Opening the PeV window of the cosmos with LHAASO

Qiang Yuan

on behalf of the LHAASO collaboration

Purple Mountain Observatory

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The LHAASO collaboration

Zhen Cao[1,2,3], F. Aharonian[4,5], Q. An[6,7], Axikegu[8], L. X. Bai[9], Y. X. Bai[1,3], Y. W. Bao[10], D. Bastieri[11], X. J. Bi[1,2,3], Y. J. Bi[1,3], H. Cai[12], J. T. Cai[11], Zhe Cao[6,7], J. Chang[13], J. F. Chang[1,3,6], B. M. Chen[14], E. S. Chen[1,2,3], J. Chen[9], Liang Chen[1,2,3], Liang Chen[15], Long Chen[8], M. J. Chen[1,3], M. L. Chen[1,3,6], Q. H. Chen[8], S. H. Chen[1,2,3], S. Z. Chen[1,3], T. L. Chen[16], X. L. Chen[1,2,3], Y. Chen[10], N. Cheng[1,3], Y. D. Cheng[1,3], S. W. Cui[14], X. H. Cui[17], Y. D. Cui[18], B. D'Ettorre Piazzoli[19], B. Z. Dai[20], H. L. Dai[1,3,6], Z. G. Dai[7], Danzengluobu[16], D. della Volpe[21], X. J. Dong[1,3], K. K. Duan[13], J. H. Fan[11], Y. Z. Fan[13], Z. X. Fan[1,3], J. Fang[20], K. Fang[1,3], C. F. Feng[22], L. Feng[13], S. H. Feng[1,3], Y. L. Feng[13], B. Gao[1,3], C. D. Gao[22], L. Q. Gao[1,2,3], Q. Gao[16], W. Gao[22], M. M. Ge[20], L. S. Geng[1,3], G. H. Gong[23], Q. B. Gou[1,3], M. H. Gu[1,3,6], F. L. Guo[15], J. G. Guo[1,2,3], X. L. Guo[8], Y. Q. Guo[1,3], Y. Y. Guo[1,2,3,13], Y. A. Han[24], H. H. He[1,2,3], H. N. He[13], J. C. He[1,2,3], S. L. He[11], X. B. He[18], Y. He[8], M. Heller[21], Y. K. Hor[18], C. Hou[1,3], H. B. Hu[1,2,3], S. Hu[9], S. C. Hu[1,2,3], X. J. Hu[23], D. H. Huang[8], Q. L. Huang[1,3], W. H. Huang[22], X. T. Huang[22], X. Y. Huang[13], Z. C. Huang[8], F. Ji[1,3], X. L. Ji[1,3,6], H. Y. Jia[8], K. Jiang[6,7], Z. J. Jiang[20], C. Jin[1,2,3], T. Ke[1,3], D. Kuleshov[25], K. Levochkin[25], B. B. Li[14], Cheng Li[6,7], Cong Li[1,3], F. Li[1,3,6], H. B. Li[1,3], H. C. Li[1,3], H. Y. Li[7,13], J. Li[1,3,6], K. Li[1,3], W. L. Li[22], X. R. Li[1,3], Xin Li[6,7], Xin Li[8], Y. Li[9], Y. Z. Li[1,2,3], Zhe Li[1,3], Zhuo Li[26], E. W. Liang[27], Y. F. Liang[27], S. J. Lin[18], B. Liu[7], C. Liu[1,3], D. Liu[22], H. Liu[8], H. D. Liu[24], J. Liu[1,3], J. L. Liu[28], J. S. Liu[18], J. Y. Liu[1,3], M. Y. Liu[16], R. Y. Liu[10], S. M. Liu[8], W. Liu[1,3], Y. Liu[11], Y. N. Liu[23], Z. X. Liu[9], W. J. Long[8], R. Lu[20], H. K. Lv[1,3], B. Q. Ma[26], L. L. Ma[1,3], X. H. Ma[1,3], J. R. Mao[29], A. Masood[8], Z. Min[1,3], W. Mitthumsiri[30], T. Montaruli[21], Y. C. Nan[22], B. Y. Pang[8], P. Pattarakijwanich[30], Z. Y. Pei[11], M. Y. Qi[1,3], Y. Q. Qi[14], B. Q. Qiao[1,3], J. J. Qin[7], D. Ruffolo[30], V. Rulev[25], A. Sáiz[30], L. Shao[14], O. Shchegolev[25,31], X. D. Sheng[1,3], J. Y. Shi[1,3], H. C. Song[26], Yu. V. Stenkin[25,31], V. Stepanov[25], Y. Su[32], Q. N. Sun[8], X. N. Sun[27], Z. B. Sun[33], P. H. T. Tam[18], Z. B. Tang[6,7], W. W. Tian[2,17], B. D. Wang[1,3], C. Wang[33], H. Wang[8], H. G. Wang[11], J. C. Wang[29], J. S. Wang[28], L. P. Wang[22], L. Y. Wang[1,3], R. N. Wang[8], W. Wang[18], W. Wang[12], X. G. Wang[27], X. J. Wang[1,3], X. Y. Wang[10], Y. Wang[8], Y. D. Wang[1,3], Y. J. Wang[1,3], Y. P. Wang[1,2,3], Z. H. Wang[9], Z. X. Wang[20], Zhen Wang[28], Zheng Wang[1,3,6], D. M. Wei[13], J. J. Wei[13], Y. J. Wei[1,2,3], T. Wen[20], C. Y. Wu[1,3], H. R. Wu[1,3], S. Wu[1,3], W. X. Wu[8], X. F. Wu[13], S. Q. Xi[1,3], J. Xia[7,13], J. J. Xia[8], G. M. Xiang[2,15], D. X. Xiao[16], G. Xiao[1,3], H. B. Xiao[11], G. G. Xin[12], Y. L. Xin[8], Y. Xing[15], D. L. Xu[28], R. X. Xu[26], L. Xue[22], D. H. Yan[29], J. Z. Yan[13], C. W. Yang[9], F. F. Yang[1,3,6], J. Y. Yang[18], L. L. Yang[18], M. J. Yang[1,3], R. Z. Yang[7], S. B. Yang[20], Y. H. Yao[9], Z. G. Yao[1,3], Y. M. Ye[23], L. Q. Yin[1,3], N. Yin[22], X. H. You[1,3], Z. Y. You[1,2,3], Y. H. Yu[22], Q. Yuan[13], H. D. Zeng[13], T. X. Zeng[1,3,6], W. Zeng[20], Z. K. Zeng[1,2,3], M. Zha[1,3], X. X. Zhai[1,3], B. B. Zhang[10], H. M. Zhang[10], H. Y. Zhang[22], J. L. Zhang[17], J. W. Zhang[9], L. X. Zhang[11], Li Zhang[20], Lu Zhang[14], P. F. Zhang[20], P. P. Zhang[14], R. Zhang[7,13], S. R. Zhang[14], S. S. Zhang[1,3], X. Zhang[10], X. P. Zhang[1,3], Y. F. Zhang[8], Y. L. Zhang[1,3], Yi Zhang[1,13], Yong Zhang[1,3], B. Zhao[8], J. Zhao[1,3], L. Zhao[6,7], L. Z. Zhao[14], S. P. Zhao[13,22], F. Zheng[33], Y. Zheng[8], B. Zhou[1,3], H. Zhou[28], J. N. Zhou[15], P. Zhou[10], R. Zhou[9], X. X. Zhou[8], C. G. Zhu[22], F. R. Zhu[8], H. Zhu[17], K. J. Zhu[1,2,3,6], and X. Zuo[1,3]

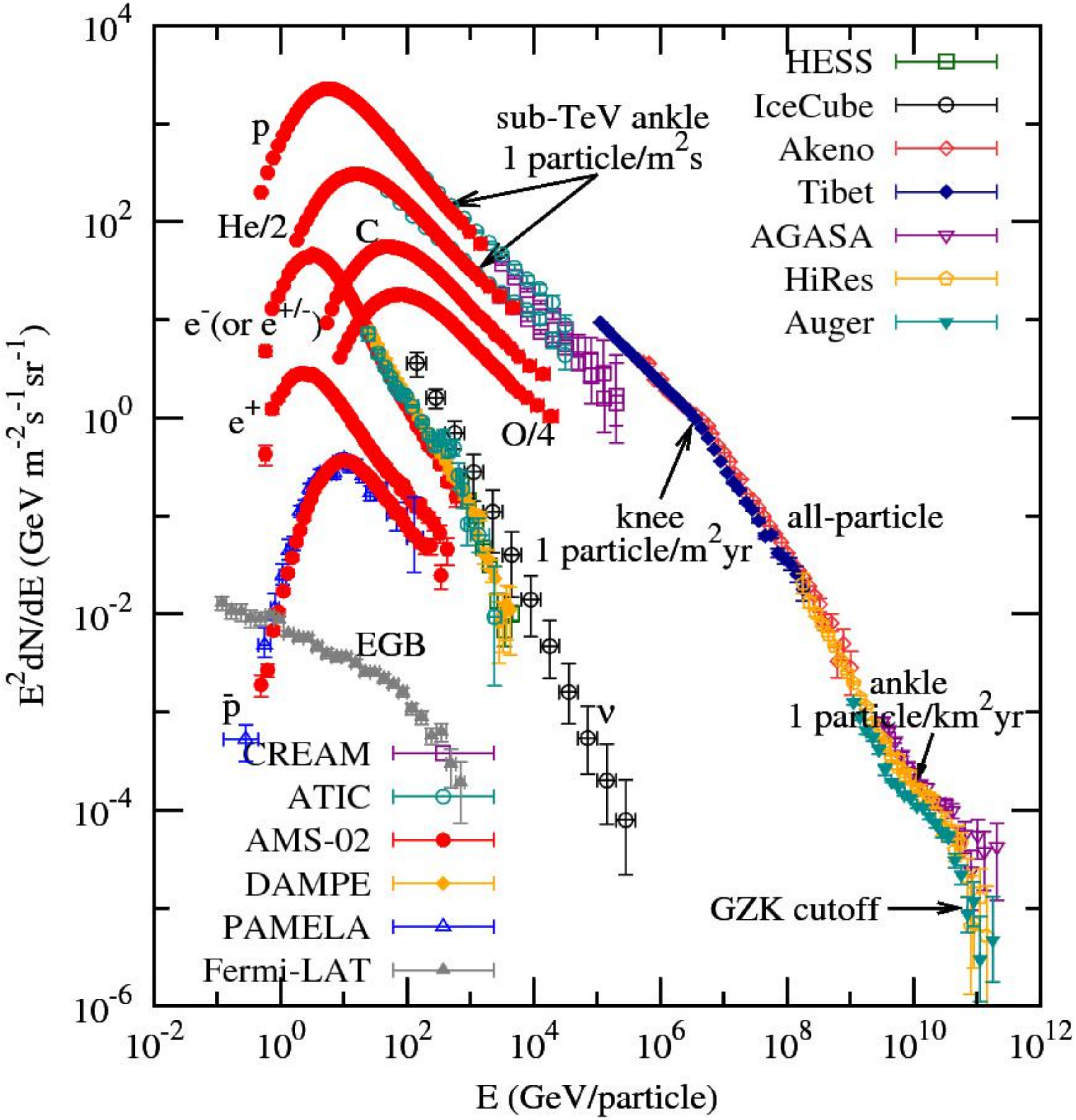
[1] Key Laboratory of Particle Astrophysics & Experimental Physics Division & Computing Center, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, People's Republic of China; licong@ihep.ac.cn, chensz@ihep.ac.cn, wusha@ihep.ac.cn
[2] University of Chinese Academy of Sciences, 100049 Beijing, People's Republic of China
[3] TIANFU Cosmic Ray Research Center, Chengdu, Sichuan, People's Republic of China
[4] Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, 2 Dublin, Ireland
[5] Max-Planck-Institut for Nuclear Physics, P.O. Box 103980, D-69029 Heidelberg, Germany
[6] State Key Laboratory of Particle Detection and Electronics, People's Republic of China
[7] University of Science and Technology of China, 230026 Hefei, Anhui, People's Republic of China; yangrz@ustc.edu.cn, lbing@ustc.edu.cn
[8] School of Physical Science and Technology & School of Information Science and Technology, Southwest Jiaotong University, 610031 Chengdu, Sichuan, People's Republic of China
[9] College of Physics, Sichuan University, 610065 Chengdu, Sichuan, People's Republic of China
[10] School of Astronomy and Space Science, Nanjing University, 210023 Nanjing, Jiangsu, People's Republic of China
[11] Center for Astrophysics, Guangzhou University, 510006 Guangzhou, Guangdong, People's Republic of China
[12] School of Physics and Technology, Wuhan University, 430072 Wuhan, Hubei, People's Republic of China
[13] Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, 210023 Nanjing, Jiangsu, People's Republic of China
[14] Hebei Normal University, 050024 Shijiazhuang, Hebei, People's Republic of China
[15] Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 200030 Shanghai, People's Republic of China
[16] Key Laboratory of Cosmic Rays (Tibet University), Ministry of Education, 850000 Lhasa, Tibet, People's Republic of China
[17] National Astronomical Observatories, Chinese Academy of Sciences, 100101 Beijing, People's Republic of China
[18] School of Physics and Astronomy & School of Physics (Guangzhou), Sun Yat-sen University, 519000 Zhuhai, Guangdong, People's Republic of China
[19] Dipartimento di Fisica dell'Università di Napoli "Federico II," Complesso Universitario di Monte Sant'Angelo, via Cinthia, I-80126 Napoli, Italy
[20] School of Physics and Astronomy, Yunnan University, 650091 Kunming, Yunnan, People's Republic of China
[21] D'epartement de Physique Nucl'eaire et Corpusculaire, Facult'e de Sciences, Universit'e de Genève, 24 Quai Ernest Ansermet, 1211 Geneva, Switzerland
[22] Institute of Frontier and Interdisciplinary Science, Shandong University, 266237 Qingdao, Shandong, People's Republic of China
[23] Department of Engineering Physics, Tsinghua University, 100084 Beijing, People's Republic of China
[24] School of Physics and Microelectronics, Zhengzhou University, 450001 Zhengzhou, Henan, People's Republic of China
[25] Institute for Nuclear Research of Russian Academy of Sciences, 117312 Moscow, Russia
[26] School of Physics, Peking University, 100871 Beijing, People's Republic of China
[27] School of Physical Science and Technology, Guangxi University, 530004 Nanning, Guangxi, People's Republic of China
[28] Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, People's Republic of China
[29] Yunnan Observatories, Chinese Academy of Sciences, 650216 Kunming, Yunnan, People's Republic of China
[30] Department of Physics, Faculty of Science, Mahidol University, 10400 Bangkok, Thailand
[31] Moscow Institute of Physics and Technology, 141700 Moscow, Russia
[32] Key Laboratory of Radio Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, 210023 Nanjing, Jiangsu, People's Republic of China
[33] National Space Science Center, Chinese Academy of Sciences, 100190 Beijing, People's Republic of China

