LHAASO highlight results

Shoushan Zhang

on behalf of the LHAASO collaboration

Institute of High Energy Physics，CAS，China

LHC Days in Split

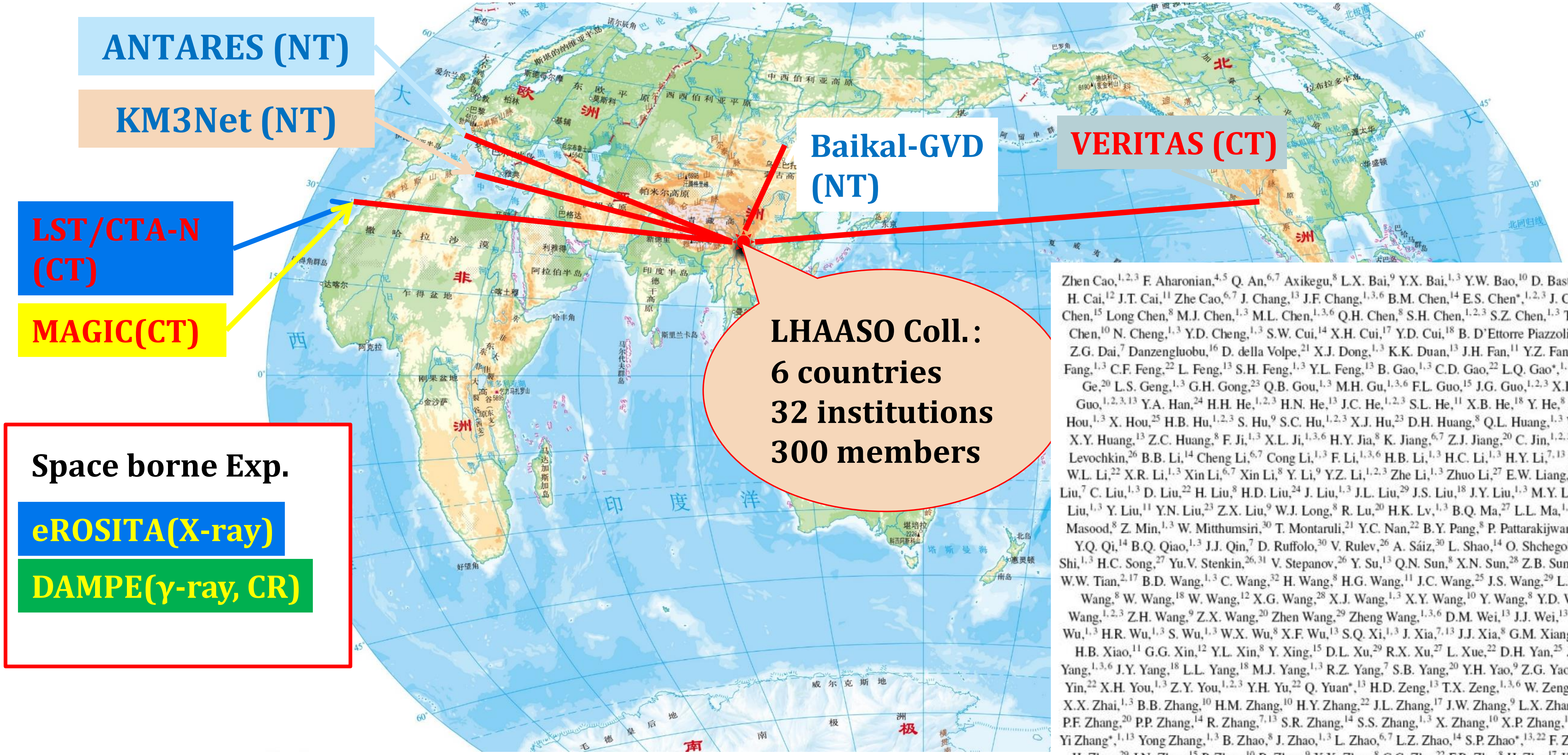
30 Sep. - 4 Oct., 2024 Hvar, Croatia

Outline

- **Introduction**
- Gamma Ray Astronomy
- CR Spectra around the Knees
- New Physics Searches
- Summary & Outlook

LHAASO: Multi-Messenger Collaboration Network

The LHAASO collaboration has signed MOUs with 8 international detector 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] 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)

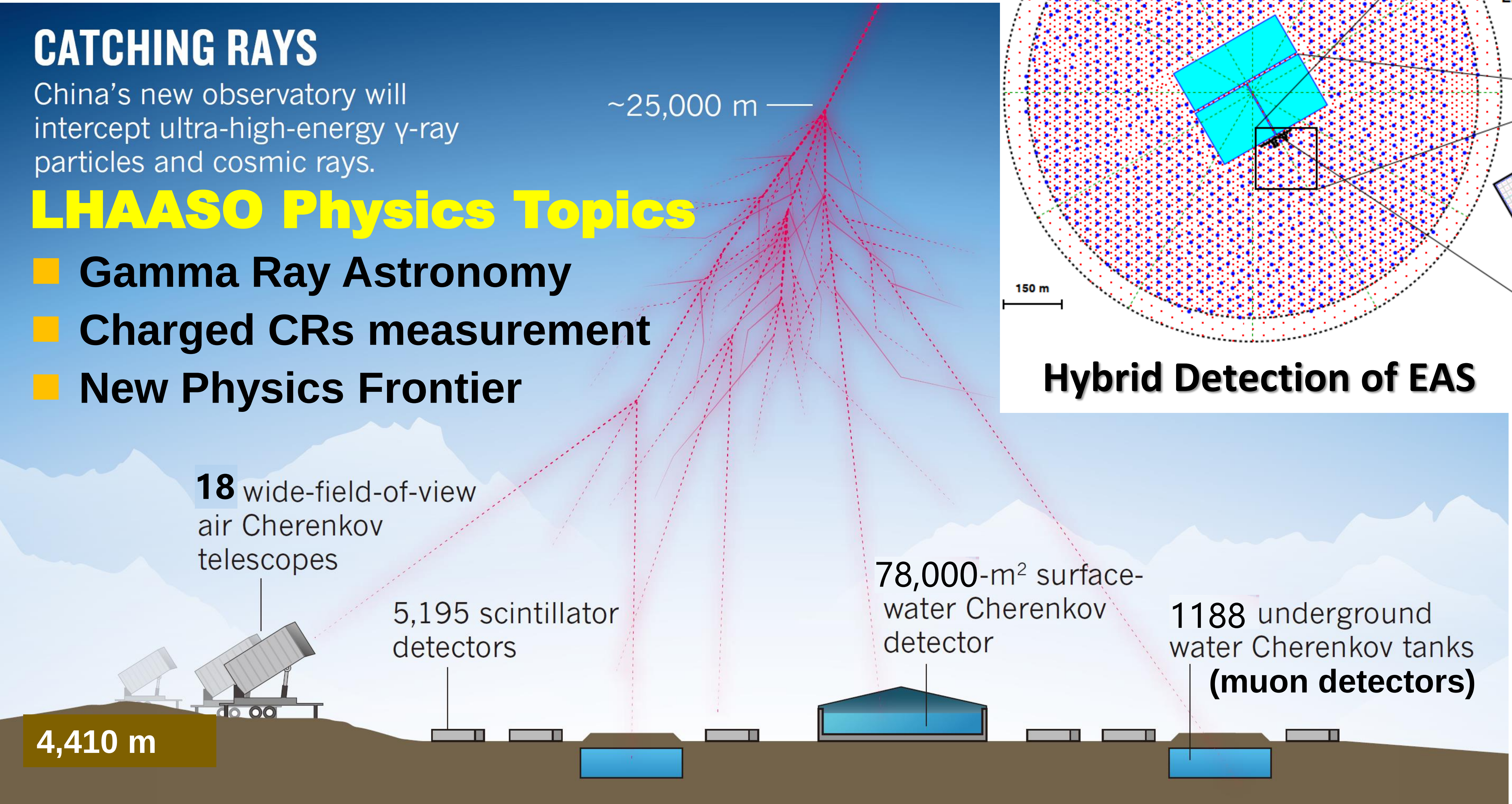
(Aug. 2018, at 4410 m a.s.l.)

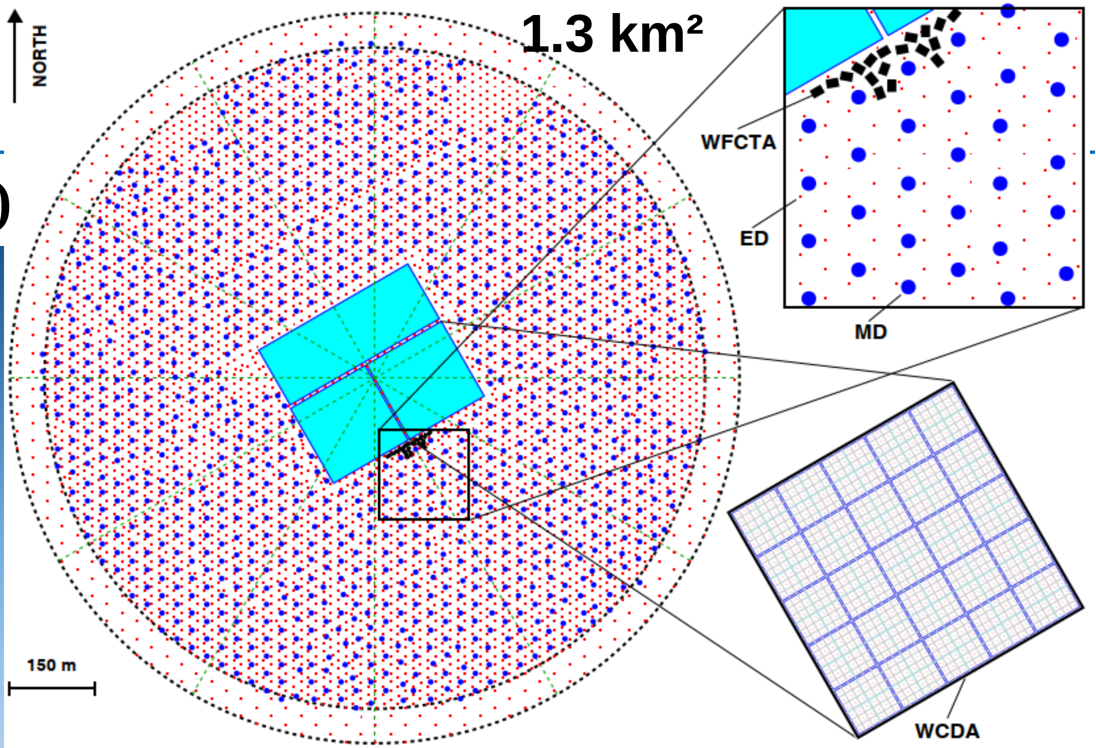
High Energy Cosmic Rays

Large High Altitude Air Shower Observatory (LHAASO)

