Telescope Array Experiment in the Multi-messenger Astrophysics Era

- Introductions of TA detectors and analysis
- New items for monitoring and calibrations
- On-going extension projects
- Recent results on the energy spectrum studies

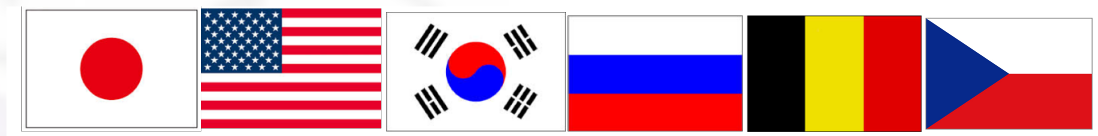
→Lots of our results will be shown by Grisha!

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

Telescope Array collaboration

141 collaborators from 36 institutes

in 6 countries



T. Abu-Zayyad[a], R. Aida[b], M. Allen[a], R. Anderson[a], R. Azuma[c], E. Barcikowski[a], J.W. Belz[a], D.R. Bergman[a], S.A. Blake[a], R. Cady[a], B.G. Cheon[d], J. Chiba[e], M. Chikawa[f], E.J. Cho[d], W.R. Cho[g], H. Fujii[h], T. Fujii[i], T. Fukuda[c], M. Fukushima[j,k], W. Hanlon[a], K. Hayashi[c], Y. Hayashi[i], N. Hayashida[j], K. Hibino[l], K. Hiyama[j], K. Honda[b], T. Iguchi[c], D. Ikeda[j,*], K. Ikuta[b], N. Inoue[m], T. Ishii[b], R. Ishimori[c], H. Ito[u], D. Ivanov[a,n], S. Iwamoto[b], C.C.H. Jui[a], K. Kadota[o], F. Kakimoto[c], O. Kalashev[p], T. Kanbe[b], K. Kasahara[q], H. Kawai[r], S. Kawakami[i], S. Kawana[m], E. Kido[j], H.B. Kim[d], H.K. Kim[g], J.H. Kim[a], J.H. Kim[d], K. Kitamoto[f], S. Kitamura[c], Y. Kitamura[c], K. Kobayashi[e], Y. Kobayashi[c], Y. Kondo[j], K. Kuramoto[i], V. Kuzmin[p], Y.J. Kwon[g], J. Lan[a], S.I. Lim[t], J.P. Lundquist[a], S. Machida[c], K. Martens[k], T. Matsuda[h], T. Matsuura[c], T. Matsuyama[i], J.N. Matthews[a], M. Minamino[i], K. Miyata[e], Y. Murano[c], I. Myers[a], K. Nagasawa[m], S. Nagataki[u], T. Nakamura[v], S.W. Nam[t], T. Nonaka[j], S. Ogio[i], M. Ohnishi[j], H. Ohoka[j], K. Oki[j], D. Oku[b], T. Okuda[w], M. Ono[u], A. Oshima[i], S. Ozawa[q], I.H. Park[t], M.S. Pshirkov[x], D.C. Rodriguez[a], S.Y. Roh[s], G. Rubtsov[p], D. Ryu[s], H. Sagawa[j], N. Sakurai[i], A.L. Sampson[a], L.M. Scott[n], P.D. Shah[a], F. Shibata[b], T. Shibata[j], H. Shimodaira[j], B.K. Shin[d], J.I. Shin[g], T. Shirahama[m], J.D. Smith[a], P. Sokolsky[a], R.W. Springer[a], B.T. Stokes[a], S.R. Stratton[a,n], T. Stroman[a], S. Suzuki[h], Y. Takahashi[j], M. Takeda[j], A. Taketa[y], M. Takita[j], Y. Tameda[j], H. Tanaka[i], K. Tanaka[z], M. Tanaka[i], S.B. Thomas[a], G.B. Thomson[a], P. Tinyakov[p,x], I. Tkachev[p], H. Tokuno[c], T. Tomida[aa], S. Troitsky[p], Y. Tsunesada[c], K. Tsutsumi[c], Y. Tsuyuguchi[b], Y. Uchihori[ab], S. Udo[l], H. Ukai[b], F. Urban[x], G. Vasiloff[a], Y. Wada[m], T. Wong[a], Y. Yamakawa[j], R. Yamane[i], H. Yamaoka[h], K. Yamazaki[i], J. Yang[t], Y. Yoneda[i], S. Yoshida[r], H. Yoshii[ac], X. Zhou[f], R. Zollinger[a], Z. Zundel[a]

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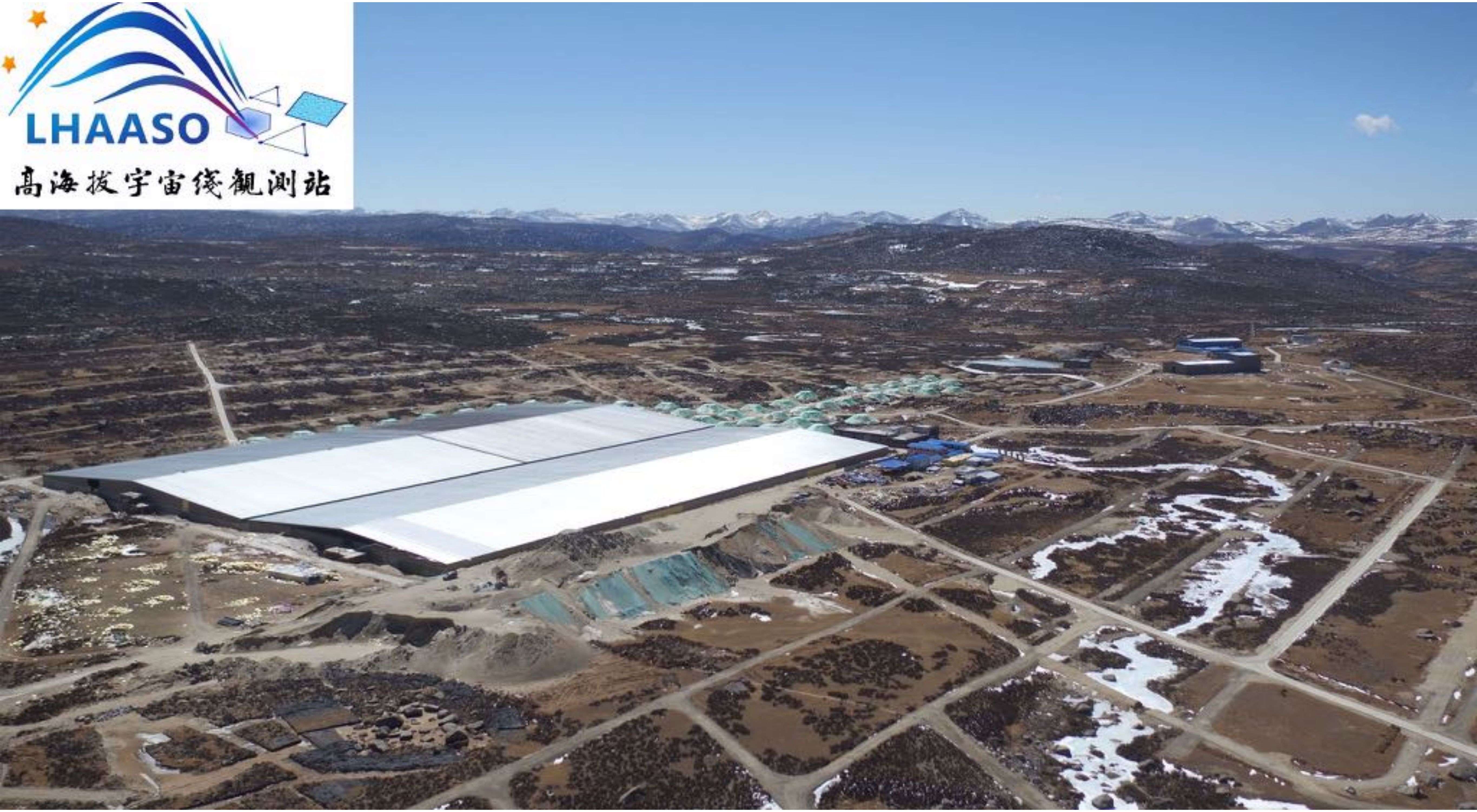
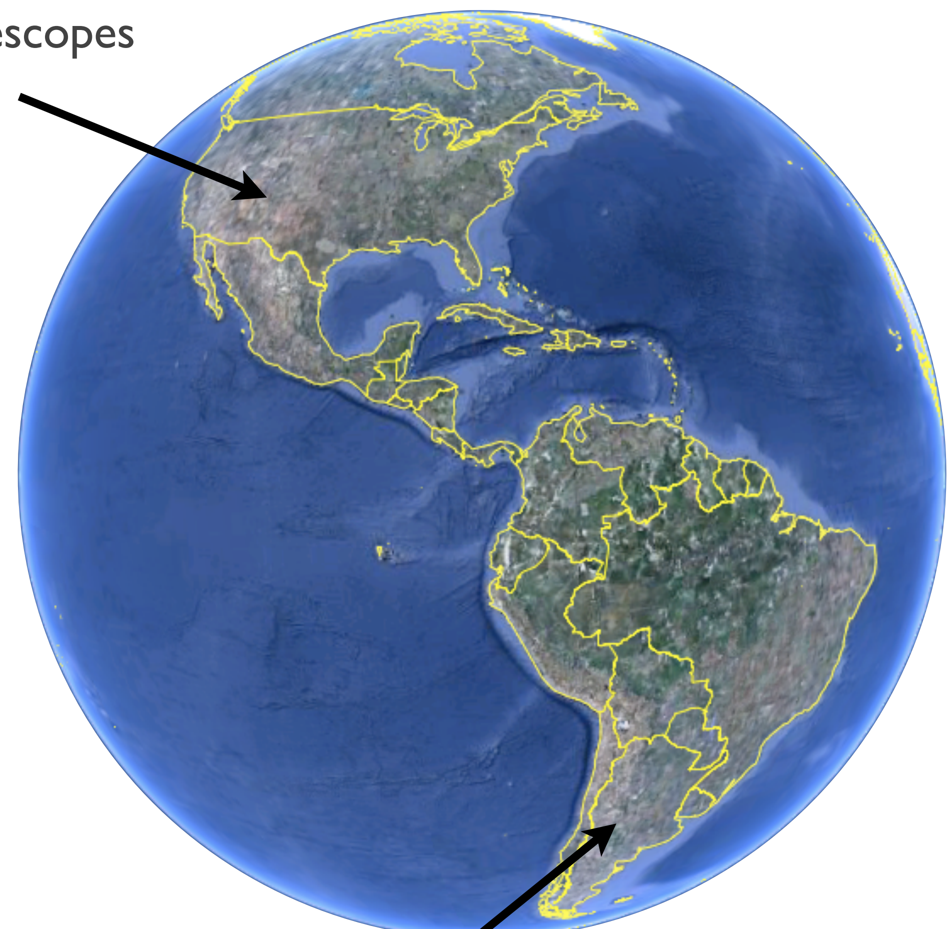
Congratulations, LHAASO!



Pierre Auger Observatory and Telescope Array

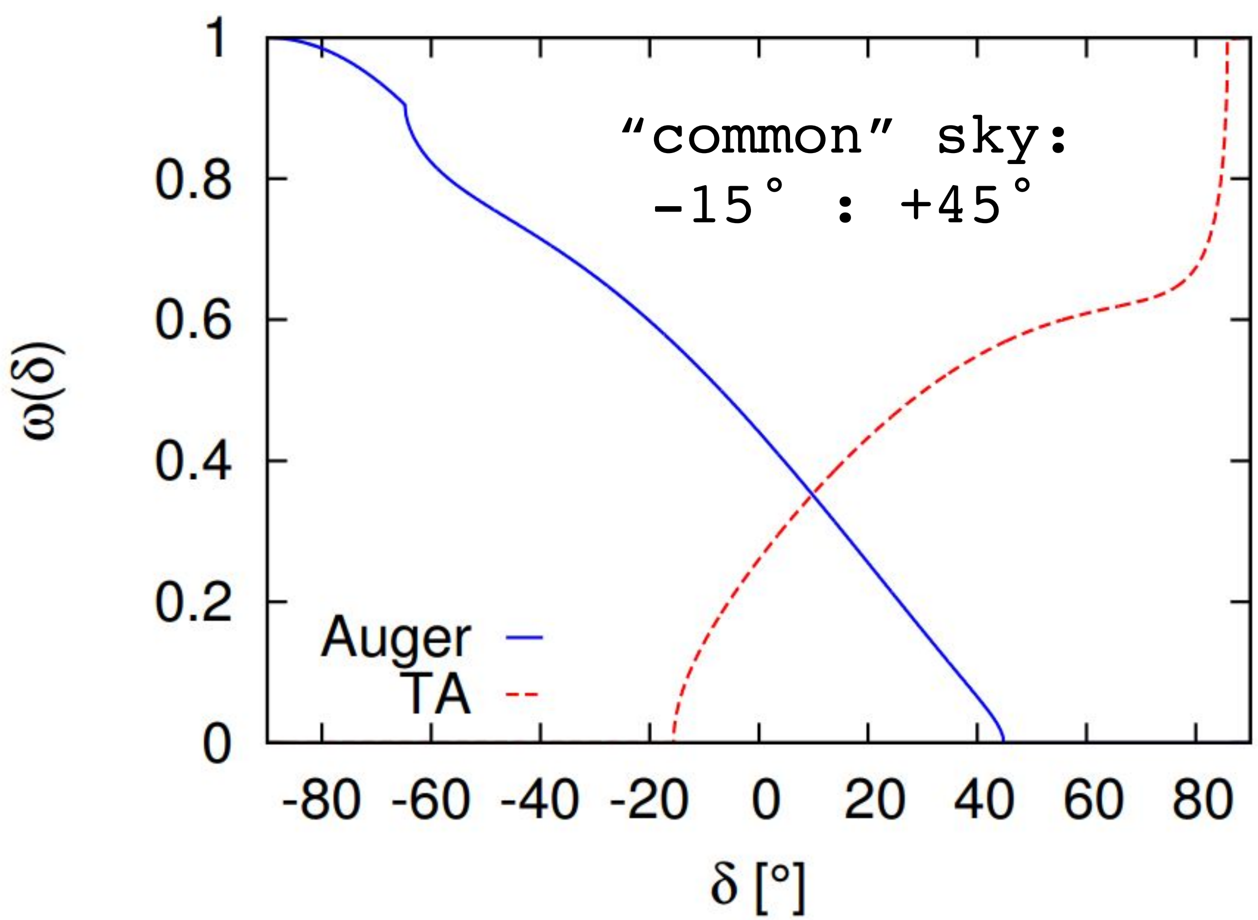
Telescope Array = the largest cosmic ray observatory in the northern hemisphere

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 700 km^2
36 fluorescence telescopes



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Relative exposure of Auger and TA

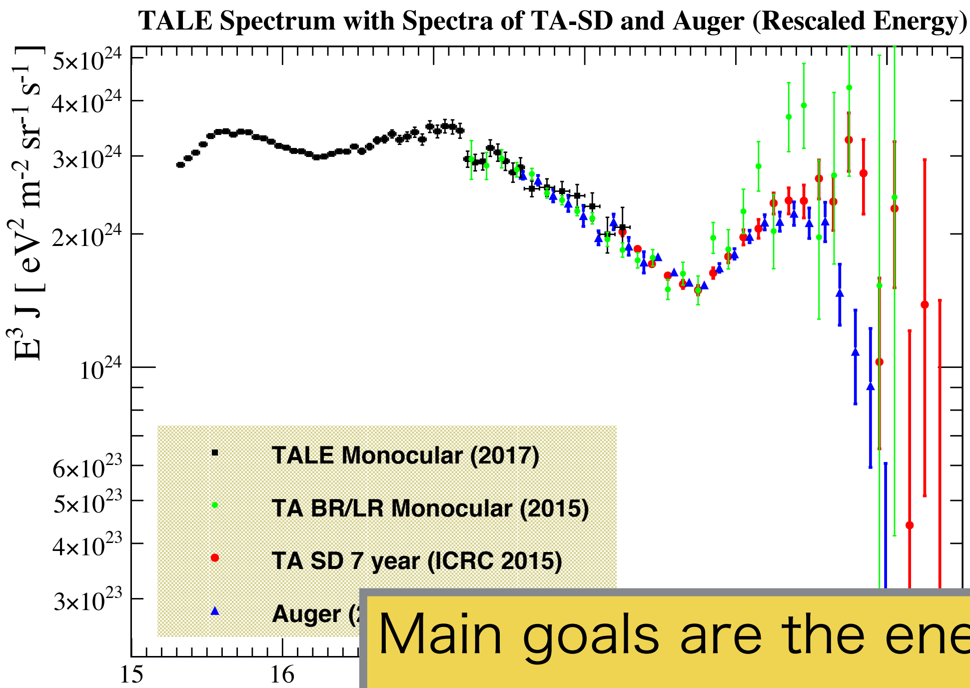


Together full sky coverage: perfect for anisotropy studies

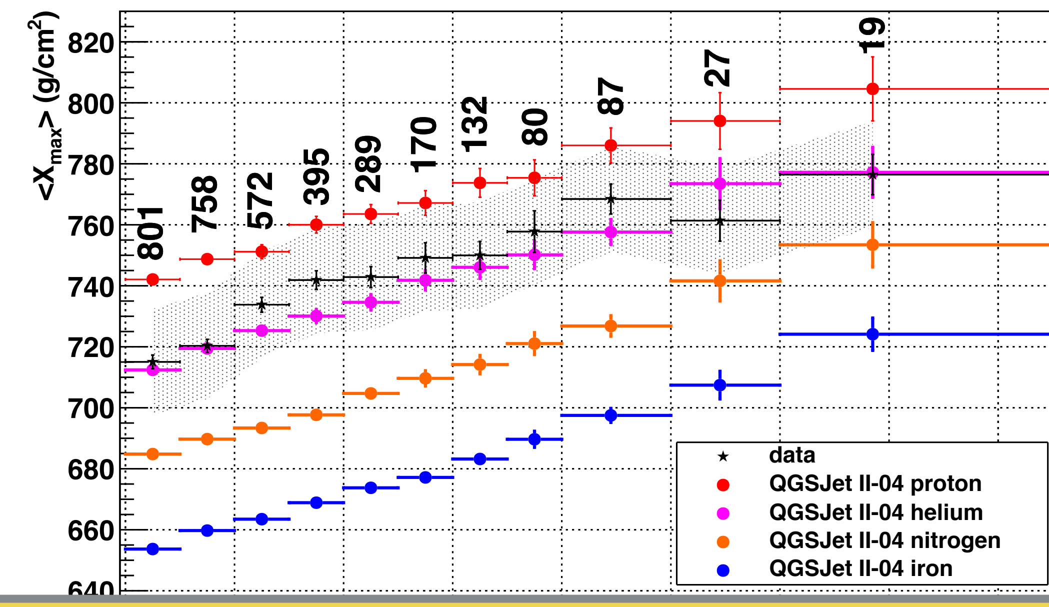
R. Engle, TA 10th anniversary symposium, 2018

