東京大学宇宙線研究所「共同利用成果発表会」 2022年 1/25 – 1/26

チベット高原での 高エネルギー宇宙線の研究

佐古　崇志 (東京大学宇宙線研究所)

For the Tibet ASγ Collaboration

令和 3年度チベット実験関係
共同利用研究採択課題一覧

F16 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）

F17 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）

F18 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）

F19 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 790万円　→　配分額 180万円

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 985万円　→　配分額 238.5万円

宇宙線研での研究打ち合わせに使用。

剰余は繰り越し予定。

ご支援、どうもありがとうございます！

活動状況

査読付き論文（2件）
- “First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies”
  M. Amenomori et al., PRL, 126, 141101 (2021)
- “Gamma-Ray Observation of the Cygnus Region in the 100-TeV Energy Region”
  M. Amenomori et al., PRL, 127, 031102 (2021)

国際会議(口頭発表、8件）
●ICRC 2021
- “Modeling of the TeV cosmic-ray anisotropy based on intensity mapping in an MHD-simulated heliosphere”
- “Gamma-ray Observation of the Cygnus Region with the Tibet Air Shower Array”
- “Gamma-ray Observation of SNR G106.3+2.7 with the Tibet Air Shower Array”
- “Observation of ultra-high-energy diffuse gamma rays from the galactic plane with the Tibet air shower array”
- “A northern sky survey for ultra-high-energy gamma-ray source using the Tibet air-shower array and muon-detector array”
- “Sensitivity of the Tibet hybrid experiment (Tibet-III + MD) for primary proton spectra between 30 TeV and a few hundreds of TeV’s”
- “Highlights from gamma-ray observation by the Tibet ASgamma experiment”

●TeVPA 2021
- “Recent results from the Tibet ASγ experiment”

国内学会(口頭発表、7件）
● 2021 9/14 – 9/17, 日本物理学会(オンライン)
- チベット空気シャワー観測装置による超高エネルギーガンマ線源の観測(4)
- チベット空気シャワー観測装置による銀河面からのsub-PeV拡散ガンマ線の観測
- チベット空気シャワー観測装置を用いた数TeV領域でのガンマ線バースト探索

● 2022 3/14 – 3/19, 日本物理学会
- チベット実験で観測された宇宙線異方性の太陽圏磁場による変調(3)
- Tibet-III と MD による 100 TeV 周辺陽子スペクトルの観測

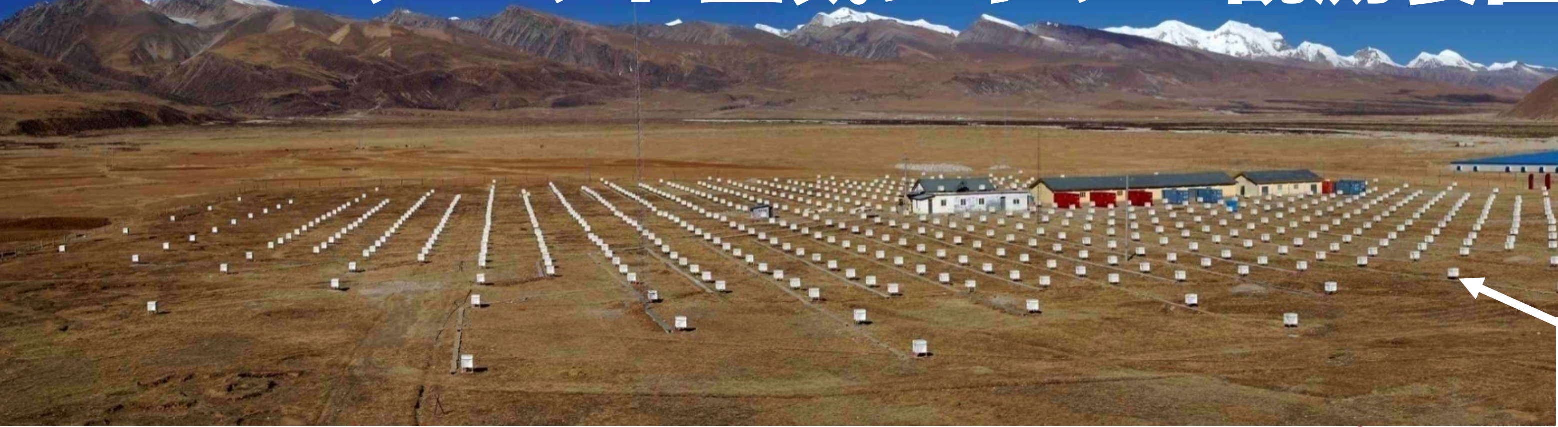
● 2022 3/1 – 3/2, ISEE合同研究集会(オンライン予定)
- TeV 領域宇宙線異方性の太陽圏磁場による変調
- Tibet ASγ 実験での最近のガンマ線観測

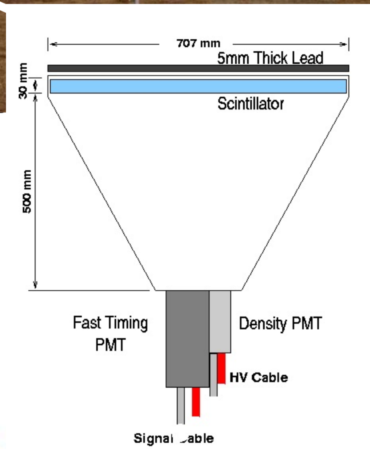
The Tibet ASγ Collaboration

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

(1) Department of Physics, Hirosaki University, Hirosaki 036-8561, Japan (2) School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China (3) Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China (4) National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China (5) Department of Mathematics and Physics, Tibet University, Lhasa 850000, China (6) Department of Physics, Hebei Normal University, Shijiazhuang 050016, China (7) University of Chinese Academy of Sciences, Beijing 100049, China (8) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao 266237, China (9) Institute of Modern Physics, SouthWest Jiaotong University, Chengdu 610031, China (10) Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan (11) Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan (12) Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan (13) Faculty of Systems Engineering, Shibaura Institute of Technology, Omiya 330-8570, Japan (14) Department of Physics, Shinshu University, Matsumoto 390-8621, 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

