Status and results of the Telescope Array observatory

Grigory I. Rubtsov for the Telescope Array Collaboration

9th international Workshop in Air Shower Detection at High Altitudes 2018
September 18, 2018, Moscow

Telescope Array Collaboration

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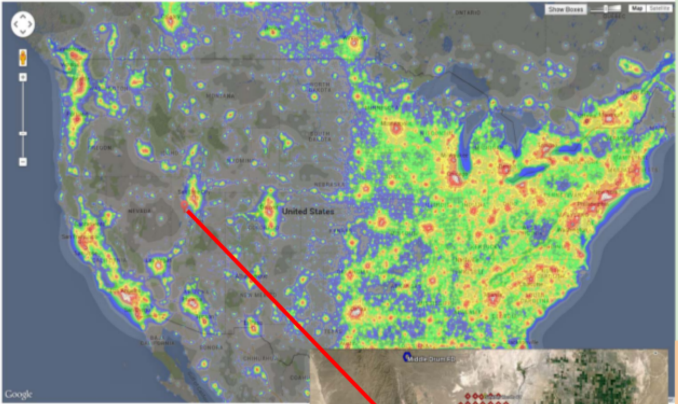
Belgium, Japan, Korea, Russia, USA

Telescope Array Observatory



U.S. Light Pollution Map

Largest cosmic ray observatory in the Northern hemisphere.

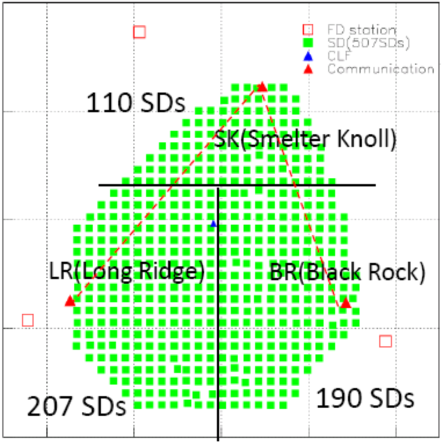
~700 km^2 → ≲ *land* area of New York City.

Millard County, Utah
39.30° N
112.91° W
1550 m ASL

~800 g/cm^2 vertical depth

The High Energy component of Telescope Array – 38 fluorescence telescopes (9728 PMTs) at 3 telescope stations overlooking an array of 507 scintillator surface detectors (SD) - operational as of 2008.

Telescope Array surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- 10 years of operation

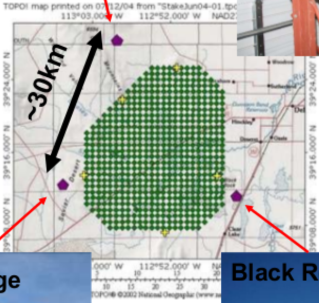
Largest UHECR statistics in the Northern Hemisphere

TA Fluorescence Detectors

Middle Drum

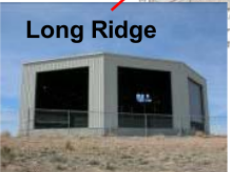
14 telescopes @ station
256 PMTs/camera

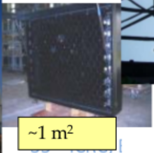
Reutilized from HiRes-I

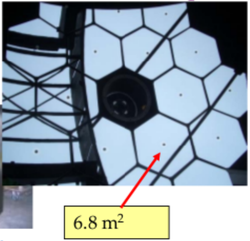


New Telescopes

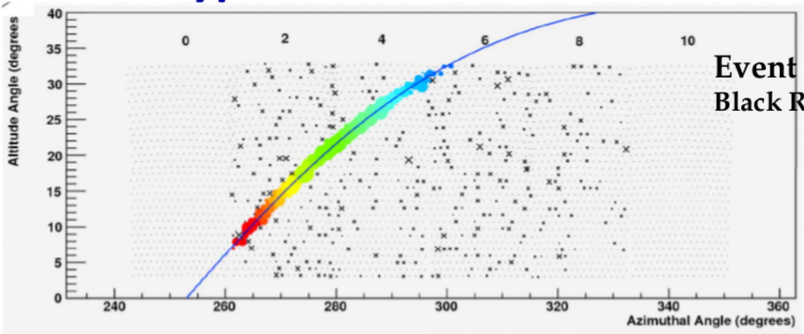
12 telescopes/station
256 PMTs/camera



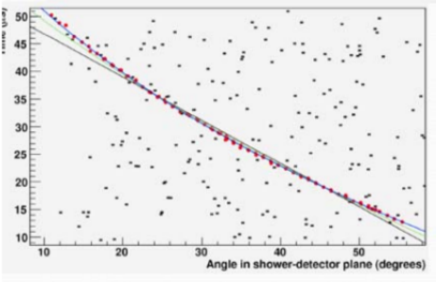




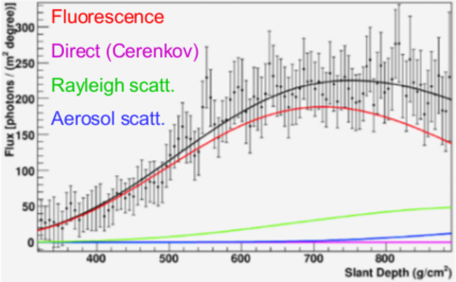
Typical Fluorescence Event



Event Display
Black Rock Mesa



Monocular timing fit (time vs angle)

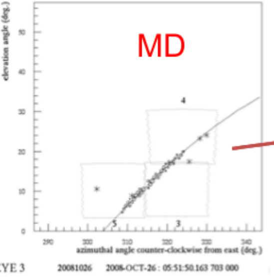


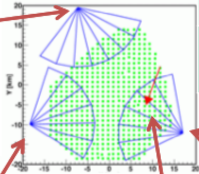
Reconstructed Shower Profile

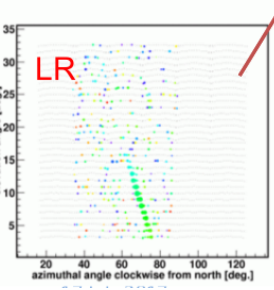
Example Event

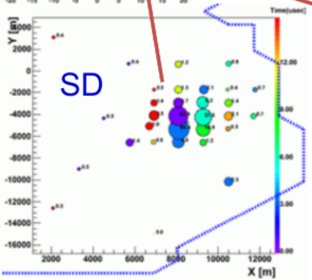
	θ[°]	ϕ[°]	x[km]	y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88

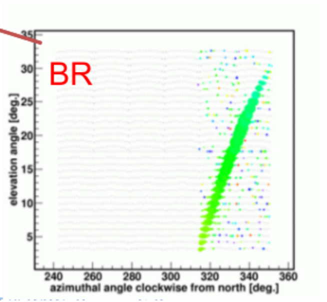
Event from 2008-10-26











Outline

Selected Telescope Array results on the ultra-high-energy cosmic rays:

- **I. Energy spectrum**
- II. Anisotropy
- III. Mass composition
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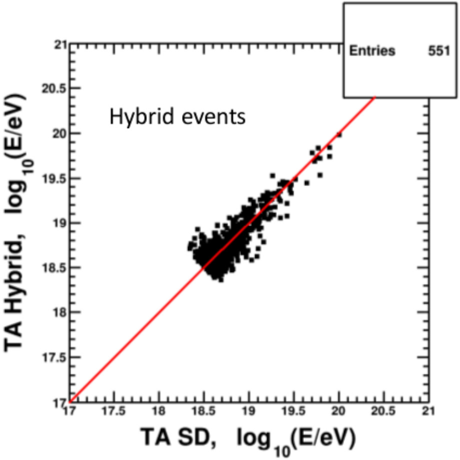
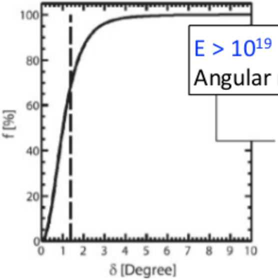
Energy Scale Check and Resolution

