First observation of sub-PeV galactic diffuse gamma rays by the Tibet ASgamma experiment

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PHYSICAL REVIEW LETTERS **126**, 141101 (2021)

Editors' Suggestion Featured in Physics

Selected as Editors' Suggestion & VIEWPOINT

First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

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(Tibet AS$_\gamma$ Collaboration)

Physics — VIEWPOINT

Signs of PeVatrons in Gamma-Ray Haze

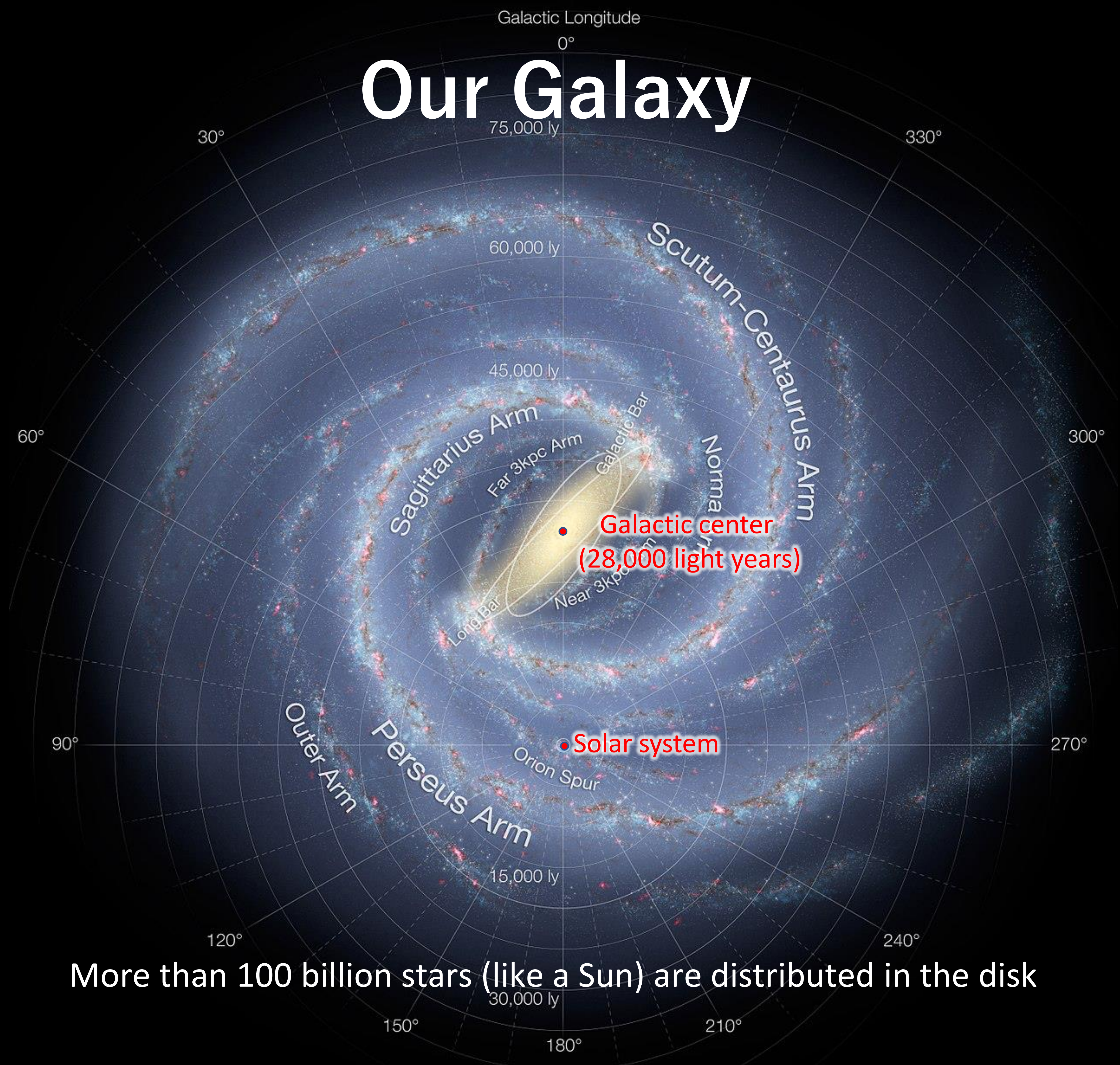
A diffuse glow of high-energy gamma rays hints at the presence of powerful cosmic accelerators, called PeVatrons, within the disk of our Galaxy.

By Petra Huentemeyer

Outline

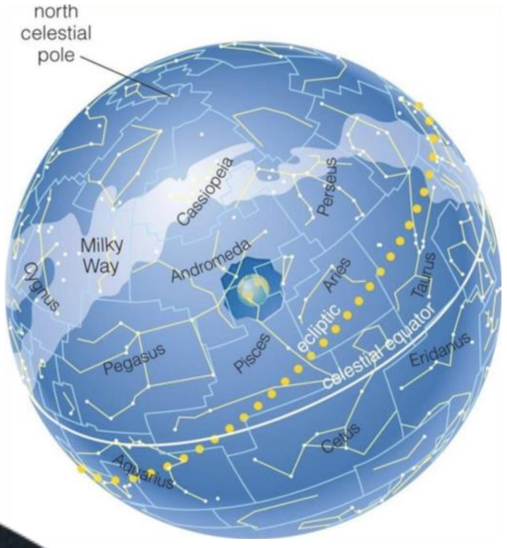
- Gamma rays from the Milky Way
- Gamma-ray detection method
- Scientific interpretation
- Some arXiv e-prints after the publication
- Living PeVatron candidates
- Future prospects & Summary

Our Galaxy

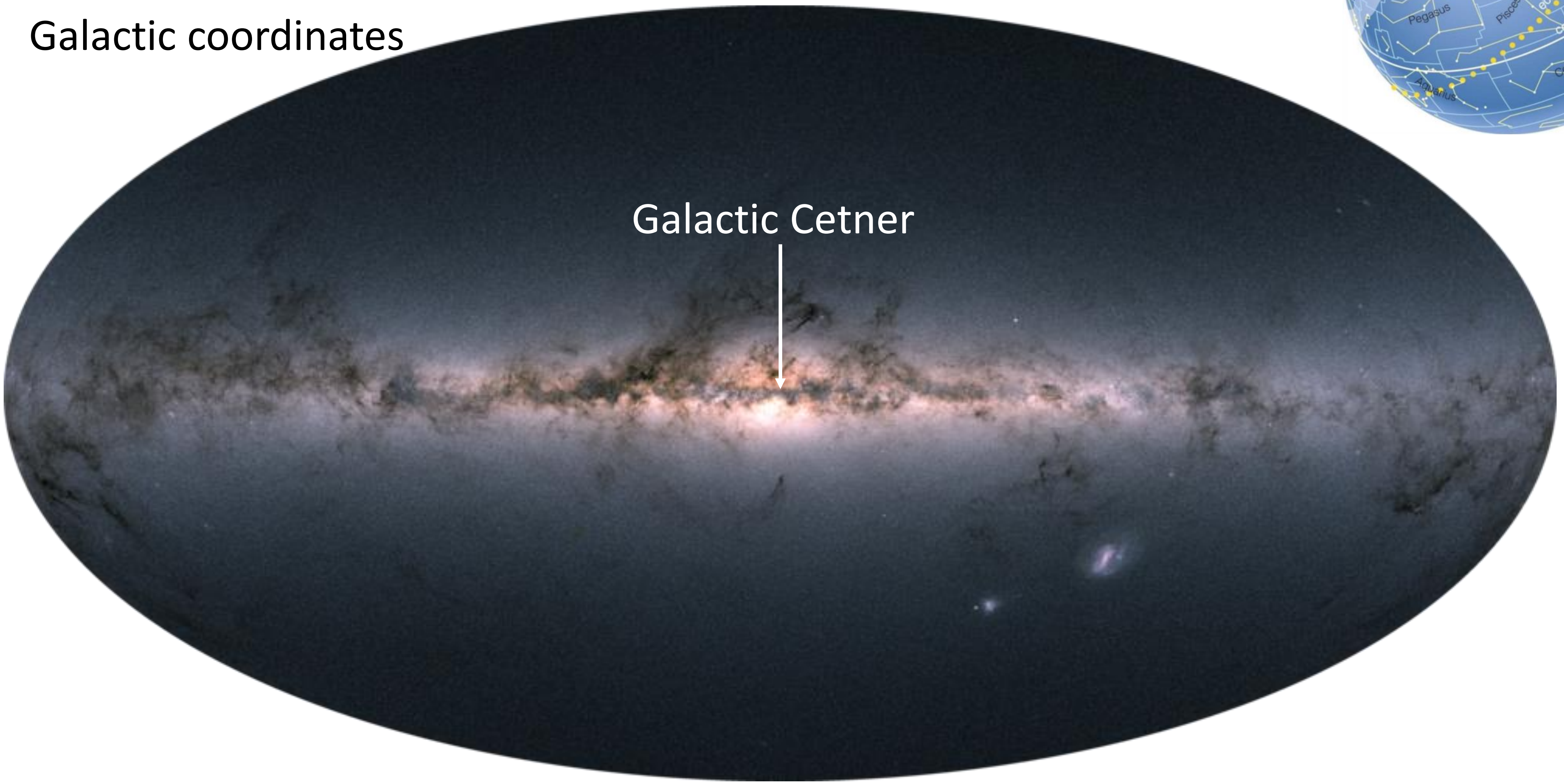


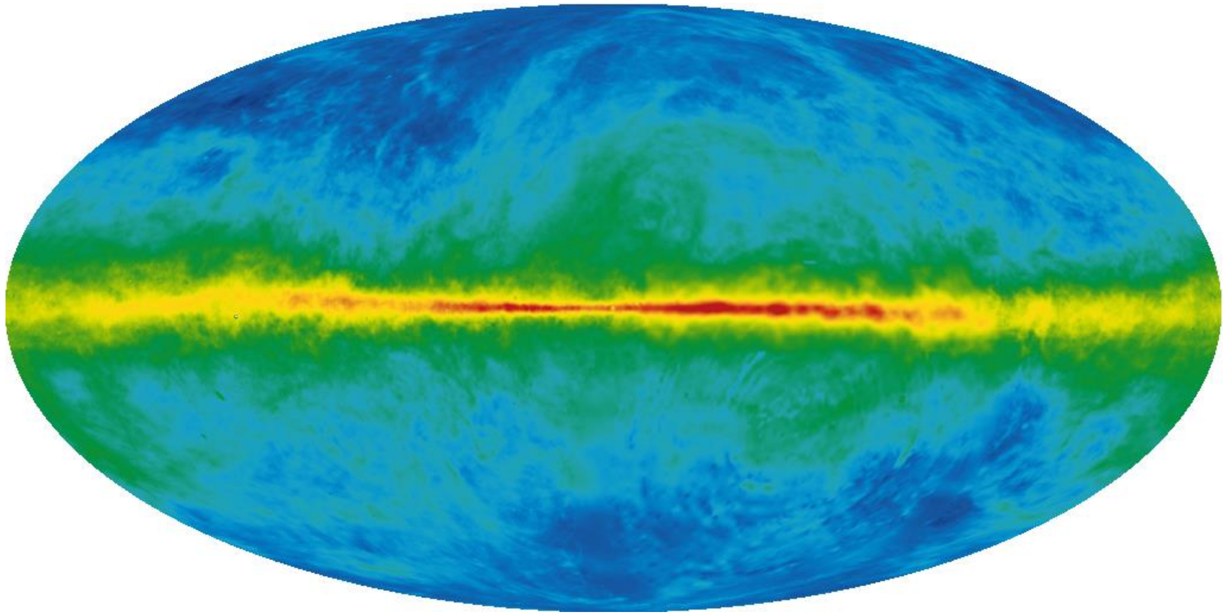
More than 100 billion stars (like a Sun) are distributed in the disk

Milky Way by Optical Observation



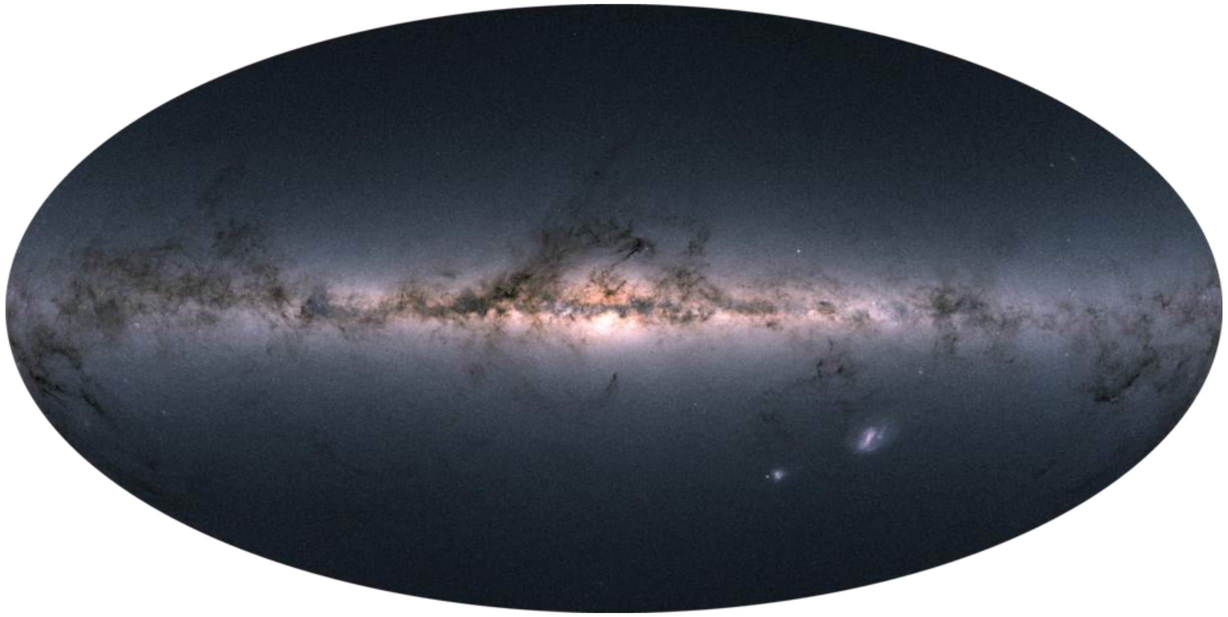
Galactic coordinates





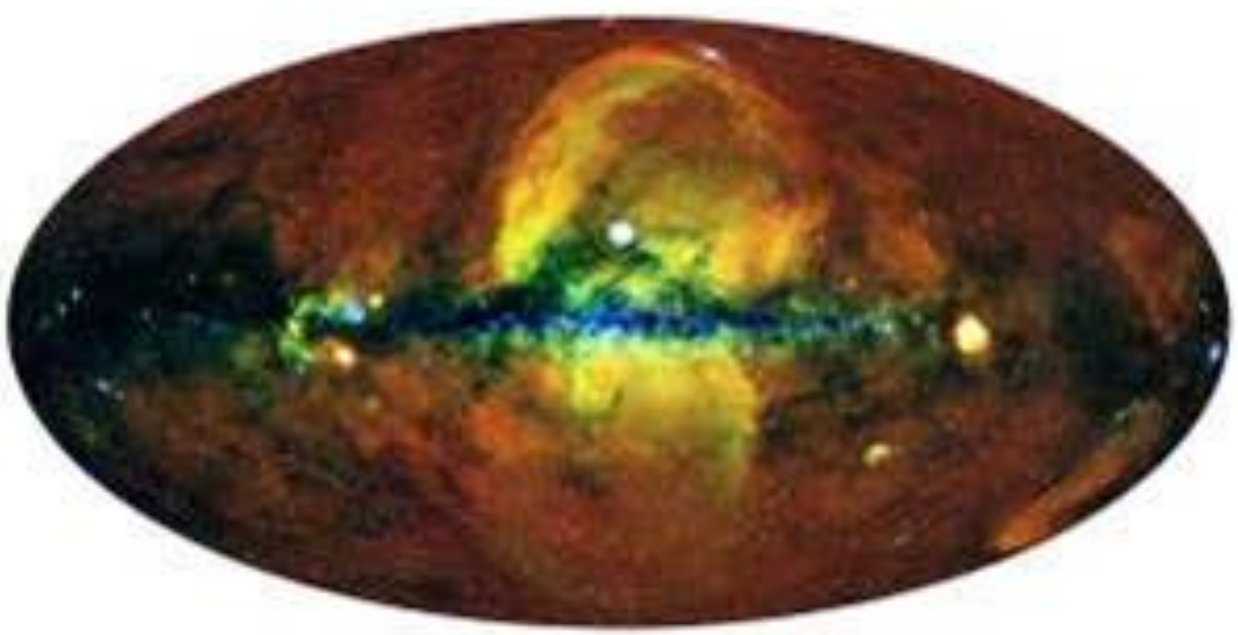
Radio: Atomic Hydrogens

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



Optical: Stars

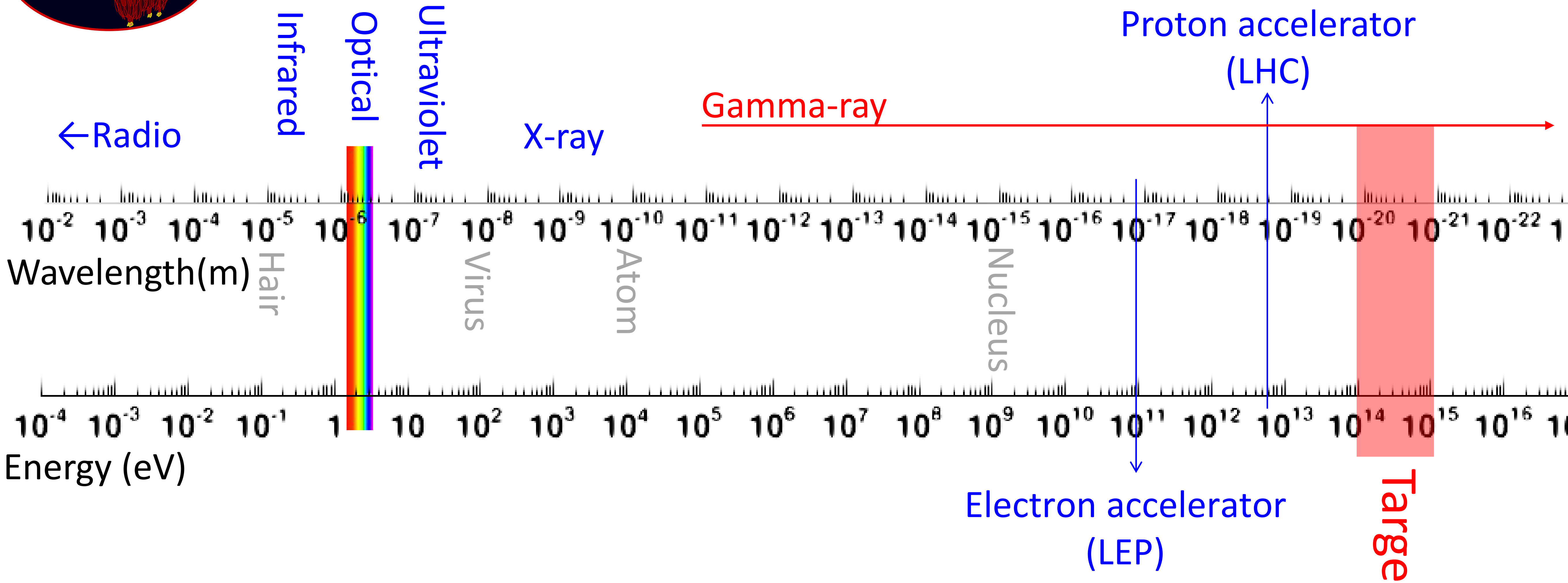
Copyright: ESA/Gaia/DPAC



X-Ray：Hot plasma

Copyright: eROSITA (MPE/IKI)

Observational Energy



The energy of electromagnetic waves is expressed in wavelengths.

Electron volt (eV): Unit of energy commonly used in particle physics.

10^{15} eV = 1 Peta electron volt (PeV)

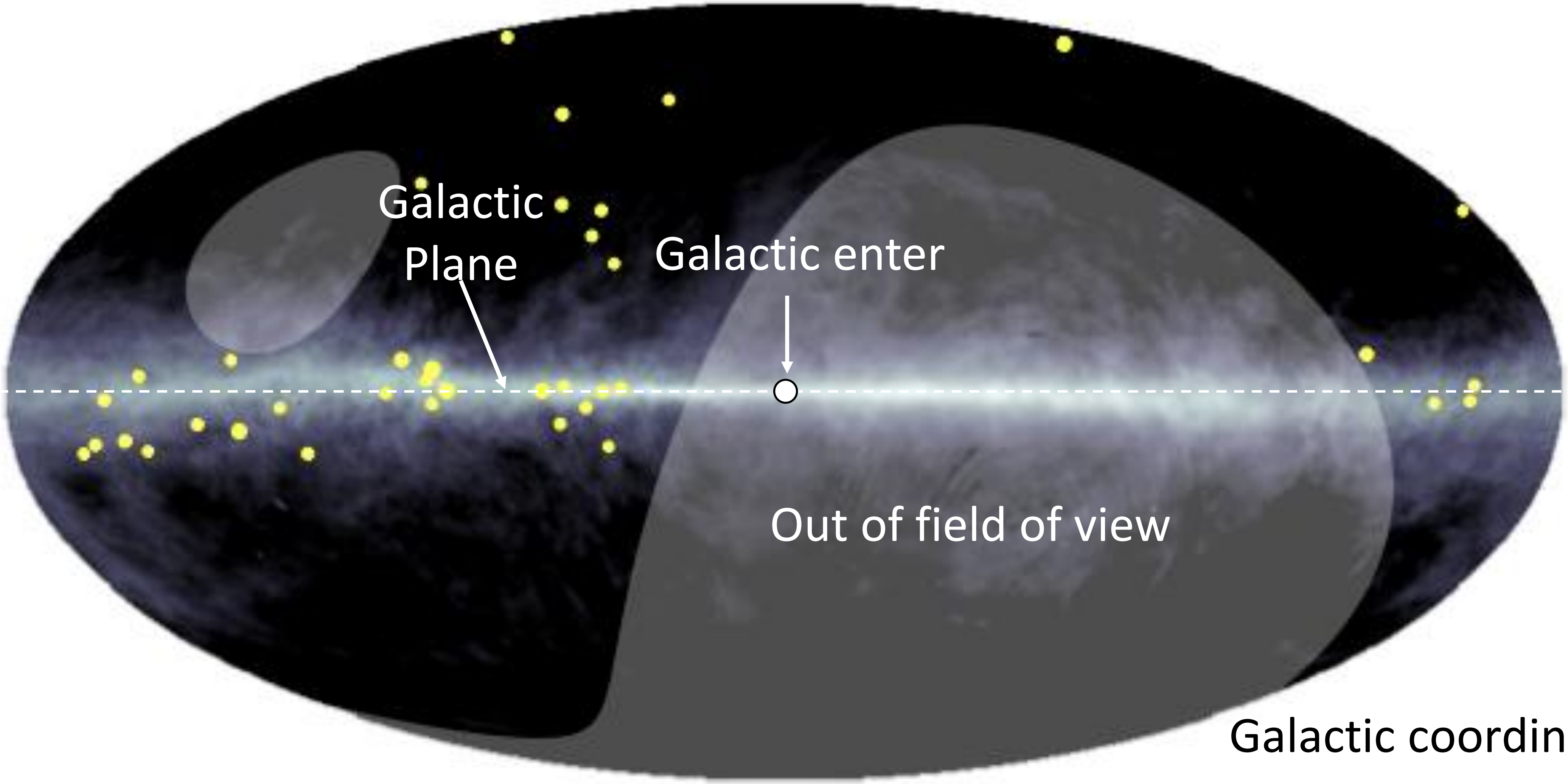
→ 1000 trillion times energy than visible light!

Highest Energy γ Rays from the Milky Way

23 ultra-high-energy (>0.398 PeV) gamma-ray events along (|b|<10^o the Milky Way!

(2 years of data during period between 2014 and 2017)

The highest energy 0.957 (+0.166- 0.141) PeV (~1 PeV) gamma ray is detected



0.398 – 0.957 PeV (sub-PeV) gamma rays & Atomic hydrogen (HI) distribution

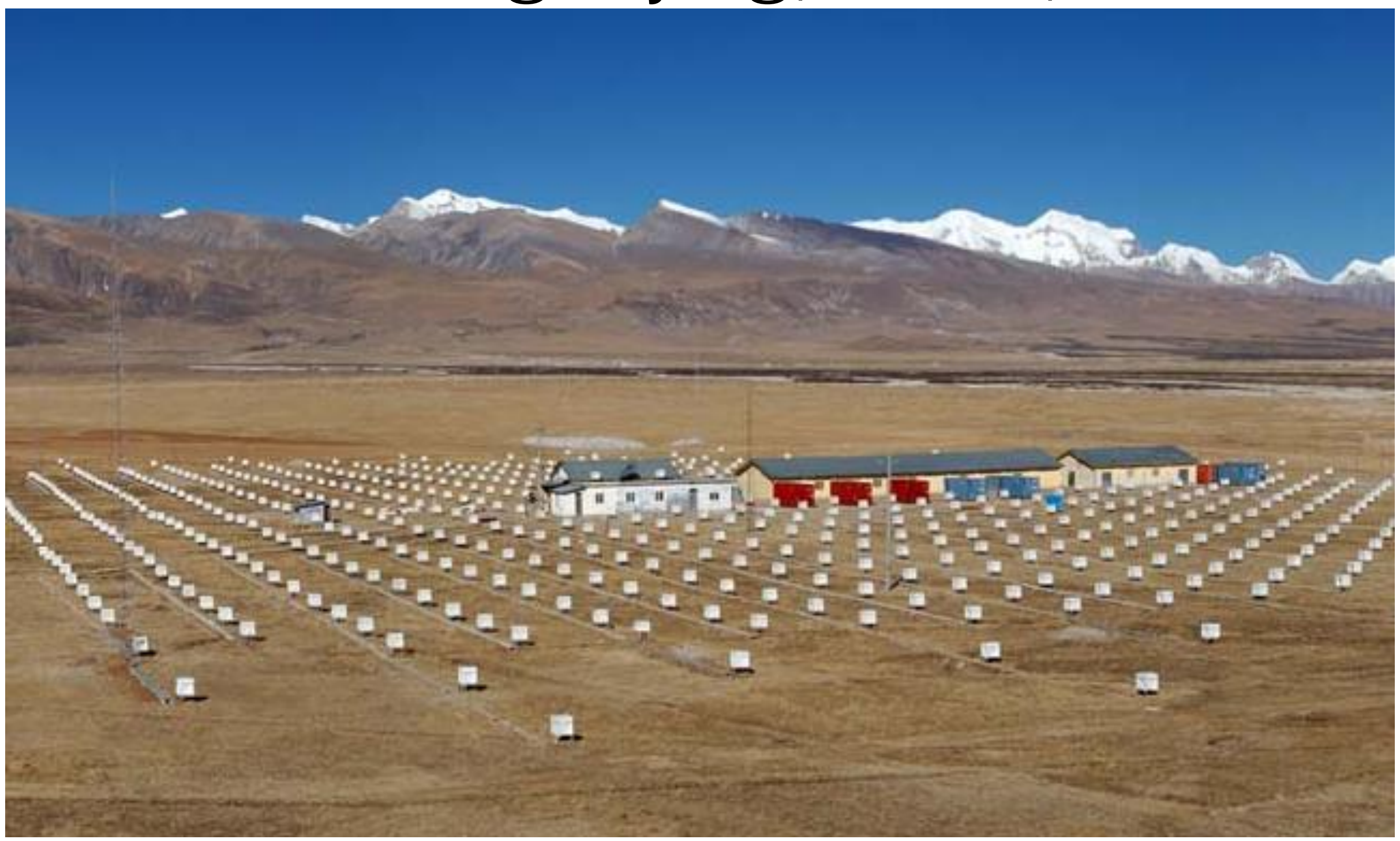
HI data available at https://lambda.gsfc.nasa.gov/product/foreground/fg_combnh_map.cfm

→ Gamma rays from inside of our Galaxy

§ Gamma-Ray Detection Method

Tibet ASγ Experiment

Yangbajing, Tibet, China at the altitude of 4300m



Surface air shower array 65,000m^2 scintillation detectors

Observation regardless day and night with wide field of view.

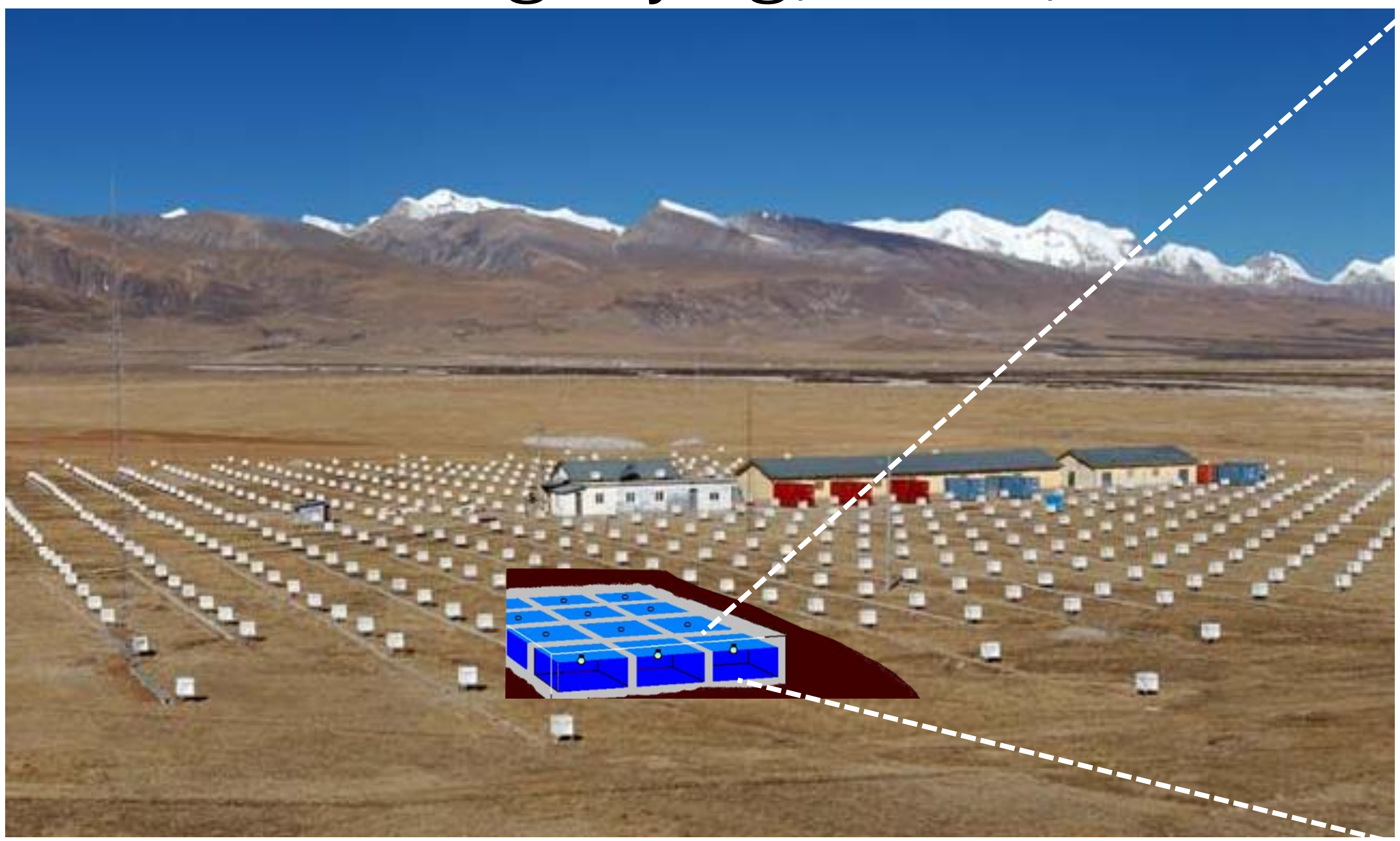
Underground muon detectors 3400m^2 (Before filling water)

Low-cost large-area muon detector
→ utilize to discriminate gamma ray signals from cosmic ray background.

Key technology! in this study

Tibet ASγ Experiment

Yangbajing, Tibet, China at the altitude of 4300m



Surface air shower array 65,700m^2 with plastic scintillation detectors

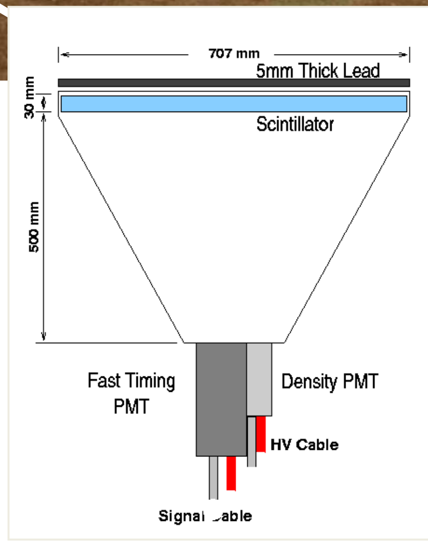
Observation regardless day and night with wide field of view.

Underground muon detectors 3400m^2 (Before filling water)

Low-cost large-area muon detector
→ utilize to discriminate gamma ray signals from cosmic ray background.

