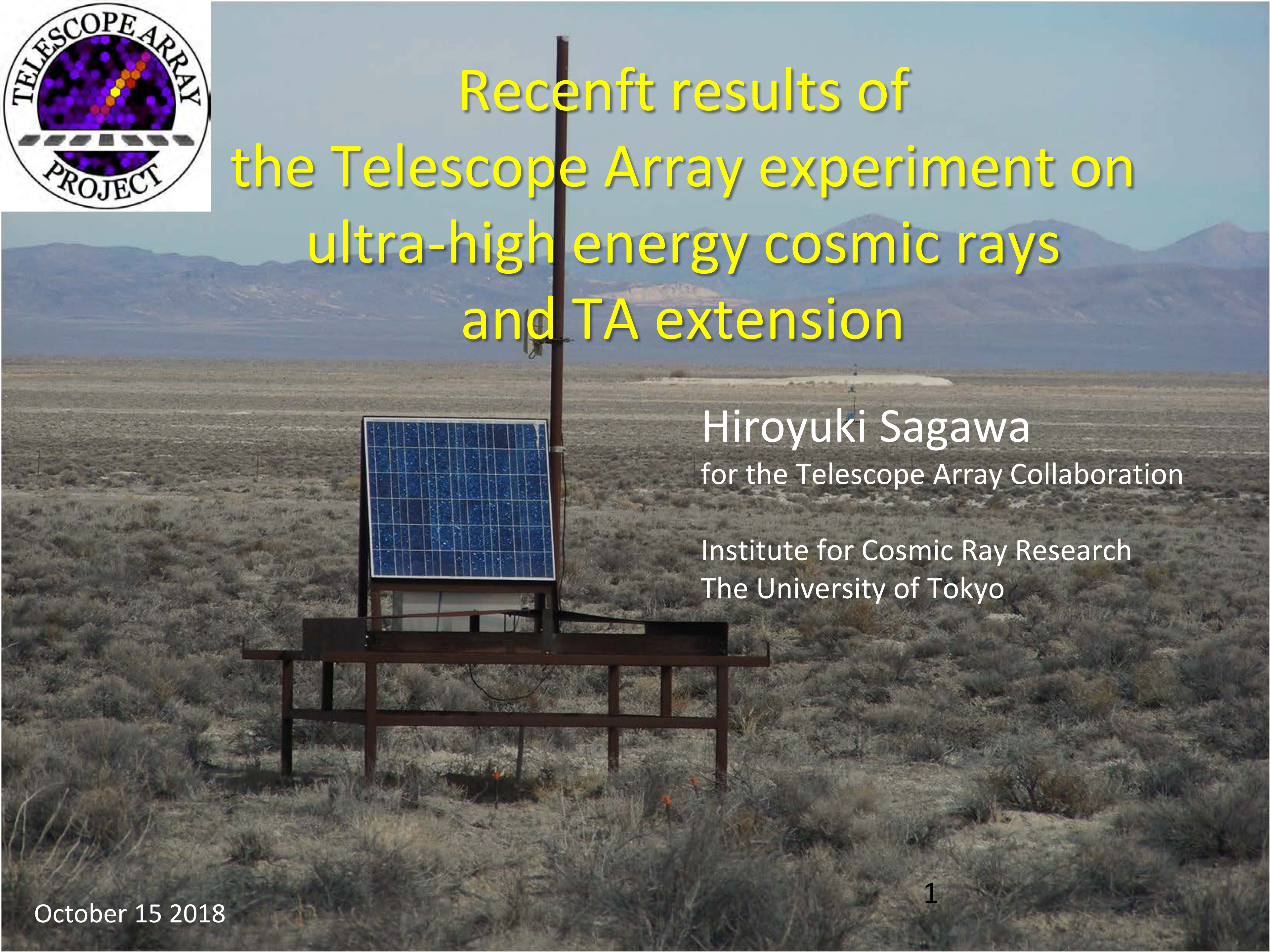


Recenft results of the Telescope Array experiment on ultra-high energy cosmic rays and TA extension

Hiroyuki Sagawa
for the Telescope Array Collaboration

Institute for Cosmic Ray Research
The University of Tokyo

October 15 2018

INSTITUTE FOR COSMIC RAY RESEARCH (ICRR)

- Director: Prof. Kajita

東京大学宇宙線研究所長
梶田隆章

Nobel Prize winner in Physics 2015

- Research
  - Study on cosmic rays
  - Studies with cosmic rays
    - Cosmic rays in a broad sense
    - Astroparticle physics, elementary particles

- Numbers of staffs and students (JFY2017)
  - 126 staffs (60 researchers) hired by ICRR
  - 65 graduate students

FACILITIES INSIDE JAPAN: 4 OBSERVATORIES

②KAGRA (gravitational wave observatory) at Kamioka

①Super-Kamiokande Neutrino observatory at Kamioka

③Norikura

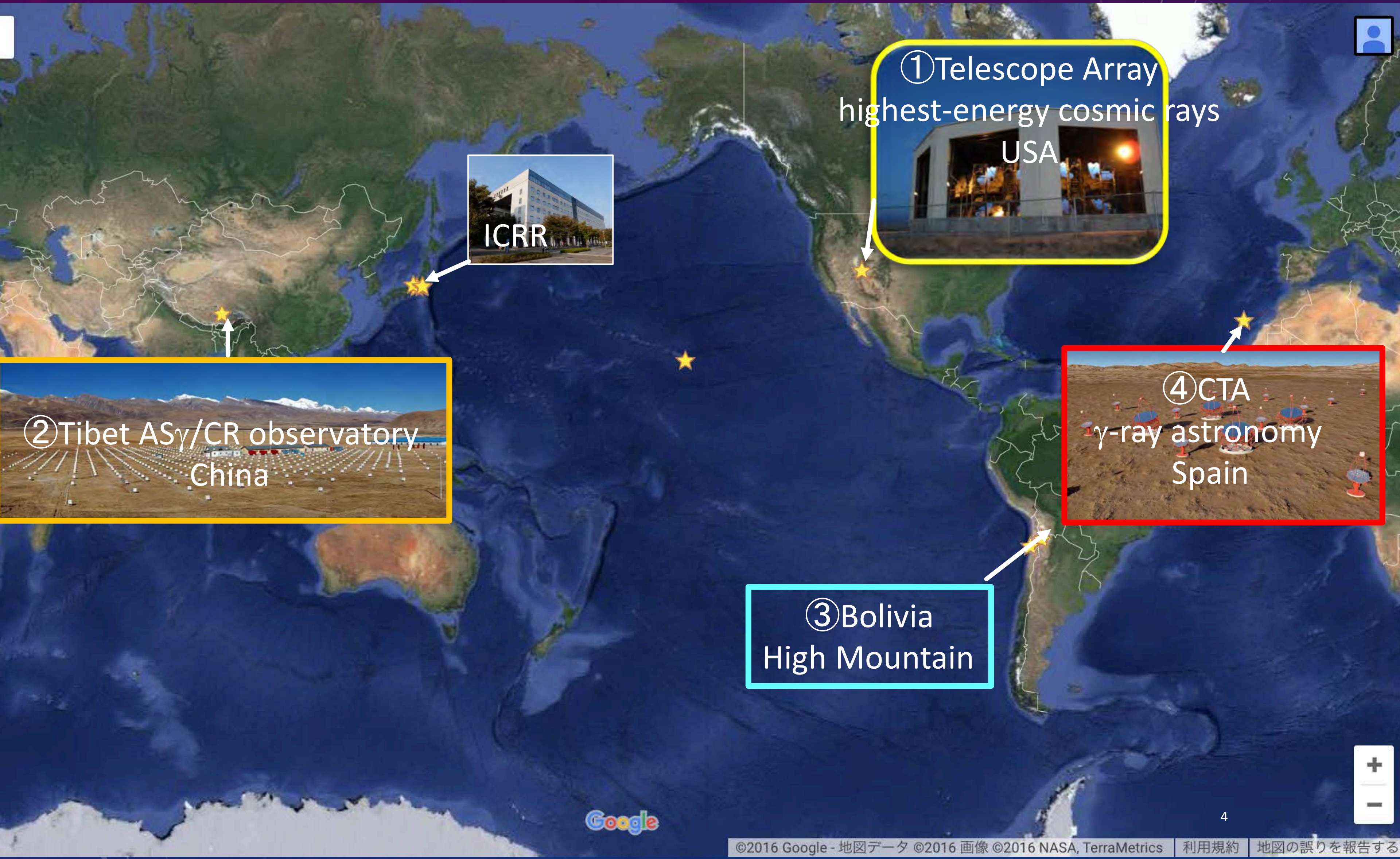
④Akeno

ICRR

Kashiwa Campus

UTokyo Main Campus

OBSERVATIONAL CORES OUTSIDE JAPAN: 4 SITES



①Telescope Array
highest-energy cosmic rays
USA

ICRR

②Tibet ASγ/CR observatory
China

③Bolivia
High Mountain

④CTA
γ-ray astronomy
Spain

11 Science Questions in Physics of the Universe

The Discover cover story is based on the 105-page National Research Council Committee on Physics of the Universe report Connecting Quarks with the Cosmos: 11 Science Questions for the New Century.

(Discover Magazine's Cover Story For February 2002)

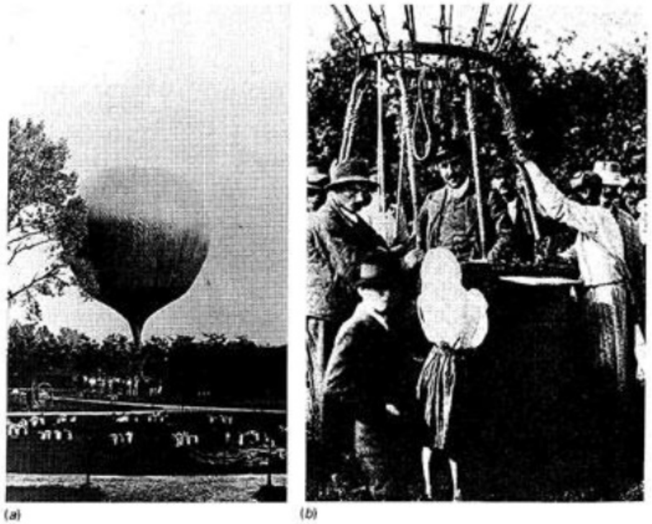
1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultra-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons stable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

Content

- Introduction
  - Cosmic rays / Ultra-High Energy Cosmic Rays (UHECR)
  - Telescope Array (TA)
- Recent results
  - Energy Spectrum
  - Composition
  - Anisotropy
- TA extension
  - TAx4
  - TALE

Cosmic Rays

- 1912 Victor Hess discovered cosmic rays



(a) (b)

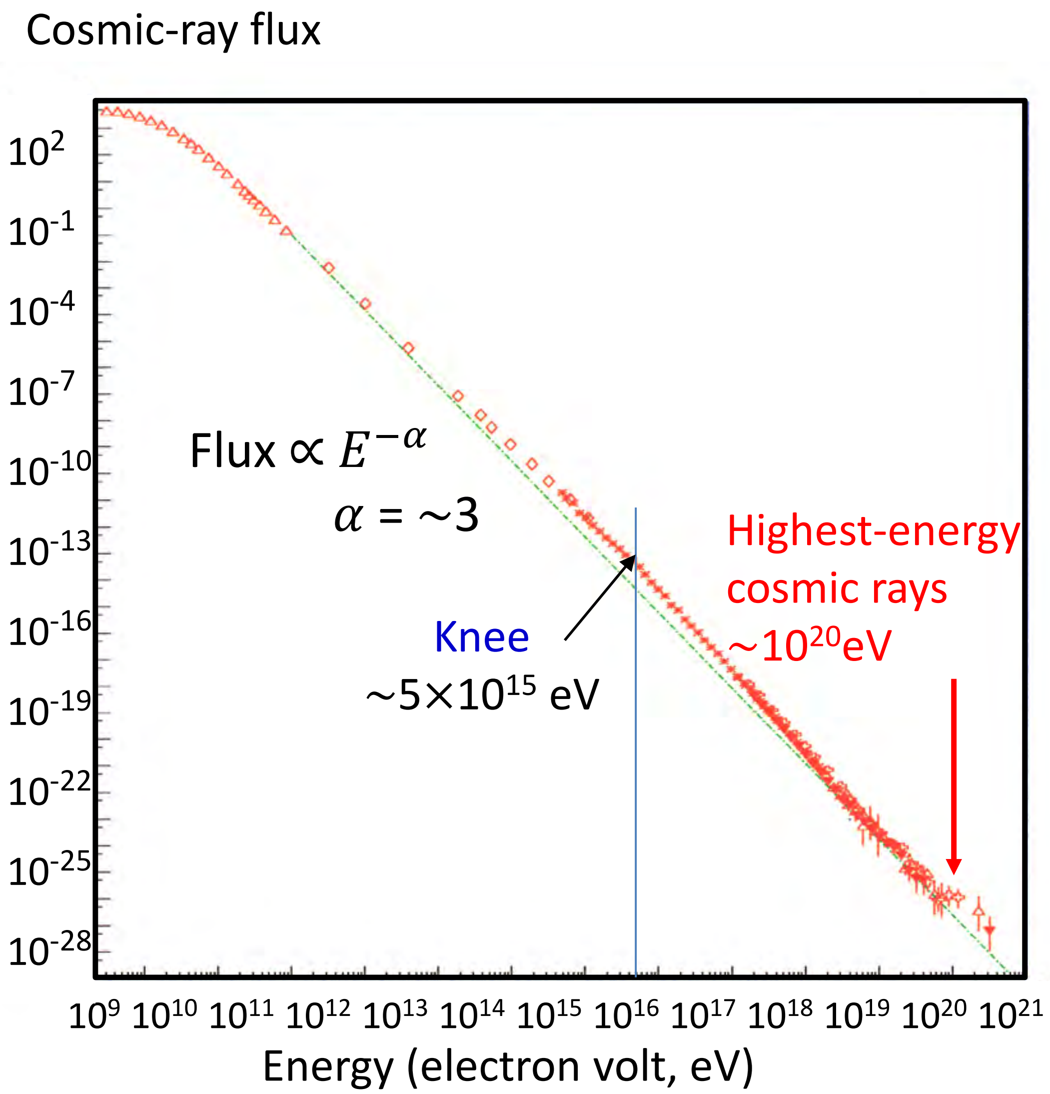
- Since then, we knew cosmic rays are
  - High-energy elementary particles that travel the universe
  - Main component: protons; others: nuclei and electrons
  - Arrive at the earth uniformly (~0.1% level anisotropy)

Recently
TA hotspot (E>57 EeV)
Auger discovered dipole structure (E>8 EeV)
Auger found evidence of correlation for Star Burst Galaxies (E>39 EeV)

Cosmic Rays

- 1930s～1940s Elementary particles were discovered using cosmic rays
  - Positrons, muons, pions …
- 1950s～
  - The mission of the discovery of elementary particles → particle accelerator experiments
  - The mission of cosmic rays → subjects such as observations of the universe

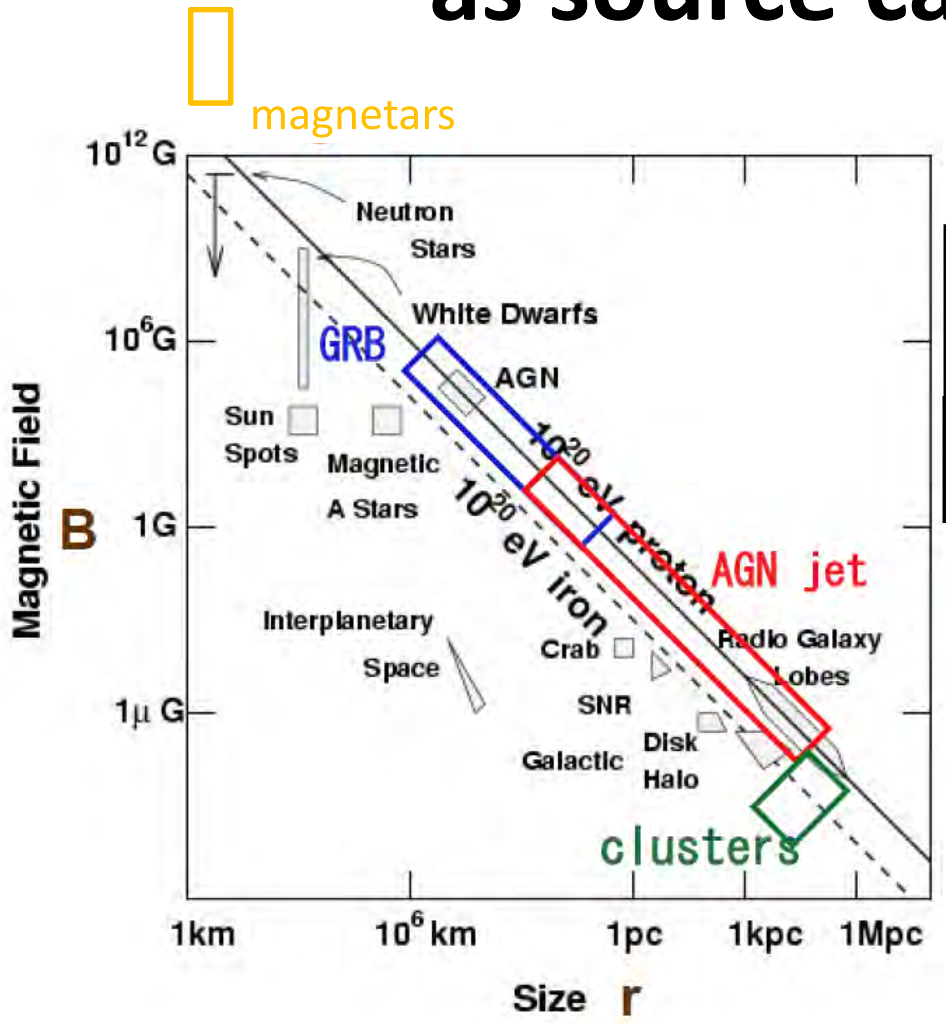
Energy spectrum of cosmic rays



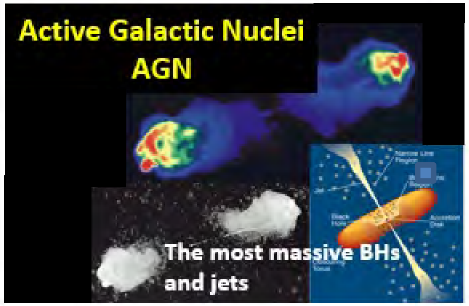
Acceleration of cosmic rays
to Knee energy (~5×10^{15} eV)
could be explained by
shock wave acceleration
(sourc spectral index α=2.0 ~ 2.2)
at supernova explosions in the Galaxy

What are the most powerful accelerators generating cosmic rays of 10^{20} eV?

