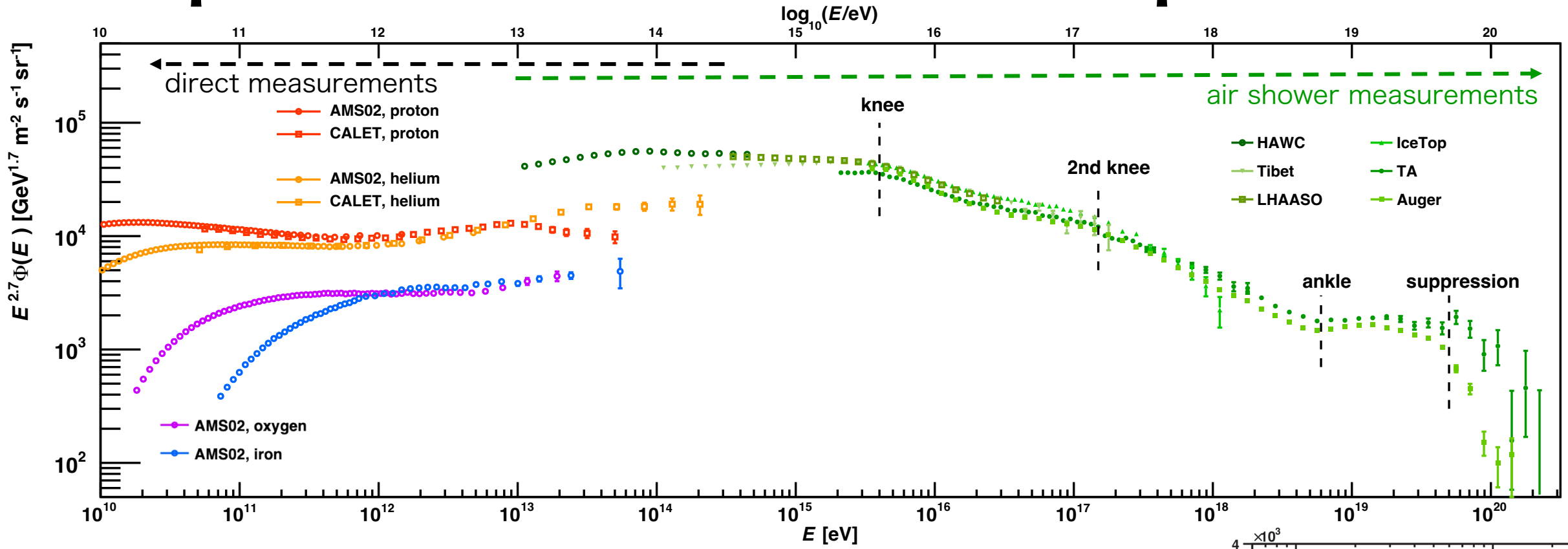
Tibet/ALPACAによるガンマ線天文学

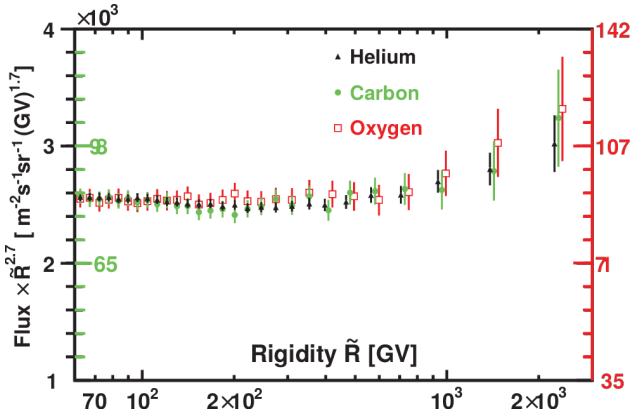
Keitaro Fujita(ICRR, Tibet/ALPACA group)

高エネルギー現象で探る宇宙の多様性Ⅳ

CR Spectrum and mass composition



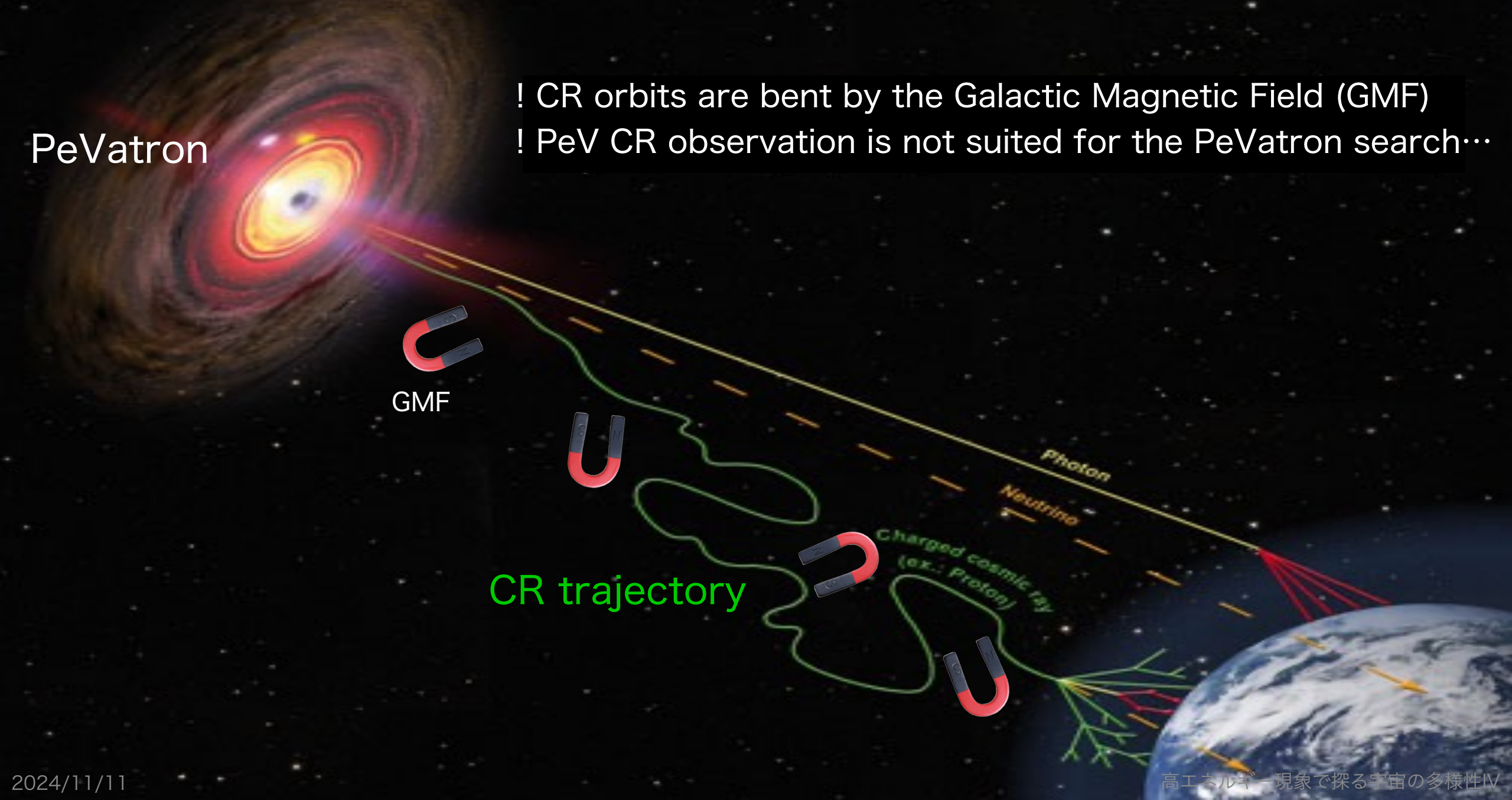
- cosmic ray energy spectra (multiply $E^{2.7}$) up to 10^{20} eV
  - Rigidity (momentum/charge) dependent structure in low energy
  - lots of break points (knee, 2nd knee, ankle, suppression)
    - knee ~ max. energy of proton? by PeVatron?
    - $E_{\mathrm{knee}} \times 25 \sim E_{\mathrm{2nd\ knee}}$ (charge dependence??)



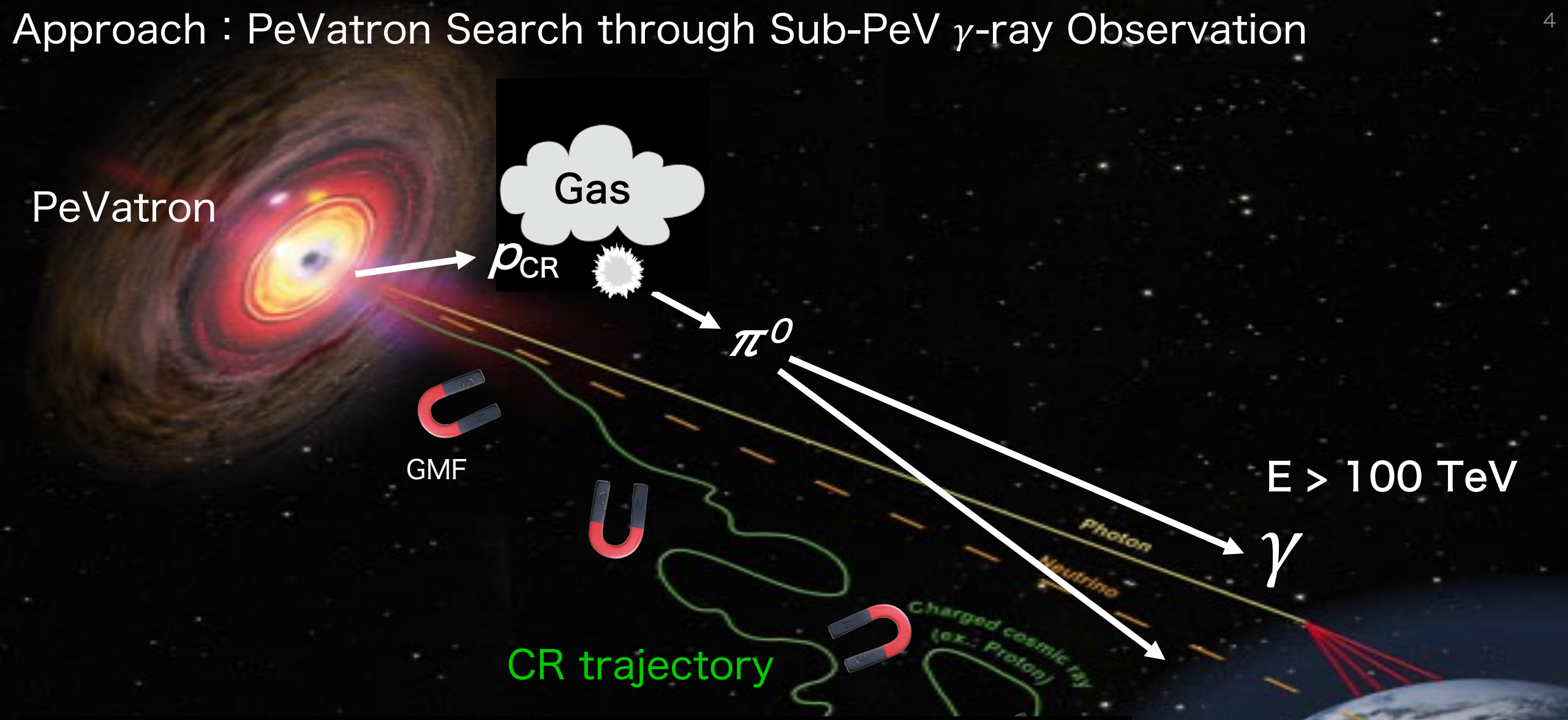
Phys. Rev. Lett. 119, 251101 (2017)

