

Tibet China (4300m a.s.l.)



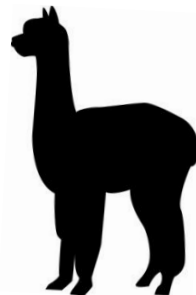
Chacaltaya Bolivia (4740m a.s.l.)



Sub-PeV Gamma Rays Observed with Extensive Air Shower Arrays

Kazumasa KAWATA (ICRR, University of Tokyo)

For the Tibet AS γ / ALPACA Collaboration





Outline

1. Introduction
2. Tibet AS γ Experiment
3. Galactic Diffuse Gamma Rays
4. PeVatron Candidates
5. ALPACA Project
6. Summary



Tibet AS γ Collaboration



M. Amenomori¹, S. Asano², Y. W. Bao³, X. J. Bi⁴, D. Chen⁵, T. L. Chen⁶, W. Y. Chen⁴, Xu Chen^{4,5}, Y. Chen³, Cirennima⁶, S. W. Cui⁷, Danzengluobu⁶, L. K. Ding⁴, J. H. Fang^{4,8}, K. Fang⁴, C. F. Feng⁹, Zhaoyang Feng⁴, Z. Y. Feng¹⁰, Qi Gao⁶, A. Gomi¹¹, Q. B. Gou⁴, Y. Q. Guo⁴, Y. Y. Guo⁴, Y. Hayashi², H. H. He⁴, Z. T. He⁷, K. Hibino¹², N. Hotta¹³, Haibing Hu⁶, H. B. Hu⁴, K. Y. Hu^{4,8}, J. Huang⁴, H. Y. Jia¹⁰, L. Jiang⁴, P. Jiang⁵, H. B. Jin⁵, K. Kasahara¹⁴, Y. Katayose¹¹, C. Kato², S. Kato¹⁵, I. Kawahara¹¹, T. Kawashima¹⁵, K. Kawata¹⁵, M. Kozai¹⁶, D. Kurashige¹¹, Labaciren⁶, G. M. Le¹⁷, A. F. Li^{4,9,18}, H. J. Li⁶, W. J. Li^{4,10}, Y. Li⁵, Y. H. Lin^{4,8}, B. Liu¹⁹, C. Liu⁴, J. S. Liu⁴, L. Y. Liu⁵, M. Y. Liu⁶, W. Liu⁴, X. L. Liu⁵, Y.-Q. Lou^{20,21,22}, H. Lu⁴, X. R. Meng⁶, Y. Meng^{4,8}, K. Munakata², K. Nagaya¹¹, Y. Nakamura¹⁵, Y. Nakazawa²³, H. Nanjo¹, C. C. Ning⁶, M. Nishizawa²⁴, R. Noguchi¹¹, M. Ohnishi¹⁵, S. Okukawa¹¹, S. Ozawa²⁵, L. Qian⁵, X. Qian⁵, X. L. Qian²⁶, X. B. Qu²⁷, T. Saito²⁸, Y. Sakakibara¹¹, M. Sakata²⁹, T. Sako¹⁵, T. K. Sako¹⁵, T. Sasaki¹², J. Shao^{4,9}, M. Shibata¹¹, A. Shiomi²³, H. Sugimoto³⁰, W. Takano¹², M. Takita¹⁵, Y. H. Tan⁴, N. Tateyama¹², S. Torii³¹, H. Tsuchiya³², S. Udo¹², H. Wang⁴, Y. P. Wang⁶, Wangdui⁶, H. R. Wu⁴, Q. Wu⁶, J. L. Xu⁵, L. Xue⁹, Z. Yang⁴, Y. Q. Yao⁵, J. Yin⁵, Y. Yokoe¹⁵, N. P. Yu⁵, A. F. Yuan⁶, L. M. Zhai⁵, C. P. Zhang⁵, H. M. Zhang⁴, J. L. Zhang⁴, X. Zhang³, X. Y. Zhang⁹, Y. Zhang⁴, Yi Zhang³³, Ying Zhang⁴, S. P. Zhao⁴, Zhaxisangzhu⁶, X. X. Zhou¹⁰ and Y. H. Zou^{4,8}

1 Department of Physics, Hiroshima Univ., Japan.

2 Department of Physics, Shinshu Univ., Japan.

3 School of Astronomy and Space Science, Nanjing Univ., China.

4 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS, China.

5 National Astronomical Observatories, CAS, China.

6 Department of Mathematics and Physics, Tibet Univ., China.

7 Department of Physics, Hebei Normal Univ., China.

8 Univ. of Chinese Academy of Sciences, China.

9 Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong Univ., China.

10 Institute of Modern Physics, SouthWest Jiaotong Univ., China.

11 Faculty of Engineering, Yokohama National Univ., Japan.

12 Faculty of Engineering, Kanagawa Univ., Japan.

13 Faculty of Education, Utsunomiya Univ., Japan.

14 Faculty of Systems Engineering, Shibaura Institute of Technology, Japan.

15 Institute for Cosmic Ray Research, Univ. of Tokyo, Japan.

16 Polar Environment Data Science Center, Joint Support-Center for Data Science Research, Research Organization of Information and Systems, Japan.

17 National Center for Space Weather, China Meteorological Administration, China.

18 School of Information Science and Engineering, Shandong Agriculture Univ., China.

19 Department of Astronomy, School of Physical Sciences, Univ. of Science and Technology of China, China.

20 Department of Physics and Tsinghua Centre for Astrophysics (THCA), Tsinghua Univ., China.

21 Tsinghua Univ.-National Astronomical Observatories of China (NAOC) Joint Research Center for Astrophysics, Tsinghua Univ., China.

22 Department of Astronomy, Tsinghua Univ., China.

23 College of Industrial Technology, Nihon Univ., Japan.

24 National Institute of Informatics, Japan.

25 National Institute of Information and Communications Technology, Japan.

26 Department of Mechanical and Electrical Engineering, Shangdong Management Univ., China.

27 College of Science, China Univ. of Petroleum, China.

28 Tokyo Metropolitan College of Industrial Technology, Japan.

29 Department of Physics, Konan Univ., Japan.

30 Shonan Institute of Technology, Japan.

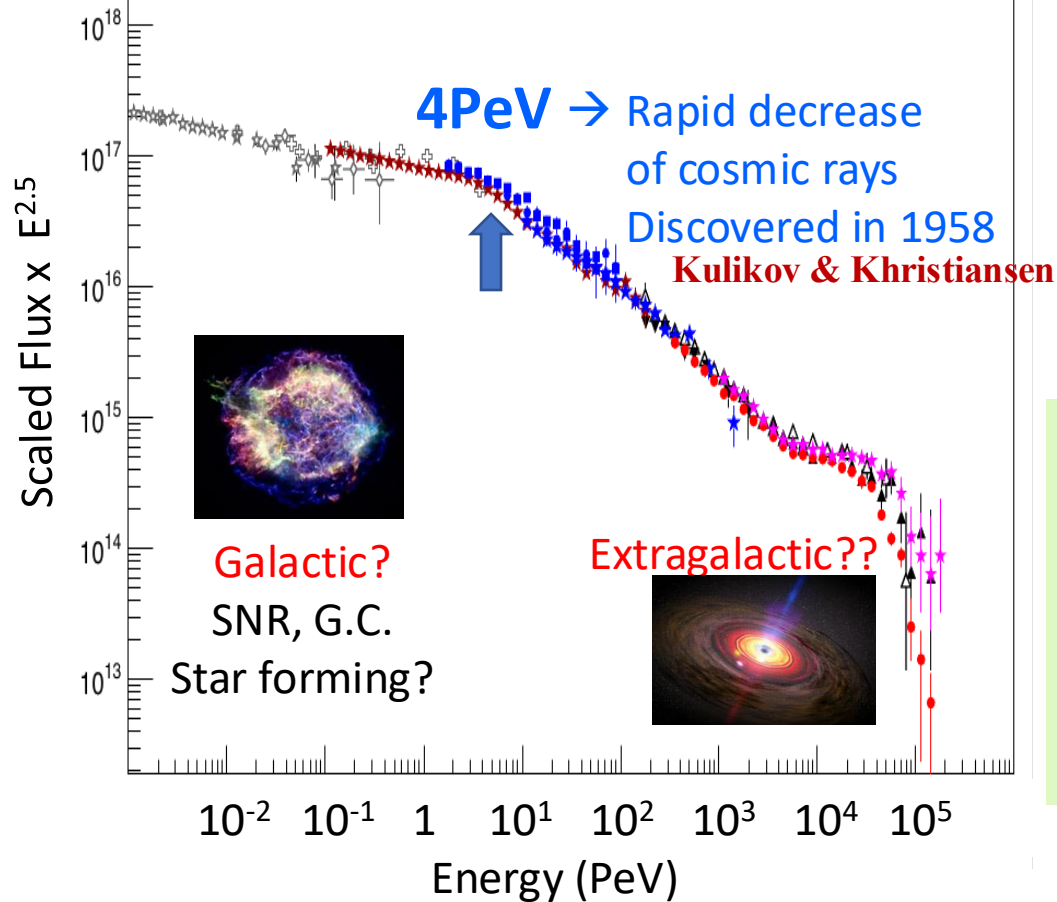
31 Research Institute for Science and Engineering, Waseda Univ., Japan.

32 Japan Atomic Energy Agency, Japan.

33 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.



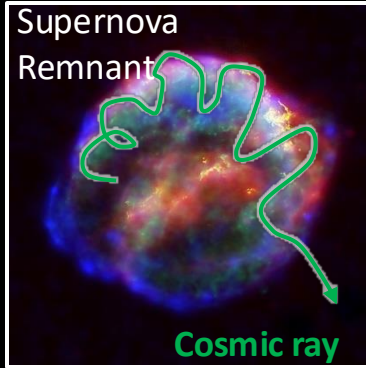
Introduction



- ❖ Wide energy range
- ❖ Main component is proton
- ❖ Rate decreases to 1/100 when energy is 10 times higher

As an open question,
Did/Do “PeVatrons” really exist in
our Galaxy?

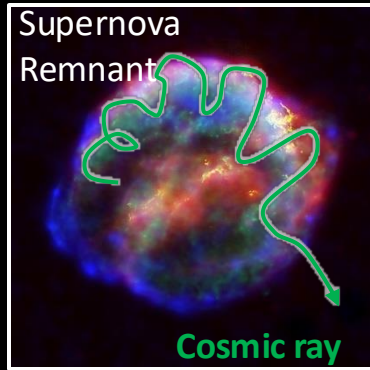
PeVatron: Cosmic super-accelerators
can accelerate to Peta electron volt



PeVatrons
in past/present

Cosmic rays from the source
lost original directions due to magnetic field

Earth



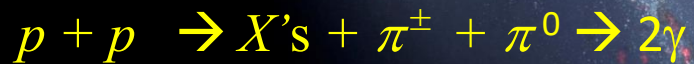
PeVatrons

in past/present

Sub-PeV gamma ray

Earth

Cosmic rays interact with
interstellar gas, and produce γ rays



(γ -ray energy is $\sim 10\%$ of cosmic ray's) $\rightarrow$ sub-PeV gamma rays

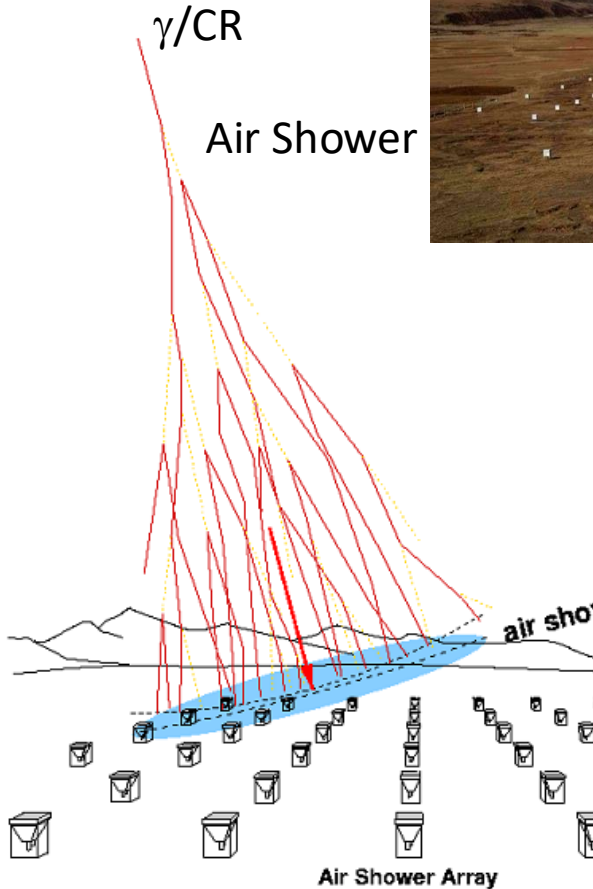


Tibet Air Shower Array



γ/CR

Air Shower

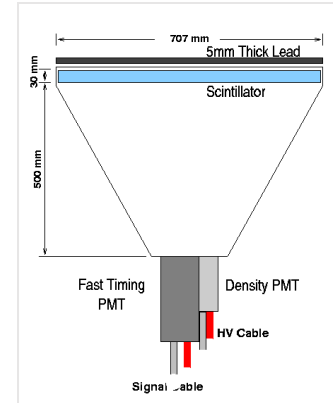


□ Site: Tibet (90.522°E , 30.102°N) 4,300 m a.s.l.

