M. Amenomori *et al.* Phys. Rev. Lett. **126**, 141101

Physics See Viewpoint: Signs of PeVatrons in Gamma-Ray Haze

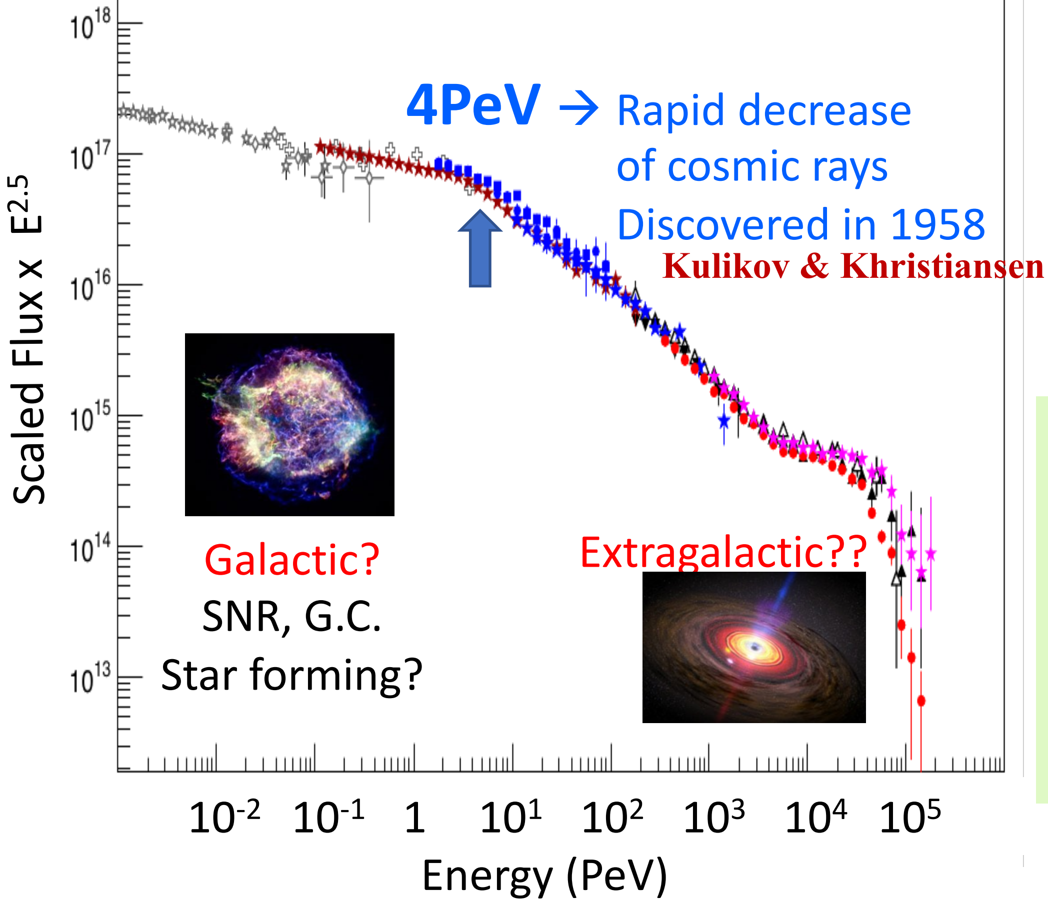
Diffuse Gamma Rays and PeV Cosmic Rays with the Tibet ASγ Experiment

Kazumasa KAWATA (ICRR, University of Tokyo)
For the Tibet ASγ Collaboration

Outline

- ✓ Introduction
- ✓ The Tibet ASγ Experiment
- ✓ First detection of UHE (> 100 TeV) γ rays
- ✓ Sub-PeV diffuse γ rays from the Milky Way galaxy
- ✓ Other PeVatron Candidates
- ✓ Summary

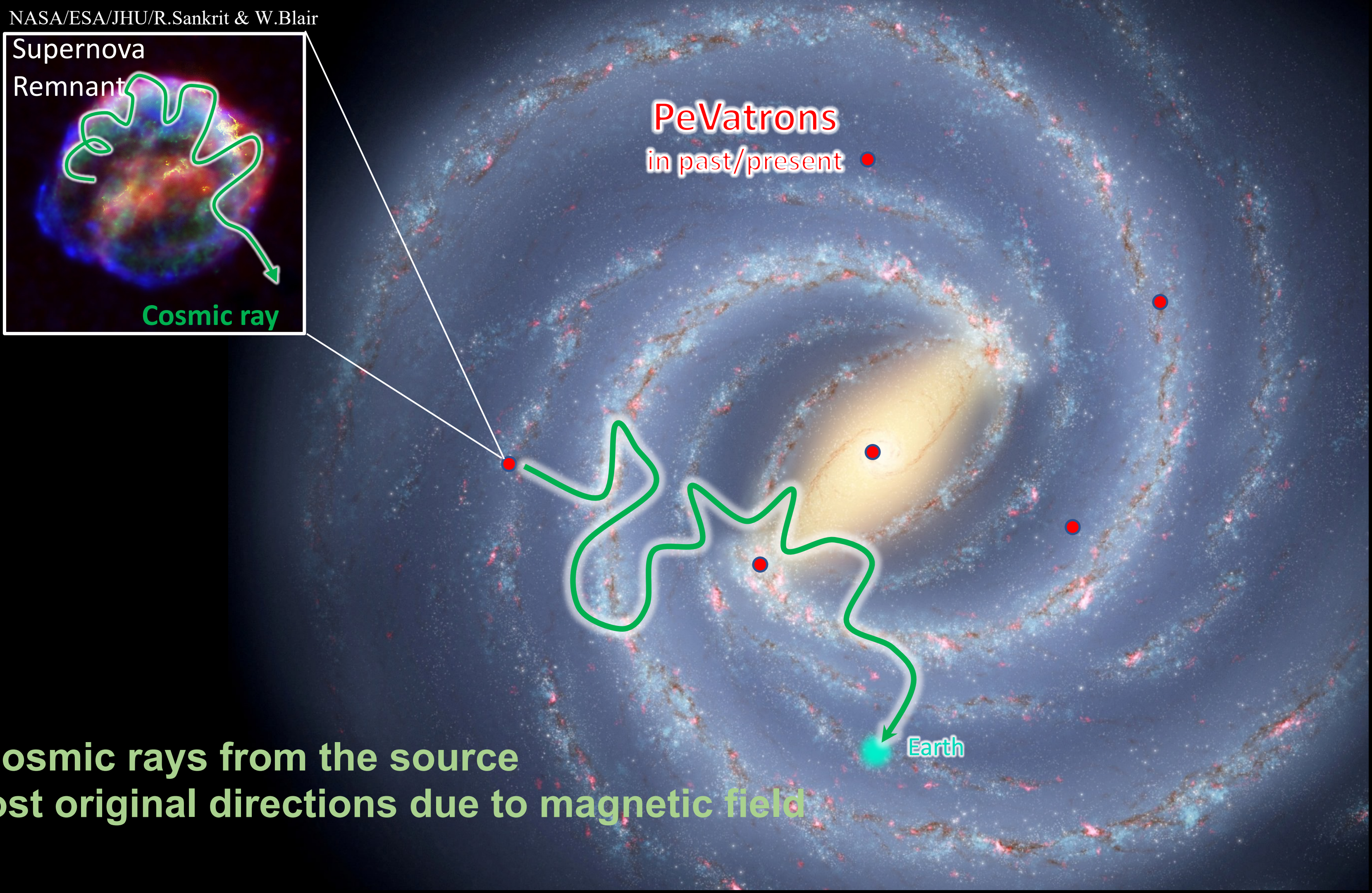
Introduction



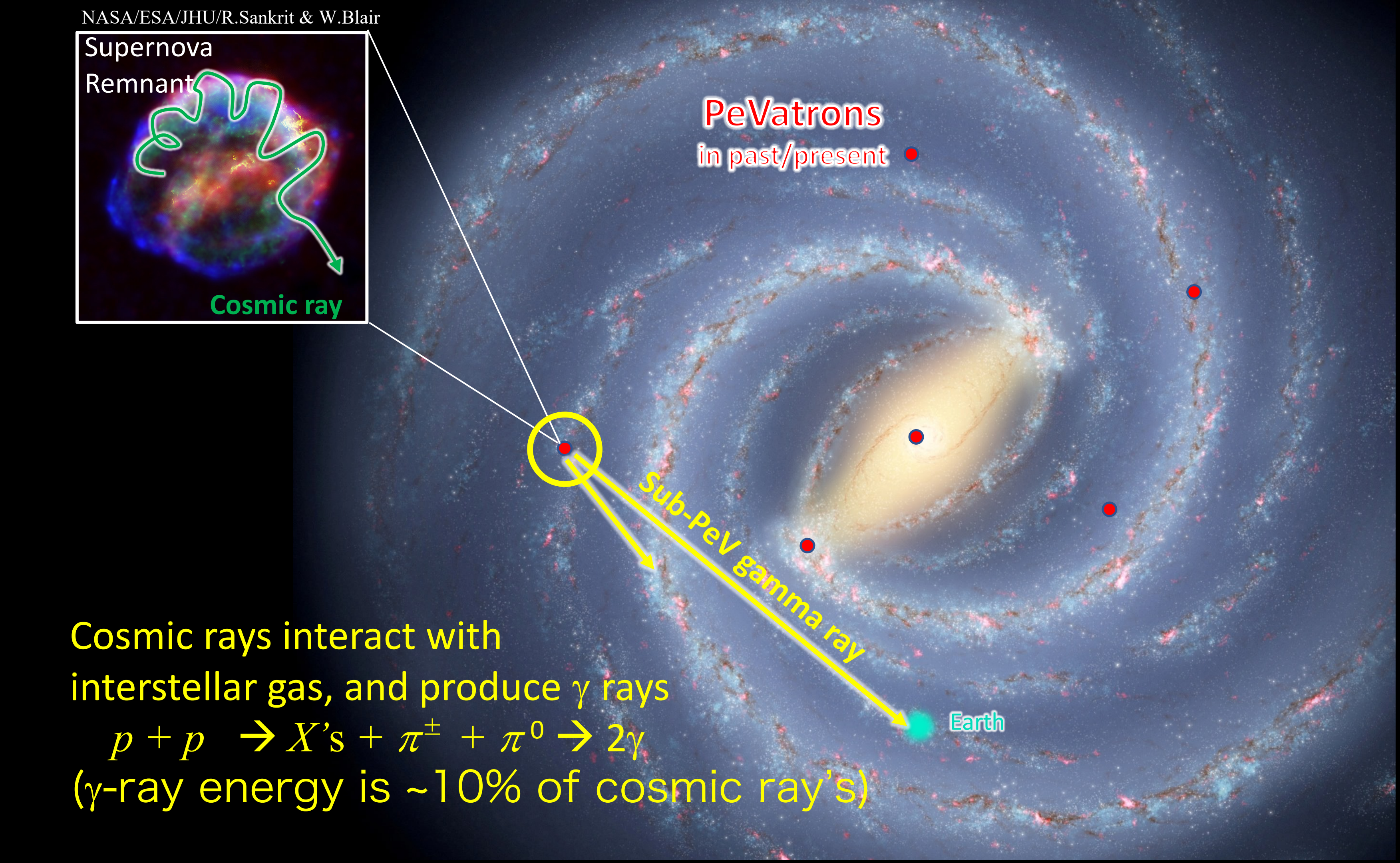
- ❖ Wide energy range
- ❖ Main component is proton
- ❖ Rate decreases to 1/100 when energy is 10 times higher

