東京大学宇宙線研究所「共同利用研究成果発表会」 2023年 2月 21-22日

チベット高原での高エネルギー宇宙線の研究

加藤 勢 (東京大学宇宙線研究所)

For the Tibet ASγ Collaboration

Tibet ASγ Collaboration

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

1 Department of Physics, Hirosaki Univ., Japan.
2 School of Astronomy and Space Science, Nanjing Univ., China.
3 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS, China.
4 National Astronomical Observatories, CAS, China.
5 Department of Mathematics and Physics, Tibet Univ., China.
6 Department of Physics, Hebei Normal Univ., China.
7 Univ. of Chinese Academy of Sciences, China.
8 Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong Univ., China.
9 Institute of Modern Physics, SouthWest Jiaotong Univ., China.
10 Department of Physics, Shinshu Univ., Japan.
11 Faculty of Engineering, Kanagawa Univ., Japan.
12 Faculty of Education, Utsunomiya Univ., Japan.
13 Faculty of Systems Engineering, Shibaura Institute of Technology, Japan.
14 Faculty of Engineering, Yokohama National Univ., 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 National Institute of Informatics, Japan.
21 National Institute of Information and Communications Technology, Japan.
22 Department of Mechanical and Electrical Engineering, Shangdong Management Univ., China.
23 College of Science, China Univ. of Petroleum, China.
24 Tokyo Metropolitan College of Industrial Technology, Japan.
25 Department of Physics, Konan Univ., Japan.
26 College of Industrial Technology, Nihon Univ., Japan.
27 Shonan Institute of Technology, Japan.
28 Research Institute for Science and Engineering, Waseda Univ., Japan.
29 Japan Atomic Energy Agency, TJapan.
30 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.

令和 5年度チベット実験関係
共同利用研究採択課題一覧

F 8 チベット高原での高エネルギー宇宙線の研究（継続）
(瀧田正人　東京大学宇宙線研究所)

F 9 チベット空気シャワーアレイによる10TeV宇宙線強度の恒星時日周変動の観測（継続）
(宗像一起　信州大学理学部)

F10 Knee領域一次宇宙線組成の研究（継続）
(片寄祐作　横浜国立大学大学院工学研究院)

F11 宇宙線による太陽の影を用いた太陽周辺磁場の時間変動の研究（継続）
(西澤正己　国立情報学研究所情報社会相関研究系)

チベットグループ共同利用研究経費執行状況

研究費：　申請額805.6万円　→　配分額182万円

Tibet空気シャワー観測装置、YAC空気シャワーコア観測装置、地下ミューオン観測装置の維持・運転に必要な経費の一部に使用。

旅費：　申請額980万円　→　配分額235万円

中国出張や宇宙線研での研究打ち合わせ等に使用。

ご支援、どうもありがとうございました！

Activities in the 2023 FY

International conferences：

1. CRA2023, 2023/5/16-19	1 talk
2. ASTRONUM2023, 2023/6/25-30	1 talk
3. International Cosmic Ray Conference (ICRC2023), 2023/7/26-8/3	5 talks
4. The 1st IReNA-Ukakuren joint Workshop “Advancing Professional Development in Nuclear Astrophysics and Beyond”, 2023/8/28-9/1	1 talk
5. 18th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2023), 2023/8/28-9/1	1 talk
6. TeV Particle Astrophysics (TeVPA2023), 2023/9/11-15	1 talk
7. AGU23, 2023/12/11-15	1 poster
8. AIA2023, 2024/3/25-29	1 talk

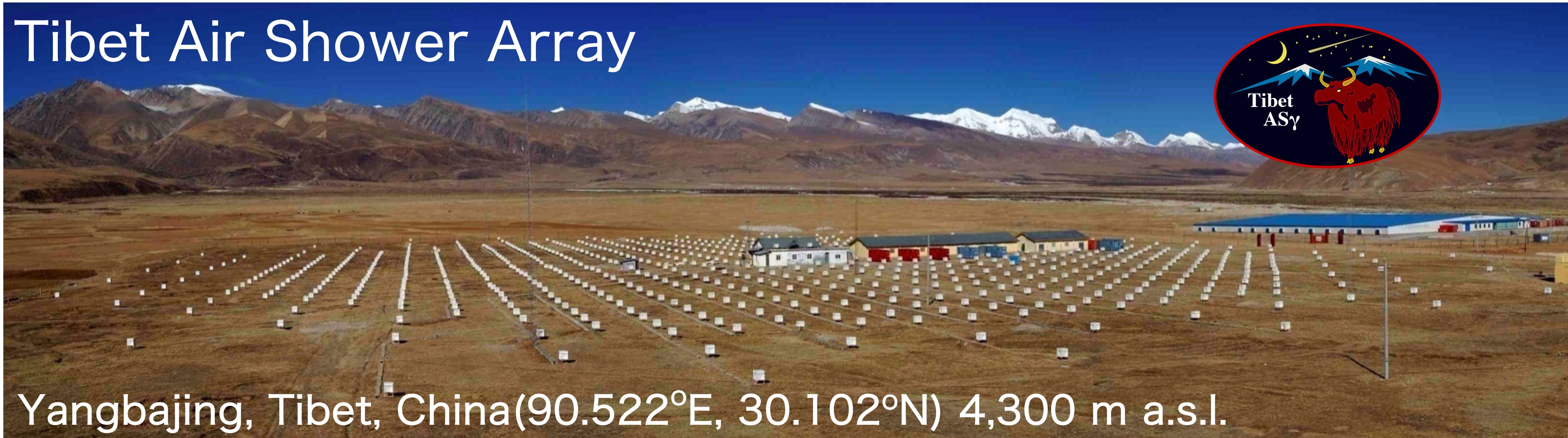
Domestic conferences：

1. 物理学会, 2023/9/16-19	3 talks
2. Young Researchers’ Workshop, 2023/7/19-20	1 talk
3. アタカマコンパクトアレイで探る星間ガス：星・惑星形成から銀河まで, 2023/11/29-30	1 talk
4. 東北大学天文学教室談話会, 2024/1/15	1 talk
5. SNR workshop 2024, 2024/2/29-3/1予定	1 talk
6. 空気シャワー観測による宇宙線の起源探索研究会, 2024/3/26-27予定	1 talk
7. 物理学会, 2024/3/18-21	2 talks

