Gamma-ray Observation of SNR G106.3+2.7 with the Tibet Air Shower Array

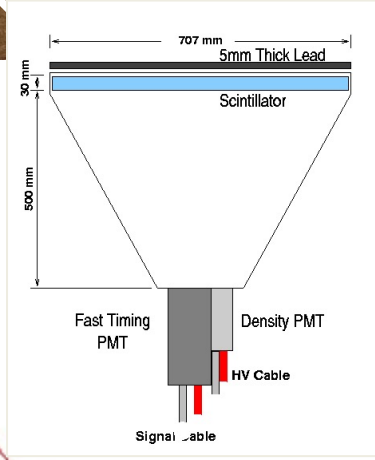
M. Ohnishi
For the Tibet ASγ Collaboration
ICRC 2021, 12 – 23 July

The 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), 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), 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), T. Kawashima(15), K. Kawata(15), M. Kozai(16), D. Kurashige(11), Labaciren(6), G. M. Le(17), A. F. Li(18,9,4), 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), 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), 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) and X. X. Zhou(10)

(1) Department of Physics, Hirosaki University, Hirosaki 036-8561, Japan (2) Department of Physics, Shinshu University, Matsumoto 390-8621, Japan
(3) School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China (4) Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China (5) National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China (6) Department of Mathematics and Physics, Tibet University, Lhasa 850000, China (7) Department of Physics, Hebei Normal University, Shijiazhuang 050016, China (8) University of Chinese Academy of Sciences, Beijing 100049, China (9) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao 266237, China (10) Institute of Modern Physics, SouthWest Jiaotong University, Chengdu 610031, China (11) Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan (12) Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan (13) Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan (14) Faculty of Systems Engineering, Shibaura Institute of Technology, Omiya 330-8570, Japan (15) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan (16) Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara 252-5210, Japan (17) National Center for Space Weather, China Meteorological Administration, Beijing 100081, China (18) School of Information Science and Engineering, Shandong Agriculture University, Taian 271018, China (19) Department of Astronomy, School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China (20) Department of Physics and Tsinghua Centre for Astrophysics (THCA), Tsinghua University, Beijing 100084, China (21) Tsinghua University-National Astronomical Observatories of China (NAOC) Joint Research Center for Astrophysics, Tsinghua University, Beijing 100084, China (22) Department of Astronomy, Tsinghua University, Beijing 100084, China (23) College of Industrial Technology, Nihon University, Narashino 275-8575, Japan (24) National Institute of Informatics, Tokyo 101-8430, Japan (25) National Institute of Information and Communications Technology, Tokyo 184-8795, Japan (26) Department of Mechanical and Electrical Engineering, Shangdong Management University, Jinan 250357, China (27) College of Science, China University of Petroleum, Qingdao 266555, China (28) Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan (29) Department of Physics, Konan University, Kobe 658-8501, Japan (30) Shonan Institute of Technology, Fujisawa 251-8511, Japan (31) Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan (32) Japan Atomic Energy Agency, Tokai-mura 319-1195, Japan (33) Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210034, China

Tibet Air Shower Array



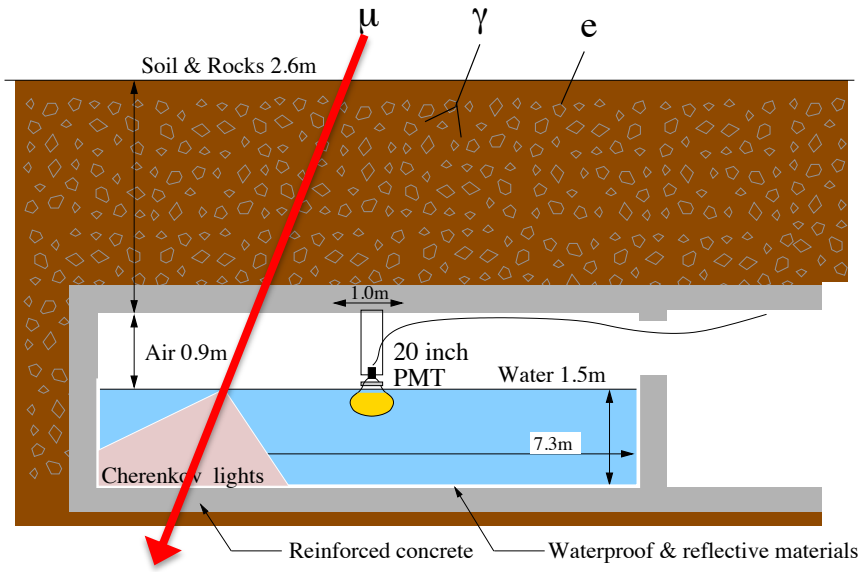
- Tibet, China (90.522°E, 30.102°N) 4,300 m a.s.l.

