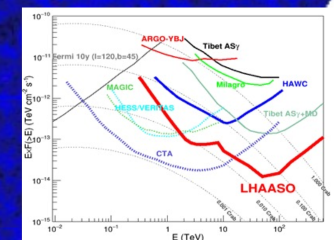
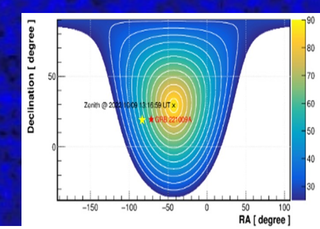
Highlights from Large High Altitude Air Shower Observatory



Dmitri Semikoz

APC, Paris

On behalf of LHAASO collaboration



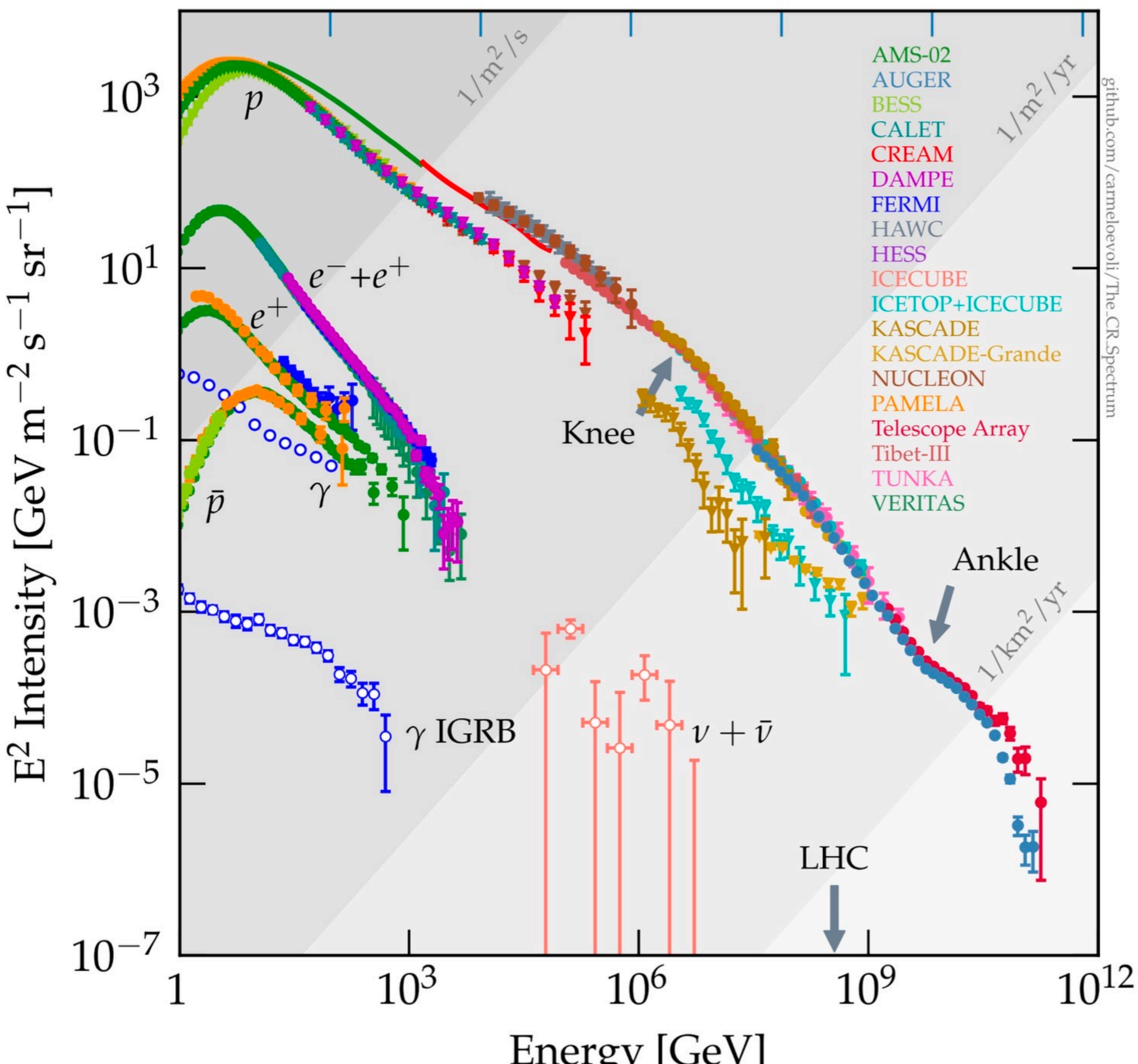
Plan

- Introduction: LHAASO detector
- Cosmic rays at knee
- First LHAASO catalog of gamma-ray sources
- Diffuse gamma-ray emission from Galaxy
- GRB 221009A
- Cygnus region
- Micro-quasars
- Dark matter limits
- Conclusions

Introduction:

LHAASO detector

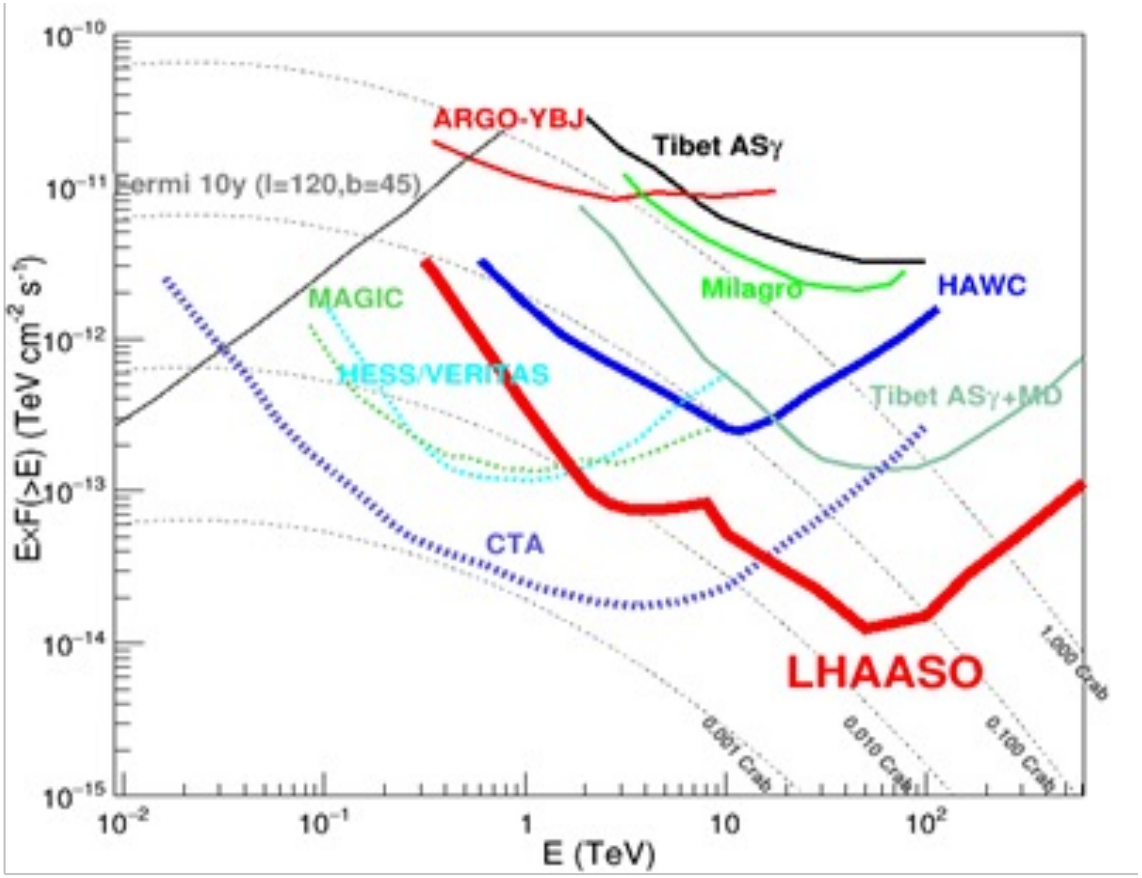
Cosmic ray energy spectrum

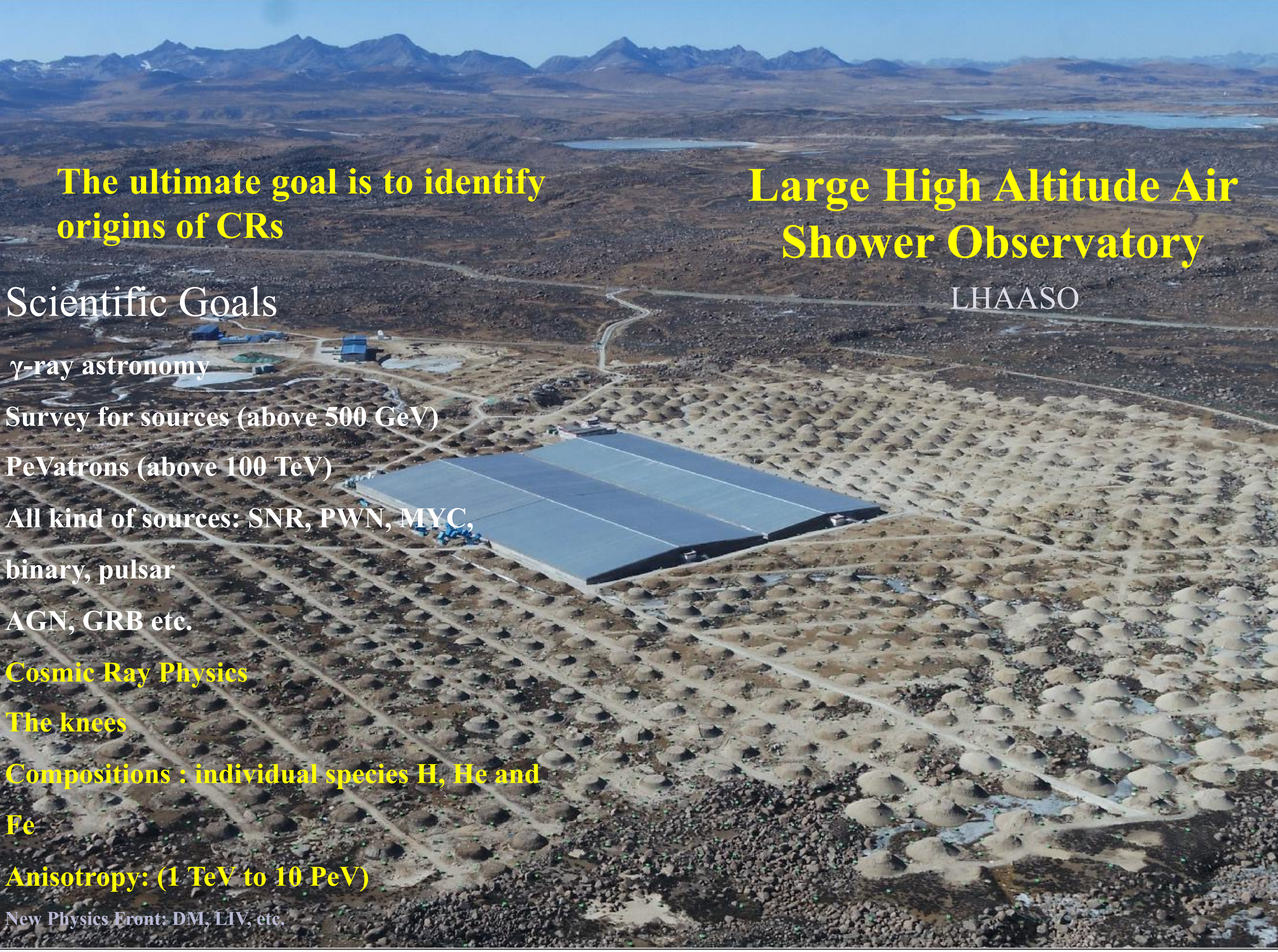


From C.Evoli

LHAASO sensitivity

With large FOV and high sensitivity, LHAASO is an ideal detector for sky survey to search VHE and UHE sources!





Large High Altitude Air Shower Observatory

LHAASO

The ultimate goal is to identify origins of CRs

Scientific Goals

γ-ray astronomy

Survey for sources (above 500 GeV)

PeVatrons (above 100 TeV)

All kind of sources: SNR, PWN, MYC, binary, pulsar

AGN, GRB etc.

Cosmic Ray Physics

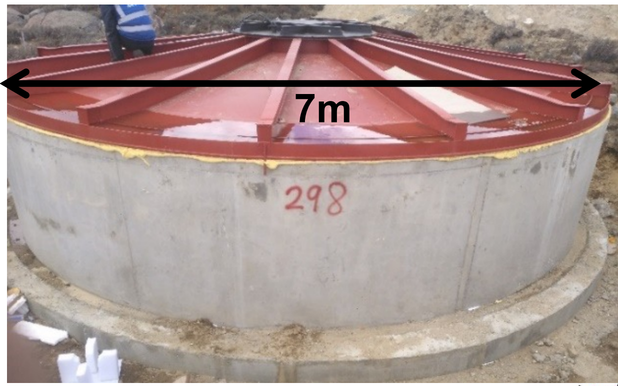
The knees

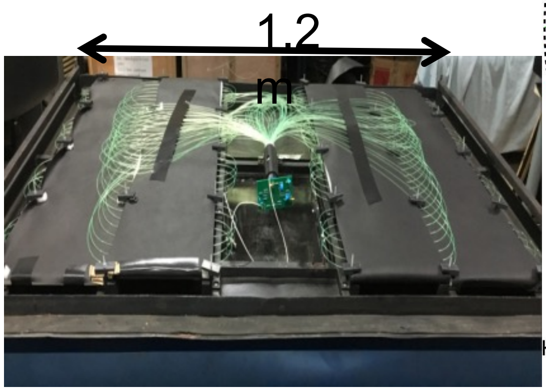
Compositions : individual species H, He and Fe

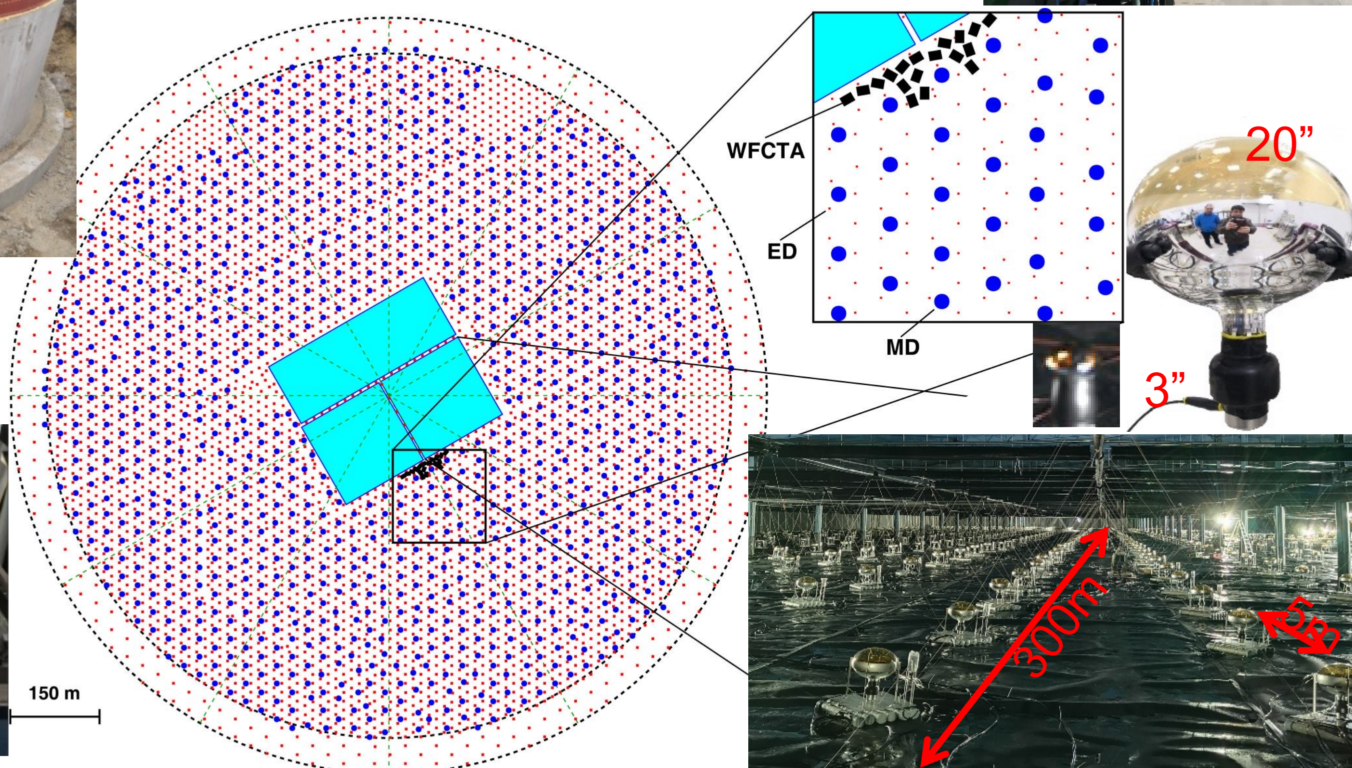
Anisotropy: (1 TeV to 10 PeV)

New Physics Front: DM, LIV, etc.