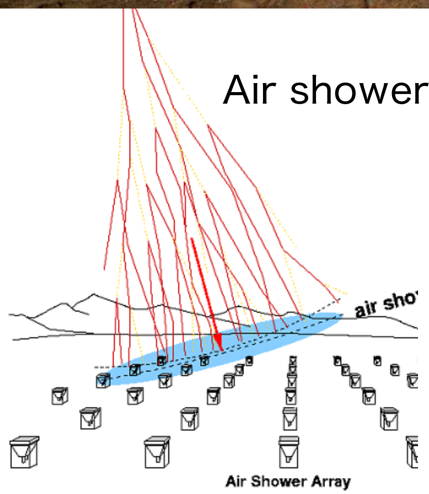
Refereed papers：

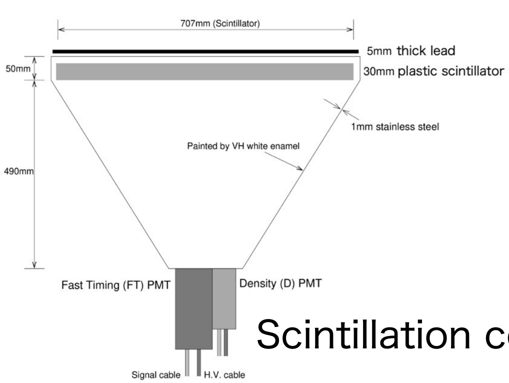
1. “Observation of Gamma Rays up to 320 TeV from the Middle-aged TeV Pulsar Wind Nebula HESS J1849−000”, Amenomori et al., ApJ 954,200(2023)

Tibet Air Shower Array



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

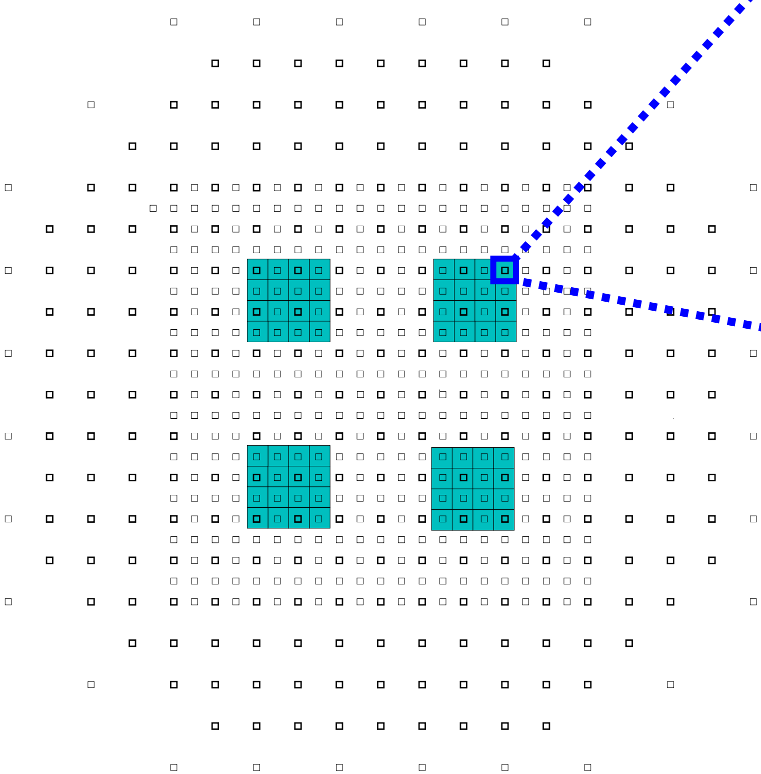




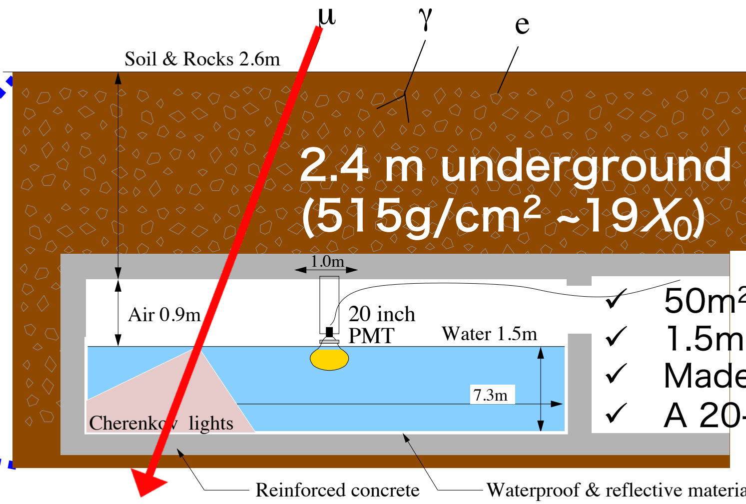
Scintillation counter

- ✓ Scintillation counters ($0.5m^2$) arranged over $65,700m^2$
- ✓ Observation of air shower ptcl.s to determine the energy & incoming direction of primary CRs
- ✓ Wide F.O.V. (~ 2 sr) & continuous operation
- ✓ Physics :
  - CR physics in the TeV-PeV range :
    - Chemical composition, anisotropy, the Sun's shadow
  - γ-ray astronomy in the TeV-sub-PeV range :
    - Search for Galactic PeVatron

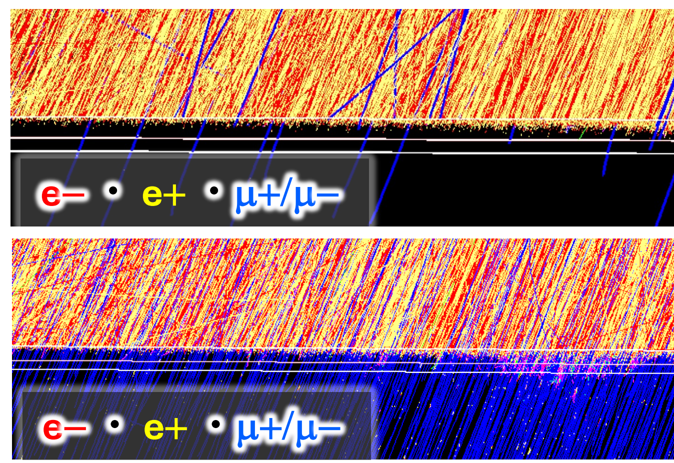
Underground Muon Detector Array (MD Array)



MD : 3400m²



- ✓ 50m²×2.4m
- ✓ 1.5m-depth water layer
- ✓ Made of concrete
- ✓ A 20-inch PMT suspended



200TeV γ shower

Few muons (~1 μ)

200TeV CR shower

Many muons (~100 μ)

Quantification of the shower muon component leads to
good γ/h separation
Rejection power for BGCRs : >99.9% @ E>100TeV
γ-ray survival ratio : ~90% @ 〃

