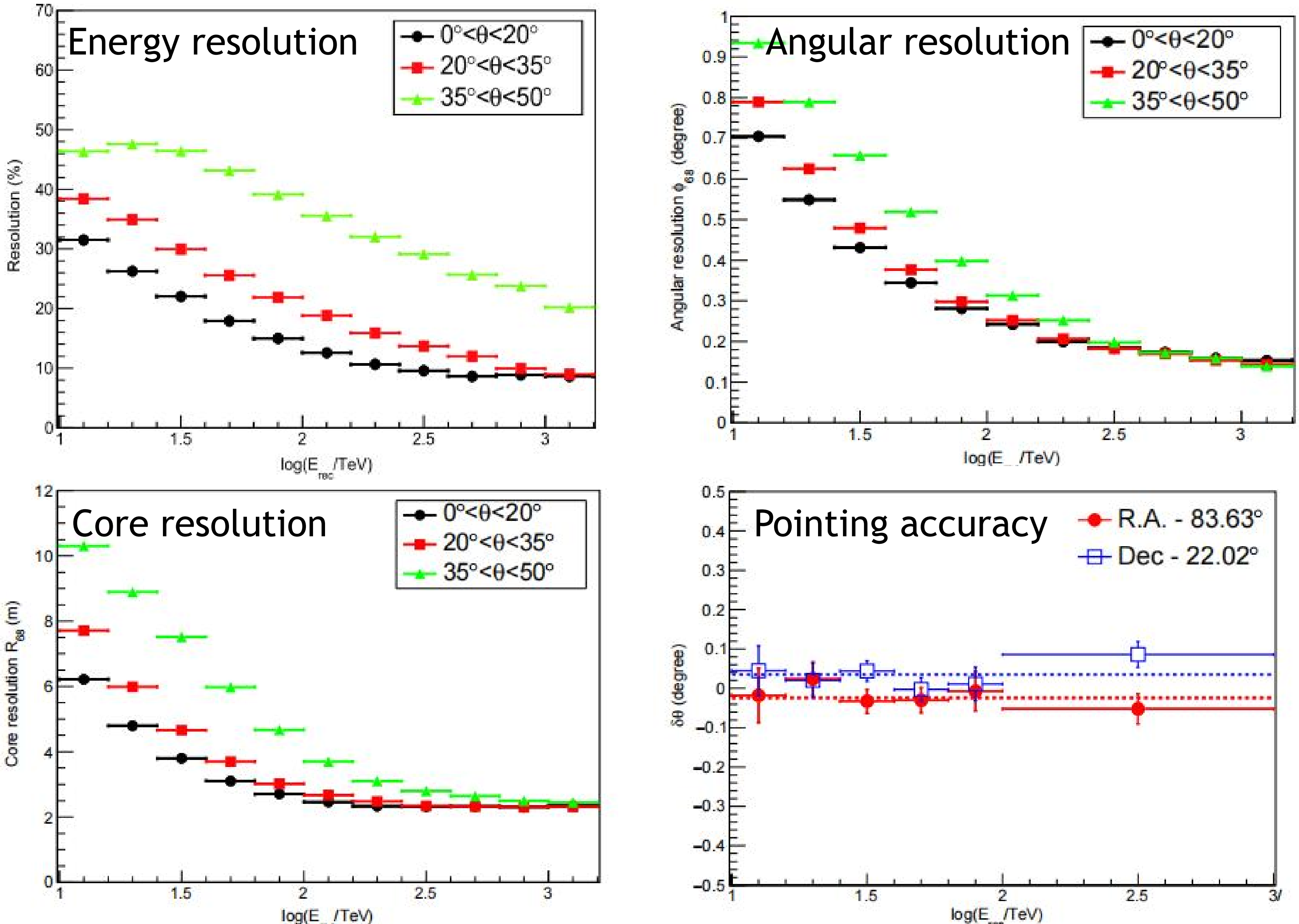
LHAASO detector - KM2A



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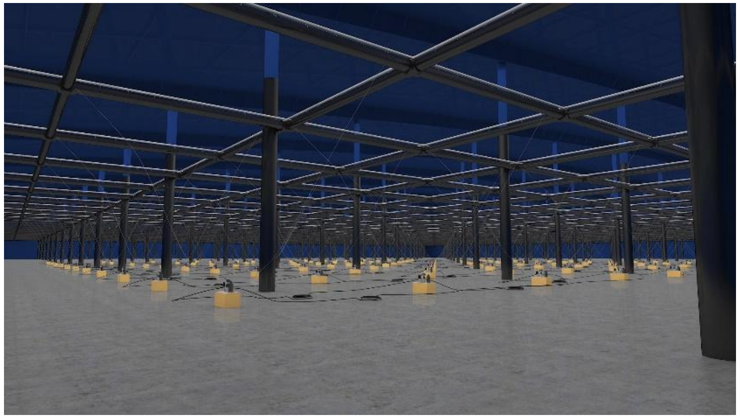
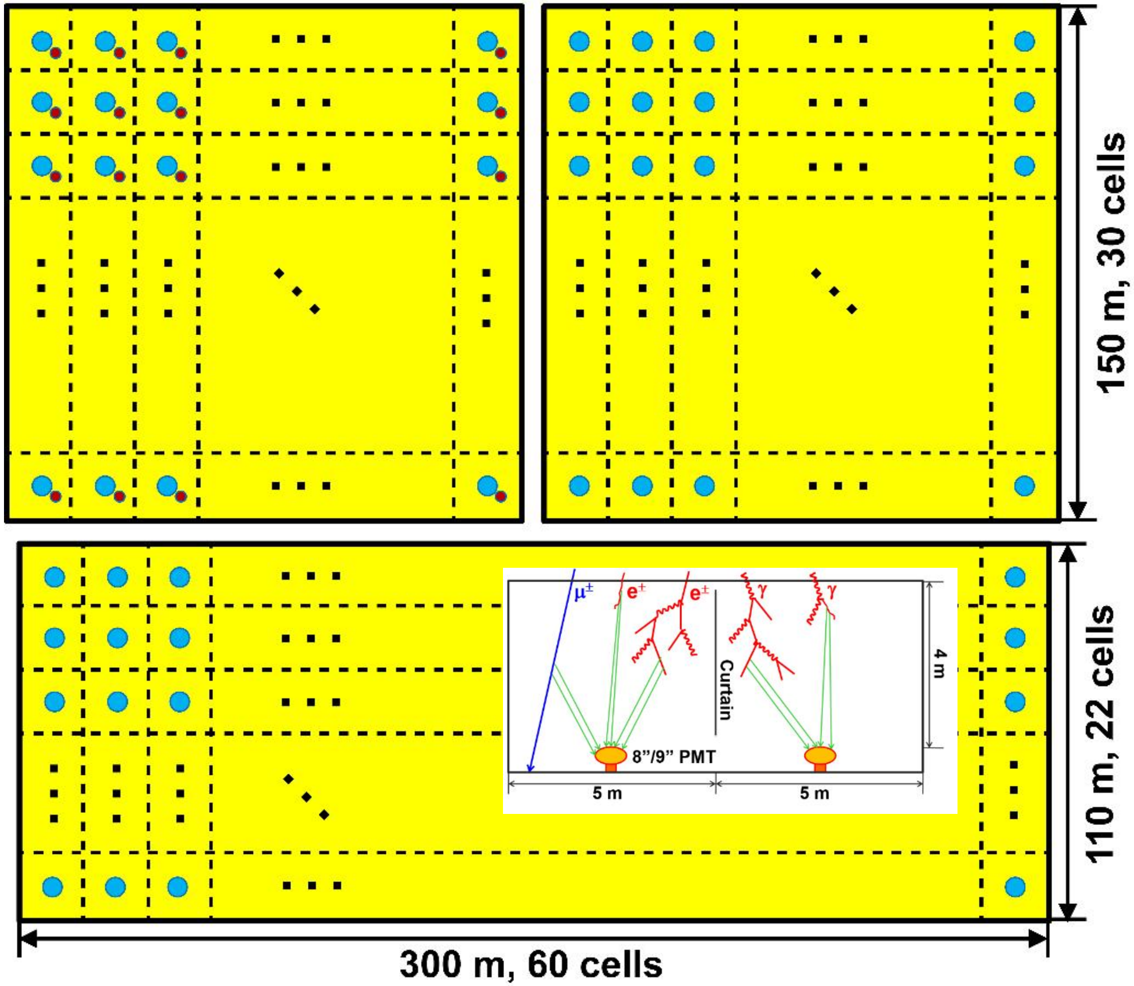
LHAASO detector - WCDA

