Reference:
Abbasi, R.U., et al., ApJL, 790, L21
Published July 2014

Highest-Energy Cosmic-Ray Hotspot Observed by the Telescope Array Experiment

Kazumasa Kawata
ICRR, University of Tokyo
For the Telescope Array Collaboration

29 institutions, 126 members

Telescope Array Collaboration

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Outline

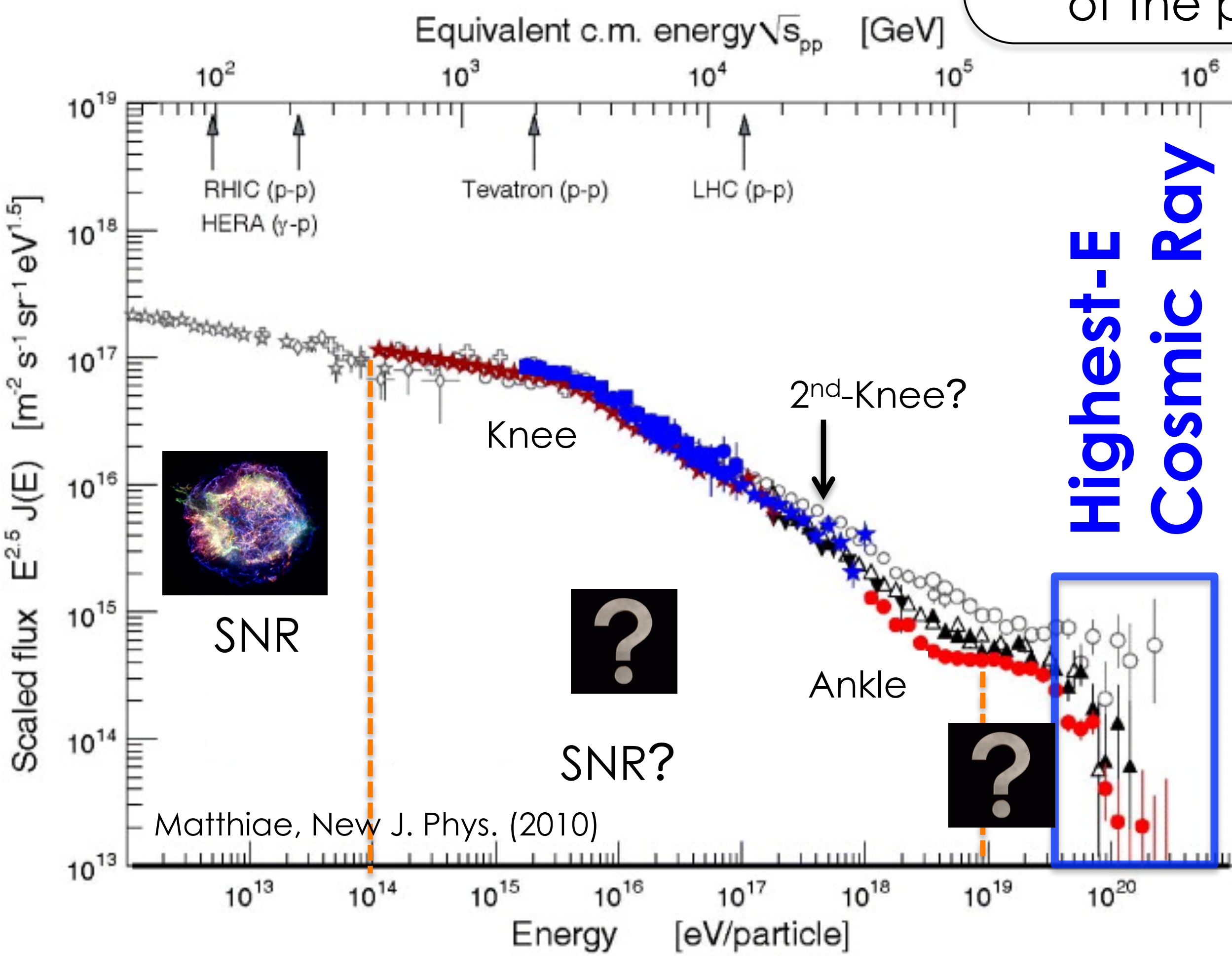
- Highest-Energy Cosmic Ray
- Telescope Array Experiment
- Hotspot Analysis & Result
- Discussions
- Summary & Future Prospects

+ New 1-year result

Highest-Energy Cosmic Ray

- Cosmic rays
  Power-law spectrum
  in wide energy range

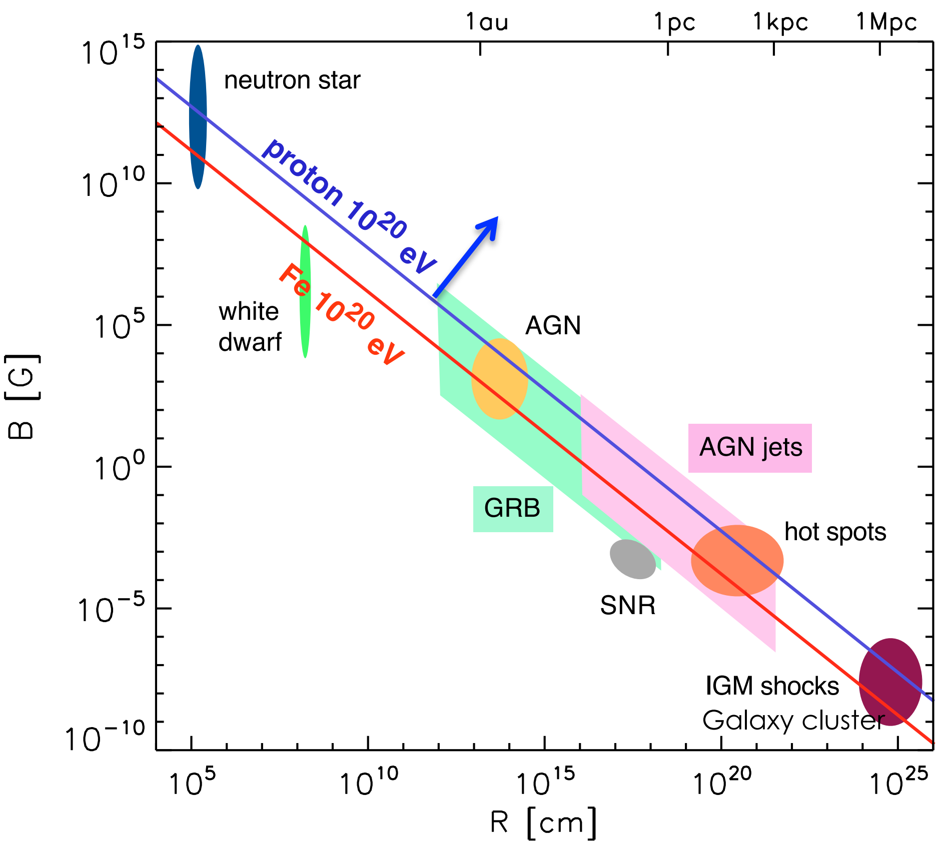
- Origin of cosmic ray up to 10^{14}eV
  - SNRs in our Galaxy
  GeV-TeV observations gave
  some indirect evidences
  of the proton acceleration



- 10^{14}eV – 10^{19}eV
  (Knee - Ankle)
  - Index changes
  - Composition changing
  - Galactic objects?

- Highest-E cosmic rays
  around 10^{20}eV
  - Flux suppression
  - Extragalactic (AGNs?)
  - 1 particle/100km²/ year

Hillas Diagram



Kotera & Olinto, Annu. Rev. Astron. Astrophys (2010)

- Larmor Radius R_L

  $=100\text{kpc}\ Z^{-1}\ (\mu G/B)(E/100\text{EeV})$
  >> galactic disk

- Source should have capability of confining particle up to E_{MAX}
- Necessary condition, but not sufficient
- E_{MAX} depends on acceleration mechanism
- Recent simulations relativistic shocks in AGN can't accelerate up to 10^{20}eV?

Motivation

Search for Violent Accelerator in the Universe

Energetic jets of active galaxy（Centaurus A）

ESO/WFI (visible); MPIfR/ESO/APEX/A.Weiss et al. (microwave); NASA/CXC/CfA/R.Kraft et al. (X-ray))

Motivation

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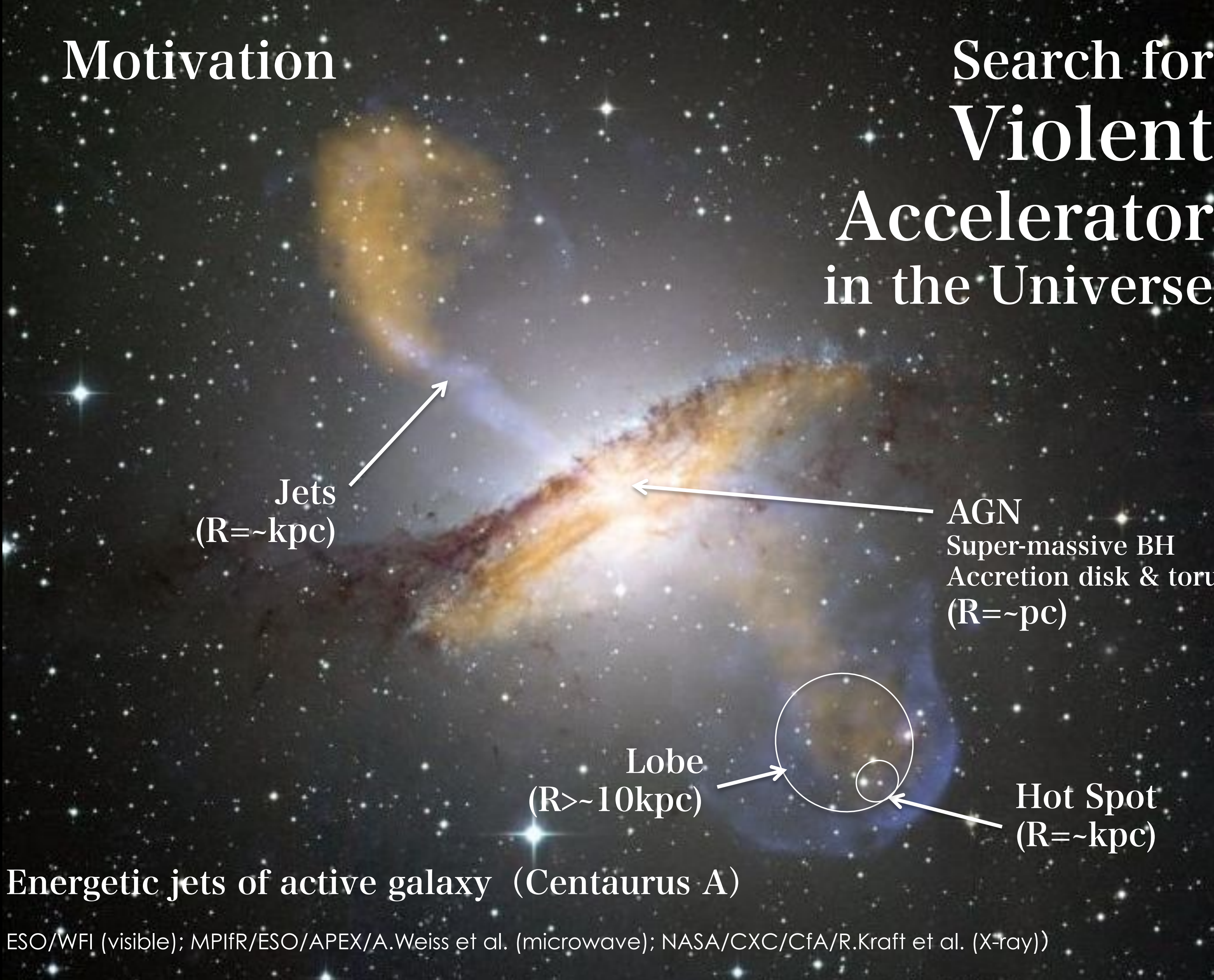

Energetic jets of active galaxy（Centaurus A）

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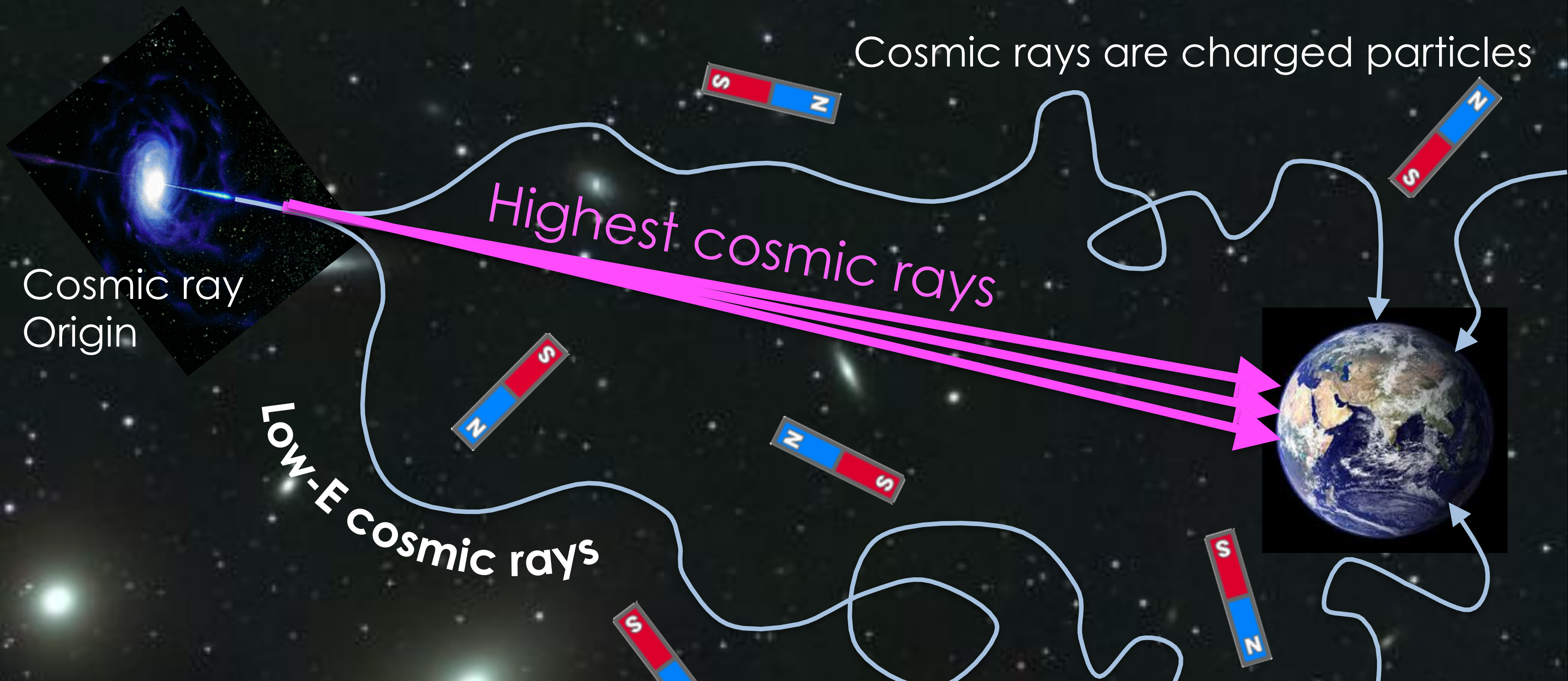
Search for Violent Accelerator in the Universe

Colliding clusters of galaxies

STScI, U. Arizona, CfA, CXC, NASA

Gamma Ray Burst
Artist view (ES0)

Why highest energy cosmic rays?