274 members, 32 institutes from 5 countries

Outline

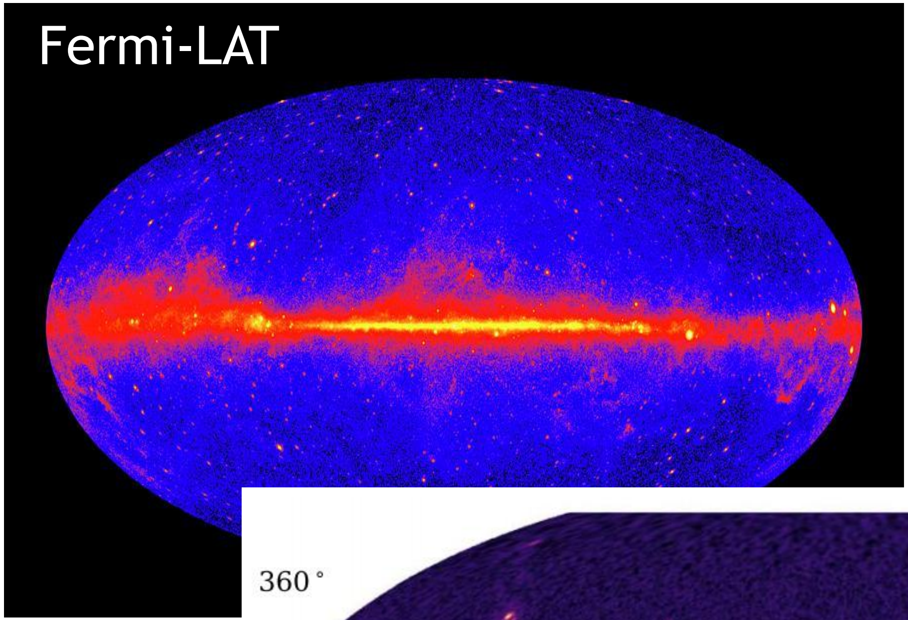
- LHAASO science
- LHAASO detector and performance
  - Kilometer Square Array (KM2A)
  - Water Cherenkov Detector Array (WCDA)
  - Wide FoV Cherenkov Telescope Array (WFCTA)
- LHAASO physical results
- Summary

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?

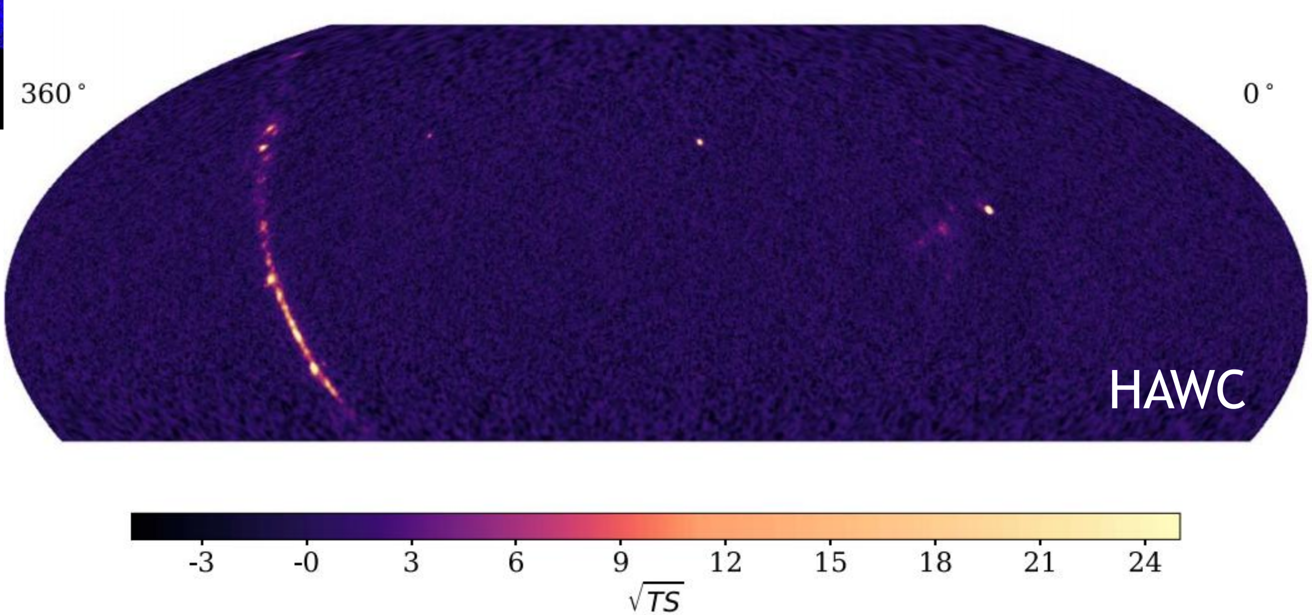
Probing CR acceleration and propagation with gamma rays



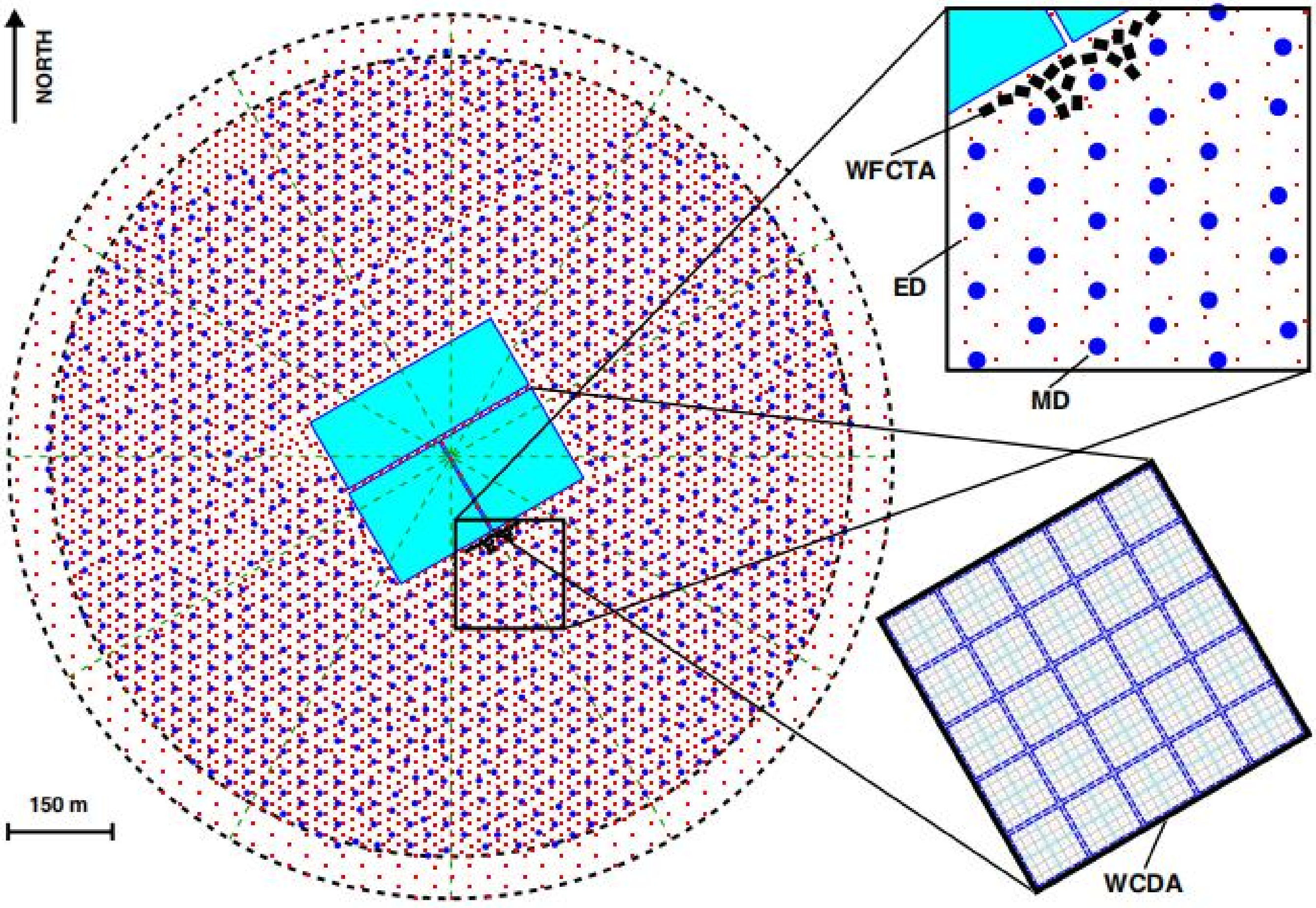
p,α + gas → π^0 → 2γ

$e^{+/-}$ + gas → γ (bremsstrahlung)

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

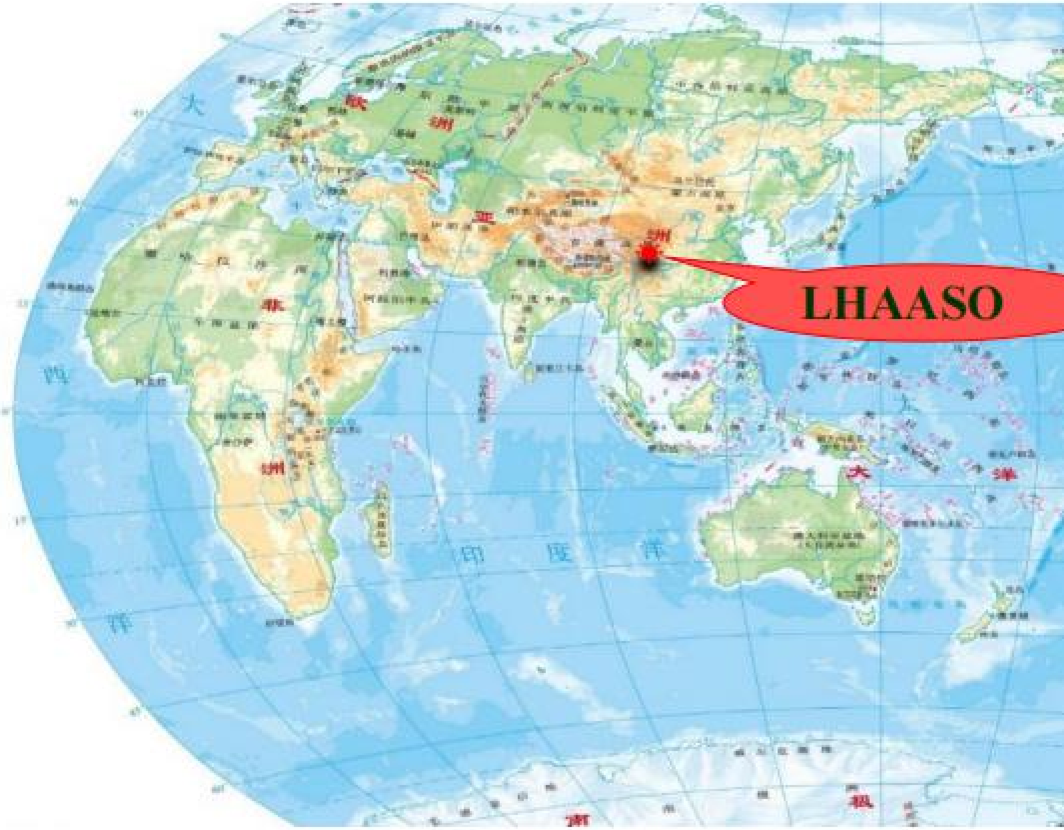


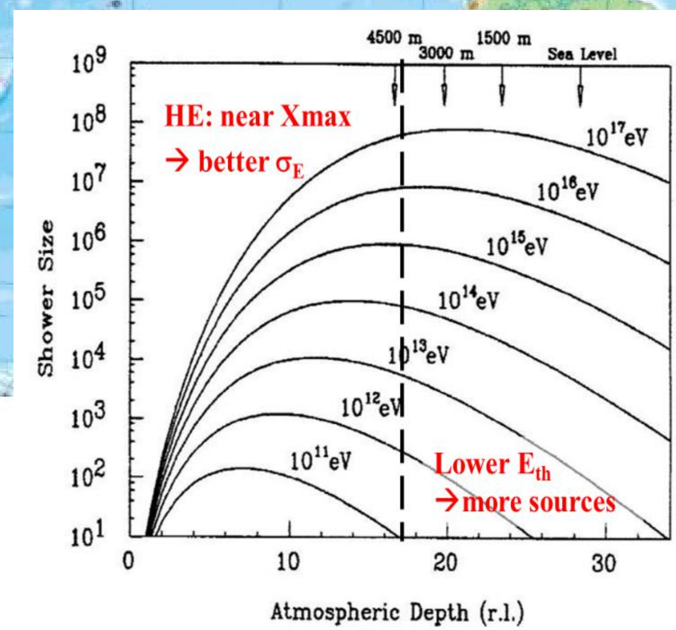
Large High Altitude Air Shower Observatory (LHAASO)



