Recent Results of sub-PeV Gamma-Ray Observation with the Tibet ASγ Experiment

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For the Tibet ASγ Collaboration

Tibet ASγ Collaboration

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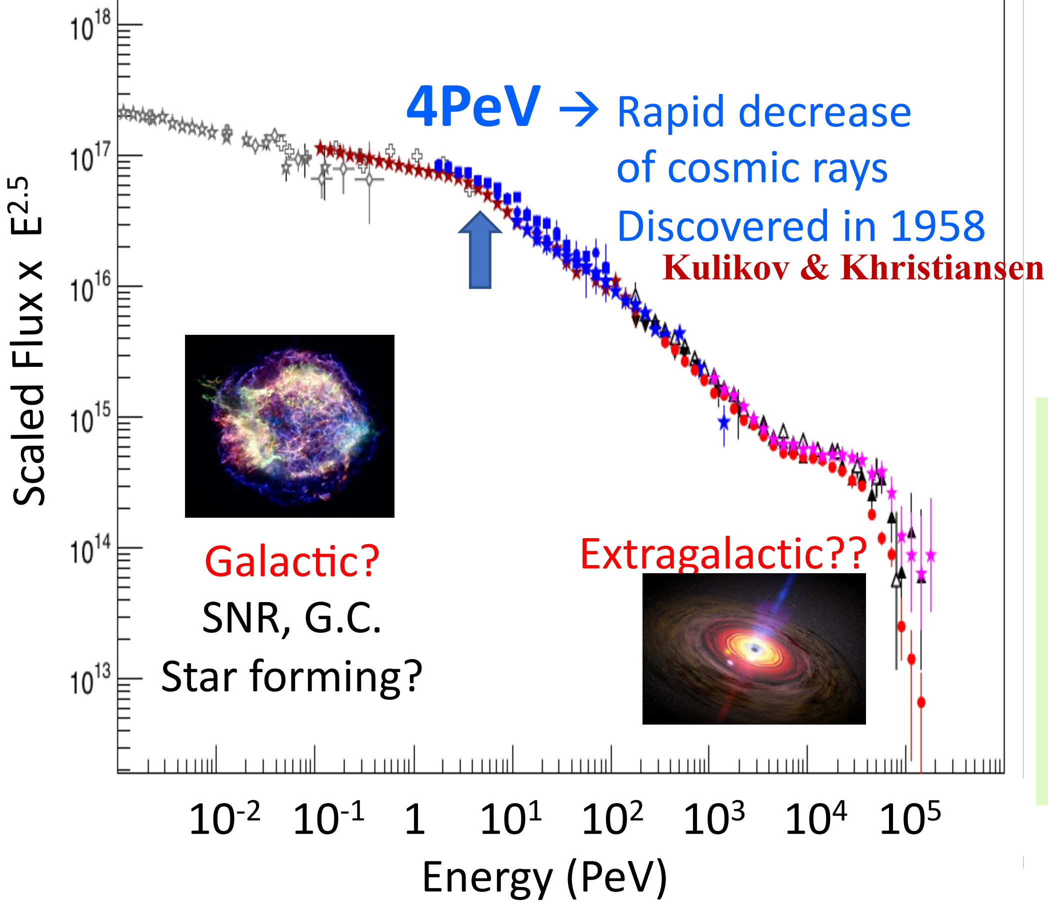
Outline

1. Introduction
2. Tibet ASγ Experiment
3. Galactic Diffuse Gamma Rays
4. PeVatron Candidates
5. Summary

Introduction

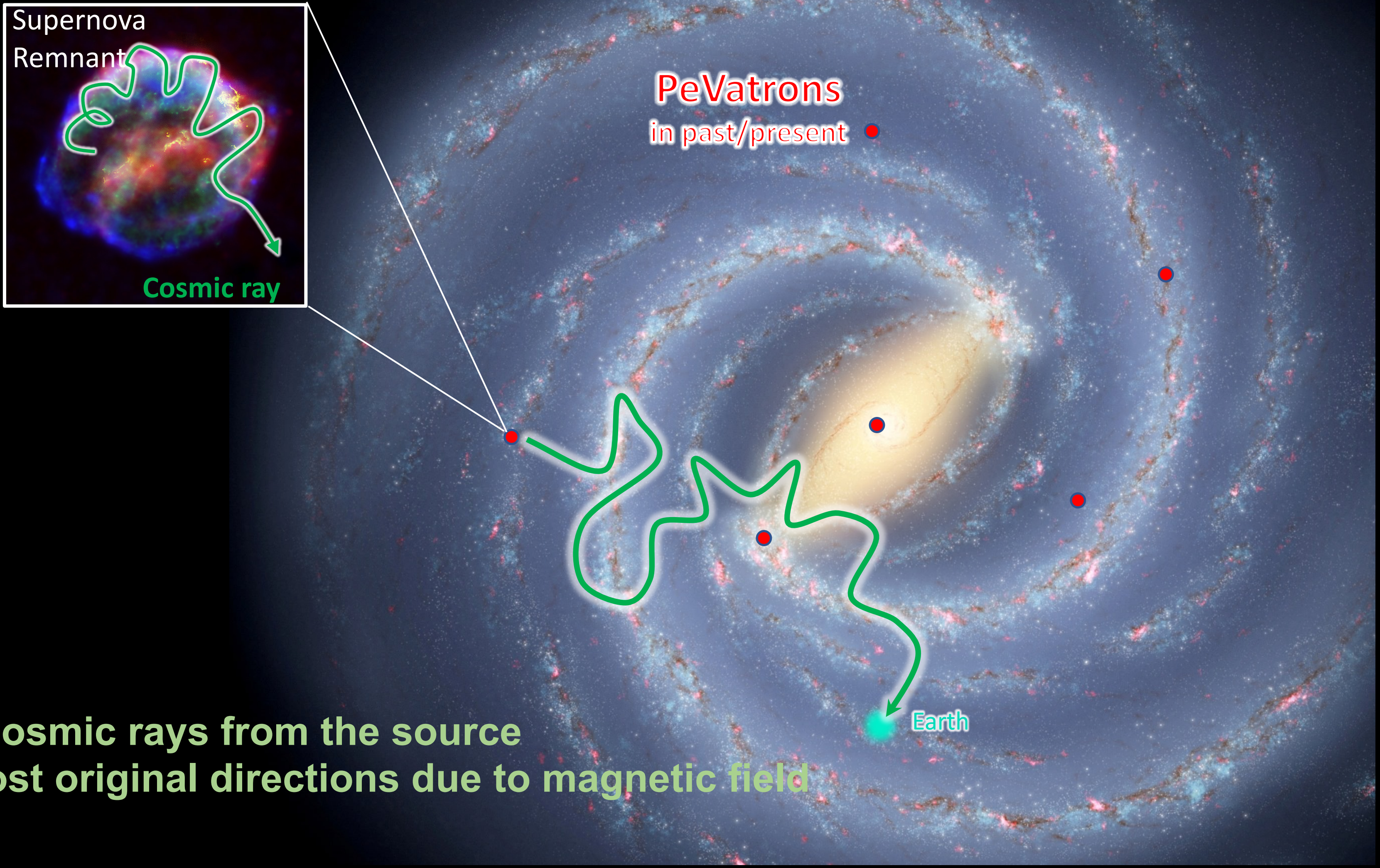


- Wide energy range
- Main component is proton
- Rate decreases to 1/100 when energy is 10 times higher

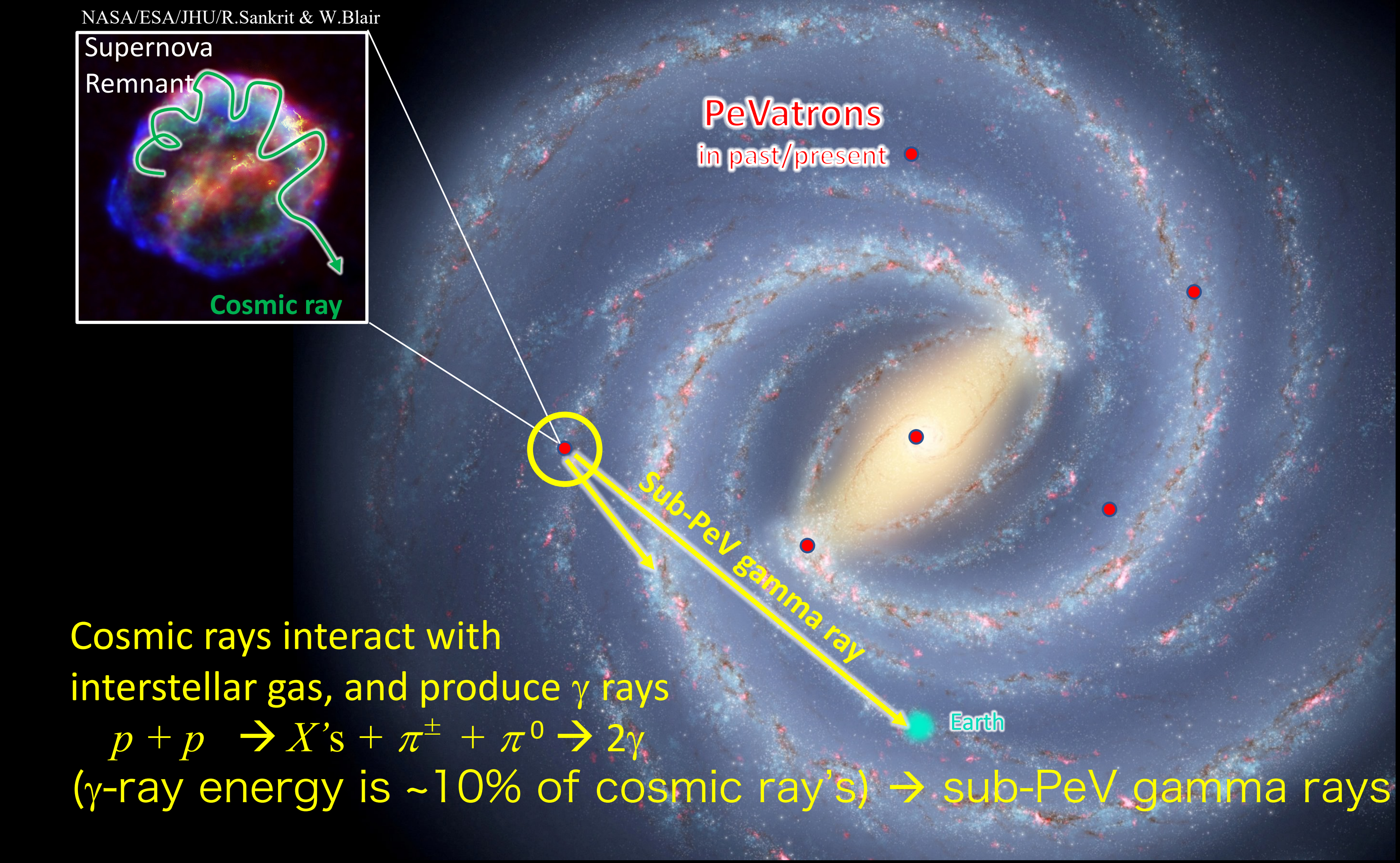
As an open question,
Did/Do "PeVatrons" really exist in our Galaxy?

PeVatron: Cosmic super-accelerators can accelerate to Peta electron volt

NASA/ESA/JHU/R.Sankrit & W.Blair



Cosmic rays from the source
lost original directions due to magnetic field

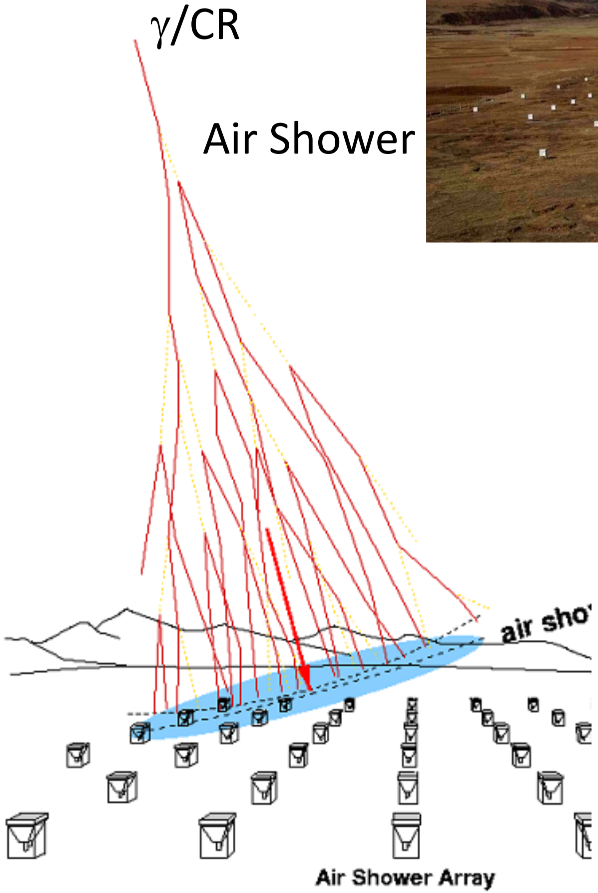


Cosmic rays interact with
interstellar gas, and produce γ rays

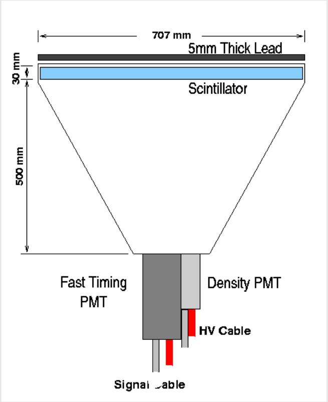
$p + p \rightarrow X\text{'s} + \pi^{\pm} + \pi^{0} \rightarrow 2\gamma$

(γ-ray energy is ~10% of cosmic ray's) → sub-PeV gamma rays

Tibet Air Shower Array



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



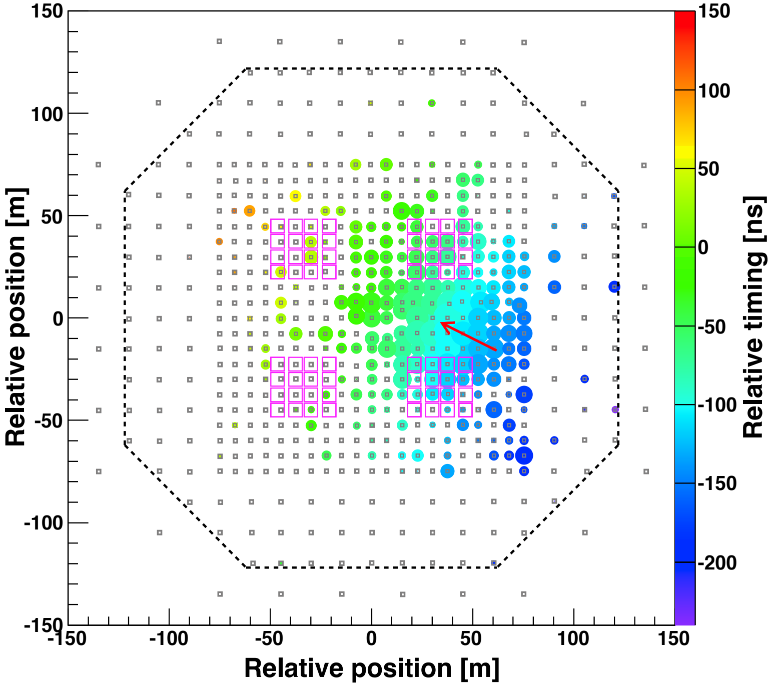
<u>Present Performance</u>

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

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

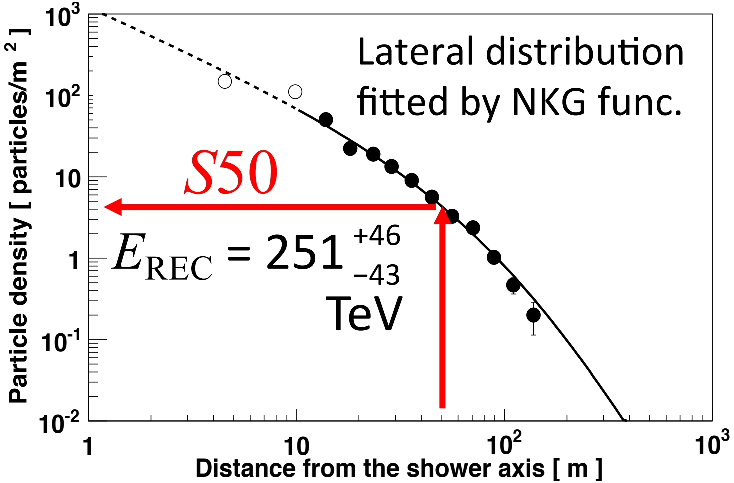
Air Shower Reconstruction

Gamma-ray candidate event



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

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



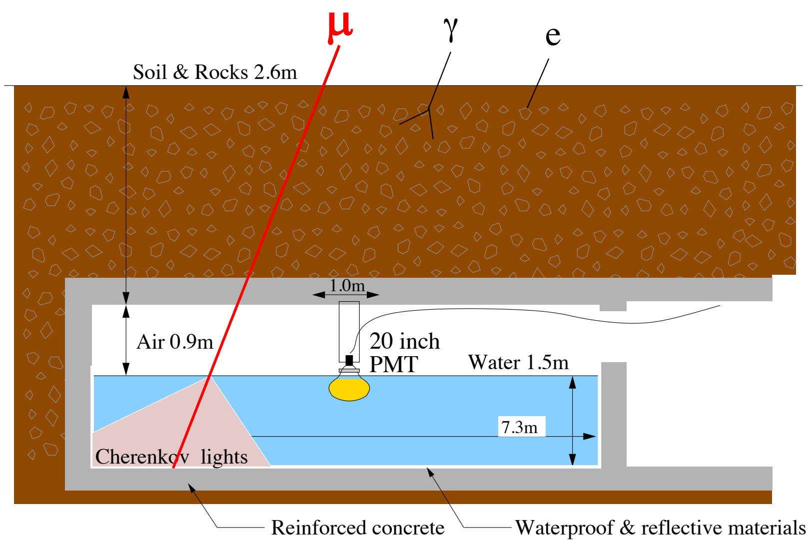
S50 improves E resolutions (10 - 1000 TeV)
→ ~40%@10 TeV , ~20%@100 TeV

