Overview of the Telescope Array Experiment

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Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives, Yukawa Institute for Theoretical Physics, Kyoto University

Introduction

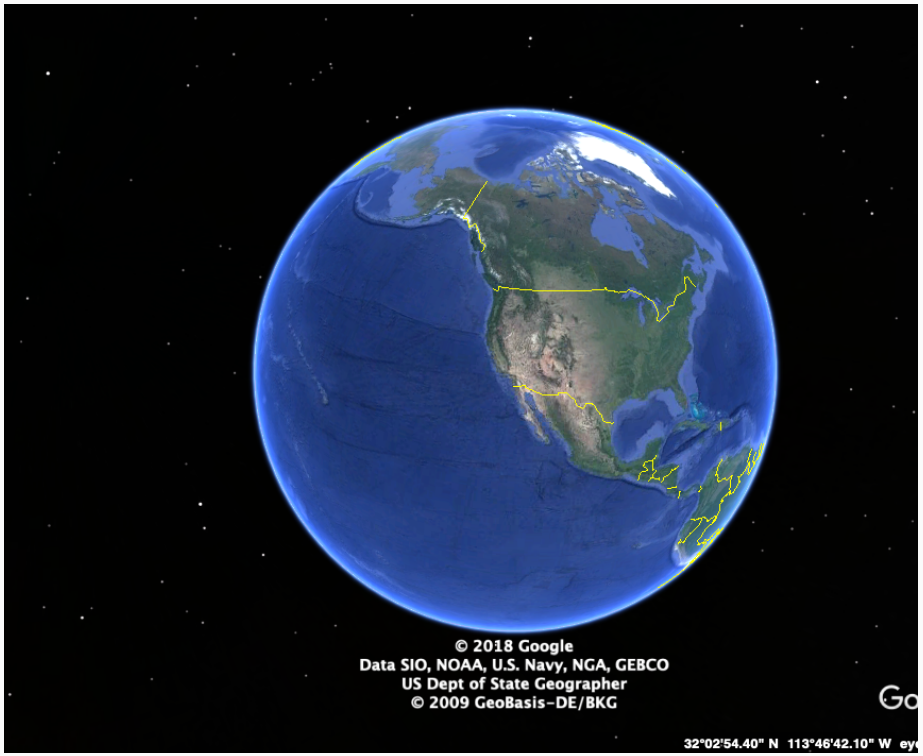
Telescope Array collaboration

R.U. Abbasi, M. Abe, T. Abu-Zayyad, M. Allen, Y. Arai, E. Barcikowski, J.W. Belz, D.R. Bergman, S.A. Blake, R. Cady, B.G. Cheon, J. Chiba, M. Chikawa, T. Fujii, K. Fujisue, K. Fujita, R. Fujiwara, M. Fukushima, R. Fukushima, G. Furlich, W. Hanlon, M. Hayashi, N. Hayashida, K. Hibino, R. Higuchi, K. Honda, D. Ikeda, T. Inadomi, N. Inoue, T. Ishii, H. Ito, D. Ivanov, H. Iwakura, H.M. Jeong, S. Jeong, C.C.H. Jui, K. Kadota, F. Kakimoto, O. Kalashev, K. Kasahara, S. Kasami, H. Kawai, S. Kawakami, S. Kawana, K. Kawata, E. Kido, H.B. Kim, J.H. Kim, J.H. Kim, M.H. Kim, S.W. Kim, Y. Kimura, S. Kishigami, M. Kuznetsov, Y.J. Kwon, K.H. Lee, B. Lubsandorzhiev, J.P. Lundquist, K. Machida, H. Matsumiya, T. Matsuyama, J.N. Matthews, R. Mayta, M. Minamino, K. Mukai, I. Myers, S. Nagataki, K. Nakai, R. Nakamura, T. Nakamura, Y. Nakamura, T. Nonaka, H. Oda, S. Ogio, M. Ohnishi, H. Ohoka, Y. Oku, T. Okuda, Y. Omura, M. Ono, R. Onogi, A. Oshima, S. Ozawa, I.H. Park, M.S. Pshirkov, J. Remington, D.C. Rodriguez, G.I. Rubtsov, D. Ryu, H. Sagawa, R. Sahara, Y. Saito, N. Sakaki, T. Sako, N. Sakurai, K. Sano, K. Sato, T. Seki, K. Sekino, P.D. Shah, F. Shibata, N. Shibata, T. Shibata, H. Shimodaira, B.K. Shin, H.S. Shin, D. Shinto, J.D. Smith, P. Sokolsky, N. Sone, B.T. Stokes, T.A. Stroman, T. Suzawa, Y. Takagi, Y. Takahashi, M. Takamura, M. Takeda, R. Takeishi, A. Taketa, M. Takita, Y. Tameda, H. Tanaka, K. Tanaka, M. Tanaka, Y. Tanoue, S.B. Thomas, G.B. Thomson, P. Tinyakov, I. Tkachev, H. Tokuno, T. Tomida, S. Troitsky, R. Tsuda, Y. Tsunesada, Y. Uchihori, S. Udo, T. Uehama, F. Urban, T. Wong, K. Yada, M. Yamamoto, K. Yamazaki, J. Yang, K. Yashiro, F. Yoshida, Y. Zhezher, and Z. Zundel

Belgium, Czech Republic, Japan, Korea, Russia, USA

Telescope Array experiment

- Largest cosmic ray detector in the Northern Hemisphere
- Located in Utah, USA, at altitude of 1400 m
- 507 surface detectors, $S = 3$ m^2, distance 1.2 km, 700 km^2 total area
- 3 fluorescense stations, 38 telescopes, $3° - 21°$ altitude coverage
- $>$ 12 years of constant data acquisition



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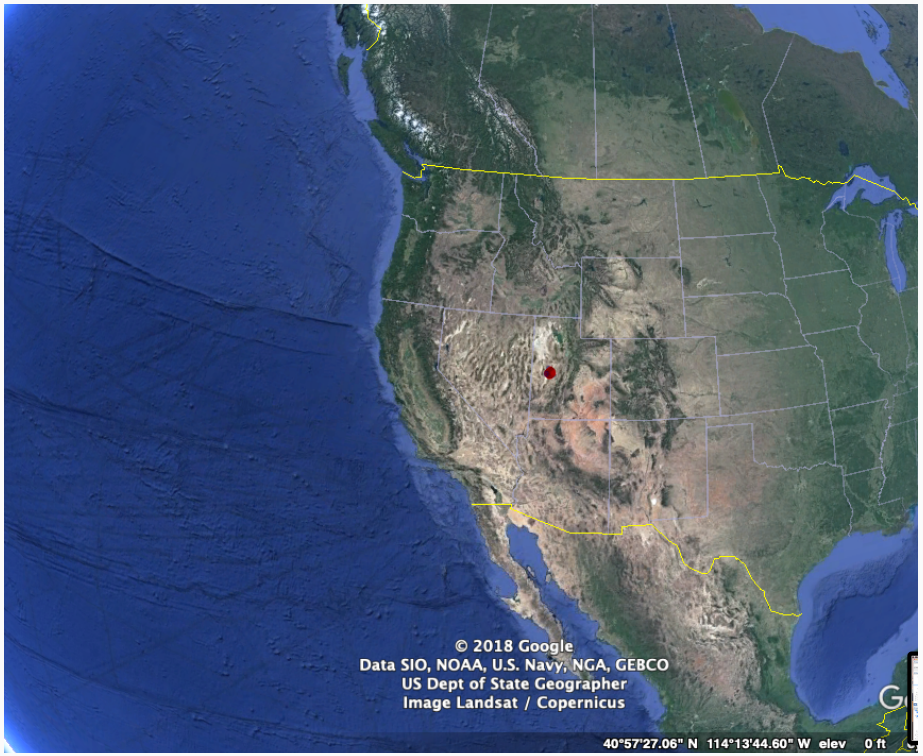

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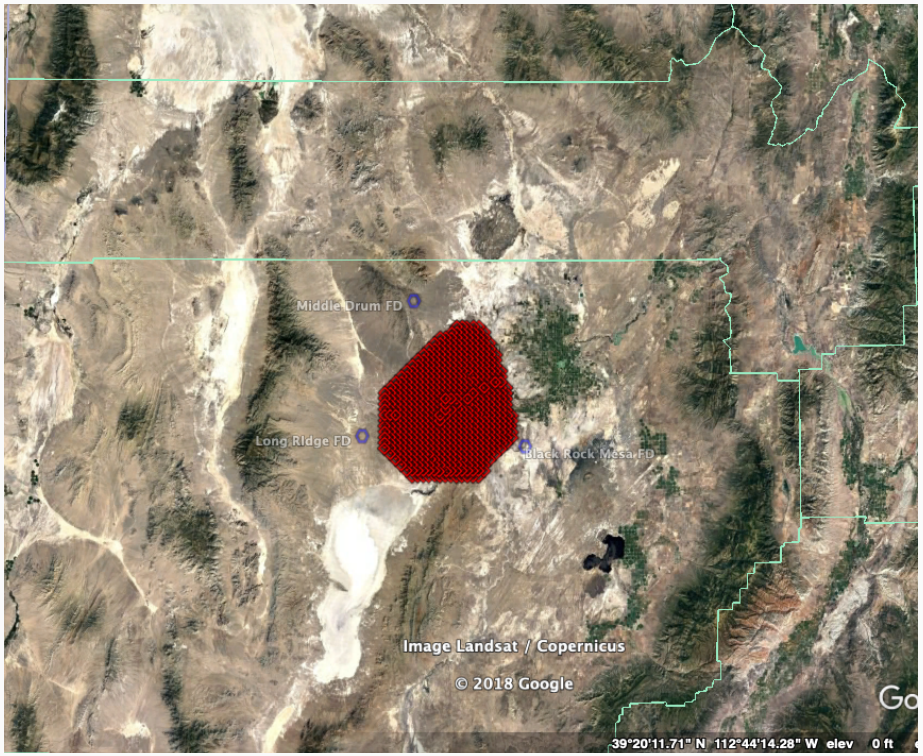

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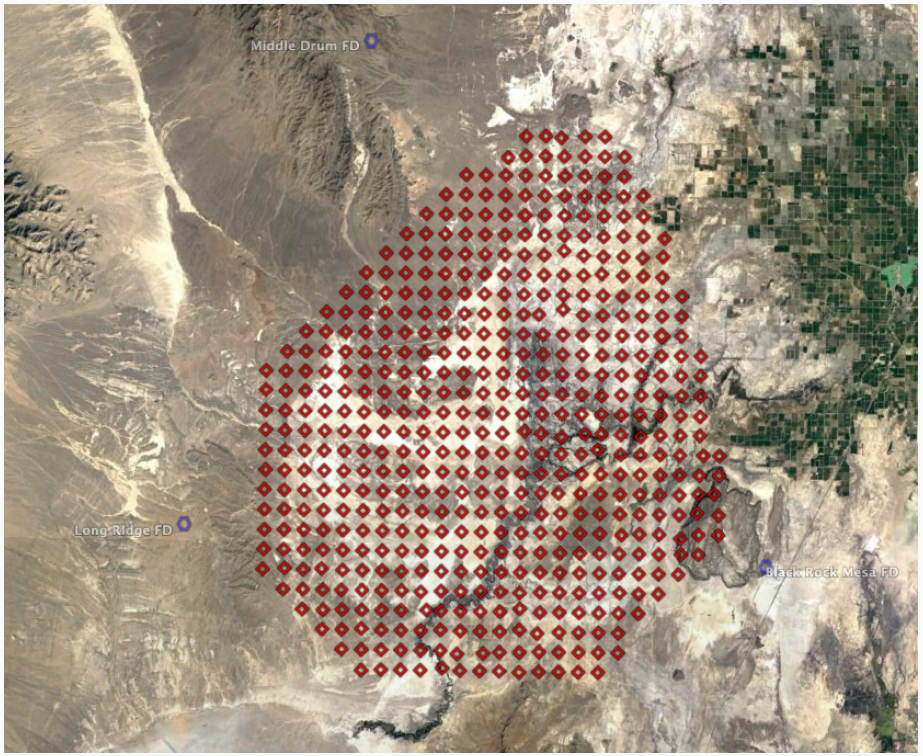