Key technology! in this study

Tibet Air Shower Array



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

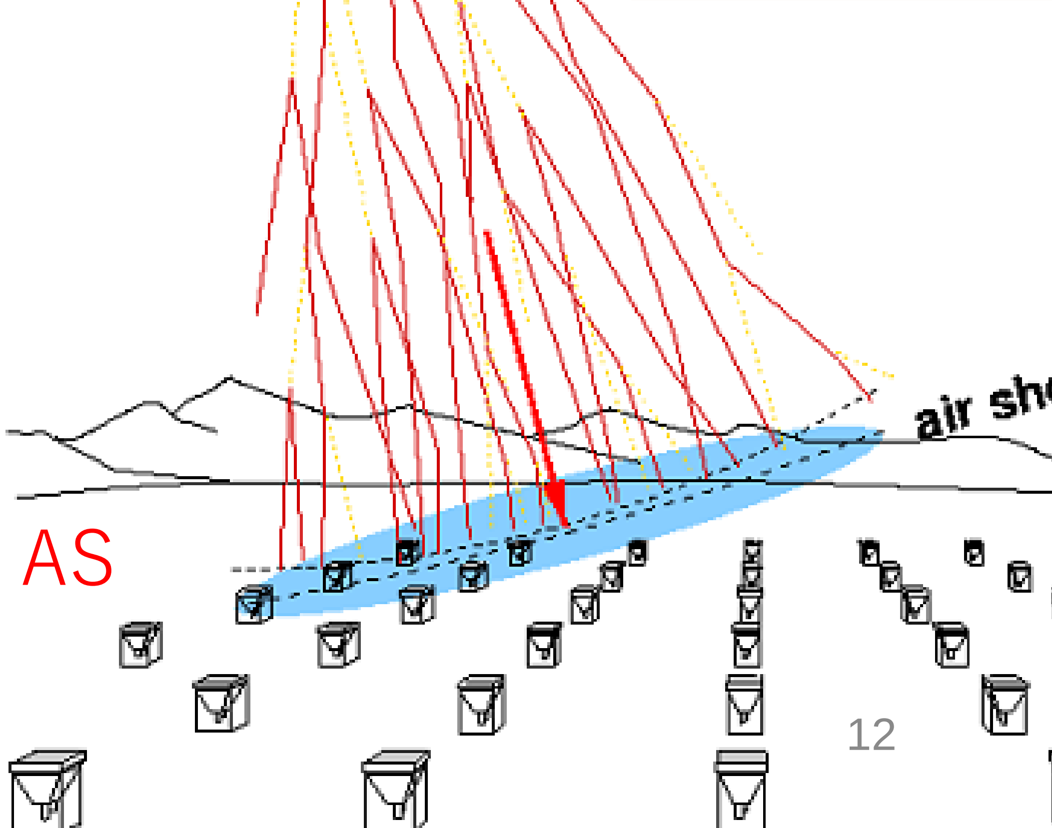
<u>Present Performance</u>

# 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 : 2^{nd} particle densities

Primary direction : 2^{nd} relative timings

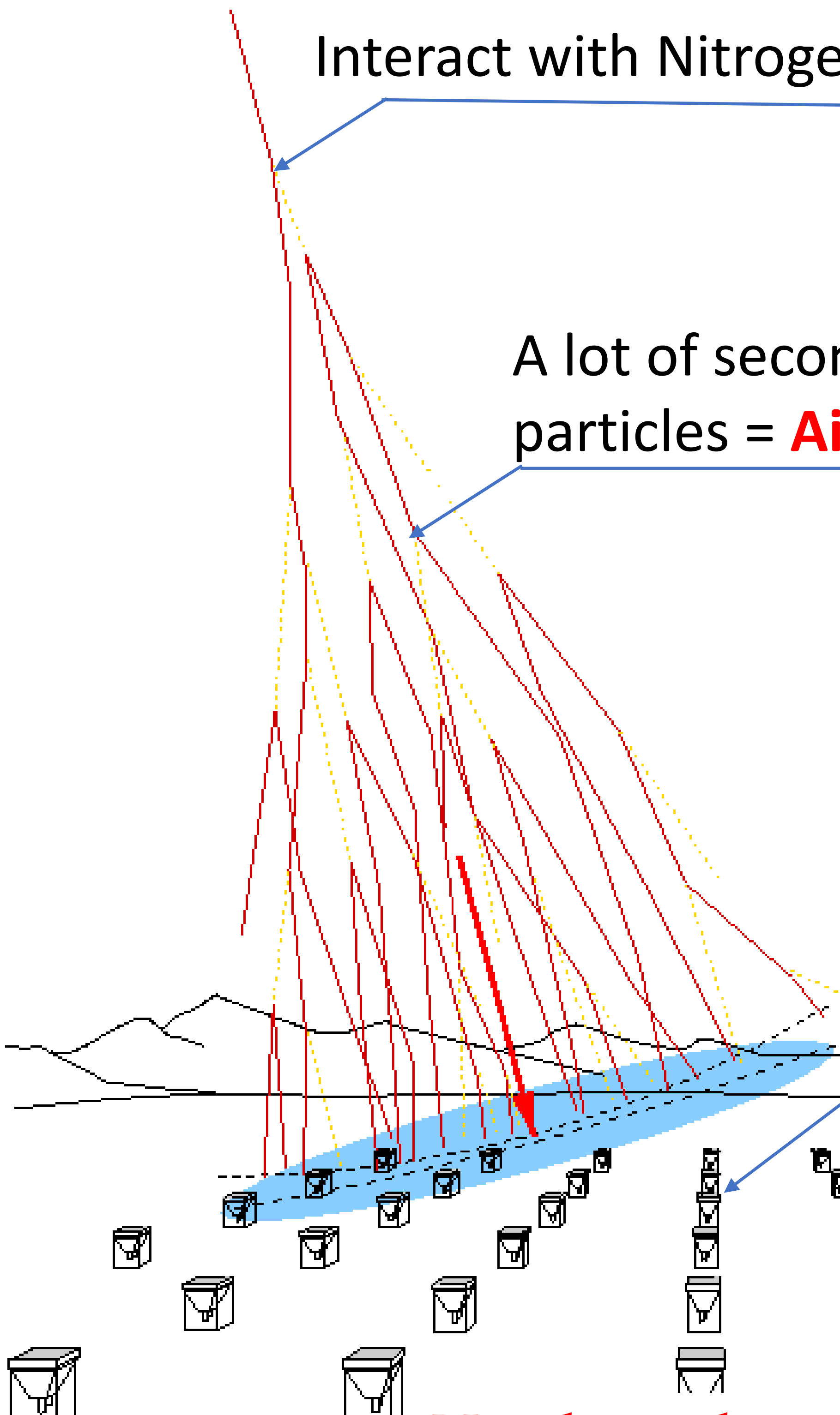


Detection Principle

Gamma ray/Cosmic ray

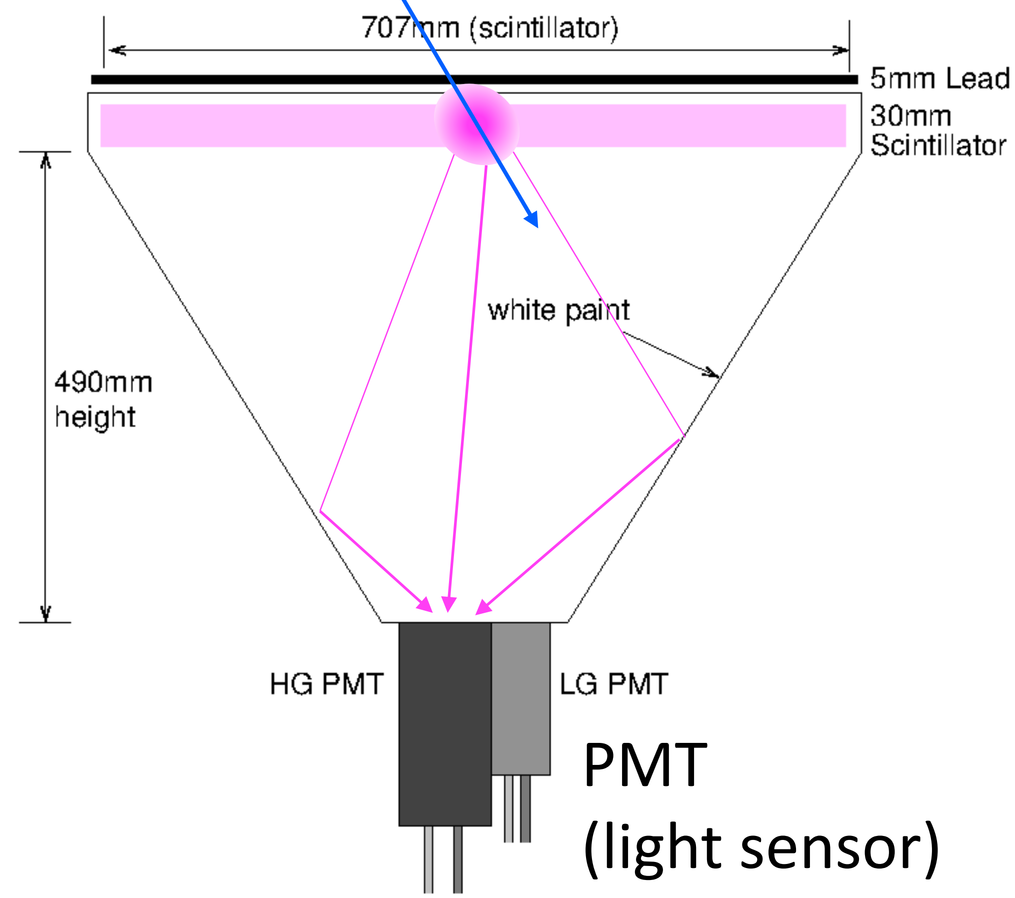
Interact with Nitrogen & Oxygen

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



Observe secondary particles by each detector

Plastic scintillator: Emit fluorescence lights when particles pass it



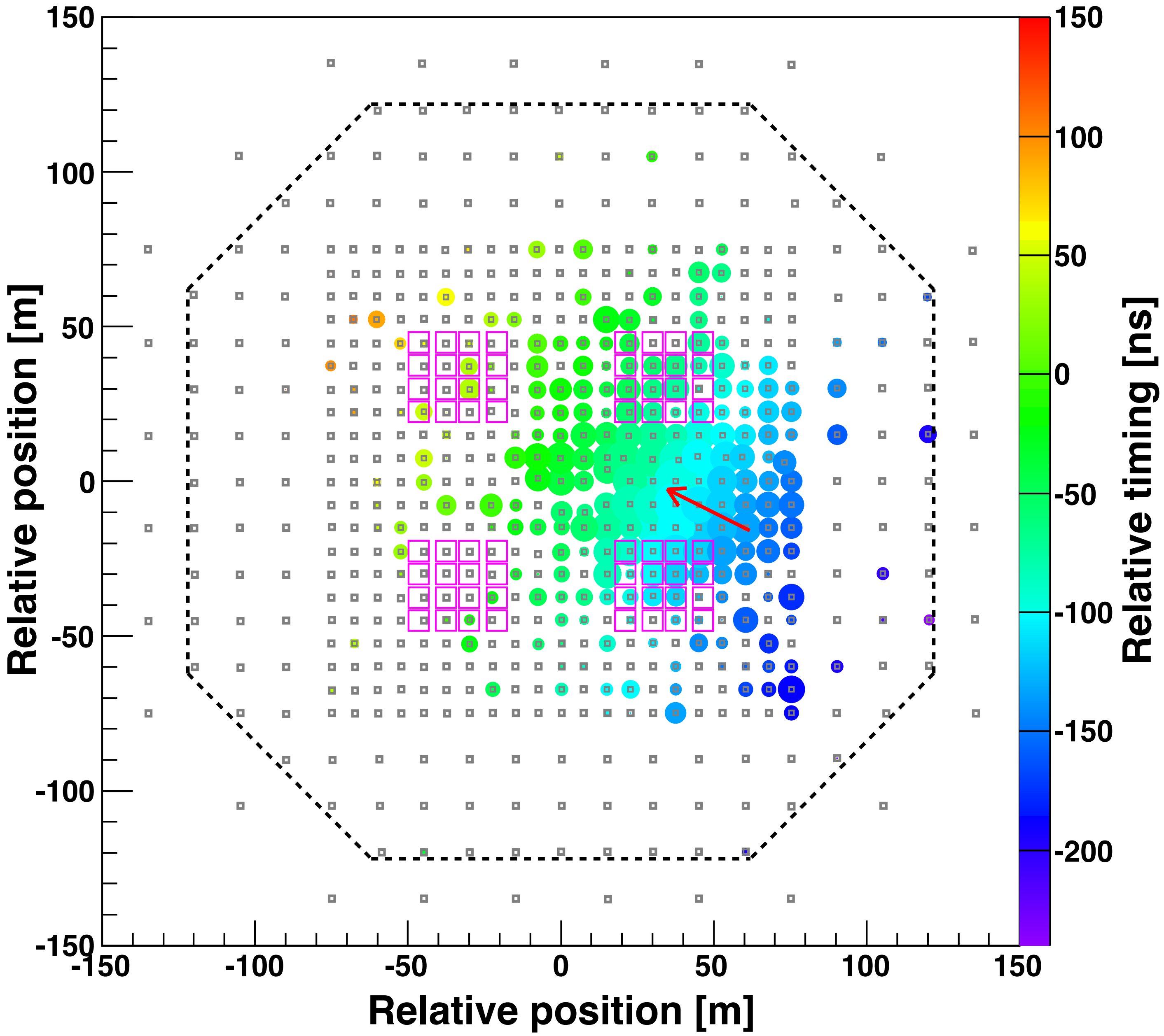
PMT (light sensor)

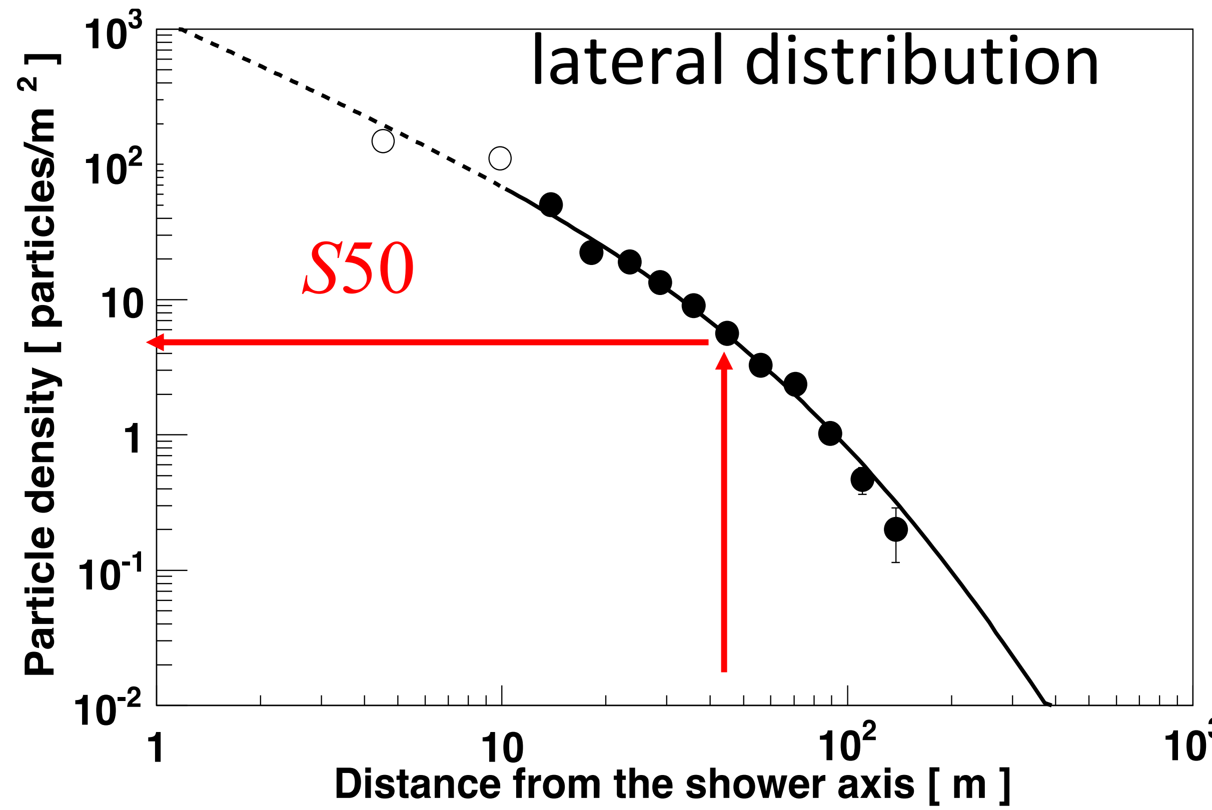
Determine the direction & energy of the gamma ray

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

Need another technique to separate γ rays from cosmic rays.

Gamma-like Event from the Crab





circle size ∝ log(# of detected particles)

circle color ∝ relative timing [ns]

fitting with NKG function

➡ E_{rec} ($S50$, θ)

Σρ (from AS array) : 3256

ΣNμ (MD) : 2.3

zenith angle : 29.8°

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

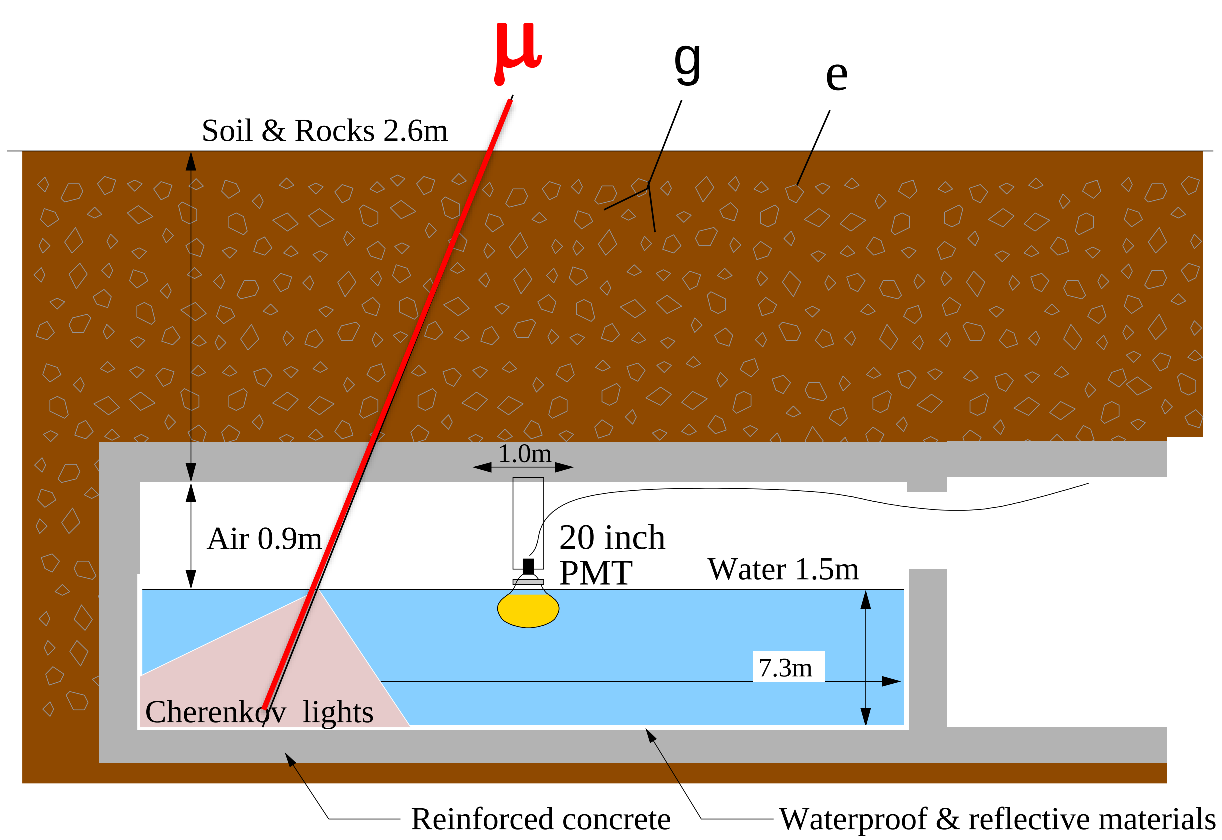
Amenomori et al., PRL ***123****, 051101 (2019)*

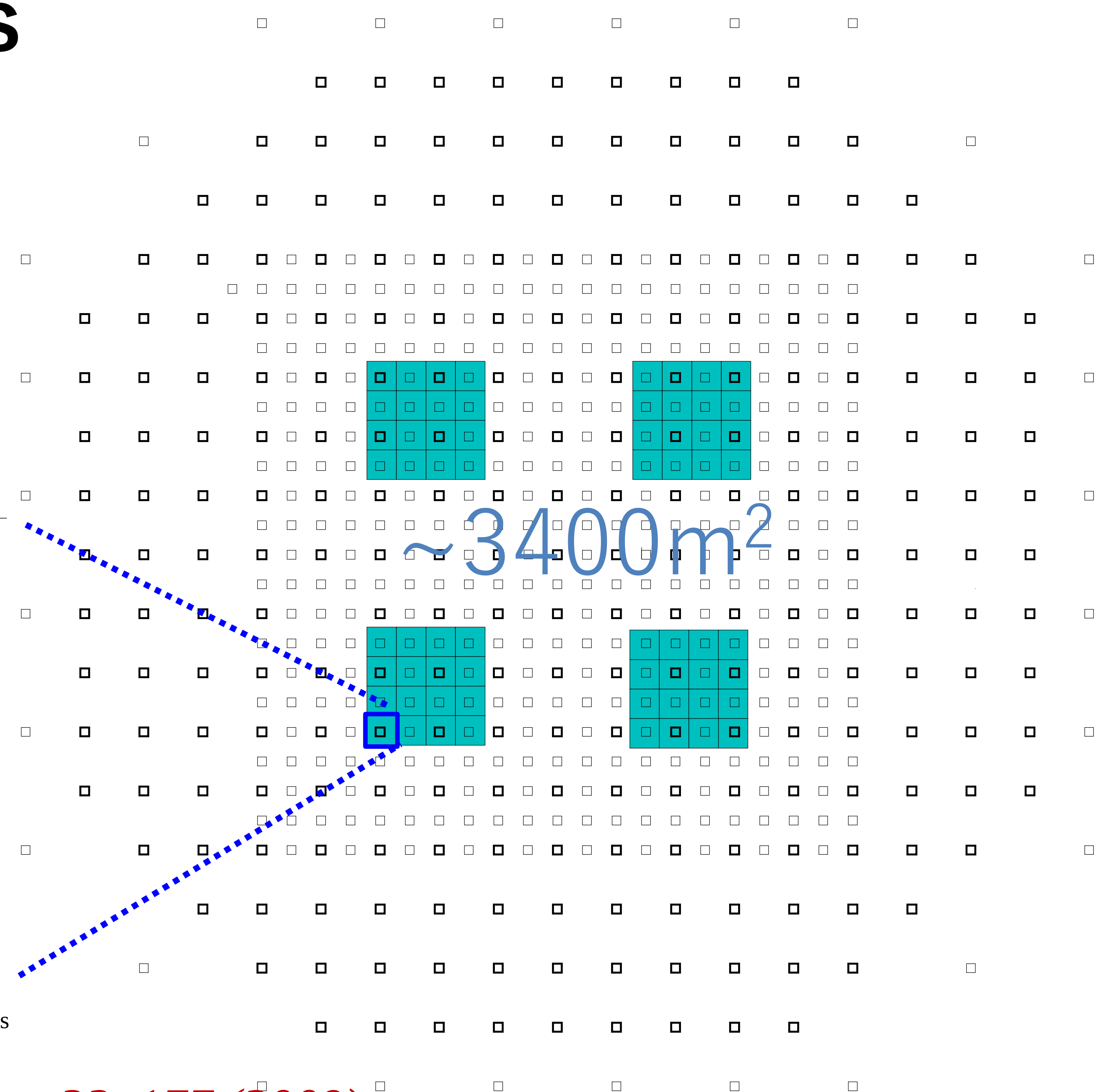
S50 improves *E* resolutions (10 - 1000 TeV)

→ ~40%@10 TeV , ~20%@100 TeV

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 et al., Astropart. Phys. 32, 177 (2009)

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

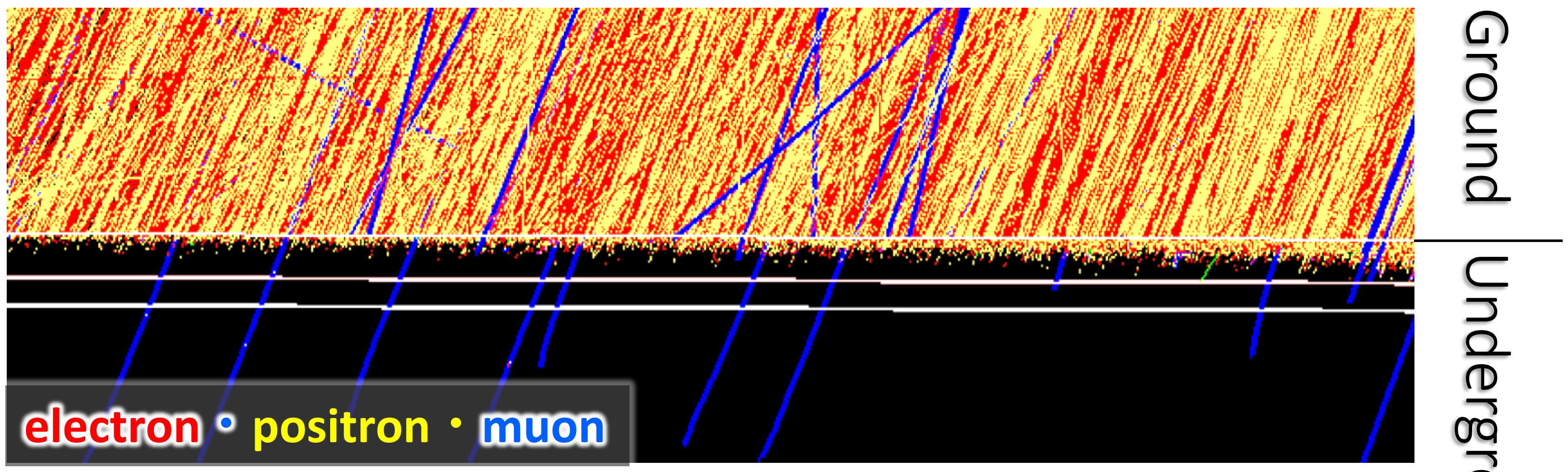
DATA: February, 2014 - May, 2017 Live time: 719 days

Gamma-Ray Selection

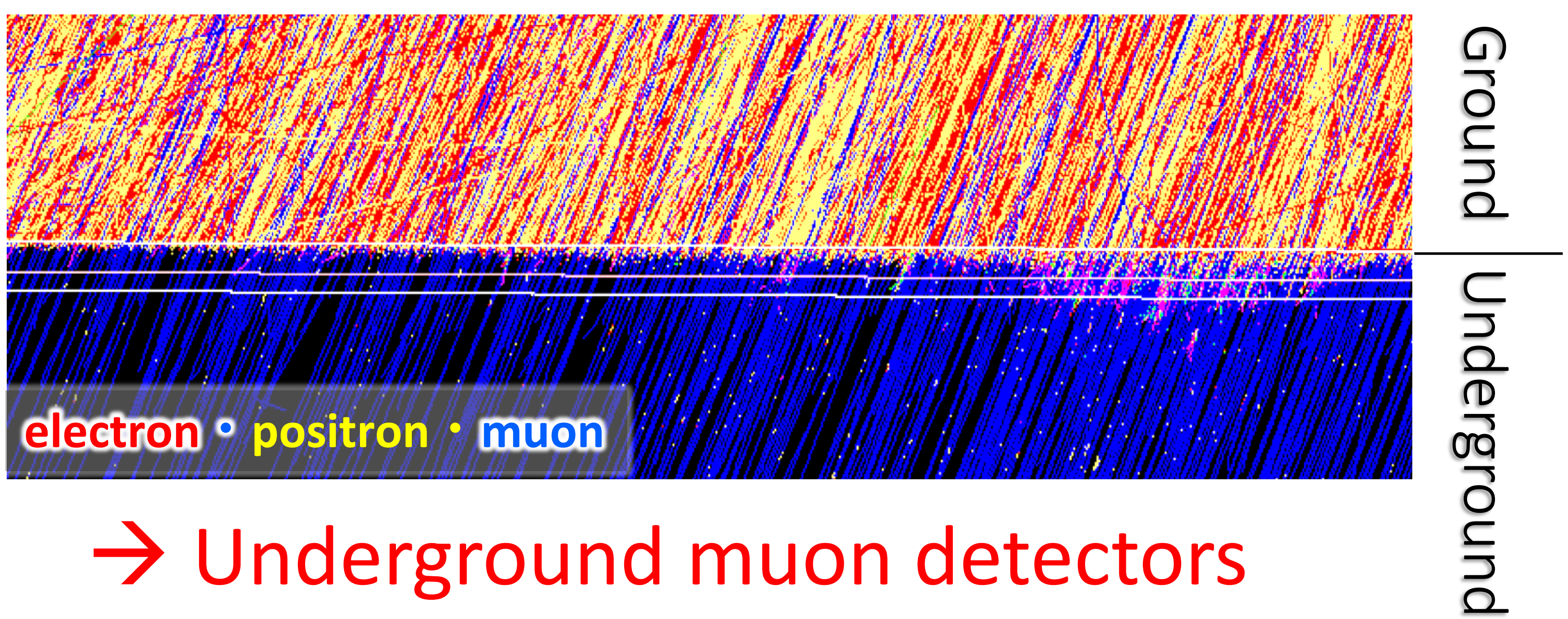
γ-ray → poor muons

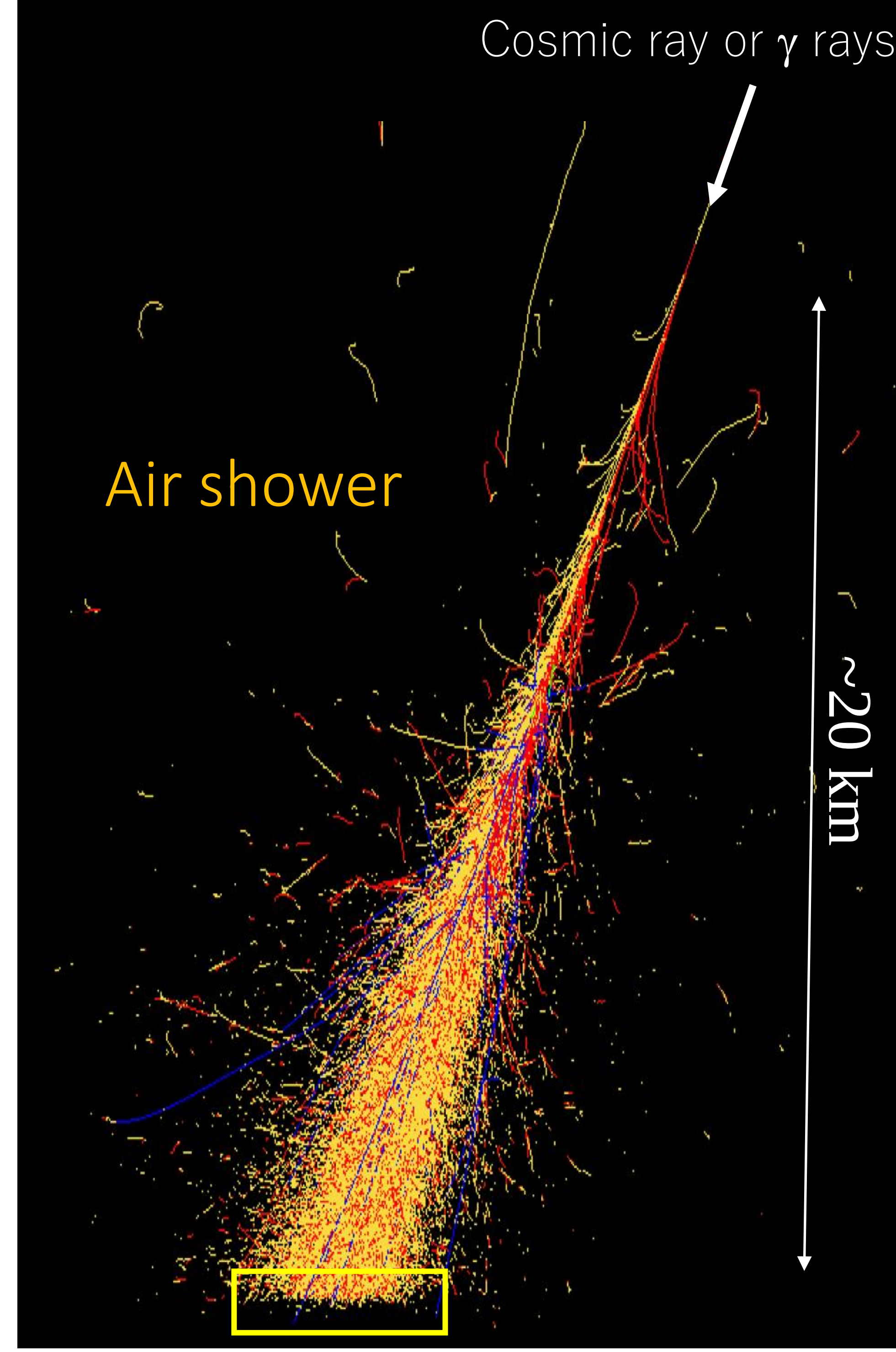
Muons can penetrate underground

0.2PeV γ-ray



0.2PeV Cosmic ray (Noise)