Astrophysical cosmic-ray accelerators as source candidates



Hillas condition E < e B r β


Active Galactic Nuclei AGN

The most massive BHs and jets


Cluster of galaxies

The largest gravitationally bounded objects


New Magnetars

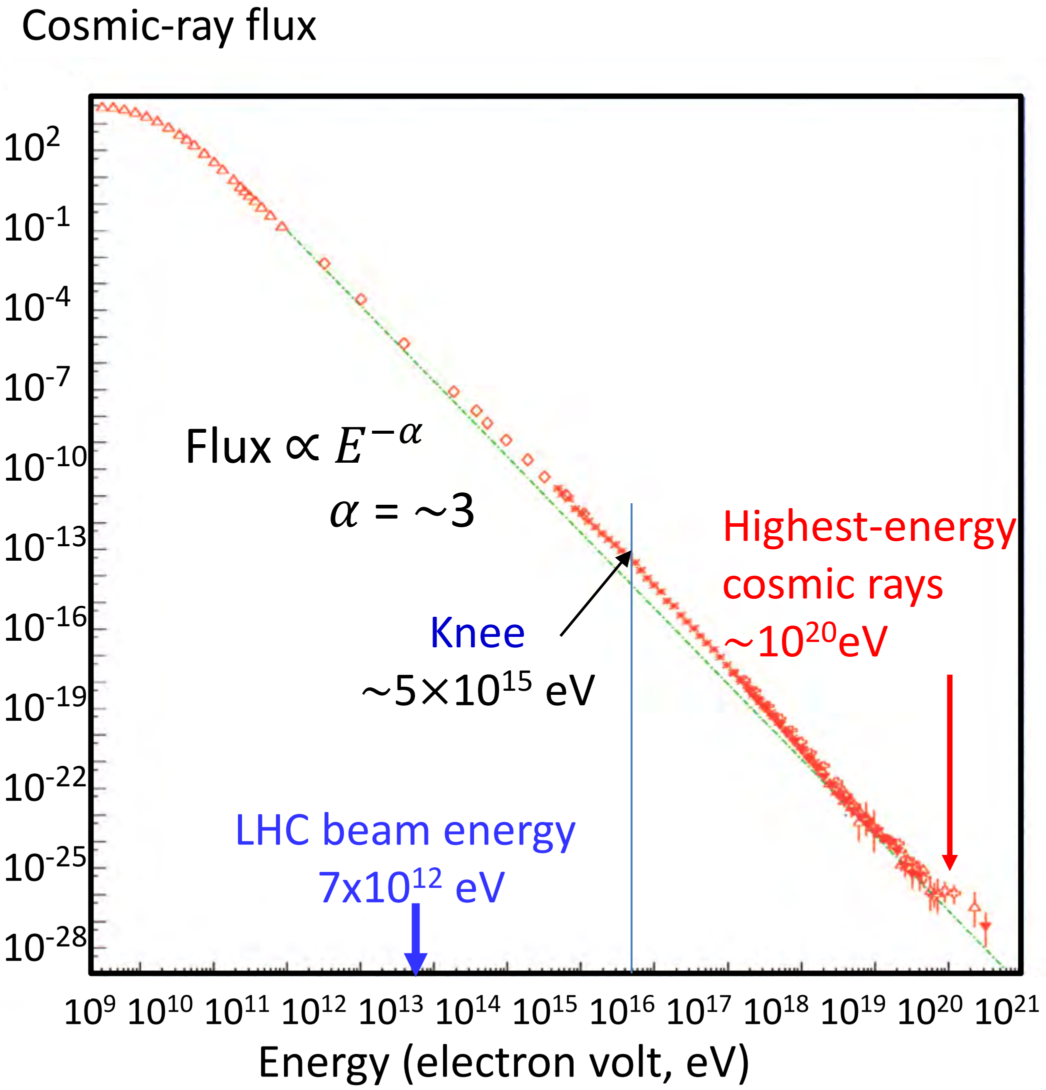
The strongest magnetic field


GRBs

Gamma-ray burst

The most violent explosions

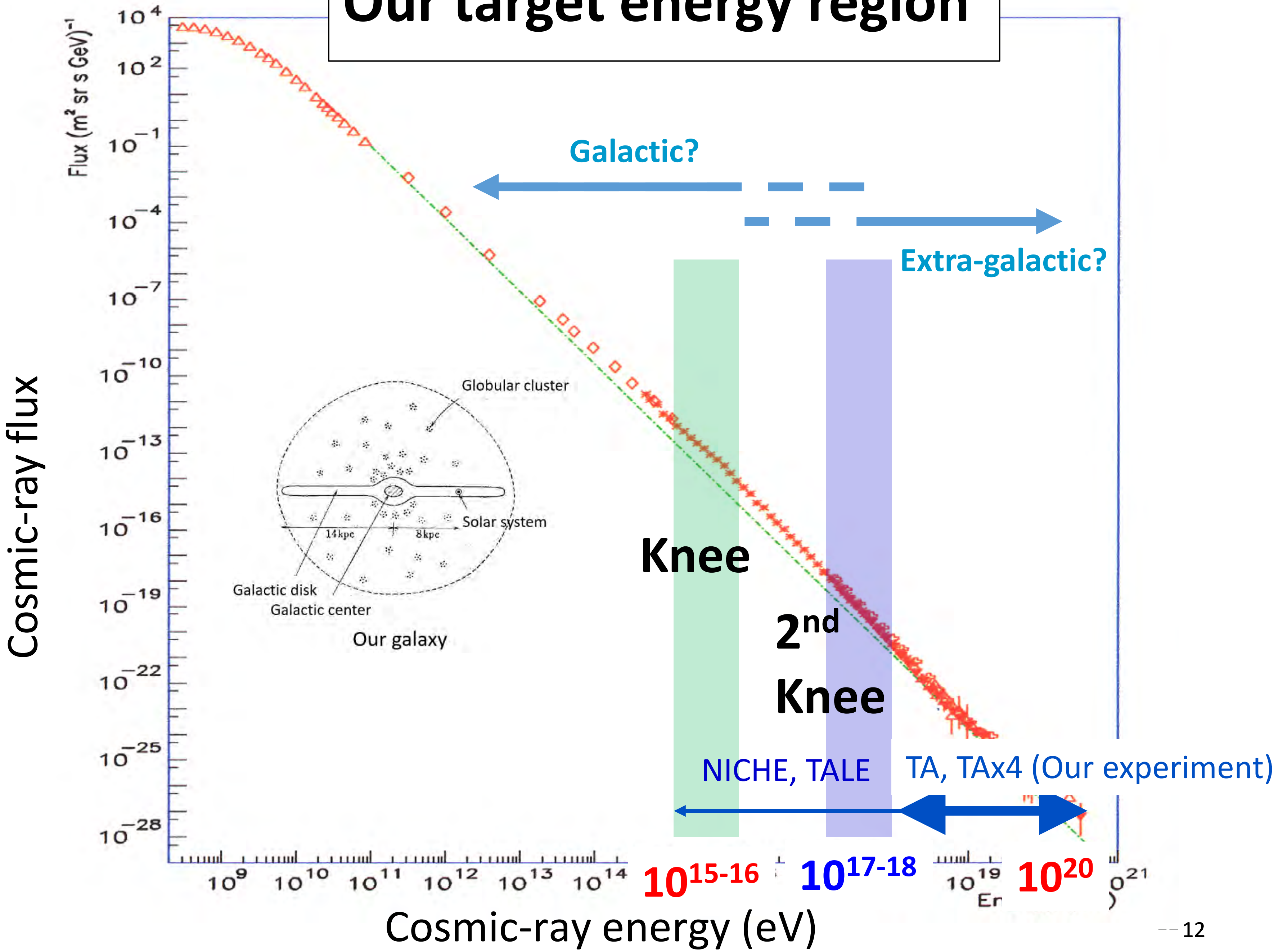
Energy spectrum of cosmic rays



Rate@10^{20} eV

<1 particles/100km^2/year

Our target energy region

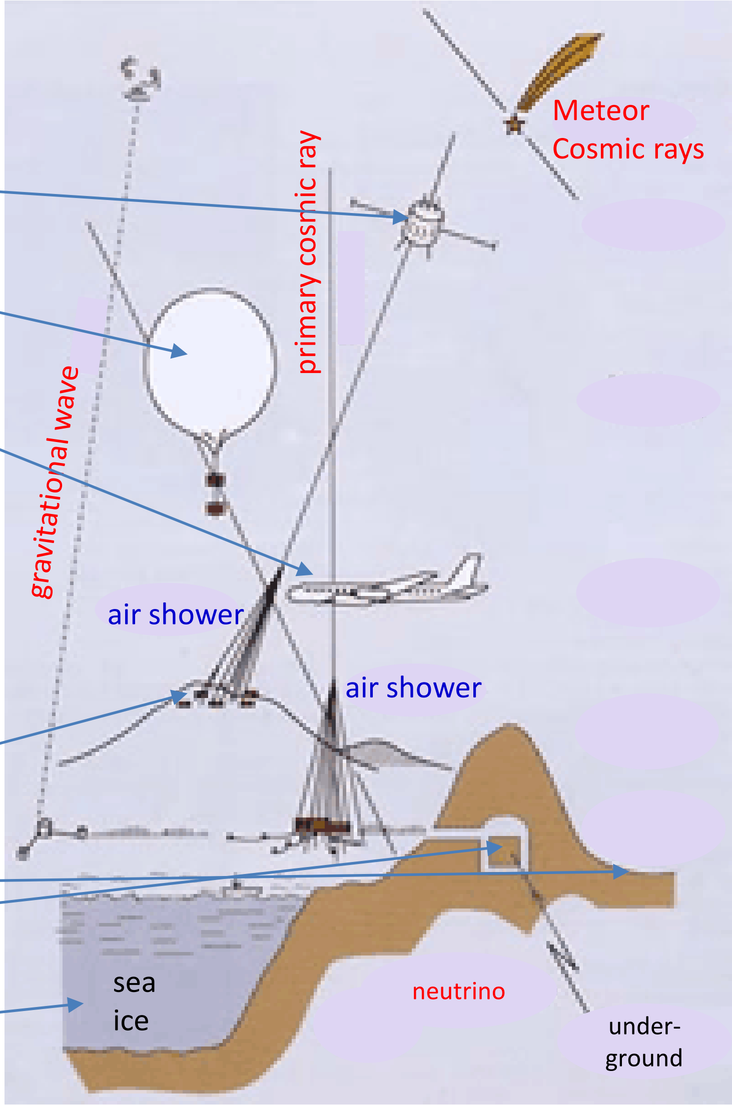


Observation of cosmic rays

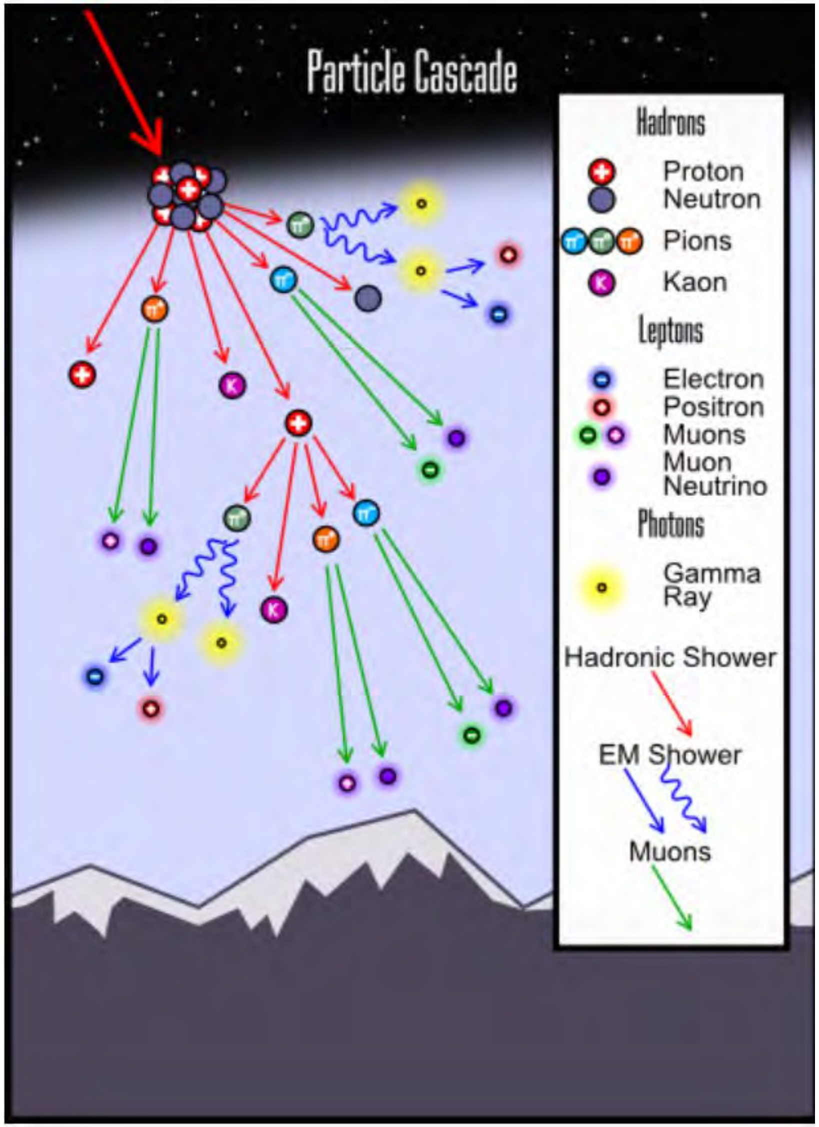
- Primary cosmic rays
  - Satellite
  - Balloon (30~40km)
  - Airplane (10~20km)

$\lesssim 10^{14}$ eV

- Secondary cosmic rays
  - Radiation produced by primary cosmic rays when they enter the atmosphere
  - High mountain (3~5km)
  - Ground (~0km)
  - Underground
  - deep sea, ice

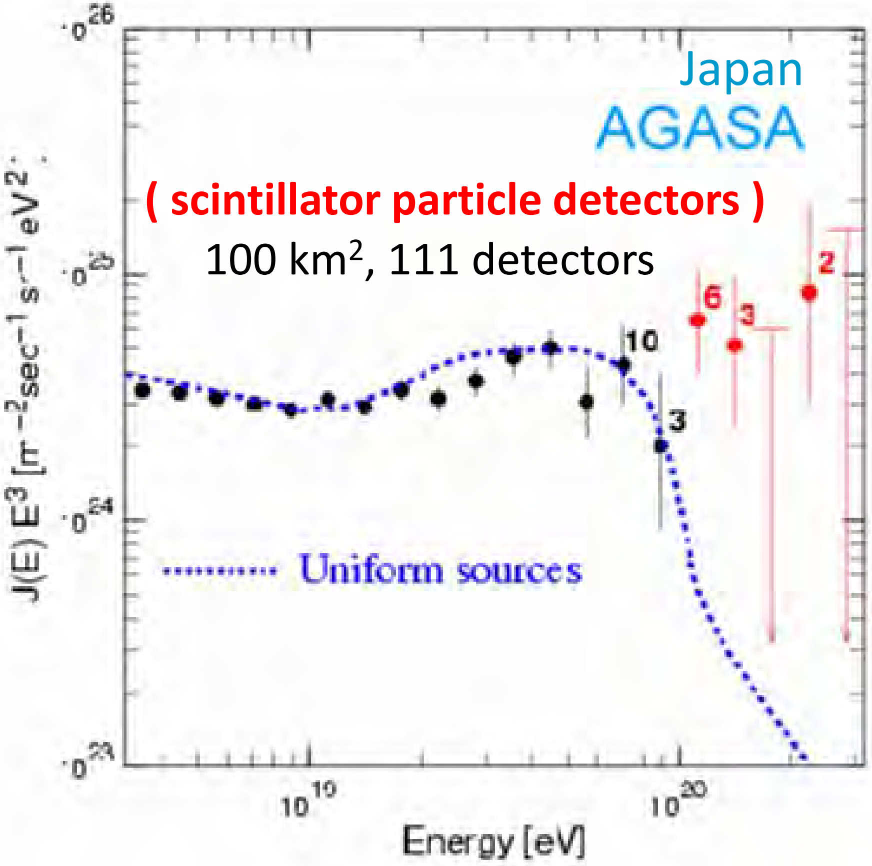


Extensive Air Showers



- A primary cosmic ray collides with a nucleus near the top of the atmosphere
- The first collision typically produces more than a thousand secondary particles
- They still retain an enormous amount of energy
- This jet of new particles repeats the collision process in a cascade which can grow to billions of particles

Energy spectra of extremely high energy cosmic rays in early 2000s

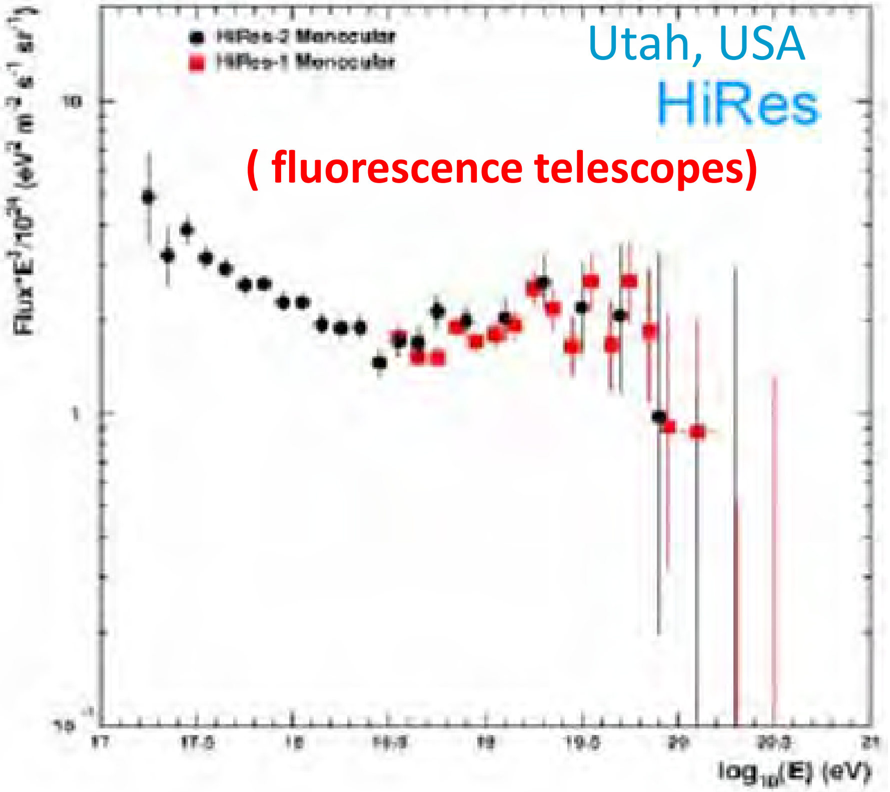


Japan

AGASA

(scintillator particle detectors)

100 km^2, 111 detectors



Utah, USA

HiRes

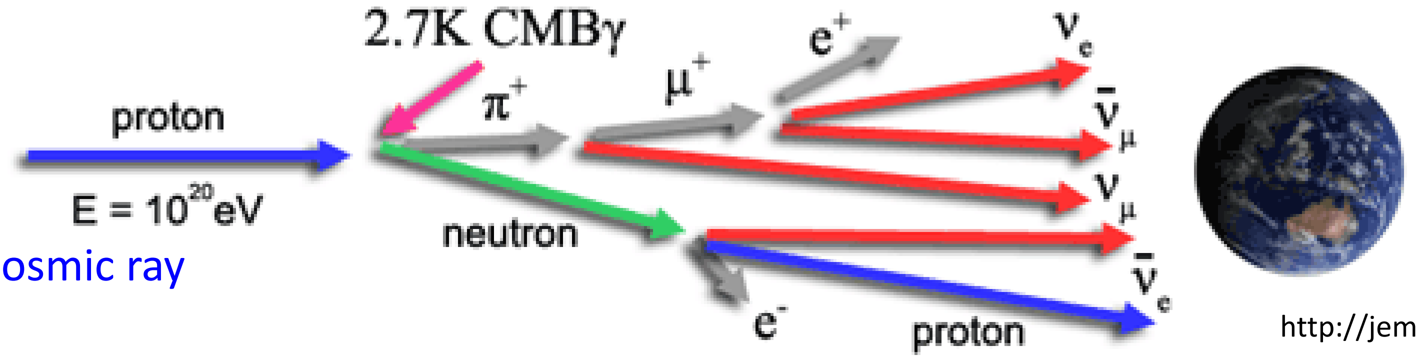
(fluorescence telescopes)

=>Next generation (Telescope Array, Auger)

Verify whether the GZK cutoff exists or not

GZK cutoff

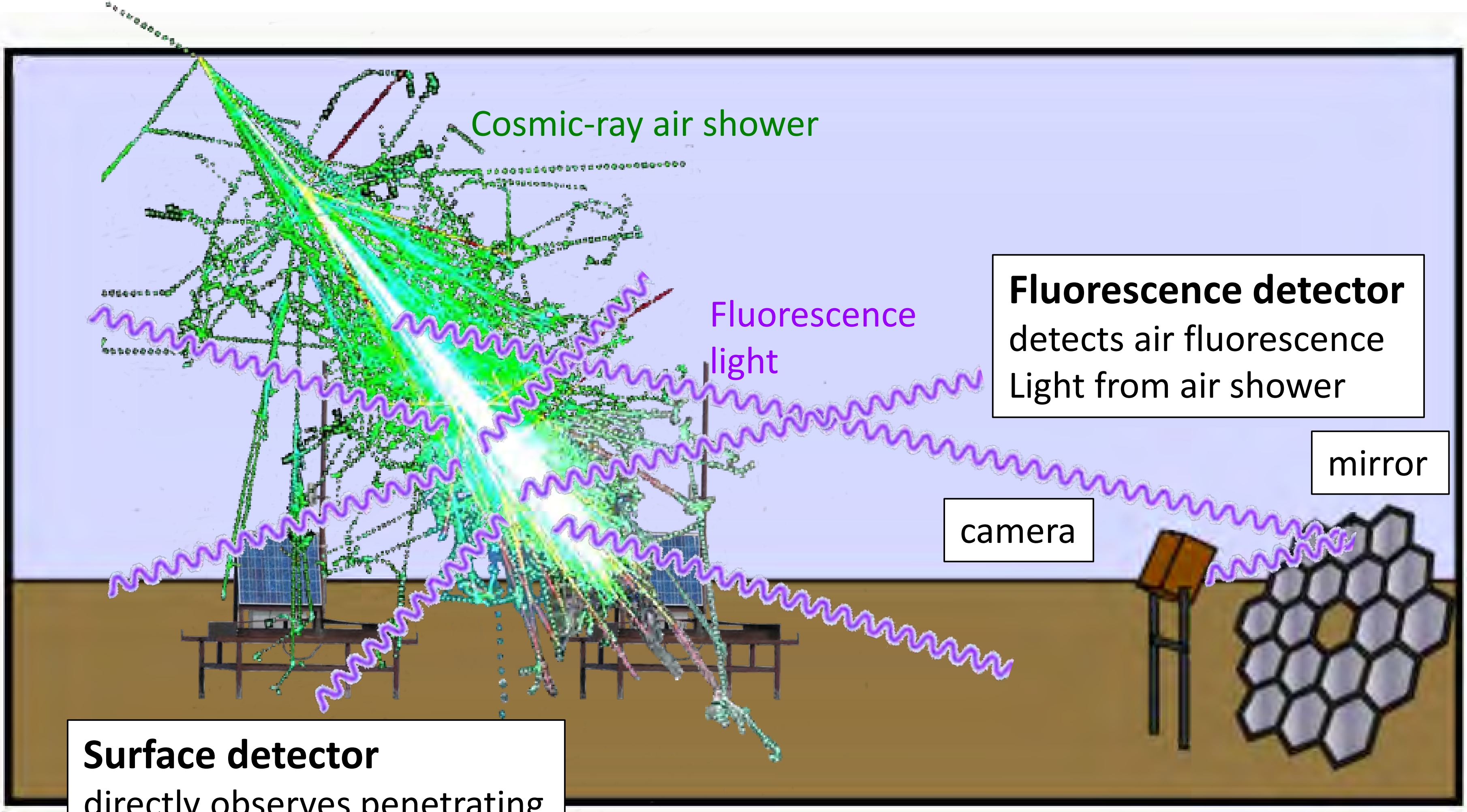
- 1964 Discovery of CMB radiation
- Greizen, Zatsepin and Kuzmin proposed in 1966
  - According to special theory of relativity,
  - (proton) cosmic rays with ~10^{20} eV coming beyond ~50 Mpc cannot arrive at the earth by the energy loss due to the interaction with CMB photon (GZK horizon)



Highest-E cosmic ray

http://jemeuso.riken.jp

Surface detector and fluorescence detector



Cosmic-ray air shower

Fluorescence light

Fluorescence detector
detects air fluorescence
Light from air shower

mirror

camera

Surface detector
directly observes penetrating
secondary particles

Telescope Array Collaboration

5 countries (Japan, USA, Korea, Russia, Belgium, Czech)

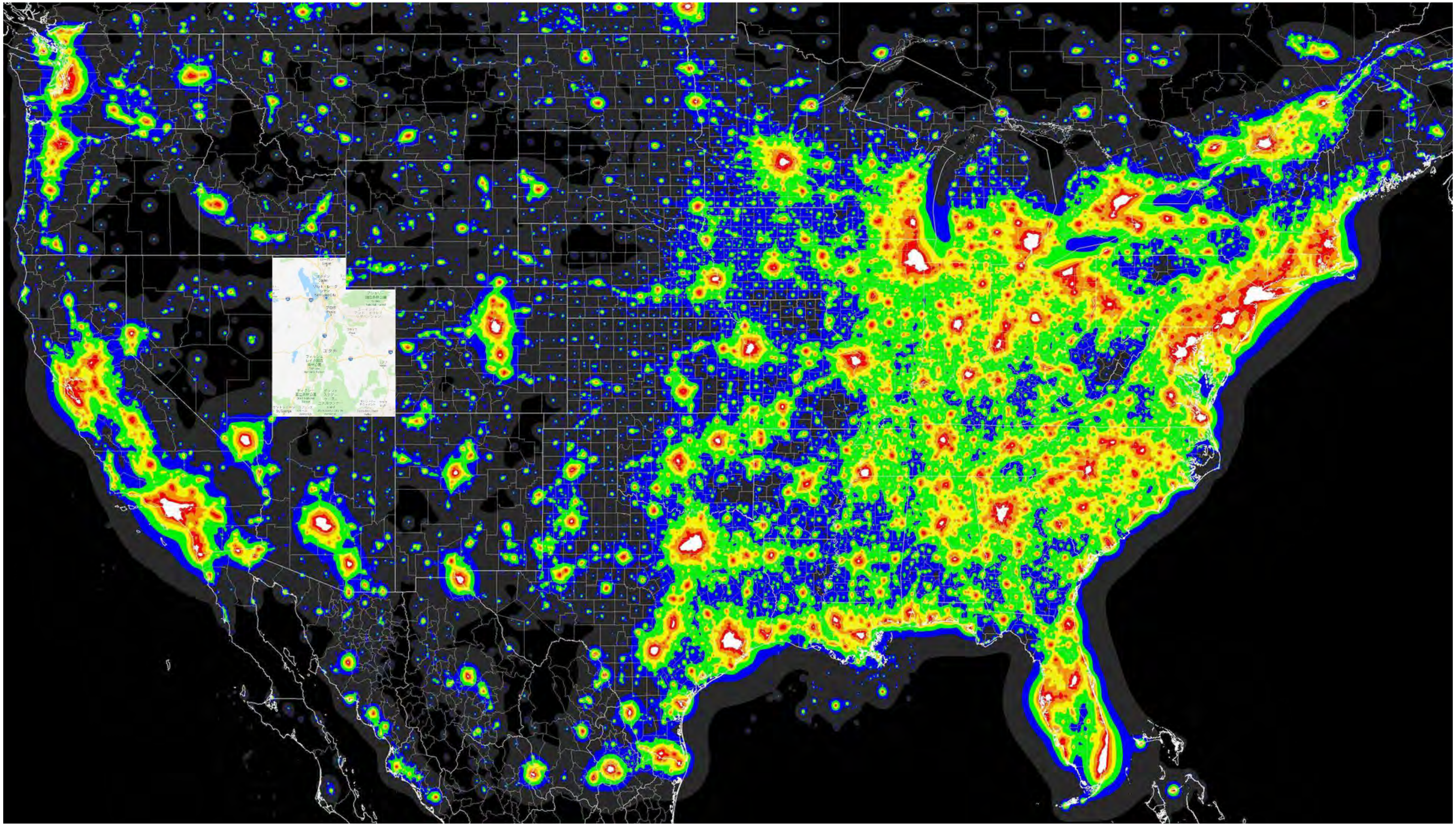
R.U. Abbasi[1], M. Abe[2], T. Abu-Zayyad[1], M. Allen[1], R. Azuma[3], E. Barcikowski[1], J.W. Belz[1], D.R. Bergman[1], S.A. Blake[1], R. Cady[1], B.G. Cheon[4], J. Chiba[5], M. Chikawa[6], A. Di Matteo[7], T. Fujii[1], K. Fujita[9], M. Fukushima[8,10], G. Furlich[1], T. Goto[9], W. Hanlon[1], M. Hayashi[11], 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[19], 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]

~130 researchers

[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 Th´eorique, Universit´e 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

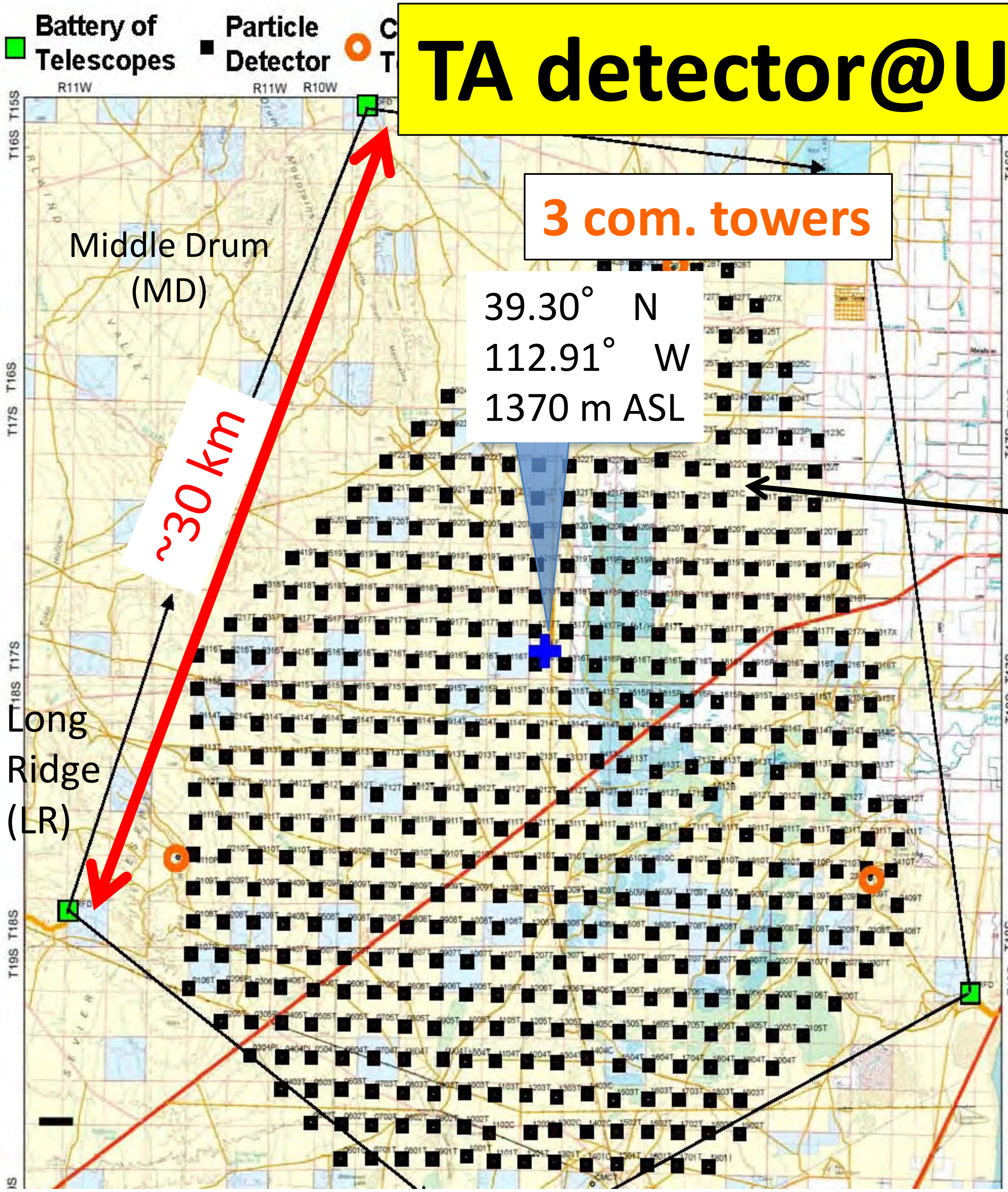
34 institutes

US Light Pollution Map



http://i.imgur.com/aOPFB.jpg

TA detector@Utah, USA



3 com. towers

39.30° N
112.91° W
1370 m ASL

Middle Drum
(MD)

