TIBET ASgamma:
Dawn of sub-PeV gamma-ray astronomy

T. K. Sako
On behalf of the Tibet ASγ Collaboration

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Tibet ASγ Collaboration

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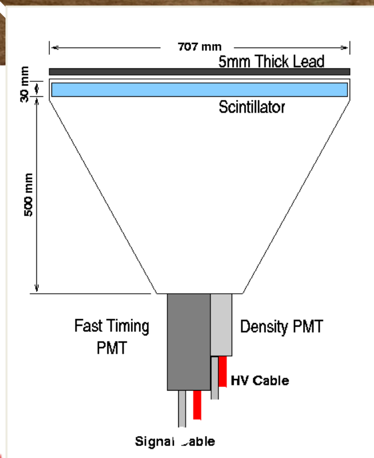
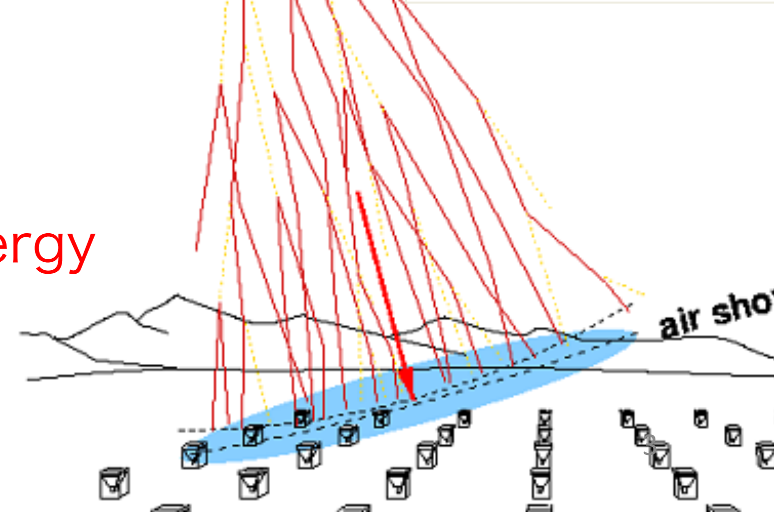
Tibet Air Shower Array

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

scintillation counters	0.5 m² x 597
area	~65,700 m²
angular resolution	~0.5°@10TeV
	~0.2°@100TeV
energy resolution	~40%@10TeV
	~20%@100TeV

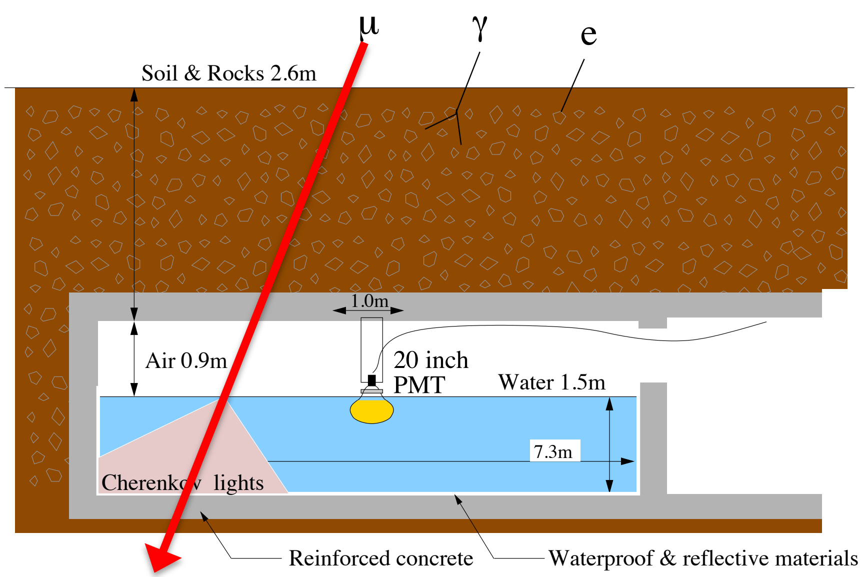
2nd particles timing ➡ arrival direction
2nd particles energy deposit ➡ primary energy

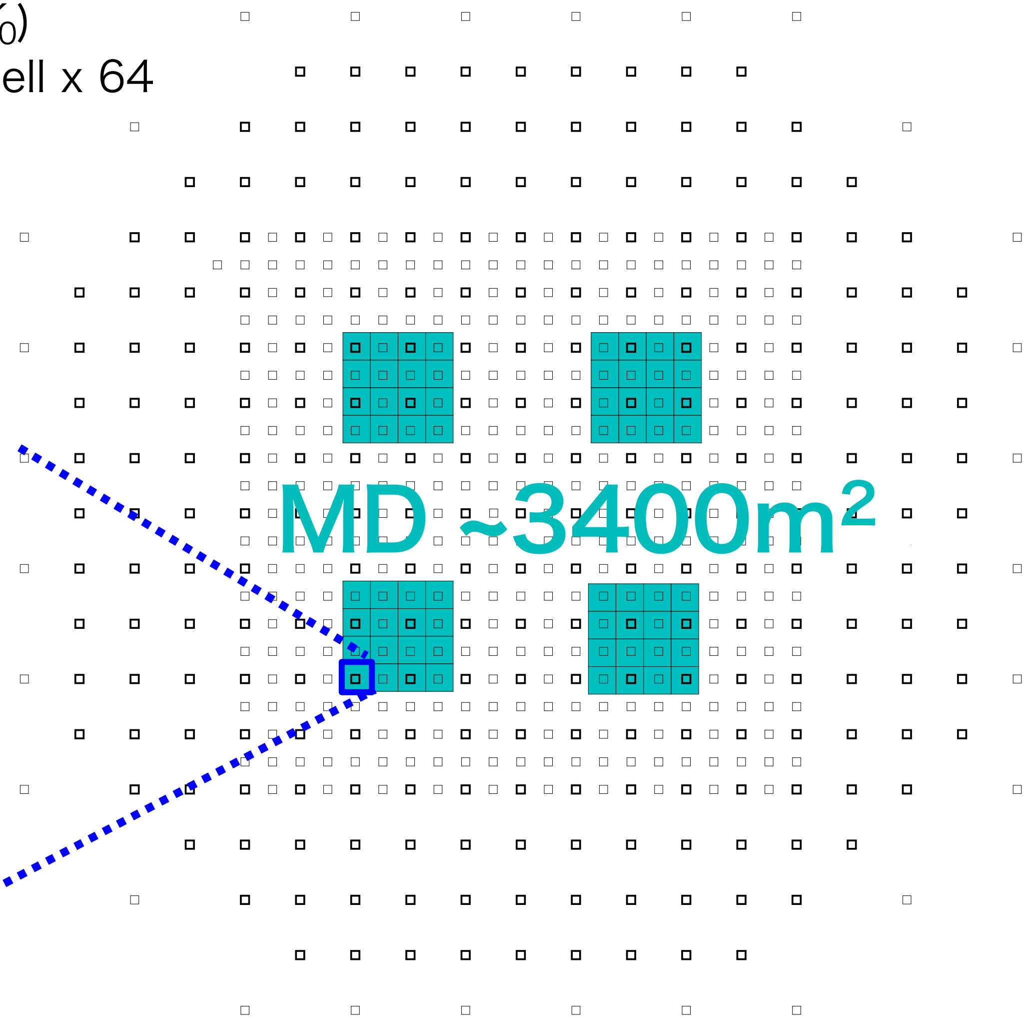




Water Cherenkov Muon Detector Array

- ✓ 2.4m underground (515g/cm^2 ~19X_0)
- ✓ 7.35m x 7.35m x 1.5m-deep water cell x 64
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + Tyvek sheets