チベット空気シャワー観測装置



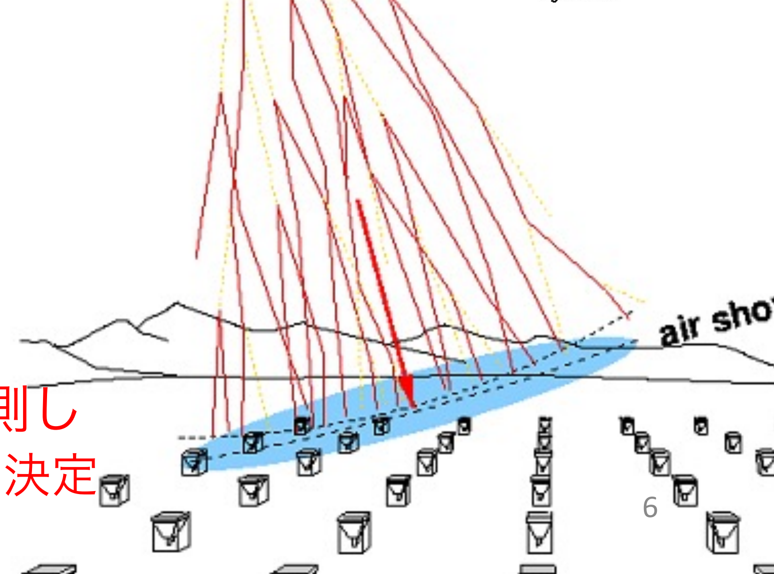


- チベット (90.522°E, 30.102°N) 標高4300 m

<u>現行スペック</u>

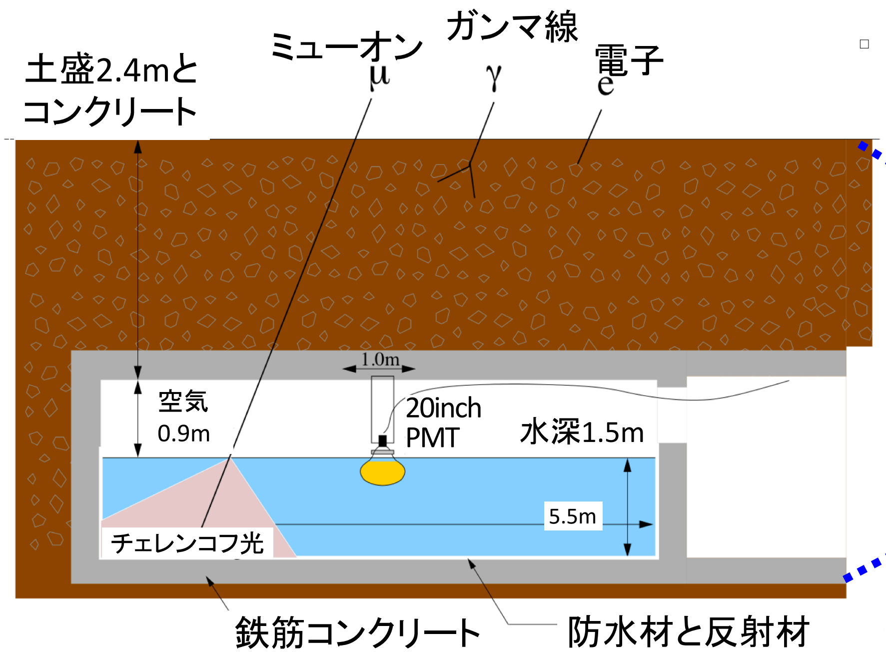
□ シンチレーション検出器数	0.5 m² x 597
□ 空気シャワー有効面積	~65,700 m²
□ 観測エネルギー	>TeV
□ 角度分解能	~0.5°@10TeV γ
	~0.2°@100TeV γ
□ エネルギー分解能	~40%@10TeV γ
	~20%@100TeV γ
□視野	~2 sr

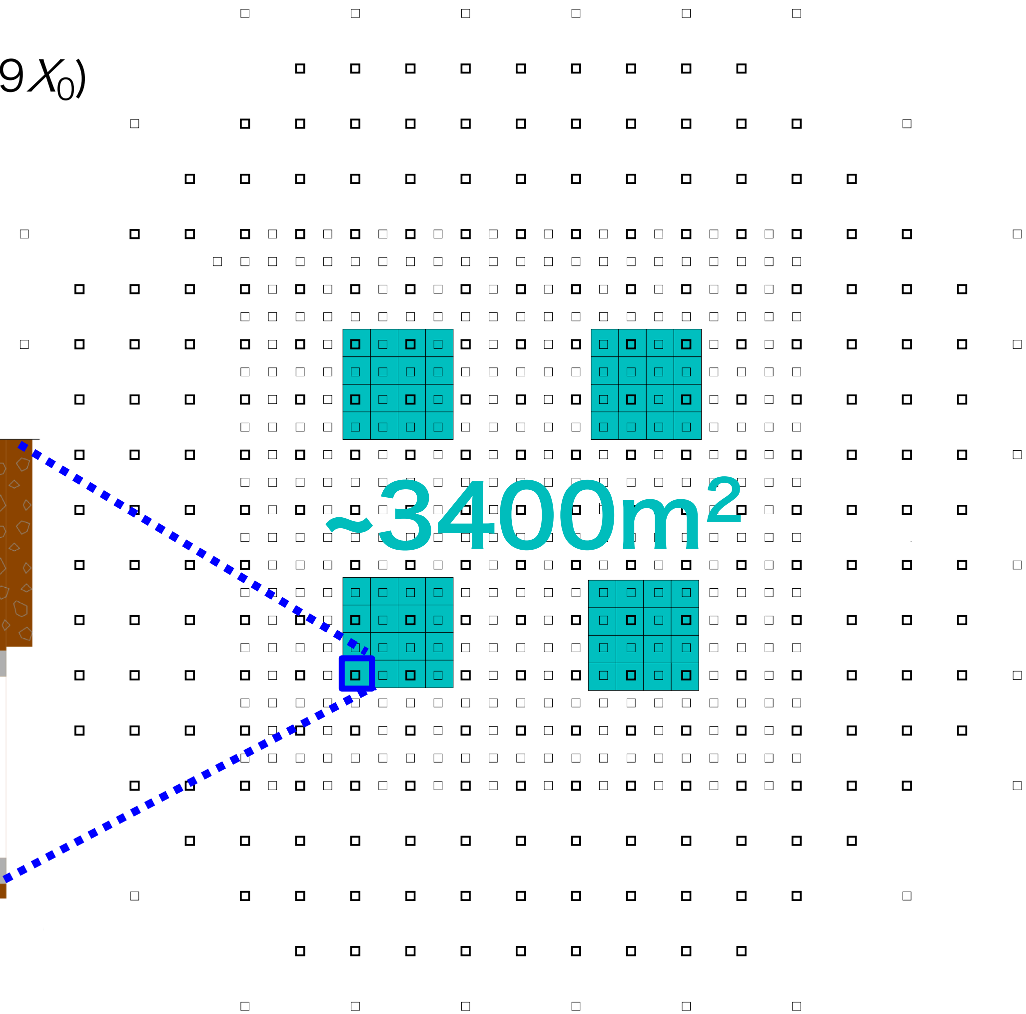
→空気シャワー中の二次粒子(主に$e^{+/-}$, γ)を観測し
一次宇宙線・ガンマ線のエネルギー、方向を決定



水チェレンコフ型ミューオン観測装置

- ✓ 地下 2.4m (物質厚 ~ 515g/cm2 ~19X_0)
- ✓ 7.35m×7.35m×水深1.5m　水槽
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ 水槽材質：コンクリート+タイベック