~30 km

Long
Ridge
(LR)

Surface Detector (SD)

507 plastic scintillator SDs (3m^2)

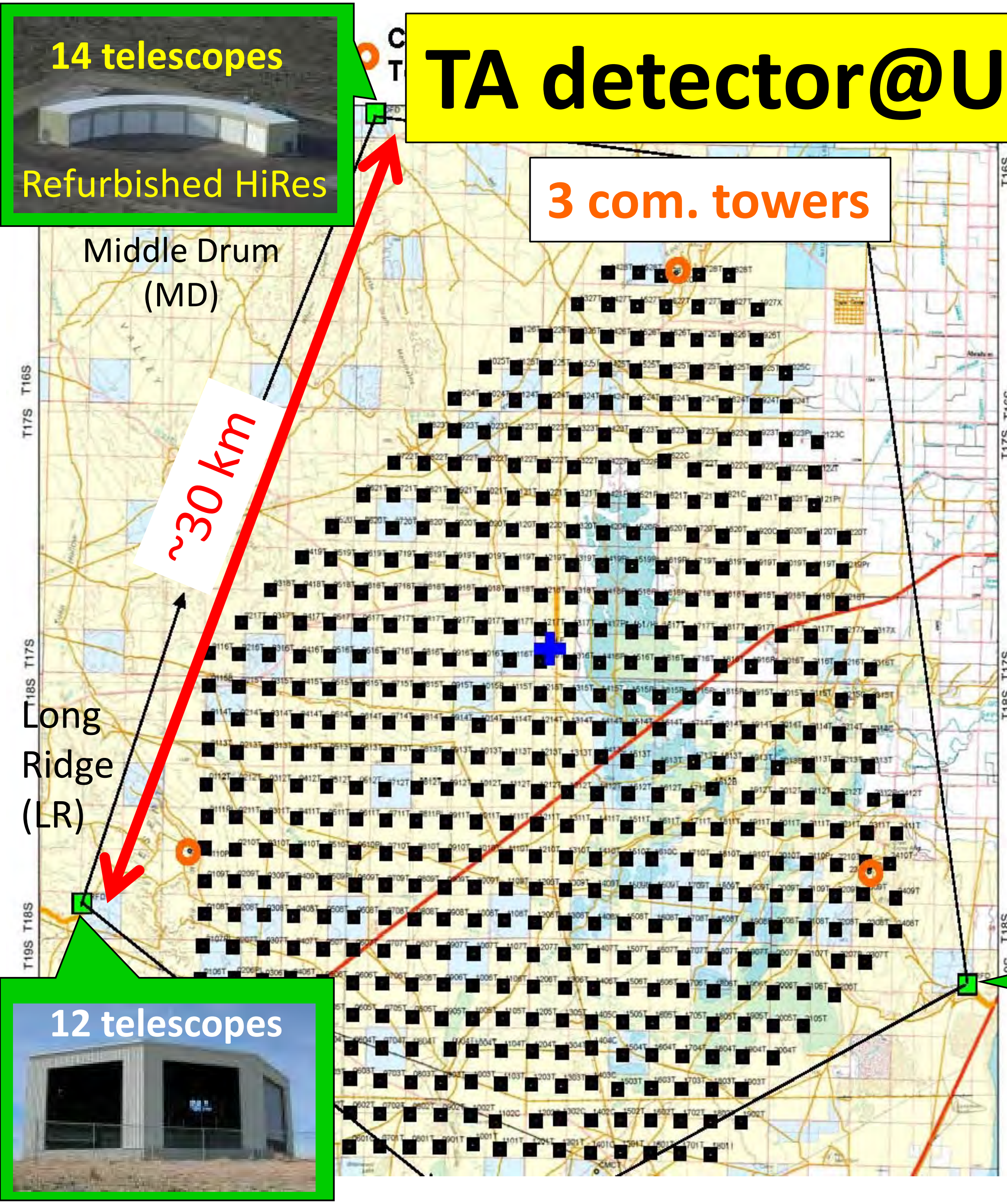
1.2 km spacing

~700 km^2

Need a large flat area

- Achievable in the western desert

TA detector@Utah, USA



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

~700 km^2

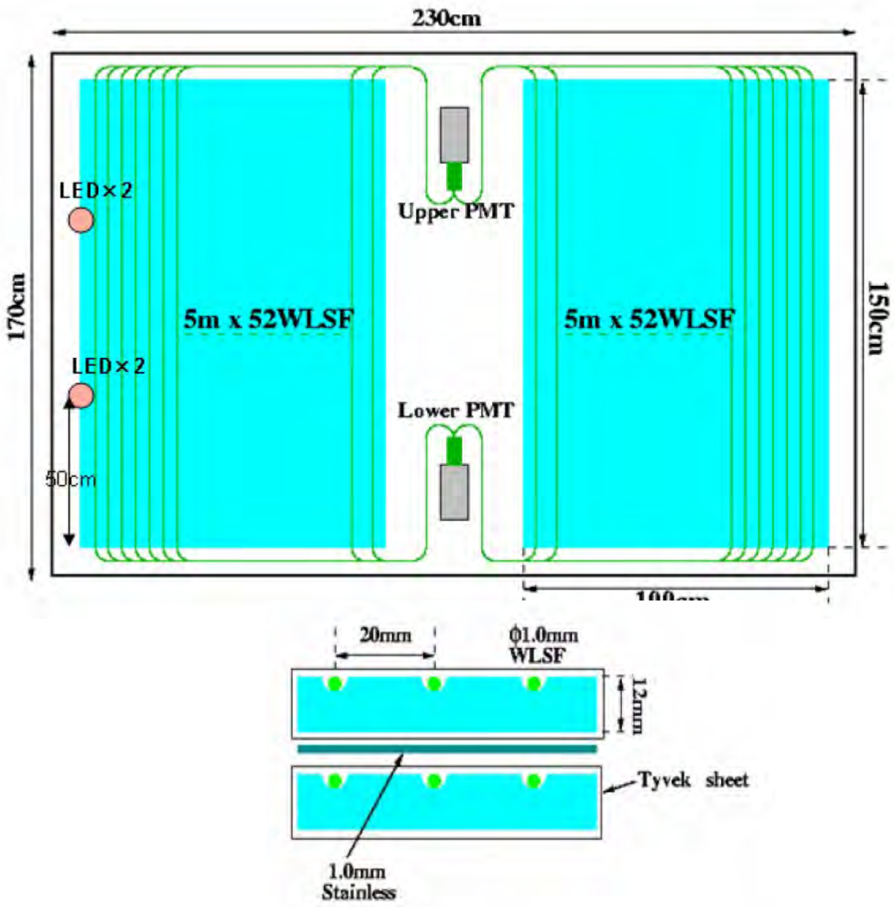
Fluorescence Detector(FD)

3 stations

38 telescopes

FD and SD: fully operational since 2008/May

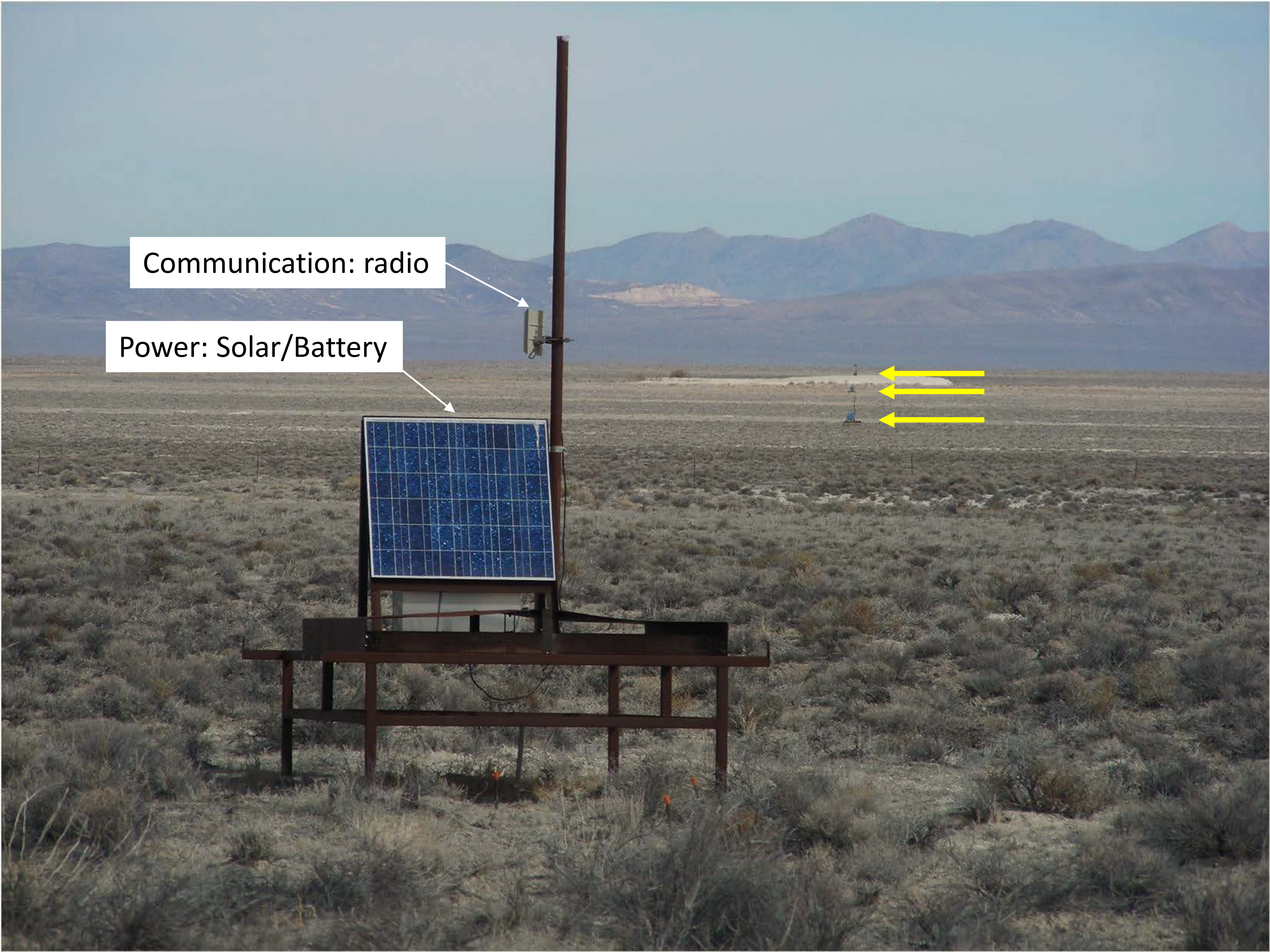
Surface Detectors (SD)



2 layers scintillator

1.2 cm thick, $3m^2$ area

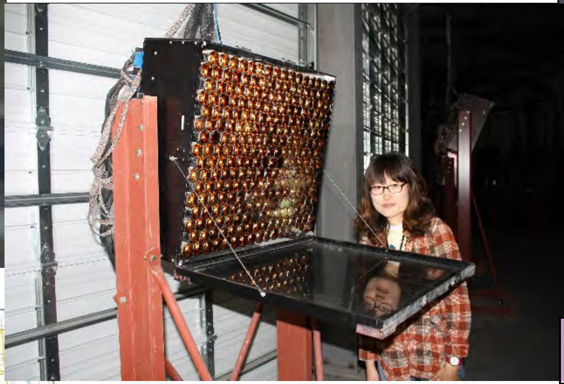
Optical fibers to PMTs


Communication: radio
Power: Solar/Battery

Fluorescence Detectors (FD)

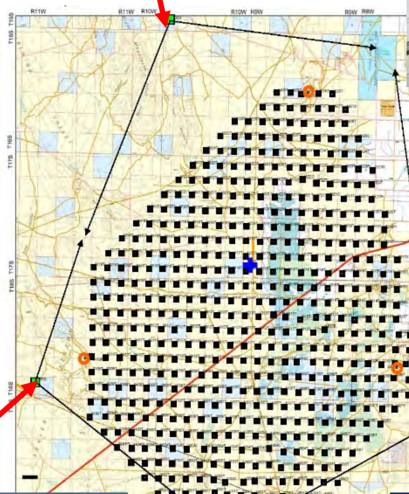
Middle Drum

14 telescopes @ station
256 PMTs/camera



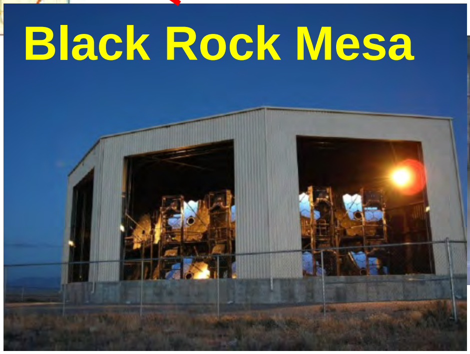
5.2 m^2

Reutilized from HiRes-I



Long Ridge

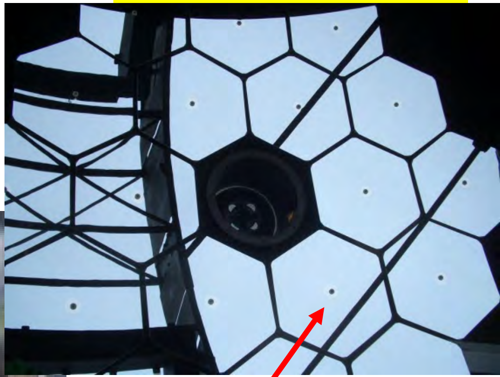
Black Rock Mesa



New Telescopes

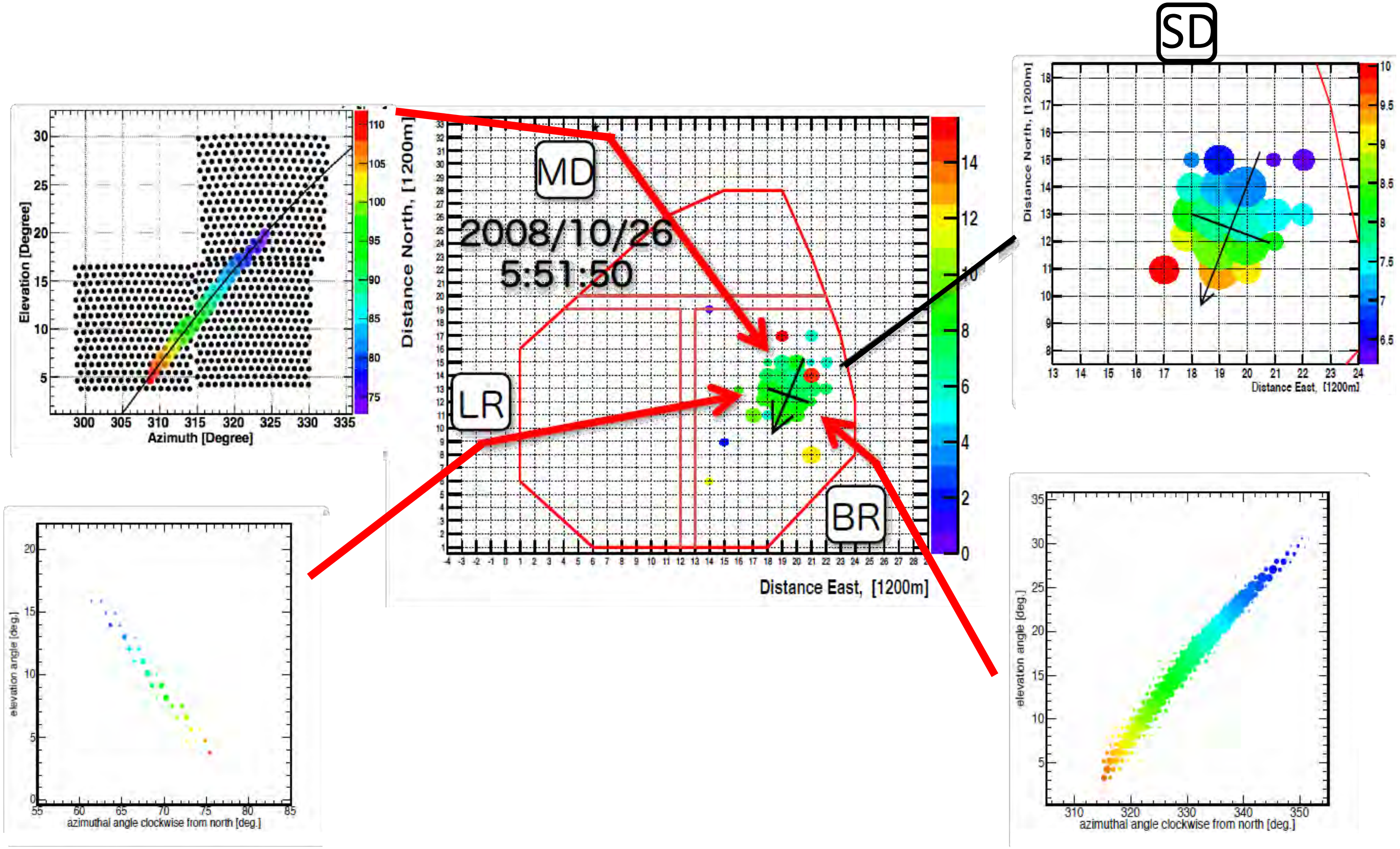
12 telescopes/station
256 PMTs/camera

~1 m^2



6.8 m^2

Hybrid event example

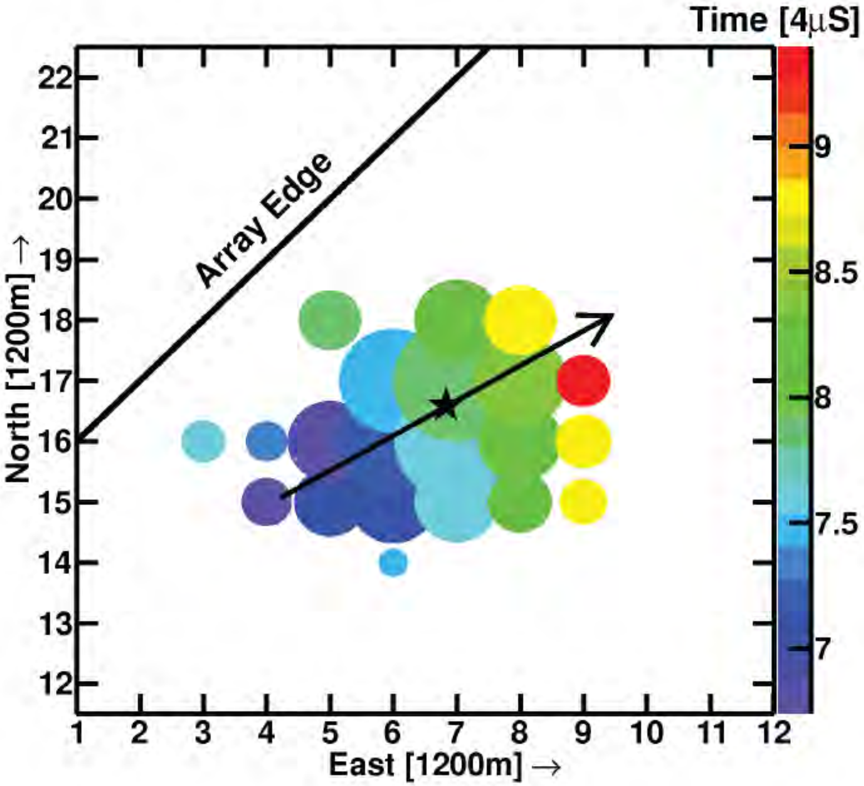


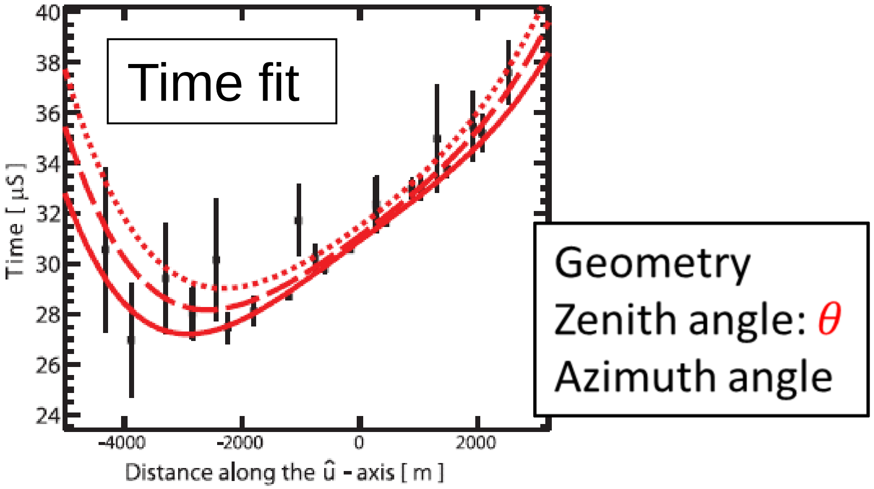
Content

- Telescope Array (TA)
- Latest results
  - Energy Spectrum
  - Composition
  - Anisotropy
- TA extension

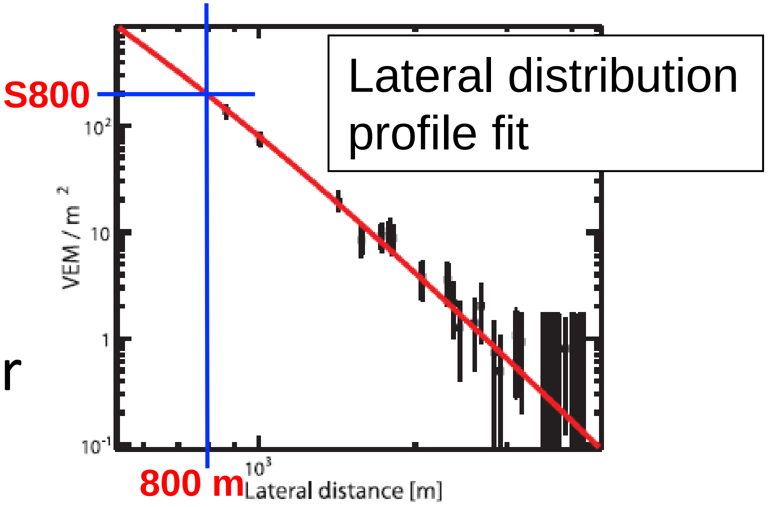
TA shower analysis with SD

An SD hit map of a typical event





Geometry
Zenith angle: θ
Azimuth angle



Lateral distribution profile fit

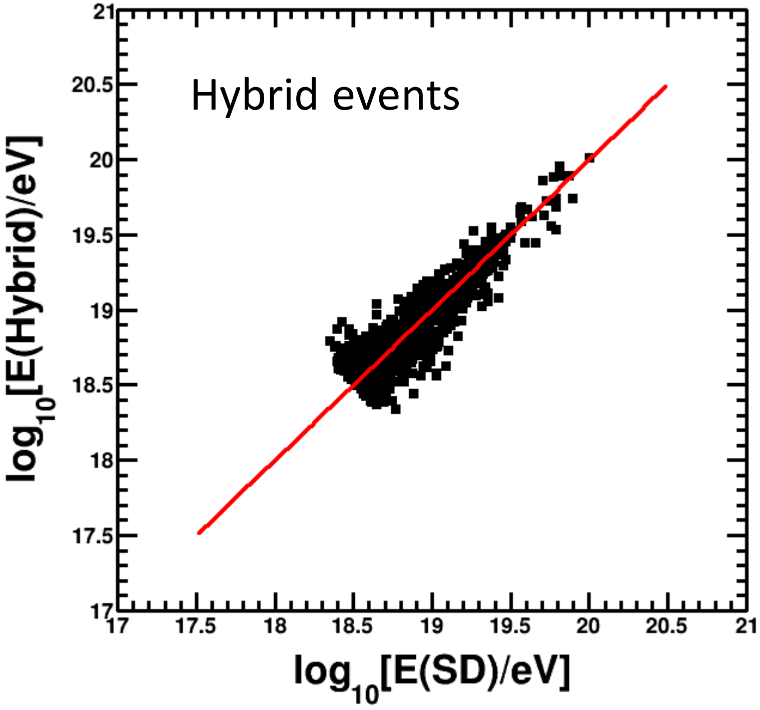
Use S800 as an energy estimator

Energy Scale Check and Resolution

Final energy is scaled by 1.27

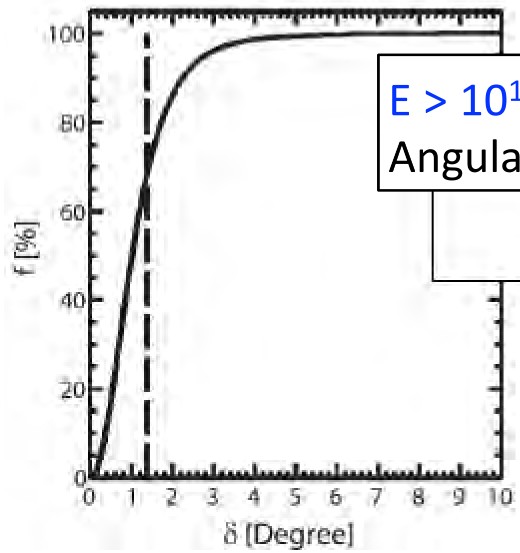
$$\left\langle \frac{E^{TBL}}{E^{FD}} \right\rangle_{hybrid} = 1.27$$

$$E^{TBL} = E(S800, sec\theta)$$



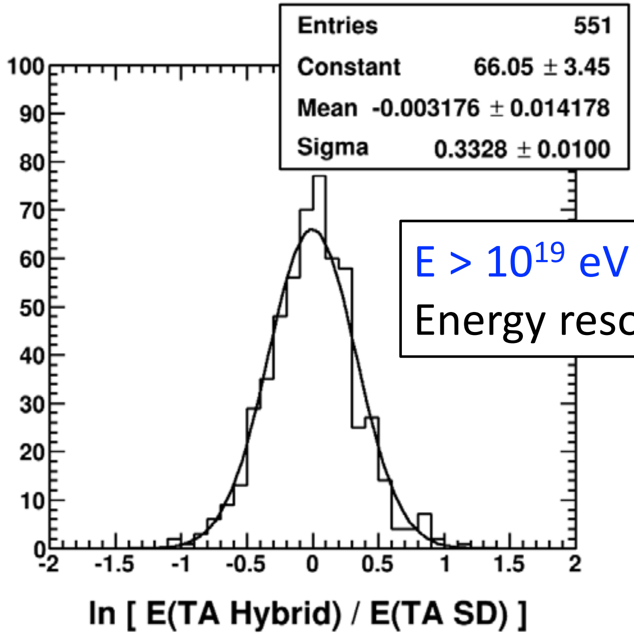
(SD scaled to FD energy: calorimetric)

