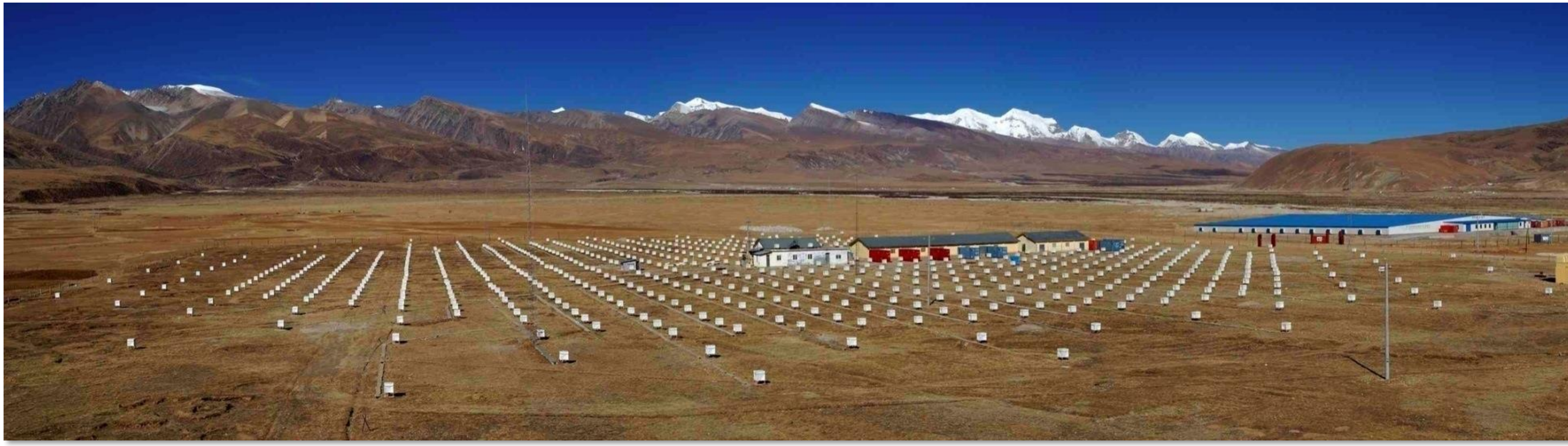


Recent results from the Tibet ASγ experiment

Masato TAKITA (ICRR, Univ. of Tokyo)

For the Tibet ASγ Collaboration,

ICRR, the University of Tokyo

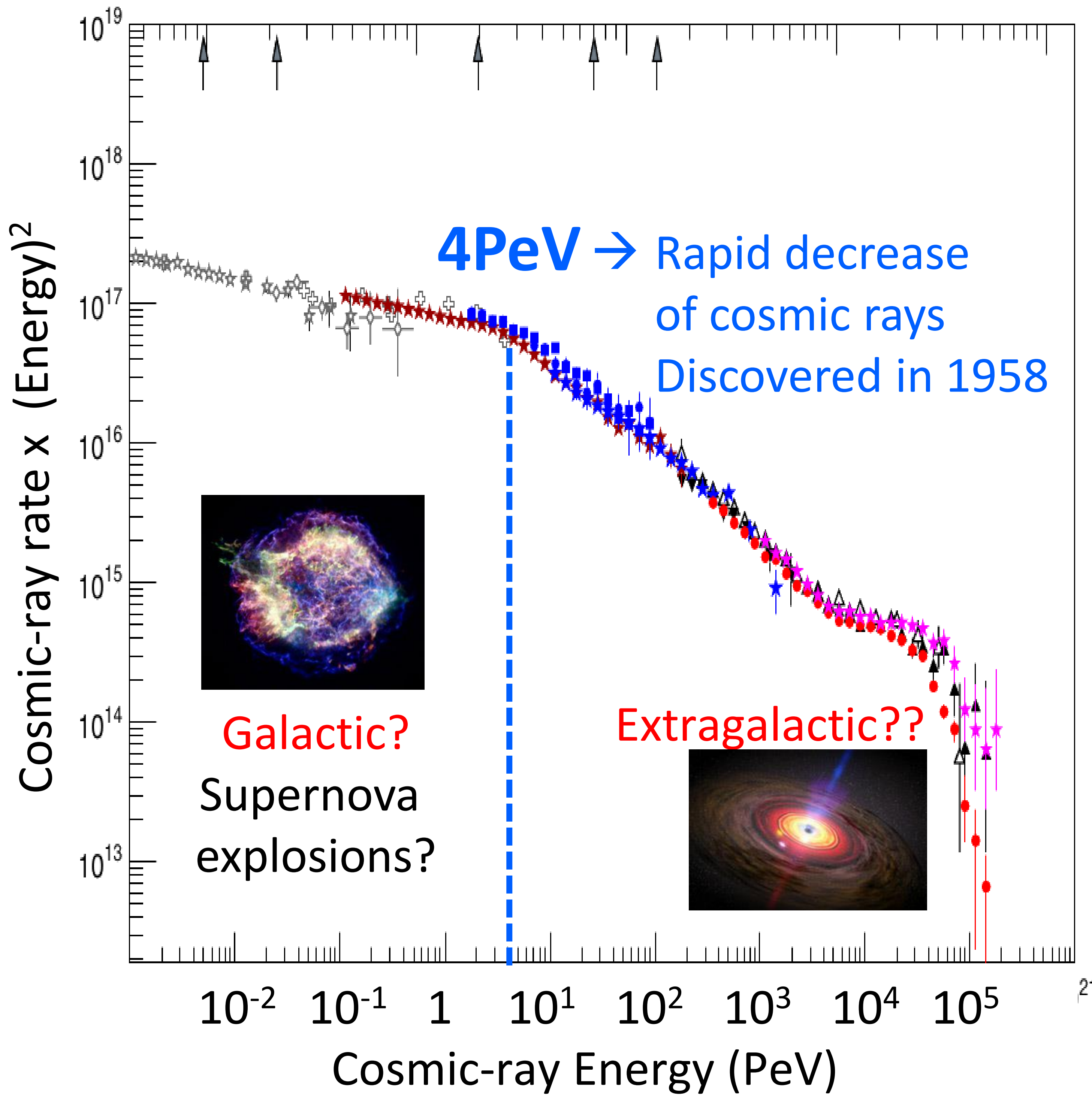
October 25, 2021 @TeVPA2021,
Online

Outline

- Introduction
- The Tibet ASγ Experiment
- Point-like and extended γ-ray sources in the 100 TeV region
- Sub-PeV diffuse γ-rays from Milky Way galaxy
- Future prospects and summary

§ Introduction

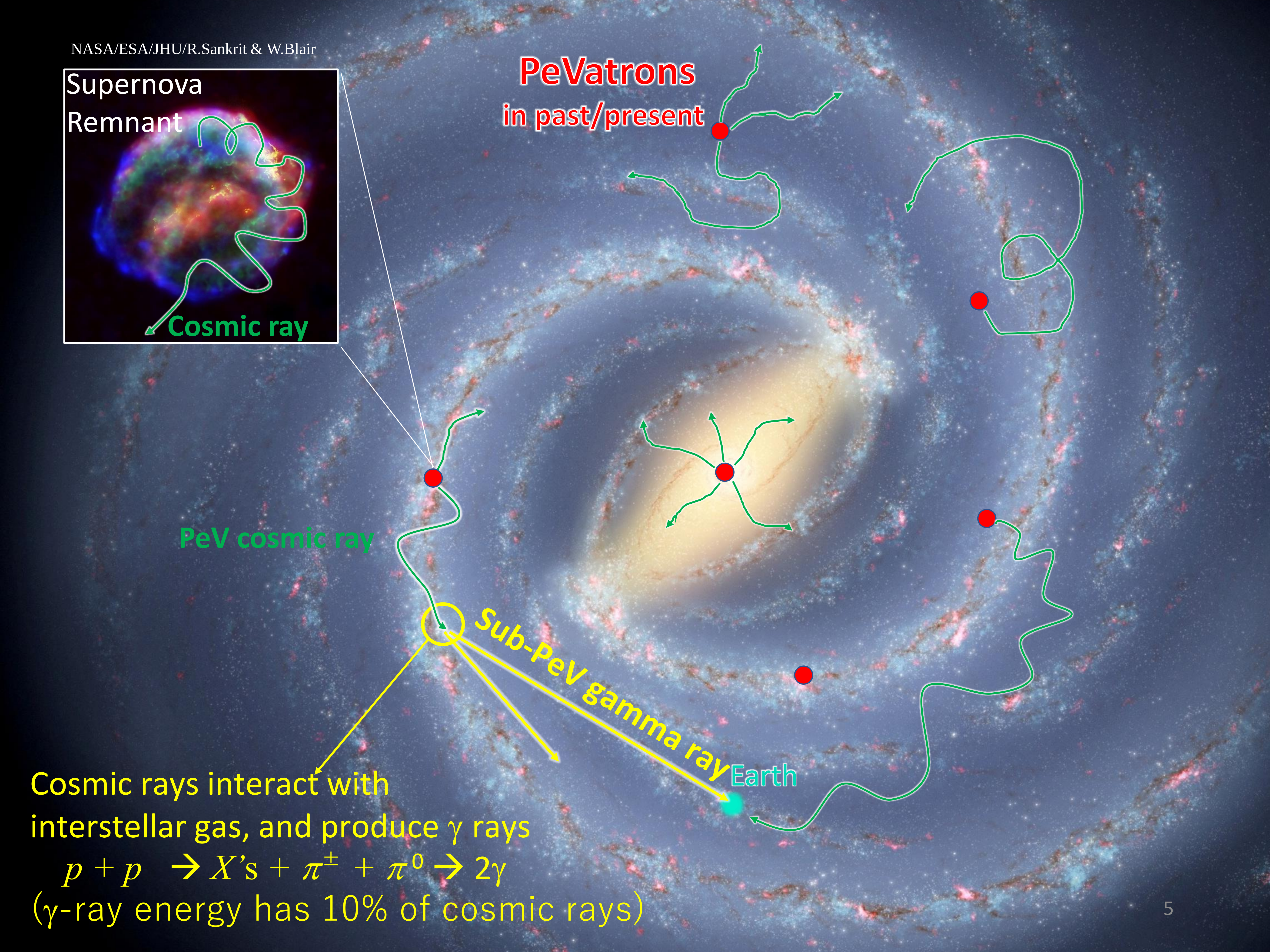
Cosmic Ray Rate & Energies



- ❖ 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 superaccelerators accelerating cosmic rays up to PeV energies


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova Remnant
Cosmic ray
PeVatrons
in past/present
PeV cosmic ray
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 has 10% of cosmic rays)

§ The Tibet ASγ experiment

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)

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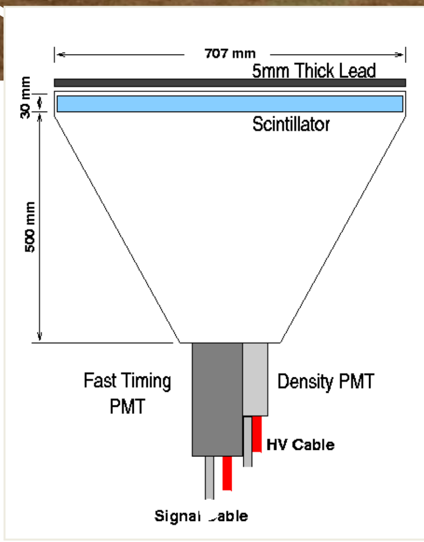
Tibet Air Shower Array



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

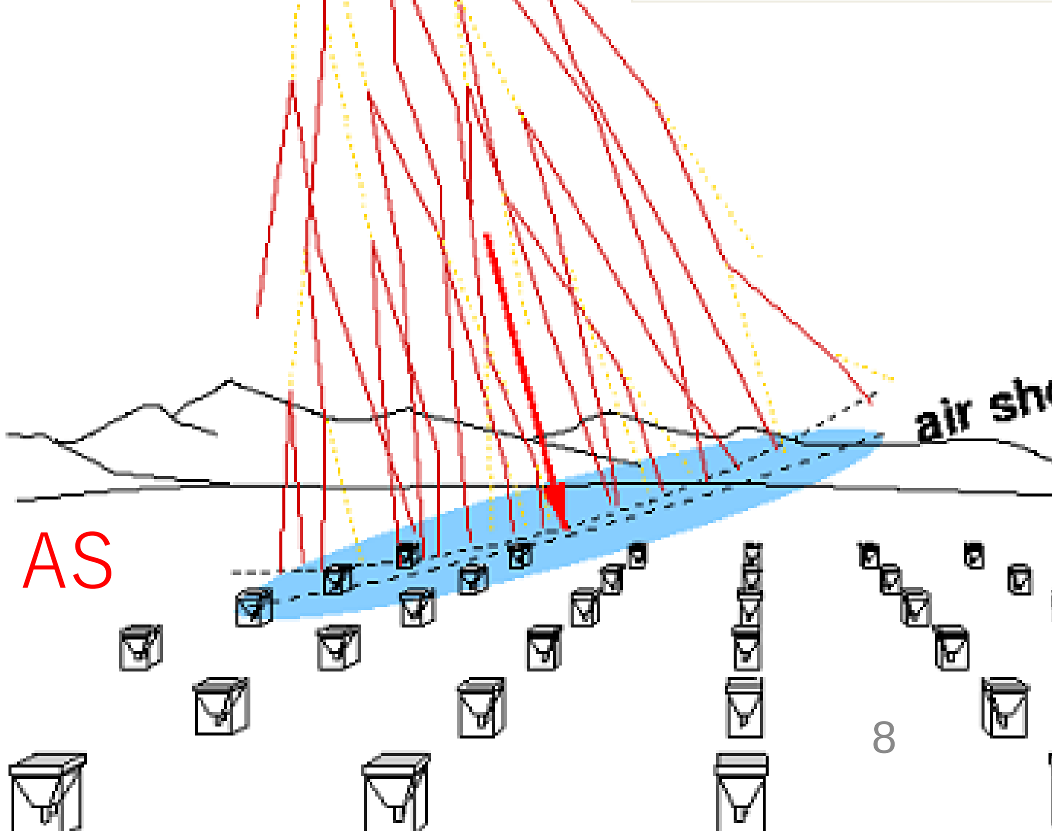
<u>Present Performance</u>

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

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

Primary energy : 2nd particle densities

Primary direction : 2nd relative timings



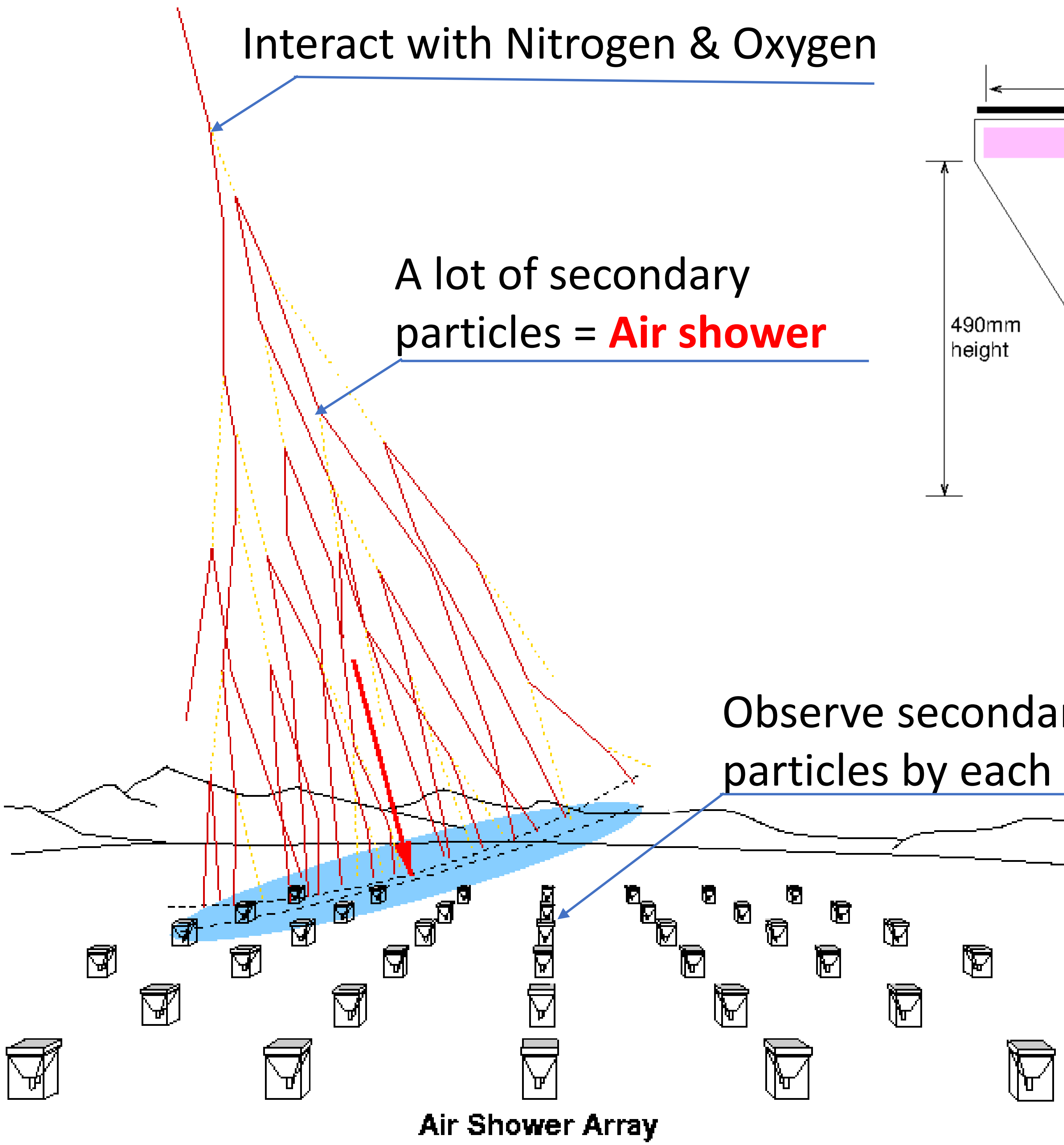
Detection Principle

Gamma ray/Cosmic ray

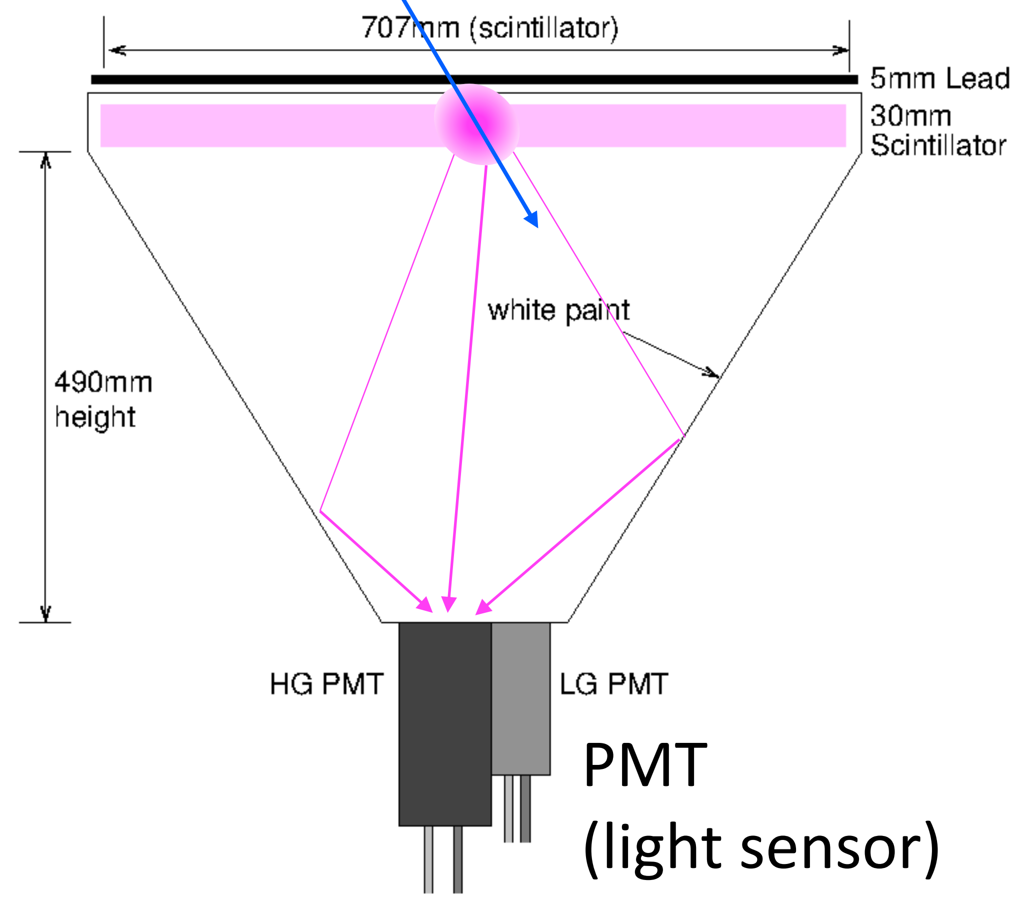
Interact with Nitrogen & Oxygen

A lot of secondary particles = **Air shower**

Observe secondary particles by each detector



0.5 m^2 Plastic scintillator: Emit fluorescence lights when particles pass it

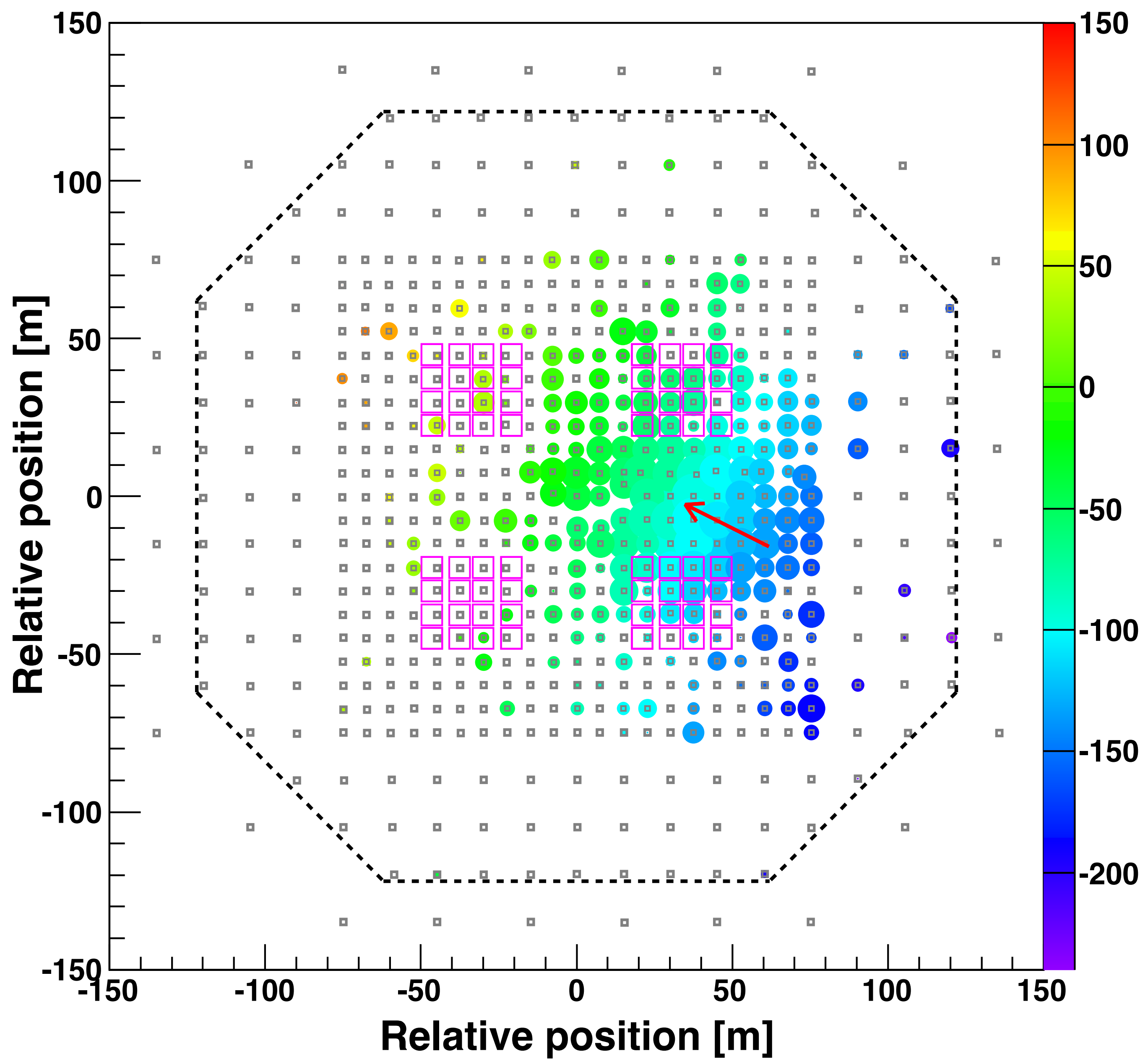


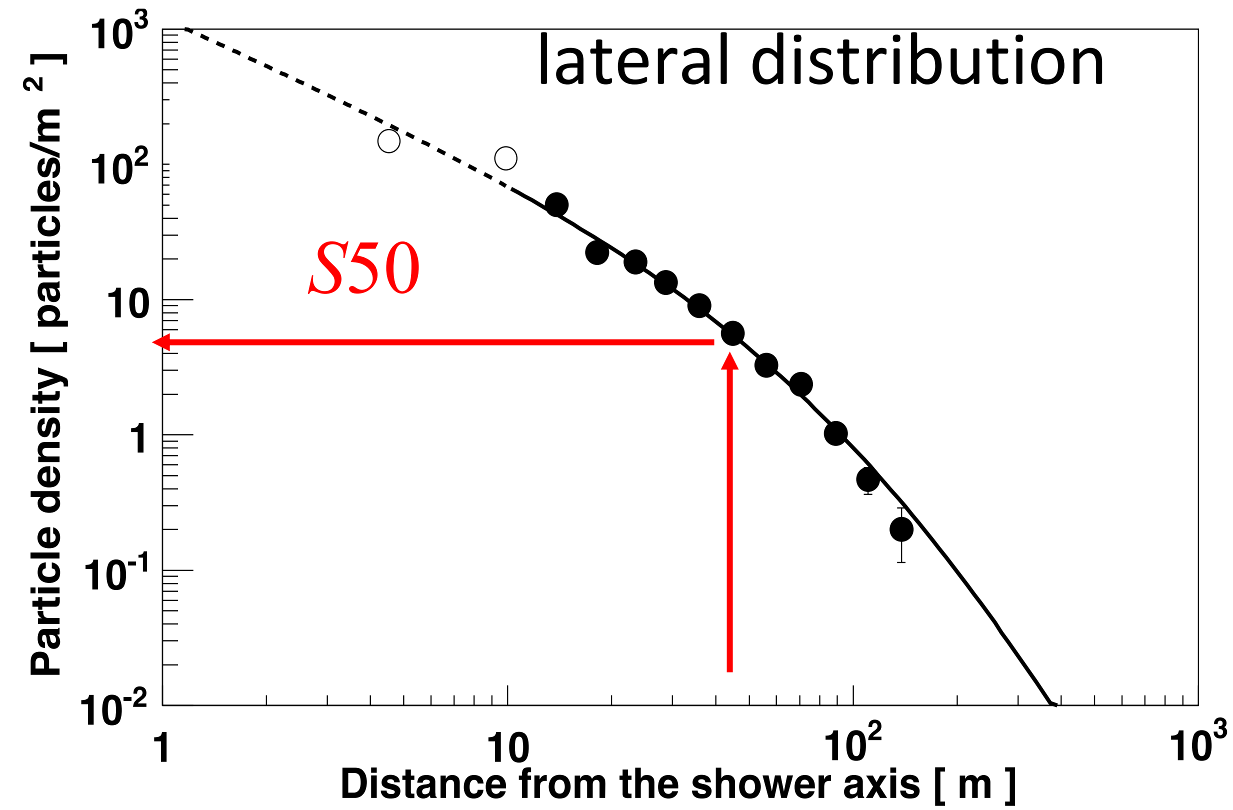
PMT (light sensor)

Determine the direction & energy of the gamma ray

- Angular resolution 0.2 deg
- Energy resolution 20% @0.1PeV

Gamma-like Event from the Crab





fitting with NKG function

➡ E_{rec} ($S50$, θ)

$\Sigma\rho$ (from AS array) : 3256

$\Sigma N\mu$ (MD) : 2.3

zenith angle : 29.8°

E_{rec} : 251^{+46}_{-43} TeV

circle size ∝ log(# of detected particles)

circle color ∝ relative timing [ns]

