The status and overview of LHAASO

Shoushan Zhang

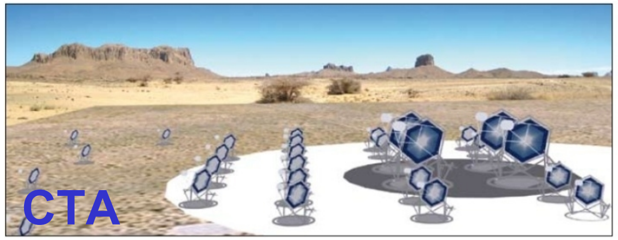
on behalf of the LHAASO collaboration

Institute of High Energy Physics，CAS，China

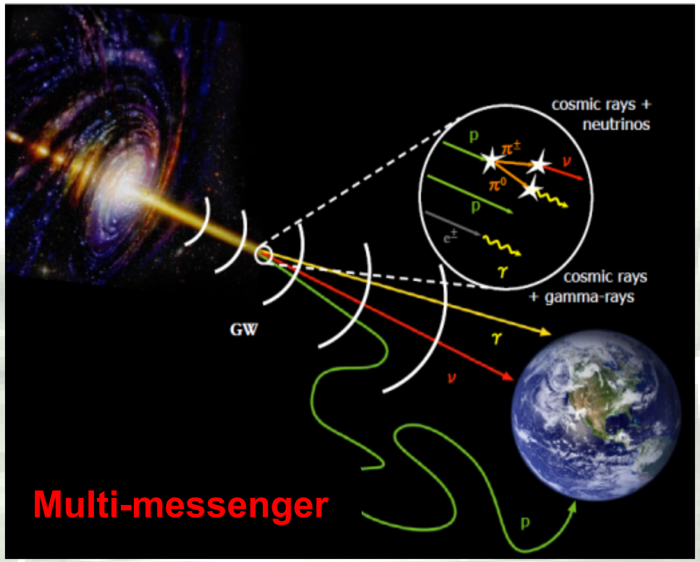
22nd International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2024)

8 July - 12 July, 2024 Fiesta Americana, Mexico

High Energy Cosmic Rays

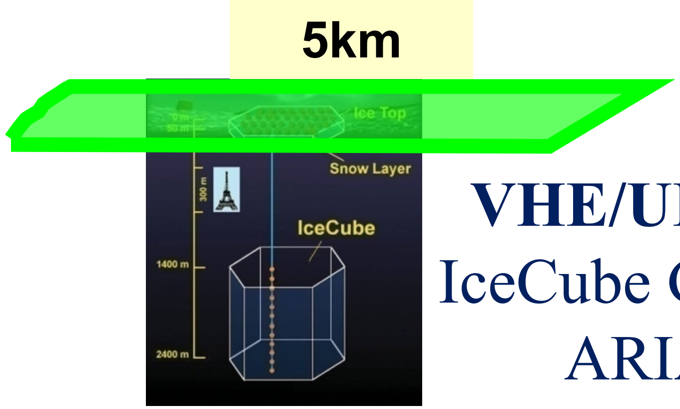


VHEγ Astronomy
LHAASO
HESS， MAGIC, CTA



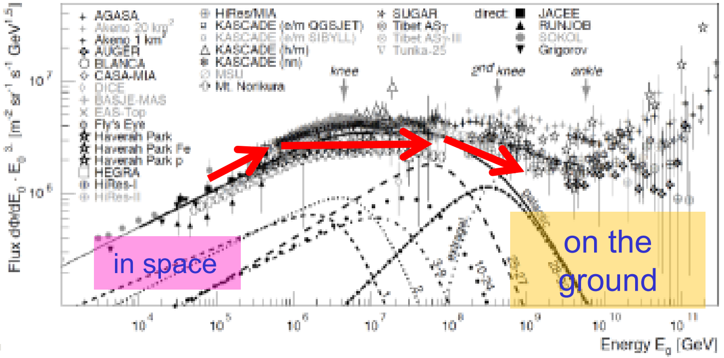
Origin of CRs
A century-old mystery

EHE CR Astronomy
TA, AUGER
JEM-EUSO



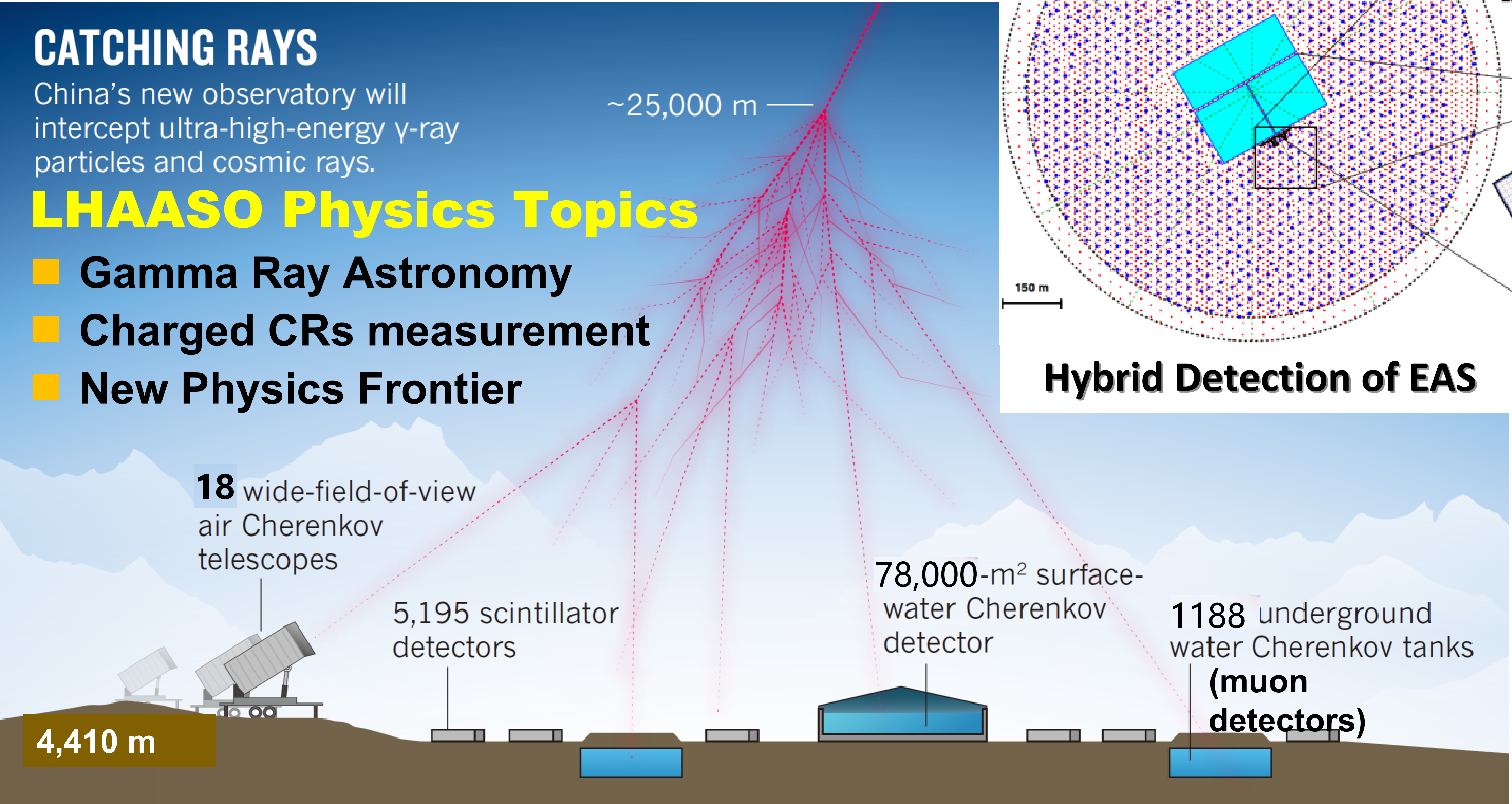
VHE/UHE Neutrinos
IceCube Gen2， KM3net
ARIANA ……

CR Features: knees
AMS02,Iss-CREAM,DAMPE,LHAASO……



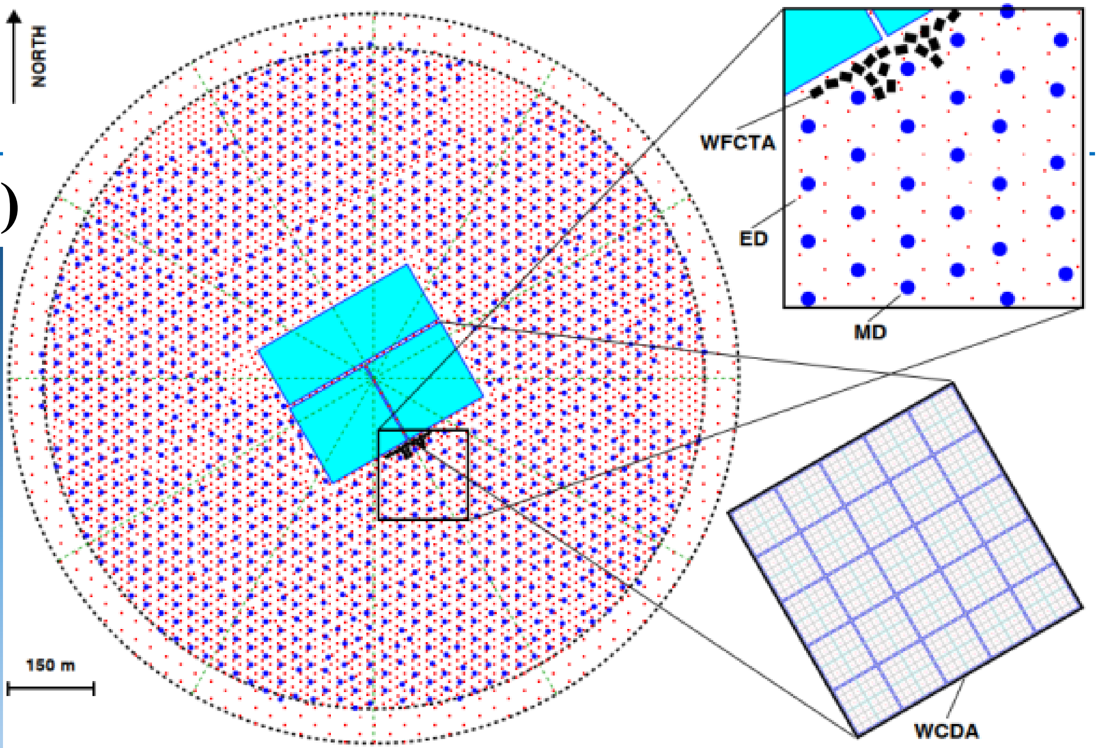
High Energy Cosmic Rays

Large High Altitude Air Shower Observatory (LHAASO)



LHAASO Physics Topics

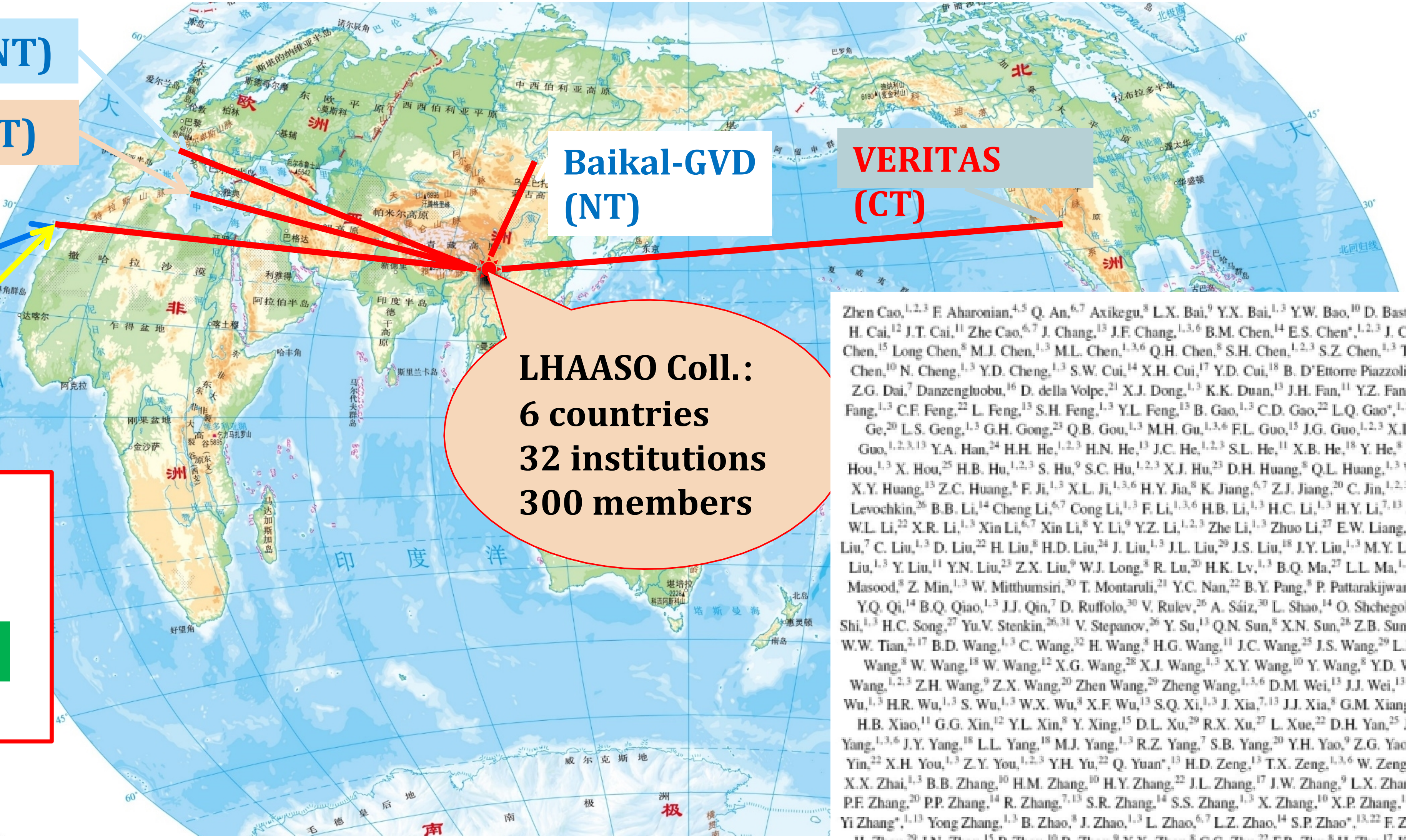
- Gamma Ray Astronomy
- Charged CRs measurement
- New Physics Frontier



Hybrid Detection of EAS

LHAASO: Multi-Messenger Collaboration Network

The LHAASO collaboration has signed MOUs with 8 international detector collaboration.



Space borne Exp.

- eROSITA(X-ray)
- DAMPE(γ-ray, CR)

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] X. Hou,[25] 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,[26] K. Levochkin,[26] 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] Jian Li,[7] Jie 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,[27] E.W. Liang,[28] Y.F. Liang,[28] 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,[29] 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,[27] L.L. Ma,[1,3] X.H. Ma,[1,3] J.R. Mao,[25] 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,[26] A. Sáiz,[30] L. Shao,[14] O. Shchegolev,[26,31] X.D. Sheng,[1,3] J.R. Shi,[1,3] H.C. Song,[27] Yu.V. Stenkin,[26,31] V. Stepanov,[26] Y. Su,[13] Q.N. Sun,[8] X.N. Sun,[28] Z.B. Sun,[32] P.H.T. Tam,[18] Z.B. Tang,[6,7] W.W. Tian,[2,17] B.D. Wang,[1,3] C. Wang,[32] H. Wang,[8] H.G. Wang,[11] J.C. Wang,[25] J.S. Wang,[29] L.P. Wang,[22] L.Y. Wang,[1,3] R.N. Wang,[8] W. Wang,[18] W. Wang,[12] X.G. Wang,[28] 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,[29] 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,[29] R.X. Xu,[27] L. Xue,[22] D.H. Yan,[25] 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,[32] Y. Zheng,[8] B. Zhou,[1,3] H. Zhou,[29] 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]

The Site

Bird's eye view of LHAASO，2021-08

- Location：29o21’ 27.6” N , 100o08’19.6” E
- Altitude: 4410 m
- 2021-07 completed built and in operation

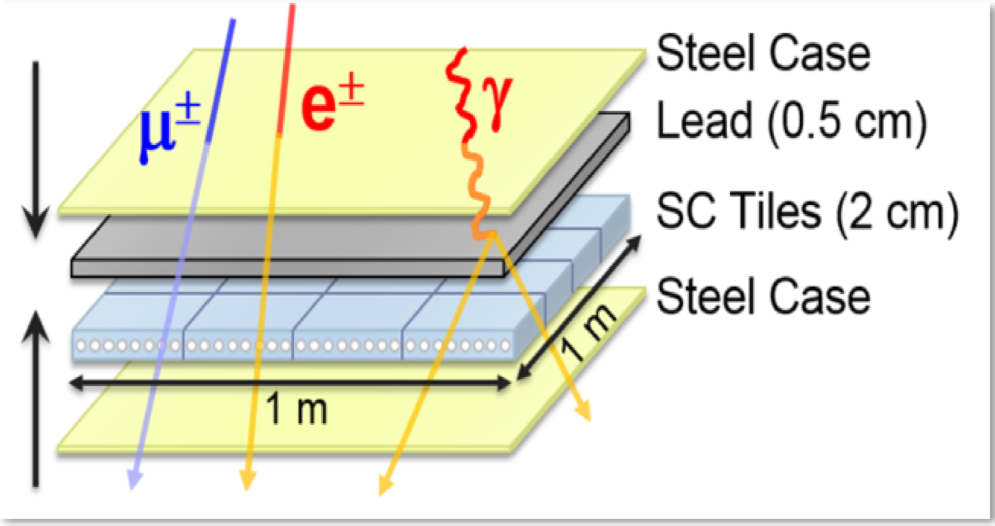
LHAASO, ***Nature*** *Astronomy* ***5:849 (2021)***

(Aug. 2018, at 4410 m a.s.l.)