$E(SD)=E^{TBL}/1.27$



$E > 10^{19}$ eV

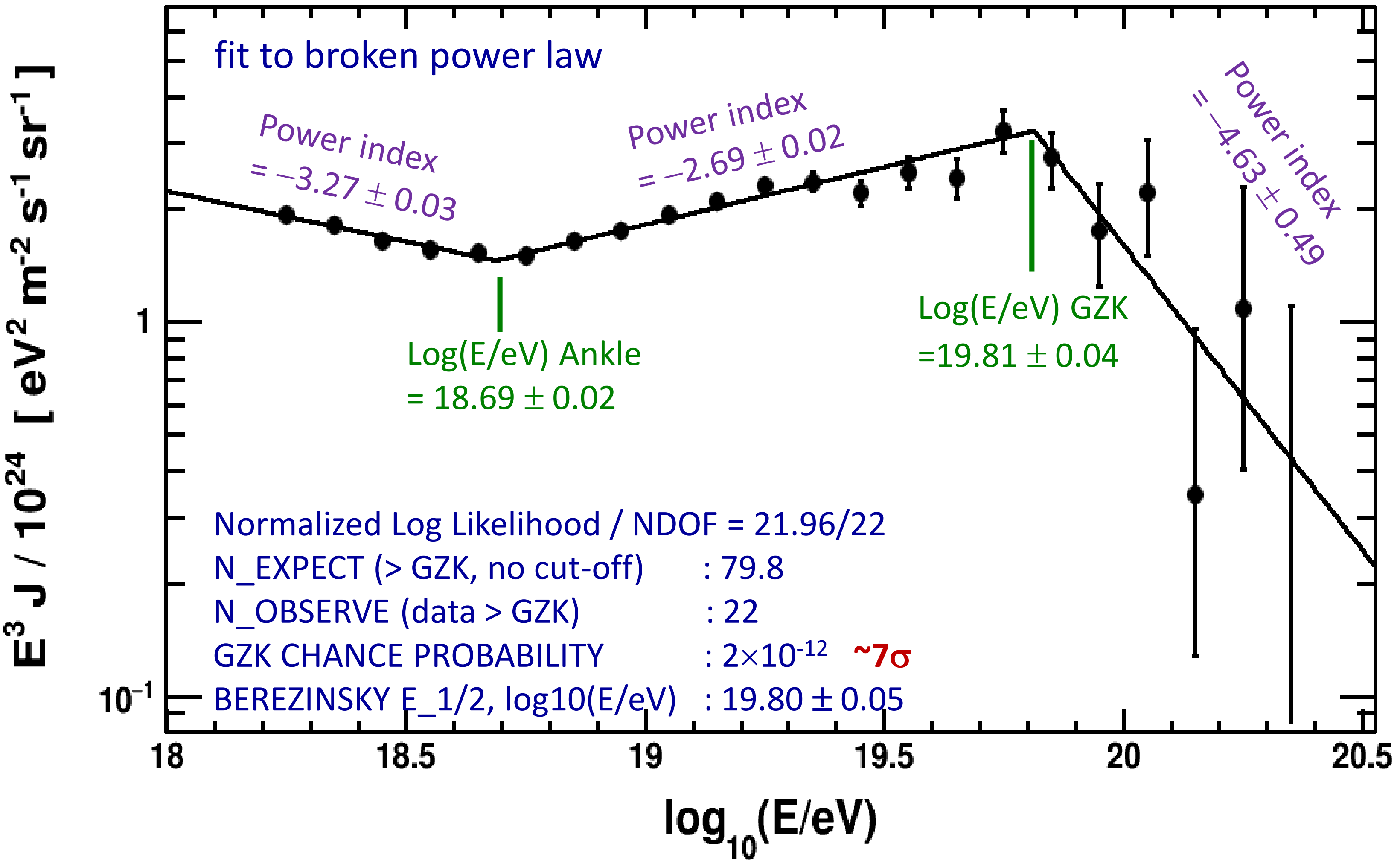
Angular resolution = 1.4°



$E > 10^{19}$ eV

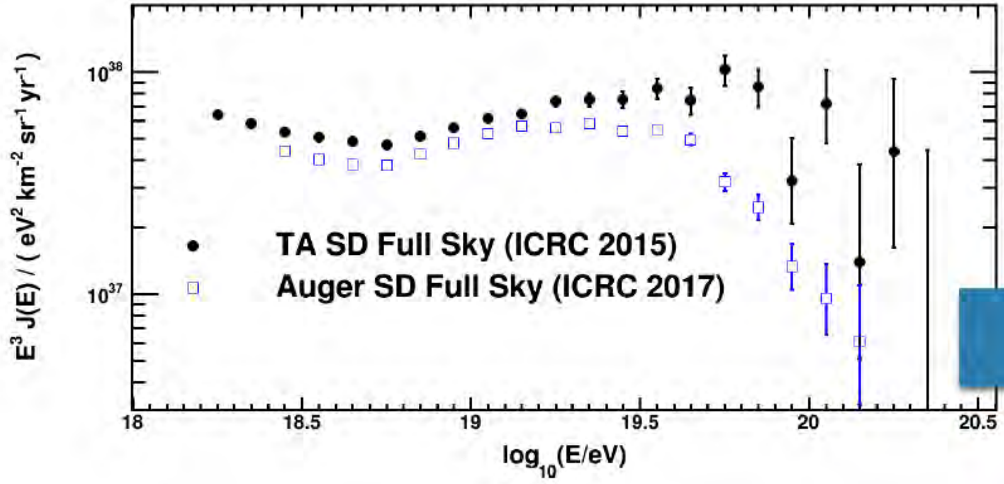
Energy resolution < 20%

TA SD Spectrum (9 years data)



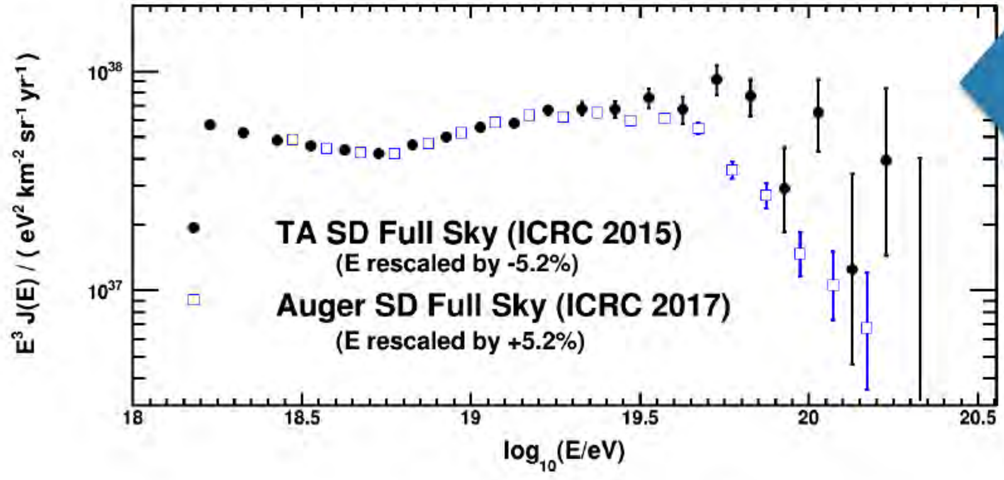
TA & Auger Spectrum WG report

Ivanov ICRC2017, CRI231
(Auger/TA spectrum WG)

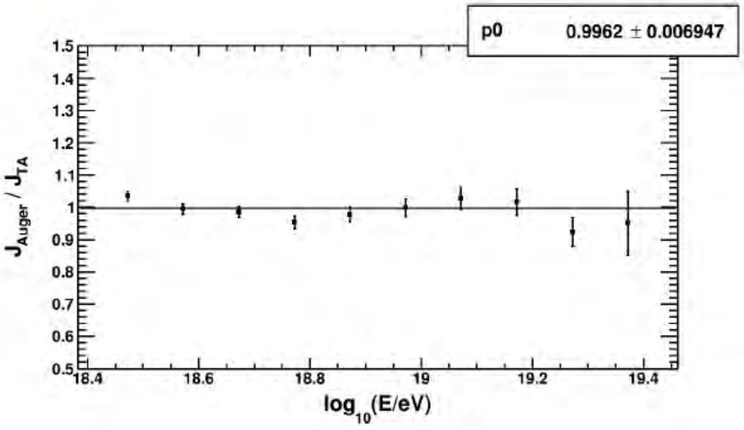


10% energy shift well within stated 14%(Auger) and 21%(TA) energy scale systematic uncertainties

- Auger energies raised by 5.2% and
- TA energies lowered by 5.2%

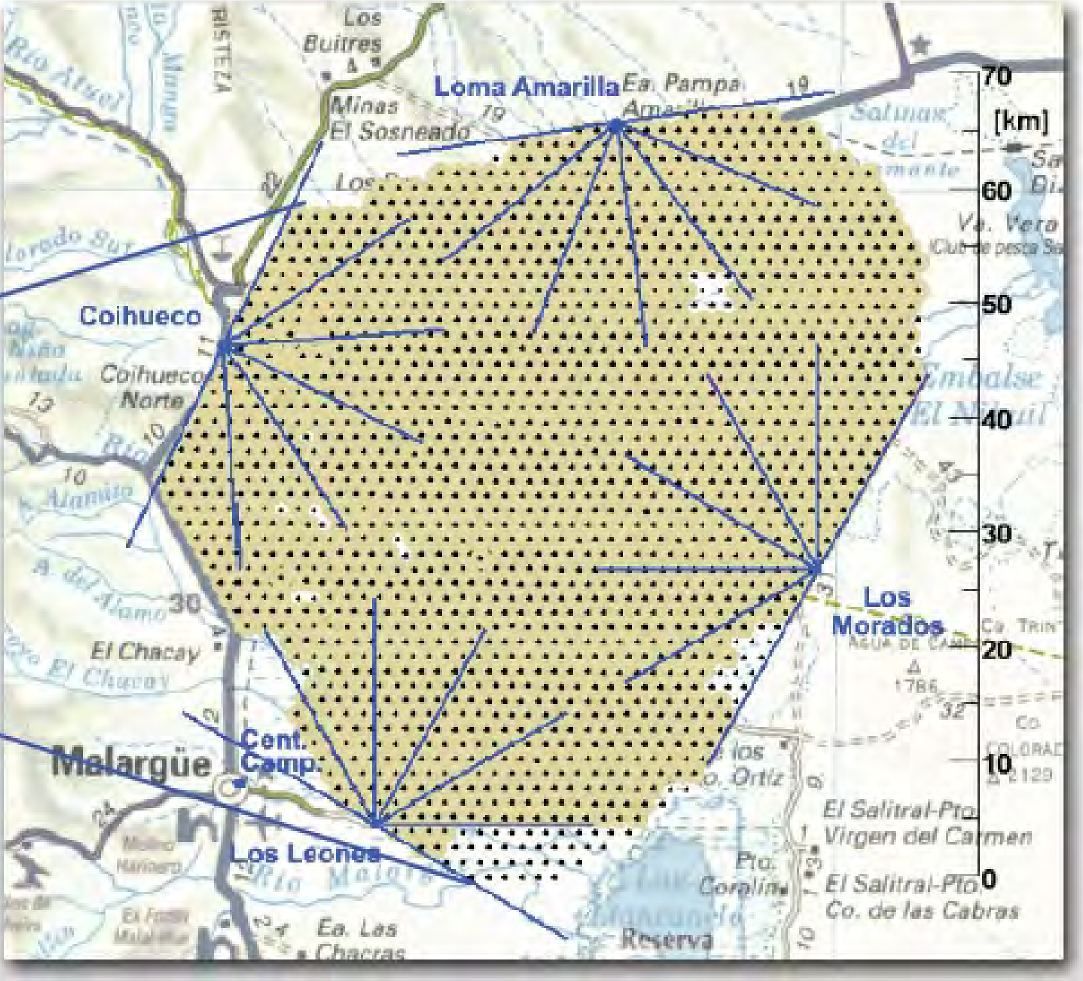


The fluxes by two experiments well overlap below $10^{19.4}$ eV



October 15, 2018

Pierre Auger Observatory in Argentina



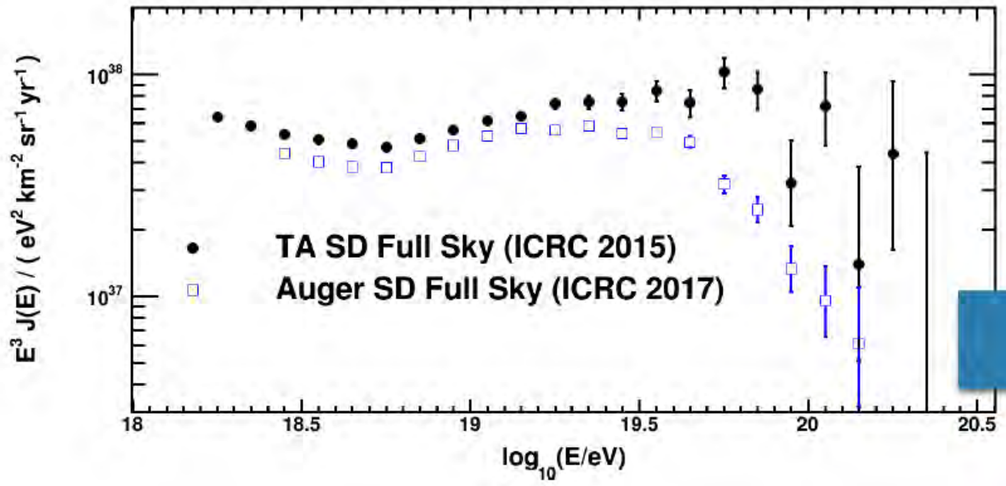
3000 km² area on a plateau 1450 m a.s.l.

1660 Detector Stations +

27 FD Telescopes at periphery

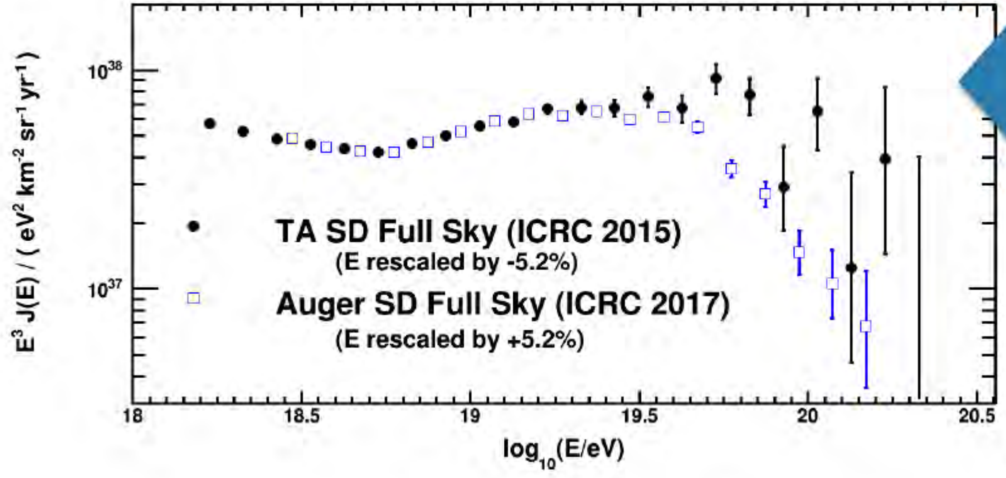
TA & Auger Spectrum WG report

Ivanov ICRC2017, CRI231
(Auger/TA spectrum WG)

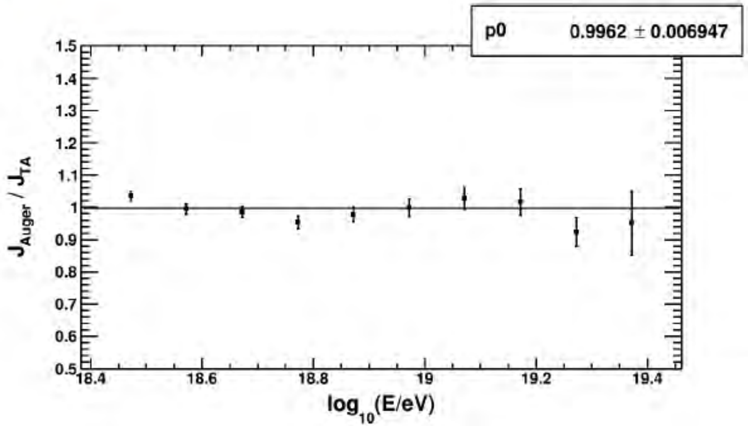


10% energy shift well within stated 14%(Auger) and 21%(TA) energy scale systematic uncertainties

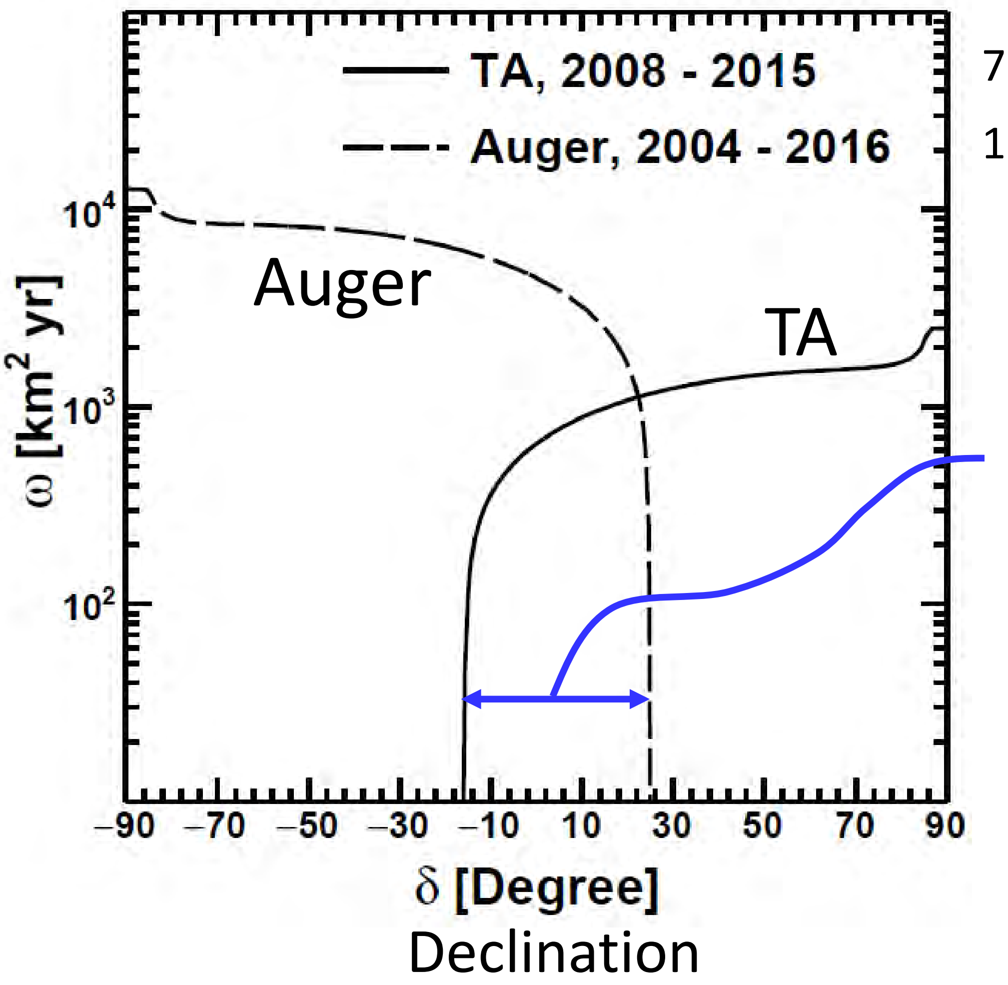
- Auger energies raised by 5.2% and
- TA energies lowered by 5.2%



The fluxes by two experiments well overlap below $10^{19.4}$ eV



Directional exposure of the TA and Auger SDs



7 years of TA SD

12 years of Auger SDs

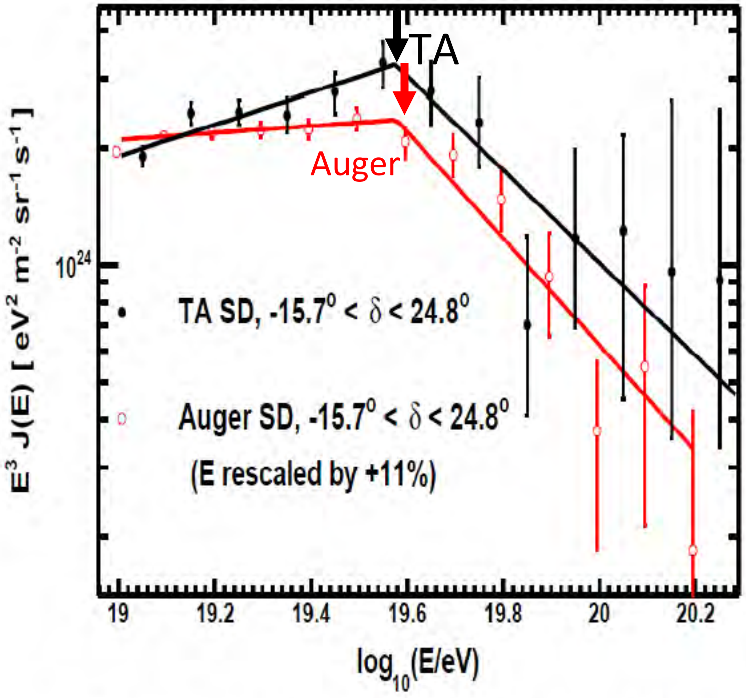
Common declination band
$-15.7° < \delta < 24.8°$

Declination dependence in TA

submitted to ApJ, arXiv:1801.07820

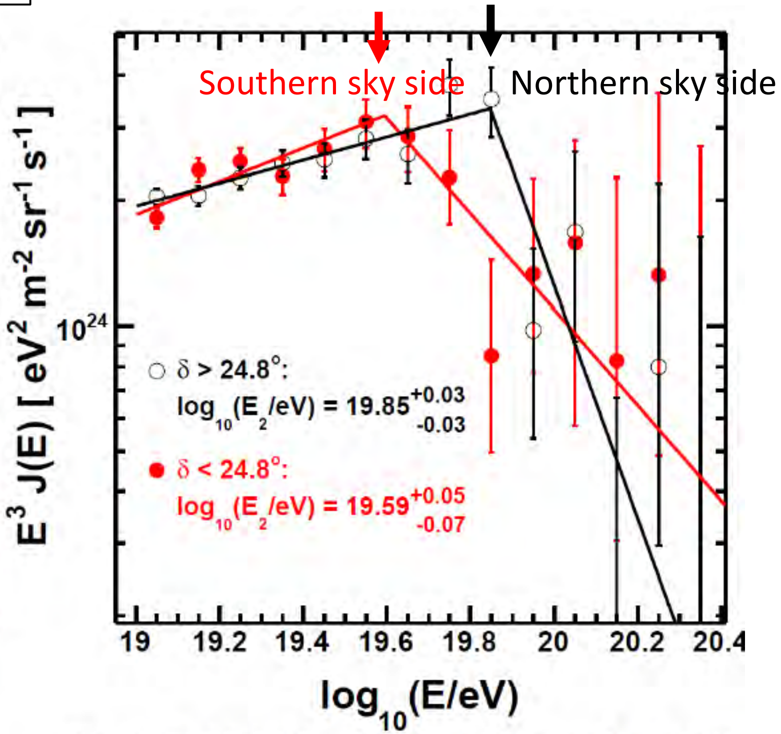
TA, Auger common declination band
-15.7° < δ < 24.8°

TA only



Energy spectra of TA and Auger in the common declination band. They agree at about 0.5σ level