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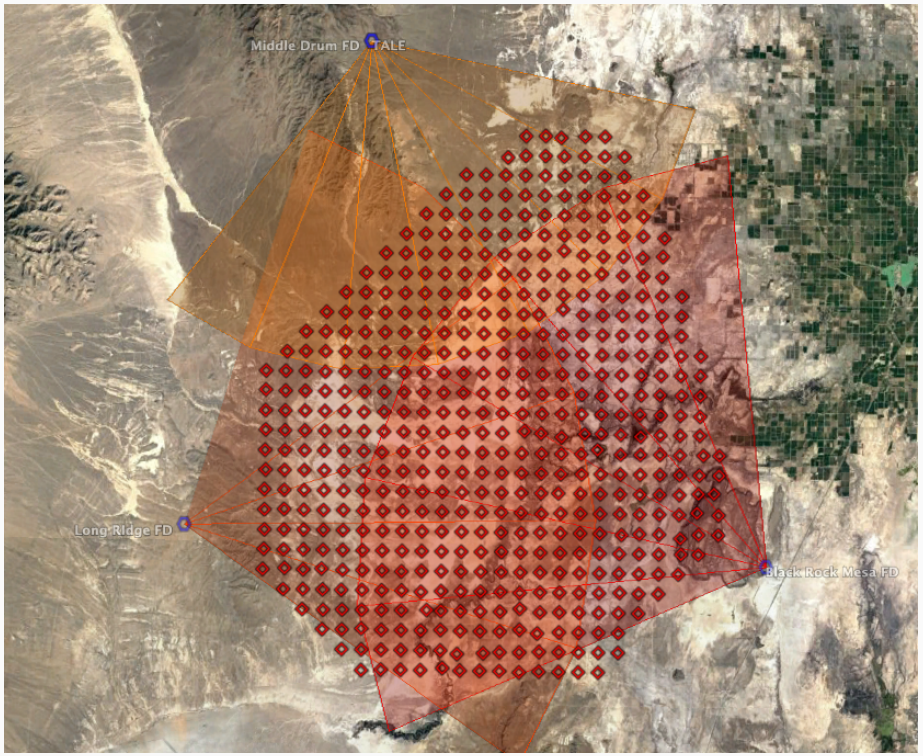
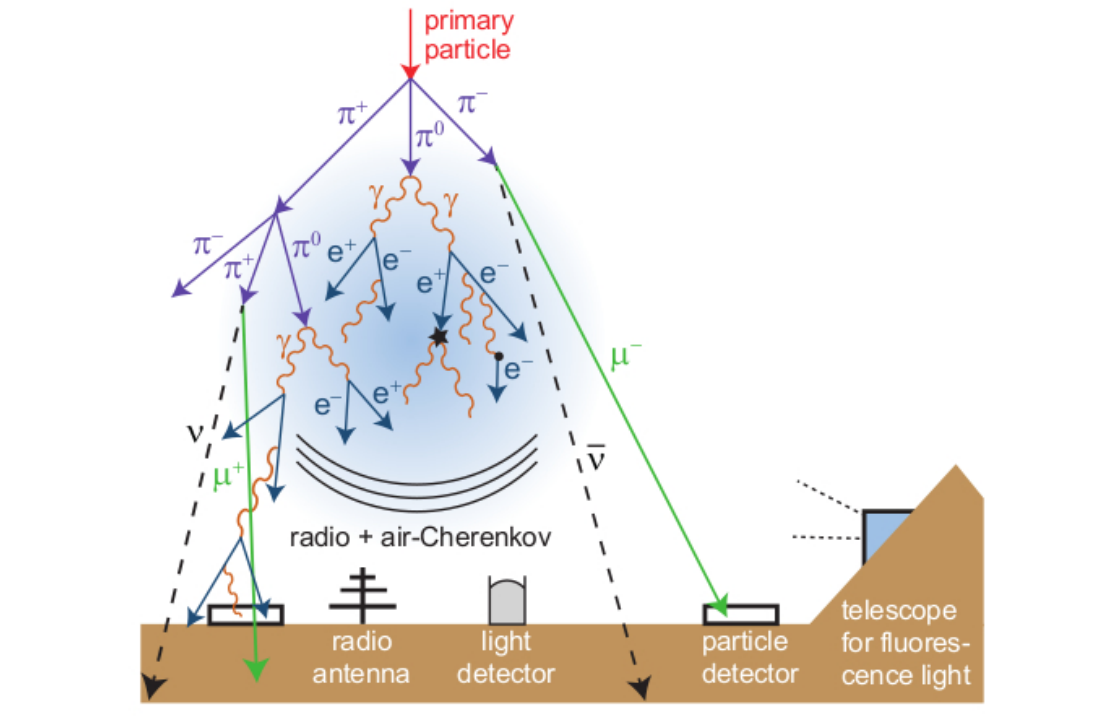


Detection of UHECR



- Fluorescence light: air molecules exitation by a propagating EAS.
- Registration of particle distribution on the ground.
- Radio-emission from the electromagnetic component of a cascade.

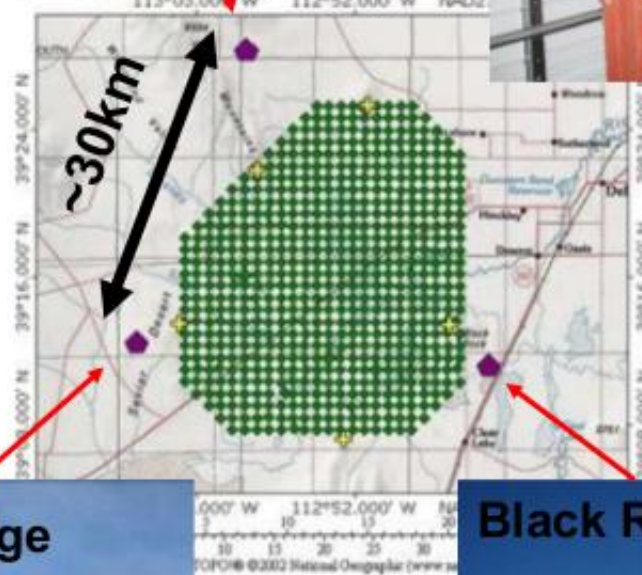
TA Fluorescence Detectors

Middle Drum

14 telescopes @ station
256 PMTs/camera

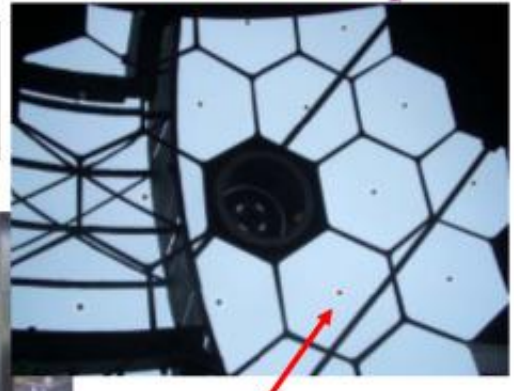
5.2 m^2

Reutilized from HiRes-I



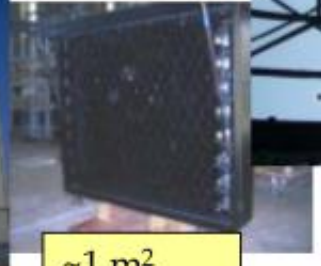
New Telescopes

12 telescopes/station
256 PMTs/camera



Long Ridge

Black Rock Mesa



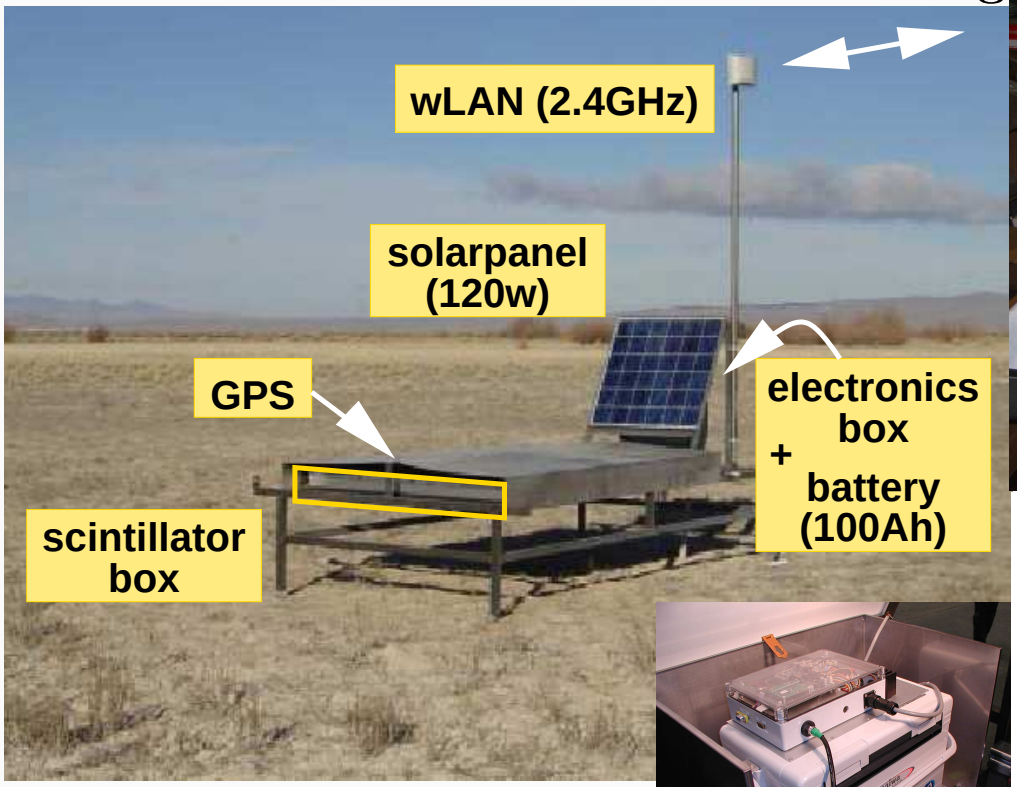
~1 m^2

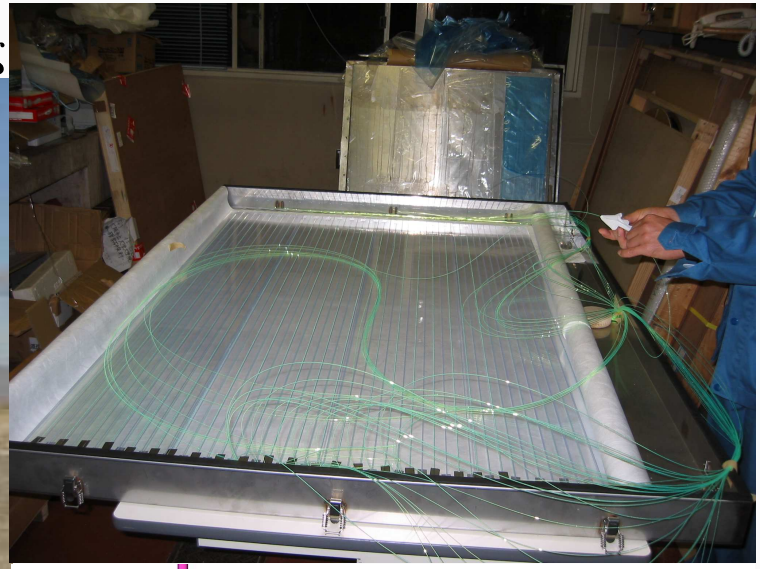
6.8 m^2

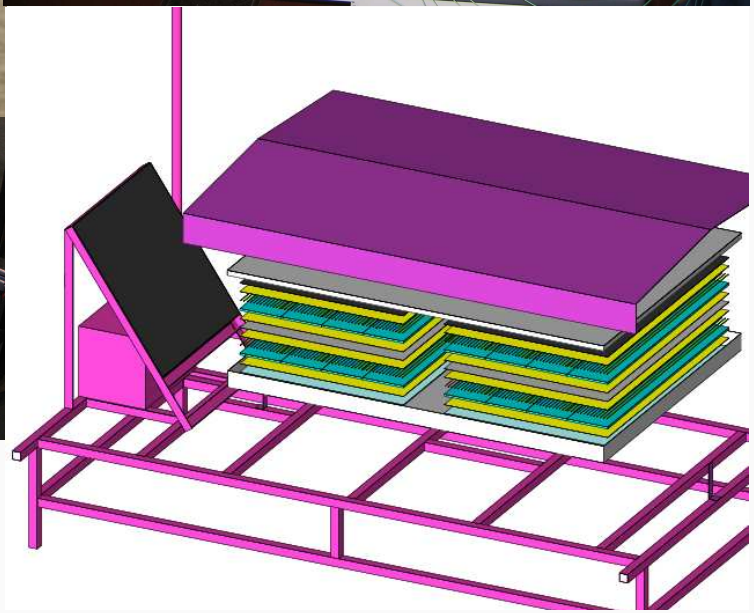
Telescope Array surface detector

< Surface Detector >

~200kg





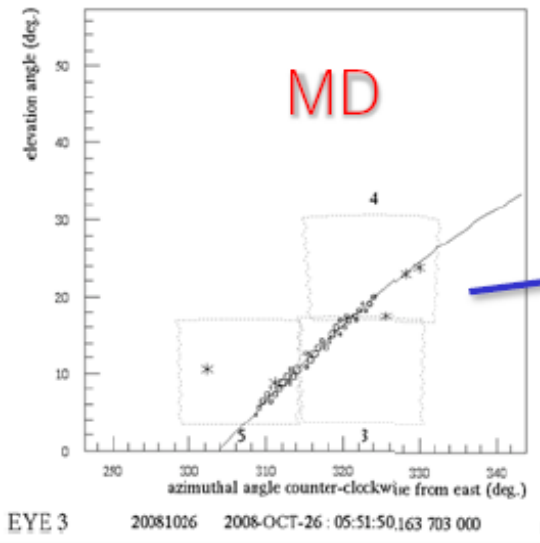


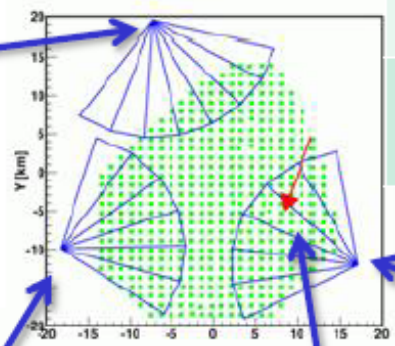
- WLSF: 1.0mmϕ (2cm separation)
- PMTs: ET 9123SA $\times$ 2
- 3m^2 (12mm $\times$ 2 layers)

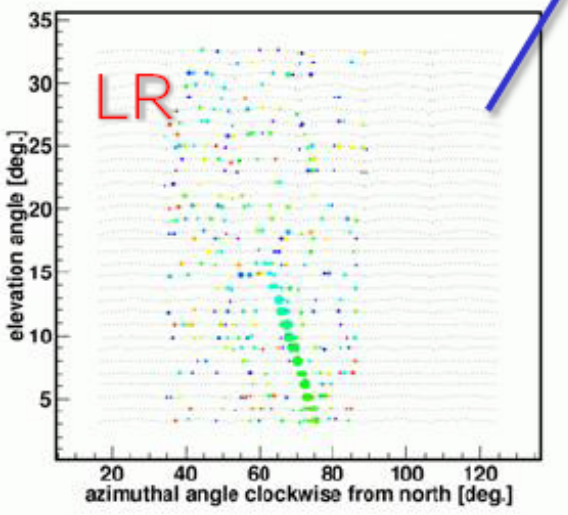
TA hybrid event example

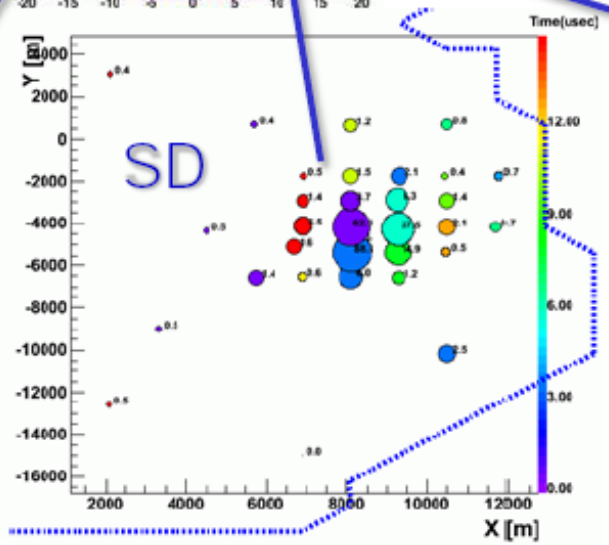
Triple FD Event (2008-10-26)