Main goals of Telescope Array

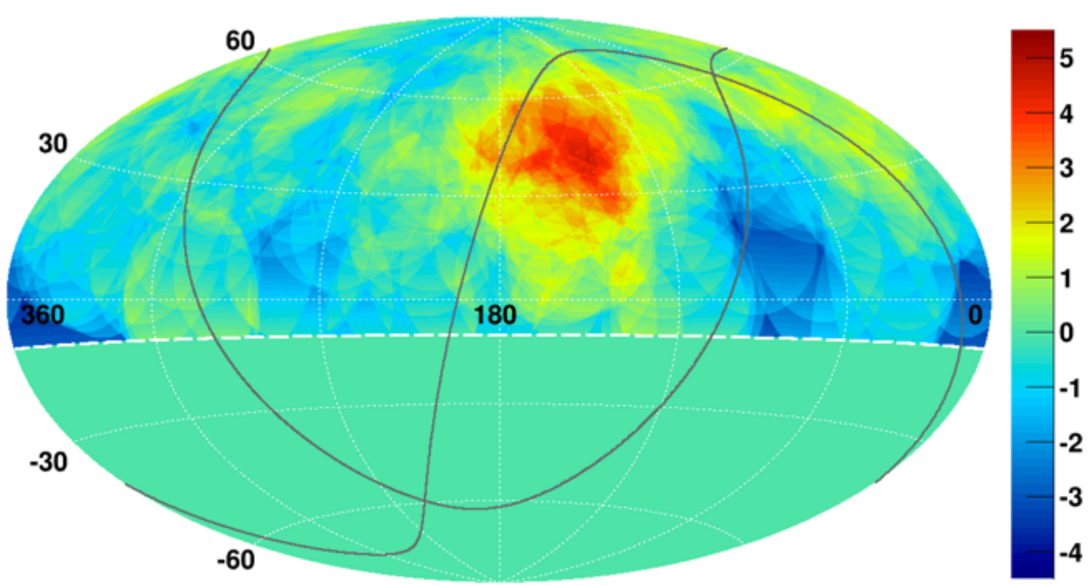
Energy Spectrum

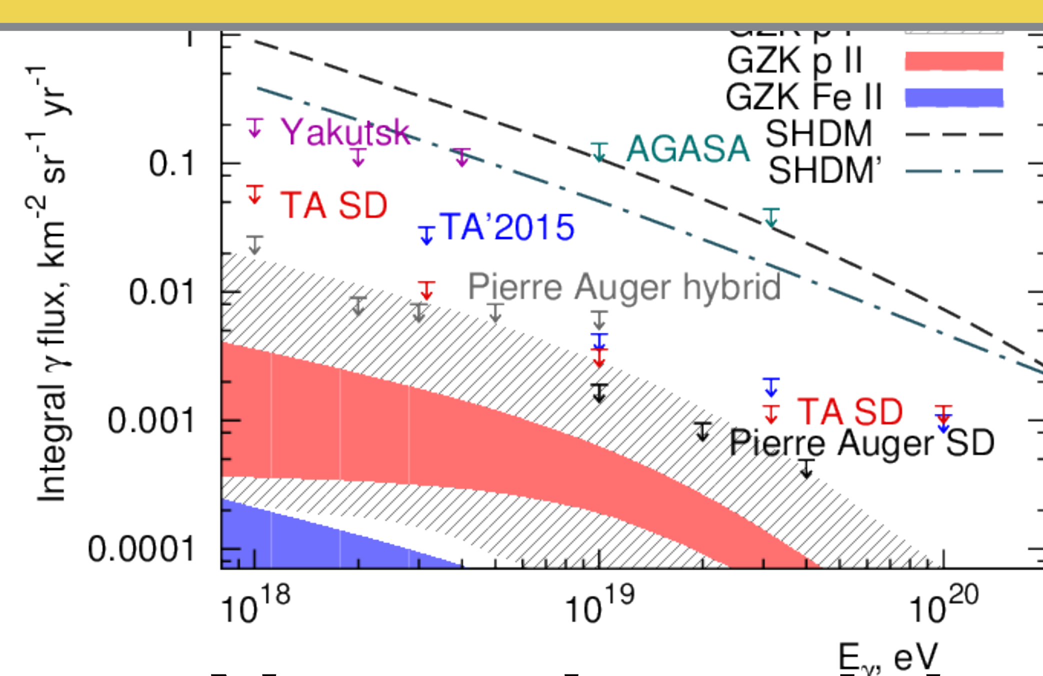


Chemical composition



Main goals are the energy spectrum, the composition, anisotropies of UHECRs.
Our main target is UHE charged particles. Even so, our experiment can contribute to the multimessenger astronomy.

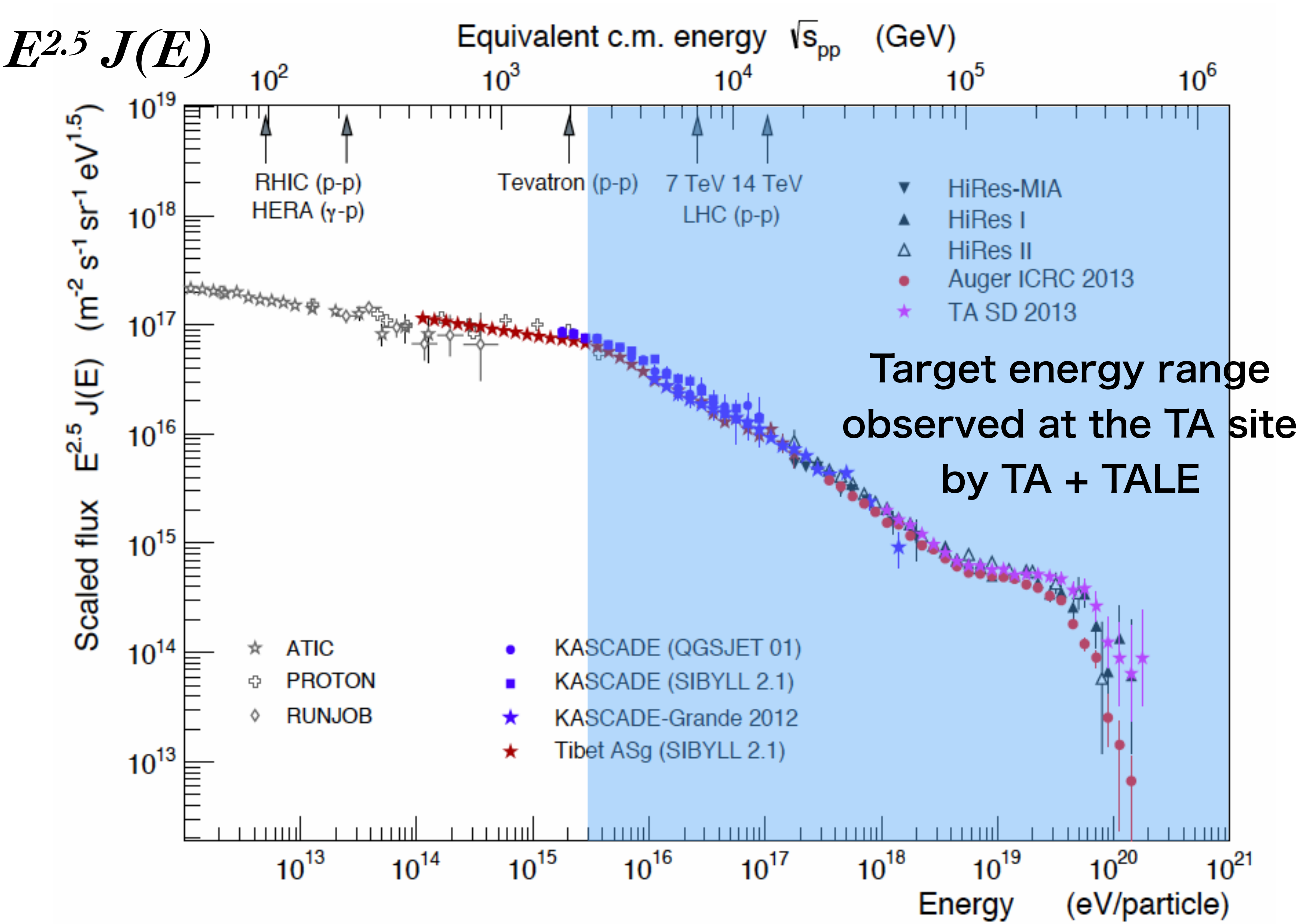




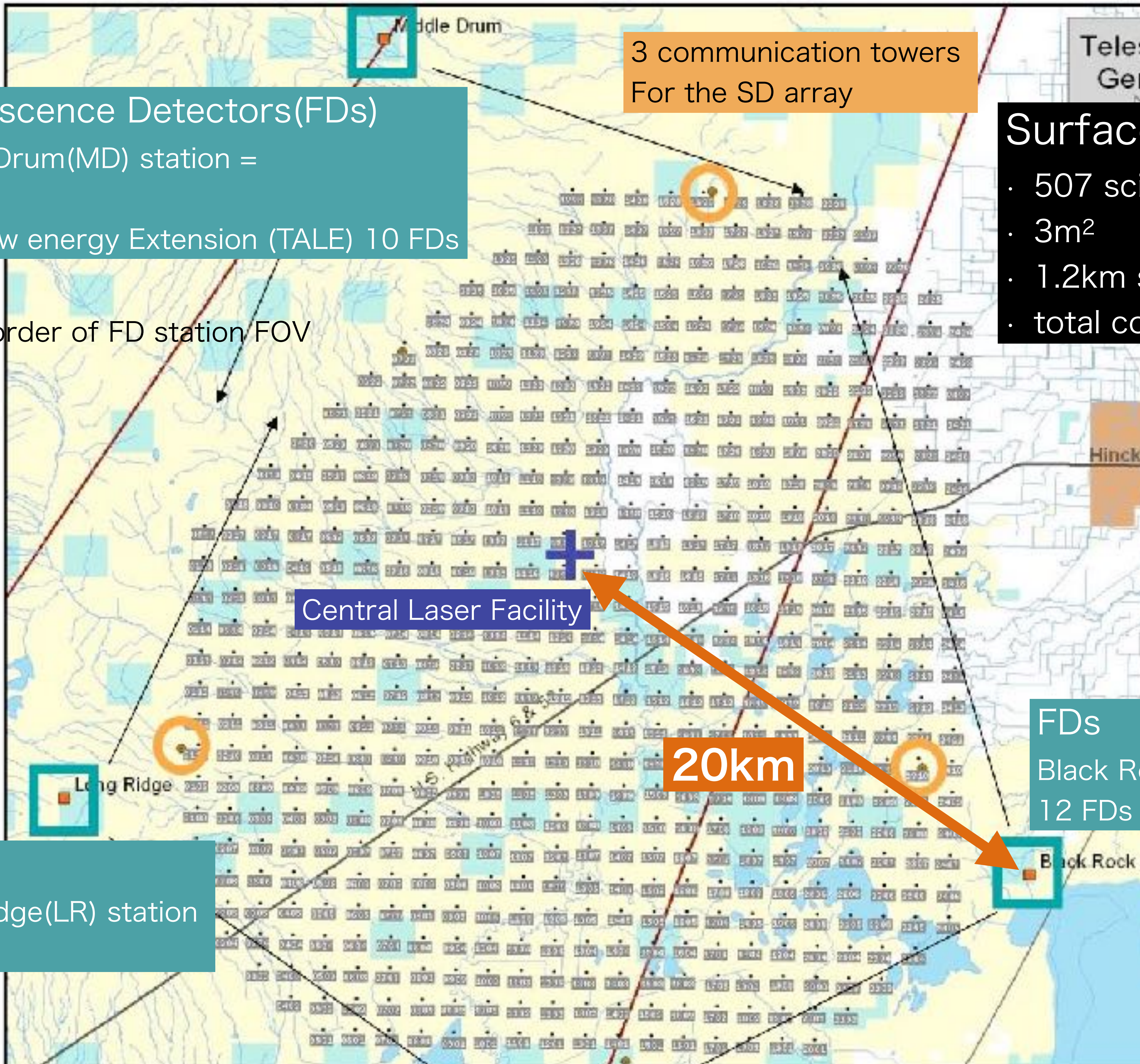
Anisotropy

Neutral particles

Telescope Array: hybrid detector covering 700km²



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

Central Laser Facility

Surface detectors(SDs)

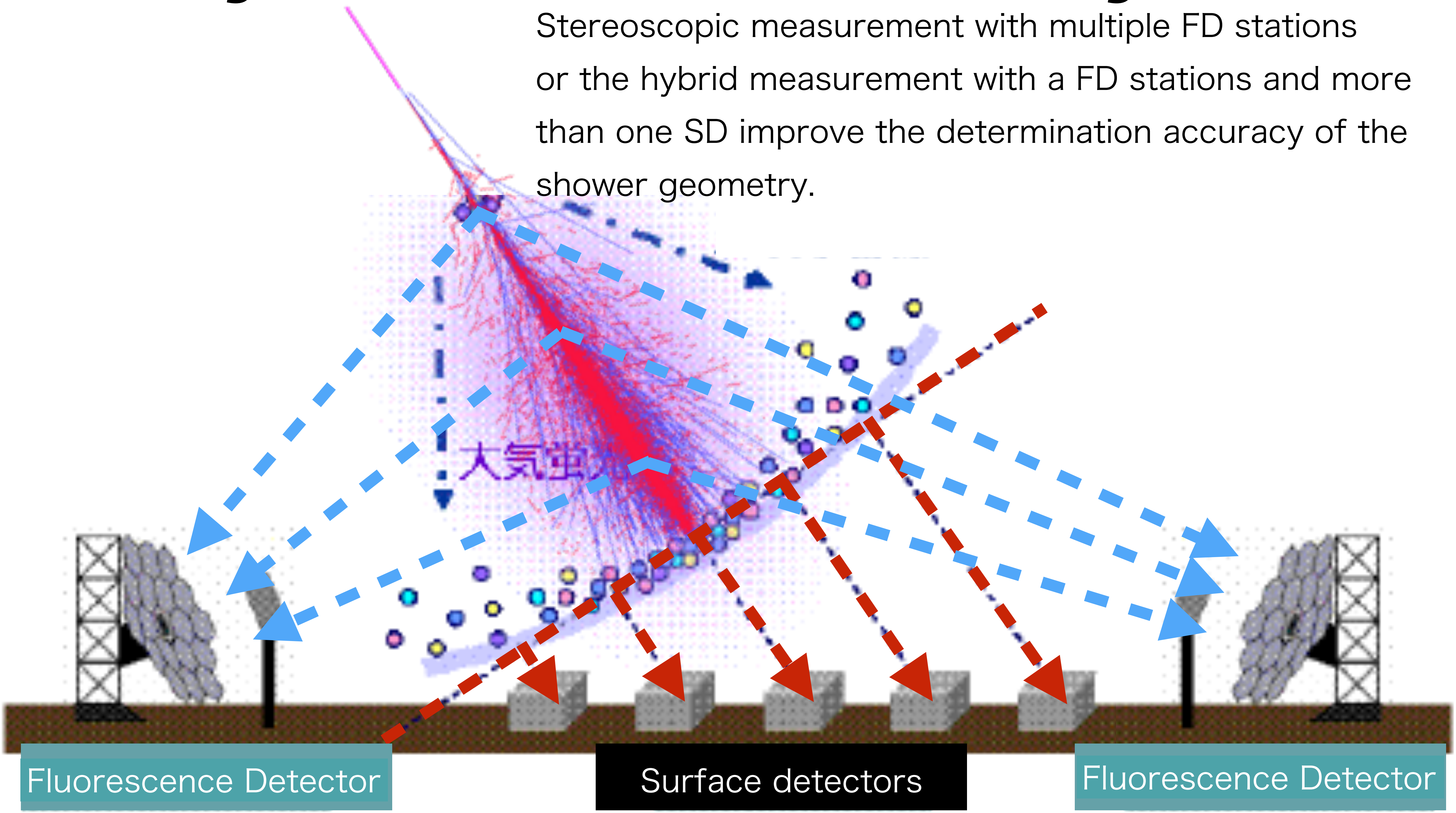
- 507 scintillation detectors
- $3m^2$
- 1.2km spacing
- total coverage ~$700km^2$

FDs
Black Rock Mesa(BRM) station
12 FDs

FDs
Long Ridge(LR) station
12 FDs

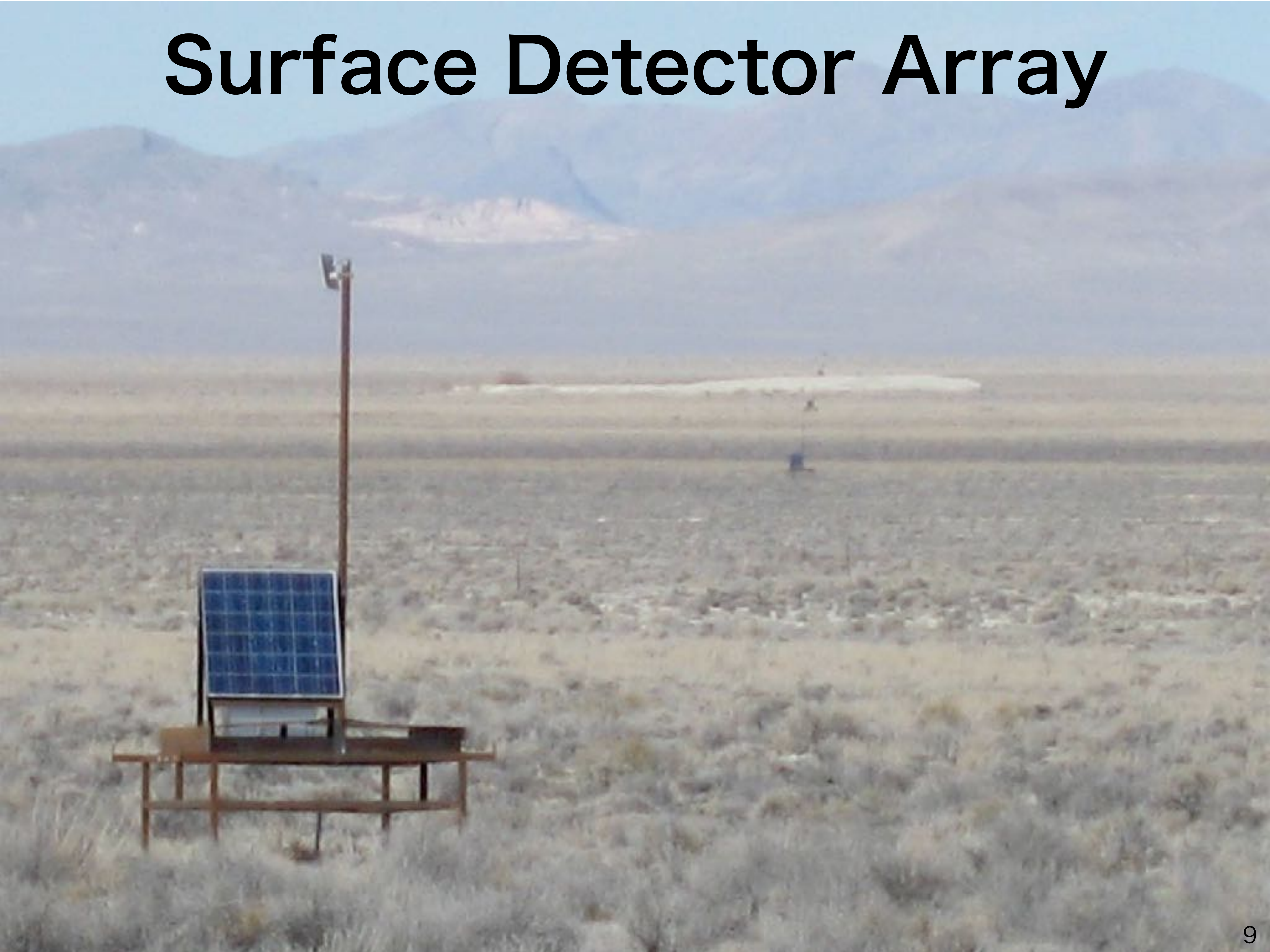
Key feature: Stereo-Hybrid

Stereoscopic measurement with multiple FD stations or the hybrid measurement with a FD stations and more than one SD improve the determination accuracy of the shower geometry.



