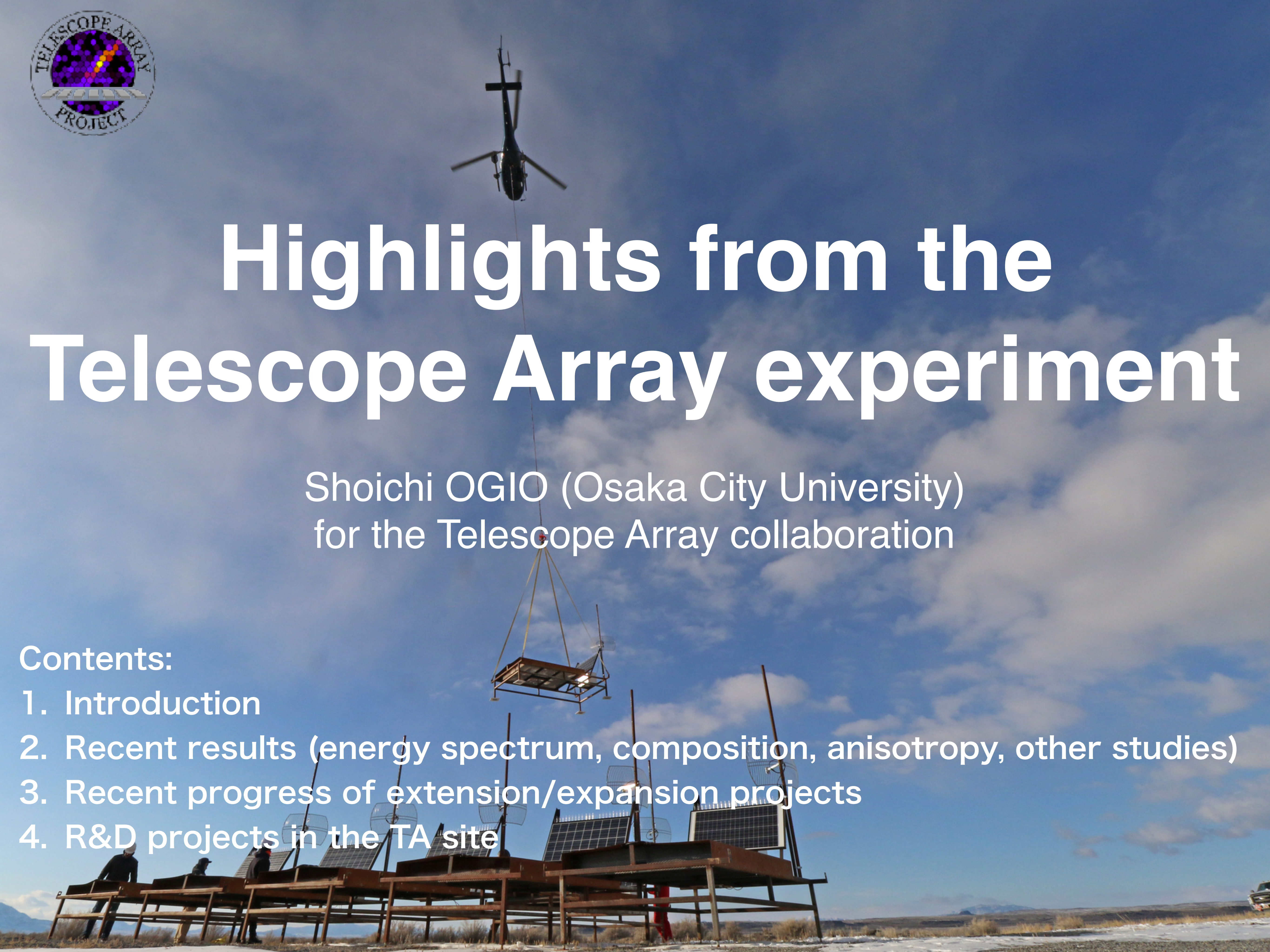
Highlights from the Telescope Array experiment

Shoichi OGIO (Osaka City University)
for the Telescope Array collaboration



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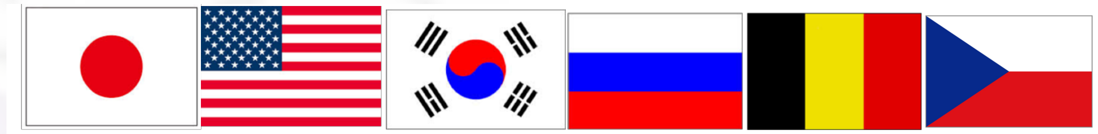
2. Recent results (energy spectrum, composition, anisotropy, other studies)
3. Recent progress of extension/expansion projects
4. R&D projects in the TA site

Telescope Array collaboration

147 collaborators from 36 institutes
in 6 countries



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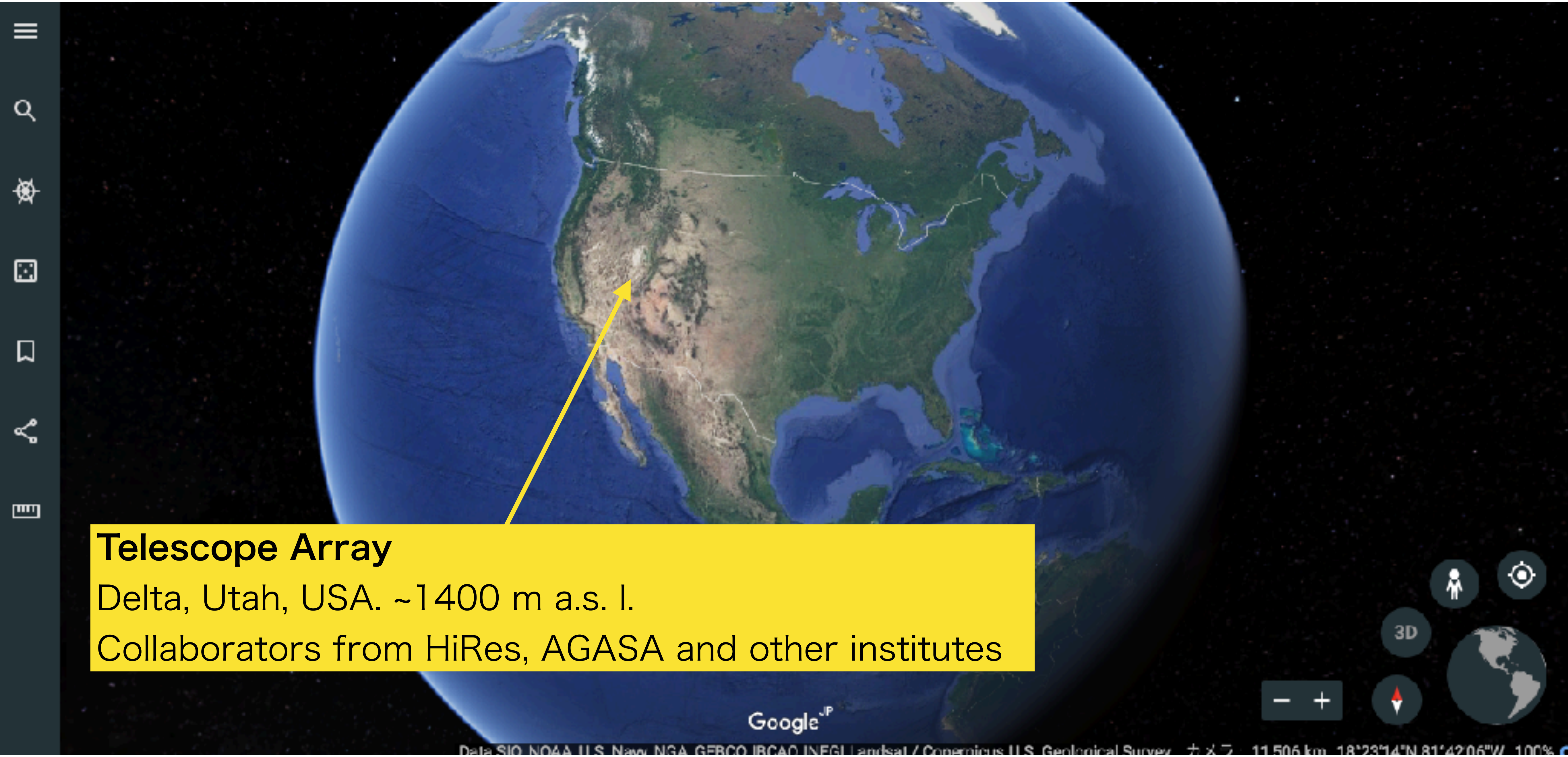
Telescope Array: The largest cosmic ray observatory in the norther hemisphere



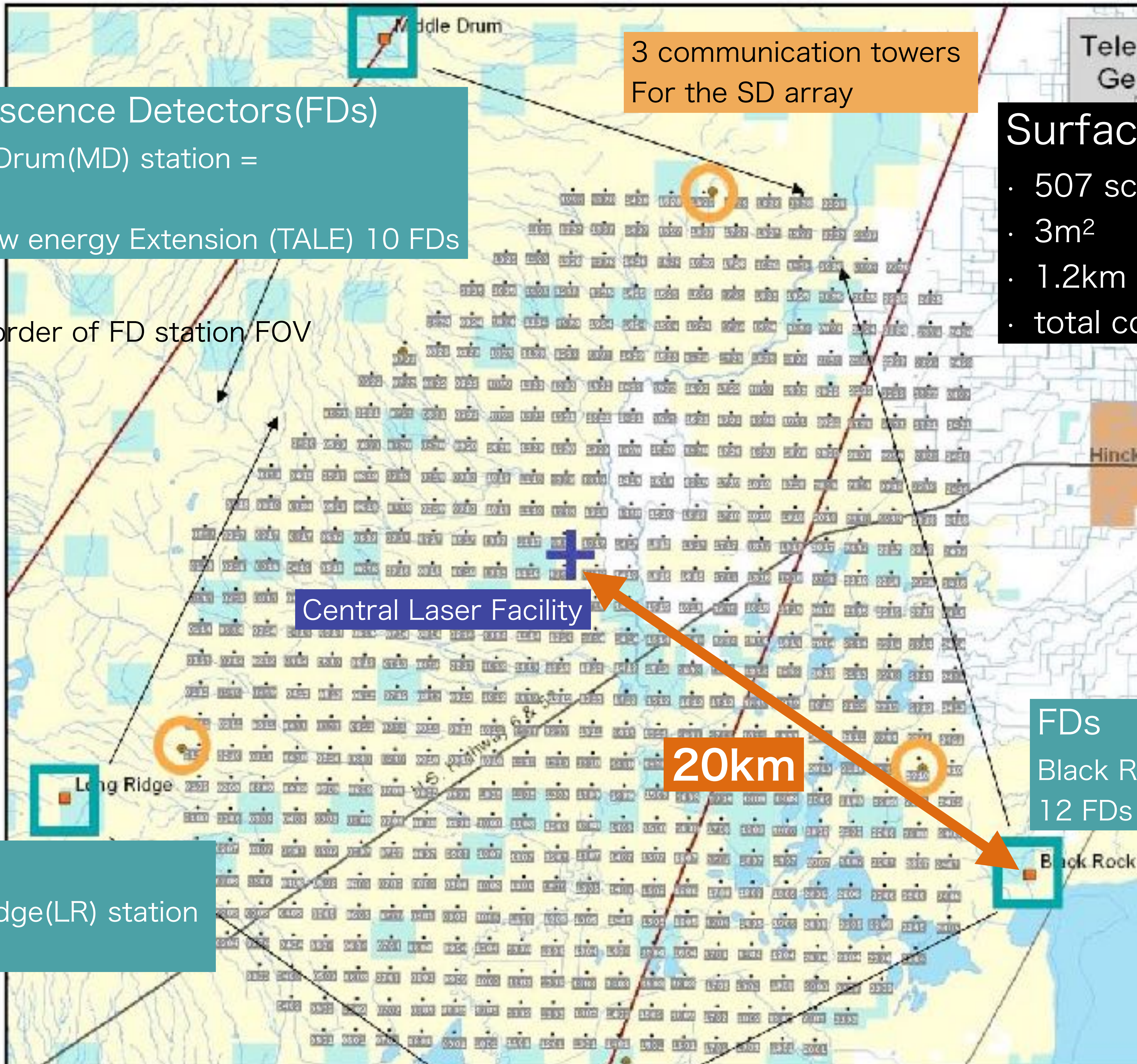
Map of the TA site

Fluorescence Detectors(FDs)
Middle Drum(MD) station =
14 FDs
+ TA Low energy Extension (TALE) 10 FDs

3 communication towers
For the SD array

Surface detectors(SDs)

- 507 scintillation detectors
- 3m^2
- 1.2km spacing
- total coverage ~700km^2



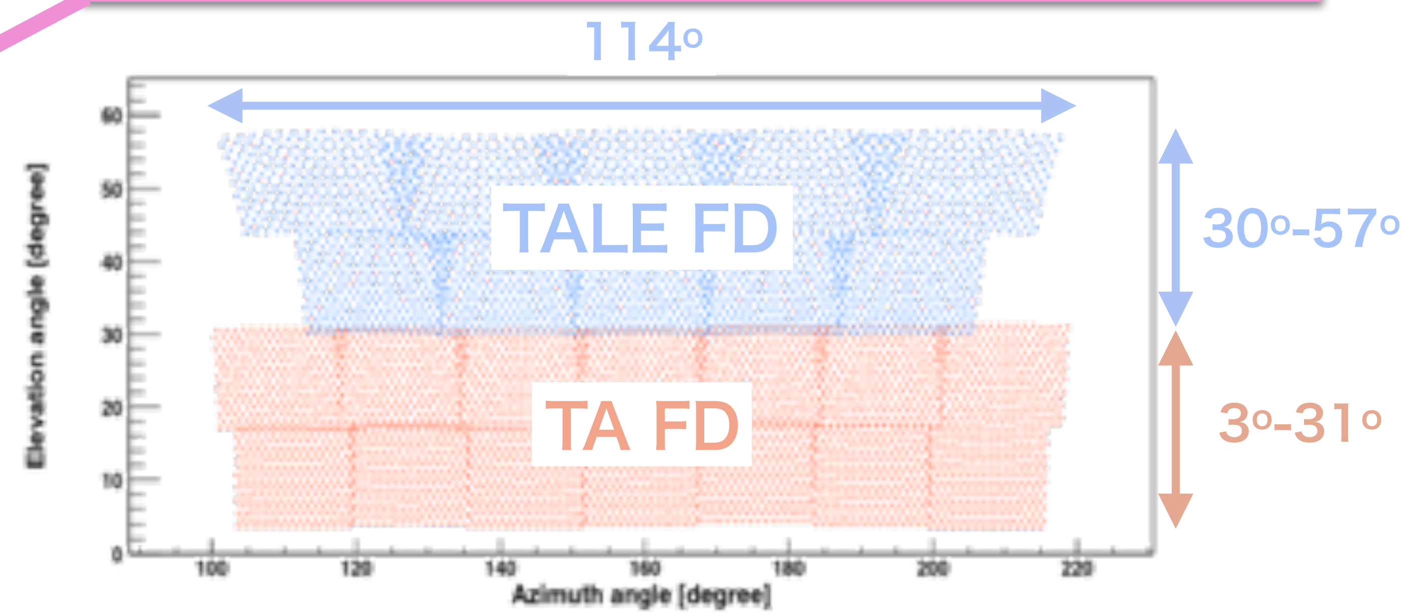
FDs
Black Rock Mesa(BRM) station
12 FDs

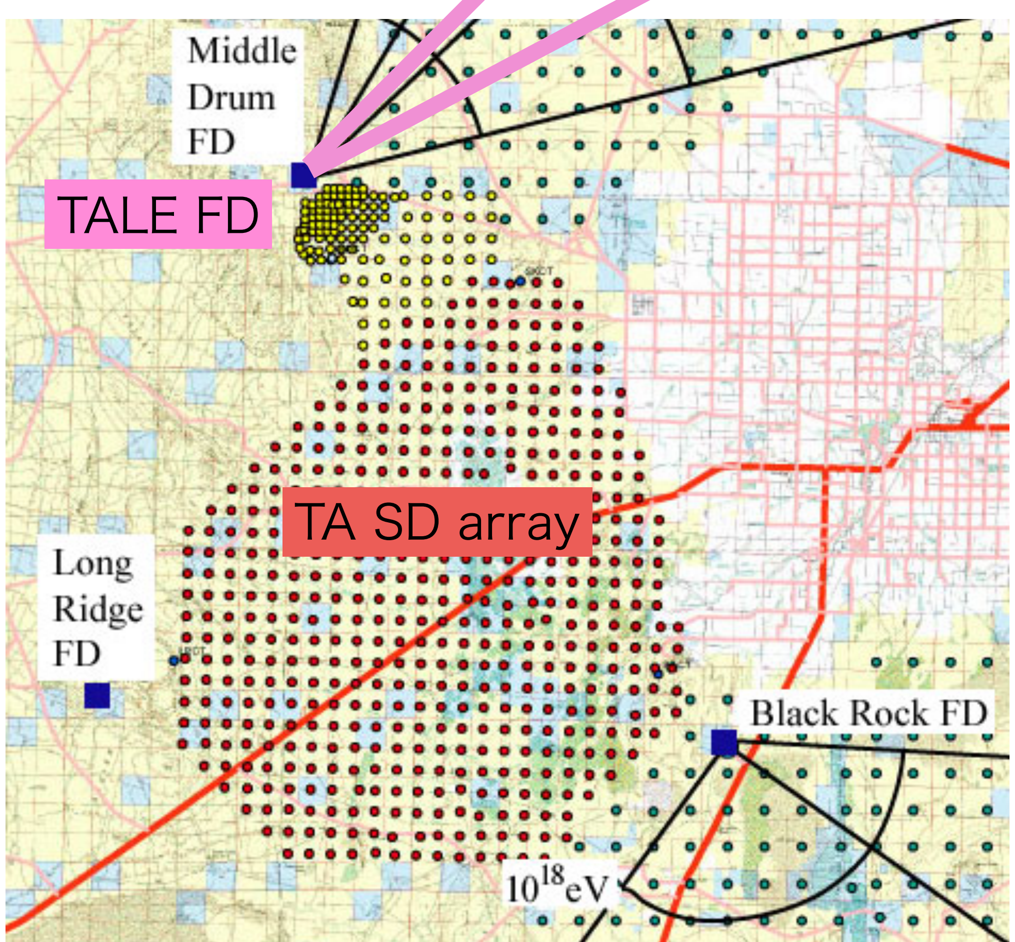
FDs
Long Ridge(LR) station
12 FDs

TALE FD

Located in TA MD site
10 FDs in the TALE station
Elevation: 30°-57° (higher elevation than MD)
Azimuthal: 114°

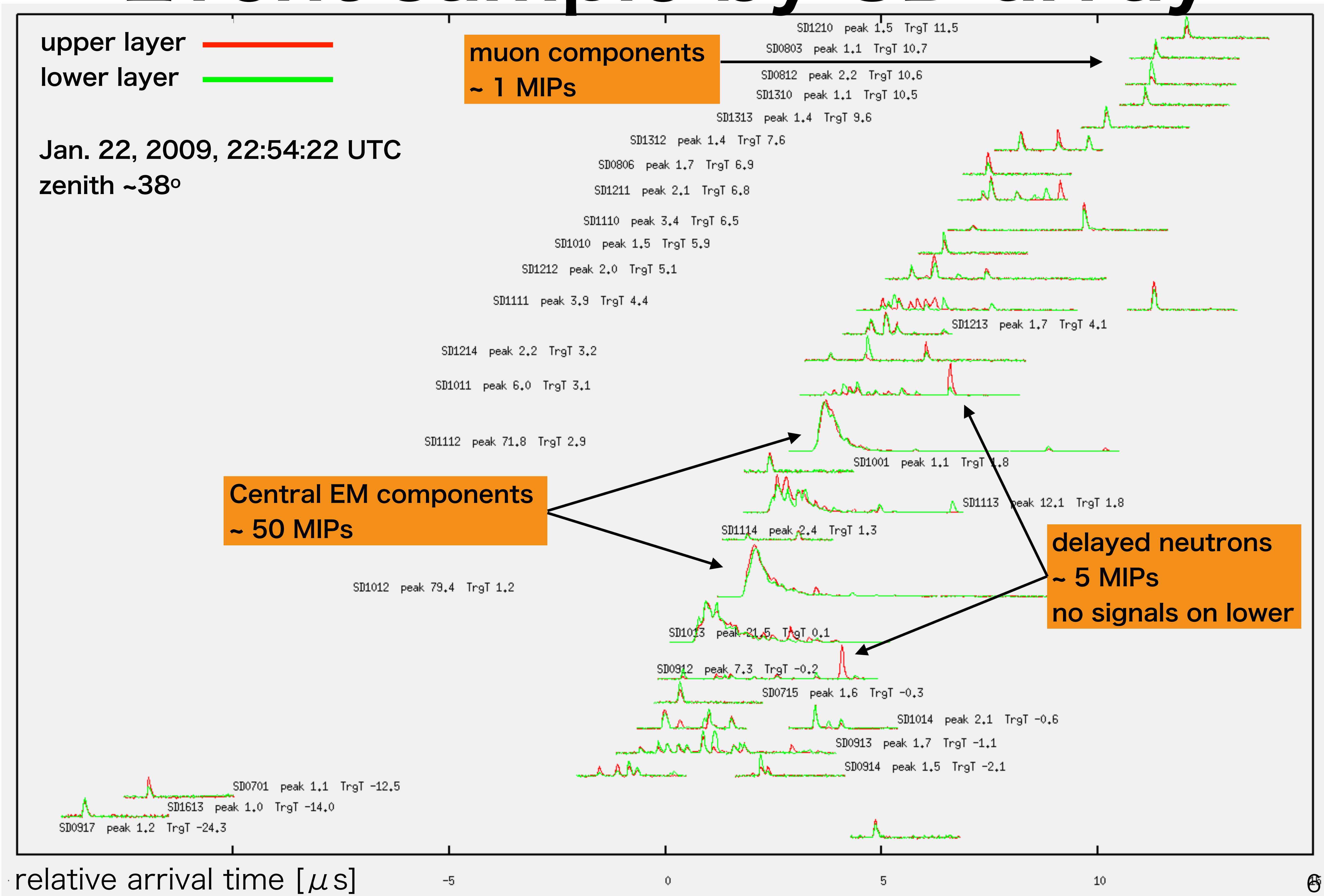
Refurbished HiRes telescopes & electronics
Mirror: same as TA FD (MD)
Elec.: 10 MHz 8bit FADC



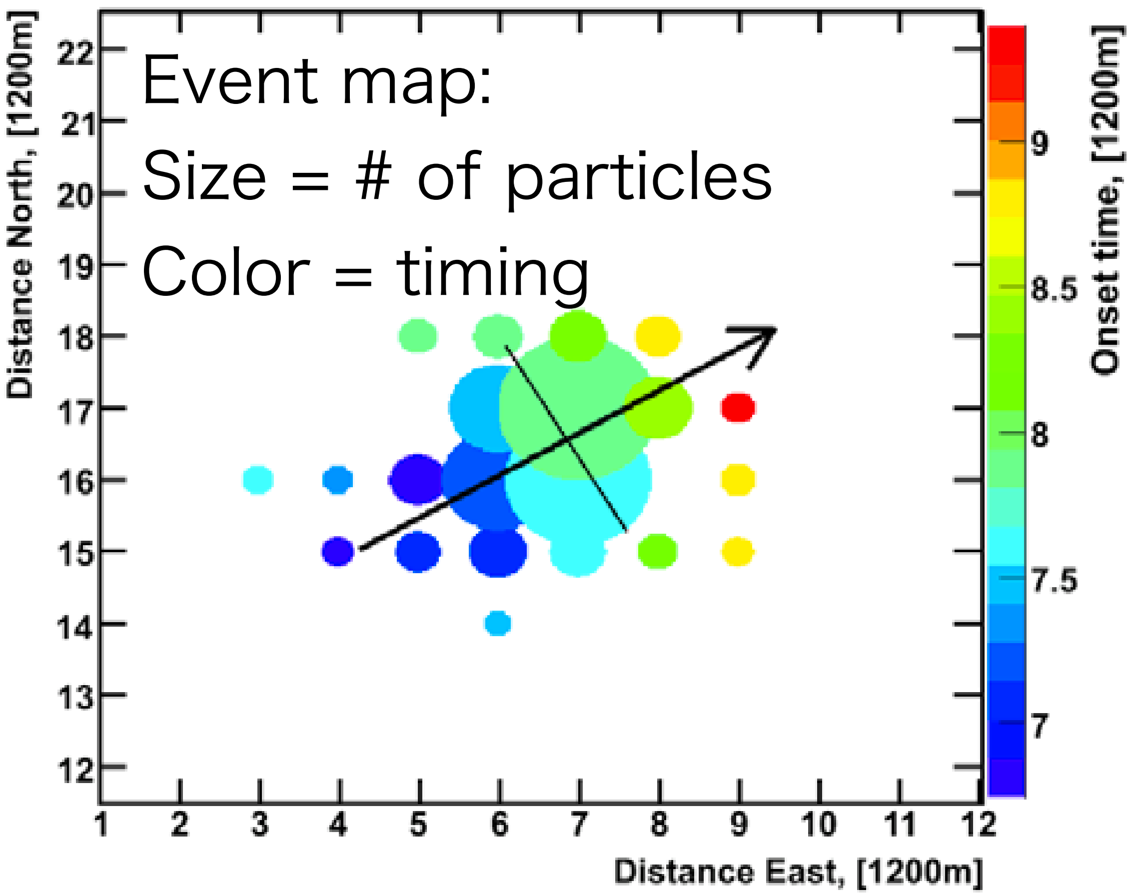


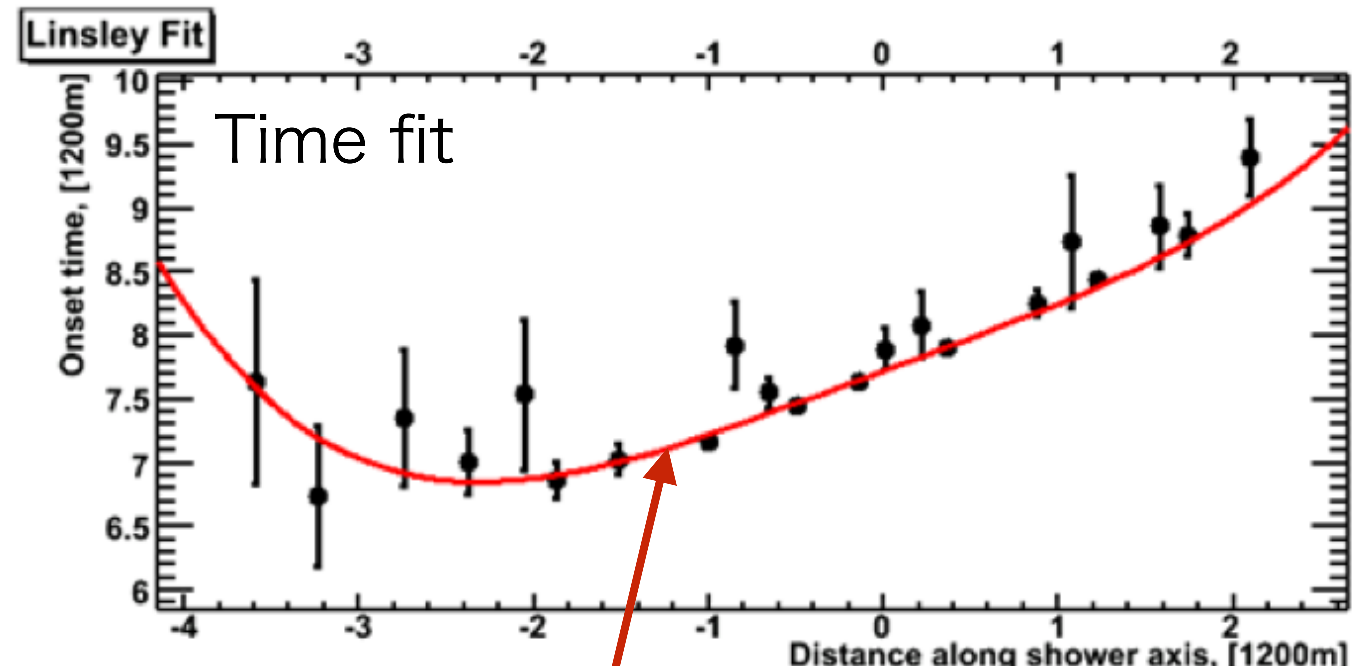
Installed in Nov. 2012
Operation since Sep. 2013
Hybrid trigger: Sep. 2018