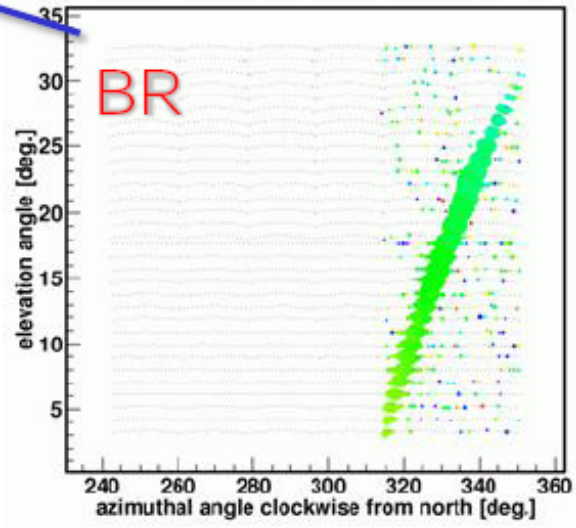
	θ[deg]	ϕ[deg]	X[km]	Y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88









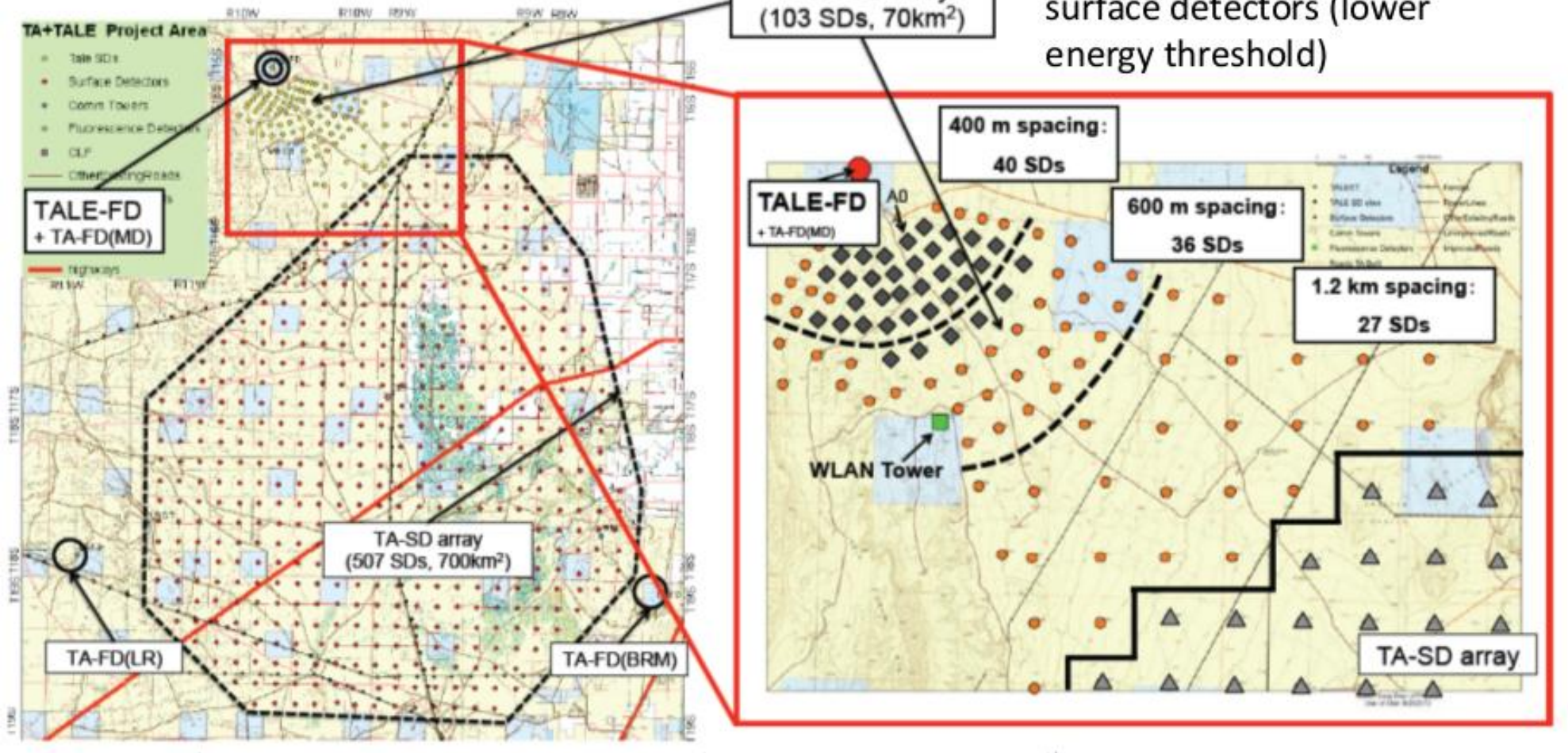


TA Low Energy Extension (TALE)

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)

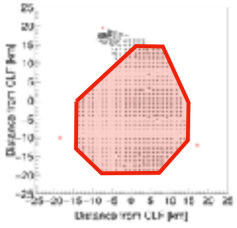


Selected experimental results

Selected TA results

1. Energy spectrum
2. Anisotropy
3. Mass composition
4. Search for UHE photons

TA SD spectrum from 11 years of data



Energy spectrum from 11 years of TA SD data,
from May 11, 2008 to May 11, 2019

γ = -3.28 ± 0.02

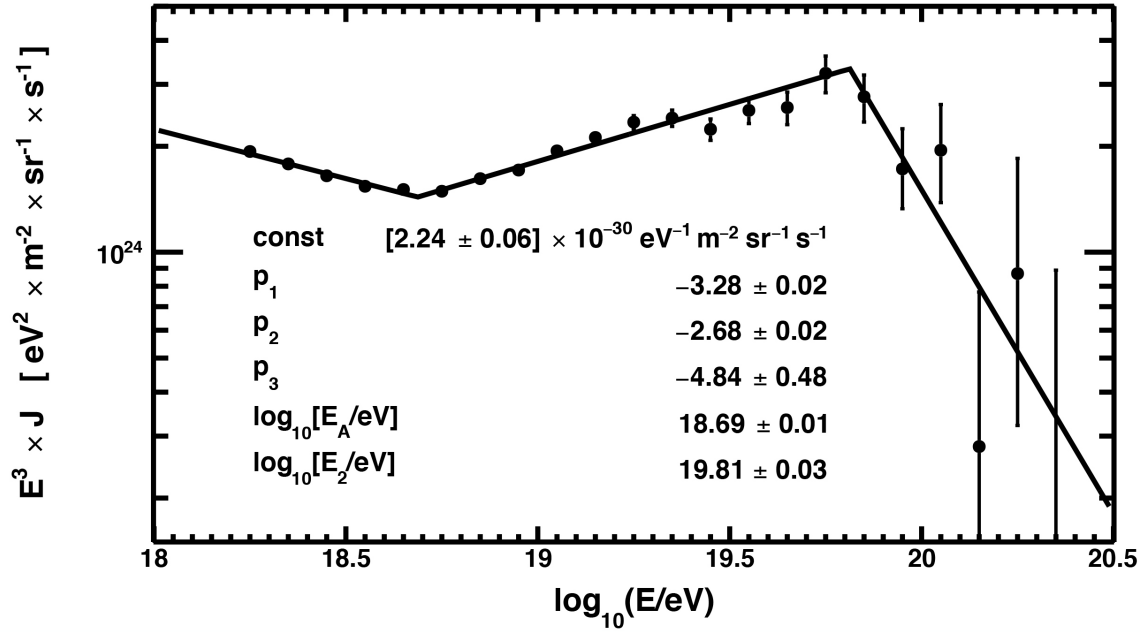
ankle @ logE = 18.69 ± 0.01

γ = -2.68 ± 0.02

cutoff @ logE = 19.81 ± 0.03

γ = -4.84 ± 0.48

logE1/2 = 19.79 ± 0.04
Significance of suppression is 8.4 σ



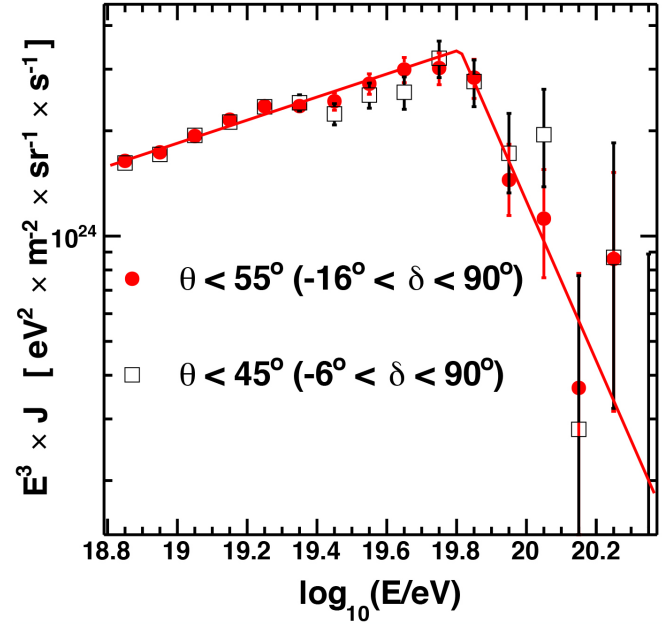
Expanding the zenith angle range
for logE > 18.8 (100 % efficiency)

γ = -2.67 ± 0.02

cutoff @ logE = 19.81 ± 0.03

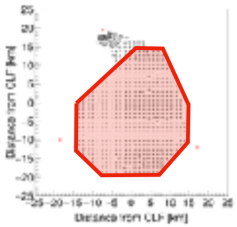
γ = -5.3 ± 0.5

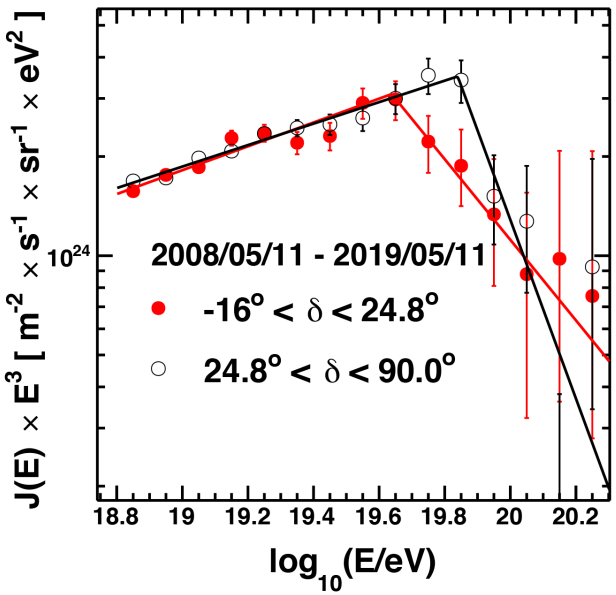
logE1/2 = 19.97 ± 0.04
Significance of suppression is 12.0 σ



Energy resolution = 18 % logE > 19.0
Energy scale systematic uncertainty = 21 %

TA SD spectrum from 11 years of data

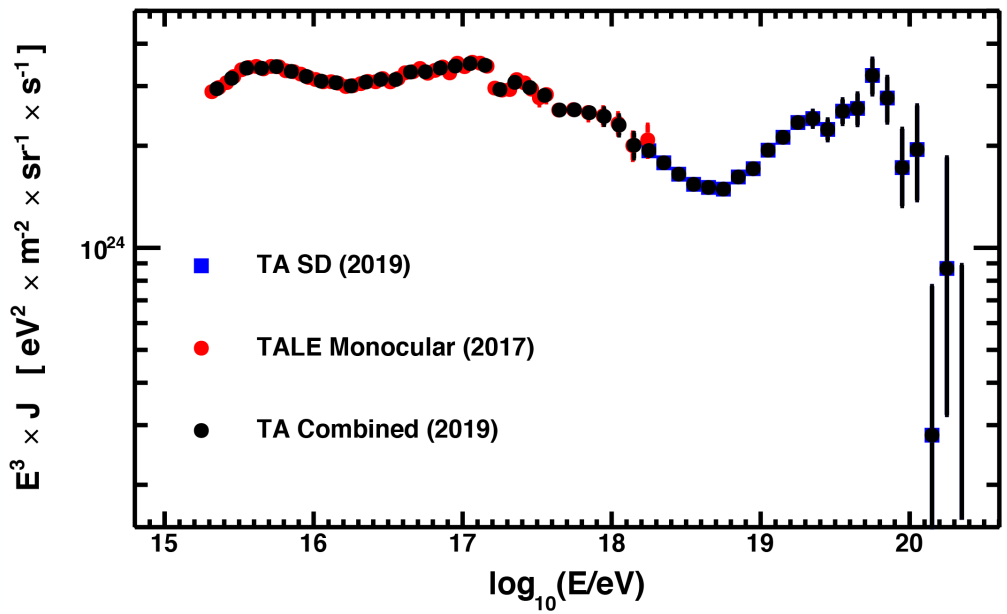




Declination dependence of the TA SD spectrum

The break point of
logE = 19.64 ± 0.04 for lower dec. band (-16° - 24.8°)
logE = 19.84 ± 0.02 for higher dec. band (24.8° - 90°)