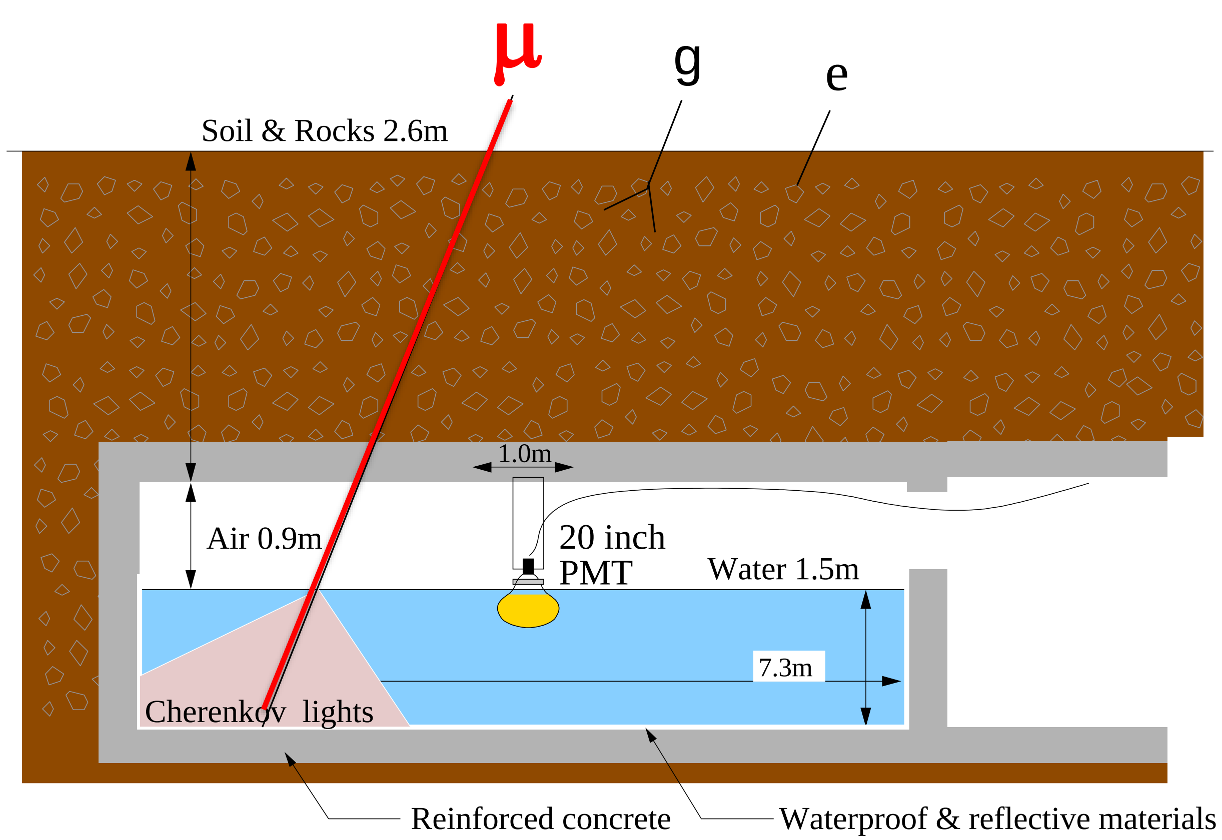
Amenomori +, PRL ***123****, 051101 (2019)*

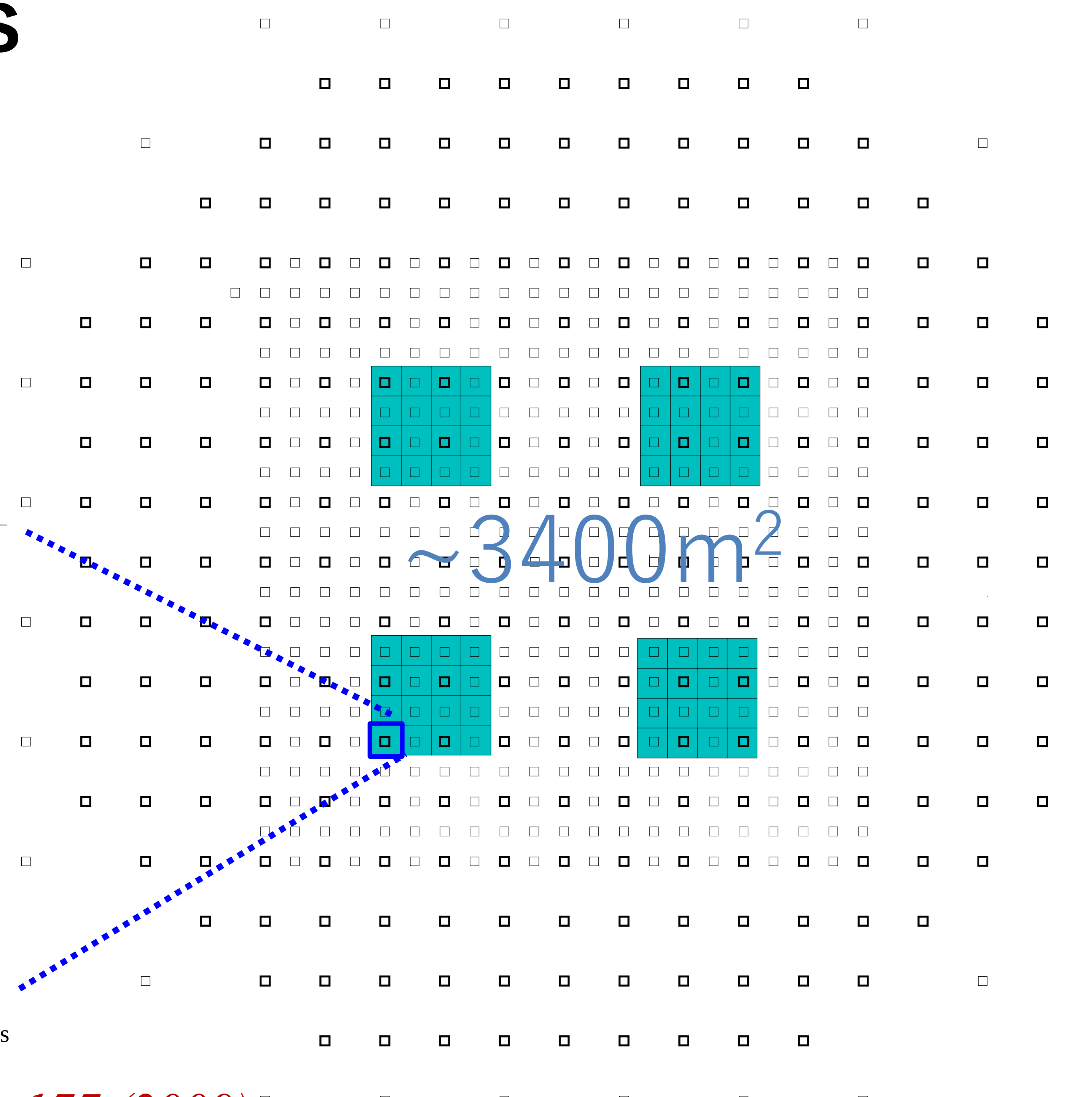
S50 improves *E* resolutions (10 - 1000 TeV)
→ ~40%@10 TeV , ~20%@100 TeV

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

Underground Water Cherenkov Muon detectors

- ✓ 2.4m underground (~515g/cm^2 ~9X_0)
- ✓ 4 pools, 16 units / pool
- ✓ 7.35m × 7.35m × 1.5m deep (water)
- ✓ 20" Φ PMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets





Basic idea: T. K. Sako+, Astropart. Phys. 32, 177 (2009)

Measurement of # of μ in AS → γ／CR discrimination

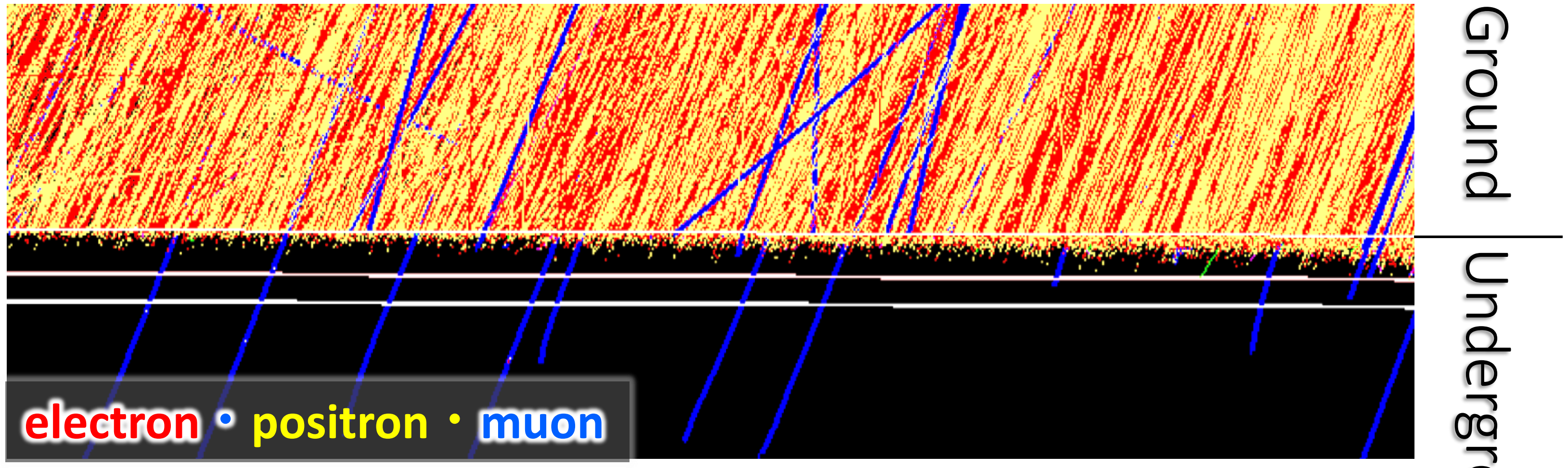
DATA: February, 2014 - May, 2017 Live time: 719 days

Gamma-Ray Selection

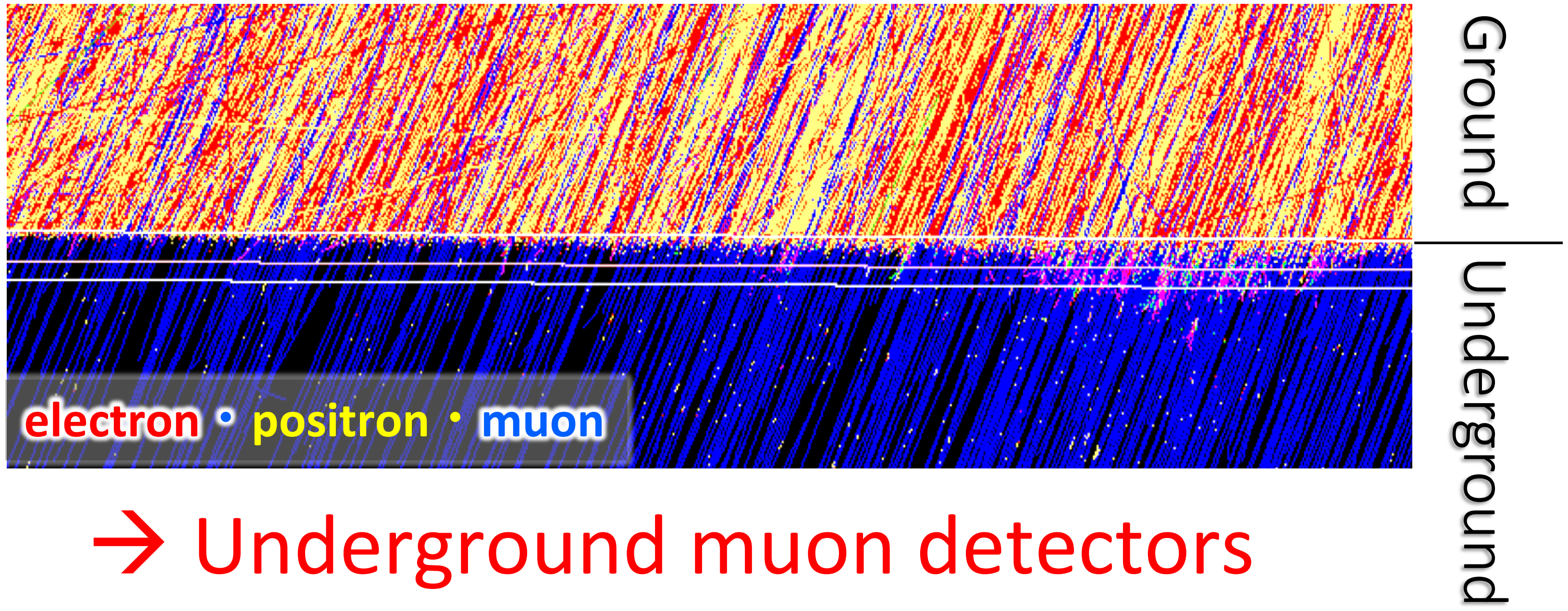
γ-ray → poor muons

Muons can penetrate underground

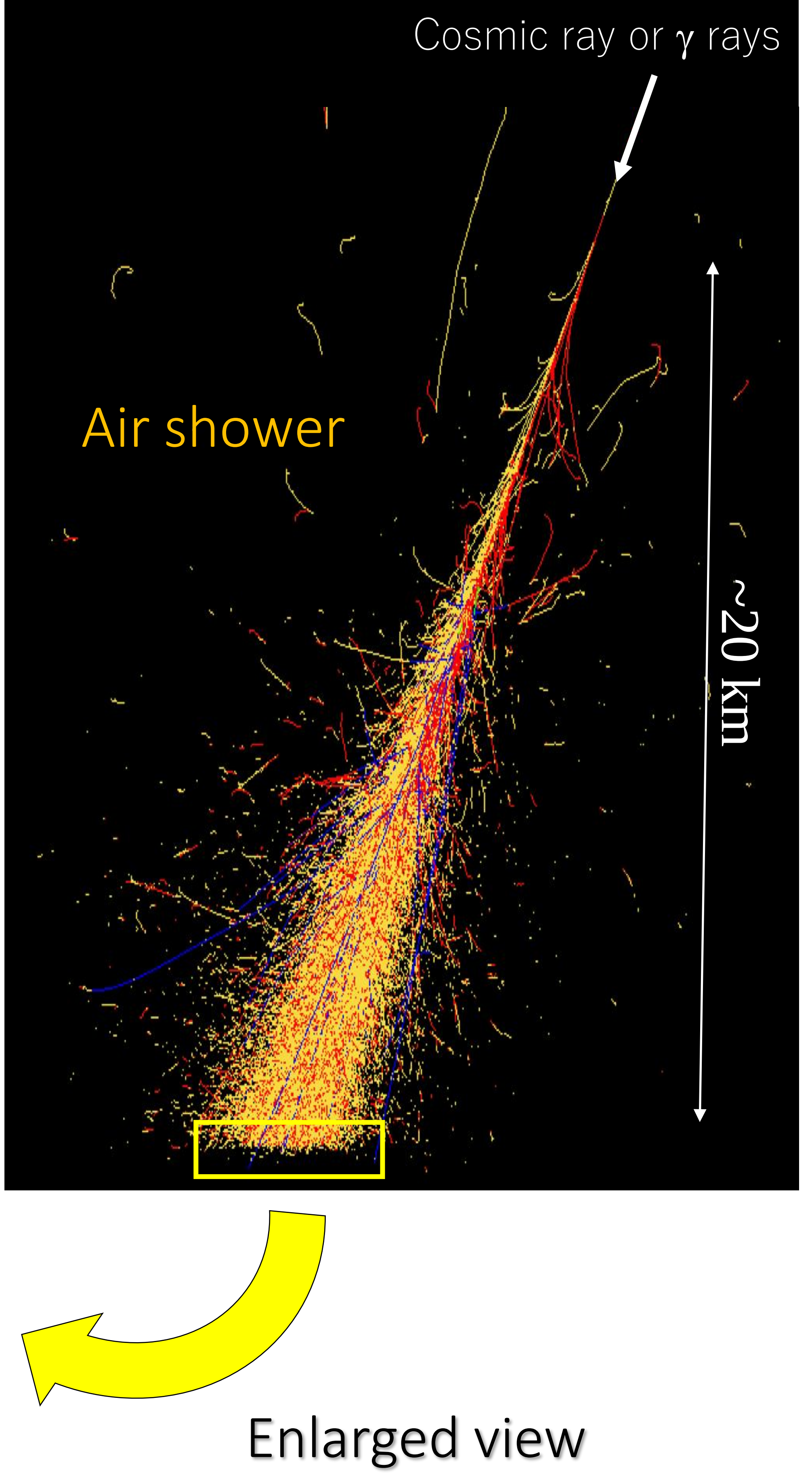
0.2PeV γ-ray



0.2PeV Cosmic ray (Noise)



→ Underground muon detectors



§ Point-like and extended γ-ray sources in the 100 TeV region

See contributions by

Indico-ID1421 (ICRC2021), Xu CHEN [all sky]

Indico-ID 334 (ICRC2021), Yusaku KATAYOSE [Cygnus]

Indico-ID1430 (ICRC2021), Munehiro OHNISHI [G106.3+2.7].

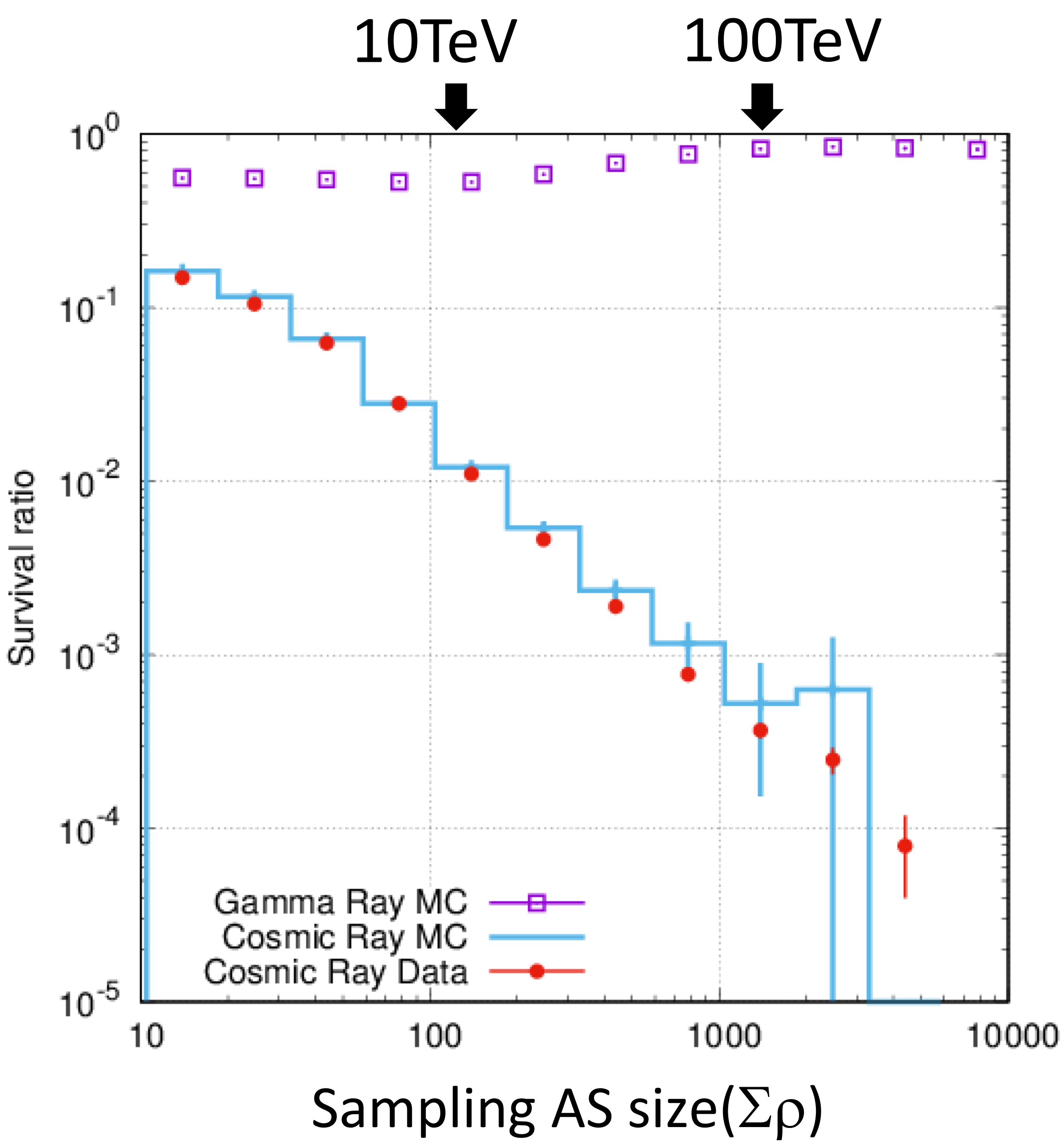
*Amenomori+, PRL, **123**, 051101, (2019)*

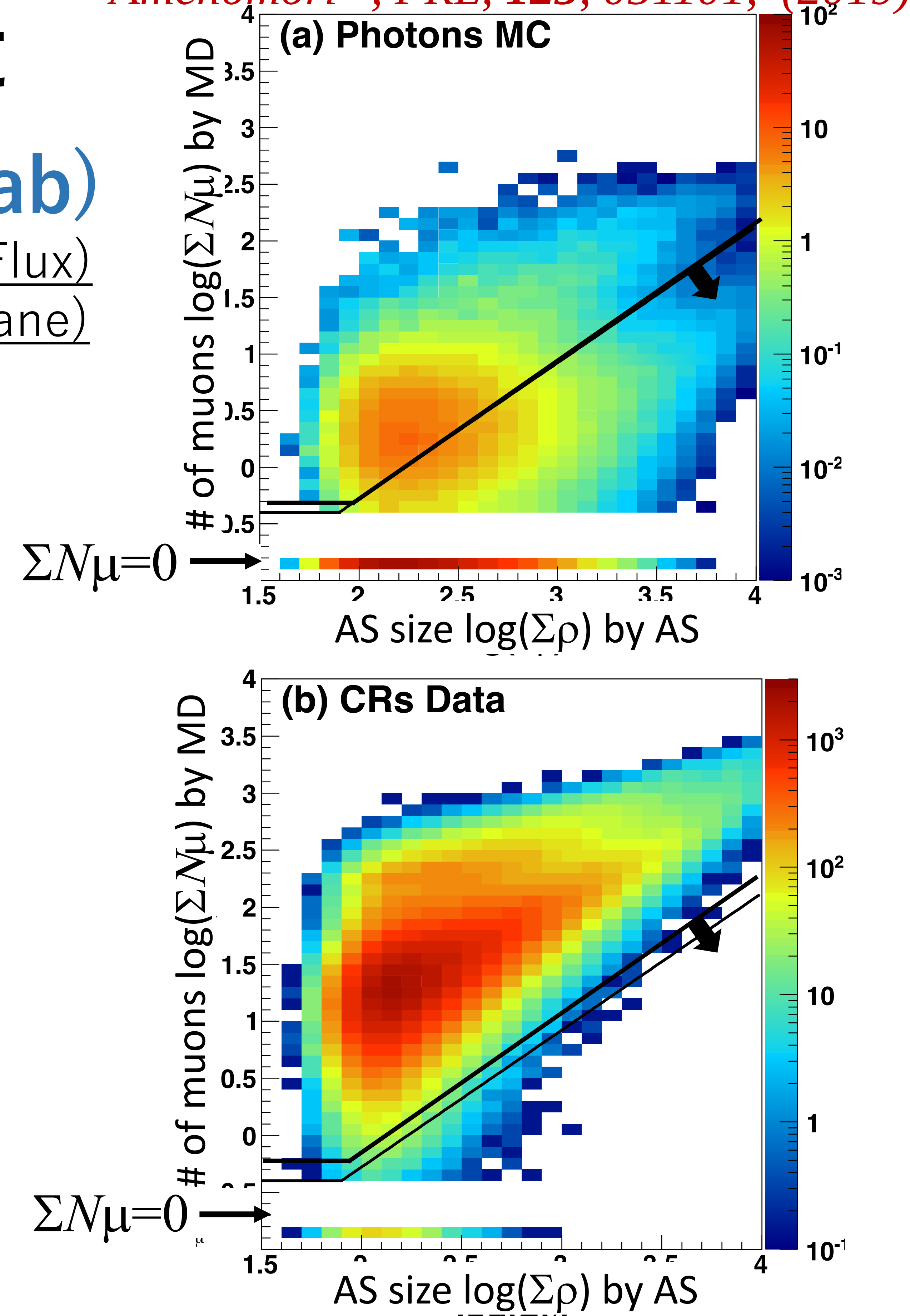
E (Σρ) vs. Nμ Plot

→Optimization of cut (Crab)

Gamma: MC sample (Crab orbit & Crab Flux)

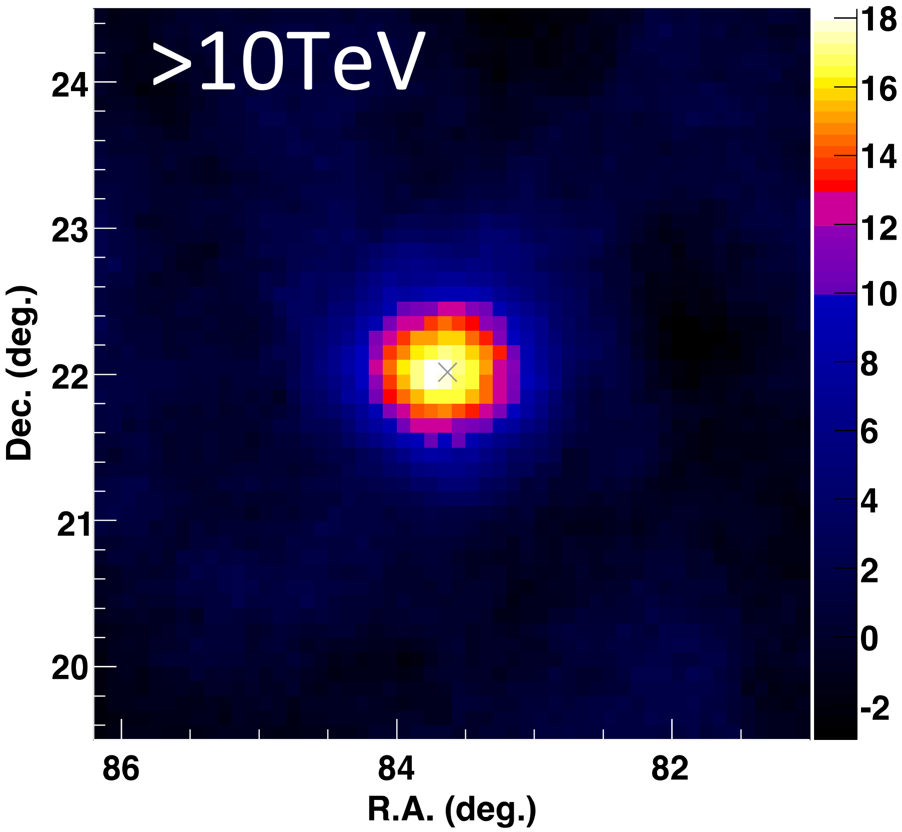
CR：DATA(excluding Crab and Galctic plane)

