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Physics See Viewpoint: Signs of PeVatrons in Gamma-Ray Haze

Observation of Ultra-High-Energy Diffuse Gamma Rays from the Galactic Plane with the Tibet Air Shower Array

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For the Tibet ASγ Collaboration

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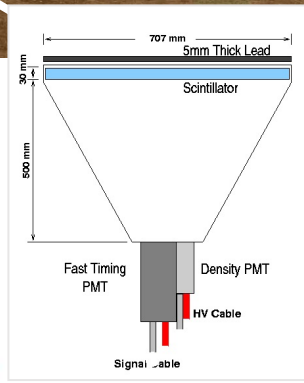
Tibet Air Shower Array



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

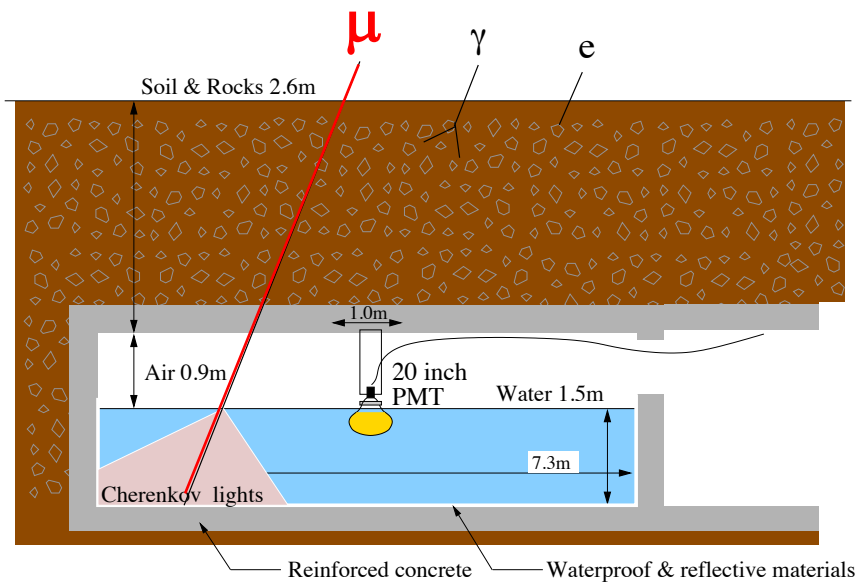
Present Performance

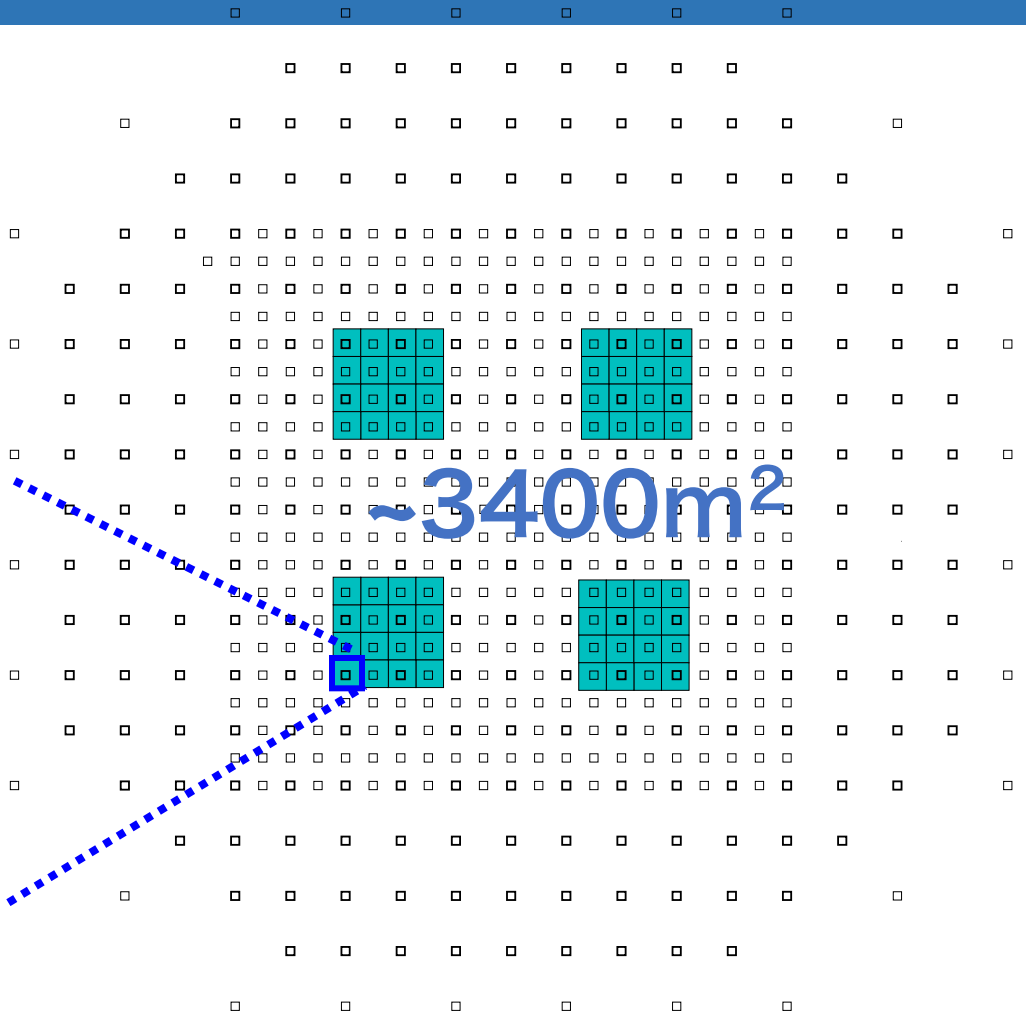
✓	# of detectors	0.5 m^2 x 597
✓	Covering area	~65,700 m^2
✓	Angular resolution	~0.5°@10TeV γ
		~0.2°@100TeV γ
✓	Energy resolution	~40%@10TeV γ
		~20%@100TeV γ