Measurement of number of muons in air showers
➡ γ／CR discrimination

Observation of gamma rays from the Crab Nebula

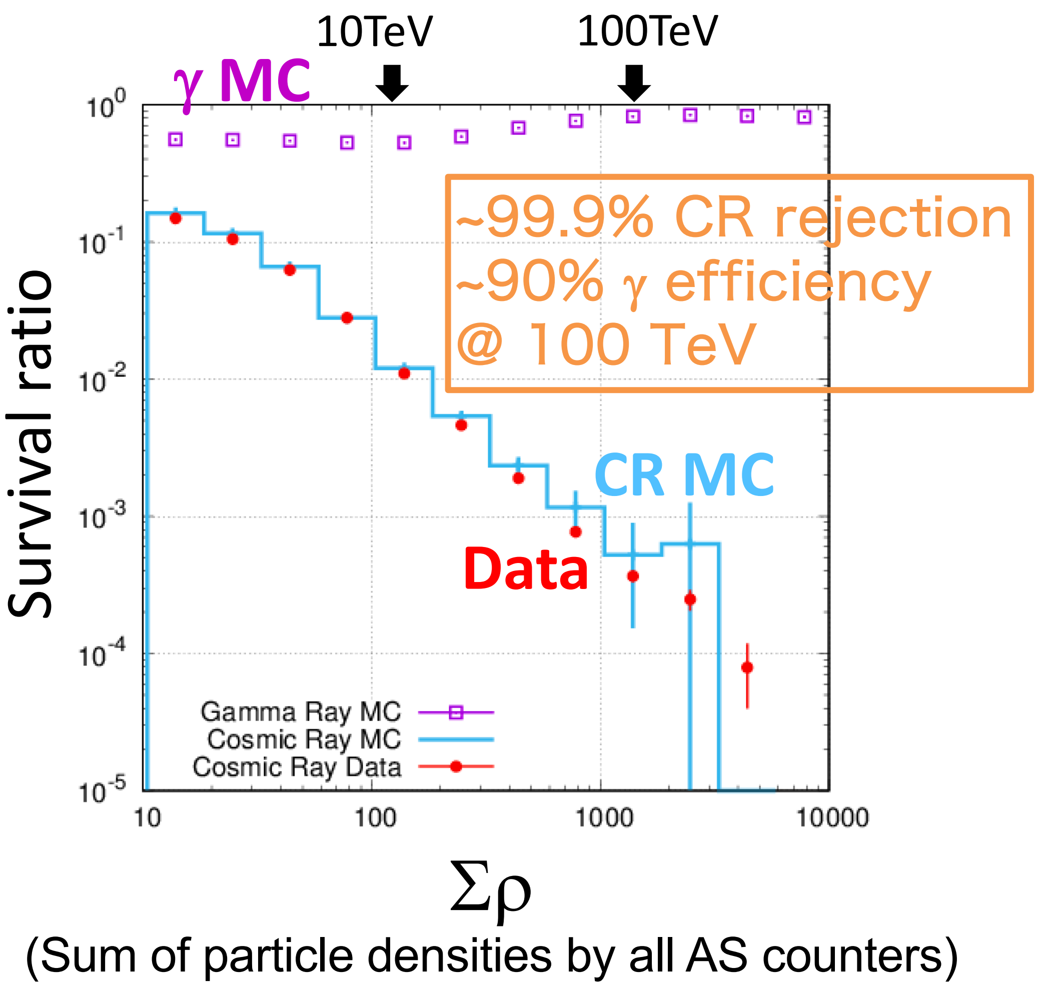
M. Amenomori et al., PRL, 123, 051101 (2019)

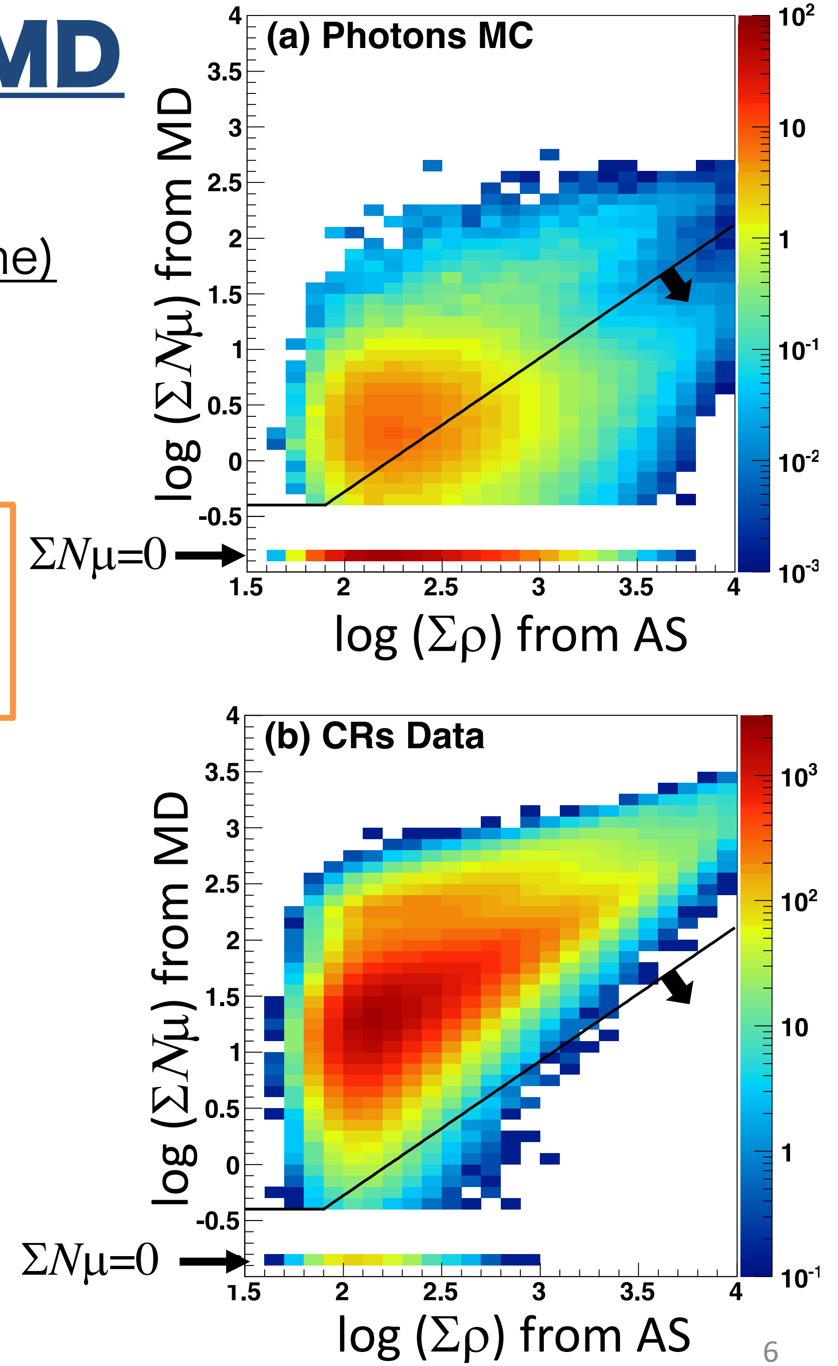
Event selection by MD

Optimization of muon cut

γ : MC sample (Crab orbit & Crab flux)

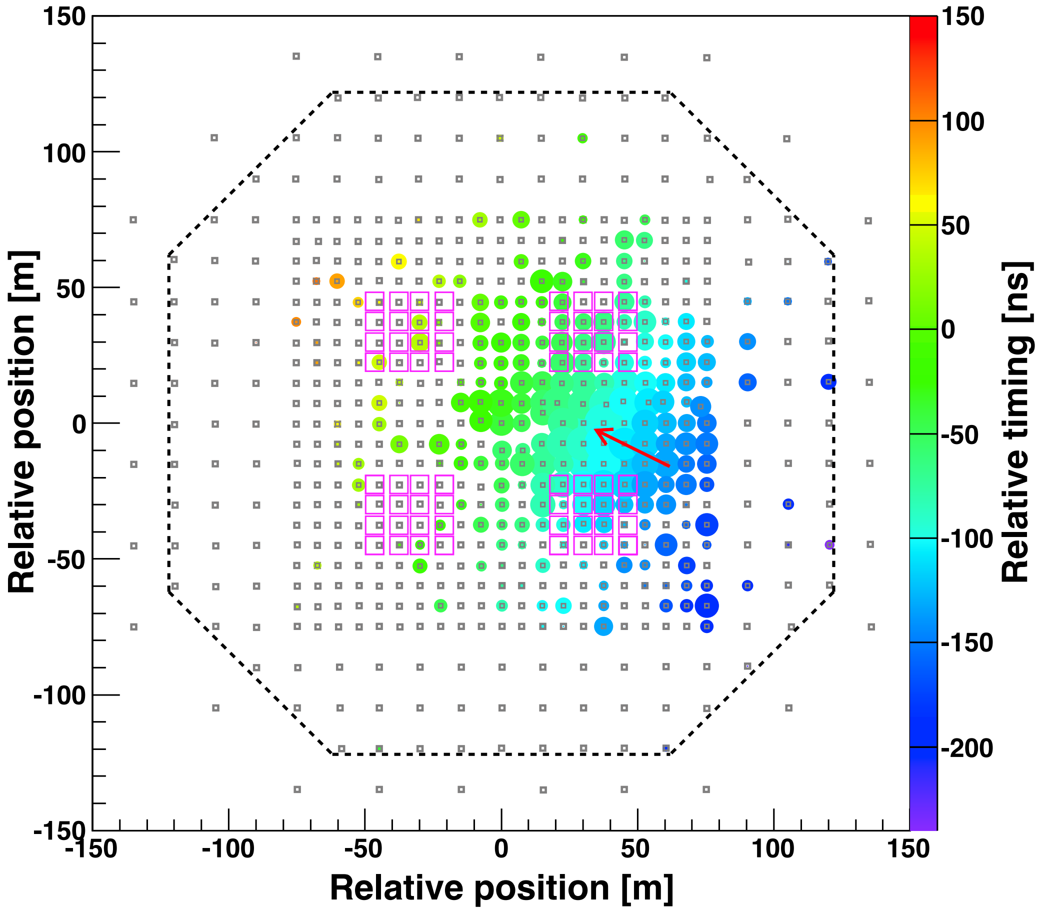
CR : Data (excluding Crab & Galactic Plane)