Present Performance

- ✓ # of detectors $0.5 \text{ m}^2 \times 597$
- ✓ Covering area $\sim 65,700 \text{ m}^2$
- ✓ Angular resolution $\sim 0.5^\circ$ @ $10 \text{ TeV } \gamma$
 $\sim 0.2^\circ$ @ $100 \text{ TeV } \gamma$
- ✓ Energy resolution $\sim 40\%$ @ $10 \text{ TeV } \gamma$
 $\sim 20\%$ @ $100 \text{ TeV } \gamma$

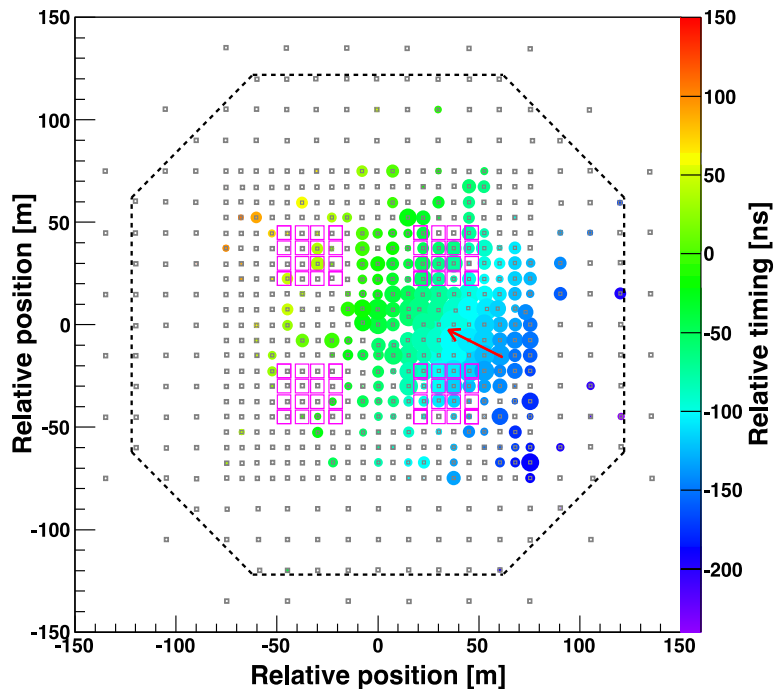
→ Observation of secondary (mainly $e^\pm, \gamma$) in AS
 Primary energy : 2nd particle densities
 Primary direction : 2nd relative timings





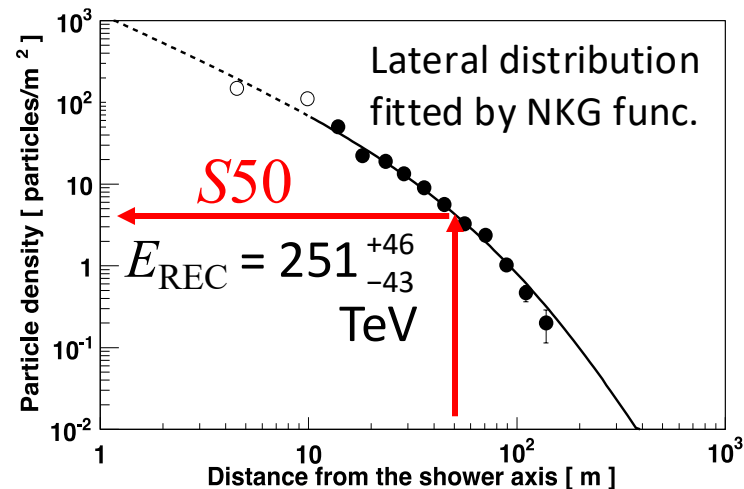
Air Shower Reconstruction

Gamma-ray candidate event



circle size $\propto \log(\# \text{ of detected particles})$
 circle color $\propto$ relative timing [ns]

Amenomori +, PRL 123, 051101 (2019)



*S50 improves E resolutions (10 - 1000 TeV)
 $\rightarrow \sim 40\% @ 10 \text{ TeV}$, $\sim 20\% @ 100 \text{ TeV}$*

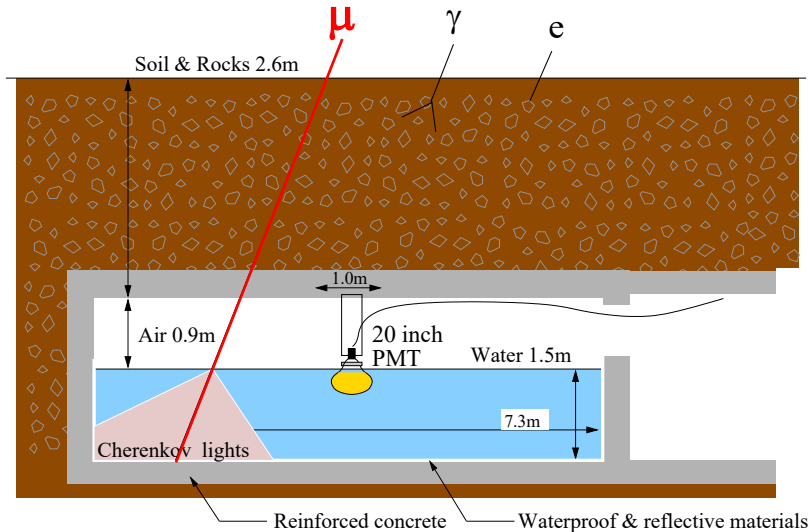
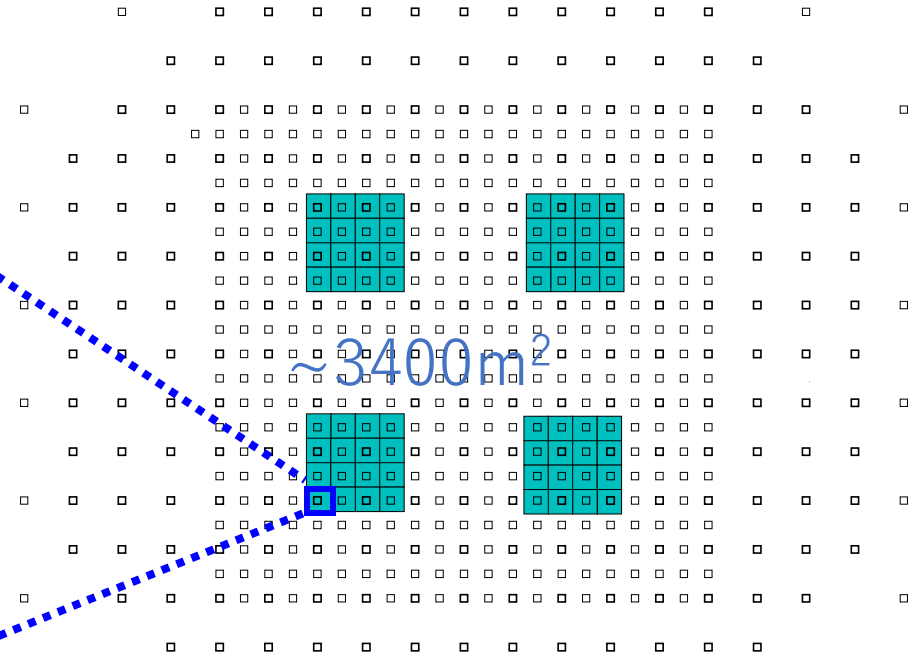
Kawata+, Experimental Astronomy 44, 1 (2017)



Underground WC Muon Detectors

- ✓ 4 pools, 16 units / pool
- ✓ 54 m² in area × 1.5m in depth / unit
- ✓ 20"ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets
- ✓ 2.4m soil overburden ($\sim 515\text{g/cm}^2 \sim 9X_0$)

Measurement of # of μ in AS $\rightarrow \gamma$ /CR discrimination
 DATA: February 2014 - May 2017 **Live time: 719 days**



$\rightarrow$ Succeeded in rejecting by $>99.9\%$ CR events

Basic idea: Sako et al., Astropart. Phys., 32, 177 (2009)

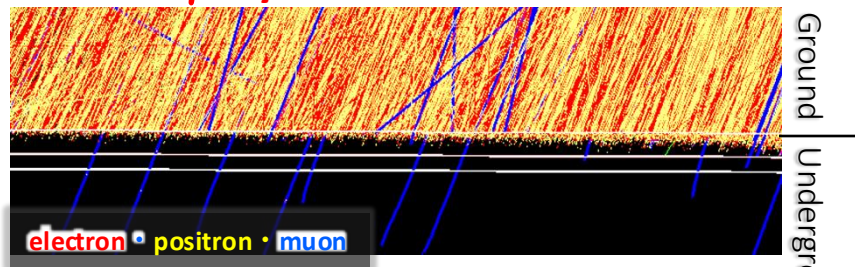


Gamma-Ray Selection

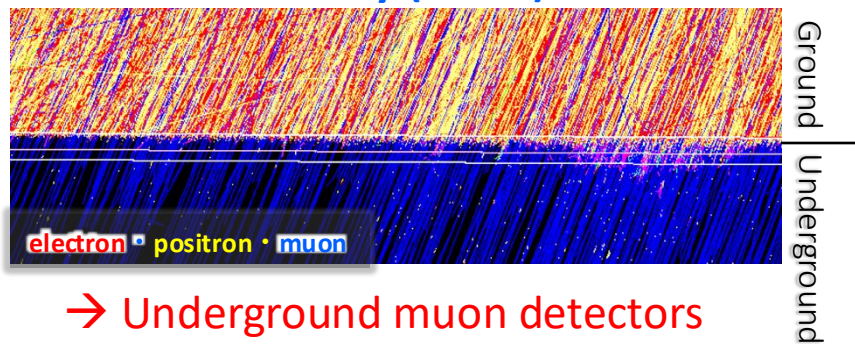
γ -ray $\rightarrow$ poor muons

Muons can penetrate underground

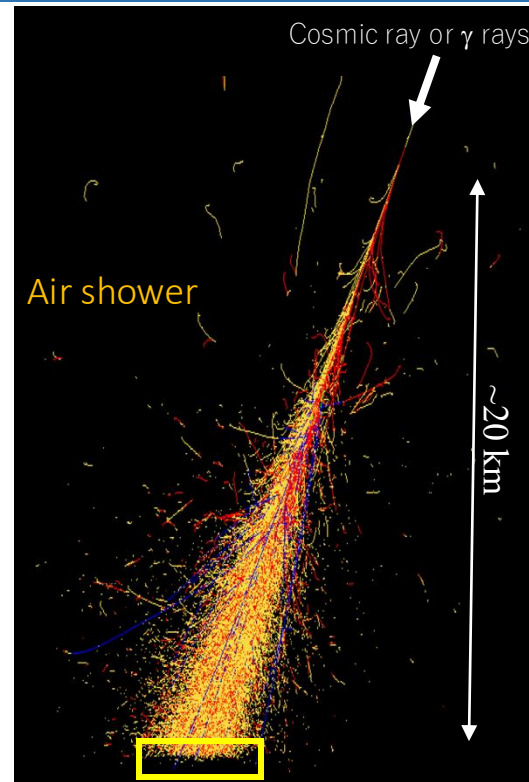
200TeV γ -ray



200TeV Cosmic ray (Noise)



$\rightarrow$ Underground muon detectors



Cosmic ray or γ rays

Air shower

~ 20 km

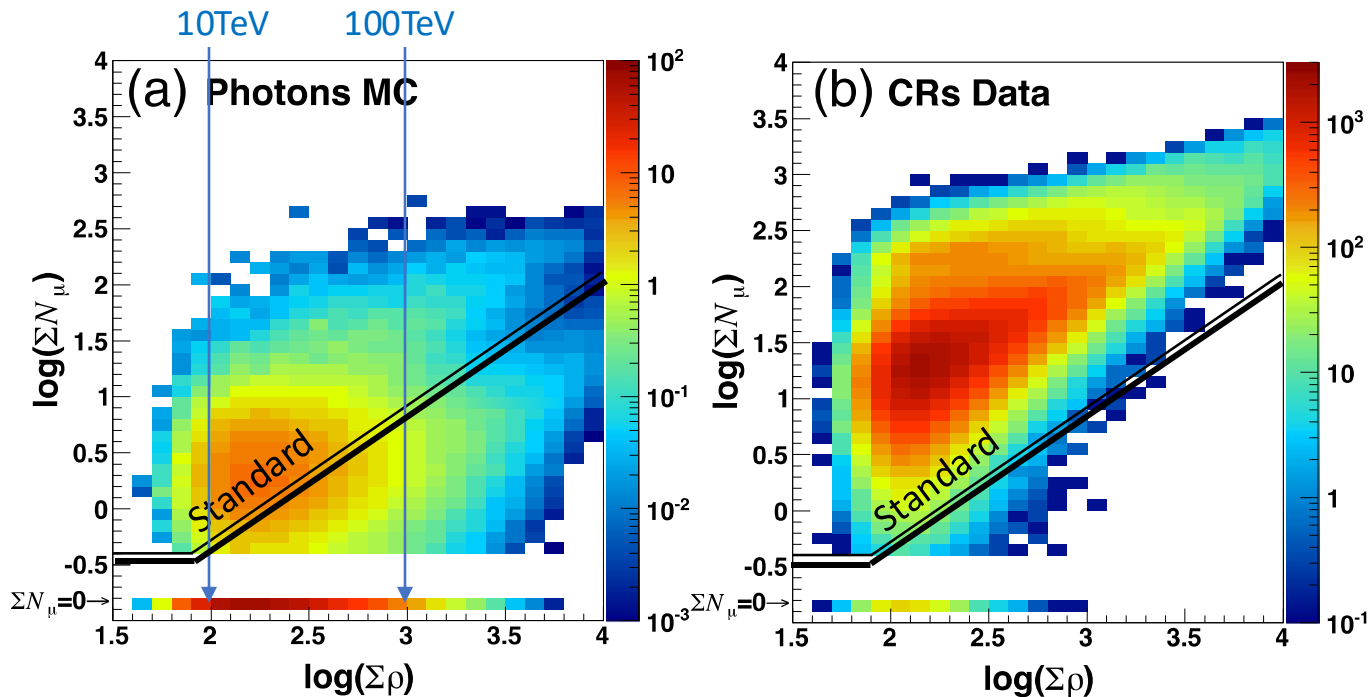
Simulated by COSMOS

Enlarged view



Muon Cut Condition (Standard)

Standard muon cut : $\Sigma N_{\mu} < 2.1 \times 10^{-3} \Sigma \rho^{1.2}$ → Optimized for the gamma-ray point-like source



Gamma Survival ratio : ~90% by MC sim (>100TeV) CR Survival ratio : $\sim 10^{-3}$ (>100TeV)



Muon Number Distribution (Crab >100 TeV)

Data/MC Comparison

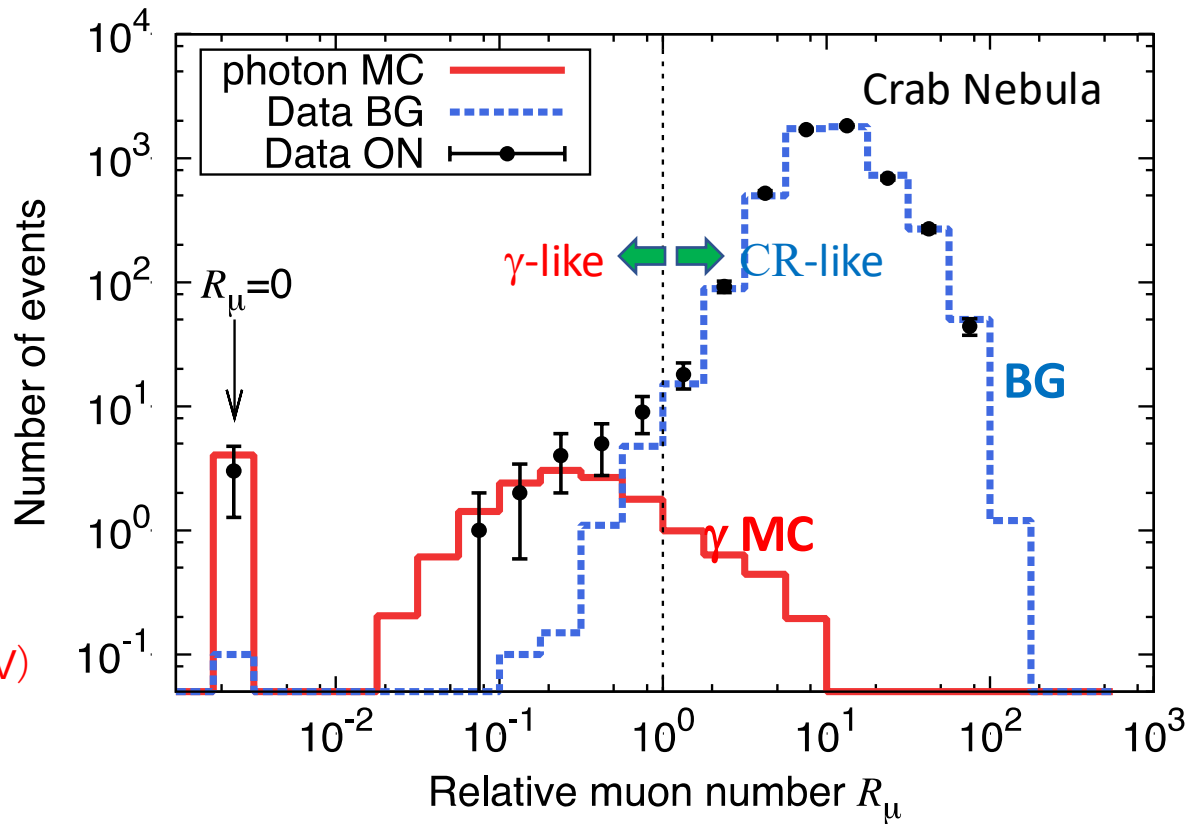
$$R_{\mu} = \frac{\text{\# of observed muons}}{\text{\# of muons at the cut value}}$$