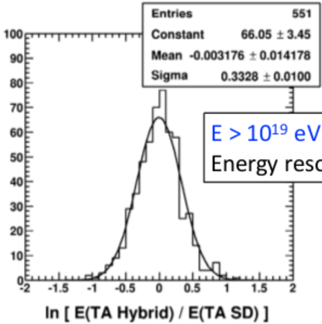


(SD scaled to FD energy: calorimetric)

$$E_{SD}/1.27 = E_{FD}$$



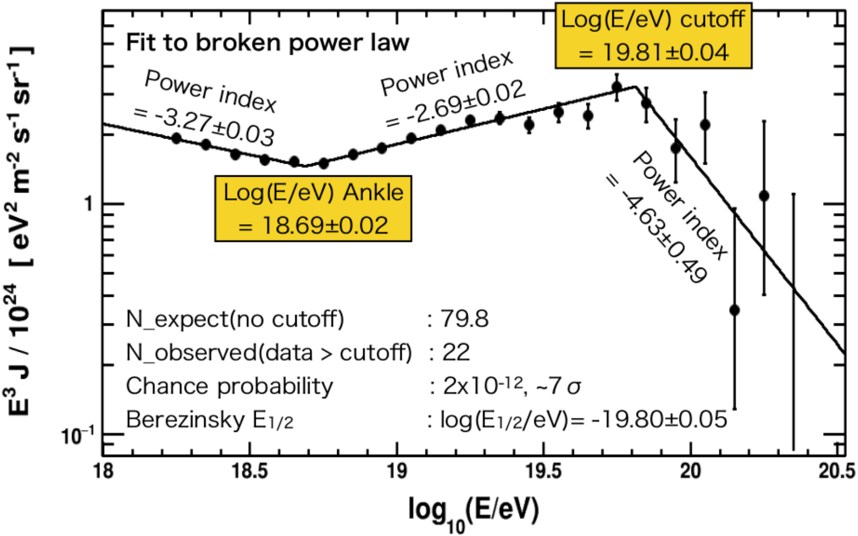
$E > 10^{19}$ eV
Angular resolution = 1.4°



$E > 10^{19}$ eV
Energy resolution < 20%

TA SD spectrum (9 yrs)

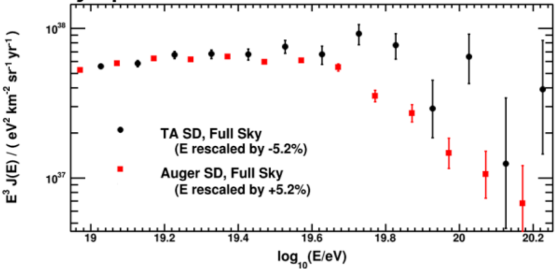
Matthews ICRC2017, CRI172



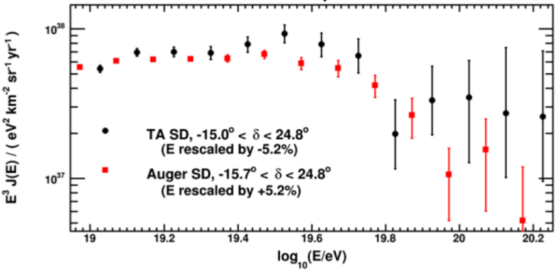
Auger and TA spectra

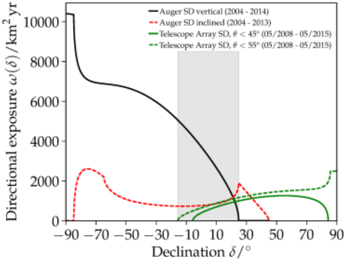
Ivanov ICRC2017, CRI231
(Auger/TA spectrum WG)

Full Sky spectra



Common declination band (-15.9° < δ < 24.8°)



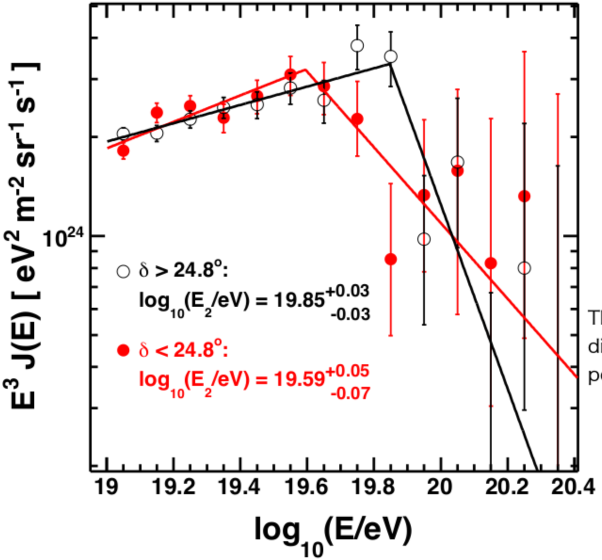


Better agreement between Auger and TA
In the common declination band

Declination dependence?

Declination dependence in TA

Submitted to Ap. J.
arXiv: 1801.07820



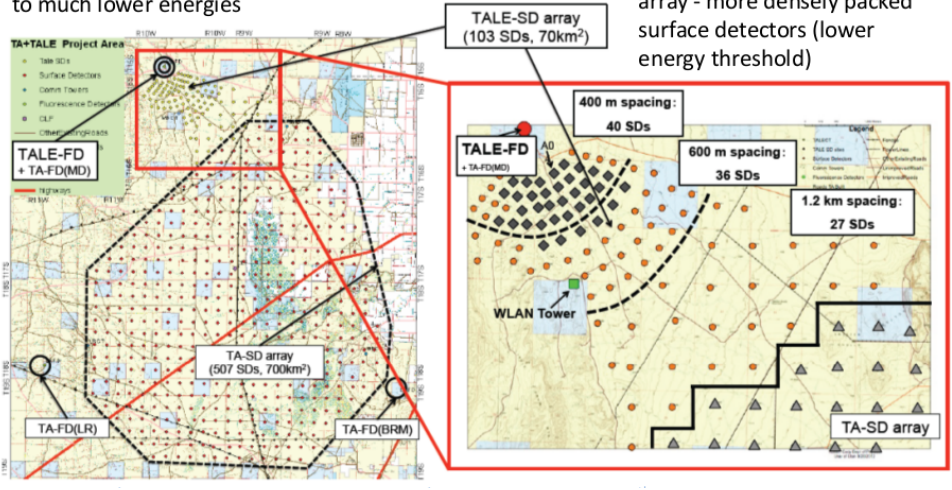
The overall significance of the difference between the two break points is 3.5 sigma

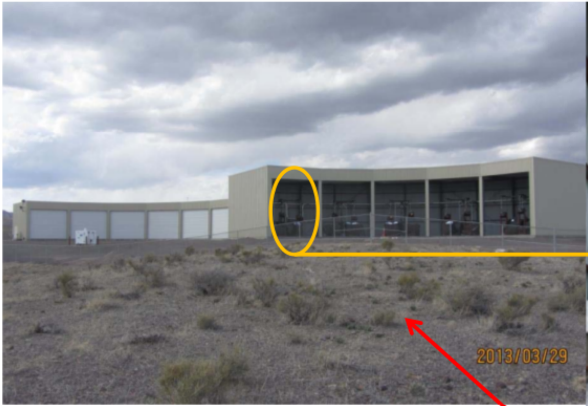
TA Low Energy Extension (TALE)