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…

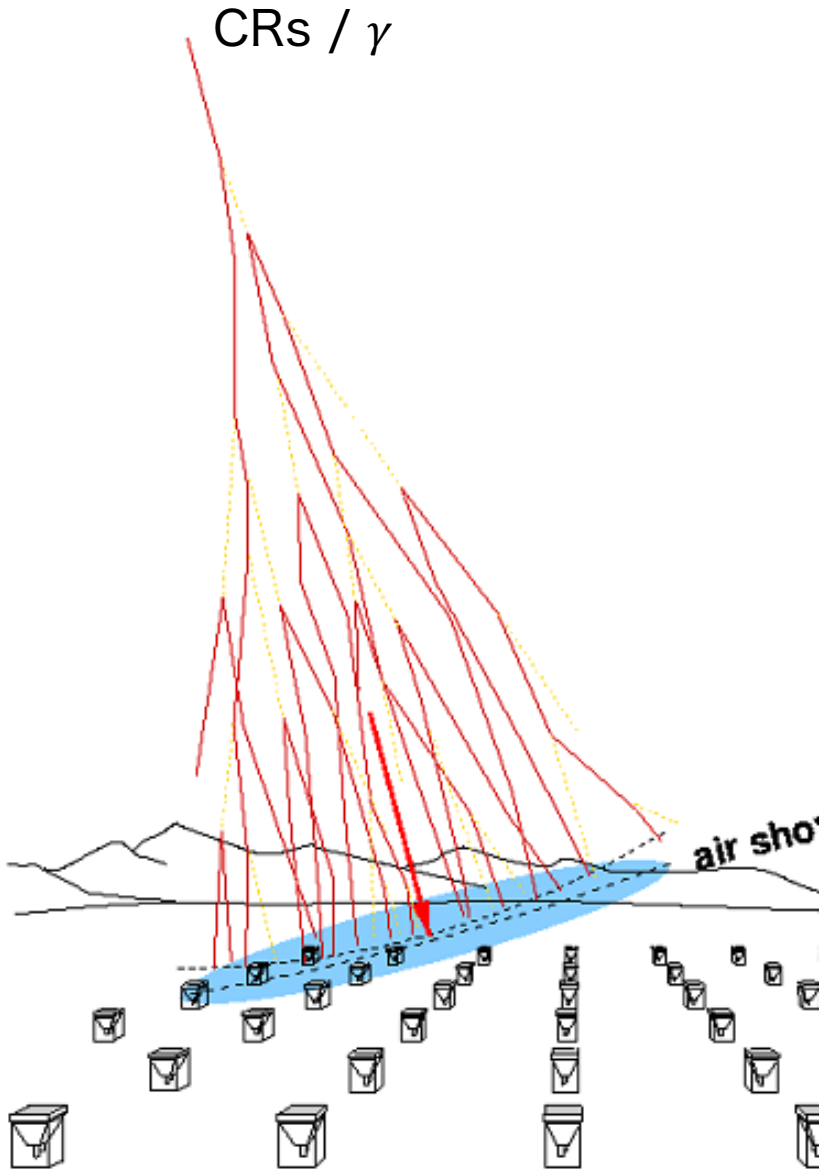


Approach : PeVatron Search through Sub-PeV γ-ray Observation



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

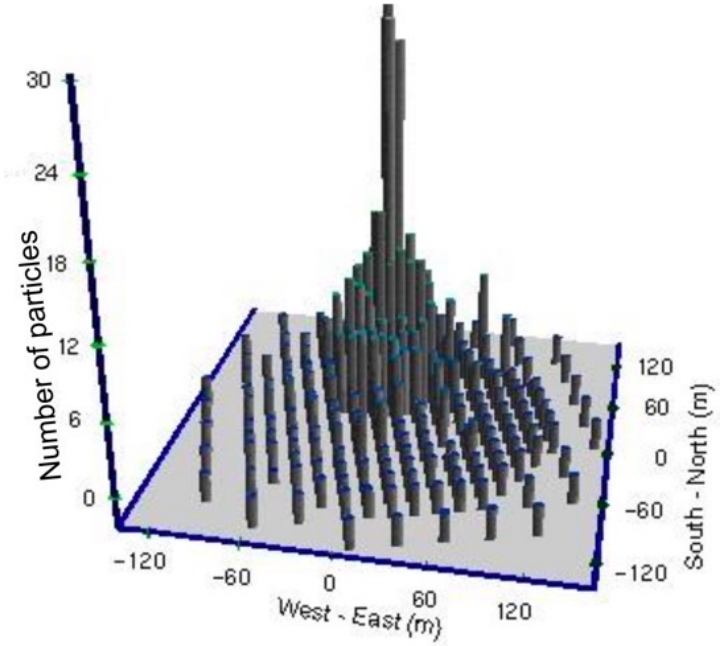
Extensive Air Shower Array



2nd particle density

↓

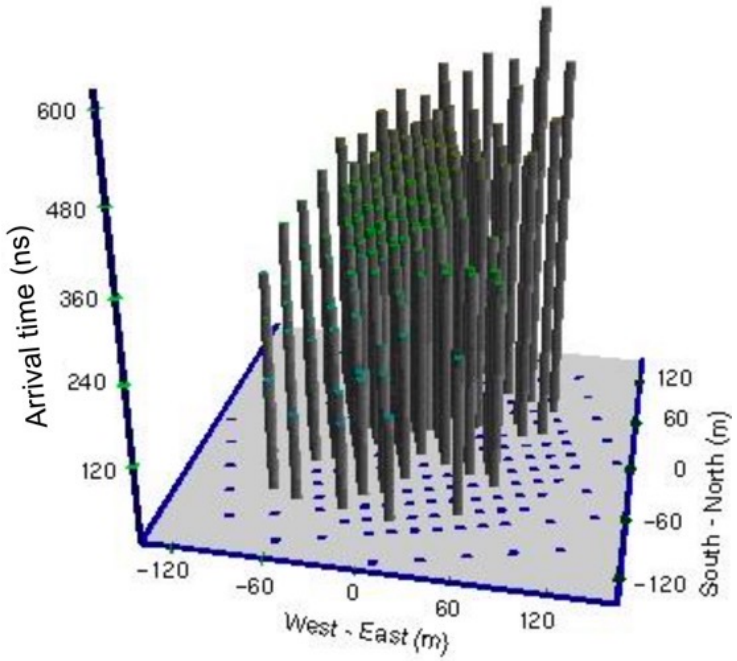
γ-ray energy



2nd particle timing

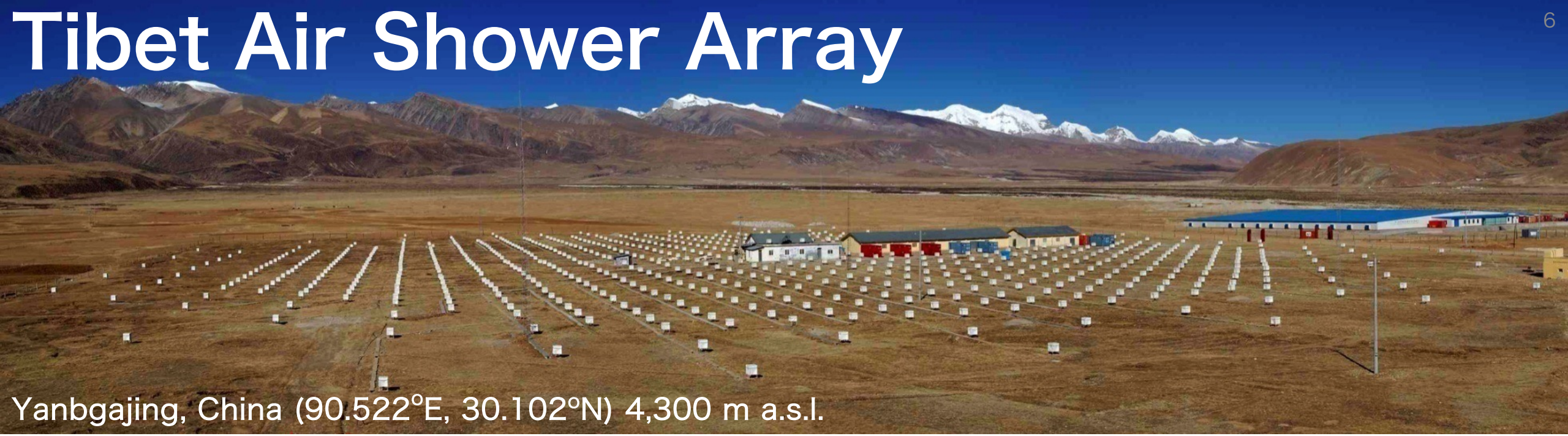
↓

γ-ray direction

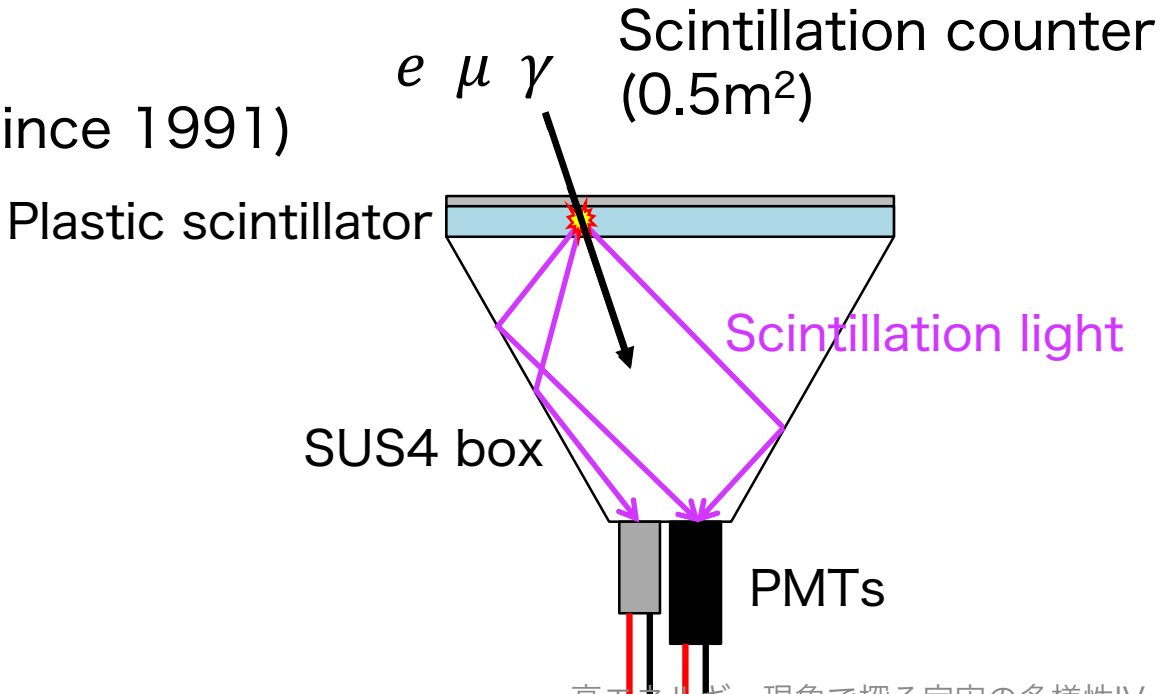


- ✓ Sampling AS ptcls w/ surface detectors
  => Energy & direction reconstruction
- ✓ Wide F.O.V. => New-source search
- ✓ Large detection area (~10^4 m^2) & High duty cycle
  => Statistical improvement

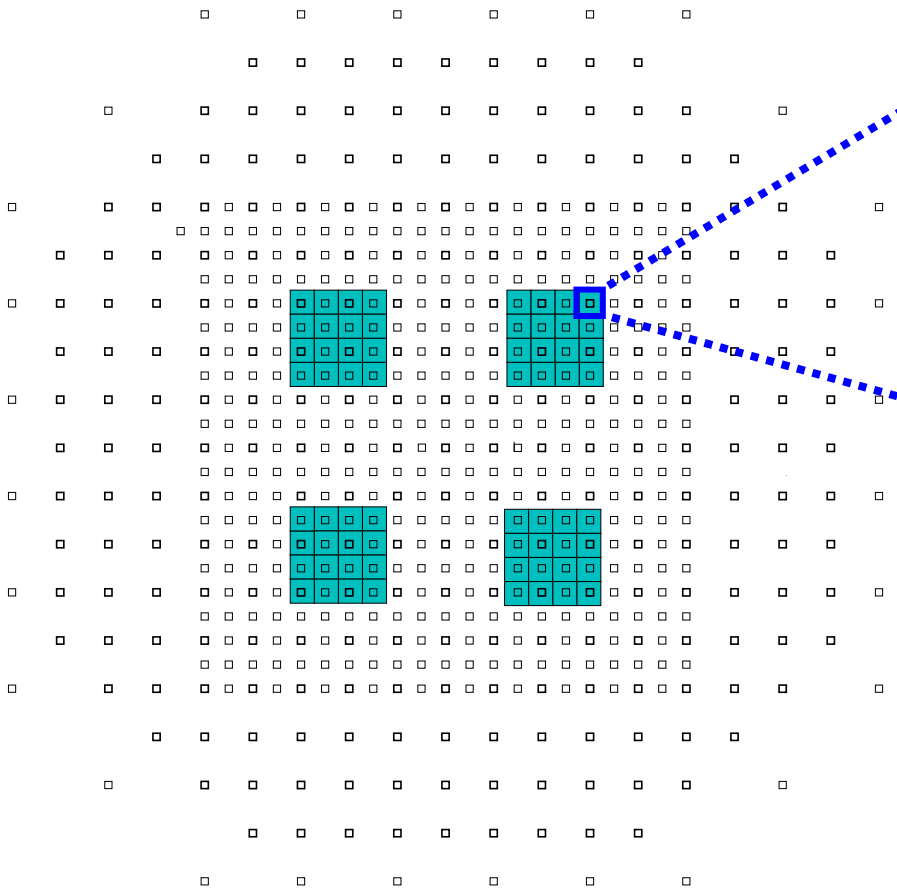
Tibet Air Shower Array



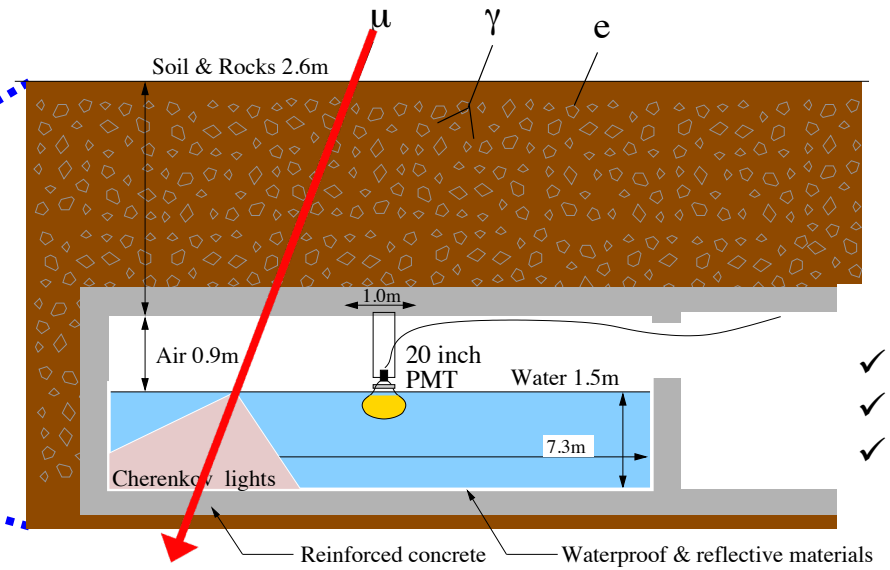
- ✓ International collaboration b/w China & Japan (since 1991)
- ✓ <u>Air Shower (AS) Array 65,700 m²</u>
  = 597 x 0.5m² scintillation counter
- ✓ Angular resolution : ~0.2° @ 100TeV γ
- ✓ Energy resolution : ~20% @ 100TeV γ



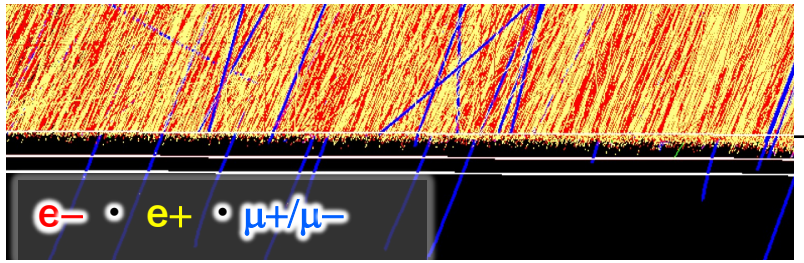
Underground Muon Detector Array (MD Array)



MD : 3400m²

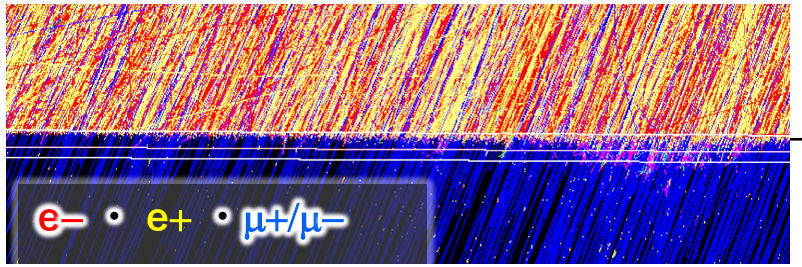


- ✓ Concrete pool
- ✓ 1.5m-depth water layer
- ✓ A 20-inch PMT suspended



200TeV γ shower

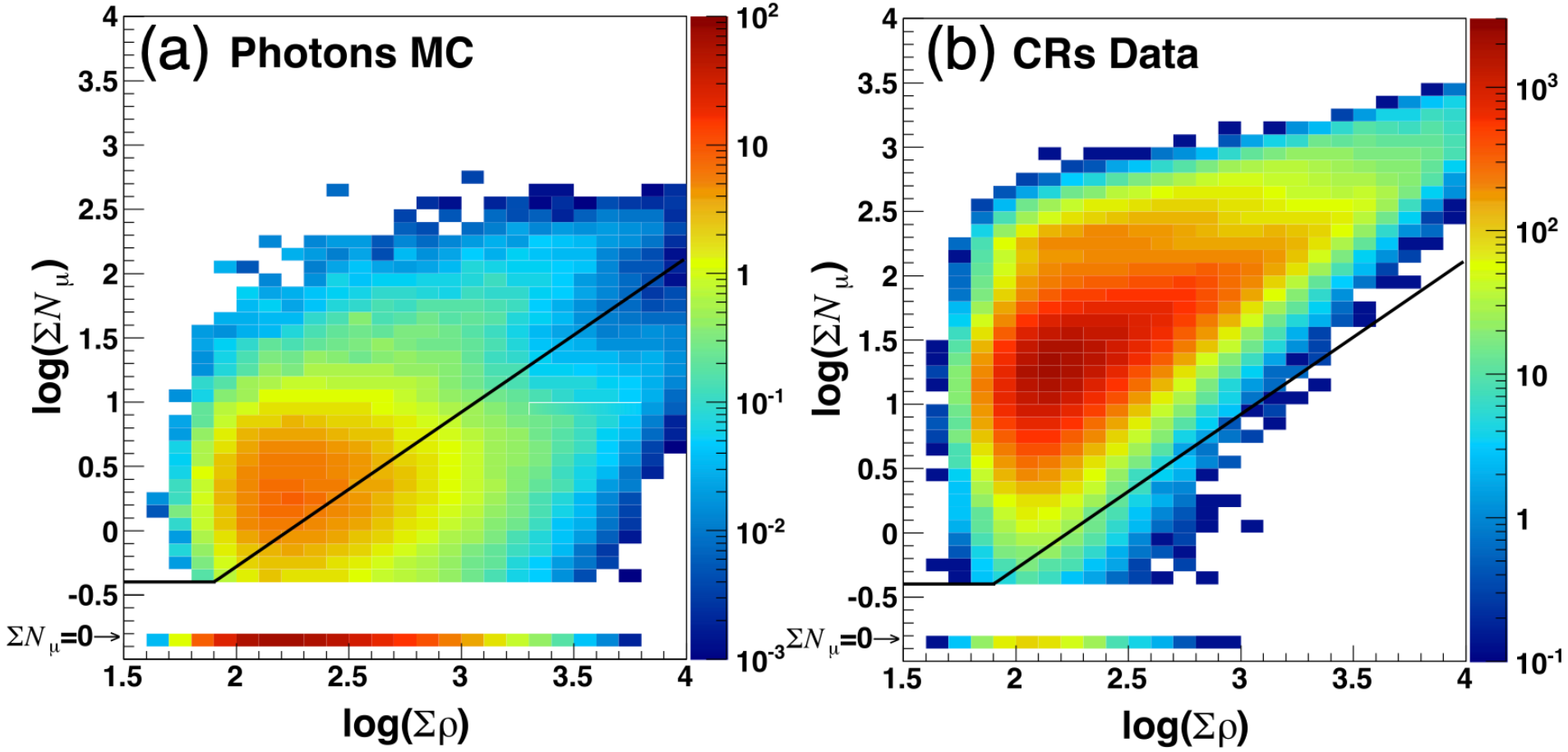
Few muons (~1 μ)



