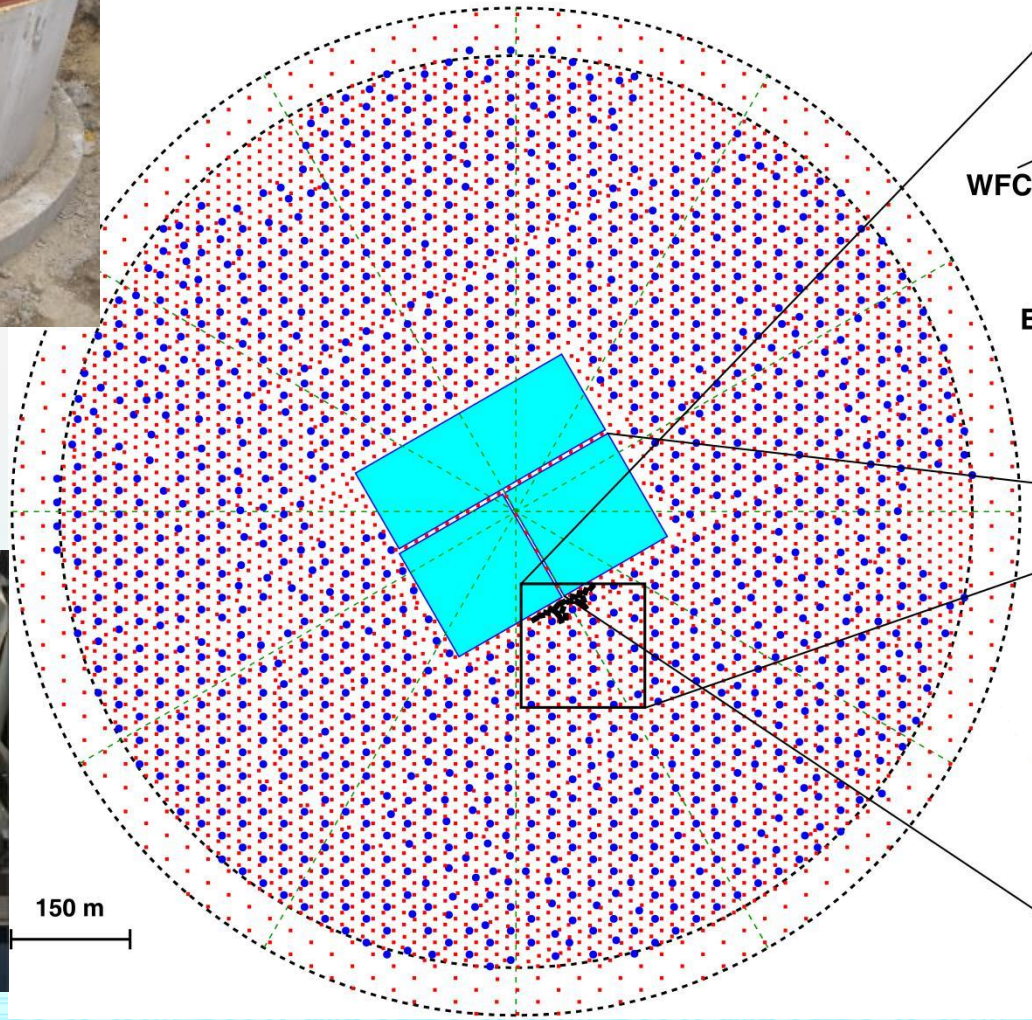
Status of LHAASO Experiment

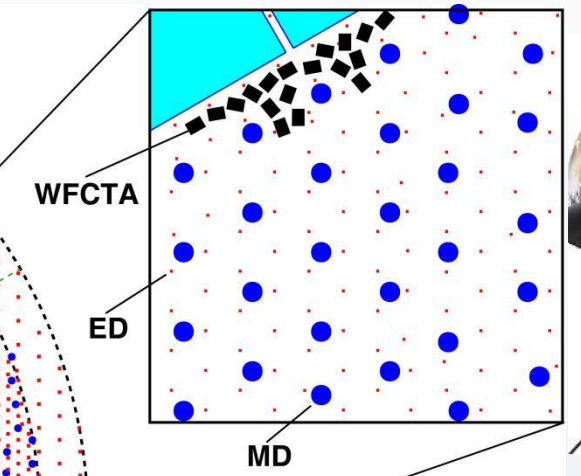
Zhen Cao on behalf of LHAASO Coll.

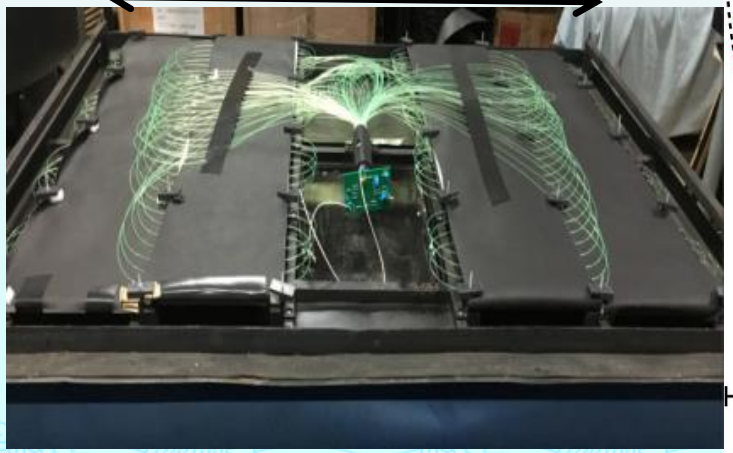
ASTRI-LHAASO Joint Workshop, on-line, March 7-8, 2023

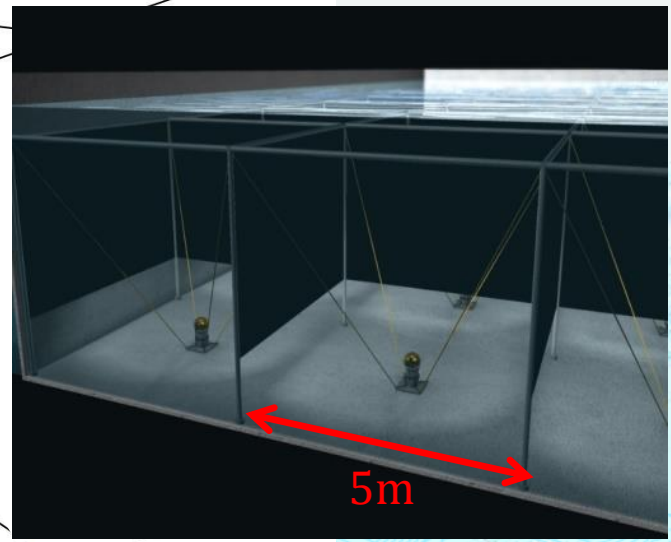
LHAASO
高海拔宇宙线观测站

LHAASO Layout





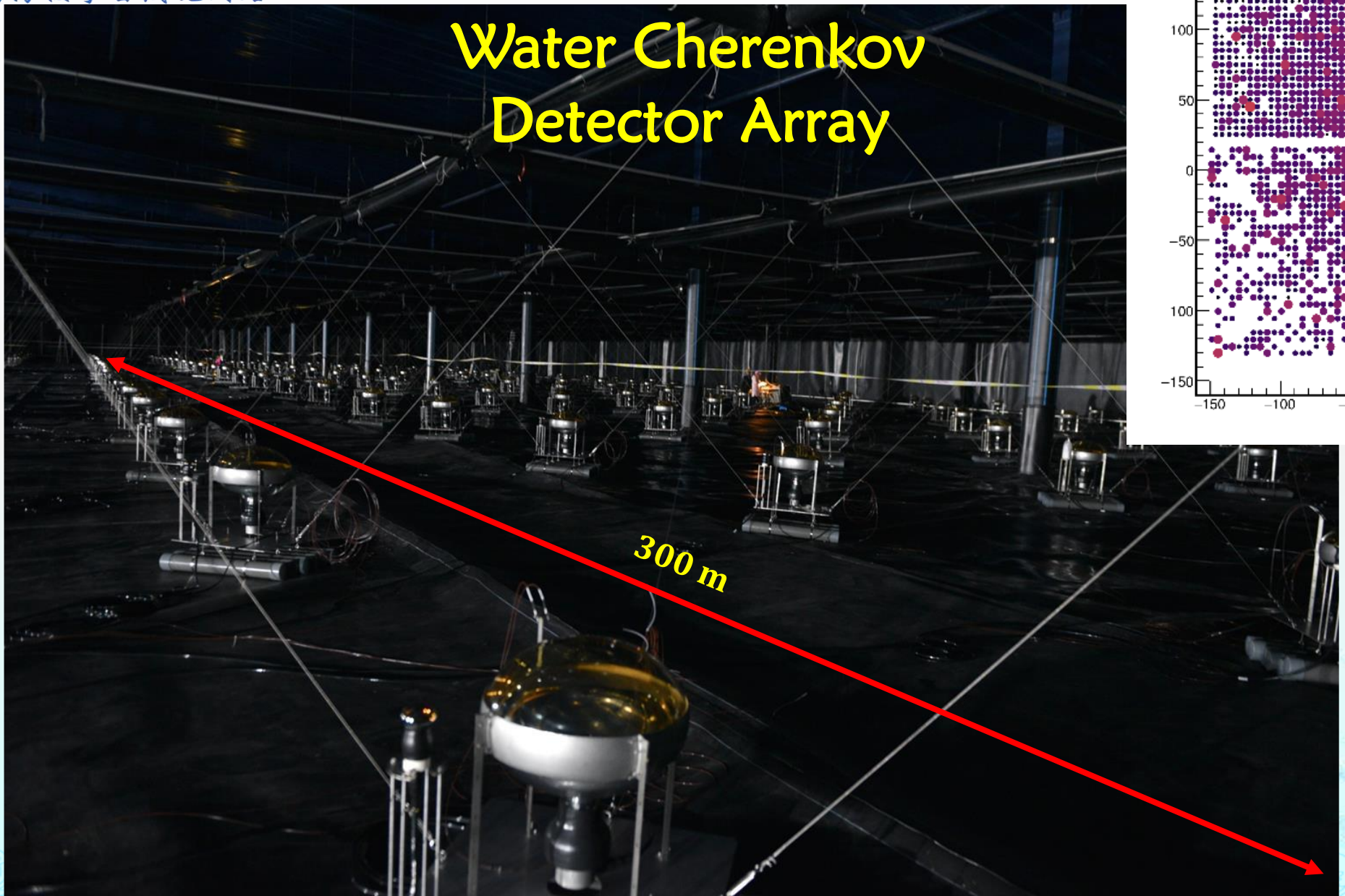


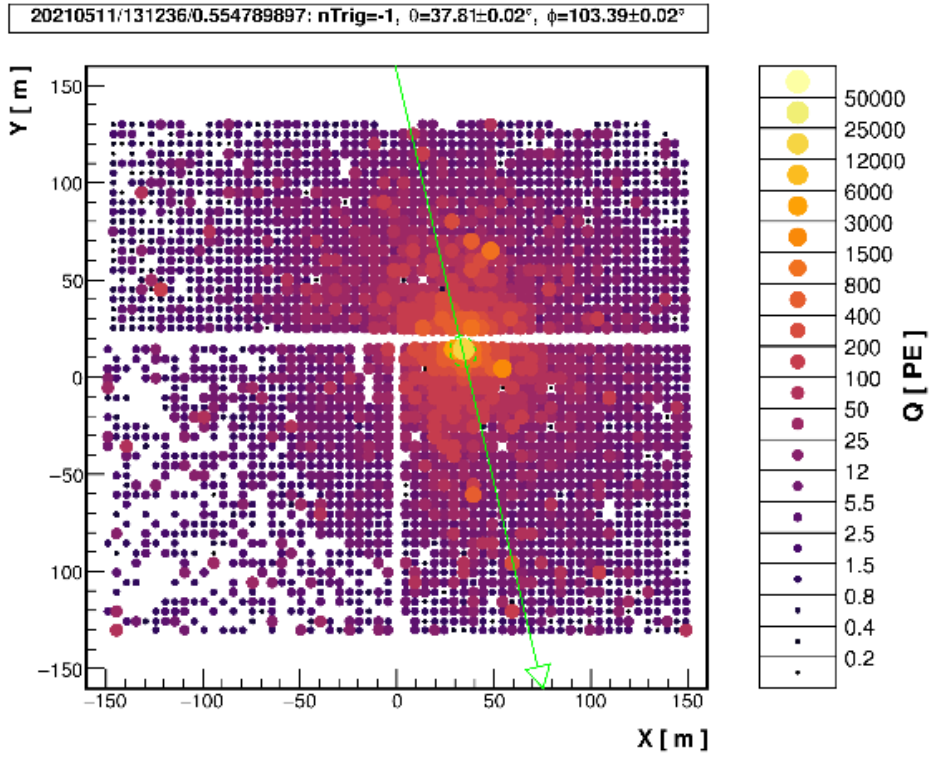


LHAASO
高海拔宇宙线观测站

LHAASO-WCDA

Water Cherenkov Detector Array





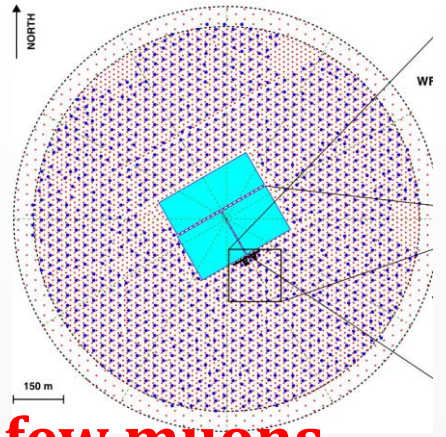
- **Area:**
  78,000 m²
- **Detector units:**
  3120
- **Energy Range:**
  0.1-10 TeV