Detecting air showers produced by cosmic rays (and gamma rays) with ~km^2 area and hybrid techniques

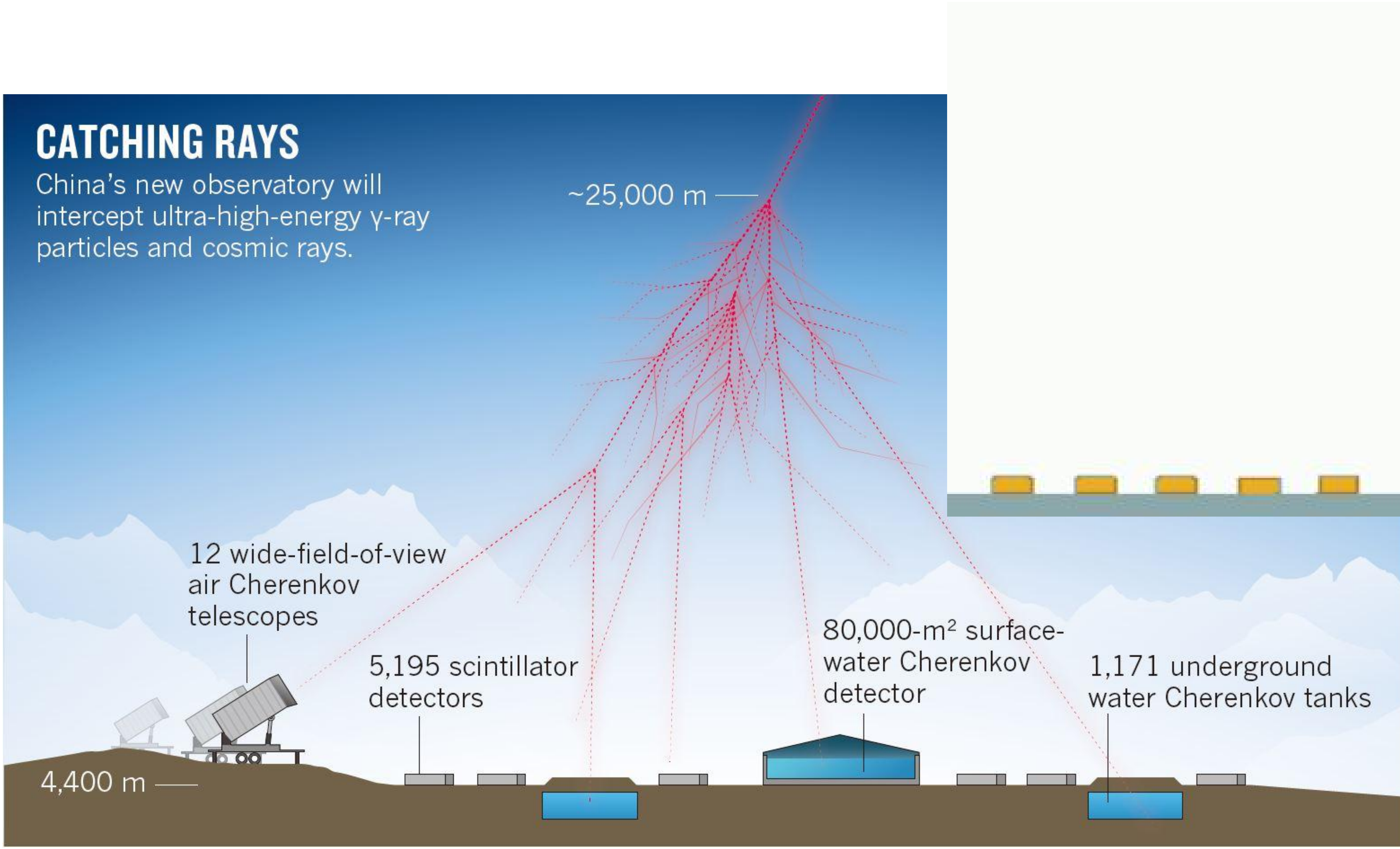
LHAASO site





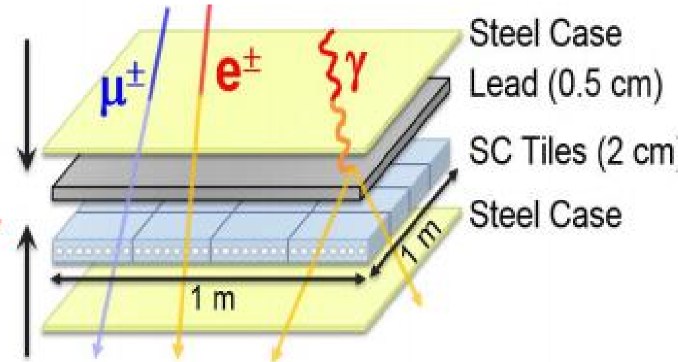
- Haizi mountain, Sichuan, China
- 4410 m above the sea level