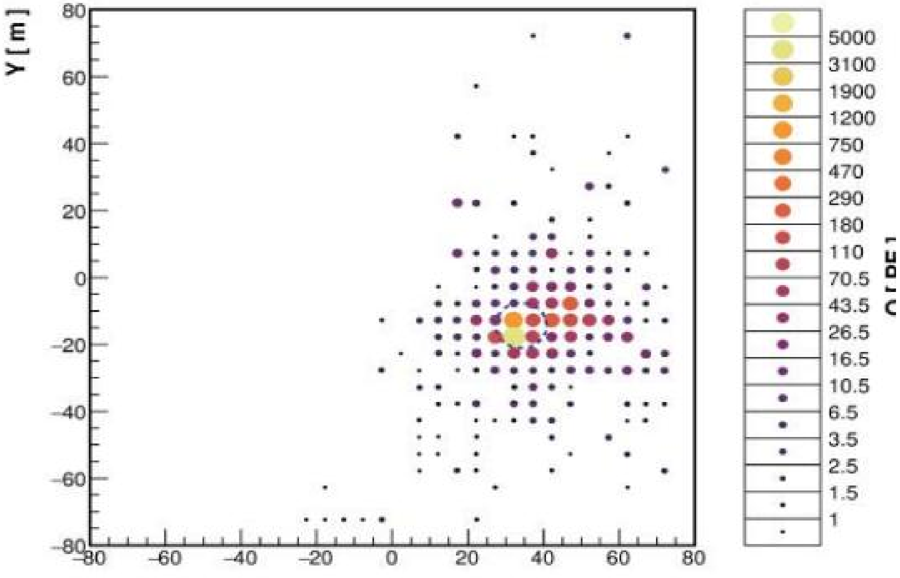




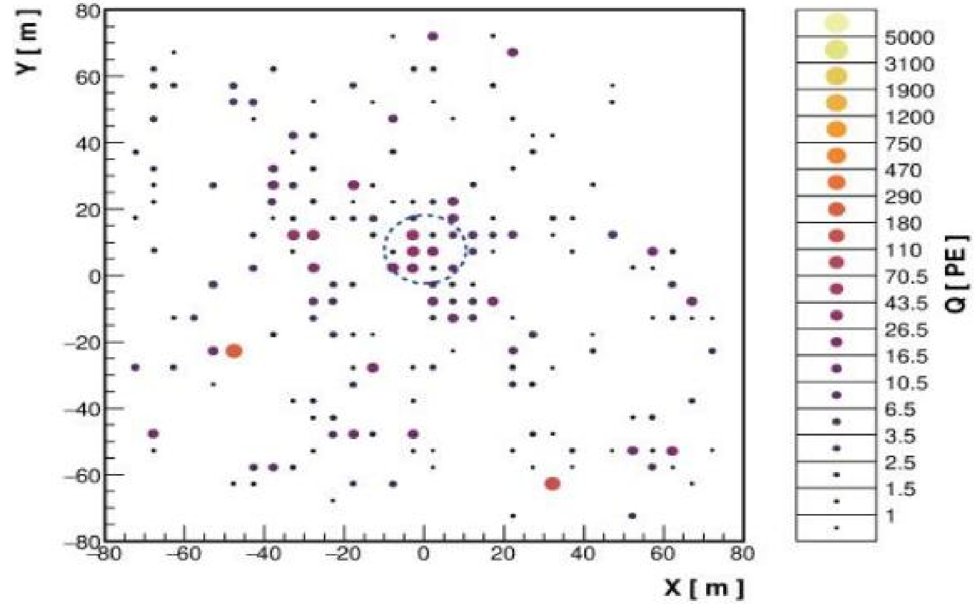
- Area: 78,000 m^2
- Covering energies from 0.3 TeV to ~PeV

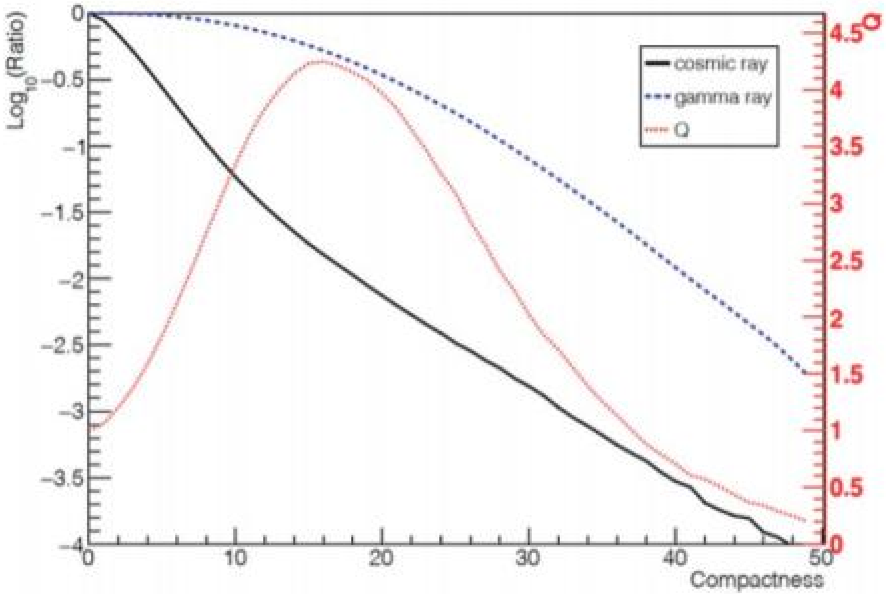
LHAASO detector - WCDA

Gamma-ray event



Cosmic ray event





$$C = N_{hit}/\text{Max}(Q_i; r > R_c)$$

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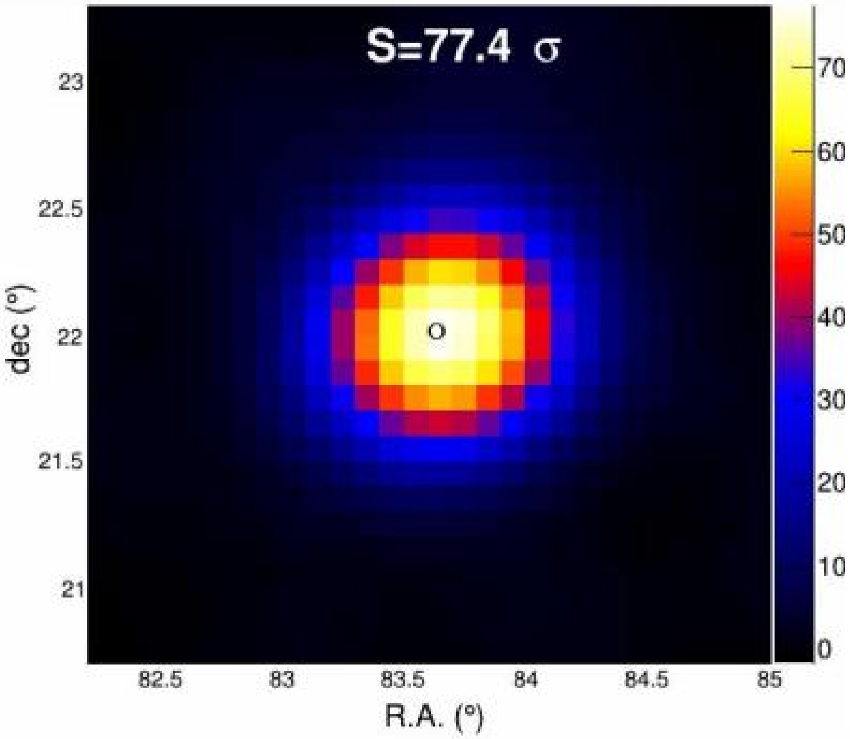
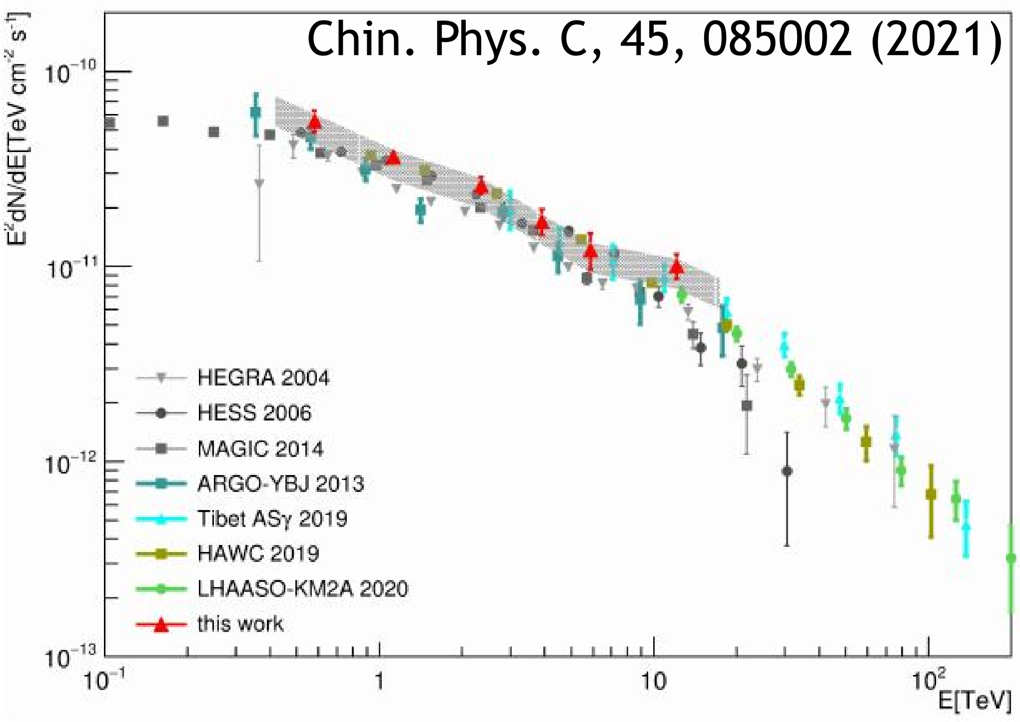
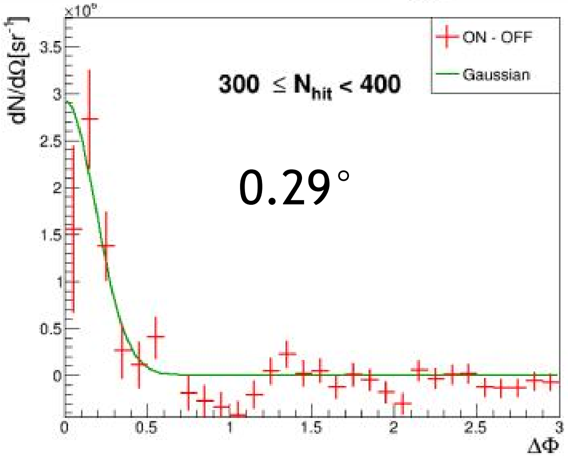
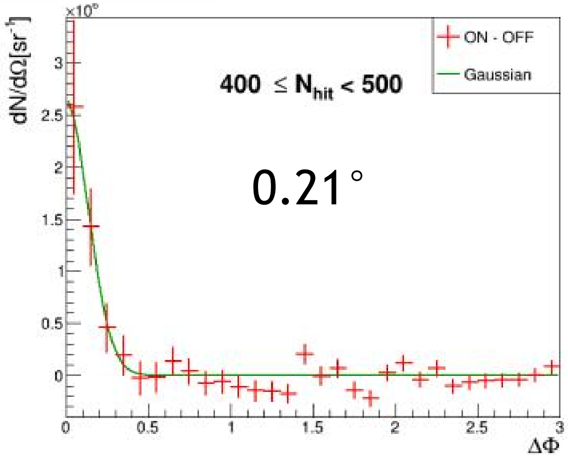
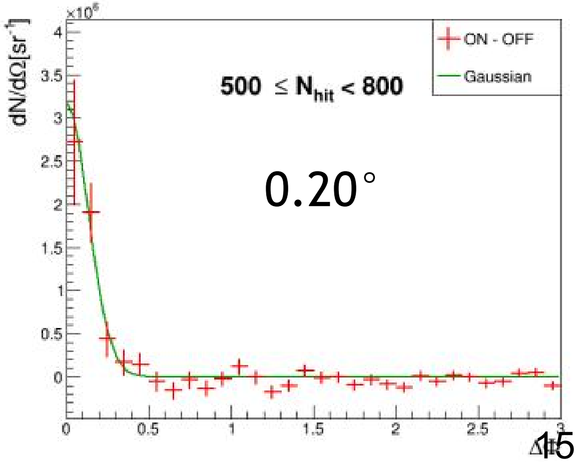
LHAASO detector - WCDA