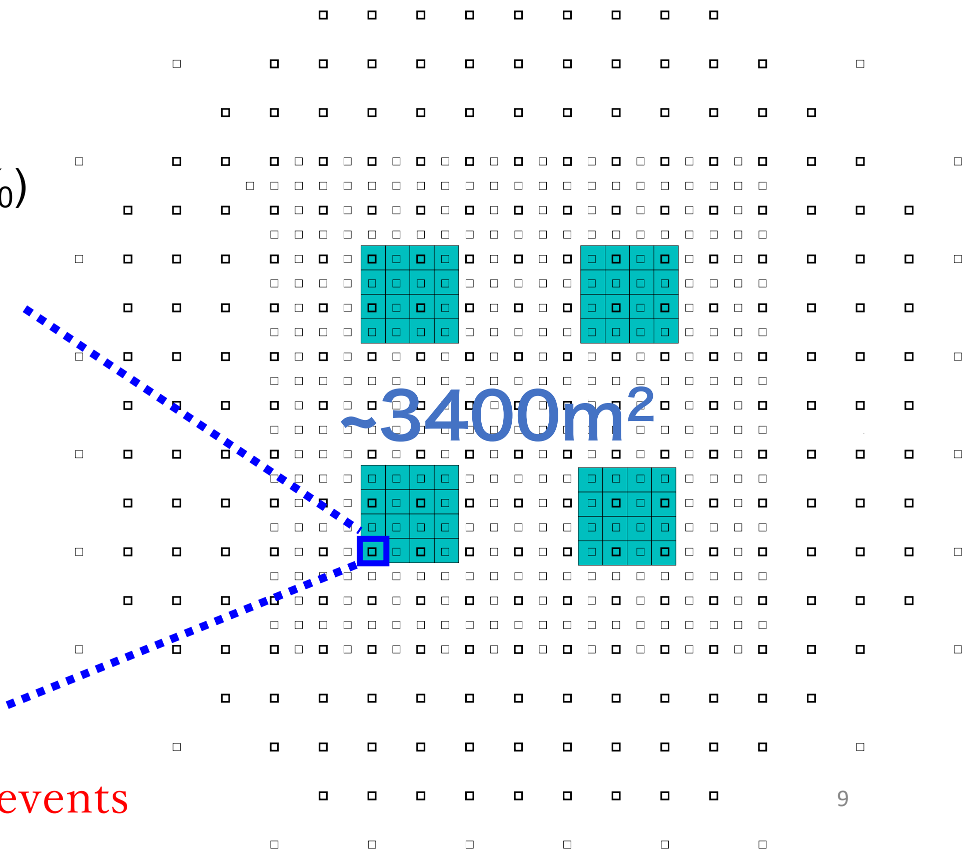
Kawata+, Experimental Astronomy ***44****, 1 (2017)*

Underground WC Muon Detectors

- ✓ 4 pools, 16 units / pool
- ✓ 54 m^2 in area ×1.5m in depth / unit
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets
- ✓ 2.4m soil overburden (~515g/cm^2 ~9X_0)

Measurement of # of μ in AS → γ／CR discrimination
DATA: February 2014 - May 2017 Live time: 719 days

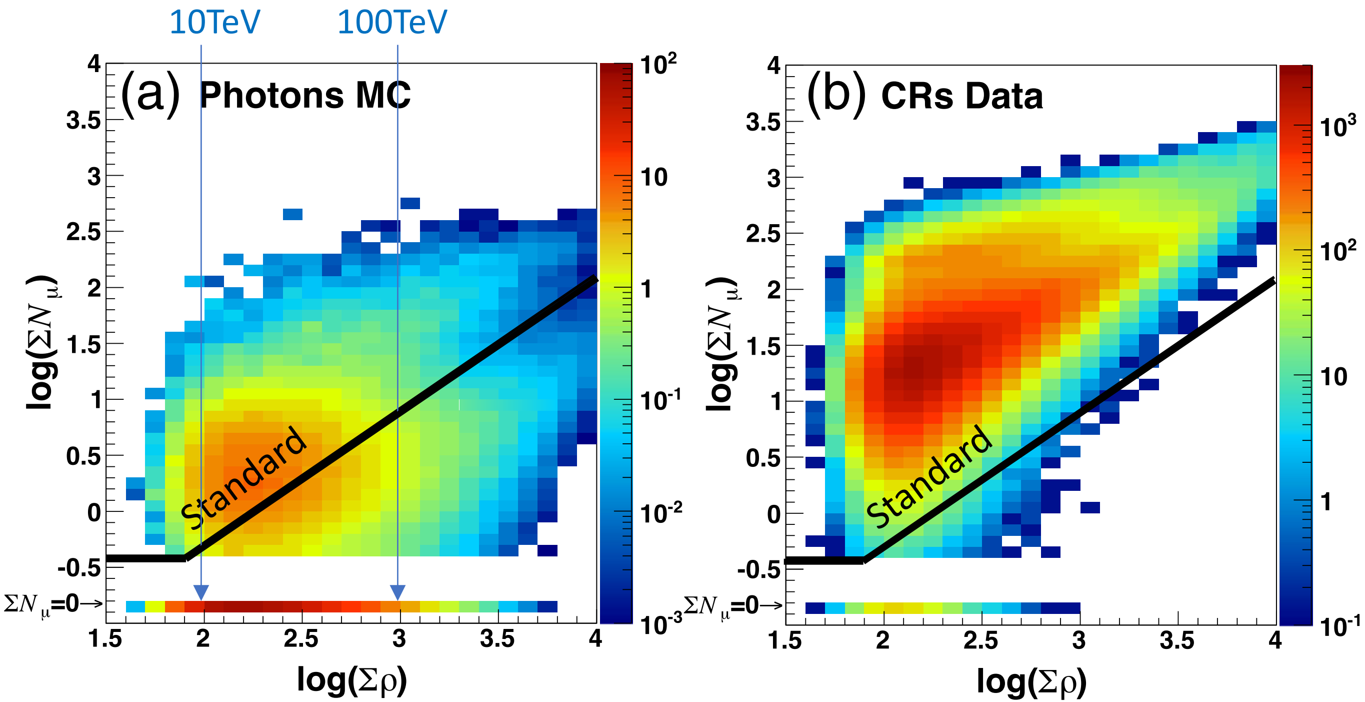




→Succeeded in rejecting by >99.9% CR events

Muon Cut Condition (Standard)

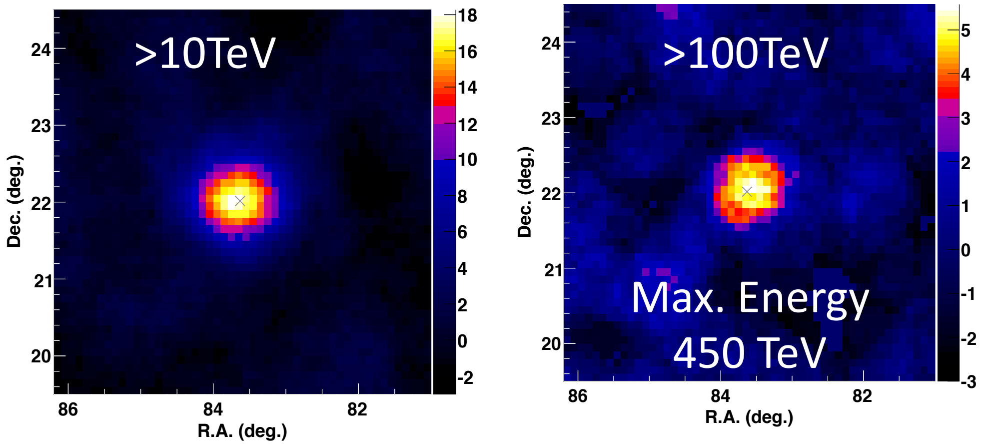
Standard muon cut : $\Sigma N\mu < 2.1 \times 10^{-3}\ \Sigma\rho^{1.2}$ → Optimized for the gamma-ray point-like source



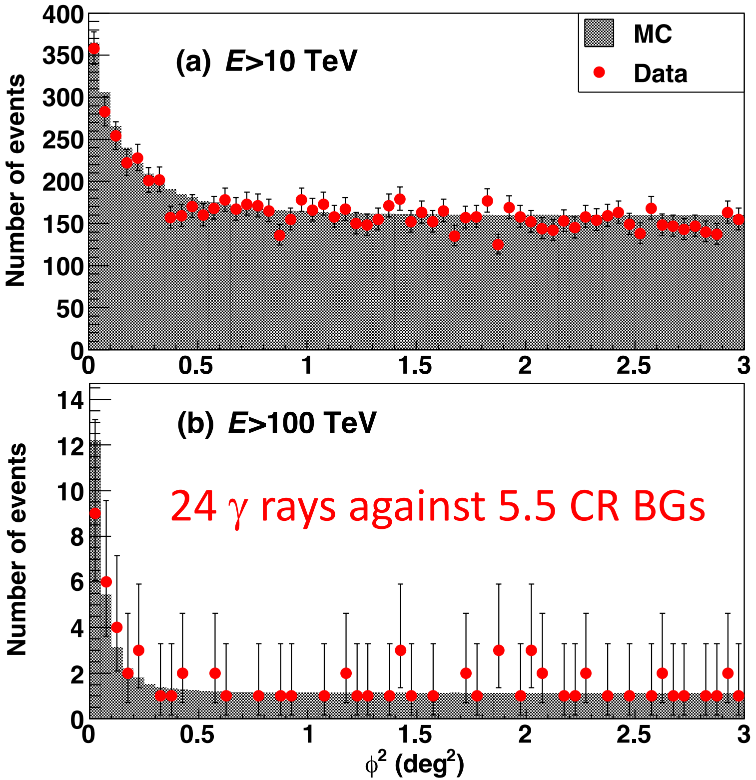
Gamma Survival ratio : ~90% by MC sim (>100TeV) CR Survival ratio : ~10^{-3} (>100TeV)

UHE γ-rays from the Crab Nebula (2019)

Amenomori et al., PRL 123, 051101 (2019)



Data vs MC



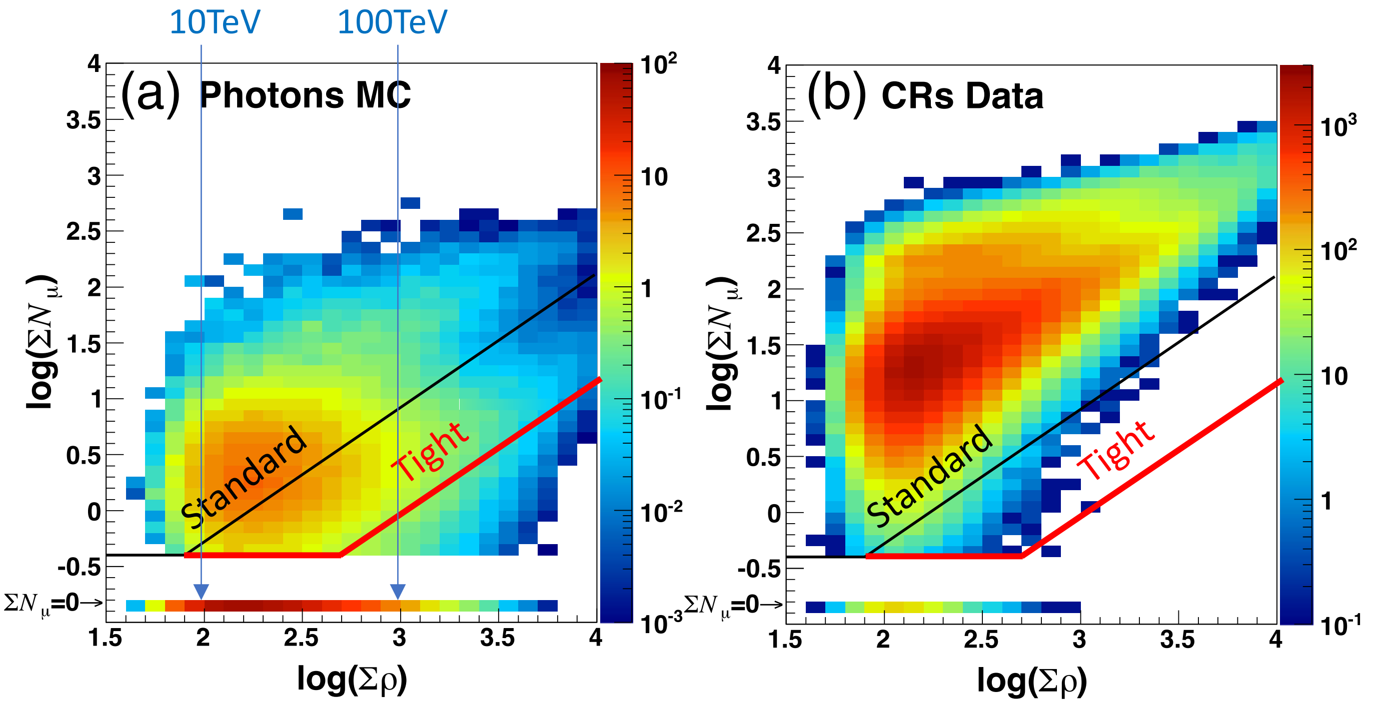
First Detection of Sub-PeV γ (5.6σ)

Other detected sources in 100 TeV region

- ✓ G106.3+2.7 *Amenomori et al., Nat. Astron, 5, 460 (2021)*
- ✓ Cygnus OB1 *Amenomori et al., PRL, 127, 031102 (2021)*
- ✓ Cygnus OB2
- ✓ HESS J1843-033 *Amenomori et al., ApJ, 932, 120 (2022)*
- ✓ HESS J1849-000 *Accepted (2023)*

Muon Cut Condition (Tight) for Diffuse γ

Tight muon cut : $\Sigma N\mu < 2.1 \times 10^{-4}\, \Sigma\rho^{1.2}$ → One order magnitude tighter than the Crab analysis

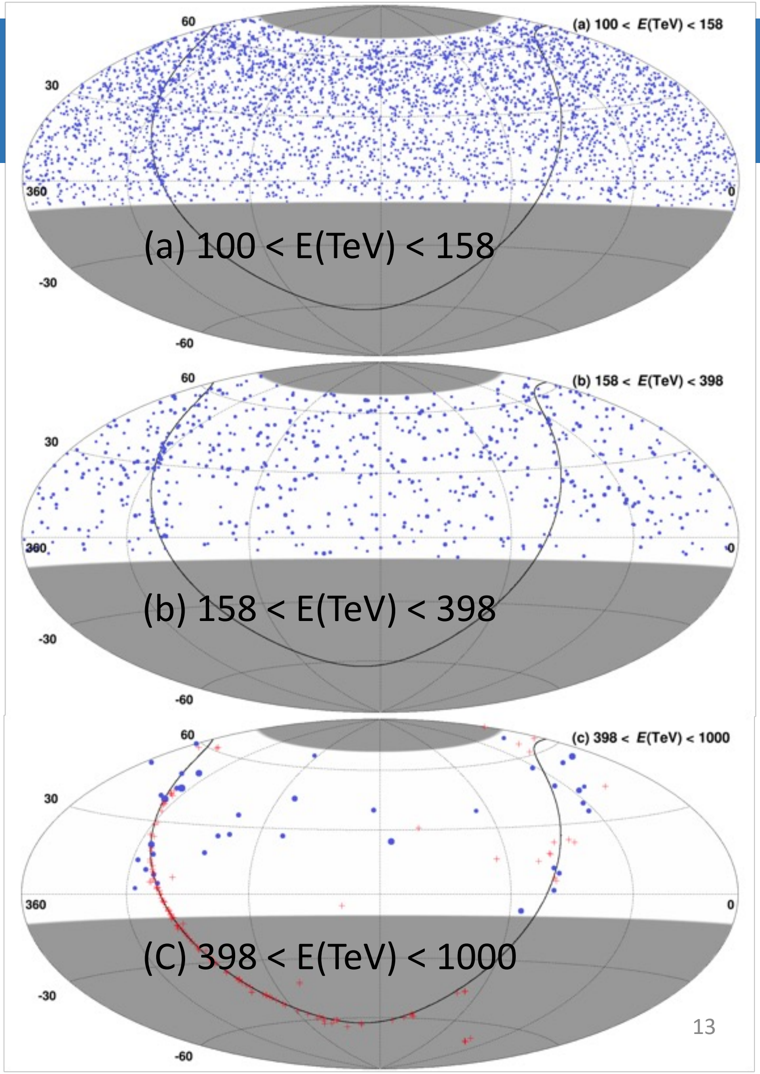


Gamma Survival ratio : ~30% by MC sim (>398TeV) CR Survival ratio : ~10^{-6} (>398TeV=$10^{2.6}$TeV)

γ-ray-like event Distribution

Gamma-ray-like events
after the tight muon cut
in the equatorial coordinates

Blue points:
Experimental data
Red plus marks:
known Galactic TeV sources



>398 TeV ($10^{2.6}$ TeV)
38 events in our FoV
23 events in $|b| < 10^{o}$
16 events in $|b| < 5^{o}$

Latitude Profile

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

Red points:
experimental data across our FoV ($22^o < l < 225^o$)
including source contribution