Event sample by SD array



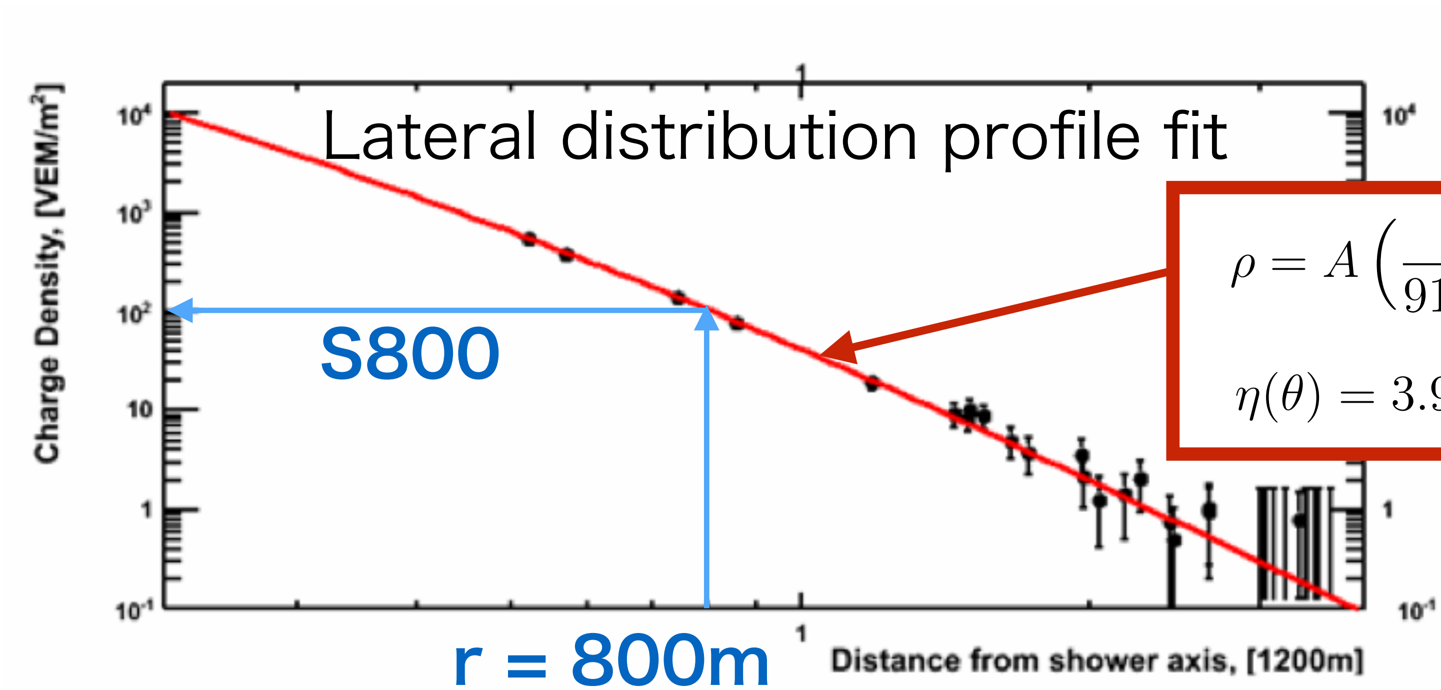
Event reconstruction





$$\tau = a\left(1 - \frac{l}{12\times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Modified empirical formula in AGASA



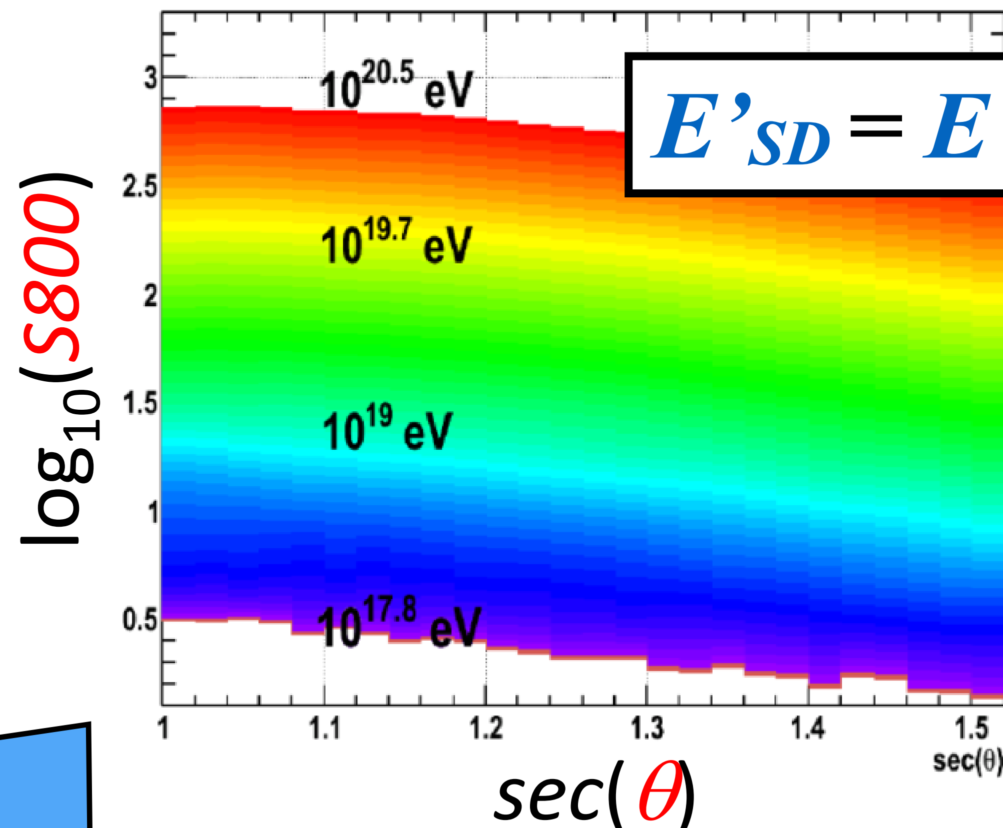
$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1 + \frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1 + \left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