LHAASO
高海拔宇宙线观测站

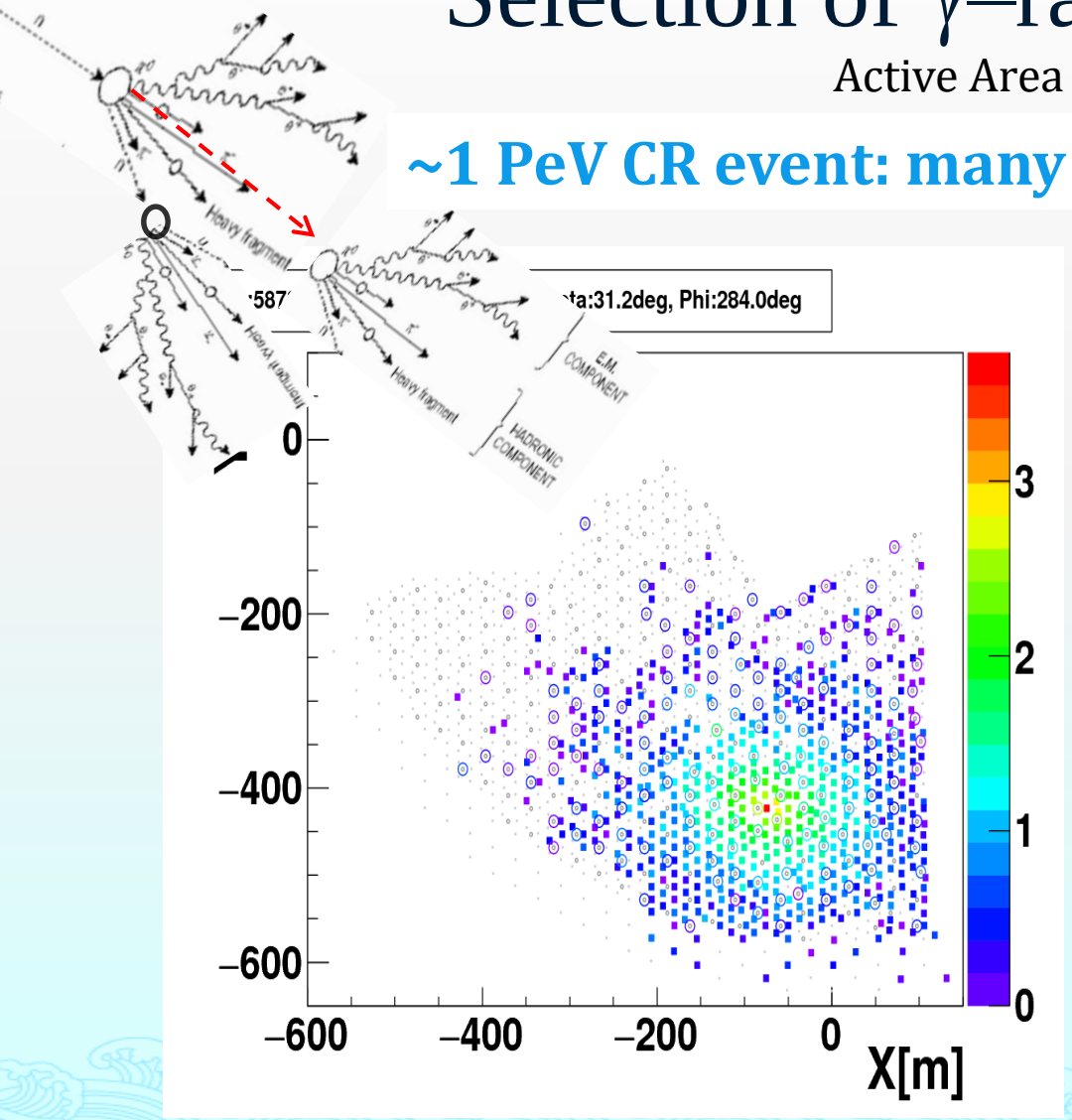
LHAASO-KM2A

Selection of γ–rays out of CR background

Active Area for Muons vs. Array Area: 4%

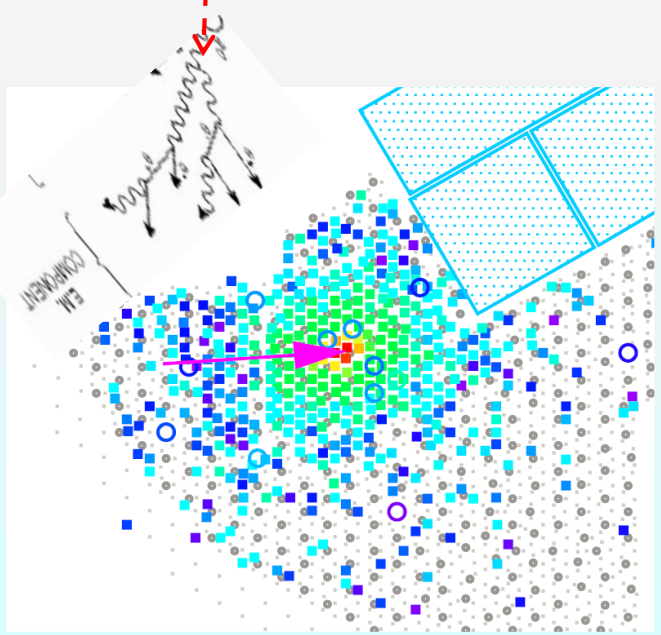


~1 PeV CR event: many muons



~ 1 PeV γ–ray event : very few muons

~1 PeV from the Crab



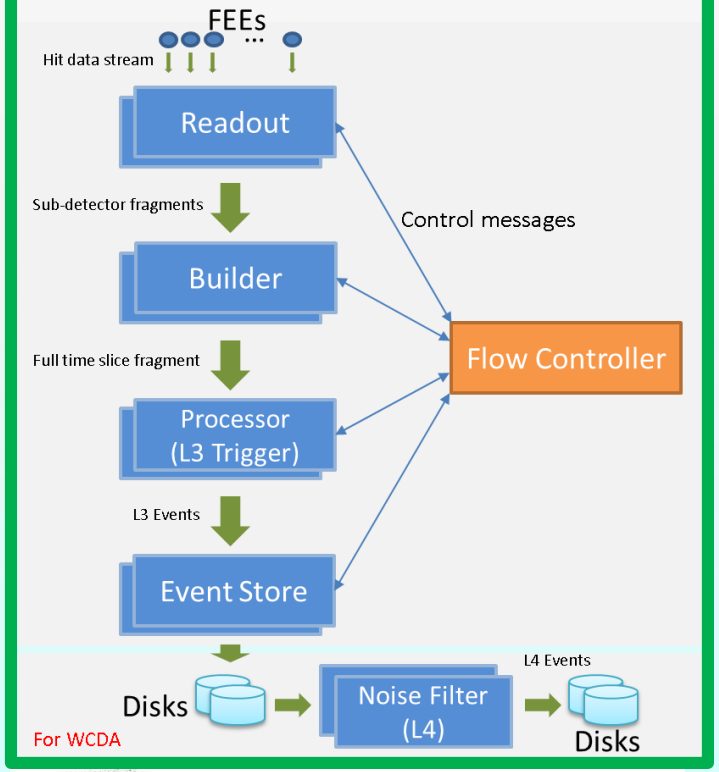
- **Area:**
  1.3 km²
- **Detectors:**
  5216 ED
  1188 MD
- **Energy Range:**
  0.01-10 PeV

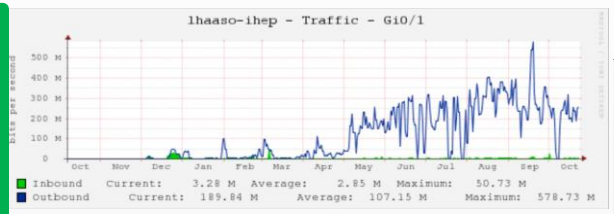
On-site Computing

`trigger-less' Data Acquisition

4 GB/s

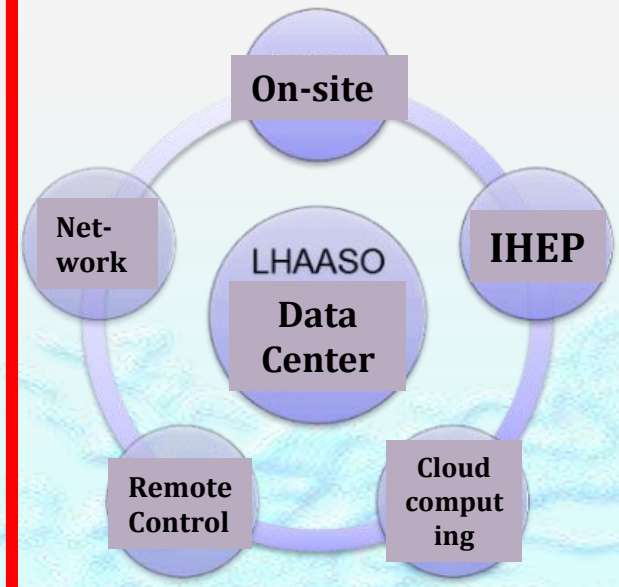
Zero `dead time'





On-site Facility

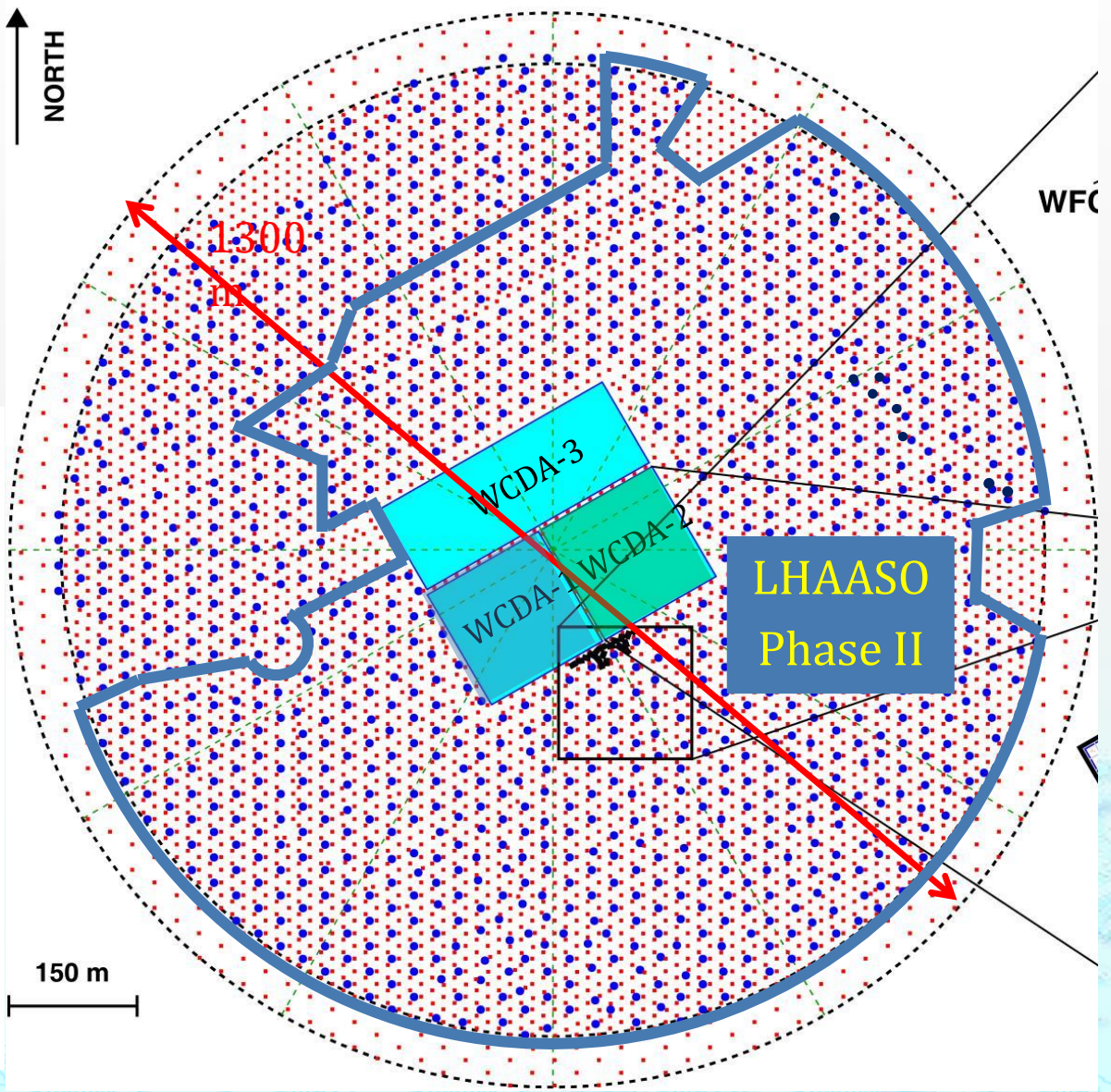
- Full functional computing room
- # of CPU Cores:
  ~10,000
- Temp Storage:
  2.5 PByte
- Data Band Width:
  2.4 Gbit/sec