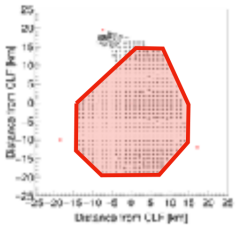
global significance = 4.3σ (local 4.7σ)

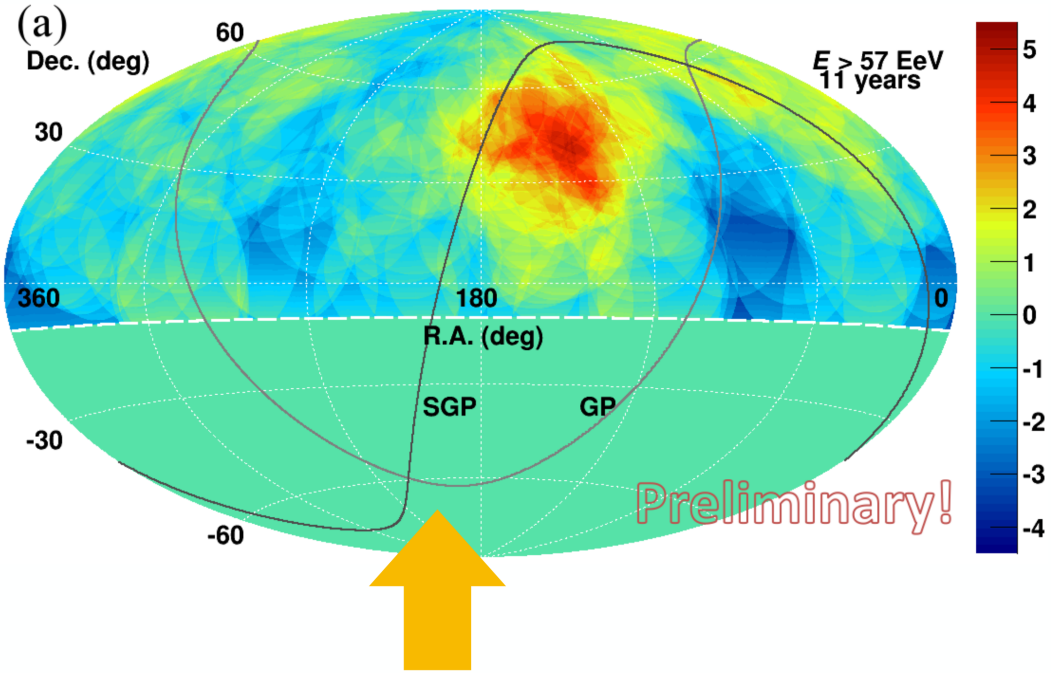


Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

knee @ logE ~ 15.5
low energy ankle @ logE = 16.22 ± 0.02
second knee @ logE = 17.04 ± 0.04
ankle @ logE = 18.69 ± 0.01
cutoff @ logE = 19.81 ± 0.03

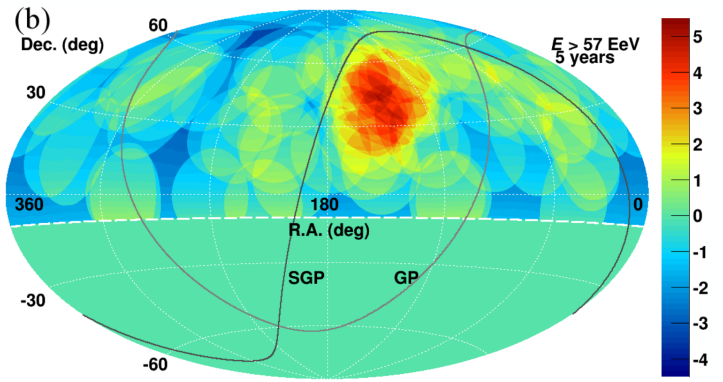
“Hotspot” update from 11 years of data





Original hotspot reported in 2014, from 5 years of data

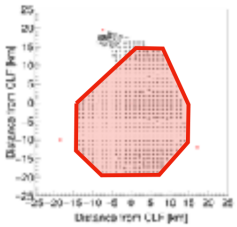
Ap. J., 790, L21(2014)
E > 57 EeV (Observed 72 events)
20° over-sampling circle
19 events fall in “Hotspot” centered at (146.7°, 43.2°)
(Expected = 4.5 events)
local significance 5.1σ, post trial significance 3.4σ



Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

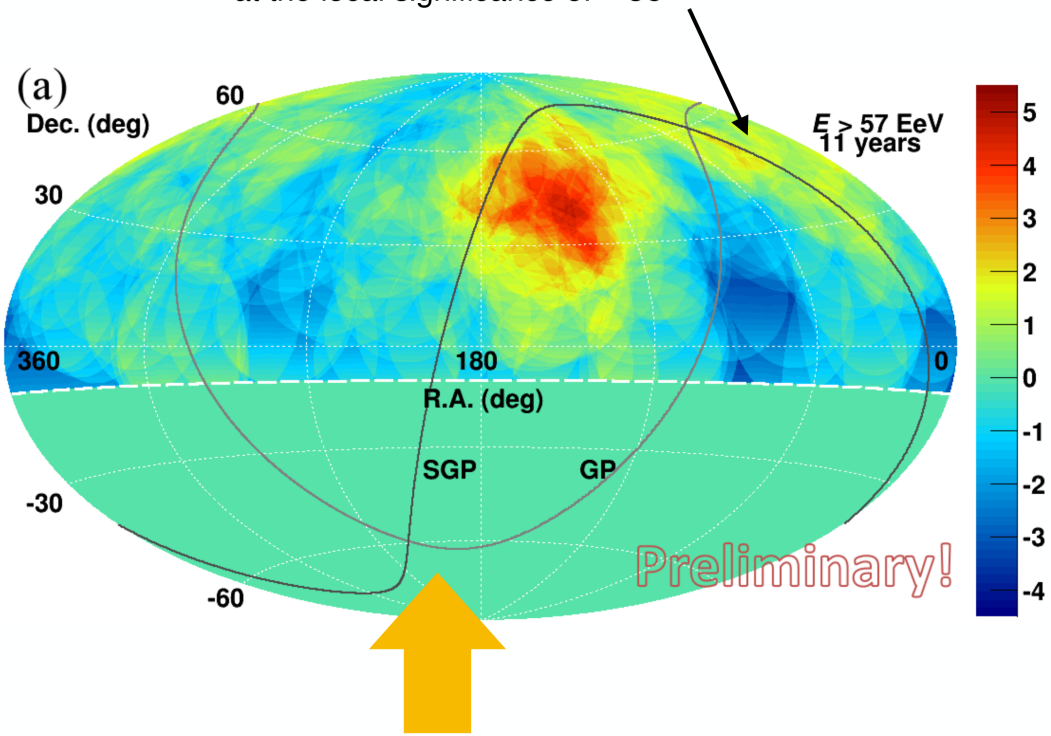
E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)

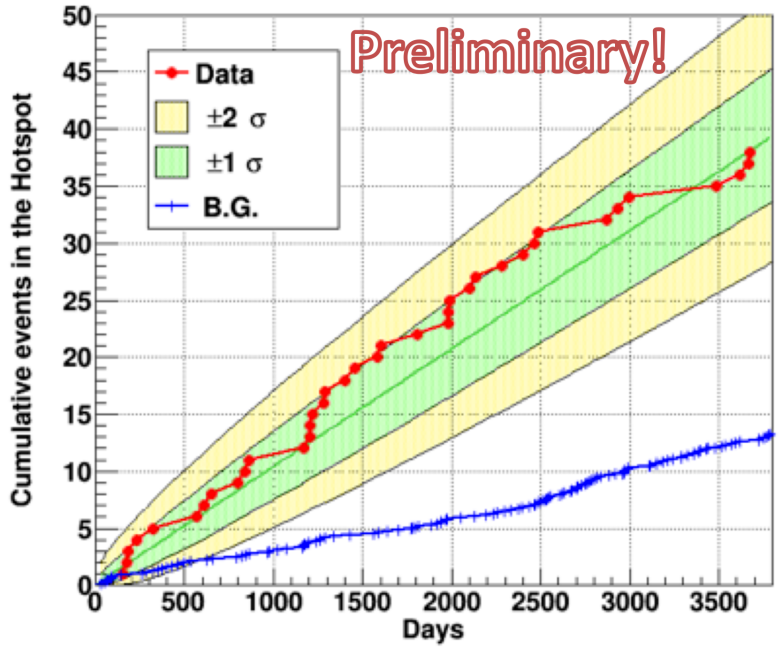
“Hotspot” update from 11 years of data



There is a marginal excess is seen along the SGP (around the Perseus-Pisces Supercluster) at the local significance of ~ 3σ

The increase rate of the events inside the hotspot circle is consistent with a constant within ±1σ fluctuation





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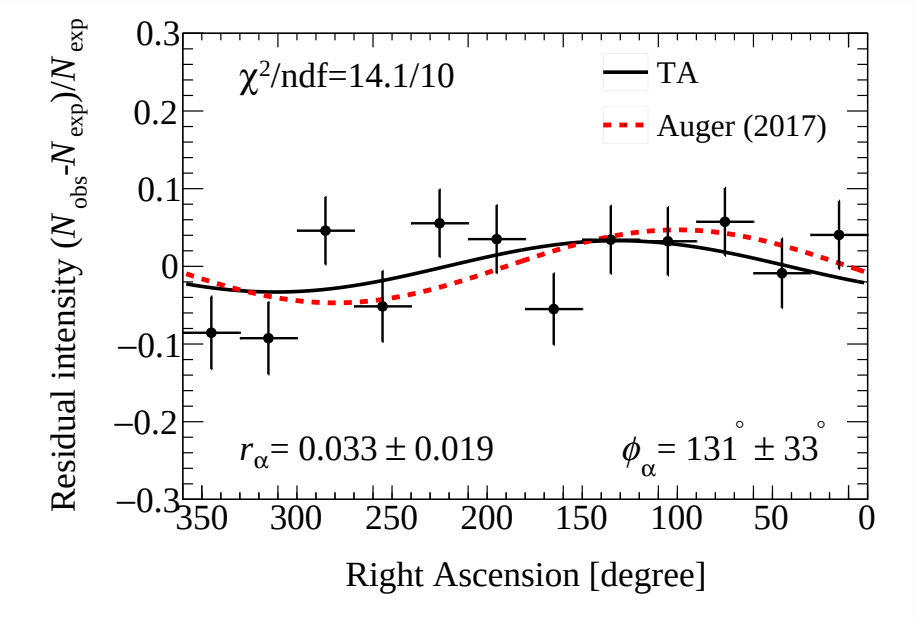
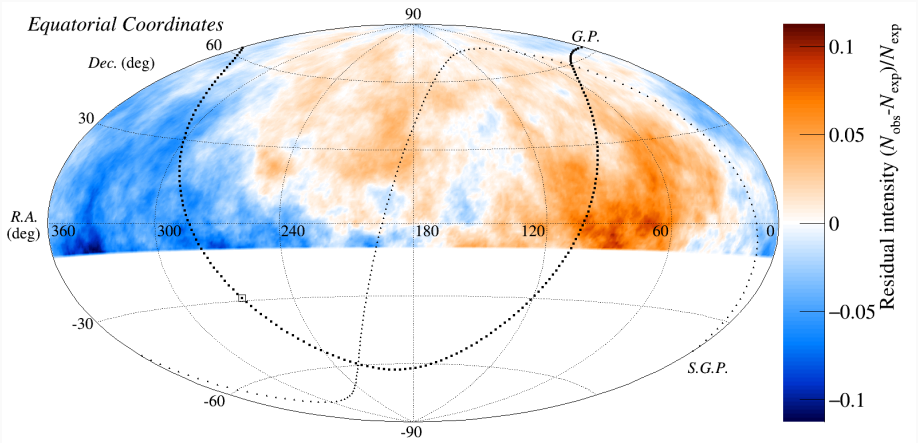
Large-scale anisotropy search

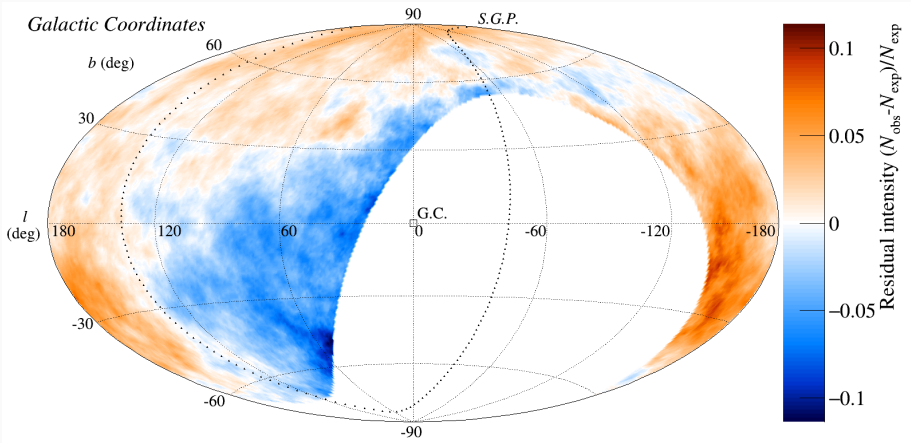
- 11-year TA SD data set 2008–2019
- $E > 8.8$ EeV
- 6032 events
- Dipole fit: amplitude of 3.3 ± 1.9 % with a phase of $131° \pm 33°$
- Compatible with an isotropic distribution at a 2σ significance level



TA, ApJL, 898, L28 (2020)

Large-scale anisotropy search

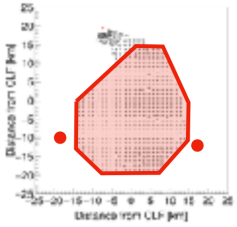


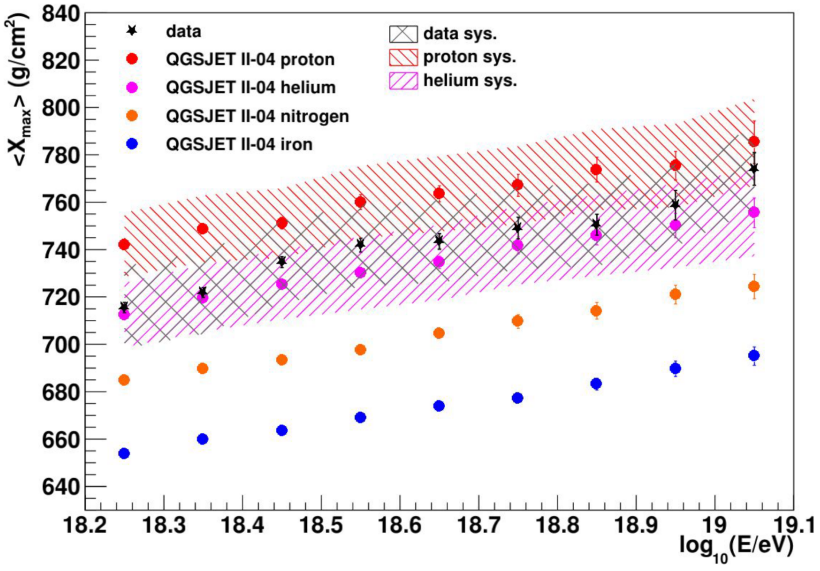


The residual-intensity sky map of UHECRs measured by TA with energies above 8.8 EeV in equatorial and galactic coordinates.
A dipole structure is seen in the common declination $\delta < 24.8°$ band shared with Auger.