$R_{\mu} < 1 \rightarrow \gamma\text{-like}$

$R_{\mu} > 1 \rightarrow \text{CR-like}$

Gamma Survival ratio :
90% by MC sim (>100TeV)

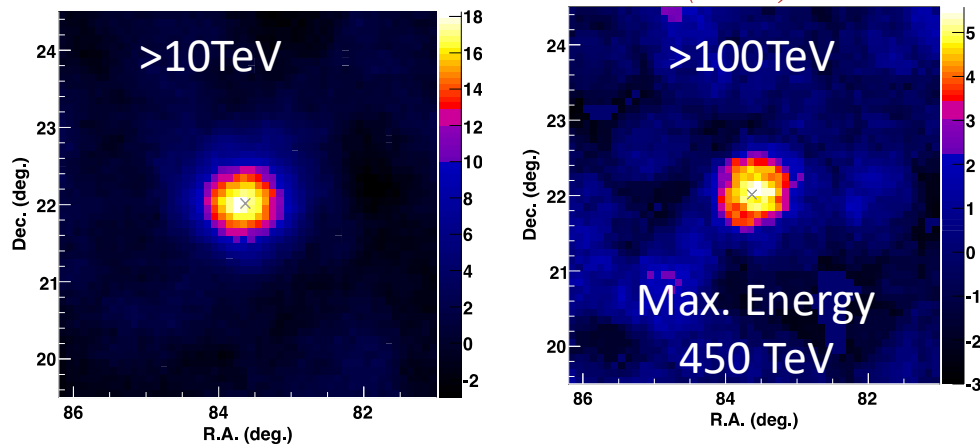
CR Survival ratio :
~0.1%(>100TeV)





UHE γ -rays from the Crab Nebula (2019)

Amenomori et al., PRL 123, 051101 (2019)

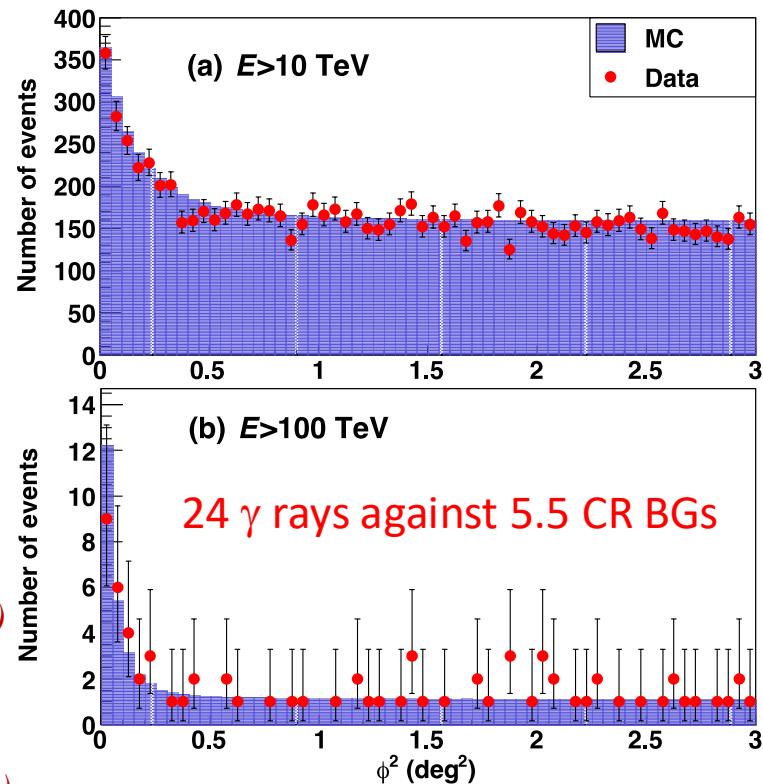


First Detection of Sub-PeV γ (5.6σ)

Other detected sources in 100 TeV region

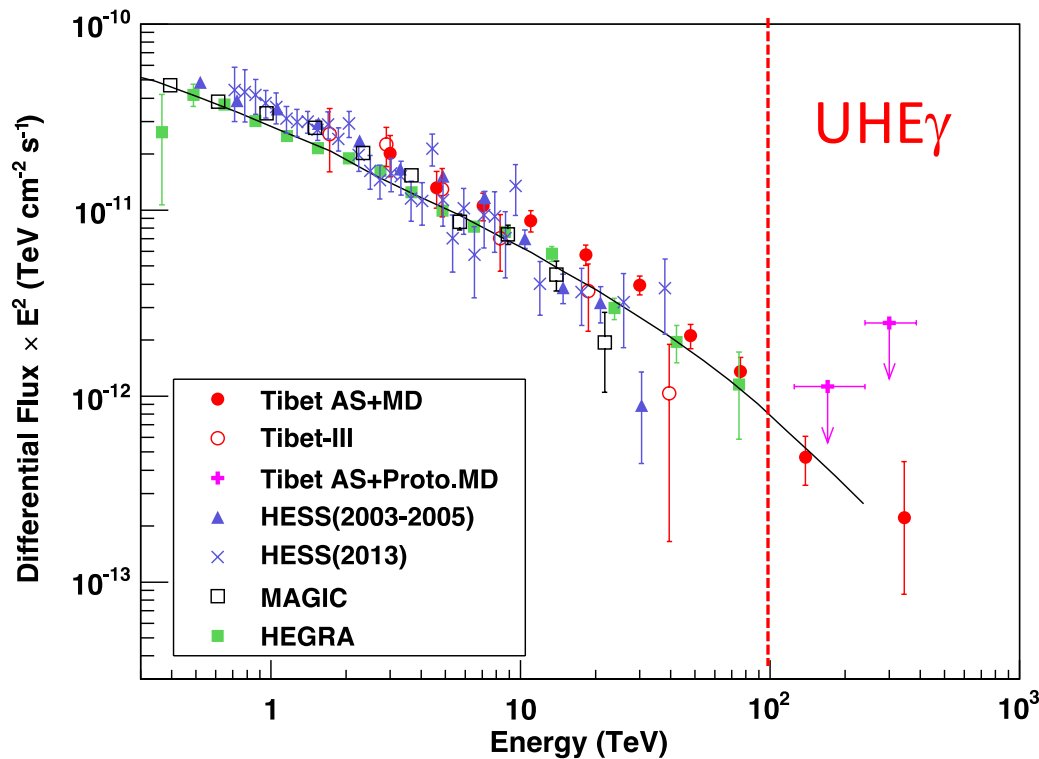
- ✓ G106.3+2.7 *Amenomori et al., Nat. Astron, 5, 460 (2021)*
- ✓ Cygnus OB1 *Amenomori et al., PRL, 127, 031102 (2021)*
- ✓ Cygnus OB2
- ✓ HESS J1843-033 *Amenomori et al., ApJ, 932, 120 (2022)*
- ✓ HESS J1849-000 *Amenomori et al., ApJ, 954, 200 (2023)*

Data vs MC





UHE γ -rays from the Crab Nebula (2019)



Amenomori+, PRL, 123, 051101, (2019)

No energy cutoff beyond 100 TeV

Thick curve :
inverse Compton model
normalized to HEGRA data

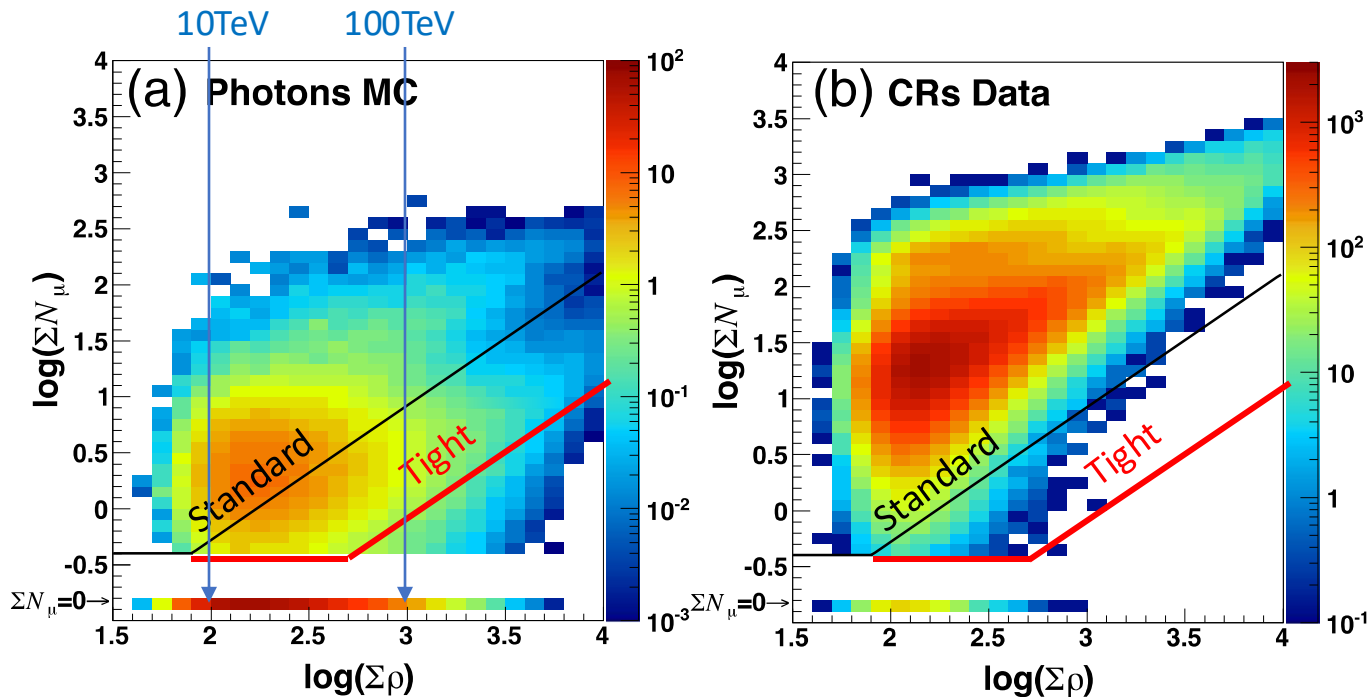
Aharonian+, ApJ, 614, 897 (2004)



Muon Cut Condition (Tight) for Diffuse γ

Tight muon cut : $\Sigma N_{\mu} < 2.1 \times 10^{-4} \Sigma \rho^{1.2}$

→ One order magnitude tighter than the Crab analysis



Gamma Survival ratio : ~30% by MC sim (>398TeV) CR Survival ratio : $\sim 10^{-6}$ (>398TeV = $10^{2.6}$ TeV)



γ -ray-like event Distribution

Amenomori et al., PRL 126, 141101 (2021)

Gamma-ray-like events
after the tight muon cut
in the equatorial coordinates

Blue points:

Experimental data

Red plus marks:

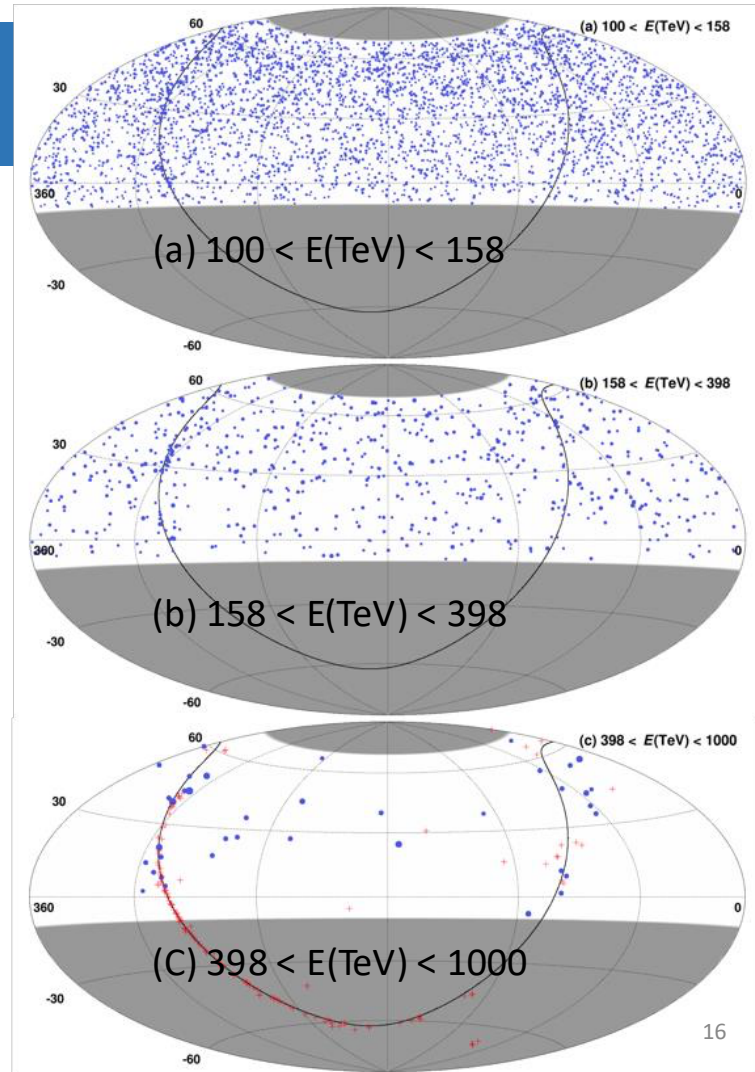
known Galactic TeV sources

>398 TeV ($10^{2.6}$ TeV)