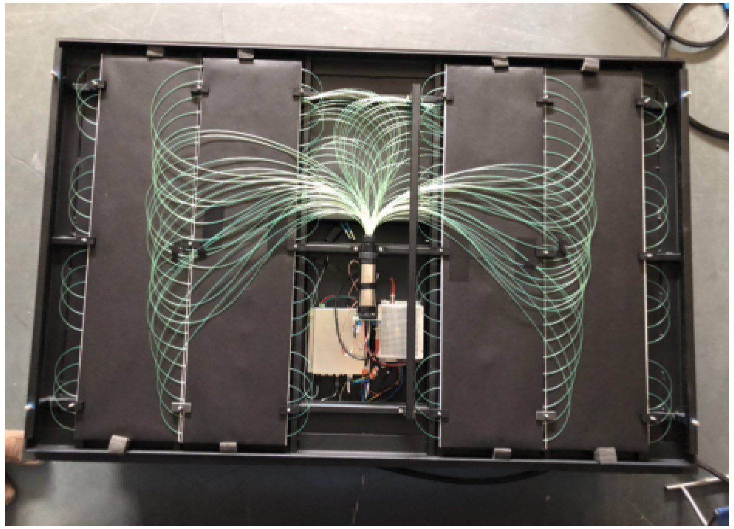
KM2A: 1.36 (km)^2

- 5195 EDs
  - 1 m^2 each
  - 15 m spacing
- 1188 MDs
  - 36 m^2 each
  - 30 m spacing

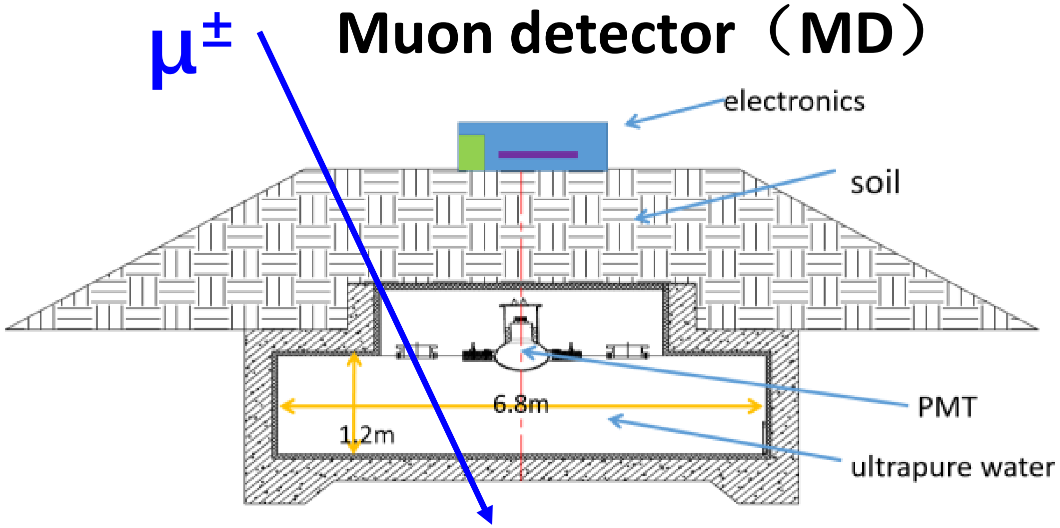
Scintillator Detectors （ED）



Inner View of one ED

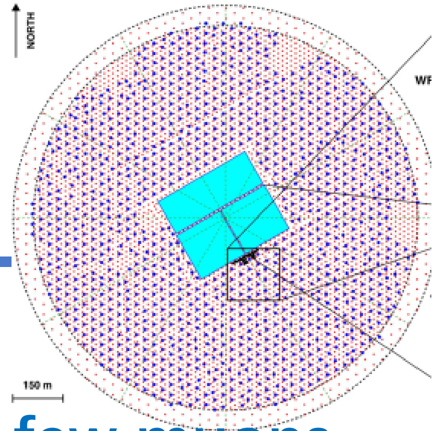


Muon detector（MD）



LHAASO-KM2A

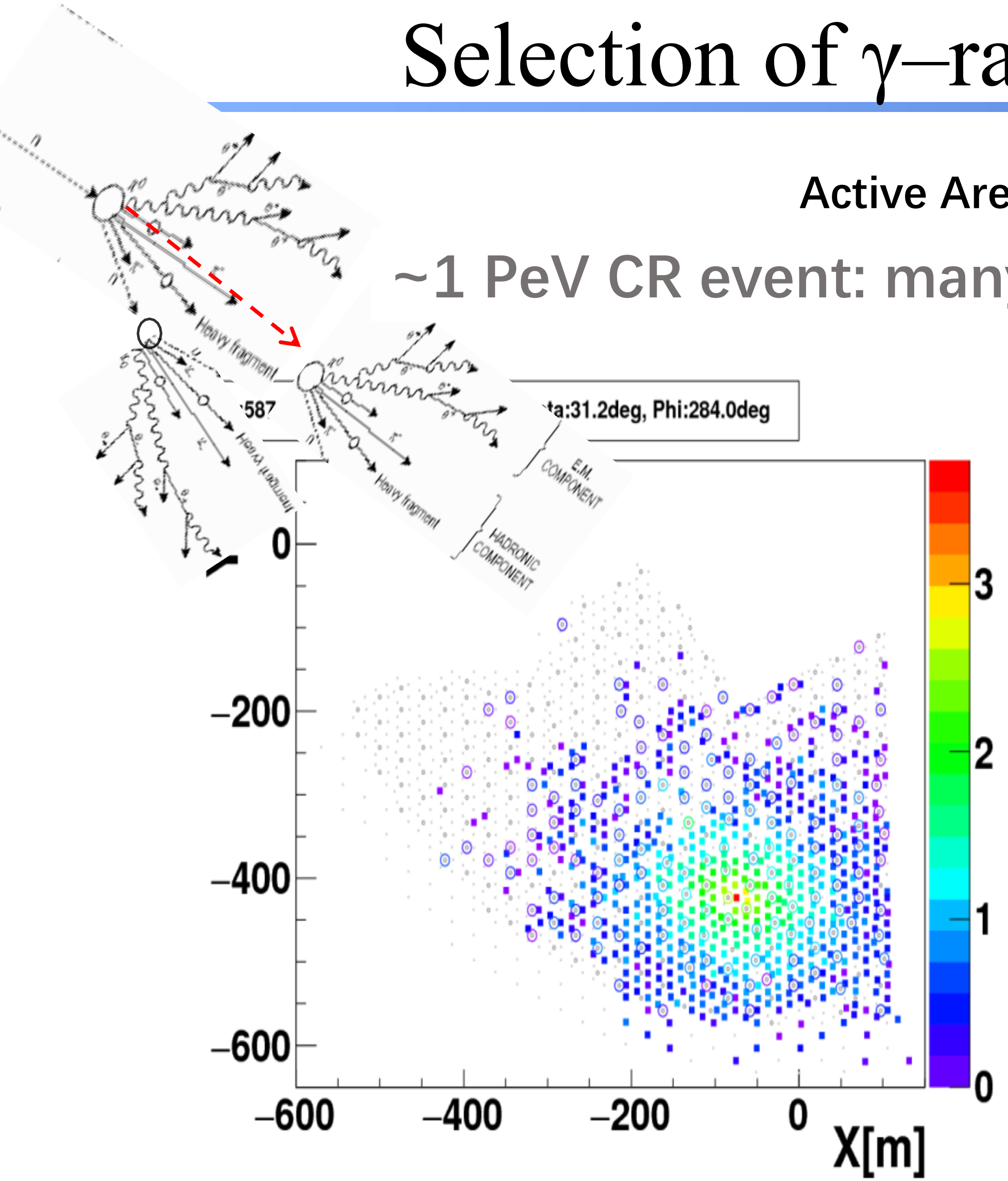
Selection of γ–rays out of CR background

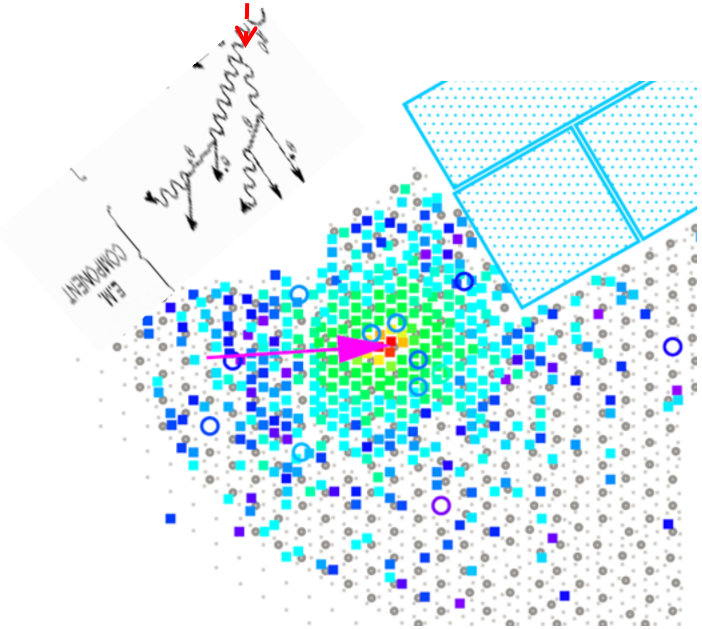


Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons ~ 1 PeV γ–ray event ： very few muons

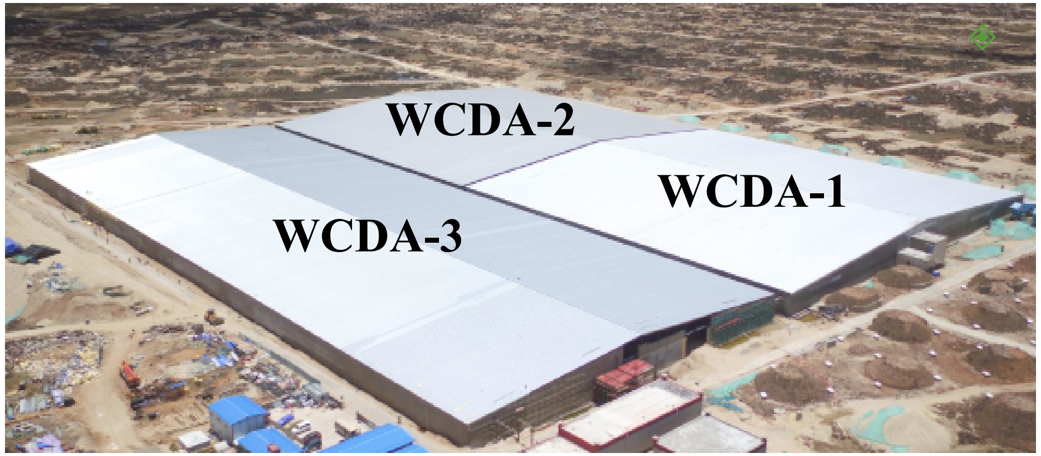
from the Crab





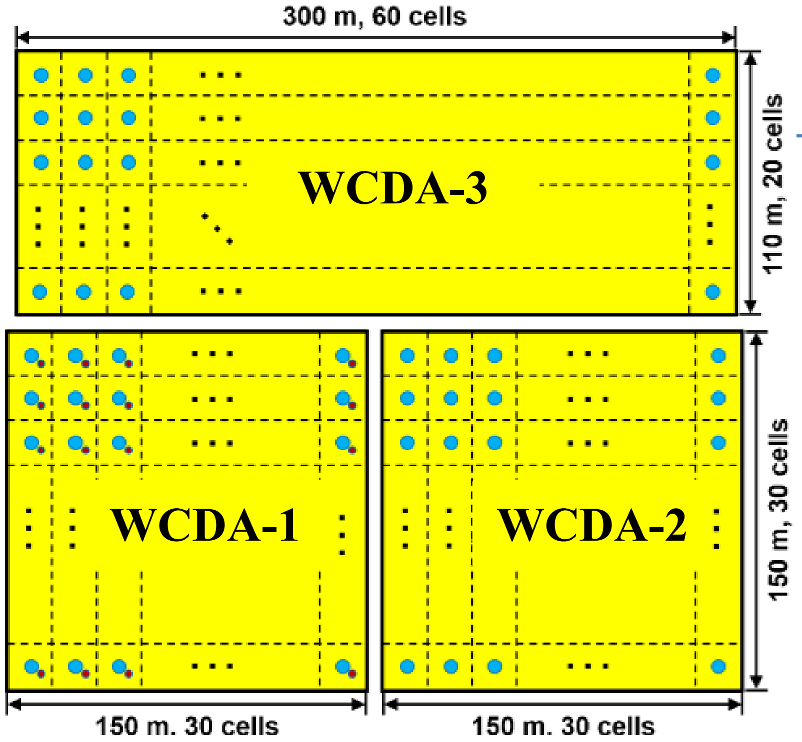
- Area：
  1.3 km^2
- Detectors：
  5216 ED
  1188 MD
- Energy Range：
  0.01-10 PeV

Water Cherenkov Detector Array (WCDA)

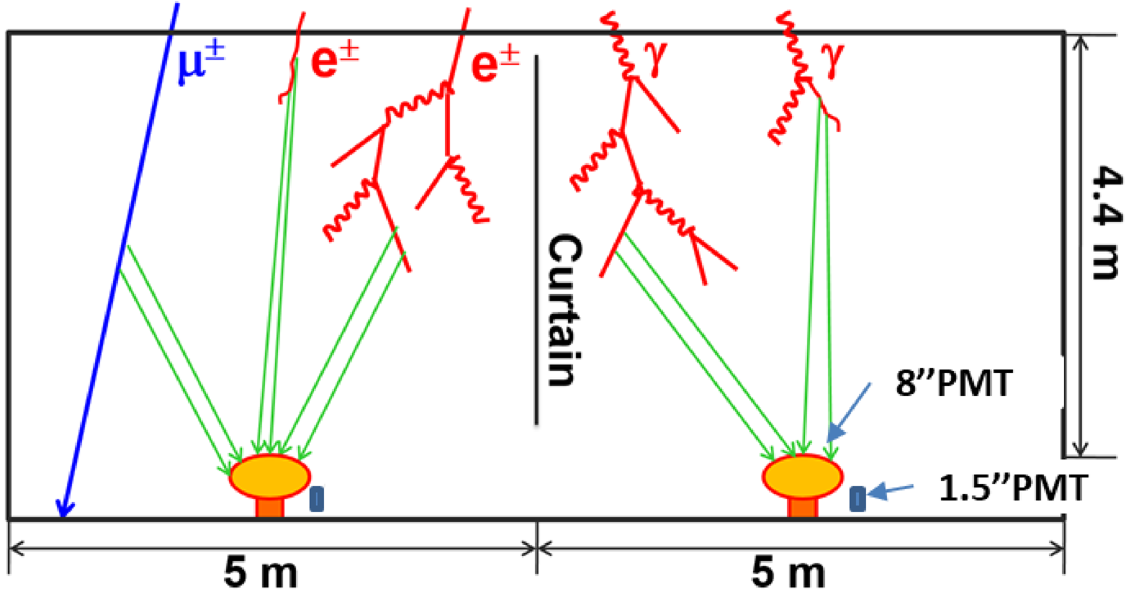


Energy rang

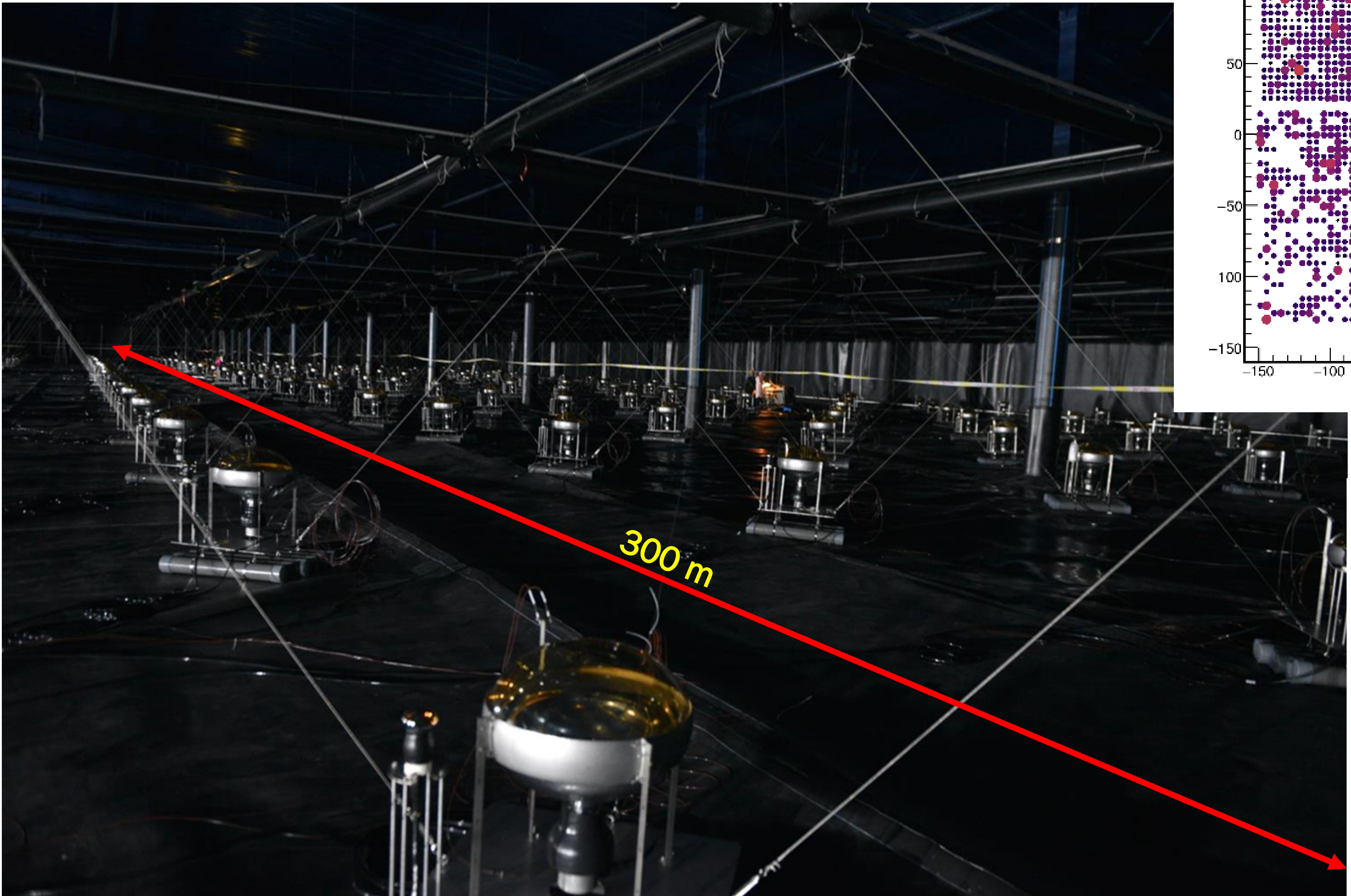
- WCDA-1
  - 300 GeV – 10 PeV
- WCDA-2 and WCDA-3
  - 100 GeV - 10 TeV