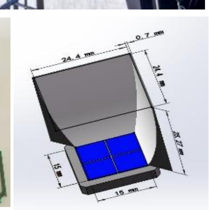








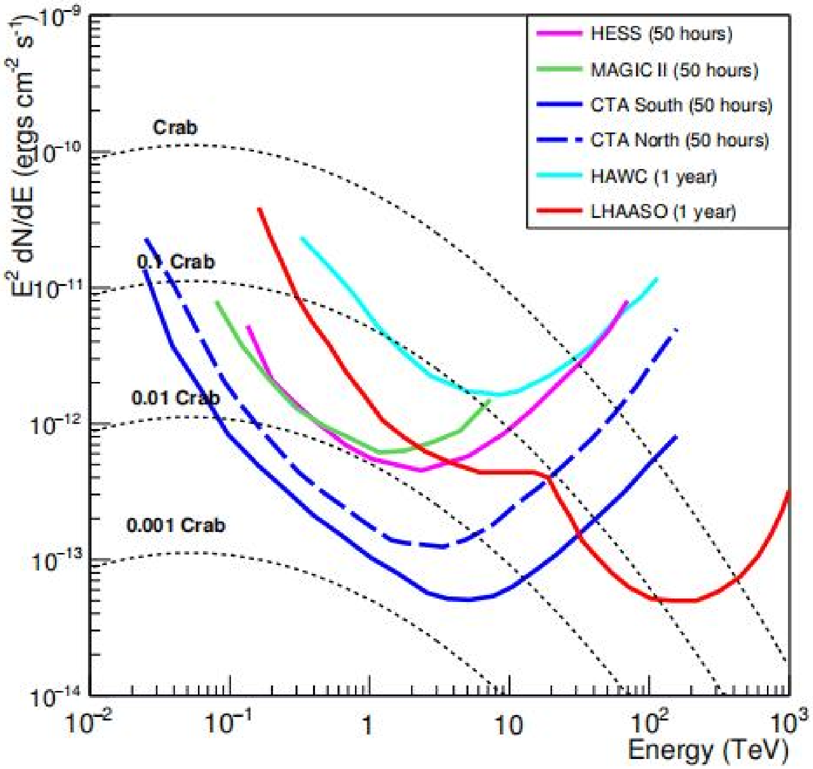
LHAASO detector - WFCTA

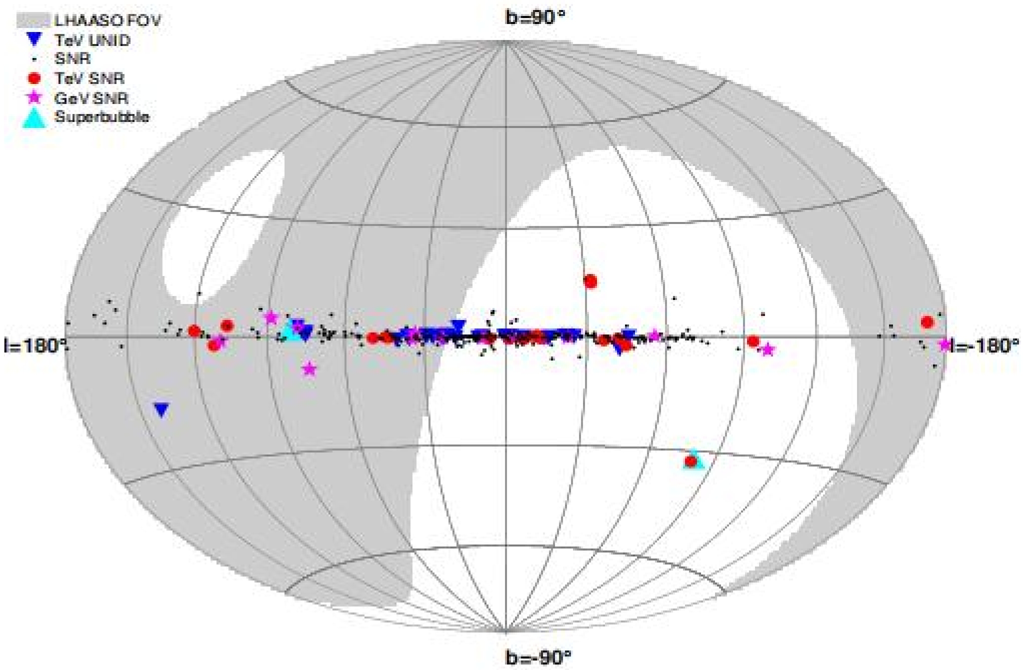


SiPM and Winston cone

- 18 Telescopes since 2021-05
- Area: 4.7 m^2 each
- FoV: 16° × 16° each
- Measuring the shower development to identify particle species
- Cross-calibrating the absolute energy scale
- Together with WCDA, KM2A to measure cosmic rays in the widest energy band (10^{12} eV - 10^{17} eV)