38 events in our FoV

23 events in $|b| < 10^\circ$

16 events in $|b| < 5^\circ$





Latitude Profile

6.6 σ

Amenomori et al., PRL 126, 141101 (2021)

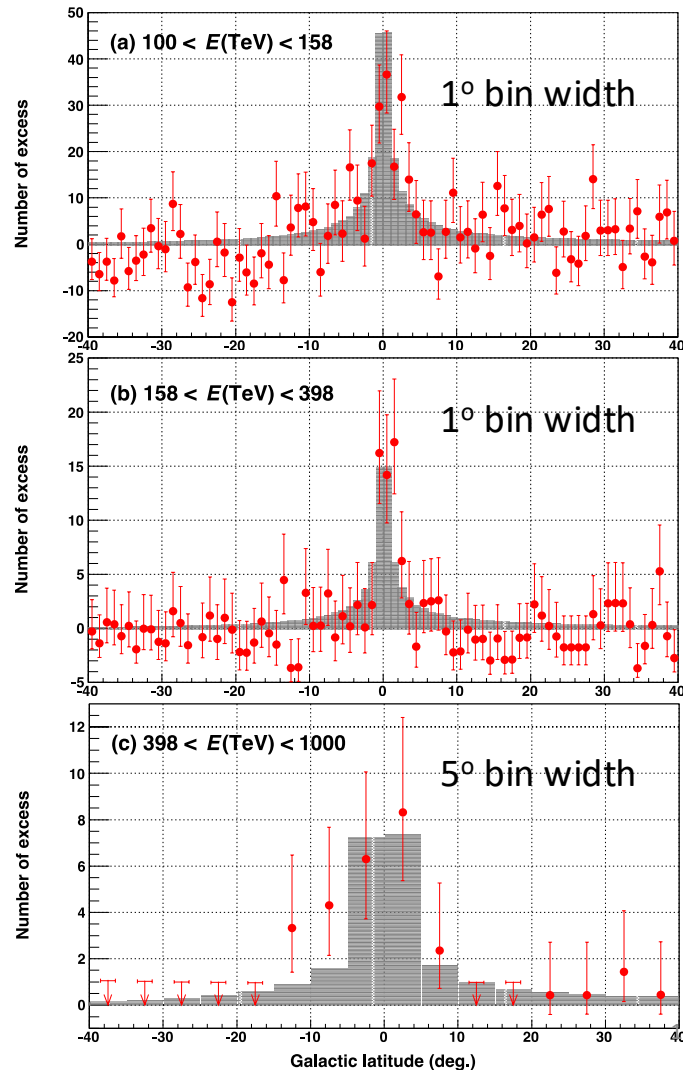
Red points:
experimental data across
our FoV ($22^\circ < l < 225^\circ$)
including source contribution

Gray shade histogram:
Model by Lipari and Vernetto

Lipari & Vernetto, PRD 98, 043003 (2018)

5.1 σ

5.9 σ

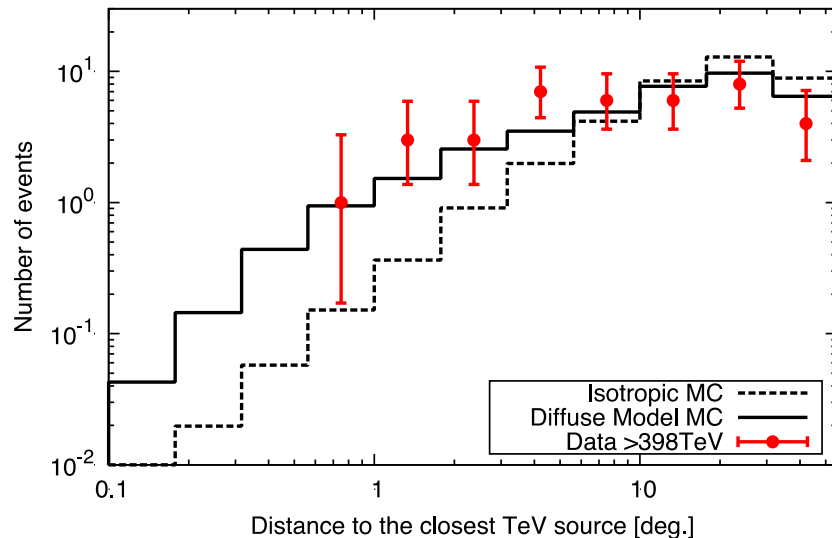




Correlation with known TeV Sources

Correlation between UHE γ -rays above 398 TeV and 60 galactic sources from TeVCat catalog including UNID, PWN, Shell, Binary, SNR..., excluding GRB, HBL, IBL, LBL, BL Lac, AGN, Blazar, FSRQ, FRI, Starburst)

- ✓ No excess around known TeV sources
- ✓ Event distribution is consistent with diffuse model



- ✓ High-energy $e^{+/-}$ lose their energy quickly.
- ✓ Cosmic-ray protons can escape farther from the source.



Strong evidence for sub-PeV γ rays induced by cosmic rays



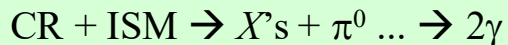
Energy Spectrum of UHE Diffuse γ Rays

Amenomori et al., PRL 126, 141101 (2021)

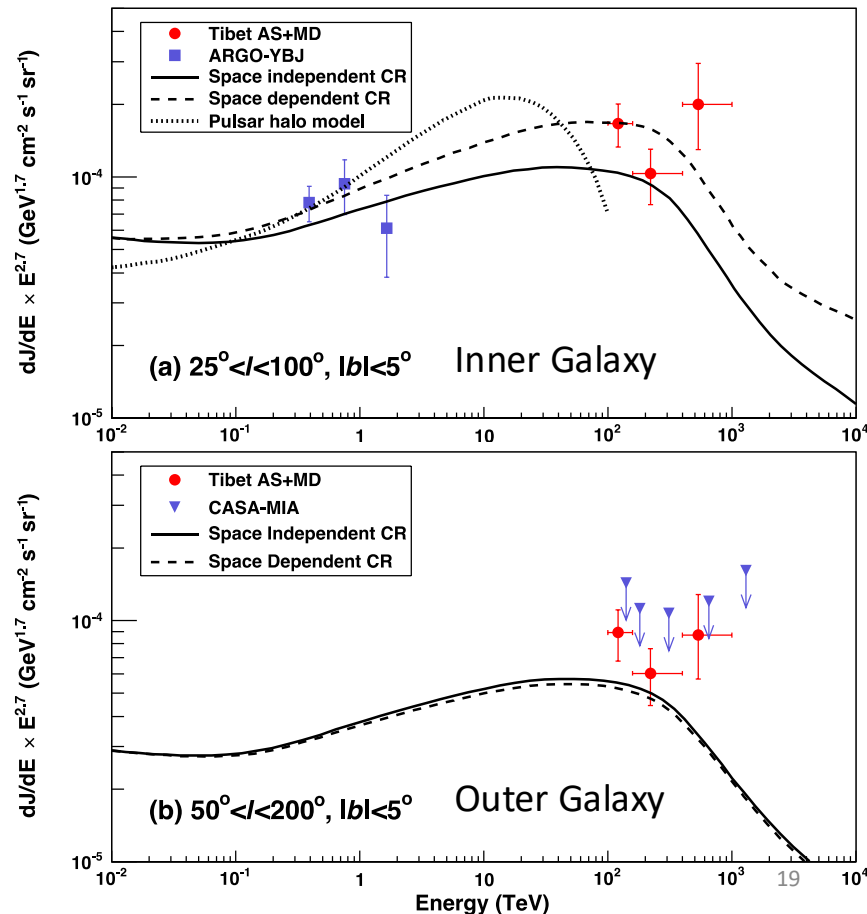
After excluding the contribution from the known TeV sources (within 0.5 degrees) listed in the TeV source catalog



The measured fluxes are overall consistent with Lipari's diffuse gamma model assuming the hadronic cosmic ray origin.



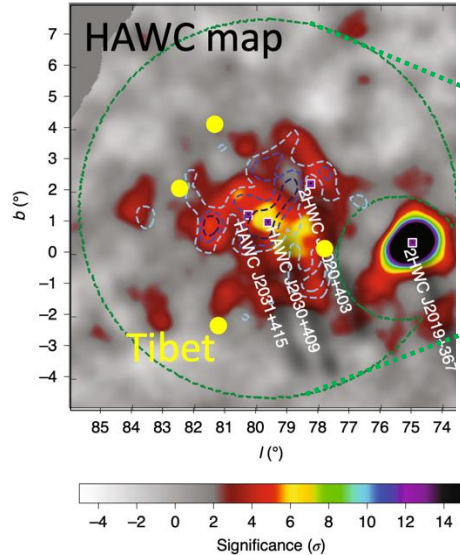
Lipari & Vernetto, PRD 98, 043003 (2018)



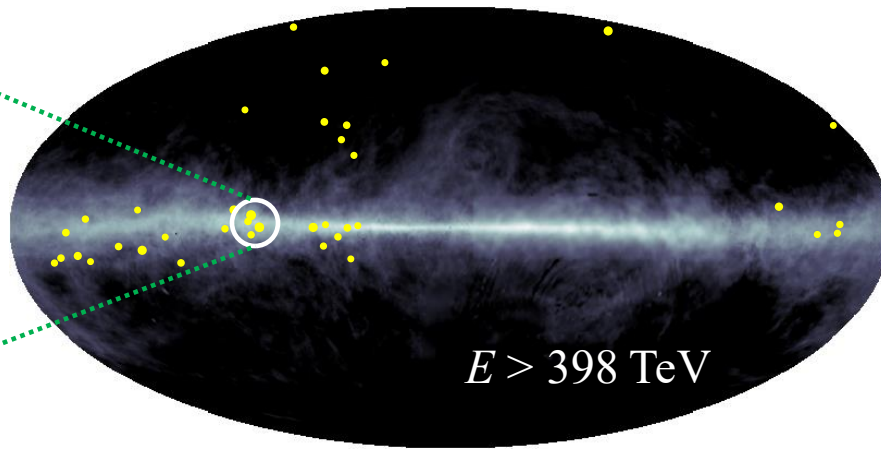


PeVatron Candidate: Cygnus Cocoon

*Abeyssekara et al.,
Nature Astronomy (2021)*

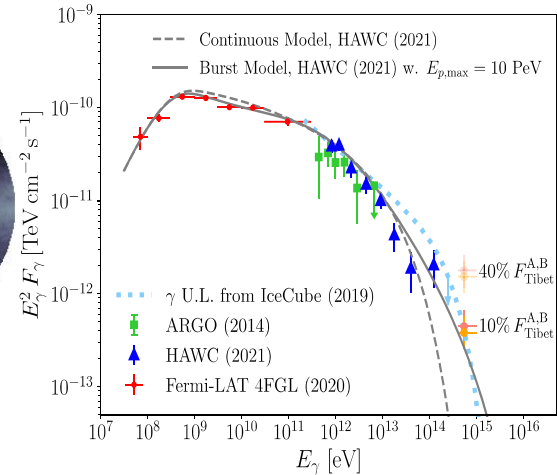


Amenomori et al., PRL 126, 141101 (2021)



Galactic Coordinates

*Fang & Murase,
ApJ, 919, 93 (2021)*



4 events above 398 TeV detected within 4°-radius-circle from the **Cygnus cocoon** which is claimed as an extended source by the ARGO-YBJ/HAWC/LHAASO and also proposed as a candidate of the PeVatrons.



LHAASO Diffuse Gamma Rays

Z. Cao et al. (LHAASO Collob.) PRL, 131, 151001 (2023)

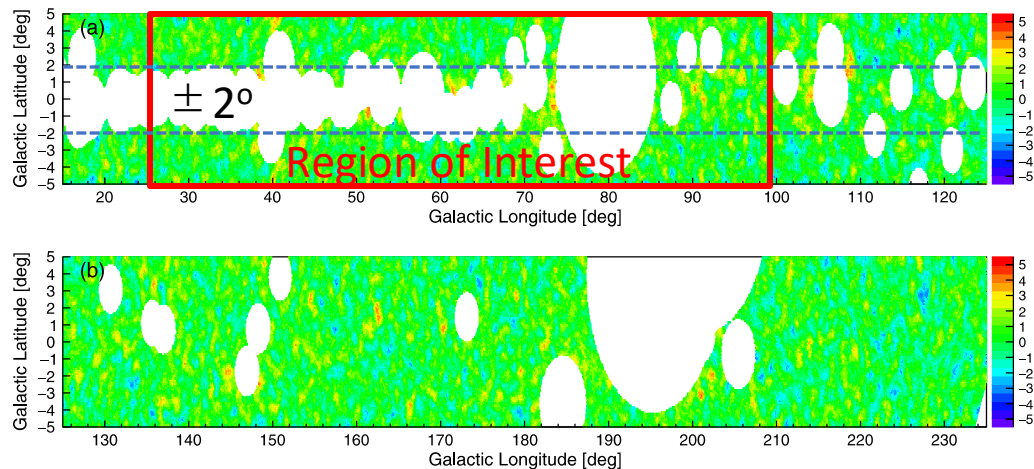
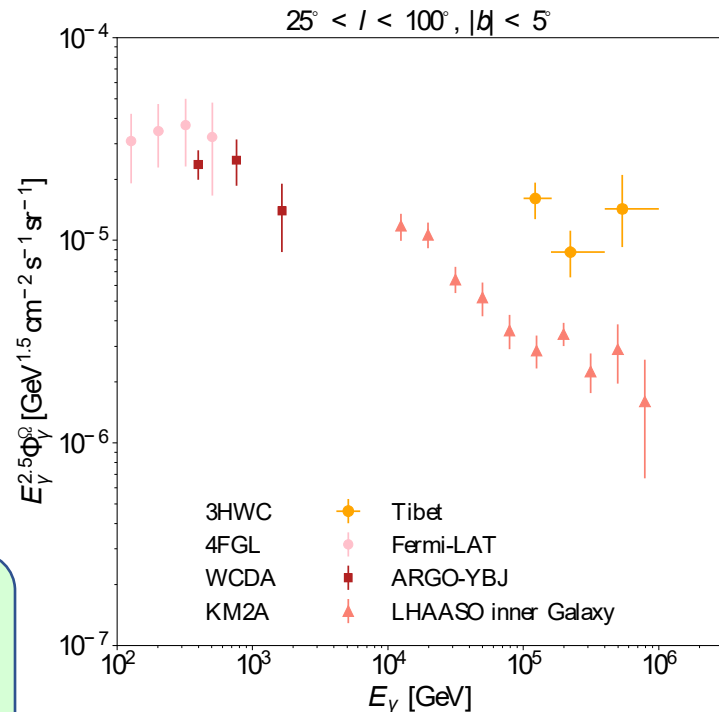


FIG. 1. The significance maps in Galactic coordinate of the inner Galaxy region [panel (a)] and outer Galaxy region [panel (b)] above 25 TeV after masking the resolved KM2A and TeVCat sources.