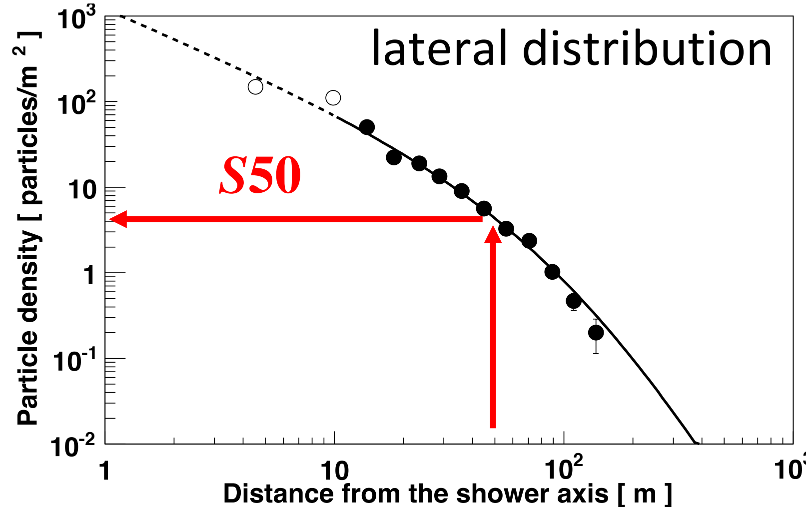




M. Amenomori et al., PRL, 123, 051101 (2019)

Crab: γ-like event display





fitting with NKG function
➡ E_{rec} ($S50$, θ)

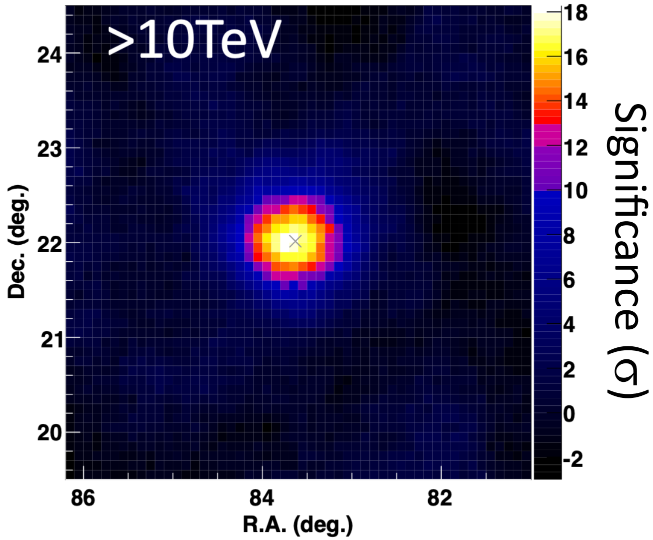
$\Sigma\rho$ (from AS array) : 3256
$\Sigma N\mu$ (MD) : 2.3
zenith angle : 29.8°
E_{rec} : 251^{+46}_{-43} TeV

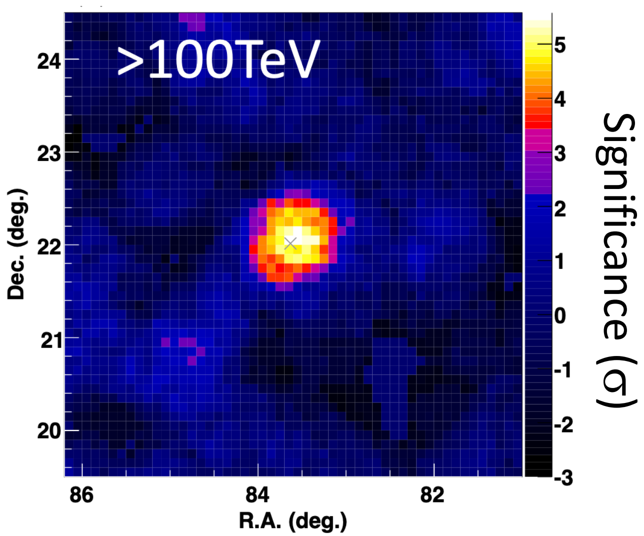
circle size ∝ log(# of detected particles)
circle color ∝ relative timing [ns]

M. Amenomori et al., PRL, 123, 051101 (2019)
Kawata+, Experimental Astronomy, 44, 1 (2017)

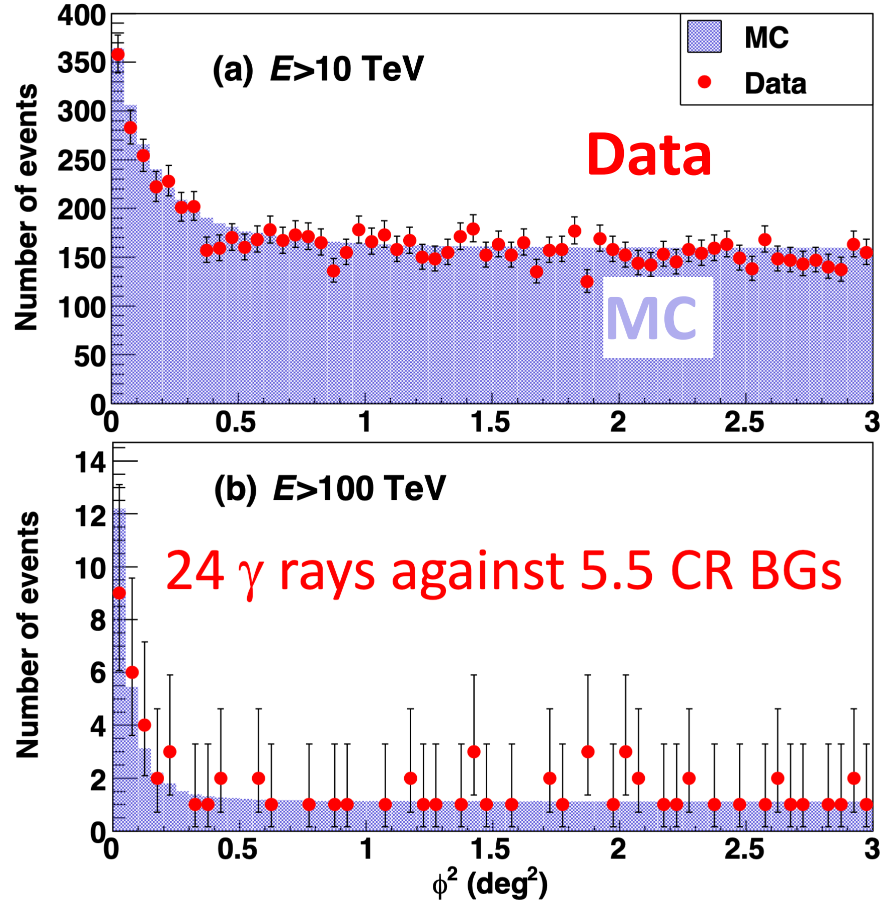
Crab Nebula: Significance map & ϕ^2 distribution