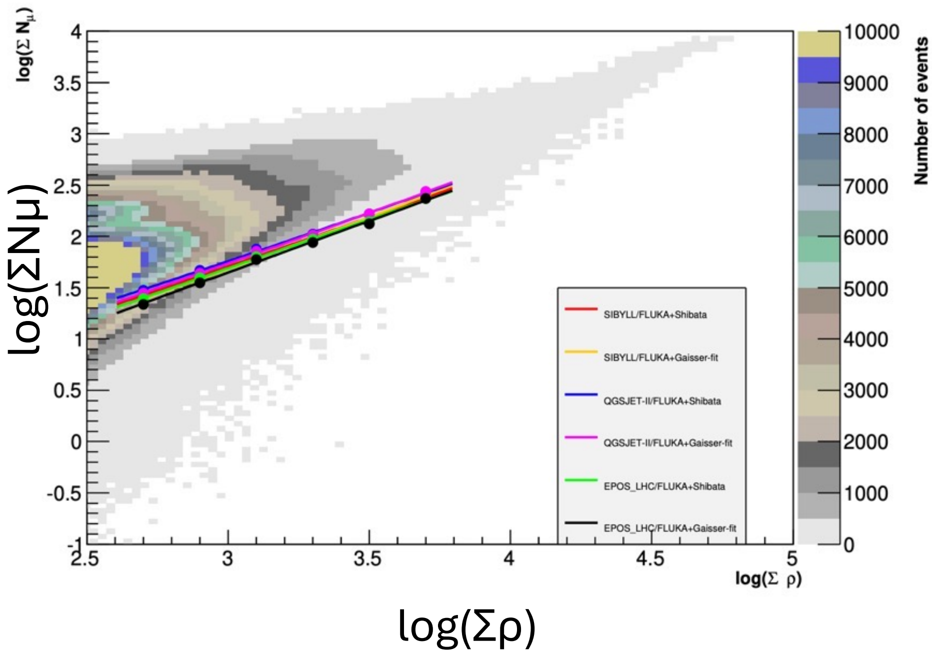
Scientific Results

This presentation gives four topics：

1. Primary Proton Spectrum in 40TeV < E < 630TeV
2. γ/hadron Separation using Neural Network (NN)
3. Modeling of the anisotropy of TeV cosmic rays
4. Sub-PeV γ rays from HESS J1849−000

Primary Proton Spectrum in 40TeV < E < 630TeV

Katayose et al., PoS(ICRC2023)301



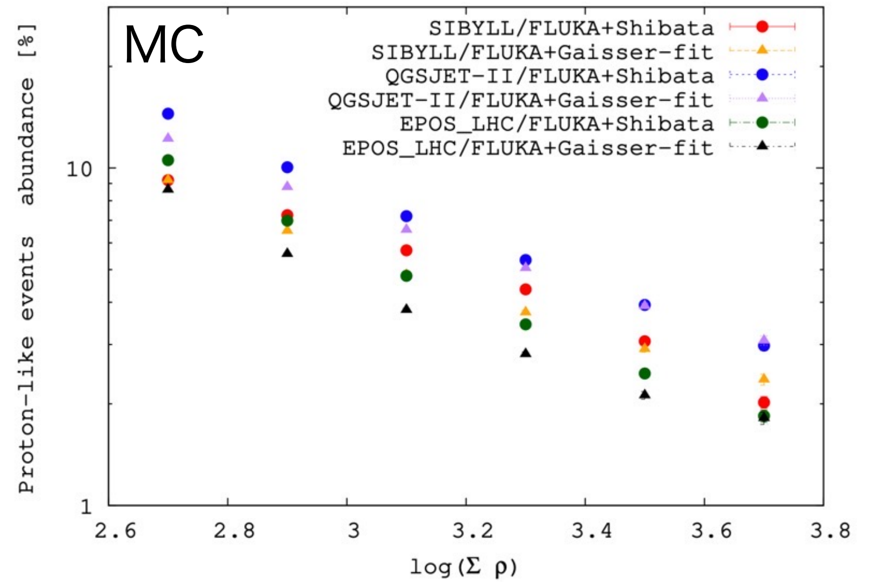


Figure 4: Proton-like shower abundance to whole well-reconstructed showers as a function of log $(\sum \rho)$ for each model when the purity is 90%.

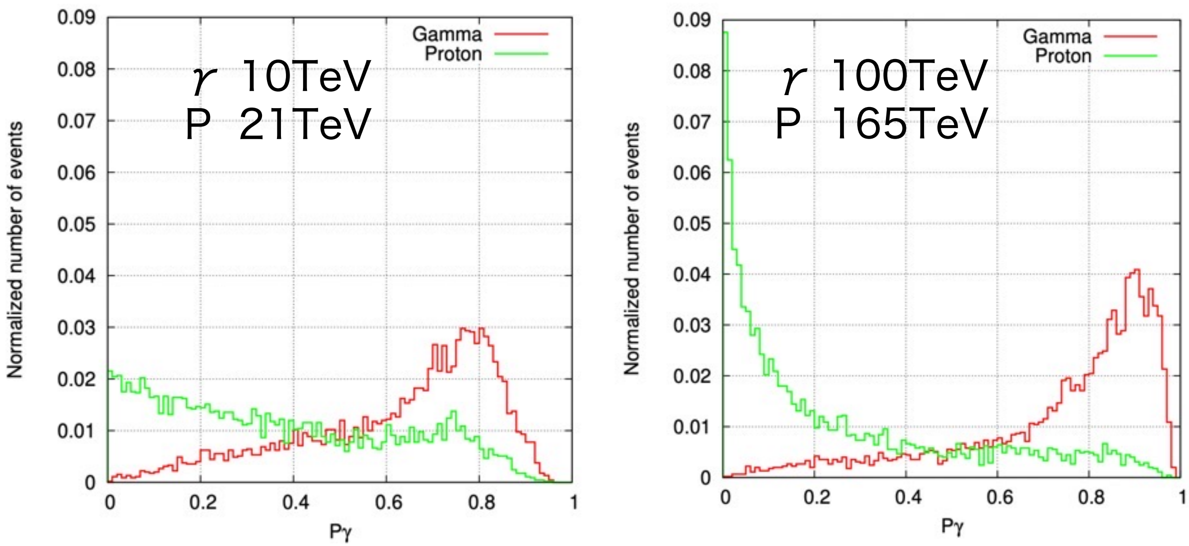
- ✓ Proton-like air shower events are extracted w/ the technique using the data recorded w/ MD array[1]
- ✓ Fraction of p-like AS events is calculated keeping high purity of p-like events (90%)