TA, ApJL, 898, L28 (2020)

TA BRM+LR+SD hybrid: <Xmax> and σ_{Xmax}

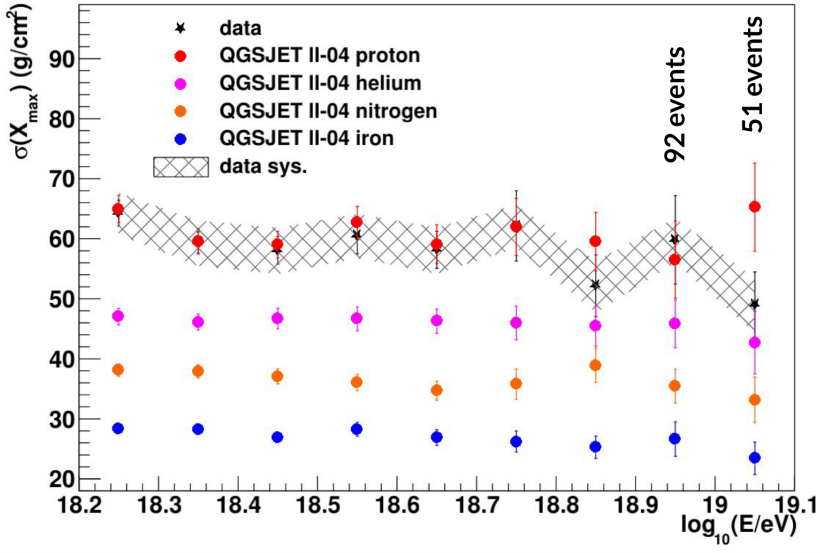




< Xmax > along with predictions of QGSJET II-04 p, He, N and Fe

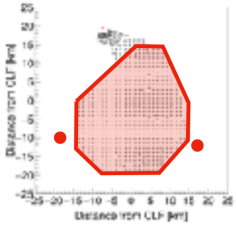
10 years data $10^{18.2}$ to $10^{19.1}$ eV
3560 events after the quality cuts

Systematic uncertainty on <Xmax> is 17 g/cm²
Xmax bias < 1 g/cm²
Xmax resolution = 17.2 g/cm²
Energy resolution = 5.7 %

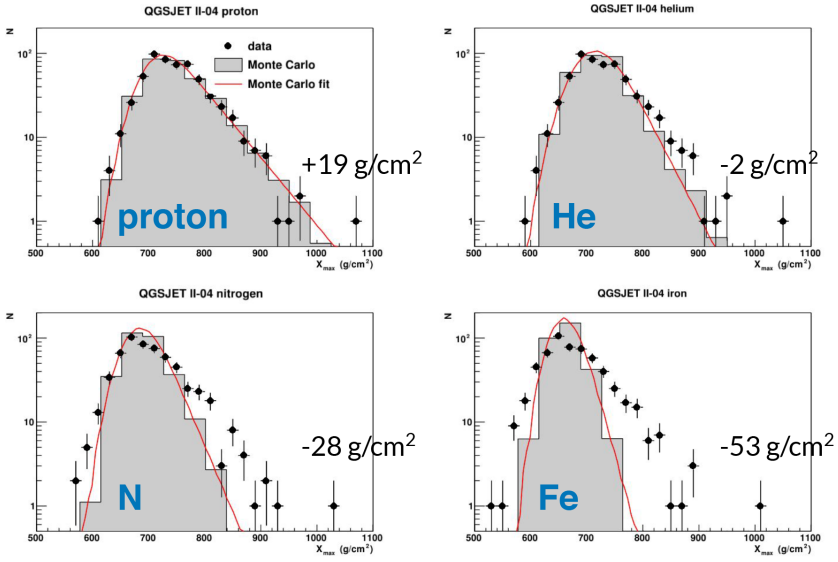


σ_{Xmax} along with predictions of QGSJET II-04 p, He, N and Fe
The measured data are compatible with the protons below 10^{19} eV.

TA BRM+LR+SD hybrid: single element model



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

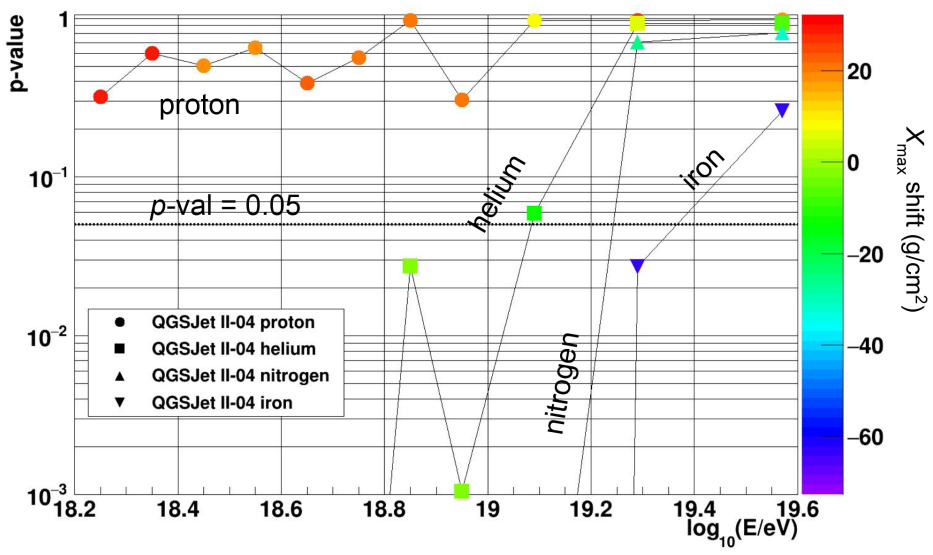


Ap. J., 858, 76(2018)
arXiv: 1801.09784

Test the agreement of data and single element models by comparing data and MC Xmax distributions including a systematic shift of data.

Proton and He agree with the data especially in the tail of distributions, whereas N and Fe do not resemble the data.

(Xmax systematic uncertainty = 17 g/cm²)



Data is compatible with QGSJET II-04 proton from $10^{18.2}$ to $10^{19.9}$ eV with systematic shifting about 20 g/cm².

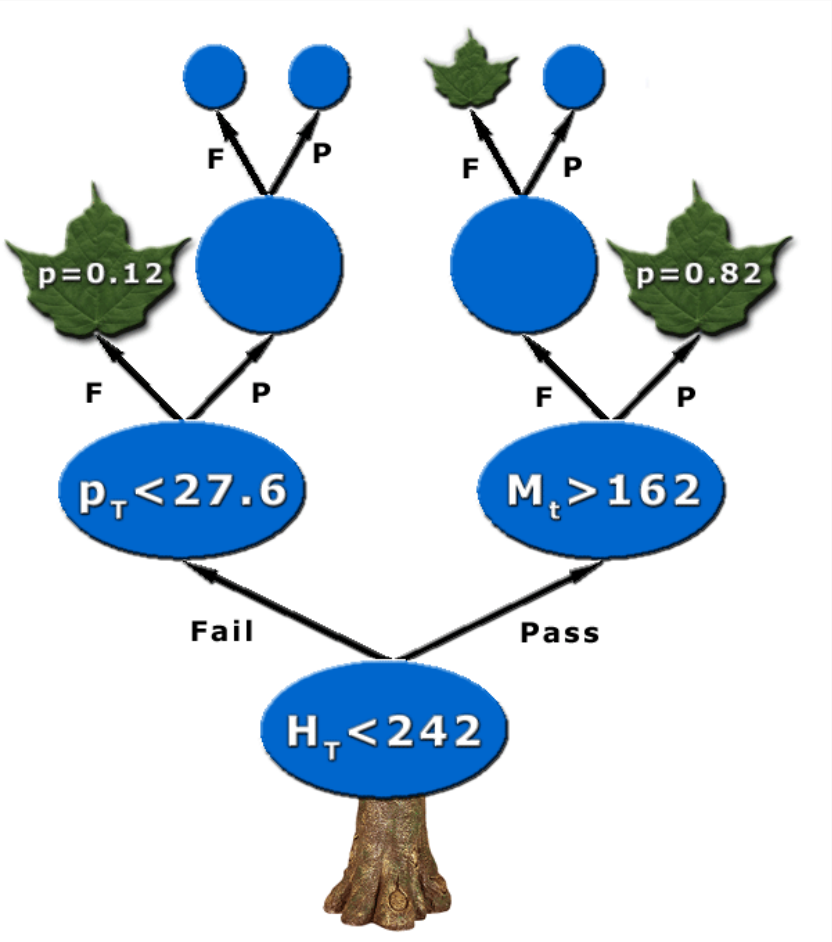
Other components are not compatible in $E < 10^{19}$eV

All 4 single components are compatible in the highest energy bin. ← low statistics (19 events)

Fe requires a shift of ~ 50 g/cm²

Mass composition study with the TA SD

Boosted Decision Trees:
ROOT::TMVA



$$(a,\, AoP,\, \ldots) \rightarrow \xi$$

SD detector array: > 90 % duty cycle, larger data statistics compared to FD

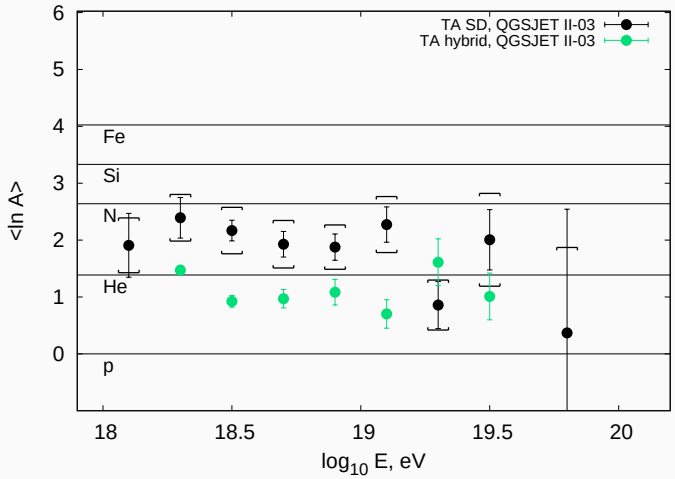
Comparison of ξ distributions for data with Monte-Carlo modelling

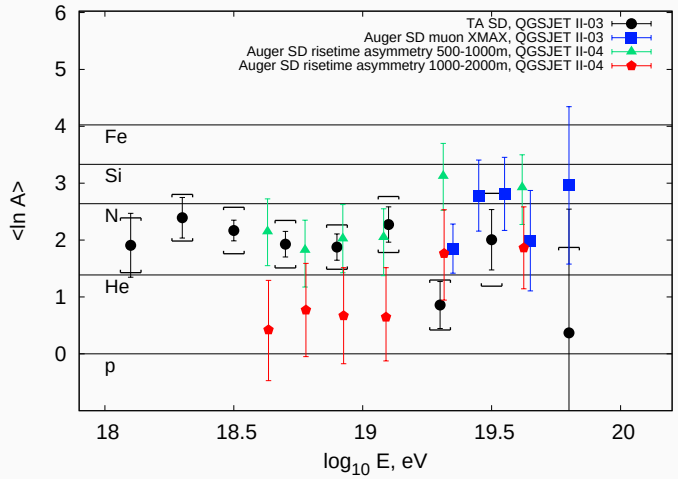
$$\Downarrow$$

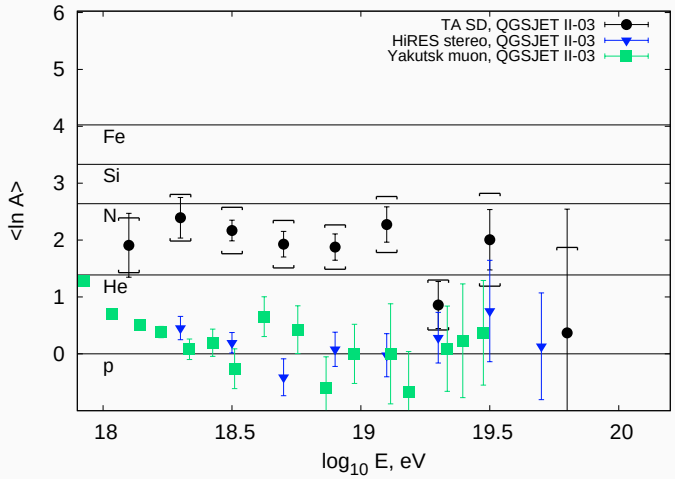
$$\langle \ln A \rangle\,(E)$$

TA, Phys. Rev. D 99, 022002 (2019)

