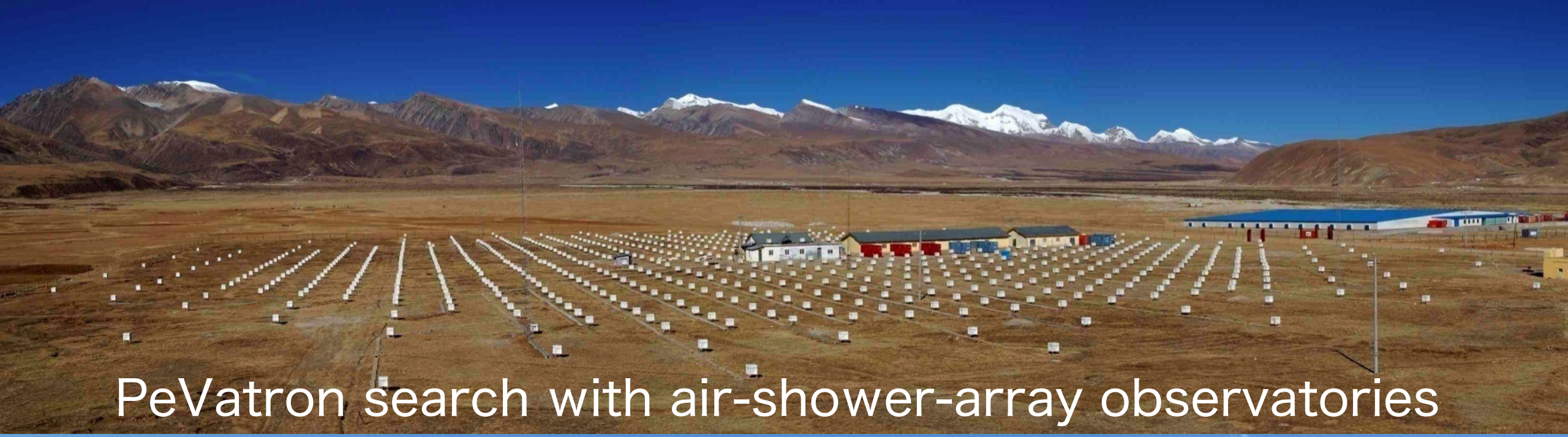


PeVatron search with air-shower-array observatories

Kato Sei (Tibet/ALPACA group)

Young Researchers' Workshop 2023/7/19-20

Cosmic Rays (CRs)

- ✓ Give us much astrophysical information, e.g.,
  - Acceleration mechanism
  - Interstellar environment (magnetic field, medium, …)
  - Nucleosynthesis (in stellar evolution, supernova, …)
- ✓ Highly important for the evolution of the Galaxy (e.g., star formation …)

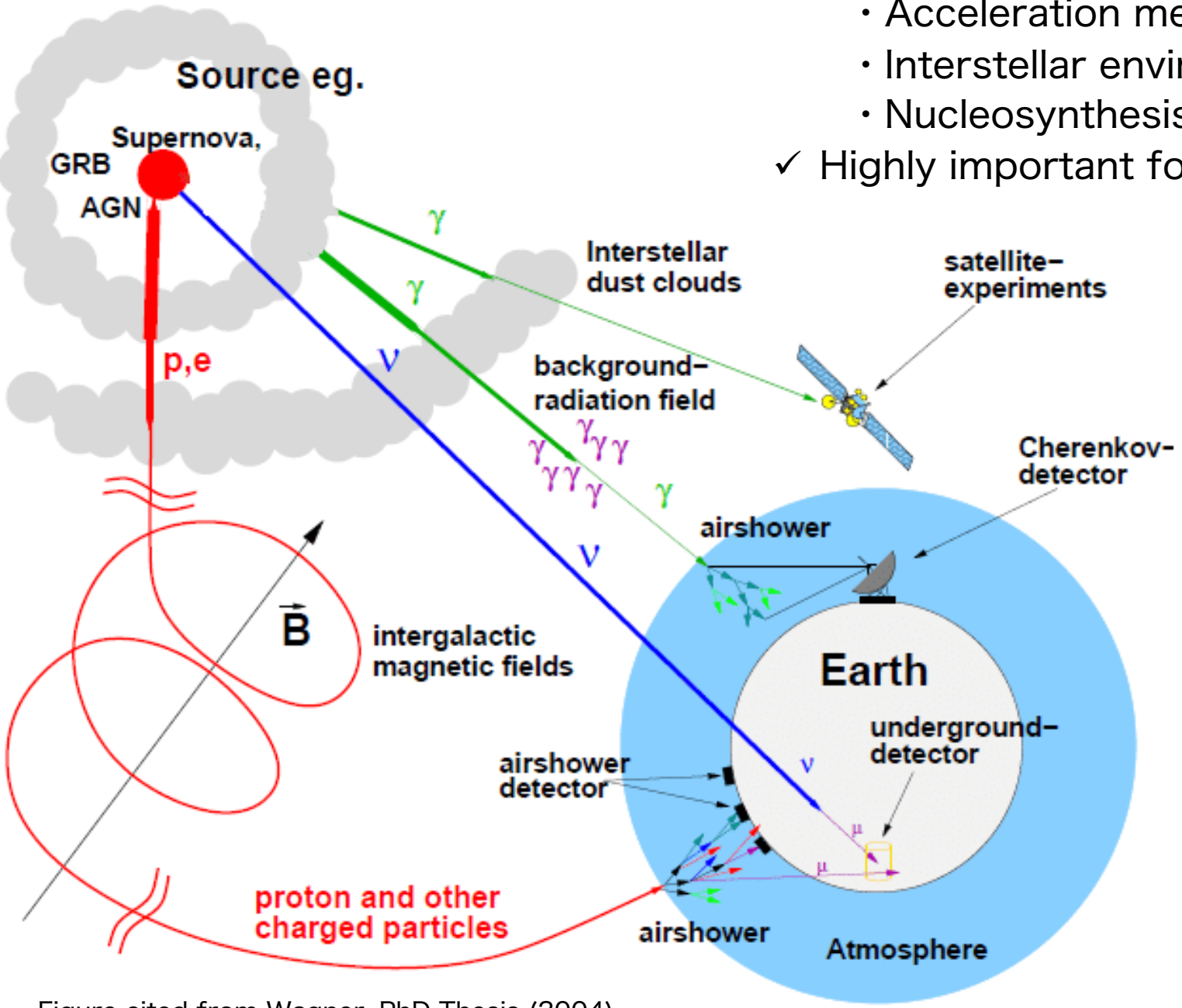
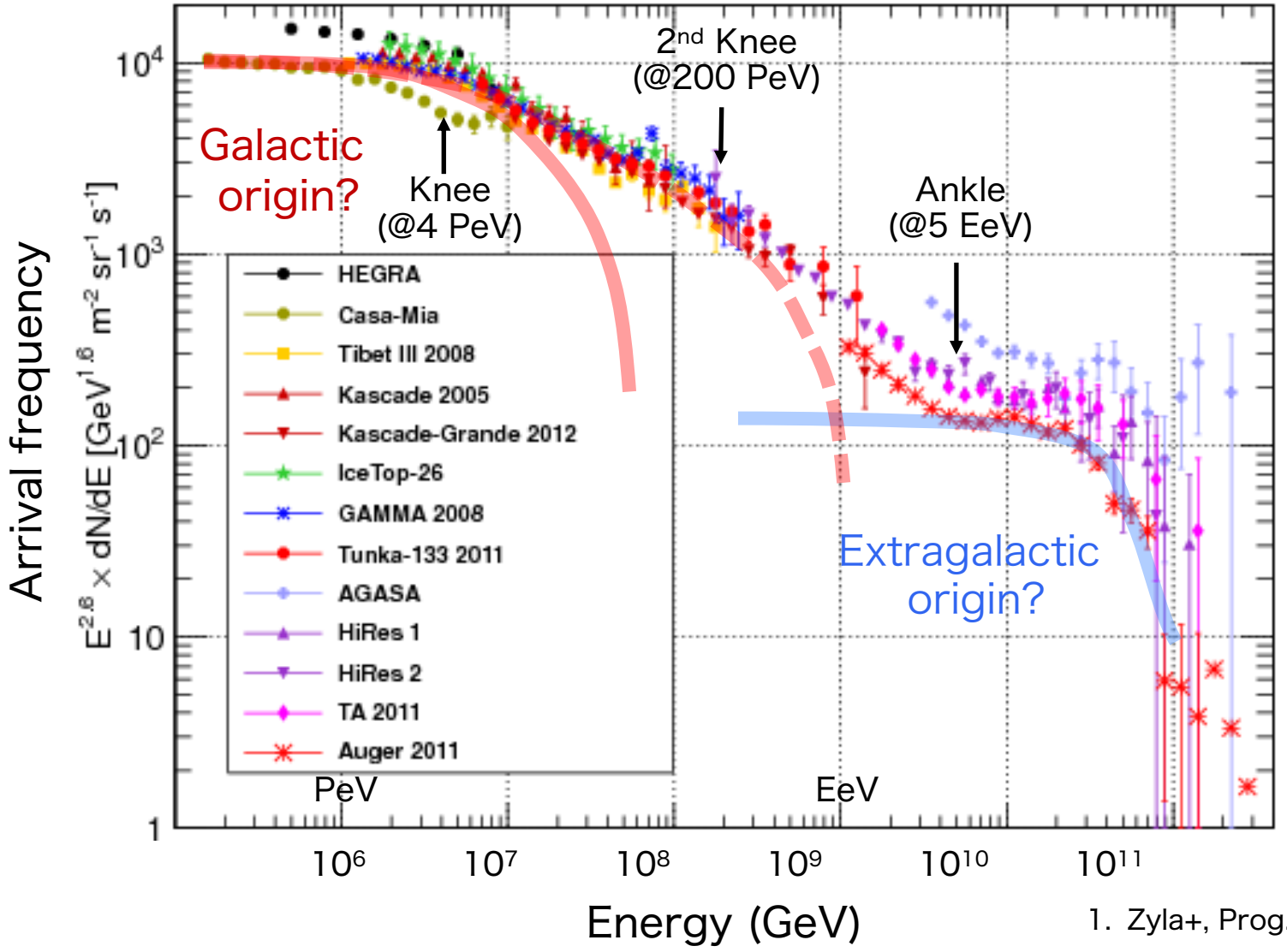


Figure cited from Wagner, PhD Thesis (2004)

* In the later of the presentation, we use “cosmic rays” to mean high-energy nuclei.

Galactic PeV Cosmic-Ray Accelerators : *PeVatrons*

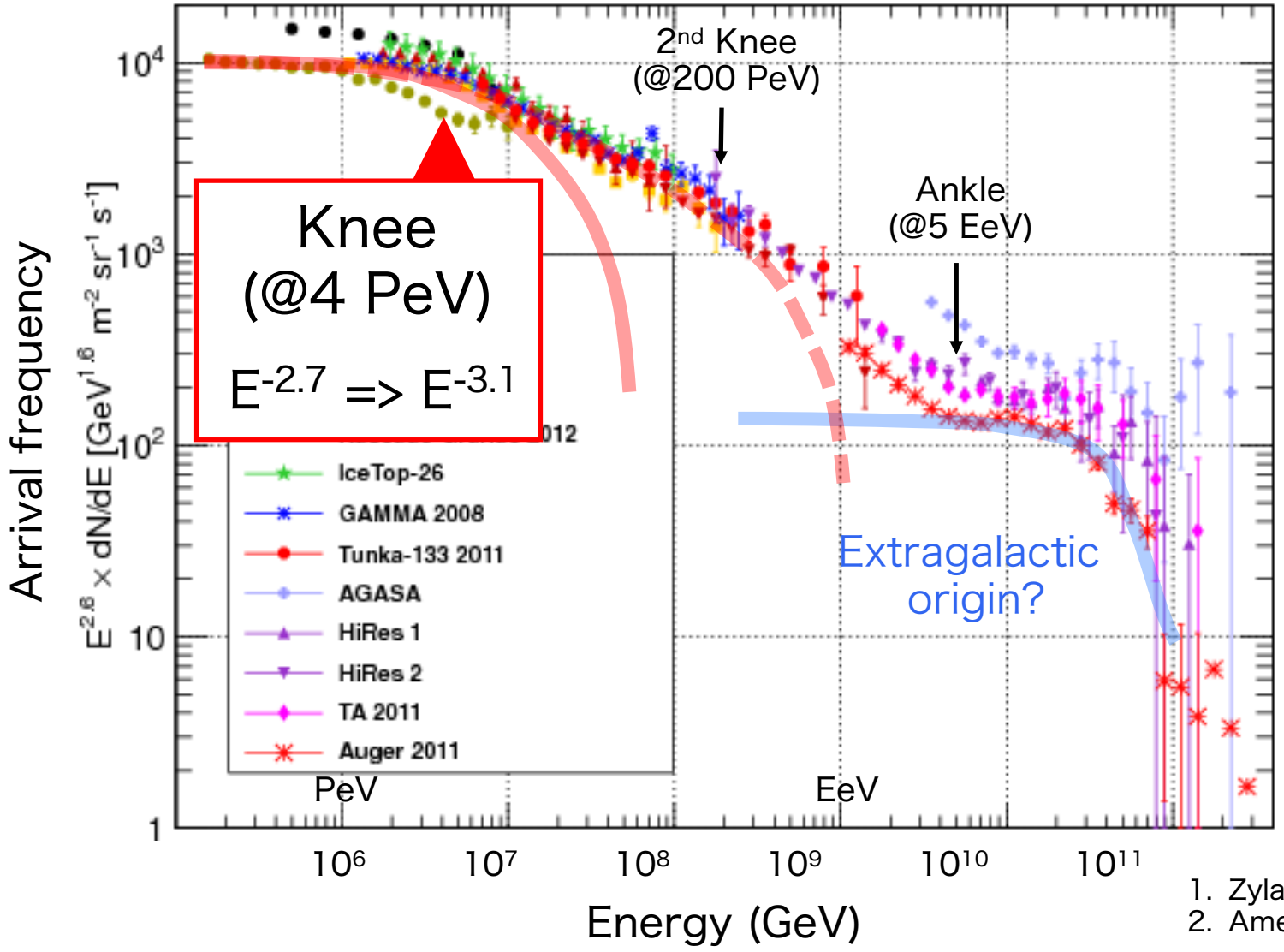
Nuclear CR spectrum observed on the Earth[1]