Significance map





Event distribution



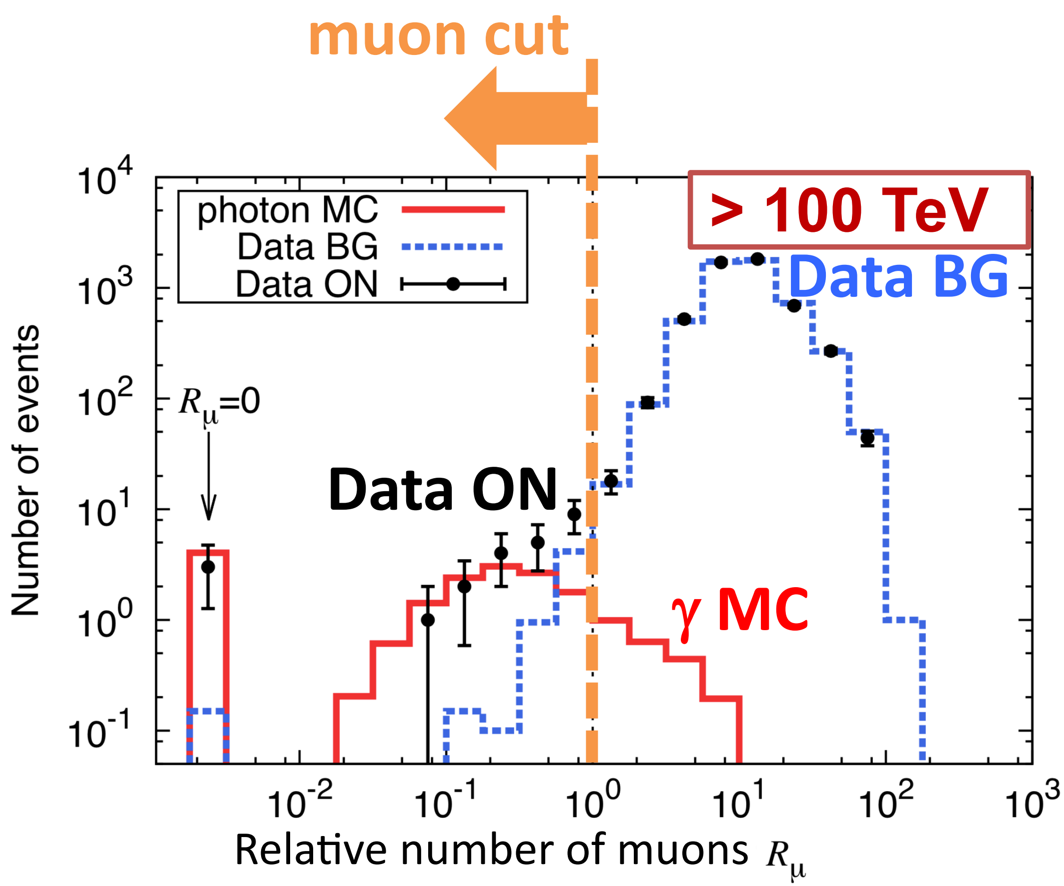
M. Amenomori et al., PRL, 123, 051101 (2019)

Number of events (integral)

Crab

Relative number of muons > 100 TeV

E_{Rec}(TeV)	after muon cut	
	*N*ON / <*N*OFF>	σ
>10.0	1691 / 1031	18.3
>15.8	915 / 472.7	17.5
>25.1	417 / 159.1	16.4
>39.8	169 / 46.9	13.2
>63.1	69 / 14.6	9.8
>100	**24 / 5.5**	**5.6**
>251	4 / 0.8	2.4

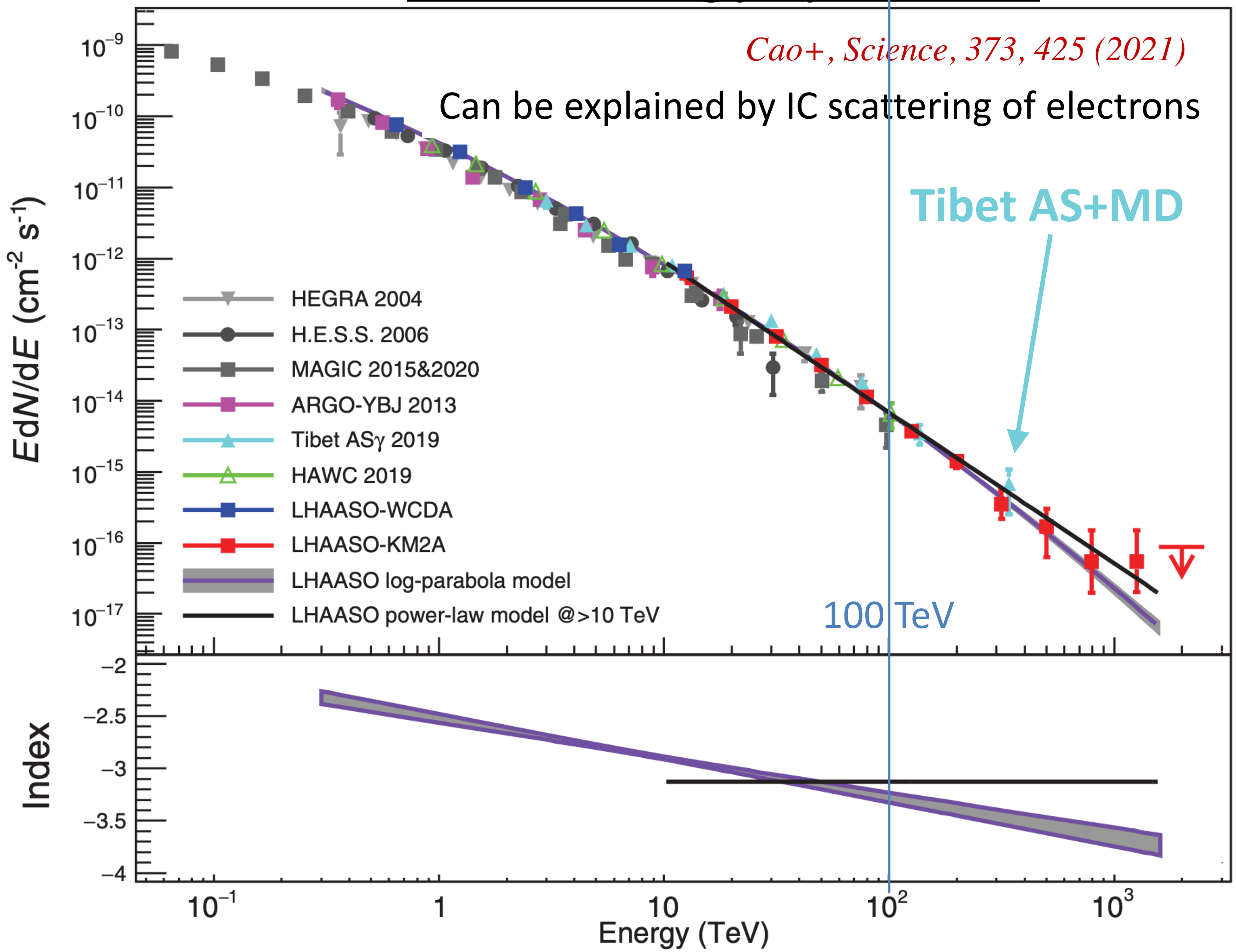


$$\left(R_\mu = \frac{\text{observed } \Sigma N_\mu}{\text{cut value of } \Sigma N_\mu}\right)$$

