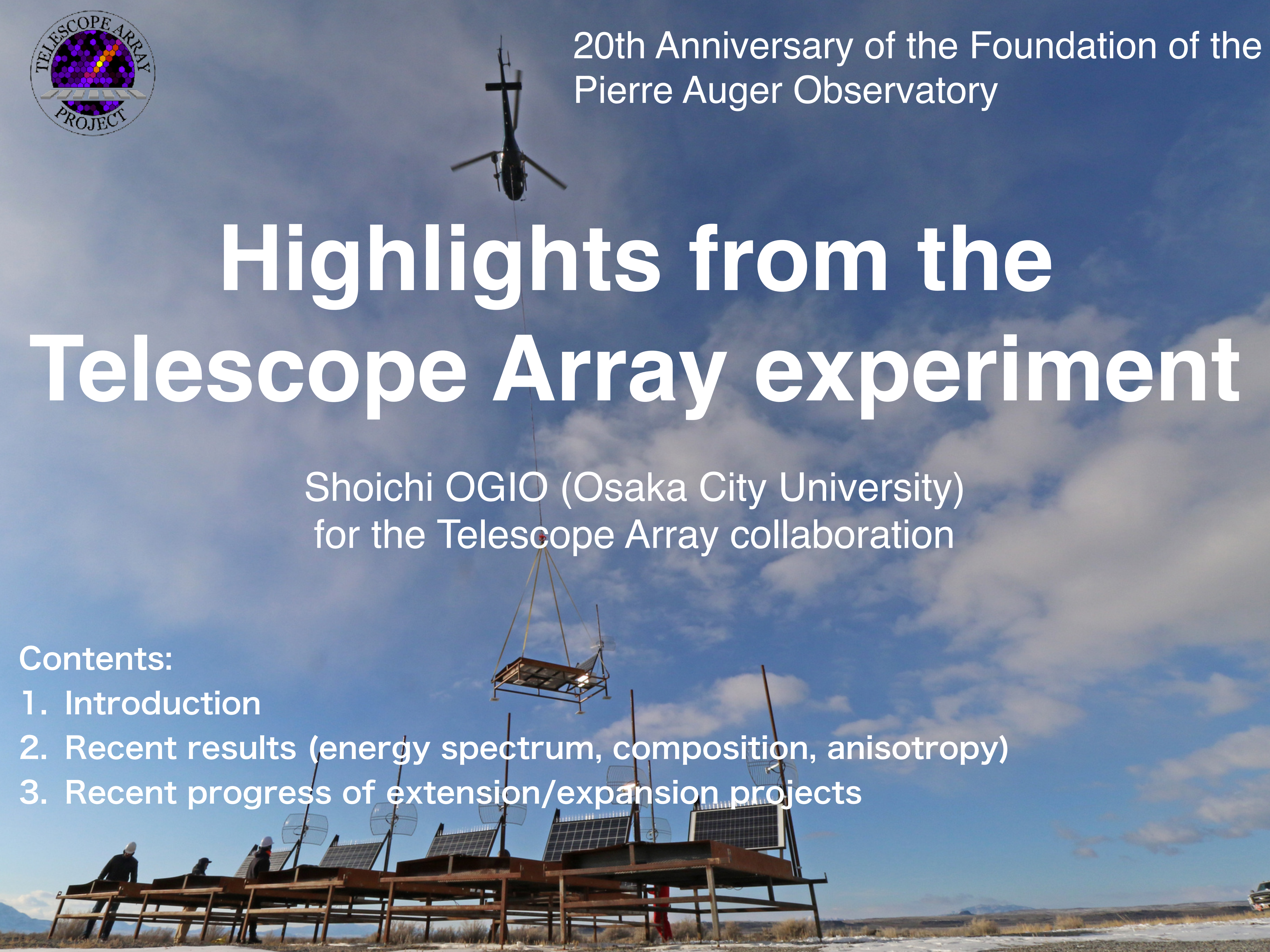


20th Anniversary of the Foundation of the Pierre Auger Observatory

Highlights from the Telescope Array experiment

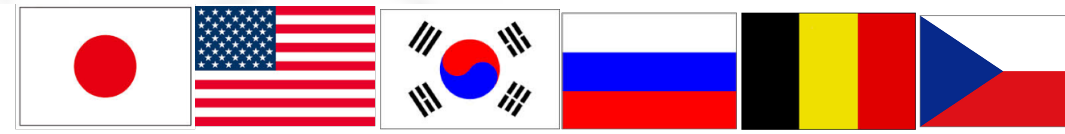
Shoichi OGIO (Osaka City University)
for the Telescope Array collaboration

Contents:

1. Introduction
2. Recent results (energy spectrum, composition, anisotropy)
3. Recent progress of extension/expansion projects

Telescope Array collaboration

147 collaborators from 36 institutes
in 6 countries



R.U. Abbasi (1), M. Abe (2), T. Abu-Zayyad (1), M. Allen (1), R. Azuma (3), E. Barcikowski (1), J.W. Belz (1), D.R. Bergman (1), S.A. Blake (1), R. Cady (1), B.G. Cheon (4), J. Chiba (5), M. Chikawa (6), A. di Matteo (7), T. Fujii (8), K. Fujita (9), R. Fujiwara (9), M. Fukushima (10,11), G. Furlich (1), W. Hanlon (1), M. Hayashi (12), Y. Hayashi (9), N. Hayashida (13), K. Hibino (13), K. Honda (14), D. Ikeda (15), T. Inadomi (16), N. Inoue (2), T. Ishii (14), R. Ishimori (3), H. Ito (17), D. Ivanov (1), H. Iwakura (16), H.M. Jeong (18), S. Jeong (18), C.C.H. Jui (1), K. Kadota (19), F. Kakimoto (3), O. Kalashev (20), K. Kasahara (21), S. Kasami (22), H. Kawai (23), S. Kawakami (9), S. Kawana (2), K. Kawata (10), E. Kido (10), H.B. Kim (4), J.H. Kim (1), J.H. Kim (24), S. Kishigami (9), V. Kuzmin (20), M. Kuznetsov (7,20), Y.J. Kwon (25), K.H. Lee (18), B. Lubsandorzhiev (20), J.P. Lundquist (1), K. Machida (14), K. Martens (11), H. Matsumiya (9), T. Matsuyama (9), J.N. Matthews (1), R. Mayta (9), M. Minamino (9), K. Mukai (14), I. Myers (1), S. Nagataki (17), K. Nakai (9), R. Nakamura (16), T. Nakamura (26), Y. Nakamura (16), T. Nonaka (10), H. Oda (9), S. Ogio (9,27), M. Ohnishi (10), H. Ohoka (10), Y. Oku (22), T. Okuda (28), Y. Omura (9), M. Ono (17), R. Onogi (9), A. Oshima (9), S. Ozawa (21), I.H. Park (18), M.S. Pshirkov (20,29), J. Remington (1), D.C. Rodriguez (1), G. Rubtsov (20), D. Ryu (24), H. Sagawa (10), R. Sahara (9), K. Saito (10), Y. Saito (16), N. Sakaki (10), T. Sako (10), N. Sakurai (9), K. Sano (16), L.M. Scott (30), T. Seki (16), K. Sekino (10), P.D. Shah (1), F. Shibata (14), T. Shibata (10), H. Shimodaira (10), B.K. Shin (9), H.S. Shin (10), J.D. Smith (1), P. Sokolsky (1), N. Sone (16), B.T. Stokes (1), S.R. Stratton (1,30), T.A. Stroman (1), T. Suzawa (2), Y. Takagi (9), Y. Takahashi (9), M. Takamura (5), M. Takeda (10), R. Takeishi (18), A. Taketa (15), M. Takita (10), Y. Tameda (22), H. Tanaka (9), K. Tanaka (31), M. Tanaka (32), Y. Tanoue (9), S.B. Thomas (1), G.B. Thomson (1), P. Tinyakov (7,20),

I. Tkachev (20), H. Tokuno (3), T. Tomida (16), S. Troitsky (20), Y. Tsunesada (9,27), Y. Uchihori (33), S. Udo (13), T. Uehama (16), F. Urban (34), T. Wong (1),

II. M. Yamamoto (16), H. Yamaoka (32), K. Yamazaki (13), J. Yang (35), K. Yashiro (5), M. Yosei (22), H. Yoshii (36), Y. Nakamura (16), Y. Zhezher (20),

III. Z. Zundel (1)

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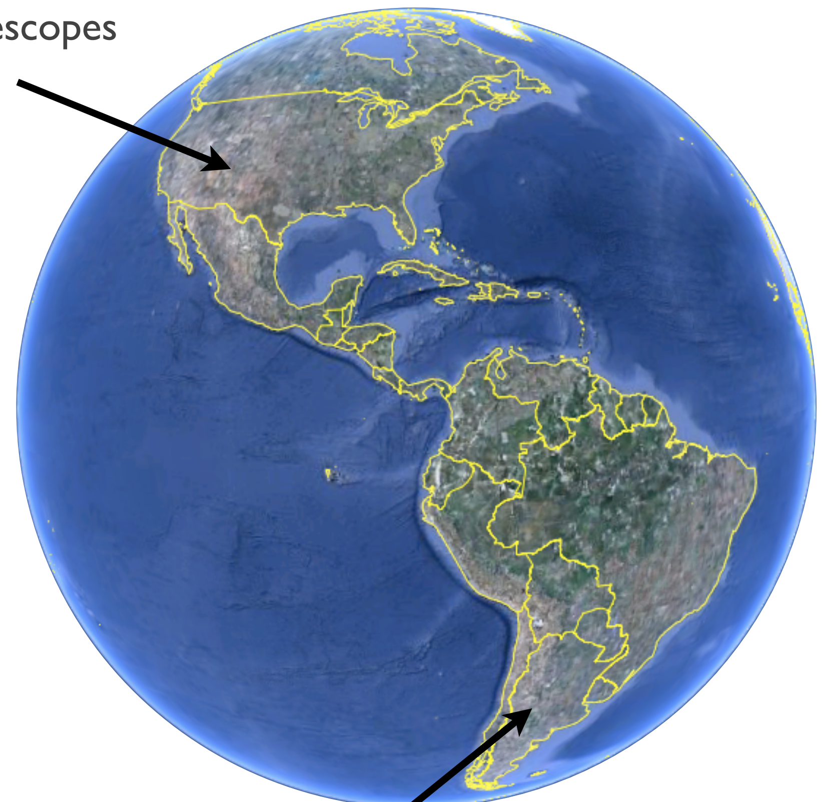
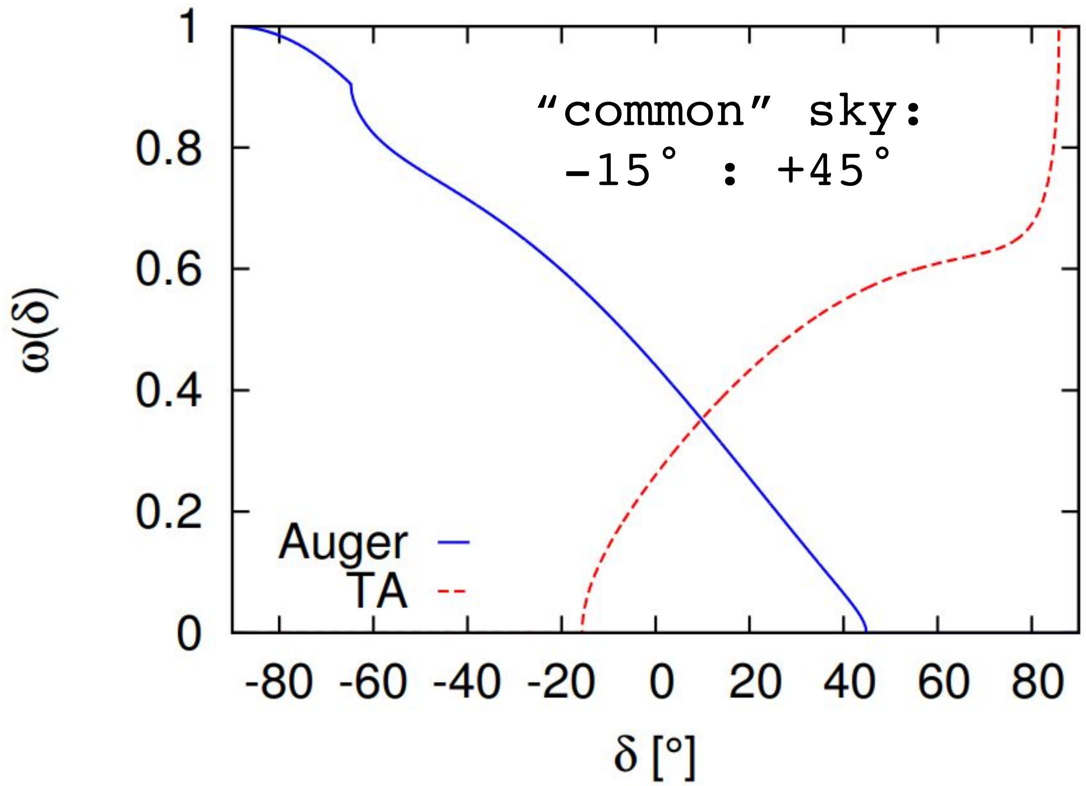
Pierre Auger Observatory and Telescope Array

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 700 km²
36 fluorescence telescopes



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Relative exposure of Auger and TA



Together full sky coverage: perfect for anisotropy studies

2

Ralph Engel, TA 10th anniversary symposium (2018)

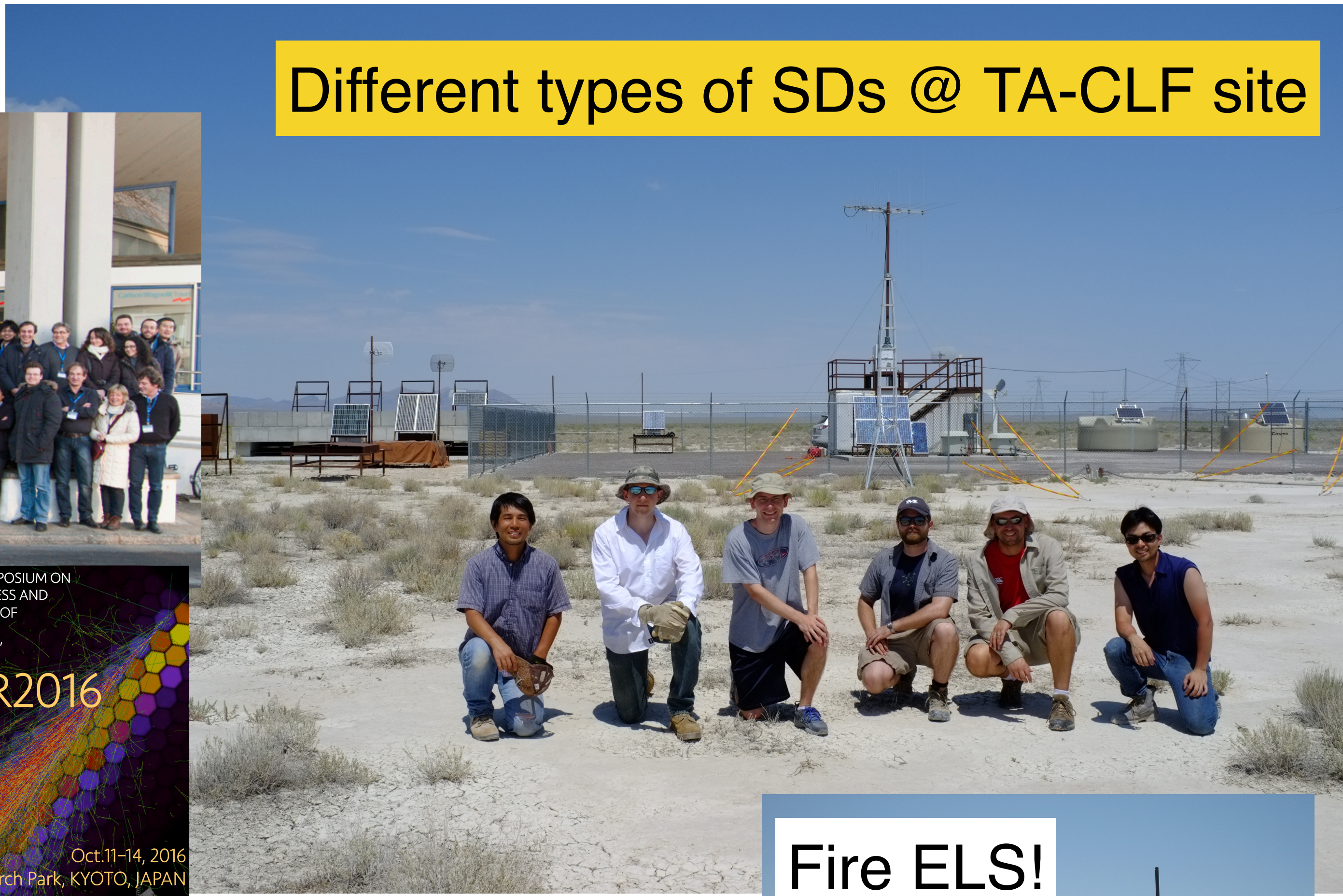
Joint efforts of Auger and TA

CERN, 2012

Series of symposia, “UHECR”, since 2010

Kyoto, 2016

Different types of SDs @ TA-CLF site

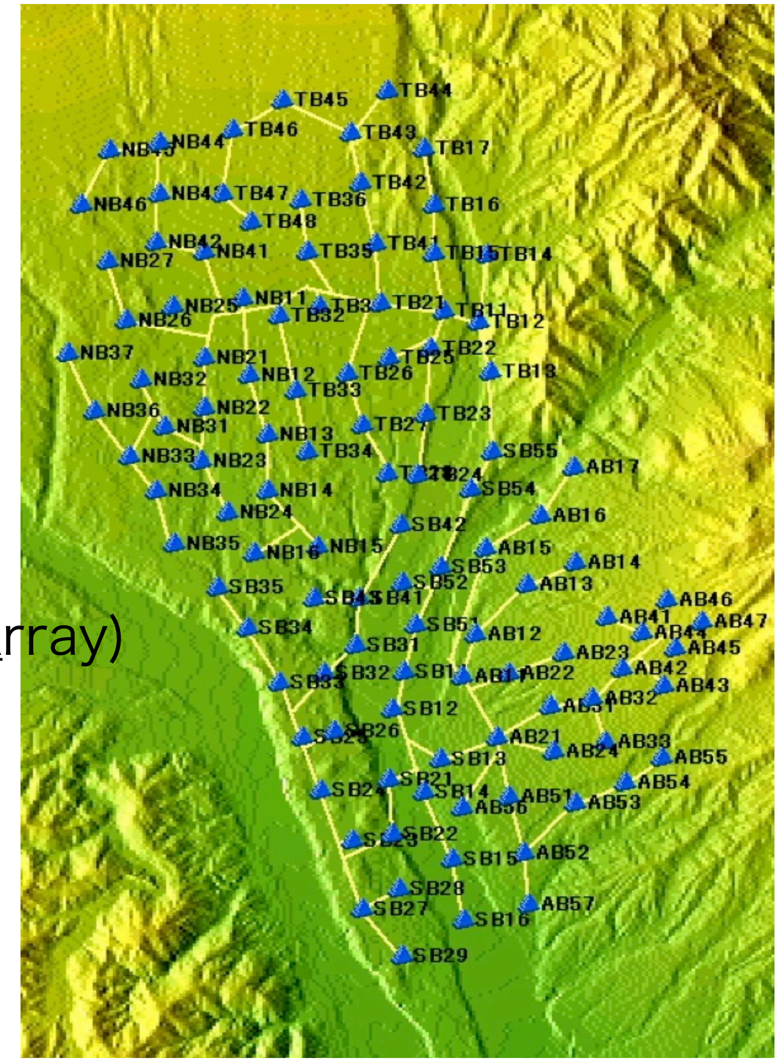


Fire ELS!

Next generation FD by FAST @ BRM station

GHz band radio detector w ELS

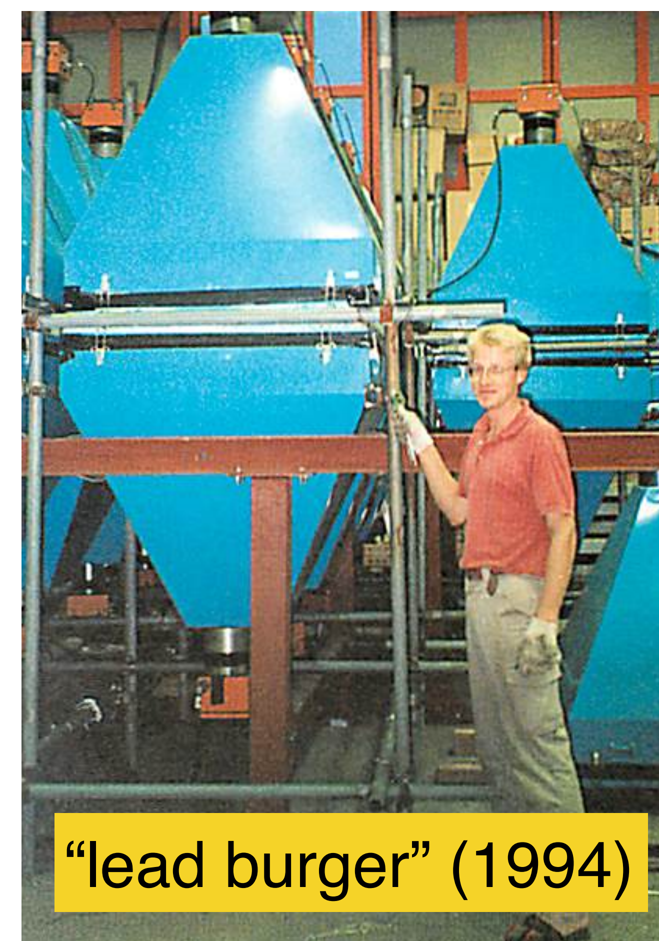
Auger SD prototypes with AGASA



AGASA

(Akeno Giant AIr Shower Array)
Akeno, Yamanashi, JAPAN
PI: Prof. M. Nagano
(1987)1990-2004
2.2m^2 SD x 111,
total coverage is 100km^2
Plastic scintillators

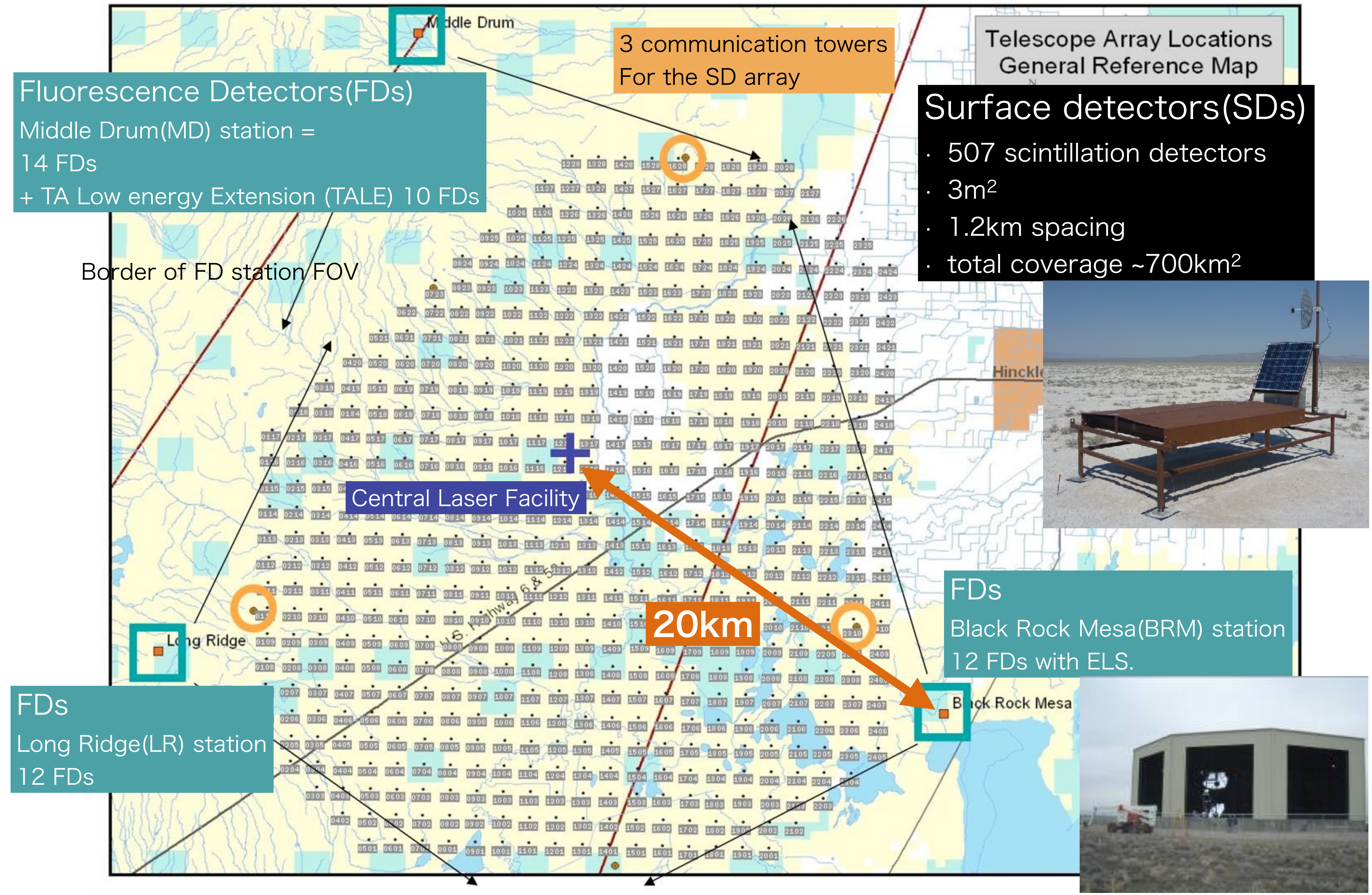
"water Cherenkov" (1996)



"lead burger" (1994)

Prof. Motohiko Nagano (1938-2014)