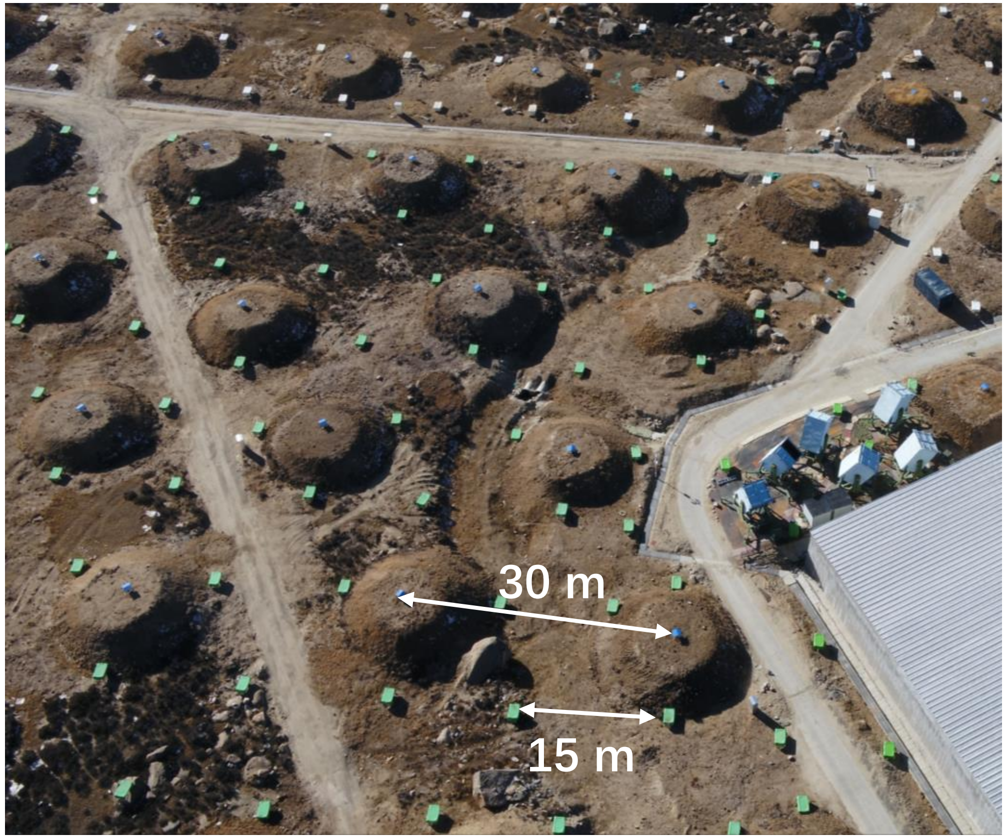
LHAASO Physics Topics

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





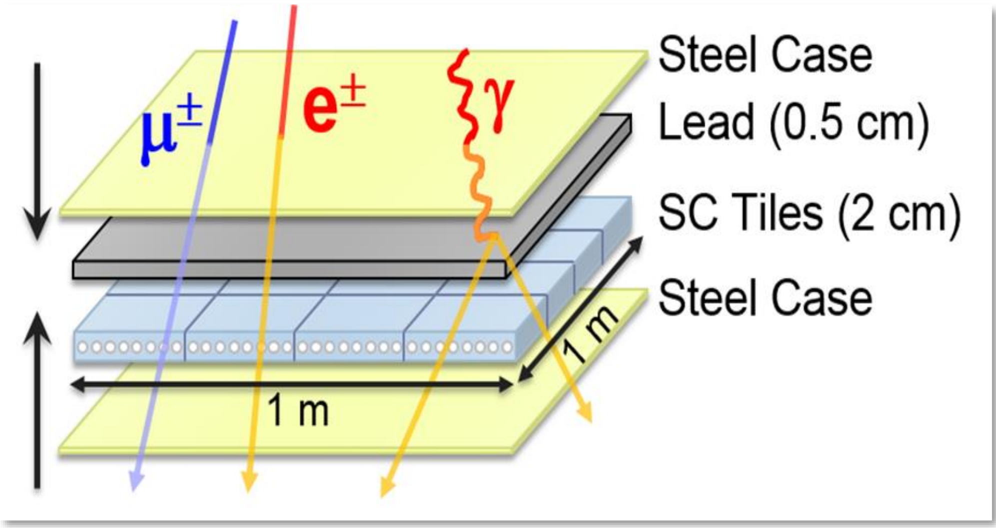
Hybrid Detection of EAS



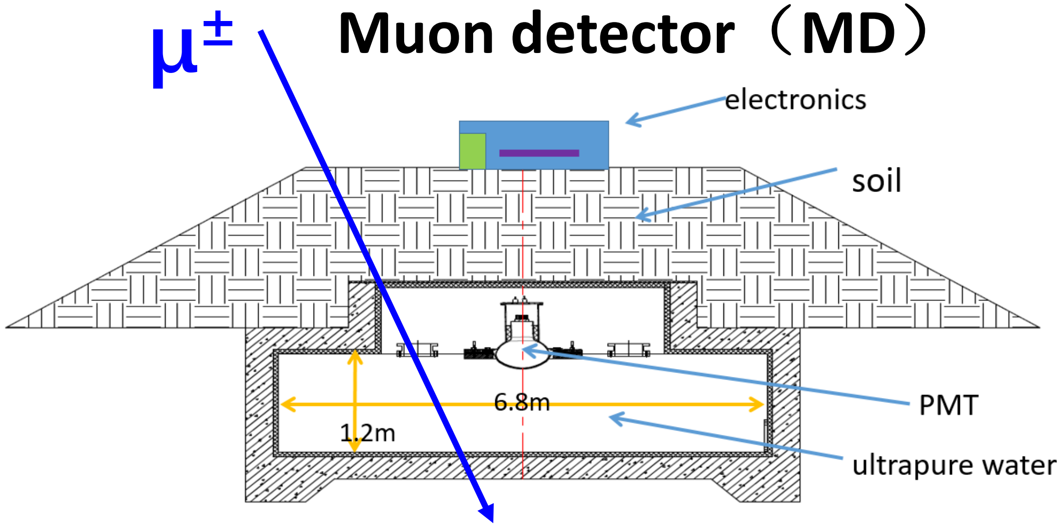
KM2A: 1.36 (km)^2

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

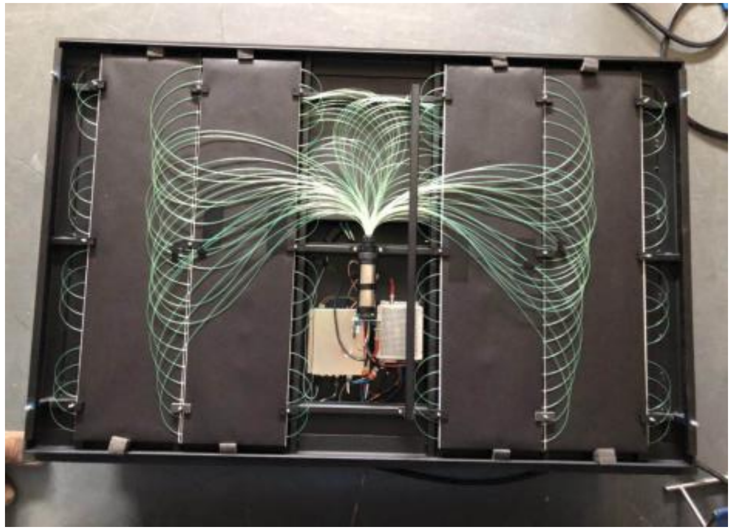
Scintillator Detectors （ED）



Muon detector（MD）

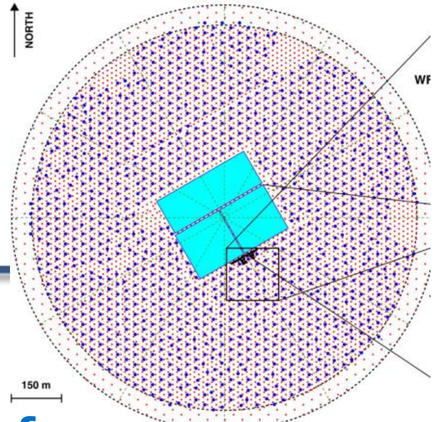


Inner View of one ED



LHAASO-KM2A

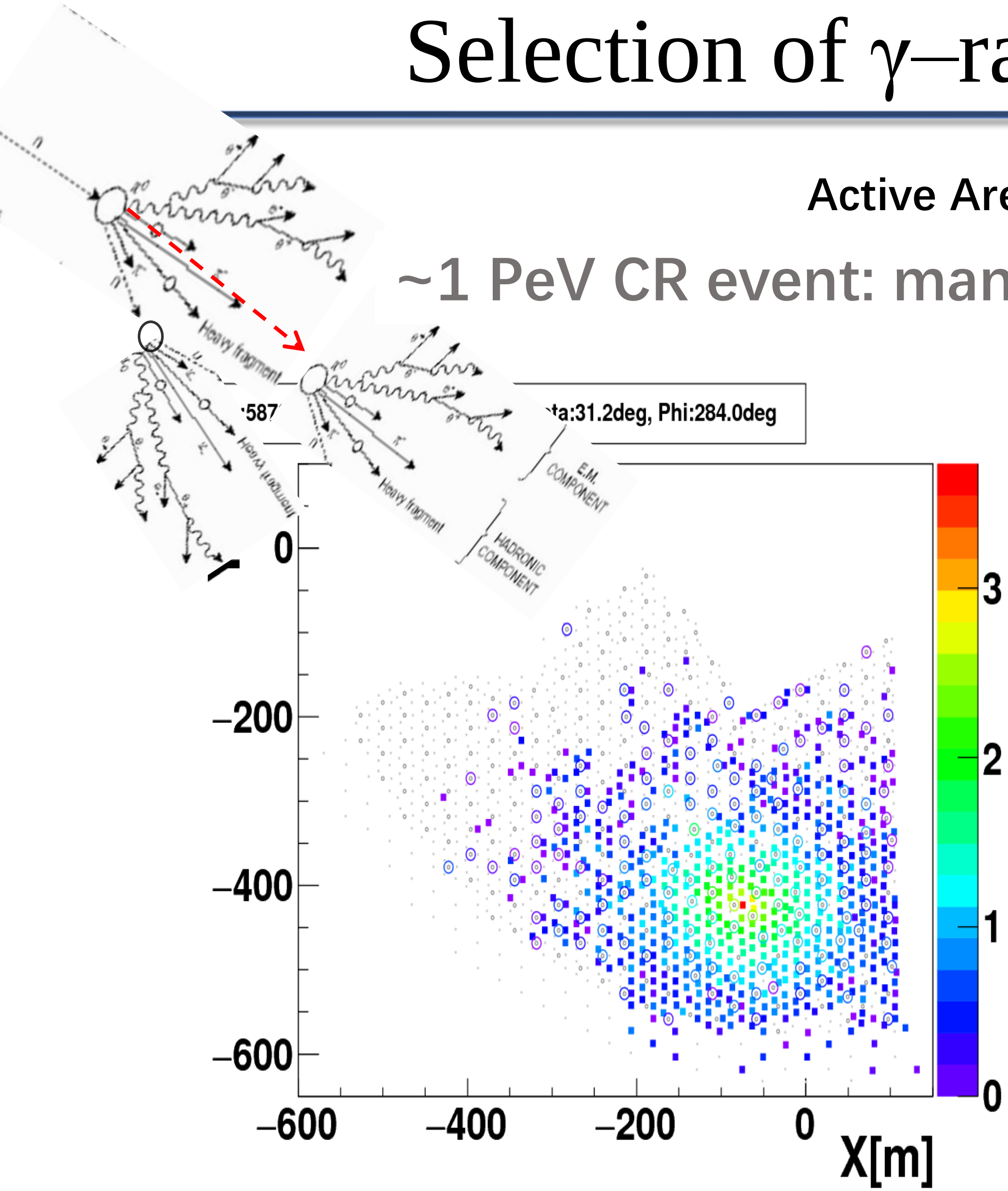
Selection of γ–rays out of CR background

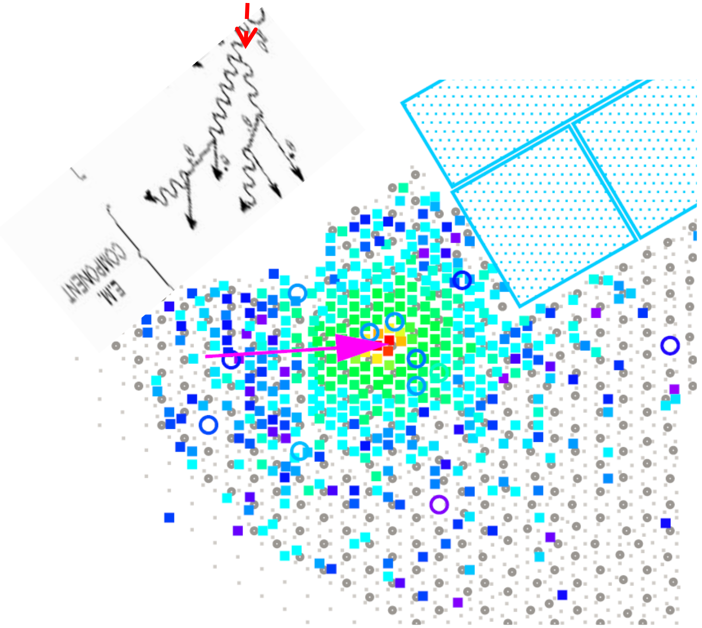


Active Area for Muons vs. Array Area: 4%

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

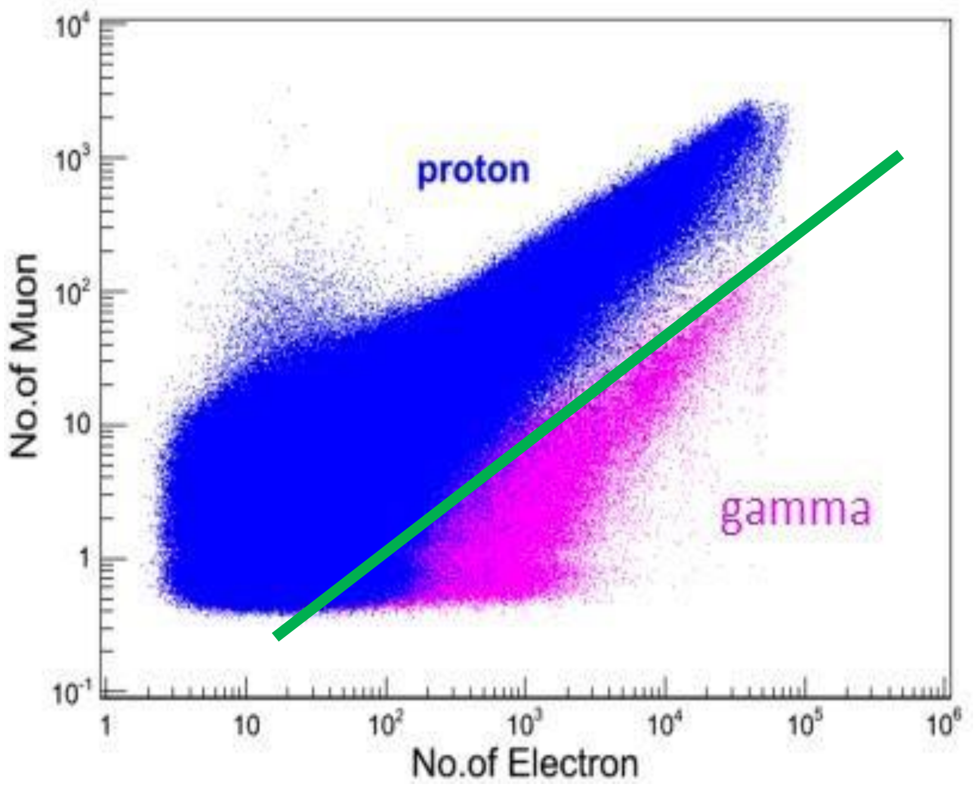
from the Crab

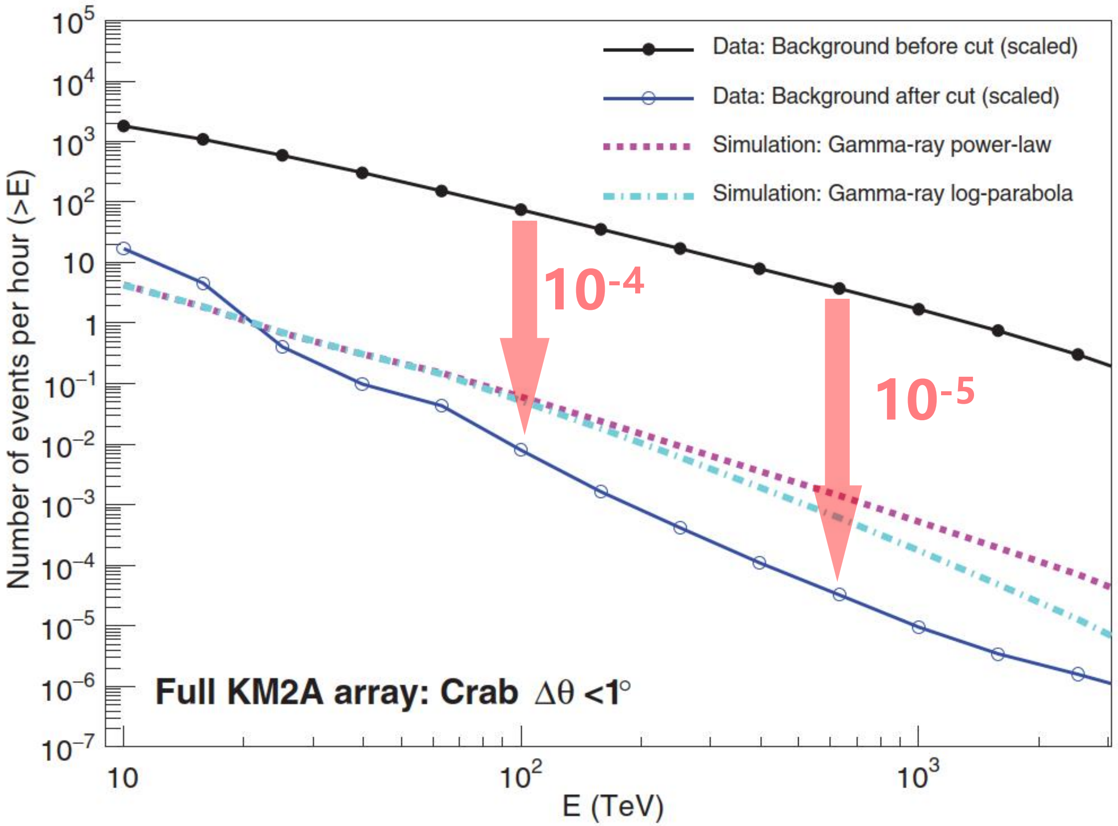




- Area：
  1.3 km^2
- Detectors：
  5216 ED
  1188 MD
- Energy Range：
  0.01-10 PeV

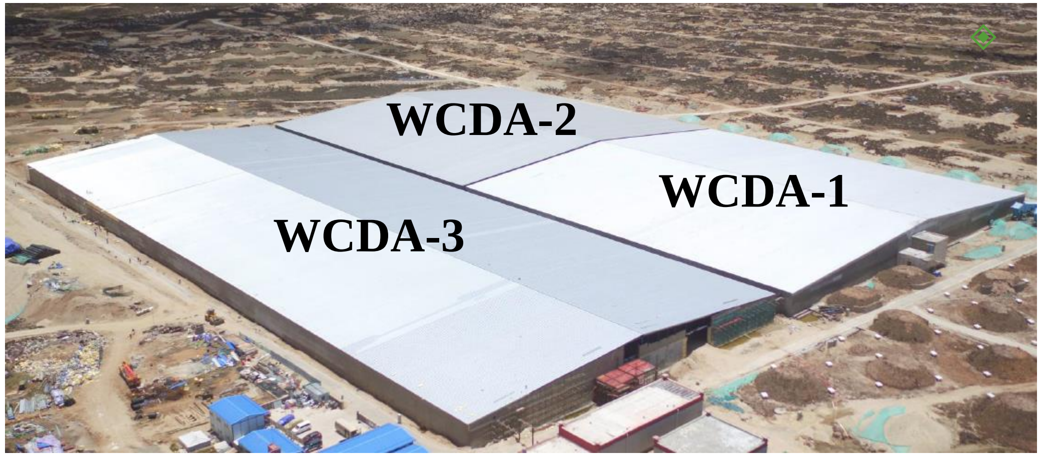
Muon information from LHAASO





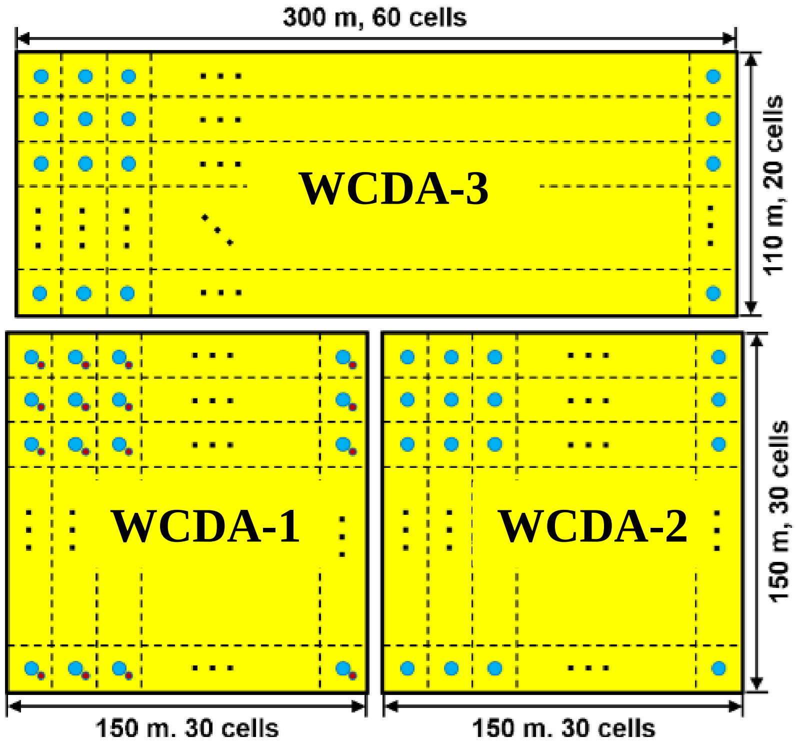
Science 373, 425 (2021)

Water Cherenkov Detector Array (WCDA)