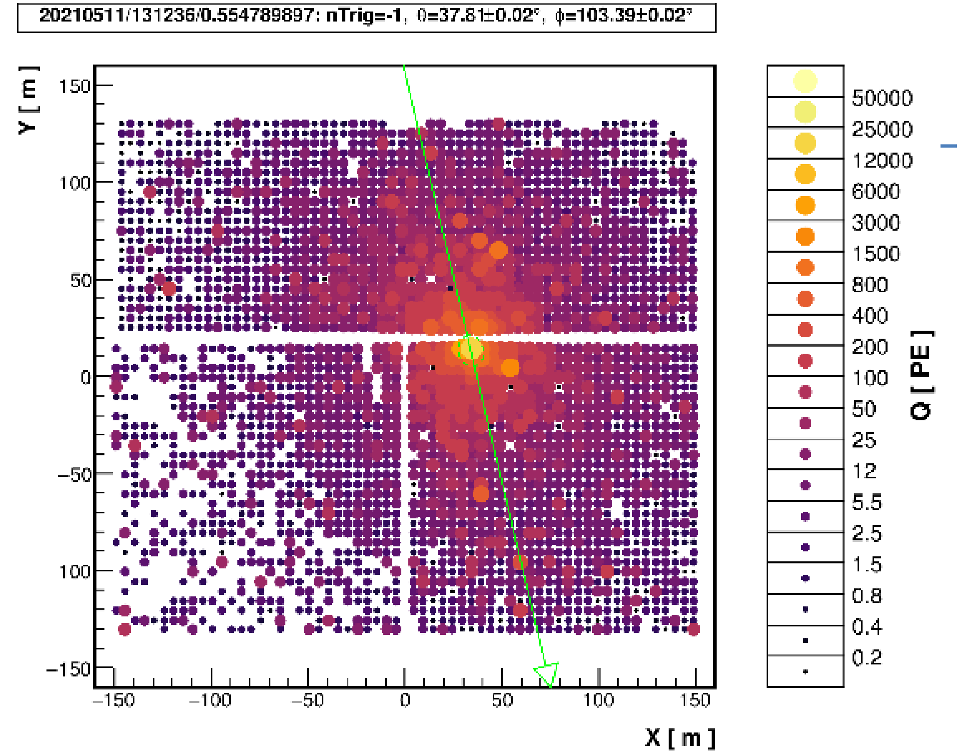


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two type of PMTs in each unit:
  - 8 inches and 1.5 inches for WCDA-1
  - 20 inches and 3 inches for WCDA-2 and WCDA-3



Inside of WCDA-3





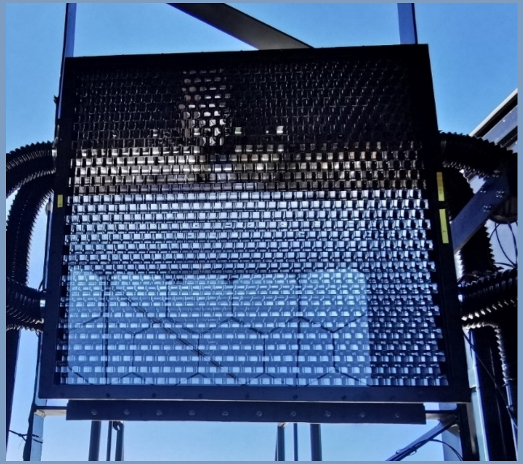
- WCDA-1 started operating in April 2019
- WCDA-2 started operating in January 2020
- WCDA-3 started operating in March 2021

Wide Field of View Cherenkov Telescope (WFCTA)

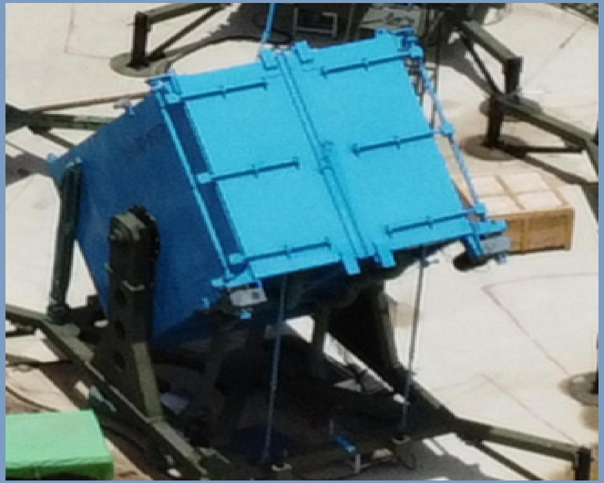
◆ **Telescope parameters:**

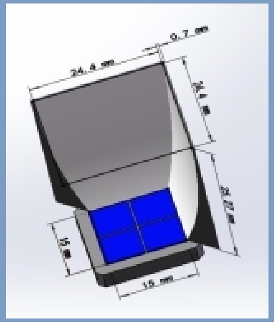
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°

Mirror



SiPM camera

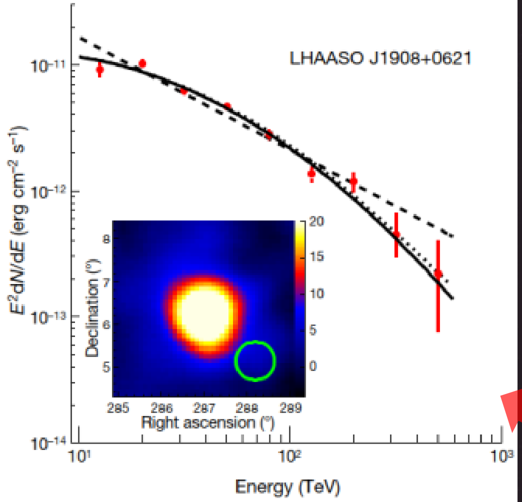


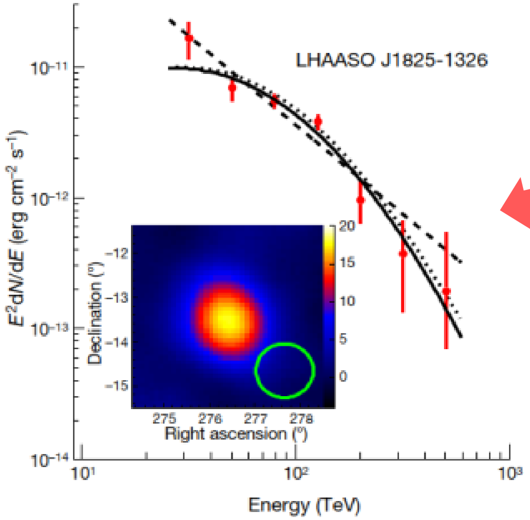


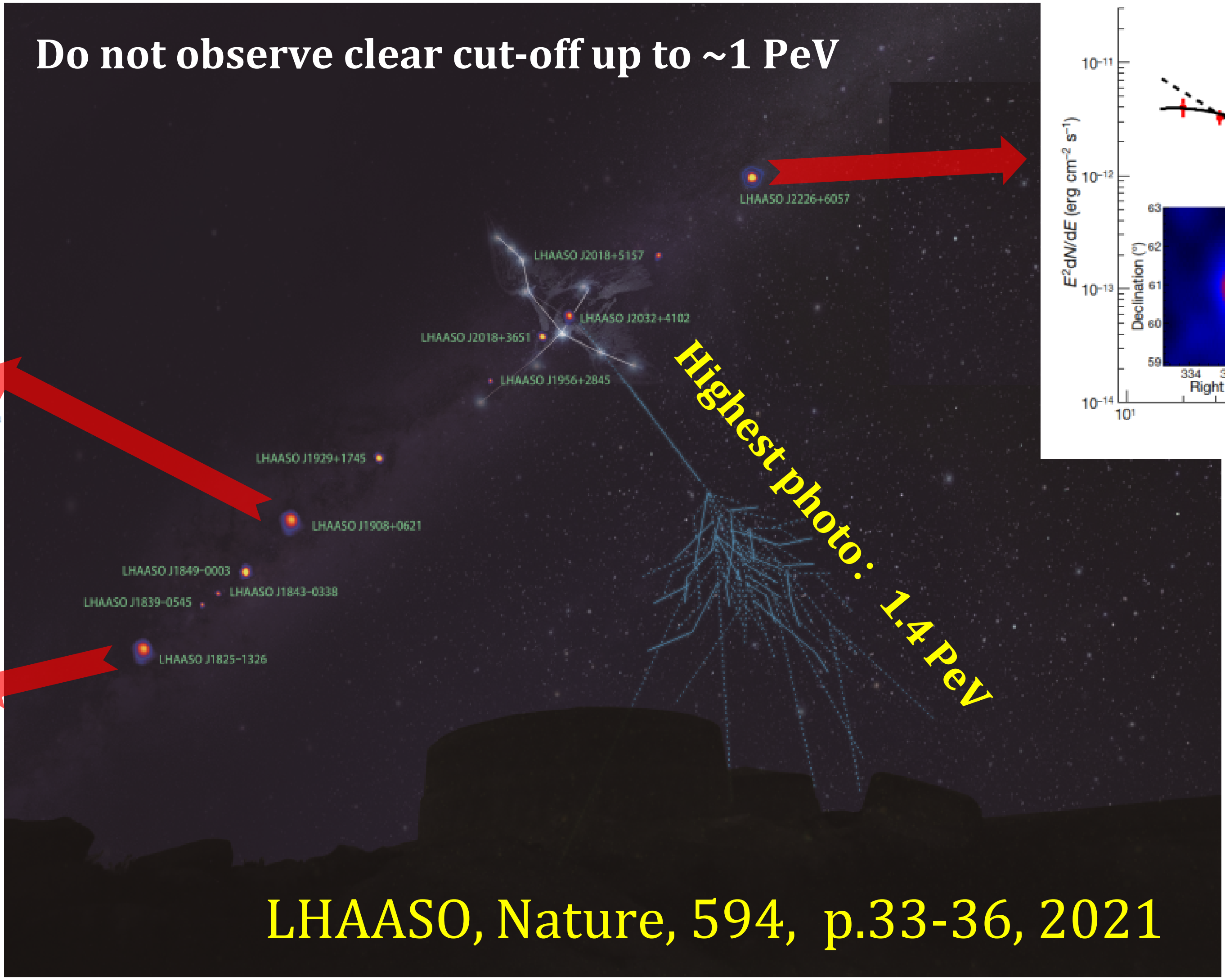
SiPM and Winstone cone

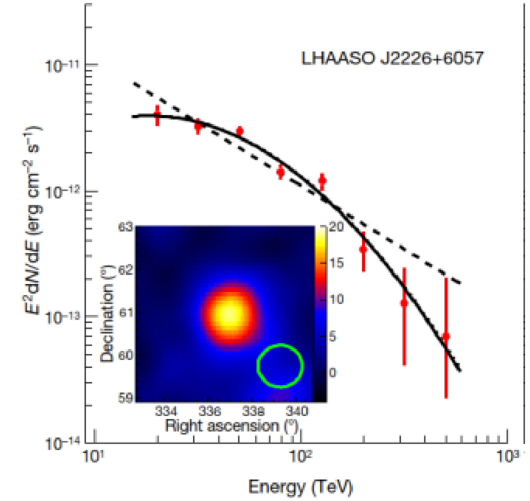
LHAASO started a new era of UHE γ-ray astronomy

2019/12-2020/12, 308 days， 1/2 array









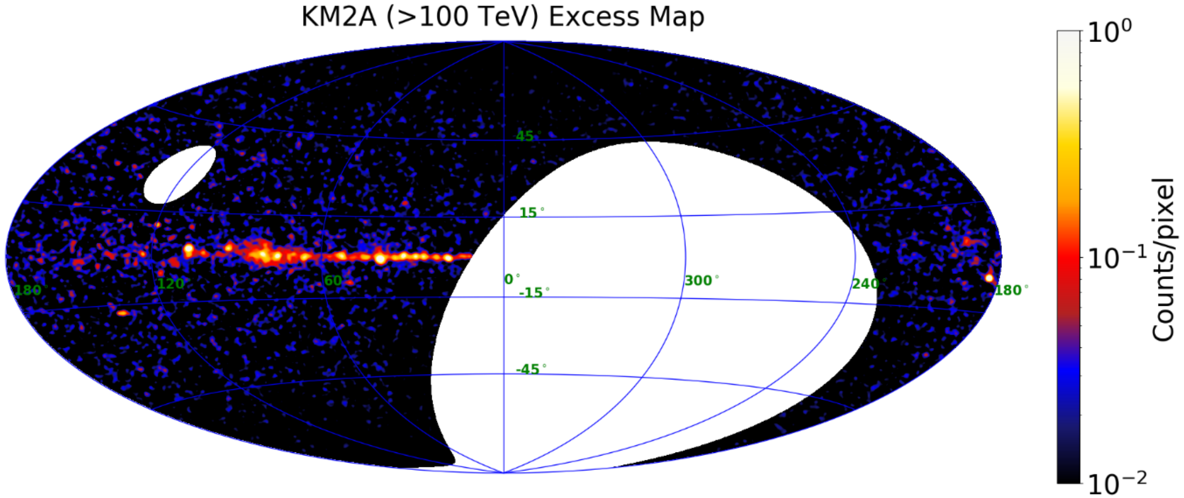
For the first time, twelve ultra-high energy gamma-ray sources have been discovered in the Milky Way, revealing the widespread existence of “petaelectron particle accelerators” in the galaxy, whose acceleration capabilities

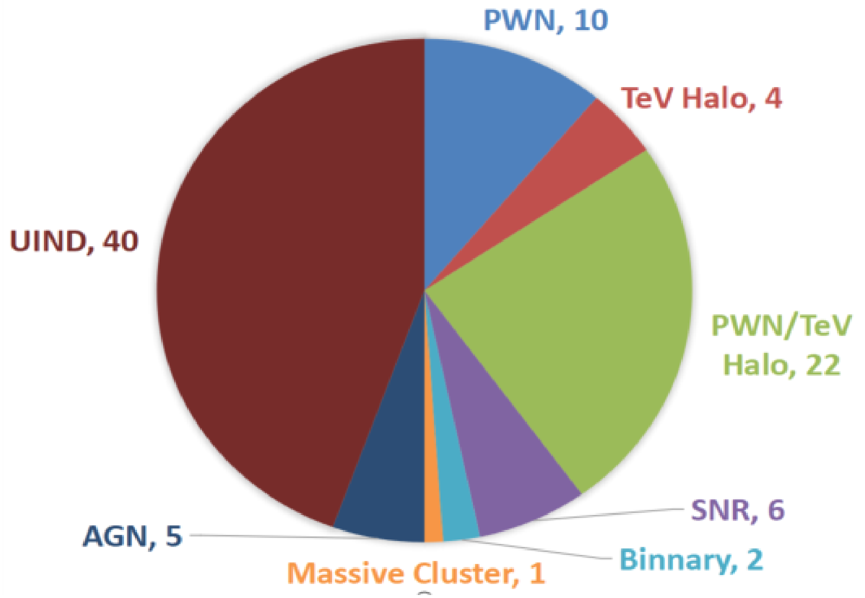
Journey of Ultra High Energy Gamma Ray Detection
The First Catalogue of Very/Ultra High Energy Gamma Sources Released

- **In 2024**： release the first catalog of very-high-energy and ultra-high-energy gamma-ray sources detected by LHAASO
  - 90 VHE/UHE gamma-ray sources
  - The number of UHE gamma-ray sources increased to 43
  - Associate with supernova remnants, pulsar wind nebulae, pulsar clouds, and massive star clusters and so on
  - This provide a crucial set of best candidate celestial bodies for uncovering the origin of high-energy cosmic rays
  - 65 sources were found to be associated with PWN, indicating that PWN is the most efficient ultra-high energy radiator

LHAASO Col., ApJS, 271:25 (2024)

- **KM2A: 2019-12 to 2022-09**
- **933 days (~730 days full array)**

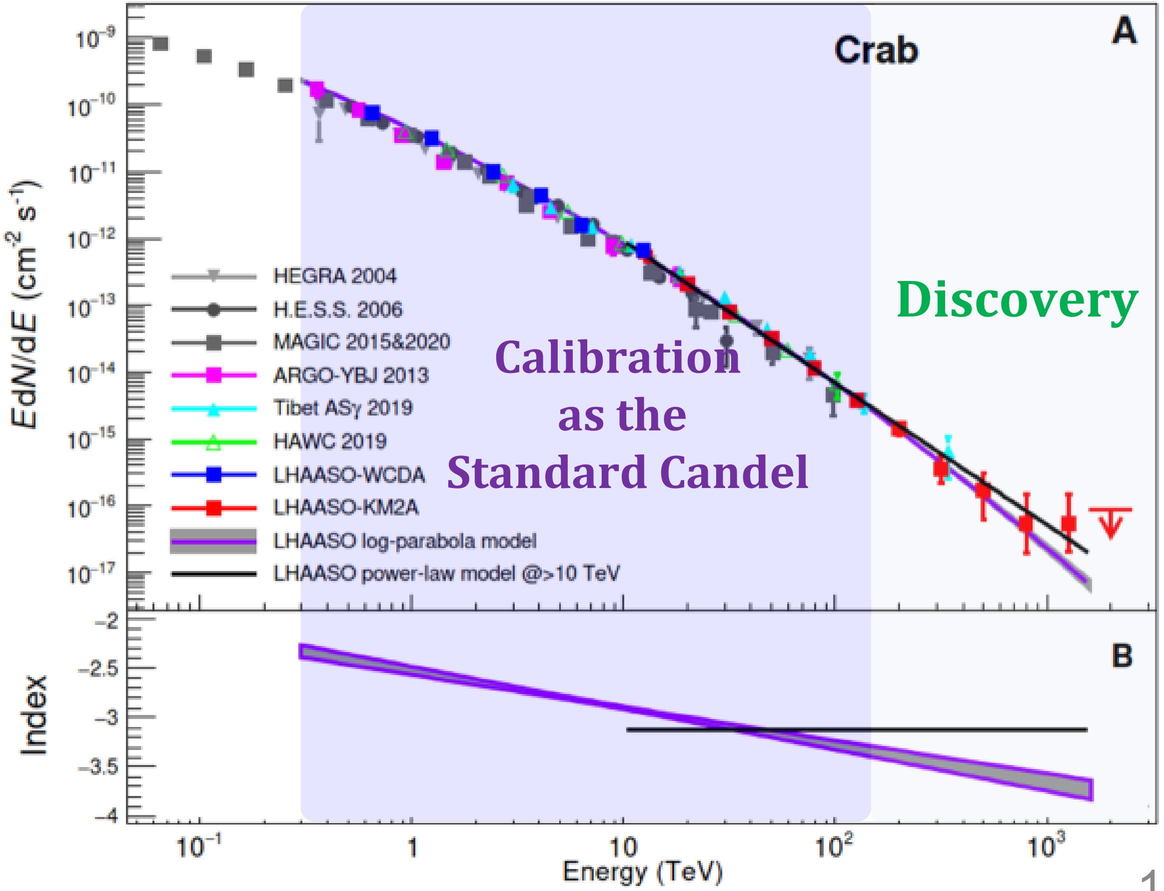




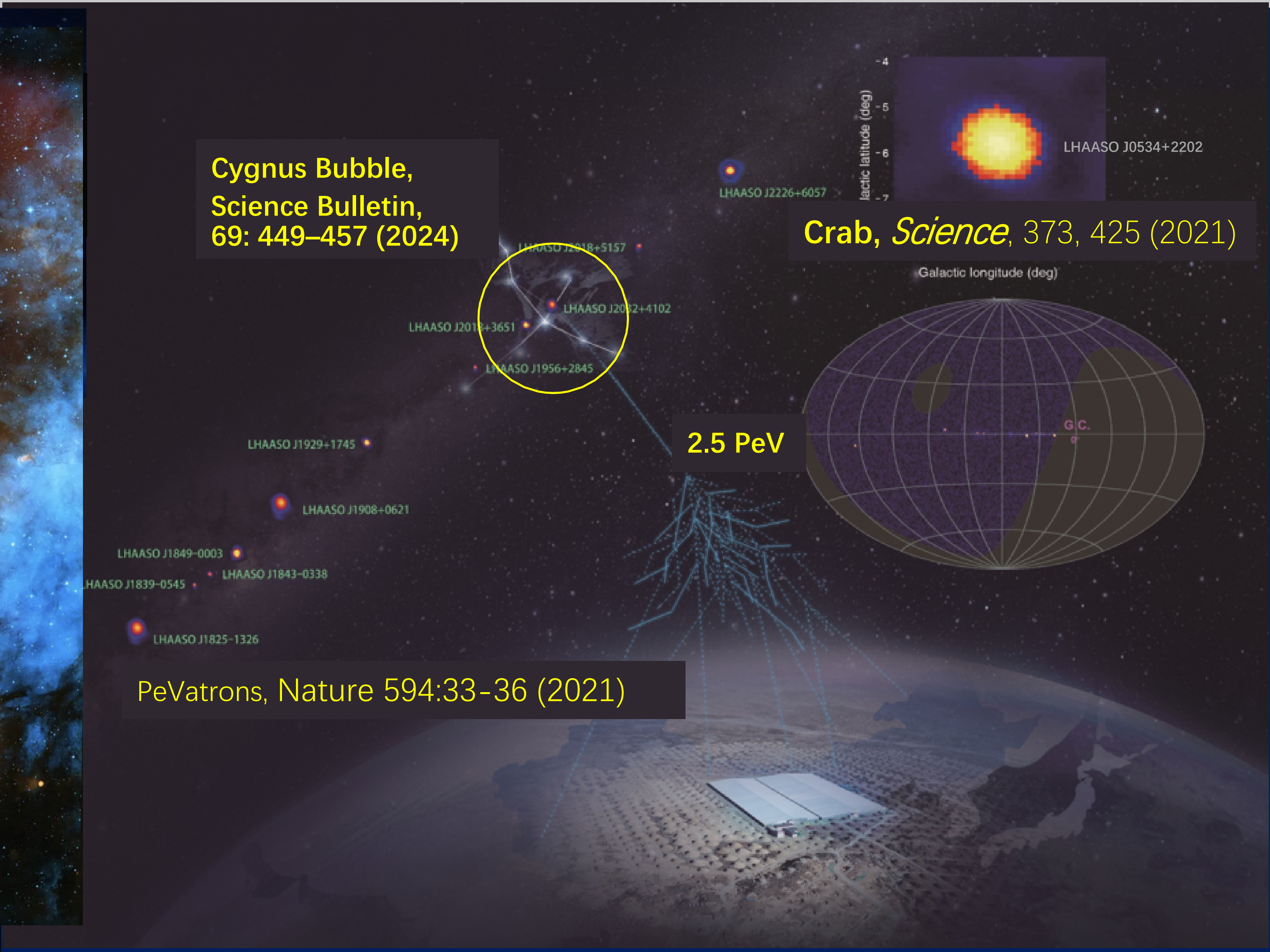
LHAASO discovers extension of the Crab spectrum to 1.1 PeV