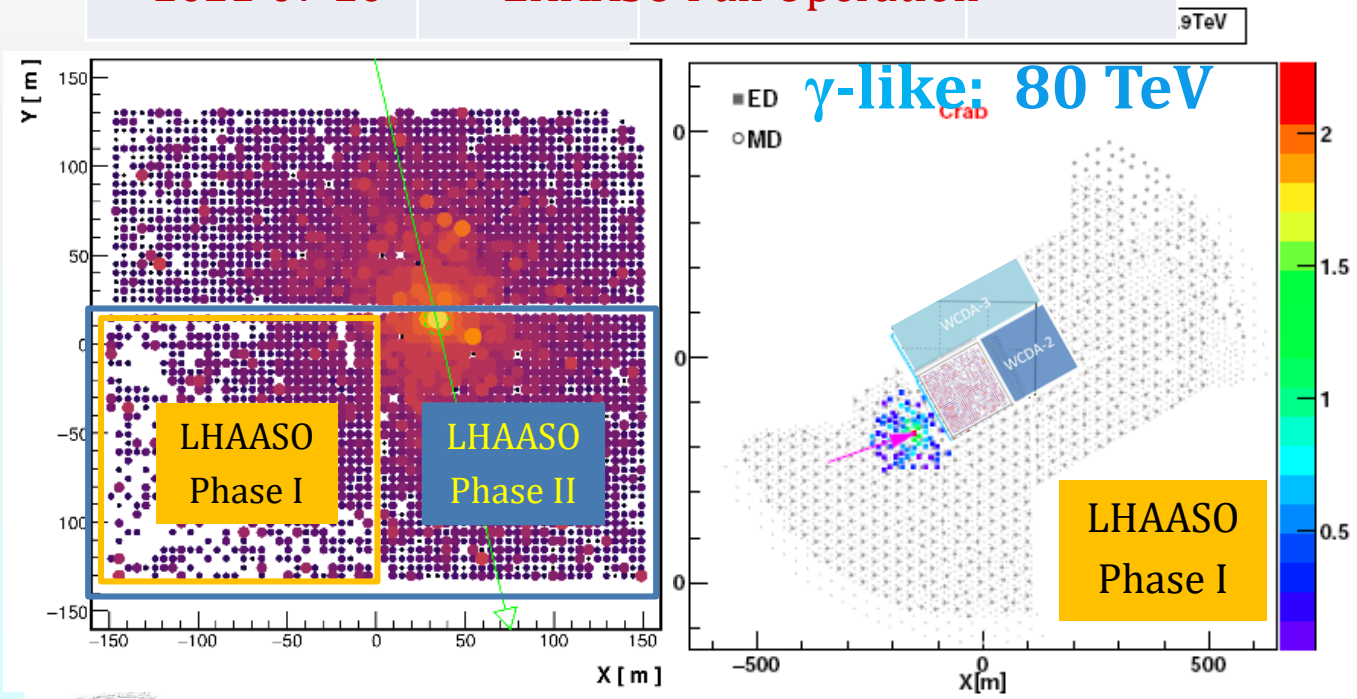


4410

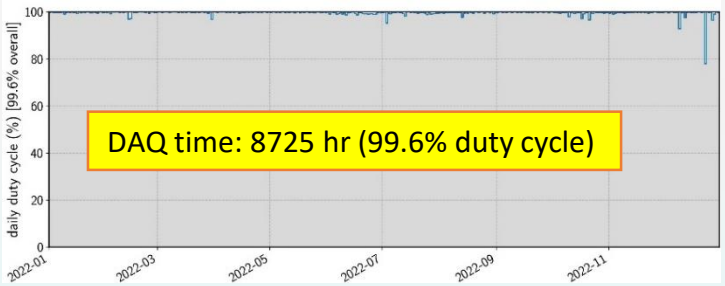
2019-12-12	Muon Counter	Scintillator Detector	WCDA
operating	594	2514	900
2020-11-30	LHAASO Phase II Operation		
operating	**917**	**3978**	**1800**
Percentage of designed sensitivity	**88%**	**76%**	**58%**
2021-07-20	LHAASO Full Operation		

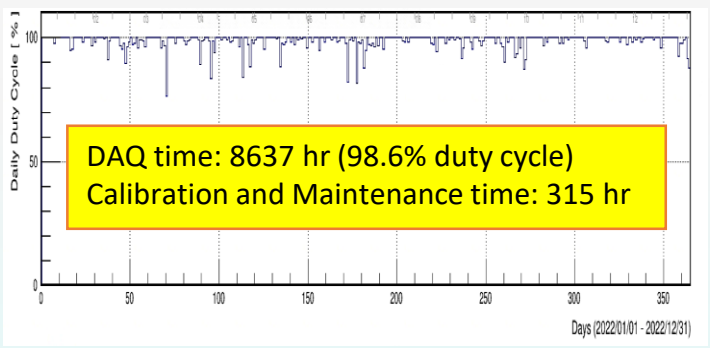
LHAASO Phase-II: Dec,2020—July,2023

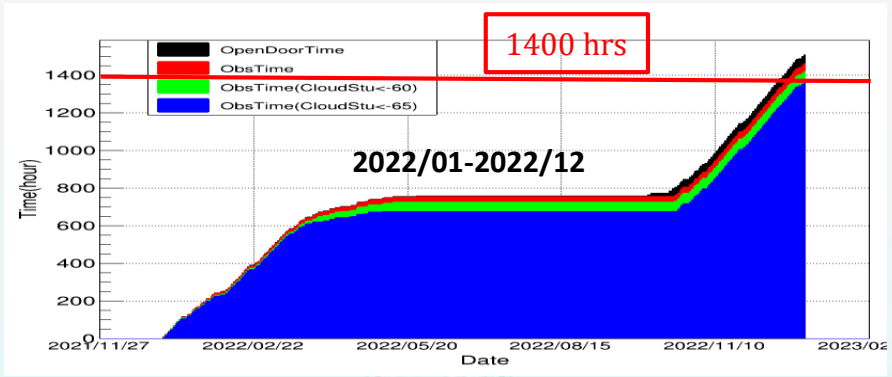


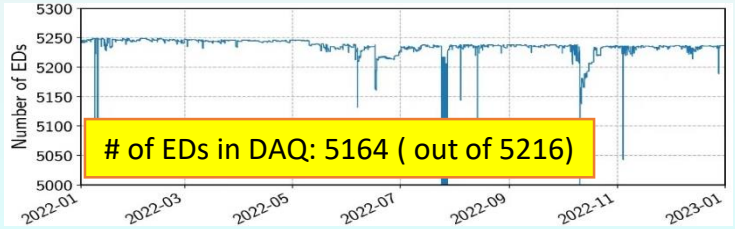


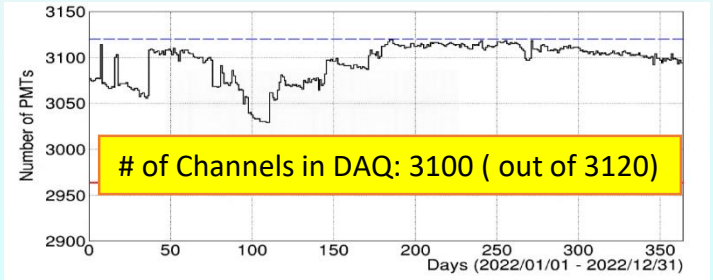
Super Stable & Fruitful Operation

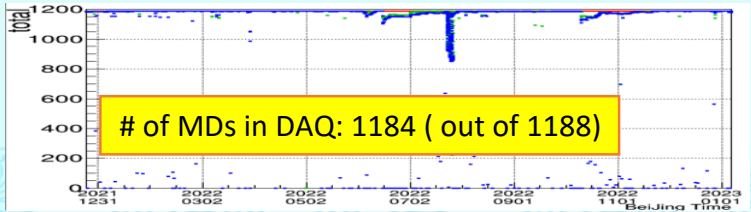












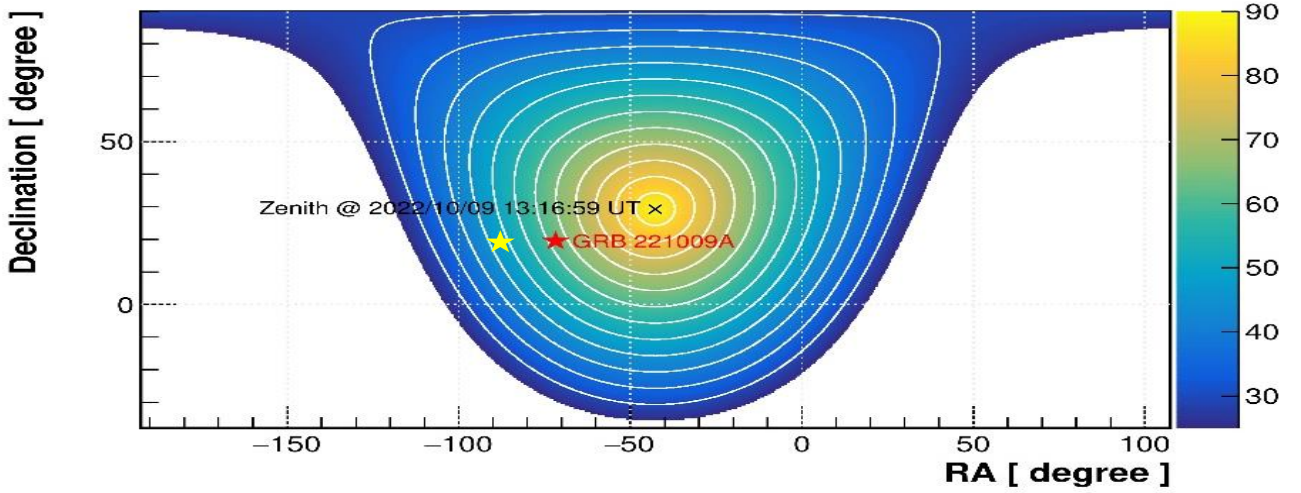
Reconstruction and Analysis

- Data procession
  - # of events: 1 trillion LE、70 billion HE、70 million hybrid
  - Amount: 11 PB
- Simulation
  - # of events: 1 billion LE、0.7 billion HE、150 million hybrid
  - Amount: 4 PB
- # of jobs: 10M for data, 50M for simulation

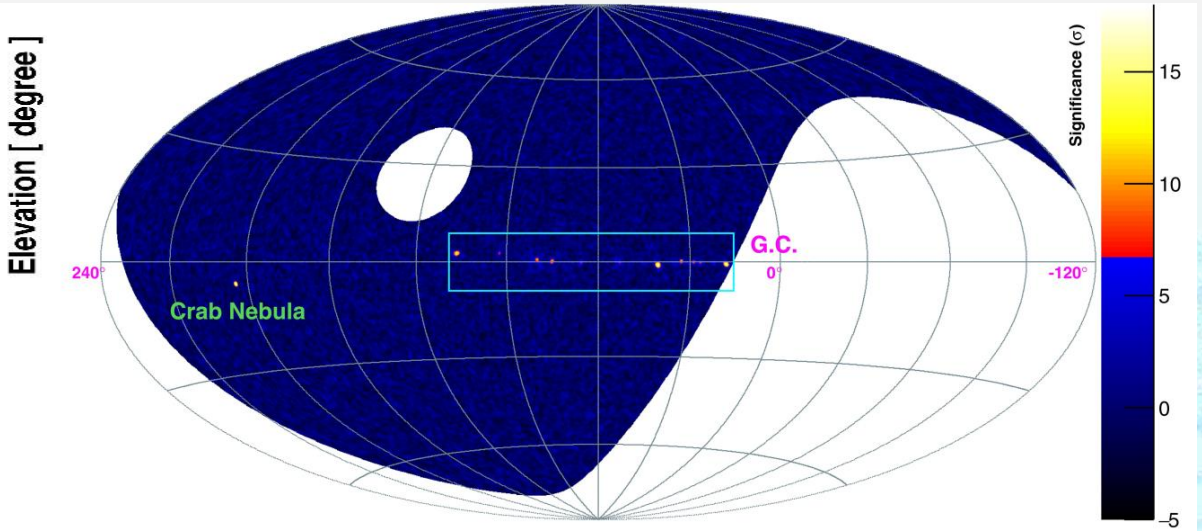
Very wide FoV, Continuously monitoring

- **FoV: ~1/6 of entire sky at any moment, good for very extended structures**
- **24 hours monitoring all sources for variability, long term variability**
- **Transient phenomena, e.g. GRB221009A**

