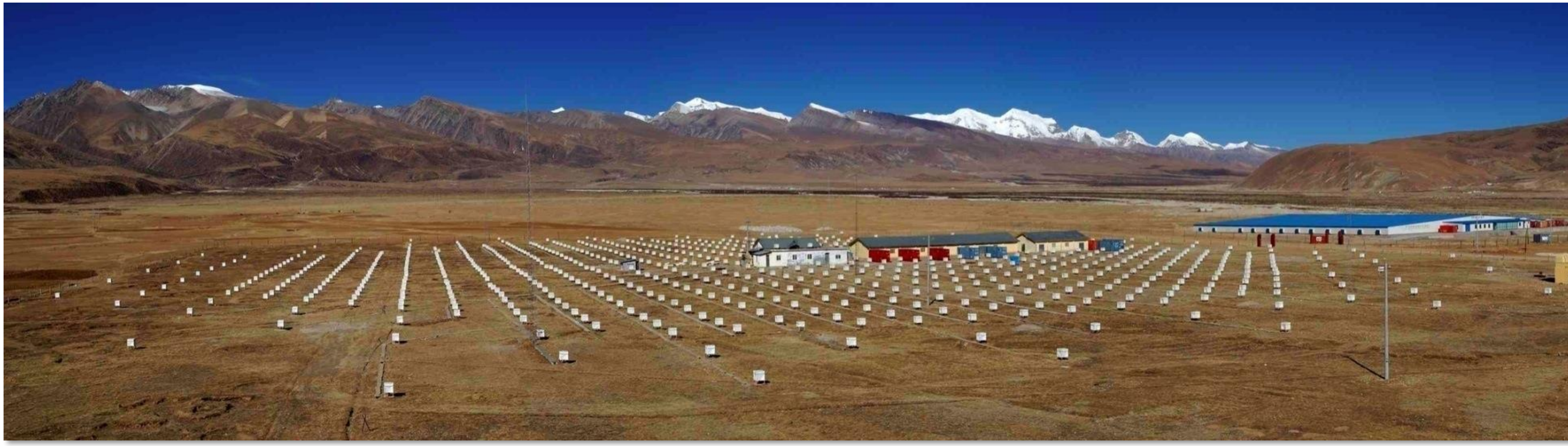


Recent results on gamma-ray observation by the Tibet ASγ experiment

Masato TAKITA (ICRR, Univ. of Tokyo)
For the Tibet ASγ Collaboration,
ICRR, the University of Tokyo

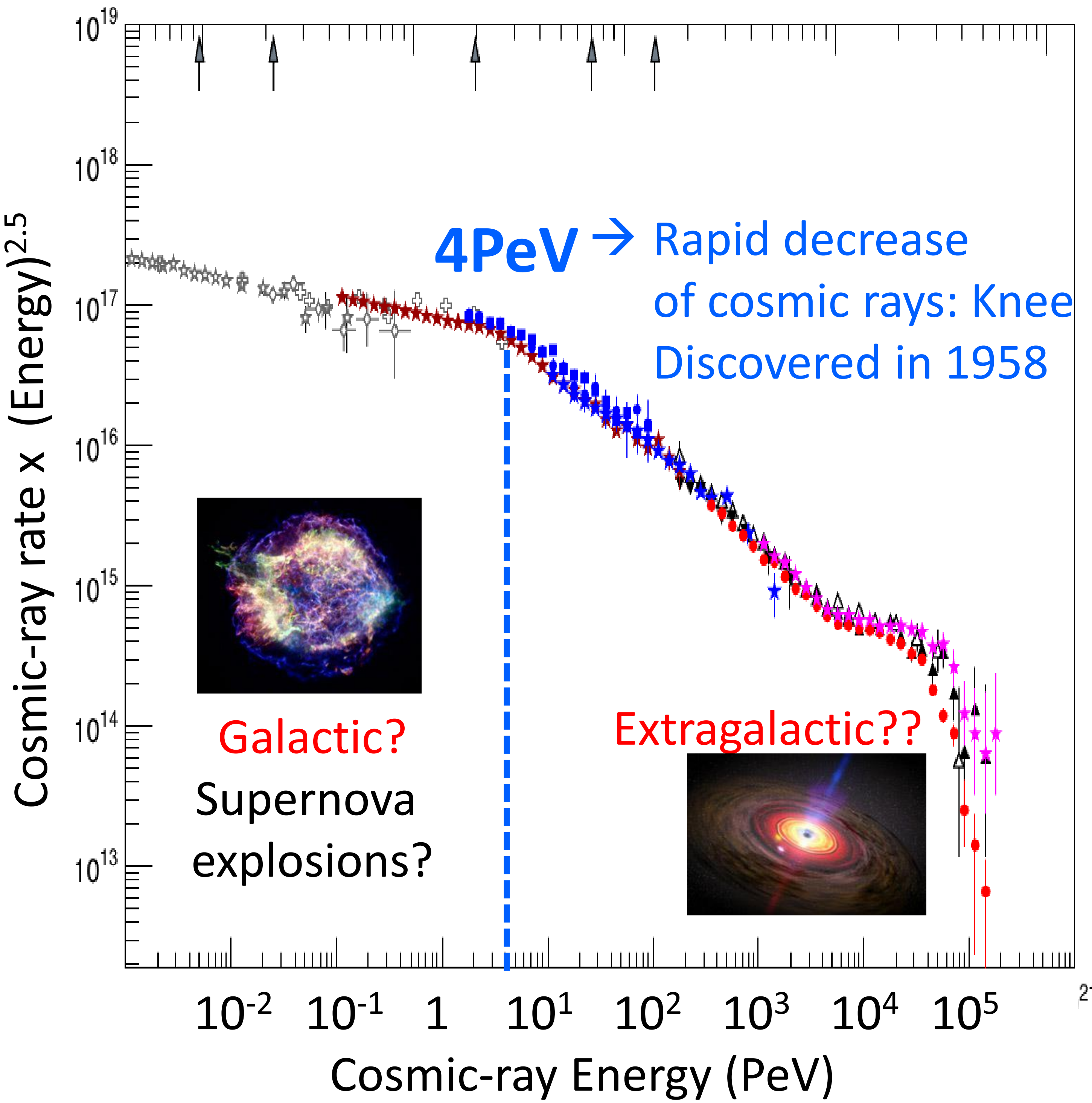
July 9, 2022 @ICHEP2022 (Bologna, Italy)

Outline

- Introduction
- The Tibet ASγ Experiment
- First detection of UHE ($>$ 100 TeV) γ rays
- Sub-PeV diffuse γ rays from the Milky Way galaxy
- Future prospect and Summary

§ Introduction

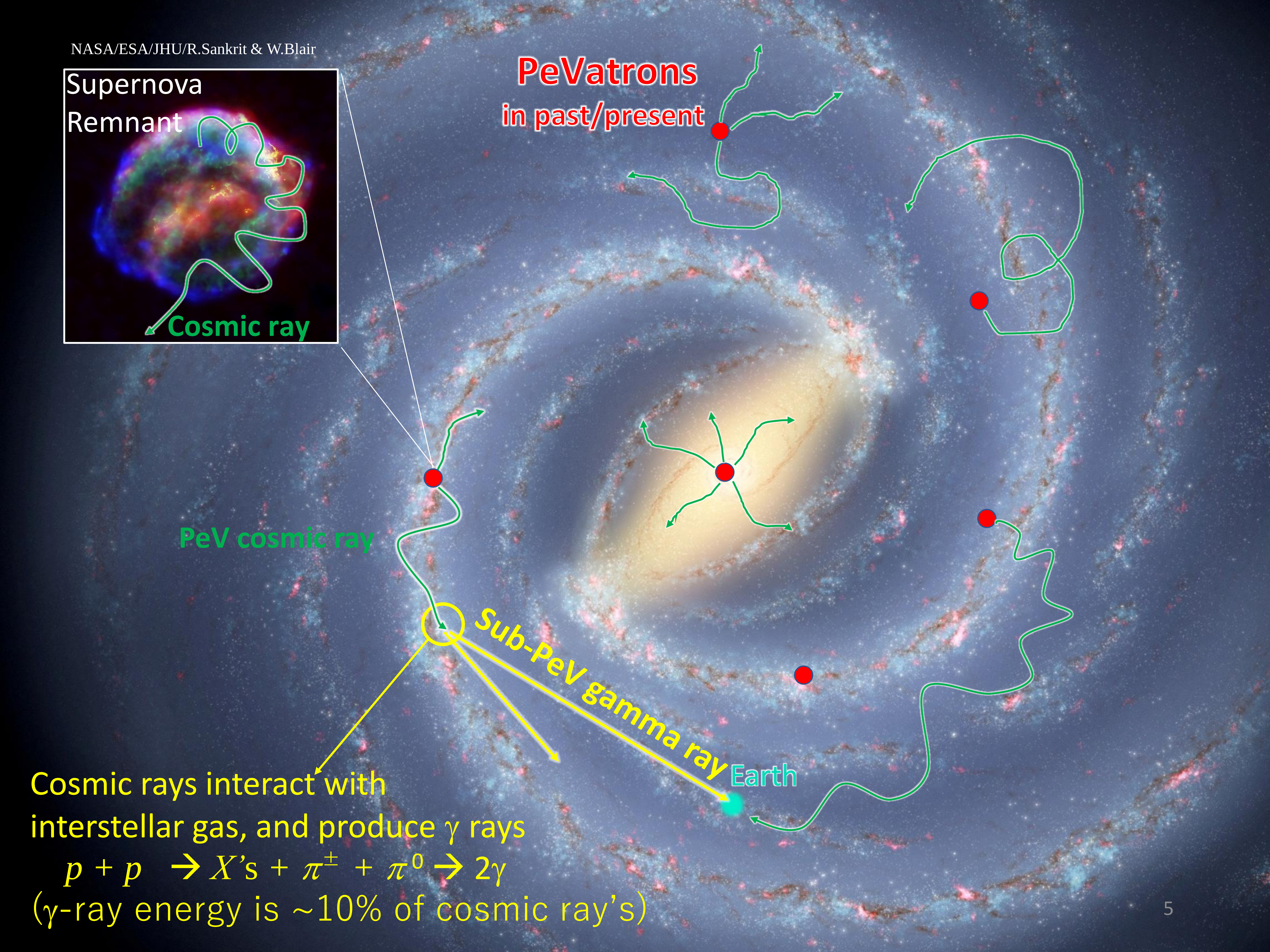
Cosmic Ray Rate & Energies



- Wide energy range
- Main component is proton
- Rate decreases to 1/1000 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
$p + p \rightarrow X$'s + $\pi^{\pm}$ + $\pi^{0} \rightarrow 2\gamma$
(γ-ray energy is ~10% of cosmic ray's)

§ The Tibet ASγ experiment

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]

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5 National Astronomical Observatories, CAS, China.
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7 Department of Physics, Hebei Normal Univ., China.
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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.
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24 National Institute of Informatics, Japan.
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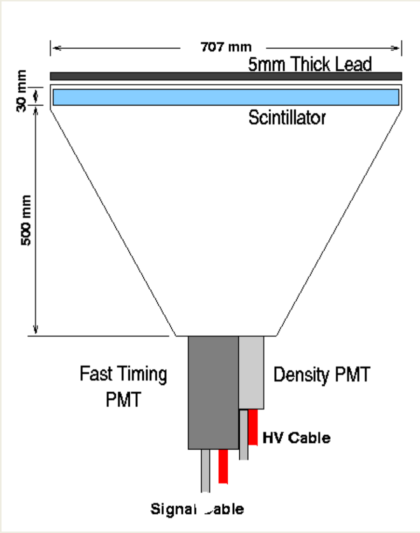
26 Department of Mechanical and Electrical Engineering, Shangdong Management Univ., China.
27 College of Science, China Univ. of Petroleum, China.
28 Tokyo Metropolitan College of Industrial Technology, Japan.
29 Department of Physics, Konan Univ., Japan.
30 Shonan Institute of Technology, Japan.
31 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

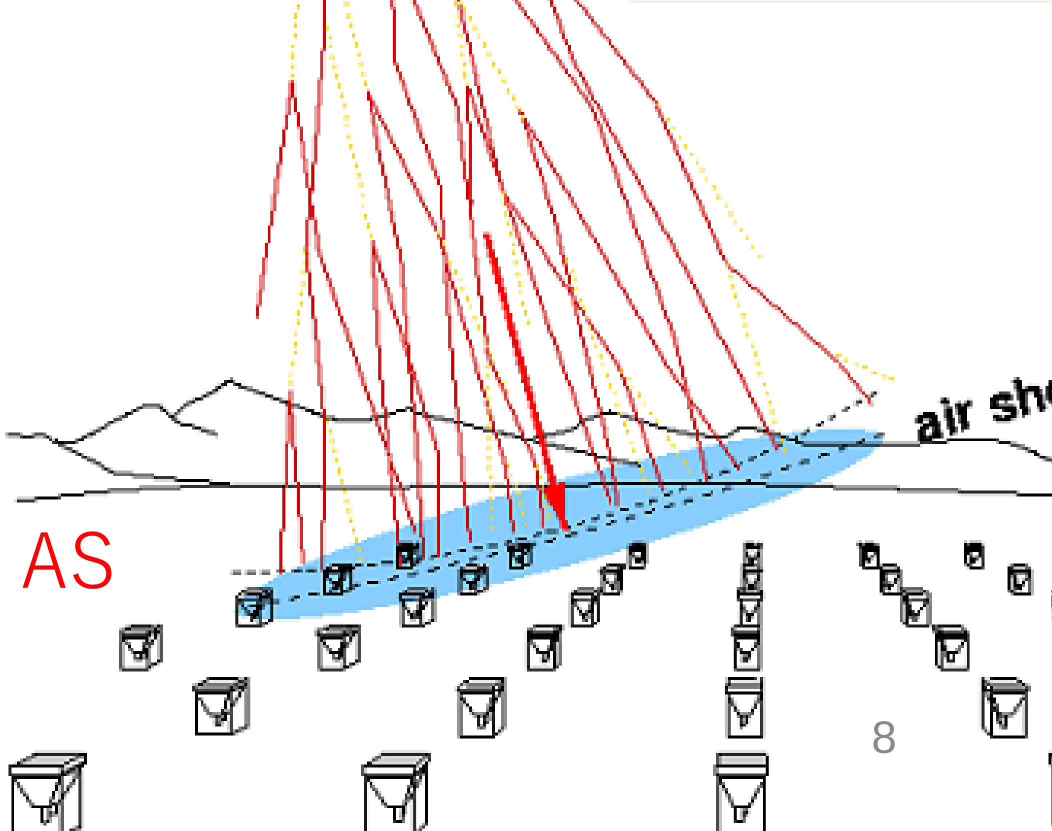


- Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

<u>Present Performance</u>

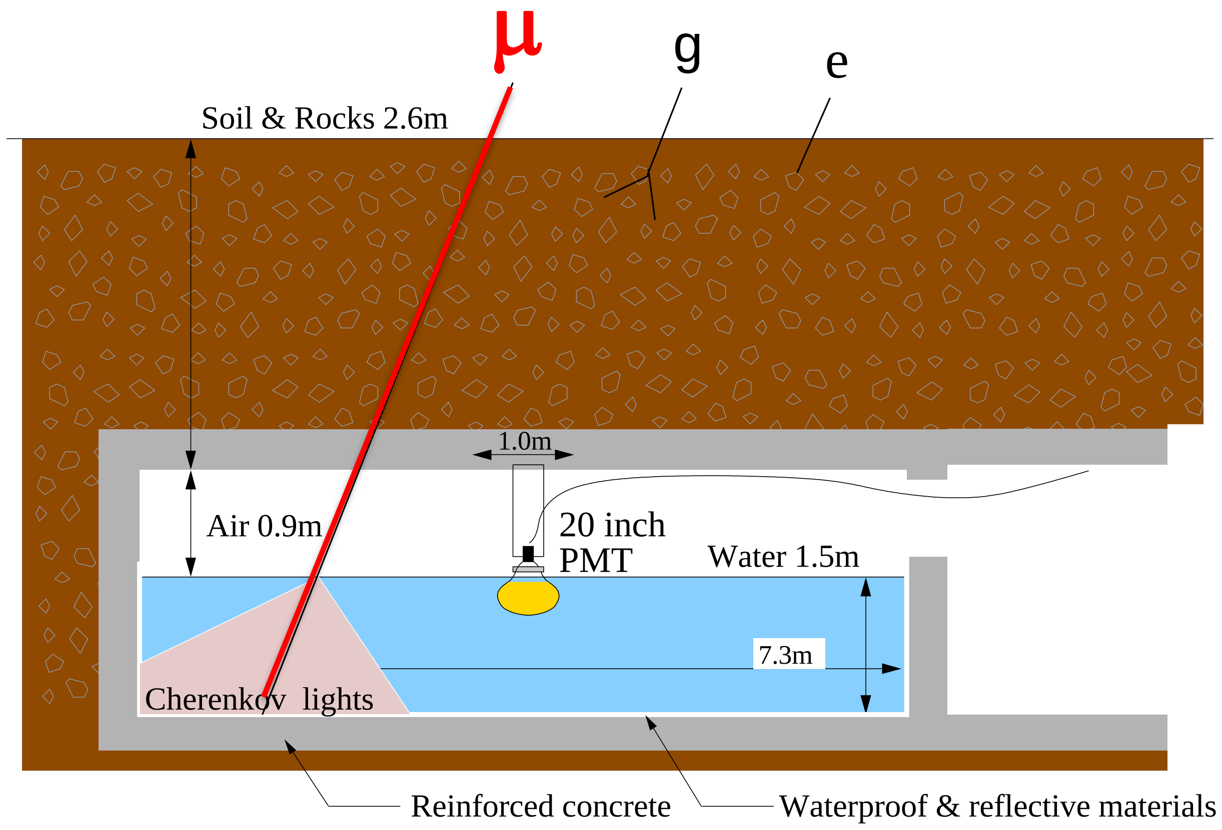
# of detectors	0.5 m^2 x 597
Effective area	~65,700 m^2
Angular resolution	~0.5° @10TeV
	~0.2° @100TeV
Energy resolution	~40%@10TeV γ
	~20%@100TeV γ