- Covering 3.5 decades of energy
- The highest photon energy up to 1.1 PeV
- Clear origin: a well-known Pulsar Wind Nebula (PWN)
- An extreme electron accelerator:
  - 2.3 PeV electron in 100 μG fields
  - Require 16% acceleration rate ($10^3\times$ higher than SNR shock waves)
- This either challenges fundamental laws of electron acceleration in high energy astrophysics
- or indicates origin of CRs above the knee

LHAASO Collaboration, Science, 373, 425 (2021)

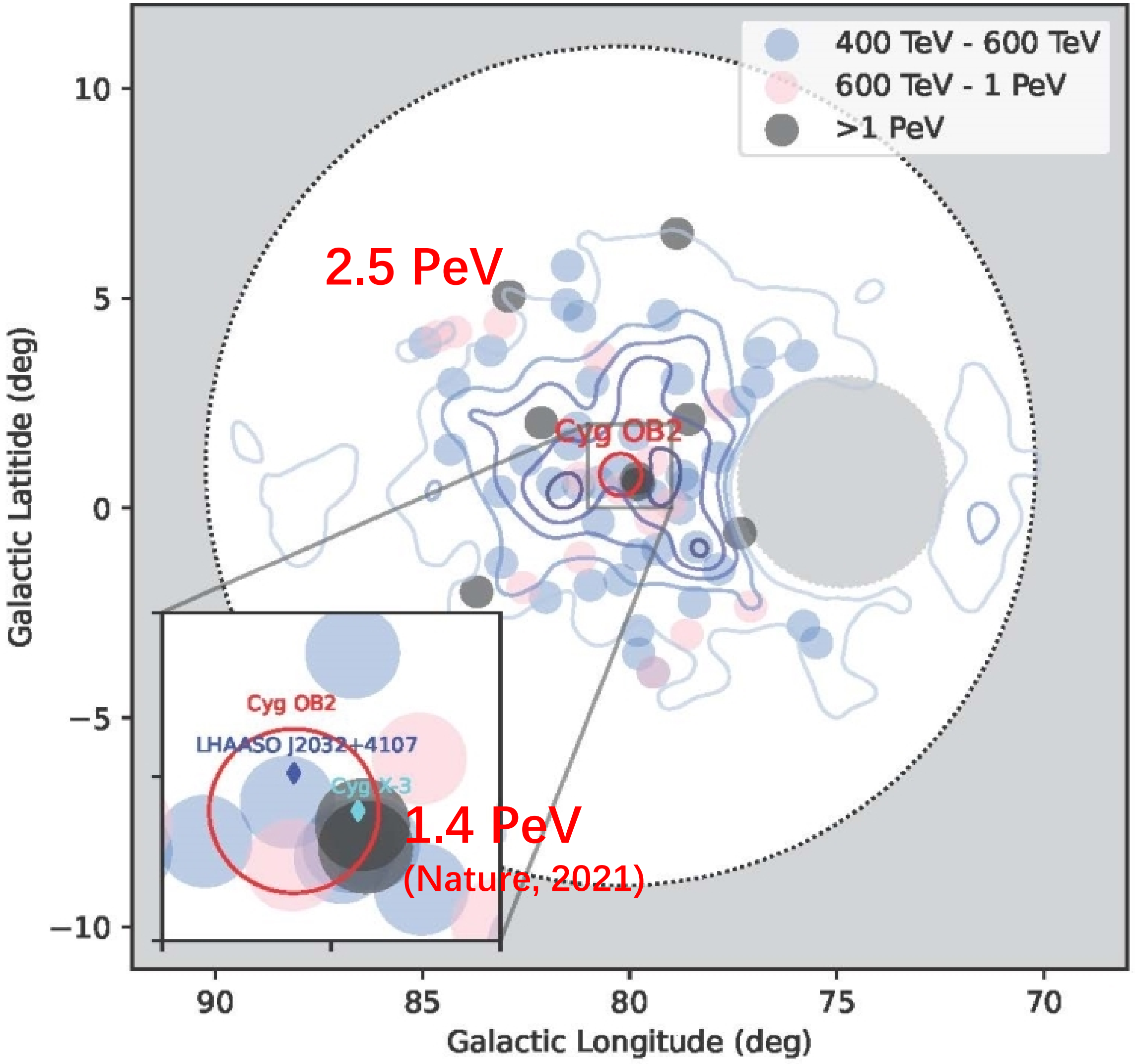


The 1^{st} CR-Source Candidate by LHAASO



A Bubble of UHE γ's centered at a complex core

Cygnus OB2, binary J2032+4107, MQ X-3



8 γ's above 1 PeV!

Energy (TeV)	Ne	Nu	Theta (deg)	Dr (m)
1087	5904	13	19.4	143
1188	5480	14	34.4	73
1208	6939	13	14.2	131
1350	6938	8	27.1	43
1379	6469	9	17.4	52
1421	6258	7	12.7	57
1784	6665	13	18.0	41
2481	13815	29	33.0	99

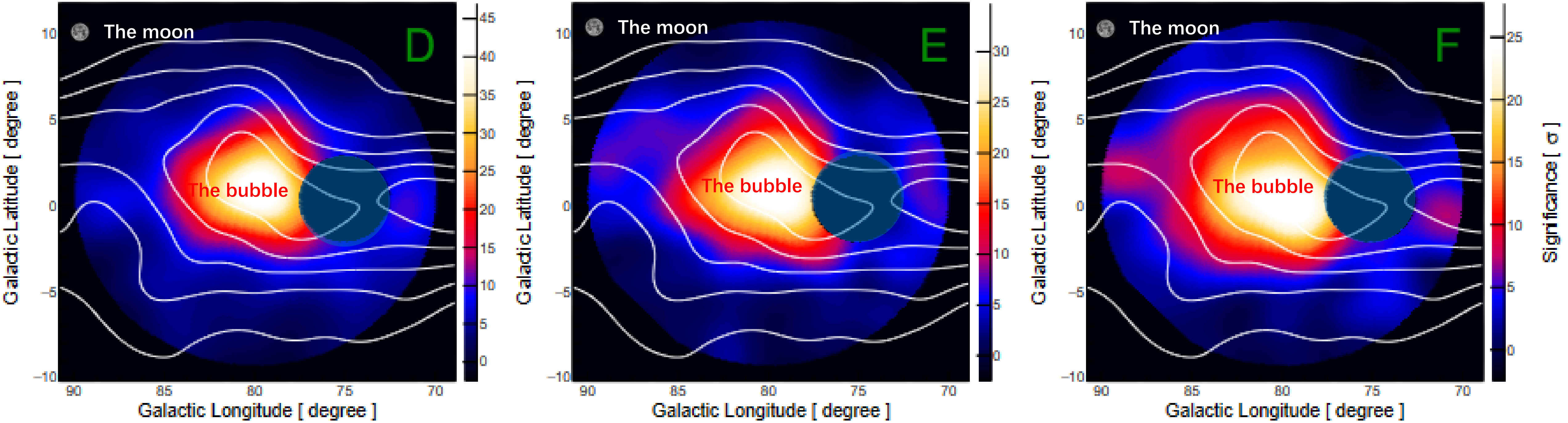
- PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

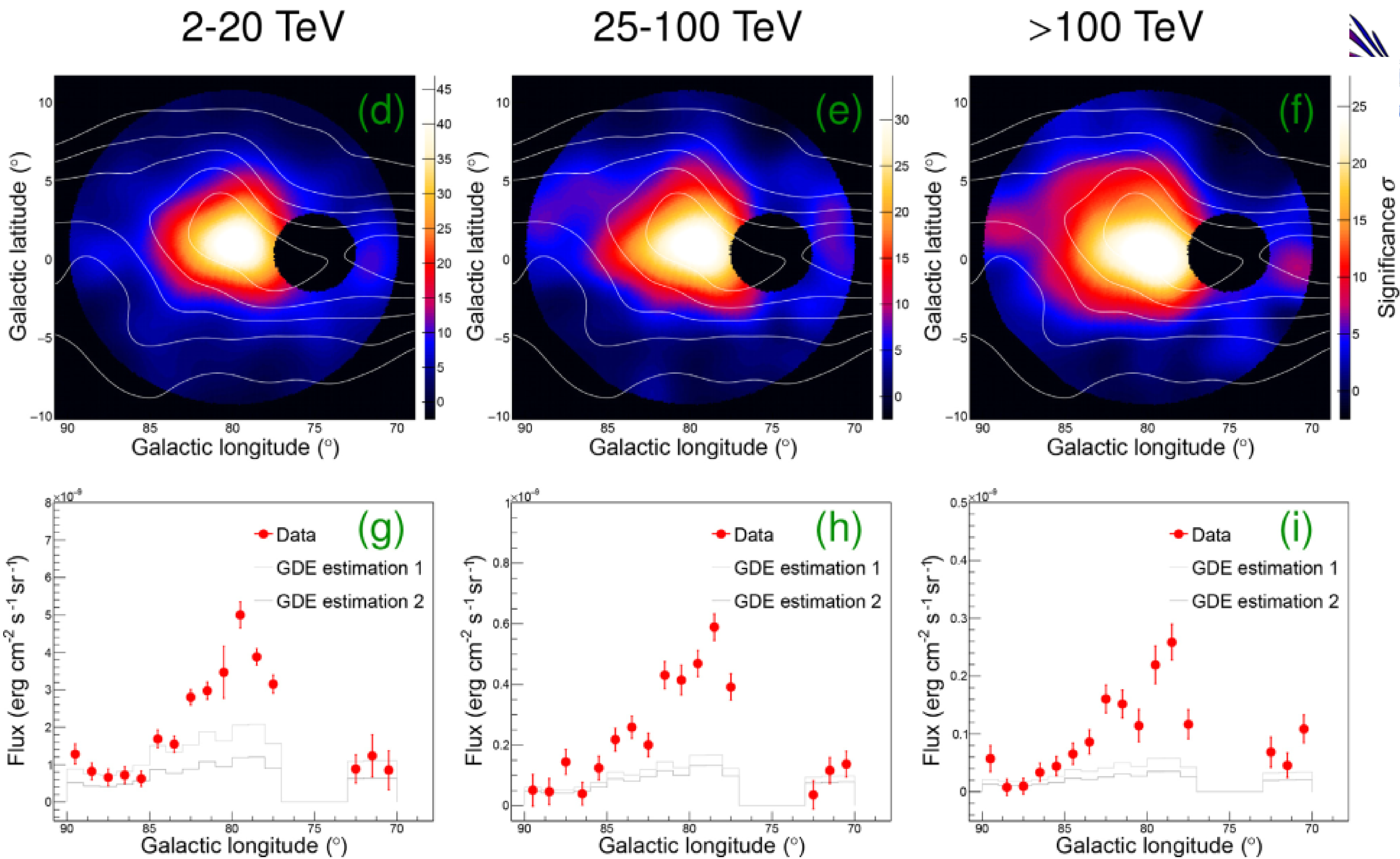
Association with HI gas distribution over ~200 pc

- The significance map is smoothed with a Gaussian kernel=1.0°
- The contour is from HI4PI 21-cm line survey

◆ Clear correlation with gas distribution indicating a hadronic origin of photons in the Bubble

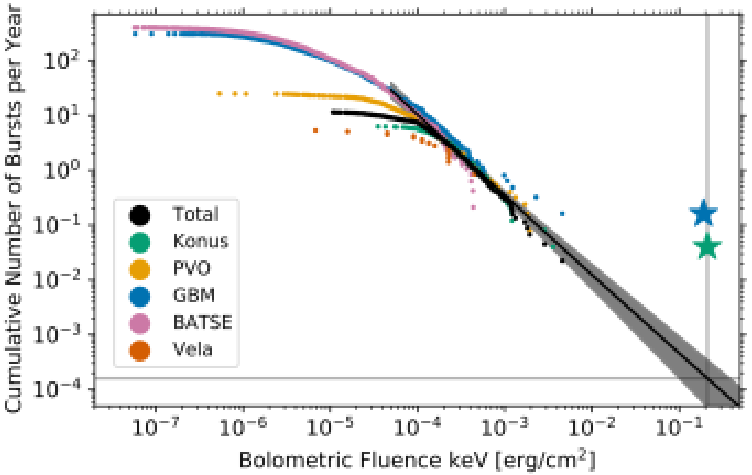
◆ The signal is elongated along the disk and extends to 10°

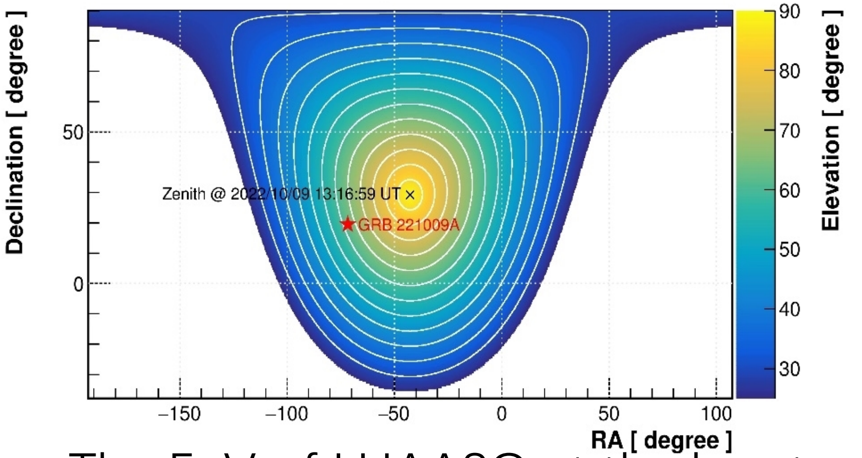



2-20 TeV
25-100 TeV
>100 TeV
(d)
(e)
(f)
Galactic latitude (°)
Galactic longitude (°)
Significance σ
(g)
(h)
(i)
Data
GDE estimation 1
GDE estimation 2
Flux (erg cm⁻² s⁻¹ sr⁻¹)
Galactic longitude (°)

GRB 221009A: The brightest of all time
The 1st GRB seen by EAS detector

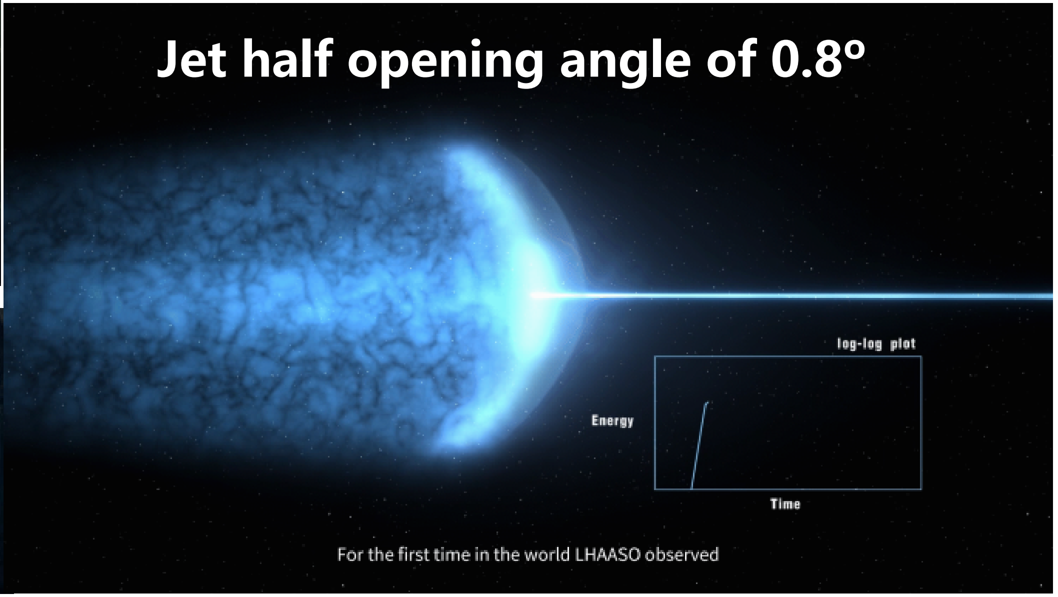
- Highest fluence / peak flux (An et al. 2023)
- Nearby
- Highest energy / peak luminosity (An et al. 2023)
- Once a 1,000/10,000 yr event (Burns et al. 2023)