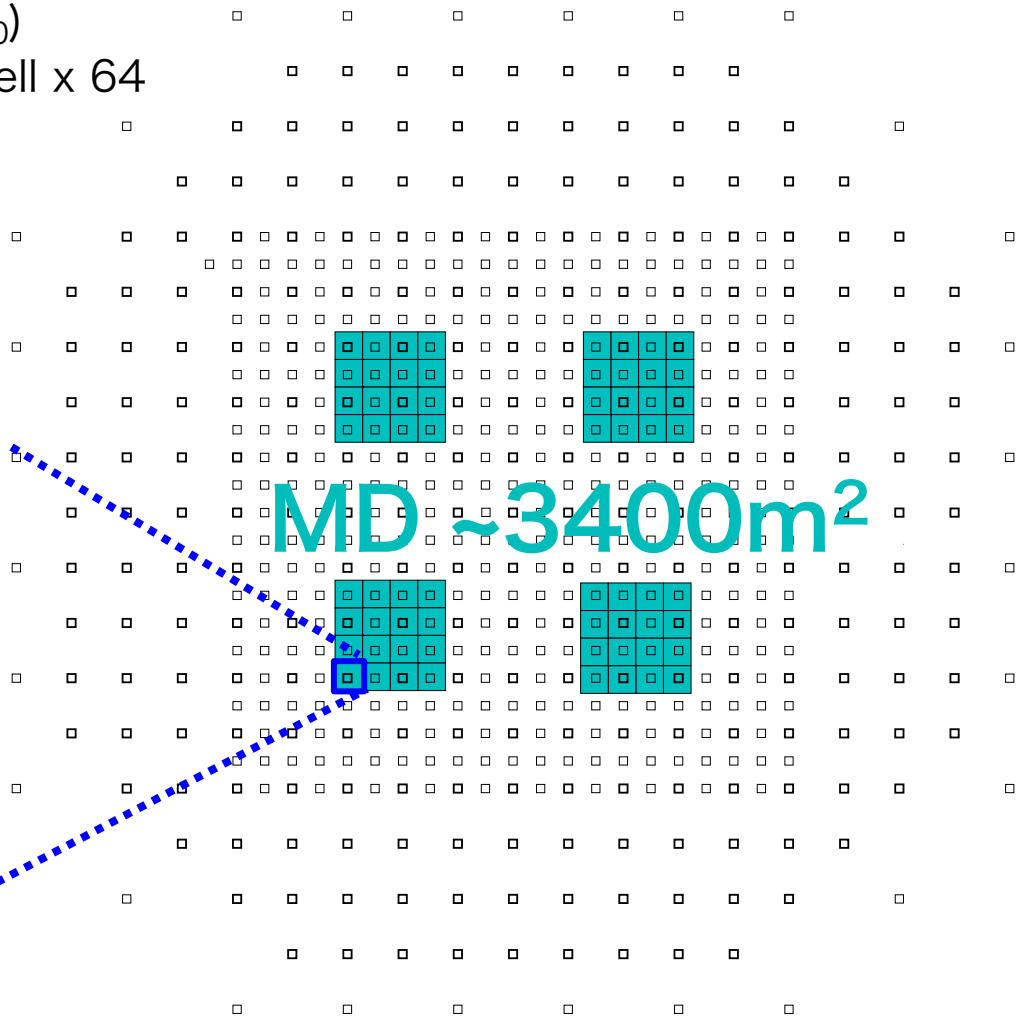
scintillation counters	0.5 m^2 x 597
area	~65,700 m^2
angular resolution	~0.5°@10TeV
	~0.2°@100TeV
energy resolution	~40%@10TeV
	~20%@100TeV