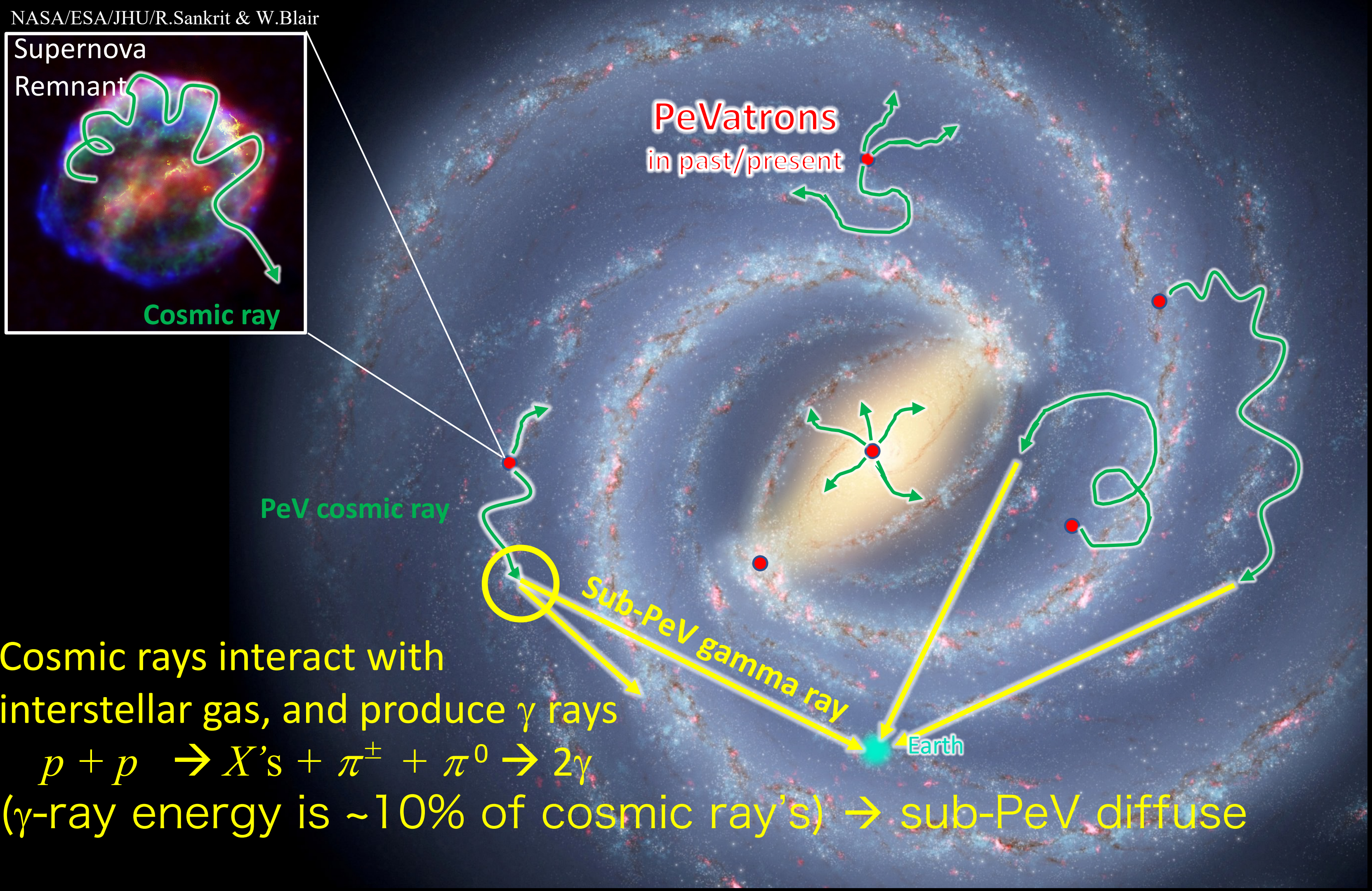
As an open question,
Did/Do “PeVatrons” really exist in our Galaxy?

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



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


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova Remnant
Cosmic ray
PeVatrons
in past/present
Sub-PeV gamma ray
Earth
Cosmic rays interact with interstellar gas, and produce γ rays
$p + p \rightarrow X\text{'s} + \pi^{\pm} + \pi^{0} \rightarrow 2\gamma$
(γ-ray energy is ~10% of cosmic ray's)



Cosmic rays interact with interstellar gas, and produce γ rays

$$p + p \rightarrow X\text{'s} + \pi^{\pm} + \pi^{0} \rightarrow 2\gamma$$

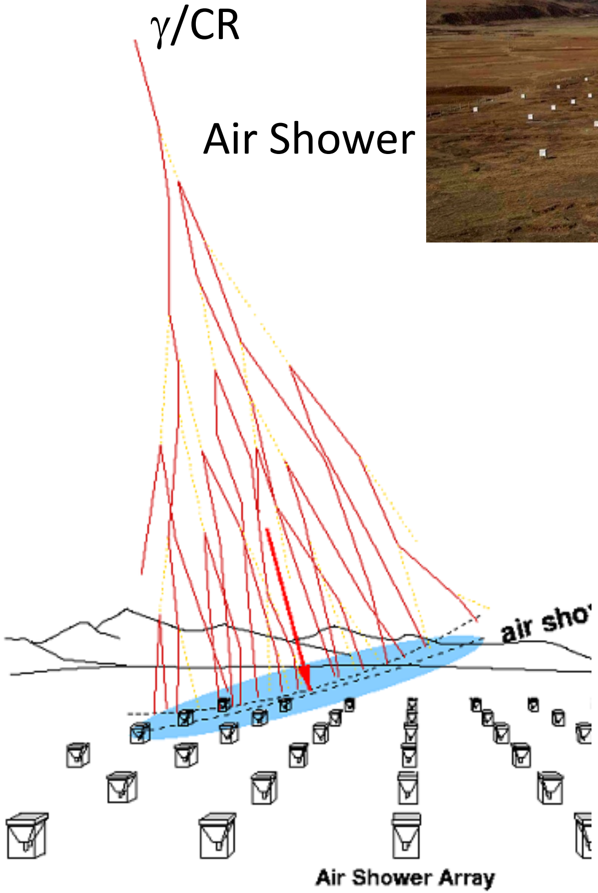
(γ-ray energy is ~10% of cosmic ray's) → sub-PeV diffuse

Tibet ASγ Collaboration

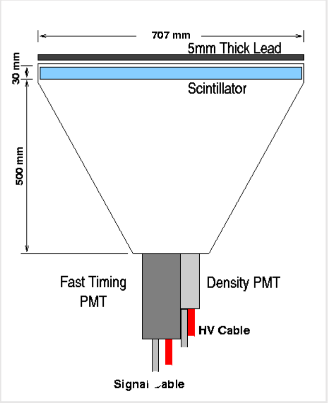
M. Amenomori[1], S. Asano[2], Y. W. Bao[3], X. J. Bi[4], D. Chen[5], T. L. Chen[6], W. Y. Chen[4], Xu Chen[4,5], Y. Chen[3], Cirennima[6], S. W. Cui[7], Danzengluobu[6], L. K. Ding[4], J. H. Fang[4,8], K. Fang[4], C. F. Feng[9], Zhaoyang Feng[4], Z. Y. Feng[10], Qi Gao[6], A. Gomi[11], Q. B. Gou[4], Y. Q. Guo[4], Y. Y. Guo[4], Y. Hayashi[2], H. H. He[4], Z. T. He[7], K. Hibino[12], N. Hotta[13], Haibing Hu[6], H. B. Hu[4], K. Y. Hu[4,8], J. Huang[4], H. Y. Jia[10], L. Jiang[4], P. Jiang[5], H. B. Jin[5], K. Kasahara[14], Y. Katayose[11], C. Kato[2], S. Kato[15], I. Kawahara[11], T. Kawashima[15], K. Kawata[15], M. Kozai[16], D. Kurashige[11], Labaciren[6], G. M. Le[17], A. F. Li[4,9,18], H. J. Li[6], W. J. Li[4,10], Y. Li[5], Y. H. Lin[4,8], B. Liu[19], C. Liu[4], J. S. Liu[4], L. Y. Liu[5], M. Y. Liu[6], W. Liu[4], X. L. Liu[5], Y.-Q. Lou[20,21,22], H. Lu[4], X. R. Meng[6], Y. Meng[4,8], K. Munakata[2], K. Nagaya[11], Y. Nakamura[15], Y. Nakazawa[23], H. Nanjo[1], C. C. Ning[6], M. Nishizawa[24], R. Noguchi[11], M. Ohnishi[15], S. Okukawa[11], S. Ozawa[25], L. Qian[5], X. Qian[5], X. L. Qian[26], X. B. Qu[27], T. Saito[28], Y. Sakakibara[11], M. Sakata[29], T. Sako[15], T. K. Sako[15], T. Sasaki[12], J. Shao[4,9], M. Shibata[11], A. Shiomi[23], H. Sugimoto[30], W. Takano[12], M. Takita[15], Y. H. Tan[4], N. Tateyama[12], S. Torii[31], H. Tsuchiya[32], S. Udo[12], H. Wang[4], Y. P. Wang[6], Wangdui[6], H. R. Wu[4], Q. Wu[6], J. L. Xu[5], L. Xue[9], Z. Yang[4], Y. Q. Yao[5], J. Yin[5], Y. Yokoe[15], N. P. Yu[5], A. F. Yuan[6], L. M. Zhai[5], C. P. Zhang[5], H. M. Zhang[4], J. L. Zhang[4], X. Zhang[3], X. Y. Zhang[9], Y. Zhang[4], Yi Zhang[33], Ying Zhang[4], S. P. Zhao[4], Zhaxisangzhu[6], X. X. Zhou[10] and Y. H. Zou[4,8]

1 Department of Physics, Hirosaki 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, TJapan.
33 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.