200TeV CR shower

Many muons (~100 μ)

γ-ray selection

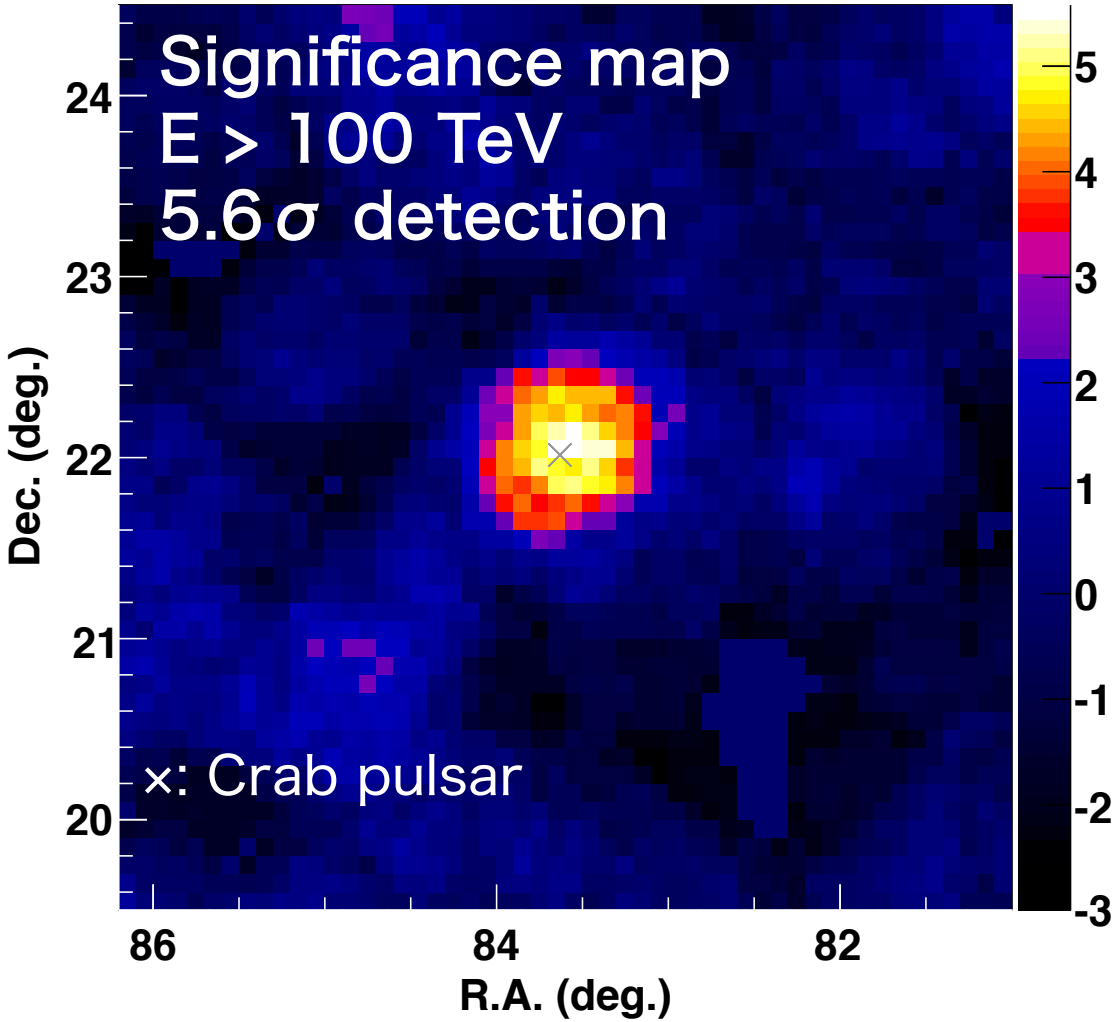


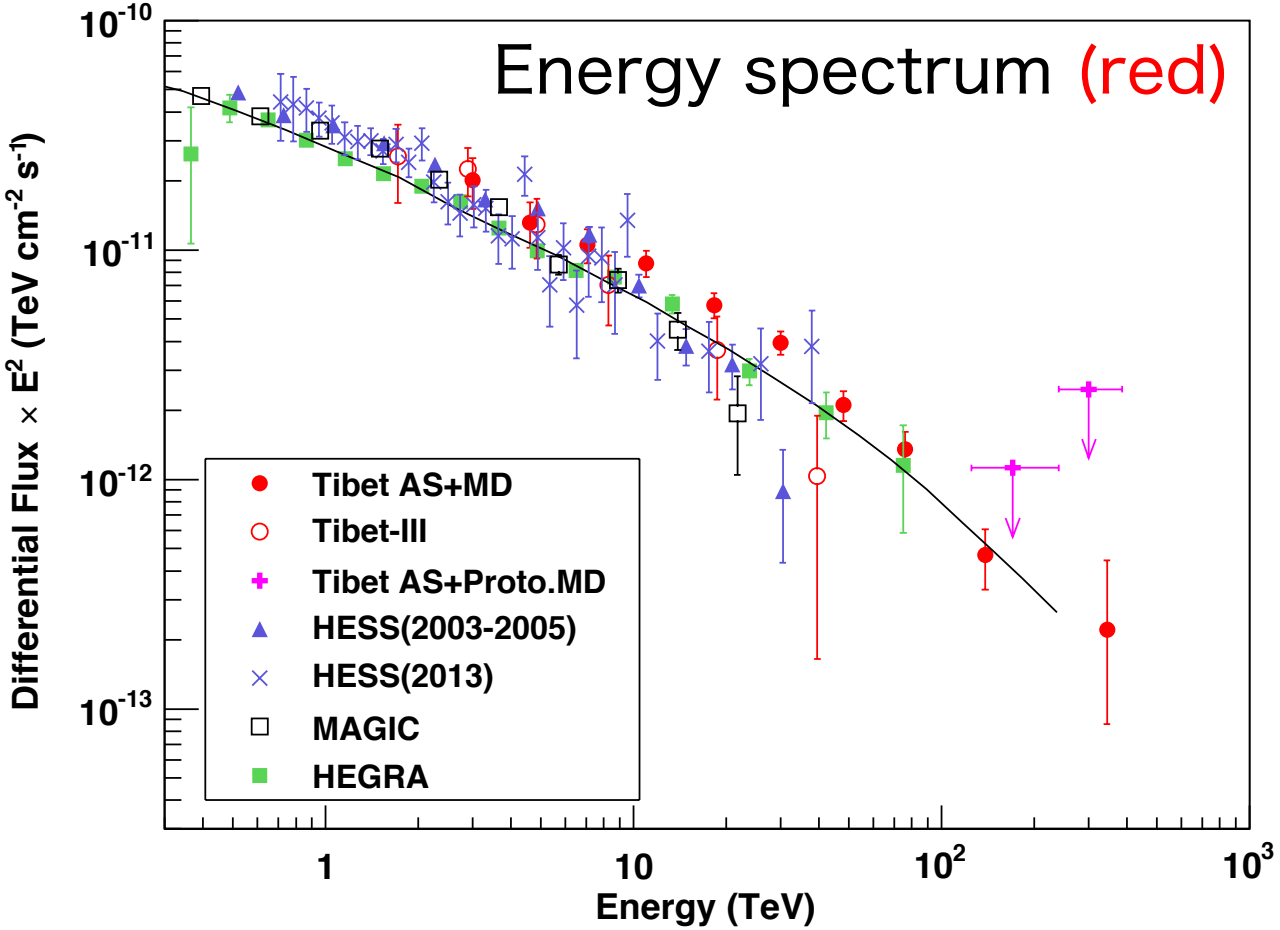
- number of muon ($\sum N_\mu$) measured by MD array as a function of sum of particle density ($\sum \rho$) measured by AS array

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

First Detection of Sub-PeV γ-ray from Crab Nebula

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



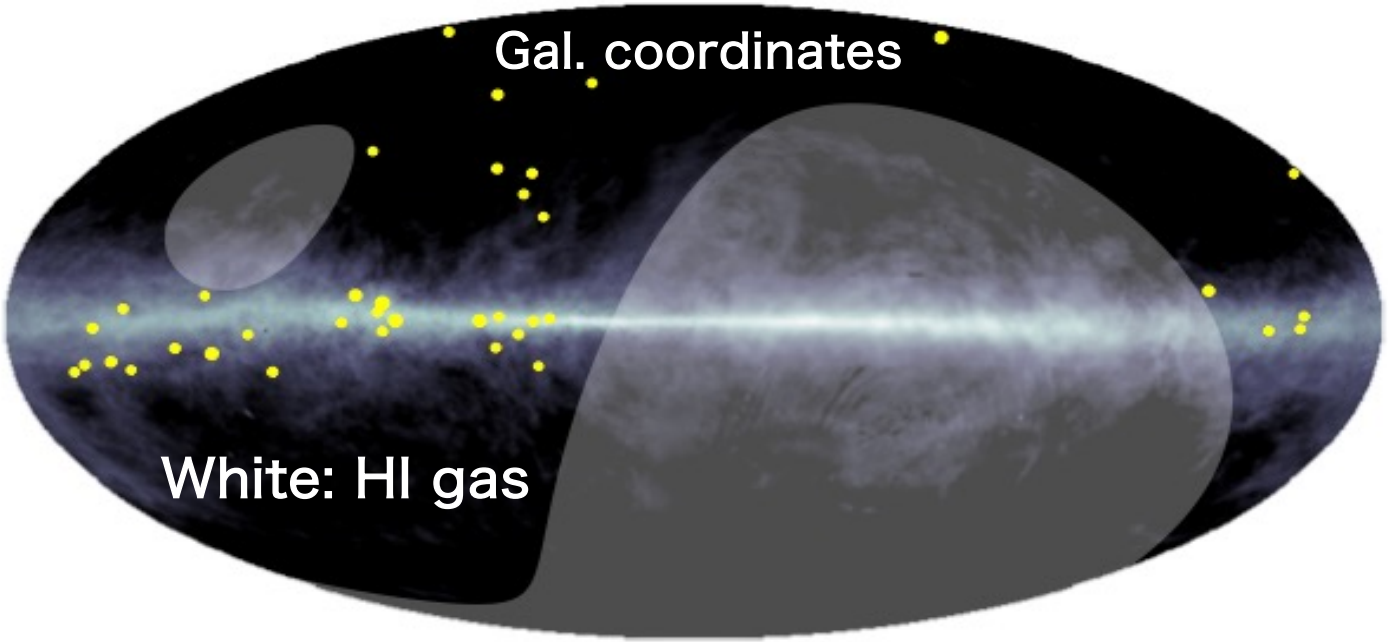


- ✓ The highest energy reaches 450 TeV
- ✓ The observed γ-rays can be explained w/ leptonic emission (inverse Compton scattering off CMB by electrons)

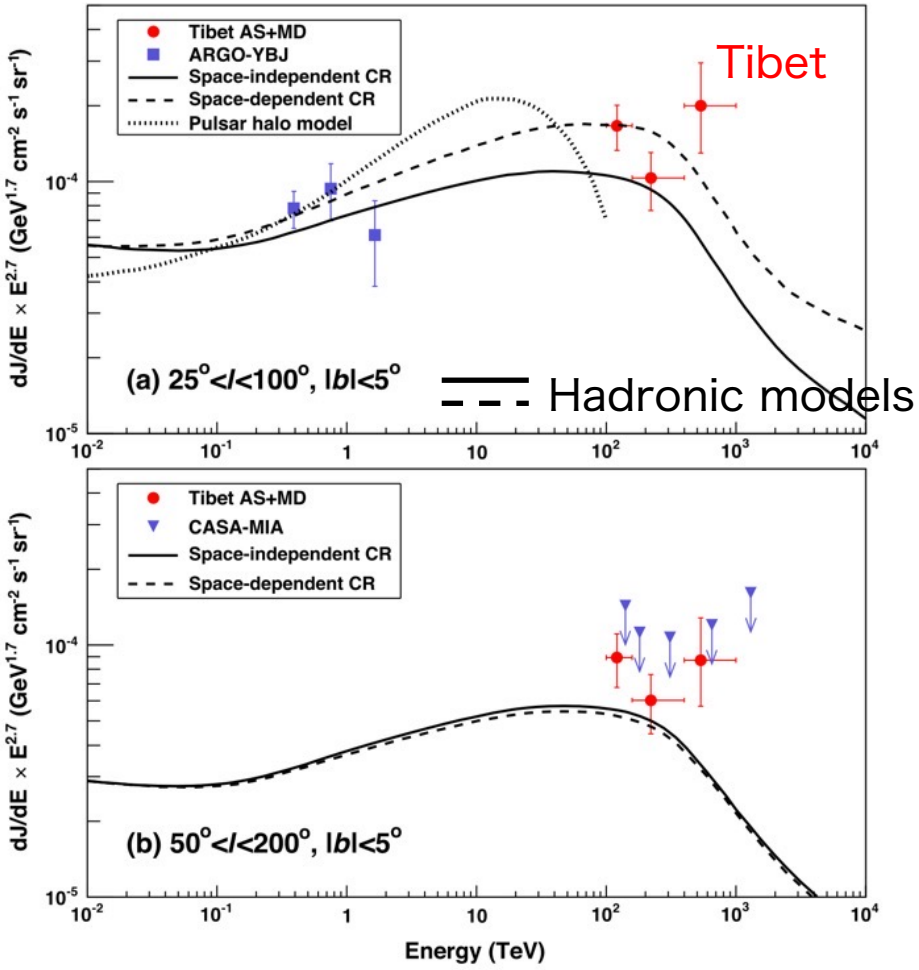
Detection of Sub-PeV Galactic diffuse γ-rays up to 1PeV

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

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



Energy spectra in two sky regions



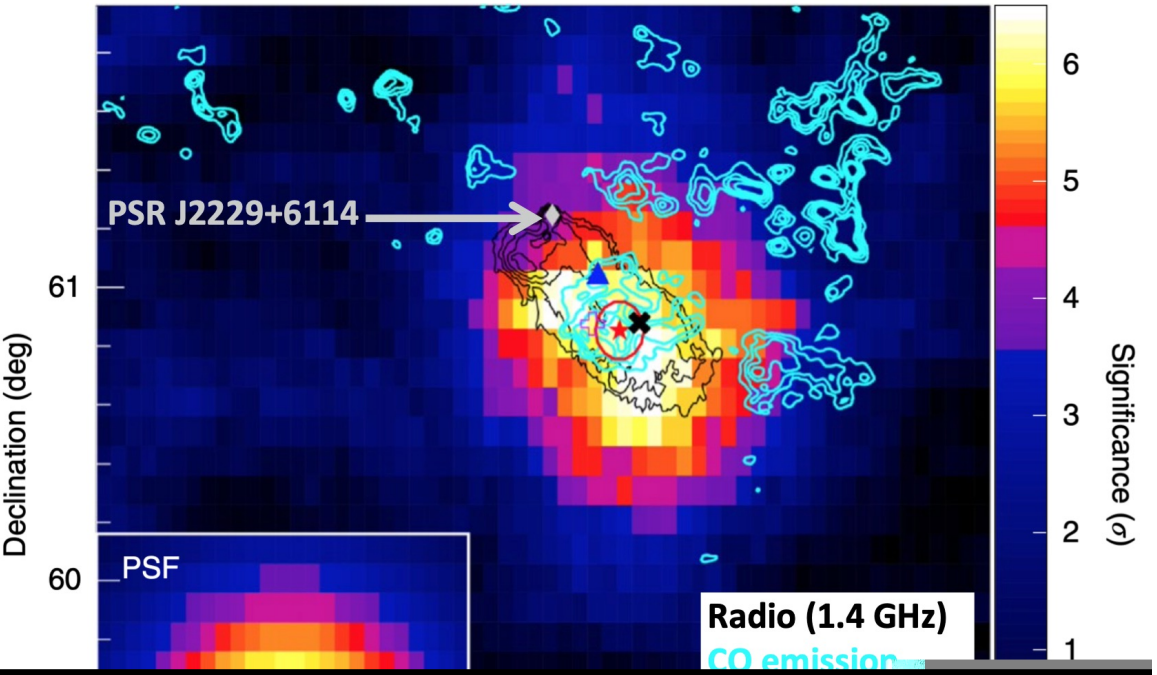
- ✓ Sub-PeV γ-ray emission from the Galactic disk
- ✓ These γ-rays would be produced from CR-gas collisions