Gamma-ray survey sensitivity

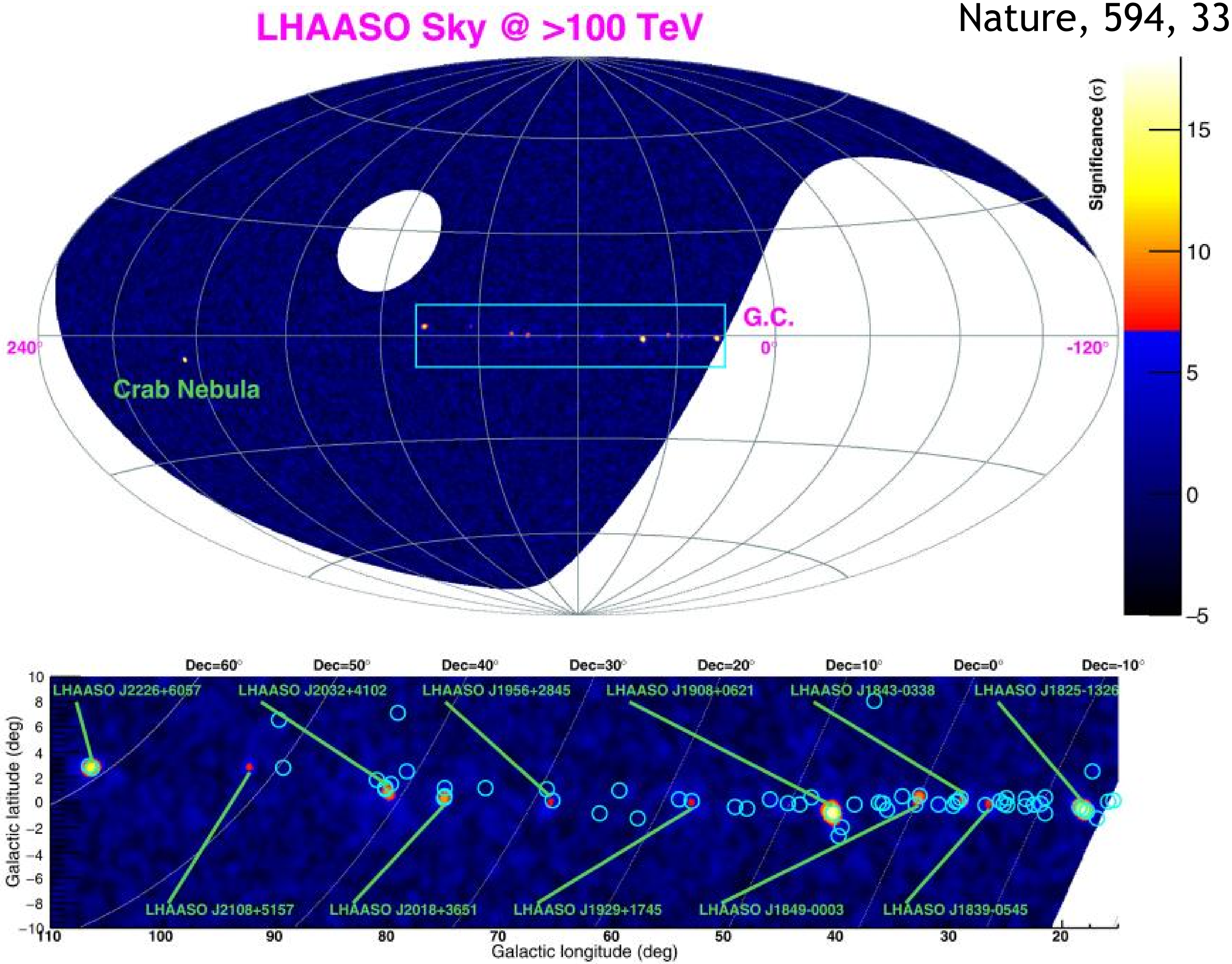




Chin. Phys. C, 46, 035002 (2022)

Survey of the UHE sky with 1/2 array

Nature, 594, 33 (2021)

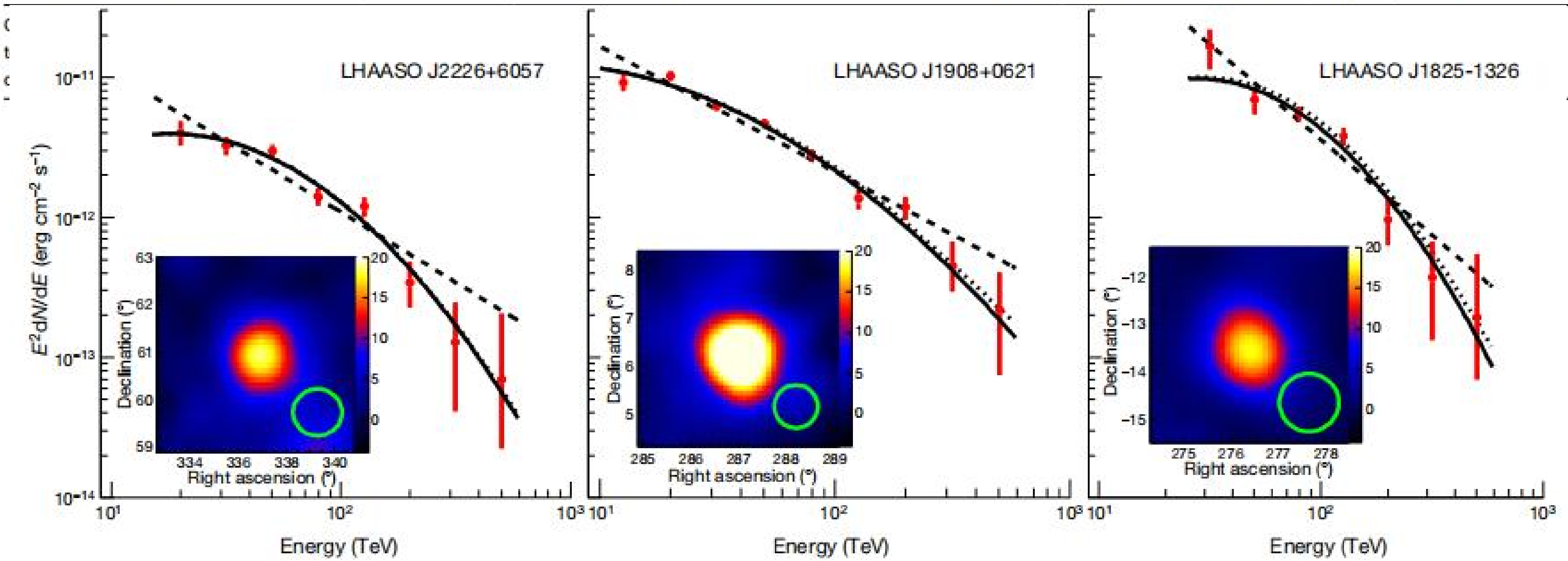


Survey of the UHE sky with 1/2 array

Table 1 | UHE γ-ray sources

Nature, 594, 33 (2021)

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)



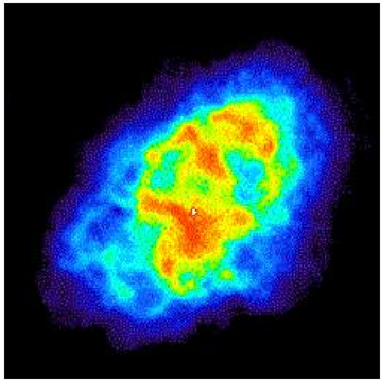
Survey of the UHE sky with 1/2 array

Nature. 594. 33 (2021)

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

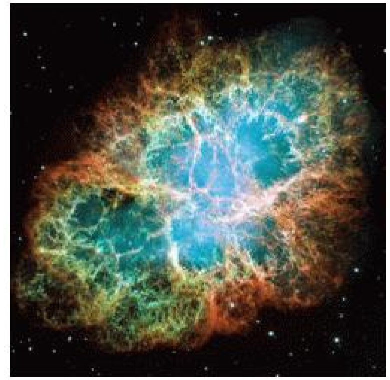
Pulsars and their wind nebulae are likely PeVatrons?

Crab nebula: Electron PeVatron

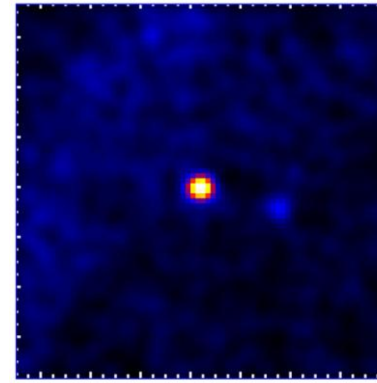


Radio wave (VLA)

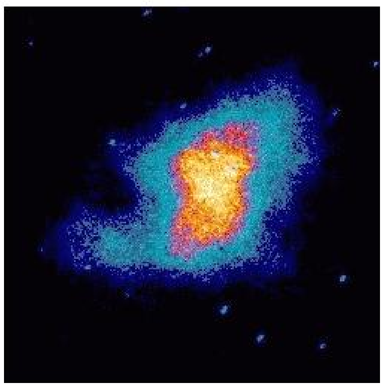
Infrared radiation (Spitzer)



Visible light (Hubble)

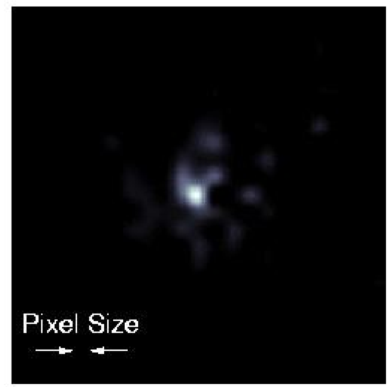


E>1 GeV (Fermi-LAT)

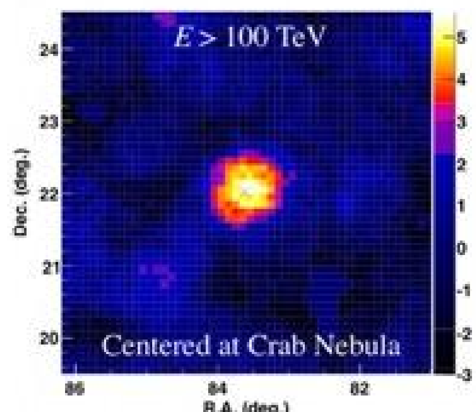


Ultraviolet radiation (Astro-1)

Low-energy X-ray (Chandra)