Empirical formula used by AGASA

S800 -> primary energy

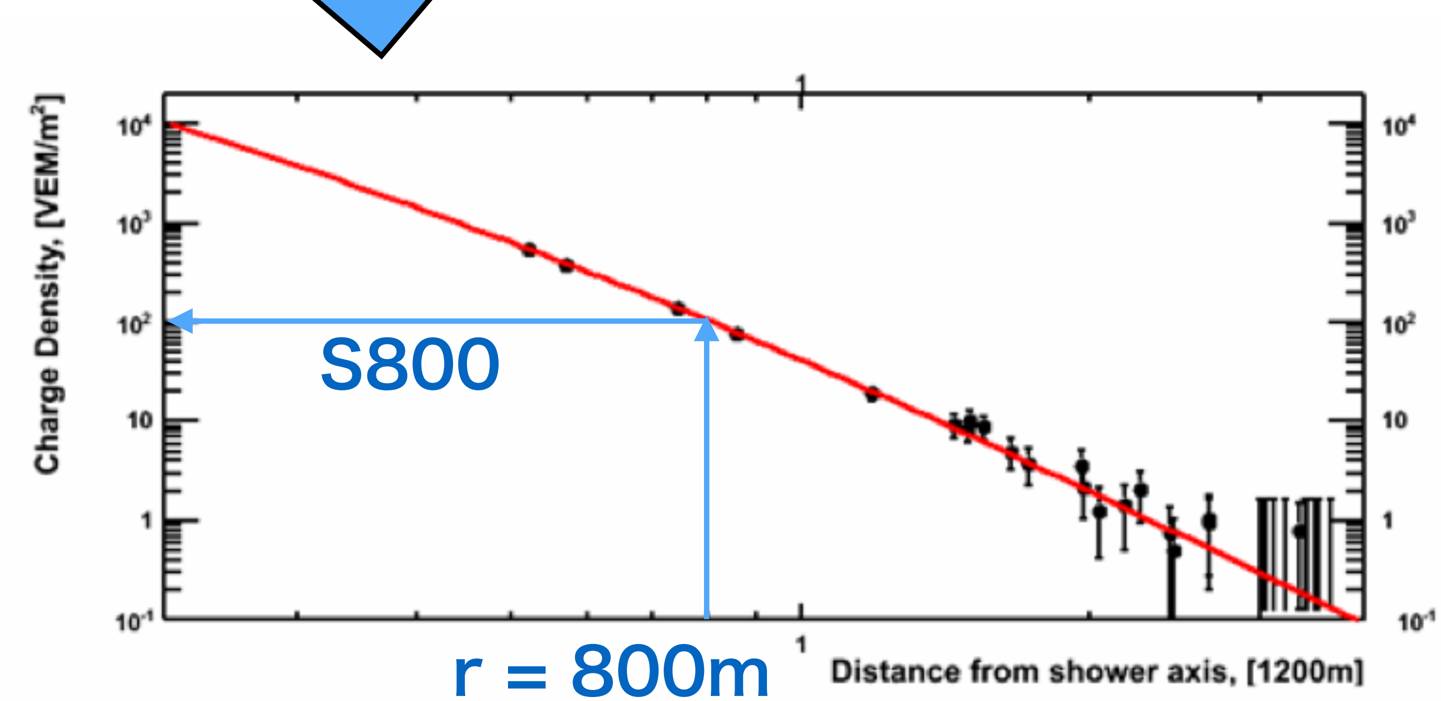
Primary energy determination

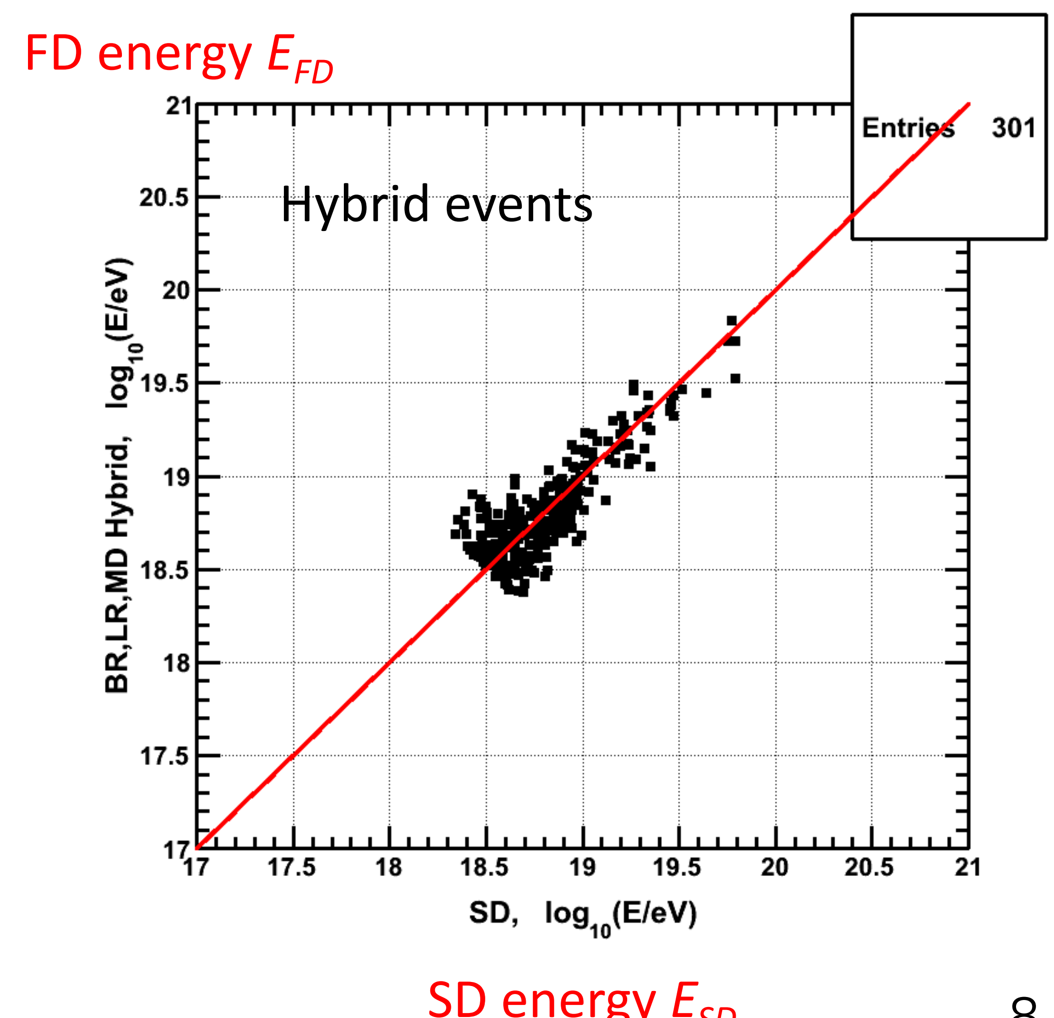


$$E'_{SD} = E'_{SD}(S800, \theta)$$

Scale to FD energy

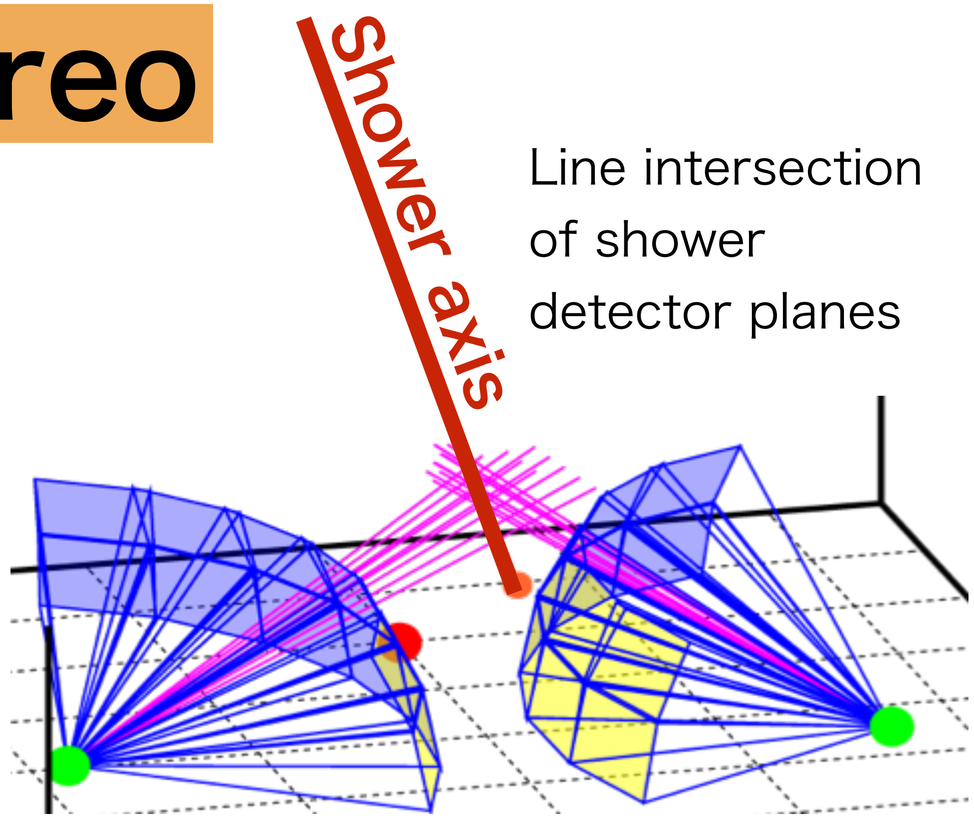
$$E_{SD} = E'_{SD} / 1.27$$



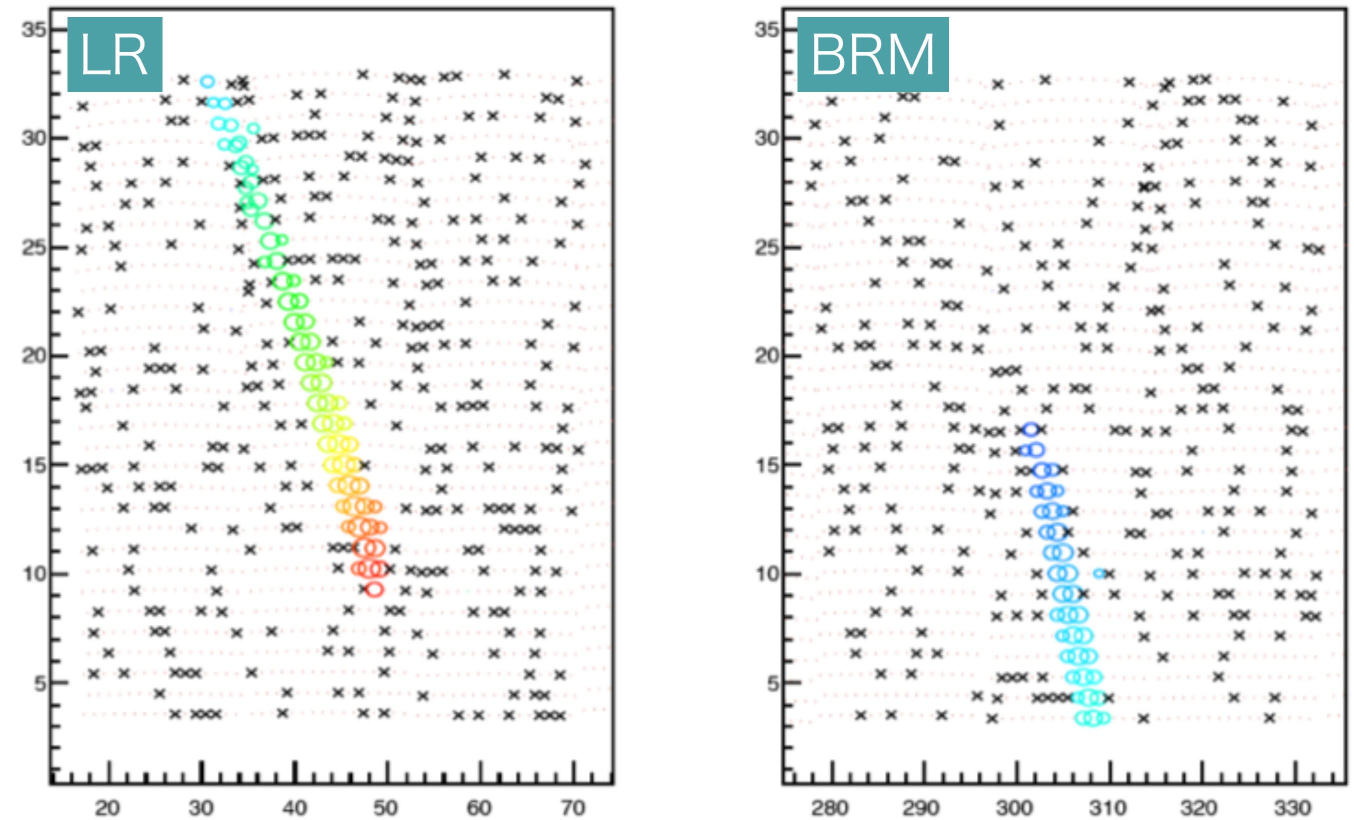


Event reconstruction

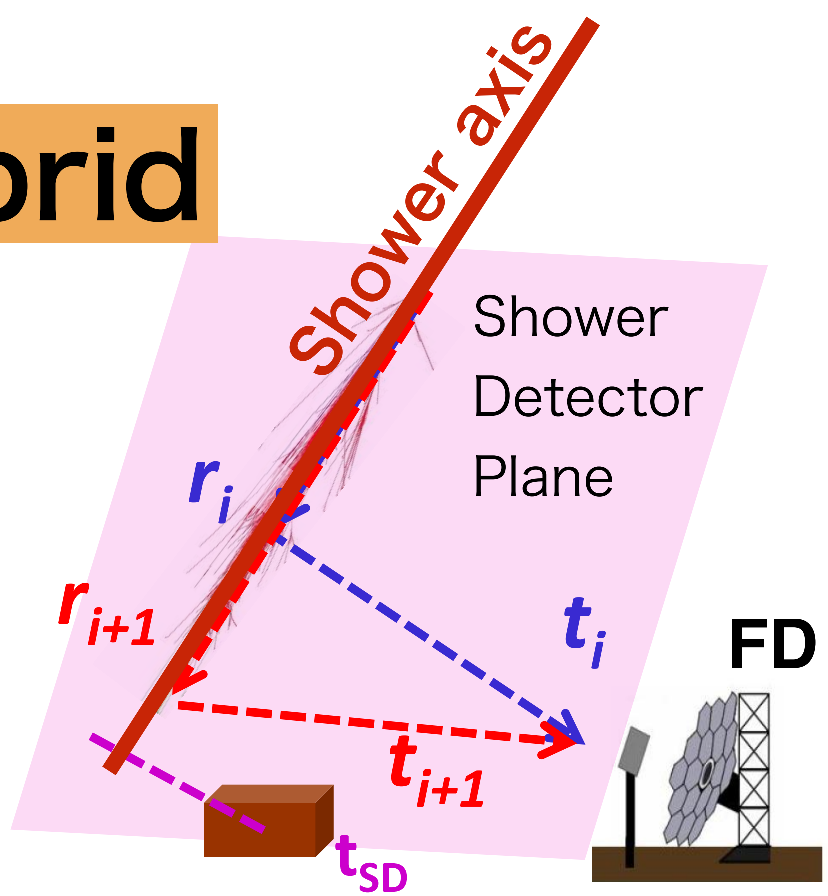
Stereo



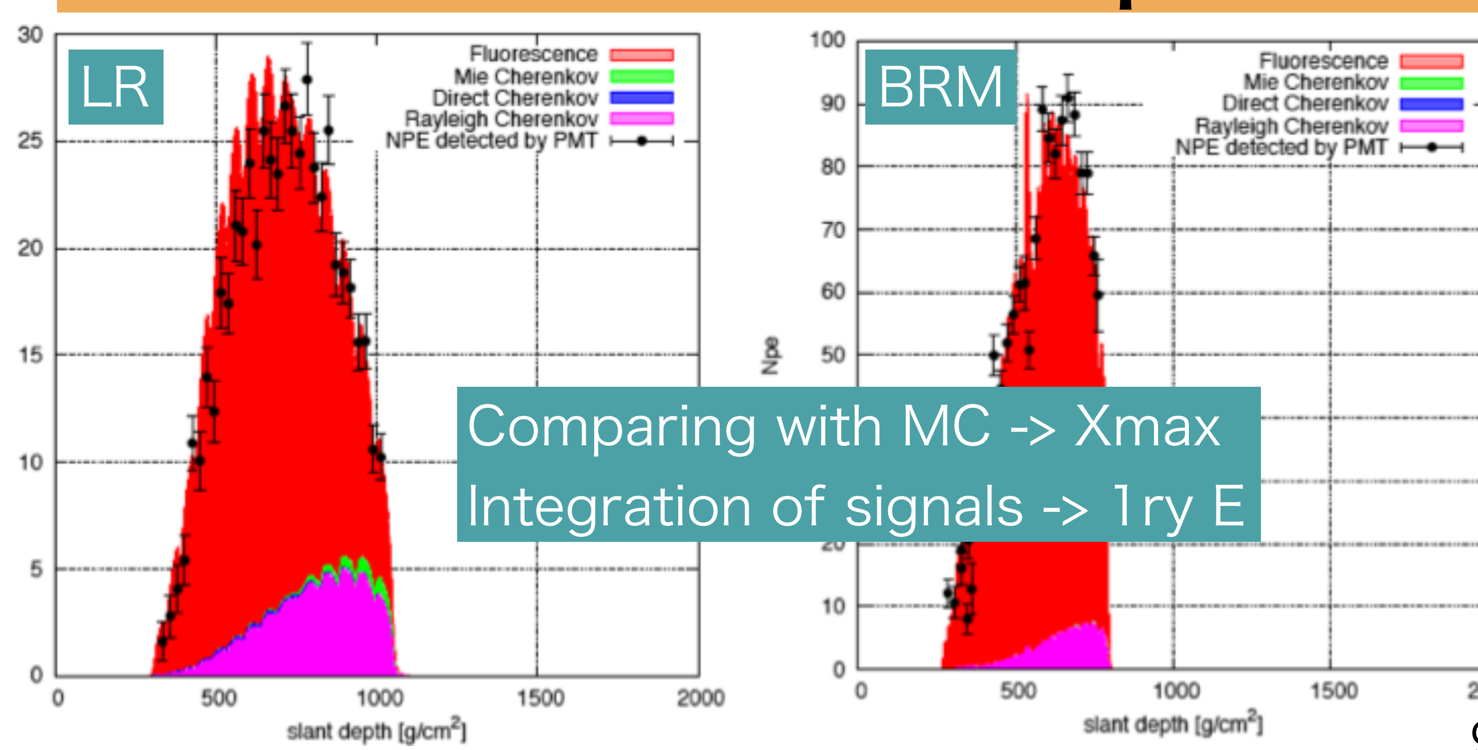
observed images



Hybrid



reconstructed shower profiles

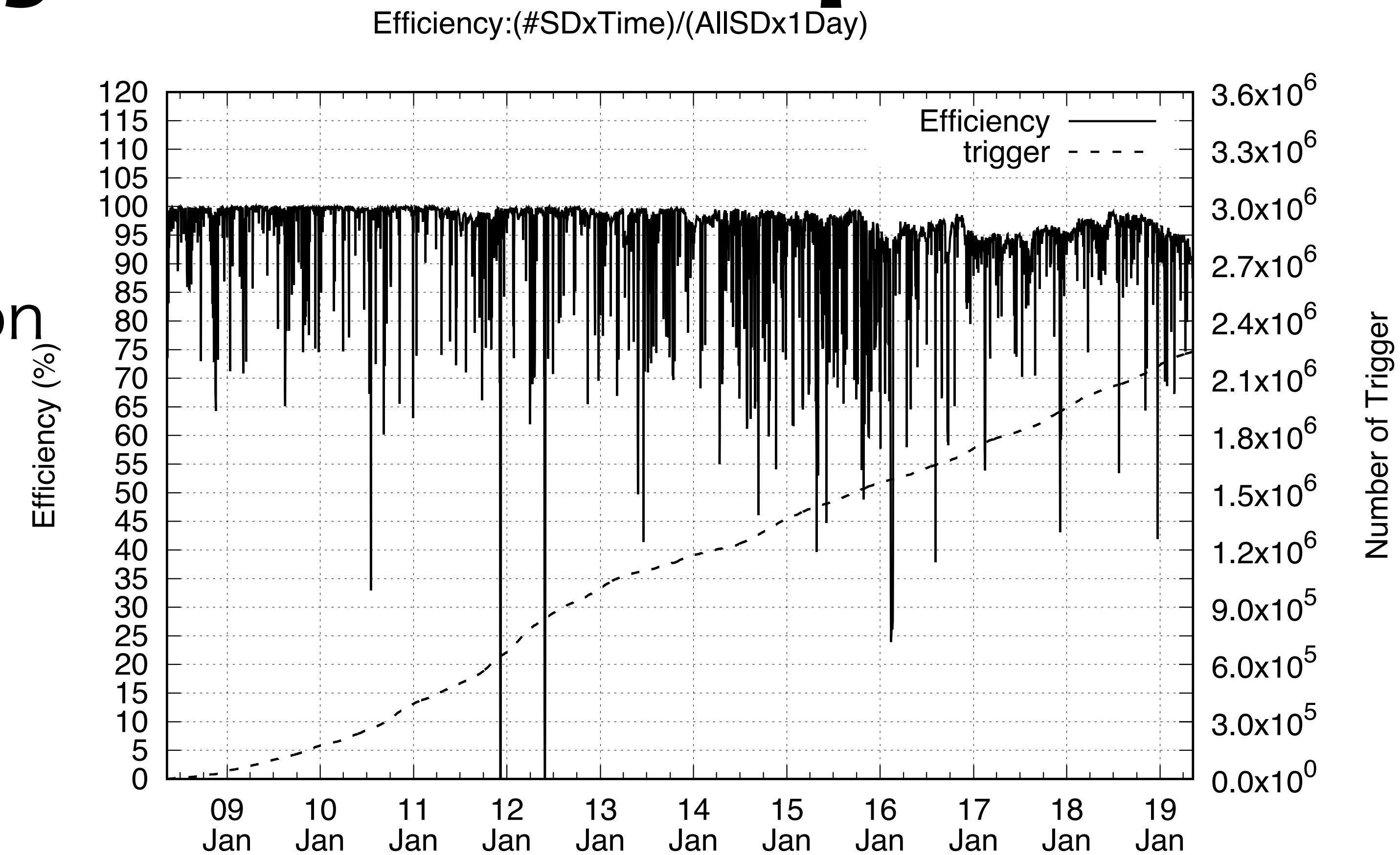


Comparing with MC -> Xmax
Integration of signals -> 1ry E

Status of 11 years of operations

SD array

94.5% of 507 SDs are in operation on 11 year average

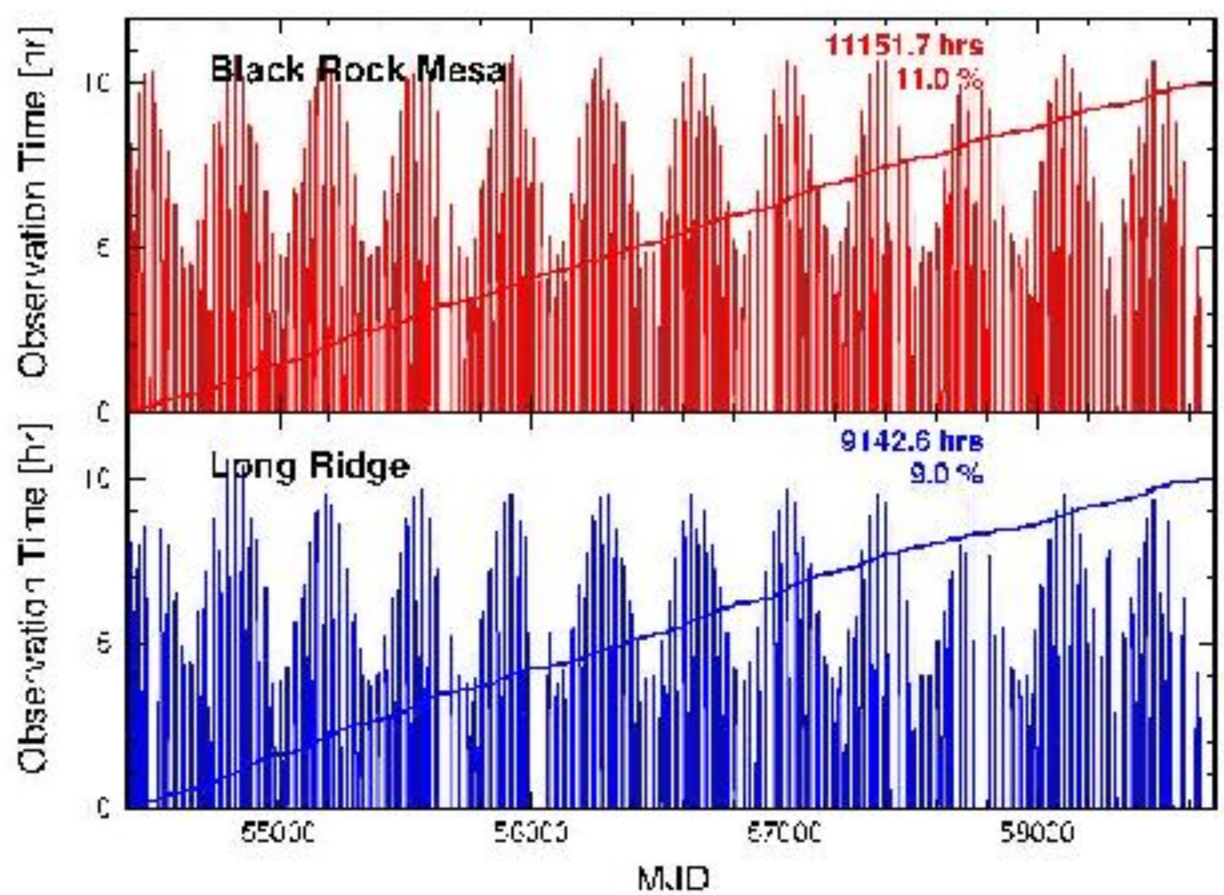


FD (BRM, LR)

Duty factors

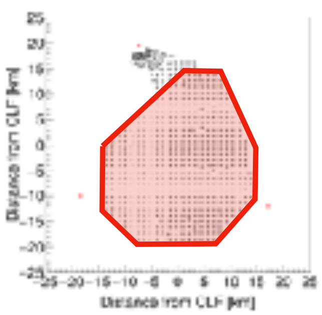
11.0% for BRM station,

9.0% for LR station



Energy spectrum

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

D. Ivanov

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)

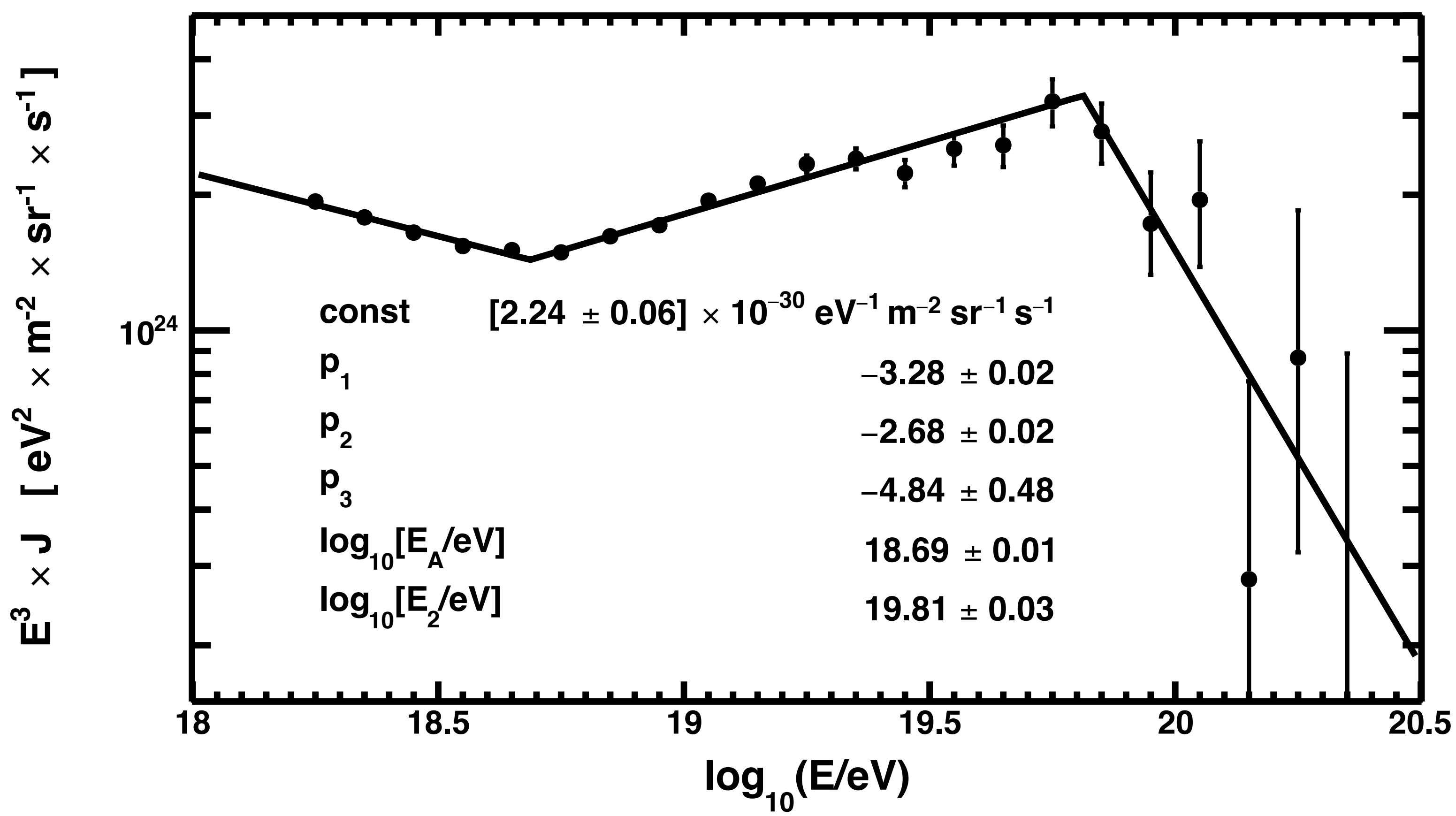
γ = -2.67 ± 0.02

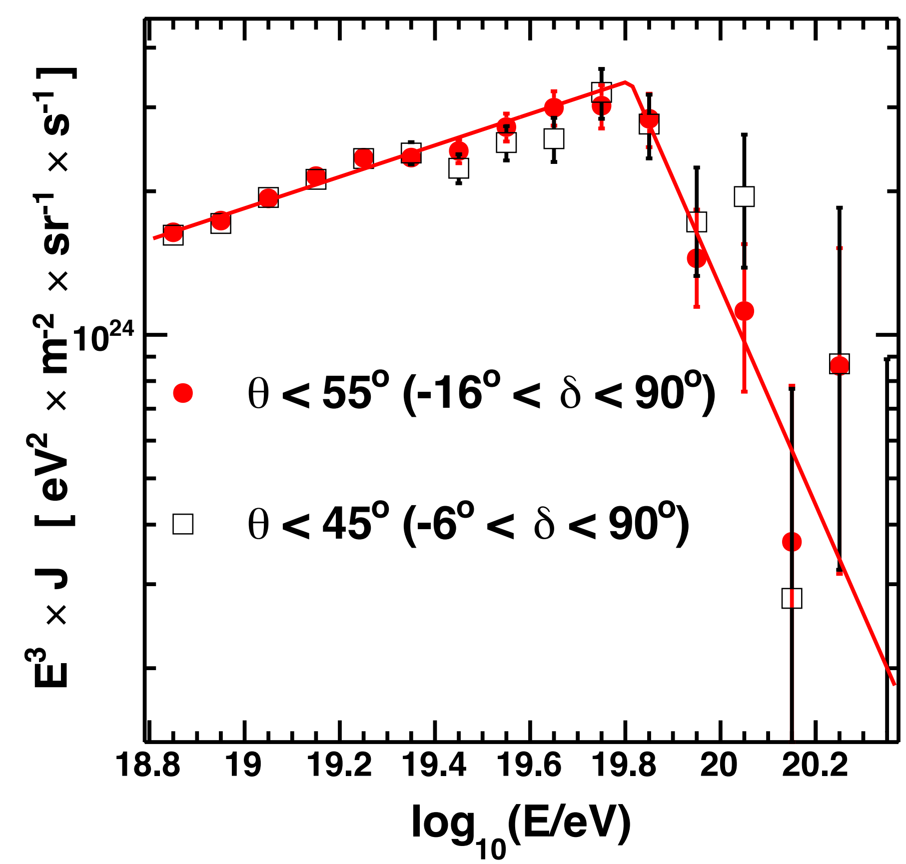
cutoff @ logE = 19.81 ± 0.03

γ = -5.3 ± 0.5

logE1/2 = 19.97 ± 0.04

Significance of suppression is 12.0 σ

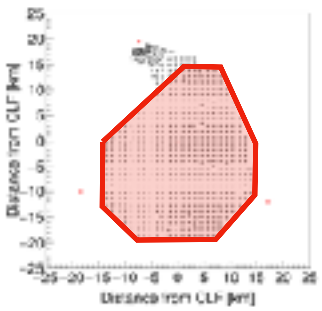




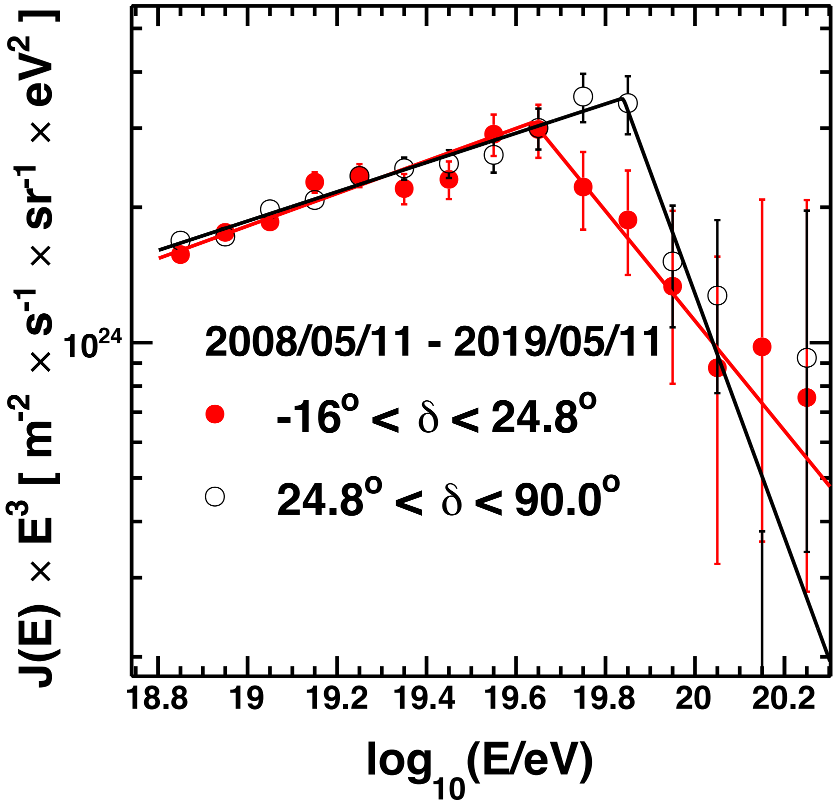
Energy resolution = 18 % logE > 19.0

Energy scale systematic uncertainty = 21 %

TA SD spectrum from 11 years of data



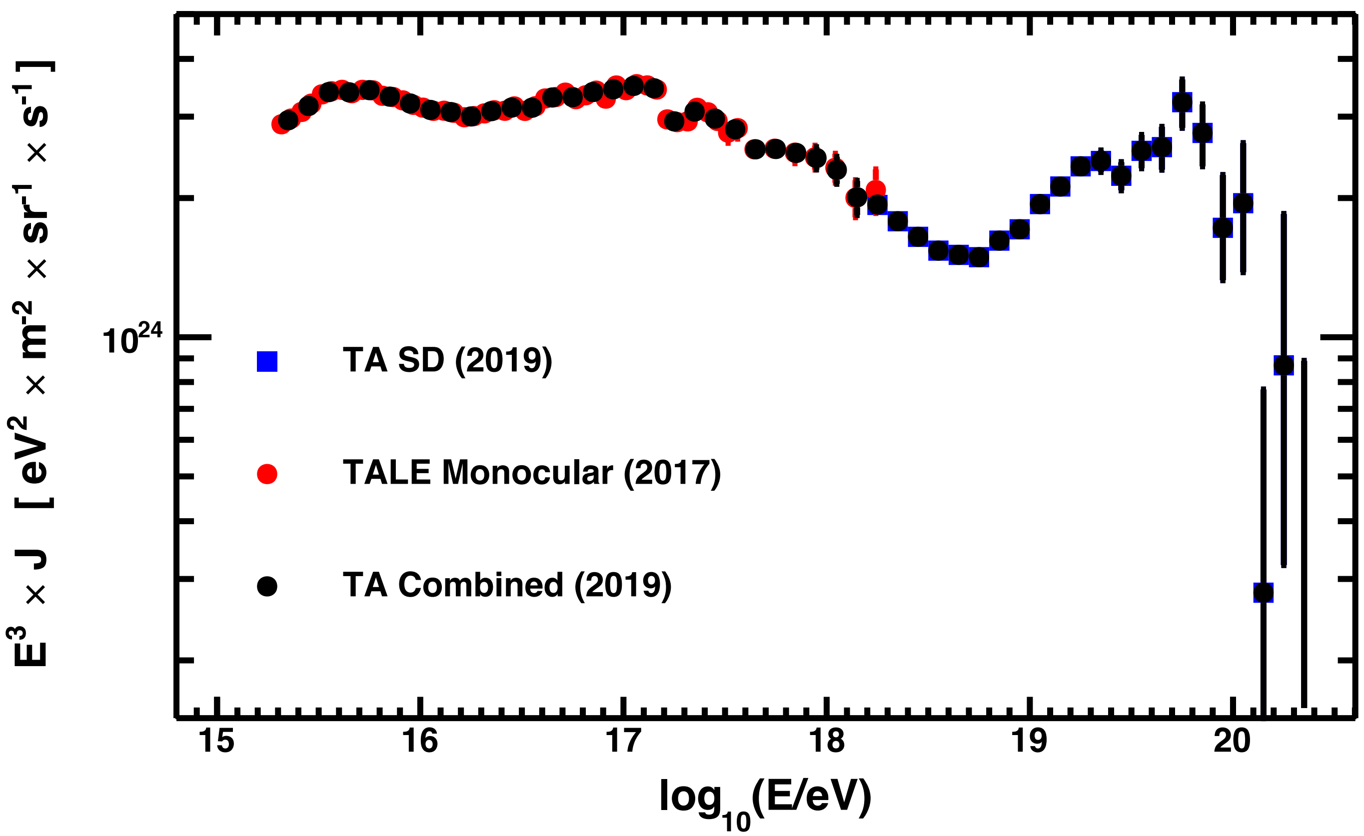
D. Ivanov



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°)

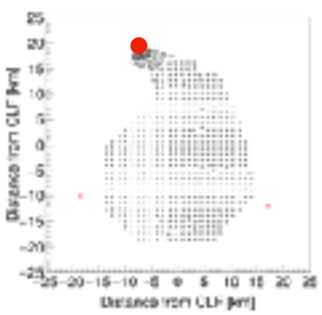
global significance = 4.3σ (local 4.7σ)



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

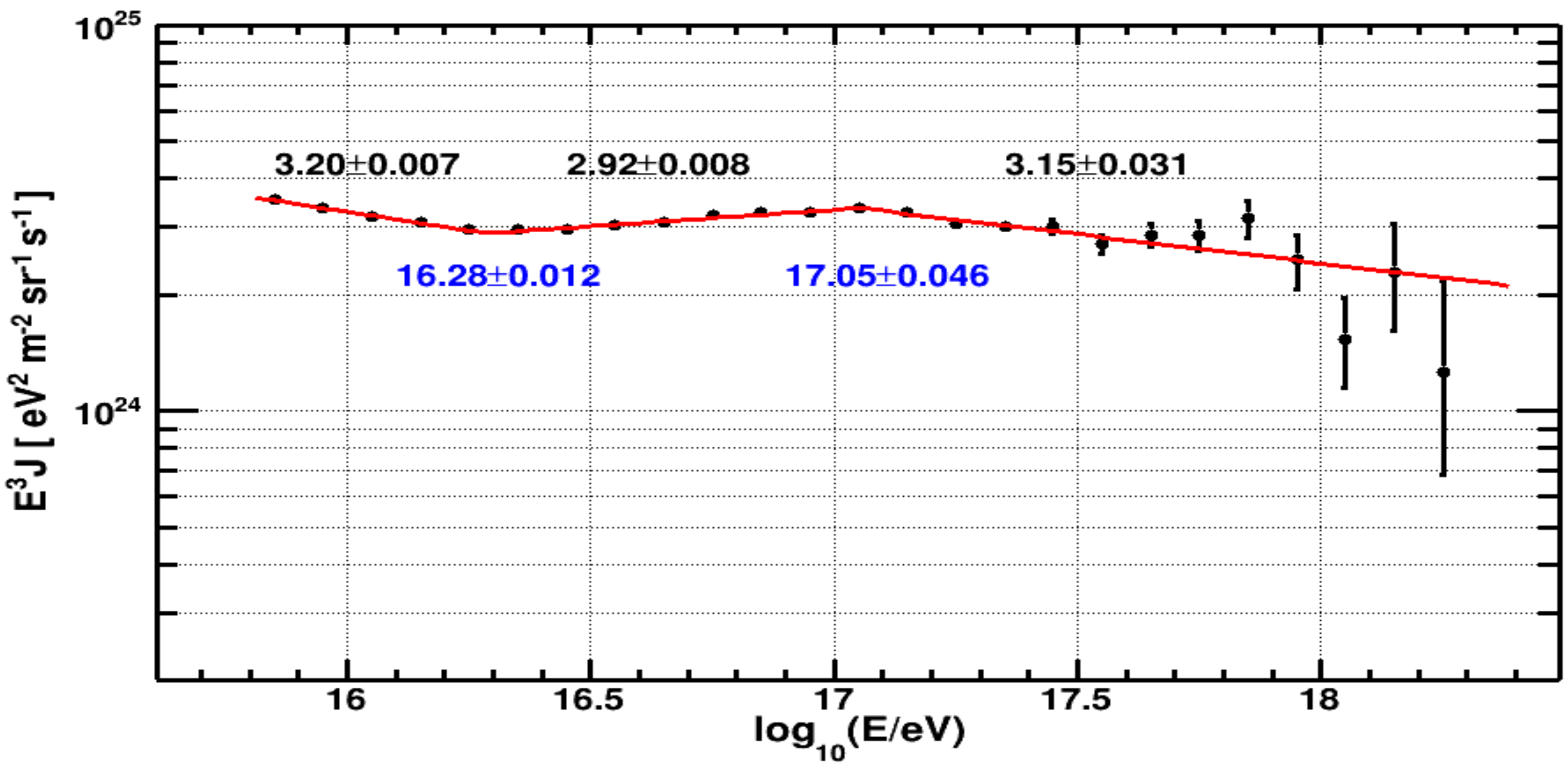
knee @ logE ~ 15.5
low energy ankle @ logE = 16.22 ± 0.02
second knee @ logE = 17.04 ± 0.04
ankle @ logE = 18.69 ± 0.01
cutoff @ logE = 19.81 ± 0.03

TALE FD monocular reconstruction



Energy spectrum from 4 years of data measured by TALE FD with monocular reconstruction (Jun. 2014 - Nov. 2018)

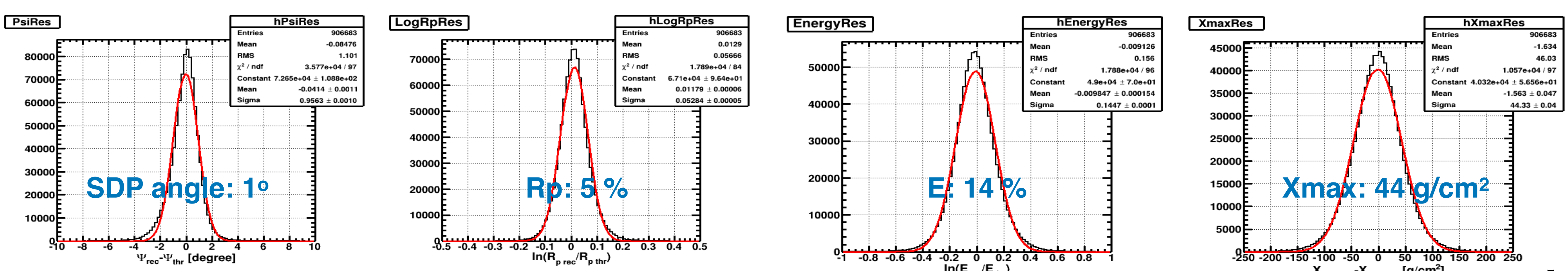
KIM, Jihee



Cherenkov-dominant and mixed events are used.