Break points are the same



Energy spectra of TA above and below δ=24.8° They disagree at ~4σ level

Global Significance ~ 3.5 σ

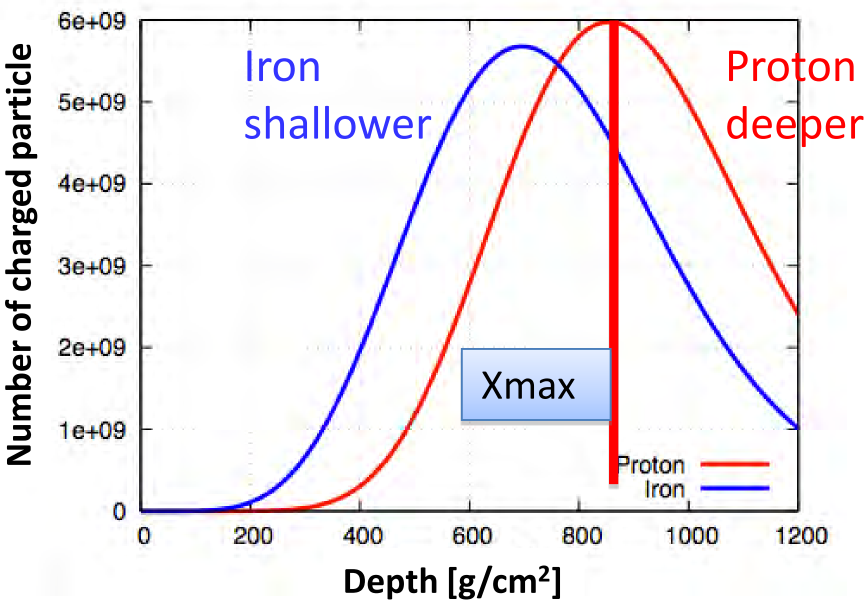
Content

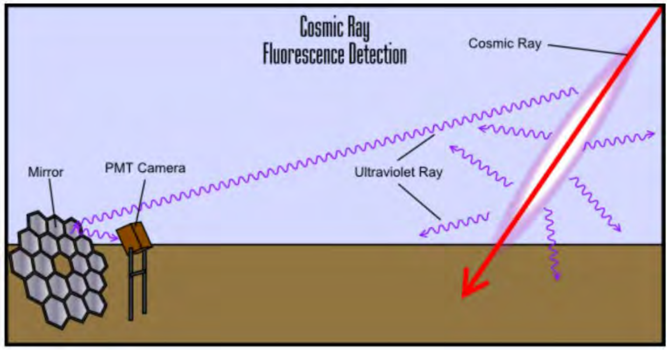
- Telescope Array (TA)
- Latest results
  - Energy Spectrum
  - Composition
  - Anisotropy
- Telescope Array Extension

Xmax Technique

- Longitudinal development of cosmic-ray showers depends on primary particle type
- FD observes longitudinal shower development
- Xmax (depth of shower maximum): the most efficient parameter for determining primary particle type

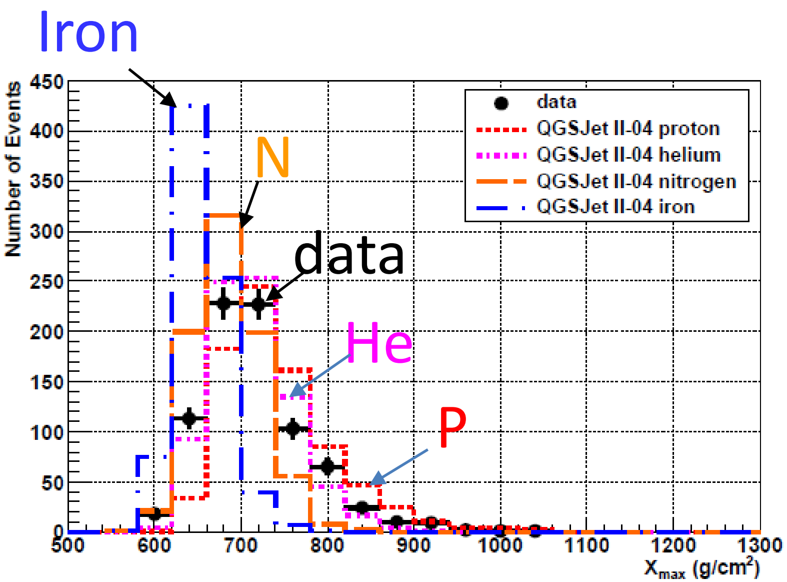
longitudinal shower development



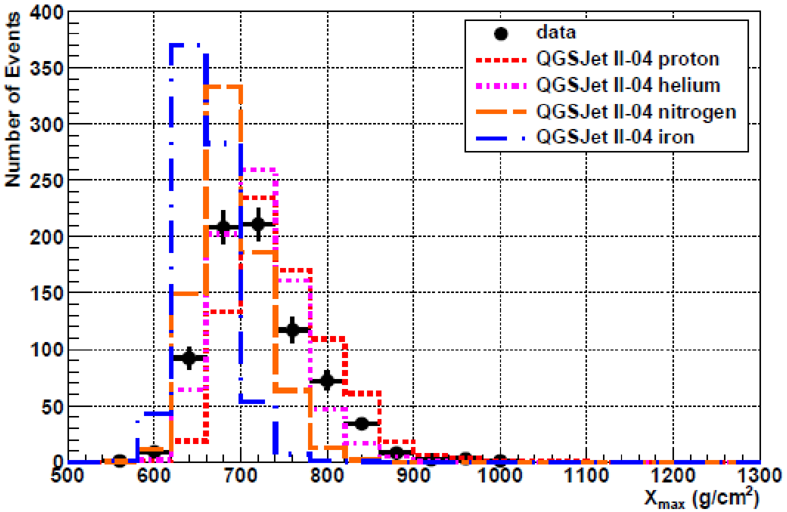


Xmax Distributions vs MC

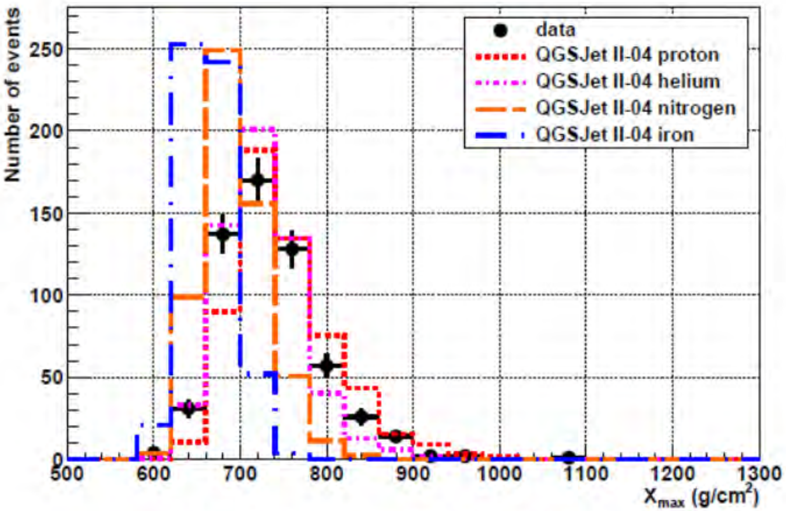
ApJ, 858 :76 (27pp), 2018



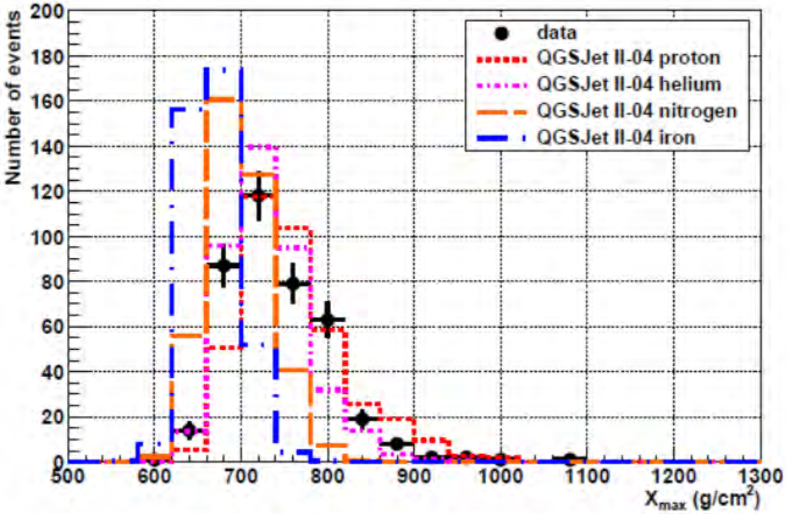
(a) $18.2 \le \log_{10}(E/\mathrm{eV}) < 18.3$



(b) $18.3 \le \log_{10}(E/\mathrm{eV}) < 18.4$

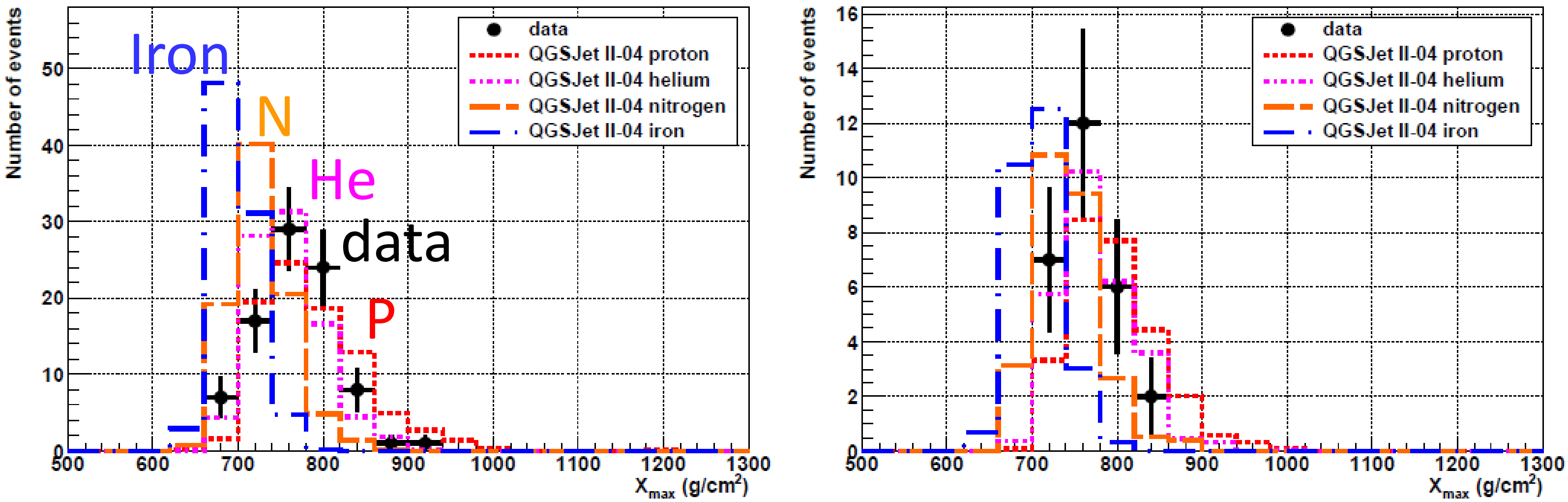


(c) $18.4 \le \log_{10}(E/\mathrm{eV}) < 18.5$



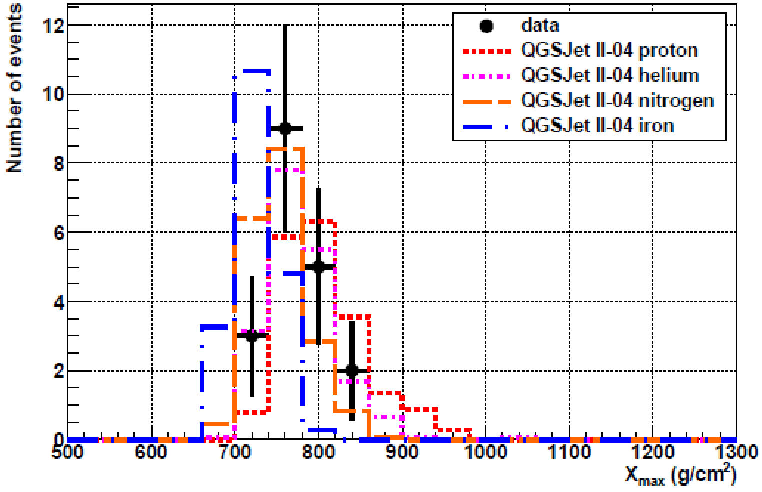
(d) $18.5 \le \log_{10}(E/\mathrm{eV}) < 18.6$

Xmax Distributions vs MC



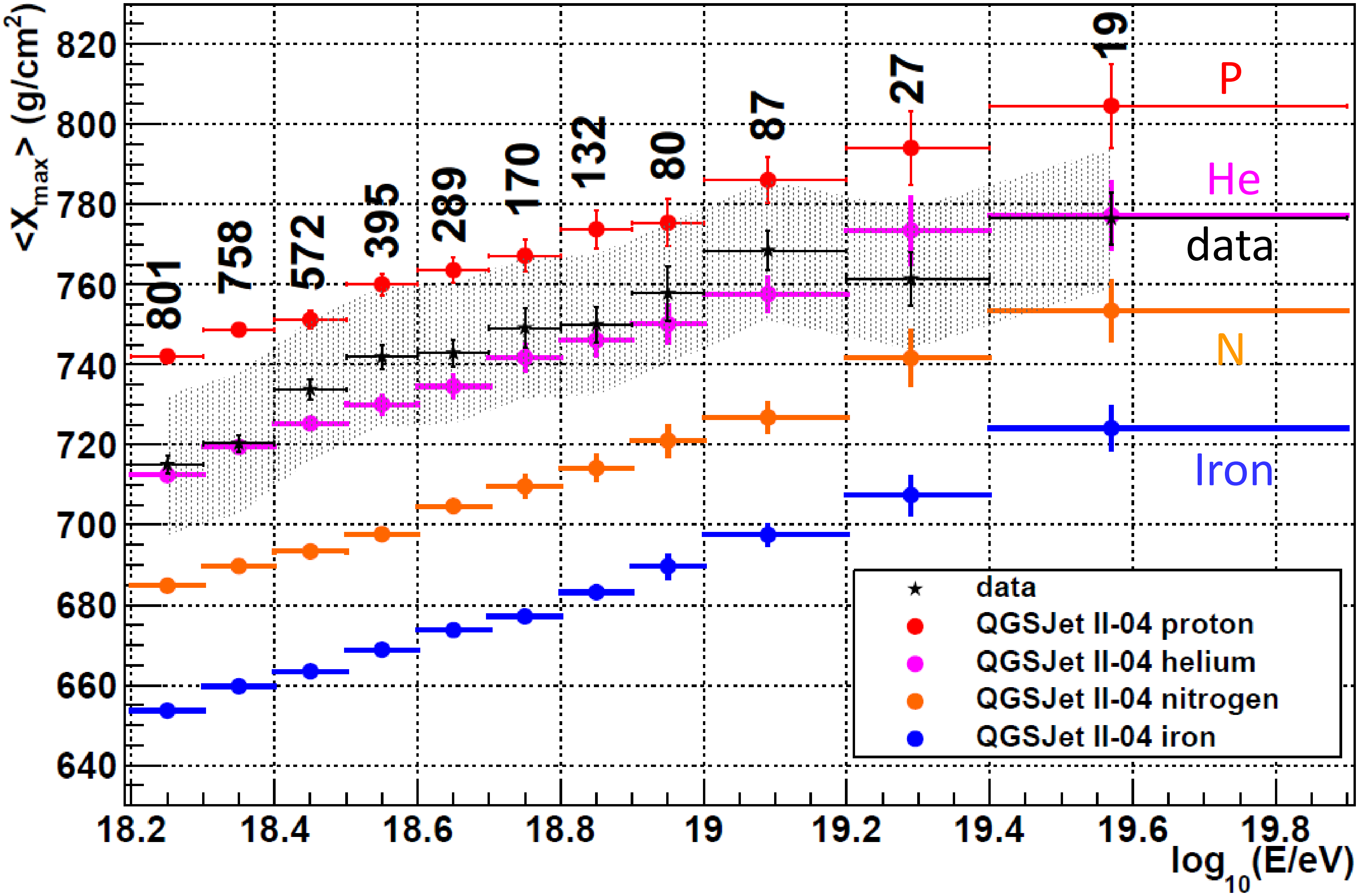
(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$

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



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

<Xmax> vs logE

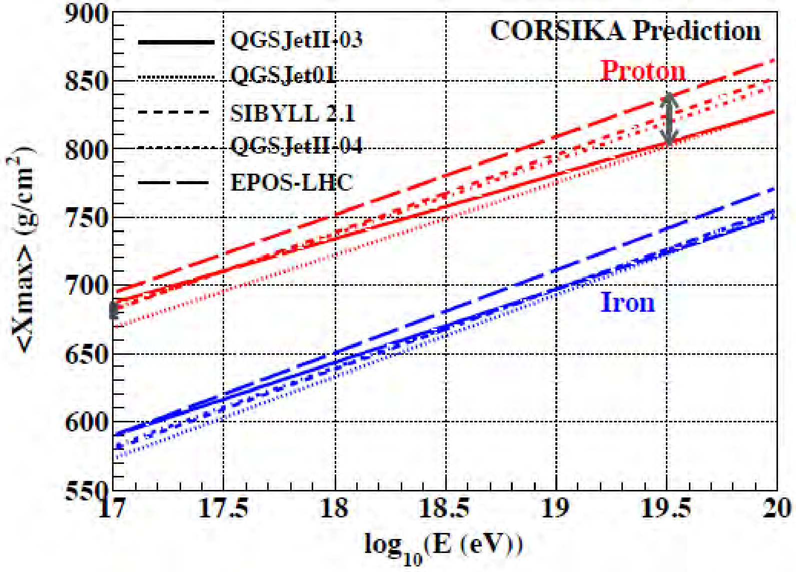

$\langle X_{max} \rangle$ (g/cm^2)
820
800
780
760
740
720
700
680
660
640
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
$\log_{10}$(E/eV)
801
758
572
395
289
170
132
80
87
27
19
P
He
data
N
Iron
★ data
● QGSJet II-04 proton
● QGSJet II-04 helium
● QGSJet II-04 nitrogen
● QGSJet II-04 iron

Interpretation of <Xmax>?

Extrapolation Uncertainties for <Xmax>

Ulrich, Engel and Unger arXiv:1010.4310v1 [hep-ph] 20 Oct 2010)
Thomson and Abbasi, arXiv:1605.05241v1 [hep-ex] 17 May 2016)

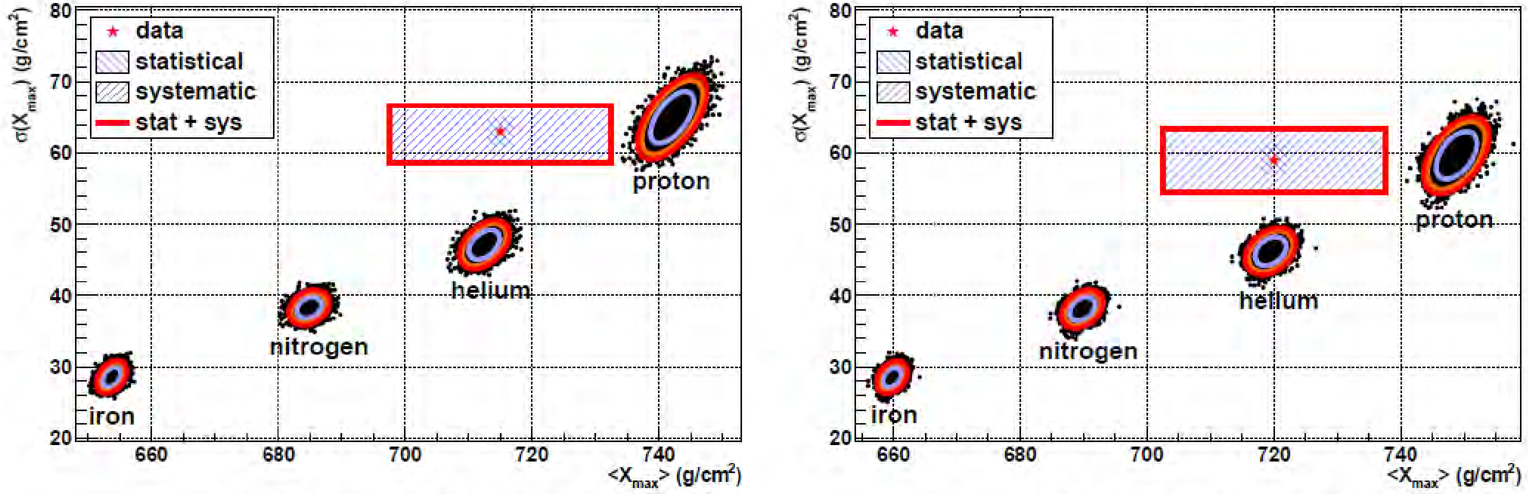
Model	<Xmax> uncertainty 10^{17}eV	<Xmax> uncertainty $10^{19.5}$eV
SIBYLL2.1	±3 g/cm2	±18 g/cm2
QGSJETII4	±3.5 g/cm2	±16 g/cm2
QGSJET01	±3 g/cm2	±18 g/cm2
EPOS-LHC	±3 g/cm2	±18 g/cm2



Uncertainty at 250 TeV (= $10^{19.5}$ eV) encompasses all the models at the ± 1σ level; smaller at 10^{17} eV.

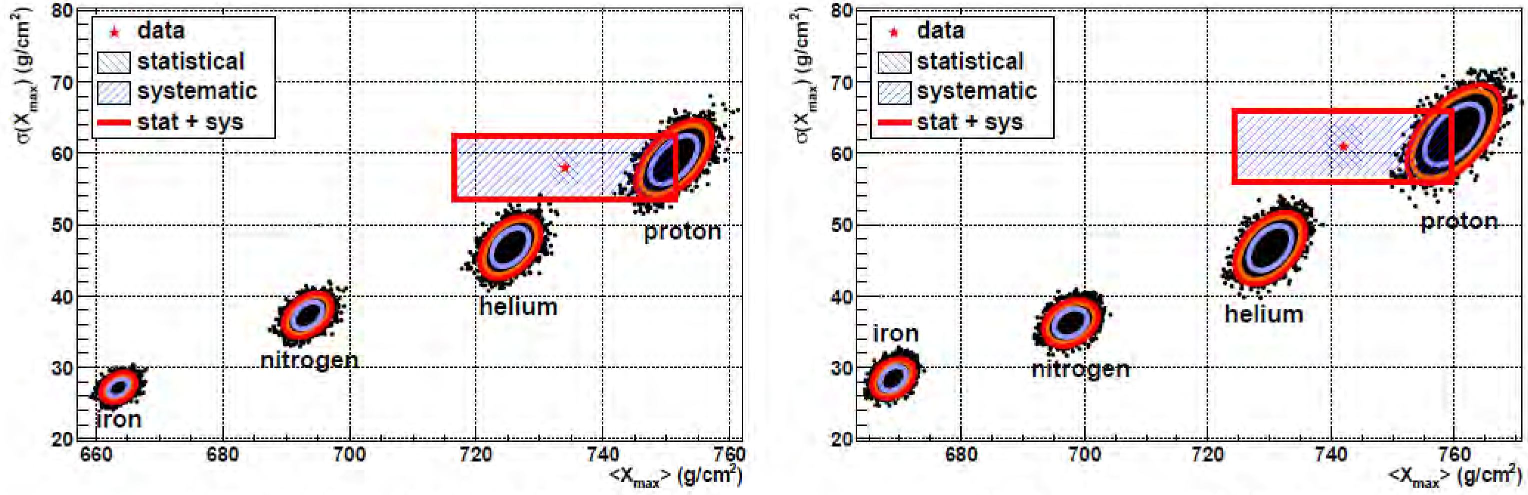
But the uncertainty is less for RMS(Xmax).