2nd particles timing ➡ arrival direction
2nd particles energy deposit ➡ primary energy

Water Cherenkov Muon Detector Array

- ✓ 2.4m underground (515g/cm^2 ~19X_0)
- ✓ 7.35m x 7.35m x 1.5m-deep water cell x 64
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + Tyvek sheets



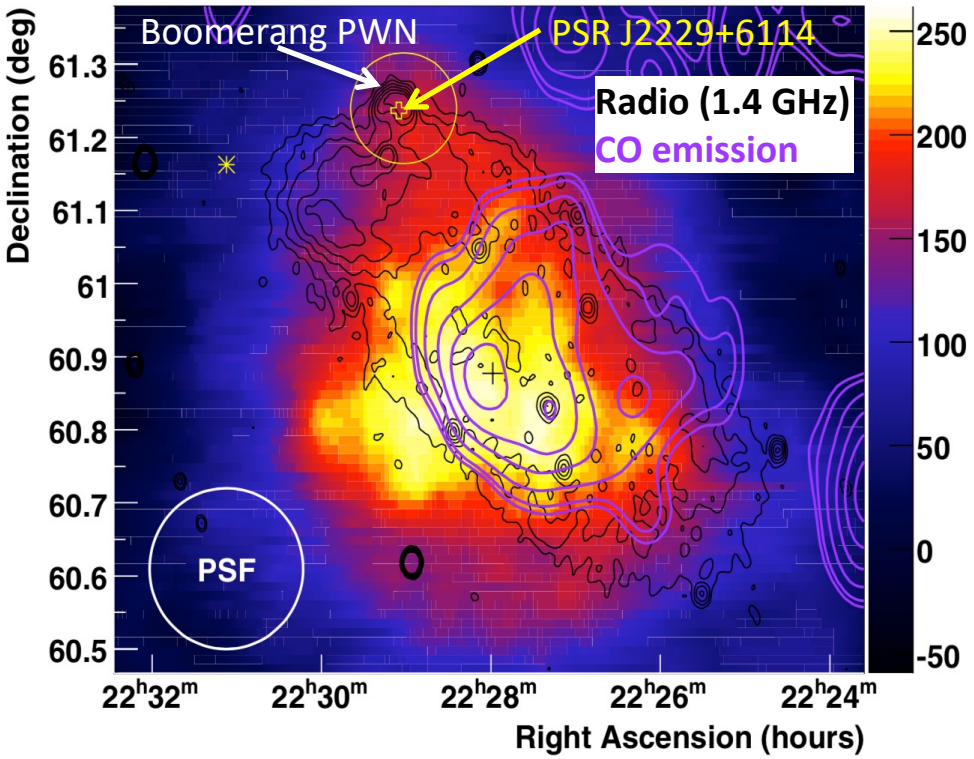


Measurement of number of muons in air showers
➡ γ／CR discrimination

SNR G106.3+2.7 observed by VERITAS & *Fermi*

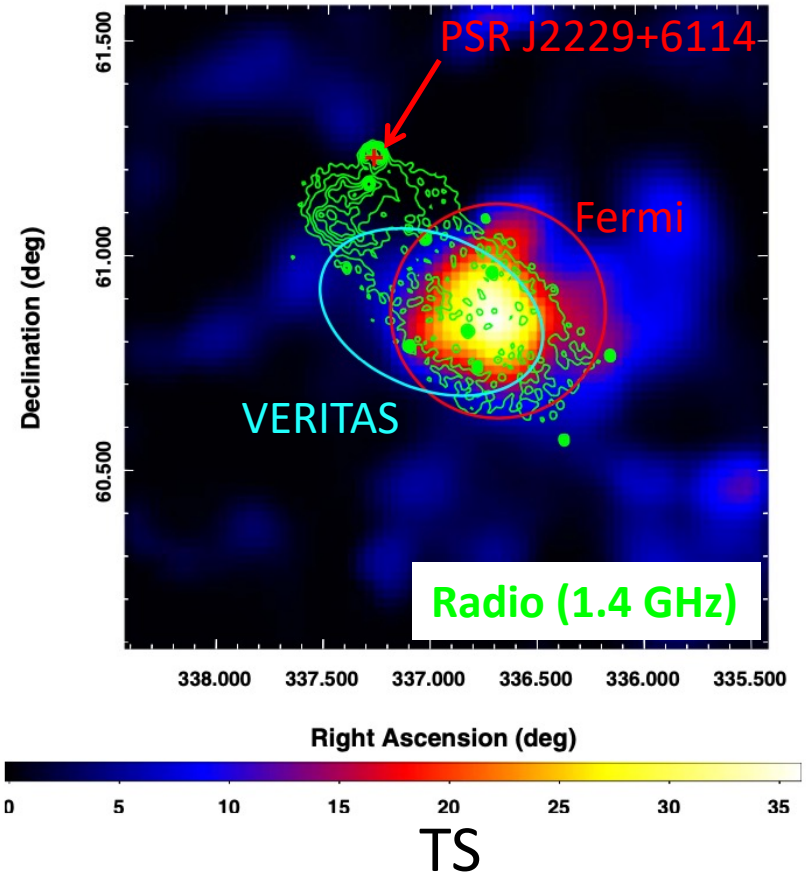
Acciari et al., ApJL, 703, L6 (2009)