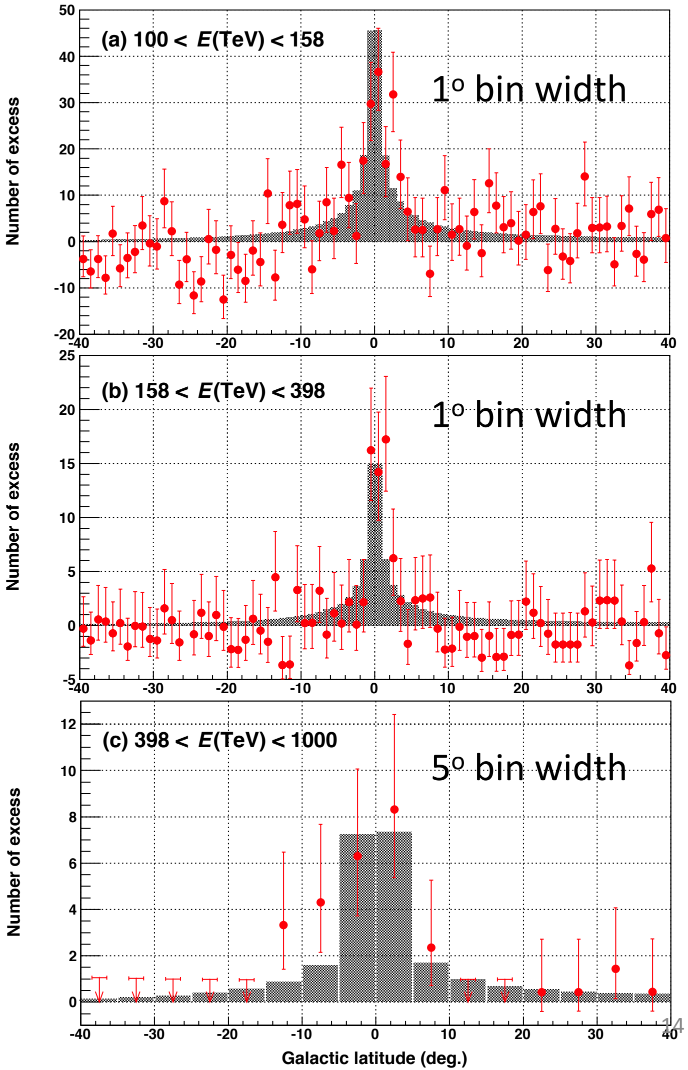
Gray shade histogram:
Model by Lipari and Vernetto

Lipari & Vernetto, PRD 98, 043003 (2018)

6.6σ

5.1σ

5.9σ



Energy Spectrum of UHE Diffuse γ Rays

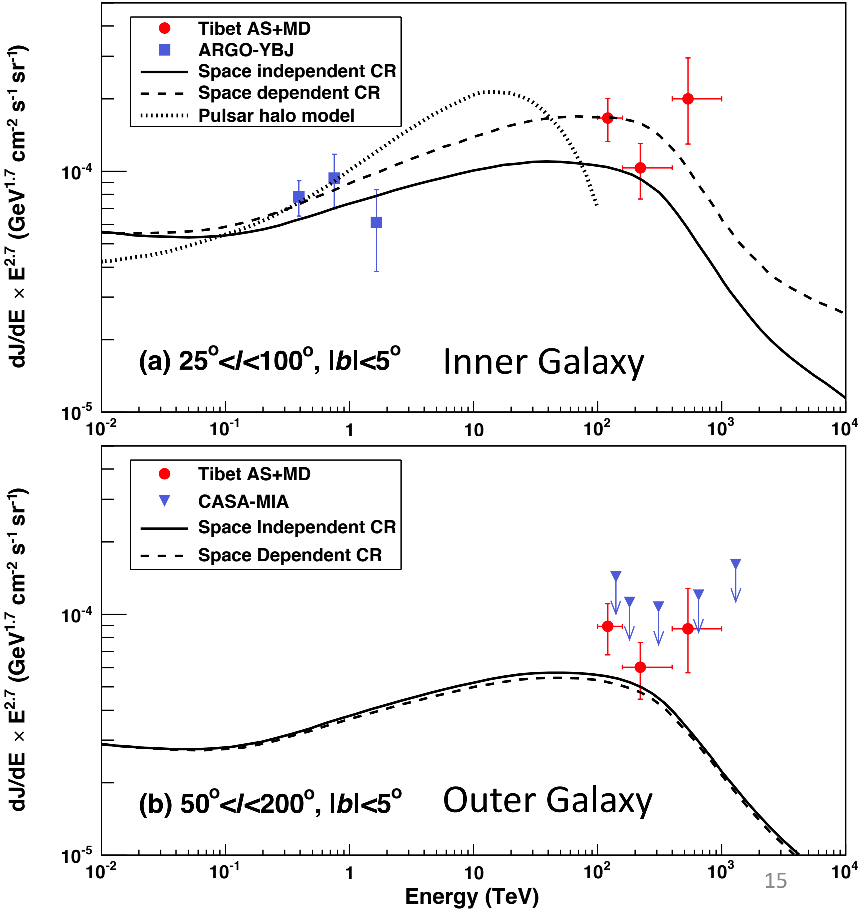
Amenomori et al., PRL 126, 141101 (2021)

After excluding the contribution from the known TeV sources (within 0.5 degrees) listed in the TeV source catalog

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

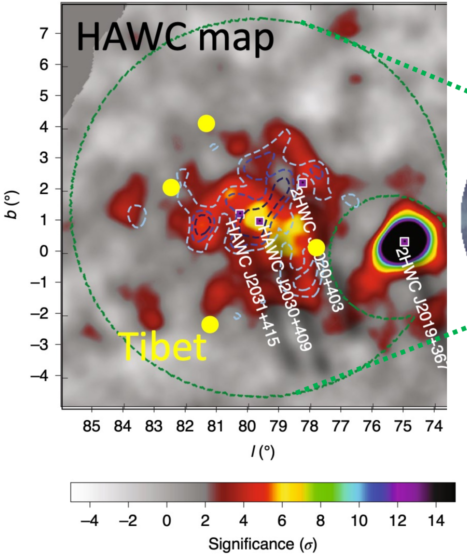
$$\mathrm{CR} + \mathrm{ISM} \rightarrow X\text{'s} + \pi^0 \ldots \rightarrow 2\gamma$$

Lipari & Vernetto, PRD 98, 043003 (2018)

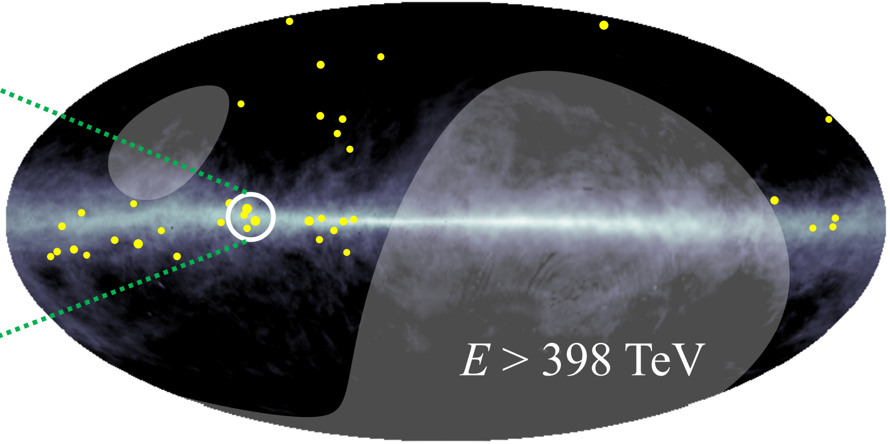


PeVatron Candidate: Cygnus Cocoon

Abeysekara et al., Nature Astronomy (2021)

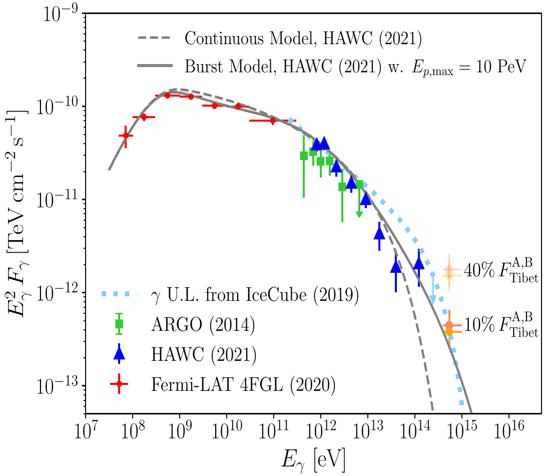


Amenomori et al., PRL 126, 141101 (2021)



Galactic Coordinates

Fang & Murase, ApJ, 919, 93 (2021)



4 events above 398 TeV detected within 4°-radius-circle from the Cygnus cocoon which is claimed as an extended source by the ARGO-YBJ/HAWC/LHAASO and also proposed as a candidate of the PeVatrons.

LHAASO Diffuse Gamma Rays

Z. Cao et al. (LHAASO Collob.) PRL, 131, 151001 (2023)

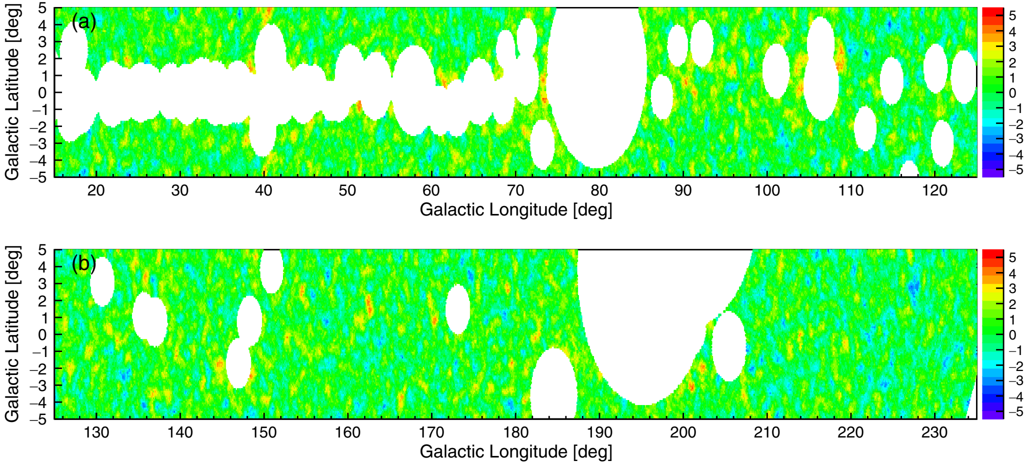
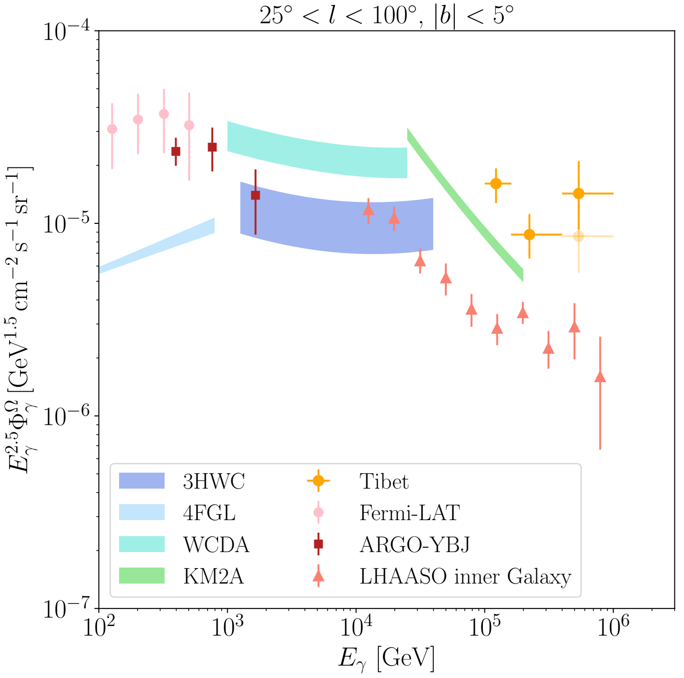


FIG. 1. The significance maps in Galactic coordinate of the inner Galaxy region [panel (a)] and outer Galaxy region [panel (b)] above 25 TeV after masking the resolved KM2A and TeVCat sources.

K. Fang & K. Murase, ApJ, 957, L6 (2023)

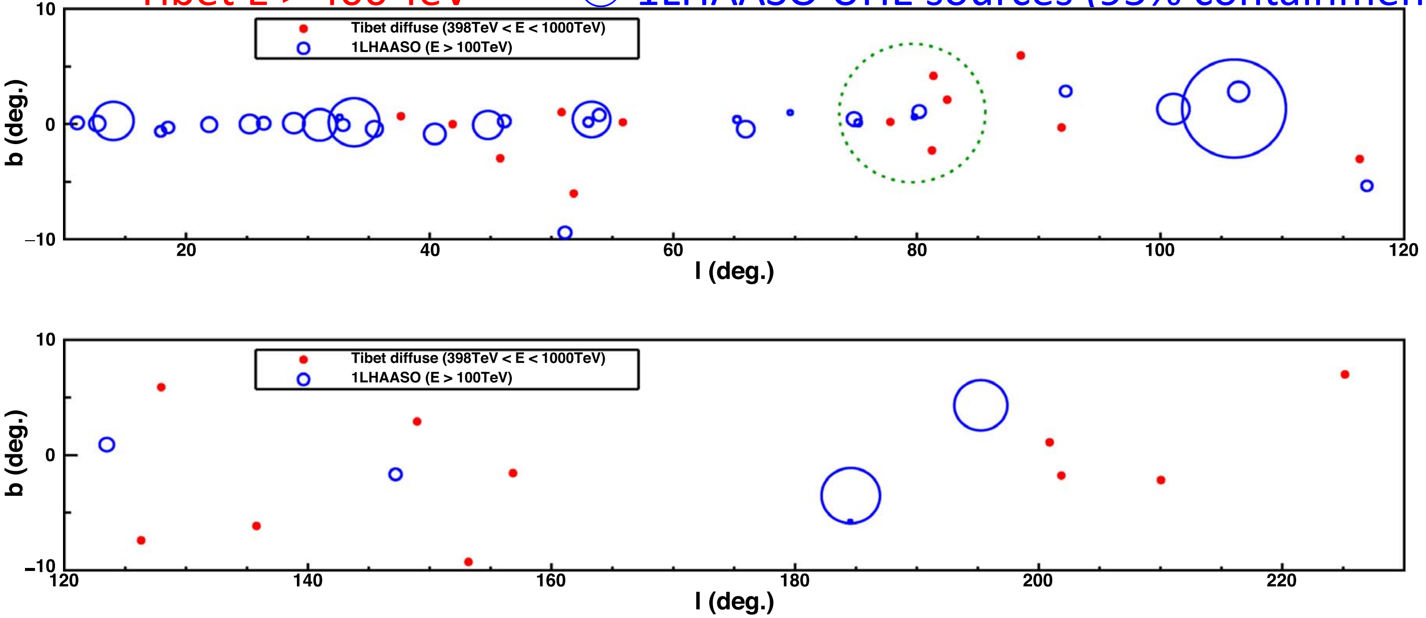


LHAASO flux: a few times lower than Tibet flux, but not directly compared, due to the large masked regions by LHAASO.

1LHAASO Catalog and Tibet UHE Diffuse Events

Kato et al. ApJ, 961, L3 (2024)

• Tibet E > 400 TeV ◯ 1LHAASO UHE sources (95% containment radius)

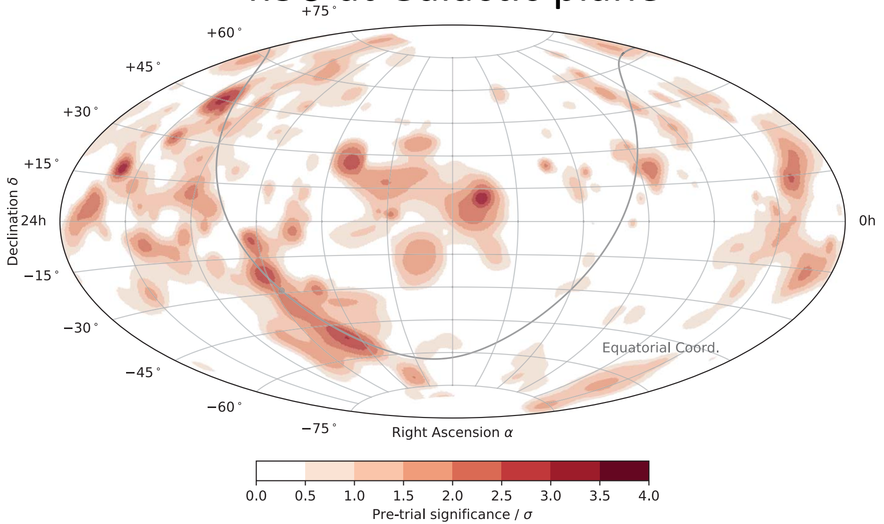


Tibet Galactic diffuse gamma rays above 400 TeV:
do NOT originate from 1LHAASO UHE (>100 TeV) sources.