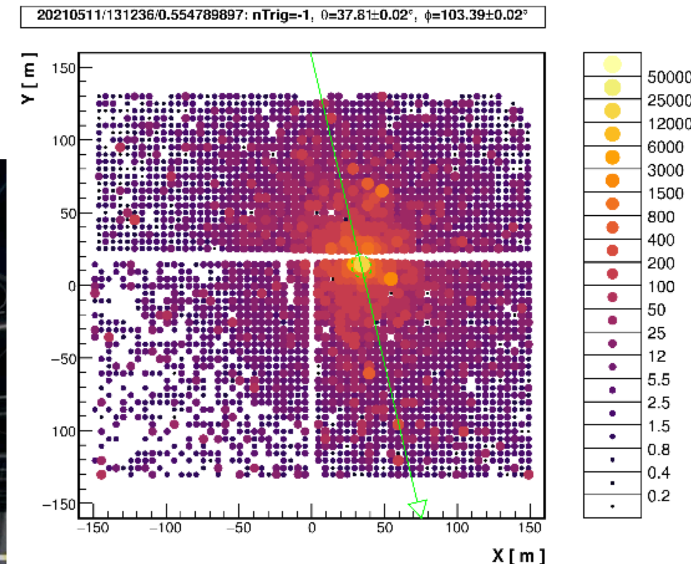
LHAASO Layout

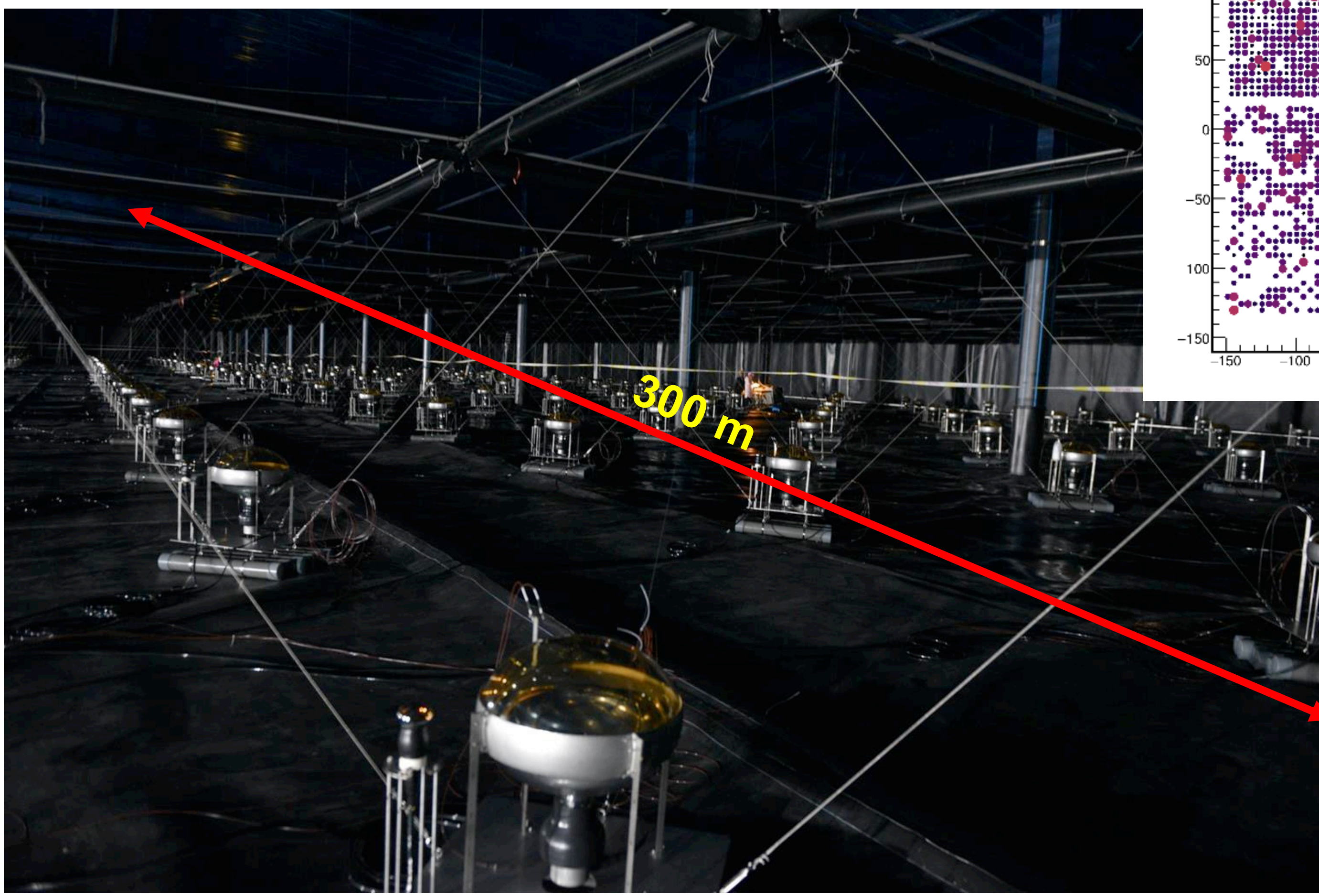






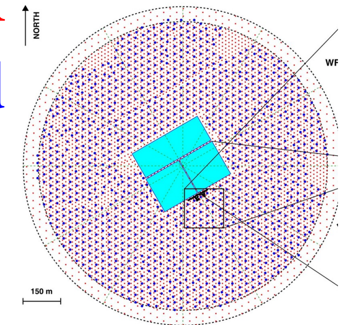
LHAASO-WCDA
Water Cherenkov Detector Array





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

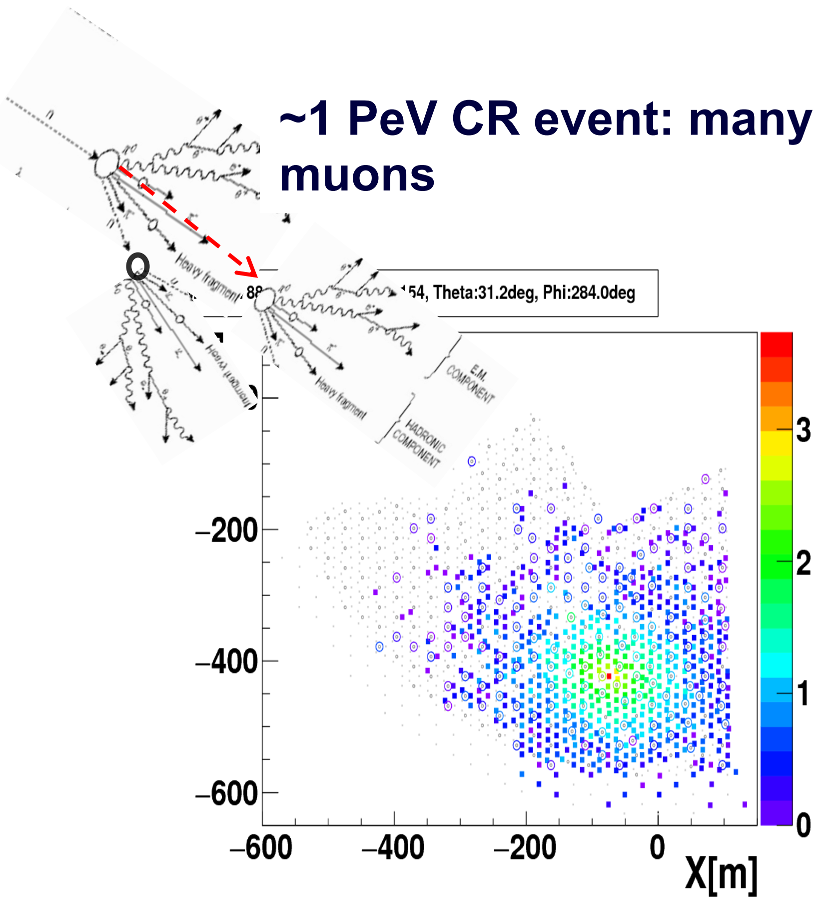
LHAASO-KM2A



Selection of γ–rays out of CR background

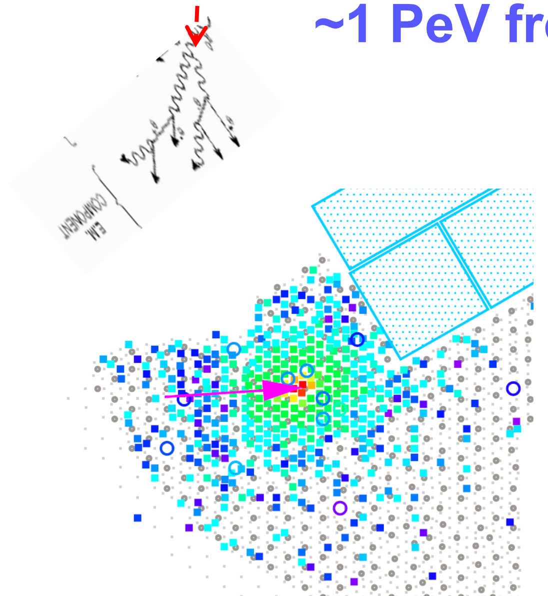
Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons



~1 PeV γ–ray event : very few muons

~1 PeV from the Crab

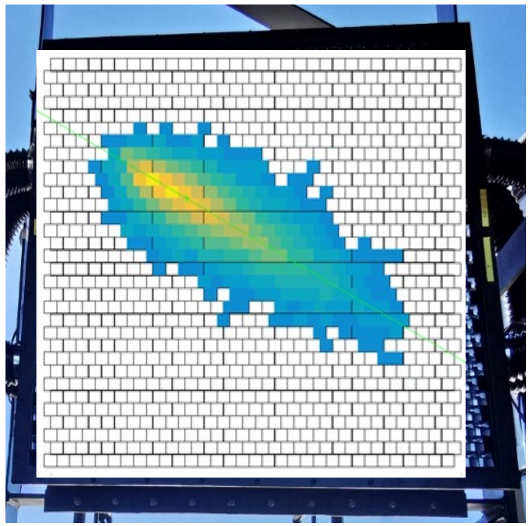


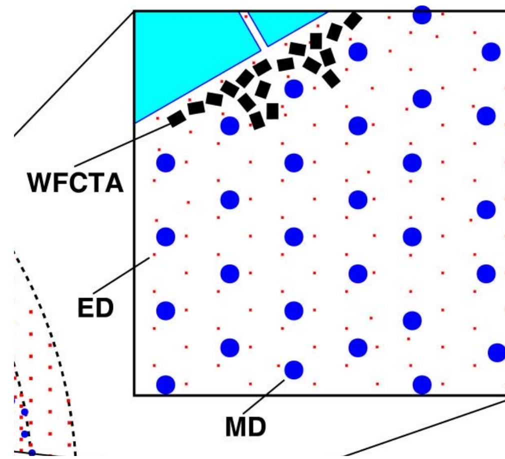
- **Area :** **1.3 km²**
- **Detectors :** **5216 ED** **1188 MD**
- **Energy Range :** **0.01-10 PeV**

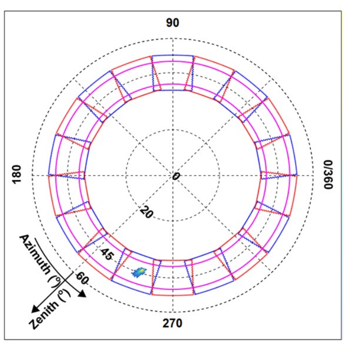
LHAASO-WFCTA

Separate of individual CR species & measure the knees

~0.1 PeV CR event

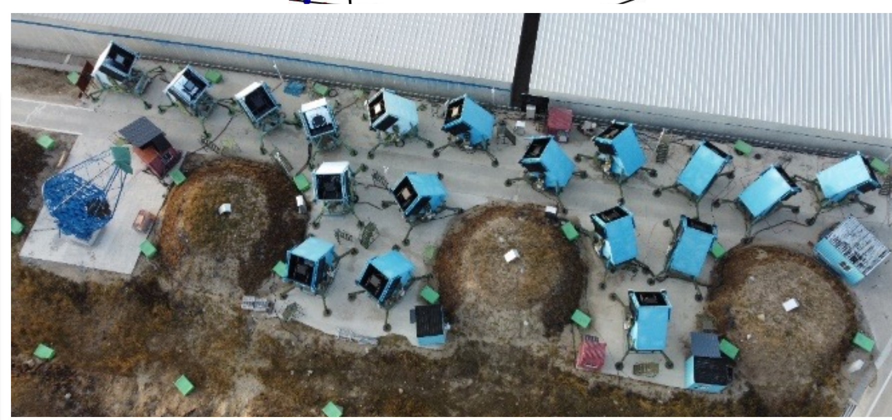




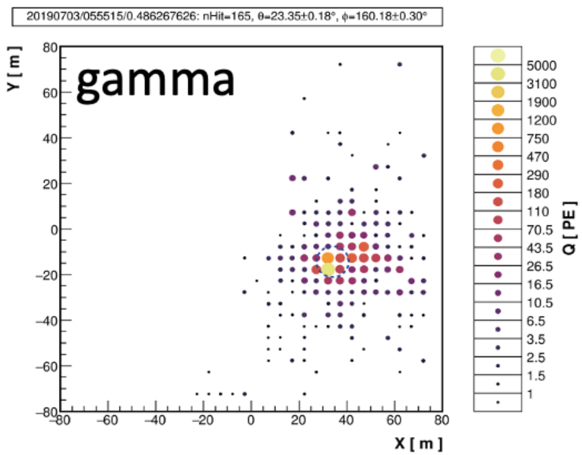


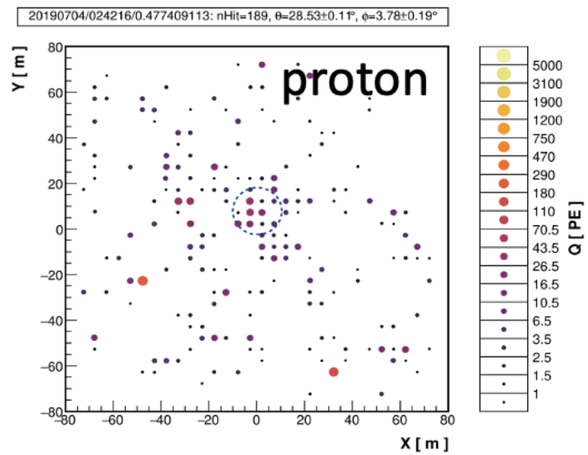
WFCTA: 18 IACTs

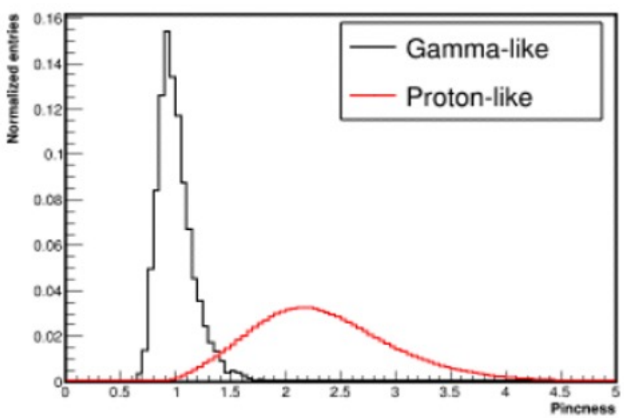
- Mirror: 5 m^2
- SiPM camera
- FOV: 16×16°
- Pixel size: 0.5°
- Energy: 0.1-100 PeV

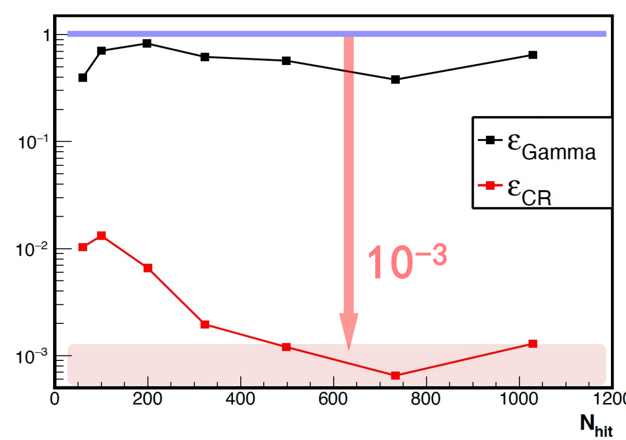


CR Background rejection in WCDA





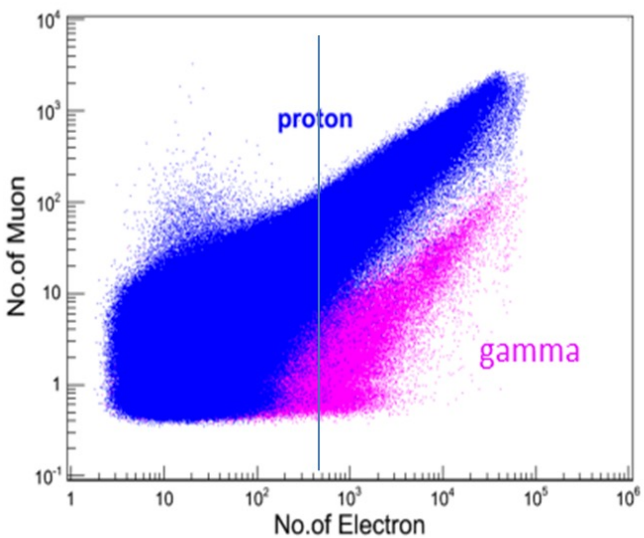


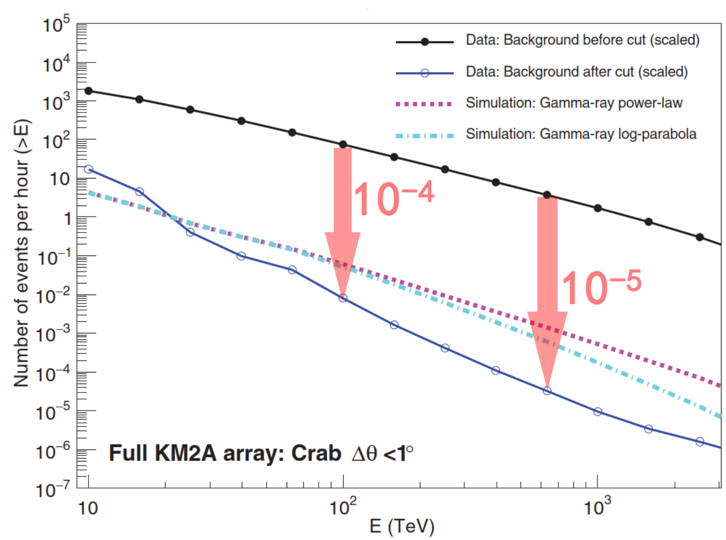


CR background Rejection in KM2A

- 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

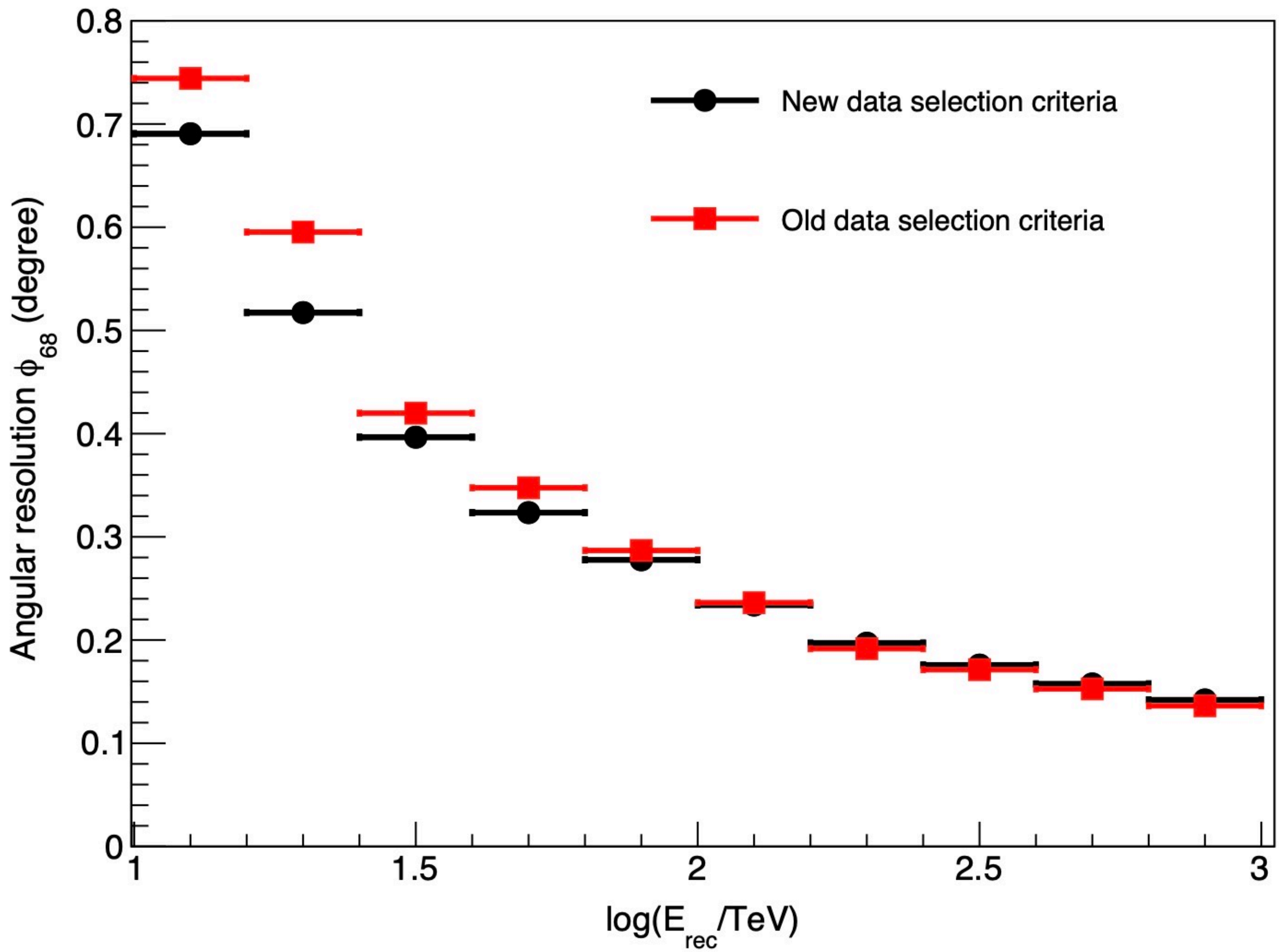
for showers with E>100 TeV from the Crab