Air shower detection

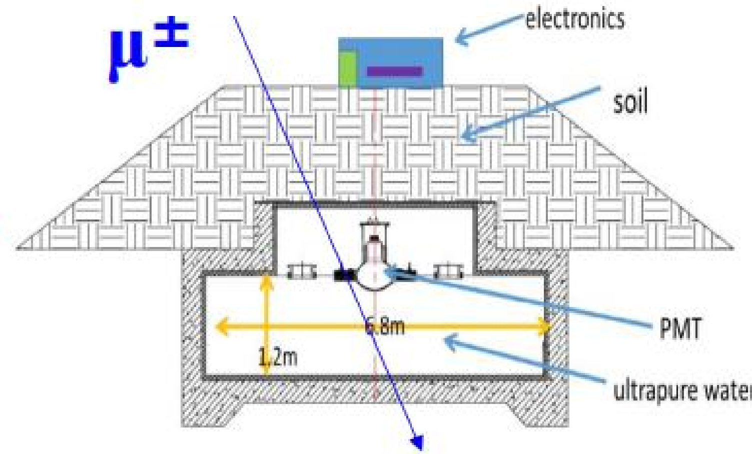


LHAASO detector - KM2A

5155 EDs

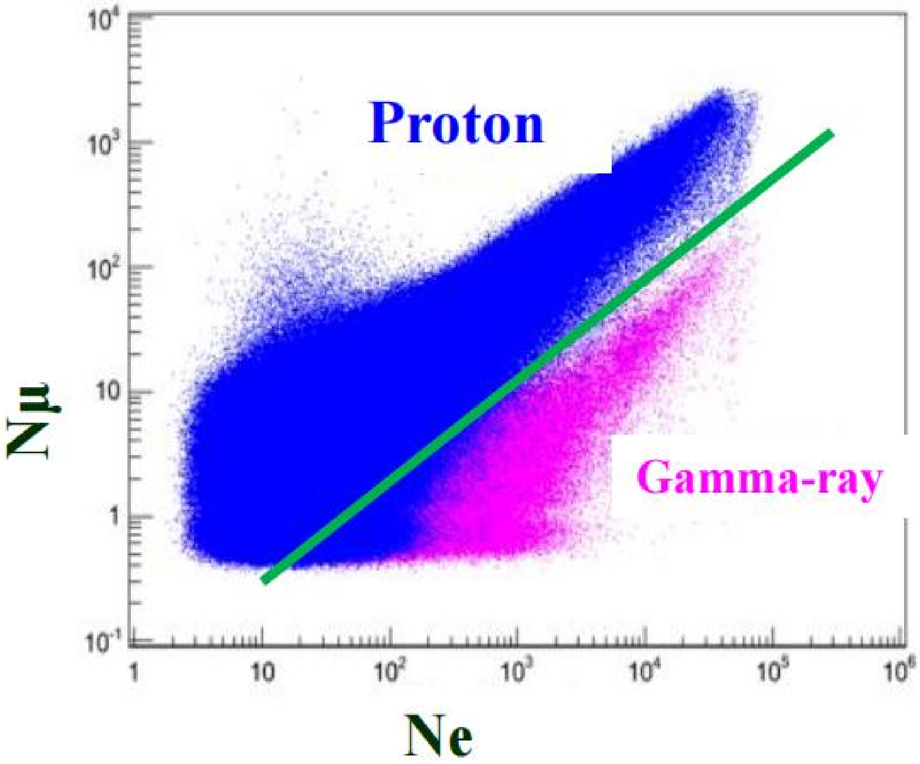


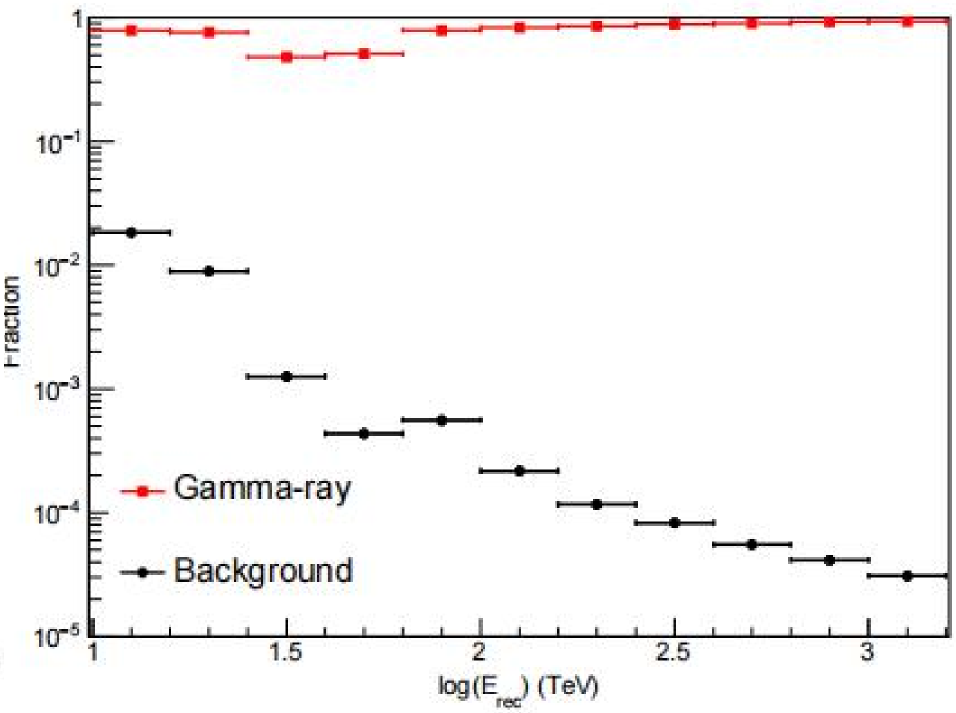
1188 MDs



- ➢ 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





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

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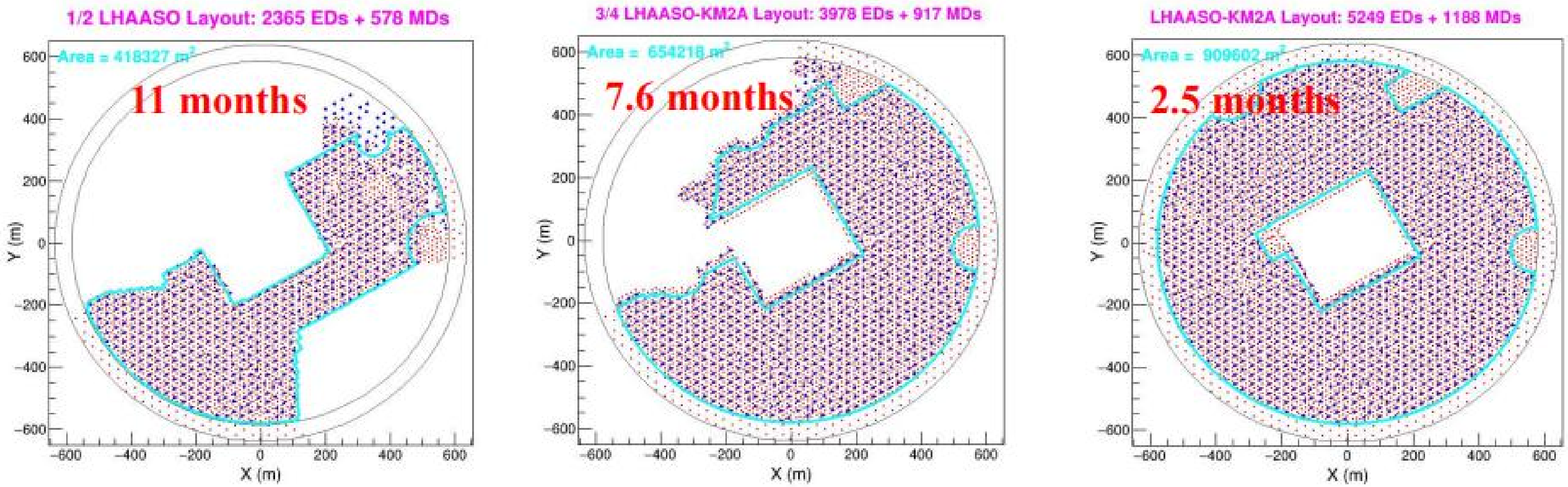
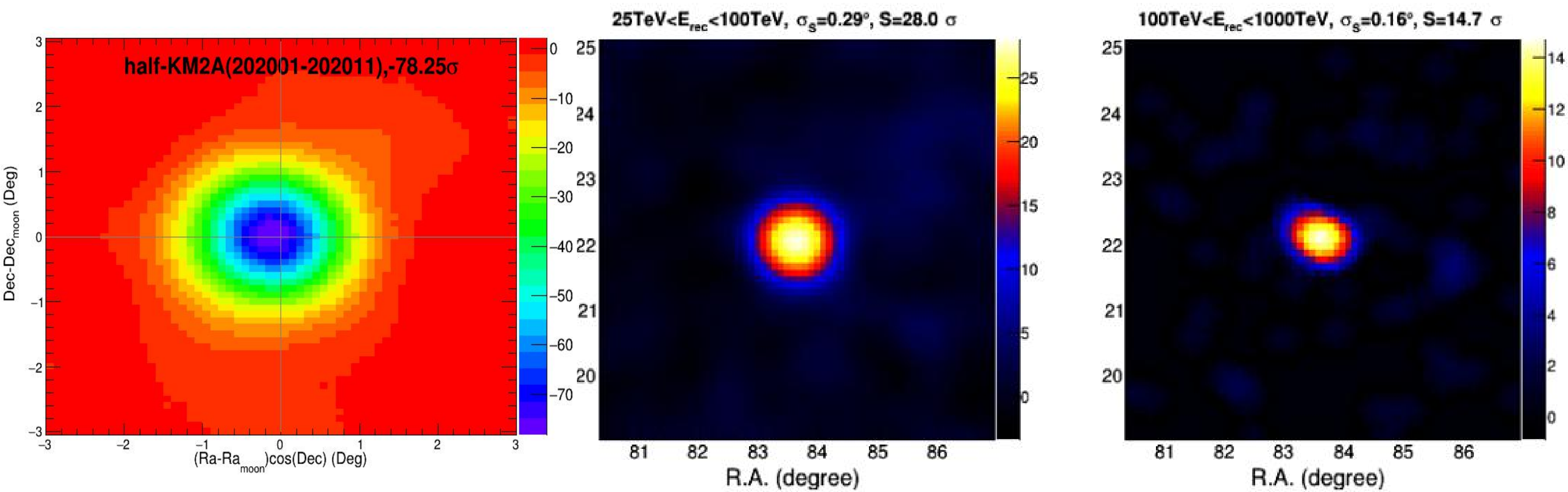
LHAASO detector - KM2A

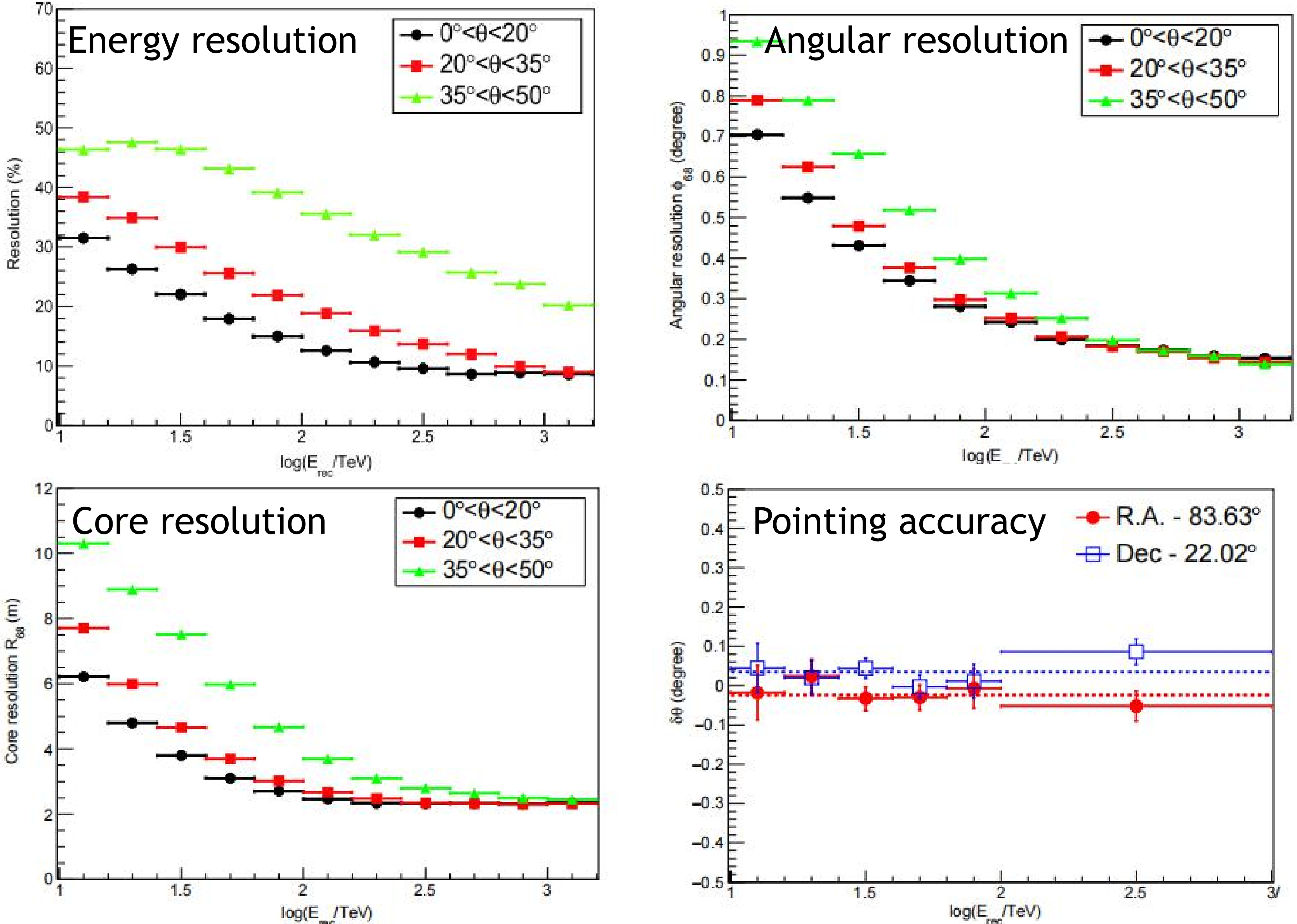


1/2: 20191217->20201130 3/4: 20201201->20210719 Full: 20210720->



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

LHAASO detector - KM2A



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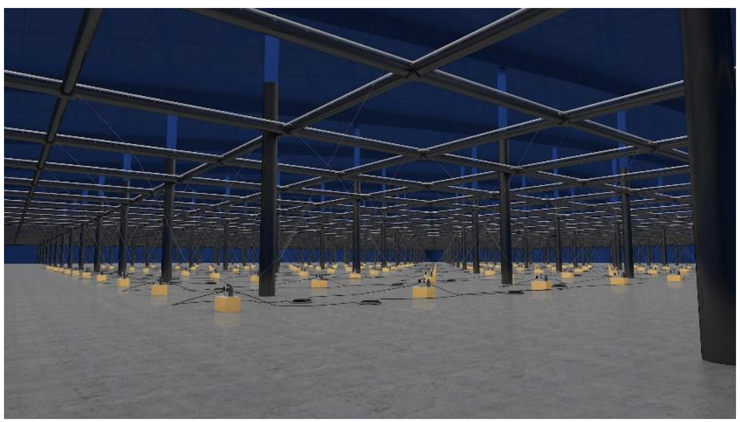
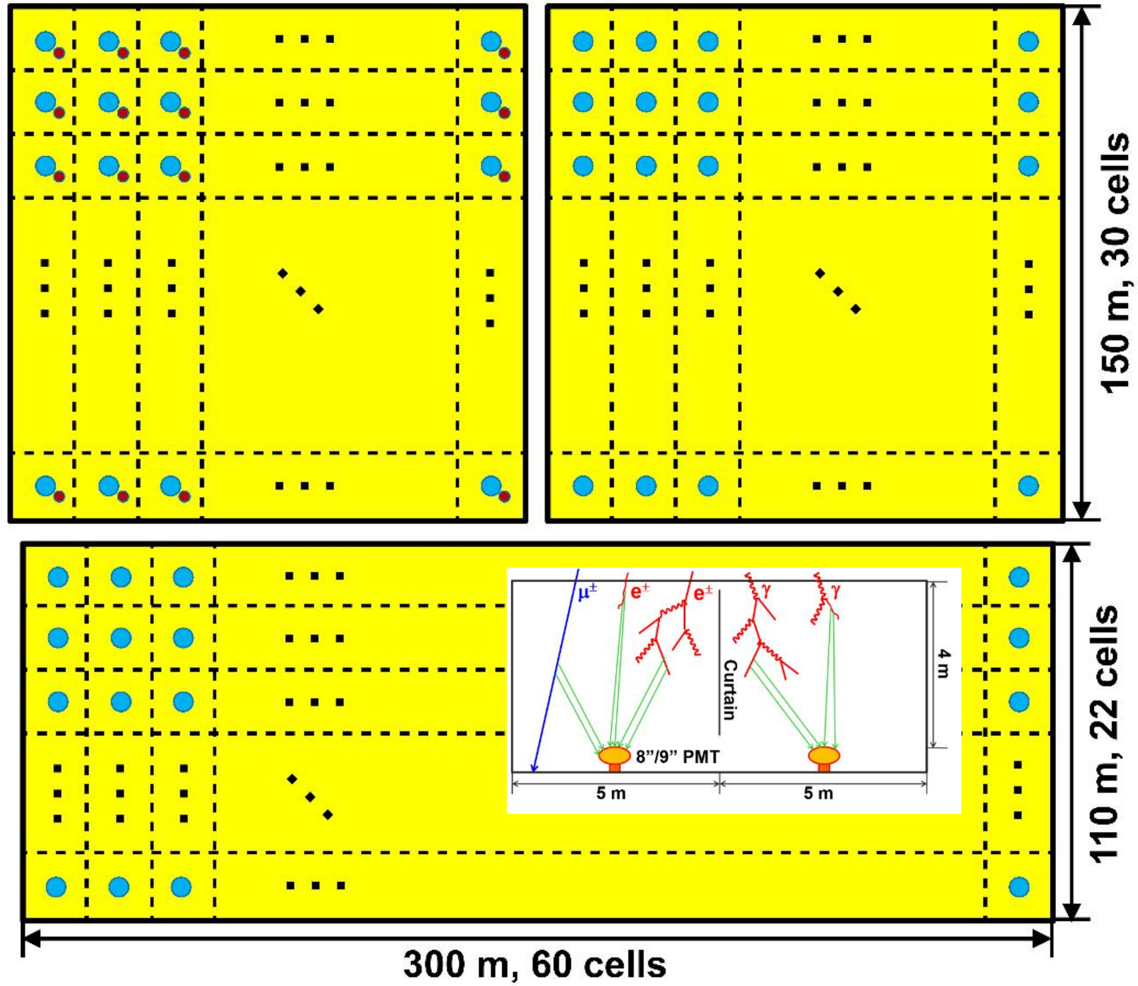
LHAASO detector - WCDA