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

Underground WC Muon Detectors

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





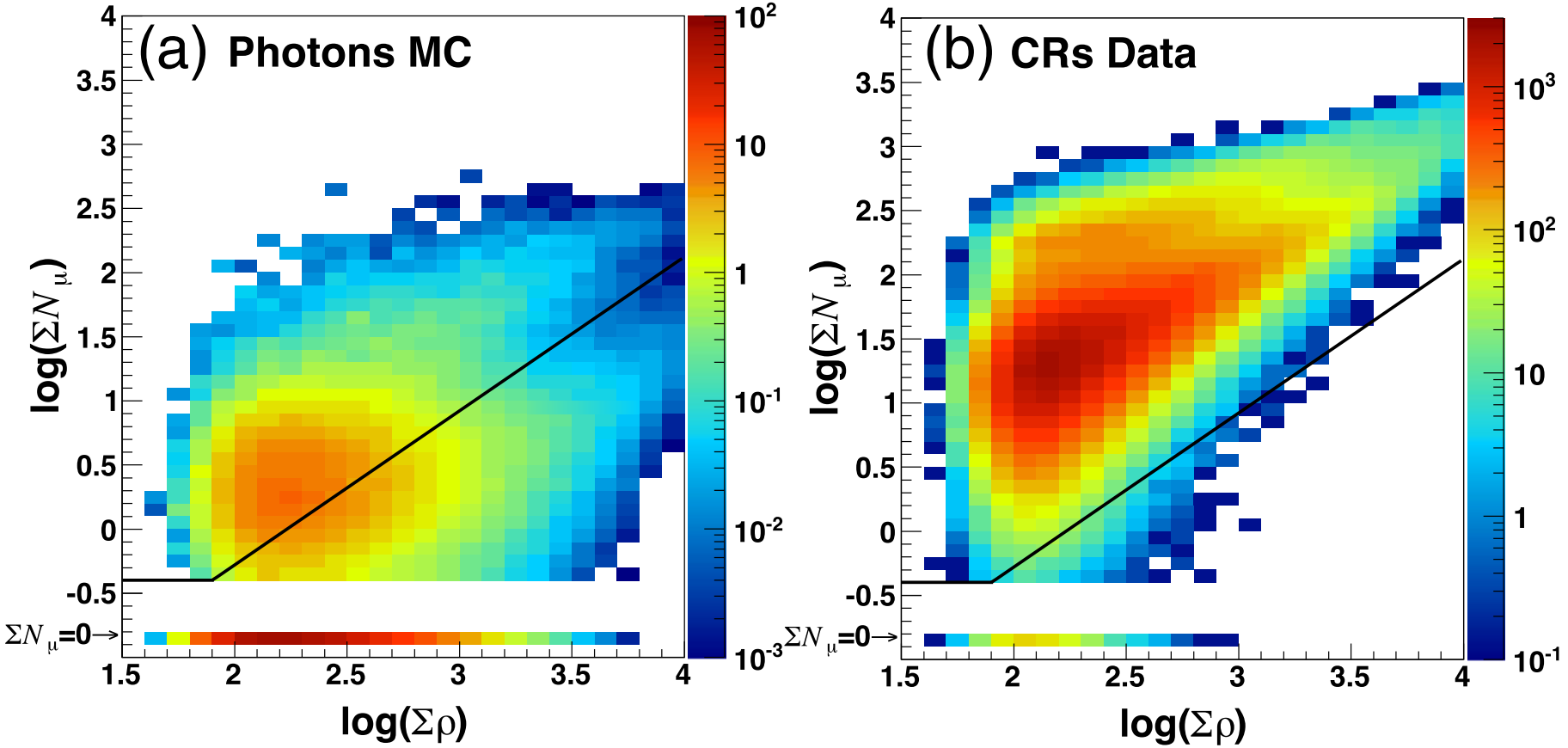
Measurement of # of μ in AS → γ／CR discrimination

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

Muon Cut Condition (Standard)

Standard muon cut : $\Sigma N\mu < 2.1 \times 10^{-3}\ \Sigma\rho^{1.2}$

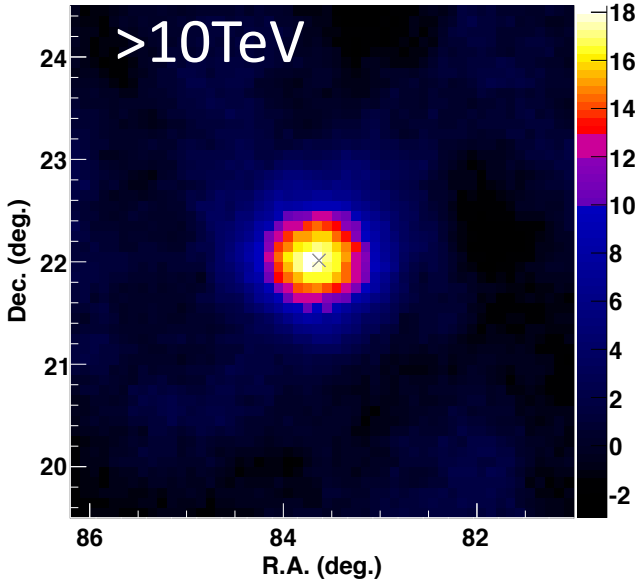
→ Optimized for the gamma-ray point-like source