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

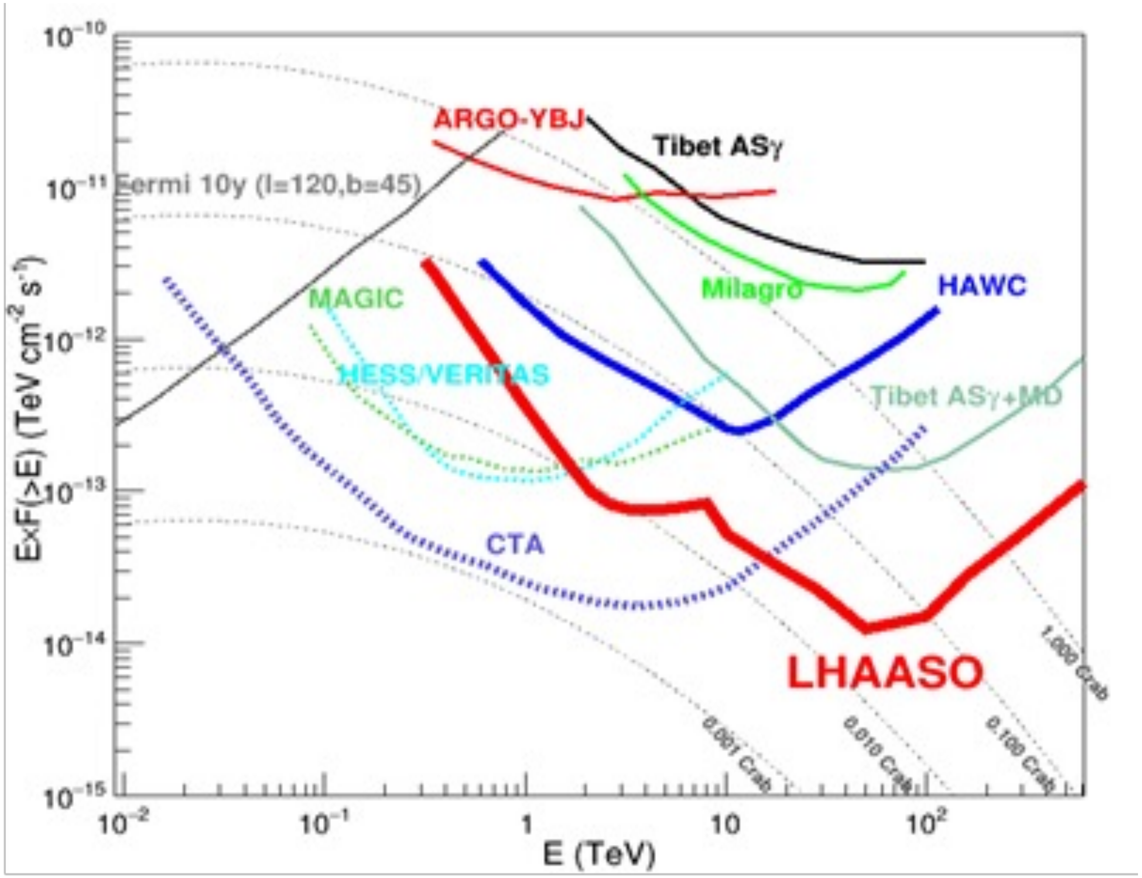
LHAASO angular resolution



LHAASO Crab study 2401.01038, *Chin.Phys.C* 48 (2024) 6, 065001

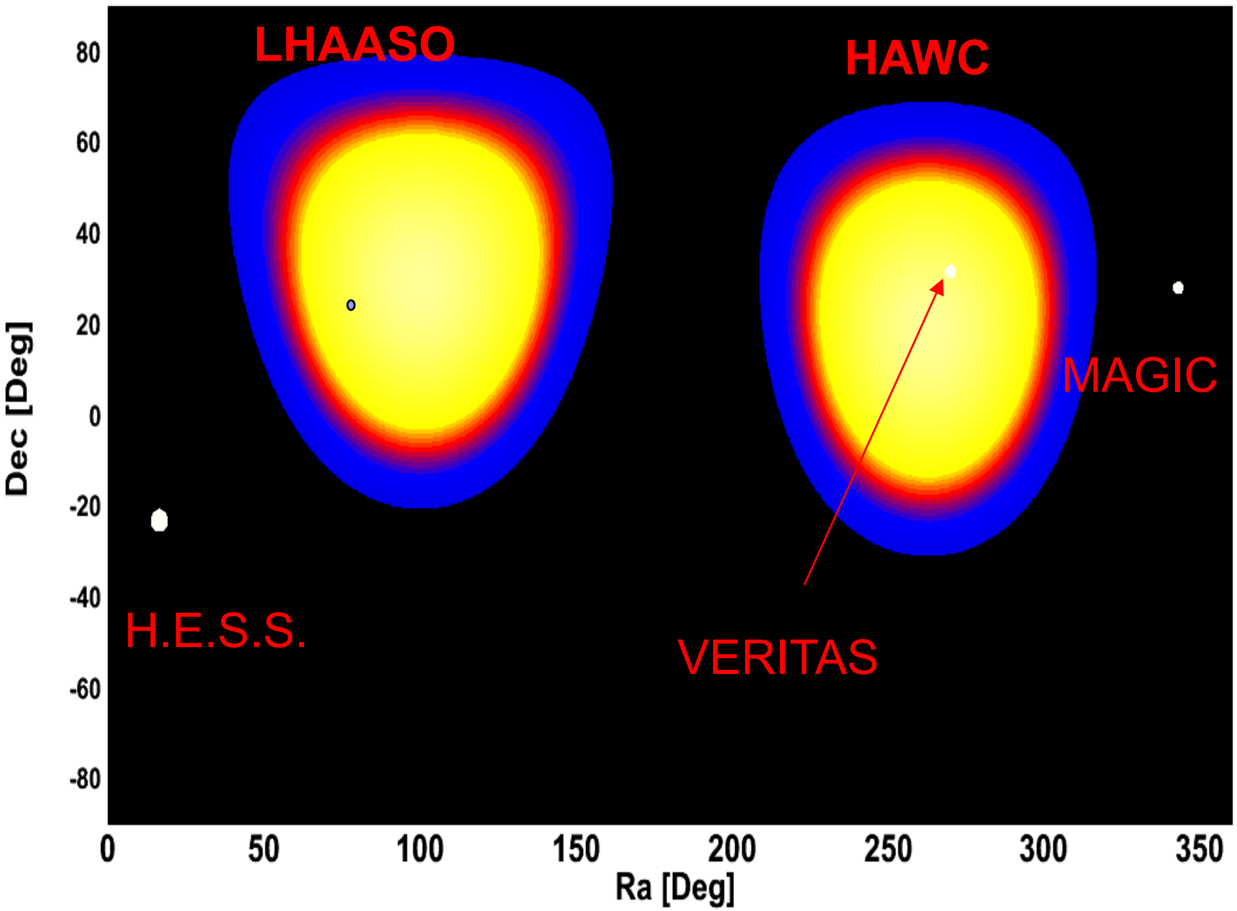
LHAASO sensitivity

With large FOV and high sensitivity, LHAASO is an ideal detector for sky survey to search VHE and UHE sources!



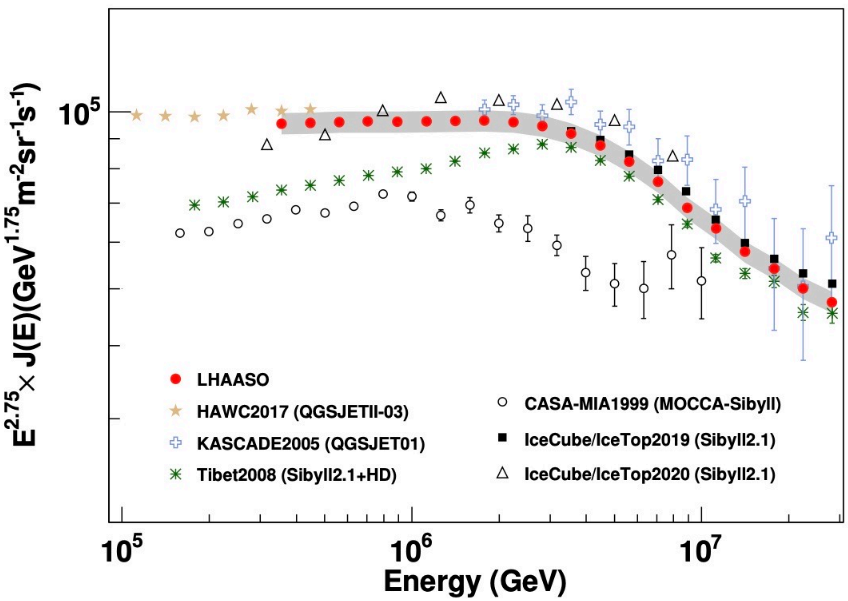
Field of view for GRB/TOO

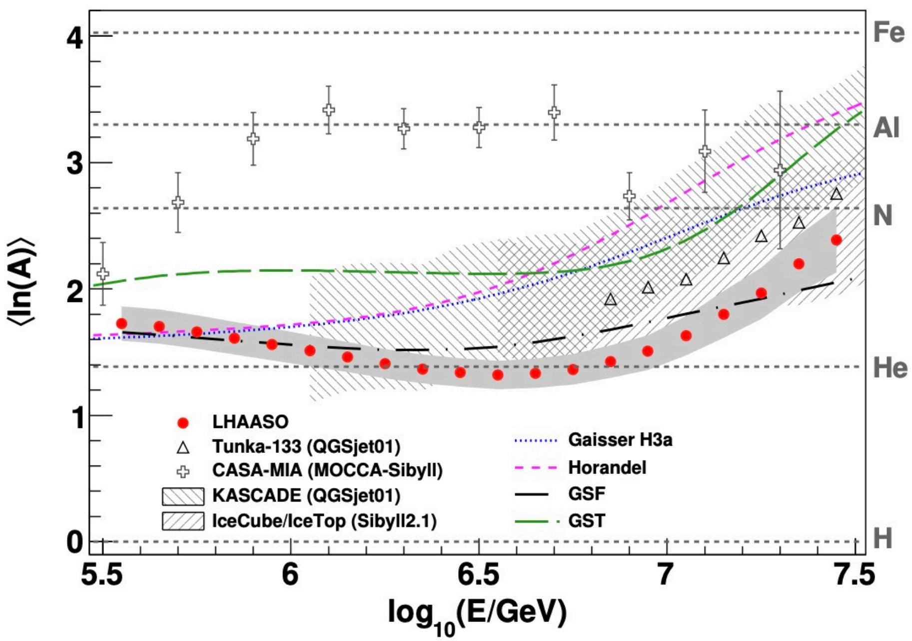
1/7 of the sky at any time



Cosmic rays at knee with LHAASO

CR spectrum and mass composition





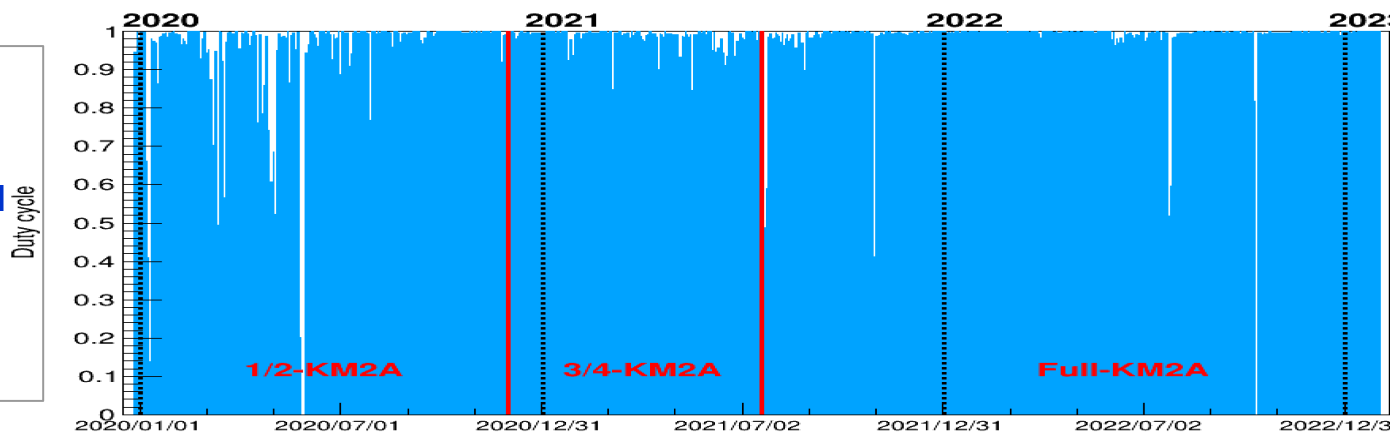
•*LHAASO collab.*, Zh.Cao et al, 2403.10010
, *Phys.Rev.Lett.* 132 (2024) 13, 131002

1 LHAASO catalog

LHAASO data used for catalog analysis

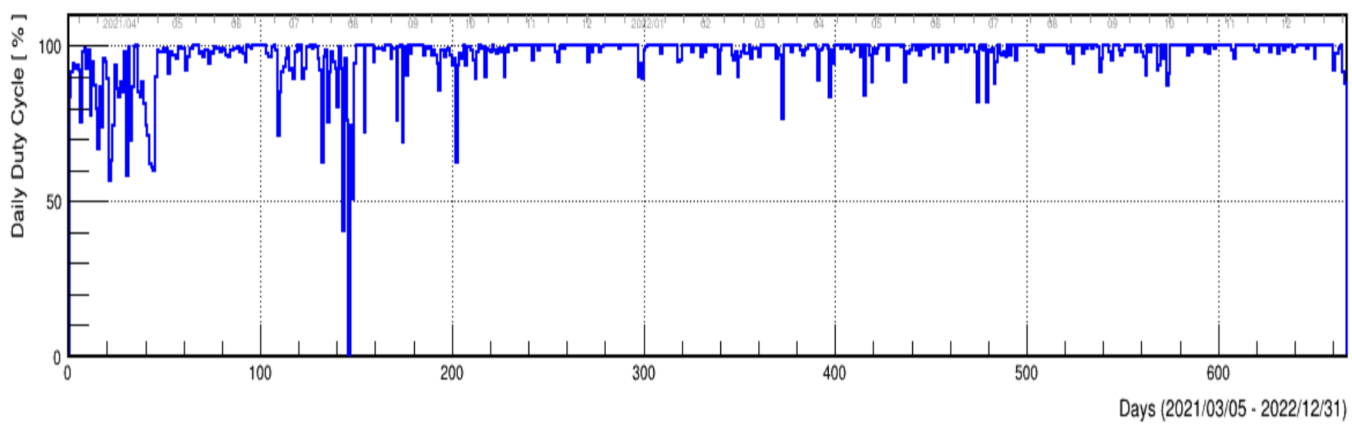
KM2A

- 2019-12 to 2022-09
- 933 days (~730 days full array)
- 1.3×10^{7} gamma-like events



WCDA

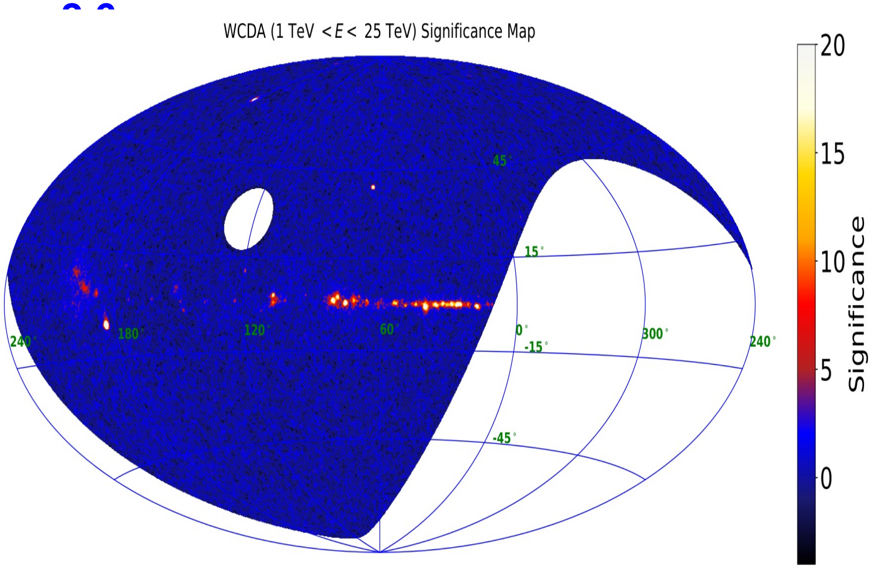
- 2021-03 to 2022-09
- 508 days
- 1.3×10^{9} gamma-like events



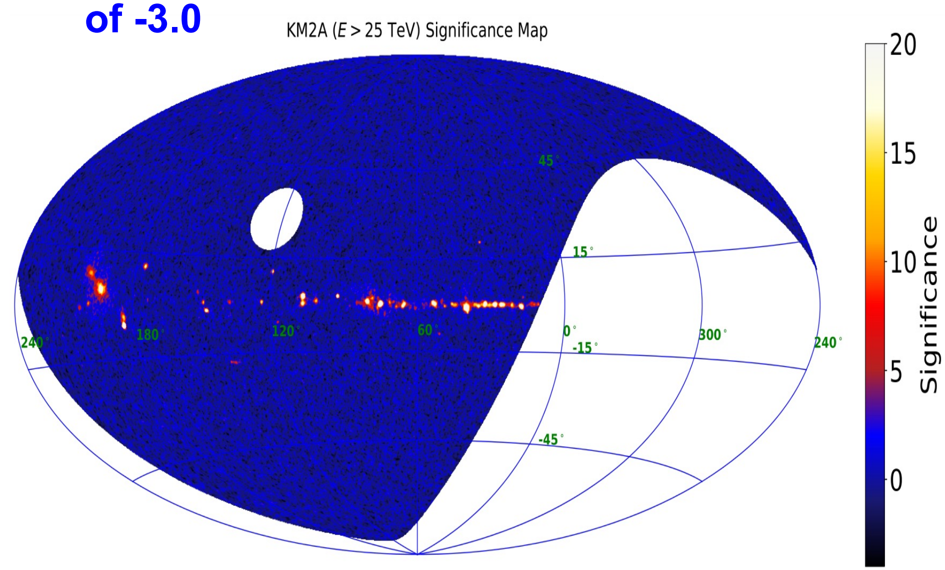
Point gamma-ray source searching

- The candidates with significance **>5σ** are used to determine ROI and also as **seeds** for next fitting.