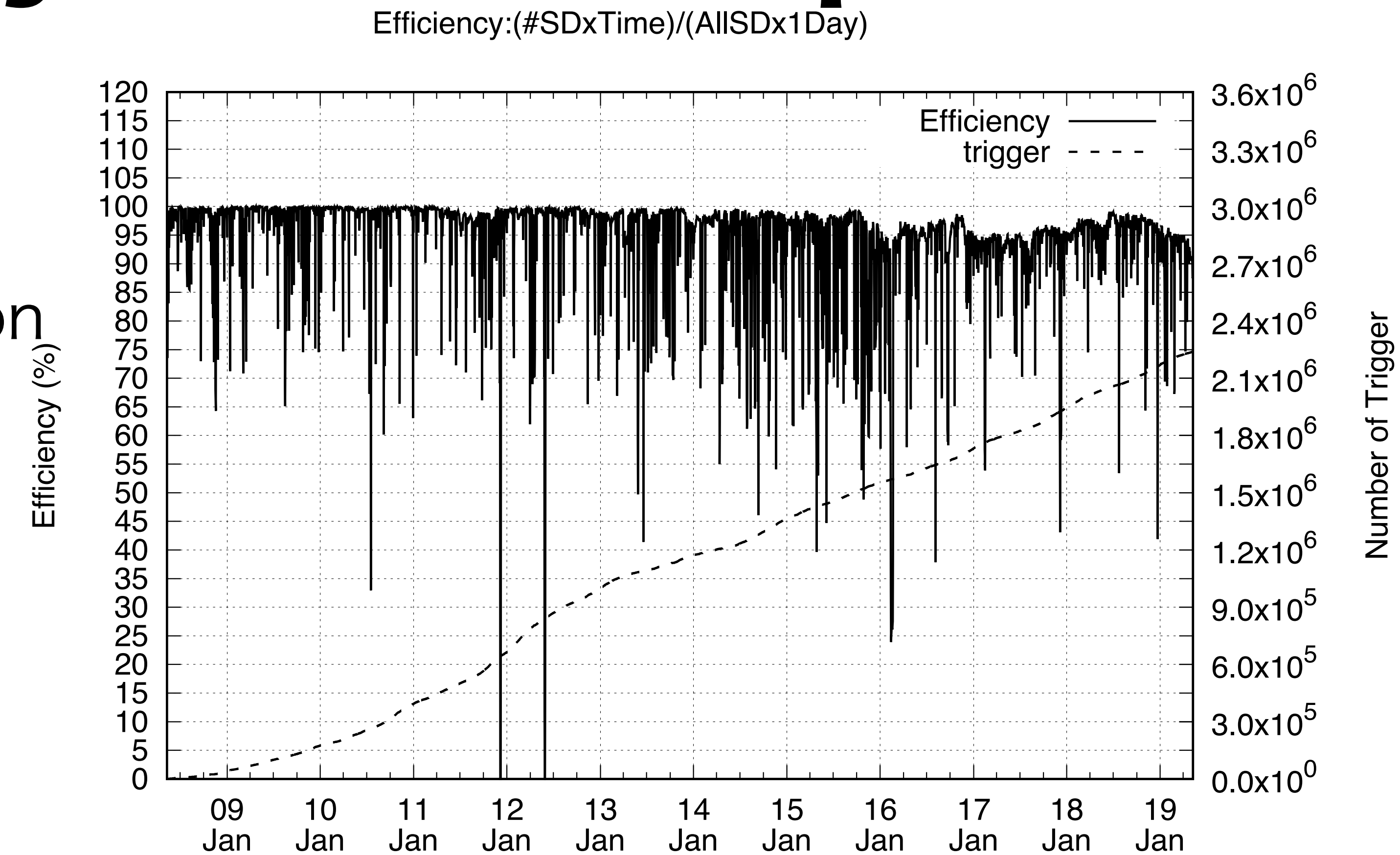
Map of the TA site



Status of 11 years of operations

SD array

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

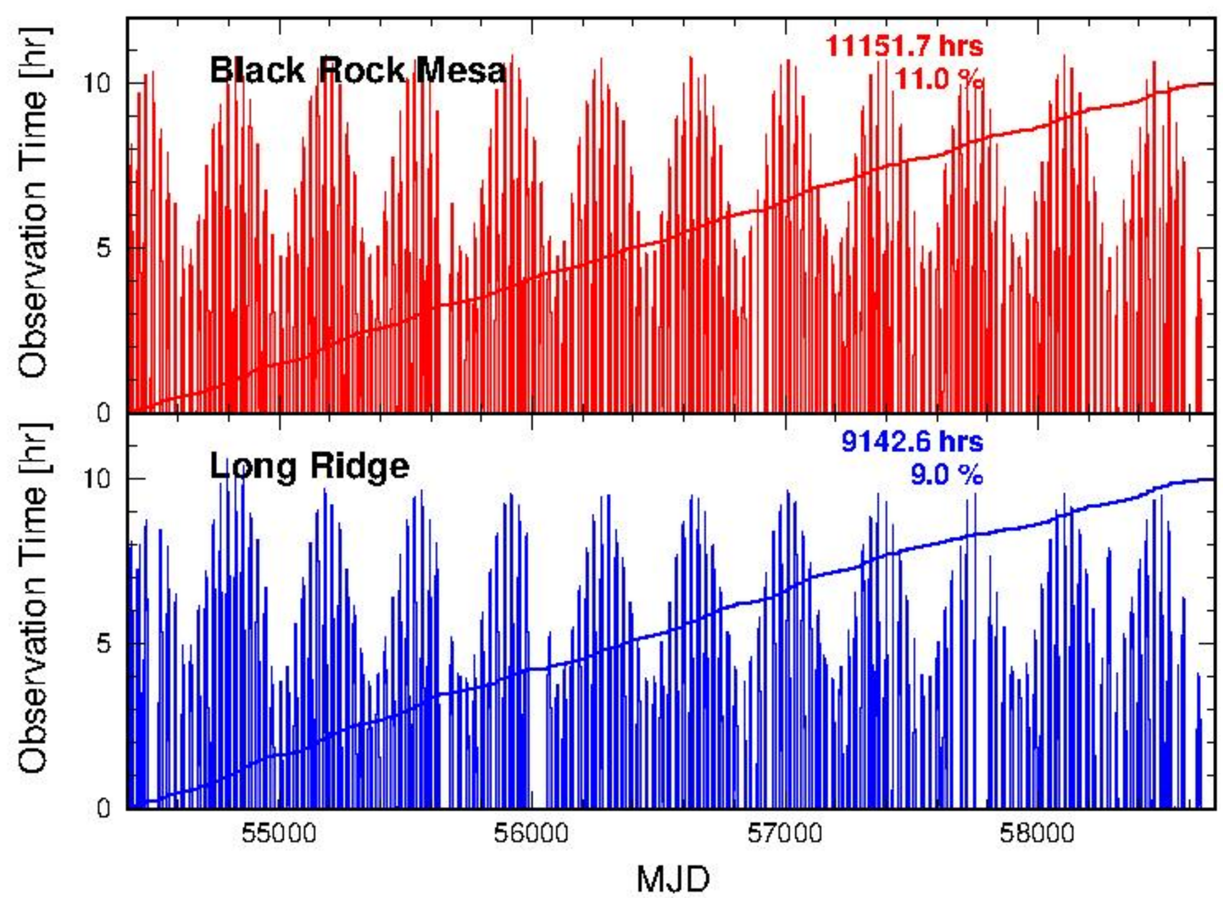


FD (BRM, LR)

Duty factors

11.0% for BRM station,

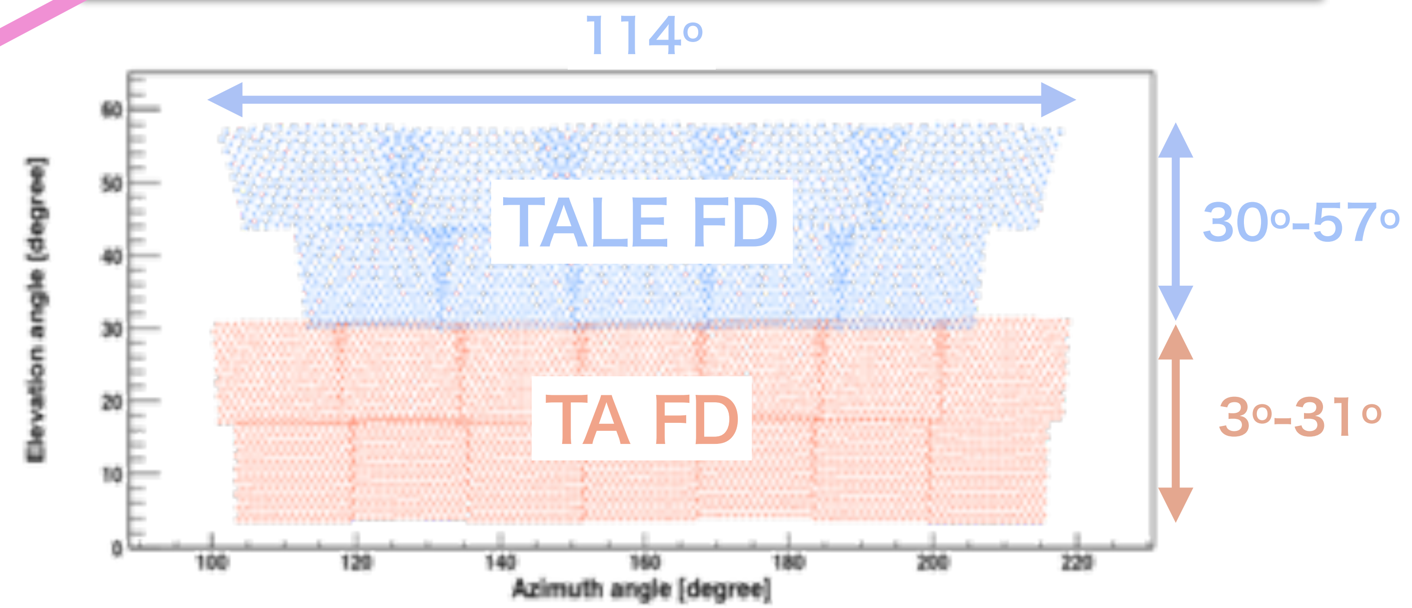
9.0% for LR station

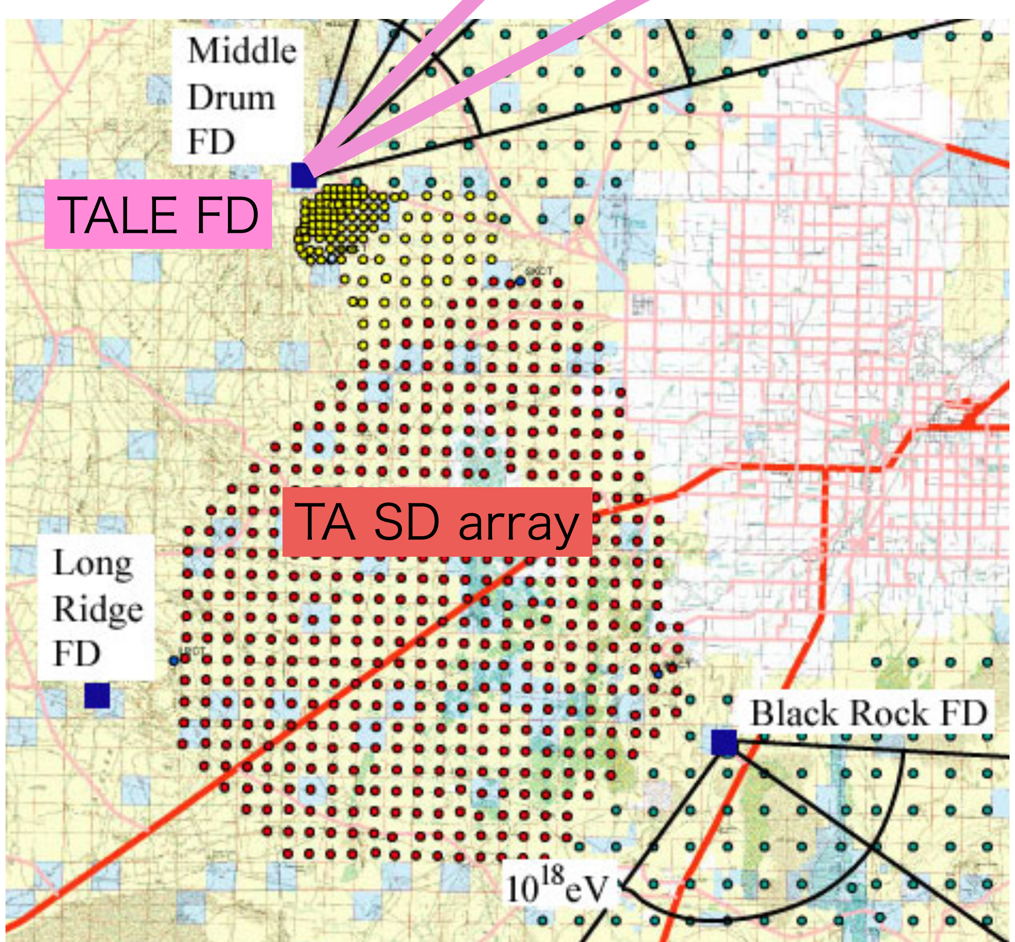


TALE FD

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

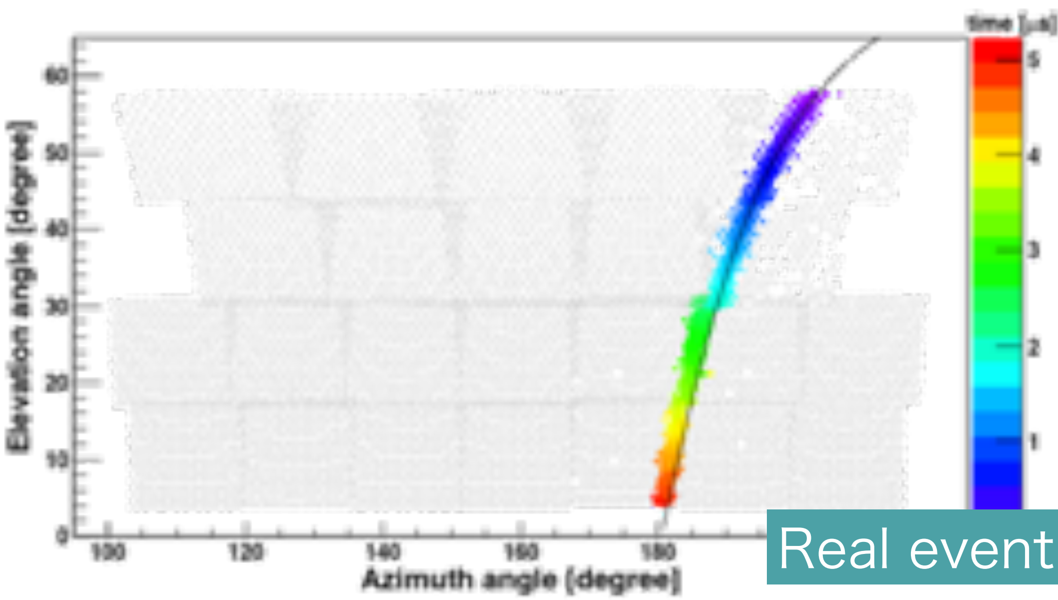
Refurbished HiRes telescopes & electronics
Mirror: same as TA FD (MD)
Elec.: 10 MHz 8bit FADC

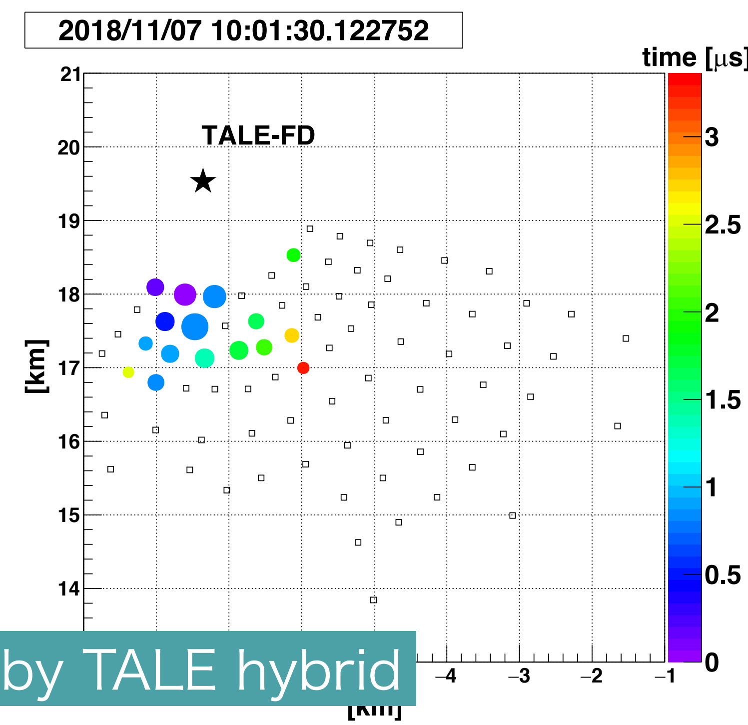




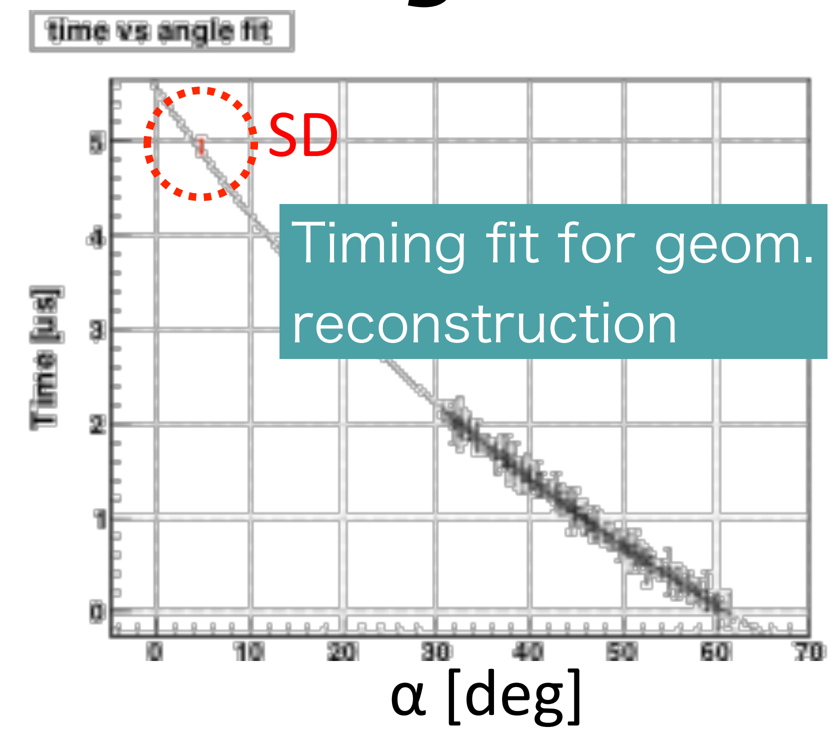
Installed in Nov. 2012
Operation since Sep. 2013
Hybrid trigger: Sep. 2018

