LHAASO and Highlights of Science results

Zhen Cao **for LHAASO Coll.**

Institute of High Energy Physics, Beijing

ICRC 2021, On-line, July, 2021

LHAASO
高海拔宇宙线观测站

LHAASO Collaboration

Scientists: 275 **Institutions: 31**

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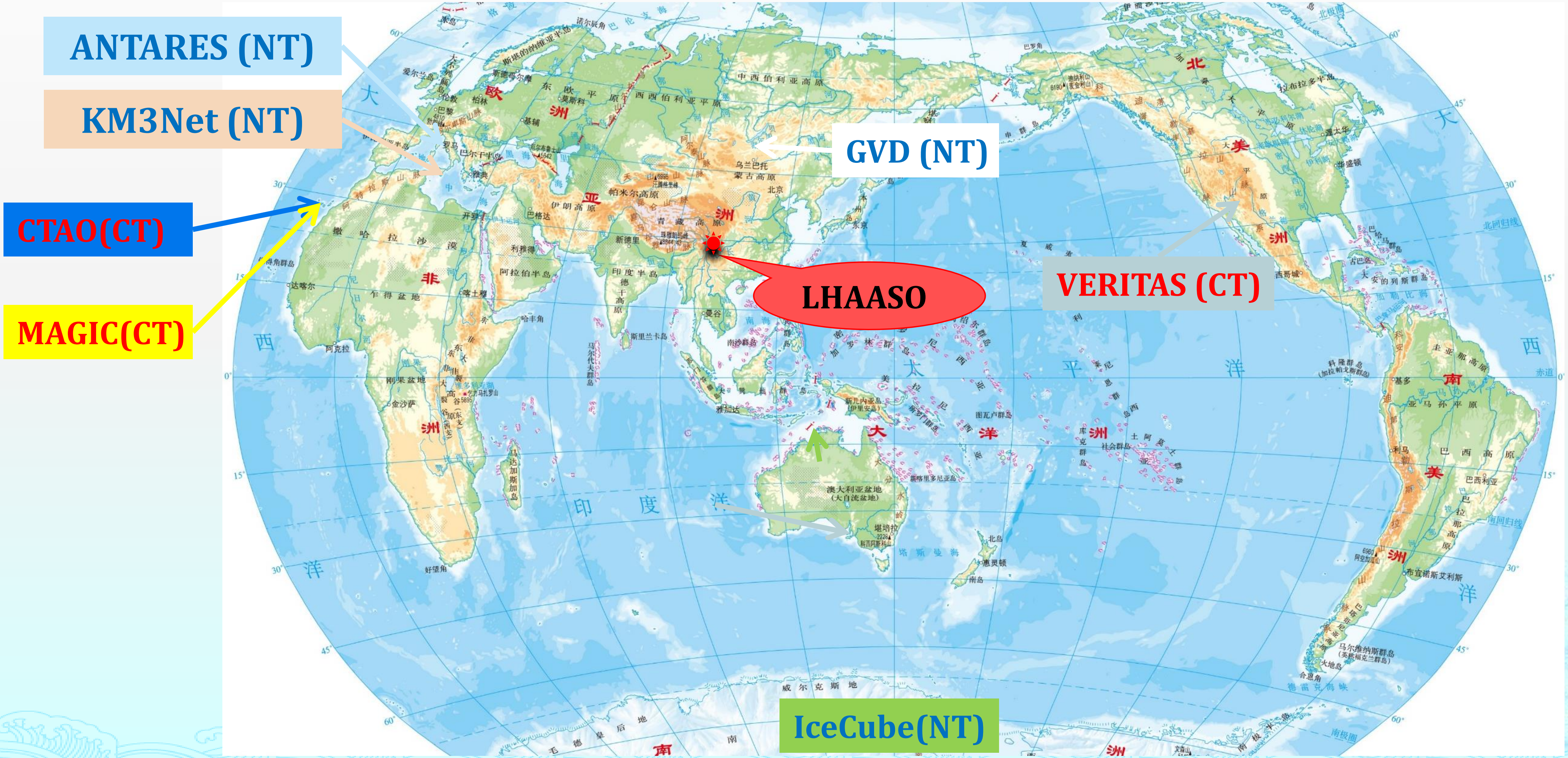
list of institutions waiting
for membership: APS, France