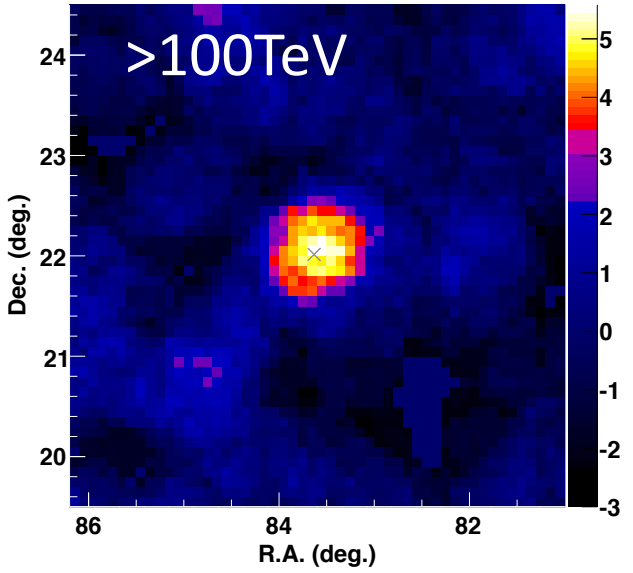


Gamma Survival ratio : ~90% by MC sim (>100 TeV)

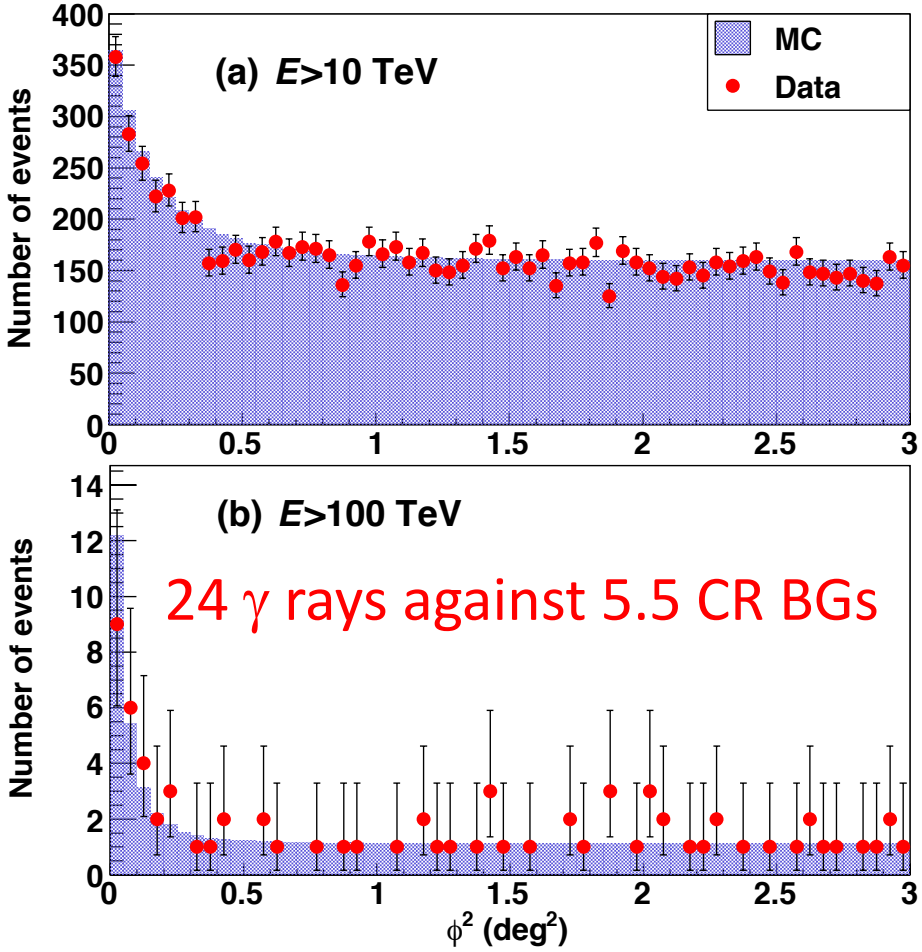
CR Survival ratio : ~10^{-3} (>100 TeV)

Sub-PeV Emission from the Crab Nebula





Data vs MC



24 γ rays against 5.5 CR BGs

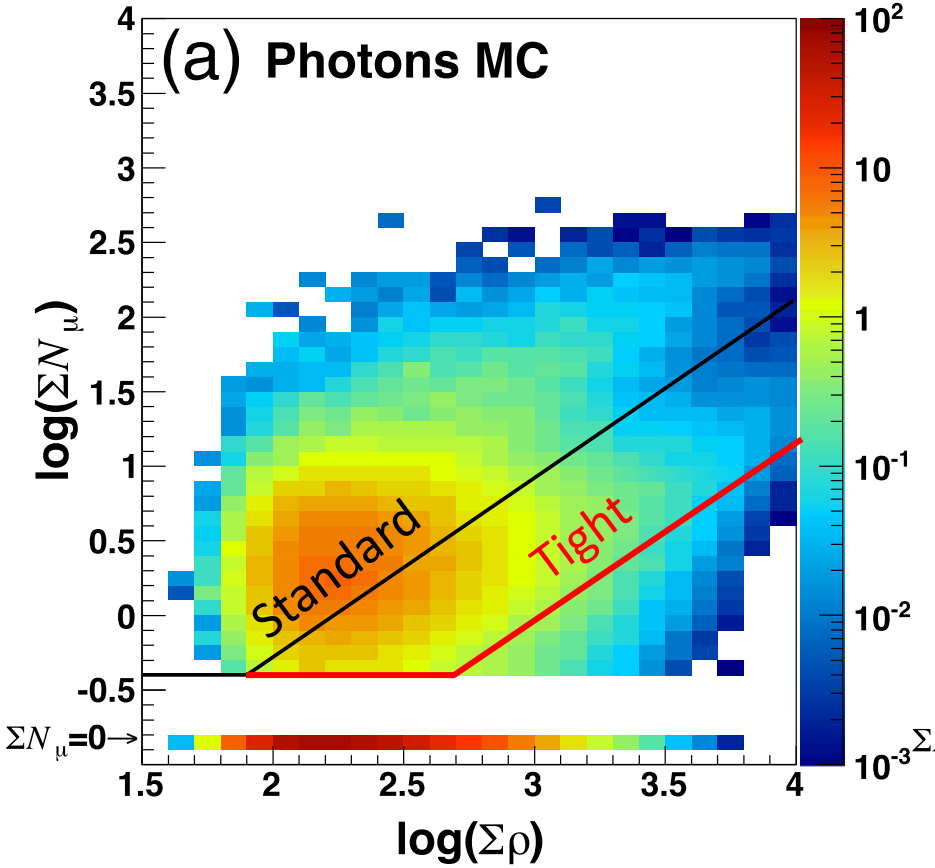
First Detection of Sub-PeV γ (5.6σ)