Tibet Air Shower Array



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



Present Performance

✓	# of detectors	0.5 m^2 x 597
✓	Covering area	~65,700 m^2
✓	Angular resolution	~0.5°@10TeV γ
		~0.2°@100TeV γ
✓	Energy resolution	~40%@10TeV γ
		~20%@100TeV γ

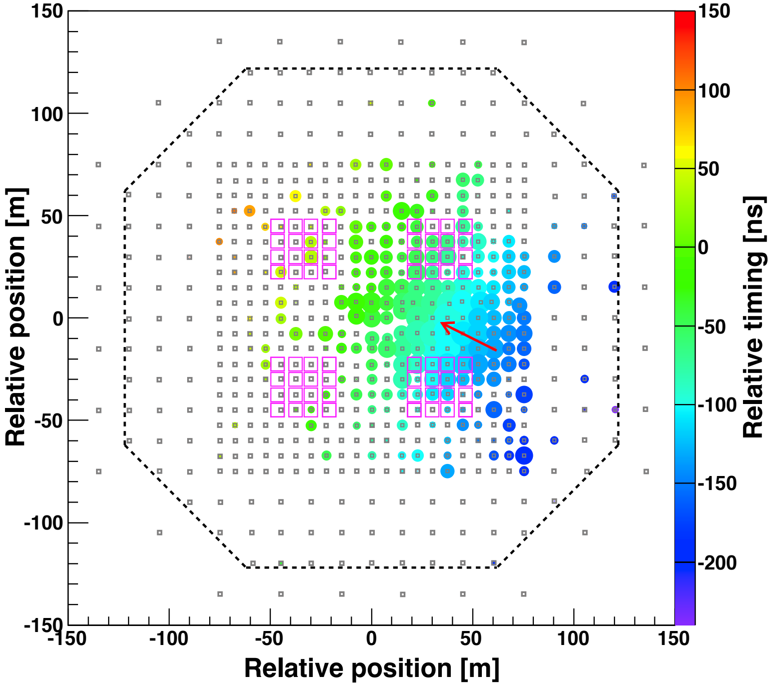
→Observation of secondary (mainly $e^{+/-}$,γ) in AS

Primary energy : 2^{nd} particle densities

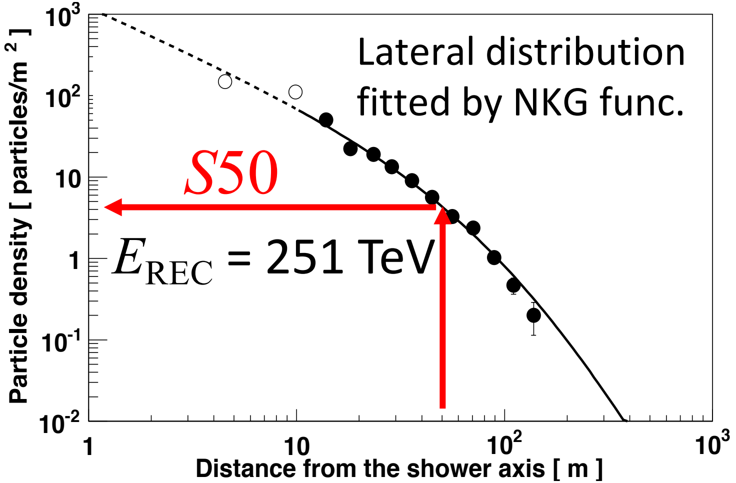
Primary direction : 2^{nd} relative timings

Air Shower Reconstruction

Gamma-ray candidate event



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



circle size ∝ log(# of detected particles)

circle color ∝ relative timing [ns]

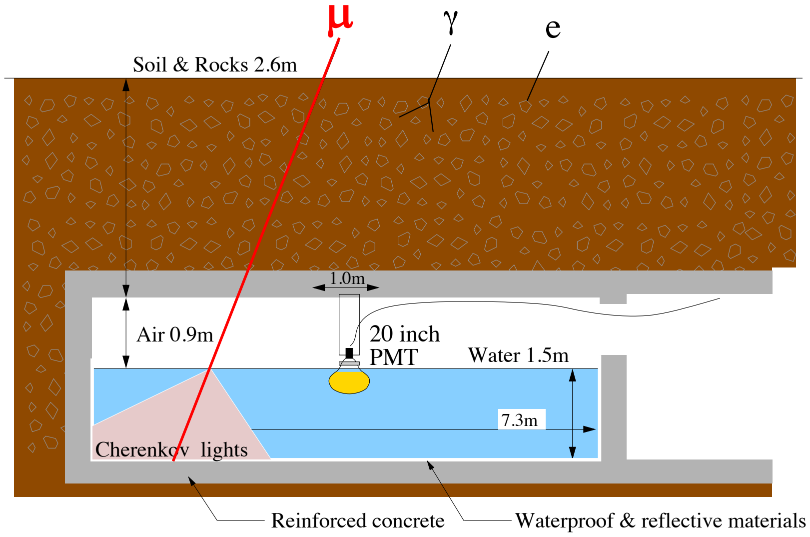
S50 improves E resolutions (10 - 1000 TeV)

→ ~40%@10 TeV , ~20%@100 TeV

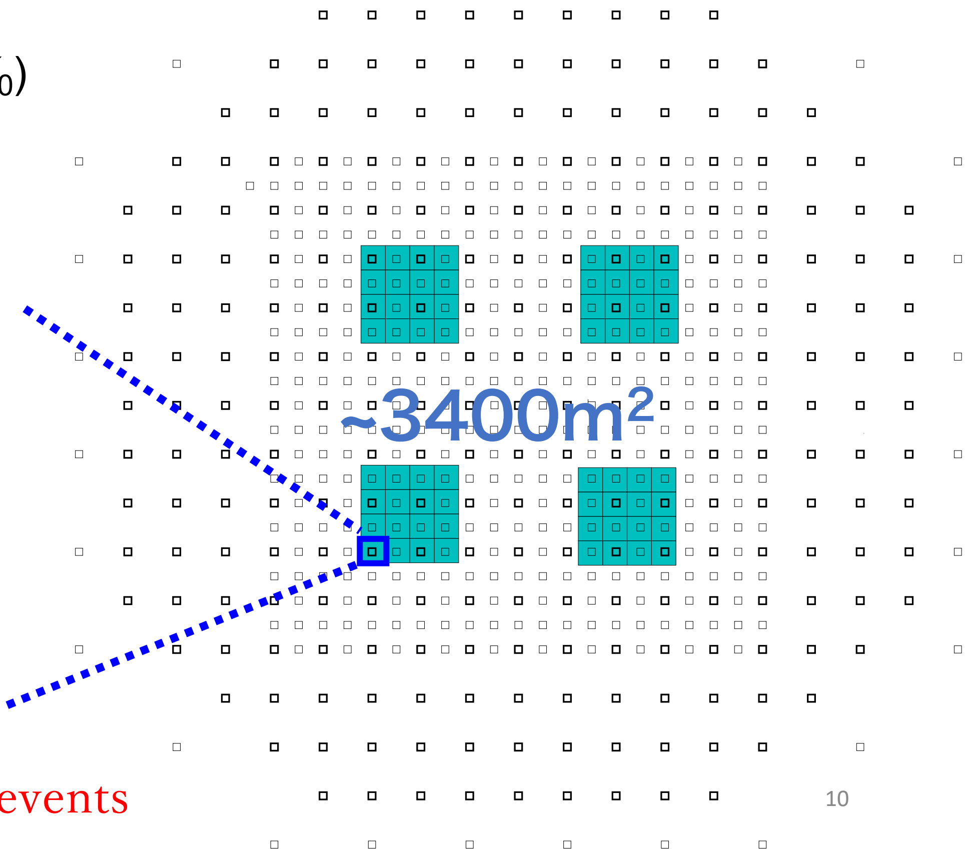
Kawata+, Experimental Astronomy ***44****, 1 (2017)*

Underground WC Muon Detectors

- ✓ 4 pools, 16 units / pool
- ✓ 54 m^2 in area ×1.5m in depth / unit
- ✓ 2.4m soil overburden (~515g/cm^2 ~9X_0)
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets



