Tibet ASγ / ALPACA

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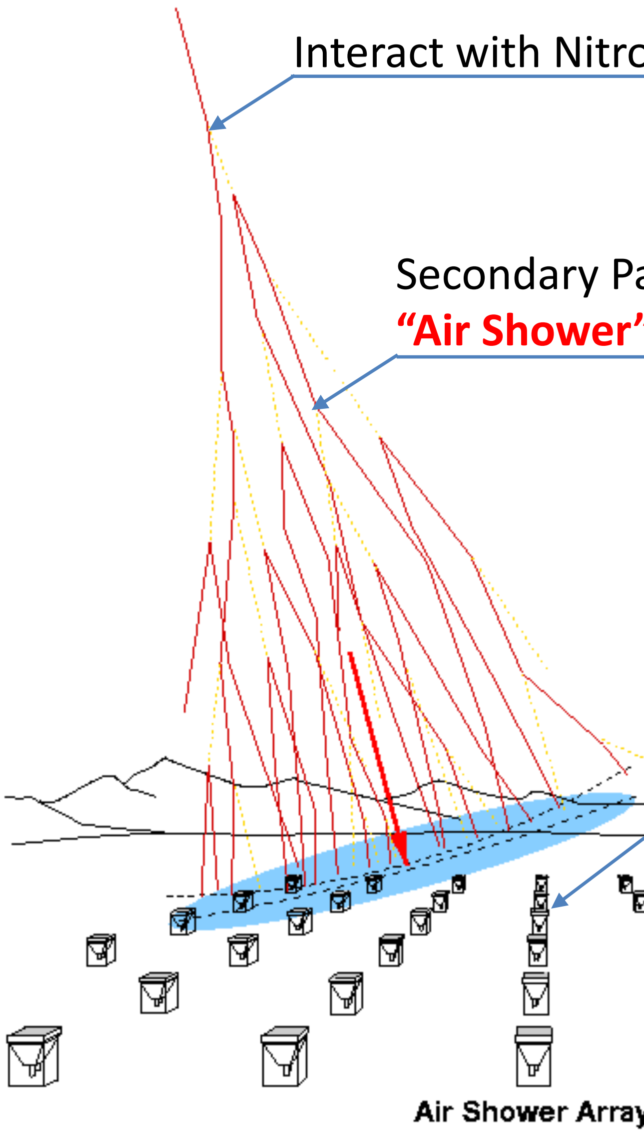
Air Shower Detection

Gamma/Cosmic Ray

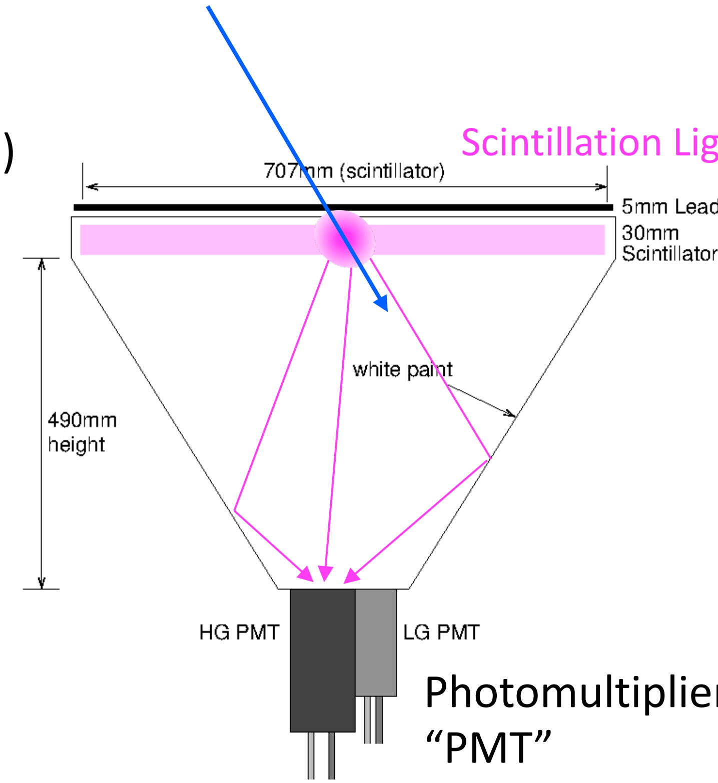
Interact with Nitrogen (Oxygen)

Secondary Particles
“Air Shower”



Surface Detectors
Measure Particles

Scintillation Lights



Photomultiplier
“PMT”

