IWARA 2018

Observation of Ultra-High-Energy Cosmic Rays with the Telescope Array Experiment and TA Extension

Kazumasa KAWATA
ICRR, University of Tokyo
For the TA Collaboration

Outline

- Introduction
- Telescope Array experiment
- Recent results
  - Energy Spectrum
  - Anisotropy
  - Mass Composition (Xmax)
- TAx4 Project

Telescope Array Collaboration

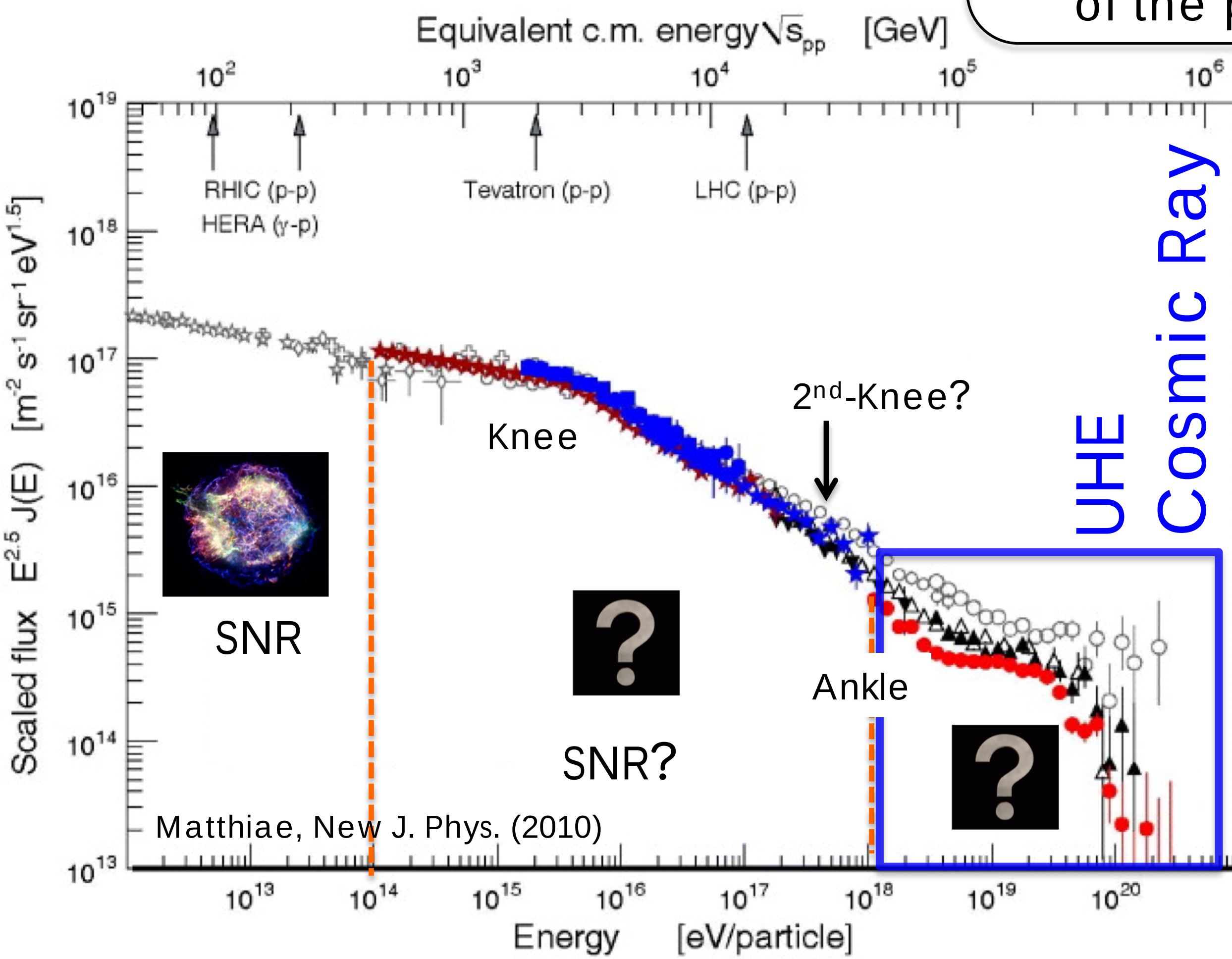
R. U. Abbasi,[1] M. Abe,[2] T. Abu-Zayyad,[1] M. Allen,[1] R. Azuma,[3] E. Barcikowski,[1] J. W. Belz,[1] D. R. Bergman,[1] S. A. Blake,[1] R. Cady,[1] B. G. Cheon,[4] J. Chiba,[5] M. Chikawa,[6] A. Di Matteo,[7] T. Fujii,[8] K. Fujita,[9] M. Fukushima,[8,10] G. Furlich,[1] T. Goto,[9] W. Hanlon,[1] M. Hayashi,[11] Y. Hayashi,[9] N. Hayashida,[12] K. Hibino,[12] K. Honda,[13] D. Ikeda,[8] N. Inoue,[2] T. Ishii,[13] R. Ishimori,[3] H. Ito,[14] D. Ivanov,[1] H. M. Jeong,[15] S. Jeong,[15] C. C. H. Jui,[1] K. Kadota,[16] F. Kakimoto,[3] O. Kalashev,[17] K. Kasahara,[18] H. Kawai,[19] S. Kawakami,[9] S. Kawana,[2] K. Kawata,[8] E. Kido,[8] H. B. Kim,[4] J. H. Kim,[1] J. H. Kim,[20] S. Kishigami,[9] S. Kitamura,[3] Y. Kitamura,[3] V. Kuzmin,[17,*] M. Kuznetsov,[17] Y. J. Kwon,[21] K. H. Lee,[15] B. Lubsandorzhiev,[17] J. P. Lundquist,[1] K. Machida,[13] K. Martens,[10] T. Matsuyama,[9] J. N. Matthews,[1] R. Mayta,[9] M. Minamino,[9] K. Mukai,[13] I. Myers,[1] K. Nagasawa,[2] S. Nagataki,[14] R. Nakamura,[22] T. Nakamura,[23] T. Nonaka,[8] H. Oda,[9] S. Ogio,[9] J. Ogura,[3] M. Ohnishi,[8] H. Ohoka,[8] T. Okuda,[24] Y. Omura,[9] M. Ono,[14] R. Onogi,[9] A. Oshima,[9] S. Ozawa,[18] I. H. Park,[15] M. S. Pshirkov,[17,25] J. Remington,[1] D. C. Rodriguez,[1] G. Rubtsov,[17] D. Ryu,[20] H. Sagawa,[8] R. Sahara,[9] K. Saito,[8] Y. Saito,[22] N. Sakaki,[8] N. Sakurai,[9] L. M. Scott,[26] T. Seki,[22] K. Sekino,[8] P. D. Shah,[1] F. Shibata,[13] T. Shibata,[8] H. Shimodaira,[8] B. K. Shin,[9] H. S. Shin,[8] J. D. Smith,[1] P. Sokolsky,[1] B. T. Stokes,[1] S. R. Stratton,[1,26] T. A. Stroman,[1] T. Suzawa,[2] Y. Takagi,[9] Y. Takahashi,[9] M. Takamura,[5] M. Takeda,[8] R. Takeishi,[15,†] A. Taketa,[27] M. Takita,[8] Y. Tameda,[28] H. Tanaka,[9] K. Tanaka,[29] M. Tanaka,[30] S. B. Thomas,[1] G. B. Thomson,[1] P. Tinyakov,[7,17] I. Tkachev,[17] H. Tokuno,[3] T. Tomida,[22] S. Troitsky,[17] Y. Tsunesada,[9] K. Tsutsumi,[3] Y. Uchihori,[31] S. Udo,[12] F. Urban,[32] T. Wong,[1] M. Yamamoto,[22] R. Yamane,[9] H. Yamaoka,[30] K. Yamazaki,[12] J. Yang,[33] K. Yashiro,[5] Y. Yoneda,[9] S. Yoshida,[19] H. Yoshii,[34] Y. Zhezher,[17] and Z. Zundel[1]

[1]*High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[2]*The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[3]*Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4]*Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[5]*Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[6]*Department of Physics, Kindai University, Higashi Osaka, Osaka, Japan*
[7]*Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[8]*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[9]*Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[10]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan*
[11]*Information Engineering Graduate School of Science and Technology, Shinshu University, Nagano, Nagano, Japan*
[12]*Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[13]*Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[14]*Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[15]*Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea*
[16]*Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[17]*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[18]*Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[19]*Department of Physics, Chiba University, Chiba, Chiba, Japan*
[20]*Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea*
[21]*Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[22]*Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan*
[23]*Faculty of Science, Kochi University, Kochi, Kochi, Japan*
[24]*Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan*
[25]*Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia*
[26]*Department of Physics and Astronomy, Rutgers University—The State University of New Jersey, Piscataway, New Jersey, USA*
[27]*Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[28]*Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan*
[29]*Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan*
[30]*Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[31]*National Institute of Radiological Science, Chiba, Chiba, Japan*
[32]*CEICO, Institute of Physics, Czech Academy of Sciences Prague, Czech Republic*
[33]*Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea*
[34]*Department of Physics, Ehime University, Matsuyama, Ehime, Japan*

Ultra-High-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

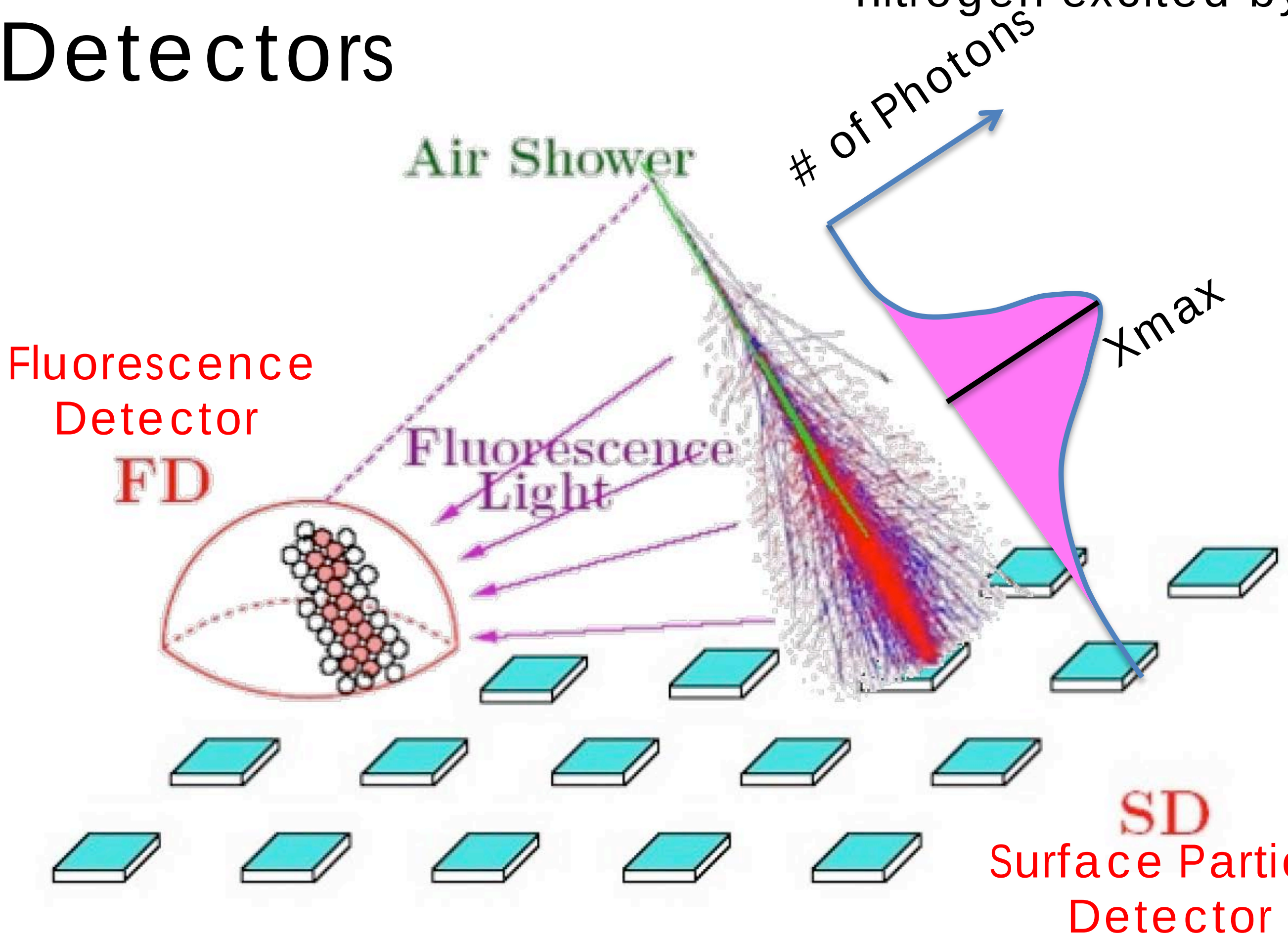


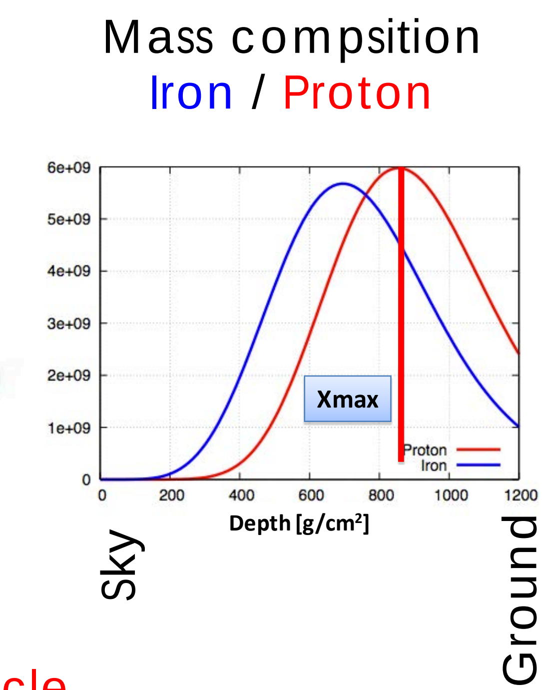
❖ 10^{14}eV – 10^{18}eV
(Knee – 2nd Knee)
- Index changes
- Composition changing
- Galactic objects?

❖ UHE cosmic rays above 10^{18}eV
- Flux suppression
- Extragalactic (AGNs?)
- ~1 event/100km^2/ yr @100EeV

Two Different Type Detectors

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

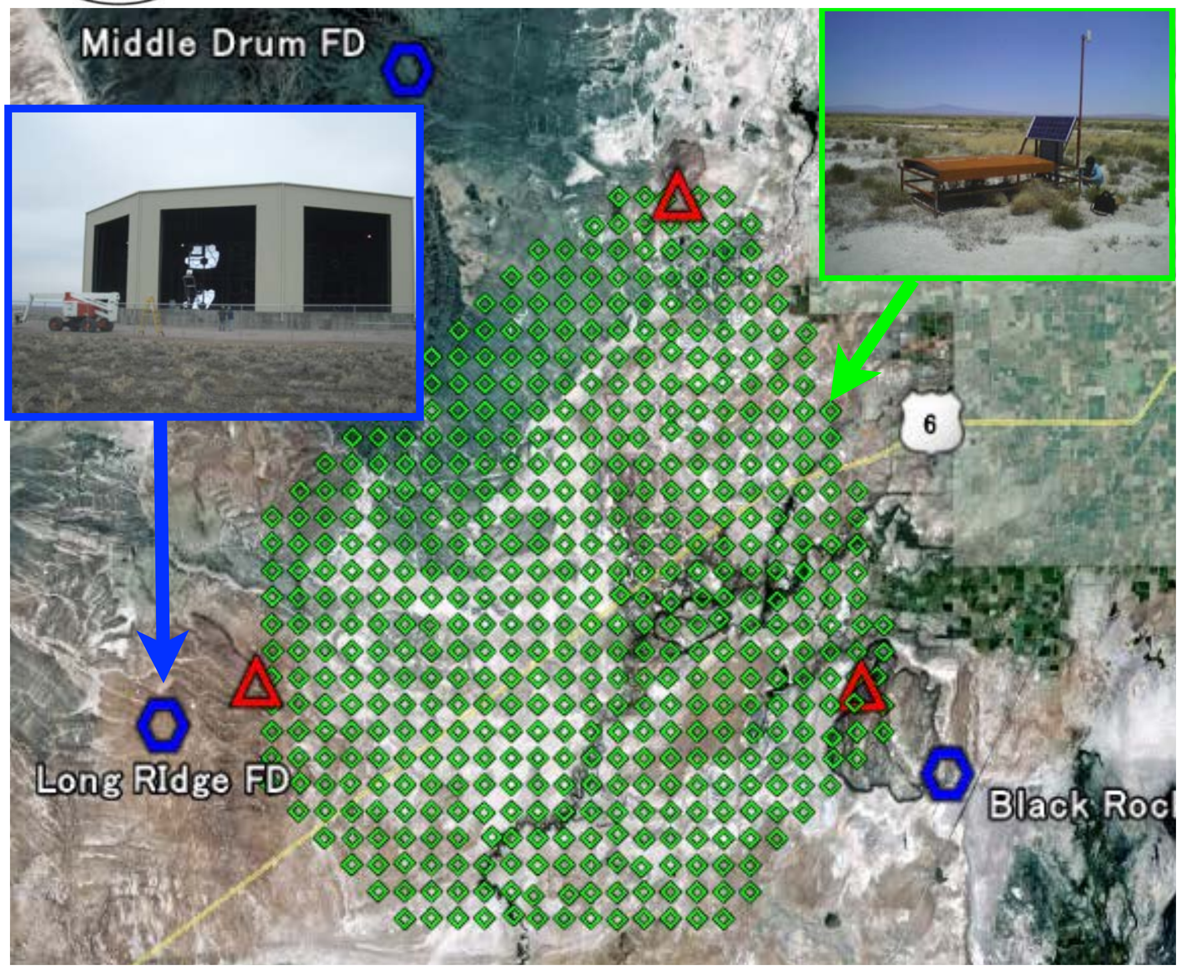




SD : Regardless of weather condition with high duty circle and wide FoV.
→ High statistical data → Anisotropy & spectral shape

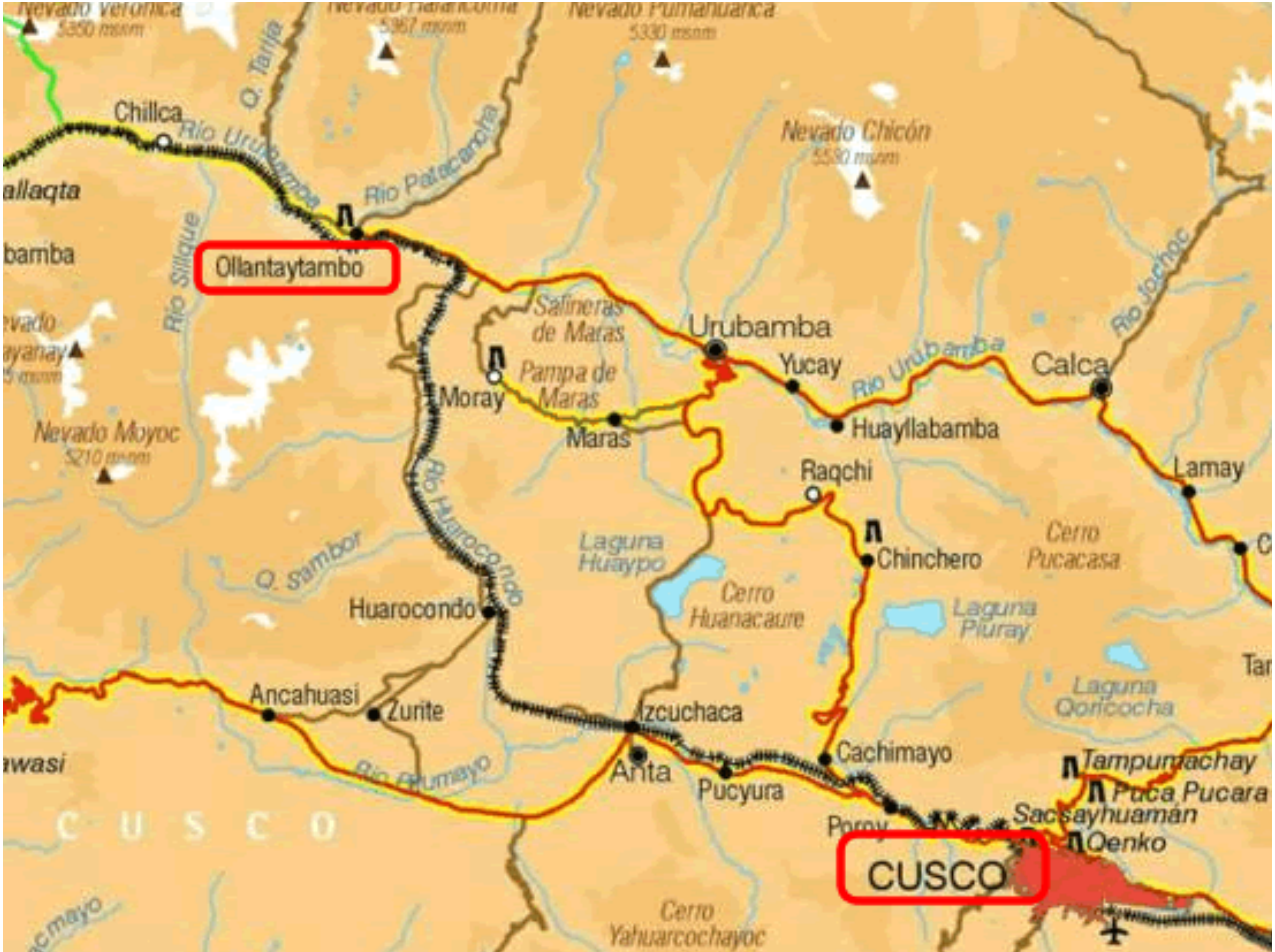
FD : limited to clear moonless night.
Longitudinal development of air shower → Mass composition (Xmax)
Measure the energy deposit calorimetrically → Absolute energy scale