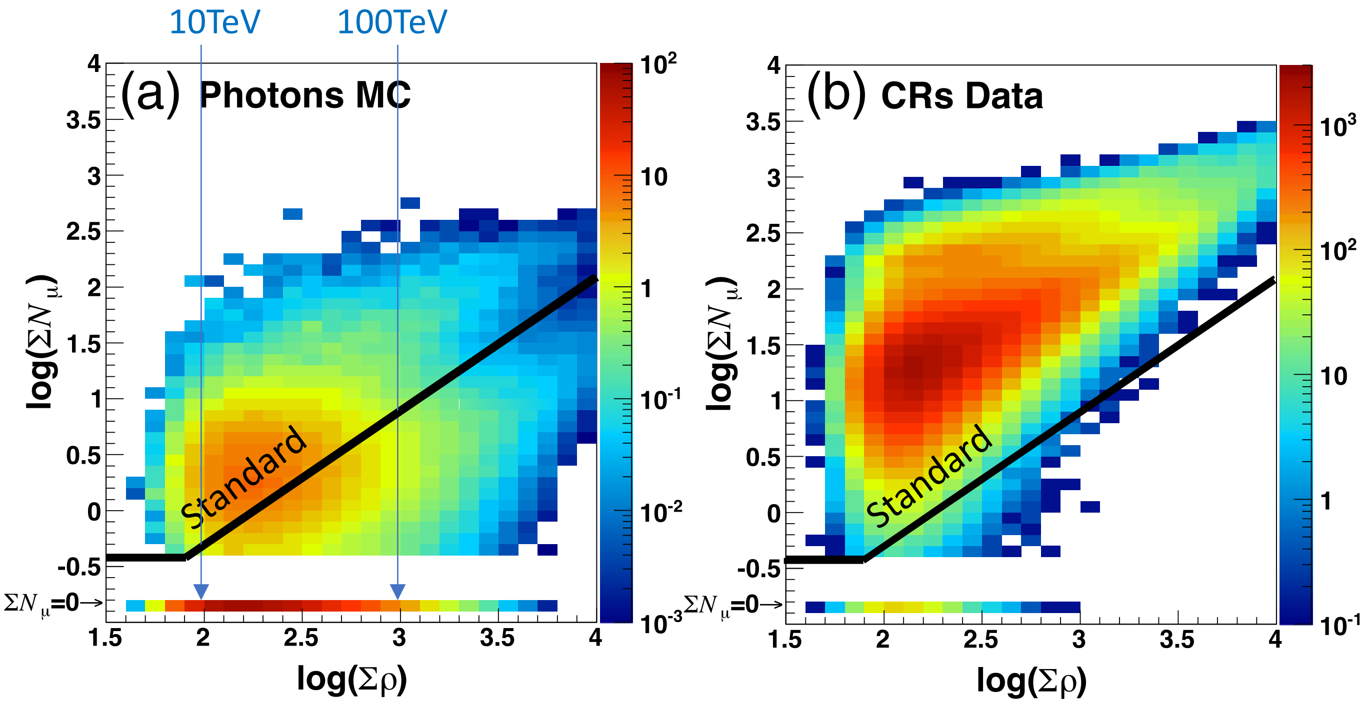
Measurement of # of μ in AS → γ／CR discrimination
DATA: February 2014 - May 2017 Live time: 719 days



→Succeeded in rejecting by >99.9% CR events

Muon Cut Condition (Standard)

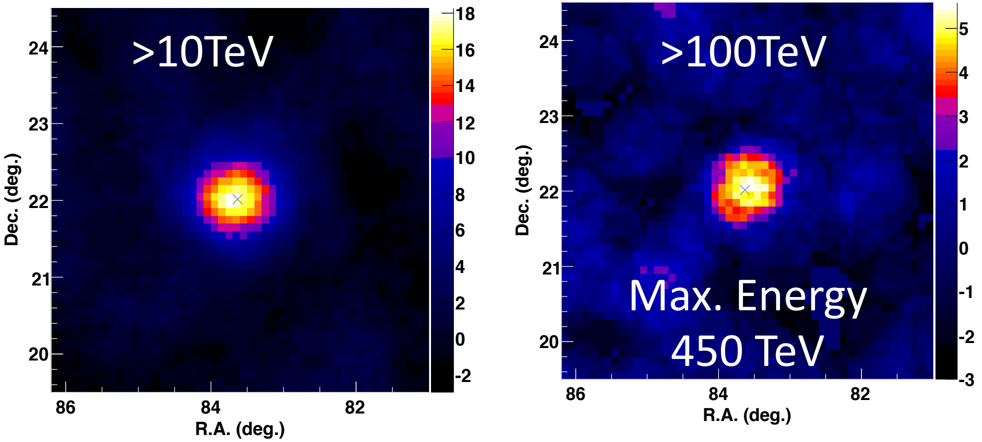
Tight muon cut : $\Sigma N\mu < 2.1 \times 10^{-3}\ \Sigma\rho^{1.2}$ → Optimized for the gamma-ray point-like source



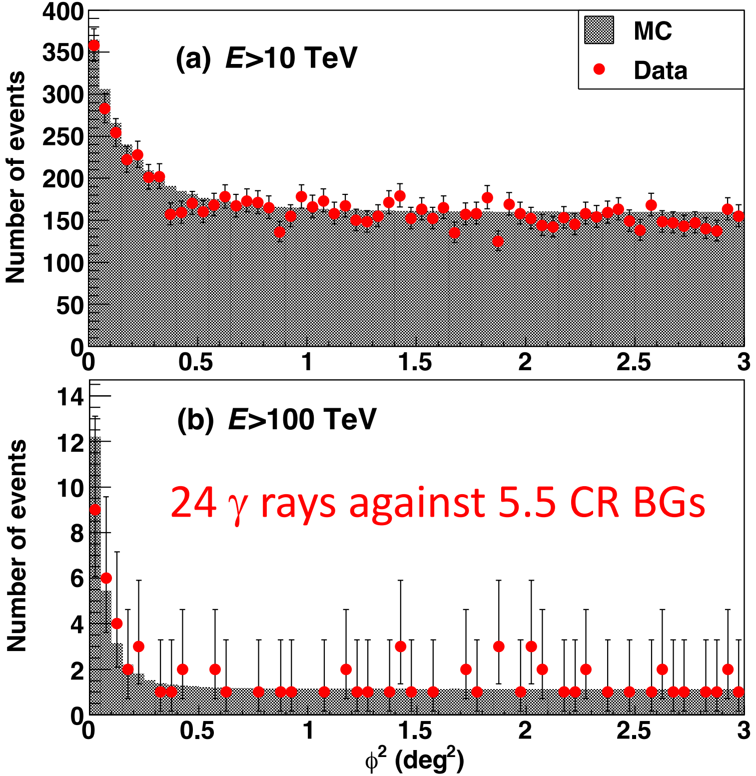
Gamma Survival ratio : ~90% by MC sim (>100TeV) CR Survival ratio : $\sim 10^{-3}$ (>100TeV)

UHE γ-rays from the Crab Nebula (2019)

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



Data vs MC

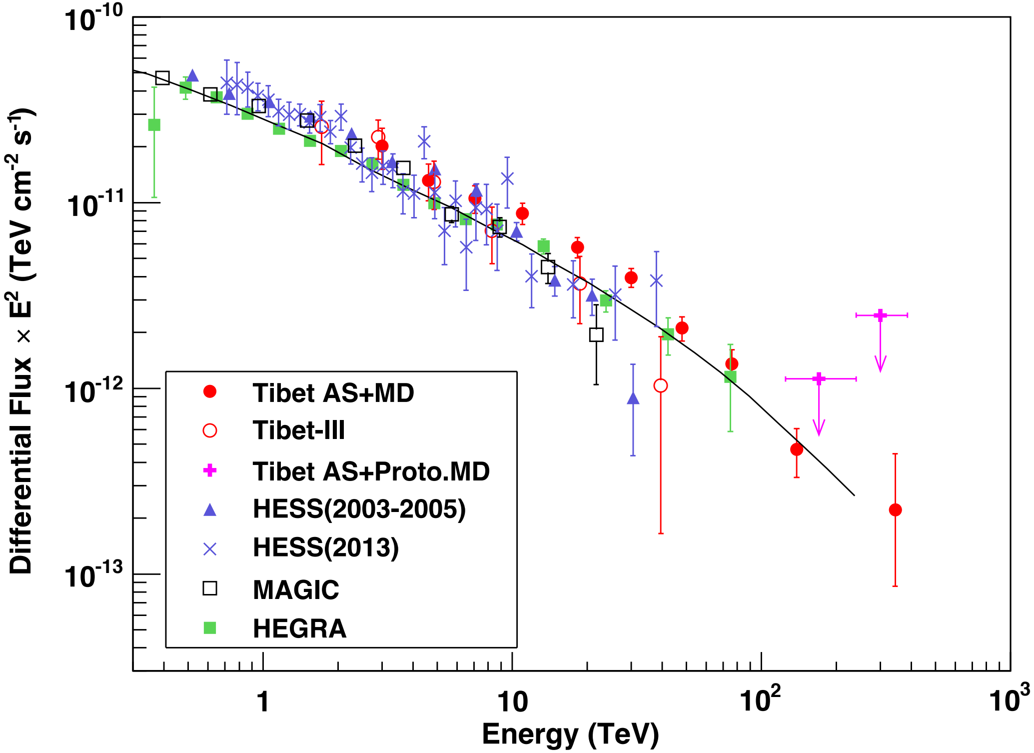


First Detection of Sub-PeV γ (5.6σ)

Other published sources in 100 TeV region

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

UHE γ-rays from the Crab Nebula (2019)



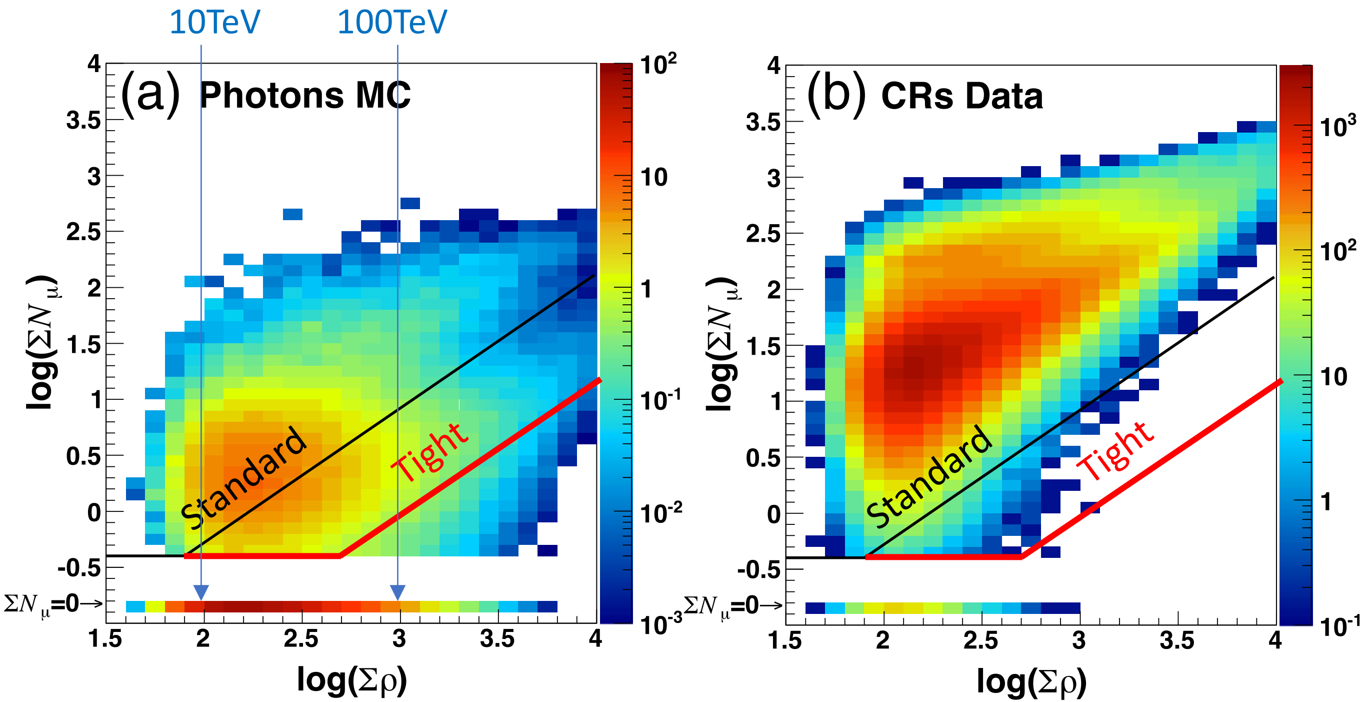
*Amenomori+, PRL, **123**, 051101, (2019)*