VERITAS



Abdo et al., ApJL, 700, L127 (2009)

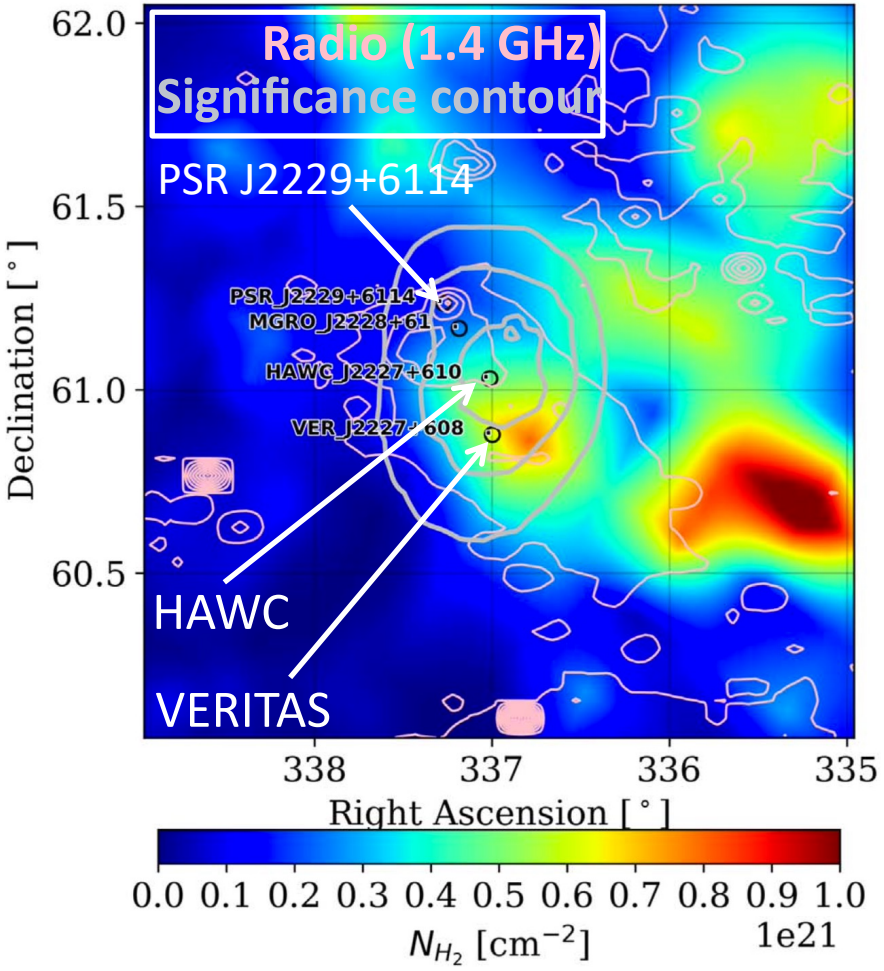
Fermi



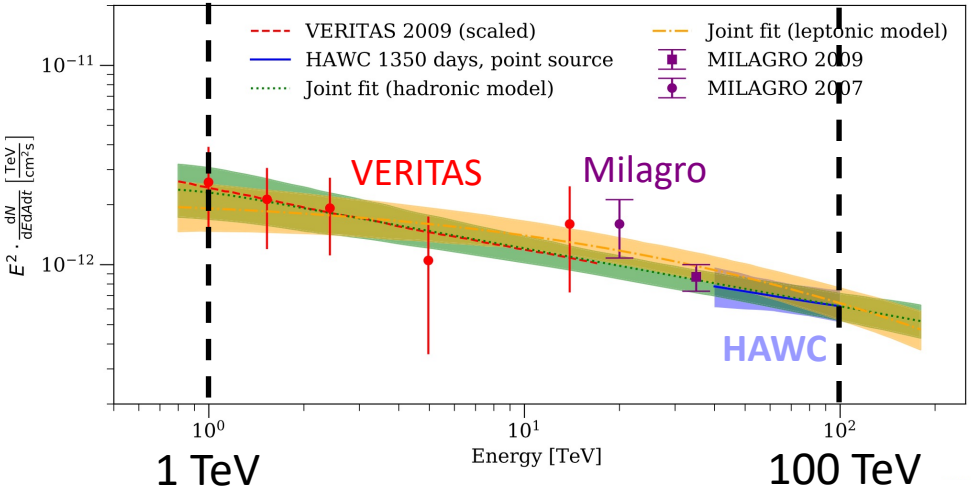
- Distance 0.8 kpc ➡ SNR size 14 pc x 6 pc *Kothes et al, ApJ, 560, 236 (2001)*
- PSR J2229+6114 : $\dot{E}$ = 2.2 x 10^{37} erg/s, age 10 kyr *Halpern et al., ApJL, 552, L125 (2001)*
- Centroid of GeV & TeV γ emission coincident with the molecular cloud location

SNR G106.3+2.7 observed by HAWC

Albert et al., ApJL, 896, L29 (2020)