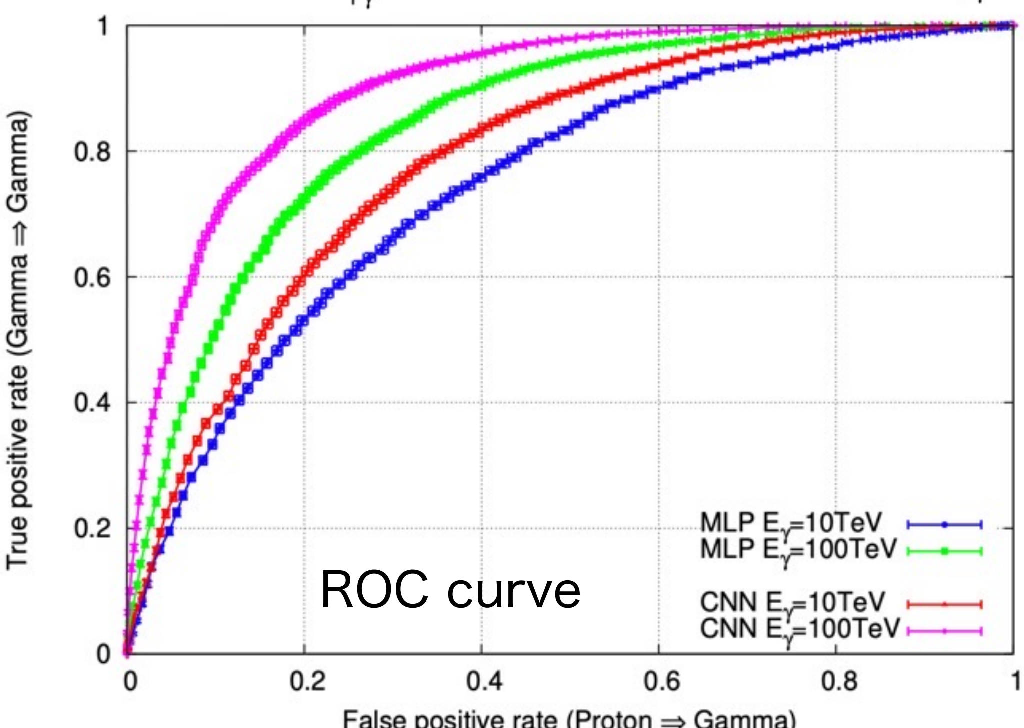
1. Kurashige et al., PTEP 2022

γ /hadron Separation using Neural Network (NN)

Output of CNN

Okukawa et al., PoS(ICRC2023)786

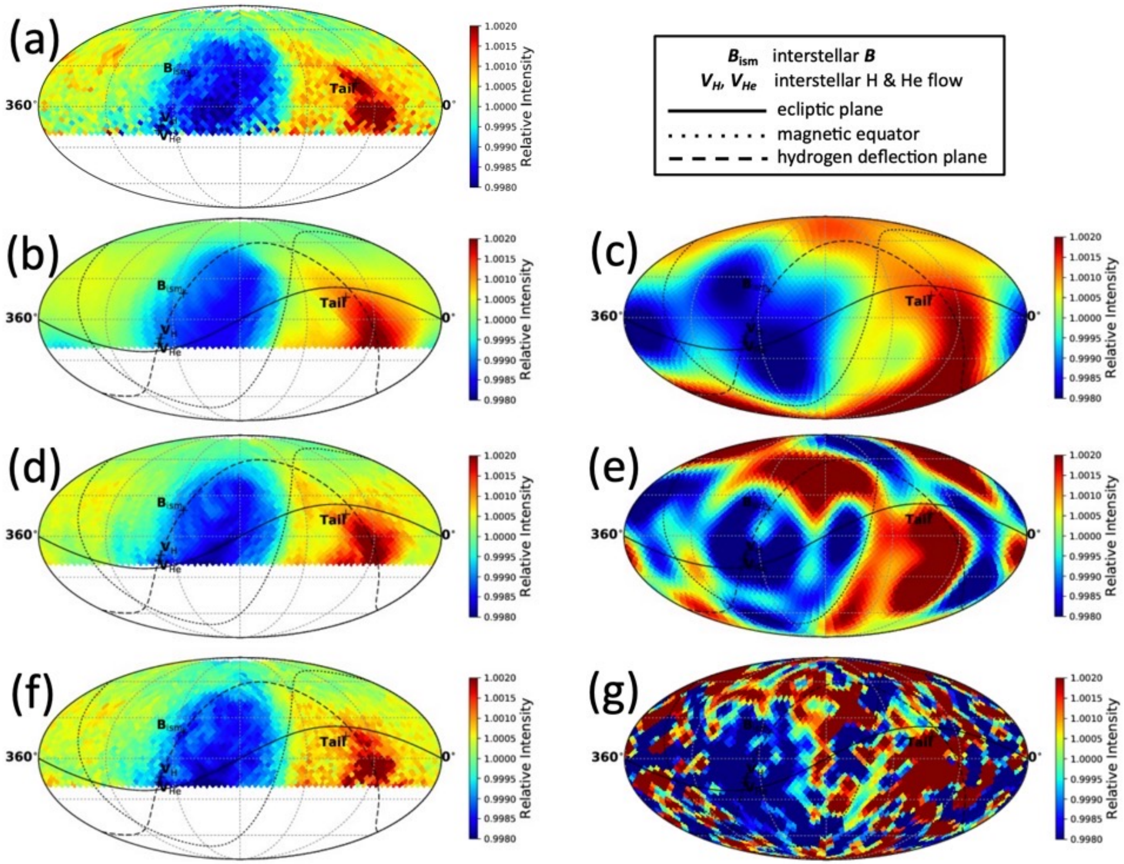


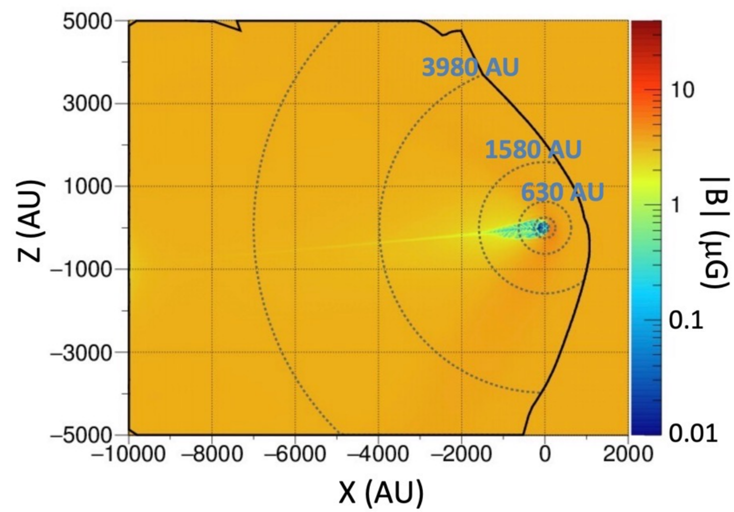


- ✓ Improvement of the sensitivity to γ rays only w/ the AS array (to make use of the 15yrs of Tibet III data w/o the MD array to search for γ-ray transients)
- ✓ Multi-Layer Perceptron (MLP) & Convolutional NN (CNN) are trained
- ✓ CNN has better performance