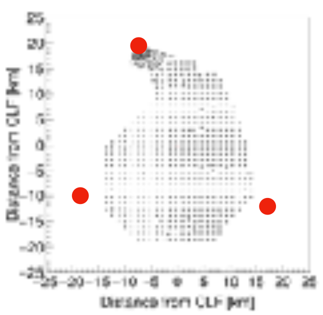
Aperture is calculated by EPO-LHC MC.

Result of resolution studies by MC

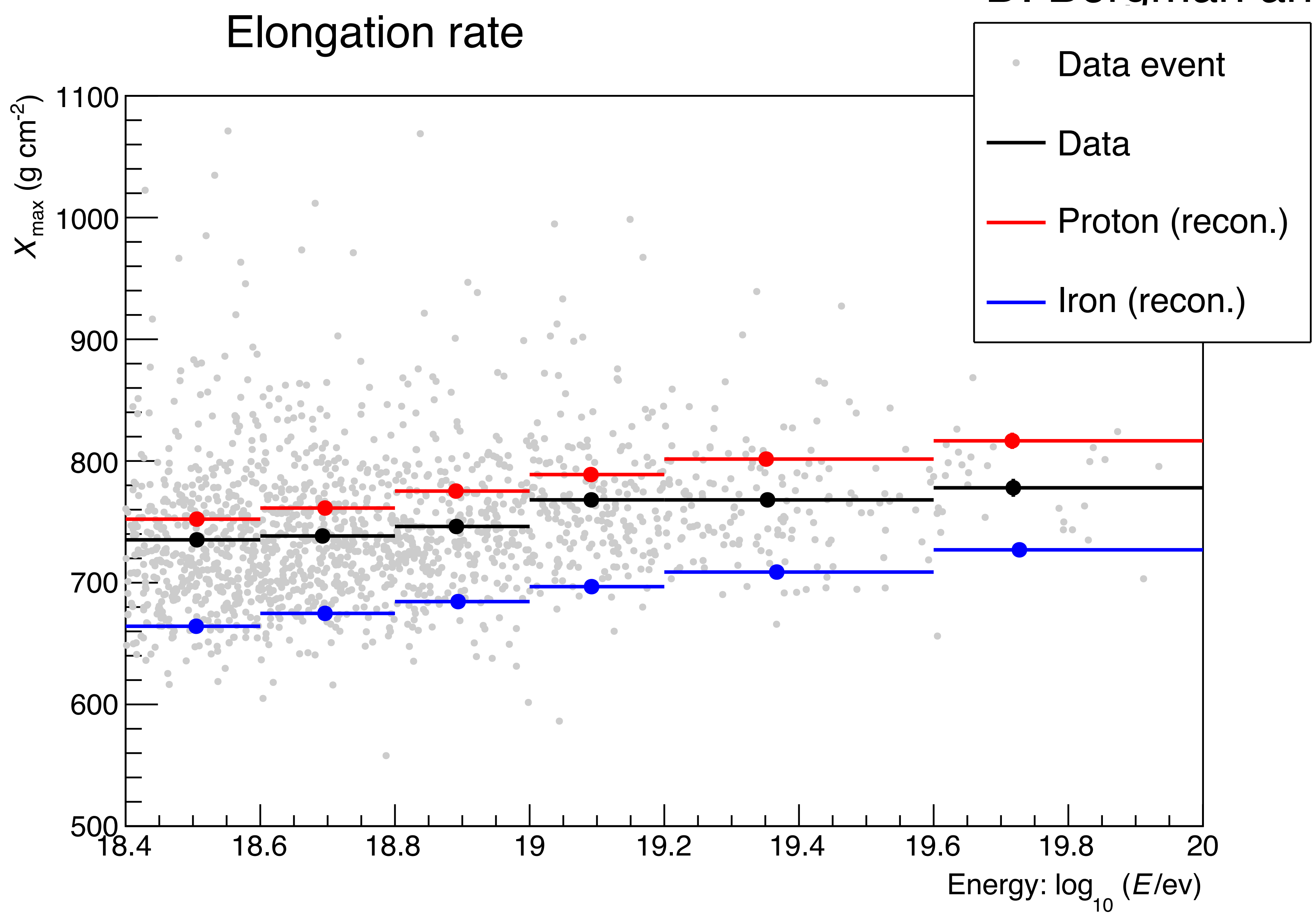


Chemical composition

TA stereo: Xmax distribution



D. Bergman and T. Stroman

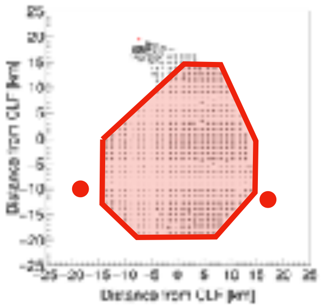


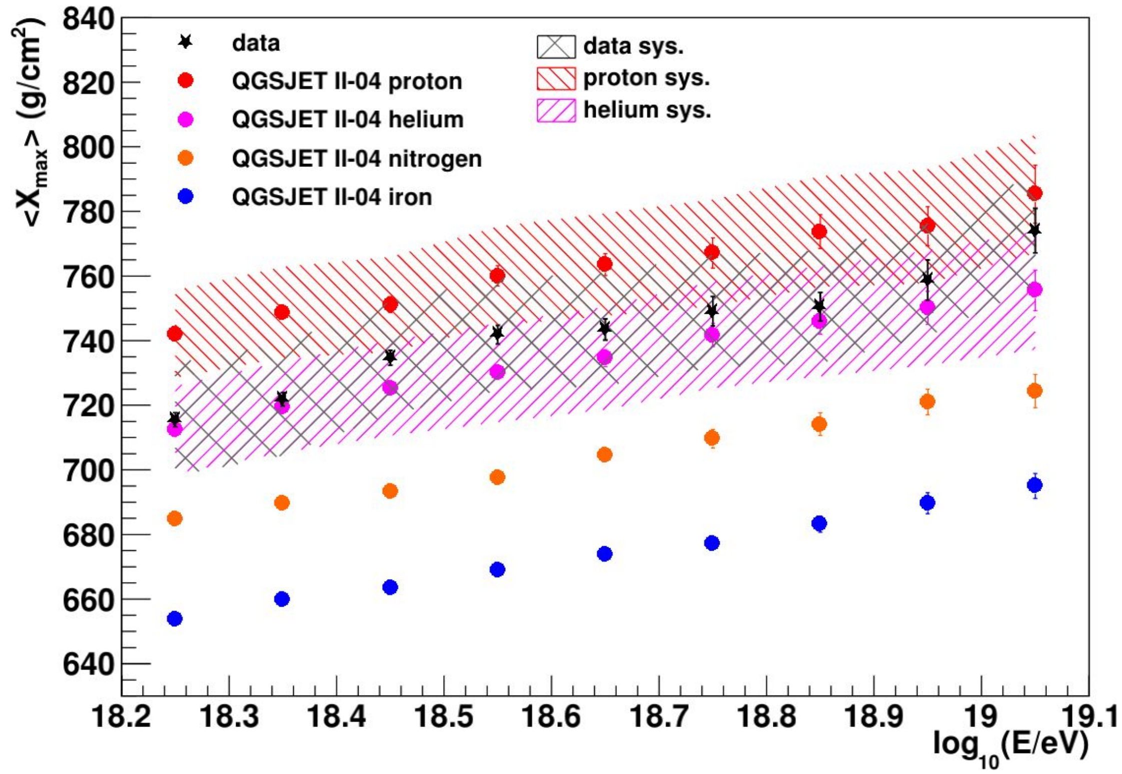
Scatter plot of Xmax vs energy.
<Xmax> from measured data and from QGSJET II-04 MC predictions (proton and iron)
Data support a light component at any energy.

Systematic uncertainty on <Xmax> is 15 g/cm^2
Xmax resolution < 25 g/cm^2 , Energy resolution < 7 % (energy dependent)
Quality cuts: Coincidence FDs within 2 ms, Downward-going, SDP angle < 170^o,
track length >= 6^o, duration >= 2 us, Xmax in FOV

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

W. Hanlon

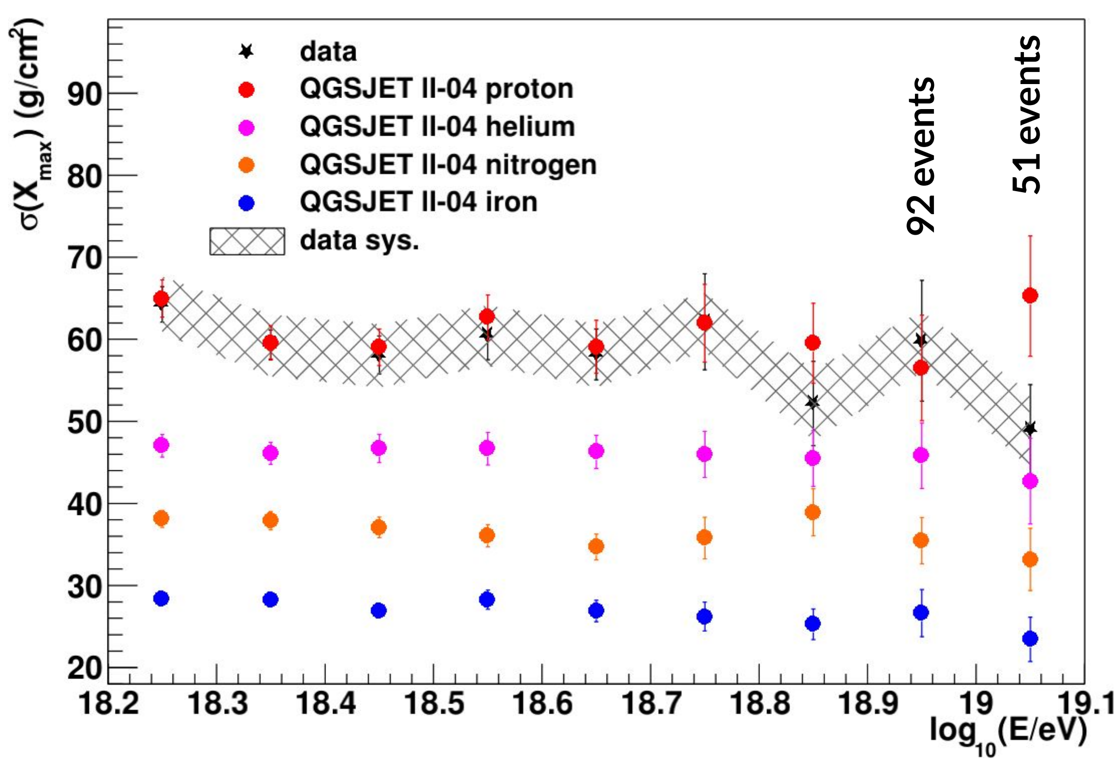




< Xmax > along with predictions of QGSJET II-04 p, He, N and Fe

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

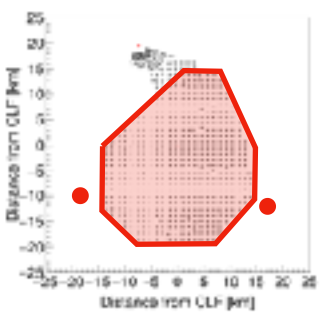
Systematic uncertainty on <Xmax> is 17 g/cm^2
Xmax bias < 1 g/cm^2
Xmax resolution = 17.2 g/cm^2
Energy resolution = 5.7 %



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.

Quality cuts:
D_{border}>100m, FD track length > 10°,
FD good PMT > 11, SDP angle < 130°,
FD track > 7us, Θ < 55°, Xmax in FOV,
Good weather

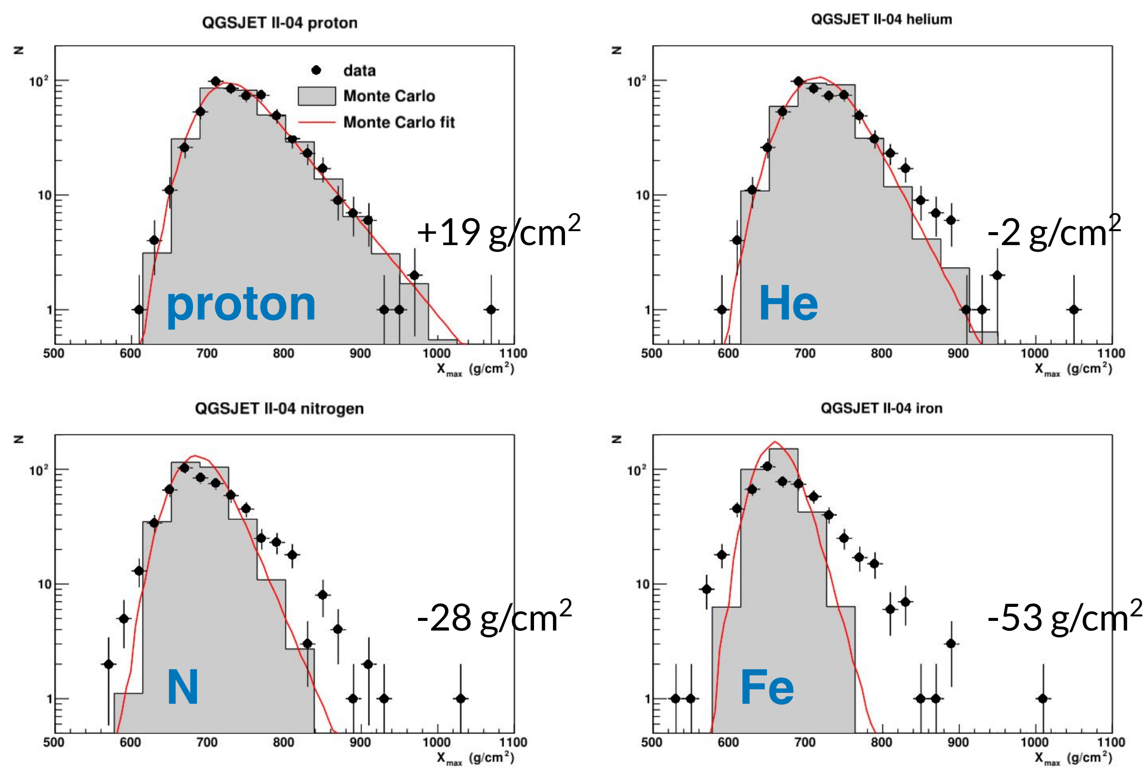
TA BRM+LR+SD hybrid: single element model



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

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

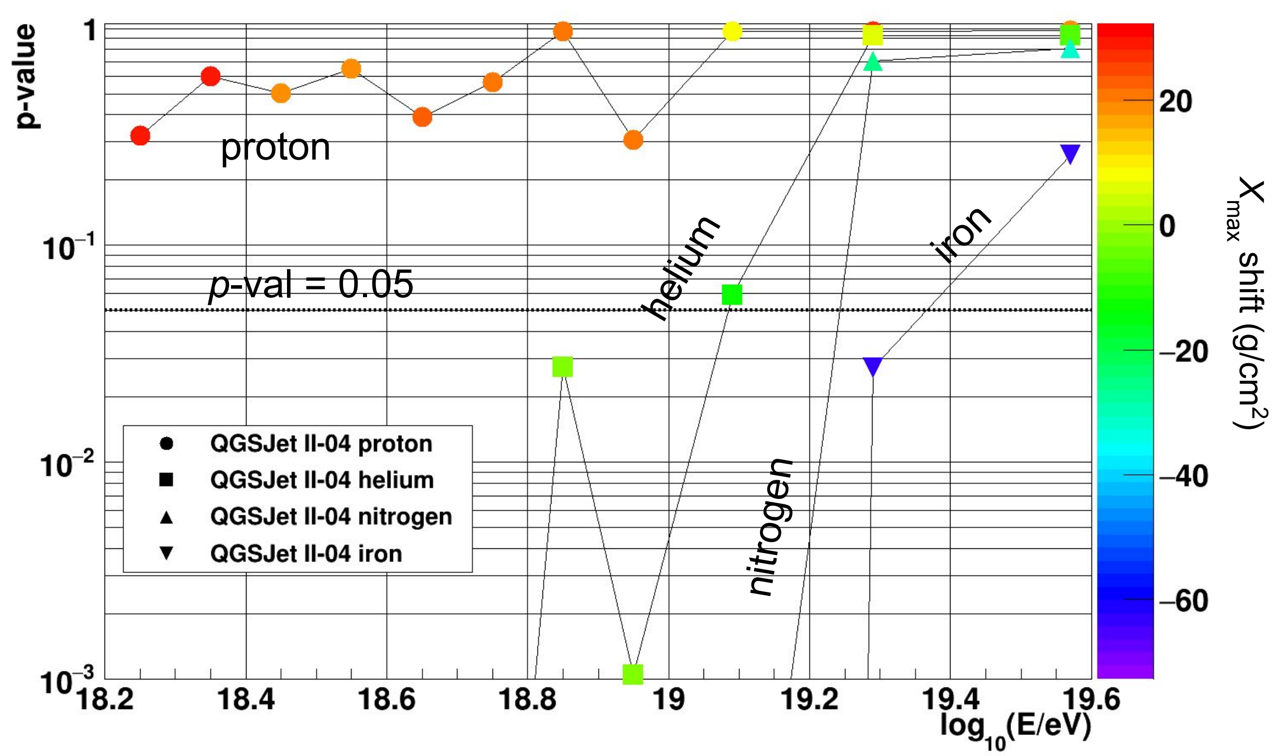
W. Hanlon



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/cm^2)



Data is compatible with QGSJET II-04 proton from $10^{18.2}$ to $10^{19.9}$ eV with systematic shifting about 20 g/cm^2.

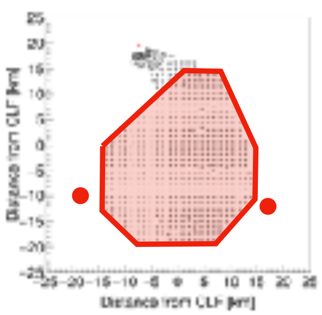
Other components are not compatible in E < 10^{19}eV

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

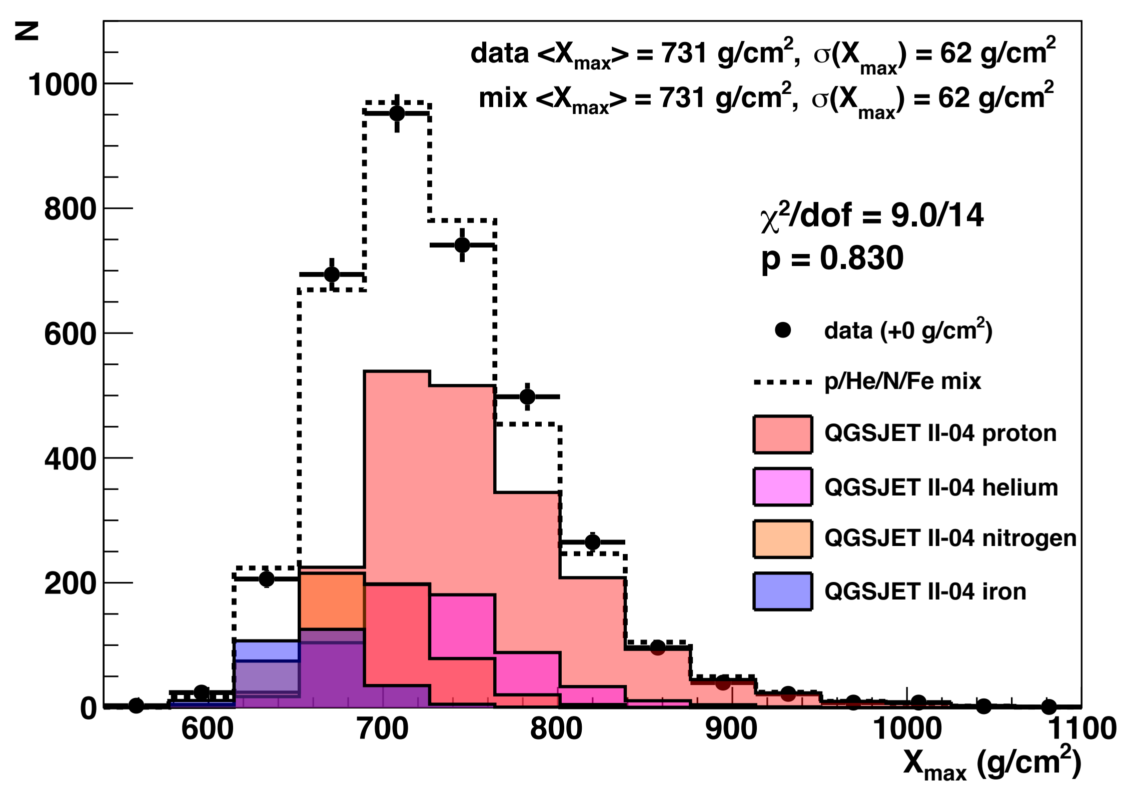
Fe requires a shift of ~ 50 g/cm^2

TA BRM+LR+SD hybrid: 4 element model

W. Hanlon



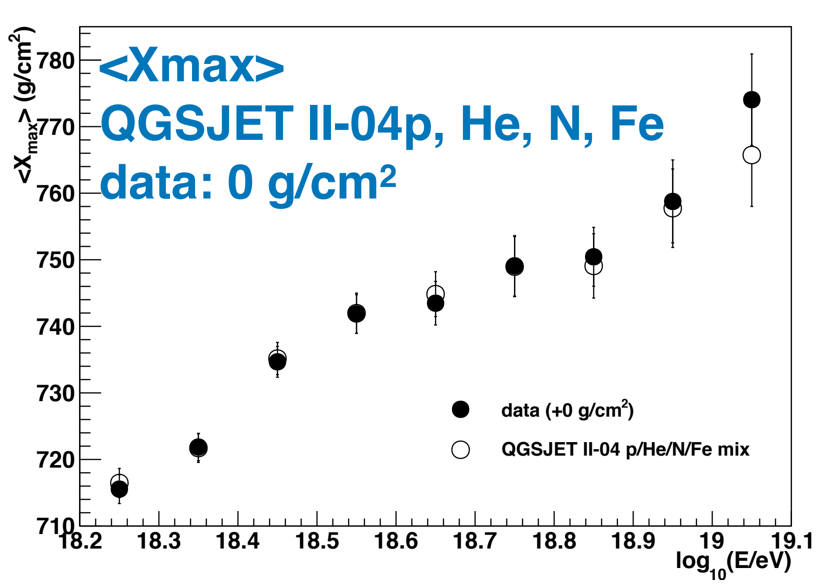
QGSJET II-04 proton, He, N, Fe, data: 0 g/cm²

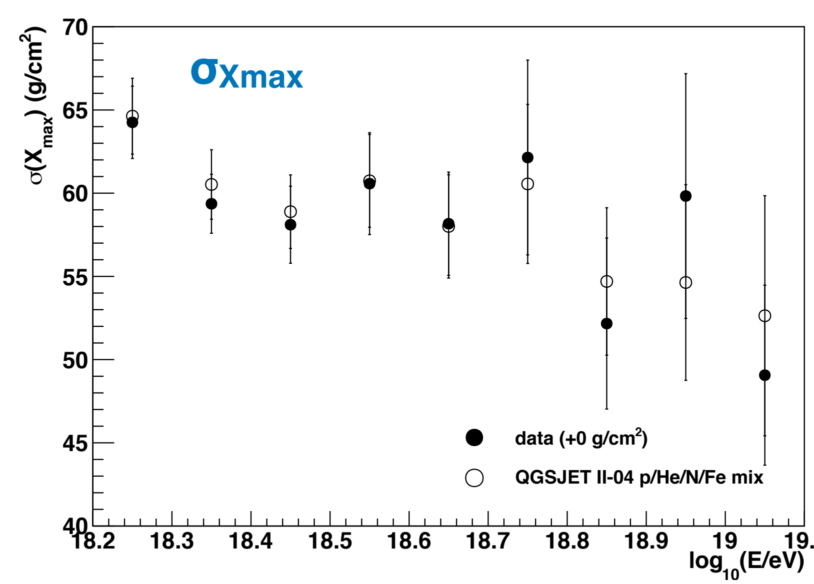


Test the agreement of data and 4 component mix by comparing data and MC Xmax distributions (No systematic shifting).

For $10^{18.2}$-$10^{19.1}$ eV, minimum χ^2 is found at the fraction, proton = 57%, He = 18%, N = 17%, Fe = 8%.