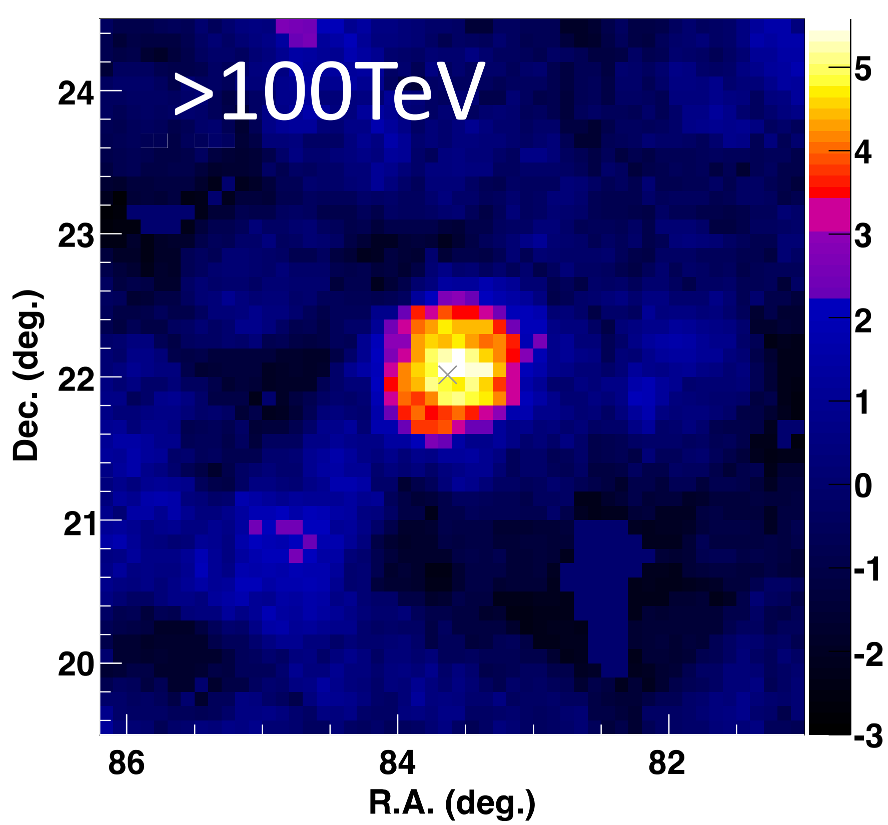




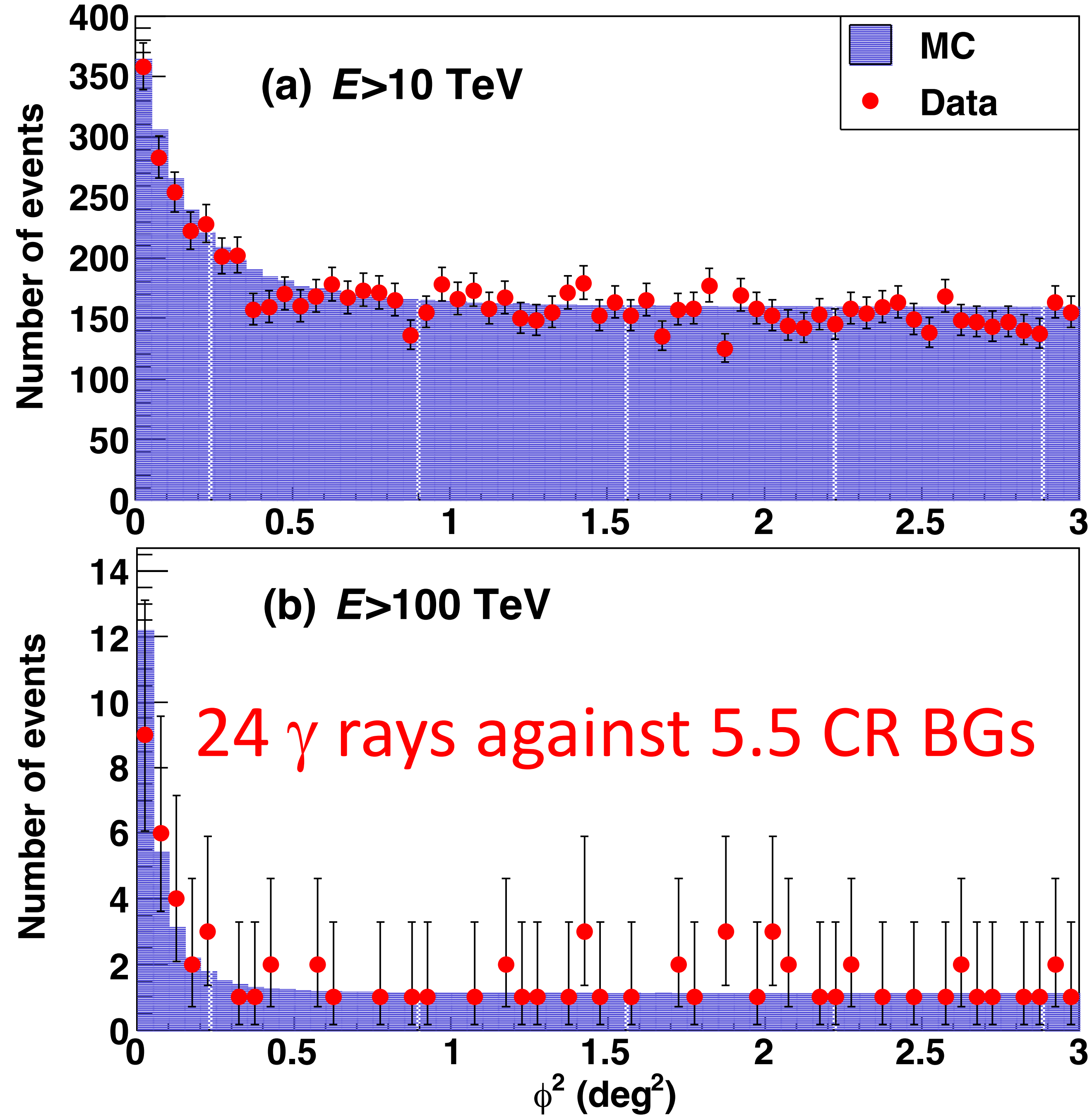
After Nμ cut,~99.9% CR rejection & ~90% γ efficiency @100 TeV

Gamma-ray Emission from Crab





Data vs MC



24 γ rays against 5.5 CR BGs

First detection of sub-PeV γ (5.6σ)

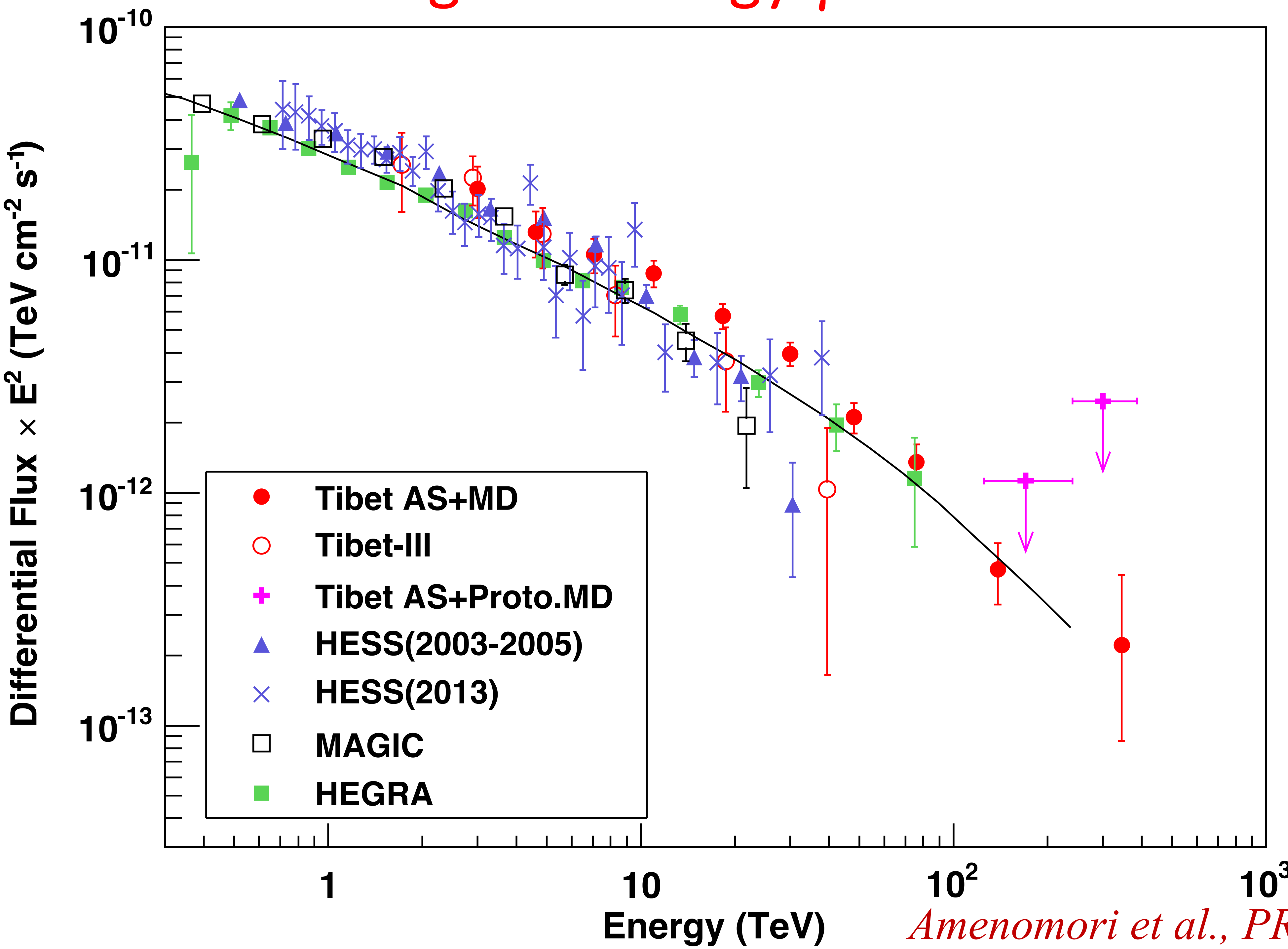
UHE γ-ray astronomy started!

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

Energy spectrum (Crab)

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

The highest energy γ ~450 TeV



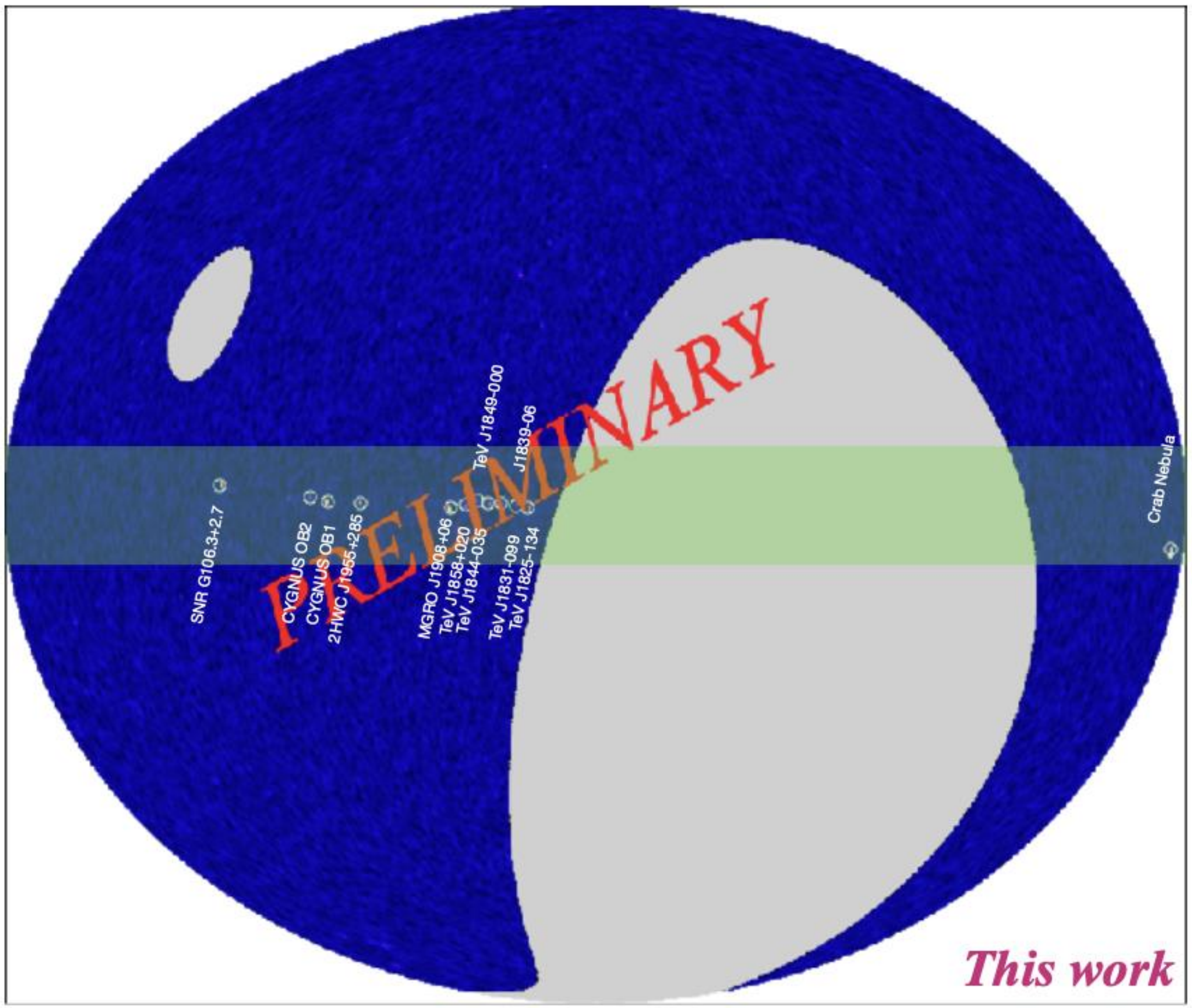
Amenomori et al., PRL (2019)

Thick curve： the expected flux by the inverse Compton model normalized to HEGRA data *Aharonian+, ApJ, 614, 897 (2004)*

Indico-ID1421 (ICRC2021), Xu Chen

12 point-like sources > 10 TeV

Allsky survey σ > 5

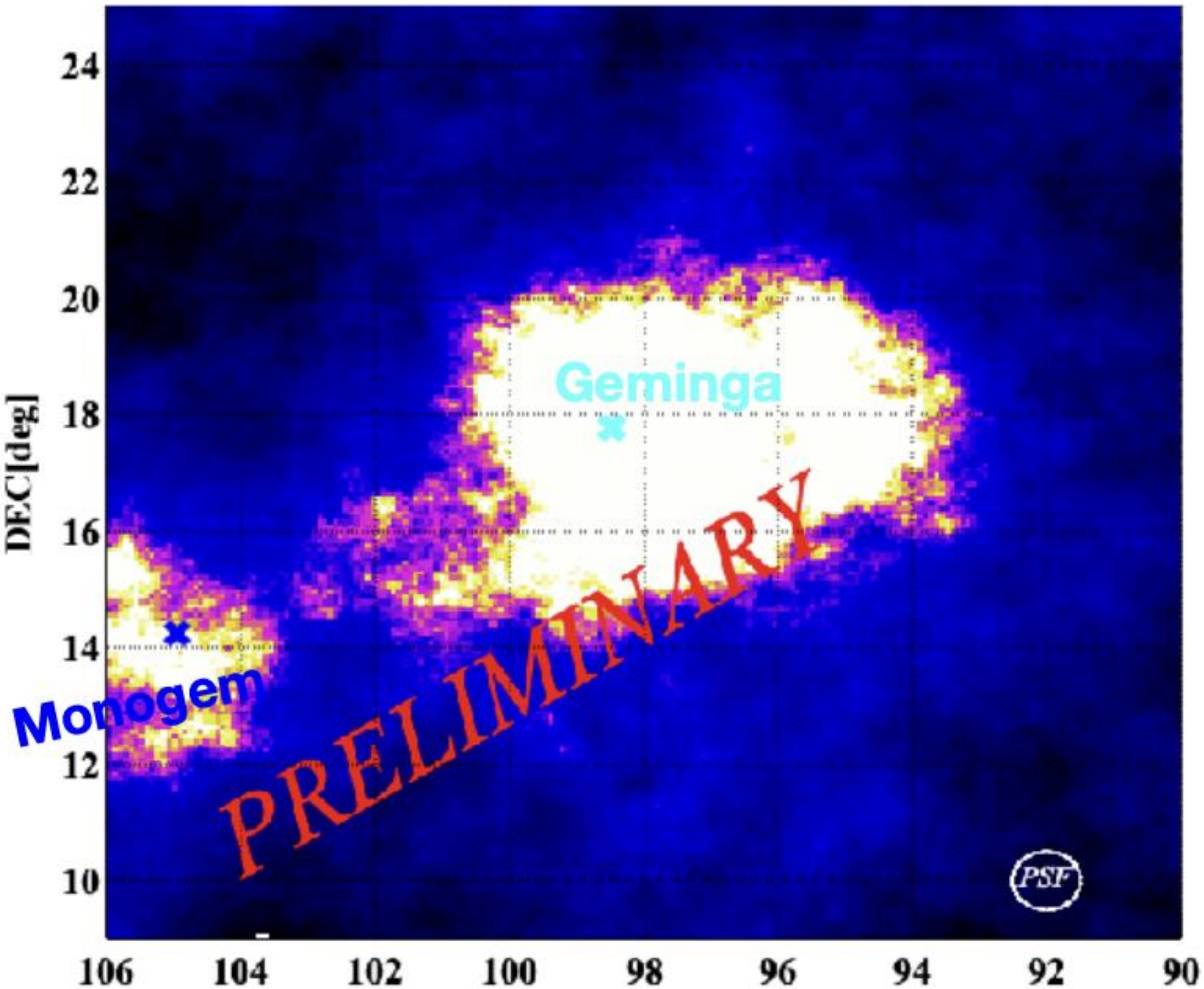


Associated Source	RA[deg]	Dec[Deg]
Crab	83.65	22.02
TeV J1825-134	276.52	-13.4
TeV J1831-099	277.58	-9.84
TeV J1840-055 TeV J1837-065	279.91	-6.03
TeV J1844-035	280.92	-3.58
TeV J1849-000	282.84	0.03
TeV J1857+026	284.70	2.66
MGRO J1908+06	287.01	6.20
2HWC J1955+285	298.87	28.63
Cygnus OB1	305.02	36.77
Cygnus OB2	308.01	41.19
SNR G106.3+2.7	336.77	60.88

This work

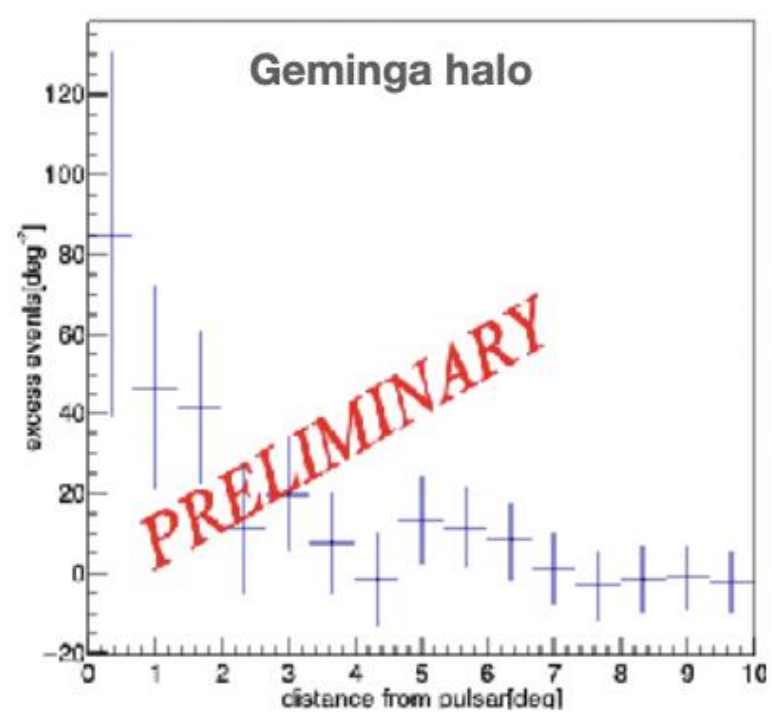
Extend gamma ray halo

Geminga



This work

- >10 TeV
- diffuse searching mode
- Equi-Dec method
- Geminga Pulasr
- Gamma ray Halo

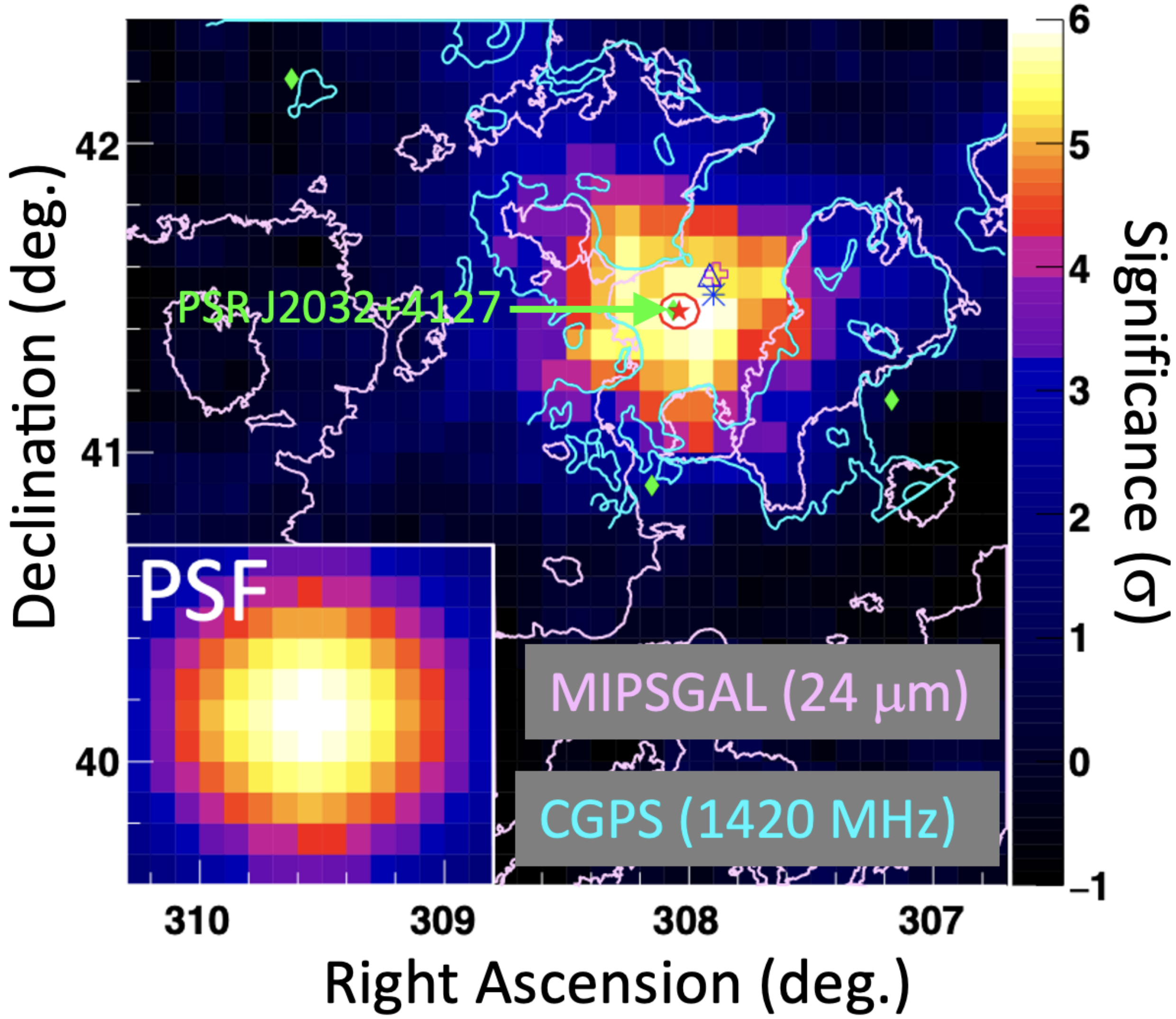


This work

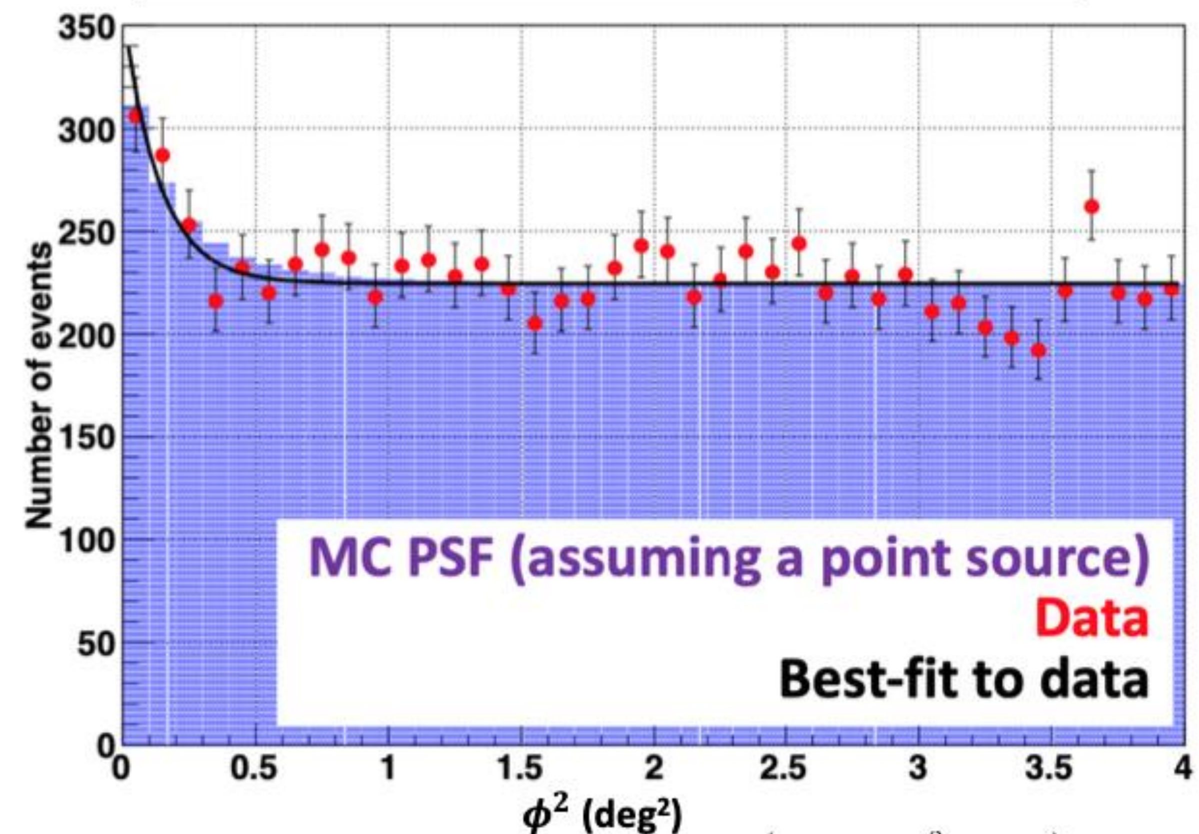
Indico-ID334 (ICRC2021), Yusaku Katayose

TASG J2032+414 (Cygnus OB2)

Significance map > 10 TeV



Angular distribution > 10 TeV



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

Fitting with Gaussian:

σ_{PSF} = 0.36° from MC simulation

σ_{EXT}: source extension

➡ **σ_{EXT} = 0.00° ± 0.14°**

Consistent with σ_{EXT} = 0.2°

★ **this work**

◆ Fermi ✚ VERITAS ✱ HAWC △ MAGIC

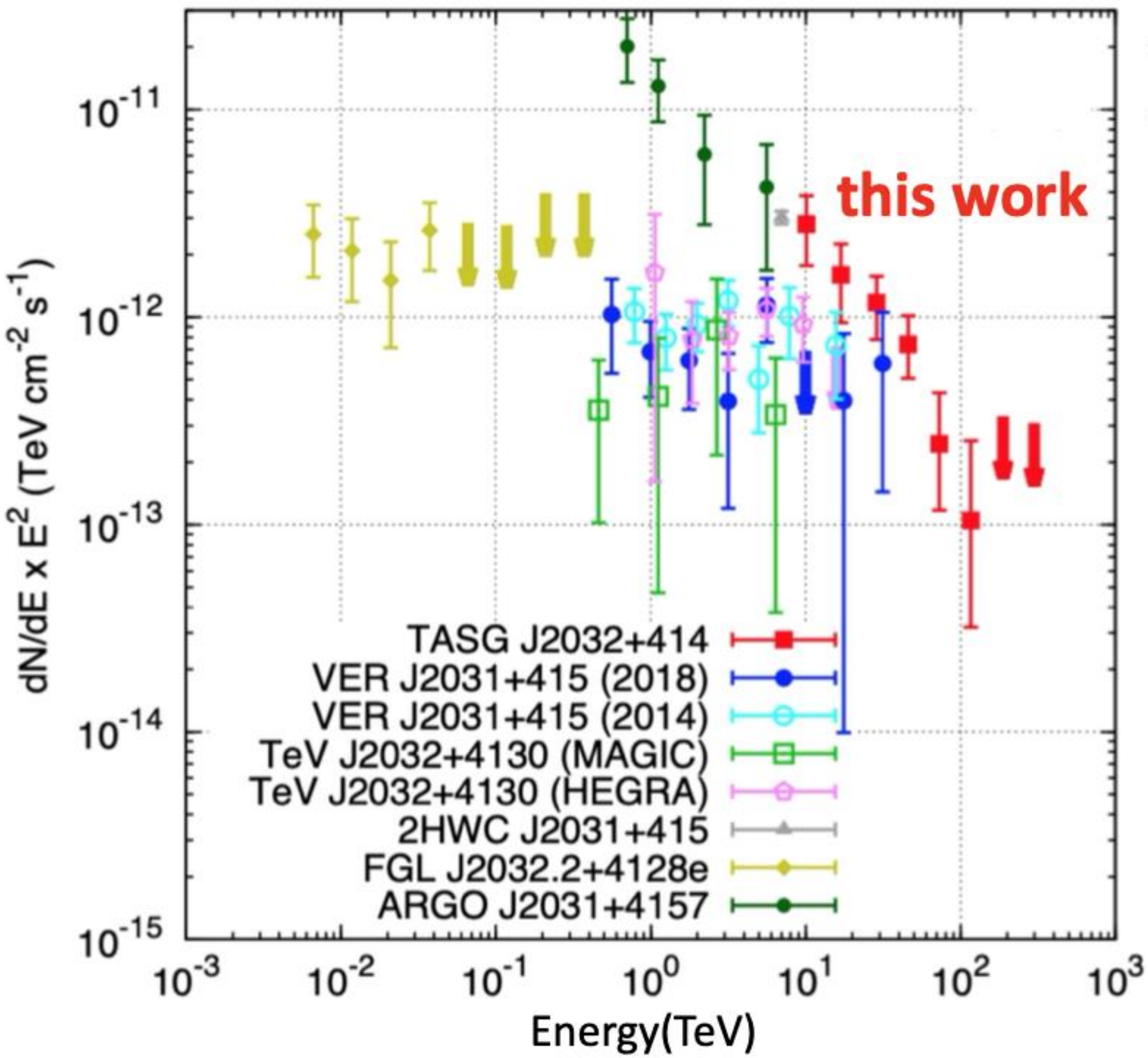
- Detection significance 5.3σ > 10 TeV
- Source position coincident with PSR J2032+4127