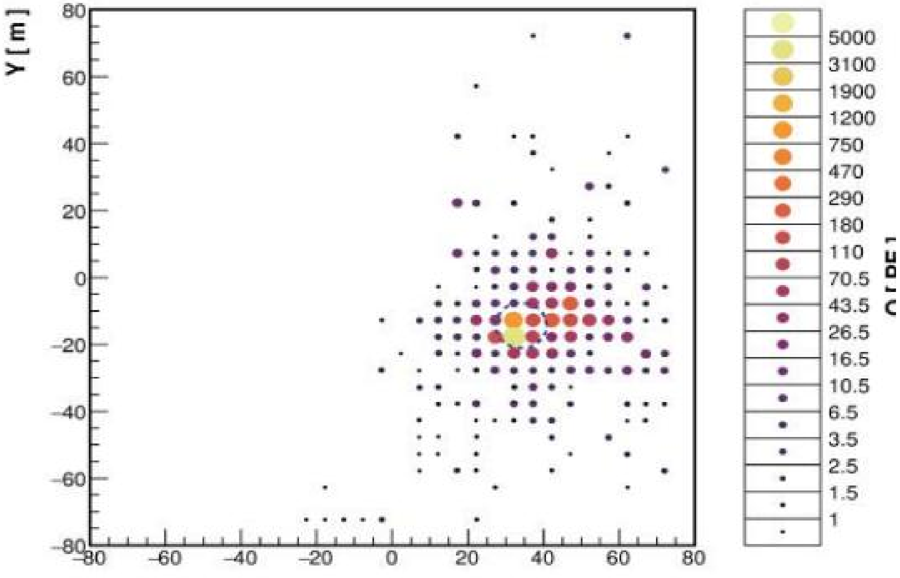




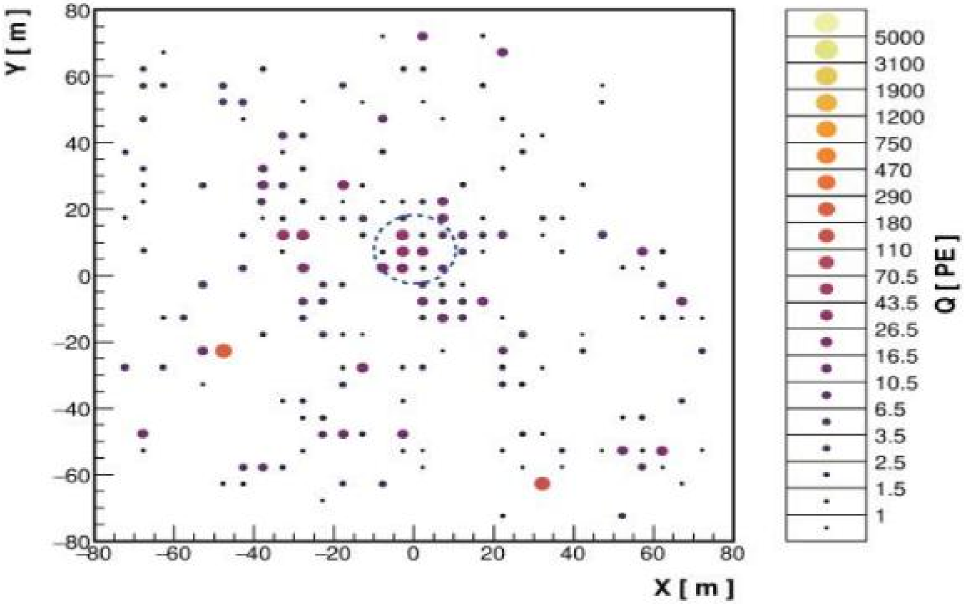
- Area: 78,000 m^2
- Covering energies from 0.3 TeV to ~PeV

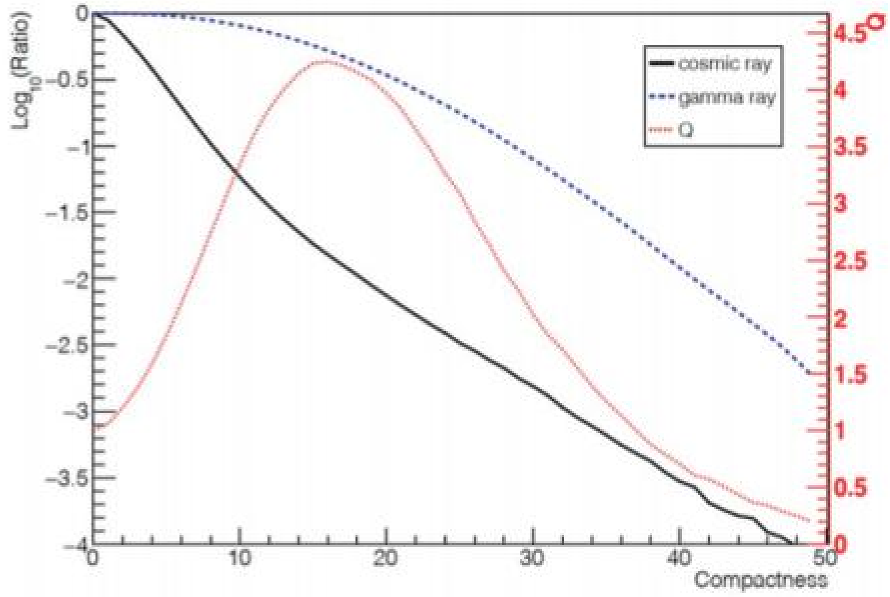
LHAASO detector - WCDA

Gamma-ray event



Cosmic ray event





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

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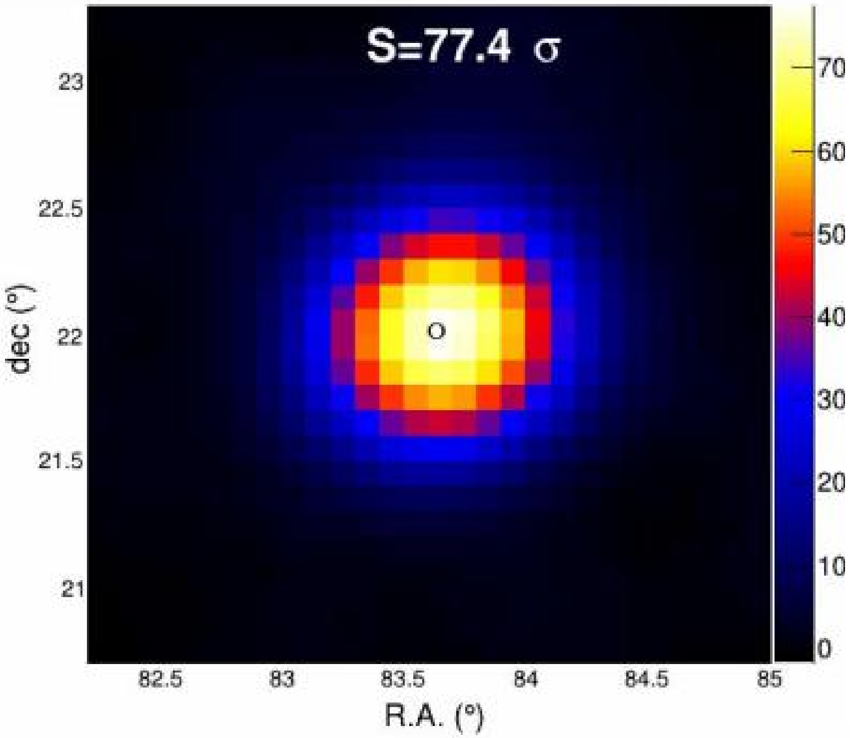
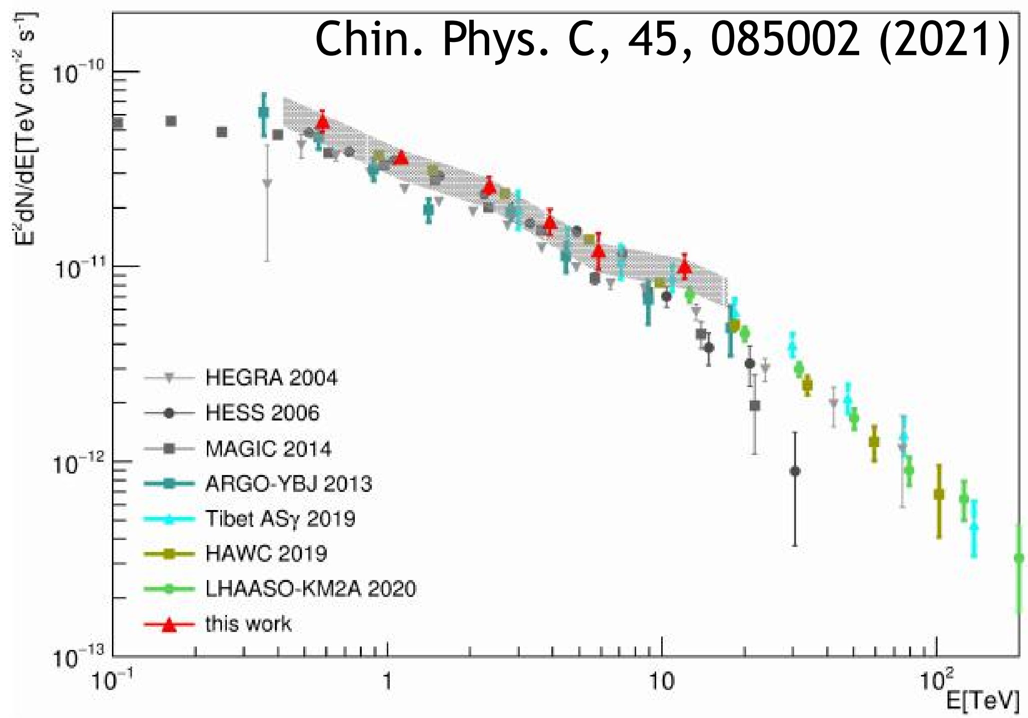
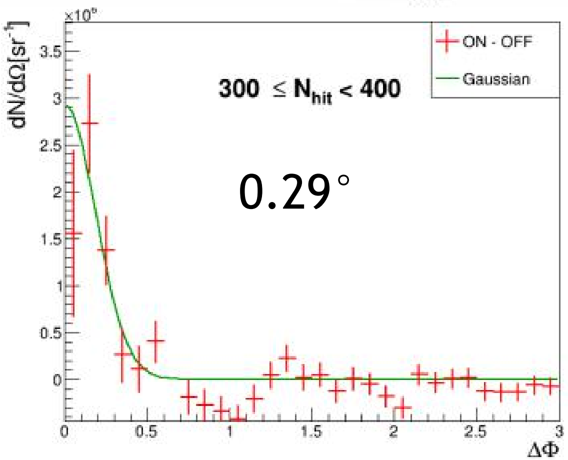
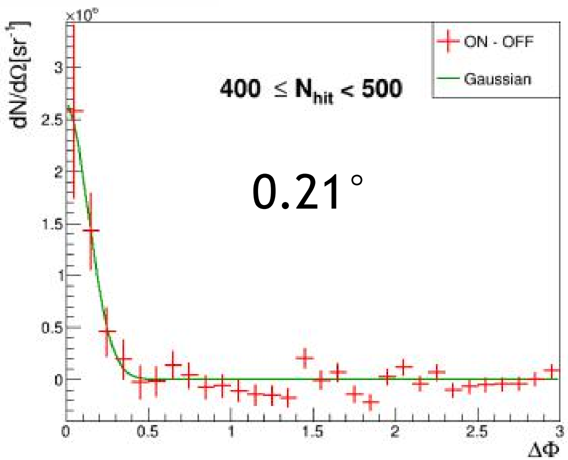
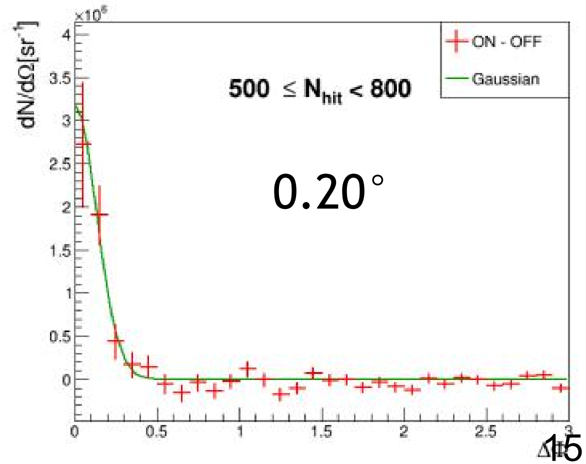
LHAASO detector - WCDA



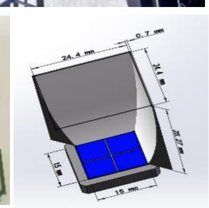








LHAASO detector - WFCTA



SiPM and Winstone 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)