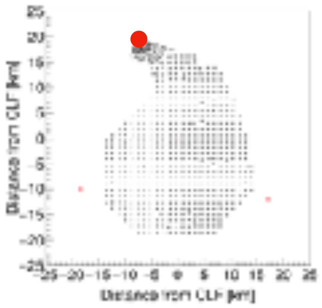
(Xmax systematic uncertainty = 17 g/cm²)





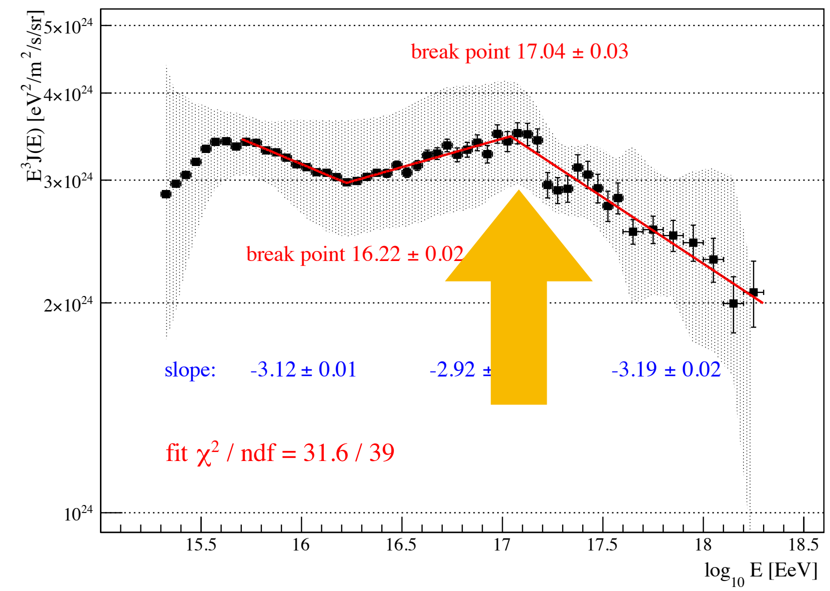
<Xmax> and σ_{Xmax} of the 4 element mix are within the statistical uncertainty of the data.

TALE FD monocular reconstruction



T. AbuZayyad

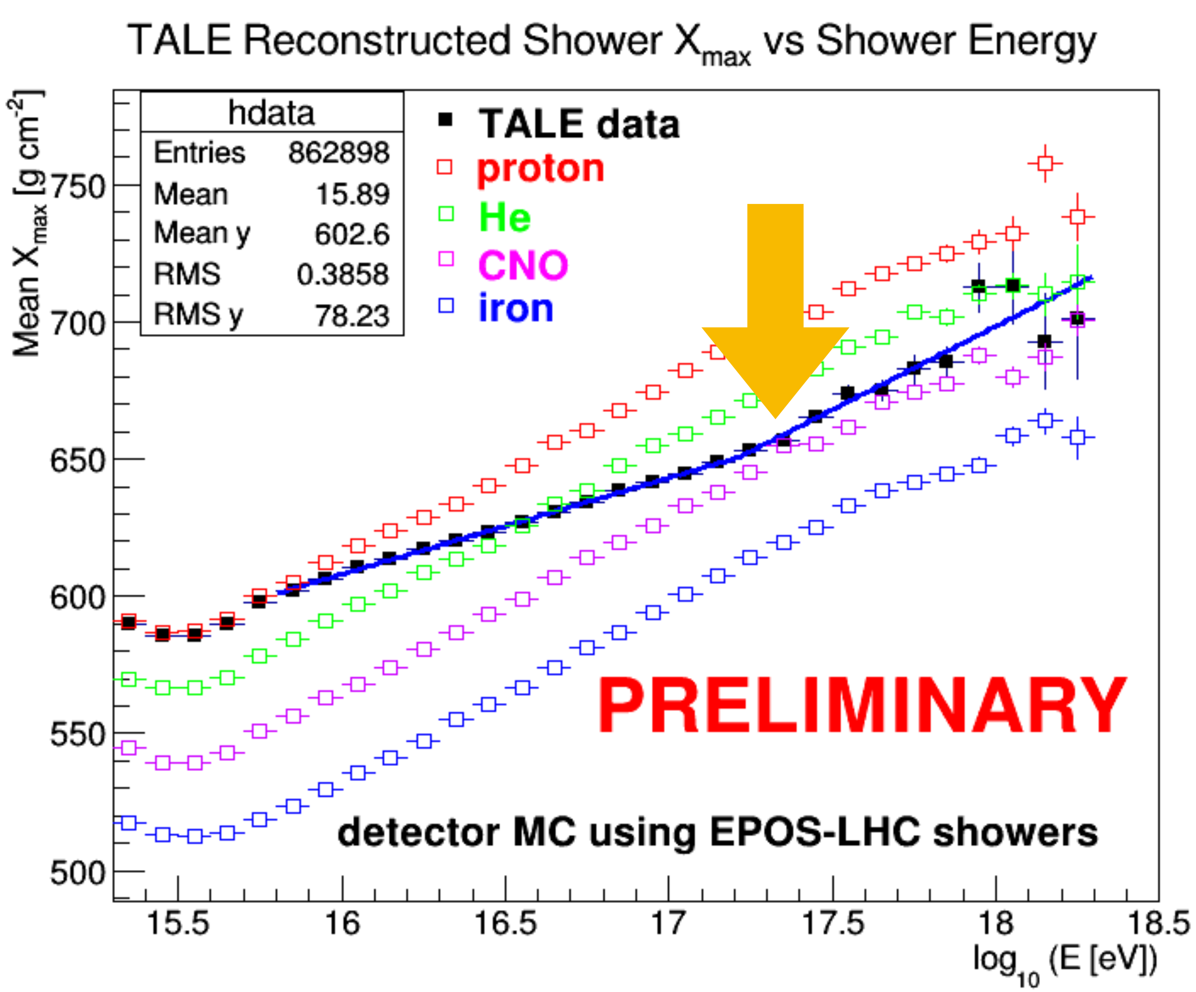
TALE FD monocular spectrum (2 years)
Ap. J., 865, 74(2018), arXiv: 1803.01288

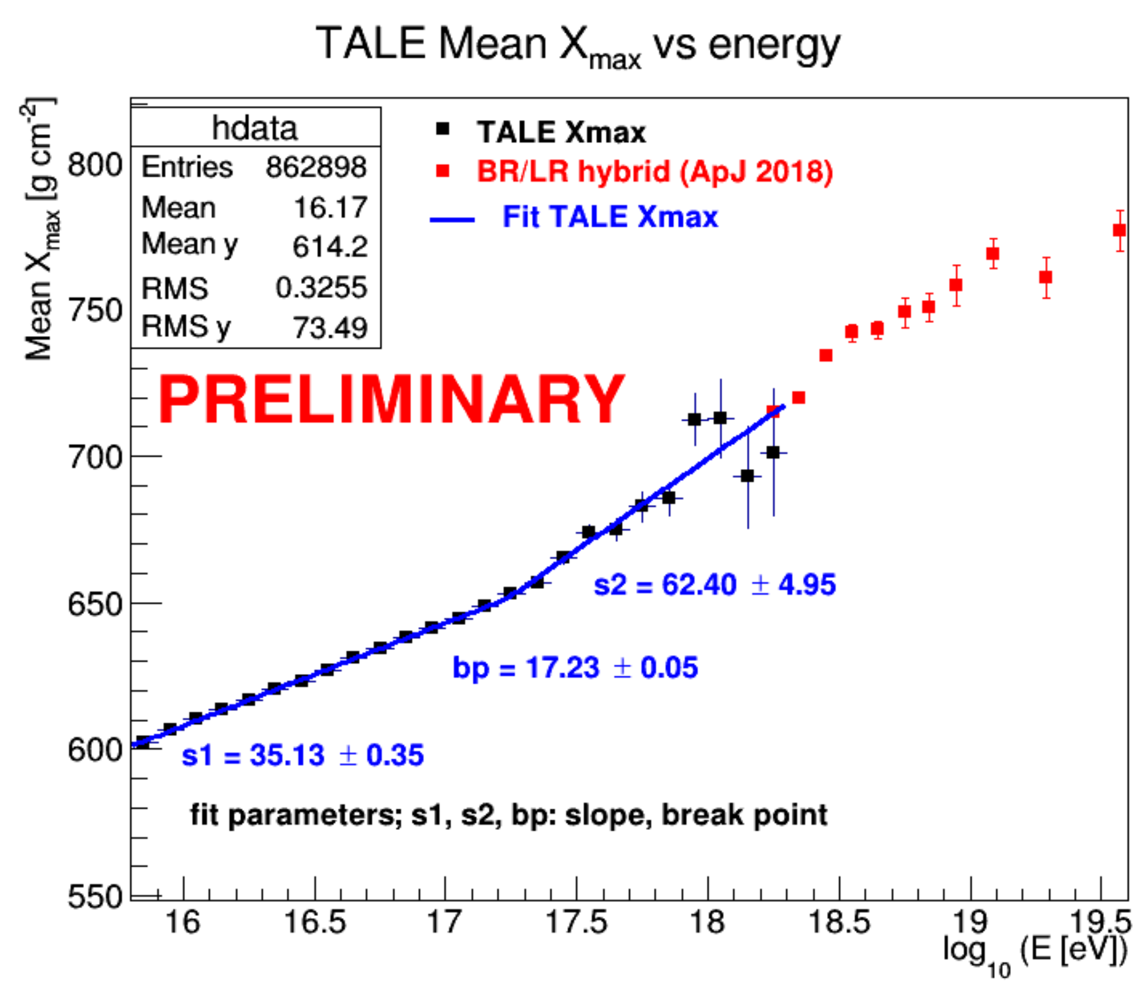


Xmax measured by TALE FD with monocular reconstruction
4 years of data (Jun. 2014 - Nov. 2018)

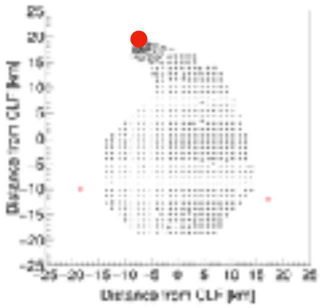
Change in Xmax elongation rate at an energy of ~10^{17} eV
(It is likely correlated with 2nd knee in the energy spectrum)

Smooth connection of the low(TALE) and the high(BR/LR hybrid) energy rails.





TALE FD monocular reconstruction

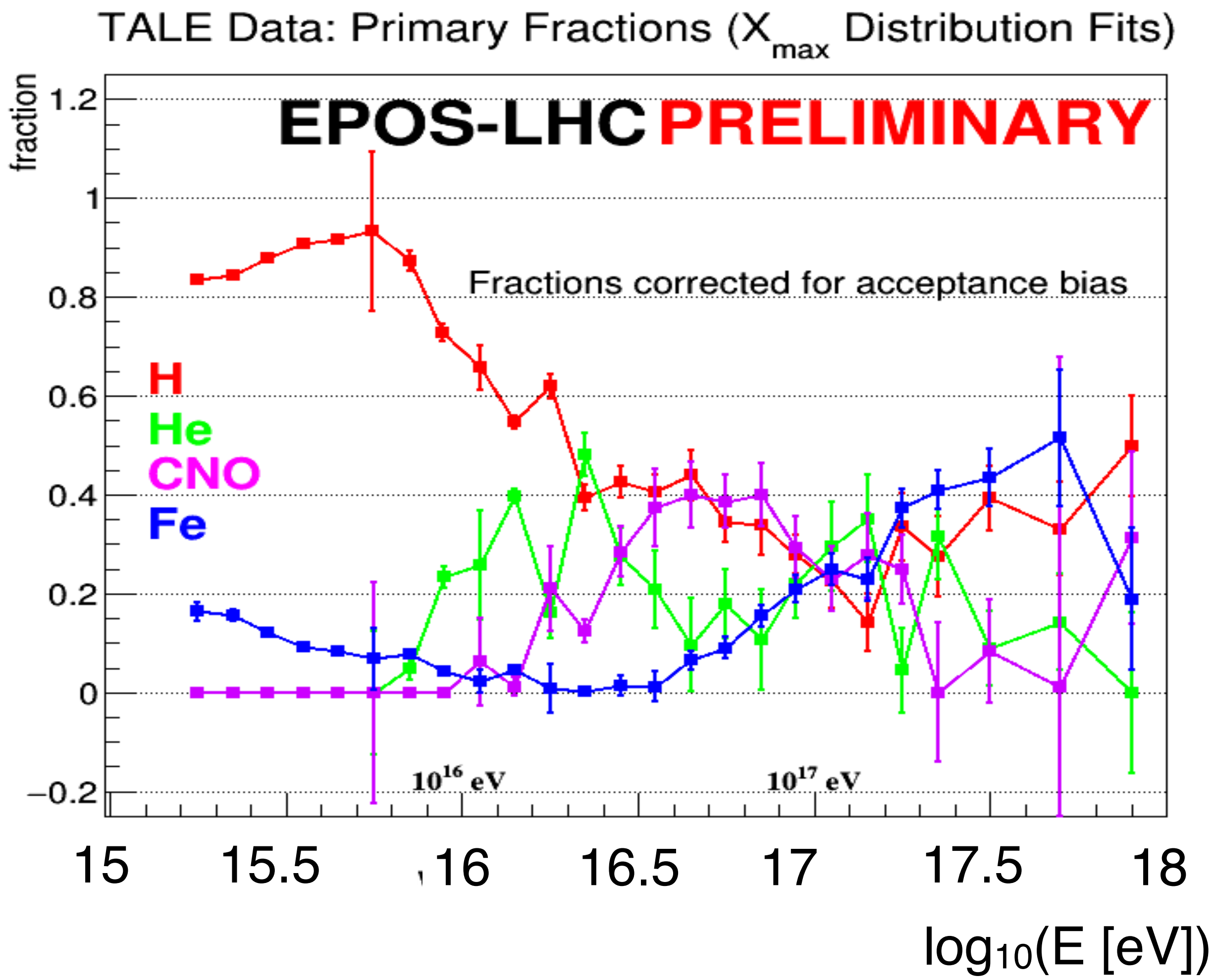


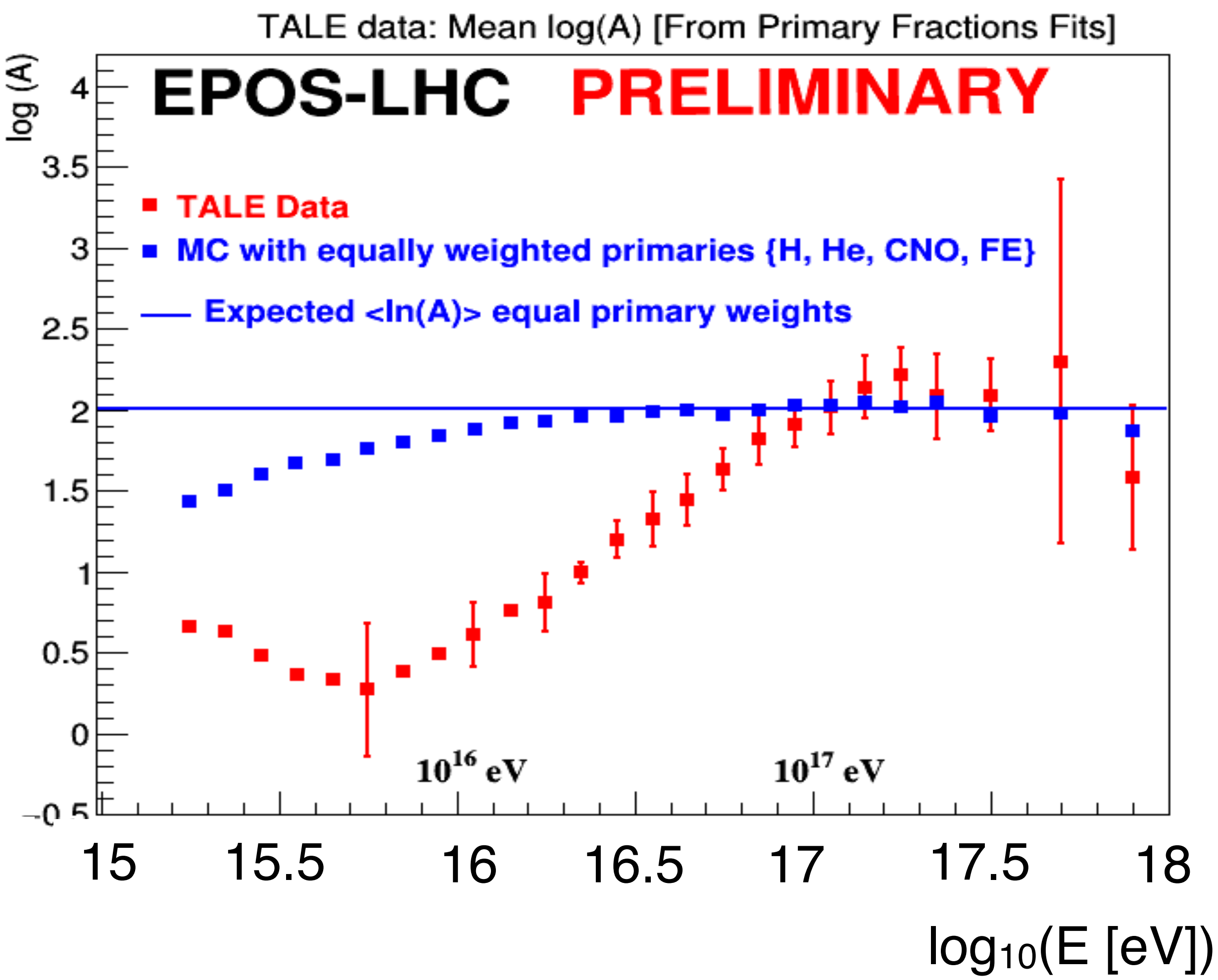
T. AbuZayyad

Xmax measured by TALE FD with monocular reconstruction
4 years of data (Jun. 2014 - Nov. 2018)

4 component fit to measured Xmax distribution

Change in composition from predominantly light mix at lower energy to heavy mix at ~ 10^{17} eV

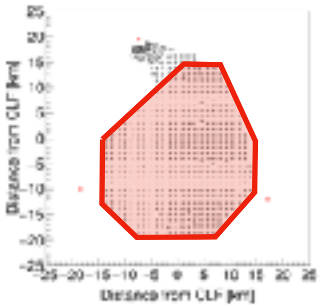


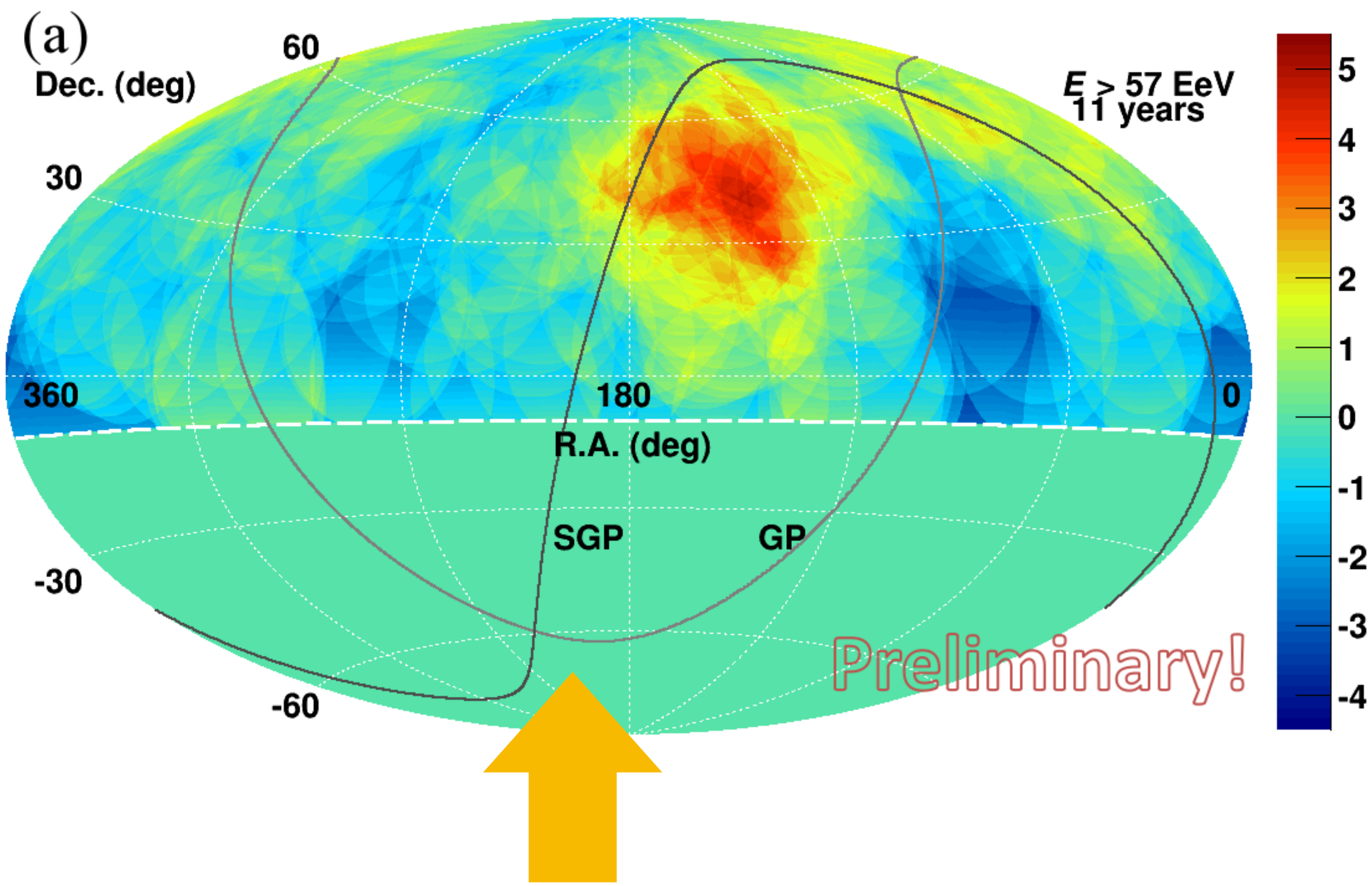


Anisotropy study

"Hotspot" update from 11 years of data

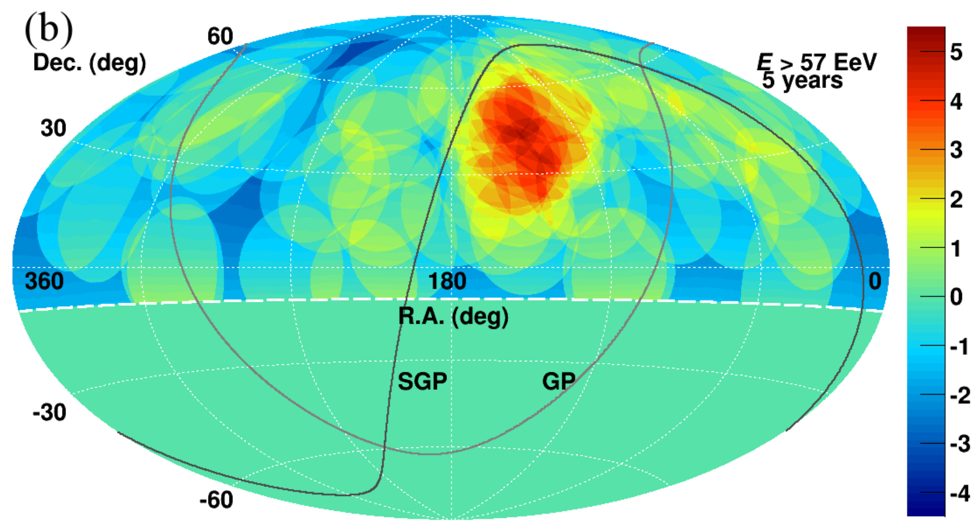
K. Kawata





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

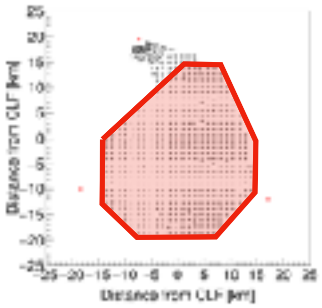


Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

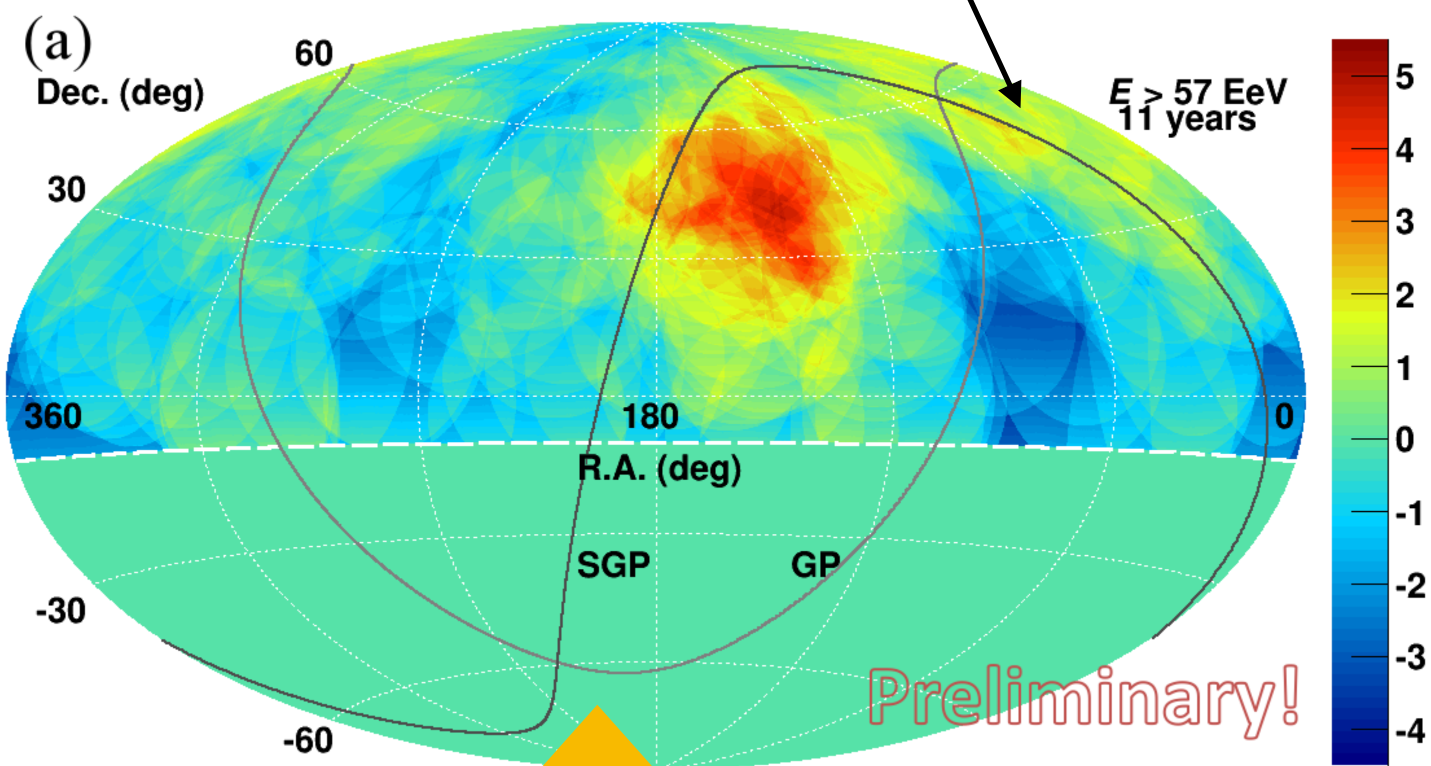
E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)