1. Zyla+, Prog. Theor. Exp. Phys. 2021 (2021)

Galactic PeV Cosmic-Ray Accelerators : *PeVatrons*

Nuclear CR spectrum observed on the Earth[1]

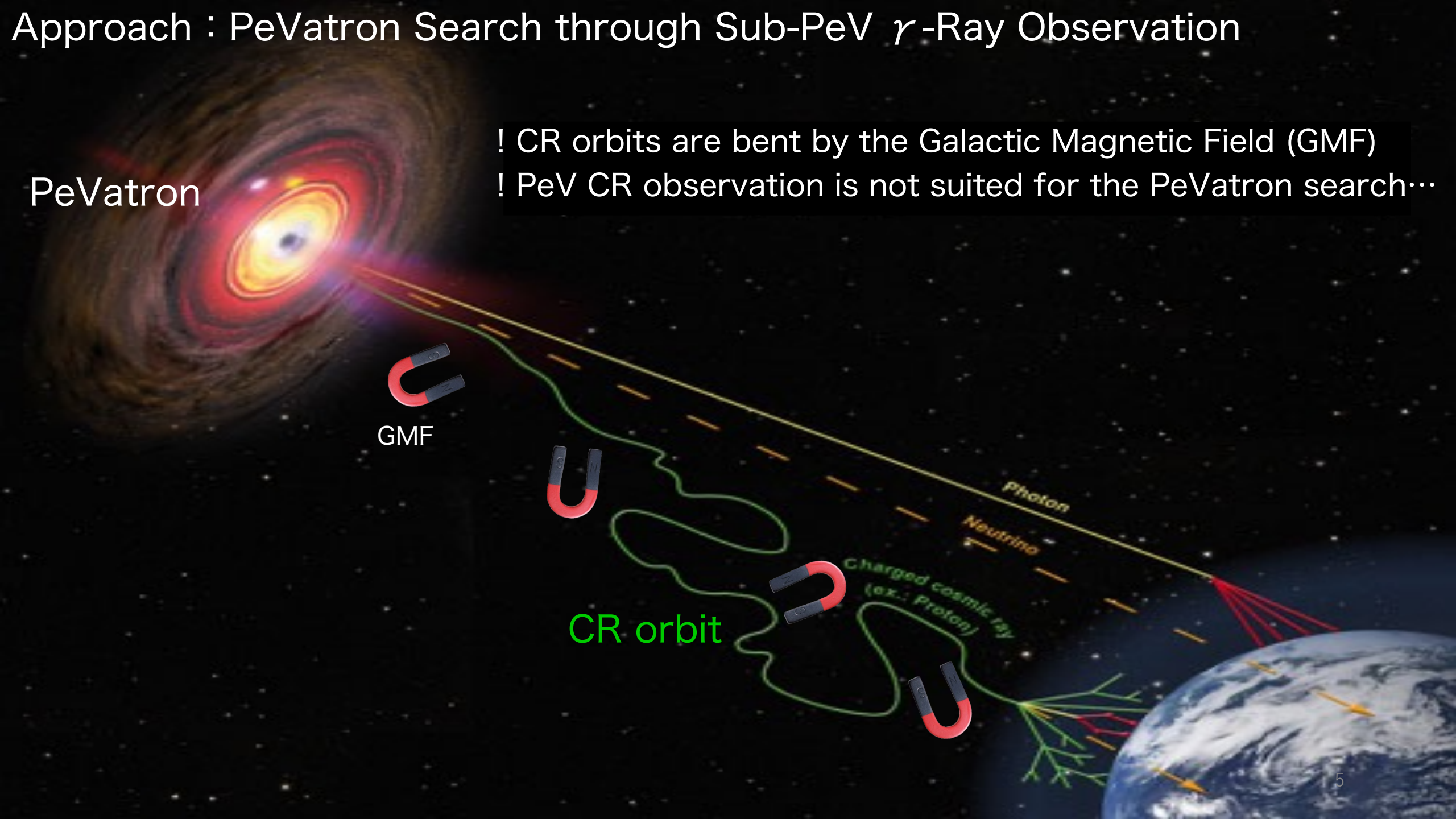


1. Zyla+, Prog. Theor. Exp. Phys. 2021 (2021)
2. Amenomori+, PRL 126, 141101,(2021)

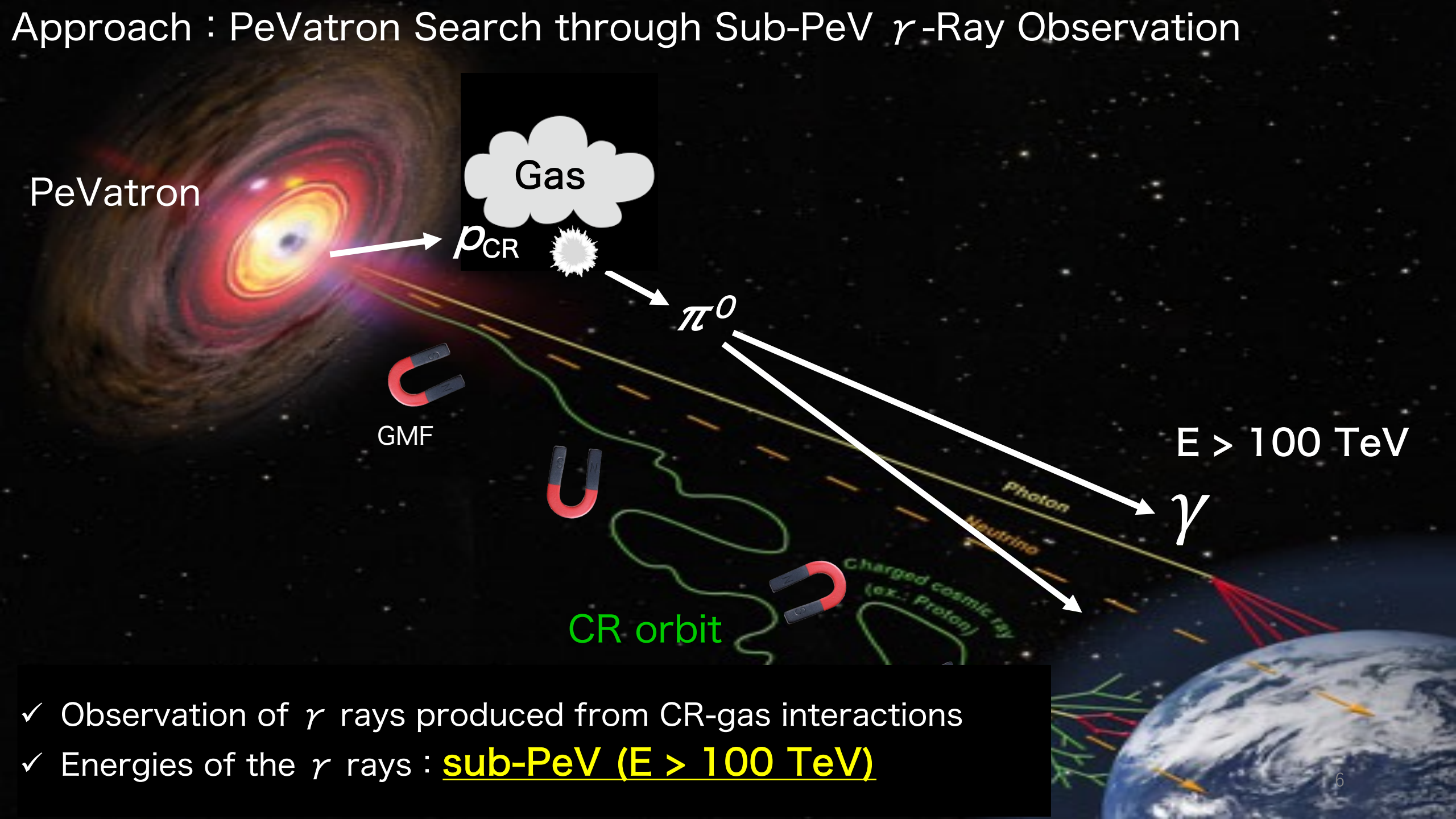
! *PeVatrons* have not been localized yet.

Approach：PeVatron Search through Sub-PeV γ-Ray Observation

! CR orbits are bent by the Galactic Magnetic Field (GMF)
! PeV CR observation is not suited for the PeVatron search…

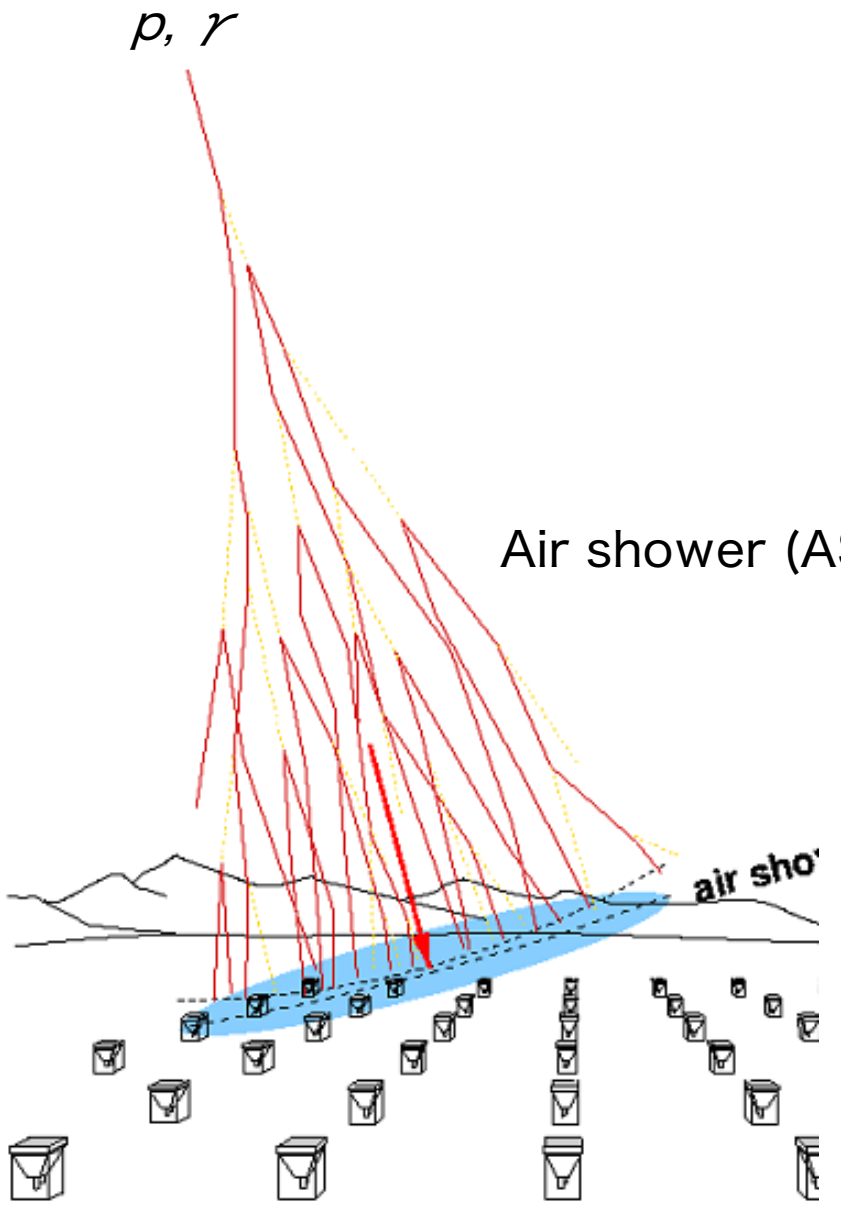


Approach : PeVatron Search through Sub-PeV γ-Ray Observation



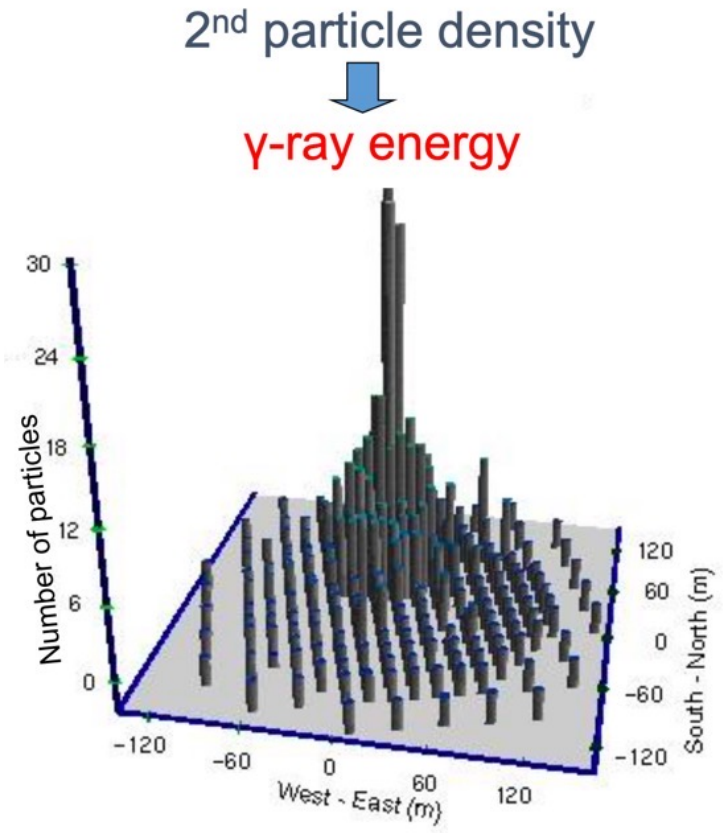
- ✓ Observation of γ rays produced from CR-gas interactions
- ✓ Energies of the γ rays : <u>sub-PeV (E > 100 TeV)</u>