LHAASO survey of the UHE sky

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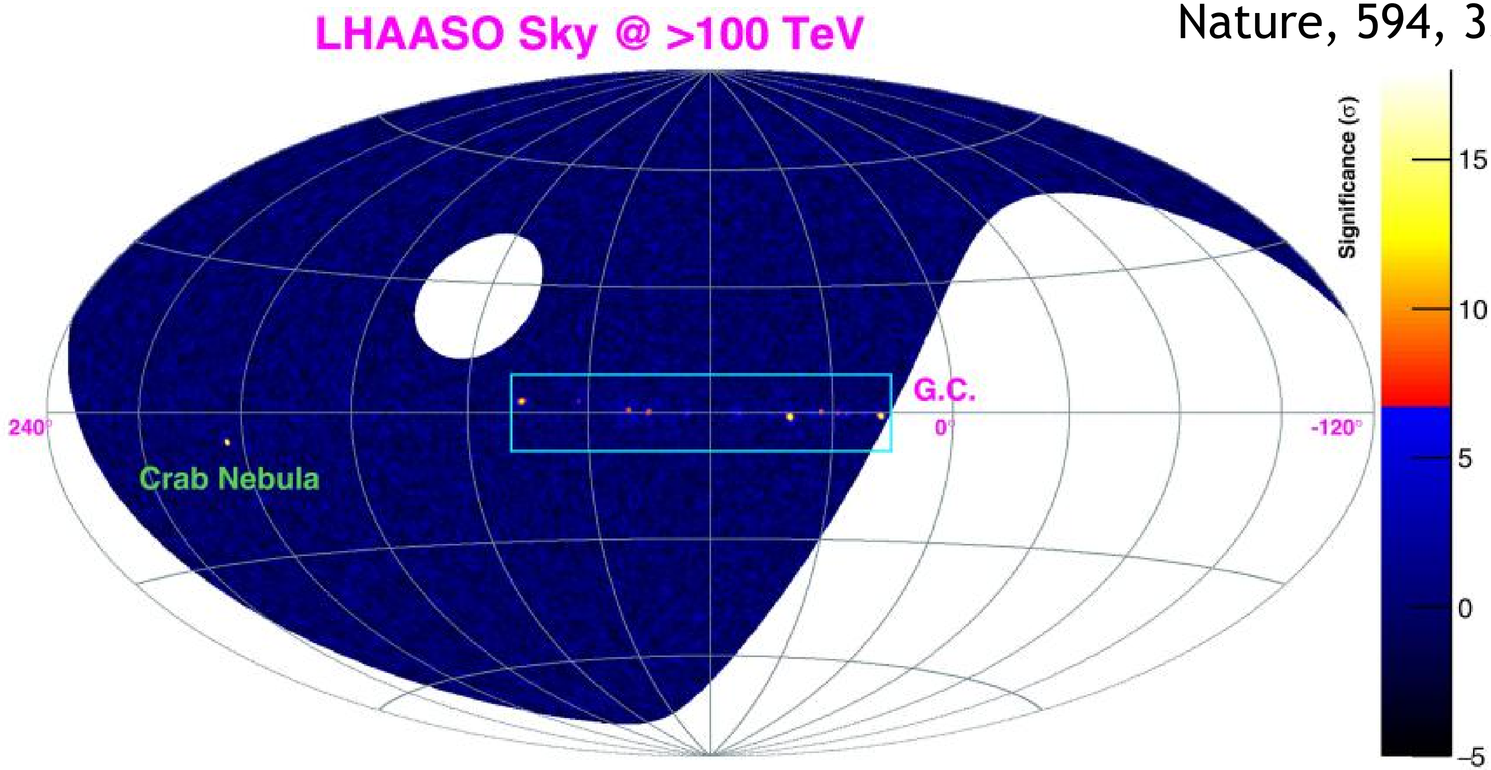

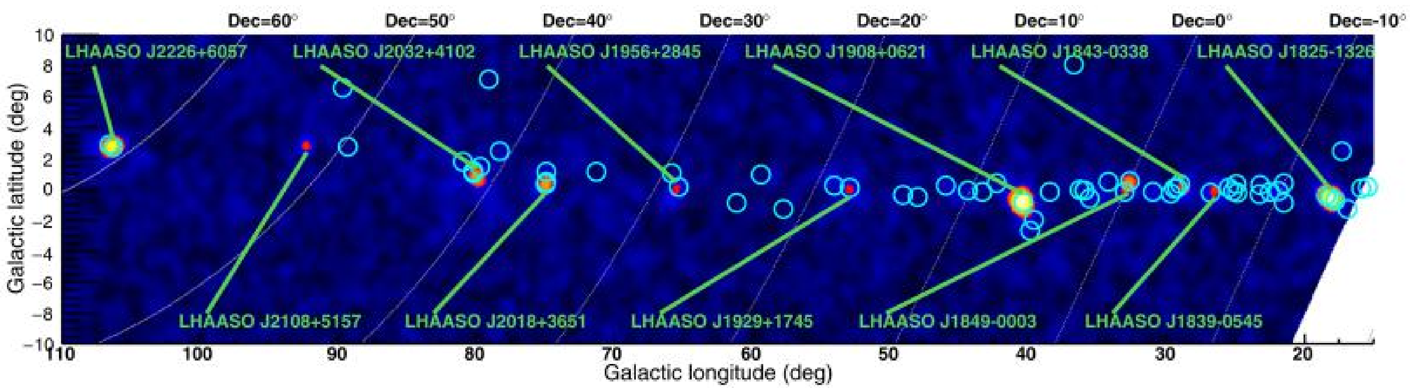

LHAASO survey of the UHE sky

Table 1 | UHE γ-ray sources

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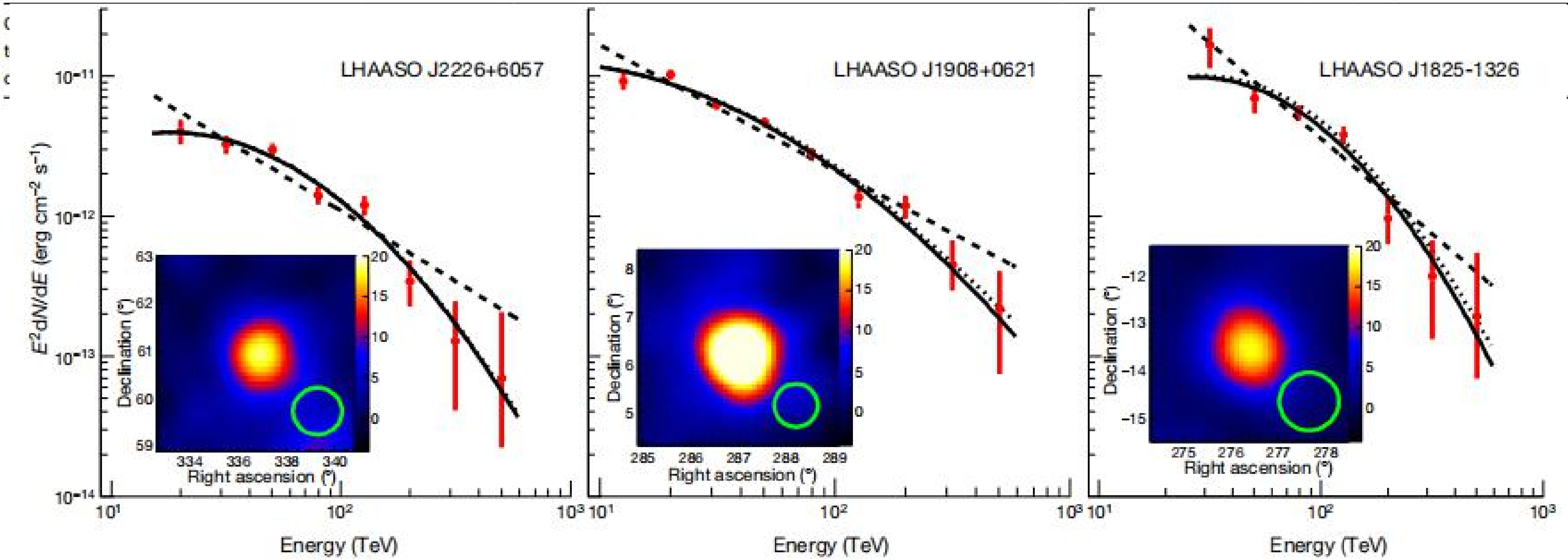
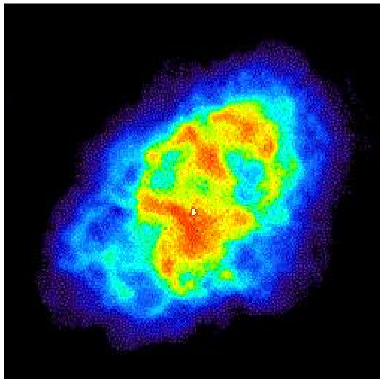
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	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)

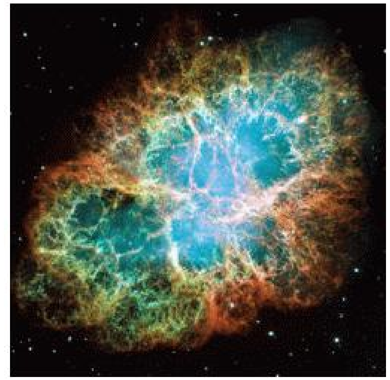


Crab nebula: Electron PeVatron

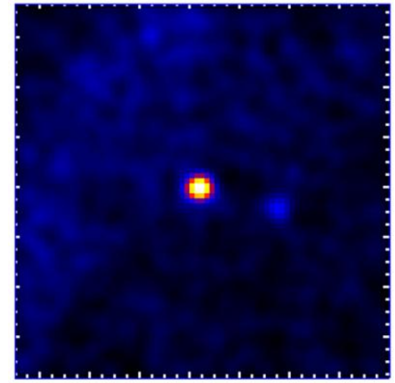


Radio wave (VLA)

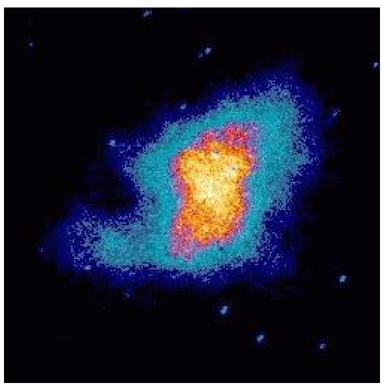
Infrared radiation (Spitzer)



Visible light (Hubble)

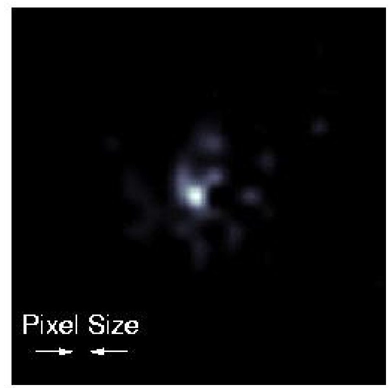


E>1 GeV (Fermi-LAT)

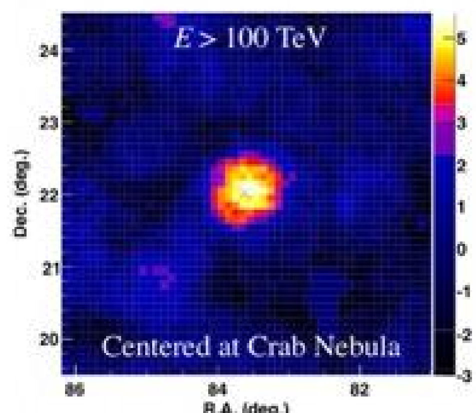


Ultraviolet radiation (Astro-1)

Low-energy X-ray (Chandra)

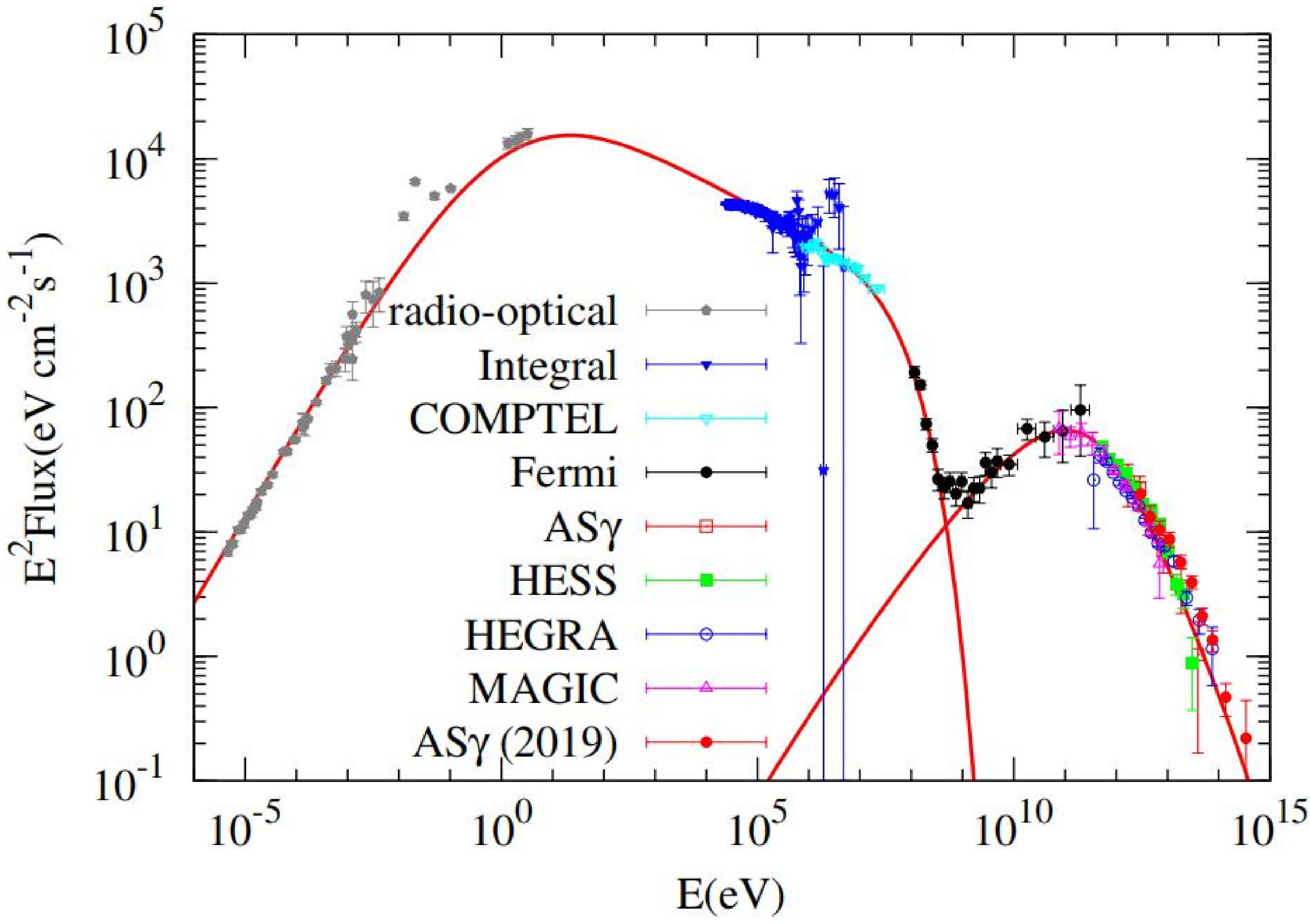


High-energy X-ray (HEFT)