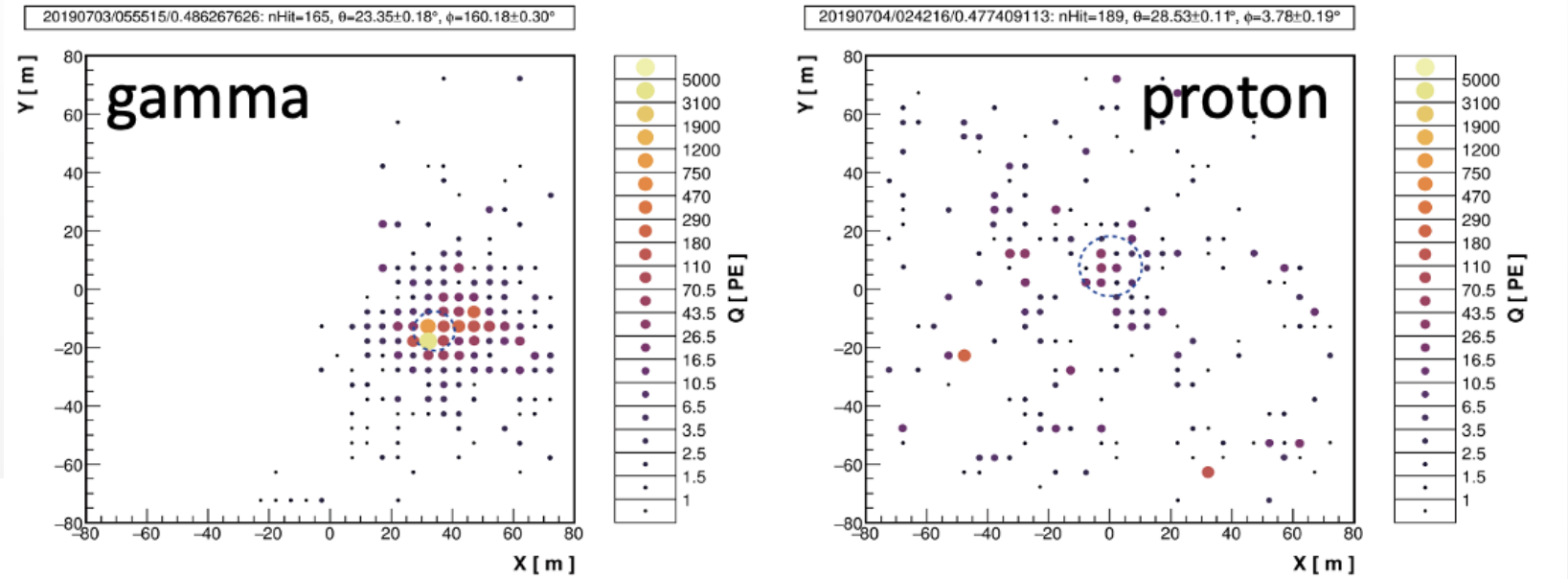
any moment

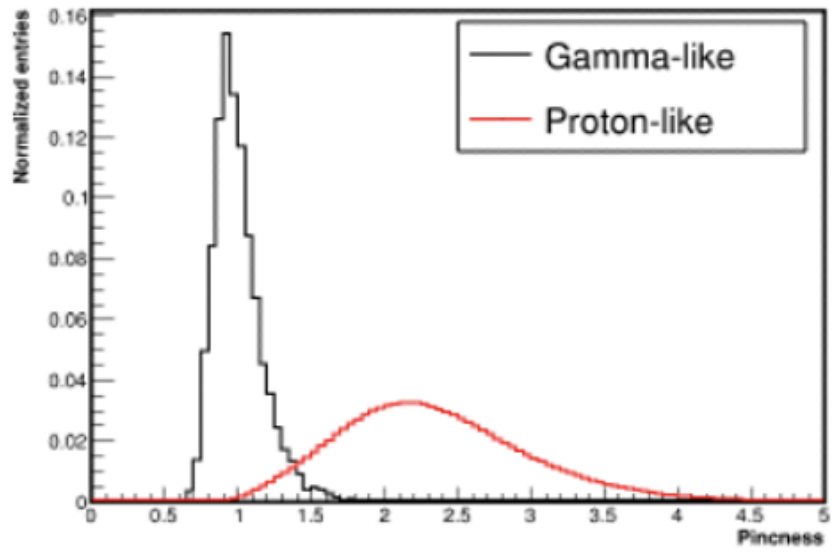


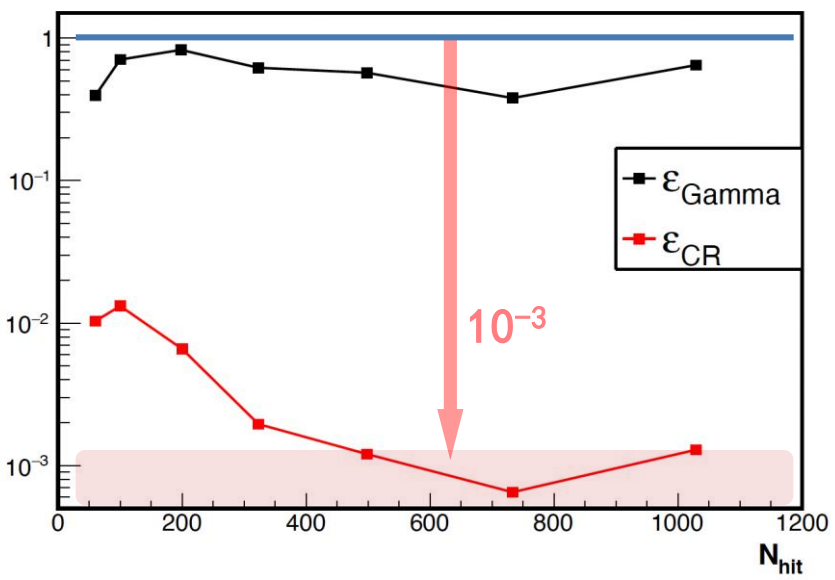
Northern sky



CR Background rejection in WCDA



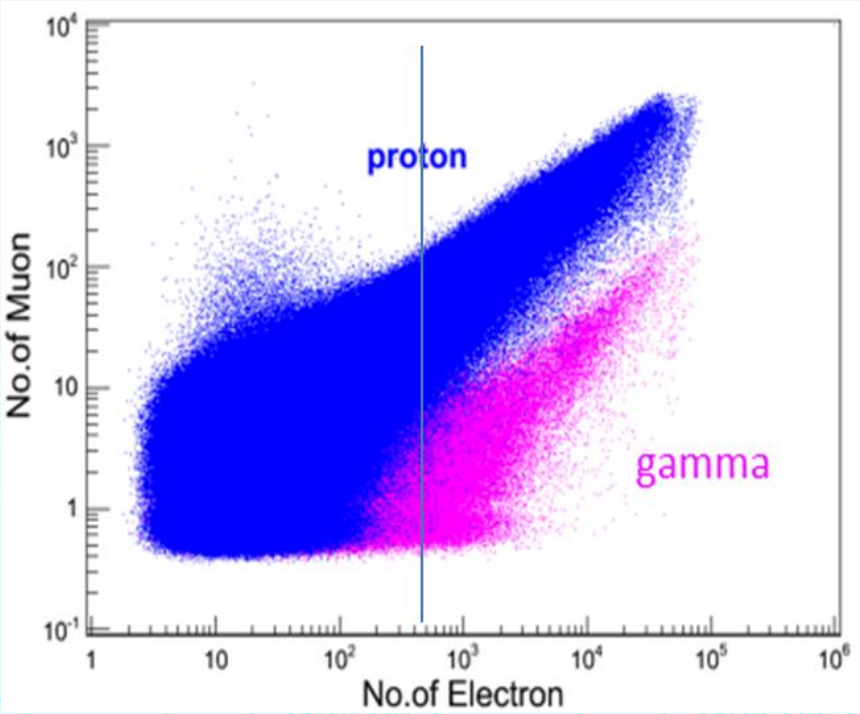


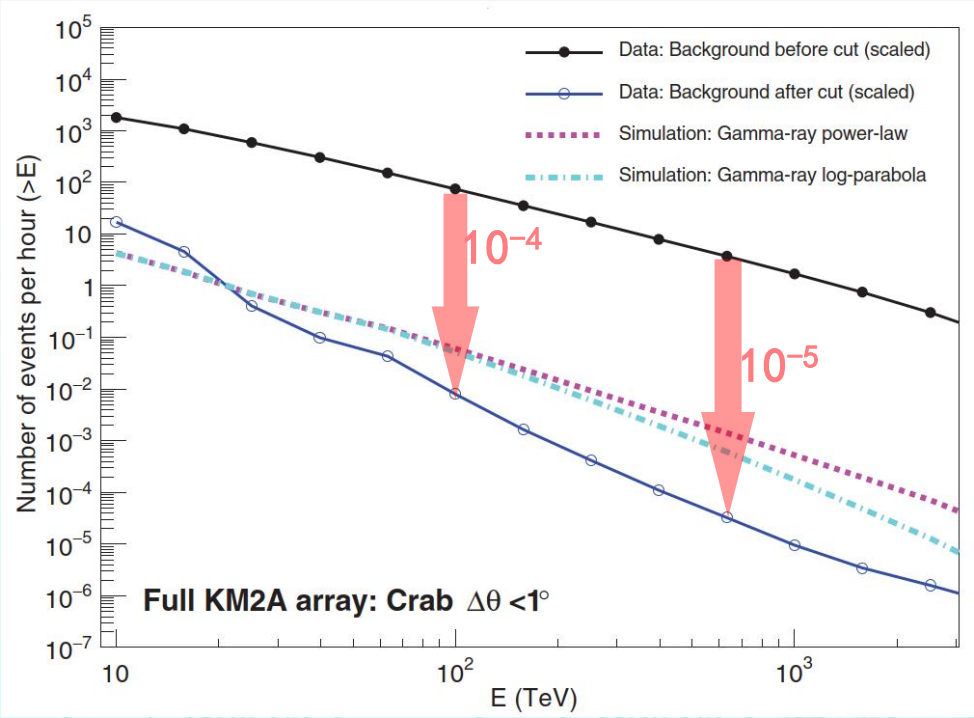


CR background Rejection by KM2A

- Counting number of measured muons in a shower
- Cutting on ratio N_μ/N_e<**1/230**
- BG-free (N_γ>10N_{CR}) Photon Counting

for showers with E>100 TeV from the **Crab**



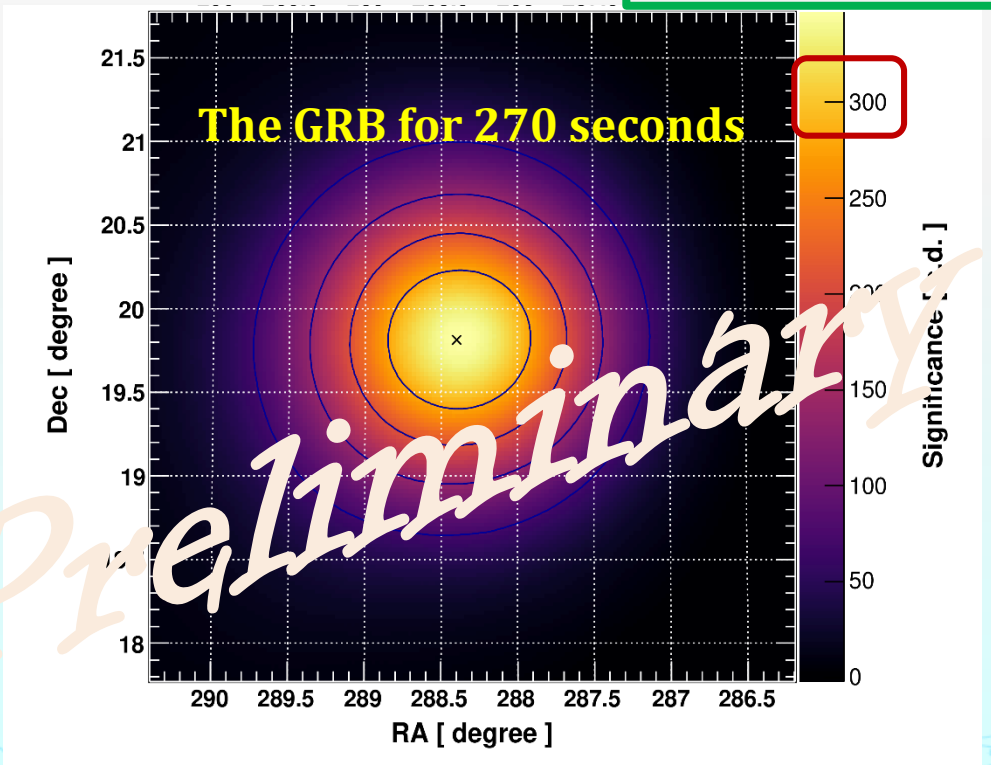


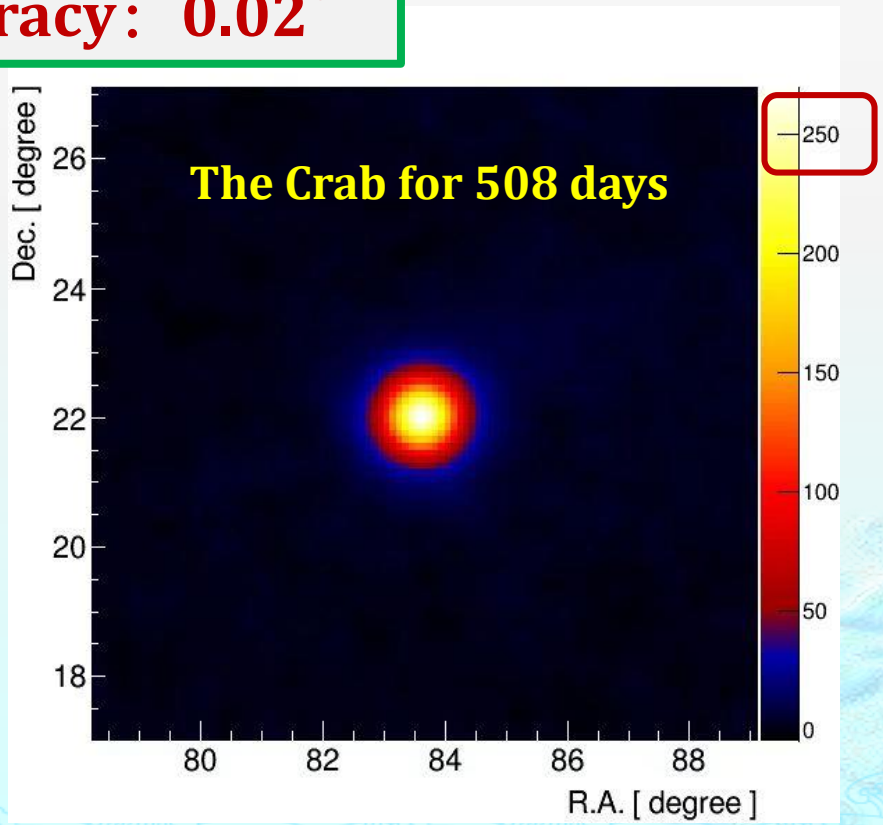
LHAASO Coll., *Science*, 373, 425 (2021)