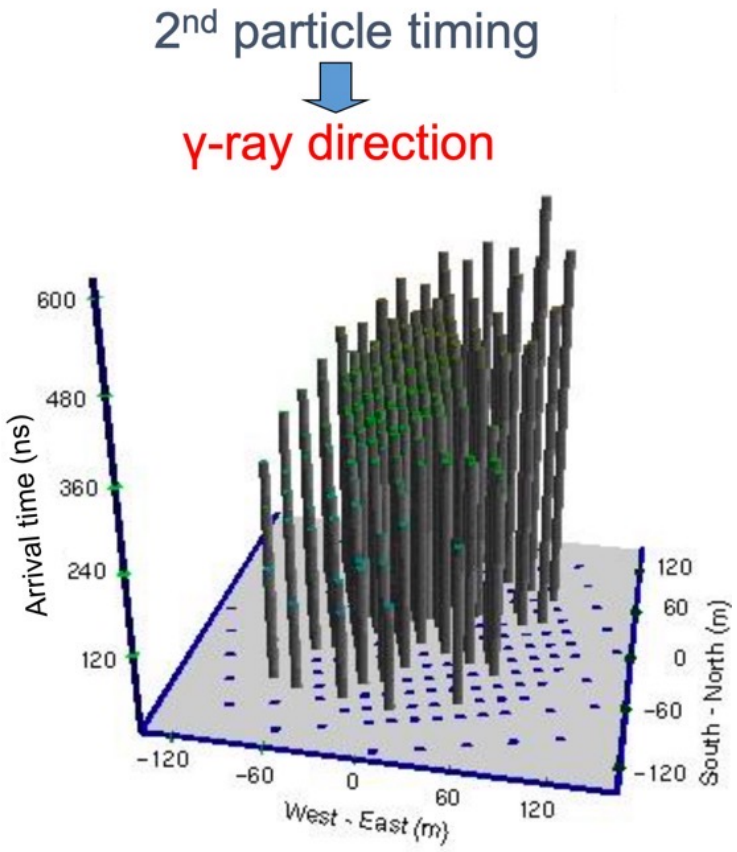
Extensive Air Shower Array



Air shower (AS)

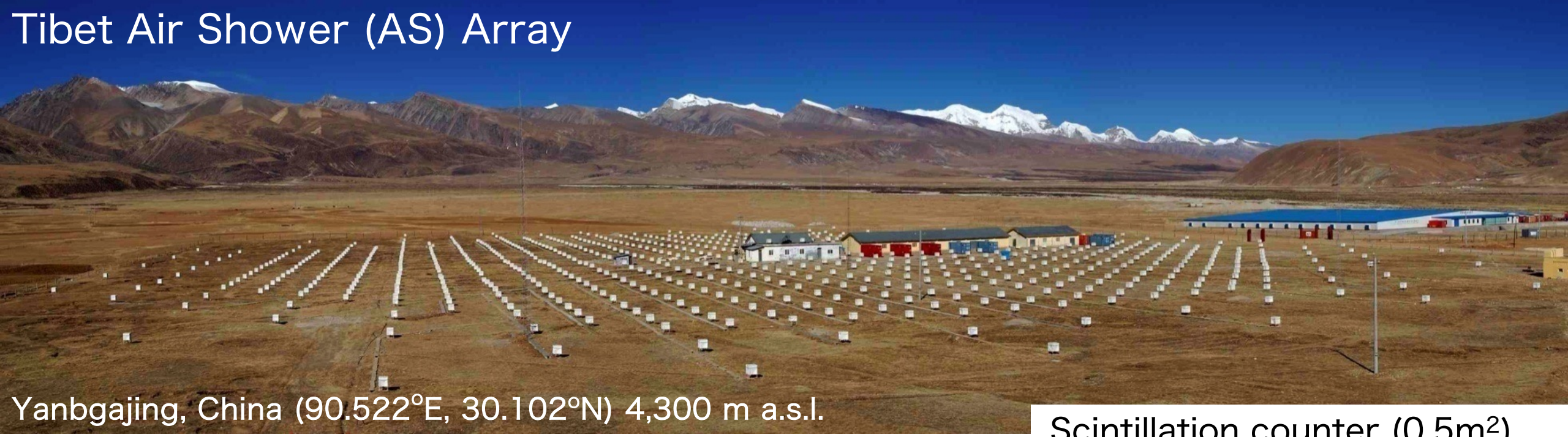
Air shower array (AS array)





- ✓ Sampling AS ptcls w/ sparsely-put detectors
  => Energy & direction reconstruction
- ✓ Wide F.O.V. => New-source search
- ✓ Large detection area (~10^4 m^2) & High duty cycle
  => Statistical improvement

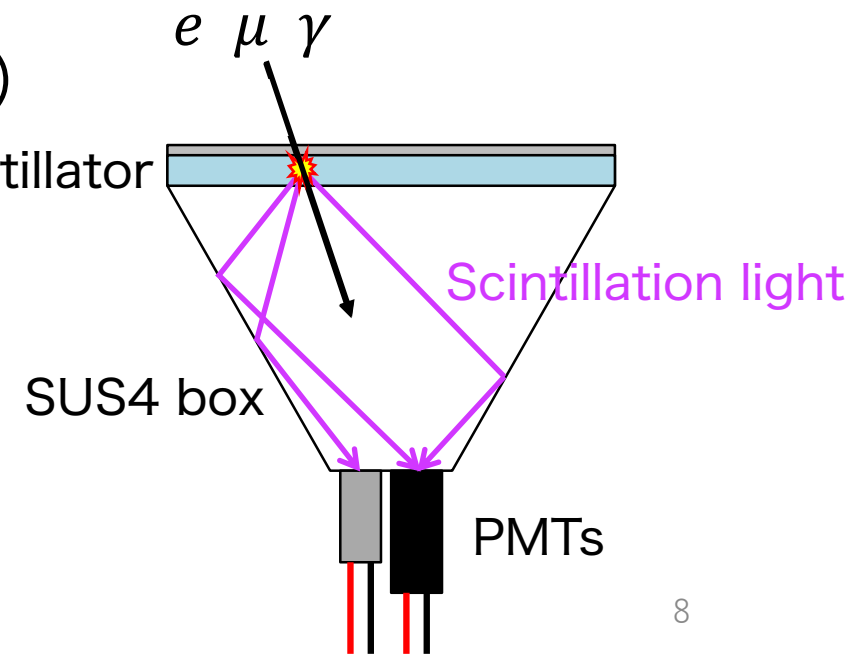
Tibet Air Shower (AS) Array



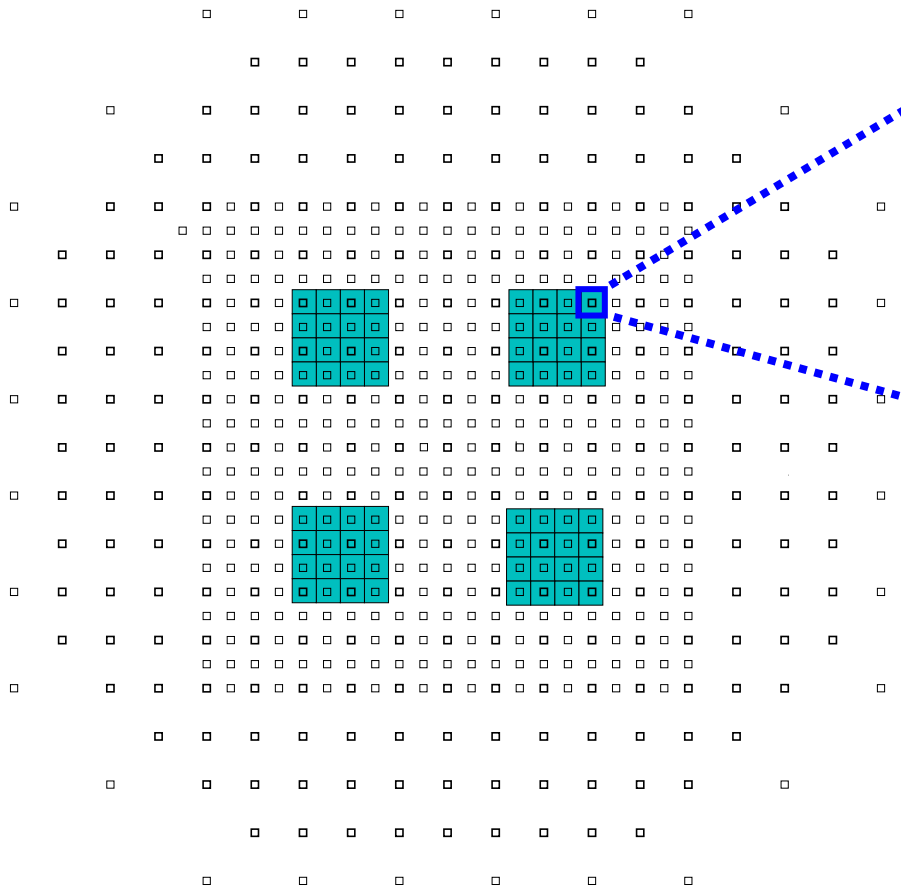
Yanbgajing, China (90.522°E, 30.102°N) 4,300 m a.s.l.

- ✓ International collaboration b/w China & Japan (since 1991)
- ✓ Air Shower (AS) Array 65,700 m²
  = 597 x 0.5m² scintillation counter
- ✓ Angular resolution : ~0.2° @ 100TeV γ
- ✓ Energy resolution : ~20% @ 100TeV γ

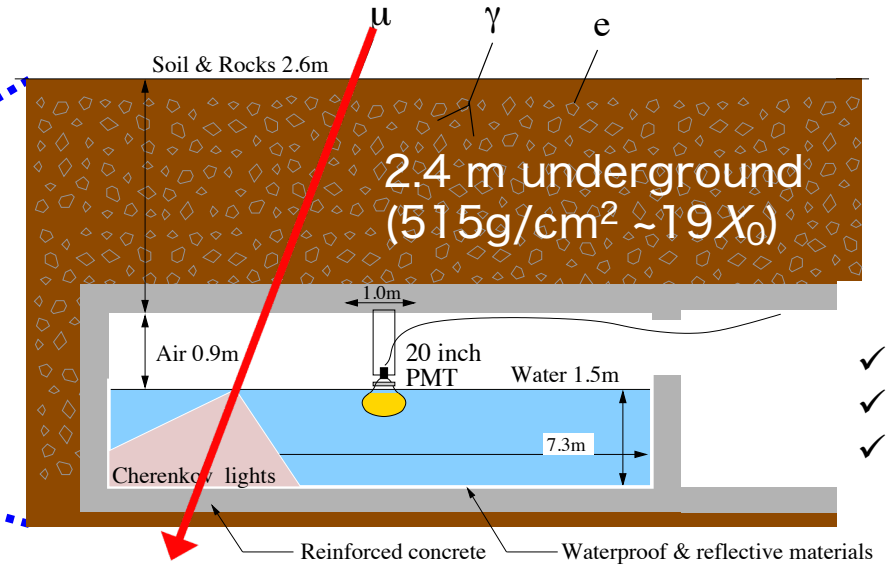
Scintillation counter (0.5m²)



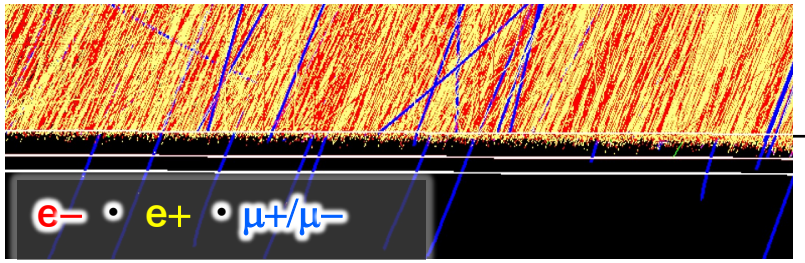
Underground Muon Detector Array (MD Array)



MD : 3400m²

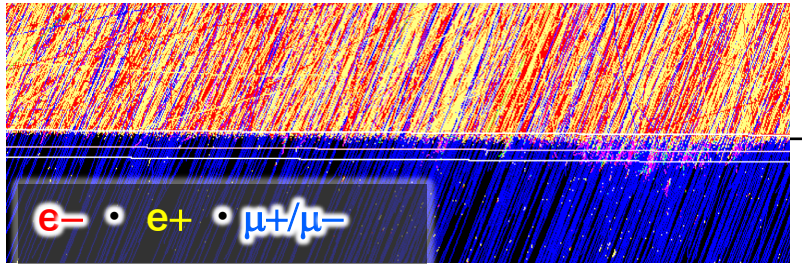


- ✓ Concrete pool
- ✓ 1.5m-depth water layer
- ✓ A 20-inch PMT suspended



200TeV γ shower

Few muons
(~1 μ)