WCDA SED: power-law with a index of



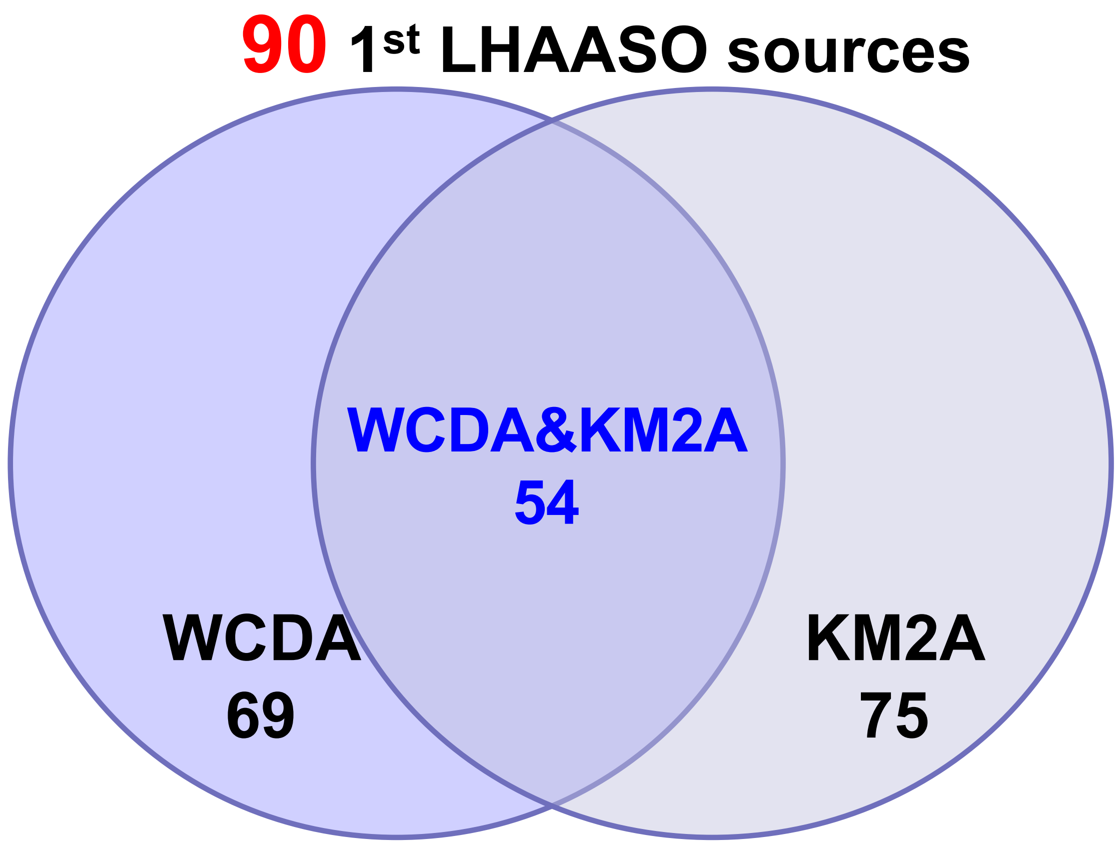
KM2A SED: power-law with a index of -3.0



Construction of the 1st LHAASO sources

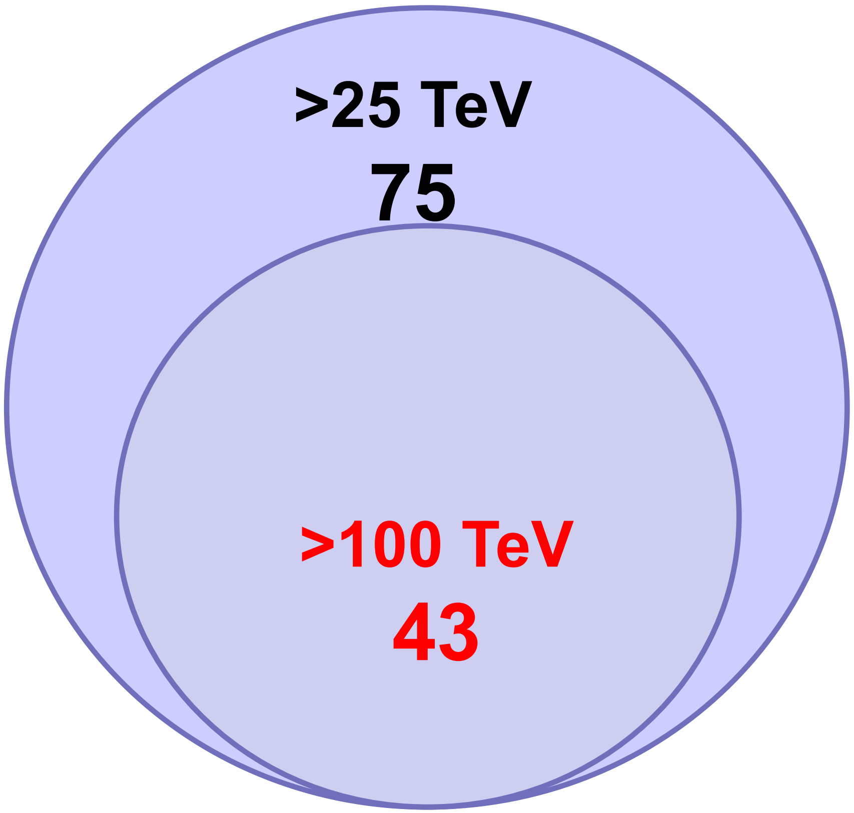
WCDA&KM2A

- Space Angle
- Position error
- Source extension



UHE gamma-ray sources

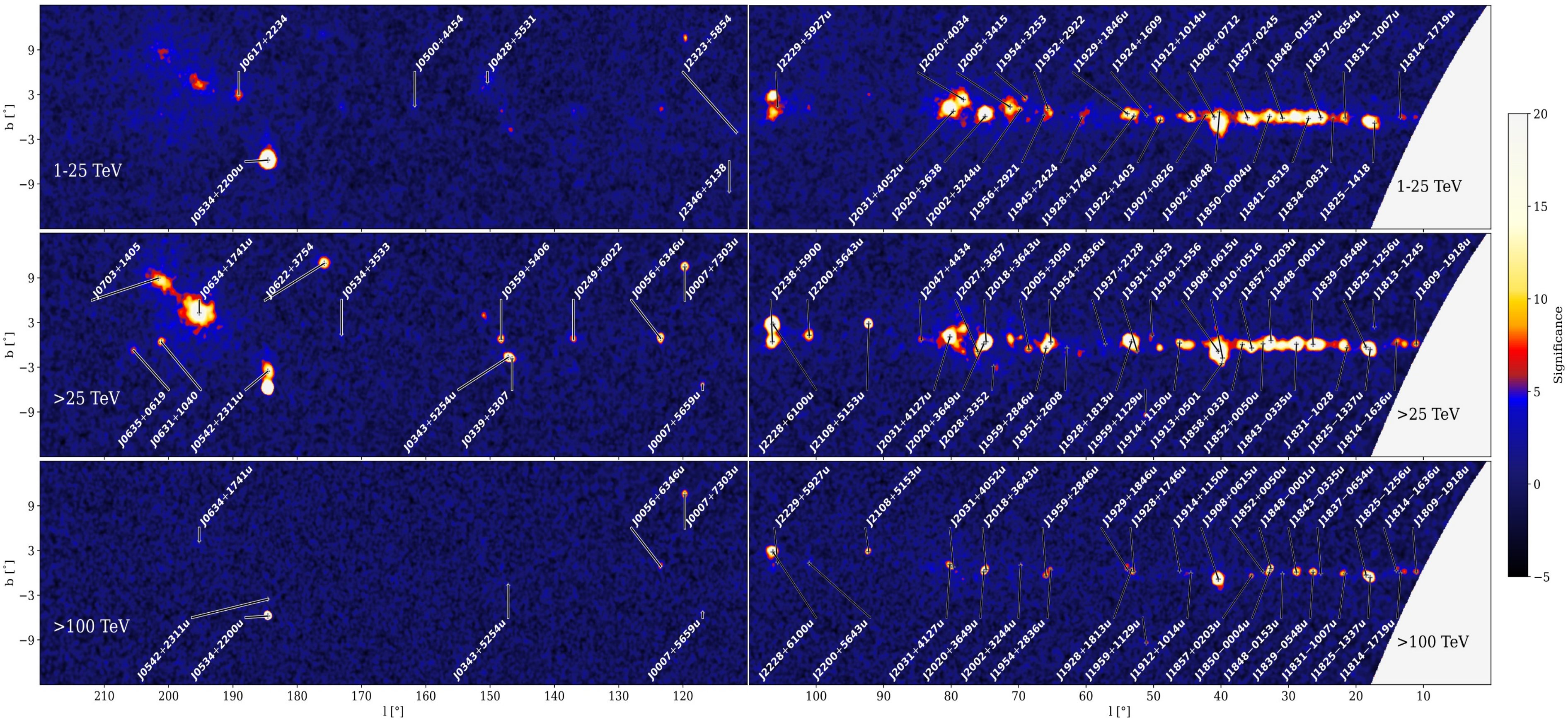
- The position and extension achieved by KM2A at >25 TeV are used.
- Sources with significance >4σ at >100 TeV are labeled as UHE sources
- LHAASO: 4 -> 43



1st LHAASO source catalog

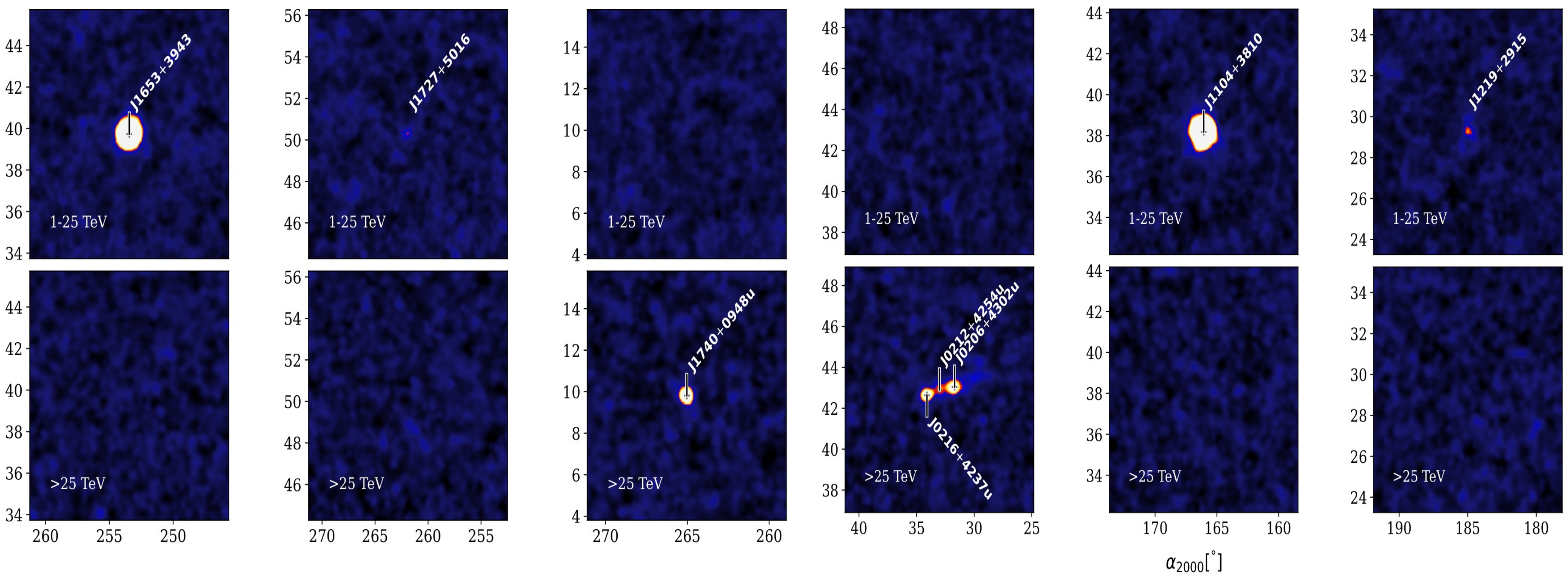
Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
1LHAASO J0007+5659u	KM2A	1.86	57.00	0.12	<0.18	86.5	0.33±0.05	3.10±0.20	43.6	
	WCDA						<0.27			
1LHAASO J0007+7303u	KM2A	1.91	73.07	0.07	0.17±0.03	361.0	3.41±0.27	3.40±0.12	171.6	CTA 1 (0.12)
	WCDA	1.48	73.15	0.10	<0.22	141.6	5.01±1.11	2.74±0.11		
1LHAASO J0056+6346u	KM2A	14.10	63.77	0.08	0.24±0.03	380.2	1.47±0.10	3.33±0.10	94.1	
	WCDA	13.78	63.96	0.15	0.33±0.07	106.1	1.45±0.41	2.35±0.13		
1LHAASO J0206+4302u	KM2A	31.70	43.05	0.13	<0.27	96.0	0.24±0.03	2.62±0.16	82.8	
	WCDA						<0.09			
1LHAASO J0212+4254u	KM2A	33.01	42.91	0.20	<0.31	38.4	0.12±0.03	2.45±0.23	30.2	
	WCDA						<0.07			
1LHAASO J0216+4237u	KM2A	34.10	42.63	0.10	<0.13	102.0	0.18±0.03	2.58±0.17	65.6	
	WCDA						<0.20			
1LHAASO J0249+6022	KM2A	42.39	60.37	0.16	0.38±0.08	148.8	0.93±0.09	3.82±0.18		
	WCDA	41.52	60.49	0.40	0.71±0.10	53.3	1.96±0.51	2.52±0.16		
1LHAASO J0339+5307	KM2A	54.79	53.13	0.11	<0.22	144.0	0.58±0.06	3.64±0.16		LHAASO J0341+5258 (0.37)
	WCDA						<0.21			
1LHAASO J0343+5254u*	KM2A	55.79	52.91	0.08	0.20±0.02	388.1	1.07±0.07	3.53±0.10	20.2	LHAASO J0341+5258 (0.28)
	WCDA	55.34	53.05	0.18	0.33±0.05	94.1	0.29±0.13	1.70±0.19		

82 sources with the Galactic latitude |b|<12º



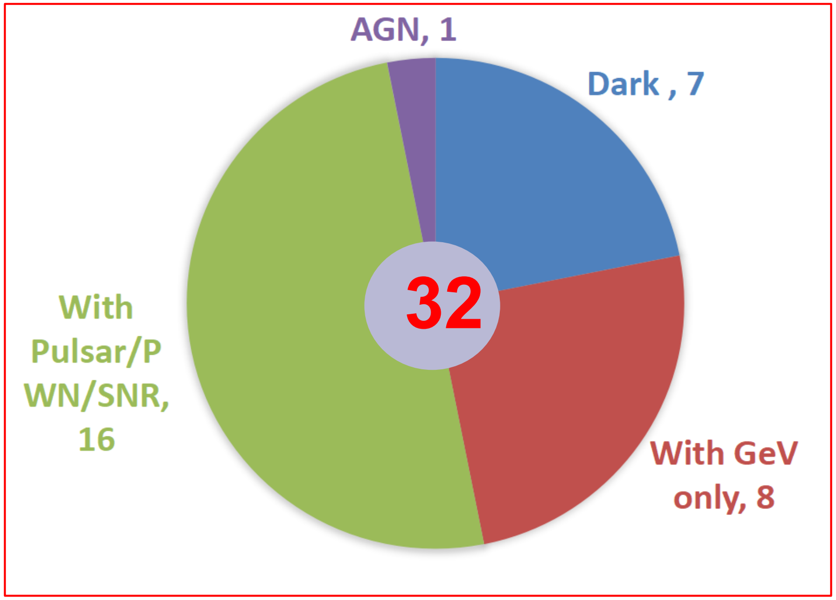
8 sources with the Galactic latitude |b|>12º

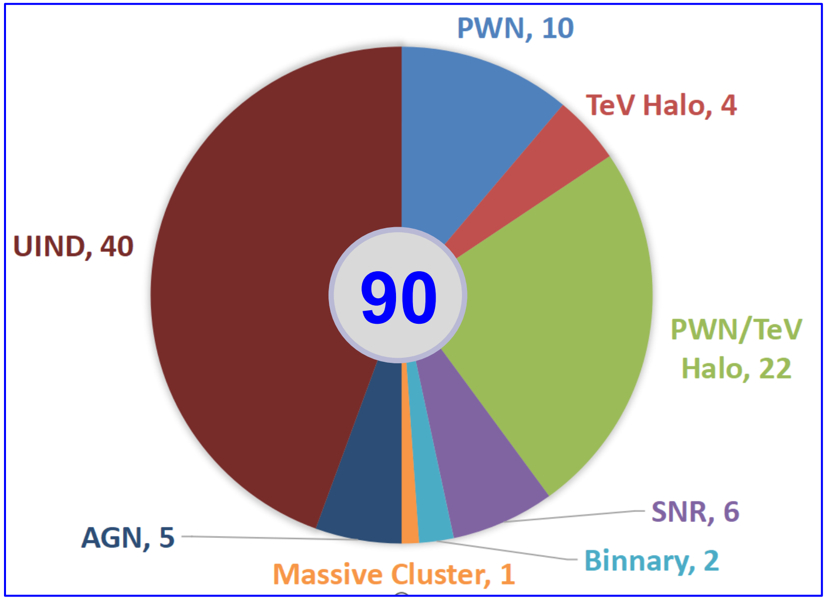
Mrk 421 z=0.031	1ES 1727+502 z=0.055	4 AGNs		Mrk 501 z=0.034	NGC 4278 z=0.002