The highest energy γ ~450 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



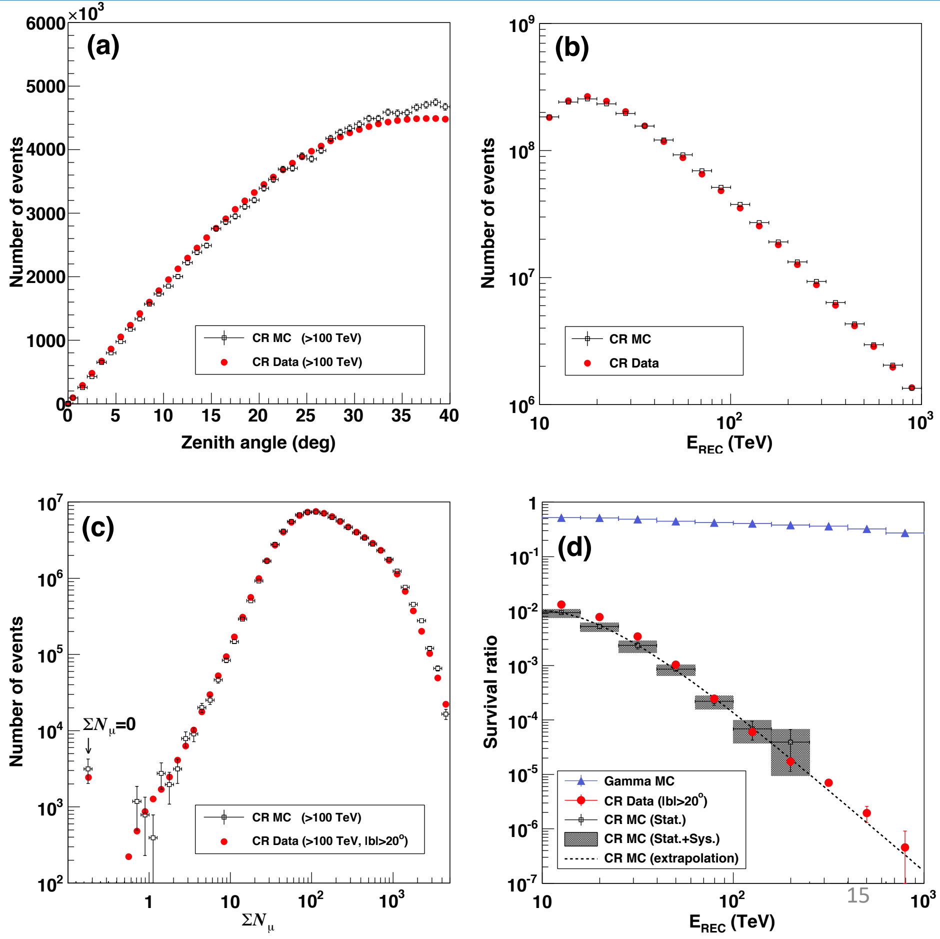
Gamma Survival ratio : ~30% by MC sim (>398TeV) CR Survival ratio : ~10^{-6} (>398TeV=$10^{2.6}$TeV)

Data/MC Comparison

- ✓ AS generation: CORSIKA
- ✓ Hadronic int. model:
  EPOS-LHC + FLUKA
- ✓ Detectors: GEANT4

Reasonable agreement!

*Note: Cosmic-ray MC simulation is not used for the flux calculation or for any optimization of the analysis.

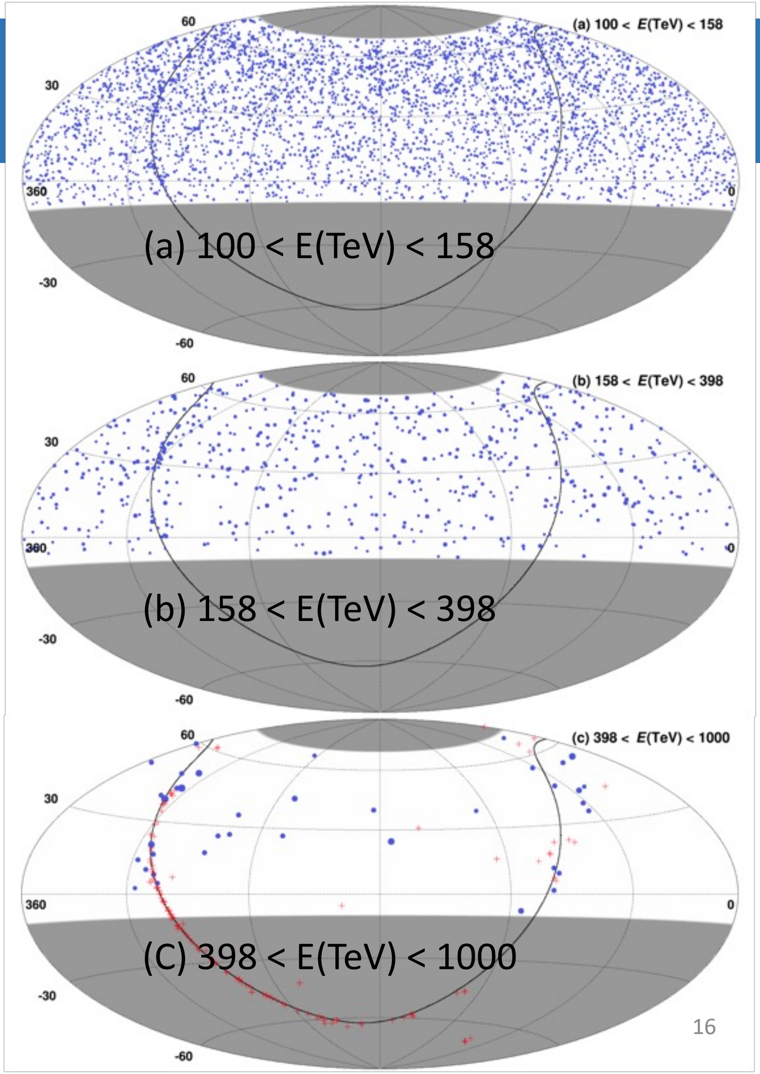


γ-ray-like event Distribution

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 $|b| < 10^{o}$
16 events in $|b| < 5^{o}$



Latitude Profile

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

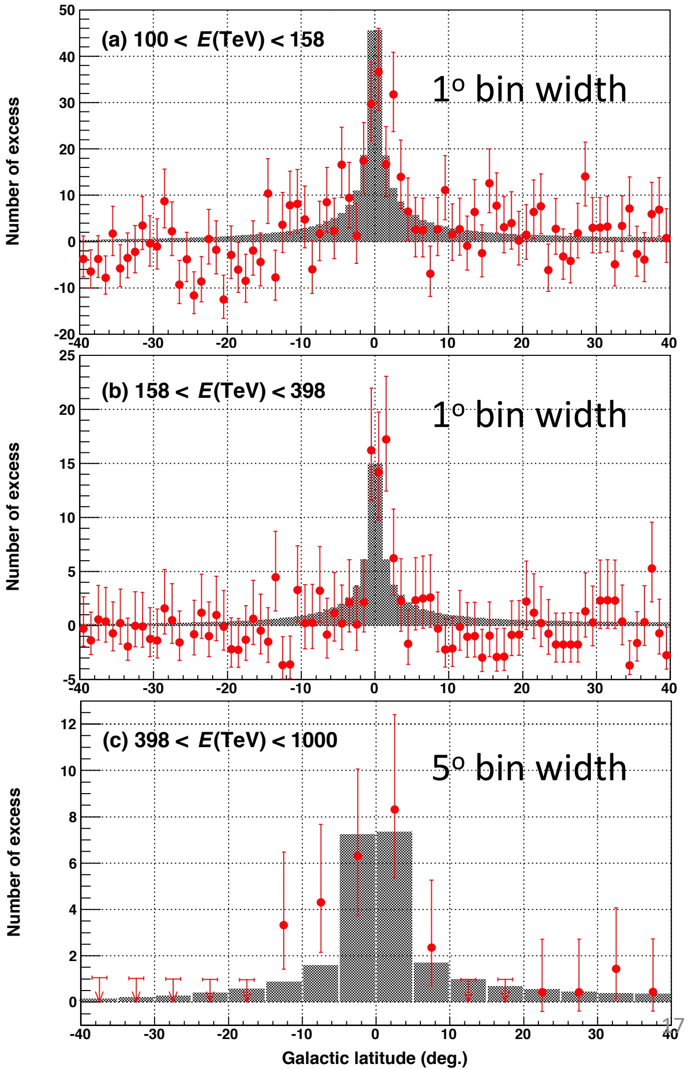
Gray shade histogram:
Model by Lipari and Vernetto

Lipari & Vernetto, PRD 98, 043003 (2018)