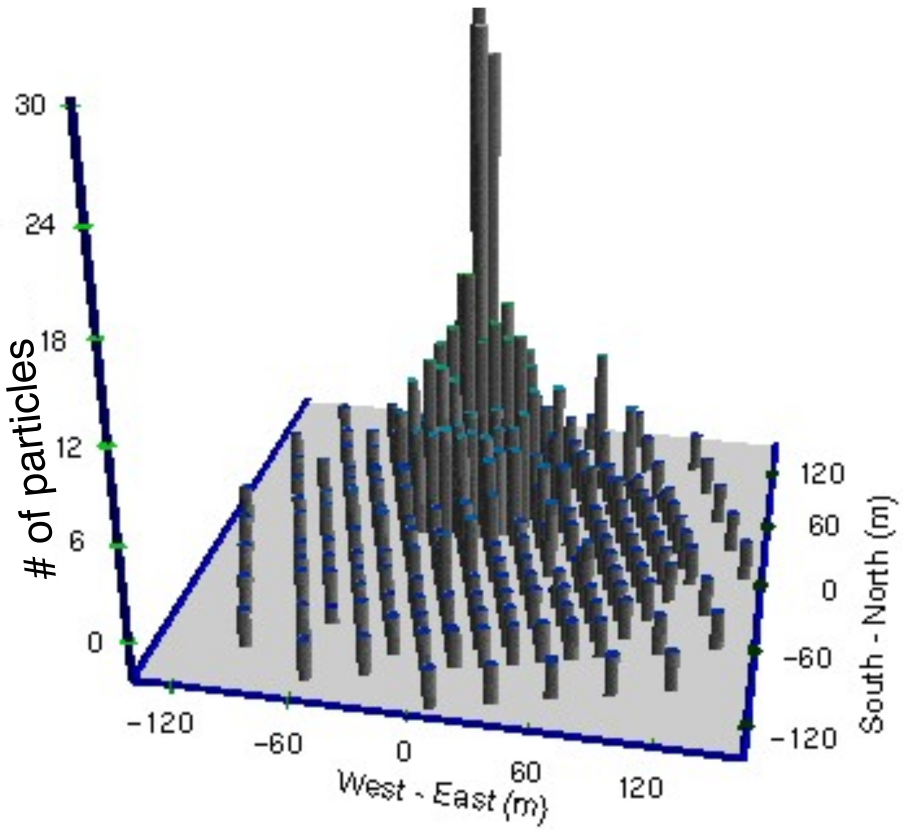
- ✓ Particle Density
- ✓ Arrival Timing

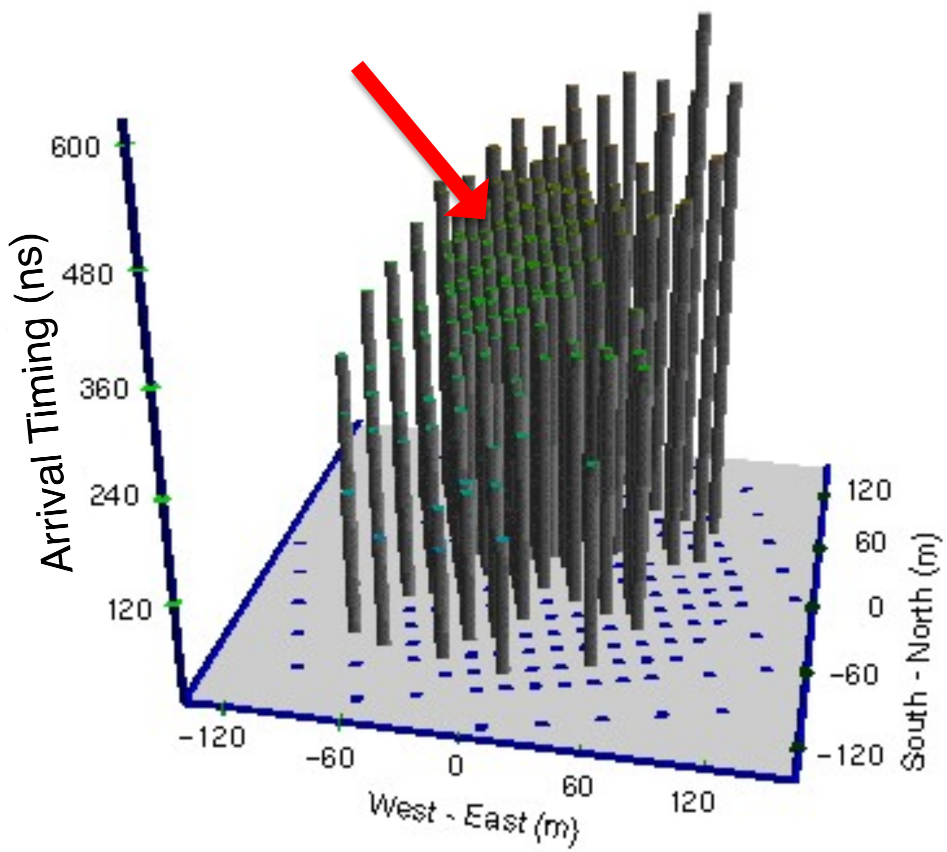
Recorded for each detector

Air Shower Detection

2^{nd} particle densities → Primary energy

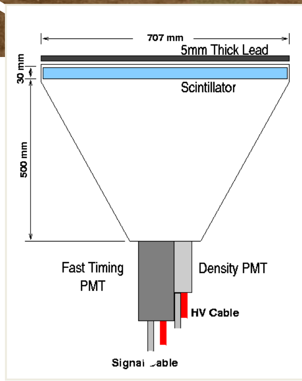
2^{nd} relative timings → Primary direction





→Observation of secondary (mainly $e^{+/-}$, γ) in AS

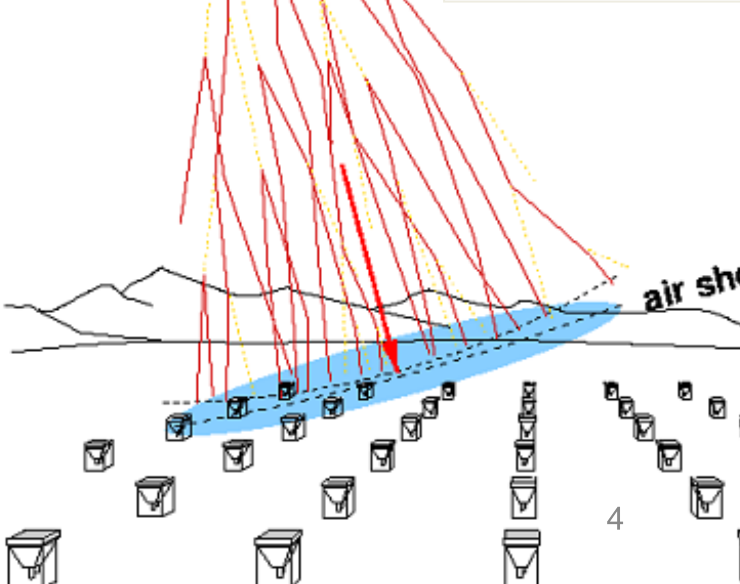
Tibet Air Shower Array



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

<u>Present Performance</u>

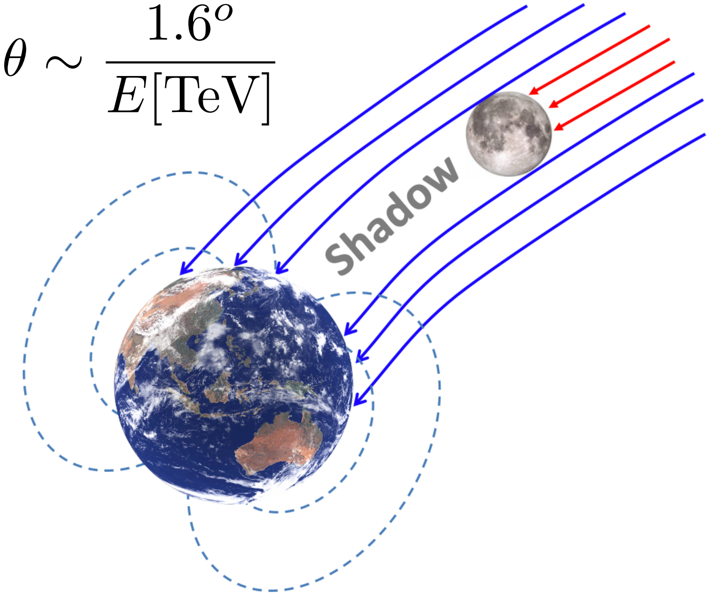
# of detectors	0.5 m² x 597
Detector Coverage	~65,700 m²
Angular resolution	~0.5°@10TeV γ
	~0.2°@100TeV γ
Energy resolution	~40%@10TeV γ
	~20%@100TeV γ



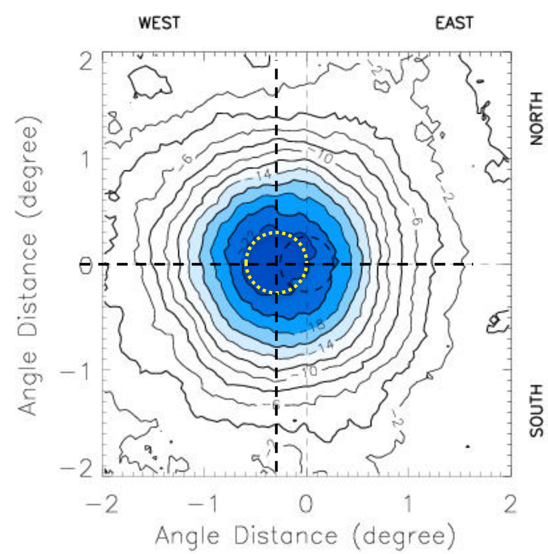
Moon as A Calibration Source

- ✓ Absolute Energy Scale
  - Energy dependence of E-W displacement
- ✓ Pointing Accuracy
  - N-S displacement
- ✓ Angular Resolution
  - Deficit Shape
- ✓ Detector Stability
  - Temporal variation
- ✓ Anti-P / P Ratio
  - Opposite-side deficit