Event reconstruction: FD hybrid



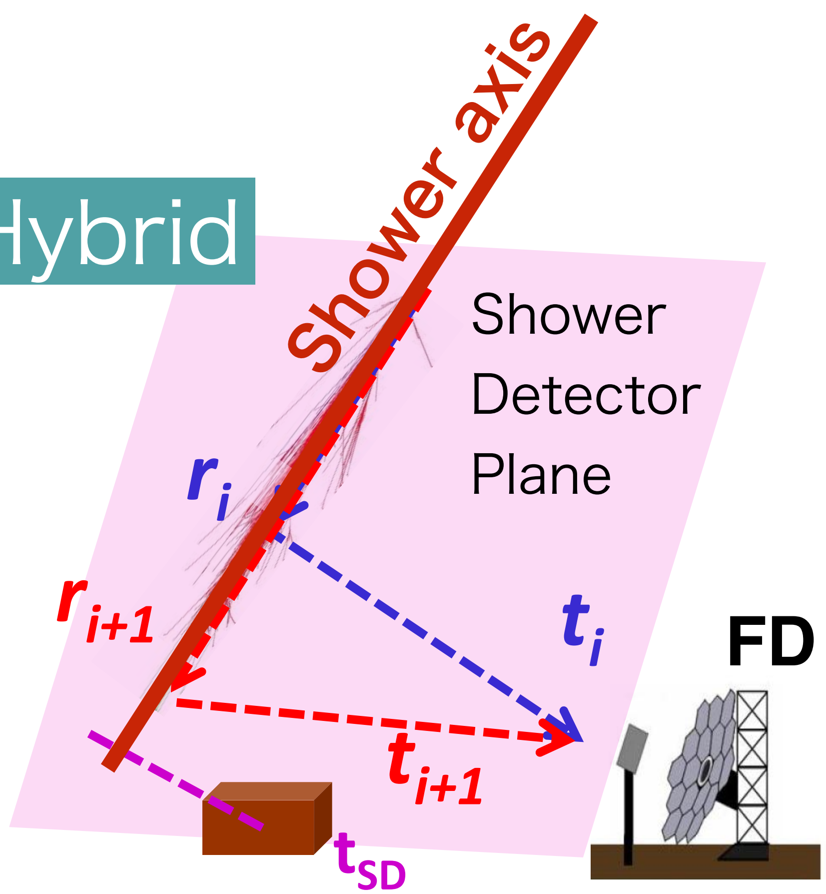


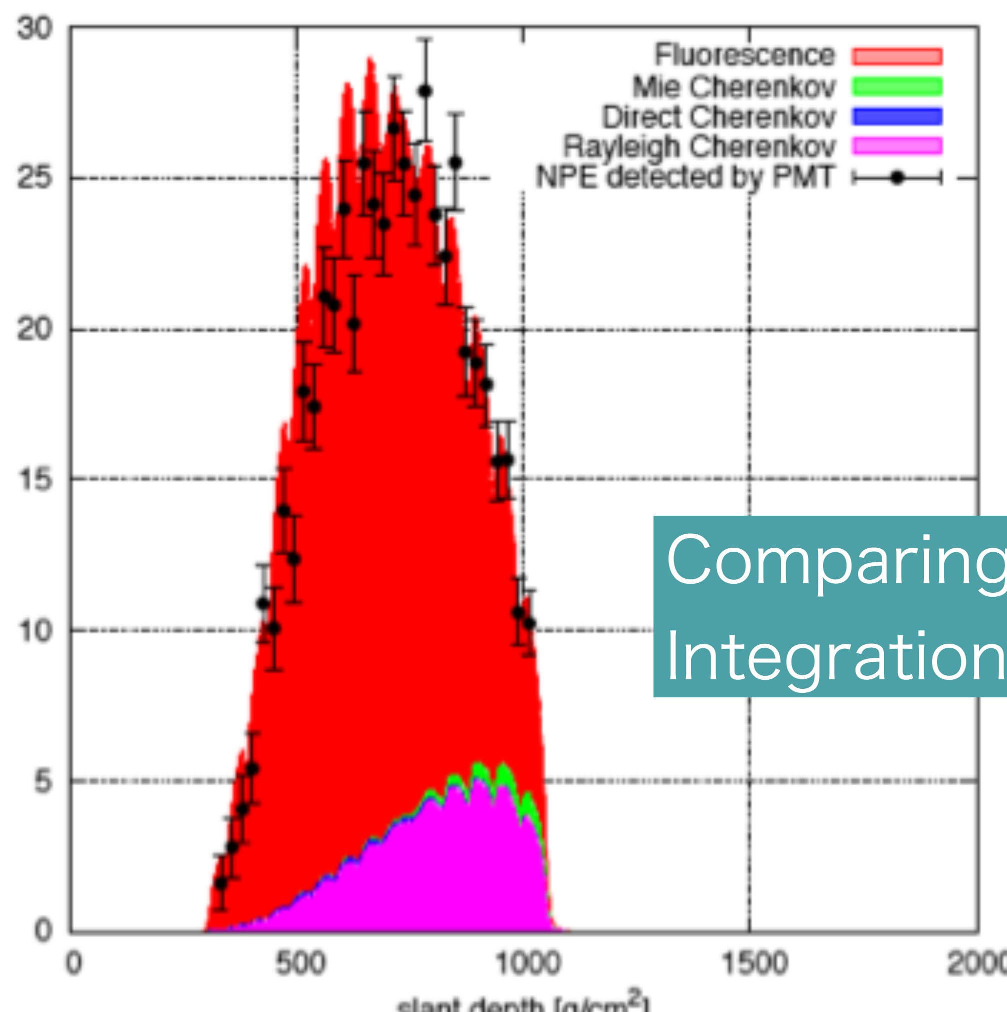
Real event by TALE hybrid



Timing fit for geom. reconstruction

Hybrid

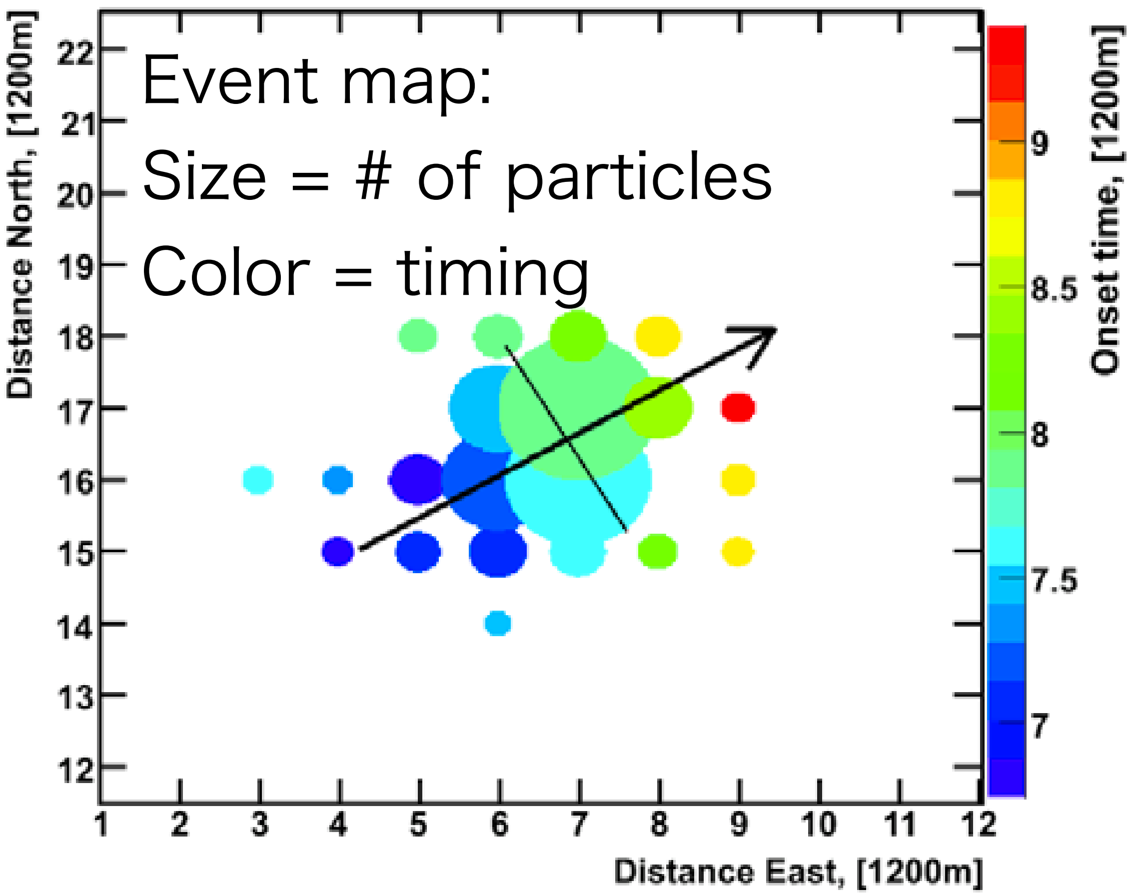


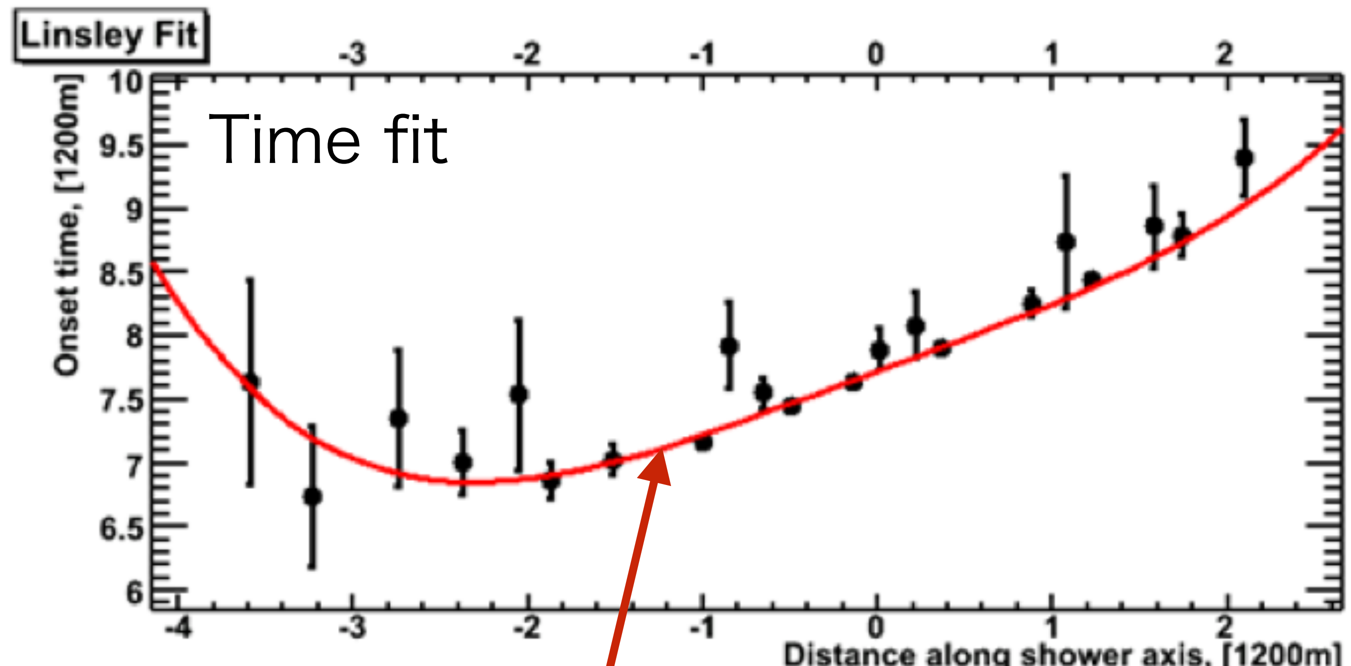


Comparing with MC -> Xmax

Integration of signals -> 1ry E

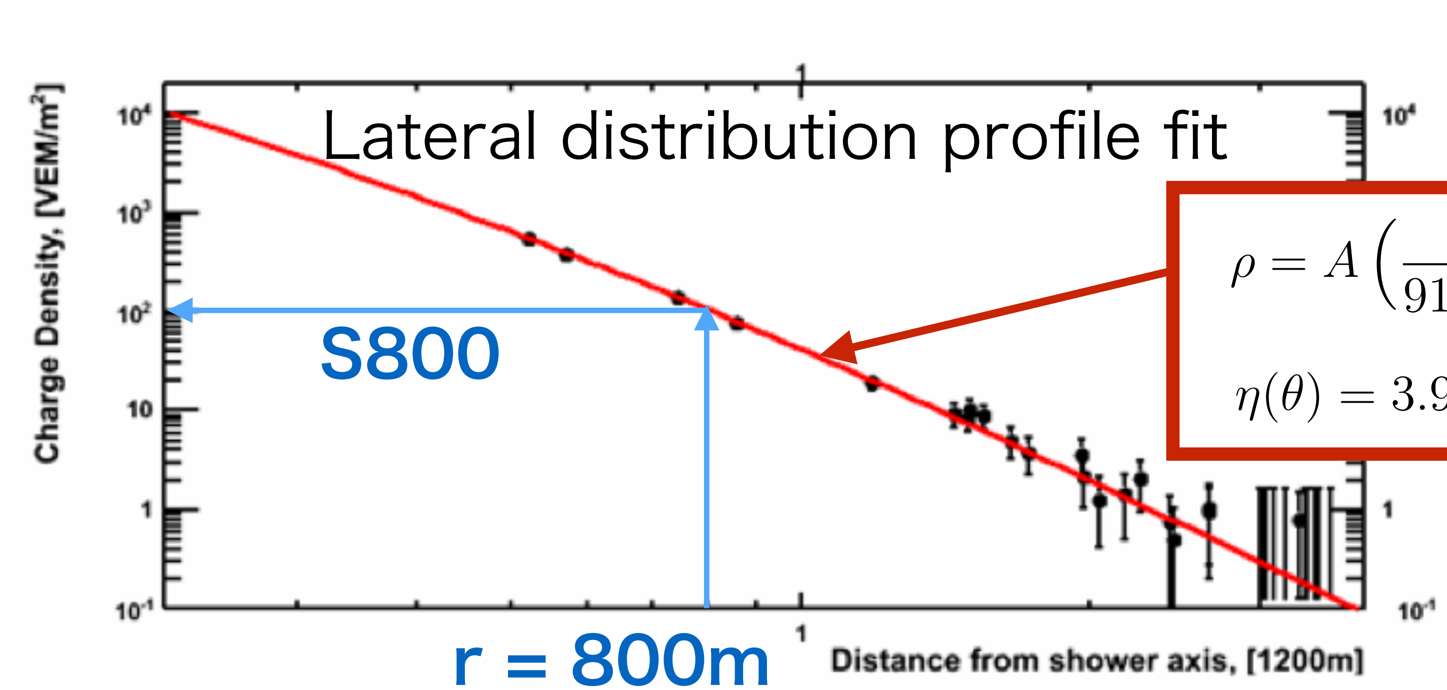
Event reconstruction: SD array





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

Modified empirical formula in AGASA



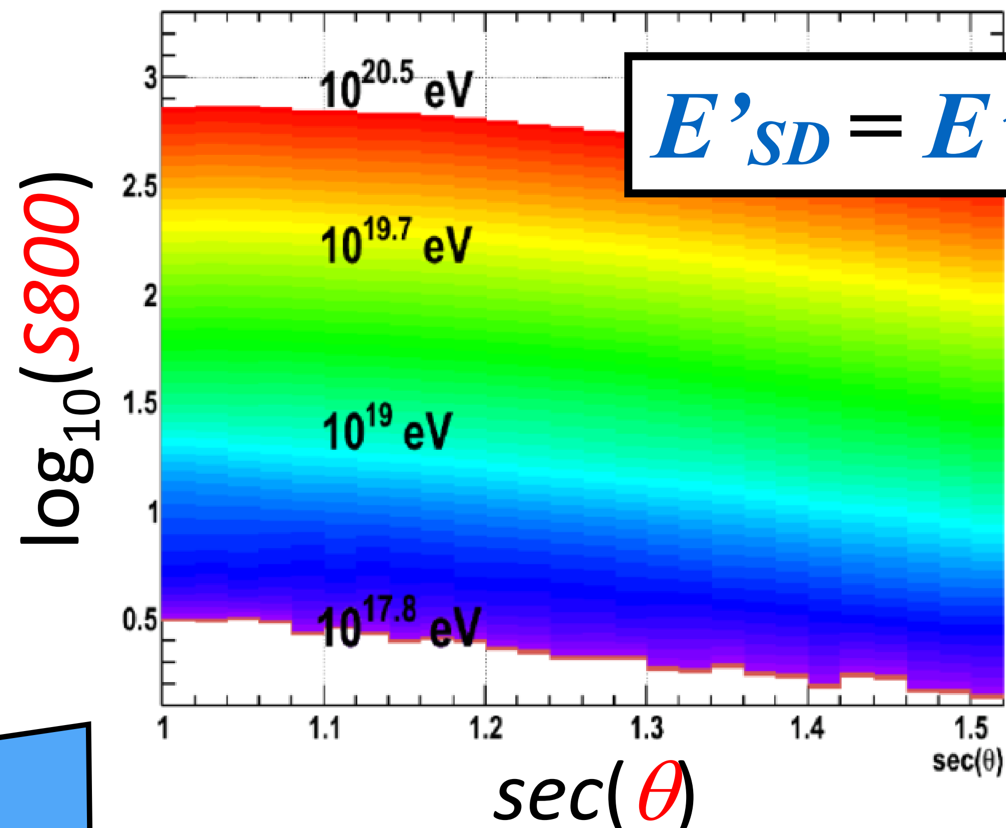
$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1 + \frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1 + \left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

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

Empirical formula used by AGASA

S800 -> primary energy

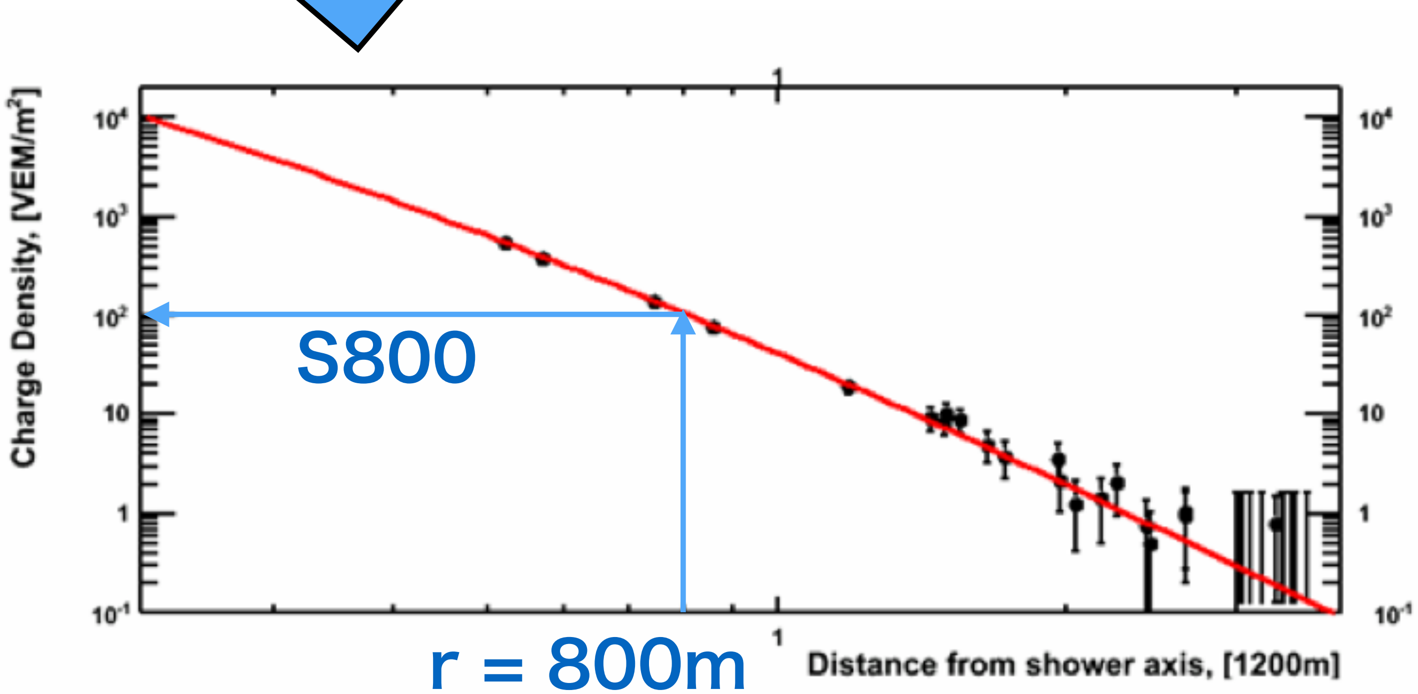
Event reconstruction: SD array



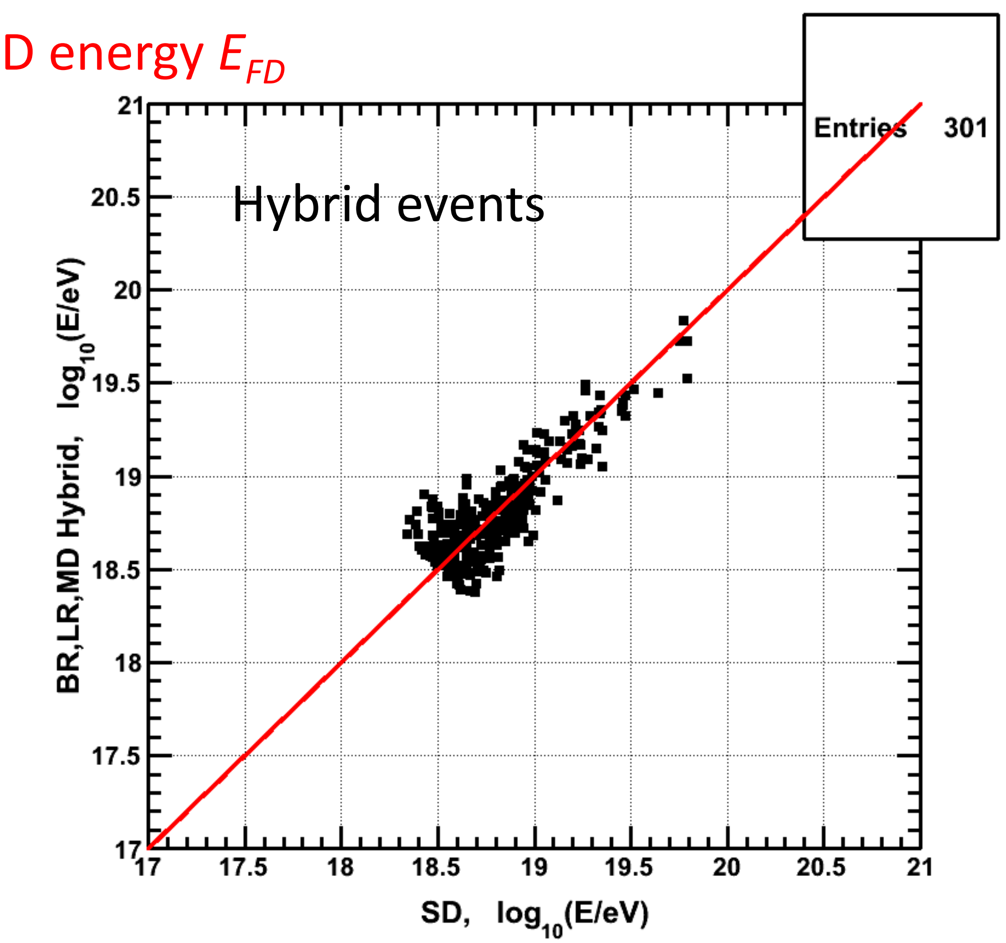
$$E'_{SD} = E'_{SD}(S800, \theta)$$

Scale to FD energy

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



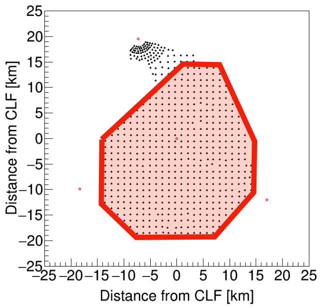
FD energy E_{FD}



SD energy E_{SD}

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)

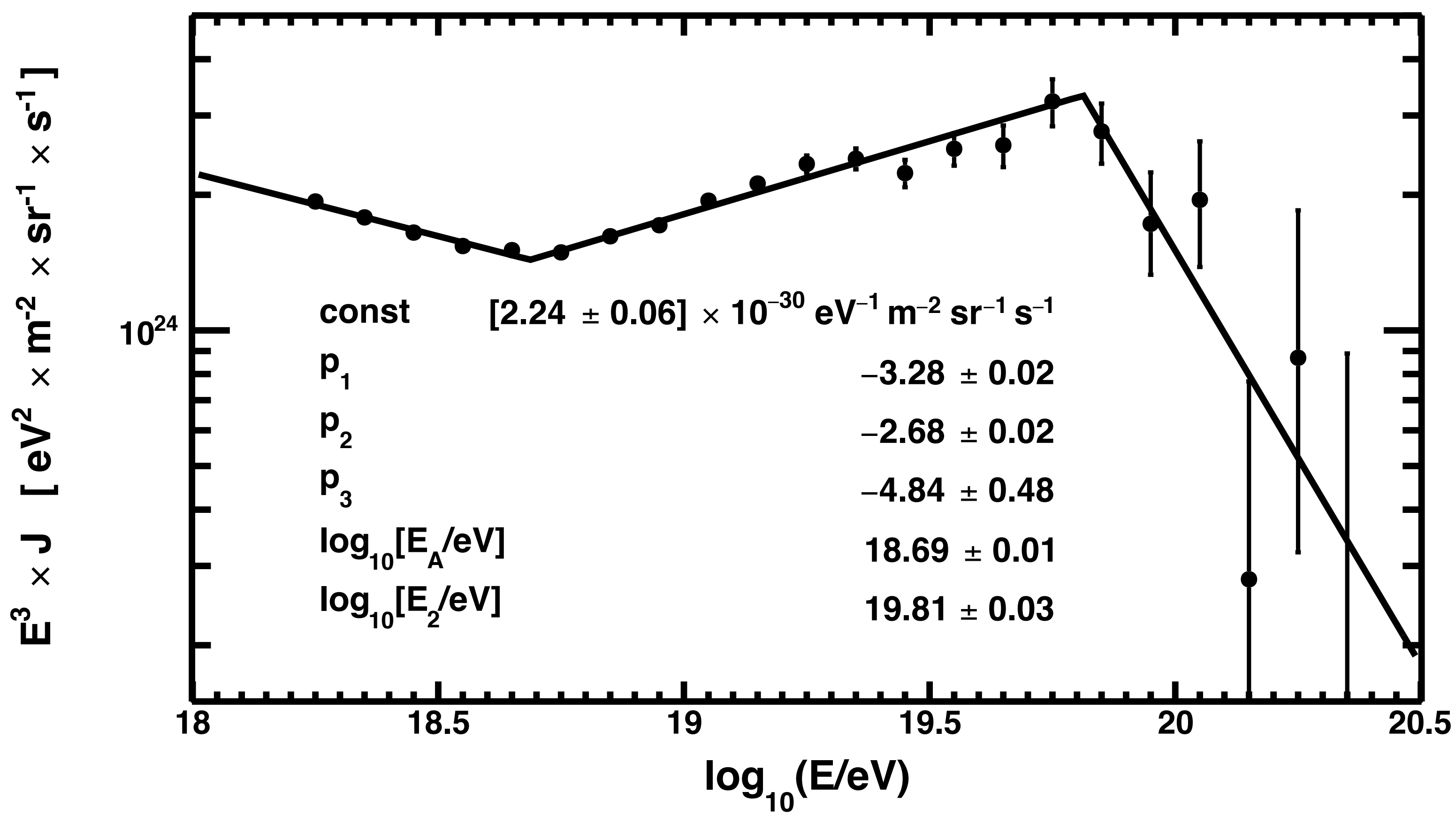
γ = -2.67 ± 0.02

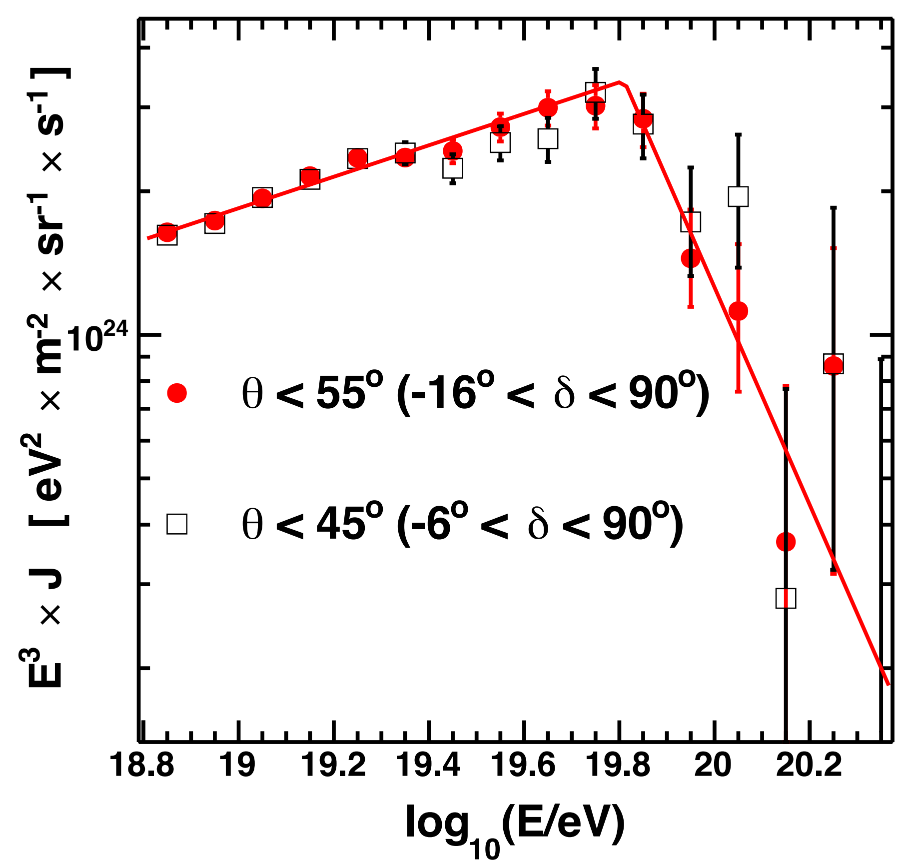
cutoff @ logE = 19.81 ± 0.03

γ = -5.3 ± 0.5

logE1/2 = 19.97 ± 0.04

Significance of suppression is 12.0 σ

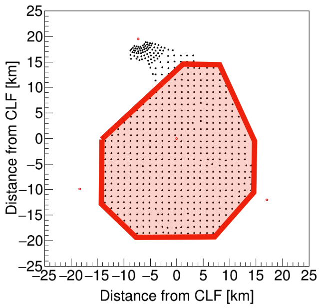




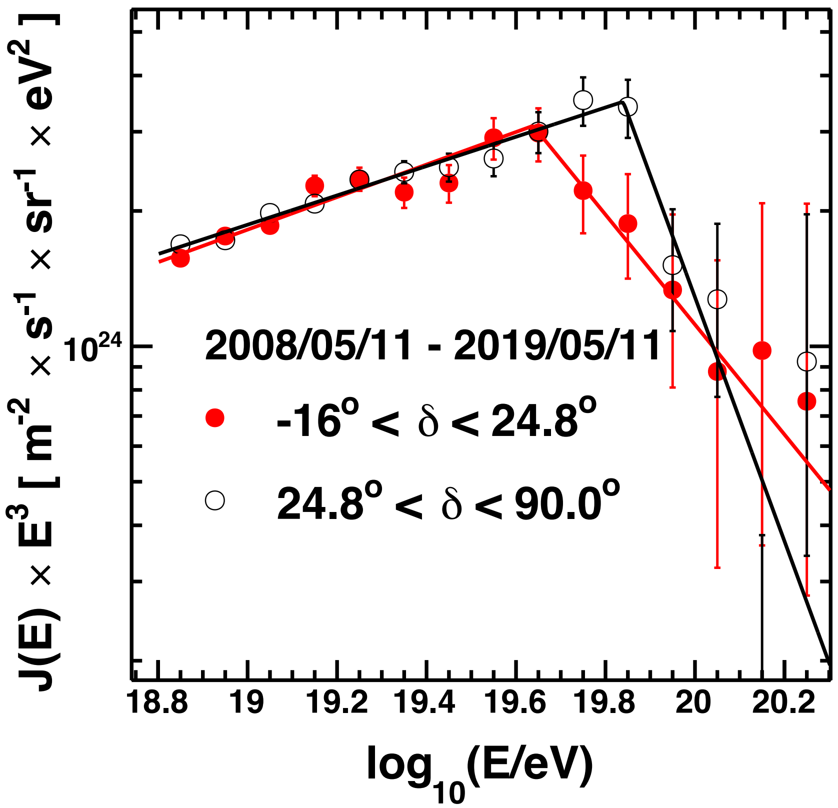
Energy resolution = 18 % logE > 19.0

Energy scale systematic uncertainty = 21 %

TA SD spectrum from 11 years of data



D. Ivanov



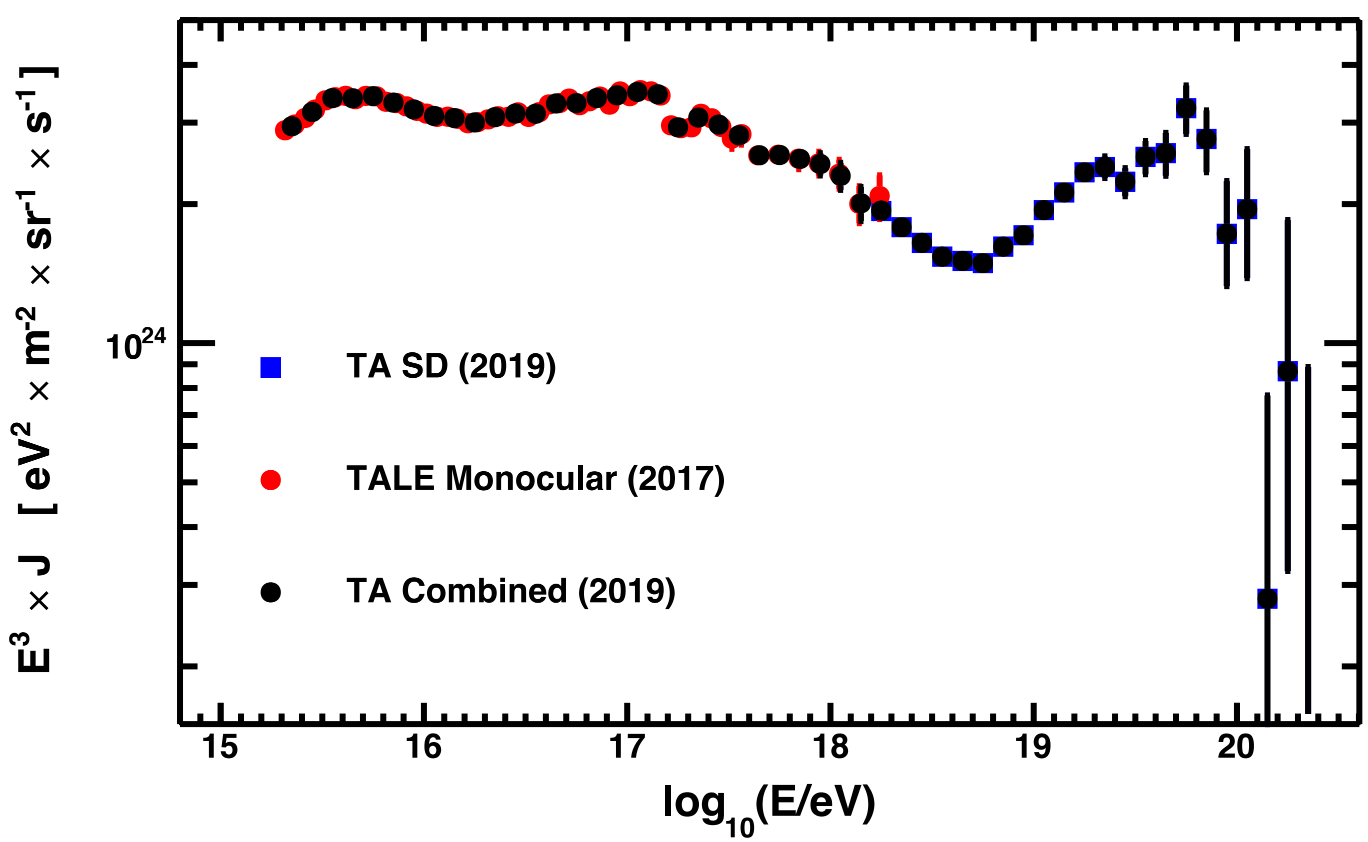
Declination dependence of the TA SD spectrum

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)

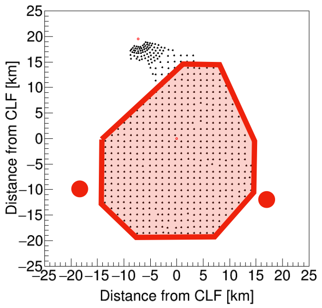


Combined TA spectrum using
2 years TALE FD monocular data +
11 years TA SD data

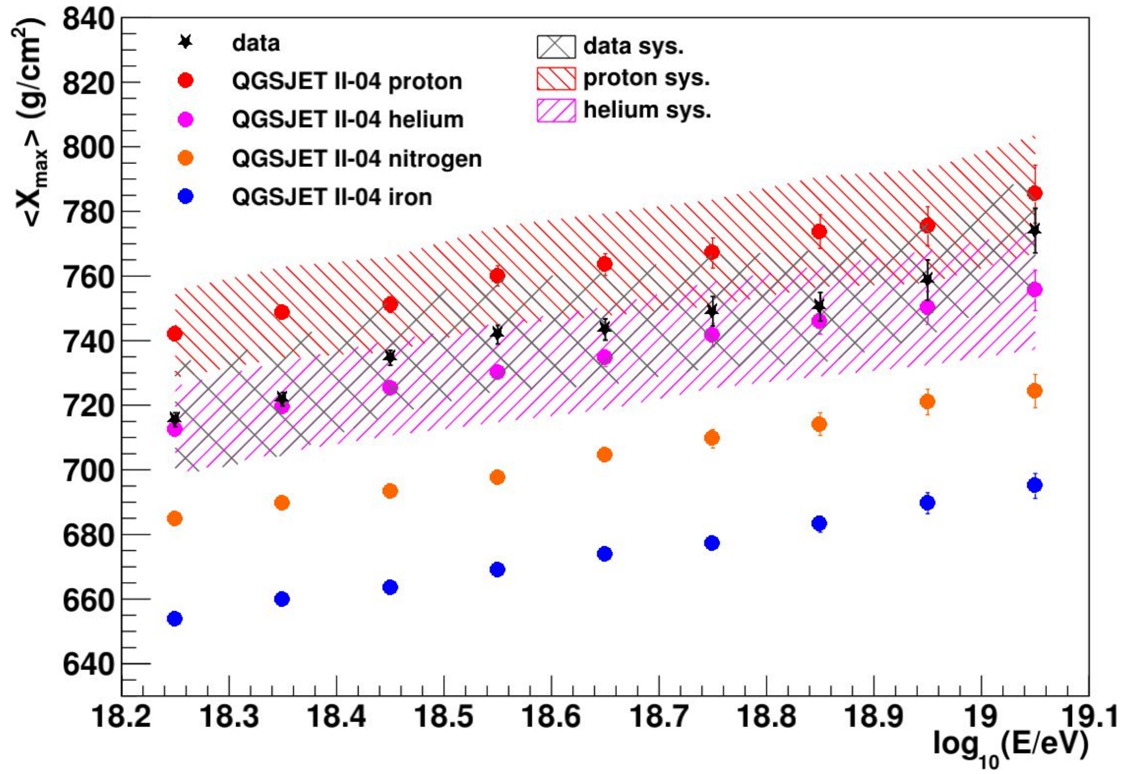
knee @ logE ~ 15.5
low energy ankle @ logE = 16.22 ± 0.02
second knee @ logE = 17.04 ± 0.04
ankle @ logE = 18.69 ± 0.01
cutoff @ logE = 19.81 ± 0.03