LHAASO flux is a few times lower than Tibet flux,
LHAASO conservatively masks most of region $l \pm 2^\circ$.
→ This discrepancy can be explained assuming
diffuse gamma ray latitude profile.

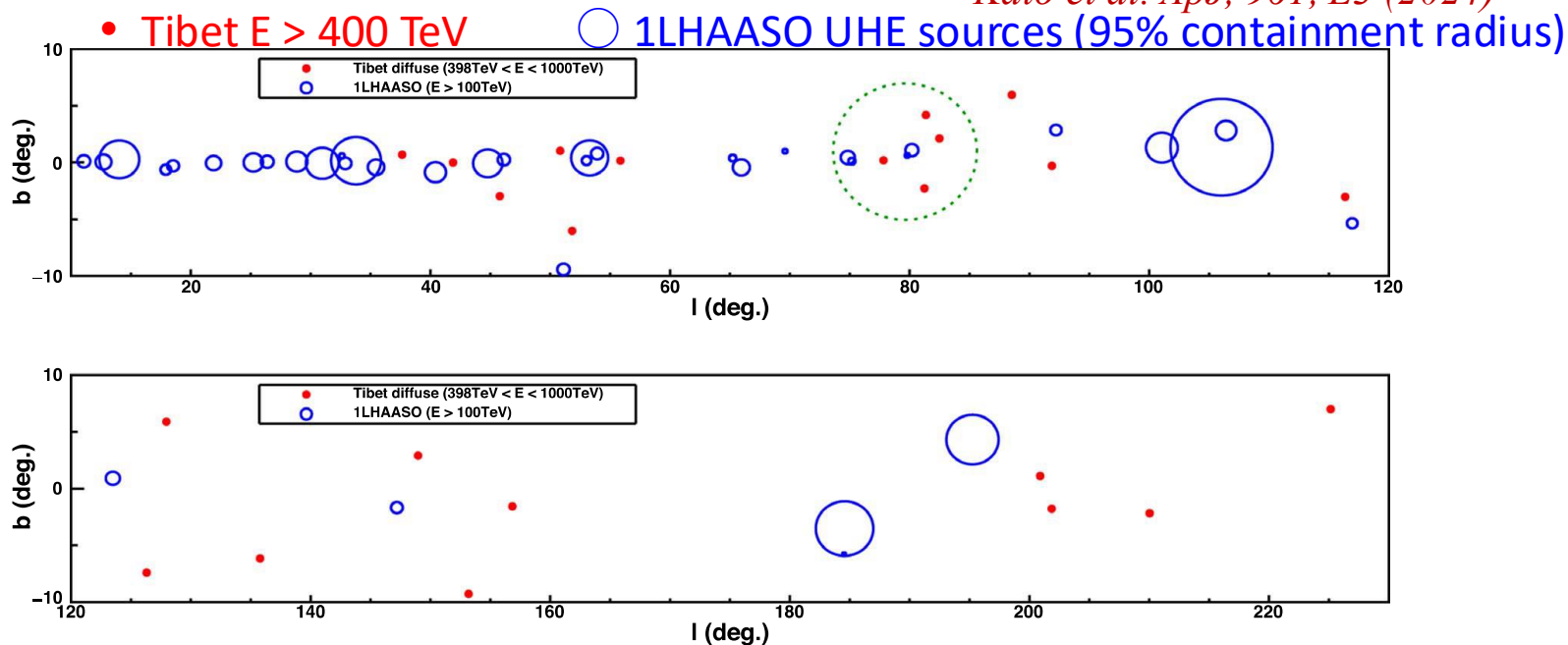
K. Fang & K. Murase, ApJ, 957, L6 (2023)





1LHAASO Catalog and Tibet UHE Diffuse Events

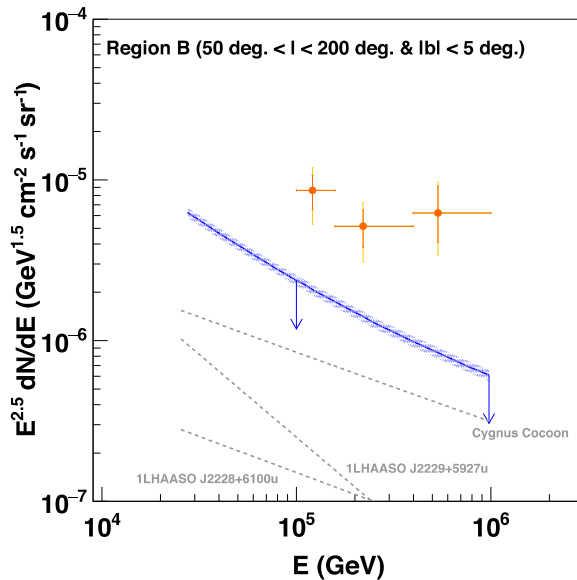
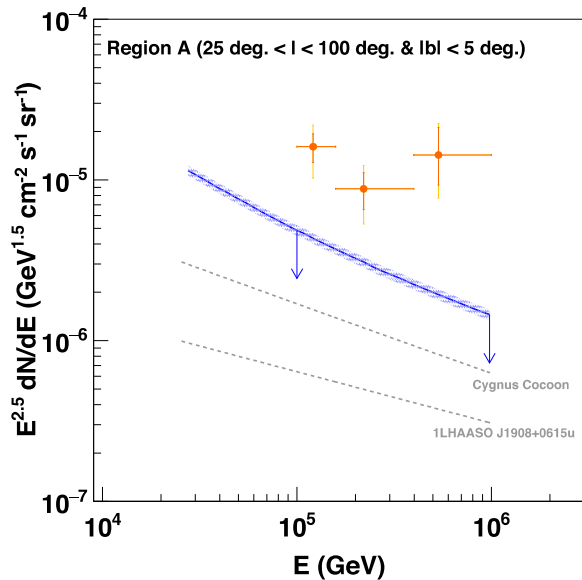
Kato et al. ApJ, 961, L3 (2024)



Tibet Galactic diffuse gamma rays above 400 TeV:
do NOT overlap with 1LHAASO UHE (>100 TeV) sources.
* Expected # of accidental overlap = 0.9 events



Source Contribution to the Tibet Diffuse



Integral flux of 1LHAASO sources (>100TeV) outside the Tibet Masked region

Kato et al. ApJ, 977, L3 (2024)

Source	Region A (25°<l<100° & b <5°)	Region B (50°<l<200° & b <5°)
Tibet GDE		
121 TeV	< 26.9%±9.9%	< 24.1%±9.5%
220 TeV	< 34.8%±14.0%	< 27.4%±11.1%
534 TeV	< 13.5% ^{+6.3%} _{-7.7%}	< 13.5% ^{+6.2%} _{-7.6%}

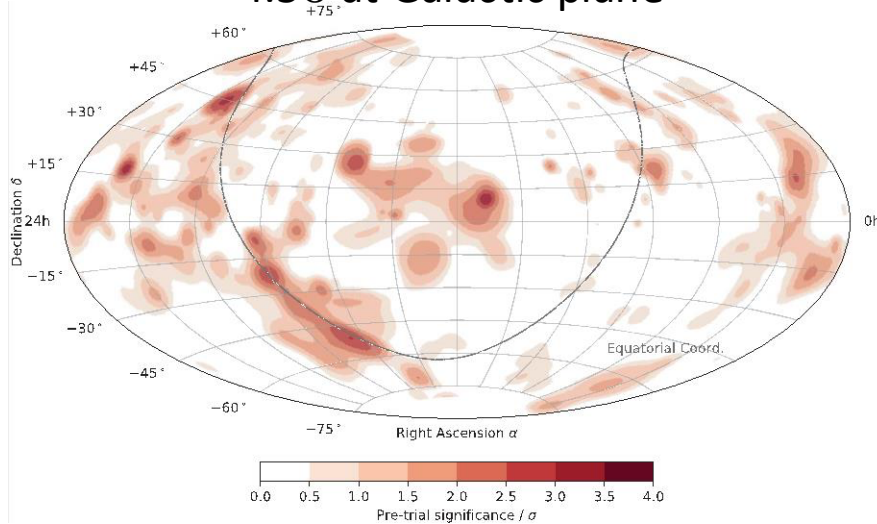
Source Contribution is subdominant



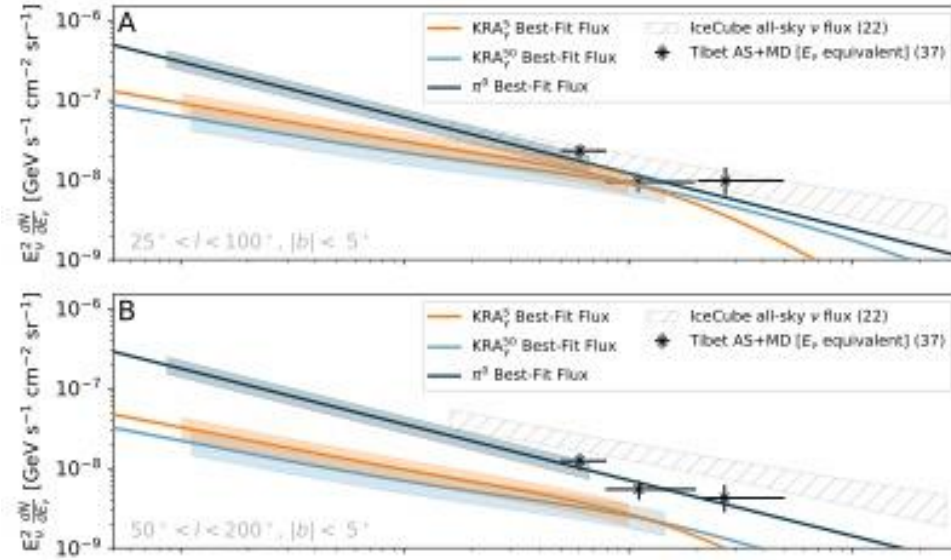
IceCube Diffuse Neutrinos

IceCube Collaboration: Science, 380, 1338 (2023)

4.5 σ at Galactic plane



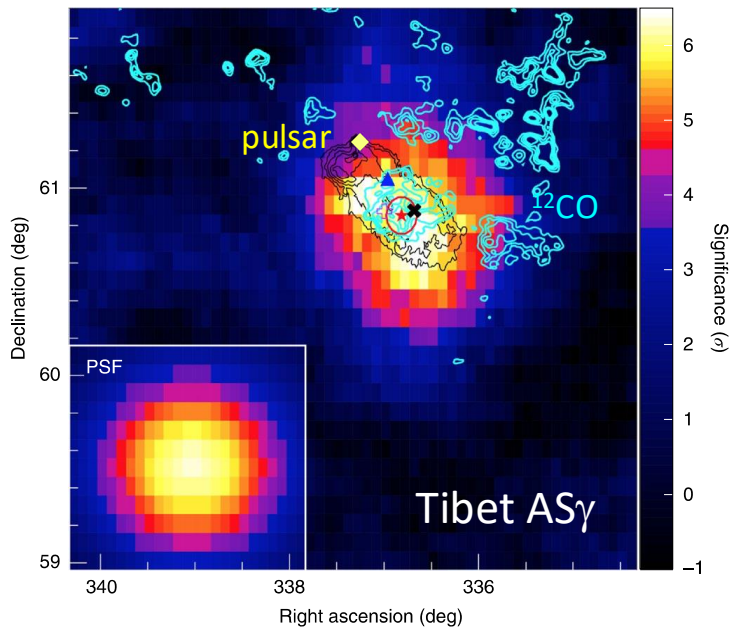
Comparison with Tibet diffuse γ -rays



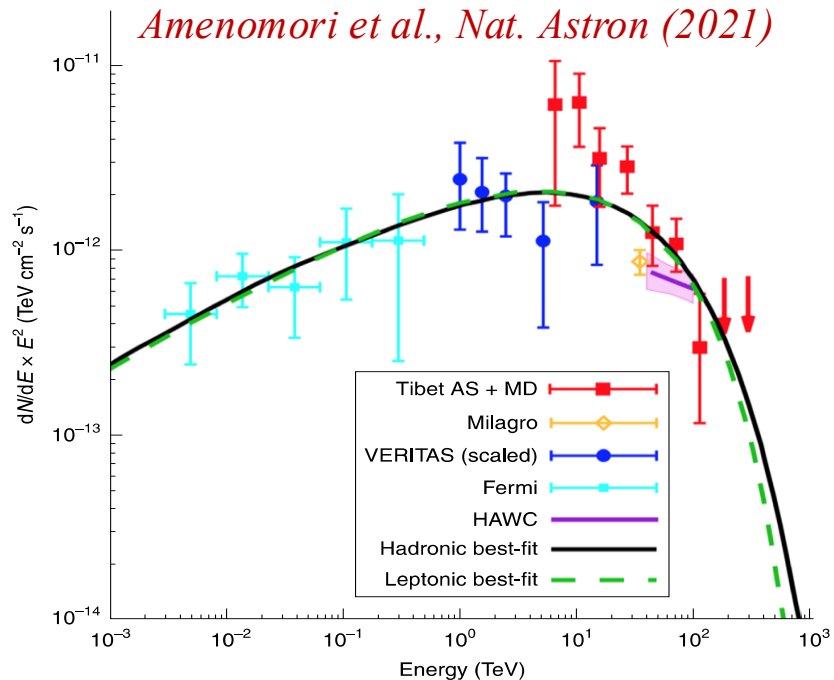
IceCube ν flux smoothly connects to the ν flux estimated from the Tibet sub-PeV γ -ray flux, assuming π^0 -model best-fit flux supporting cosmic-ray origin of Tibet sub-PeV galactic diffuse γ rays.