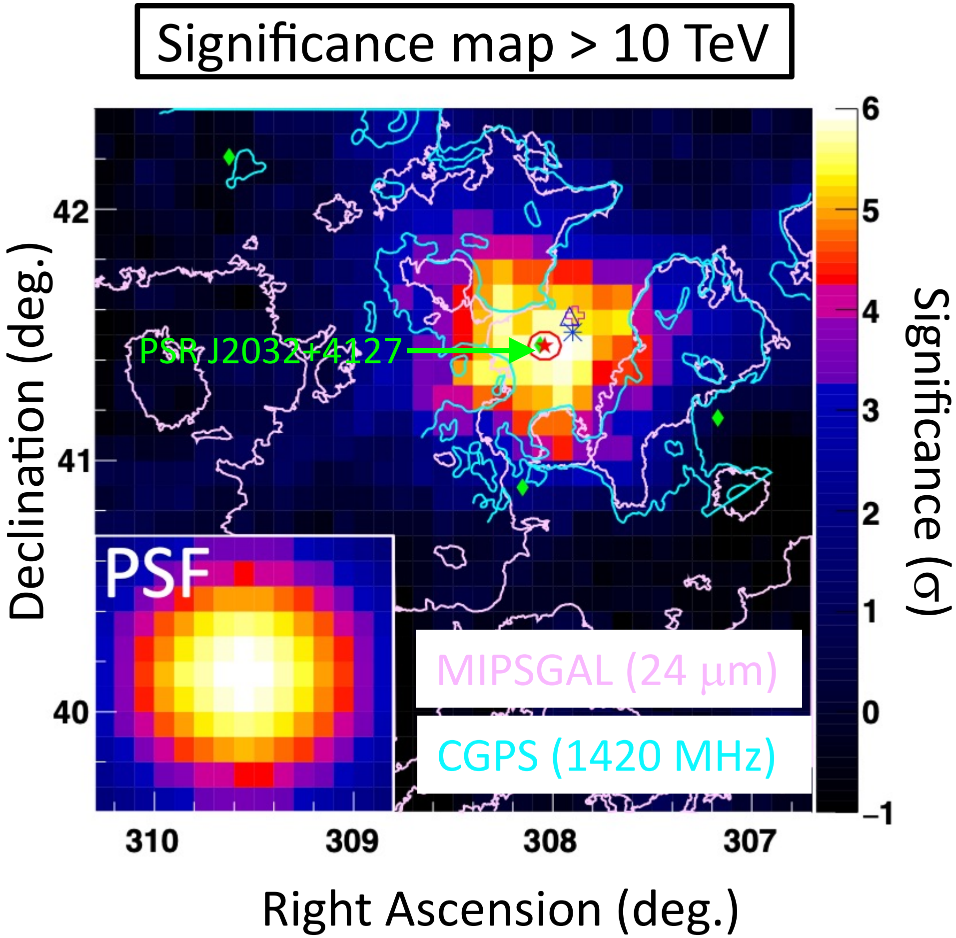


- ➢ 空気シャワー中のミューオン数を測定し、ガンマ線／核子選別
- ➢ ミューオンカット後、100TeV領域で約99.9%の宇宙線を除去、約90%のガンマ線を残す

Gamma-ray observations of point-like/extended sources in the Cygnus OB1 & OB2 regions

M. Amenomori et al., PRL, 127, 031102 (2021)

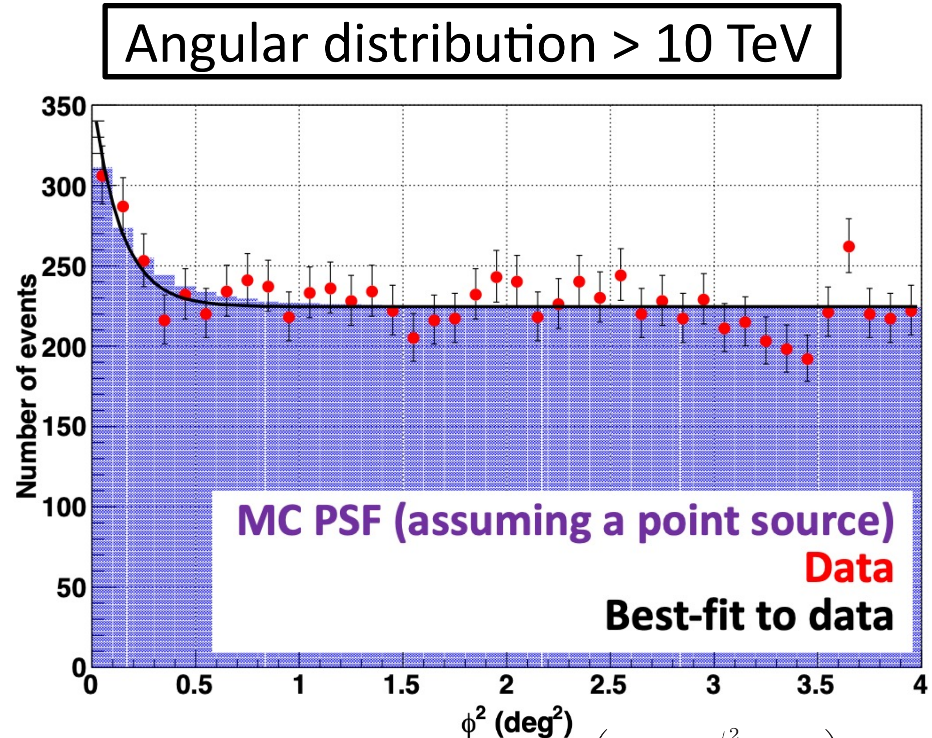
TASG J2032+414 (Cygnus OB2)



★ **this work**

Fermi, VERITAS, HAWC, MAGIC

- Detection significance 5.3σ > 10 TeV
- Source position coincident with PSR J2032+4127