Data/MC: σ(Xmax) vs <Xmax>



(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

(b) $18.3 \leq \log_{10}(E/\mathrm{eV}) < 18.4$

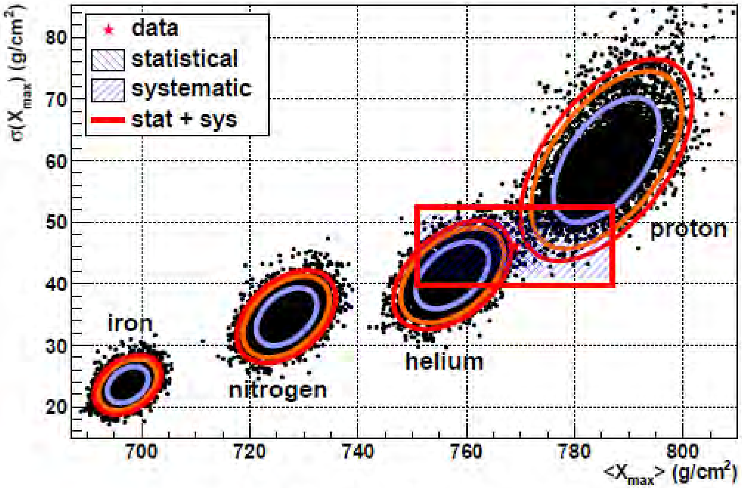


(c) $18.4 \leq \log_{10}(E/\mathrm{eV}) < 18.5$

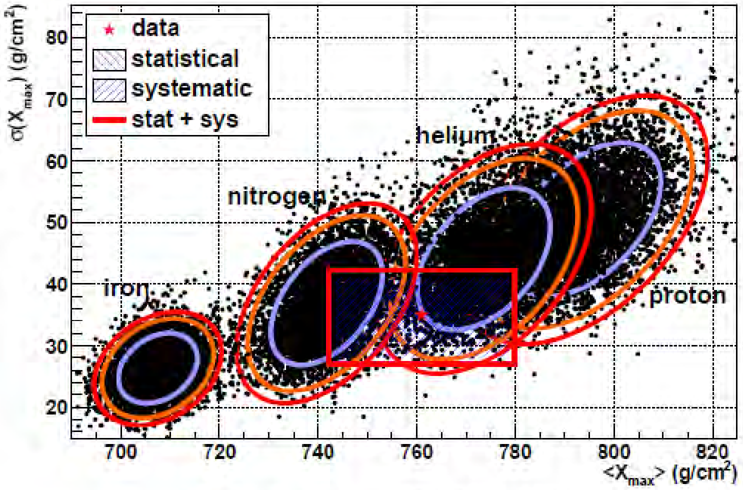
(d) $18.5 \leq \log_{10}(E/\mathrm{eV}) < 18.6$

Dots: Resampled MC with same no. of events as data; with contours 68.3% (blue), 90% (orange), and 95% (red) confidence intervals

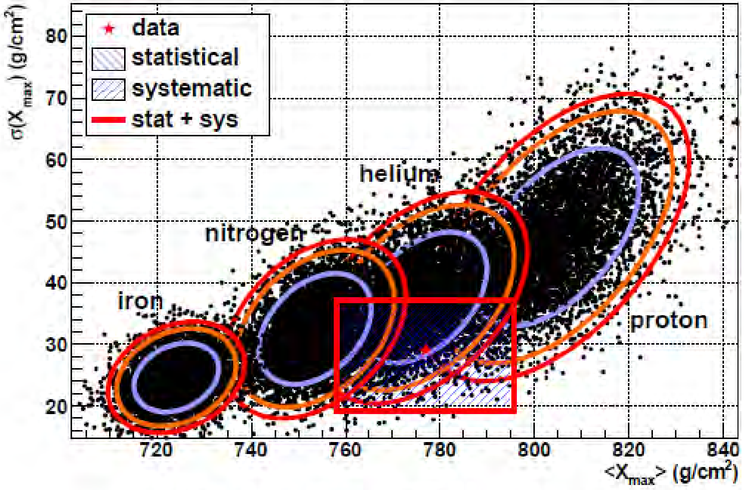
Data/MC: σ(Xmax) vs <Xmax>



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



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



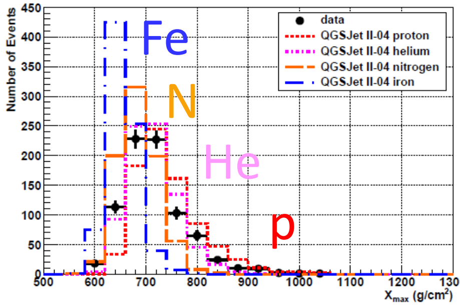
(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

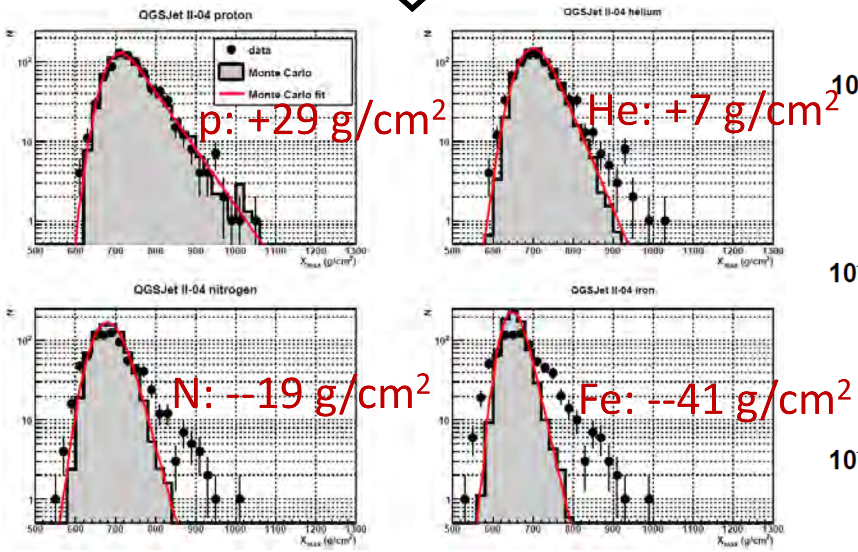
Limited Statistics above 10^{19}eV!

Dots: Resampled MC with same no. of events as data; with contours 68.3% (blue), 90% (orange), and 95% (red) confidence intervals

Xmax Shape analysis

$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$





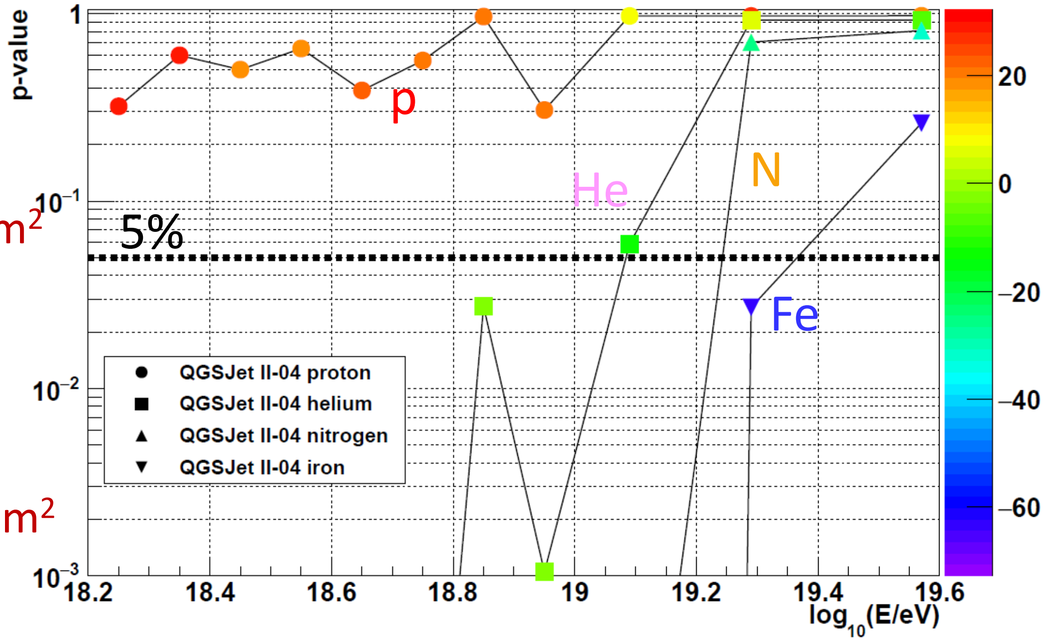
p: +29 g/cm^2

He: +7 g/cm^2

N: --19 g/cm^2

Fe: --41 g/cm^2

Color indicates the amount of shift in Xmax applied to data for best fit to MC (in g/cm^2)



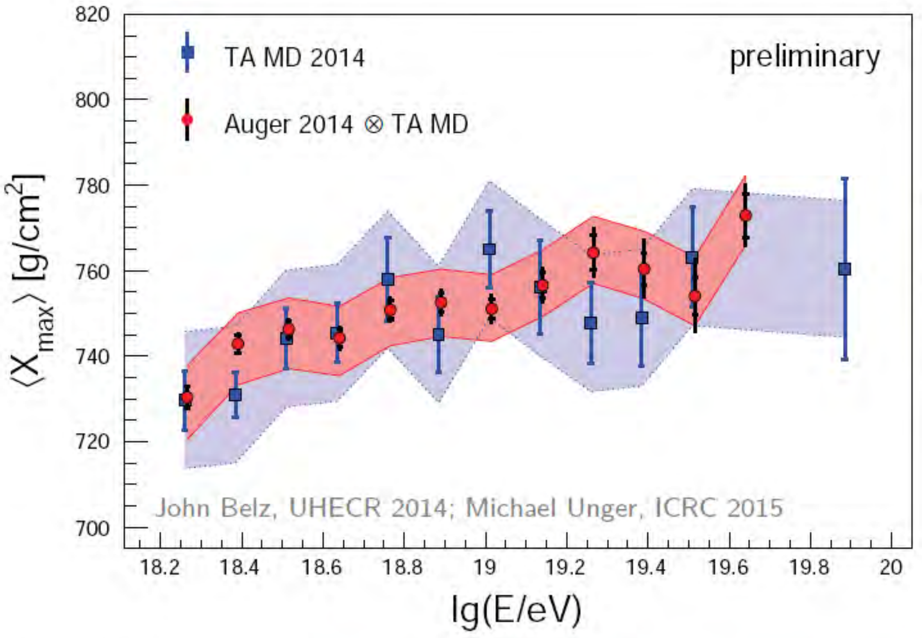
- max. log$L$ derived p rejects (at 95% C.L.) all species except H (E<$10^{19.0}$eV)
- max. log$L$ derived p FAILS to reject (at 95% C.L.) any species (E>$10^{19.2}$eV)

<Xmax>: Auger vs different TA measurements

Discrepancy Auger – TA (Black Rock Mesa/Long Ridge) is larger and energy-dependent

TA Middle Drum

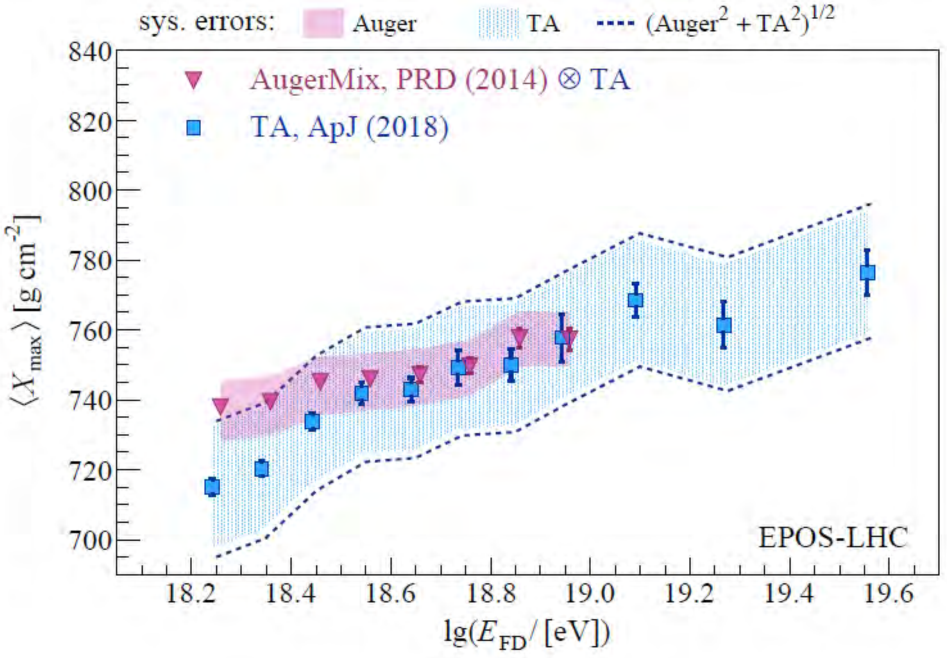
[ApP 64 (2015) 49]



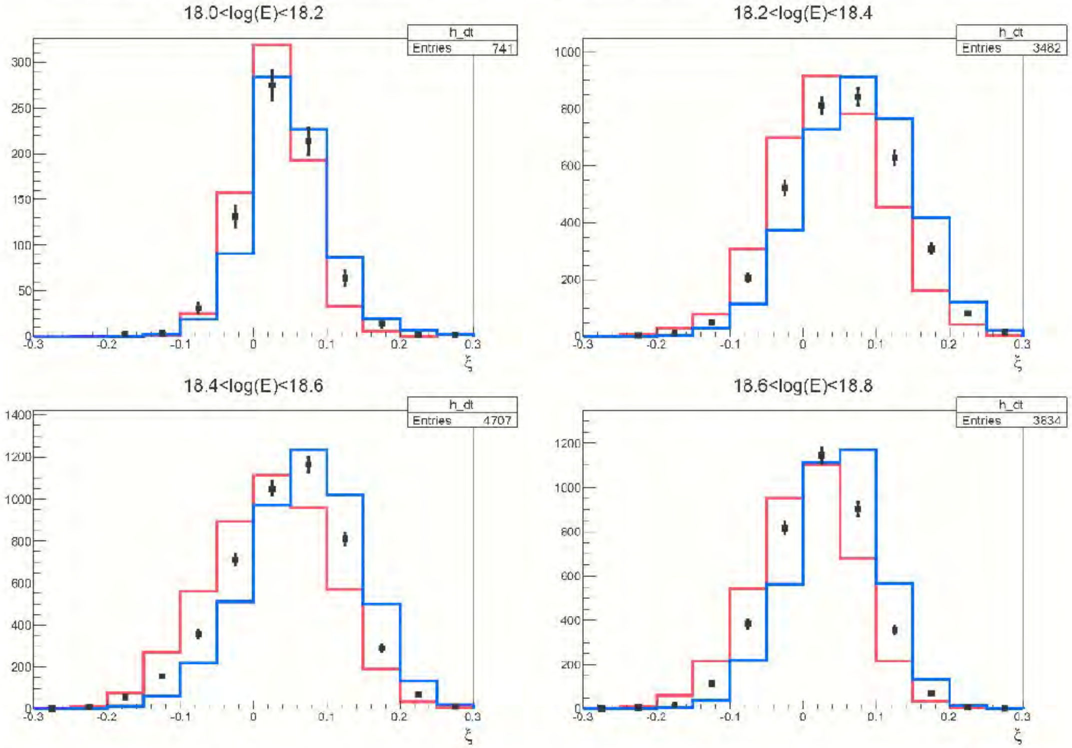
average difference: $\langle \Delta \rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$

TA Black Rock Mesa/Long Ridge

[ApJ 858 (2018) 76]



Composition Measurement by SD



— QGSJet II-03 proton

— QGSJet II-03 iron

● data

ξ

Abbasi, et al., arXiv:1808.03680

Use Monte Carlo proton showers as classifier background and iron as "signal".

Train boosted decision tree to classify individual events as proton-like or iron-like based mainly upon the shower observables related to muon production. Larger A → more muons.

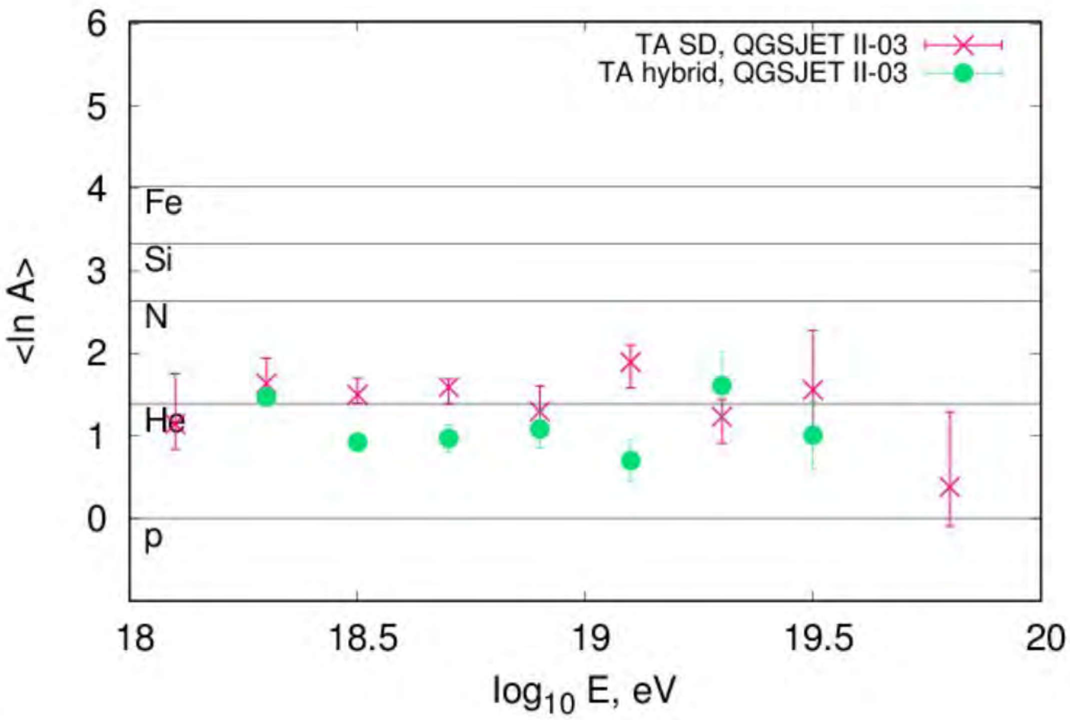
MVA and BDT analysis technique using 14 parameters measured in SDs

- Shower front curvature
- Signal Area over Peak
- Upper/Lower scintillator layer asymmetry
- Peak distributions in FADC waveforms

Divide Monte Carlo into 3 parts:

- Training set using 14+2 (+2 → energy, θ) variables to compute classification variable ξ for each event: -1 → pure bkgnd, 1 → pure signal.
- Create mixtures of proton/iron X_{max} distributions in 2.5% steps to compute <ln A> observed in the data.
- Use third part to correct for bias in ξ.

Composition Measurement by SD



<ln *A*> = 1.52 ± 0.08 (stat) ± 0.36 (sys)

SD composition opens a window into much higher statistics measurements.

~100% duty cycle

Hybrid X_{max}: 3330 events
SD MVA: 18007 events

Model systematics. Models underestimate rate of muon production in showers by ~30 - 80%

Nine years of TA SD data: 2008 - 2017

New technique. Needs comprehensive checks to verify.

Abbasi, et al., arXiv:1808.03680

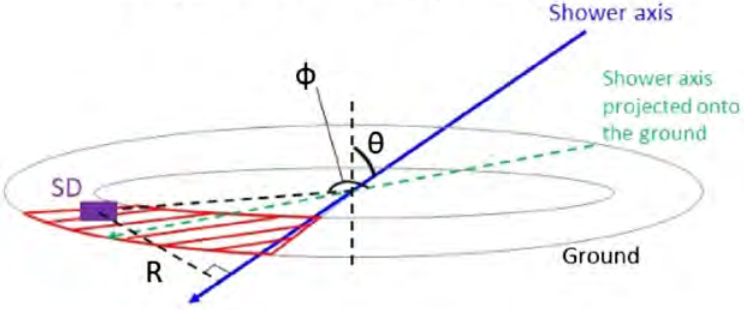
Method in TA analysis : muon purity

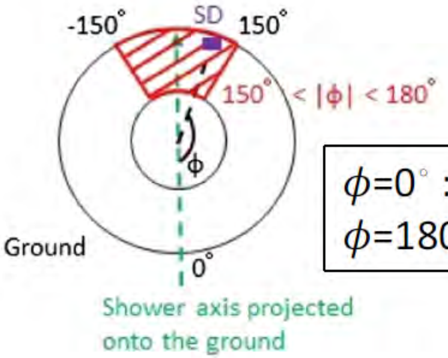
- Muon purity P

$$P = \frac{E_\mu}{E_{all}} = f(\theta, \phi, R)$$

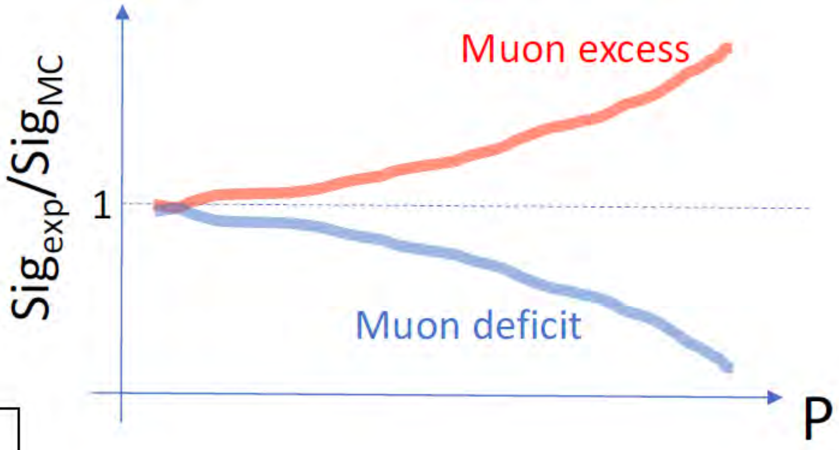
is defined by MC but only a function of geometrical parameters

- Large P with large θ, ϕ, R





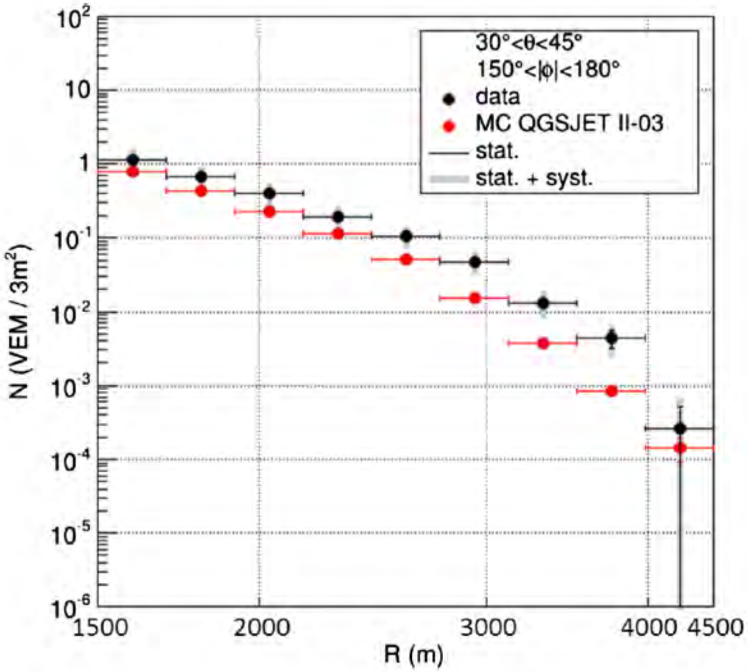
ϕ=0° : shower arrival side
ϕ=180°: shower going side

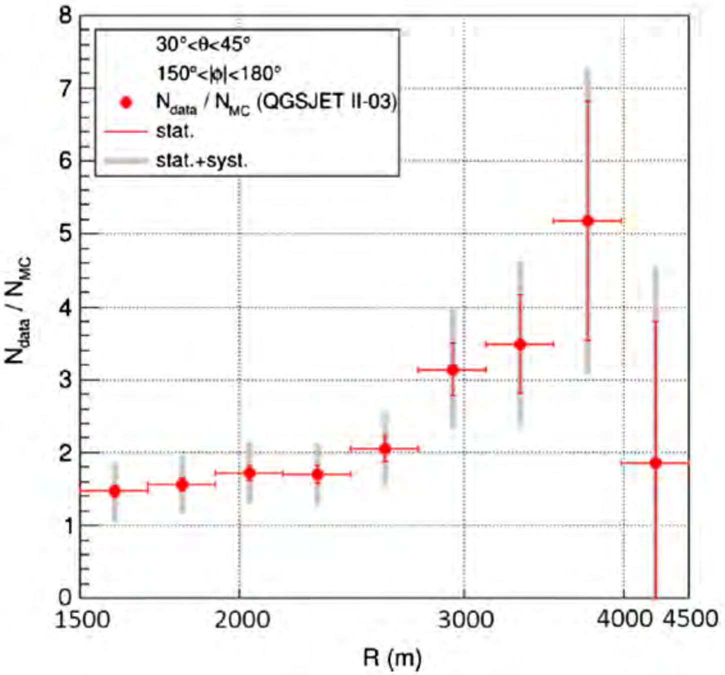


Dataset and MC

- Dataset
  - May 11, 2008 – May 11, 2015 (7 years)
  - $18.8 < \log_{10}(E_{FD}/eV) < 19.2$
  - $E_{FD} = E_{SD}/1.27$
- MC
  - E : thrown (true) energy
  - Reference : QGSJET II-03 proton
  - MC : CORSIKA 6.960 (FLUKA2008.3C+EGS4), thinning + dethinning
  - Detector : GEANT4
  - $16.55 < \log_{10}(E/eV) < 20.55$
  - $0^\circ < \theta < 60^\circ$
  - 0.05 accidental muons / station / $\pm 32\mu s$

Result 1 (data/MC vs. R)





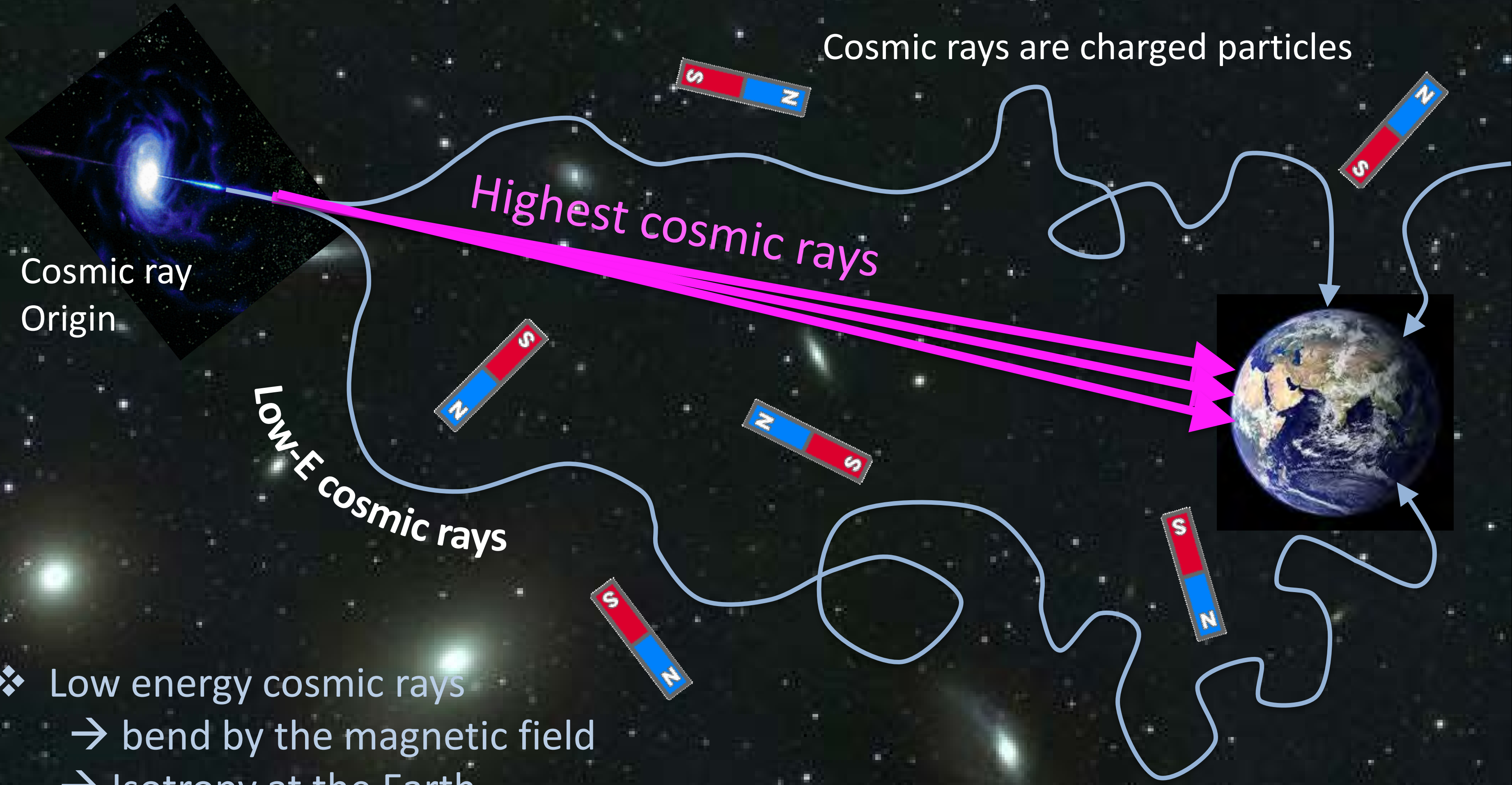
Source	Systematic error
FD energy determination	±21%
1 MIP calibration	±1.2%
Atmospheric muon cut	±1%
Poisson distribution assumption	±(<4%)
Event reconstruction	±(4–13%)
SDs not working properly	±(<1%)
Total	±(22–24%)