Association with known TeV Sources

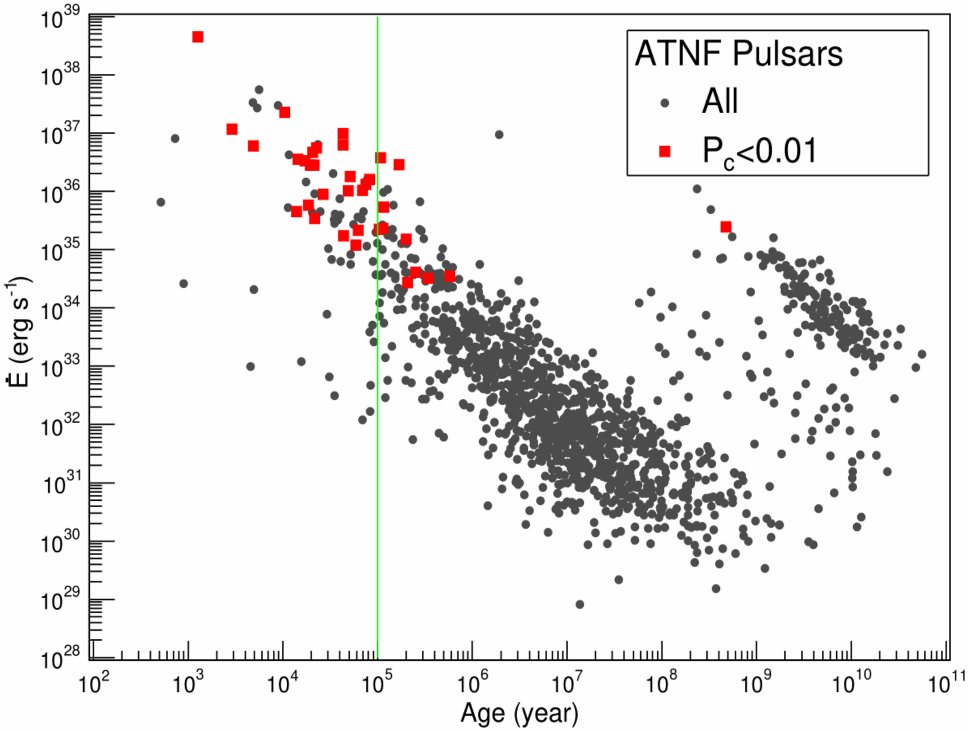
- 58 sources with TeVCat+3HAWC association
- 32 new sources (25+7)





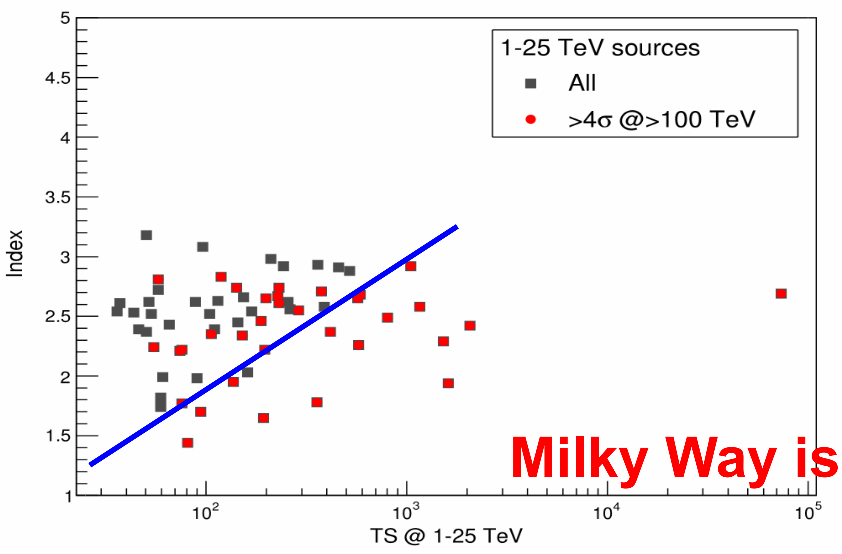
Association with ATNF pulsars

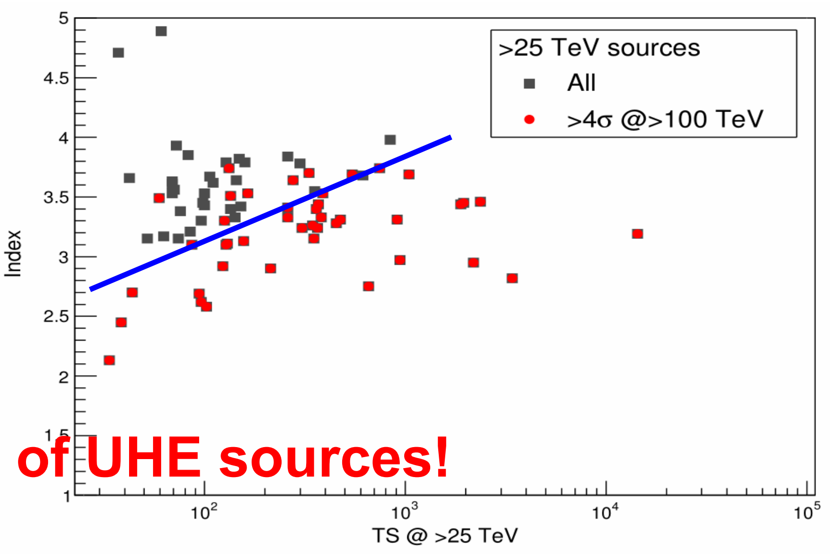
- 65 1LHAASO sources with pulsar nearby <0.5°.
- 35 associations with chance coincide probability <1%. (13 labeled as PWN or Halo in TeVCat)
- 22 new possible PWN/TeV Halo



PeVatrons

- 51% (35/69) 1-25TeV sources are UHE sources.
- 57% (43/75) >25TeV sources are UHE sources.
- 19% (8/43) UHE sources are not detected at 1-25TeV (new class?).

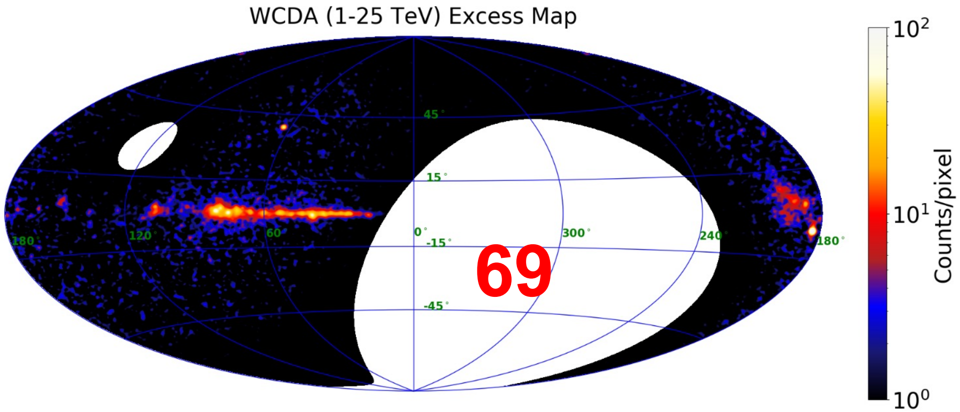


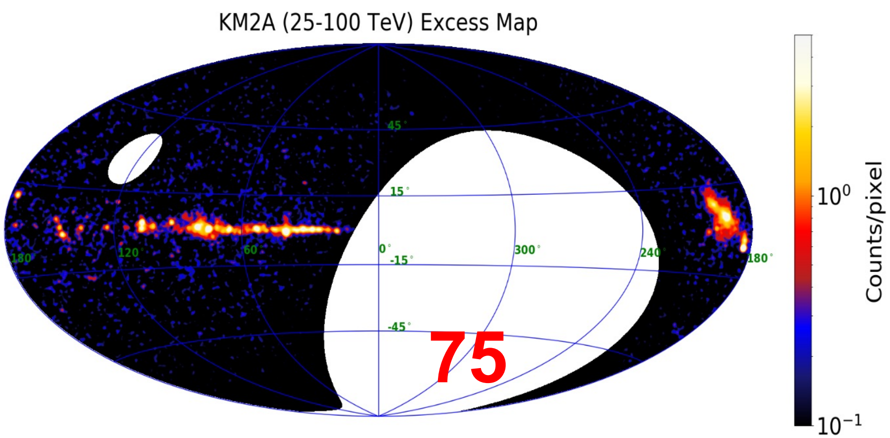


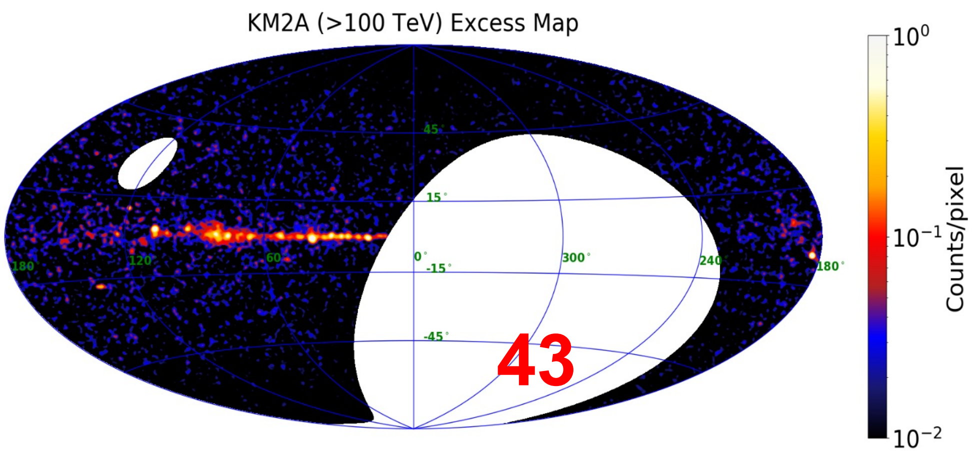
Milky Way is full of UHE sources!

1 LHAASO catalog

- 90 in 1st LHAASO sources.
- 32 new discoveries
- 43 UHE



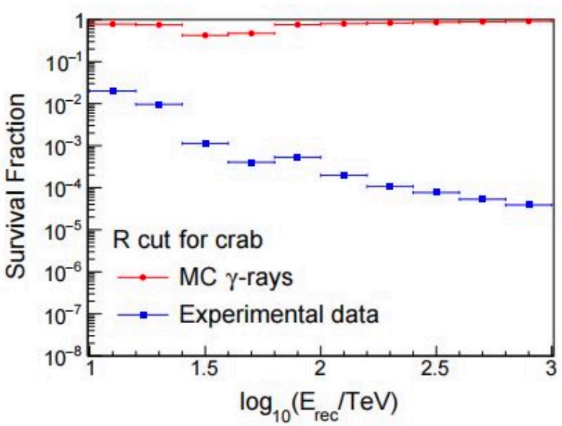


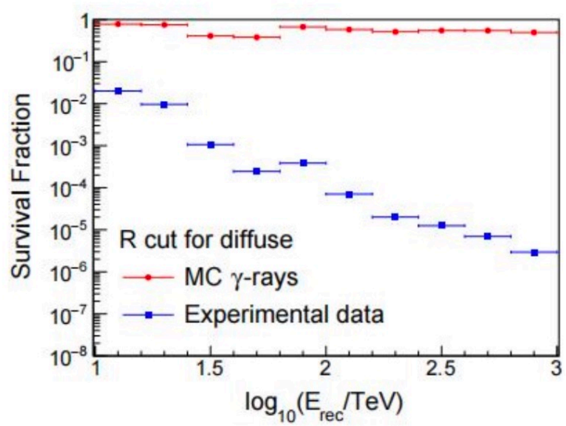


Diffuse gamma-ray emission

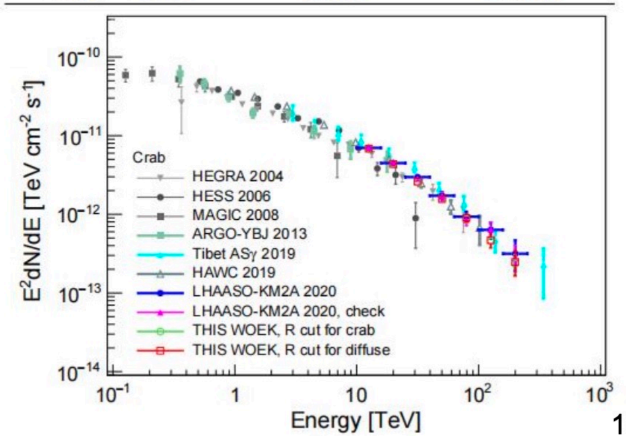
Gamma/CR discrimination

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



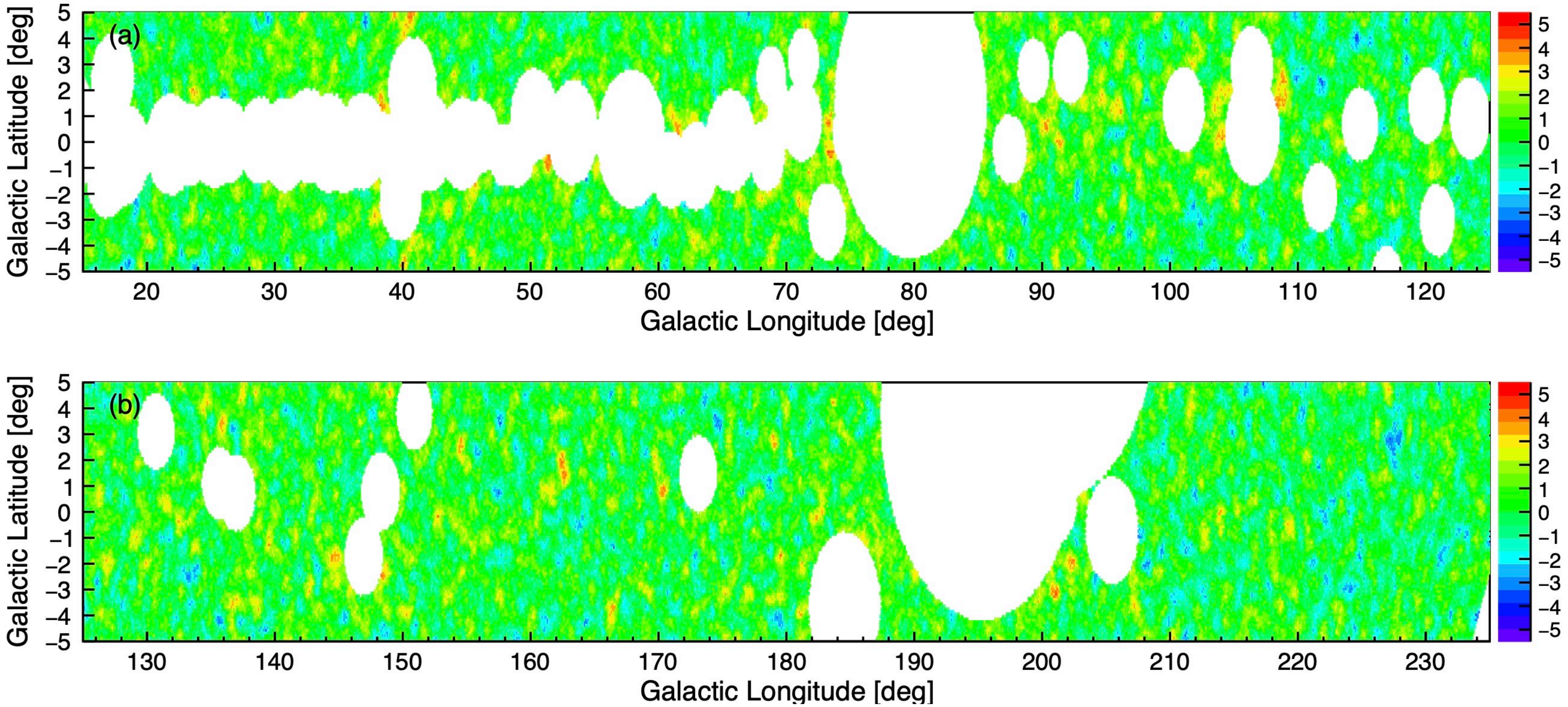


$\log(E_{rec}/\mathrm{TeV})$	R for crab	R for diffuse
1.0 – 1.2	−5.11	−5.00
1.2 – 1.4	−5.24	−3.20
1.4 – 1.6	−5.95	−5.96
1.6 – 1.8	−6.08	−6.17
1.8 – 2.0	−2.34	−2.50
2.0 – 2.2	−2.35	−2.69
2.2 – 2.4	−2.36	−2.79
2.4 – 2.6	−2.36	−2.74
2.6 – 2.8	−2.36	−2.75
2.8 – 3.0	−2.36	−2.79



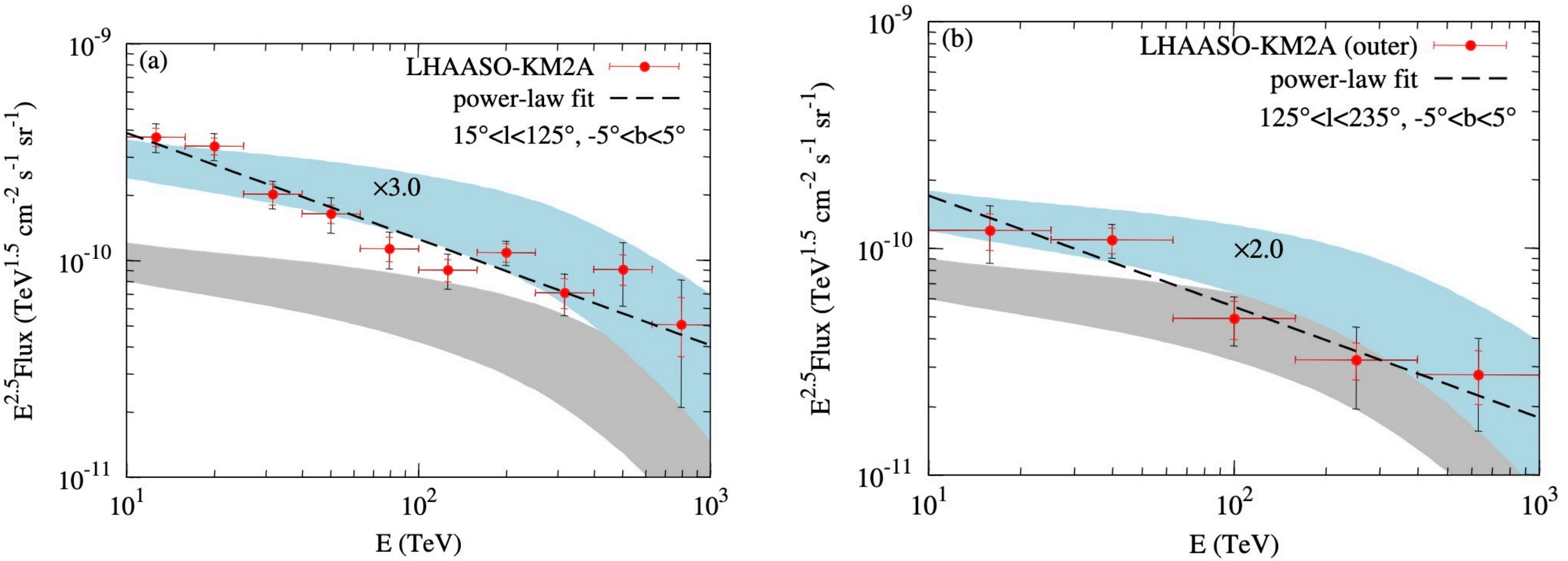
- ➢ R cuts adjusted from the Crab analysis to enable a higher $Q=S/B^{1/2}$ factor
- ➢ Efficiencies change from ~90% to ~60%

Mask LHAASO



LHAASO collaboration arXiv: 2305.05372

LHAASO diffuse



$$\Xi^{A,A'}(E,l,b) = \int_0^\infty \mathrm{d}s\, n_{\mathrm{gas}}^{A'}(\boldsymbol{x}) I_{\mathrm{CR}}^{A}(E,\boldsymbol{x})$$