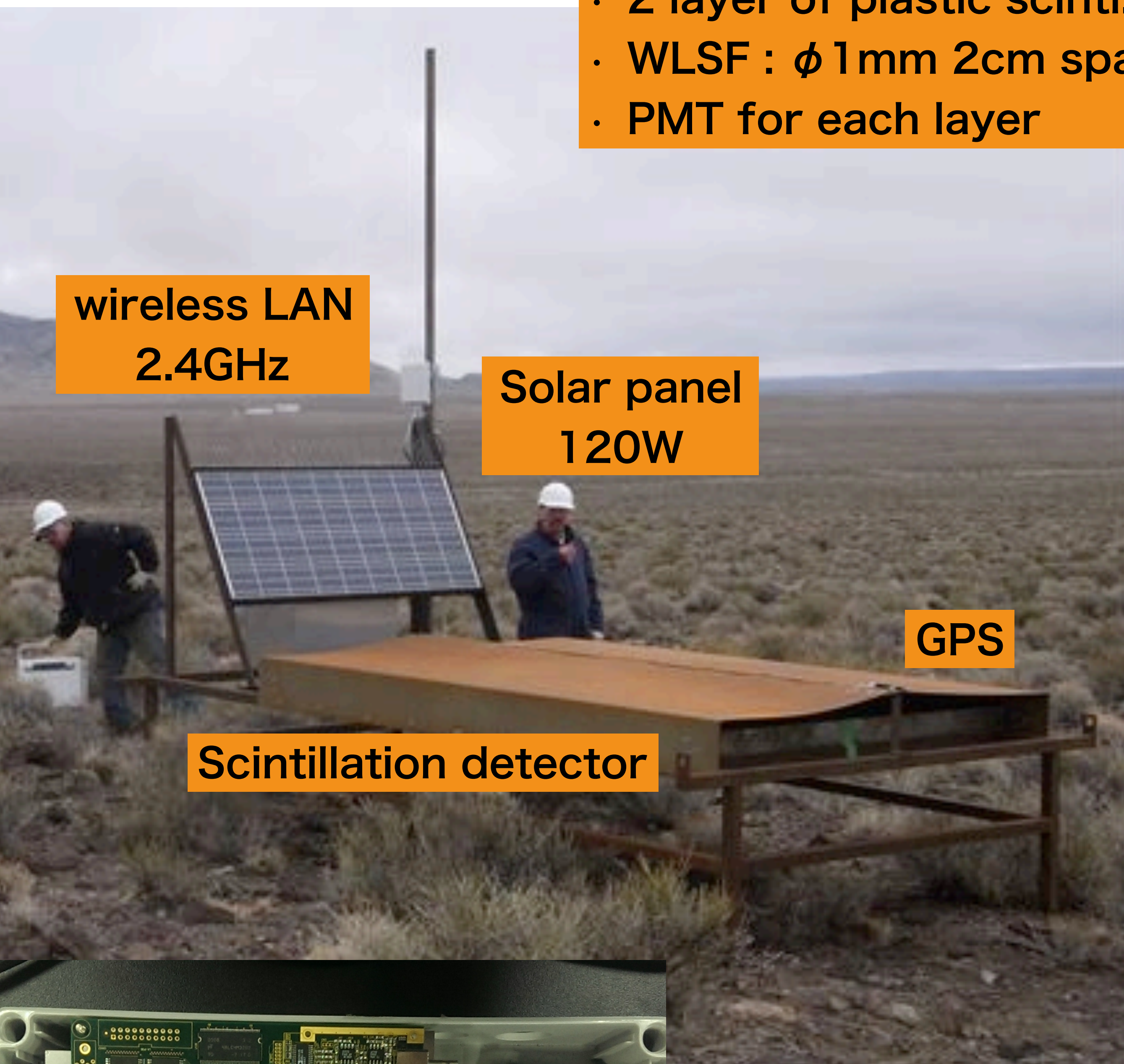
The determination accuracy on the primary energy and the depth of maximum shower development are also improved.

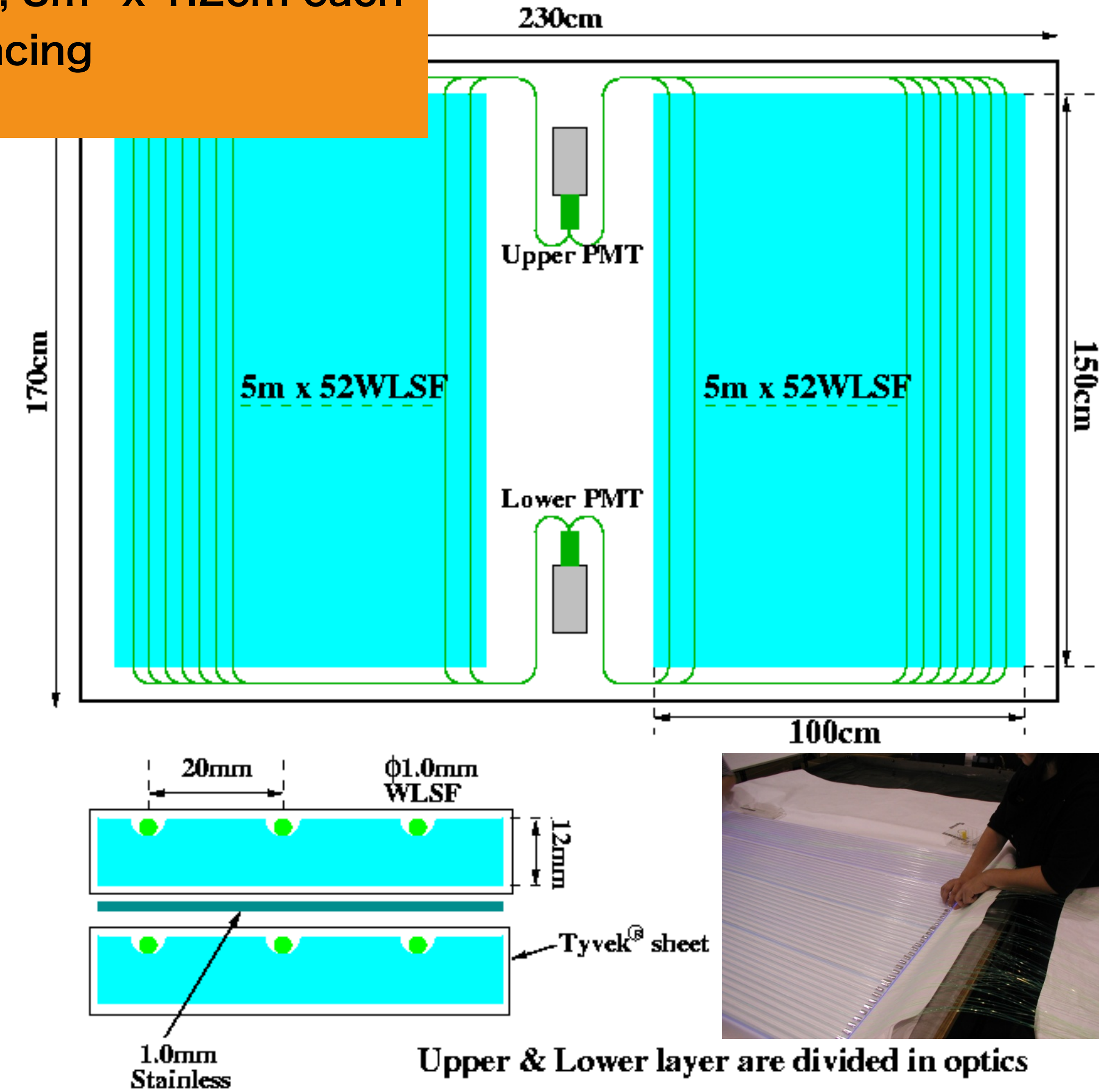
Surface Detector Array



Surface Detector

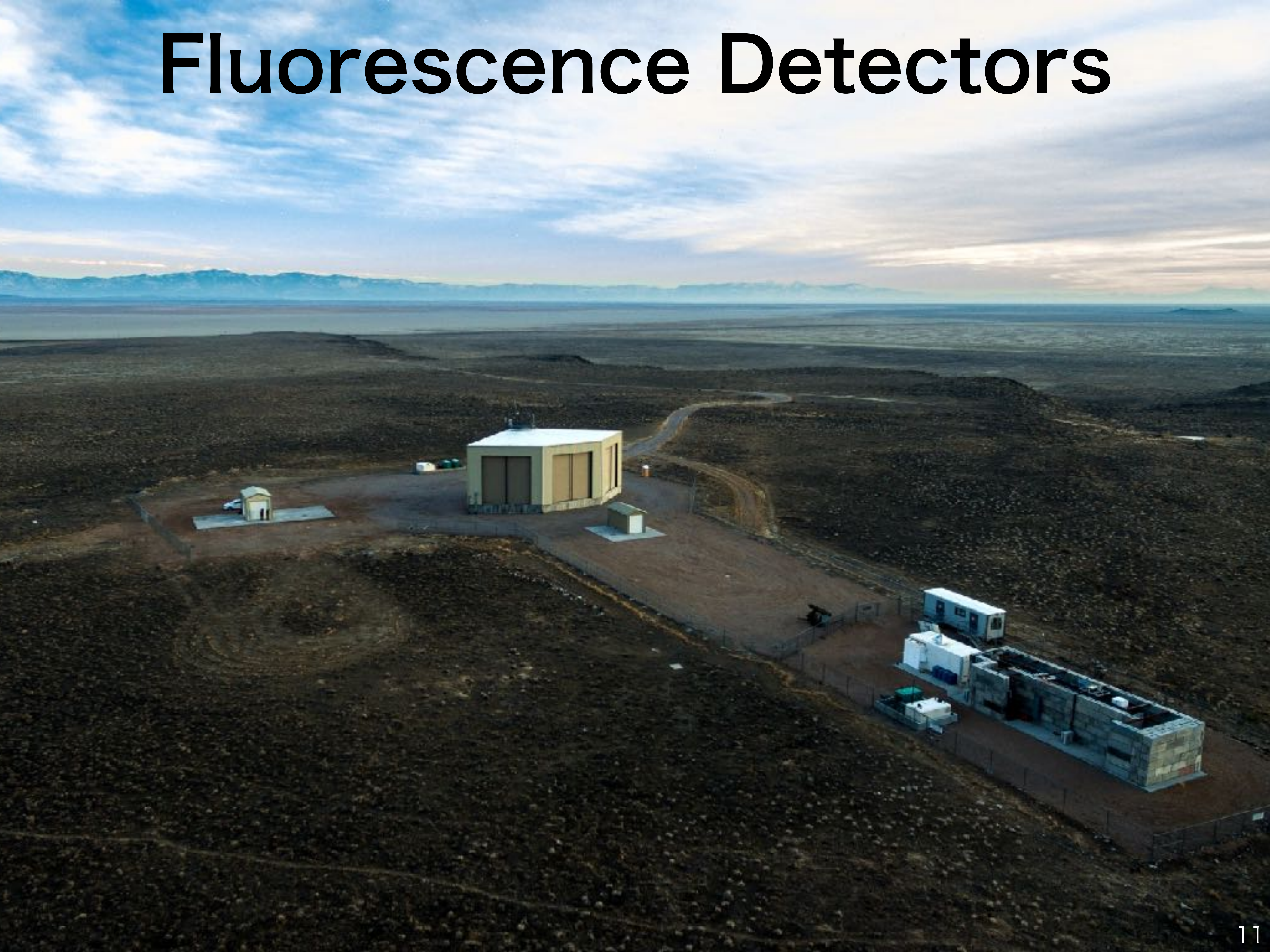
- 2 layer of plastic scinti., 3m² x 1.2cm each
- WLSF : ϕ1mm 2cm spacing
- PMT for each layer



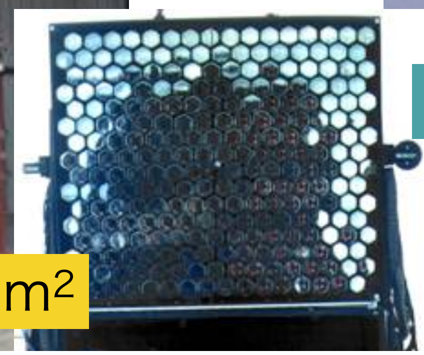


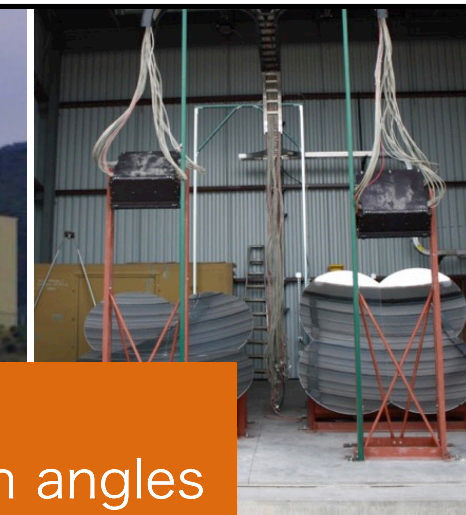
- 12bit 50MHz FADC x 2 layers
- CPU : Renesas SH4(25MHz)
- GPS, WLAN-modem
- Charge controller

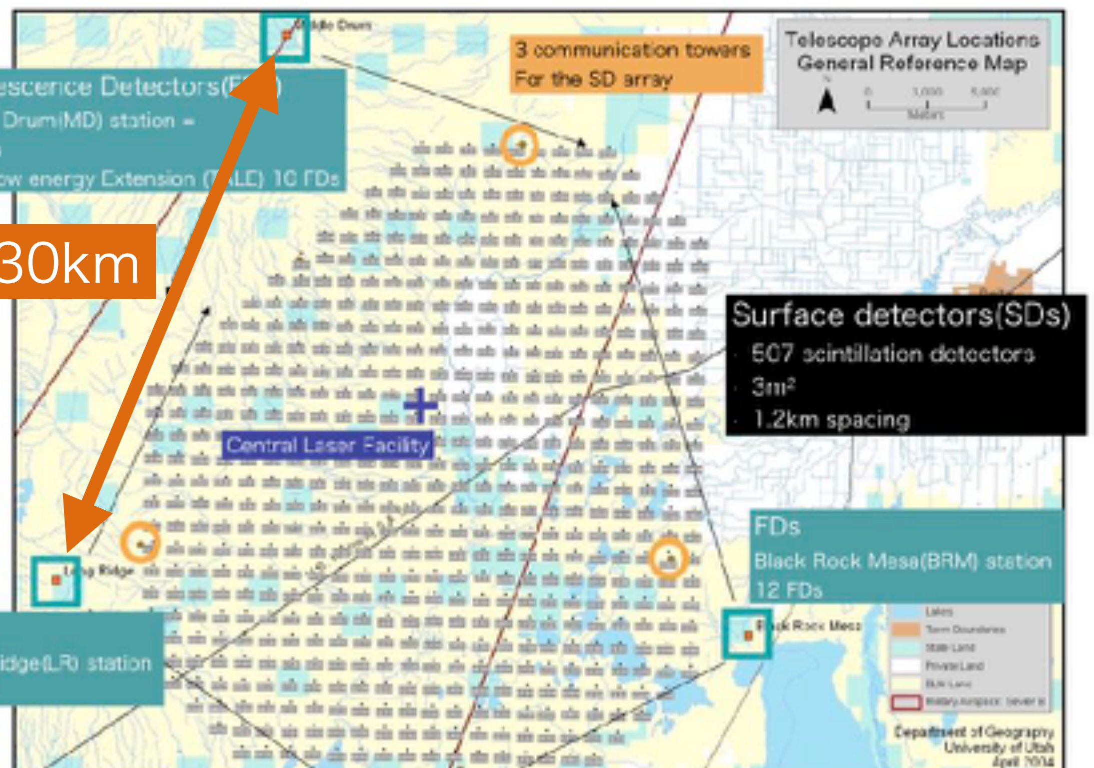
Fluorescence Detectors



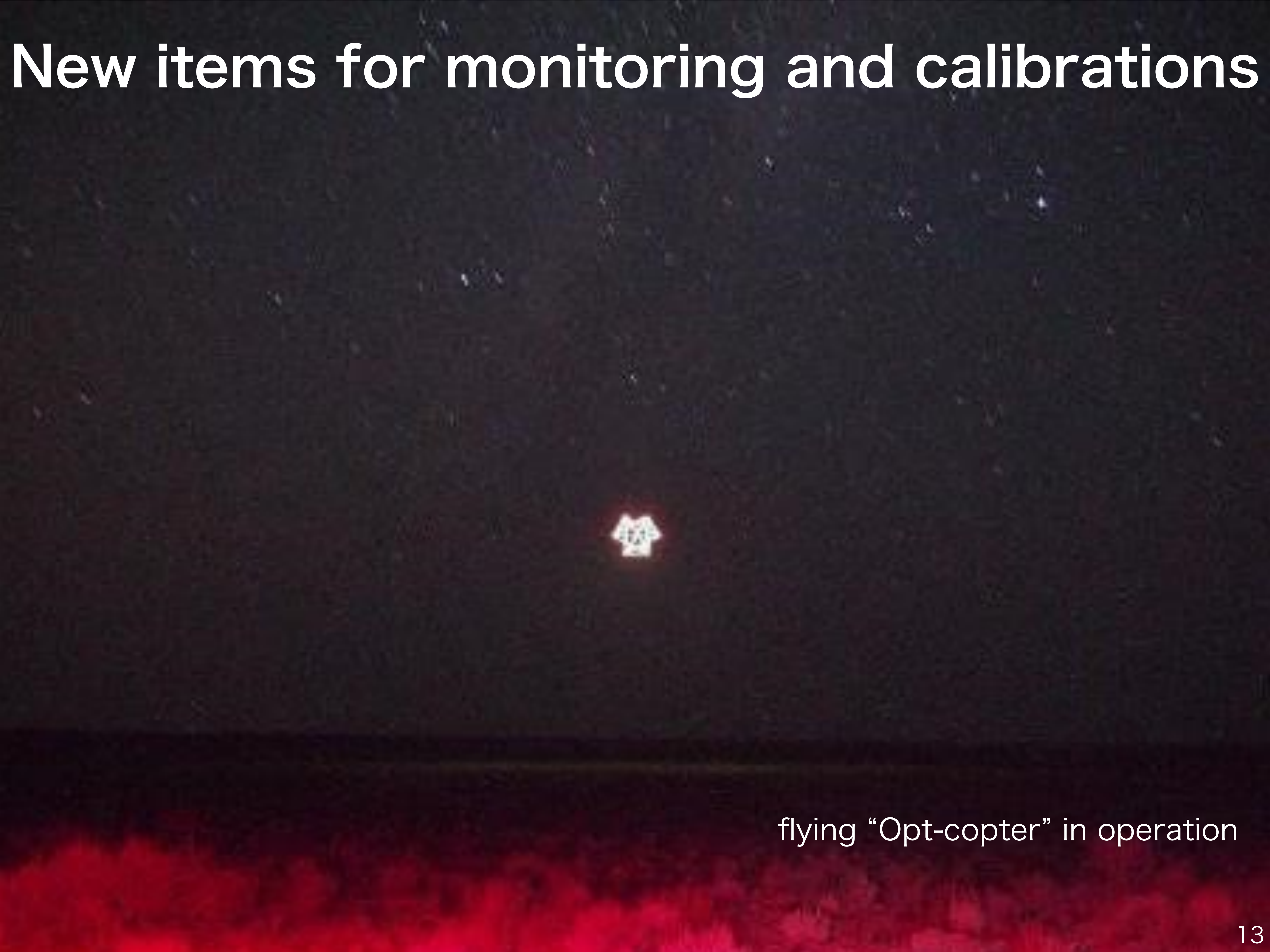
Fluorescence Detectors







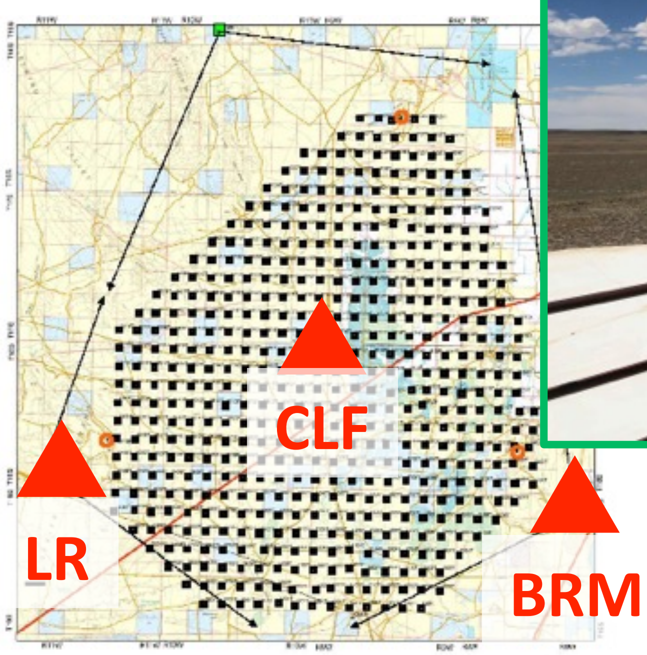
New items for monitoring and calibrations