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

σ_{PSF} = 0.36° from MC simulation

σ_{EXT}: source extension

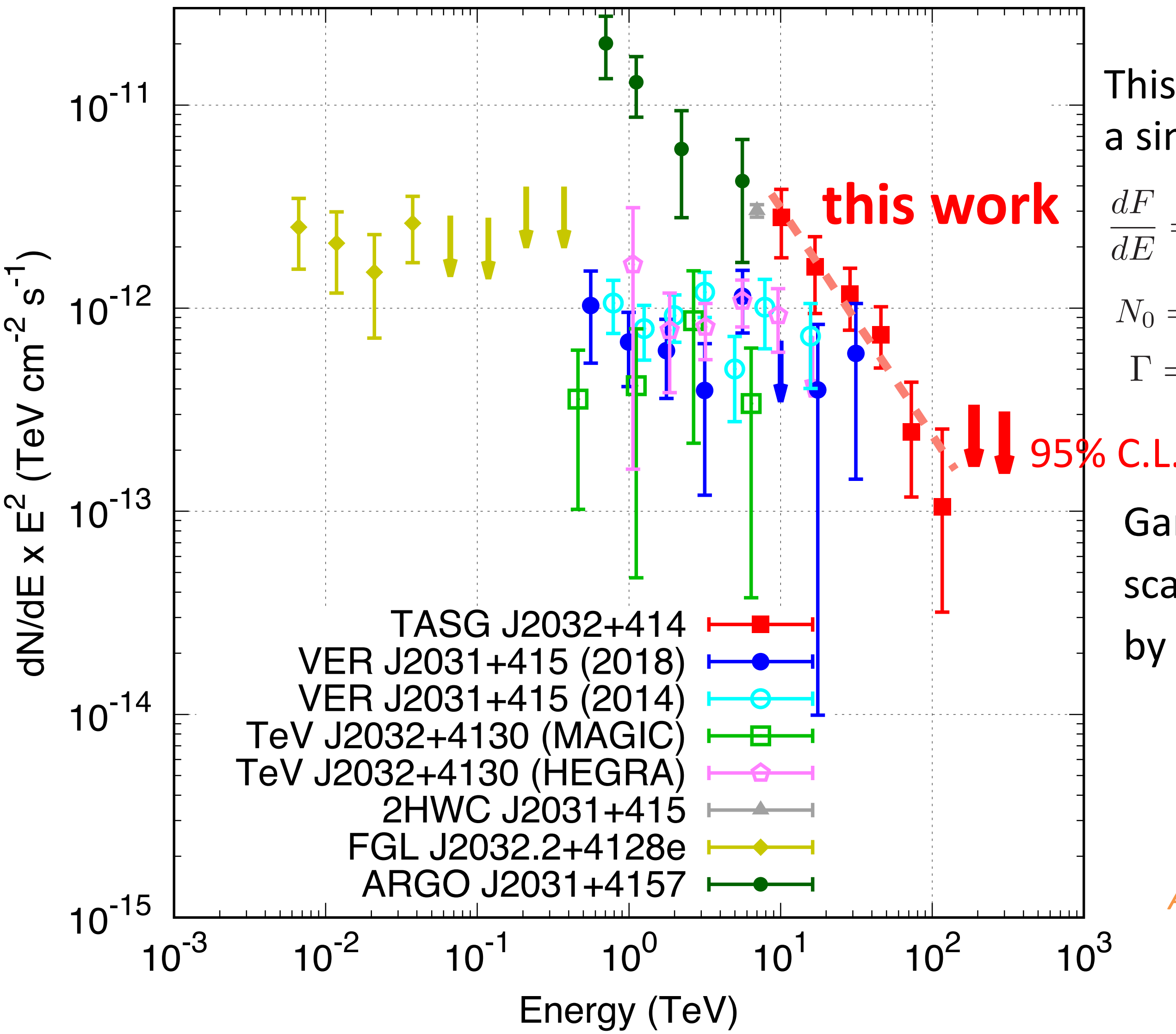
➡ σ_{EXT} = **0.00° ± 0.14°**

Consistent with previous results ($\sigma_{EXT} \approx 0.2°$)

Abeysekara+, ApJL, 867, L19 (2018)
Abeysekara+, Nat. Astron. Let. (2021)
Abdollahi+, ApJ, Suppl. Ser., 247, 33 (2020)
Taylor+, Astron. J. 125, 3145 (2003)
Beerer+, ApJ, 720, 679 (2010)
Kraemer+, Astron. J., 139, 2319 (2010)

TASG J2032+414 (Cygnus OB2)

γ-ray energy spectrum



This work can be fitted by a simple power law:

$$\frac{dF}{dE} = N_0 \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-\Gamma}$$

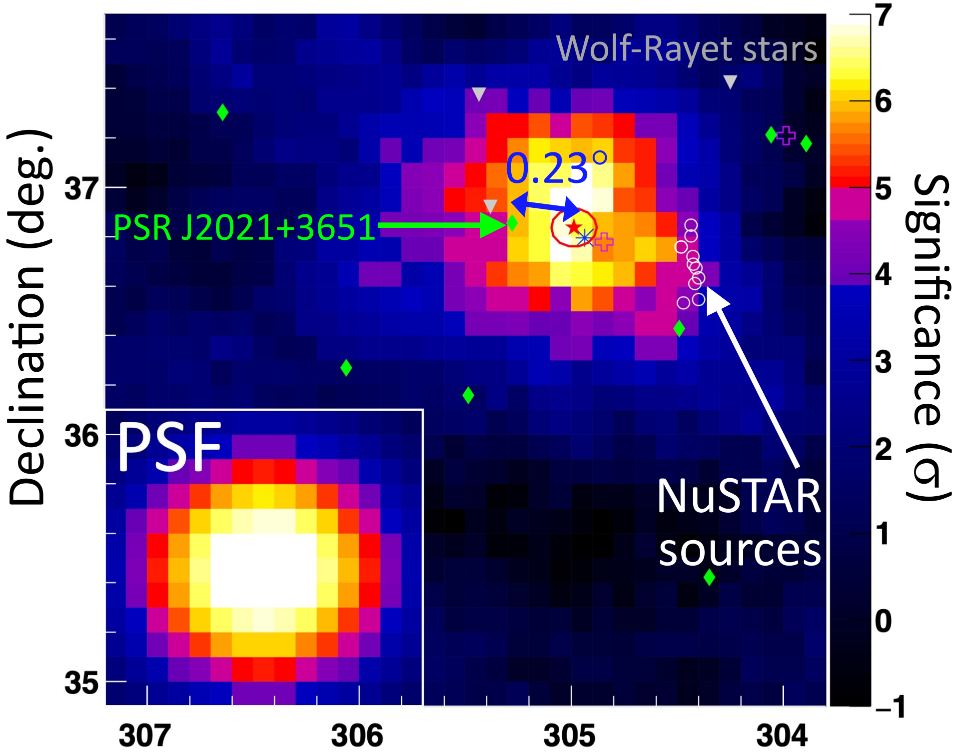
$$N_0 = (4.13 \pm 0.83) \times 10^{-16}\ \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

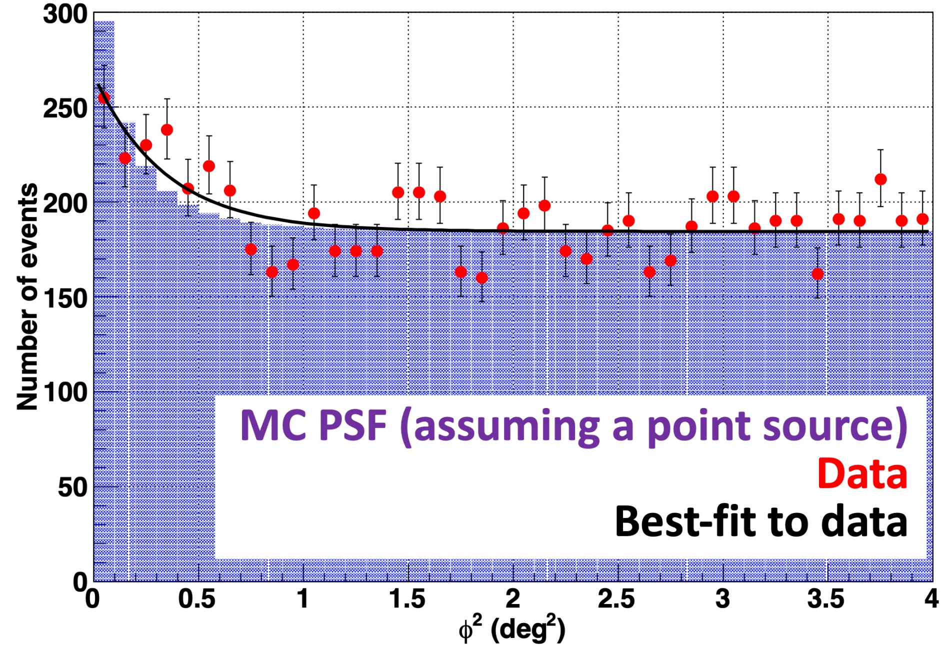
$$\Gamma = 3.12 \pm 0.21 \qquad (\chi^2/\mathrm{ndf} = 1.6/4)$$