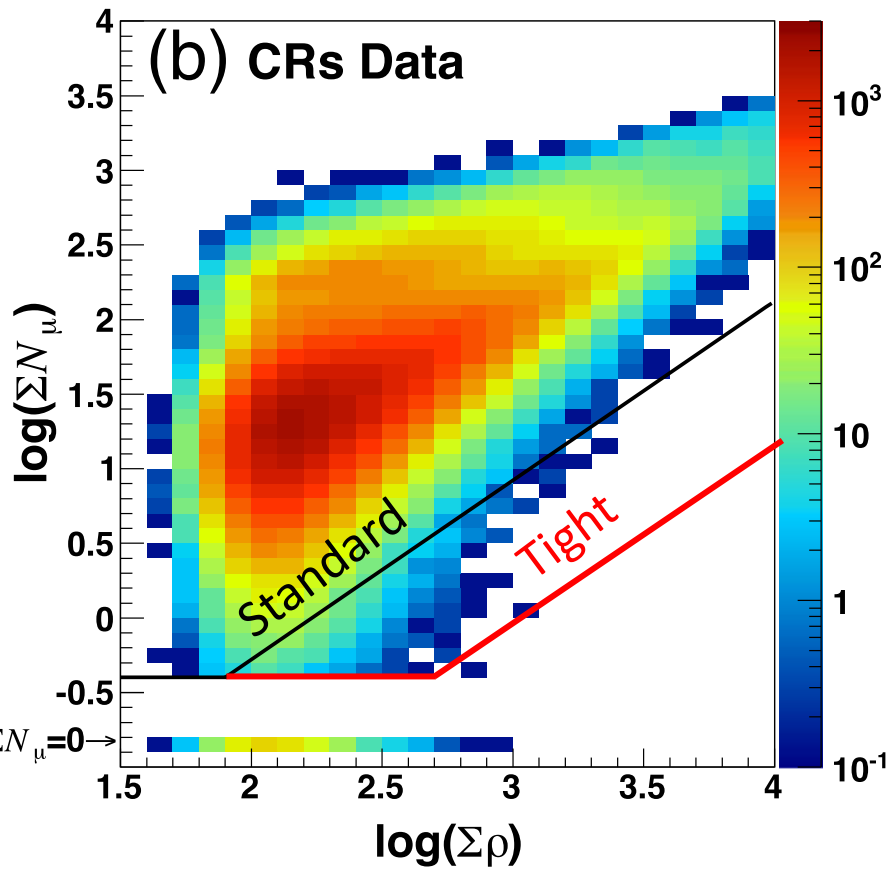
Amenomori et al., PRL 123, 051101 (2019)

Muon Cut Condition (Tight)

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)

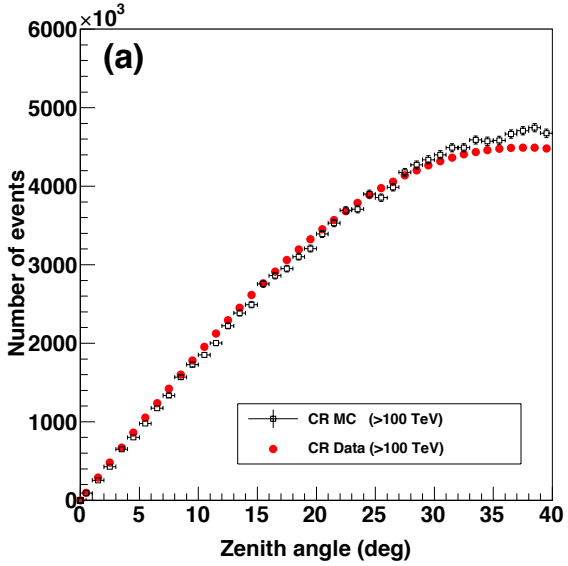
CR Survival ratio : ~10^{-6} (>398TeV=$10^{2.6}$TeV)

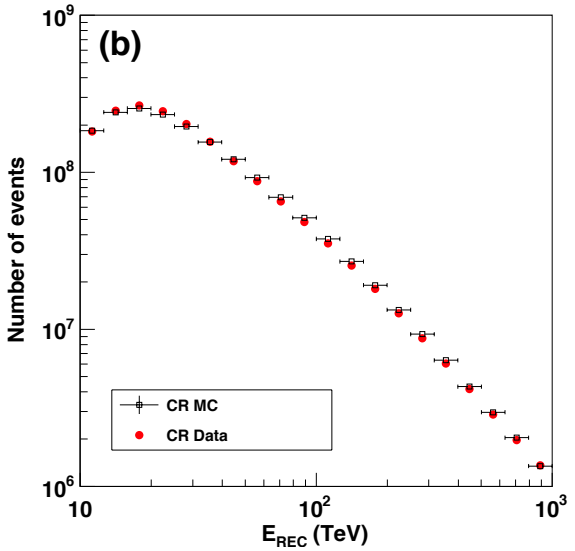
Data/MC Comparison

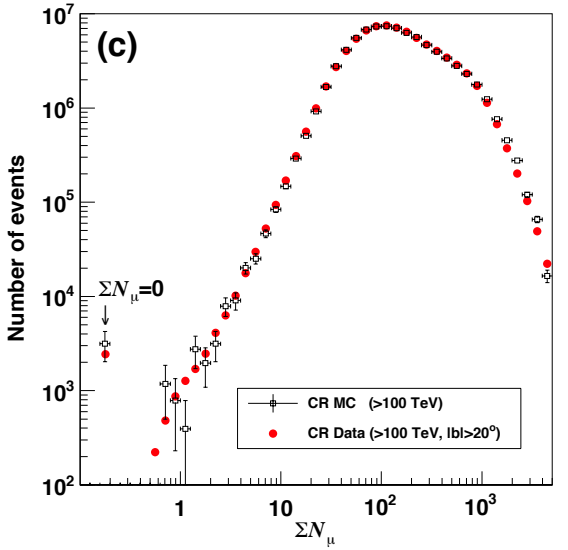
- ✓ AS generation: CORSIKA
- ✓ Hadronic int. model: EPOS-LHC + FLUKA
- ✓ Detectors: GEANT4