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)

Indico-ID334 (ICRC2021), Yusaku Katayose

TASG J2032+414 (Cygnus OB2)

γ-ray energy spectrum



This work can be fitted by a simple power law:

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

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

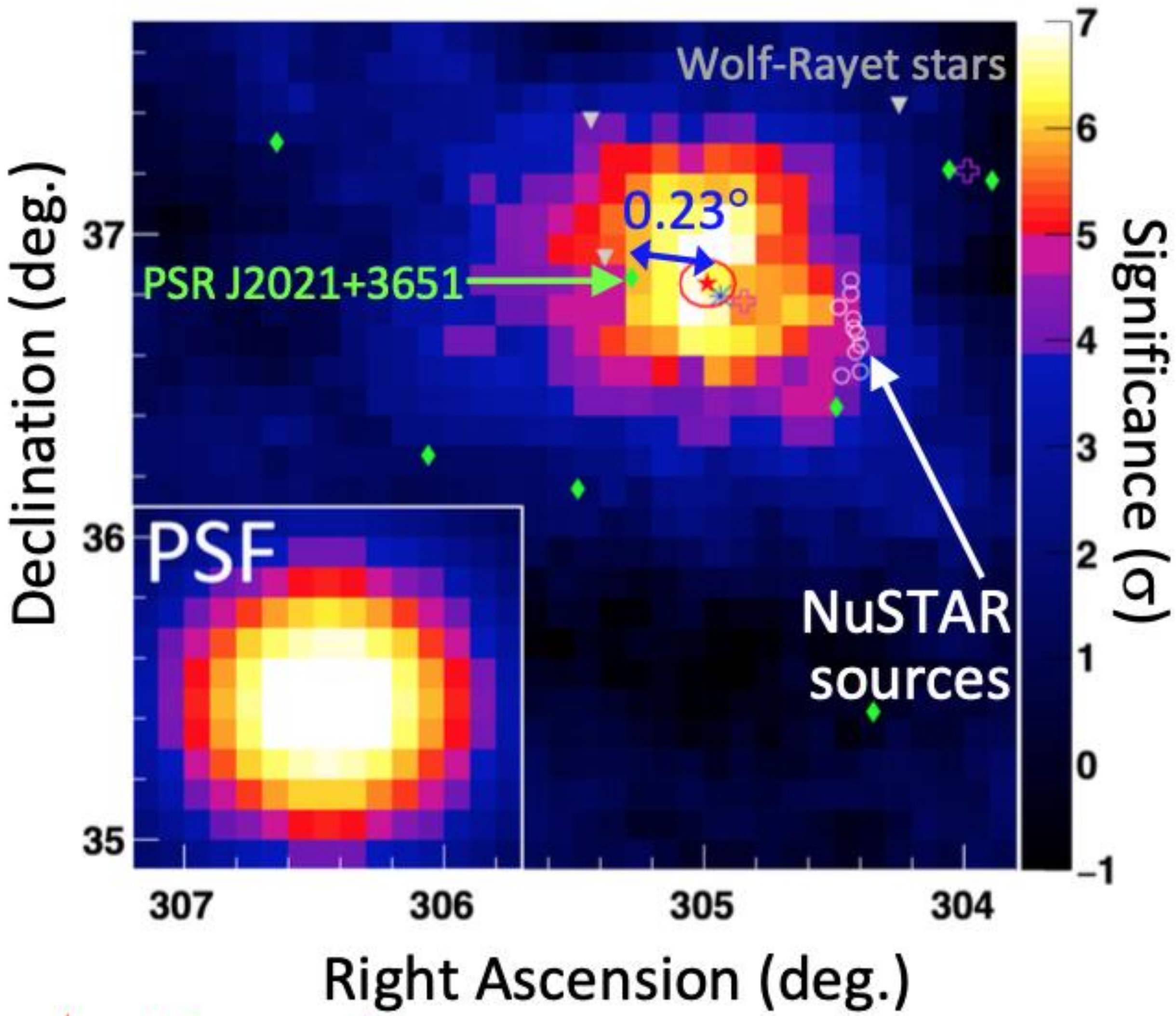
$$\Gamma = 3.12 \pm 0.21 \qquad (\chi^2/\mathrm{ndf} = 1.6/4)$$

Gamma rays likely produced via IC scattering by electrons produced by PSR J2021+3651

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)

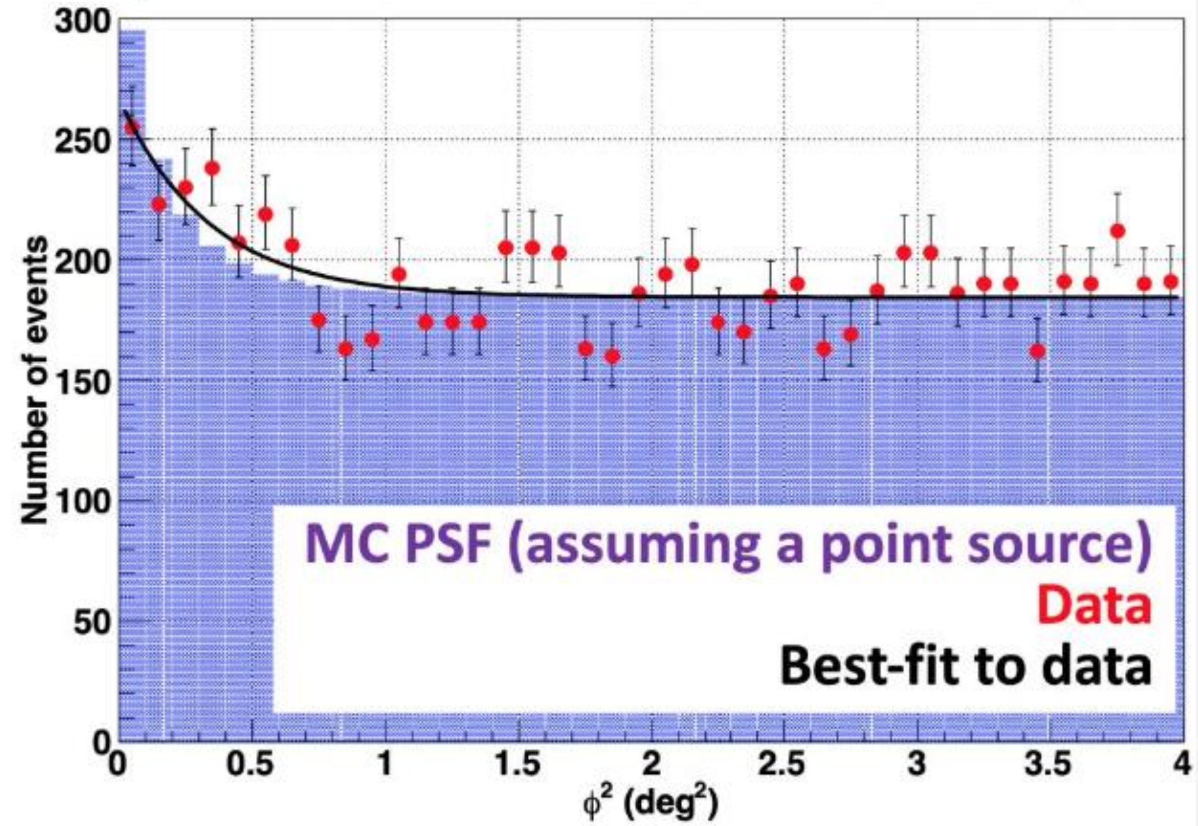
Significance map > 10 TeV



★ this work

♦ Fermi ✚ VERITAS ✱ HAWC

Angular distribution > 10 TeV



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 Veritas/HAWC

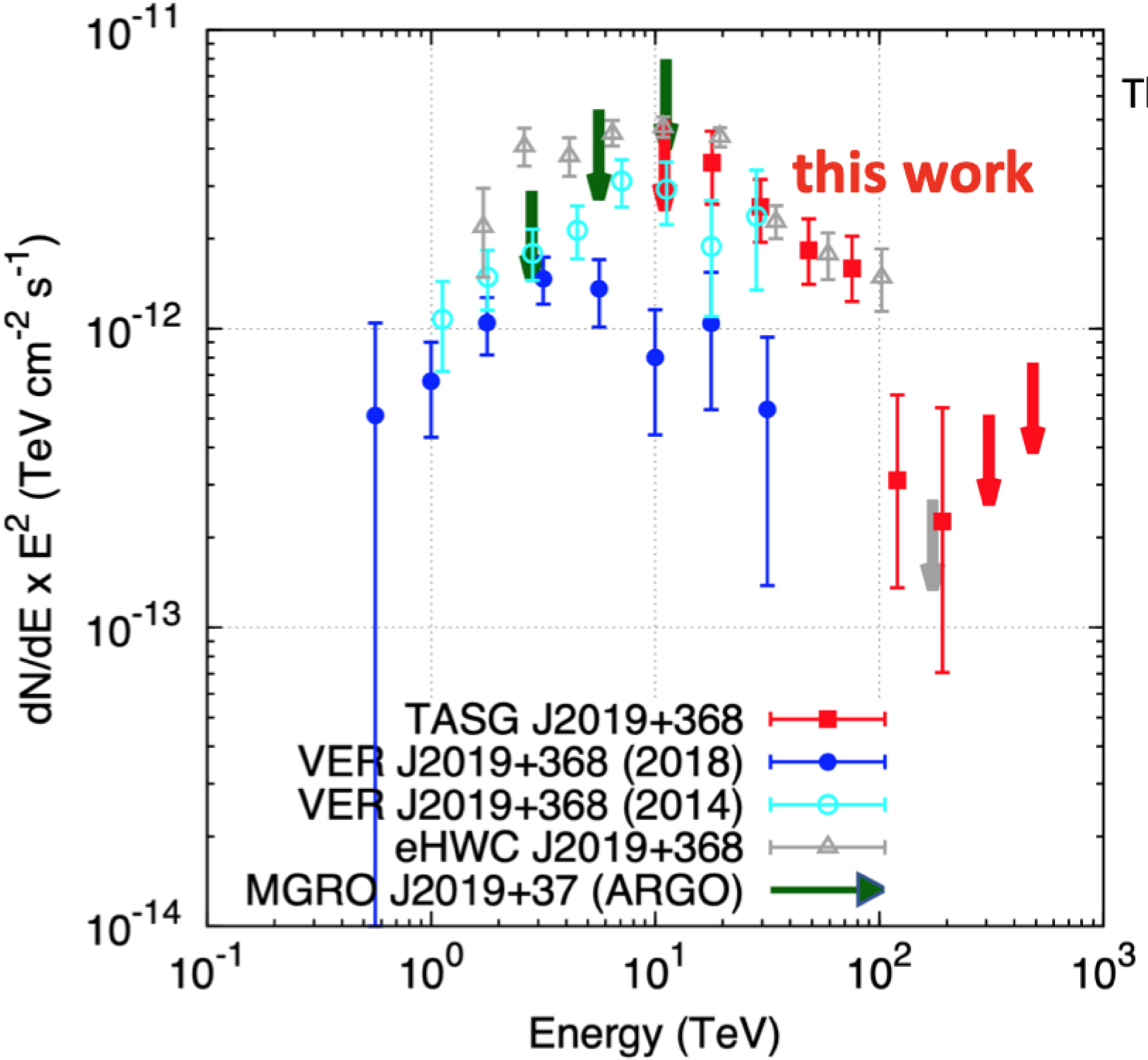
- Detection significance 6.7σ > 10 TeV
- Source position coincident with PWN G75.2+0.1 0.23° west of PSR J2021+3651

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)

Indico-ID334 (ICRC2021), Yusaku Katayose

TASG J2019+368 (Cygnus OB1)

γ-ray energy spectrum



This work can be fitted by

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

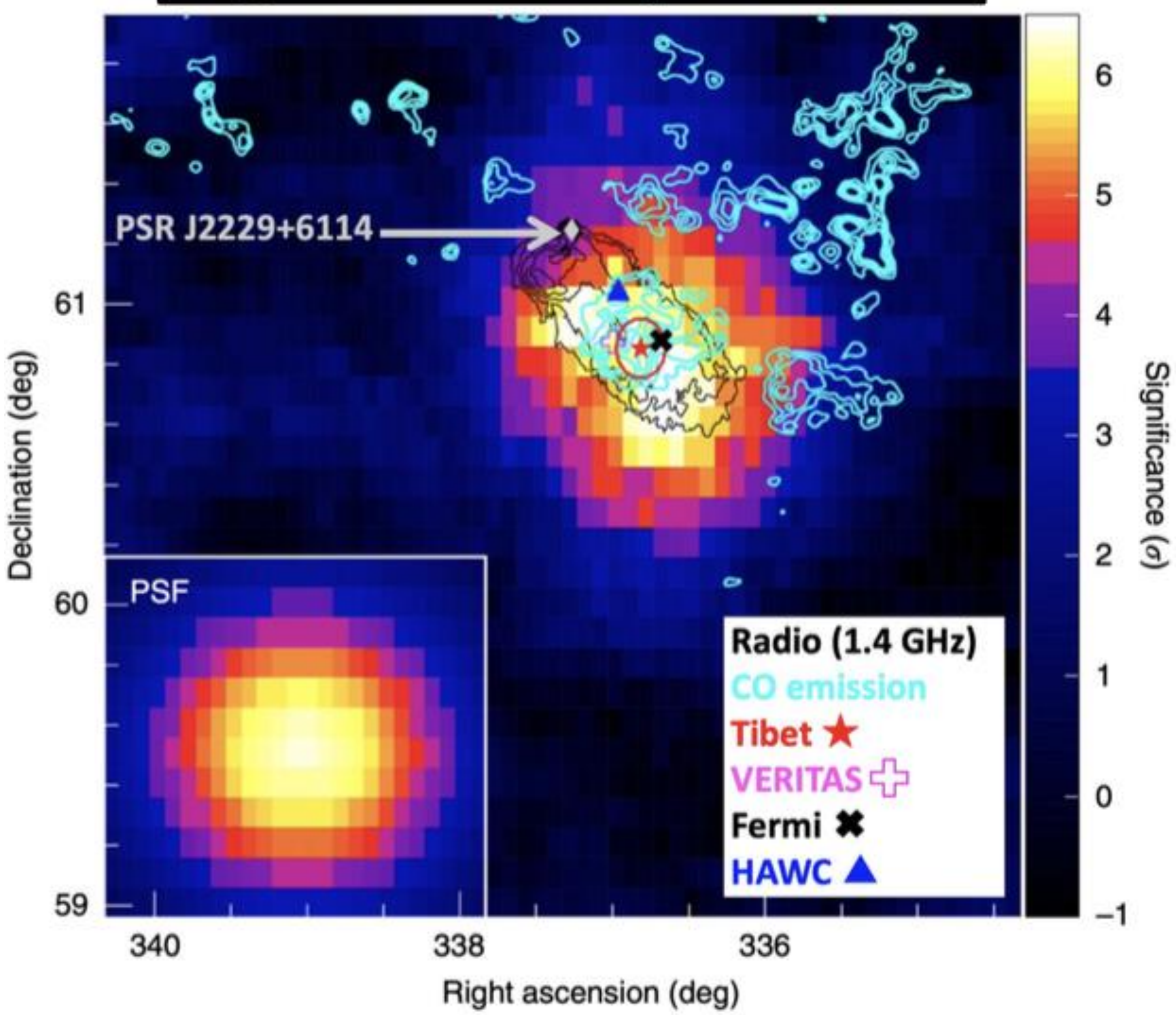
$$N_0 = (3.6 \pm 2.0) \times 10^{-15}\ \mathrm{TeV^{-1}cm^{-2}s^{-1}}$$

$$\Gamma = 1.6 \pm 0.5$$

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

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

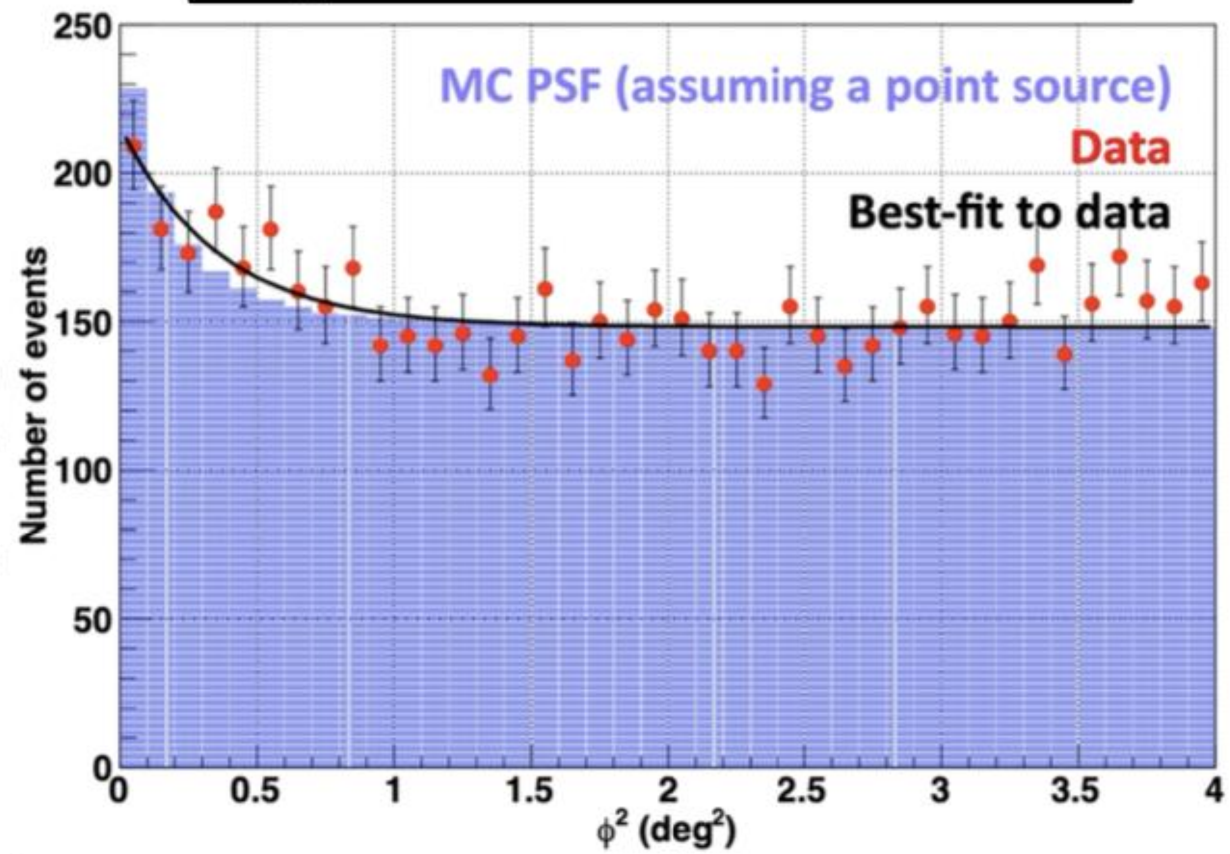
Significance map > 10 TeV



- Tibet source position: R.A. = 336.82°±0.16°
  Dec = 60.85°±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)

Angular distribution > 10 TeV



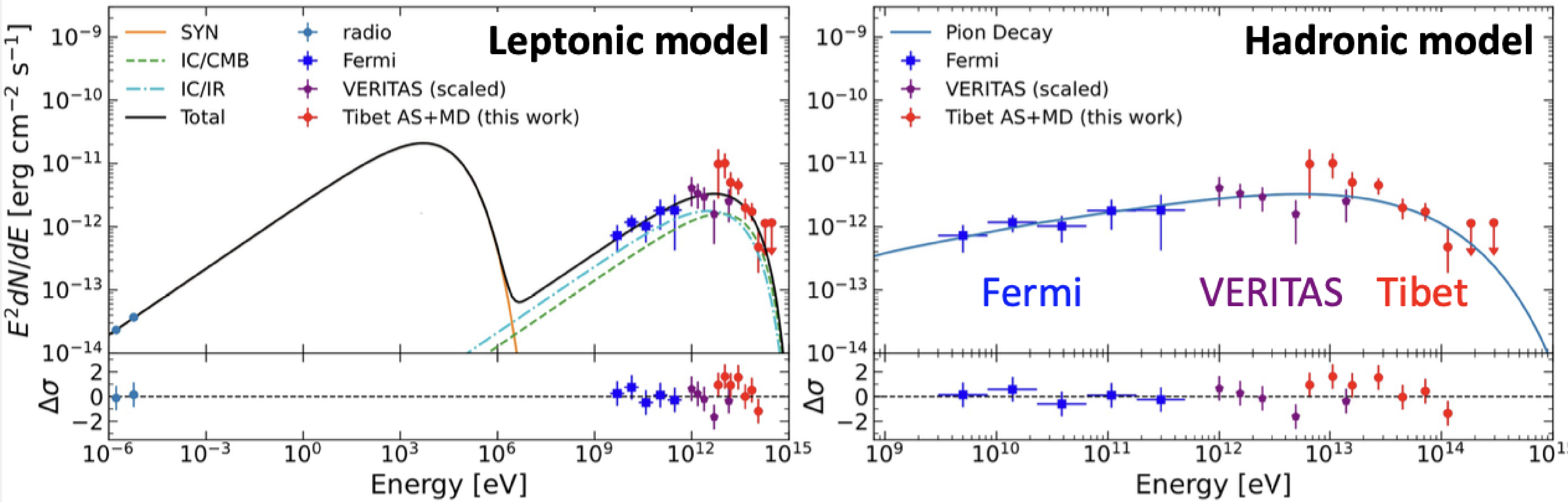
- Fitting with Gaussian: $A\exp\left(-\frac{\phi^2}{2(\sigma_{\rm PSF}^2+\sigma_{\rm EXT}^2)}\right)$

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

➡ **σ_{EXT} = 0.24°±0.10°**

※ 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 $\propto E^{-\alpha} \exp(-E/E_{cut})$ using *naima* package *(Zabalza, arXiv:1509.03319)*

	α	E_{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
- $E_{\mathrm{cut}} \sim 0.5$ PeV

Leptonic model

- Inverse Compton scattering of ambient photons by electrons injected by PSR J2229+6114
- $E_{\mathrm{cut}} \sim 190$ TeV, $B \sim 9\ \mu$G
- $W_e \sim 1.4 \times 10^{47}$ 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

§ Sub-PeV diffuse γ rays from the Milky Way galaxy

See a contribution by
Indico-ID301 (ICRC2021), Kazumasa KAWATA .

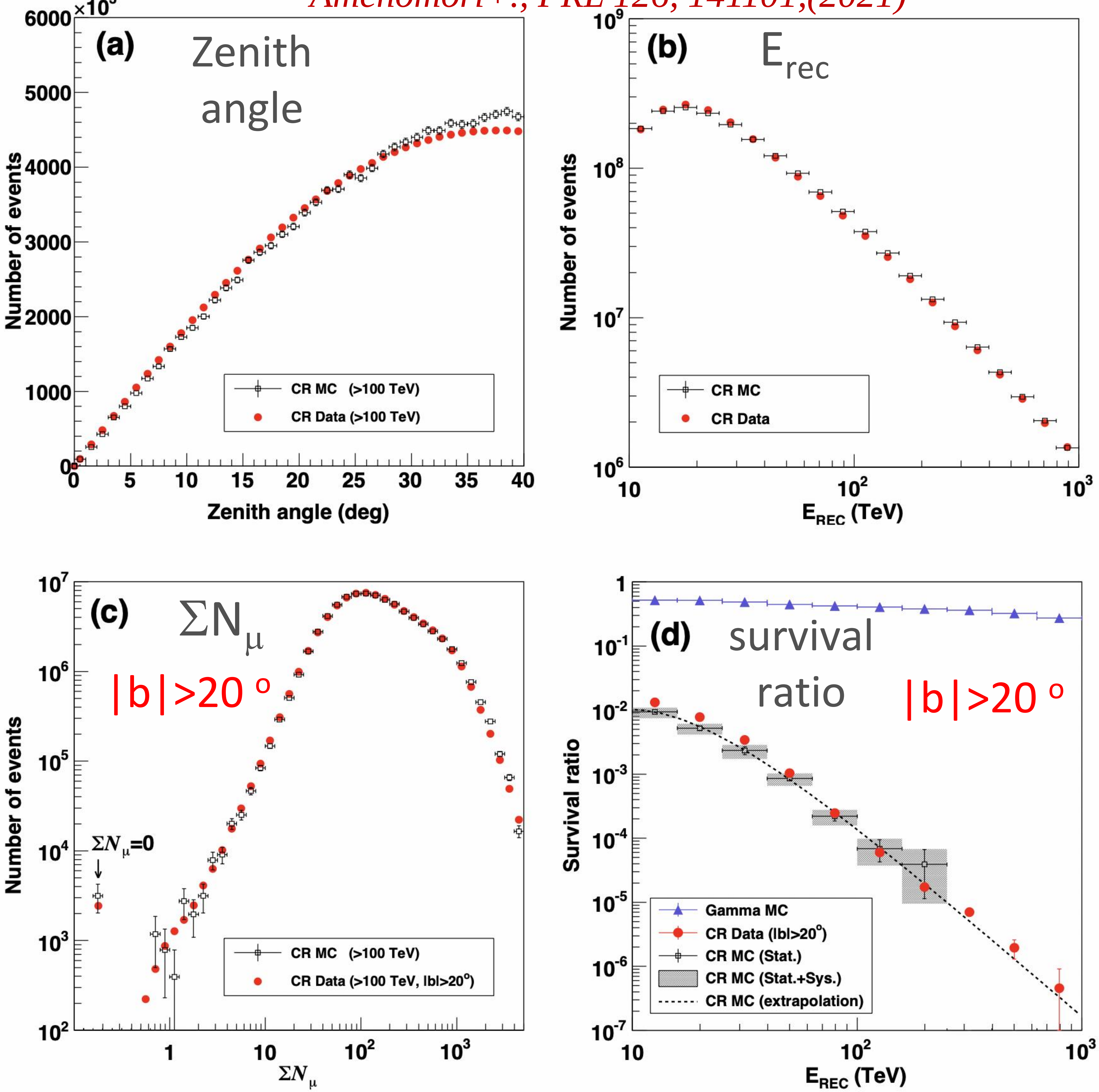
Amenomori+., PRL 126, 141101,(2021)

CR MC

vs.

DATA

Reasonable agreement!