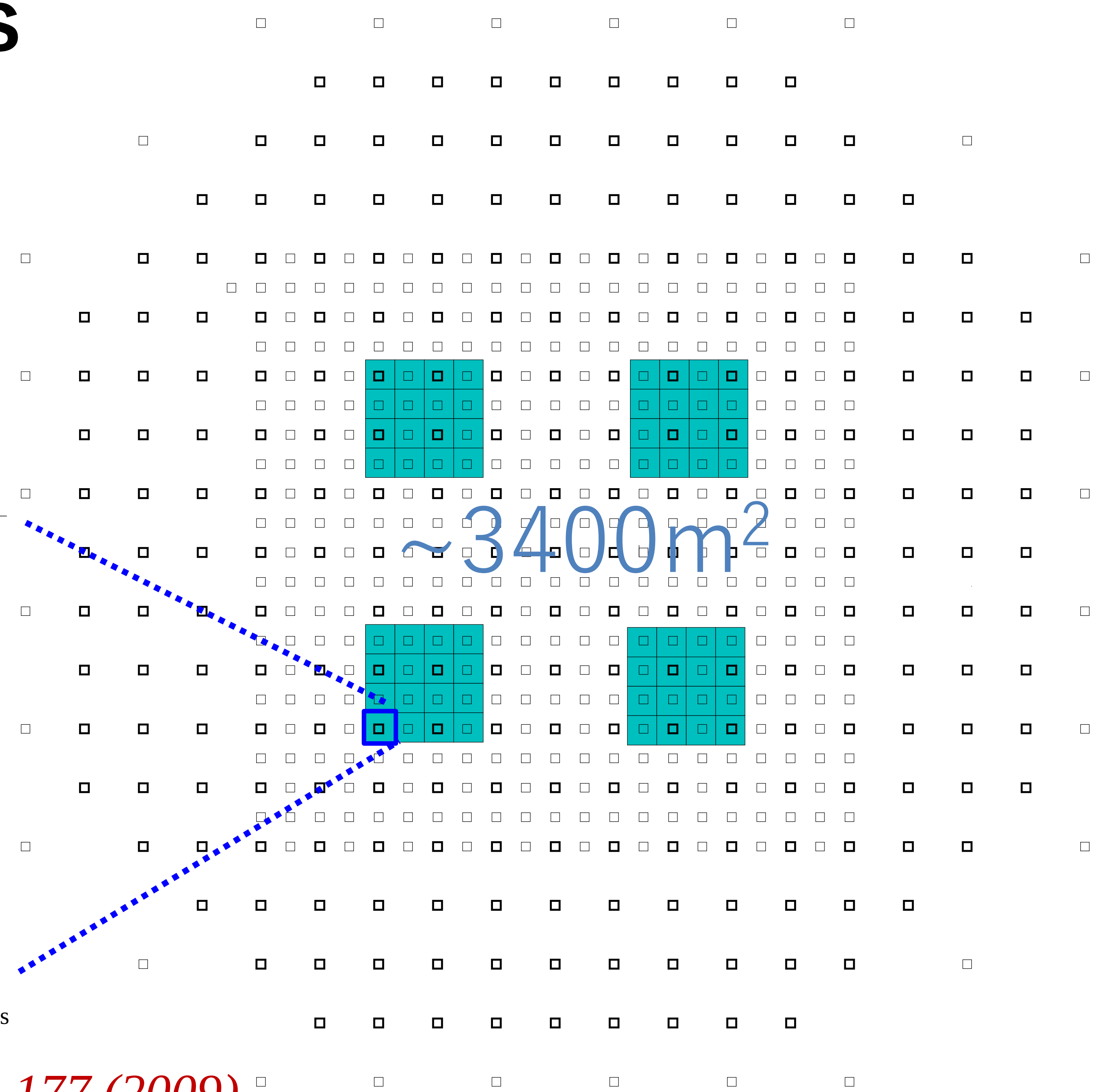
→Observation of secondary (mainly e$^{+/-}$, γ) in AS
Primary energy : 2nd particle densities
Primary direction : 2nd relative timings



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





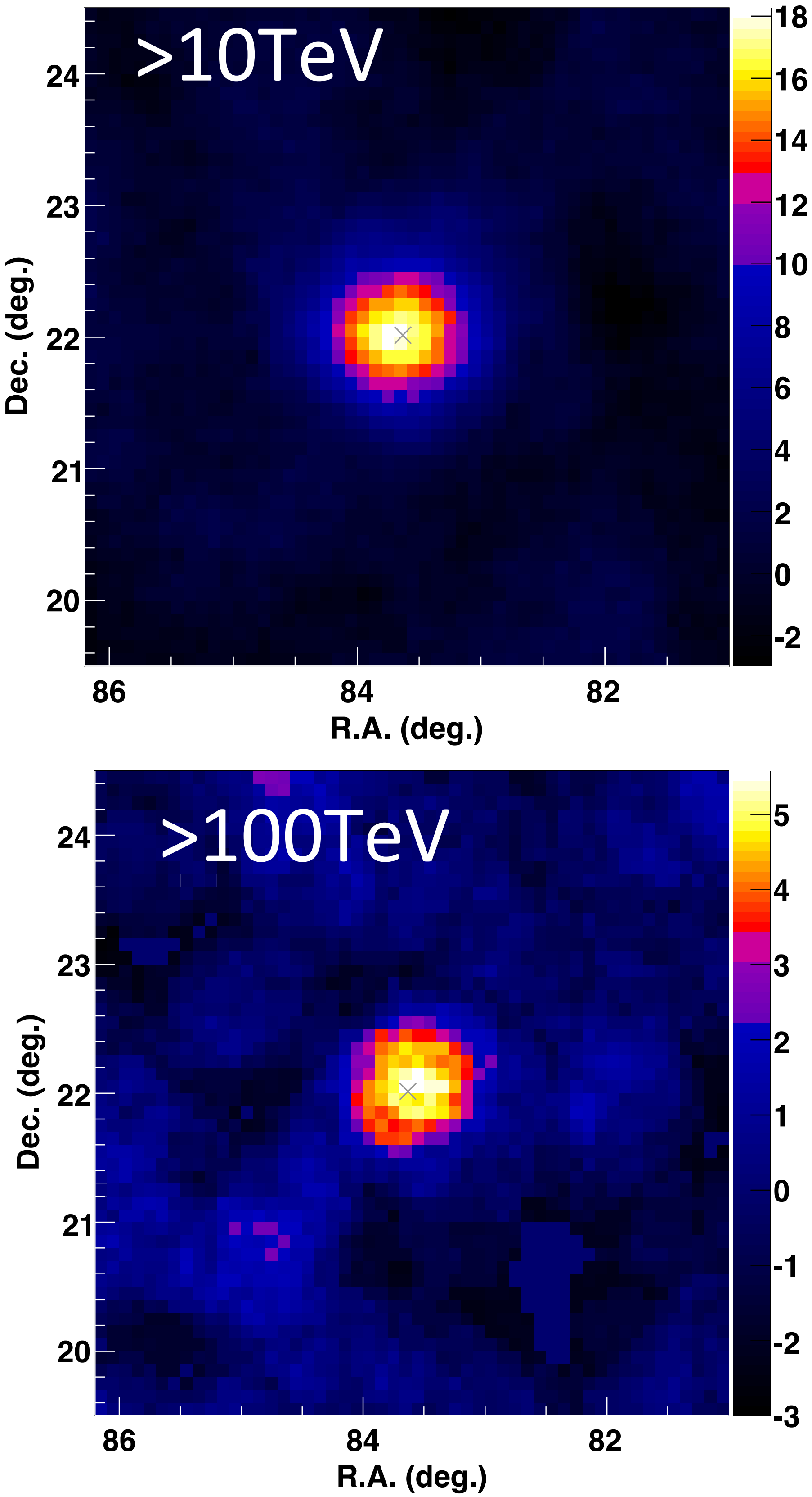
Basic idea: T. K. Sako+, Astropart. Phys. 32, 177 (2009)

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

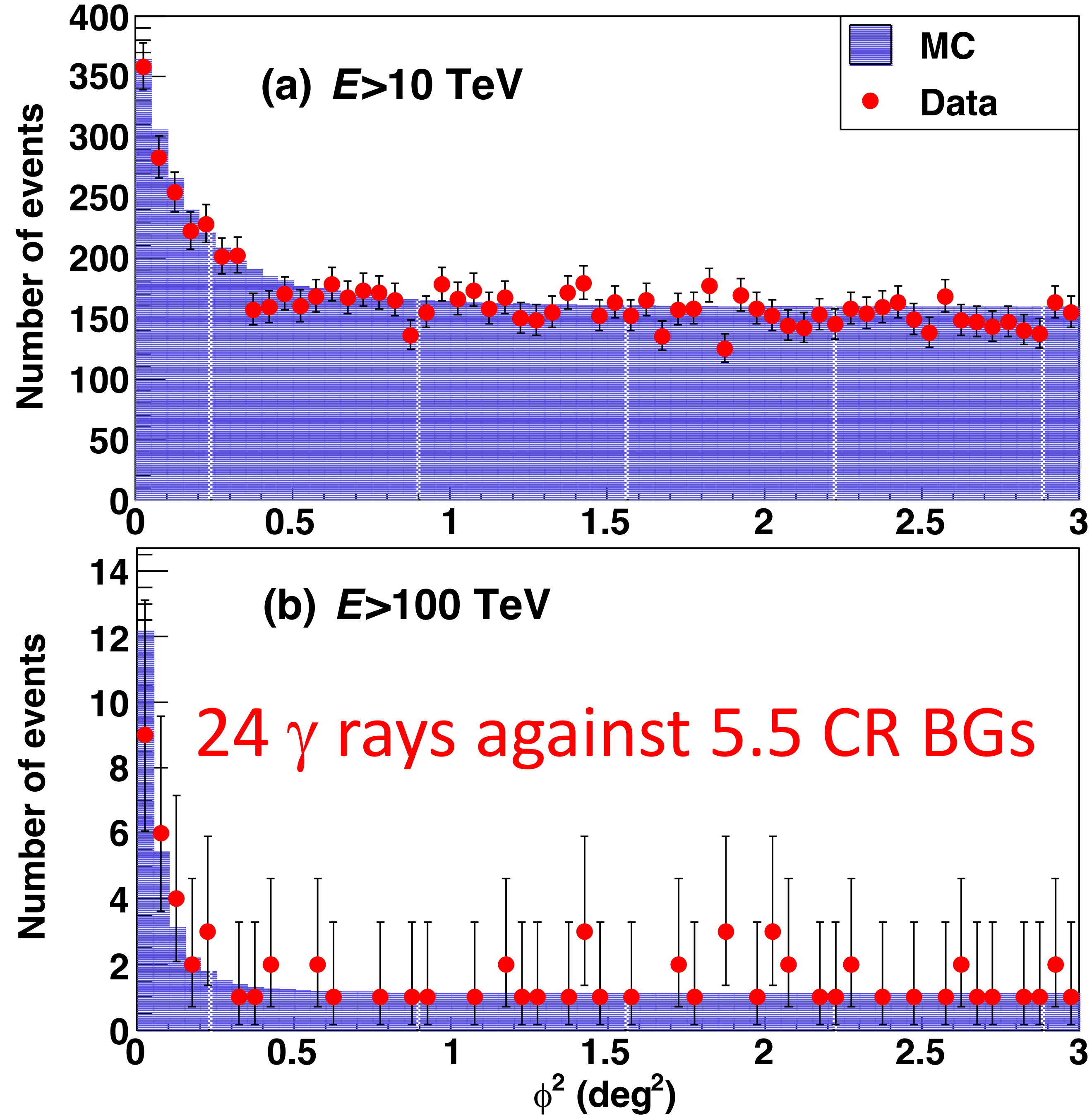
DATA: February, 2014 - May, 2017 Live time: 719 days

§ First detection of UHE (>100 TeV) γ rays

Gamma-ray Emission from Crab



Data vs MC



First detection of sub-PeV γ (5.6σ)

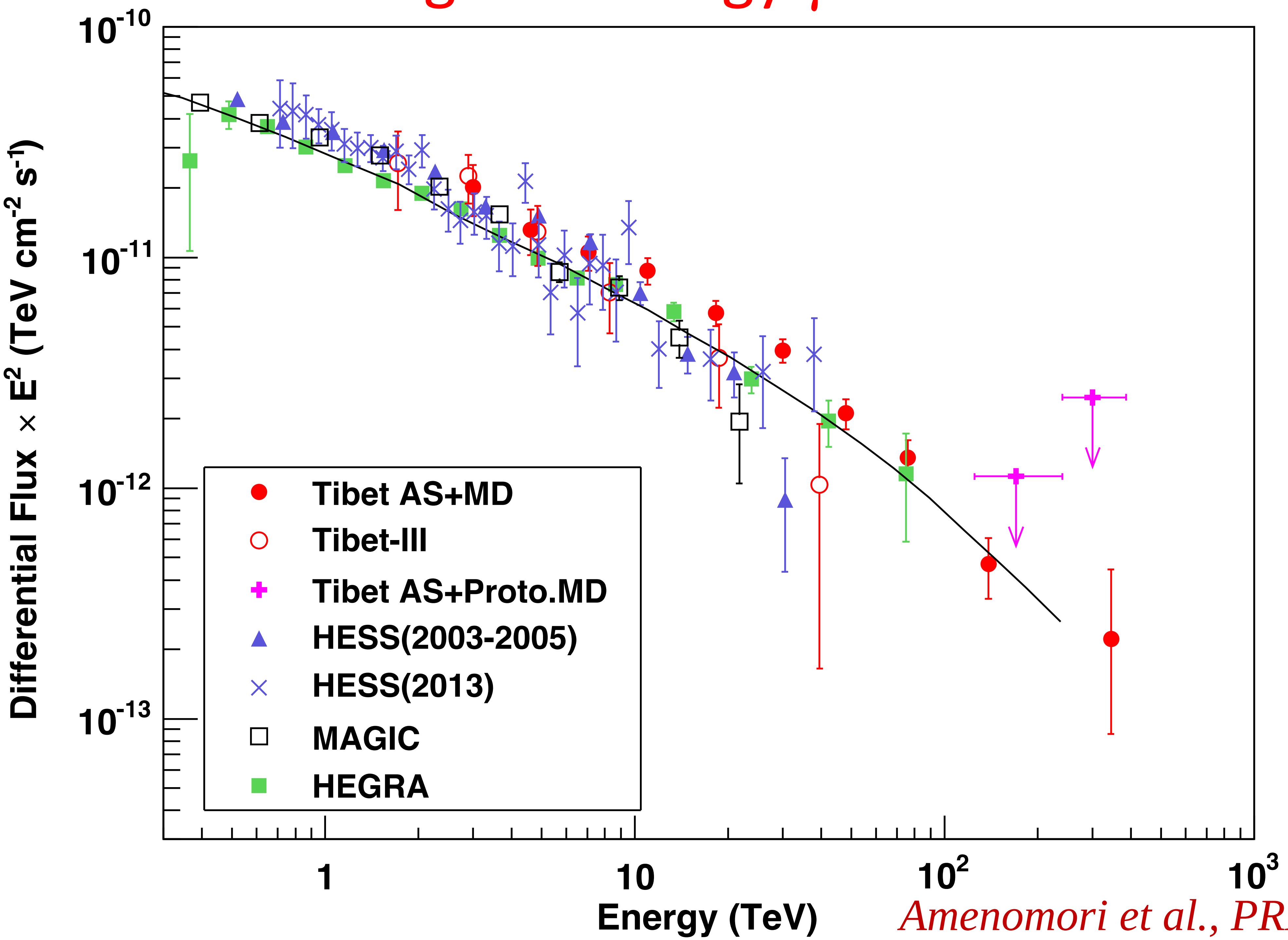
UHE γ-ray astronomy started!