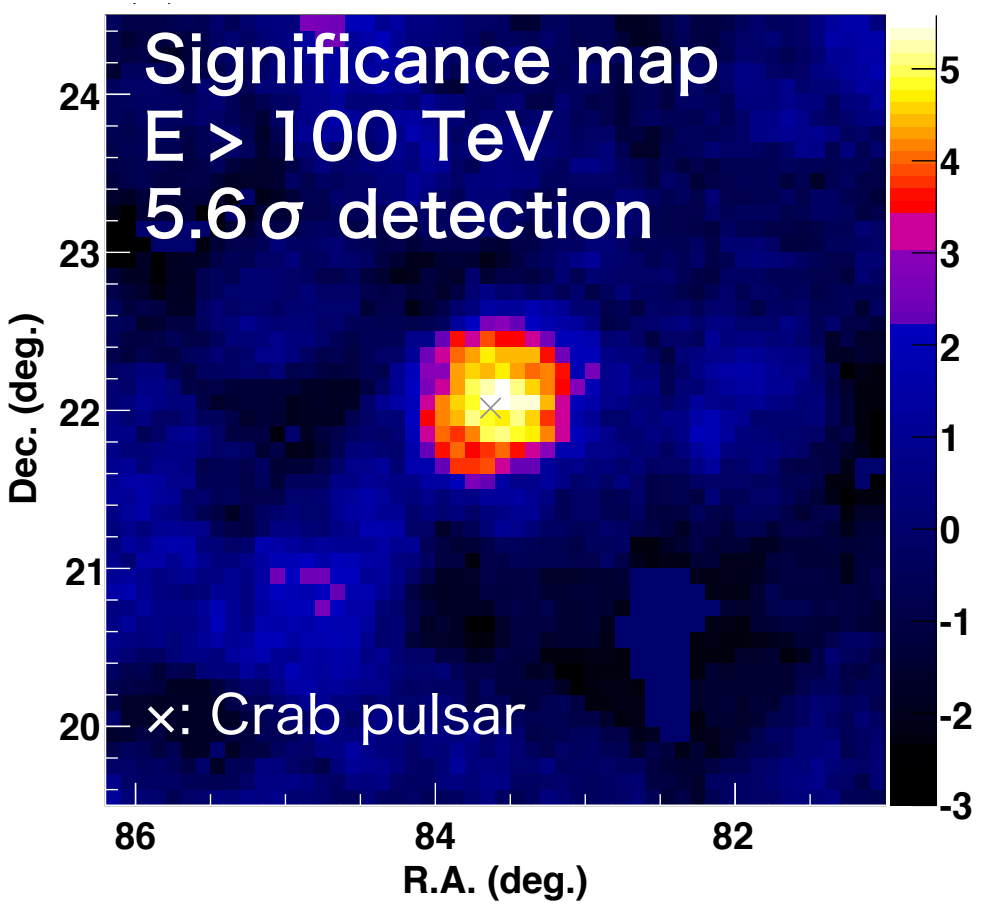
200TeV CR shower

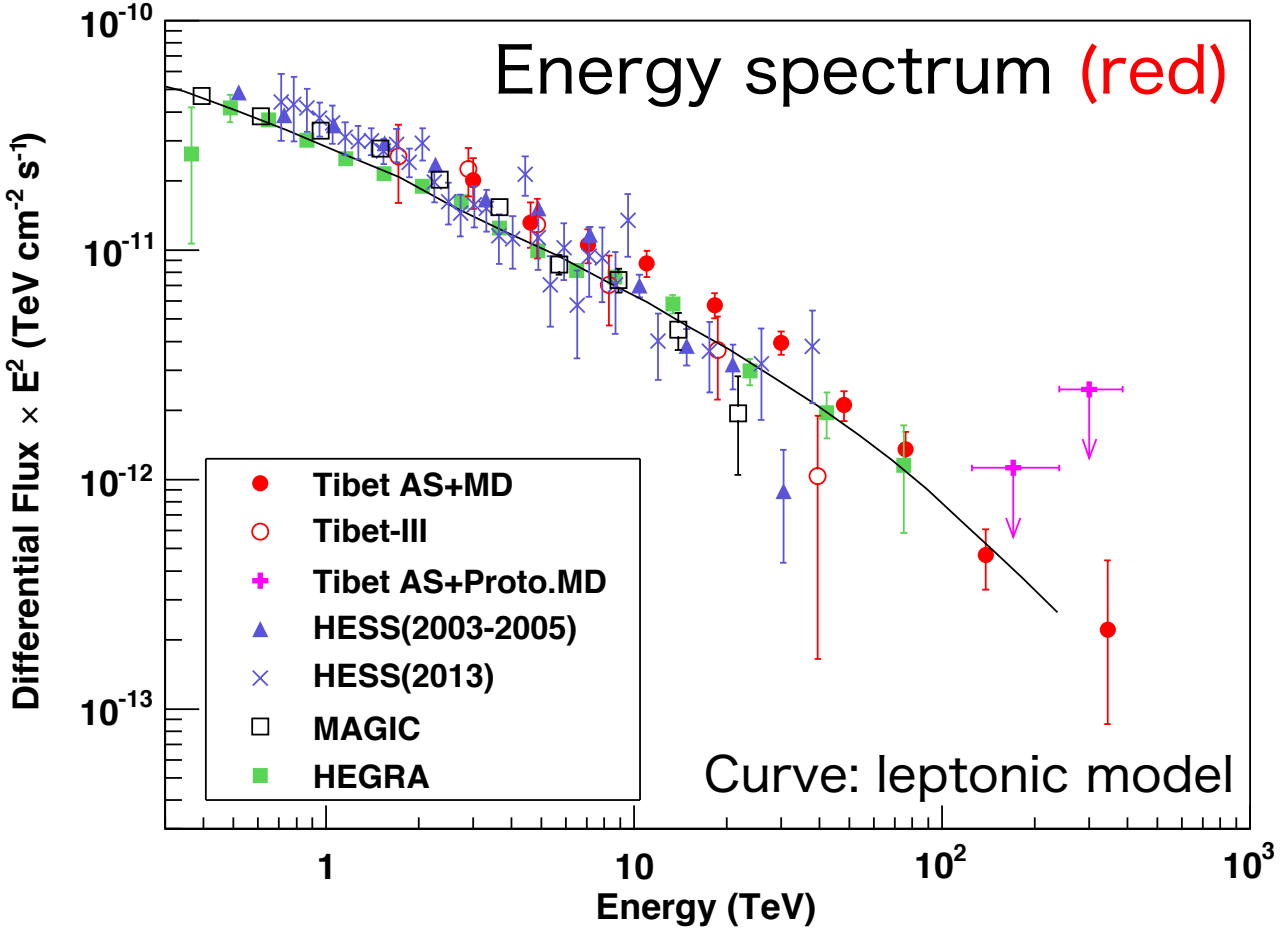
Many muons
(~100 μ)

Effective background CRs rejection : > 99.9% @ E > 100TeV
γ-ray survival ratio : ~ 90% @ 〃

First Detection of Sub-PeV γ Rays from the Crab Nebula

Amenomori et al., PRL 123, 051105 (2019)



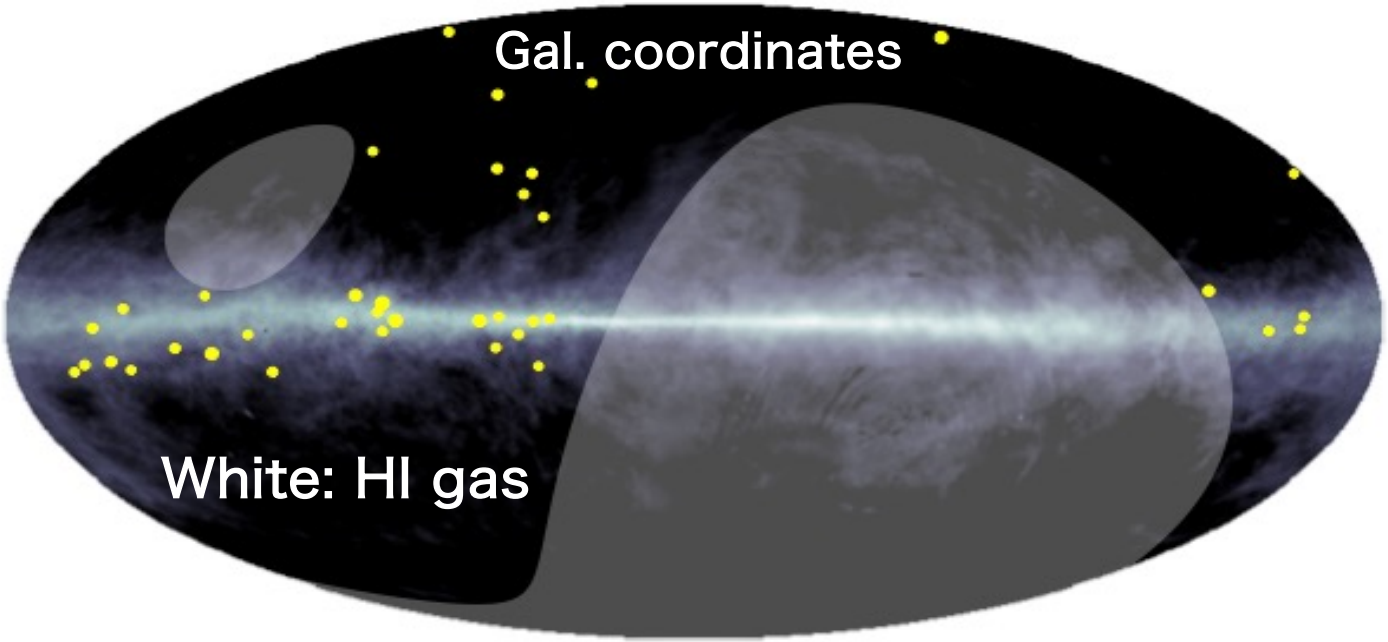


- ✓ The highest energy reaches 450 TeV
- ✓ The observed γ rays can be explained w/ leptonic emission (inverse Compton scattering off CMB by electrons)

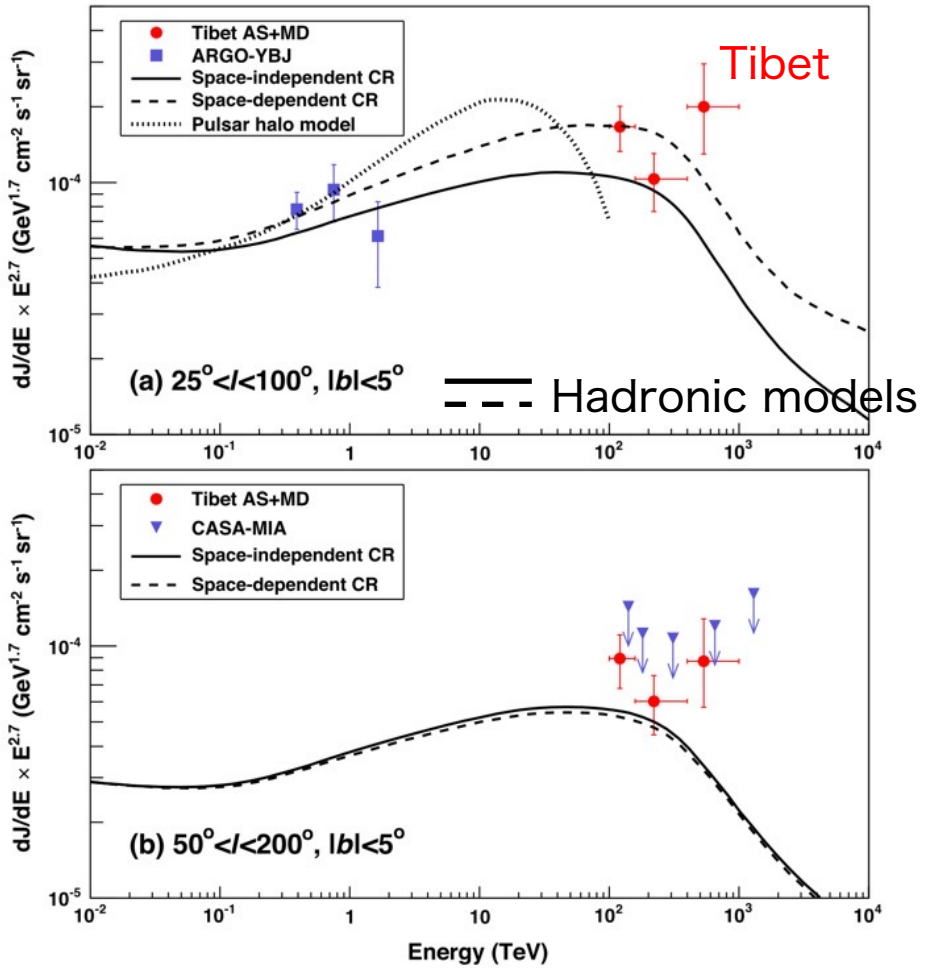
Detection of Sub-PeV Galactic Diffuse γ Rays up to 1 PeV