PeVatron Candidate: SNR G106.3+2.7



Detected by
VERITAS,
HAWC,
Tibet ASγ,
MAGIC,
LHAASO



- ✓ Spectrum extends beyond 100 TeV (HAWC, Tibet ASγ, LHAASO)
- ✓ Shell-type SNR near the pulsar ($t_{\text{age}} \sim 10 \text{ kyr?}$, $d = 800 \text{ pc?}$)
- ✓ Extended γ -ray excess ($\sigma_{\text{EXT}} = 0.24^\circ \pm 0.10^\circ$)
- ✓ γ -ray excess is coincident with the molecular clouds (MCs) and SNR, not pulsar

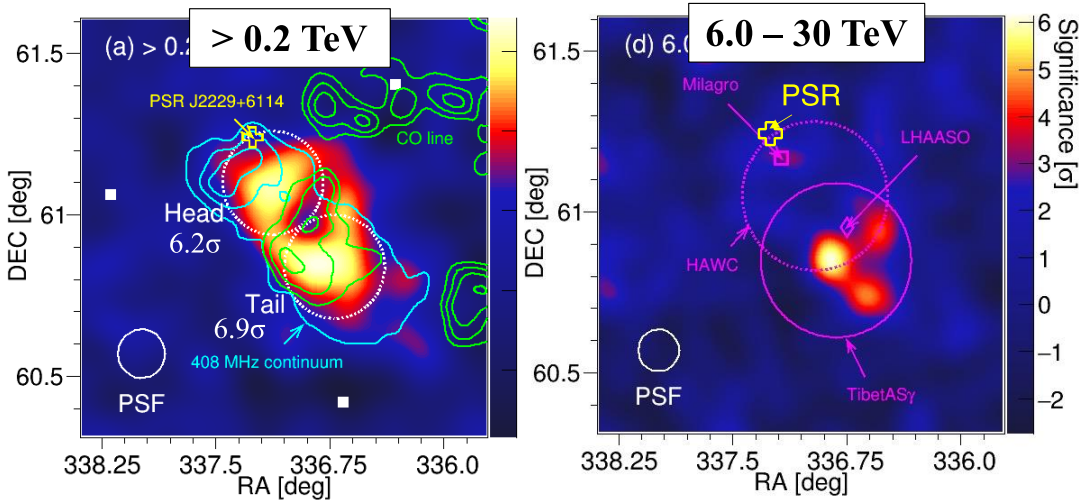
$$E_{\text{p,cut}} = \sim 500 \text{ TeV}$$

$$W_{\text{p}} = \sim 5 \times 10^{47} \text{ erg}$$

($> 1 \text{ GeV}$)



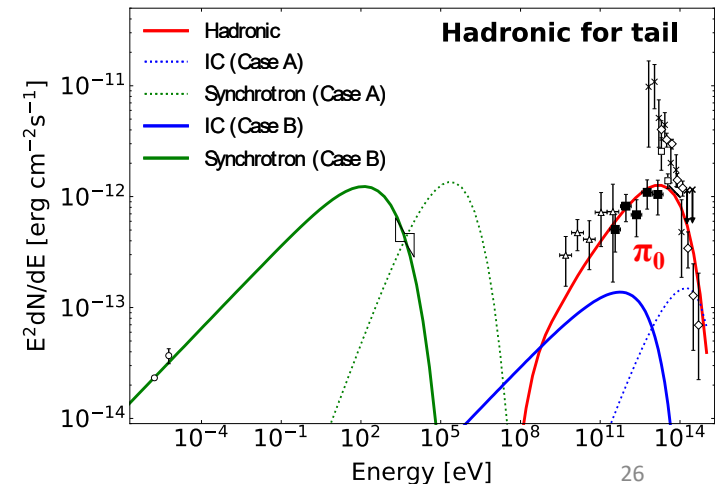
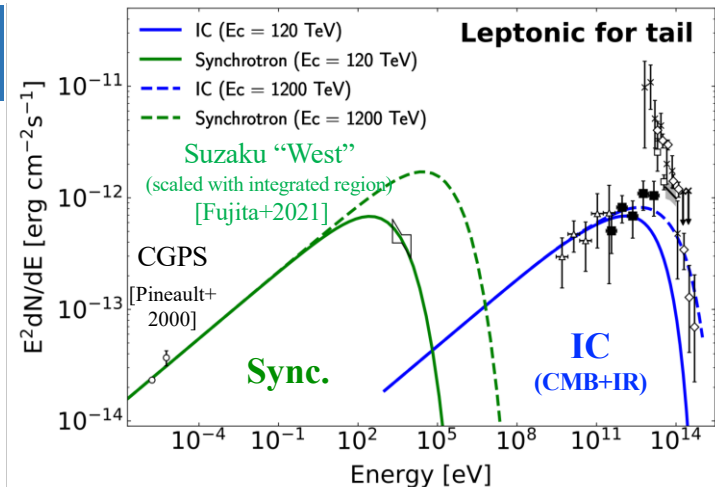
MAGIC: SNR G106.3+2.7



- ✓ HE emissions are consistent with Tibet ASγ
- ✓ SED for tail region favors hadronic model

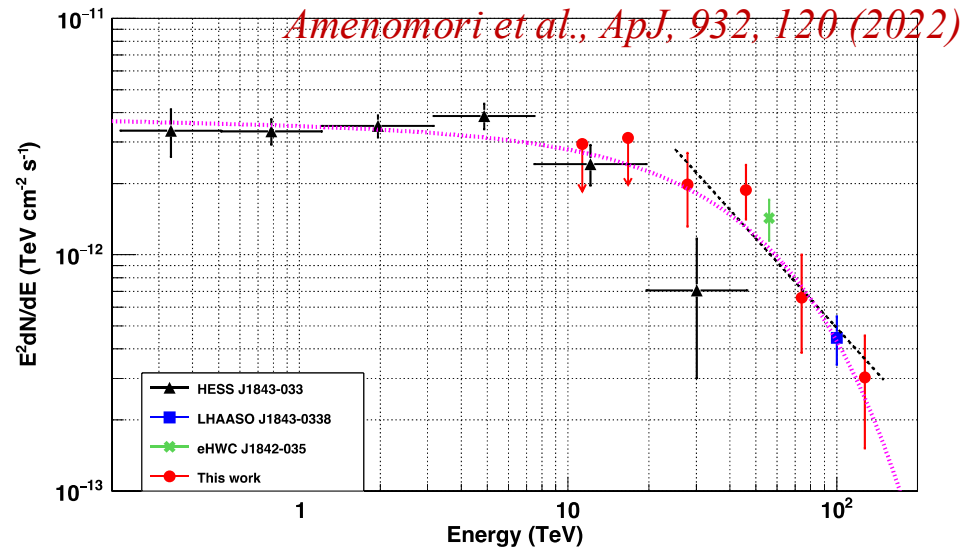
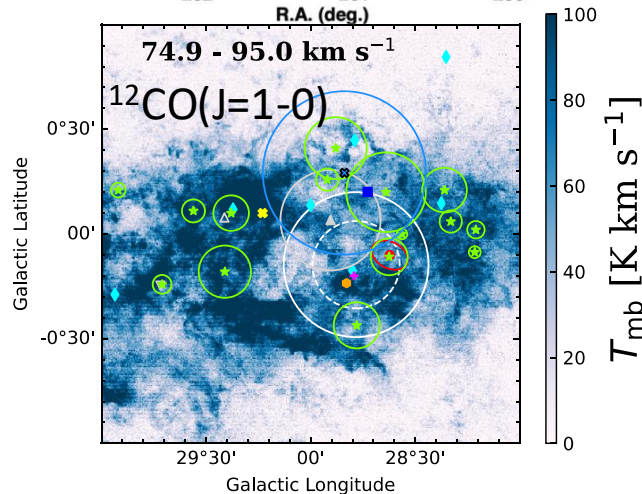
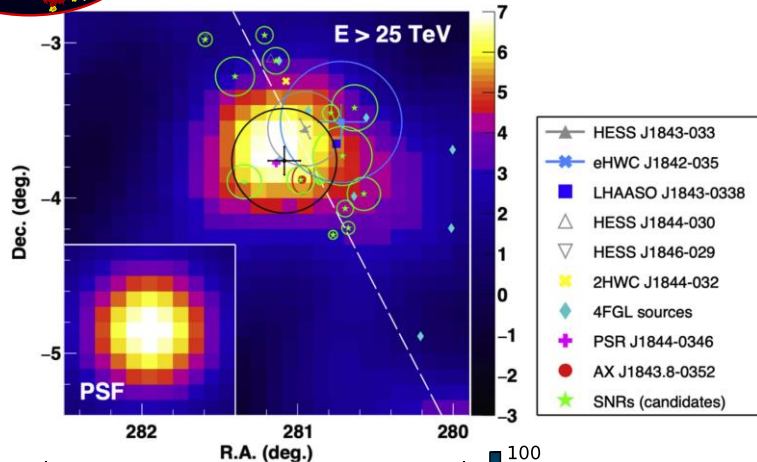
Abe et al. (MAGIC Collab.), A&A, 671, 12 (2023)

Oka et al. (MAGIC Collab.), CTA workshop





PeVatron Candidate: HESS J1843-033



Candidate sources ($T_{\text{age}}=2.7\text{kyr?}$, $d=9.6\text{kpc}$)

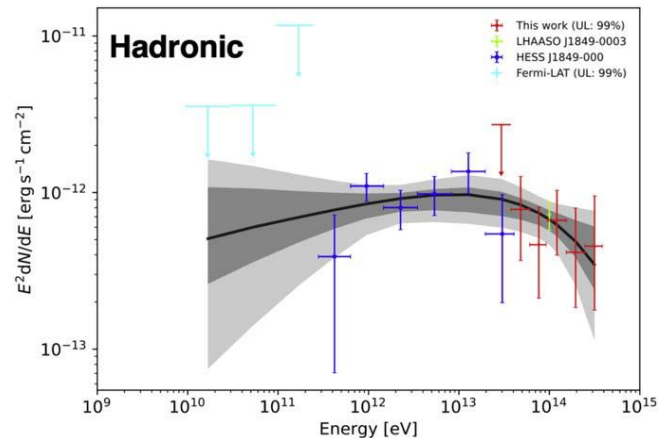
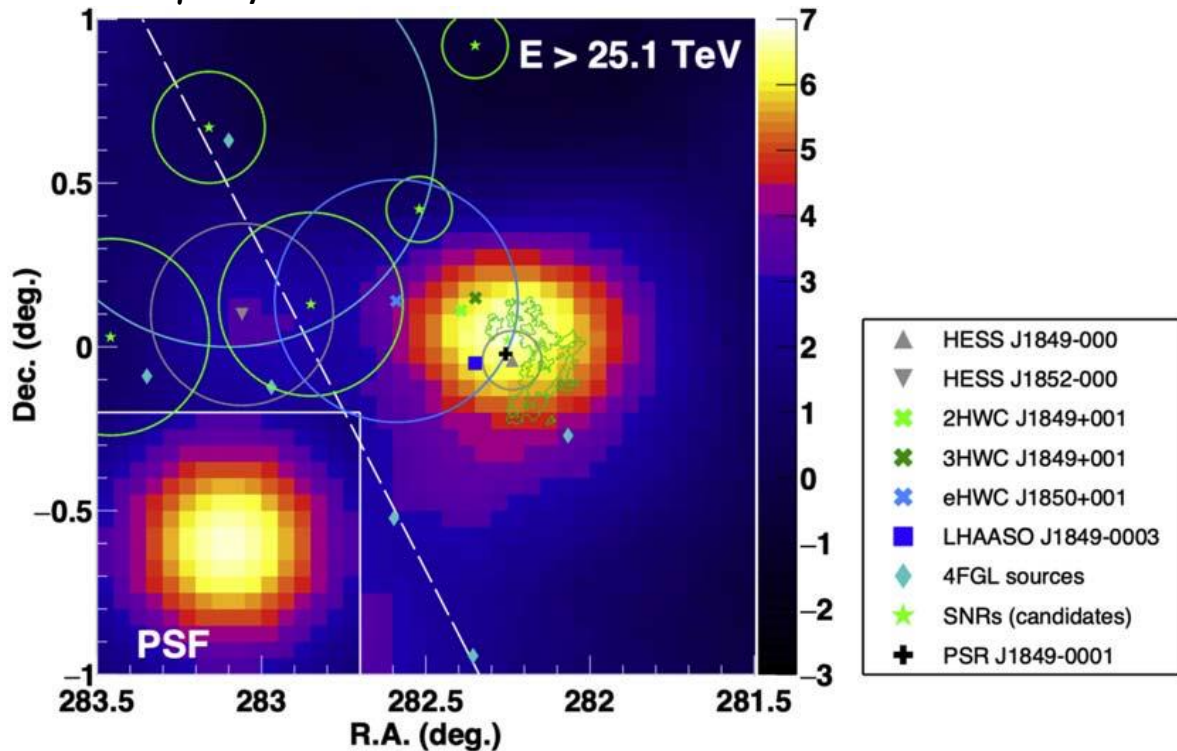
- ✓ Shell-type SNR G28.6+0.1? or PSR J1844-00346?
- ✓ Extended γ -ray excess ($\sigma_{\text{EXT}}=0.34^\circ \pm 0.12^\circ$)
- ✓ γ -ray excess is coincident with the MCs
- ✓ Proton cutoff: ~ 500 TeV assuming the Hadronic model
 $W_p = \sim 6 \times 10^{49}$ erg ($>1\text{TeV}$)



PeVatron Candidate: HESS J1849-000

Amenomori et al., ApJ, 954, 200 (2023)

- ✓ A middle-aged PWN ($T_{\text{age}}=42.9\text{kyr}$, $d=7\text{kpc}$)
- ✓ γ -ray excess is coincident with the MCs

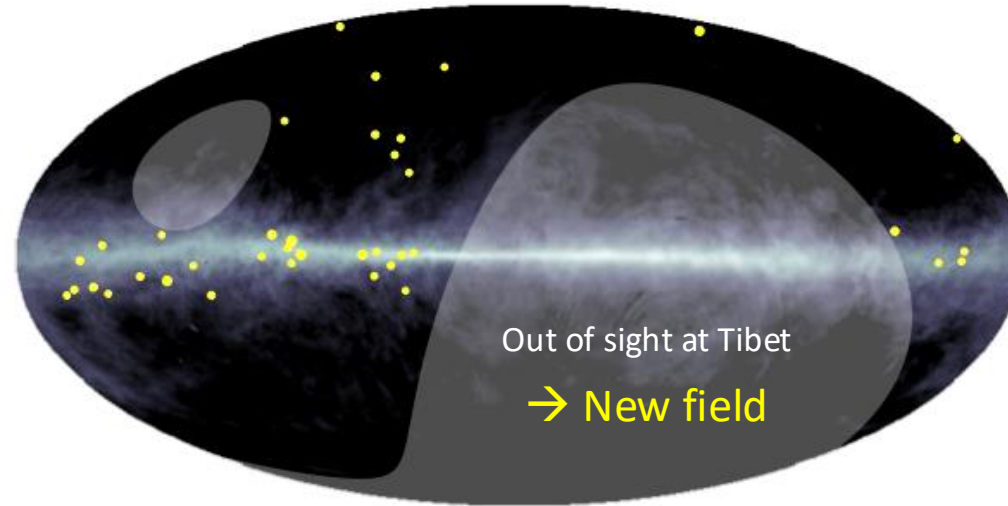


- ✓ Proton cutoff ~ 5 PeV
assuming the Hadronic model
 $W_p = \sim 1.1 \times 10^{49}$ erg ($>1\text{TeV}$)
- ✓ Spectrum can be also modeled
with the Leptonic scenario (IC)