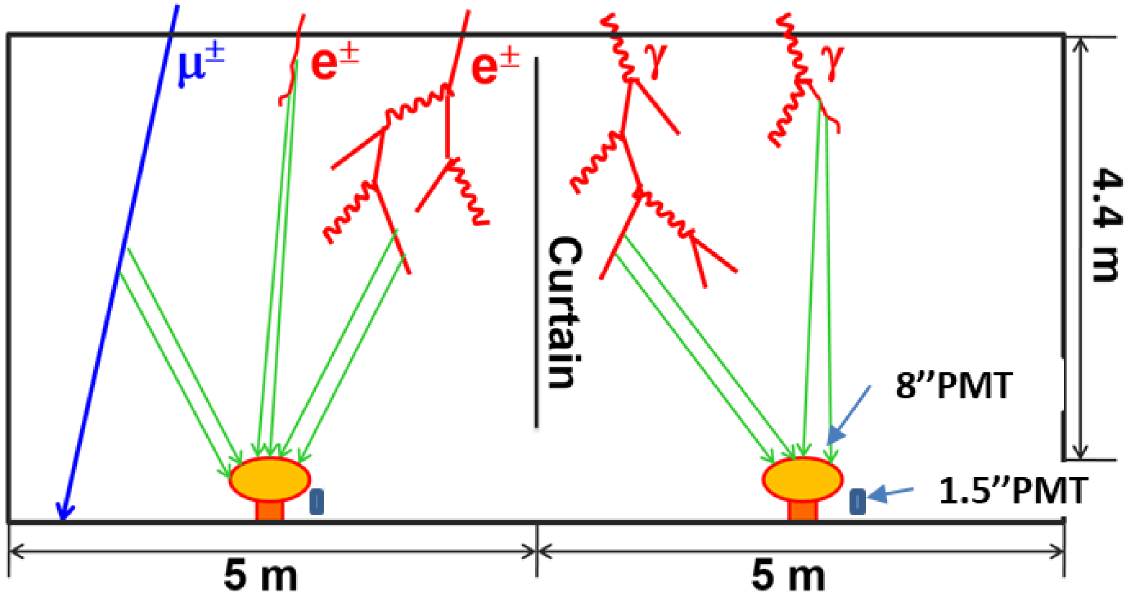


Energy rang

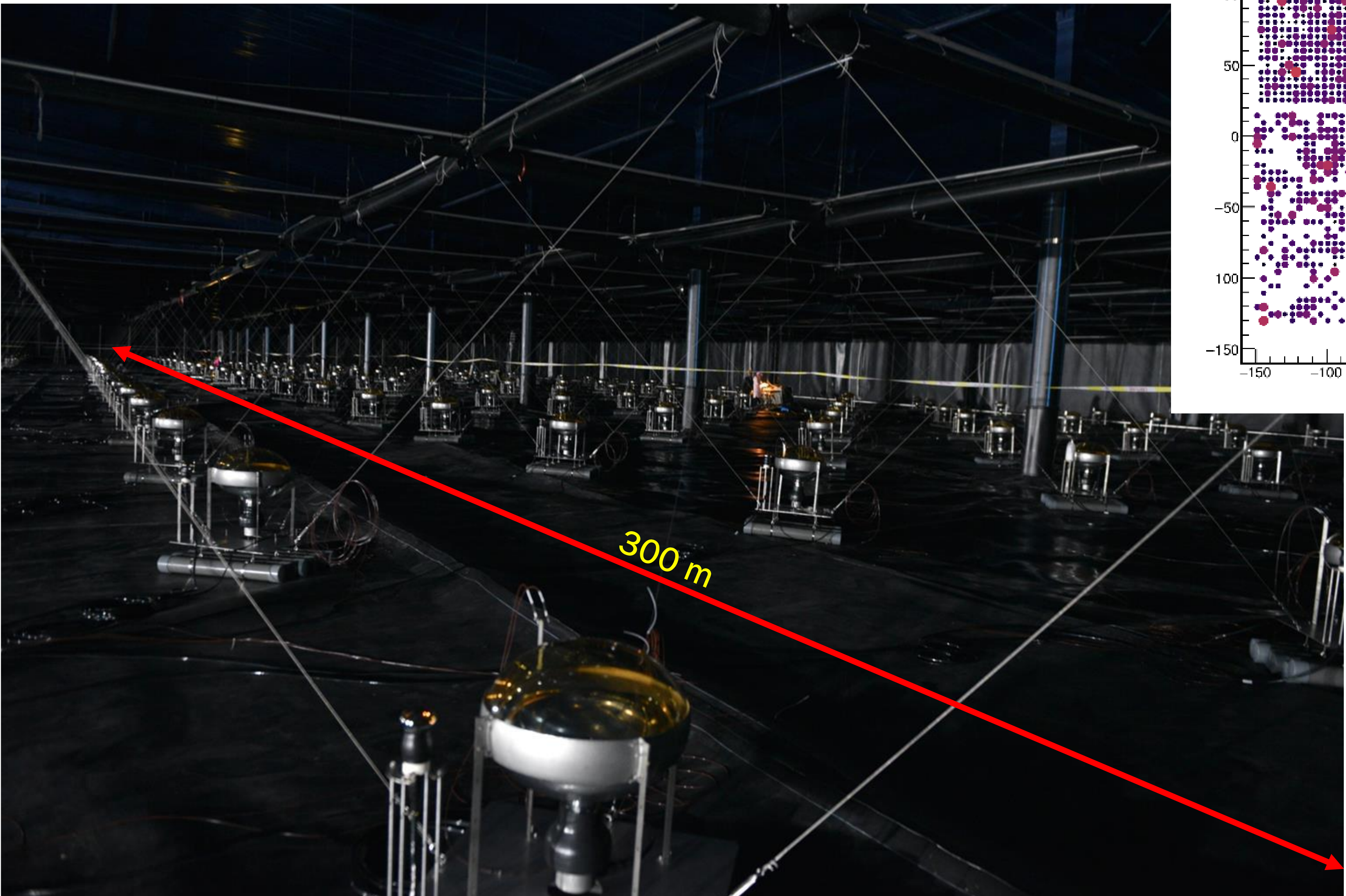
- WCDA-1
  - 300 GeV – 10 PeV
- WCDA-2 and WCDA-3
  - 100 GeV - 10 TeV

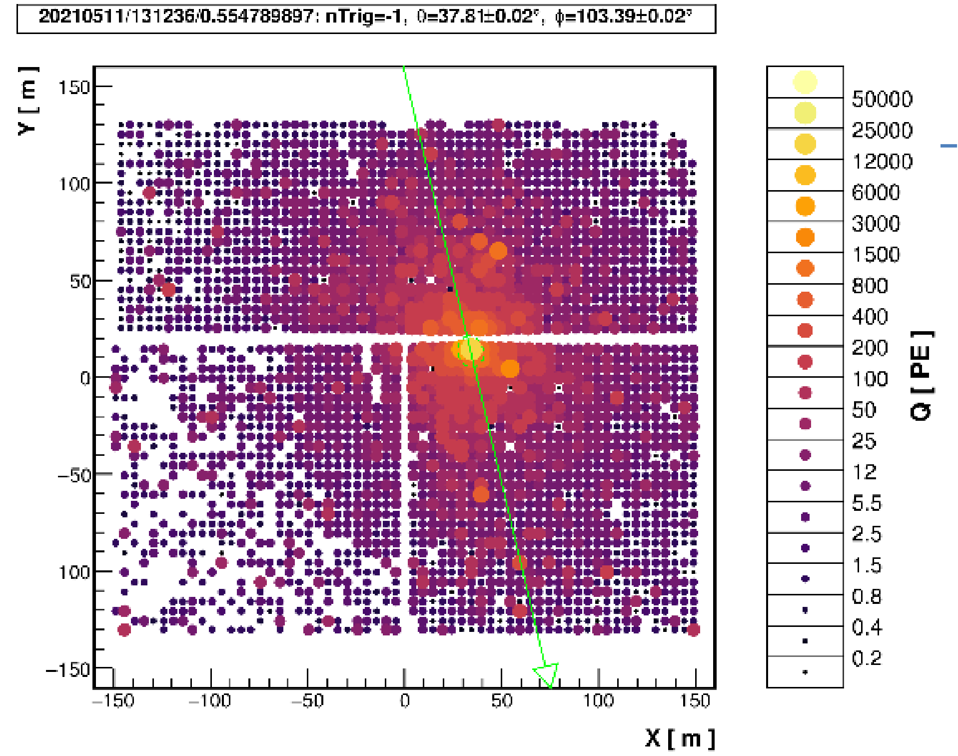


- Total area: $78,000m^2$
- Total units: 3,120
- Unit size: $5m \times 5m \times 4.4m$
- Two type of PMTs in each unit:
  - 8 inches and 1.5 inches for WCDA-1
  - 20 inches and 3 inches for WCDA-2 and WCDA-3



Inside of WCDA-3





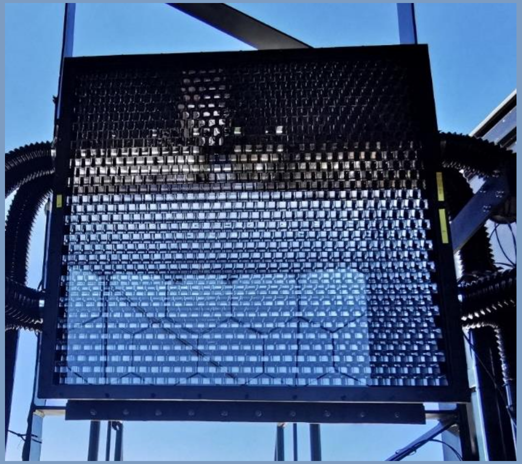
- WCDA-1 started operating in April 2019
- WCDA-2 started operating in January 2020
- WCDA-3 started operating in March 2021

Wide Field of View Cherenkov Telescope (WFCTA)

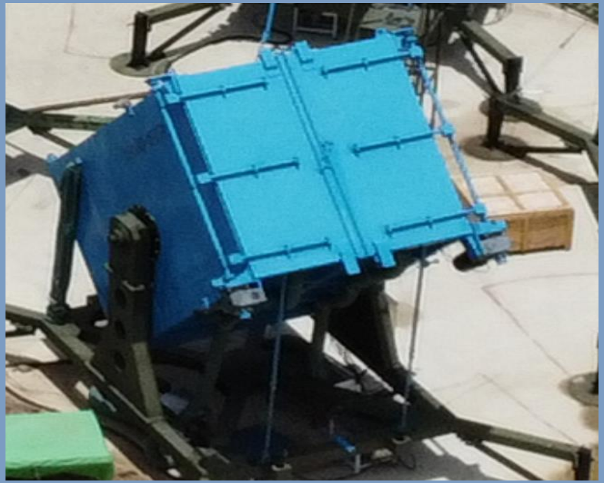
◆ **Telescope parameters:**

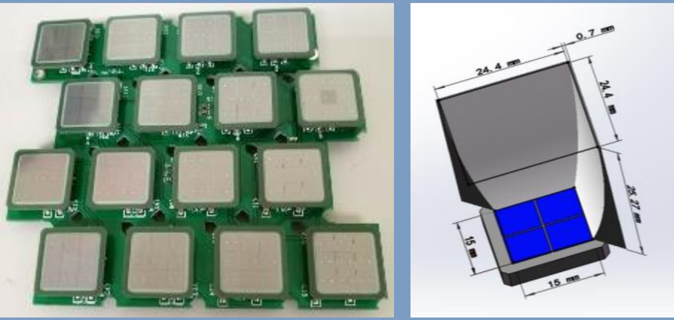
- ~5 m^2 spherical mirror
- Camera: 32×32 SiPMs array
- FOV: 16° × 16°
- Pixel size: 0.5°

Mirror



SiPM camera





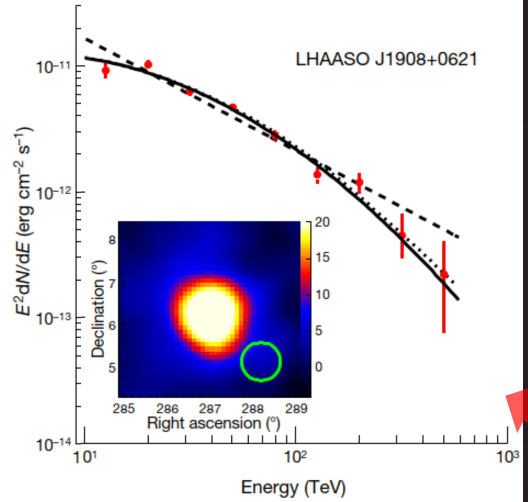
SiPM and Winstone cone

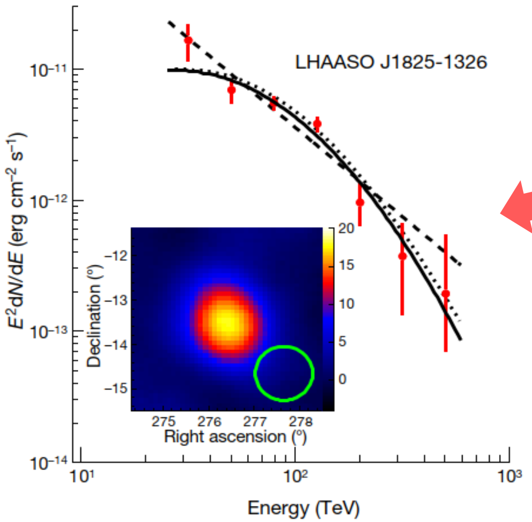
Outline

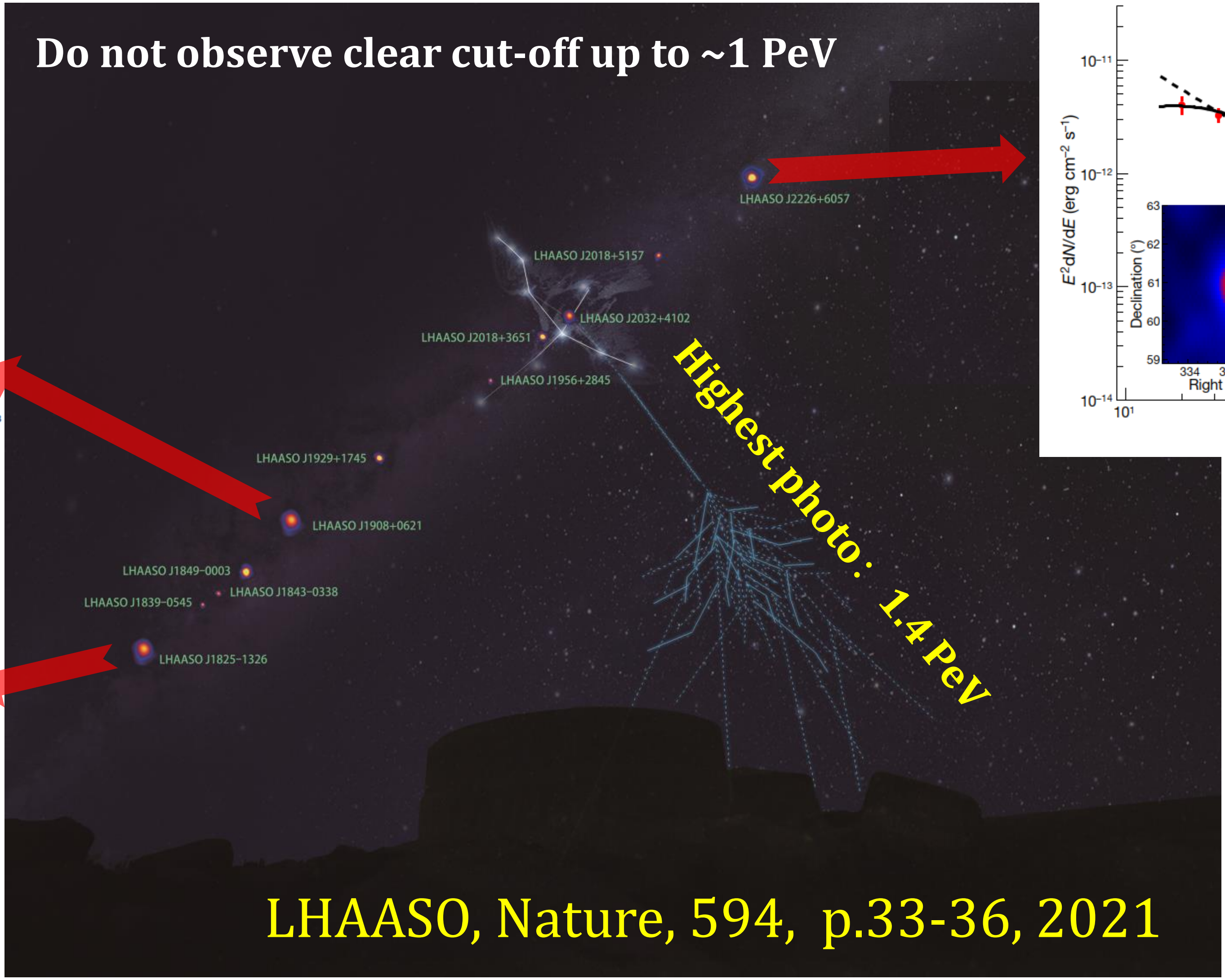
- Introduction
- **LHAASO results in Gamma Ray Astronomy**
- CR Spectra around the Knees
- New Physics Searches
- Summary & Outlook

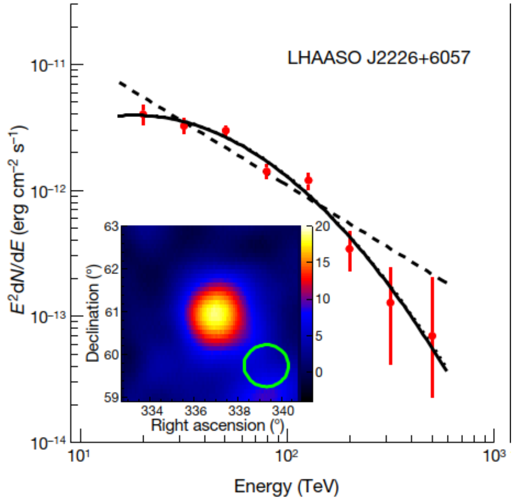
LHAASO started a new era of UHE γ-ray astronomy

2019/12-2020/12, 308 days，1/2 array









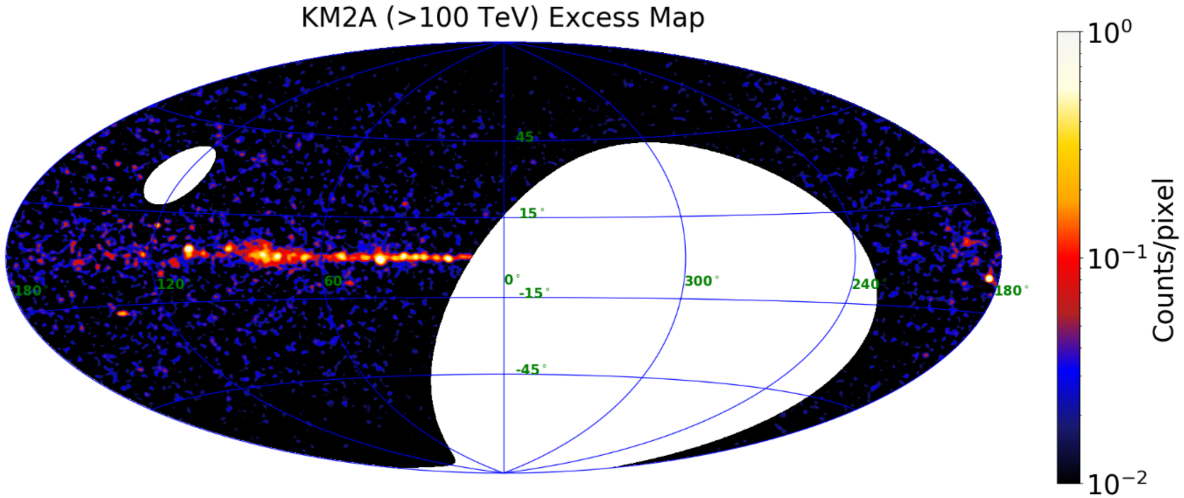
For the first time, twelve ultra-high energy gamma-ray sources have been discovered in the Milky Way, revealing the widespread existence of “petaelectron particle accelerators” in the galaxy, whose acceleration capabilities have surpassed traditional understanding.