- Low energy cosmic rays
  - → bend by the magnetic field
  - → Isotropy at the Earth
- Highest energy cosmic rays
  - → Almost go straight against magnetic field
  - → Possible to find cosmic-ray origin directly

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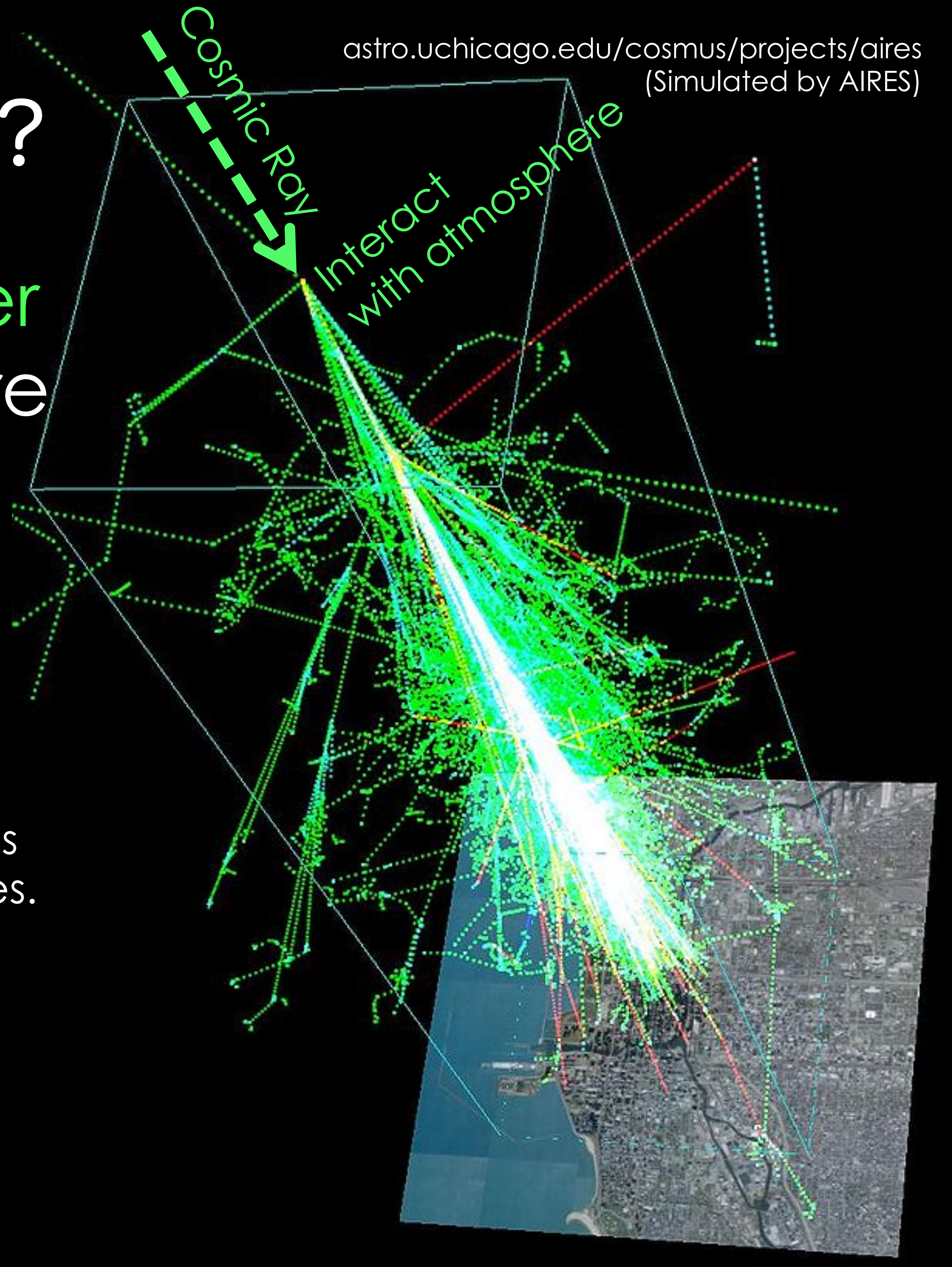
What do we see?

Detect Air Shower in the atmosphere



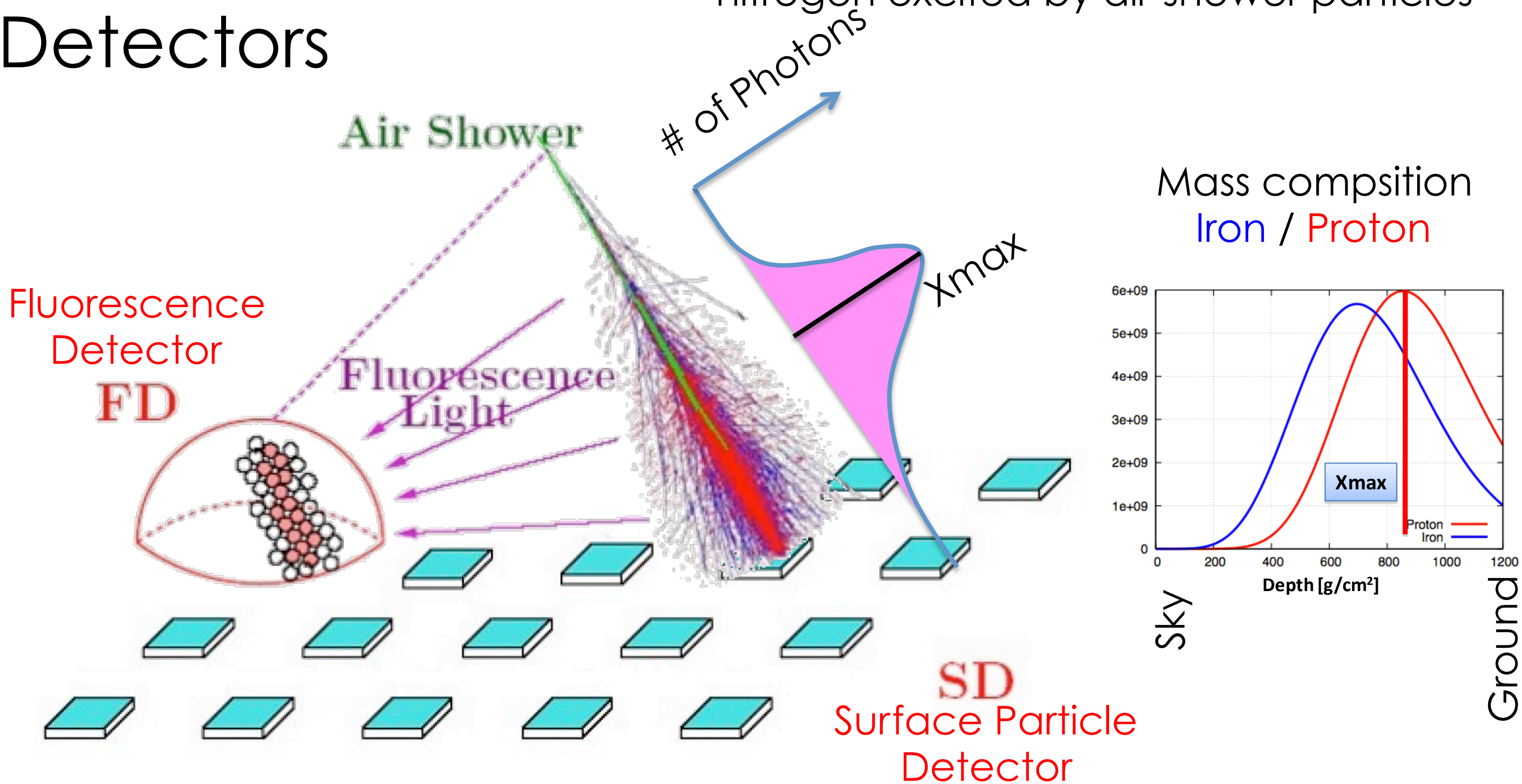
When cosmic ray interact with nuclei in atmosphere, many secondary particles are generated.

✧ A highest-E cosmic ray makes more than 100 billion particles.

✧ Air shower expand across a few km on the ground

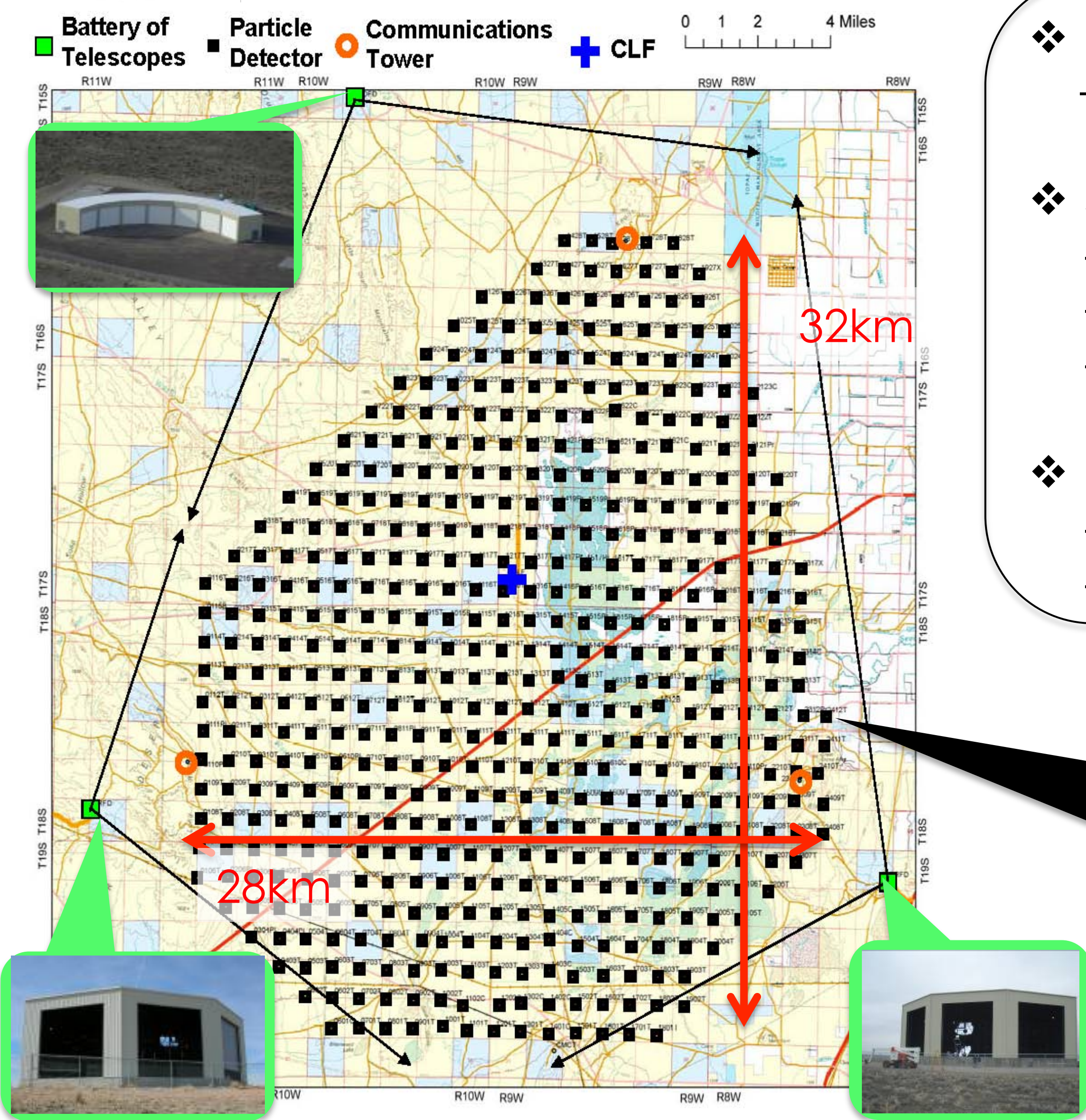
Two Different Type Detectors

Detect fluorescence lights emitted from nitrogen excited by air-shower particles



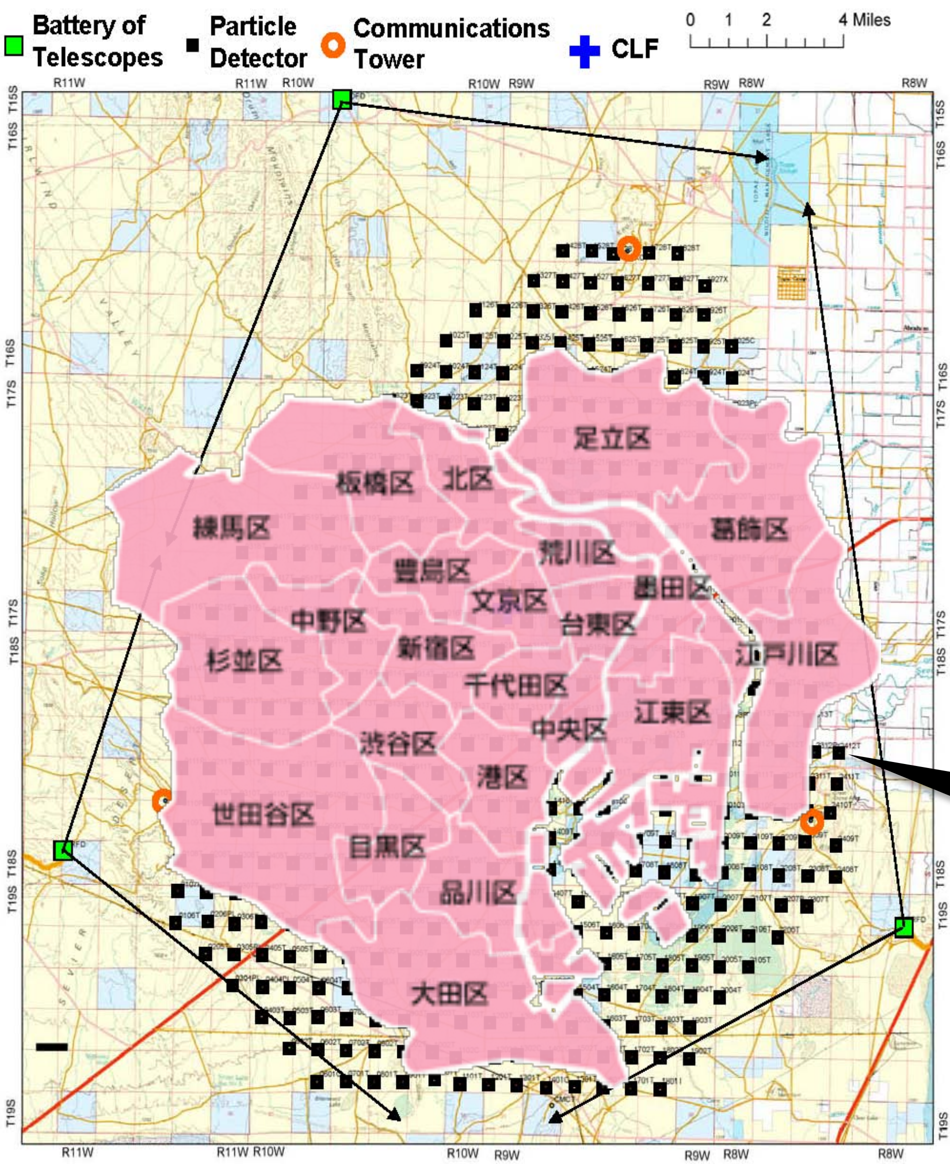
SD : Regardless of weather condition with high duty circle and wide FoV.
→ High statistical data → Anisotropy & spectral shape
FD : limited to clear moonless night.
Longitudinal development of air shower → Mass composition (Xmax)
Measure the energy deposit calorimetrically → Absolute energy scale