Chemical composition

TA BRM+LR+SD hybrid: <Xmax> and σ Xmax



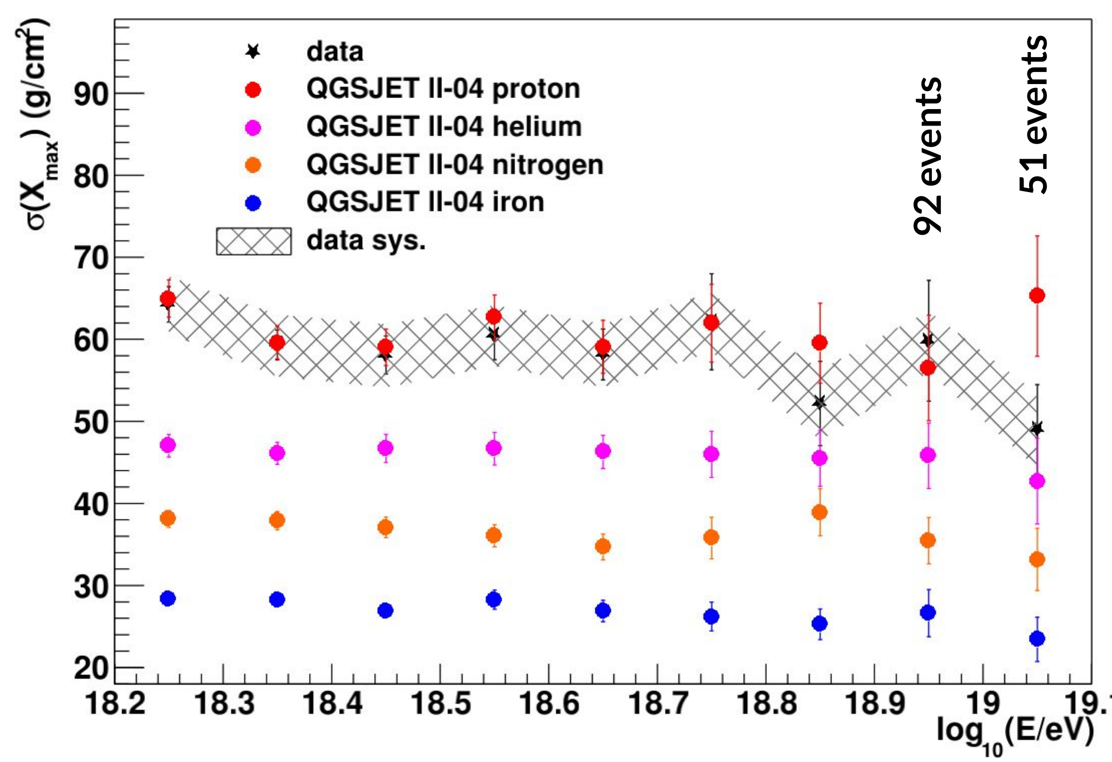
W. Hanlon



< 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

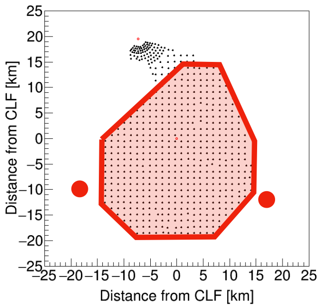
Systematic uncertainty on <Xmax> is 17 g/cm^2
Xmax bias < 1 g/cm^2
Xmax resolution = 17.2 g/cm^2
Energy resolution = 5.7 %



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

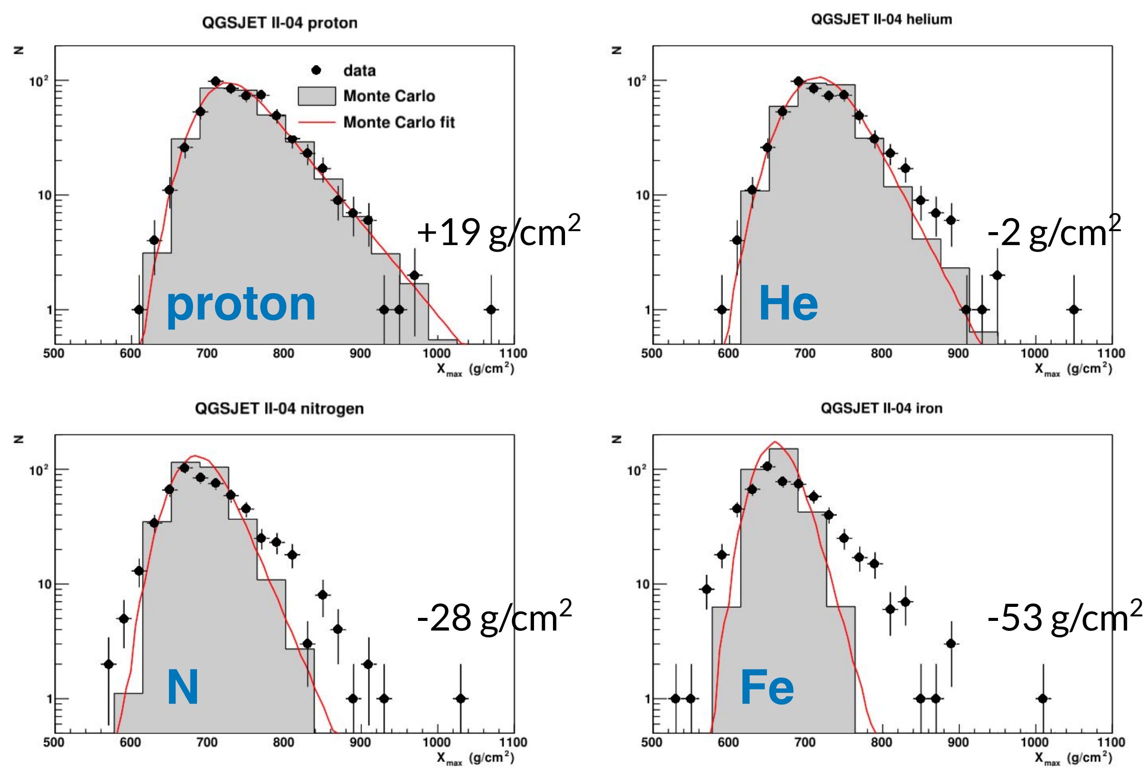
TA BRM+LR+SD hybrid: single element model



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

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

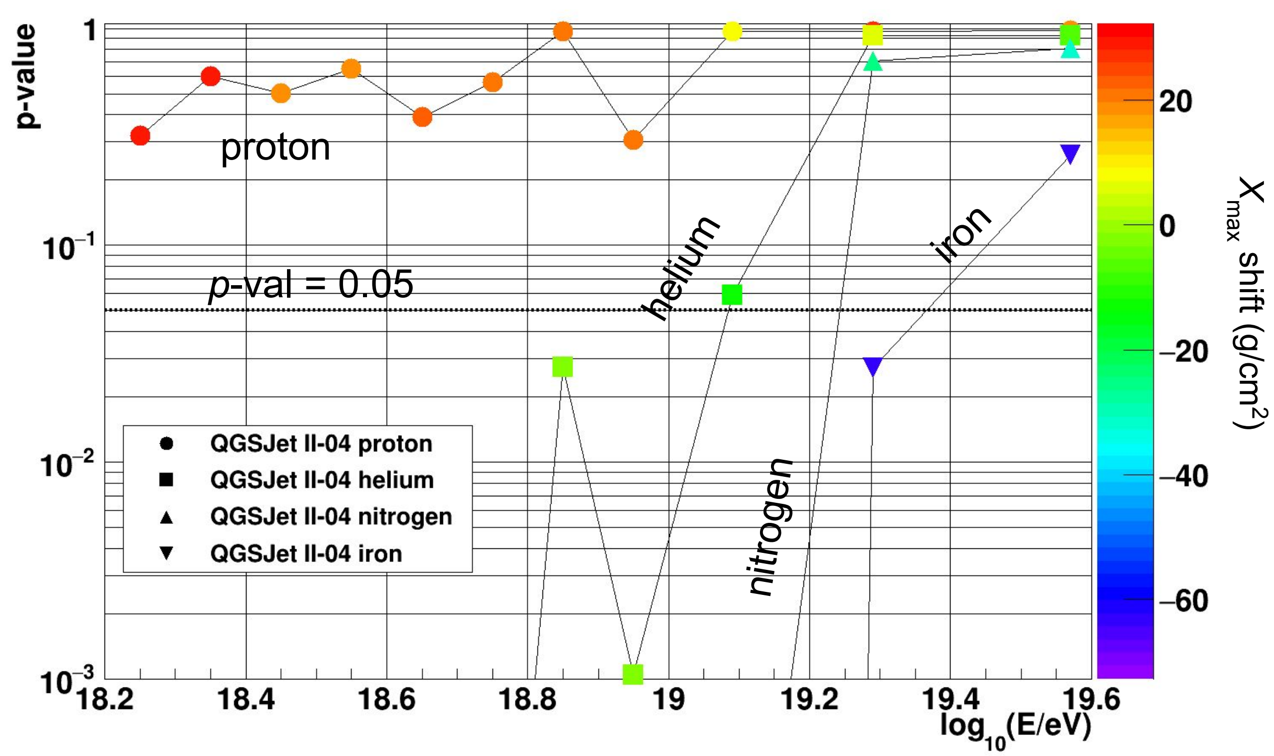
W. Hanlon



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

Proton MC agrees 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)



Plot of p-values indicating the compatibility:

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.

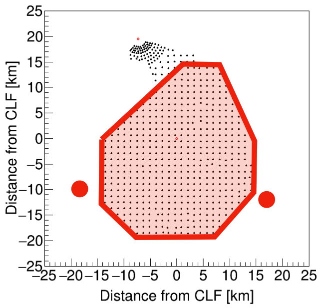
Other components are not compatible in E < 10^{19}eV

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

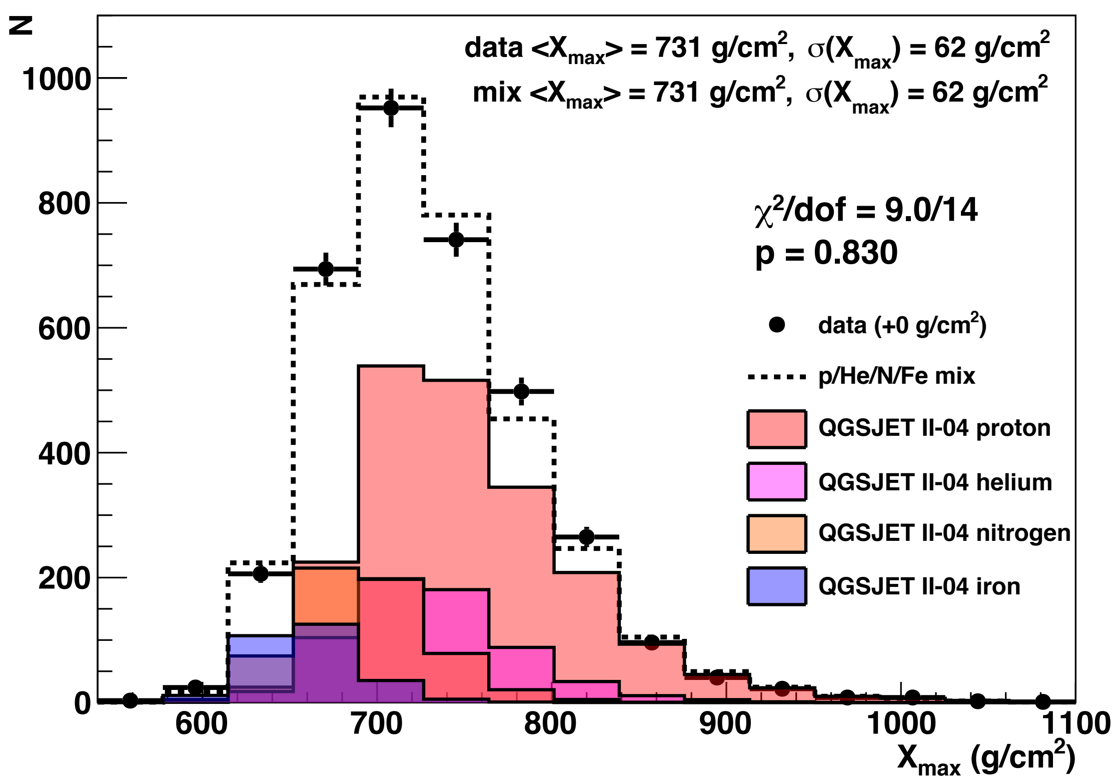
Fe requires a shift of ~ 50 g/cm^2

TA BRM+LR+SD hybrid: 4 element model

W. Hanlon



QGSJET II-04 proton, He, N, Fe, data(+0 g/cm²)

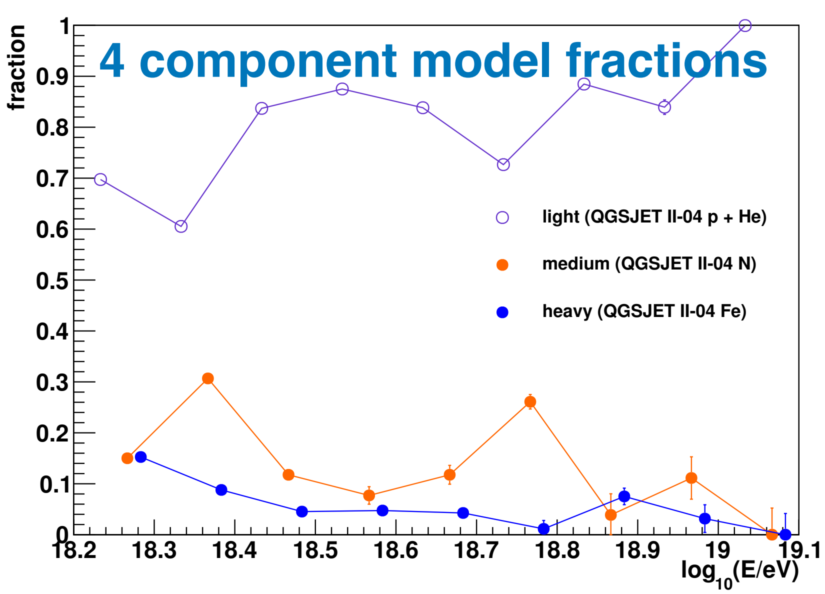


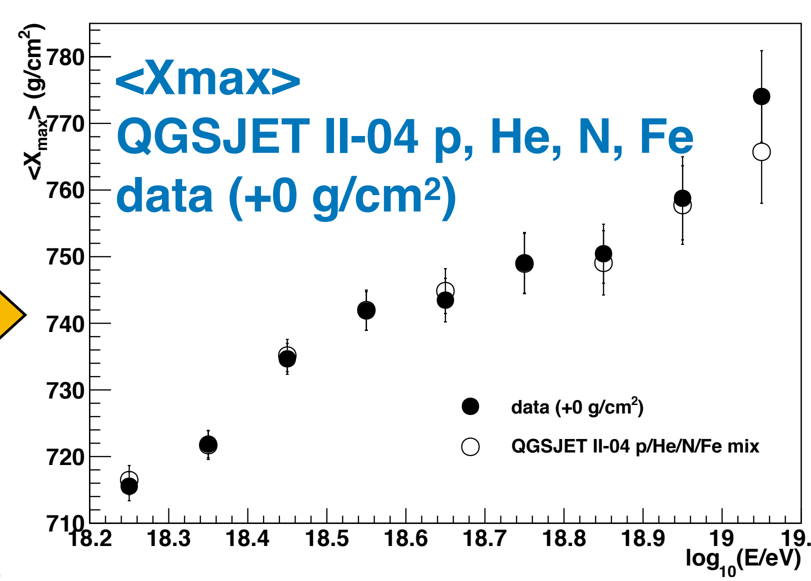
Test the agreement of data and 4 component mix by comparing data and MC Xmax distributions (No systematic shifting).

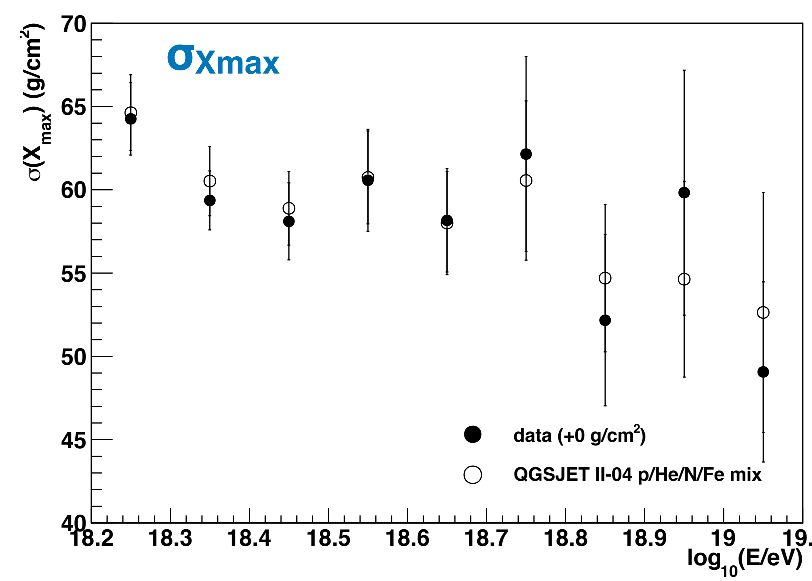
For $10^{18.2}$-$10^{19.1}$ eV, minimum χ^2 is found at the fraction,
proton = 57%, He = 18%, N = 17%, Fe = 8%.

(Xmax systematic uncertainty = 17 g/cm²)

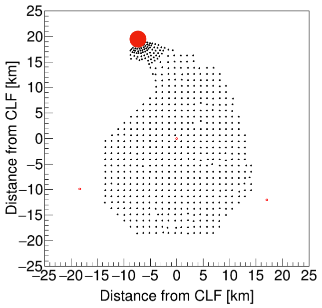
<Xmax> and σ_{Xmax} from the best fit fractions are well within the statistical uncertainty of the data without any systematic shifts.





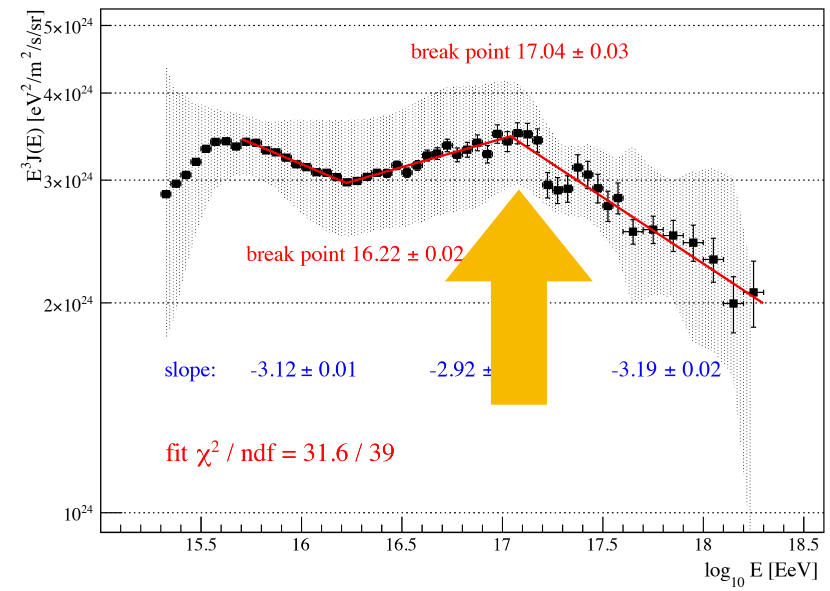


TALE FD monocular reconstruction



T. AbuZayyad

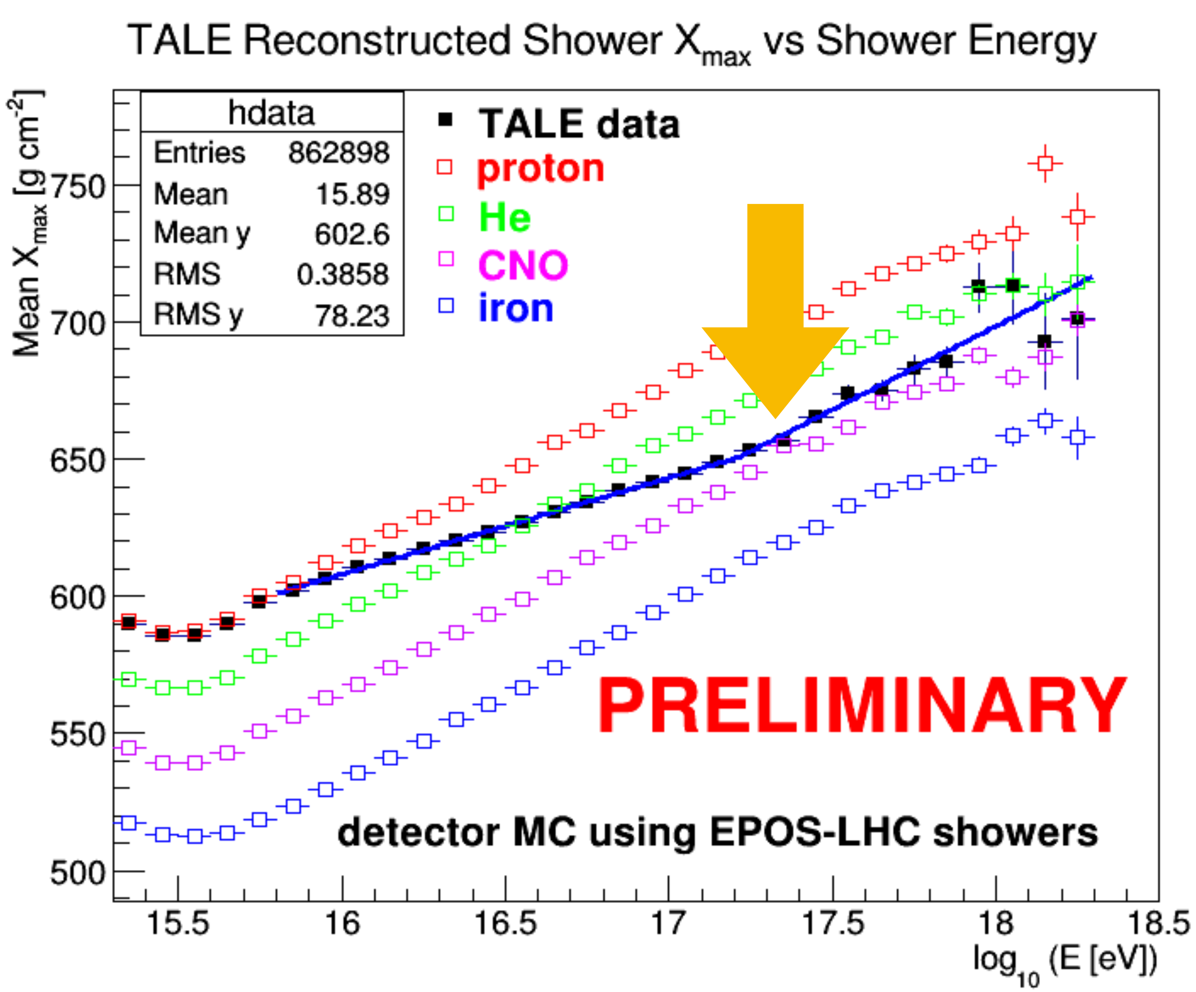
TALE FD monocular spectrum (2 years)
Ap. J., 865, 74(2018), arXiv: 1803.01288

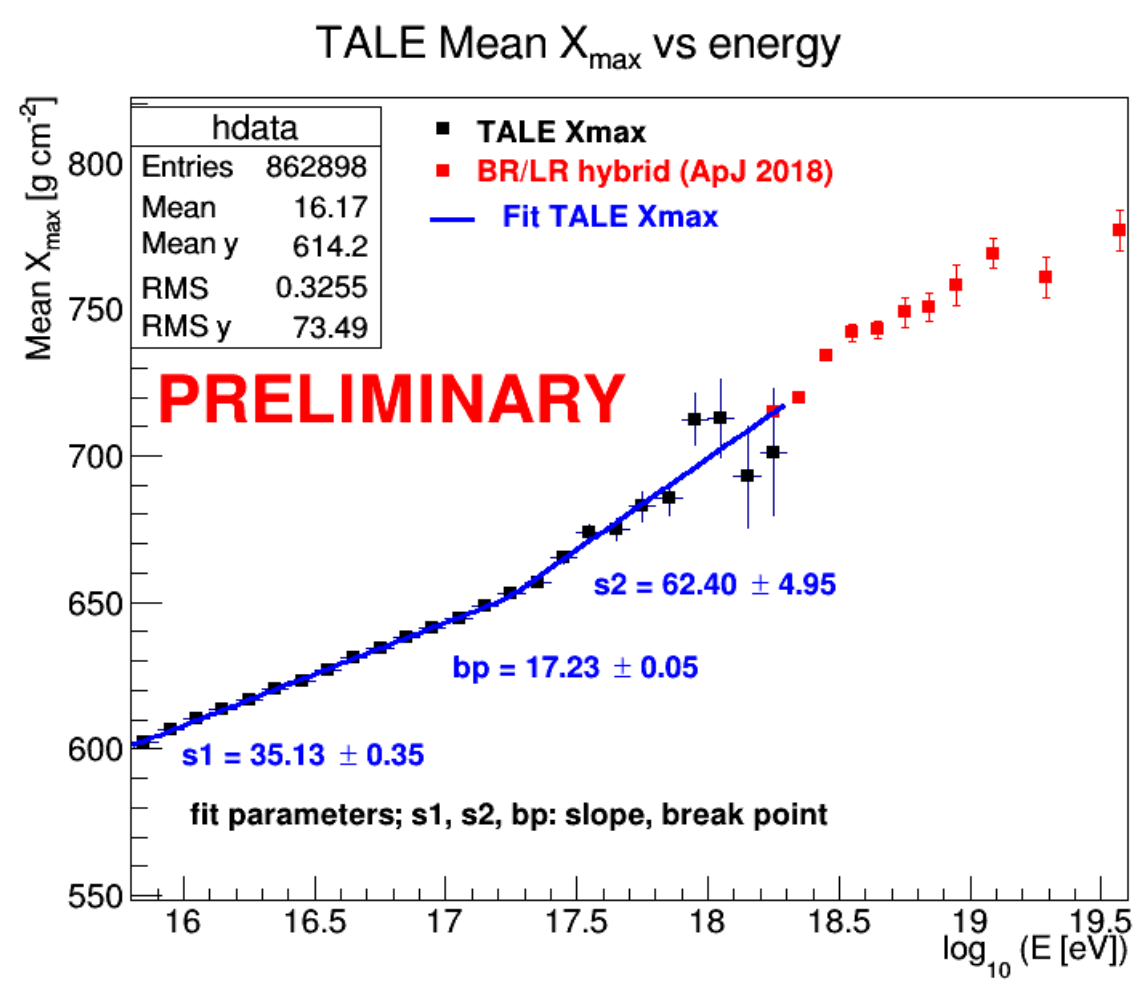


Xmax measured by TALE FD with monocular reconstruction
4 years of data (Jun. 2014 - Nov. 2018)

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

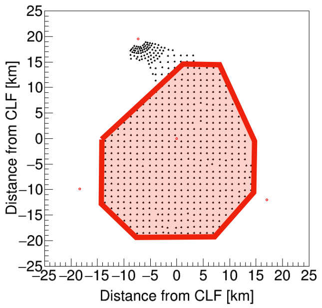
Smooth connection of the low(TALE) and the high(BR/LR hybrid) energy rails.