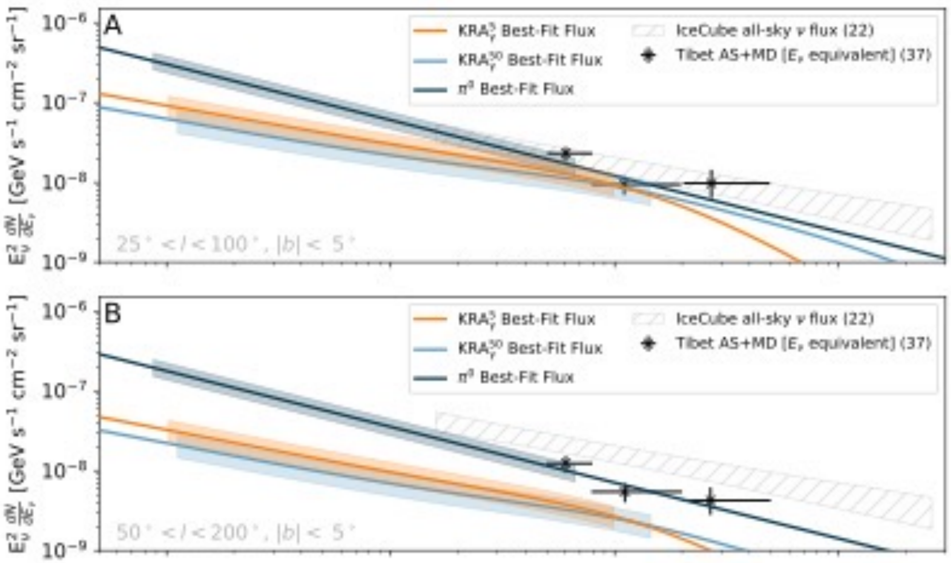
IceCube Diffuse Neutrinos

IceCube Collaboration: Science, 380, 1338 (2023)

4.5σ at Galactic plane

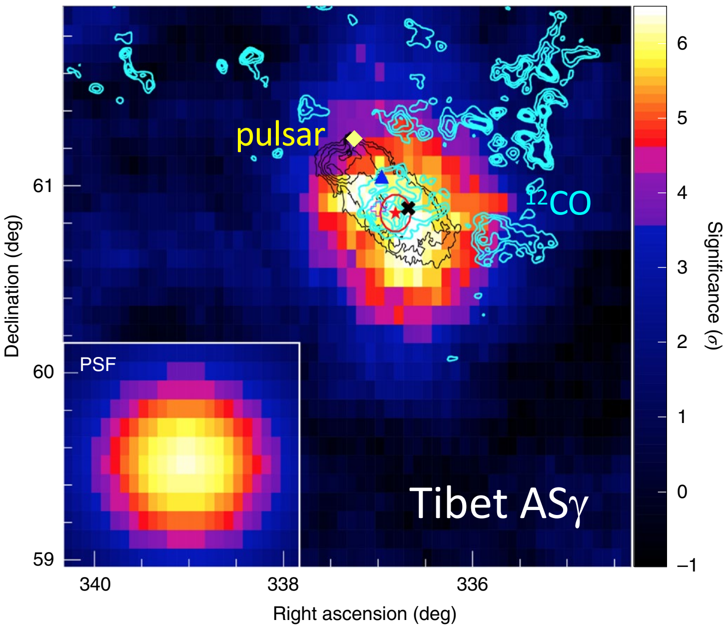


Comparison with Tibet diffuse γ-rays



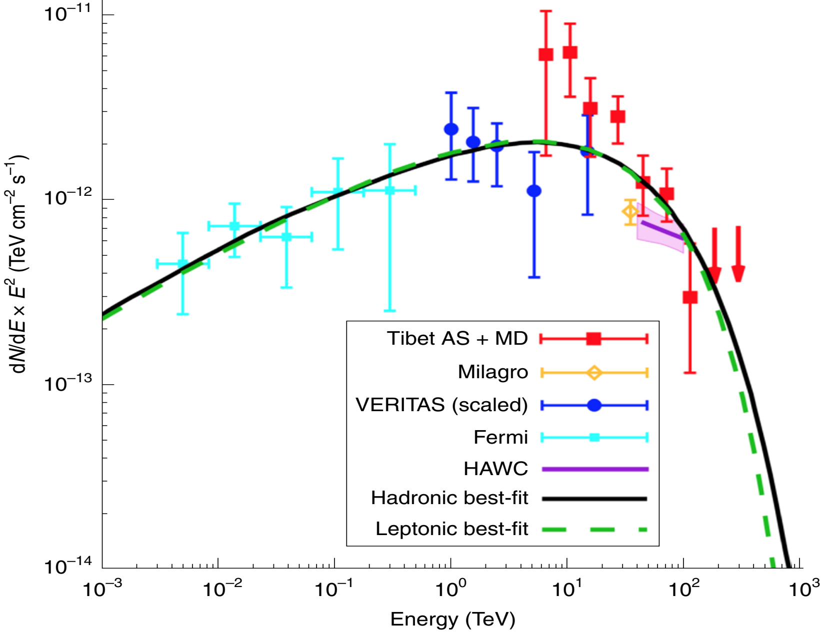
IceCube ν flux smoothly connects to the ν flux estimated from the Tibet sub-PeV γ-ray flux, assuming π⁰ -model best-fit flux supporting cosmic-ray origin of Tibet sub-PeV galactic diffuse γ rays.

PeVatron Candidate: SNR G106.3+2.7



Detected by
VERITAS,
HAWC,
Tibet ASγ,
MAGIC,
LHAASO

Amenomori et al., Nat. Astron (2021)

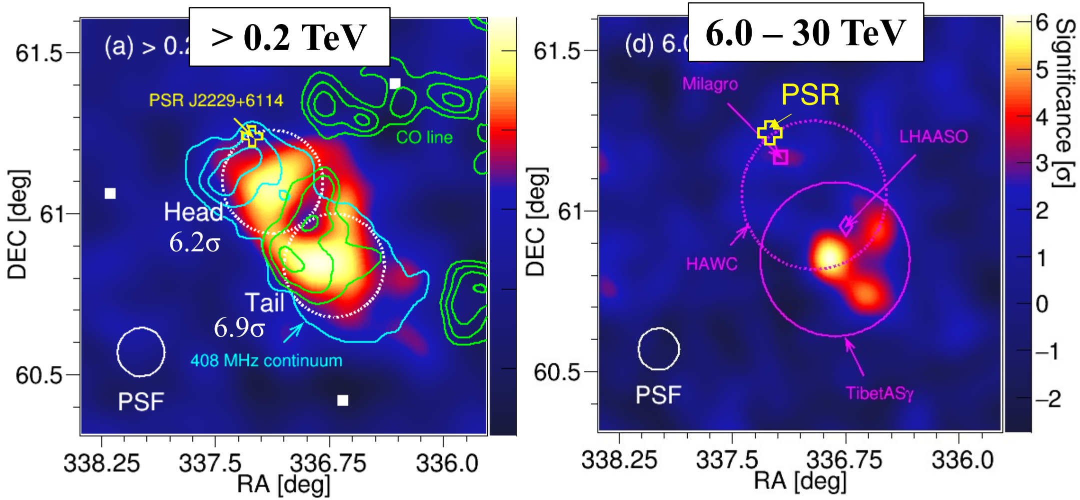


- ✓ Spectrum extends beyond 100 TeV (HAWC, Tibet ASγ, LHAASO)
- ✓ Shell-type SNR near the pulsar (t_{age}~10kyr?, d=800pc?)
- ✓ Extended γ-ray excess (σ_{EXT}=0.24° ± 0.10°)
- ✓ γ-ray excess is coincident with the molecular clouds (MCs) and SNR, not pulsar

$E_{p,cut}$ = ~500 TeV

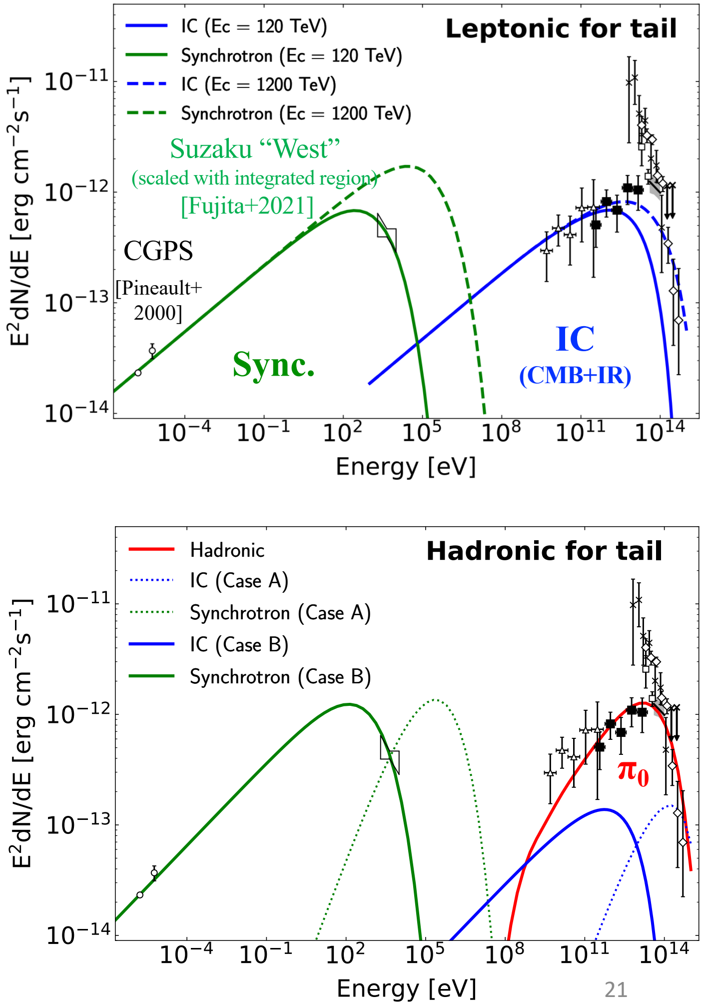
W_p = ~5 x 10^{47} erg (>1GeV)

MAGIC: SNR G106.3+2.7

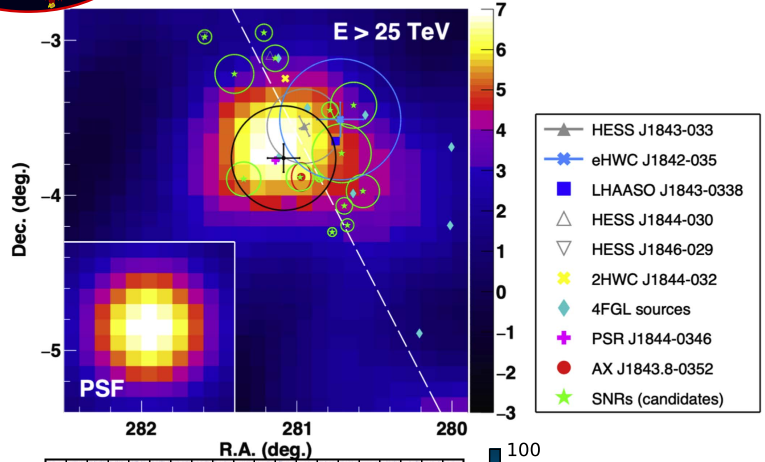


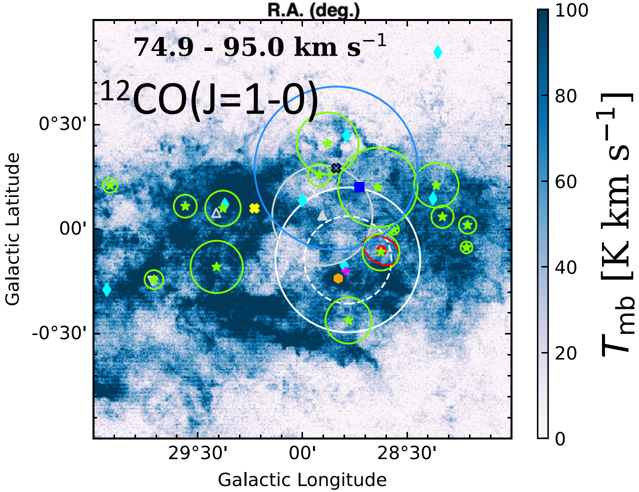
- ✓ HE emissions are consistent with Tibet ASγ
- ✓ SED for tail region favors hadronic model

Abe et al. (MAGIC Collab.), A&A, 671, 12 (2023)
Oka et al. (MAGIC Collab.), CTA workshop

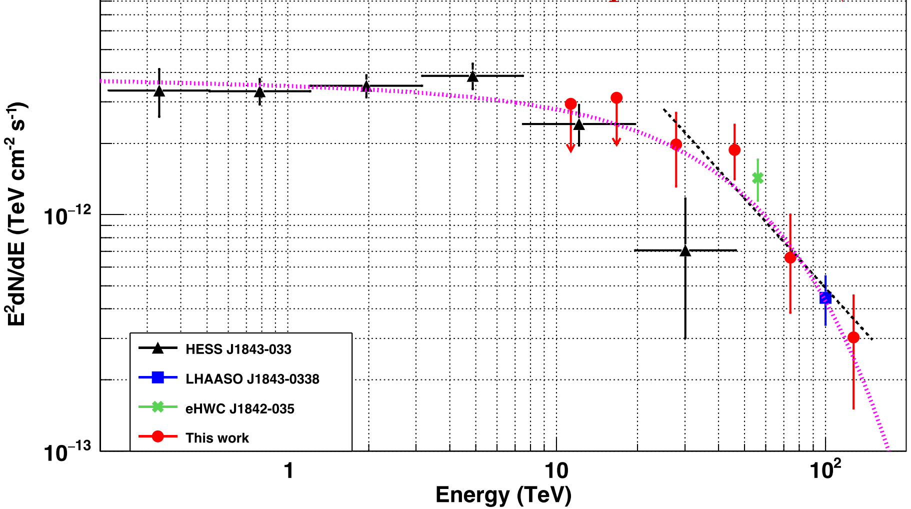


PeVatron Candidate: HESS J1843-033





Amenomori et al., ApJ, 932, 120 (2022)



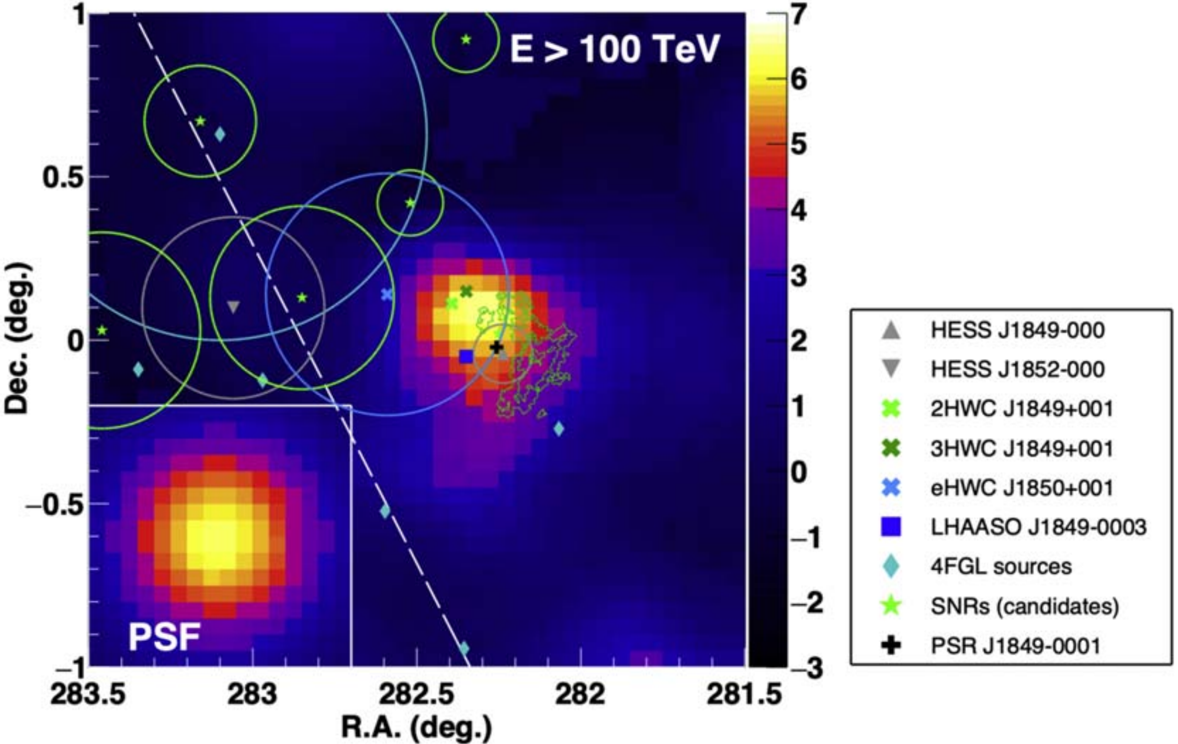
<u>Candidate sources</u> ($Tage$=2.7kyr?, d=9.6kpc)

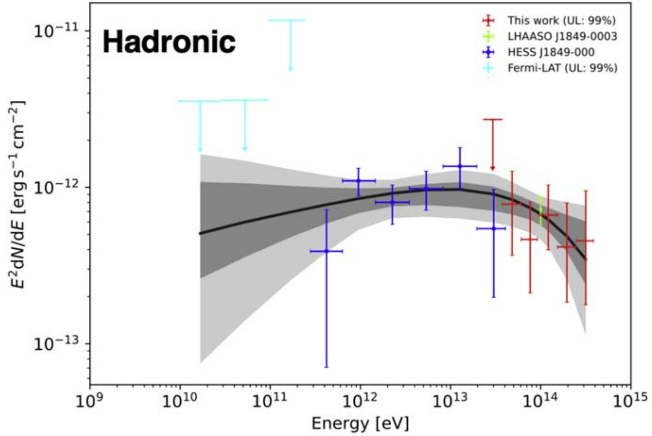
- ✓ Shell-type SNR G28.6+0.1? or PSR J1844-00346?
- ✓ Extended γ-ray excess (σ_{EXT}=0.34° ± 0.12°)
- ✓ γ-ray excess is coincident with the MCs
- ✓ Proton cutoff: ~500 TeV assuming the Hadronic model
  W_p = ~6 x 10^{49} erg (>1TeV)

PeVatron Candidate: HESS J1849-000

Amenomori et al., ApJ, 954, 200 (2023)

- ✓ A middle-aged PWN (T_{age}=42.9kyr, d=7kpc)
- ✓ γ-ray excess is coincident with the MCs

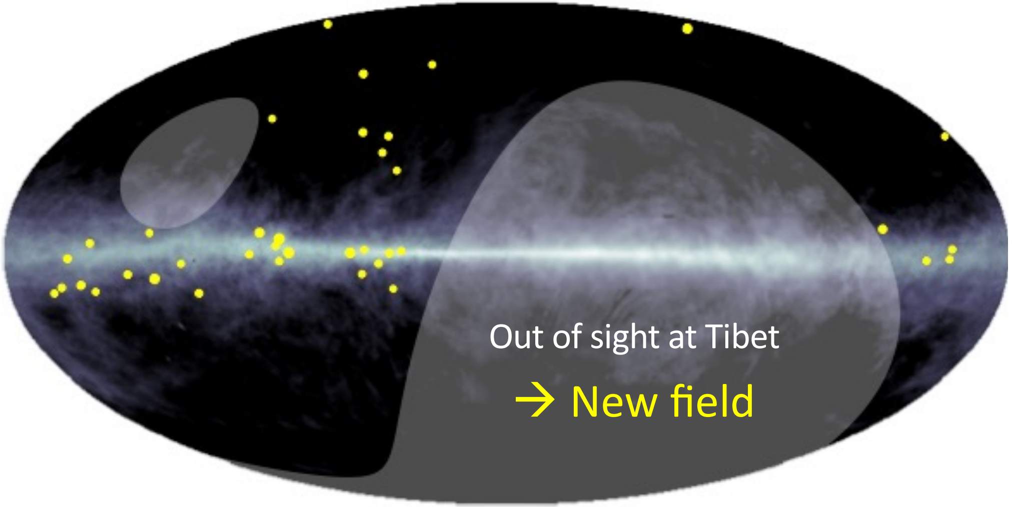




- ✓ Proton cutoff ~5 PeV assuming the Hadronic model W_p = ~1.1 x 10^{49} erg (>1TeV)
- ✓ Spectrum can be also modeled with the Leptonic scenario (IC)

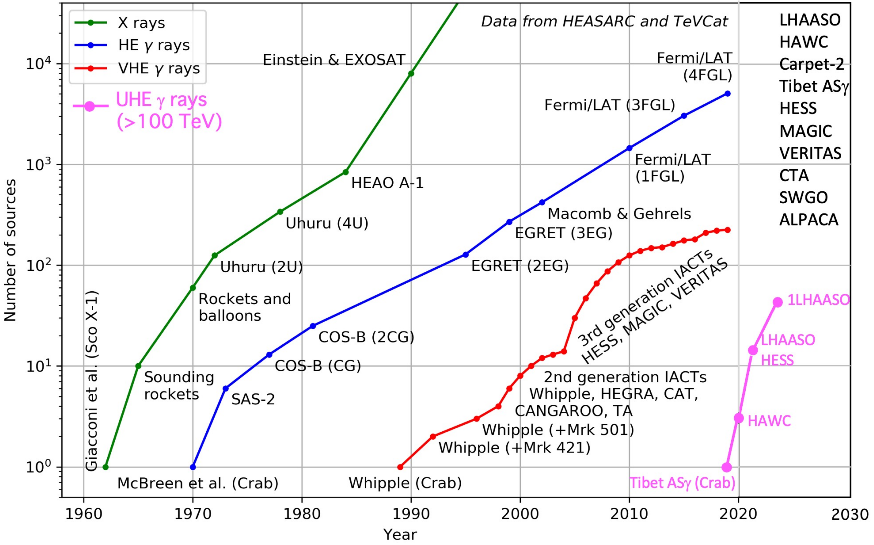
Projects in the Southern Hemisphere

UHE diffuse gamma rays



>40 UHE sources

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/

Go South!