Gamma rays likely due to IC scattering by electrons produced by PSR J2032+4127

Abeysekara+, ApJ, 861, 134 (2018)
Aliu+, ApJ, 783, 16 (2014)
Albert+, ApJL, 675, L25 (2008)
Aharonian+, A&A, 431, 197 (2005)
Abeysekara+, Nat. Astron. Let. (2021)
Bartoli+, ApJL, 745, L22 (2012)

TASG J2019+368 (Cygnus OB1)





★ **this work**

◆ Fermi ✚ VERITAS ✱ HAWC

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

σ_{PSF} = 0.30° from MC simulation

σ_{EXT}: source extension

➡ **σ_{EXT} = 0.28° ± 0.07°**

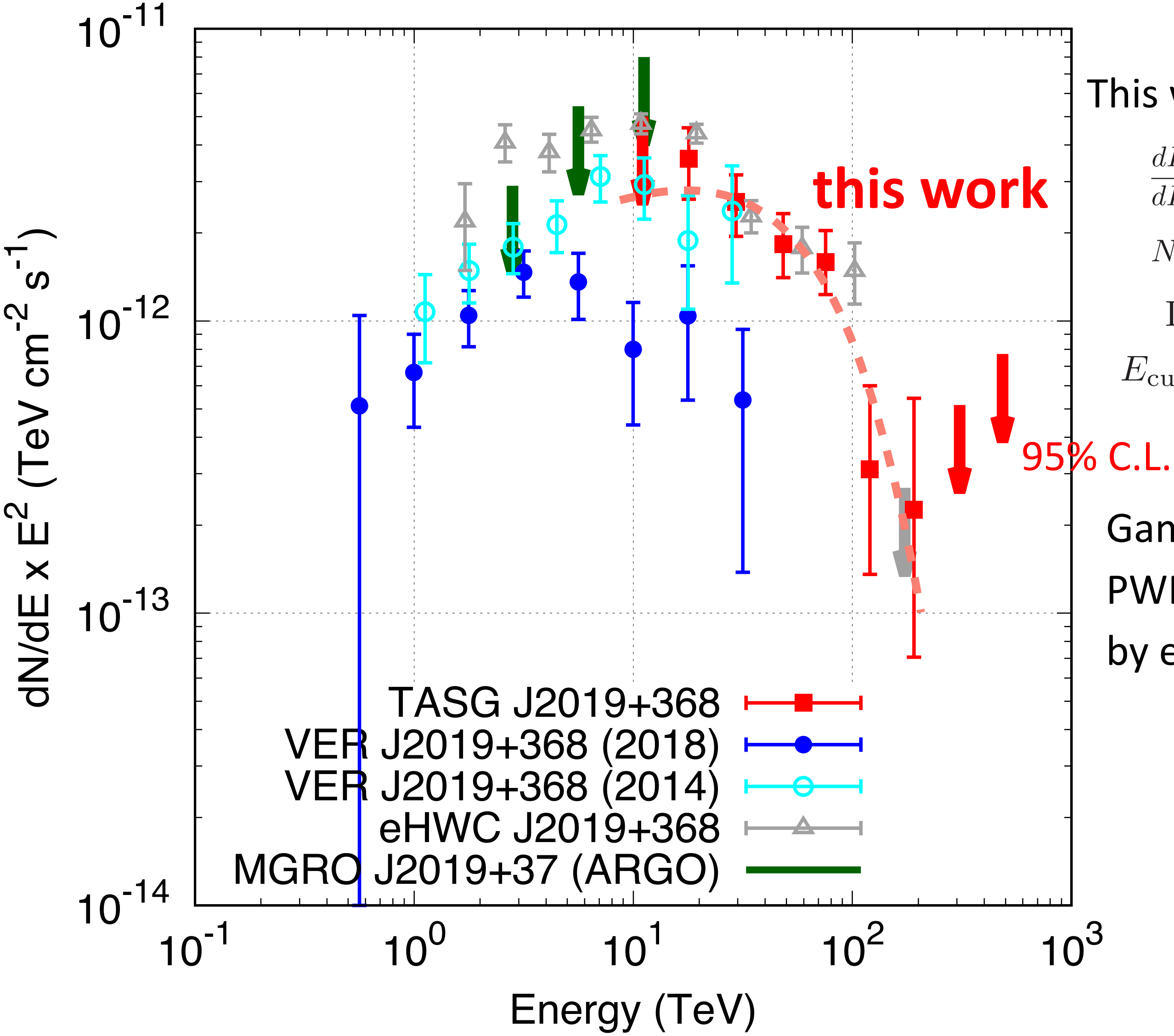
Consistent with previous results ($\sigma_{EXT} \approx$ 0.2° - 0.3°)

- Detection significance 6.7σ > 10 TeV
- Source position coincident with PWN G75.2+0.1 0.23° west of PSR J2021+3651

Abdollahi+, ApJ, Suppl. Ser., 247, 33 (2020)
Van der Hucht, New Astron. Rev. 45, 135 (2001)
Abeysekara+, ApJ, 861, 134 (2018)
Albert+, ApJ, 905, 76 (2020)
Gotthelf+, ApJ, 826, 25 (2016)

TASG J2019+368 (Cygnus OB1)

γ-ray energy spectrum



This work can be fitted by

$$\frac{dF}{dE} = N_0 \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

$$N_0 = (3.6 \pm 2.0) \times 10^{-15}\ \mathrm{TeV^{-1}cm^{-2}s^{-1}}$$

$$\Gamma = 1.6 \pm 0.5$$

$$E_{\mathrm{cut}} = 44 \pm 21\ \mathrm{TeV} \quad (\chi^2/\mathrm{ndf} = 3.0/4)$$