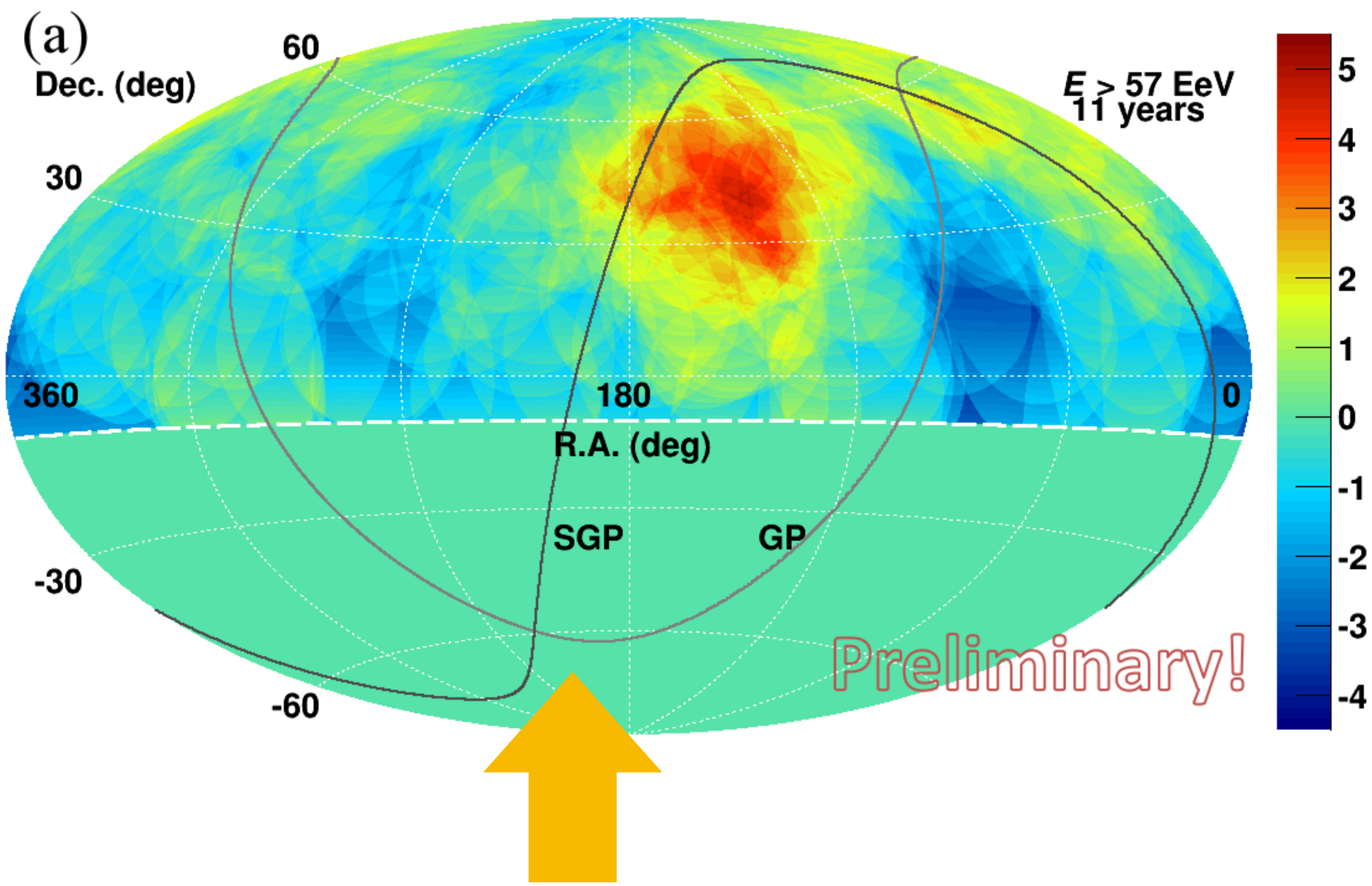


Anisotropy study

“Hotspot” update from 11 years of data

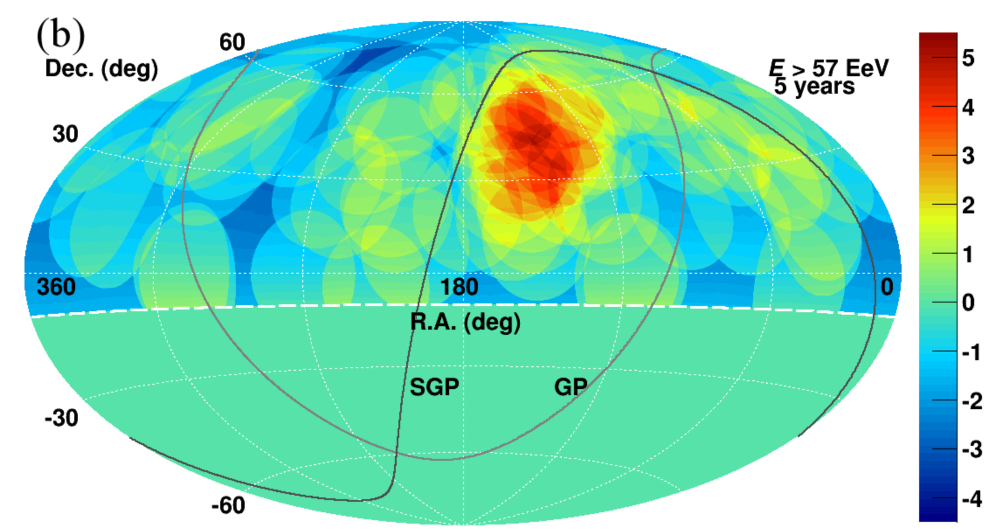


K. Kawata



Original hotspot reported in 2014, from 5 years of data

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

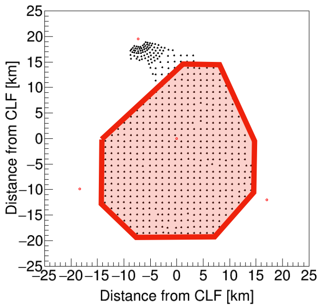


Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3^{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)

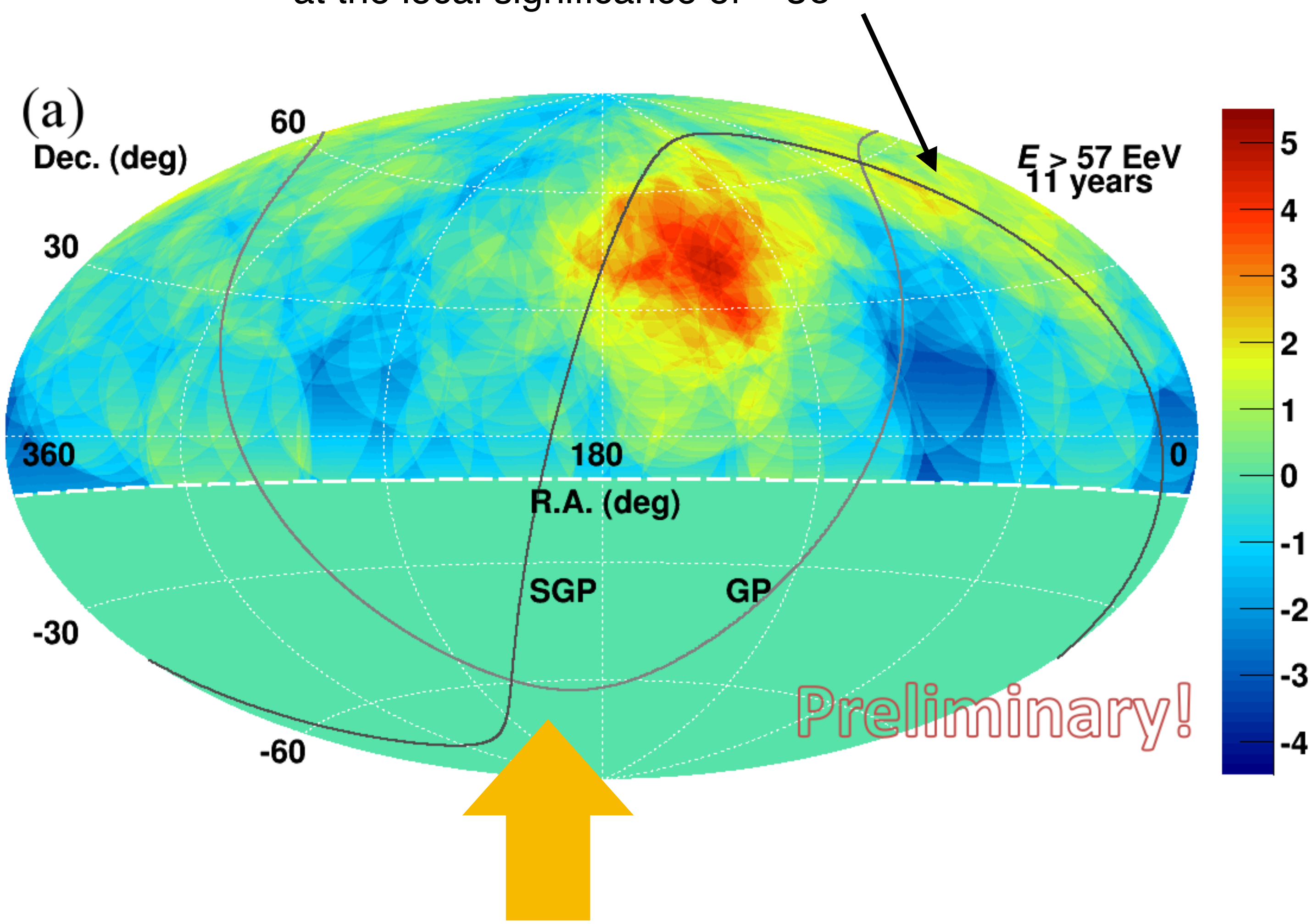
“Hotspot” update from 11 years of data

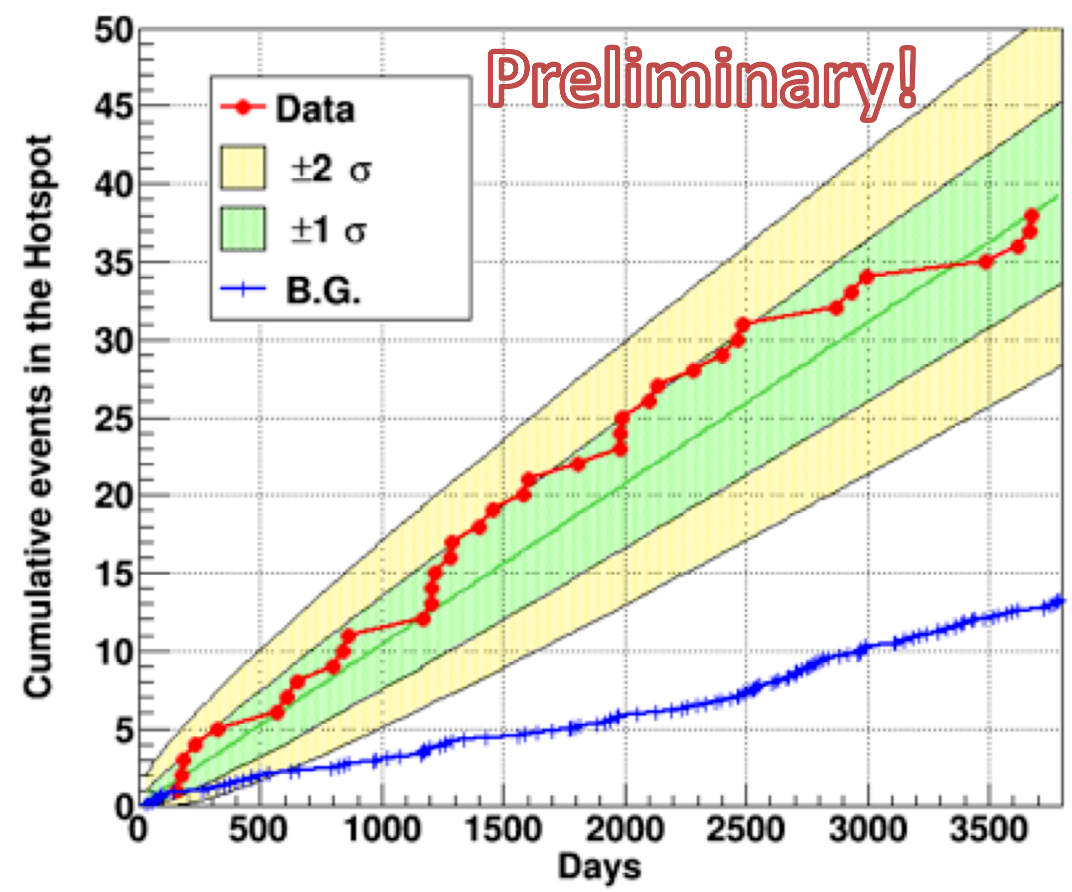
K. Kawata



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

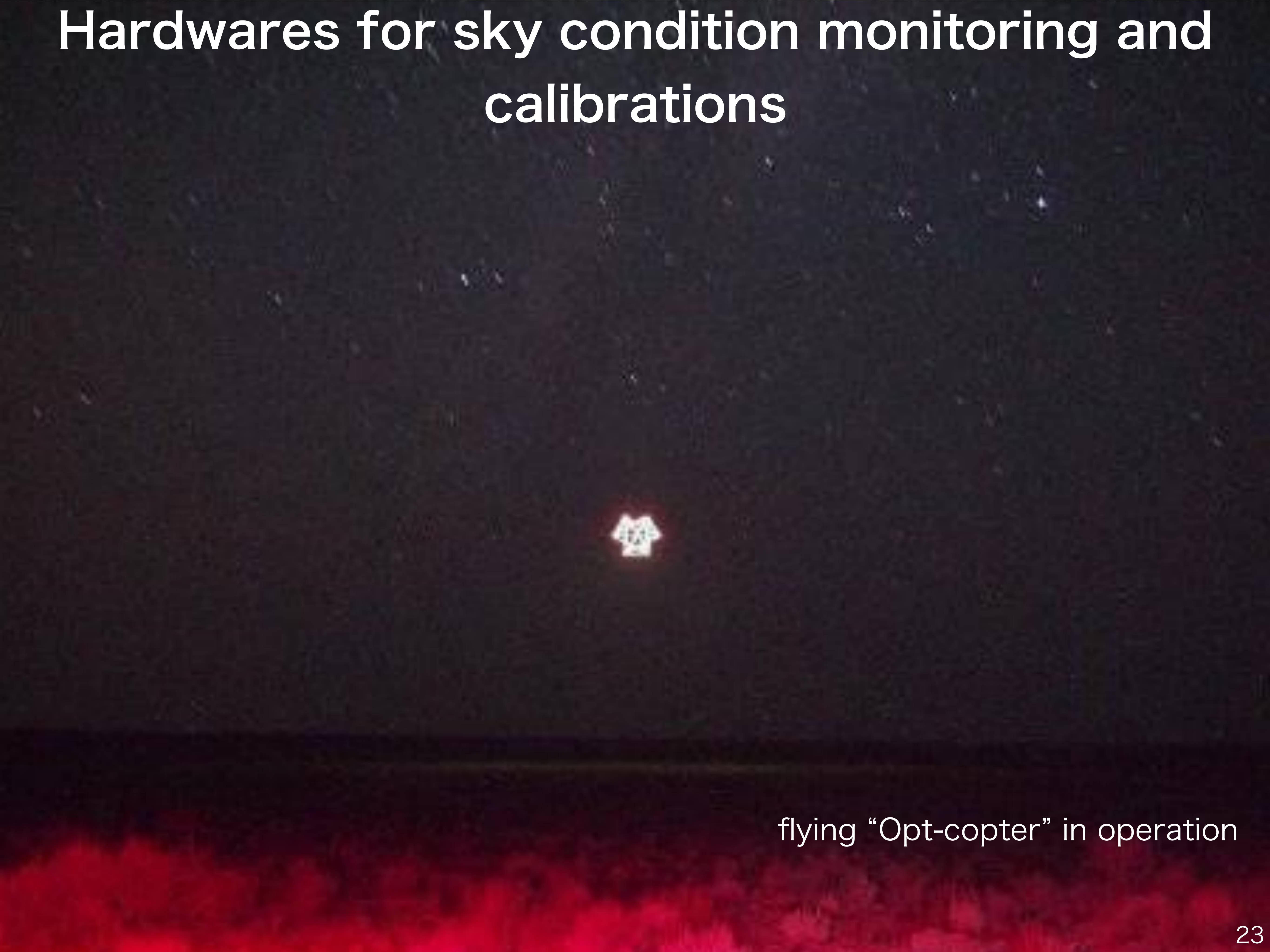




Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, 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)

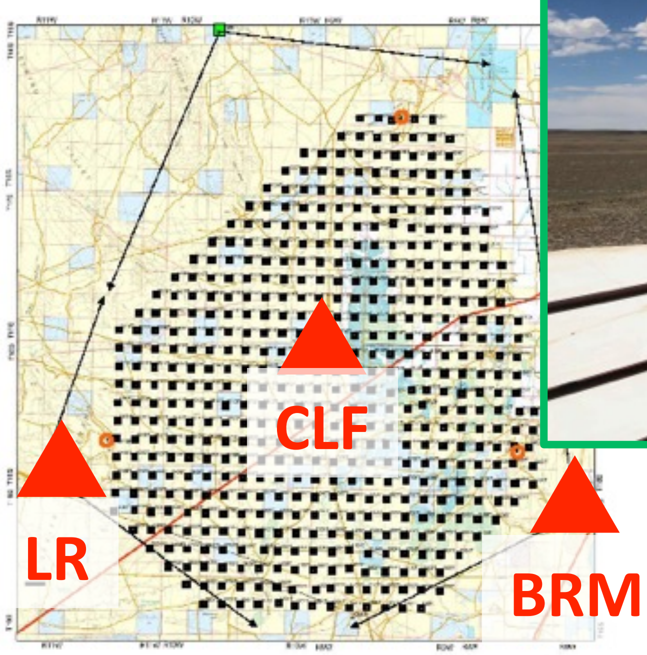
Hardwares for sky condition monitoring and calibrations

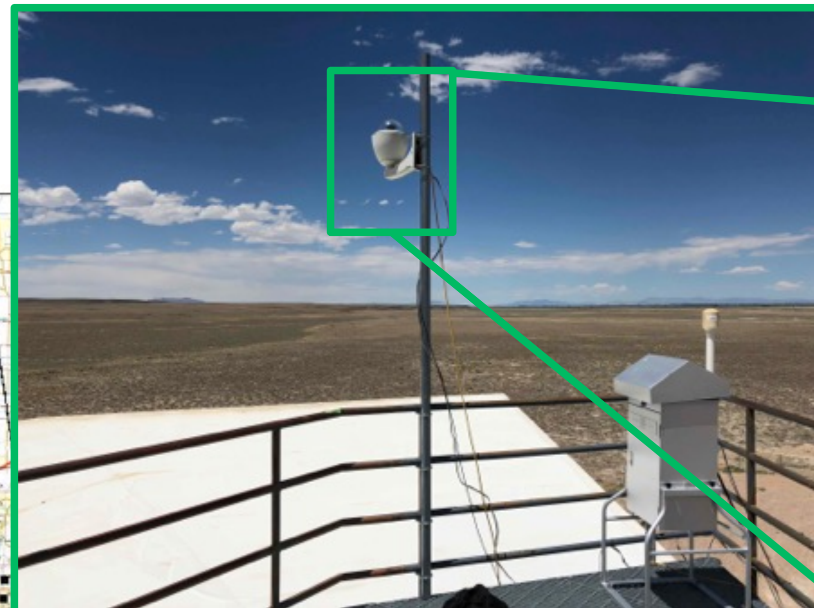


flying “Opt-copter” in operation

CCD cloud monitoring system: hardwares

K. Yamazaki



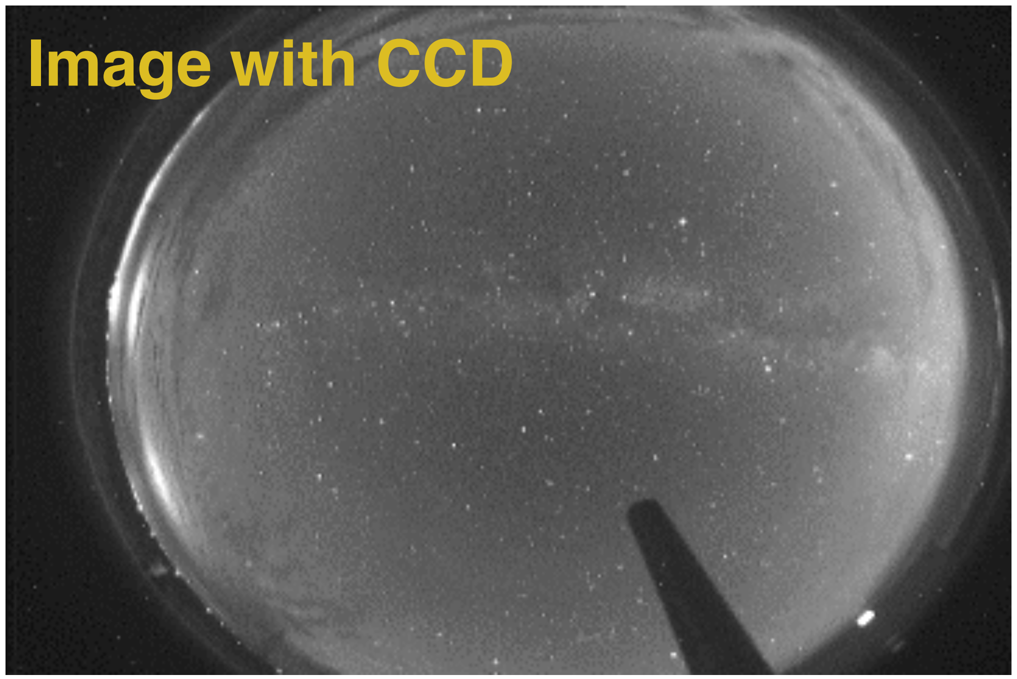


- 3 sets in TA site
- every 1 min.
- 8 sec exposure
- size: 720 × 480 pixels (346KB / 1 photo)
- FOV: 185.0° × 154.1°

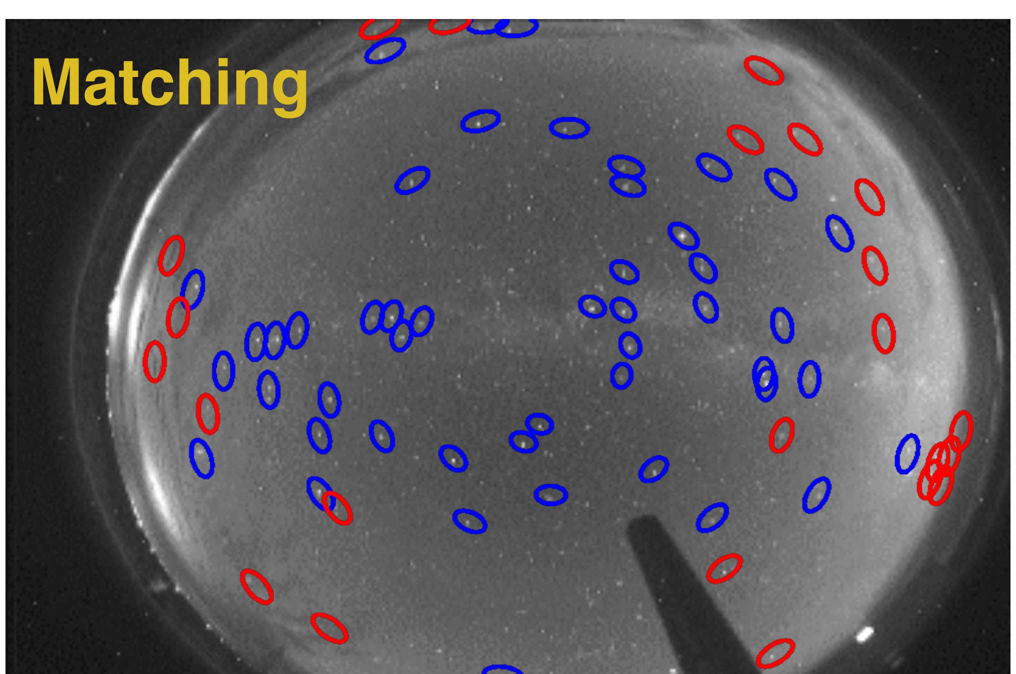
Cloud monitoring system: scoring

K. Yamazaki

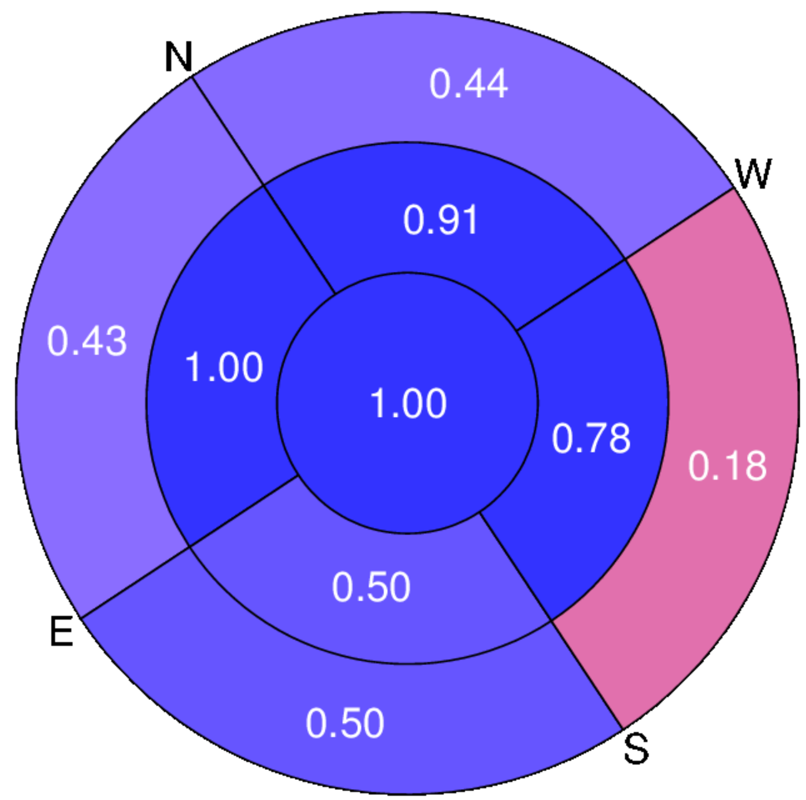
Searching the listed stars on SAO star catalog (> 3.5 mag.) in each picture
→ Score = number of matched stars / total expected # of stars in FOV



Nov. 20, 2014, 1:40 - 12:00 UTC



Dividing the sky into 9 regions
(by zenith and azimuth)
→ Scoring for each region