“Hotspot” update from 11 years of data

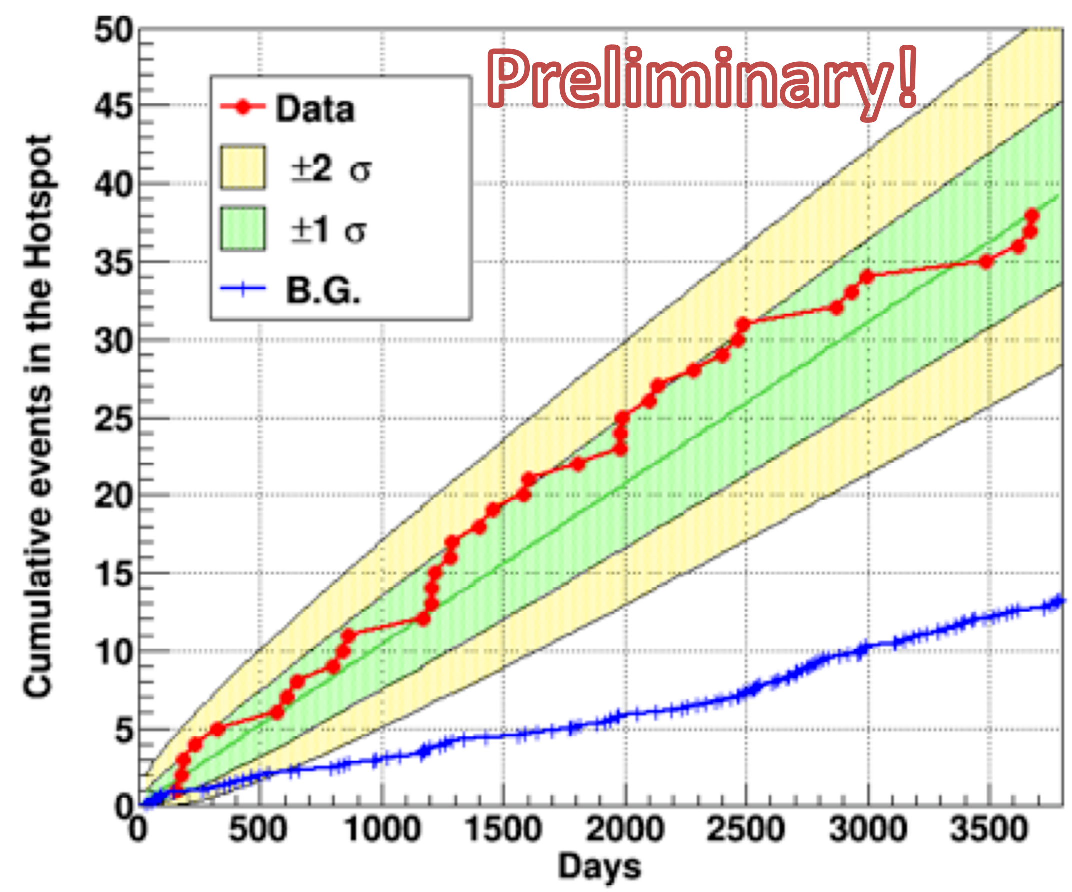
K. Kawata



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



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^{o}, δ=40.3^{o}, 25^{o} radius, 22^{o} from SGP), expected=14.2 events

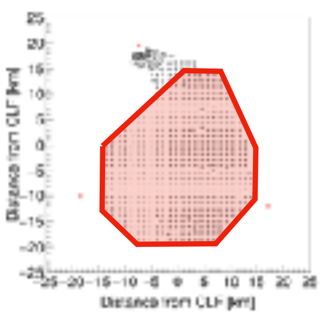
local significance = 5.1 σ, chance probability → 2.9σ

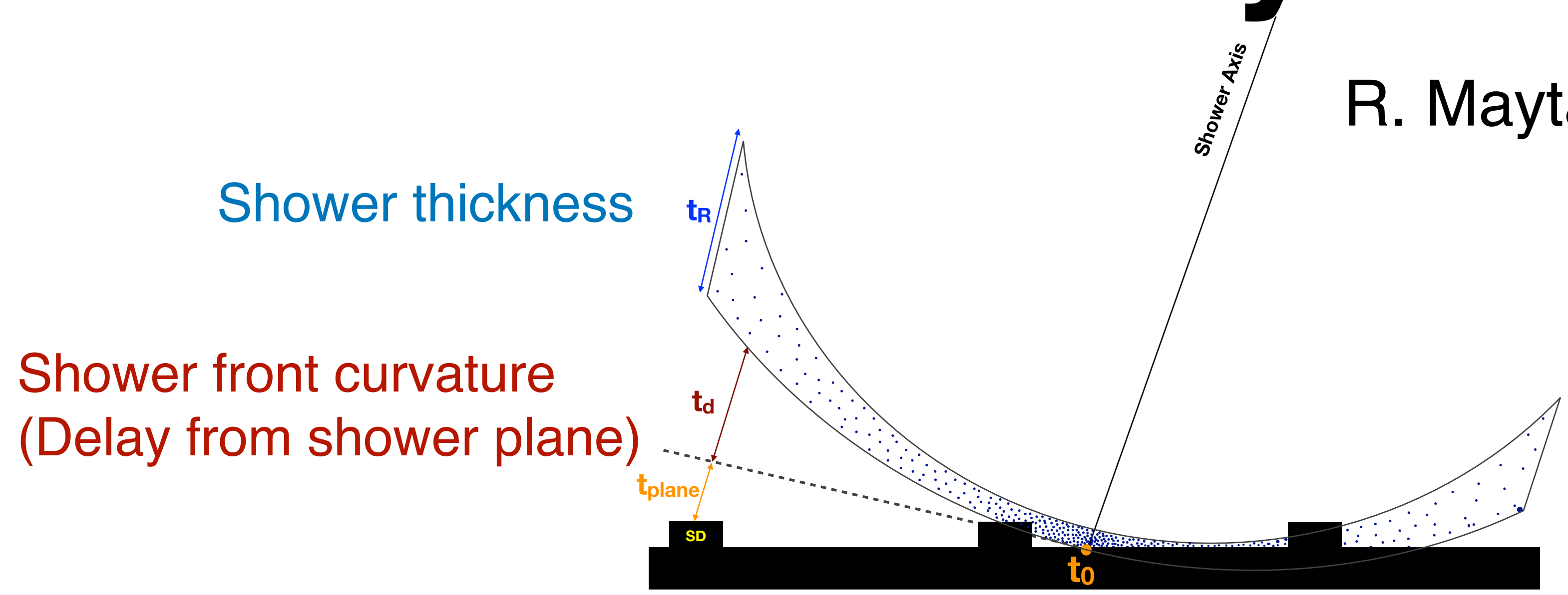
25^{o} over-sampling radius shows the highest local significance (scanned 15^{o} to 35^{o} with 5^{o} step)

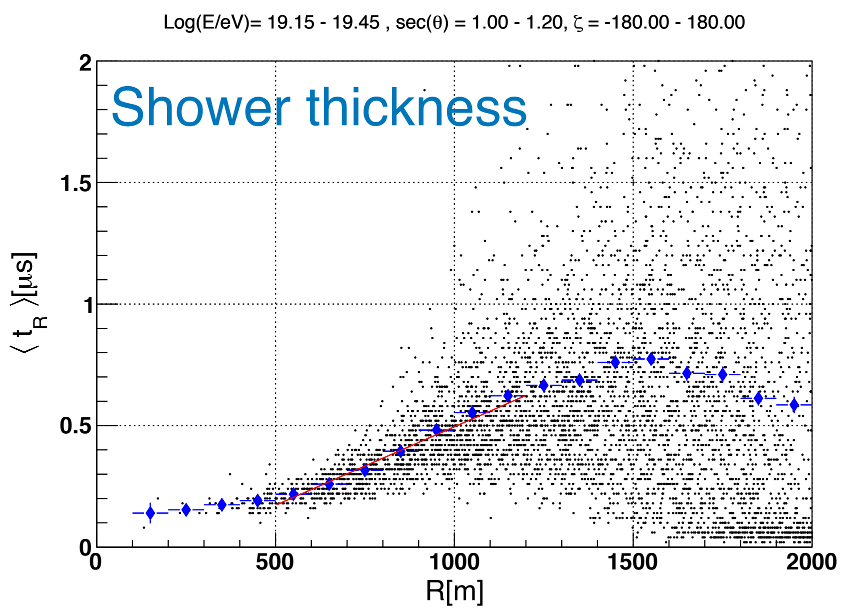
Other studies

EAS time structure analysis

R. Mayta





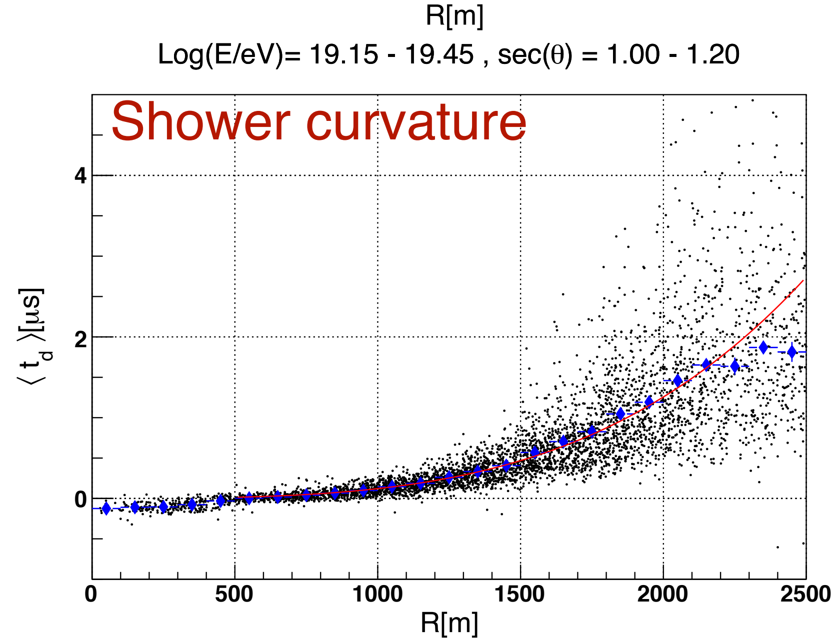


Analyzing the shower structure (curvature and thickness) as functions of R, θ and E using 11 years of TA SD data.

Averaged shower thickness, $< t_R >$, are fitted to a linear function,

$$\langle t_R \rangle = b + a \times R$$

where a and b are the fitting parameters.

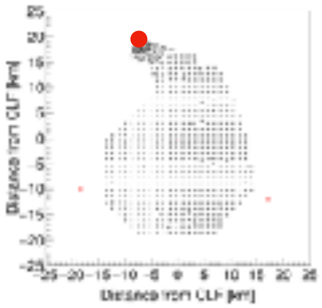


Averaged delay from the plane, $< t_d >$, are fitted to the function,

$$t_d = 2.6 \times \left(1 + \frac{R}{30\mathrm{m}}\right)^A \times \rho^B [m^{-2}][ns]$$

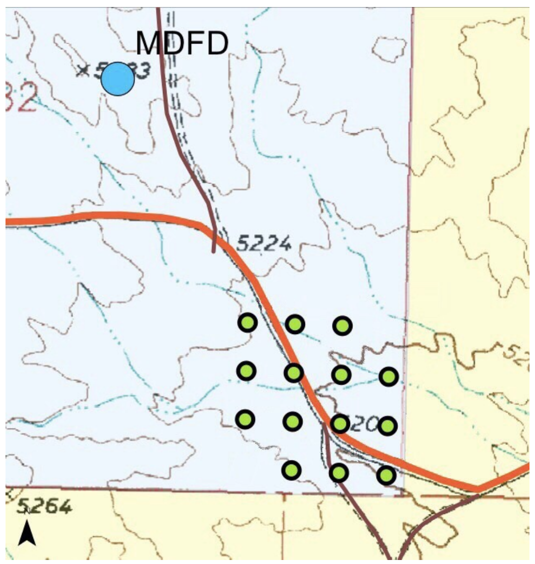
where, ρ is the particle density at R. A and B are the fitting parameters.

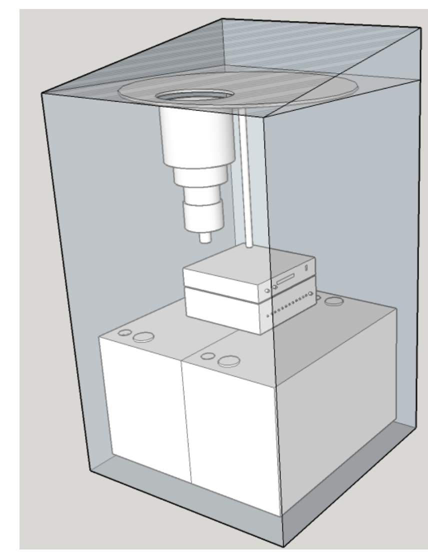
Non Imaging CHErenkov array (NICHE)



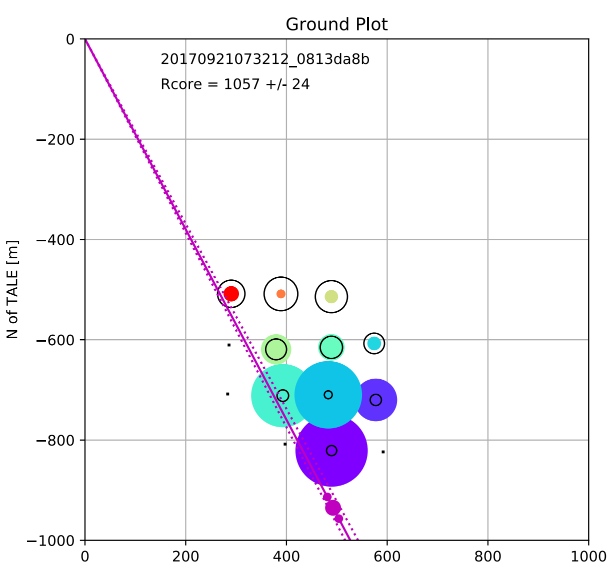
NICHE is a low energy extension of TALE sensitivity in order to measure the chemical composition of cosmic rays in the energy from 1 to 100 PeV.

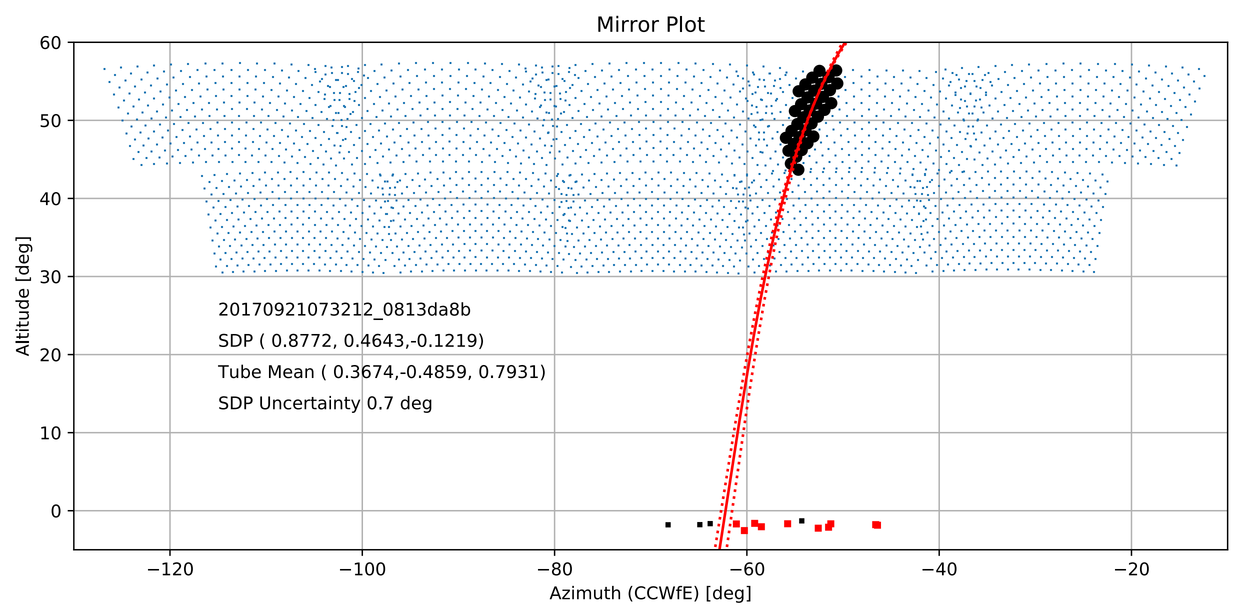
D. Bergman
Y. Omura

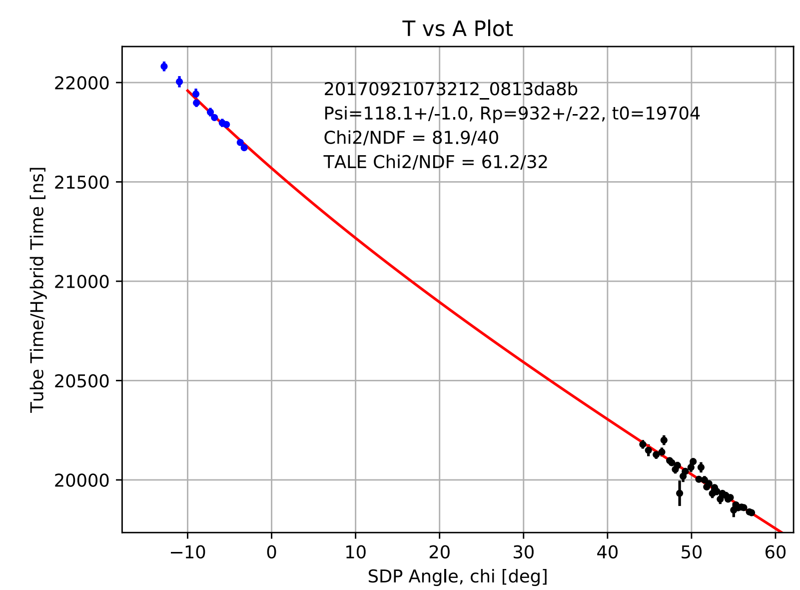




14 Cherenkov light detectors (3inch PMT+45º Winston corn), ~ 800 m from TALE FD, 100 m spacing.
Deployment started Sep. 2017, commissioning until Feb. 2019.



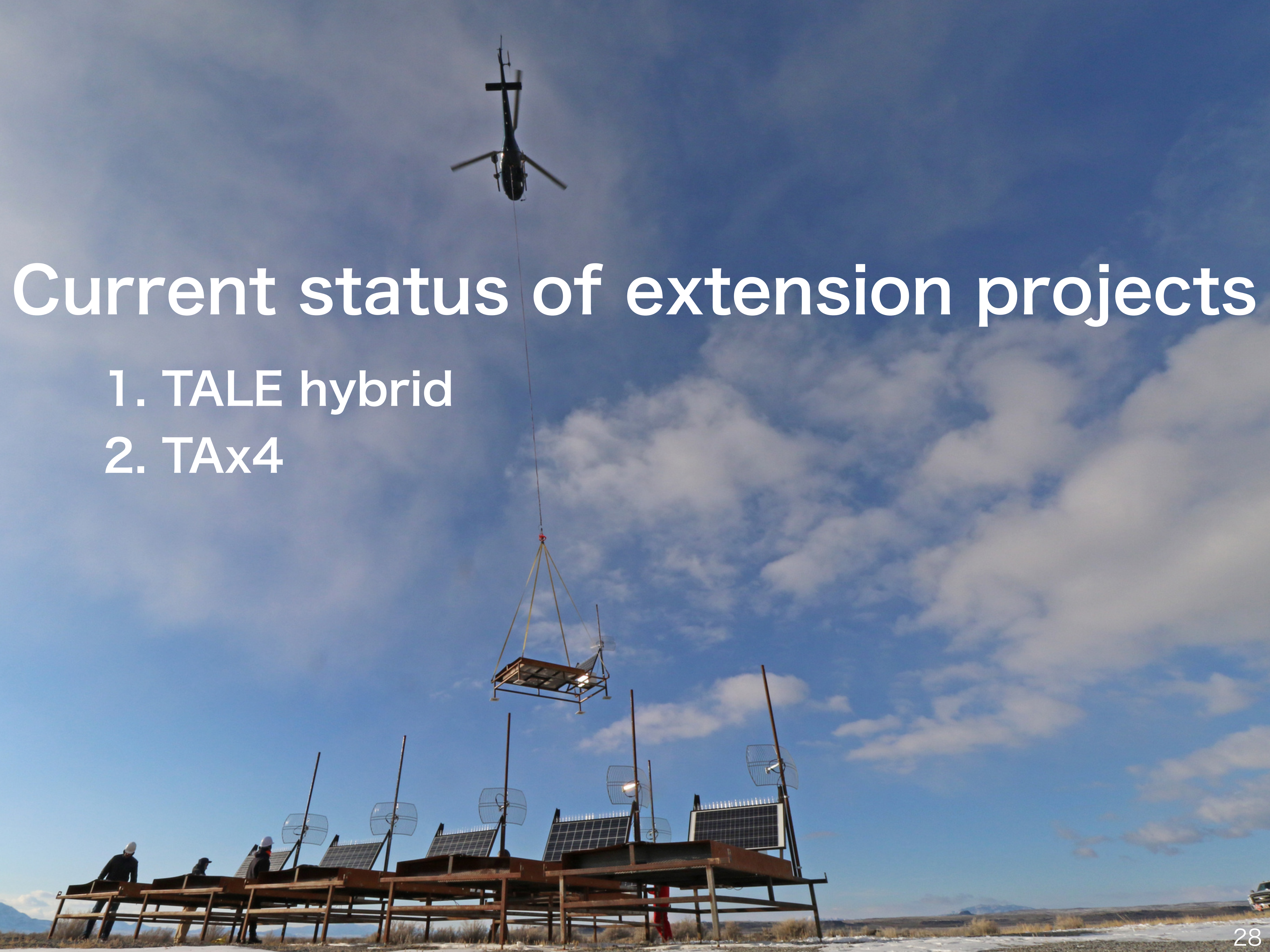




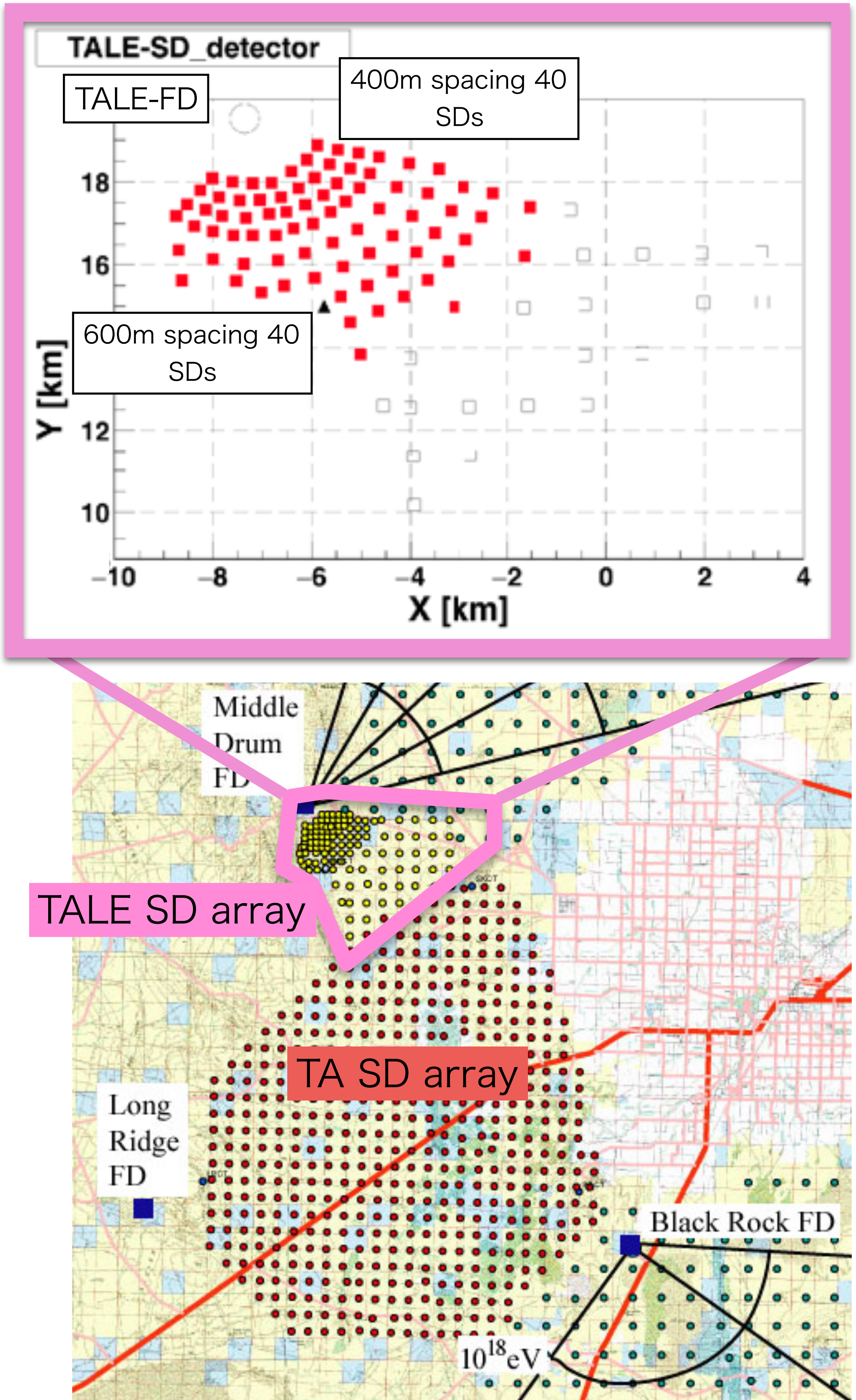
A coincidence event detected by NICHE and by TALE-FD at Sep. 21, 2017. And a hybrid geometry reconstruction from NICHE and TALE-FD data.