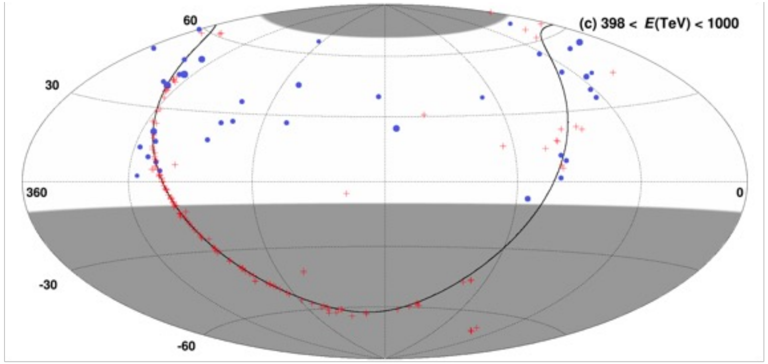
6.6σ

5.1σ

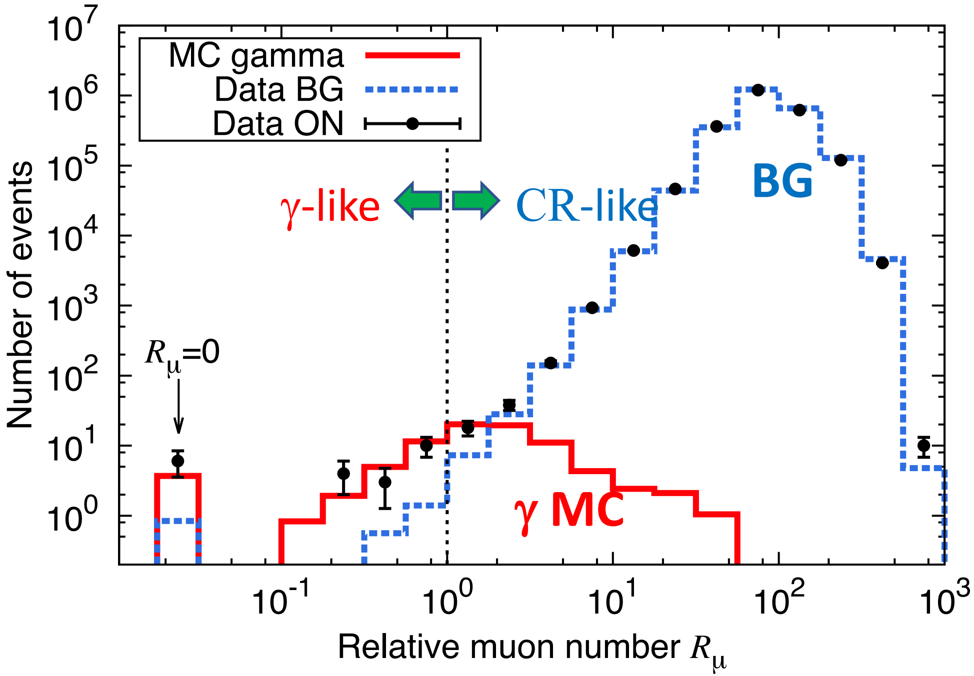
5.9σ



Muon Number Distribution (>398 TeV)



- ON region $|b| < 10^{o}$
- BG region $|b| > 20^{o}$



Gamma Survival ratio :
30% by MC sim (>398TeV)

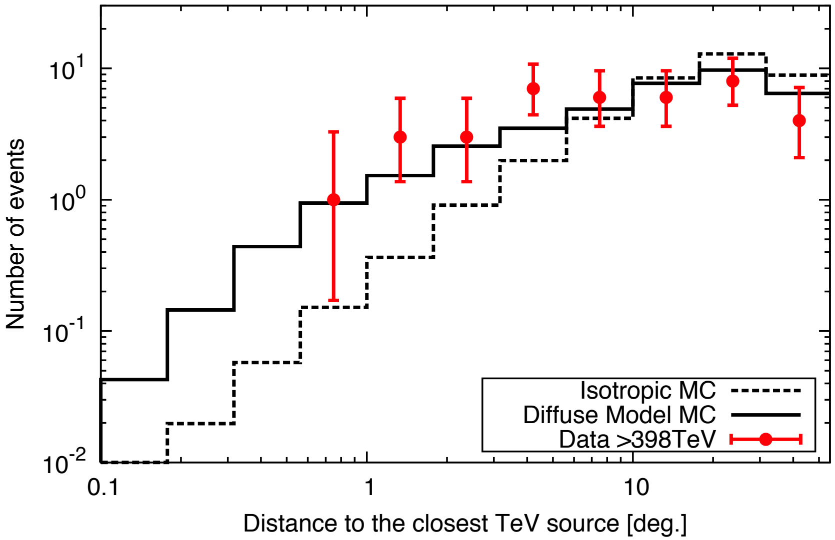
CR Survival ratio :
$\sim 10^{-6}$ (>398TeV=$10^{2.6}$TeV)

$$R\mu = \frac{\text{Observed \# of muons}}{\text{\# of muons at the cut value}}$$

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

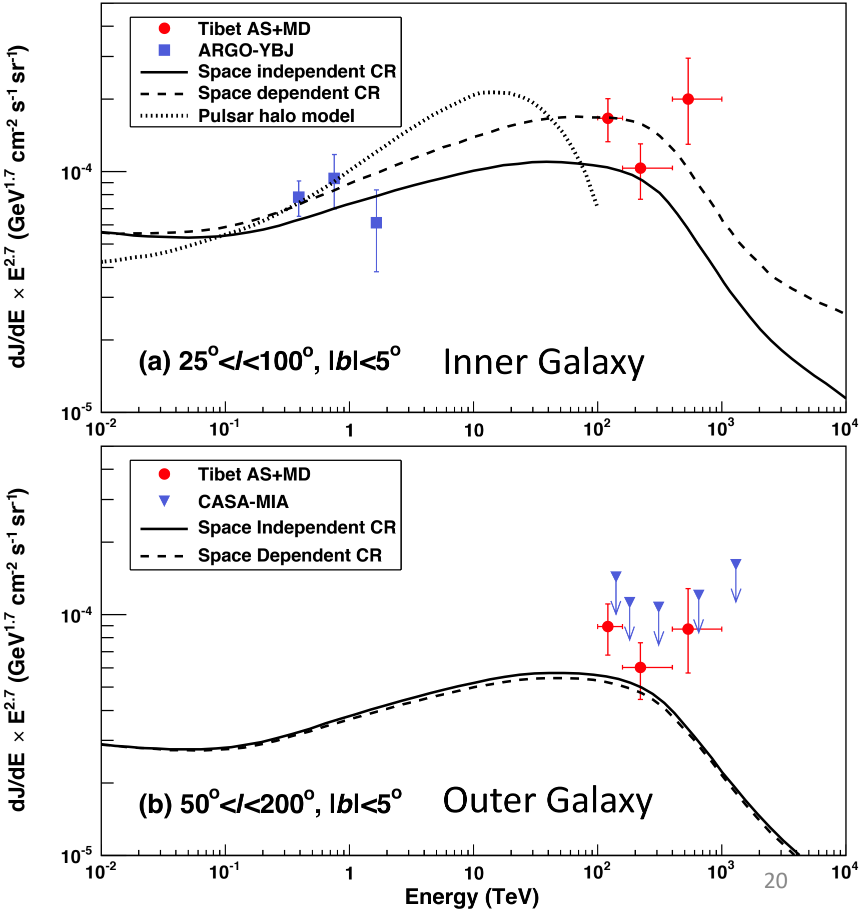
Energy Spectrum of UHE Diffuse γ Rays

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

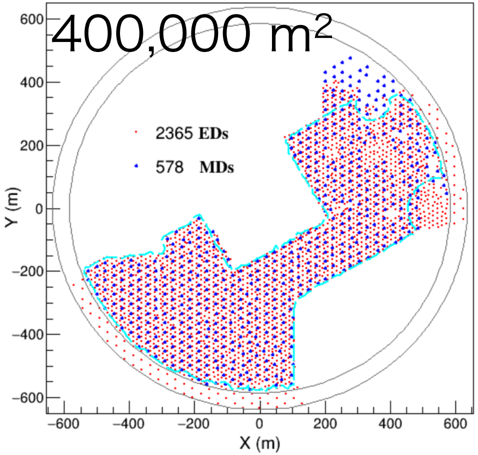
The measured fluxes are overall consistent with Lipari's diffuse gamma model assuming the hadronic cosmic ray origin.

$$CR + ISM \rightarrow X\text{'s} + \pi^0 \ldots \rightarrow 2\gamma$$

Lipari & Vernetto, PRD 98, 043003 (2018)