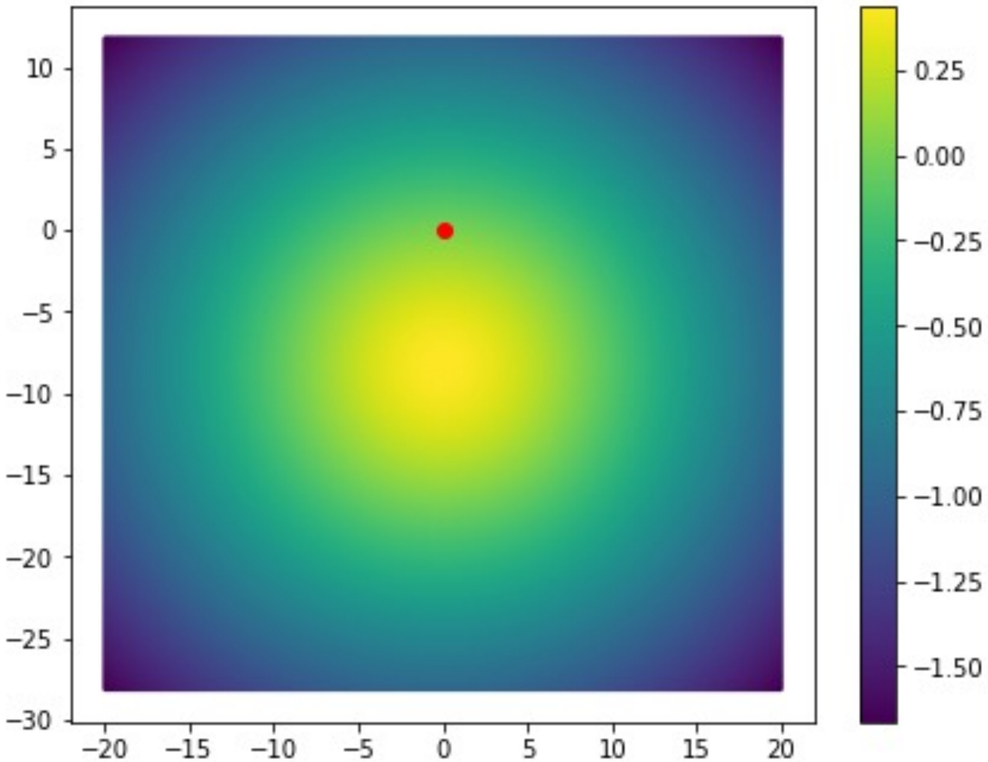
$$I_\nu(E,l,b) = \sum_{A,A'} \int_E^\infty \mathrm{d}E'\, \Xi^{A,A'}(E',l,b) \frac{\mathrm{d}\sigma^{AA'\to\nu}(E',E)}{\mathrm{d}E}$$

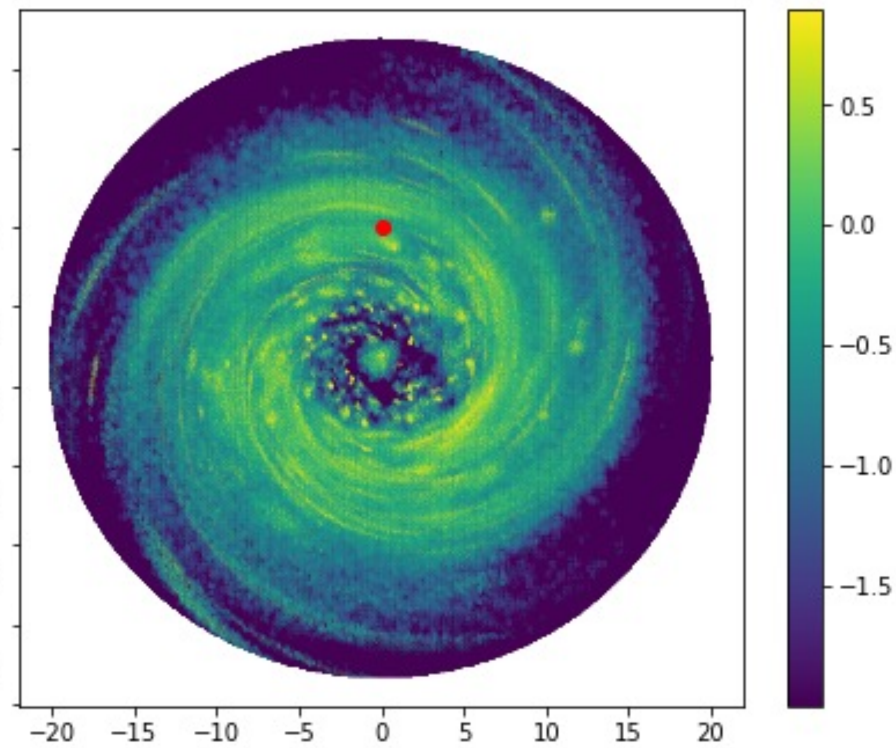
arXiv: 2305.05372

1 PeV CR density in the Gal. plane

Lipari & Vernetto (2018)

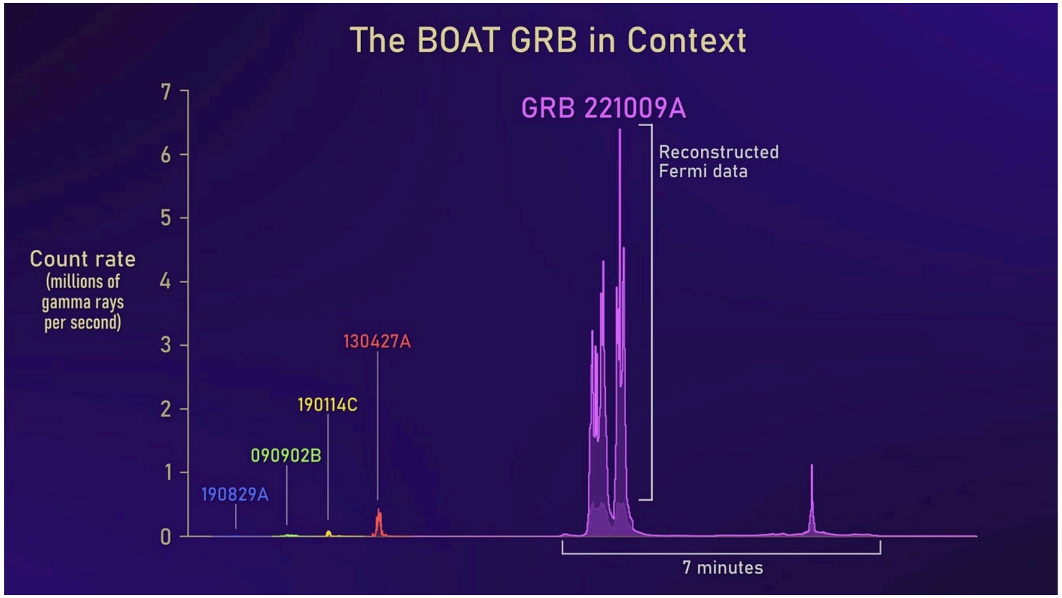
G.Giacinti & D.S., 2305.10251

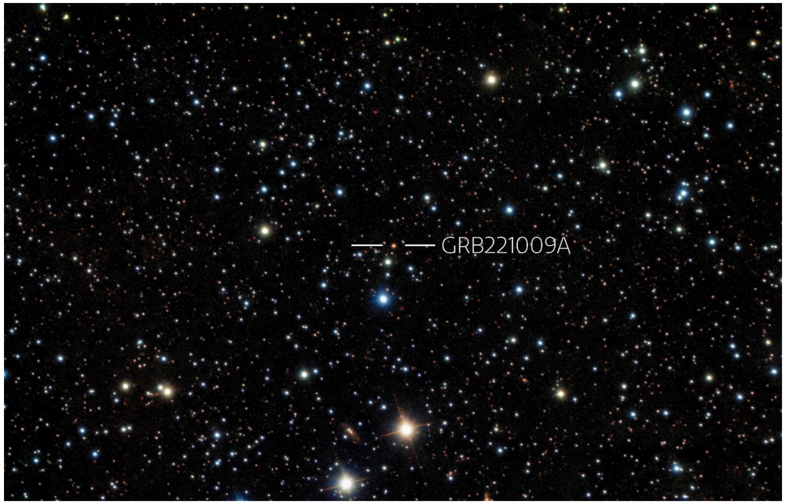


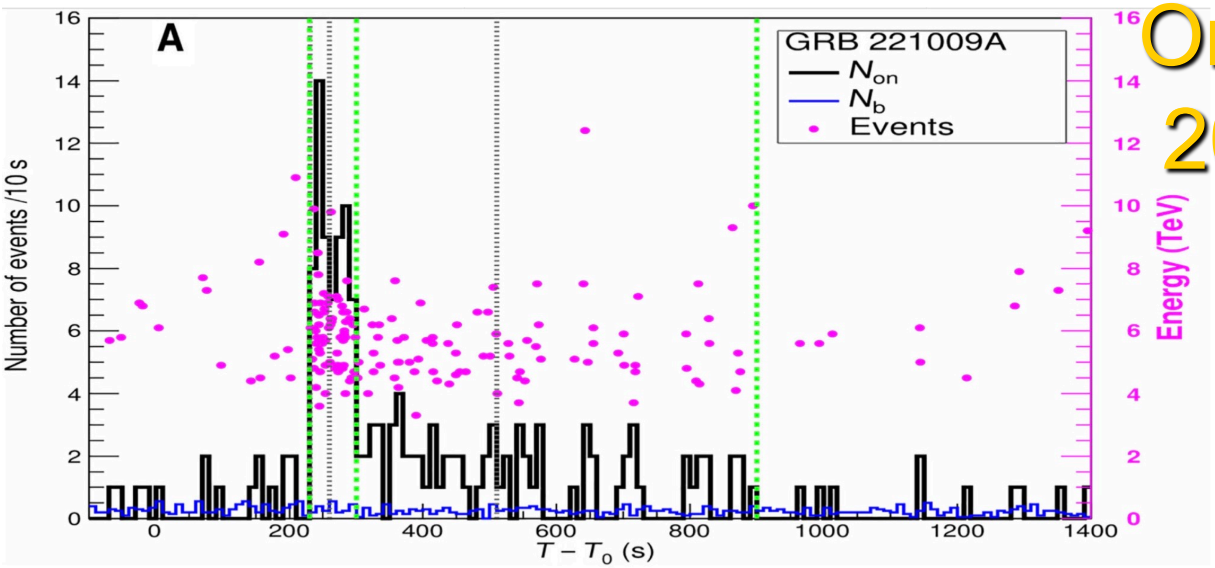


Detection of GRB 221009A by LHAASO WCDA and km2a

Brightest over all time GRB in 57 years

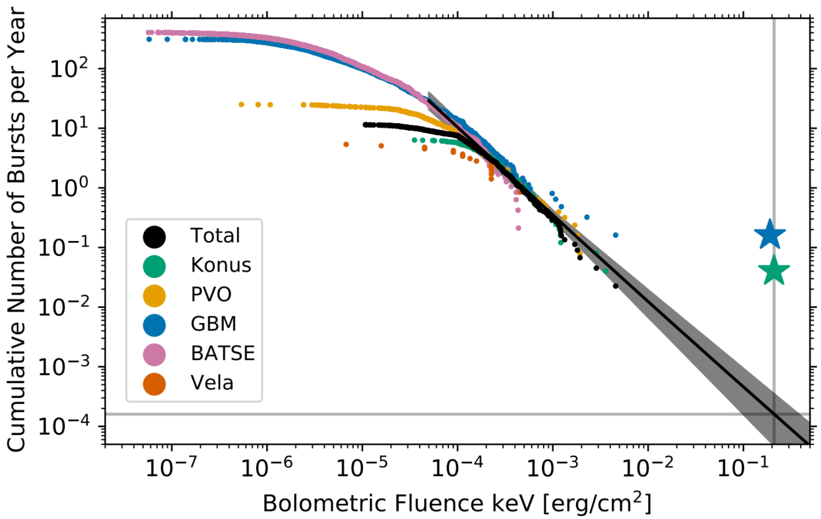


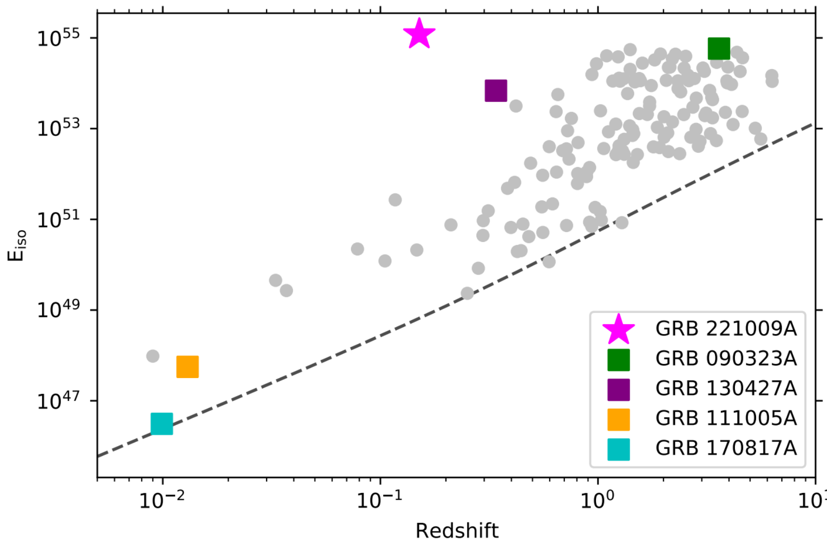




One time in 200-1000 years

GRB 221009A: A very rare event





Fluence: >5 × 10 $^{-2}$ erg/cm^2

R_GRB≤ 6.1 × 10^{-4} Gpc^{-3} yr^{-1}

R<10^-3 yr

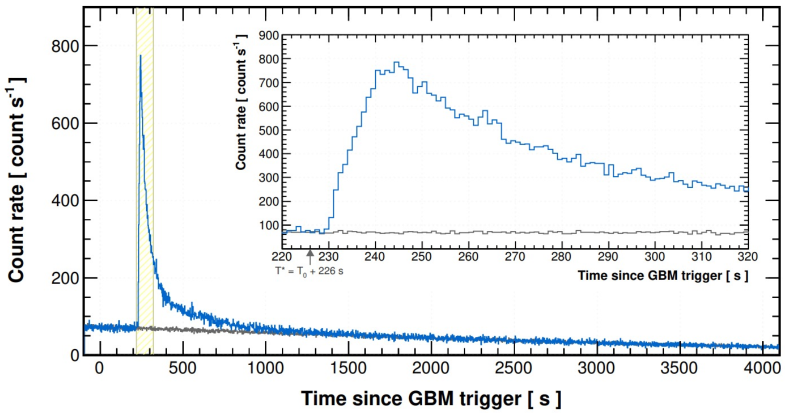
z=0.151 volume ~ 1 Gpc^3

Buns et al. 2023

LHAASO GRB221009A

- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector

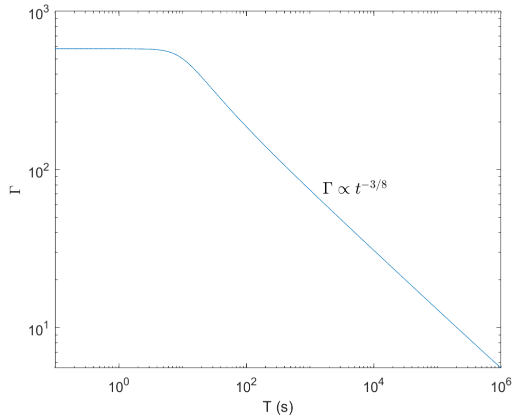
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- TeV count rate light curve: Smooth temporal profile – **external shock origin**



First time detection of the TeV afterglow onset !

What we've learnt from the GRB 221009A

Initial Lorentz Factor Γ_0



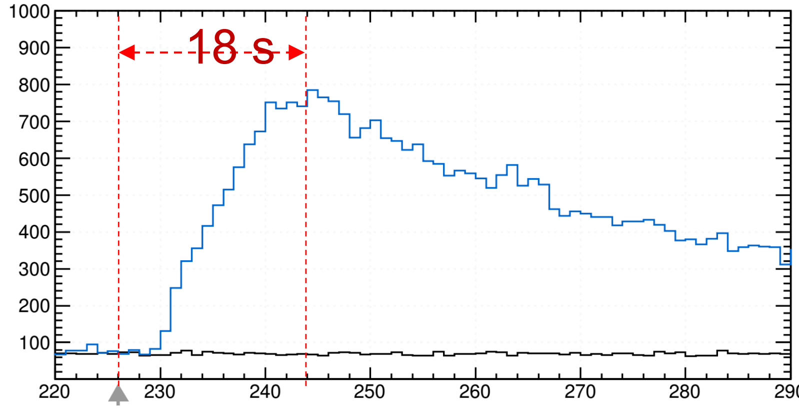
- From T* to the peak (energy-independent peak time), it takes

  ~18 s

- The bulk Lorentz factor is estimated as

$$\Gamma_0 = \left(\frac{3E_k}{32\pi n m_p c^5 t_{\rm peak}^3}\right)^{1/8} = 440 E_{k,55}^{1/8} n_0^{-1/8} \left(\frac{t_{\rm peak}}{18\,{\rm s}}\right)^{-3/8}$$

it is among the highest values for all GRBs



LHAASO, Science, June 8, 2023

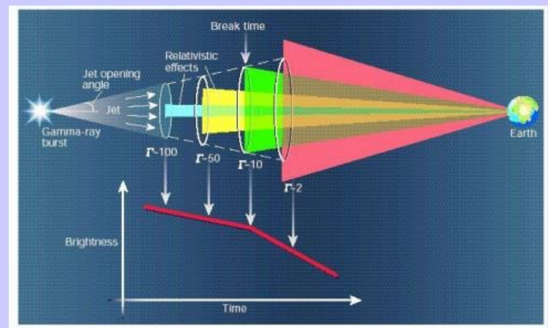
A narrow GRB jet

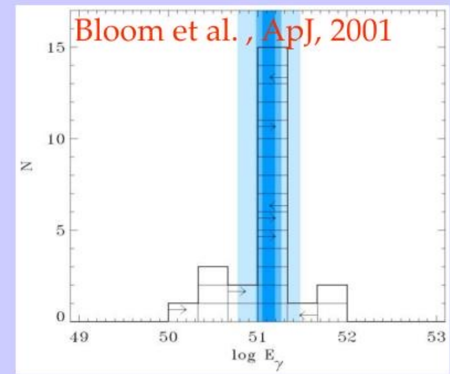
- Jet breaks have been seen in optical/X-ray bands
- First time seeing a jet break at TeV band
- Helps to understand the total energy of the GRB

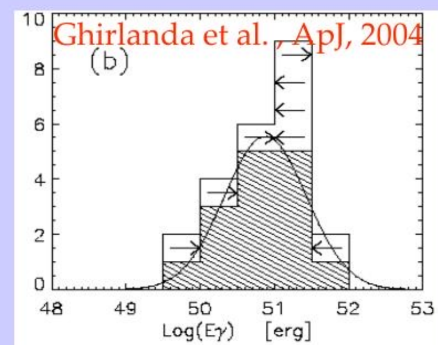
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{b,2}}{670\,\mathrm{s}}\right)^{3/8}$$

$$E_{\gamma,j} = E_{\gamma,\mathrm{iso}}\theta_0^2/2 \sim 7.5 \times 10^{50}\ \mathrm{erg}\, E_{\gamma,\mathrm{iso},55}(\theta_0/0.7^\circ)^2$$

➢ assuming jet angles derived from the break time of the optical afterglow light curve, the collimation-corrected radiated energy is clustered around ~10^{51} erg.