MoU of Collaboration: VERITAS, ANTARES, GVD

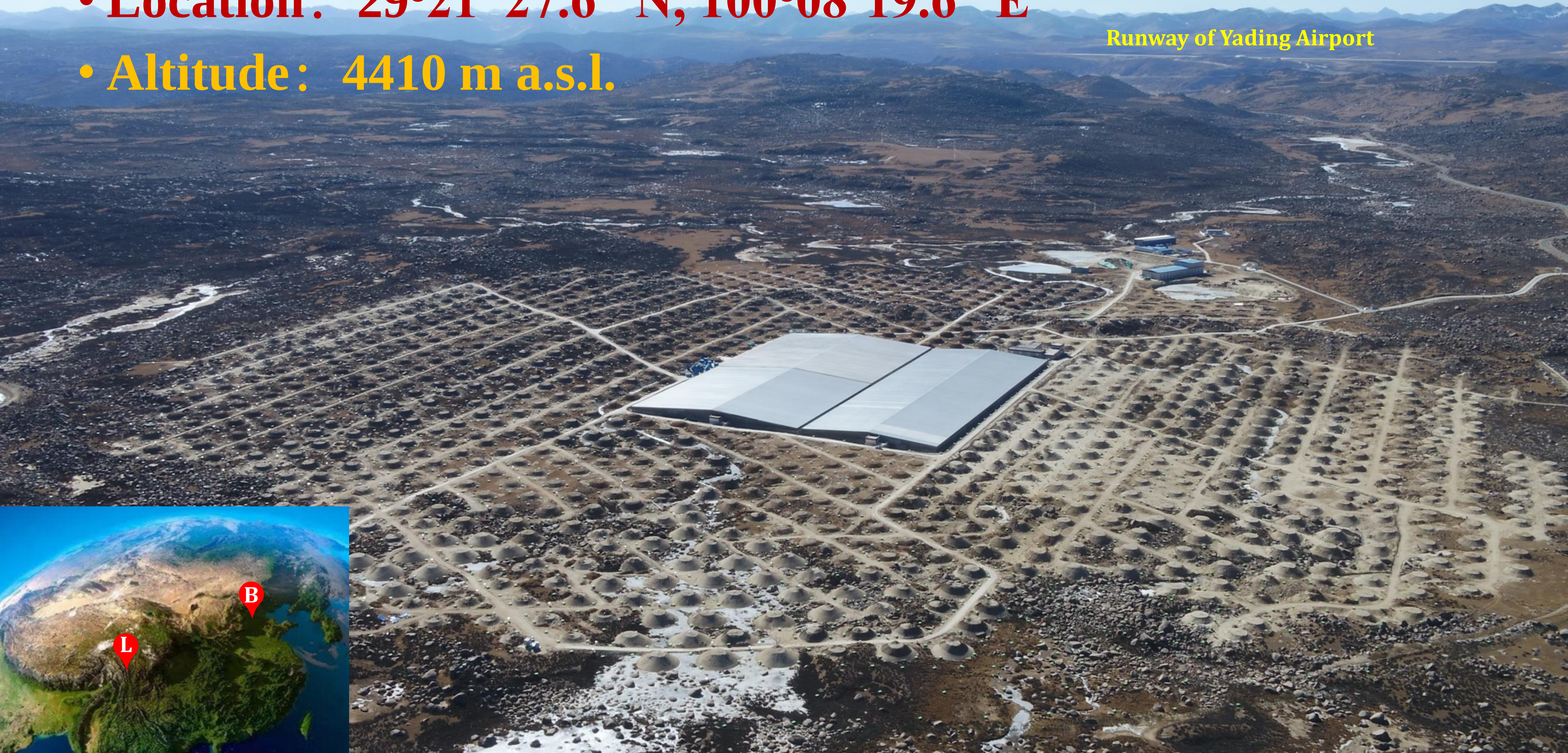
CTAO, MAGIC, IceCube

Multi-Messenger Collaboration Network

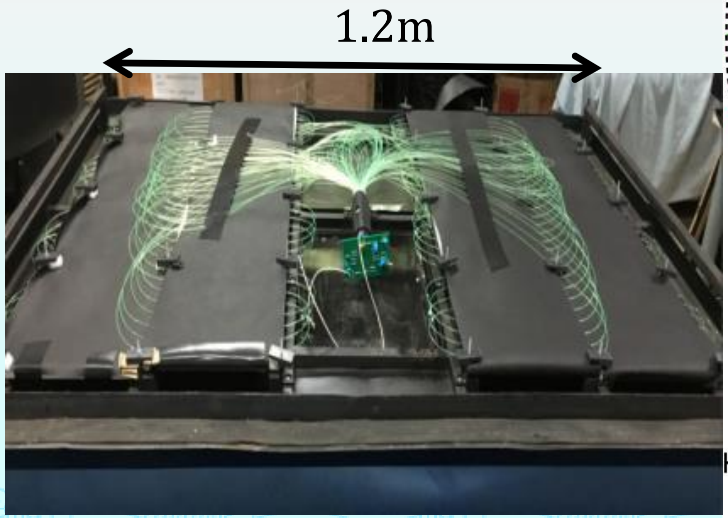


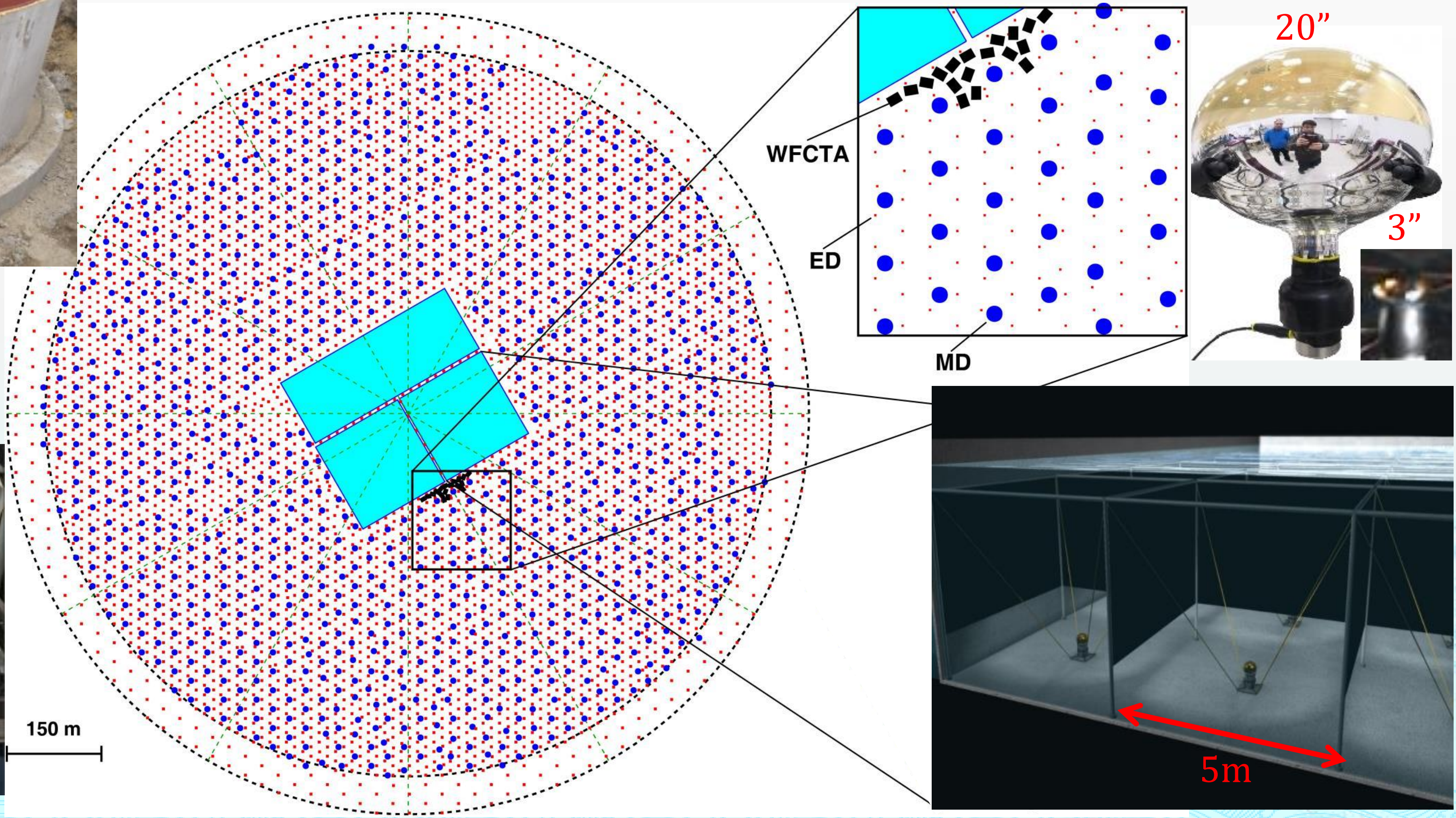
Bird-eyes' View of LHAASO, March, 2021

- **Location: 29º21' 27.6" N, 100º08'19.6" E**
- **Altitude: 4410 m a.s.l.**



LHAASO Layout





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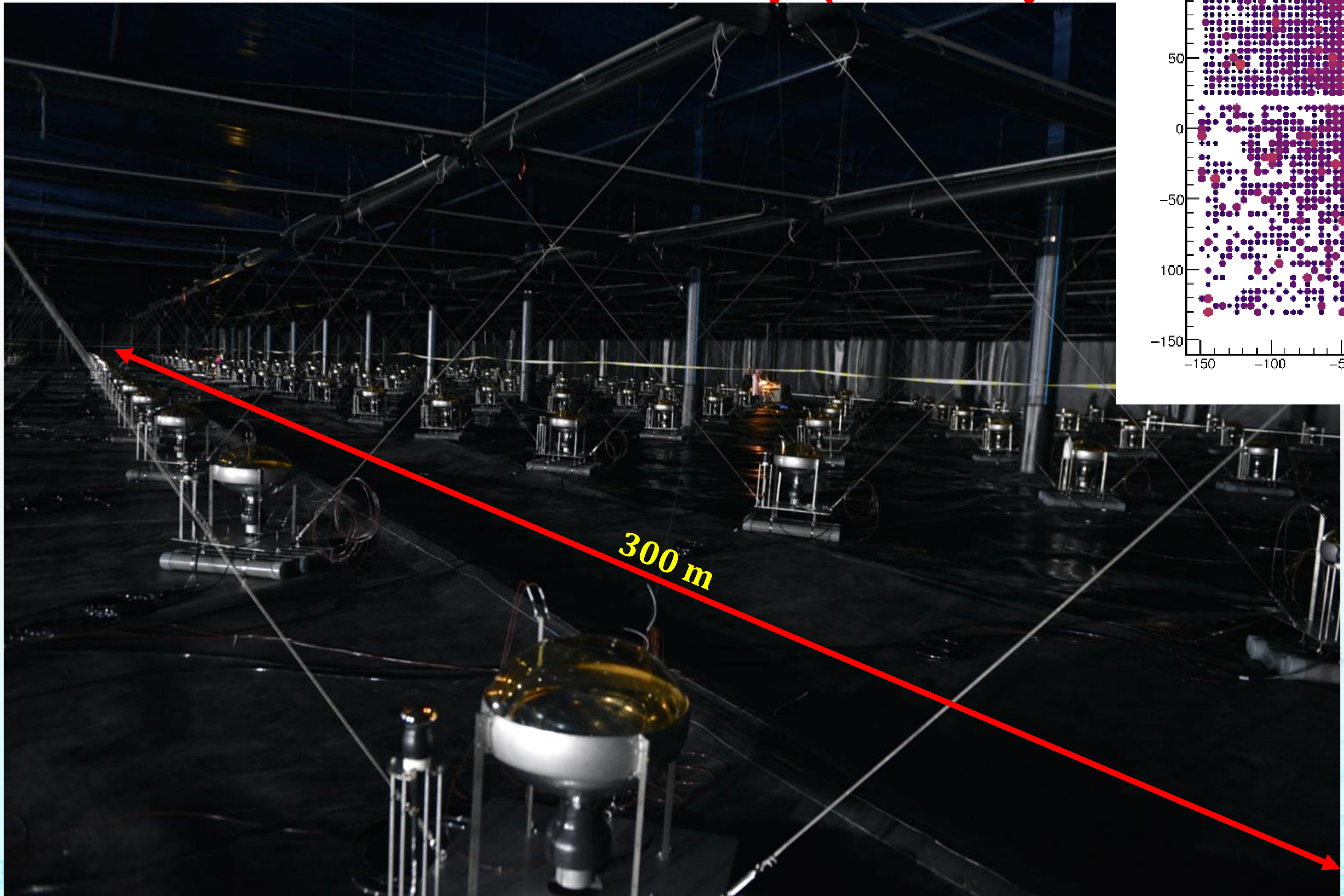
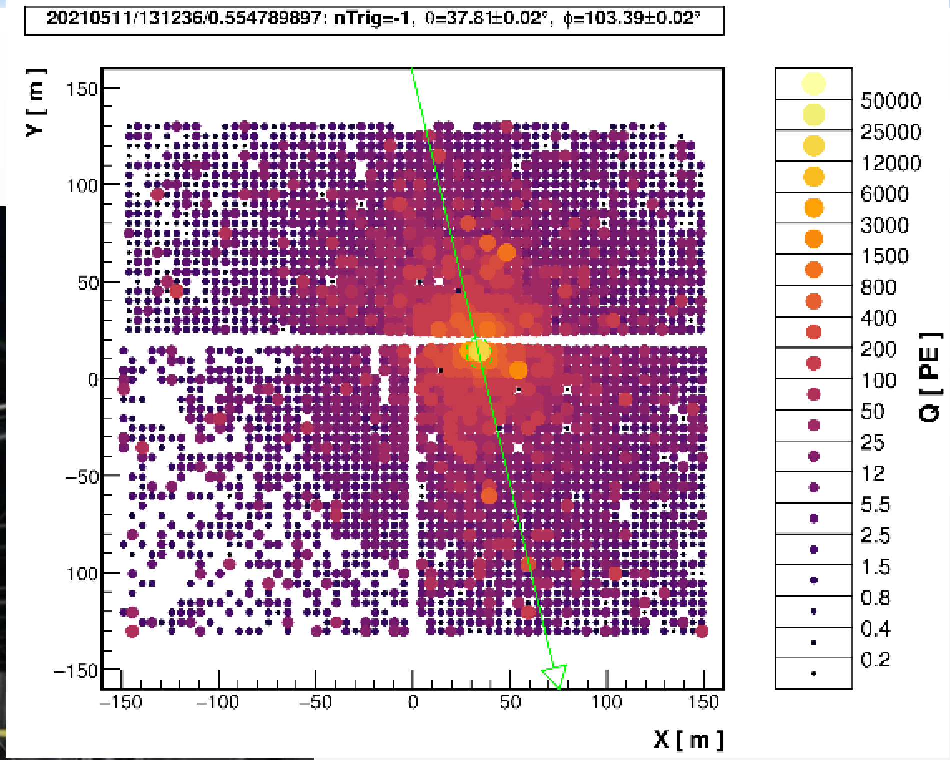
Water Cherenkov Detector Array (WCDA)





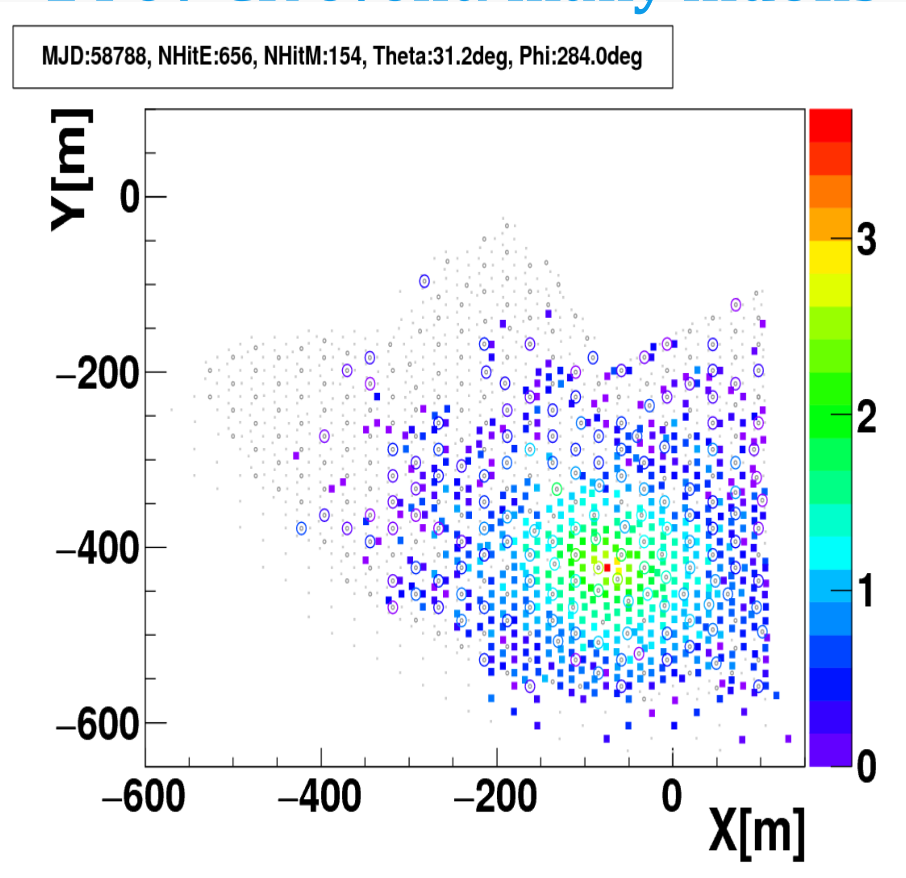
- **Area:**
  78,000 m^2
- **Detector units:**
  3120
- **Energy Range:**
  0.1-10 TeV

KM2A

Selection of γ–rays out of CR background

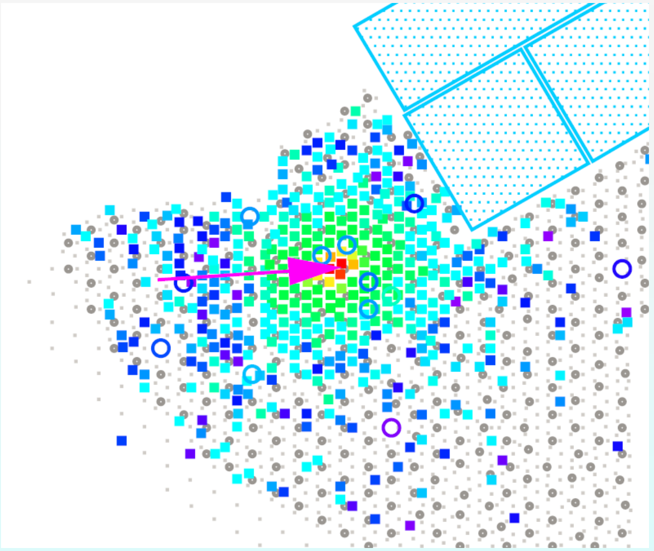
Active Area for Muons vs. Array Area: 4%

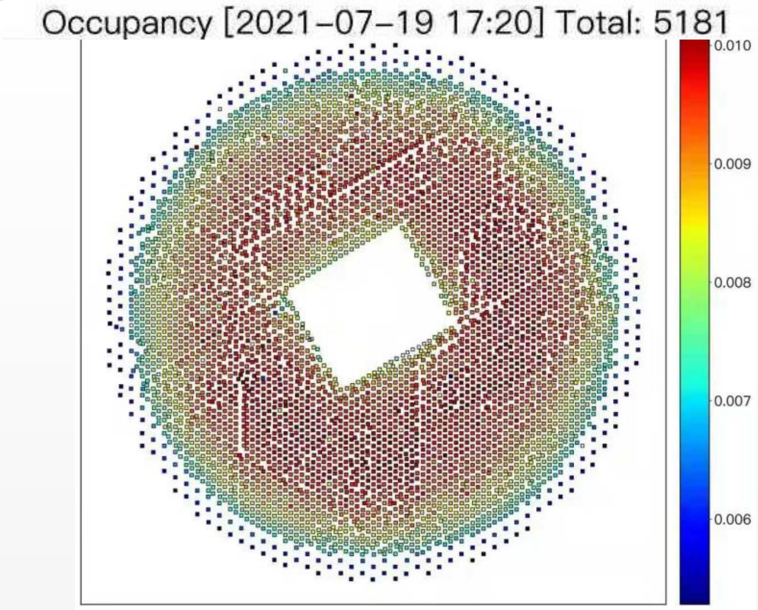
~1 PeV CR event: many muons



~ 1 PeV γ–ray event : very few muons

~1 PeV from the Crab

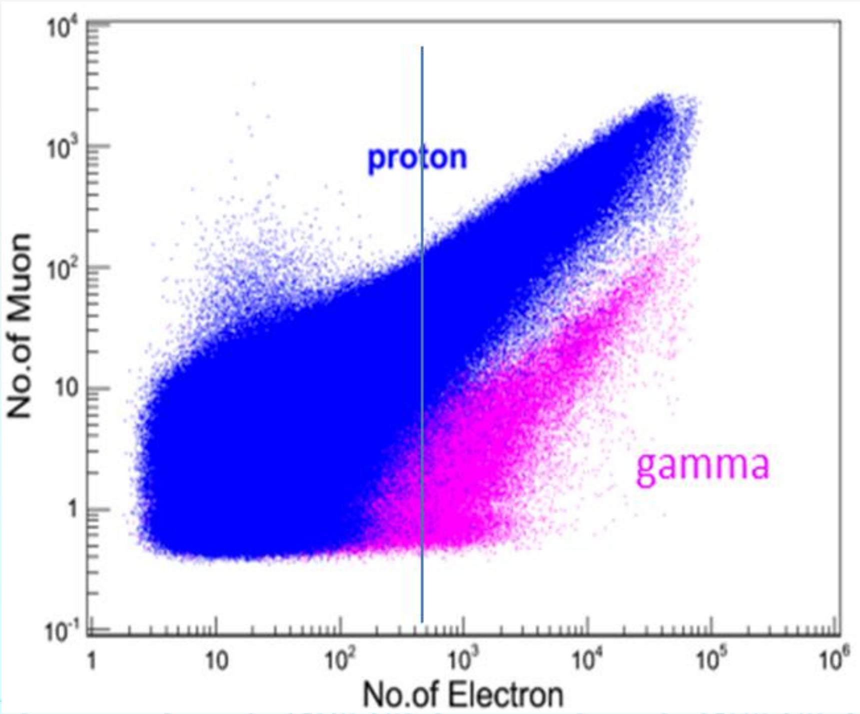


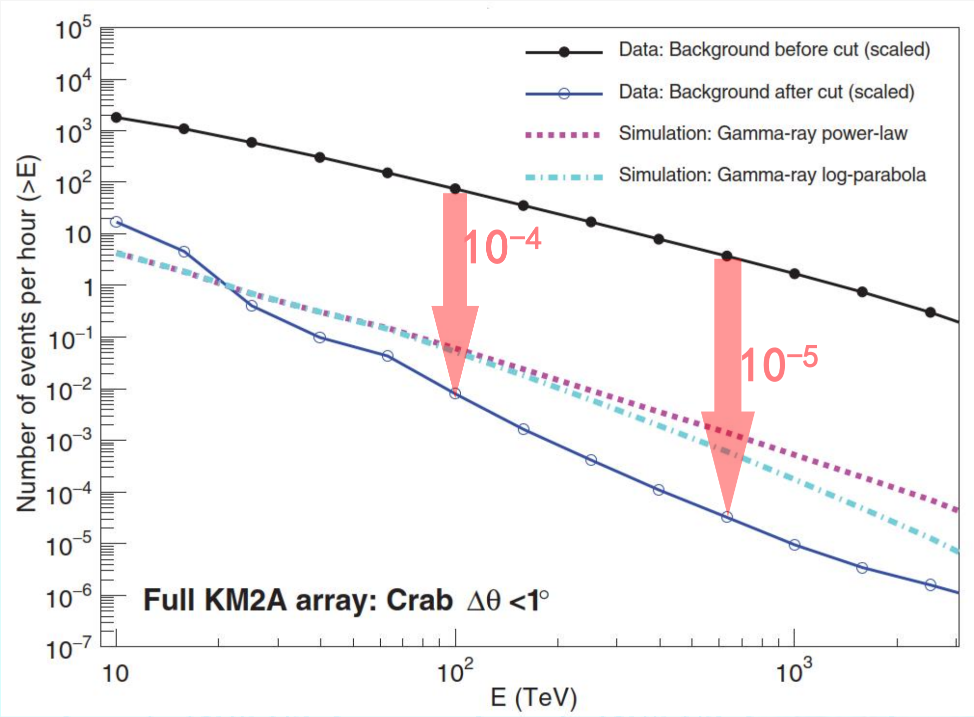


- **Area:**
  1.3 km^2
- **Detectors:**
  5195 ED
  1188 MD
- **Energy Range:**
  0.01-10 PeV

CR background Rejection Power

- Counting number of measured muons in a shower
- Cutting on ratio N_μ/N_e<**1/230**
- BG-free ($N_\gamma > 10N_{CR}$) Photon Counting
  for showers E>100 TeV from the Crab