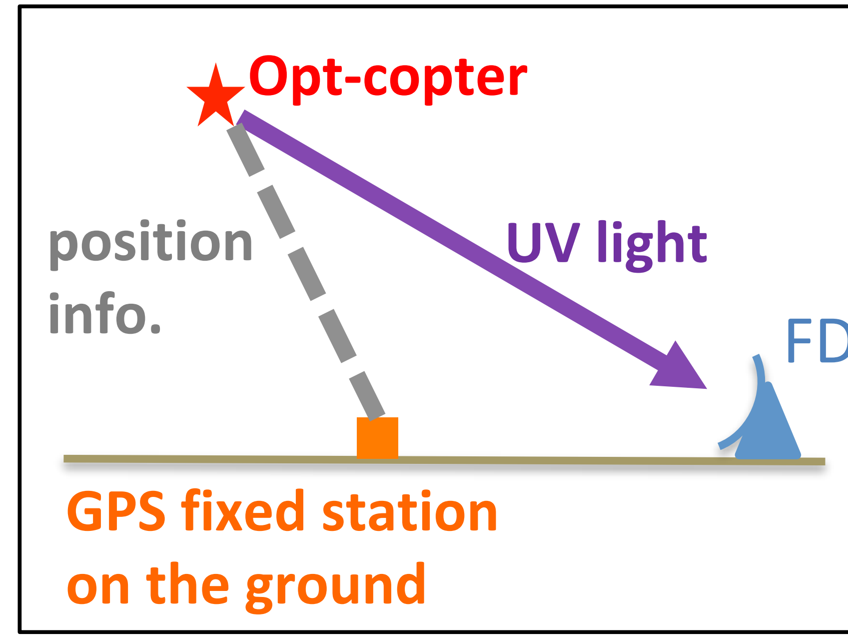
Listed star (3.5 mag.) at the SAO catalog

matched star

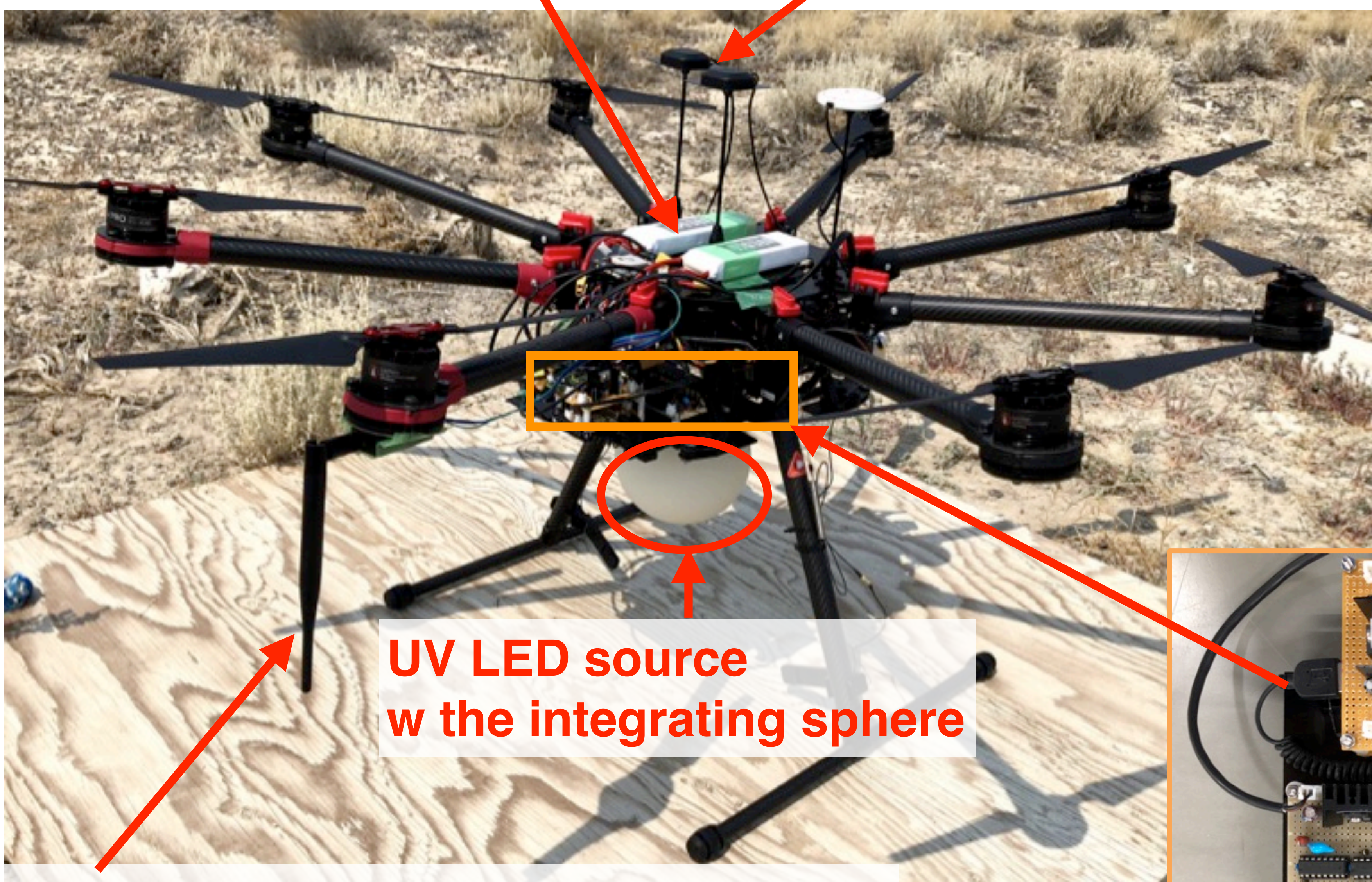
not seen, expected position

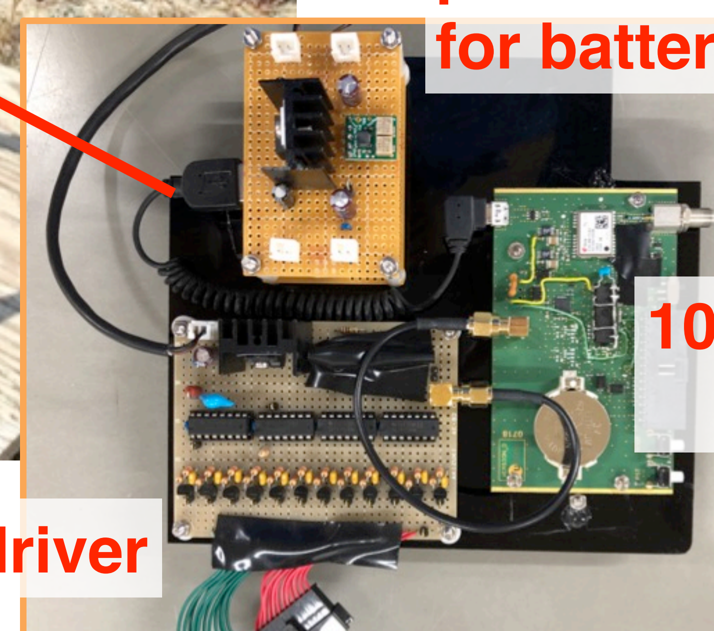
“Opt-copter” (drone + light source + hi-res GPS)

T. Tomida

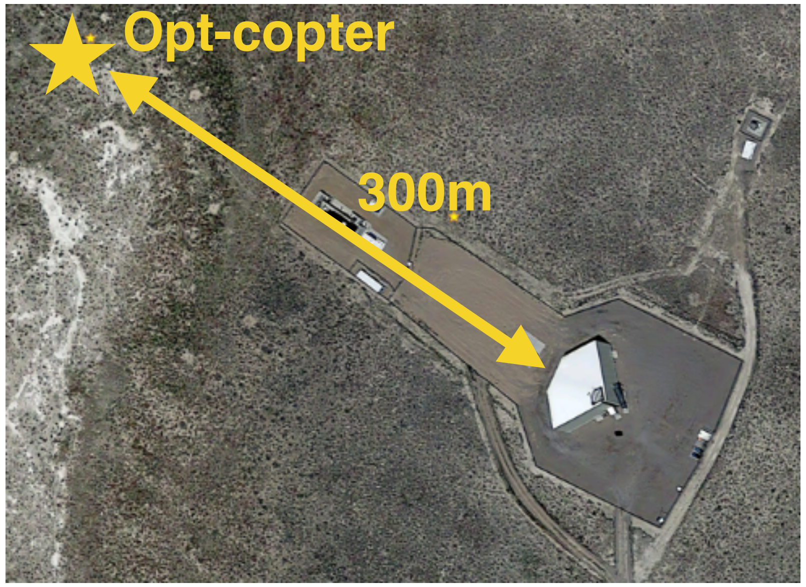


conceptual image





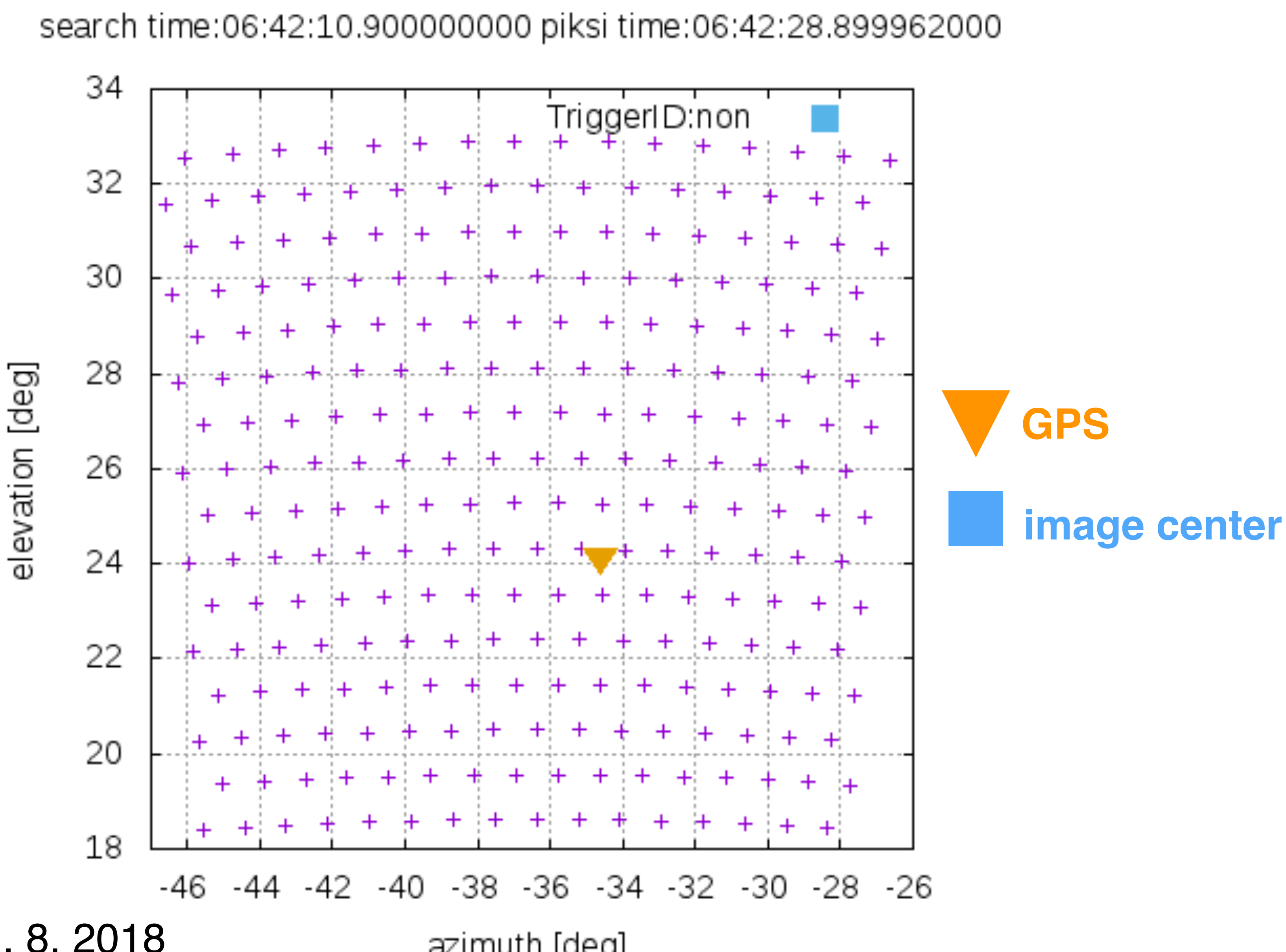
Opt-copter in operation

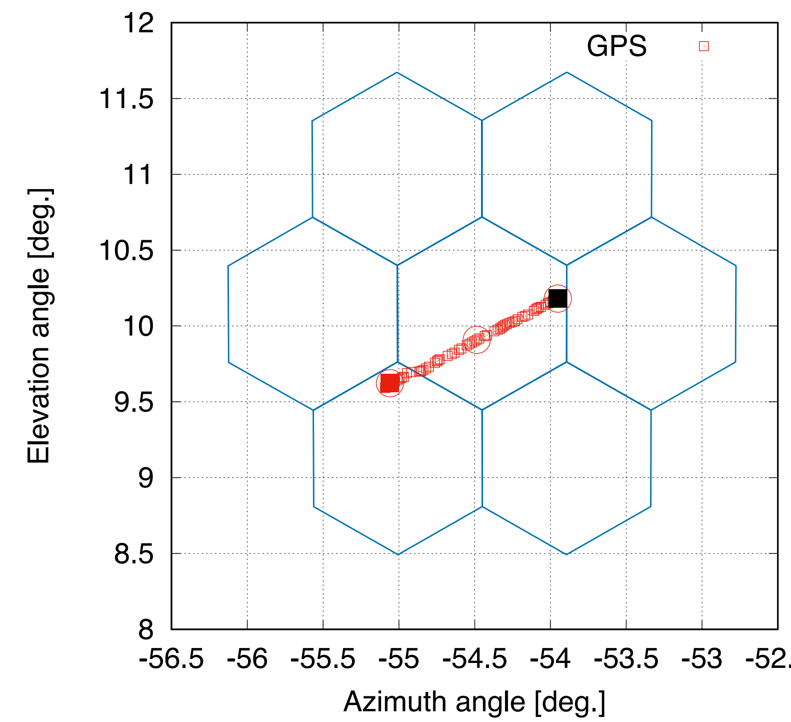


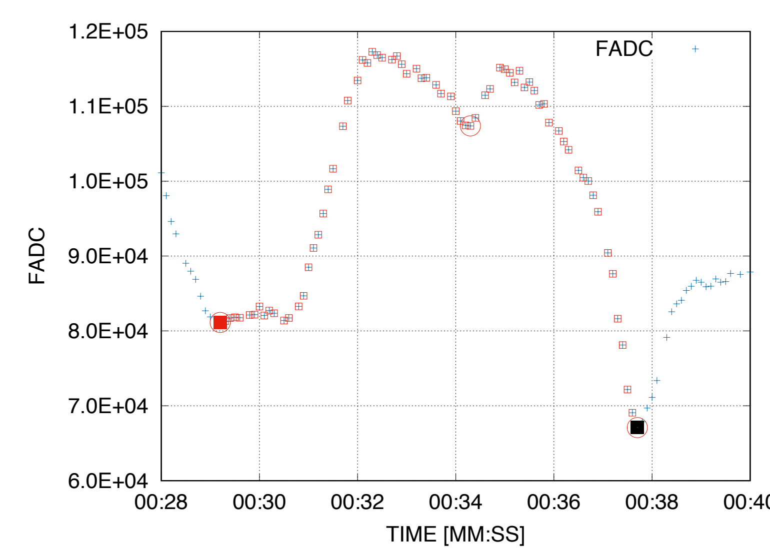
T. Tomoda

Main target of the calibration with “Opt-copter”:
Precise measurement of FD optics and geometry

Location by GPS is matched very well with the image center, however …



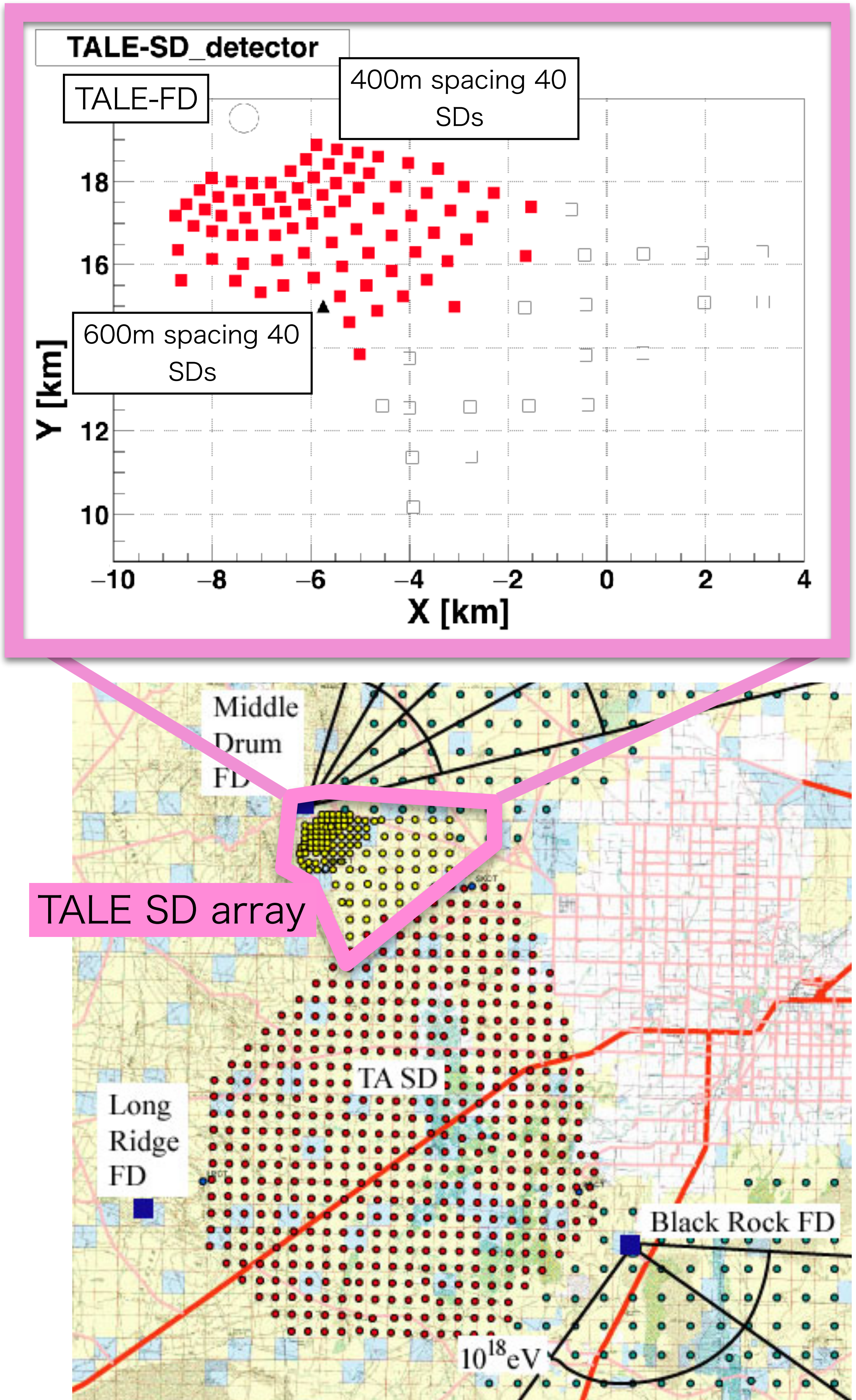




Current status of extension projects

1. TALE hybrid
2. NICHE
3. TAx4

TALE hybrid



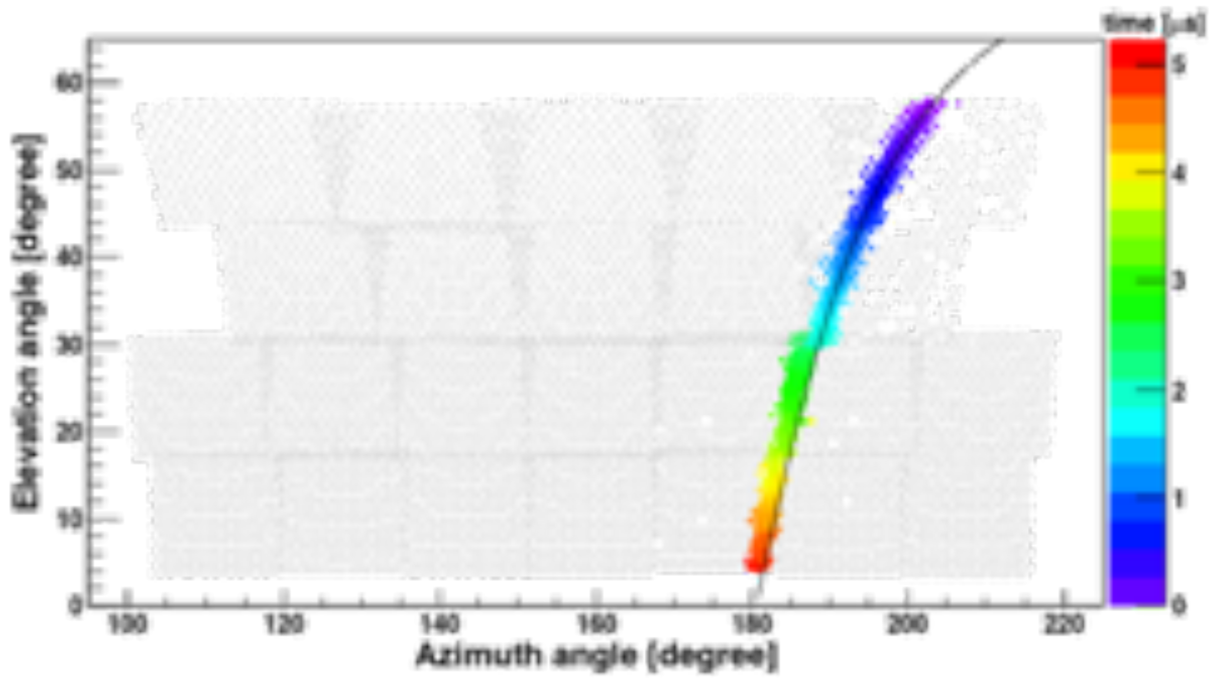
TALE hybrid =
low energy extension of TA hybrid
sensitivity down to 10^{16} eV, with
FDs observing higher elevation and
Densely-arrayed SDs
Precise measurement of the composition :
FD + SD hybrid measurement

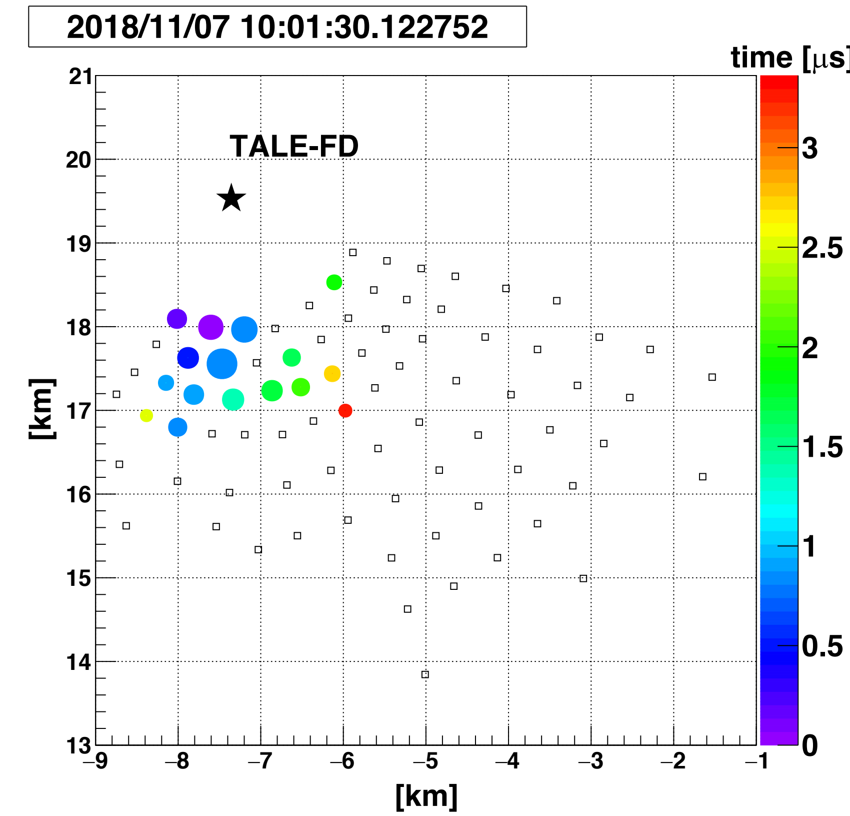
TALE-FD : 10 telescopes (Sep. 2013 ~)
elevation : 30°~57°, azimuthal : 114°
TALE-SD array : 80 SDs (Feb. 2018 ~)
TALE-hybrid started running from Sep. 2018

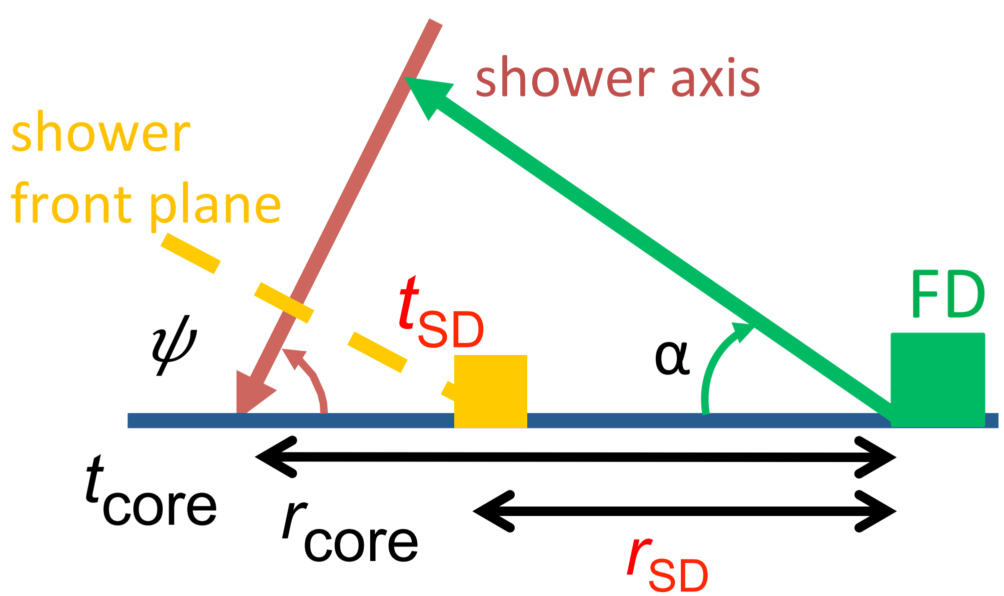
Expected specifications of TALE hybrid
Threshold energy E : logE=16.0
Event rate : ~5,000 events/year
$\Delta\theta$ = 1.0° (FD mono : 5.3°)
ΔXmax = 20 g/cm^2 (FD mono : 40 g/cm^2)

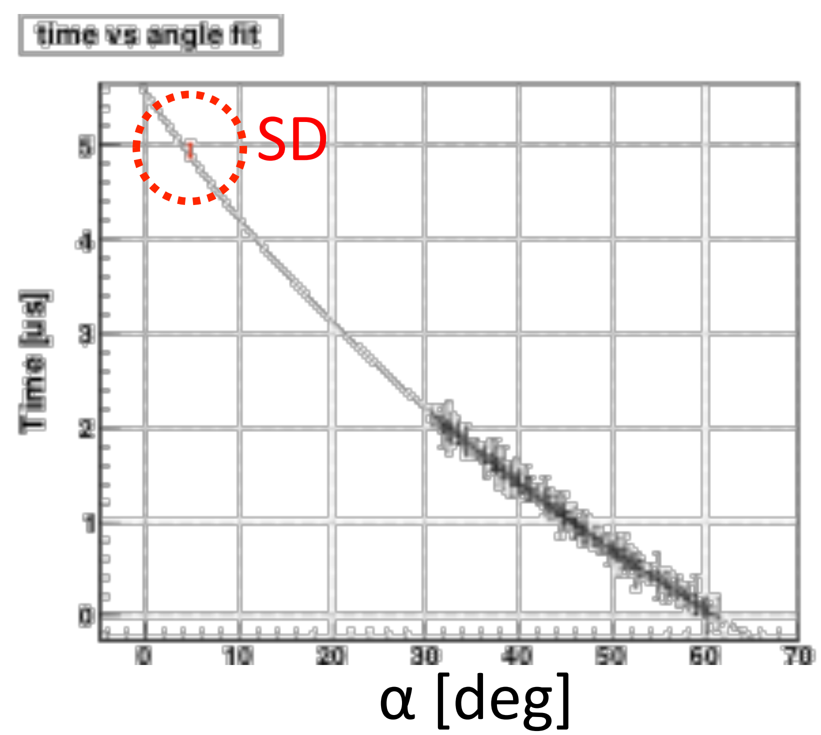
TALE Hybrid: real event sample

Real hybrid event samples in Nov. 7, 2018









Zen.[deg]	Azi.[deg]
23.6	-33.5
CoreX[km]	CoreY[km]
7.33	17.63
Xmax[g/cm^2]	E[eV]
823	$10^{17.94}$