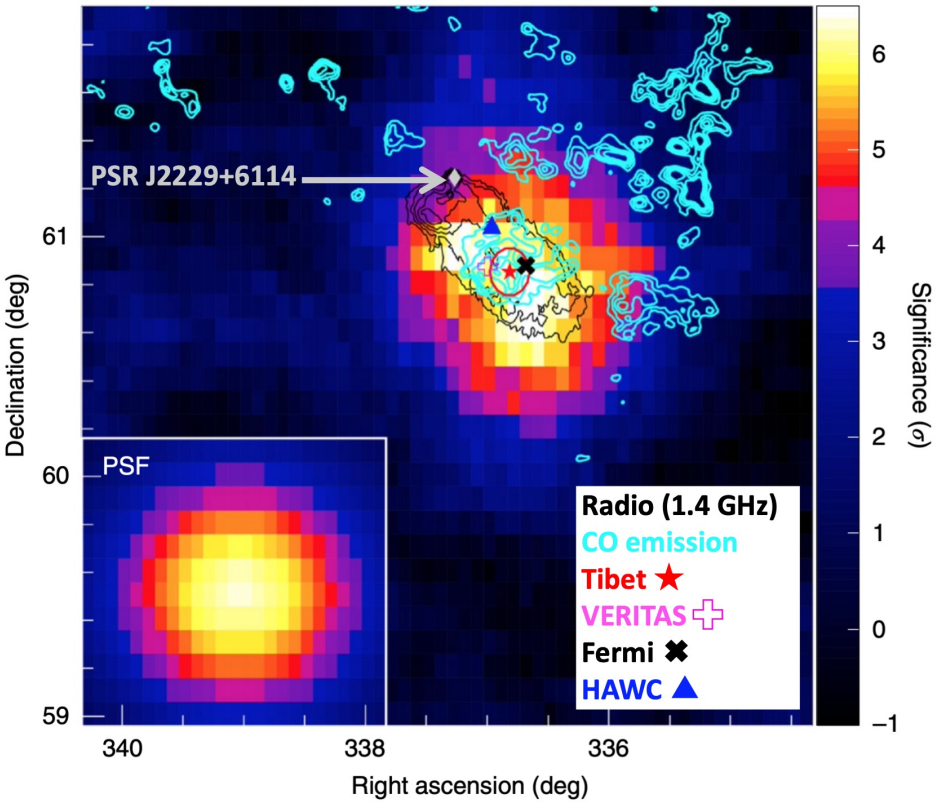
Energy spectrum



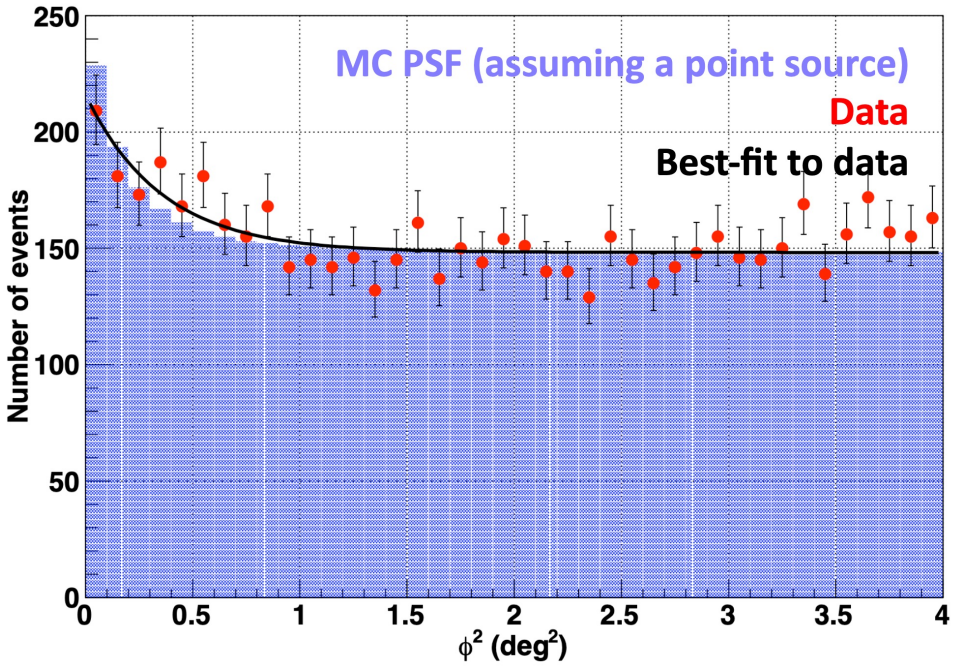
- Source location consistent with the location of PSR J2229+6114 as well as the molecular cloud
- Measured the γ-ray spectrum from 40 TeV up to 100 TeV

SNR G106.3+2.7 observed by Tibet ASγ (this work)

Significance map > 10 TeV