(e.g., ALPACA [2022-24], Mega ALPACA, SWGO, CTA, …) & Neutrinos

Conclusions

- ✓ Tibet ASγ experiment successfully observed UHE gamma rays from the Crab Nebula for the first time and opened new energy window. (Now >40 UHE γ ray sources detected by LHAASO, HAWC, H.E.S.S. and Tibet ASγ)
- ✓ Tibet ASγ experiment successfully observed Galactic diffuse gamma rays between 100 TeV and 1 PeV for the first time.
- ✓ Tibet UHE events (>400 TeV) do not originate from LHAASO UHE (>100 TeV) sources.
- ✓ IceCube diffuse neutrino flux smoothly connects to Tibet ASγ diffuse gamma-ray flux assuming π^0 best-fit model supporting the cosmic-ray origin.
- ✓ Tibet ASγ experiment found a few PeVatron candidates associated with the molecular clouds.

These facts indicate strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.
→ Search for more PeVatron candidates! → Go South!

Backup slides

Composition Dependence

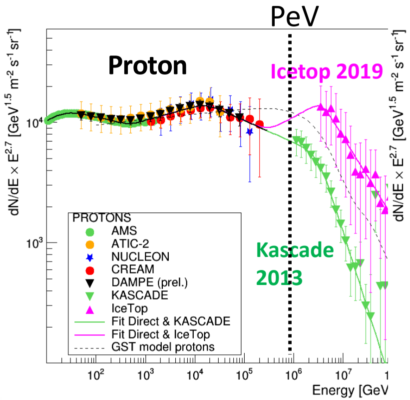
CRs interact with interstellar gas
(γ-ray energy has 10% of CRs)

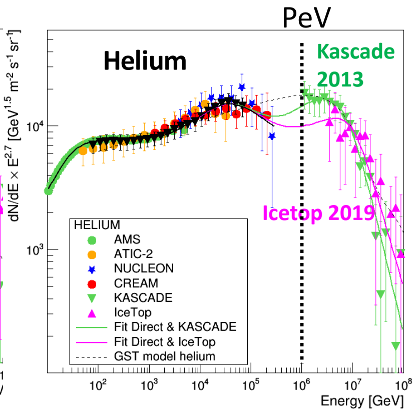
$$\mathrm{CR} + \mathrm{ISM} \rightarrow X\text{'s} + \pi^0 \ldots \rightarrow 2\gamma$$

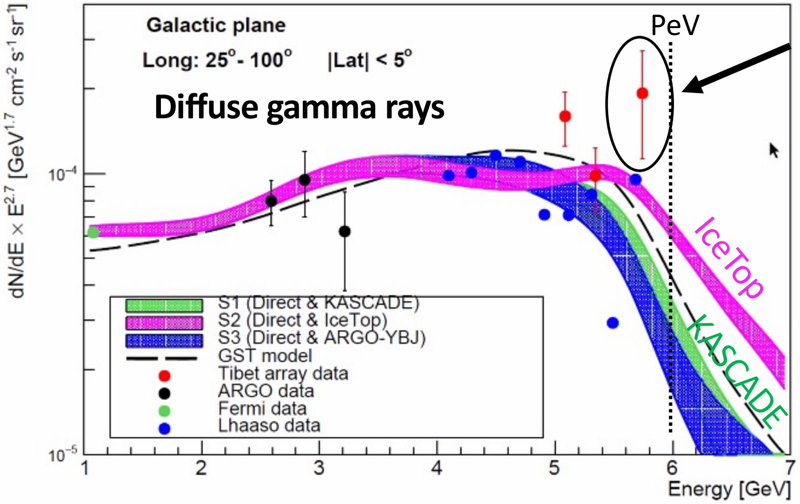
→ Diffuse gamma-ray spectrum depends on the CR composition

Vernetto & Lipari (ICRC2021)

factor 1.5 – 2 difference@~600 TeV

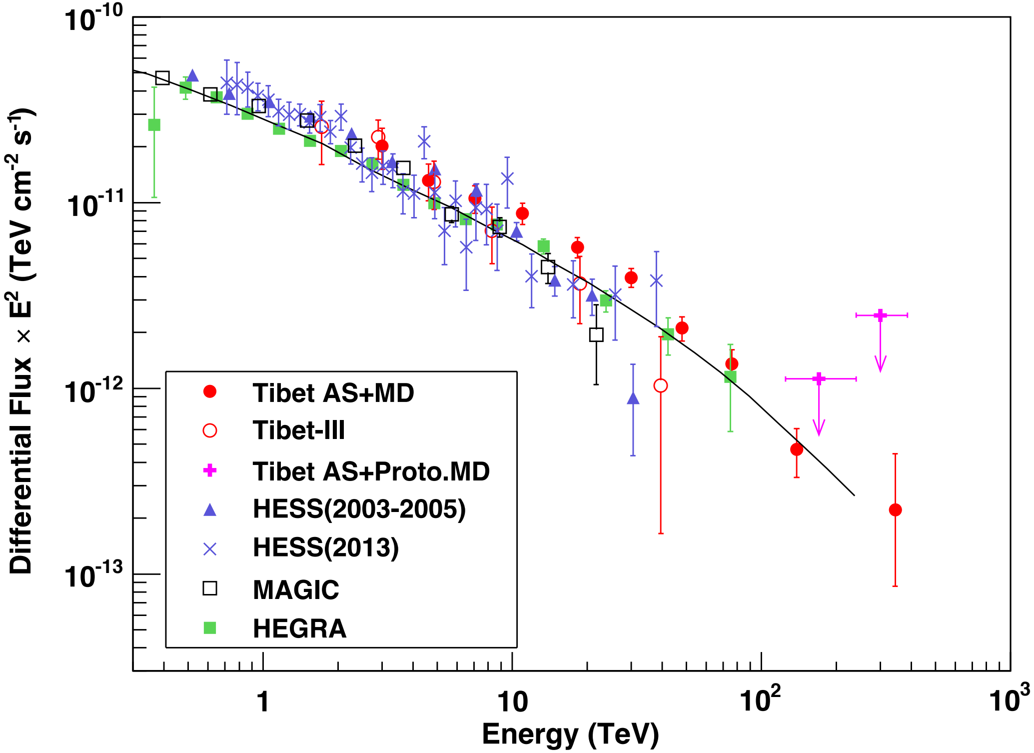






4 ev / 10 ev from Cygnus cocoon (< 4°)

UHE γ-rays from the Crab Nebula (2019)



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

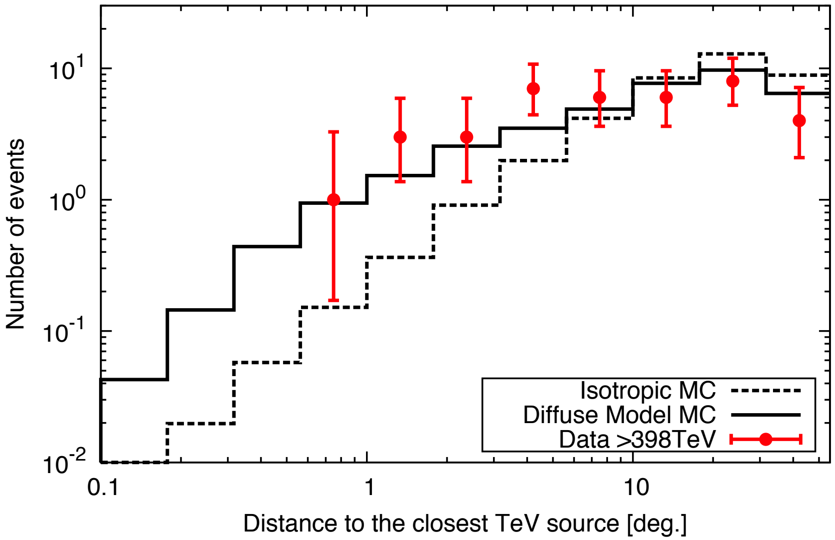
The highest energy γ ~450 TeV

Thick curve：
inverse Compton model
normalized to HEGRA data
Aharonian+, ApJ, 614, 897 (2004)

Correlation with known TeV Sources

Correlation between UHE γ-rays above 398 TeV and 60 galactic sources from TeVCat catalog including UNID, PWN , Shell, Binary, SNR…, excluding GRB, HBL, IBL, LBL, BL Lac, AGN, Blazar, FSRQ, FRI, Starburst)

- ✓ No excess around known TeV sources
- ✓ Event distribution is consistent with diffuse model



- ✓ High-energy $e^{+/-}$ lose their energy quickly.
- ✓ Cosmic-ray protons can escape farther from the source.

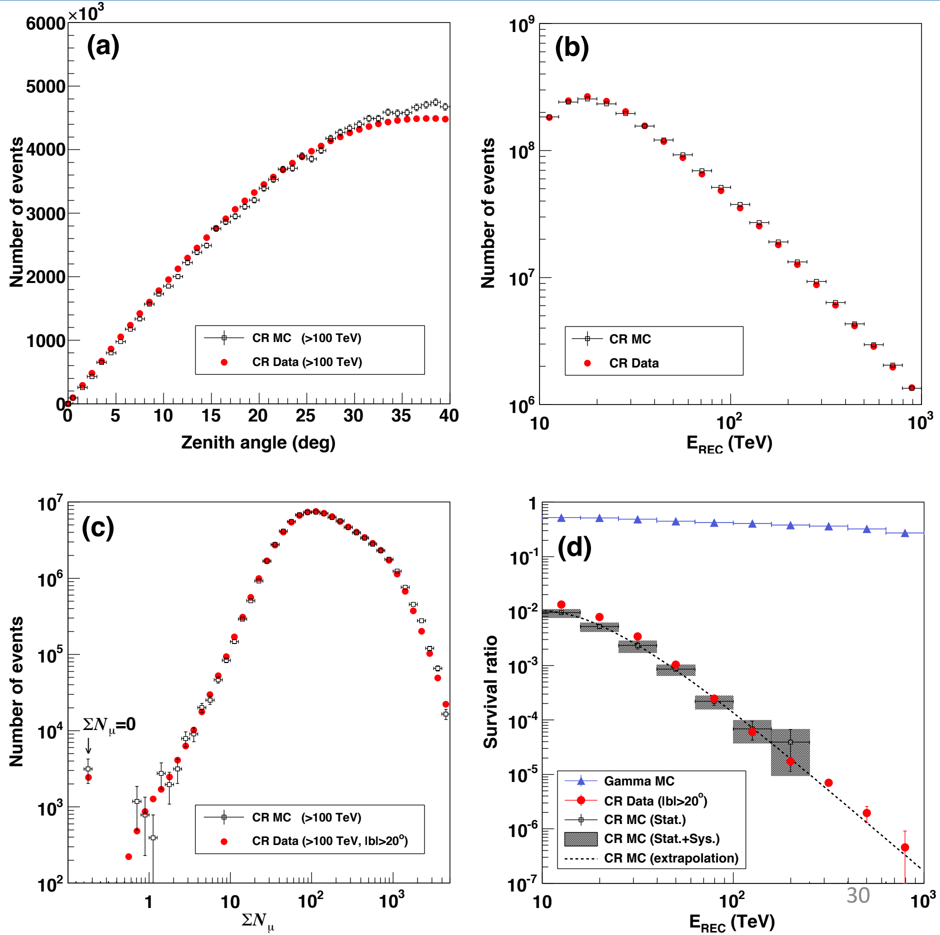
Strong evidence for sub-PeV γ rays induced by cosmic rays

Data/MC Comparison

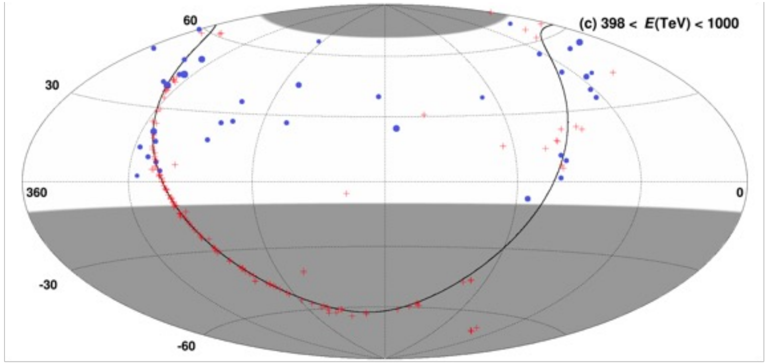
- ✓ AS generation: CORSIKA
- ✓ Hadronic int. model:
  EPOS-LHC + FLUKA
- ✓ Detectors: GEANT4

Reasonable agreement!

*Note: Cosmic-ray MC simulation is not used for the flux calculation or for any optimization of the analysis.

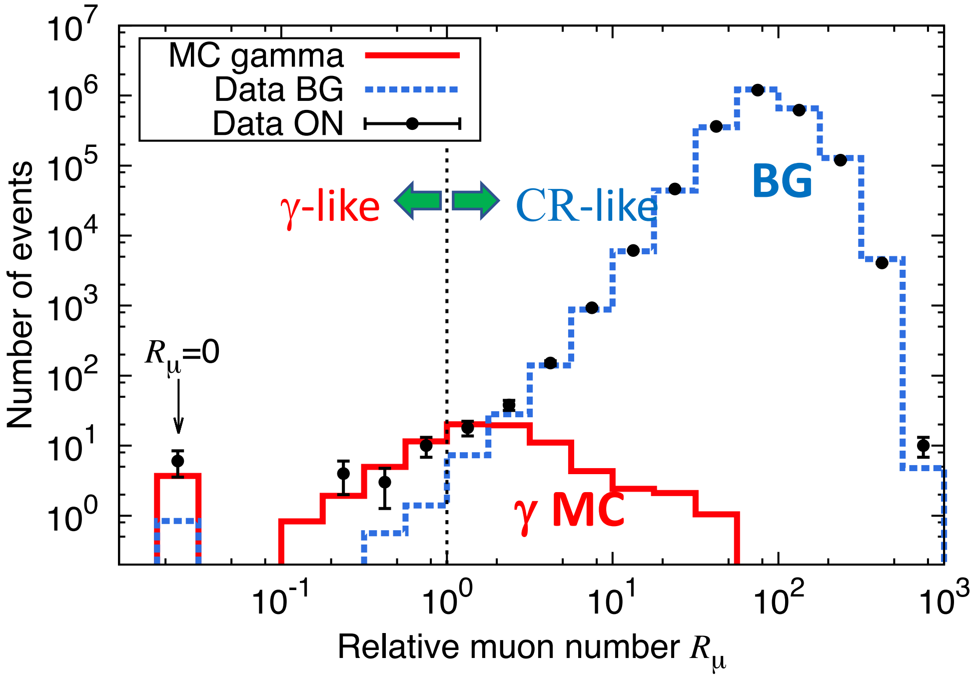


Muon Number Distribution (>398 TeV)



● ON region $|b| < 10^{o}$

BG region $|b| > 20^{o}$



Gamma Survival ratio :
30% by MC sim (>398TeV)

CR Survival ratio :
$\sim 10^{-6}$ (>398TeV=$10^{2.6}$TeV)

$$R\mu = \frac{\text{Observed \# of muons}}{\text{\# of muons at the cut value}}$$