GRB221009A and Crab as calibration targets

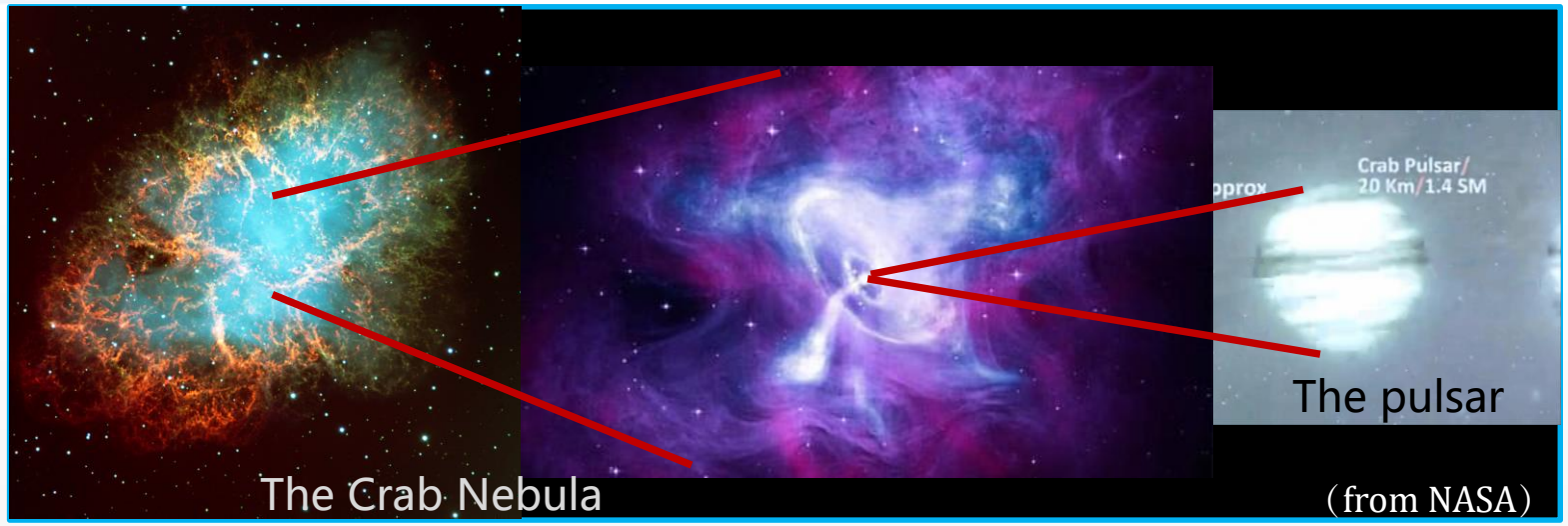
- The burst of 64k photons in **270 seconds** versus the exposure of the Crab for 508 days

Pointing accuracy： 0.02°



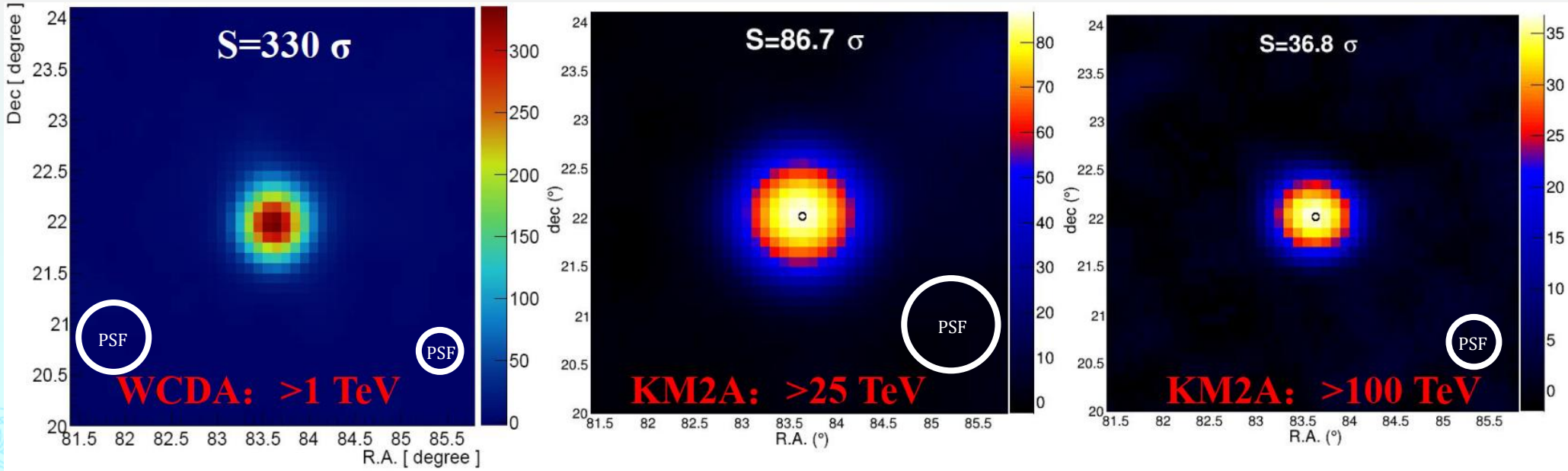


Standard candle for γ-ray Observation



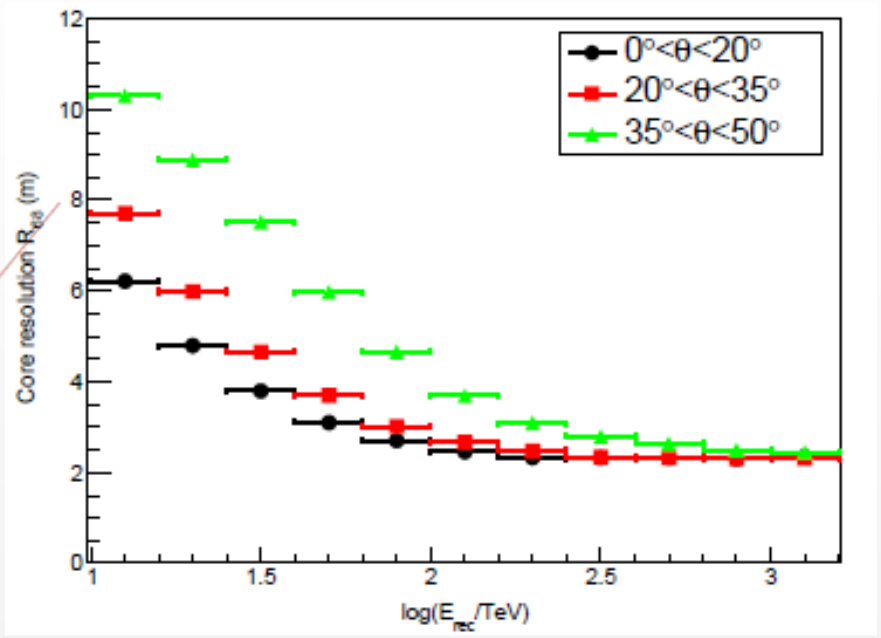
The coverage of 3.5 orders of magnitudes of energy

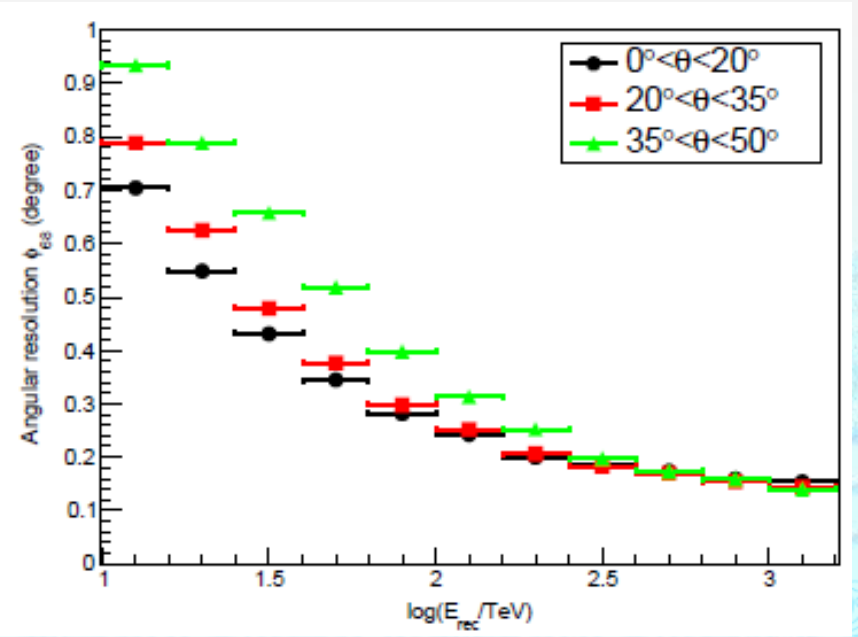
	1 - 12 TeV	25-100 TeV	0.1-1.2 PeV
PSF:	0.22°	0.30°	0.15°



Performances

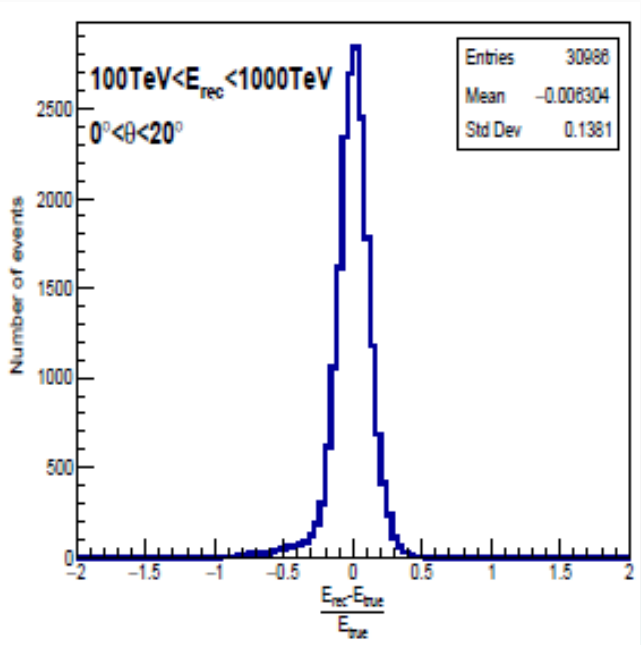
- Arrival direction: resolution of **0.26˚** @100 TeV
- Shower core location: resolution of **3 m** @100 TeV
  - Zenith angle effect