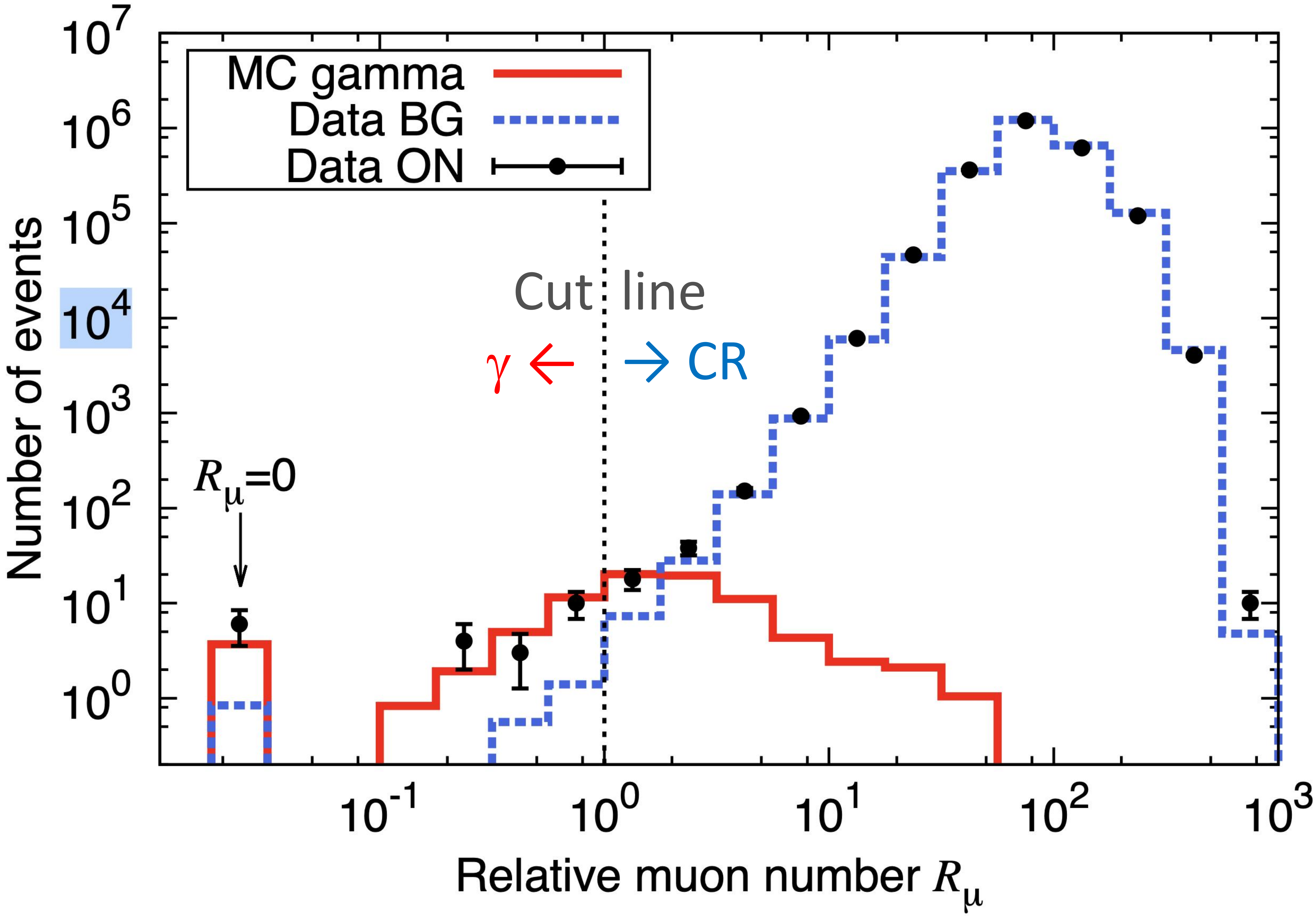


$O(10^{-6})$

>0.398

PeV

Relative muon number distribution for events > 0.398 PeV



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Event Distribution >100 TeV (Fig.1) Tight muon cut

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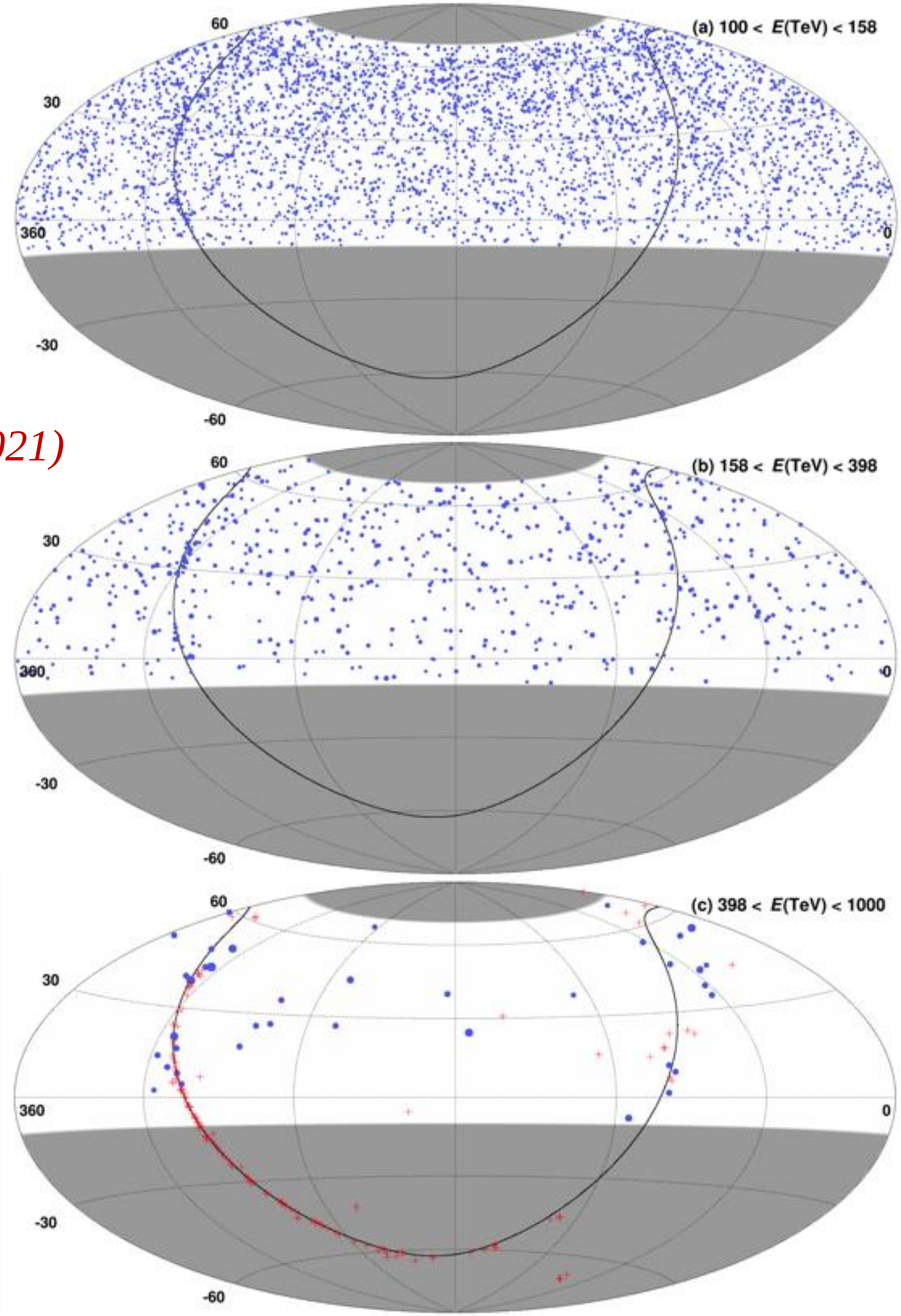
Blue points:
Tibet AS +MD
(Circle size ∝ Energy)

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



Equatorial coordinates

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

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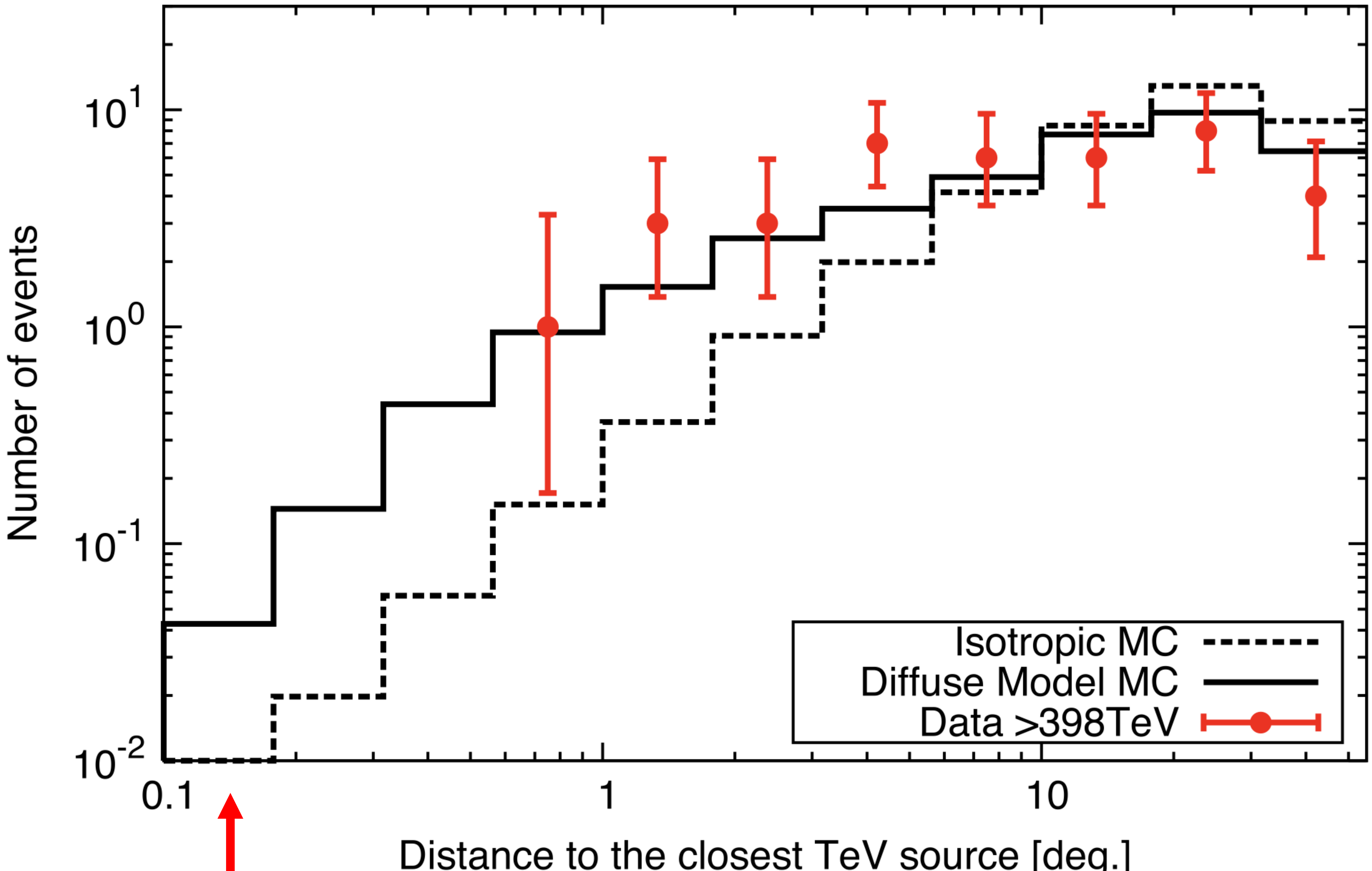

Surprisingly, no peak around 0 -> no correlation with known TeV sources!

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

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

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 $22° < l < 225°$). The ratios (α) of exposures between the ON and OFF regions are 0.135 for $|b| < 5°$ and 0.27 for $|b| < 10°$, respectively.

	$\|b\| < 5°$			$\|b\| < 10°$		
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 ($25° < l < 100°, \|b\| < 5°$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50° < l < 200°, \|b\| < 5°$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
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	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

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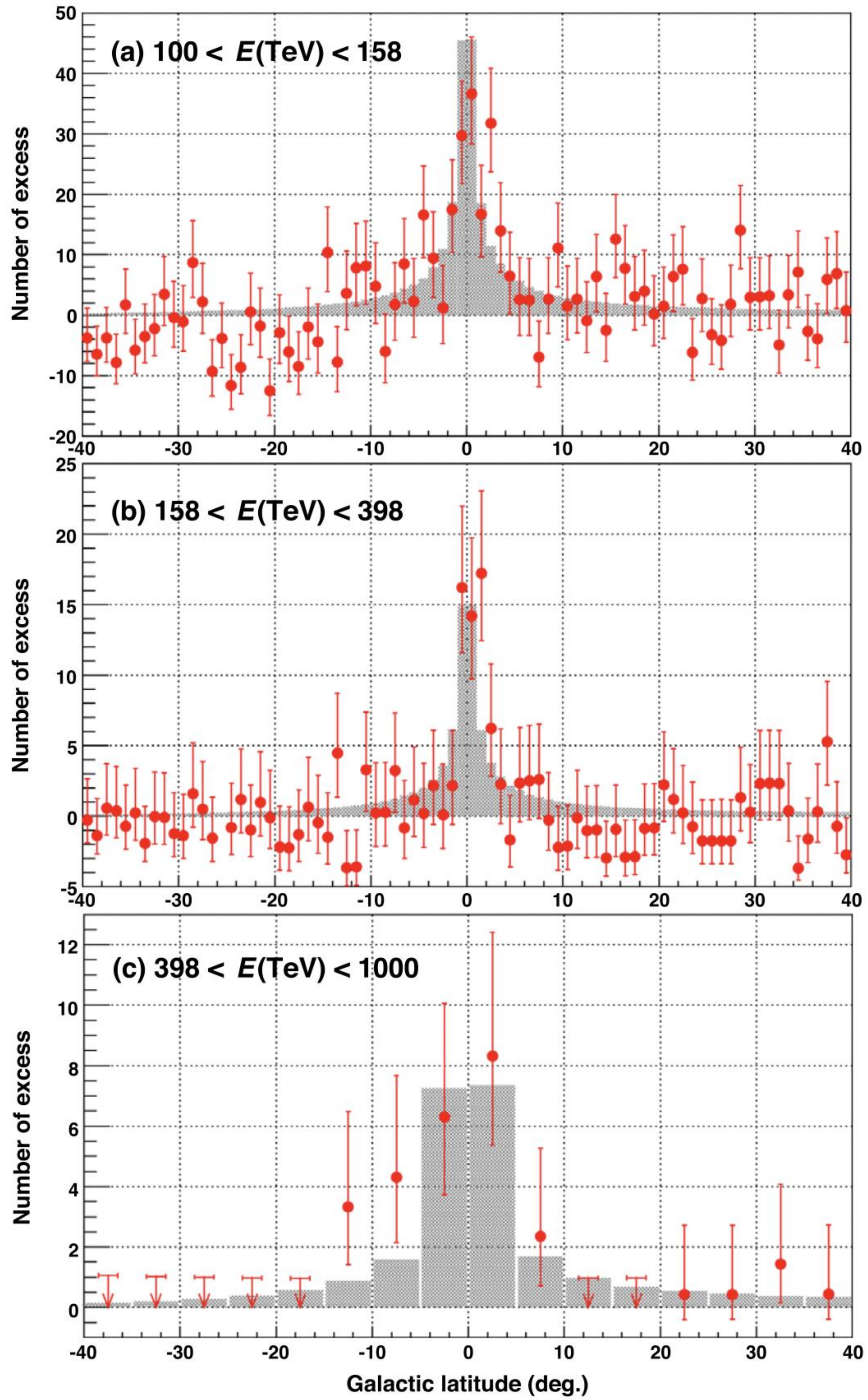
Galactic latitude distributions

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

# of ev

# of ev

# of ev



-40° 0 40°

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

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

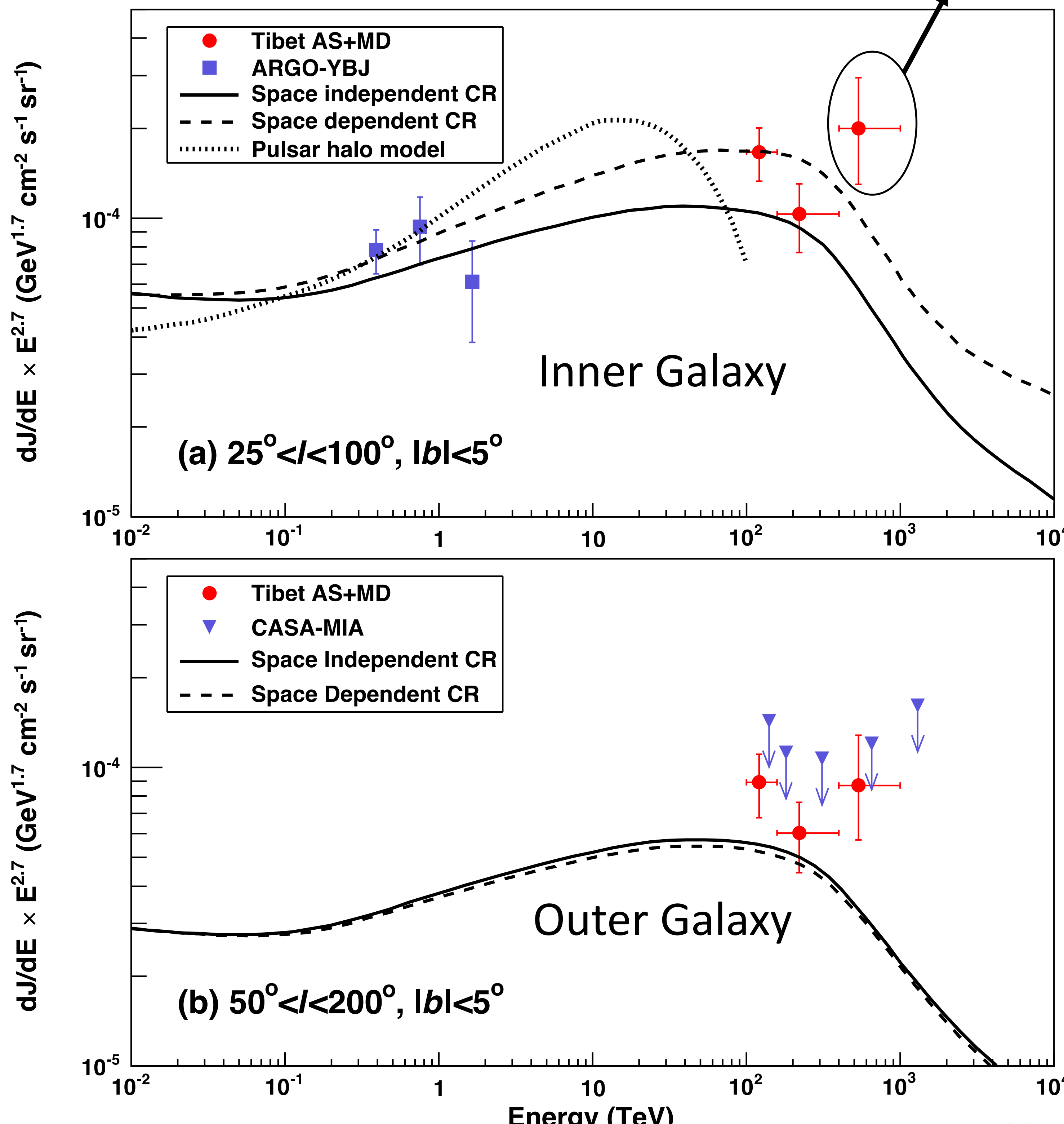
Models: Lipari & Vernetto, PRD 98, 143003, (2018)

Energy Spectrum (Fig.4)

After excluding the contribution from the known TeV sources (within 0.5° in radius) listed in the TeV source 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.

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



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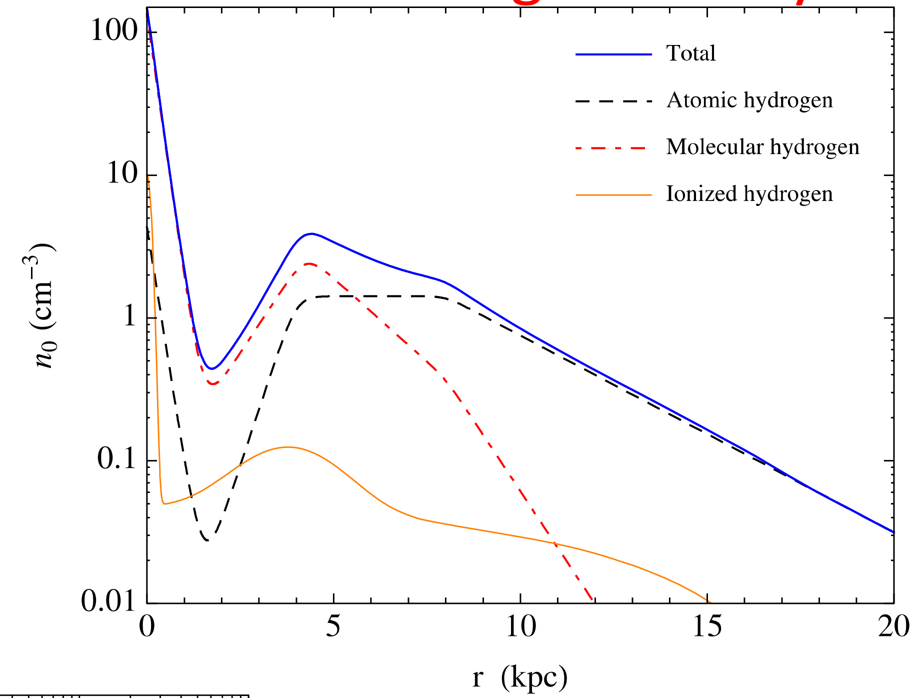
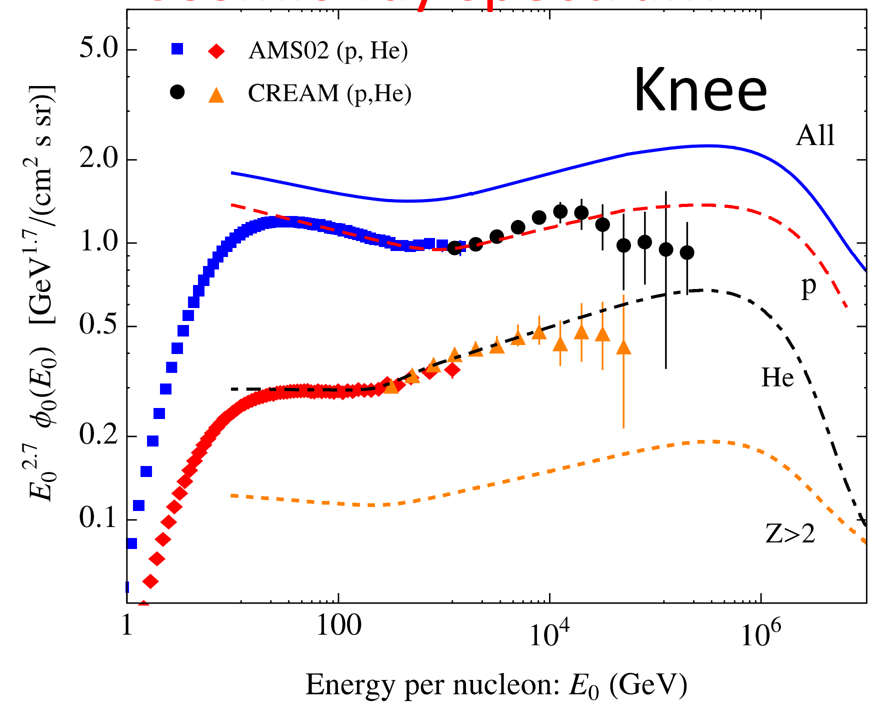
Diffuse γ-ray Model

Lipari & Vernetto, PRD (2018)

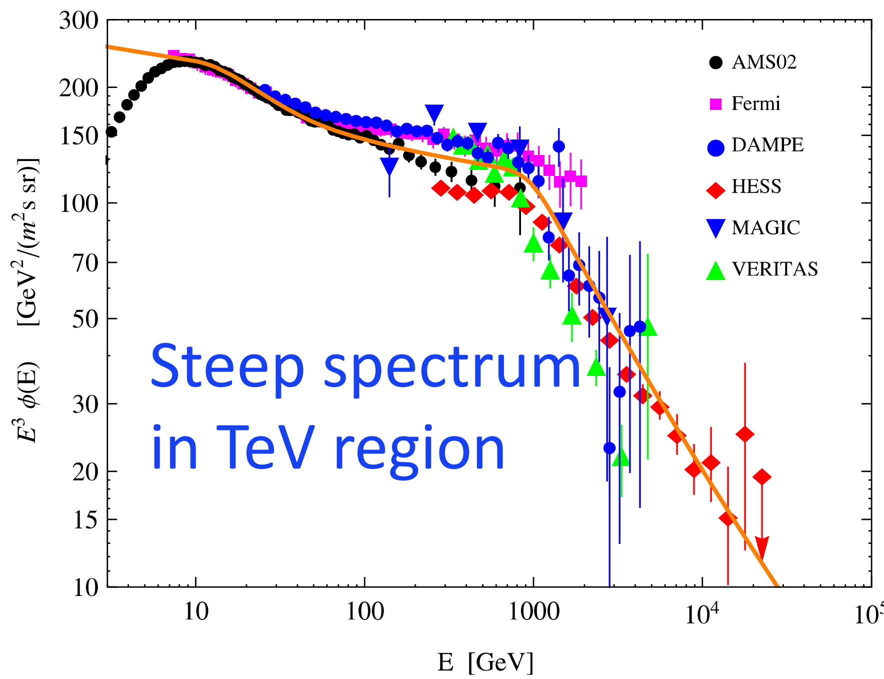
Interstellar gas density

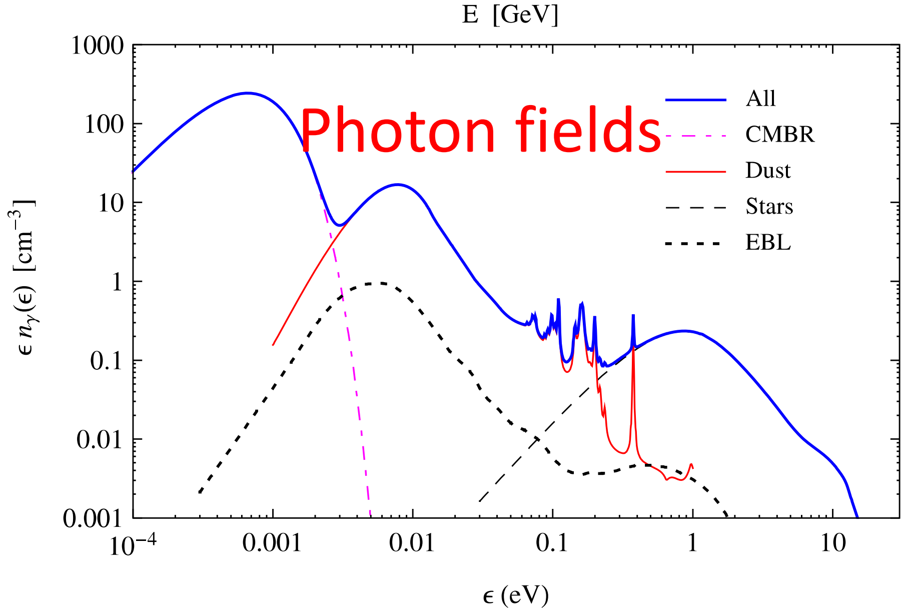


Cosmic-ray spectrum



Electron/Positron

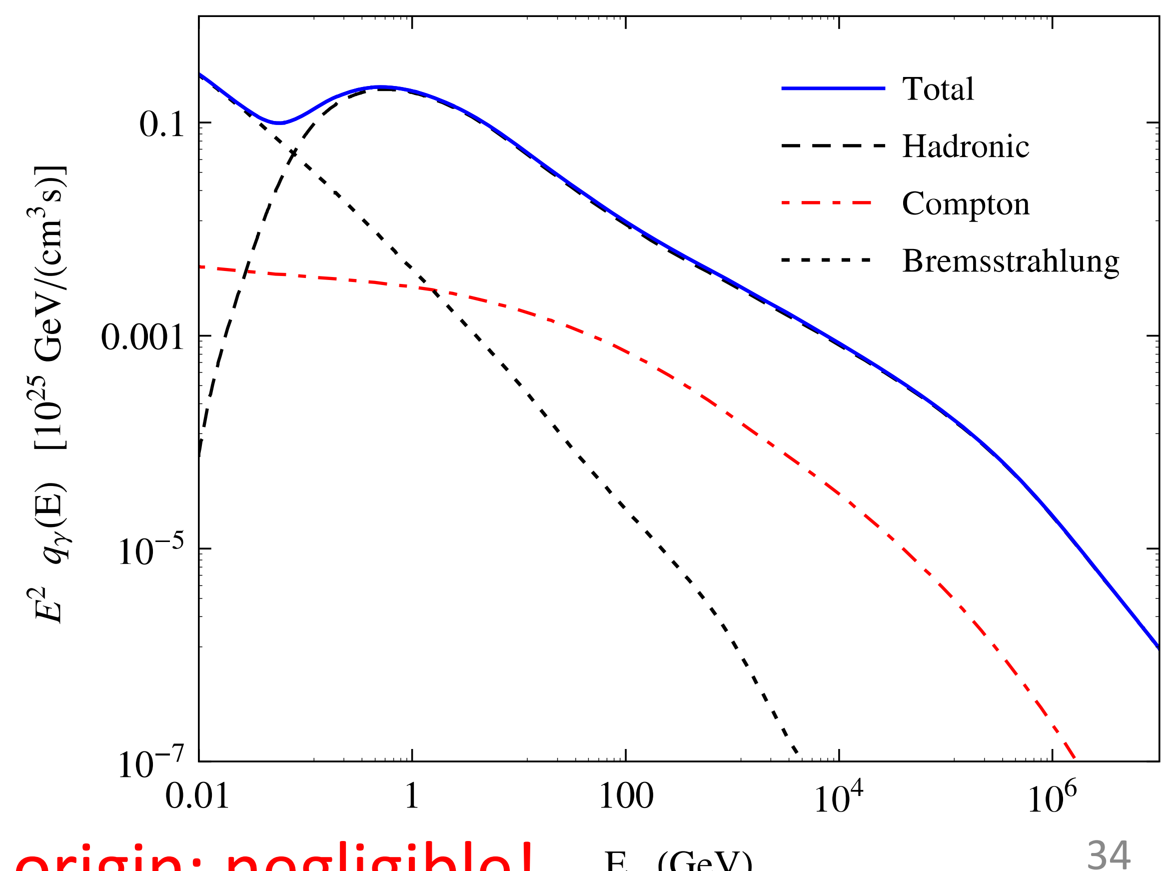




Bremss.