Telescope Array (TA)

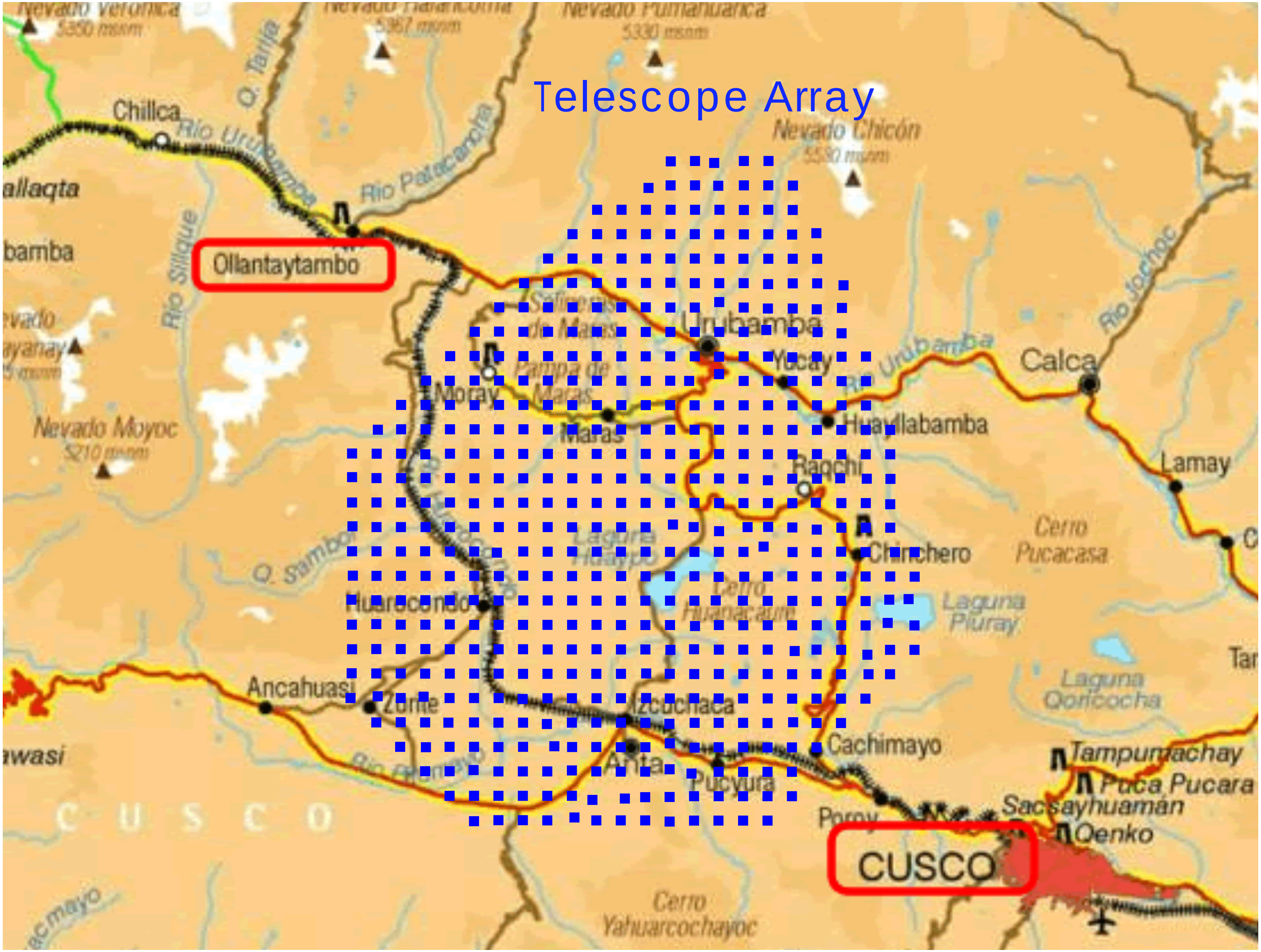


- Utah, USA
  - 39.3°N, 112.9°W
  - 1400m asl.
- Surface Detector (SD)
  - 3m^2 Scintillation det.
  - 507 detectors
  - 1.2km spacing
  - Effective area 700km^2
- Fluorescence Det. (FD)
  - 3 stations
  - 12 telescopes/station

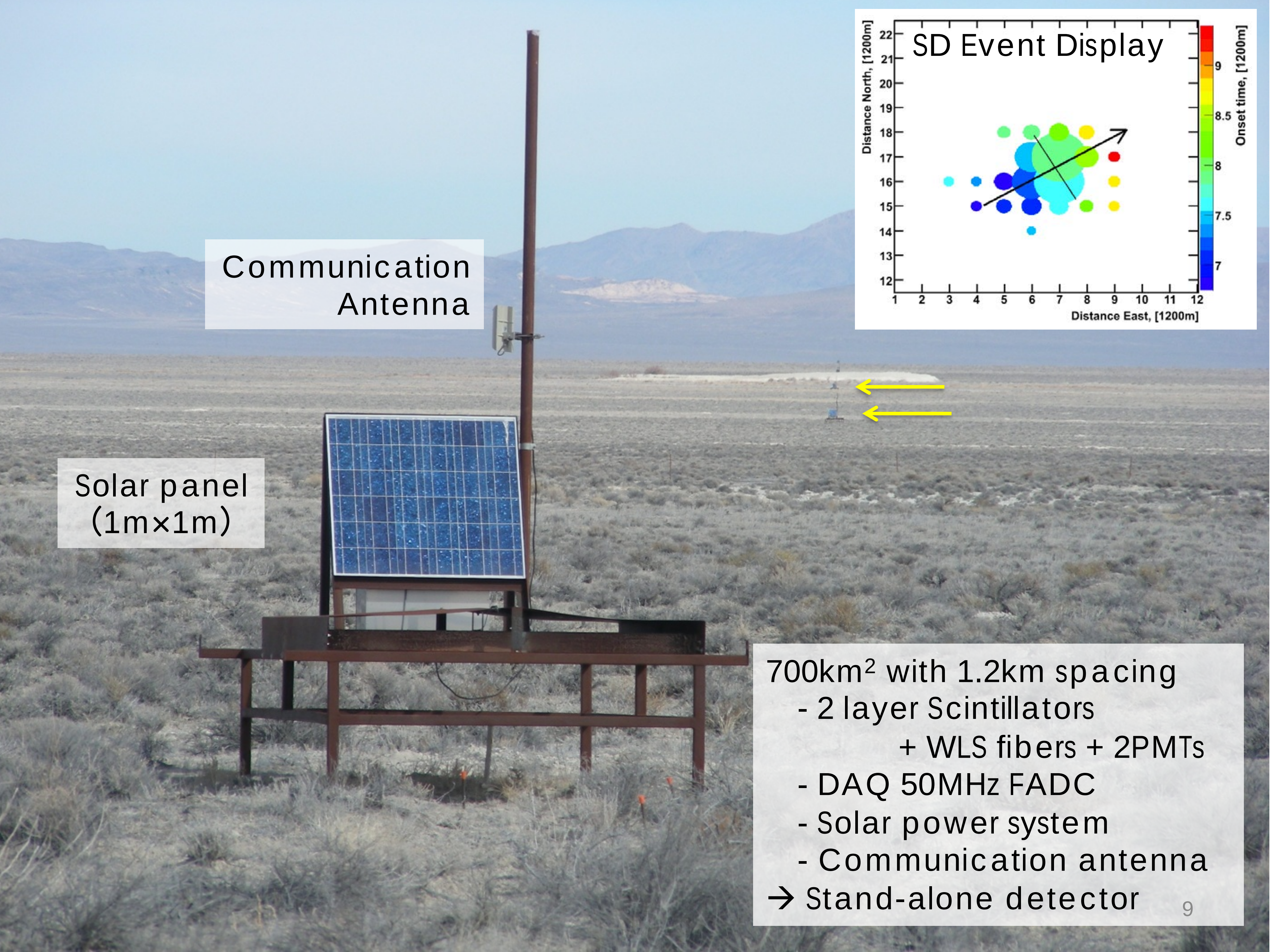
The TA is the largest aperture hybrid cosmic ray detectors in the northern hemisphere.



Nevado Veronica
5350 msnm
Nevado Halancoma
5367 msnm
Nevado Pumahuanca
5330 msnm
Q. Tarijo
Chillca
Río Urubamba
Río Patacancha
Nevado Chicón
5530 msnm
allaqta
bamba
Río Silique
Ollantaytambo
Salineras de Maras
Urubamba
Río Jochoc
Yucay
Río Urubamba
Calca
Pampa de Maras
Moray
Maras
Huayllabamba
Nevado Moyoc
5210 msnm
Río Huarocondo
Raqchi
Lamay
Cerro Pucacasa
Chinchero
Laguna Huaypo
Q. Sambor
Cerro Huanacaure
Laguna Piuray
Huarocondo
Laguna Qoricocha
Ancahuasi
Zurite
Izcuchaca
Cachimayo
Tampumachay
Río Plumayo
Anta
Pucyura
Puca Pucara
Sacsayhuamán
C U S C O
Poroy
Qenko
CUSCO
Cerro Yahuarcochayoc



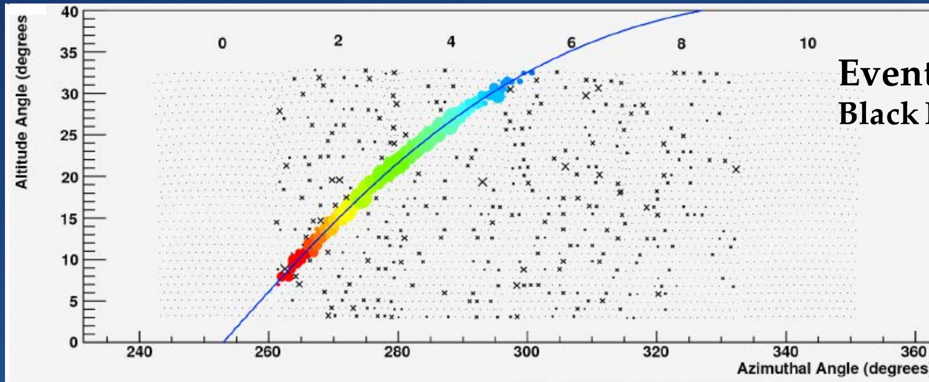
Telescope Array
Nevado Verónica
5350 msnm
Nevado Chicón
5530 msnm
Chillca
Río Urubamba
Río Patacancha
Ollantaytambo
Urubamba
Yucay
Calca
Moray
Maras
Huayllabamba
Racchi
Lamay
Chinchero
Cerro Pucacasa
Laguna Huaypo
Cerro Huanacaure
Laguna Piuray
Nevado Moyoc
5210 msnm
Huarocondo
Ancahuasi
Zurite
Izcuchaca
Cachimayo
Anta
Pucyura
Poroy
Laguna Qoricocha
Tampumachay
Puca Pucara
Sacsayhuamán
Qenko
CUSCO
Cerro Yahuarcochayoc
Río Jochoc
Río Urubamba



700km² with 1.2km spacing
- 2 layer Scintillators + WLS fibers + 2PMTs
- DAQ 50MHz FADC
- Solar power system
- Communication antenna

→ Stand-alone detector

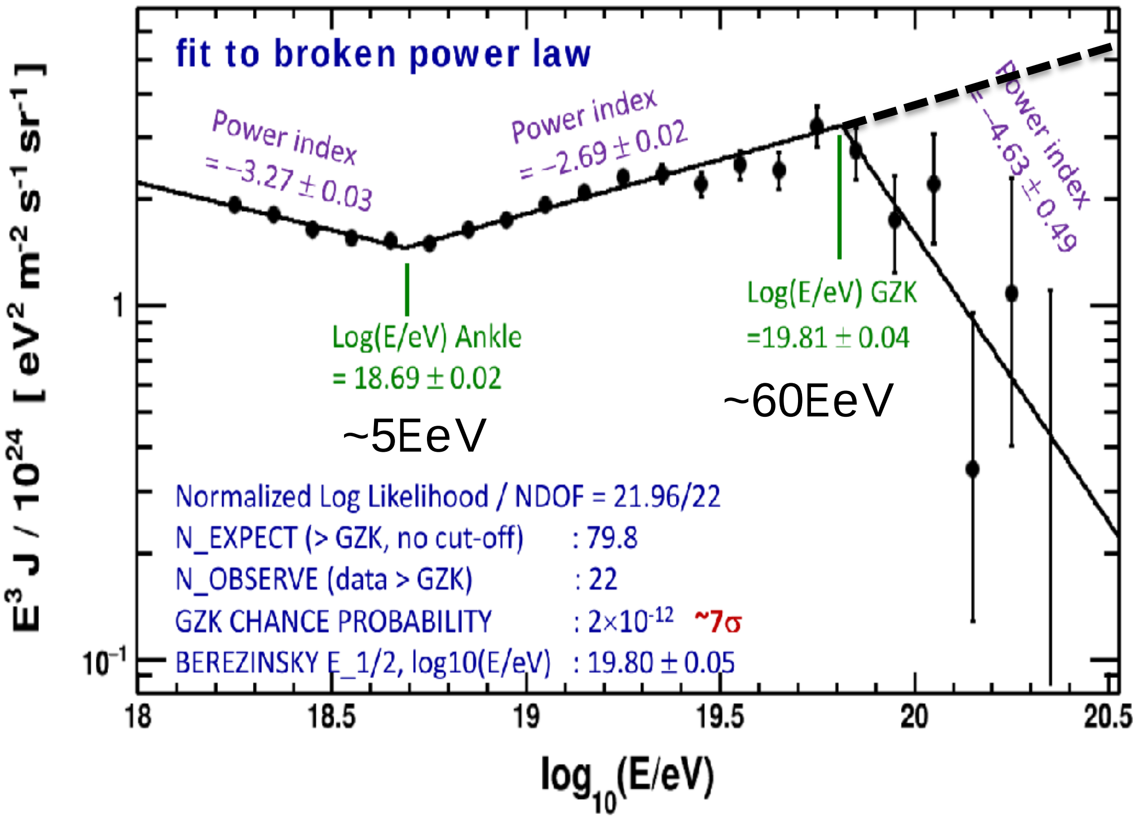
Event Display
Black Rock Mesa



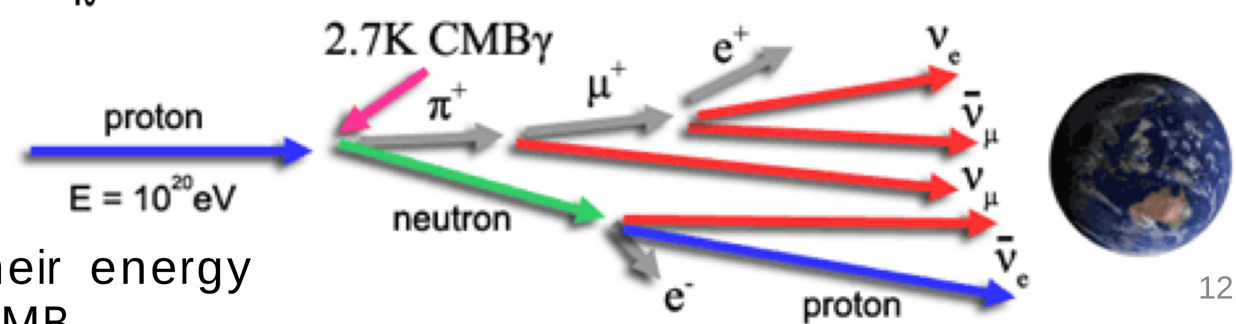
Energy Spectrum

SD Energy Spectrum (9 years)

ICRC2017

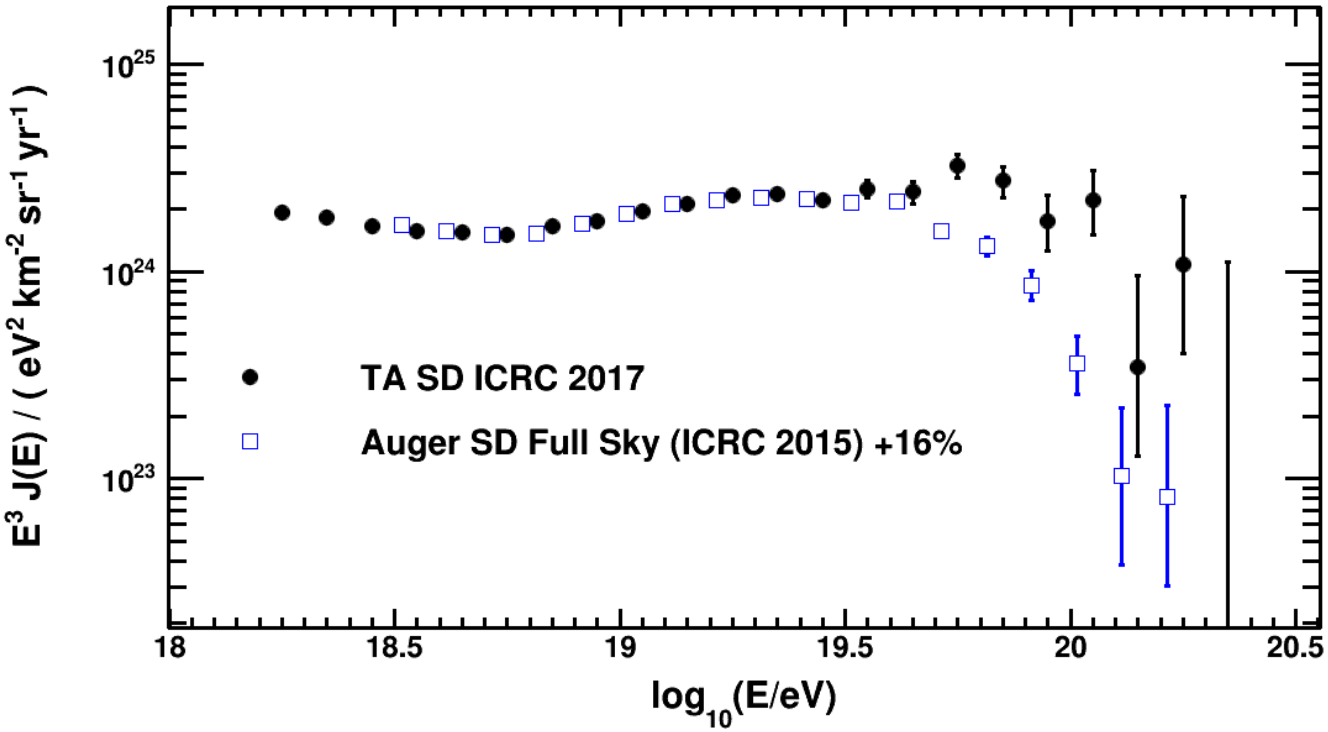


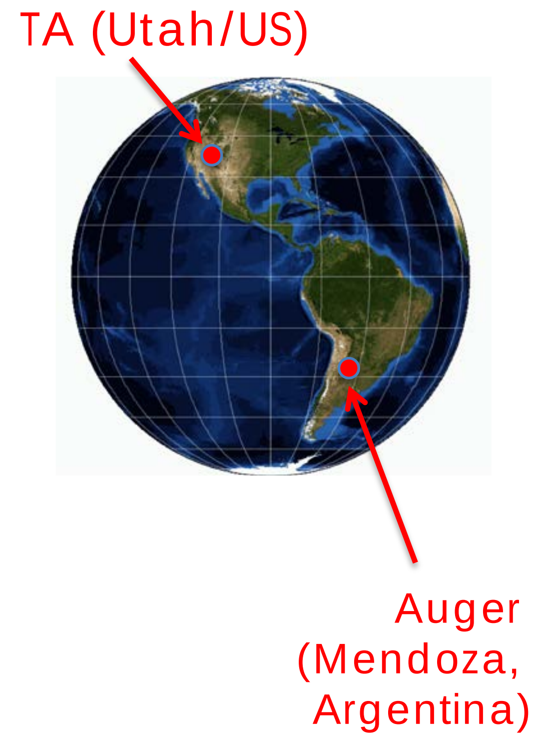
- ✓ Ankle break ~5EeV
- ✓ Suppression ~60EeV consistent with the GZK
- ✓ Suppression ($>10^{19.8}$eV):
  N (continue) = 79.8
  N (observed) = 22
- ✓ Continuous spectrum is excluded at 7σ



Protons rapidly loss their energy by interaction with CMB.