Telescope Array Experiment



- Desert in Utah, USA
  - 39.30°N, 112.91°W
- Surface Particle Detector (SD)
  - $3m^2$ Scintillation Detector
  - 507 det. With 1.2km spacing
  - Distributed across $700km^2$
- Fluorescence Detector (FD)
  - 3 stations
  - 12 telescopes / station

Telescope Array Experiment



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    ~Tokyo 23 wards
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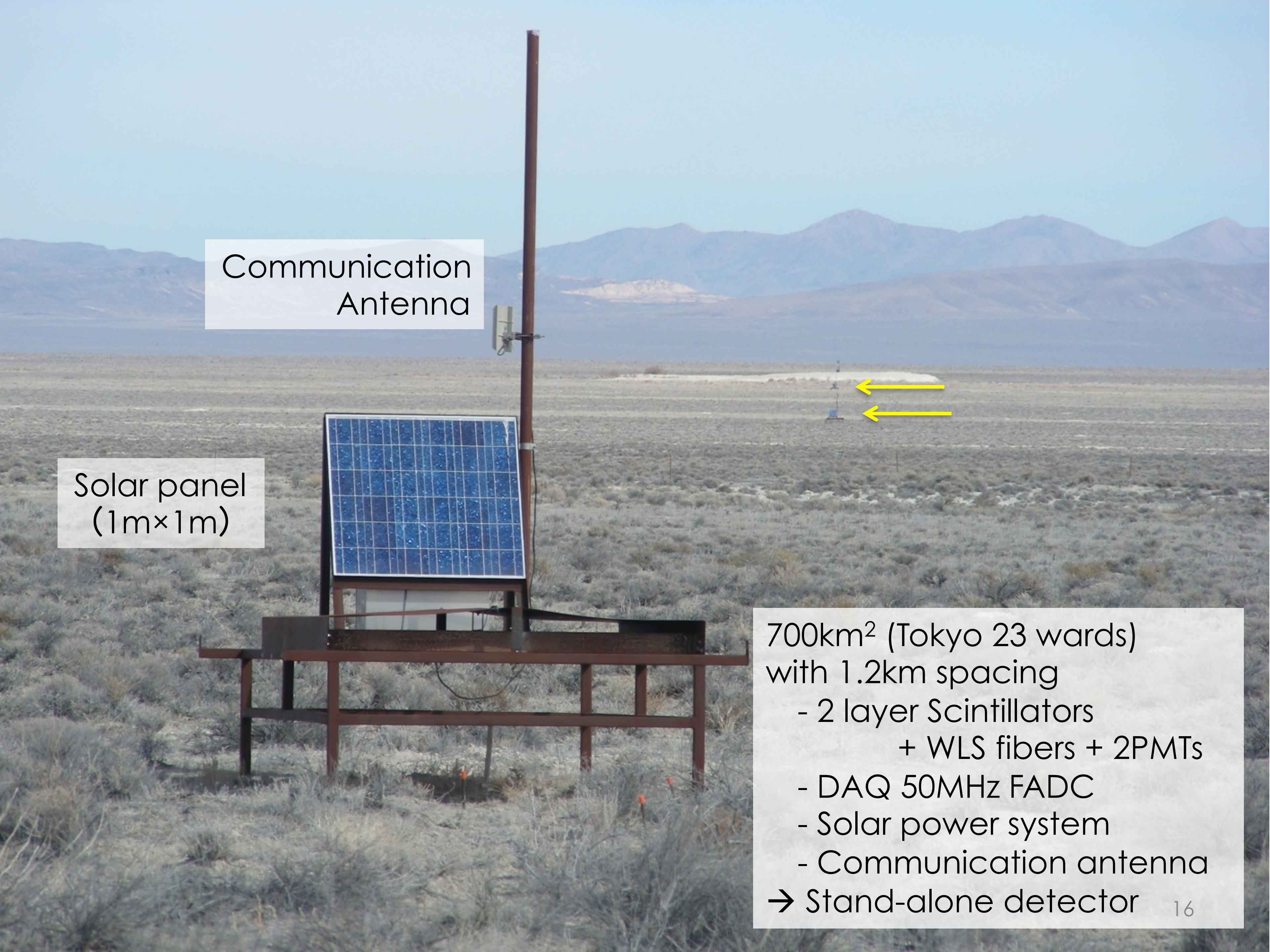
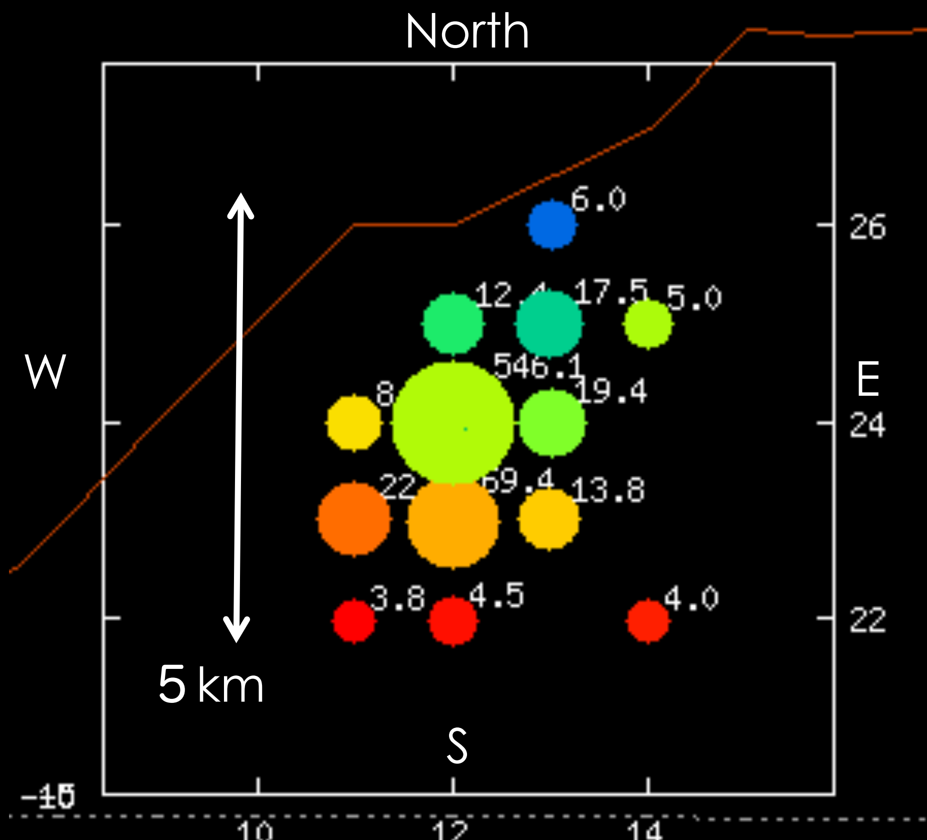
Detect fluorescence lights emitted from
nitrogen excited by air-shower particles

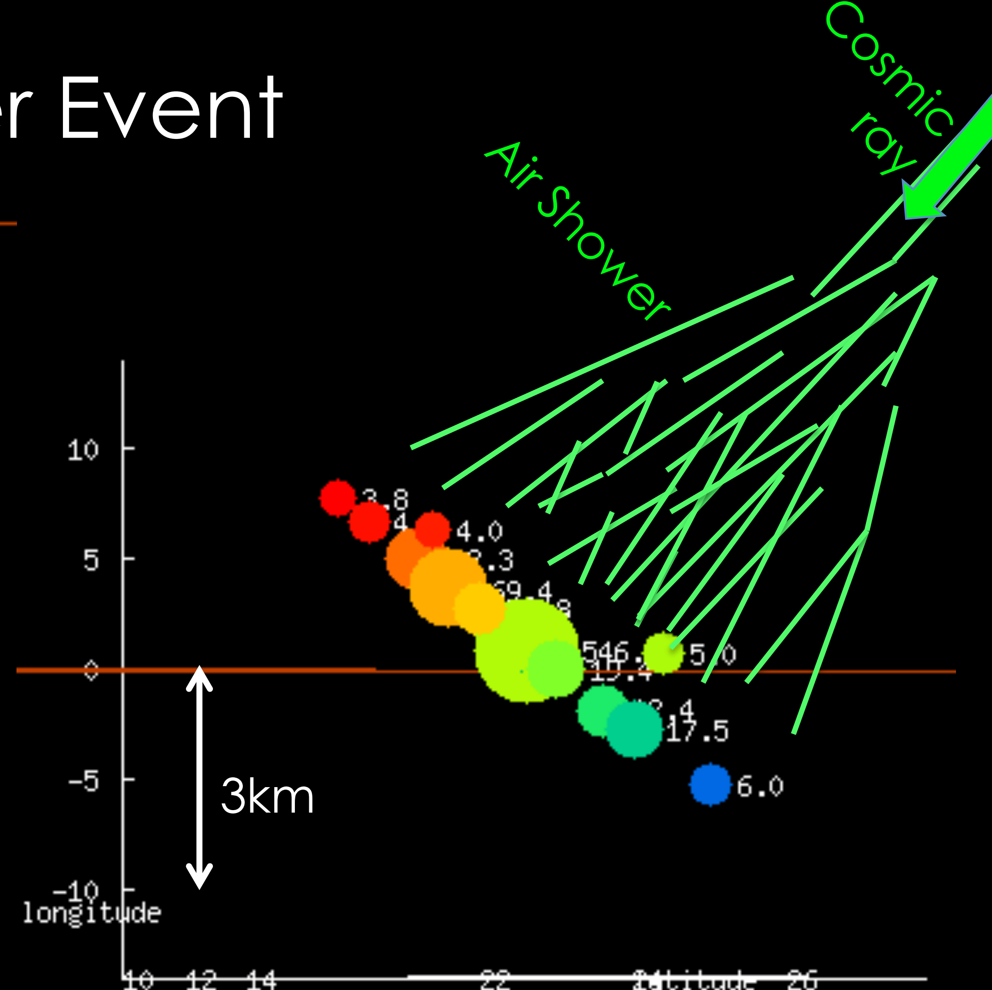

Communication Antenna
Solar panel (1m×1m)
700km² (Tokyo 23 wards)
with 1.2km spacing
- 2 layer Scintillators
+ WLS fibers + 2PMTs
- DAQ 50MHz FADC
- Solar power system
- Communication antenna
→ Stand-alone detector


Scintillator
DAQ records
signal size & timing

Recorded Air Shower Event



Upper view



Side view

Radius : Signal size → Cosmic ray energy
Color : Signal timing Blue→ Early Red→Late
→ Cosmic ray direction

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SD Data Set

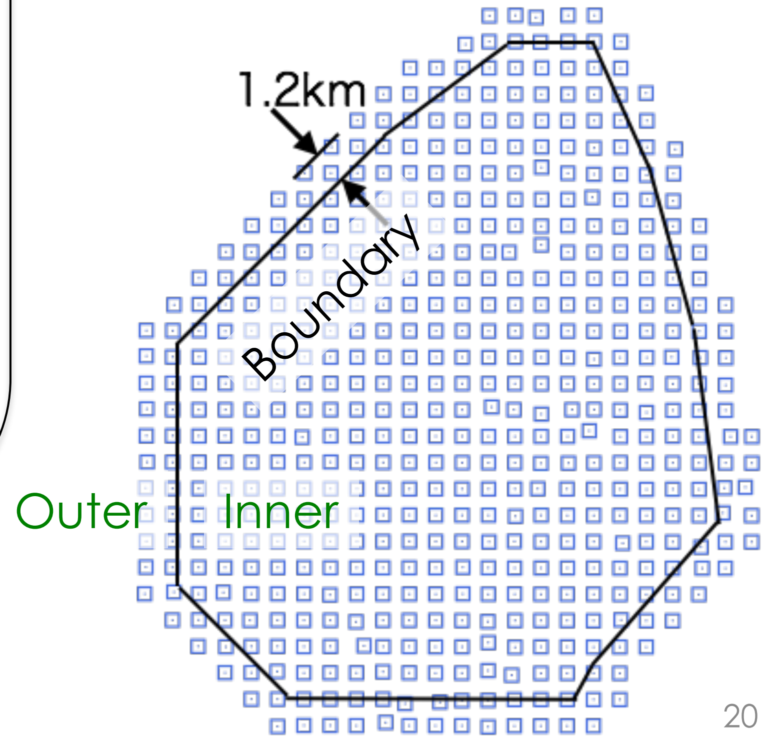
❖ Period :
2008 May – 2013 May (5 years)

❖ Cut conditions :
- # of used detectors >=4
- Zenith angle < 55°
- Energy > 57EeV
(which corresponds to the energy determined by the AGN correlation analysis by the Auger group in 2007)
- No boundary cut
(increase +20 events, but worsen E & angular resolutions)