Angular distribution > 10 TeV



➢ Fitting with Gaussian: $A \exp\left(-\frac{\phi^2}{2(\sigma_{\rm PSF}^2 + \sigma_{\rm EXT}^2)}\right)$

σ_{PSF} = 0.35° from MC simulation
σ_{EXT}: source extension

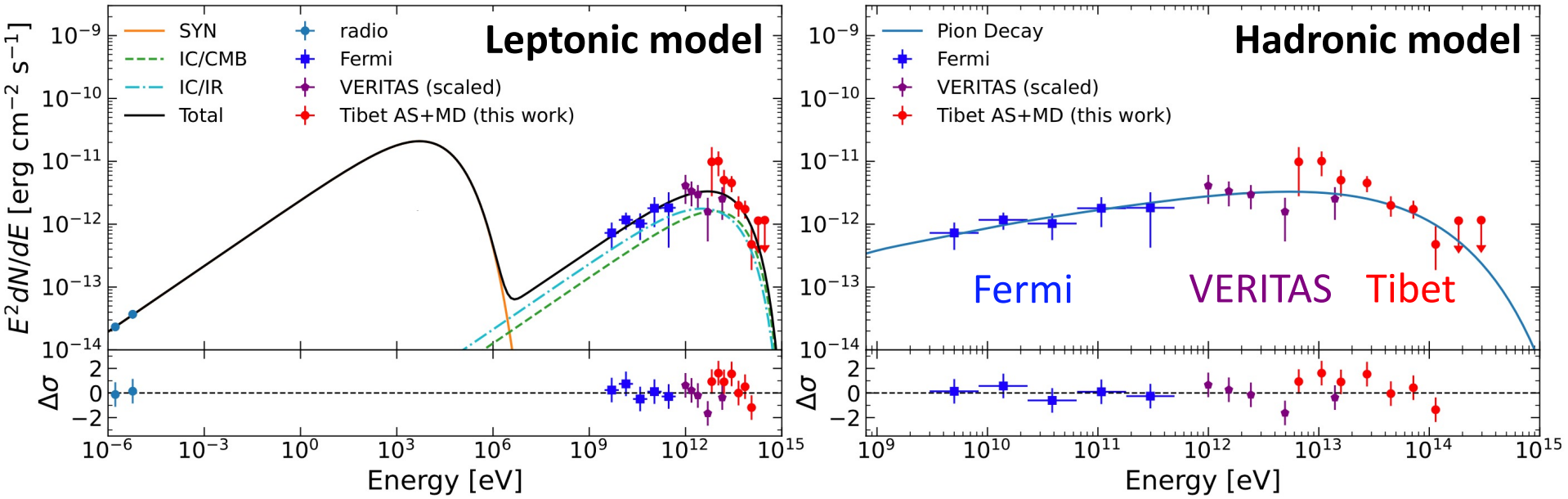
➢ Tibet source position: R.A. = 336.82°±0.16°
Dec = 60.85°±0.10°