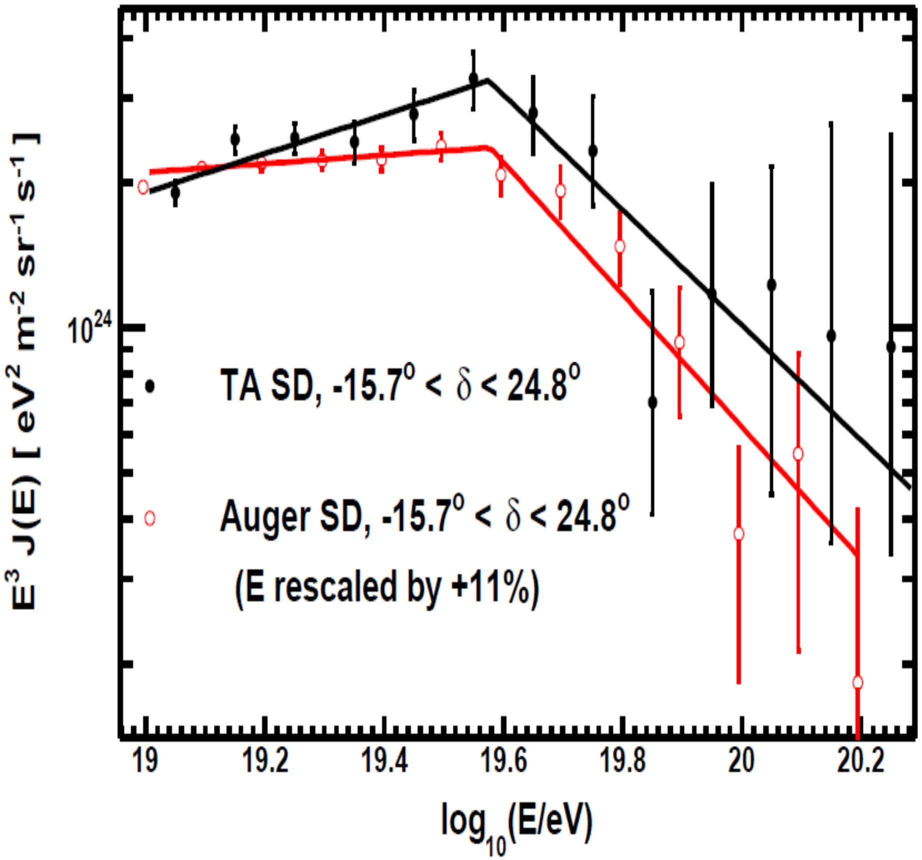
Comparison with Auger



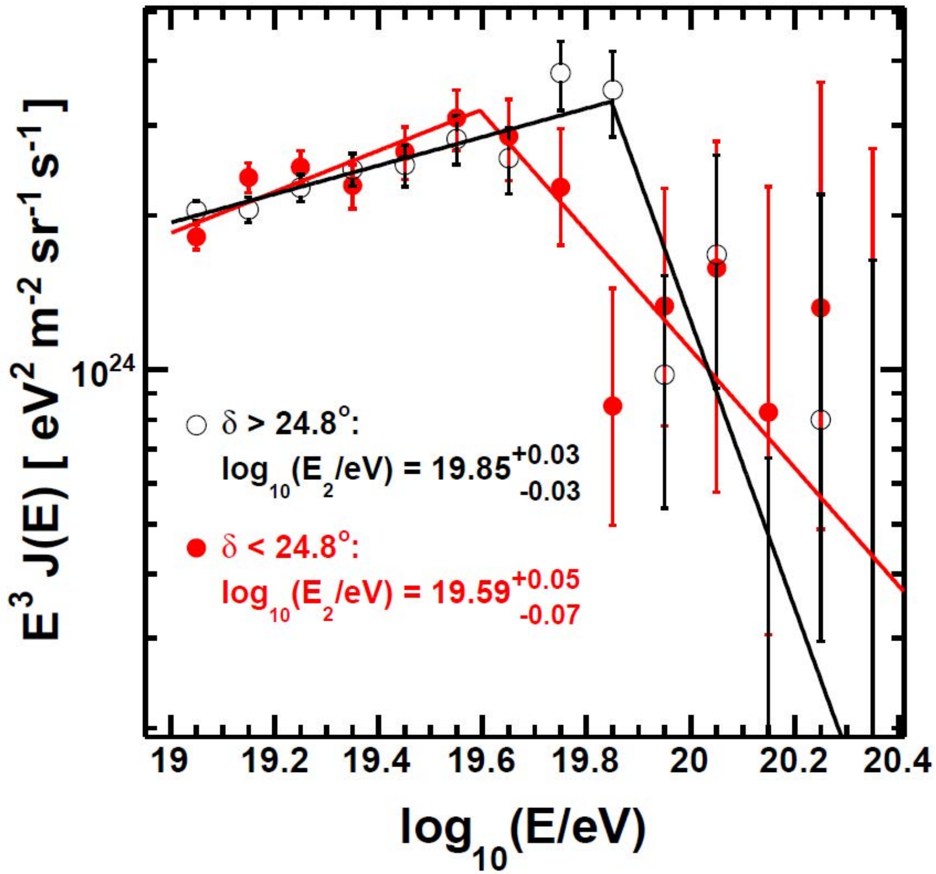


After matching energy scale at the ankle break,
the location of the suppression energy is clear different.
→ Systematics or physics?

Declination Dependence

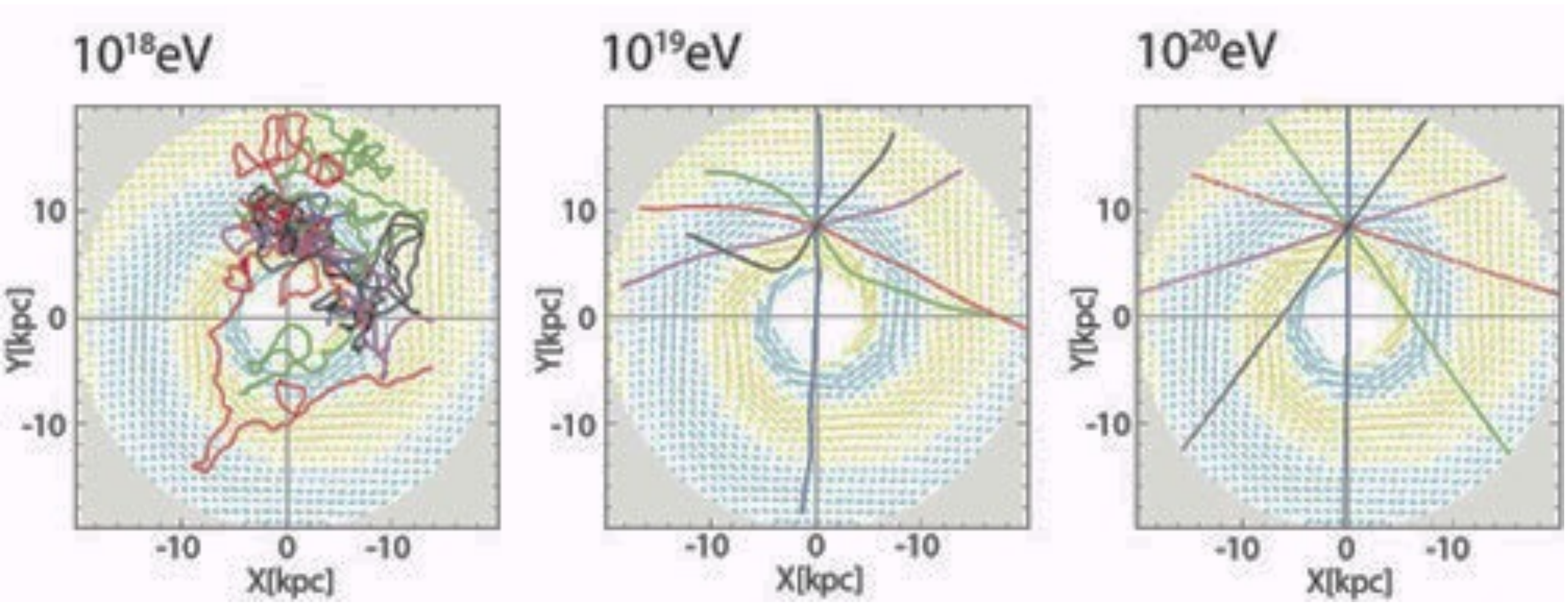


Energy spectra of TA and Auger in the common declination band. The locations of the high energy breaks agree to within 1σ



Energy spectra of TA above and below δ=24.8° The locations of the breaks disagree at ~3.2σ level

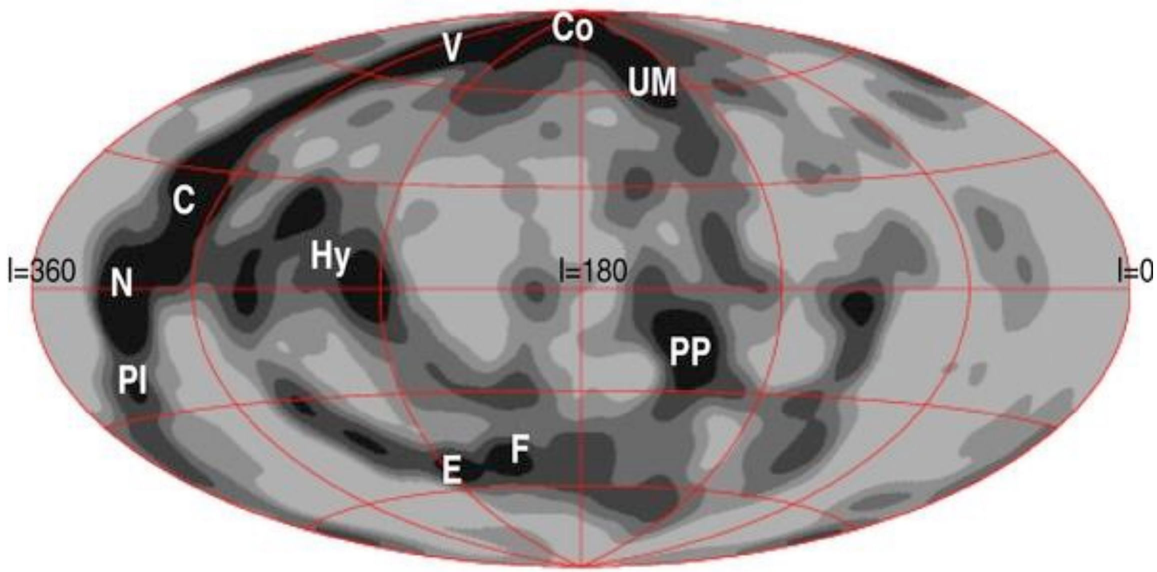
Anisotropy



Possible particle astronomy?

Correlation with LSS

P. Tiynakov
ICRC2017



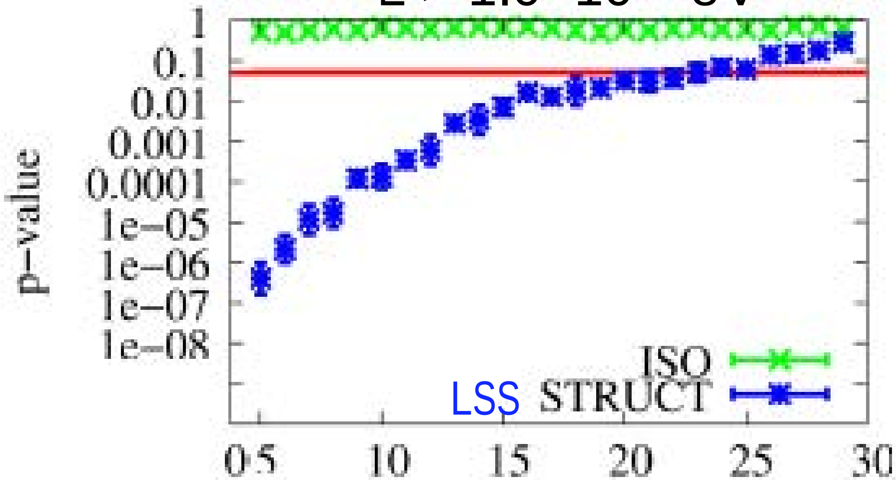
C: Centaurus SCl (60 Mpc);
Co: Coma Cl (90 Mpc);
E: Eridanus Cl (30 Mpc);
F: Fornax Cl (20 Mpc);
Hy: Hydra SCl (50 Mpc);
N: Norma SCl (65 Mpc);
PI: Pavo-Indus SCl (70 Mpc);
PP: Perseus-Pisces SCl (70 Mpc);
UM: Ursa Major Cl (20 Mpc);
and V: Virgo Cl (20 Mpc).

- ❖ Large-Scale Structure model 2MASS Galaxy catalog (XSCz)
- ❖ Grey Pattern: Model with 6° radius circle smearing angle
  → Matter density ∝ Cosmic-ray density

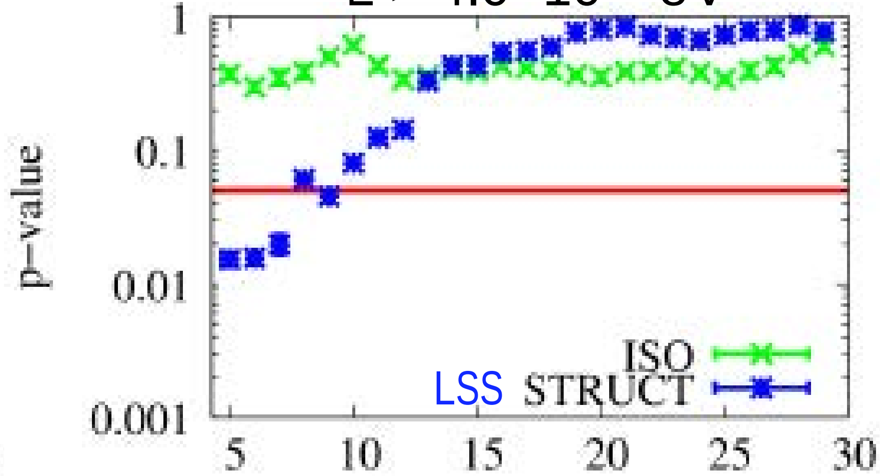
We investigate correlation between arrival directions of the UHECRs and the LLS model (and isotropic model).

Correlation with LSS

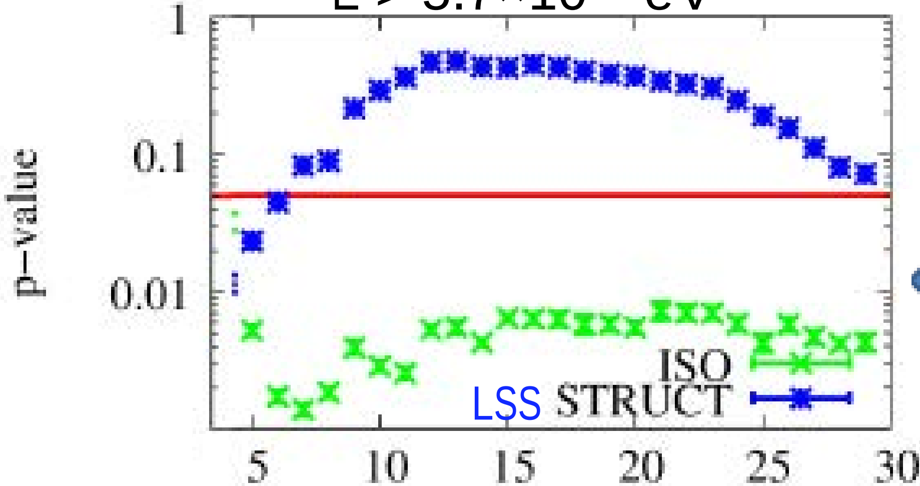
E > 1.0×10^{19} eV



E > 4.0×10^{19} eV



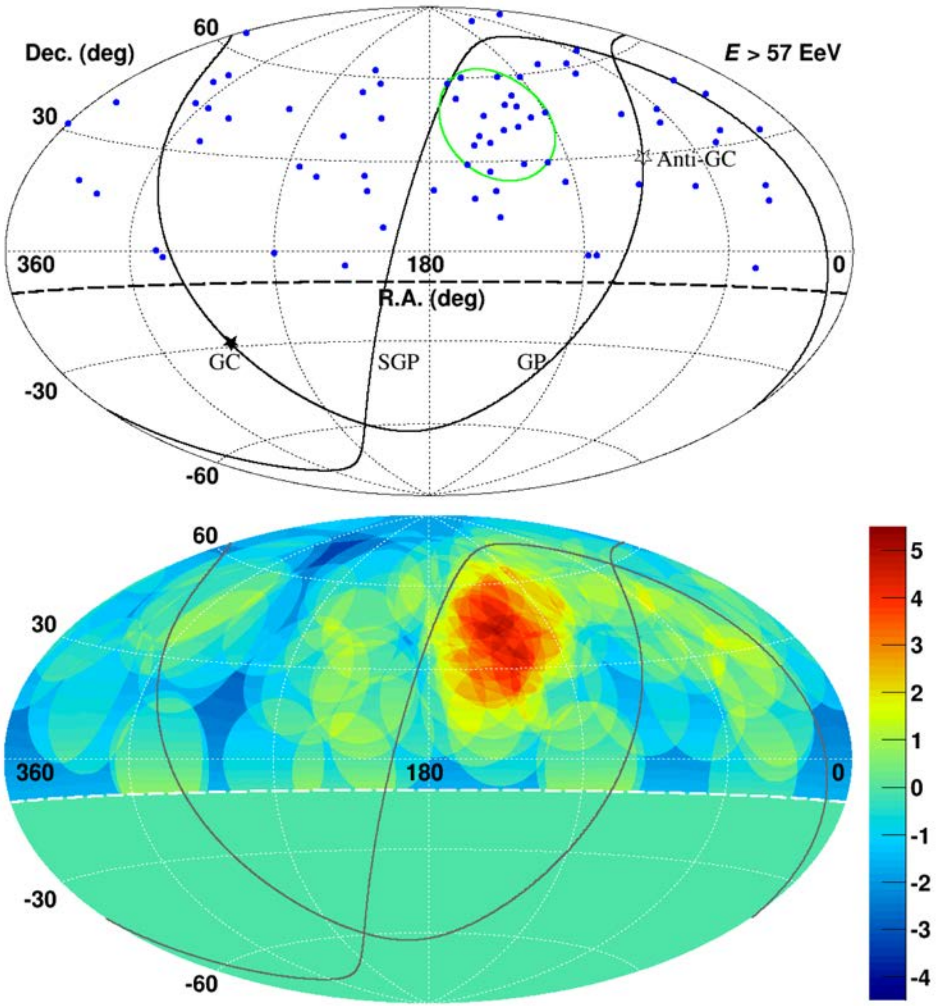
E > 5.7×10^{19} eV



x-axis : smearing angle
Y-axis : compatibility between the expected and the data

E>5.7×10^{19} eV
Consistent with LSS
Inconsistent with isotropy

Hotspot (>57EeV, 5 years)