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

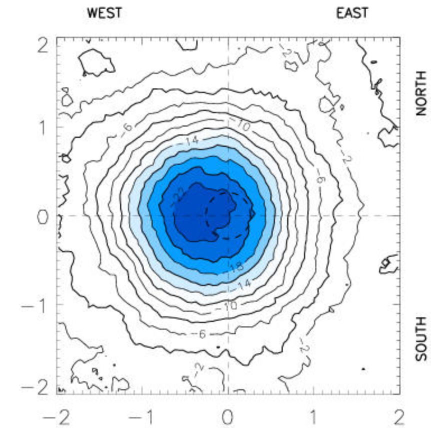


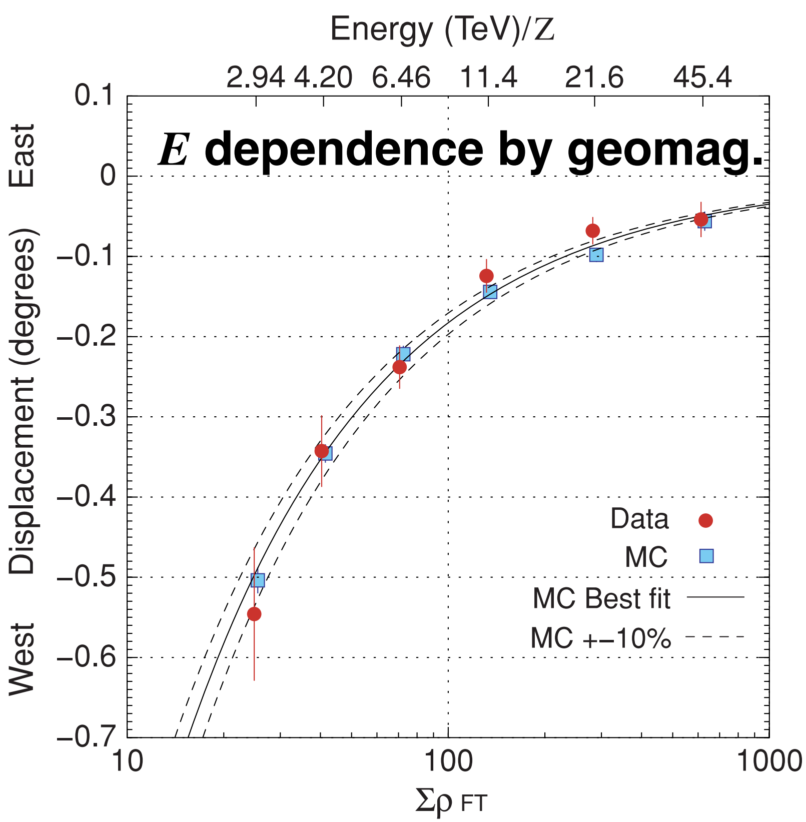
CRs are bent by the geomagnetic field

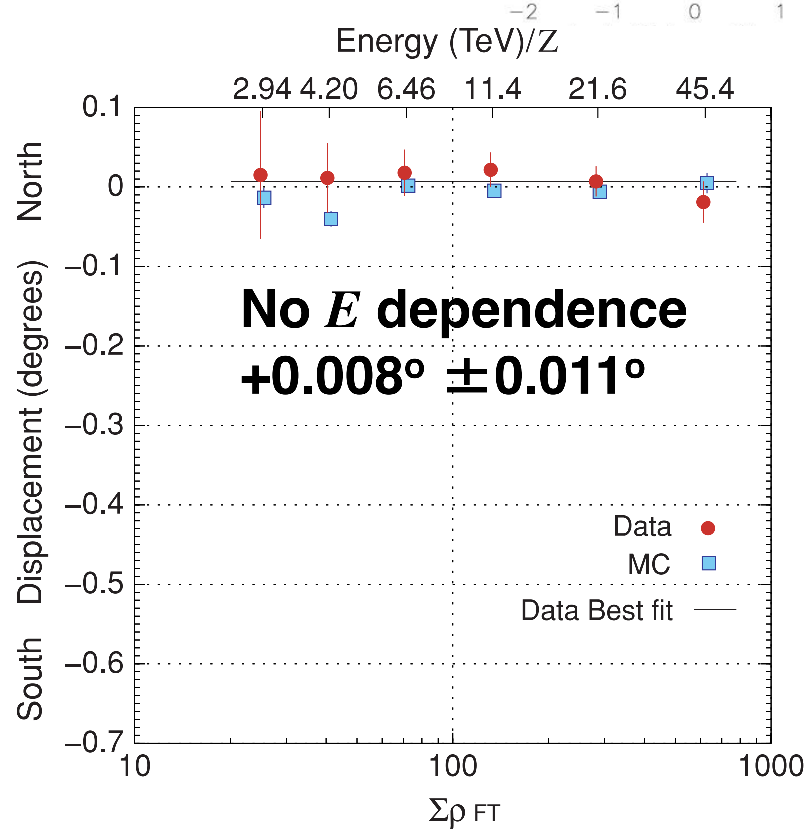


Moon Shadow Displacement

- ✓ Absolute Energy → East-West position
- ✓ Pointing Accuracy → North-South position







Absolute *E* error = ±12%

Best-fit = -4.5%(±8.6stat.±6.7sys.)%

Pointing error = ±0.014°

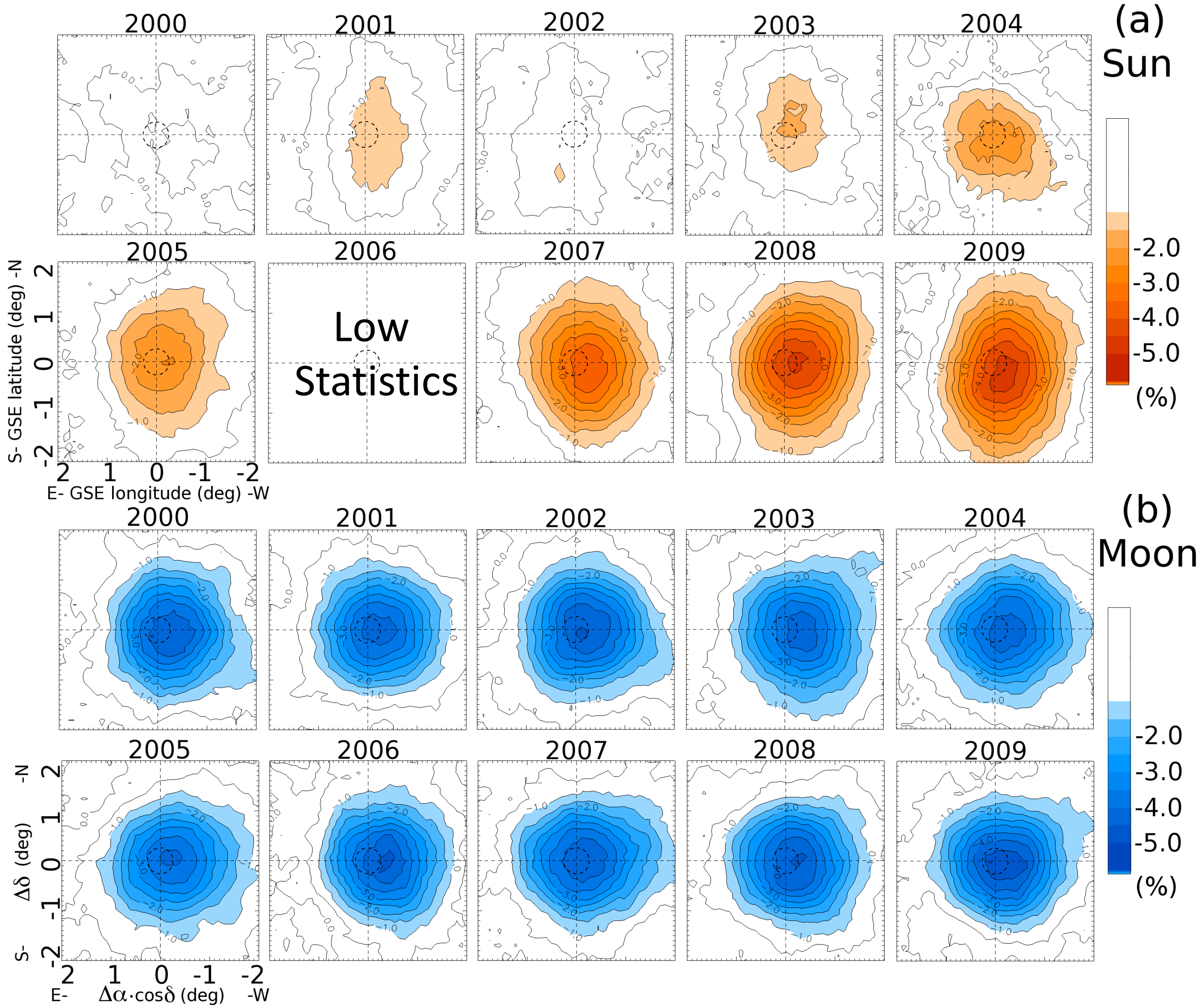
Amenomori et al., ApJ (2009)

Sun

2000-2009
Tibet-III
(>3TeV)

Moon

→ A clear solar-cycle variation of the deficits
CRs are scattered by solar magnetic field.

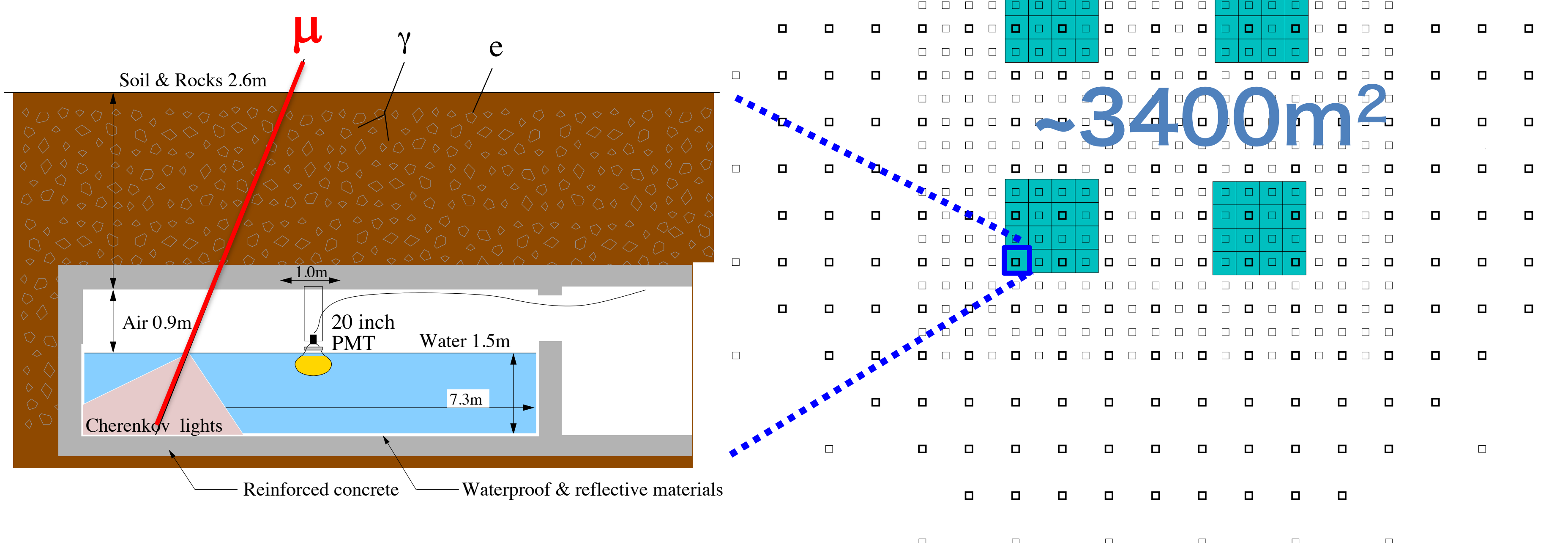


→ Shift to westward by geomagnetic field
Detector stability calibration

Amenomori et al., ApJ (2018)