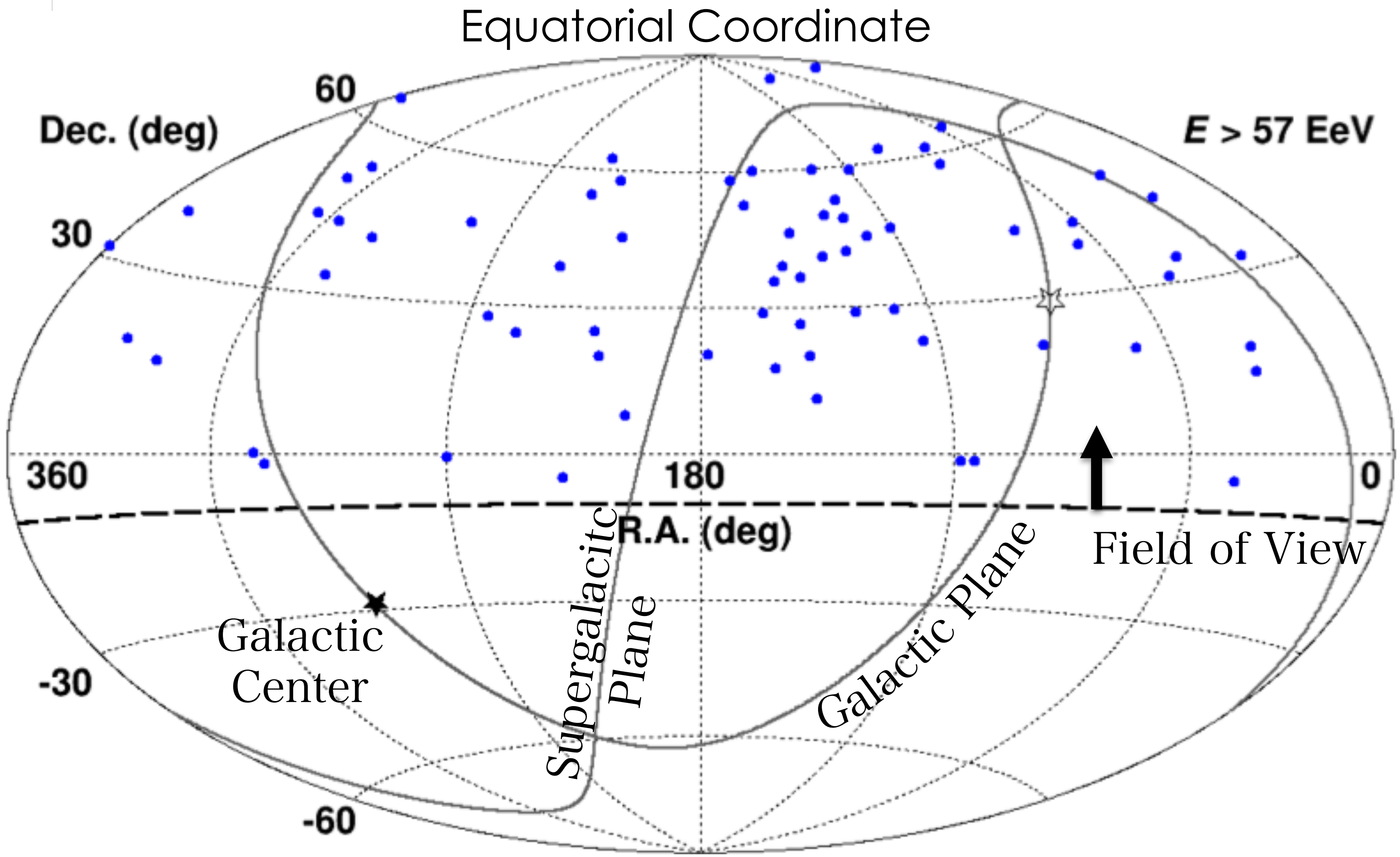
= 72 events

Resolutions	Inner	Outer
Angular	1.0°	1.7°
Energy	15%	20%

→ Good enough to search for intermediate-scale anisotropy



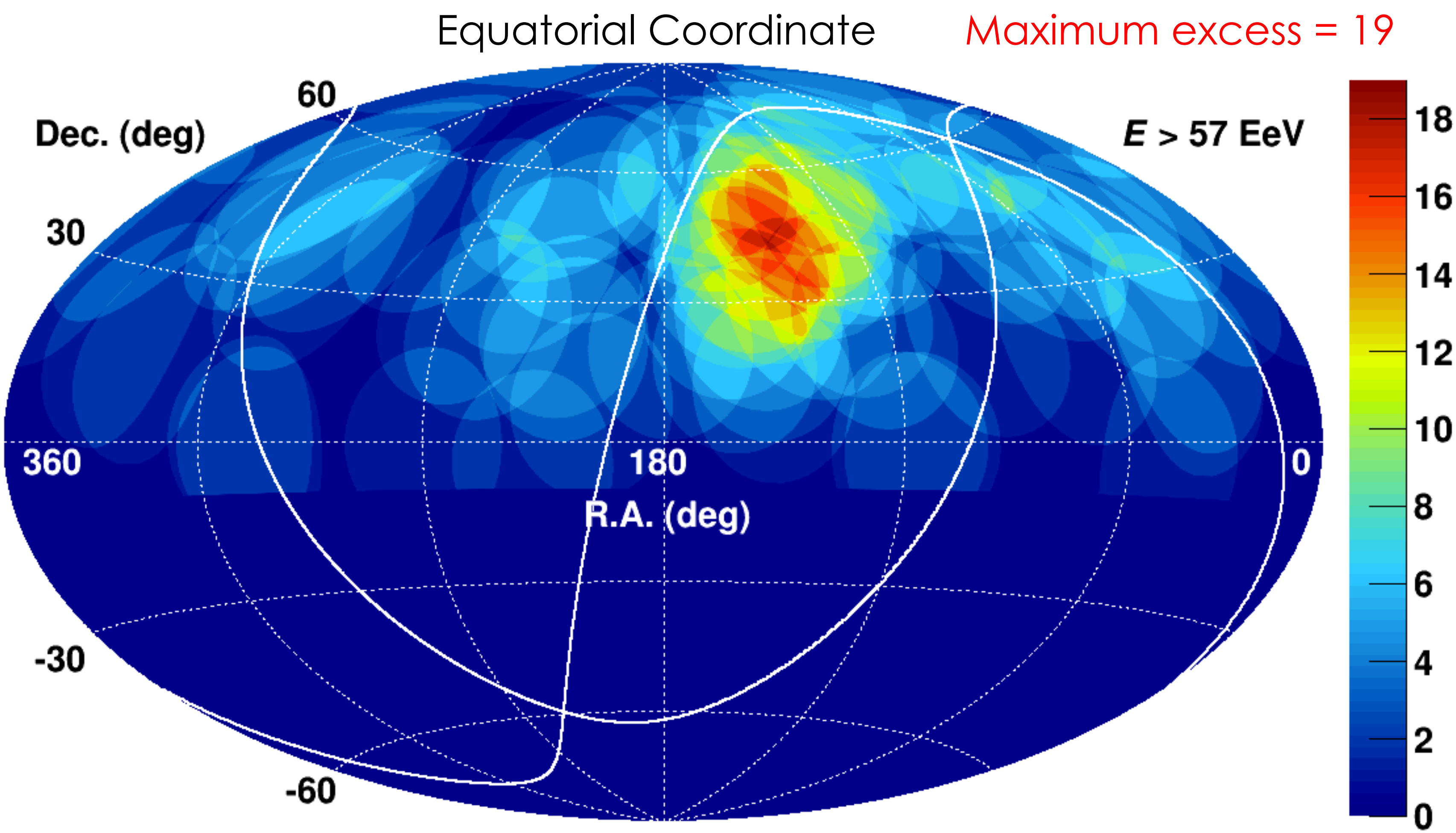
Directions of Cosmic Rays



72 TA events on the equatorial coordinate

Full event table is available in the ApJL online journal :
http://iopscience.iop.org/2041-8205/790/2/L21/suppdata/apjl498370t1_mrt.txt

Events Summed Over 20°-radius-circle

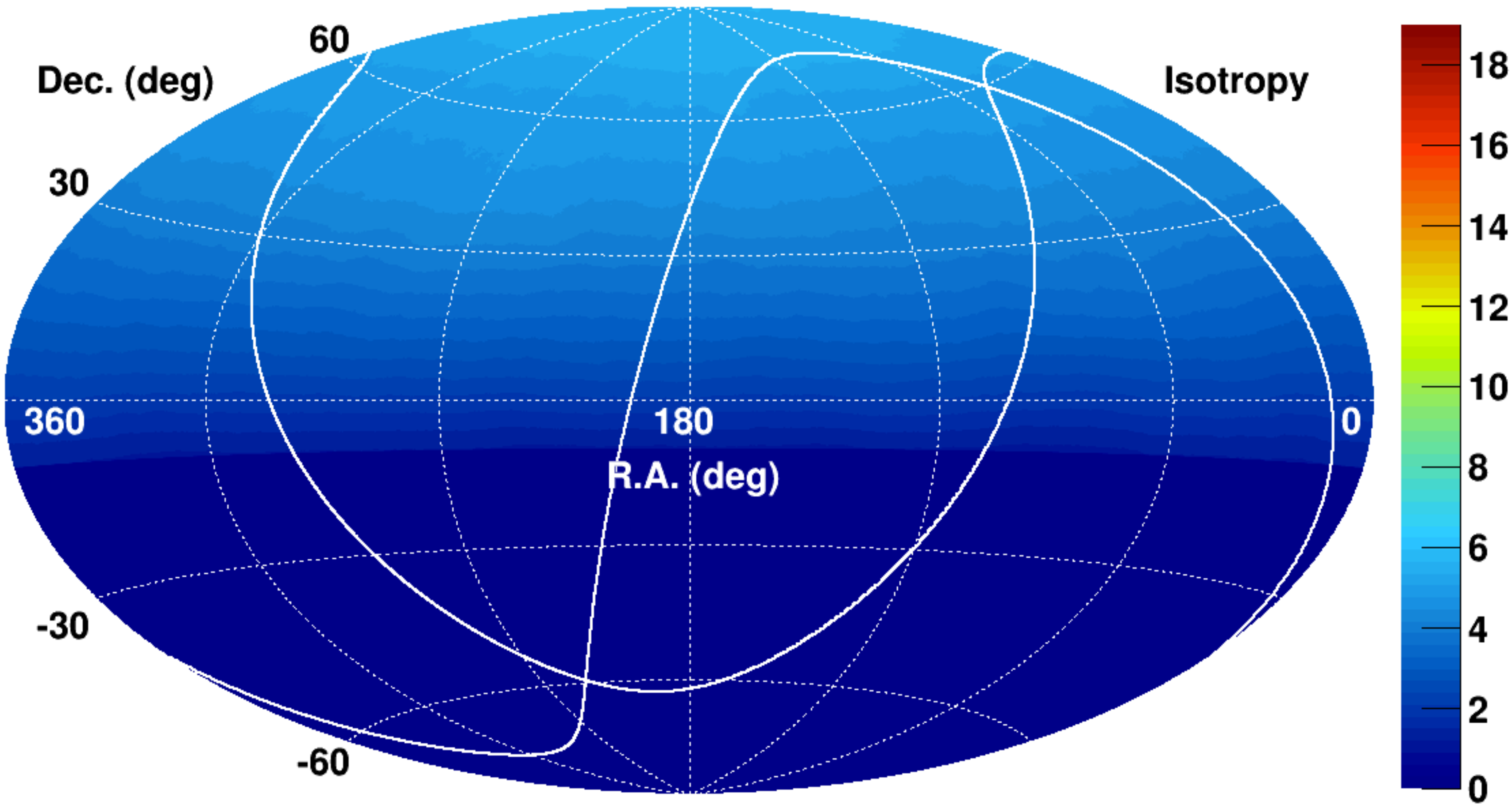


20°-radius circle was used for intermediate-scale anisotropy search around 1EeV by the AGASA, HiRes and TA. (Kawata et al. 2013 ICRC)

Isotropic Sky Background

(Events Summed Over 20°-radius-circle)

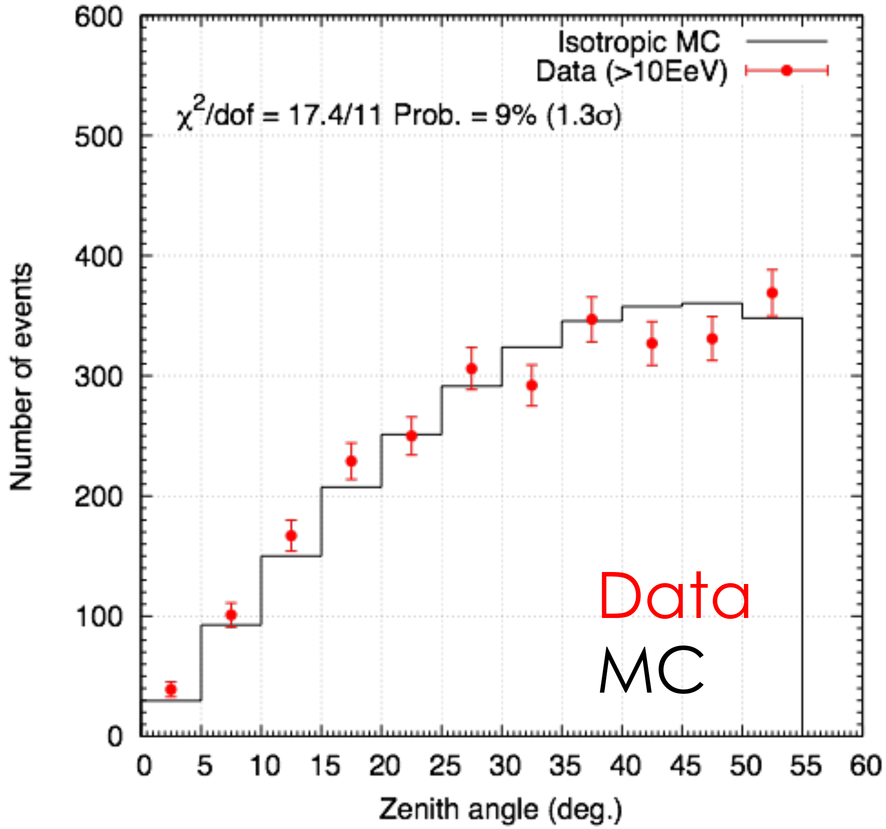
Equatorial Coordinate B.G at Dec 40° = ~4.5