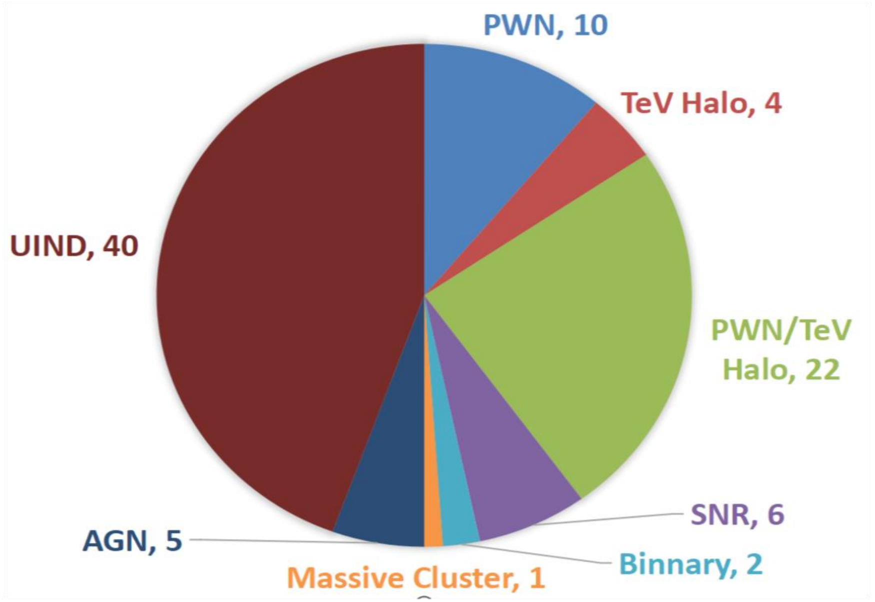
Journey of Ultra High Energy Gamma Ray Detection
The First Catalogue of Very/Ultra High Energy Gamma Sources Released

- 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)

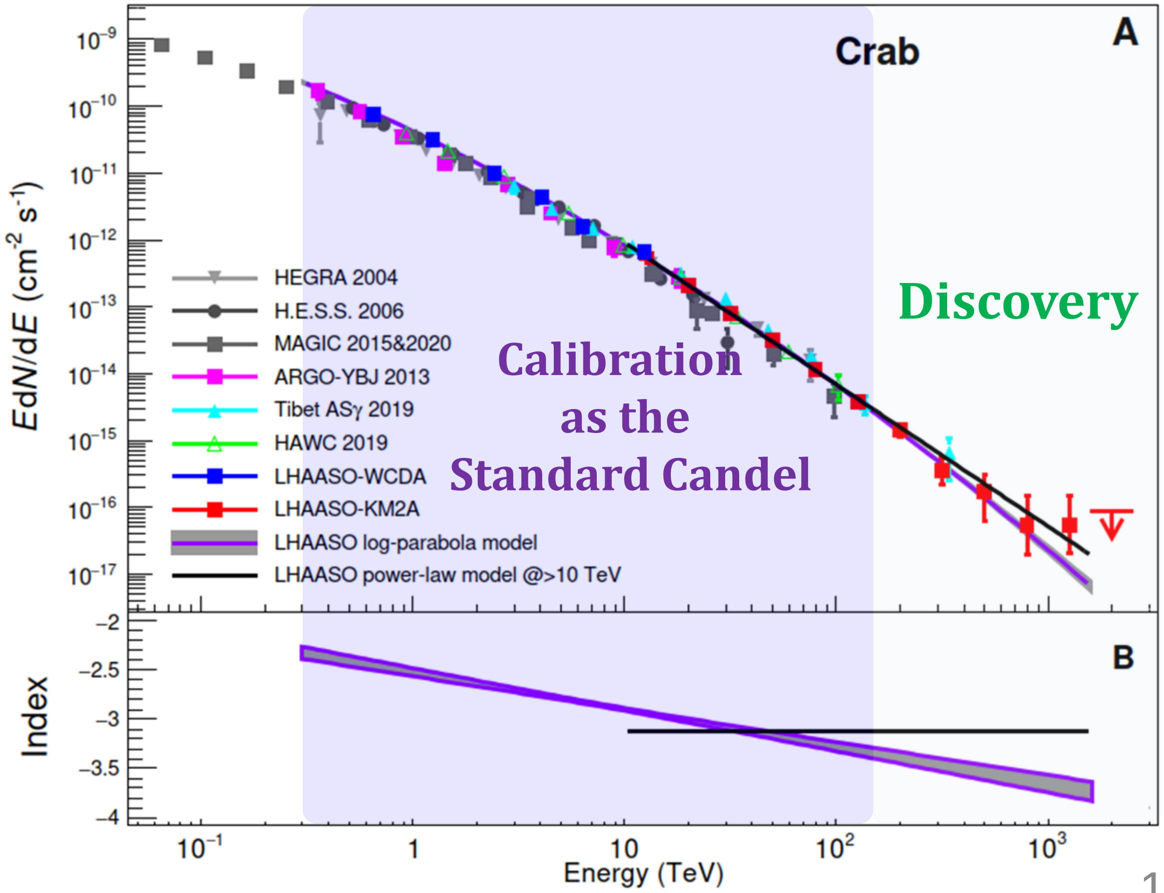
- **KM2A: 2019-12 to 2022-09**
- **933 days (~730 days full array)**





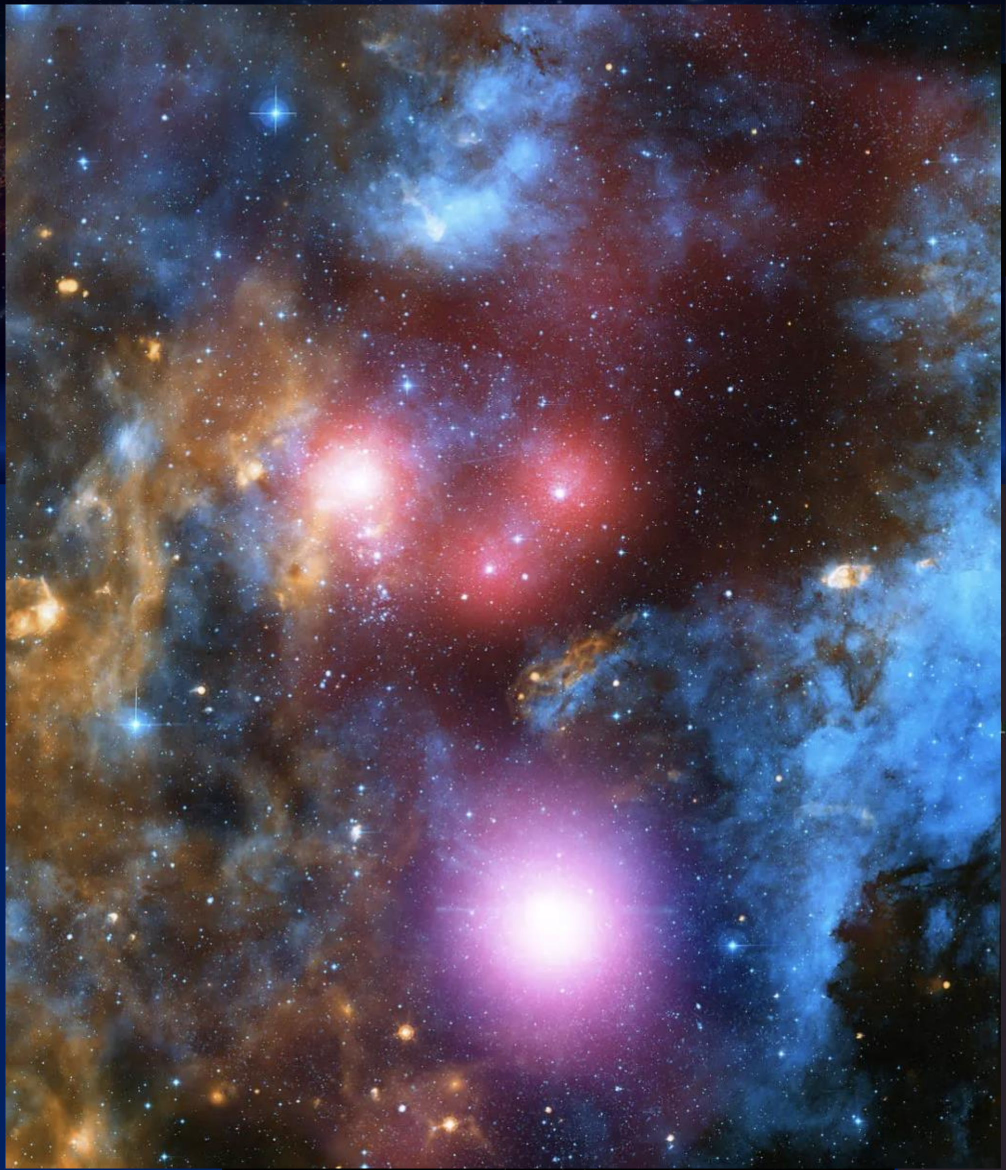
LHAASO discovers extension of the Crab spectrum to 1.1 PeV

- Covering 3.5 decades of energy
- The highest photon energy: 1.1 PeV → 1.4 PeV
- Clear origin: a well-known Pulsar Wind Nebula (PWN)
- An extreme electron accelerator:
  - 2.3 PeV →2.8PeV electron in 100 μG fields
  - Require 16%→26% 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

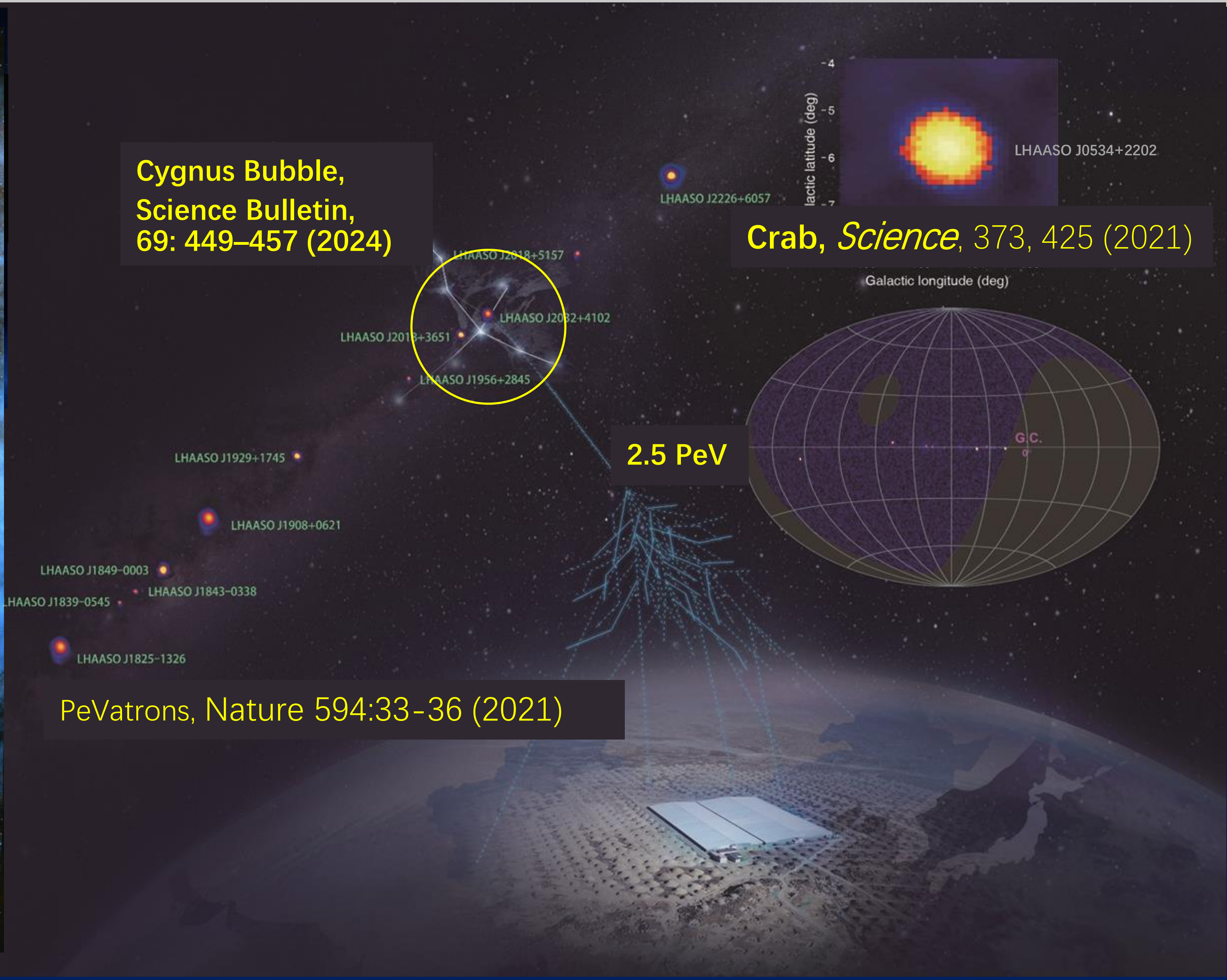


LHAASO Collaboration, Science, 373, 425 (2021)

The 1st CR-Source Candidate by

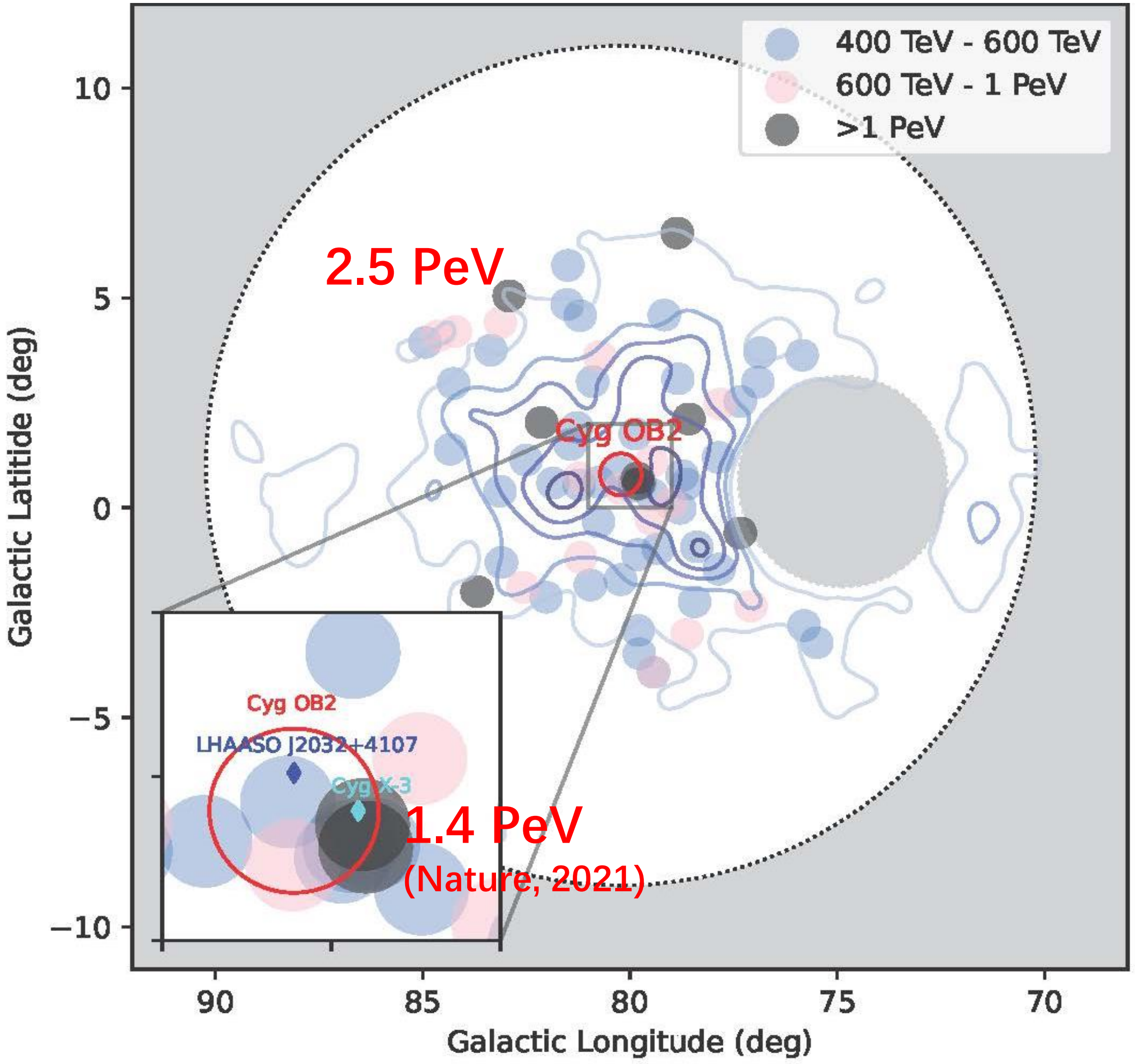


For the first time in the world LHAASO observed



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

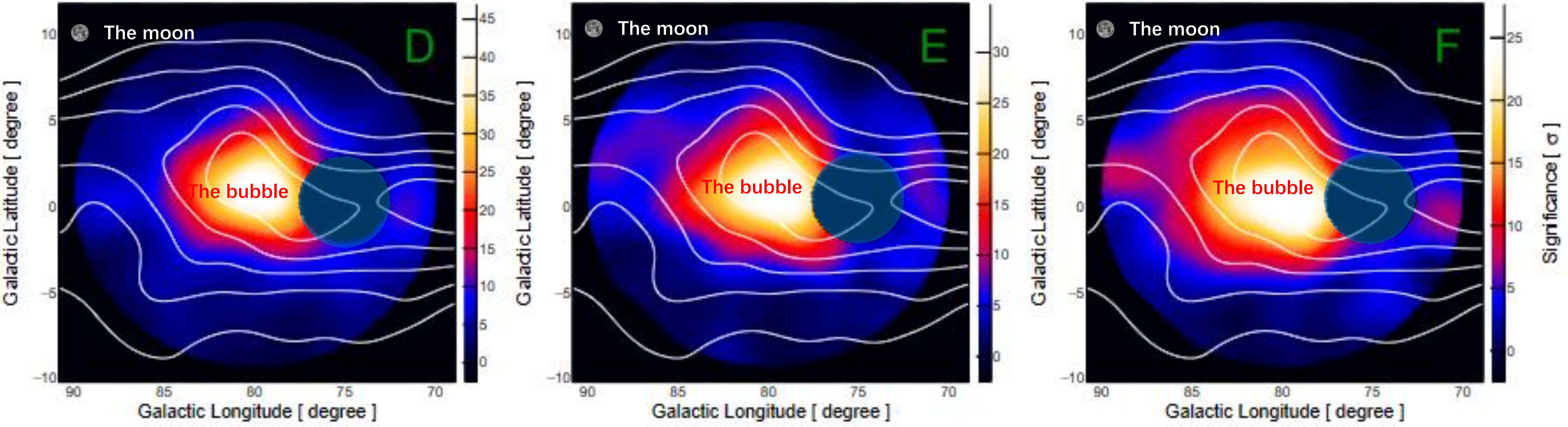
- PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