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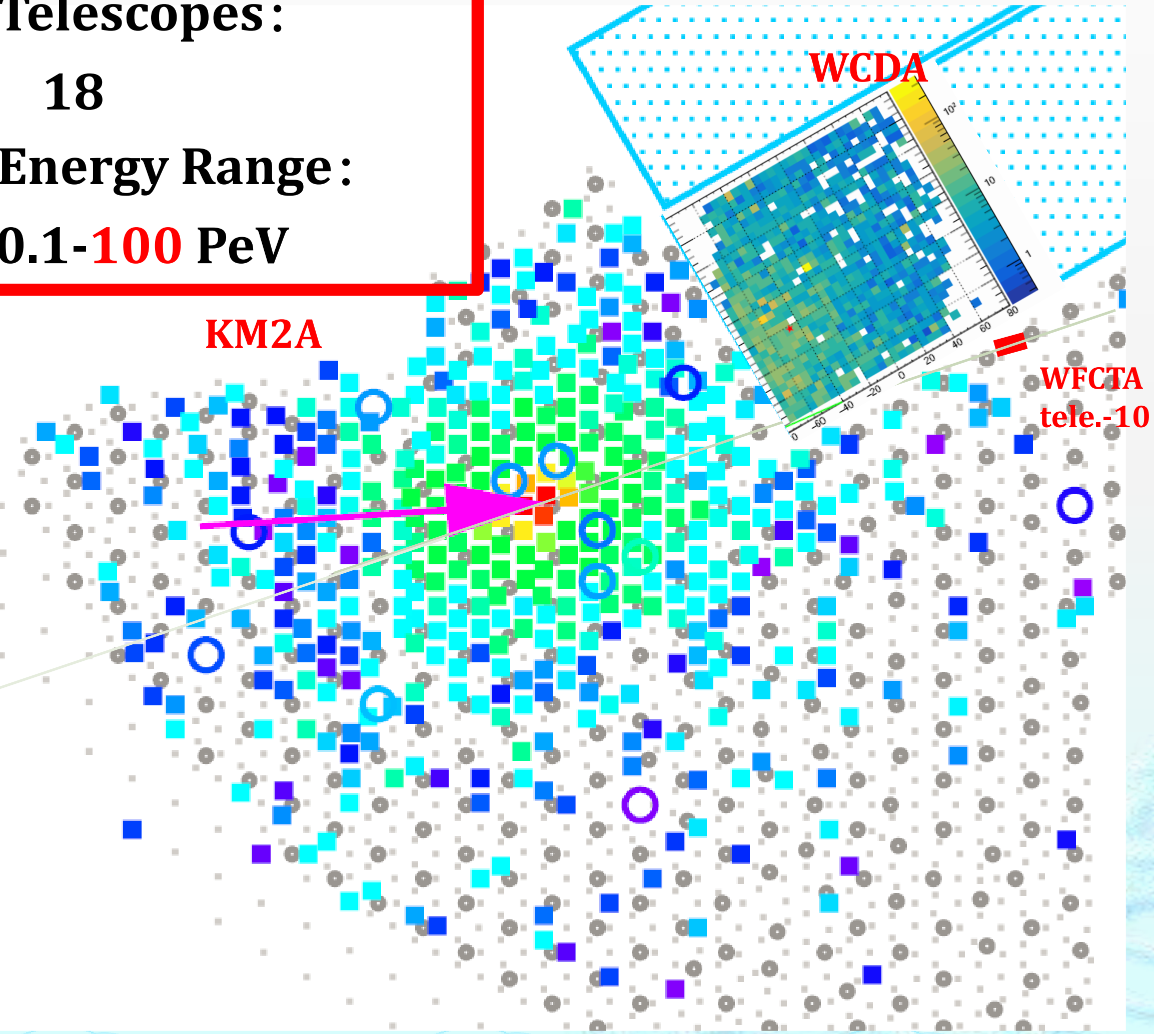
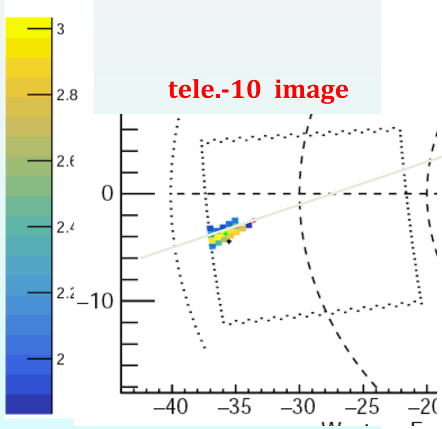
Wide FoV C-Telescope Array (WFCTA)

Cross-checking inside Collaboration

- **Telescopes：**
  18
- **Energy Range：**
  0.1-100 PeV

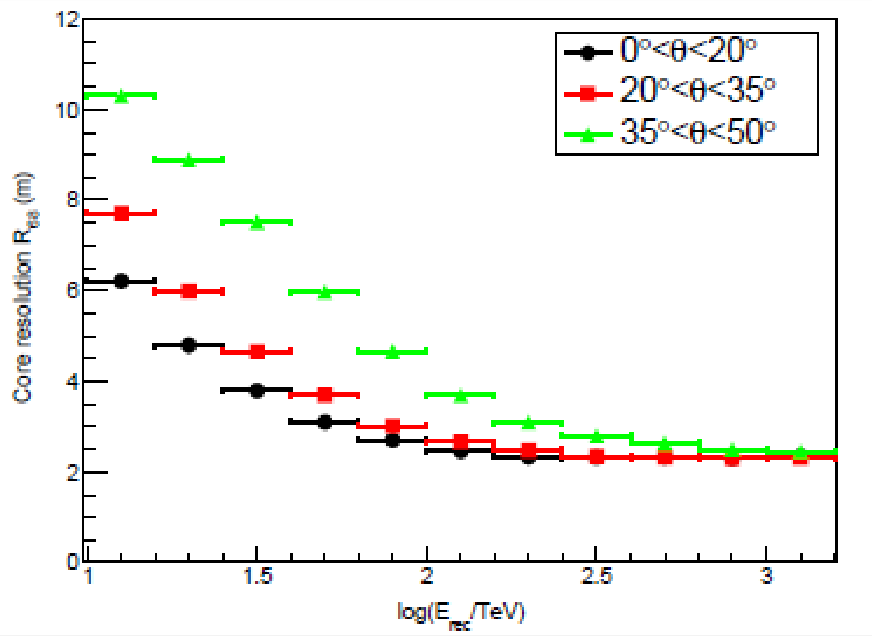


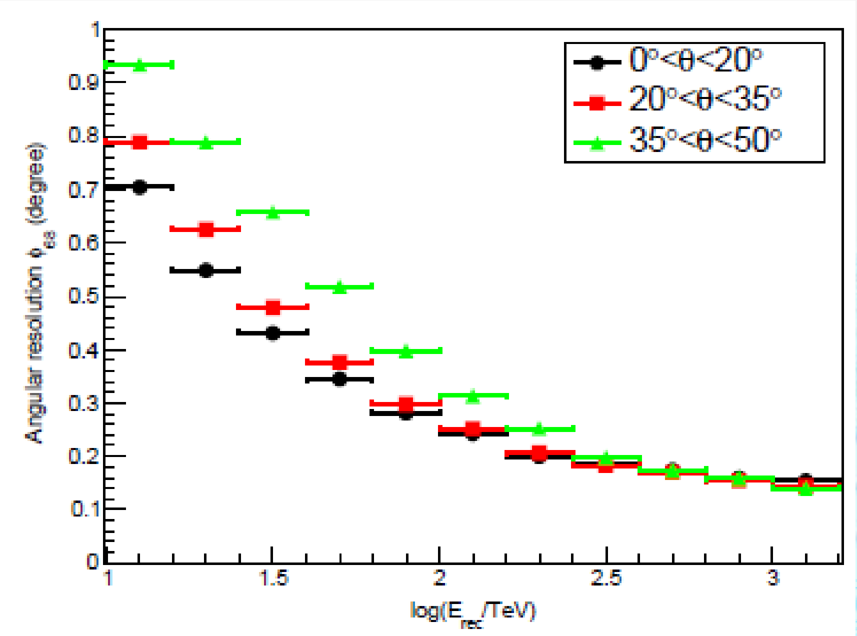
- WFCTA measured the event simultaneously
  L/W~2.6, N_{pe}~9100 in 11 pixels
- **Energy： 0.9±0.2 PeV**
- KM2A measured the event
  $N_{particle}$~4574 in 395 EDs
- **Energy： 0.9±0.1 PeV**
- **Chance probability: <0.1%**
  N_{μ}~15 in 11 MDs



KM2A performances

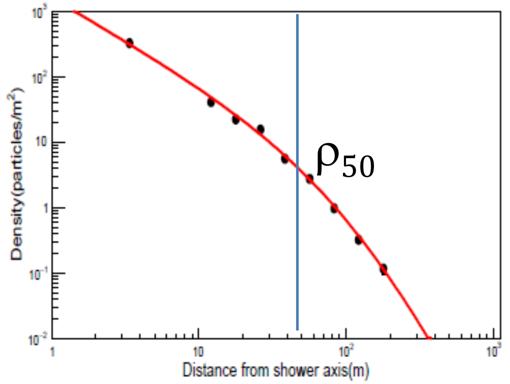
- Shower geometrical reconstruction
  - Arrival direction: resolution of **0.26°** @100 TeV
  - Shower core location: resolution of **3 m** @100 TeV
  - Zenith angle effect

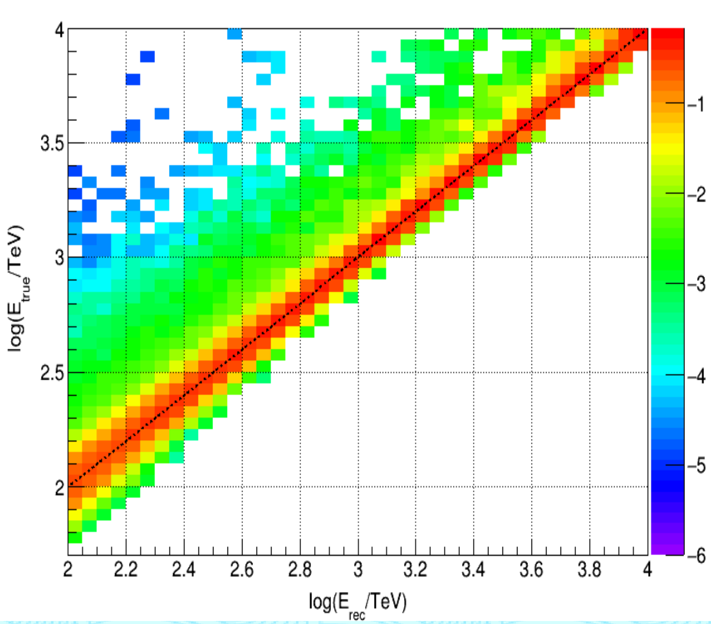


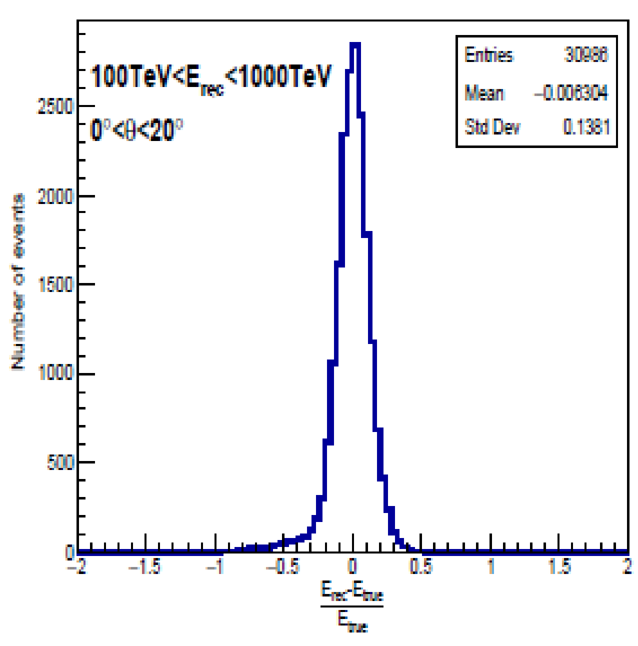


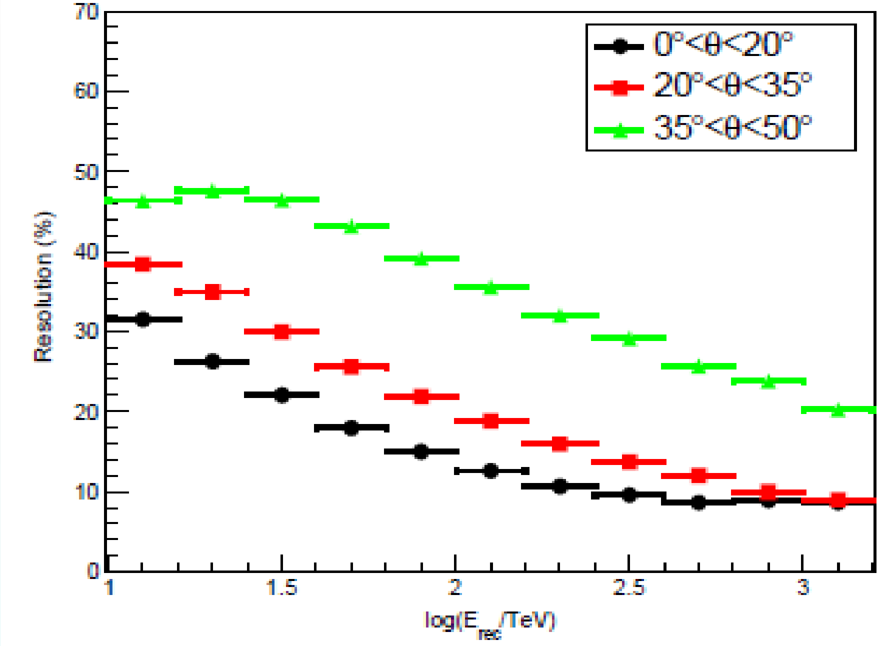
Shower Energy Reconstruction by KM2A

- Lateral distribution: modified NKG function
- Energy estimator: ρ_{50} particle density
- Gaussian Resolution function >100 TeV: **14%**
- Linear response function





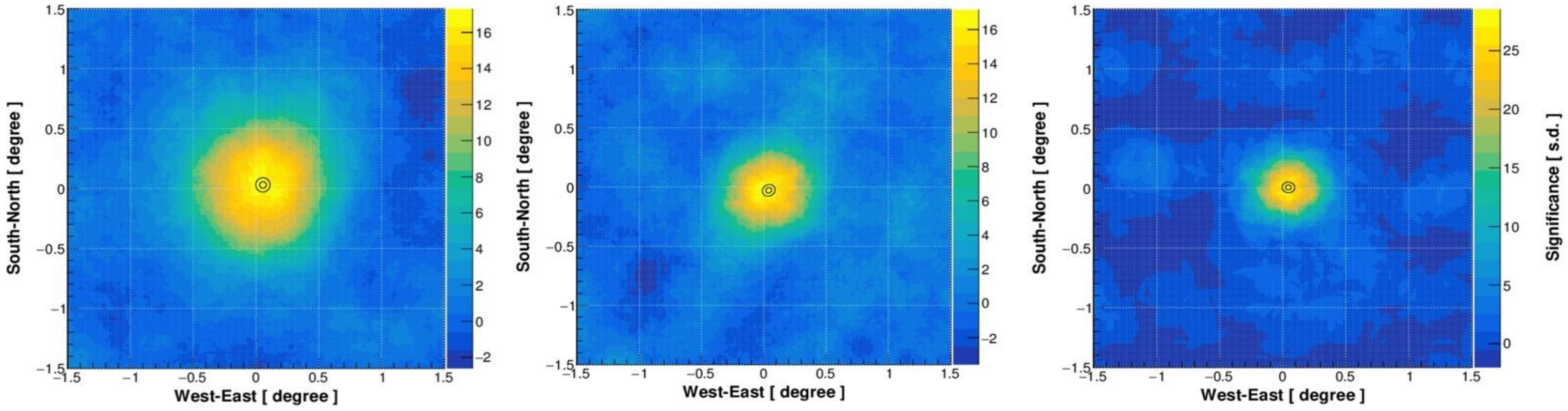


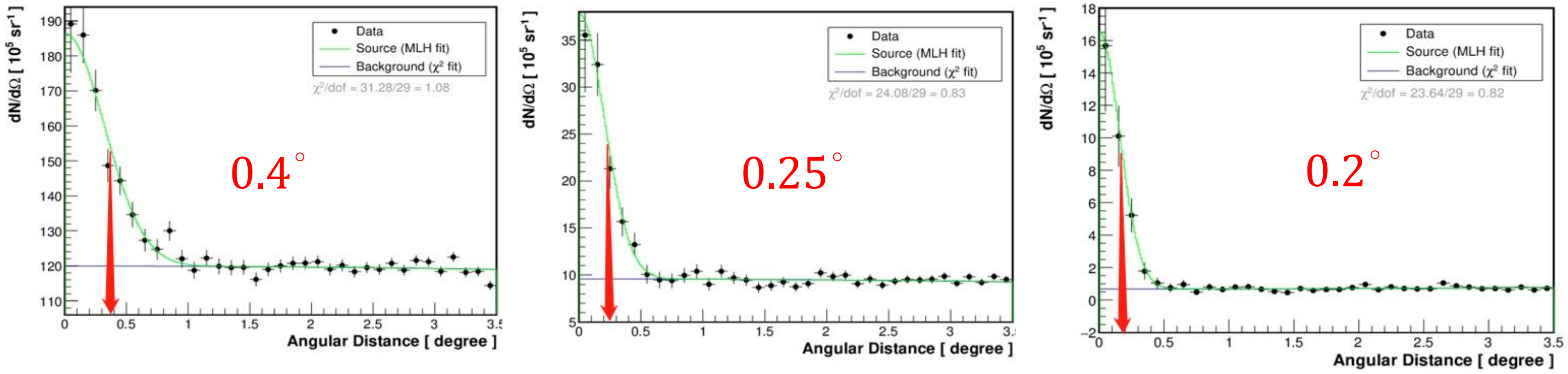


WCDA Pointing and Resolution

- Pointing accuracy is already good, though we still found the orientation of WCDA-1 29.45° towards west instead of 30.00° that results in an even better pointing