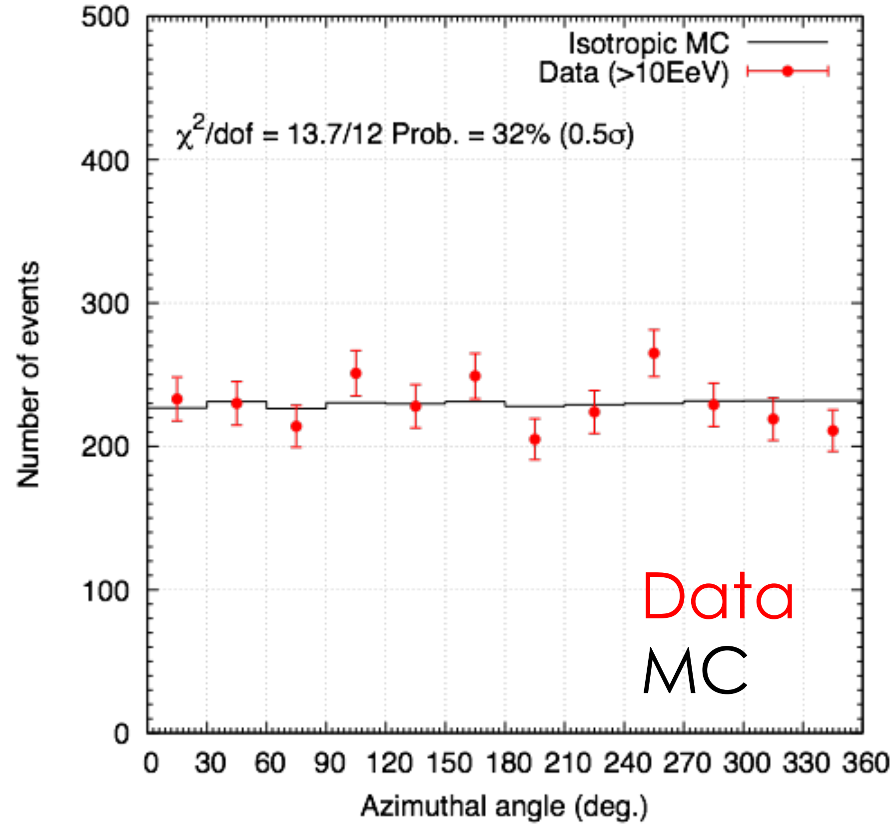


By the MC simulation assuming TA geometrical exposure

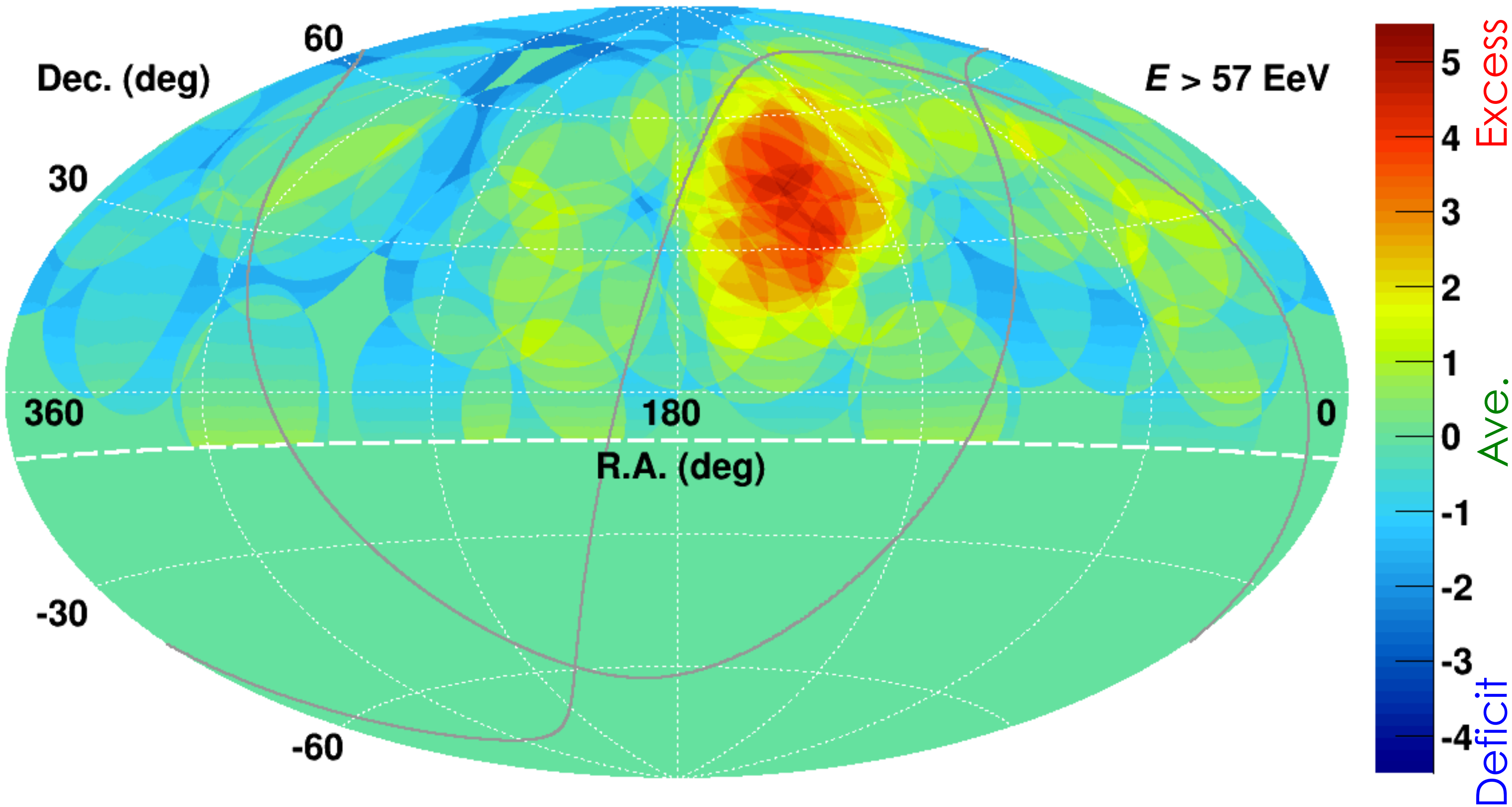
Data/MC Comparison(>10EeV)

MC simulation was verified
by high-statistics control sample (>10EeV)





Significance Map 5 years



Found cosmic ray “hotspot” at specific region

→ Max Significance 5.1σ at R.A.=146.7°, Dec.=43.2°

Chance Probability

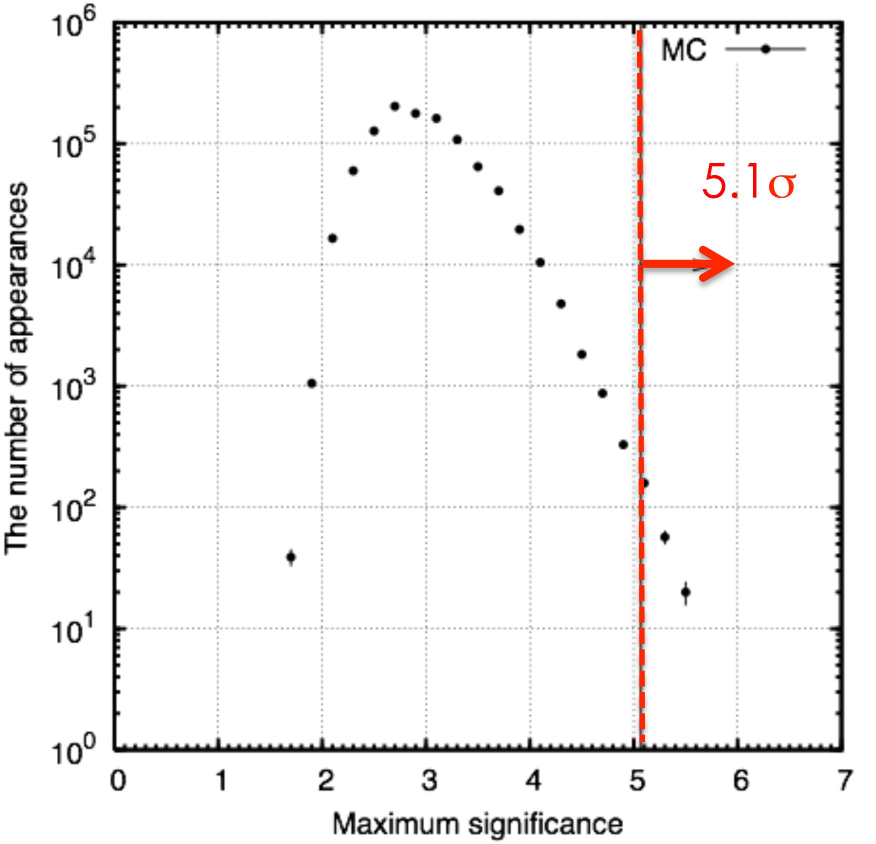
Random 72 events assuming isotropy
(TA geometrical exposure)

↓

Adopt same analysis & create significance maps
(by five oversampling radius : 15, 20, 25, 30, 35 deg.)

↓

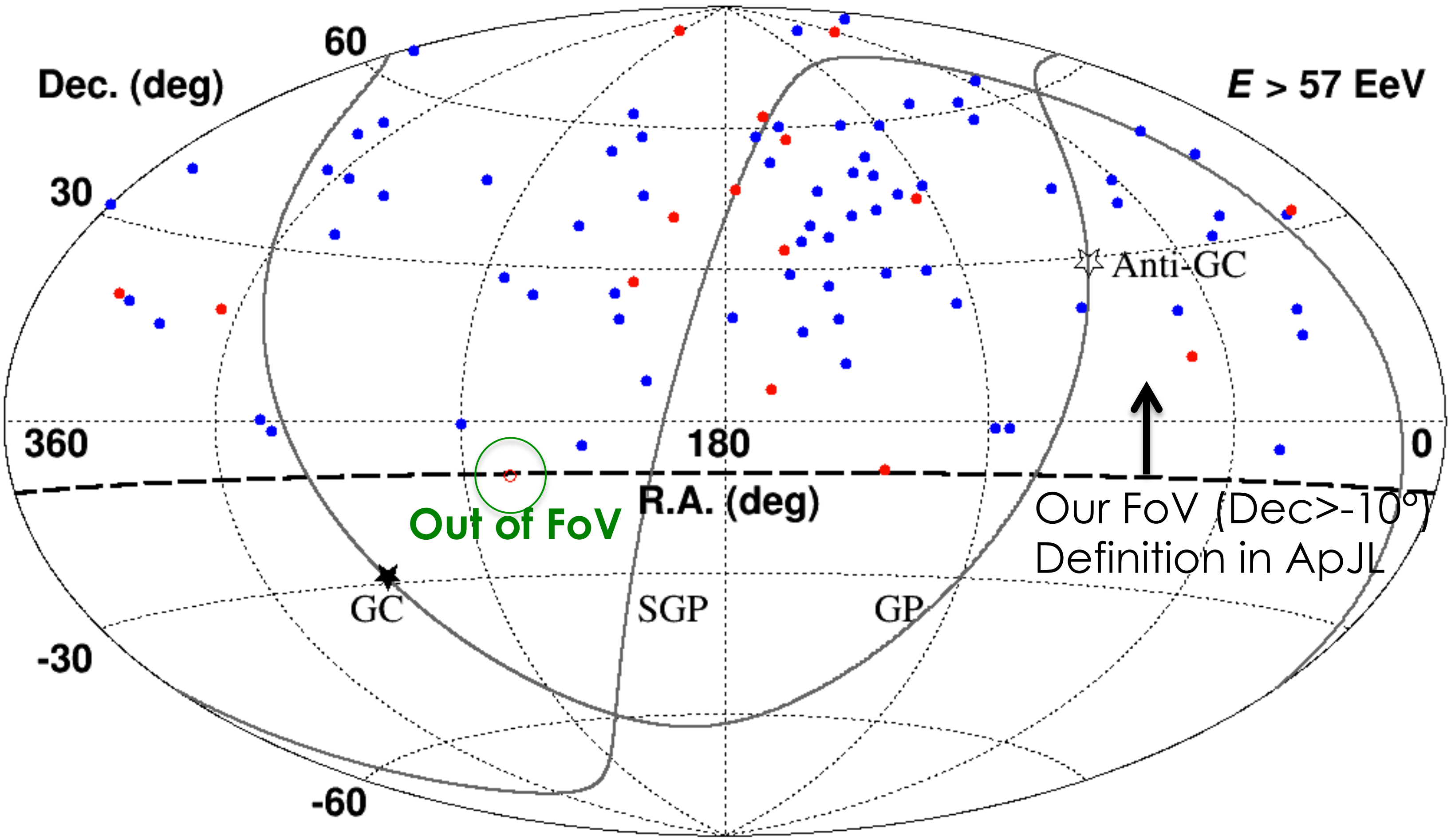
Search for maximum significance in the FoV



Repeat 1 million times
How many $>5.1\sigma$?