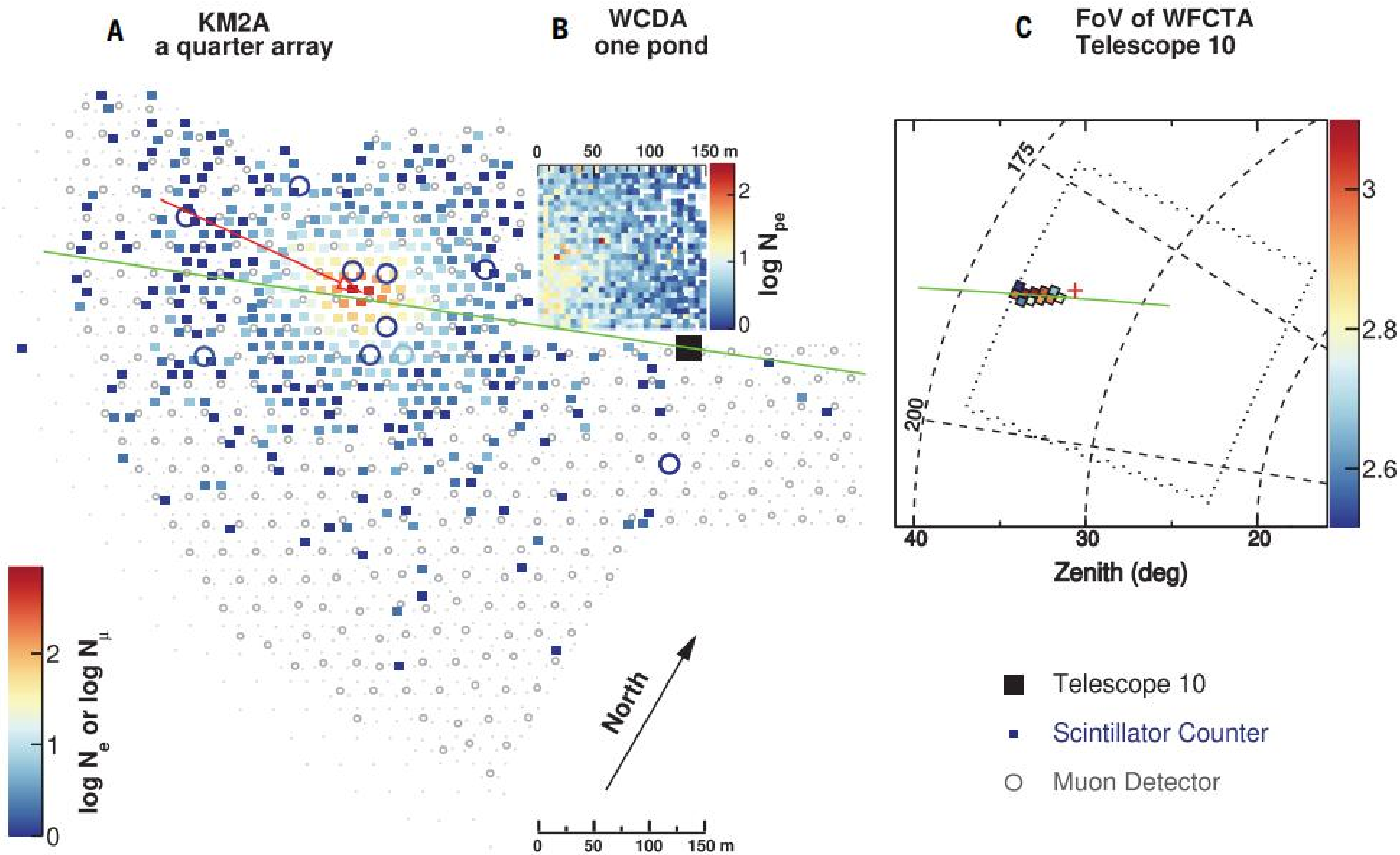


E>100 TeV (ASγ)

Crab nebula: Electron PeVatron



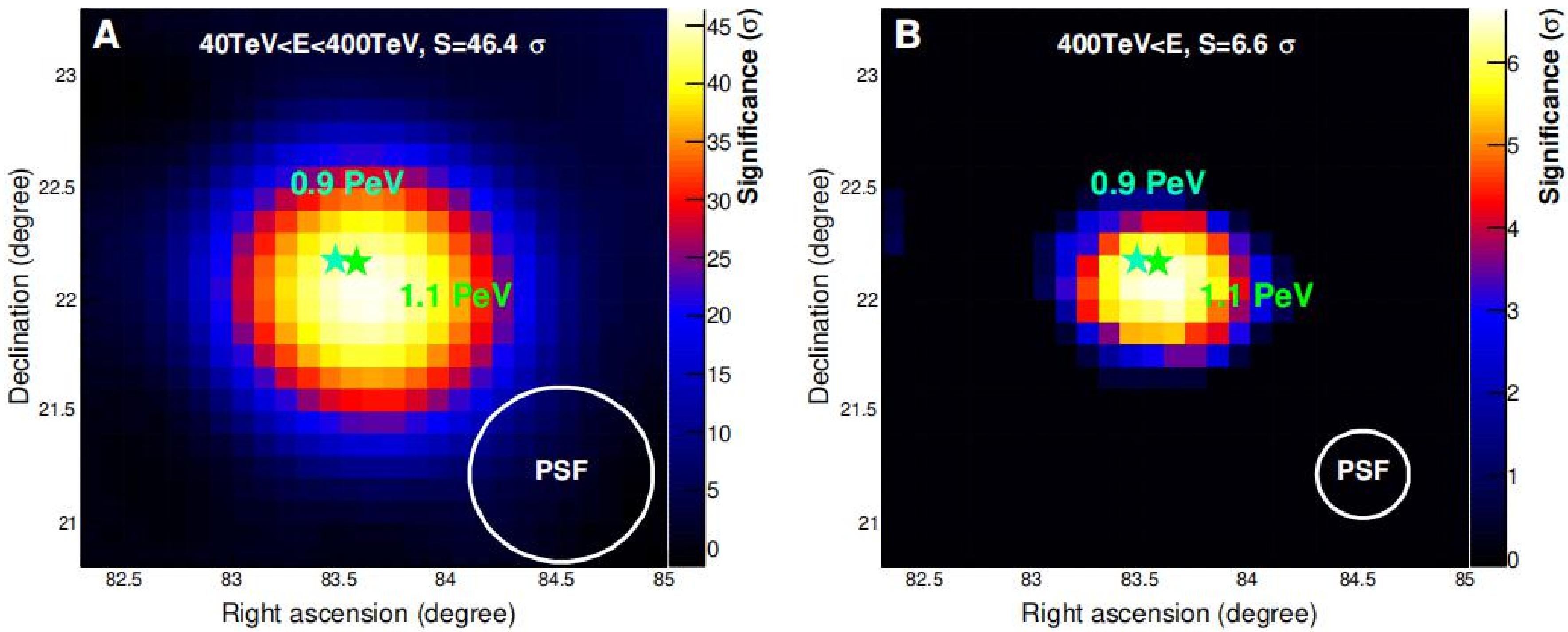
Crab nebula: Electron PeVatron



KM2A: 0.88+/-0.11 PeV
WFCTA: $0.92^{+0.28}_{-0.20}$ PeV

Science, 373, 425 (2021)

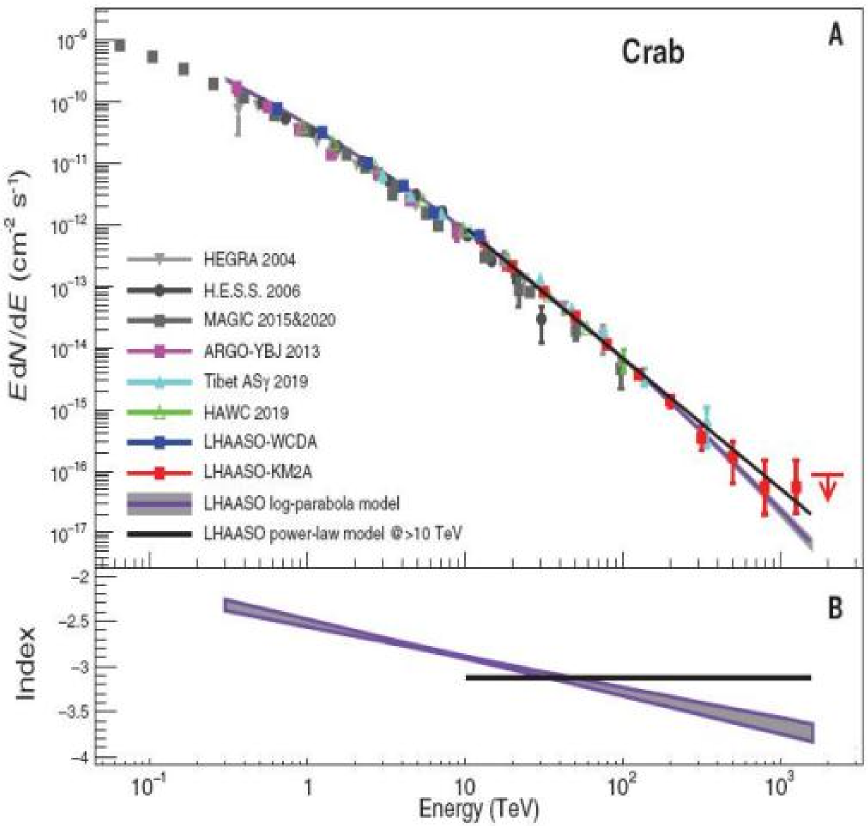
Crab nebula: Electron PeVatron

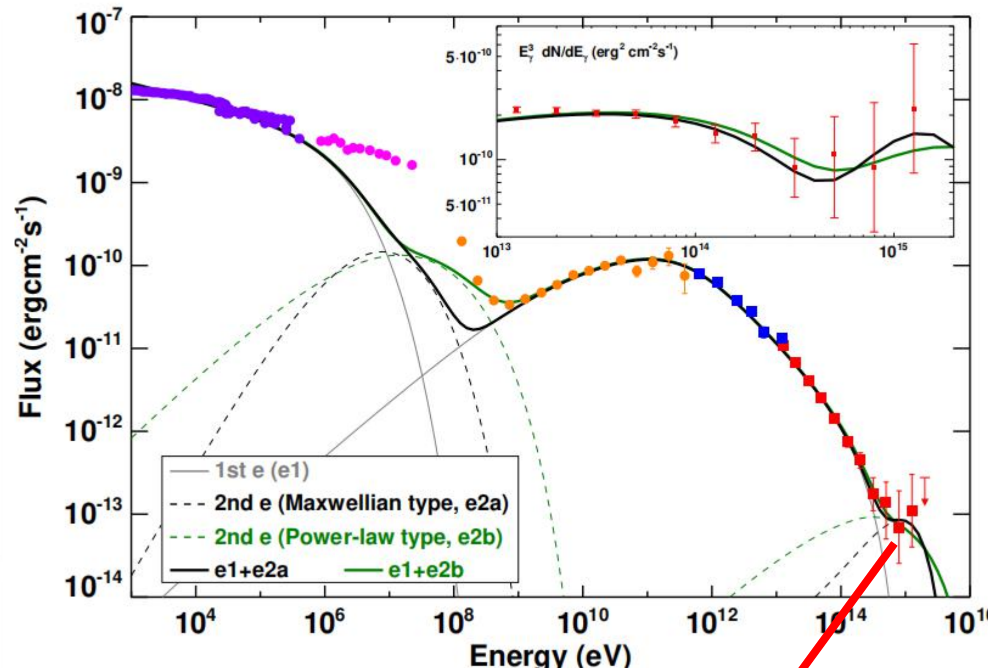


E (PeV)	δE (PeV)	N_e	N_μ	θ (°)	D_{edge} (m)	ψ (°)	P (%)	Arrival time
1.12	0.09	5094	14	13.0	89	0.15	0.03	2021-01-04 16:45:06
0.88	0.11	4996	15	33.9	139	0.21	0.1	2020-01-11 17:59:18
0.57	0.13	2408	9	40.8	125	0.08	0.7	2020-05-22 03:54:56
0.46	0.05	2432	6	21.7	52	0.11	0.3	2020-11-05 21:23:28
0.40	0.04	1859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