Data Table

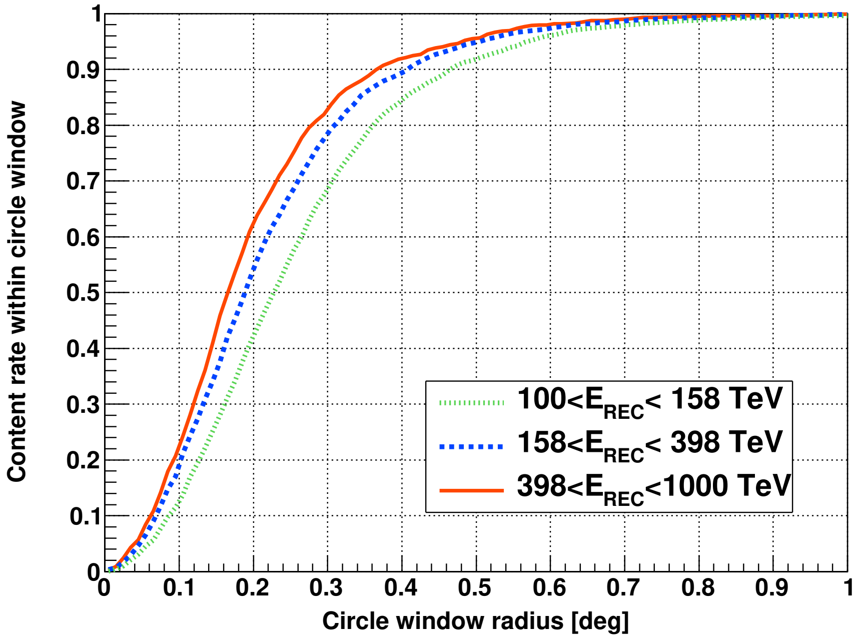
TABLE S1. Number of events observed by the Tibet AS+MD array in the direction of the galactic plane. The galactic longitude of the arrival direction is integrated across our field of view (approximately $22^\circ < l < 225^\circ$). The ratios (α) of exposures between the ON and OFF regions are 0.135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

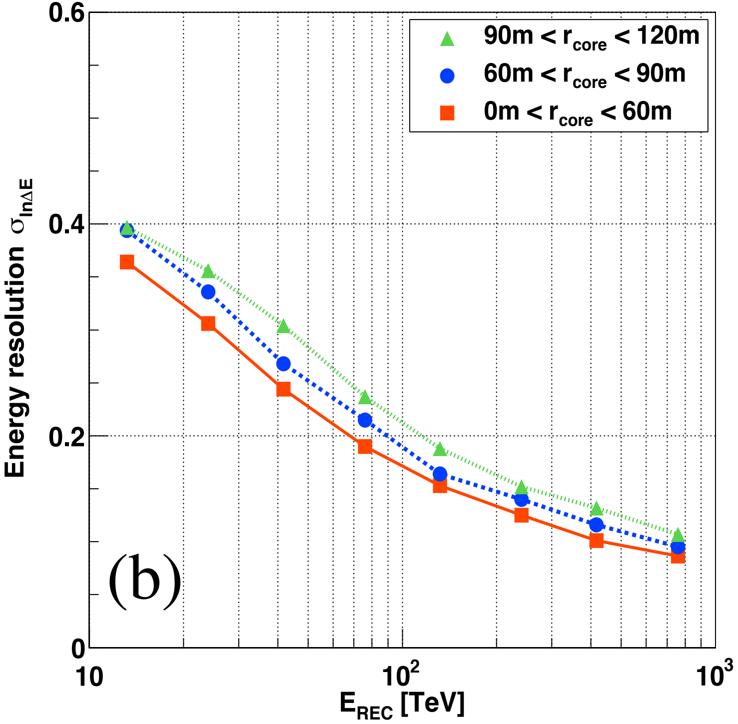
Energy bin (TeV)	$\lvert b\rvert < 5^\circ$ $N_{\rm ON}$	$\lvert b\rvert < 5^\circ$ $N_{\rm BG}$ $(= \alpha N_{\rm OFF})$	$\lvert b\rvert < 5^\circ$ Significance (σ)	$\lvert b\rvert < 10^\circ$ $N_{\rm ON}$	$\lvert b\rvert < 10^\circ$ $N_{\rm BG}$ $(= \alpha N_{\rm OFF})$	$\lvert b\rvert < 10^\circ$ 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 ($25^\circ < l < 100^\circ, \lvert b\rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50^\circ < l < 200^\circ, \lvert b\rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
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	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

Angular/Energy Resolutions





CASA-MIA Observation

TABLE 1

LIMITS TO DIFFUSE EMISSION

Region ($50° < l < 200°$)	Median Energy (TeV)	Significance (σ)	J_γ/J_{CR} 90% C.L. (10^{-5})
$-2° < b < 2°$ ……..	140	+1.78	7.2
	180	+1.81	3.8
	310	+2.56	5.2
	650	+1.12	3.2
	1300	+0.07	4.6
$-5° < b < 5°$ ……..	140	+1.63	3.4
	180	+0.08	2.6
	310	+0.86	2.4
	650	+1.60	2.6
	1300	+0.06	3.5
$-10° < b < 10°$……	140	+2.39	2.8
	180	+1.79	2.2
	310	+0.87	2.3
	650	+0.91	1.8
	1300	−0.56	2.3

NOTE.—Tabulated upper limits to diffuse gamma-ray emission from the plane of the Galaxy. Although positive excesses are seen, we do not view these as statistically significant enough to claim detections. Flux limits are tabulated for bands along the Galactic plane from $|b| < 2°$ to $|b| < 10°$. Median energy is quoted for integral flux limits. Selected spatial regions and energy bands are not statistically independent.

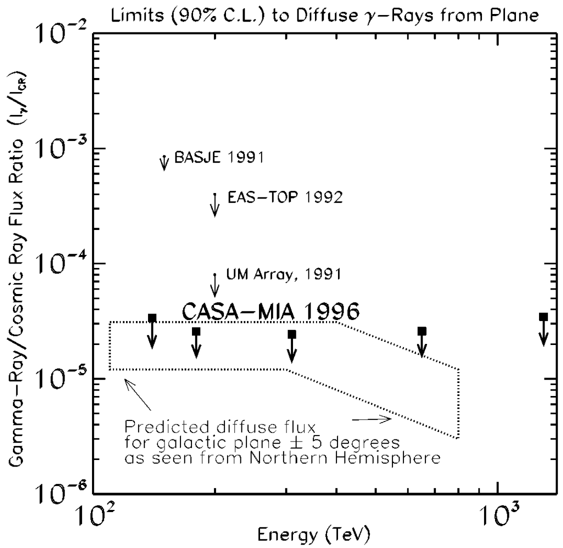


FIG. 4.—CASA-MIA sensitivity to diffuse gamma-ray emission from the central plane of the Galaxy ($|b| < \pm 5°$, $50° < l < 200°$). Sensitivities are given in terms of the fraction of gamma rays relative to the detected all-particle flux of cosmic rays at the Earth. Also shown are limits from previous experiments (BASJE—Kakimoto et al. 1991; EAS-TOP—Aglietta et al. 1992, UM—Matthews et al. 1991). Predicted flux from Aharonian (1991).

Borione et al., Astrophys. J. 493, 175 (1998)

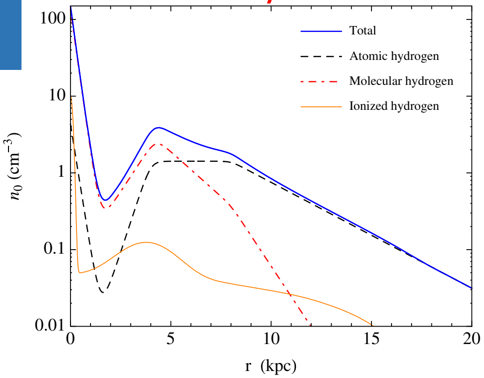
$[I_\gamma] / [I_{CR}] \sim 3 \times 10^{-5}$

Diffuse Model

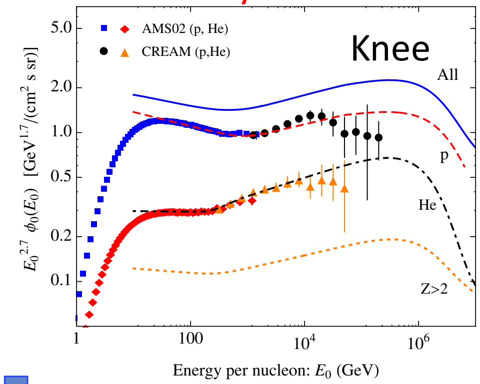
Lipari & Vernetto, PRD (2018)

Model can reproduce global structure
(not considered of the local structures)

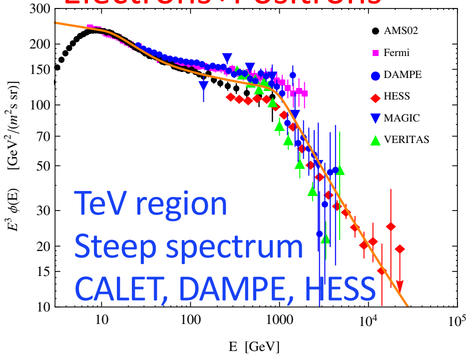
Gas density

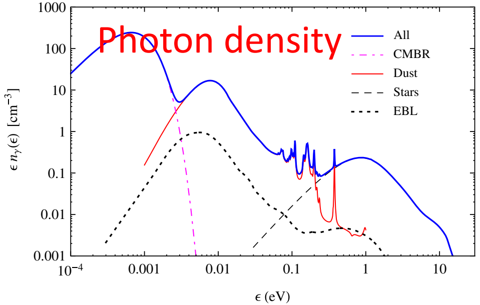


Cosmic rays



Electrons+Positrons

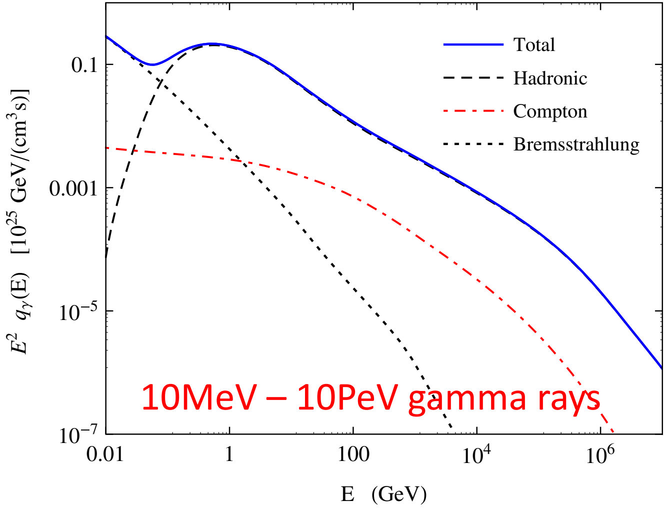




Brems.

Hadronic

Compton



Tibet ASγ

Cosmic Ray Pool × ISM

High-energy cosmic rays

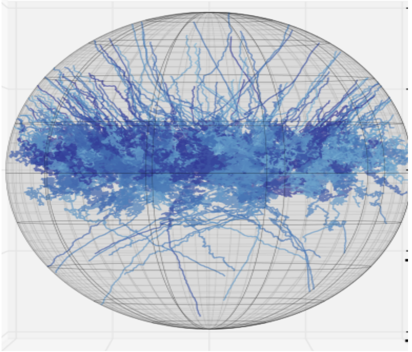
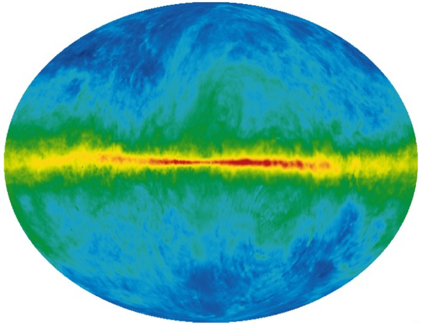


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop

×

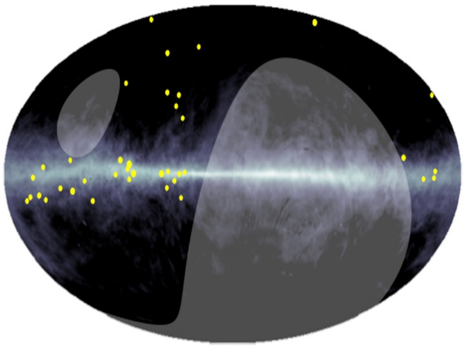
Interstellar matter



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

=

High-energy gamma rays



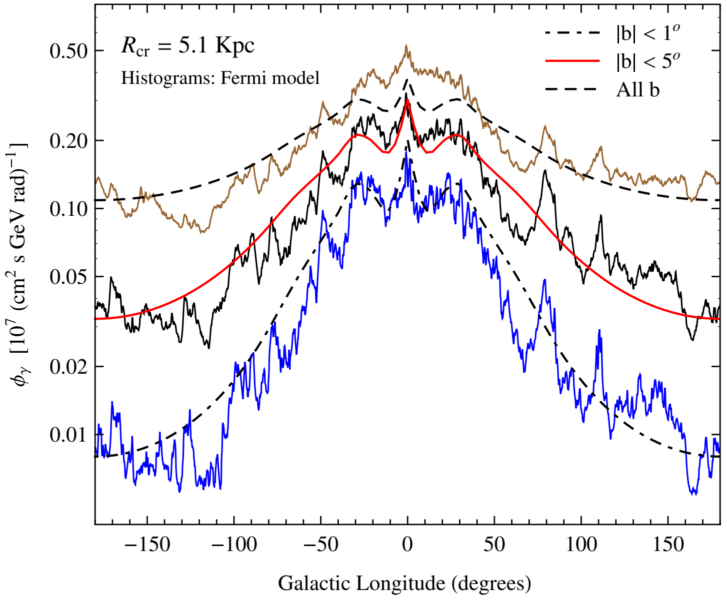
This Work

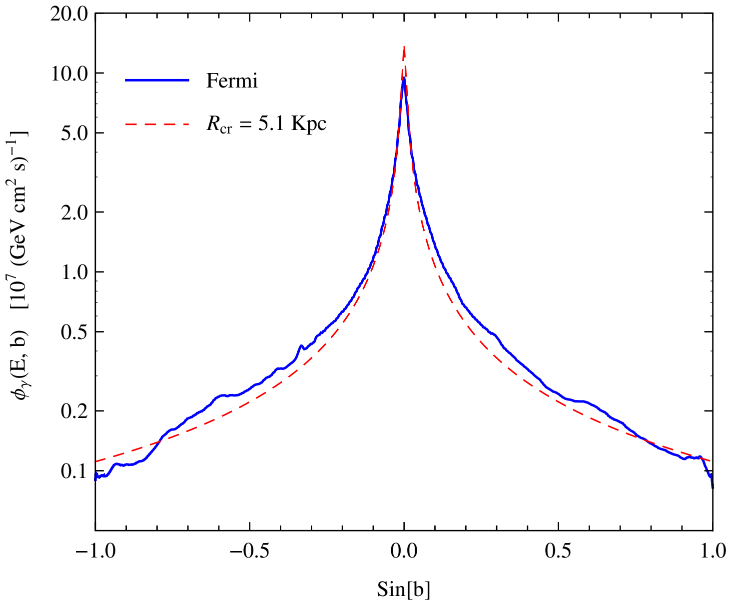
✓ This work proves a theoretical model that cosmic rays produced by PeVatrons are trapped in the Galactic magnetic field for millions of years, forming a pool of cosmic rays.

Reproducing Fermi-LAT Results

Model can reproduce global structure
(not taken into account of local structure)

Lipari & Vernetto, PRD (2018)

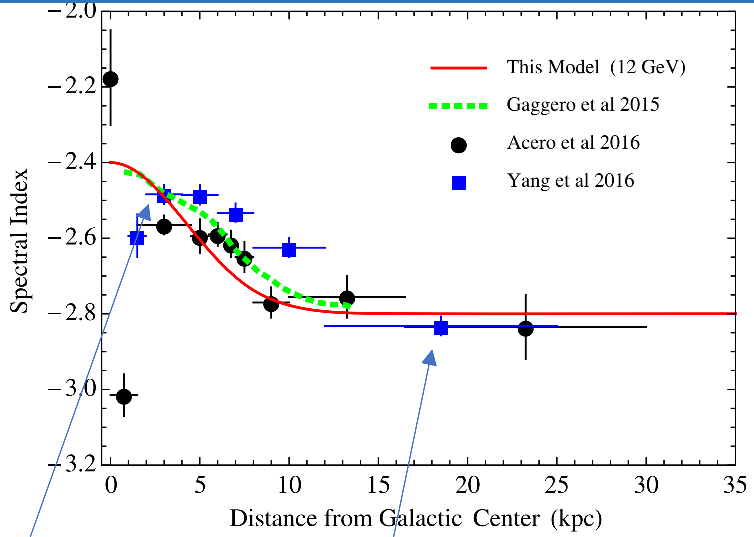


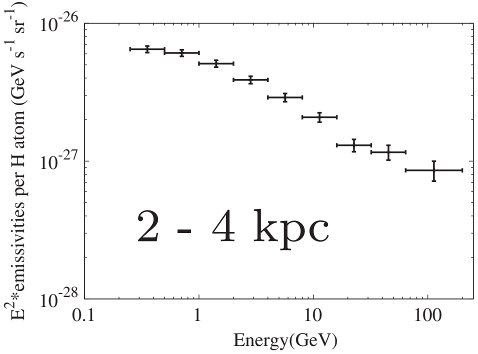


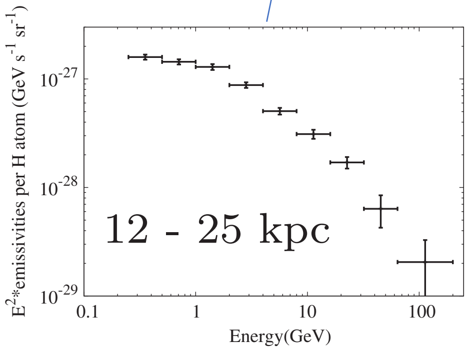
Space Dependence of CR Spectrum

Lipari & Vernetto, PRD (2018)

Harder gamma-ray spectral index, getting closer to the G.C. @12 GeV

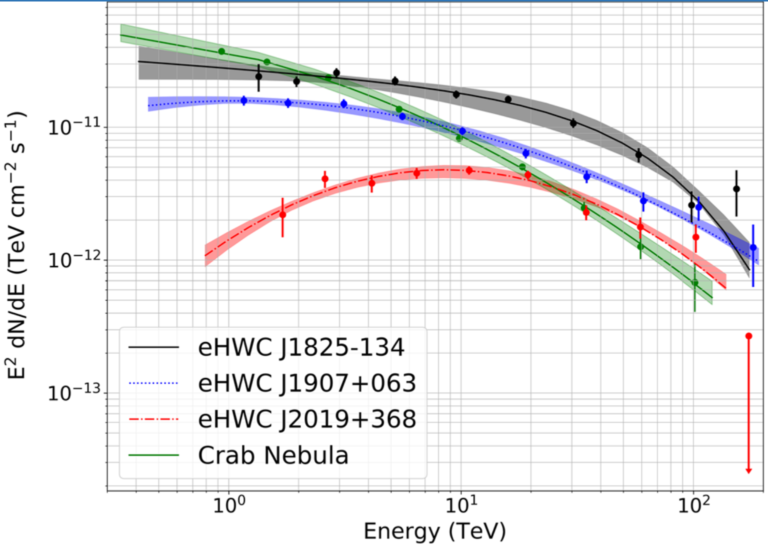






Yang et al., Phys. Rev. D 93, 123007 (2016)

How to Identify PeVatrons



eHWC J1825-134 (PWN?)