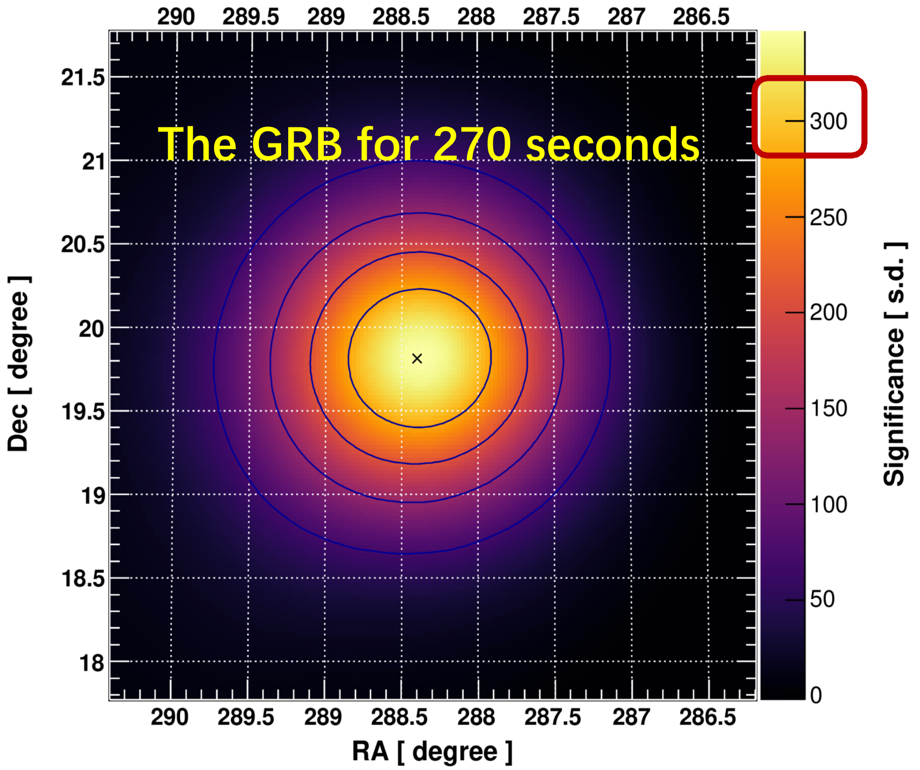
The FoV of LHAASO at the burst

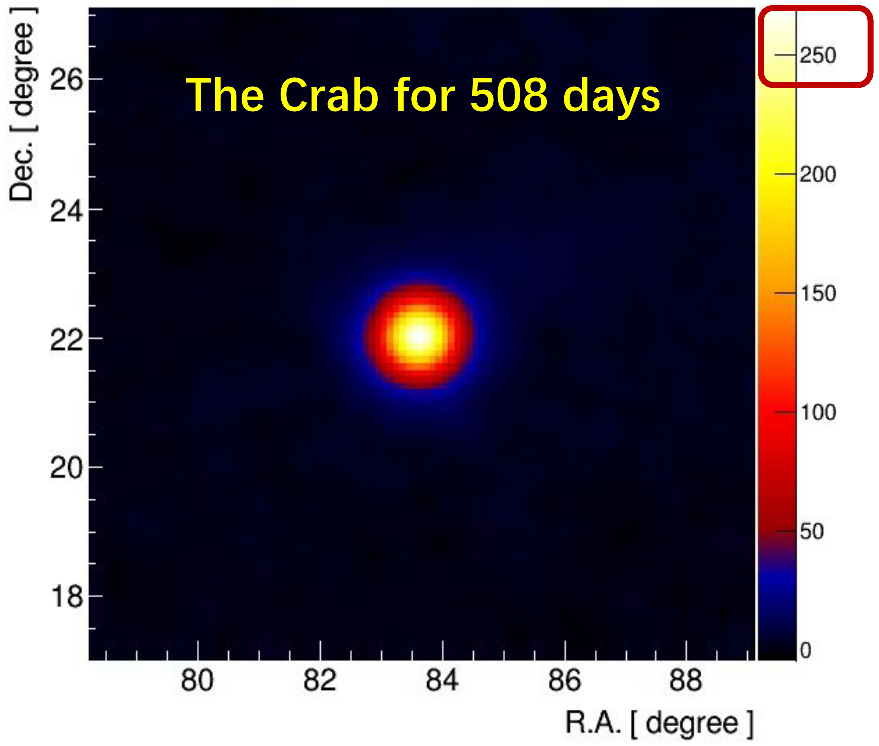
By Bing Zhang



Even much less chance for it in the middle of FoV of LHAASO

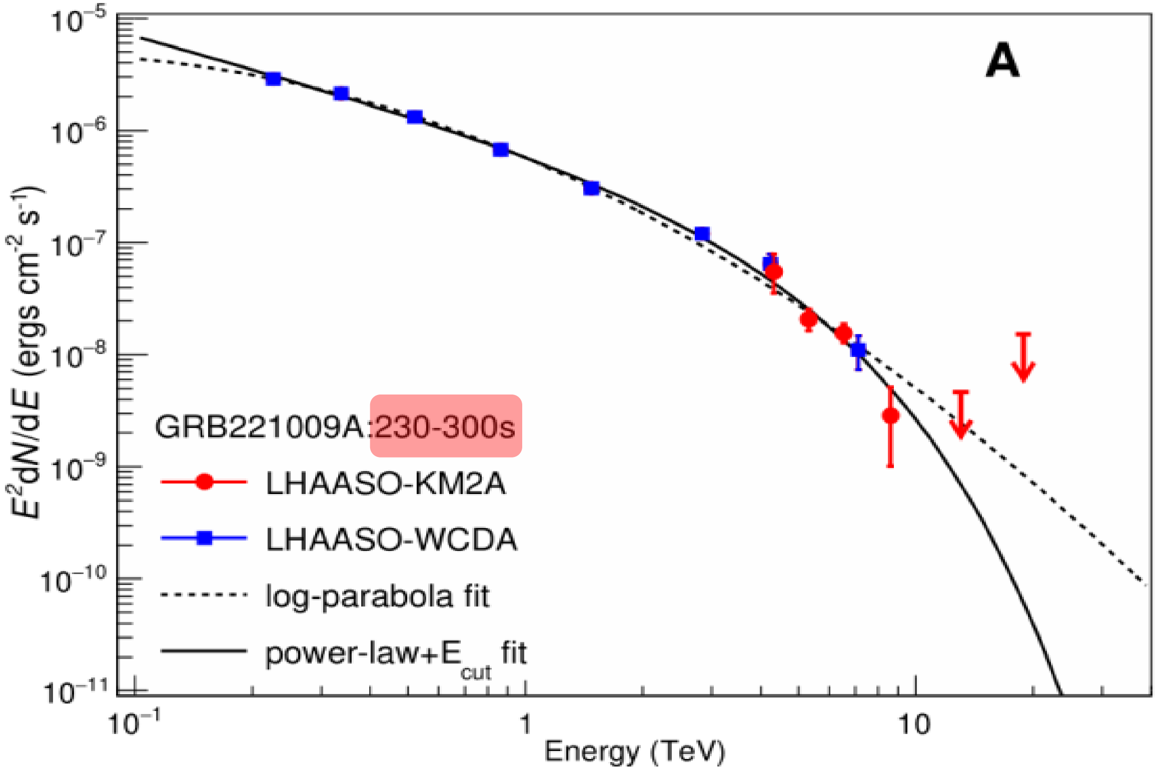
- The burst of 64k photons in **270 seconds** versus the exposure of the Crab for 508 days

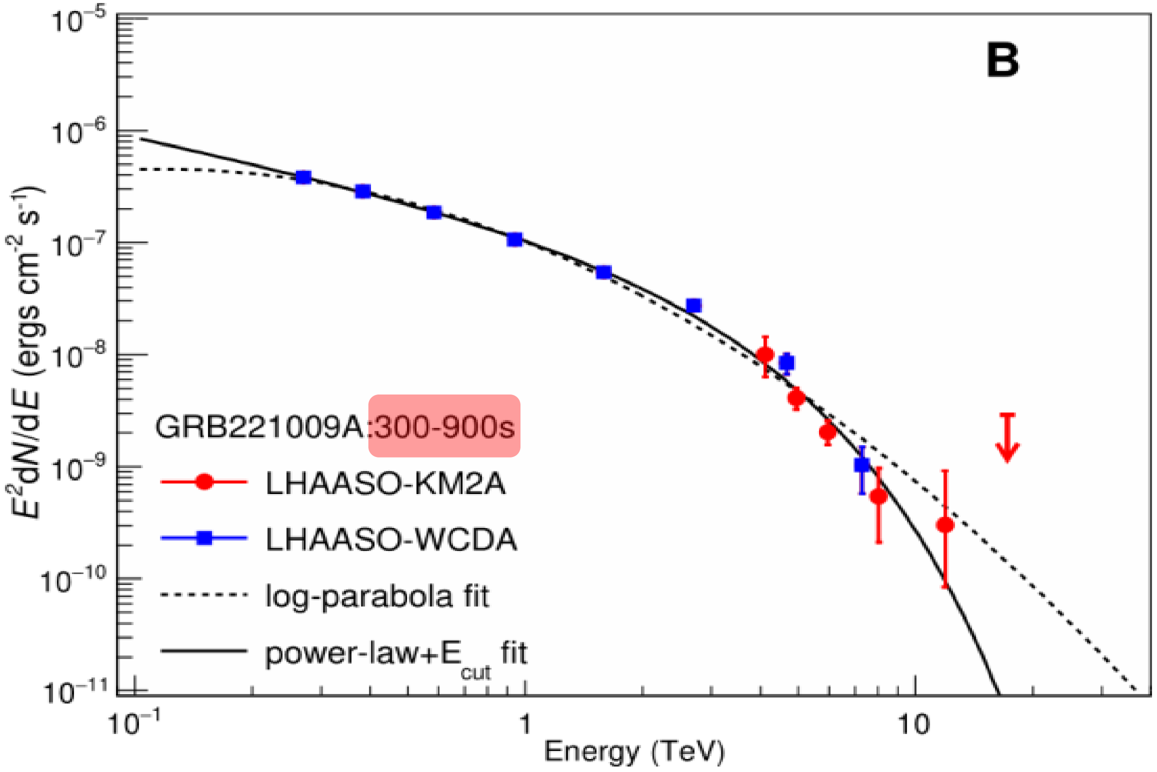




SED in two phases: bright and fading

- The "best fit" among $E^{-\gamma}$, $E^{-\Gamma}$ ($\Gamma=\Gamma_0+k\,log(E/E_0)$) and $E^{-\gamma}\exp\{-E/E_c\}$
  power-law, log-parabola and power law + cut-off
- **The power law + cut-off is favored**

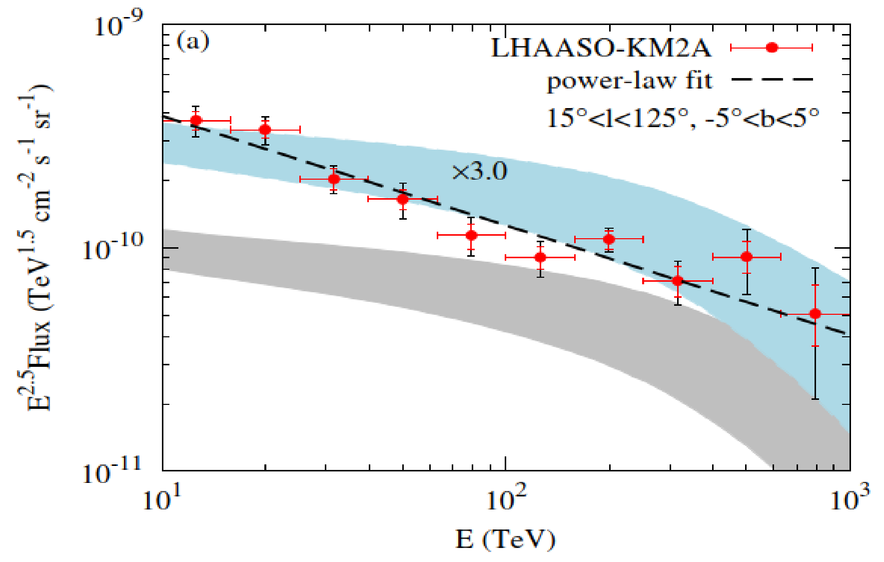


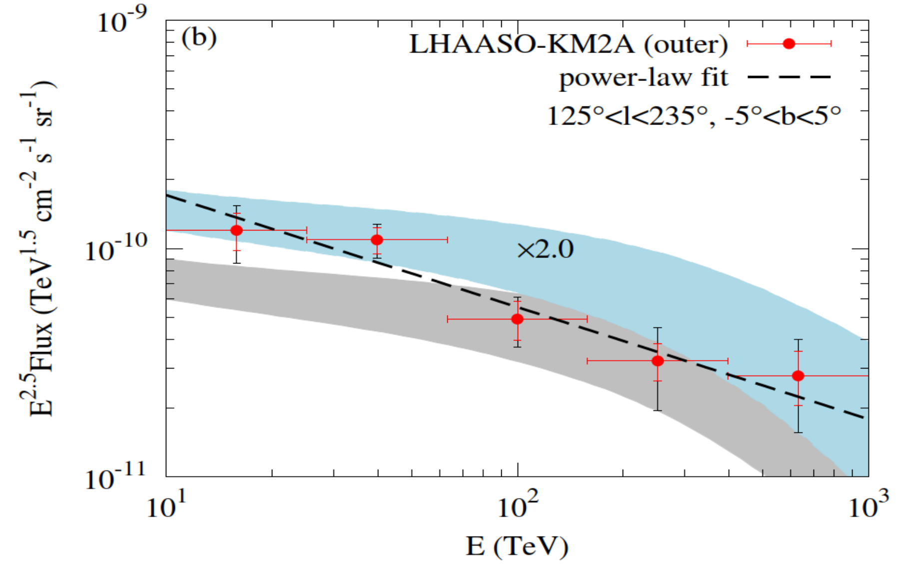


UHE diffuse γ emission of the Galactic plane from 10 TeV to 1 PeV

- Measured fluxes are higher by a factor of 2~3 than predictions (the local CR interaction with l.o.s. gas): unresolved sources or propagation effect?
- The diffuse emission from two regions of the Galactic plane was observed with high significance;
- Firstly detected in the outer Galaxy region! Spectral indices of both inner and outer regions are about -3; deviation from single power-law is not evident by the current data.

PRL 131:151001 (2023)





Testing Lorentz Invariance for any violation

- Using the most energetic γ-rays observed by LHAASO
  - The Lorentz symmetry was tested for the 1st order effect w/ the breaking energy 10^5 higher than the Planck scale, a dozen of times higher than the previous result
  - The 2nd order effect is still possible, w/ the breaking energy 10^3 below the Planck scale

Process: $\gamma \rightarrow e^+e^-$

$$E_{\rm LIV}^{(1)} \gtrsim 9.57 \times 10^{23}\ {\rm eV}\left(\frac{E_\gamma}{\rm TeV}\right)^3,$$

$$E_{\rm LIV}^{(2)} \gtrsim 9.78 \times 10^{17}\ {\rm eV}\left(\frac{E_\gamma}{\rm TeV}\right)^2.$$

Process: $\gamma \rightarrow 3\gamma$

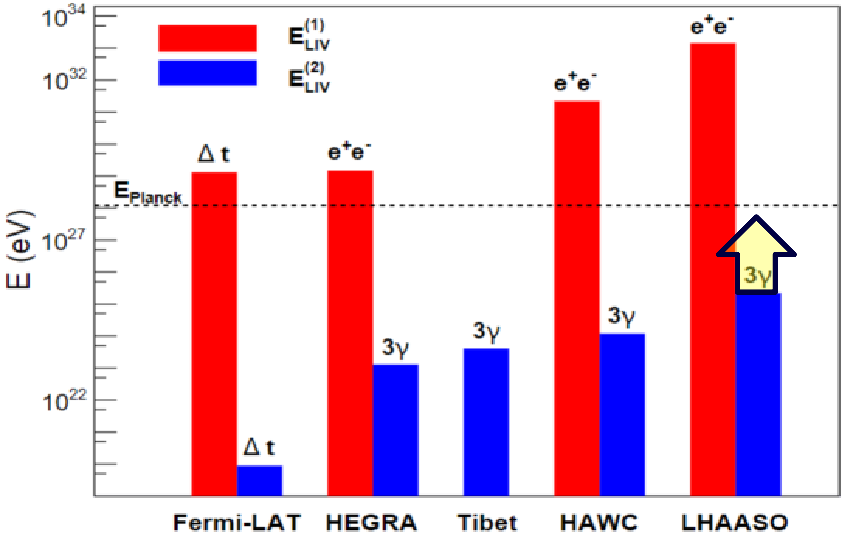
$$\Gamma_{\gamma\rightarrow 3\gamma} = 5 \times 10^{-14}\frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

$$E_{LIV}^{(2)} > 3.33 \times 10^{19}{\rm eV}\left(\frac{L}{\rm kpc}\right)^{0.1}\left(\frac{E_\gamma}{\rm TeV}\right)^{1.9}.$$

Source	L (kpc)	$E_{\rm max}$ (PeV)	$E_{\rm cut}^{95\%}$ (PeV)	$E_{\rm LIV}^{(1)}$ (eV) $\times 10^{32}$	$E_{\rm LIV}^{(2)}$ (eV) $\times 10^{23}$	$E_{\rm LIV}^{(2)}$ (3γ) (eV) $\times 10^{25}$
Crab Nebula	2.0	0.88 ± 0.11	$0.75^{+0.04}_{-0.04}$	$4.04^{+0.69}_{-0.62}$	$5.5^{+0.61}_{-0.58}$	$1.04^{+0.11}_{-0.10}$
J2032+4102	1.4	1.42 ± 0.13	$1.14^{+0.06}_{-0.06}$	$14.2^{+2.42}_{-2.18}$	$12.7^{+1.41}_{-1.34}$	$2.21^{+0.23}_{-0.22}$

$E_{\rm planck} = 1.22 \times 10^{19}$ GeV

$10^5\ E_{\rm planck}$ $0.1\%\ E_{\rm planck}$



3 orders of magnitudes below the Planck-scale

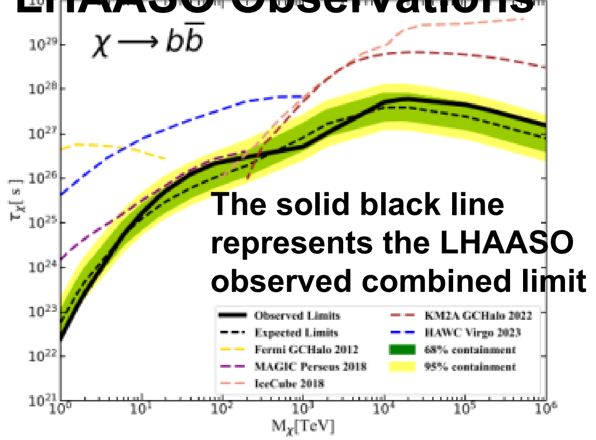
LHAASO Coll., PRL 128, 051102 (2022)

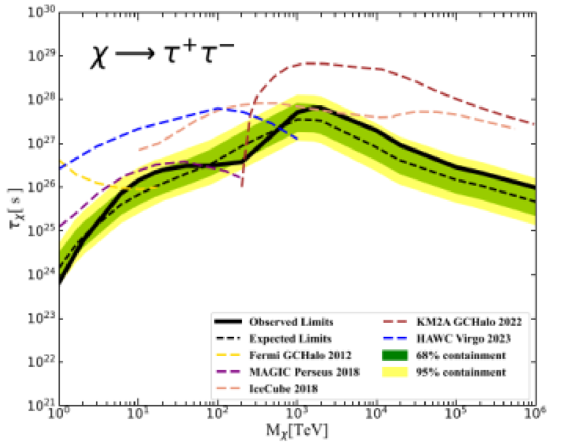
LHAASO: Constraints on Heavy Decaying Dark Matter