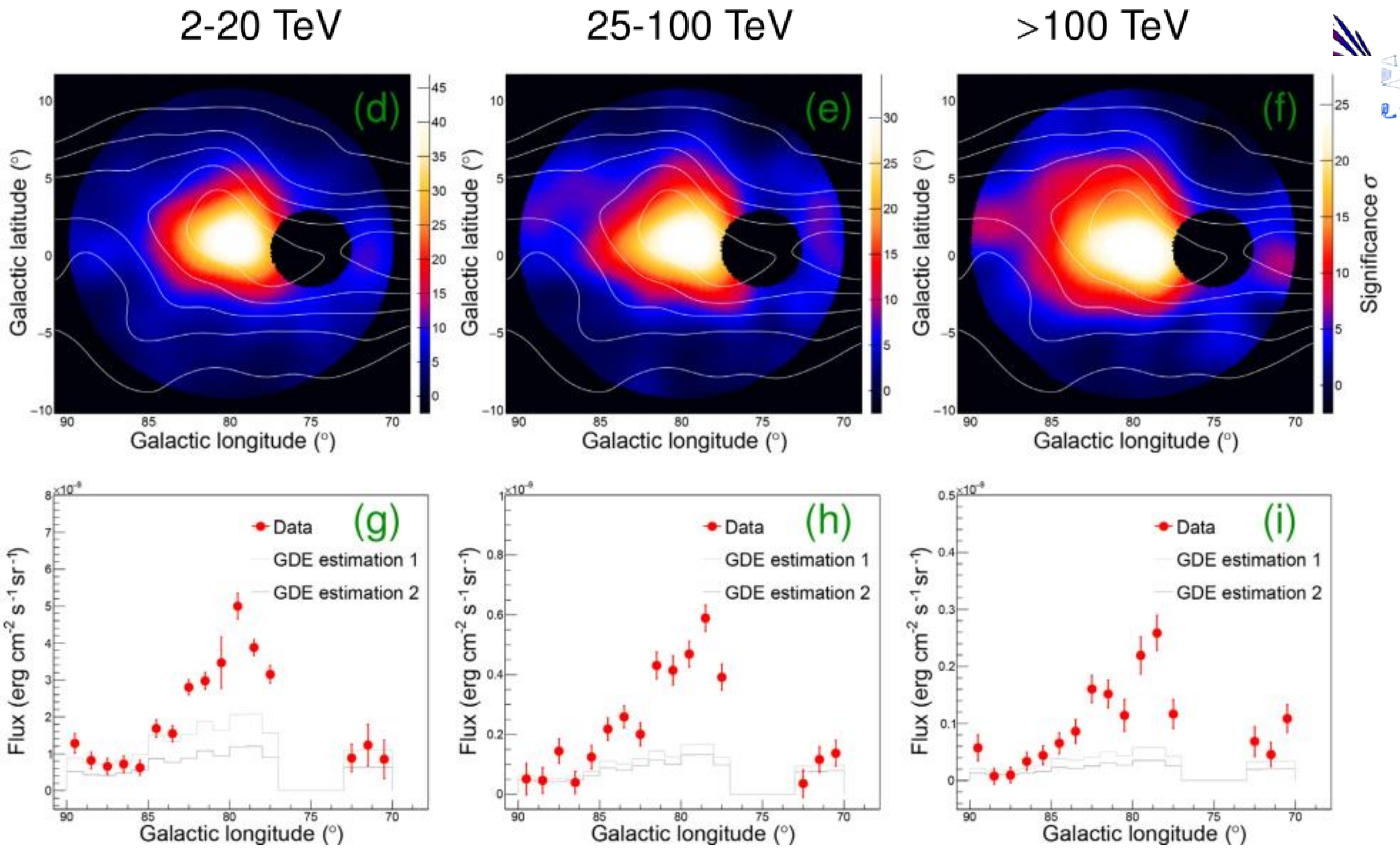
Association with HI gas distribution over ~200 pc

- 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

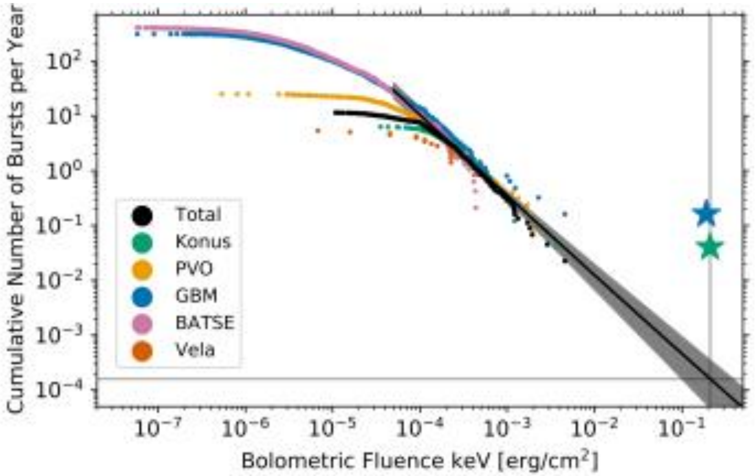
◆ The signal is elongated along the disk and extends up to 10°

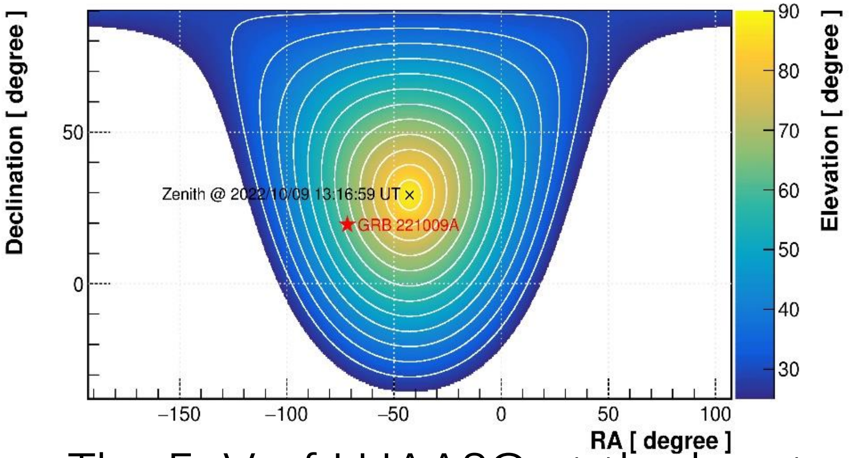



2-20 TeV
25-100 TeV
>100 TeV
(d)
(e)
(f)
Galactic latitude (°)
Galactic longitude (°)
Significance σ
(g)
(h)
(i)
Data
GDE estimation 1
GDE estimation 2
Flux (erg cm^{-2} s^{-1} sr^{-1})
Galactic longitude (°)

GRB 221009A: The brightest of all time
was detected by LHAASO

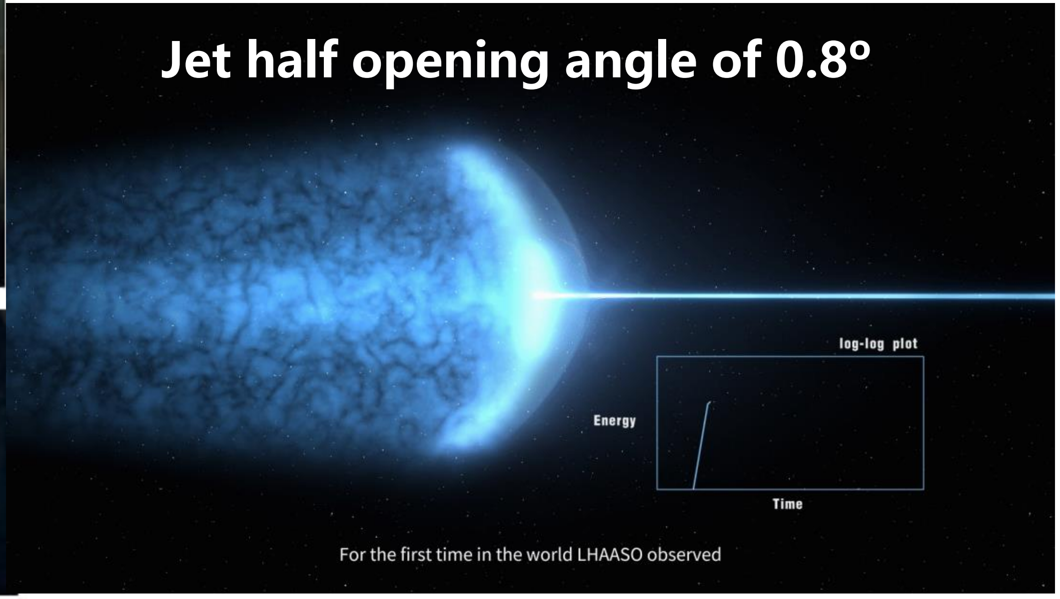
- Highest fluence / peak flux (An et al. 2023)
- Nearby
- Highest energy / peak luminosity (An et al. 2023)
- Once a 1,000/10,000 yr event (Burns et al. 2023)





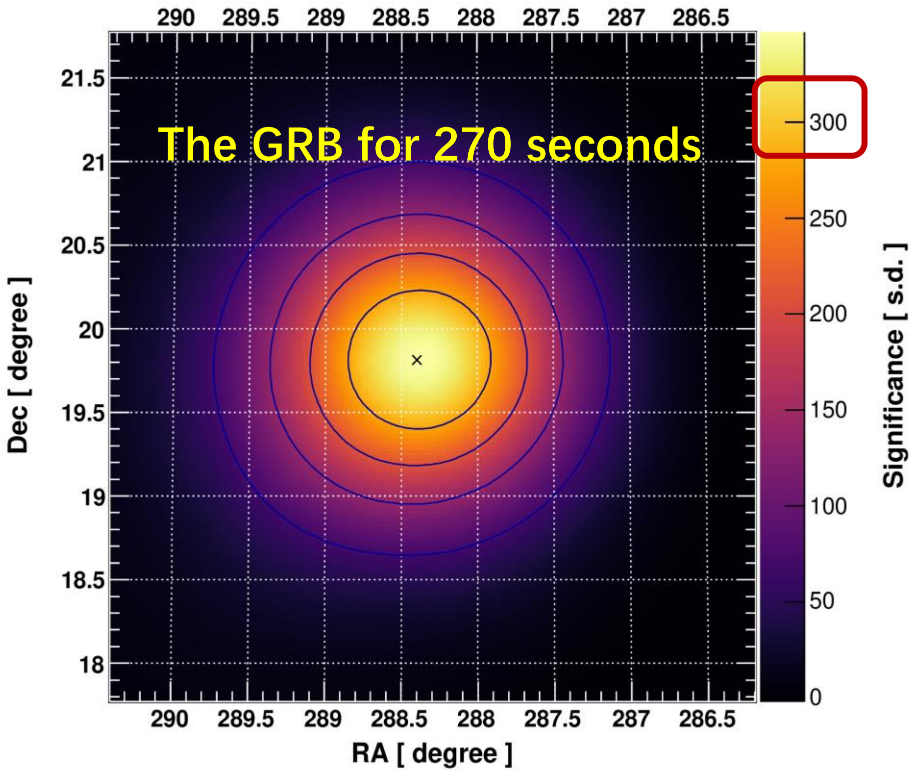
The FoV of LHAASO at the burst

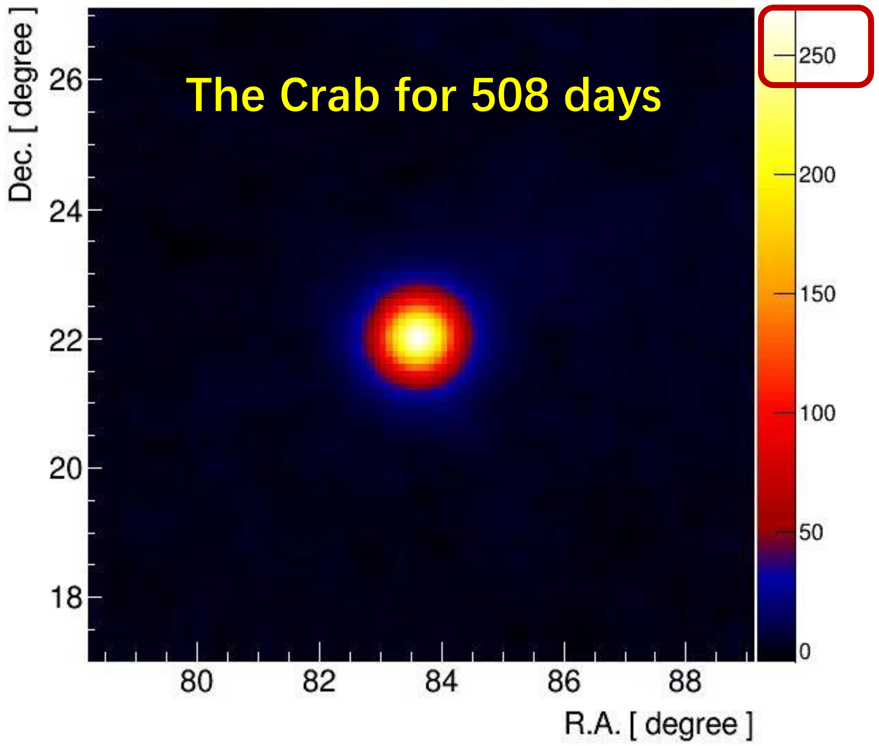
By Bing Zhang



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



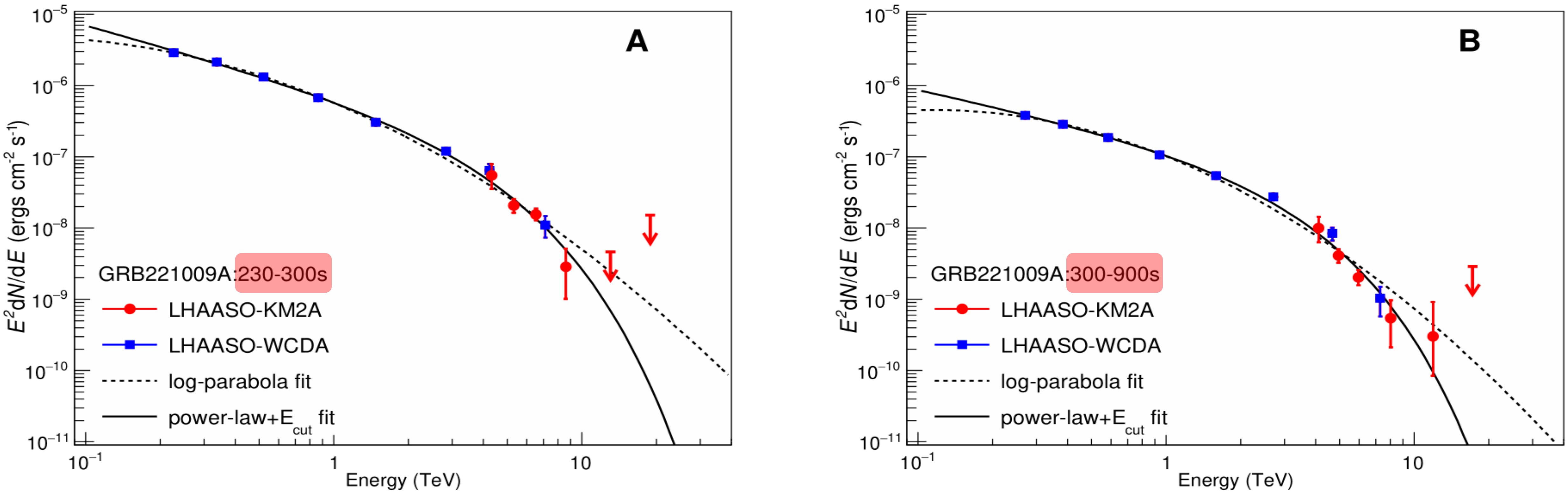


SED in two phases: bright and fading

- 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

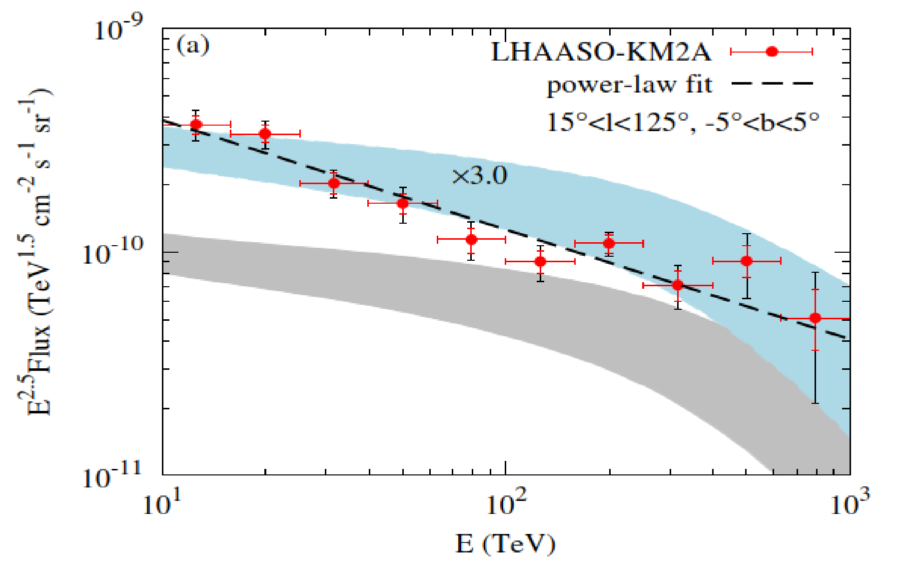
- **The power law + cut-off is favored**