Hadronic

IC



Diffuse e origin: negligible!

Arrival Directions of the 38 events (> 0.398 PeV)
See PRL supplemental materials

TABLE S3. Event IDs and arrival directions in the equatorial coordinates (Right Ascension, Declination) of the gamma-ray like events with $398 < E < 1000$ TeV observed by the Tibet AS+MD array during period between February 2014 and May 2017.

TASG Event ID	R.A. J2000 (degrees)	Dec. J2000 (degrees)
TASG-D01-001	18.74	55.31
TASG-D01-002	26.44	68.23
TASG-D01-003	35.21	54.46
TASG-D01-004	49.16	44.38
TASG-D01-005	55.90	43.25
TASG-D01-006	62.31	38.11
TASG-D01-007	63.13	55.26
TASG-D01-008	63.72	34.74
TASG-D01-009	67.01	46.54
TASG-D01-010	96.16	9.02
TASG-D01-011	98.31	11.21
TASG-D01-012	99.60	1.58
TASG-D01-013	114.74	−7.55
TASG-D01-014	127.01	38.26
TASG-D01-015	174.45	24.48
TASG-D01-016	183.43	39.60
TASG-D01-017	228.12	26.53
TASG-D01-018	230.56	44.40
TASG-D01-019	243.22	66.27
TASG-D01-020	255.47	26.46
TASG-D01-021	256.49	35.31
TASG-D01-022	261.10	25.56
TASG-D01-023	264.29	17.95
TASG-D01-024	284.38	4.50
TASG-D01-025	286.96	7.96
TASG-D01-026	290.28	16.36
TASG-D01-027	291.45	10.03
TASG-D01-028	293.62	20.36
TASG-D01-029	295.63	2.30
TASG-D01-030	297.17	13.82
TASG-D01-031	305.44	44.21
TASG-D01-032	307.08	39.02
TASG-D01-033	308.69	43.92
TASG-D01-034	309.49	51.05
TASG-D01-035	312.33	40.23
TASG-D01-036	320.32	49.46
TASG-D01-037	354.97	49.65
TASG-D01-038	359.96	59.19

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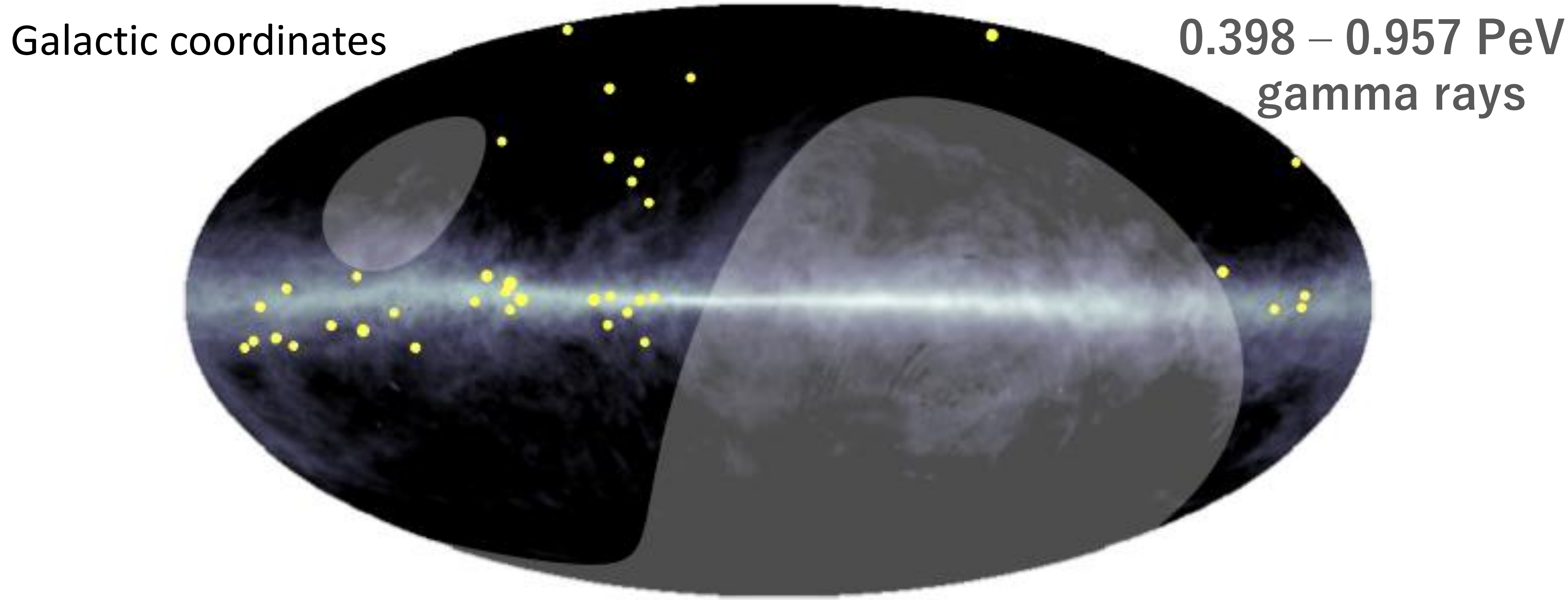
Electron origin? vs Proton origin?



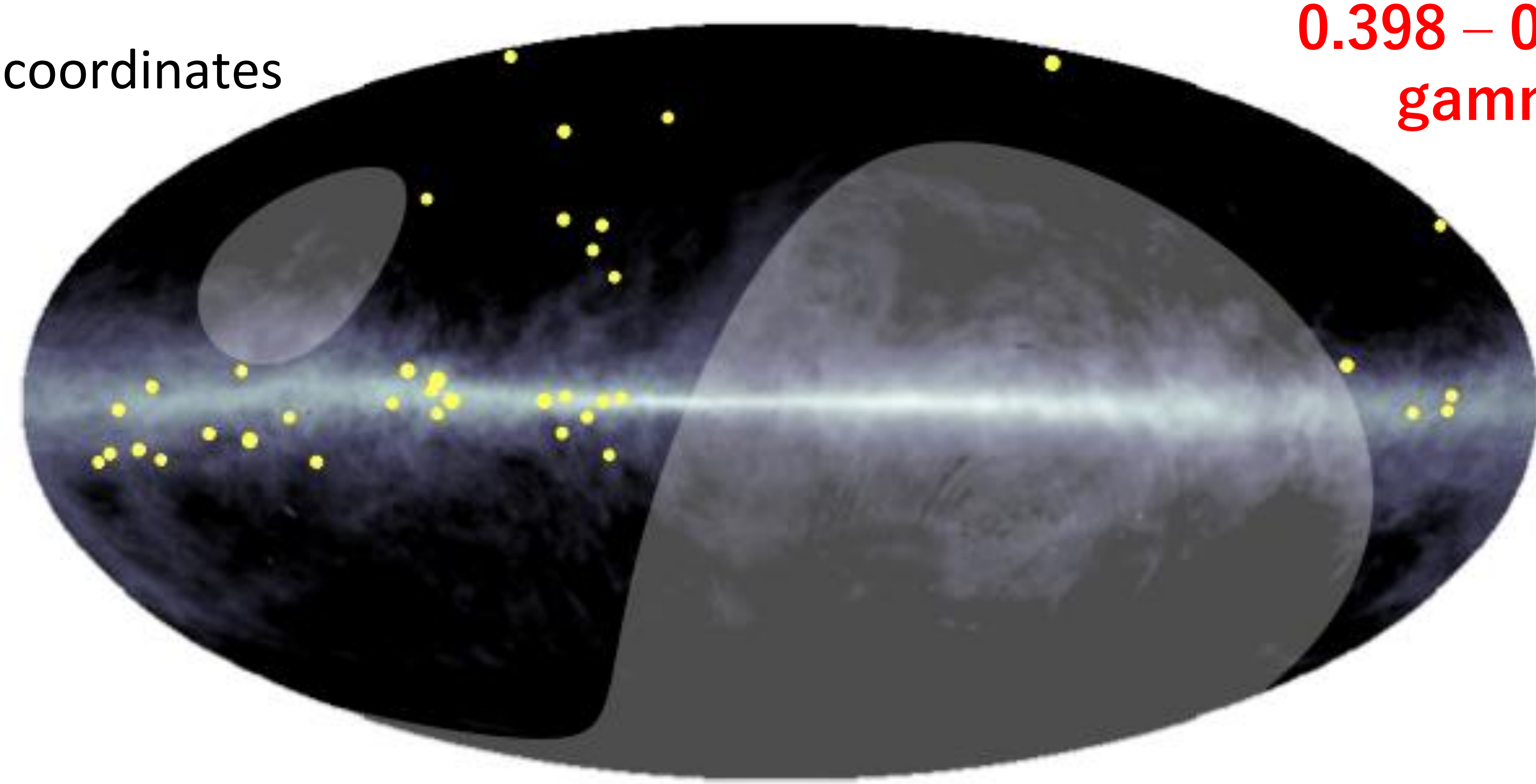
- ✓ Gamma rays are coming isolated from known gamma-ray sources.
  → **Electrons** lose their energy quickly, so they **should stay near the object**.
  → **Protons** don't lose energy and **can escape farther from the object**.

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

Scientific Interpretation

Galactic coordinates

0.398 – 0.957 PeV gamma 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.

Scientific Interpretation

High-energy cosmic rays

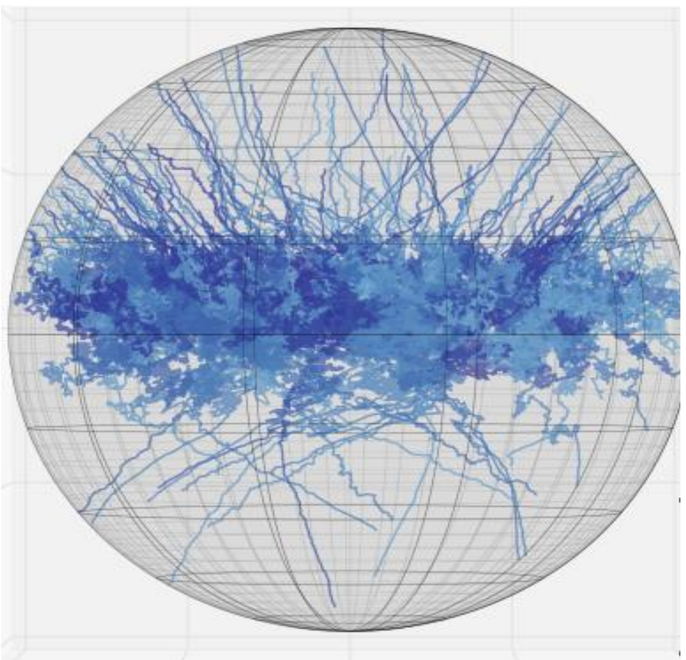
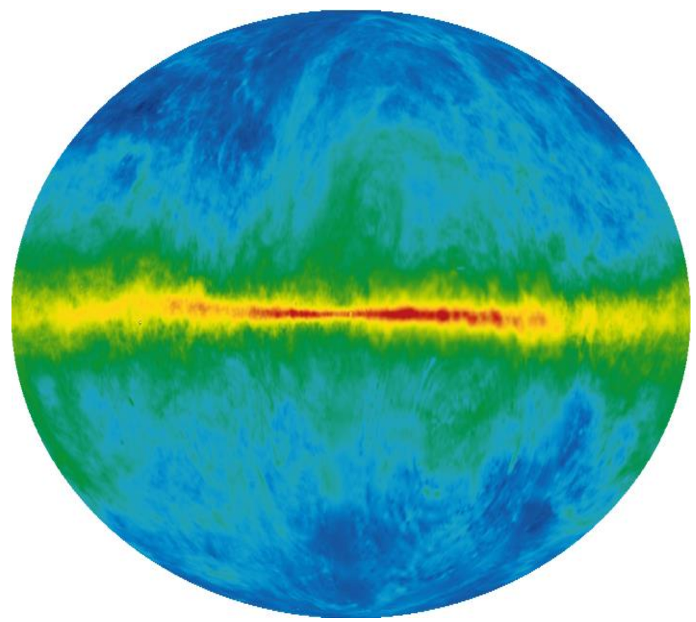


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop

+

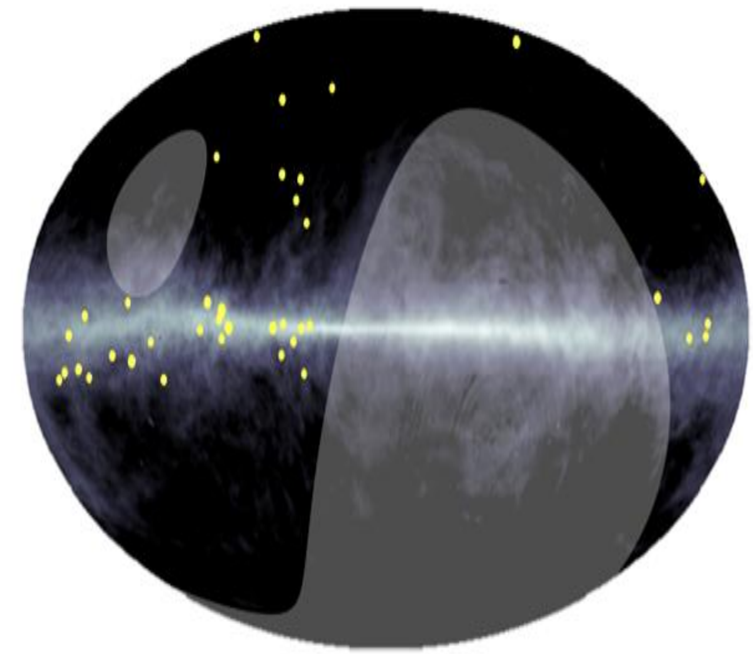
Interstellar matter



Radio (21cm) HI Map
Hartmann et al. (1997)
Dickey & Lockman (1990)

=

High-energy gamma rays



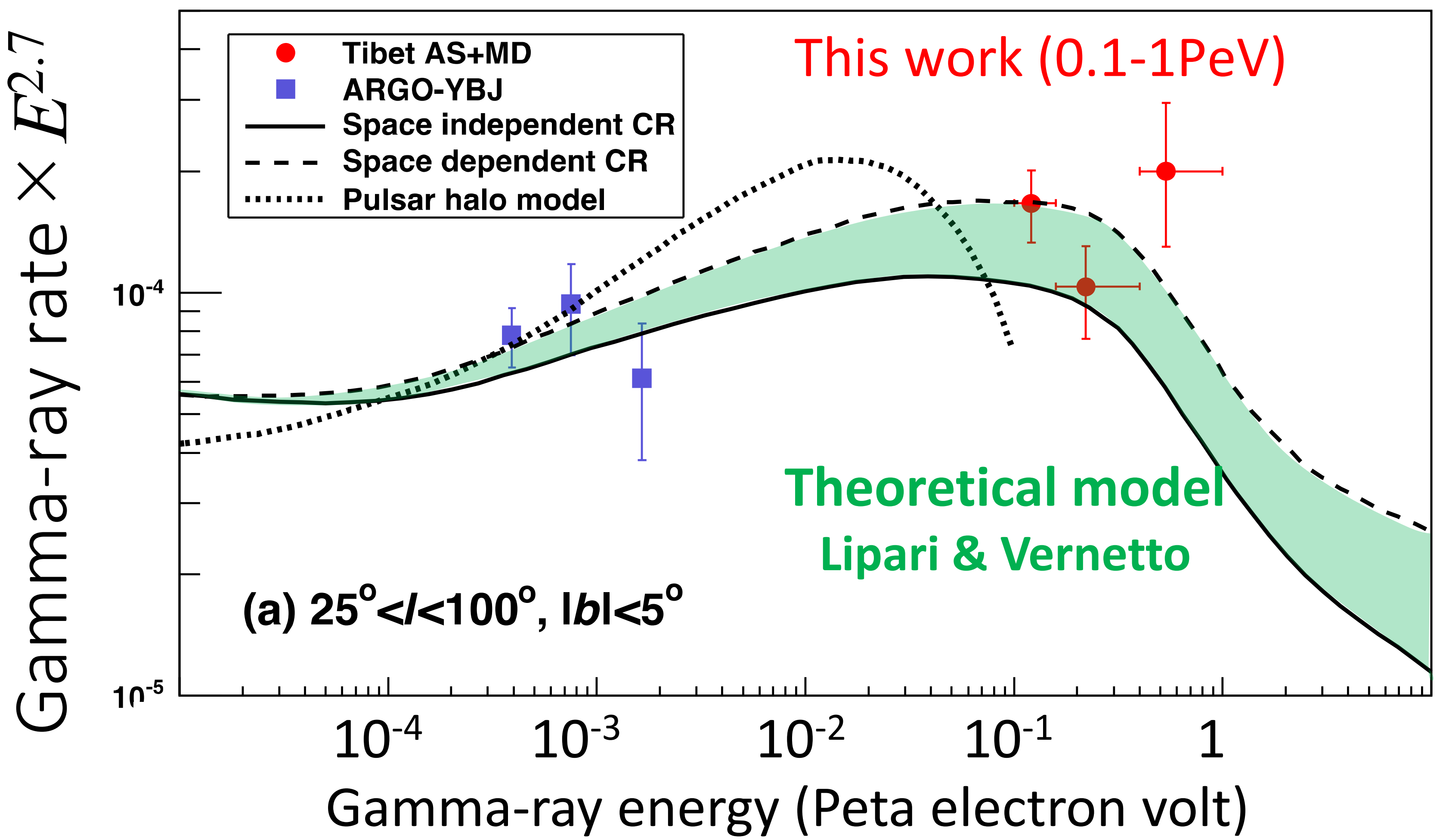
This Work

✓ This work proves a theoretical model that cosmic rays produced by PeVatrons are trapped in the Galactic magnetic field for a long time forming a pool of cosmic rays.

Scientific Interpretation

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

The measured γ-ray rates are consistent with the expected one from cosmic-ray pool scenario assuming the cosmic-ray rate observed on Earth.



✓ It is verified that the high-energy cosmic rays propagated to Earth can be explained by the cosmic-ray pool produced by PeVatrons in the past/present Galaxy.

Some related arXiv e-prints or papers have appeared since the publication of sub-PeV galactic diffuse gamma rays by the Tibet ASγ experiment

Multi-messenger Implications of Sub-PeV Diffuse Galactic Gamma-Ray Emission

arXiv:2104.09491 Ke Fang and Kohta Murase

Abstract

The diffuse Galactic gamma-ray flux between 0.1 and 1 PeV has recently been measured by the Tibet ASγ Collaboration. The flux and spectrum are consistent with the decay of neutral pions from hadronuclear interactions between Galactic cosmic rays and the interstellar medium (ISM). We derive the flux of the Galactic diffuse neutrino emission from the same interaction process that produces the gamma rays. Our calculation accounts for the effect of gamma-ray attenuation inside the Milky Way and uncertainties due to the spectrum and distribution of cosmic rays, gas density, and infrared emission of the ISM. We find that the contribution from the Galactic plane to the all-sky neutrino flux is <~ 5 − 10% around 100 TeV. The Galactic and extragalactic neutrino intensities are comparable in the Galactic plane region. Our results are consistent with the upper limit reported by the IceCube and ANTARES Collaborations, and predict that next-generation neutrino experiments may observe the Galactic component. We also show that the Tibet ASγ data imply either an additional component in the cosmic-ray nucleon spectrum or contribution from discrete sources, including Pevatrons such as superbubbles and hypernova remnants, and PeV electron accelerators. Future multi-messenger observations between 1 TeV and 1 PeV are crucial to decomposing the origin of sub-PeV gamma rays.

Diffuse gamma ray + Hypernova remnants (Hadronic origin)

p + IMS → X's + π's + π0 … → 2γ …
$E_\gamma \sim 0.1\, E_p$

→gamma ray energy spectrum depends on proton energy spectrum

Due to uncertainty in proton spectrum at Earth, a factor 2 uncertainty in gamma ray energy spectrum exists. (Murase vs. Lipari)

→ Missing part -> some source origin

→ e.g. Hypernova Remnants (10^{52} erg) cosmic ray acceleration: 10-100PeV ~10 HNRs may explain Tibet data.