- N_{data}/N_{MC} >1 and increases with R
- N_{data}/N_{MC} => 1 @ R>4000m because BG dominates

Content

- Telescope Array (TA)
- Latest results
  - Energy Spectrum
  - Composition
  - Anisotropy
- TA extension

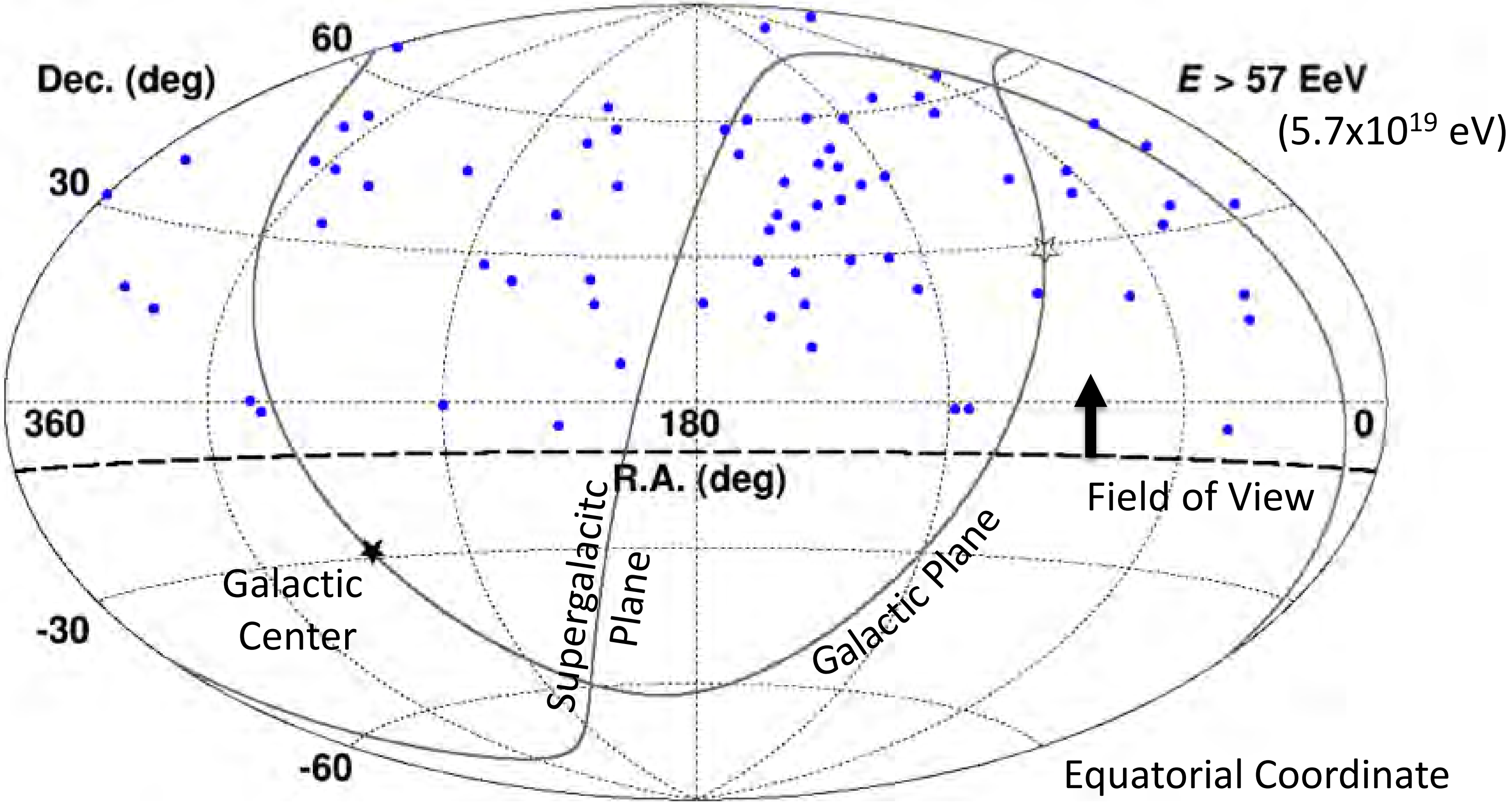
Why highest energy cosmic rays?


Cosmic rays are charged particles

- 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 hotspot

Directions of the Highest-energy Cosmic Rays

5 year data



72 TA events

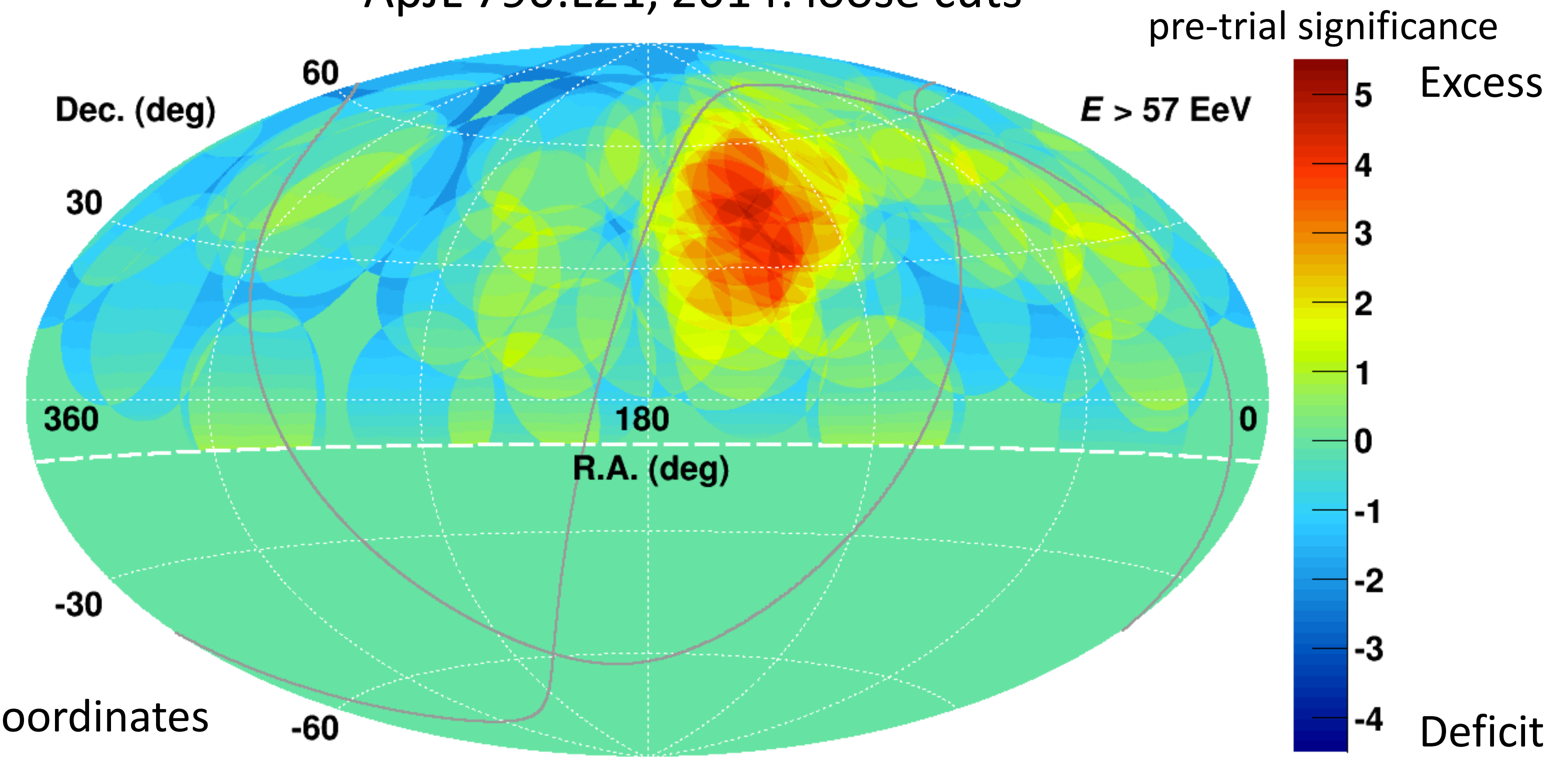
Full event table is available in the ApJL online journal :

http://iopscience.iop.org/2041-8205/790/2/L21/suppdata/apjl498370t1_mrt.txt

TA Hotspot (5 years data)

72 events with E > 57 EeV

ApJL 790:L21, 2014: loose cuts



Equatorial coordinates

Oversampling circle radius: 20°

Maximum pre-trial significance : ~ 5σ

at RA=146.7°, Dec=+43.2°

Post-trial significance: 3.4σ

Observed: 19

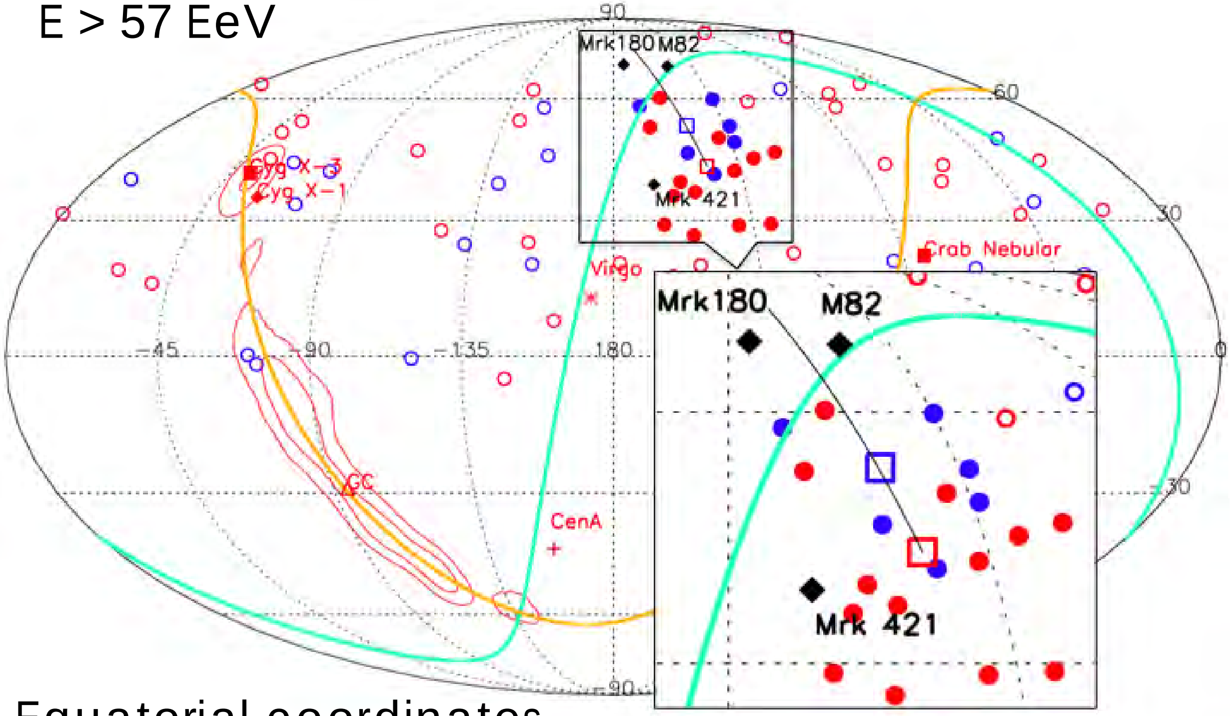
Expected : 4.5

(26% of events in 6% of area)

Is M82 or Mrk 180 the source?

H.N. He, A.Kusenko, S.Nagataki, et al., arXiv:1411.5273

E > 57 EeV



Equatorial coordinates

	Energy or comment	Hotspot
🔵	> 75 EeV	inside
🔴	< 75 EeV	
○	> 75 EeV	outside
⭕	< 75 EeV	

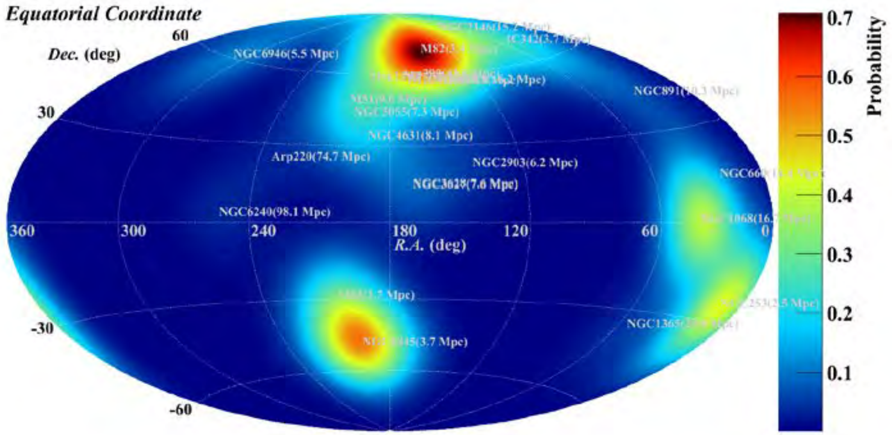
- M82: starburst galaxy at 3.5 – 3.8 Mpc
- Mrk 180: bright blazar at ~185 Mpc

Star Burst Galaxies and highest energy cosmic rays

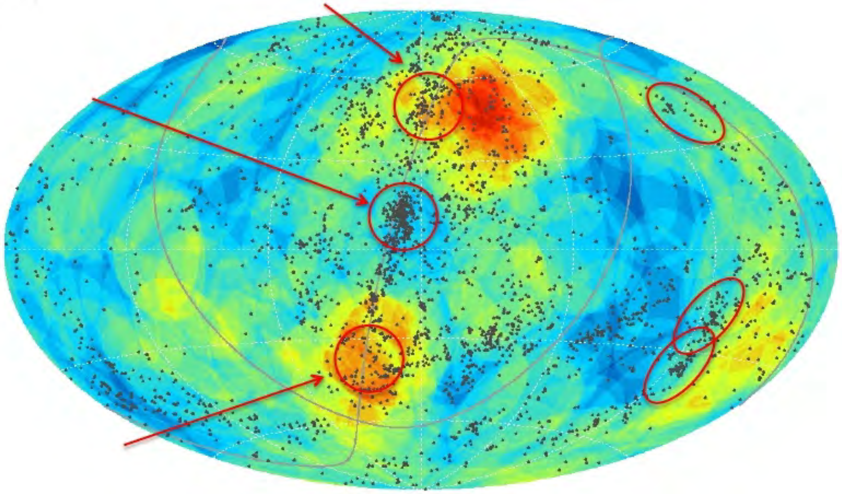
Recently Auger found that the starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4.0 sigma,
The highest value of the test statistic being for energies above 39 EeV

TA is checking this hypothesis

Starburst galaxies

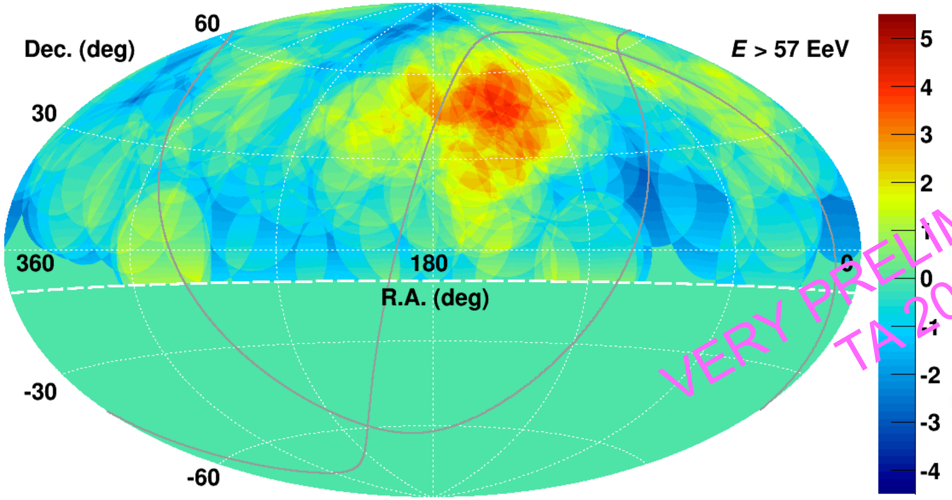


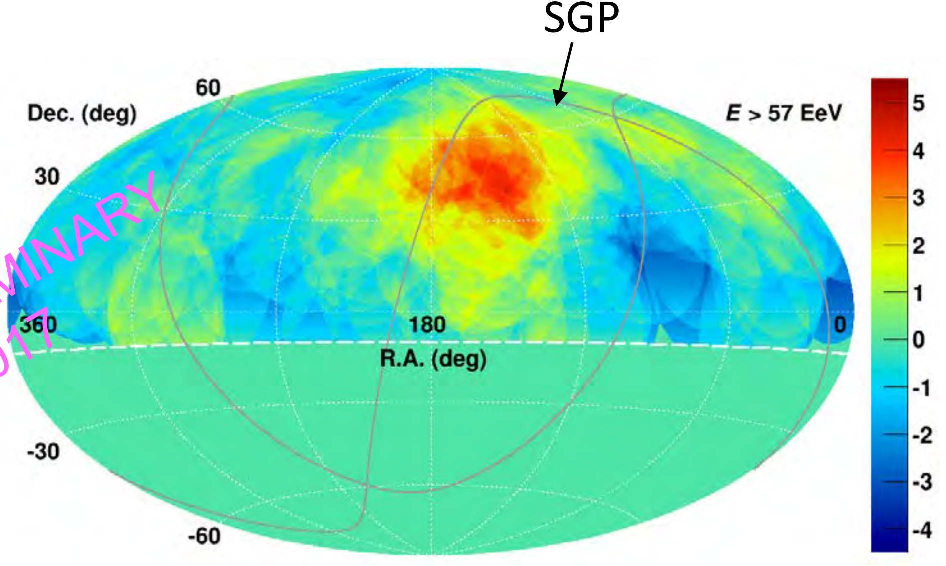
TA and Auger significance
For 20-degree-radius oversampling
(E > 57 EeV using original E scales)



Hotspot with 9 years data

143 events with E > 57 EeV





With original 20° oversampling, spot looks larger…. Thus, scan over 15°, 20°, 25°, 30°, & 35°

With 25° oversampling,
Maximum pre-trial significance: ~5σ
at RA=144.3°, Dec=+40.3°
Observed: 34
Expected : 13.5

Post-trial significance : 3σ

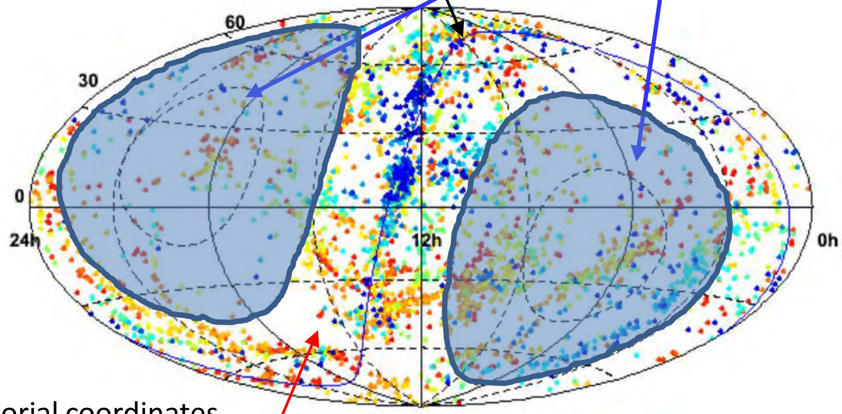
submitted to PRL, arXiv:1707.04967

Spectral Anisotropy

(from the point of regions with more/less nearby objects)

Super-Galactic Plane (SGP)

Off source region



Equatorial coordinates

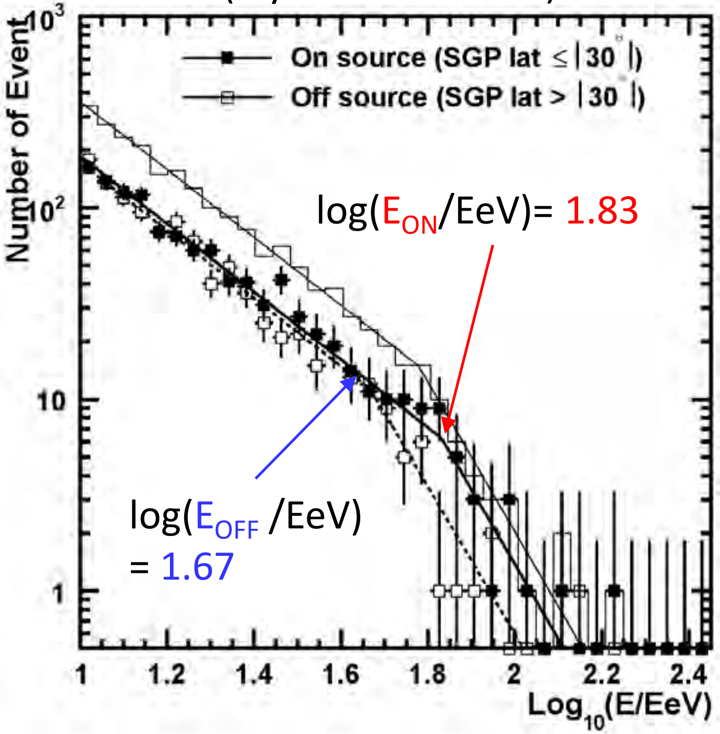
Colored dots: 2MRS galaxies (E < 75Mpc)

On source region (within 30º from SGP)

more nearby objects

TA energy distributions

(5 years of SD data)



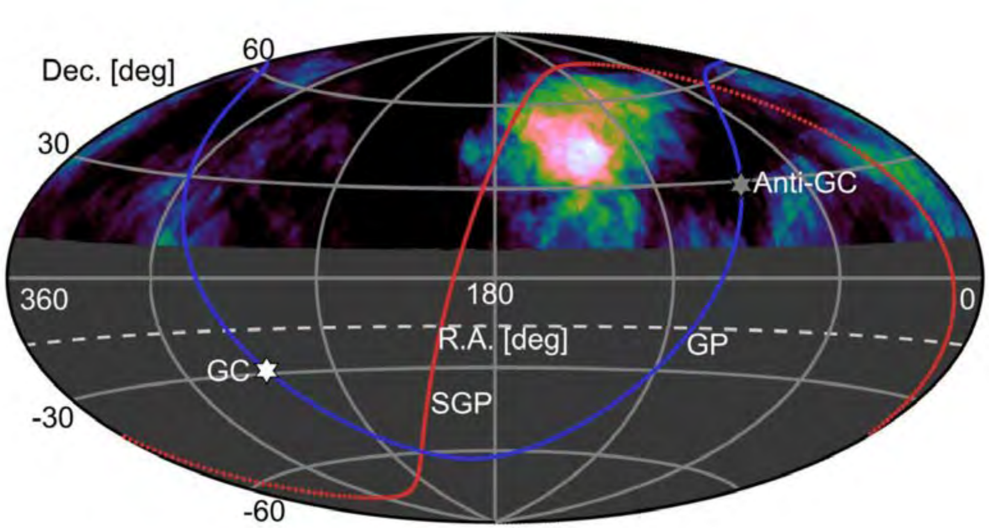
$\log(E_{ON}/\mathrm{EeV}) = 1.83$

$\log(E_{OFF}/\mathrm{EeV}) = 1.67$

E_{ON} and E_{OFF}: 3.2σ difference

ApJL, 862:91 (6pp), 2018

Spectral anisotropy



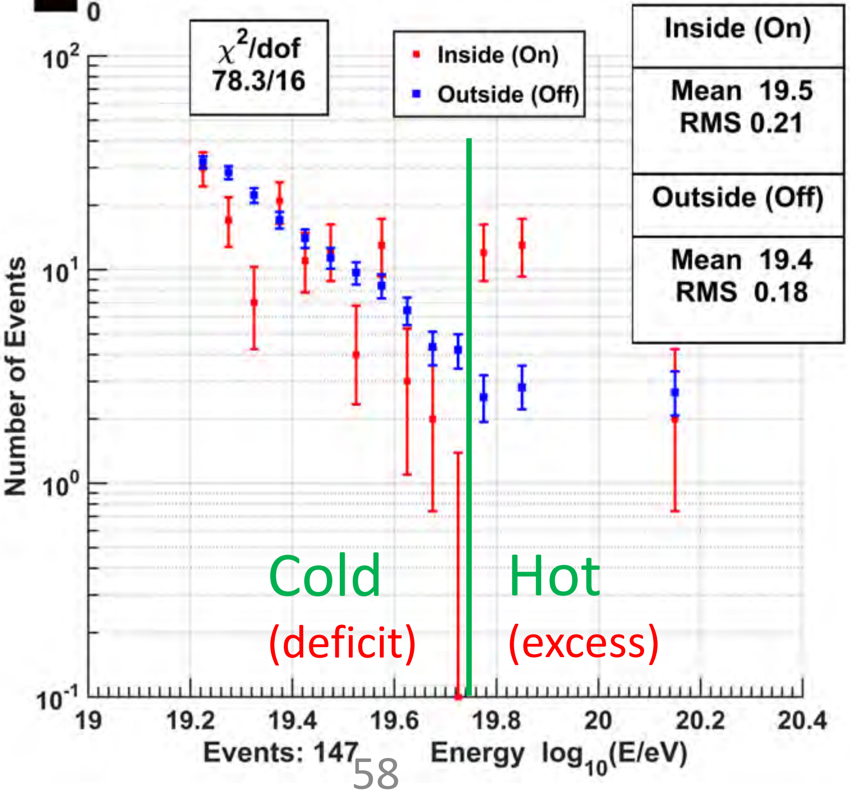
Maximum pre-trial signif. at (R.A., Decl.) = (139°, 45°) for average spherical cap size <r> of radius 30°