➢ **First Detection of sub-PeV γ**

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

Crab: Energy spectrum



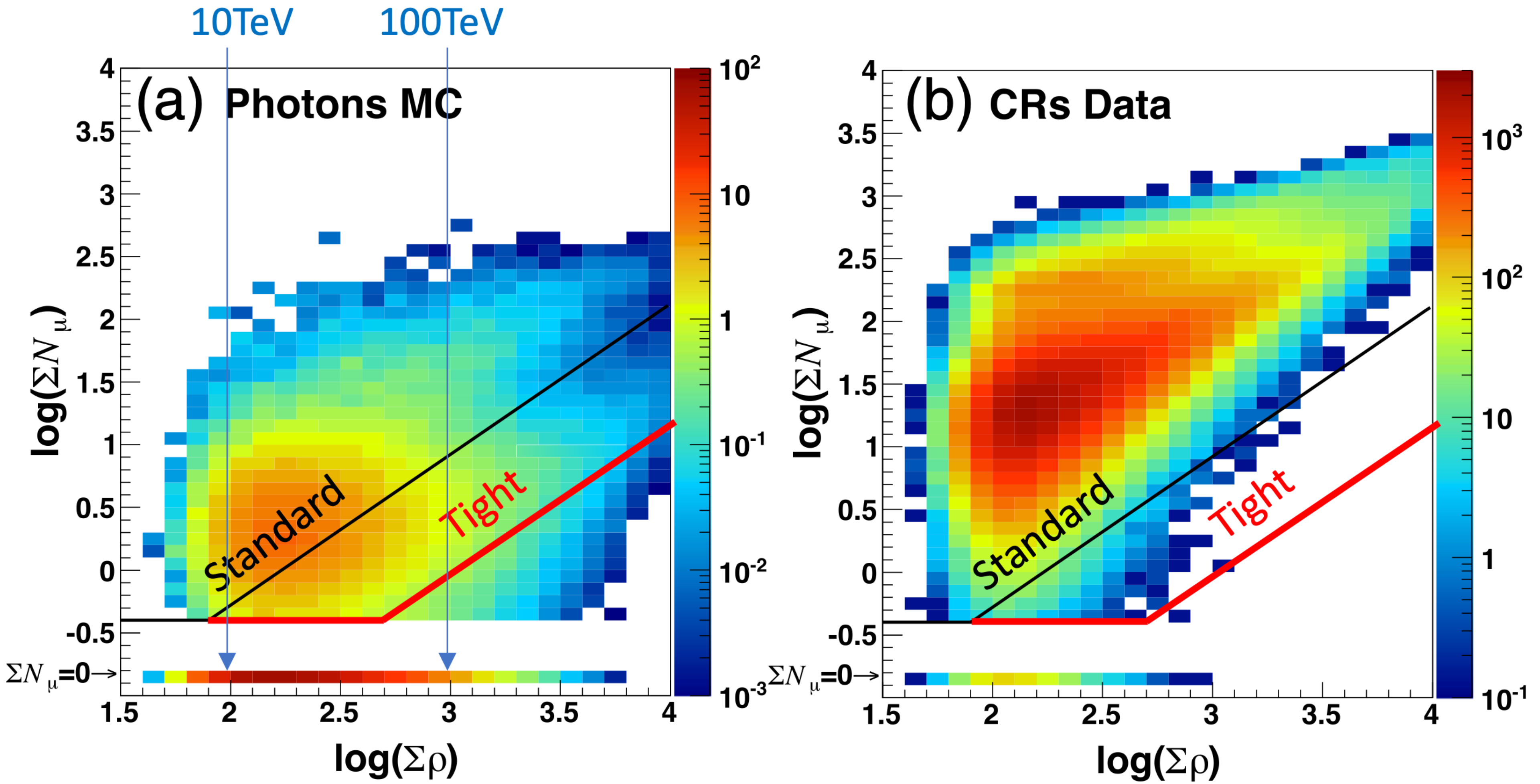
Other publications on γ-ray observation in the 100 TeV region:

- ✓ SNR G106.3+2.7 — *M. Amenomori et al., Nature Astronomy Letters, 5, 460 (2021)*
- ✓ Cygnus OB1 & OB2 — *M. Amenomori et al., PRL, 127, 031102 (2021)*
- ✓ HESS J1843-033 — *M. Amenomori et al., ApJ, 932, 120 (2022)*

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

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

Tight Muon Cut condition for diffuse γ-ray observation



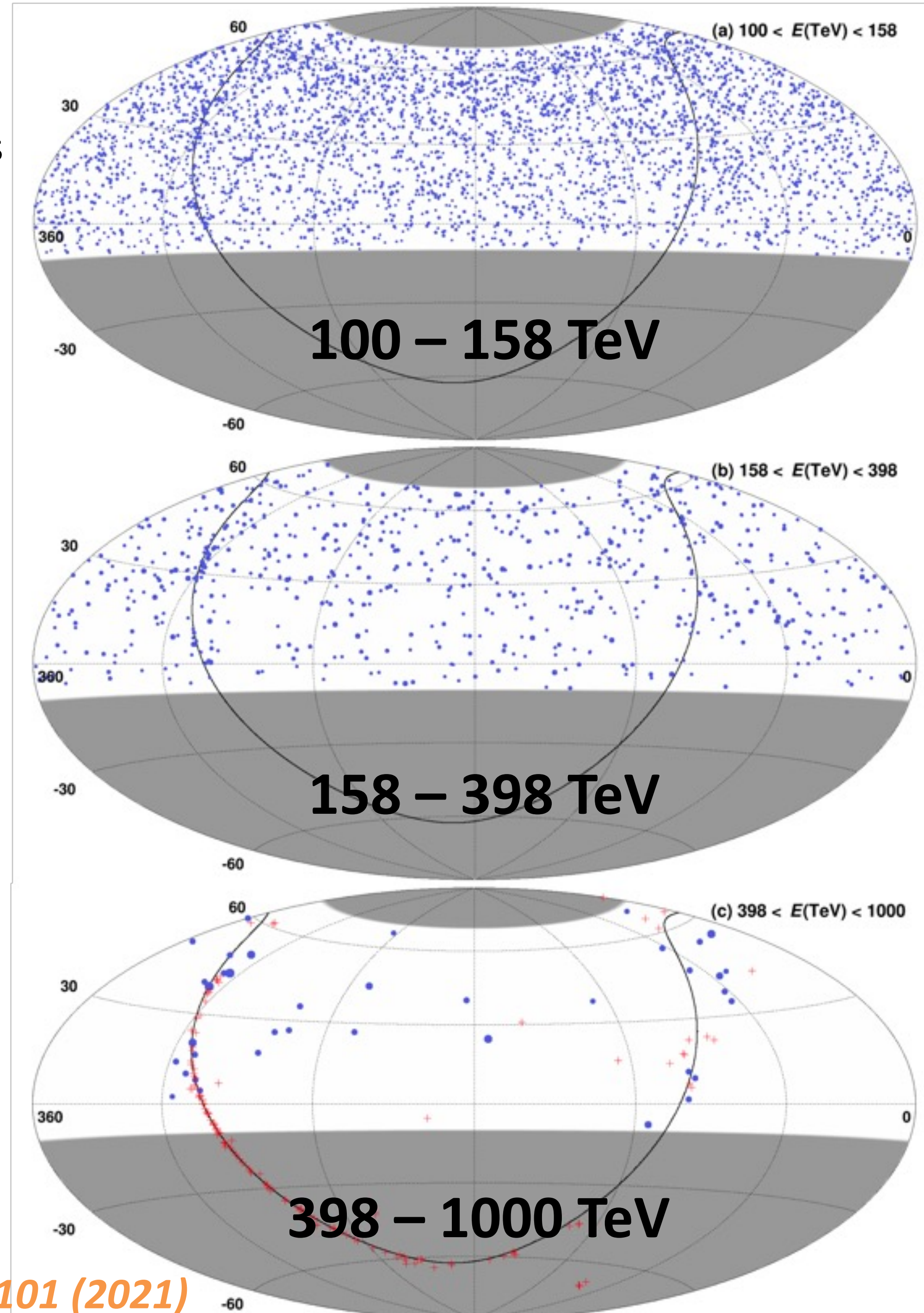
γ-ray survival ratio ~30% > 398 TeV by MC sim.

=

$10^{2.6}$ TeV

CR survival ratio ~10^{-6} > 398 TeV

Event Distribution



Blue points:
Experimental data
(Circle size ∝ Energy)

Red plus marks:
known Galactic TeV sources
(TeVCat catalog)