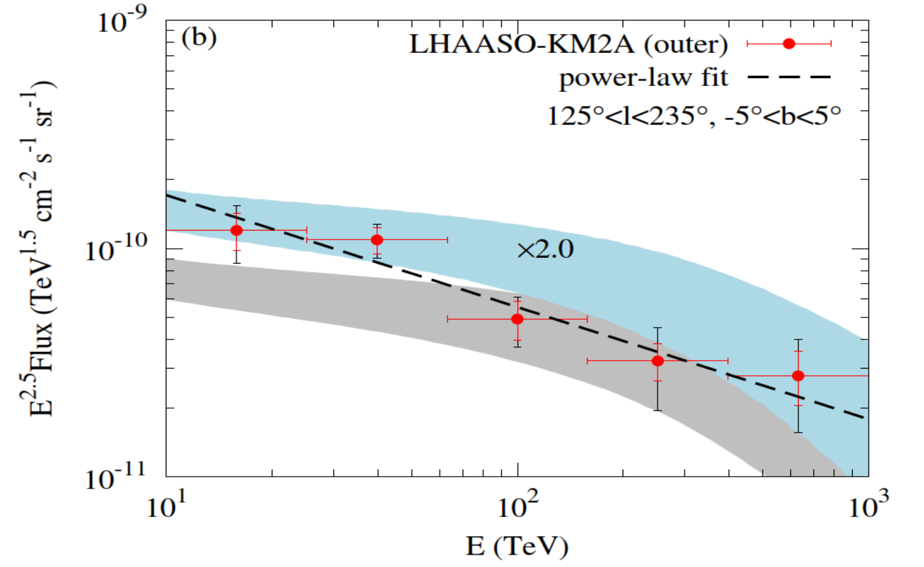


UHE diffuse γ emission of the Galactic plane from 10 TeV to 1 PeV

- **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.**

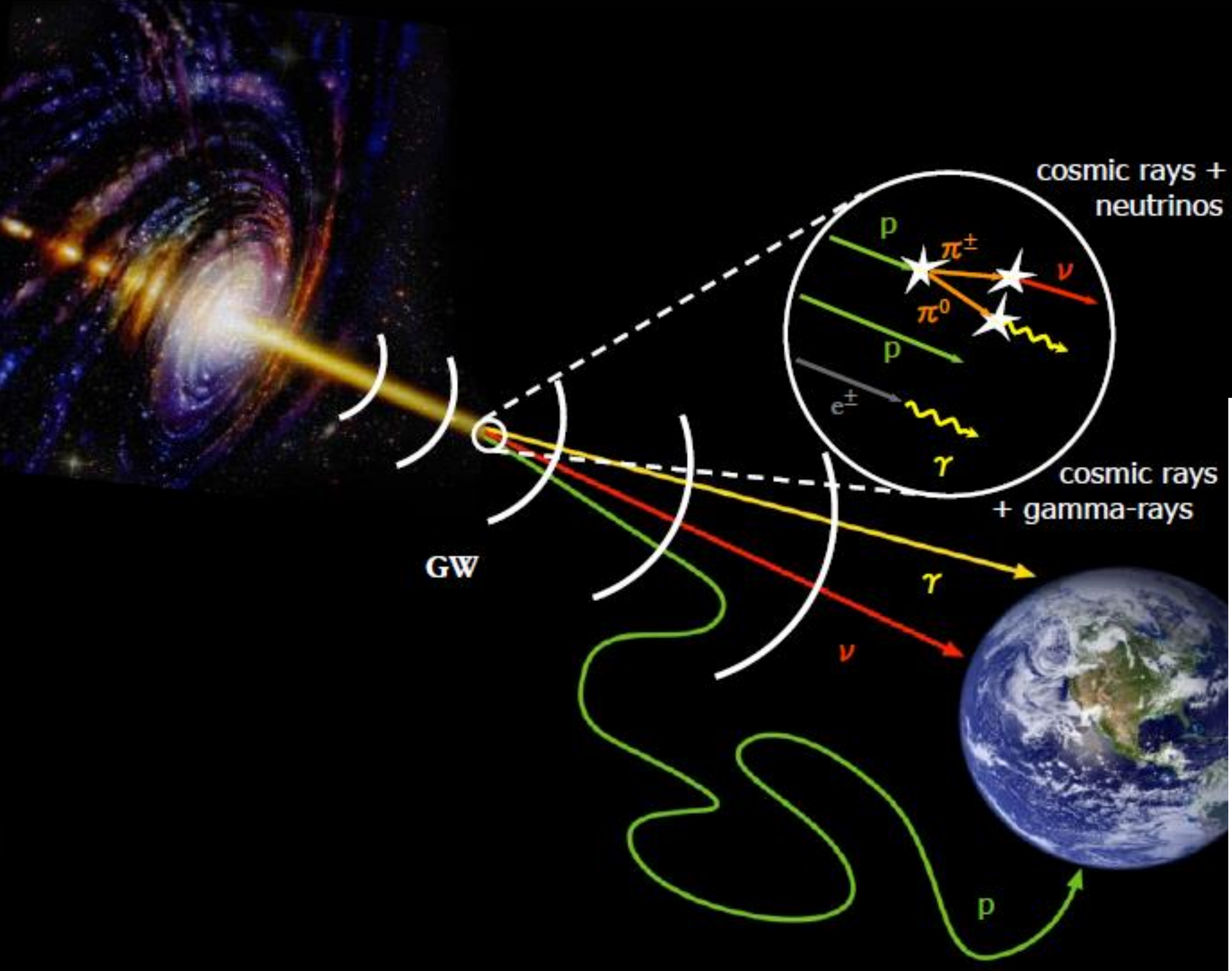
PRL 131:151001 (2023)

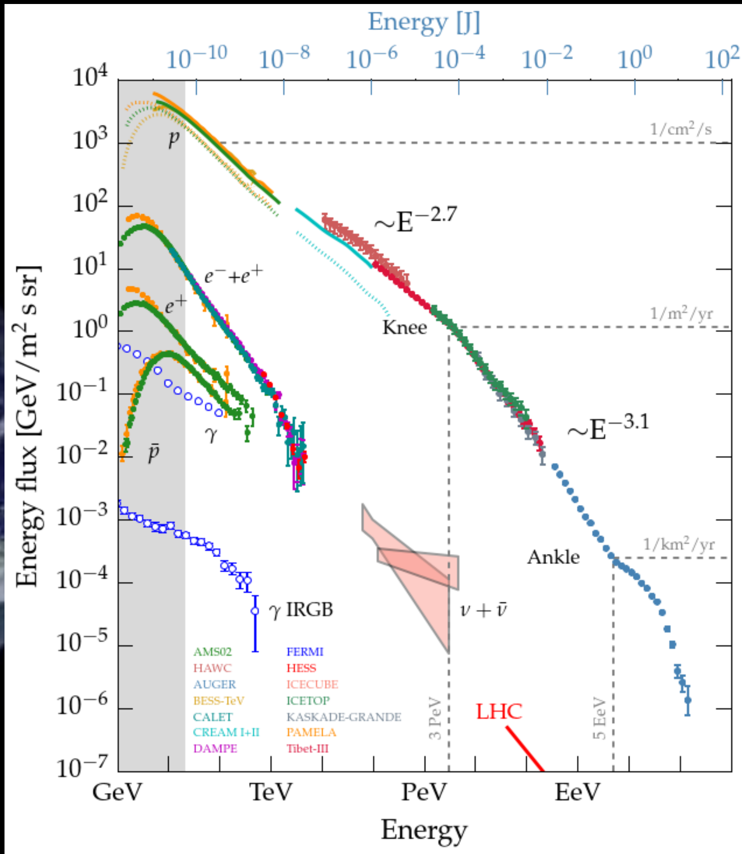




Outline

- Introduction
- Gamma Ray Astronomy
- **LHAASO results in CR Spectra around the Knees**
- New Physics Searches
- Summary & Outlook

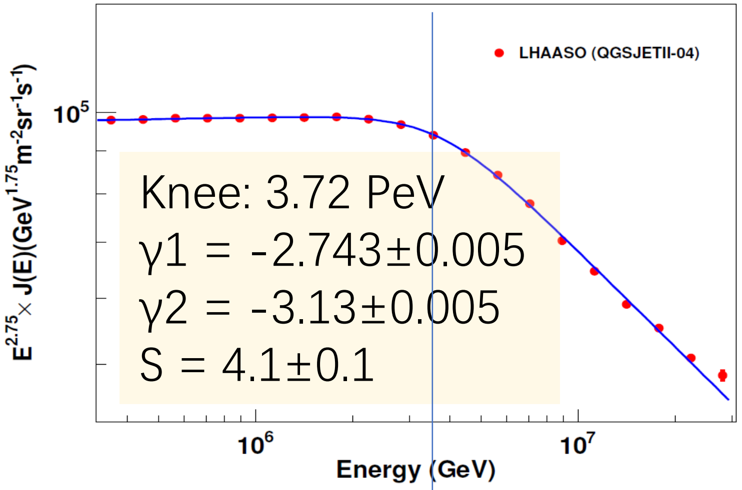

cosmic rays +
neutrinos
p
π±
ν
π0
p
e±
γ
cosmic rays
+ gamma-rays
GW
γ
ν
p

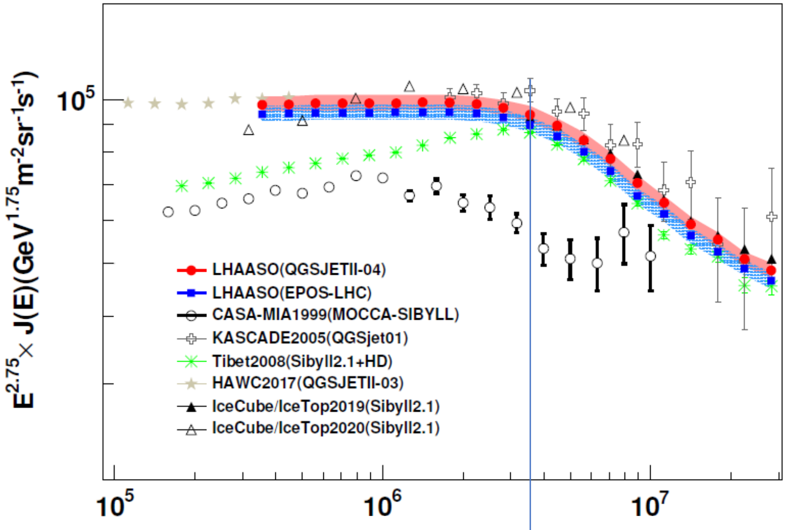

Energy [J]
Energy flux [GeV/m² s sr]
Energy
GeV
TeV
PeV
EeV
~E−2.7
~E−3.1
Knee
Ankle
1/cm²/s
1/m²/yr
1/km²/yr
p
e−+e+
e+
p̄
γ
γ IRGB
ν + ν̄
3 PeV
5 EeV
LHC
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASKADE-GRANDE
PAMELA
Tibet-III

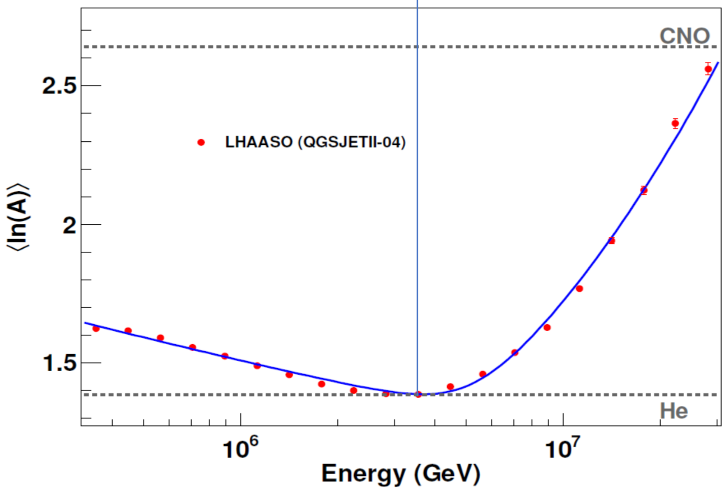
All-particle energy spectrum & composition by LHAASO

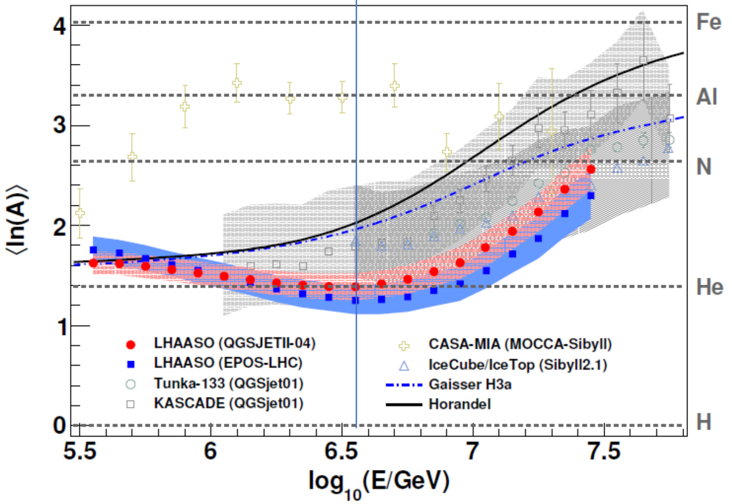
(from 0.3 to 30 PeV)

LHAASO Collaboration, PHYSICAL REVIEW LETTERS 132, 131002 (2024)









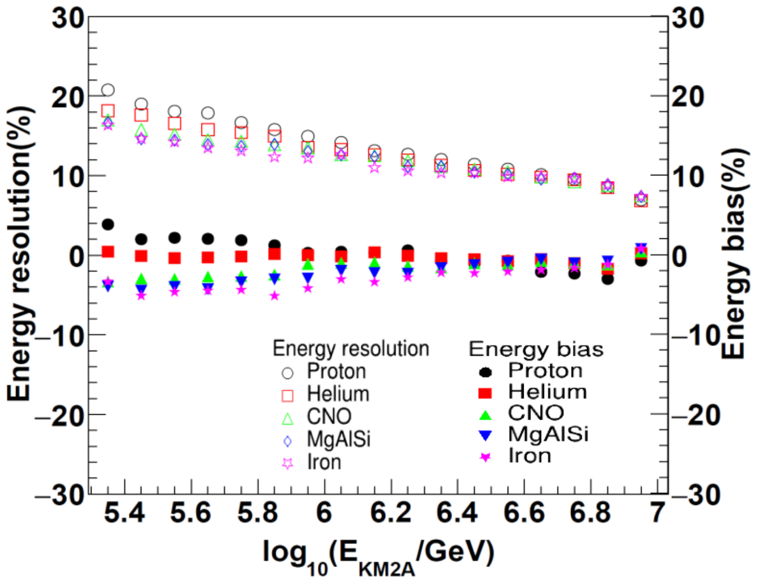
- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

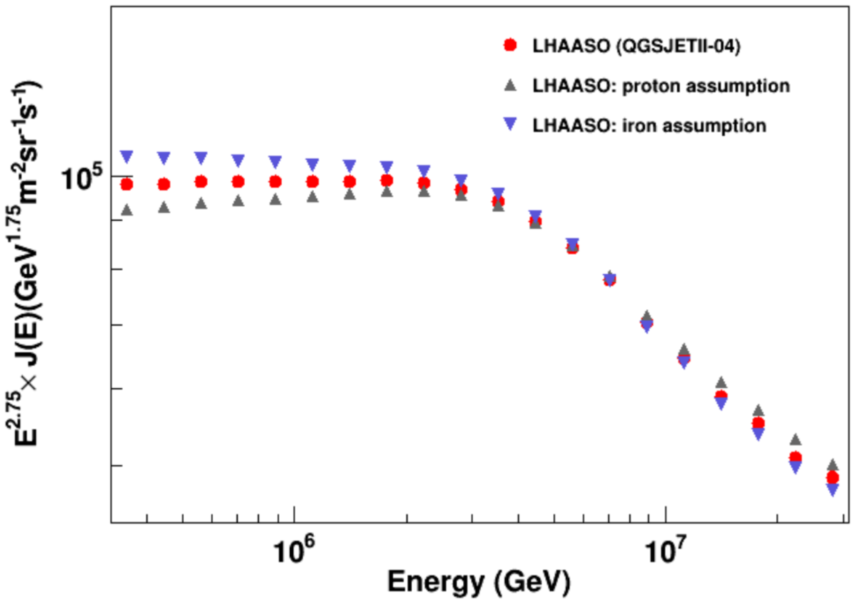
Energy reconstruction

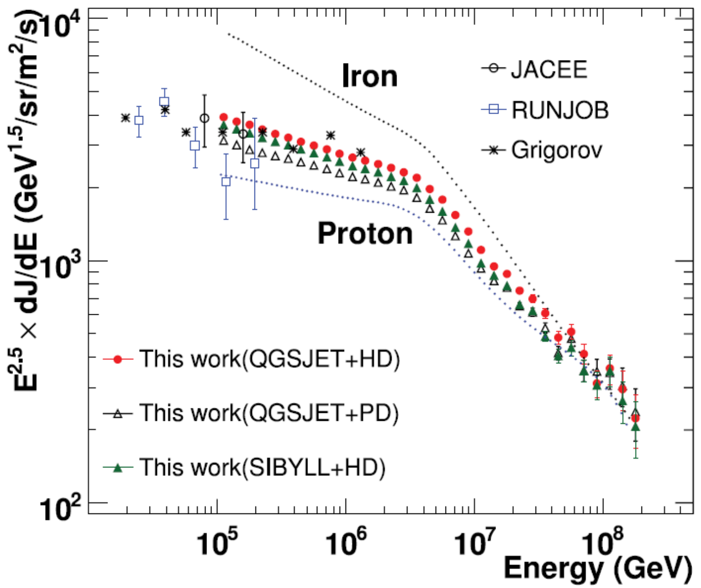
- Energy reconstruction independent of the primary CR component
- Scintillator detector array（ED）： Electromagnetic component （N_e）
- Muon detector array （MD）： *hadron component* $\pi^{\pm} \rightarrow \mu$ （N_μ）