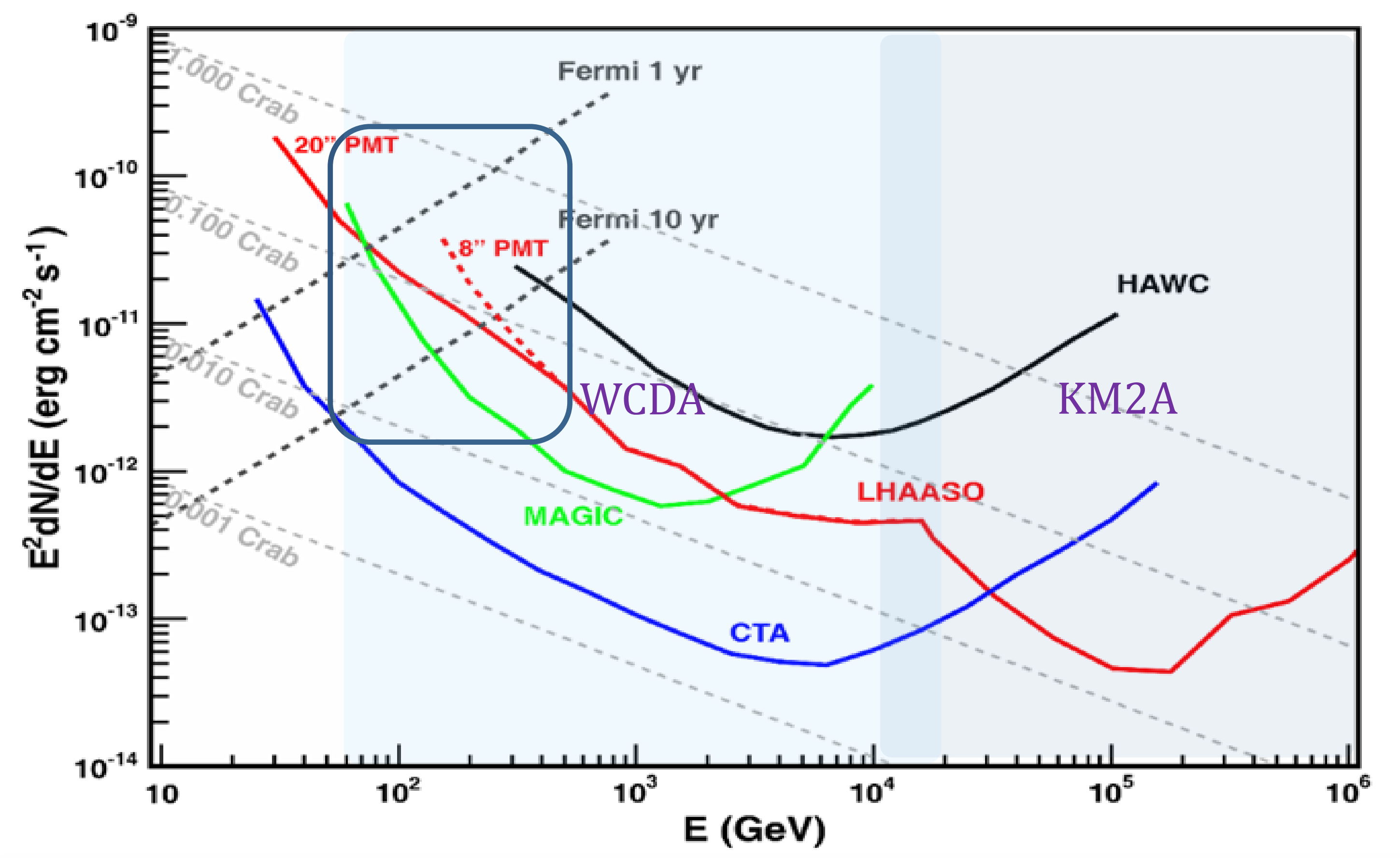
N_{det}: 100-200 N_{det}: 200-300 N_{det}: 300-500

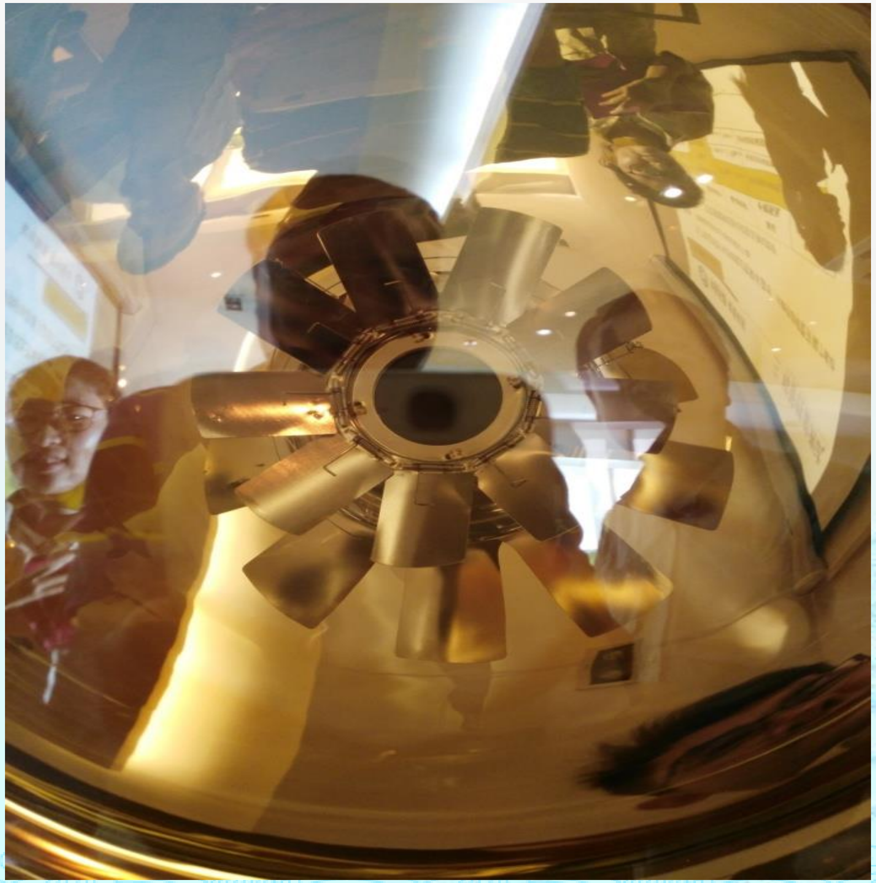


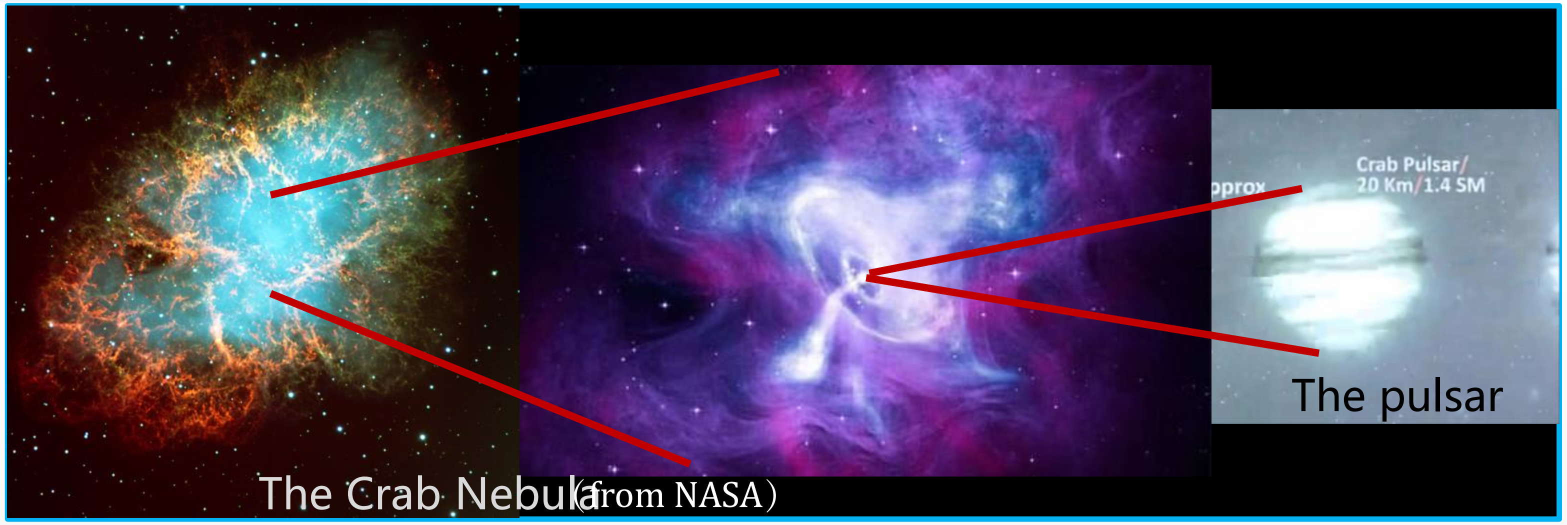


20” PMTs used in 70% WCDA

- Enhancement of the sensitivity below 300 GeV
- Transient Phenomena： GRB、AGN-flares、multi-messenger astronomy ...

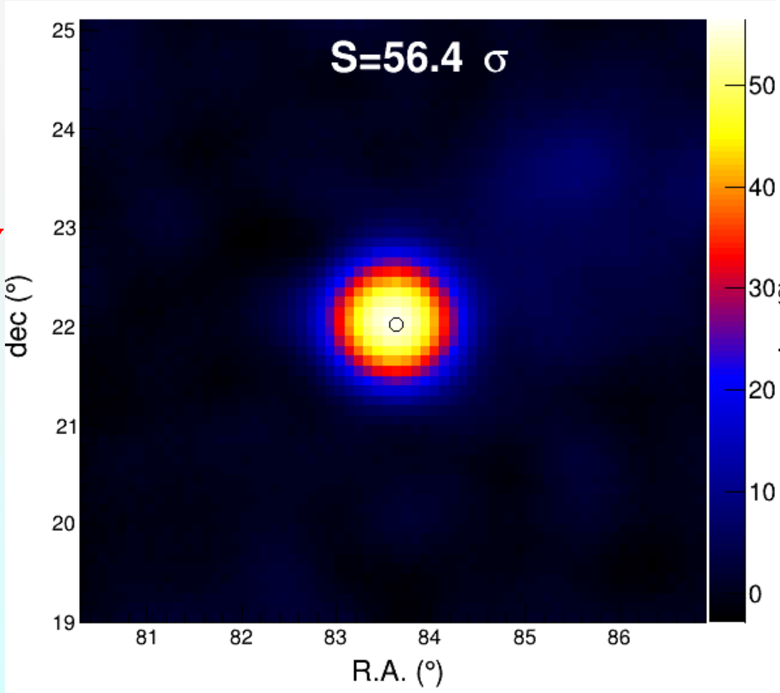


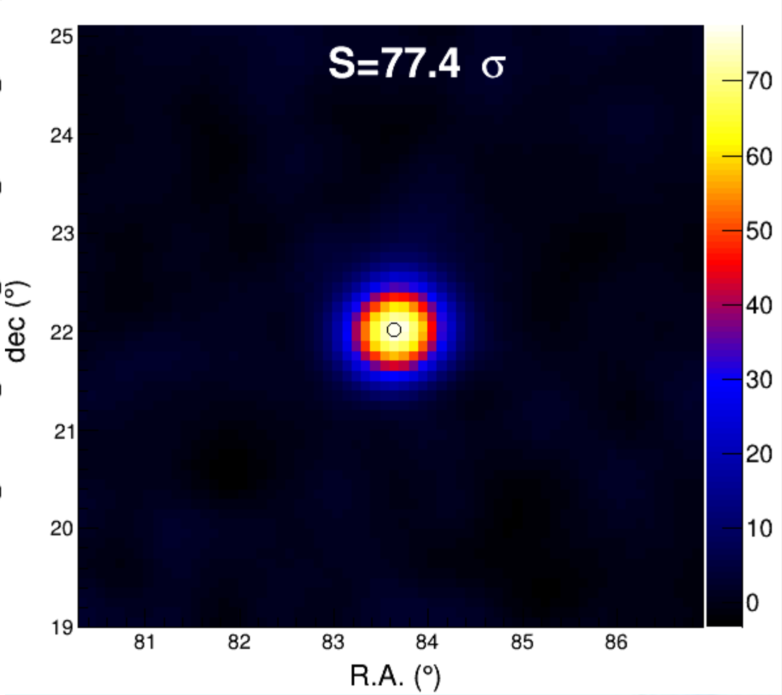




KM2A

- 2019-09-11 ~2020-07-07
- Pointing accuracy <0.1°
- Angular Resolution: 0.26°
- Energy: >25 TeV





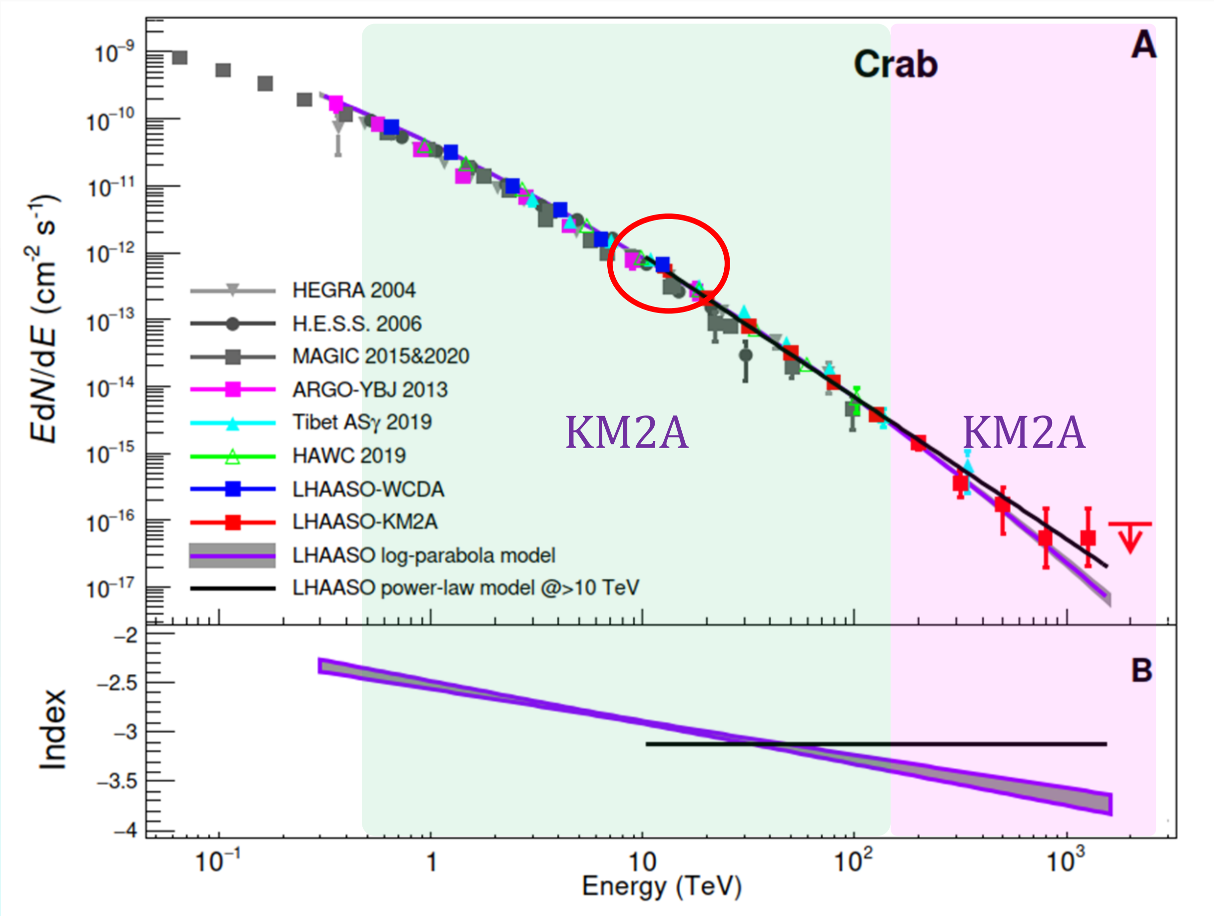
WCDA

- 2019-04-19 ~2020-03-11
- Pointing accuracy: <0.1°
- Angular Resolution: 0.22°
- Energy: >1 TeV