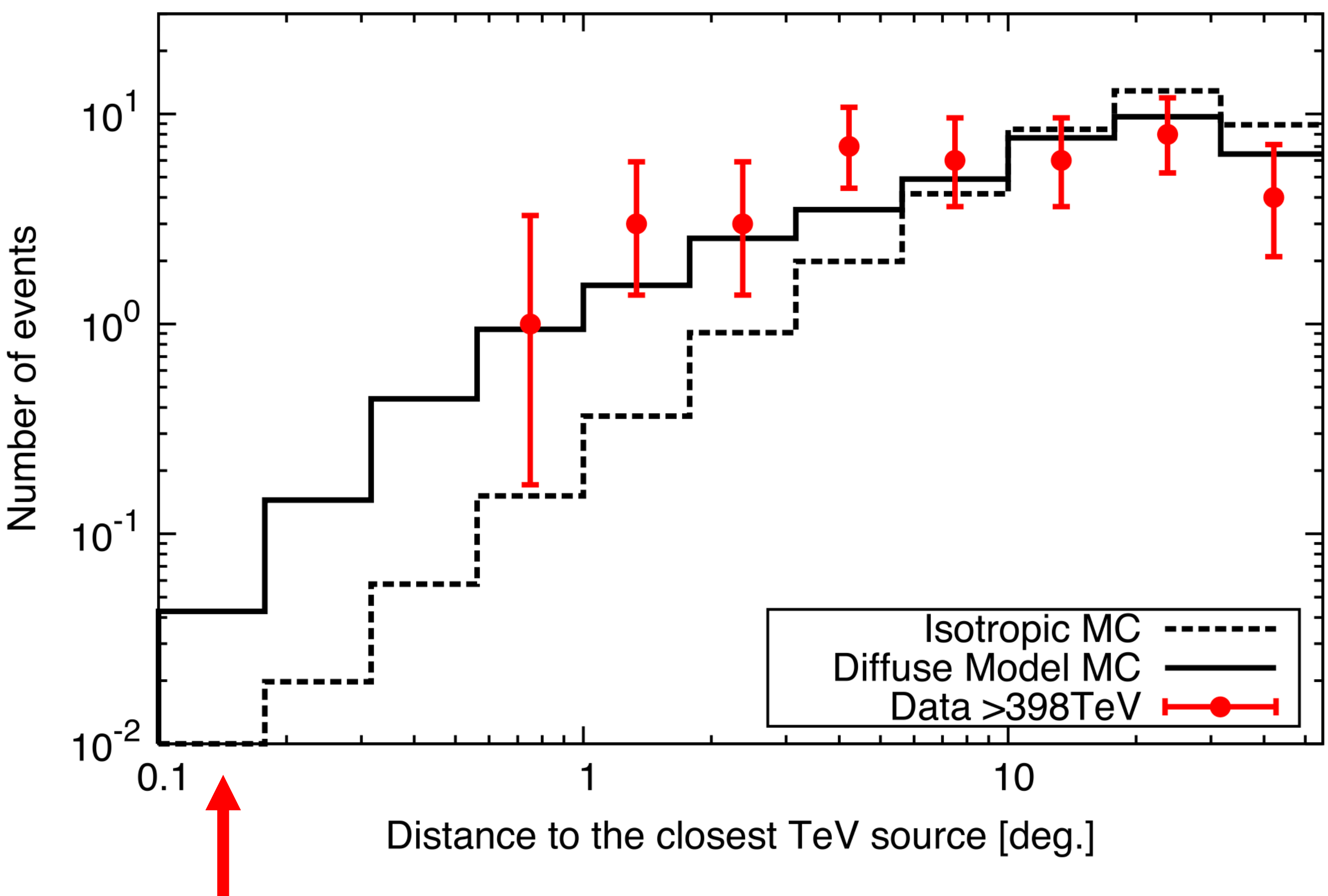
>0.398 PeV ($10^{2.6}$ TeV)
38 events in our FoV

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

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

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

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



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

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

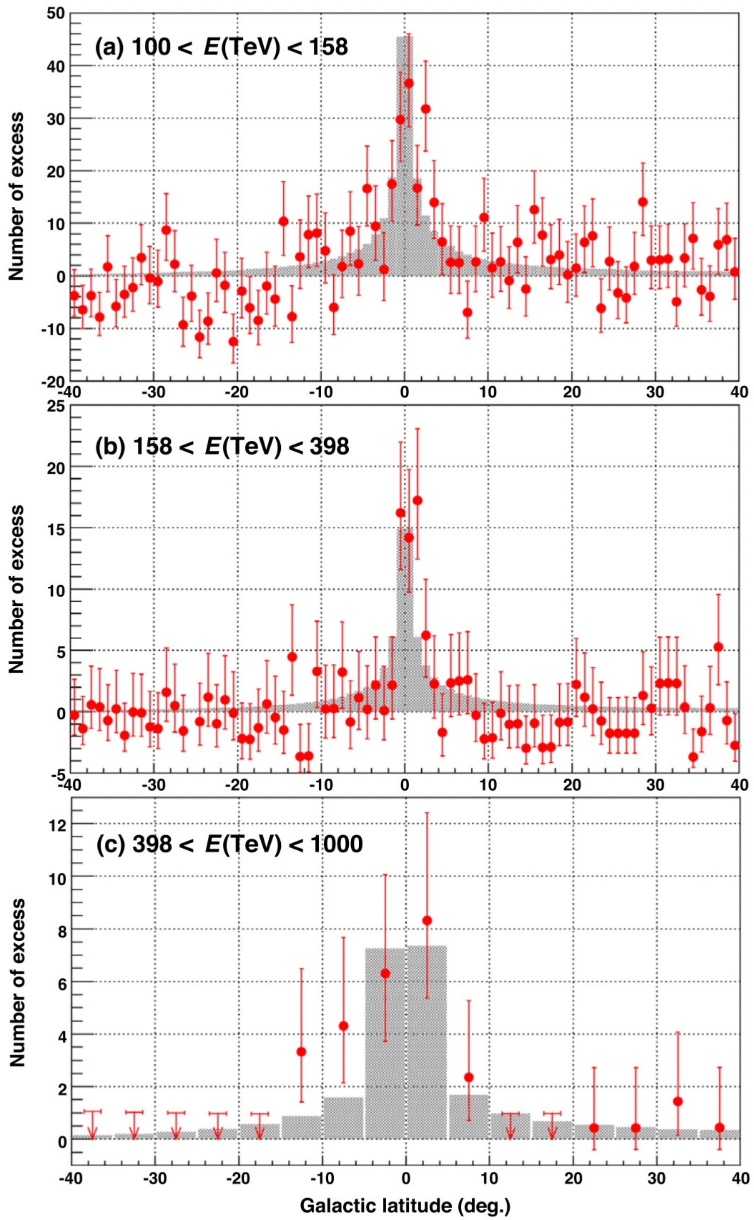
Galactic latitude distributions

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

100 – 158 TeV

158 – 398 TeV

398 – 1000 TeV



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

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

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

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

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

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

	$\vert b\vert < 5^\circ$			$\vert b\vert < 10^\circ$		
Energy bin (TeV)	N_{ON}	N_{BG} ($= \alpha N_{\mathrm{OFF}}$)	Significance (σ)	N_{ON}	N_{BG} ($= \alpha N_{\mathrm{OFF}}$)	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.

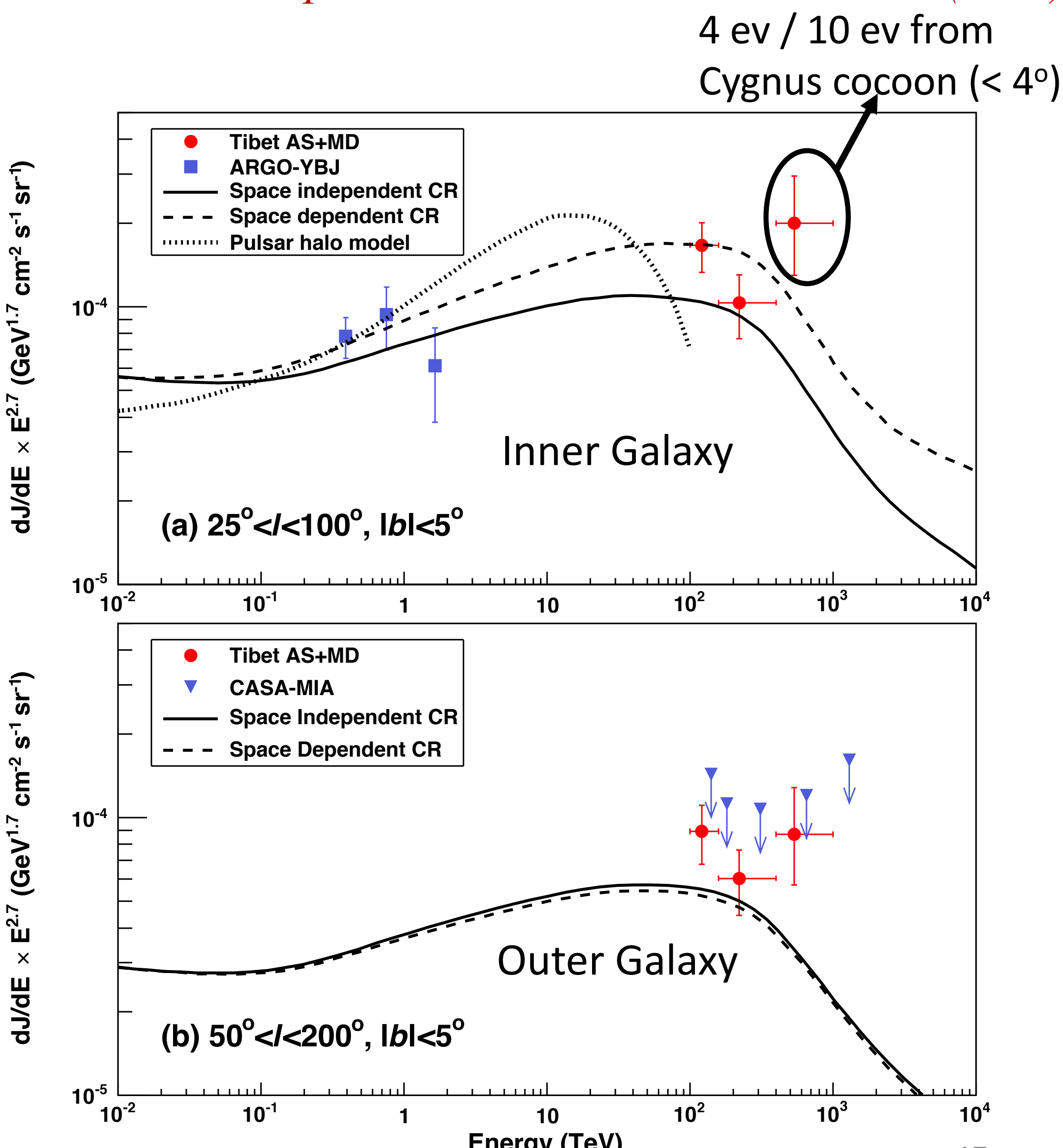
Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ, \vert b\vert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50^\circ < l < 200^\circ, \vert b\vert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
100 – 158	121	$(3.16 \pm 0.64) \times 10^{-15}$	$(1.69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