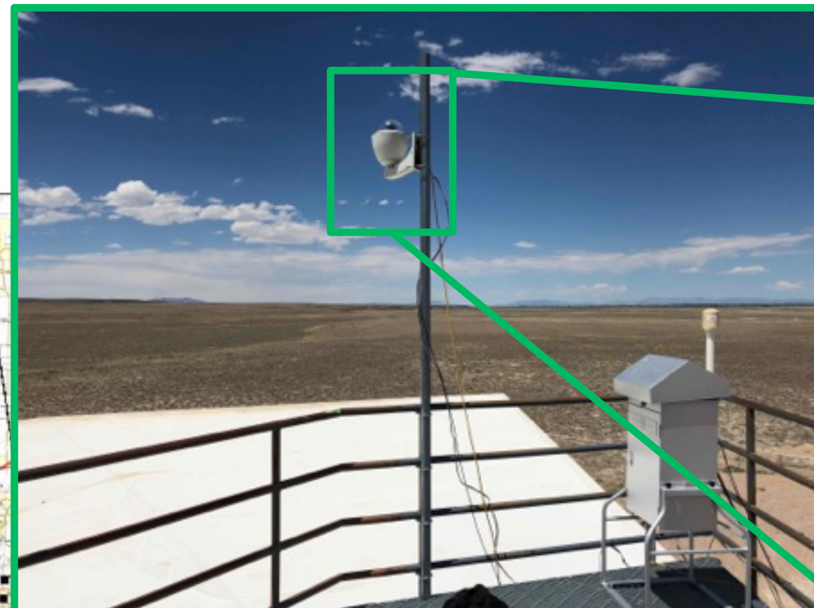


flying “Opt-copter” in operation

New items for calibrations and monitoring (1)

CCD cloud monitoring system



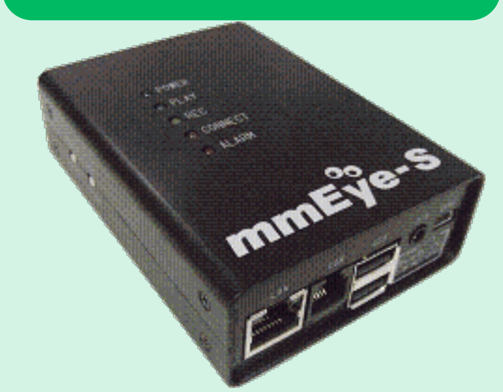


Fish eye lens
FE185C057HA-1

CCD camera (VIS)
WAT120N+

Housing

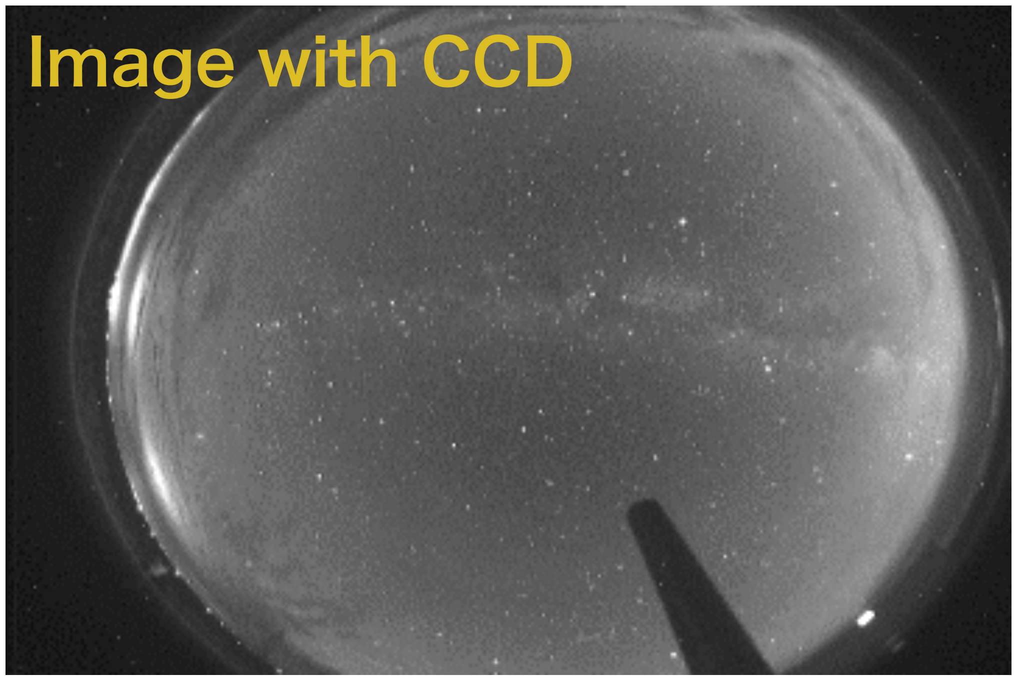
Image server
mmEye-S



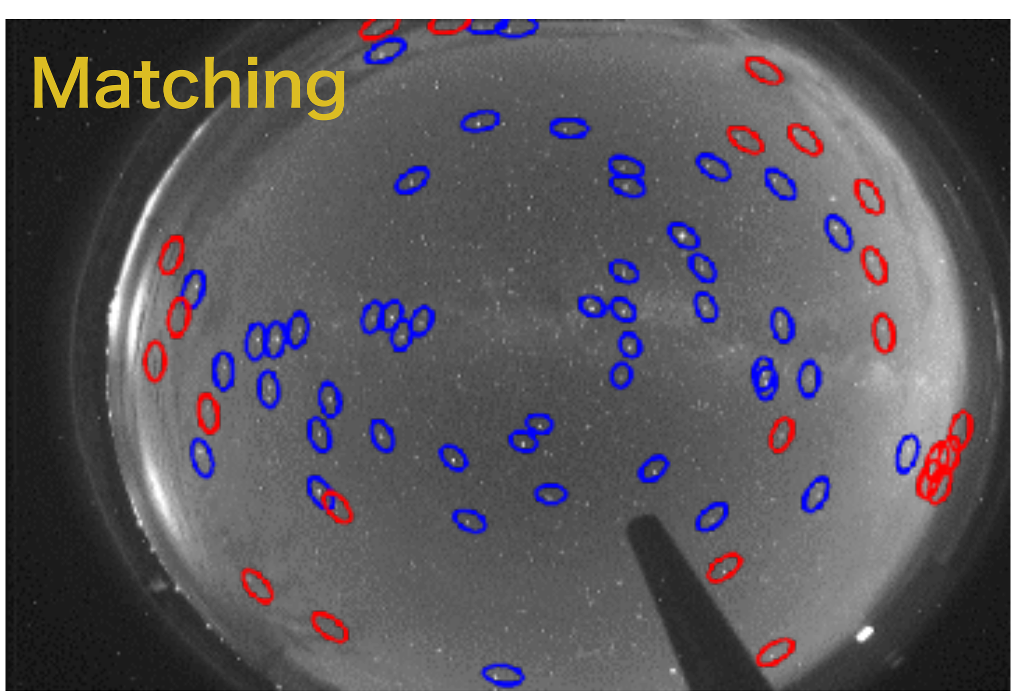
- 3 sets in TA site
- every 1 min.
- 8 sec exposure
- size: 720 × 480 pixels (346KB / 1 photo)
- FOV: 185.0° × 154.1°

Cloud monitoring: scoring

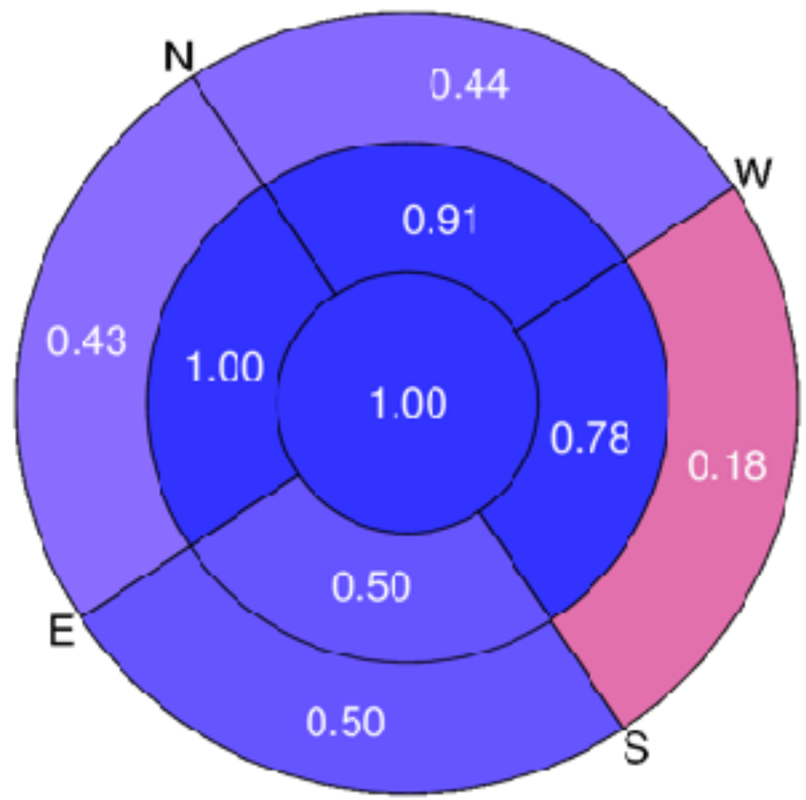
Searching the listed stars at SAO star catalog (> 3.5 mag.) in each picture
→ Score = number of matched stars / total expected # of stars in FOV



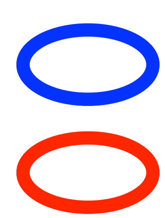
Nov. 20, 2014, 1:40 - 12:00 UTC



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

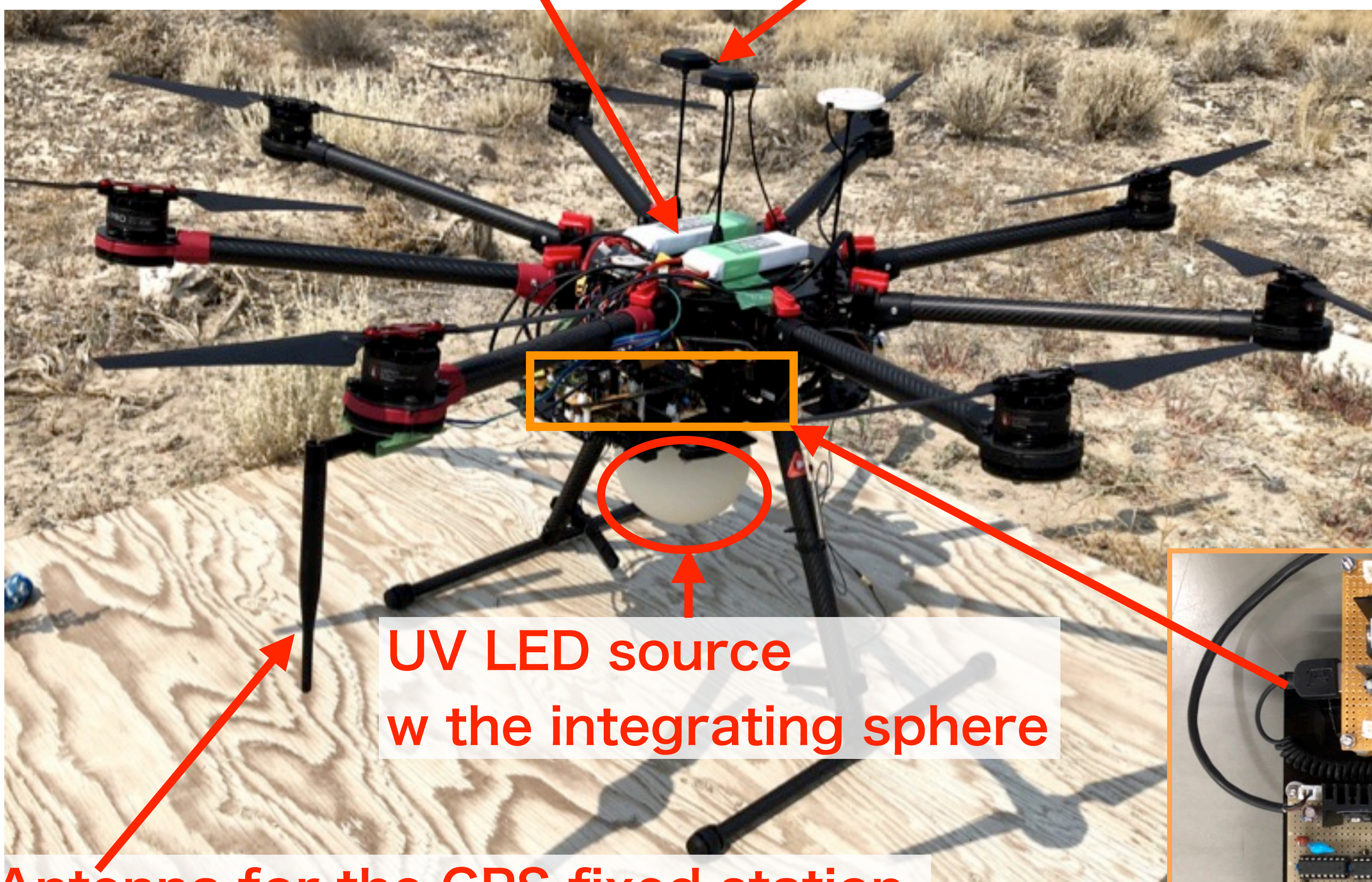


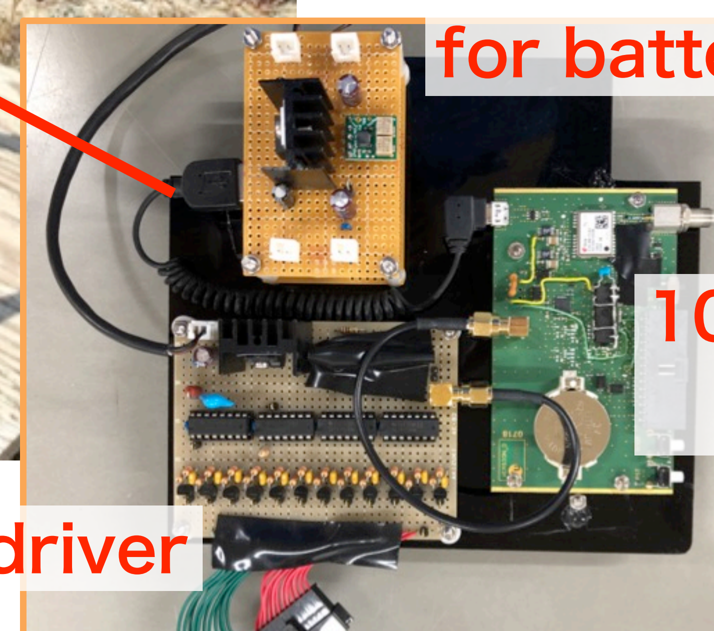
Listed star (3.5 mag.) at the SAO catalog

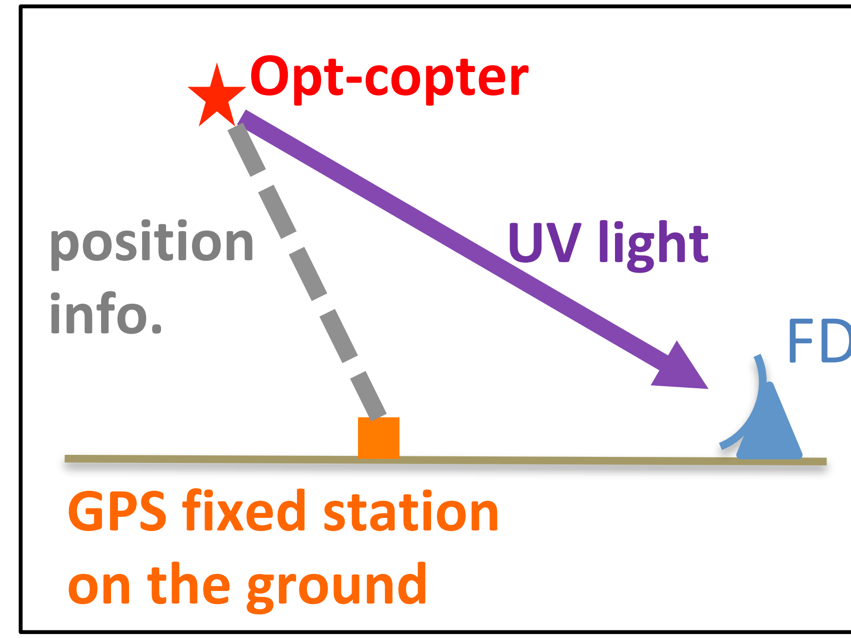


New items for calibrations and monitoring (2)