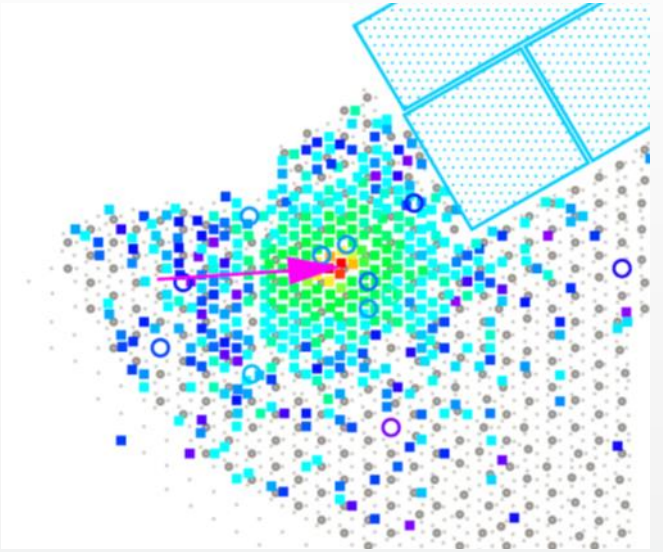


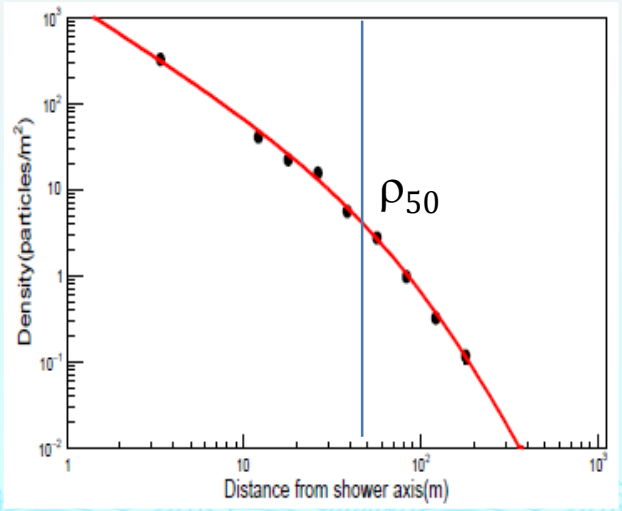


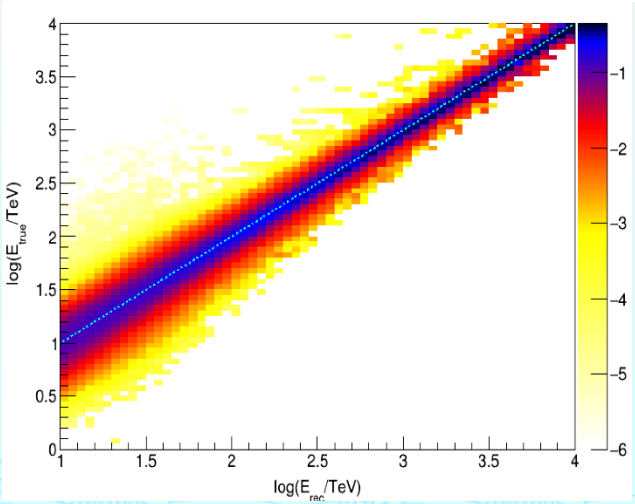
γ-ray Energy and the Resolution

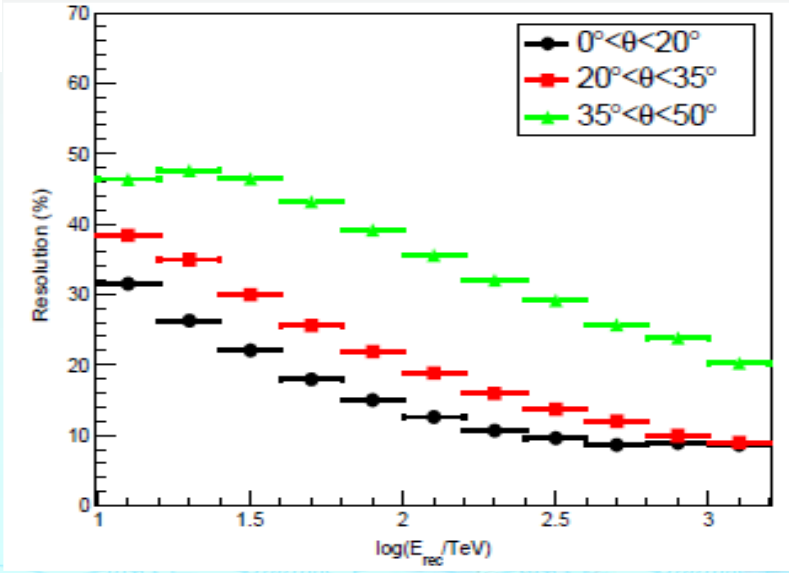
- **δE/E~14%**
  (E>100 TeV)
- Linear response
- Lateral distribution
- **ρ_{50}** E-estimator











Discovery in KM2A Survey

Our Galaxy is full of PeVatrons

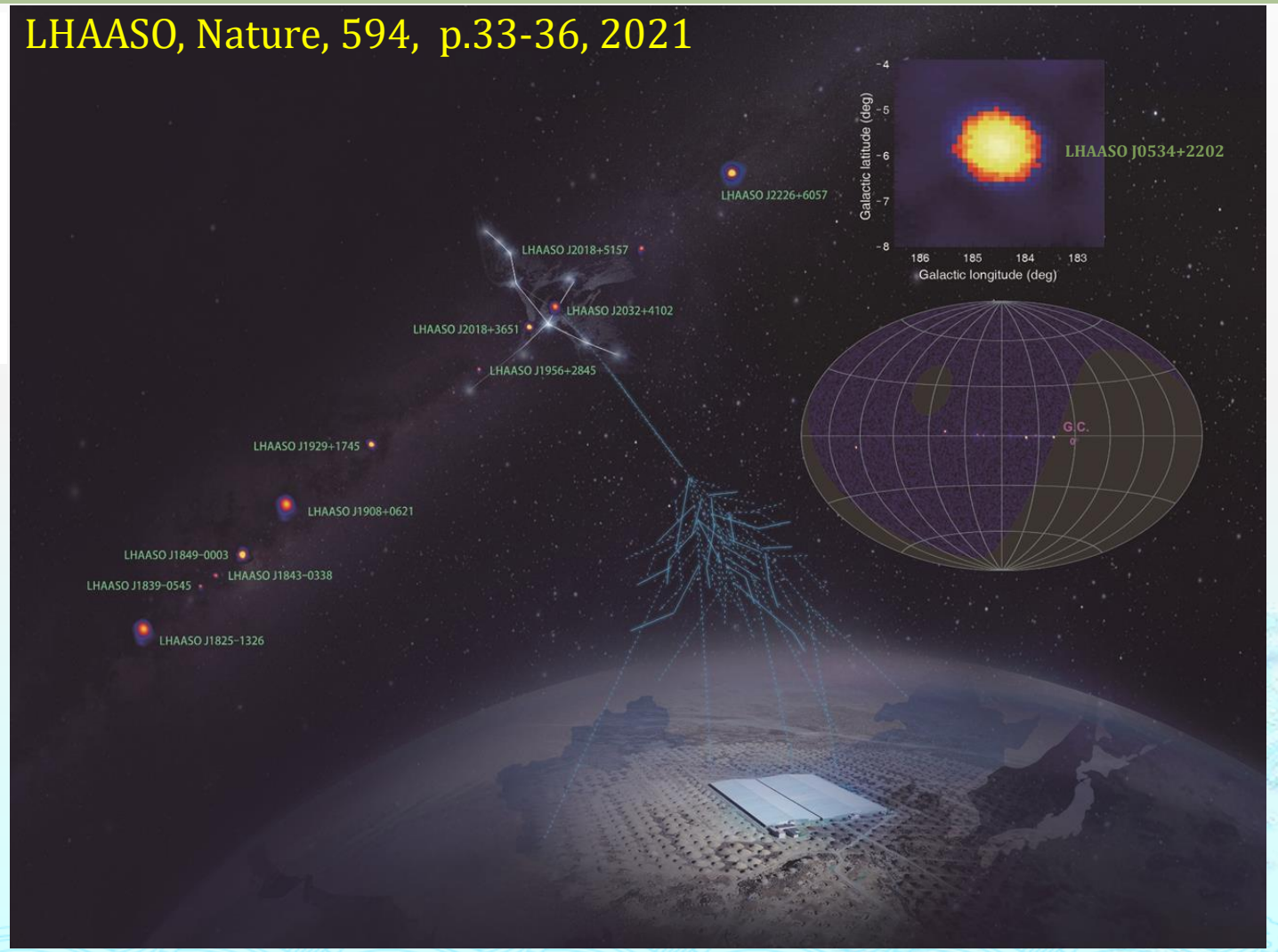
Table 1 | UHE γ-ray sources

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

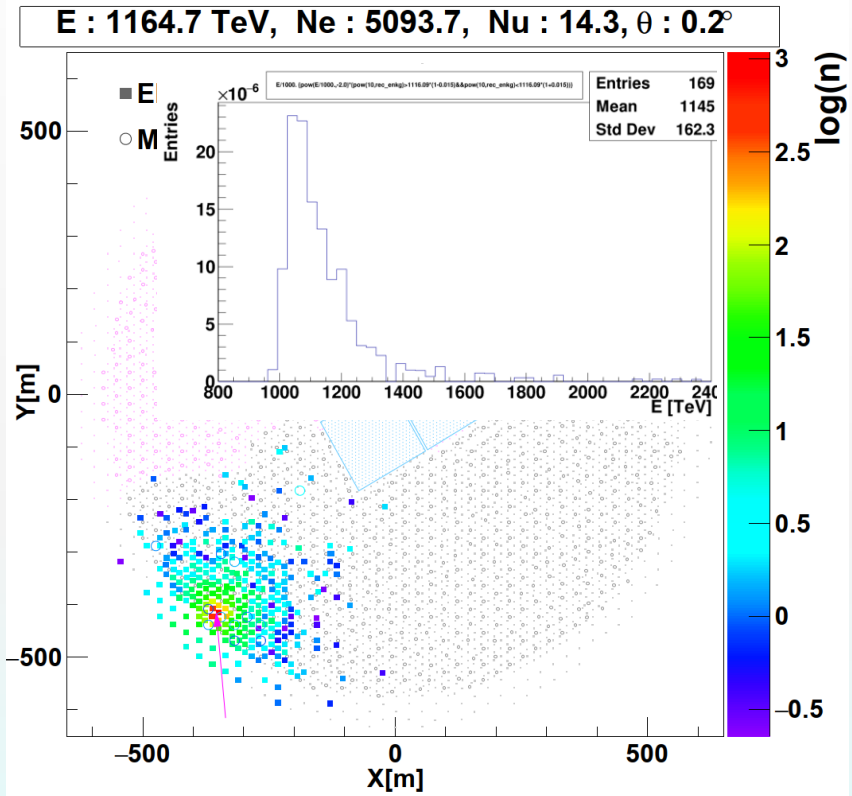
- **High Standard: significance >7σ**
- **BG-free: Cosmic Ray background rejection rate $<10^{-4}$**
- **High Statistics: 530 UHE photons many more now**