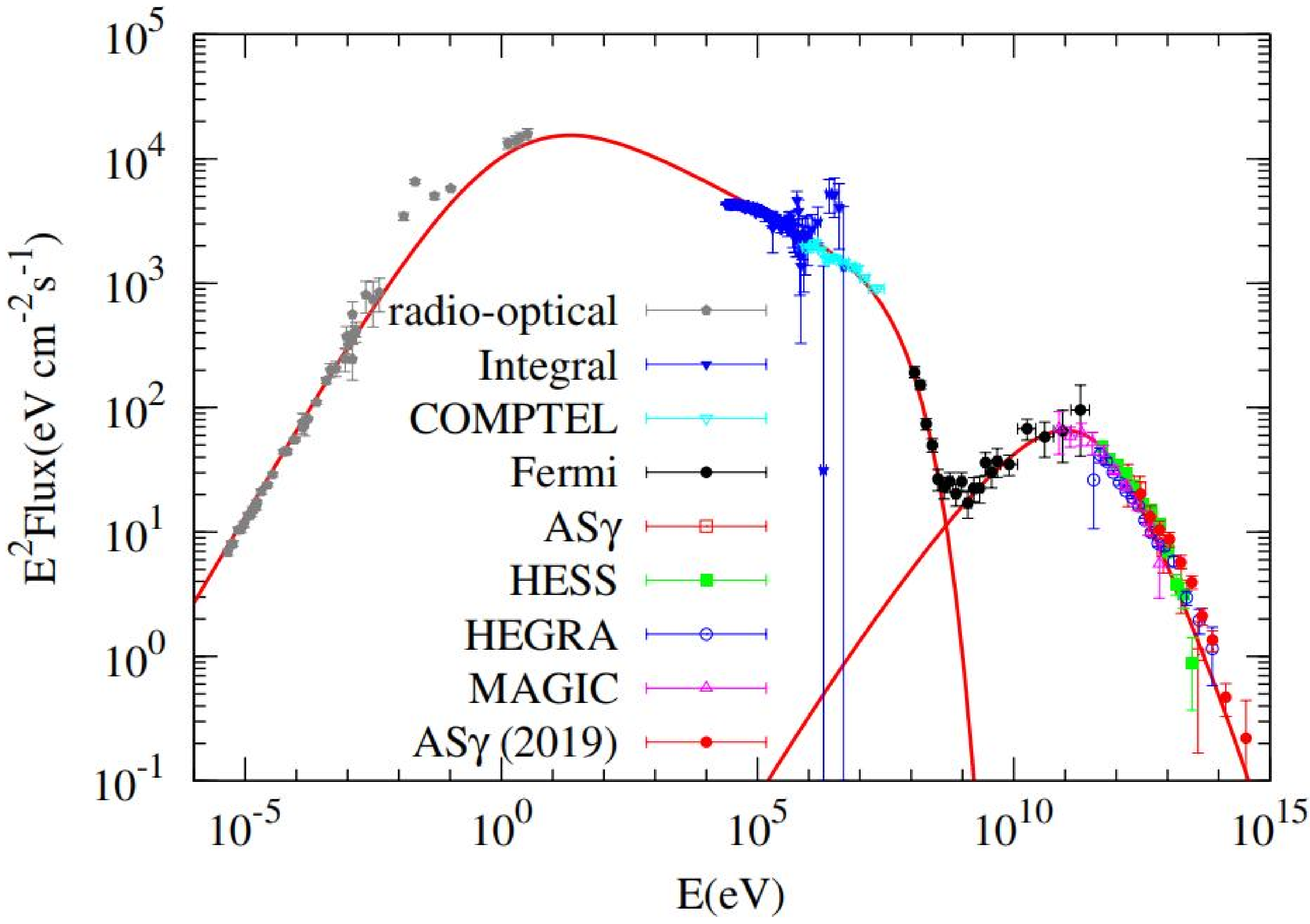


High-energy X-ray (HEFT)

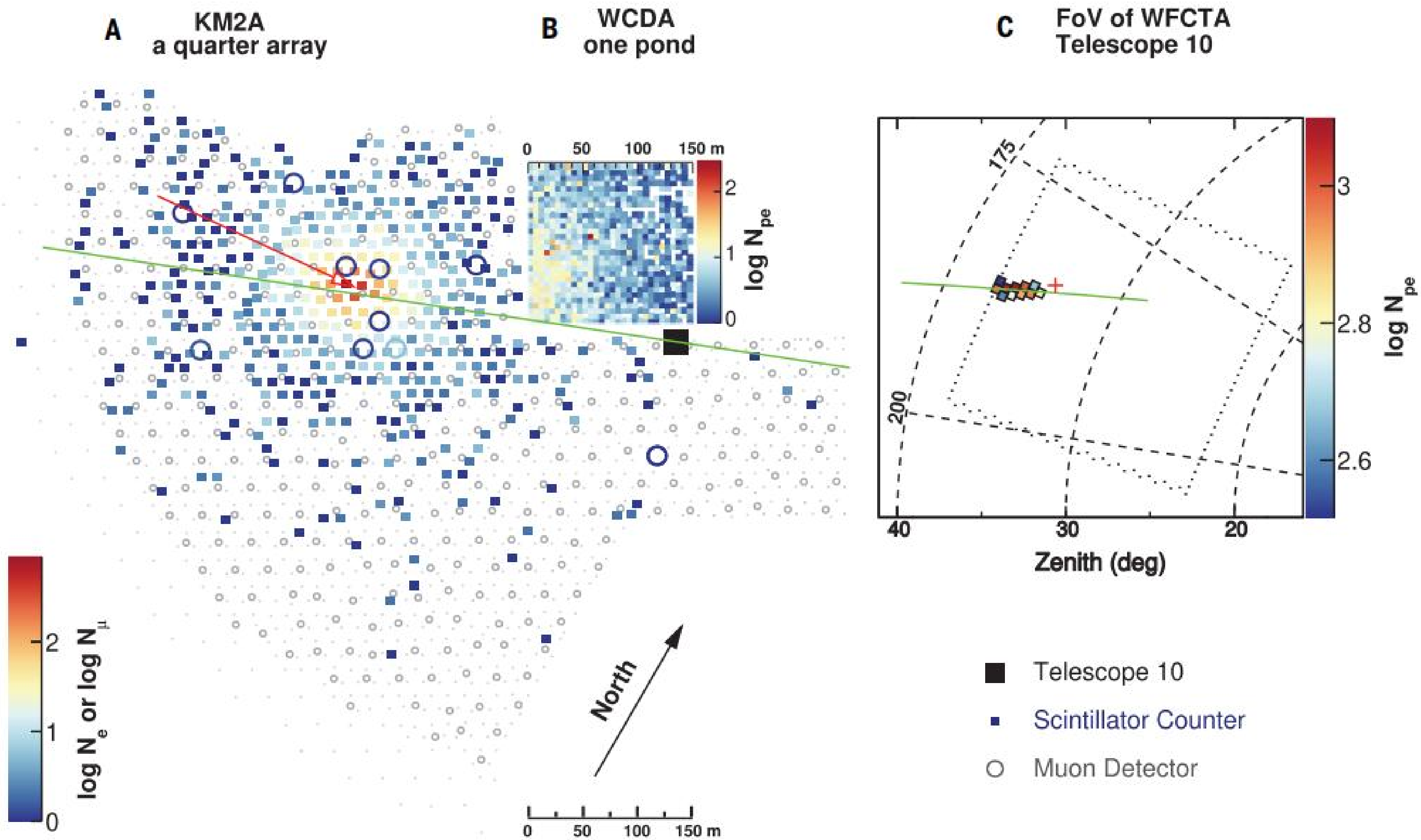


E>100 TeV (ASγ)