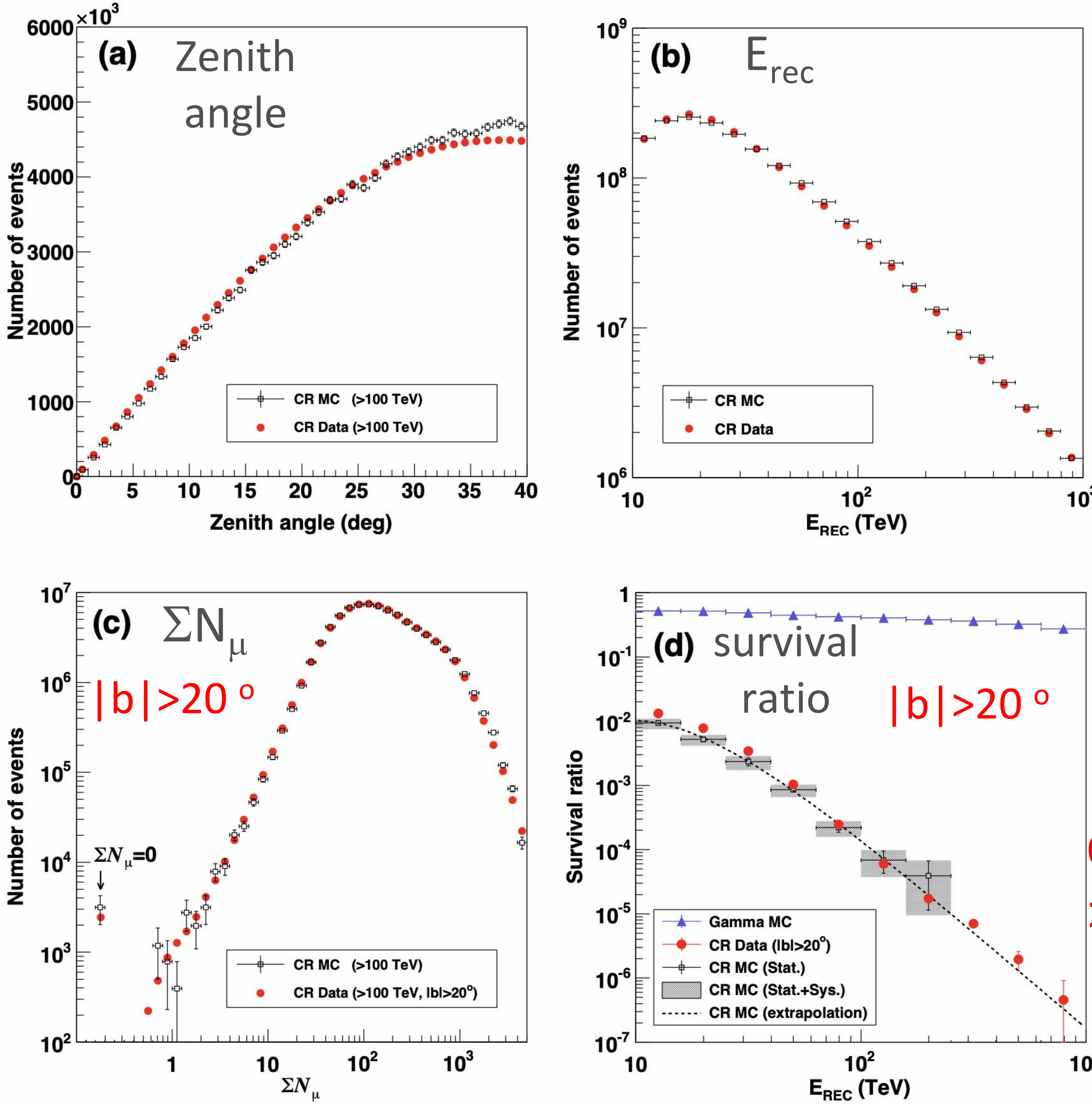


Enlarged view

→ Underground muon detectors

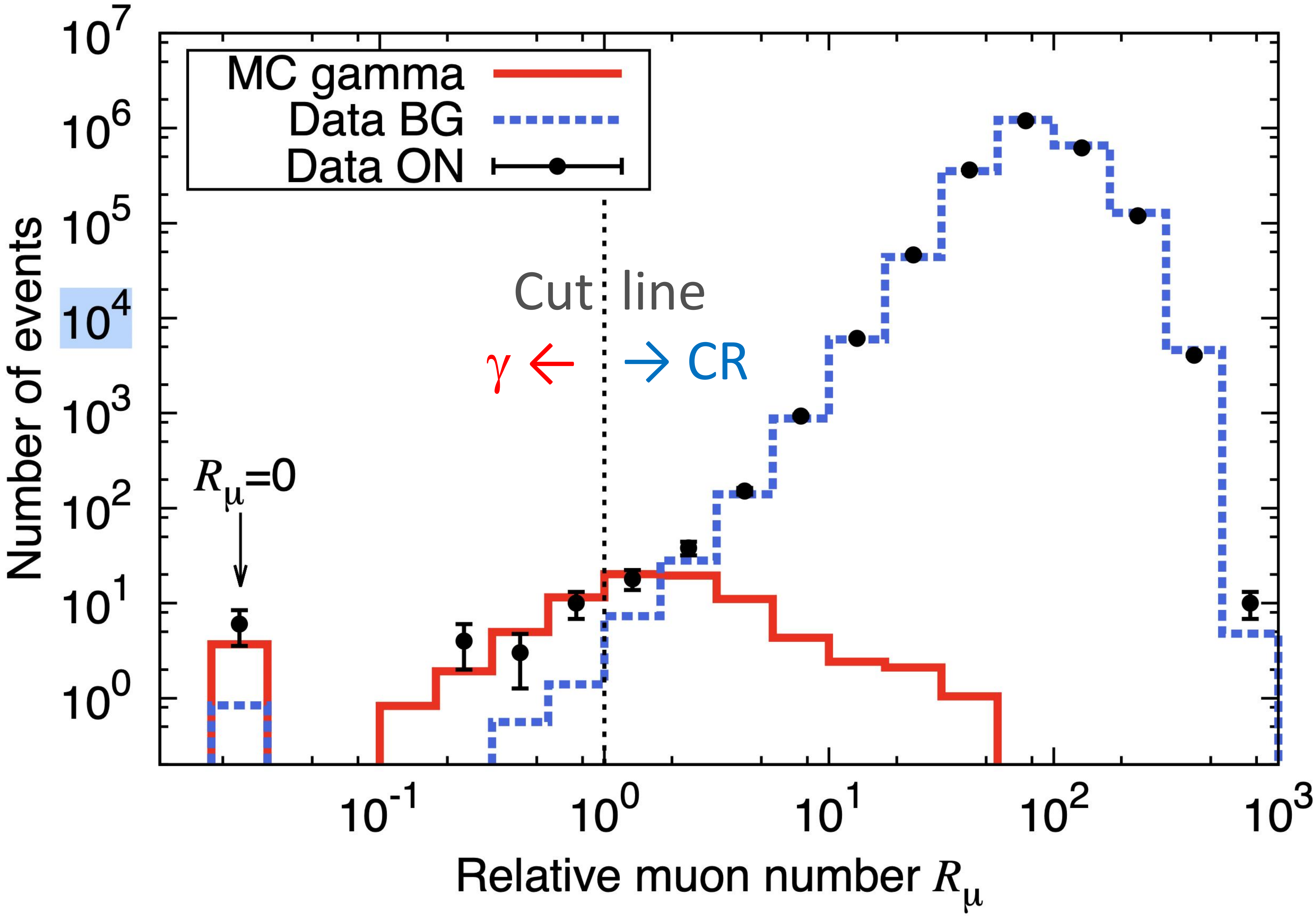
CR MC
vs.
DATA

Reasonable agreement!



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

Relative muon number distribution for events > 0.398 PeV



Amenomori, et al., PRL (2021)

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

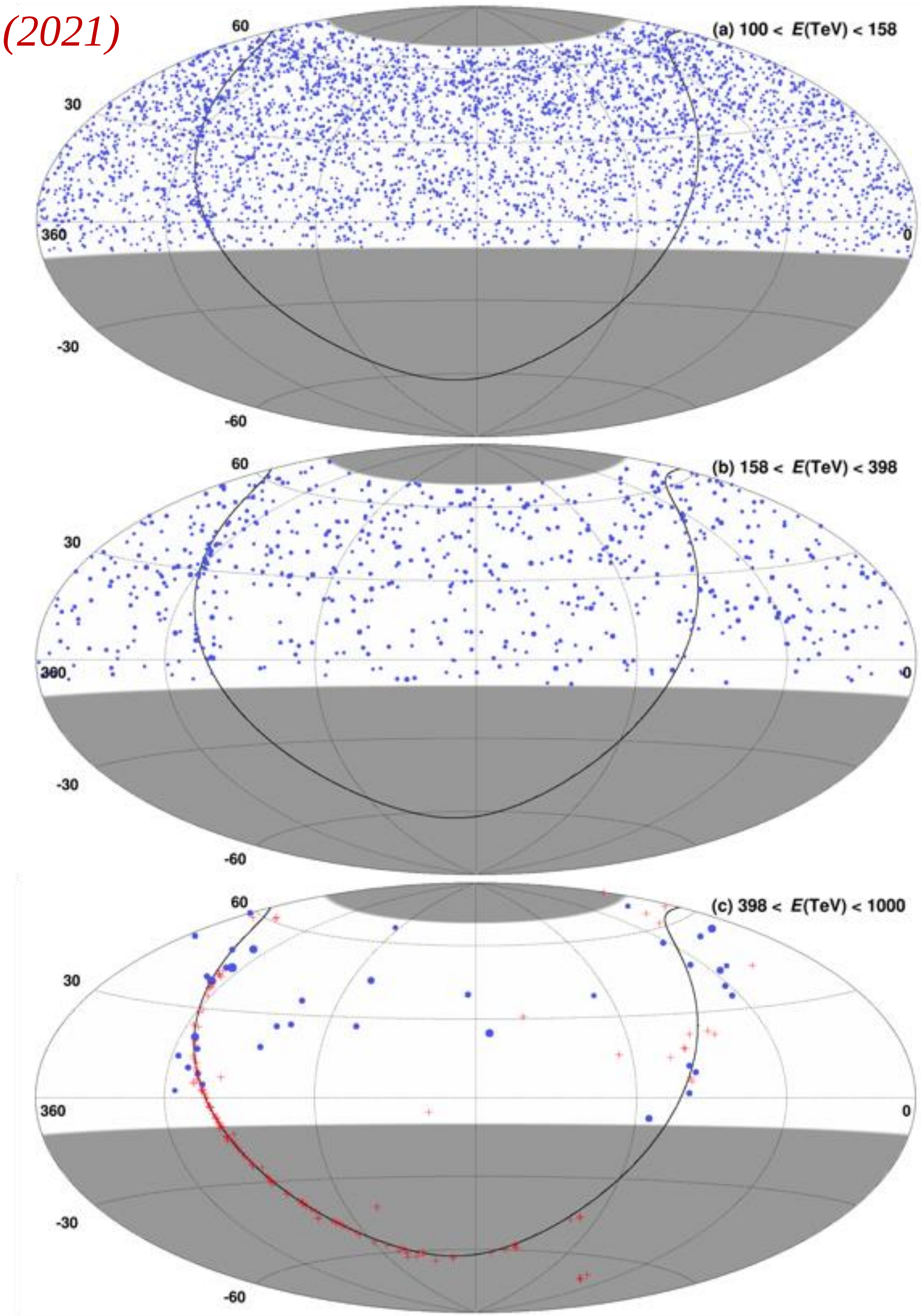
Blue points:
Tibet AS +MD
(Circle size ∝ Energy)

Red plus marks:
TeV sources
(TeVCat catalog)

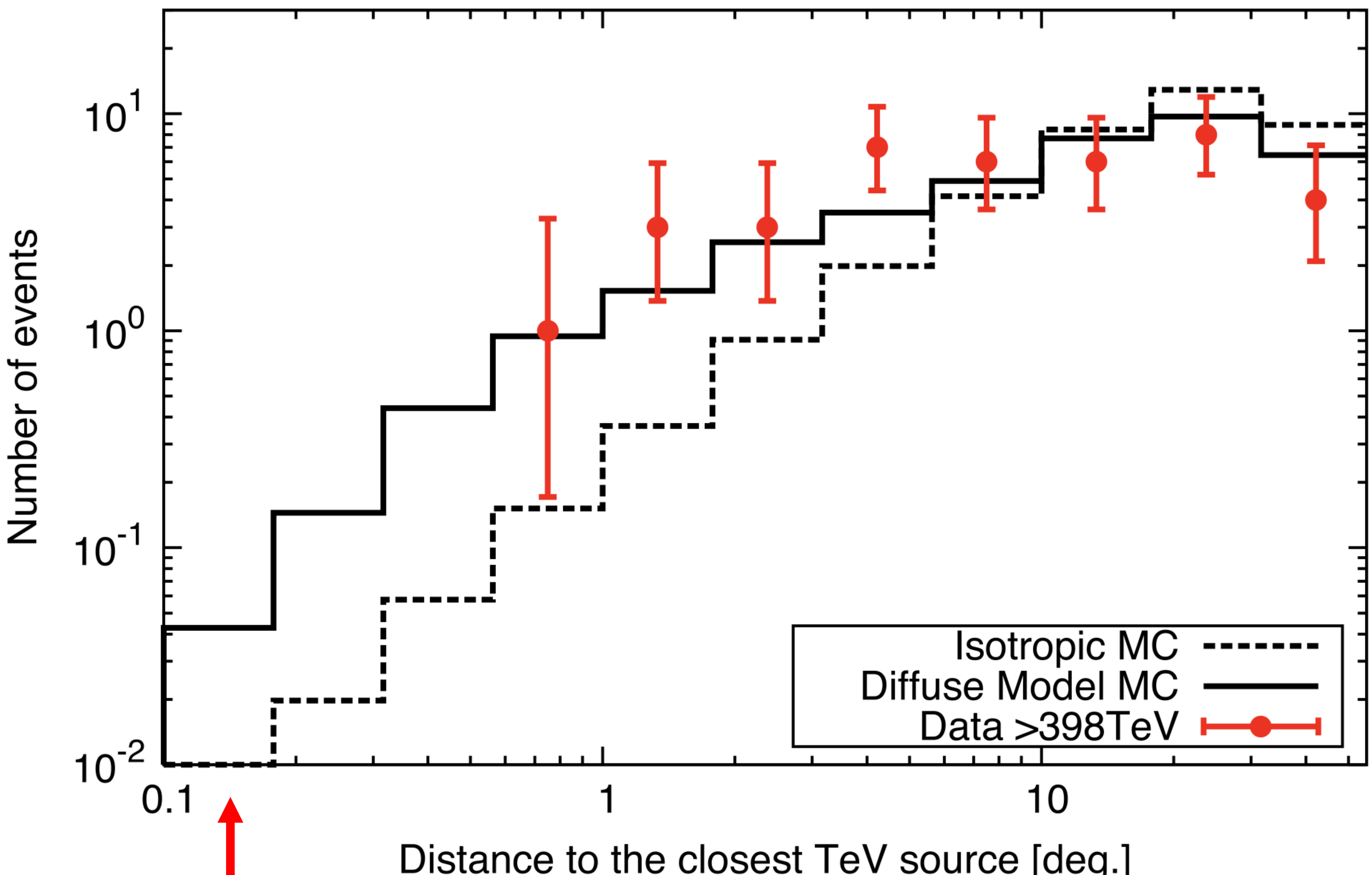
>0.398 PeV ($10^{2.6}$ TeV)
38 events in our FoV

→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



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

Models: 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.

	$\lvert b\rvert < 5^\circ$			$\lvert b\rvert < 10^\circ$		
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.

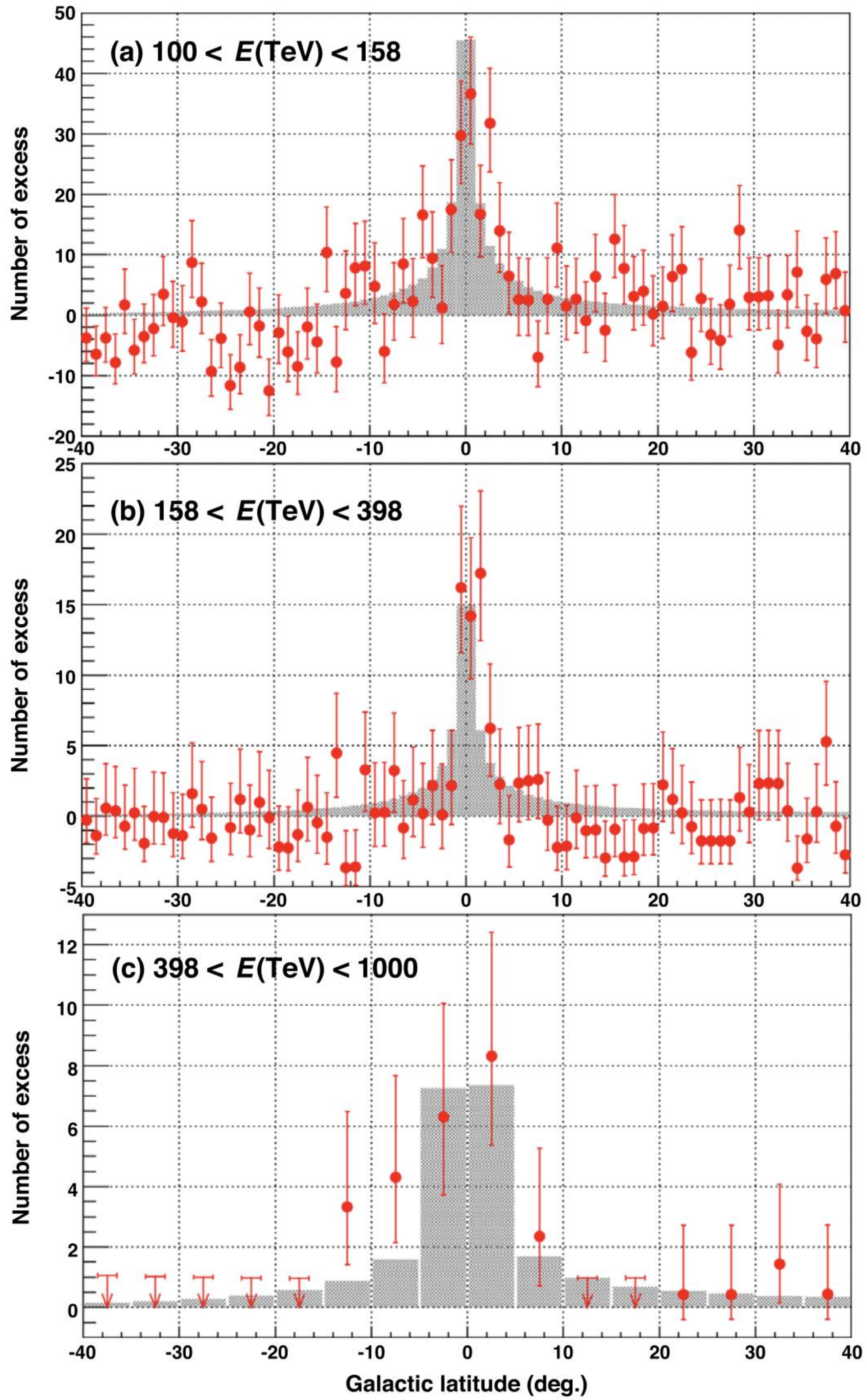
Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ, \lvert b\rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50^\circ < l < 200^\circ, \lvert b\rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
100 – 158	121	$(3.16 \pm 0.64) \times 10^{-15}$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

Galactic latitude distributions

of ev

# of ev

# of ev



-40° 0 40°

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

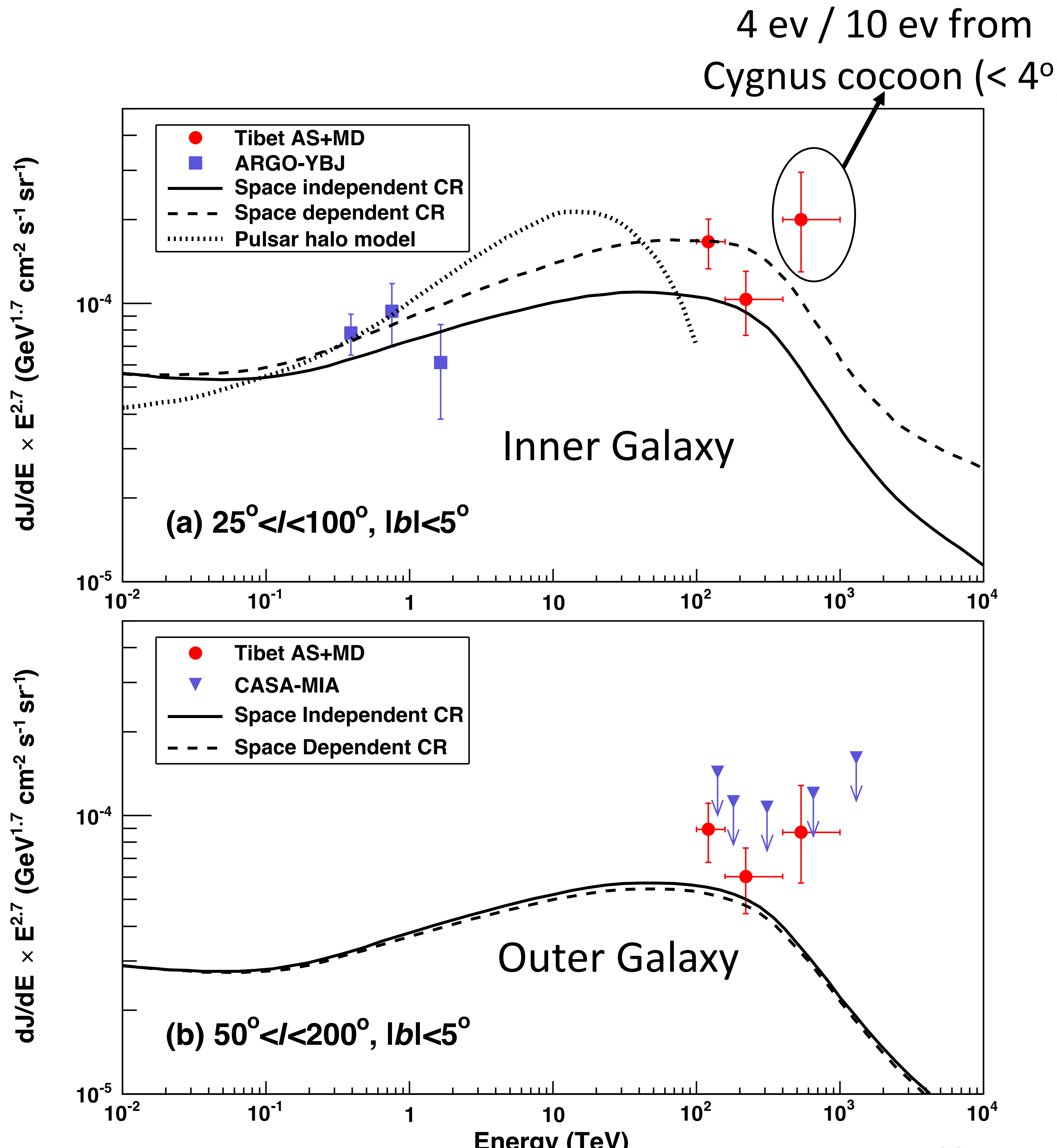
Model: Lipari & Vernetto, PRD 98, 143003, (2018) *Amenomori, et al., PRL (2021)*

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)

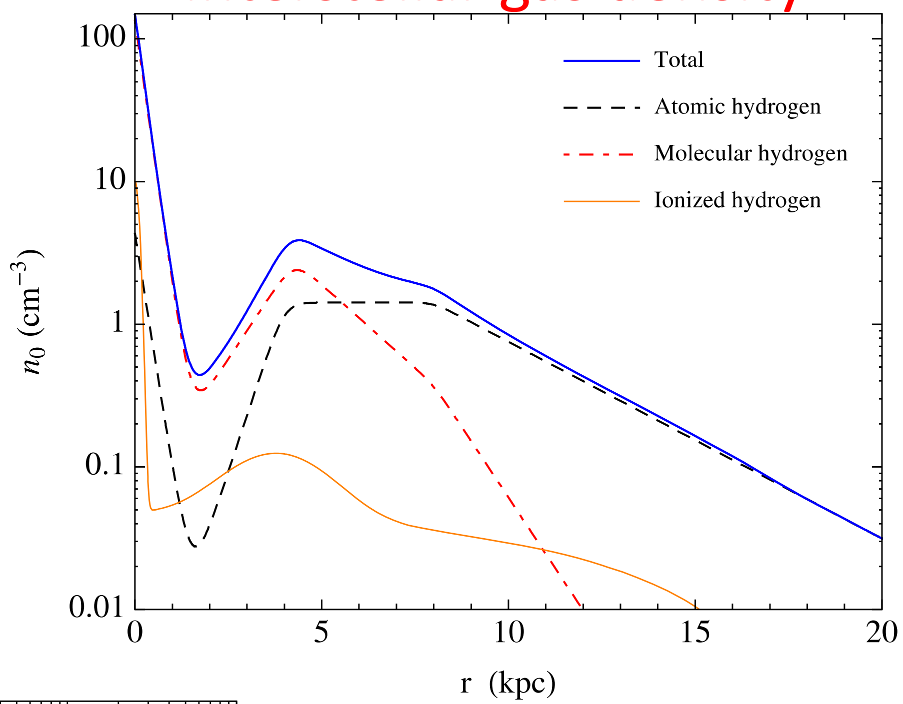
The measured fluxes are reasonably consistent with Lipari's galactic diffuse gamma-ray model assuming the hadronic cosmic-ray origin.



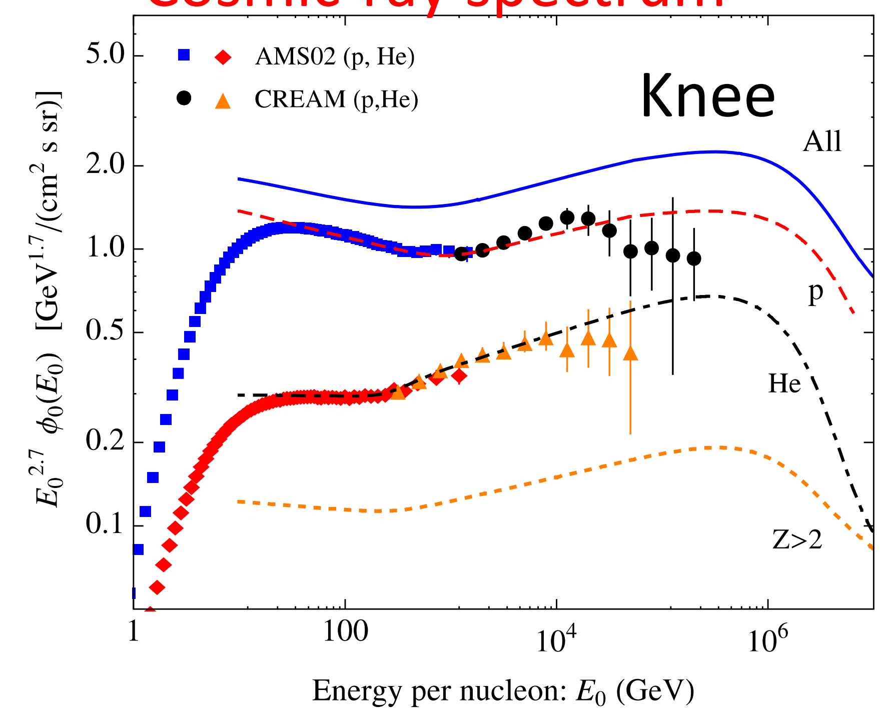
Diffuse γ-ray Model

Lipari & Vernetto, PRD (2018)

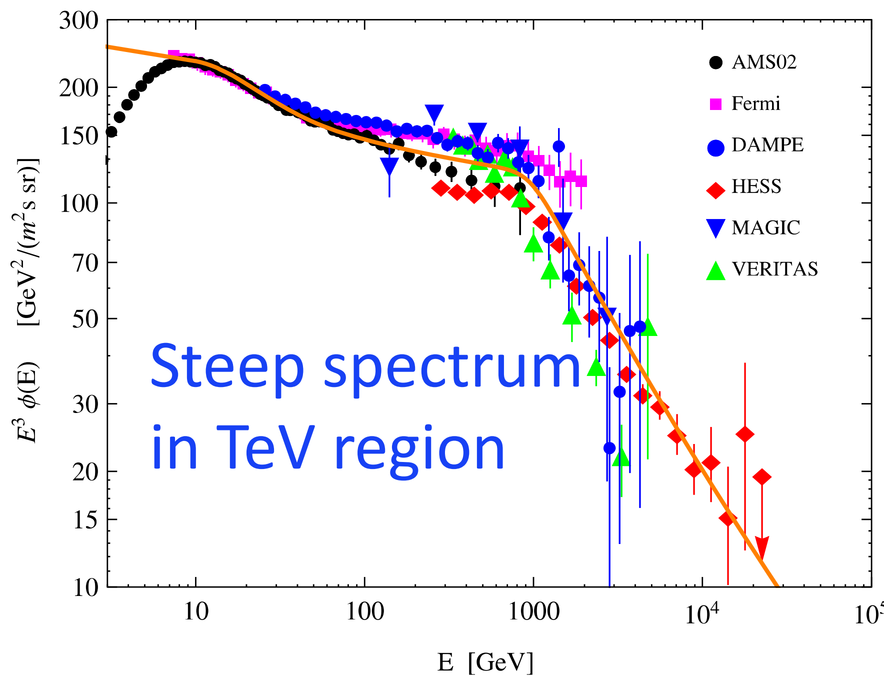
Interstellar gas density



Cosmic-ray spectrum



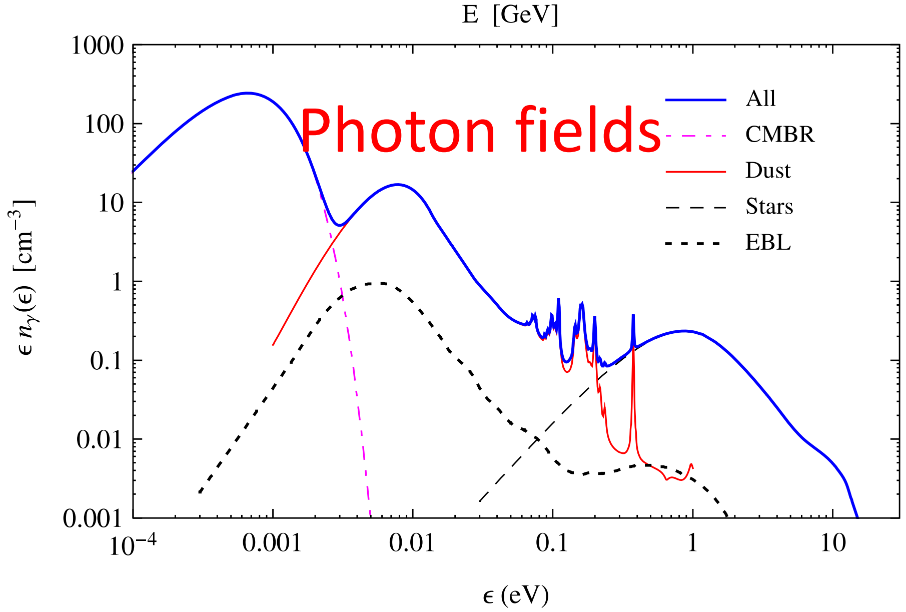
Electron/Positron

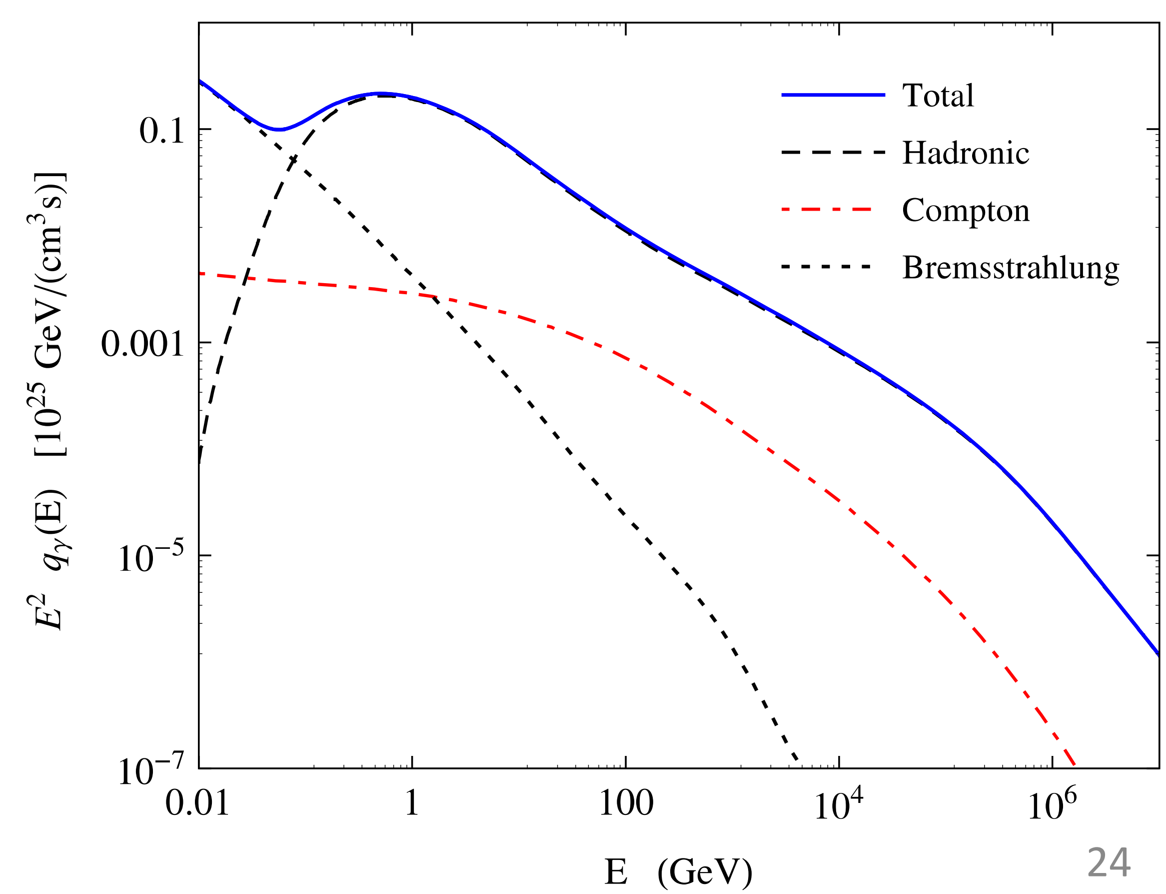


Bremss.