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

Distribution of γ-ray events w/ E > 400 TeV (Yellow)
5.9σ detection



Energy spectra in two sky regions



- ✓ Ubiquitous sub-PeV γ-ray emission from the Galactic disk
- ✓ These γ rays would be produced from CR-gas collisions[1, 2]

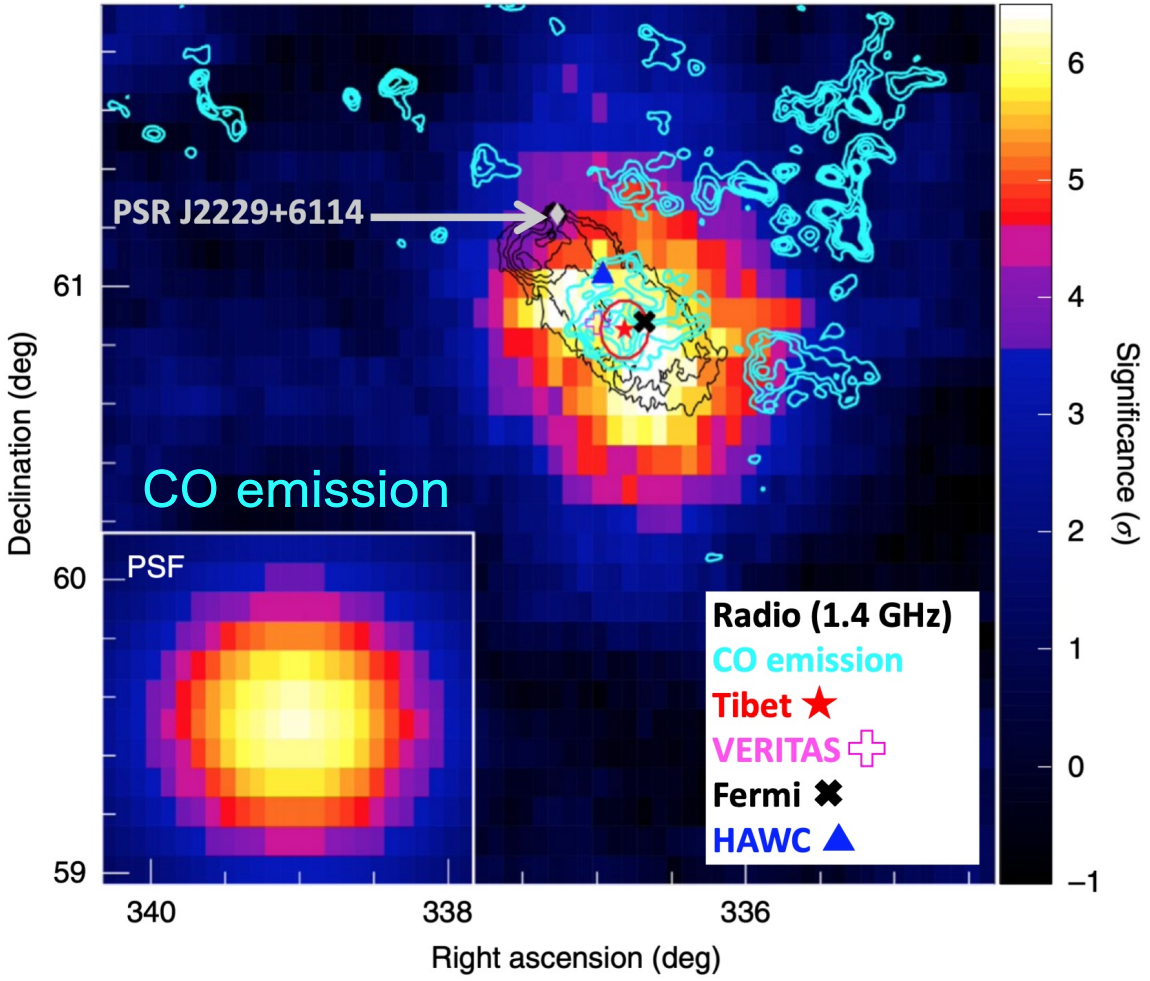
=> Strong support for the existence of PeVatron(s) in the Galaxy

1. Vernetto & Lipari, PRD (2018)
2. IceCube Collaboration, Science (2023)

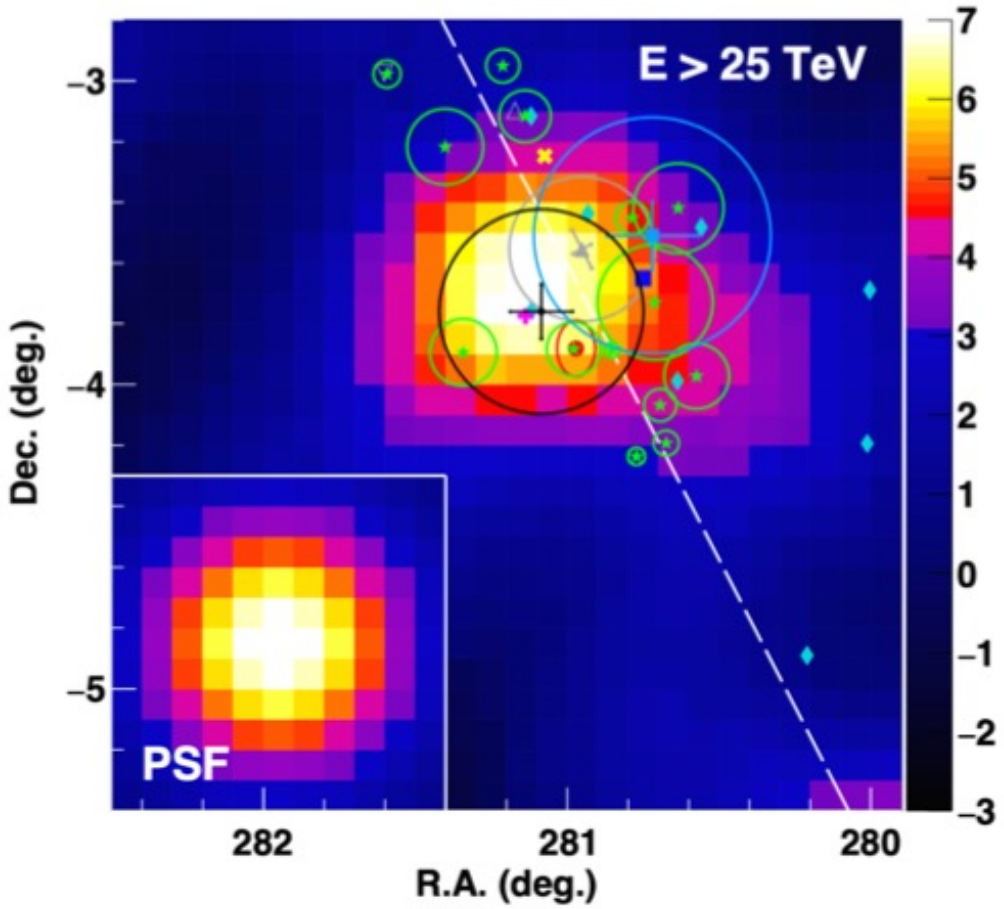
Detection of Gamma Rays from Individual Sources

Amenomori+, Nat. Astron. Lett (2021)
Amenomori+, PRL (2021)
Amenomori+, ApJ (2022)
Amenomori+ in prep.

SNR G106.3+2.7 (E >10 TeV)



HESS J1843-033 region (E > 25 TeV)



- ✓ γ rays from SNR G106.3+2.7, HESS J1843-033, Cygnus OB1 & Ob2 associations…
- ✓ Spectral analysis performed up to E > 100 TeV
- ✓ Some PeVatron candidates found (CR-proton acceleration up to E ~ 500 TeV??)

Short Summary

✓ Results of the Tibet AS + MD arrays：

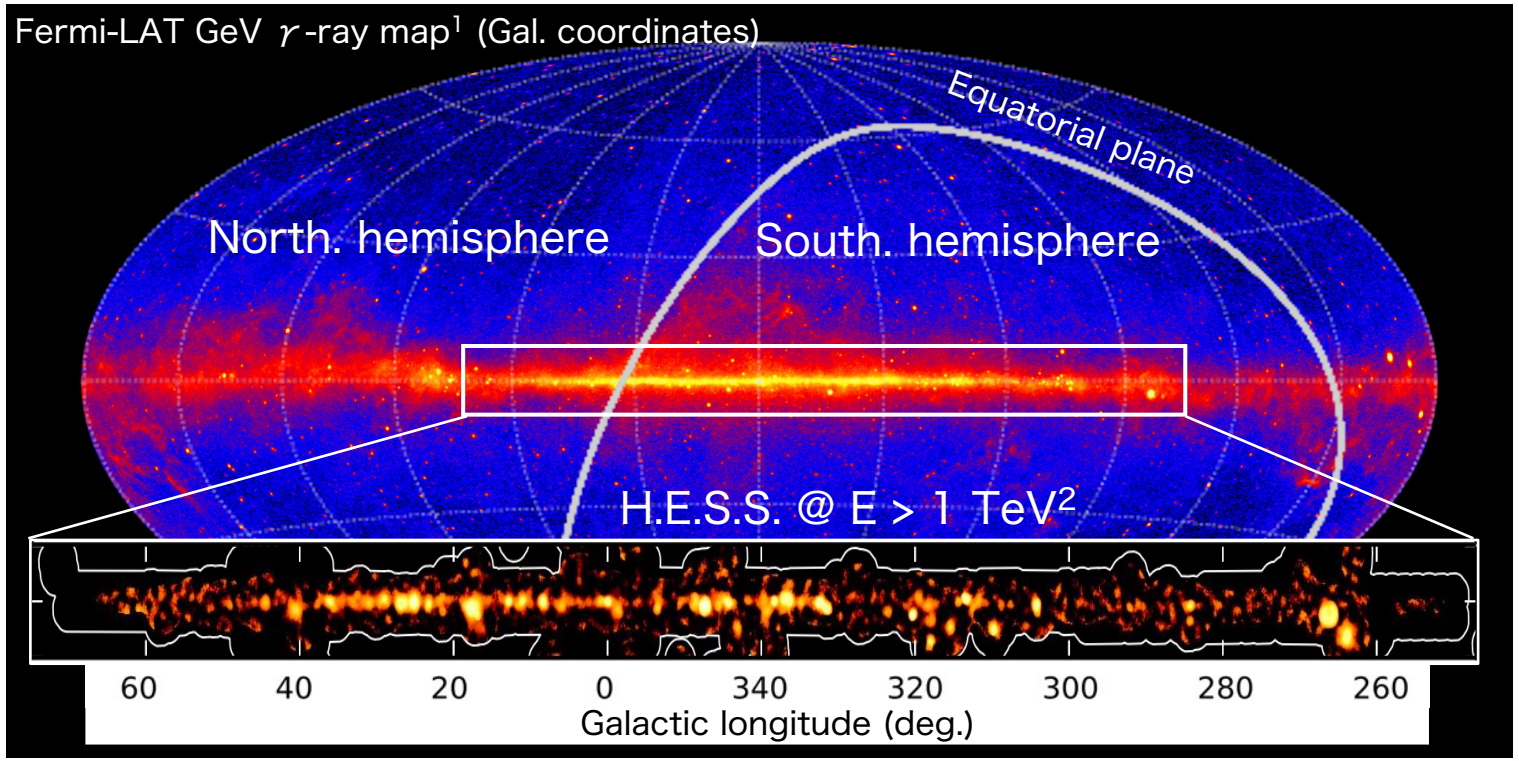
1. Sub-PeV γ rays from the Crab Nebula => 1st detection of sub-PeV γ rays
2. Galactic diffuse γ rays => Evidence for PeVatron(s) in the Galaxy
3. Observation of individual sources => some PeVatron candidates

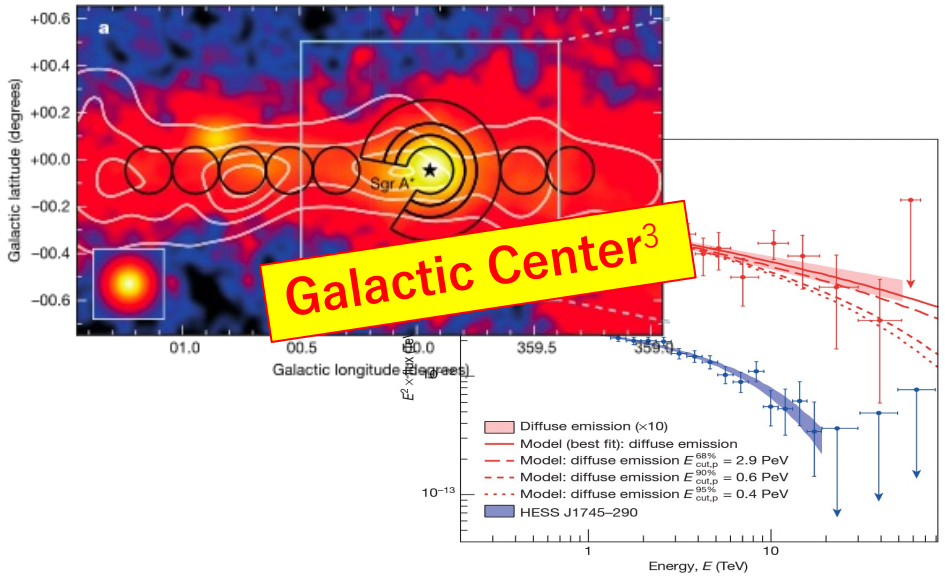
(e.g., SNR G106.3+2.7)