Crab nebula: Electron PeVatron



Crab nebula: Electron PeVatron

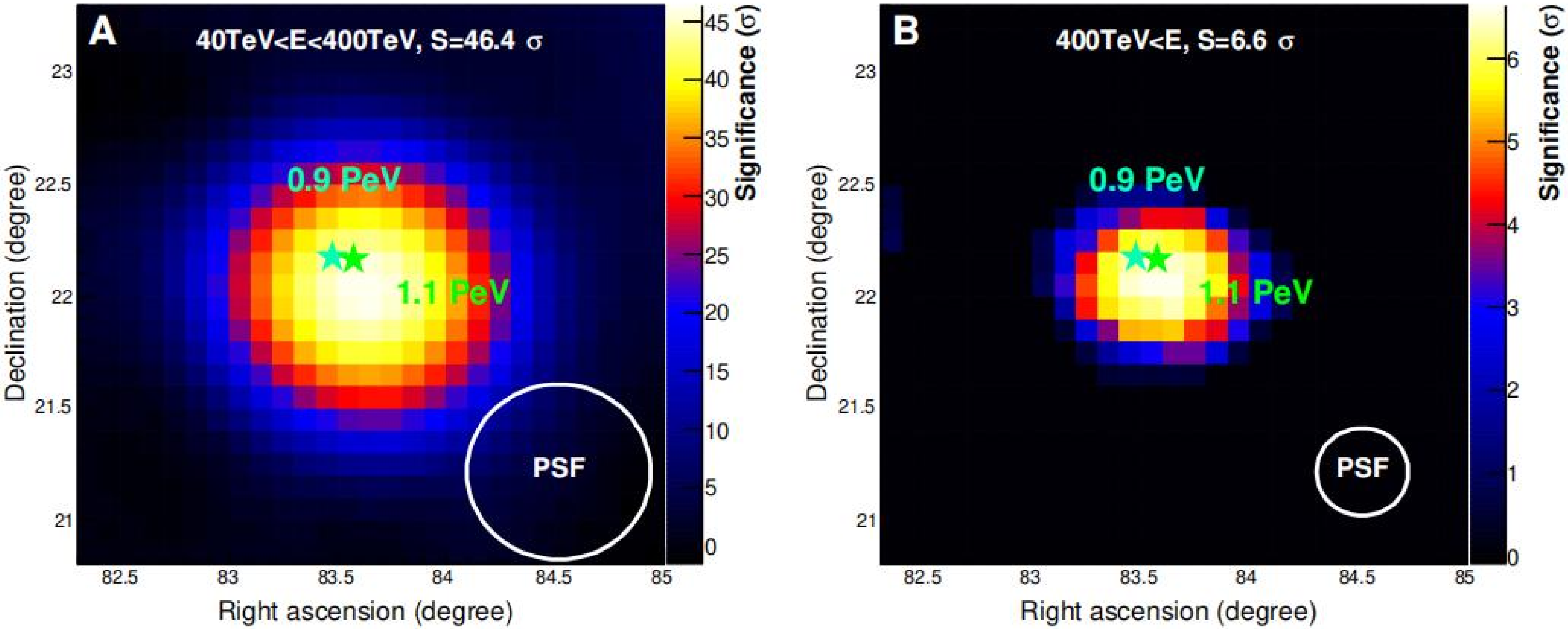


KM2A: 0.88+/-0.11 PeV

WFCTA: $0.92^{+0.28}_{-0.20}$ PeV

Science, 373, 425 (2021)

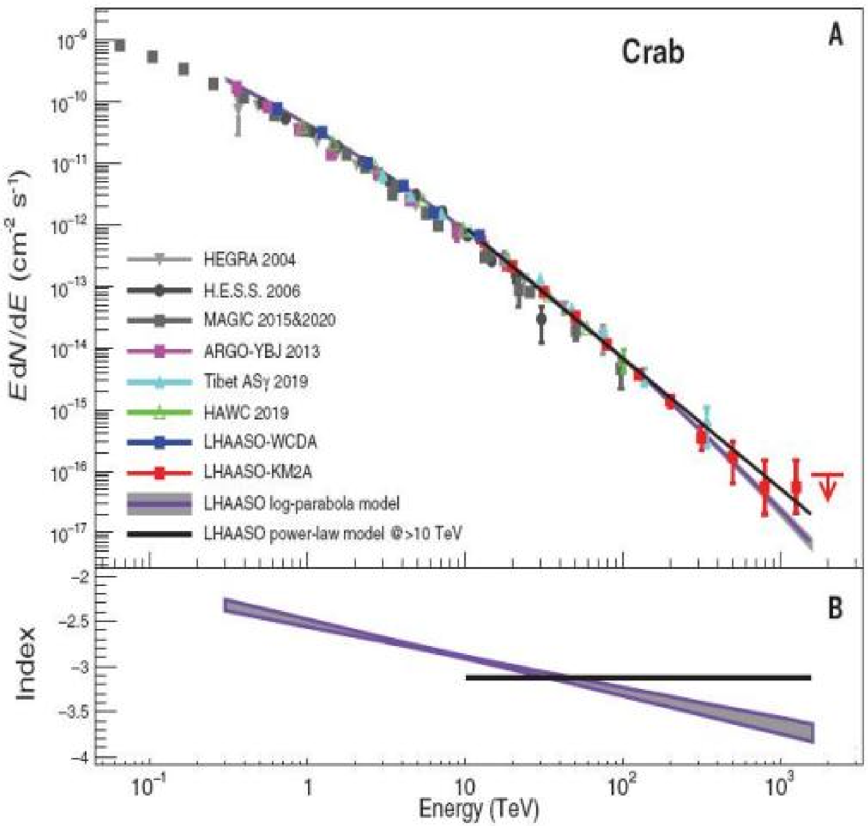
Crab nebula: Electron PeVatron

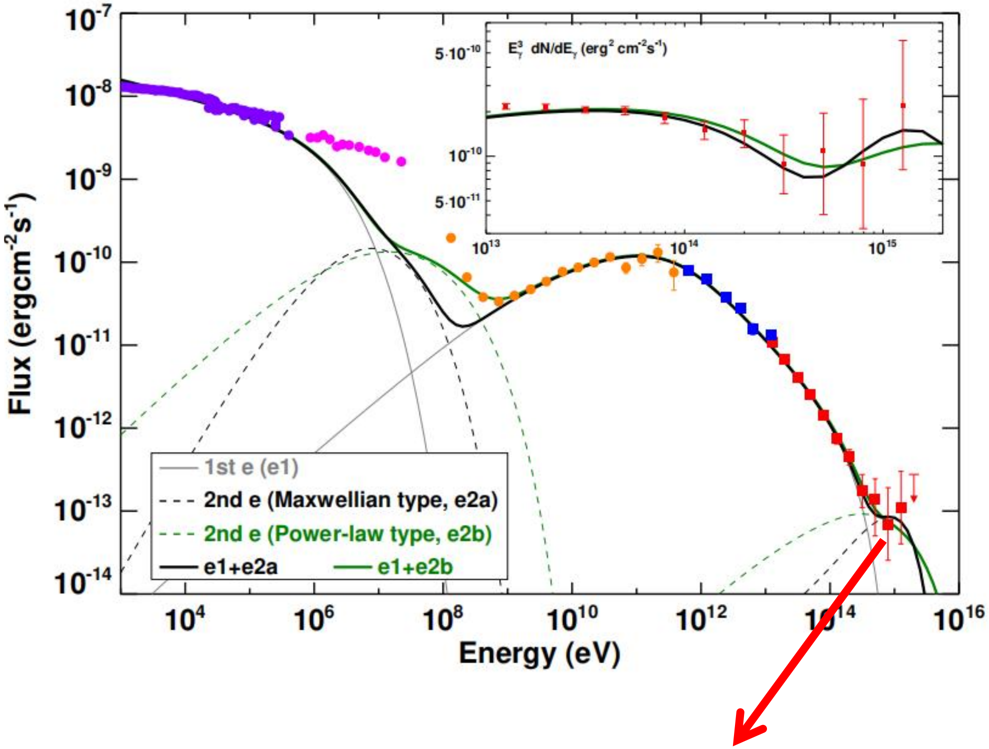


E (PeV)	δE (PeV)	N_e	N_μ	θ (°)	D_{edge} (m)	ψ (°)	P (%)	Arrival time
1.12	0.09	5094	14	13.0	89	0.15	0.03	2021-01-04 16:45:06
0.88	0.11	4996	15	33.9	139	0.21	0.1	2020-01-11 17:59:18
0.57	0.13	2408	9	40.8	125	0.08	0.7	2020-05-22 03:54:56
0.46	0.05	2432	6	21.7	52	0.11	0.3	2020-11-05 21:23:28
0.40	0.04	1859	3	23.1	65	0.10	0.2	2020-04-30 09:57:54

Science, 373, 425 (2021)

Crab nebula: Electron PeVatron

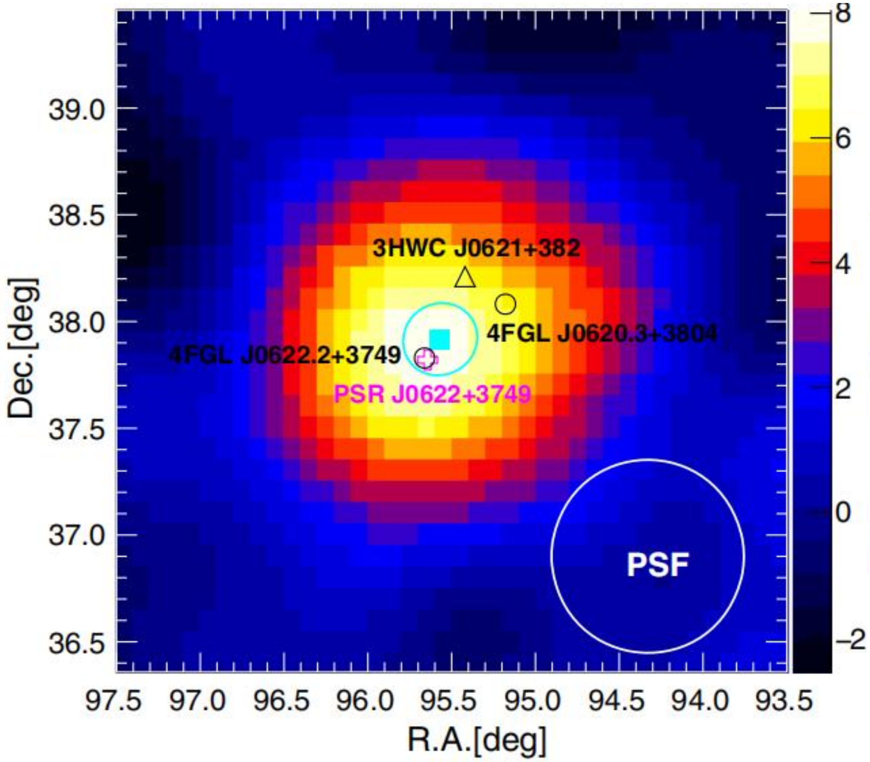




Possible new feature?