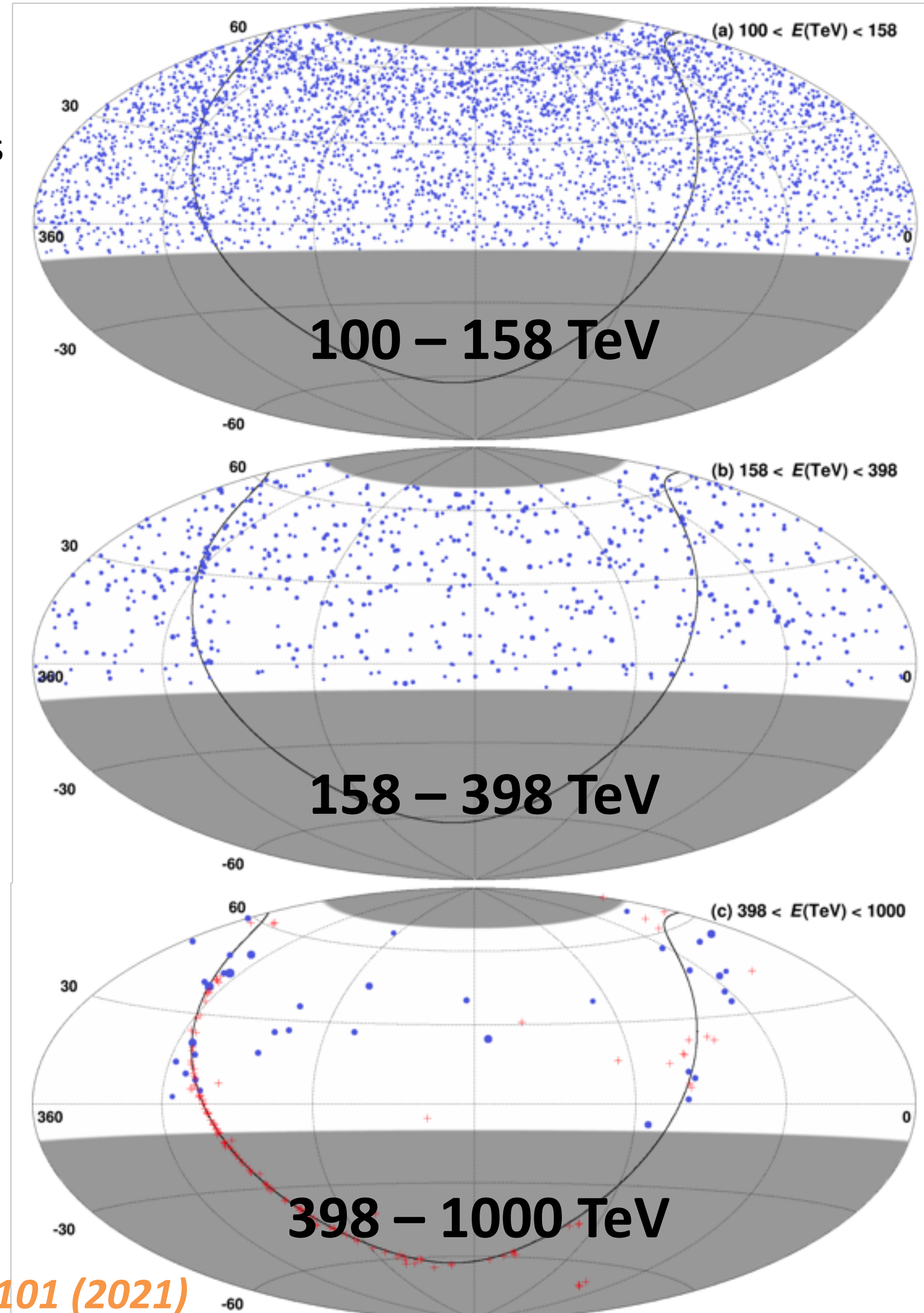
Gamma rays likely produced in PWN G75.2+0.1 via IC scattering by electrons

Observation of sub-PeV diffuse γ rays from the Milky Way galaxy

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

Event Distribution

Equatorial coordinates



Blue points:
Tibet AS +MD
(Circle size ∝ Energy)

Red plus marks:
TeV sources
(TeVCat catalog)

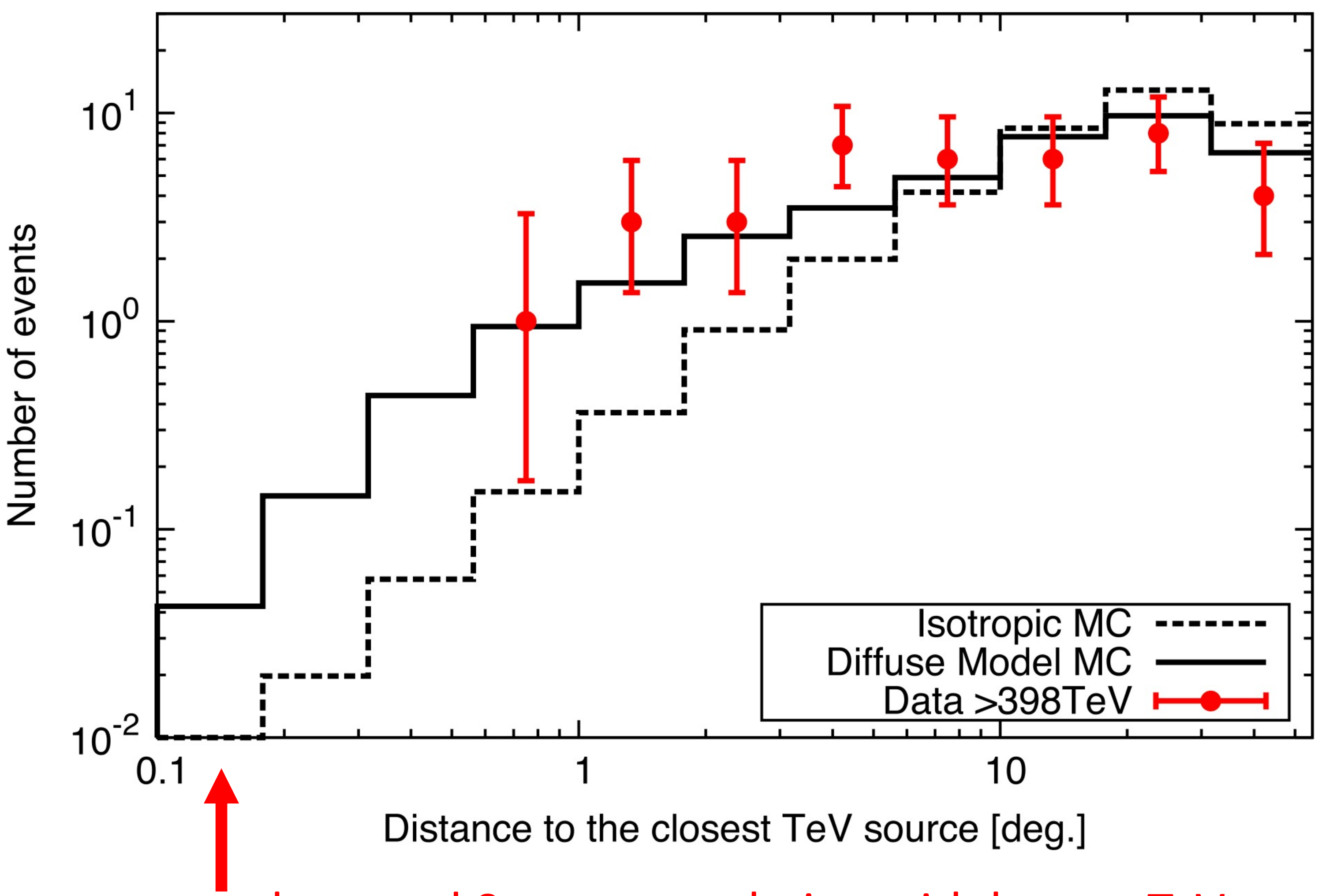
>0.398 PeV ($10^{2.6}$ TeV) 38 events in our FoV