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

Energy spectrum (Crab)

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

The highest energy γ ~450 TeV



Amenomori et al., PRL (2019)

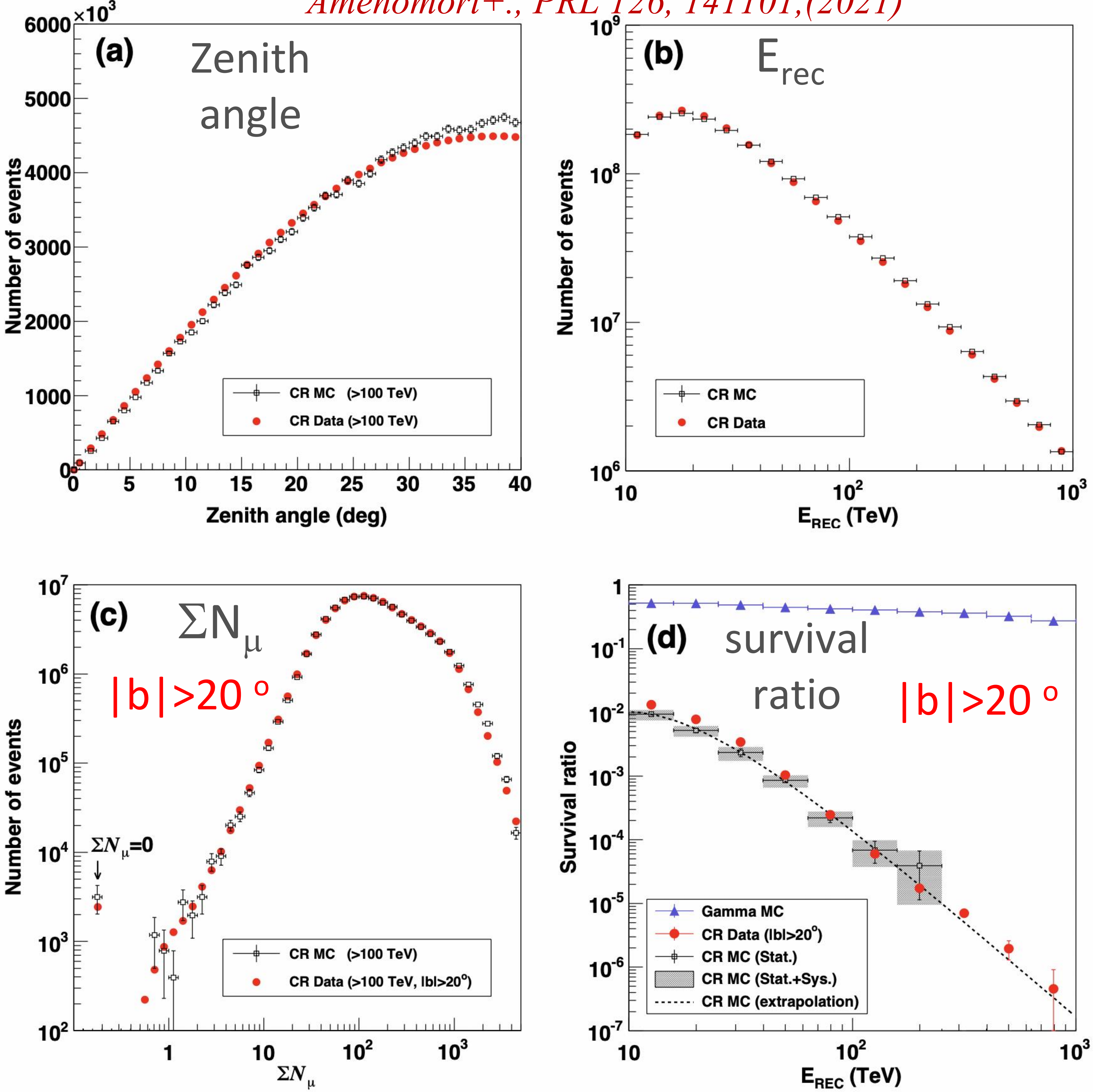
Thick curve： the expected flux by the inverse Compton model normalized to HEGRA data *Aharonian+, ApJ, 614, 897 (2004)*

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

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

CR MC vs. DATA

Reasonable agreement!



$O(10^{-6})$
>0.398 PeV

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

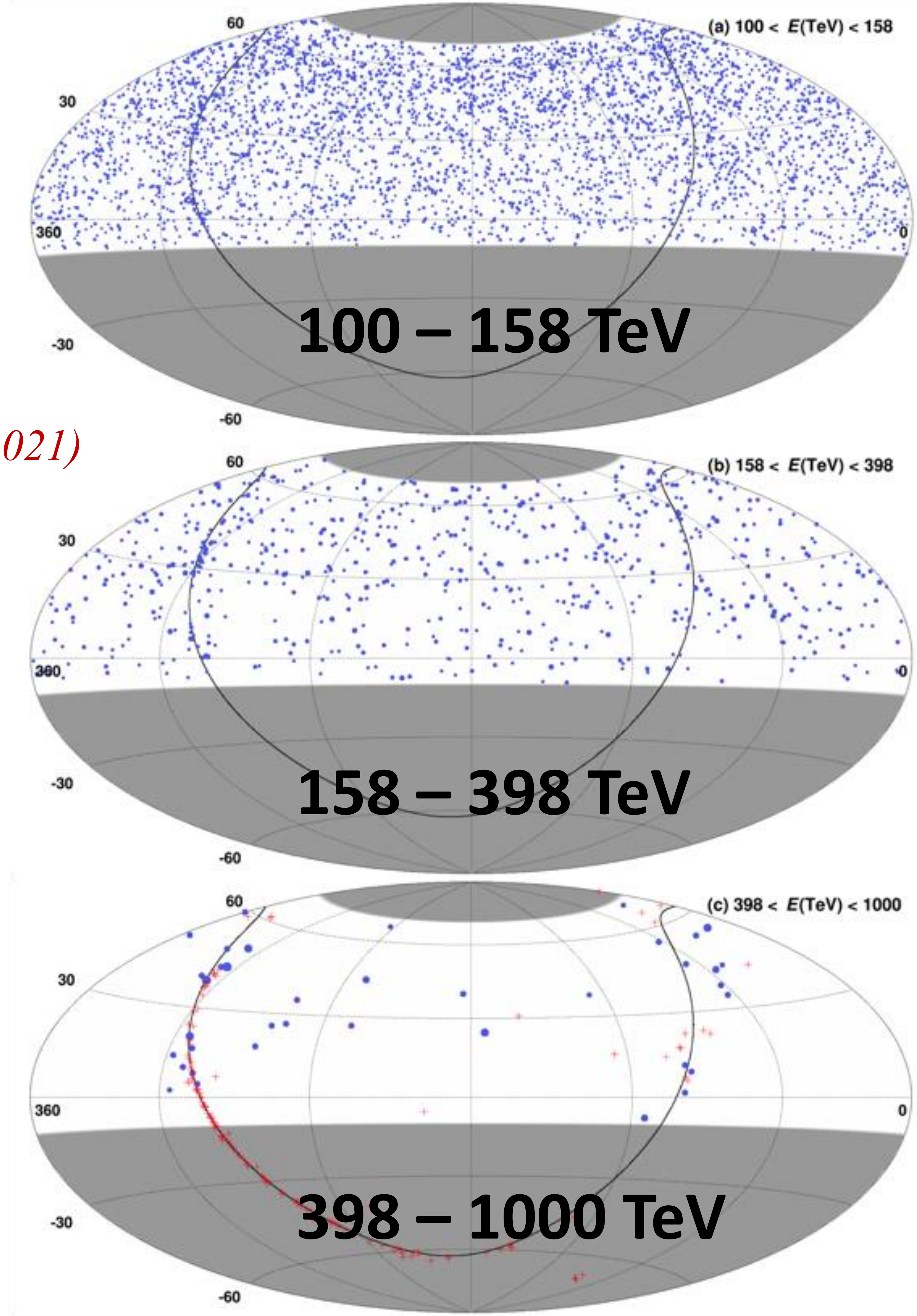
Amenomori+., PRL 126, 141101,(2021)

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

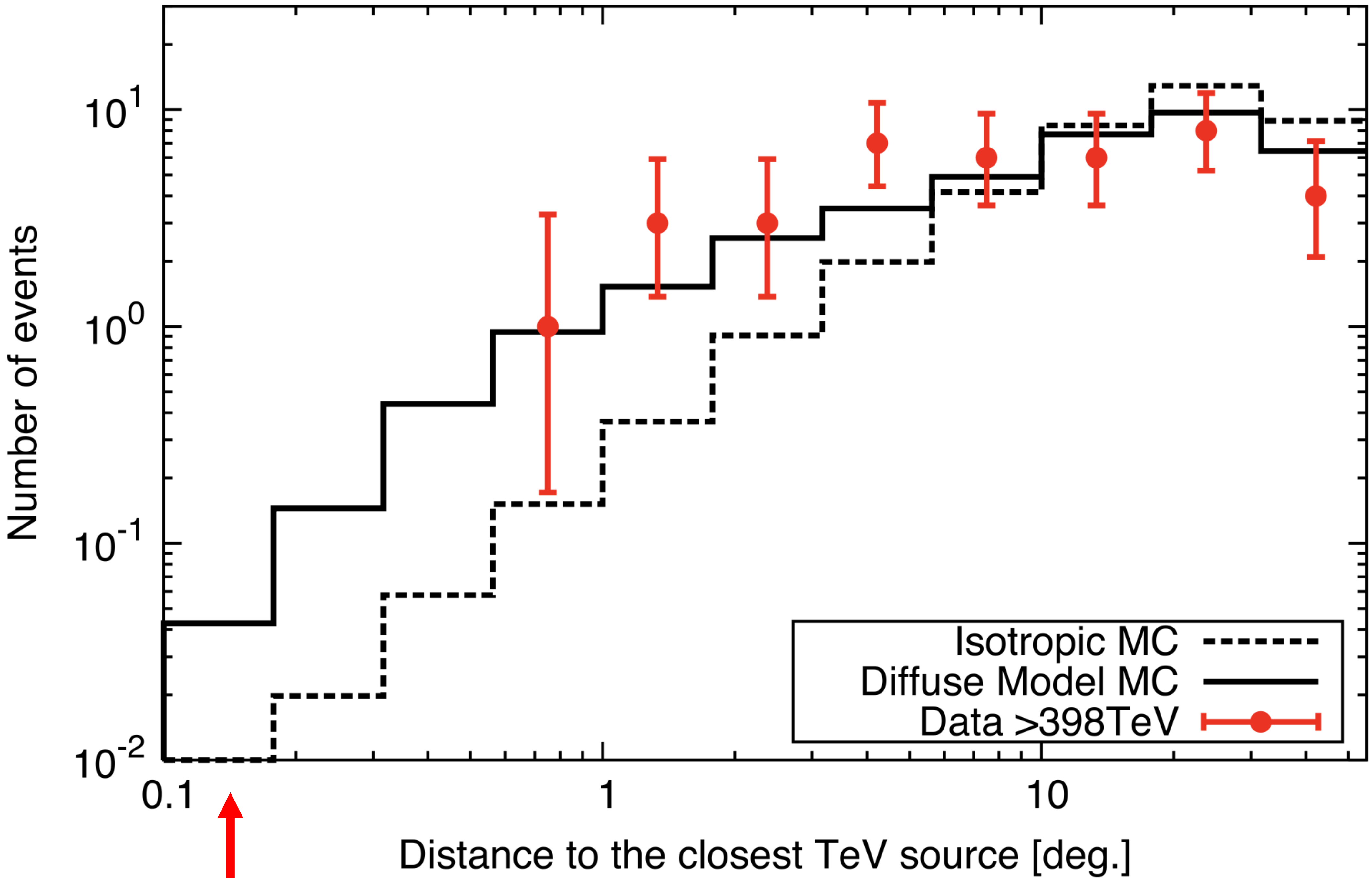
→Not from known TeV sources!
& No signal > 10 TeV around them



Equatorial coordinates

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

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



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 $22^\circ < l < 225^\circ$). 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

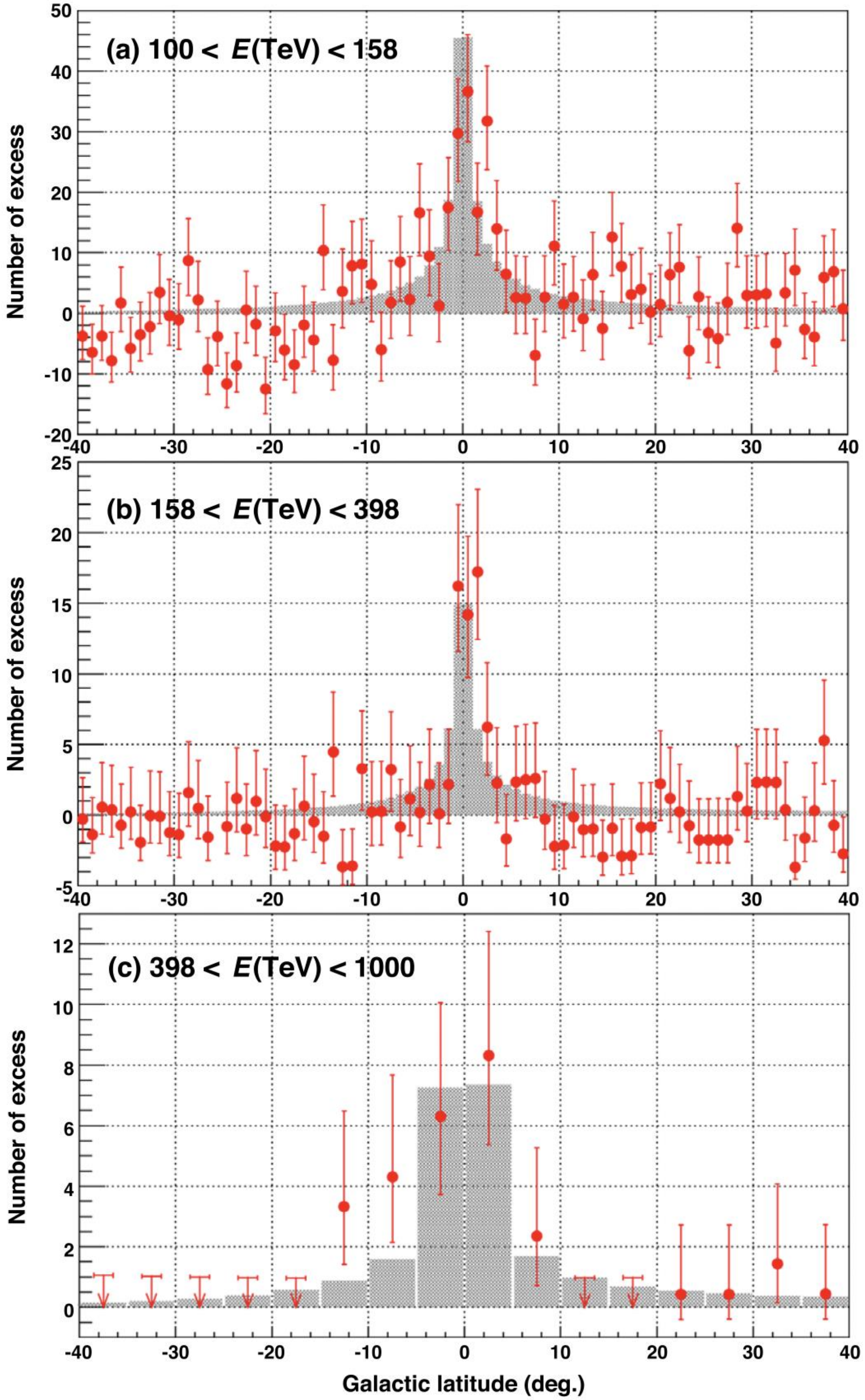
TABLE S2. Galactic diffuse gamma-ray fluxes measured by the Tibet AS+MD array.