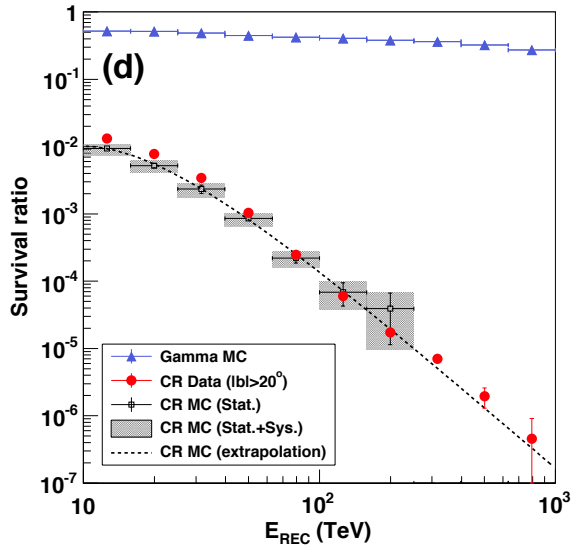
Reasonable agreement!

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







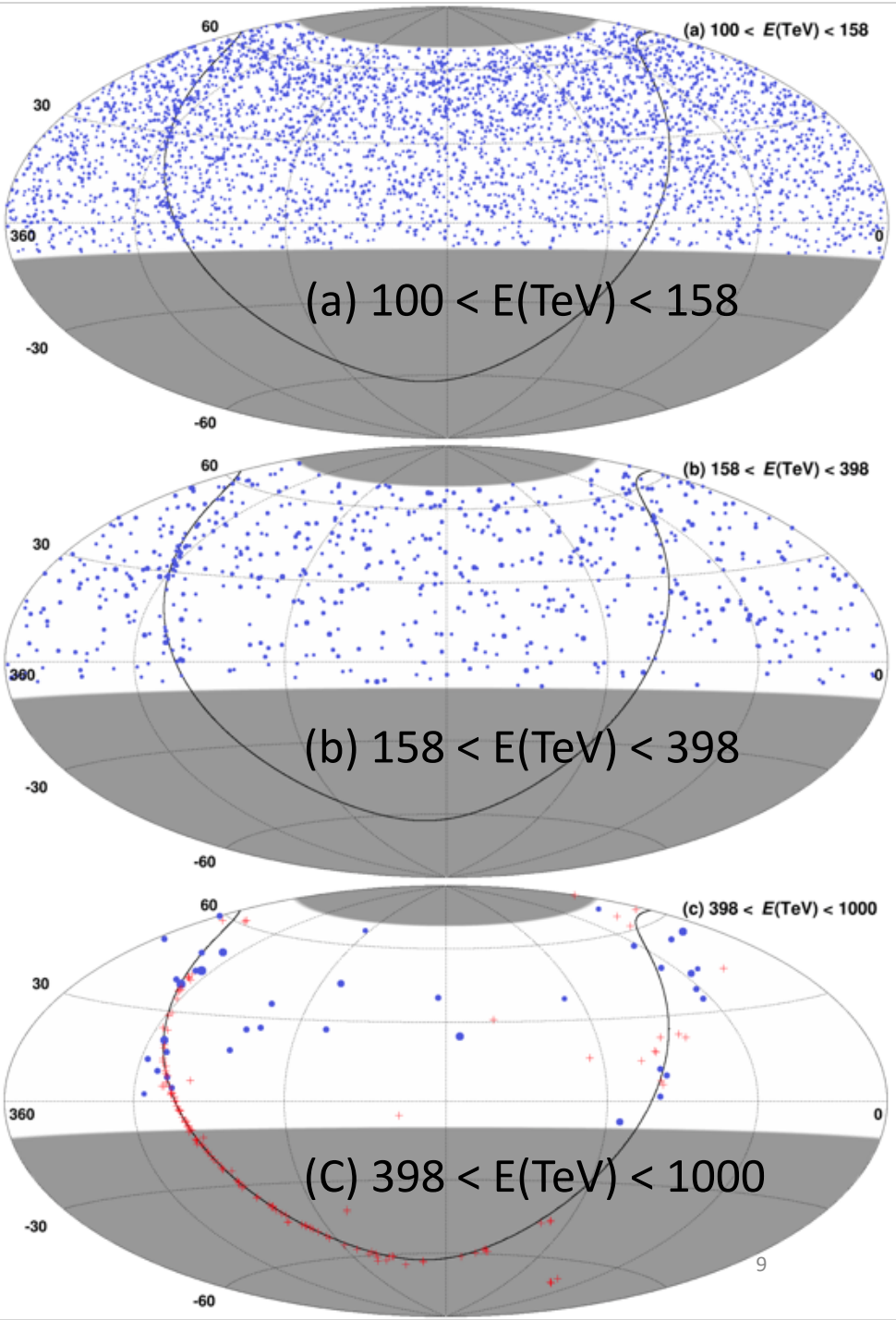


γ-ray-like event Distribution

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 $|b| < 5^{o}$