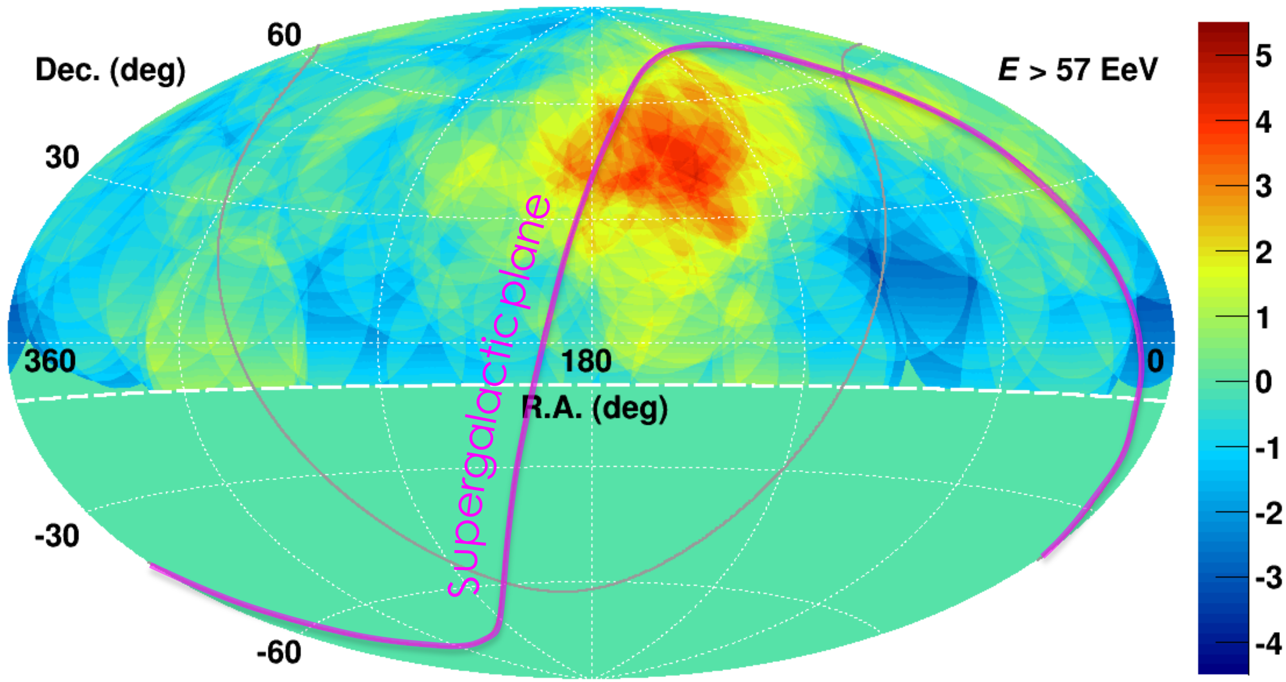
R.U. Abbasi+2014, ApJL

- ✓ 5-year observation by the TA SD
- ✓ Observed 72 events with E>57 EeV
- ✓ Indication of UHECR hotspot
- ✓ Local significance 5.1σ

- ✓ Assuming 5 search window radii (15^o, 20^o, 25^o, 30^o, 35^o), Global significance 3.4σ

Almost double statistics

Hotspot (>57EeV, 9 years)



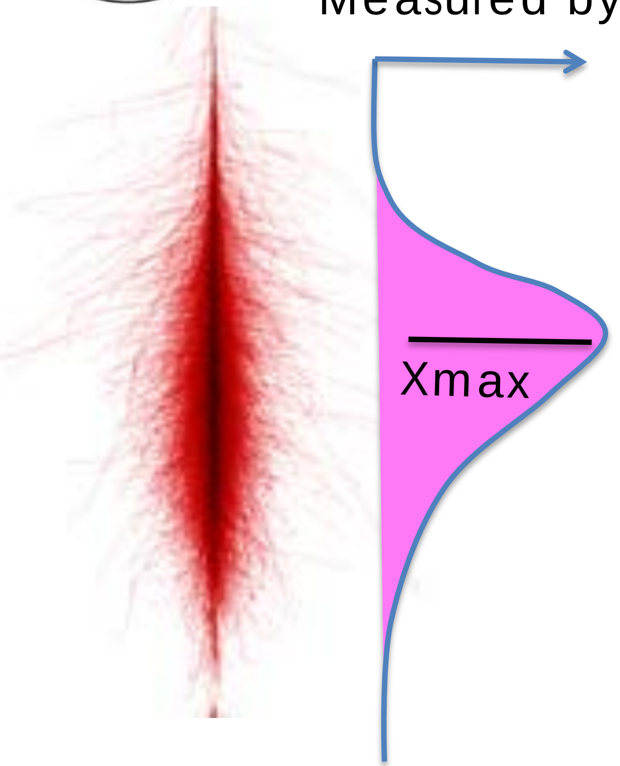
- Total events: 143 events
- Best circle center : RA. =144.3°, Dec. = 40.3°
- Best circle radius : 25°
- Observed in the Hotspot circle : 34
- Expected in the hotspot circle : 13.5
- Local (pre-trial) Significance : 5.0σ
- Global (post-trial) Significance 3σ

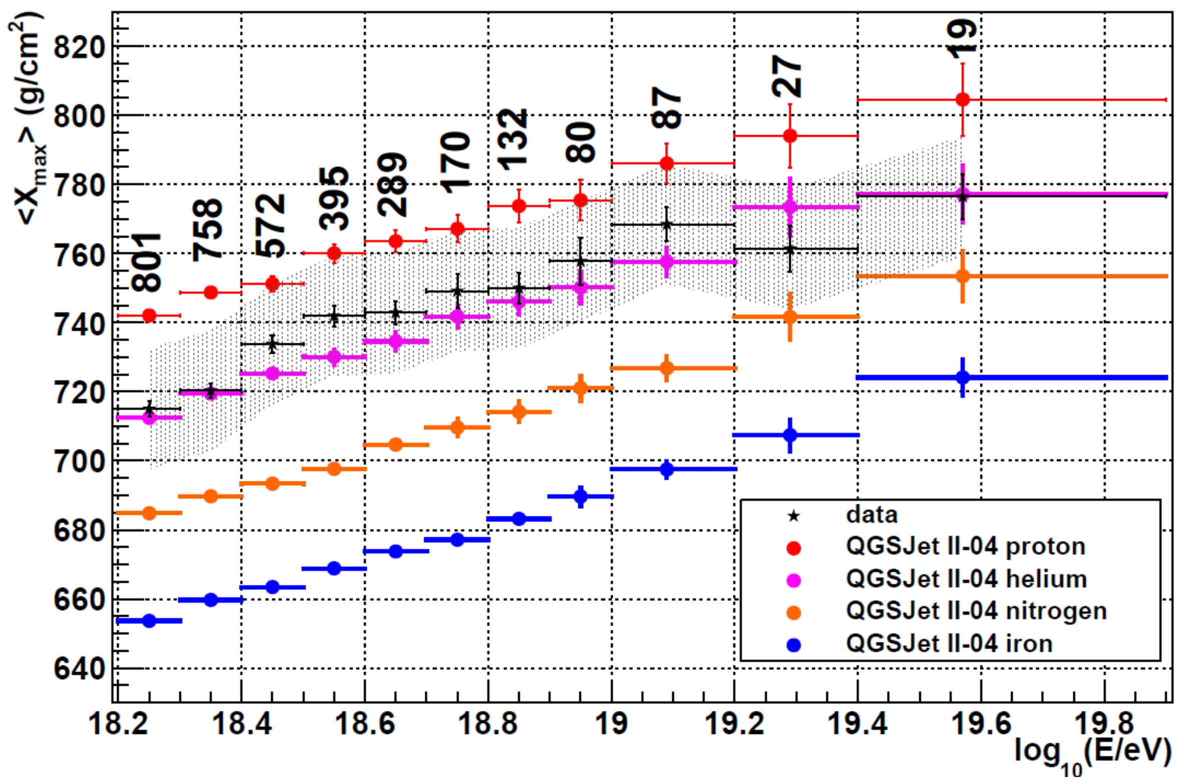
Mass Composition

Averaged X_{max}

Ap. J., 858, 76(2018)
arXiv: 1801.09784

Measured by FD





- ✓ Air showers induced by the lighter composition penetrate into the deeper atmosphere.
- ✓ Consistent with proton or light components (QGSJET-II-04)
- ✓ We need more statistics for E > $10^{19.6}$ eV

TAx4 Experiment

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

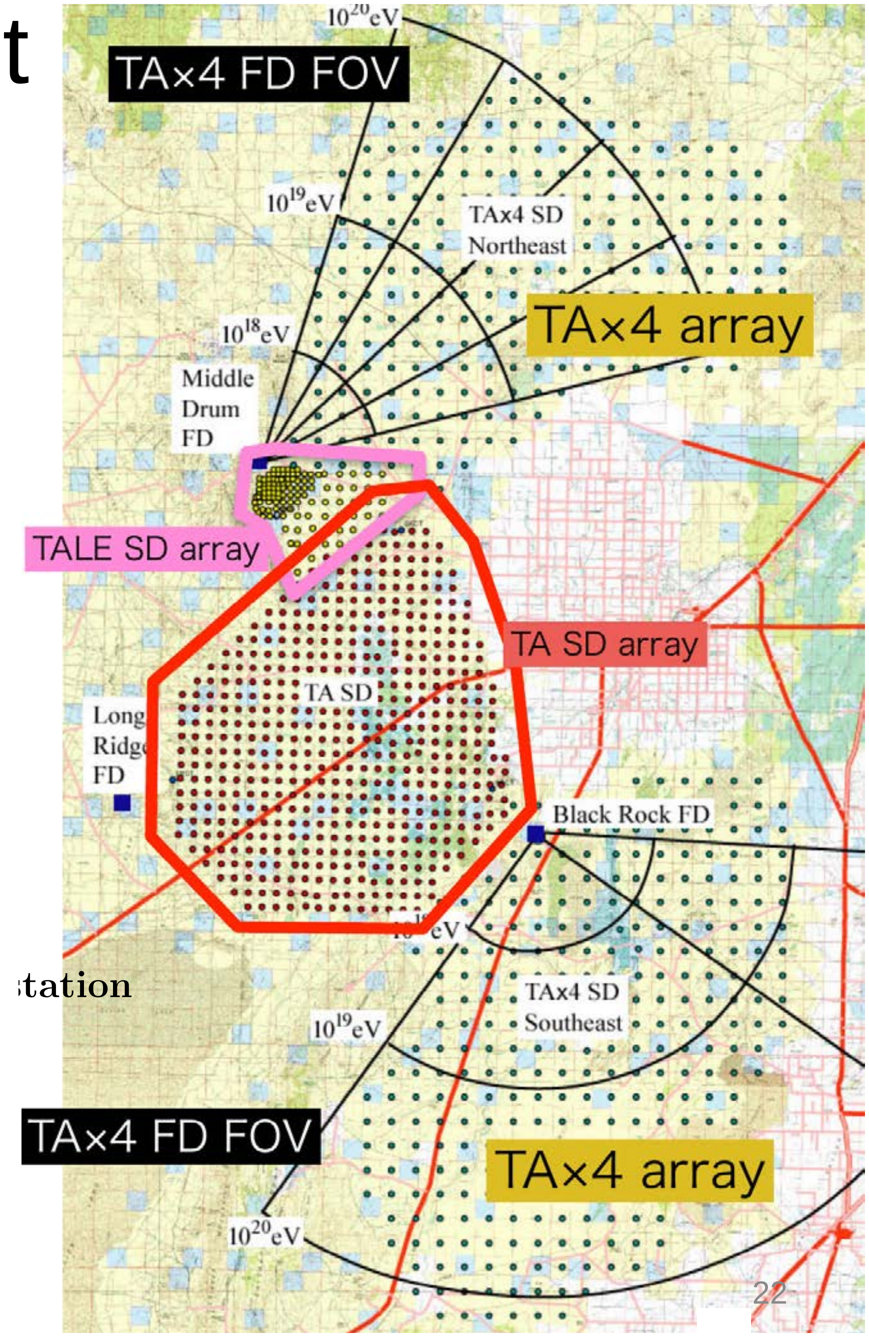
❖ extend SD array by 4 times (3,000km²)

1. Add 500 scint. counters with 2.1 km spacing
2. Add two FD stations

→ Approved and under construction

❖ Science

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



Summary

- Recent results for 9 years
  - E Spectrum : significant suppression consistent with GZK cutoff (7σ $>10^{19.8}$eV)
  - Anisotropy : Indication of Hotspot>57EeV (3σ)
  - Composition : proton or light components ($10^{18.2}$eV<E<$10^{19.6}$eV)
- TA Extension : TAx4 (TA aperture x4)
  - Under construction

BACK POCKETS

MD TAx4

Commissioning now

BR TAx4 Shelter Installation

2018-08-16

Width of X_{max} distribution (σ_{Xmax})

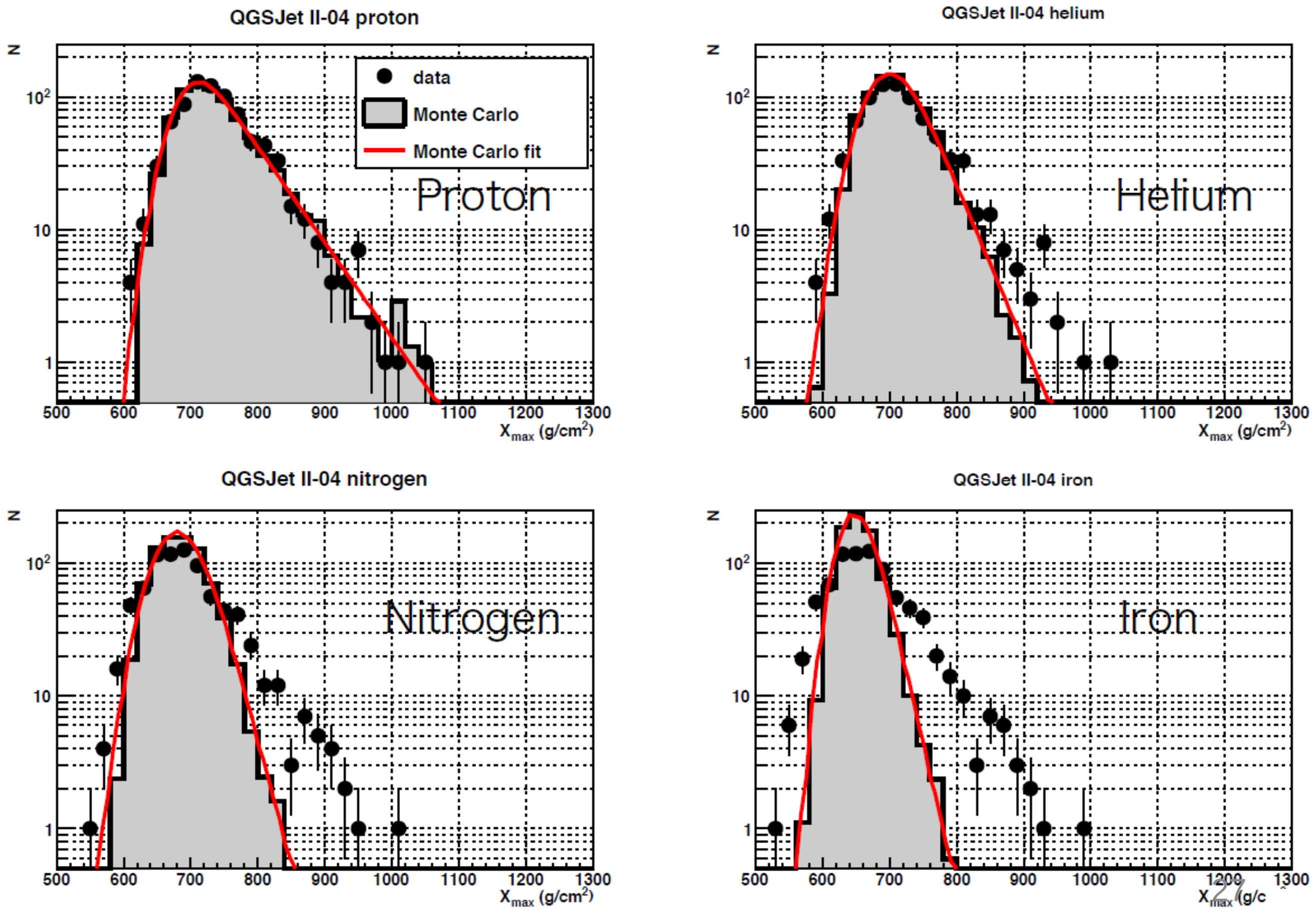
Compare shape of X_{max} distributions of Data and MC allowing Xmax shift

Ap. J., 858, 76(2018)
arXiv: 1801.09784

18.2 < log(E/eV) < 18.3

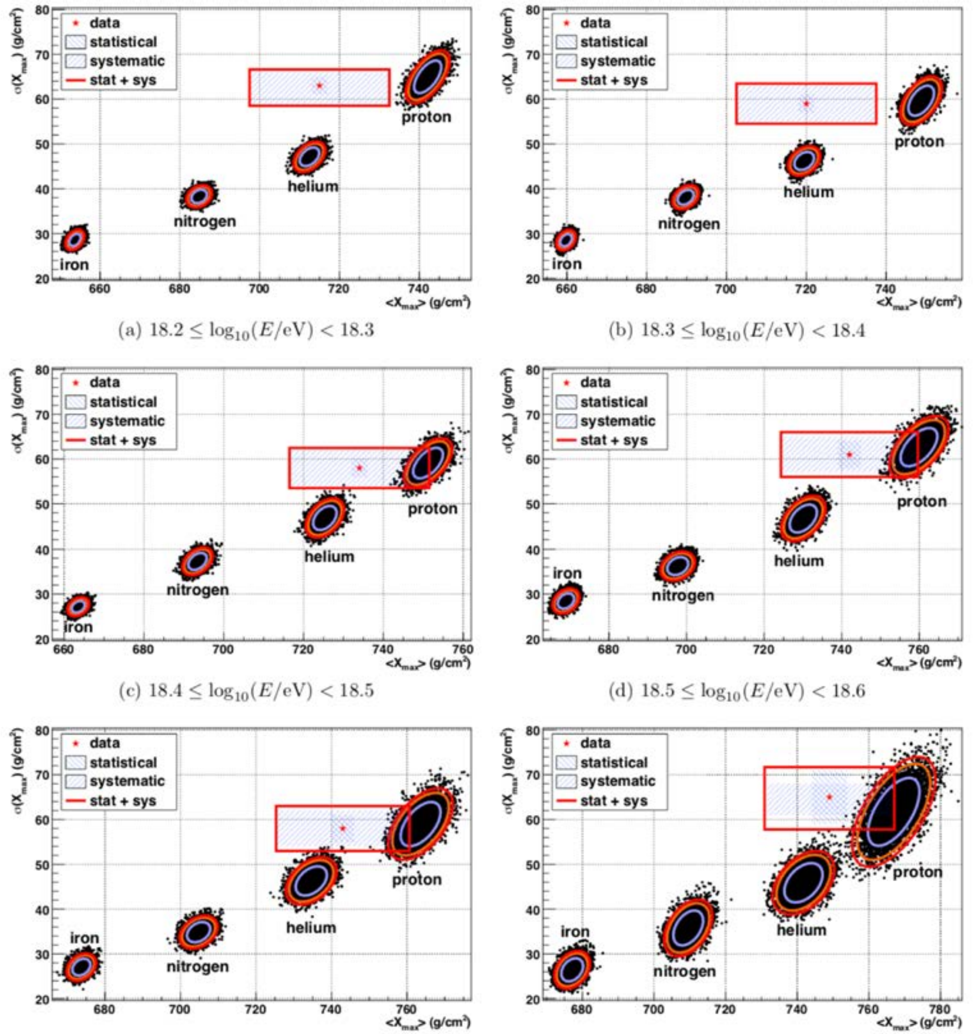
Xmax shift
proton : +29g/cm²
He : +7g/cm²
N : -21g/cm²
Fe : -43g/cm²

Systematic uncertaiinty
<Xmax> : 17.4g/cm²



$\langle X_{max} \rangle$ vs. σ_{max} Plane ($<10^{18.8}$eV)

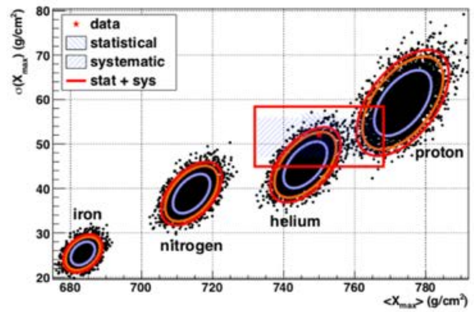
- Data/MC Comparison
- Data : Red rectangle
  (including systematics)
- MC : Contours
  (5000 MC sets)
- In lower energies $<10^{18.8}$eV,
  allowing shift 10-20g/cm^2
  data looks like protons



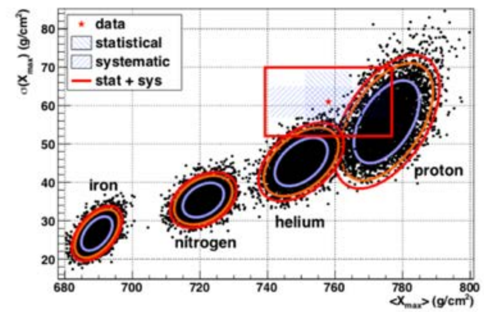
(a) $18.2 \leq \log_{10}(E/\text{eV}) < 18.3$
(b) $18.3 \leq \log_{10}(E/\text{eV}) < 18.4$
(c) $18.4 \leq \log_{10}(E/\text{eV}) < 18.5$
(d) $18.5 \leq \log_{10}(E/\text{eV}) < 18.6$
(e) $18.6 \leq \log_{10}(E/\text{eV}) < 18.7$
(f) $18.7 \leq \log_{10}(E/\text{eV}) < 18.8$