PSR J1826-1334

PSR J1826-1256

A few SNRs …

eHWC J1907+063 (PWN?)

PSR J1907+0602

SNR G40.5-0.5

eHWC J2019+368 (PWN?)

✓ Hard spectral index (~ -2)

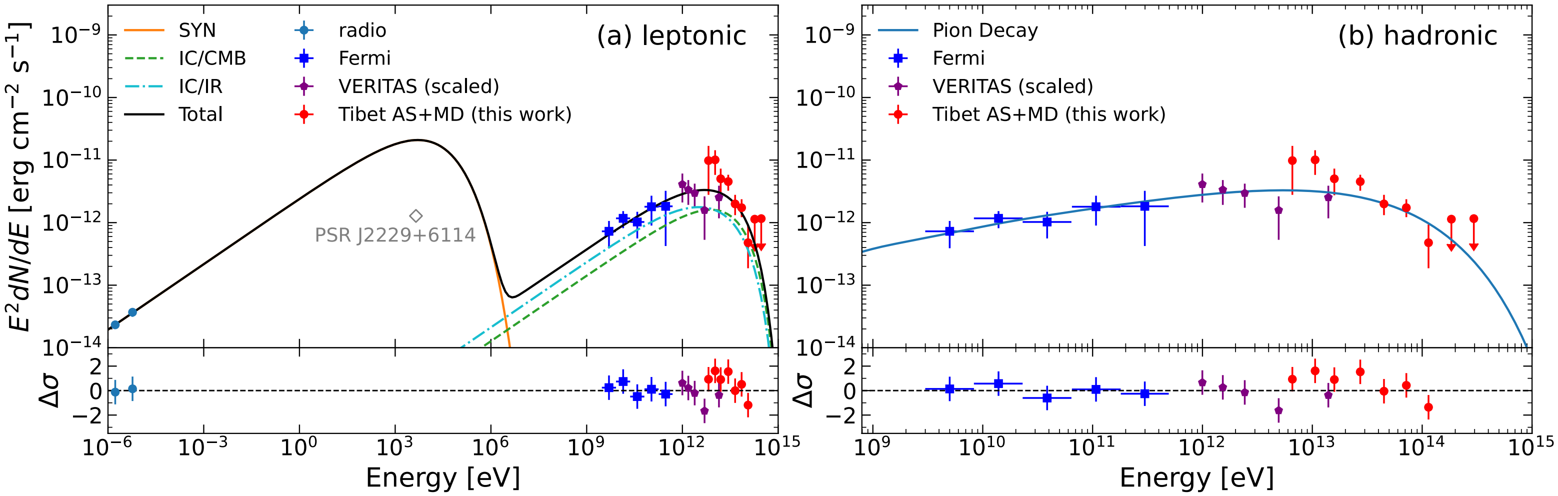
✓ Extended morphology

Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{\mathrm{TS}}$ > 56 TeV	Nearest 2HWC source	Distance to 2HWC source(°)	$\sqrt{\mathrm{TS}}$ > 100 TeV
eHWC J0534 + 220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534 + 220	0.02	4.44
eHWC J1809 − 193	272.46 ± 0.13	-19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809 − 190	0.30	4.82
eHWC J1825 − 134	276.40 ± 0.06	-13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825 − 134	0.07	7.33
eHWC J1839 − 057	279.77 ± 0.12	-5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837 − 065	0.96	3.06
eHWC J1842 − 035	280.72 ± 0.15	-3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844 − 032	0.44	2.70
eHWC J1850 + 001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849 + 001	0.20	3.04
eHWC J1907 + 063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908 + 063	0.16	7.30
eHWC J2019 + 368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019 + 367	0.02	4.85
eHWC J2030 + 412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031 + 415	0.34	3.07

Abeysekara et al., PRL, 124, 021102 (2020)

PeVatron Candidate: SNR G106.3+2.7

Amenomori et al., Nat. Astron (2021)



Electron spectrum: α=-2.3, E_{cut}=190TeV
Magnetic field: B=8.6μG
→ Cooling time τ_{sync}=0.9kyr << SNR age 10kyr

The required total energy of electrons is ~ 1.4 × 10^{47} erg, which only takes up ~ 2% of the spin-down energy released in the entire pulsar lifetime. If the rest of the spin-down energy goes into the magnetic field, the average magnetic field in the PWN would be much larger than the required value of 8 μG and results in very large fluxes at radio and X-ray wavelengths.

Pulsar Halo Model of Diffuse γ-Rays

Tim Linden and Benjamin J. Buckman, PHYSICAL REVIEW LETTERS 120, 121101 (2018)

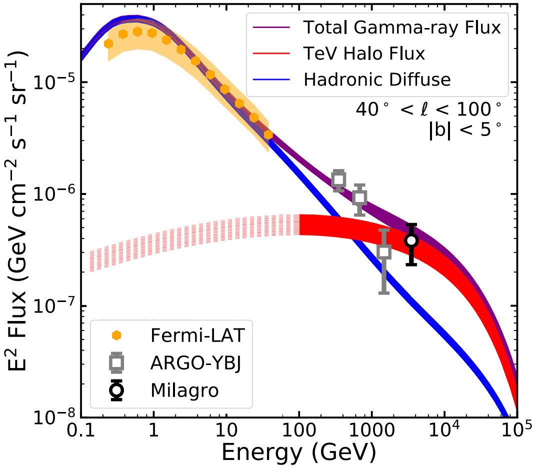


FIG. 1. The contribution of subthreshold TeV halos to the diffuse γ-ray emission along the galactic plane in the region $40° < \ell < 100°$, and $|b| < 5°$, compared to observations by the Fermi-LAT (described in the text), ARGO-YBJ [5], and Milagro [1]. The background (blue) corresponds to the predictions of 128 GALPROP models of diffuse γ-ray emission [8]. The contribution from TeV halos (red) is described in the text. TeV halos naturally reproduce the TeV excess observed by Milagro, while remaining consistent with ARGO-YBJ observations. The dashed red region indicates our ignorance of low-energy γ-ray emission from TeV halos.

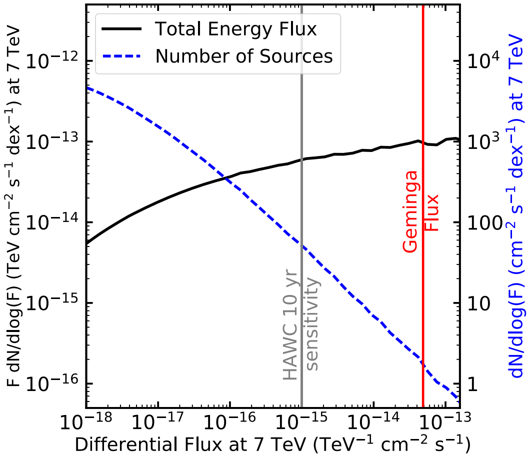
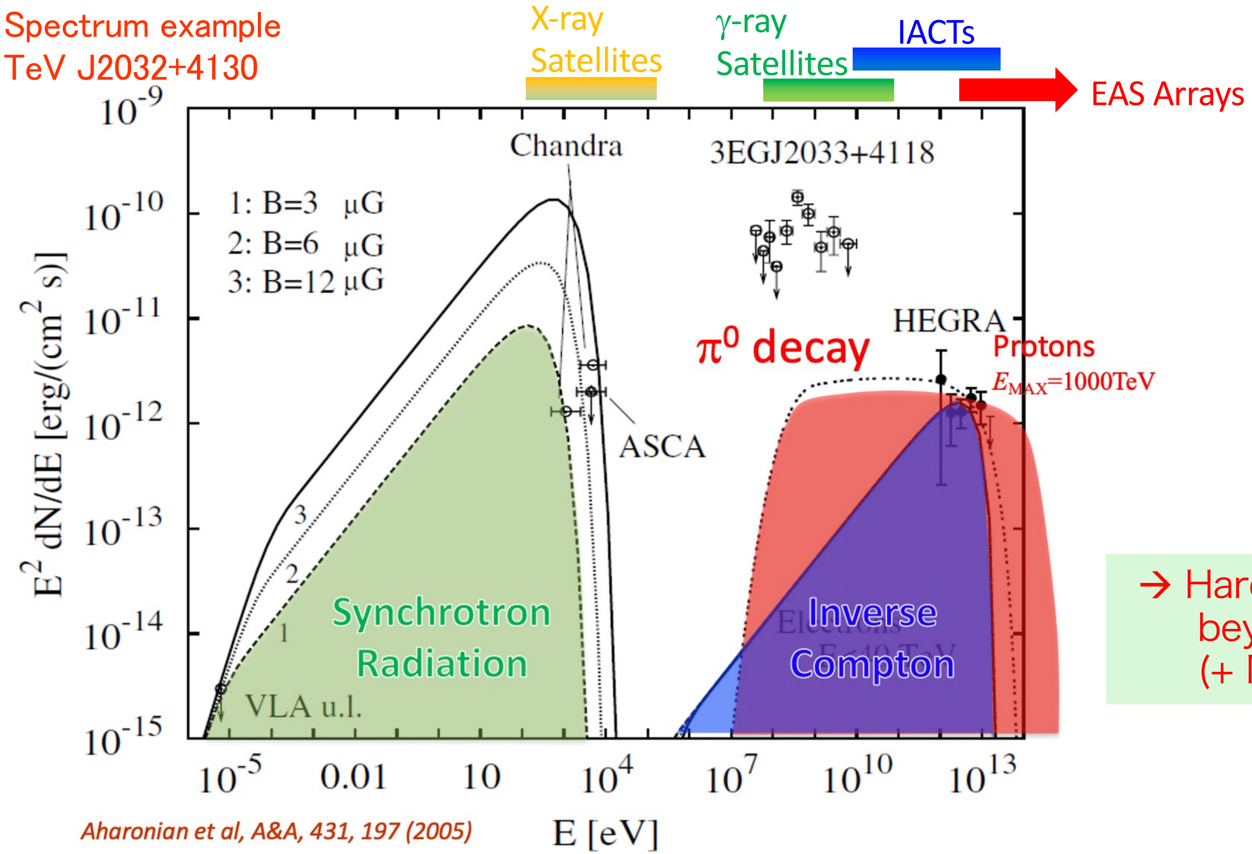


FIG. 3. The contribution of individual TeV halos to the TeV excess in the region $40° < \ell < 100°$, and $|b| < 5°$. We normalize our results at 7 TeV [19], assuming that individual TeV halos convert their spin-down luminosity into 7 TeV γ rays with an identical efficiency as Geminga. Vertical lines correspond to the flux of Geminga, and the projected 10 yr HAWC sensitivity. Results are shown for the total γ-ray flux [$FdN/d\log_{10}(F)$, black, left y axis], which indicates that most of the γ-ray intensity stems from the bright TeV halos, as well as for the source count [$dN/d\log_{10}(F)$, blue, right y axis], which indicates that 10 yr HAWC data will observe ~50 TeV halos in the ROI. For illustrative purposes, in this plot we show the contribution from TeV halos with individual fluxes exceeding Geminga, predicting the existence of only ~1 such system.

How to Identify PeVatrons

Spectrum example
TeV J2032+4130



Aharonian et al, A&A, 431, 197 (2005)

→ Hard spectral index (–2) beyond 100 TeV (+ Molecular Cloud)

How to Identify PeVatrons

- γ-ray beyond 100 TeV by Tibet, HAWC etc. in North,
  ALPACA, SWGO in south will come soon
- Spectral index $\alpha \sim -2$ in TeV by IACTs
- Coincident with molecular cloud observed by radio
- π^0 cutoff around 70 MeV by γ-ray satellites
- Dark in X-ray observation
- Deep observation by IACTs to resolve sources
- Coincident with HE neutrino by IceCube

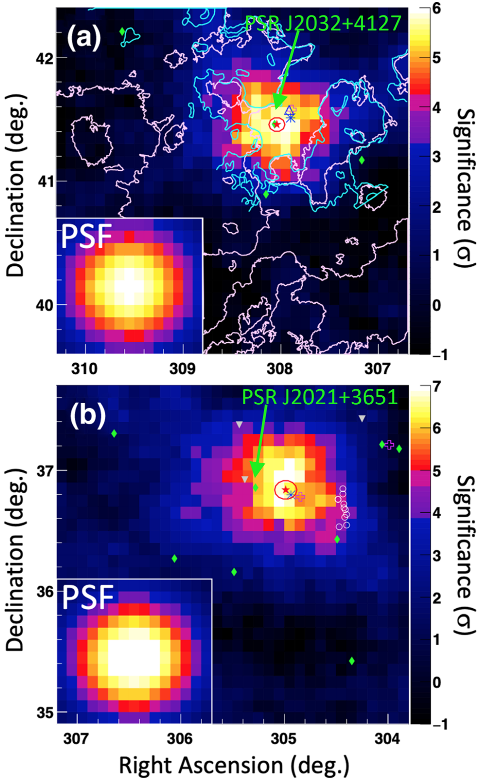
Multi-wavelength Multi-particle Observations

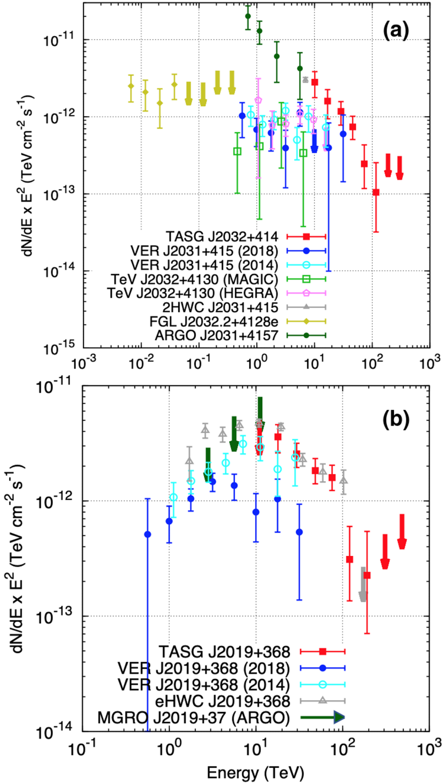
Cygnus OB1 & OB2 in the 100 TeV region

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

Cyg. OB2

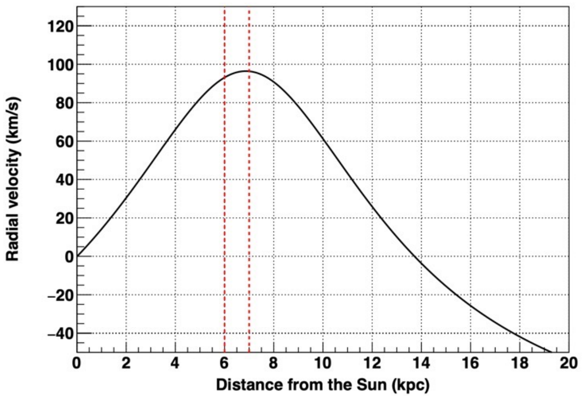
Cyg. OB1

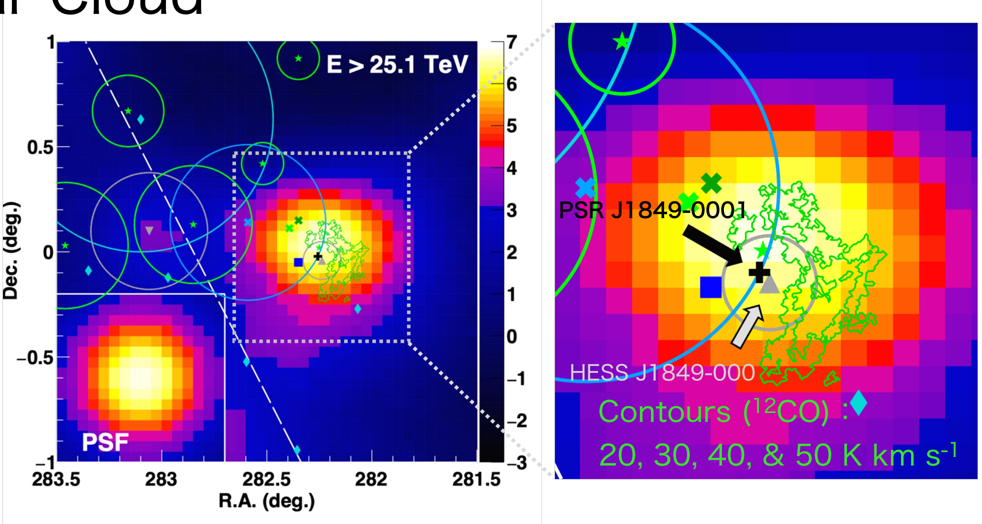




Detection of a Molecular Cloud

Distance-velocity map





- ✓ Analysis of archive ^{12}CO (J=1-0) data (FUGIN[1])
- ✓ Assumed istance : 7 kpc[2]
- ✓ Integration of velocity range of 93-100 km s^{-1}

  => A ~20 pc size cloud w/ T_b ~20 K km s^{-1} @ the west of HESS J1849-000
- ✓ Overlap b/w γ-ray emission & cloud
- ✓ Gas density : np = Xco T_{mb} / R ~ 70 cm^{-3} (Xco = 2×10^{20} cm^{-2} (K km s^{-1})$^{-1}$)[3]

  => Can provide the gas density of ≳ 10 cm^{-3}

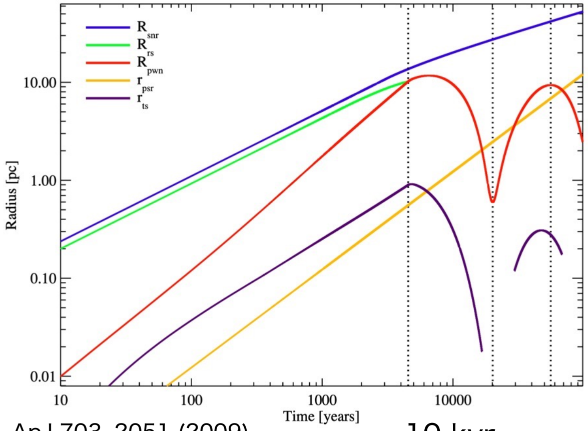
1. Umemoto+, PASJ 69, 5 (2017)
2. Gotthelf+, ApJL 729, L16 (2011)
3. Bolatto+, Ann. Rev. Astron. Astrophys 51, 207 (2013)

Possible Acceleration Mechanism of PeV CRs

✓ CR acceleration in a <u>PWN-SNR composite system</u>[1,2] ??