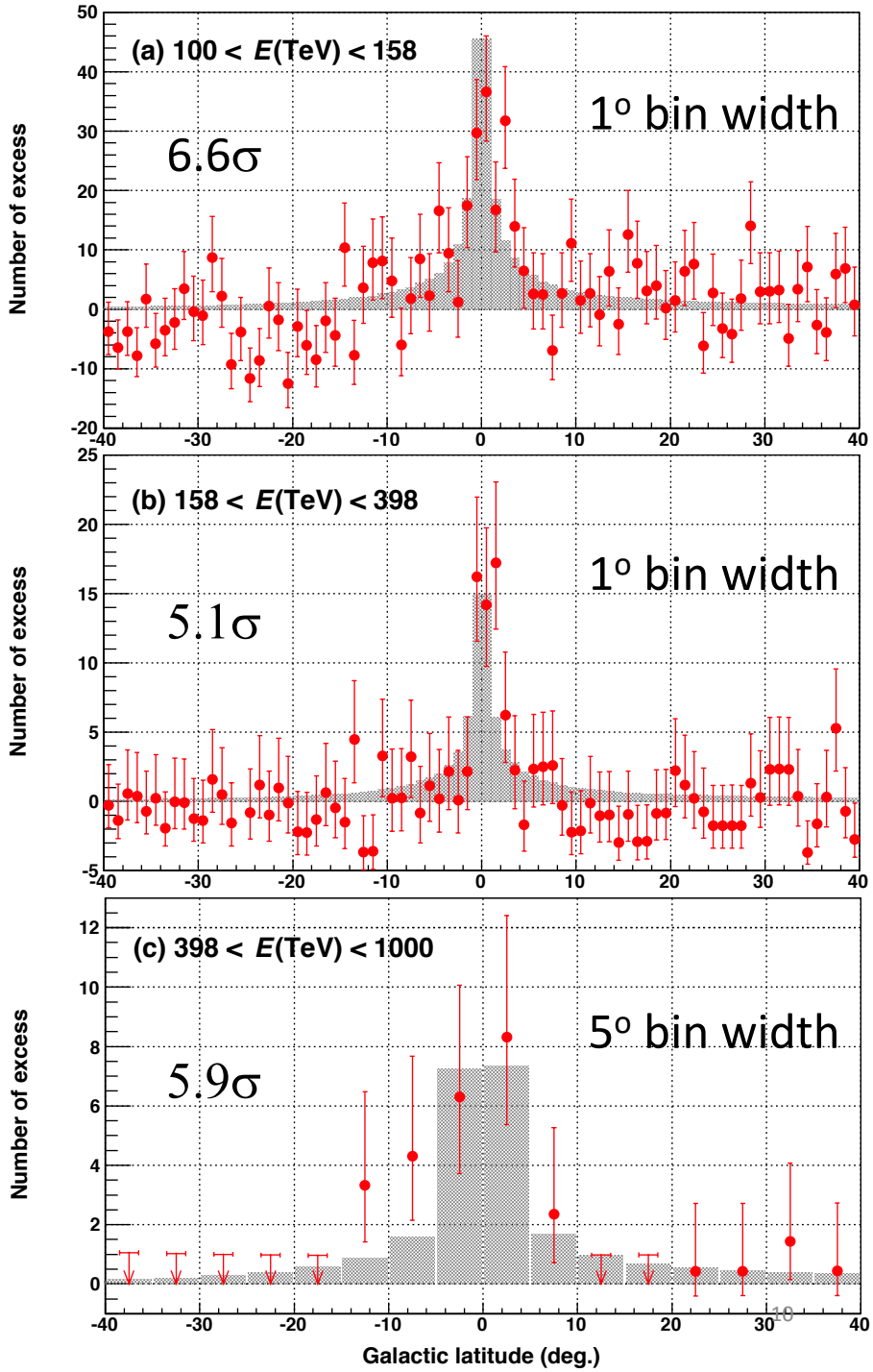


Latitude Profile

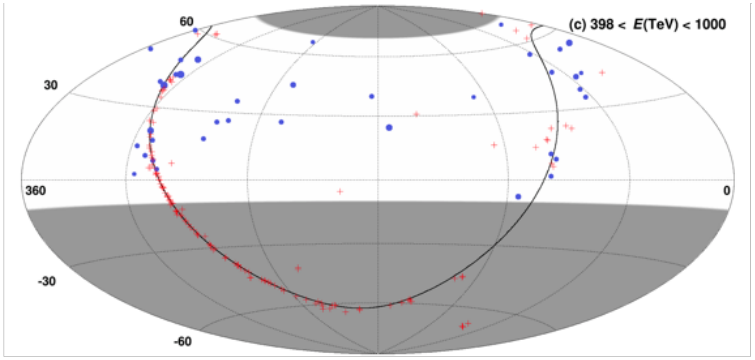
Red points:
experimental data across our FoV ($22^o < l < 225^o$)
including source contribution

Gray shade histogram:
Model by Lipari and Vernetto

Lipari & Vernetto, PRD 98, 043003 (2018)