$\langle X_{max} \rangle$ vs. σ_{max} Plane ($>10^{18.8}$eV)

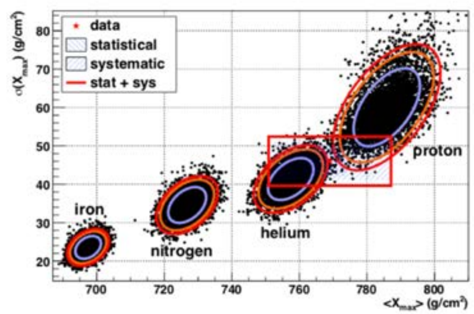
- Data/MC Comparison
- Data : Red rectangle (including systematics)
- MC : Contours (5000 MC sets)
- In lower energies $<10^{18.8}$eV, allowing shift 10-20g/cm^2 data looks like protons
- In higher energies $>10^{18.8}$eV, data points looks like heavier primary than protons



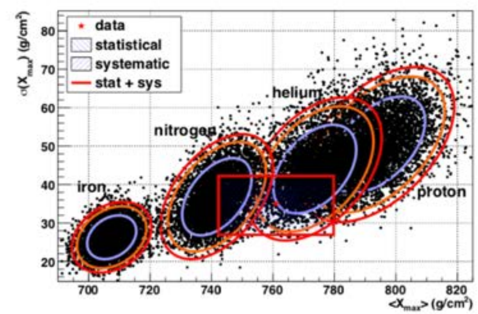
(a) $18.8 \le \log_{10}(E/\mathrm{eV}) < 18.9$



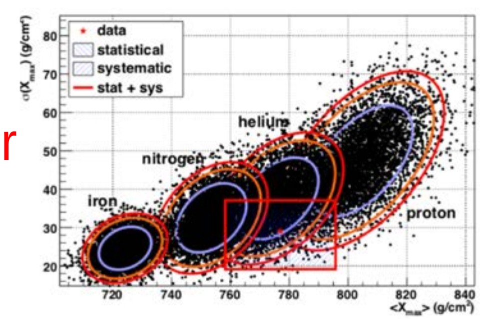
(b) $18.9 \le \log_{10}(E/\mathrm{eV}) < 19.0$



(c) $19.0 \le \log_{10}(E/\mathrm{eV}) < 19.2$

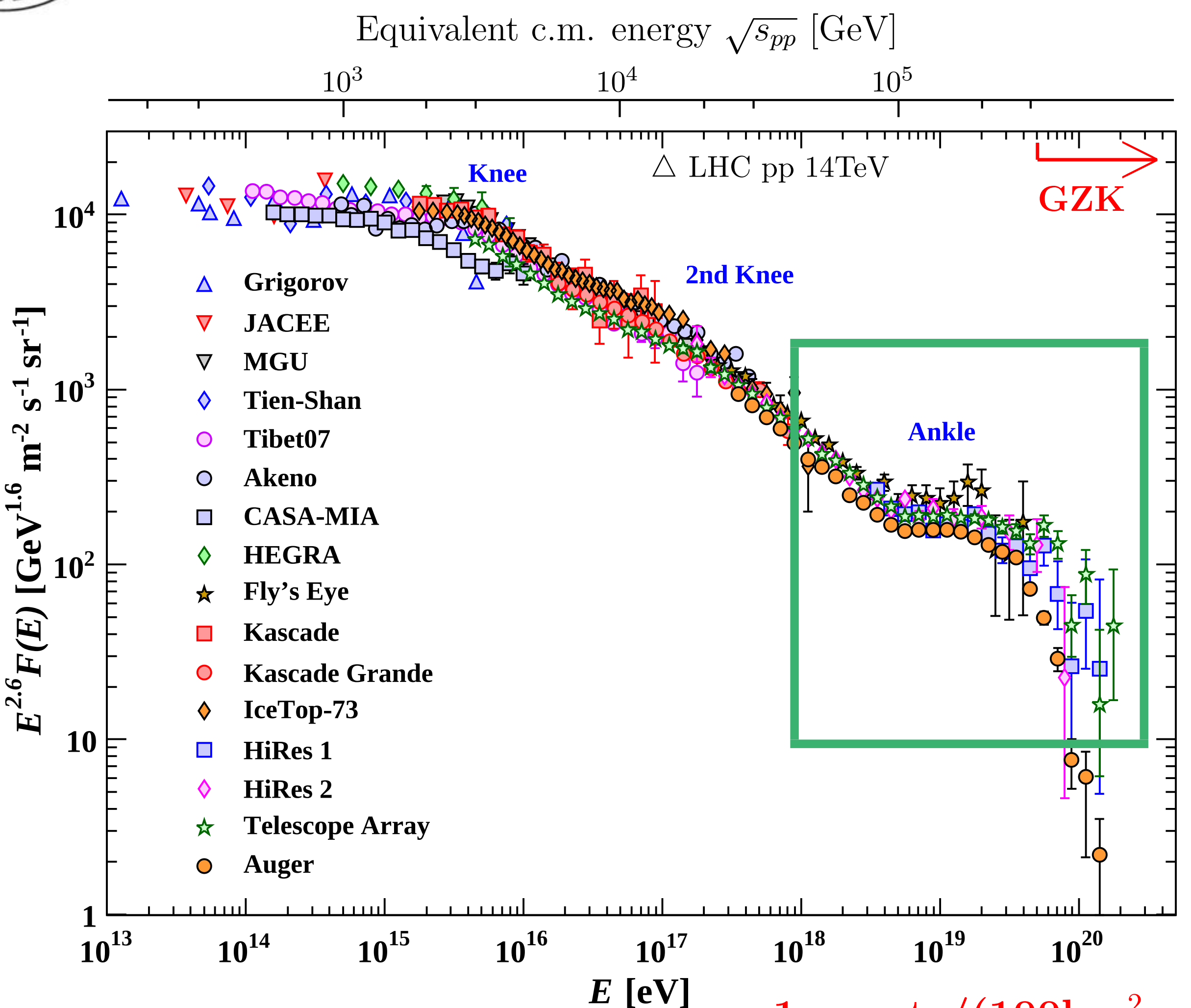


(d) $19.2 \le \log_{10}(E/\mathrm{eV}) < 19.4$



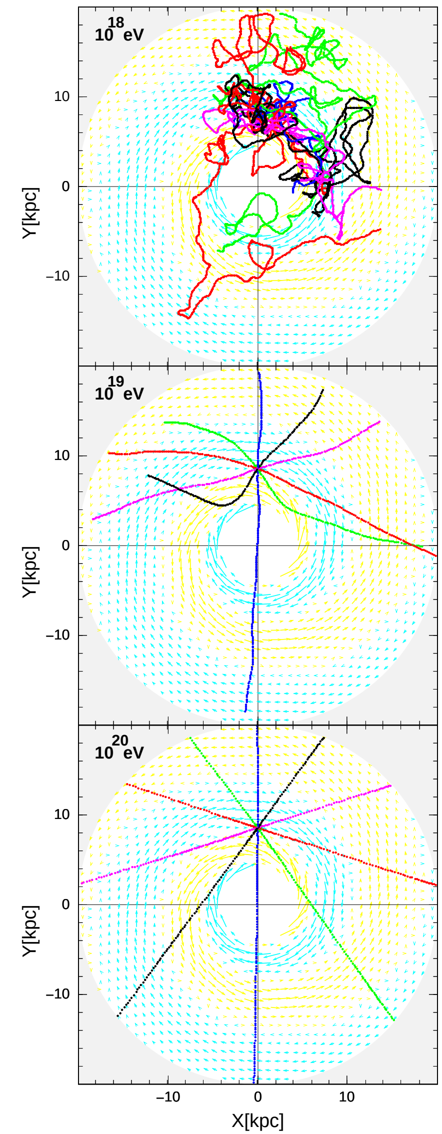
(e) $19.4 \le \log_{10}(E/\mathrm{eV}) < 19.9$

Ultra-High-Energy Cosmic Rays

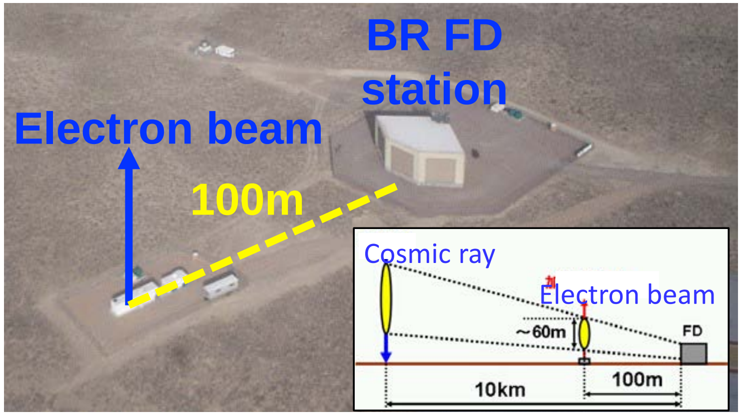


PDG2016

$\sim$1 events/(100km^{2}yr) @ 10^{20}eV

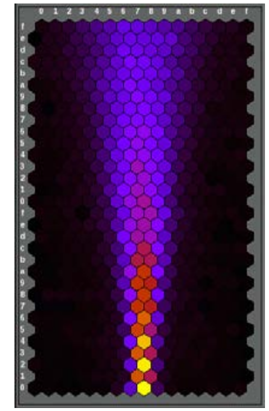


Electron Light Source (ELS)



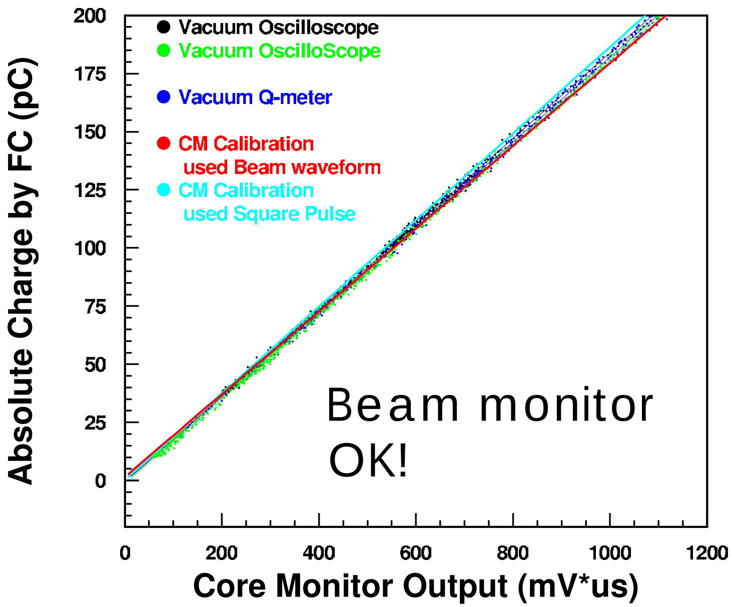
- 40-MeV, 10^9 electrons (typical)
- End-to-end FD energy calibration

preliminary



An image of data Measured with FD

T. Shibata
ICRC2013

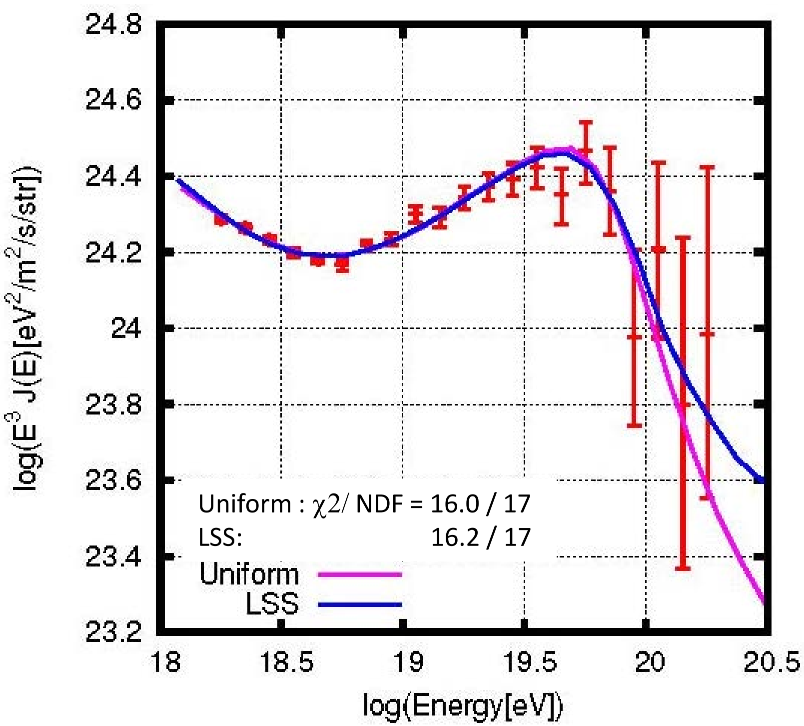


- ❖ Beam monitors have been calibrated. (Faraday Cap, Core monitor)
- ❖ MC simulation has been developed.
- ❖ Test fluorescence yield models
  - TA model(Kakimoto modifiend+Flash) :
    Data/MC = 1.18±0.01(stat)±0.18(syst)
  - Common Model (based on AirFly)
    Data/MC = 0.96±0.01(stat)±0.15(syst)

We expect that we can calibrate true energy scale of the FD with the ELS in near future.

Astrophysical Scenario: TA

Fit with extra-galactic proton



Source Distribution

- Uniform
- LSS (~2MASS XSCz)

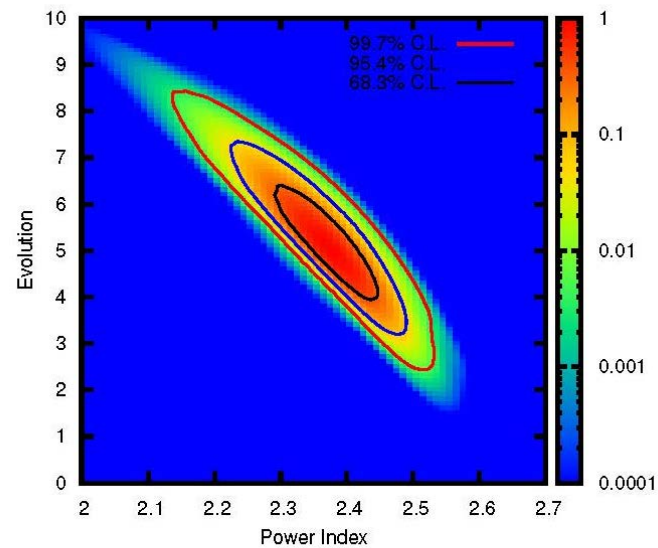
Energy Loss with

- CMB
- Infra-Red

using CRPropa 2.0 simulation checked with analytic ΔE.
No magnetic field.

4-parameter fit

- Injection spectrum : E^{-p}
  $E_{max} = 10^{21}$ eV
- Evolution : $(1+z)^m$
- Flux normalization
- Energy scale



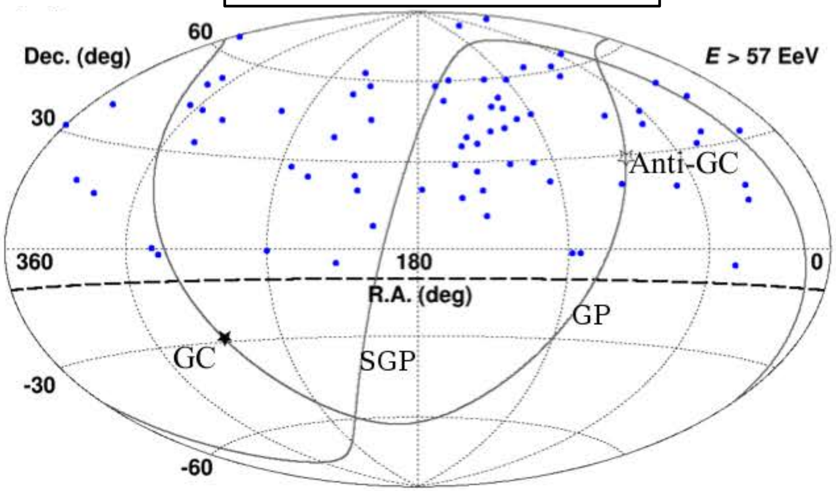
For LSS
P = 2.37 +0.08 –0.08
m = 5.2 +1.2 -1.3
Log E'/E = - 0.02 +0.04 –0.05

E. Kido
ICRC 2013

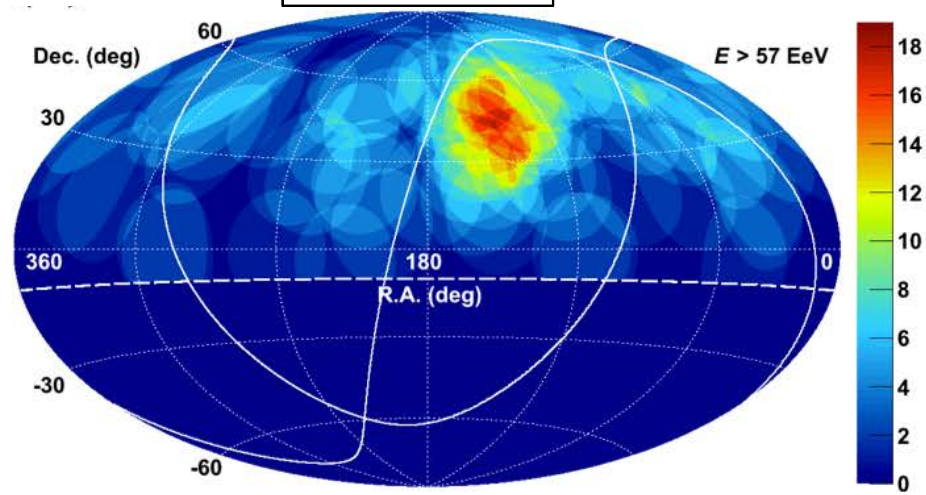
TELESCOPE ARRAY PROJECT

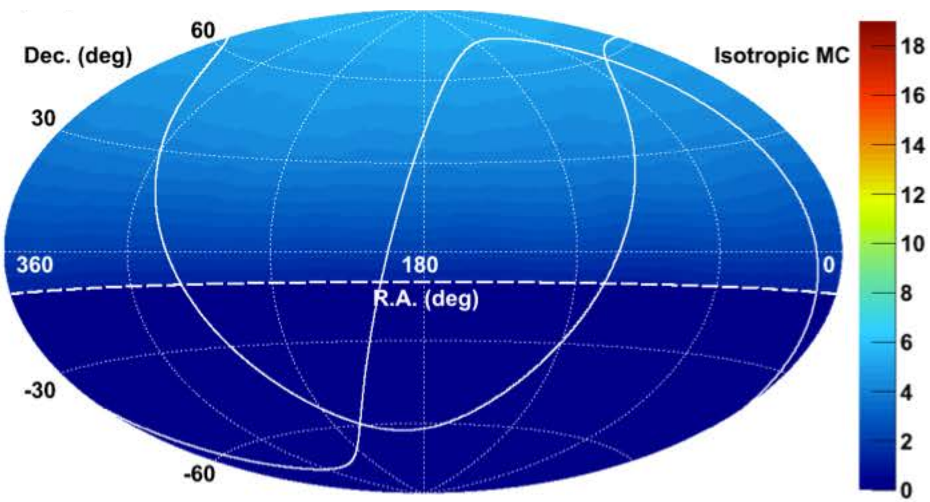
Hotspot

Event distribution

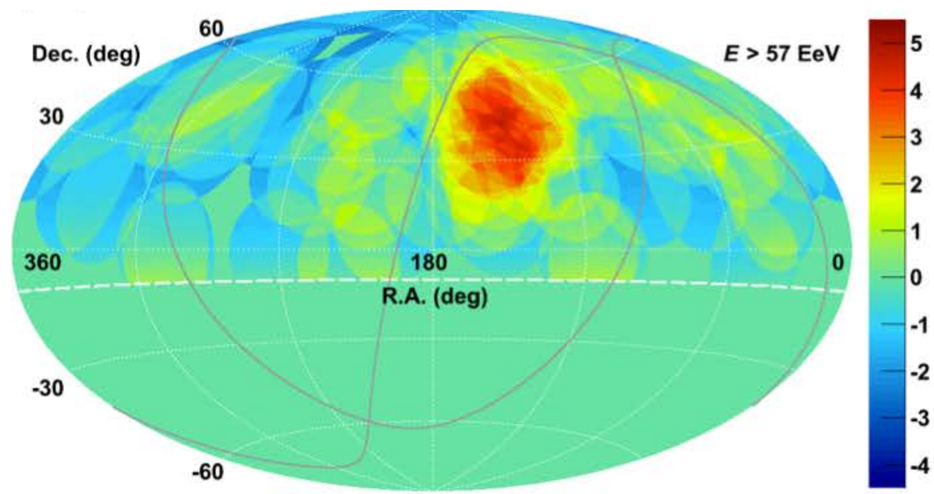


Observed





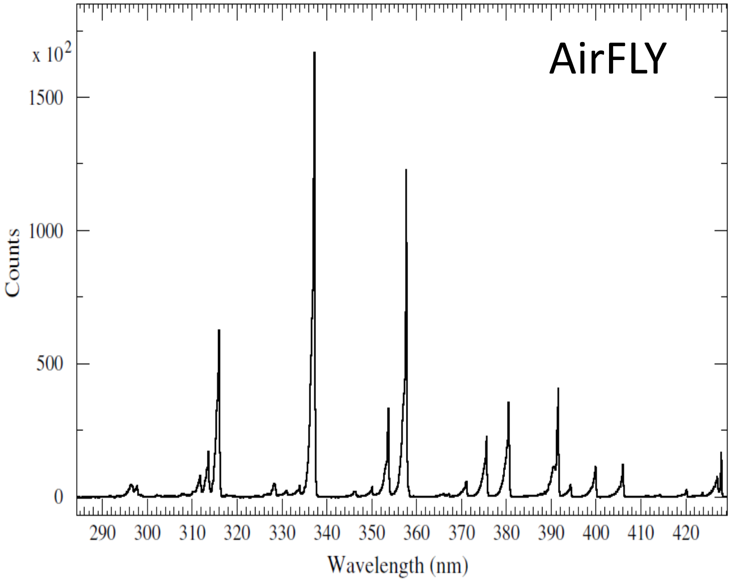
Background



Significance

Air Fluorescence : Reference model established

Reference Model proposed by B. Keilhauer & experimental groups at UHECR2012 @CERN.