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”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets



Basic idea: T. K. Sako et al., Astropart. Phys. 32, 177 (2009)

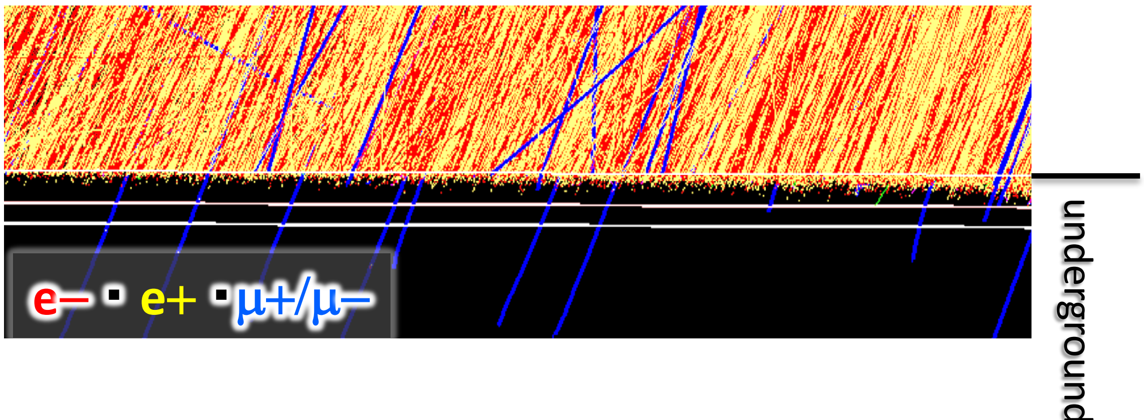
Measurement of # of μ in AS → γ／CR discrimination