Galactic to Extra-Galactic Transition

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

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

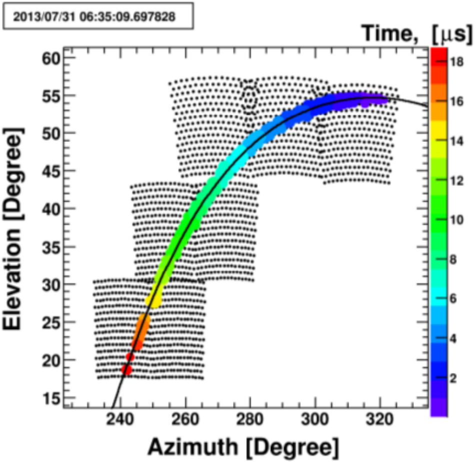


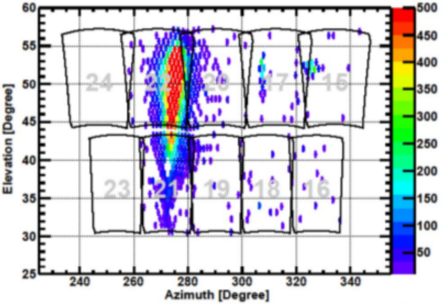


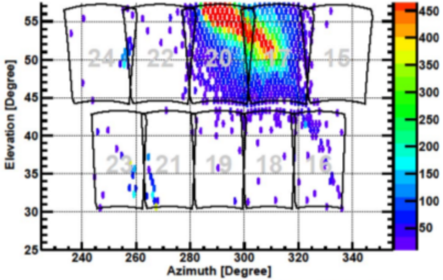
TALE-FD : 10 telescopes (Sep. 2013 ~)
elevation : 31°~59°, azimuthal : 114°

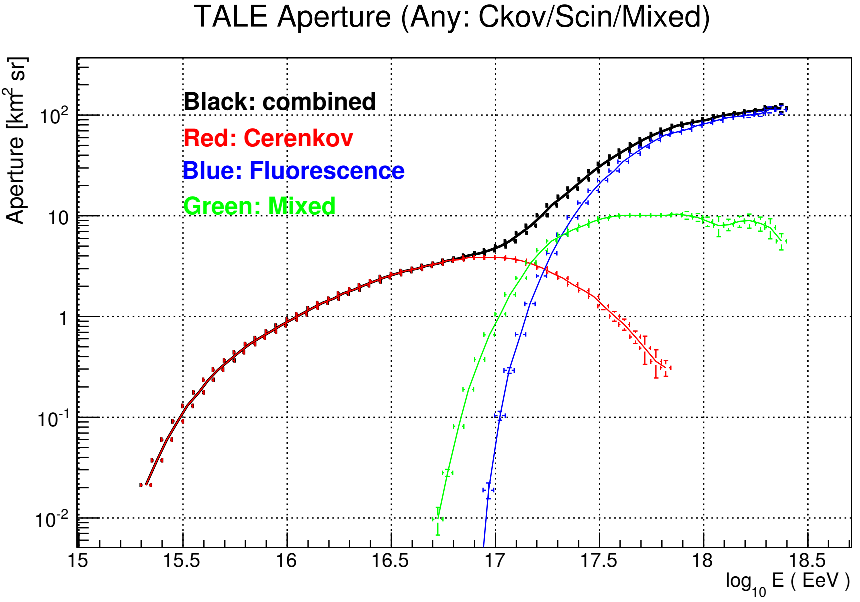
TALE-SD array : 80 SDs (Feb. 2018 ~)

Nearby Events with Cerenkov







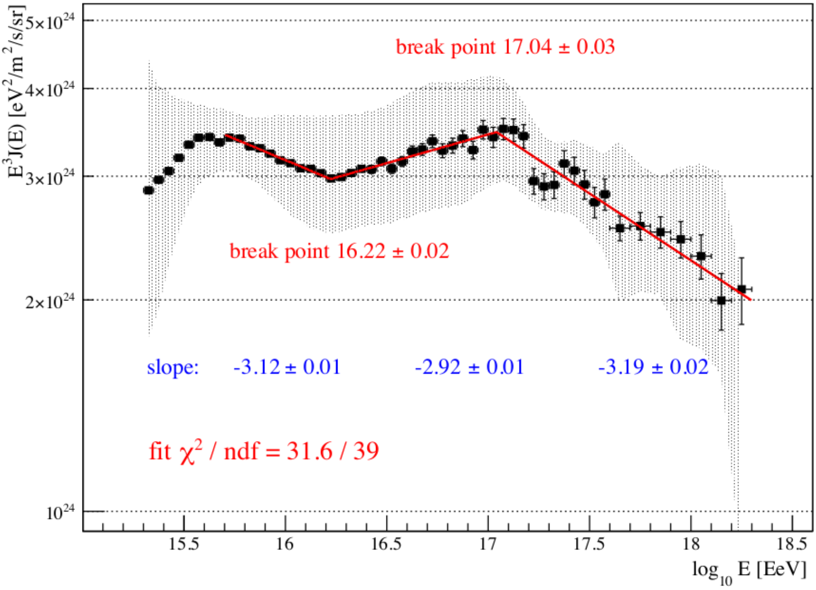


TALE Aperture (Any: Ckov/Scin/Mixed)
Black: combined
Red: Cerenkov
Blue: Fluorescence
Green: Mixed
Aperture [km^2 sr]
10^{-2}
10^{-1}
1
10
10^2
15
15.5
16
16.5
17
17.5
18
18.5
$\log_{10}$ E (EeV)

TALE-FD mono spectrum(2yrs)