- Spectrum at 1013 hPa and 293 K: AirFLY
- Extinction, T and humidity dep. : AirFLY, N.Sakaki et al.
- Normalization (AF Yield at 337nm) : open

$$Y_\lambda^{NEW\,2012}(T,P,RH)(\mathrm{ph/MeV}) = Y_{337nm}(T_r,P_r)\cdot I_\lambda(T_r,P_r)\cdot \frac{1+\dfrac{P_r}{P'^{\nu'}_{air}(T_0)}\left(\dfrac{T_0}{T_r}\right)^{1/2-\alpha}}{1+\dfrac{P}{P'^{\nu'}_{air}(T_0,RH)}\left(\dfrac{T_0}{T}\right)^{1/2-\alpha}}$$

$T_r = T_0 = 293K$
$P_r = 800hPa$

B. Keilhauer et al., UHECR 2012 arXiv:1210.1319

M. Ave et al. AirFLY collaboration ApP 28(2007)41

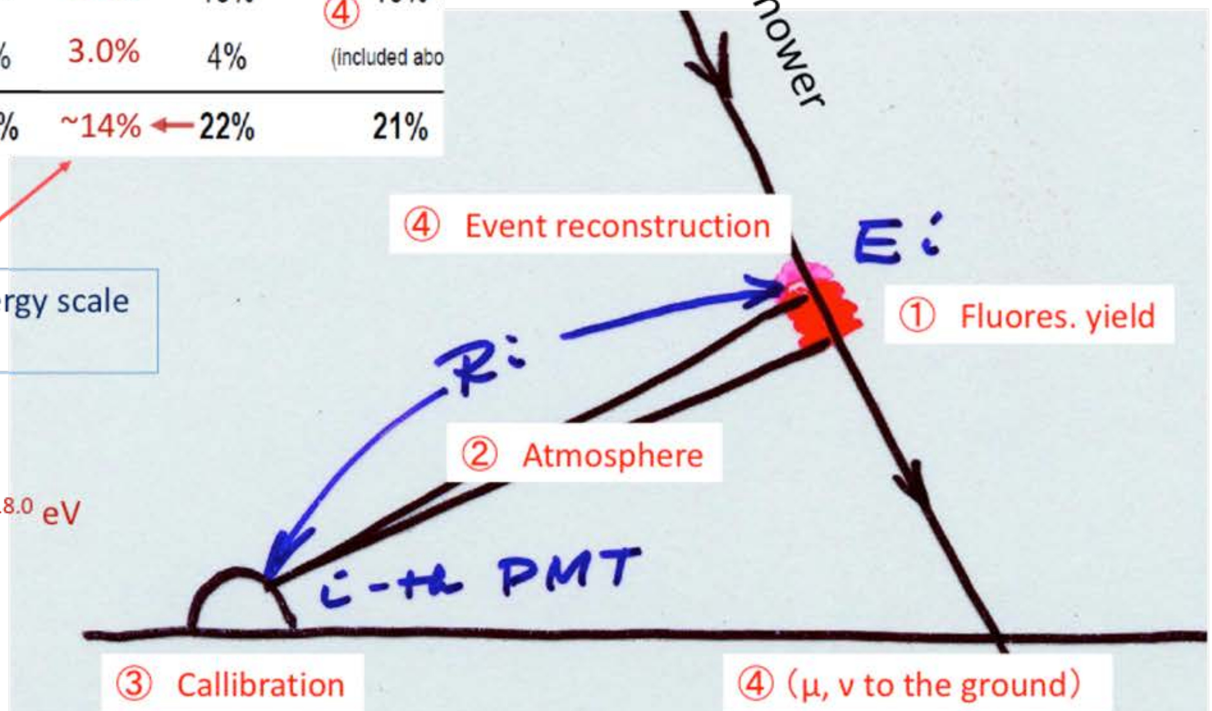
T. Shibata, ICRC 2013

FD Energy Scale

	HiRes		Auger	TA
Calibration	10%	9.9%	9.5%	③ 10%
Fluorescence yield	6%	3.6%	14%	① 11%
Atmosphere	5%	6.2%	8%	② 11%
Reconstruction	10%	6.5%	10%	④ 10%
Invisible energy	5%	3.0%	4%	(included abo
Total Systematic Uncertainty	17%	~14% ←	22%	21%

Auger updated energy scale in ICRC 2013

Energy Increased by 16% at $10^{18.0}$ eV and 10% at 10^{19} eV

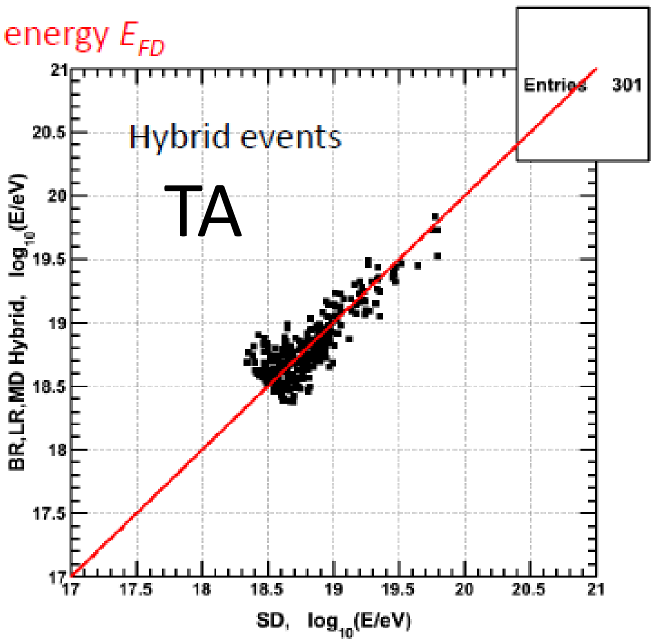


V. Verzi, ICRC2013

A. Lettessier-Selvon ICRC2013

Energy Calibration E'_{SD} (S_{38} for Auger) vs E_{FD} using hybrid events

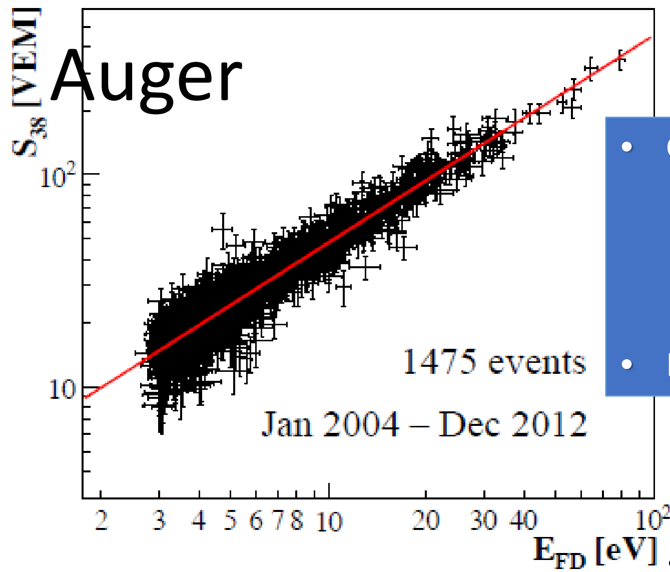
FD energy E_{FD}



SD energy E_{SD}

$E_{SD} = E'_{SD}/1.27$

- S-800 = # of particles at D=800m
- S-800(E'_{SD} , th) map is obtained by air shower simulation.



$$E_{SD} = A\, S_{38}^{B} \qquad A = 0.190 \times 10^{18}\ \text{eV} \qquad B = 1.025$$

- S_{38} = # of VEMs at $\theta=38^0$ and D=1000m
- Zenith attenuation of VEMs obtained from Constant Intensity Cut (CIC)

- Good correlation (~linear) with particle density at 1000m (Auger) , 800m (TA) from core for $10^{18.5} < E < 10^{19.8}$ eV.
- Limited statistics for $10^{19.5}$ eV < E

- Auger E-scale updated (ICRC2013) using (nearly) reference model.
- TA E-scale unchanged:
  - Spectrum: FLASH
  - Yield: Kakimoto et al. extended
  - same as HiRes

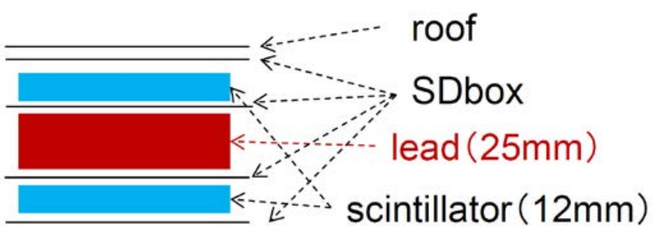
V. Verzi, ICRC2013

ICRC2013
Poster, 118, 298

TA muon detector project

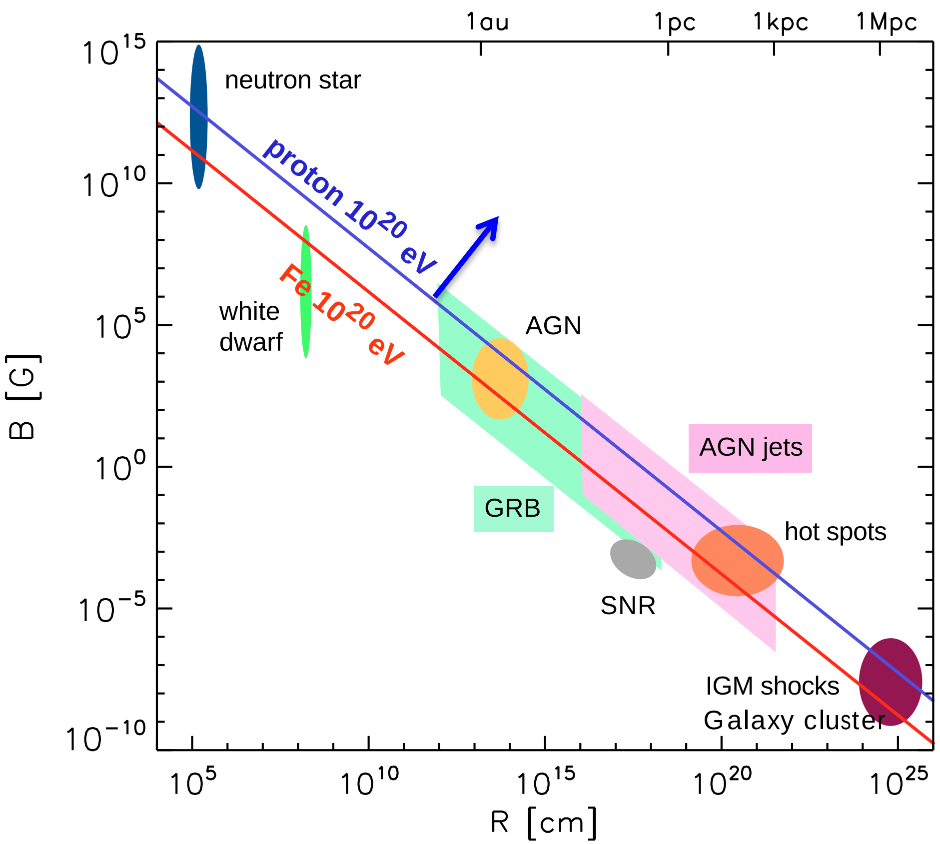
- One set of 24-m^2 scintillator detector with concrete absorber on the top
  - 8x(3-m^2 scintillator detectors)
- Lead layer sandwiched between two scintillators
  - First 9 m^2: 12x(0.75 m^2)
    - 1 segment was deployed inside CLF

will be installed outside CLF early next year



- Auger water → TA site

Hillas Diagram



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

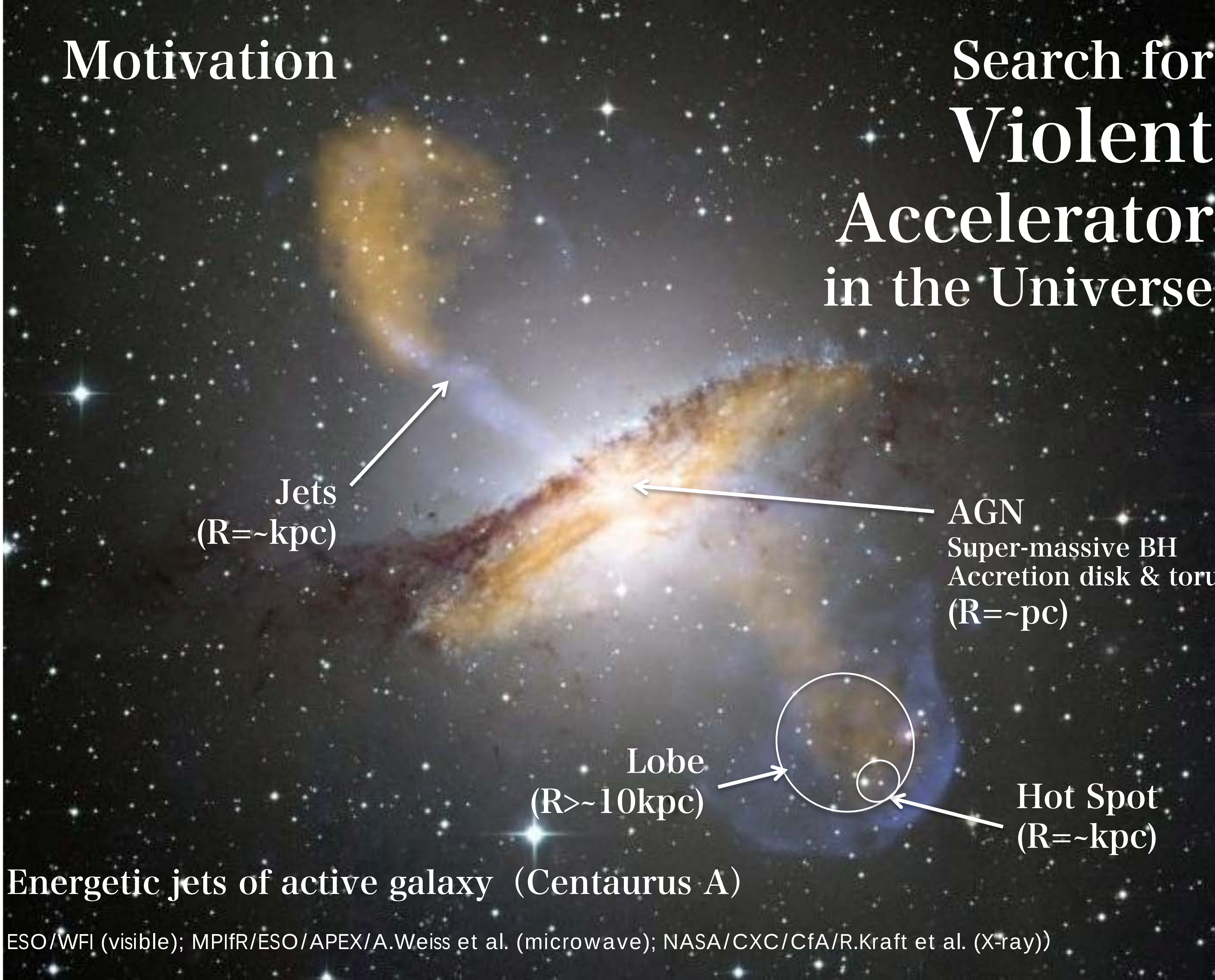
- Larmor Radius R_L

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

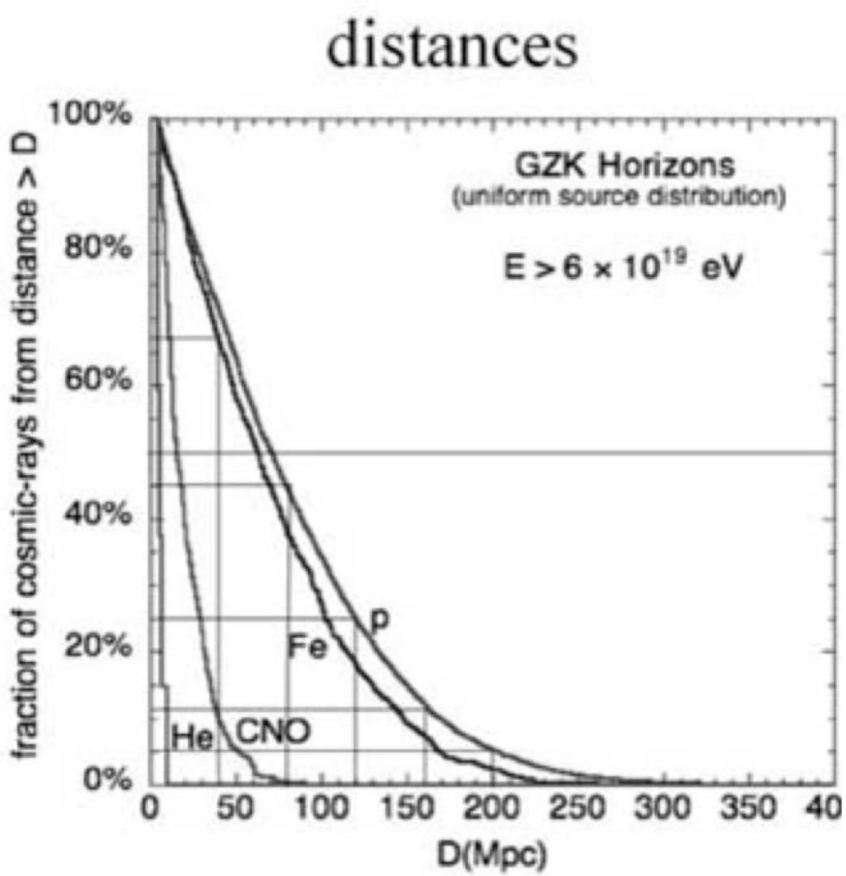
Search for Violent Accelerator in the Universe