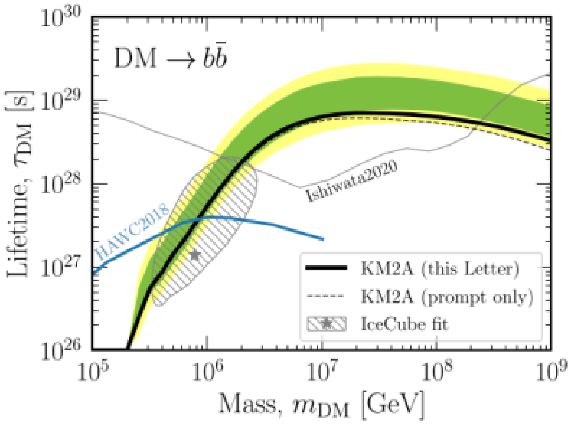
- 570 Days of LHAASO Observation on the Galactic halo
  - The strongest constraints on heavy DM (1 PeV to 10PeV) lifetime is ~10 times higher than existing limits
  - Highly constrains the hypothesis of DM as a source of HE ν's
  - Highlighted by PRL in 2022.
- 19 Dwarf Galaxies are observed

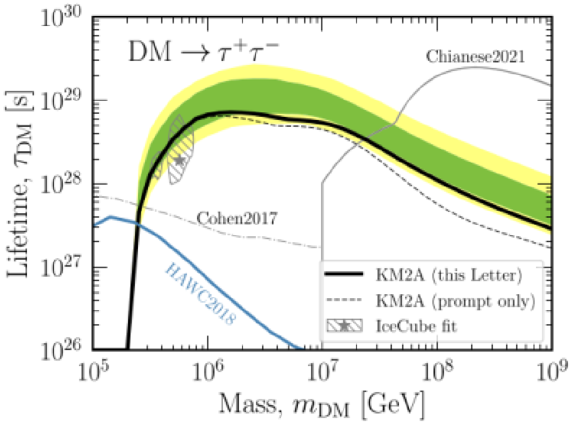
Source	RA. (deg)	DEC. (deg)	θ_{max} (deg)	$\log_{10} J_{obs}$ (GeV^2cm^{-5})
Boötes I	210.02	14.50	0.47	18.2 ± 0.4
Canes Venatici I	202.02	33.56	0.53	17.4 ± 0.3
Canes Venatici II	194.29	34.32	0.13	17.6 ± 0.4
Coma Berenices	186.74	23.90	0.31	19.0 ± 0.4
Draco	260.05	57.92	1.30	18.8 ± 0.1
Draco II*	238.20	64.56	–	18.1 ± 2.8
Hercules	247.76	12.79	0.28	16.9 ± 0.7
Leo I	152.12	12.30	0.45	17.8 ± 0.2
Leo II	168.37	22.15	0.23	18.0 ± 0.2
Leo IV	173.23	−0.54	0.16	16.3 ± 1.4
Leo V	172.79	2.22	0.07	16.4 ± 0.9
Pisces II*	344.63	5.95	–	16.9 ± 1.6
Segue 1	151.77	16.08	0.35	19.4 ± 0.3
Sextans	153.26	−1.61	1.70	17.5 ± 0.2
Triangulum II*	33.32	36.18	–	20.9 ± 1.3
Ursa Major I	158.71	51.92	0.43	17.9 ± 0.5
Ursa Major II	132.87	63.13	0.53	19.4 ± 0.4
Ursa Minor	227.28	67.23	1.37	18.9 ± 0.2
Willman 1*	162.34	51.05	–	19.5 ± 0.9

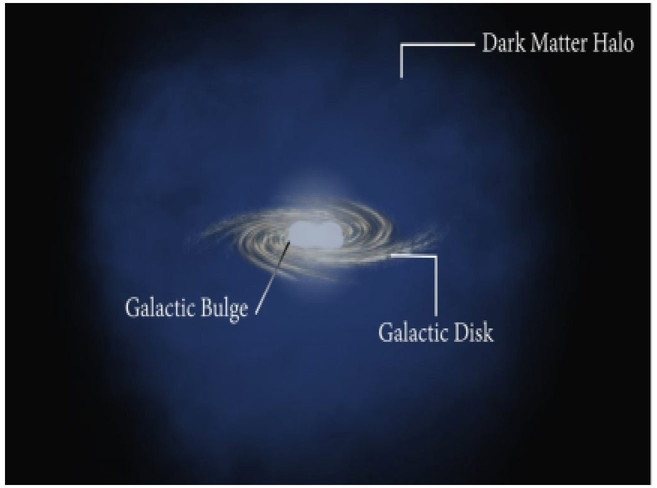
Constraints on Ultra Heavy Dark Matter Properties from Dwarf Spheroidal Galaxies with LHAASO Observations





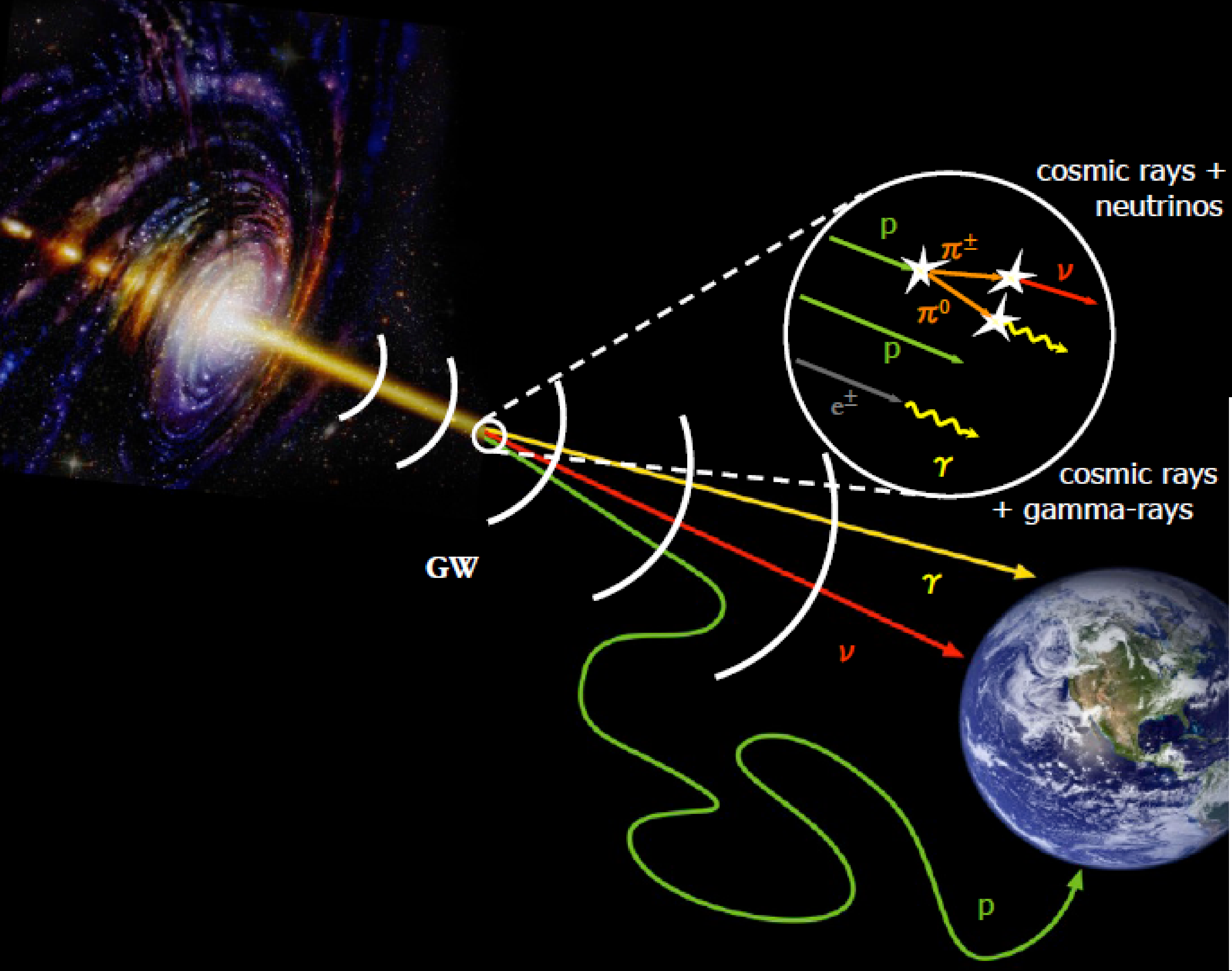


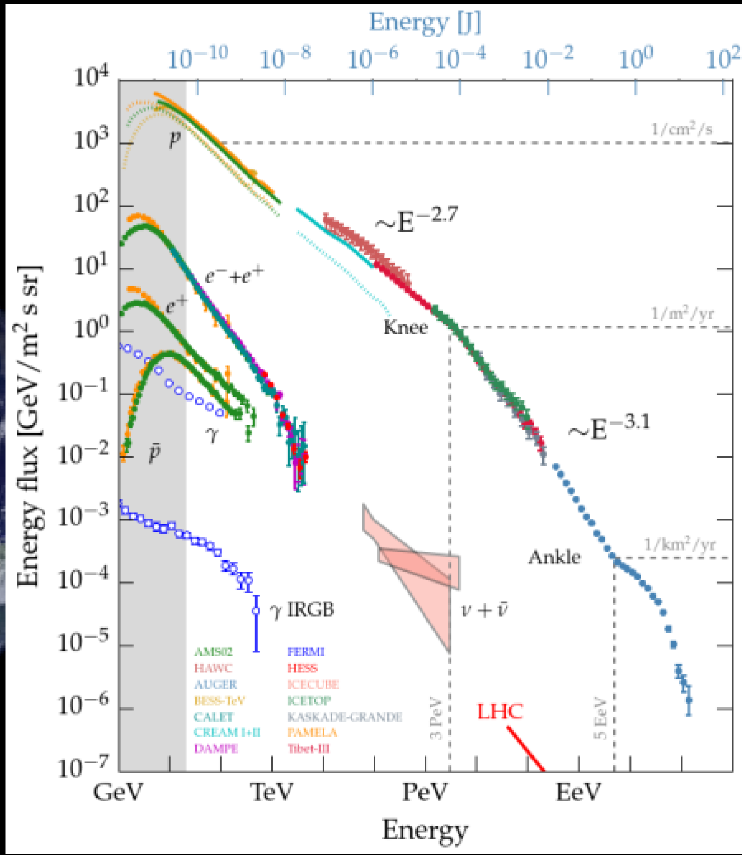




LHAASO collaboration, PRL 129, 261103 (2022)

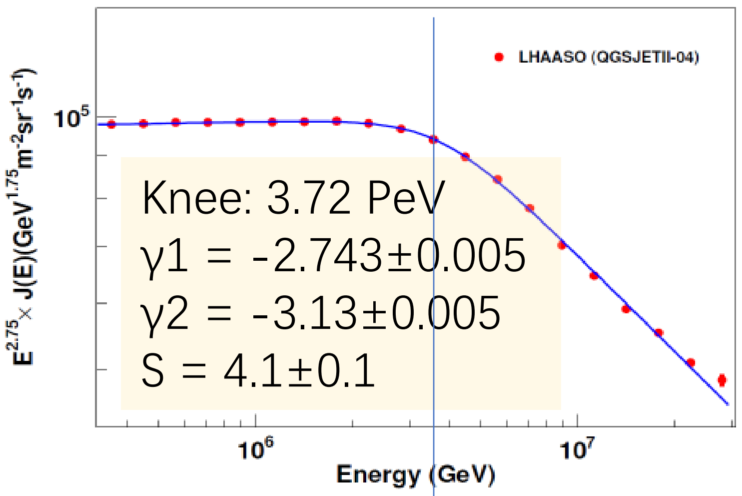
arXiv:2406.08698v1，Accepted by PRL（2024）

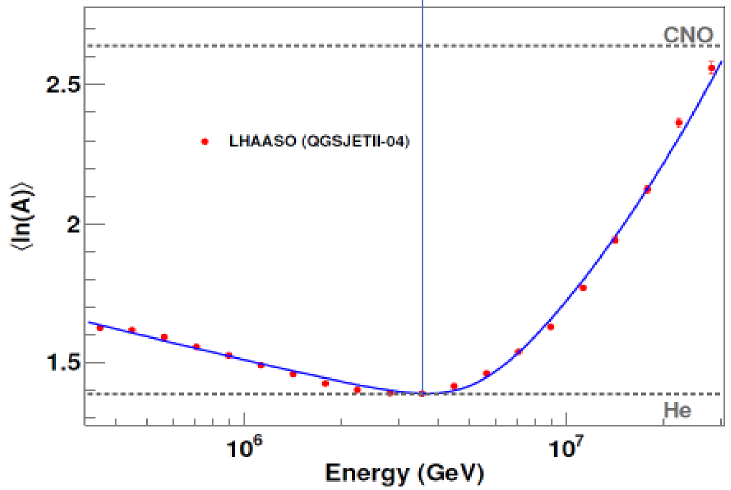

cosmic rays +
neutrinos
p
π±
ν
π0
p
e±
γ
cosmic rays
+ gamma-rays
GW
γ
ν
p

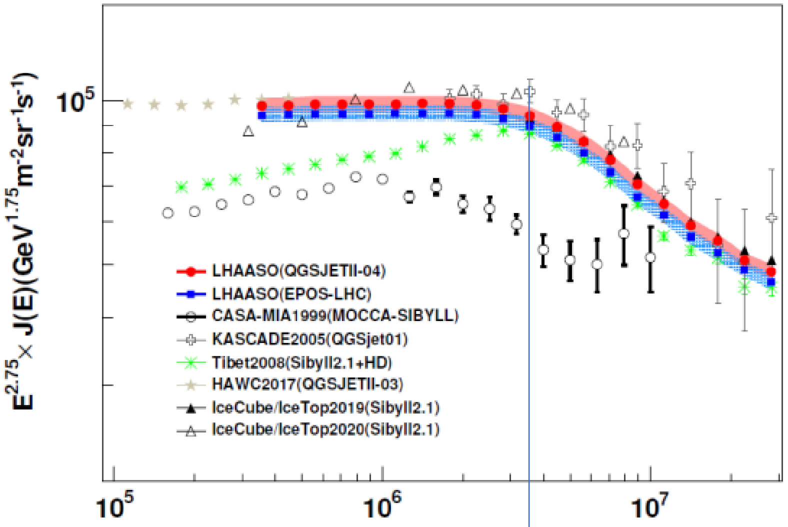

Energy [J]
10^-10 10^-8 10^-6 10^-4 10^-2 10^0 10^2
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
Energy flux [GeV/m² s sr]
1/cm²/s
p
~E^-2.7
e⁻+e⁺
e⁺
1/m²/yr
Knee
γ
p̄
~E^-3.1
1/km²/yr
Ankle
γ IRGB
ν + ν̄
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASKADE-GRANDE
PAMELA
Tibet-III
3 PeV
LHC
5 EeV
GeV TeV PeV EeV
Energy

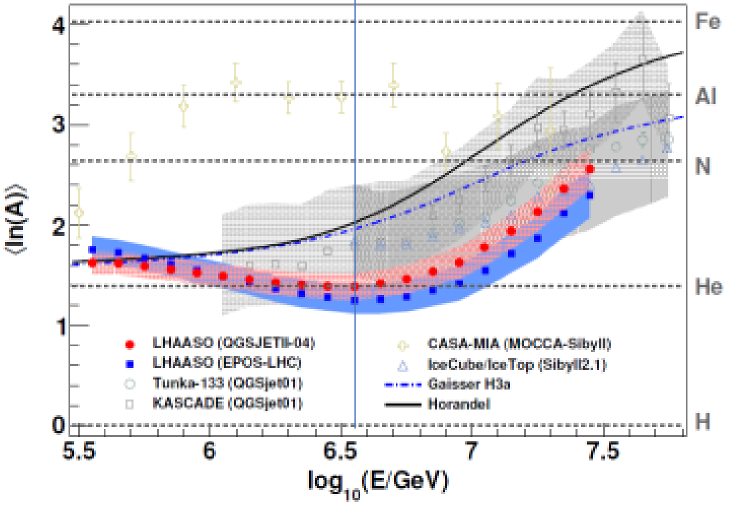
All-particle energy spectrum & composition by LHAASO

(from 0.3 to 30 PeV)









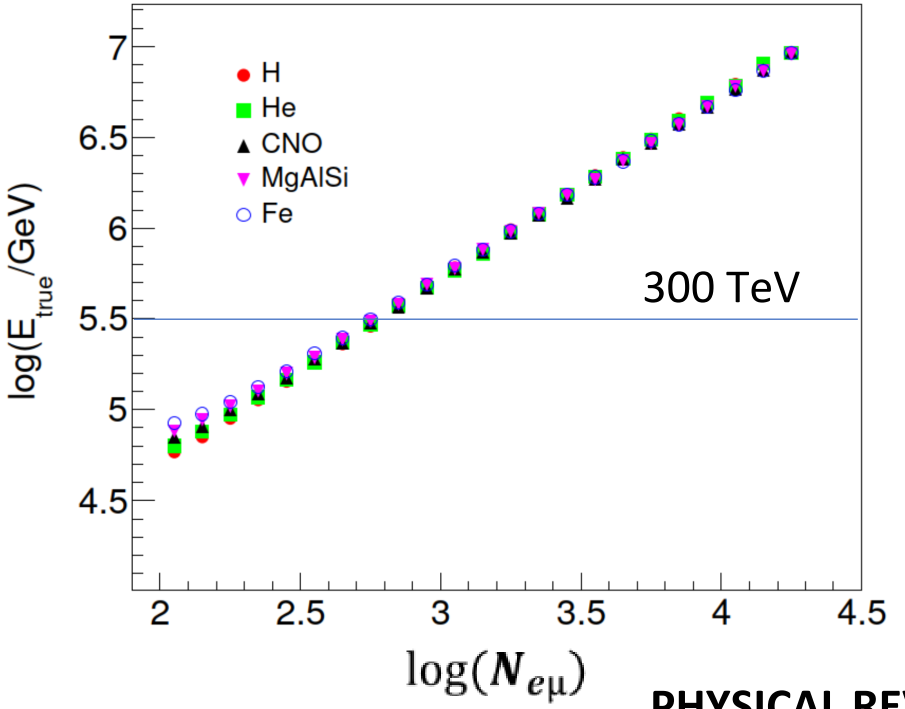
- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