SED of the Crab: "standard Candle" & PeVatron

LHAASO, Science, DOI10.1126/science.abg5137, 2021

- **LHAASO:**
  - **Covering 3.5 decades of energy**
  - **Agreeing with other experiments below 100 TeV**
  - **Self cross-checking between WCDA & KM2A**
- **LHAASO:**
  - **Unique UHE SED**
  - **A PeVatron without ambiguity**
  - **Clear origin: a well-known PWN**



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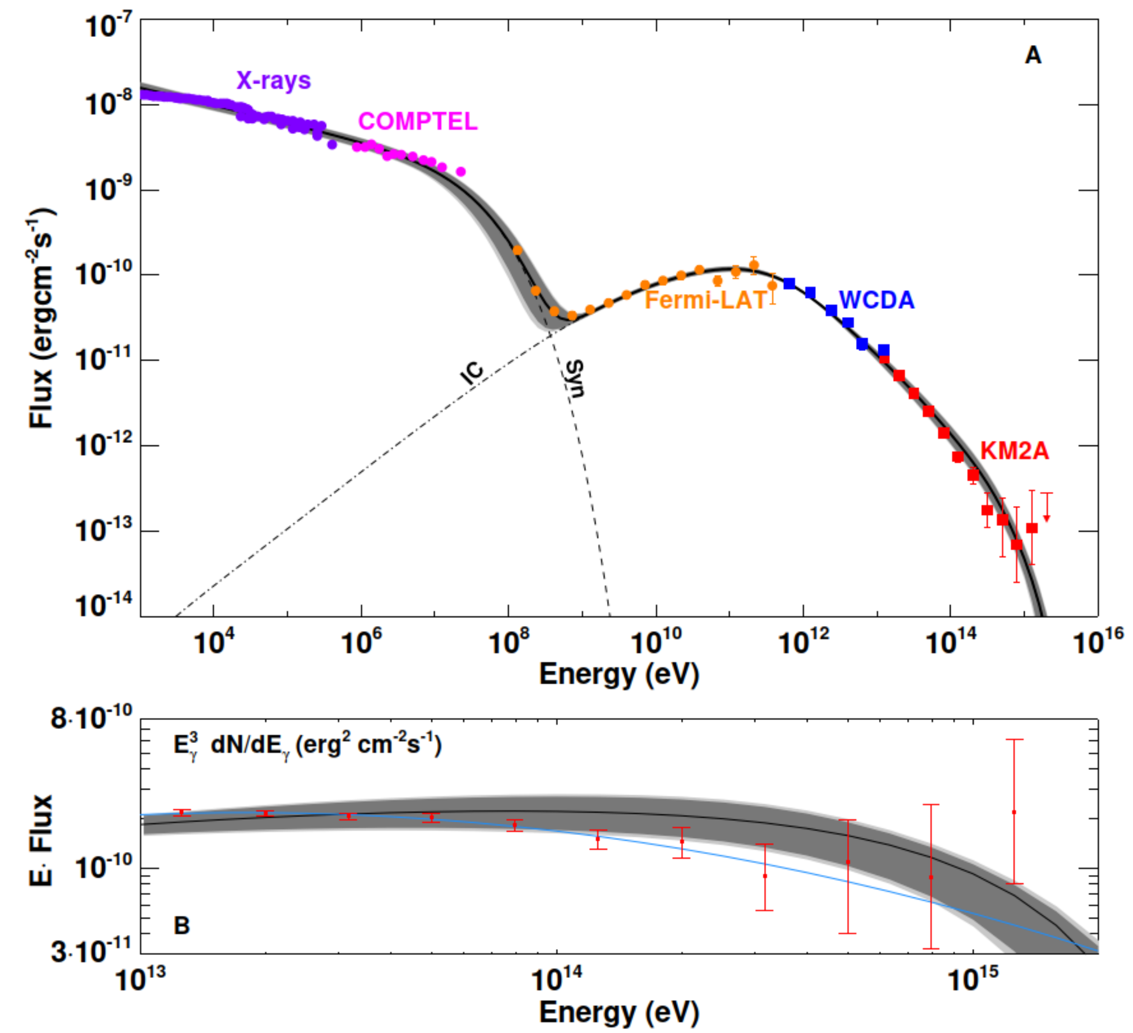
SED of the Crab: Extreme E-accelerator

LHAASO, Science, DOI10.1126/science.abg5137, 2021

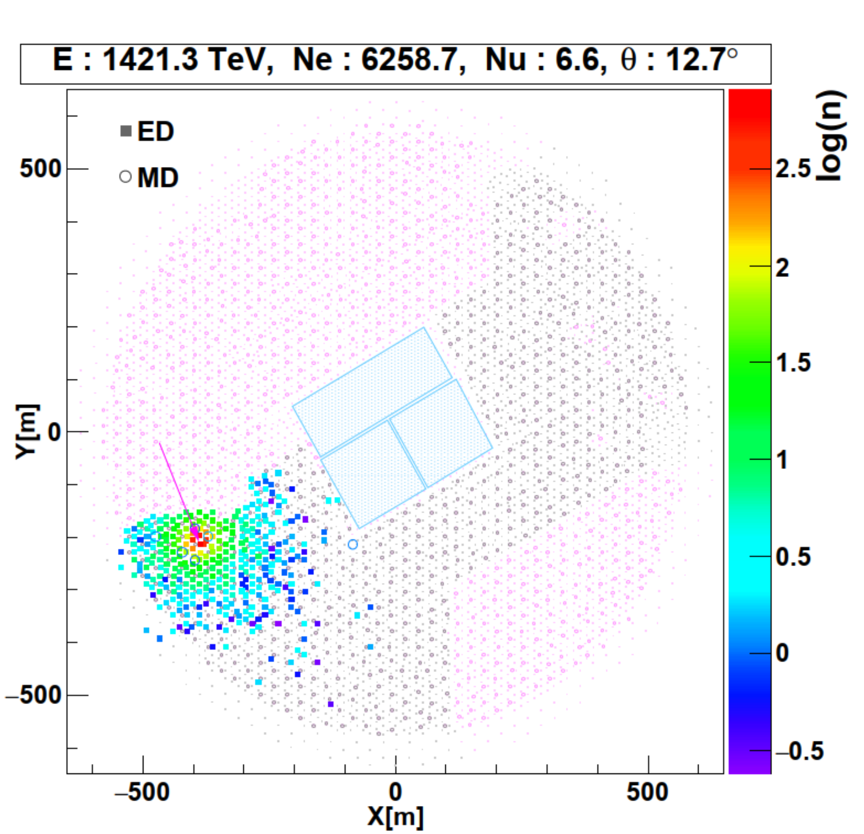
- **Perfect interpretation of one-zone electronic origin up to 50TeV**
- **Reasonable extension up to 1 PeV, with a deviation of 4 σ**
- **An extreme e-accelerator:**
  - **2.3 PeV electrons**
  - **in ~0.025 pc core region**
  - **accelerating efficiency of 15% (1000× better than SNR shock waves)**
- **Can not rule out proton origin of photons ~1 PeV, yet**
- **1 or 2 photons are expected above 1 PeV per year that enables a clarification in 2 or 3 years**

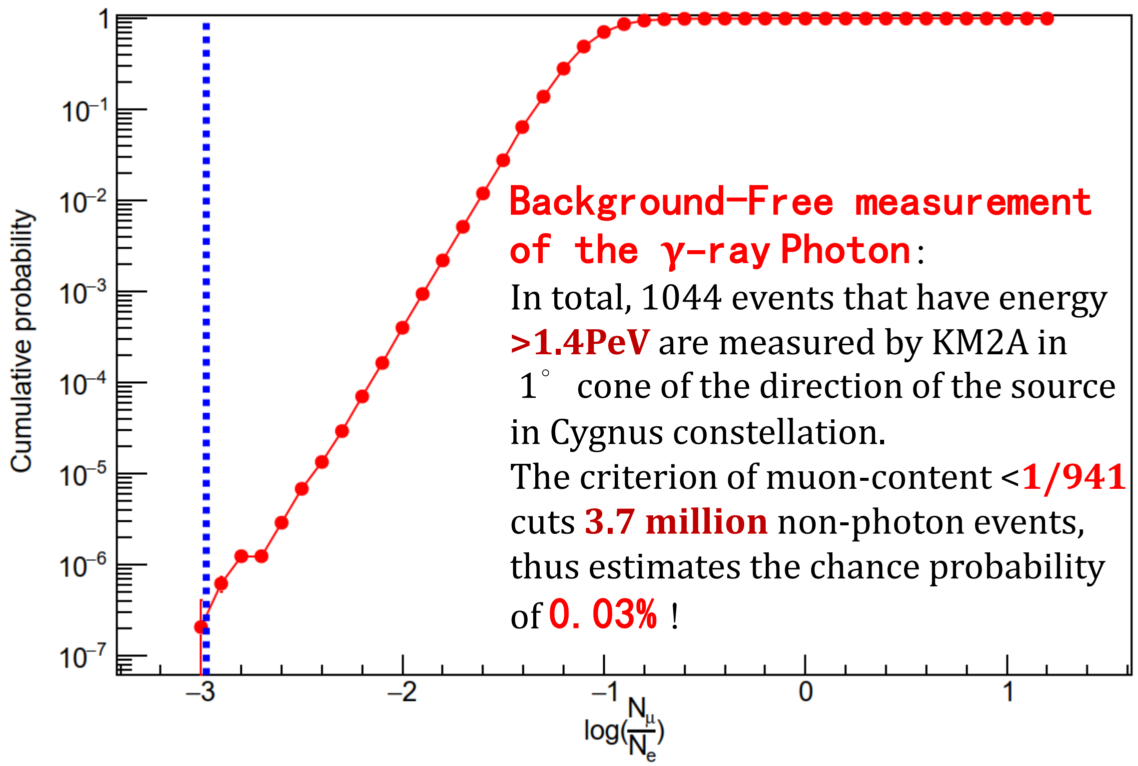


Record by KM2A

1.4 PeV Photon from Cygnus Direction

LHAASO, Nature, 594, p.33-36, 2021





Background-Free measurement of the γ-ray Photon:

In total, 1044 events that have energy **>1.4PeV** are measured by KM2A in 1° cone of the direction of the source in Cygnus constellation.

The criterion of muon-content <**1/941** cuts **3.7 million** non-photon events, thus estimates the chance probability of **0.03%** !