P = 371 / 1,000,000 trials
= 3.7×10^{-4} (3.4σ)

6-Year Data by TA



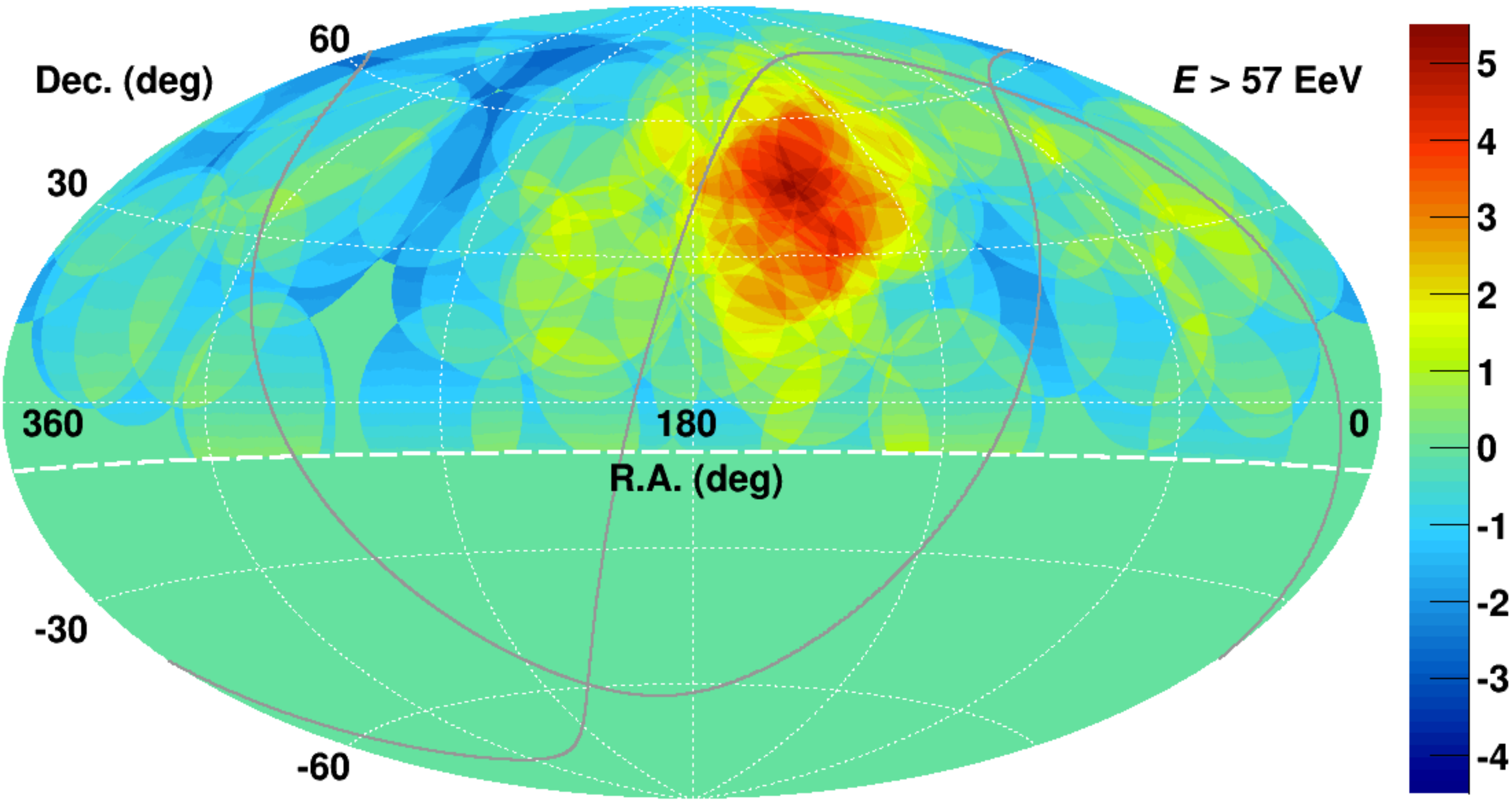
5-year data
New 1-year data

Period:
2008 May 11 – 2014 May 11 (87 events)

Significance Map 6 years

New!

Oversampling with 20°-radius circle



Max significance **5.55σ** (N_{on} = 23, N_{bg}=5.49)
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Chance probability of appearing in isotropic sky → **4.0σ**

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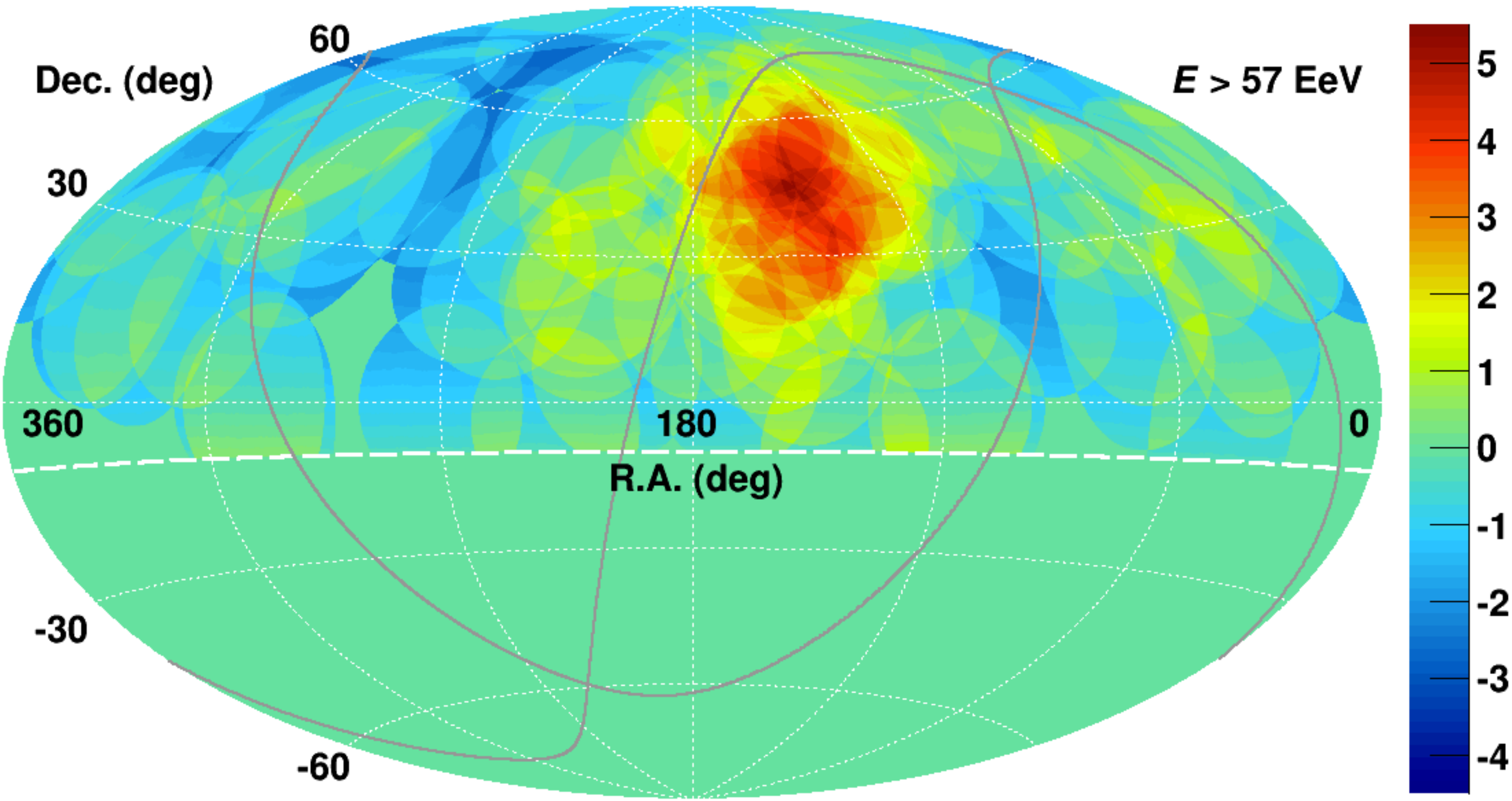
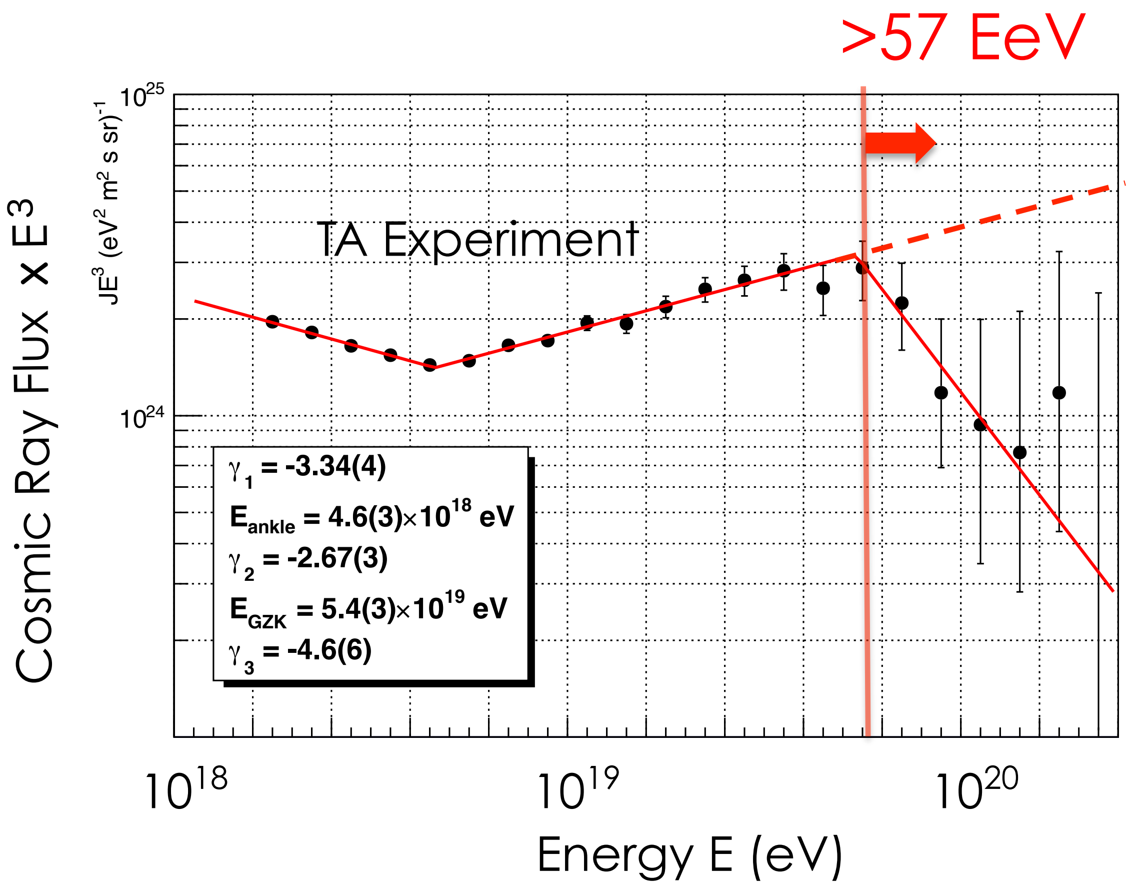
What is the Origin?



Spectrum Measured by TA SD

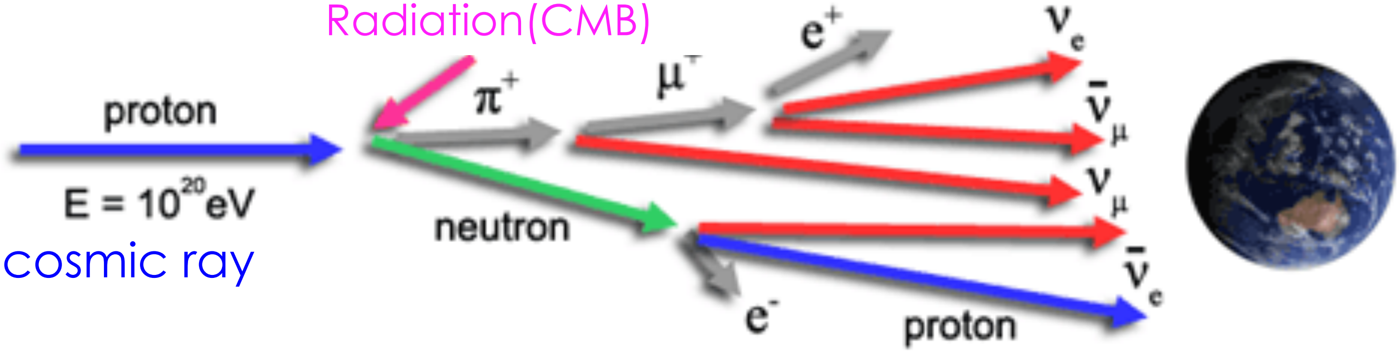


Suppression is observed at 5.5σ

One of interpretations : GZK effect

GZK Effect

Cosmic Background Radiation(CMB)



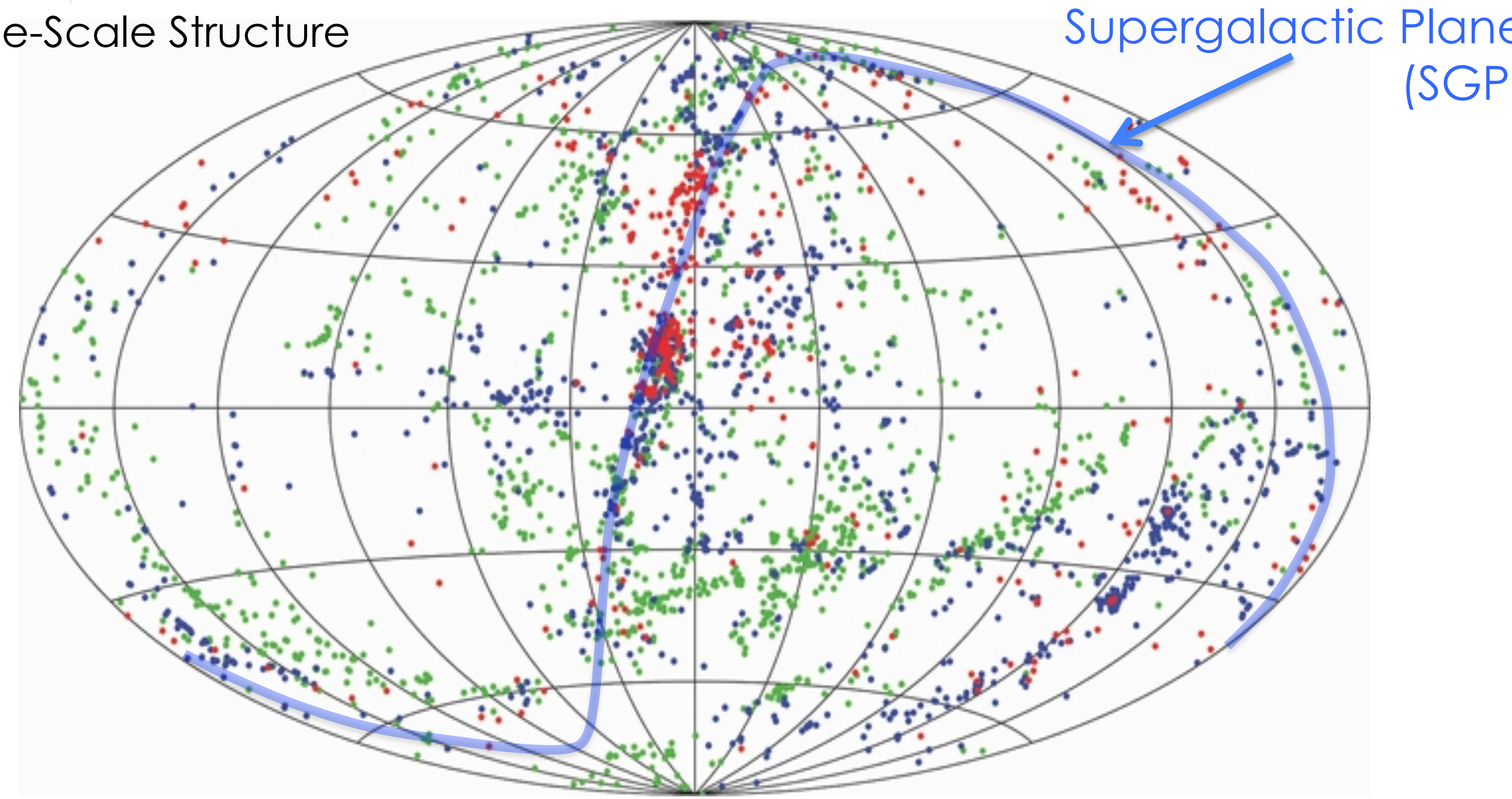
Highest-E cosmic ray

Highest energy region

- ❖ Highest-E cosmic ray travel beyond 50Mpc rapidly loss their energy by interaction with the cosmic microwave background. → Greisen-Zatsepin-Kuzmin (GZK) Effect