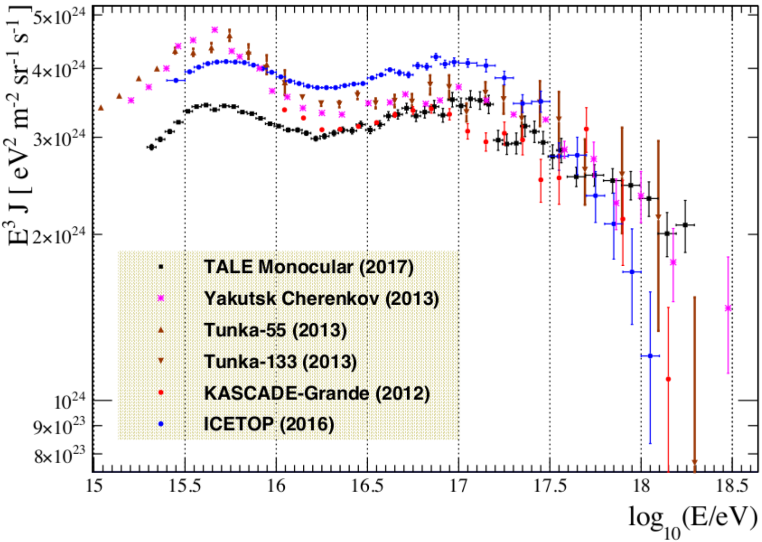
Data: Jun. 2014 - Mar. 2016

Submitted to Astroparticle physics
arXiv: 1803.01288



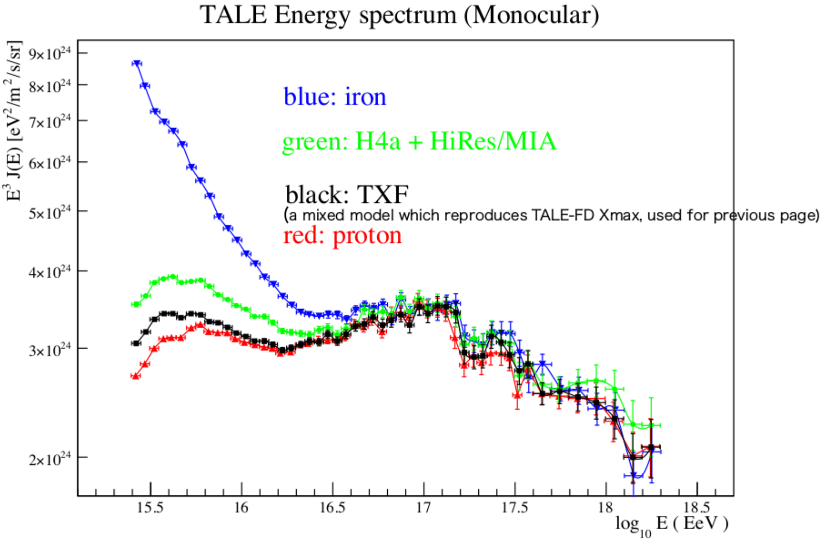
Compared to recent measurements

Submitted to Astroparticle physics
arXiv: 1803.01288



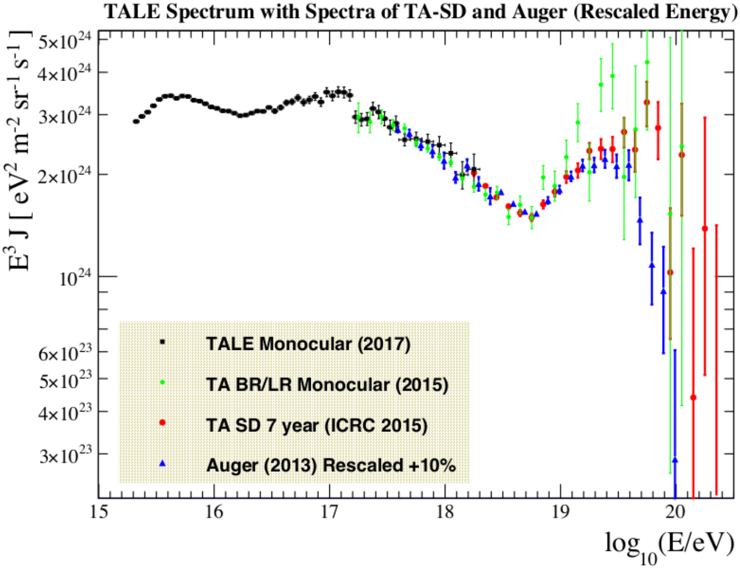
Exposure depends on composition

Submitted to Astroparticle physics
arXiv: 1803.01288



Full range TA spectrum

Submitted to Astroparticle physics
arXiv: 1803.01288



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TA SD data

9-year data: 12.05.2008 – 11.05.2017

"anisotropy set"

- zenith angle <55°
- core inside array boundary
- angular resolution: <1.5°
- energy resolution: ~20%

- 3691 above 10 EeV
- 257 above 40 EeV
- 108 above 57 EeV

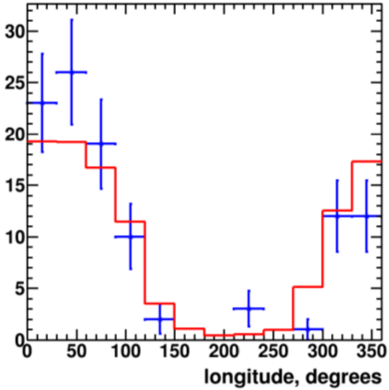
"hotspot set"

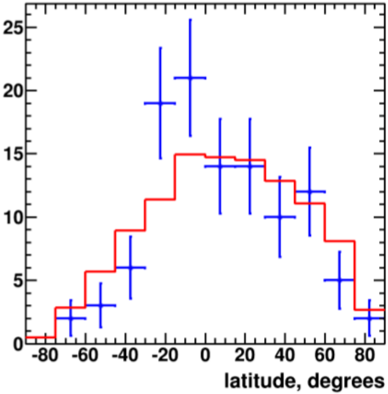
- loose cuts (4 stations)
- angular resolution: <1.7°

- 143 above 57 EeV
- 23 above 100 EeV

Global anisotropy

supergalactic coordinates

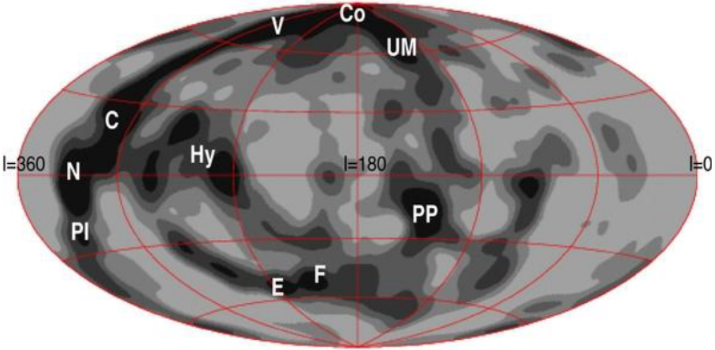




Kolmogorov-Smirnov p-value = 0.01 for SG latitude, E>57 EeV

other thresholds/coordinates = isotropic

Large-Scale Structure

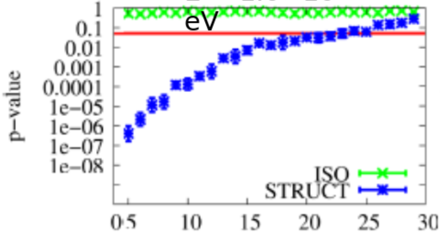


C: Centaurus SCl (60 Mpc); Co: Coma Cl (90 Mpc); E: Eridanus Cl (30 Mpc); F: Fornax Cl (20 Mpc); Hy: Hydra SCl (50 Mpc); N: Norma SCl (65 Mpc); PI: Pavo-Indus SCl (70 Mpc); PP: Perseus-Pisces SCl (70 Mpc); UM: Ursa Major Cl (20 Mpc); and V: Virgo Cl (20 Mpc).

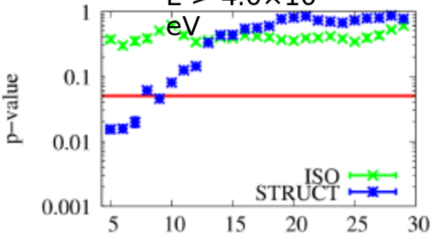
- **Sky map of expected flux at *E* > 57 EeV (Galactic coordinates)**;
- smearing angle is 6°.

Large-Scale Structure

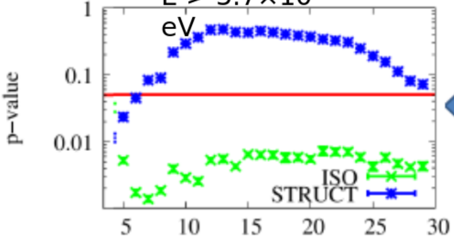
E > 1.0×10^{19} eV



E > 4.0×10^{19} eV



E > 5.7×10^{19} eV

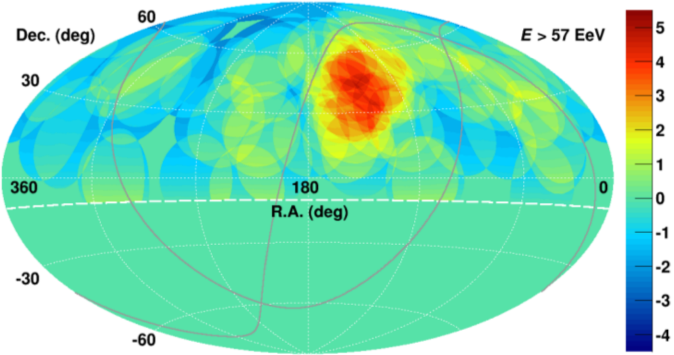


E>5.7×10^{19} eV
Consistent with LSS
Inconsistent with isotropy

Hot spot

E>57 EeV - Years 1-5 excess map

TA 2014



Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7°, Dec=+43.2°
Best circle radius: 20°
Local significance : 5 σ
Global significance : 3 σ