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	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

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

Galactic latitude distributions

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



# of ev

# of ev

# of ev

-40º 0 40º

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

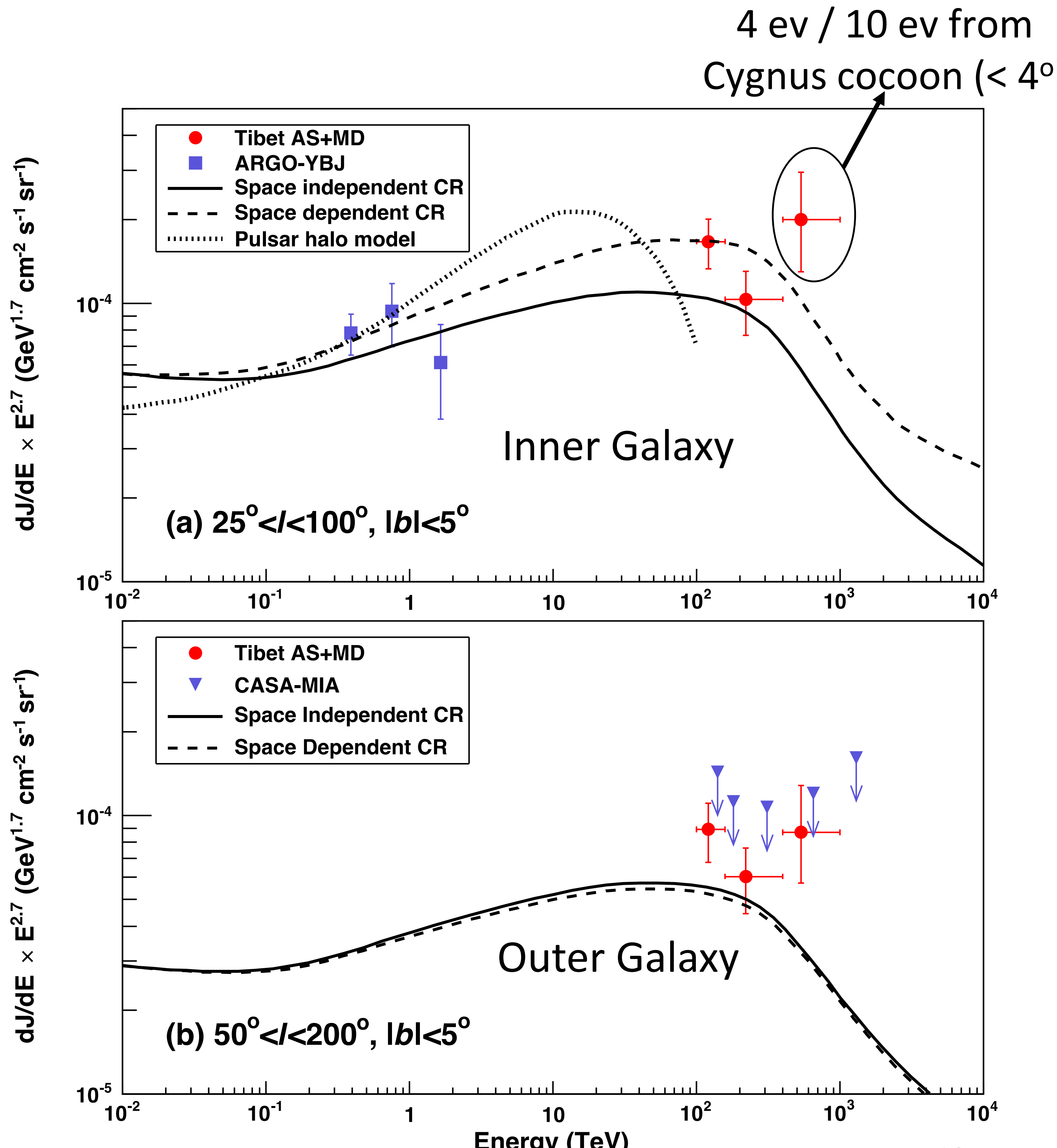
Model: Lipari & Vernetto, PRD 98, 143003, (2018)

Energy Spectrum (Fig.4)

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

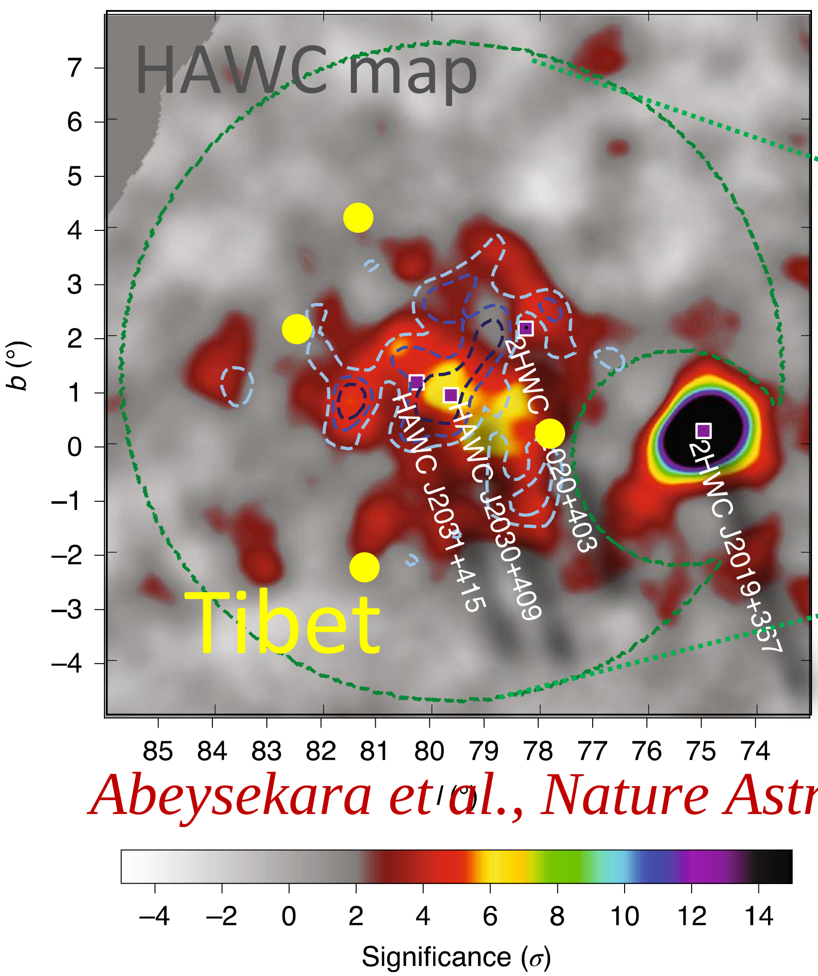
After excluding the contribution from the known TeV sources (within 0.5° in radius) listed in the TeV source catalog
(~13% to the diffuse flux, but no contamination to events > 0.398 PeV)

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

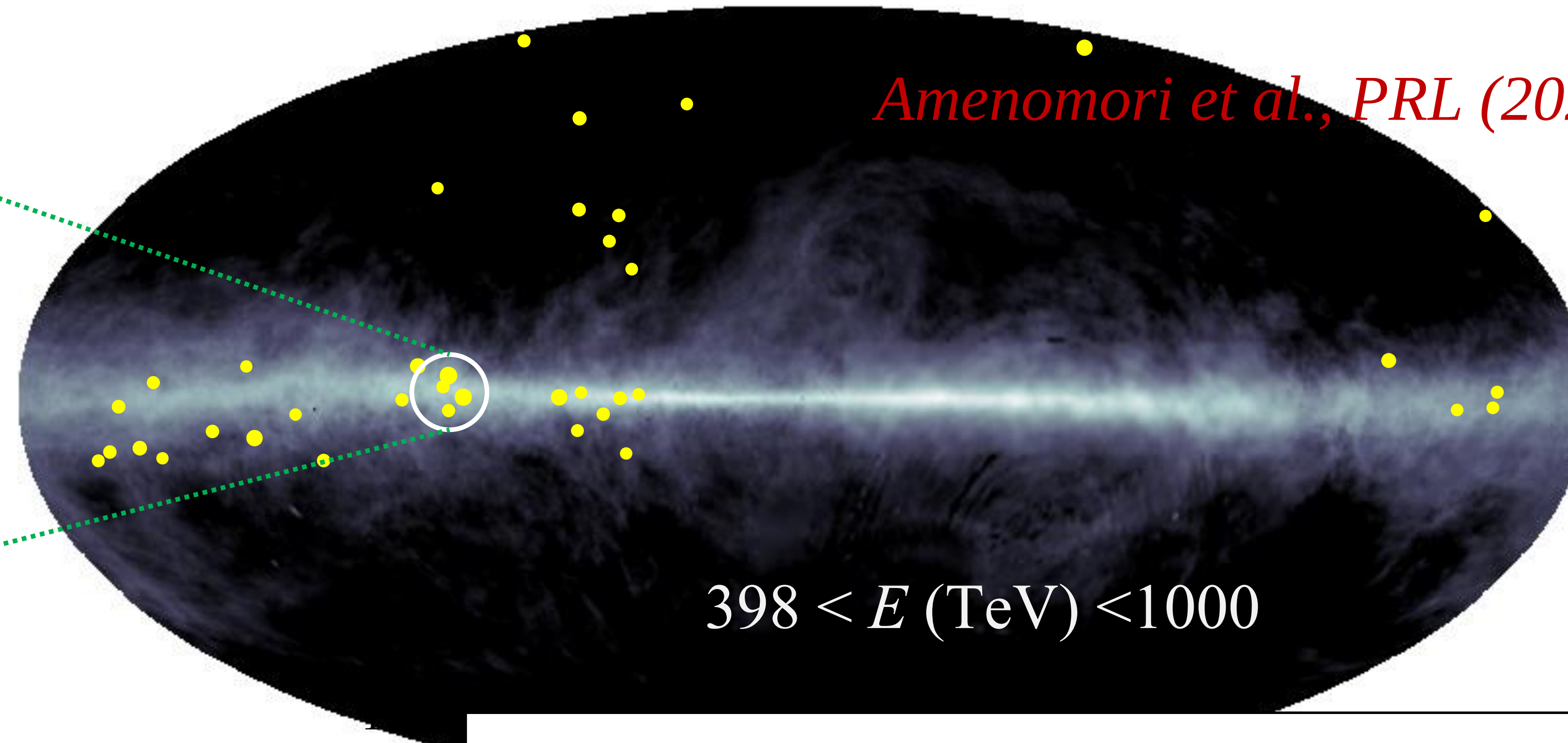


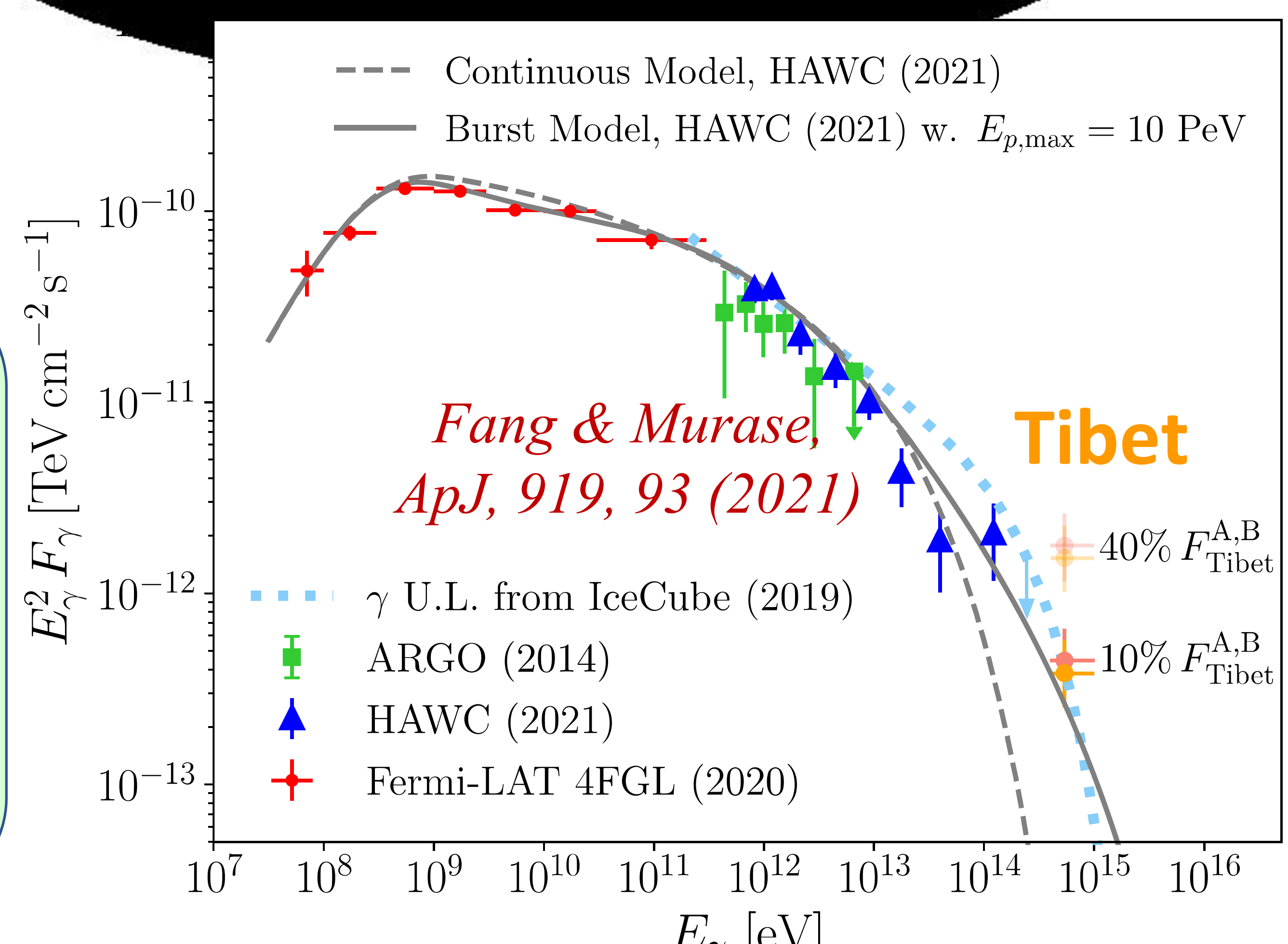
Amenomori+., PRL 126, 141101,(2021)

Cygnus Cocoon Region



We found 4 events in the circle with radius 4º



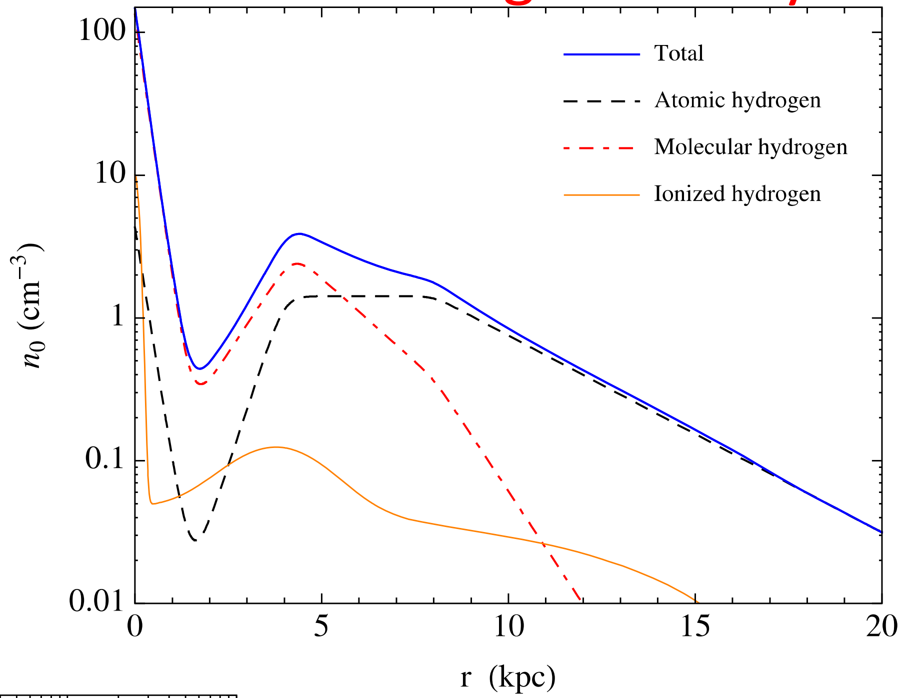


- ✓ Star forming region (Cyg. OB2)
- ✓ π^0 decay model (π^0 shoulder)
- ✓ Spectral softening >10 TeV
  →CRs escape from the source a long time ago?
- ✓ Spectrum extends up to PeV?