Modeling of the anisotropy of TeV cosmic rays

T. K. Sako et al., PoS(ICRC2023)1238



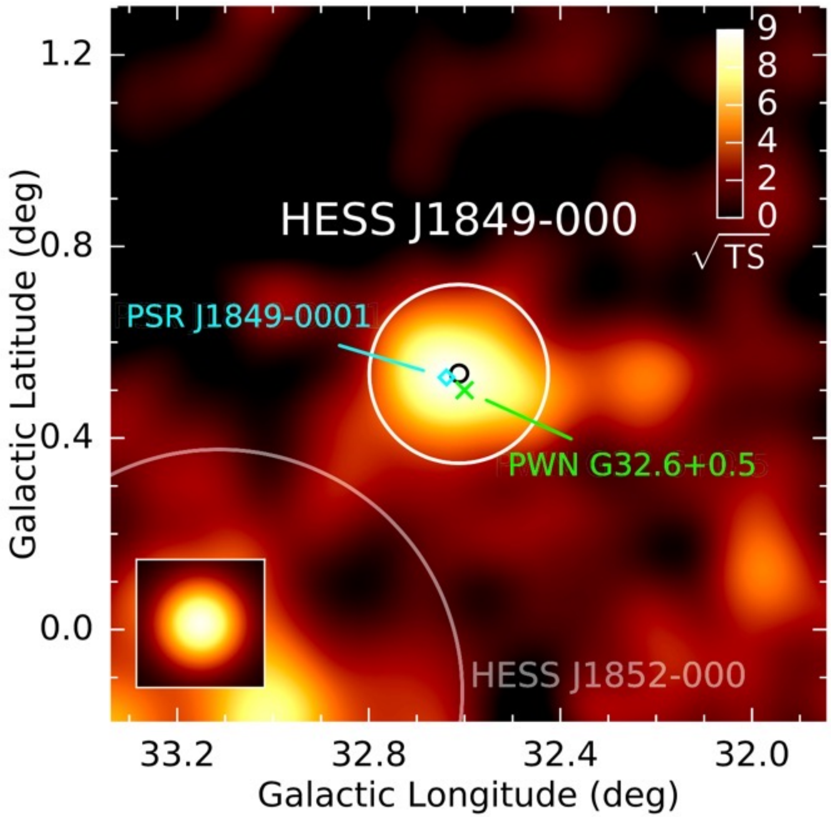


- ✓ TeV CR anisotropy @ some outer boundaries of the heliosphere is calculated based on the anisotropy observed @ Earth
- ✓ More detailed structure emerges as going more distant from the heliosphere
- ✓ Both positive & negative polarity phases should be considered in the MHD simulation

“Observation of Gamma Rays up to 320 TeV from the Middle-aged TeV Pulsar Wind Nebula HESS J1849−000”, Amenomori et al., ApJ 954,200(2023)

HESS J1849–000

$\sqrt{TS}$ maps @ E > 400GeV (H.E.S.S.[1])



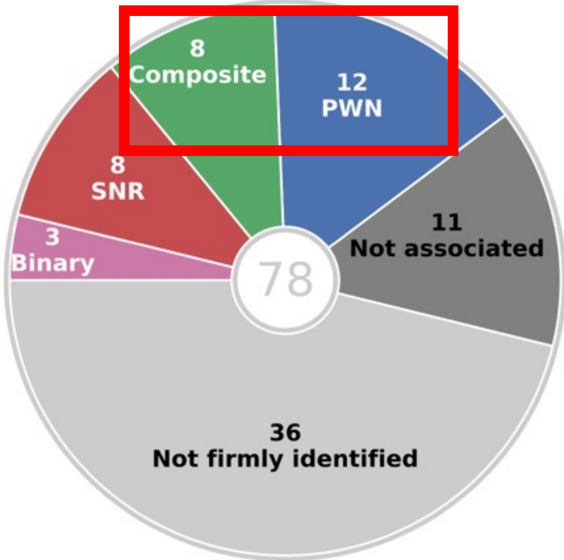
1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. H.E.S.S. Collaboration, A&A 612, A2 (2018)
3. Abeysekara et al., PRL 124, 021102 (2020)
4. Cao et al., Nature 594, 33 (2021)
5. Cao et al., arXiv:2305.17030v2 (2023)

✓ PSR J1849–0001 in the center of TeV γ-ray emission
=> Middle aged pusar-wind nebula (PWN)[1,2]
✓ IntF(> 1TeV) = 2.3% Crab & Γ ~ 2.0[1]
✓ Nearby HAWC (>56TeV)[3] & LHAASO (>100TeV)[4,5] src.s
! No detailed study of the origin of the γ-ray emission

Gamma-Ray Sources Associated w/ Pulsar Wind Nebulae

H.E.S.S. Gal. Plane Survey[1]

20/78 sources are associated w/ PWNe



35 1LHAASO sources associated w/ PSRs[2]