→Not from known TeV sources!
& No signal > 10 TeV around them

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

Distribution of distance to the closest TeV source for events > 0.398 PeV

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



no peak around 0 -> no correlation with known TeV sources

Diffuse Model: Lipari & Vernetto, PRD 98, 143003, (2018)

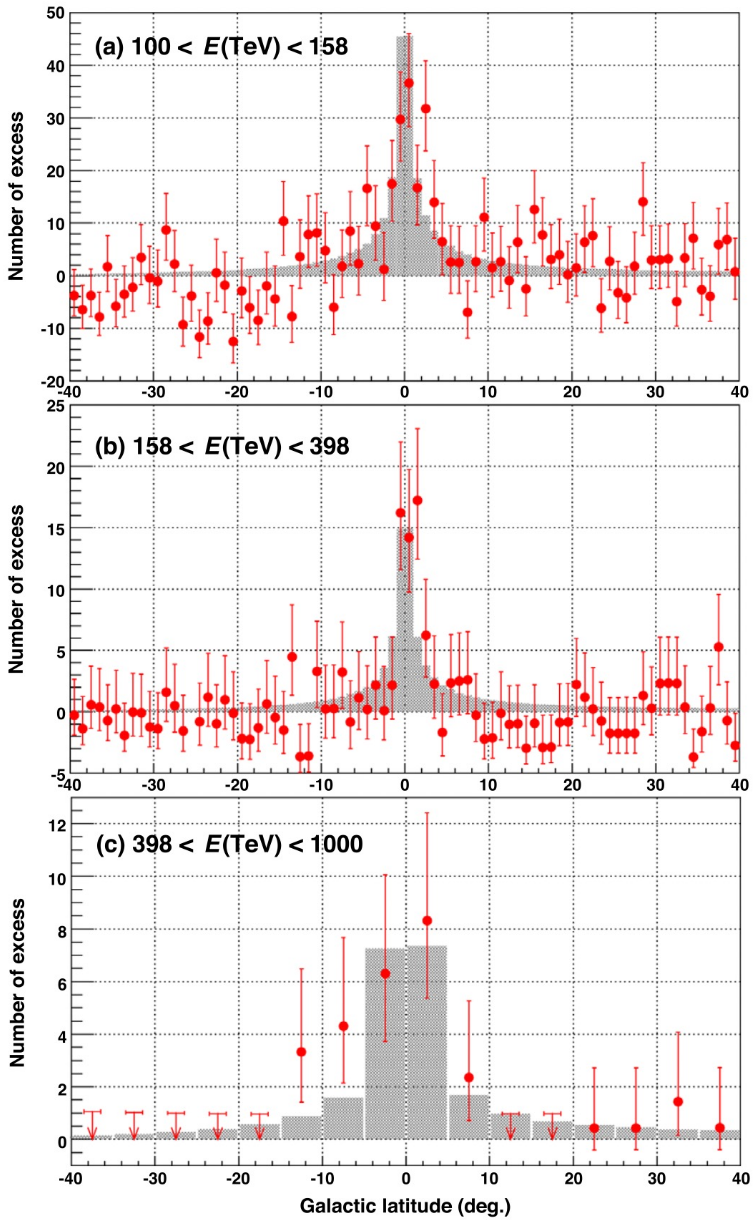
Galactic latitude distributions

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

100 – 158 TeV

158 – 398 TeV

398 – 1000 TeV



Shaded Histograms: Model shape normalized to DATA (|b|<5°)

Model: Lipari & Vernetto, PRD 98, 143003, (2018)

Number of sub-PeV events in the direction of galactic plane observed by Tibet AS+MD array

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

Highest gamma-ray energy = 0.957 (+ 0.166 - 0.141) PeV
(Eres ~10 % around 400 TeV & energy scale uncertainty ~13% in quadrature)

TABLE S1. Number of events observed by the Tibet AS+MD array in the direction of the galactic plane. The galactic longitude of the arrival direction is integrated across our field of view (approximately $22^\circ < l < 225^\circ$). The ratios (α) of exposures between the ON and OFF regions are 0.135 for $|b| < 5^\circ$ and 0.27 for $|b| < 10^\circ$, respectively.

	$\|b\| < 5^\circ$			$\|b\| < 10^\circ$		
Energy bin (TeV)	N_{ON}	N_{BG} ($= \alpha N_{OFF}$)	Significance (σ)	N_{ON}	N_{BG} ($= \alpha N_{OFF}$)	Significance (σ)
100 – 158	513	333	8.5	858	655	6.6
158 – 398	117	58.1	6.3	182	114	5.1
398 – 1000	16	1.35	6.0	23	2.73	5.9

TABLE S2. Galactic diffuse gamma-ray fluxes measured by the Tibet AS+MD array.