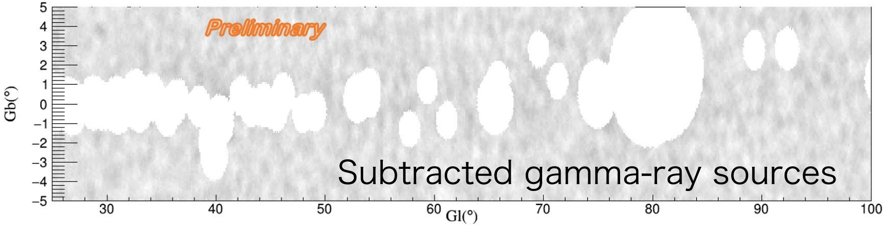


Preliminary Result by LHAASO

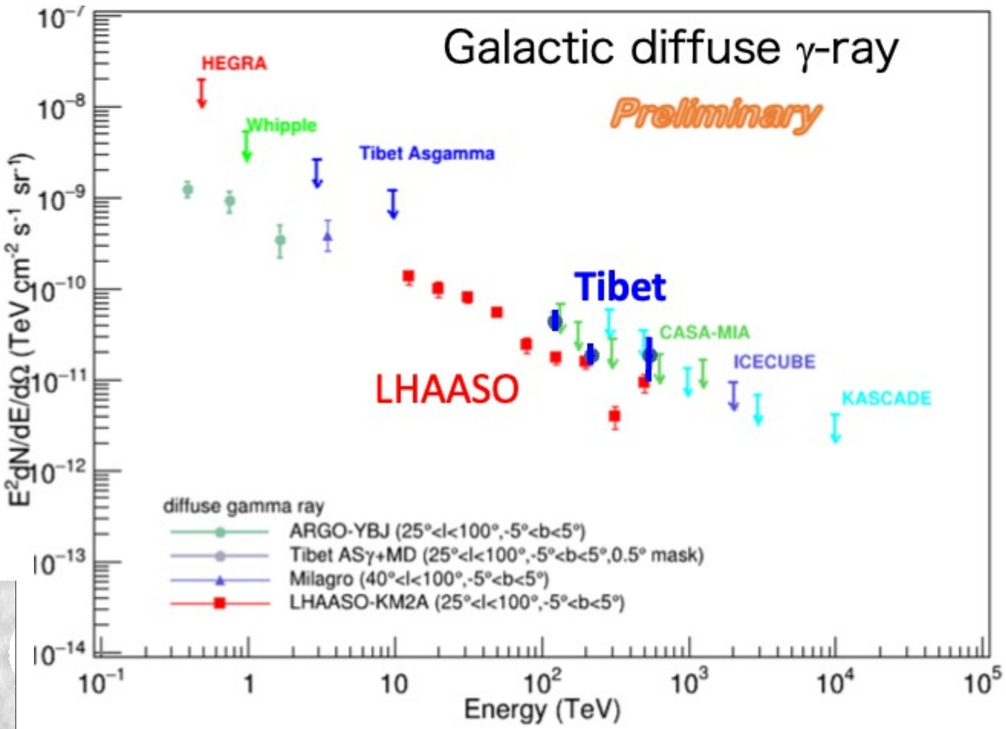


KM2A(1/2 Array) Detectors Distribution

Masked radius $R < 2\sqrt{p.s.f^2 + \sigma_{ext}^2}$



S. P. Zhao ICRC2021



Composition Dependence

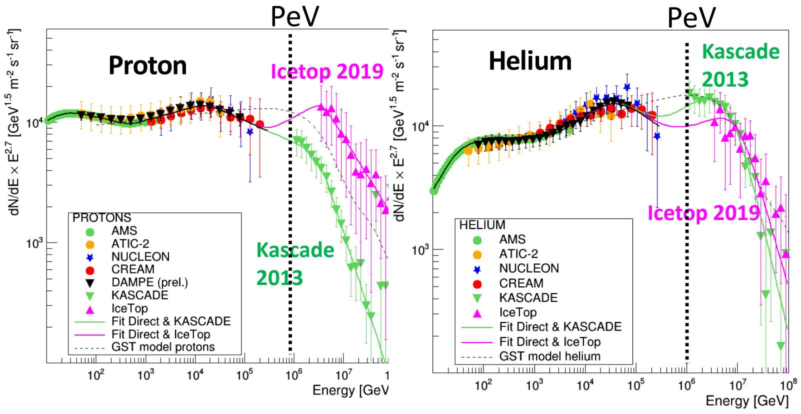
CRs interact with interstellar gas
(γ-ray energy has 10% of CRs)

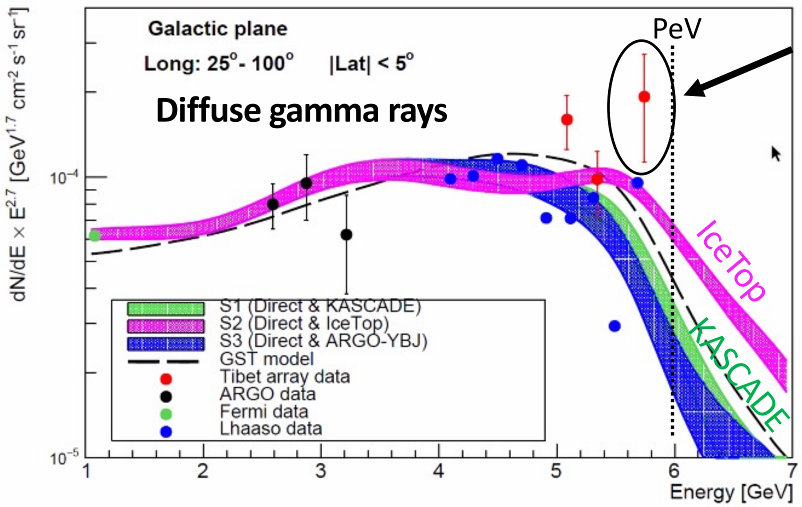
CR + ISM → X's + π^0 … → 2γ

→ Diffuse gamma-ray spectrum depends on the CR composition

Vernetto & Lipari (ICRC2021)

factor 1.5 – 2 difference@~600 TeV

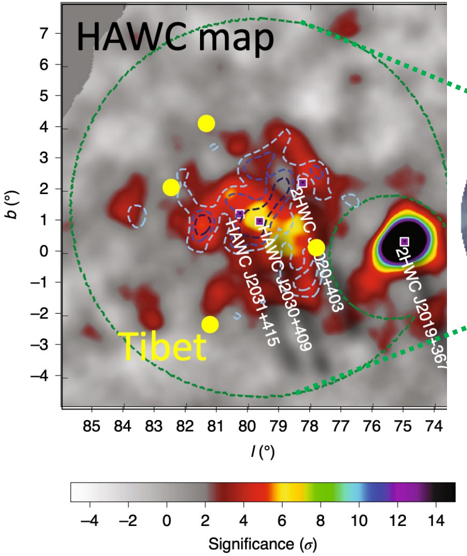


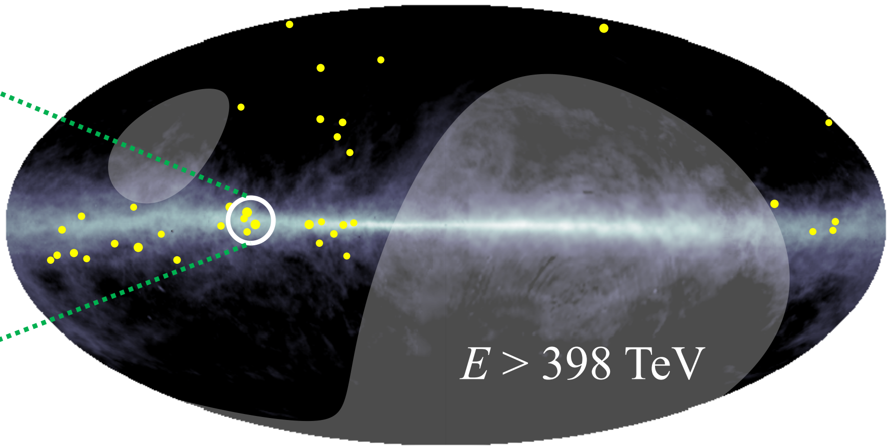


4 ev / 10 ev from Cygnus cocoon (< 4°)

PeVatron Candidate: Cygnus Cocoon

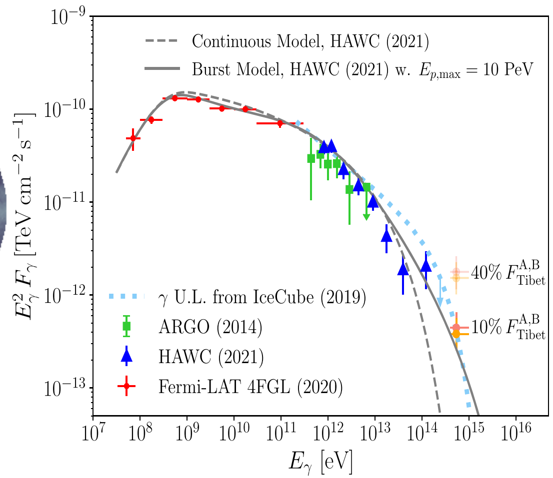
Abeysekara et al., Nature Astronomy (2021)





Galactic Coordinates

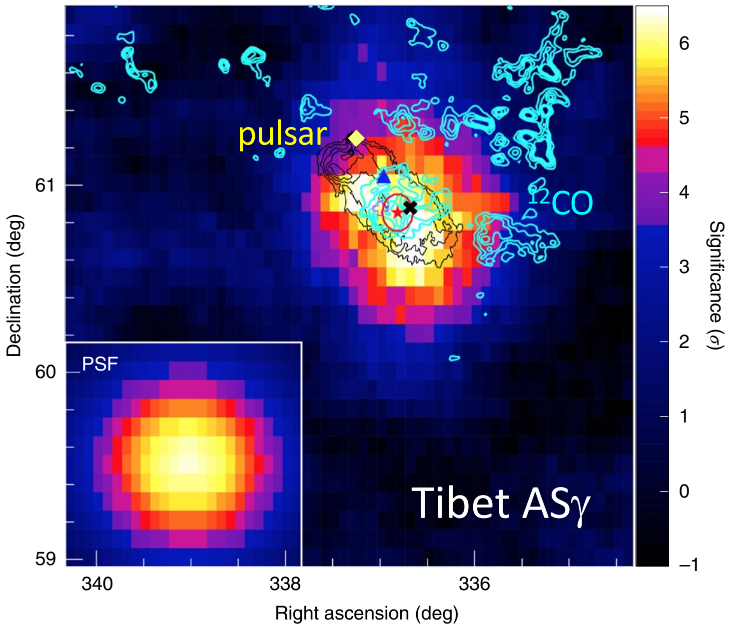
Fang & Murase, ApJ, 919, 93 (2021)

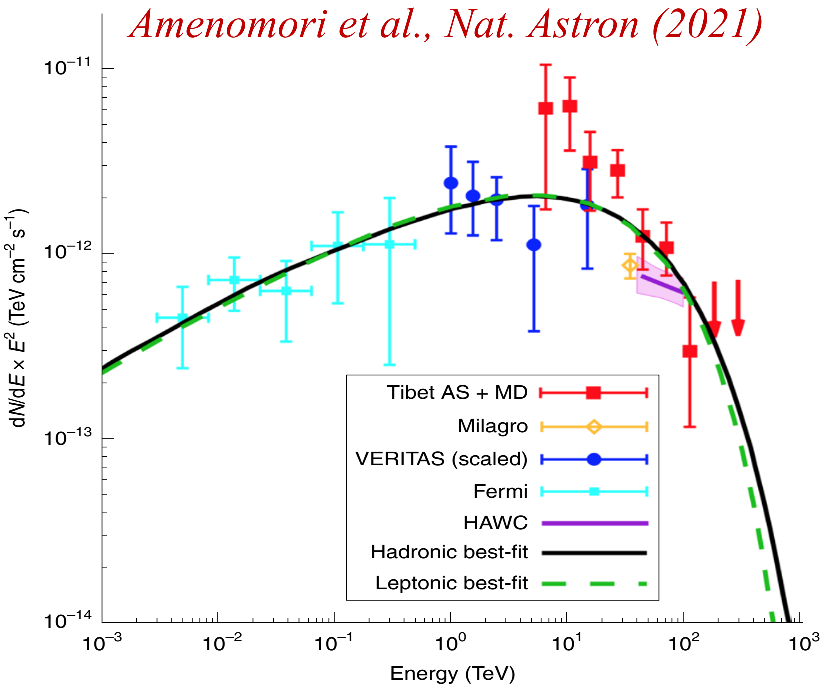


4 events above 398 TeV detected within 4°-radius-circle from the Cygnus cocoon which is claimed as an extended source by the ARGO-YBJ and HAWC and also proposed as a candidate of the PeVatrons.