Current status of extension projects

1. TALE hybrid
2. TAx4



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)

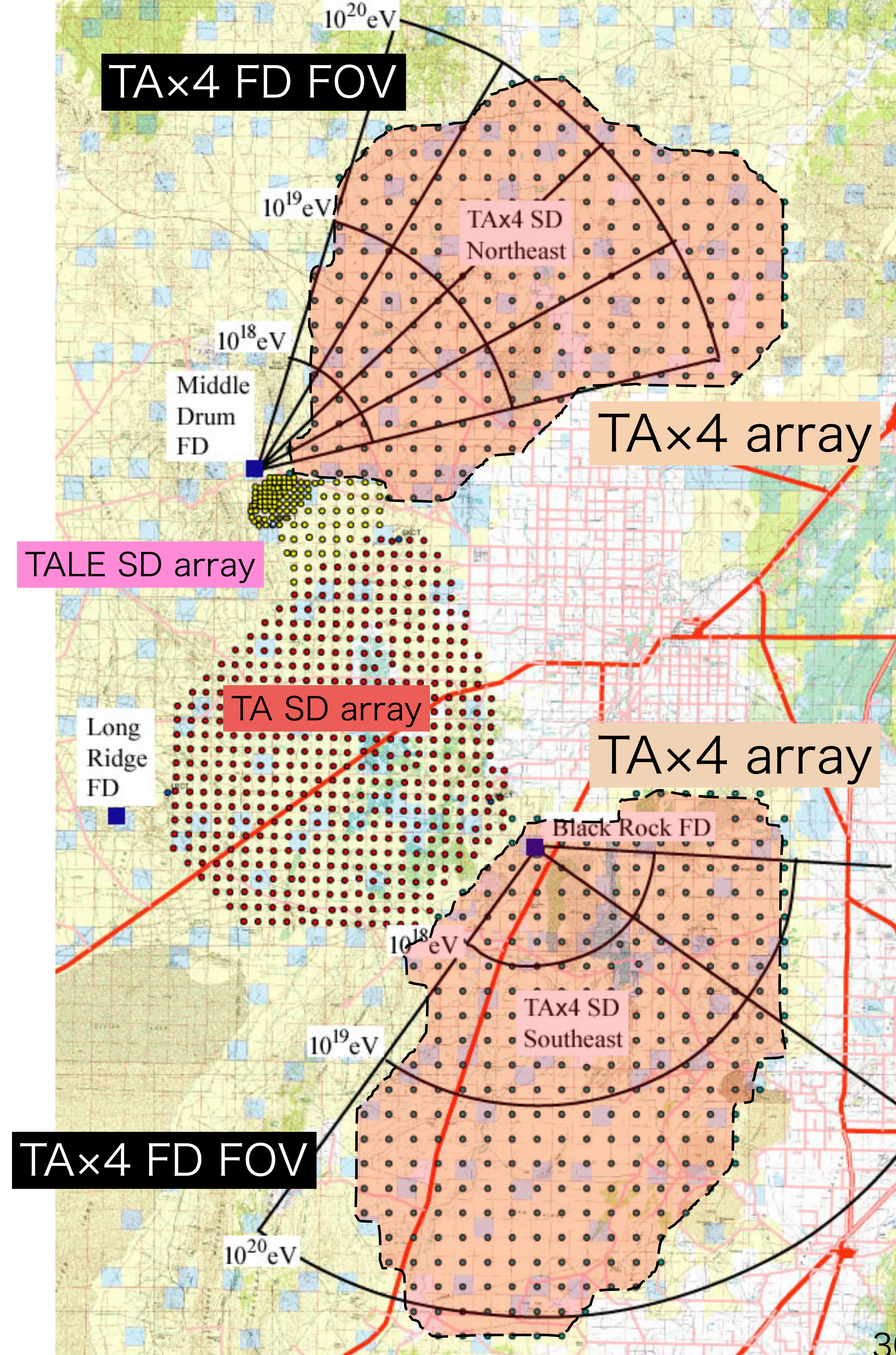
TA×4

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

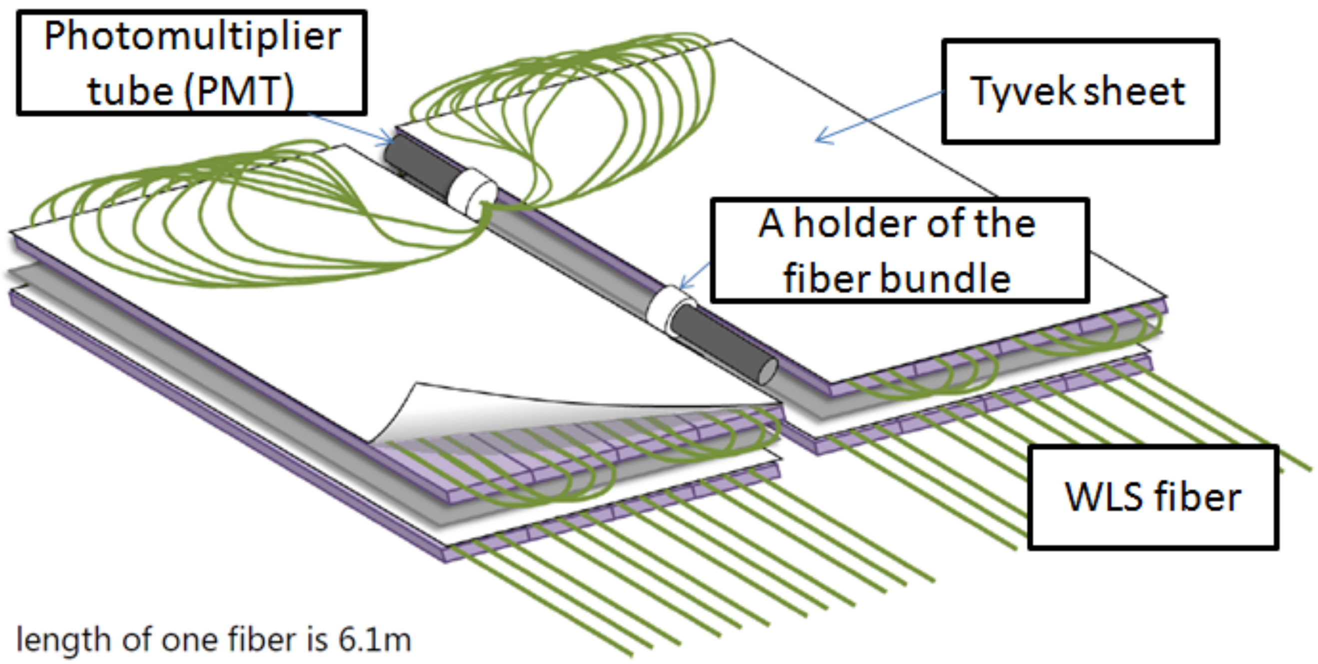
SD array of ~3000 km²
by **500** SDs
with **2 km** spacing

＋

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

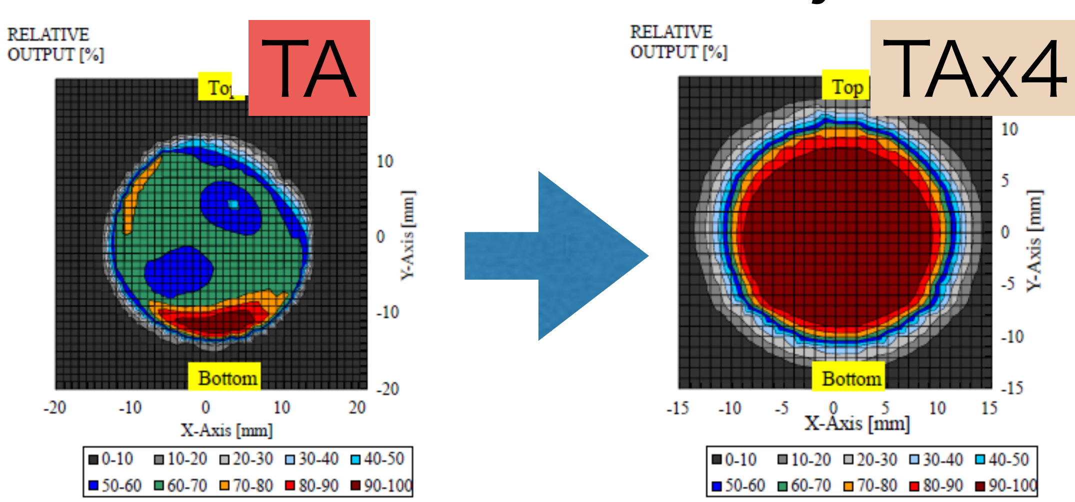


TA×4

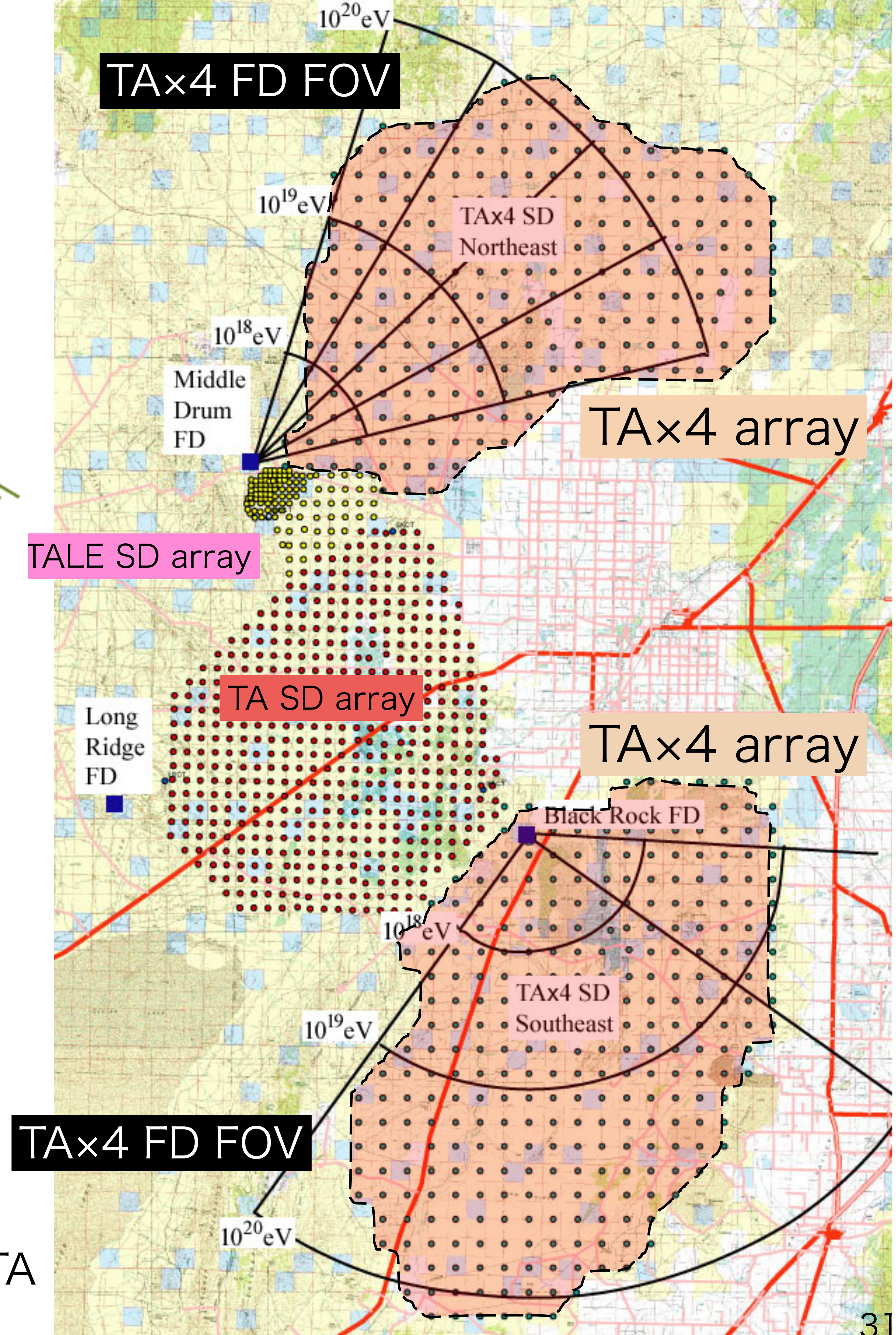


New PMT(Hamamatsu R8619)

- QE~20% @500nm (TA: ~10%)
- Linear range max@~50mA (TA: ~25mA)
- Photo-cathode uniformity



→ reduce total length of WLSF ~33% of TA

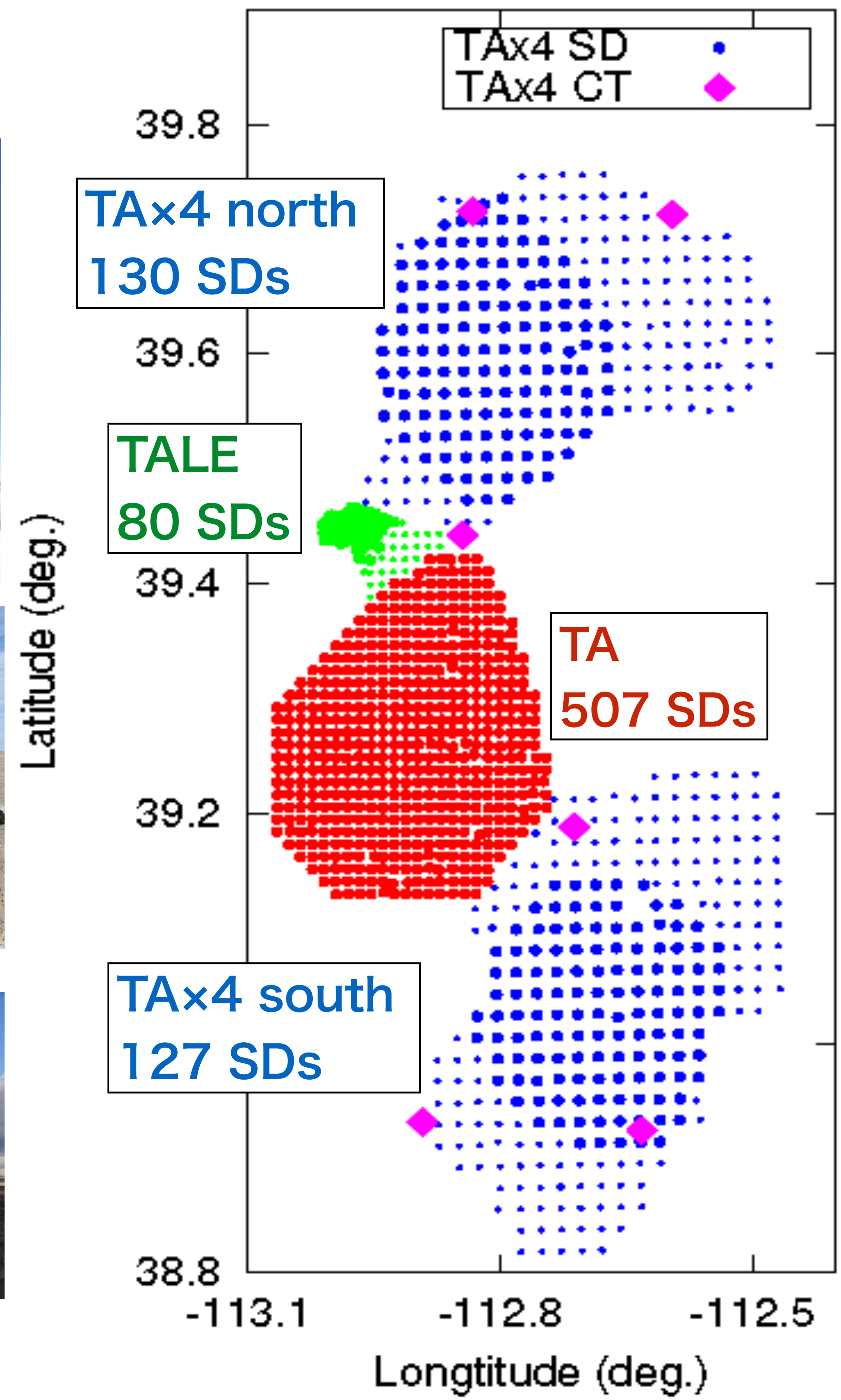


TA×4

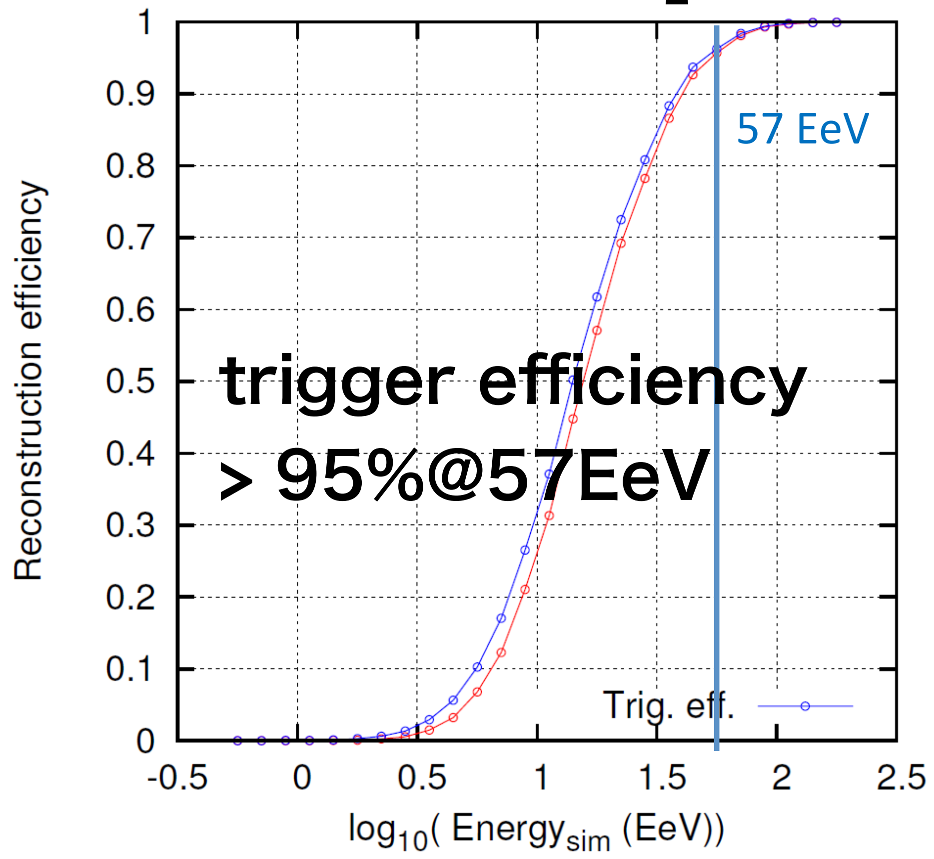
Feb. 19 - Mar. 12, 2019

257 SDs
6 communication towers

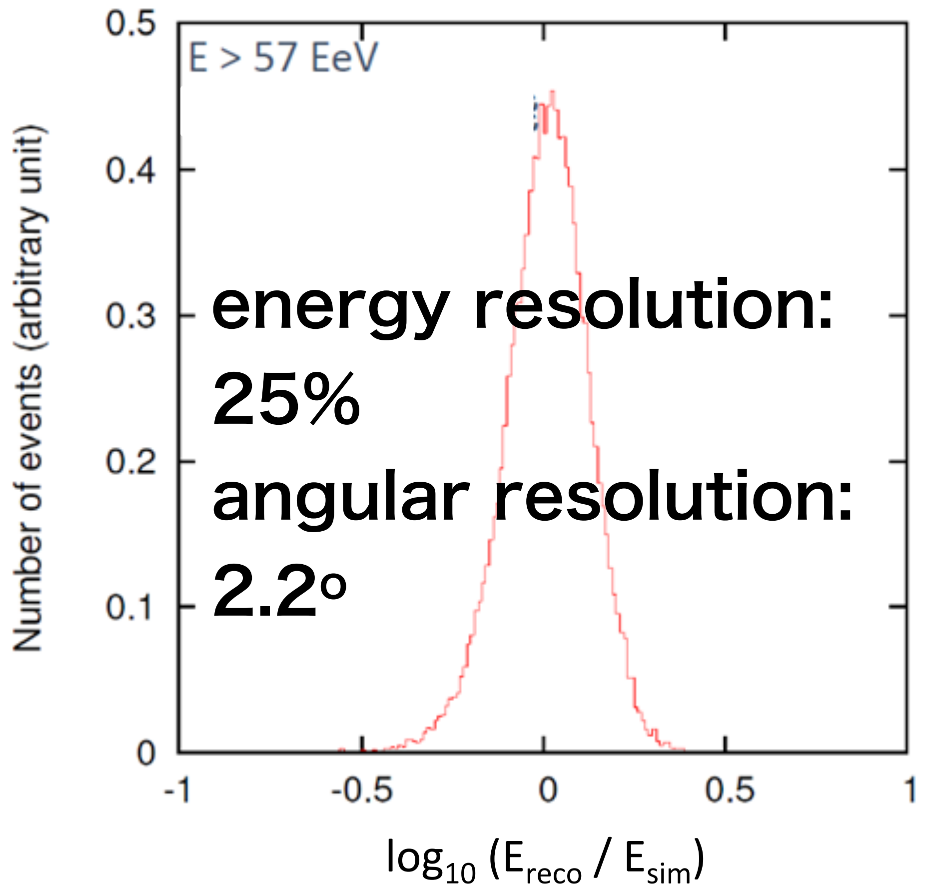
were installed in the site



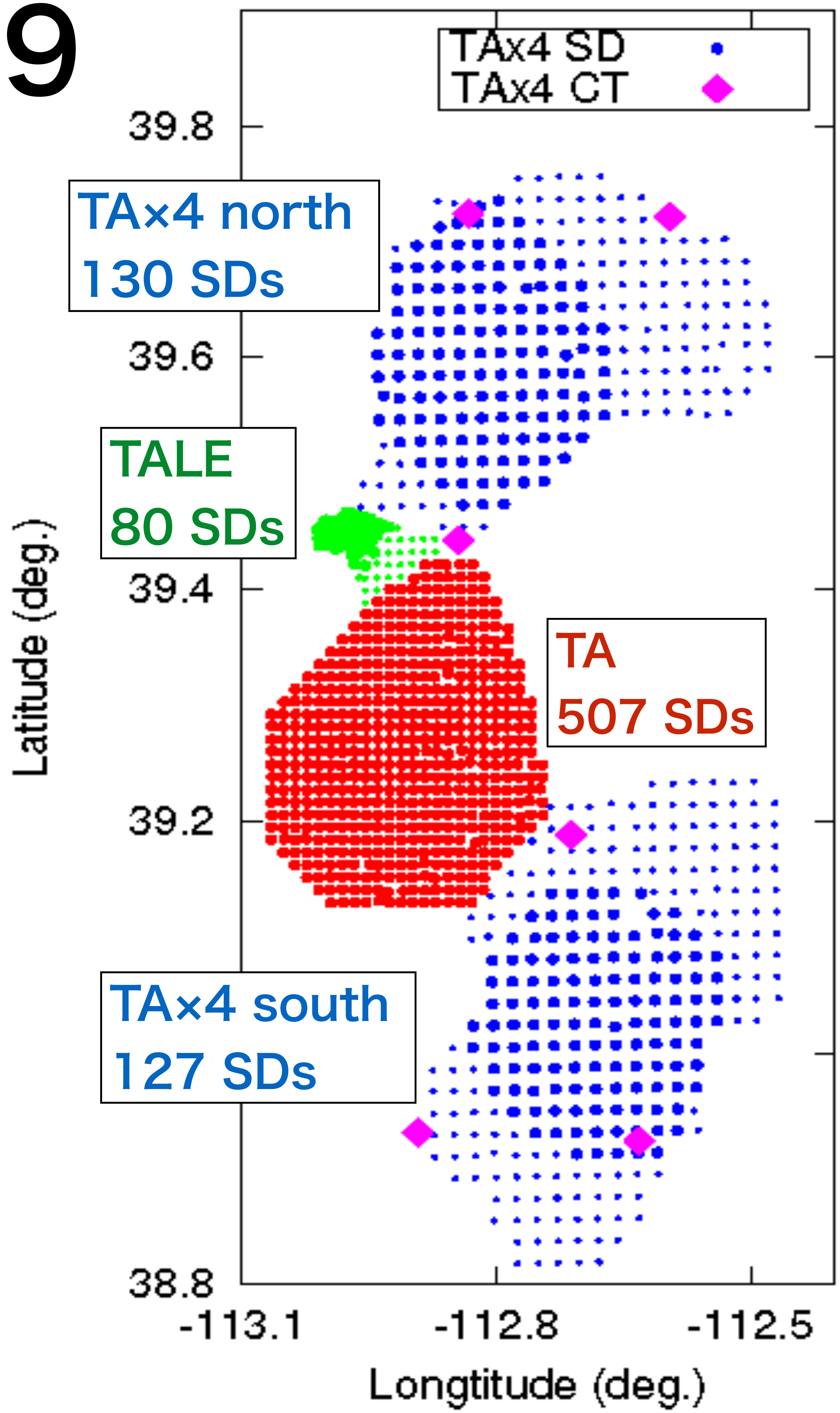
TA×4@Apr. 2019



Reconstruction efficiency
log10(Energy_sim (EeV))
57 EeV
Trig. eff.
trigger efficiency
> 95%@57EeV



Number of events (arbitrary unit)
log10 (E_reco / E_sim)
E > 57 EeV
energy resolution:
25%
angular resolution:
2.2°



TAx4 SD
TAx4 CT
TA×4 north
130 SDs
TALE
80 SDs
TA
507 SDs
TA×4 south
127 SDs
Latitude (deg.)
Longtitude (deg.)