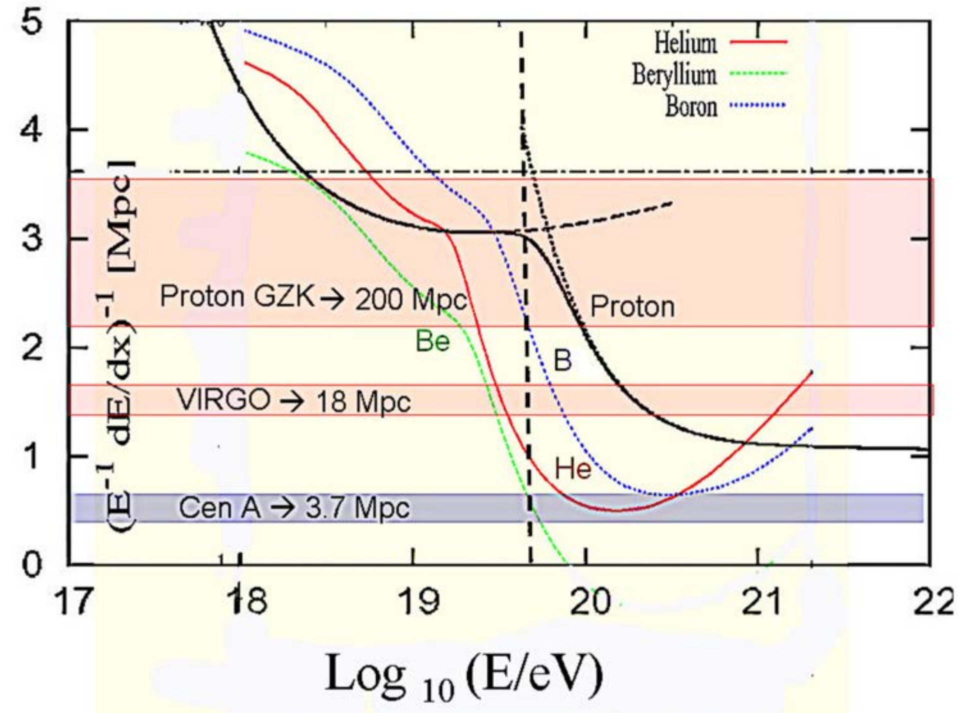


Energetic jets of active galaxy（Centaurus A）

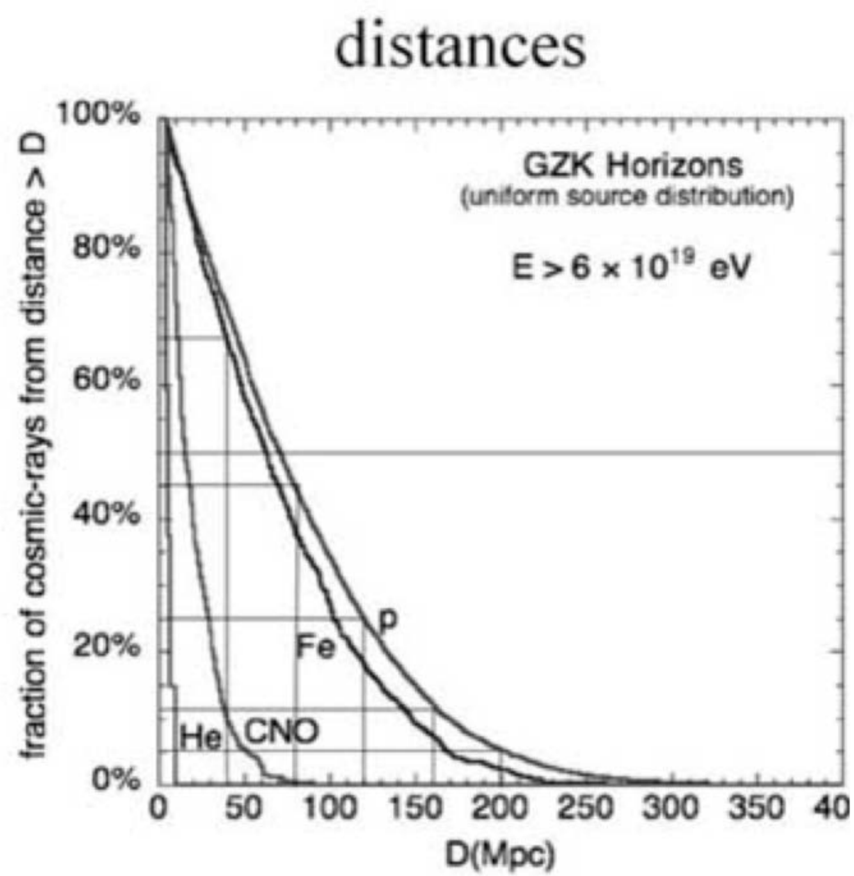
ESO/WFI (visible); MPIfR/ESO/APEX/A.Weiss et al. (microwave); NASA/CXC/CfA/R.Kraft et al. (X-ray))

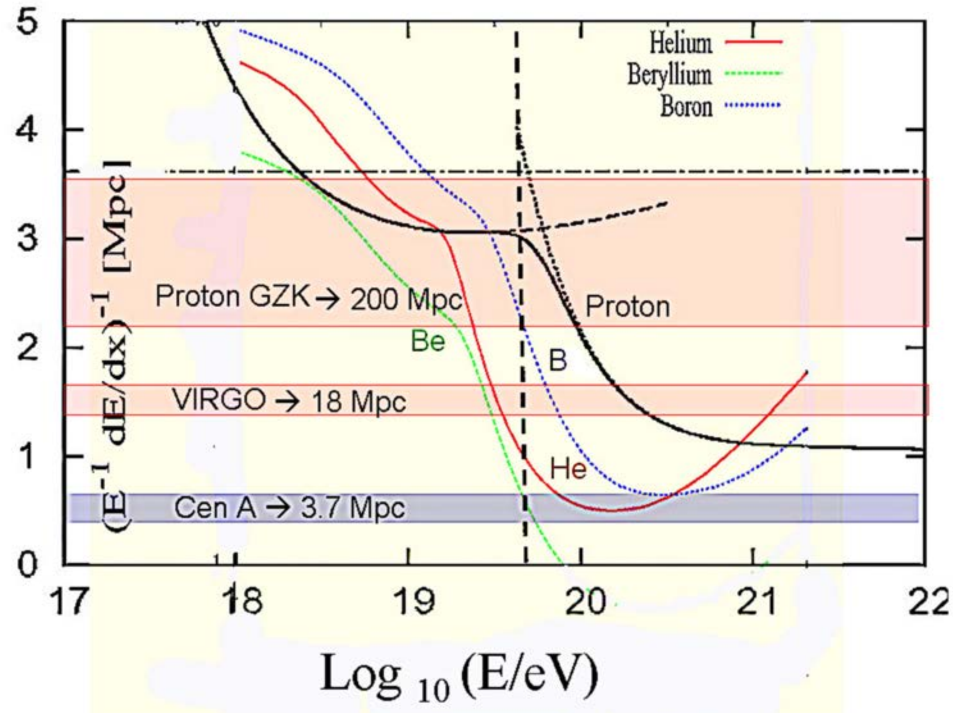
GZK Horizons
Composition Dependence





GZK Horizons
Composition Dependence





Intergalactic Magnetic Field

Generally random MF

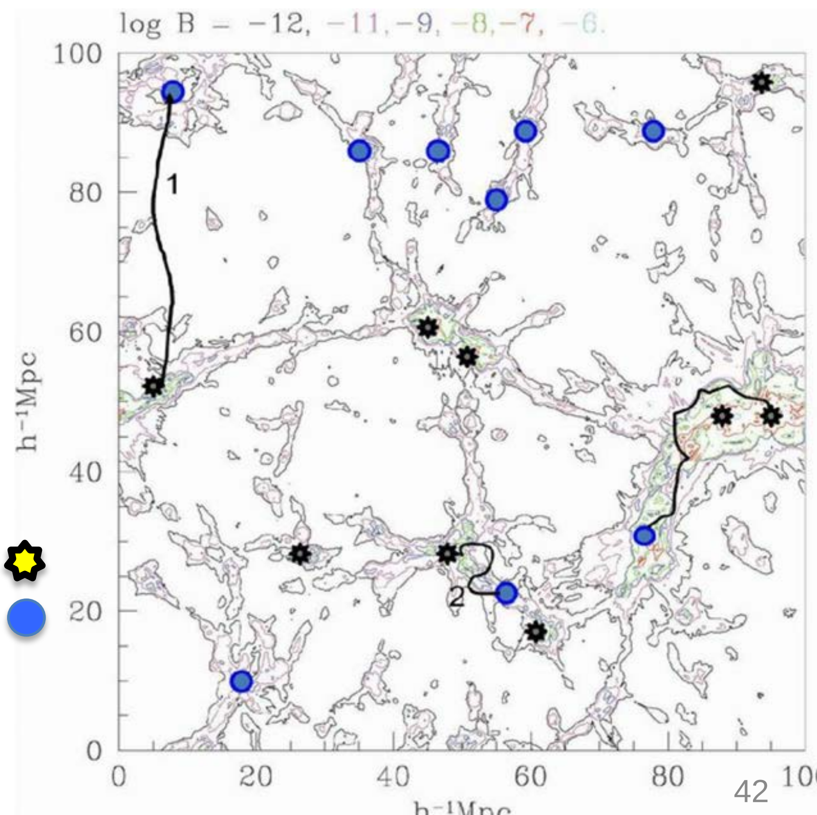
Very difficult to measure IGMF

→ Large uncertainty ~10^{-17}G < B < ~10^{-9}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

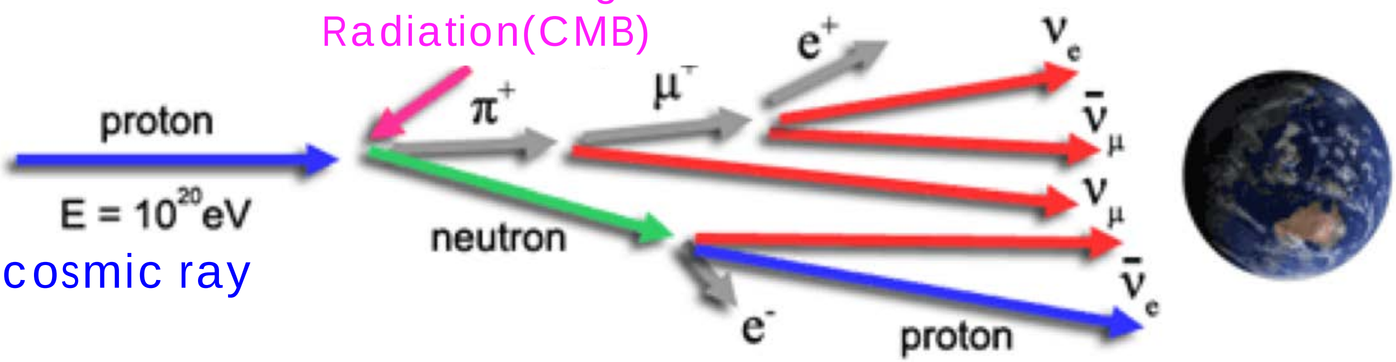
UHECR sources

Virtual observers

Ryu, Das & Kang, ApJ (2010)

GZK Effect

Cosmic Background Radiation(CMB)



Highest-E cosmic ray

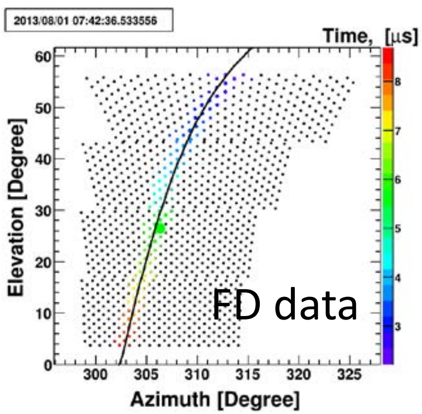
<u>Highest energy region</u>

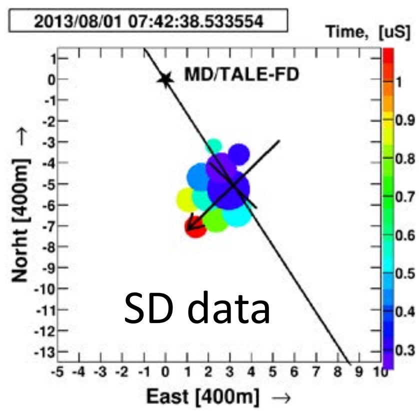
❖ Highest-E cosmic ray travel beyond 50Mpc rapidly loss their energy by interaction with the cosmic microwave background. → Greisen-Zatsepin-Kuzmin (GZK) Effect

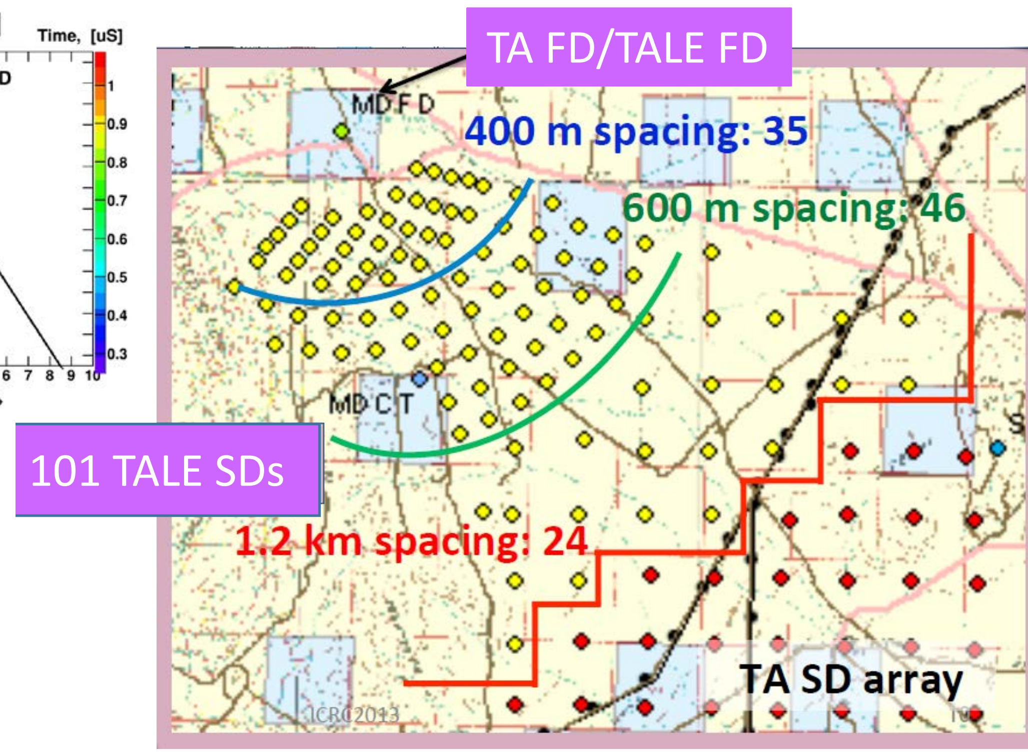
Highest-E cosmic rays can not reach the Earth from the distant universe. Therefore, Origin of cosmic rays should be limited to local universe

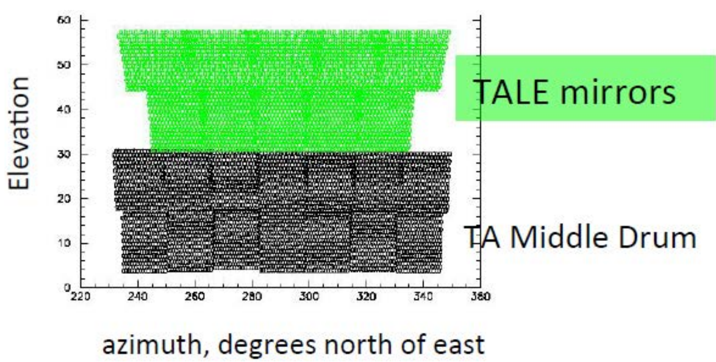
TALE (TA Low-E Extension)

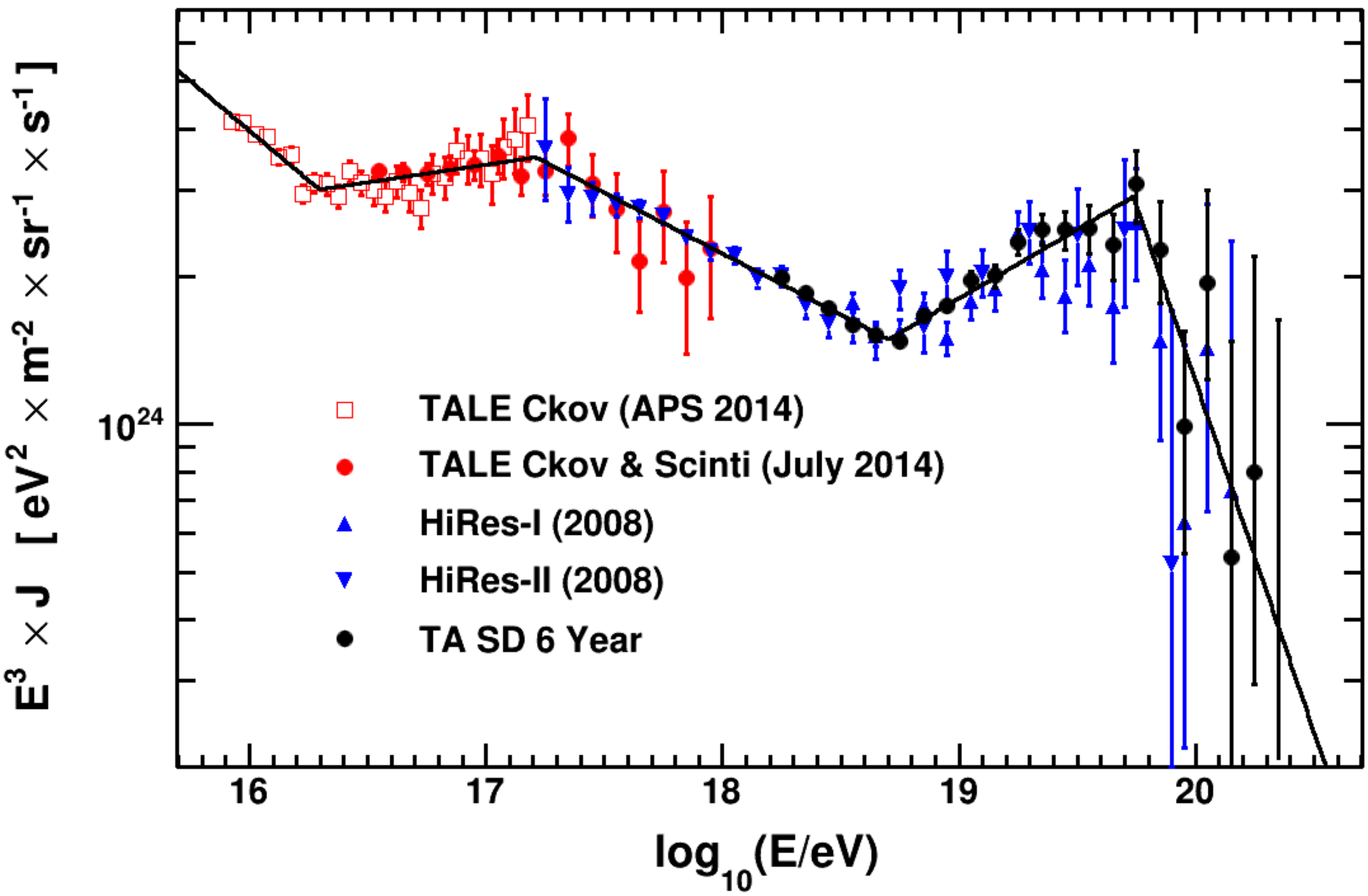
- ❖ Target range $10^{16.5}$-10^{19}eV
  - Second Knee
  - Change of mass composition
  - LHC center of mass E
- ❖ TALE is operating partly now