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

PeVatron candidate

※Fang+, PRL 129, 071101 (2022)

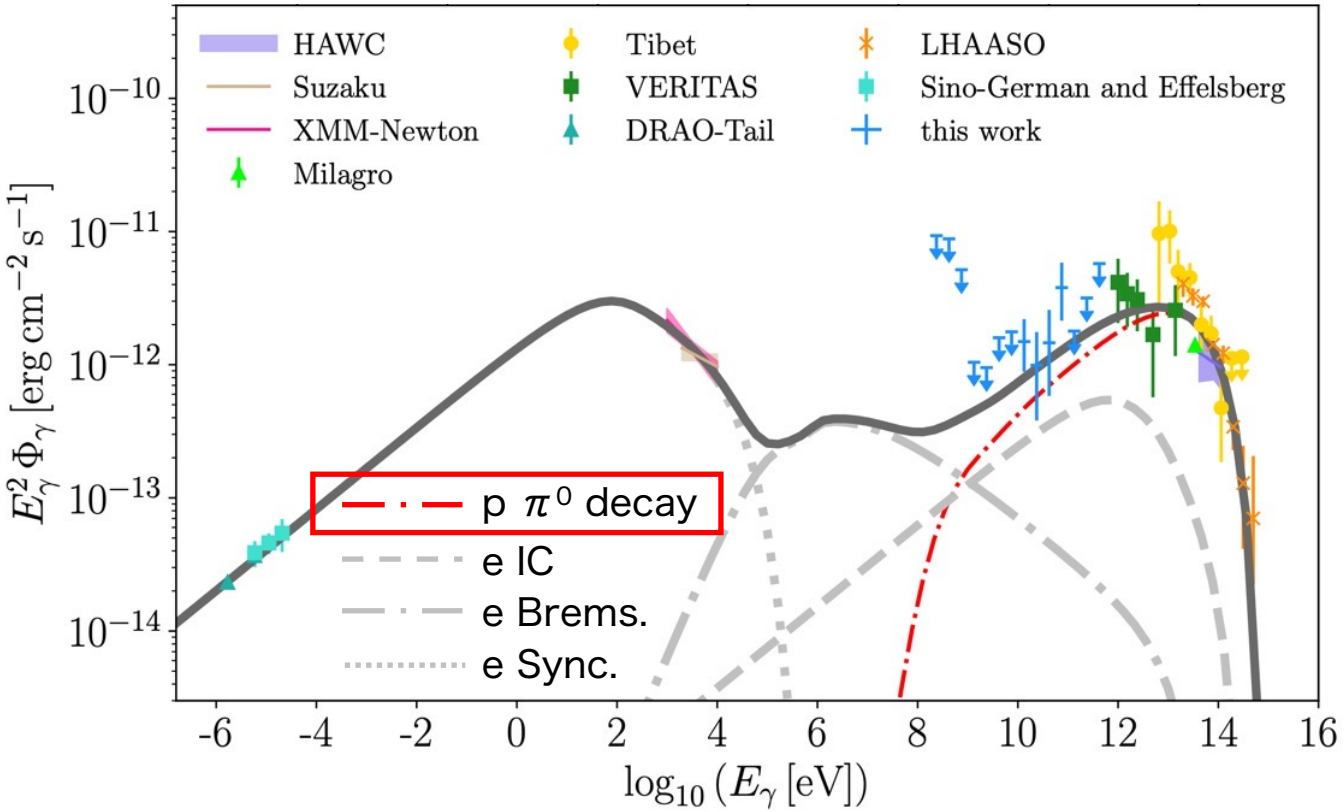
SNR G106.3+2.7 (E >10 TeV)



[redacted]

Amenomori+, Nat. Astron. Lett (2021)

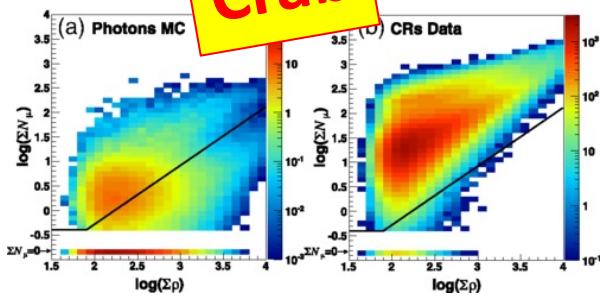
multi-wavelength flux interpretation※

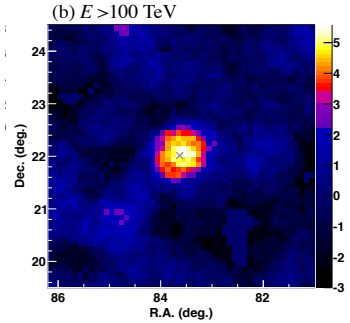


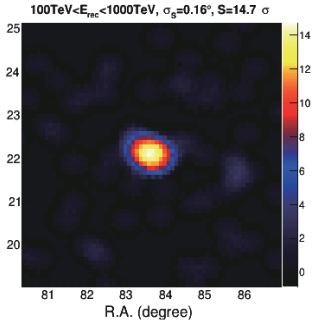
- ✓ γ-ray emissions with molecular clouds
- ✓ CR-proton acceleration up to E ~ 500 TeV

Sub-PeV gamma-ray astronomy (>100 TeV, 2019~)

Crab

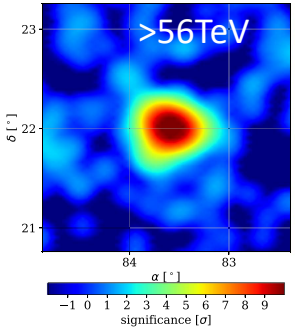






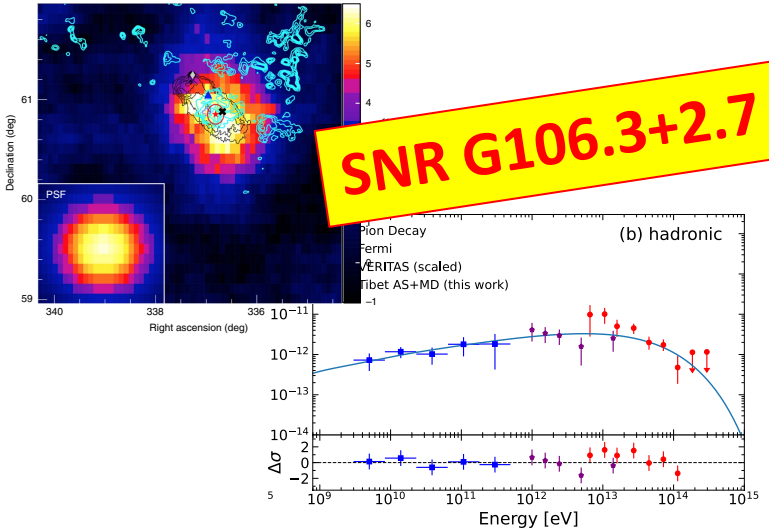
Tibet AS γ Collaboration, PRL 123, 051101 (2019)

LHAASO Collaboration, Chin. Phys. C45, 023002 (2021)



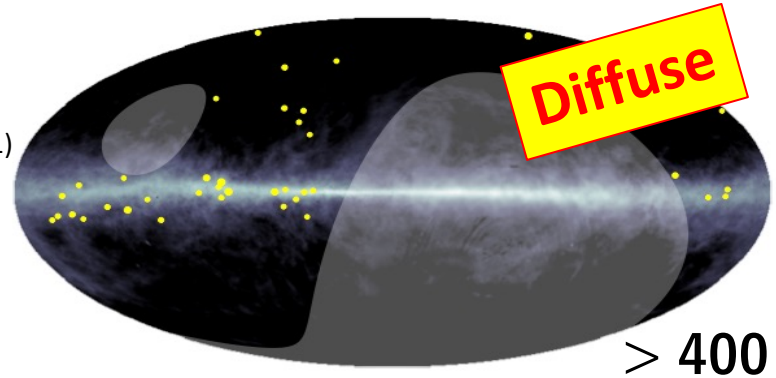
HAWC Collaboration, ApJ 881:134 (2019)

SNR G106.3+2.7



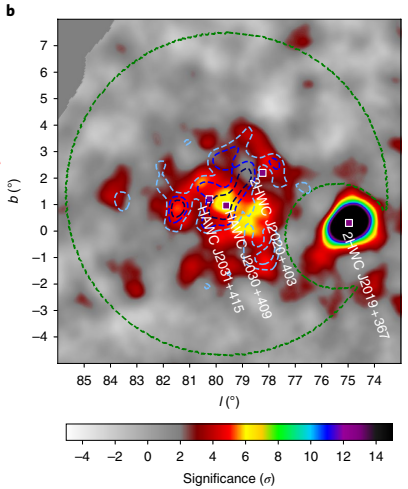
Tibet AS γ Collaboration, Nature Astron., 5, 460-464 (2021)

Diffuse

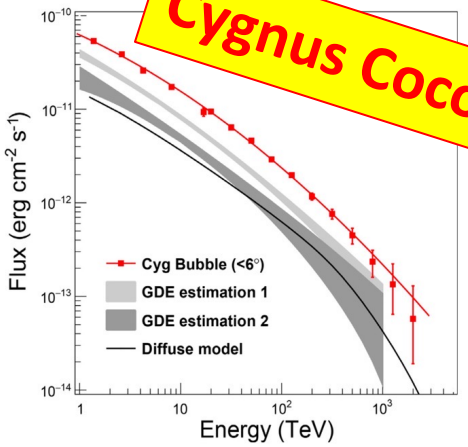


> 400 TeV

Tibet AS γ Collaboration, PRL 126, 141101 (2021)

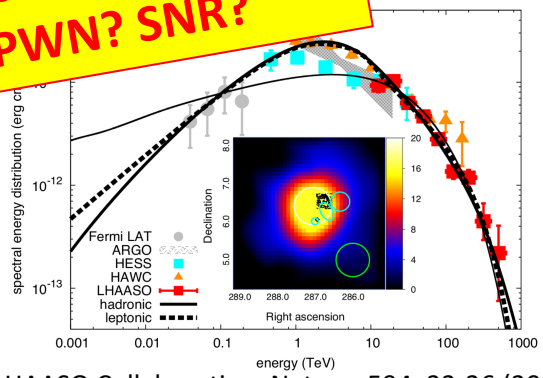


Cygnus Cocoon



LHAASO Collaboration Sci. Bull. 69, 449 (2024)

LHAASO J1908+0621
PWN? SNR?



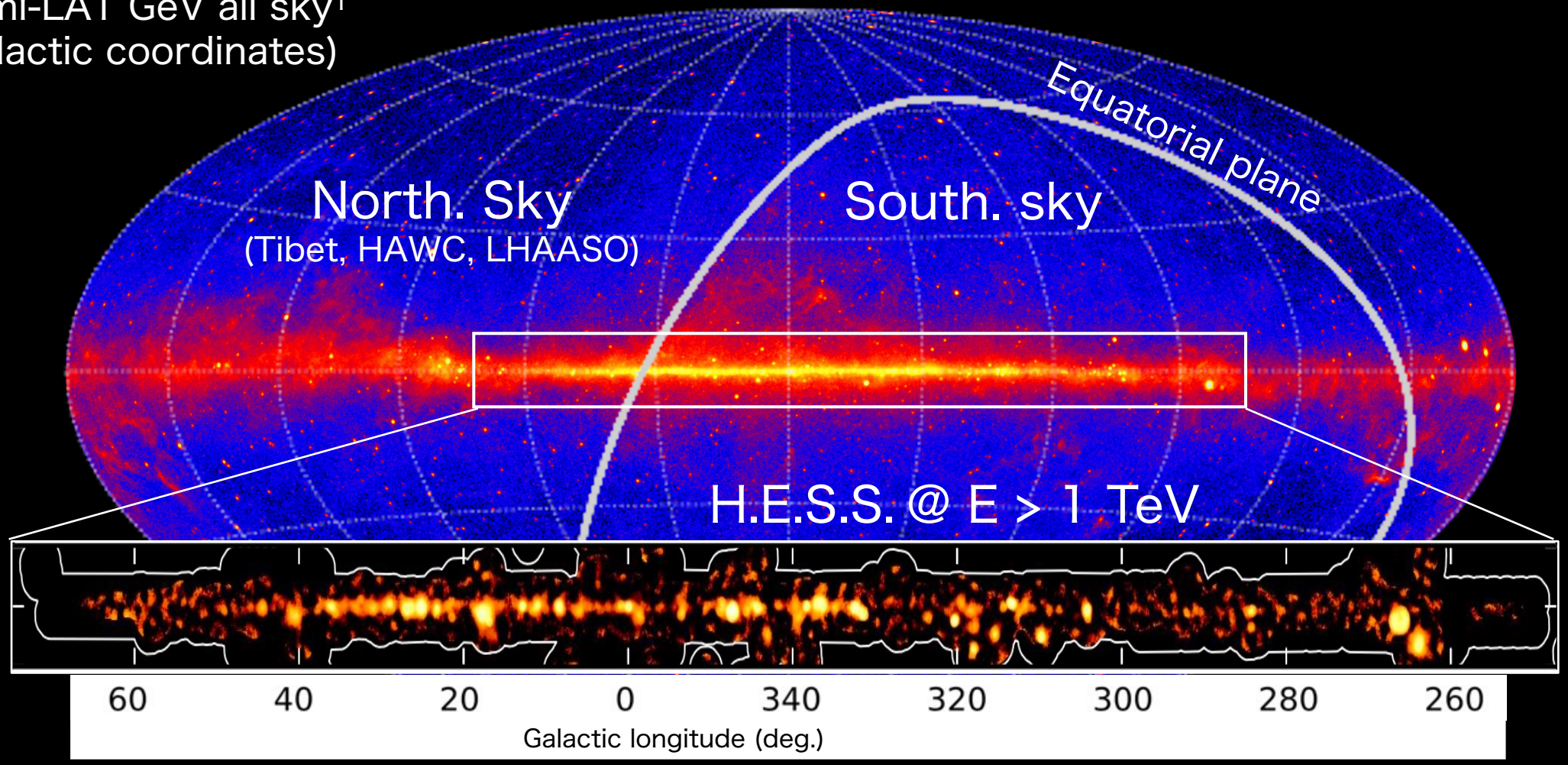
LHAASO Collaboration, Nature, 594, 33-36 (2021)

Tibet AS γ, HAWC, and LHAASO <u>in the northern hemisphere</u>

Southern Sky is ...

https://svs.gsfc.nasa.gov/14090
H.E.S.S. Collaboration, A&A 612, A1 (2018)

Fermi-LAT GeV all sky[1]
(Galactic coordinates)