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

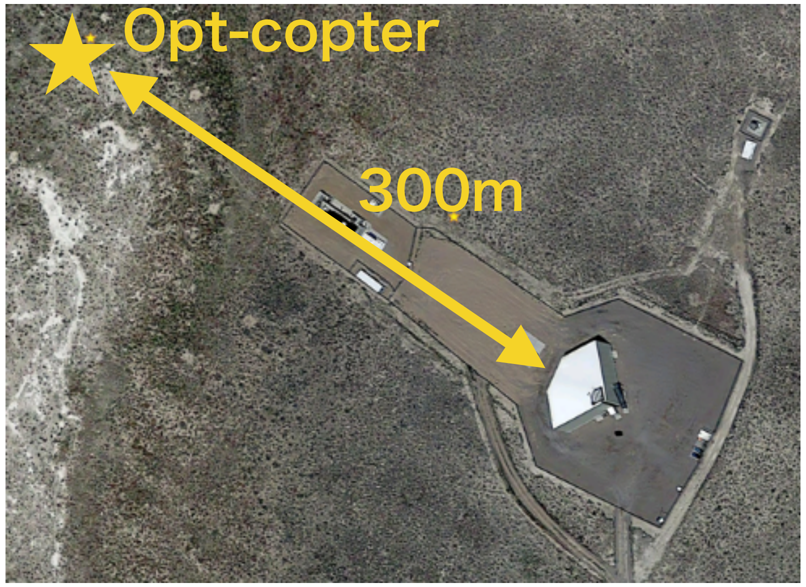






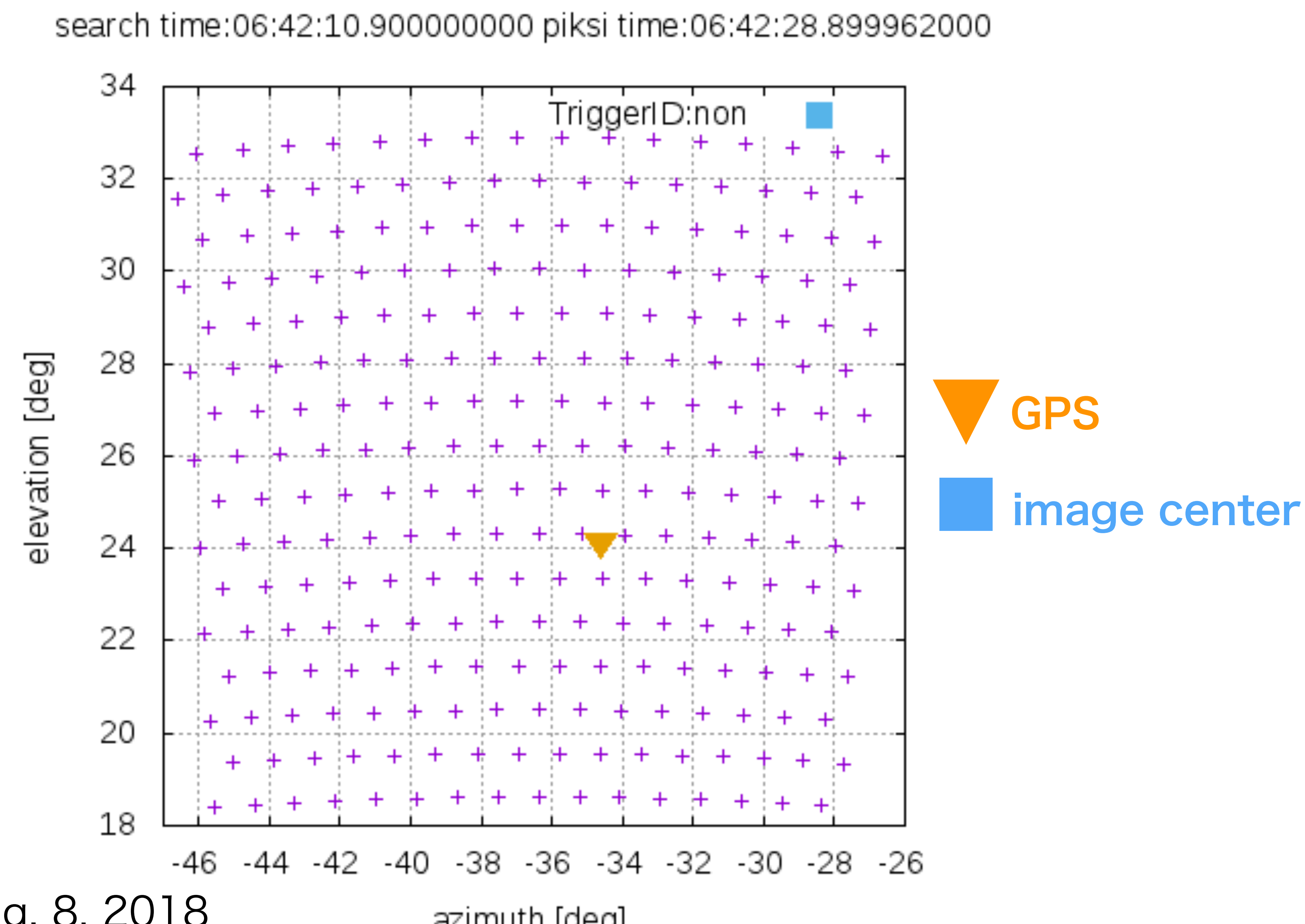
conceptual image

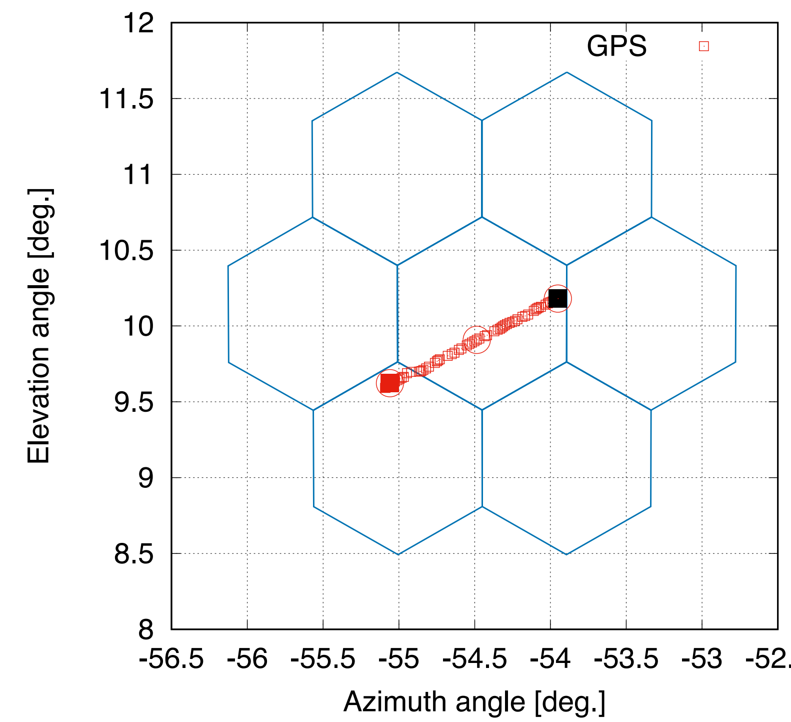
Opt-copter in operation

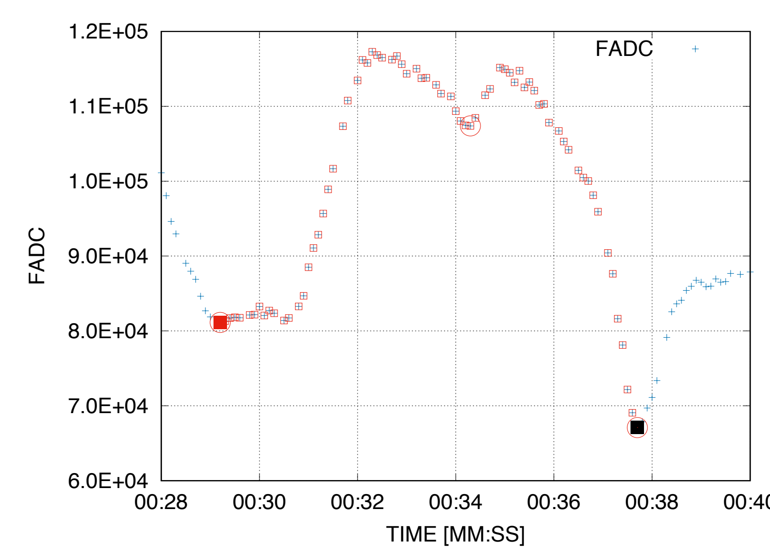


Main target of the calibration with “Opt-copter”:
Precise measurement of FD optics and geometry

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







Extensions of TA experiment

1. TA Low energy Extension: TALE
2. Expansion of effective area: TAx4

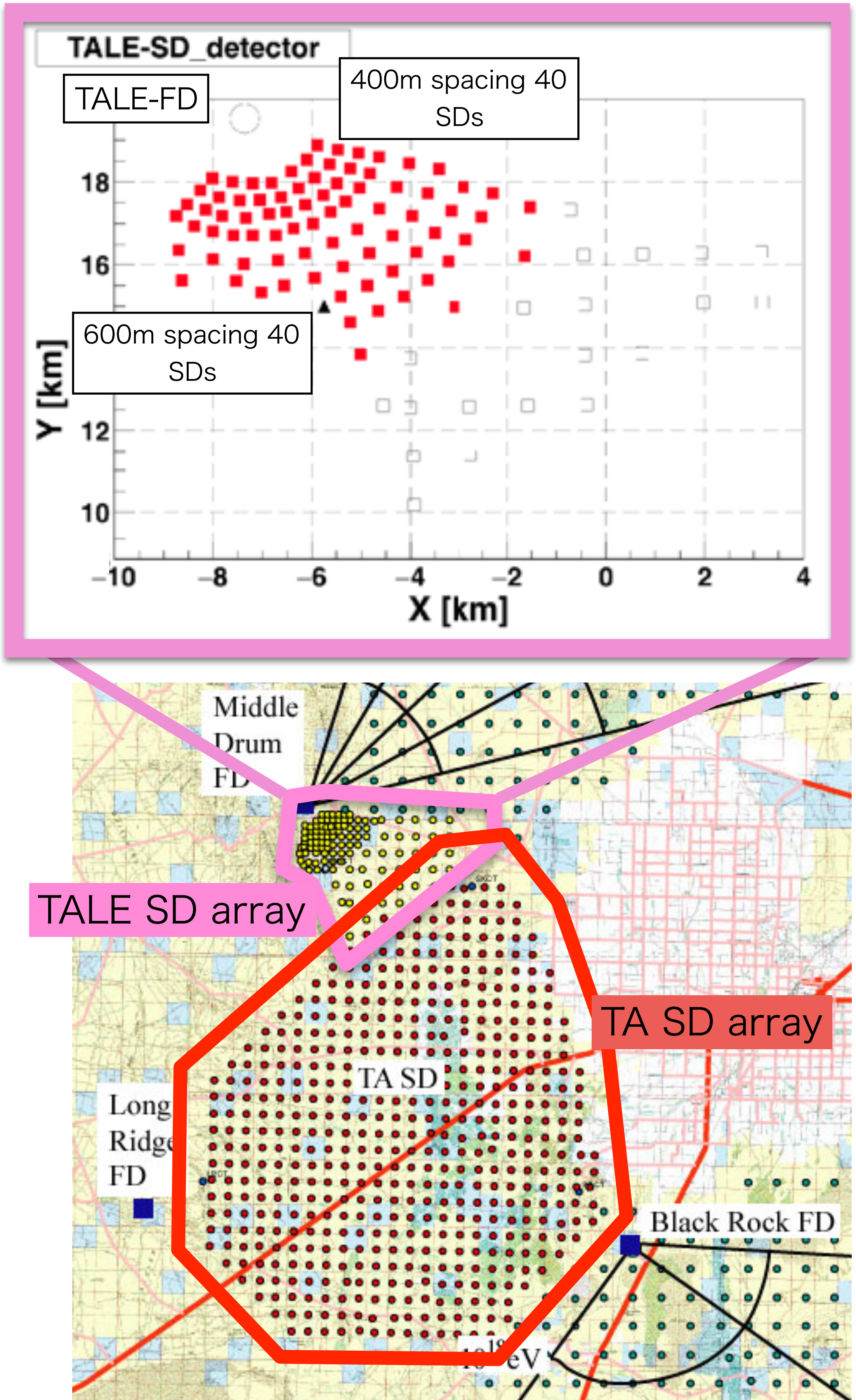
TALE


Middle Drum station
TALE FD station


TALE FDs


TALE SDs prepared for deployment

TALE hybrid



Low energy extension of TA 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 (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

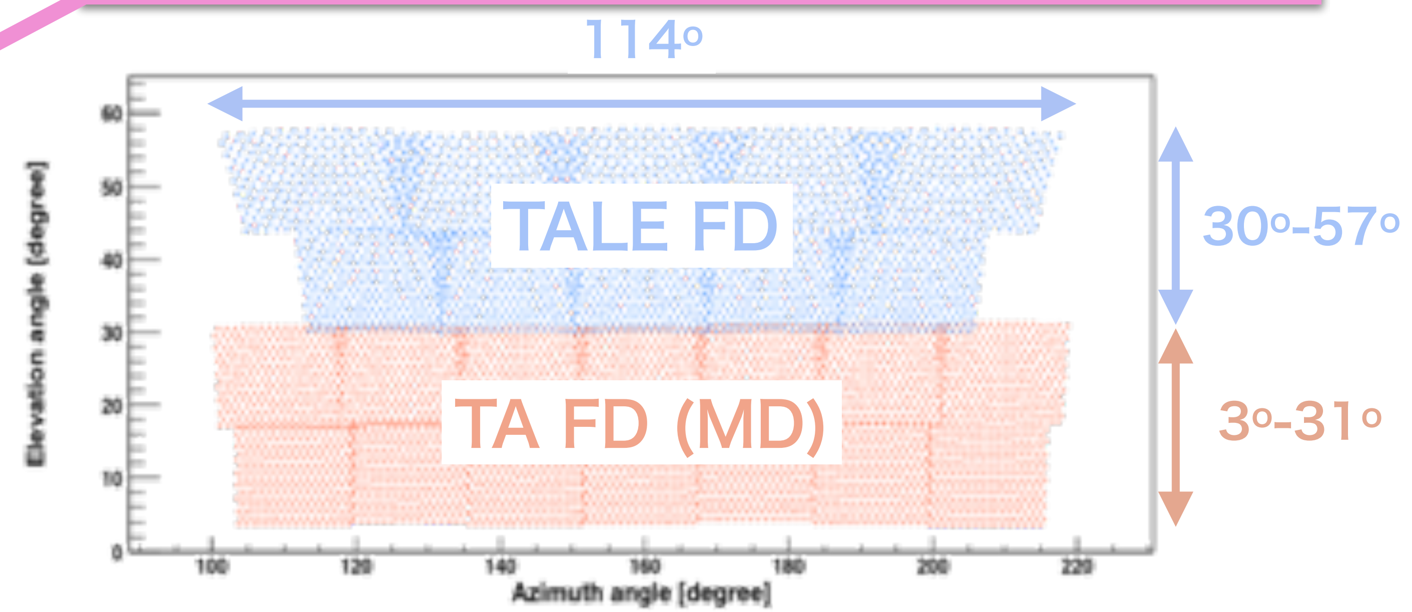
$\Delta\theta$ = 1.0° (FD mono : 5.3°)

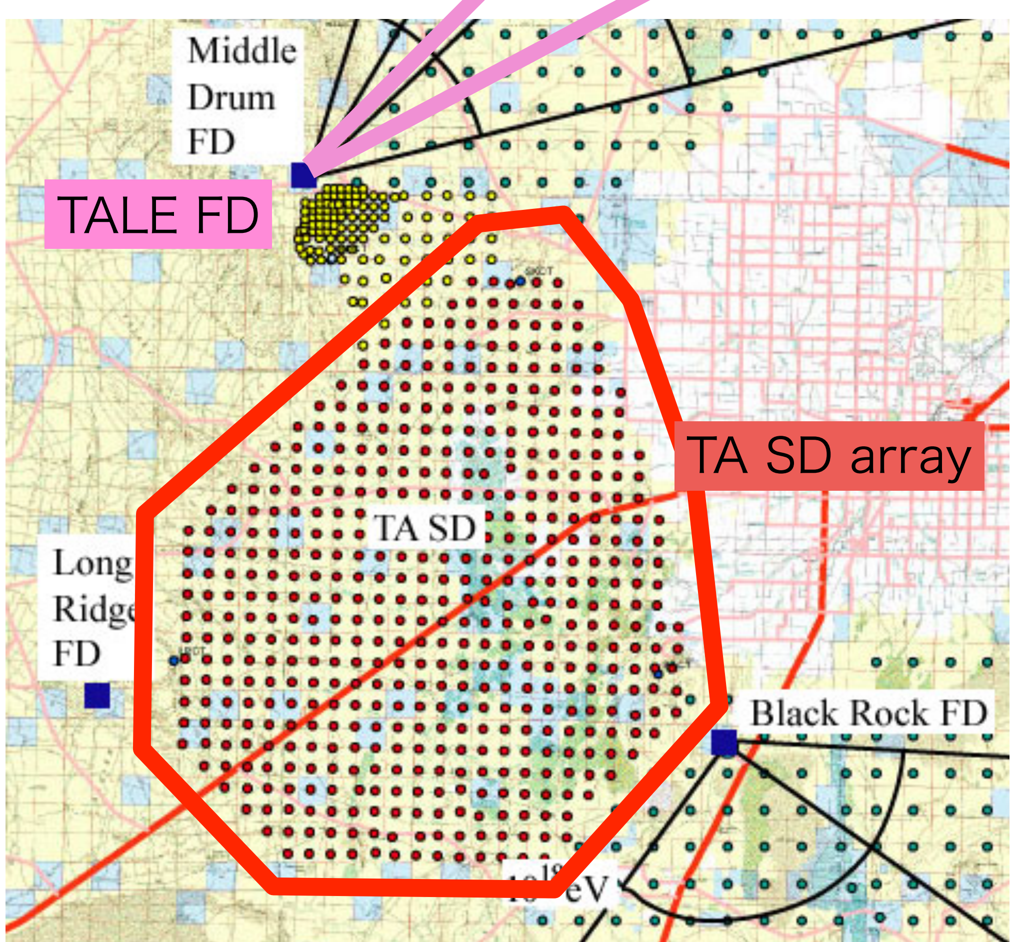
ΔXmax = 20 g/cm^2 (FD mono : 60g/cm^2)

TALE FD

TALE FD station and TA MD are very close together
10 FDs in the TALE station
Elevation: 30°-57° (higher elevation than MD)
Azimuthal: 114°