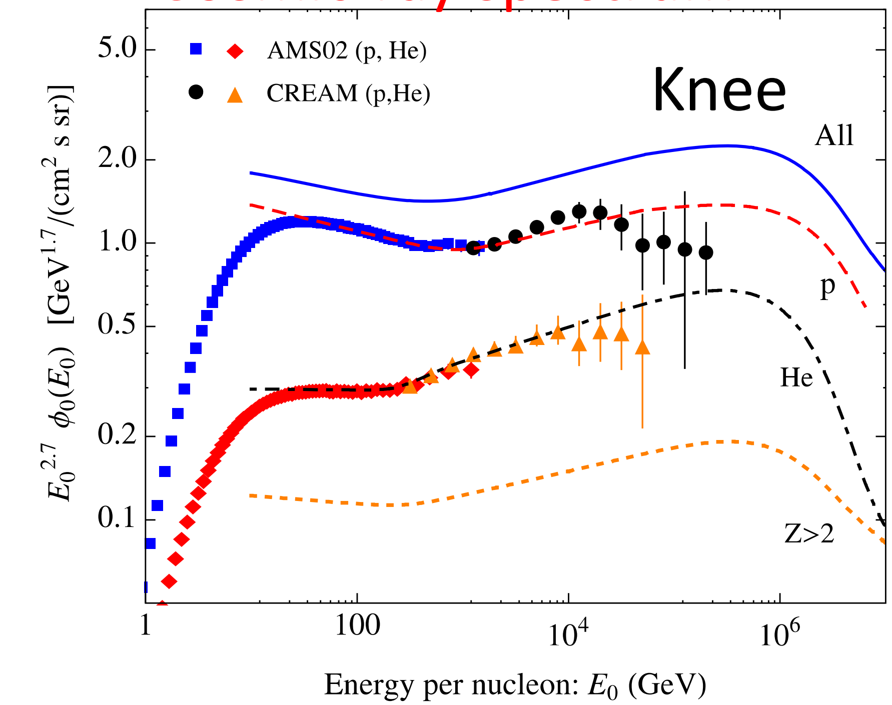
Diffuse γ-ray Model

Lipari & Vernetto, PRD (2018)

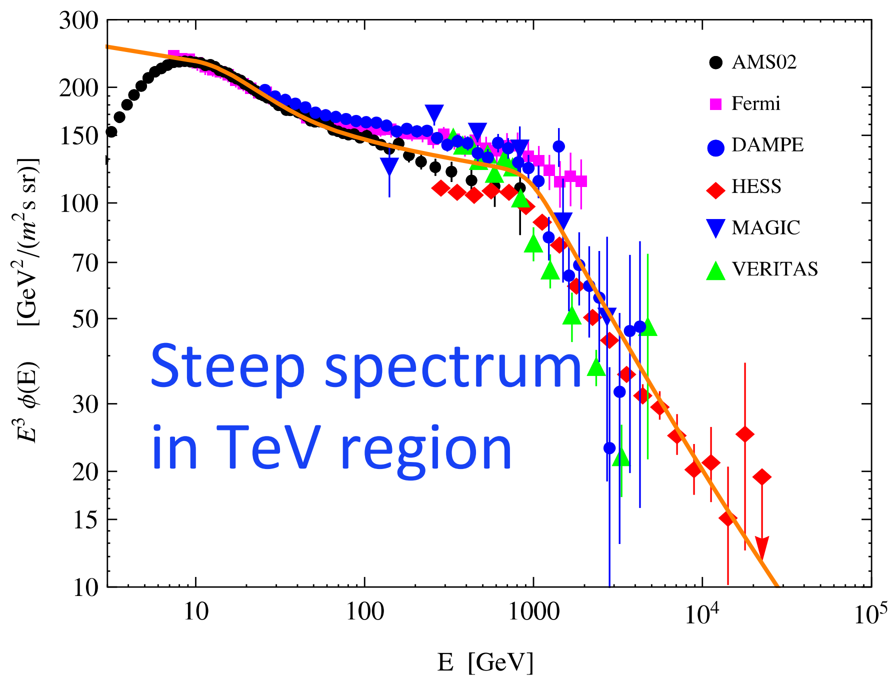
Interstellar gas density

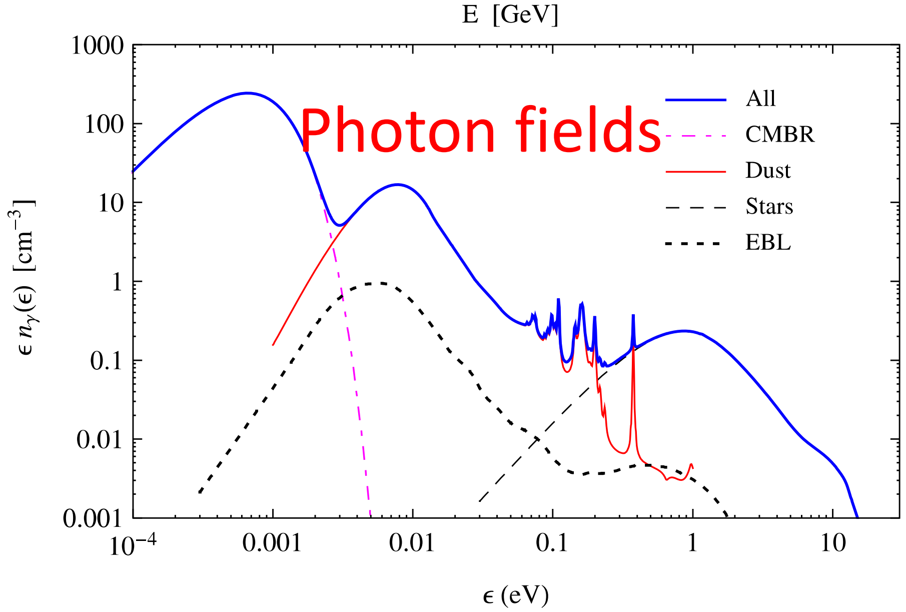


Cosmic-ray spectrum



Electron/Positron

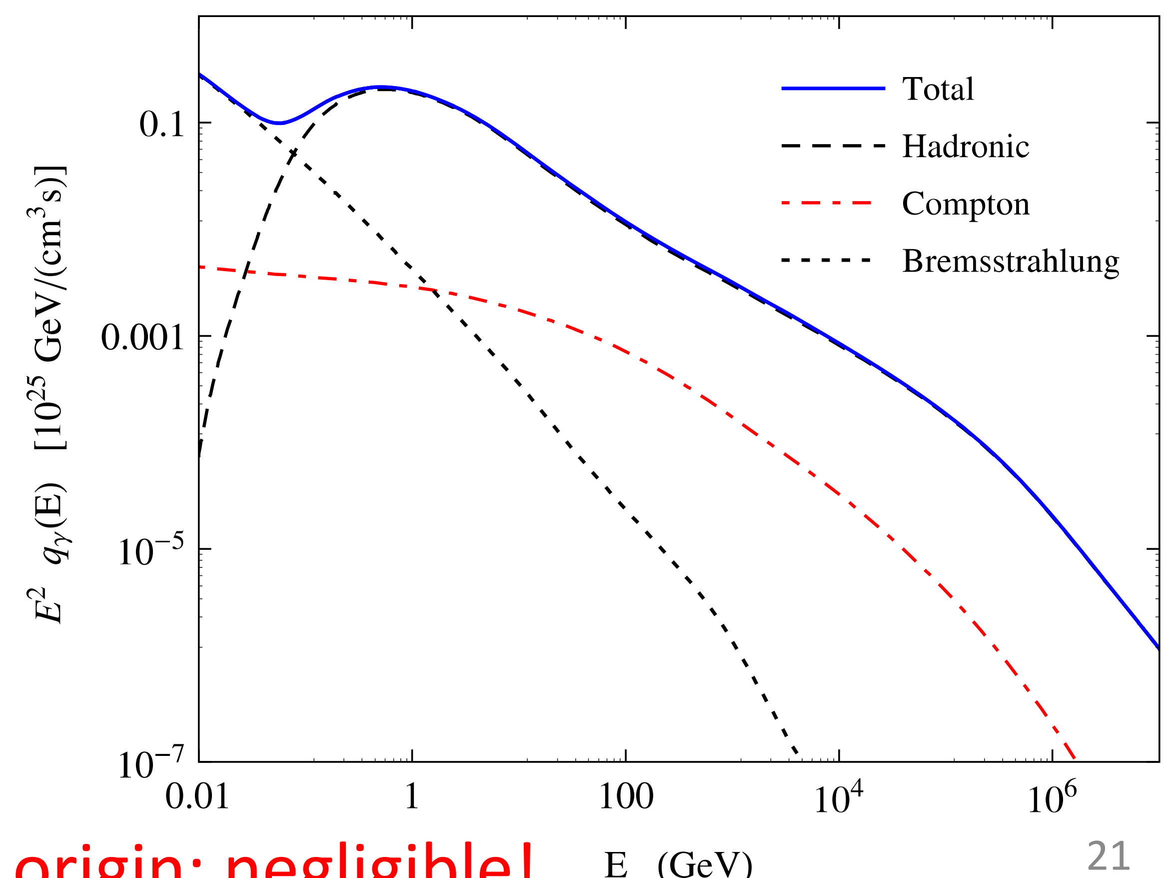




Bremss.

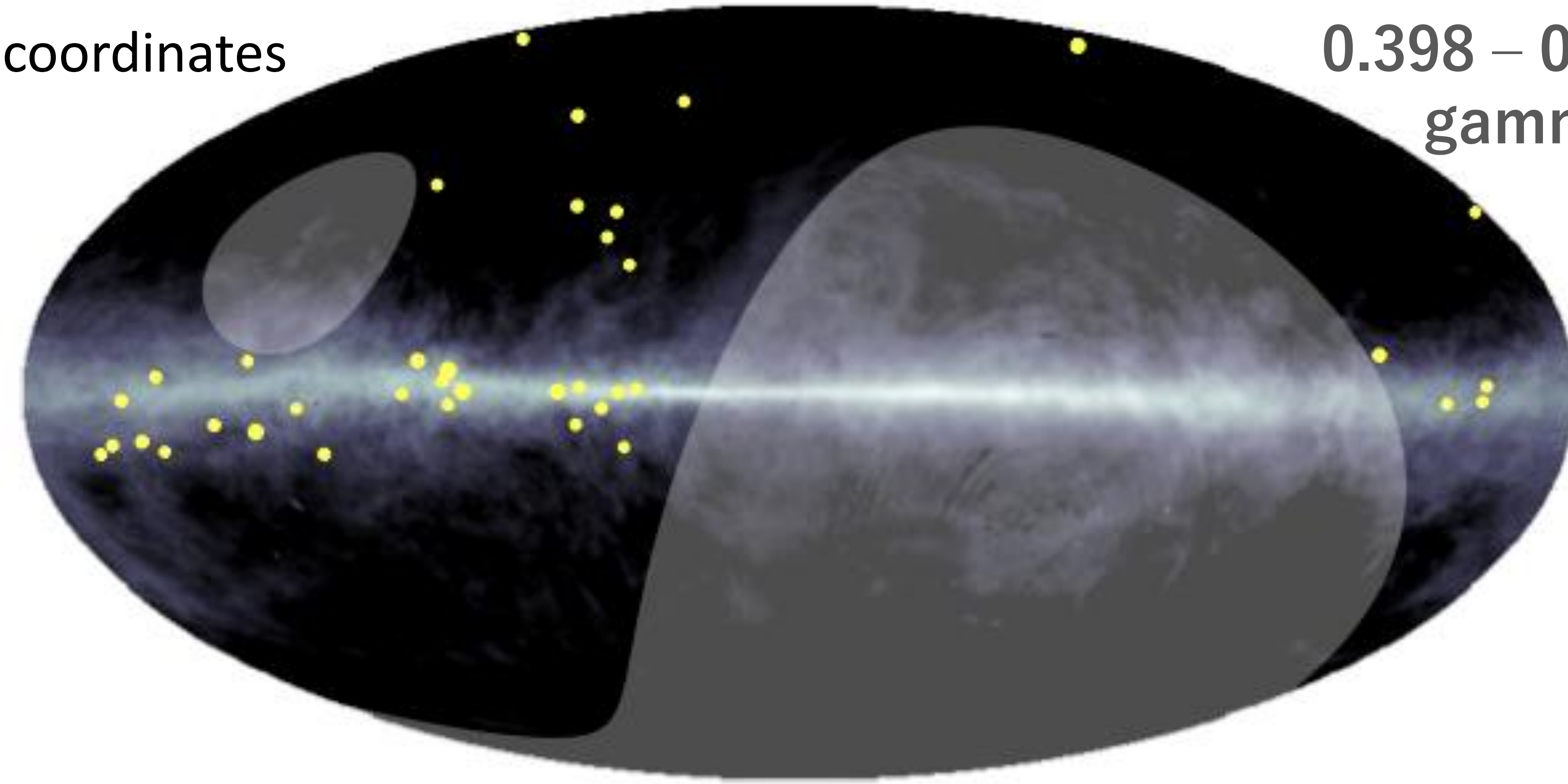
Hadronic

IC



Diffuse e origin: negligible!

Electron origin? vs Proton origin?

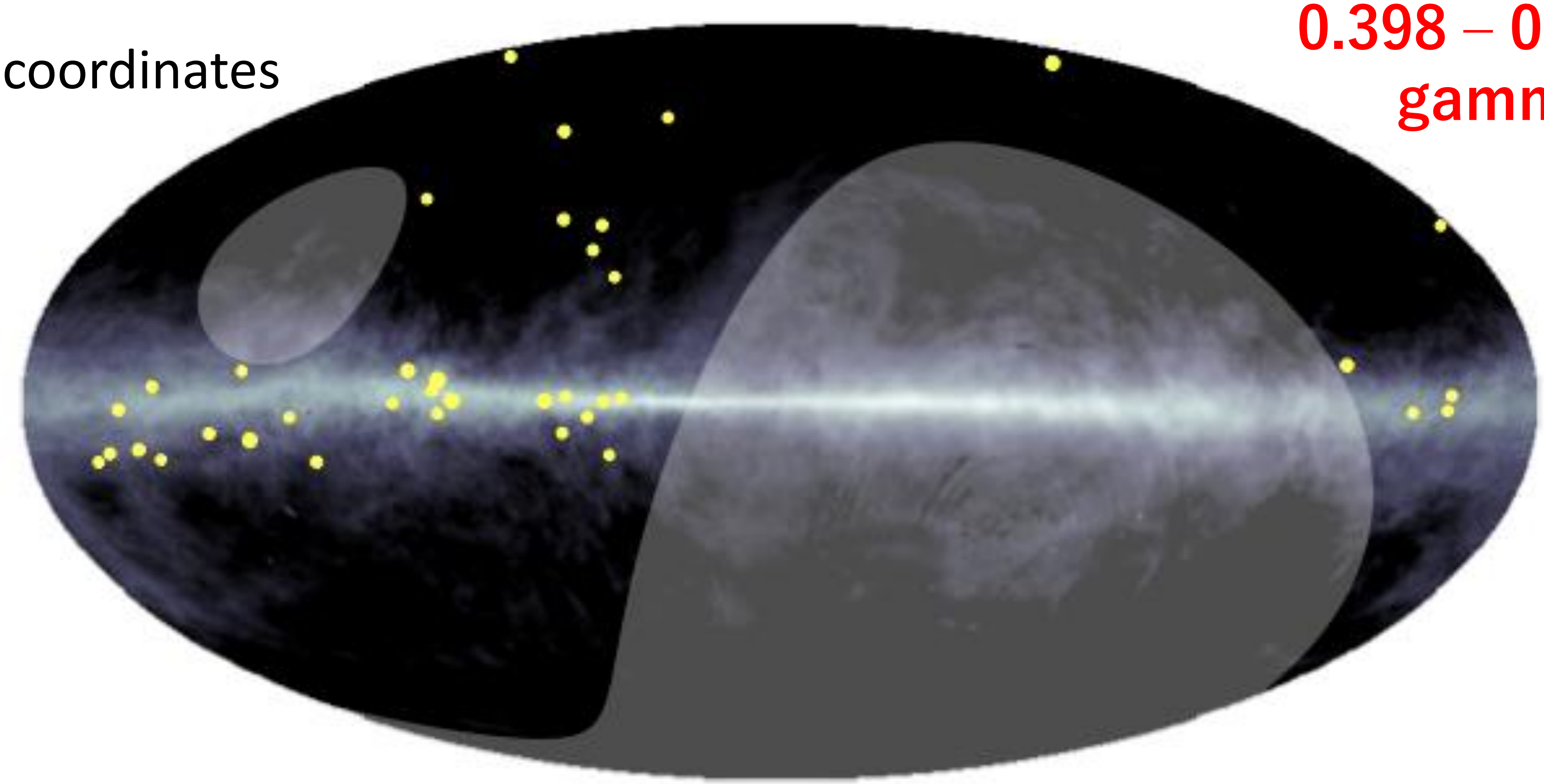


✓ Gamma rays are coming isolated from known gamma-ray sources.
→ **Electrons** lose their energy quickly, so they **should stay near the object**.
→ **Protons** don't lose energy and **can escape farther from the object**.