p/γ Separation

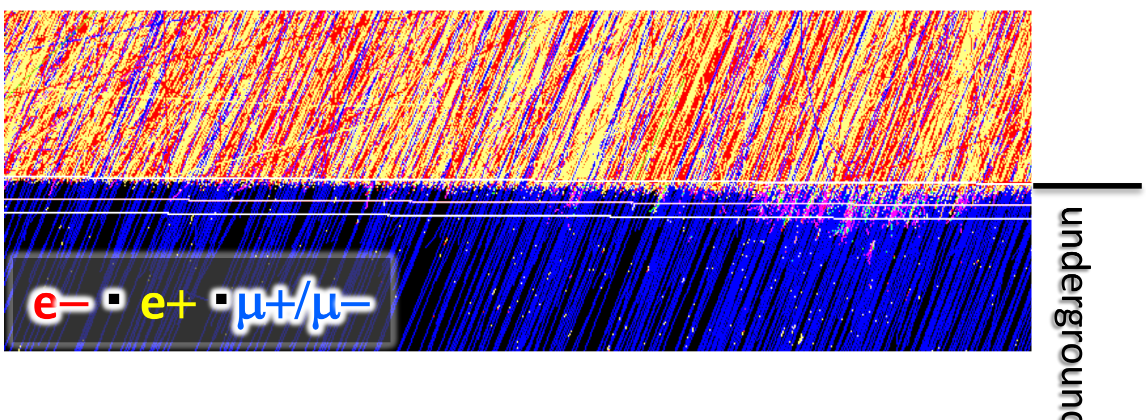
γ−ray induced AS → **Muon less**

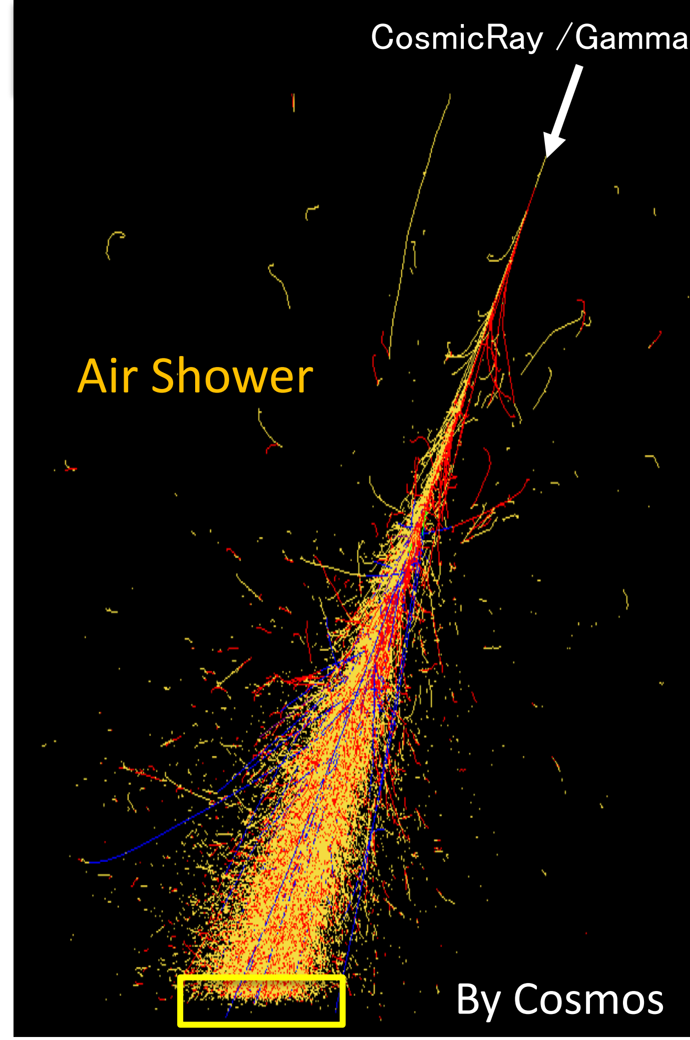
Muons penetrate to underground

200 TeV Gamma Ray



200 TeV Cosmic Ray





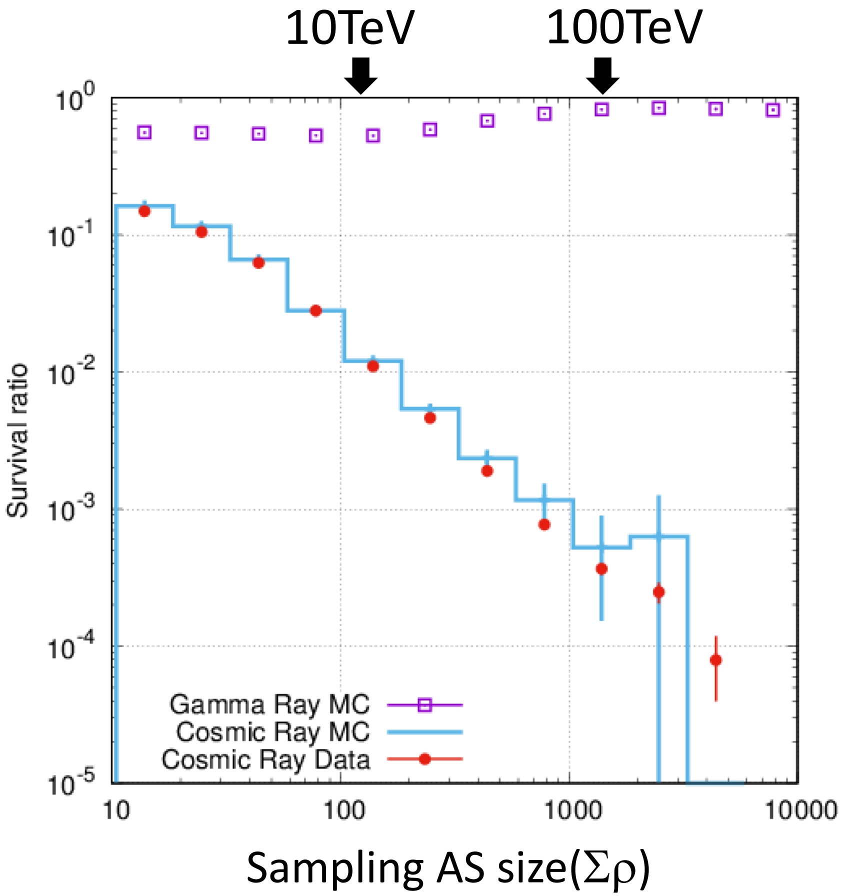
Enlarged view around ground

E ($\Sigma\rho$) vs. $N\mu$ Plot

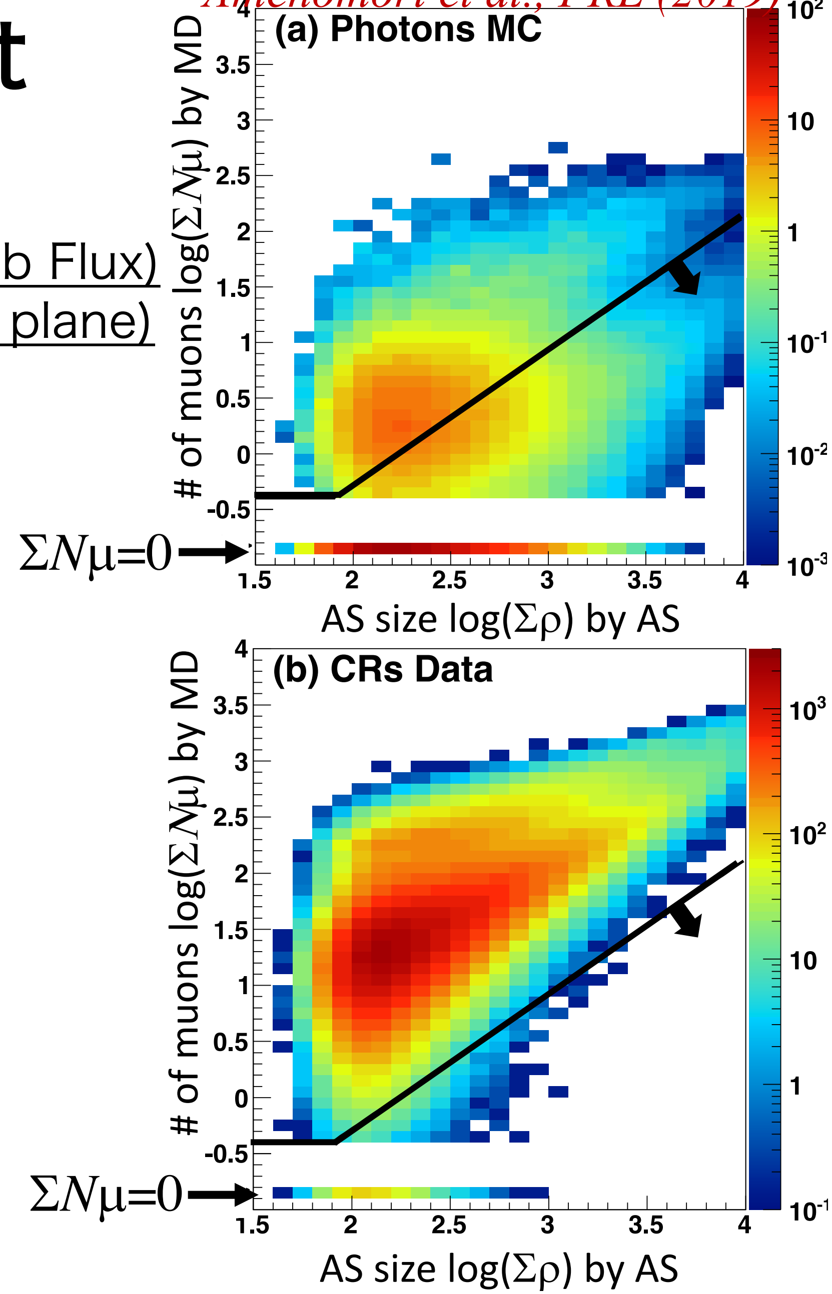
→Optimization of cut

Gamma: MC sample（Crab orbit & Crab Flux)

CR：DATA(excluding Crab and Galctic plane)

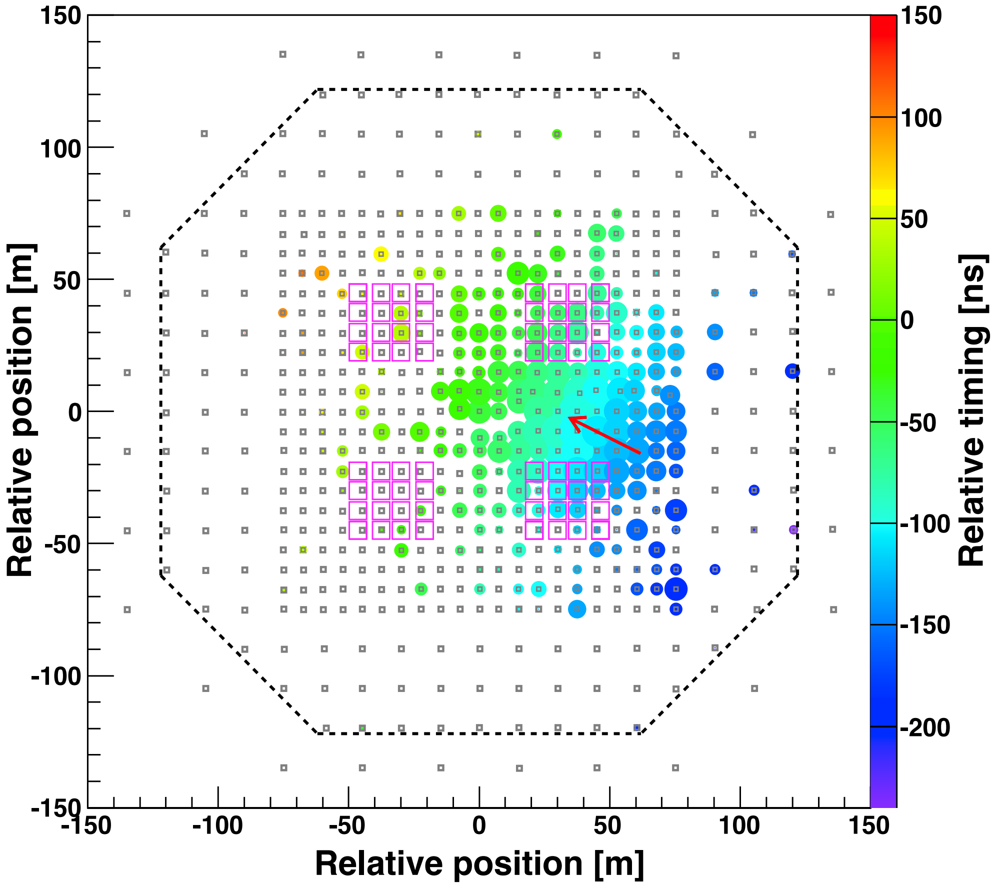


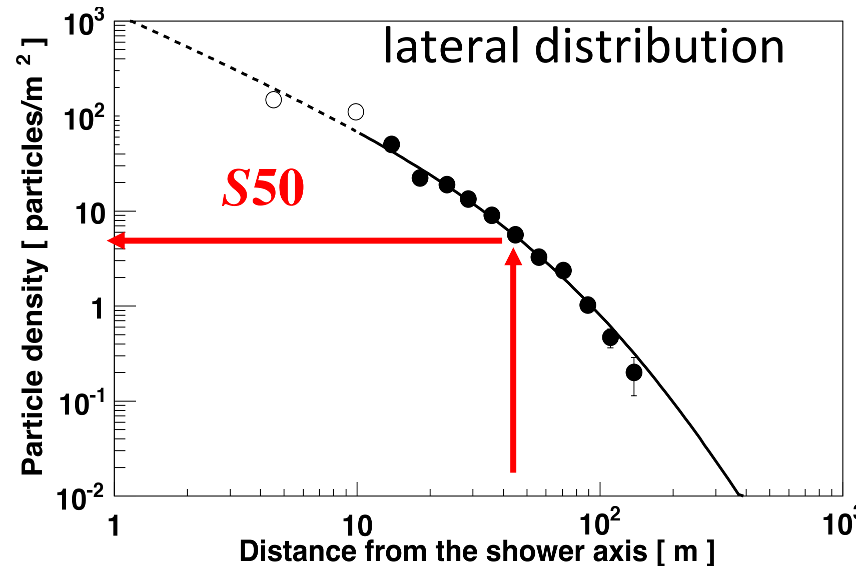
Amenomori et al., PRL (2019)