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



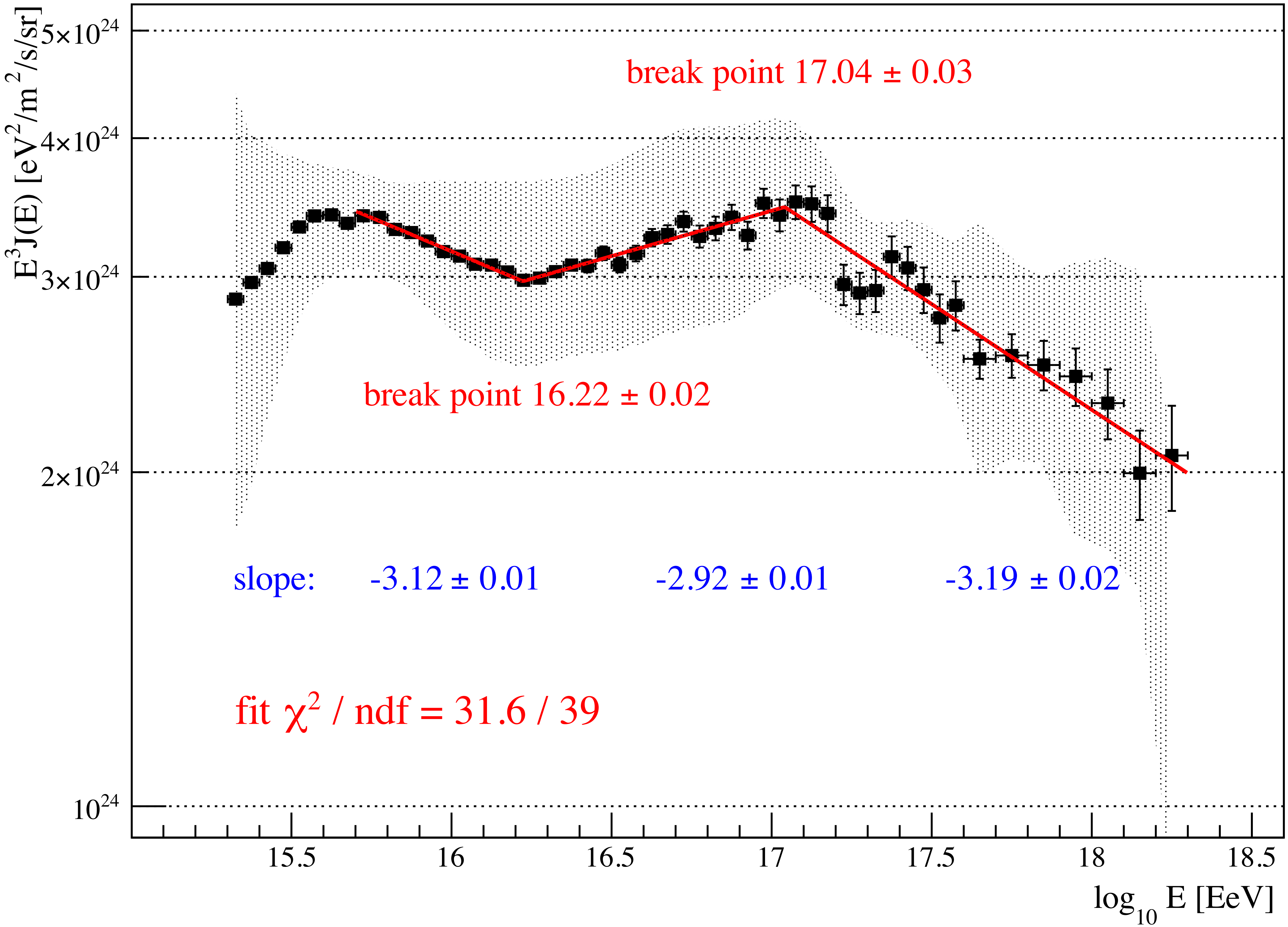


Installed in Nov. 2012
Operation from Sep. 2013
Hybrid trigger out Sep. 2018

TALE-FD mono spectrum(2yrs)

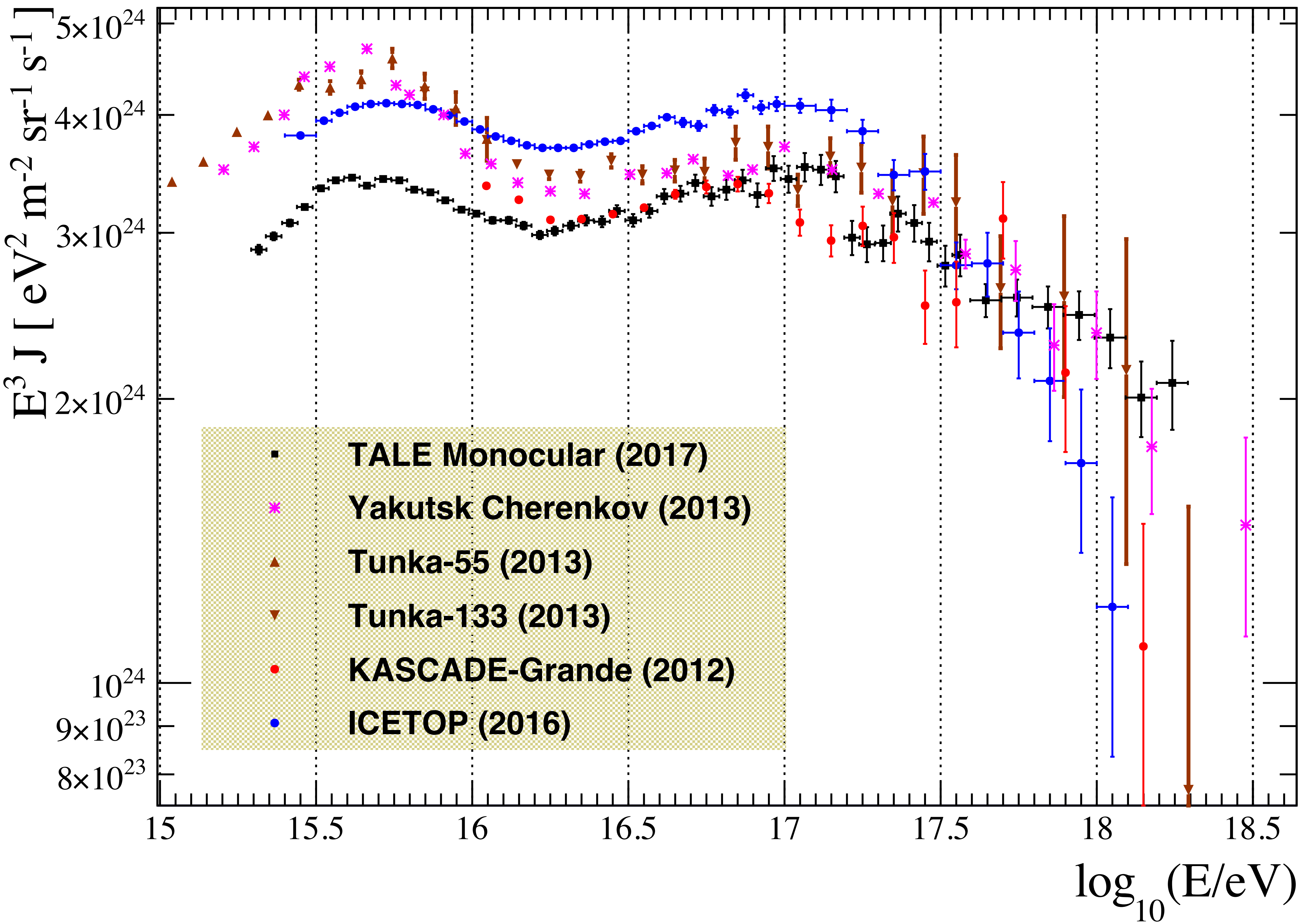
Data: Jun. 2014 - Mar. 2016

Ap. J., 865, 74(2018)
arXiv: 1803.01288



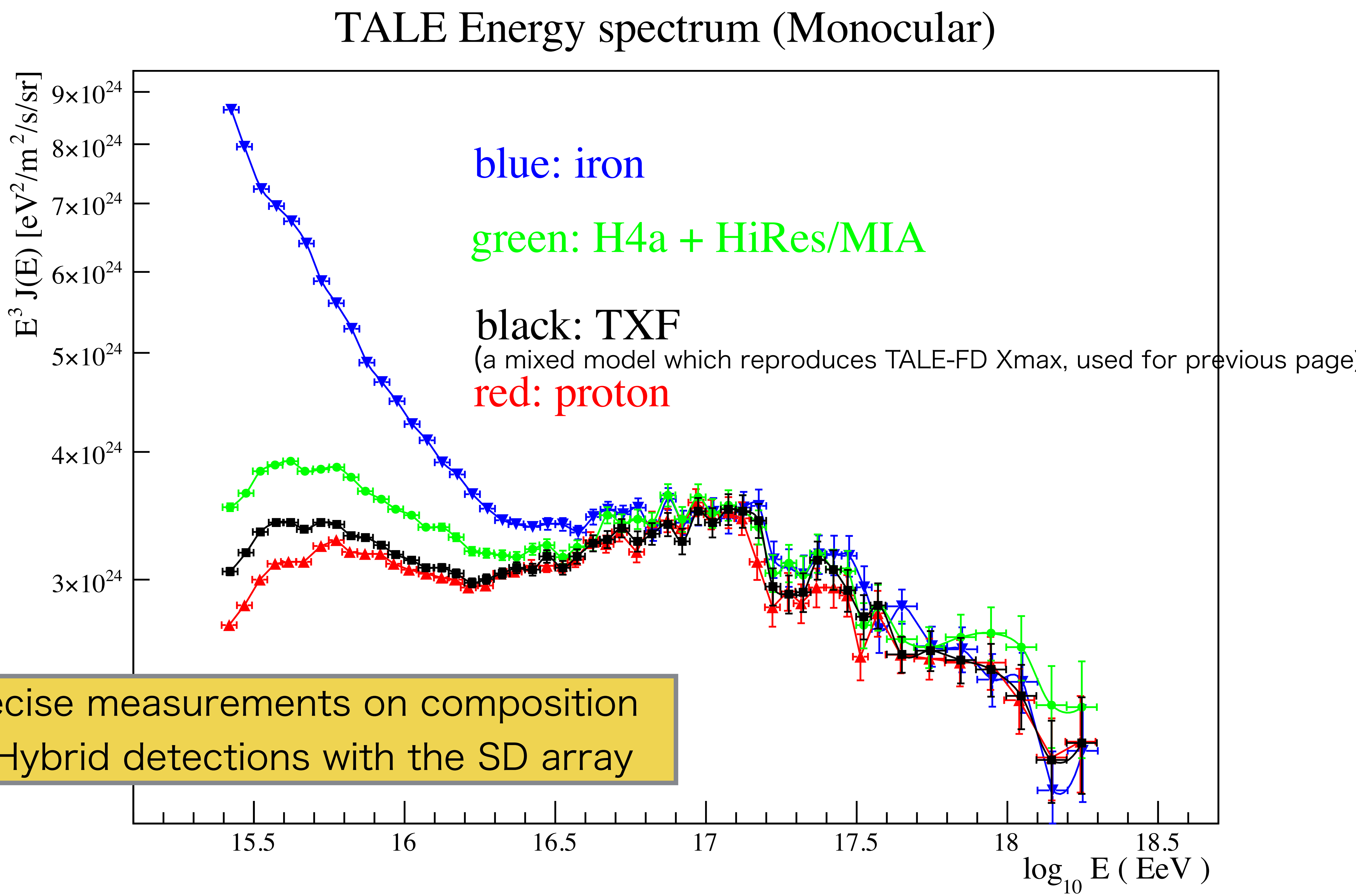
Compared to recent measurements

Ap. J., 865, 74(2018)
arXiv: 1803.01288



Exposure depends on composition

Ap. J., 865, 74(2018)
arXiv: 1803.01288

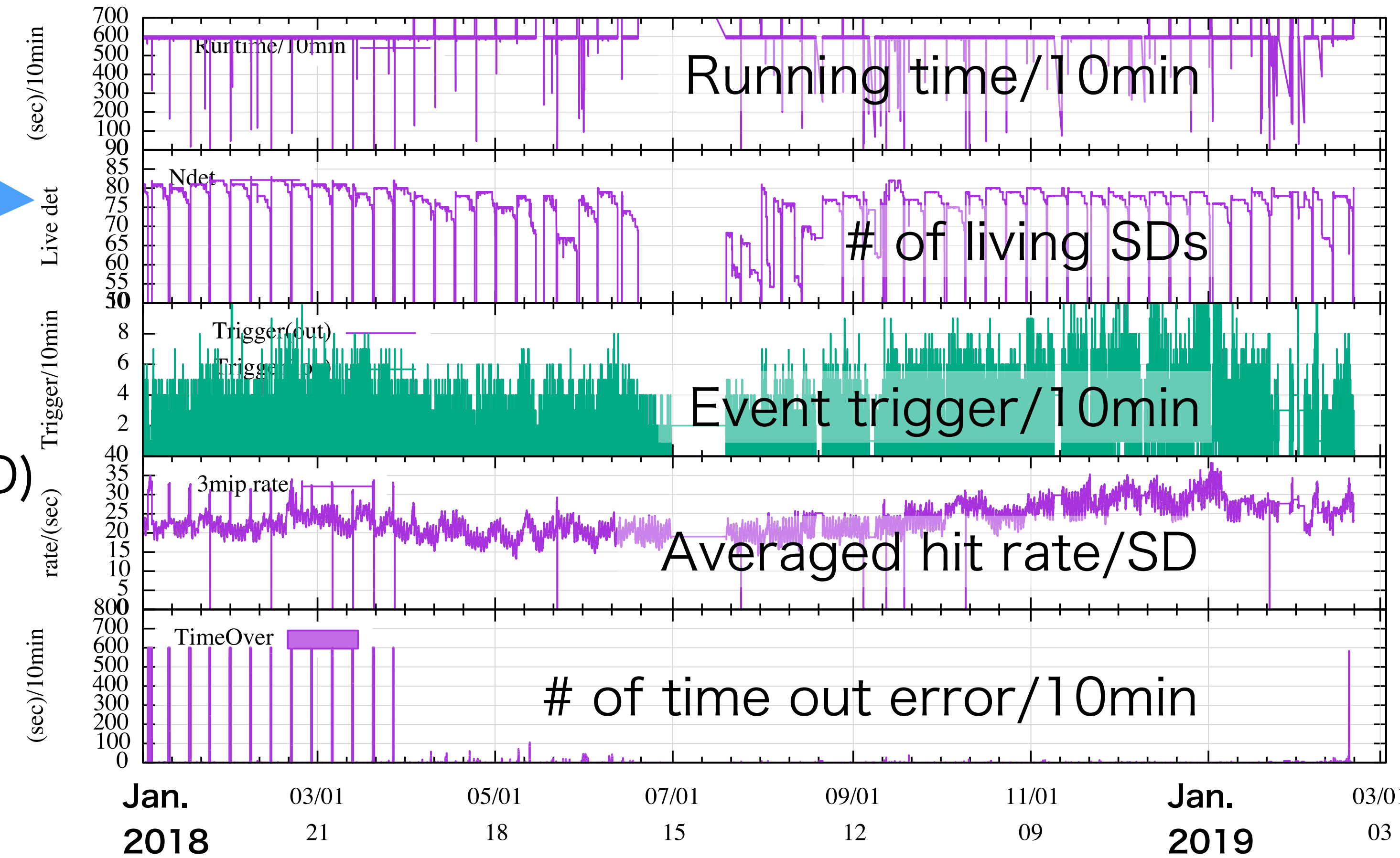


Precise measurements on composition
→ Hybrid detections with the SD array

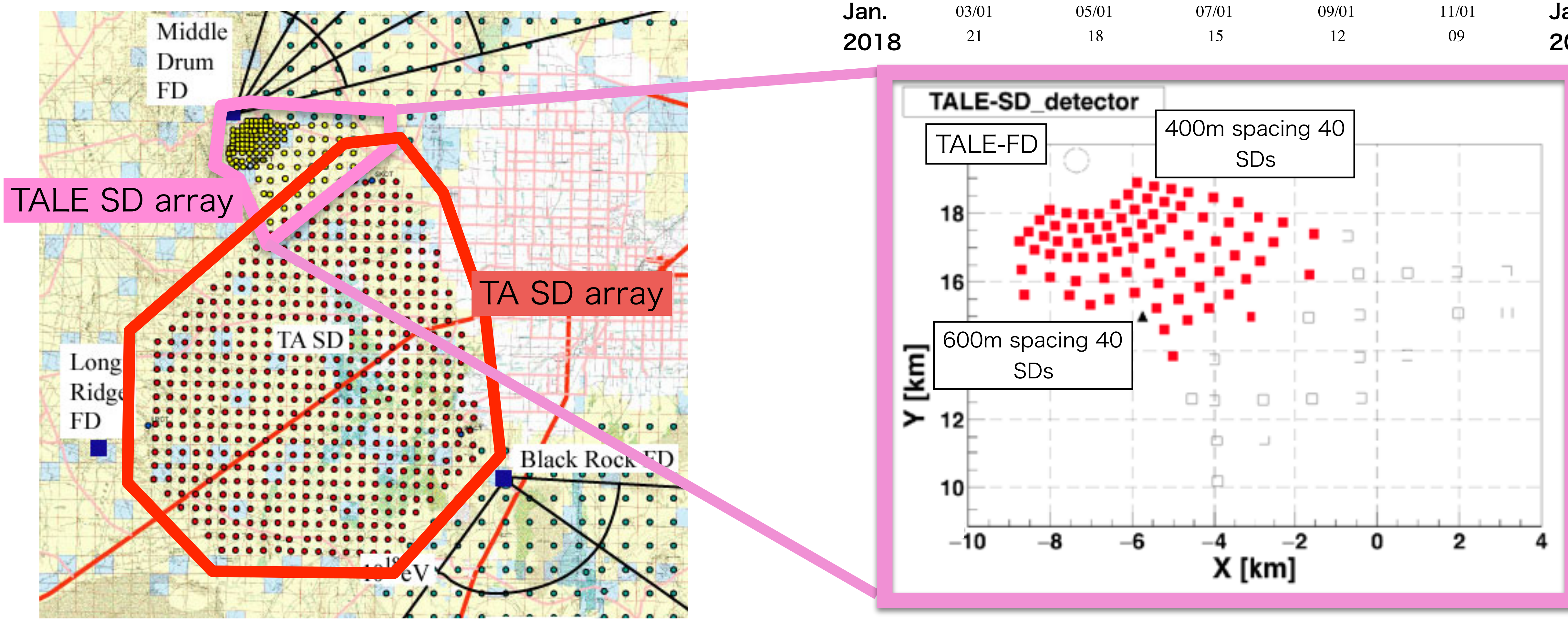
TALE SD array

80 SDs covering 30km^2
Running from Feb. 2018
# of living SD ~ 80
DAQ bug fixed at Apr. 2018

Status plot (Jan. 2018 -)



Triggering conditions:
Storing waveform in SD: > 0.3 MIP (750Hz/SD)
Hit: > 3 MIPs (20Hz/SD)
Air shower event: 5 hit SDs in 8us window (3/10min)