Hadronic

Compton





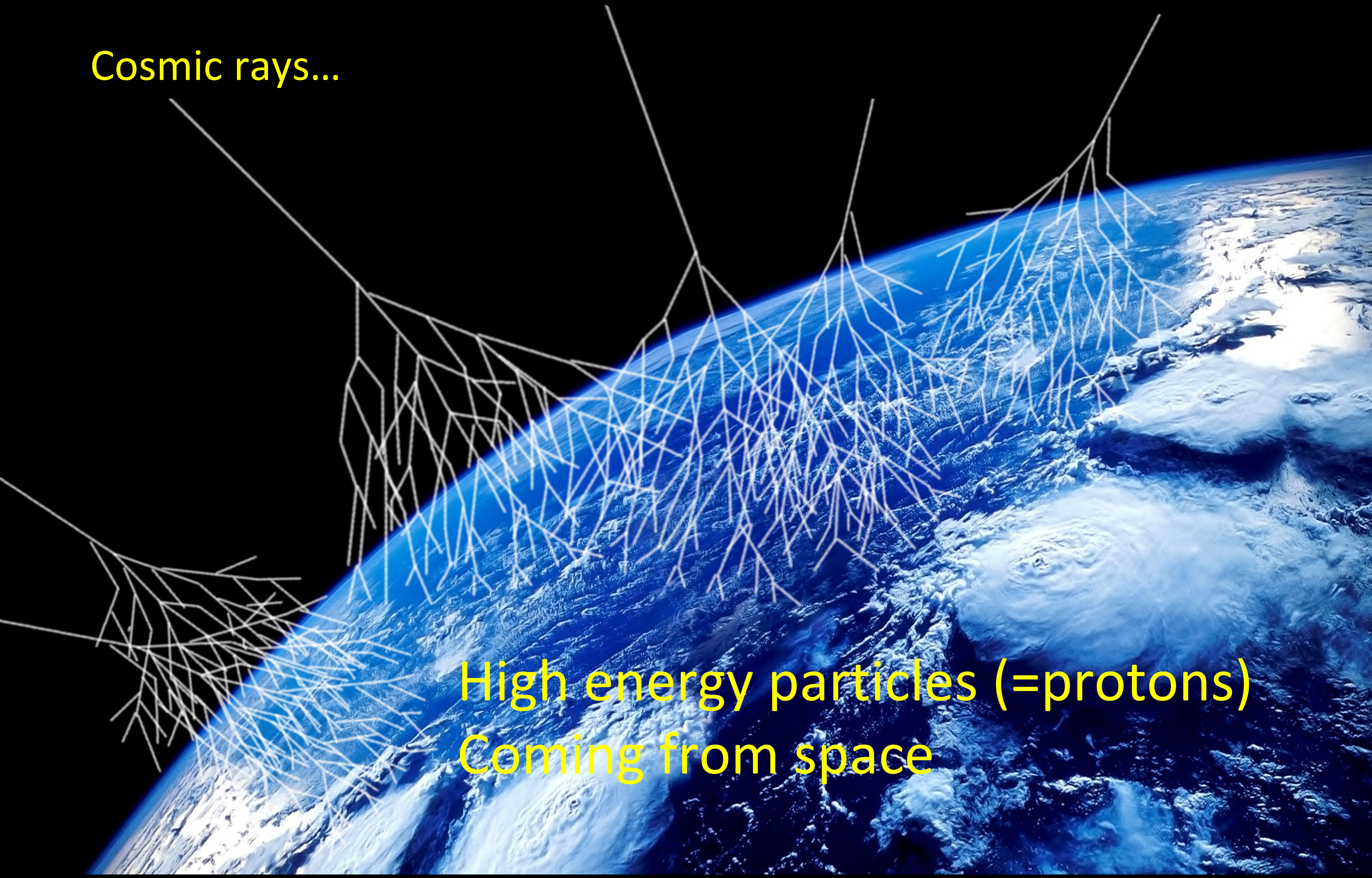
Arrival Directions of the 38 events (> 0.398 PeV)
See PRL supplemental materials

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

§ Scientific Interpretation

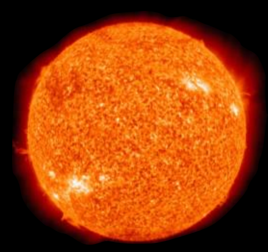
Cosmic rays…



High energy particles (=protons)
Coming from space

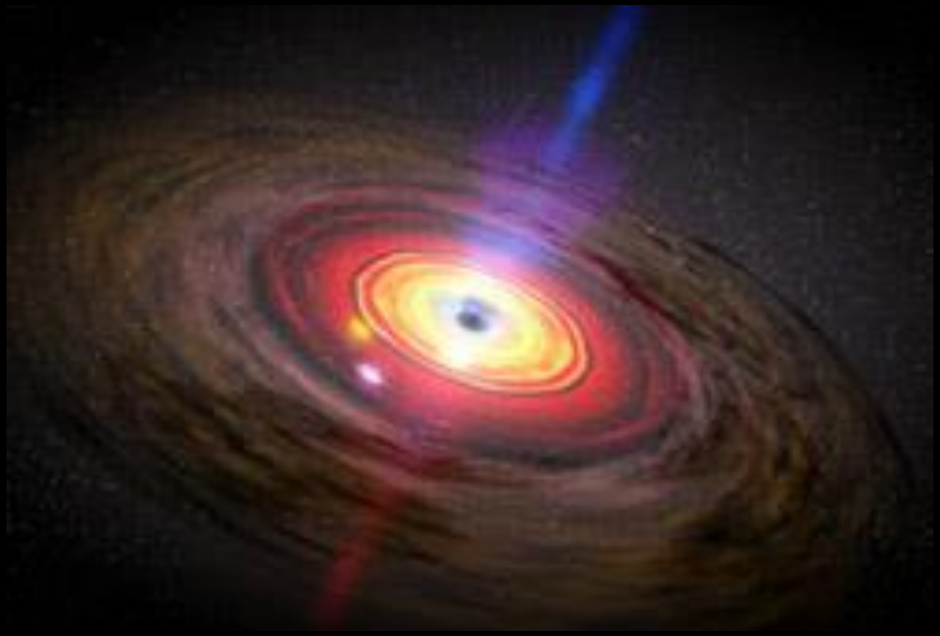
Cosmic rays…

Where do they come from?



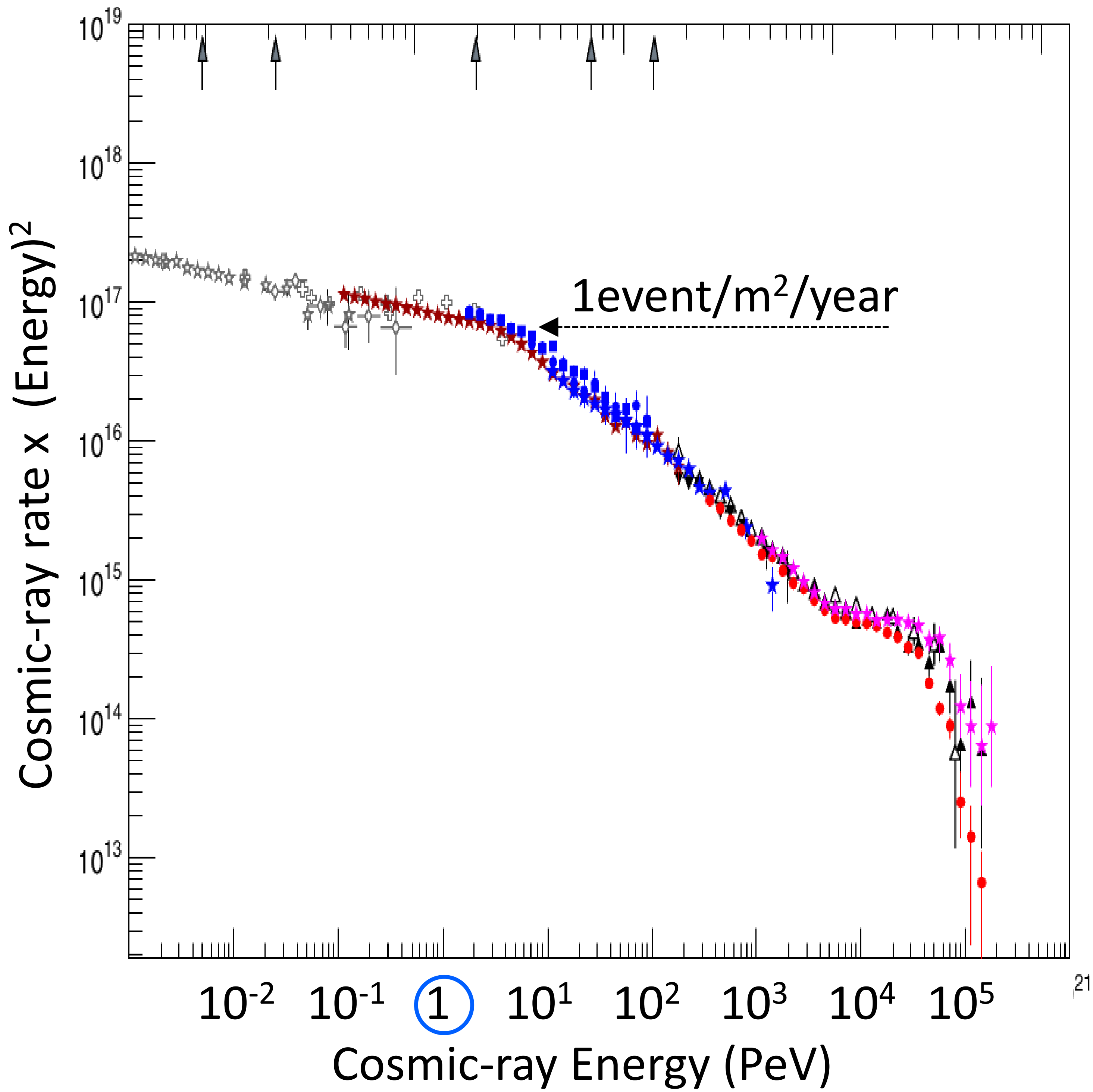
Sun

Supernova remnant?
(after star explosion)



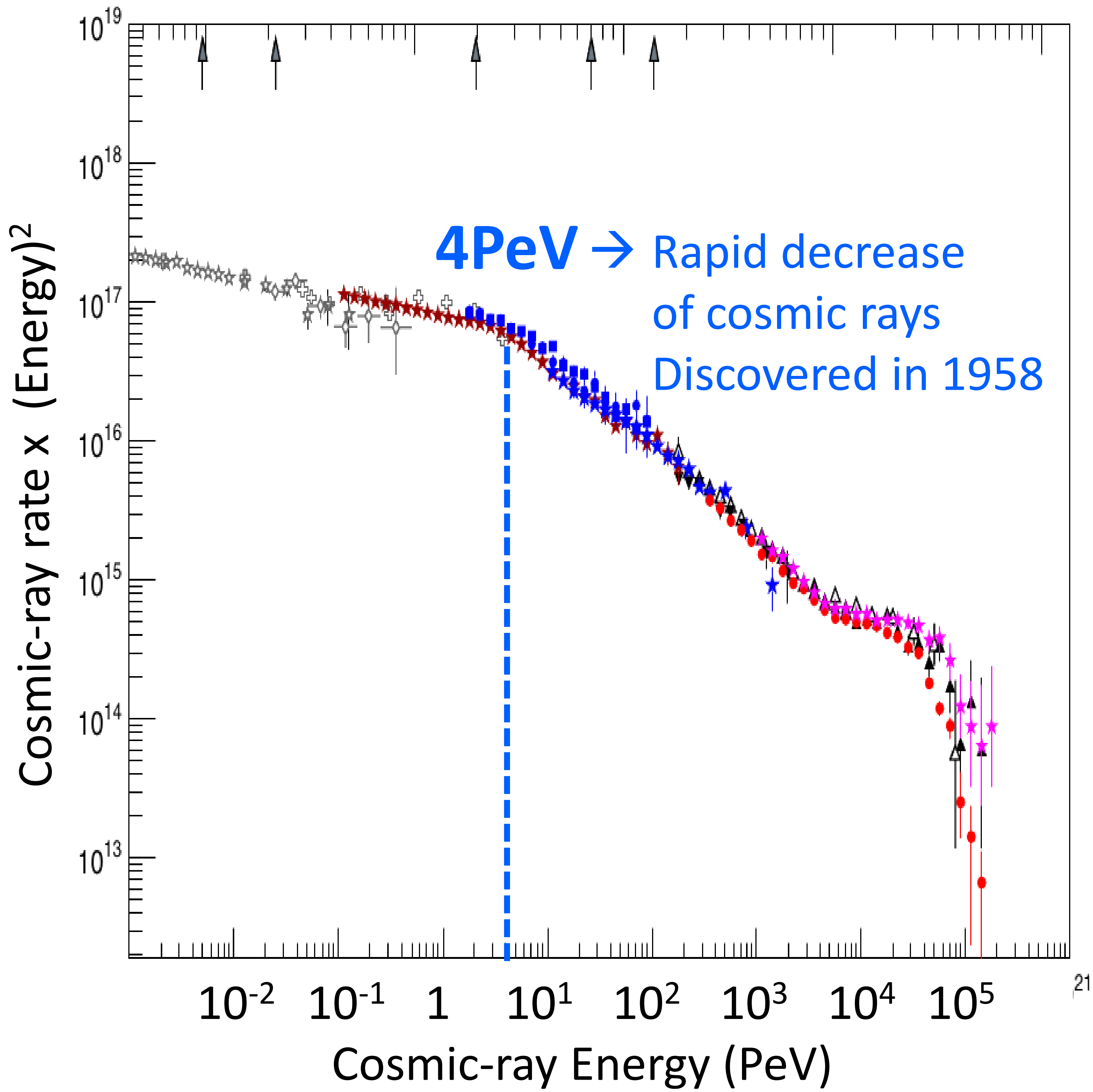
Active galaxy??
(massive blackhole)

Cosmic Ray Rate & Energies



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

Cosmic Ray Rate & Energies



- Wide energy range
- Main component is proton
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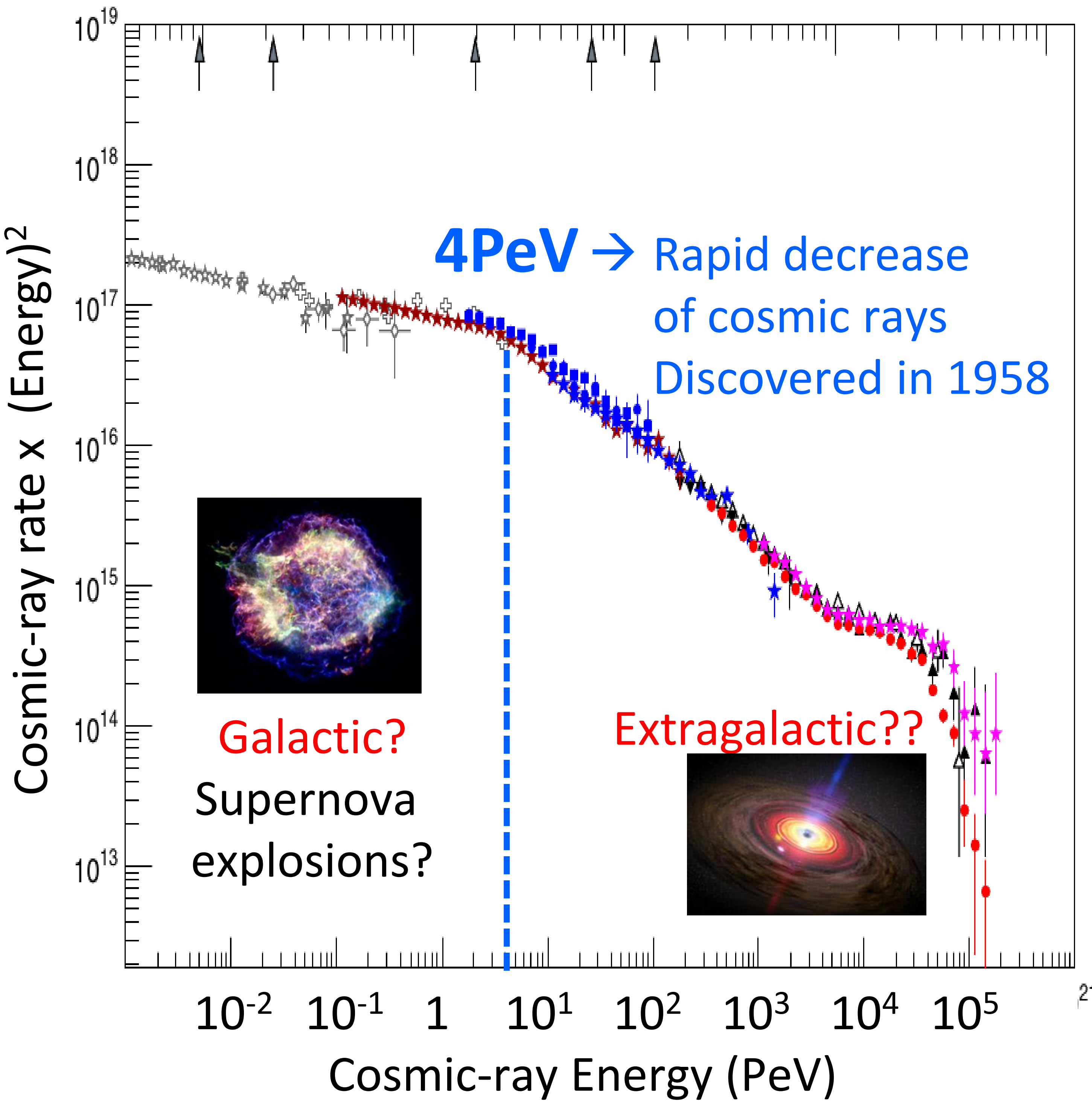
Cosmic Ray Rate & Energies

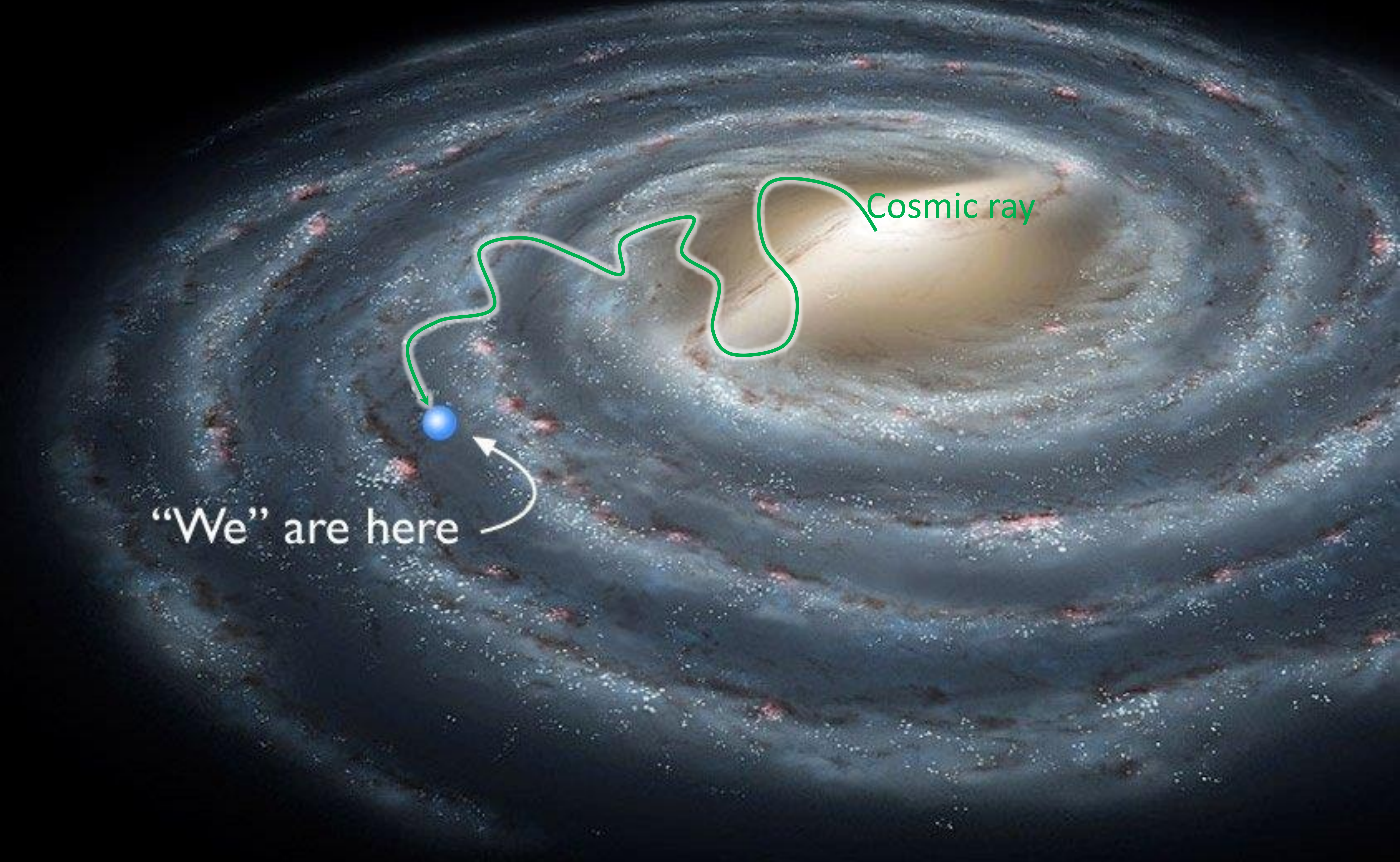


- ❖ Wide energy range
- ❖ Main component is proton
- ❖ Rate decreases to 1/100 when energy is 10 times higher

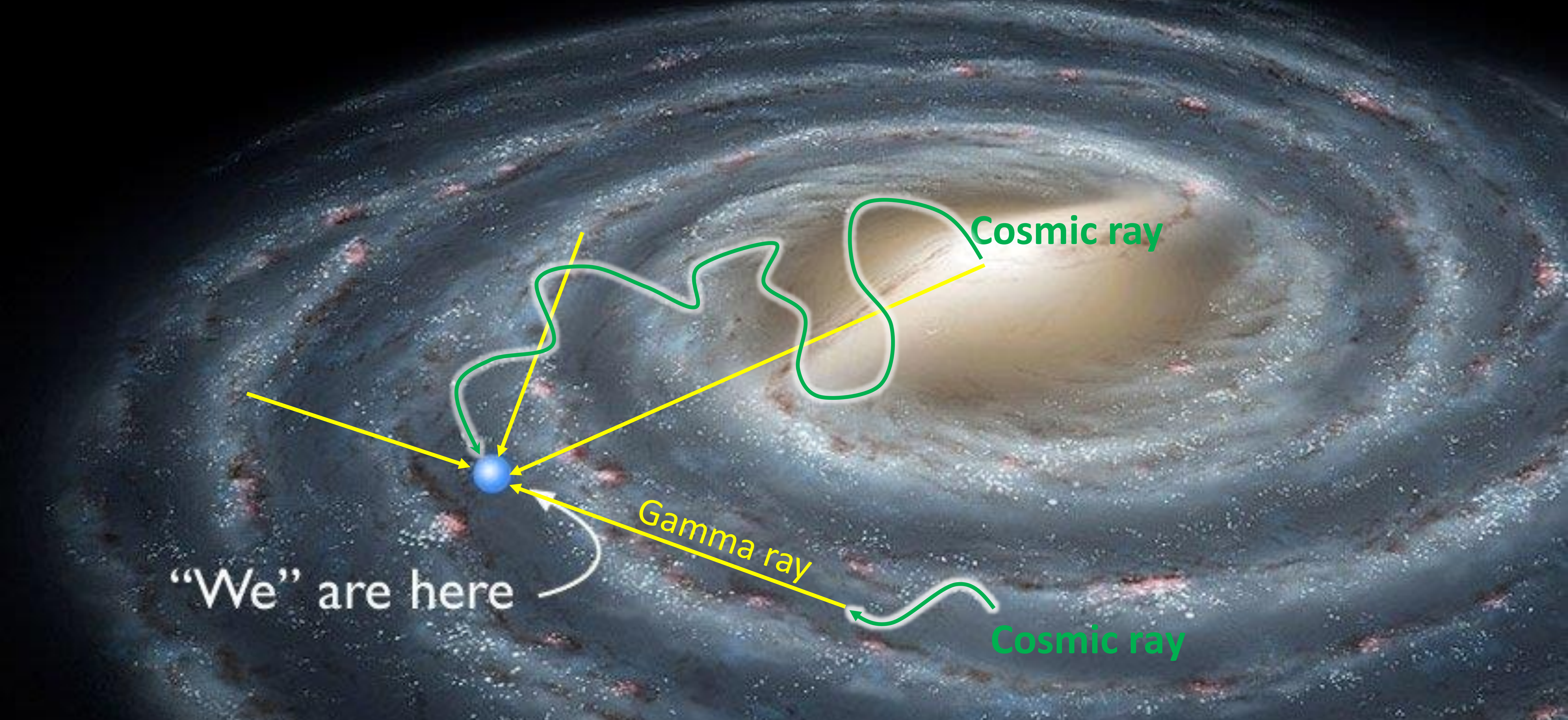
As an open question, Did/Do “PeVatrons” really exist in our Galaxy?

PeVatron: Cosmic superaccelerators can accelerate to Peta electron volt

Cosmic rays with electric charge are bent by
the magnetic field in the universe, and lose their directions



Cosmic rays with electric charge are bent by
the magnetic field in the universe, and lose their directions



Cosmic rays interact with interstellar gas, and produce γ rays
Gamma rays go straight unaffected by magnetic field,
pointing back to the sources.

History of Cosmic-Ray Physics

1912 Discovery of cosmic rays (Hess)

1934 Supernova hypothesis as cosmic-ray origin (Baade & Zwicky)

1949 Acceleration theory of cosmic rays (E. Fermi)

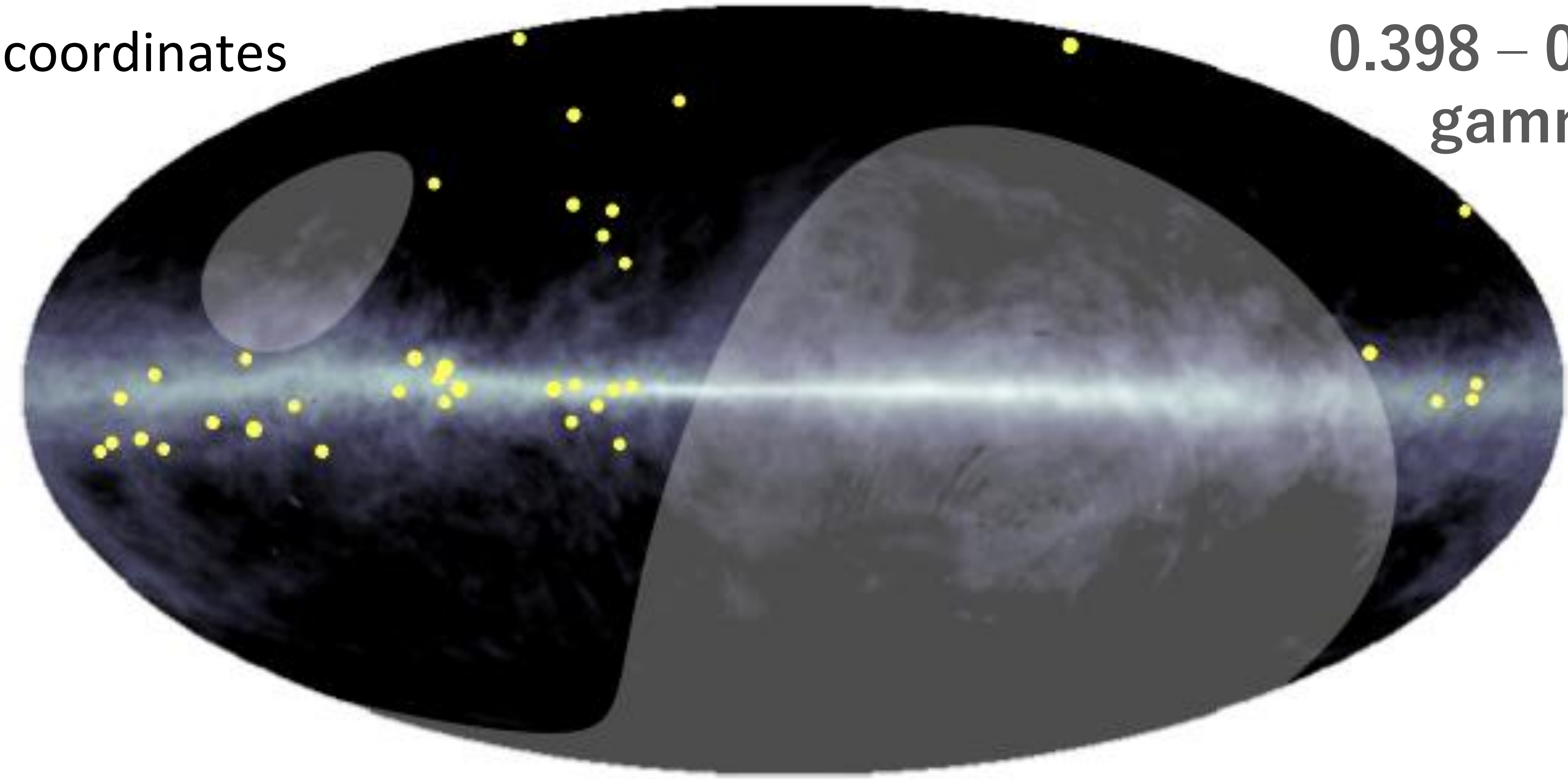
1958 Discovery of rapid decrease in cosmic-ray flux (Kulikov & Khristiansen)
→ Cosmic rays below a few PeV are/were produced in our Galaxy? = PeVatrons

1970s-1990s Detection of γ rays from Milky Way (OSO-3, SAS-2, COS-B, EGRET)
→ 1/10000th PeV γ rays induced by cosmic rays in our Galaxy

2013 Detection of 1/1000th PeV γ rays induced by cosmic rays in SNR
(Fermi-LAT satellite + Ground γ-ray telescope)

Despite exhaustive searches for **PeVatrons** over last 20 years, researchers have no conclusive evidence yet.
→ A mystery for 60 years in cosmic-ray physics

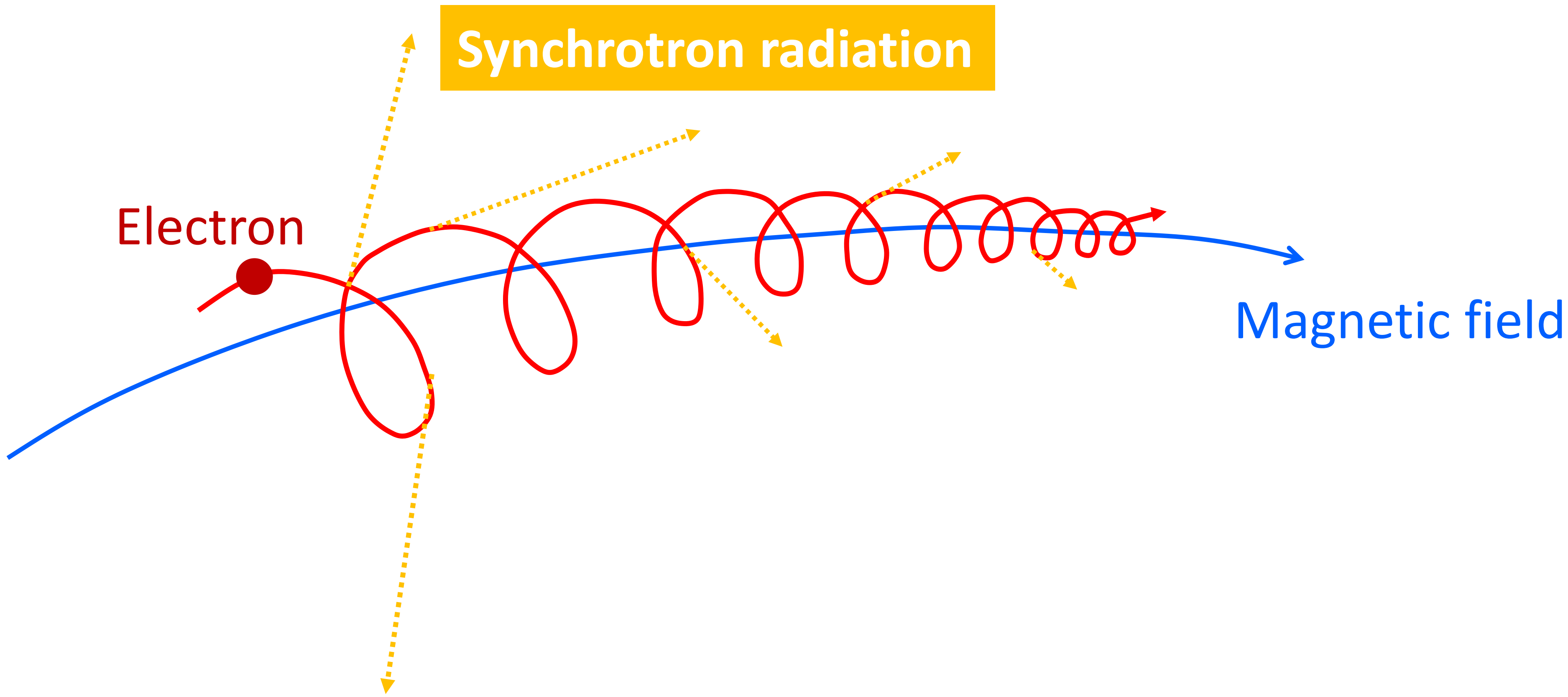
Scientific Interpretation



✓ Highest–energy gamma rays, including one Peta–electron–volt, are discovered to be spread out along the Milky Way, rather from known gamma–ray objects.