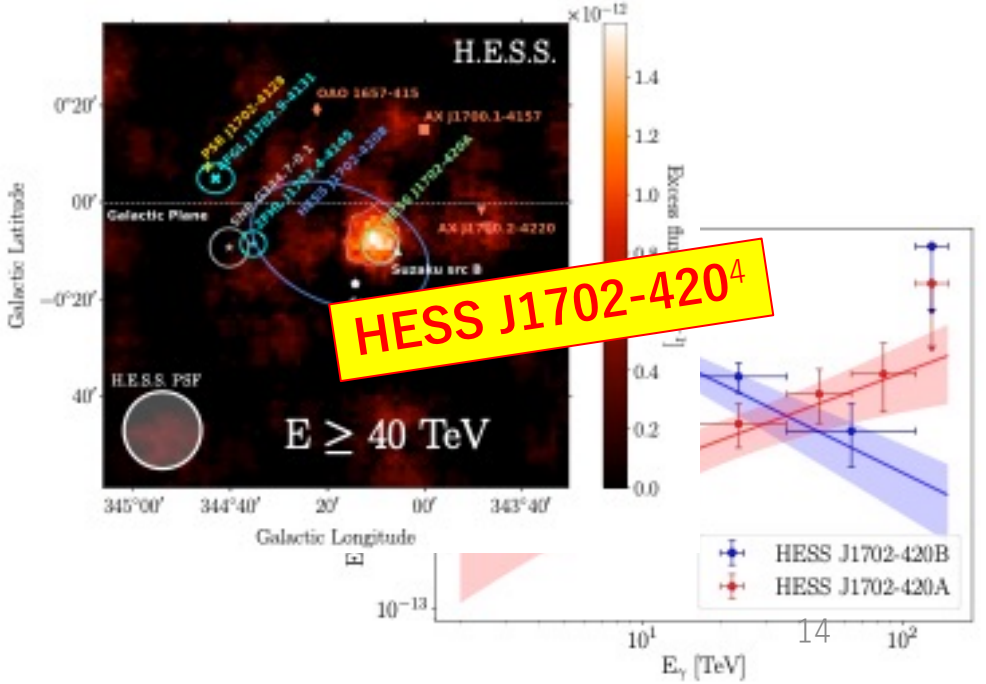
! Questions still to be resolved：

1. Where is a robust PeVatron??
2. What kind of source class represents PeVatrons?? (SNR? PWN? YMC?)

Go South!







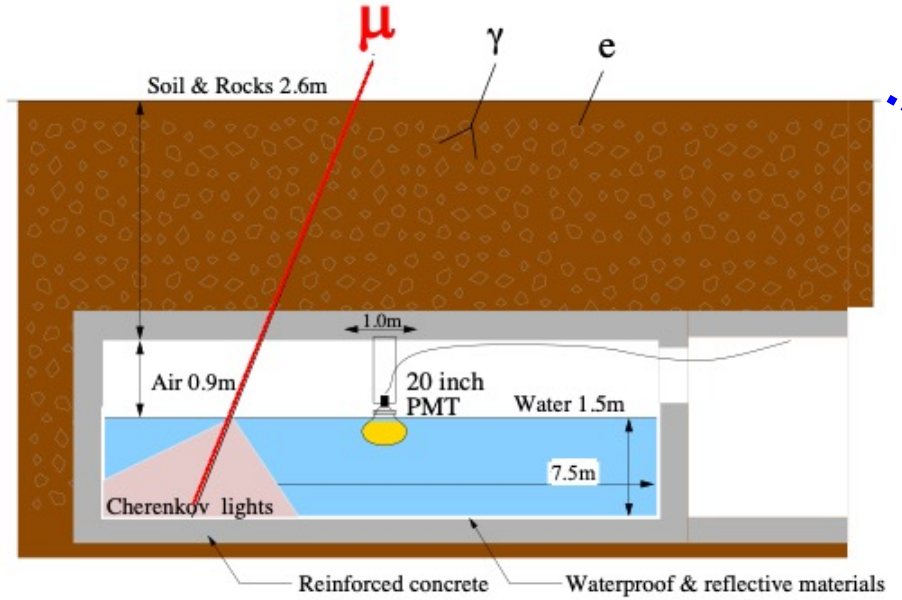
- ✓ ~ 80 sources detected in the TeV range by H.E.S.S.[1] (e.g., Gal. Center[3], HESS J1702-420[4], Westerlund1[5]...)
- ✓ Still to be explored in the sub-PeV range
- ✓ Robust identification of PeVatrons needed

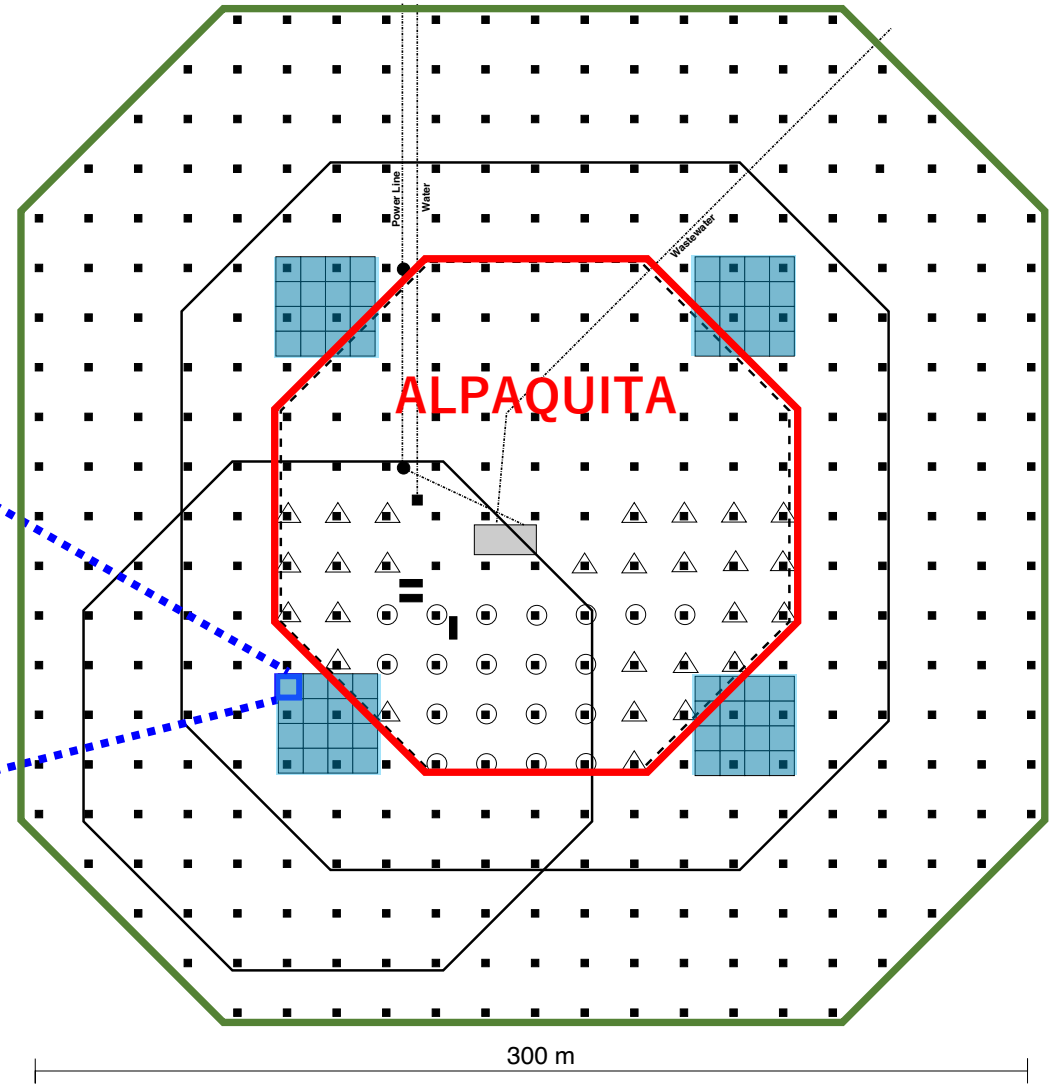
1. https://svs.gsfc.nasa.gov/14090
2. H.E.S.S. Collaboration, A&A 612, A1 (2018)
3. 〃, Nature 531, 476 (2016)
4. 〃, A&A 653, A152 (2021)
5. 〃, A&A 666, A124 (2022)

ALPACA Experiment (2024~)

- ✓ International collaboration b/w Bolivia, Mexico & Japan

1. Air Shower (AS) Array ~83,000m²
   = 401 x 1m² Scintillation Detector
2. MD array ~3600m² w/ 2.5m underground
   = 64 × 56m² MD cells

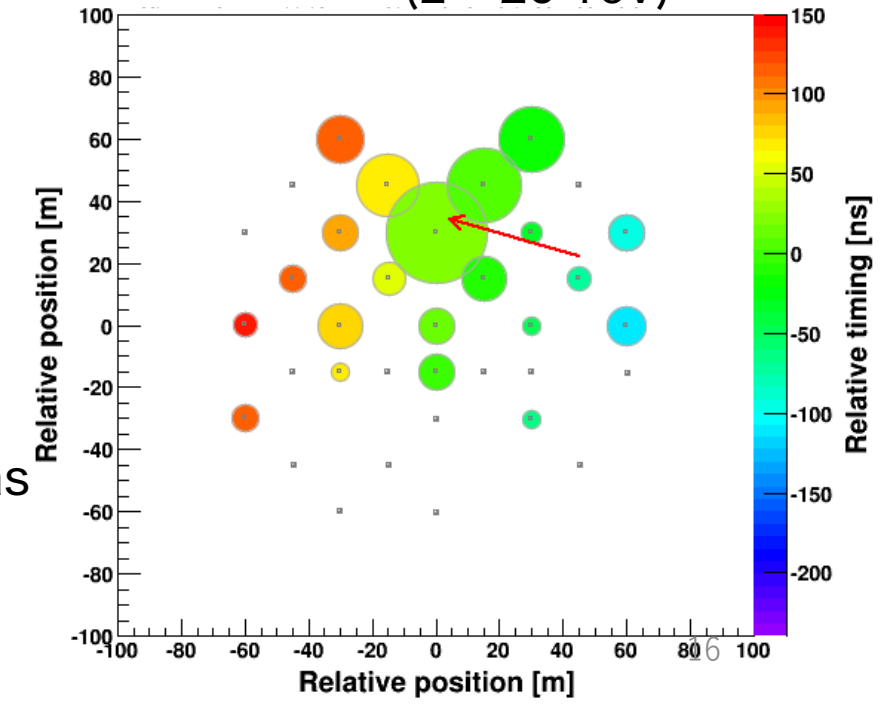




- ✓ Effective BGCR rejection (>99.9% @100TeV)
- ✓ Angular resolution ~0.2° @100TeV
- ✓ Energy resolution ~20% @100TeV

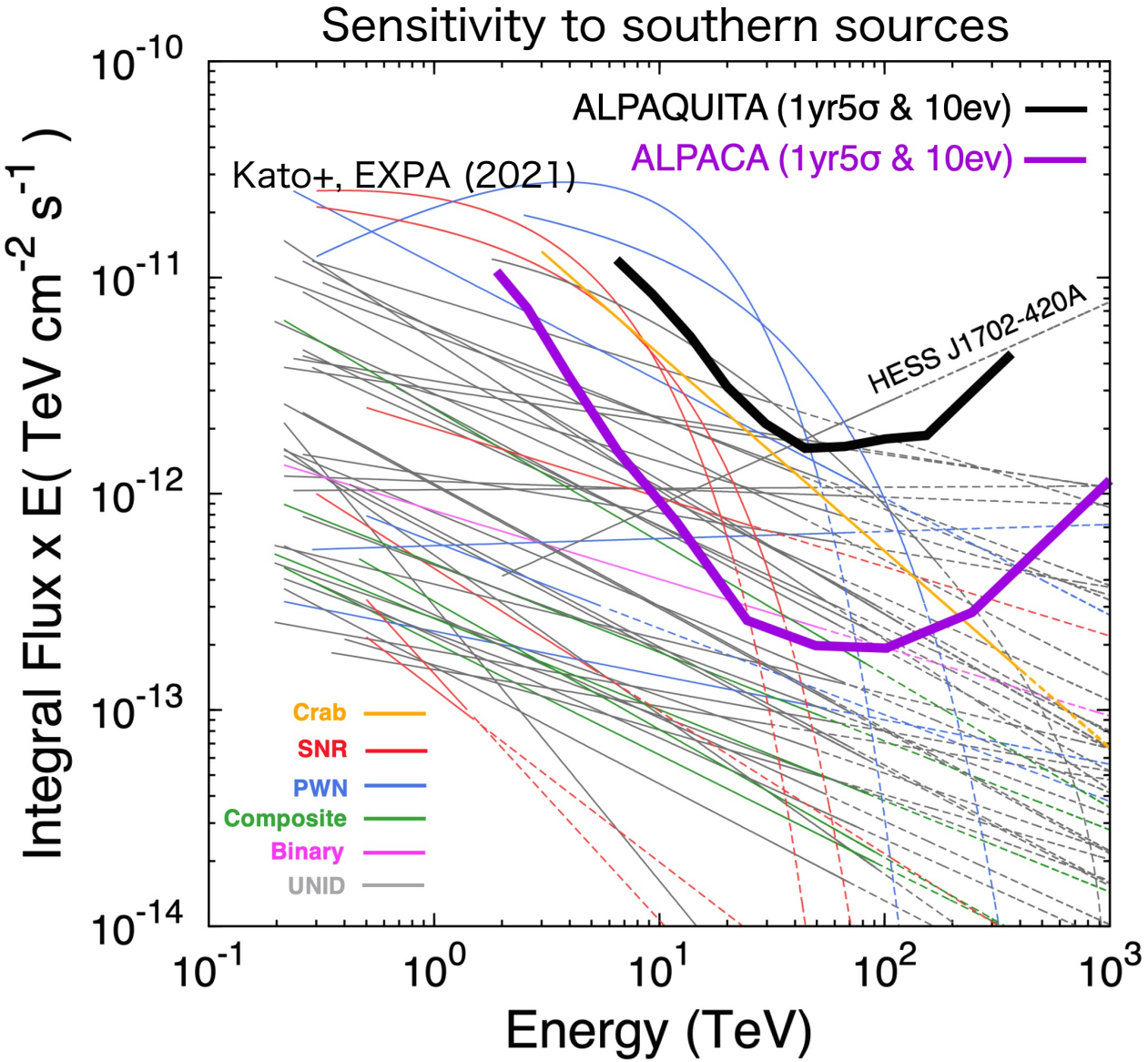
ALPAQUITA Air Shower Array

Event display of the 1st light
(E ~ 20 TeV)