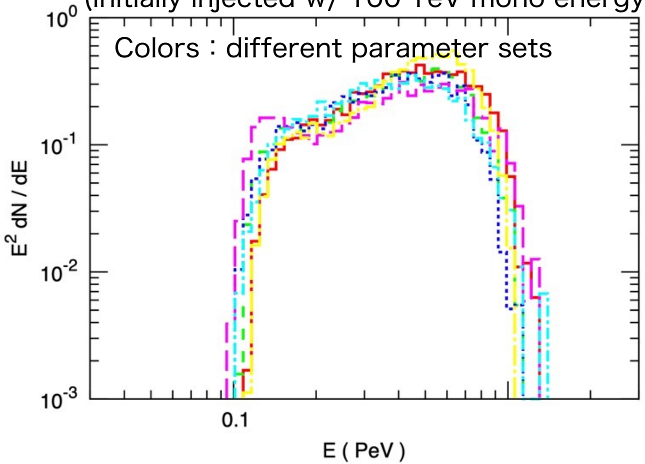
- CR protons pre-accelerated up to ~100 TeV in the SNR FS are re-accelerated up to ~ 1 PeV in the PWN compressed by the SNR reverse shock
- ~10^{49} erg is given to the accelerated particles[1]
- PWN is compressed to ~10% of the original size[1,2]
- *B* of the PWN is amplified up to ~ 100 μG[1]
  => compact synchrotron X-ray emission by $e^{\pm}$ of PWN origin??

Evolution of the size of the system



10 kyr

Energy spectrum of CR protons[2]
(Initially injected w/ 100 TeV mono energy)

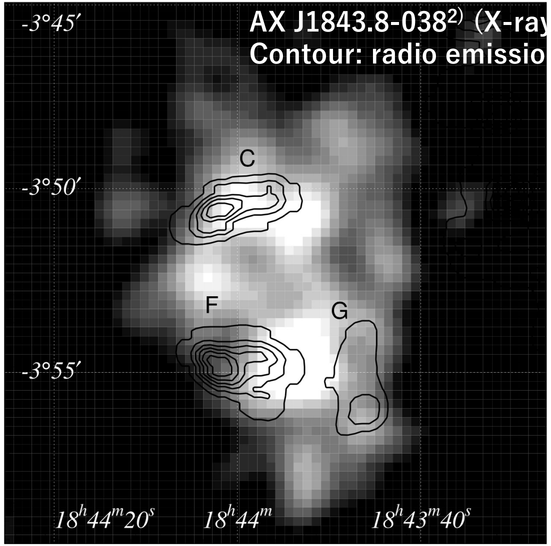


1. Gelfand+, ApJ 703, 2051 (2009)
2. Ohira+, MNRAS 478, 926 (2018)

Discussion (1): Association of TASG J1844-038 w/ SNR G28.6-0.1 (1)

SNR G28.6-0.1

- Nonthermal radio[1)] & X-rays[2)] by electron synchrotron radiation
- Shell-type SNR[2)]
- Distance: 9.6$\pm$0.3 kpc[3)]
- Age: 2.7 kyr[2)] or 19 kyr[3)]



TASG J1844-038's radius: $\sigma = 0.34° \pm 0.12°$

AX J1843.8-0352's radius (X-rays): $\sigma_{mean} = 0.075°$ (4.5')[4)]

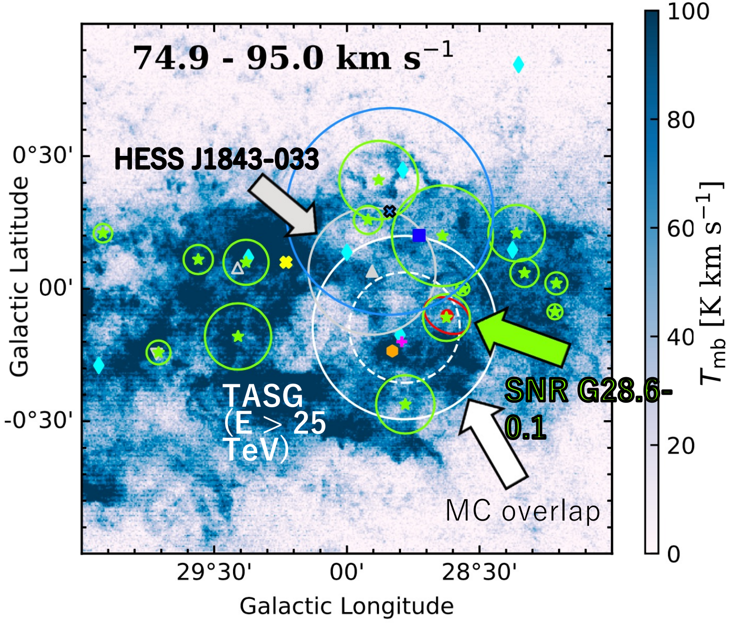
Discrepancy in their extensions at the 2.3 σ level

=> Contribution of gamma rays of hadronic origin ?
(CR interaction w/ ambient molecular clouds ?)

1) Helfand et al., ApJ 341, 151 (1989)
2) Bamba et al., PASJ 53, L21 (2001)
3) Ranasinghe & Leahy, MNRAS 477, 2243 (2018)
4) Ueno et al., ApJ 588, 338 (2003)

Discussion (1): Association of TASG J1844-038 w/ SNR G28.6-0.1 (2)

[12]CO (J = 1 - 0) map from the FUGIN data[1)]



Several resemblances to SNR G106.3+2.7[2)]:

1. Overlapping molecular clouds (MCs),
2. Max. energy of CR protons: ≃ 500TeV, &
3. Average of the estimated ages is ≃ 10 kyr.

=> **Could have been a PeVatron in the past??**

Diffusion time of CR protons through MCs[3)]:

$$\tau_{\rm diff} = \frac{R_{\rm cl}^2}{6D(E)} \sim 1.2\cdot 10^4 \chi^{-1} \left(\frac{R_{\rm tot}}{20\ {\rm pc}}\right)^2 \left(\frac{E}{\rm GeV}\right)^{-0.5} \left(\frac{B}{10\ \mu{\rm G}}\right)^{0.5}\ {\rm yr}$$

where R, size of MCs & χ , suppression factor.

Assuming χ = 0.1 & B = 10 μ G (n_H ~ 100 cm^{-3}),

$\tau_{\rm diff}\,(R_{\rm TASG}, E_{\rm CR} > 250\ {\rm TeV}) \lesssim 2.0\ {\rm kyr}$ &

$\tau_{\rm diff}\,(R_{\rm HESS}, E_{\rm CR} \simeq 10\ {\rm TeV}) \simeq 4.9\ {\rm kyr}.$

Acceptable compared w/ the SNR's age

1) Umemoto et al., PASJ 69, 78 (2017)
2) Amenomori et al., Nat. Astron. 5, 460 (2021)
3) Gabici et al., Astrophys. Space Sci. 309, 365 (2007)

Amenomori et al., ApJ 932, 120 (2022)

TASG J1844-038

Discussion (2): Association of TASG J1844-038 w/ PSR J1844-0346

PSR J1844-0346

- Gamma-ray PSR discovered by the Einstein@home project[1)]
- P = 113 ms, τ_c = 12 kyr & $\dot{E} = 4.2 \times 10^{36}$ erg s^{-1}
- Pseudo distance: 4.3 kpc[2)]

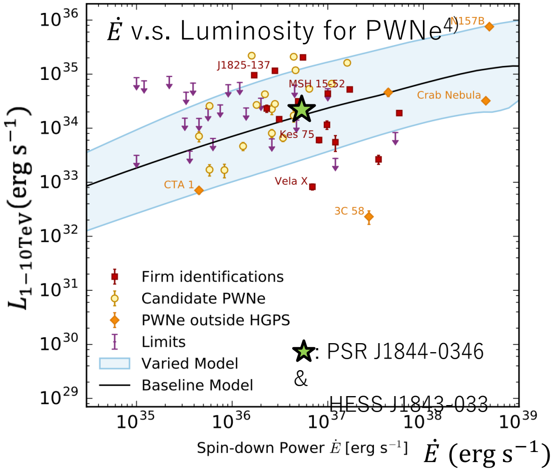
HESS J1843-033[3)]

- L (1 TeV < E < 10 TeV) = 2.4×10^{34} erg s^{-1} [3)] (@ 4.3 kpc)
- Size: $\simeq$ 18 pc (@ 4.3 kpc)
- Spectral index: $\simeq$ 2.0 (from the ECPL fit in this work)

=> has characteristics typical of TeV PWNe[4)].

ICS off CMB is acceptable

- $e^{\pm}$ w/ E ≈ 90 TeV scatters off CMB up to $E_{\gamma,\mathrm{cutoff}} \approx$ 50 TeV[5)].
- Size of TASG J1844-038: $\simeq$ 26 pc (@ 4.3 kpc)
- Assuming Geminga-like env.[6)] with B = 3 μG, D = 4.4×10^{27} cm^2 s^{-1},
  $\tau_{\mathrm{diff}} \simeq$ 8 kyr
- Cooling time of $e^{\pm}$ by sync. & ISC[5)]: $\tau_{\mathrm{cool}} \simeq$ 11 kyr
  => $\tau_{\mathrm{diff}} < \tau_{\mathrm{cool}}$ & $\tau_{\mathrm{diff}} < \tau_c$



1) Clark et al., ApJ 834, 106 (2017)
2) Devin et al., A&A 647, 68 (2021)
3) H.E.S.S. collaboration, A&A 612, A1 (2018)
4) H.E.S.S. collaboration, A&A 612, A2 (2018)
5) Hinton & Hofmann, Ann. Rev. of Astron. & Astrophys. 47, 523 (2009)
6) Abeysekara et al., Science 358, 911 (2017b)

Moon Shadow as a Calibration Source

✓Absolute Energy Scale

- Energy dependence of E-W displacement

✓Pointing Accuracy

- N-S displacement

✓Angular Resolution

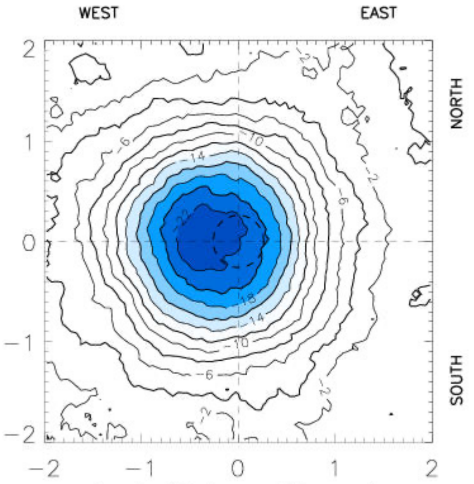
- Deficit Shape

✓Detector Stability

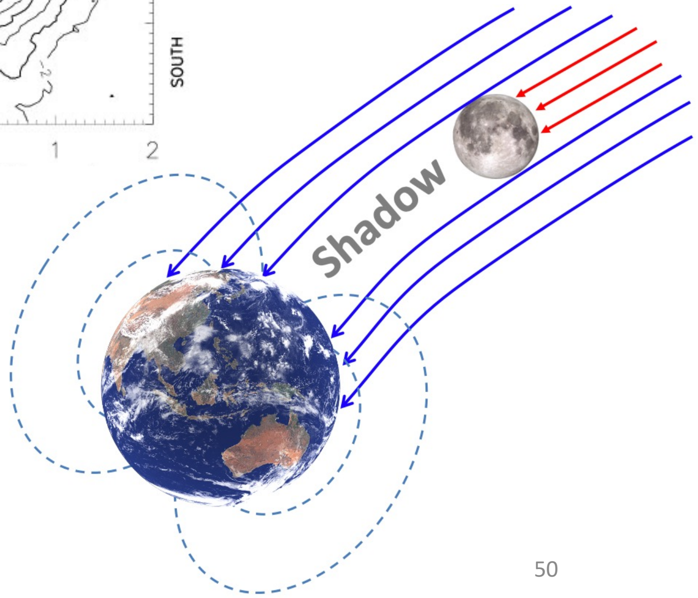
- Temporal variation

✓Anti-P / P Ratio

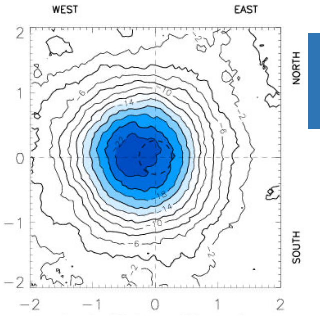
- Opposite-side deficit



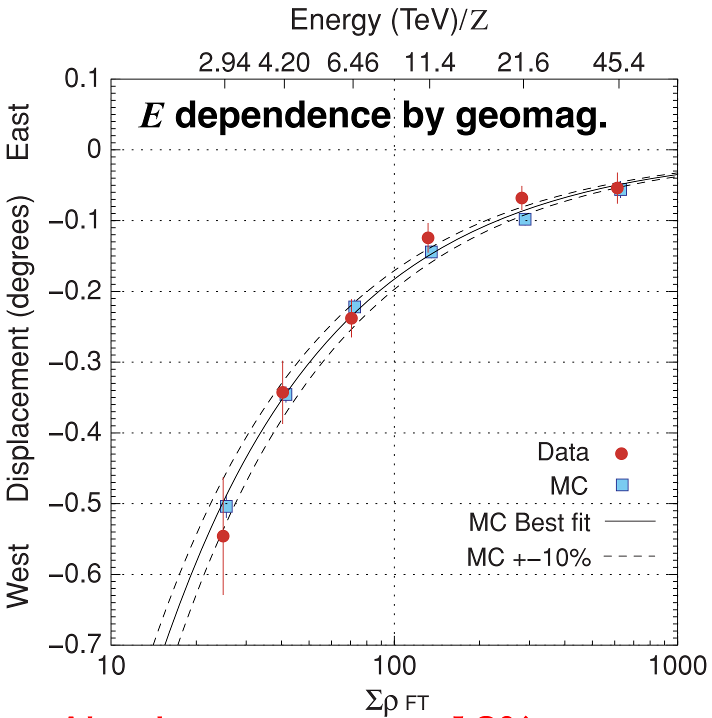
$$\Delta\theta \sim \frac{1.6^o}{E[\mathrm{TeV}]}$$

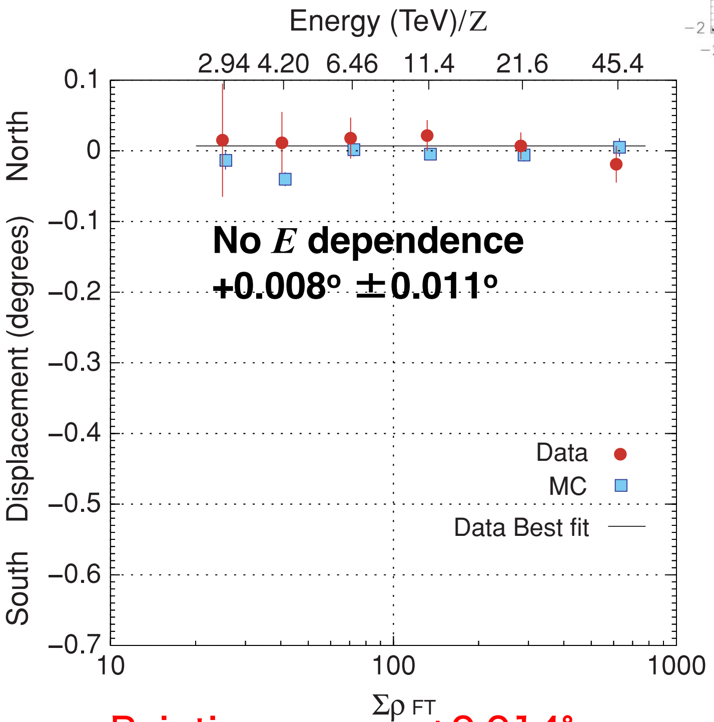


Moon Shadow as a Calibration Source



✓ Tibet ASγ experiment first time utilized the Moon shadow as the absolute energy calibration.





Absolute *E* error = ±12%

Best-fit = -4.5%(±8.6stat.±6.7sys.)%

Pointing error = ±0.014°

Amenomori et al., ApJ (2009), ICRC2005