Science, 373, 425 (2021)

J0621+3755: an extended pulsar halo



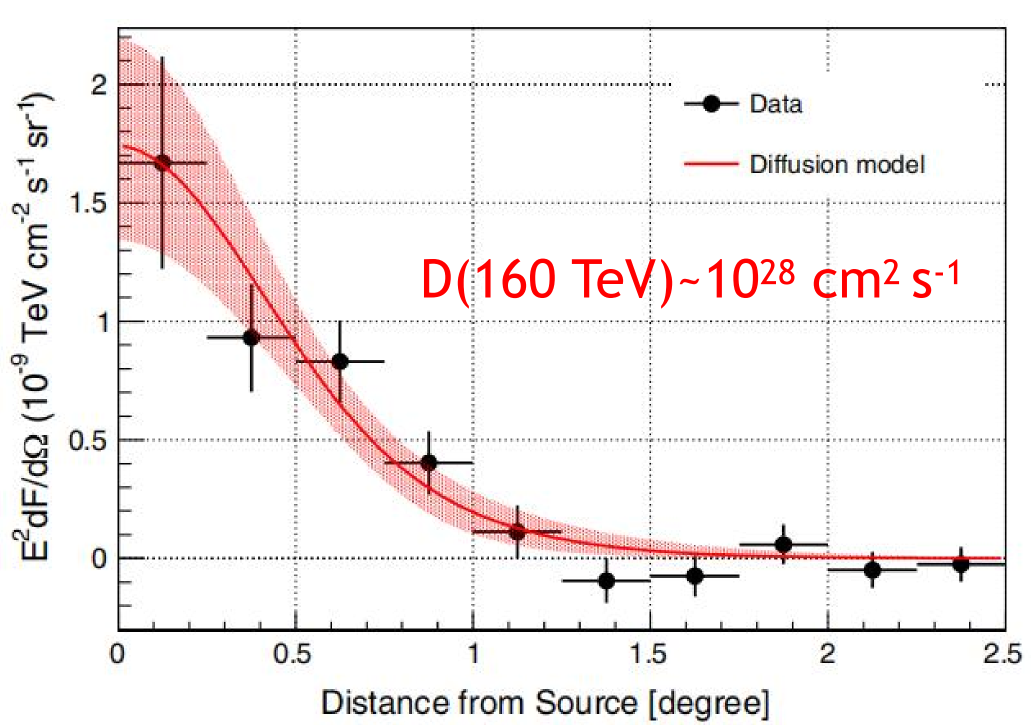


TABLE II. Comparison of the properties of pulsars J0622 + 3749, Geminga, and Monogem.

Name	P (s)	$\dot{P}$ (10^{-14} s s^{-1})	L_{sd} (10^{34} erg s^{-1})	τ (kyr)	d (kpc)	Ref.
J0622 + 3749	0.333	2.542	2.7	207.8	1.60	[25]
Geminga	0.237	1.098	3.3	342.0	0.25	[59]
Monogem	0.385	5.499	3.8	110.0	0.29	[59]

PRL, 126, 241103 (2021)

J0621+3755: an extended pulsar halo

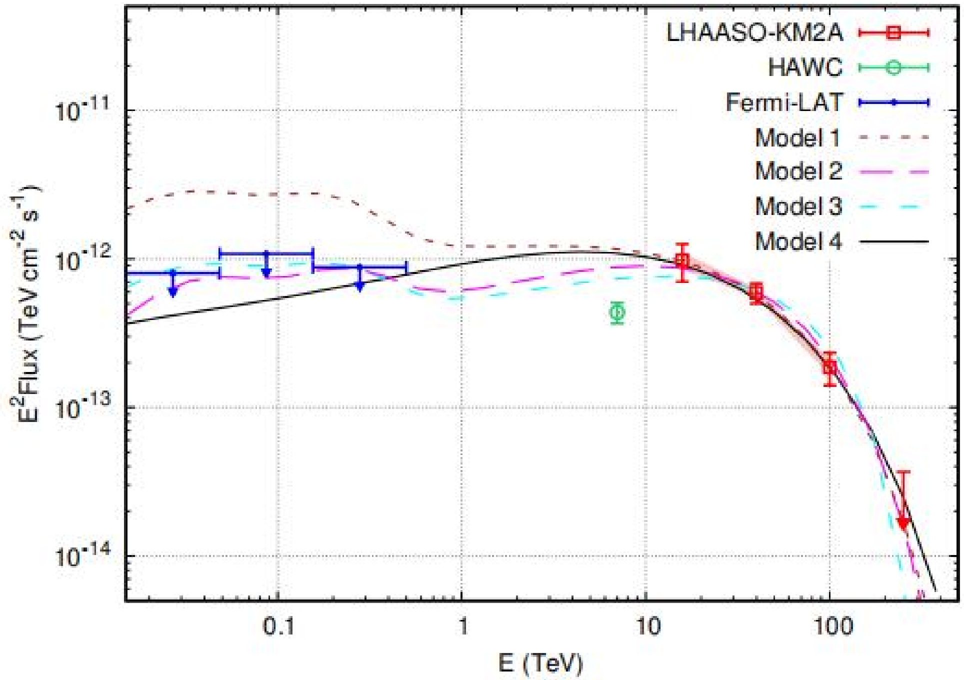


TABLE S1. Model parameters to fit the wide-band SED.

Model	α	β	E_c (TeV)	η
1	1.0	1.0	100	0.30
2	0.0	1.0	70	0.20
3	1.0	5.0	300	0.20
4[a]	1.5	1.0	150	0.40

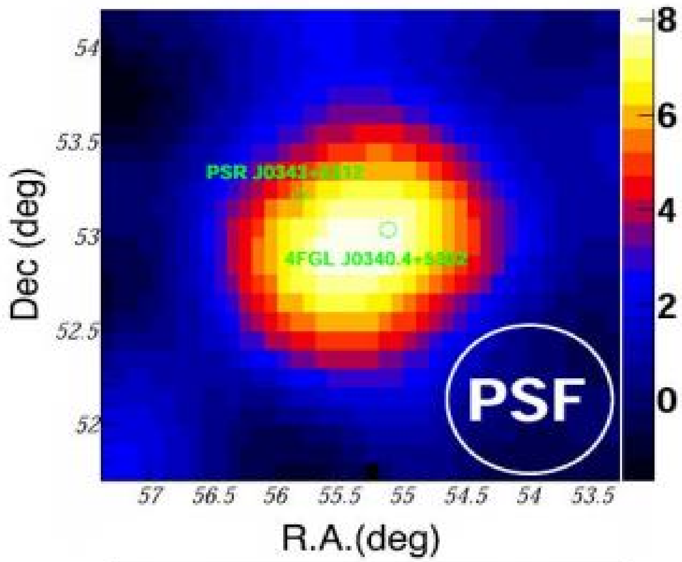
[a] This is a two-zone diffusion model with a slow-diffusion zone size of 50 pc. See the text for details.

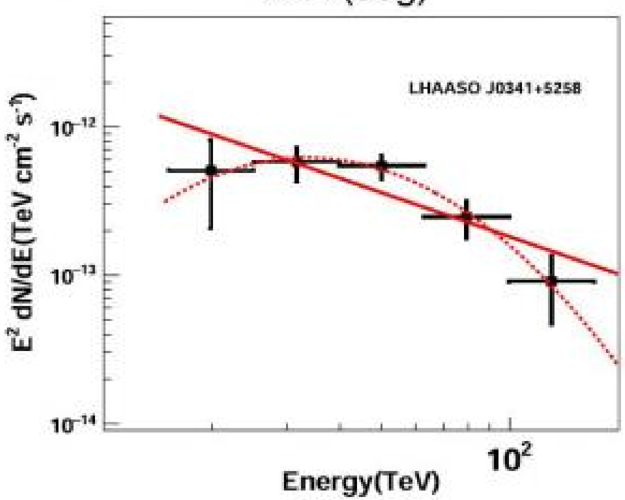
Multi-wavelength spectrum is consistent with a two-zone diffusion model

PRL, 126, 241103 (2021)

New ultra-high-energy sources

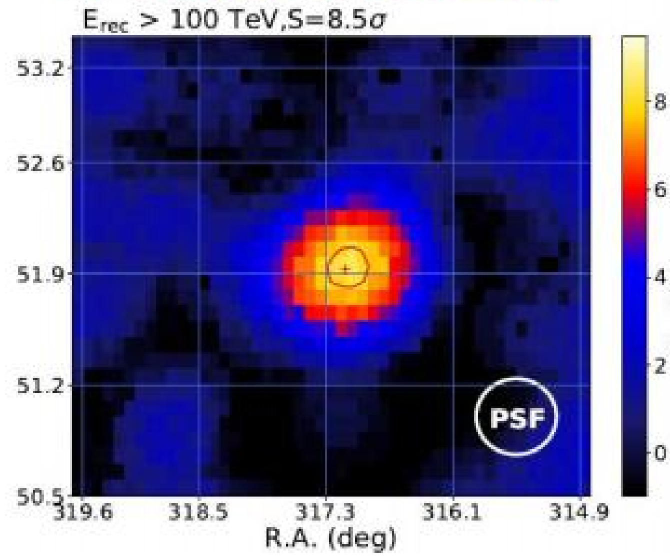
LHAASO J0341+5258

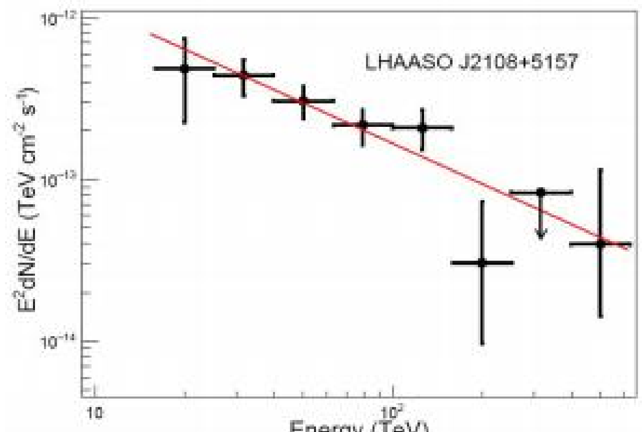




ApJL, 917, L4 (2021)