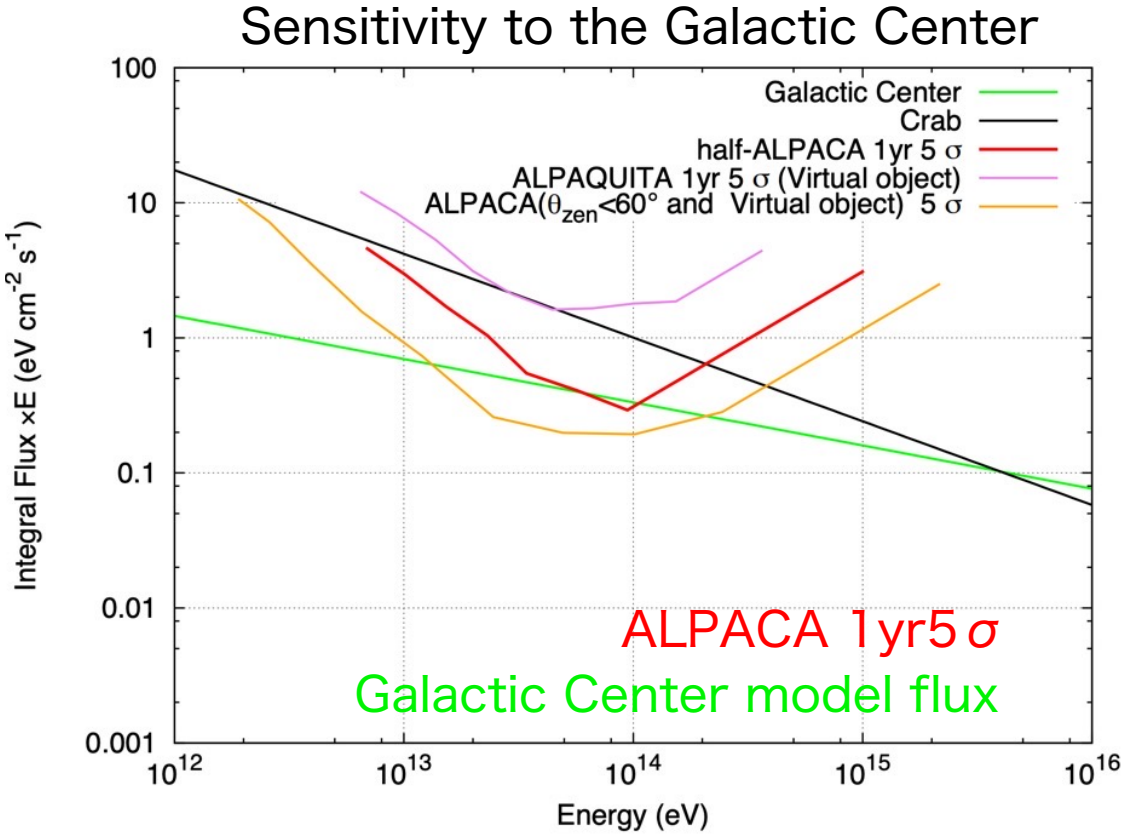
- ✓ AS trigger condition : Any 4 detectors with >0.7 ptcls w.i. 600ns
  → Trigger rate ~50Hz
- ✓ DAQ has started on September 2022
- ✓ A 900 m² MD to be constructed shortly

Simulation Study：Sensitivity to Gamma Rays Using MD



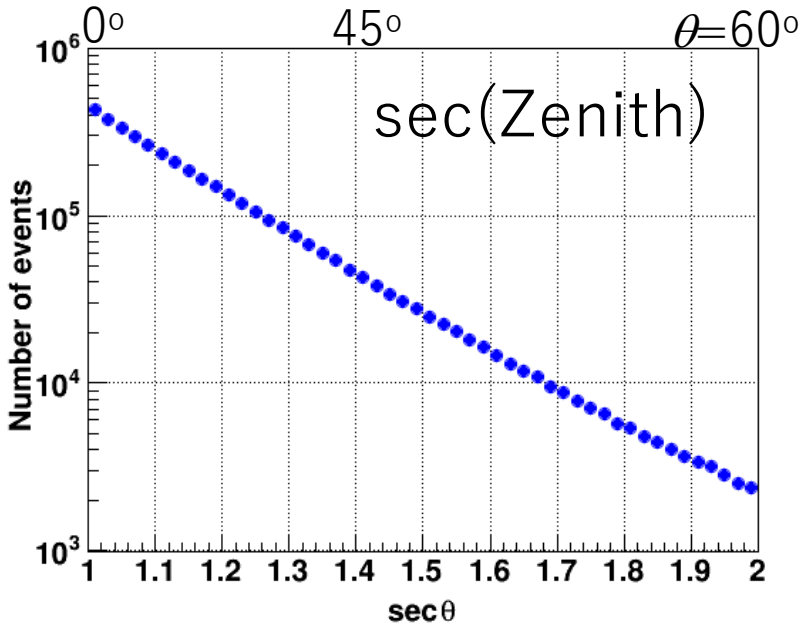
✓ Source detection (E > 100 TeV in one year)：

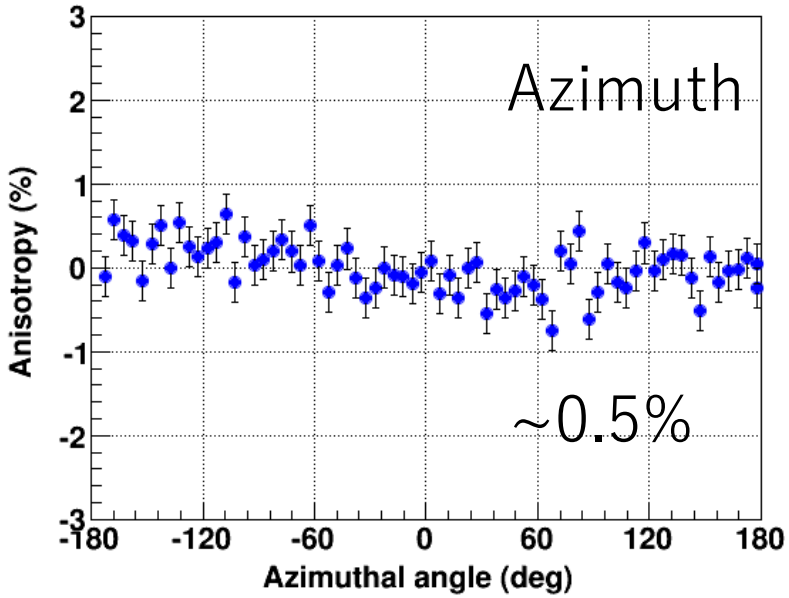
- ALPAQUITA w/ MD：~ 5 sources
- ALPACA：> 20 sources



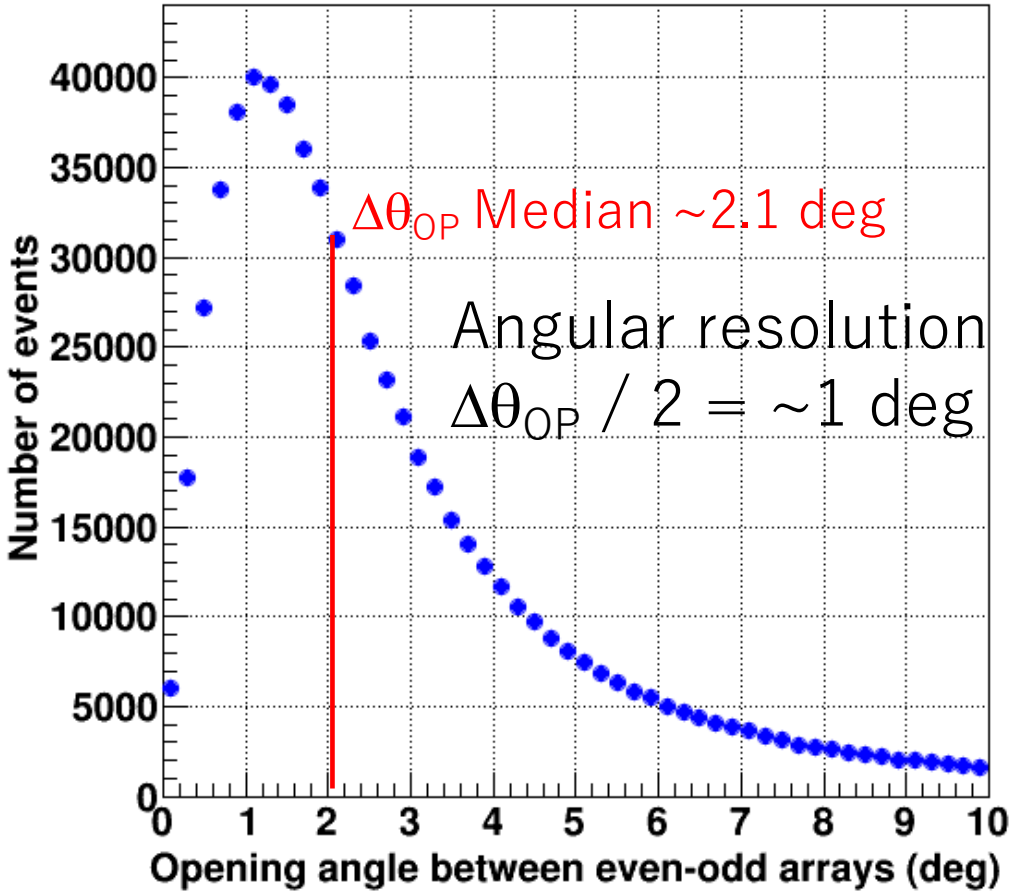
✓ Detect of sub-PeV gamma-rays in 1-yr obs.

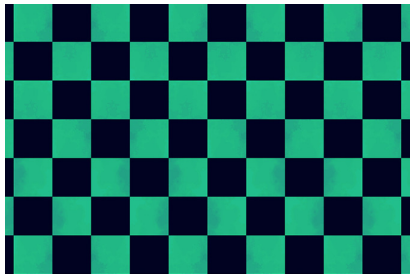
ALPAQUITA Event Distributions





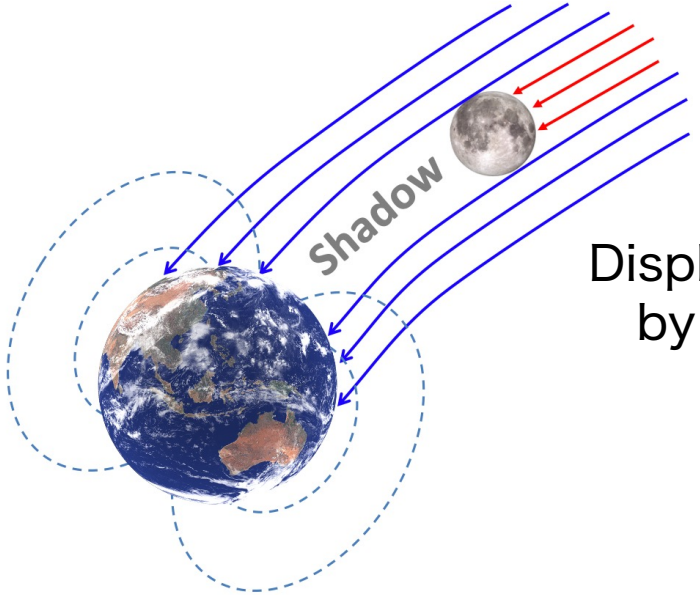
Even-Odd opening angle：
Opening angle between directions by two independent arrays (even and odd arrays)