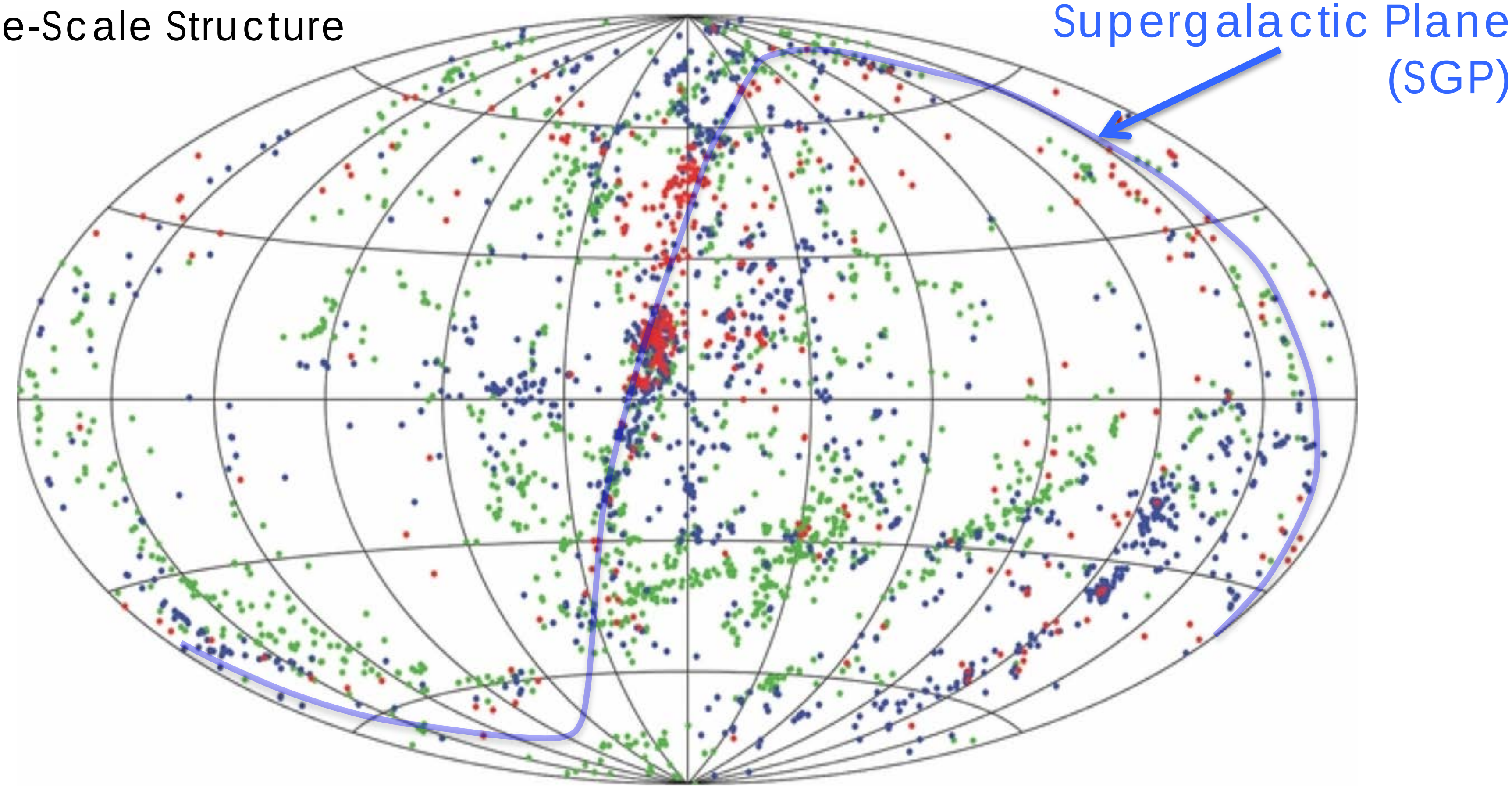




$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
16
17
18
19
20
$\log_{10}(E/eV)$
TALE Ckov (APS 2014)
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year

Galaxy Distribution in Local Universe

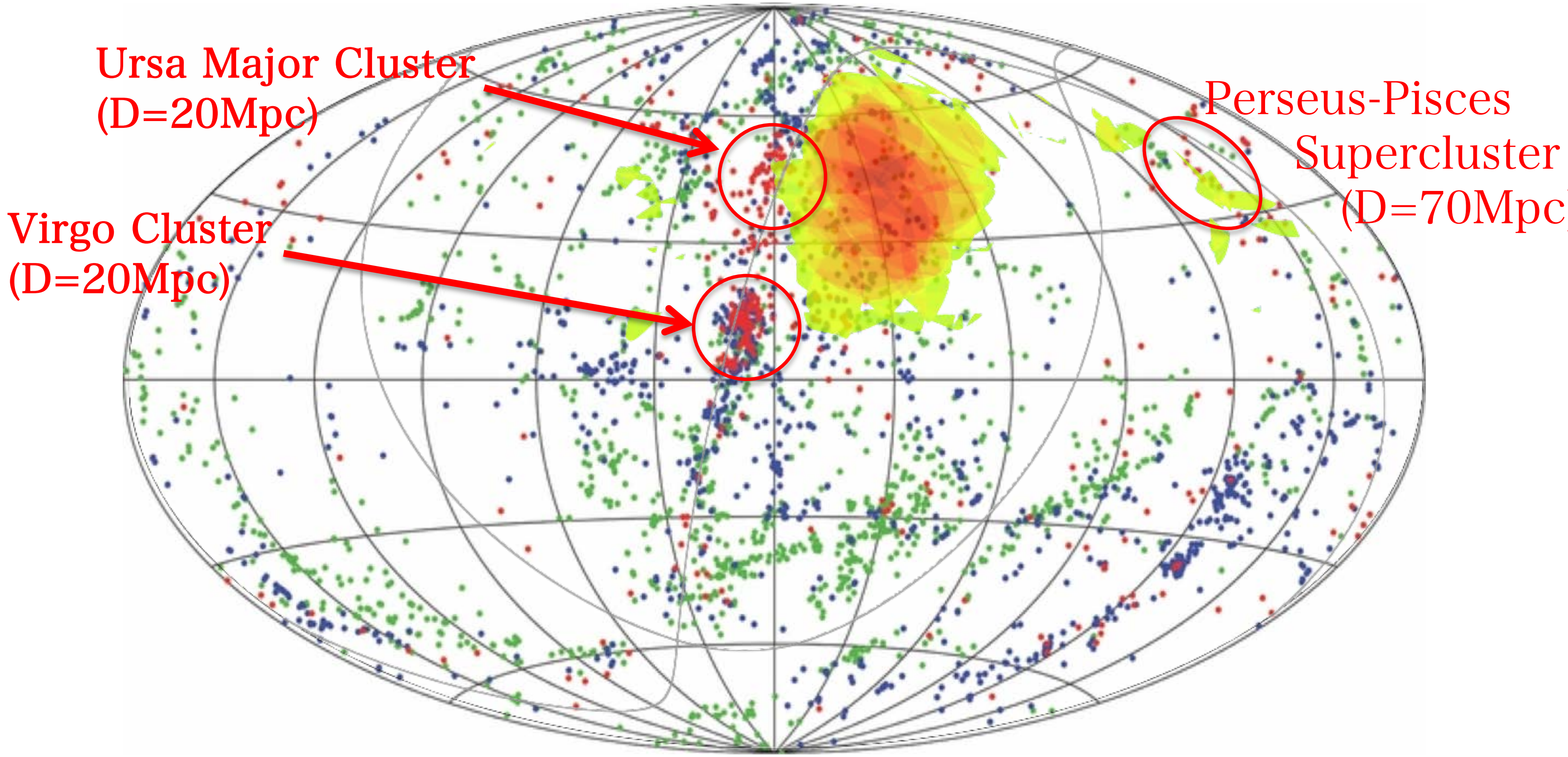
Large-Scale Structure (LSS)



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

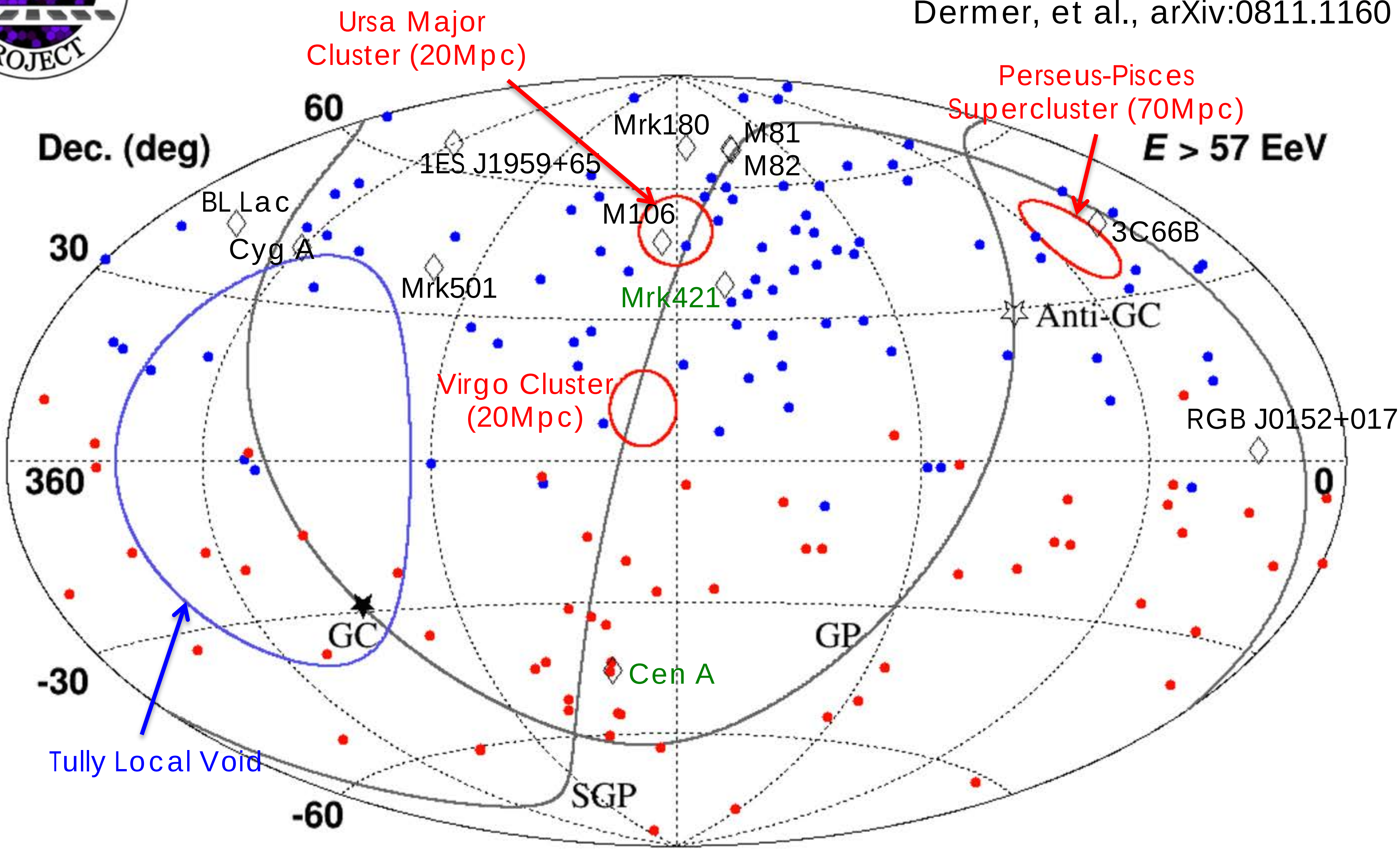


2MASS catalog velocity 0 – 3000 km/s
John P. Huchra, et al 2012, ApJ, 199, 26
+ 5-year TA data (Color contour)

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

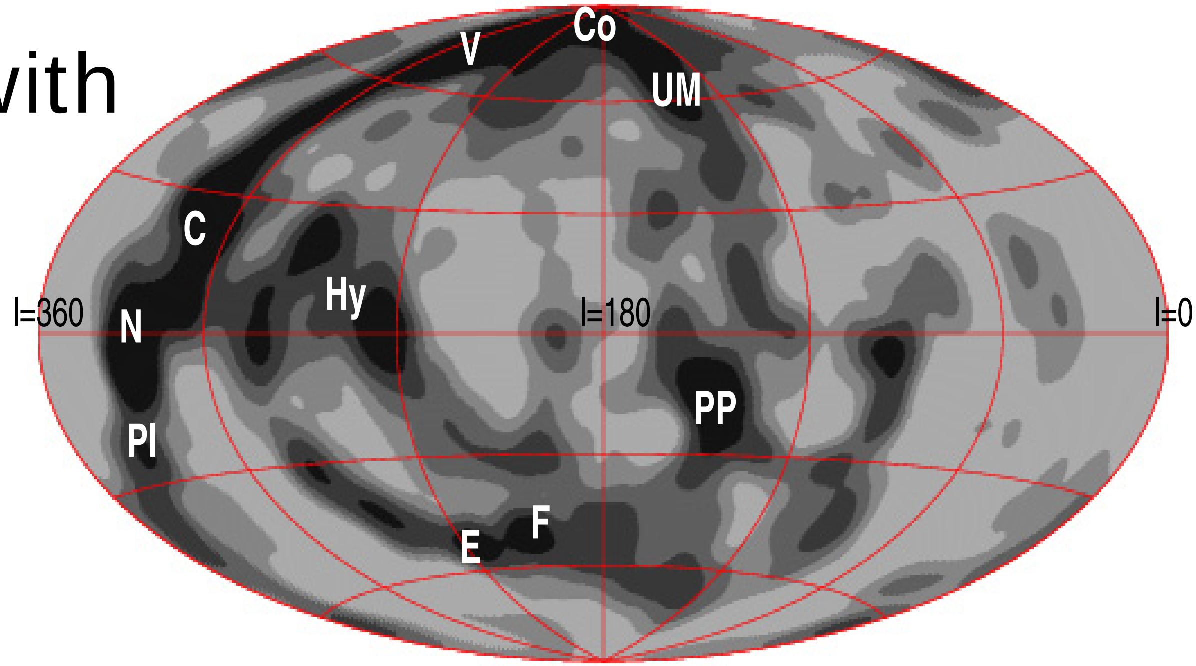
Dermer, et al., arXiv:0811.1160



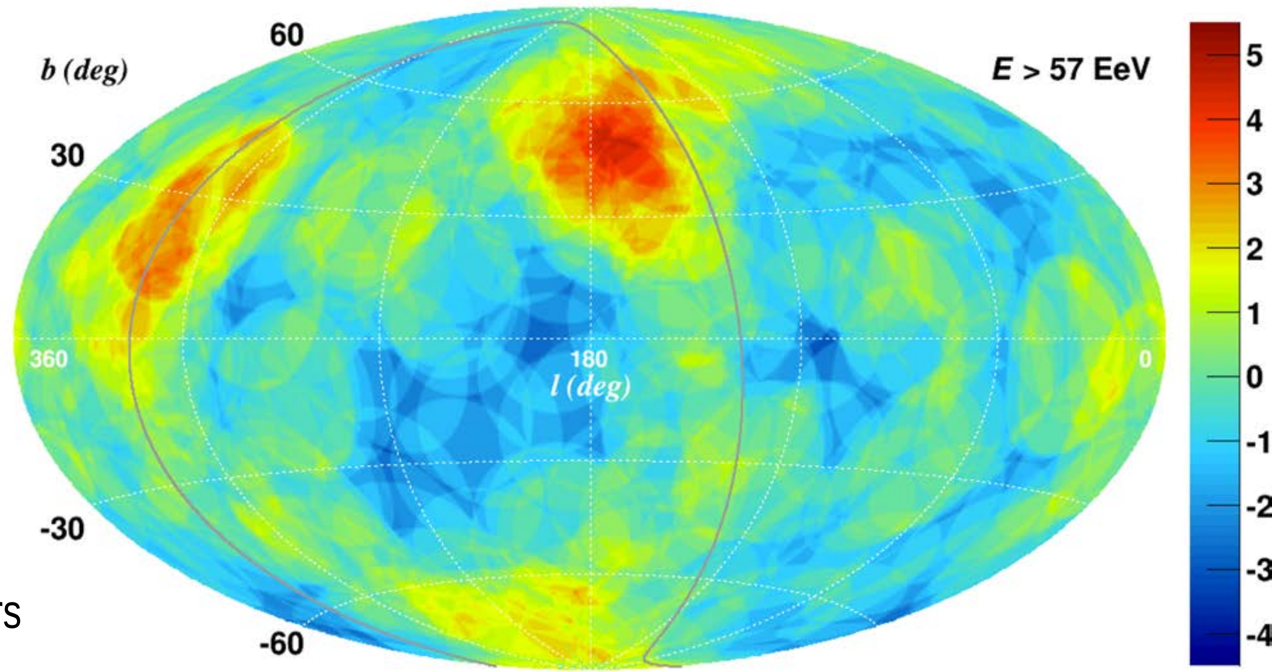
TA : 2008 May – 2014 May (6.0 years) 87 events

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

Comparison with Large-Scale Structure

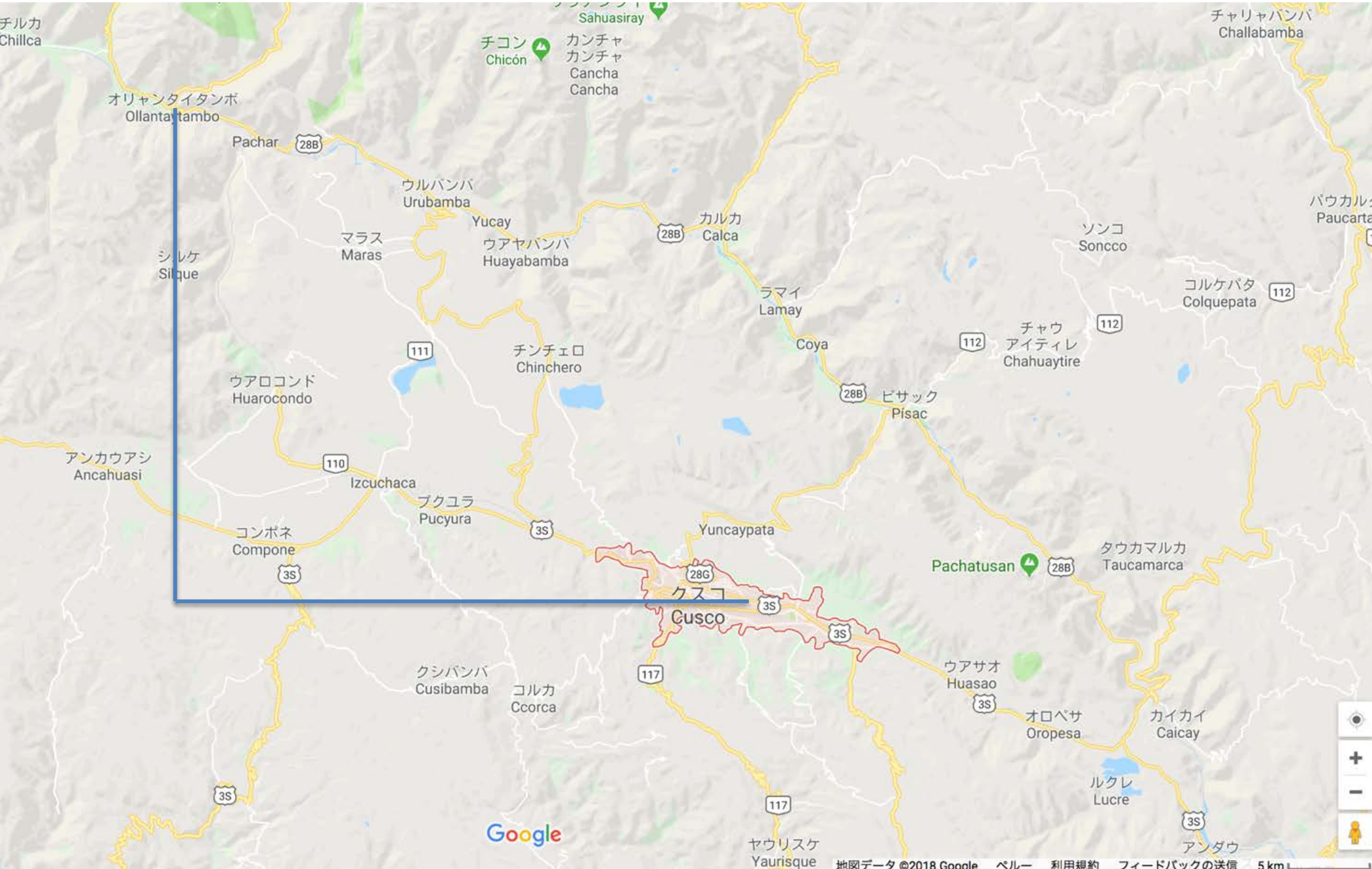


Sky map of expected flux at E > 57 EeV (Galactic coordinates). The smearing angle is 6○. The letters indicate the nearby structures as follows: C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); UM: Ursa Major (20 Mpc); and V: Virgo cluster (20 Mpc).



No correction for E scale difference b/w TA and PAO !!

TA 7 years + PAO 10 years


チルカ
Chillca
Sahuasiray
チコン
Chicón
カンチャカンチャ
Cancha Cancha
チャリャバンバ
Challabamba
オリャンタイタンボ
Ollantaytambo
Pachar
28B
ウルバンバ
Urubamba
Yucay
マラス
Maras
ウアヤバンバ
Huayabamba
カルカ
Calca
シルケ
Silque
ラマイ
Lamay
ソンコ
Soncco
パウカルタ
Paucartam
コルケパタ
Colquepata
112
チャウアイティレ
Chahuaytire
Coya
111
チンチェロ
Chinchero
ウアロコンド
Huarocondo
ピサック
Pisac
アンカウアシ
Ancahuasi
110
Izcuchaca
プクユラ
Pucyura
3S
コンポネ
Compone
Yuncaypata
Pachatusan
タウカマルカ
Taucamarca
28G
クスコ
Cusco
ウアサオ
Huasao
クシバンバ
Cusibamba
コルカ
Ccorca
117
オロペサ
Oropesa
カイカイ
Caicay
ルクレ
Lucre
ヤウリスケ
Yaurisque
アンダウ
Google
地図データ ©2018 Google
ペルー
利用規約
フィードバックの送信
5 km