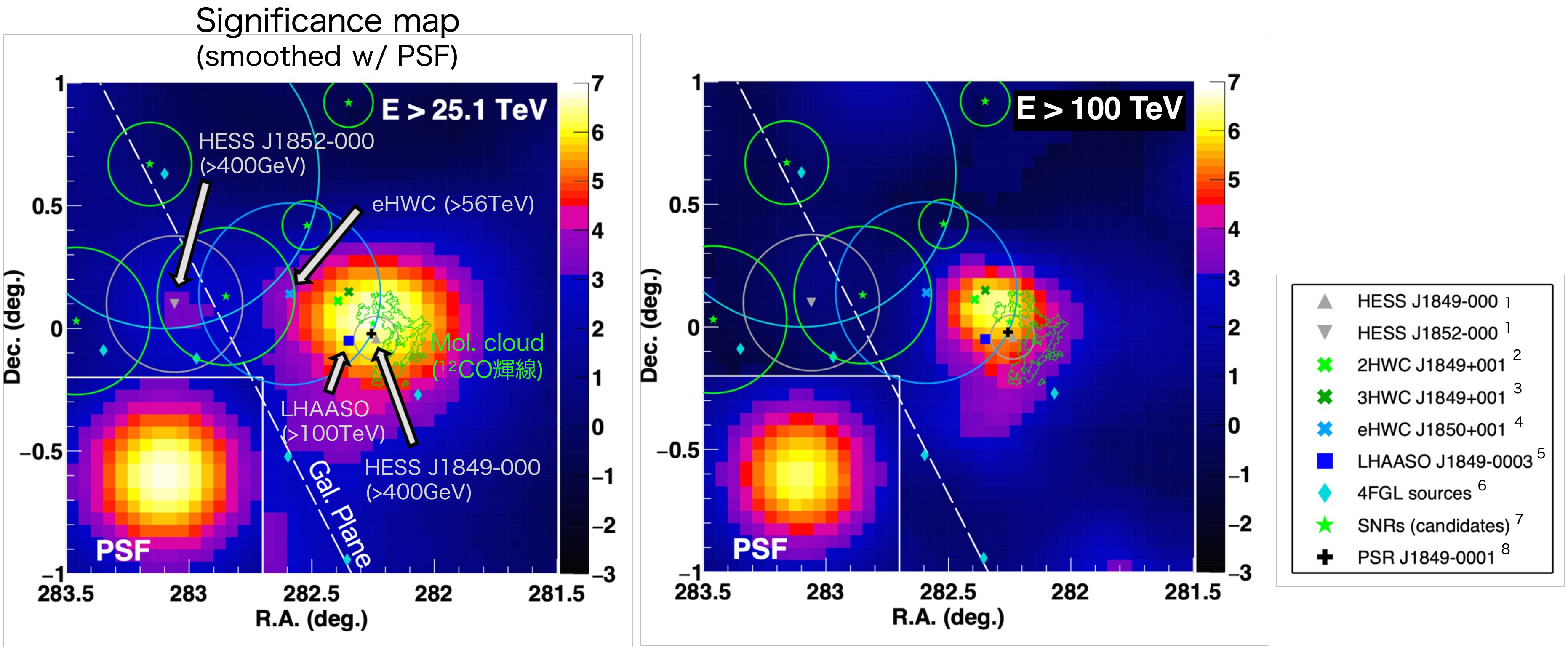
15 sources w/ identified PWNe/TeV Halo

Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	-	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

- ✓ PWNe could occupy a large fraction of VHE/UHE src.s
- ✓ Potential CR acceleration theoretically discussed[3,4,5,6]

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. arXiv:2305.17030v2 (2023)
3. Cheng et al., ApJ 300, 500 (1986)
4. Zhang et al., MNRAS 497, 3477–3483 (2020)
5. Liu & Wang, ApJ 922, 221 (2021)
6. Spencer et al., PoS(ICRC2023)690

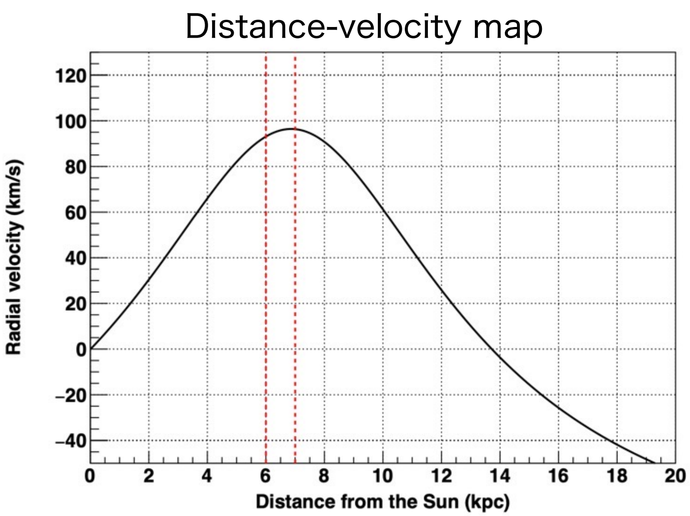
Detection of γ Rays from HESS J1849-000

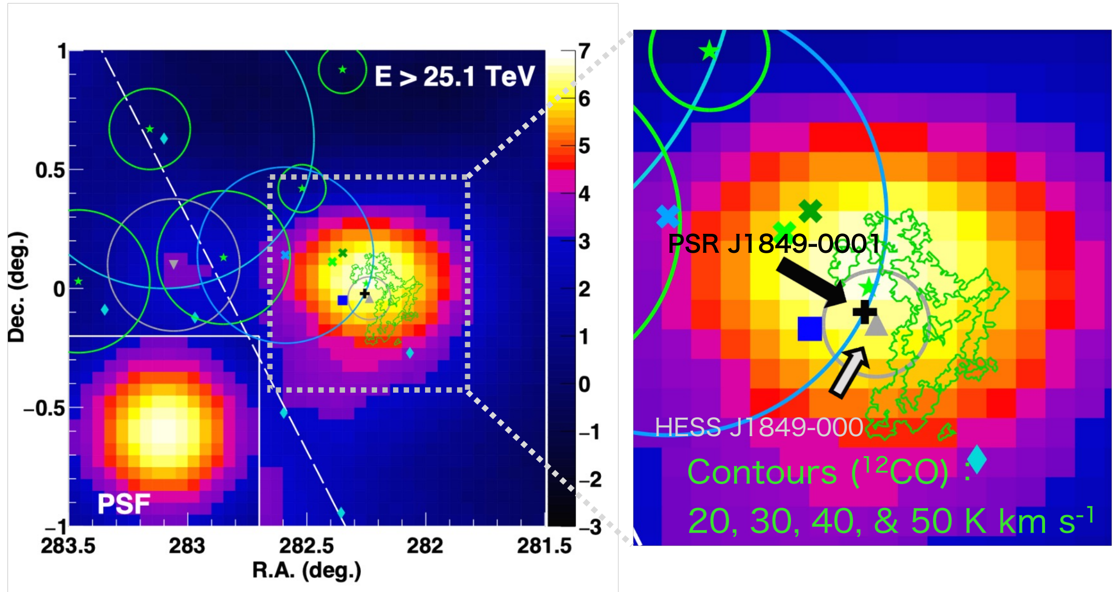


- ✓ Detection significance : **4.0σ @ E > 25TeV & 4.4σ @ E > 100 TeV**
- ✓ Position unc. of the significant region : 0.22° @ E > 100 TeV
  => Positionally consistent w/ HESS J1849-000
- ✓ Deviation from HESS J1852-000[1] : 3.0σ @ E > 100 TeV => Unlikely the source