Mass composition study with the TA SD



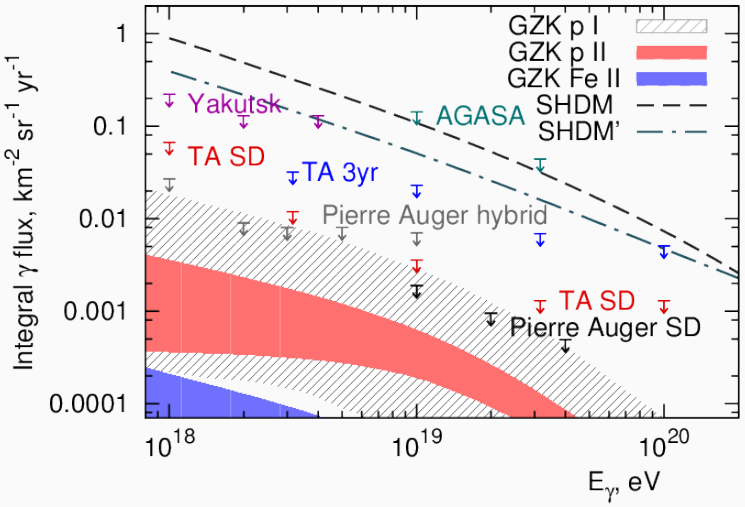




$$\langle \ln A \rangle = 2.0 \pm 0.1(stat.) \pm 0.44(syst.)$$

TA, Phys. Rev. D 99, 022002 (2019)

Search for point sources of UHE photons



Diffuse photon search with the TA SD: [TA], Astropart.Phys. 110 (2019) 8-14
Hadron background is highly isotropic

⇓

Assume that photons are emitted by point source

⇓

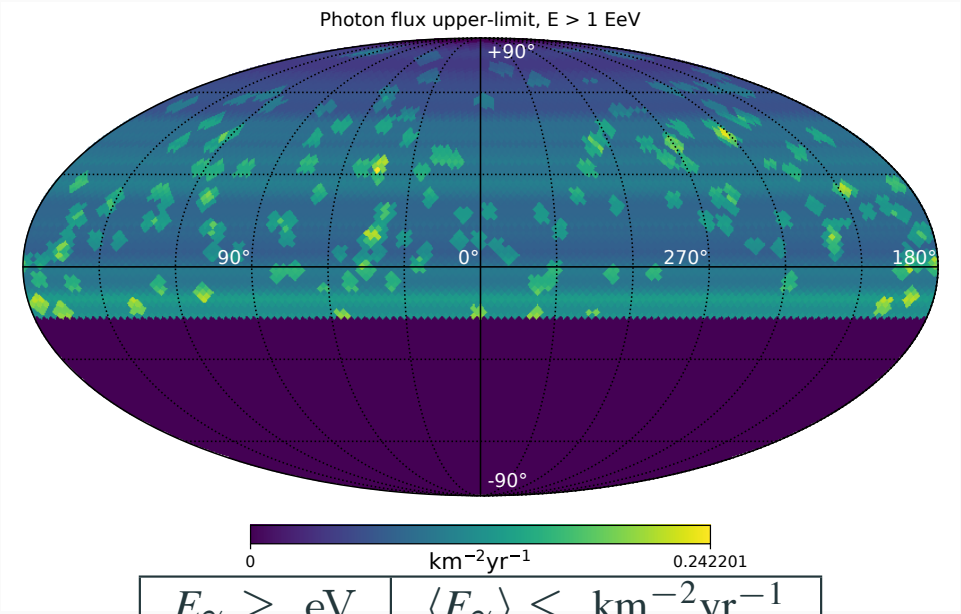
In angular vicinity of the source the photon/hadron ratio would be larger than in full TA field of view

⇓

Easier to separate photons from hadrons!

Results: point-source photon flux upper-limits

95% C.L.



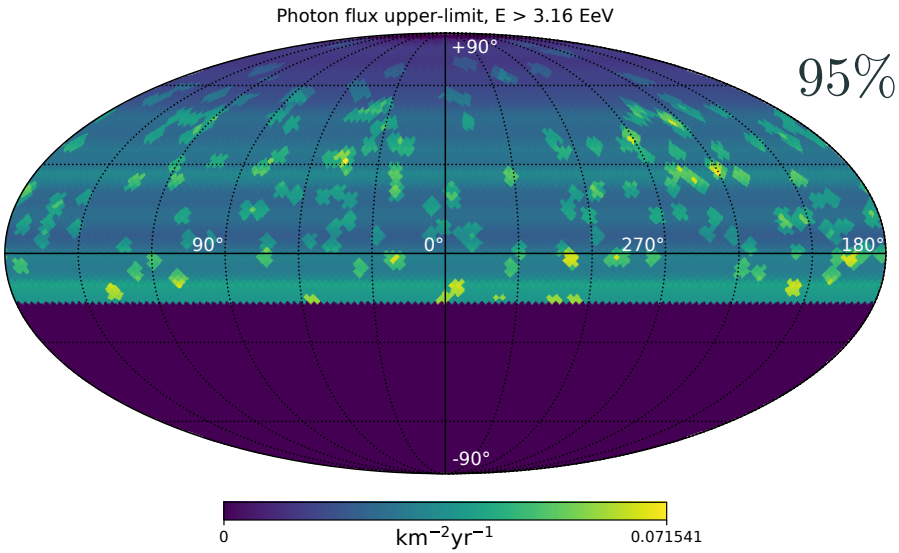
$E_\gamma \geq$, eV	$\langle F_\gamma \rangle \leq$, km^{-2}yr^{-1}
$10^{18.0}$	0.094
$10^{18.5}$	0.029
$10^{19.0}$	0.010
$10^{19.5}$	0.0071
$10^{20.0}$	0.0058

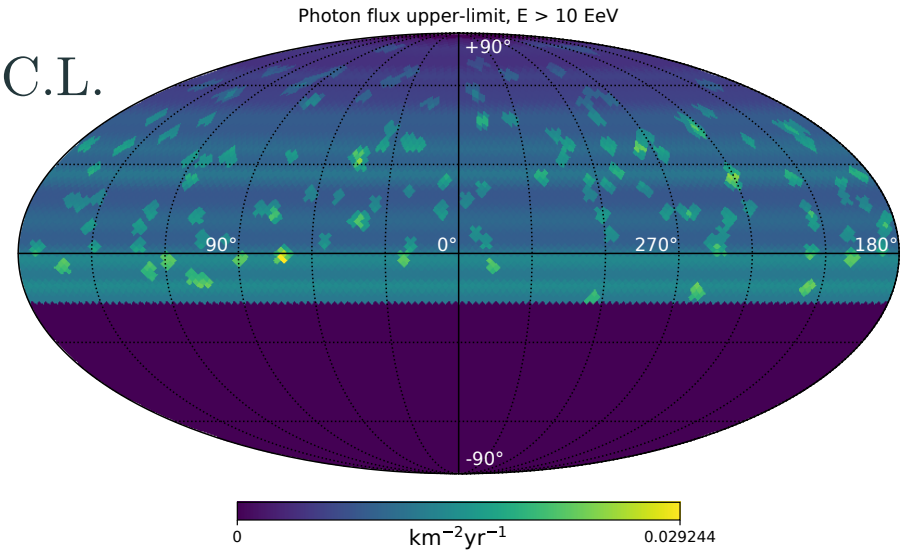
Pierre Auger: $\langle F_\gamma \rangle \leq 0.035$ km^{-2}yr^{-1} (1° ang.res., $10^{17.3} \leq E \leq 10^{18.5}$ eV)

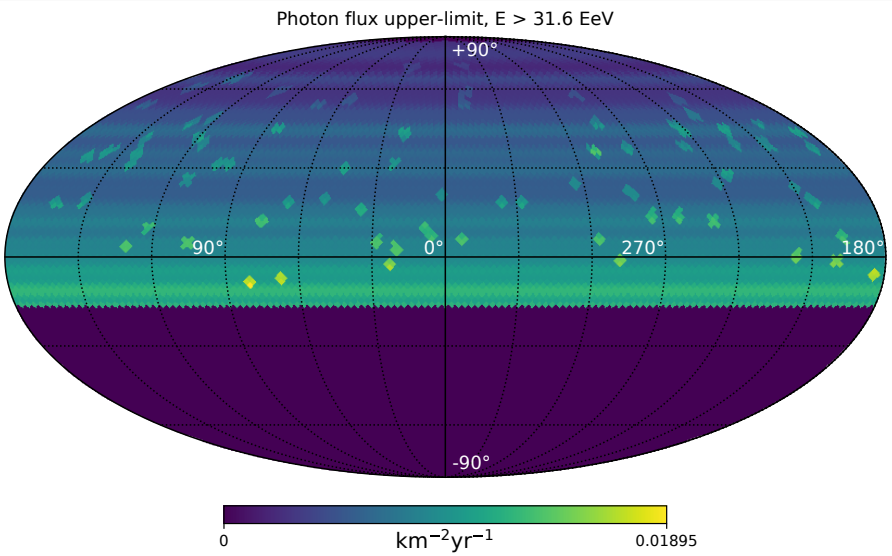
TA, MNRAS 492 (2020), 3984

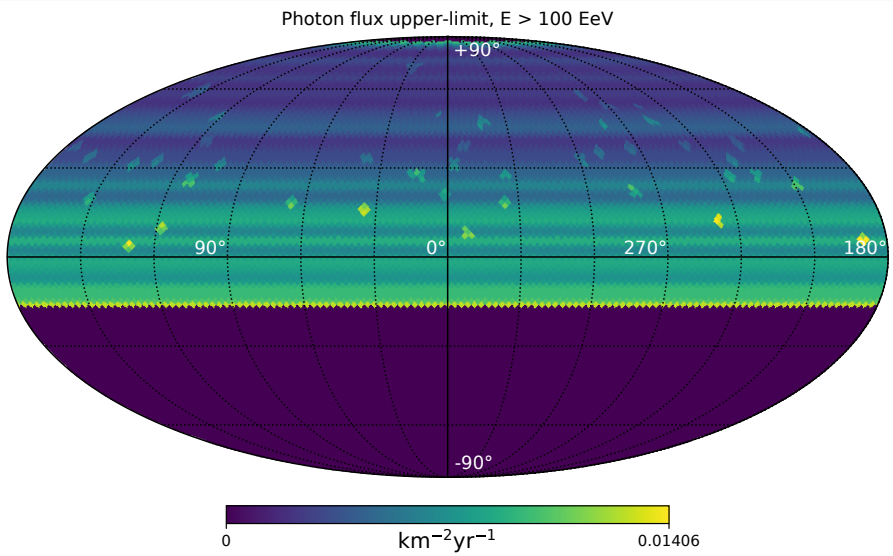
Results: point-source photon flux upper-limits

95% C.L.





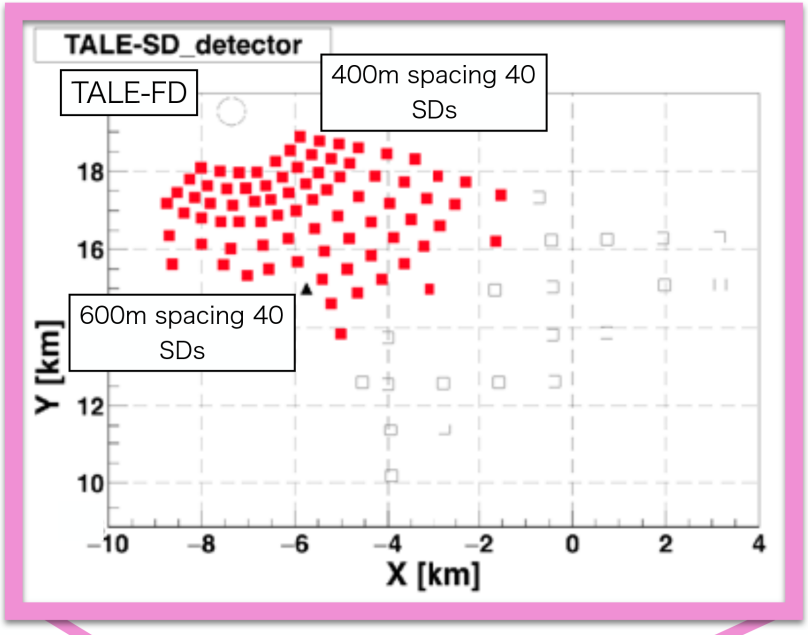


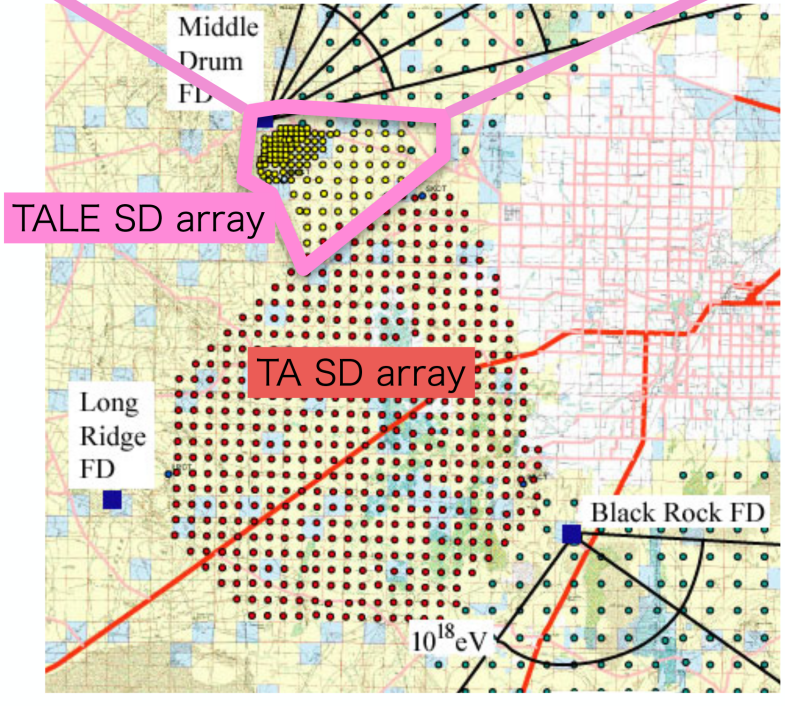


TA, MNRAS 492 (2020), 3984

Future prospects

TALE hybrid





TALE hybrid =
low energy extension of TA hybrid
sensitivity down to 10^{16} eV, with
FDs observing higher elevation,
Densely-arrayed SDs
Precise measurement of the composition :
FD + SD hybrid measurement