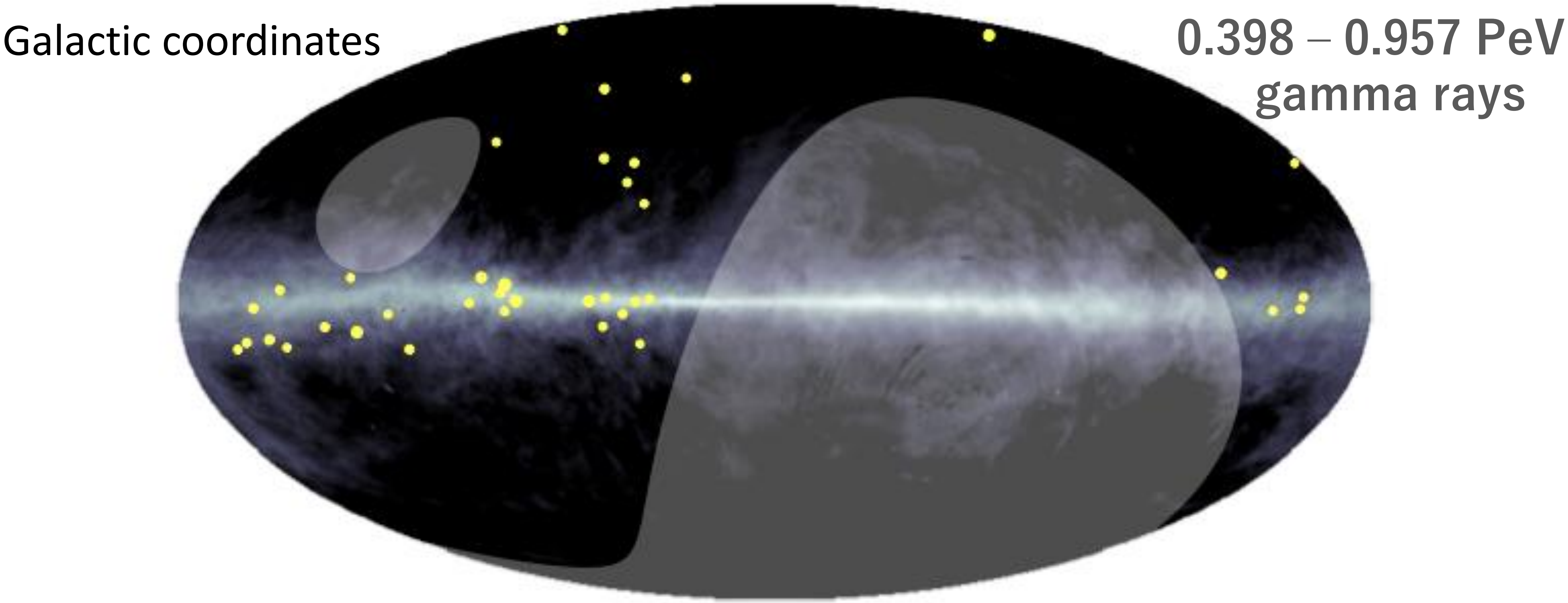
→ Gamma rays coming directly from the objects are difficult to identify cosmic–ray proton origin, since they could be gamma rays produced by collisions of "electrons" with photons.

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**.

Electron origin? vs Proton origin?

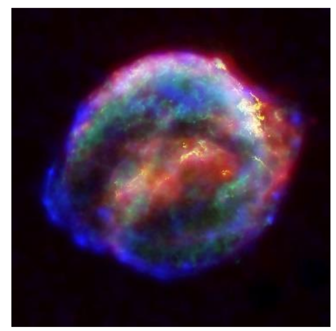


- ✓ Gamma rays are coming isolated from known gamma-ray sources.
  - → **Electrons** lose their energy quickly, so they **should stay near the object**.
  - → **Protons** don't lose energy and **can escape farther from the object**.

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

PeVatrons & Cosmic-Ray Pool

Supernova (SN) explosion occurs every 30 years in our Galaxy



In SN remnants, cosmic rays are accelerated within 10,000 years after explosion → "PeVatron"

Cosmic rays has been trapped by galactic magnetic field for a longt time forming a cosmic-ray pool

Cosmic rays in galactic magnetic field
3 – 30 PeV

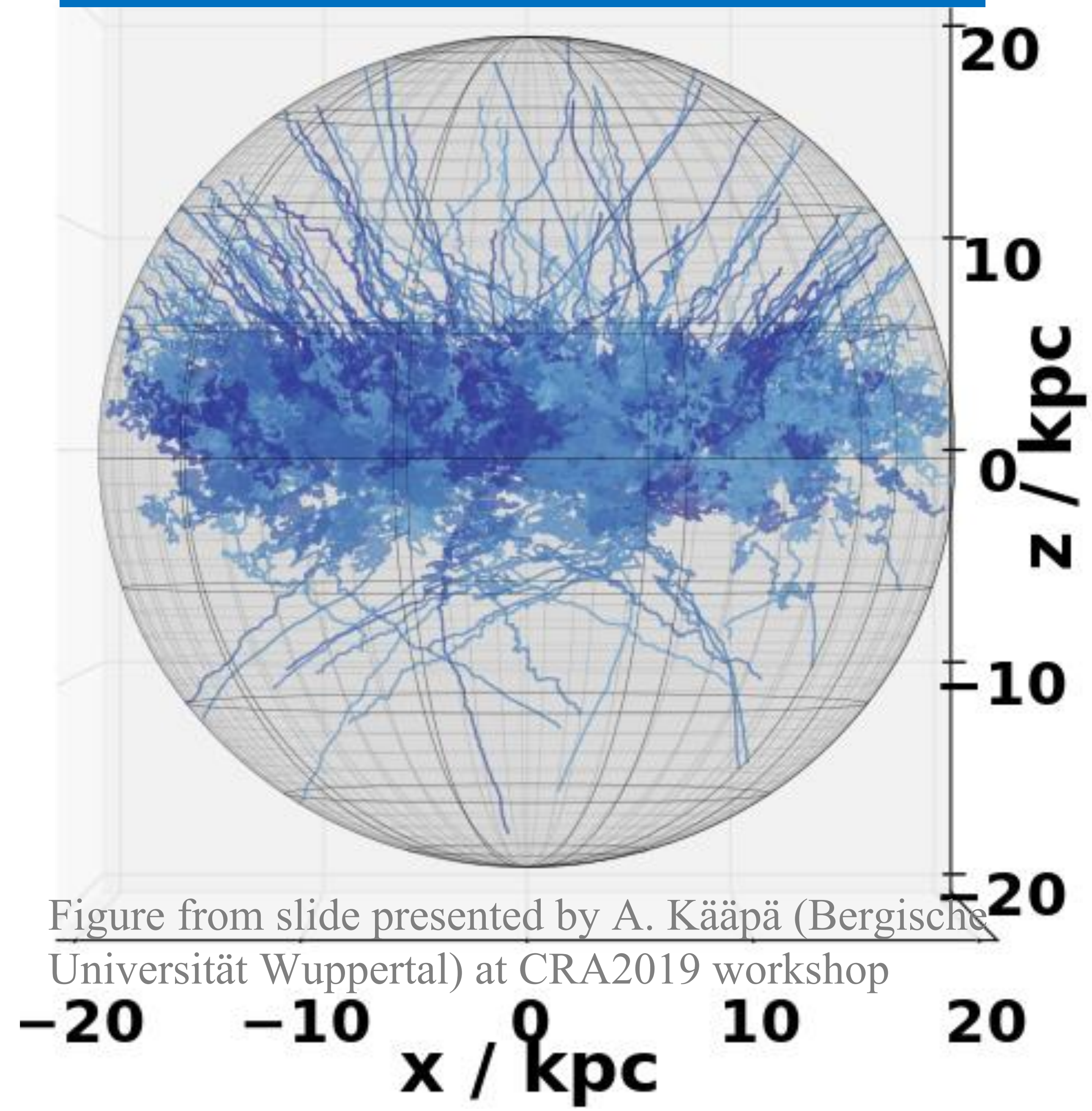
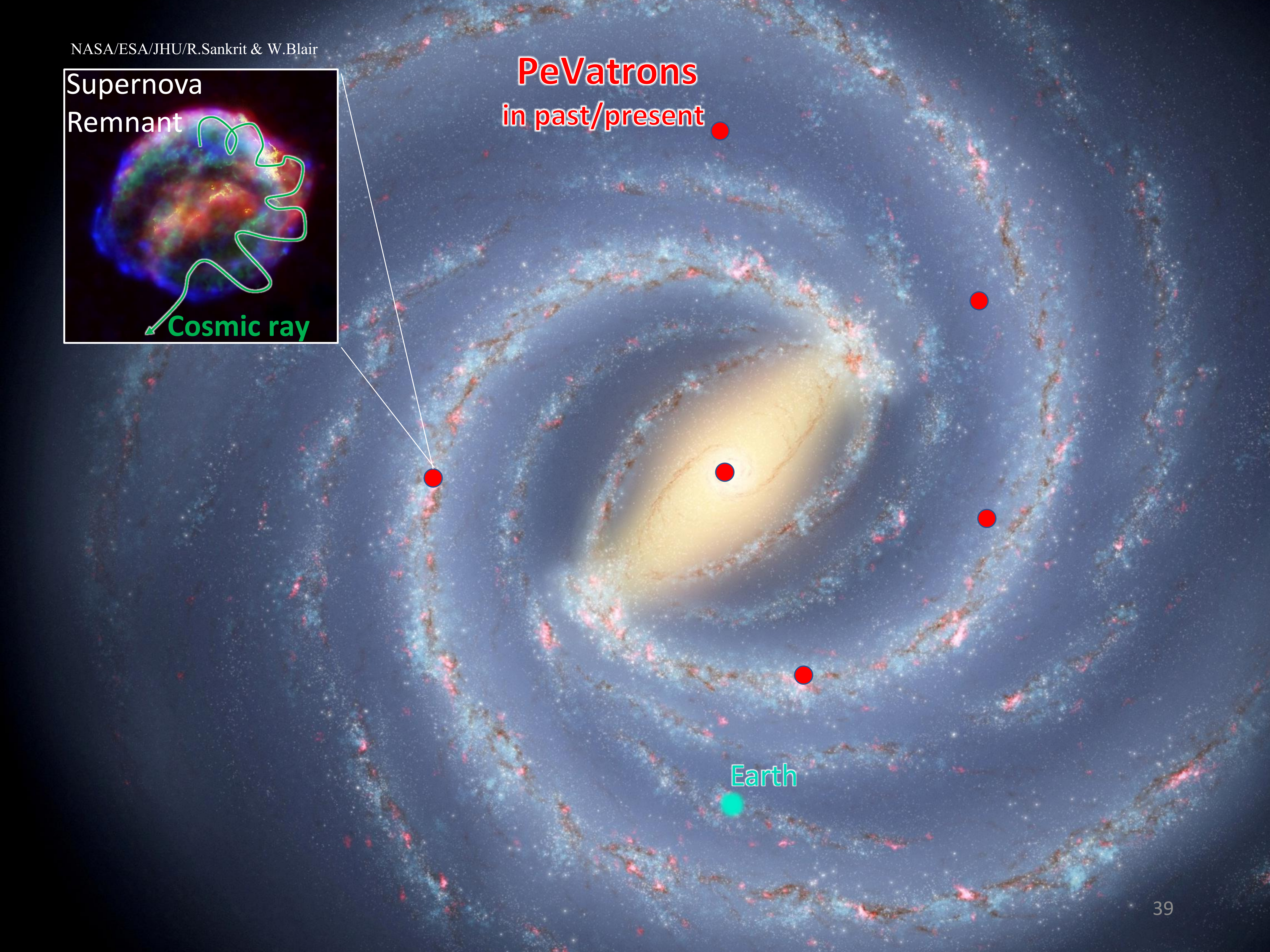
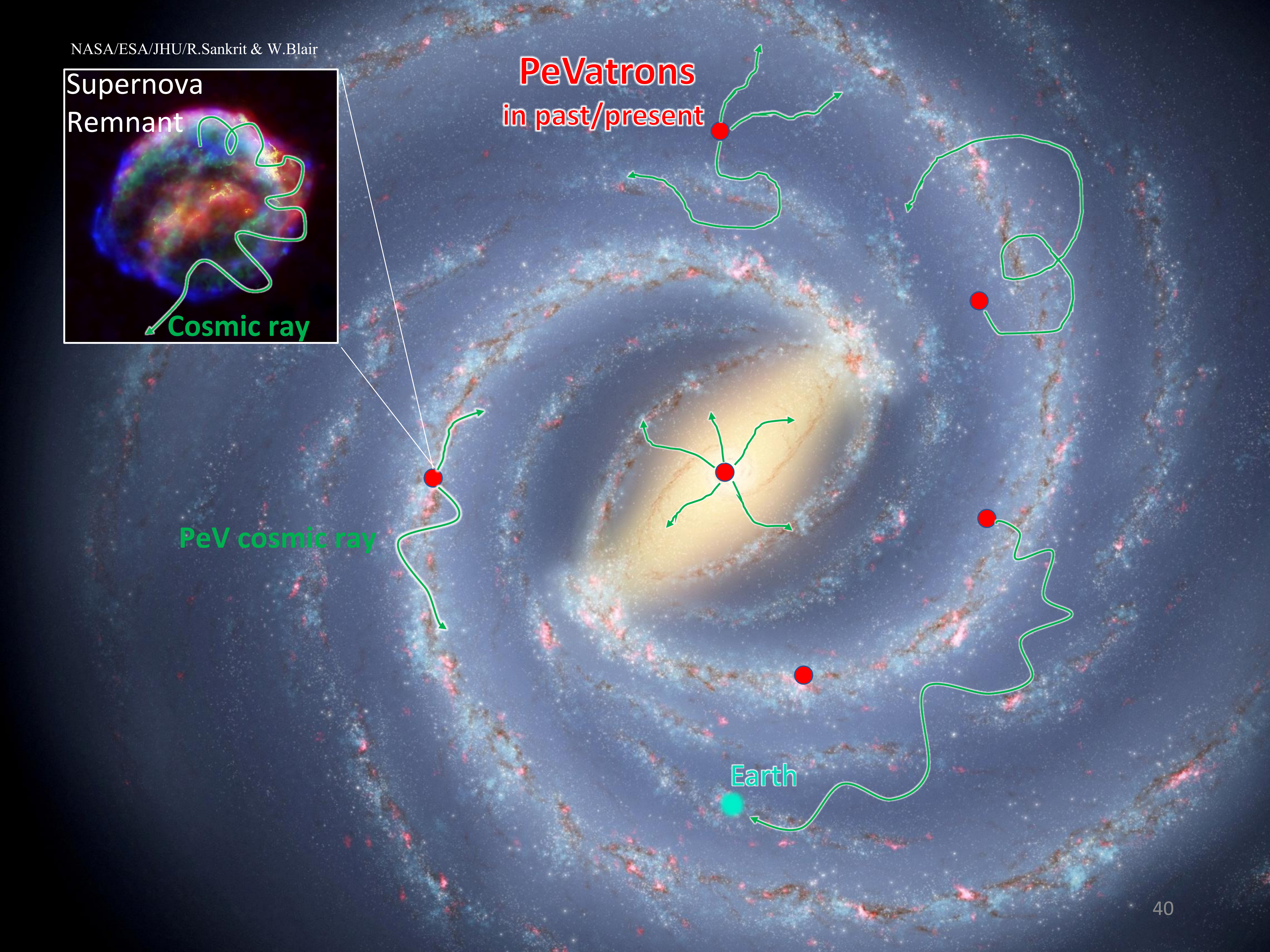


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova
Remnant
Cosmic ray
PeVatrons
in past/present
Earth


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova Remnant
Cosmic ray
PeVatrons
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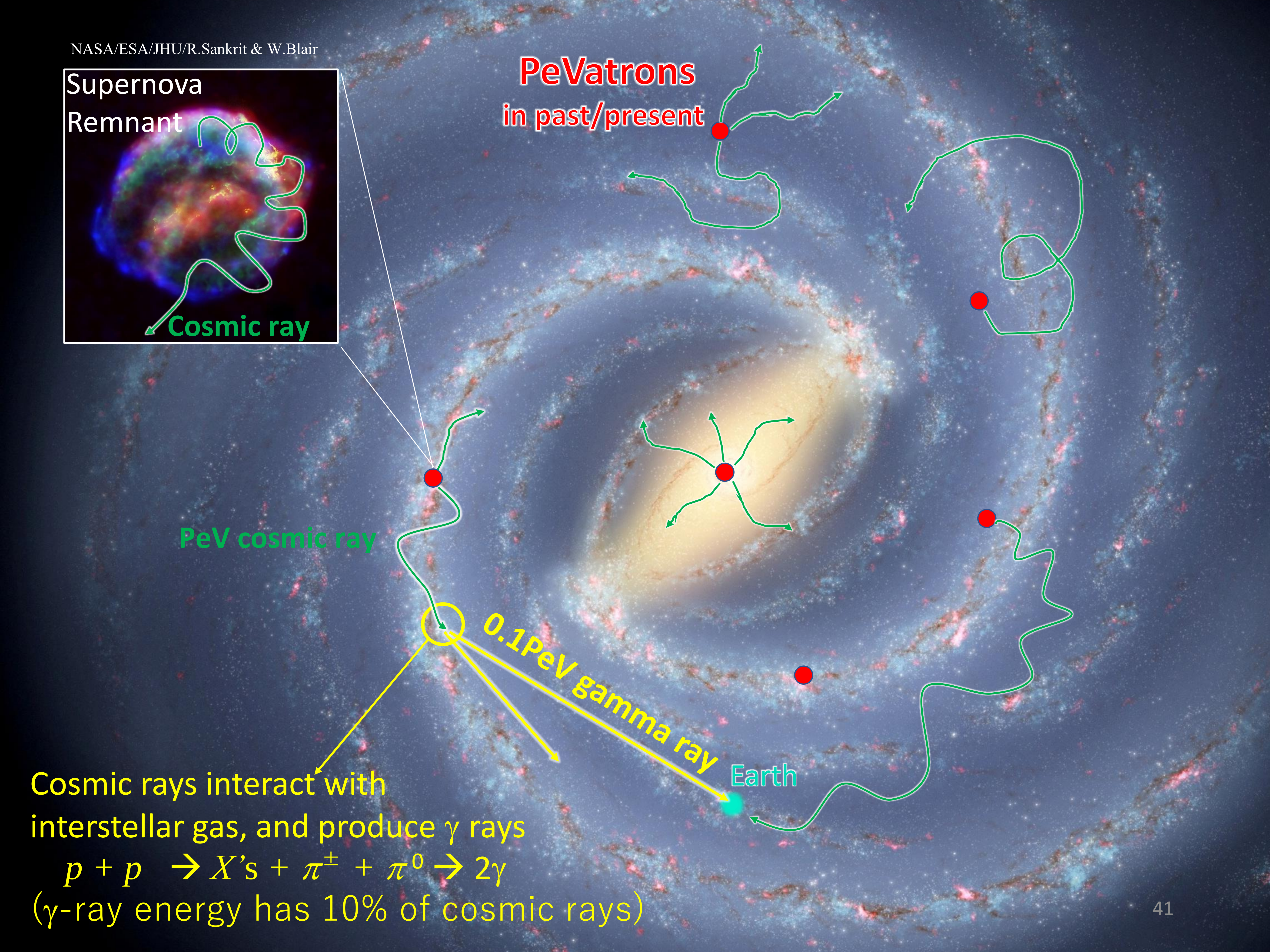
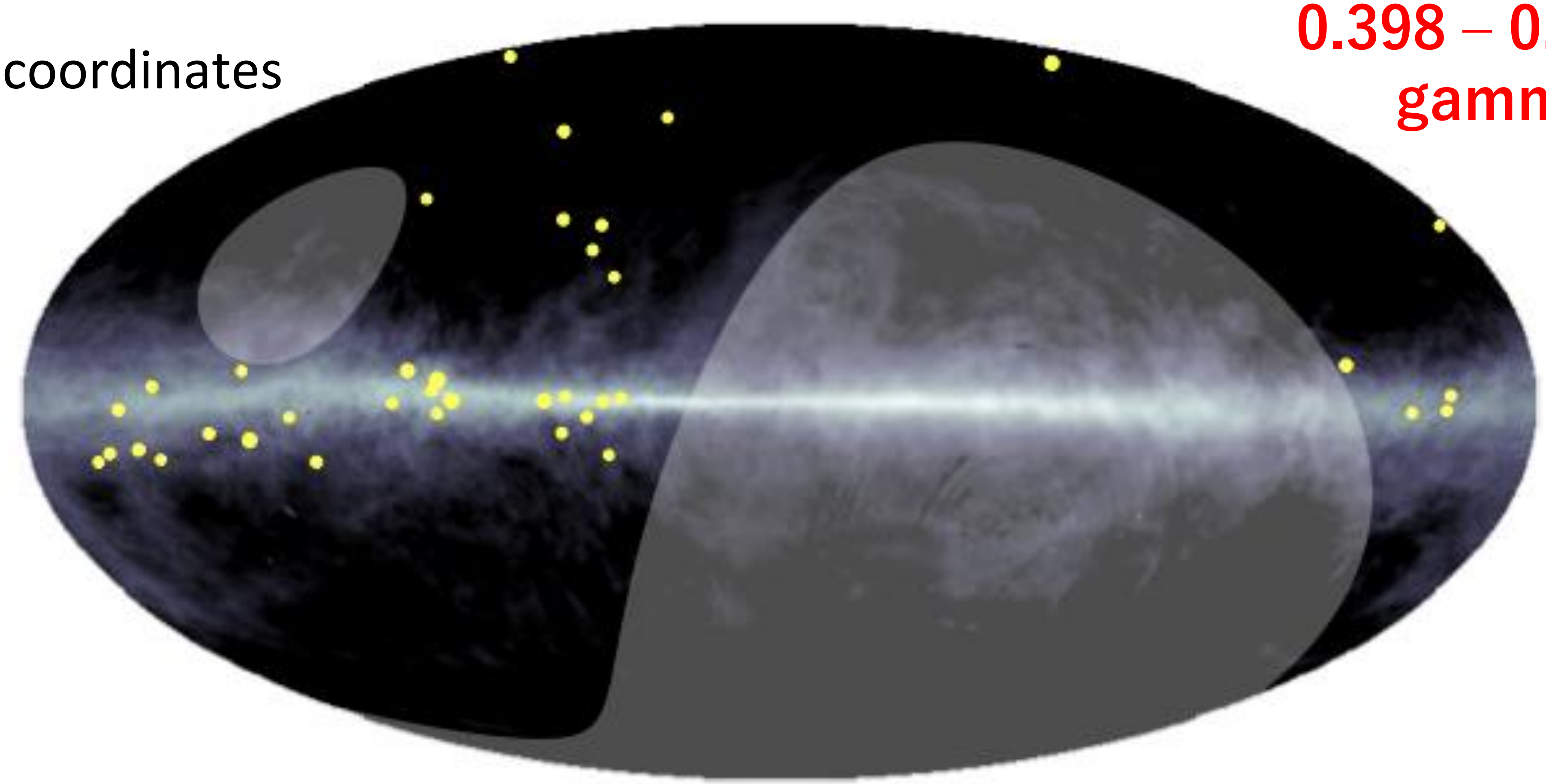
Earth


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova Remnant
Cosmic ray
PeVatrons
in past/present
PeV cosmic ray
0.1PeV 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)

Scientific Interpretation



✓ 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

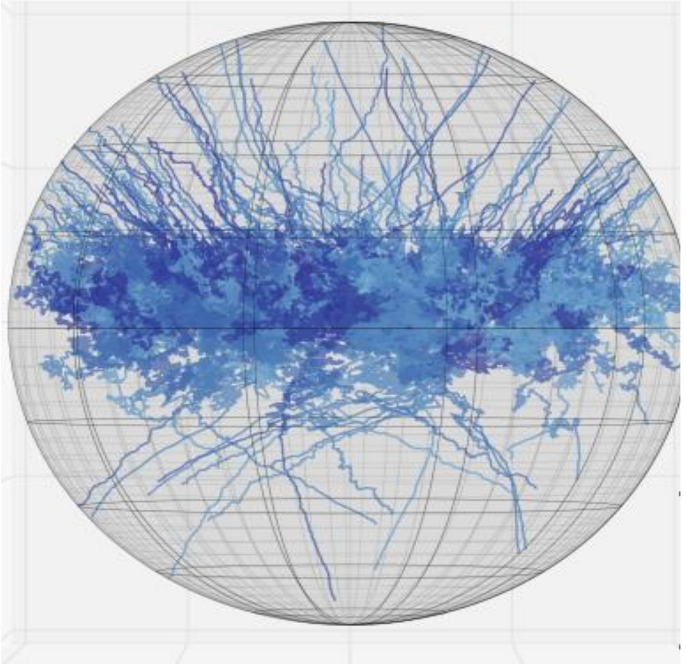
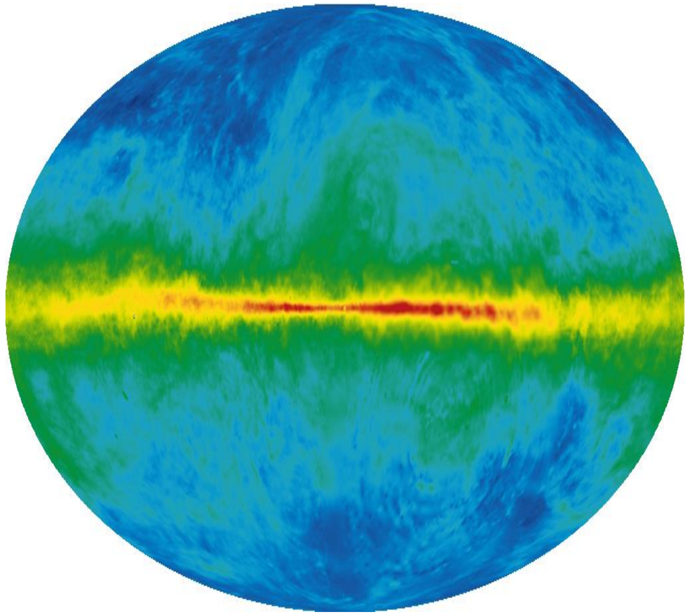


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop

+

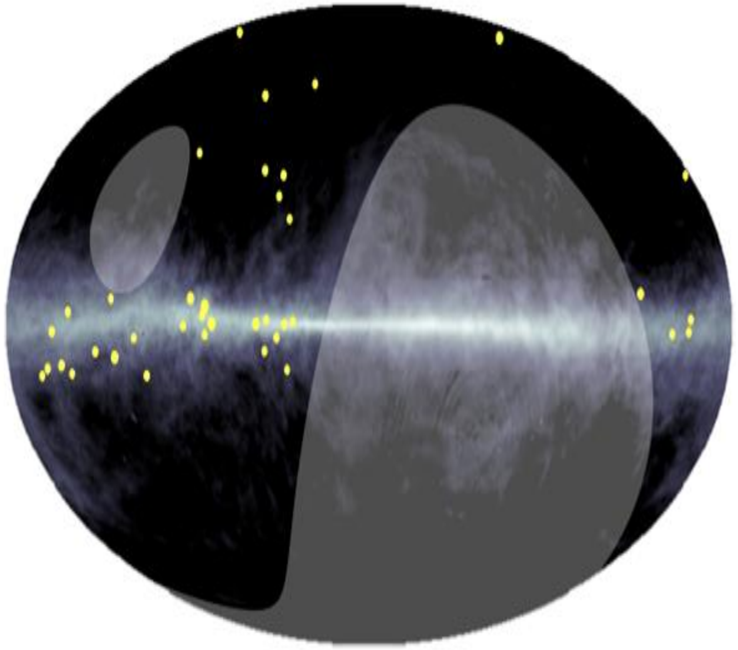
Interstellar matter



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

=

High-energy gamma rays

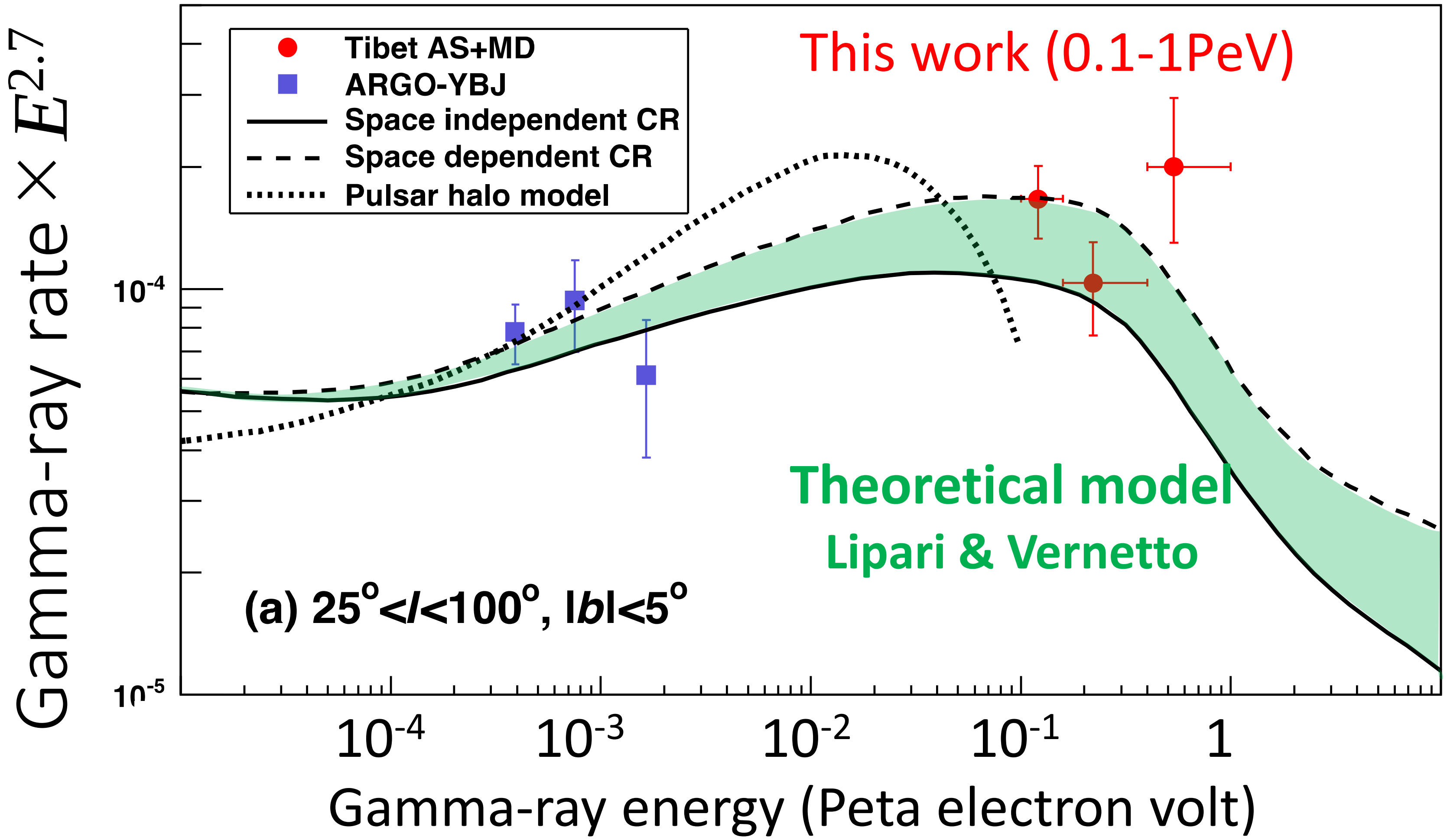


This Work

✓ 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

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 arXiv e-prints after the publication

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.