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

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





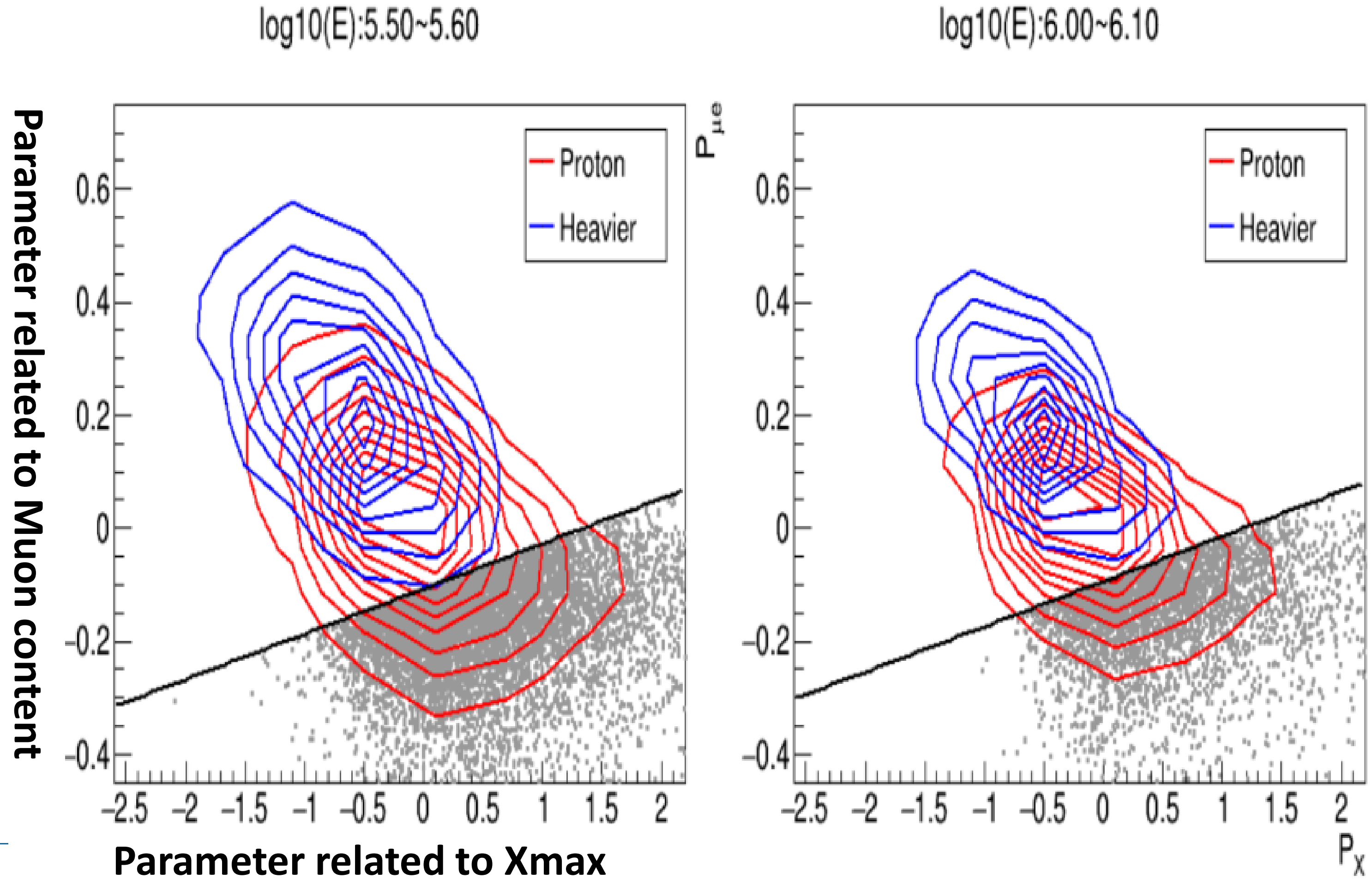


PHYSICAL REVIEW D 106, 123028 (2022)

Proton Shower Selection: shower maximum depth & μ-content

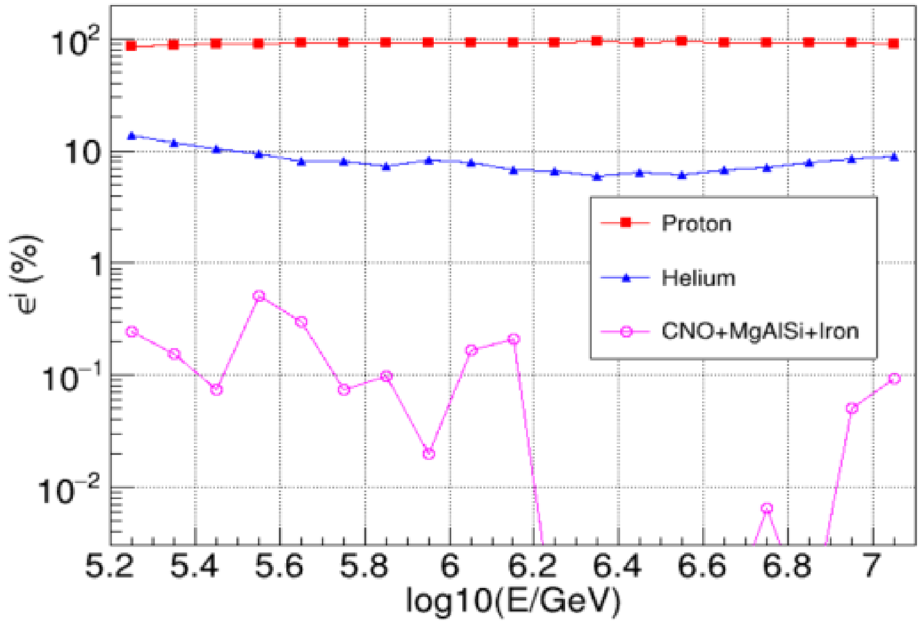
Proton Purity： $\epsilon^p = \frac{N_{sel}^P}{N_{sel}^{MC}} > 90\%$

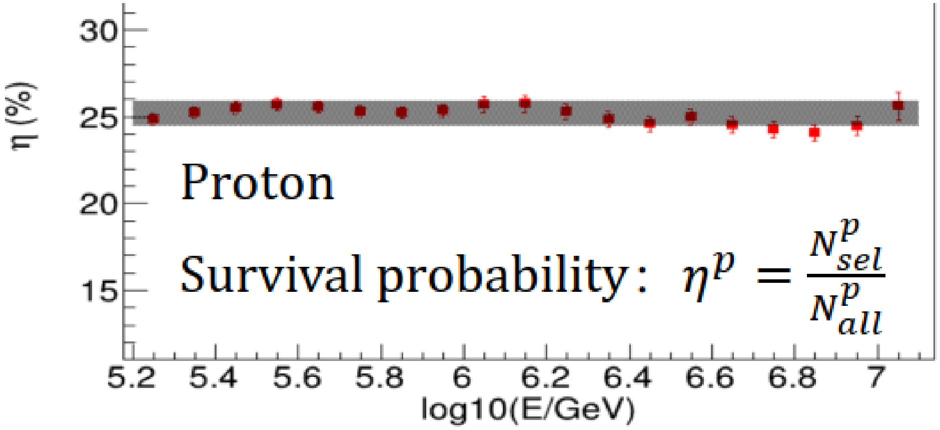
$(for\ Eproton > 300\text{TeV})$



Composition： $\epsilon^i = \frac{N_{sel}^i}{\Sigma N_{sel}^i}$ i= H, He, Other

$(After\ selection)$





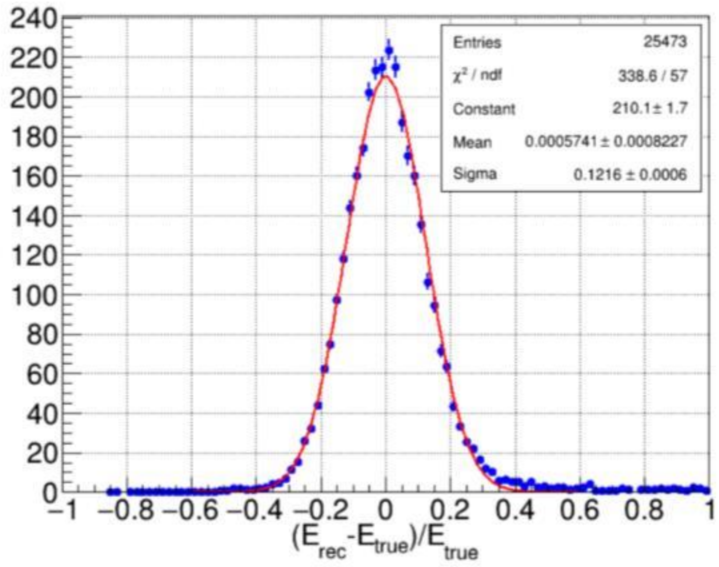
Proton

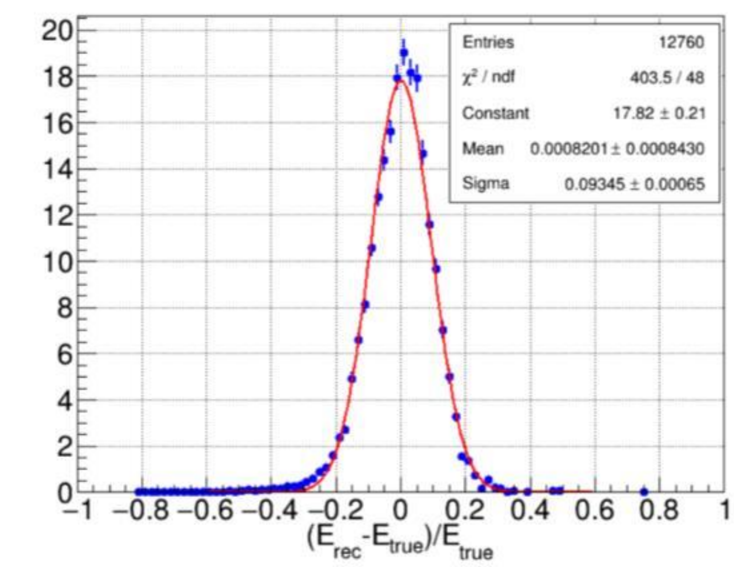
Survival probability： $\eta^p = \frac{N_{sel}^p}{N_{all}^p}$

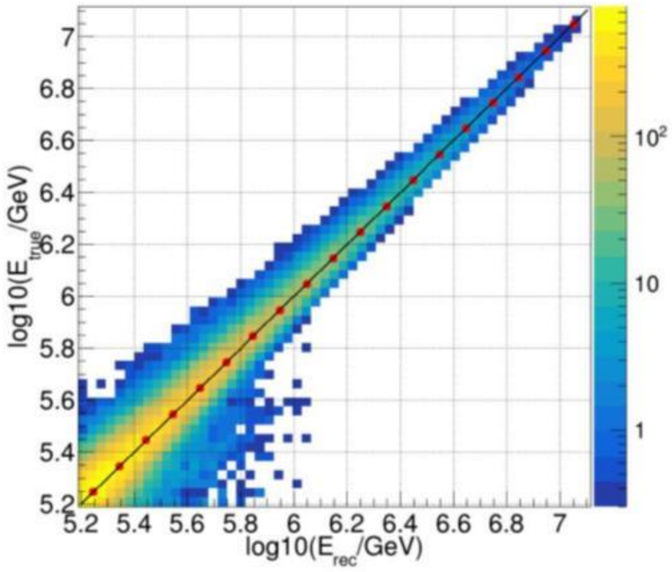
Proton Energy Reconstruction

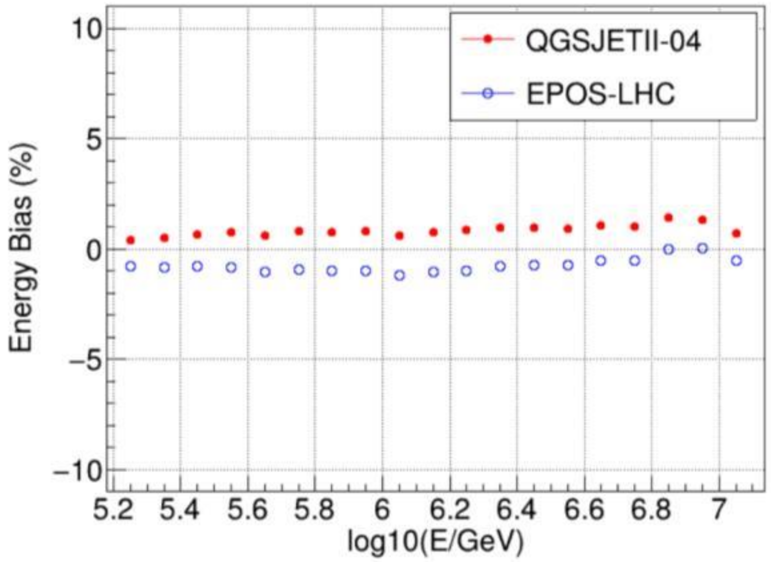
- **Energy Resolution： <15%**
- **Systematic Bias： <2%**
  (independent of shower energy)
- **Uncertainty mainly due to hadronic interaction models： ~1.4%**

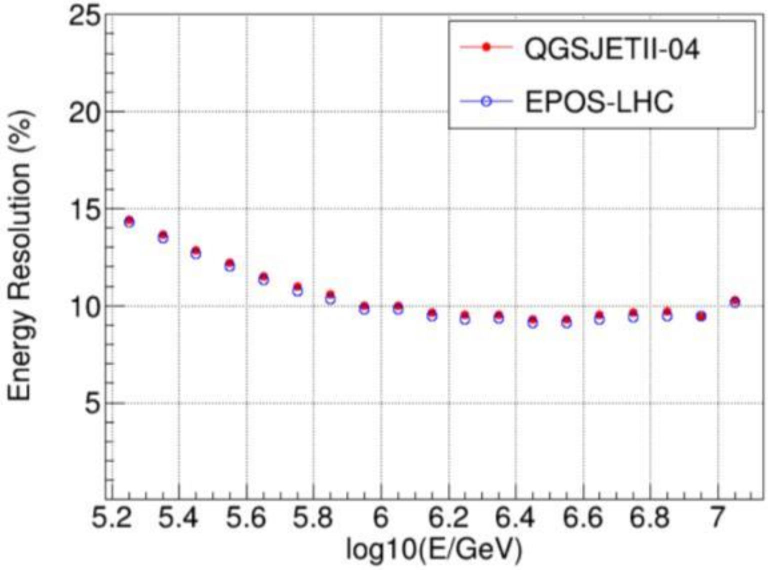
$$N_{c\mu} = N_{ph} + CN_u$$
$$E_{rec} = kN_{c\mu}$$











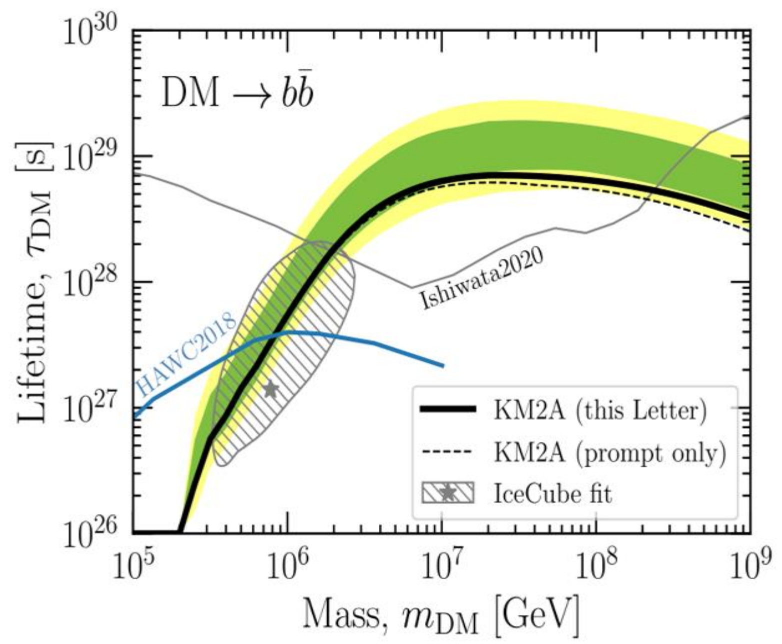
Outline

- Introduction
- Gamma Ray Astronomy
- CR Spectra around the Knees
- **New Physics Searches**
- Summary & Outlook

LHAASO constraints on dark matter

The strongest constraints on heavy dark matter decay lifetime

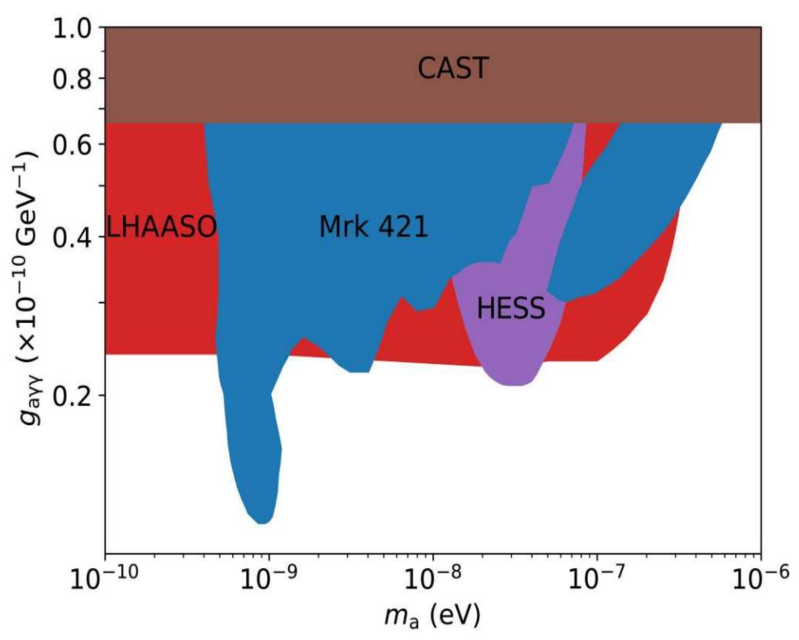
Galactic Halo UHE γ-ray



PRL 129:261103(2022)