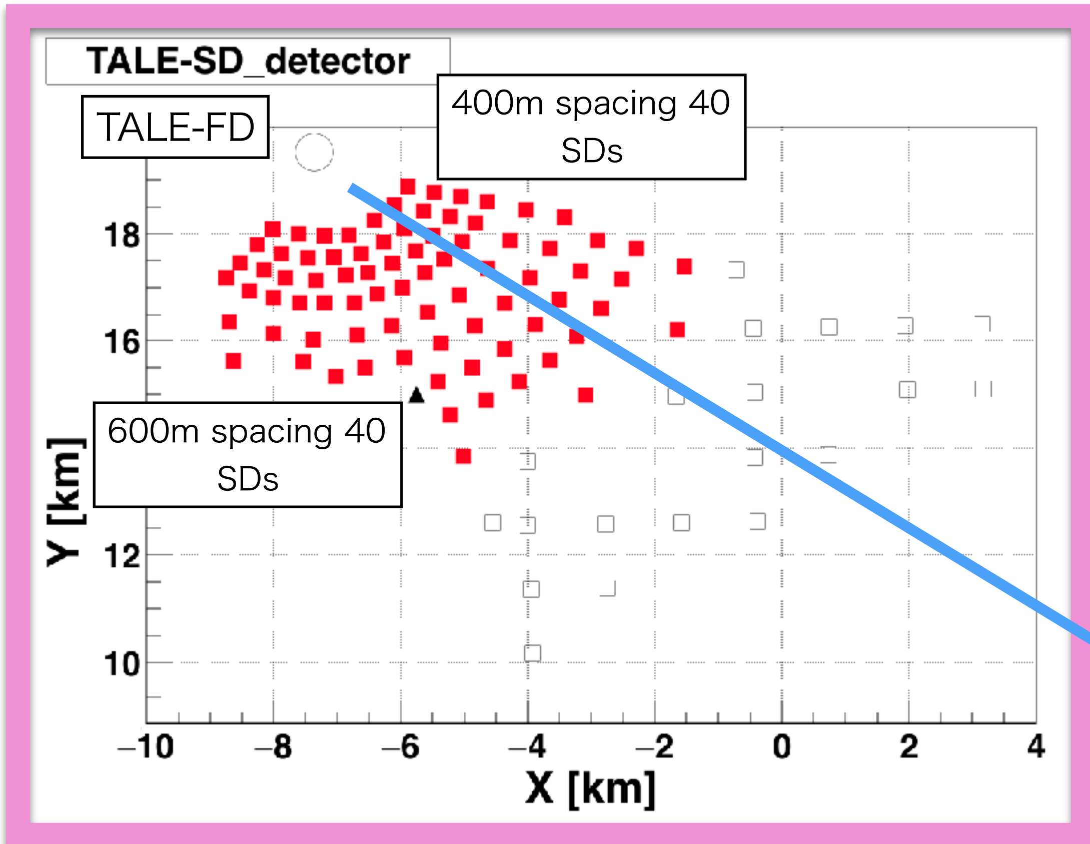
TALE future plan: lower energy

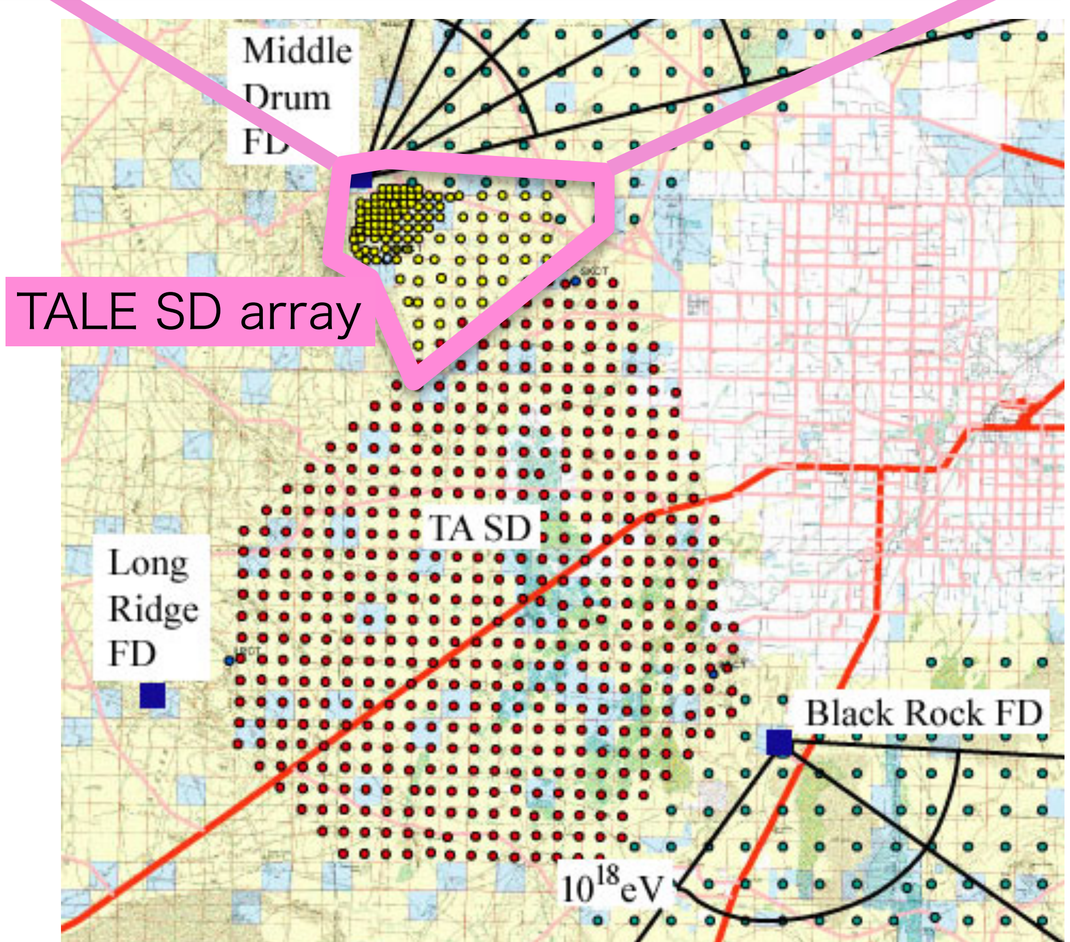
Additionally install **50 SDs with 200m spacing** near the TALE FD station (< 2km), to archive lower the threshold energy:

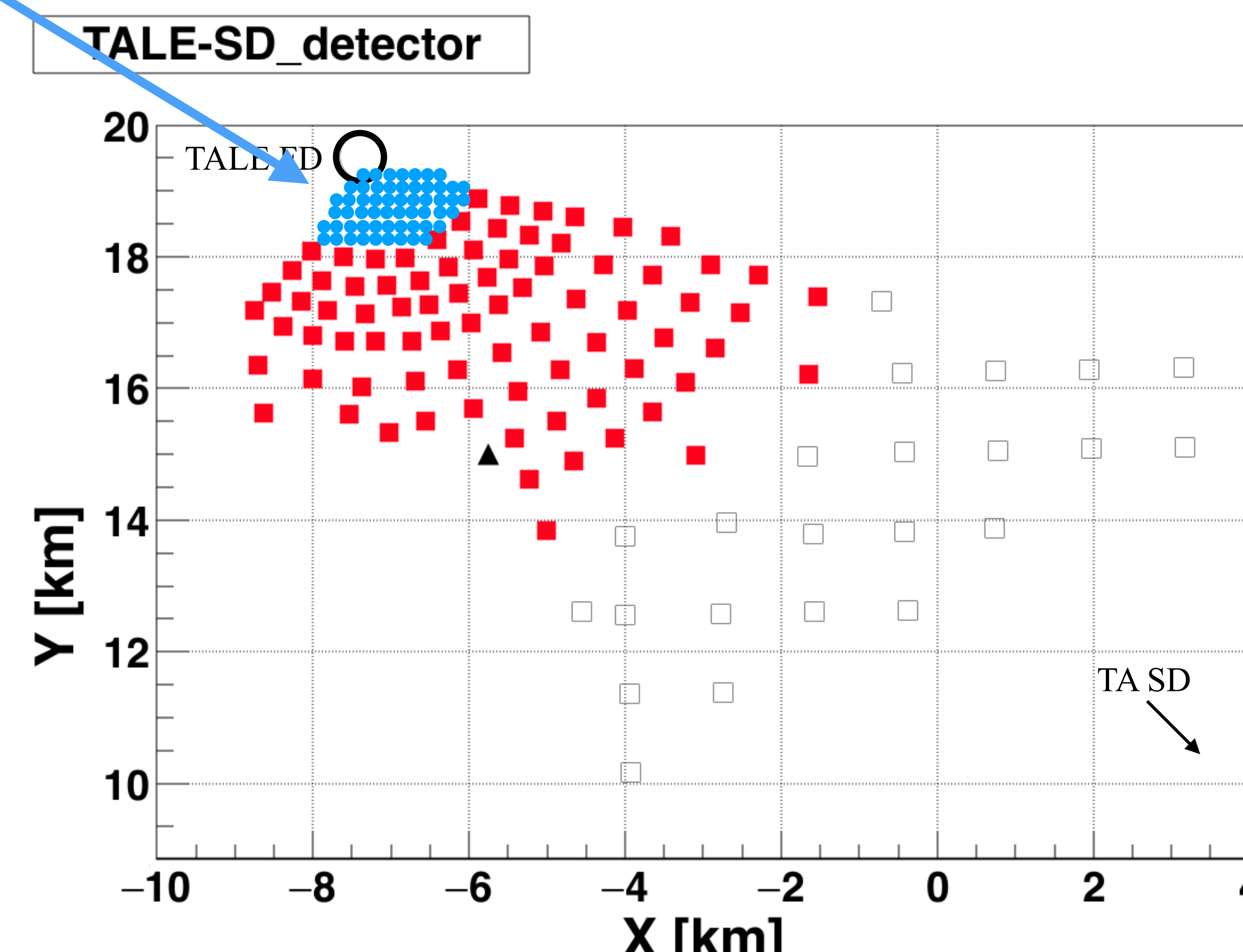
for SD, E_{mode} = $10^{15.5}$ eV

for FD-SD hybrid, E_{mode} =$10^{16.3}$ eV

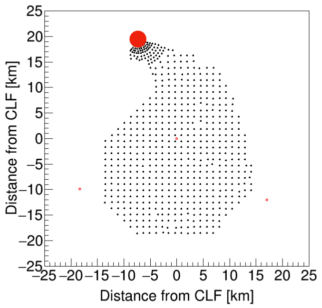
1.5M$ for 5yrs approved by JSPS in 2019





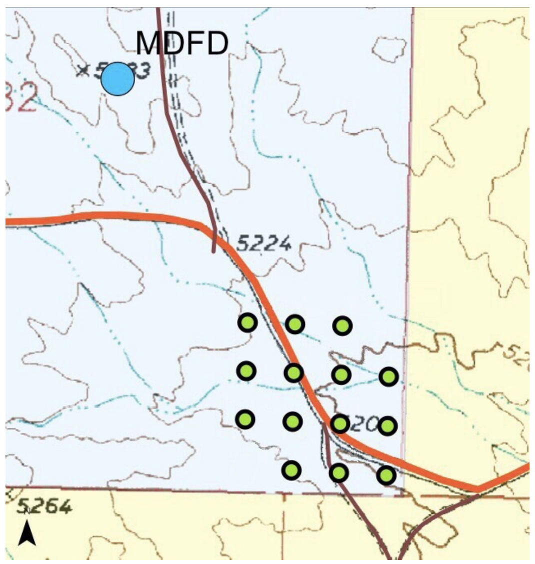


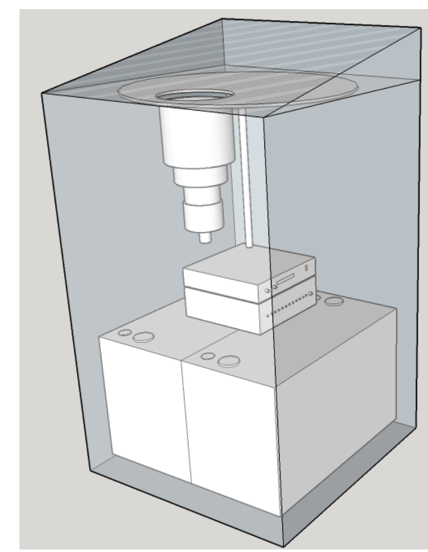
Non Imaging CHErenkov array (NICHE)



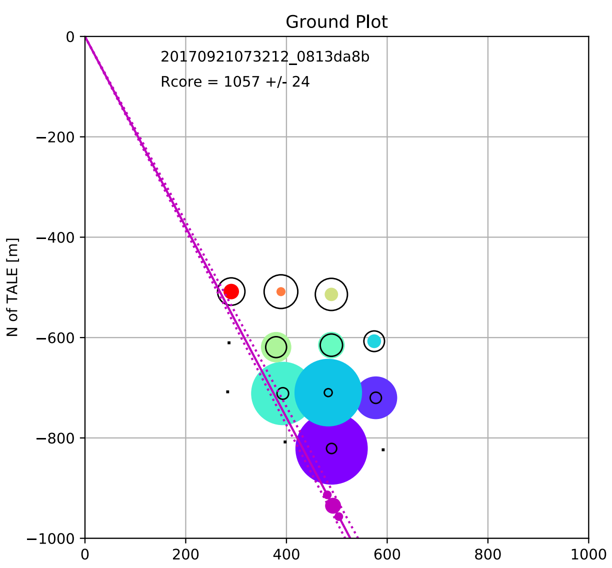
NICHE is a low energy extension of TALE sensitivity in order to measure the chemical composition of cosmic rays in the energy from 1 to 100 PeV.

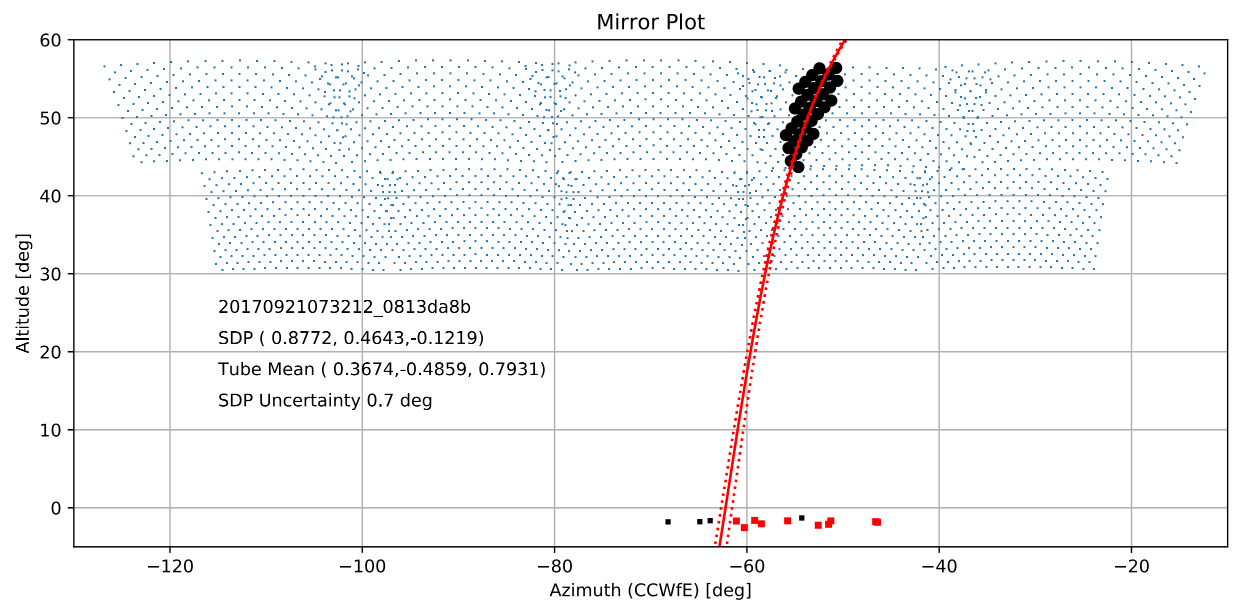
D. Bergman
Y. Omura

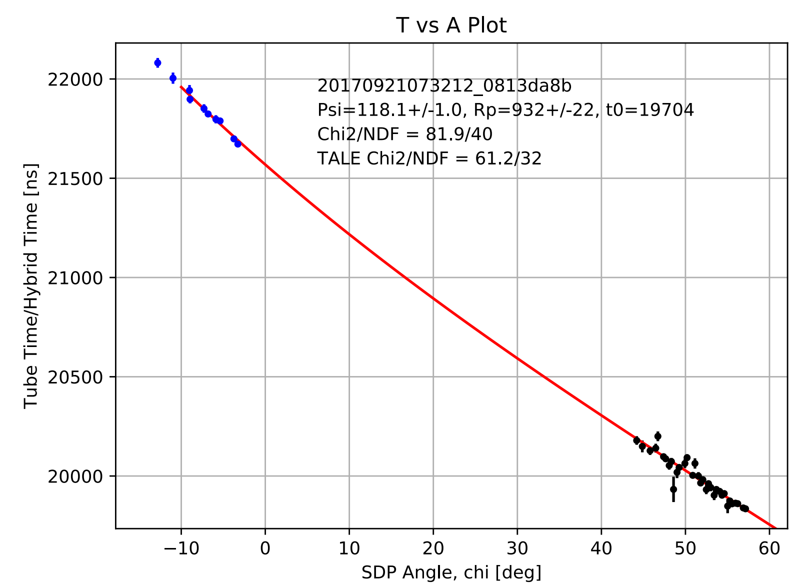




14 Cherenkov light detectors (3 inch PMT + 45° Winston corn), ~ 800 m from TALE FD, 100 m spacing.
Deployment started Sep. 2017, commissioning until Feb. 2019.







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.

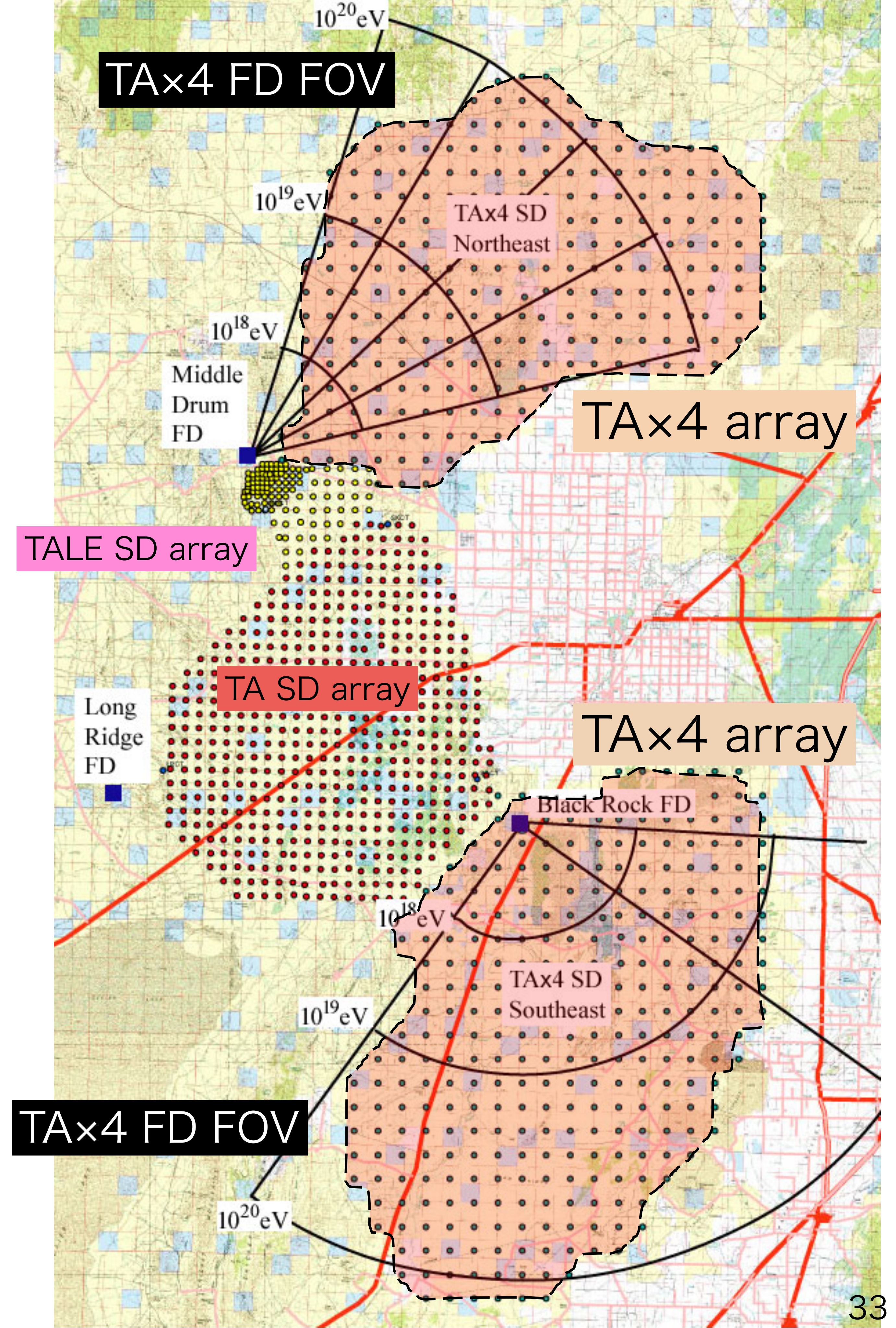
TA×4

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

SD array of ~3000 km²
by TA + additional **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