Highest-E cosmic rays can not reach the Earth from the distant universe. Therefore, Origin of cosmic rays should be limited to local universe

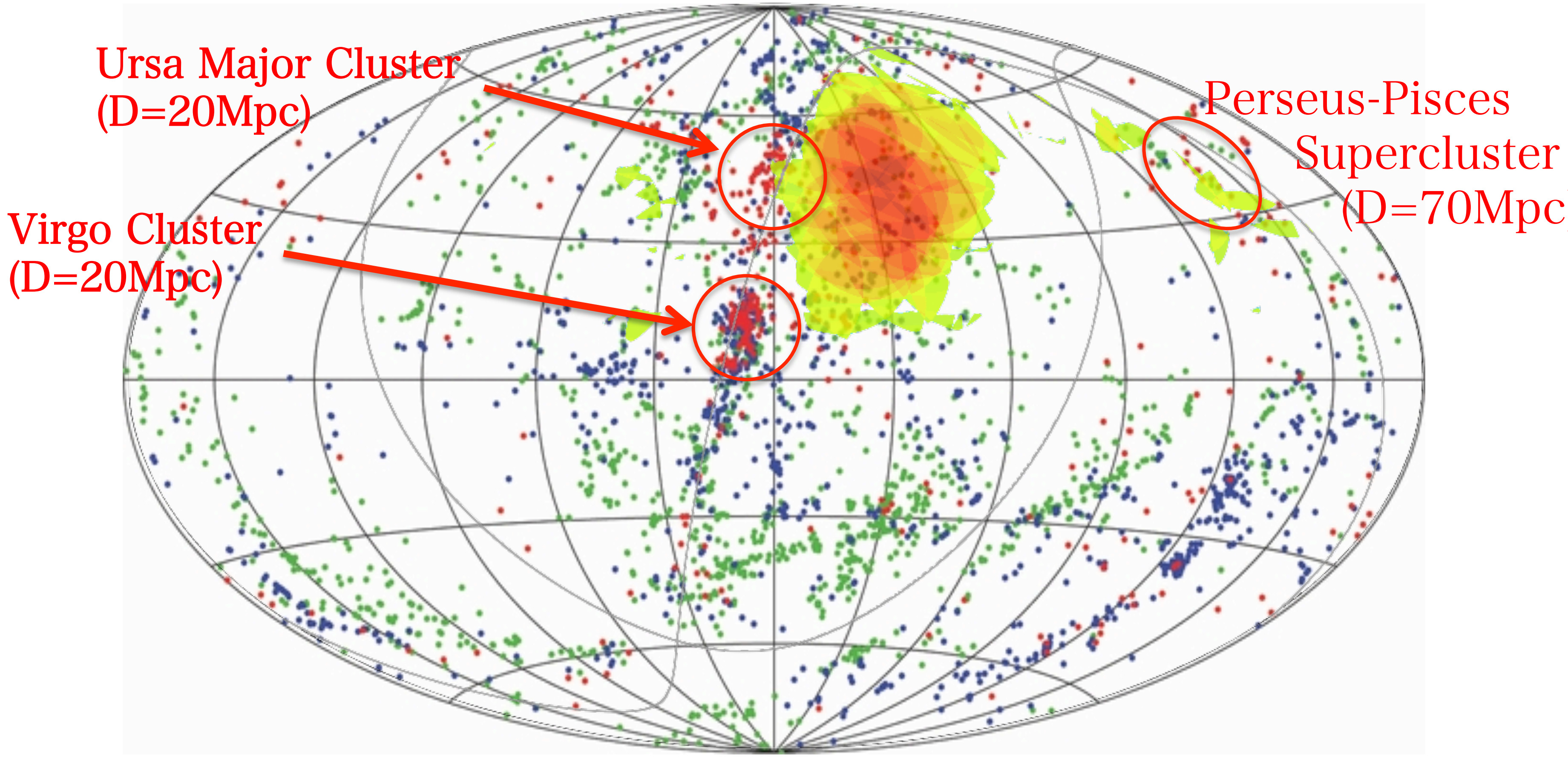
Galaxy Distribution in Local Universe



2MASS catalog velocity 0 – 3000 km/s
John P. Huchra, et al 2012, ApJ, 199, 26
→ high completeness catalog

Heliocentric velocity (Rough Distance)
Red: 0-1000km/s (D = 0-15Mpc)
Blue: 1000-2000km/s (D = 15-30Mpc)
Green: 2000-3000km/s (D = 30-45Mpc)

Nearby Galaxy Clusters

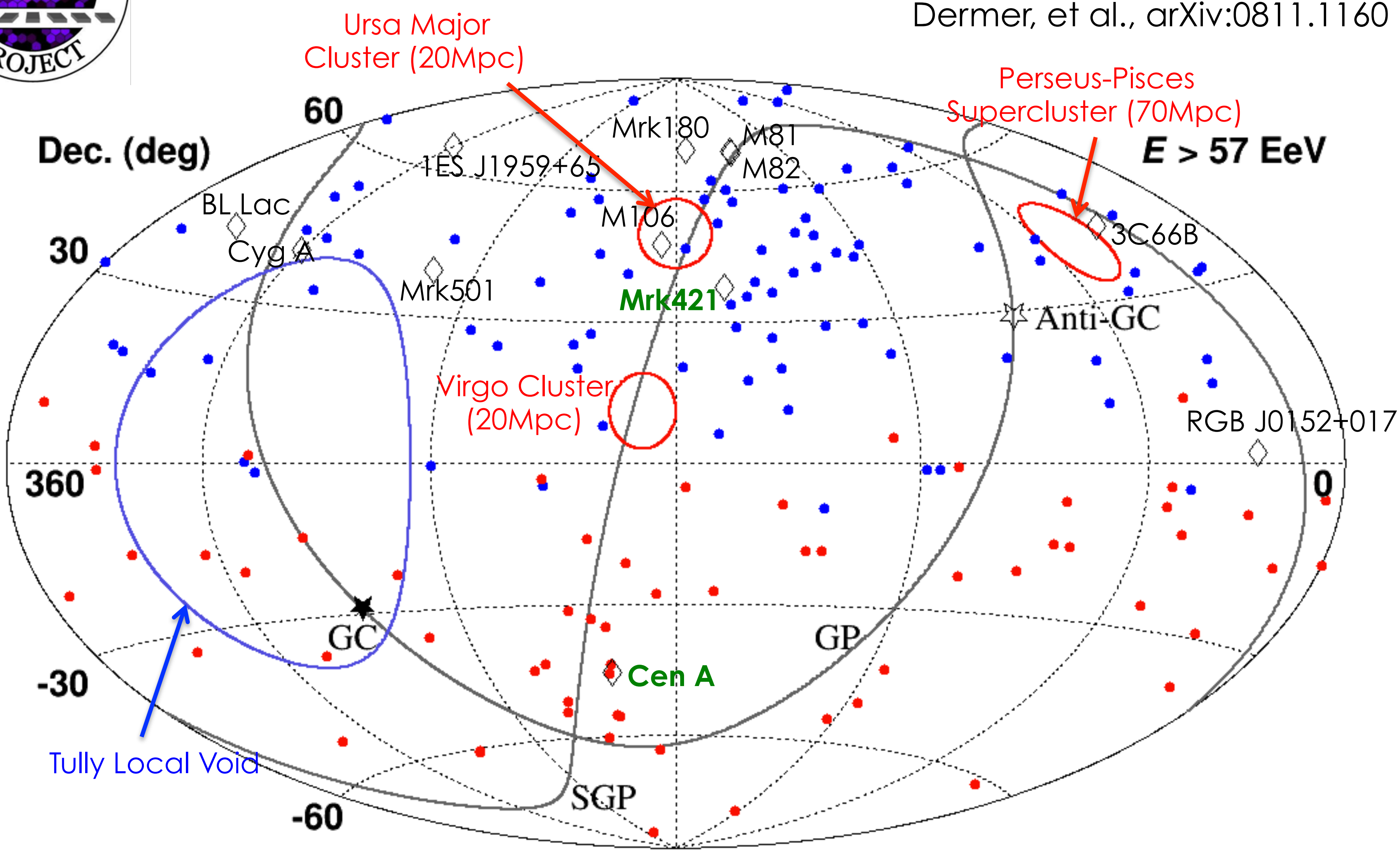


2MASS catalog velocity 0 – 3000 km/s
John P. Huchra, et al 2012, ApJ, 199, 26
+ 5-year TA data (Color contour)

Heliocentric velocity (Rough Distance)
Red: 0-1000km/s (D = 0-15Mpc)
Blue: 1000-2000km/s (D = 15-30Mpc)
Green: 2000-3000km/s (D = 30-45Mpc)

Nearby Prominent AGNs

Dermer, et al., arXiv:0811.1160



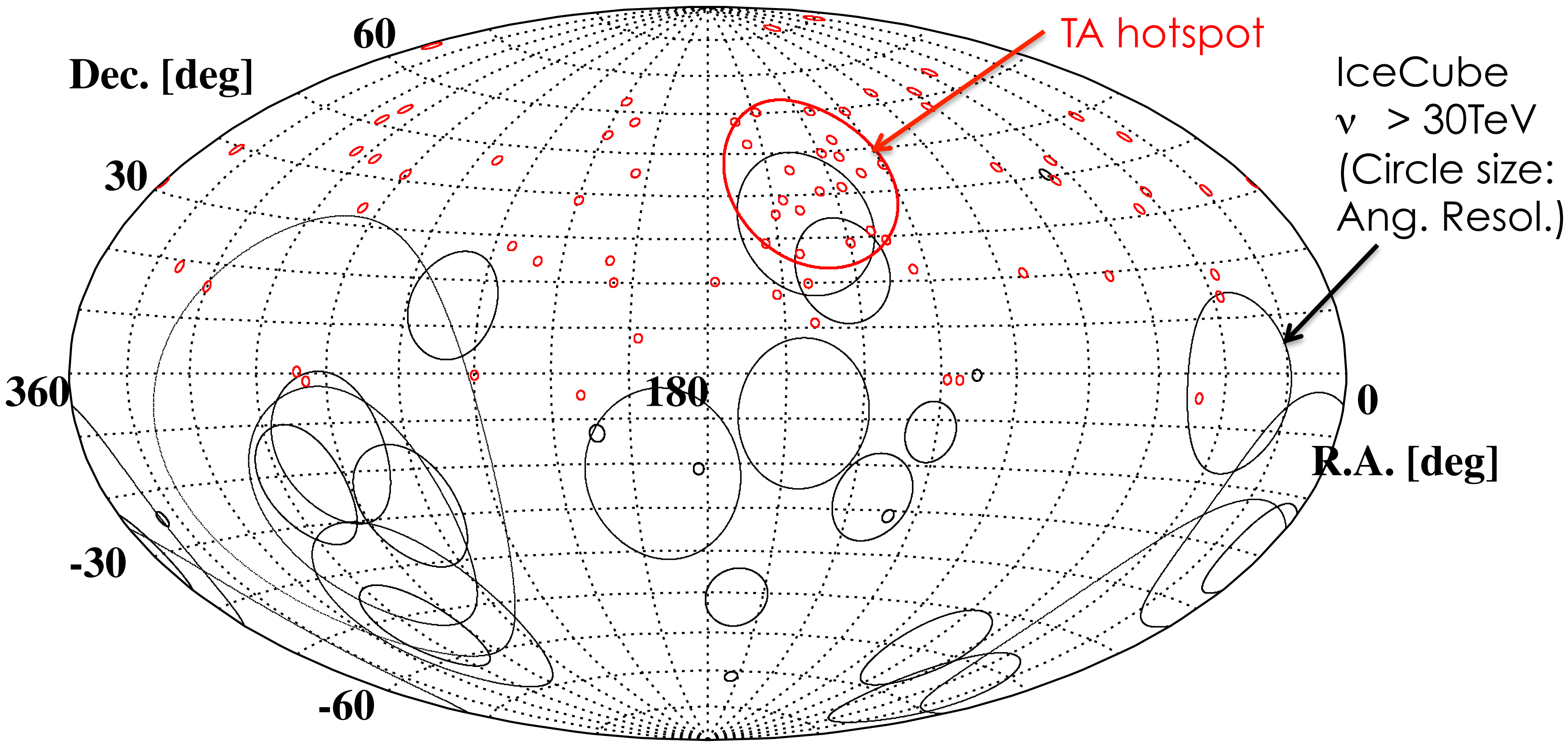
TA : 2008 May – 2014 May (6.0 years) 87 events

Auger : 2004 May – 2009 Nov (5.5 years) 62 events

IceCube Neutrino

Fang, Fujii, Linden & Olinto, arXiv:1404.6237

UHECRs + photons → TeV-PeV Neutrinos



Two IceCube neutrinos among northern 4 events are coincident with the TA hotspot. → 2σ level by chance

Discussions

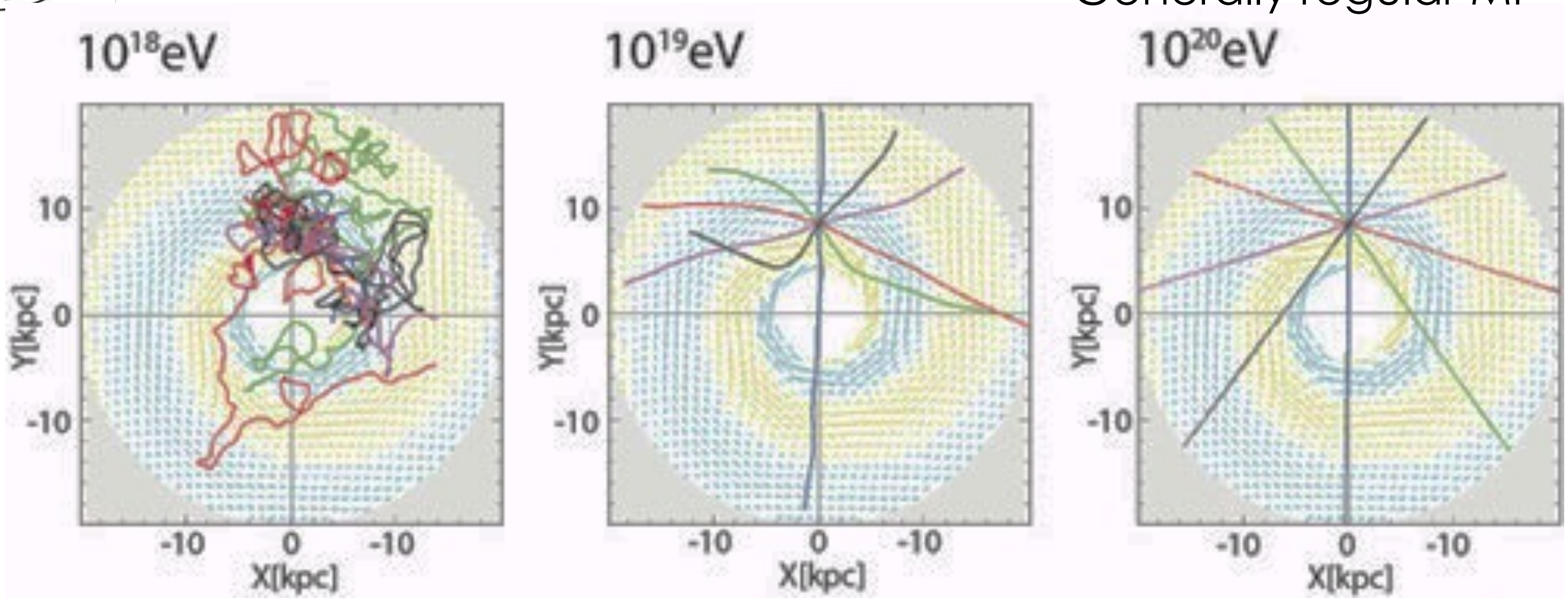
- There is no specific high-E sources behind the hotspot.
- TA Hotspot is shifted from Supergalactic plane by 17°.
- Virgo cluster is really the brightest source in our FoV?