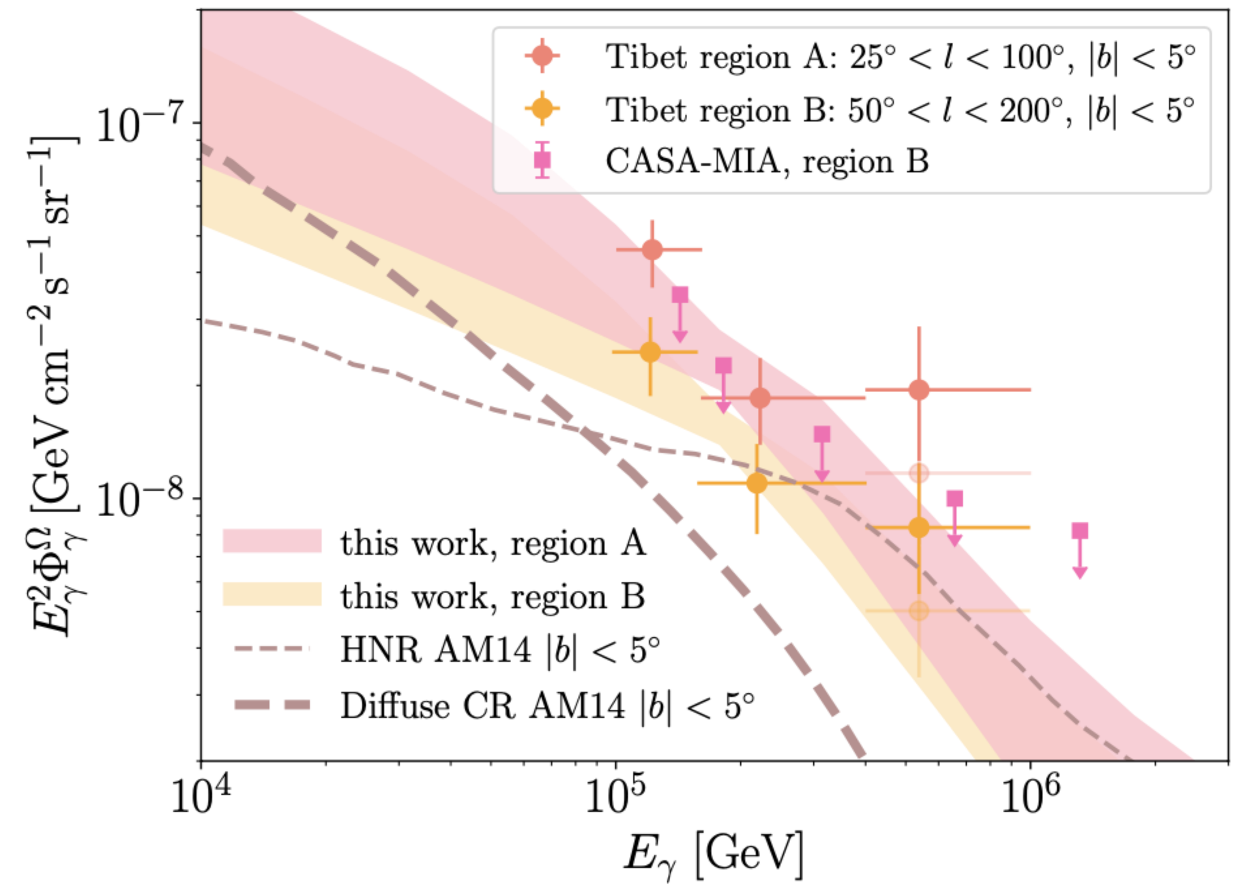
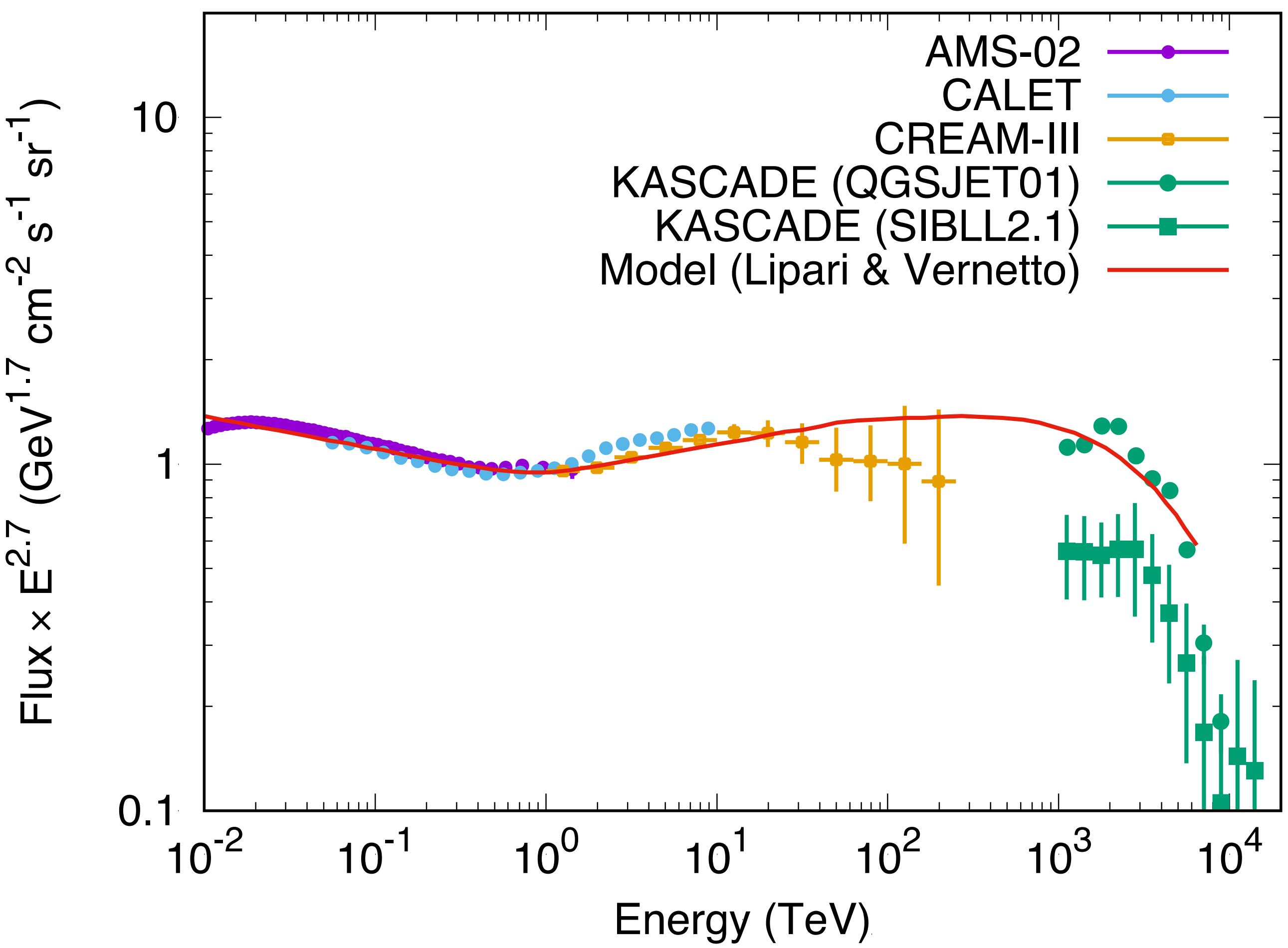
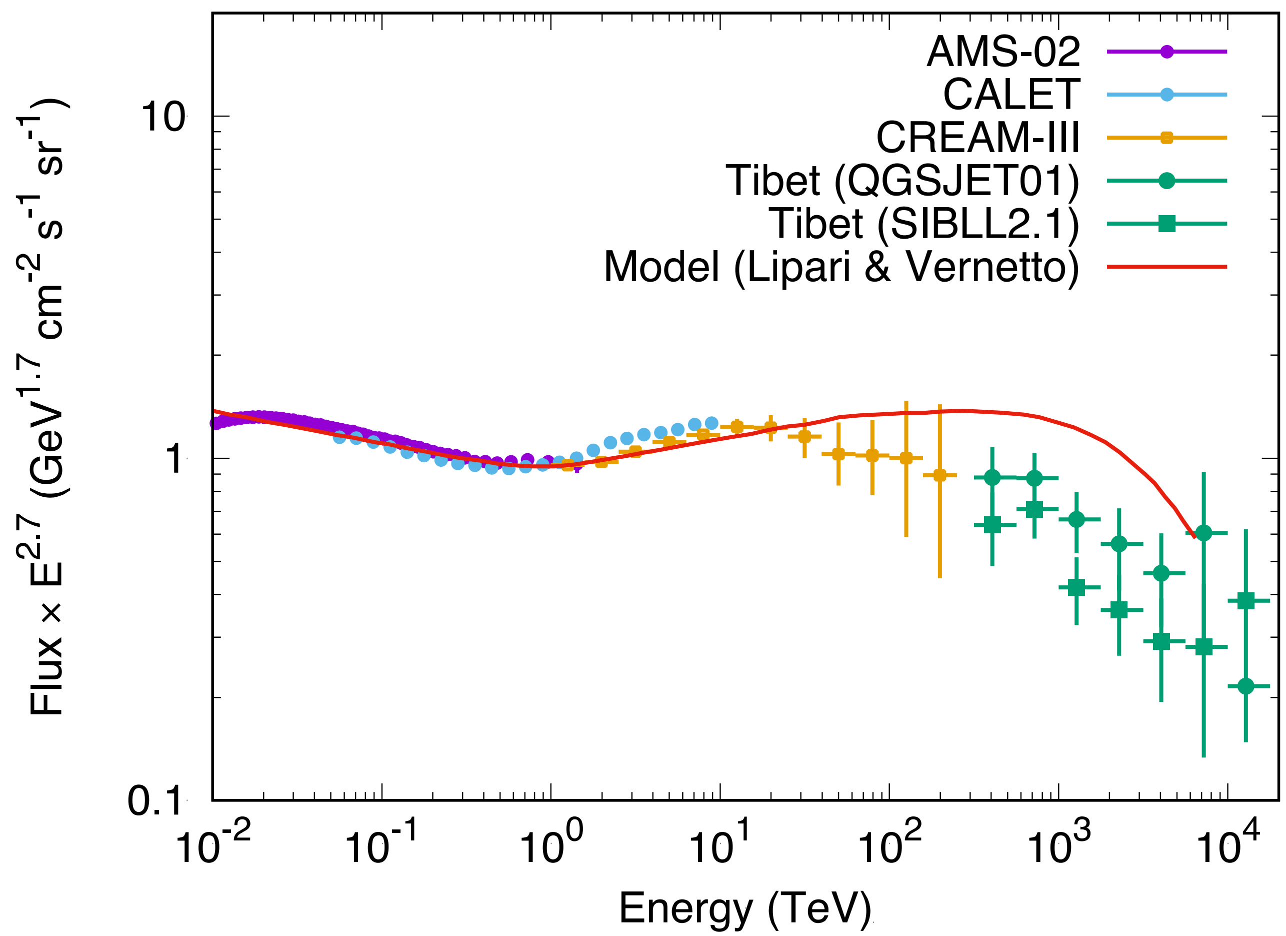
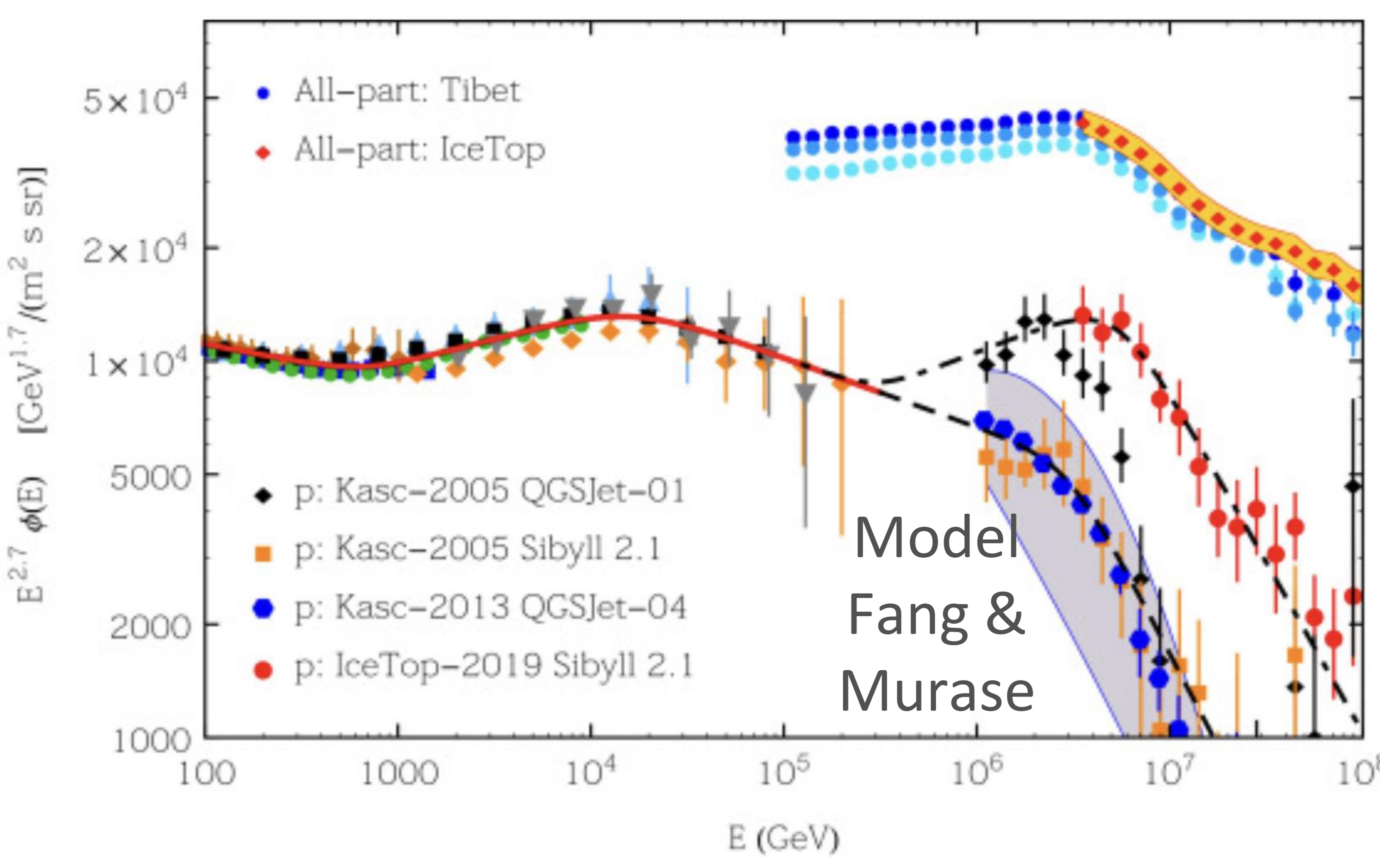


Figure 1. The diffuse Galactic gamma-ray intensity from two sky regions, *region A*: $25° < l < 100°$, $|b| < 5°$, and *region B*: $50° < l < 200°$, $|b| < 5°$. The red and orange data points are the Tibet ASγ measurement of the diffuse γ-ray emission from the two regions (Amenomori et al. 2021). In 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!)

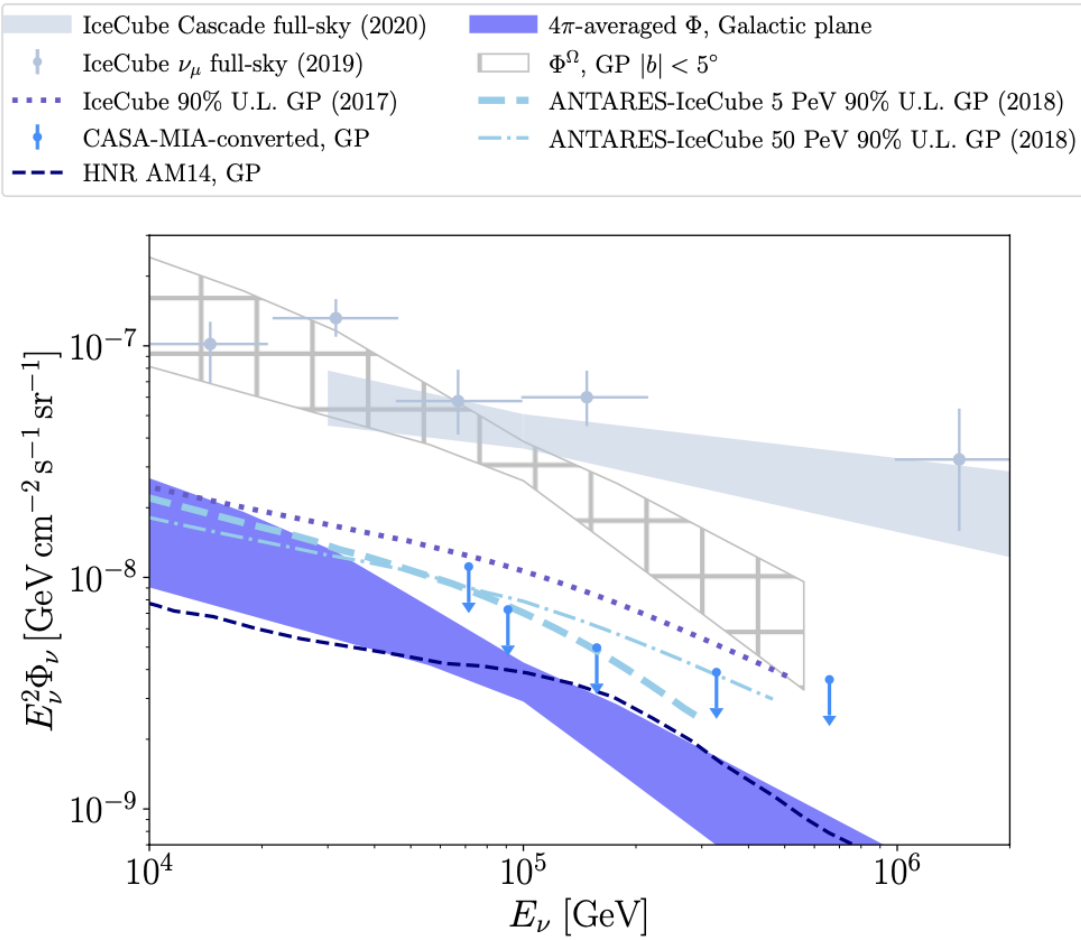
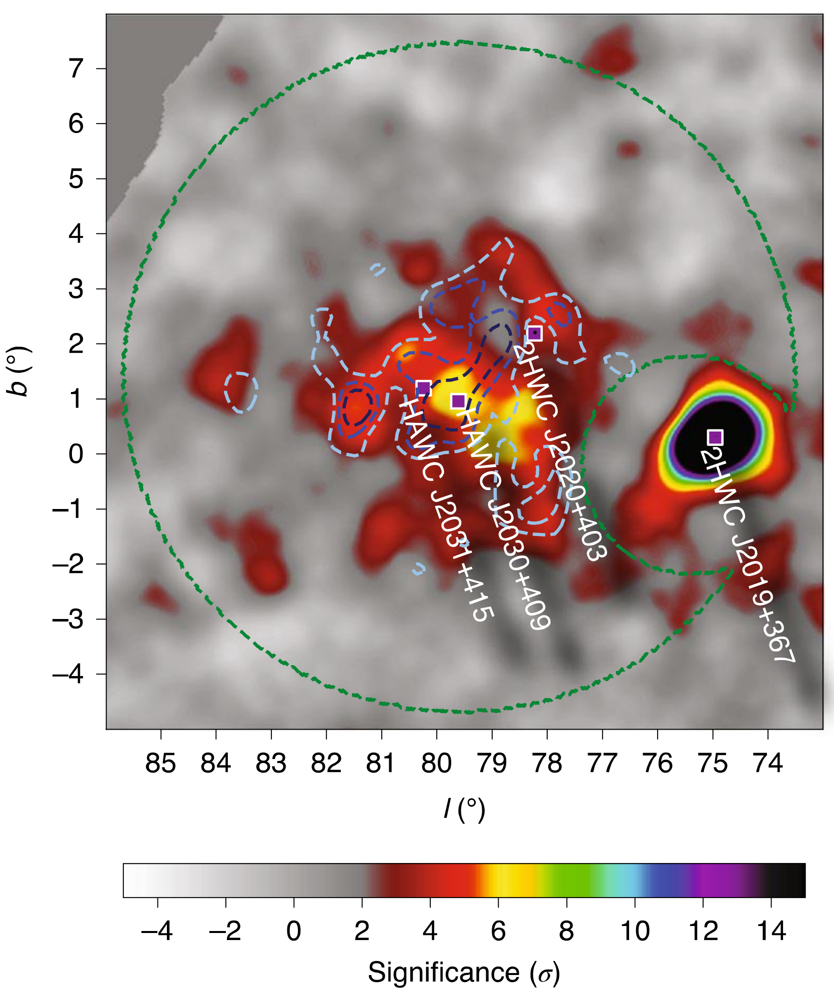


Figure 2. All-sky-averaged intensity of all flavor diffuse neutrinos from the GP, compared to neutrino observations. The GP neutrino intensity, $E_\nu^2 \Phi_\nu$, (blue shaded band) is derived with the best-fit gamma-ray intensities in Figure 1. The model is consistent with the combined upper limits 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?

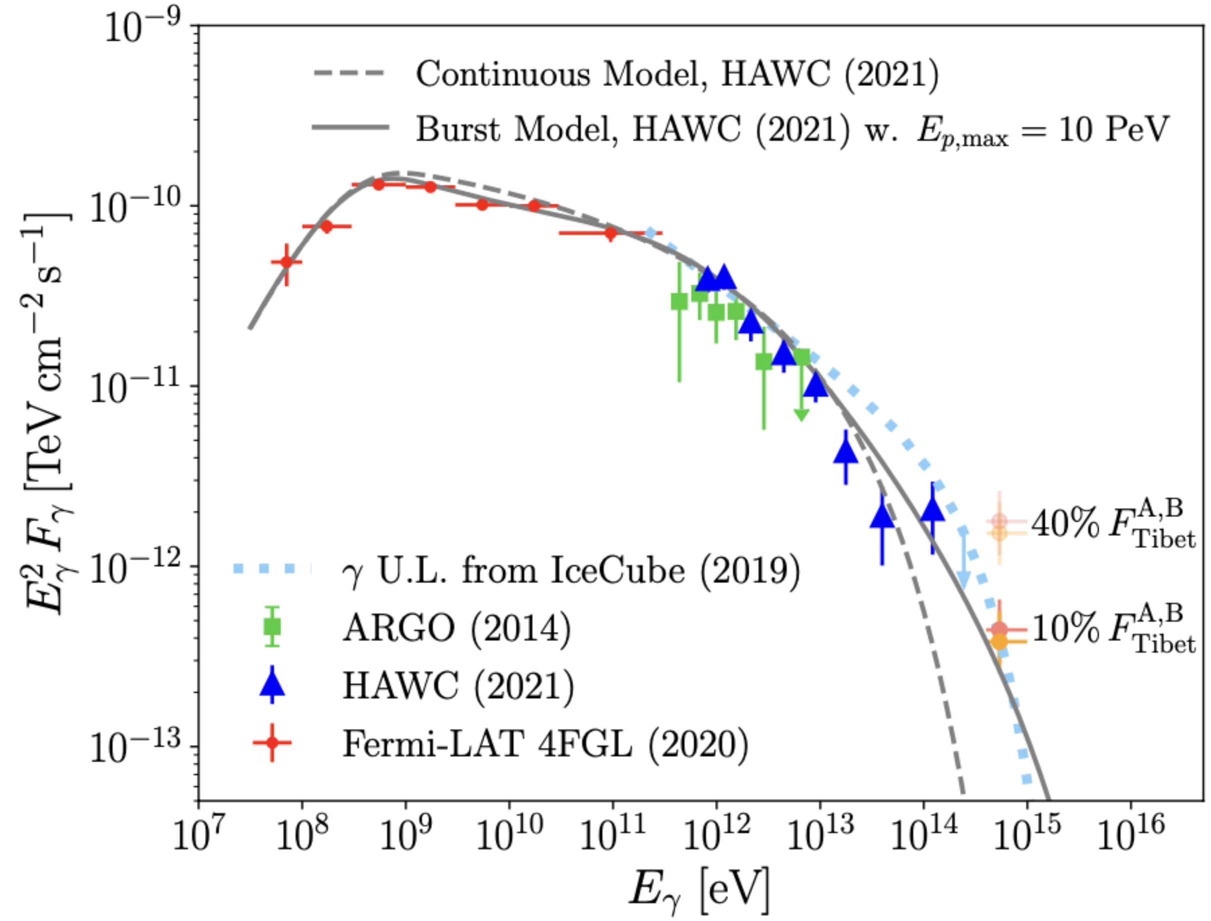


Figure 3. Spectral energy distribution of the Cygnus Cocoon measured by *Fermi*-LAT (Abdollahi et al. 2020), ARGO-YBJ (Bartoli et al. 2014), and HAWC (Abeysekara et al. 2021). The light pink and orange flux points indicate 40% of the Tibet ASγ flux of regions A and B (Amenomori et al. 2021). The thick 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.

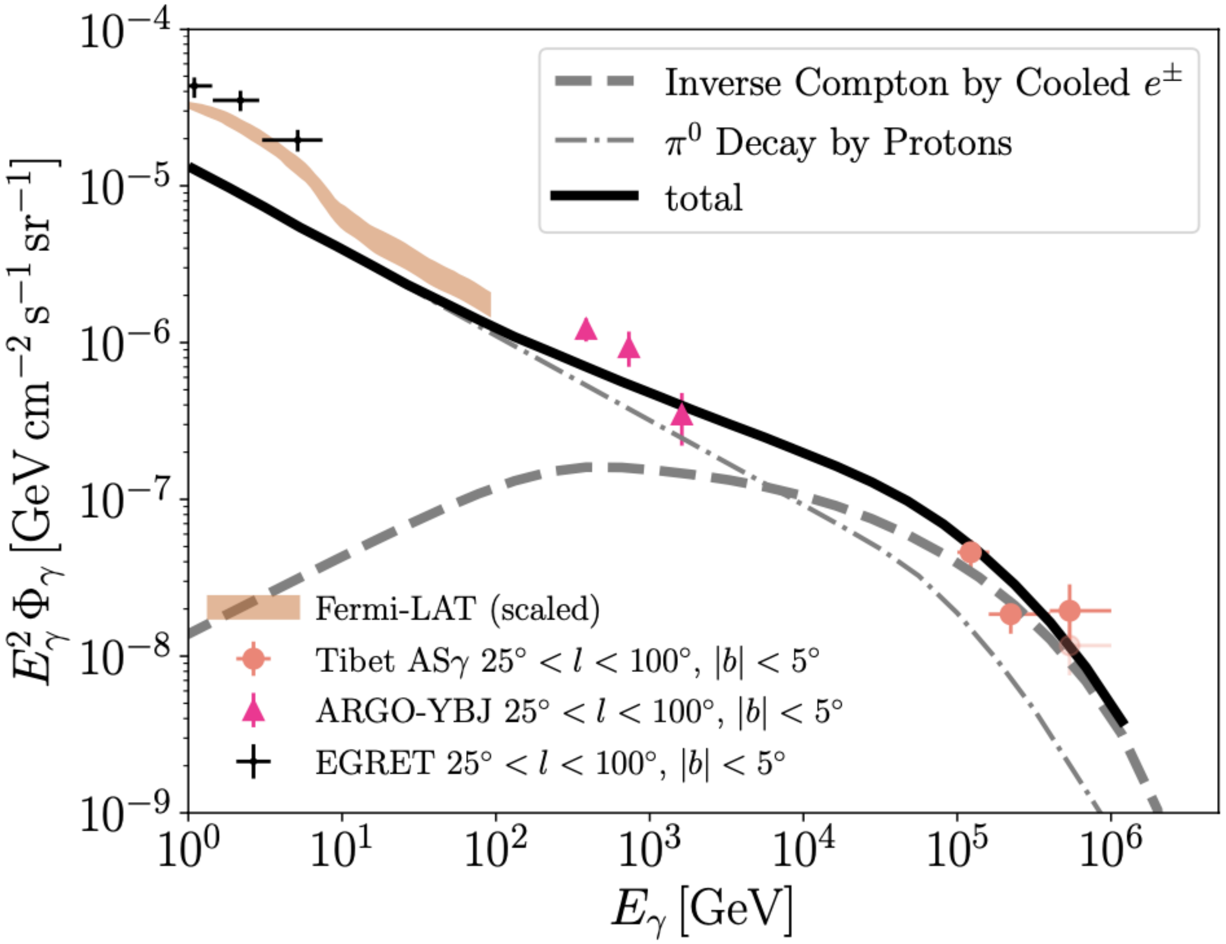


Figure 4. Demonstration of a hybrid γ-ray emission model, in which the inverse Compton of relativistic electrons (grey dashed curve) explains the Tibet ASγ measurement in the region $25° < l < 100°$ (red round data points), and π^0 decay by Galactic diffuse protons (grey dash-dotted curve) explains the 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.

Multi-messenger Implications of Sub-PeV Diffuse Galactic Gamma-Ray Emission
arXiv:2104.09491 Ke Fang and Kohta Murase

Conclusion

While the diffuse Galactic interpretation of the Tibet ASγ data seems the most natural, discrete sources may still significantly contribute especially at the highest energies. This is especially the case if the cosmic- ray nucleon spectrum is as steep as $E^{-2.7}$ with a break energy of ~1 PeV. If a crucial fraction of the highest- energy events detected by the Tibet ASγ experiment is associated with the Cygnus Cocoon, the presence of an efficient Pevaron would be supported. The Tibet ASγ data can also be explained by unresolved Pevatrons such as hypernova remnants in the Cygnus region and (or) other part of the Galaxy. Finally, the leptonic scenario is not excluded. Future multi-messenger observations by not only neutrino telescopes but also near-future gamma-ray experiments such as LHAASO, ALPACA, and SWGO are necessary to discriminate between these scenarios. The spatial distribution would give us crucial information, and observations in the southern sky are relevant (Ahlers & Murase 2014; Huentemeyer et al. 2019). A few or dozens of sources are sufficient to explain the sub-PeV gamma-ray intensity, which is promising for source identification.

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)

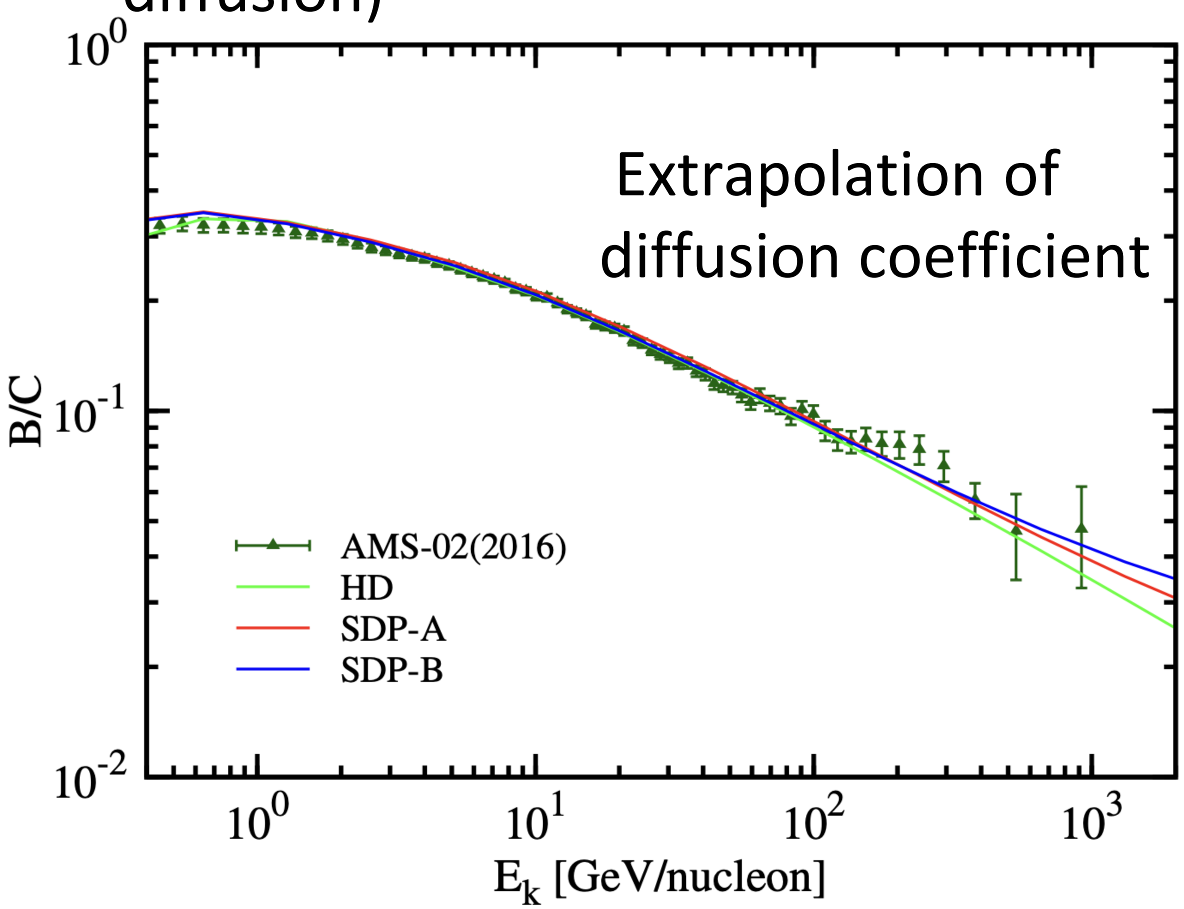
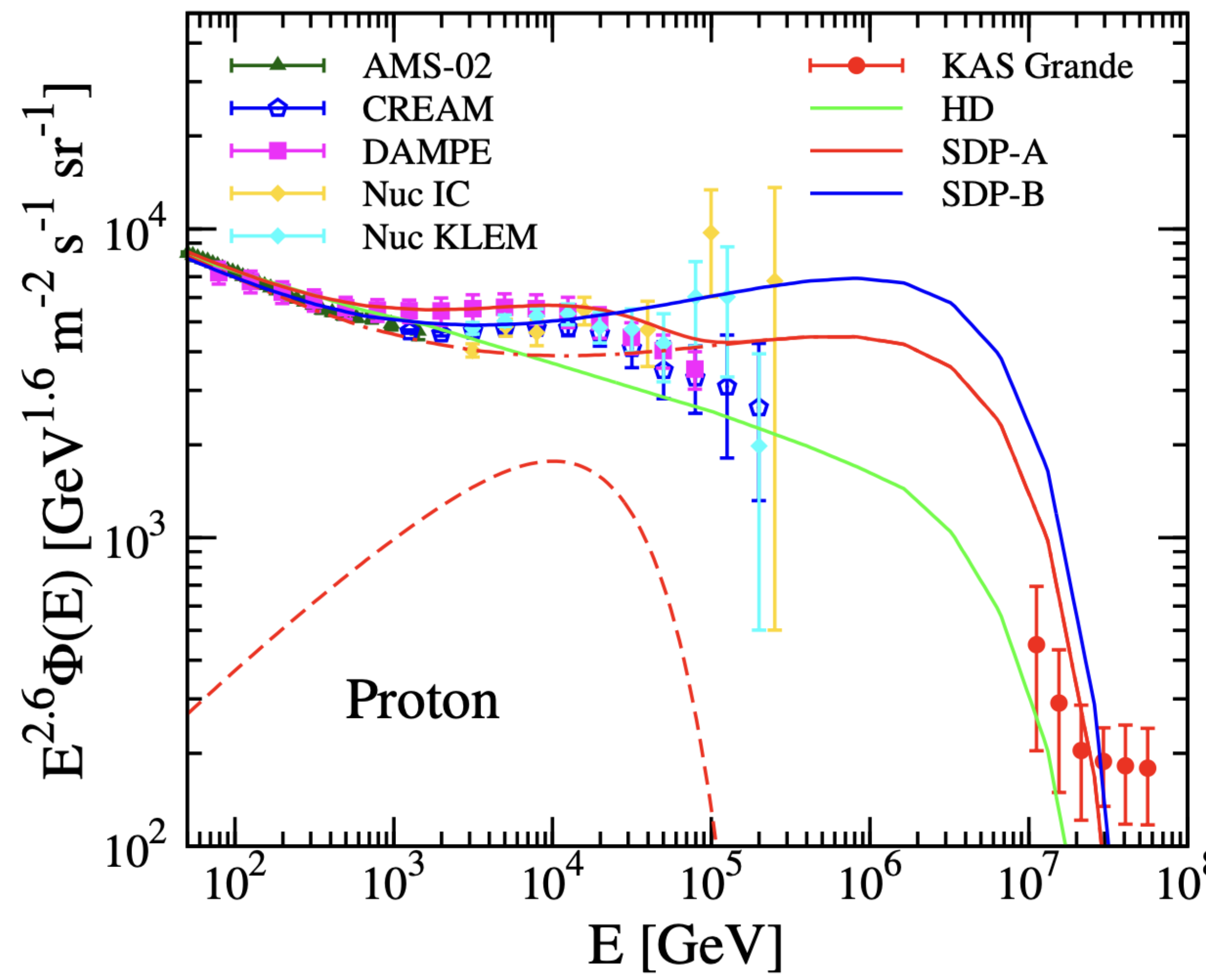
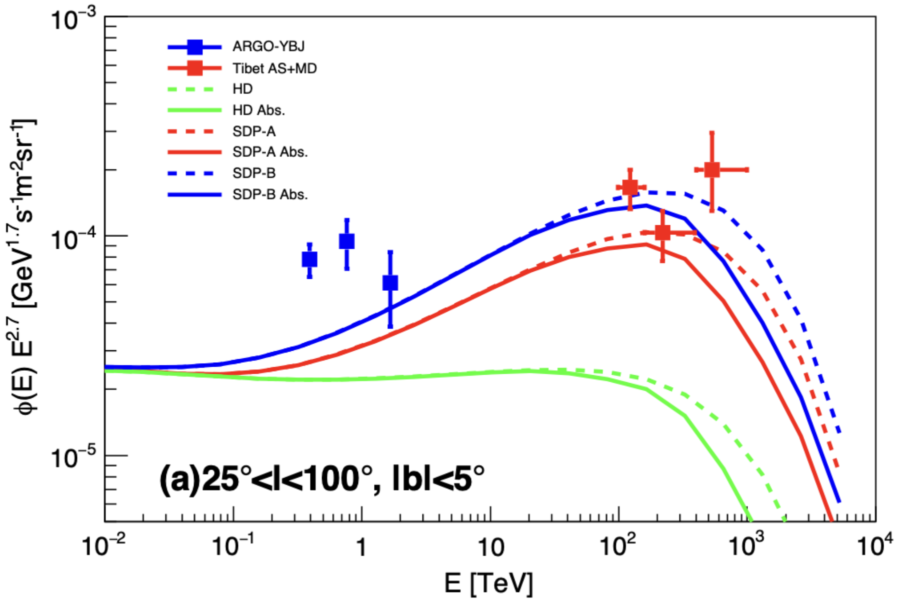


Fig. 1. Calculation of B/C ratio to obtain the propagation parameters in HD, SDP-A and SDP-B models, with B/C data taken from the AMS-02 measurement (Aguilar et al. 2016).