Strong constraints on the axion–γ-ray coupling constant

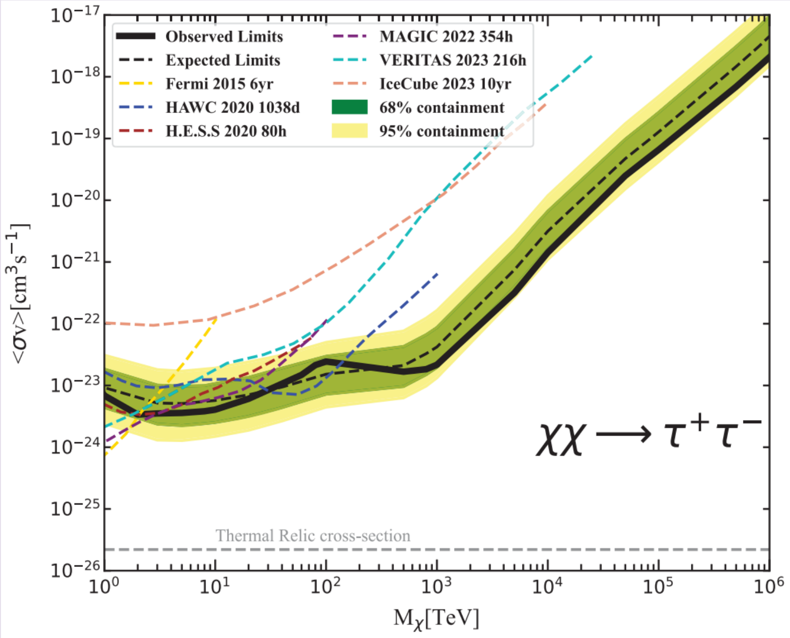
GRB VHE γ-ray



Science Advances 9:eadj2778 (2023)

The strongest constraints on dark matter annihilation cross section

Dwarf galaxies UHE γ-ray

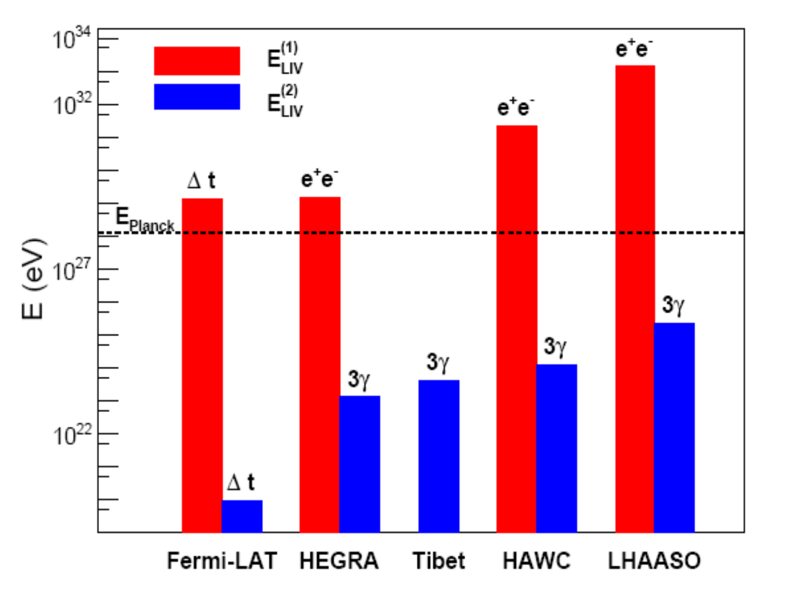


PRL 133:061001 (2024)

LHAASO Constraints on Lorentz Invariance Violation (LIV)

- **Using decay of PeV γ-ray**

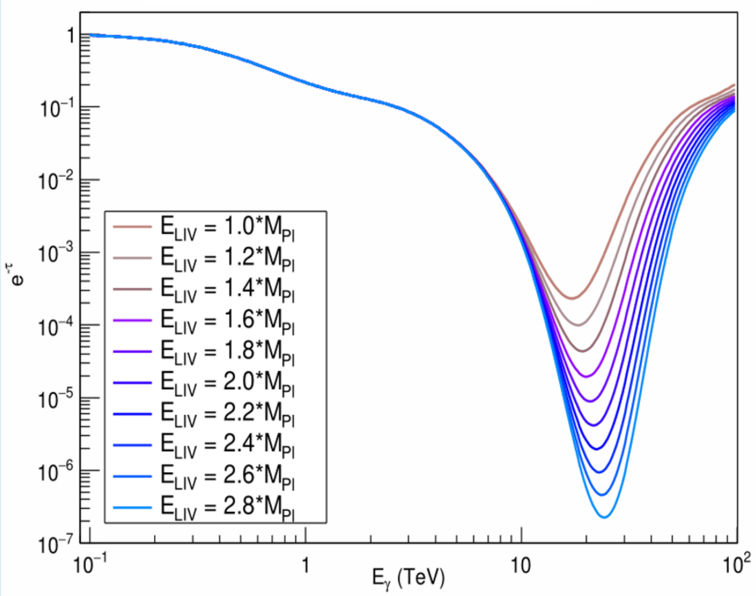
$$E_\gamma^2 - p_\gamma^2 = \pm|\alpha_n|p_\gamma^{n+2}$$



PRL 128:051102(2022)

- **Using the EBL absorption on 10 TeV γ-ray (EBL)**

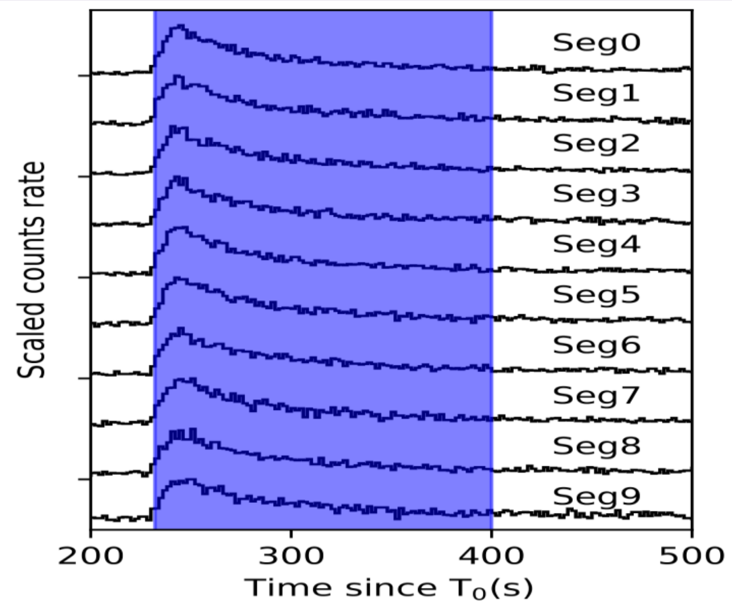
$$\epsilon_{thr} = \frac{m_e^2}{E} + \frac{E^2}{8E_{LIV}^{(1)}}$$



Science Advances 9:eadj2778 (2023)

- **Using the time lag of different energy γ-ray**

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



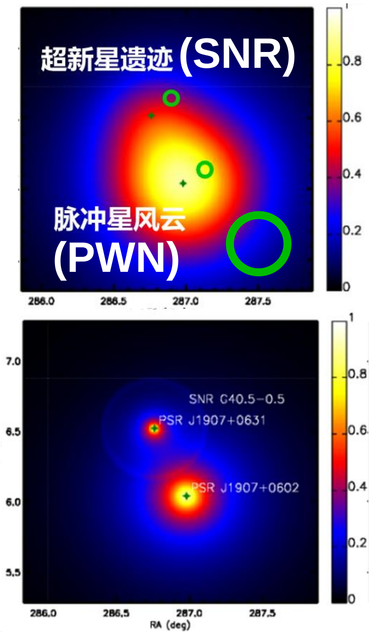
PRL 133, 071501(2024)

Summary & Outlook

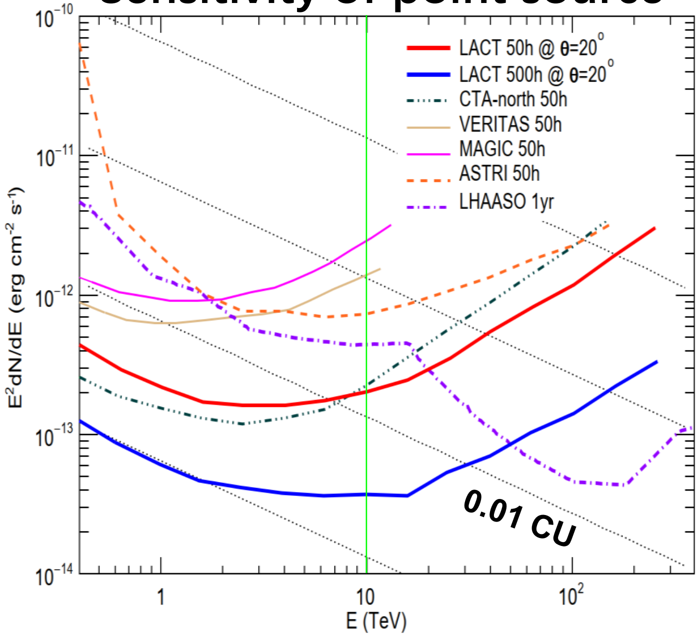
- LHAASO full array has been stably operating since 2021
- LHAASO open-up a new UHE γ-astronomy era with many new discoveries
  - 43 UHE γ-sources are detected and published in catalogs w/~40% of them unidentified
  - The first CR source as a super-PeVatron is found
  - The BOAT GRB brings us many new views of GRB afterglow, the highest energy photon from the GRB opens opportunities exploring for new physics
  - Diffuse photon flux is found a factor 2 or 3 higher than expectation, a big issue!
- Measuring CR Spectra of Individual Species (Proton, Helium, Iron…) around knees is a big step towards understanding the knee feature
- Progresses in New Physics Search: massive DM, axion DM and LIV
- There are more interesting new phenomena waiting to be further revealed!

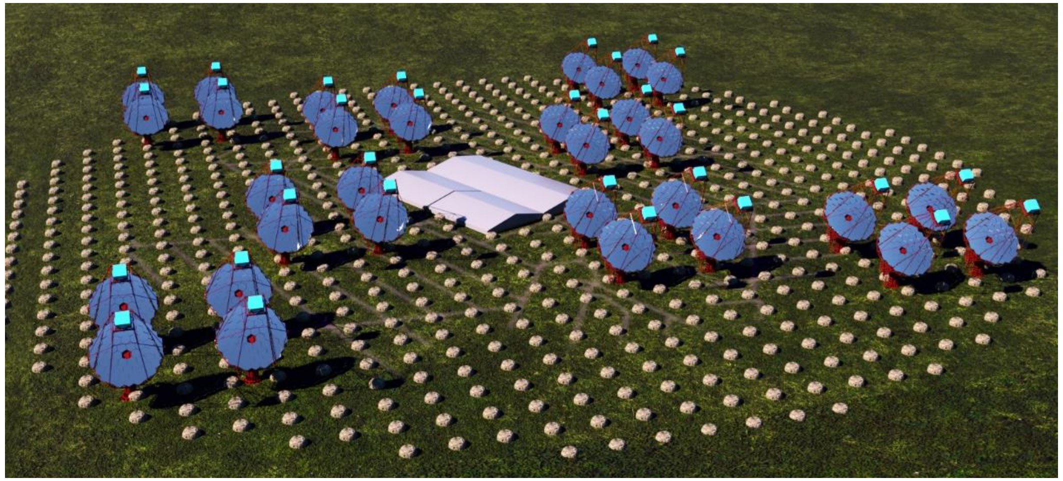
Future Missions: UHE IACT array with LHAASO

- Large Array of Cherenkov Telescopes (LACT)
  - Next generation of Image Atmosphere Cherenkov Telescope experiment
  - 32 telescopes built on LHAASO site
  - Angular resolution
    - **LACT: < 0.05° @ > 10 TeV**
    - LHAASO: ~0.2° @ > 100 TeV
  - **LHAASO MD array provides excellent γ/p discrimination**
  - Matching the LHAASO sensitivity with 500 hr/yr
  - To identify the gamma ray sources in PeVatrons and measure their morphology in details.
- LACT project started construction this year and the full array will be completed by 2028



Sensitivity of point source





A prototype in LHAASO

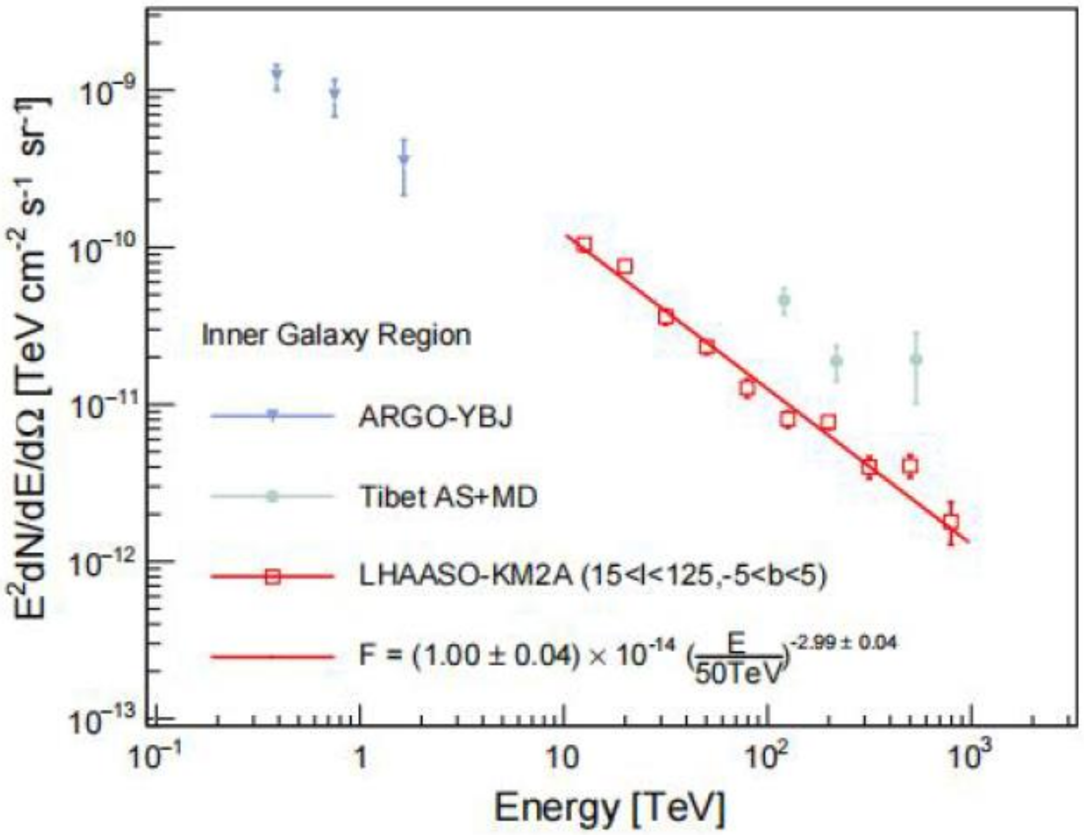
A prototype in Chengdu

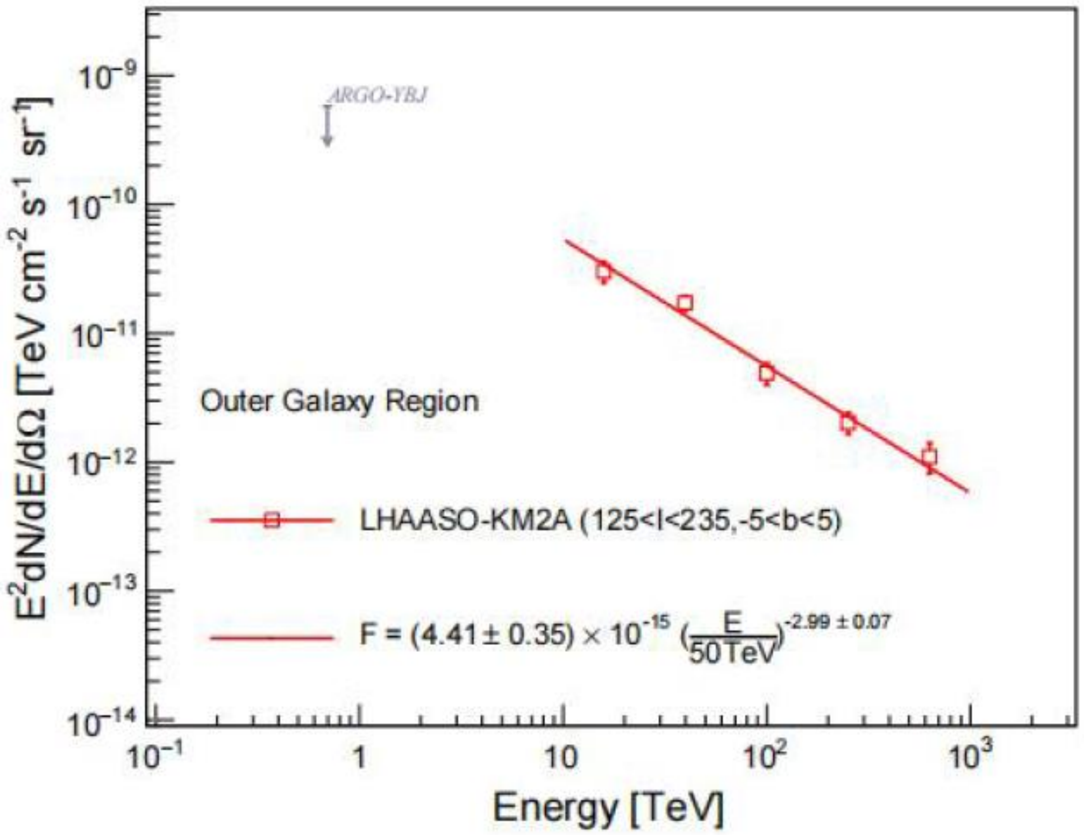
LACT Construction Plan

	Construction plan	2024	2025		2026	2027	2028
		1-12	1-7	8-12	1-12	1-12	1-12
1	First telescope optimization and commissioning						
2	Second telescope construction and commissioning						
3	The next six telescopes construction and commissioning (total 8 tels)						
4	The full array complete the construction and commissioning (total 32 tels)						

Thanks !

LHAASO diffuse results





- First detection of VHE diffuse emission from outer Galactic plane
- Spectra follow power-law forms with an index of ~3