TALE-FD : 10 telescopes are in operation since Sep. 2013

→ Installed 80 SDs with 400m, 600m spacing TALE-SD array in operation since Feb. 2018
TALE-hybrid started running at Sep. 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 : 44 g/cm^2)

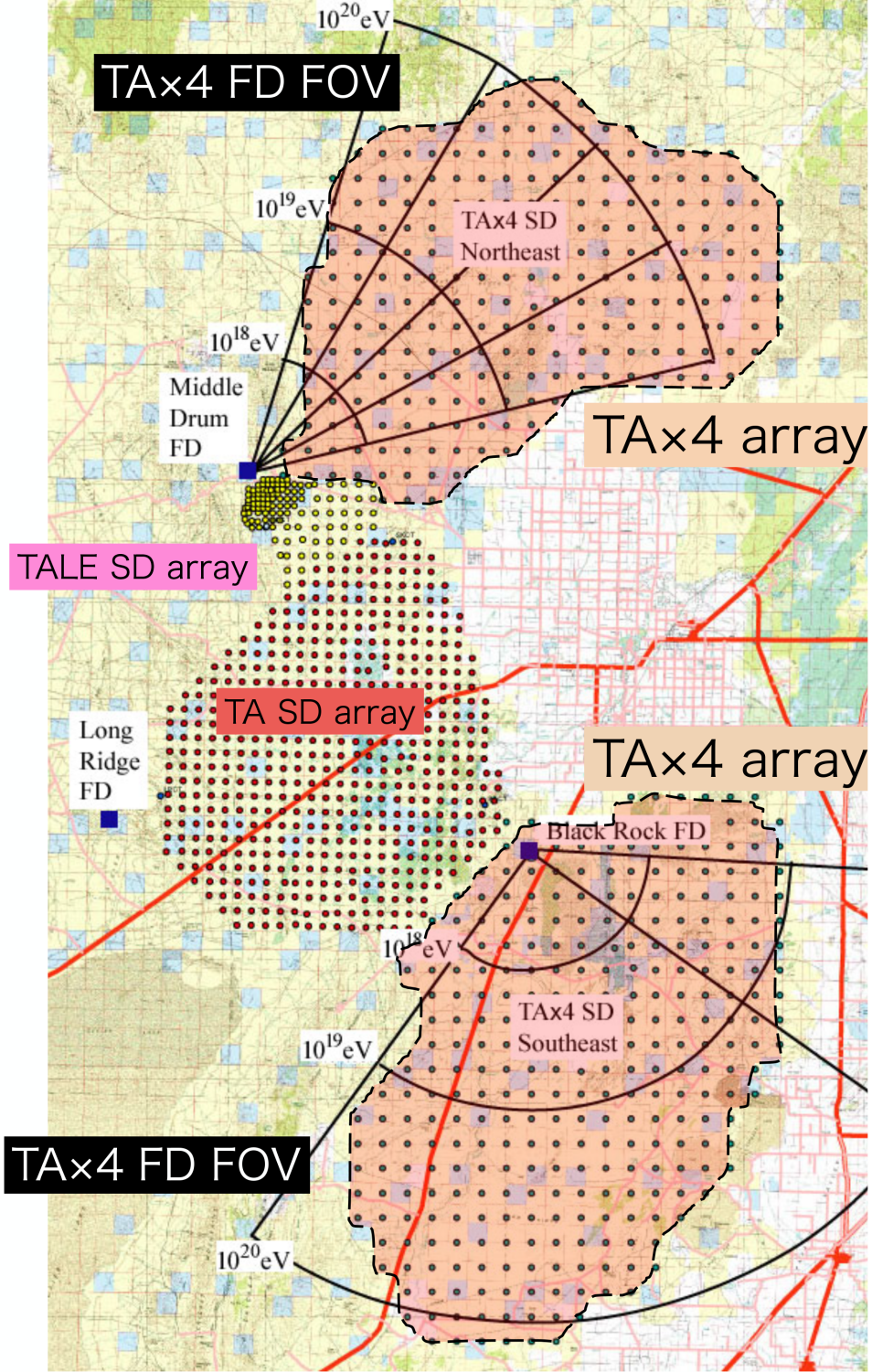
TA×4

In order to increase
the event statistics@UHE
↓
To increase the coverage from
TA = 700 km²
↓
TAx4 = 3,000km²

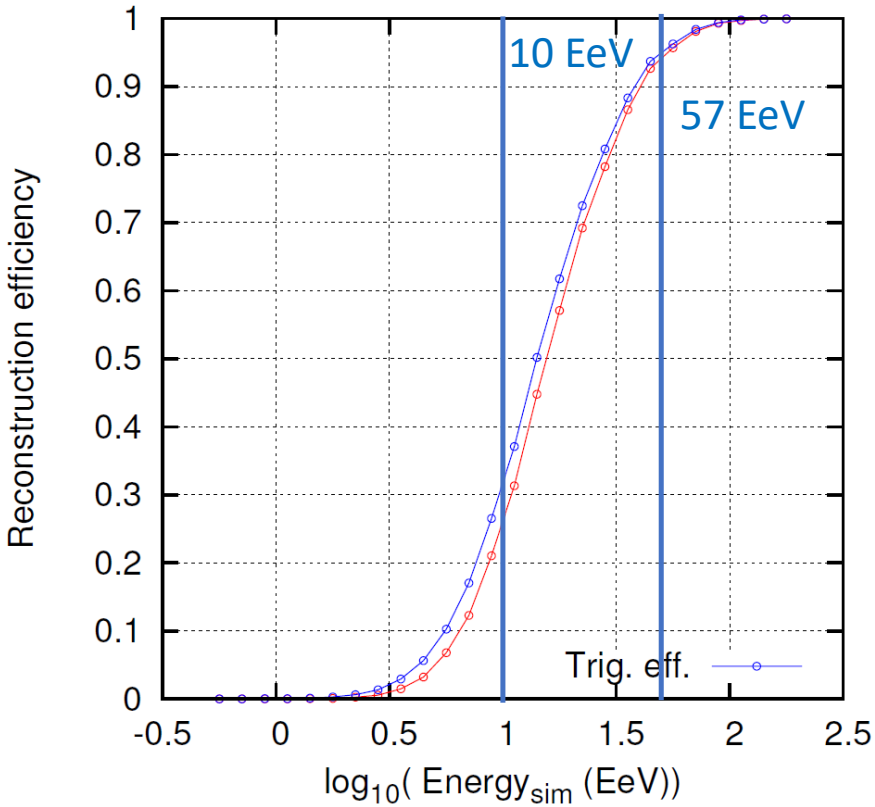
SD array of ~3000 km²
by **500** SDs
with **2 km** spacing

＋

2 FD stations (12 HiRes-II telescopes)
4 FDs at the northern station
8 FDs at the southern station



Expectation of the performance of SD Array



SD array: square grid with 2.08 km spacing

Trigger condition: adjacent 3 SDs within 14 usec

E > 57 EeV:

- Reconstruction efficiency > 95%
- Angular resolution: 2.2°
- Energy resolution: ～25%

Deployment of Assembled SDs

Construction of North FD Station

16th Feb. 2018

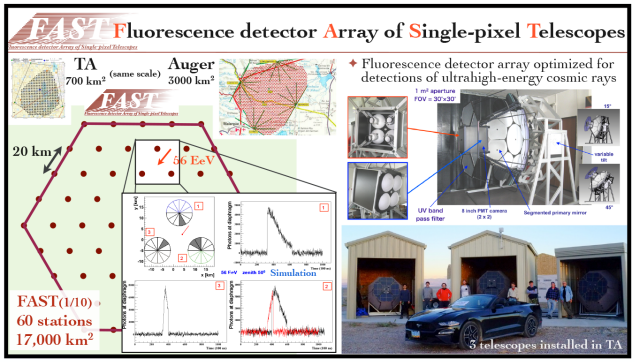
First light was observed.

(camera 28: Xe Flasher)

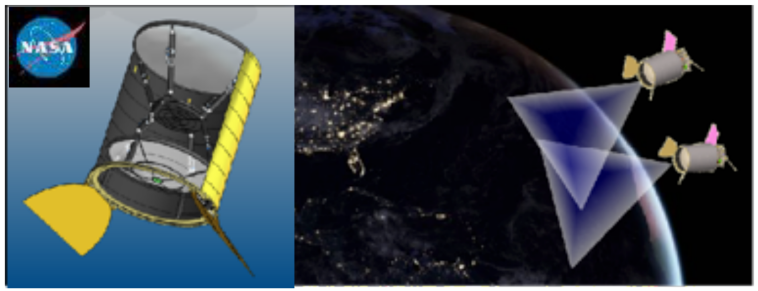
Stable operation was started from 8th June 2018.

TA site: Platform for next generation

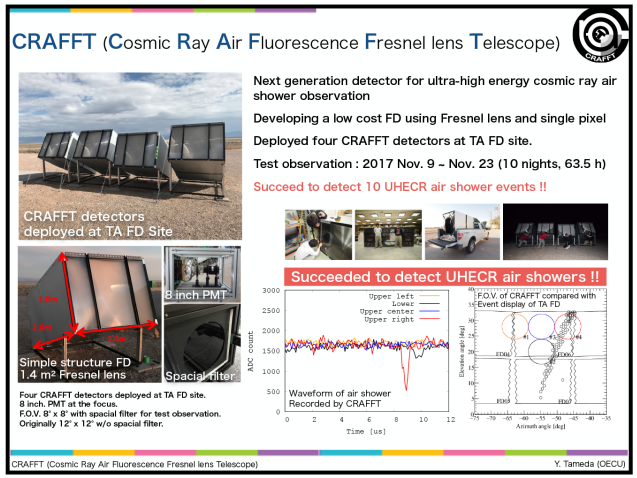
FAST



EUSO-TA
(connect to POEMMA)



CRAFFT



Summary

What's your targeted physics in next decades?

- Physics beyond the Standard model in it's connection with multimessenger astrophysics as a probe tool.

What we need to accomplish?

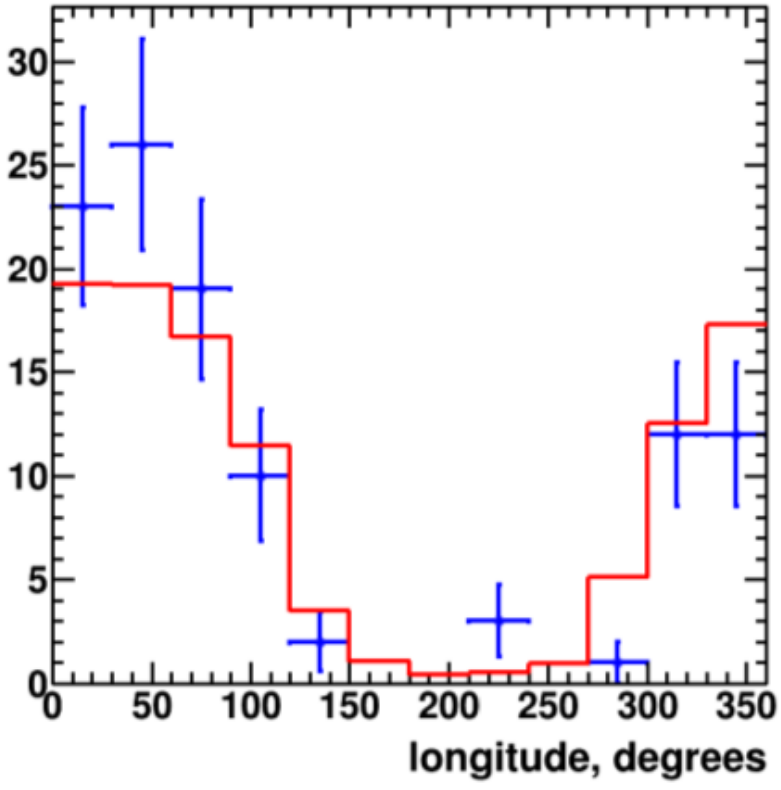
- Enlarge the statistics of current experiments as well as understand the EAS physics better to be able to accurately interpret the observations.

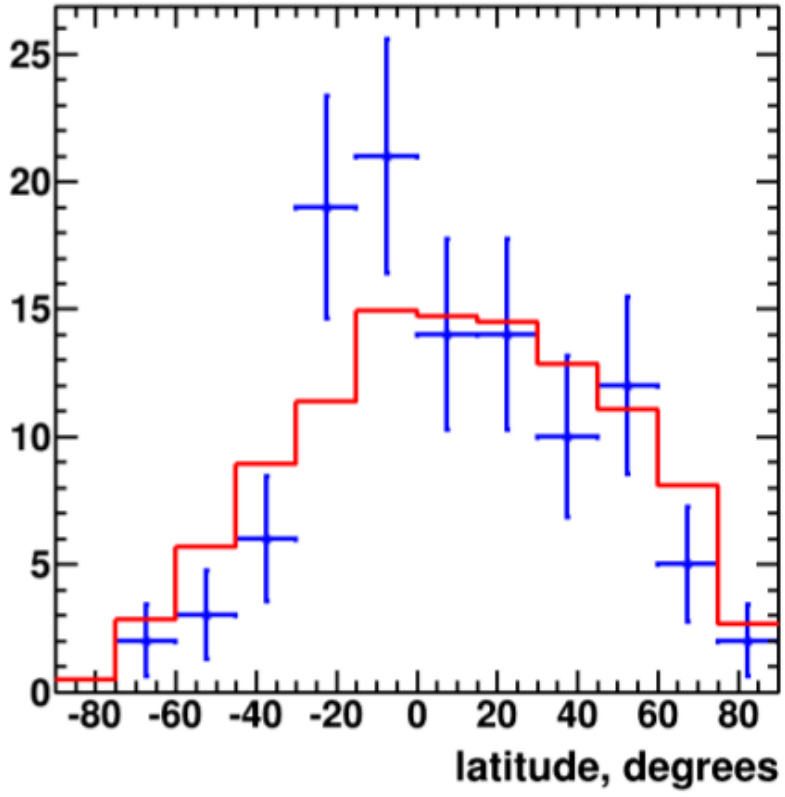
Supported by Russian Science Foundation

Thank you for your attention!