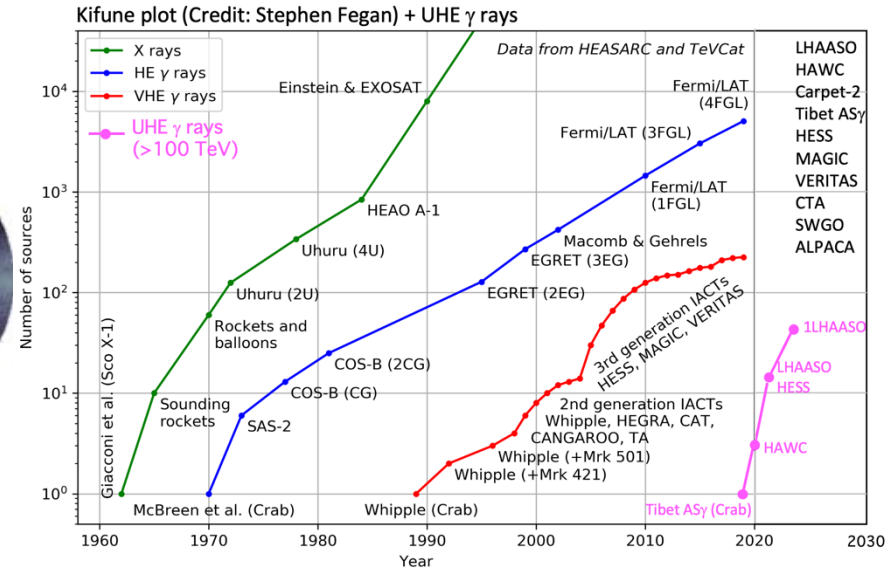


Projects in the Southern Hemisphere

UHE diffuse gamma rays



>40 UHE sources



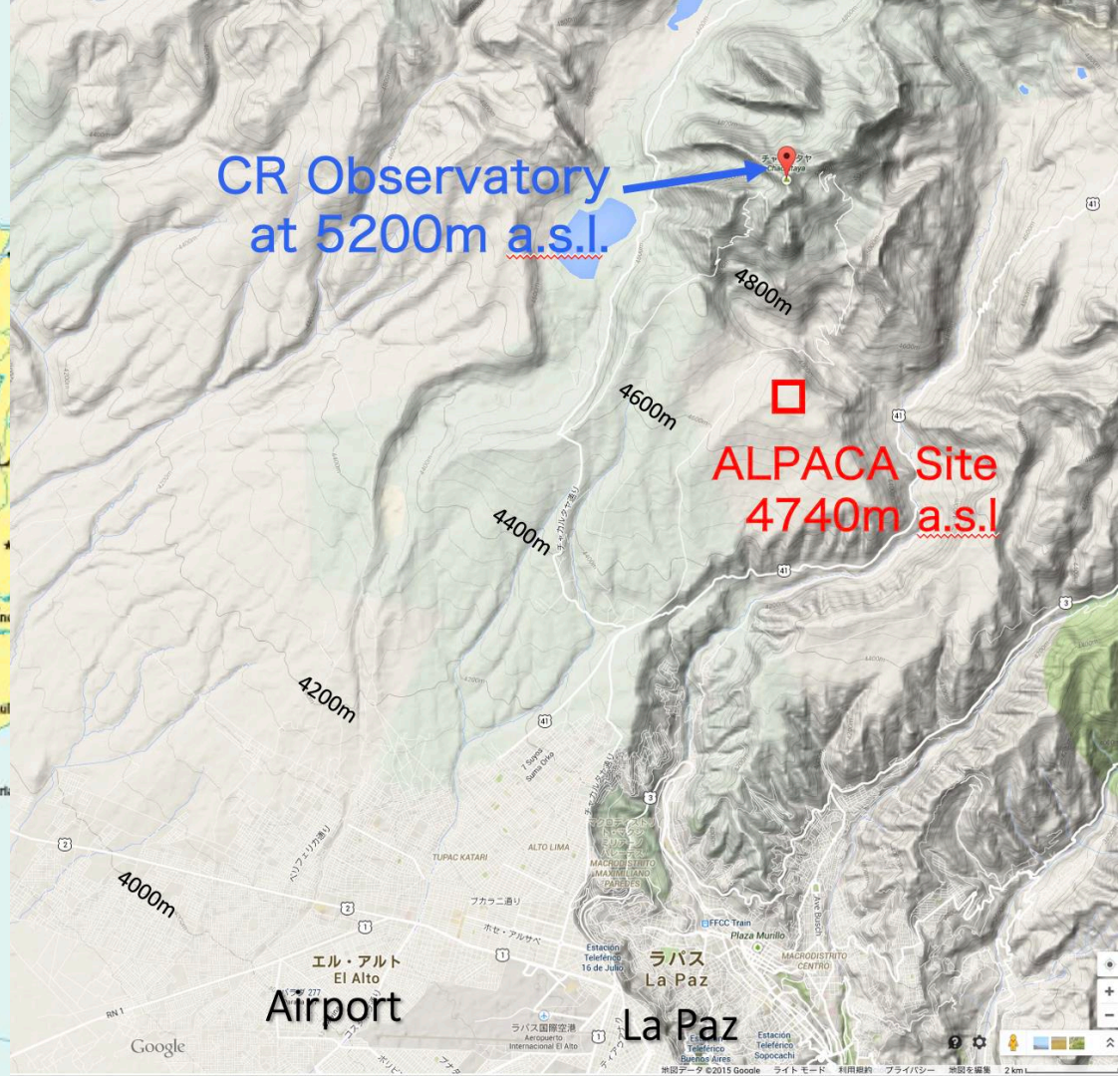
Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example <http://adsabs.harvard.edu/abs/1996NCimC..19..953K>).
 The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on HEASARC maintained by Stephen A. Drake (retrieved 2017-09-28) : https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/how_many_xray.html
 The data for the number of VHE (TeV) gamma-ray sources is from TeVCat maintained by Deirdre Horan and Scott Wakely (retrieved 2017-09-28) : <http://tevcat.uchicago.edu/>

Go South!

(e.g., ALPACA [2026-], SWGO, Mega ALPACA, CTAO-south, ...) & Neutrinos



Narita→LA (10 hours)
LA→Lima (9 hours)
Lima→La Paz (2 hours)



ALPACA Collaboration



M. Anzorena¹, E. de la Fuente^{2,3}, K. Fujita¹, R. Garcia¹, Y. Hayashi⁴, K. Hibino⁵, N. Hotta⁶, G. Imaizumi¹, Y. Katayose⁷, C. Kato⁴, S. Kato⁸, T. Kawashima¹, K. Kawata¹, M. Kobayashi⁷, S. Kobayashi⁴, T. Koi⁹, H. Kojima¹⁰, P. Miranda¹¹, S. Mitsuishi⁴, A. Mizuno¹, K. Munakata⁴, Y. Nakamura¹, M. Nishizawa¹², Y. Noguchi⁷, S. Ogio¹, M. Ohishi¹, M. Ohnishi¹, A. Oshima^{9,13}, M. Rajjevic¹¹, H. Rivera¹¹, T. Saito¹⁴, T. Sako¹, T. K. Sako¹⁵, S. Shibata¹⁰, A. Shiomi¹⁶, M. Subieta¹¹, F. Sugimoto¹, N. Tajima¹⁷, W. Takano⁵, Y. Takeyama⁷, M. Takita¹, N. Tamaki¹, Y. Tameda¹⁸, K. Tanaka¹⁹, R. Ticona¹¹, H. Tsuchiya²⁰, Y. Tsunesada^{21,22}, S. Udo⁵, G. Yamagishi⁷, Y. Yamanaka¹, K. Yamazaki⁹ and Y. Yokoe¹

¹Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan.

²Departamento de Física, CUCEI, Universidad de Guadalajara, Guadalajara, México.

³Doctorado en Tecnologías de la Información, CUCEA, Universidad de Guadalajara, Zapopan, México.

⁴Department of Physics, Shinshu University, Matsumoto 390-8621, Japan.

⁵Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan.

⁶Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan.

⁷Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan.

⁸Institut d'Astrophysique de Paris, CNRS UMR 7095, Sorbonne Université, 98 bis bd Arago 75014, Paris, France,

⁹College of Science and Engineering, Chubu University, Kasugai 487-8501, Japan.

¹⁰Chubu Innovative Astronomical Observatory, Chubu University, Kasugai 487-8501, Japan.

¹¹Instituto de Investigaciones Físicas, Universidad Mayor de San Andrés, La Paz 8635, Bolivia.

¹²National Institute of Informatics, Tokyo 101-8430, Japan.

¹³College of Engineering, Chubu University, Kasugai 487-8501, Japan.

¹⁴Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan.

¹⁵Department of Information and Electronics, Nagano Prefectural Institute of Technology, Ueda 386-1211, Japan.

¹⁶College of Industrial Technology, Nihon University, Narashino 275-8575, Japan.

¹⁷RIKEN, Wako 351-0198, Japan.

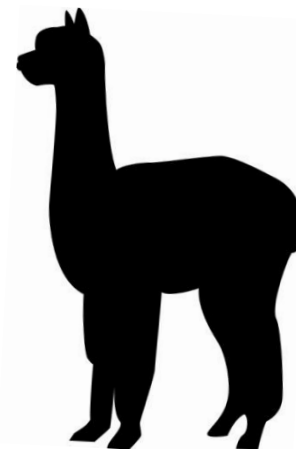
¹⁸Faculty of Engineering, Osaka Electro-Communication University, Neyagawa 572-8530, Japan.

¹⁹Graduate School of Information Sciences, Hiroshima City University, Hiroshima 731-3194, Japan.

²⁰Japan Atomic Energy Agency, Tokai-mura 319-1195, Japan.

²¹Graduate School of Science, Osaka Metropolitan University, Osaka 558-8585, Japan.

²²Nambu Yoichiro Institute for Theoretical and Experimental Physics, Osaka Metropolitan University, Osaka 558-8585, Japan.



ALPACA Project



1. Air Shower (AS) Array $\sim 83,000\text{m}^2$

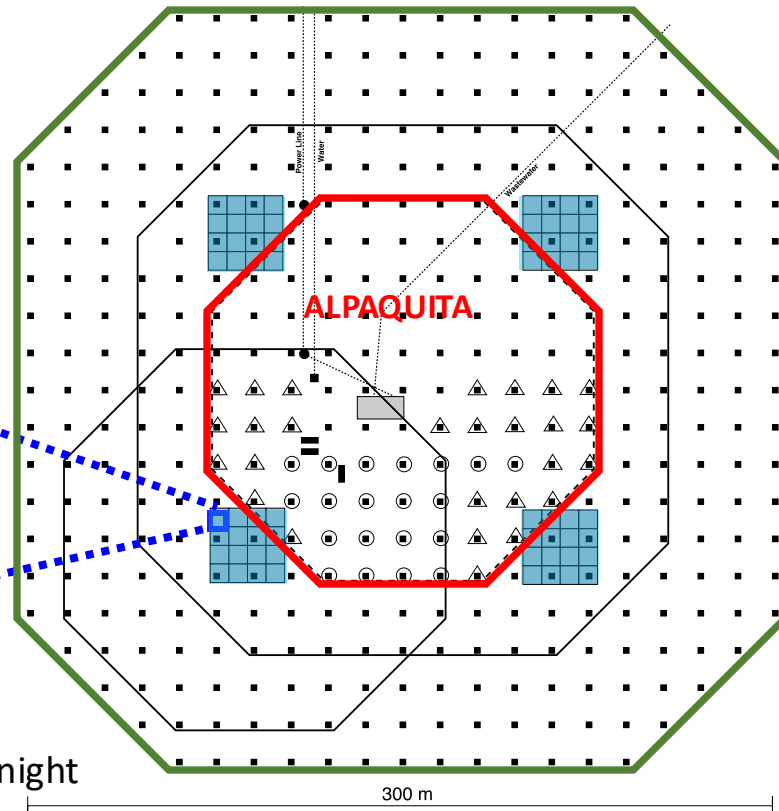
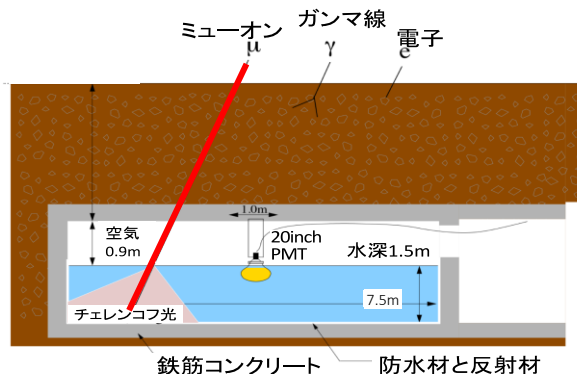
= 401 x 1m^2 Scintillation Detector

= **4 times larger than ALPAQUITA**

2. Underground Muon Detector (MD) $\sim 3600\text{m}^2$

= Water-Cherenkov-Type, 2.5m overburden ($\sim 19X_0$)

56m^2 with 20" ϕ PMT x 96 Cells



- ✓ γ -ray induced AS has much less muons
CR background rejection rate $> 99.9\%$ @ 100TeV
- ✓ Wide FoV ($\sim 2\text{sr}$), 24-hour observation regardless day and night
 - Angular resolution $\sim 0.2^\circ$ @ 100TeV
 - Energy resolution $\sim 20\%$ @ 100TeV

ALPAQUITA Air Shower Array



Chacaltaya plateau in Bolivia at 4740m a.s.l.
¼ALPACA-scale air shower array
97 x 1m² scinti. detectors with 15m spacing
Effective area ~18,000m²



1m² 5mm lead plate
1m² Scintillator
(50cm x 50cm x 5cm x4)

Inverse pyramid shape
Stainless steel box
(White painted inside)

2-inch PMT x1

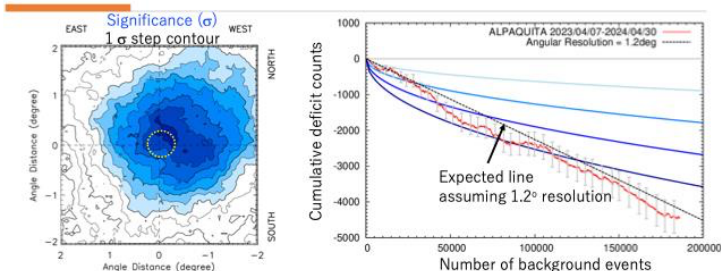
Cosmic ray mode energy ~5 TeV

2023 Apr. Full operation

Cosmic-Ray Observations by ALPAQUITA



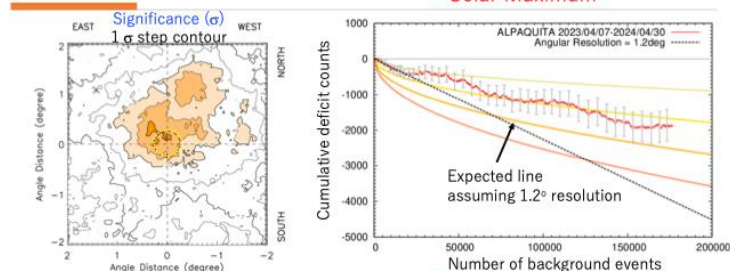
Moon Shadow Results (Apr 2023 – Apr 2024)



- ✓ Moon shadow is clearly observed $\sim 10\sigma$
- ✓ The number of deficits increases linearly, $\sim 1^\circ$ angular resolution
- ✓ Shadow center is shifted 0.3° westward (by geomagnetic field)

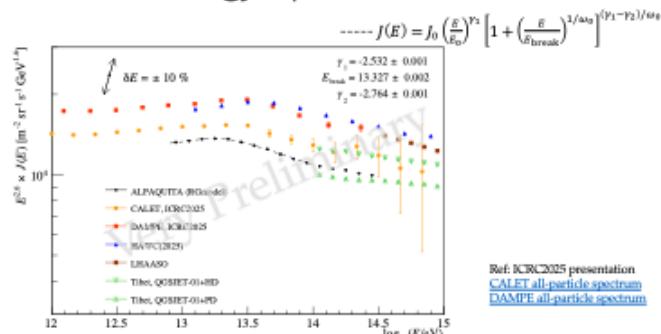
Sun Shadow Results (Apr 2023 – Apr 2024)

$\sim$ Solar Maximum



- ✓ Sun shadow is successfully observed $\sim 5\sigma$
- ✓ The number of deficits is half of the Moon shadow?
- ✓ Shadow center is shifted northward?