Energy Spectrum

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

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

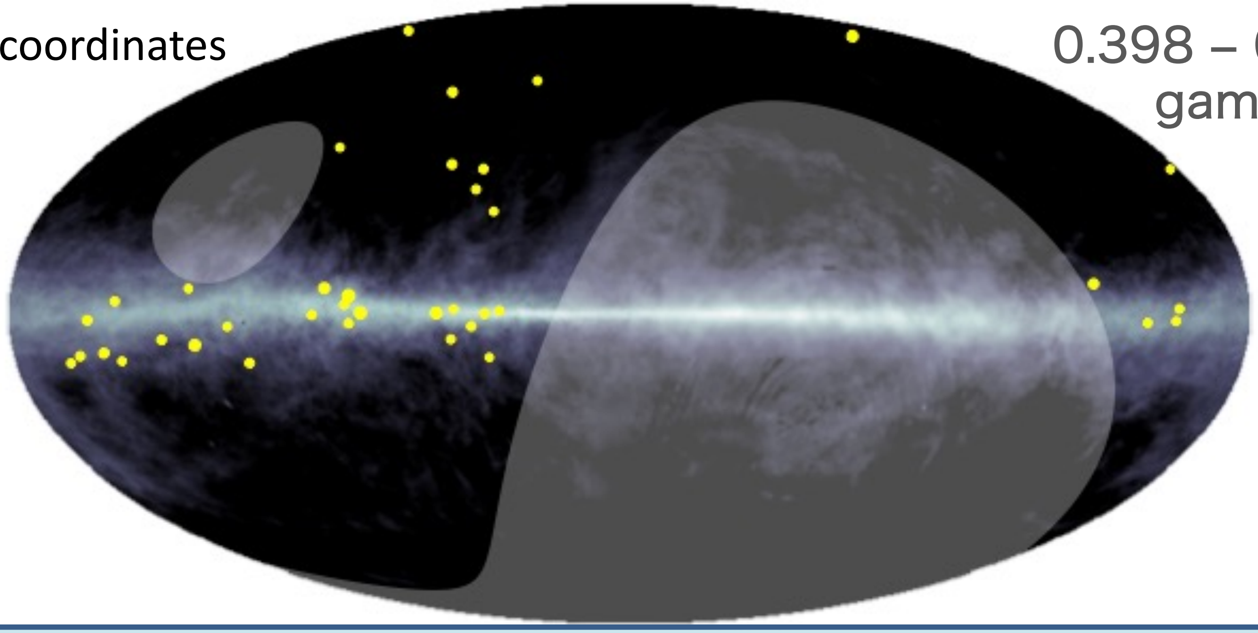
The measured fluxes are reasonably consistent with Lipari's galactic diffuse gamma-ray model assuming the hadronic cosmic-ray origin.



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

Electron origin? vs Proton origin?

Galactic coordinates



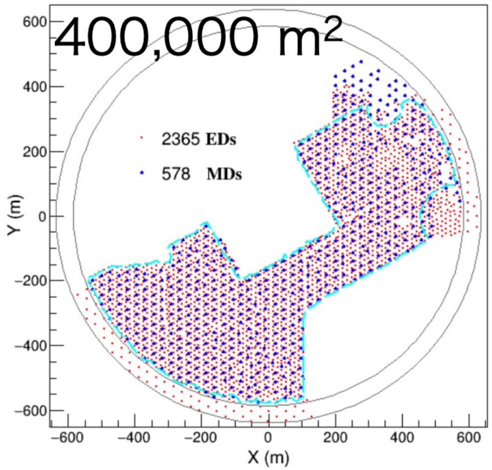
0.398 – 0.957 PeV gamma rays

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

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

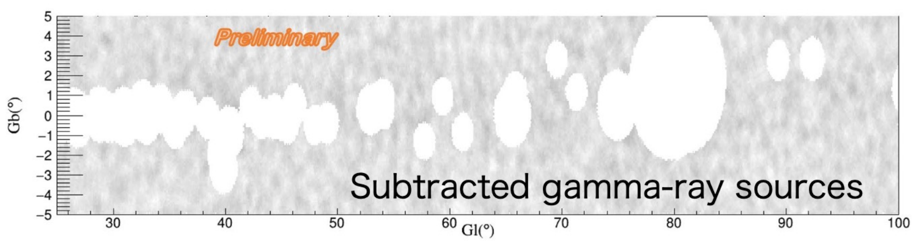
✓ This is the first evidence for existence of PeVatrons, in the past and/or present Galaxy, which accelerate protons up to the Peta electron volt (PeV) region.