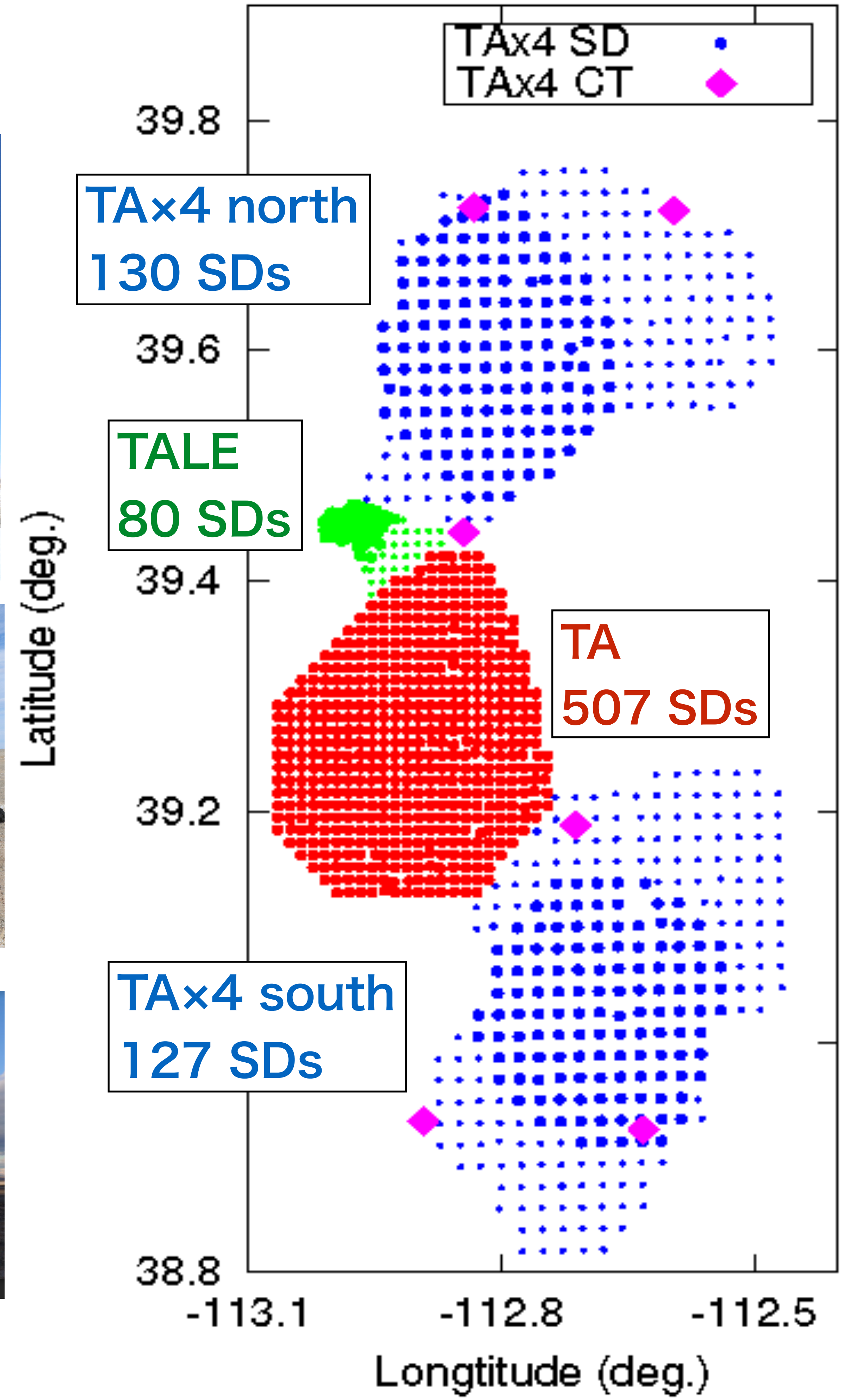


TA×4

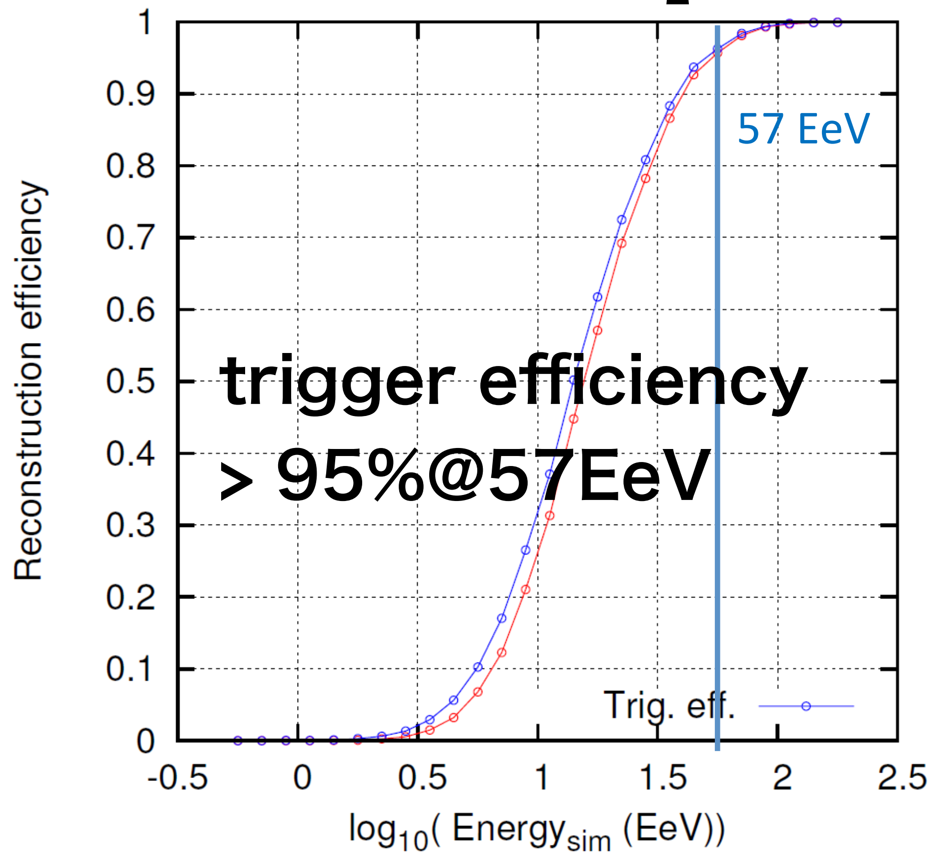
Feb. 19 - Mar. 12, 2019

257 SDs
6 communication towers

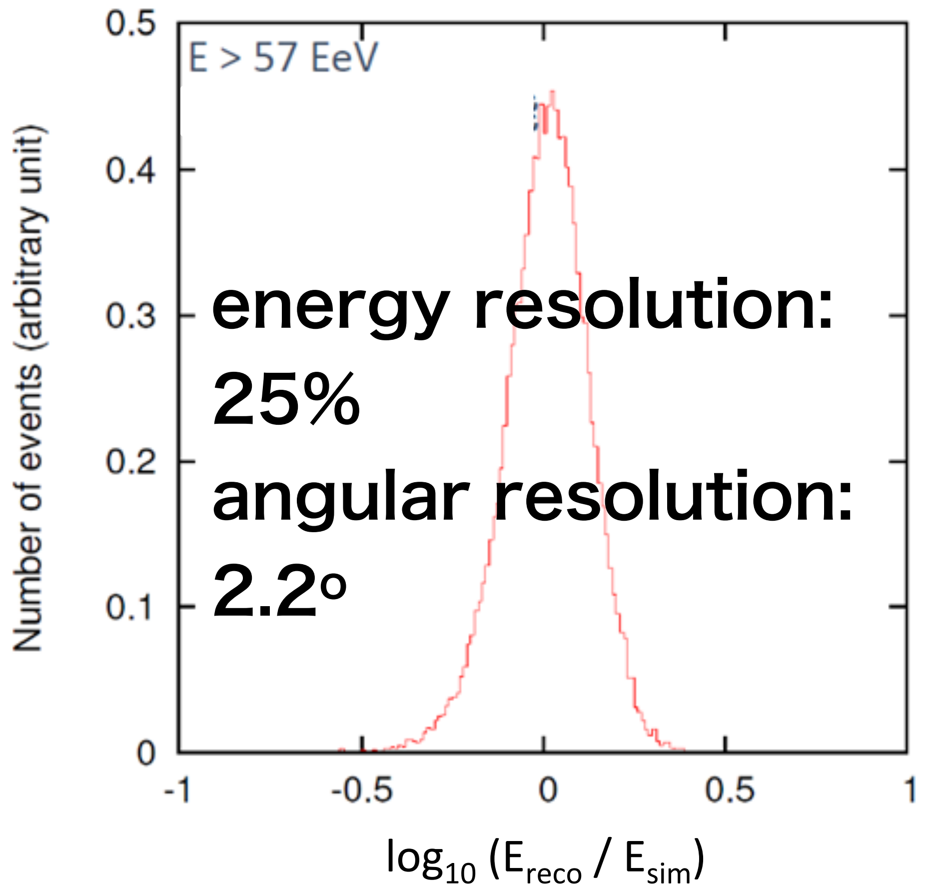
were installed in the site



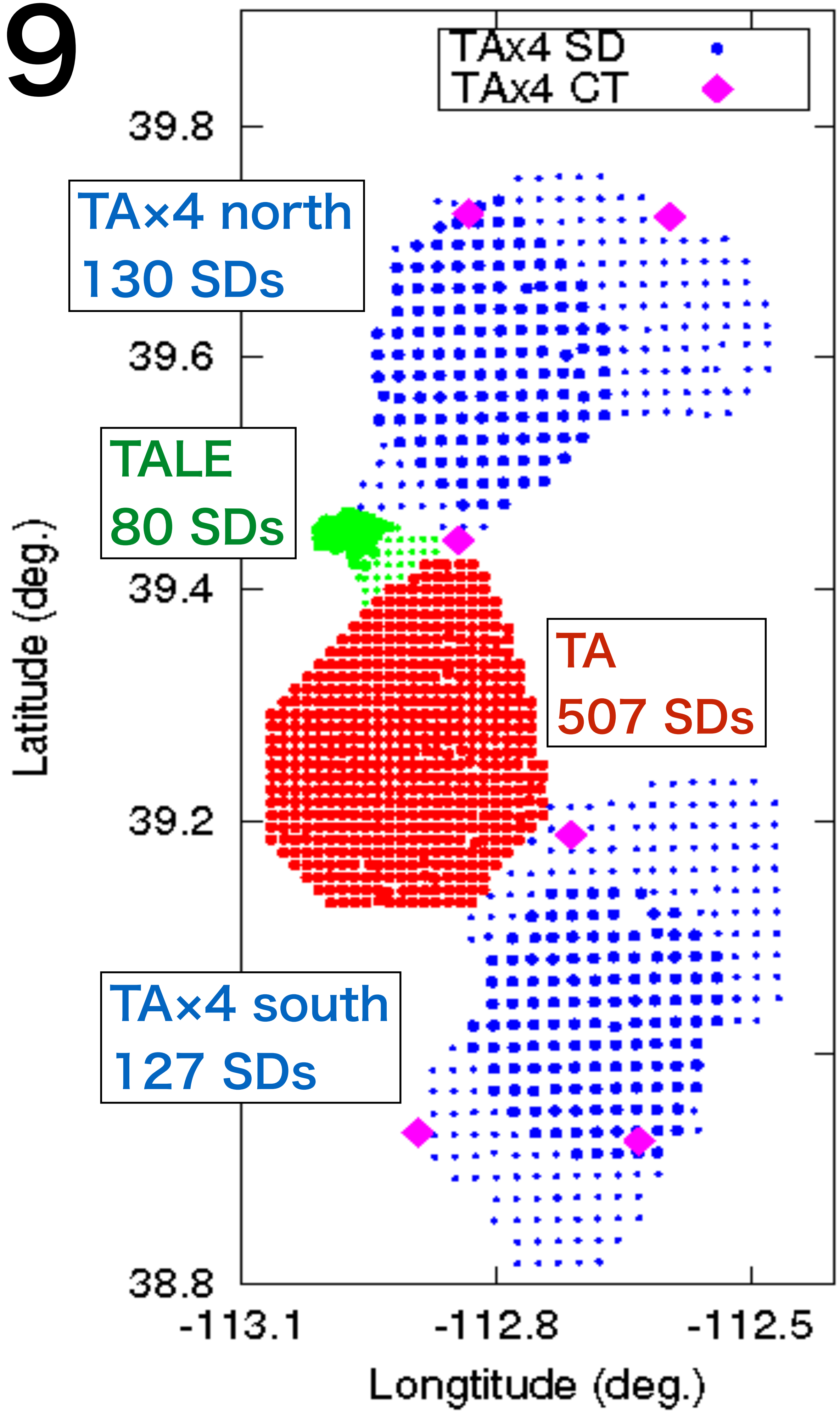
TA×4@Apr. 2019



Reconstruction efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.5
0
0.5
1
1.5
2
2.5
log10(Energysim (EeV))
57 EeV
Trig. eff.
trigger efficiency
> 95%@57EeV



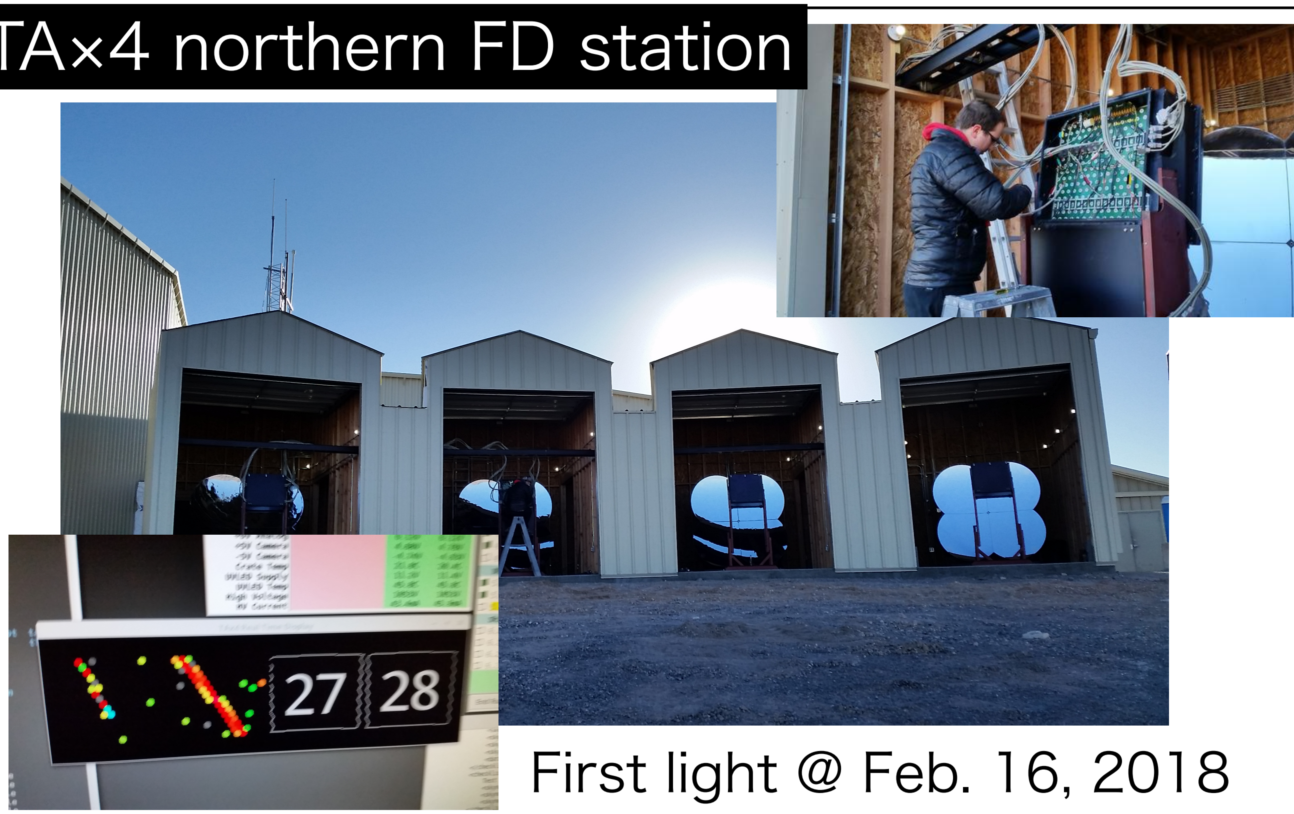
Number of events (arbitrary unit)
0.5
0.4
0.3
0.2
0.1
0
-1
-0.5
0
0.5
1
log10 (Ereco / Esim)
E > 57 EeV
energy resolution:
25%
angular resolution:
2.2°



TAx4 SD
TAx4 CT
39.8
39.6
39.4
39.2
38.8
Latitude (deg.)
-113.1
-112.8
-112.5
Longtitude (deg.)
TA×4 north
130 SDs
TALE
80 SDs
TA
507 SDs
TA×4 south
127 SDs

TA×4

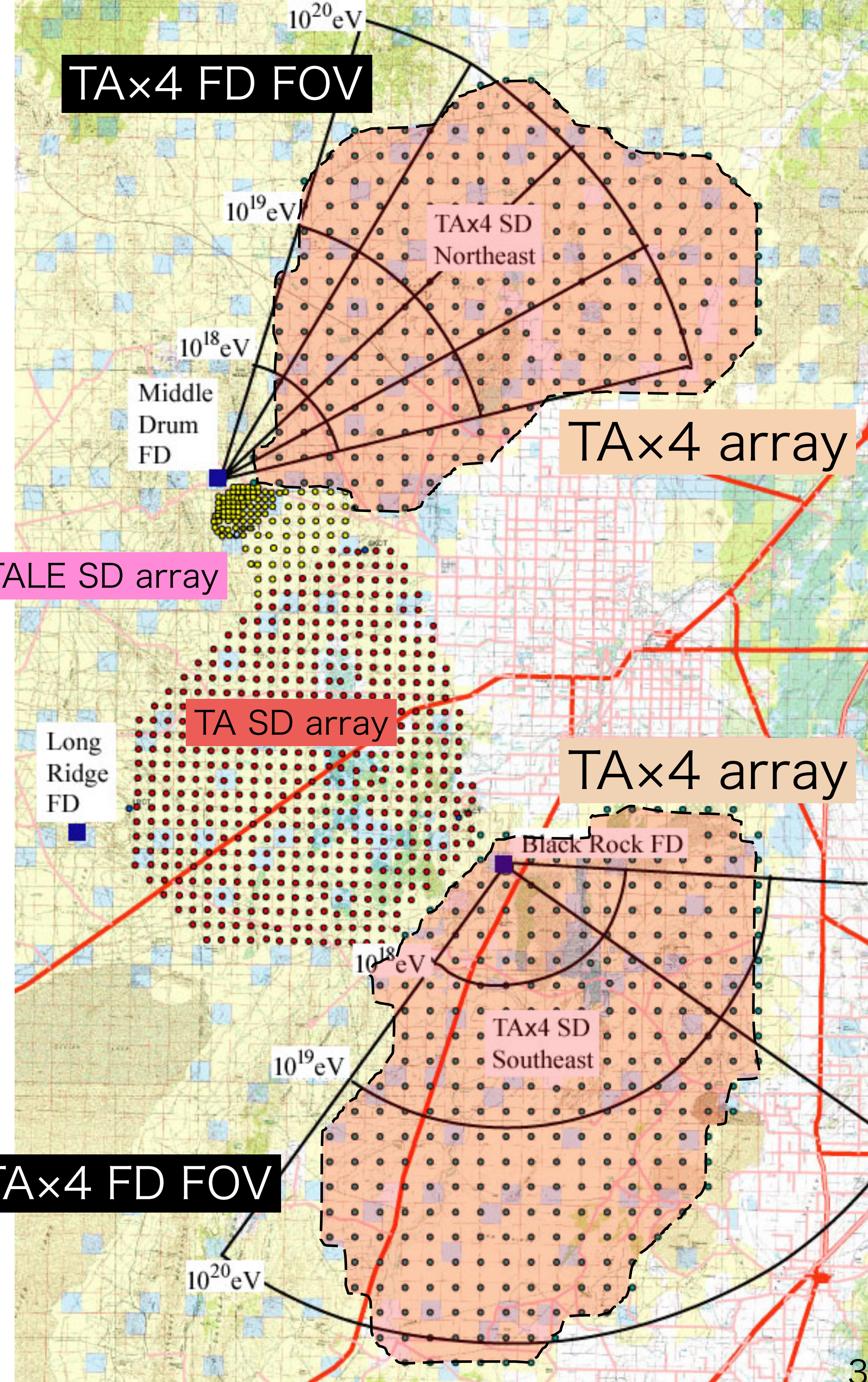
TA×4 northern FD station



First light @ Feb. 16, 2018

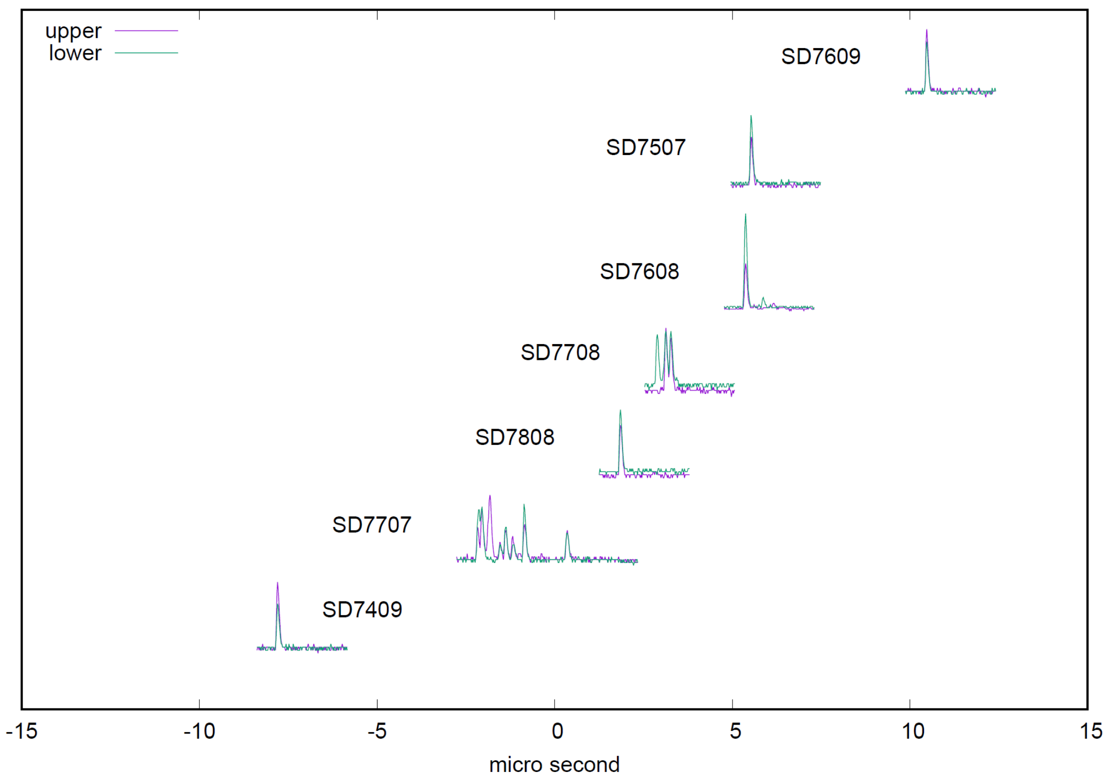
TA×4 southern FD station

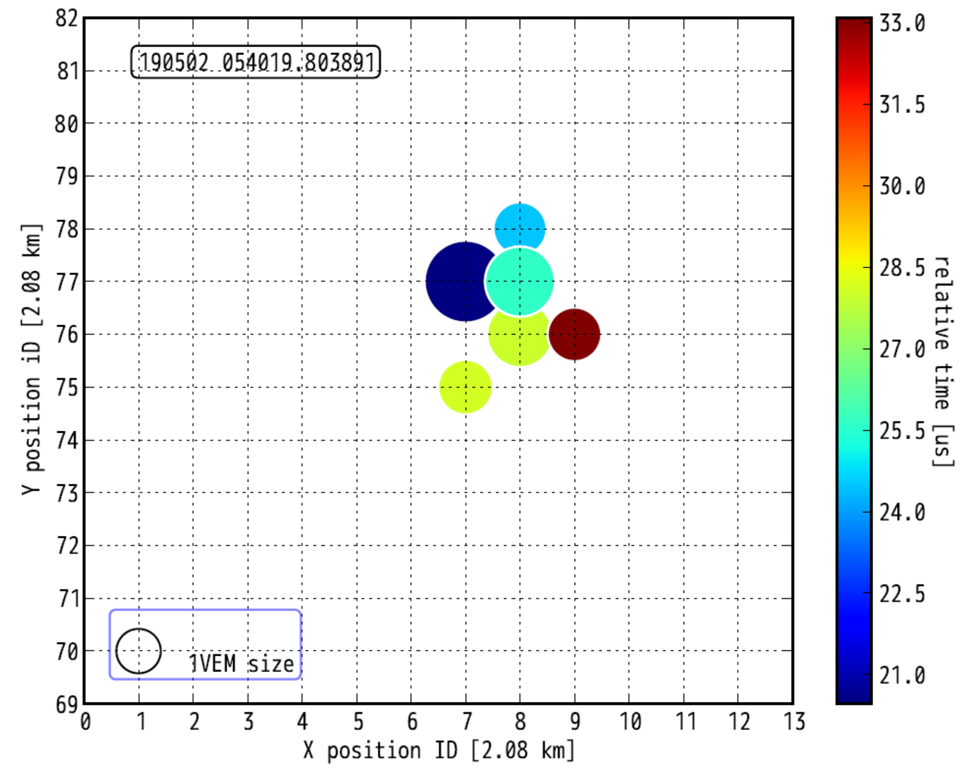
First light @ Oct. 22, 2019

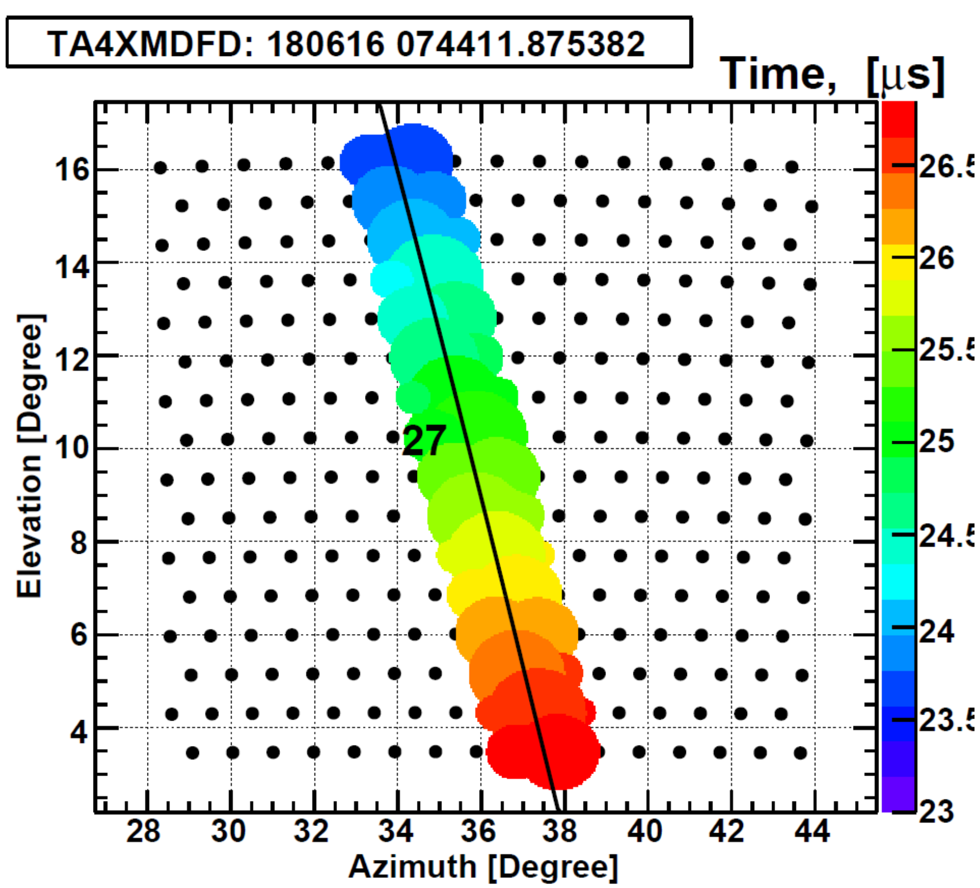


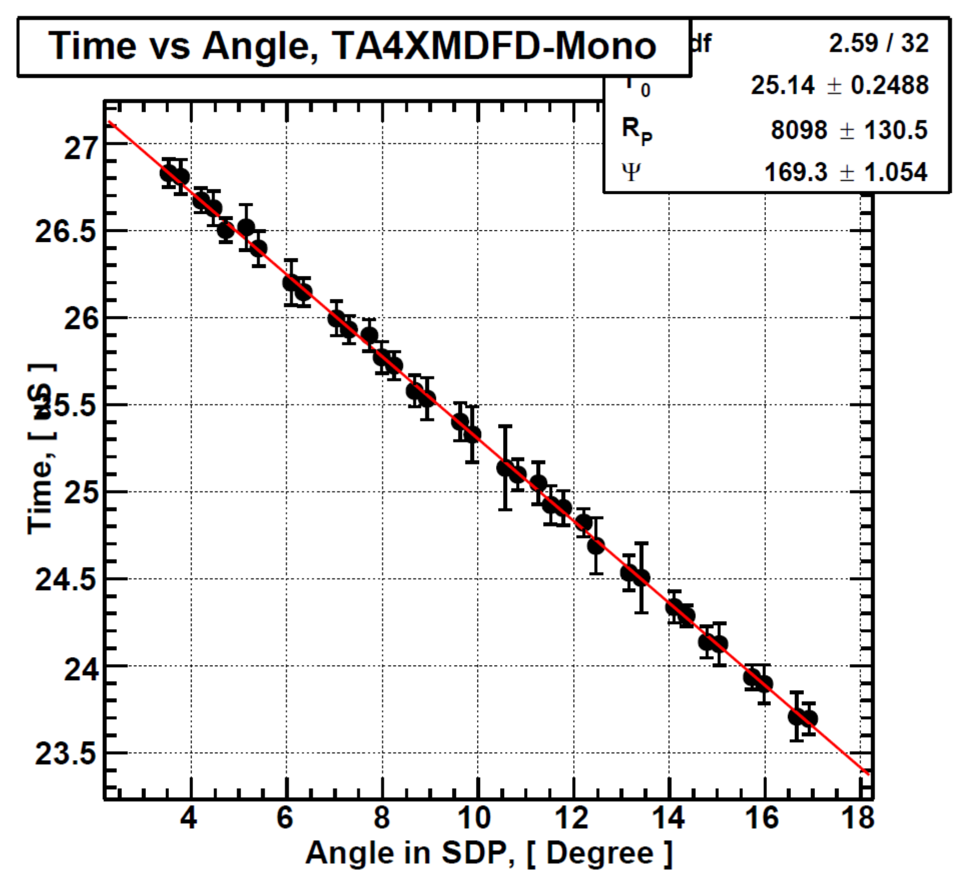
TA×4 hybrid: real event sample

Real hybrid event samples in May, 2019









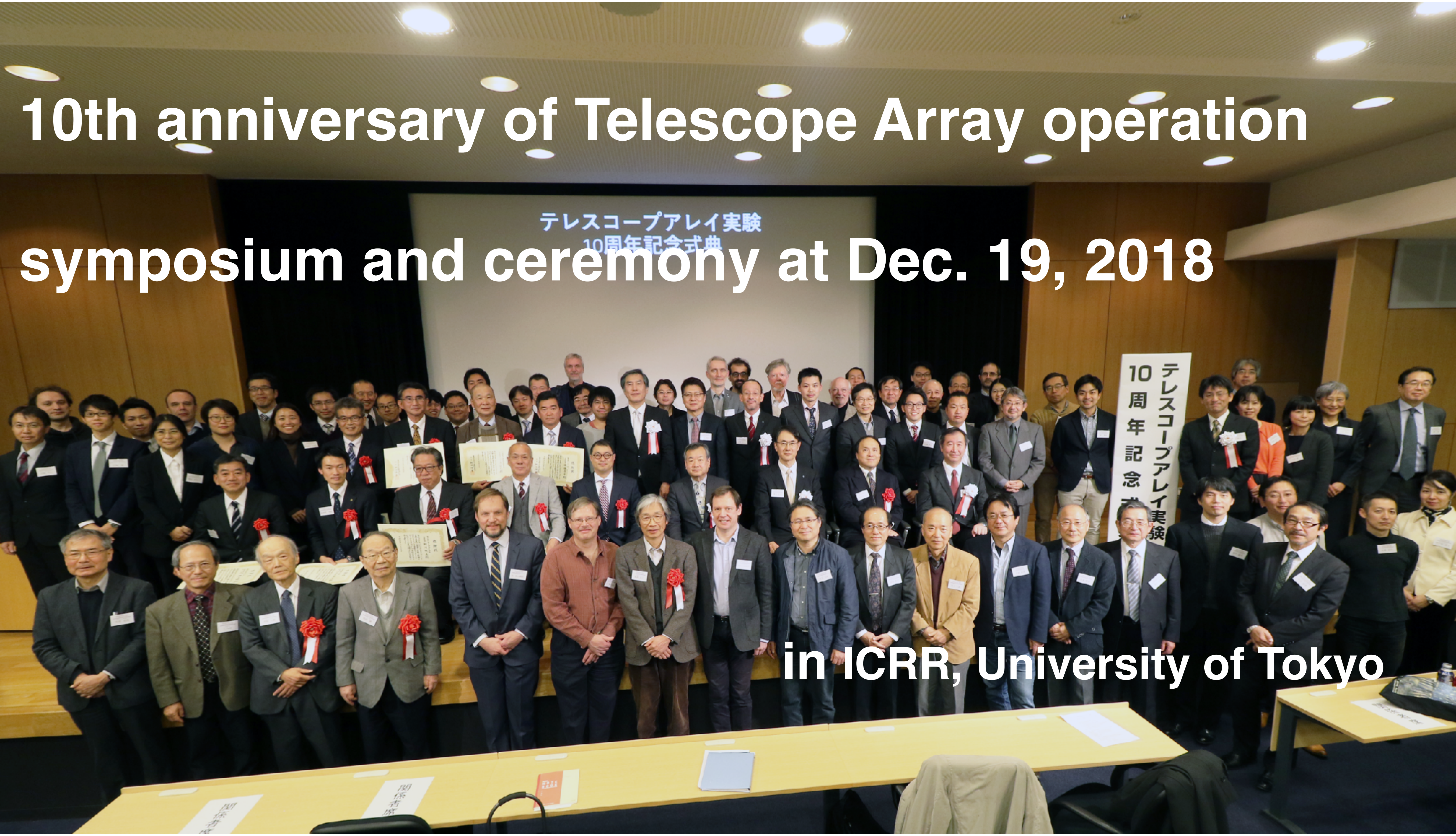
Summary(1/3)

- 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(2/3)

10th anniversary of Telescope Array operation

symposium and ceremony at Dec. 19, 2018



in ICRR, University of Tokyo

Thank you very much for your continuous support!

Congratulations!

I would like to express
my congratulations on
20th anniversary of the Foundation of the
Pierre Auger Observatory

BACKUP