What we've learnt from GRB 221009A

Upper limit in prompt phase

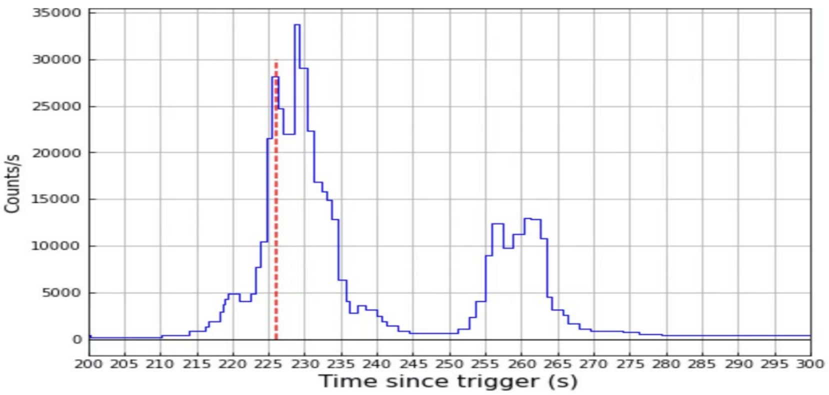
- The most strict limit on the prompt TeV emission

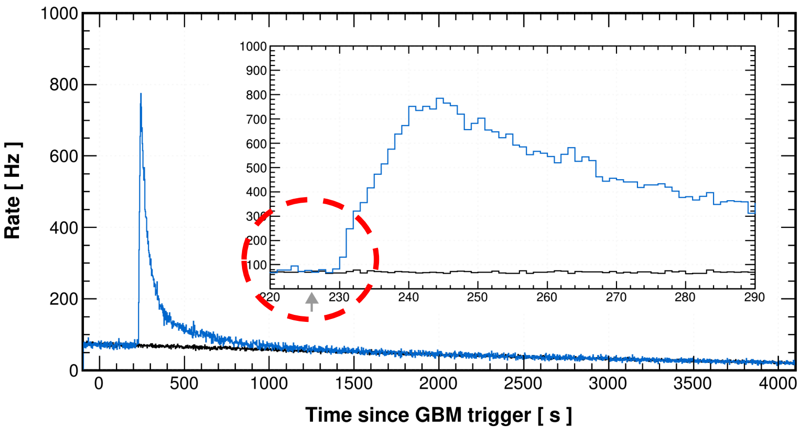
$R = F_{TeV}/F_{MeV} < 2 \times 10^{-5}$

1. A large $\gamma\gamma$ absorption optical depth ?
2. Or a magnetized jet?

$$R_{\rm in} \sim 2\Gamma_0^2 c t_v = 10^{15}\,{\rm cm}\,(\Gamma_0/440)^2\,(t_v/0.082\,{\rm s})$$

$$\tau_{\gamma\gamma} \sim \sigma_{\gamma\gamma} n'_t \frac{R_{\rm in}}{\Gamma_0} \sim 190 \left(\frac{R_{\rm in}}{10^{15}\,{\rm cm}}\right)^{-1} \left(\frac{\Gamma_0}{440}\right)^{-2} \left(\frac{\varepsilon_t}{h\nu_m}\right)^{\beta_1+1}$$





GRB 221009A KM2A

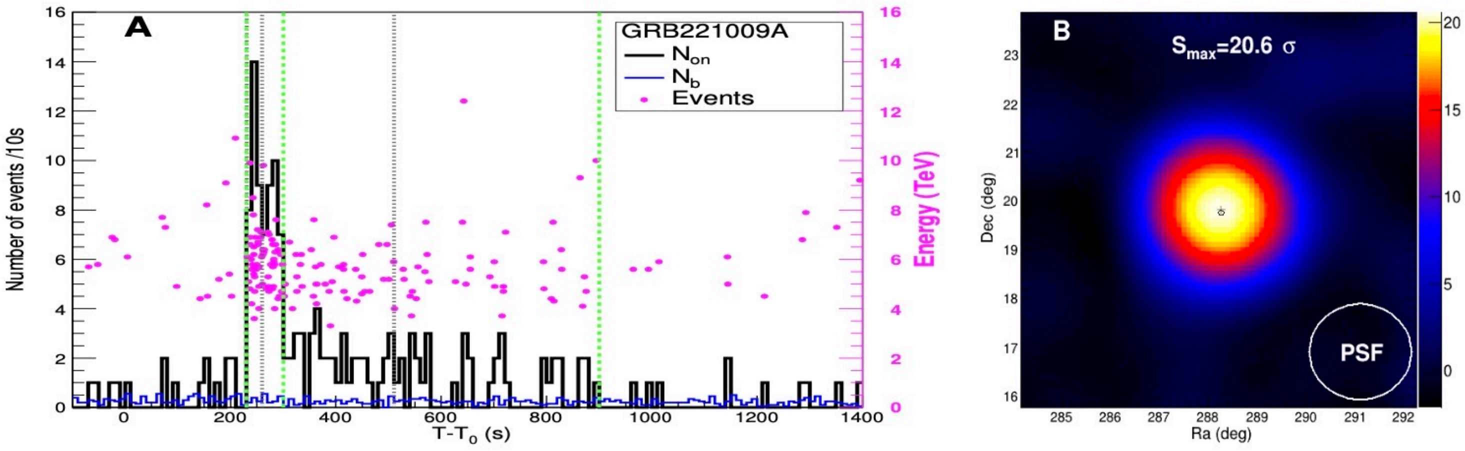


Figure 1: **The light curve and significance map of GRB 221009A obtained by KM2A.** (A) The gamma-ray-count light curve obtained by KM2A with each time-bin of 10s. The black curve indicates the events from the angular cone centered on the GRB, and the blue curve indicates the number of events due to cosmic ray background estimated from 20 similar angular cones at off-source directions with the same zenith angle. The gray dashed lines indicate the peak times of the multi-pulsed emission observed by GECAM-C (*10*) in the MeV band. The green dashed lines indicate the times of T_0+230s, T_0+300s, and T_0+900s. The pink points indicate the energy marked by the right label and the arrival time of each event. The energies of each event were reconstructed assuming the spectra shown in panel B of Figure 2. (B) The significance map around GRB 221009A as observed by KM2A. The plus sign and corresponding length denote the position and error determined by KM2A. The black circle denotes the position of the GRB reported by Fermi-LAT. The white circle shows the size of the PSF that contains 68% of the events.

LHAASO collab., Sci.Adv. 9 (2023) 46, adj2778 e-Print: 2310.08845

GRB 221009A км2а

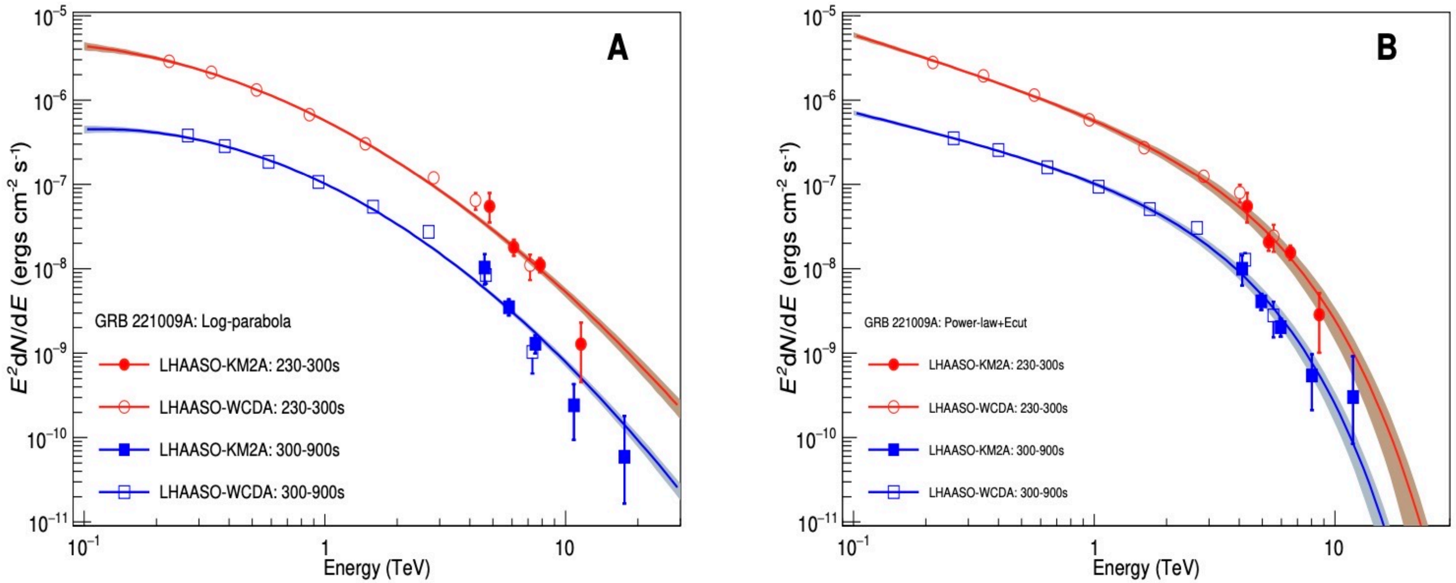
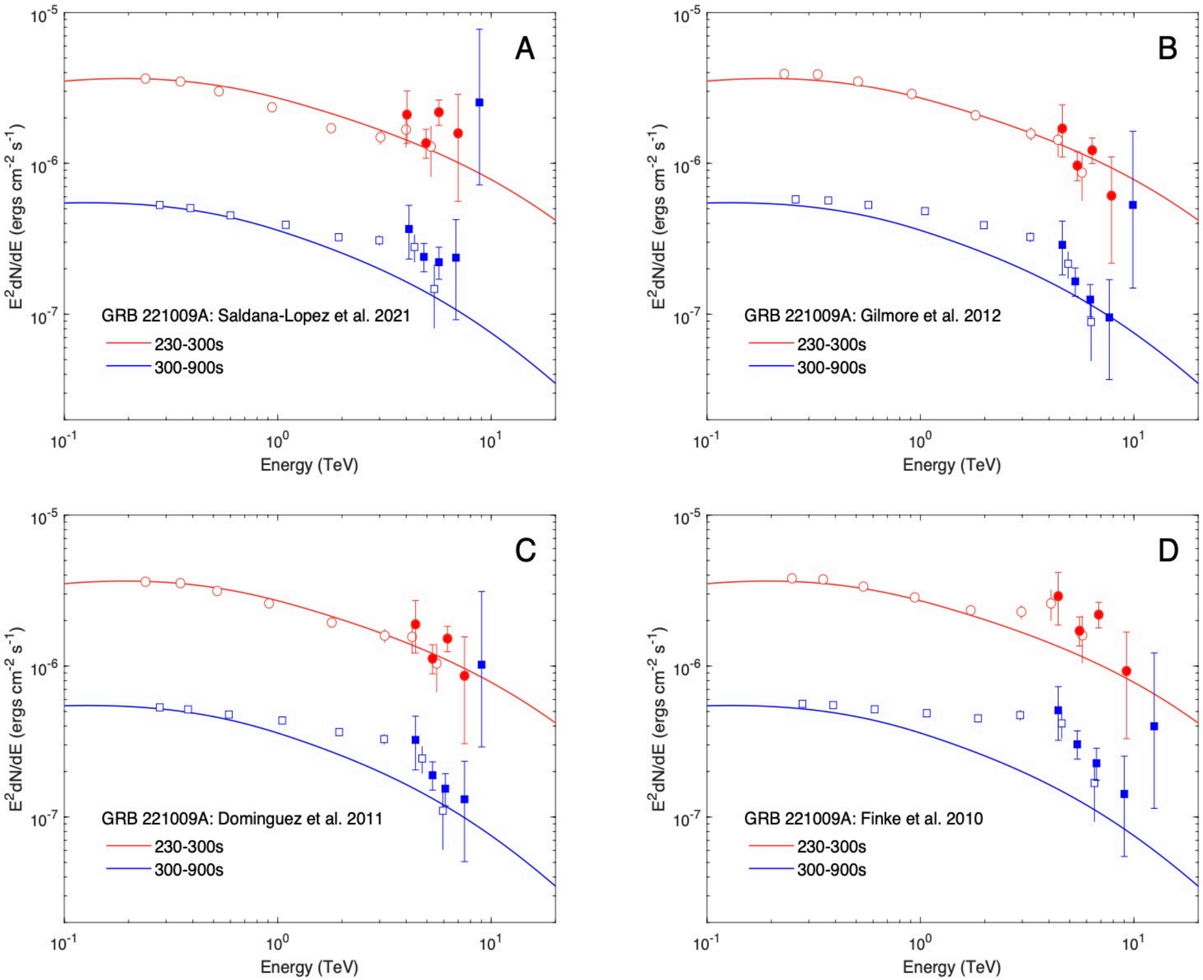


Figure 2: **Observed VHE spectra of GRB 221009A by LHAASO for the two intervals.** Interval 1 is from T_0+230s to T_0+300s (red points) and interval 2 is from T_0+300s to T_0+900s (blue points). The solid lines indicate the best-fitting results, and the shaded regions indicate the 1-sigma error region. (A) The log-parabola function is used to fit the observational data. (B) The power-law with exponential cutoff function is adopted to fit the observational data.

LHAASO collab., Sci.Adv. 9 (2023) 46, adj2778 e-Print: 2310.08845

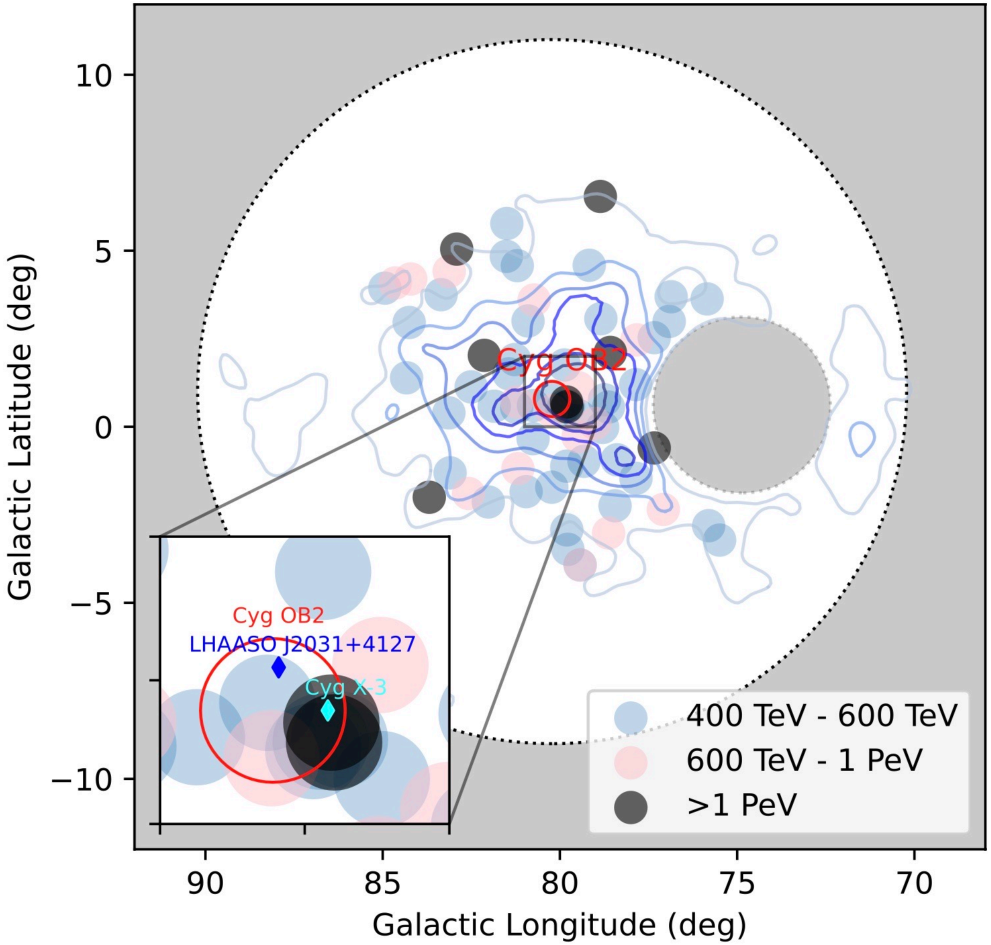
GRB 221009A км2а



LHAASO collab., Sci.Adv. 9 (2023) 46, adj2778 e-Print: 2310.08845

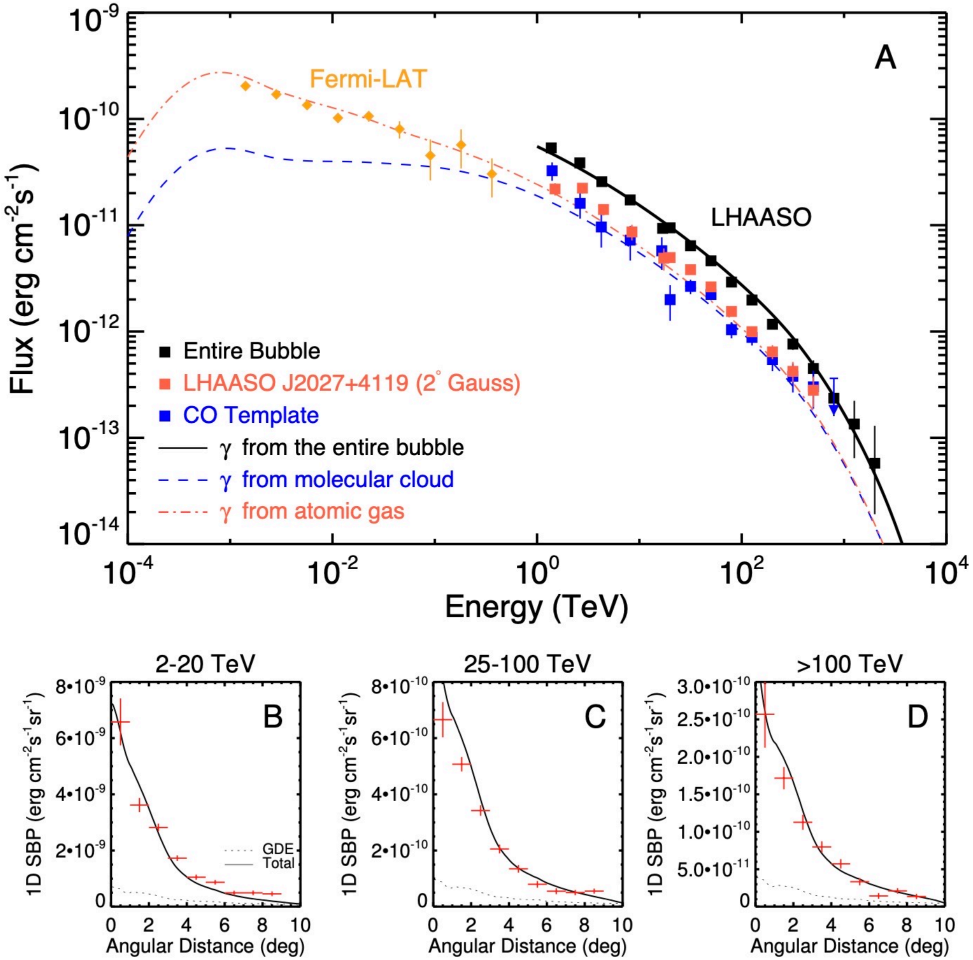
Cygnus region with LHAASO

Cygnus region



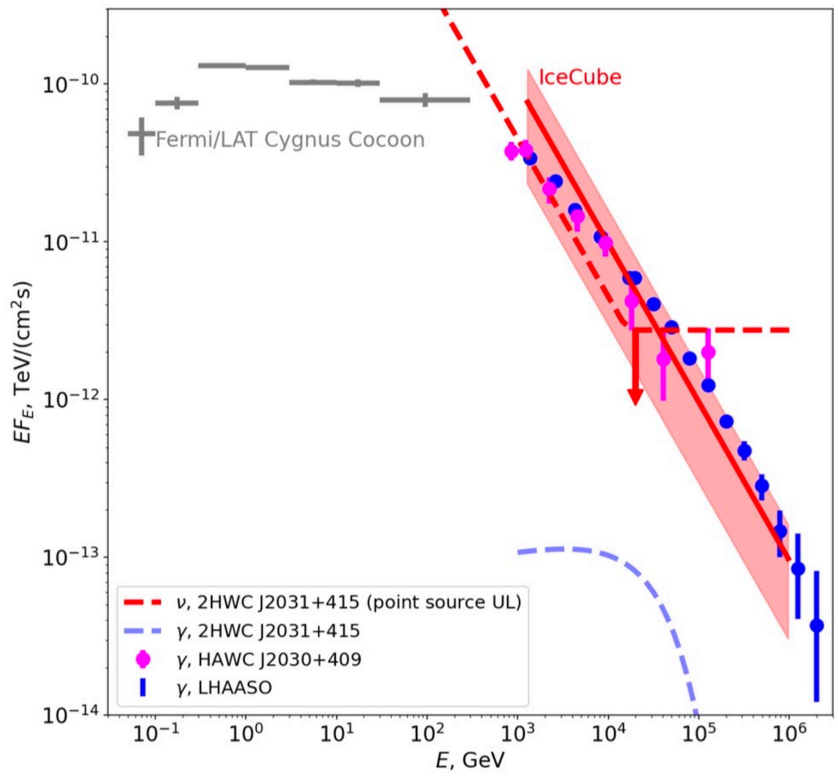
•*LHAASO collab.*, Zh.Cao et al, 2310.10100, *Sci.Bull.* 69 (2024) 4, 449