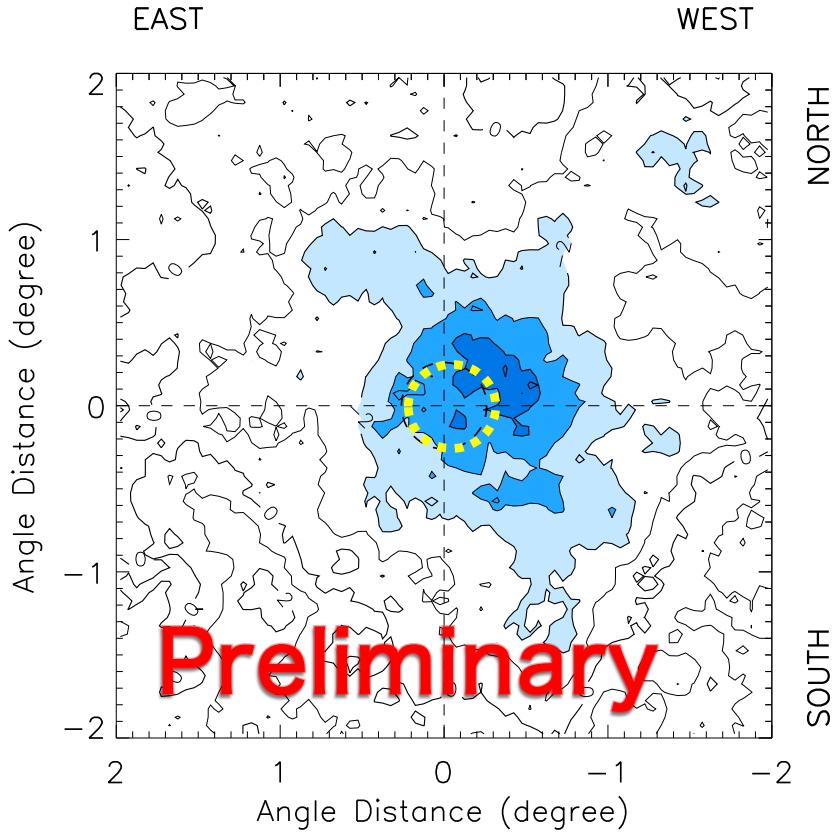
Moon Shadow Detection

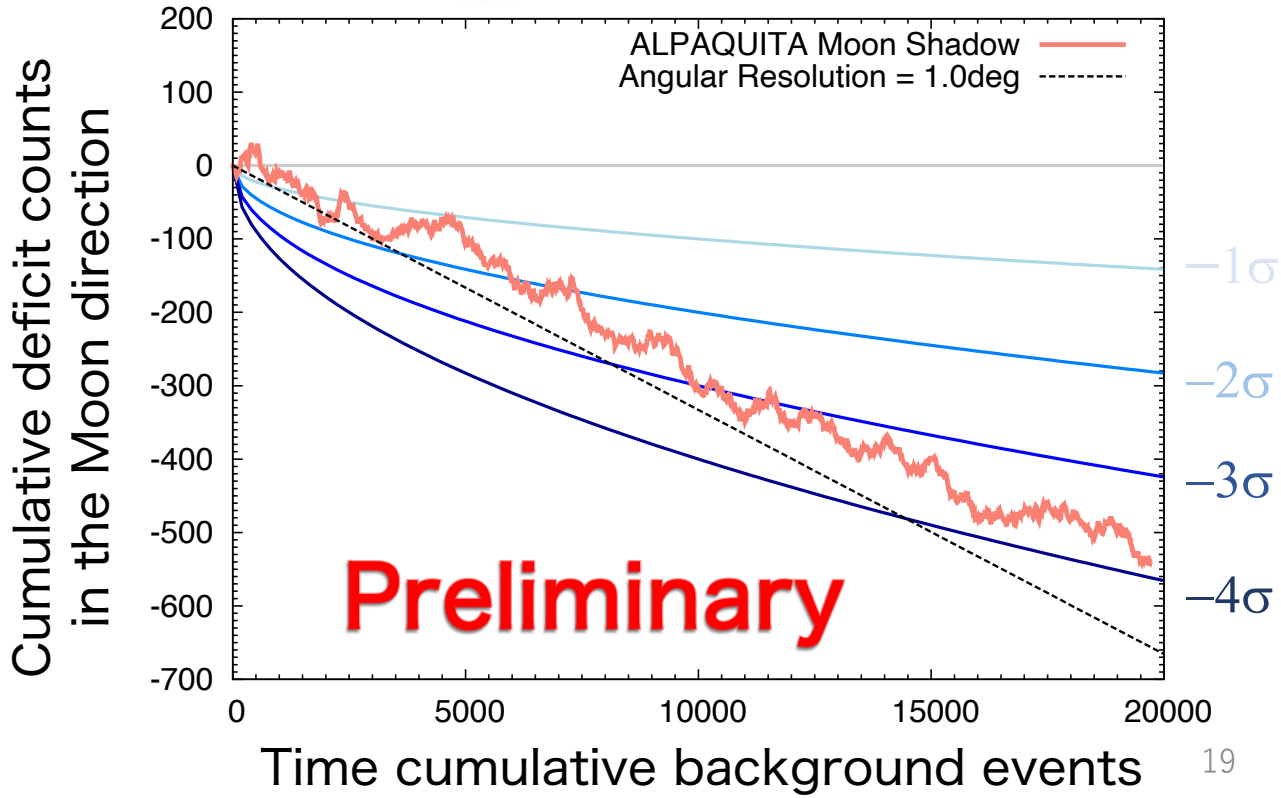
- ✓ Deficit in the CR events in the Moon direction
- ✓ We can check
  - Angular resolution (Shadow extension)
  - Pointing accuracy (N-S offset)
  - Absolute energy scale (E-W offset)



Displacement
by geomagnetic field

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





Summary

- ✓ Sub-PeV gamma-ray astronomy is developed in the northern hemisphere by the Tibet air shower array, HAWC & LHAASO
- ✓ Results of the Tibet AS + MD arrays :
  1. Sub-PeV γ rays from the Crab Nebula => 1st detection of sub-PeV γ rays
  2. Galactic diffuse γ rays => Evidence for PeVatron(s) in the Galaxy
  3. Observation of individual sources => Some PeVatron candidates (e.g., SNR G106.3+2.7)
- ✓ The next frontier, the southern sky, is explored by ALPACA (2024~) to make robust identification of PeVatrons
- ✓ Prototype ALPAQUITA is now in operation & obtained data are under analysis
- ✓ Stay tuned for the newest results of the data analysis in ICRC2023

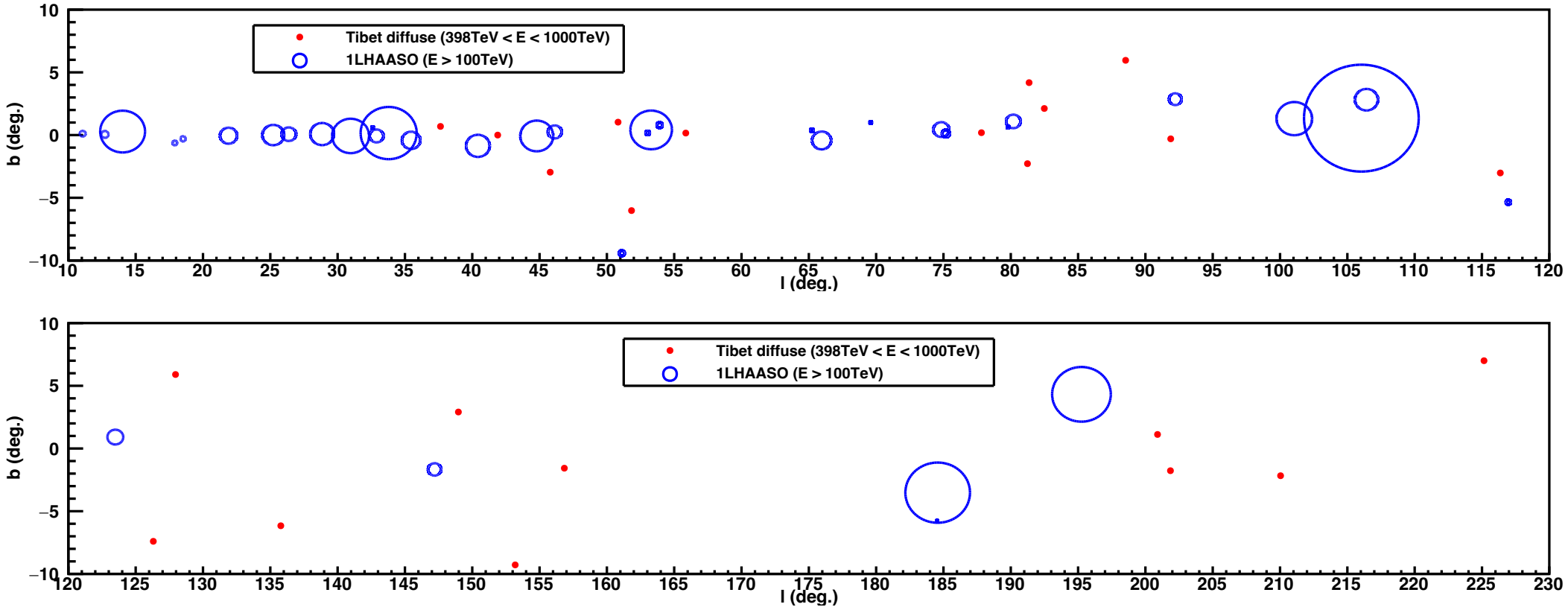
Backup slides

Tibet Galactic Diffuse Gamma Rays & LHAASO UHE Sources

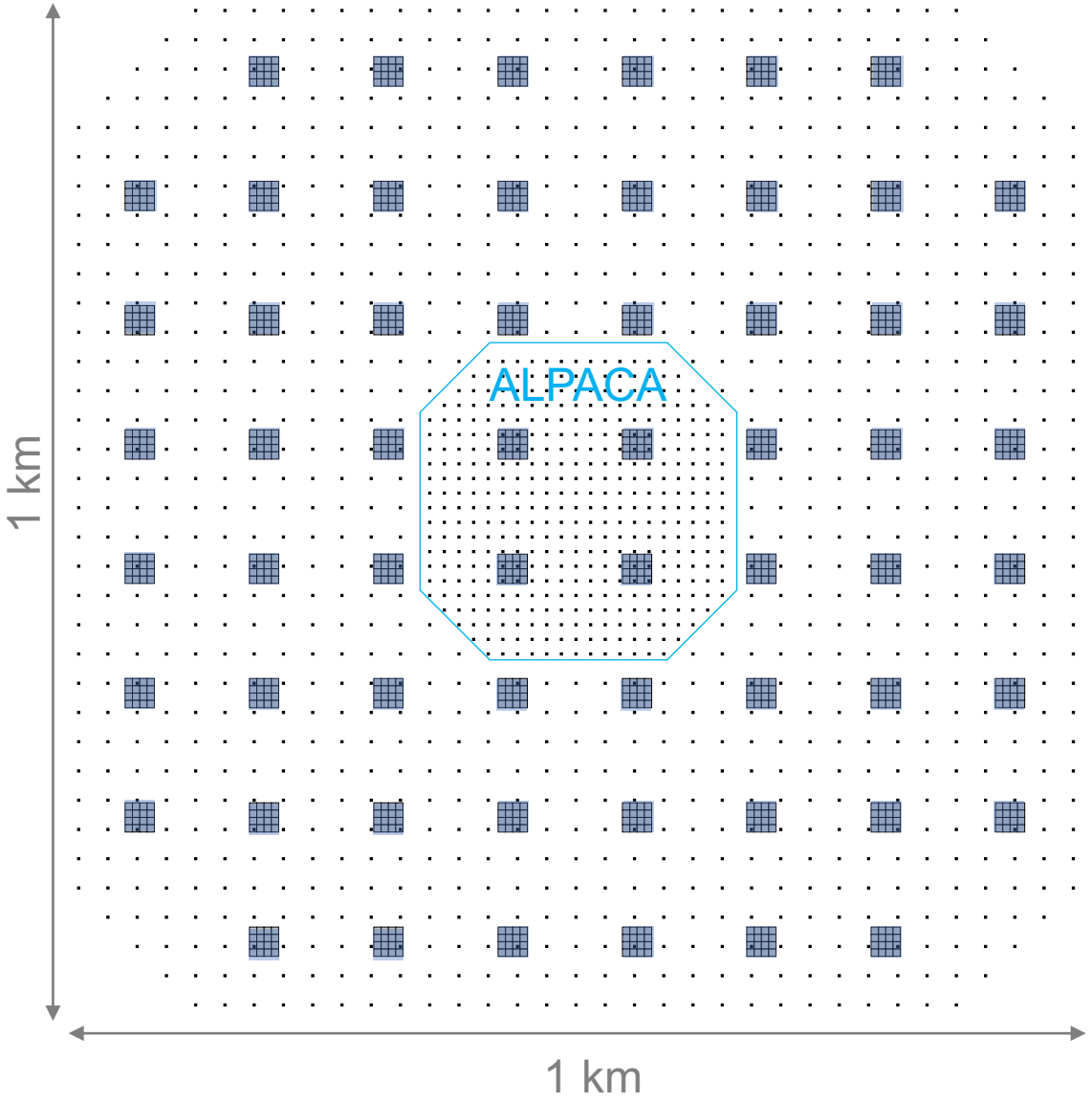
1. arXiv:2305.17030v1

- ✓ LHAASO has claimed detection of 43 UHE g-ray sources @ E > 100 TeV (>4 σ)[1]
- ✓ No Tibet diffuse events w/ E > 398 TeV comes from the LHAASO sources

Tibet diffuse (E > 398 TeV, |b| < 10 deg.) : 23 events to reconstruct energy spectra
LHAASO source extension (E > 100 TeV) : Gaussian radius containing 95% of g rays



Mega ALPACA



1 km^2 AS + MD array

30 m spacing AS array

Area 1,011,600 m^2

# of det. 1185

15 m spacing AS array

Area 82,800 m^2

# of det. 313

(Additional to 15 m spacing)

# of total det. 1185 + 313 = 1498

Muon Detector (MD) Array

900 m^2 (16 Cells) x 60

= 54,000 m^2

# of cells 960

Mega ALPACA sensitivity