TALE Hybrid

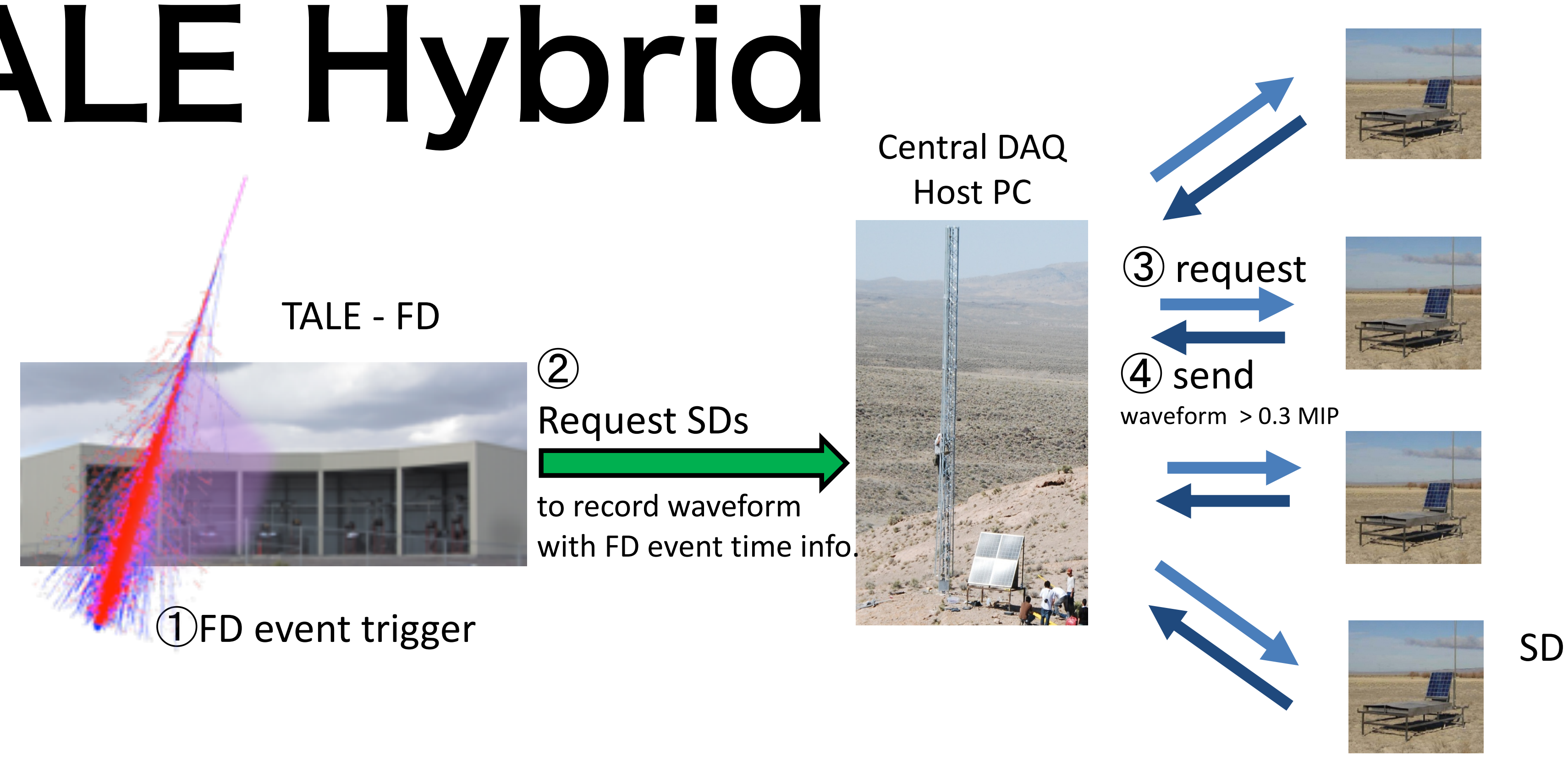
Hybrid DAQ installed Sep. 2018

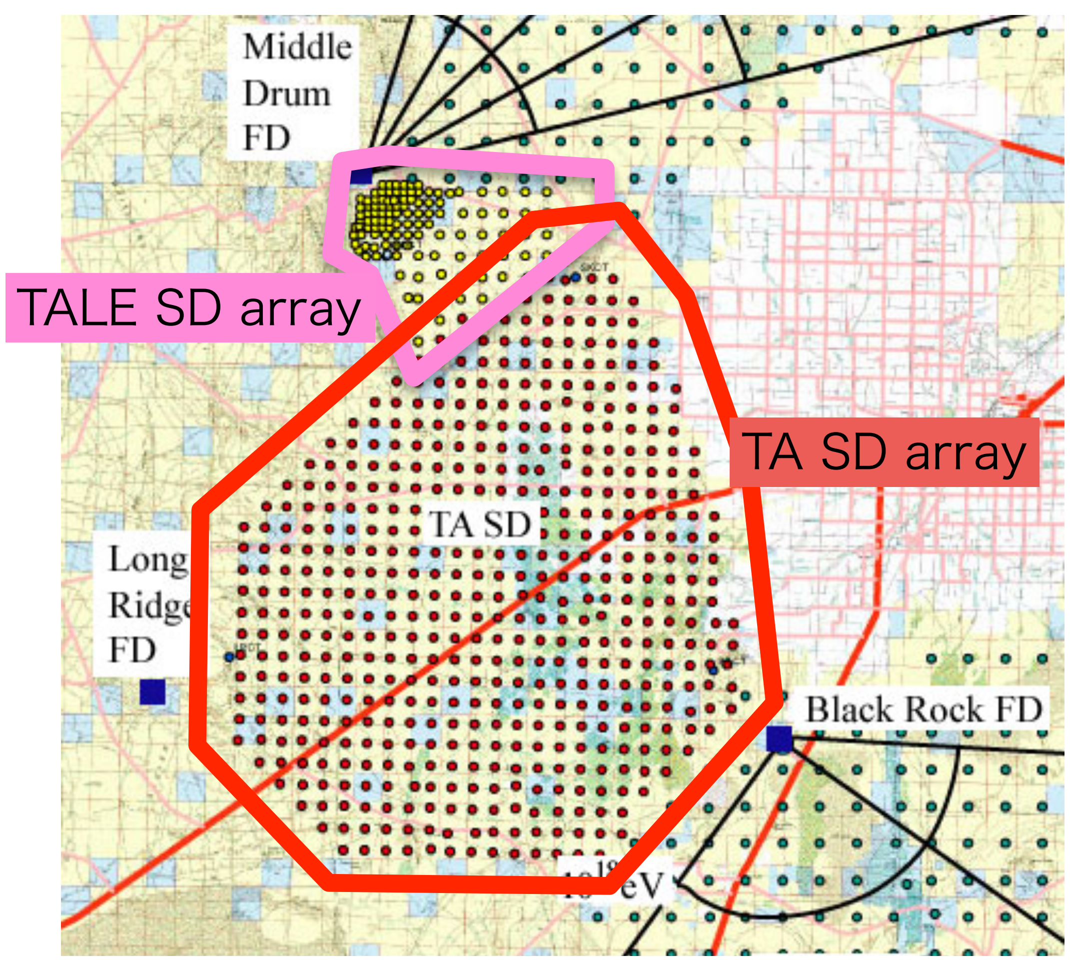
# of hit PMT > 5 &

Event duration > 500ns

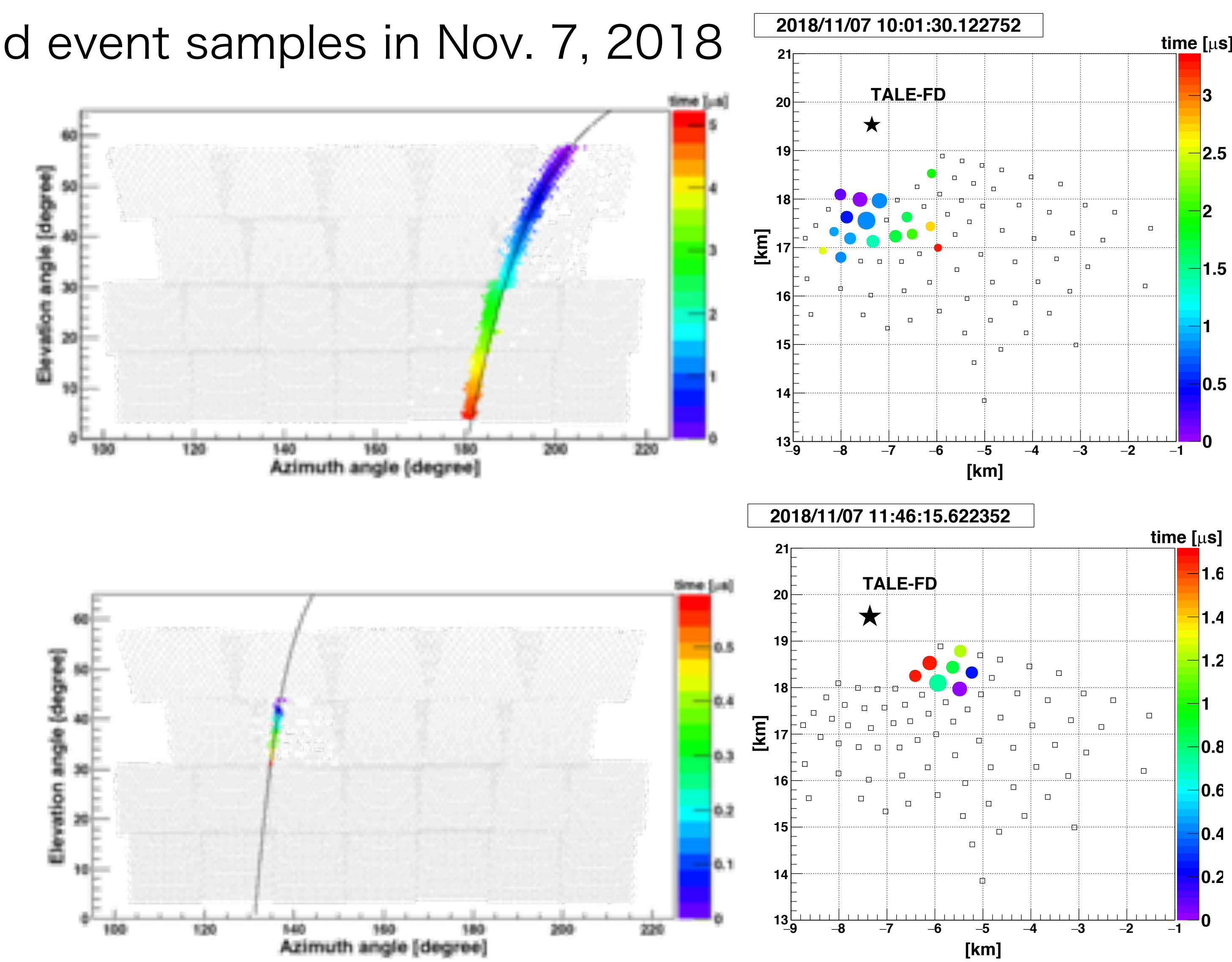
→ Hybrid trigger

Hybrid triggering rate ~ 0.05Hz

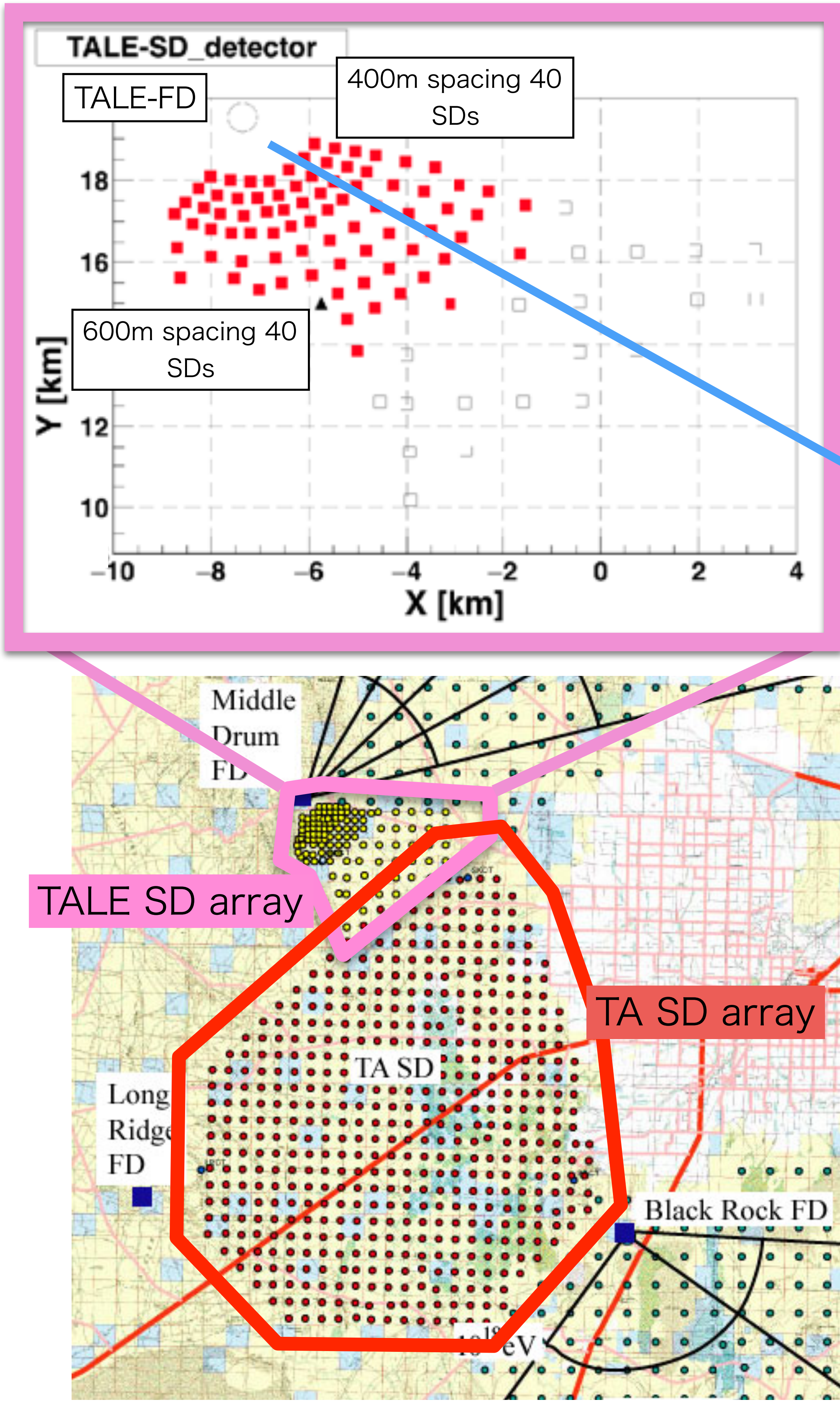




Real hybrid event samples in Nov. 7, 2018



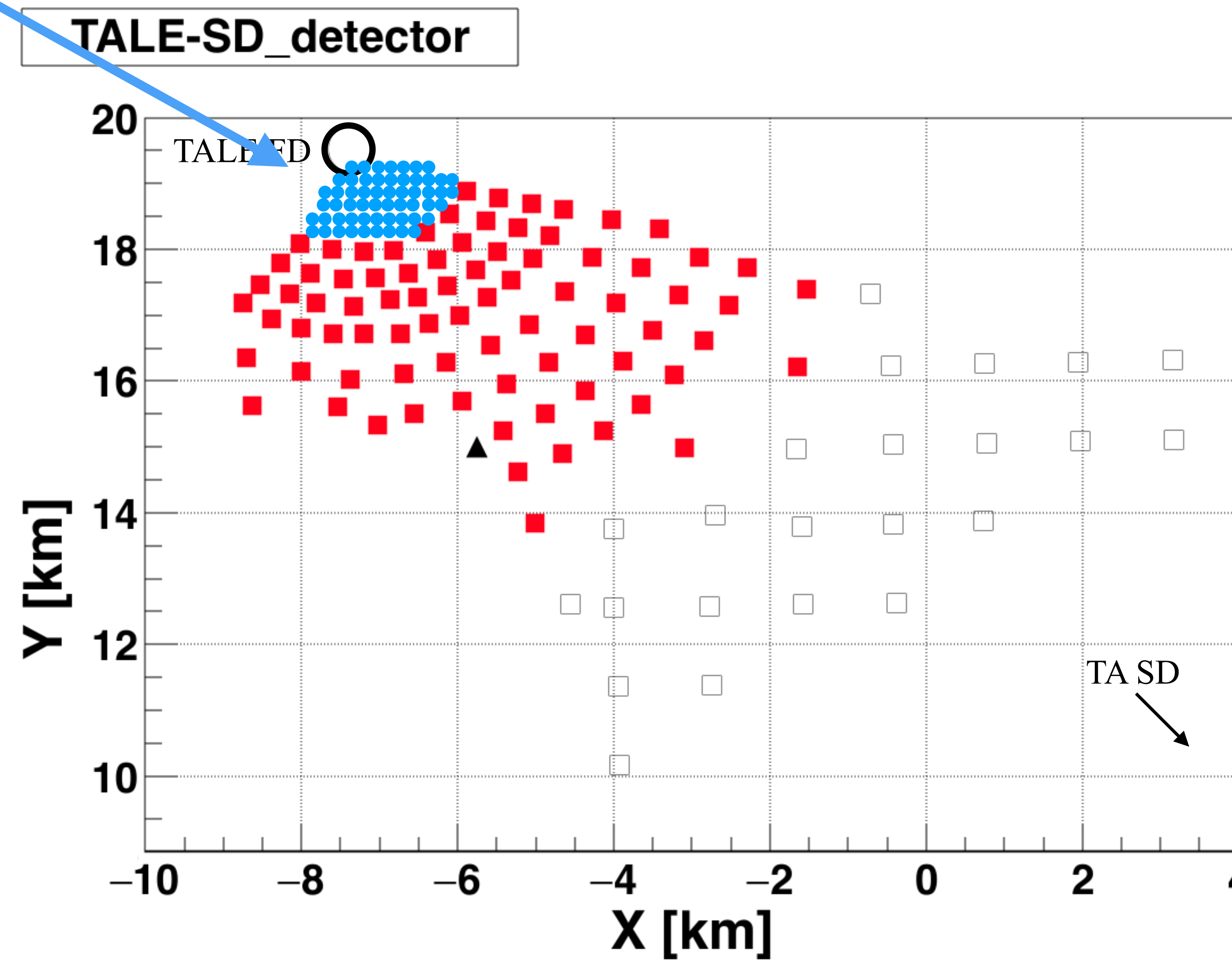
TALE future plan: lower energy



Additionally install **57 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



TA×4

SD array ~3000 km²

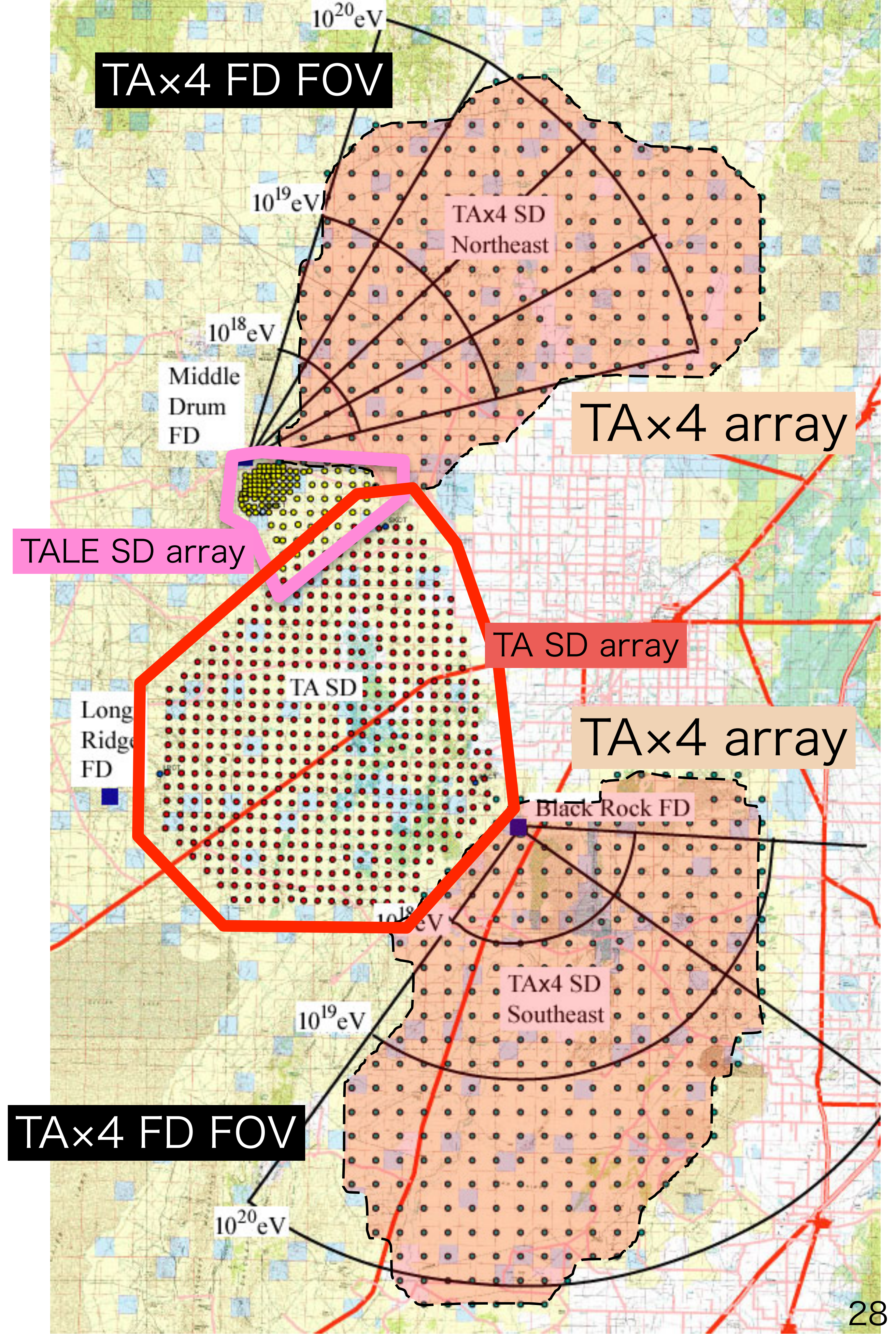
500 scintillator SDs

2.08 km spacing

2 FD stations (12 HiRes-II telescopes)

4 FDs at the northern station

8 FDs at the southern station

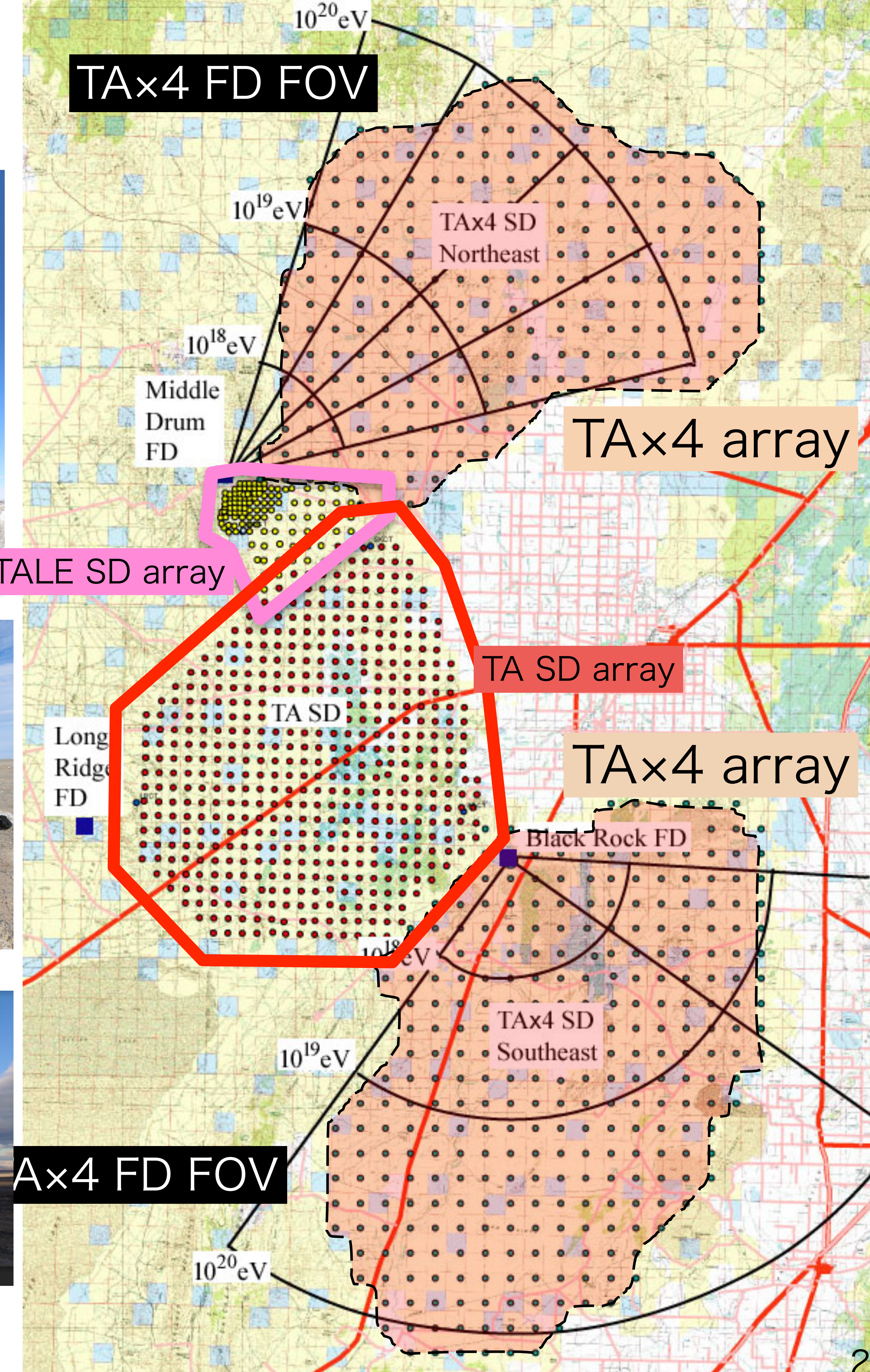


TA×4

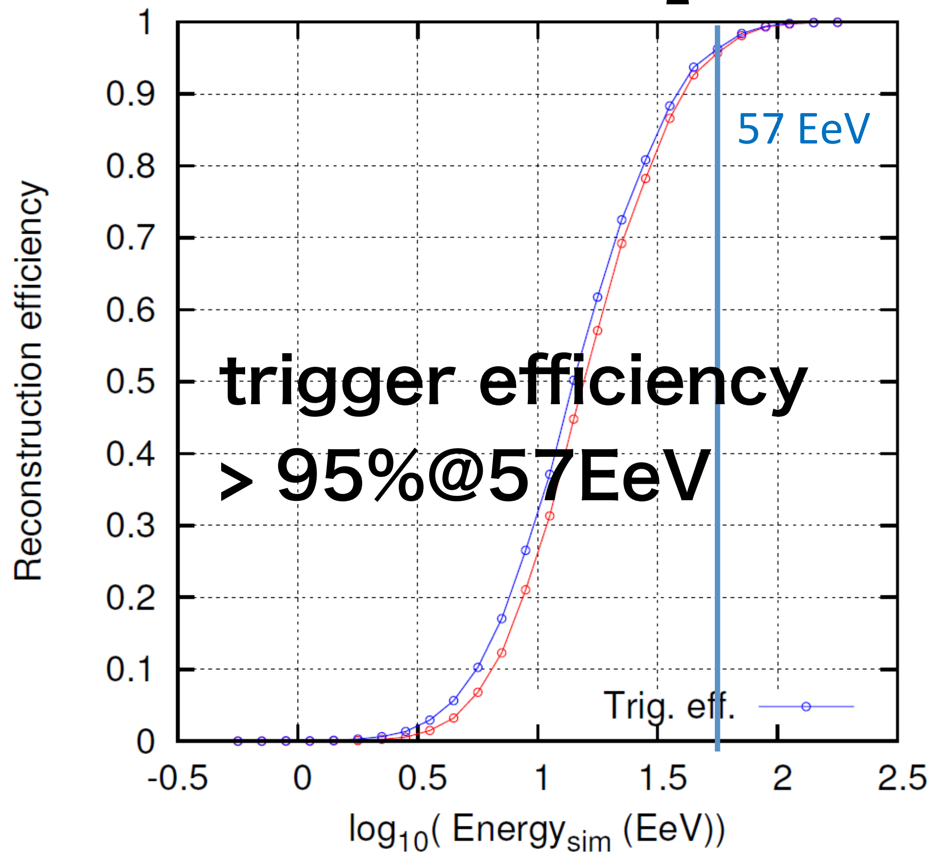