After Nμ cut,~99.9% CR rejection & ~90% γ efficiency @100 TeV

Gamma-like Event from the Crab





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

Amenomori et al., PRL (2019)

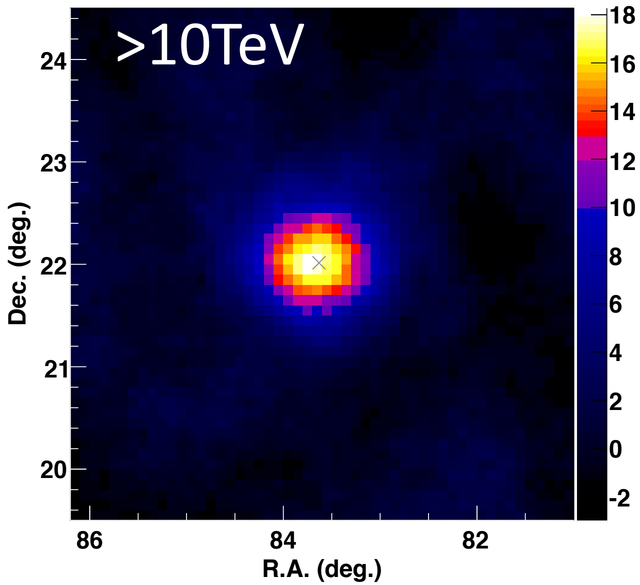
fitting with NKG function
➡ E_{rec} ($S50$, θ)

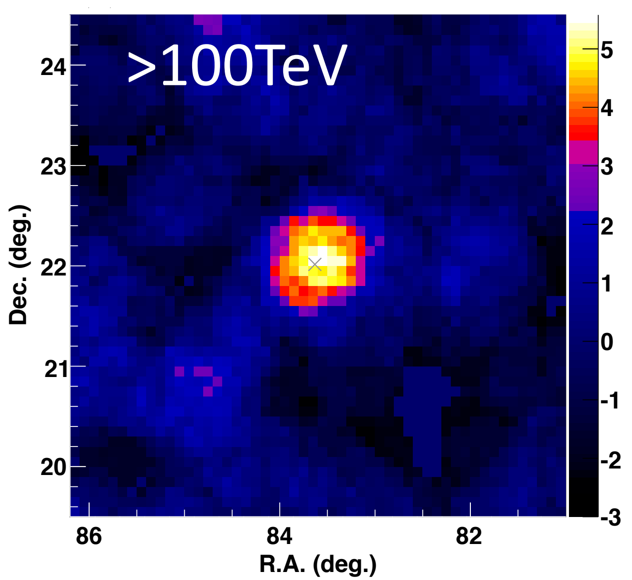
$\Sigma\rho$ (from AS array) : 3256
$\Sigma N\mu$ (MD) : 2.3
zenith angle : 29.8°
E_{rec} : 251^{+46}_{-43} TeV

S50 improves E resolutions (10 - 1000 TeV)
→ ~40%@10 TeV , ~20%@100 TeV

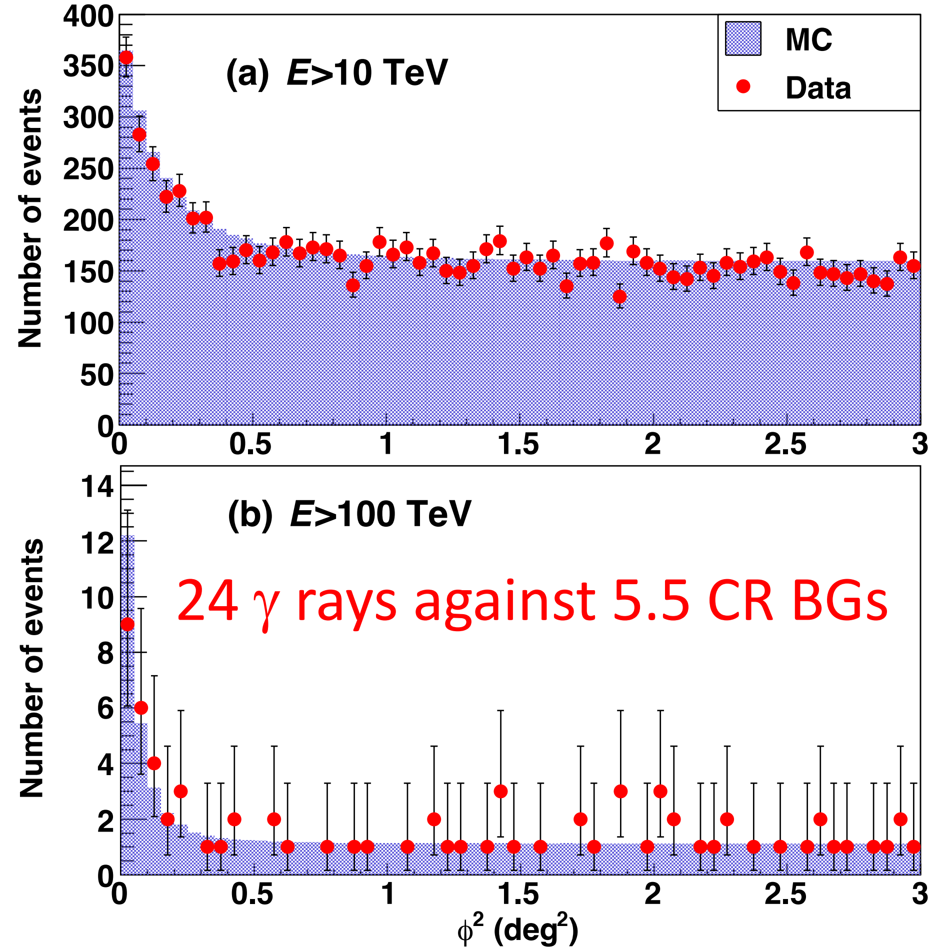
Kawata et al., Exp. Astro. (2017)