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

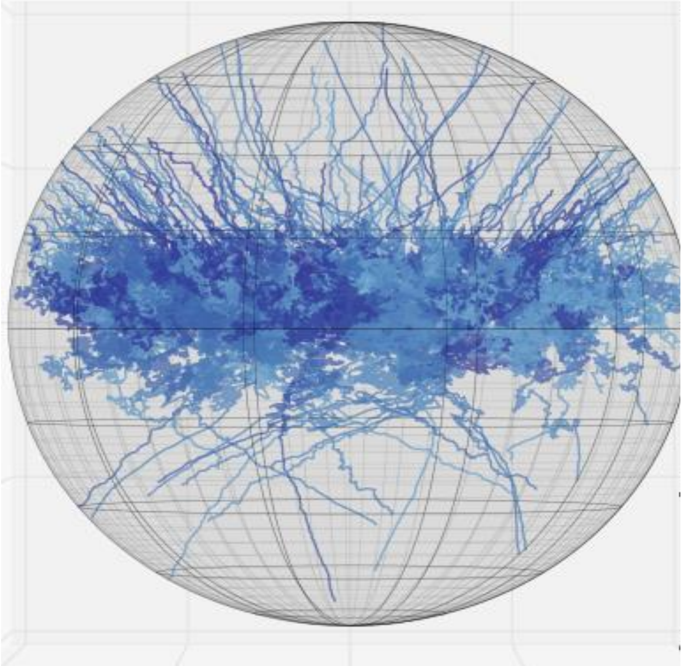
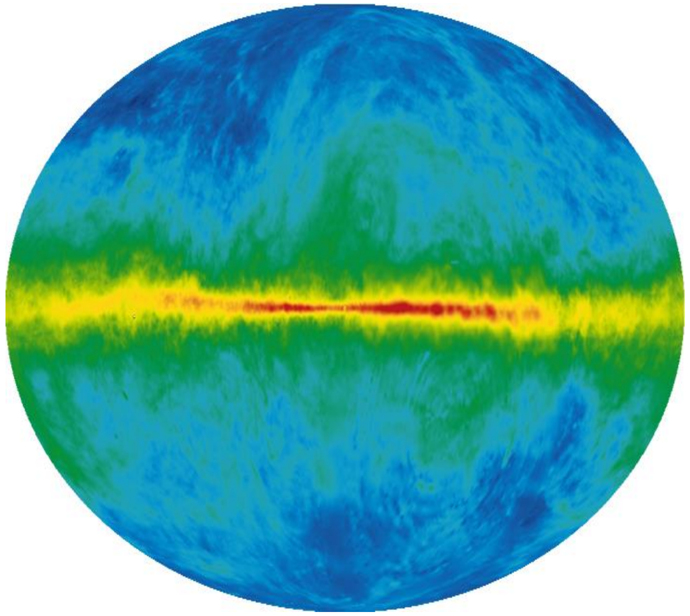


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop

+

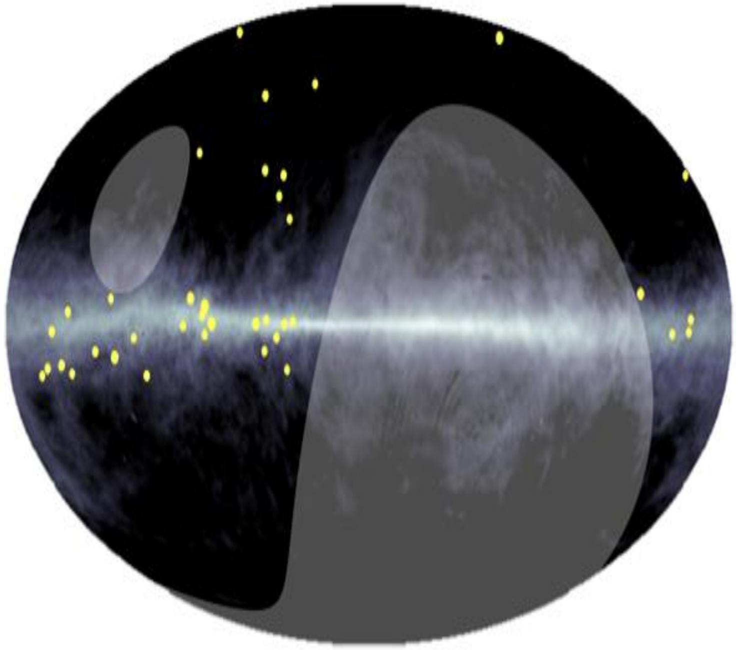
Interstellar matter



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

=

High-energy gamma rays

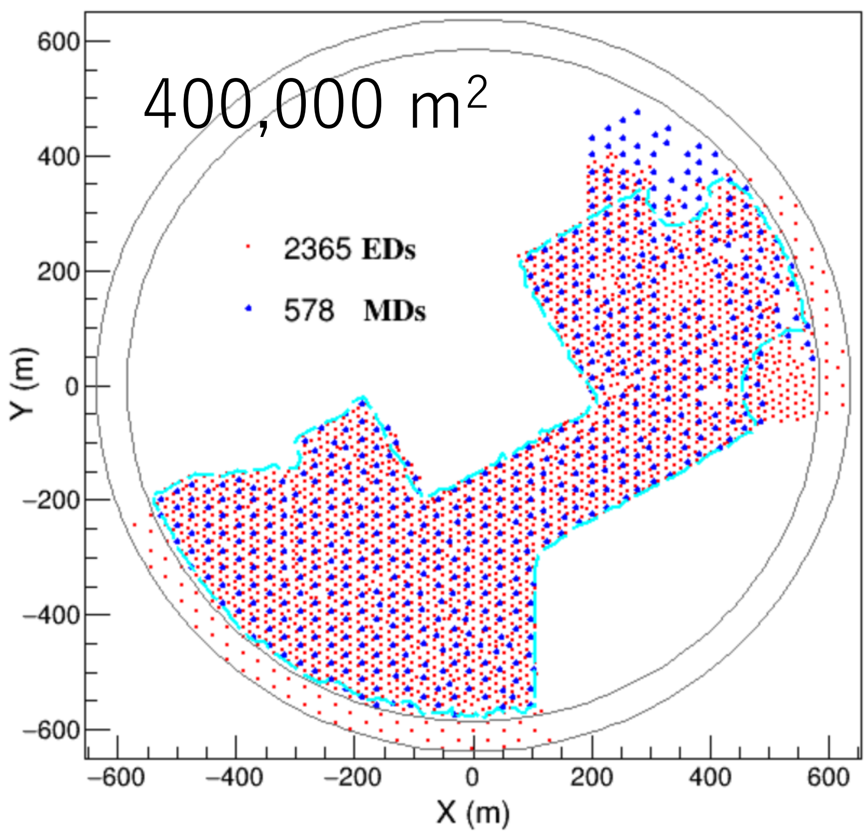


This Work

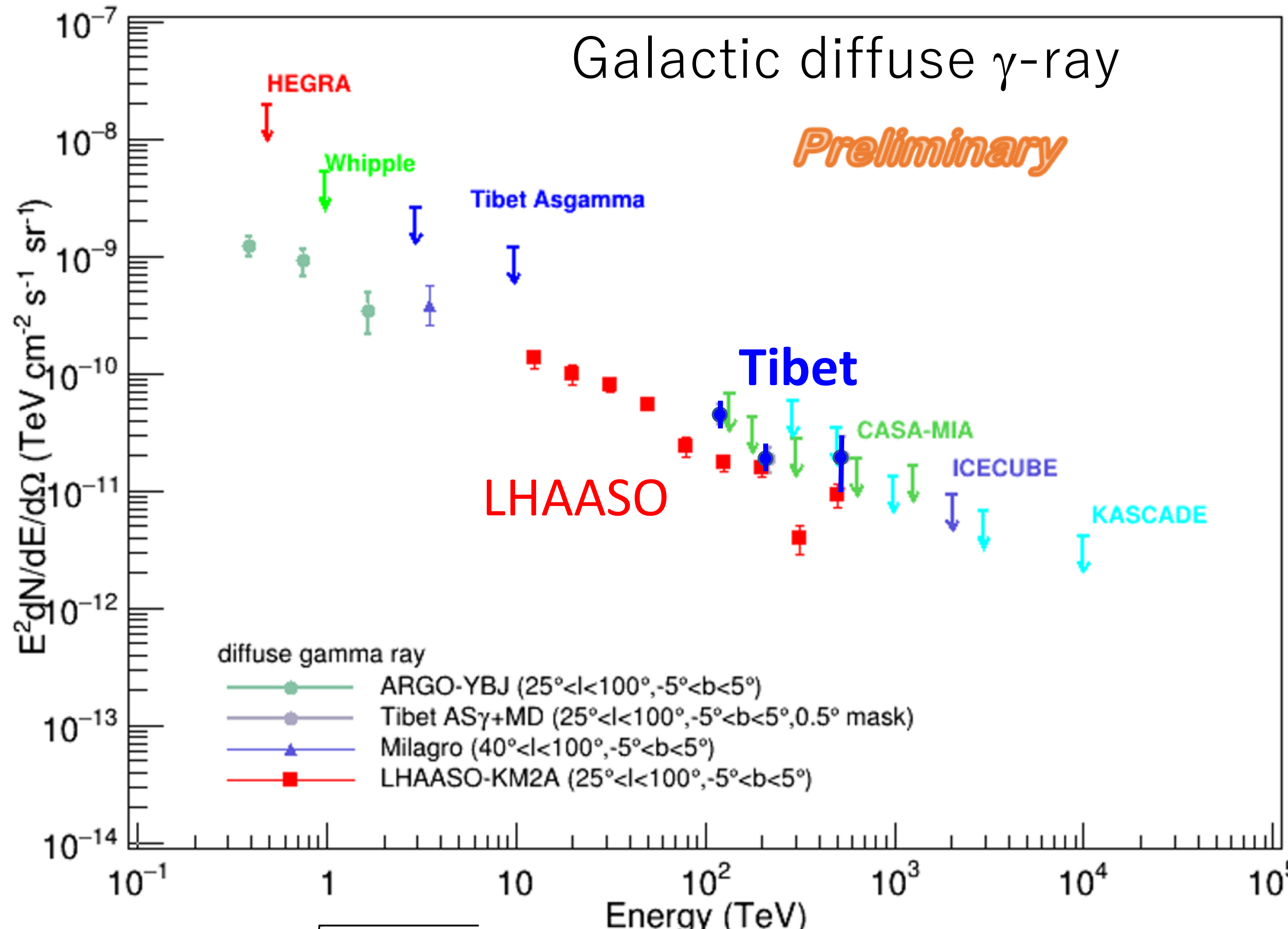
✓ This work proves a theoretical model that cosmic rays produced by PeVatrons are trapped in the Galactic magnetic field for a long time forming a pool of cosmic rays.

LHAASO Experiment (ICRC2021)

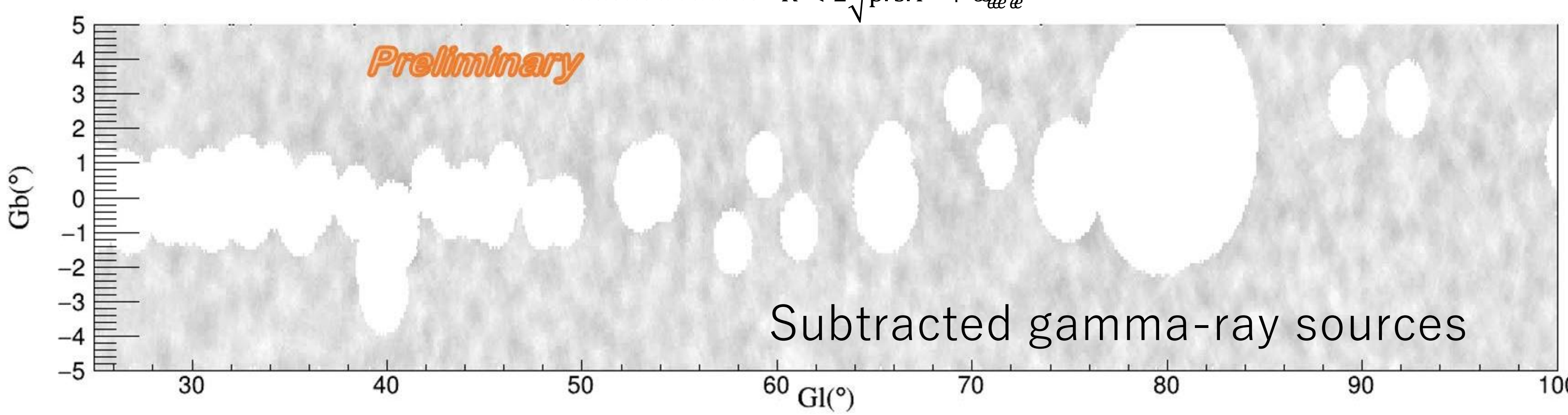
S. P. Zhao ICRC2021



KM2A(1/2 Array) Detectors Distribution
Data: 2019/12/27 ~ 2020/11/30



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

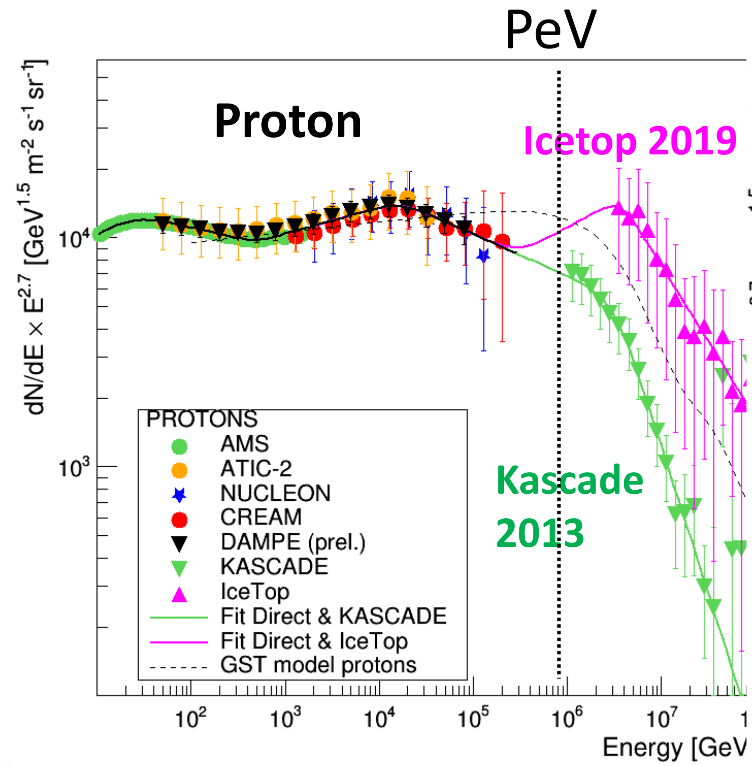


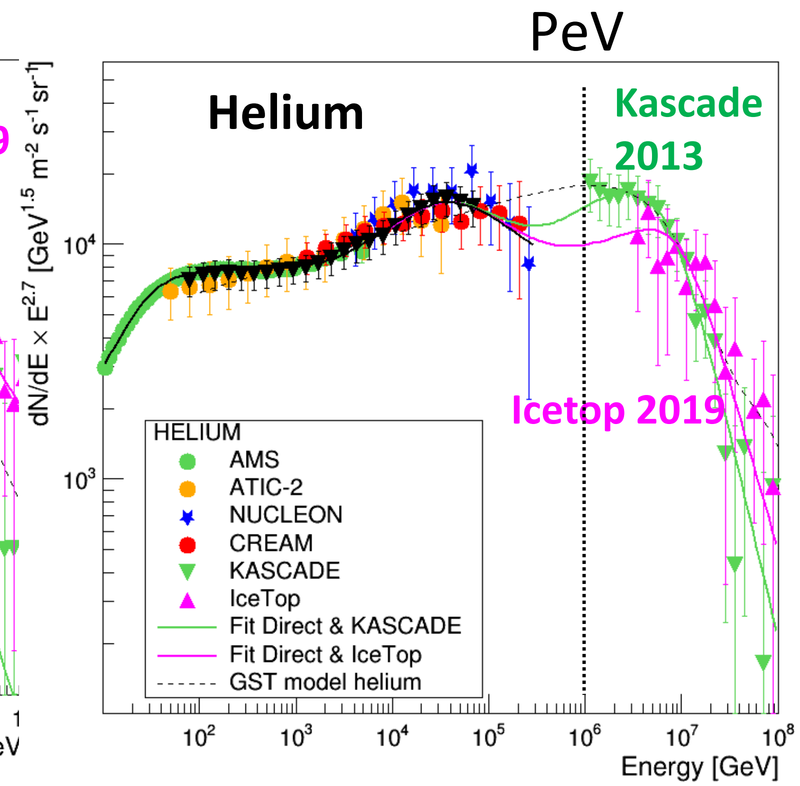
Composition Dependence (ICRC2021)