Feb. 19 - Mar. 12, 2019

257 SDs
6 communication towers

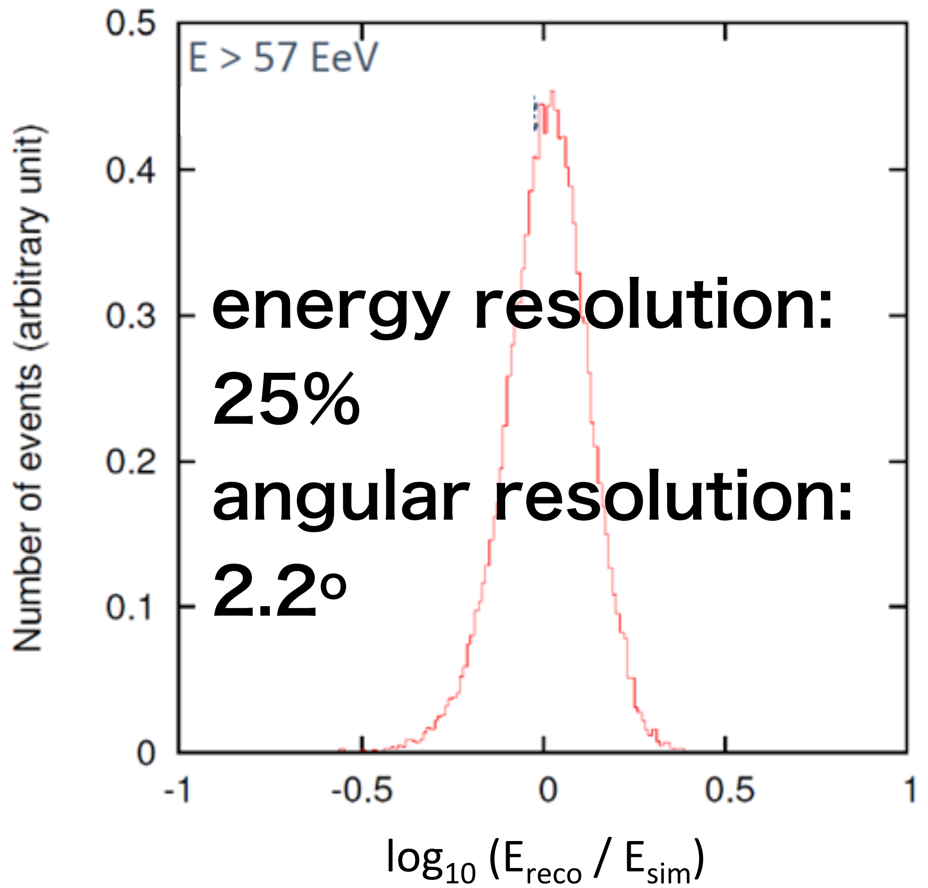
were installed in the site



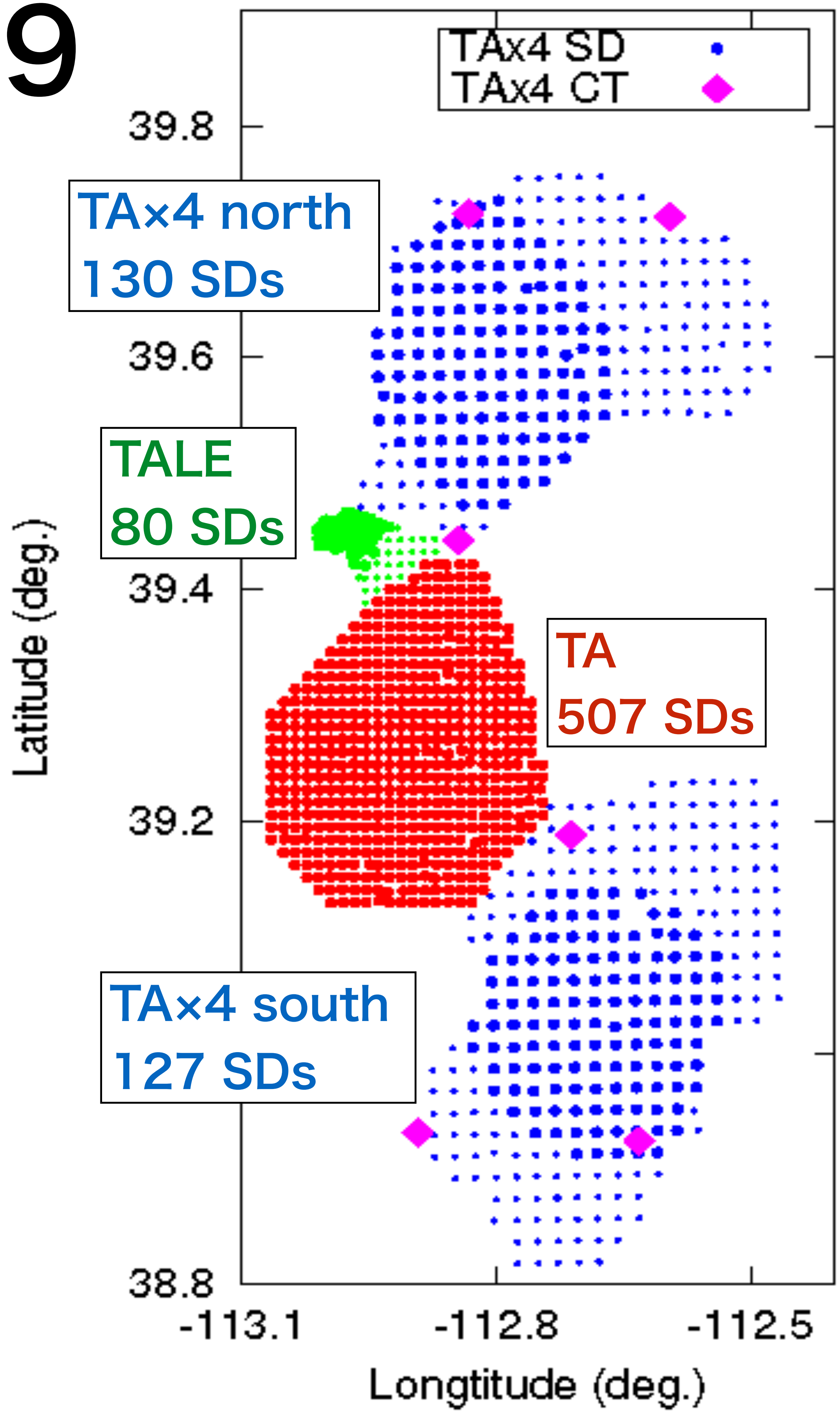
TA×4@Apr. 2019



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



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



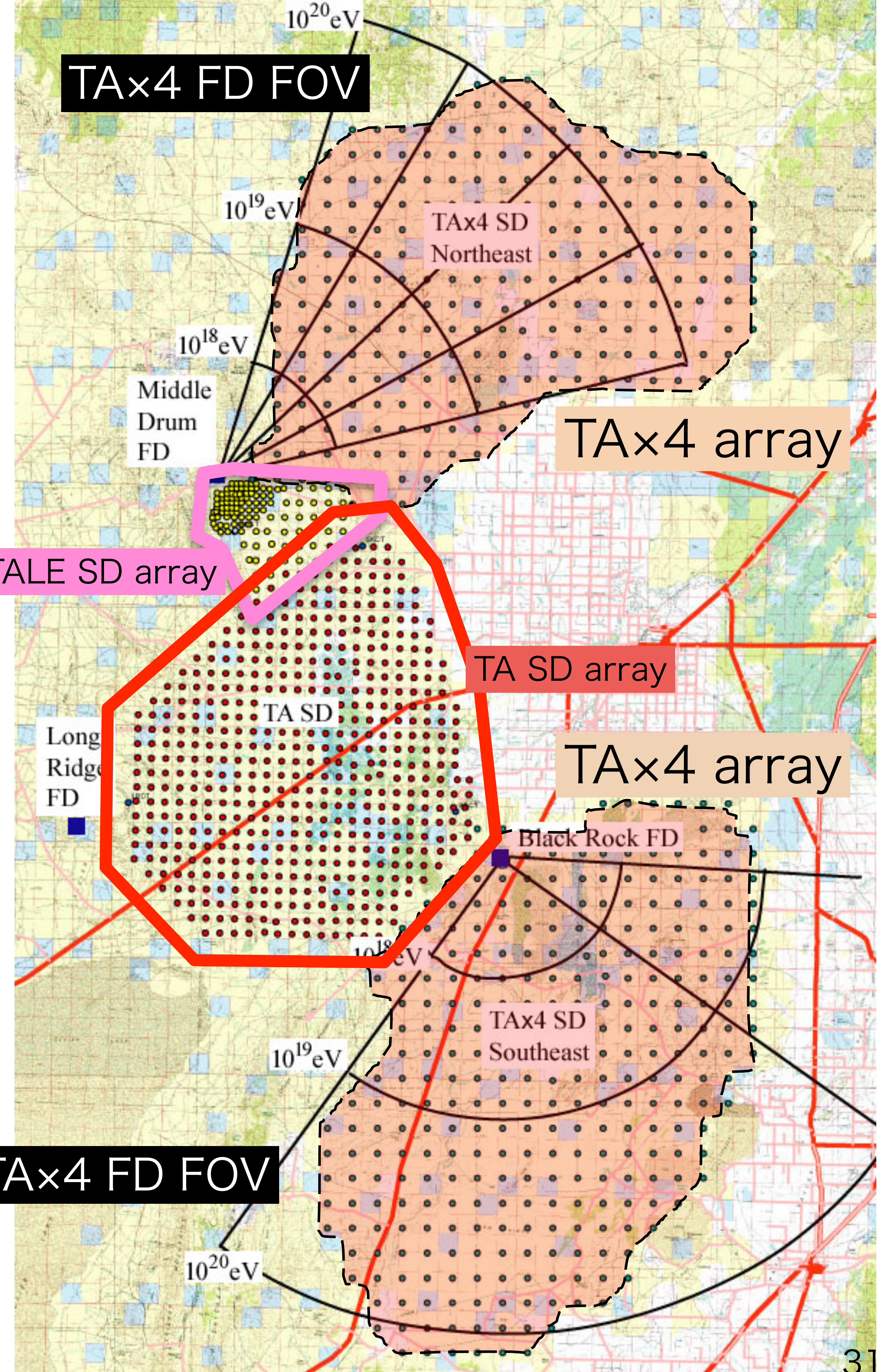
TAx4 SD
TAx4 CT
TA×4 north
130 SDs
TALE
80 SDs
TA
507 SDs
TA×4 south
127 SDs
Latitude (deg.)
Longtitude (deg.)

TA×4

TA×4 northern FD station

First light @ Feb. 16, 2018

TA×4 southern FD station



Summary

- Telescope Array is UHECR observatory in the northern hemisphere.
- TA is stably running more than 10 years.
- Full TALE SD is now on-line!
    - Hybrid measurement has extended the energy reach below ~10^{16} eV
- TAx4 starts running.