Gamma-ray Emission from Crab





Data vs MC

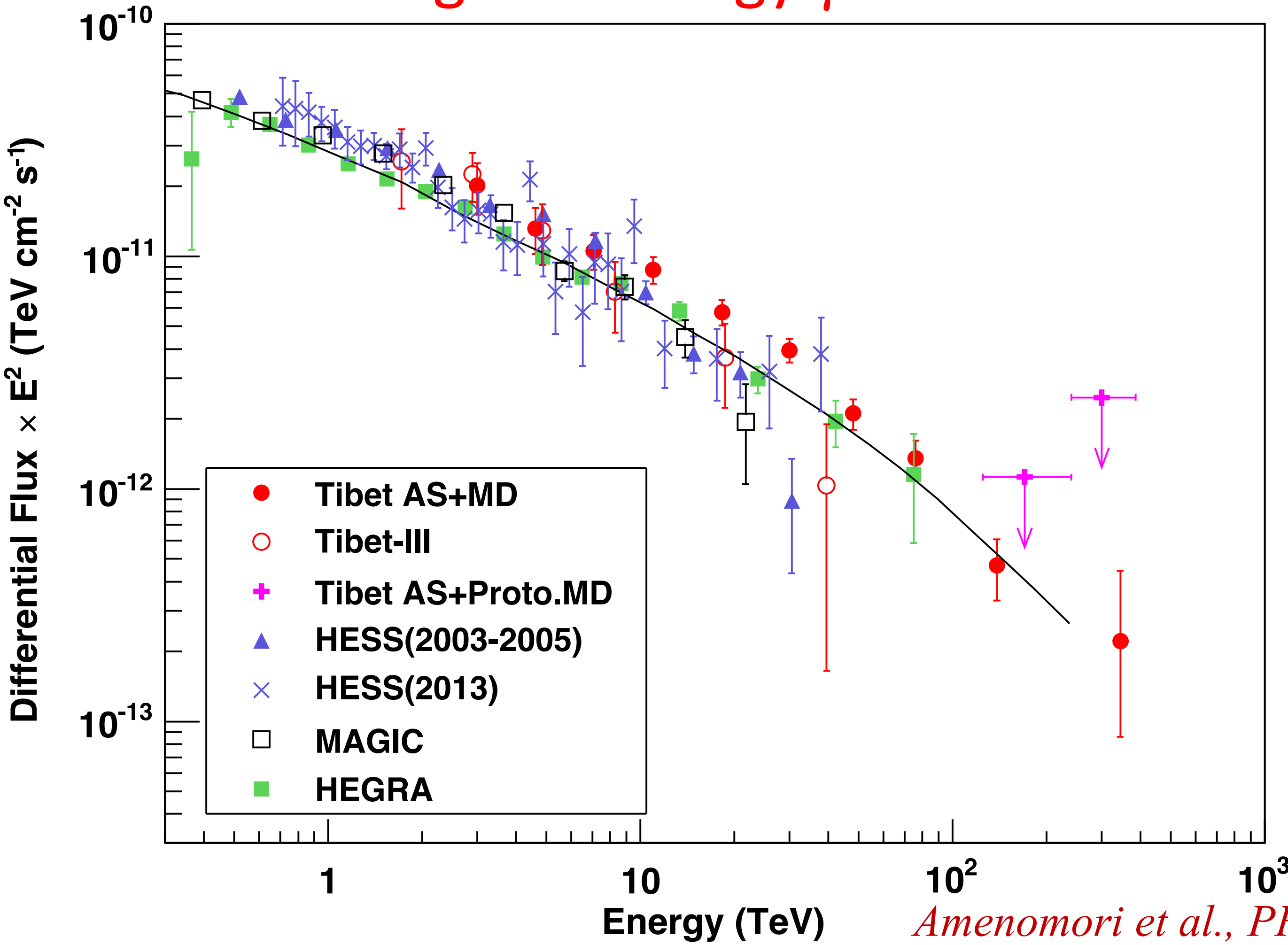


First Detection of Sub-PeV γ (5.6σ)

Amenomori et al., PRL
Supplemental Material (2019)

Energy spectrum of the Crab

The highest energy γ ~450 TeV



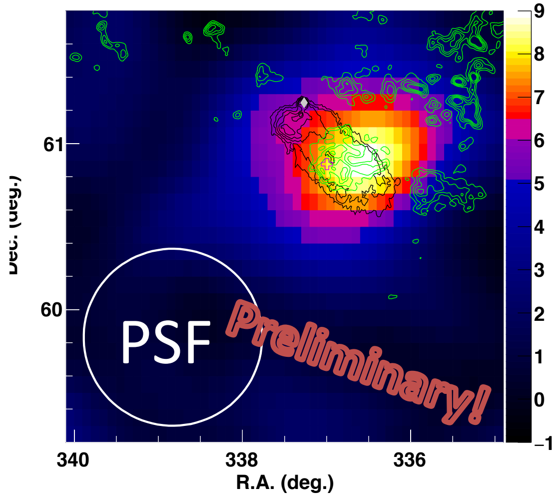
Amenomori et al., PRL (2019)

Thick curve： the expected flux by the inverse Compton model normalized to HEGRA data *Aharonian+, ApJ, 614, 897 (2004)*

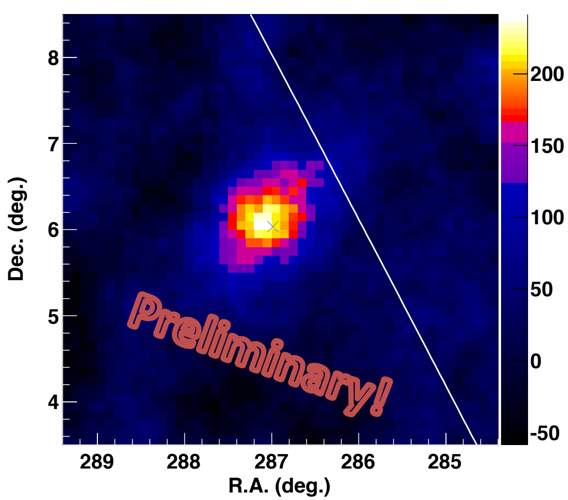
Extended Sources (>10 TeV)

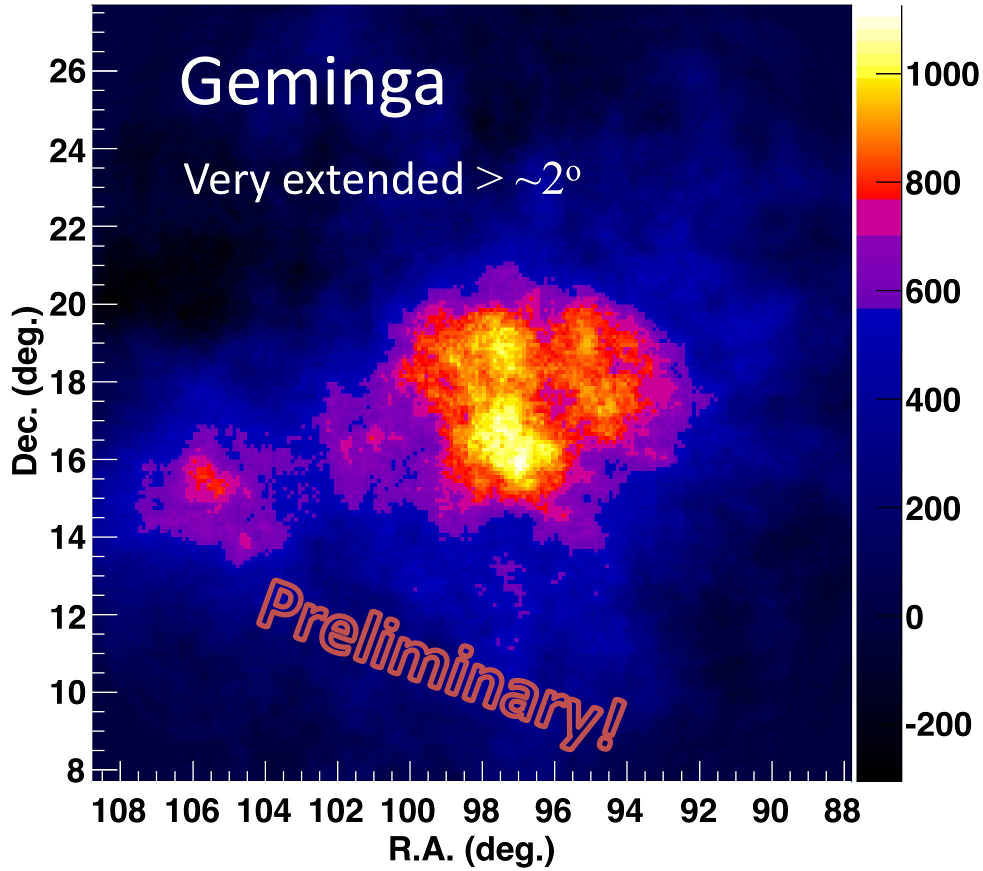
From ICRC2019

SNR G106.3+2.7



MGRO J1908+06



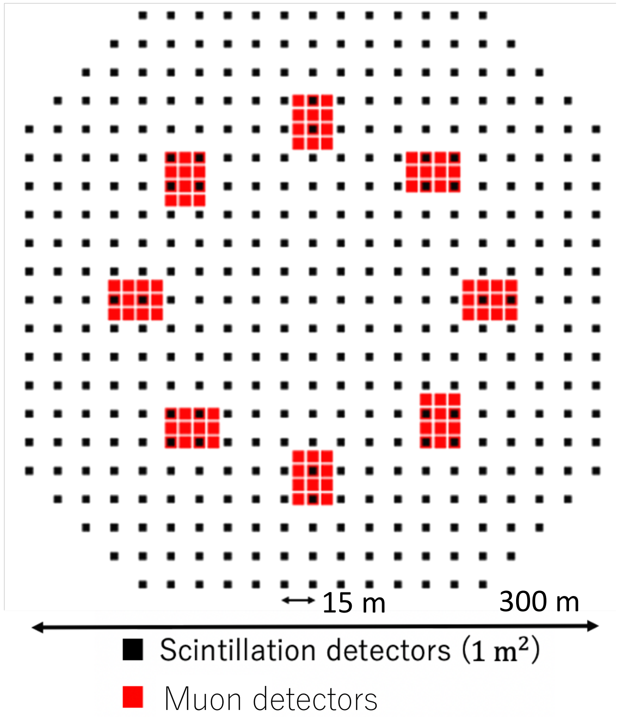


Spectrum beyond 100 TeV??