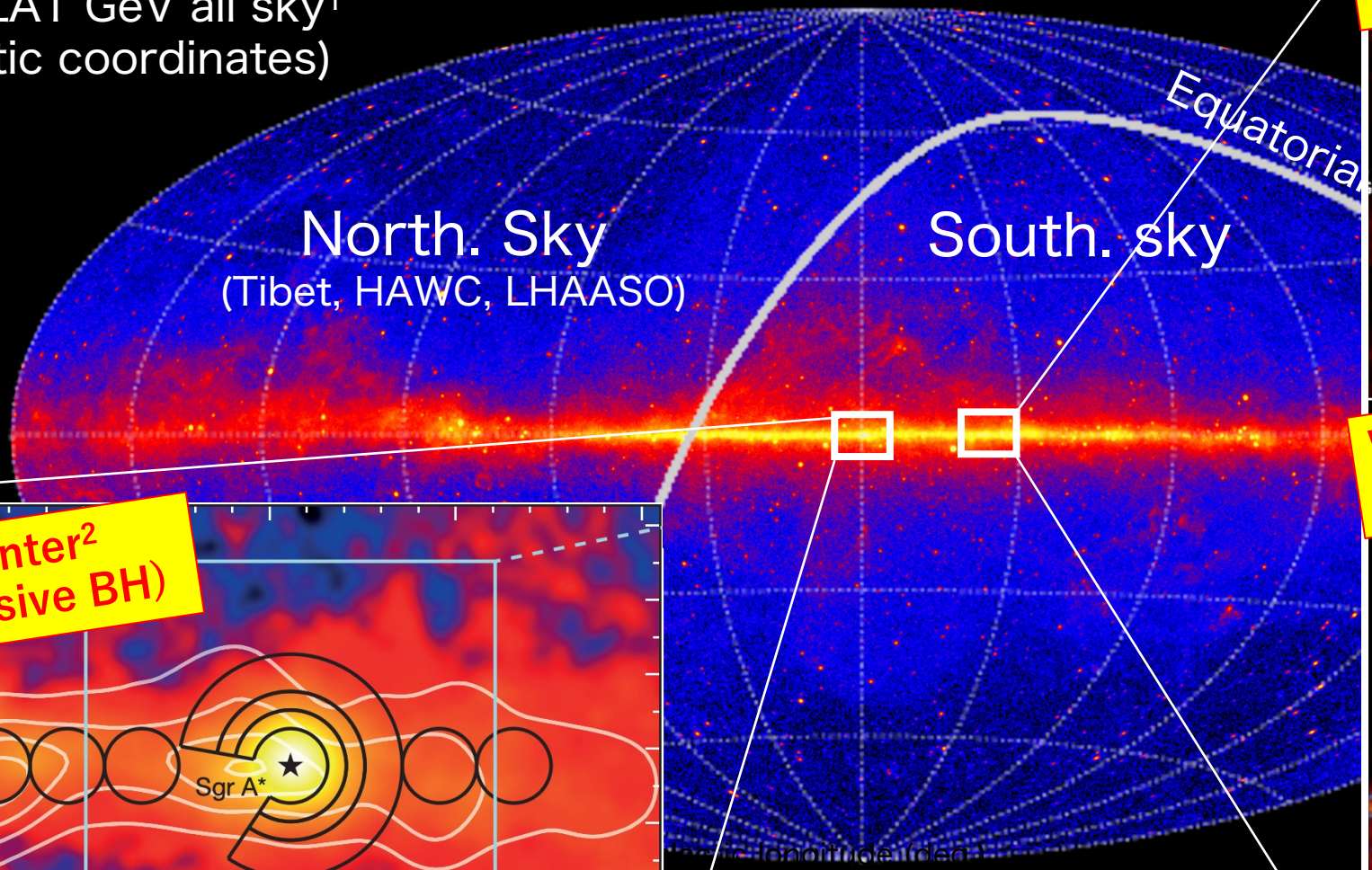


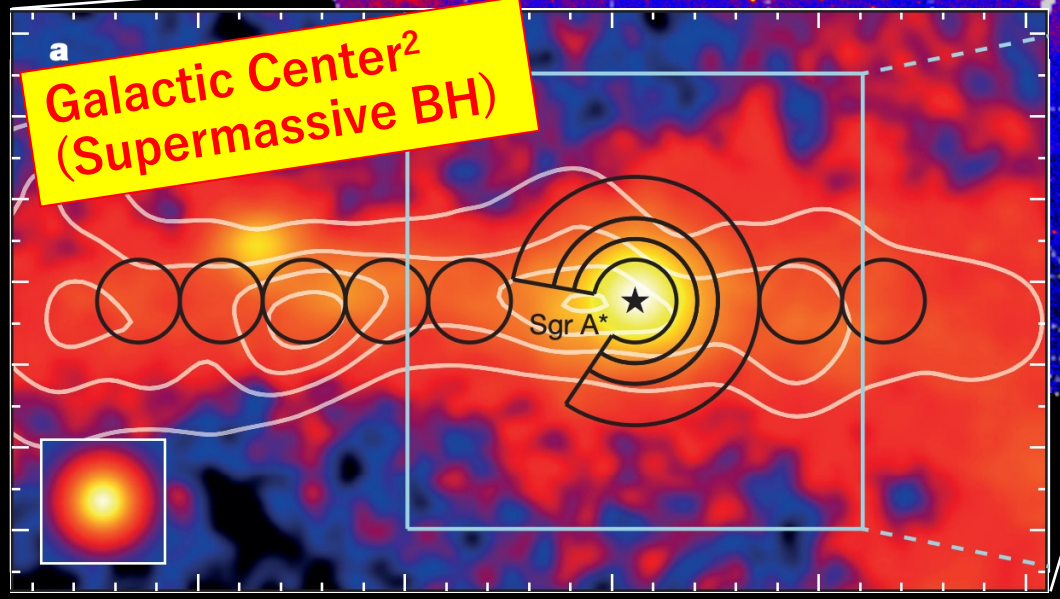
✓ Very rich in HE sources (~80 TeV sources[2])

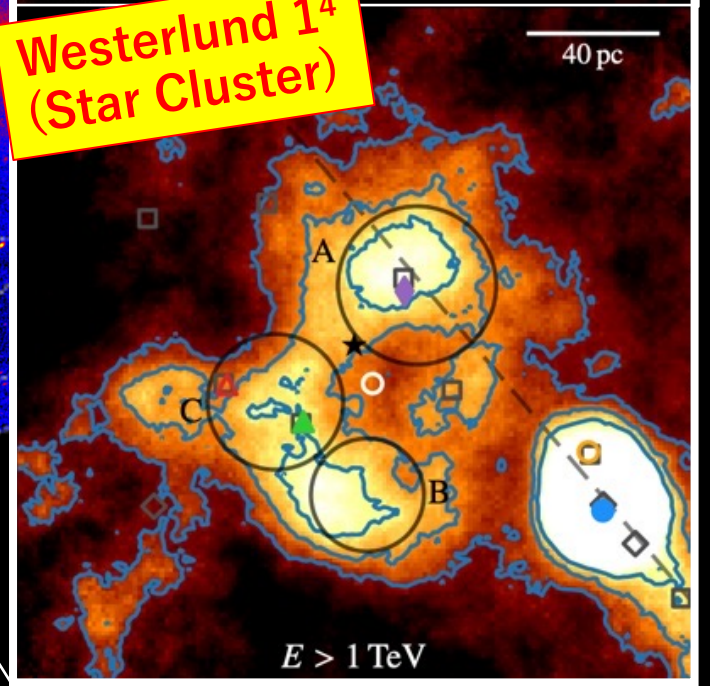
! Inaccessible by the current sub-PeV γ-ray observatories

Southern Sky is ...

Fermi-LAT GeV all sky[1]
(Galactic coordinates)



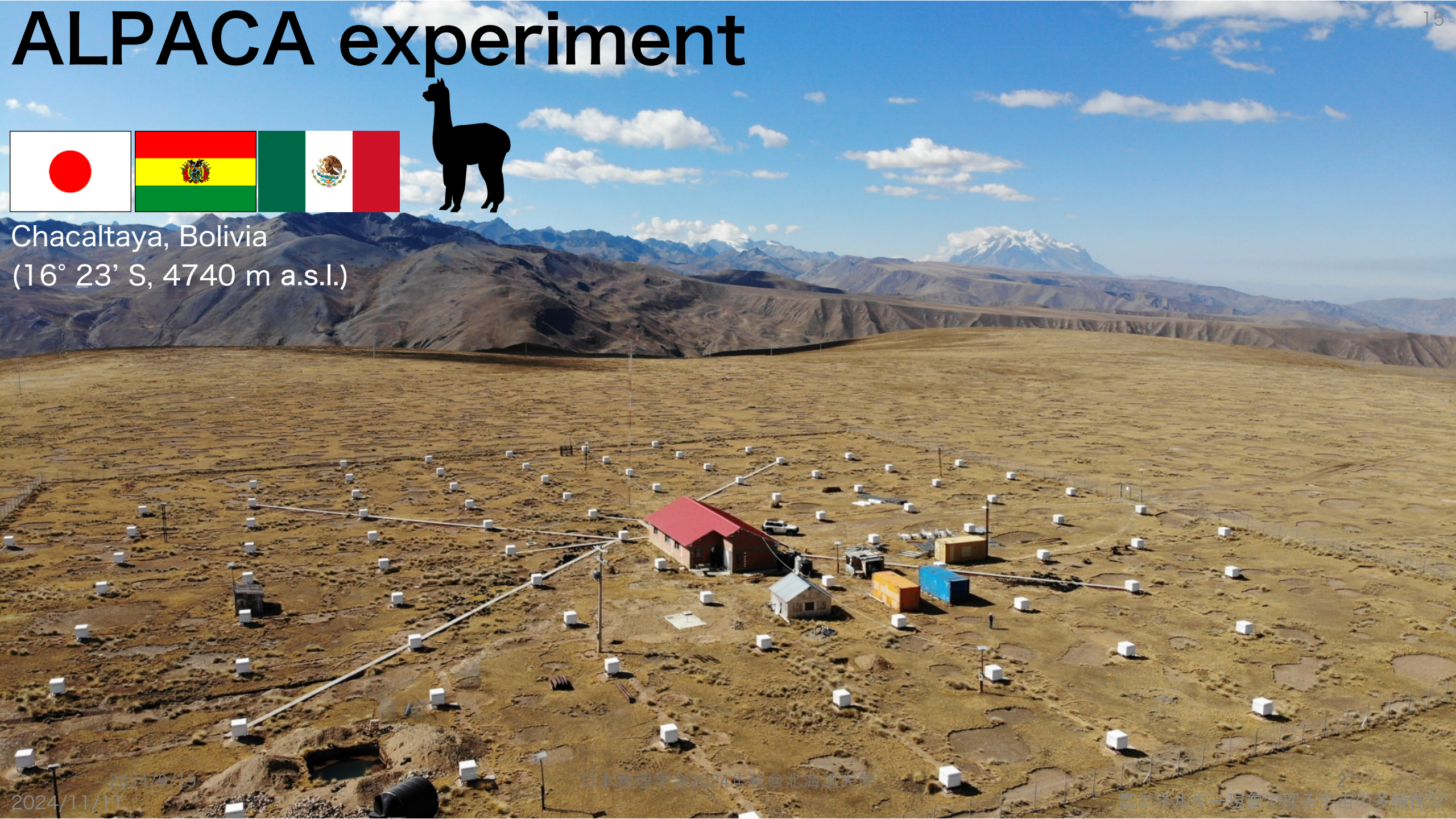




1. https://svs.gsfc.nasa.gov/14090
2. H.E.S.S. Collaboration, Nature 531, 476 (2016)
3. 〃, A&A 653, A152 (2021)
4. 〃, A&A 666, A124 (2022)

Many PeVatron candidates in the southern sky!!

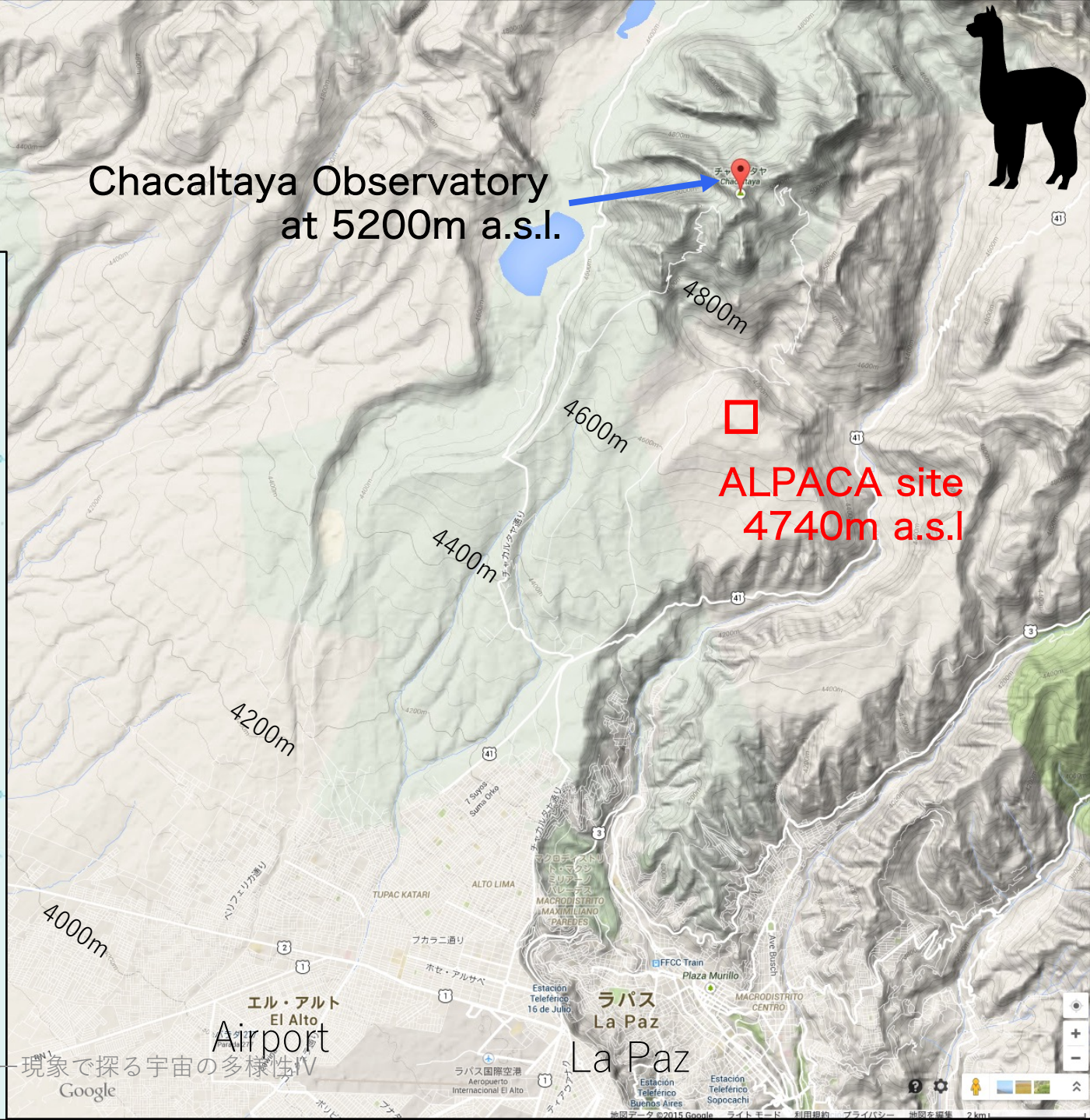
ALPACA experiment



Chacaltaya, Bolivia
(16° 23’ S, 4740 m a.s.l.)

ALPACA site

Chacaltaya Observatory
at 5200m a.s.l.