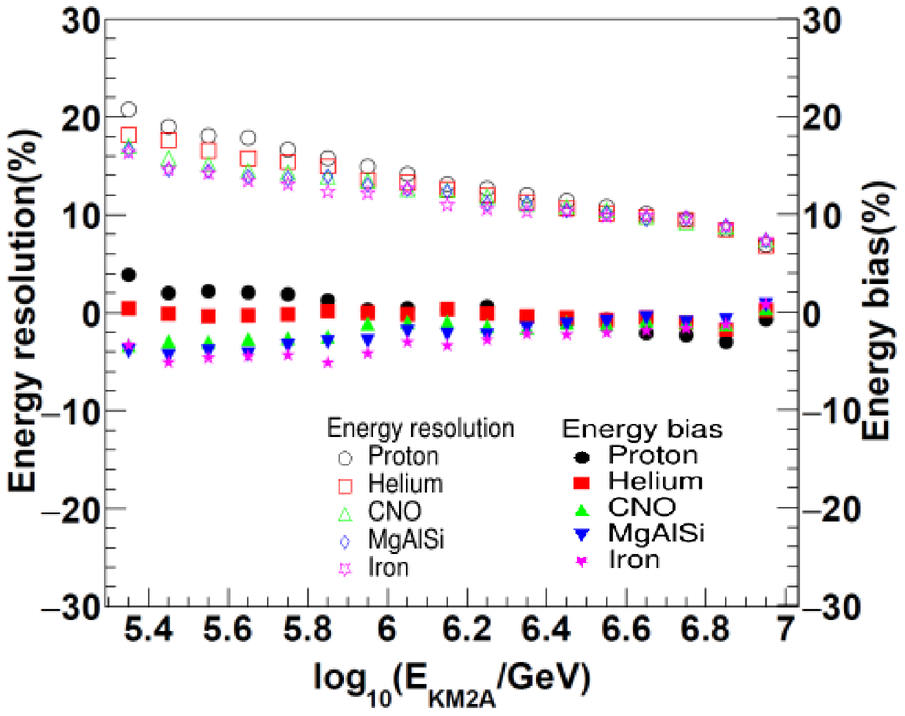
Energy reconstruction

- Energy reconstruction independent of primary CRs components
- Scintillator detector array（ED）： Electromagnetic component （N_e ）
- Muon detector array （MD）： *hadron component* $\pi^{\pm} \rightarrow \mu$ （ N_μ ）

$$E_0 = E_e + E_\mu \approx N_e^{max} \times \xi_c^e + \alpha N_\mu \times \xi_c^\pi \qquad N_{e\mu} = N_e + aN_\mu \qquad E_{rec} = b \times N_{e\mu}$$

J. Matthews, Astropart. Phys. 22, 387 (2005)



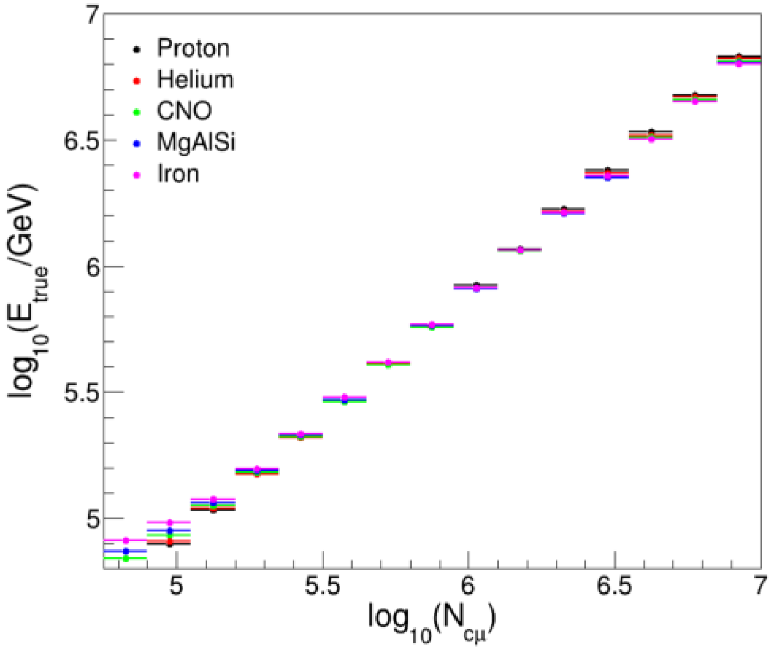


PHYSICAL REVIEW D 106, 123028 (2022)

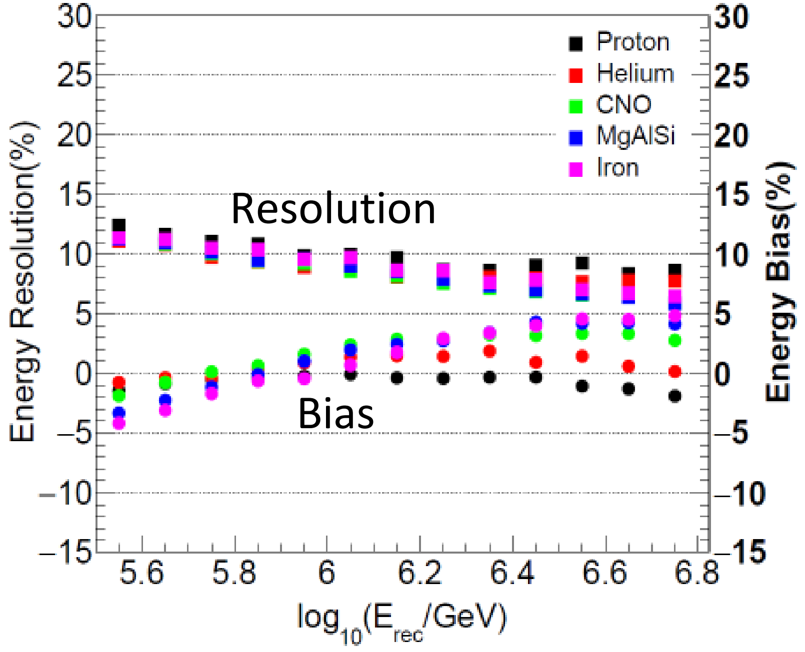
Energy reconstruction

- **Energy reconstruction independent of primary CRs components**
- **Cherenkov telescopes（WFCTA）： Electromagnetic component （ N_{pe}^{0} ）**
- **Muon detector array （MD）： *hadron component* $\pi^{\pm} \rightarrow \mu$ （ N_{μ} ）**

$$N_{c\mu} = N_{pe}^{0} + CN'_{u} \quad (C = 140)$$
$$E_{rec} = kN_{c\mu}$$

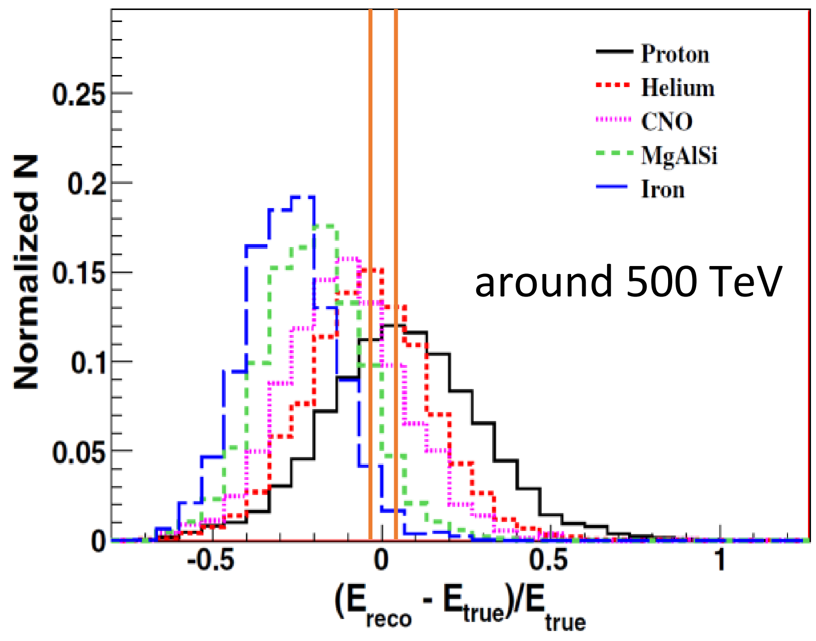


Proton and helium: <2%



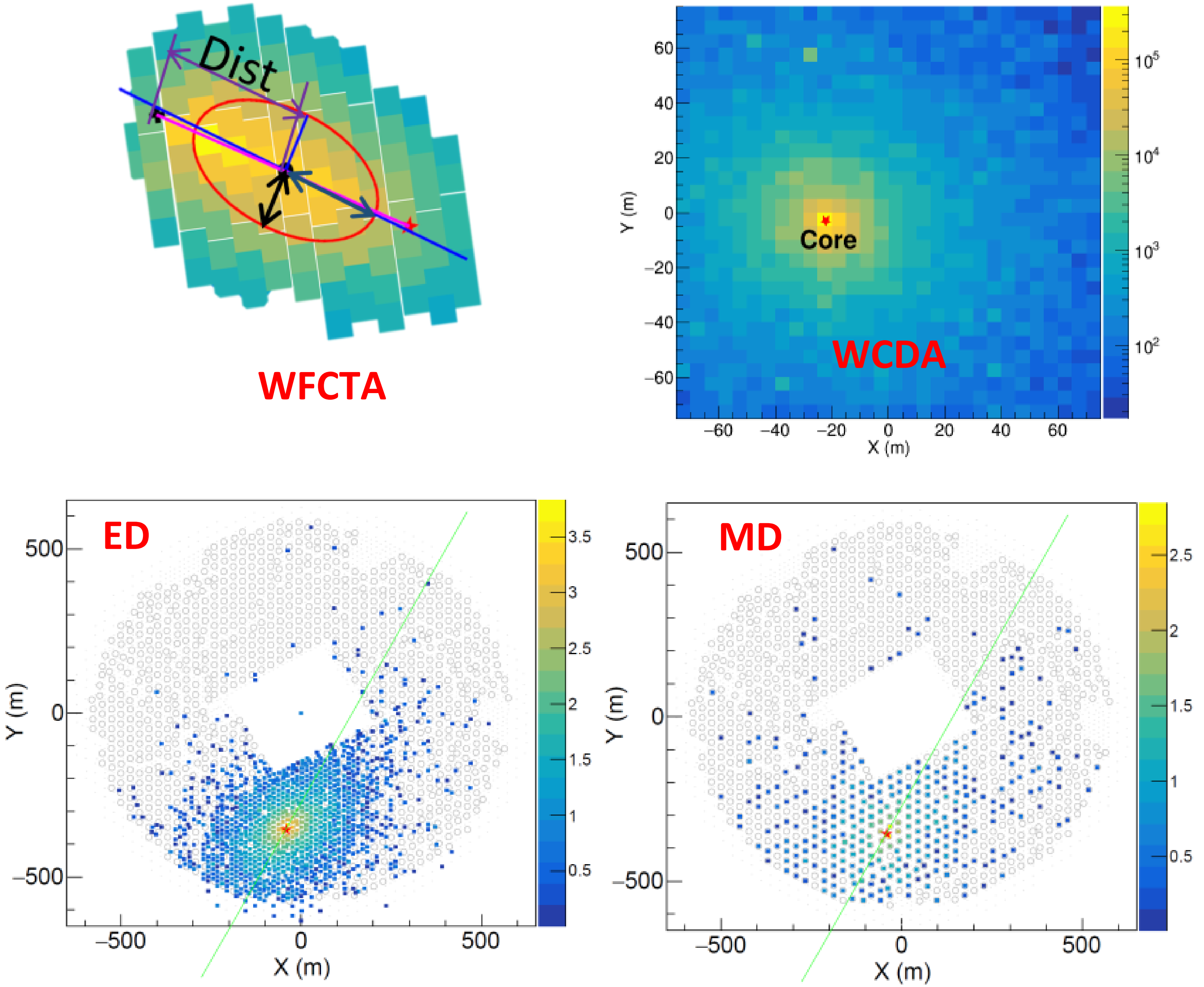
PHYSICAL REVIEW D 107, 043036 (2023)

Proton and helium: ~7%



PHYSICAL REVIEW D 92, 092005 (2015)

Hybrid measurement of LHAASO



- Mass sensitive parameters
  - X_{max} and Hillas parameters of Cherenkov image
  - Energy deposit of secondary particles near the shower core
  - Number of secondary particles near the shower core
  - Number of muons
- Shower reconstruction
  - Shower core and direction are reconstructed by WCDA or KM2A
  - Shower core resolution: $< 3\ m\ @E > 100\ TeV$
  - Shower direction resolution: $< 0.3°\ \ @E > 100\ TeV$

Mass sensitive parameters

$PDist = Dist' - (a_d \times N_{\mu e}^2 + b_d \times N_{\mu e})$

$N_{\mu e} = N_e + 45N_\mu$

$Dist' = Dist - k_p \times R_p$

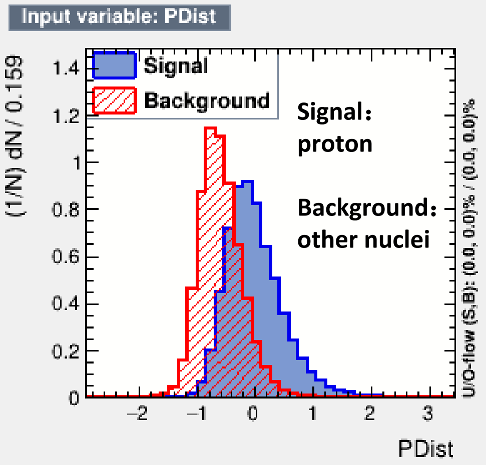
(Dist is related to Xmax)

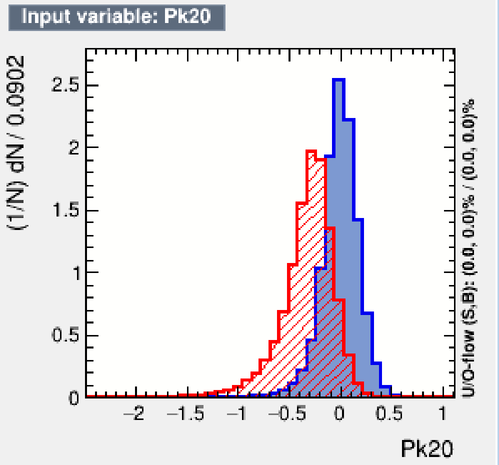
$Pk20 = \rho 20 - 1.2 \times N_{\mu e}$

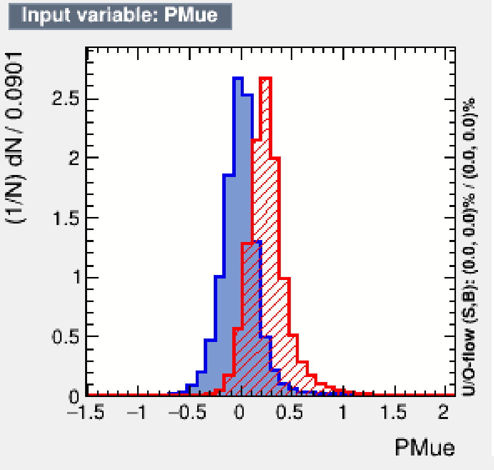
(Number of particles near the show core)

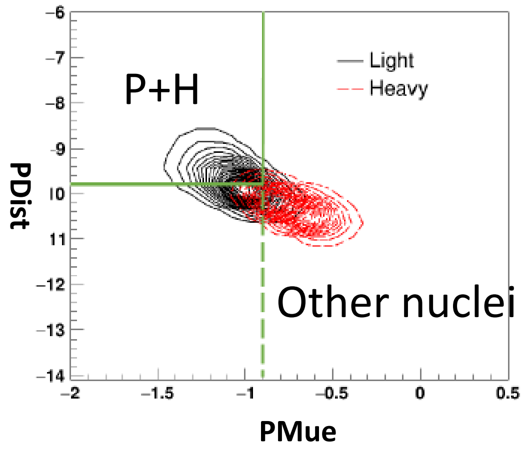
PMue= $log(N_\mu / N_e^{0.82})$

(Number of muons)