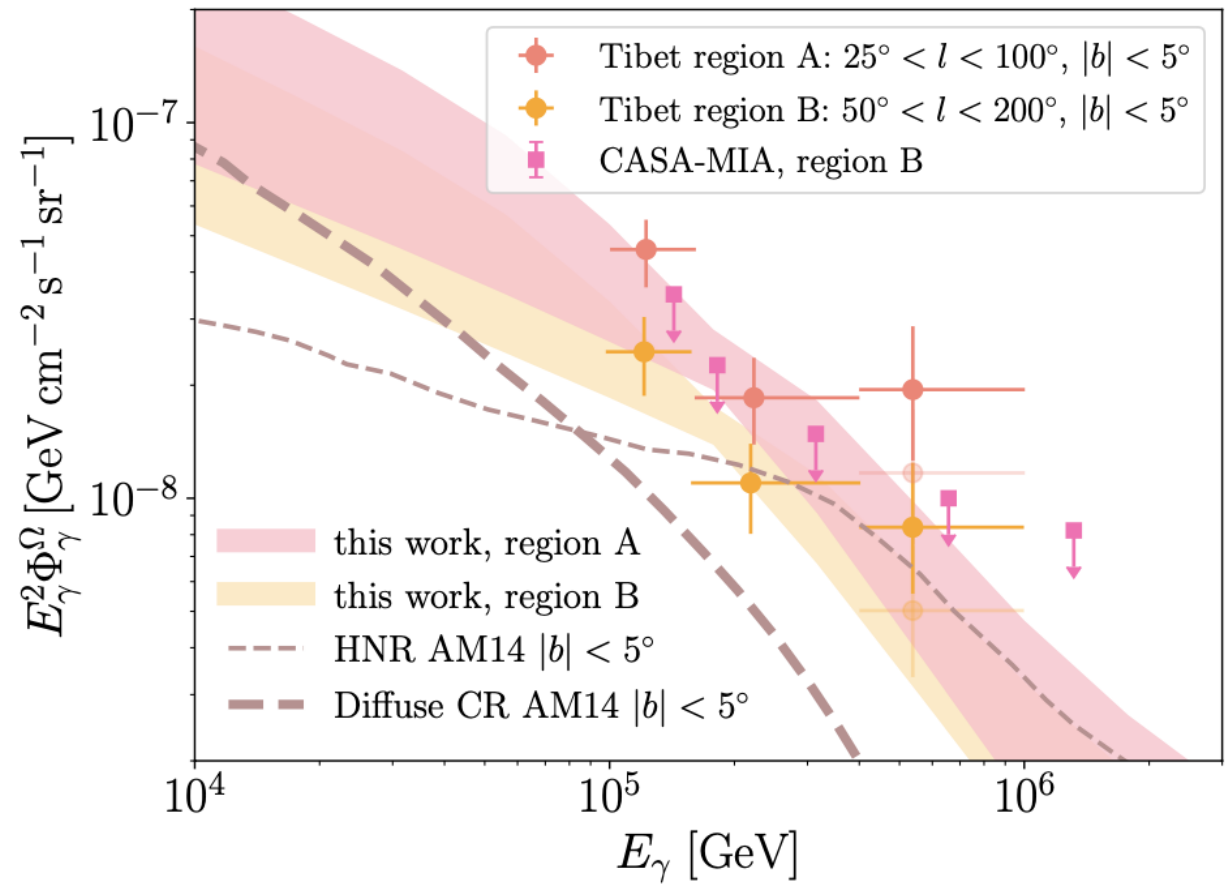
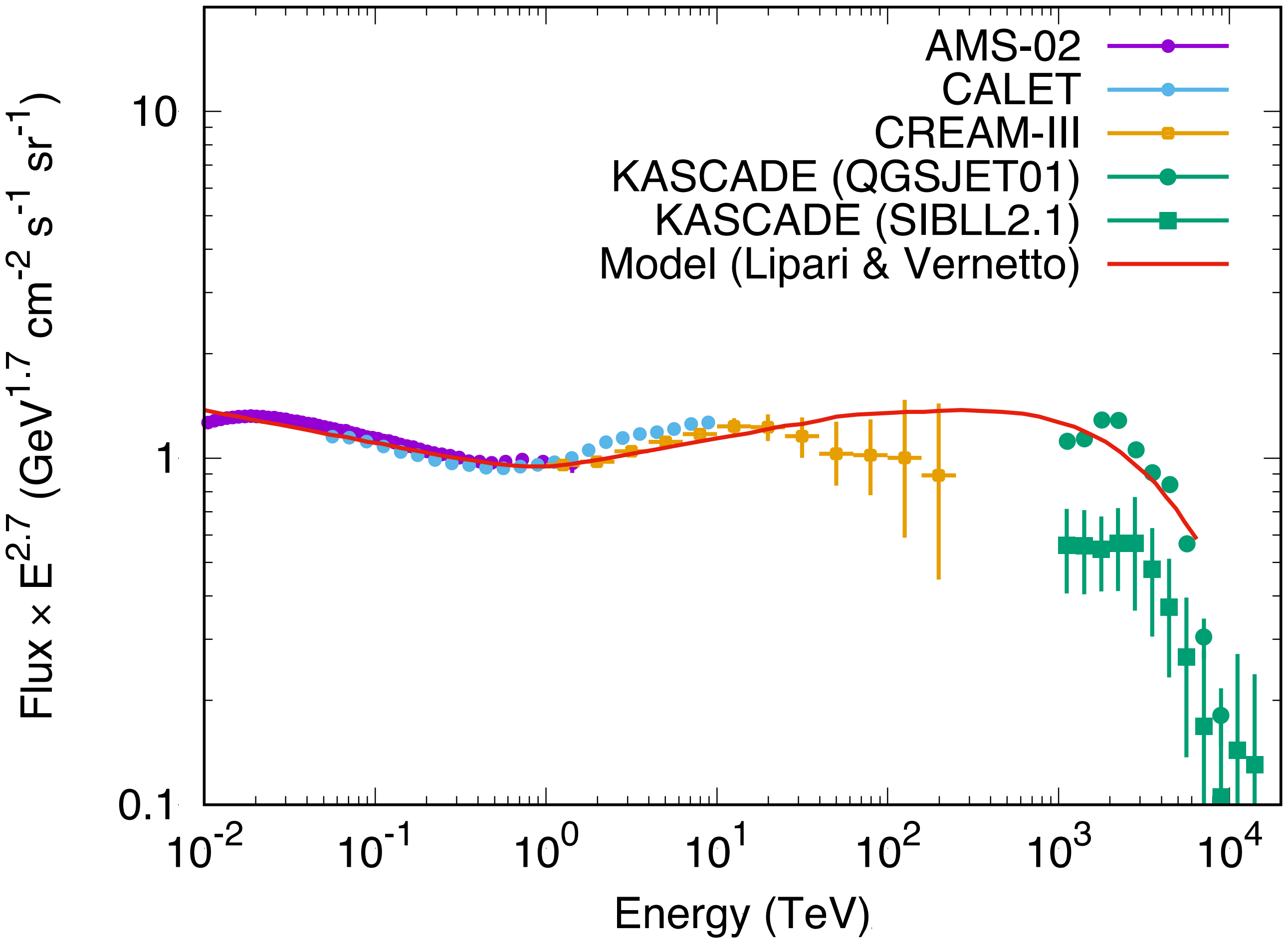
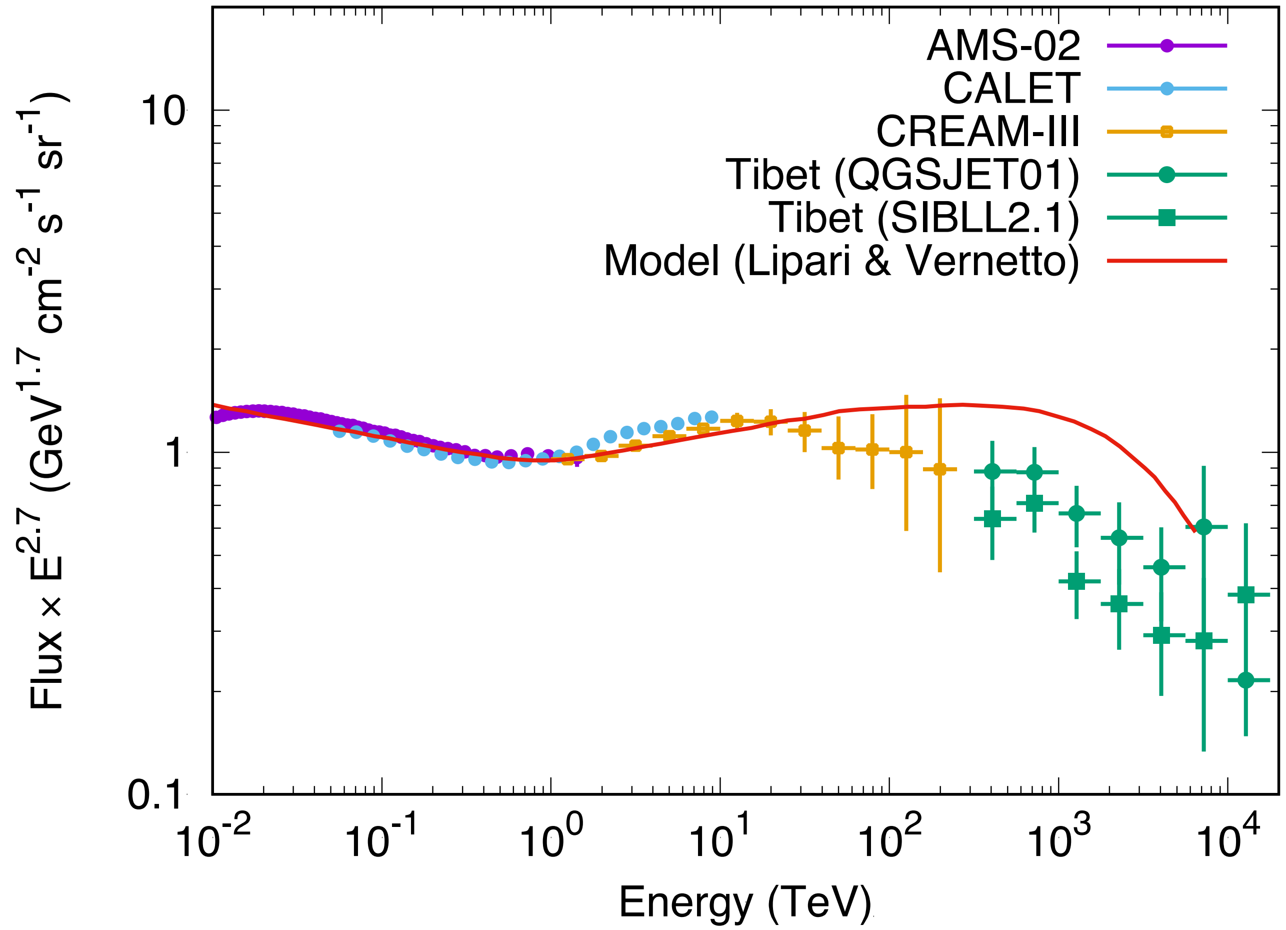
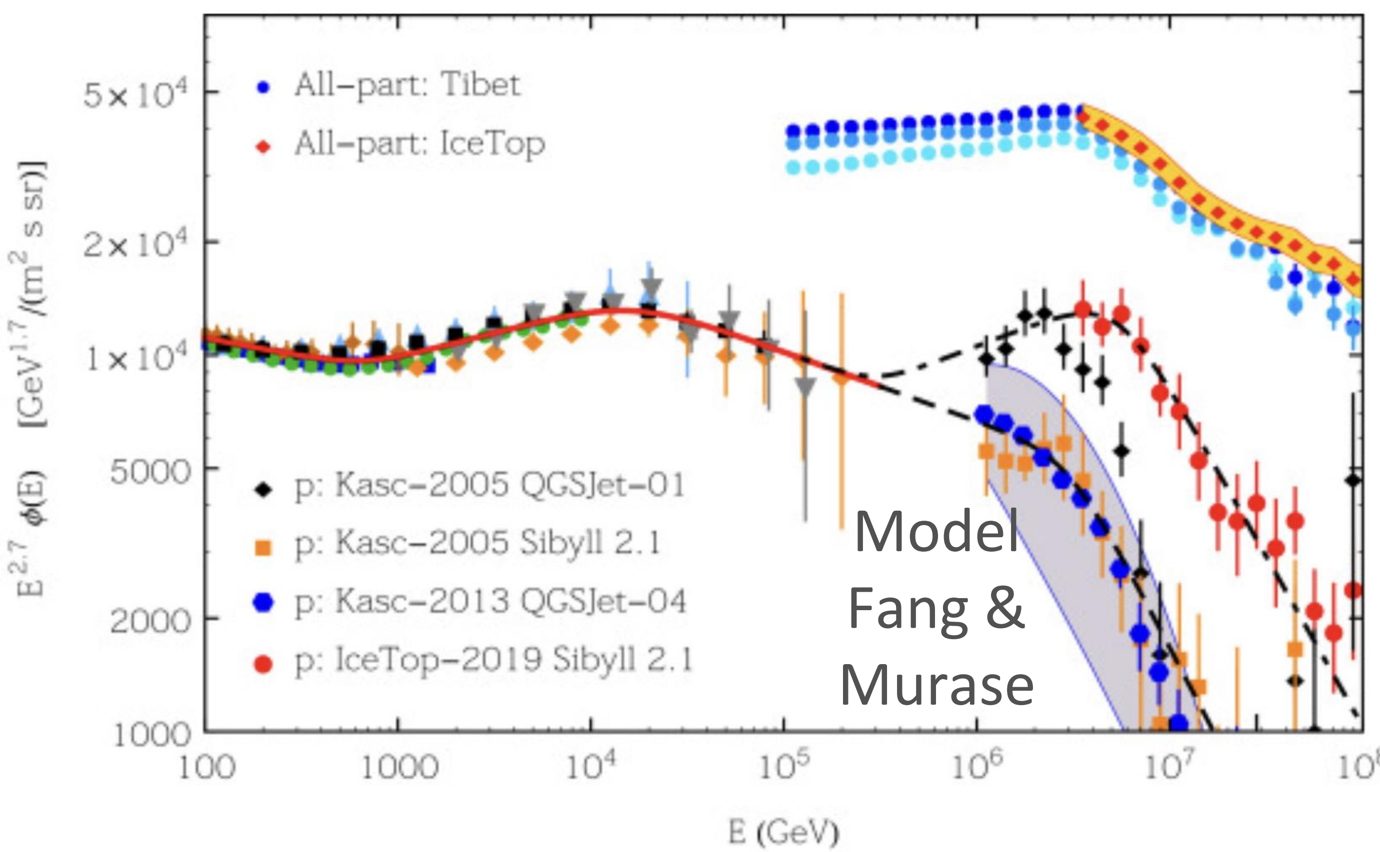


Figure 1. The diffuse Galactic gamma-ray intensity from two sky regions, *region A*: $25° < l < 100°$, $|b| < 5°$, and *region B*: $50° < l < 200°$, $|b| < 5°$. The red and orange data points are the Tibet ASγ measurement of the diffuse γ-ray emission from the two regions (Amenomori et al. 2021). In the last energy bin, the fainter data points indicate the residual intensity after removing events relevant to Cygnus Cocoon. The red and orange bands are the best-fit γ-ray models derived in this work, accounting for uncertainties in the gamma-ray attenuation and cosmic-ray models. The brown long and short dashed curves indicate the diffuse gamma-ray spectra for the GP and unresolved hypernova remnants, respectively, which are taken from Ahlers & Murase (2014) for $|b| < 5°$.

Proton Spectrum







Neutrino Expectation

IceCube all sky (4π) flux

Expected galactic diffuse neutrino flux
（normalized by all sky 4π average flux)

→ Galactic diffuse neutrinos contribute to ∼5 – 10% of total IceCube neutrino flux (Mostly extragalactic!)

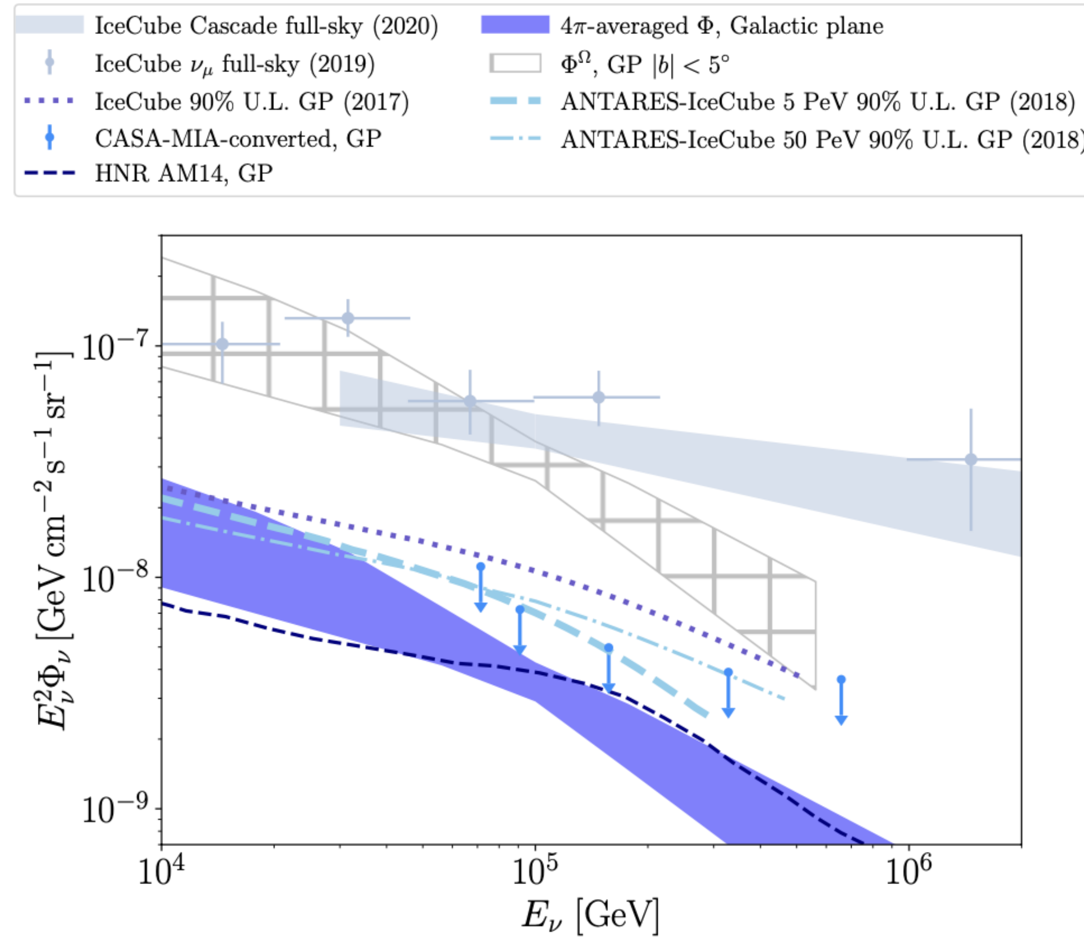
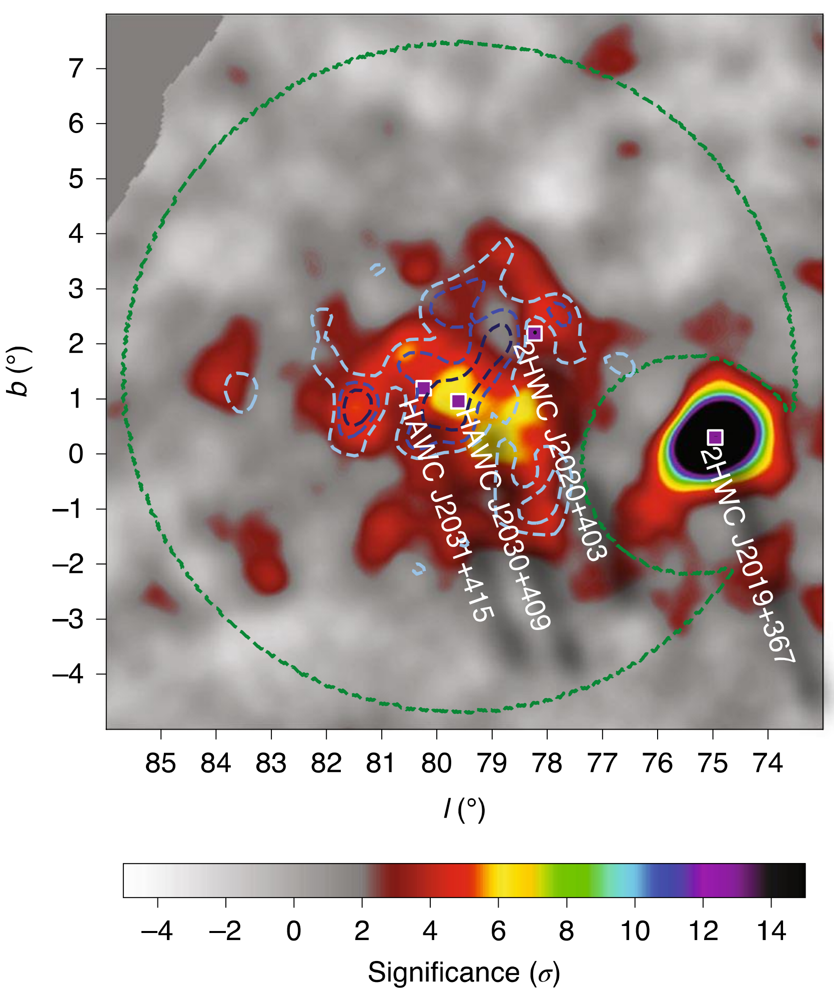


Figure 2. All-sky-averaged intensity of all flavor diffuse neutrinos from the GP, compared to neutrino observations. The GP neutrino intensity, $E_\nu^2\Phi_\nu$, (blue shaded band) is derived with the best-fit gamma-ray intensities in Figure 1. The model is consistent with the combined upper limits at 90% confidence level posed by ANTARES and IceCube (sky blue dashed and dash-dotted curves; Albert et al. 2018), the 90% limits with 7-year IceCube data (blue dotted curve; Aartsen et al. 2017), and the upper limits on neutrinos from the GP (blue downward arrows), which are derived from the CASA-MIA gamma-ray limits in region B, assuming that sources follow the SNR distribution (cyan downward arrows; Borione et al. 1998). The hatched band shows the intensity $E_\nu^2\Phi_\nu^\Omega$ of the $|b| < 5°$ region, which is comparable to the isotropic neutrino background from the IceCube Cascade (light blue data points; Aartsen et al. 2020) and muon neutrino (light blue shaded area; Stettner 2019) data below ~ 100 TeV.

Cygnus Cocoon (Hadronic Origin)

In Cygnus Cocoon region,
4 ev (>400 TeV) exist.



- ✓ π^0 origin is likely.
- ✓ Soft energy spectrum > 10TeV
  →high-enery cosmic rays escaping?
- ✓ Tension against IceCUBE ν upper limit?

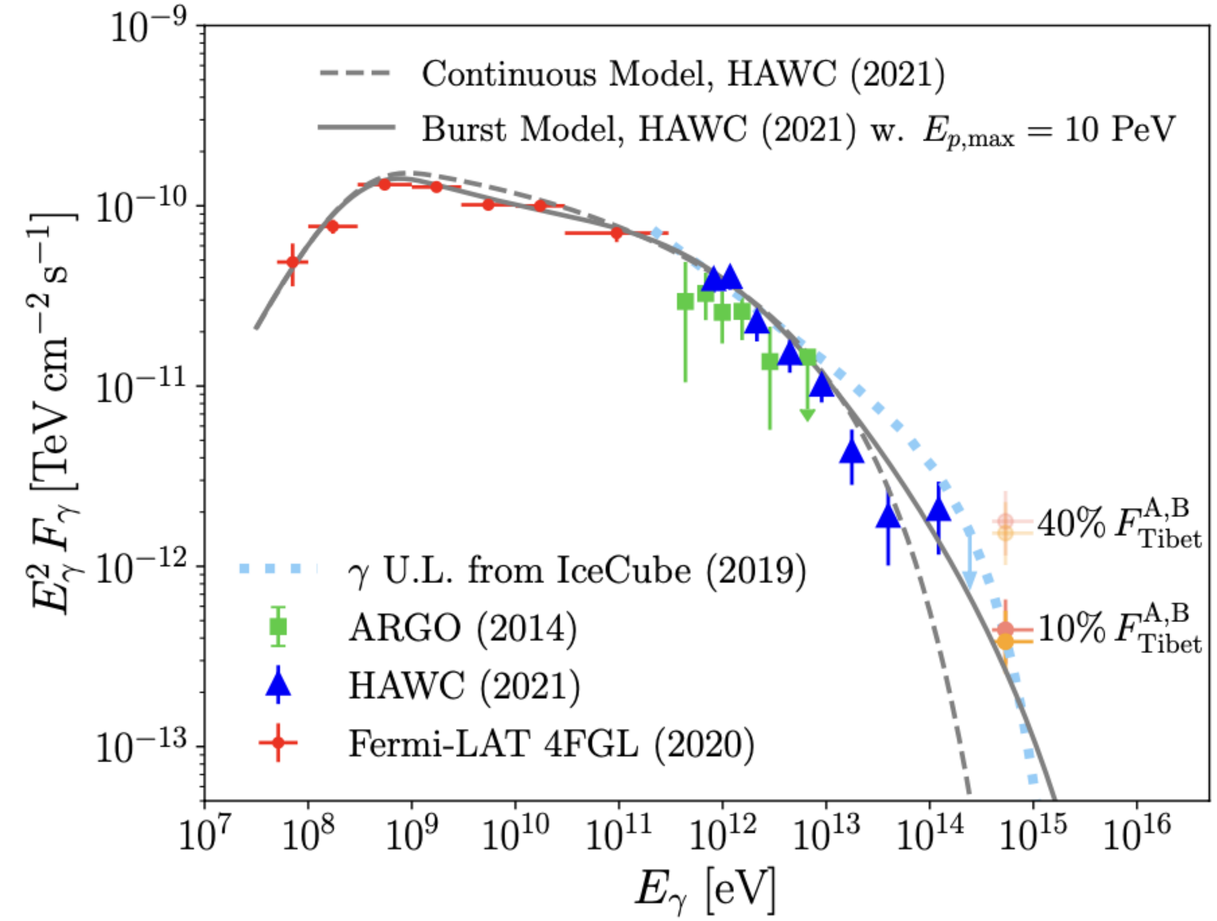


Figure 3. Spectral energy distribution of the Cygnus Cocoon measured by *Fermi*-LAT (Abdollahi et al. 2020), ARGO-YBJ (Bartoli et al. 2014), and HAWC (Abeysekara et al. 2021). The light pink and orange flux points indicate 40% of the Tibet ASγ flux of regions A and B (Amenomori et al. 2021). The thick pink and orange markers additionally scale the fluxes to the HAWC size of the Cygnus Cocoon. The blue dotted curve shows the limit on the γ-ray flux based on the non-detection of neutrinos from the region by IceCube (Kheirandish & Wood 2019). The two γ-ray emission models from Abeysekara et al. (2021) are shown for comparison. A significant detection of the Cygnus Cocoon at the estimated flux level may favor the burst model and the presence of a Pevatron.

Diffuse gamma ray + Inverse Compton Sources (Leptonic origin)

Trying to explain the missing part by gamma rays by electron inverse-Compton scatterings

Electrons + CMB → gamma rays
(Emax (Electron)-> 3PeV)

Unresolved PWN?
HAWC TeV Halo sources?

High energy electrons stay around a Source, due to strong synchrotron radiation cooling!
→ Dependent on diffusion coefficient, but realistic models?

Should be bright at TeV energies!
→ IACT (telescopes) will check 23 directions.

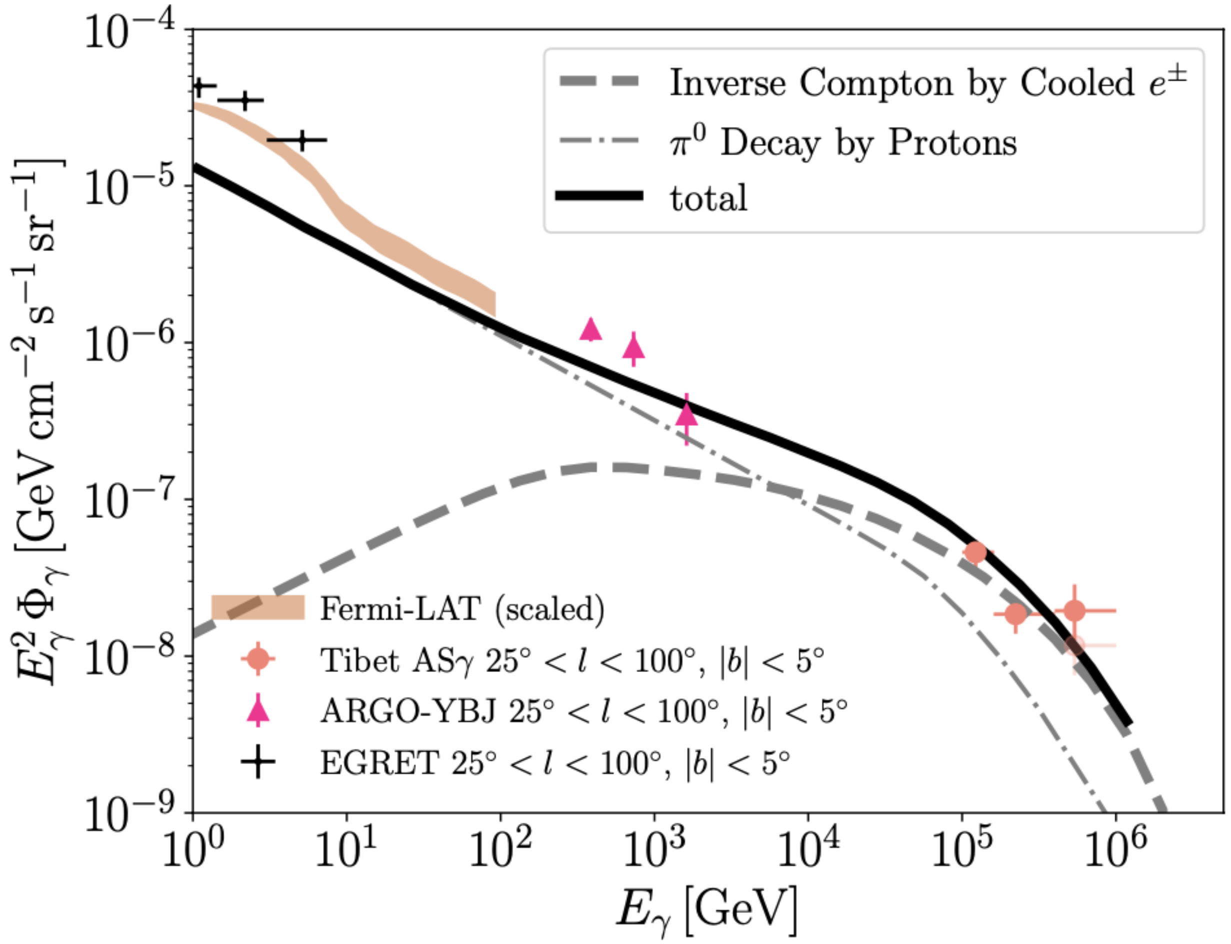


Figure 4. Demonstration of a hybrid γ-ray emission model, in which the inverse Compton of relativistic electrons (grey dashed curve) explains the Tibet ASγ measurement in the region $25° < l < 100°$ (red round data points), and π^0 decay by Galactic diffuse protons (grey dash-dotted curve) explains the lower-energy observations of the same region by EGRET (black plus markers; Hunter et al. 1997), *Fermi*-LAT (brown shaded region, scaled from Ackermann et al. 2012b to the EGRET flux), and ARGO-YBJ (pink triangle data points; Bartoli et al. 2015). The electrons are assumed to have an intrinsic spectrum $dN/dE_e \propto E_e^{-2}$ and maximum energy $E_{e,\max} = 3$ PeV.