Hot spot

Years 1-9 bin scan

TA very preliminary

"Li-Ma":
approximation to Poisson statistics based on on-source/off-source exposure

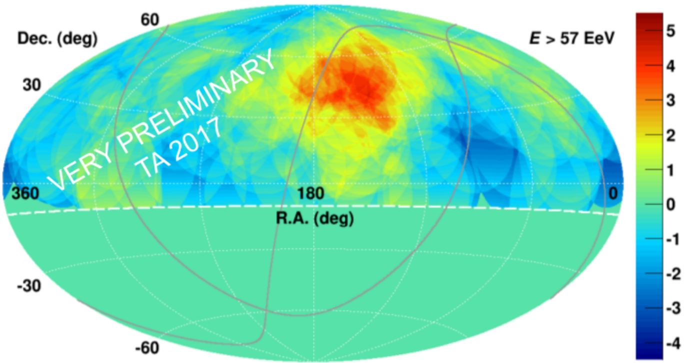
- "On": inside the circle, "off": the rest
- Scan for circle center (0.1 deg steps) and radius (15^o, 20^o, 25^o, 30^o, 35^o)

Bin size	15	20	25	30	35
σ	4.4	4.7	5.1	5.0	4.7

- Find the strongest excess ⇨ local significance
- Repeat the procedure for isotropic Monte-Carlo sets ⇨ global significance (look-elsewhere correction = penalty factor)

Hot spot

E>57 EeV - Years 1-9 excess map

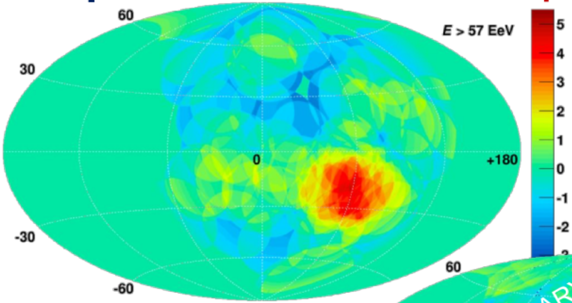


Total events: 143
Observed: 34
Expected : 13.5

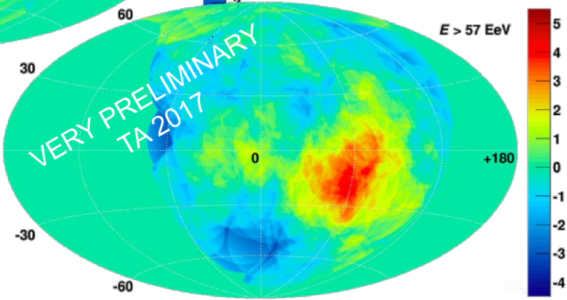
Best circle center: RA=144.3°, Dec=+40.3°
Best circle radius: 25°
Local significance : 5 σ
Global significance : 3 σ

Hot spot

Supergalactic coordinates

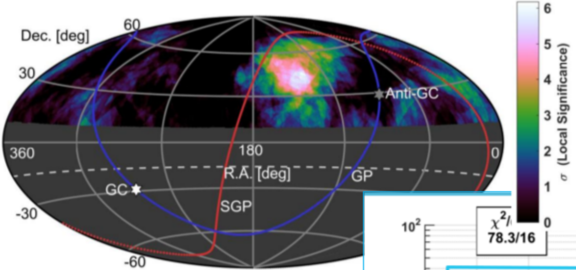


years 1-5
20° circles

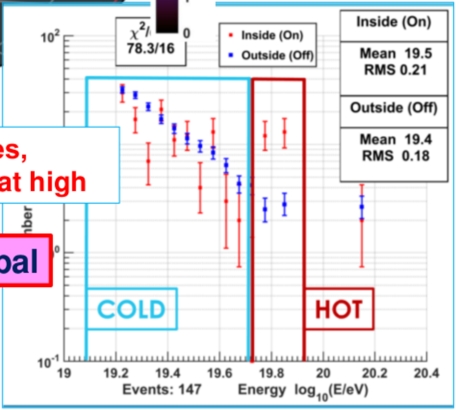


years 1-9
25° circles

Spectral anisotropy at the hot spot



$E \geq 10^{19.2}$ eV



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

3.7σ global

arXiv:1803.01288

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UHECR $\gtrsim 10^{18}$ eV composition measurements

Experiment	detector	Observable
HiRes	fluorescence stereo	X_{MAX}
Pierre Auger	fluorescence + SD (hybrid)	X_{MAX}
Telescope Array	stereo	X_{MAX}
Telescope Array	hybrid	X_{MAX}
Telescope Array	SD	multiple
Yakutsk	muon	ρ_μ
Yakutsk	LDF slope	η
Pierre Auger	SD	X^{μ}_{MAX}
Pierre Auger	SD	risetime asymmetry

SD – surface detector

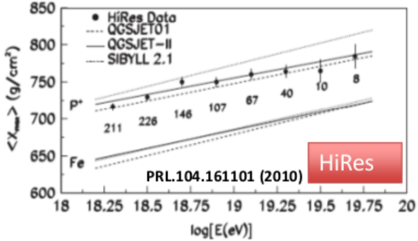
X_{MAX} *– depth of the shower maximum*

X^{μ}_{MAX} *– muon production depth*

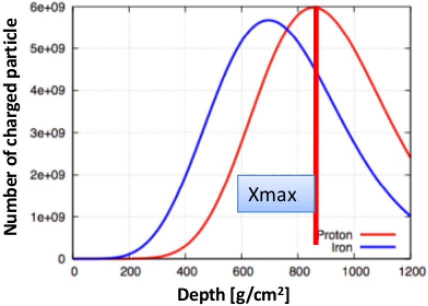
risetime – time from 10% to 50% for the total integrated signal

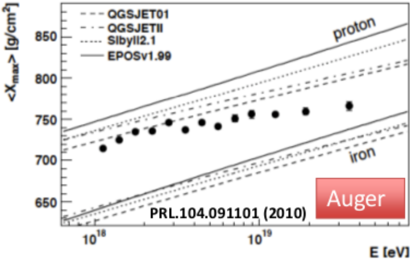
Xmax Technique

- Shower longitudinal development depends on primary particle type.
- FD observes shower development directly.
- Xmax is the most efficient parameter for determining primary particle type.