Preliminary Results by LHAASO

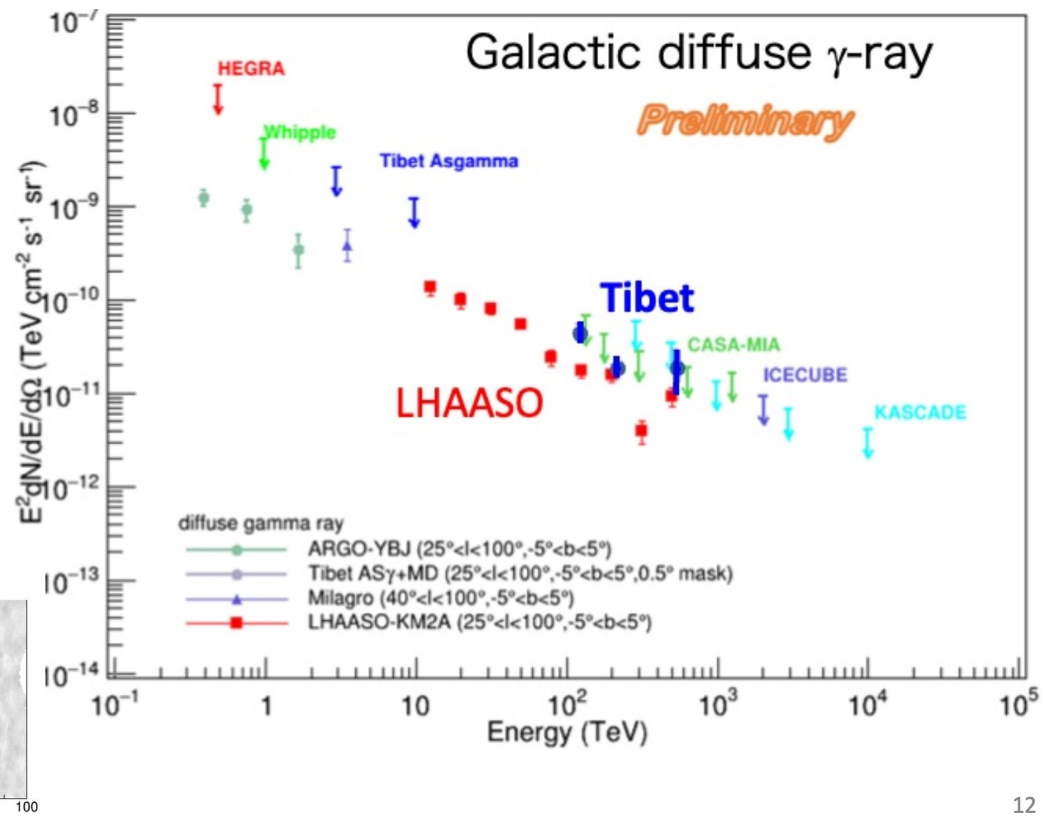


KM2A(1/2 Array) Detectors Distribution

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



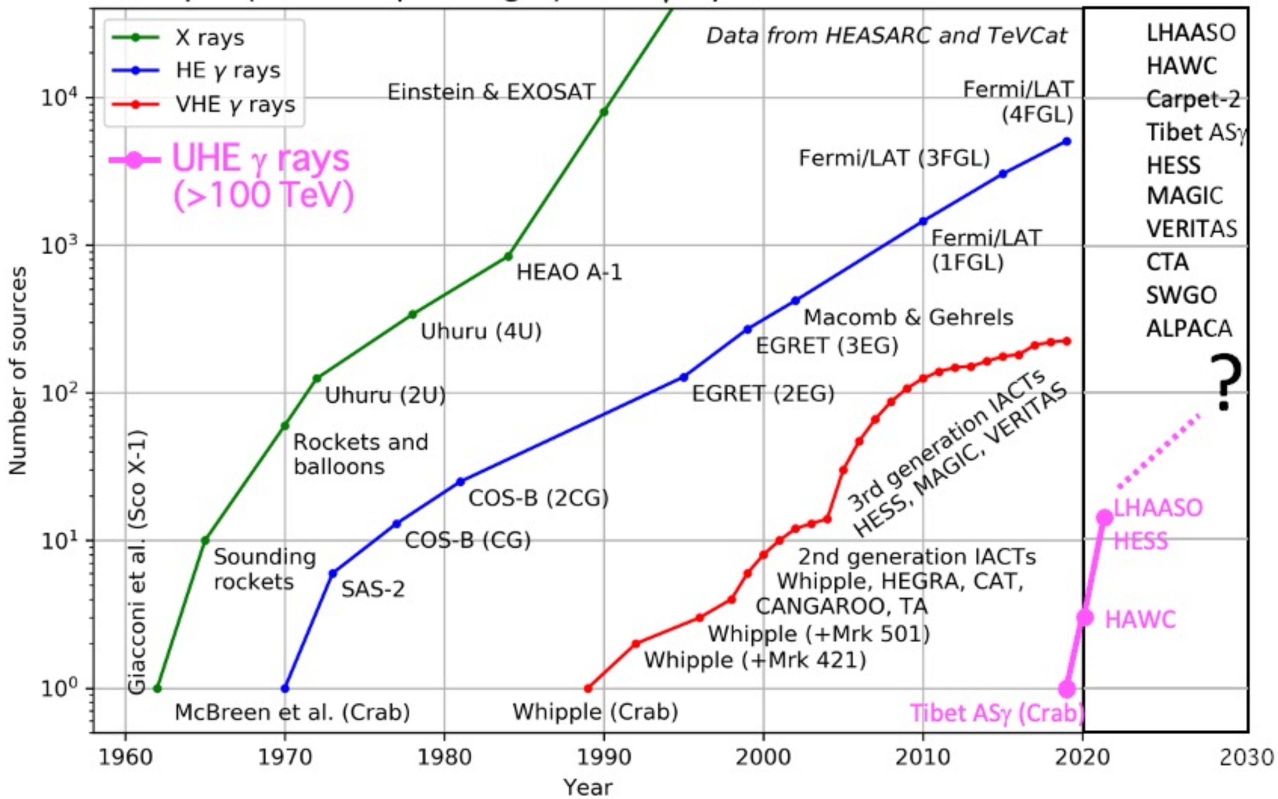
S. P. Zhao ICRC2021



Future prospects

UHE γ-ray astronomy $E > 100$ TeV

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

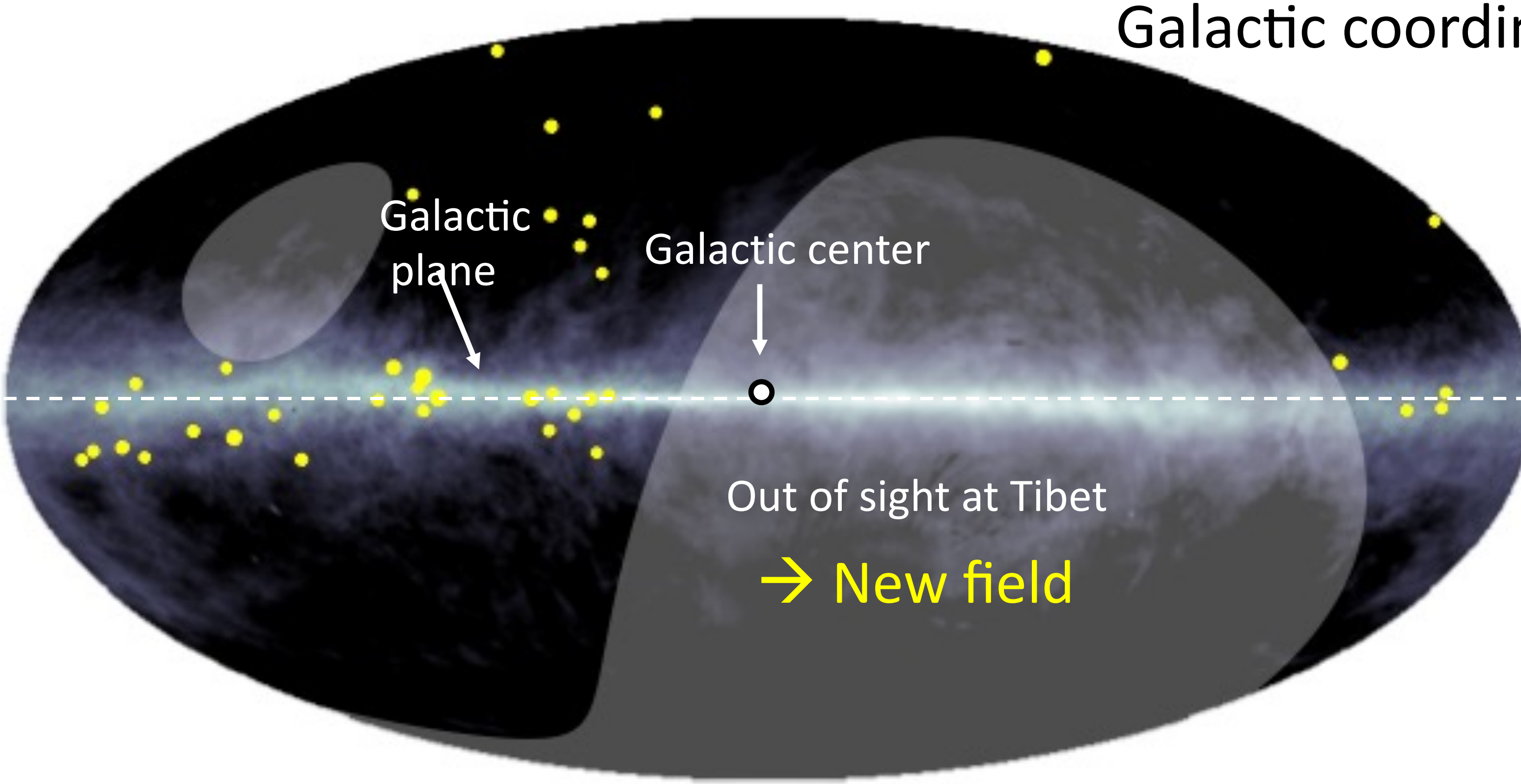


Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example http://adsabs.harvard.edu/abs/1996NCimC..19..953K).
The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on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



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

Summary

- Sub-PeV gamma-ray observations by Tibet ASγ experiment

➢ Crab Nebula *M. Amenomori et al., PRL, 123, 051101 (2019)*

First detection of sub-PeV gamma rays from any astrophysical source

➡ Now, a dozen of UHE γ-ray sources discovered

by Tibet ASγ, HAWC, LHAASO. *M. Amenomori et al., PRL, 127, 031102 (2021)*

➢ Galactic diffuse sub-PeV gamma rays

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

➡ Experimental verification for the theoretical model of
high-energy “cosmic-ray pool” in Milky Way galaxy

- Future prospects

➢ Sub-PeV observations of the southern sky as well as the the northern sky

➡ Observatories in the southern hemisphere necessary