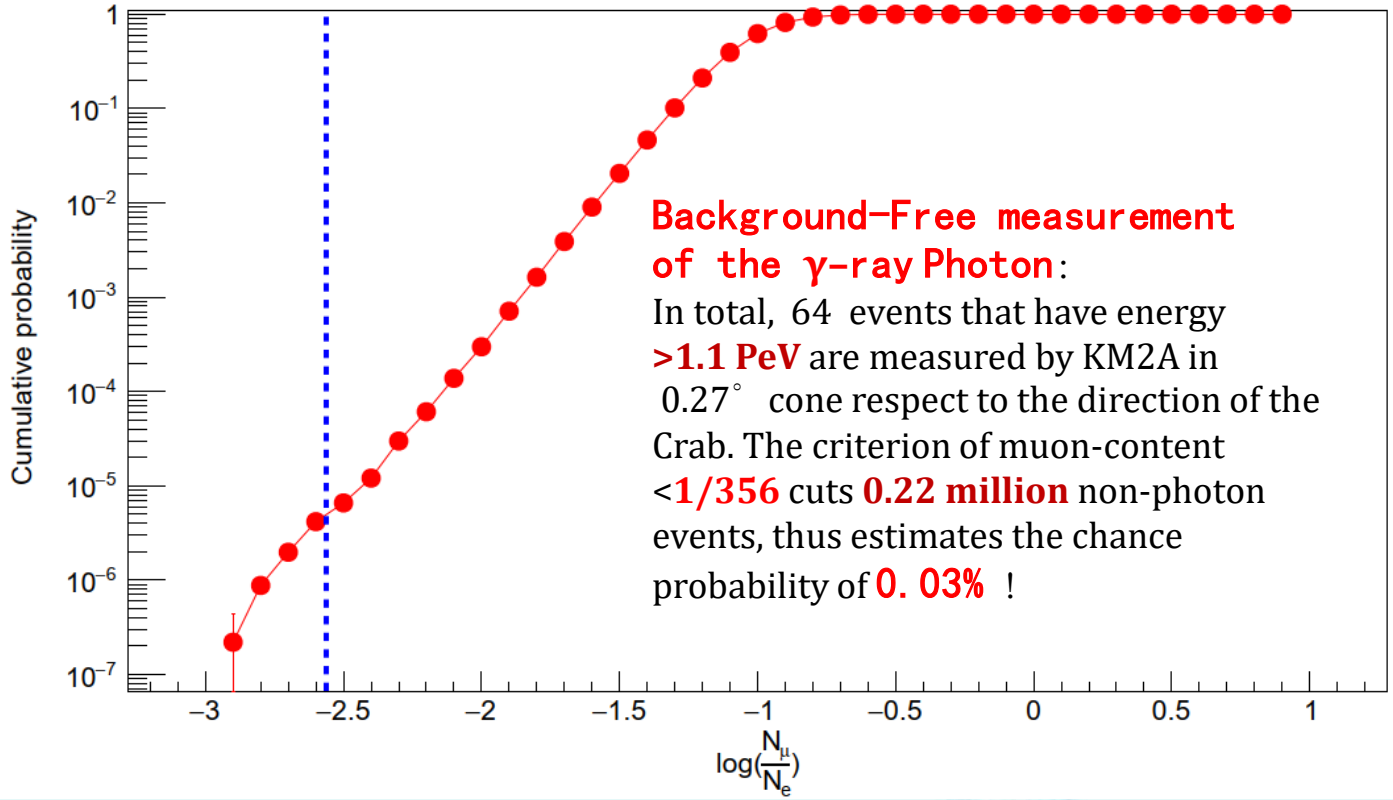
LHAASO, Nature, 594, p.33-36, 2021



Special attention to PeV Photons: 1.1 PeV

LHAASO, Science, *373*, 425-430, 2021





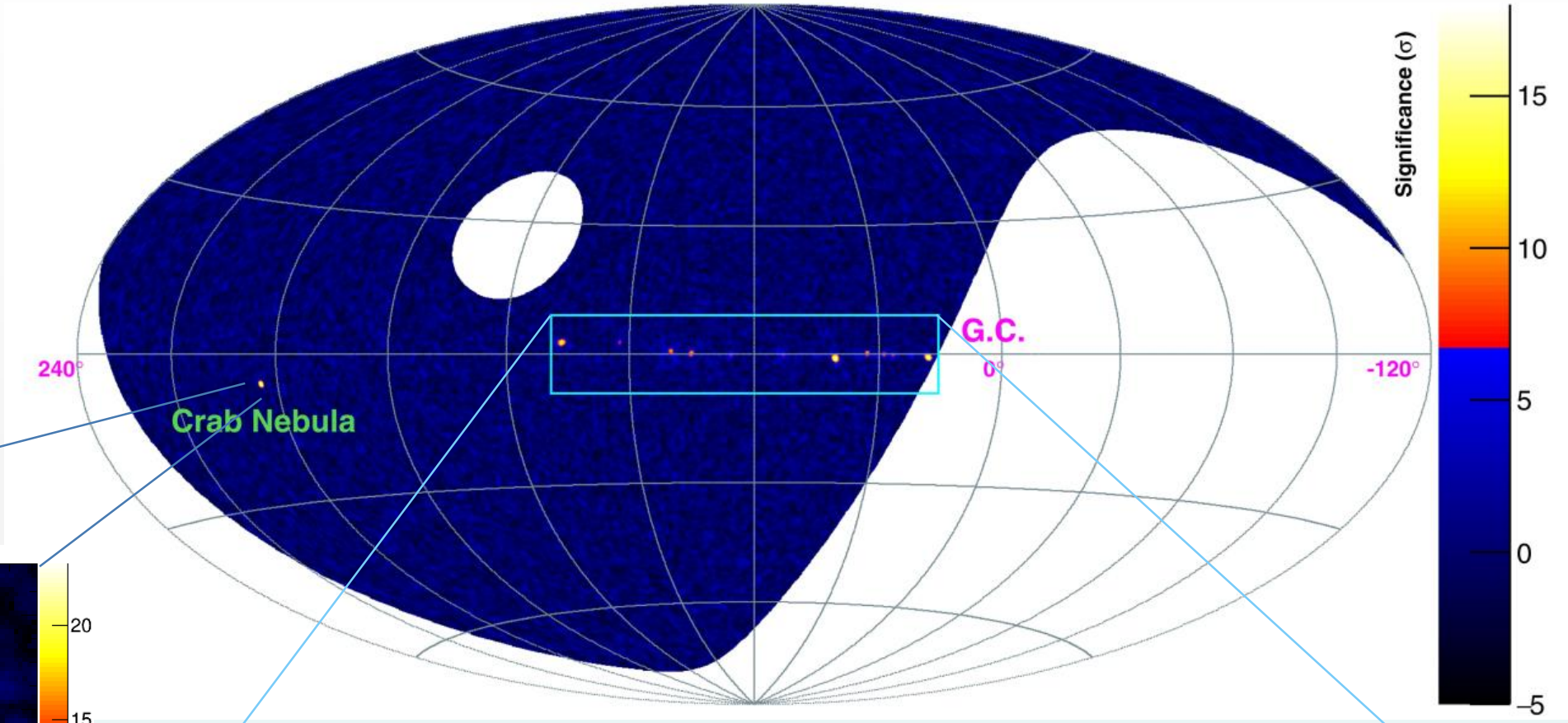
Background-Free measurement of the γ-ray Photon:
In total, 64 events that have energy **>1.1 PeV** are measured by KM2A in 0.27° cone respect to the direction of the Crab. The criterion of muon-content **<1/356** cuts **0.22 million** non-photon events, thus estimates the chance probability of **0.03%** !

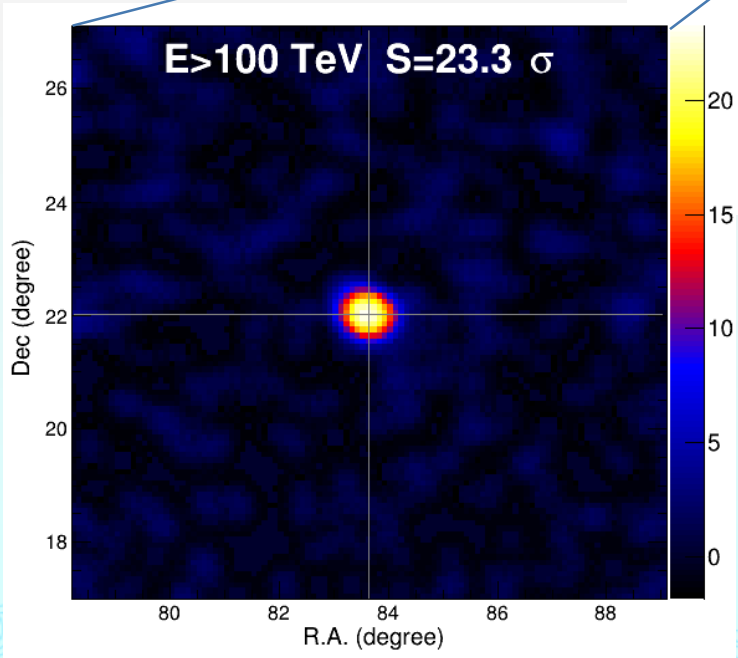
HE Record from Cygnus Direction at 1.4 PeV, renewed by > 2 PeV

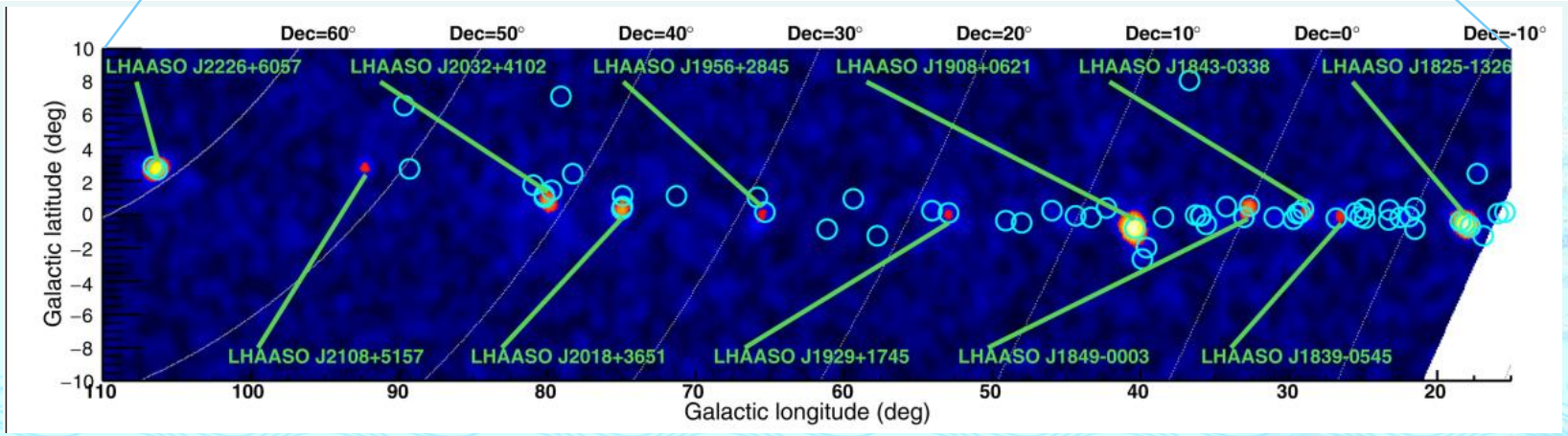
More than 10 photons above 1 PeV have been recorded.
everyone is well studied by simulating large number of events around them and analyzing for chance probability

LHAASO
高海拔宇宙线观测站

UHE γ–ray (0.1-1 PeV) Sky Map







LHAASO Catalog Ver-0 (potential counterparts)

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

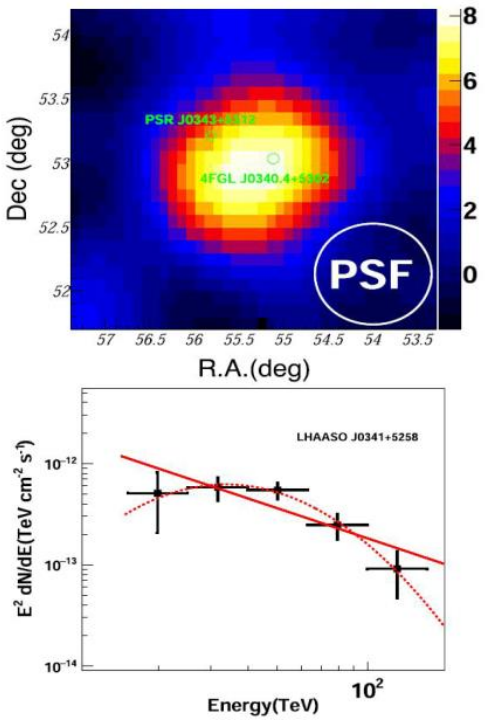
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR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

Discovery of New Sources

LHAASO Catalog Ver-1

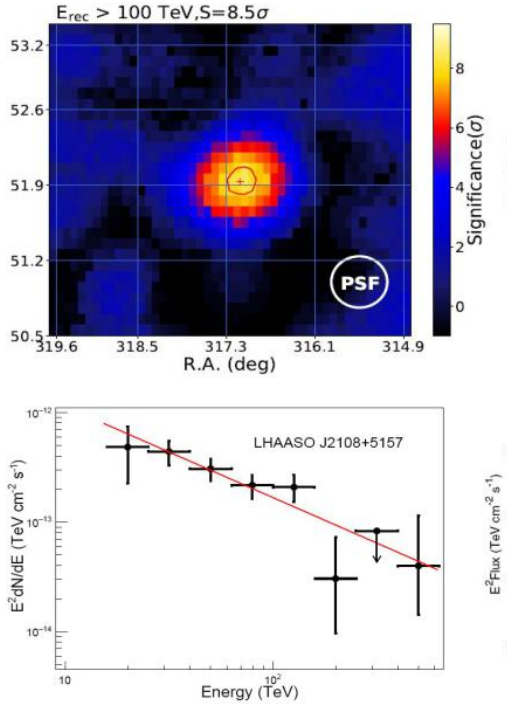
will be published soon with many new VHE/UHE sources discovered

LHAASO J0341+5258



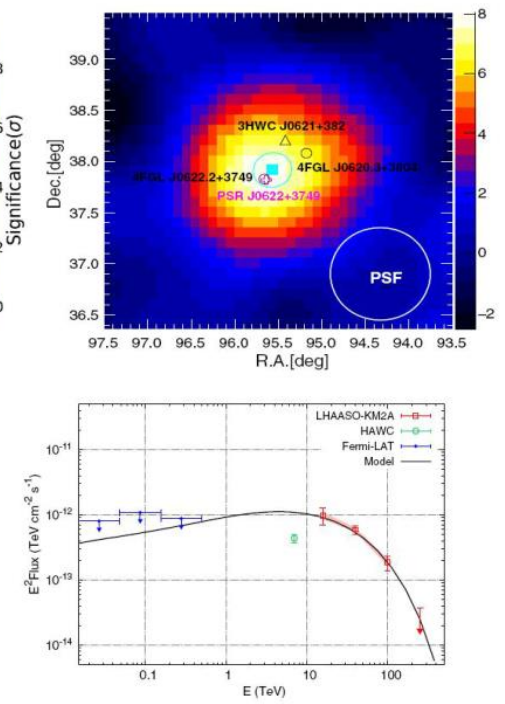
ApJL 917:L4 (2021)