Shower longitudinal development

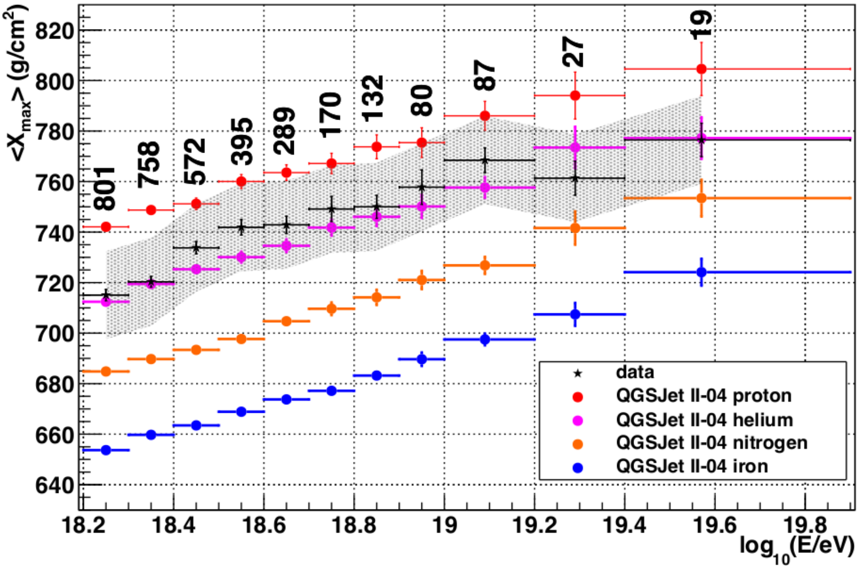




<Xmax> plot: BRM-LR hybrid

Data: 27 May 2008 - 29 Nov. 2016

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



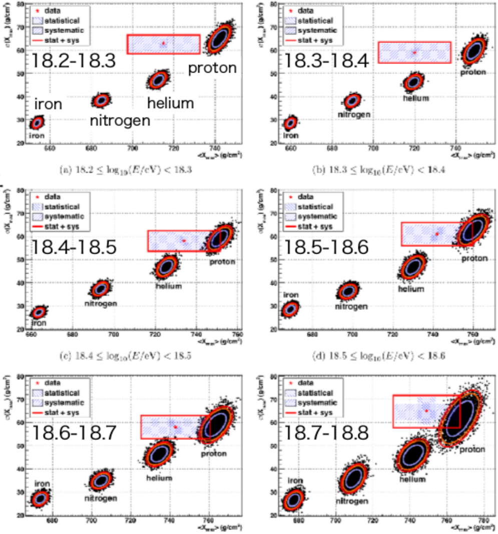
$\langle X_{max} \rangle$-$\sigma_{X_{max}}$ plot: BRM-LR hybrid

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

Compare Data and MC using both $\langle X_{max} \rangle$ and width of distribution($\sigma_{X_{max}}$)

- Data : rectangles
- MC: contours
  Repeating 5,000 sets of MCs
  (Each set = the same # of events, 4 primary types)

In lower energies, log E < 18.8, allowing 10-20g/cm² shifts, Data points looks like "proton".



(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) $18.5 \le \log_{10}(E/\mathrm{eV}) < 18.6$
(e) $18.6 \le \log_{10}(E/\mathrm{eV}) < 18.7$
(f) $18.7 \le \log_{10}(E/\mathrm{eV}) < 18.8$

Systematic uncertaiinty
$\langle X_{max} \rangle$: 17.4g/cm²
$\sigma_{X_{max}}$: 21.2g/cm²

Shape of Xmax distributions: BRM-LR hybrid

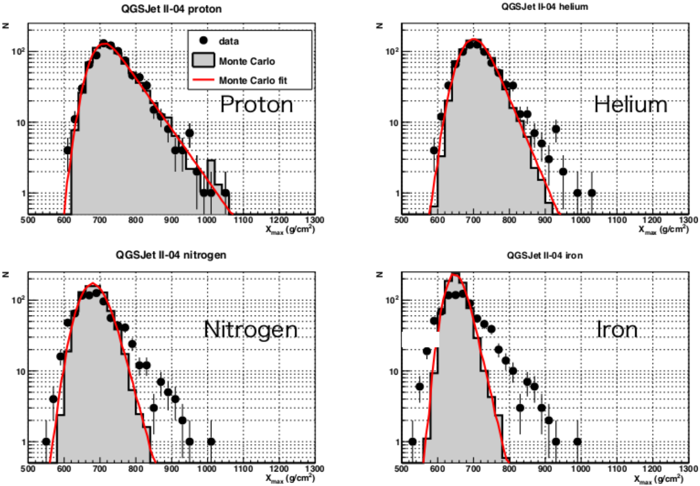
Compare shape of X_{max} distributions of Data and MC allowing Xmax shift

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

Xmax shift
proton : +29g/cm^2
He : +7g/cm^2
N : -21g/cm^2
Fe : -43g/cm^2

Systematic uncertaiinty
<Xmax> : 17.4g/cm^2

$18.2 < \log(E/eV) < 18.3$



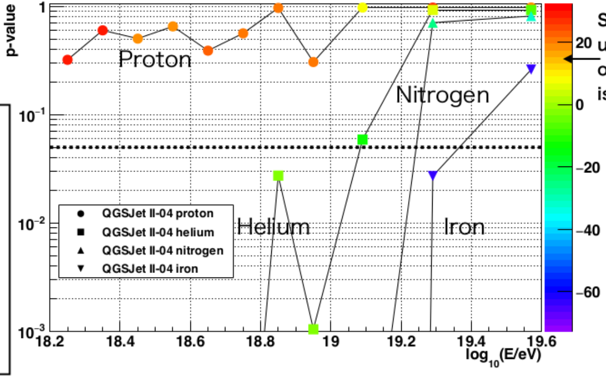
<Xmax> plot: BRM-LR hybrid

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

We cannot reject protons as being compatible with the data for all energy
(Best fit Xmax shifts are slightly larger than 17.2 g/cm^2)

For helium, the shapes of the data and Monte Carlo do not agree for $\log_{10}(E/eV) < 19.0$
(Best fit Xmax shifts are smaller than protons)

Color of the markers indicate best-fit shift of Xmax

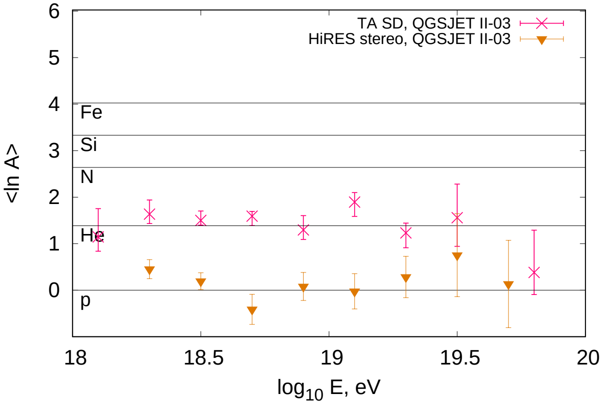


Systematic uncertainty of <Xmax> is 17.2 g/cm^2

In $E > 10^{19.2}$ eV, data with current statistics is not capable of discriminating primary types.

Not tested with mixed composition

Alternative technique: mass composition with the surface detector data



Outline

Selected Telescope Array results on the ultra-high-energy cosmic rays:

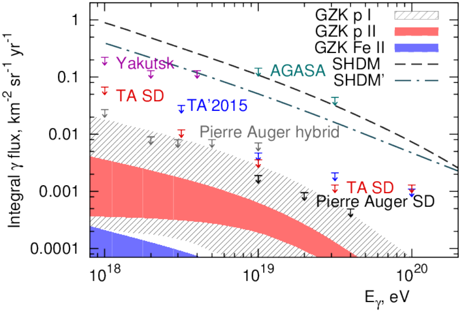
- I. Energy spectrum
- II. Anisotropy
- III. Mass composition
- **IV. Search for photons and neutrino**
- V. Prospects

Search for ultra-high-energy photons and neutrino

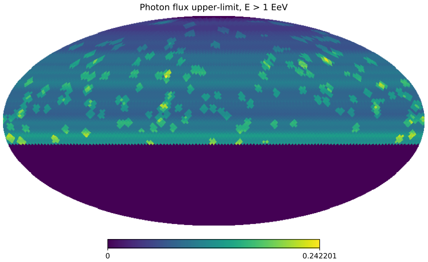
- We search for photons and neutrino with the surface detector data
- Both primaries produce younger showers than hadronic ones
- Multiple SD observables are affected: **front curvature, Area-over-peak, number of FADC signal peaks,** $\chi^2/d.o.f.$**,** S_b