Discovery in KM2A Survey

Our Galaxy is full of PeVatrons

LHAASO, Nature, 594, p.33-36, 2021

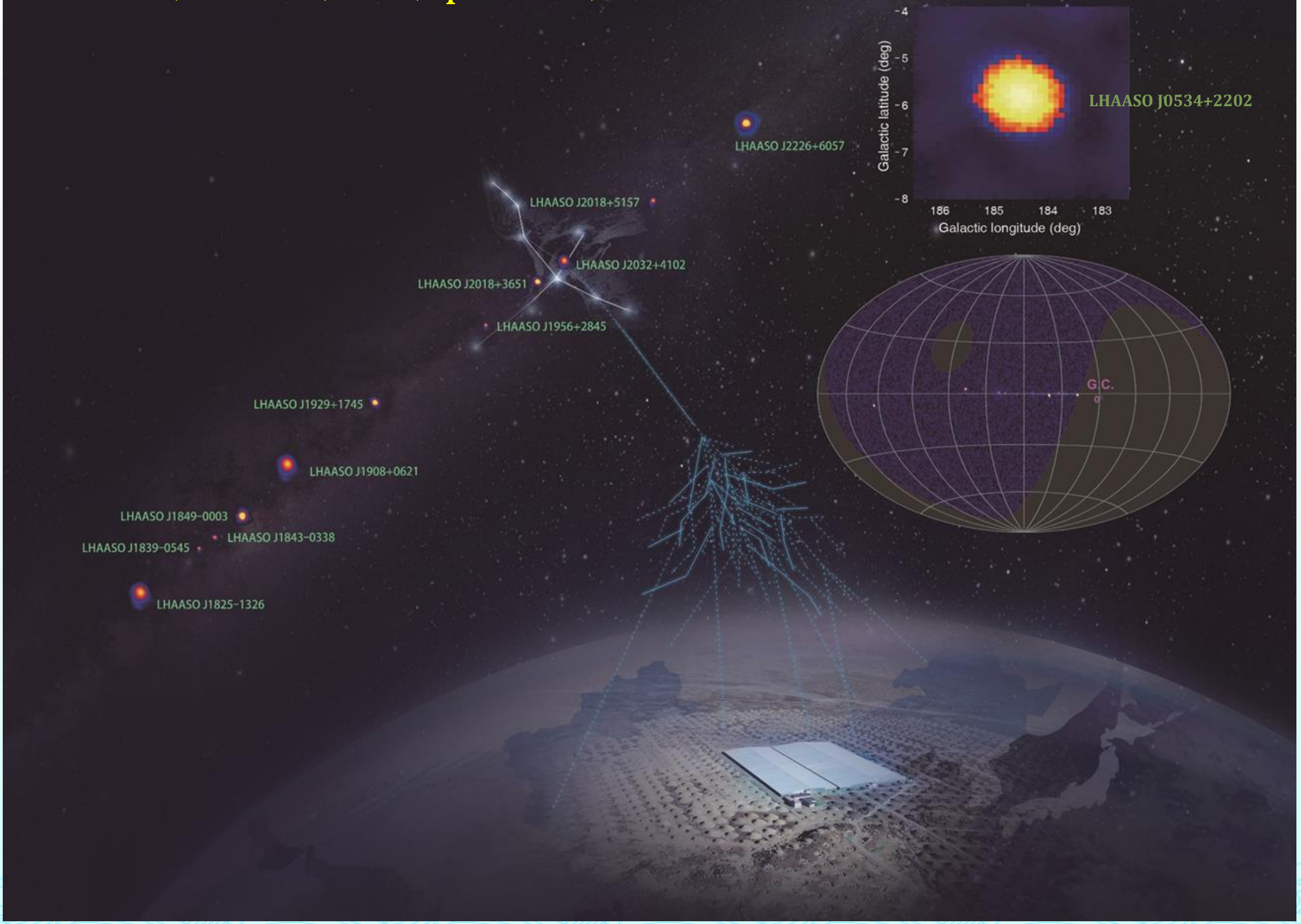


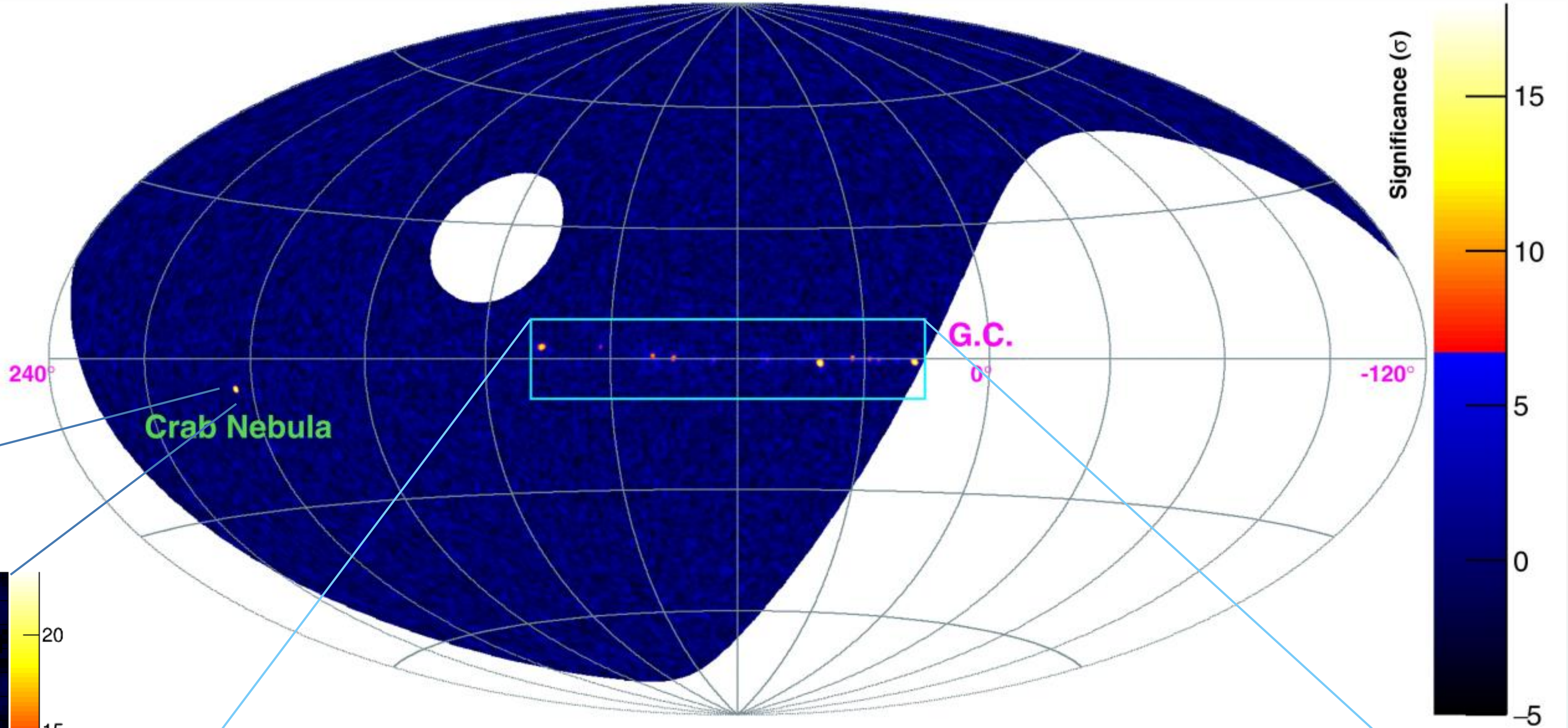
Table 1 | UHE γ-ray sources

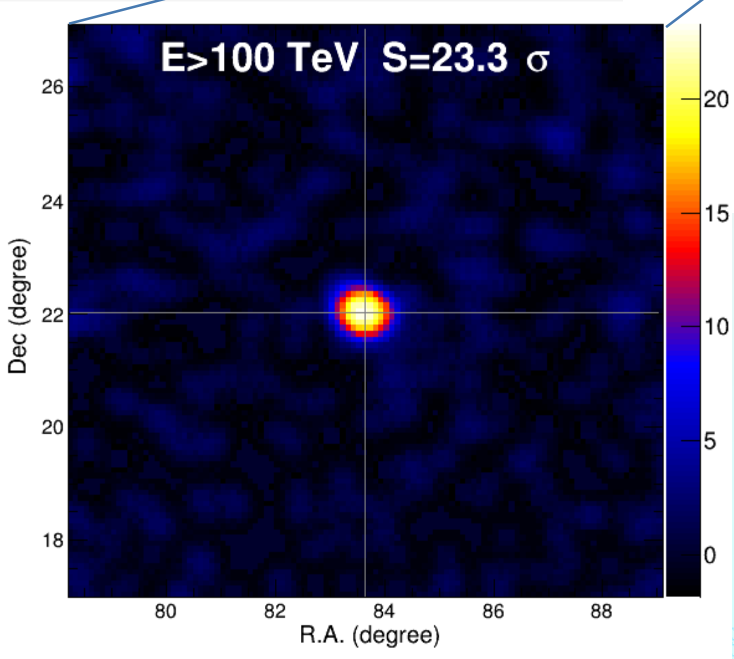
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65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

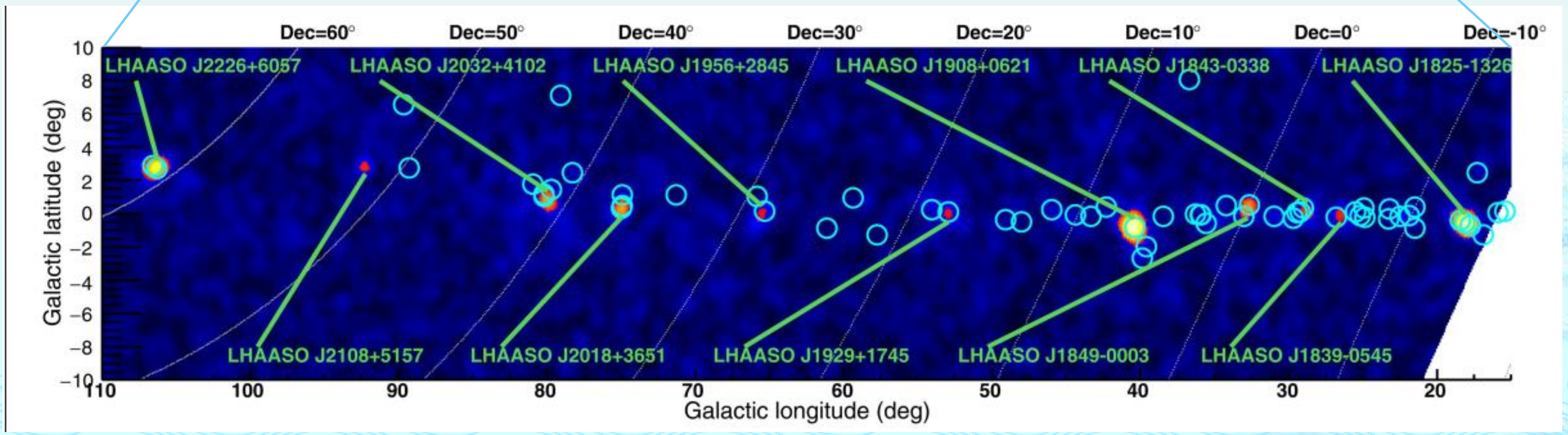
12 PeVatrons are discovered

- **High Standard： significance >7σ**
- **BG-free： Cosmic Ray background rejection rate $<10^{-4}$**
- **High Statistics： 530 UHE photons**
- **Multiple Type of Sources**