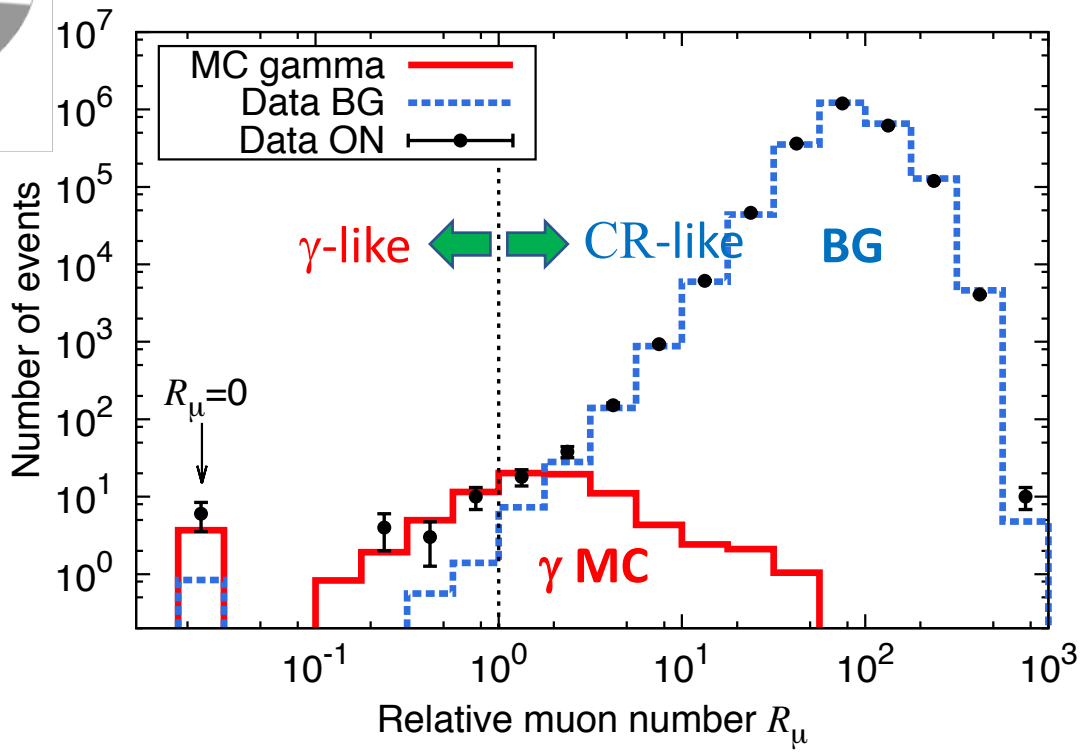


Muon Number Distribution (>398 TeV)



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

- ON region $|b| < 10^{o}$
- BG region $|b| > 20^{o}$



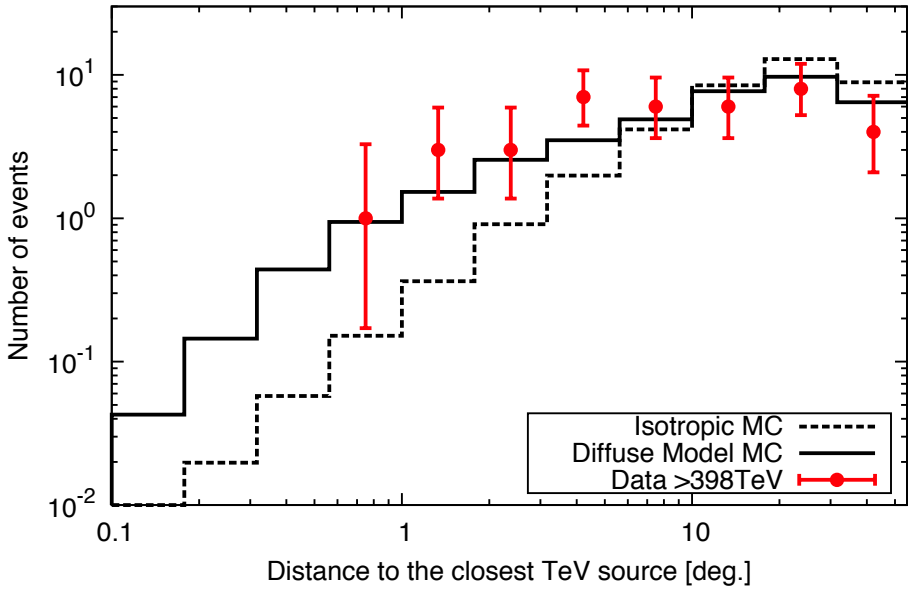
Gamma Survival ratio : 30% by MC sim (>398TeV)

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

Correlation with known TeV Sources

Correlation between UHE gamma rays above 398 TeV and
60 sources from TeVCat catalog (UNID, PWN , Shell, Binary, SNR…)
(Excluded 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

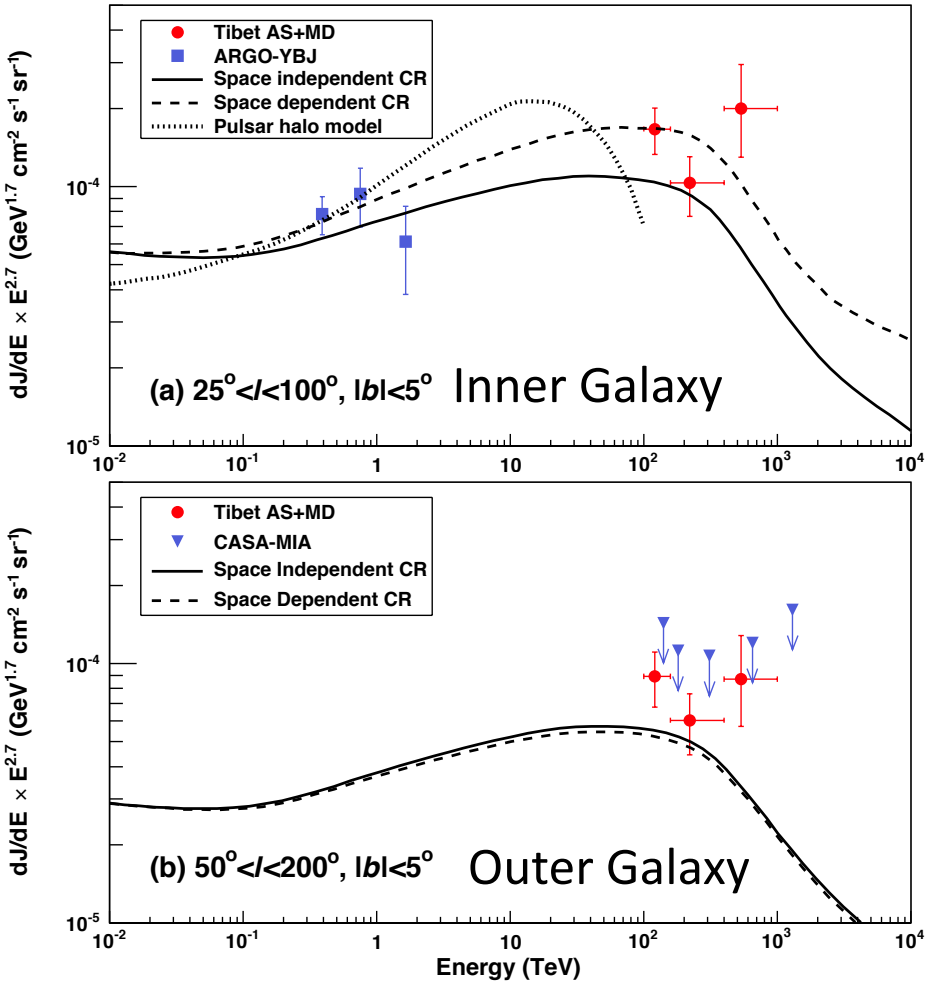
Energy Spectrum of UHE Diffuse γ Rays

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.