1. H.E.S.S. Collaboration, A&A 612, A1 (2018)
2. Abeysekara+, ApJ 843, 40 (2017)
3. Albert+, ApJ 905, 76 (2020)
4. Abeysekara+, PRL 124, 021102 (2020)
5. Cao+, Nature 594, 33 (2021)
6. Abdollahi+, ApJS 247, 33 (2020)
7. Anderson+, A&A 605, A58 (2017)
8. Gotthelf+, ApJL 729, L16 (2011)

Detection of a Molecular Cloud @ the Position of HESS J1849





✓ **Analysis of archive FUGIN ^{12}CO J=1–0 data[1]**

✓ Assumed distance : 7 kpc[2]

✓ Integration in 93–100 km s^{-1} (6-7 kpc)

=> **Molecular cloud w/ ~20 pc size (T_B ~20 K km s^{-1}) @ the west side of HESS J1849–000**

✓ If the cloud size along the l.o.s. is ~ 20 pc, the gas density is

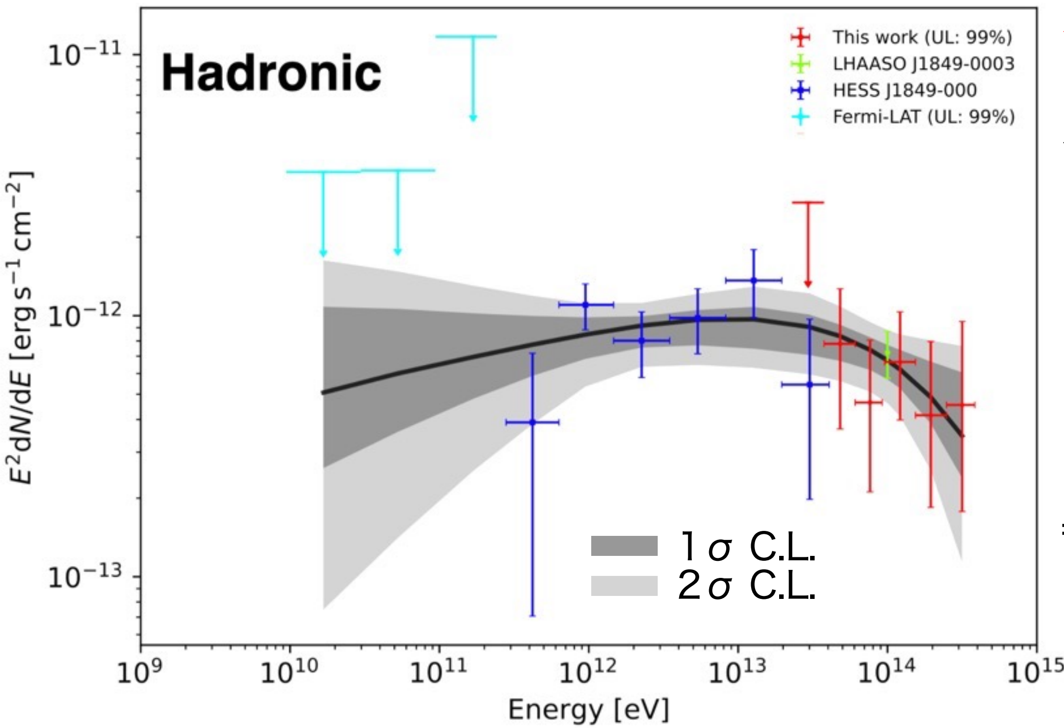
$$n_p = X_{co}\, T_{mb} / R \sim 70\ \mathrm{cm^{-3}} \quad (X_{co} = 2\times10^{20}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\ s^{-1}})^{-1})^{3}$$

> 10 cm^{-3} can be provided

1. Umemoto+, PASJ 69, 5 (2017)
2. Gotthelf+, ApJL 729, L16 (2011)
3. Bolatto+, Ann. Rev. Astron. Astrophys 51, 207 (2013)

Hadronic emission model (Naima[1])

1. Zabalza, PoS(ICRC2015) 922 (2015)



✓ First spectral modeling including the sub-PeV energy range

✓ Assumptions：

- $\pi^0 \rightarrow 2\gamma$ from CR-gas collisions
- n_p = 10 cm^{-3}
- CR spectrum：

$$\frac{dN_p}{dE} = A_p \left(\frac{E}{10\ \mathrm{TeV}} \right)^{-\alpha_p} \exp\left(-\frac{E}{E_{p,\mathrm{cut}}} \right) \mathrm{eV}^{-1}$$