Galactic cosmic ray propagation: sub-PeV diffuse gamma-ray and neutrino emission

Bing-Qiang Qiao,[1] Wei Liu,[1] Meng-Jie Zhao,[1,2] Xiao-Jun Bi,[1,2] and Yi-Qing Guo[1] (arXiv:2104.03729)

Position dependence of diffusion coefficient (the inner in Galaxy, the slower diffusion)

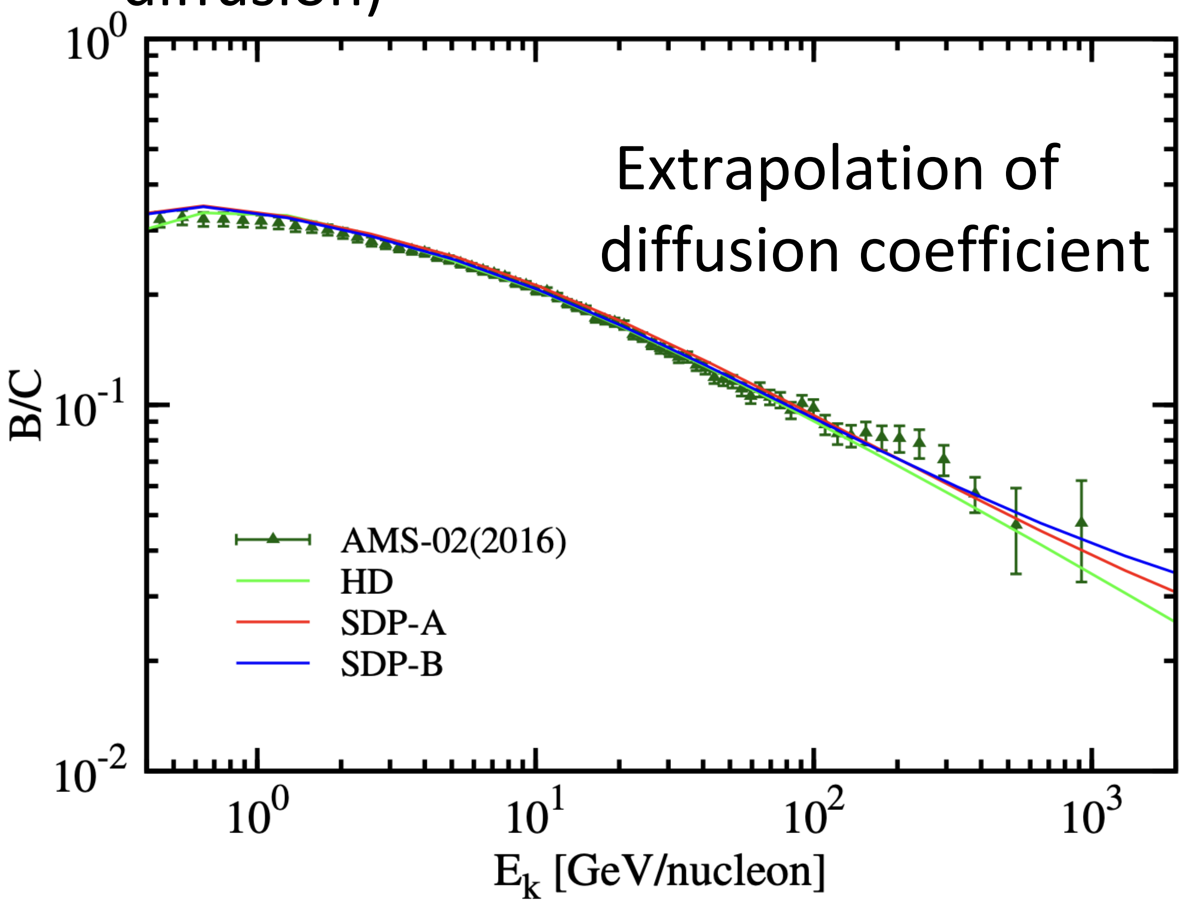
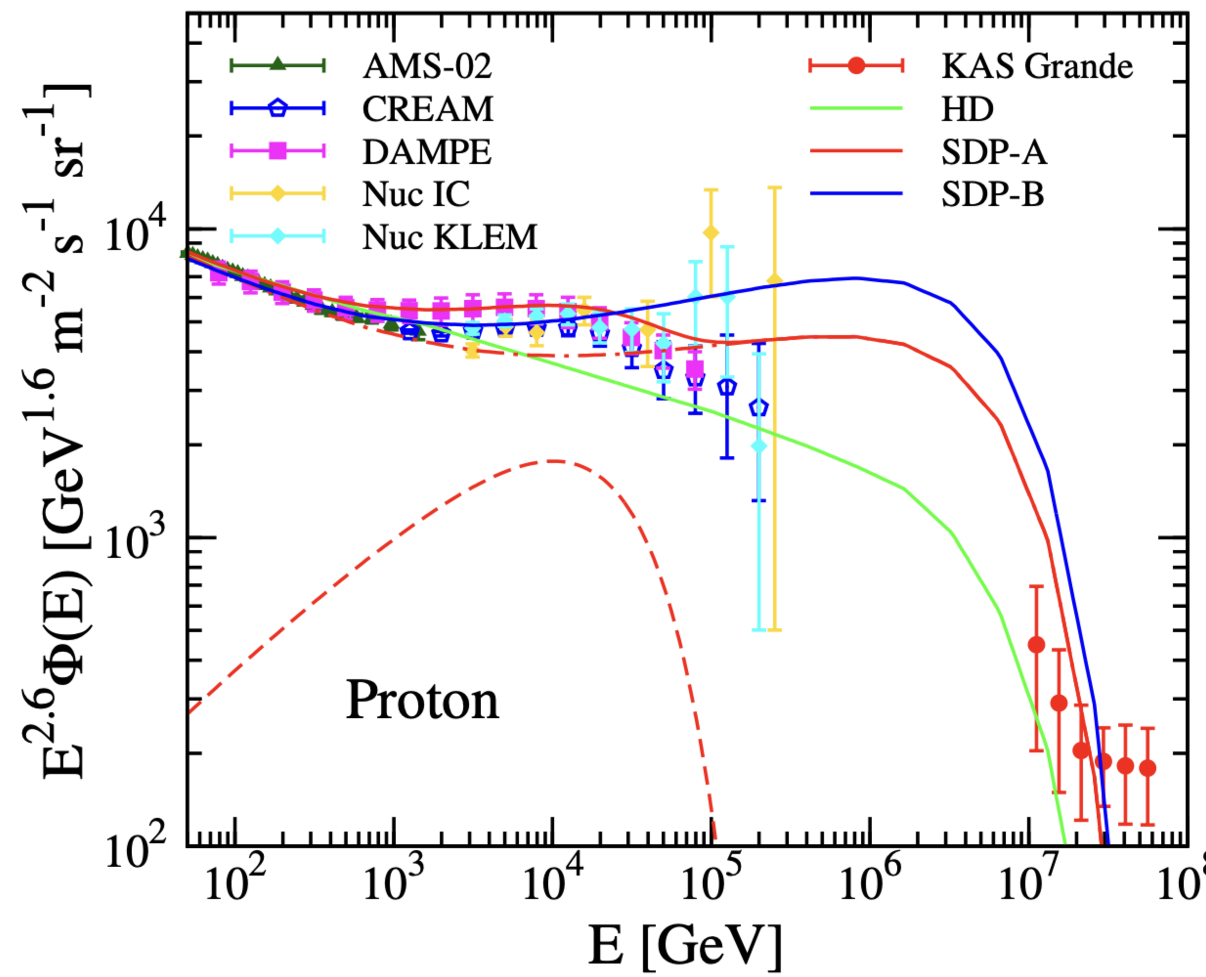


Fig. 1. Calculation of B/C ratio to obtain the propagation parameters in HD, SDP-A and SDP-B models, with B/C data taken from the AMS-02 measurement (Aguilar et al. 2016).



Gamma-ray data well explained

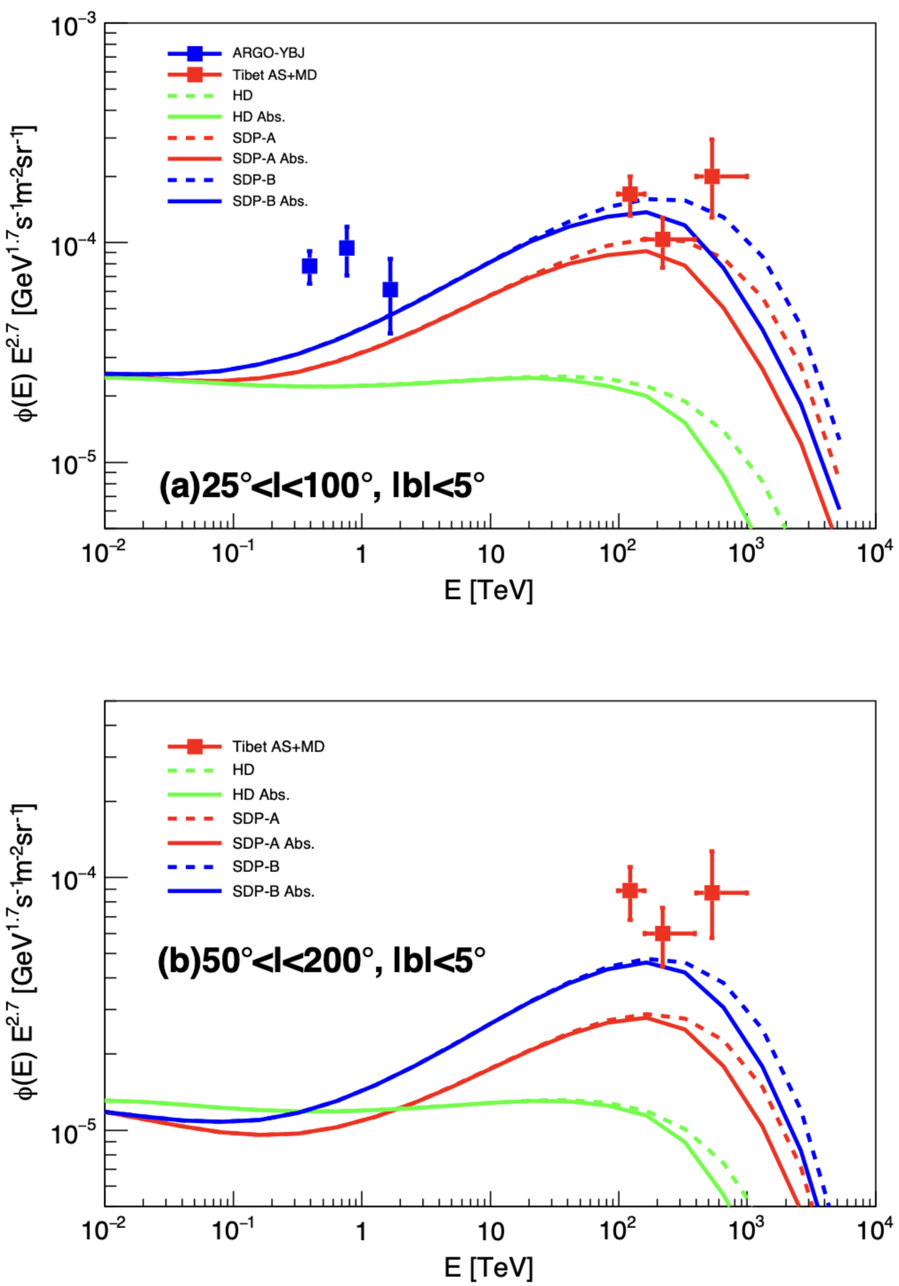


Fig. 3. Calculated diffuse gamma-ray spectra in three propagation models. The gamma ray data are taken from ARGO-YBJ (Bartoli et al. 2015) and Tibet AS+MD (Amenomori et al. 2021) experiments.

IceCUBE neutrinos → ~10% from Galactic plane

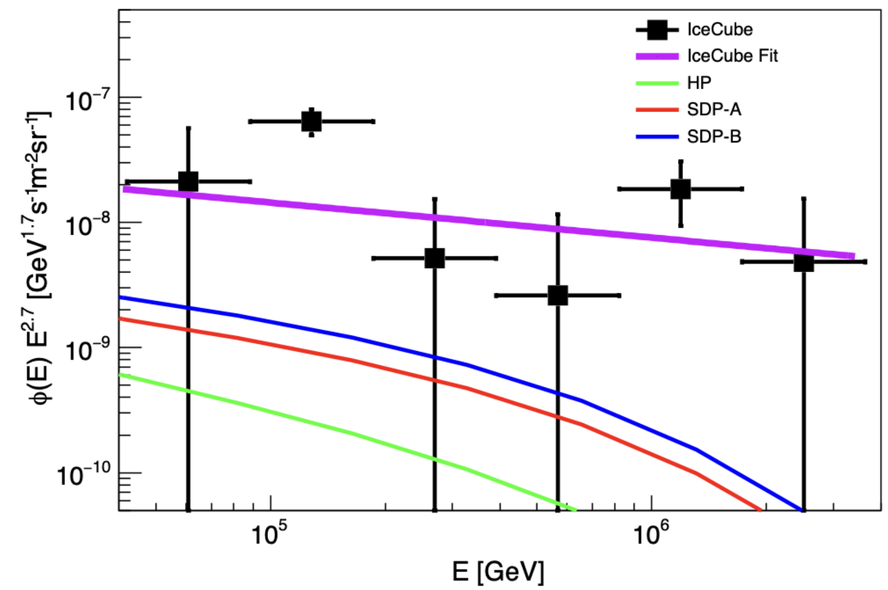


Fig. 5. Diffuse neutrino flux calculated by the three propagation models. The data are taken from the ICE-CUBE 7.5 years' observation (Abbasi et al. 2020). The violet line is the power-law fitting to the data, with normalization $\Phi = 6.37 \times 10^{18}$ $\mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$ at 100 TeV and power index $\gamma = -2$

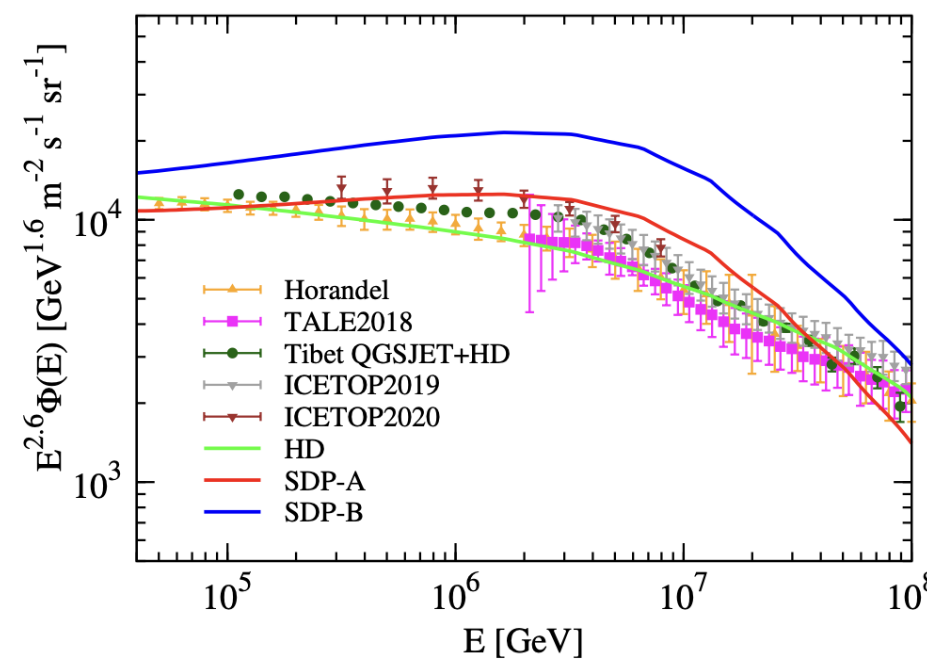


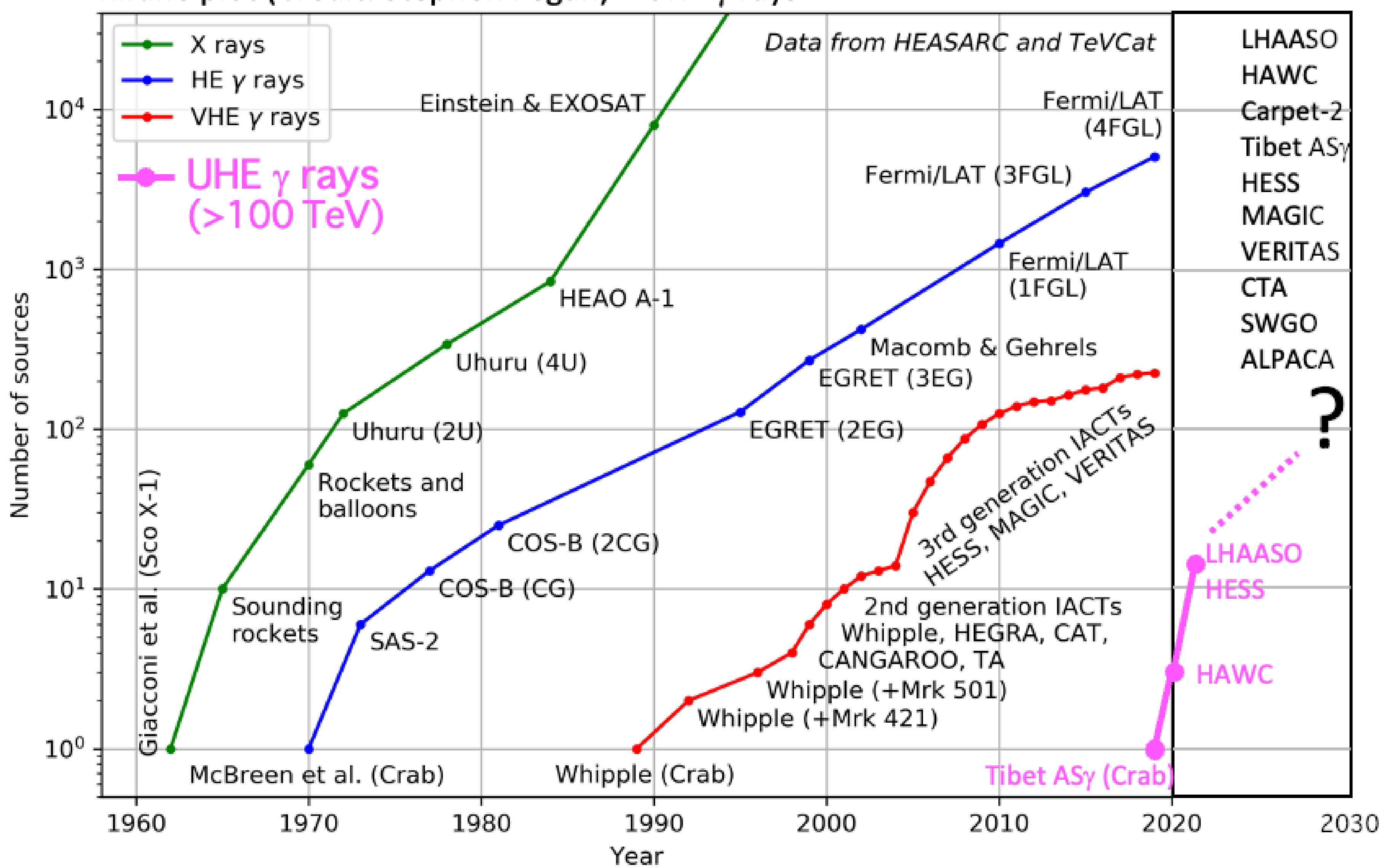
Fig. 4. Calculated all-particle spectra in three propagation models. The all-particle data are taken from Horandel (Hörandel 2003), TALE (Abbasi et al. 2018), IceTop (Aartsen et al. 2019, 2020a) and Tibet (Amenomori et al. 2008).

Local cosmic ray flux at Earth is low, by a factor of 2!?

§ Future Prospects & Summary

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

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

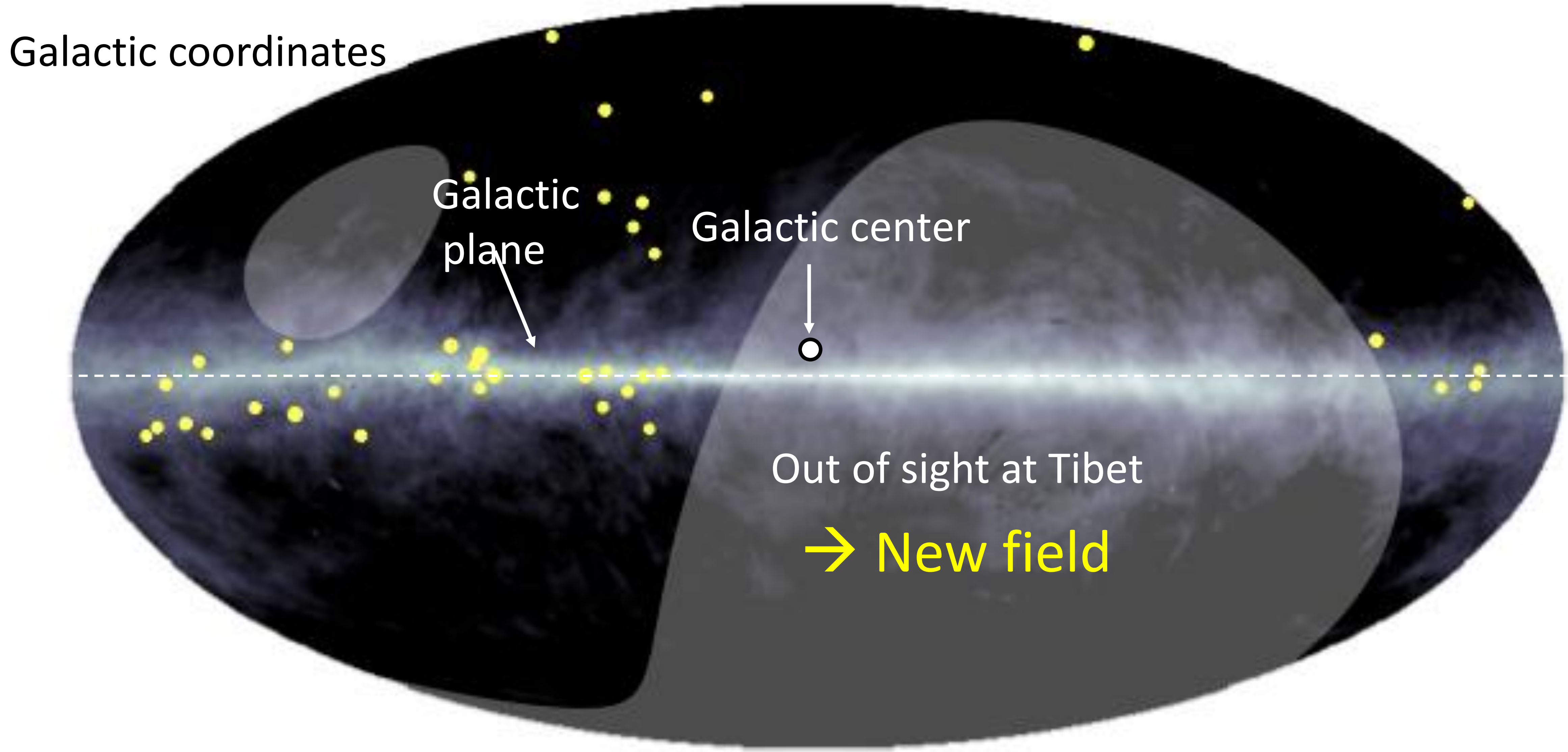


Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example http://adsabs.harvard.edu/abs/1996NCimC..19..953K).
The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on 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 (>100 TeV).
- ✓ A dozen of UHE γ-ray source discovered (Tibet ASγ, HAWC, LHAASO) in northern sky.

→ UHE γ-ray observatories necessary in southern hemisphere

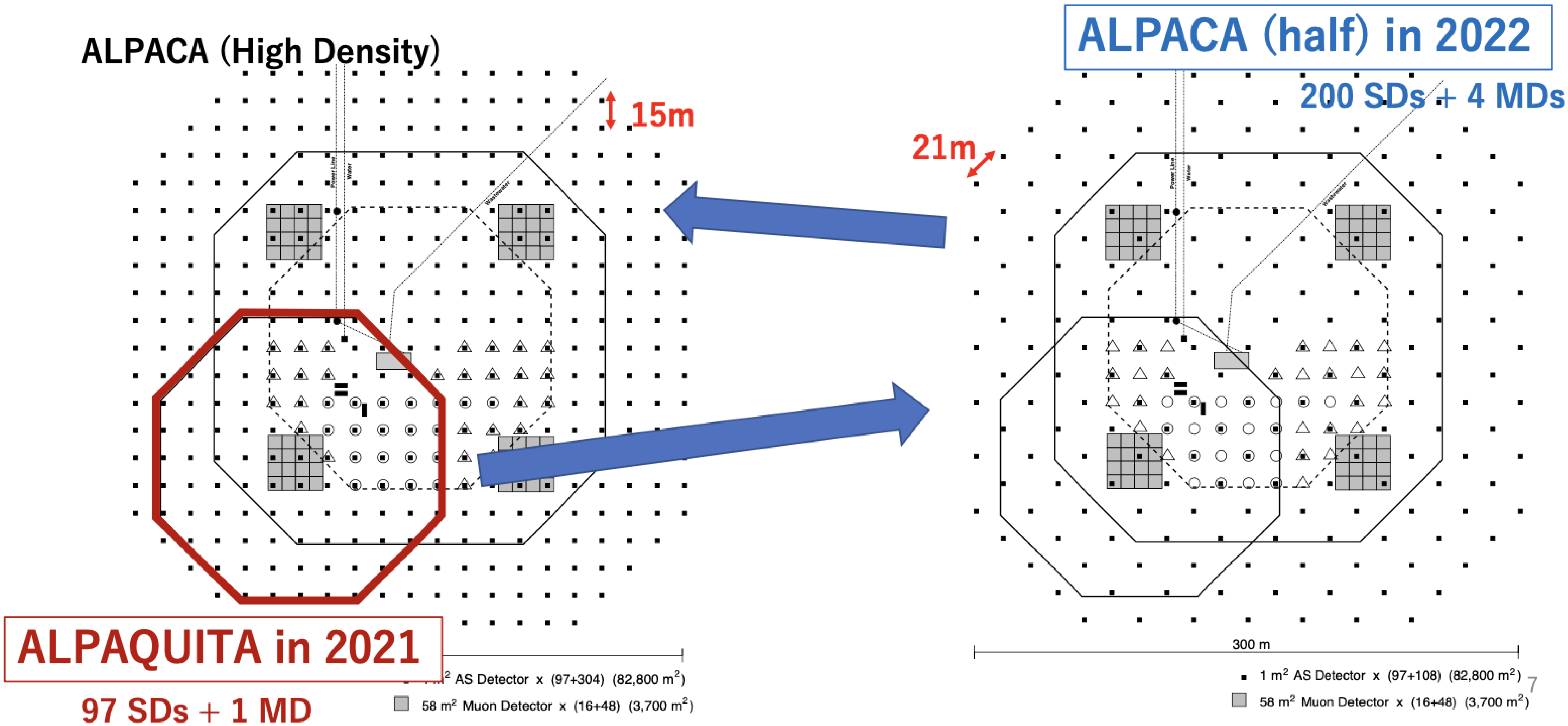
Go South! (e.g., ALPACA [2022], Mega ALPACA, SWGO, CTA, …) & Neutrinos



- ✓ PeVatron hunting in Northern and Southern hemispheres
- ✓ Blackhole at the Galactic center (A candidate of PeVatron)
- ✓ Hot gas bubble around the Galactic center
- ✓ Survey heavy dark matter search

From Indico-ID777 (ICRC2021) Takashi Sako

ALPACA staging



From Indico-ID777 (ICRC2021) Takashi Sako

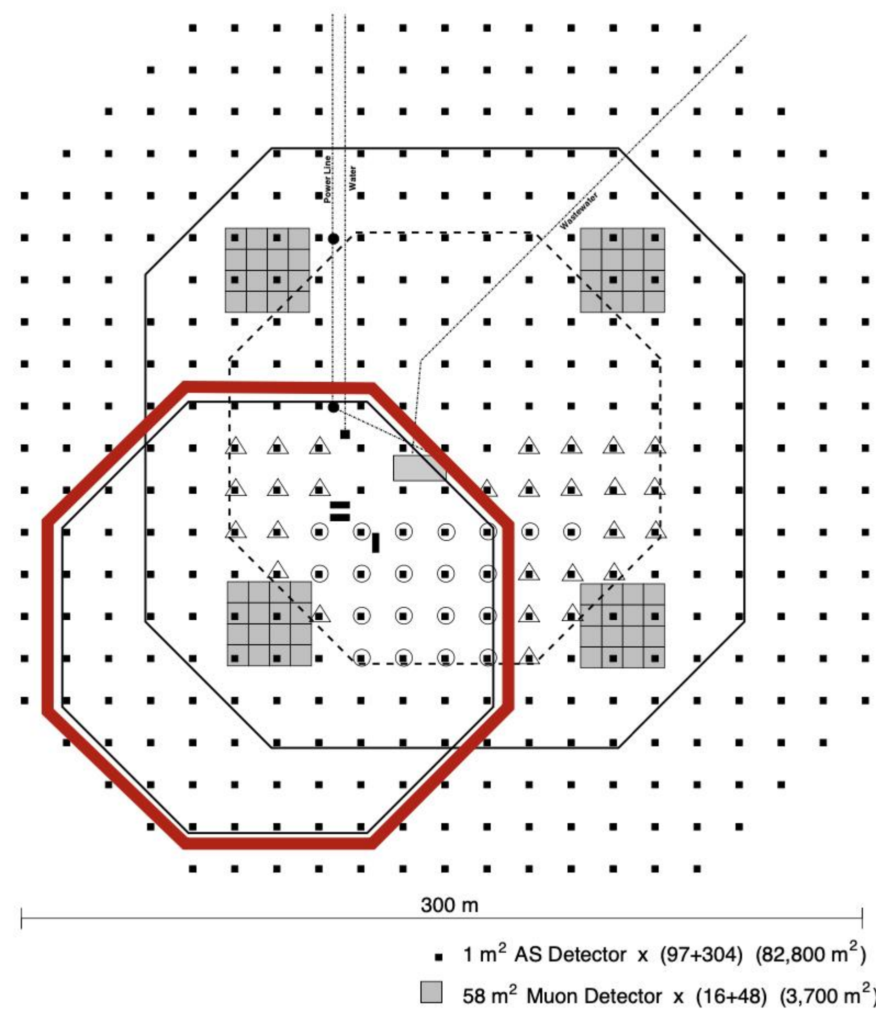
ALPAQUITA
(little ALPACA)

- Prototype array of 25% ALPACA area coverage
  - 97 surface detectors
  - 1 MD
- Targets
  - **Start operation in 2021**
  - Infrastructure establishment
  - A few bright >100TeV sources
  - CR anisotropy

S. Kato ID:857

T.K. Sako ID:722
(north observation)



Summary

Unraveling 60-Year-Old Mystery,

✓ 13 point-like or extended gamma-ray sources > 10 TeV
-> Energy spectra in the 100 TeV region so far from Crab,
Cygnus OB1 & OB2 , and G106.3+2.7 [First detection in the
100 TeV region from SNR + molecular cloud]

✓ First detection of diffuse sub-PeV gamma rays from our galaxy
->Evidence for existence of PeVatrons
in past and /or present Milky Way galaxy
->Experimental verification for the theoretical model of
high-energy "cosmic-ray pool" in Milky Way galaxy

✓ Future prospects: Go South! & Neutrinos

Appendix : 10 yrs ago, Gus Sinnis @ TeVPA 2011

CONCLUSIONS

- EXTENSIVE AIR SHOWER ARRAYS HAVE PROVEN CAPABILITIES NEEDED IN GAMMA-RAY ASTRONOMY
  - ALL-SKY COVERAGE
  - LARGE/DIFFUSE SOURCES
  - HIGH-ENERGY EMISSION (>10 TEV)
- FUTURE INSTRUMENTS (HAWC, TIBET MD, LHAASO) PROMISE LARGE ADVANCES IN SENSITIVITY 10-100X
  - VHE TRANSIENT SOURCES (AGN AND GRBS)
  - UNDERSTANDING THE GALACTIC DIFFUSE EMISSION
  - HIGHEST ENERGY PHENOMENA (>100 TEV)
  - MULTI-WAVELENGTH/MESSENGER ALERTS