ALPACA Experiment in Bolivia

- ✓ International collaboration (Japan + Bolivia + Mexico)
- ✓ Mt. Chacaltaya, Bolivia 4740m asl
- ✓ Same type of detectors as Tibet ASγ (AS 83,000m^2 + MD 5,600m^2)
- ✓ Target energy : 10 – 1000 TeV
- ✓ Construction of prototype is ongoing

- ✓ PeVatron search in the southern sky
  - Galactic center regions, diffuse gamma
  - DM signal in the direction G.C. etc..
- ✓ Cosmic-ray anisotropy
- ✓ Sun's shadow monitor

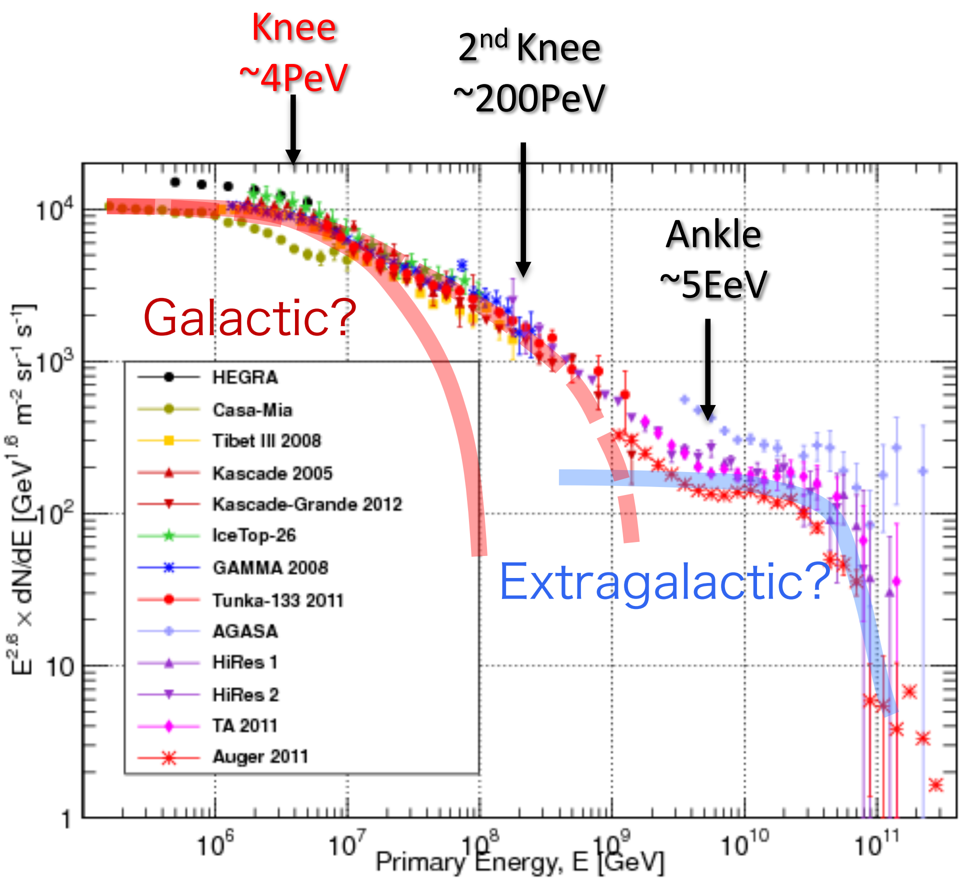








Galactic Cosmic Ray Origin



Gaisser et al. Front.Phys.(Beijing) 8 (2013) 748

- ✓ Cosmic-ray origins of Knee = PeVatrons
  → SNR?? Galactic Center?

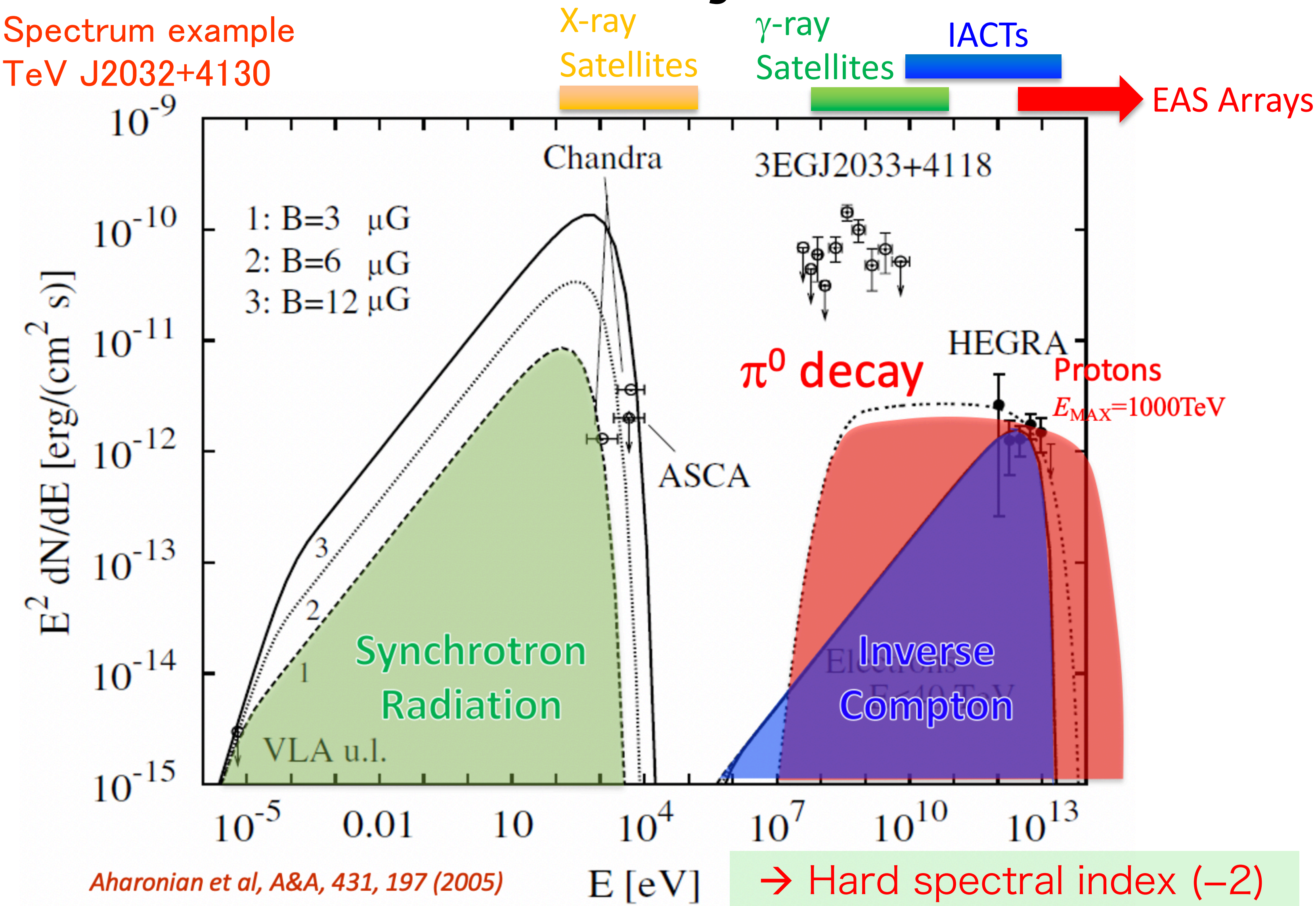
- ✓ Gamma-Ray Observation PeV protons produces ~100 TeV γ rays via π^0 decay
  (p + ISM → π^0 → 2γ)
  → Hard spectral index (–2) beyond 100 TeV
  (+ Molecular Cloud)

Different features from
Inverse Compton γ rays by HE electrons

100 TeV energy window is a key to identify Galactic CR origins!

How to Identify PeVatron

Spectrum example
TeV J2032+4130



Aharonian et al, A&A, 431, 197 (2005)

→ Hard spectral index (–2) beyond 100 TeV (+ Molecular Cloud)

How to Identify PeVatron

- γ-ray beyond 100 TeV by Tibet, HAWC etc. in North, ALPACA, SWGO in south will come soon
- Spectral index $\alpha \sim -2$ in TeV by IACTs
- Coincident with molecular cloud observed by radio
- π^0 cutoff around 70 MeV by γ-ray satellites
- Dark in X-ray observation
- Deep observation by IACTs to resolve sources
- Coincident with HE neutrino by IceCube

Multi-wavelength Multi-particle Observations