LHAASO J2108+5157

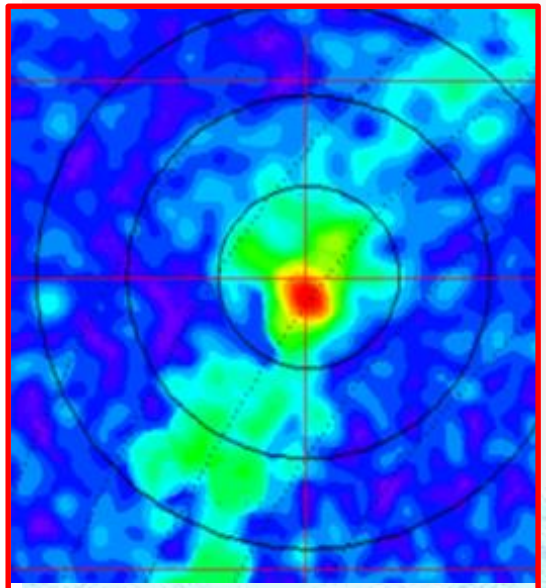


ApJL 919:L22 (2021)

Halo of PSR J0622 + 3749



PRL 126:241103 (2021)



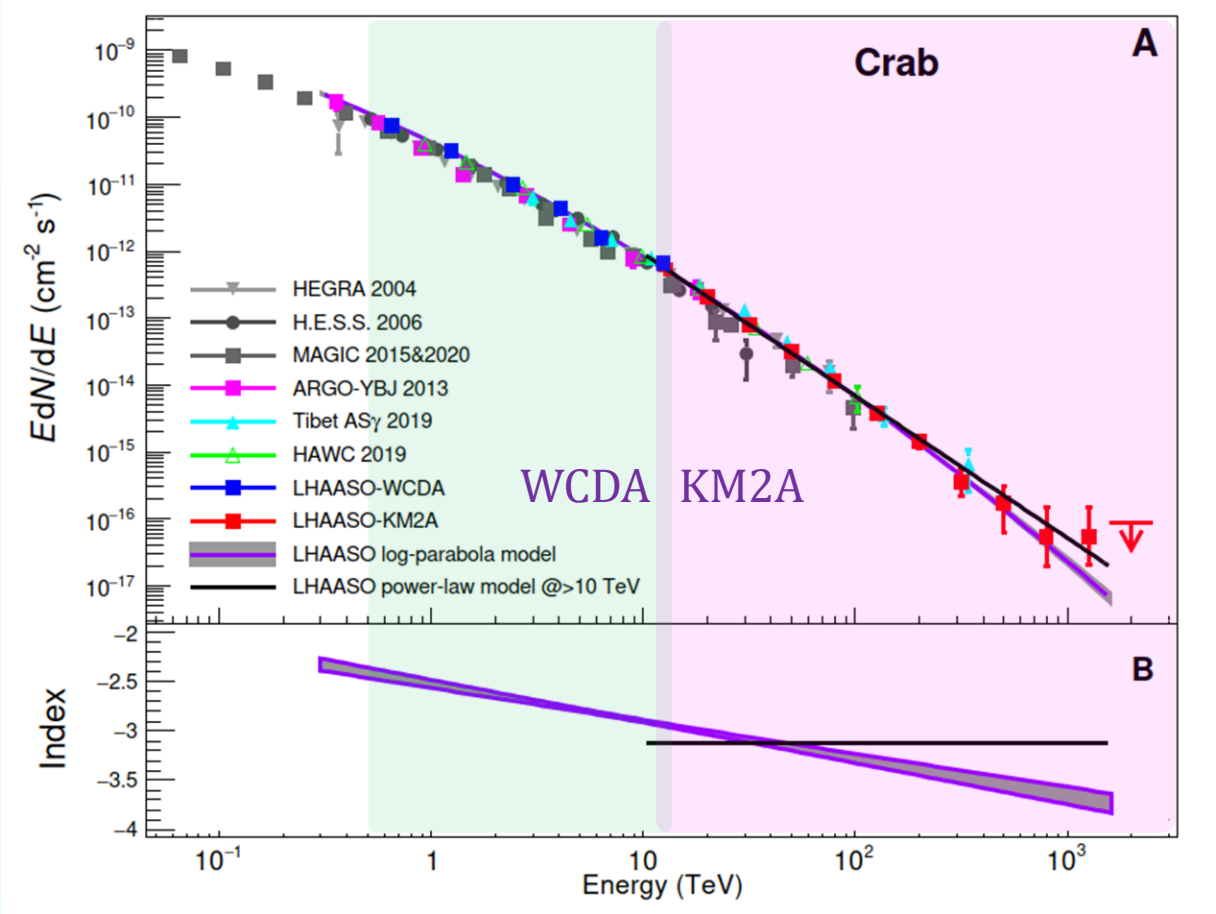
CR source candidates

http://english.ihep.cas.cn/lhaaso/index.html

SED of the Crab: "standard Candle"& PeVatron

LHAASO Coll., *Science*, 373, 425 (2021)

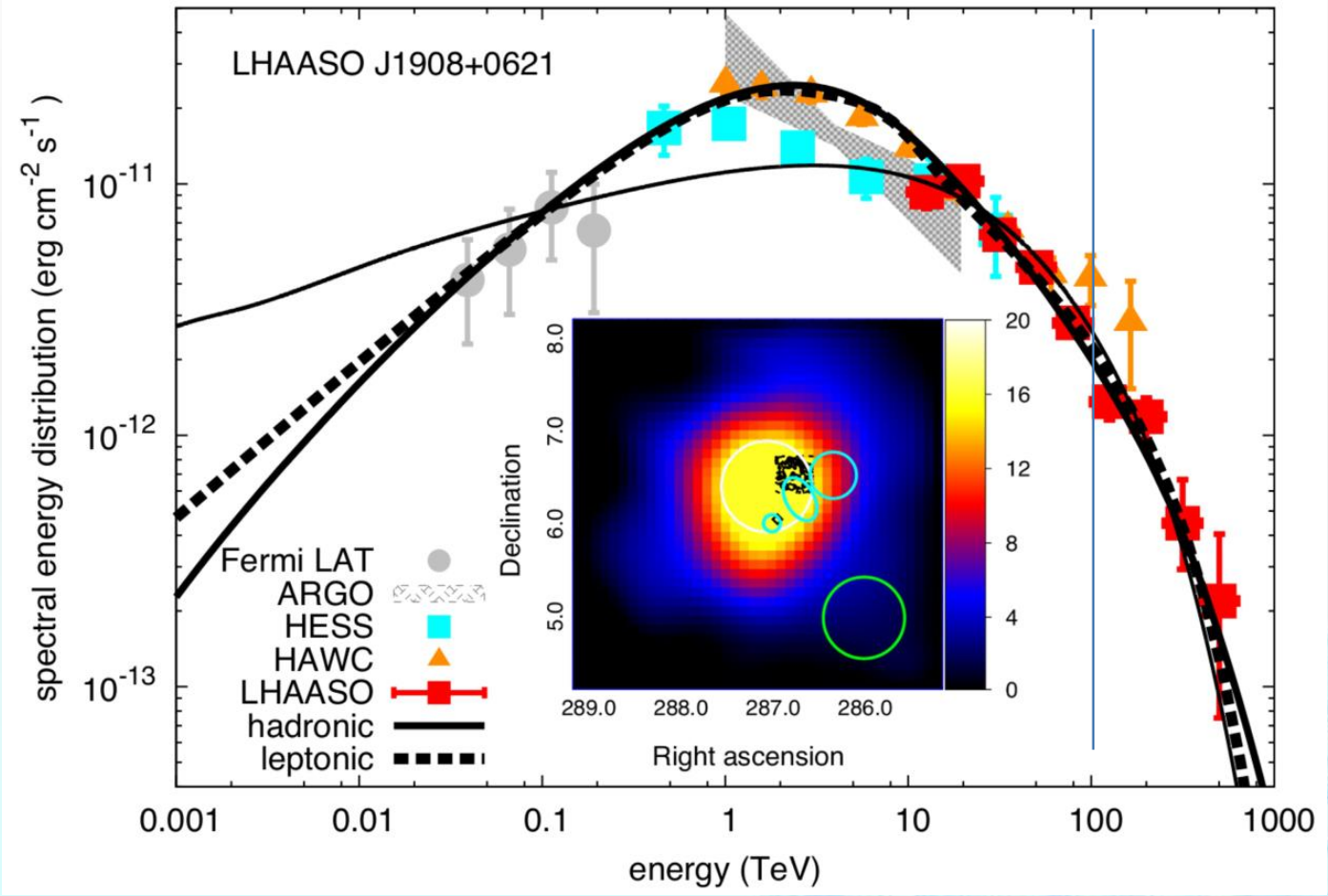
- **LHAASO:**
  - **Covering 3.5 decades of energy**
  - **Agreeing with other experiments below 100 TeV**
  - **Self cross-checking between WCDA & KM2A**
- **LHAASO-KM2A:**
  - **Unique UHE SED**
  - **A PeVatron without ambiguity**
  - **Clear origin: a well-known PWN**



Discovery Using KM2A
Onset of UHE γ–ray Astronomy

E > 0.1 PeV

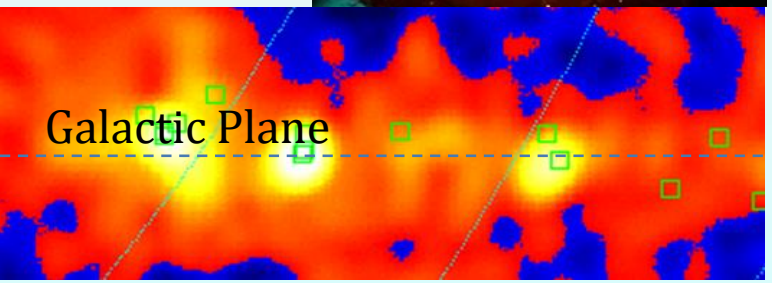
- VHE γ–ray astronomic major instrument: Sensitive below 0.1 PeV
- LHAASO: provide a statistically significant coverage of the energy range above 0.1 PeV
- Spectroscopy: 15% resolution
- Morphology: 0.3° PSF
- Multi-messenger Astronomy: UHE band



Prospects

Cyg OB2

Mrk421



- Cygnus region: cosmic ray origin
- Extra galactic sources
- Diffuse γ-ray emission
- New physics frontier exploring: LIV, DM…

Exploring Lorentz Invariance Violation

In the superluminal LIV

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

$$\alpha_0 \leq \frac{4m_e^2}{E_\gamma^2 - 4m_e^2},$$

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

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

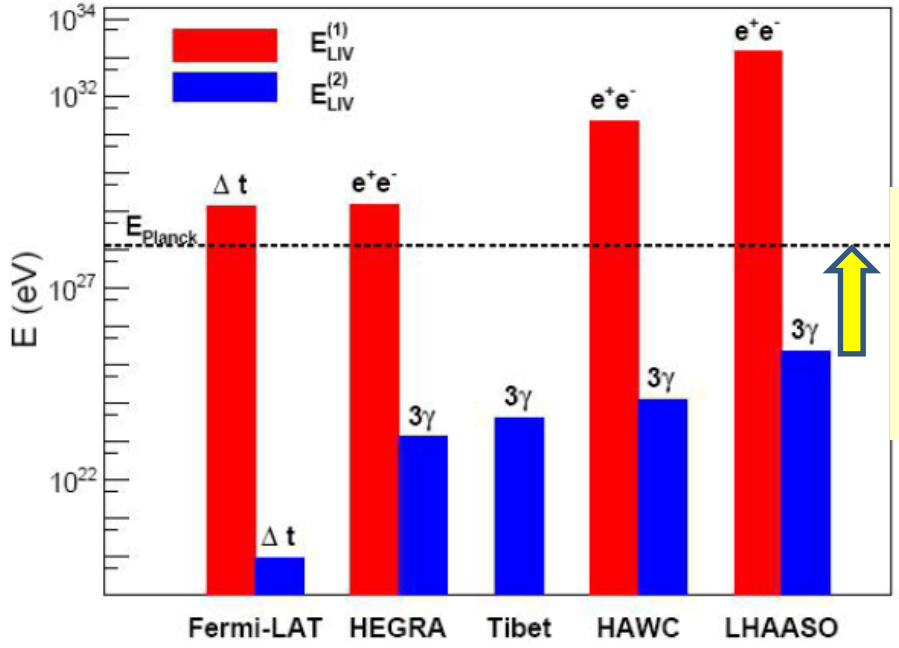
$$\gamma \rightarrow 3\gamma$$

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

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

New CLs method

Source	L (kpc)	$E_{\max}$ (PeV)	$E_{\text{cut}}^{95\%}$ (PeV)
J0534+2202	2.0	0.88	$0.75^{+0.043}_{-0.043}$
J2032+4102	1.4	1.42	$1.14^{+0.06}_{-0.06}$



3 orders of magnitudes below the Planck-scale

LHAASO Coll. PRL in press, arXiv:2106.12350

Conclusion

- LHAASO is a survey facility for UHE sources in northern sky
- Fully operation started July 2021 with a rate ~1 B events per day
- Strong separation power between γ-rays and CR background
- Photon arrival direction and energy measurements are calibrated using standard candle
- Number of PeVatrons in our galaxy is updating soon
- A couple of Pevatrons are analyzed in depth: the Crab and more
- Exploring for new phys. (see Zhe's and Sonzhan's talks)

Few words about the synergy between techniques

Synergy between EAS and IACT

Thanks for your attention!

- 3rd Generation of the survey device reaches the sensitivity of 10^{-14} TeV/cm^2/s, i.e. 12 mCU
- Precise measurements for SEDs