Cygnus region



•*LHAASO collab.*, Zh.Cao et al, 2310.10100 , *Sci.Bull.* 69 (2024) 4, 449

Neutrinos from Cygnus region



A.Neronov, D.S. and D.Savchenko, arXiv:2311.13711

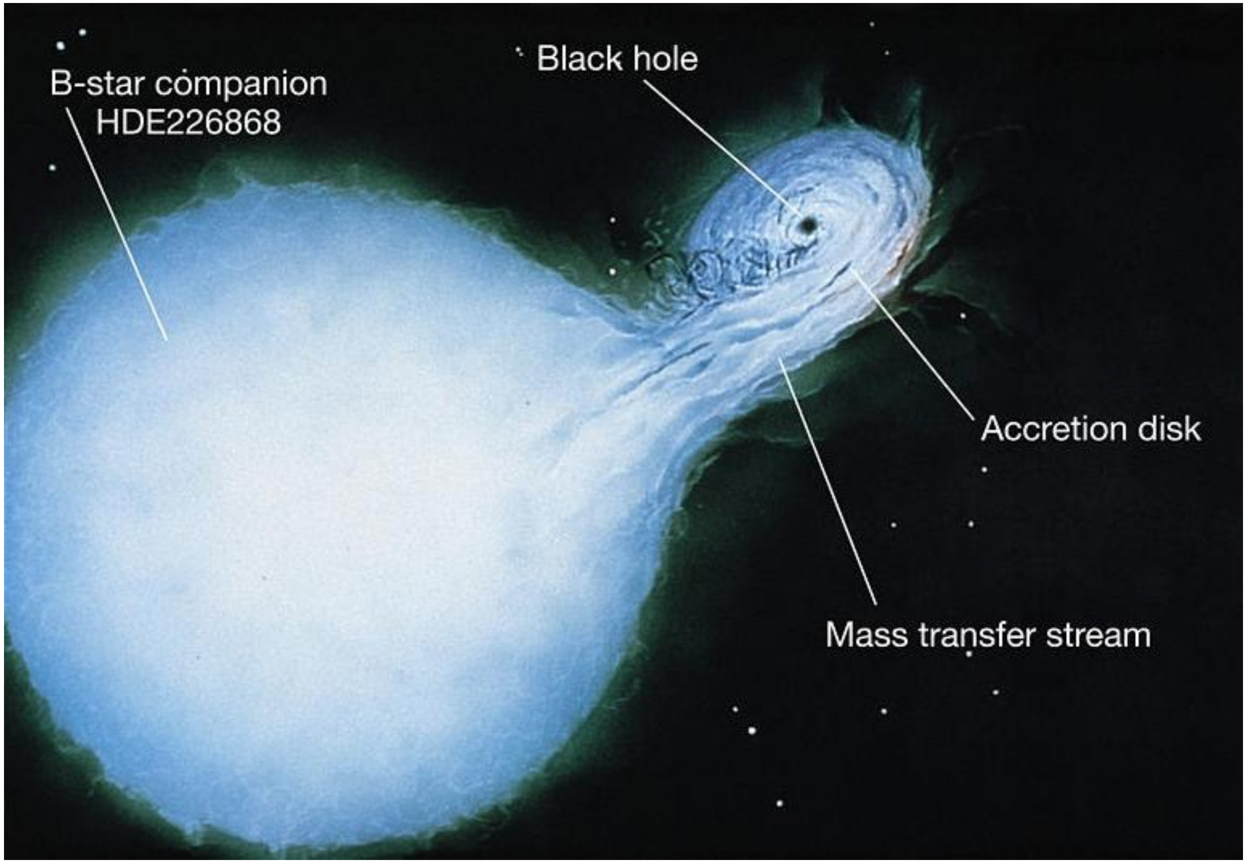
Micro-quasars

https://arxiv.org/pdf/2410.08988

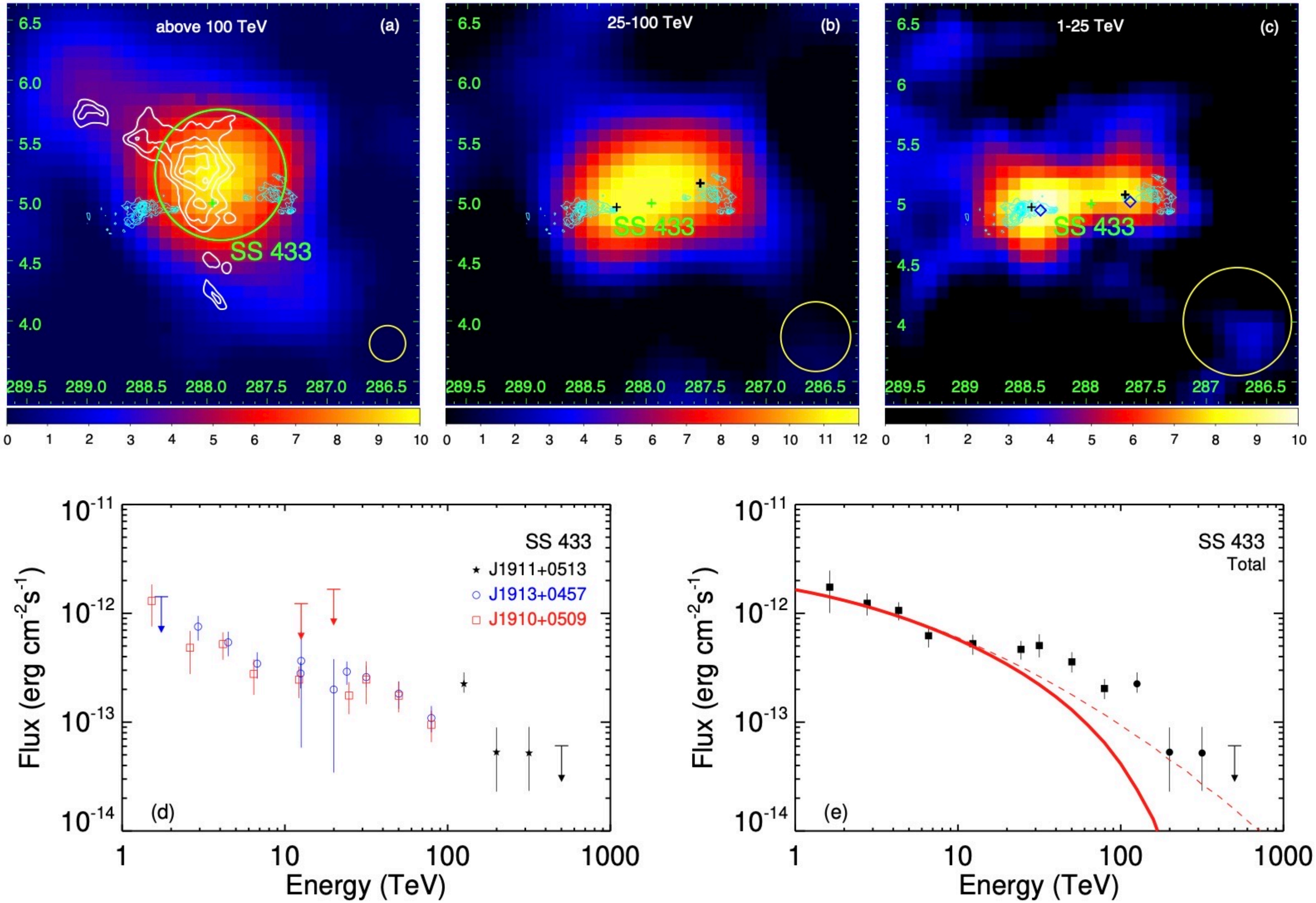
Micro-quasars

Cygnus X1:

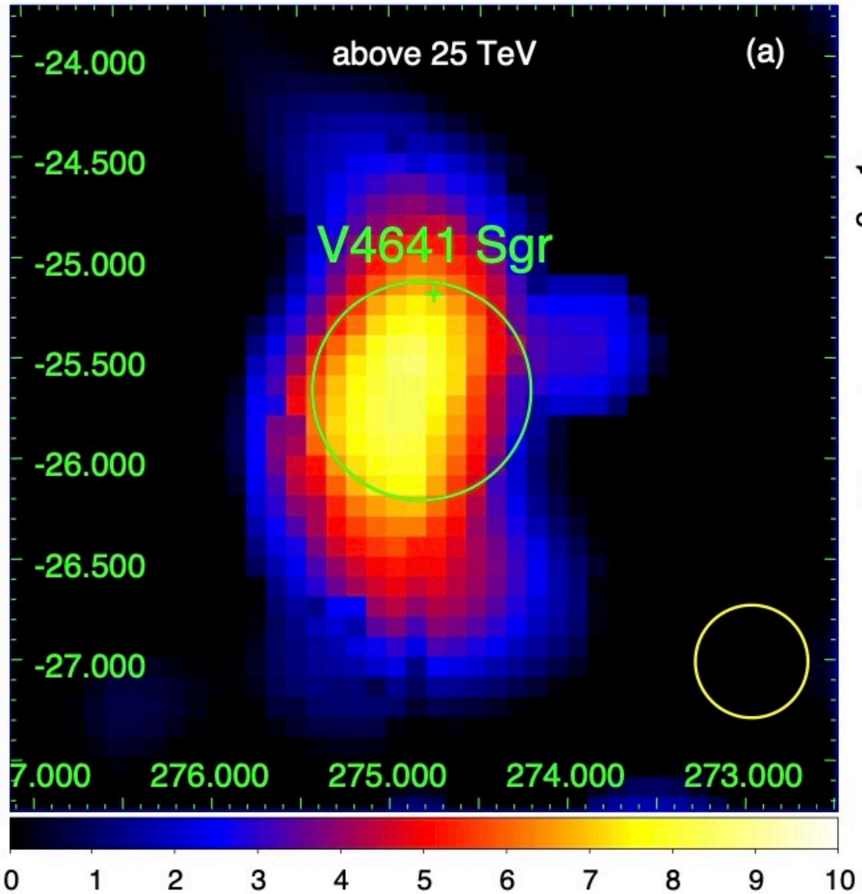
M_BH = $21M_o$

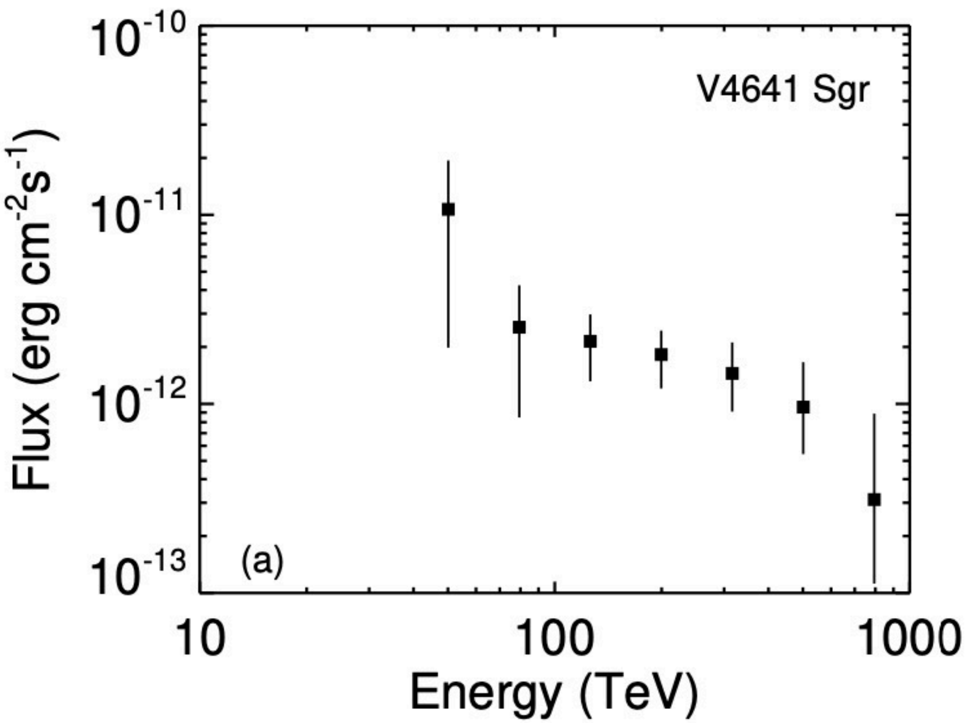


SS 433


above 100 TeV
(a)
SS 433
25-100 TeV
(b)
1-25 TeV
(c)
SS 433
J1911+0513
J1913+0457
J1910+0509
(d)
Flux (erg cm^{-2}s^{-1})
Energy (TeV)
SS 433
Total
(e)

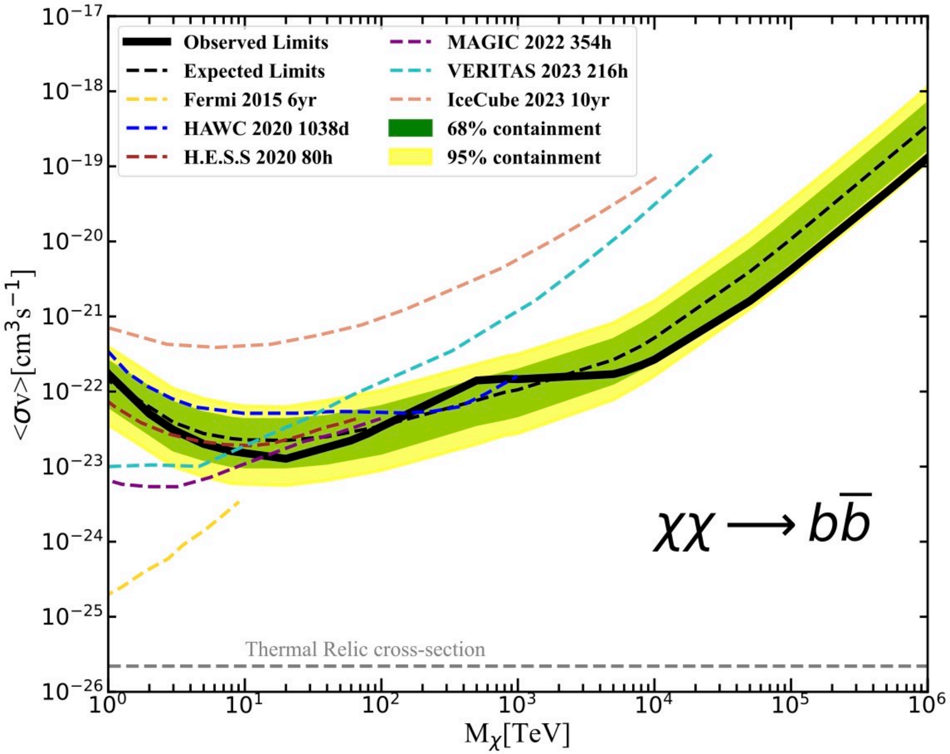
V4641 Sgr


above 25 TeV
(a)
V4641 Sgr
-24.000
-24.500
-25.000
-25.500
-26.000
-26.500
-27.000
7.000
276.000
275.000
274.000
273.000
0
1
2
3
4
5
6
7
8
9
10


V4641 Sgr
(a)
Flux (erg cm^{-2}s^{-1})
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000
Energy (TeV)

DM limits by LHAASO

DM limits from dwarf galaxies by LHAASO



LHAASO collaboration, 2406.08698

Summary

- Construction of LHAASO finished in July 2021. LHAASO operates with almost 100% duty cicle. It's one year sensitivity is better compared to 50 hours for present Cherenkov telescopes above few TeV. Above 20 TeV it is better as compared to future CTA.
- First results on logA of cosmic rays are very promissing.
- LHAASO presented first catalog of 90 gamma-ray sources from about 2 first years of observation. 32 are new sources. Number of UHE gamma-ray sources above 100 TeV increased from 4 to 43 by LHAASO observations
  - 35 sources are PWN. Crab, Geminga, milisecond pulsar
  - 7 SNR, gamma-Cygni can not be explained by leptons
  - Micro-quasars 4 detected, 2 hadronic
  - Star clusters Cygnus, w43
- Diffuse emission from Galaxy: new models requred
- GRB 221009A: detailed properties of GRB afterglow from 65000 photons in LHAASO WCDA. No new physics in KM2a, but constraints on EBL models/intrinsic spectrum from 10 TeV photons
- Cygnus region: hadronic Pevatron source in central part.
- Dark Matter: limits from dwarf Galaxies improved by 2 orders of magnitude for M_DM=1-10 PeV