See the talk by Mikhail Kuznetsov (this session)

Results: photon flux limits



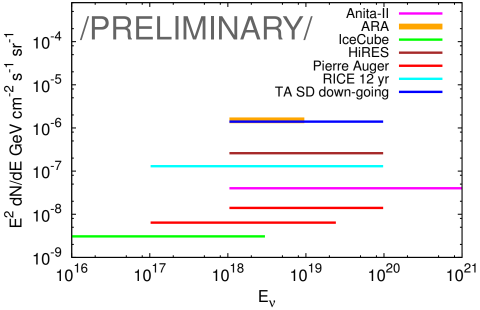
diffuse flux



point source flux

Diffuse neutrino search

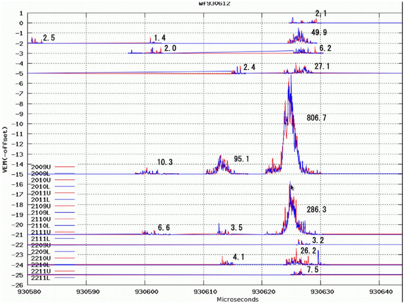
- Single flavor diffuse neutrino (down-going) flux limit for $E > 10^{18}$ eV:
  $E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$ (90% C.L.)

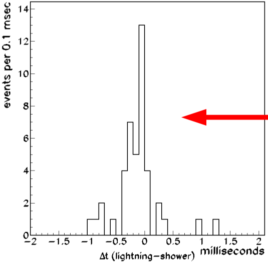


G.Rubtsov, ICRC'2017

Plot: T. Okuda

TA Observation: “Burst” Events





- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, Δt < 1 msec
  - Occasional Δt ~ 10 μsec
- “Normal” SD trigger rate < 0.01 Hz. *These cannot be cosmic ray air showers*.
- Found to have close time/space coincidence with *U.S. National Lightning Detection Network* (NLDN) activity.
- Abbasi et al. *Phys. Lett.* **A 381** (2017).

Lightnings produce EM showers: some are misidentified as photons

Outline

Selected Telescope Array results on the ultra-high-energy cosmic rays:

- I. Energy spectrum
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- IV. Search for photons and neutrino
- **V. Prospects**

Prospects

Telescope Array Observatory is under major upgrade after 10 years of successful operation.

New hardware will be accompanied with up-to-date analysis techniques.

- Detector
  - TAx4 construction
  - TALE SD operation
- Analysis
  - Machine learning techniques are widely adopted

TA×4

TA SD (~3000 km²): Quadruple area

Approved by Japanese government 2015

500 scintillator SDs

2.08 km spacing

3 yrs construction, first 180 SDs have arrived in Utah

Next 60 SDs to be prepared at ICRR and SKKU in 2018 and shipped to Utah

2 FD stations (12 HiRes-II telescopes)

Approved by US NSF 2016

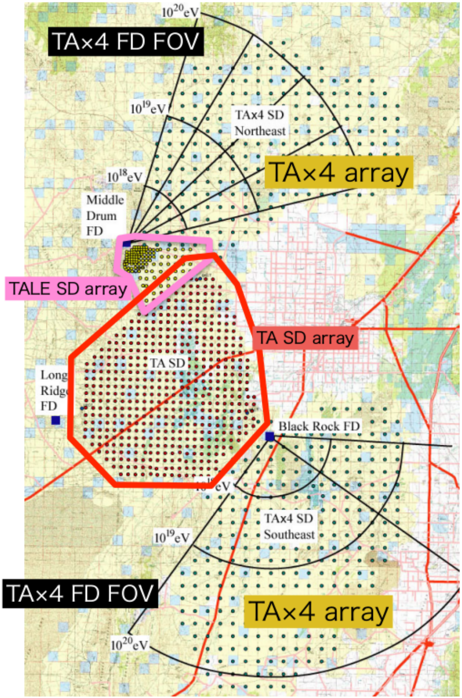
Telescopes/electronics being prepared at Univ. of Utah

First light at the northern station!

Site construction underway at the southern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data



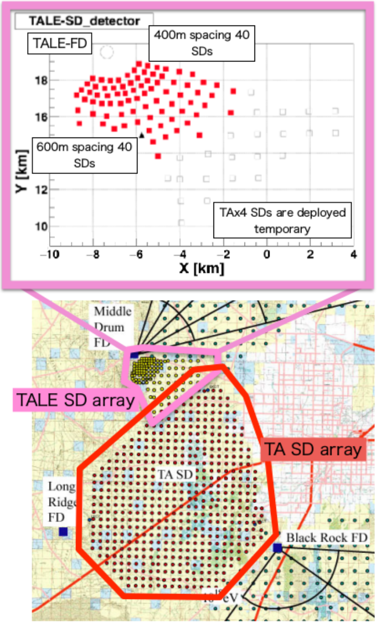
TALE hybrid


Middle Drum station
TALE FD station


TALE FDs


TALE SDs prepared for deployment

TALE hybrid



Low energy extension of TA sensitivity :

FDs observing higher elevation

Densely-arrayed SDs

Precise measurement of the composition :

FD + SD hybrid measurement

TALE-FD : 10 telescopes (Sep. 2013 ~)
elevation : 31°~59°, azimuthal : 114°

TALE-SD array : 80 SDs (Feb. 2018 ~)

Expected specifications of TALE hybrid

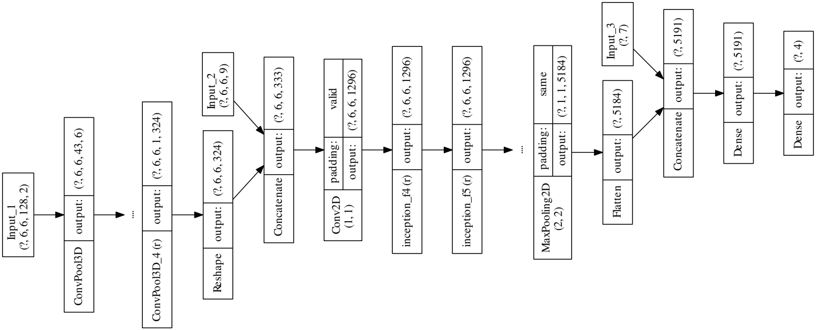
Threshold energy E : logE=16.0

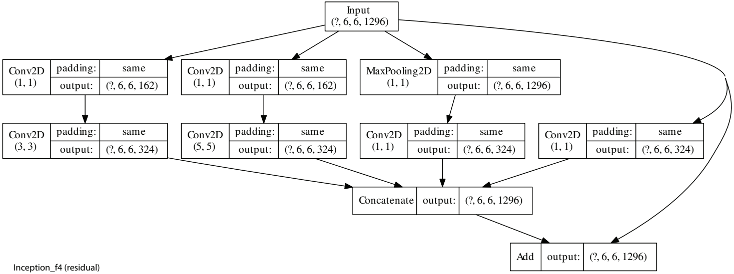
Event rate : ~5,000 events/year

$\Delta\theta$ = 1.0° (FD mono : 5.3°)

ΔXmax = 20 g/cm^2 (FD mono : 60g/cm^2)

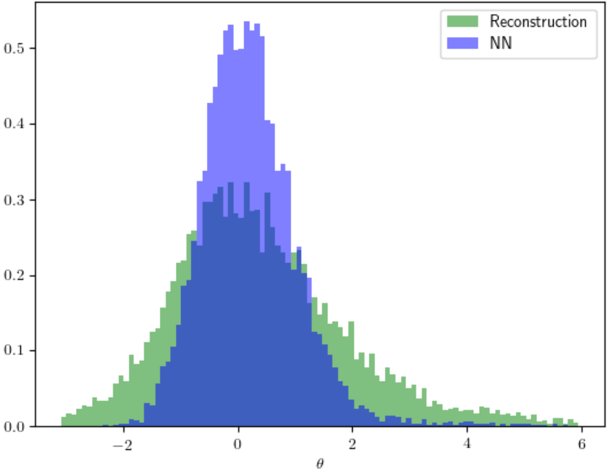
Event reconstruction with the convolutional neural network