Chacaltaya, Bolivia
(16° 23' S, 68° 08' W)

ALPACA detectors

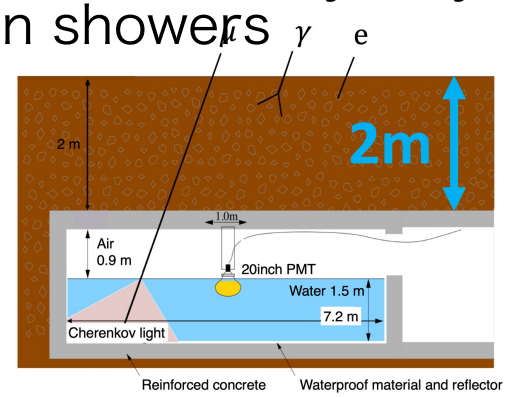
Surface Air Shower Array (Coverage: 83,000 m^2)

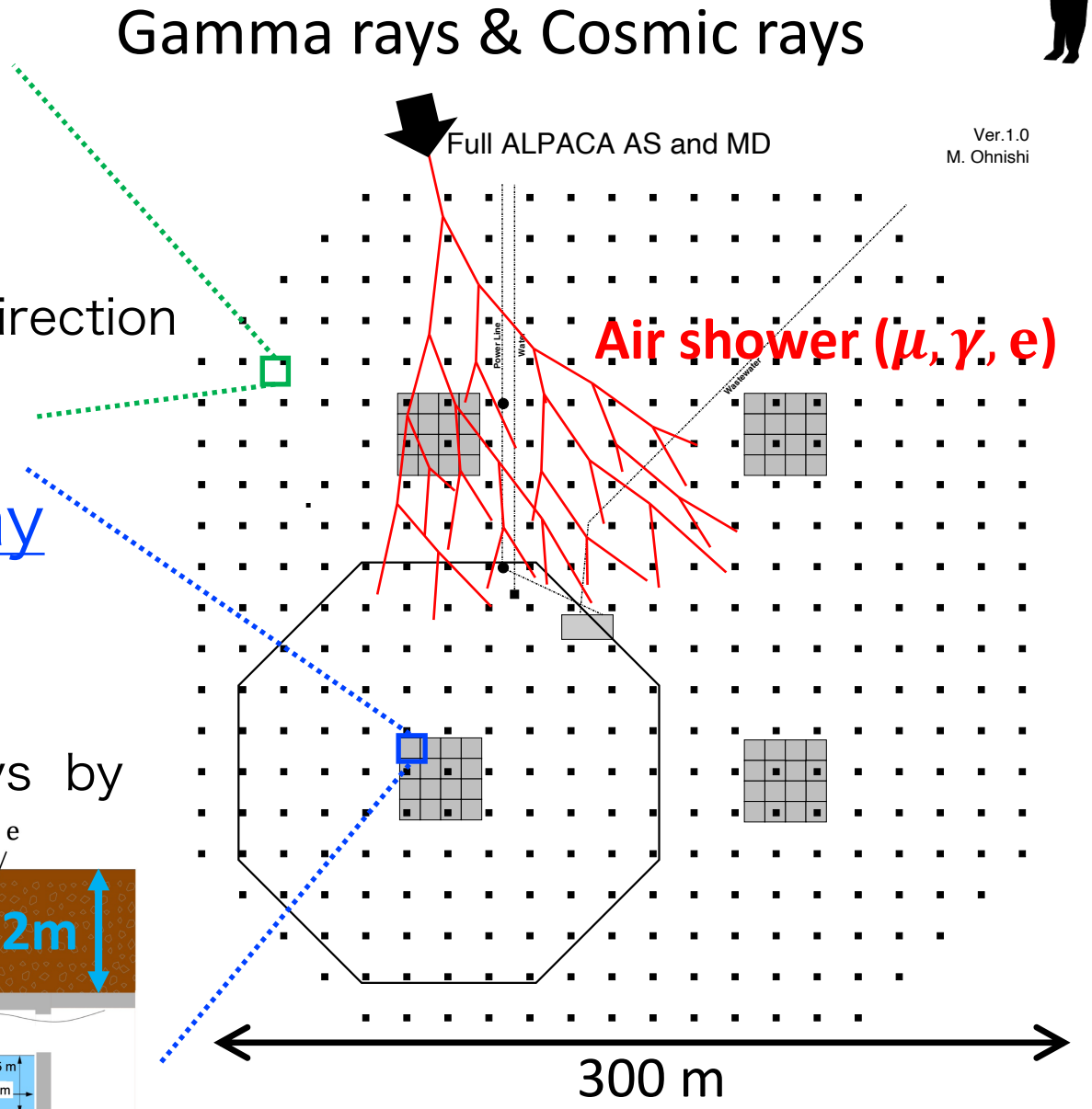
- 1 m^2 scintillation detector (× 401)
- Reconstruct the primary energy and arrival direction

Underground Muon Detector Array (Total area: 3,600 m^2)

- 56 m^2 / cells × 64 cells
- Discriminate b/w gamma rays and cosmic rays by counting the number of muons in showers

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



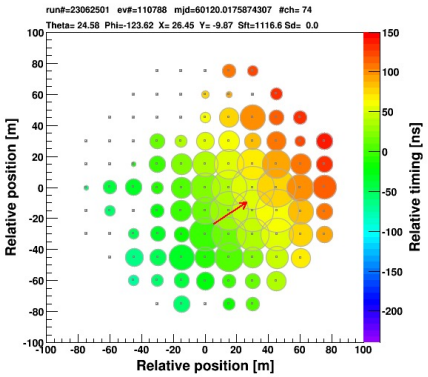


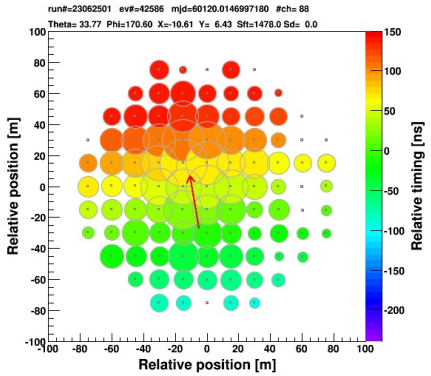
ALPAQUITA surface array

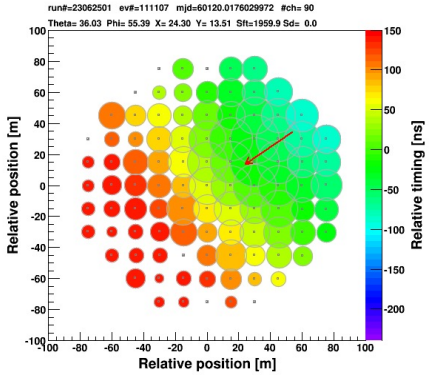
- Surface Air Shower Array (Coverage: 18,450 m^2)
  - 1 m^2 scintillation detector (× **97**)

✓ Air Shower Trigger Condition:
Any 4 detectors with > 0.7 particles within 600 ns
→ Air shower trigger rate: ~280 Hz
(Any 3 trigger has been implemented since June 2024)