PeVatron Candidate: SNR G106.3+2.7

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





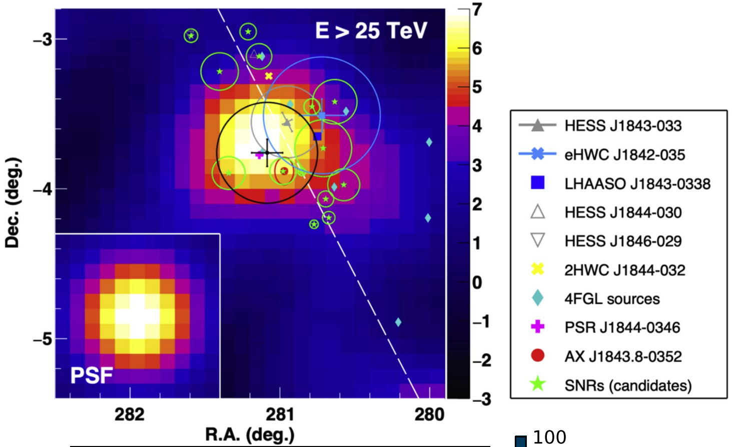
- ✓ Spectrum extends beyond 100 TeV (HAWC, Tibet ASγ, LHAASO)
- ✓ Shell-type SNR near the pulsar (t_{age}~10kyr?, d=800pc?)
- ✓ Extended γ-ray excess (σ_{EXT}=0.24° ± 0.10°)
- ✓ γ-ray excess is coincident with the could, not pulsar

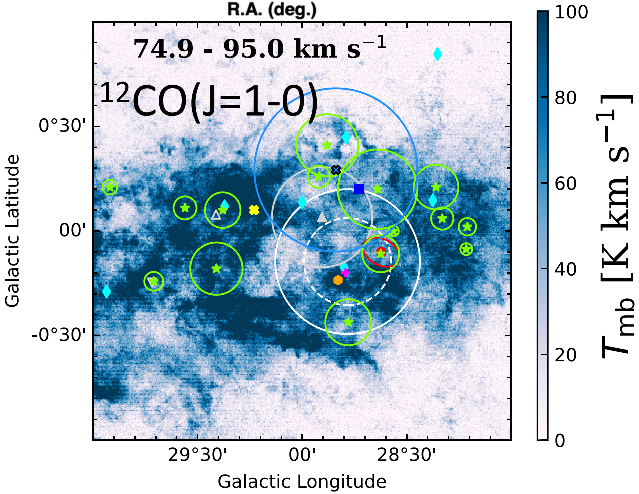
$E_{p,cut} = \sim 500$ TeV

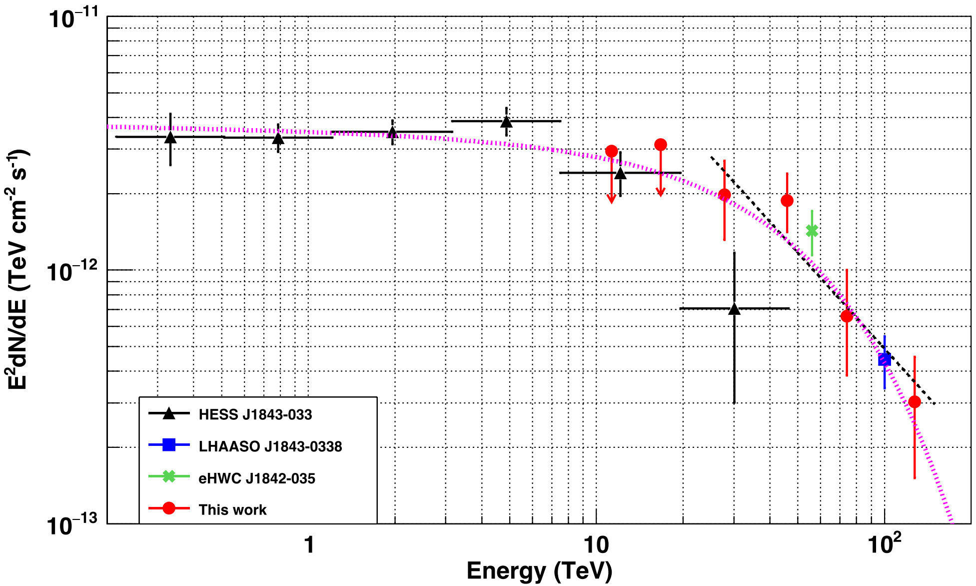
$W_p = \sim 5 \times 10^{47}$ erg

PeVatron Candidate: HESS J1943-033

Amenomori et al., ApJ, 932, 120 (2022)





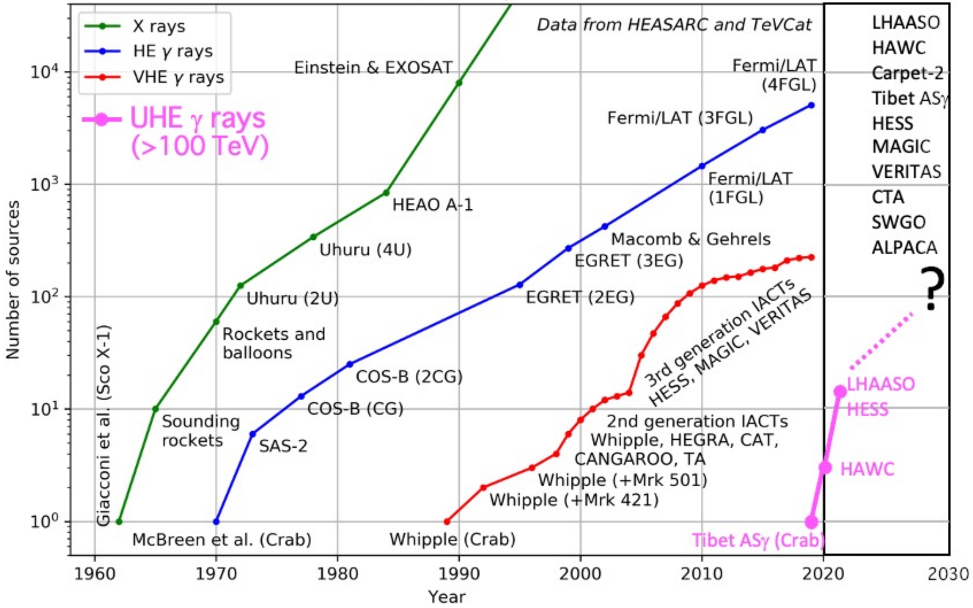


Candidate sources

- ✓ Shell-type SNR G28.6+0.1?
- ✓ PSR J1844-00346?
- ✓ γ-ray excess is coincident with the could and pulsar

UHE γ-ray astronomy $E > 100$ TeV (ICRC2021)

Kifune plot (Credit: Stephen Fegan) + UHE γ rays



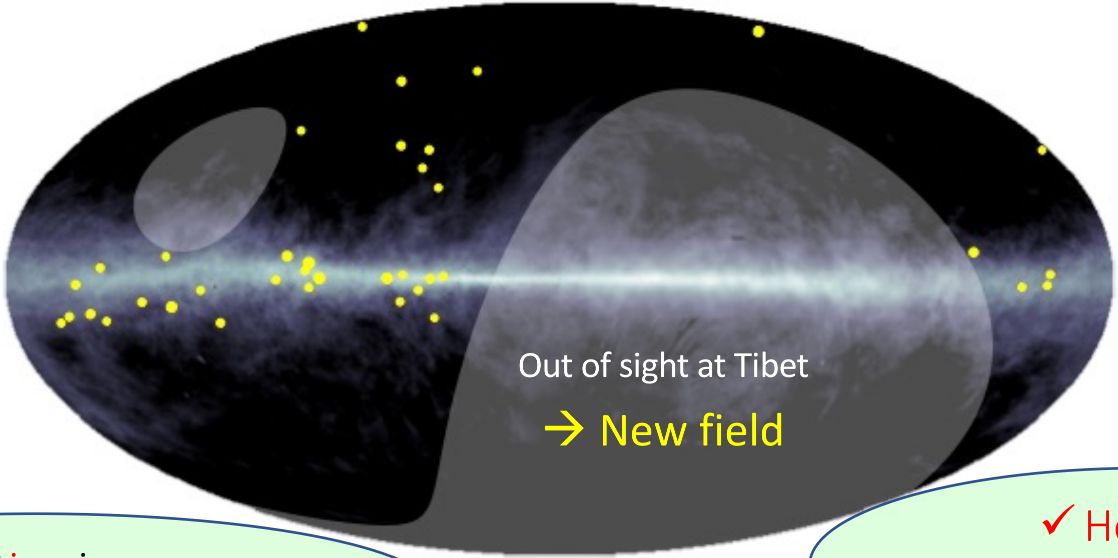
Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example http://adsabs.harvard.edu/abs/1996NCimC..19..953K).
The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on 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/

- ✓ Tibet ASγ experiment opened a new energy window UHE (>100 TeV).
- ✓ A dozen of UHE γ-ray sources discovered (Tibet ASγ, HAWC, LHAASO) in northern sky.

→ UHE γ-ray observatories necessary in southern hemisphere

Projects in the Southern Hemisphere

(e.g., ALPACA [2022-24], Mega ALPACA, SWGO, CTA, …) & Neutrinos



✓ PeVatron hunting in Northern/Southern hemispheres

✓ Hot gas bubble around the Galactic center

✓ Blackhole at the Galactic center (A candidate of PeVatron)

✓ Survey heavy dark matter search

Conclusions

- ✓ We successfully observed the galactic diffuse gamma rays in 100 TeV < E < 1 PeV for the first time.
- ✓ The highest energy of observed gamma-ray candidate is 957 TeV.
- ✓ UHE gamma-ray candidates above 400 TeV are spatially separated from known TeV gamma-ray sources beyond our angular resolution as is expected from the diffuse gamma-ray scenario.
- ✓ The measured fluxes are overall consistent with a recent model assuming the hadronic cosmic-ray origin.

These facts indicate strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.
→ Search for current active PeVatrons! → Go South!

Registration is now open!

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