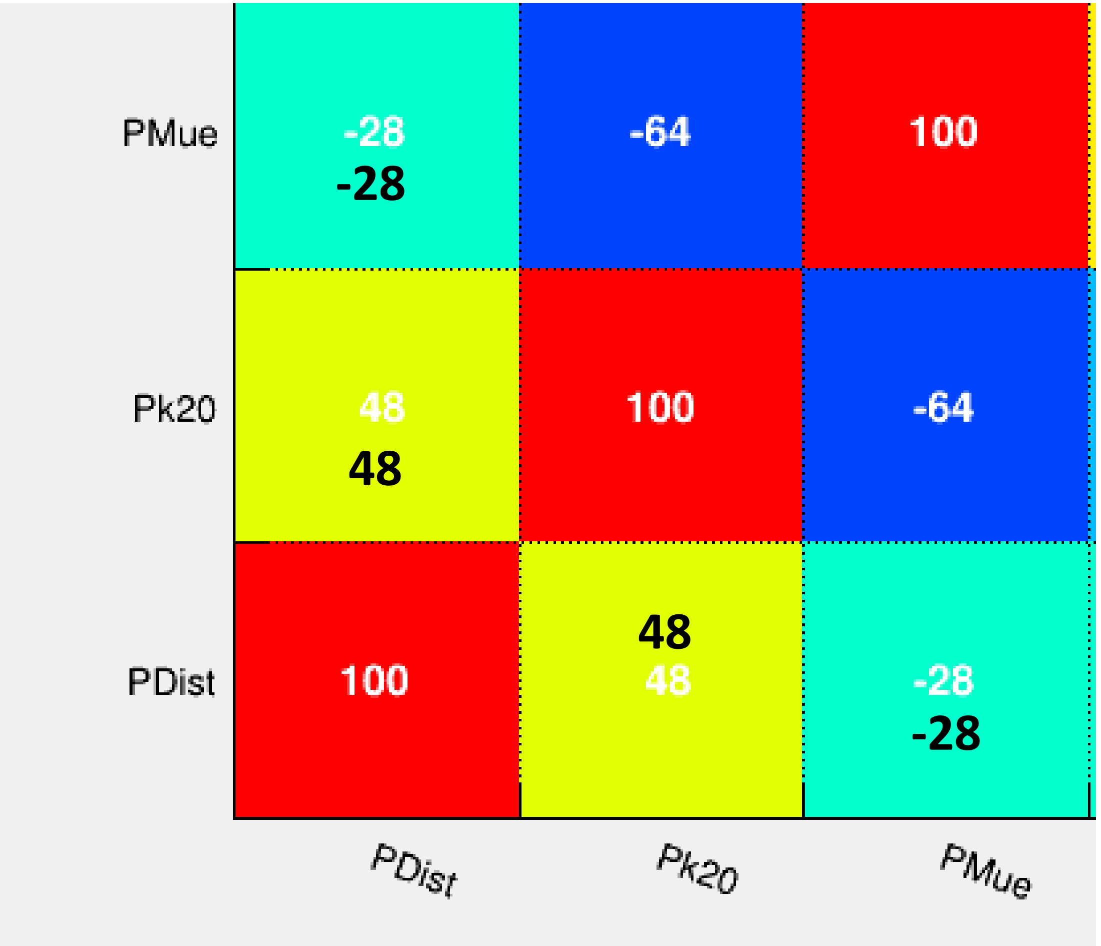








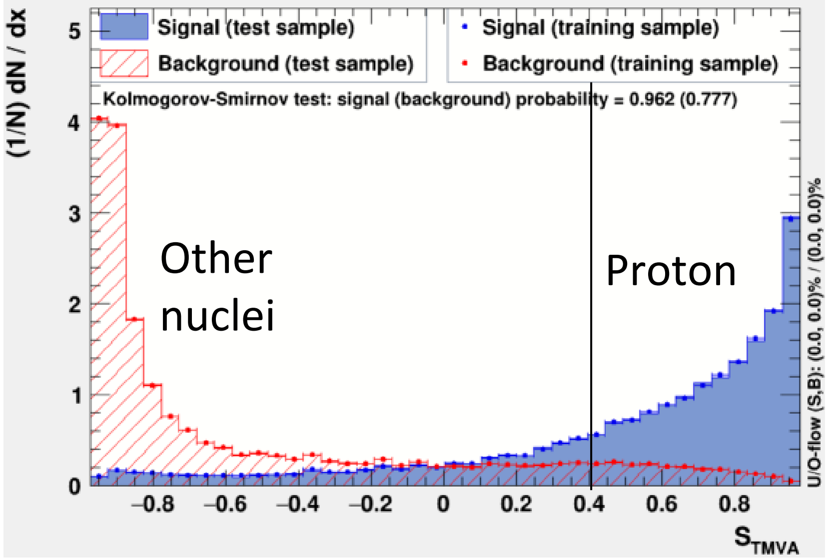
Correlation of different parameters

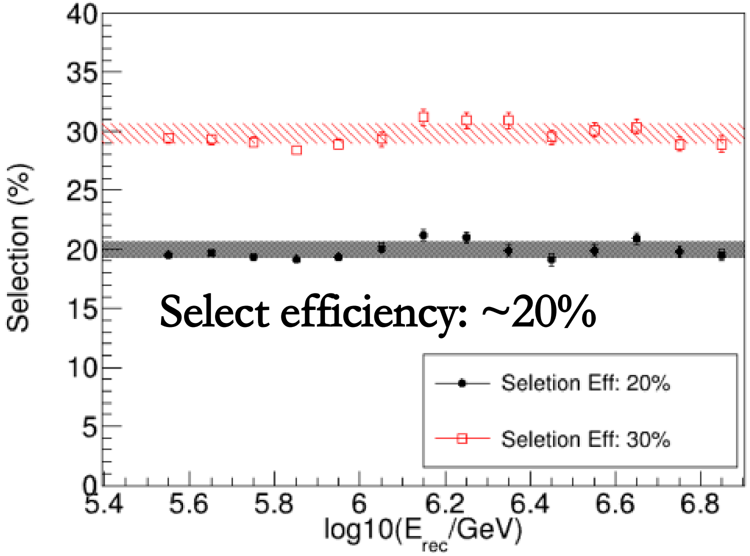


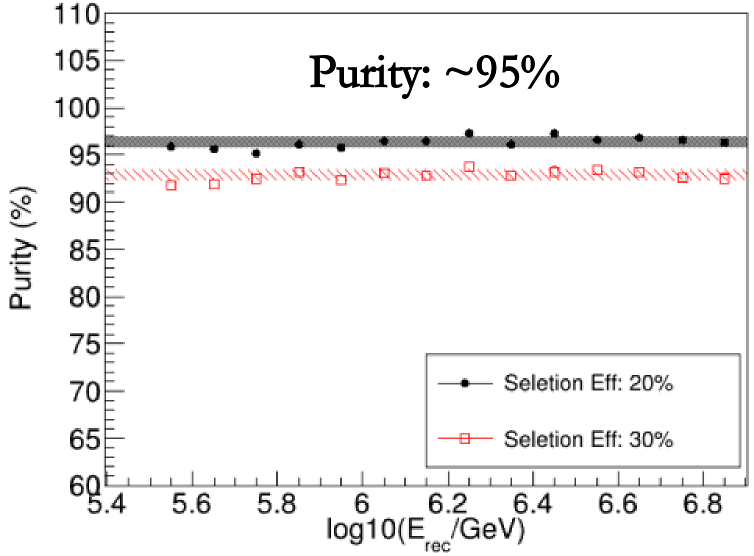
Multi-parameters analysis

TMVA(Toolkit for Multivariate Data Analysis with ROOT)

Proton





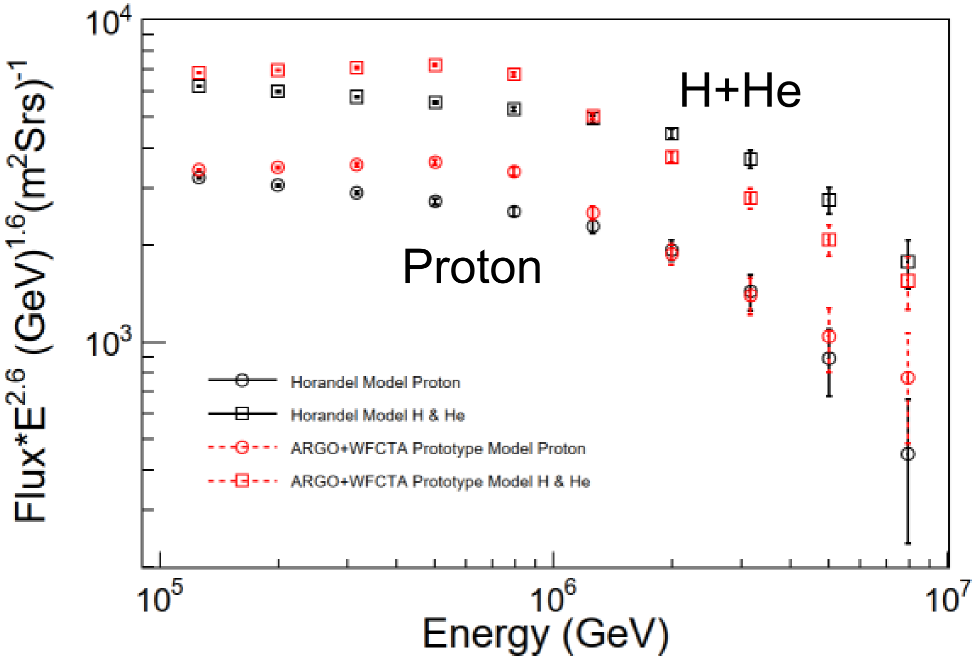


- Contamination of other nuclei： <5 %
- Aperture： ~16, 000 m^2Sr

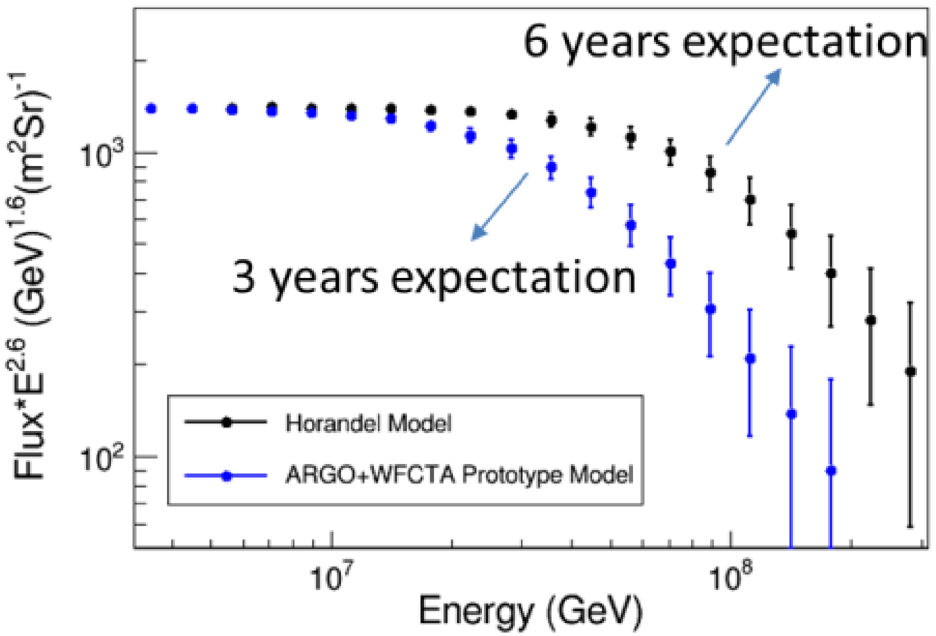
CRs Energy Spectra and Composition

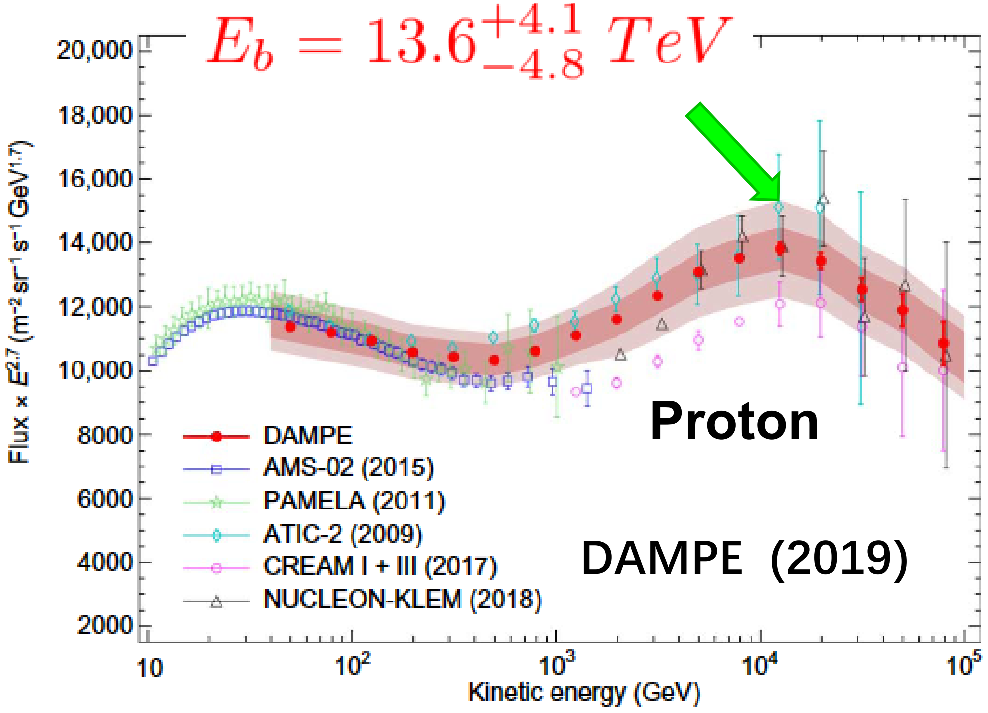
- LHAASO can achieve the knee of proton spectrum and proton + helium spectrum measurements within this year.
- The iron knee energy spectra can be achieved in three years.

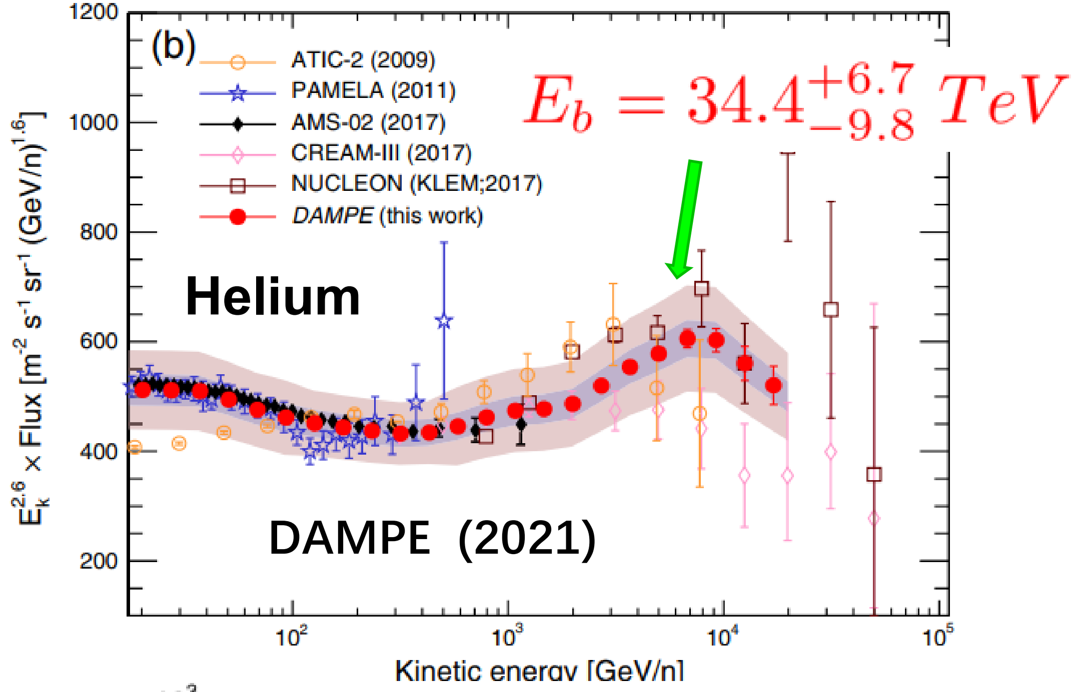
Proton knee expectation by LHAASO

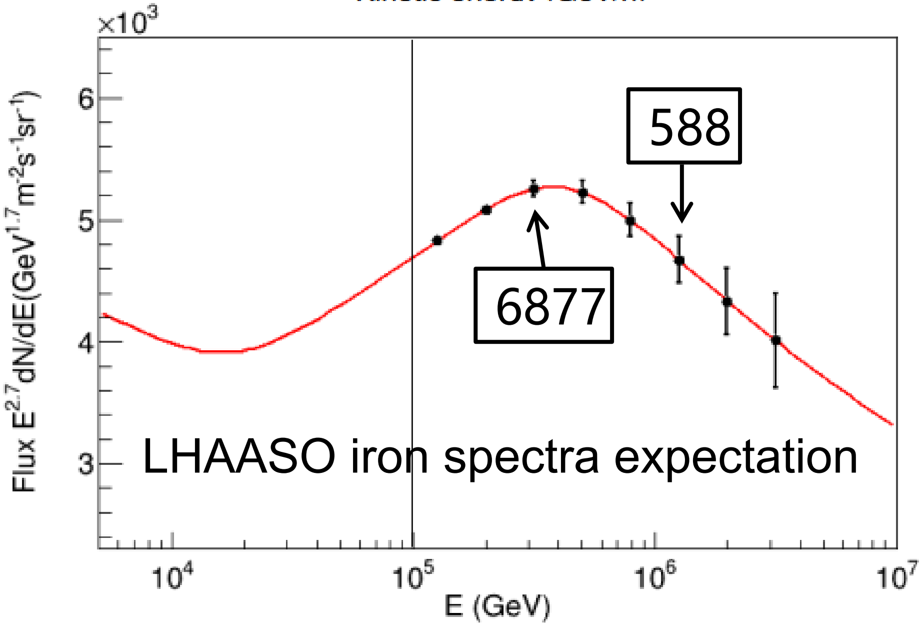


Iron knee expectation by LHAASO





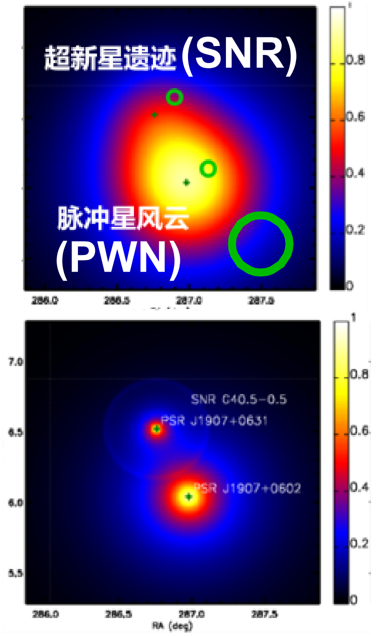


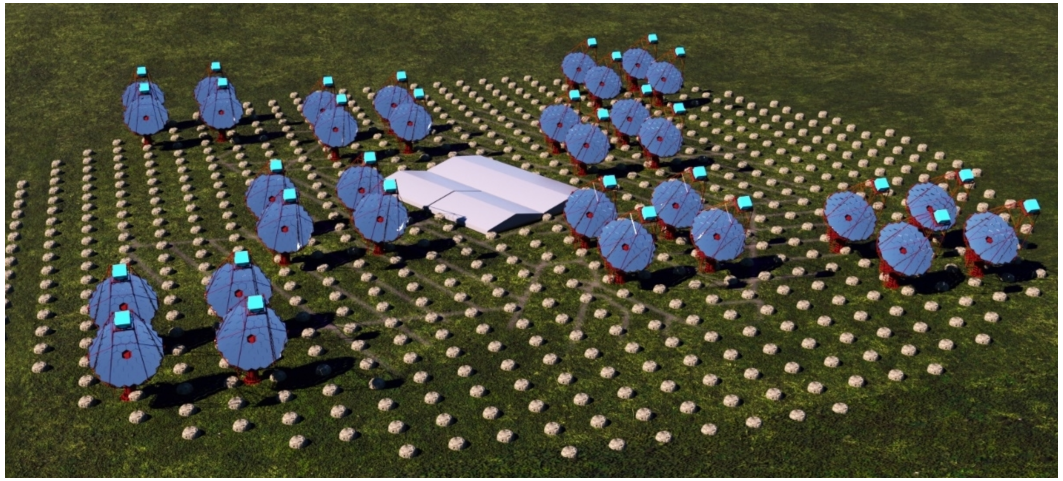


- **Break: ~13.6 TeV for Proton and ~34.4 TeV for Helium**
- **Charge Z dependent?**
  - **The ratio of Proton break and Helium break is 2.5 ± 0.8**
- **Iron spectra from 100 TeV to few PeV will be measured by LHAASO and will answer the question**

Future Missions: UHE IACT array with LHAASO

- **Large Array of Cherenkov Telescopes （LACT）**
  - Next generation of Image Atmosphere Cherenkov Telescope experiment
  - 32 telescopes built on LHAASO site
  - Angular resolution: < 0.05° @ > 10 TeV
  - **LHAASO MD array provides γ/p discrimination**
  - **Matching the LHAASO sensitivity with 500 hr/yr**
  - To identify the gamma ray sources in PeVatrons and measure their morphology in detail, which can help us to reveal the mechanism of the gamma ray emission and then deeply explore the origin of the high energy cosmic rays.
- **LACT project started construction this year and the full array will be completed by 2028**






A prototype in Chengdu
A prototype in LHAASO

Summary

- **LHAASO has been stably operating since 2021**
- **43 above 100 TeV are detected and published in catalogs w/~40% of them unidentified**
- **The first CR source as a super-PeVatron is found**
- **Diffuse photon flux is found a factor 2 or 3 higher than expectation**
- **The BOAT GRB brings us many new views of GRB afterglow, the highest energy photon from the GRB opens opportunities exploring for new physics**
- **Fundamental issues, LIV and DM, are tested w/ limits renewed constantly**
- **All particles energy spectrum from 300 TeV to 30 PeV has been measured by LHAASO-KM2A with high accuracy**
- **The spectra of proton, proton+helium knees will be finished this year**
- **The iron energy spectrum below 10 PeV will be finished next year**
- **LACT project started construction this year and the full array will be completed by 2028**

Thanks !