❖ <u>Magnetic deflection</u>
- Galactic MF
- Intergalactic MF

❖ <u>Mass Composition</u>
- TA measurement

Galactic Magnetic Field

Generally regular MF



a few degrees for 10^{20} eV in the Galactic disk
→ too small? to explain hotspot shifted from SGP

But there are many MF models (Galactic disk + Halo).
Recent models suggest large & strong magnetic halo.

Jansson, R. & Farrar, G. R., ApJL, 761, L11 (2012)
Pshirkov, M., et al., ApJ, 738, 192 (2011)
Sun, X. H., et al., A&A, 477, 573 (2008)

Intergalactic Magnetic Field

Generally random MF

Very difficult to measure IGMF

→ Large uncertainty $\sim 10^{-17}\mathrm{G} < B < \sim 10^{-9}\mathrm{G}$

$$\theta(E,d) \simeq \frac{(2dl_c/9)^{1/2}}{r_g} \simeq 0.8^\circ\, q \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

→ too small? to explain hotspot shifted from SGP

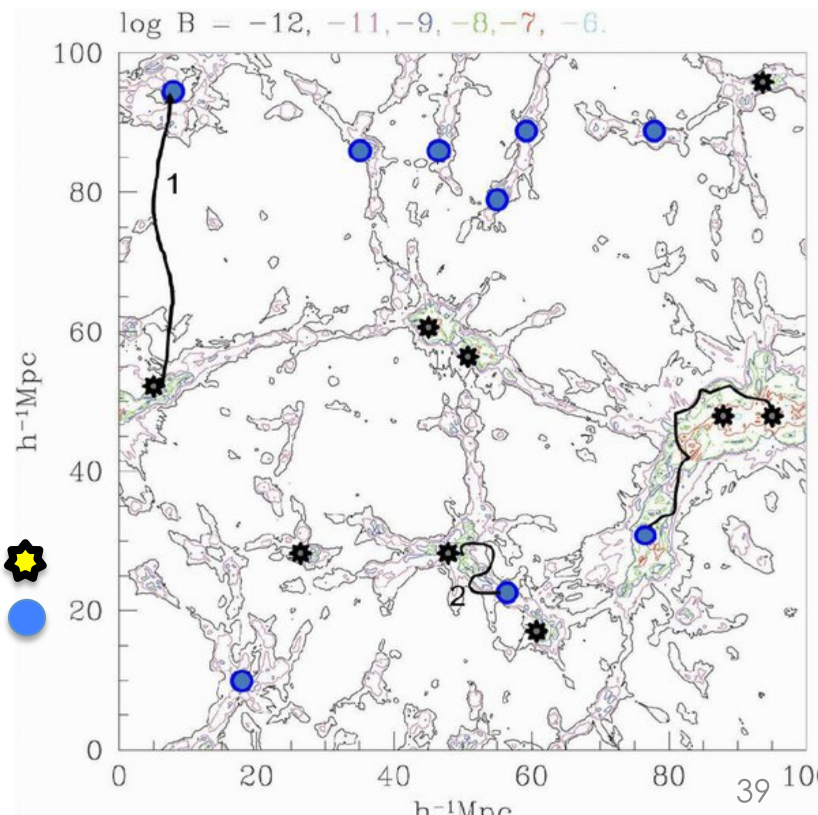
But, MF Strength depends on cluster / filament / void regions

A simulated universe

UHECR sources

Virtual observers

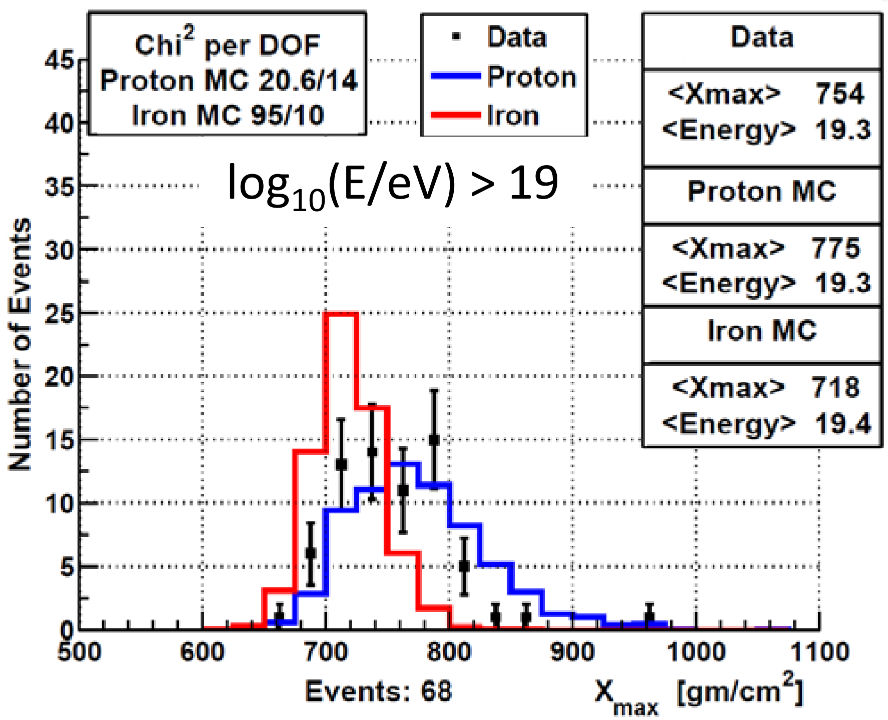
Ryu, Das & Kang, ApJ (2010)

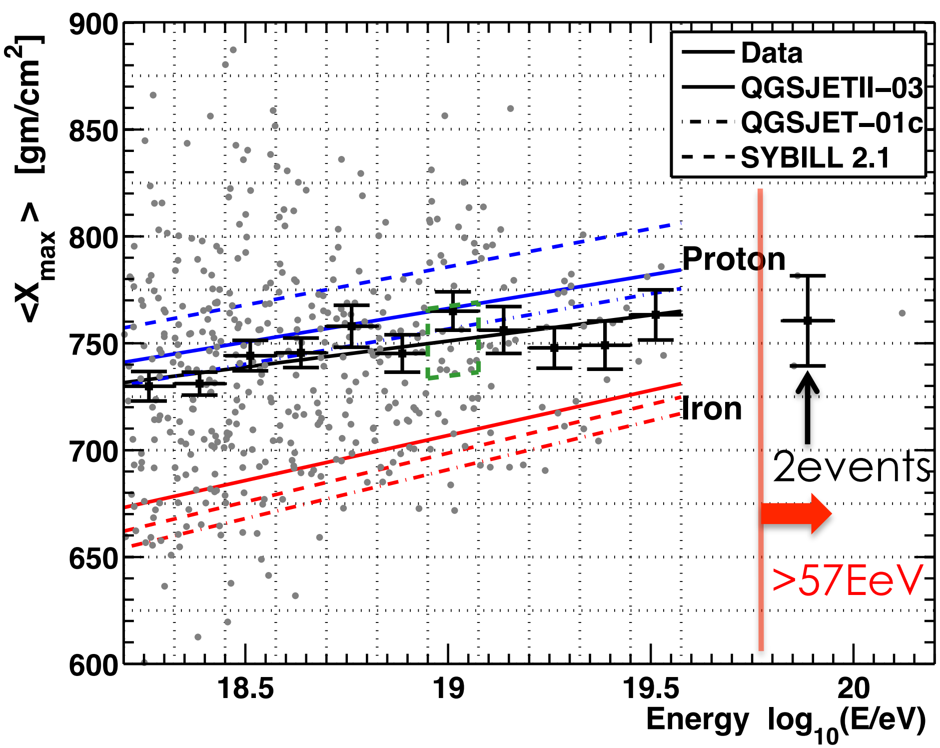


Composition (Xmax)

TA Measurement (Middle Drum Hybrid)

>10EeV : consistent with largely proton component





Abbasi, et al, (arXiv:1408.1726)

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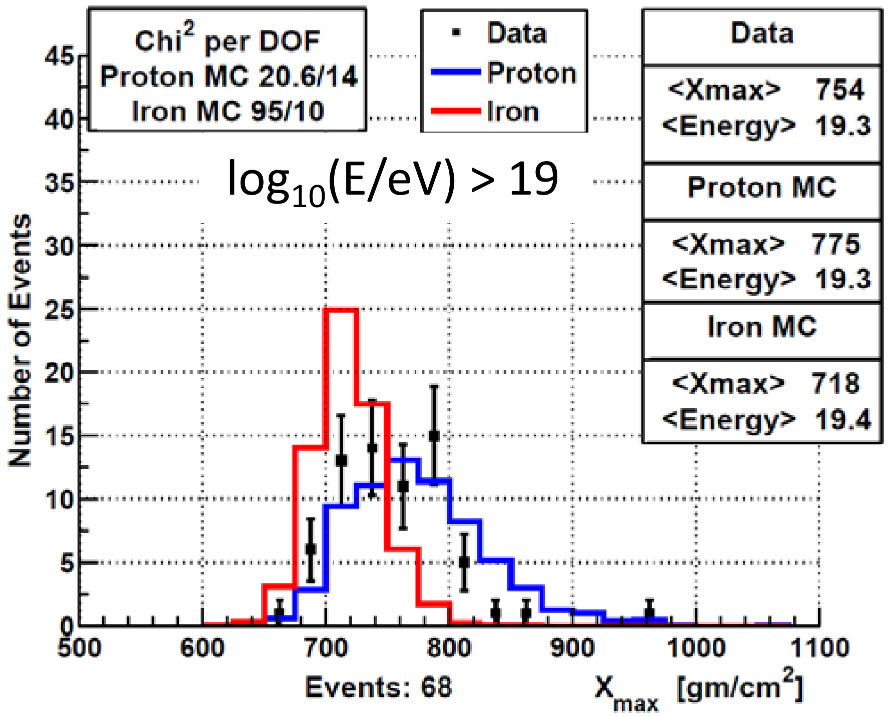

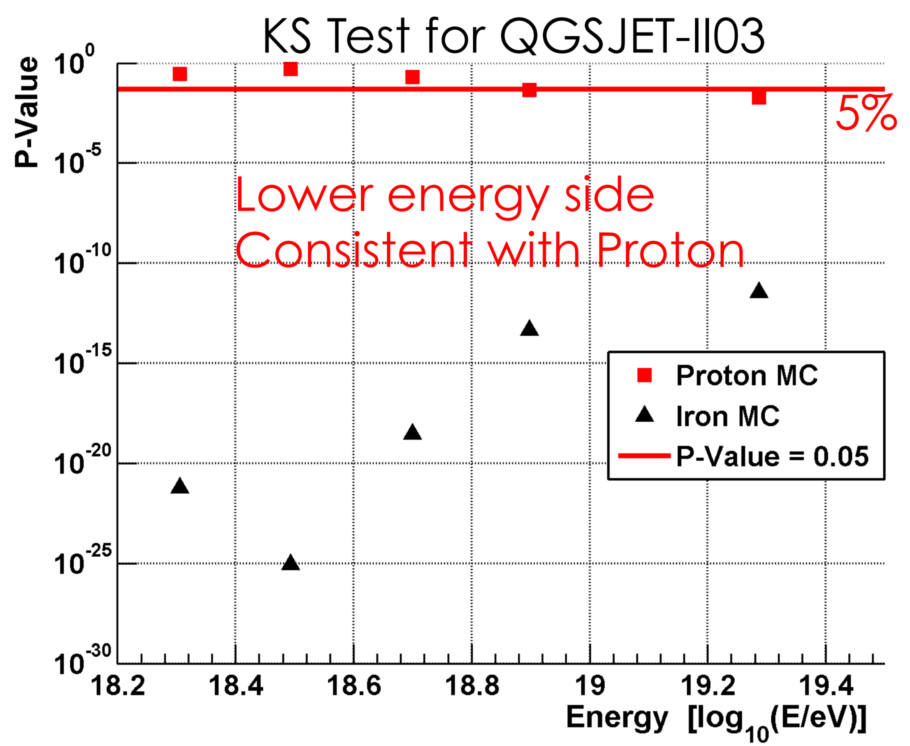

Abbasi, et al, (arXiv:1408.1726)

Summary

- Current Results
  - We found evidence for the cosmic-ray hotspot near the supergalactic plane, but shifted by ~17°.
  - Chance probability assuming the isotropic sky is estimated to be 3.4σ for 5-year data.
    → 4.0σ for 6-year data (New!)
- Future Prospects
  - To reproduce the hotspot, we will start to find the best-estimate model assuming the GMF/IGMF, the mass composition and the source distribution.
  - We are now proposing the TAx4 project.

TAx4 Proposal

✧ Now there is hint of anisotropy at >3σ level for northern sky.

❖ Plan to expand TA by 4 times (3,000km^2)

1. Add 500 scint. counters with 2.1 km spacing
2. 10 refurbished HiRes tels

❖ Science (3-year observation)

1. Anisotropy study → Expect >>5σ
2. Xmax & E Spectrum at the highest energy region
3. Search UHE photon & neutrino