Global anisotropy

supergalactic coordinates

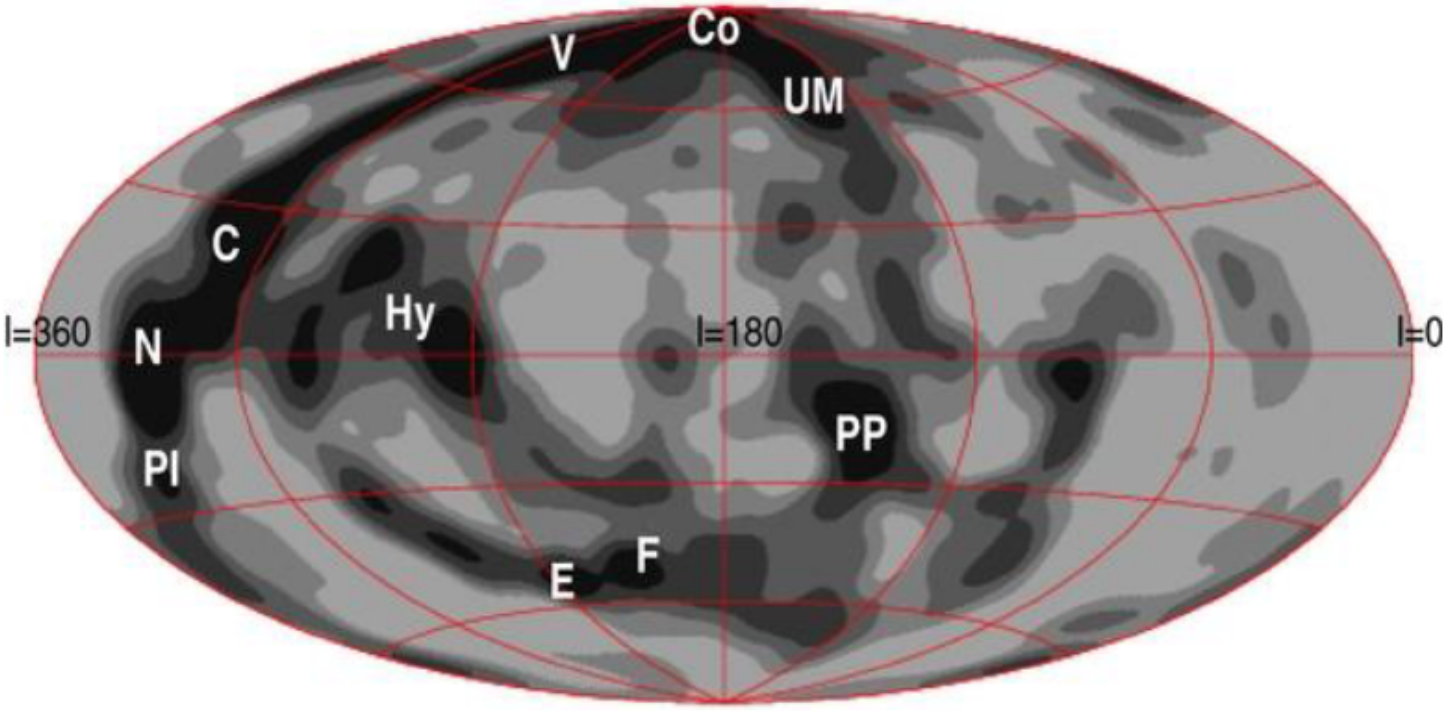




Kolmogorov-Smirnov p-value = 0.01 for SG latitude, E>57 EeV

other thresholds/coordinates = isotropic

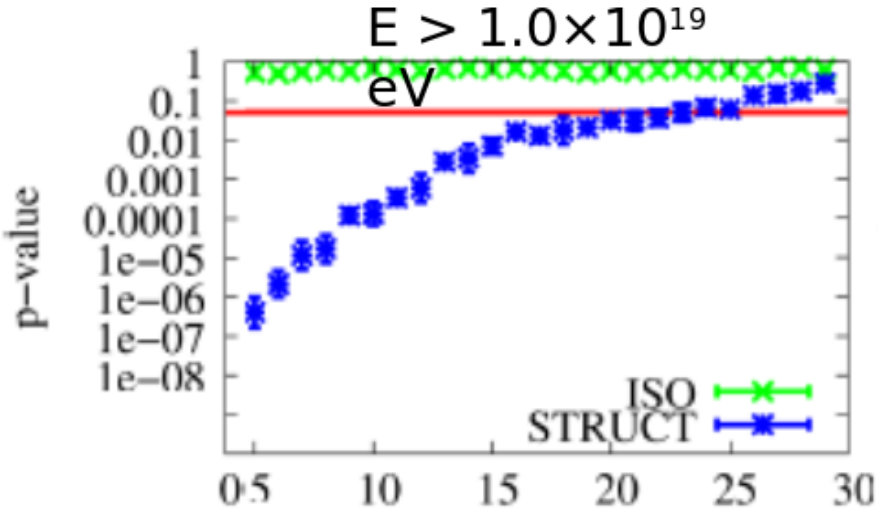
Large-Scale Structure

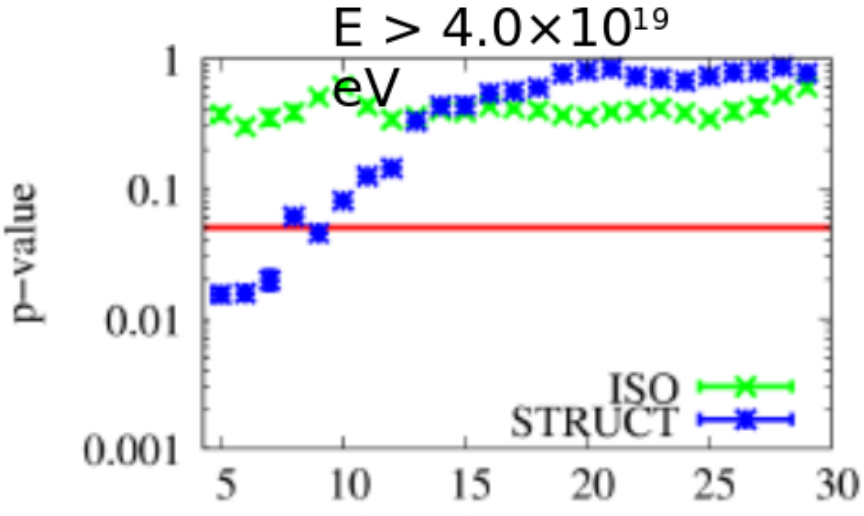


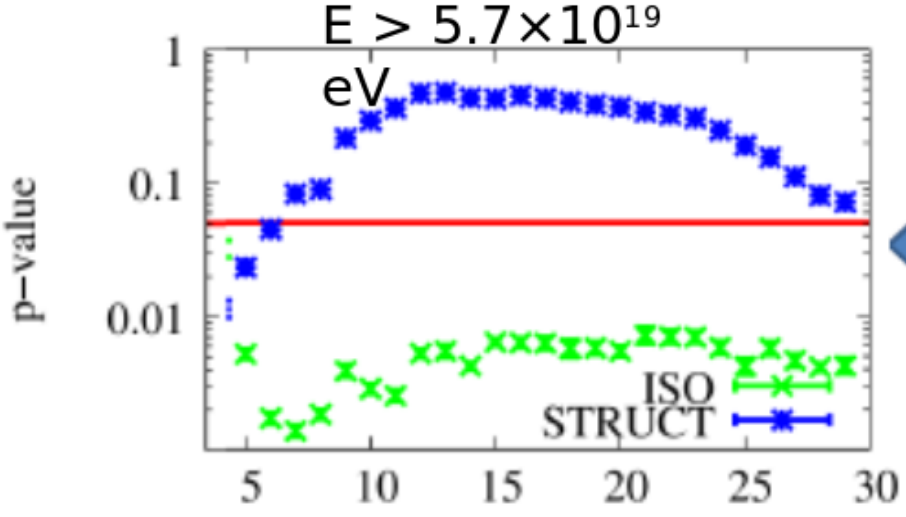
C: Centaurus SCl (60 Mpc); Co: Coma Cl (90 Mpc); E: Eridanus Cl (30 Mpc); F: Fornax Cl (20 Mpc); Hy: Hydra SCl (50 Mpc); N: Norma SCl (65 Mpc); PI: Pavo-Indus SCl (70 Mpc); PP: Perseus-Pisces SCl (70 Mpc); UM: Ursa Major Cl (20 Mpc); and V: Virgo Cl (20 Mpc).

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

Large-Scale Structure







E>5.7×10¹⁹ eV
Consistent with LSS
Inconsistent with isotropy

Observables, sensitive to the primary composition

Shower front

- Linsley curvature parameter
- Area-over-peak
- Area-over-peak slope
- Number of detectors, excluded from the shower front approximation during event reconstruction

LDF

- S_b
- Sum of signals from all detectors of the event
- Number of detectors hit
- $\chi^2/d.o.f.$ for LDF approximations

Muons

- Full number of peaks in all FADC traces of the event
- Number of peaks in the detector with the largest signal
- Assymmetry between upper and lower layers of the detector
- Number of peaks, present only in the upper layer of the detectors
- Number of peaks, present only in the lower layer of the detectors

+ zenith angle, energy of the event

TA SD neutrino search

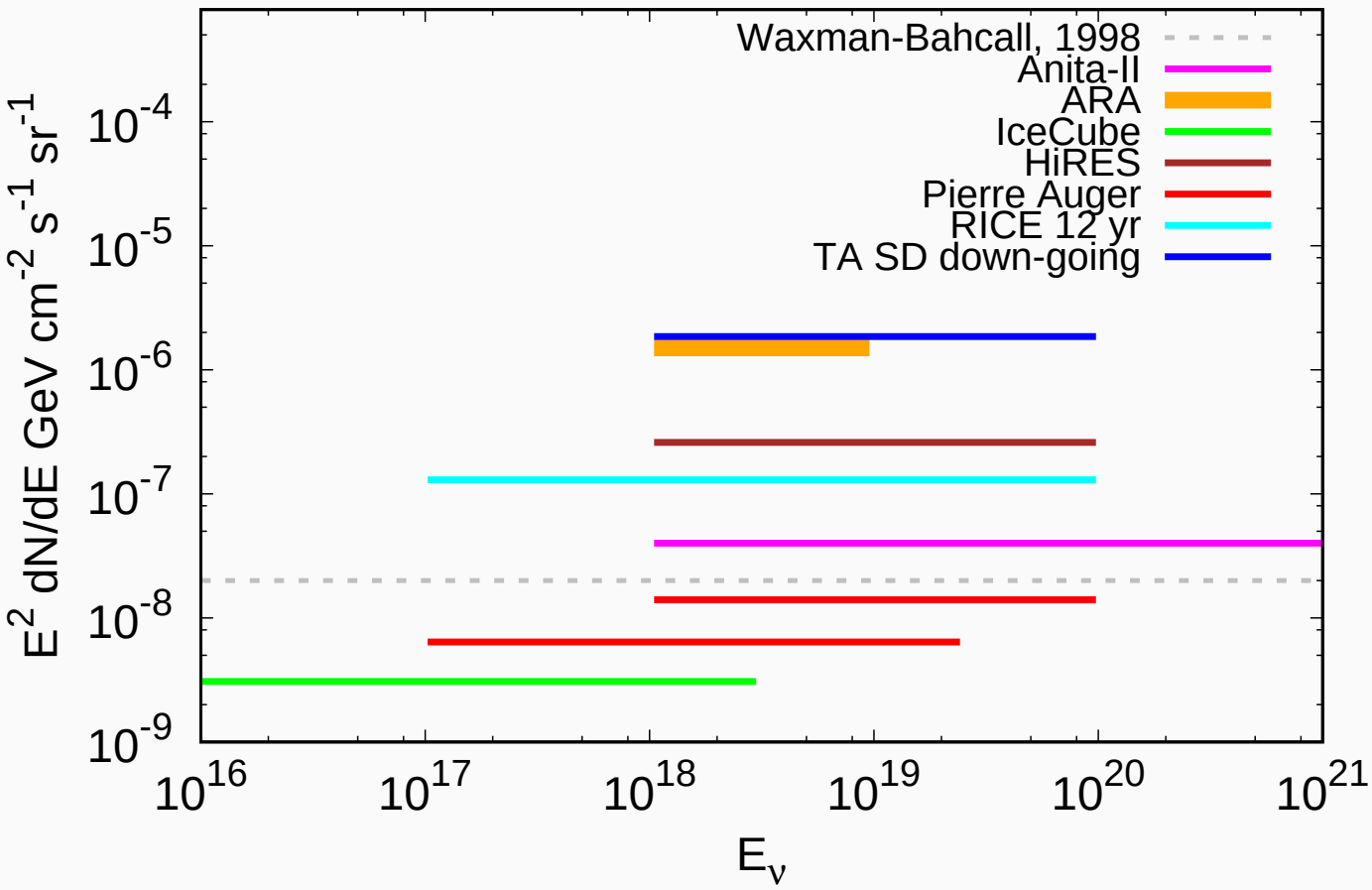
BDT-based procedure, analogous to the SD mass composition and photon search. 0 candidets in the data. Upper limit on the number of neutrino events of all flavors: $\overline{n}_\nu = 2.44$ (90% C.L.).

Upper limit on the diffuse flux of neutrino of one flavor with $E > 10^{18}$ eV:

$$EF_\nu < 1.58 \times 10^{-6}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \ (90\%\ \text{C.L.})\,.$$

TA, arXiv:1905.03738 (2019)

TA SD neutrino search



TA, arXiv:1905.03738 (2019)