Inception_f4 (residual)

/PRELIMINARY/ angular resolution with machine learning



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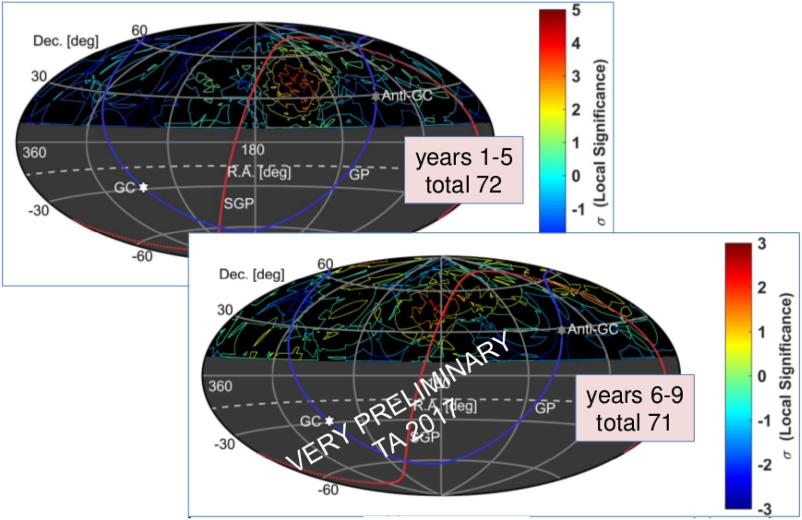
Thank you for attention!

Backup slides

Hot spot

Years 6-9 vs. 1-5

no hypothesis – no tests



Hot spot

Years 6-9 vs. 1-5

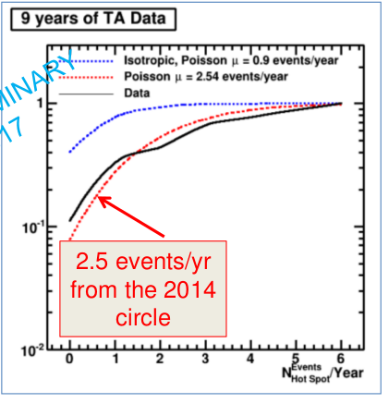
“would-be hypothesis” – “would-be tests”

global ≠ local P-value ➡ positive fluctuation, need to correct our expectations

circle defined in *[TA, ApJ 2014]* = years 1-5:
center RA=146.7°, Dec=+43.2°, radius: 20°

	Years 1-5	Years 6-9
Expected (isotropic)	4.5	3.6
Expected (hot spot)	12.5	10.0
Observed	19	5

VERY PRELIMINARY
TA 2017



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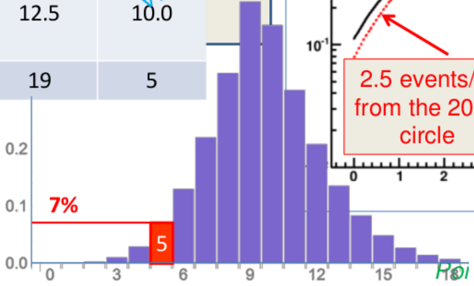
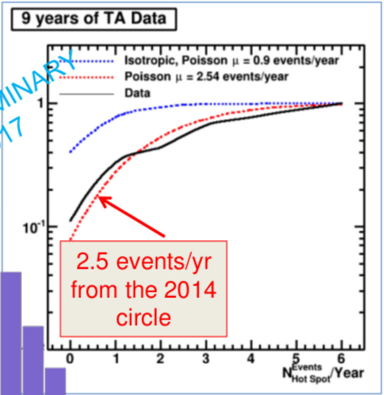
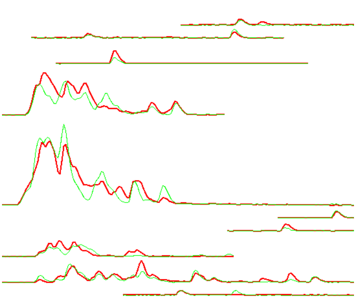
VERY PRELIMINARY TA 2017



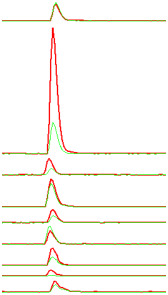


Neutrino search strategy

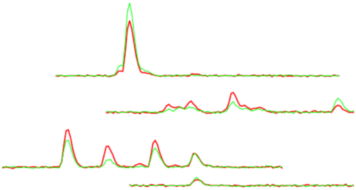
young shower, $\theta = 19.5^\circ$



old shower, 78.3°



neutrino shower, $\theta = 78.6^\circ$



- Neutrino-induced showers are young while very inclined
- Waveform has many peaks

upper layer lower layer

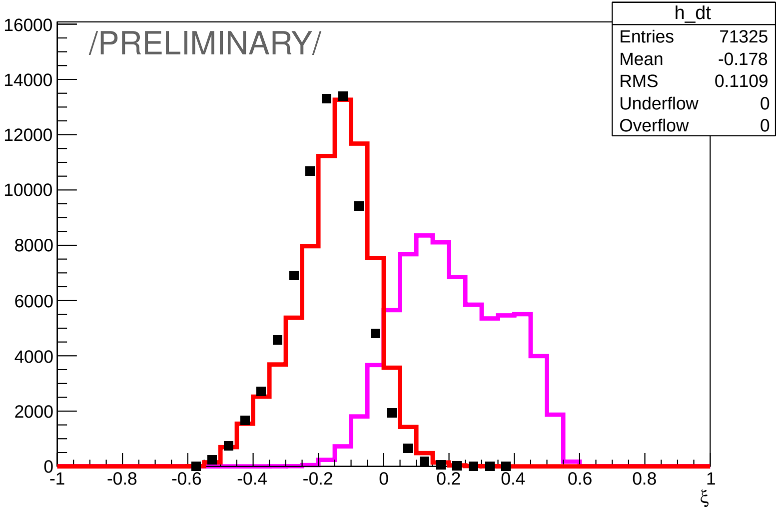
Method

- Cuts:
  - 5 or more detectors triggered
  - core distance to array boundary is larger than 1200m
  - χ^2/d.o.f. < 5
  - $45^\circ < \theta < 90^\circ$
  - no energy cut

197250 events after cuts

- Multivariate analysis is used
  - The set of observables is the same as for photon search (Energy is replaced with S_{800})
  - Method: Boosted decision tree trained with inclined proton (background) and all-flavor down-going neutrino (signal) Monte-Carlo
  - The cut on ξ is optimized in a similar to photon search way

Distribution of MVA estimator (ξ) for data and MC



data neutrino MC proton MC

Results

- 0 neutrino candidates after cuts, $\bar{n}_\nu < 2.44$ (90% C.L.)
- **Exposure:**
  - Geometric exposure for $\theta \in (45^\circ, 90^\circ)$: 8042 $\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$
  - probability to interact in the atmosphere: 1.4×10^{-5}
  - trigger, reconstruction and quality cuts efficiency $\sim 7\%$
  - ξ cut efficiency: $\sim 24\%$
  - total exposure (all flavors): $A = 1.9 \times 10^{-3}\,\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$
- Single flavor diffuse neutrino flux limit for $E > 10^{18}$ eV:
  $E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$ (90% C.L.)