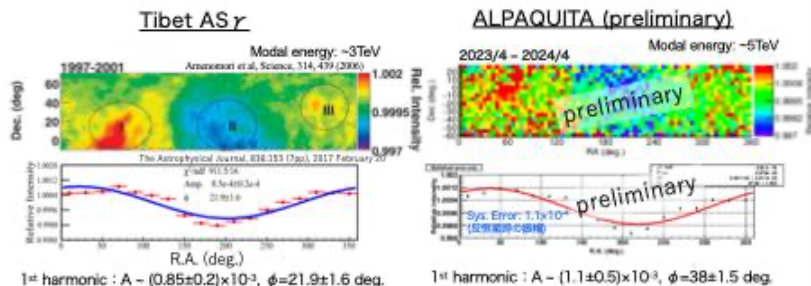
CR Energy Spectrum



Ref: ICRC2025 presentation
CALET all-particle spectrum
DAMPE all-particle spectrum

- Cosmic ray spectrum with 10 days ALPAQUITA data
- Consistent with the other recent measurements within systematic error

Anisotropy of CR intensity (in Sidereal time)

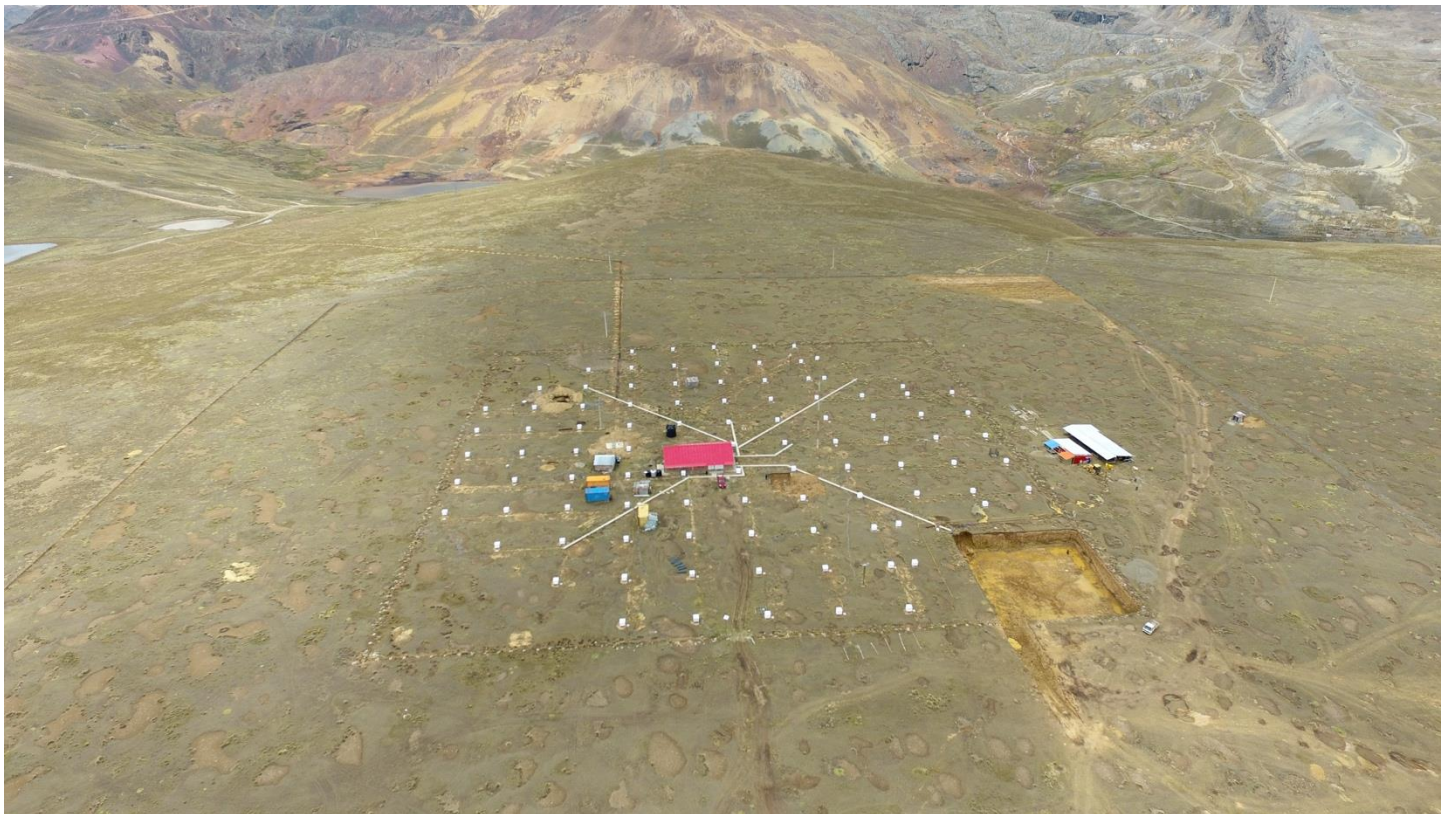


- ALPAQUITA successfully identified an anisotropy smoothly connected from the Tibet result.
- Combined analysis of the ALPAQUITA and Tibet data is ongoing.
- Anisotropy is believed to be related to the local CR source and local interstellar magnetic field.

Muon Detector Construction



Excavation for 1st MD began in November 2025



Construction

Nov 2025	Start
May 2026	1stMD
Sep 2026	4MDs

Muon Detector Construction



Excavation for 1st MD began in November 2025



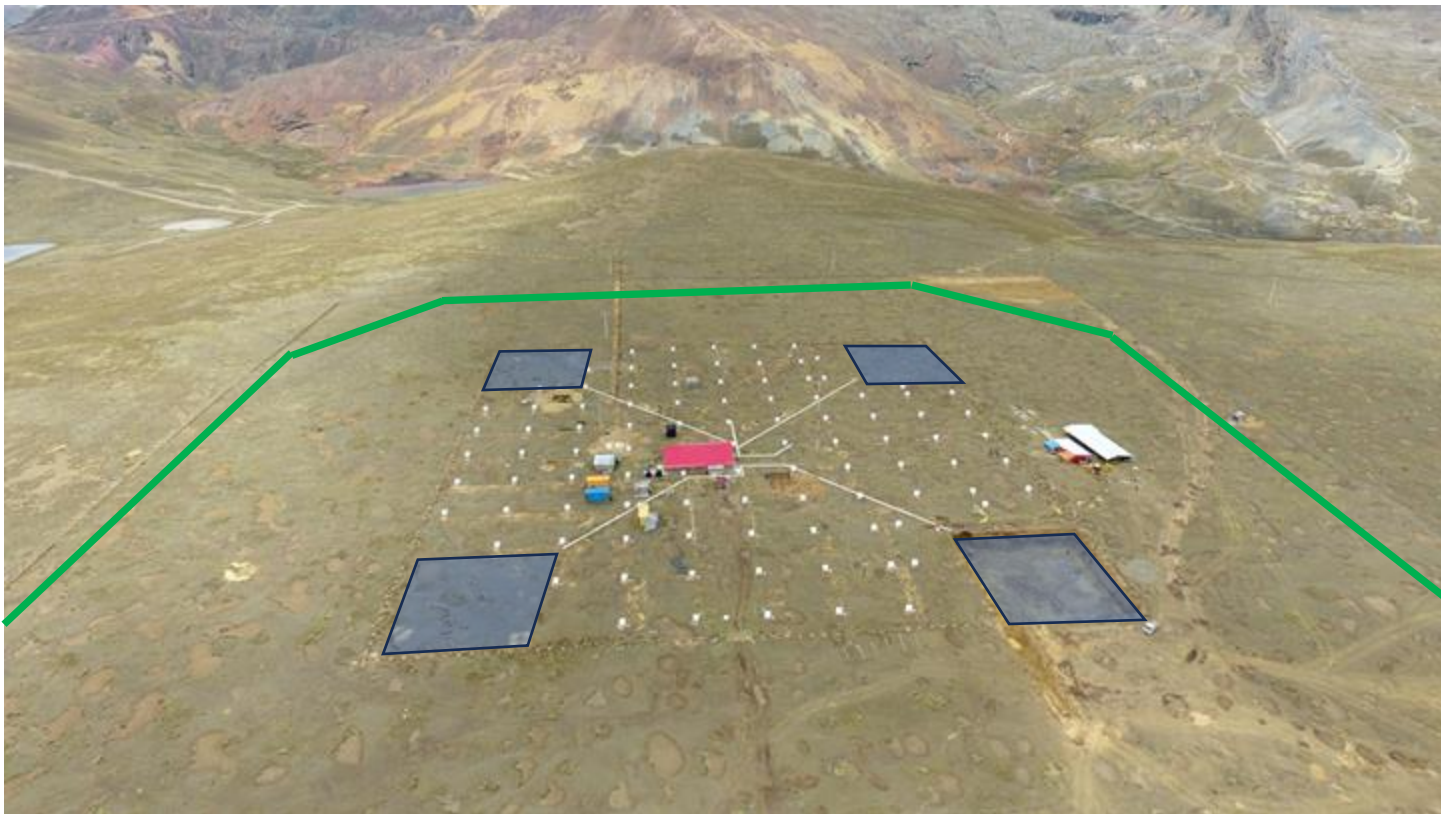
Construction

Nov 2025	Start
May 2026	1stMD
Sep 2026	4MDs

Muon Detector Construction



Deployment of scintillation detectors around MDs will start in June 2026



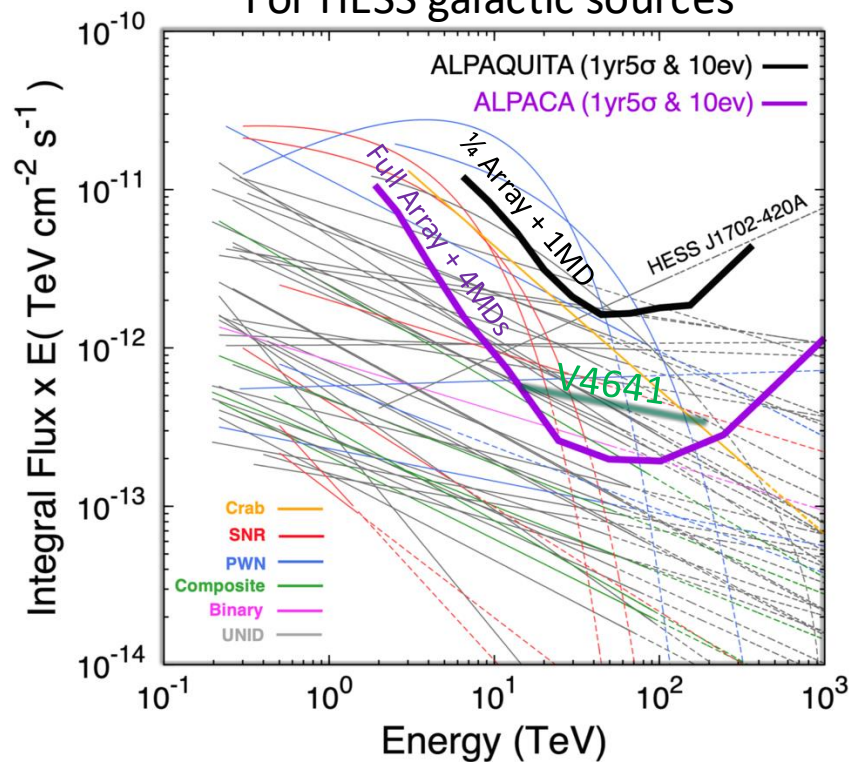
Construction

Nov 2025	Start
May 2026	1stMD
Sep 2026	4MDs

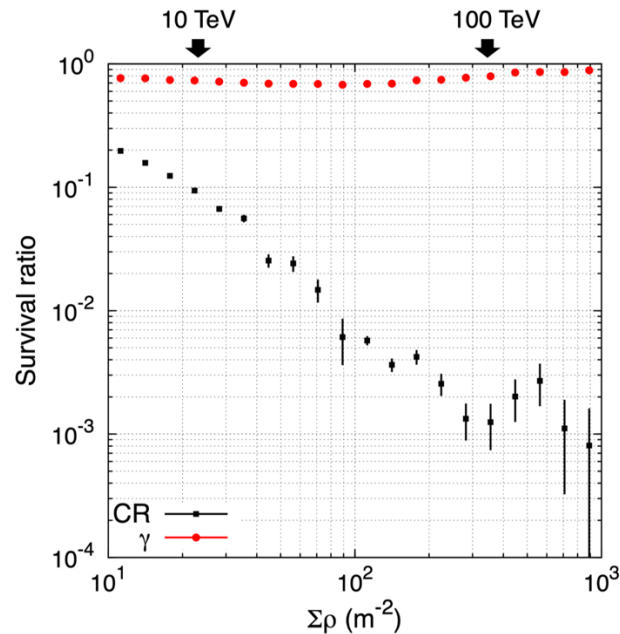
Future Gamm-Ray Sensitivity



For HESS galactic sources



- ✓ ALPACA(4MDs) will start observation in the next year
- ✓ 99.9% BG rejection while keeping 80% of photons @ 100TeV





Conclusions

- ✓ Tibet AS γ experiment successfully observed UHE gamma rays from the Crab Nebula for the first time and opened new energy window. (Now >40 UHE γ ray sources detected by LHAASO, HAWC, H.E.S.S. and Tibet AS γ)
- ✓ Tibet AS γ experiment successfully observed Galactic diffuse gamma rays between 100 TeV and 1 PeV for the first time.
- ✓ Tibet UHE events (>400 TeV) do not originate from LHAASO UHE (>100 TeV) sources. Possible source contribution from LHAASO UHE sources is less than 20-30%.
- ✓ IceCube diffuse neutrino flux smoothly connects to Tibet AS γ diffuse gamma-ray flux assuming π^0 best-fit model supporting the cosmic-ray origin.
- ✓ Tibet AS γ experiment measured the energy spectra of a few PeVatron candidates associated with the molecular clouds.

These facts indicate strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.

→ Search for more PeVatron candidates!

→ Go South, ALPACA will start soon!