Science, 373, 425 (2021)

Crab nebula: Electron PeVatron

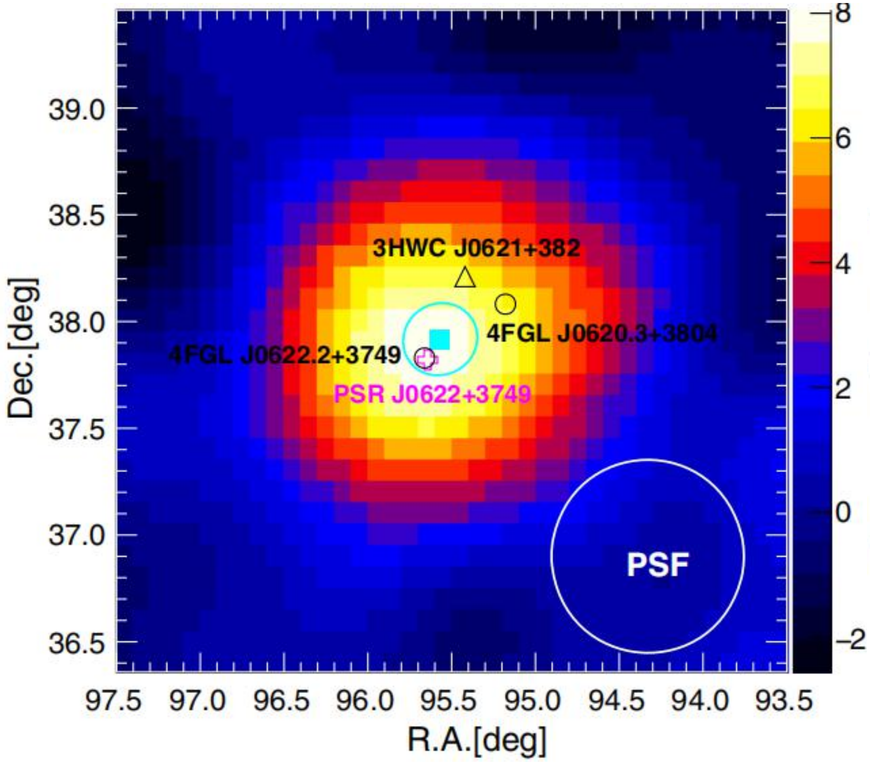




Possible new feature?

Science, 373, 425 (2021)

Extended pulsar halo: slow diffusion of $e^{+/-}$



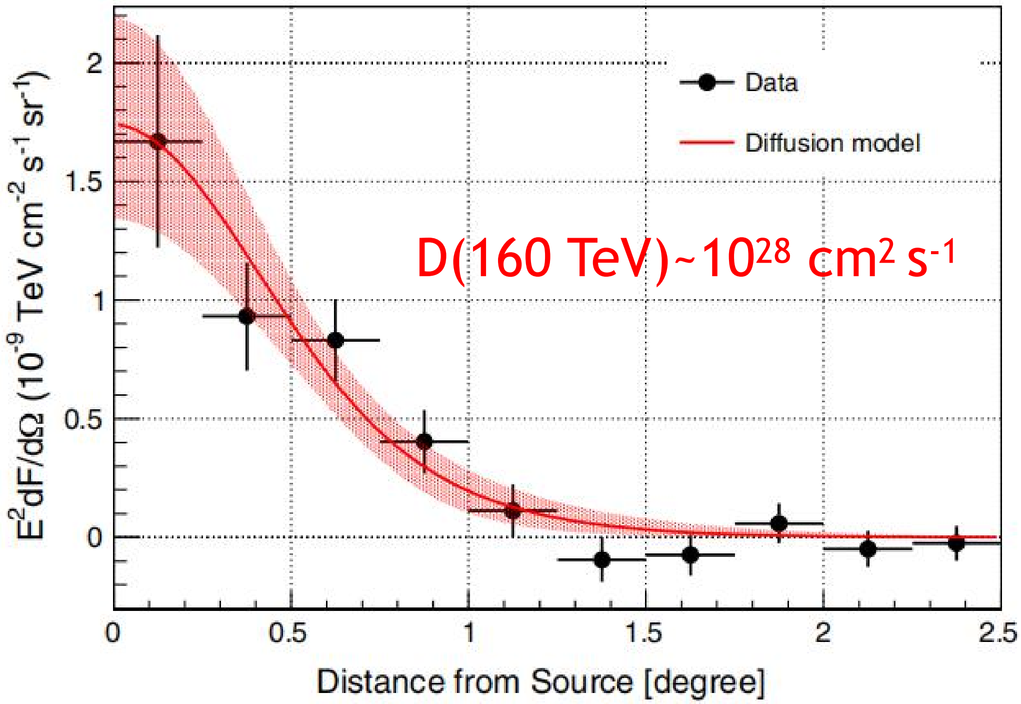


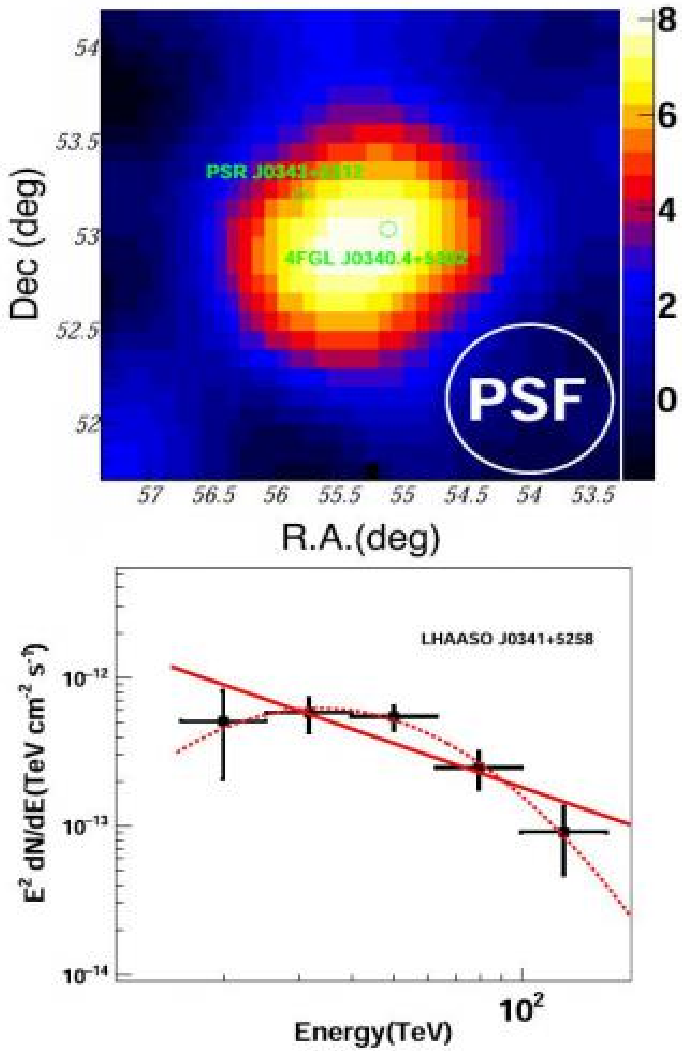
TABLE II. Comparison of the properties of pulsars J0622 + 3749, Geminga, and Monogem.

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)

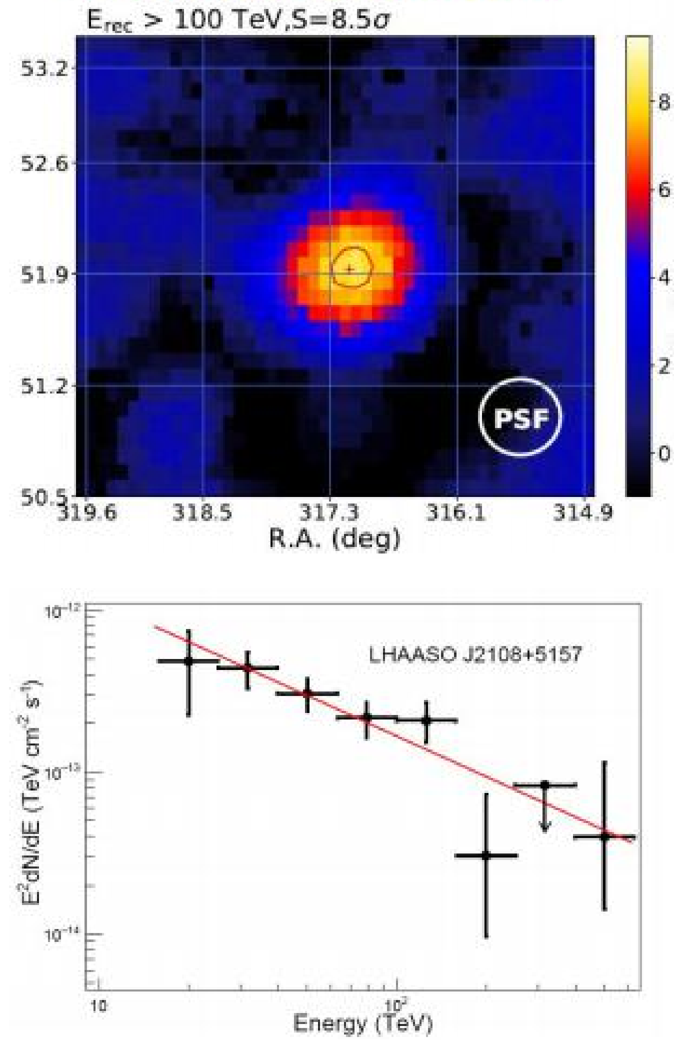
New ultra-high-energy sources

LHAASO J0341+5258



ApJL, 917, L4 (2021)

LHAASO J2108+5157



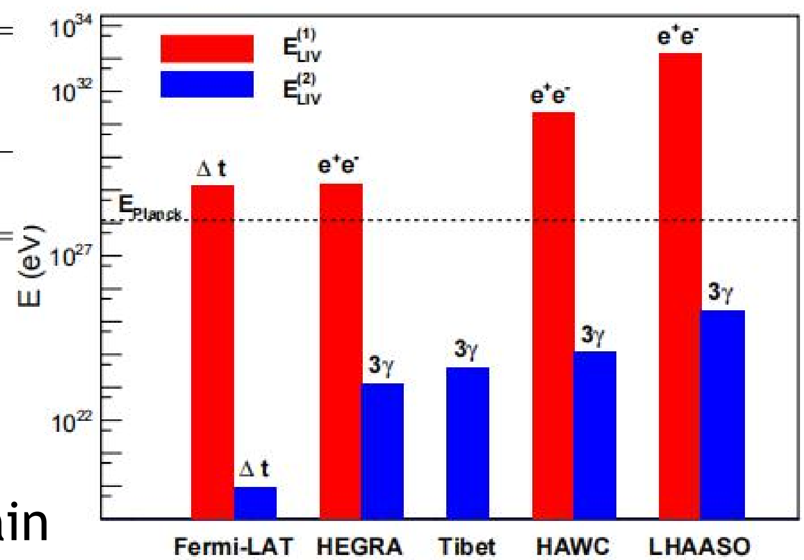
ApJL, in press (2021)

Most stringent constraints on the Lorentz invariance violation (LIV)

The fundamental symmetry of Lorentz invariance might be broken at the Planck energy scale

An effective description of the LIV is the modification of dispersion relation, $E_\gamma^2 - p_\gamma^2 = \pm|\alpha_n| p_\gamma^{n+2}$, resulting in many interesting phenomena, such as decay and splitting of photons in vaccum ($\gamma \to e^+e^-$, $\gamma \to N\gamma$)

Source	L (kpc)	E_{max} (PeV)	$E_{cut}^{95\%}$ (PeV)	$E_{LIV}^{(1)}$ (eV) $\times 10^{32}$	$E_{LIV}^{(2)}$ (eV) $\times 10^{23}$	$E_{LIV}^{(2)}$ (3γ) (eV) $\times 10^{25}$
J0534+2202	2.0	0.88	$0.75^{+0.043}_{-0.043}$	$4.04^{+0.73}_{-0.65}$	$5.5^{+0.65}_{-0.61}$	$1.04^{+0.12}_{-0.11}$
J2032+4102	1.4	1.42	$1.14^{+0.06}_{-0.06}$	$14.2^{+2.32}_{-2.10}$	$12.7^{+1.36}_{-1.29}$	$2.21^{+0.22}_{-0.21}$



The highest energy photons observed by LHAASO can give the most stringent constraints on the LIV model parameters: We exclude the first-order LIV, and constrain the second-order LIV scale to be > 10^{-3} M_{pl}

arXiv:2106.12350

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 offers the most sensitive probe of the Lorentz invariance violation models

Thank You!