✓ One MD construction starts in 2024

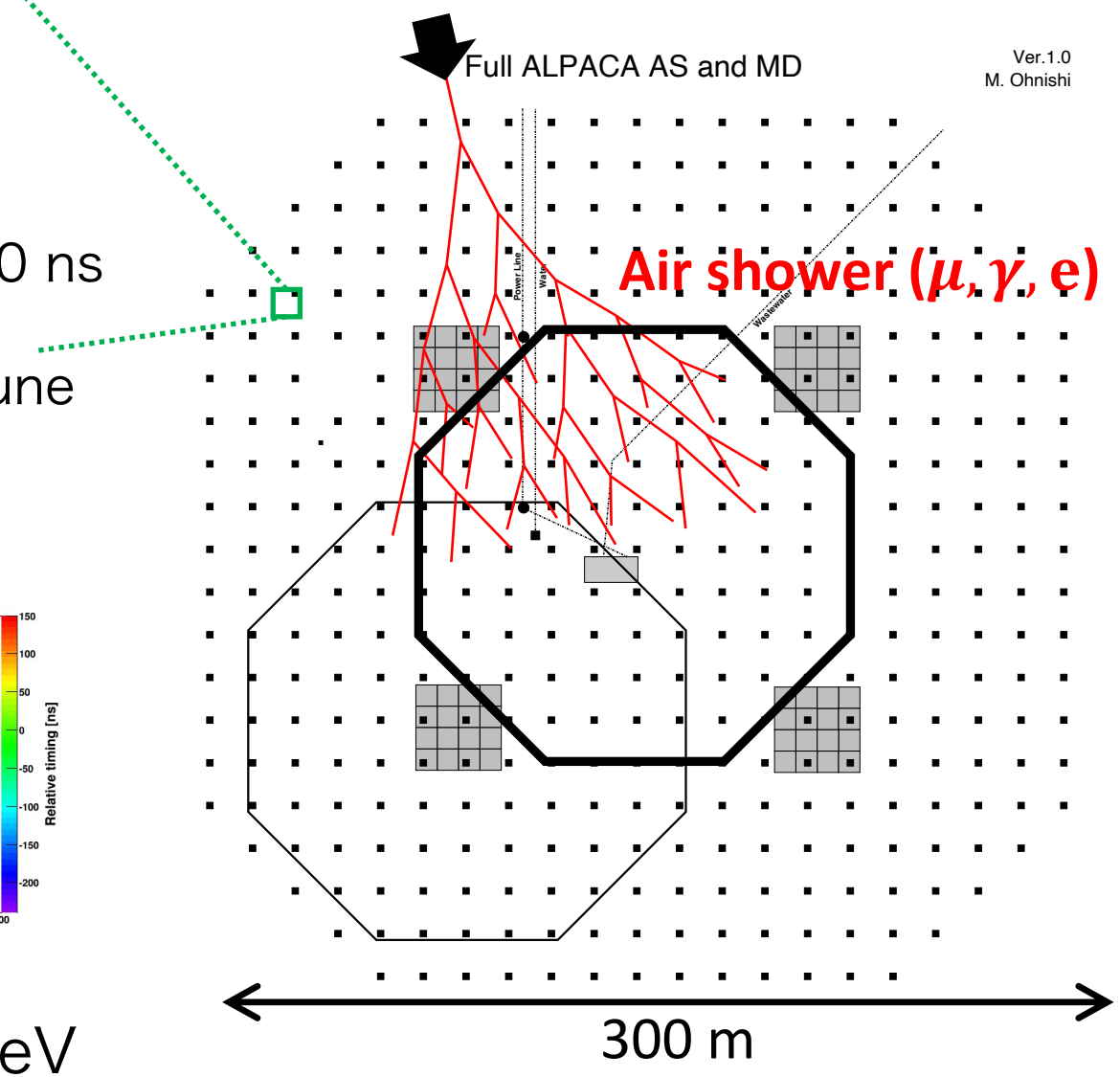




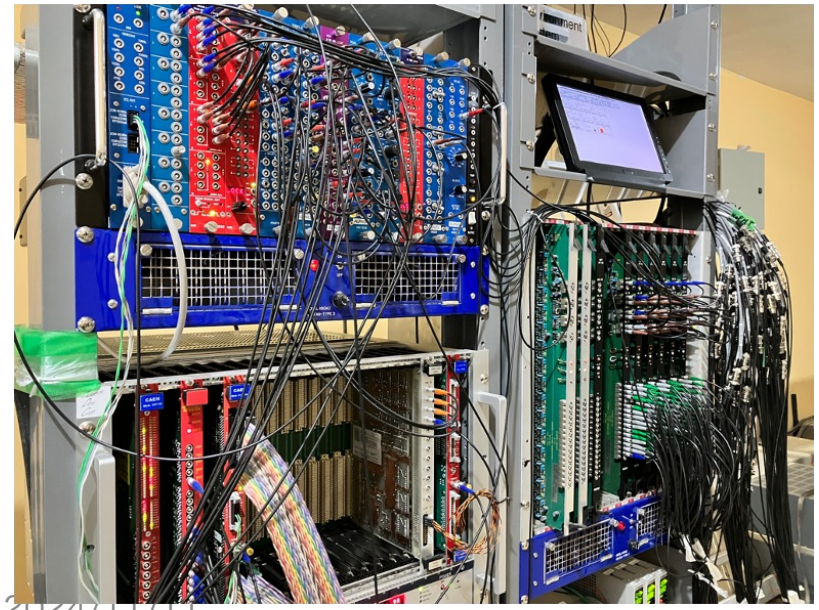


E >100 TeV

Gamma rays & Cosmic rays

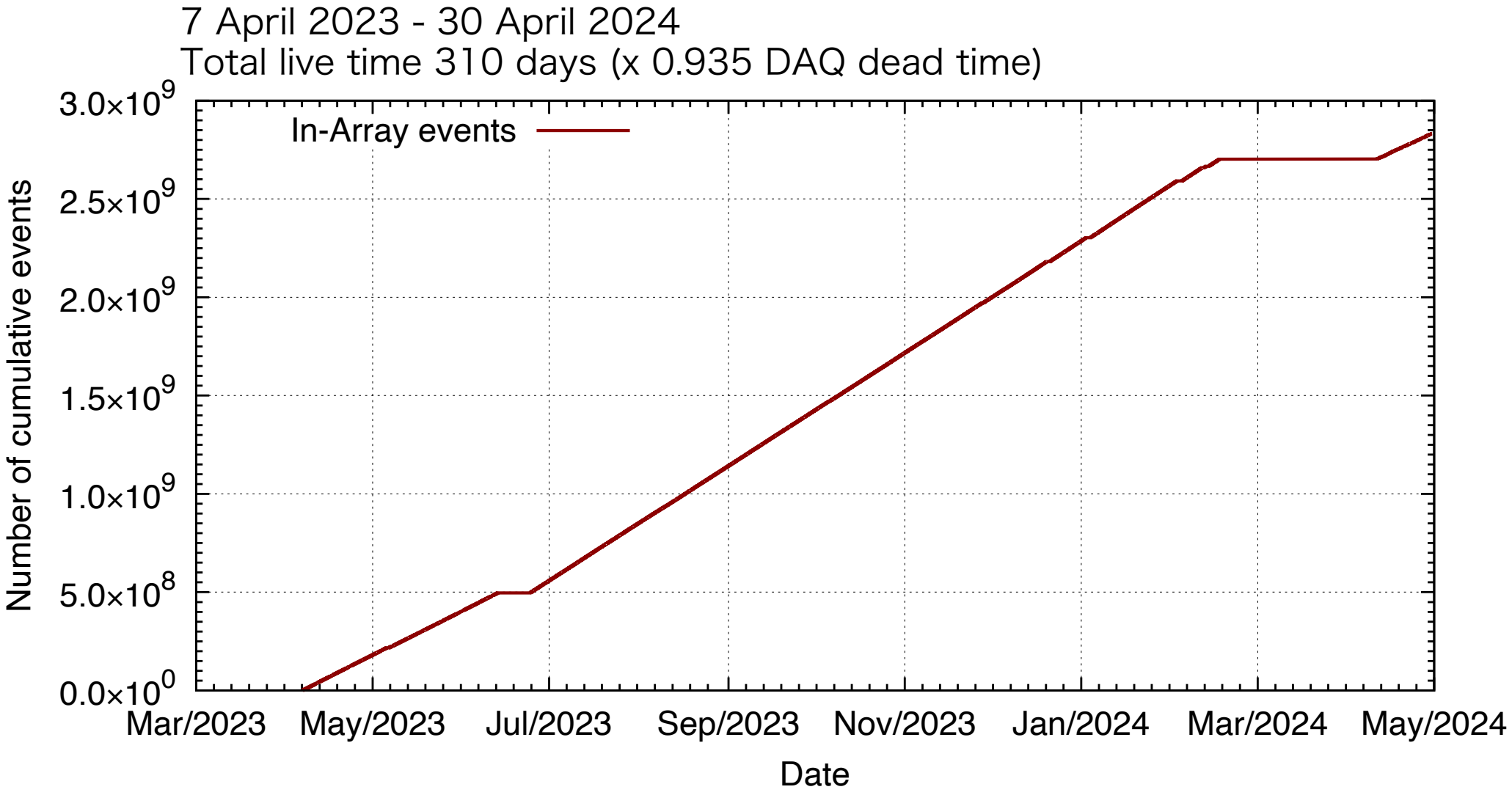


ALPAQUITA in operation

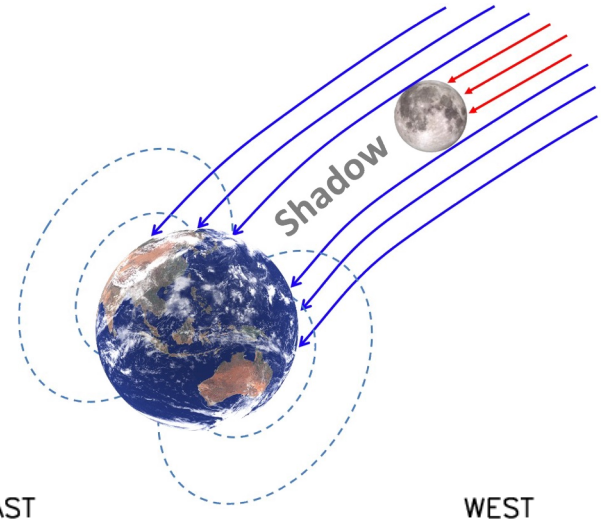


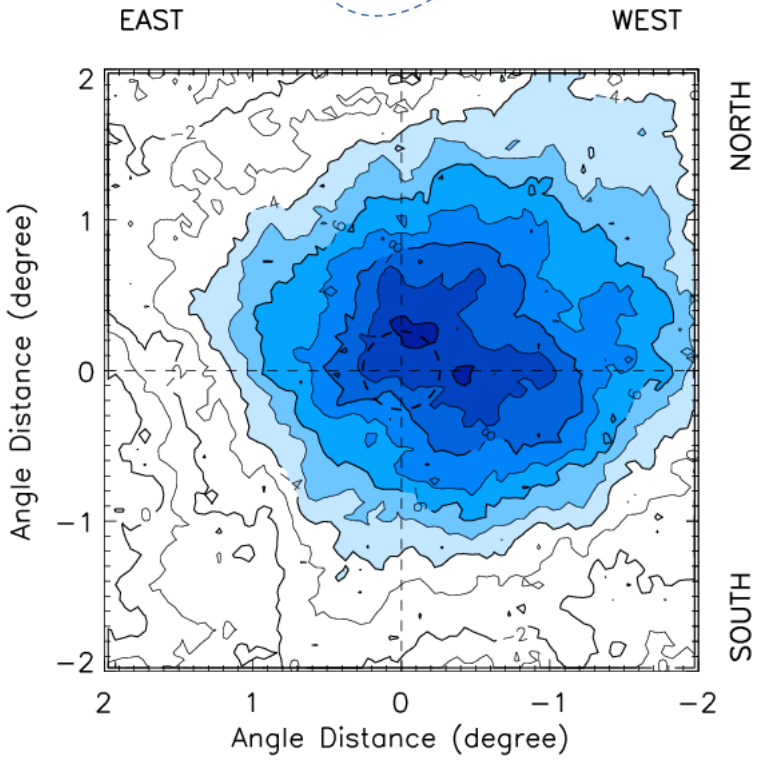
Installation of 97 ground detectors completed in 2022.
Full operation since April 2023.

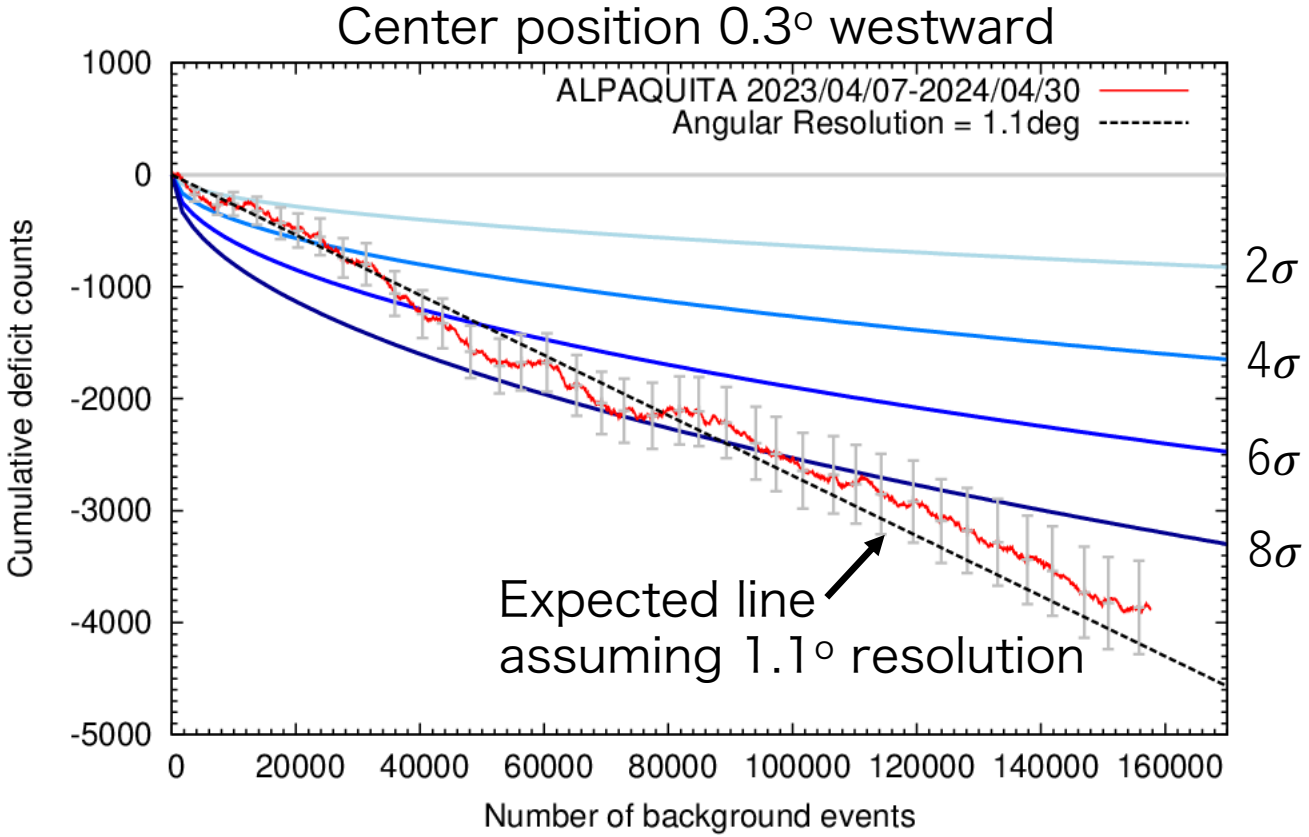
ALPAQUITA Event Rate 2023.04.07 – 2024.04.30



Moon shadow by ALPAQUITA

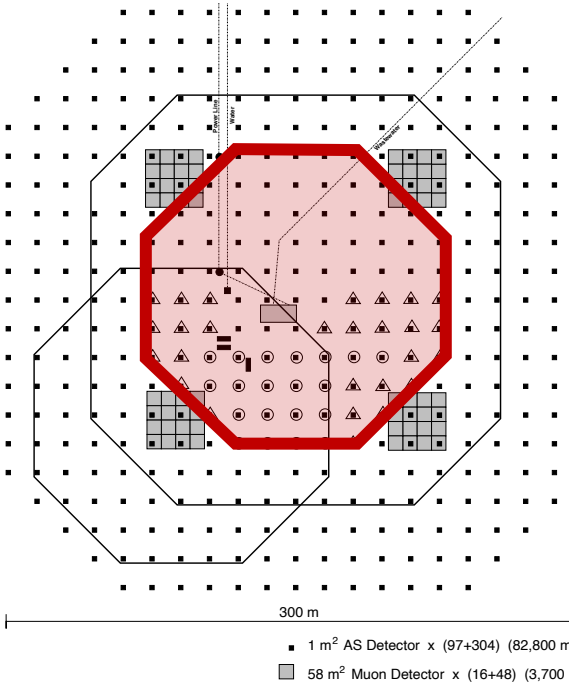




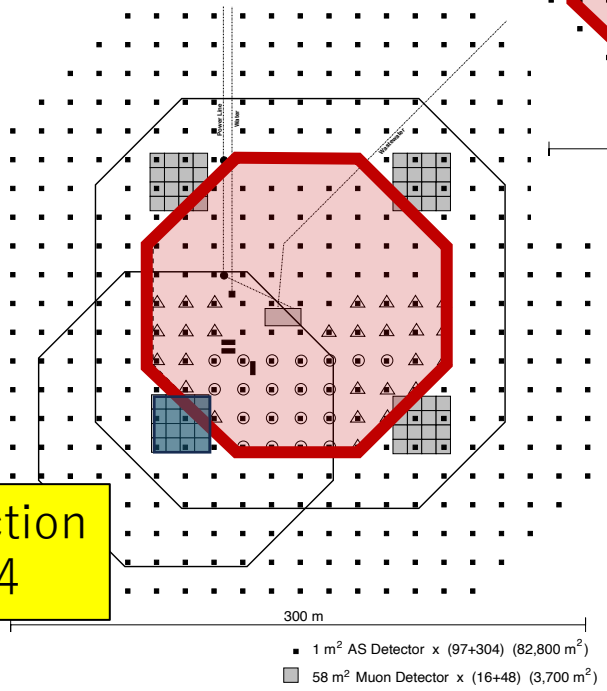


- Shadow of the moon is clearly detected at >8σ
- Evolution of the deficit depth suggests the angular resolution of 1.1 degree (mode energy = a few TeV)

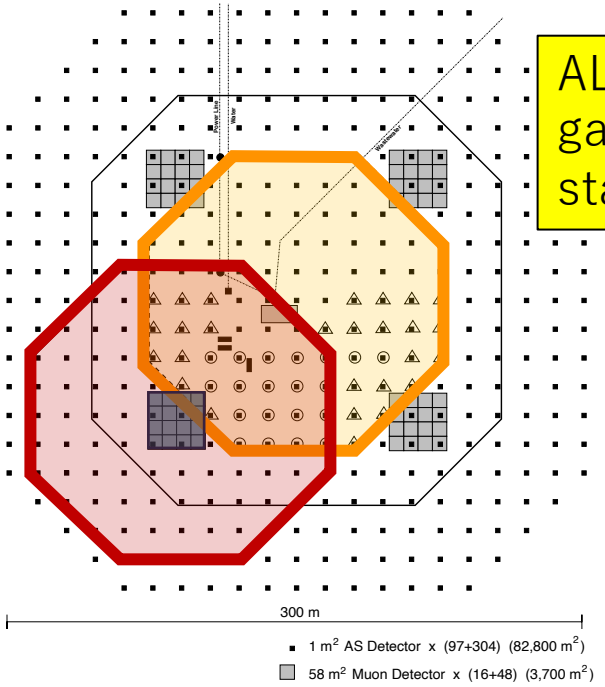
ALPACA construction plan



Current configuration

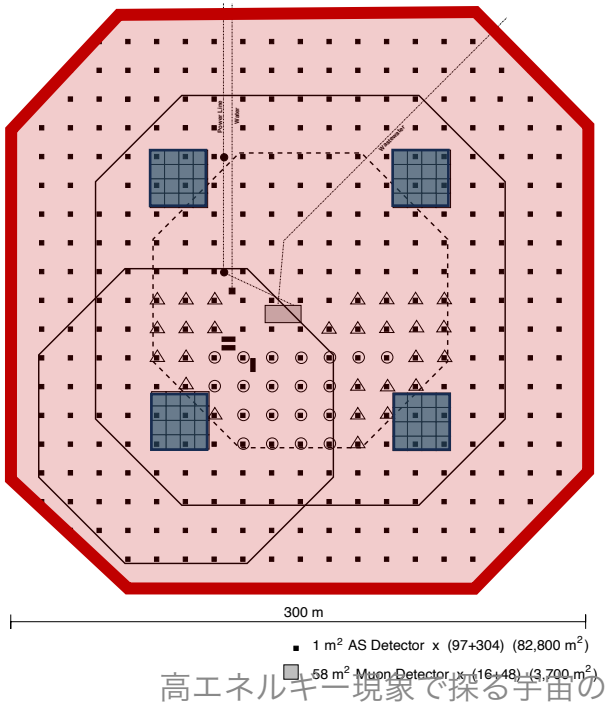


1st MD construction starts in 2024

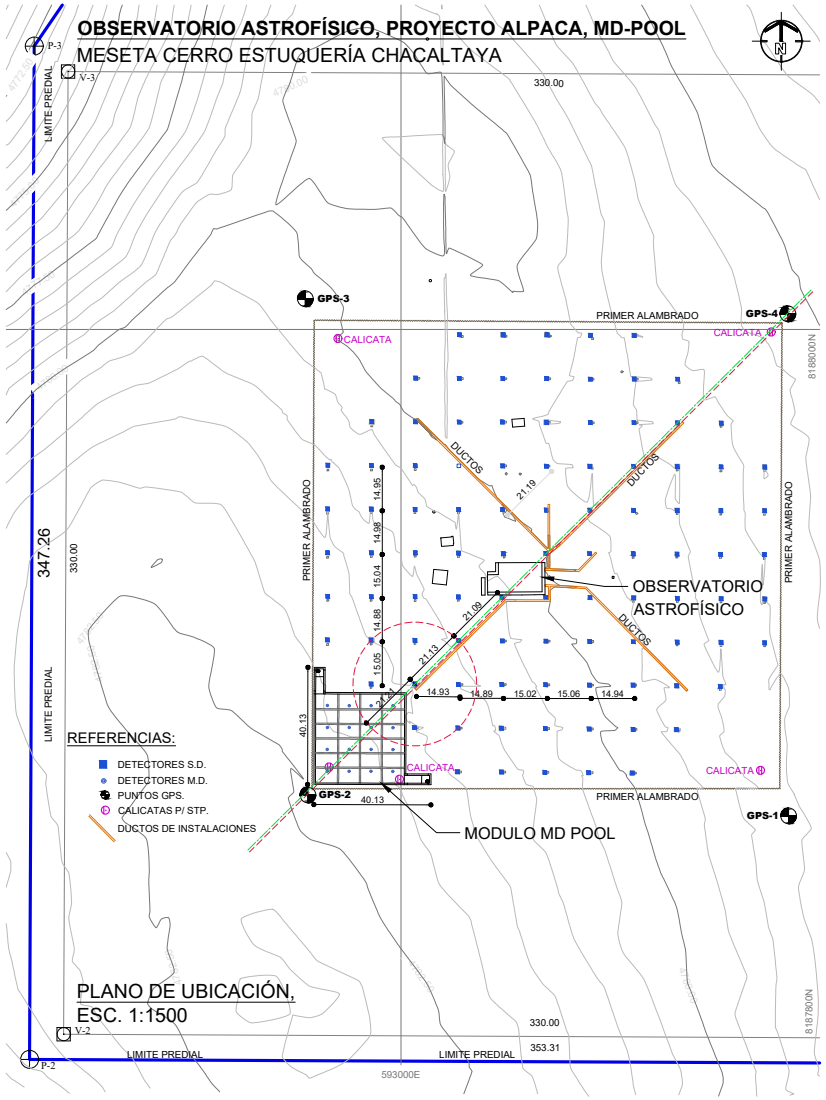


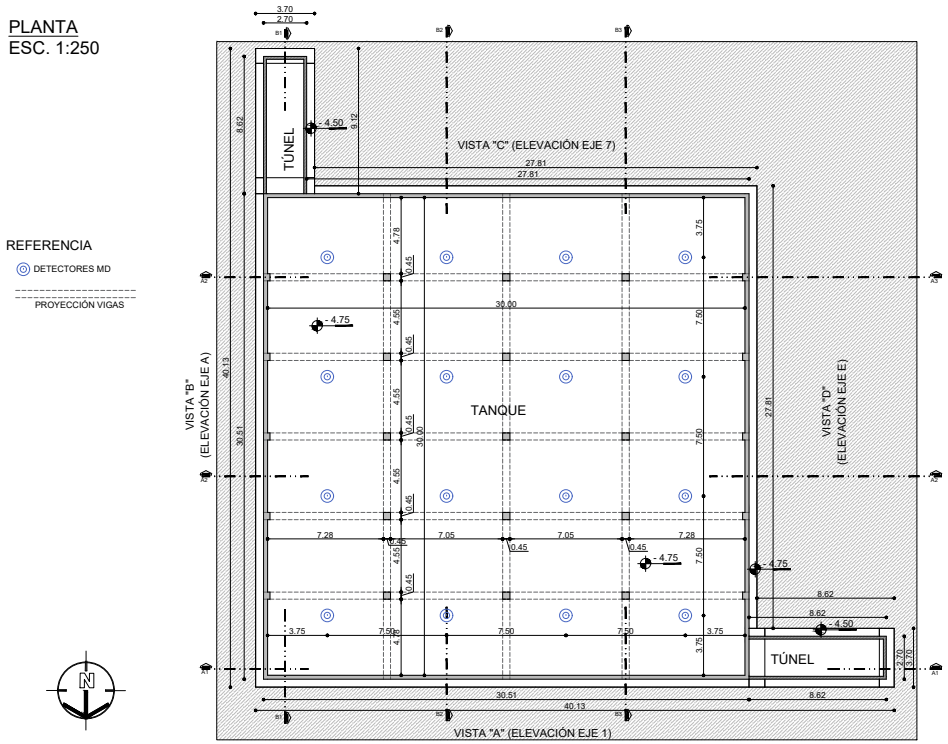
ALPAQUITA w/ MD gamma-ray sensitive observation starts in 2025