Gamma-ray data well explained



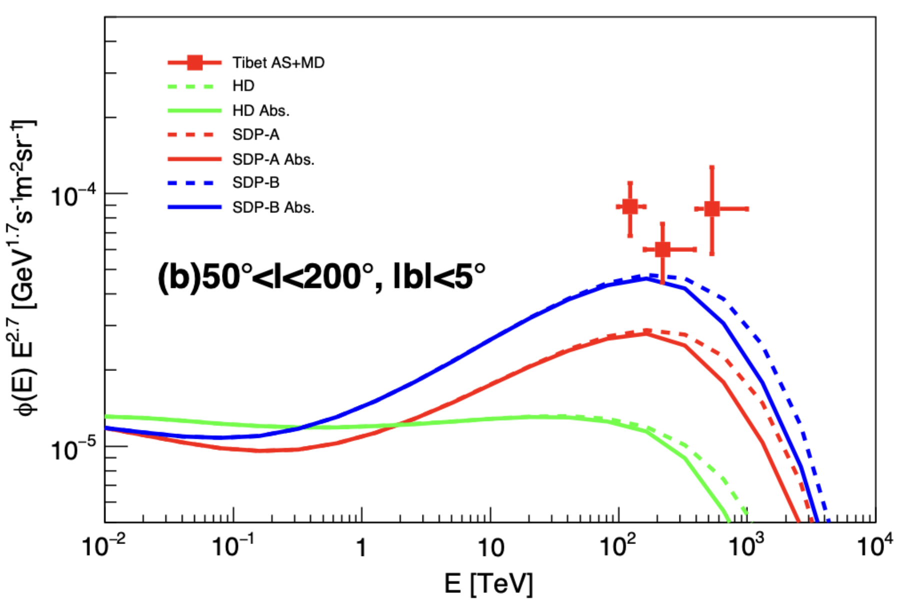


Fig. 3. Calculated diffuse gamma-ray spectra in three propagation models. The gamma ray data are taken from ARGO-YBJ (Bartoli et al. 2015) and Tibet AS+MD (Amenomori et al. 2021) experiments.

IceCUBE neutrinos → ~10% from Galactic plane

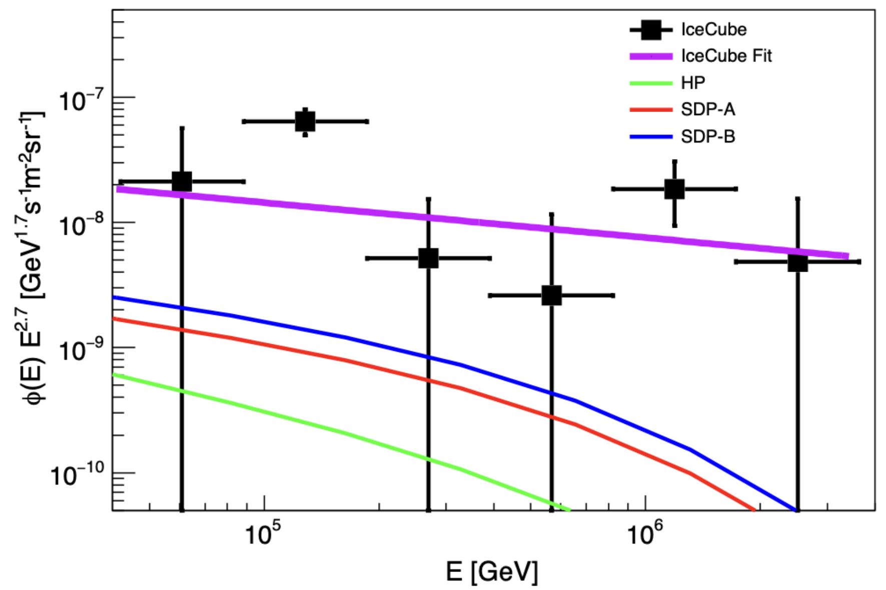


Fig. 5. Diffuse neutrino flux calculated by the three propagation models. The data are taken from the ICE-CUBE 7.5 years' observation (Abbasi et al. 2020). The violet line is the power-law fitting to the data, with normalization $\Phi = 6.37 \times 10^{18}$ $\mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$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

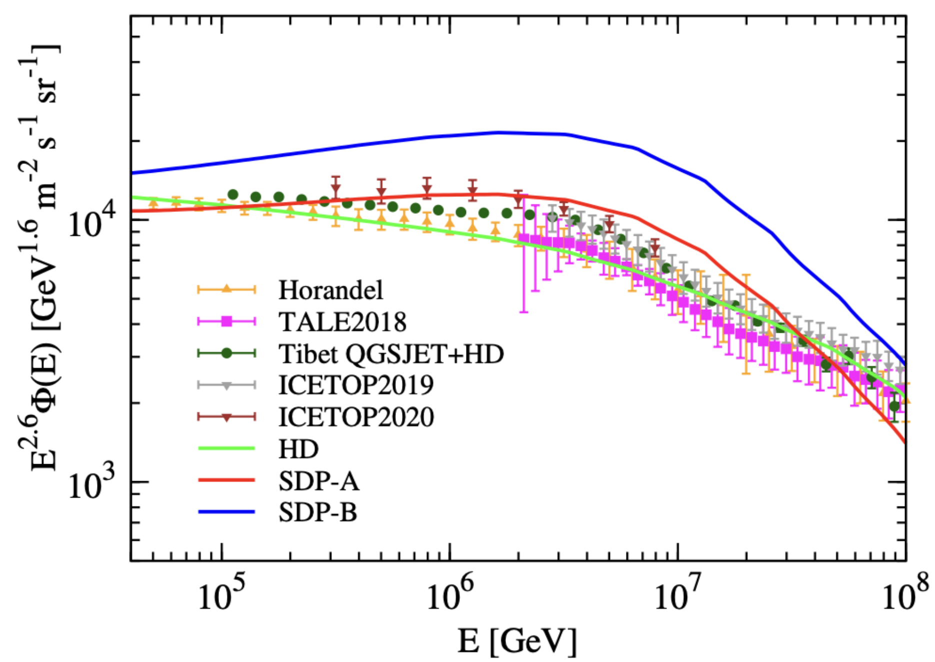


Fig. 4. Calculated all-particle spectra in three propagation models. The all-particle data are taken from Horandel (Hörandel 2003), TALE (Abbasi et al. 2018), IceTop (Aartsen et al. 2019, 2020a) and Tibet (Amenomori et al. 2008).

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

Summary of the arXiv e-prints

- Due to uncertainty in proton energy spectrum at Earth/around sources, it is possible that the expected flux of galactic diffuse gamma rays be insufficient to explain the observed diffuse gamma ray data.

  - Sufficient, if KASCADE QGSJET01 or IceTOP fluxes at Earh are correct.
  - Sufficient if local proton flux at Earth be low.
  - Insufficient, If cut off in proton flux exists below 1 PeV at Earth (KASCADE QGSJET02)

- If insufficient, possible: to explain the missing part by Hypernova Remnants (Hadronic)
  - But, we do not know where they exist.
- If insufficient might be possible, but not natural: to explain the missing part by gamma rays from sources accelerating electrons beyond PeV energies.
  - PWN?
  - PeV electrons undergo severe synchrotron radiation cooling
  - → gamma rays from sources are expected (of course, some spread depending on diffusion coefficient….) and TeV signal will be expected by IACT telescopes.
- 5 – 10 % of IceCube neutrinos originate from the galactic plane (mostly of extragalactic origin.)
  - IceCube Gen2 (2033?) will be interesting.

§ Living PeVatron candidates

Ok, then, what are active PeVatrons?

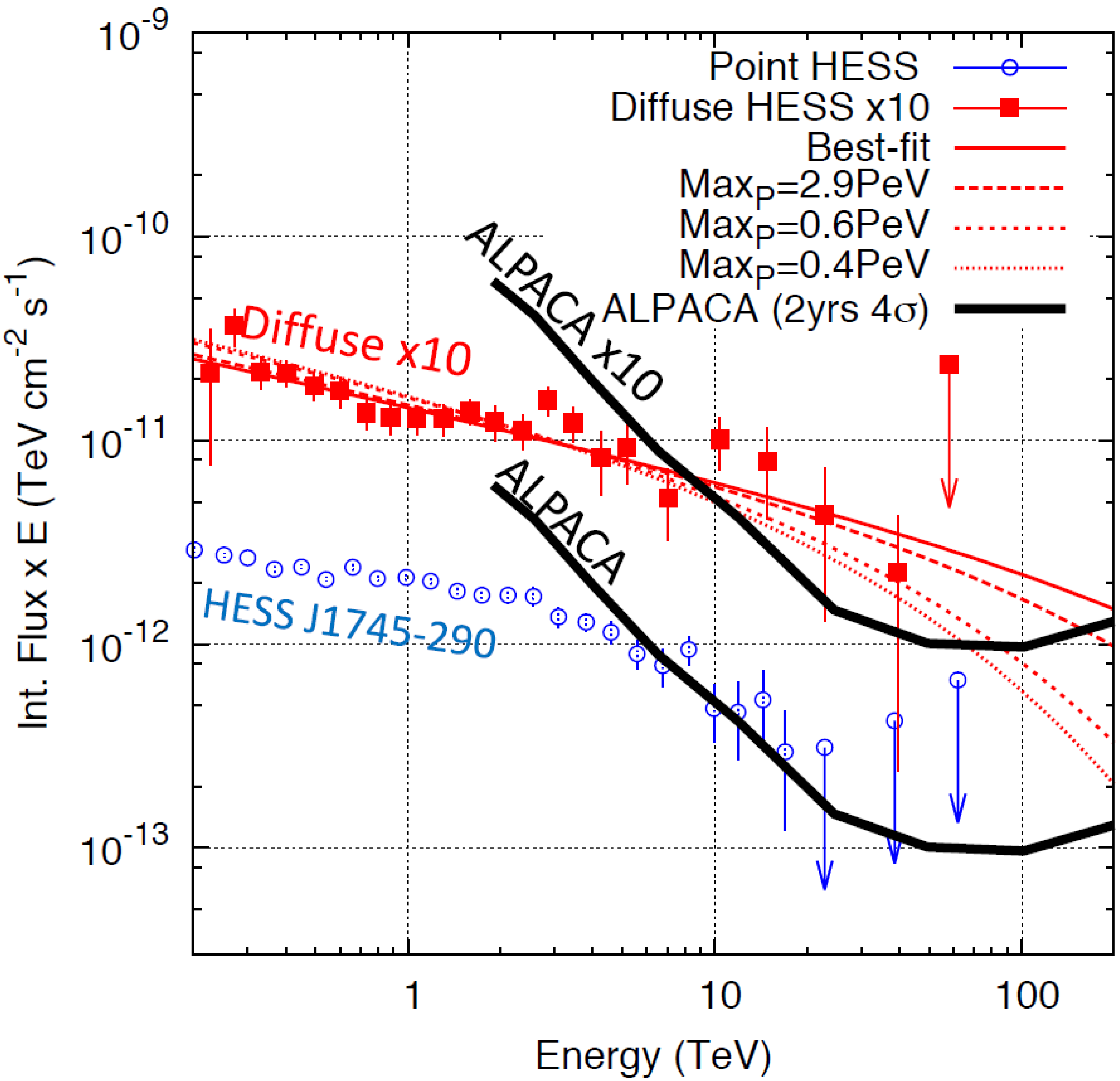
Recent Pevatron candidates

1. GC [Galactic Center region (HESS)]

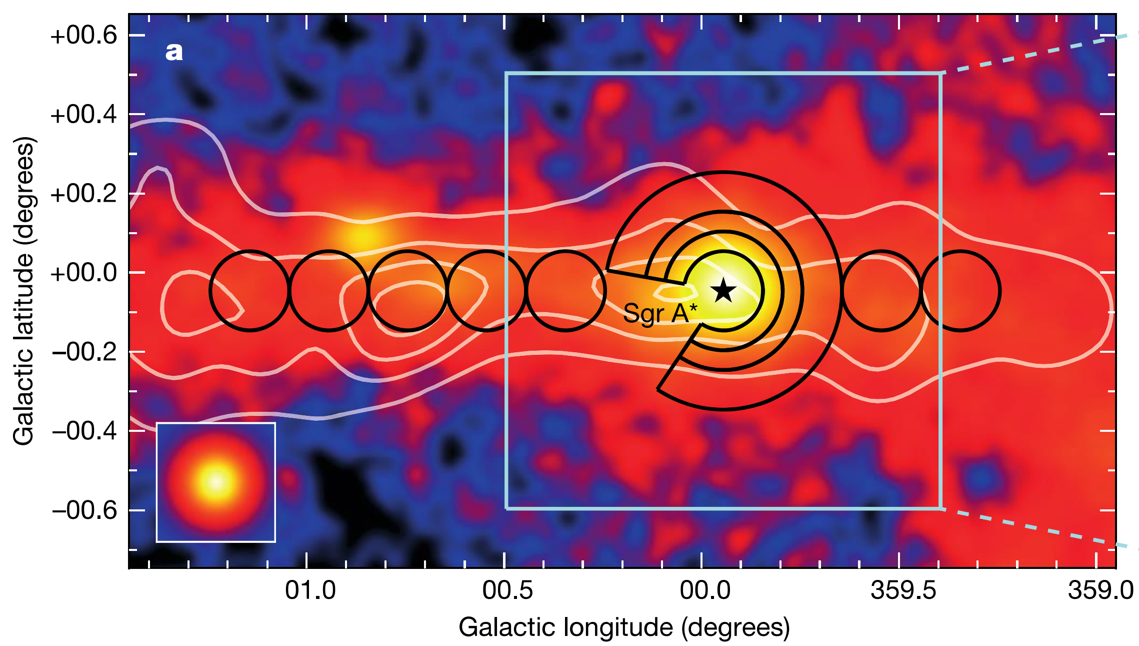
2. SNRs [e.g., SNR G106. 3+2.7 (Tibet , HAWC)]

3. Star forming regions
   [e.g., Cygnus cocoon region (Tibet, HAWC)]

1. Galactic Center region as PeVatron!?



- ✓ Detection of diffuse component (proton−like)
- ✓ >100TeV γ−ray expected
- ✓ PeVatron candidate



Abramowski, et al, Nature (2016)

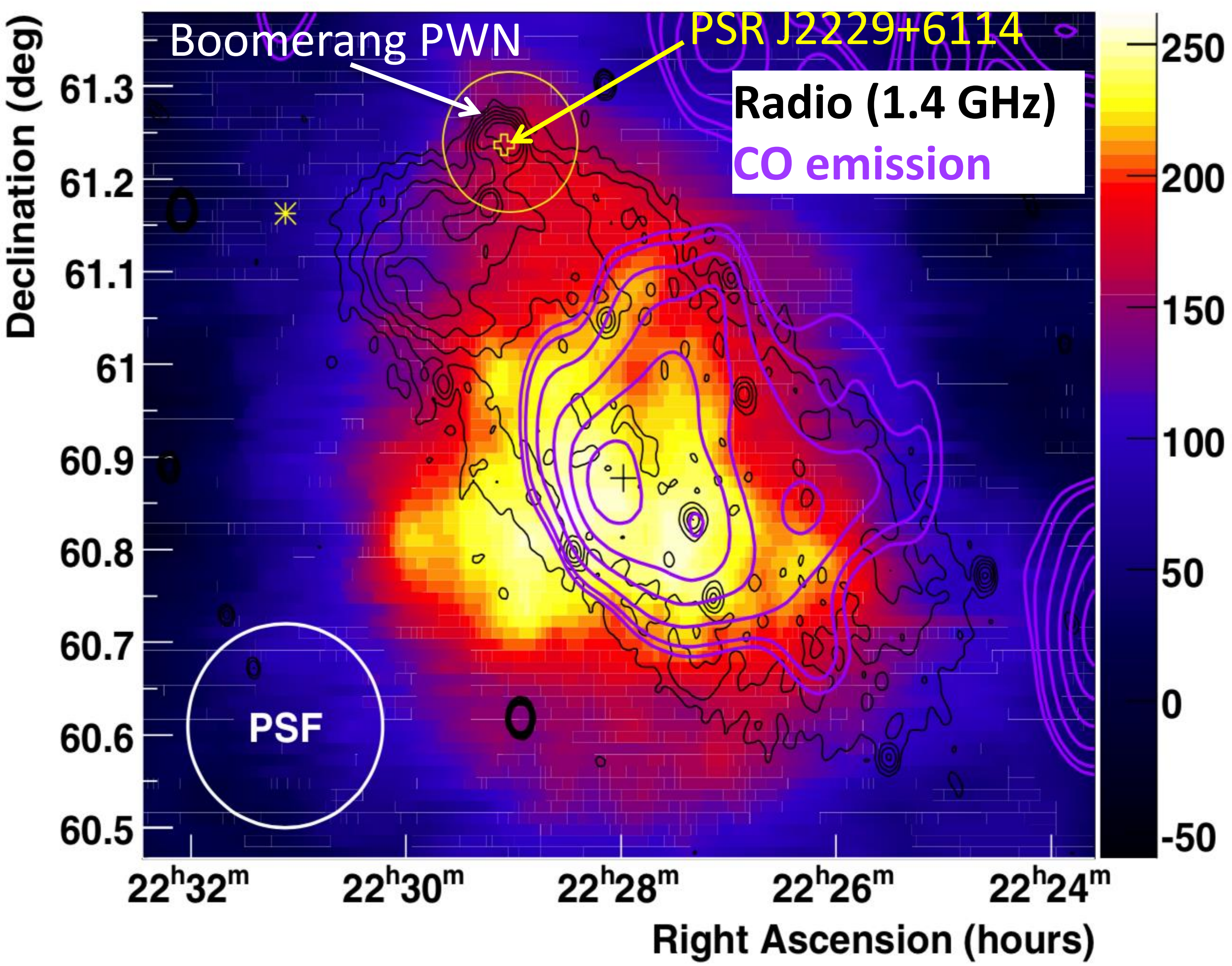
$\delta \sim -29°$

2. SNR G106.3+2.7 (Observed by VERITAS & Fermi)

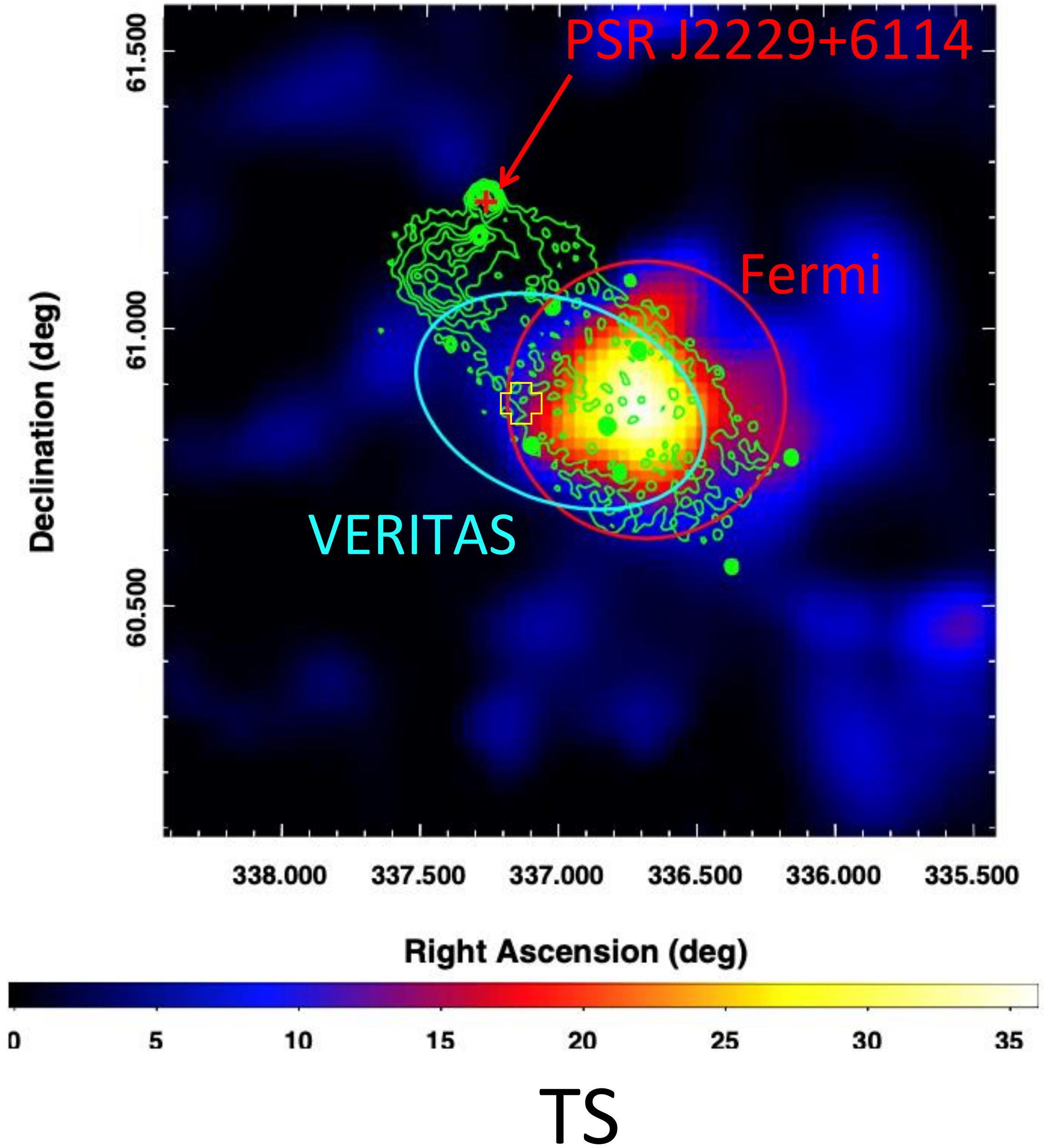
Acciari et al., ApJL, 703, L6 (2009)

Abdo et al., ApJL, 700, L127 (2009)

VERITAS



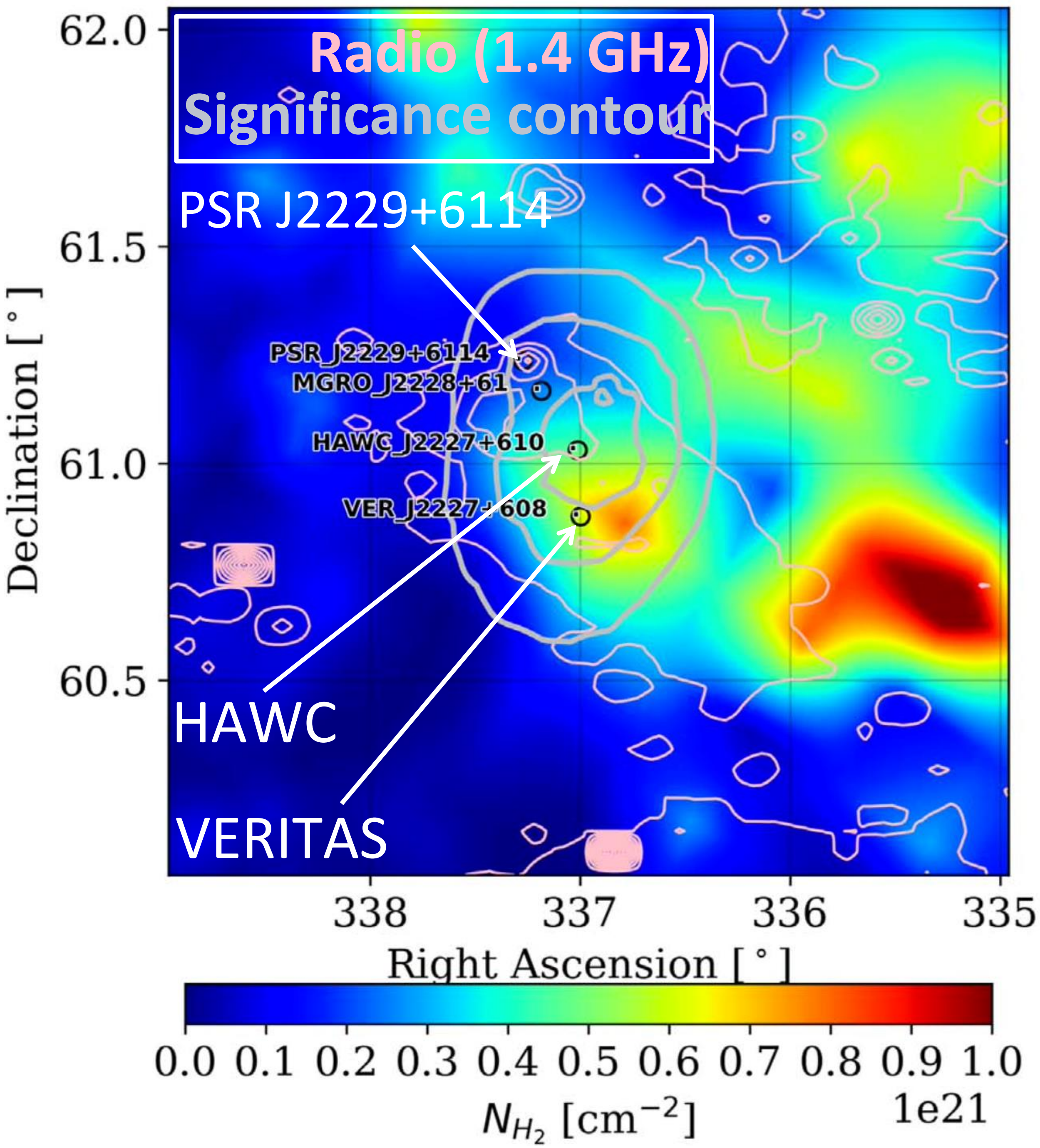
Fermi



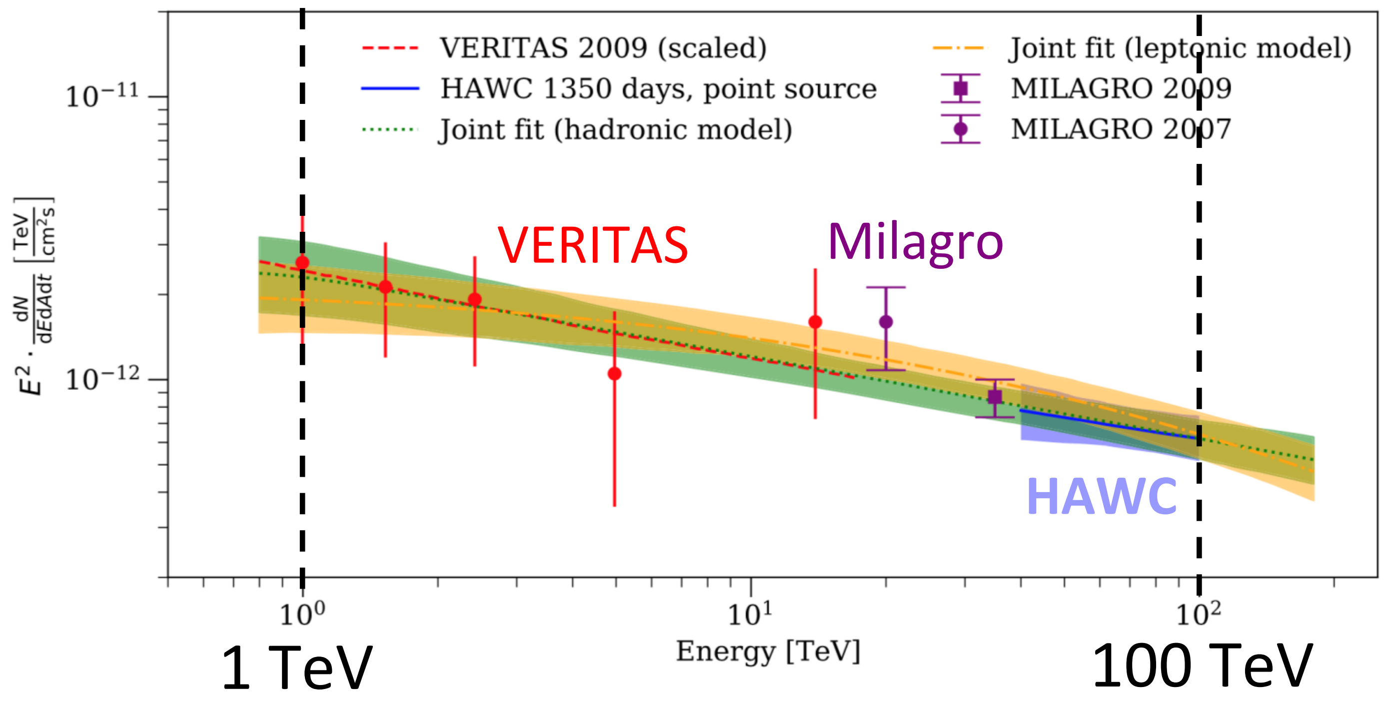
- Distance 0.8 kpc ➡ SNR G106.3+2.7 size:14 pc x 6 pc *Kothes et al, ApJ, 560, 236 (2001)*
- PSR J2229+6114 : age 10 kyrs、$\dot{E}$ = 2.2 x 10^{37} erg/s *Halpern et al., ApJL, 552, L125 (2001)*
- GeV & TeV emission region center -> consistent with molecular cloud (CO emission)

SNR G106.3+2.7 (observed by HAWC)

Albert et al., ApJL, 896, L29 (2020)



Energy spectrum

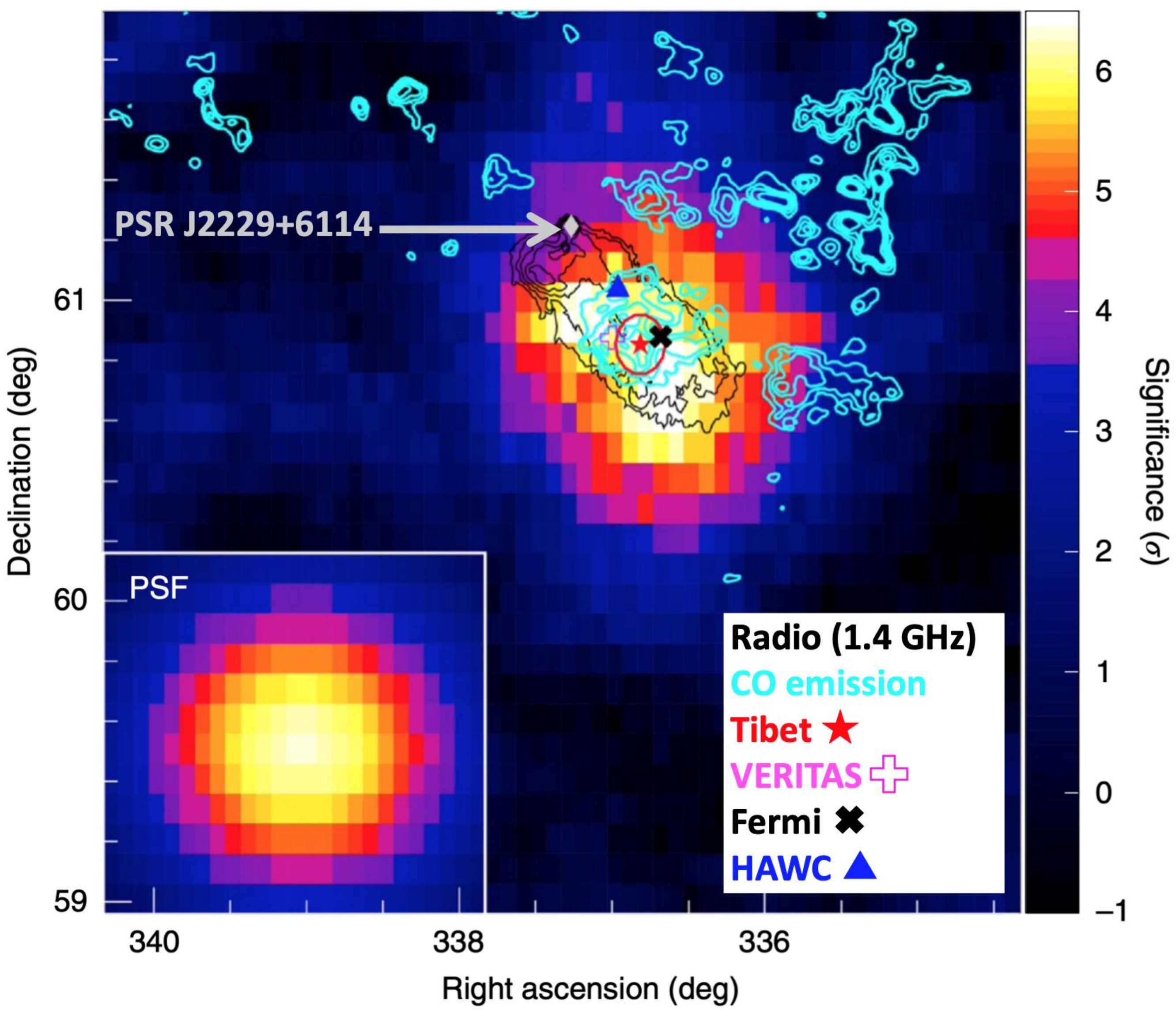


- Source position consistent with pulsar (e?) & with molecular cloud (p?)
- Energy spectrum: 40 TeV — 100 TeV

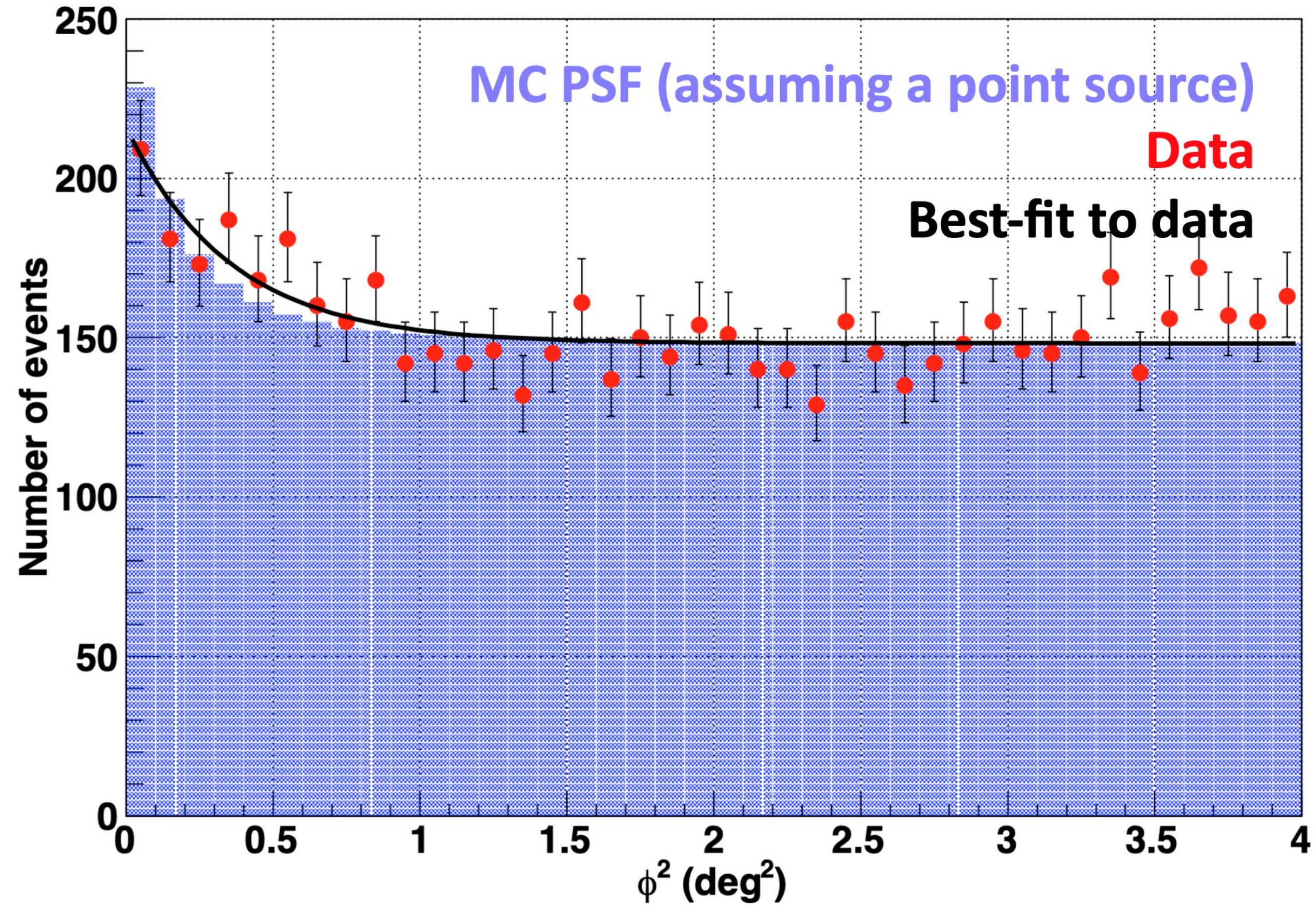
SNR G106.3+2.7 (Observed by Tibet ASγ)

M. Amenomori et al., Nature Astronomy Letters (2021) https://doi.org/10.1038/s41550-020-01294-9

Significance map by Tibet > 10 TeV



Angular distribution > 10 TeV



- Tibet source position: R.A. = 336.82°±0.16°
  Dec = 60.85°±0.10°

●Consistent with molecular cloud position

●Inconsitent with pulsar position, 0.44°apart(3.1σ including systematic errors)

※HAWC source position consistent with pulsar and with molecular cloud.