➡ **σ_{EXT} = 0.24°±0.10°**

- coincident with the molecular cloud location
- distant from PSR J2229+6114 by 0.44°
  at 3.1σ level (syst. pointing error taken into account)

※ consistent with previous results
VERITAS: σ_1 = 0.27°±0.05°, σ_2 = 0.18°±0.03°
Fermi: 0.25°-radius disk
HAWC: <0.23° (90% C.L.)

SNR G106.3+2.7: energy spectrum



Abdo et al., ApJL, 700, L127 (2009)
Xin et al., ApJ, 885, 162 (2019)
Pineault & Joncas, AJ, 120, 3218 (2000)

- Estimate parent particles' spectrum $\propto E^{-\alpha} \exp(-E/E_{\rm cut})$ using *naima* package (*Zabalza, arXiv:1509.03319*)

	α	$E_{\rm cut}$ (TeV)	$W_{e/p}$ (10^{47} erg)	B (μG)	χ^2/ndf
leptonic	$2.30^{+0.08}_{-0.07}$	190^{+127}_{-66}	$1.4^{+1.8}_{-0.7}$	$8.6^{+3.4}_{-2.5}$	12.8/15
hadronic	$1.79^{+0.08}_{-0.09}$	499^{+382}_{-180}	$5.0^{+0.7}_{-0.6}$	—	13.0/14

(※ assuming target gas density = 10 / cm^3)

(※ $W_{e/p}$: total electron/proton energy > 10 MeV/> 1 GeV)

- Difficult to clarify γ-ray emission mechanism (leptonic/hadronic) based on energy spectrum alone

Discussion

Hadronic model

- Protons accelerated by SNR shock interact with molecular cloud gas ➡ π^0 ➡ 2γ
- $E_{cut} \sim 0.5$ PeV

Leptonic model

- Inverse Compton scattering of ambient photons by electrons injected by PSR J2229+6114
- $E_{cut} \sim 190$ TeV, $B \sim 9$ μG
- $W_e \sim 1.4 \times 10^{47}$ erg: only 2% of energy released by PSR J2229+6114 during its age of 10 kyr

  98% used for B amplification ➡ *B* should be much stronger than 9 μG

  — What if pulsar age is 1 kyr?

  Diffusion length of 1 TeV electrons ~ 1.7 pc = 0.12° during 1 kyr

  ➡ inconsistent with the location of the 10 GeV γ-ray emission observed by *Fermi*

Hadronic model is favored

Summary

γ-ray observation of SNR G106.3+2.7 with the Tibet Air Shower Array

- Centroid of γ-ray emission above 10 TeV
  consistent with the molecular cloud location
  distant from PSR J2229+6114 by 0.4°
- Source extension $\sigma_{EXT} = 0.24° \pm 0.10°$
- Hadronic model is favored
- Cut-off energy of proton spectrum $E_{cut} \sim 0.5$ PeV

Please refer to:

M. Amenomori et al., Nature Astronomy Letters, 5, 460 (2021)
"Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays"

Thank you
for your attention!