UHE γ–ray (0.1-1 PeV) Sky Map



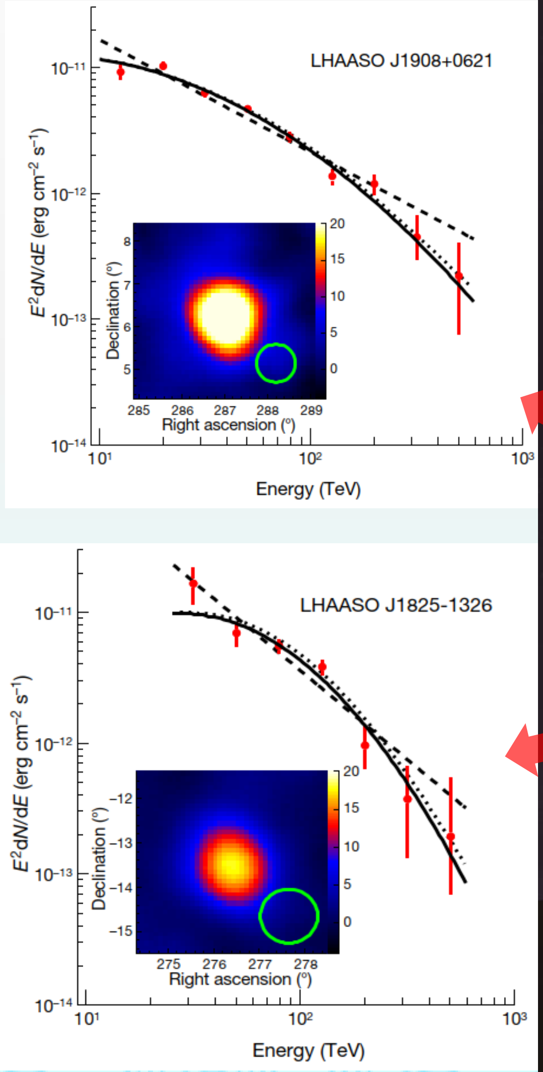


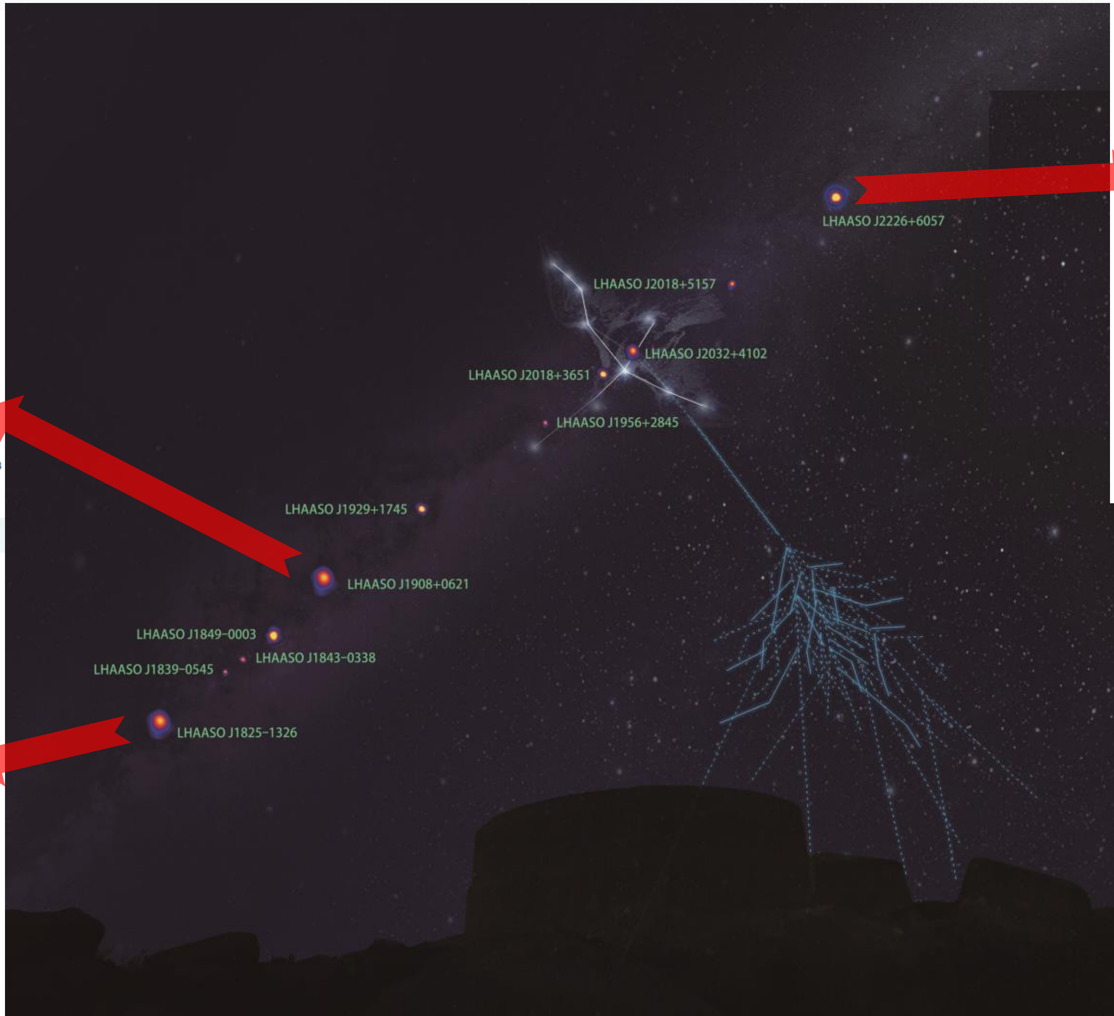


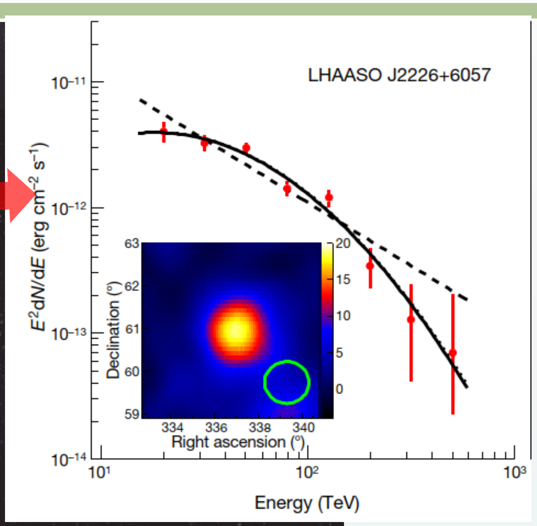
LHAASO
高海拔宇宙线观测站

Discovery in KM2A Survey

Do not observe clear cut-off up to ~1 PeV







LHAASO, Nature, 594, p.33-36, 2021

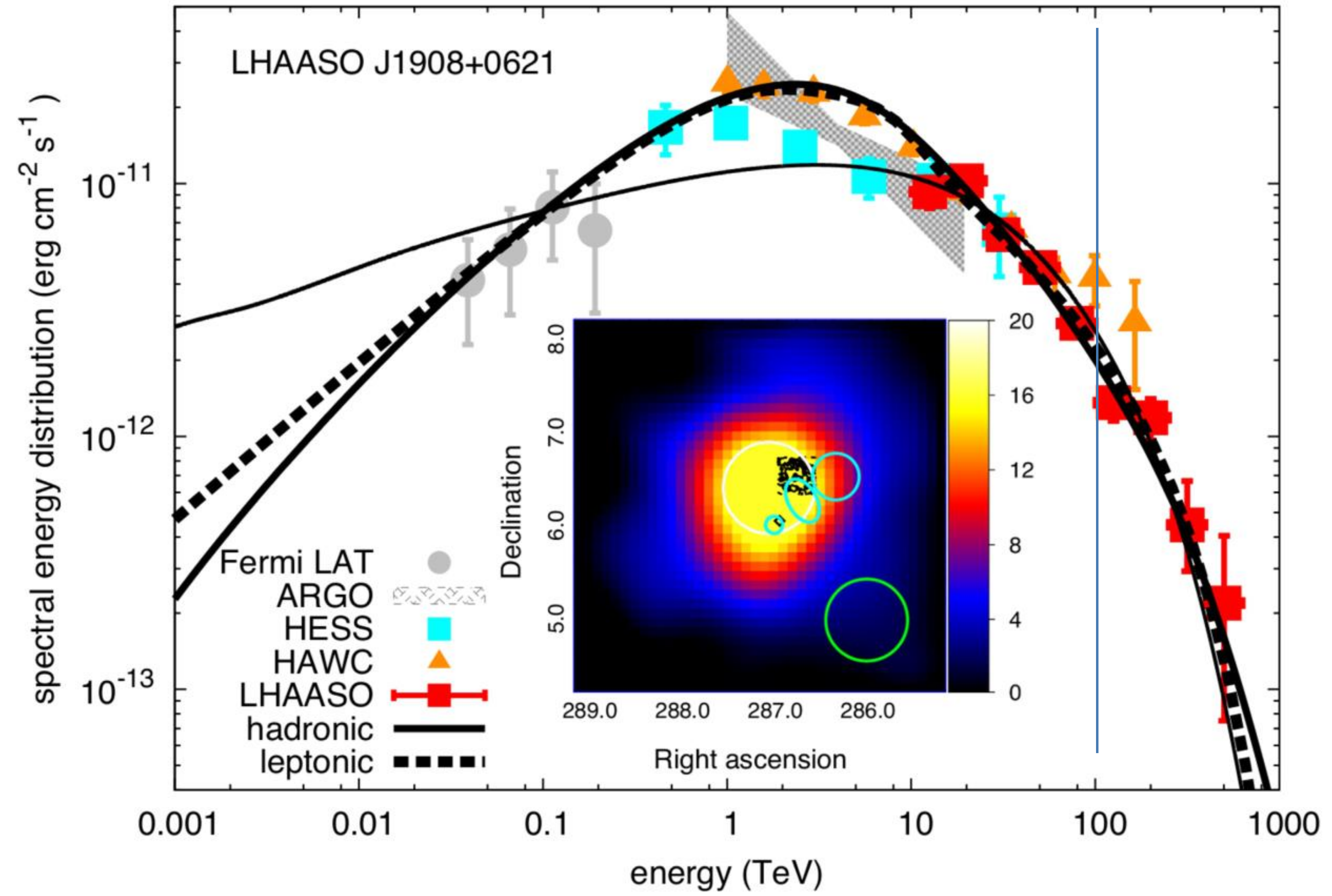
Three brightest PeVatrons

- No trend of cut-off in SED of γ-ray sources
- Updates using newer data show continuous extension to higher energies

Discovery Using KM2A
Onset of UHE γ–ray Astronomy

E > 0.1 PeV

- VHE γ–ray astronomic major instrument: Sensitive below 0.1 PeV
- LHAASO: provide a statistically significant coverage of the energy range above 0.1 PeV
- Spectroscopy: 15% resolution
- Morphology: 0.3° PSF
- Multi-messenger Astronomy: UHE band



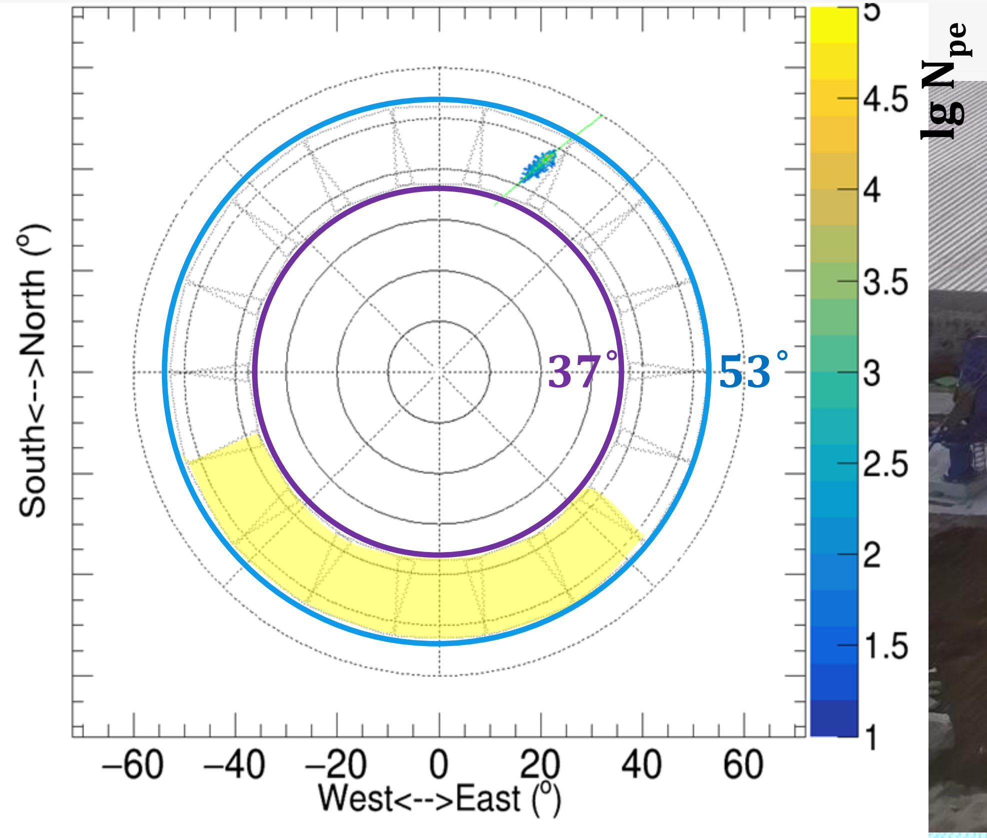
γ -ray astronomic topics with LHAASO

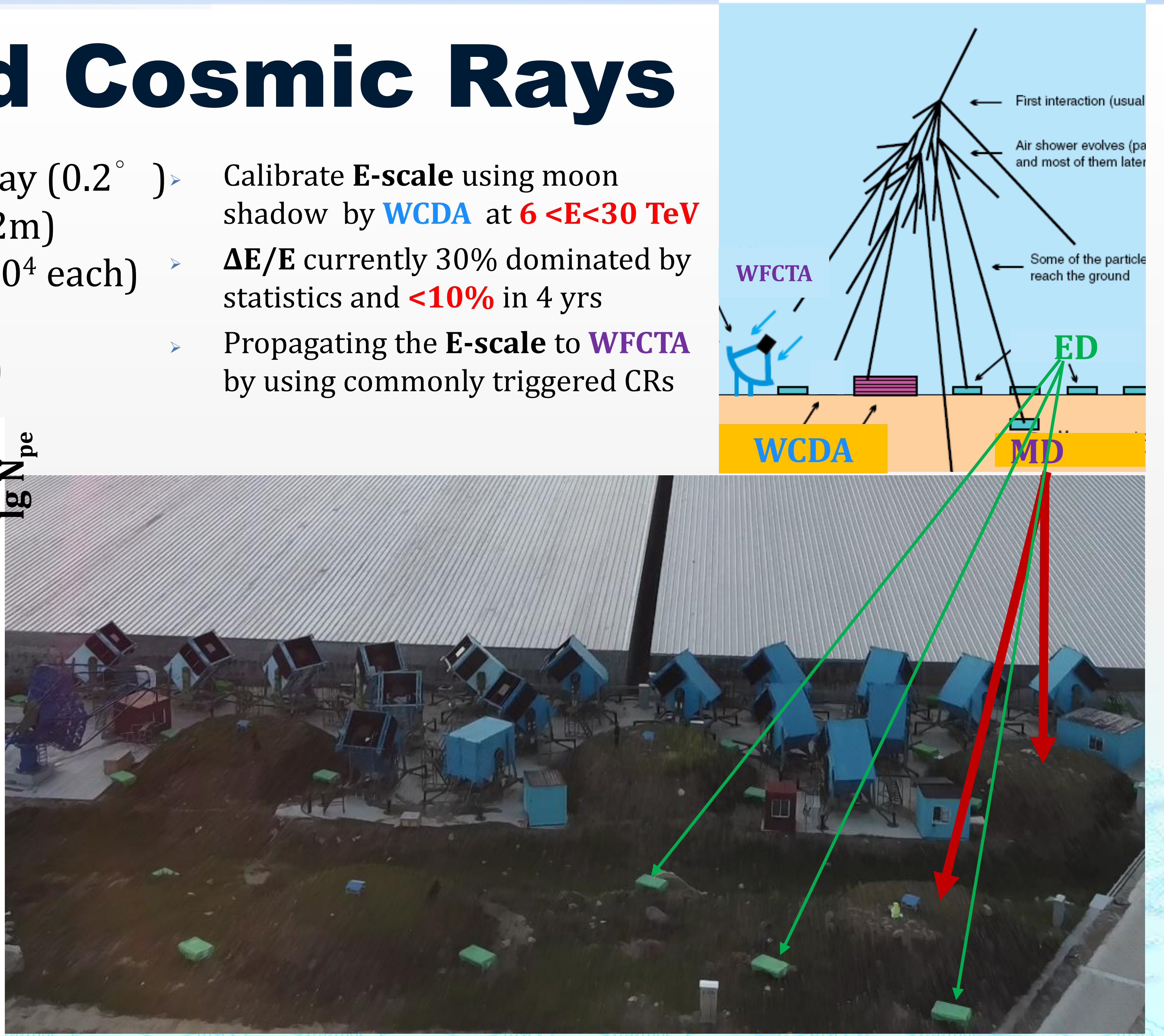
- **Pevatrons:**
  - **ID 923:** Sha Wu (16/07) **Three brightest UHE sources**
  - **ID 912:** Lingyu Wang (16/07) **Crab Nebula**
  - **ID 878:** Cong Li (15/07) **Cygnus Cocoon**
  - **ID 1081:** Min Zha (16/07) **WCDA on UHE**
- **PWN Halos**
  - **ID 964:** Yingying Guo (20/07) **Geminga and Monogem**
- **Diffuse gamma-ray**
  - **ID 1071:** Shiping zhao(19/07) **Galactic plane**
  - **ID 894:** Marco Chianese (21/07) **dark matter**
- **AGN & GRB**
  - **ID 969:** Yuhua Yao(21/07) **GRB 190829A**
  - **ID 1103:** Ran Wang(16/07) **Mark 421**

Charged Cosmic Rays

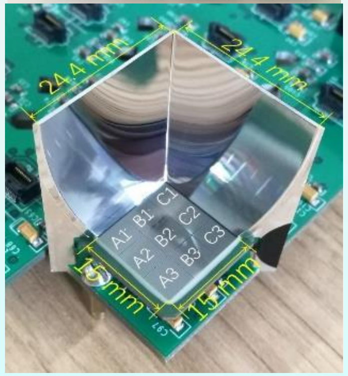
- Measuring **AS front** by WCDA or ED array (0.2°)
- Measuring **E-flux** near core by WCDA (2m)
- Measuring **μ–content** by MD array (1-10^4 each)
- Measuring $\mathbf{X_{max}}$ by WFCTA (40 g/cm^2)
- Measuring AS **Energy** by WFCTA (15%)

- Calibrate **E-scale** using moon shadow by **WCDA** at **6 <E<30 TeV**
- **ΔE/E** currently 30% dominated by statistics and **<10%** in 4 yrs
- Propagating the **E-scale** to **WFCTA** by using commonly triggered CRs

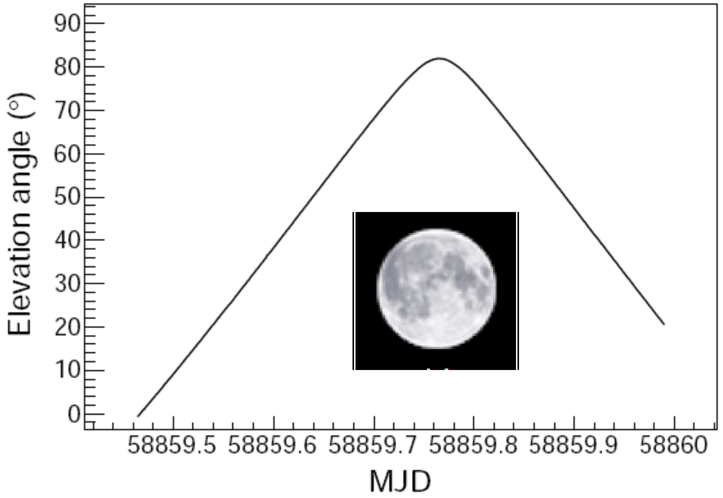


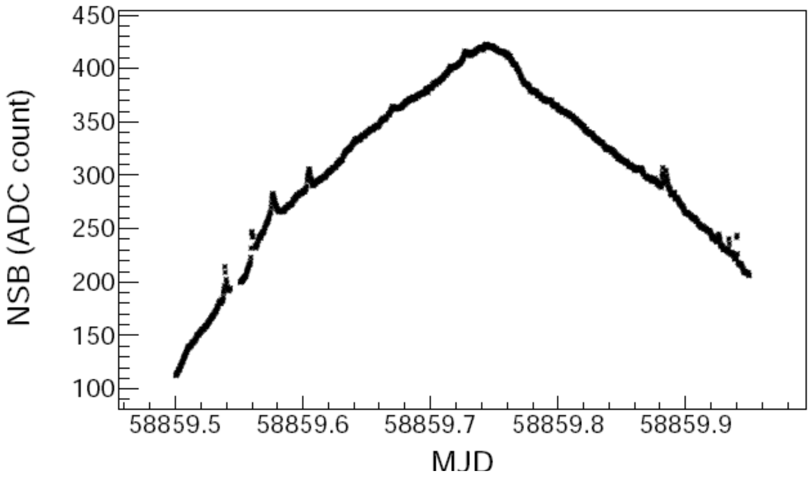


LHAASO WFCTA SiPM Camera

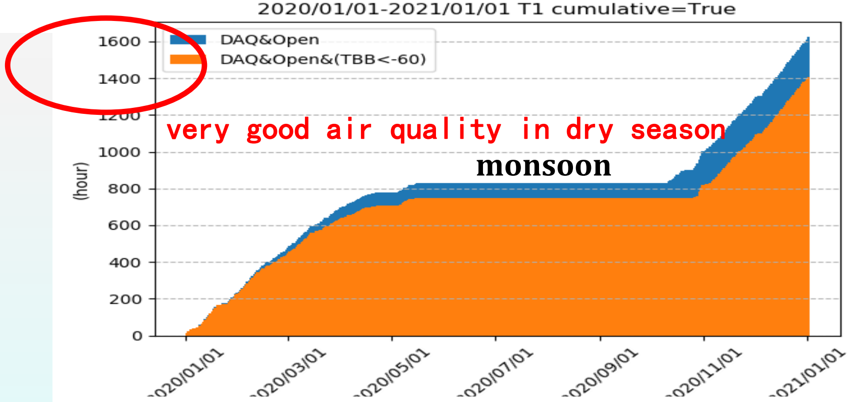


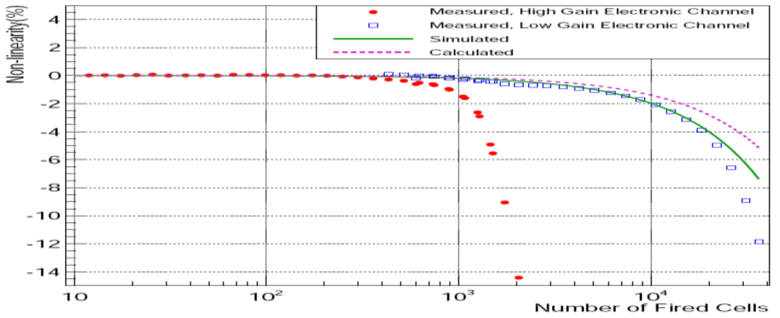
European Physical Journal C, accepted, 2021