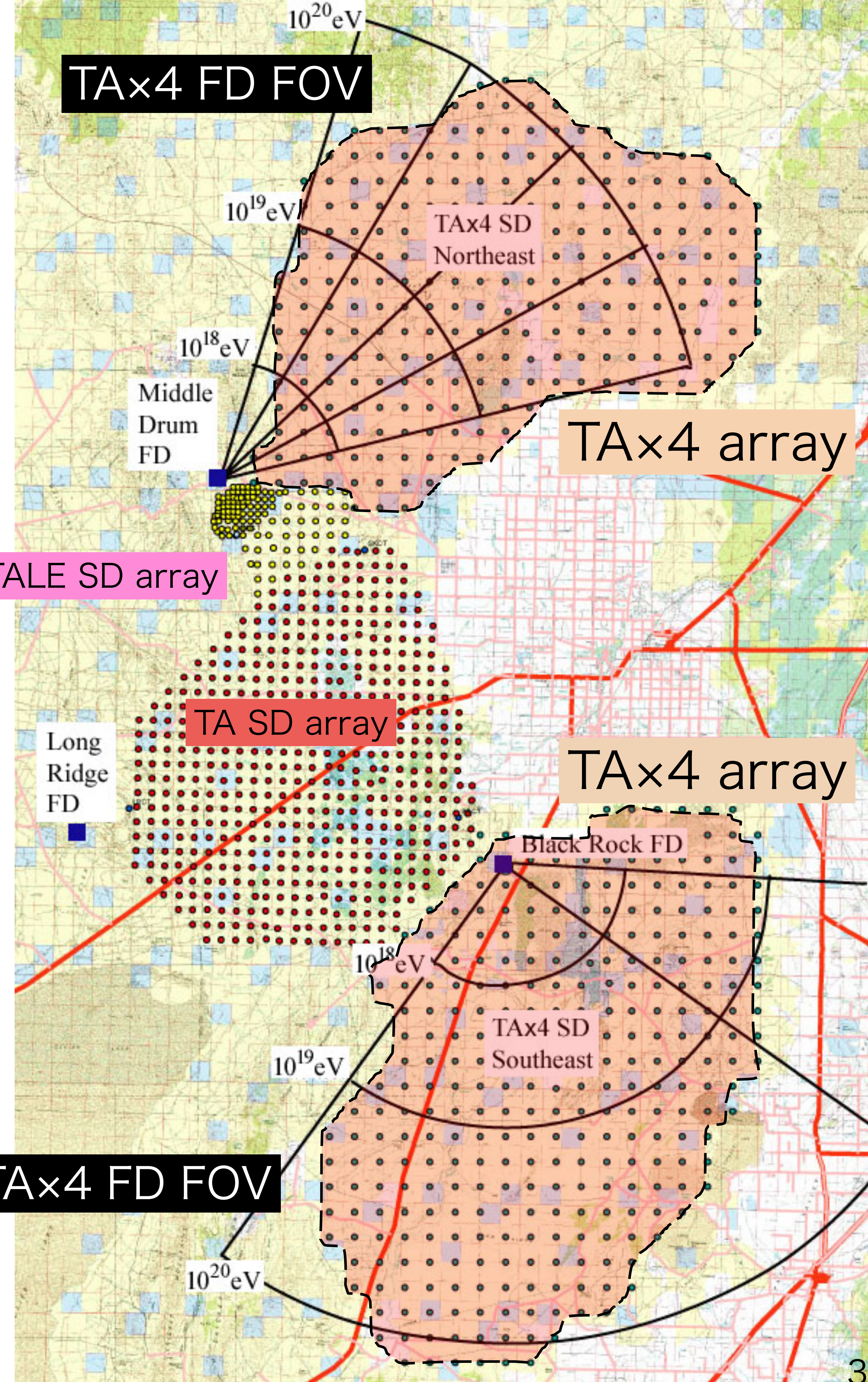
TA×4

TA×4 northern FD station

First light @ Feb. 16, 2018

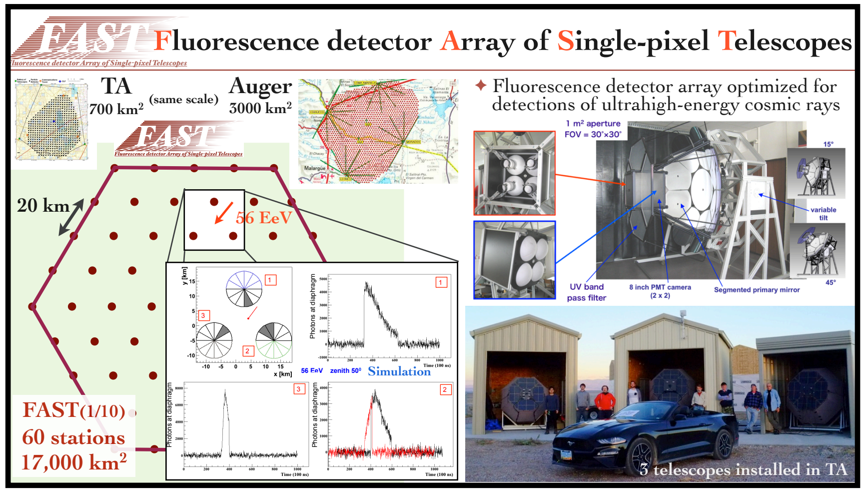
TA×4 southern FD station

under construction

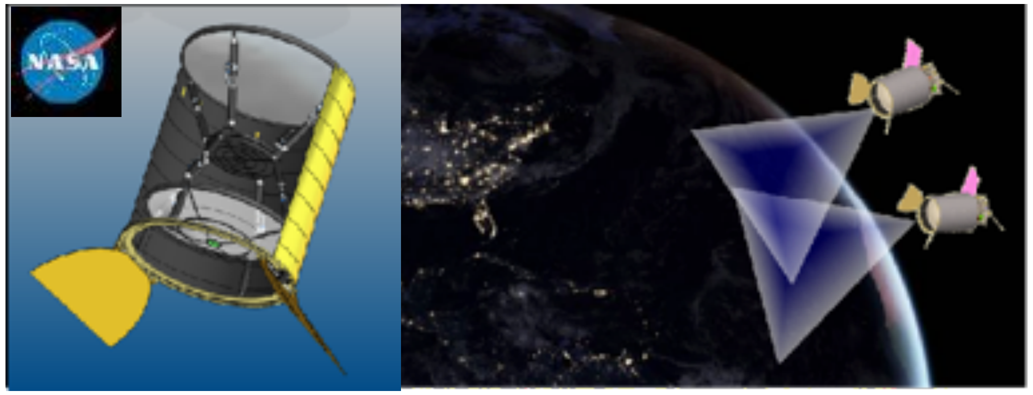


TA site: Platform for next generation

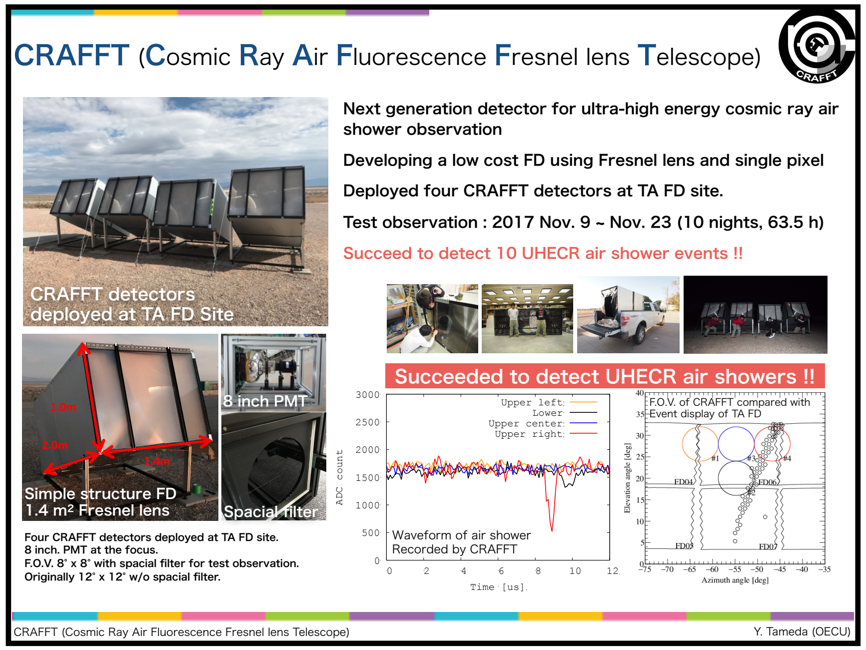
FAST



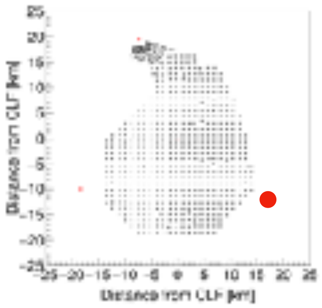
EUSO-TA (connect to POEMMA)



CRAFFT



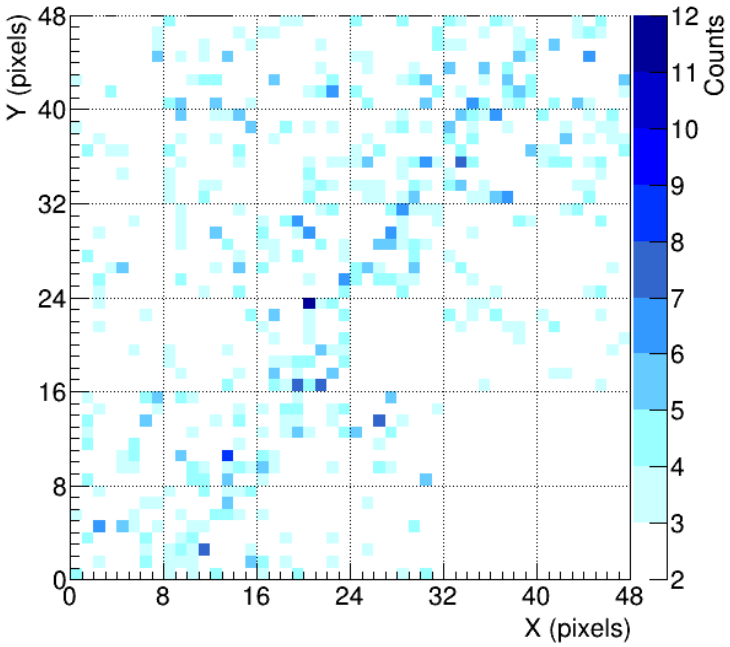
TA site: Platform for future



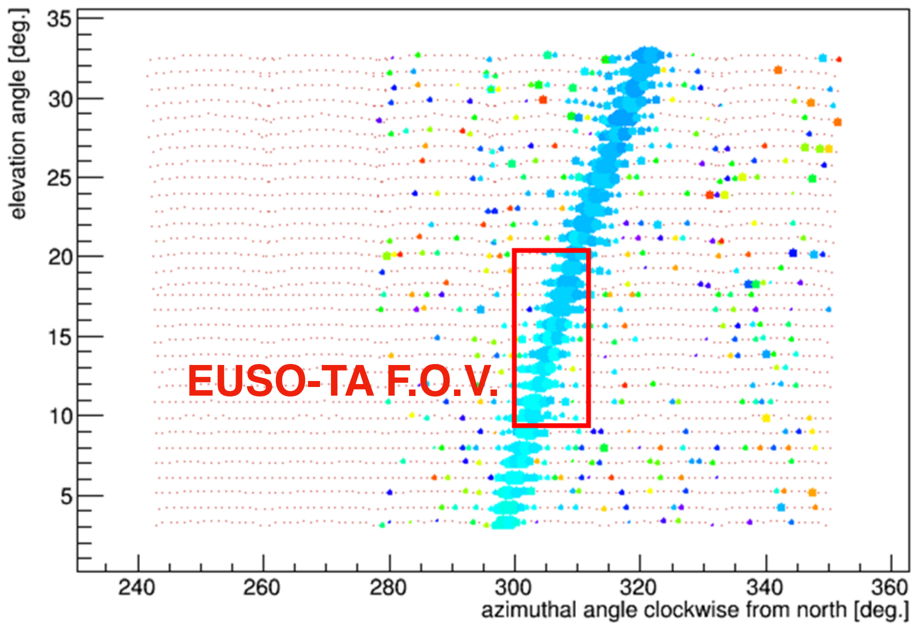
F. Biscotti for JEM-EUSO collaboration

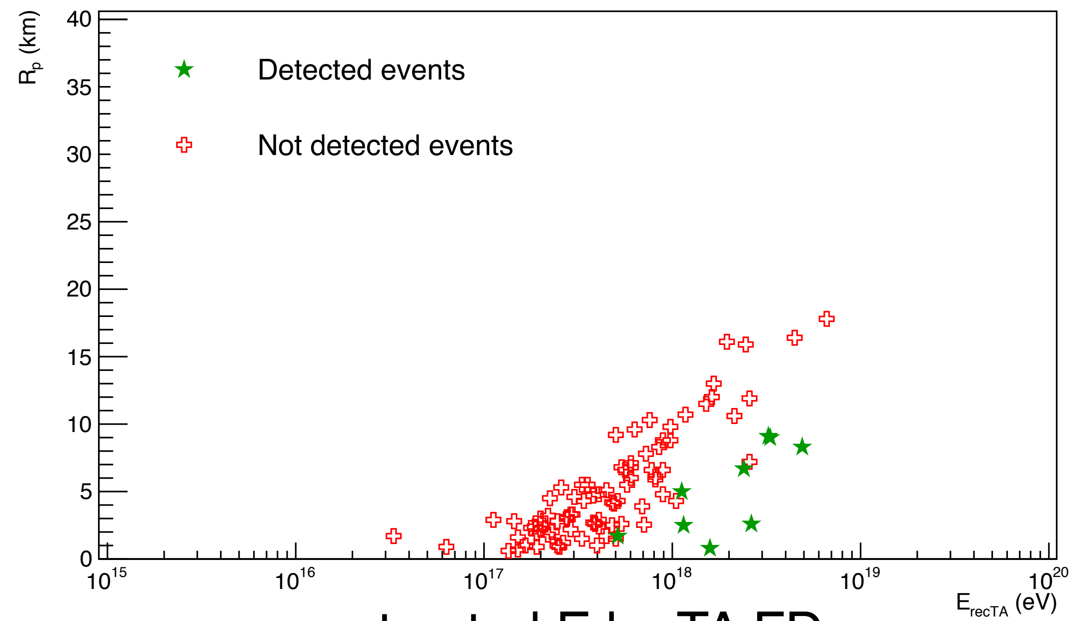
UHECR event on May 13, 2015

EUSO-TA
(external trigger from TA BRM)



TA BRM-FD
R_p = 2.5km, logE = 18



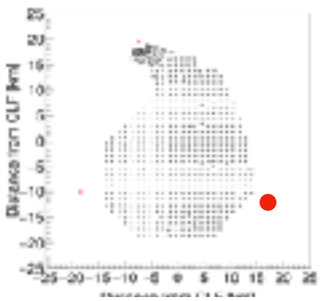


reconstructed R_p by TA FD

reconstructed E by TA FD

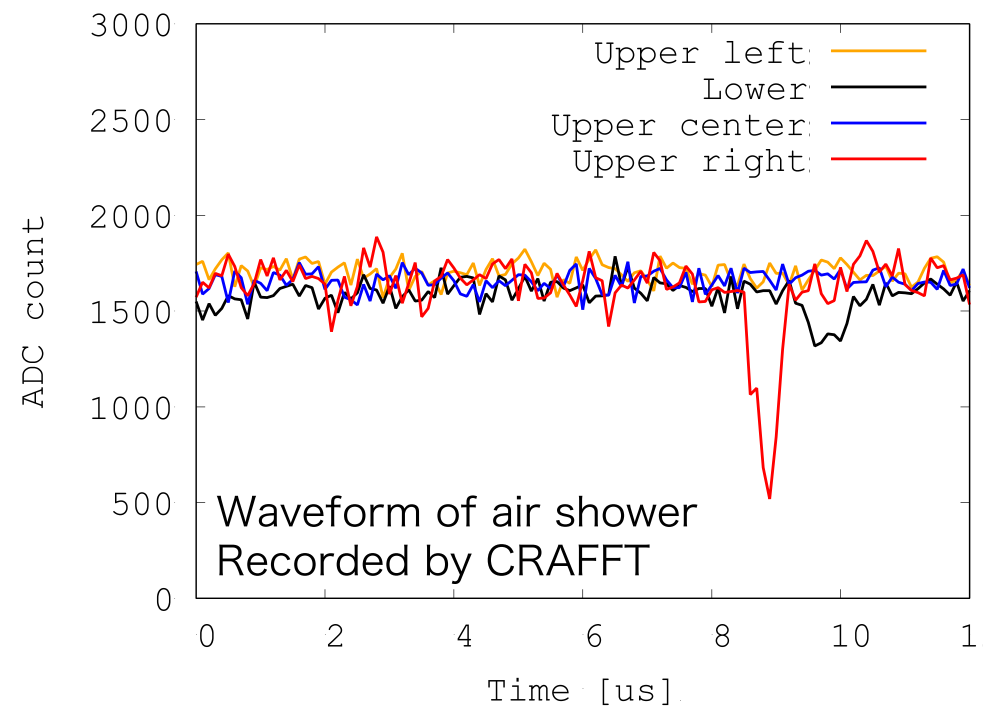
TA site: Platform for future

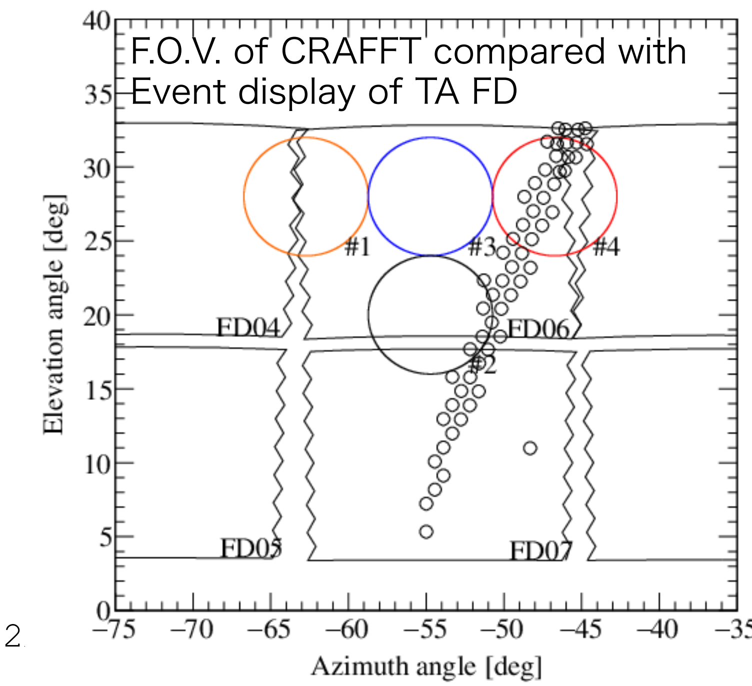
Y. Tameda for CRAFFT collaboration



(1.4m² fresnel lens
+ 8 inch PMT)
x 4 telescopes

One of events detected by TA FD & CRAFFT

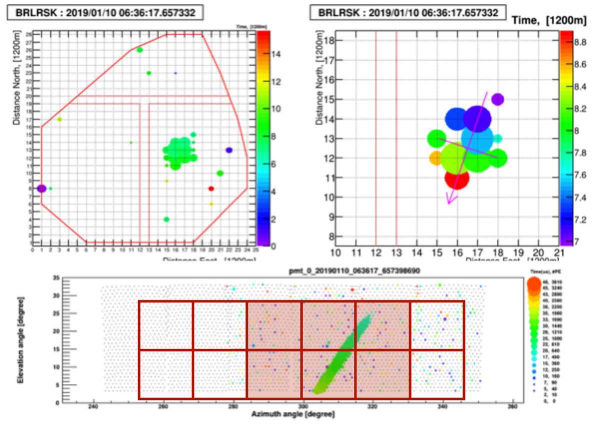


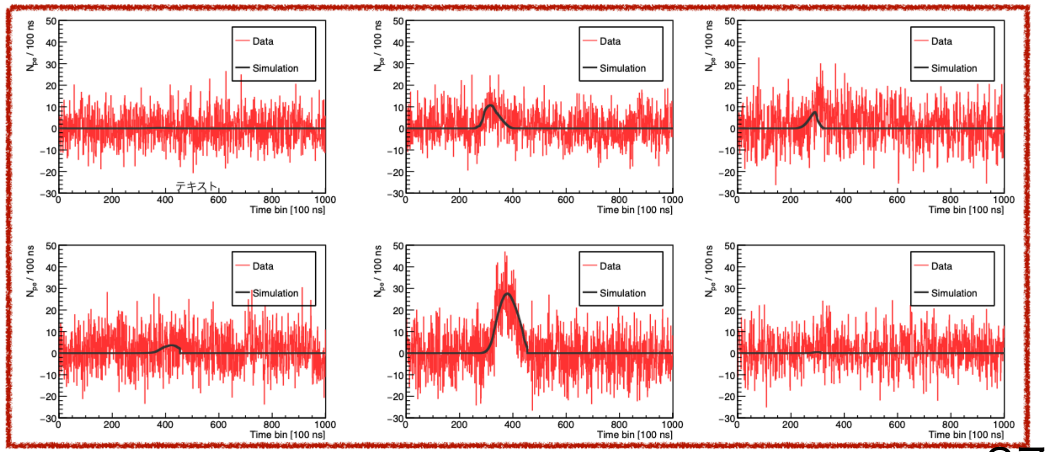


T. Fujii for FAST collaboration

FAST

One of the highest energy events detected by
TA FD, SD and FAST prototype

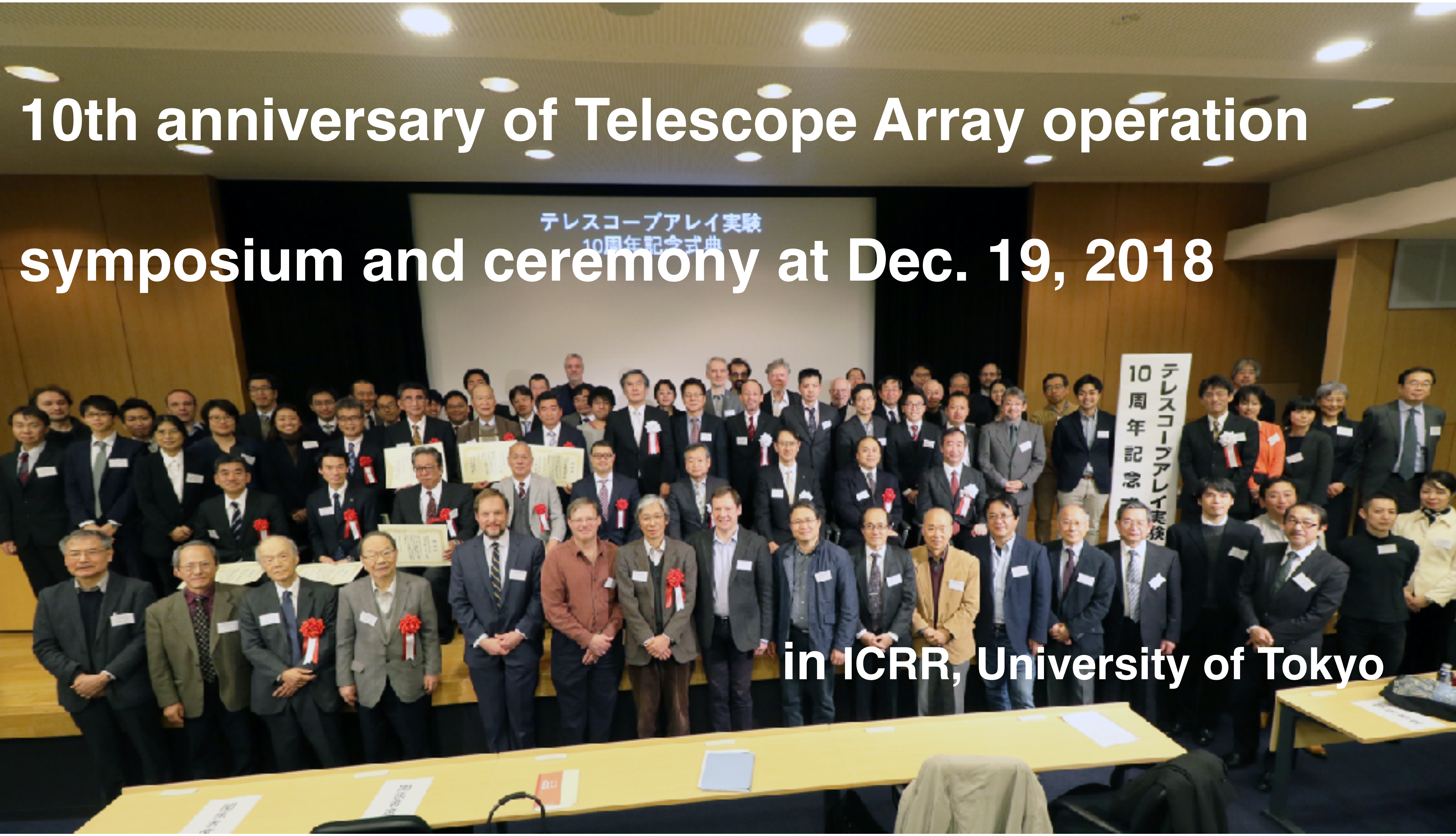




Summary(1/2)

- Telescope Array is UHECR observatory in the northern hemisphere.
- Hybrid = Fluorescence Detectors + 700 km^2 Surface Detector array
- Energy spectrum from 11 year observations by TA SD array
  - Indication of the declination dependence
- TA Low Energy Extension (TALE) FD have measured energy spectrum.
- TA FD stereo and hybrid Xmax measurements
  - Below $10^{19.1}$ eV TA hybrid data is found to be compatible with mixtures composed of predominantly light elements such as protons and helium.
- Hot spot from 11 years of data, it is seen in the direction of Ursa Major (post trial 3σ significance). It now appears larger(extended) than we originally thought.
- NICHE is in operation since Sep. 2017.
- We need much more data at high energy end –> TAx4 is in operation!
- Full TALE SD is now on-line! Hybrid observations since Sep. 2018.
  - Hybrid measurement has extended the energy reach below ~10^{16} eV
- TA site is a platform for FUTURE!

Summary(2/2)



10th anniversary of Telescope Array operation

symposium and ceremony at Dec. 19, 2018

in ICRR, University of Tokyo

Thank you for your continuous support toward 20th anniversary !