=>

$$\log_{10} A_p = 33.93^{+0.09}_{-0.11}$$

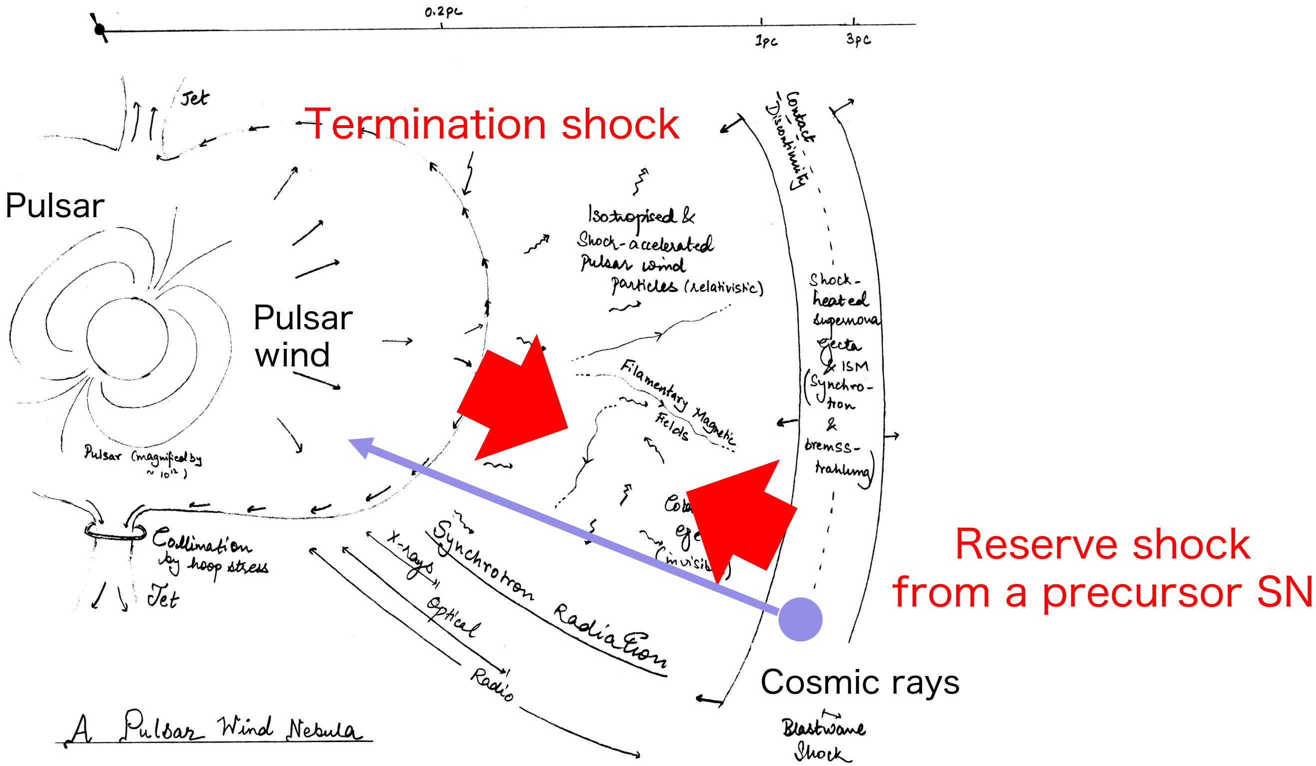
$$\alpha_p = 2.01^{+0.12}_{-0.21}$$

$$\log_{10}(E_{p,\mathrm{cut}}/\mathrm{TeV}) = 3.73^{+2.98}_{-0.66}$$

Wp(1TeV<E<10PeV) $= (1.1 \pm 0.2) \times 10^{49}$ erg

Possible acceleration of CR protons beyond PeV

PeV CR acceleration in a PWN-SNR composite system



✓ CRp's accelerated up to ~100 TeV in the SNR FS could be re-accelerated up to ~ 1 PeV in the PWN compressed by the SNR reverse shock[1,2]

1. Gelfand+, ApJ 703, 2051 (2009)
2. Ohira+, MNRAS 478, 926 (2018)

PeV CR acceleration in a PWN-SNR composite system

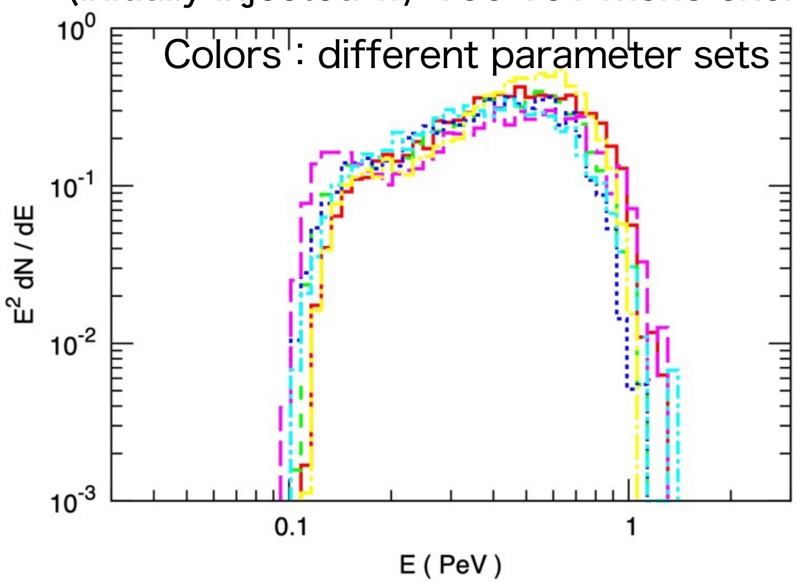
Benefits：

- PeV CR can be produced irrespective of environmental parameters[1]
- ~10^{49} erg given to HE ptcls[2]
- B-field of the compressed PWN is amplified up to ~ 100 μG[2]
  => Produces observed synchrotron X-rays by $e^{\pm}$ of PWN origin??
- Compression of PWN takes place @ ~ 10 kyr aft. SN => Invisible SNR

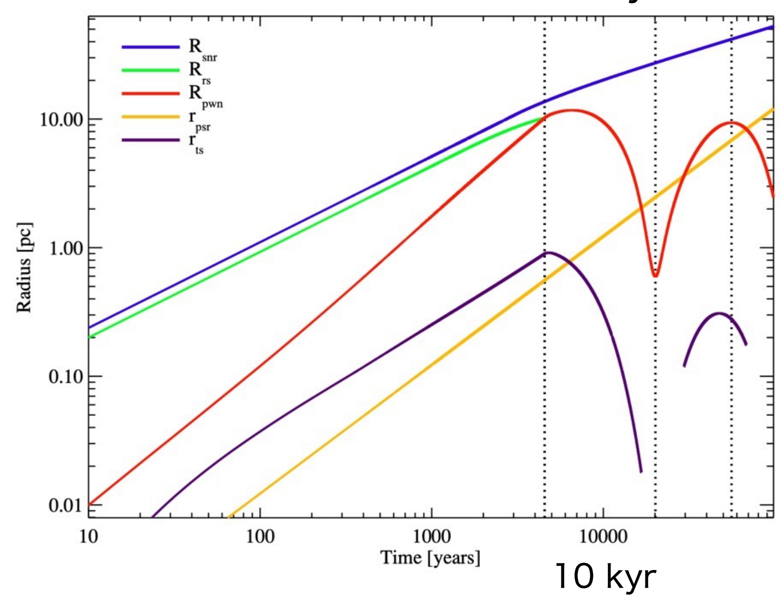
Future observation：

- Neutrino obs. w/ IceCube-Gen2[3] => Constraint on γ-ray flux from hadrons
- Accurate measurement of sub-PeV γ-ray energy spectrum

Energy spectrum of CR protons[1]
(Initially injected w/ 100 TeV mono energy)



Evolution of the size of the system[2]



1. Ohira+, MNRAS 478, 926 (2018)
2. Gelfand+, ApJ 703, 2051 (2009)

Summary

- ✓ Obs. of UHE γ up to 320 TeV w/o clear cutoff from PWN HESS J1849−000 by the Tibet AS+MD

  Detection significance : 4.0 σ @ > 25TeV & 4.4 σ @ > 100TeV

- ✓ 1st spectral measurement in 40 TeV < E < 320 TeV

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (2.86 \pm 1.44)\times 10^{-16} \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-2.24\pm 0.41} \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

- ✓ Detection of ~20 pc size MC @ the west side of the src. n_p ~ 70 cm^{-3}

- ✓ Leptonic scenario : ICS $e^{\pm}$ efficiently accelerated by PWN ?? (Γ_e = −1.5)

- ✓ Hadronic scenario : PeV CR acceleration in a PWN-SNR composite system??

  Further theoretical & observational studies needed