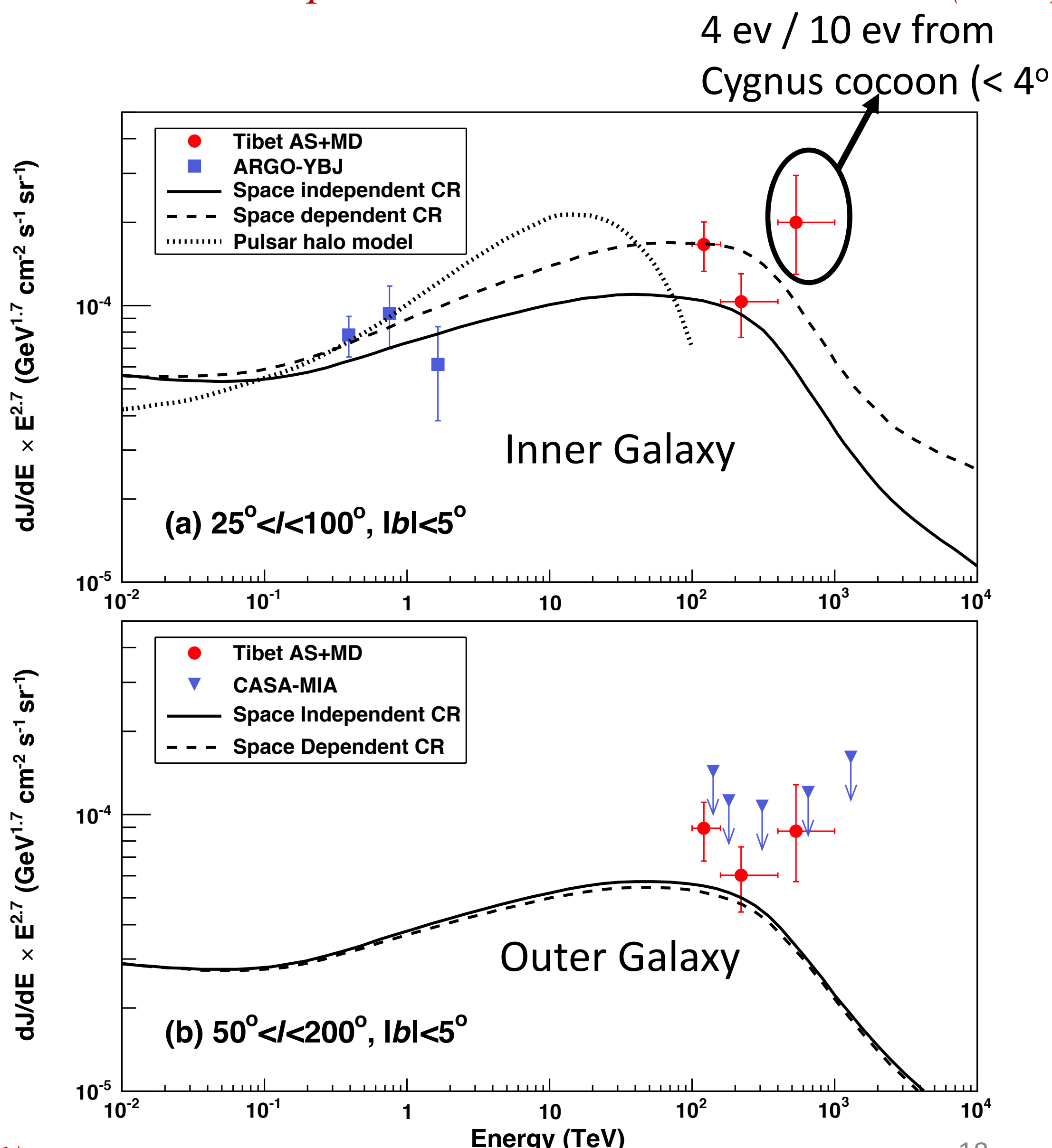
Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ, \|b\| < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50^\circ < l < 200^\circ, \|b\| < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
100 – 158	121	$(3.16 \pm 0.64) \times 10^{-15}$	$(1.69 \pm 0.41) \times 10^{-15}$
158 – 398	220	$(3.88 \pm 1.00) \times 10^{-16}$	$(2.27 \pm 0.60) \times 10^{-16}$
398 – 1000	534	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

Energy Spectrum

Models: Lipari & Vernetto, PRD 98, 143003, (2018)

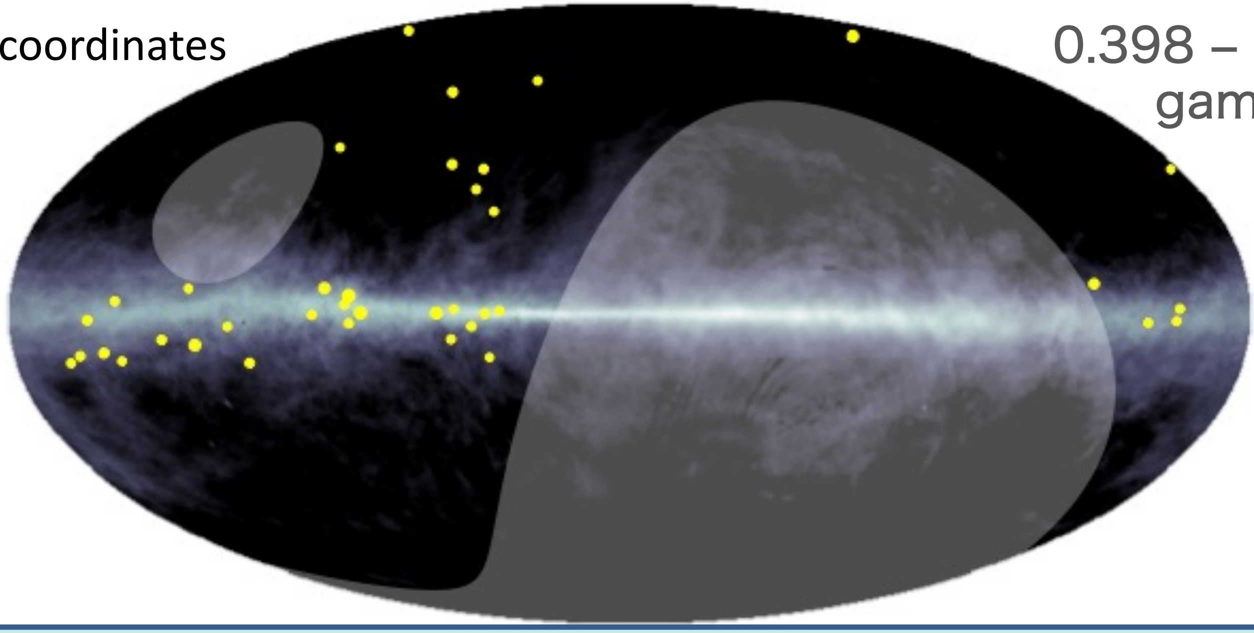
After excluding the contribution from the known TeV sources (within 0.5° in radius) listed in the TeVCat catalog
(~13% to the diffuse flux, but no contamination to events > 0.398 PeV)

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



Amenomori+., PRL 126, 141101,(2021)

Electron origin? vs Proton origin?



- ✓ Observed gamma rays are isolated, not coming from known gamma-ray sources.
  → **Electrons** lose their energy quickly, so they **should stay near the source**.
  → **Protons** don't lose energy and **can escape farther from the source**.

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

- ✓ This is the first evidence for existence of PeVatrons, in the past and/or present Galaxy, which accelerate protons up to the Peta electron volt (PeV) region.

Summary

Recent results of gamma-ray observations with the Tibet air shower array

Cygnus OB1 & OB2

M. Amenomori et al., PRL, 127, 031102 (2021)

- TASG J2032+414 (Cygnus OB2)
  - (R.A., Dec.) = $(308.04° \pm 0.08°, 41.46° \pm 0.06°)$, coincident with PSR J2032+4127

- TASG J2019+368 (Cygnus OB1)
  - (R.A., Dec.) = $(304.99° \pm 0.11°, 36.84° \pm 0.08°)$, coincident with PWN G75.2+0.1.

sub-PeV galactic diffuse γ-rays

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

- First detection of diffuse γ-rays from the Galaxy in the sub-PeV energy region
- Evidence for existence of past and/or present PeVatrons in our Galaxy

Thank you for your attention!