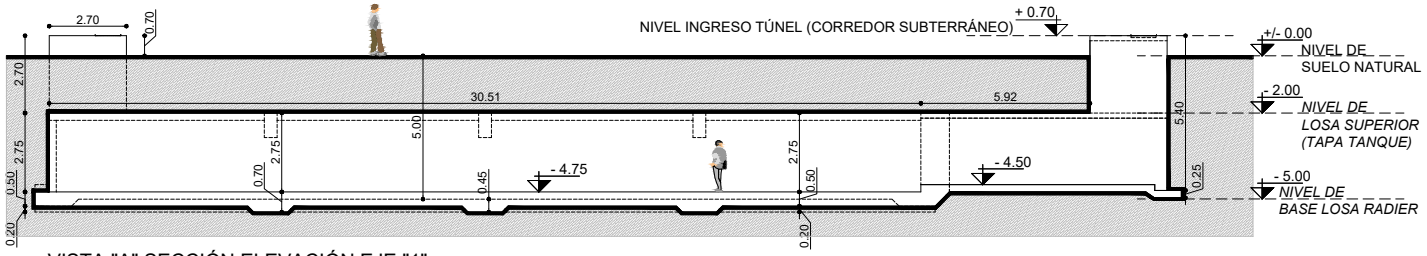
Full ALPACA construction in 2025



Final design of muon detector



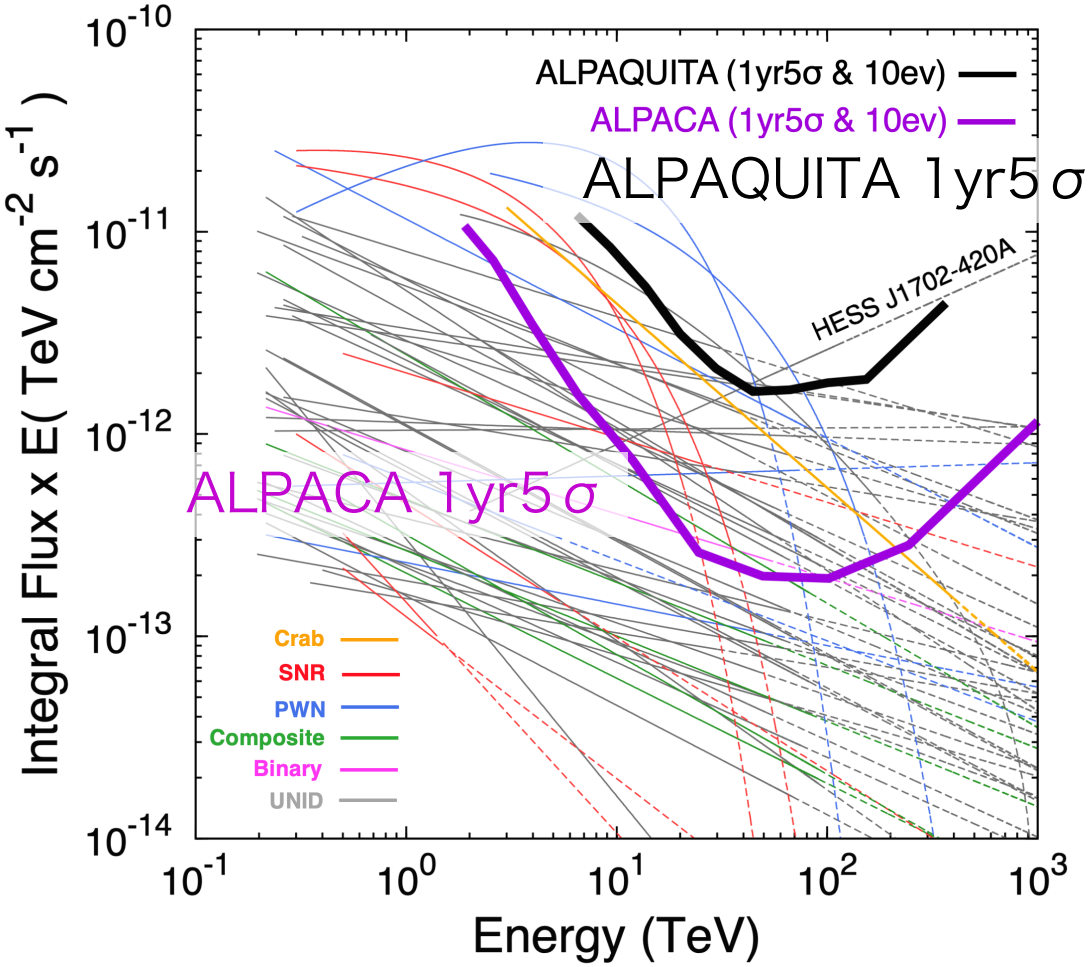




VISTA "A" SECCIÓN ELEVACIÓN EJE "1",
ESC. 1:200

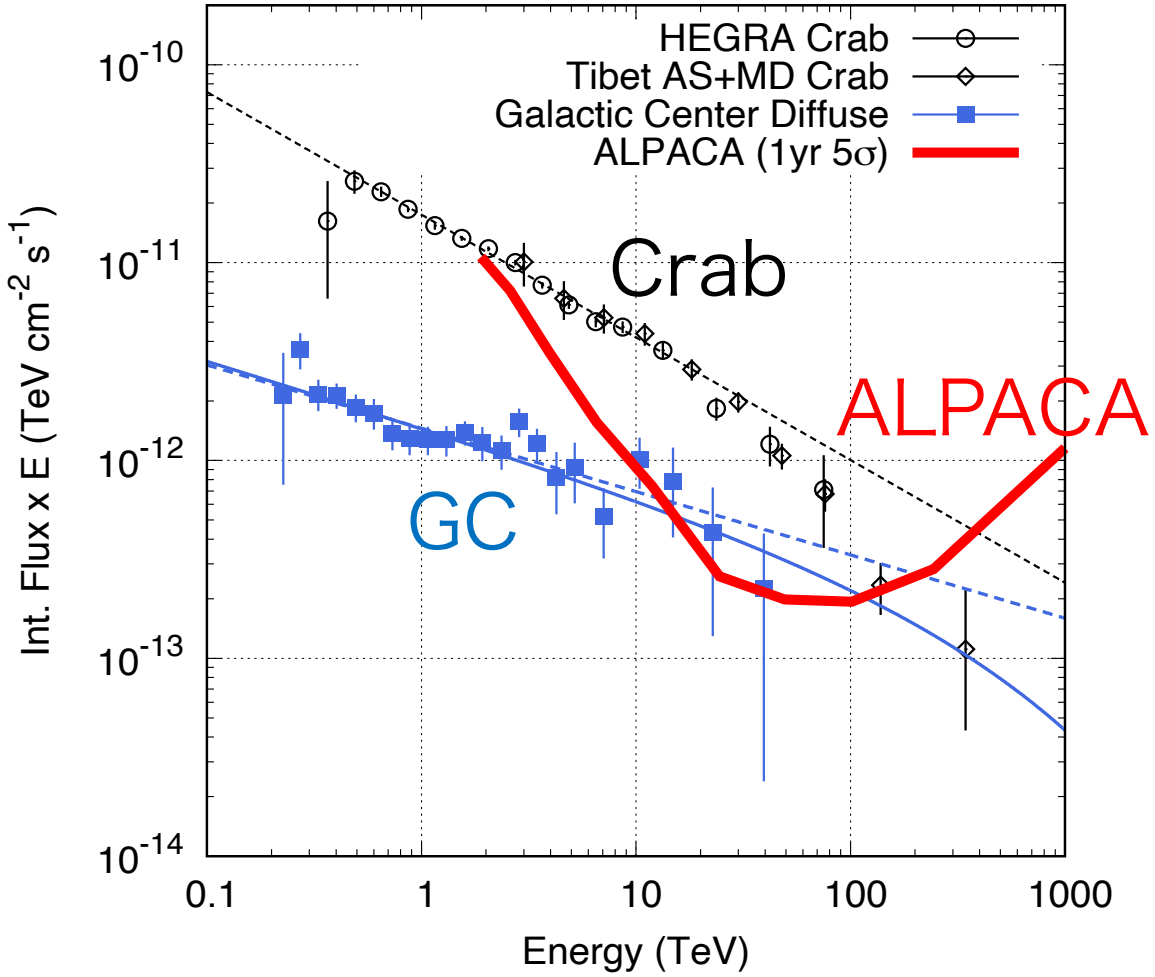
Sensitivity to gamma-ray sources

for gamma-ray sources w/i F.O.V.



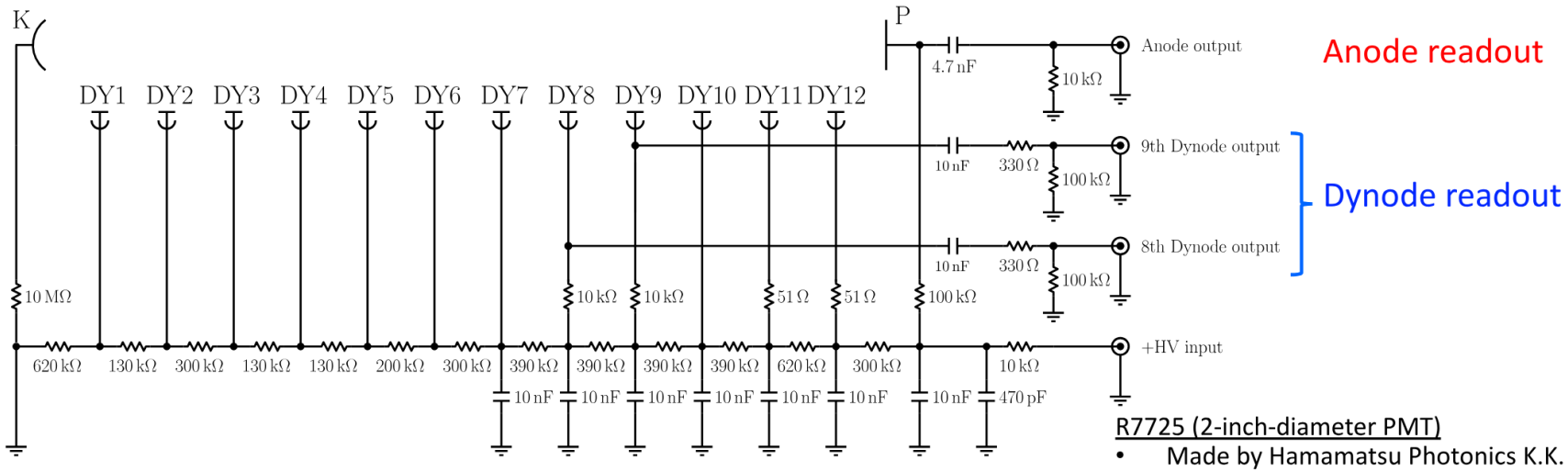
S.Kato et al., Experimental Astronomy (2021) 52:85-107

for Galactic Center



Beyond sub-PeV

- Multi-readout PMT was developed to extend dynamic range

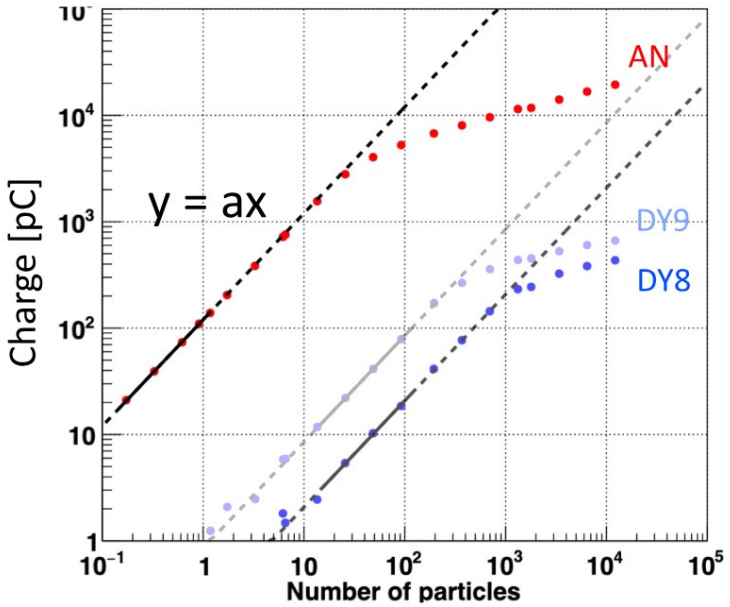


Anode readout

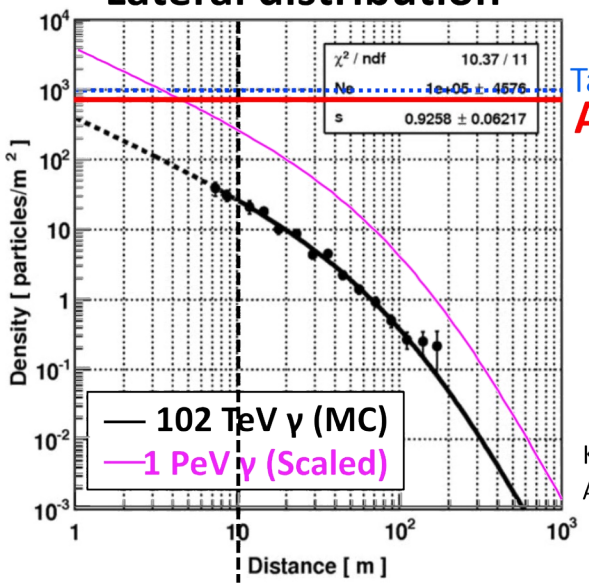
Dynode readout

R7725 (2-inch-diameter PMT)

- Made by Hamamatsu Photonics K.K.
- High voltage: 1750 V (Max.: 2000 V)
- Number of dynodes: **12**



Lateral distribution



Target: 1,000 particles

Achieved: ~700 particles (~3 PeV)

K. Kawata, et al., Experimental Astronomy, 44:1-9 (2017).

Summary

- Sub-PeV gamma-ray astronomy is started in the northern hemisphere by the Tibet air shower array, HAWC & LHAASO
- Results of the Tibet AS + MD arrays:
  - Sub-PeV γ-rays from the Crab Nebula
  - Galactic diffuse γ-rays
  - Observation of PeVatron candidates

- Next frontier, the southern sky, is explored by ALPACA
  - Galactic center etc.
- Prototype ALPAQUITA is now in operation & obtained data are under analysis