“cold spot” at lower energies,
same place as the hot spot at high

7 years of TA SD data

$E>10^{19.2}$ eV

red points: events inside the circle
blue points: expectation defined outside the circle



Post-trial significance: 3.7σ

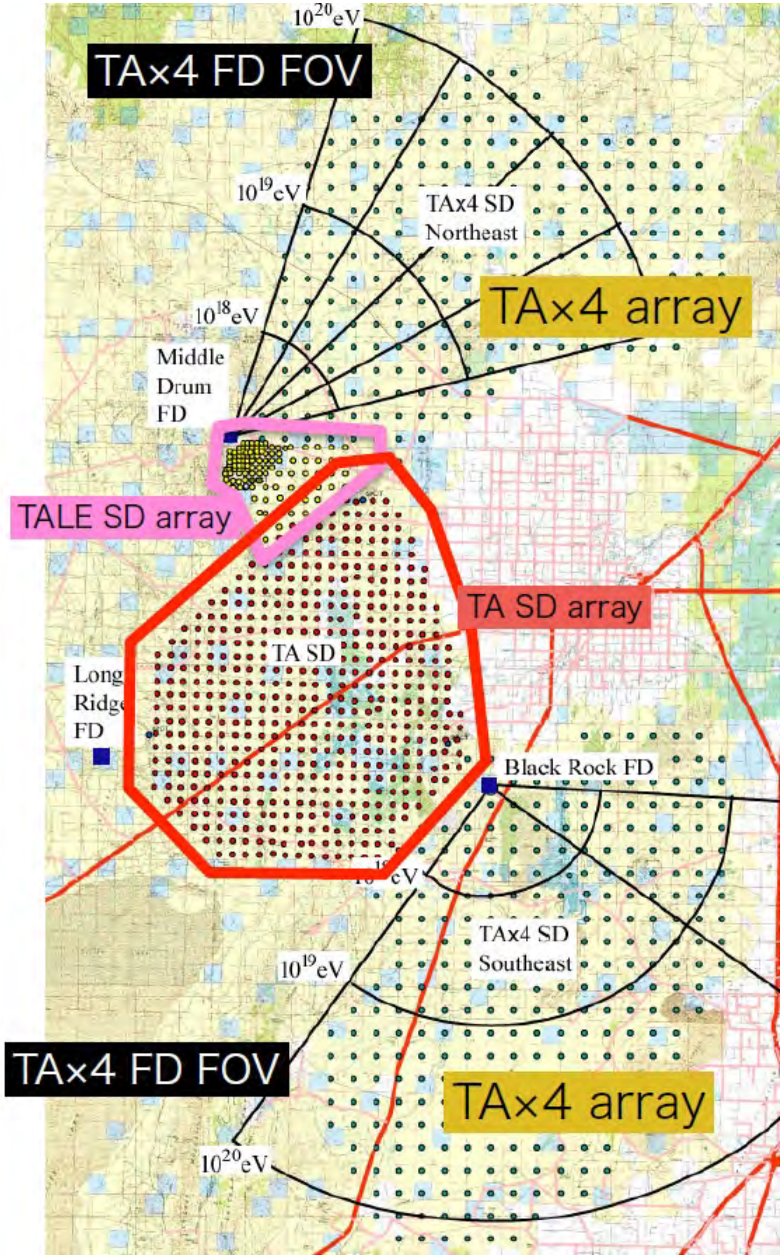
Scanned for $\log_{10}E$ > 19.0, 19.1, 19.2, 19.3
radius <r> = 15°, 20°, 25°, 30°

October 15, 2018

Content

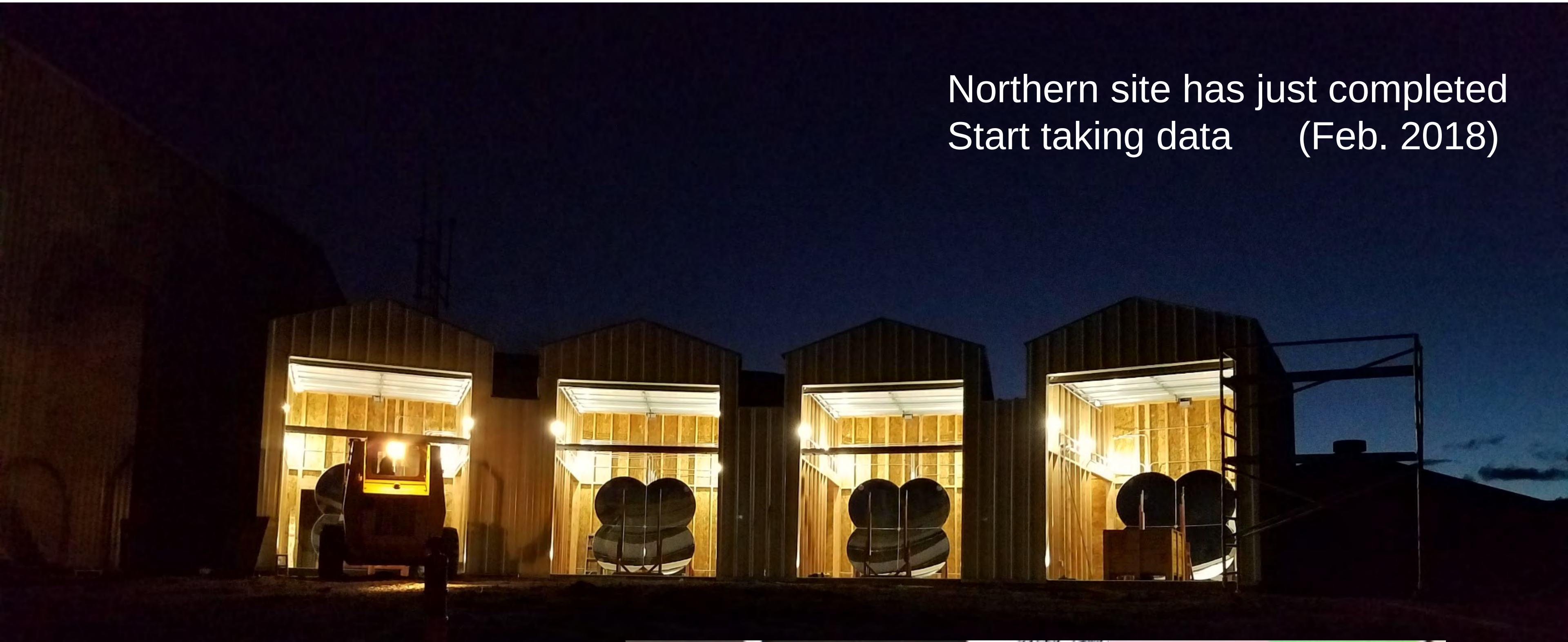
- Telescope Array (TA)
- Latest results
  - Energy Spectrum
  - Composition
  - Anisotropy
- TA extension
  - TAx4
  - TALE SD and NICHE

TA extension



- TAx4
  - quadruple TA to accelerate the pace of data collection
  - Surface detector(~3000 km^2)
    - 500 scintillator SDs with 2.1 spacing
    - under construction
      - Waiting for BLM permission
  - Fluorescence detector
    - 2 FD stations (12 HiRes-II telescopes)
      - First light at the northern station
      - The southern station: under construction
- TALE
  - 103 SDs constructed (by Feb. 2017) … to improve Xmax resol.

TAx4 FD



Northern site has just completed
Start taking data (Feb. 2018)

TAx4 SD

Japan

Utah, USA

① Scintillator counter assembly (Japan)

@Utah, USA

② Final assembly @workshop

③ Assembled SDs @workshop

④ Staking (for SD positioning and follow-up surveys)
  - finished by ATVs or helicopter in 2017

Plan

– Permission from Bureau of Land Management

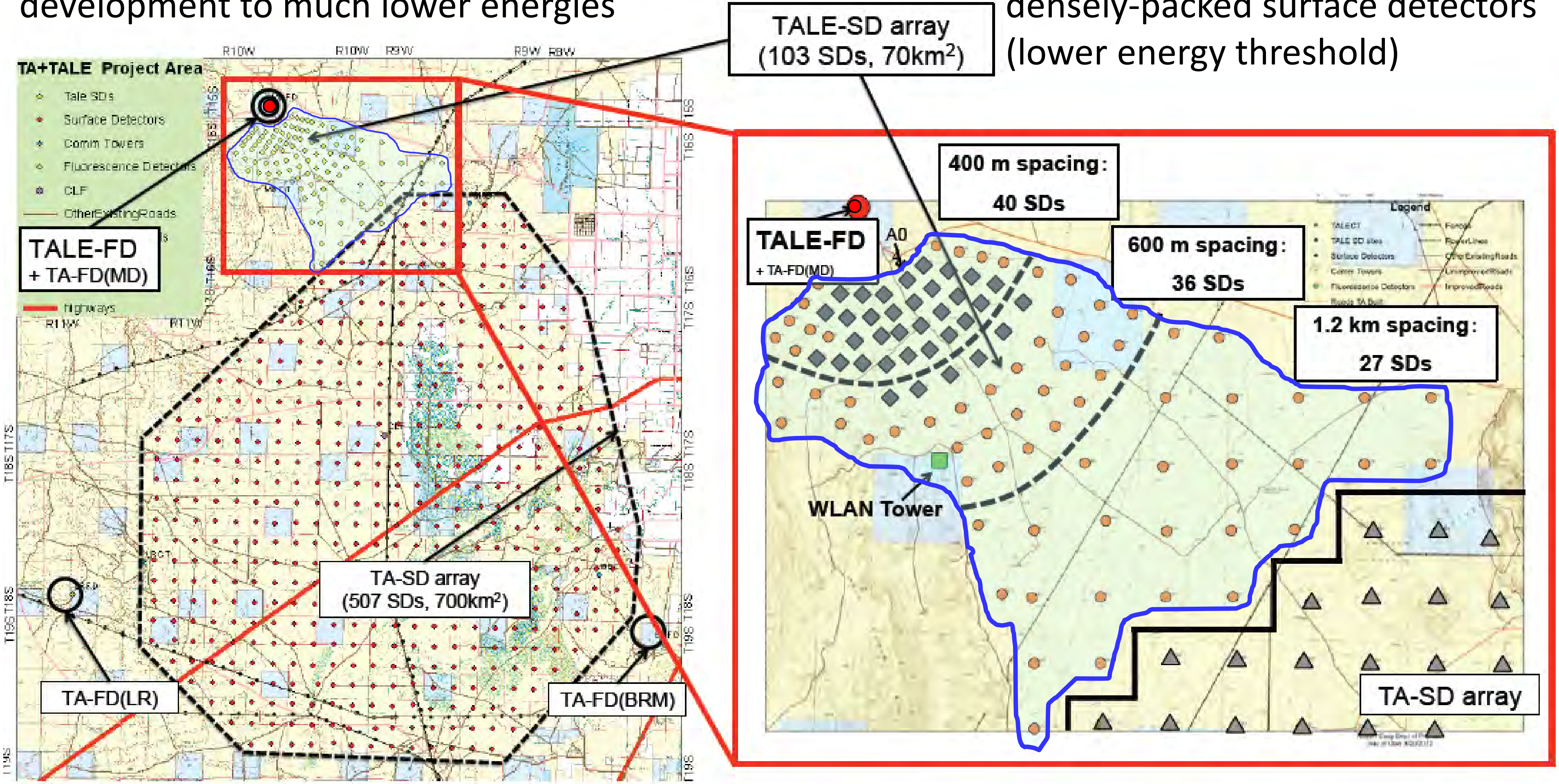
– TAx4 SD deployment: planned in early 2019 by helicopter

TA Low-energy Extension (TALE)

Galactic to Extra-Galactic Transition

TALE-FD: 10 reused HiRes telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

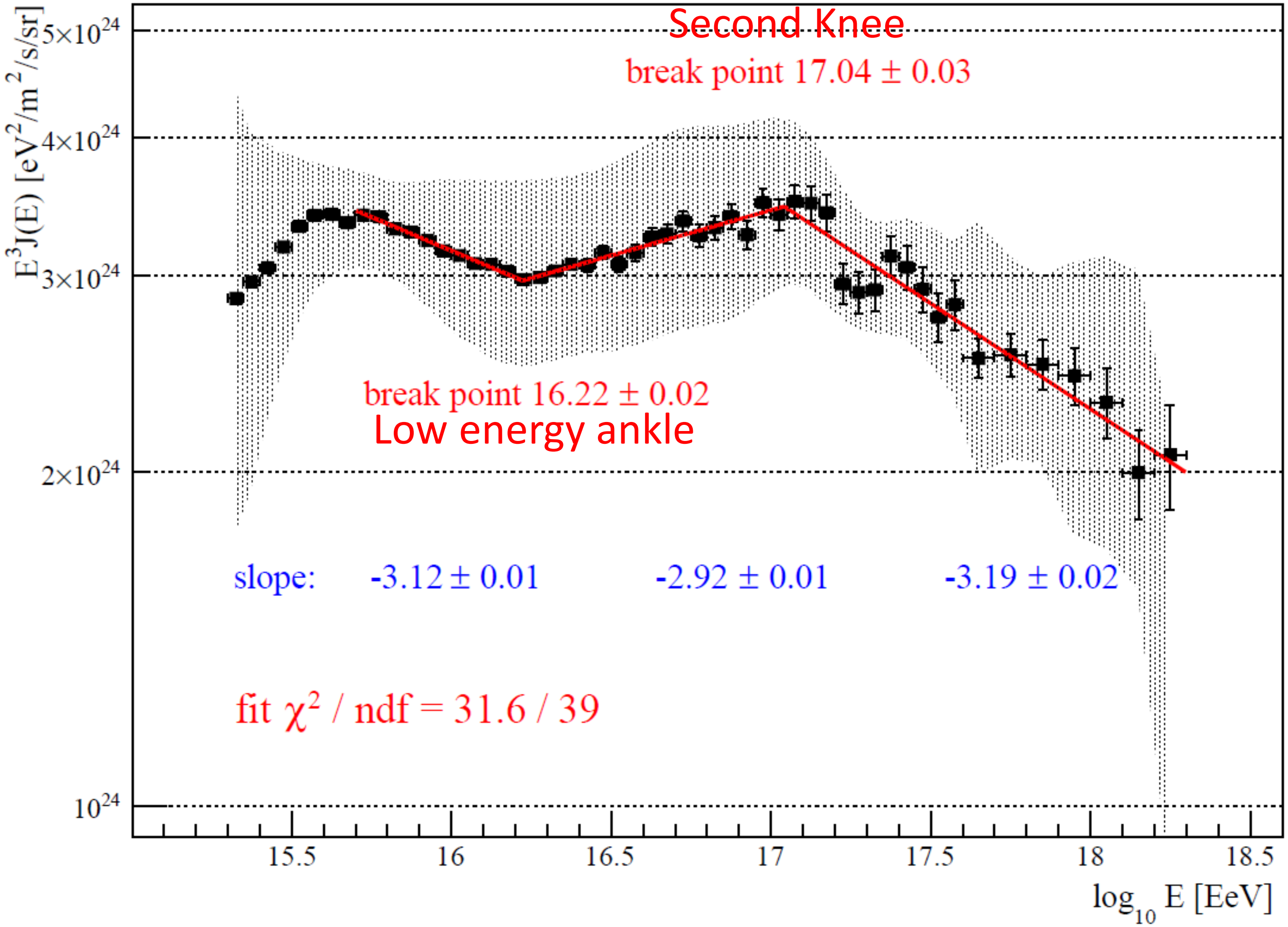
TALE-SD array: Graded infill surface detector array - more densely-packed surface detectors (lower energy threshold)



October 15, 2018

TALE energy spectrum (monocular)

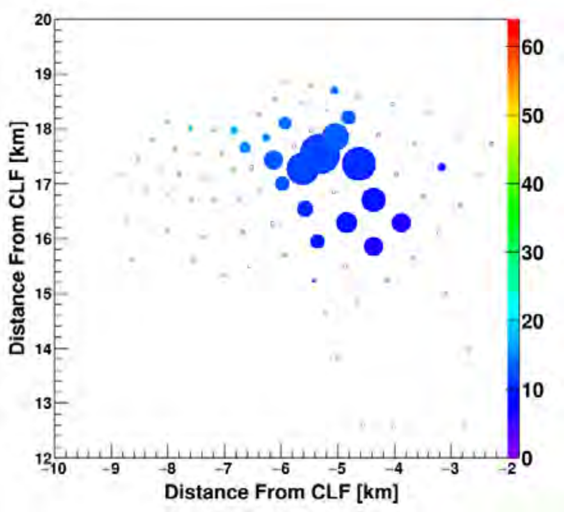
submitted to ApJ, arXiv:1803.01288



TALE SD Array

Full TALE SD Array (103) deployed in Feb 2017 – started stable operation

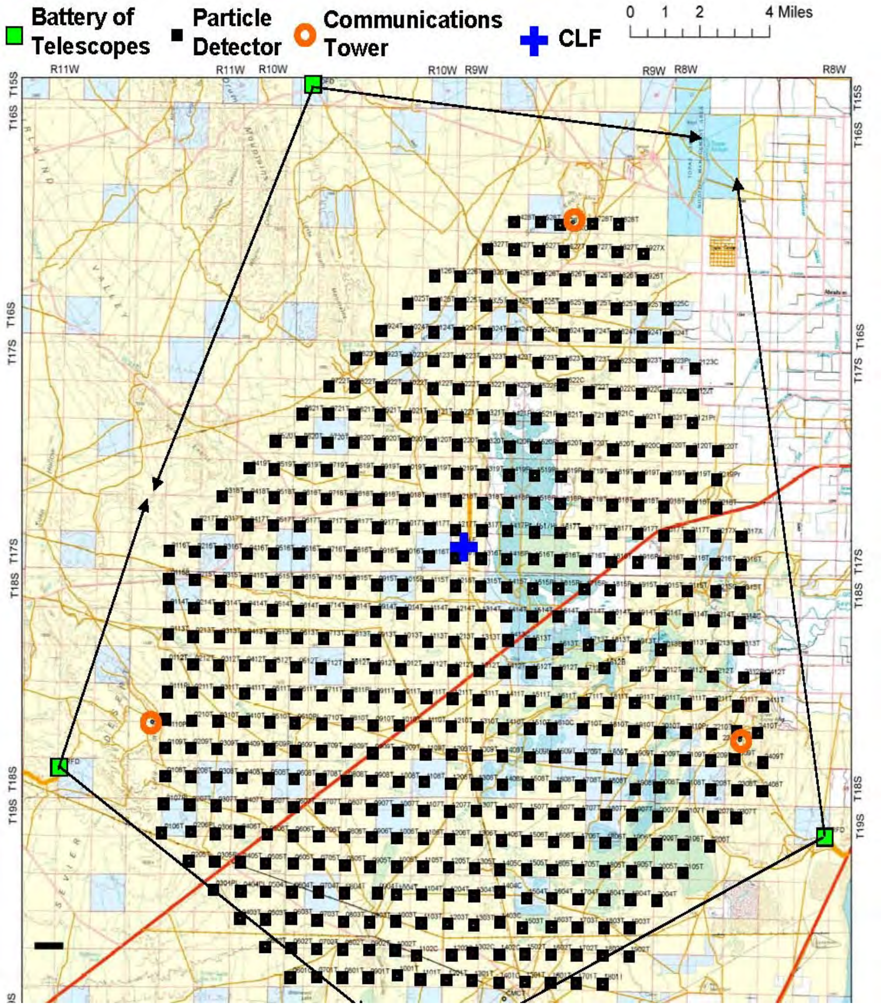
2017 March 13 10:23:06



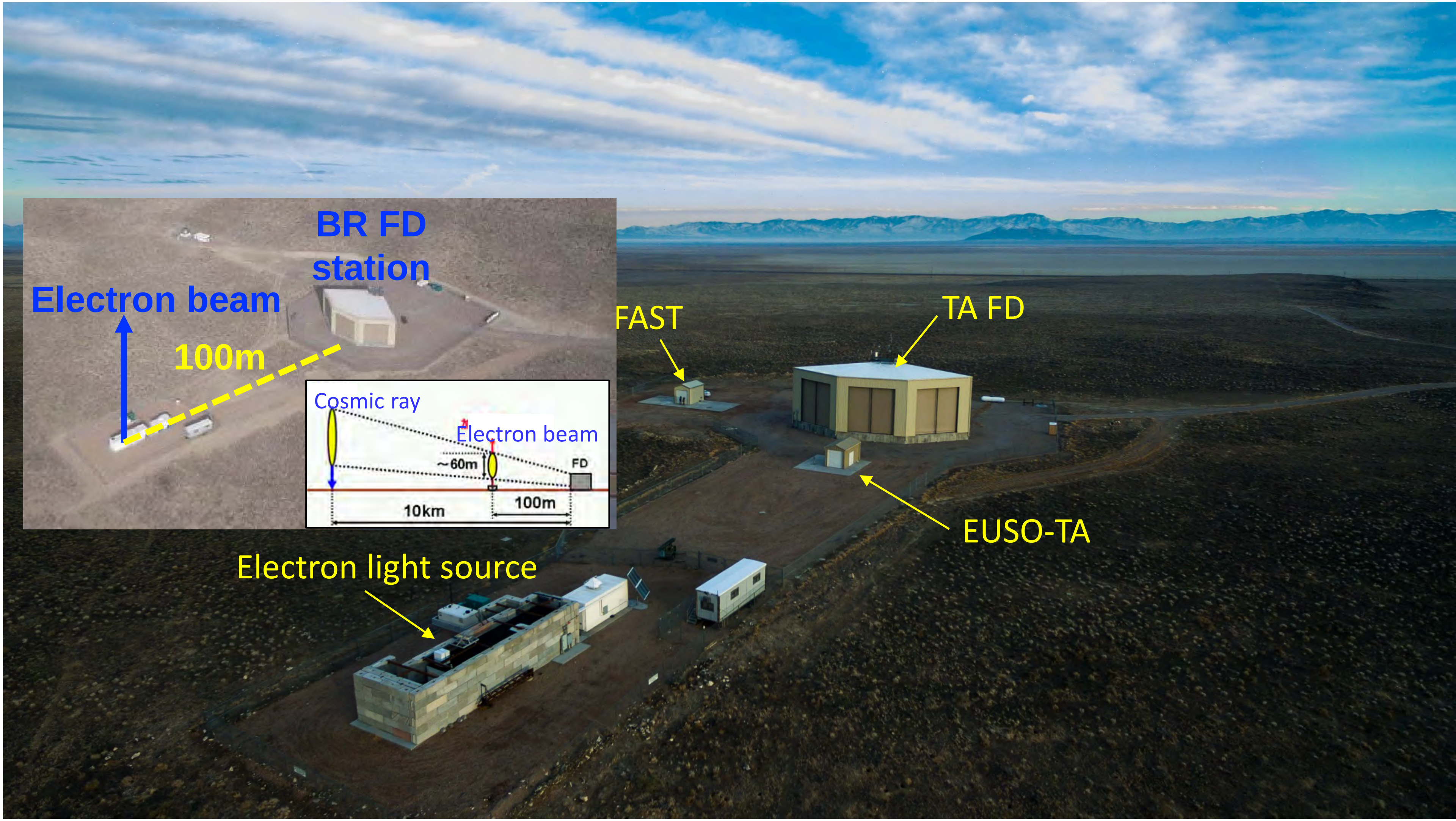
October 15, 2018

TA site is worldwide

- Open for interesting studies and R&D!



BRM FD site


BR FD station
Electron beam
100m
Cosmic ray
Electron beam
~60m
FD
10km
100m
FAST
TA FD
EUSO-TA
Electron light source

Conclusions

- TA SD/FD and TALE FD energy spectrum shows spectral features ($10^{15.4}$ eV < E < over 10^{20} eV)
  - ankle ($10^{18.69}$ eV), cutoff ($10^{19.81}$ eV)
  - 2nd ankle in lower energy region
- TA Xmax: compatible with light composition (E > ~$10^{18.2}$ eV)
- TA hotspot (3σ) now appears larger than we originally thought
- **TAx4** is coming soon; construction underway
- Full TALE SD was deployed and is in stable operation.