- Fit given assuming 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} = 0.24°±0.10°**

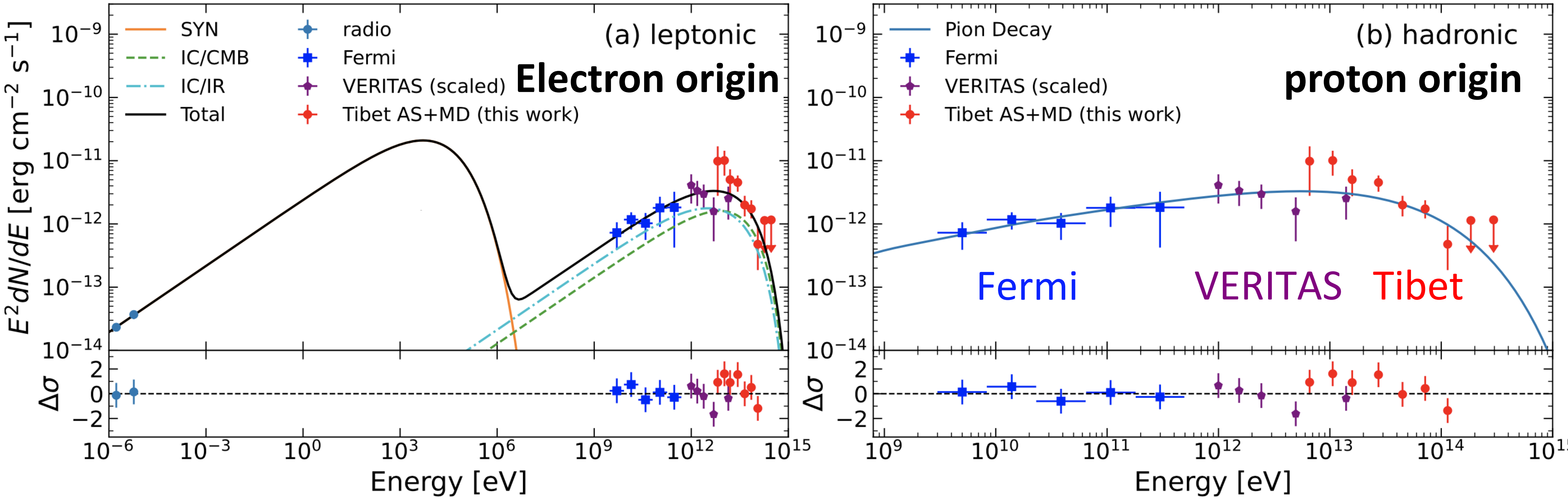
※ consistent with previous results

VERITAS: σ_1 = 0.27°±0.05°, σ_2 = 0.18°±0.03°

Fermi: 0.25°-radius disk

HAWC: <0.23° (90% C.L.)

Energy spectrum (SNR G106.3+2.7, Tibet ASγ



Abdo et al., ApJL, 700, L127 (2009)
Xin et al., ApJ, 885, 162 (2019)
Pineault & Joncas, AJ, 120, 3218 (2000)

- *By naima* package *(Zabalza, arXiv:1509.03319)*
  Parent particle energy spectrum ∝ $E^{-\alpha} \exp(-E/E_{cut})$

	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

(※ Target gas density = 10 / cm³ を仮定)

- Difficult to discriminate gamma-ray emission mechanisms (electron or proton) by spectral shape alone.

Discussion

In the case of proton origin

- Protons accelerated by SNR in collision with molecular cloud produce π^0 decaying into 2γ.
- $E_{cut} \sim 0.5$ PeV、power law index $\alpha \sim 1.8$

In the case of electron origin

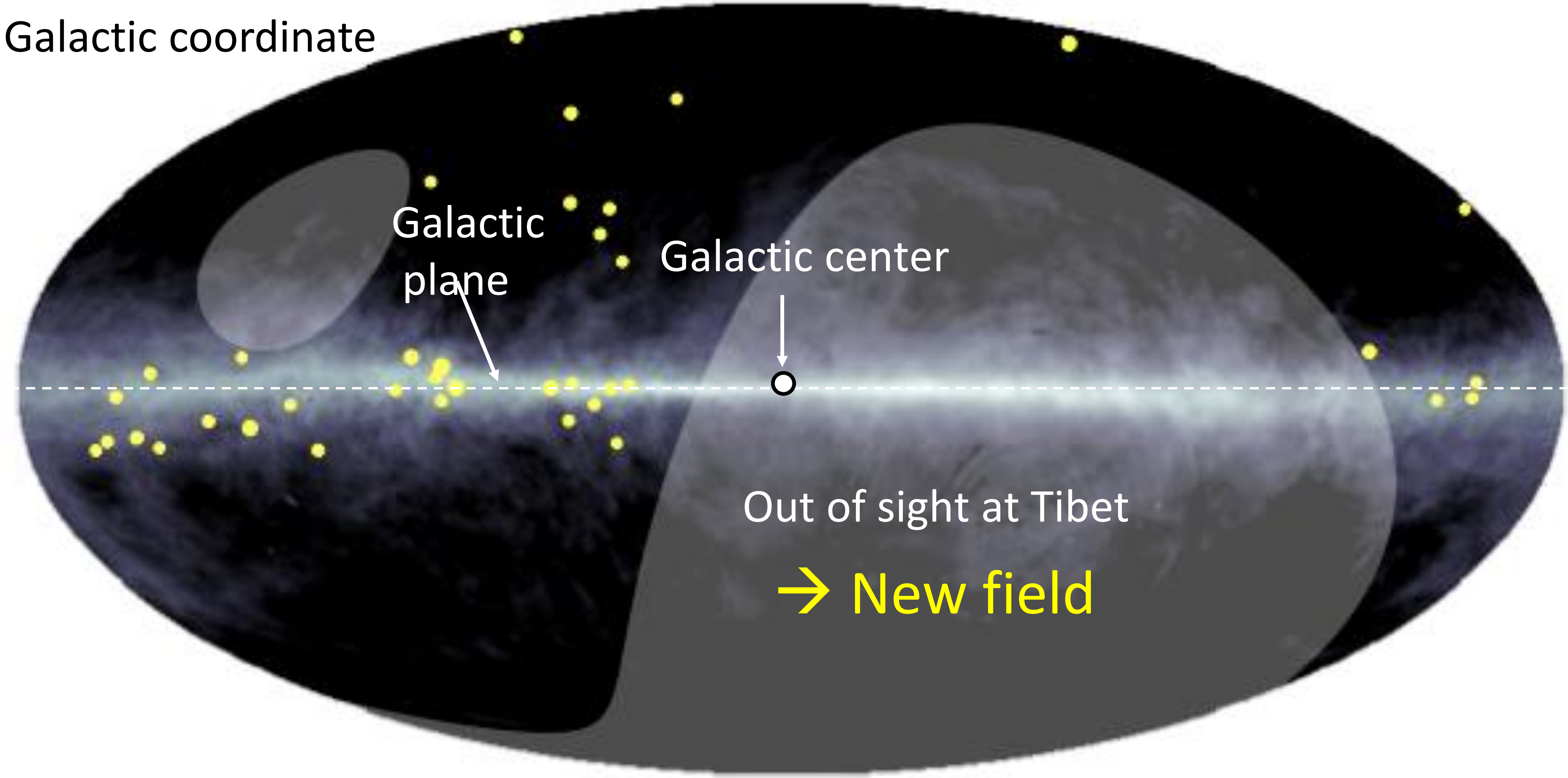
- Electrons suppled by pusar produce gamma rays via inverse Compton scantterings.
- $E_{cut} \sim 190$ TeV、power law index $\alpha \sim 2.3$、 magnetic field B $\sim 9\ \mu$G
- $W_e \sim 1.4 \times 10^{47}$ erg is 2 % of total energy released by pulsar during 10 kyrs ->
  Magnetic field may be much stronger, if the rest 98 % is consumed by its production.
  ➡ If pulsar age is younger (1 kyrs)？
  1 TeV electrons extend by ~ 1.7 pc = 0.12° during 1kyrs.
  ➡ Can not explain gamma-ray emission region by Fermi (~10 GeV).

Proton origin is likely.

3. Cygnus cocoon already appeared in some of the previous slides.

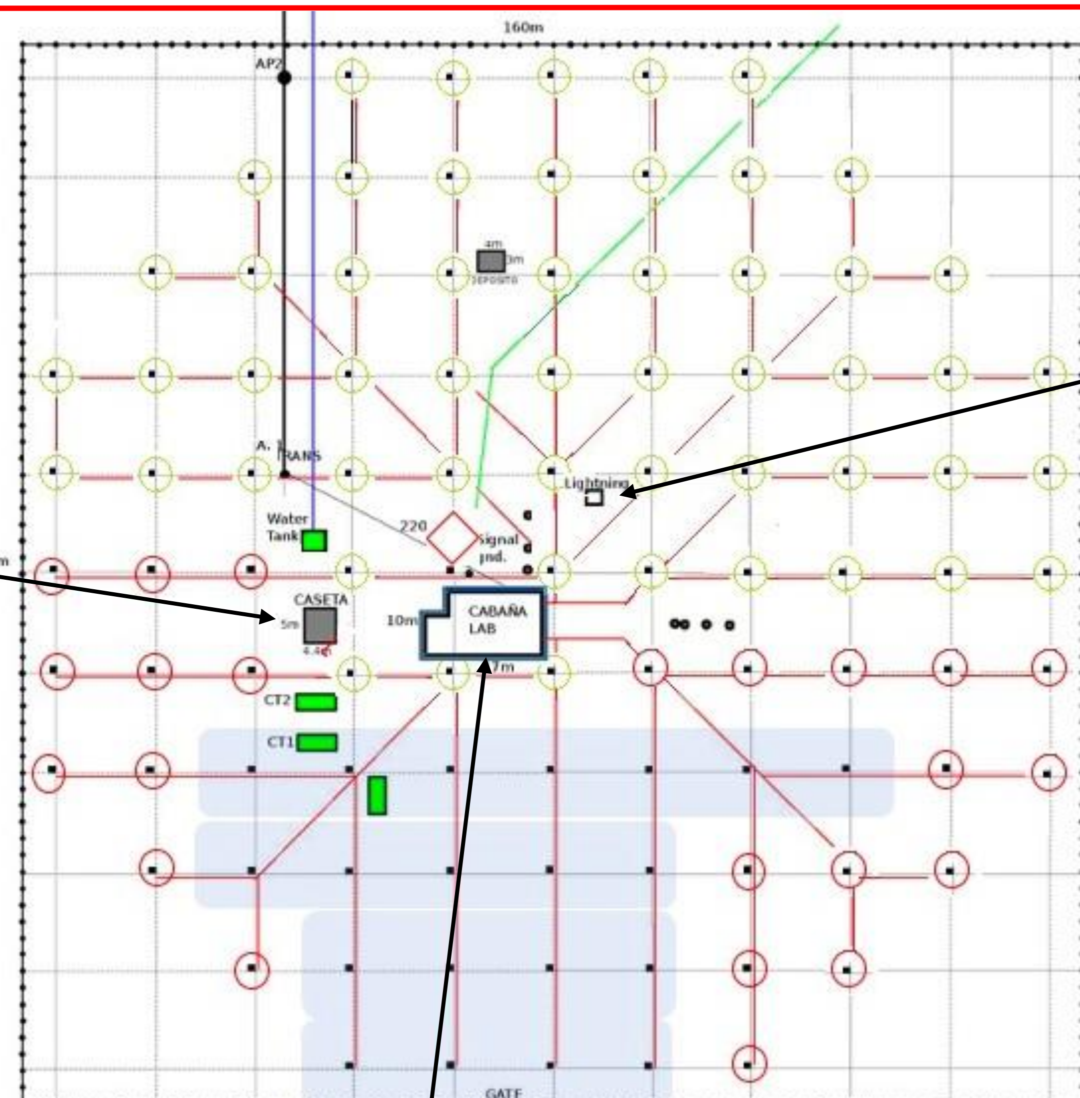
§ Future Prospects & Summary

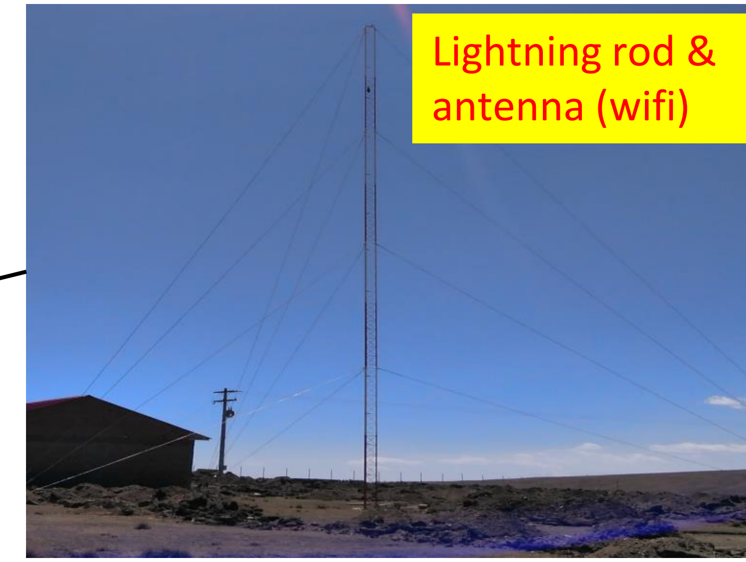
Observations in the Southern Hemisphere by ALPACA (2022), SWGO(?)



- ✓ 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

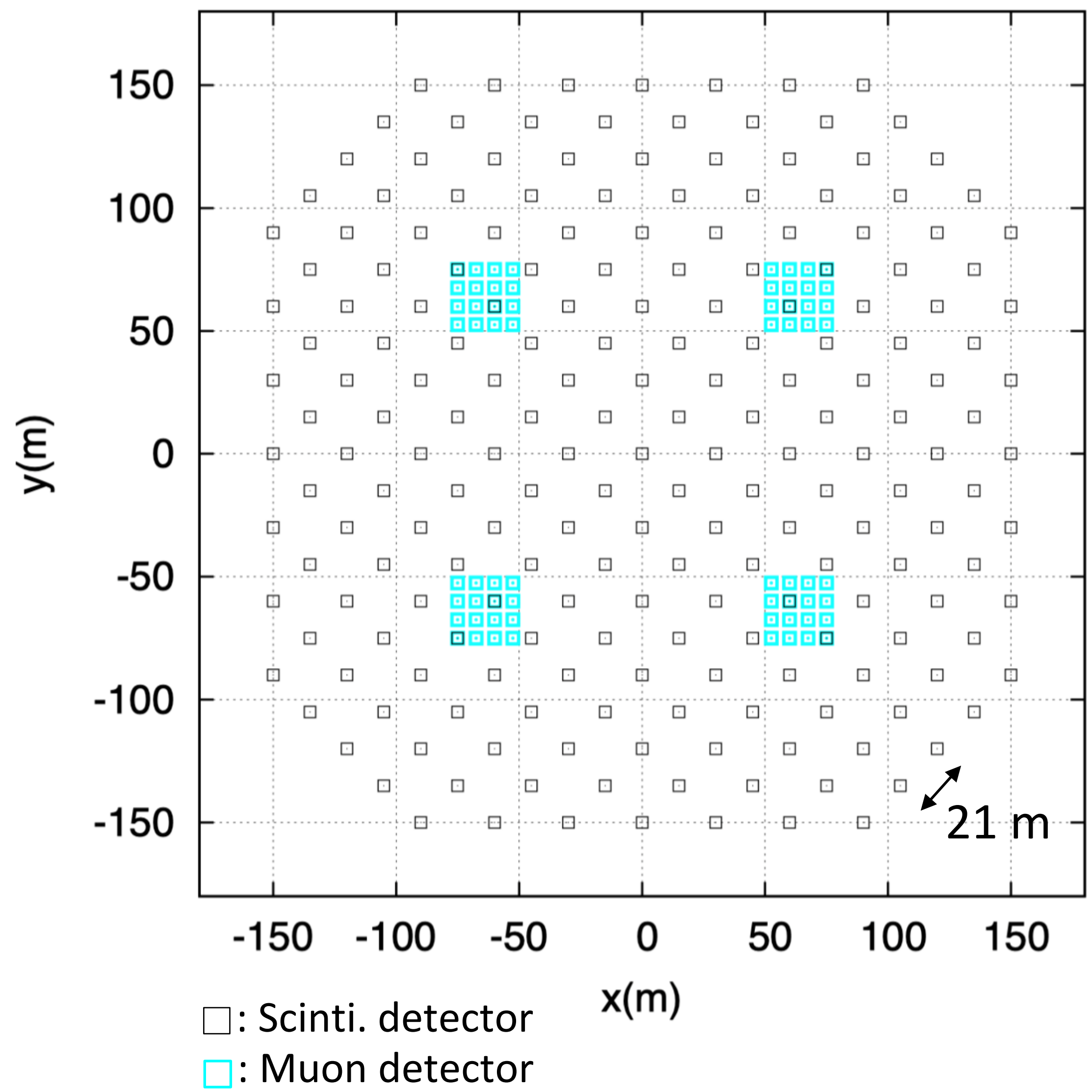
ALPAQUITA (prototype ¼ of ALPACA) in 2021 or 2022





The Half ALPACA Experiment (in 2022)

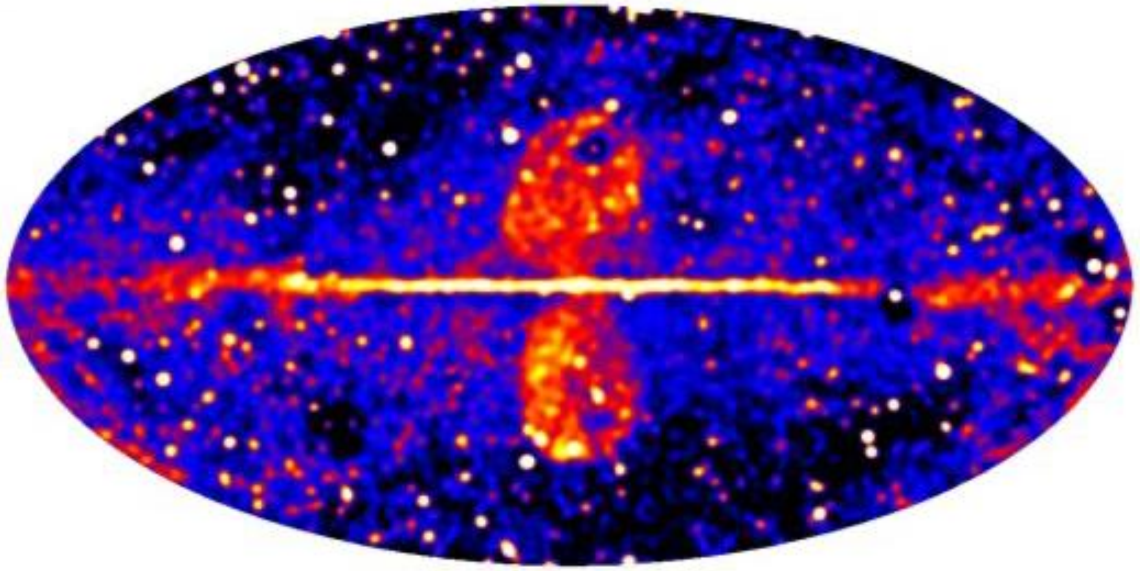
1st phase of the ALPACA experiment



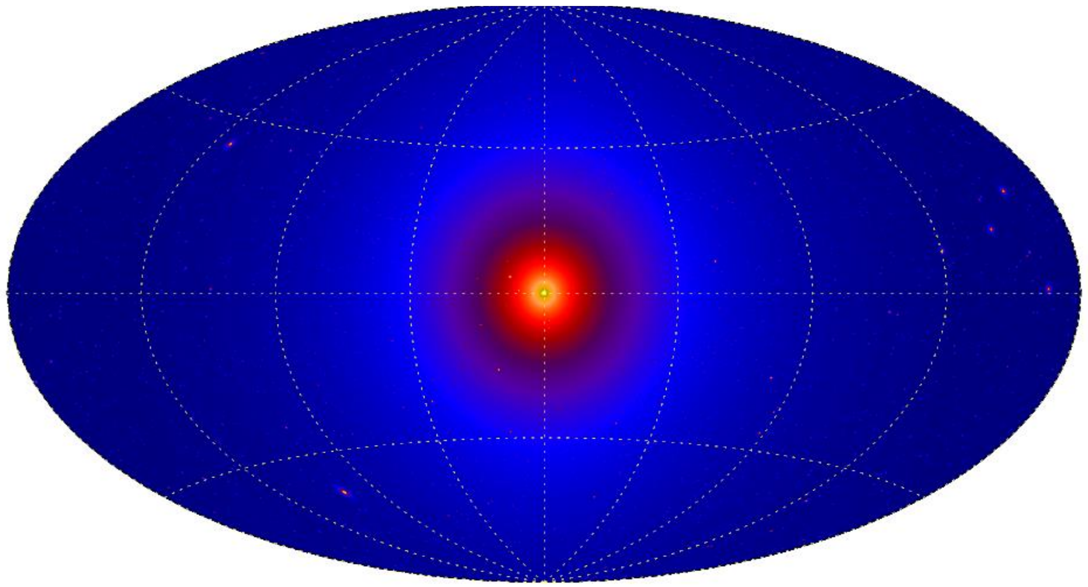
- Surface AS array : Consists of 200 scinti. Detectors
  Geometrical area : 83,000 m^2
- MD array : Consists of 64 MD cells
  Geometrical area : 3,600 m^2

Observations in the Southern Hemisphere

Hot gas bubble structure
An explosion at Galactic center
10 million years ago? *Fermi-LAT*



Unknown
γ-rays from Super Heavy Dark Matter
Pieri+, PRD (2011)



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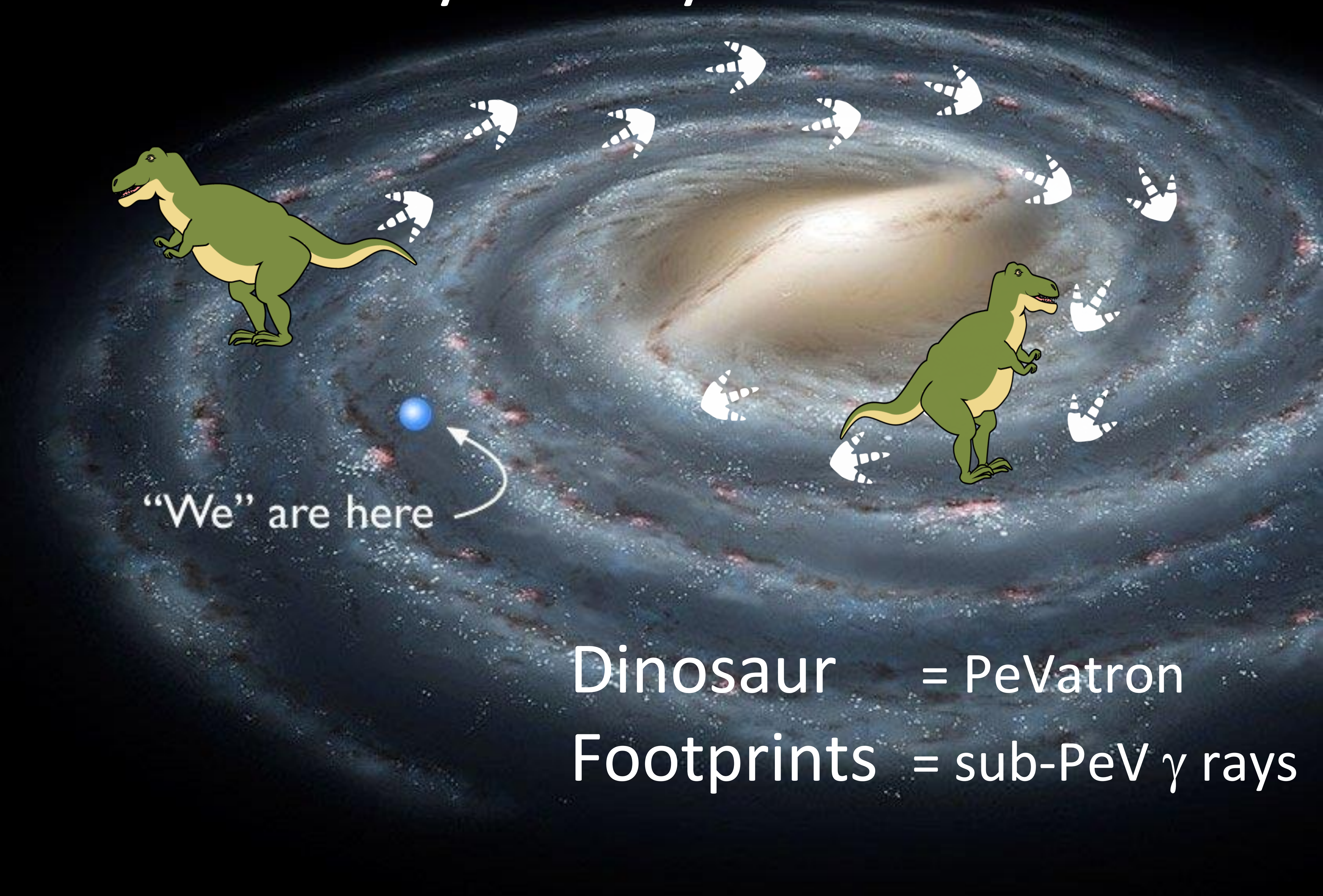
Summary

Unraveling 60-Year-Old Mystery,

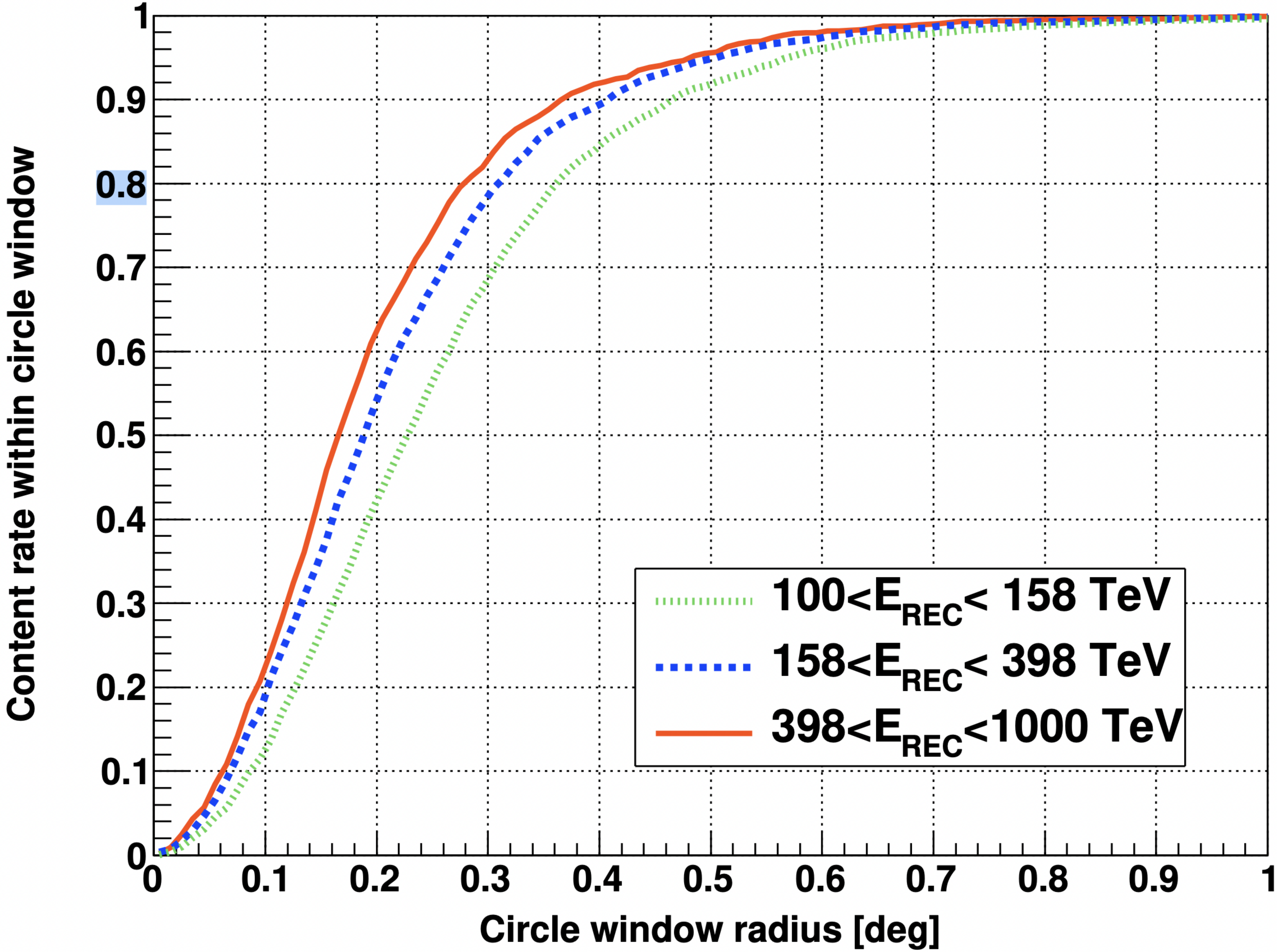
- ✓ Highest energy sub-PeV (0.1-1 PeV) gamma rays from the Milky Way galaxy
- ✓ Evidence for existence of PeVatrons in past/present Milky Way galaxy
- ✓ Experimental verification for the theoretical model of high-energy “cosmic-ray pool” in the Milky Way galaxy

Thank you for your attention!



END

Thank you for your attention!



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100<E_REC< 158 TeV
158<E_REC< 398 TeV
398<E_REC<1000 TeV