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

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

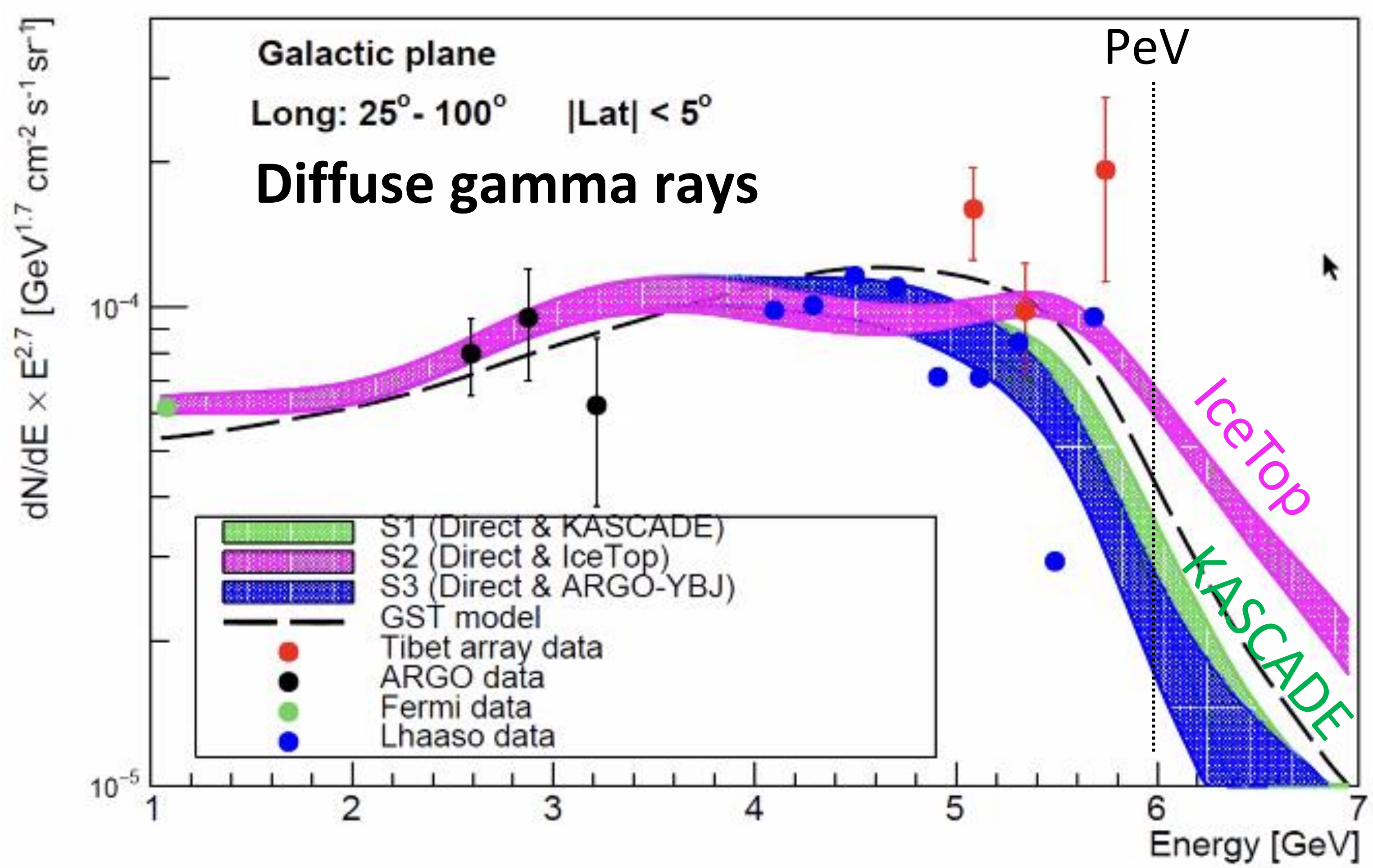
→ Diffuse gamma-ray spectrum depends on the CR composition





Vernetto & Lipari (ICRC2021)

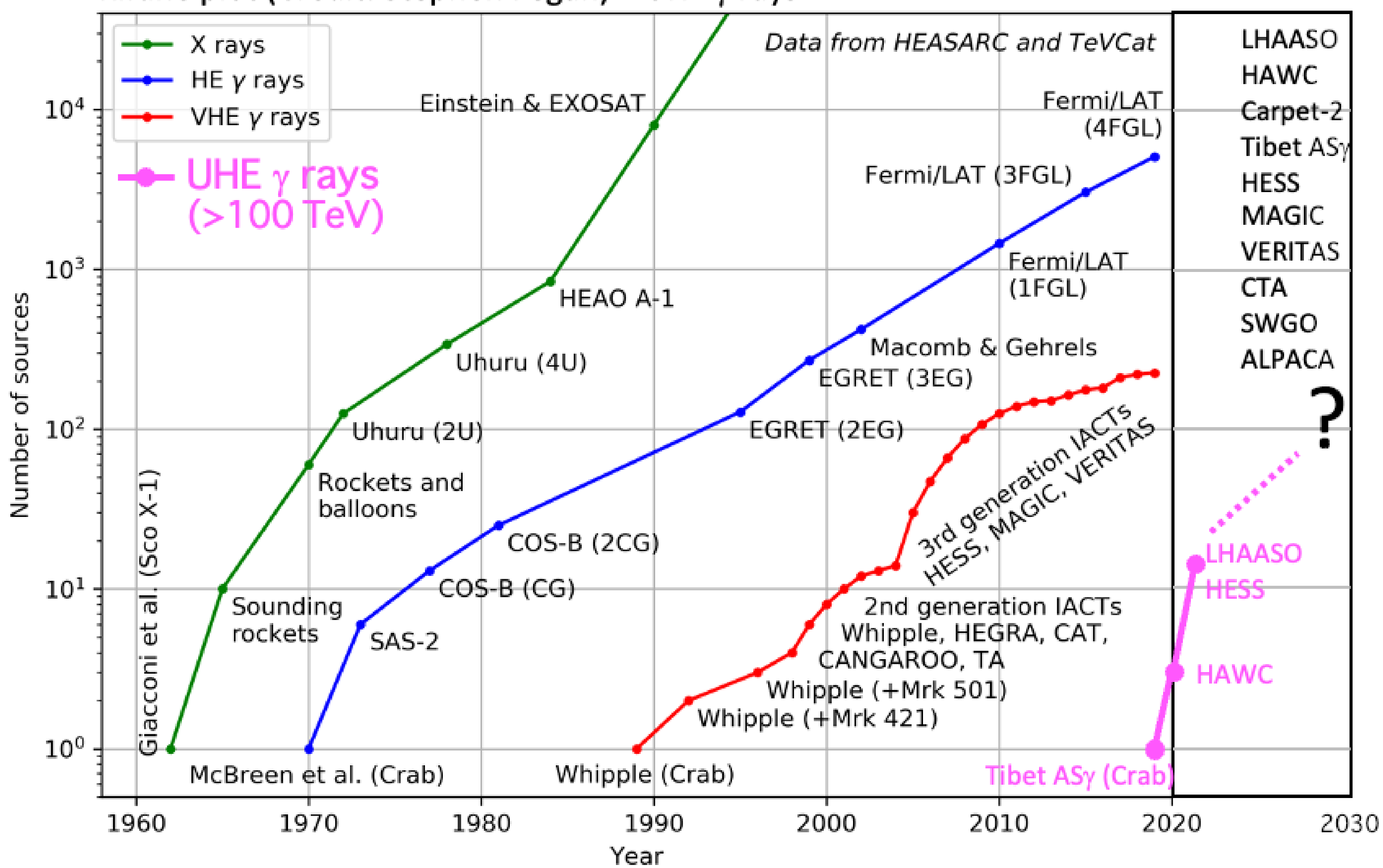
factor 1.5 – 2 difference
@ ~600 TeV



§ Future Prospect & Summary

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

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

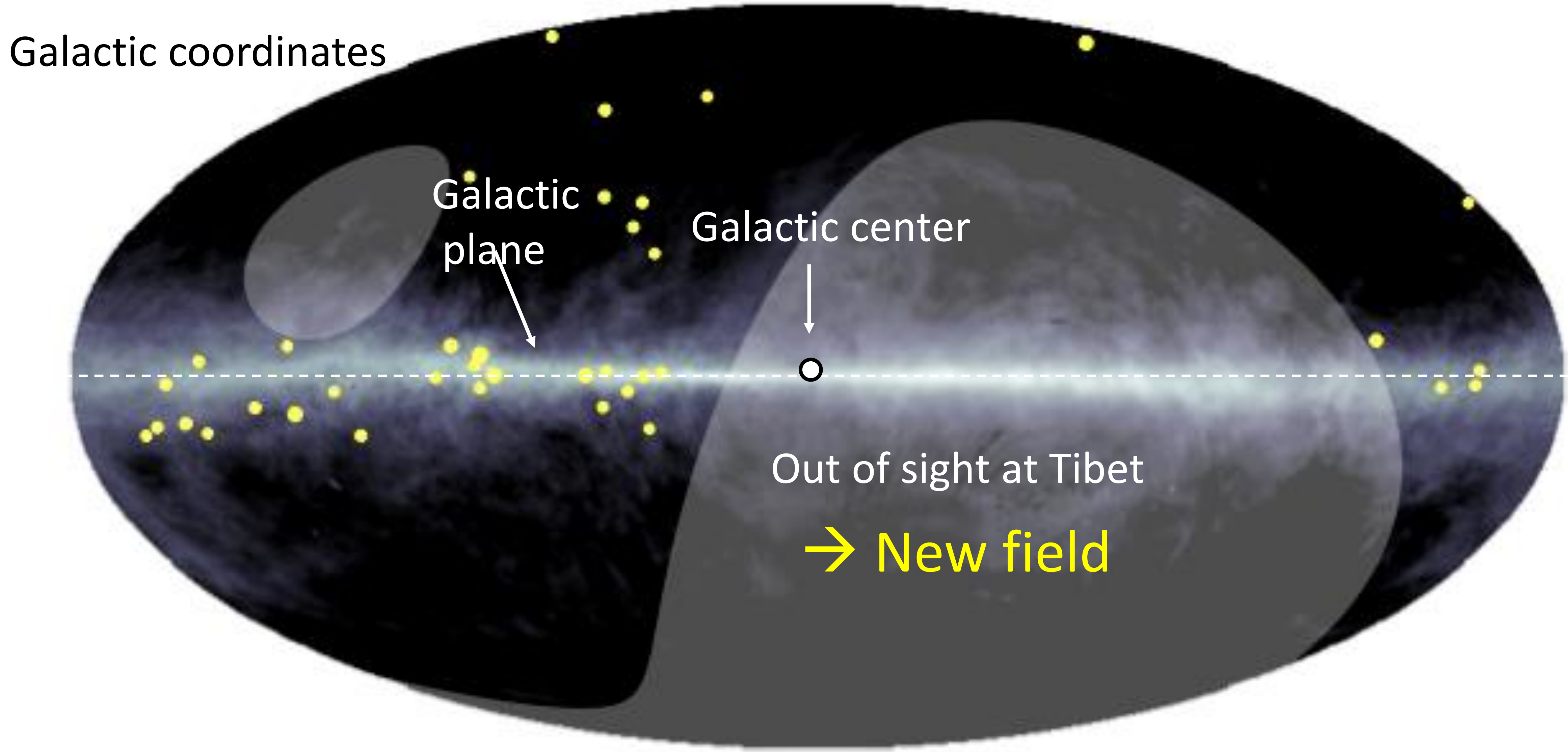


Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example http://adsabs.harvard.edu/abs/1996NCimC..19..953K).
The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on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

Go South! (e.g., ALPACA [2022-24], 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

Summary

Unraveling 60-Year-Old Mystery,

- ✓ Tibet ASγ experiment: First detection of UHE (>100 TeV) γ-rays from Crab, 2019 and Opening of UHE γ-ray astronomy.

  -> Now, a dozen of UHE γ-ray sources discovered by Tibet ASγ, HAWC, LHAASO.

- ✓ Tibet ASγ experiment : First detection of sub-PeV diffuse gamma rays from our galaxy

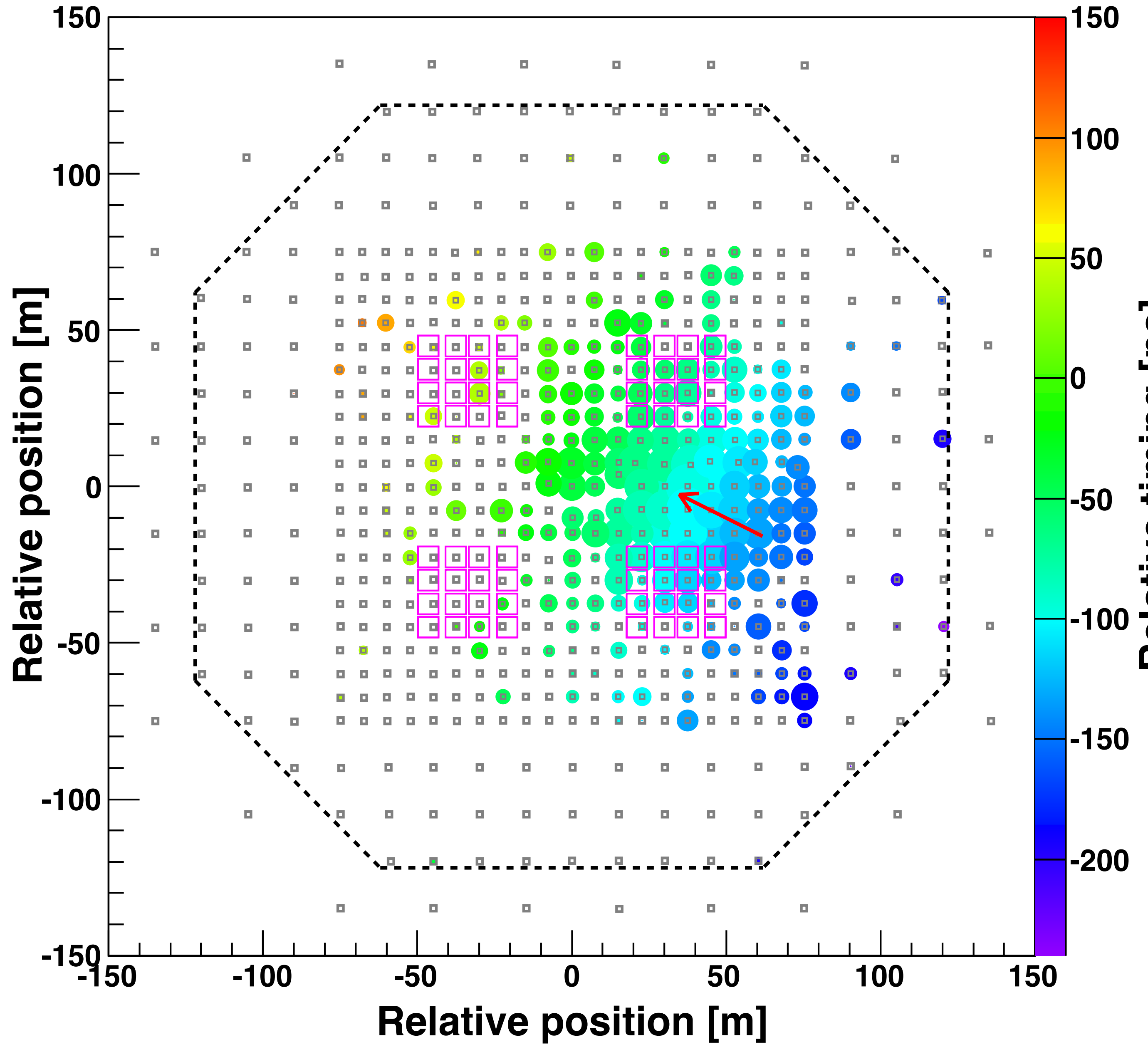
  ->Evidence for existence of PeVatrons in past and /or present Milky Way galaxy