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

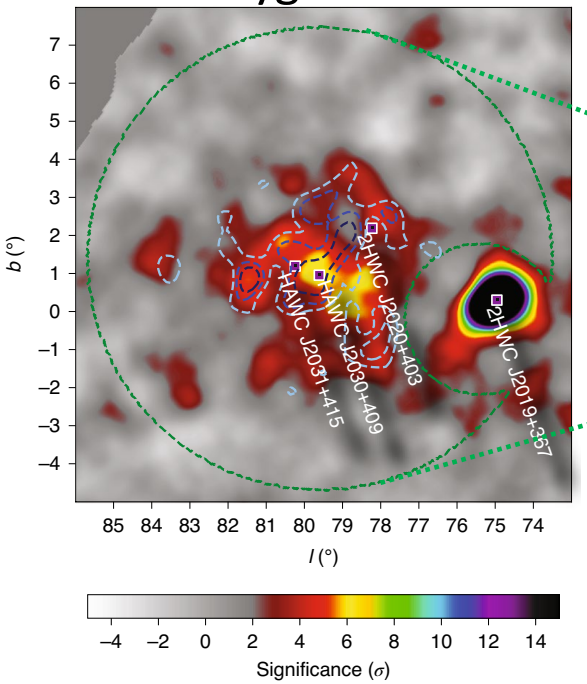
Lipari & Vernetto, PRD 98, 043003 (2018)



Cygnus Cocoon as a PeVatron candidate

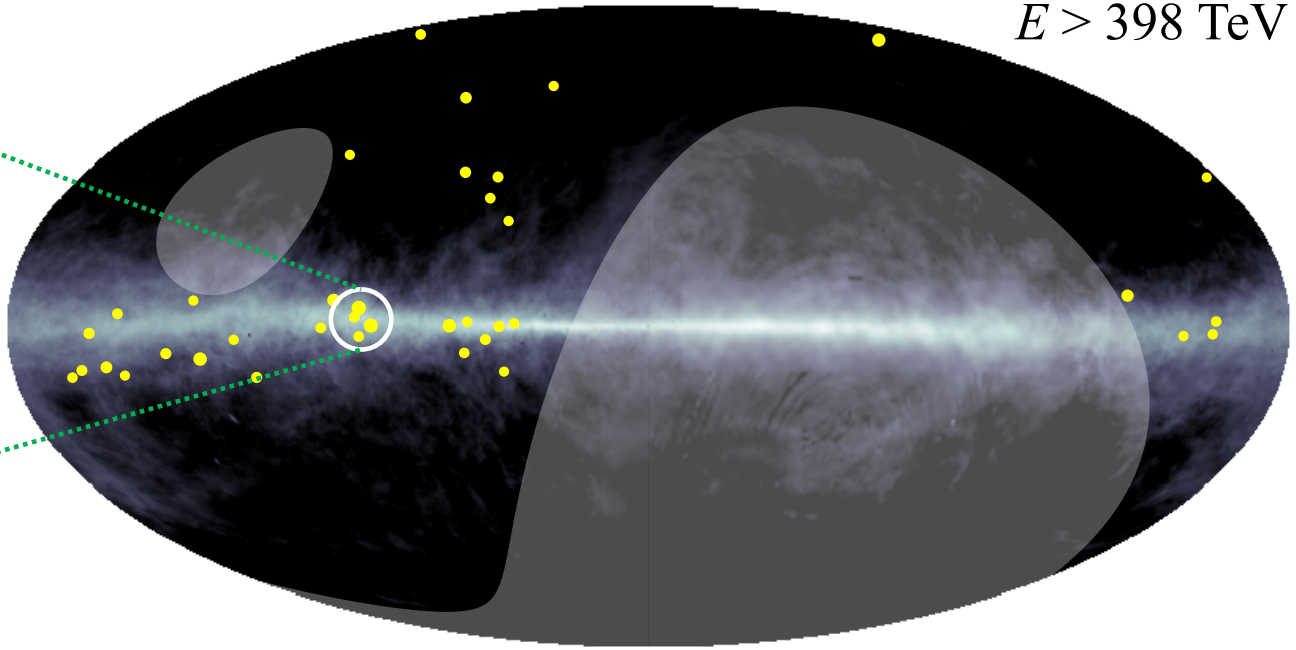
Abeysekara et al., Nature Astronomy (2021)

HAWC Cygnus Cocoon



Galactic Coordinates

$E > 398$ TeV



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 and HAWC and also proposed as a candidate of the PeVatrons.

Conclusions

- ✓ We successfully observed the galactic diffuse gamma rays in 100 TeV < E < 1 PeV. Especially, we found 16 (23) gamma-ray like events against 1.39 (2.7) BG events within $|b| < 5^{o}$ ($|b| < 10^{o}$), which corresponds to 5.9σ (5.9σ).
- ✓ The highest energy of observed gamma-ray is 957 TeV.
- ✓ 38 gamma rays above 398 TeV are spatially separated from known TeV gamma-ray sources beyond our angular resolution as is expected from the diffuse gamma-ray scenario.
- ✓ The measured fluxes are overall consistent with a recent model assuming the hadronic cosmic-ray origin.

These facts indicate strong evidence that cosmic rays are accelerated beyond PeV energies in our Galaxy and spread over the Galactic disk.