- SiPM enables an operation of WFCTA with full moon
- Effective Operational time 1400 hrs per year
- 0.5° pixels with dynamic range 10-32,000 pe enable a coverage 100 TeV - 100 PeV

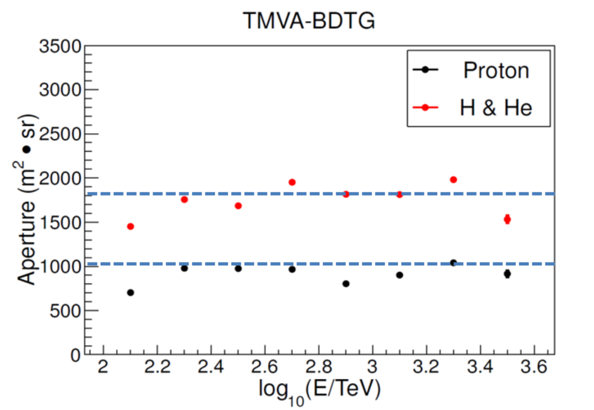


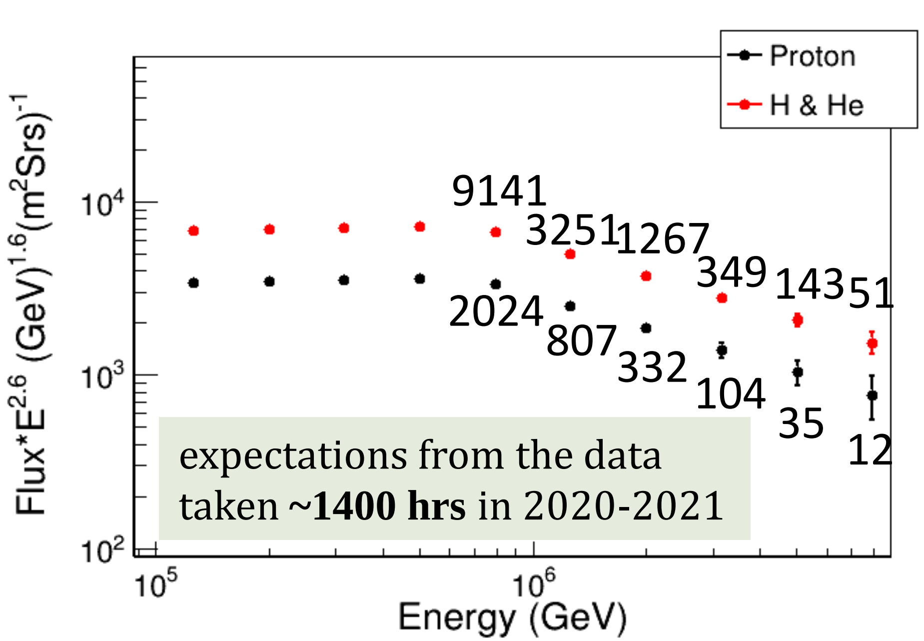


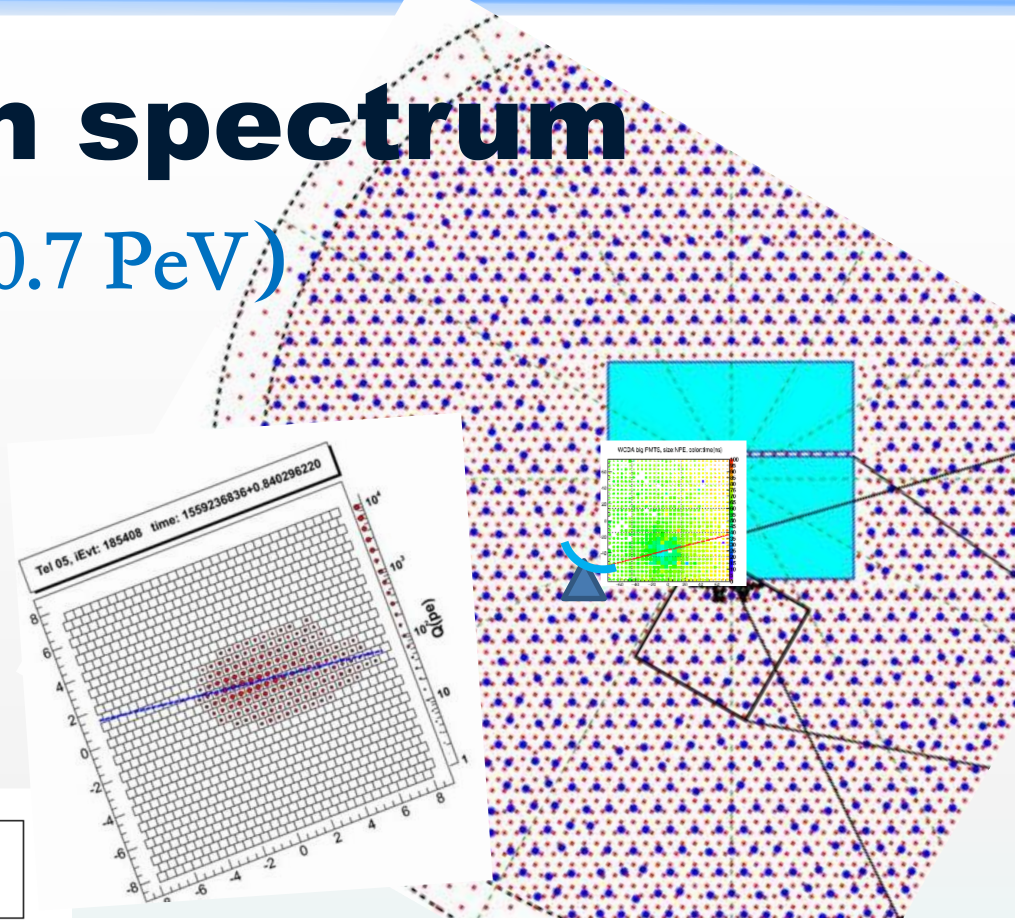
The knee of Proton spectrum

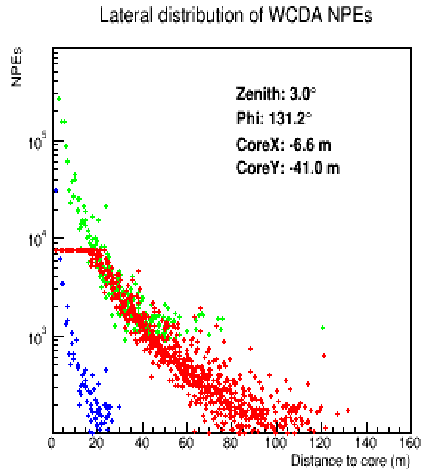
(E$_b$~0.7 PeV)

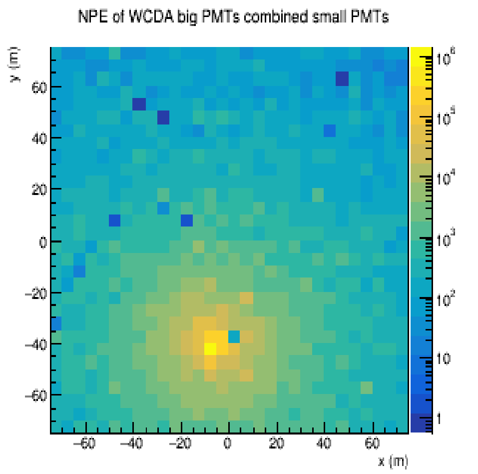
- Coincident events by **WCDA** and **6 telescopes**
- Shower cores in **WCDA-1**
- Selecting pure **proton** showers by **3** parameters: aperture of **1000** m^2 sr
- **H+He** showers: aperture of **1800** m^2 sr







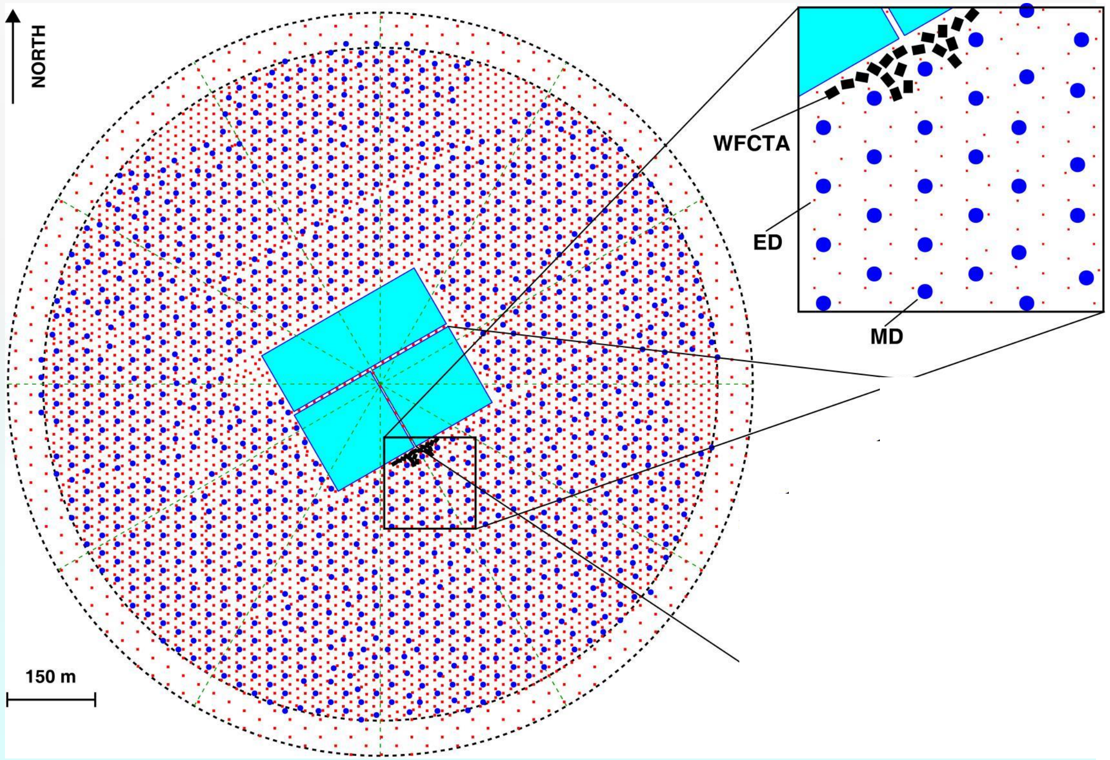


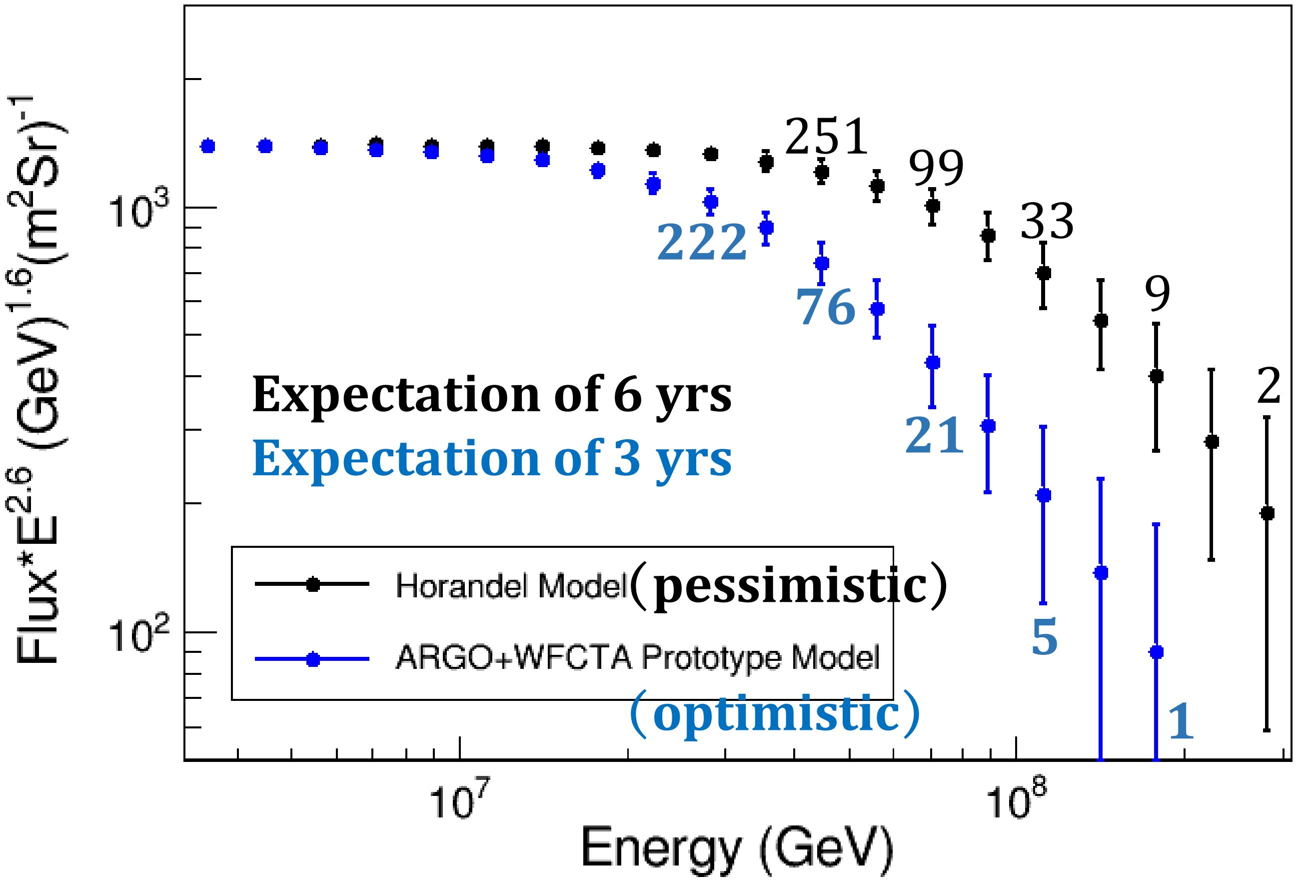


The knee of Fe spectrum

（E_b~24 or 50PeV）

- Coincident events by both WFCTA and full KM2A
- Shower cores are in 1 km^2
- Incline showers touch down at the depth of 840 g/cm^2





CR related topics with LHAASO

- Absolute **E-scale Calibration** for the CR measurements (talk 897)
- Large Scale **Anisotropy** of CRs (talk 871)
- Muon-content and longitudinal development of air showers (talk 872, poster 940), reconstruction and calibration issues (posters 944, 921, 1275, 1280, 1281)

Conclusion

- LHAASO is complete now, all detectors are in DAQ today!
- 12 PeVatrons are discovered in our galaxy
- A photon at 1.4 PeV is recorded from Cygnus YMC direction
- Implications：
  1. Our galaxy is full of PeVatrons accelerating particles over 1 PeV
  2. Onset of "UHE (>0.1 PeV) Astronomy"
  3. Potential CR origins: many type of candidates
  4. The Crab: extreme electron-PeVatron emitting 1.1 PeV photon and posing challenges
- More discoveries are expected, not only for gamma ray astronomy but also for charged CRs