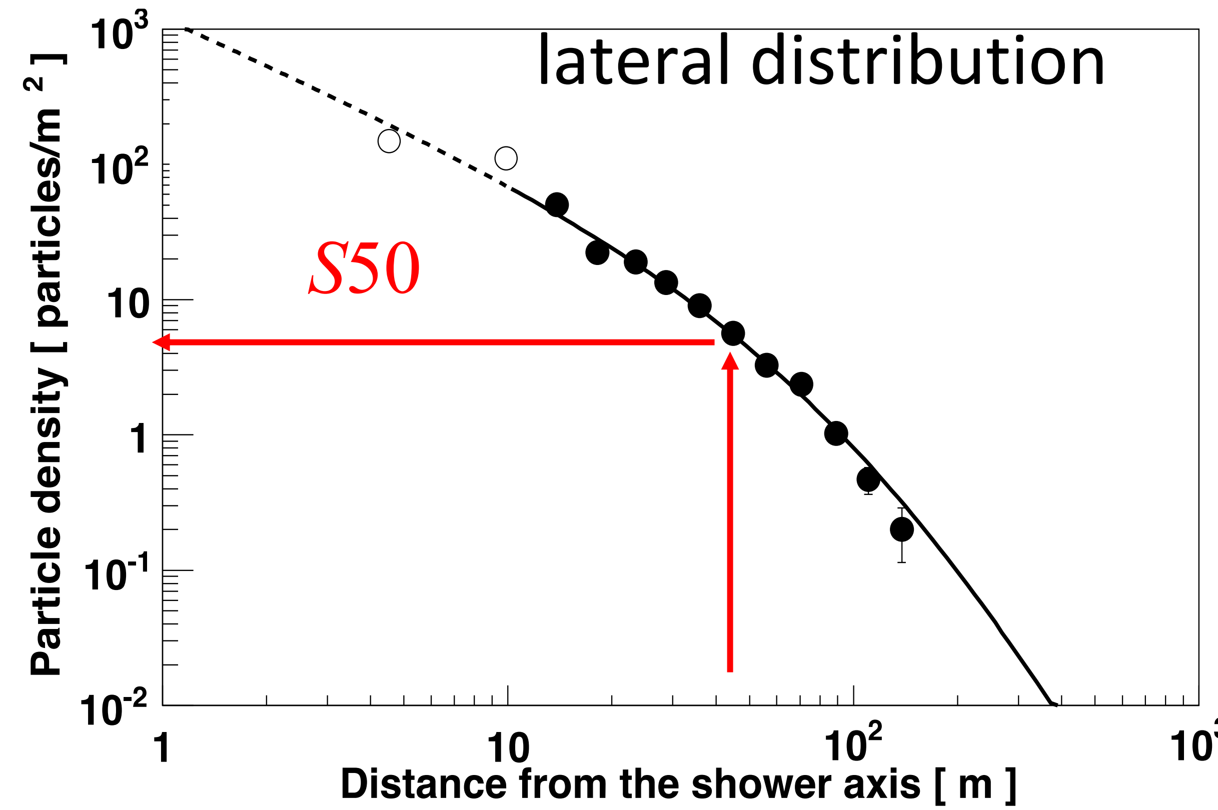
  ->Experimental verification for the theoretical model of high-energy "cosmic-ray pool" in Milky Way galaxy

- ✓ Future prospect: Go South! & Neutrinos

Back-up

Gamma-like Event from the Crab





circle size ∝ log(# of detected particles)
circle color ∝ relative timing [ns]

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

fitting with NKG function

➡ $E_{rec}(S50, \theta)$

Σρ (from AS array)	: 3256
$\Sigma N\mu$ (MD)	: 2.3
zenith angle	: 29.8°
E_{rec}	: 251^{+46}_{-43} TeV

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

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

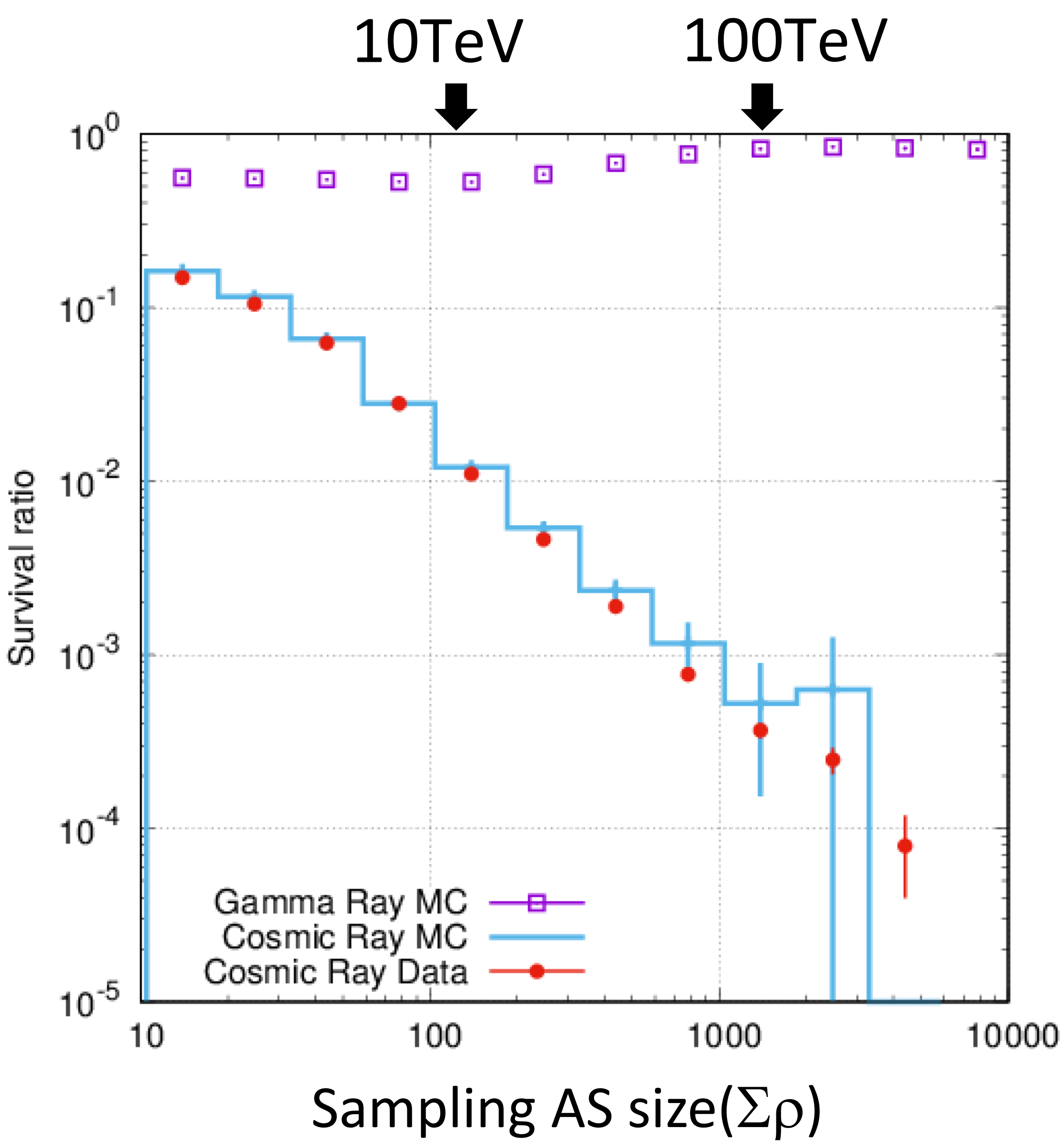
Amenomori+, PRL, **123**, 051101, (2019)

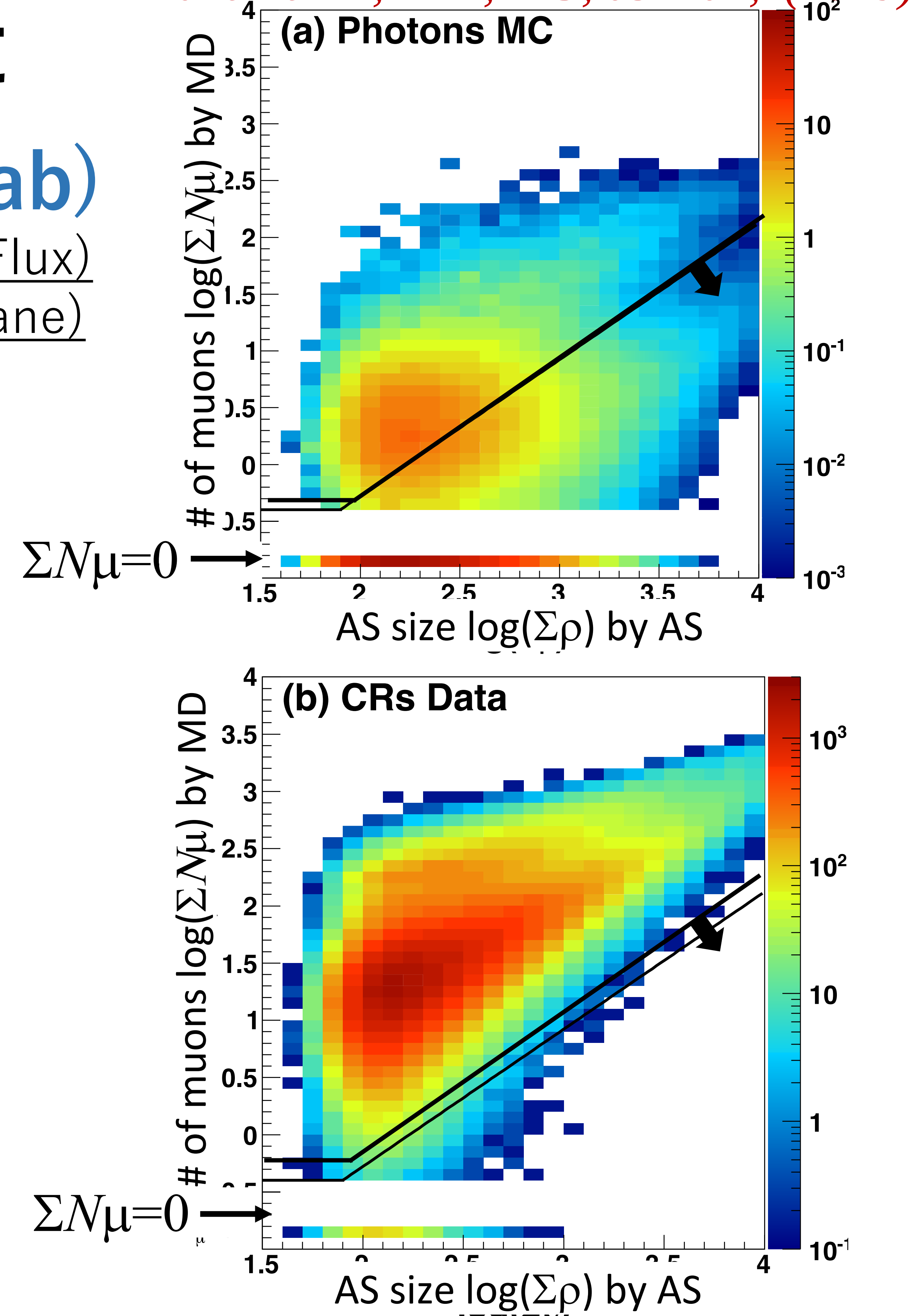
E (Σρ) vs. Nμ Plot

→Optimization of cut (Crab)

Gamma: MC sample（Crab orbit & Crab Flux)

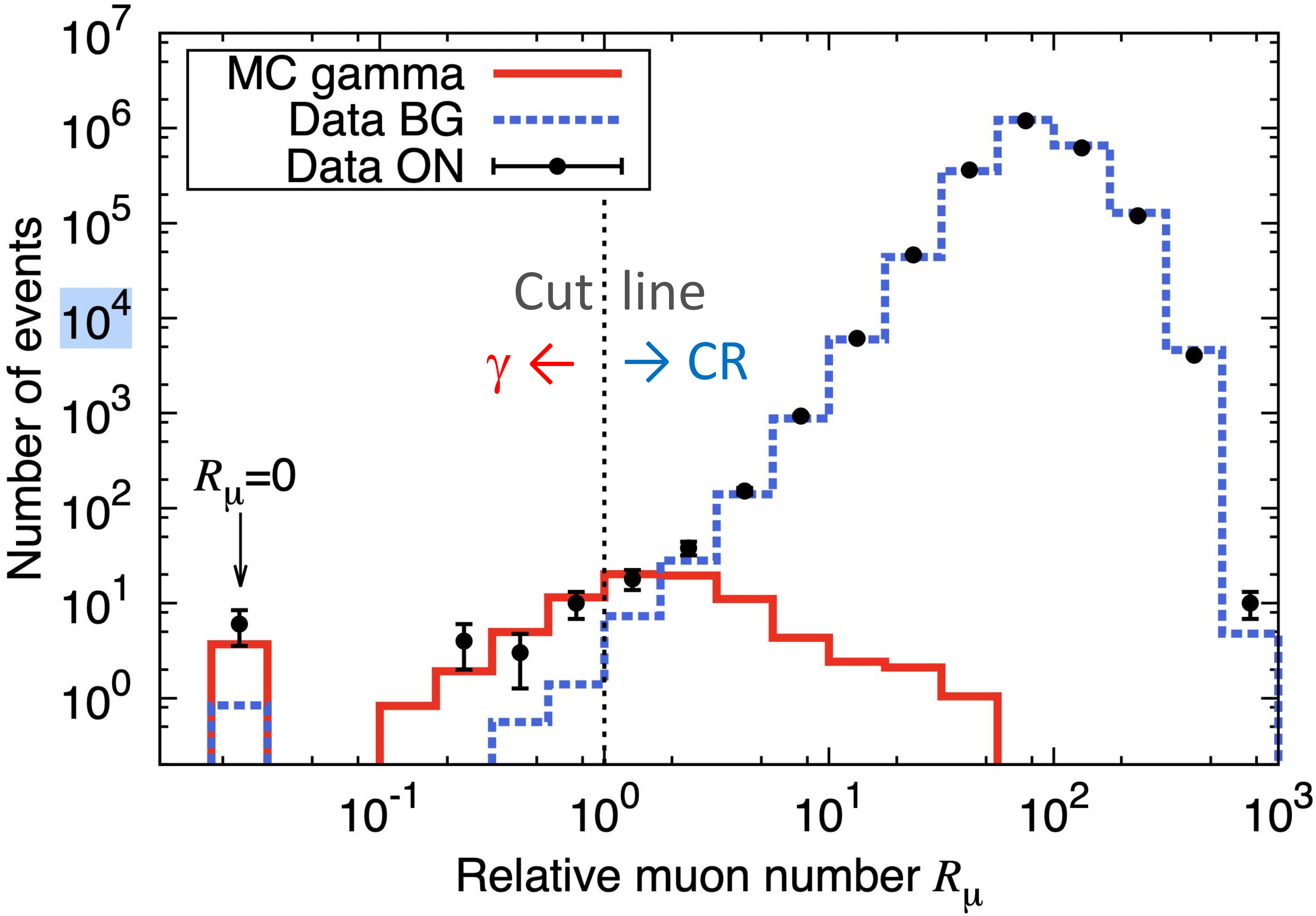
CR：DATA(excluding Crab and Galctic plane)





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

Relative muon number distribution for events > 0.398 PeV



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

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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