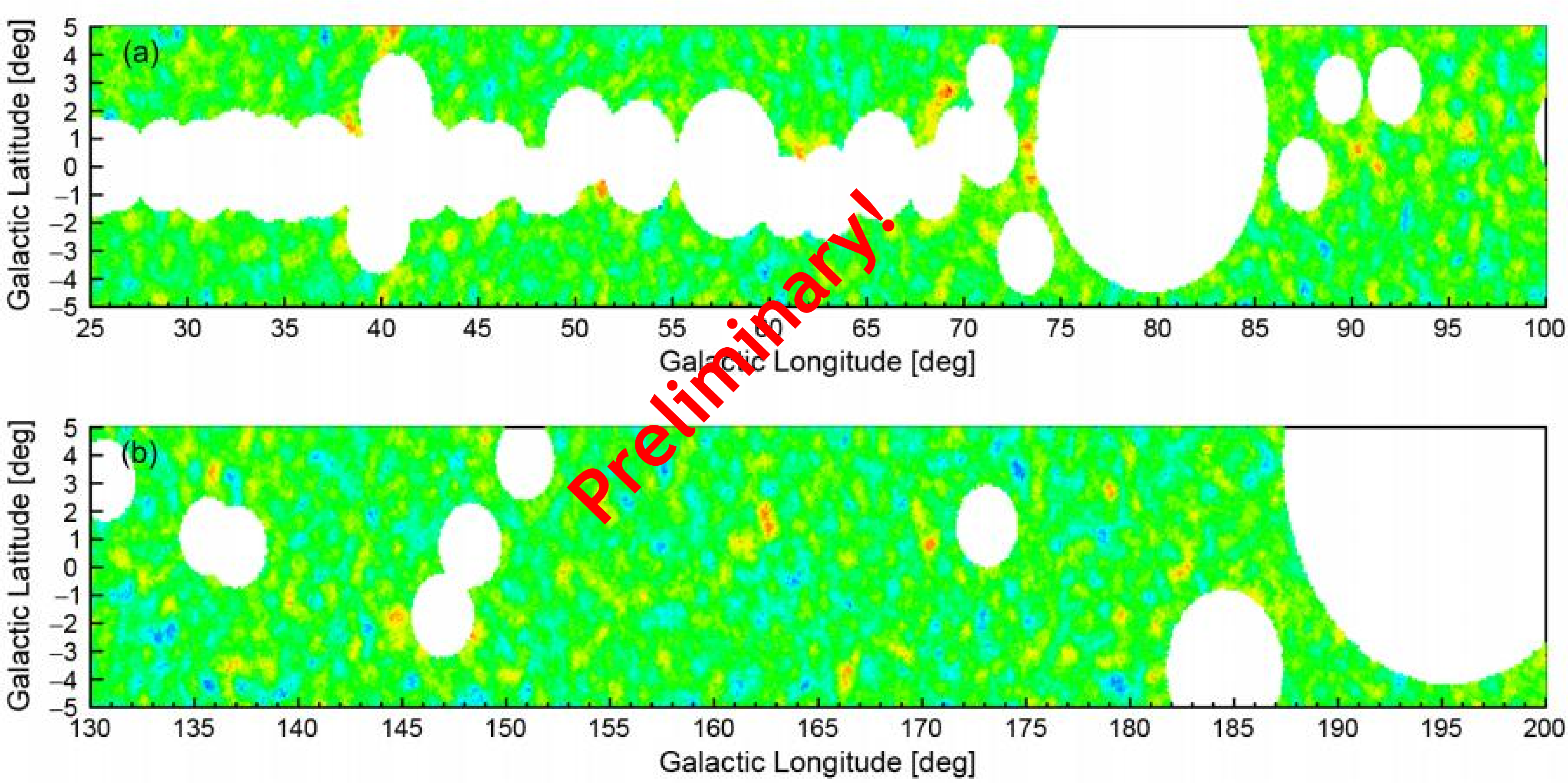
LHAASO J2108+5157



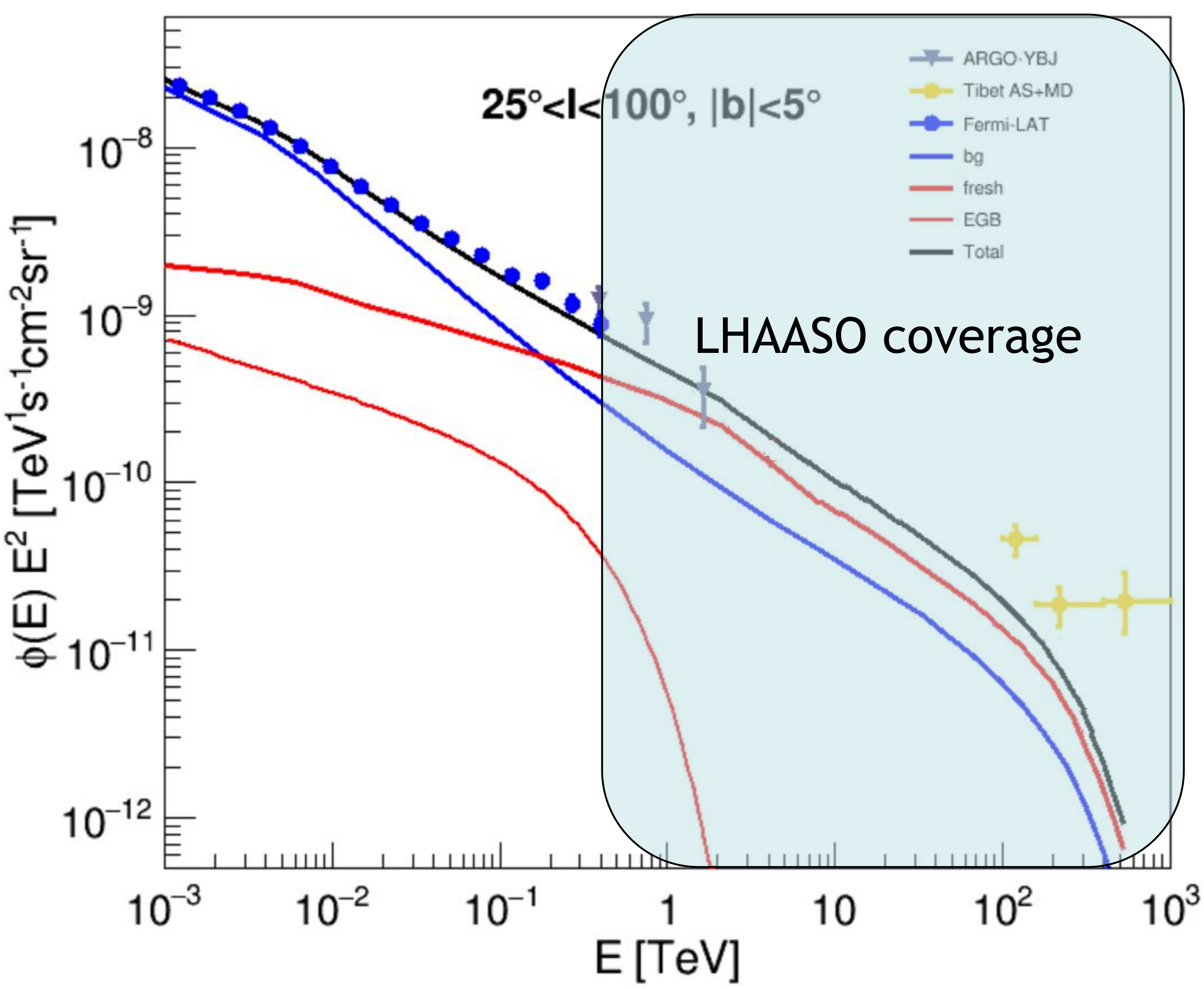


ApJL, 919, L22 (2021)

Diffuse gamma rays from Galactic plane



Diffuse gamma rays from Galactic plane



Summary

- LHAASO is a km^2 scale cosmic ray and gamma-ray observatory which is dedicated to surveying the ultra-high-energy sky with unprecedented sensitivity
- LHAASO starts its full operation since July 2021
- Its first data with partial array opens successfully the PeV window of the gamma-ray Universe, reveals a dozen of PeVatrons in the Milky Way
- LHAASO is expected to discover a large amount of VHE sources and to precisely measure the VHE diffuse emission in a wide energy band, uncovering the mystery of the Galactic cosmic ray acceleration and propagation

Thank You!