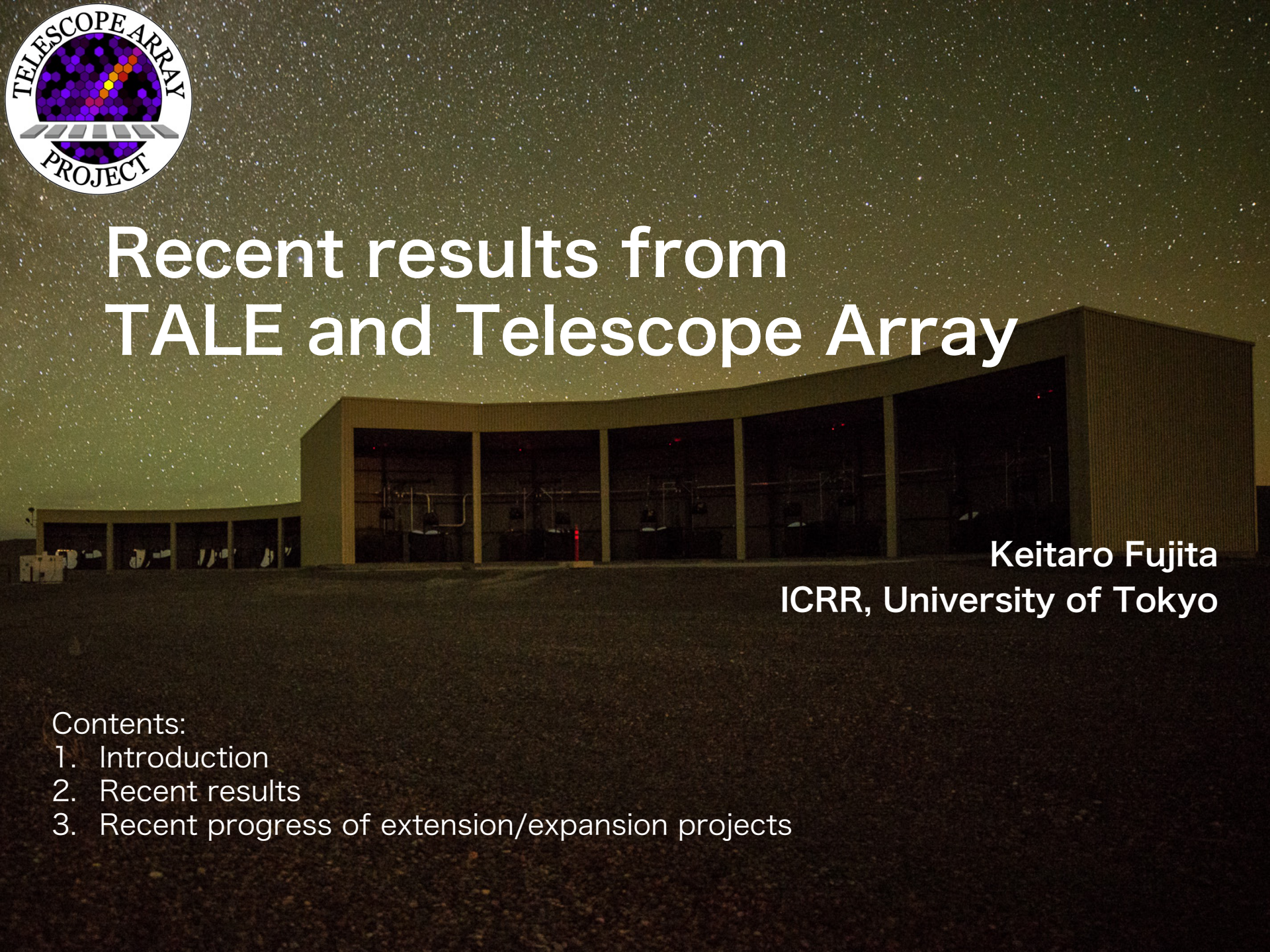

Recent results from TALE and Telescope Array

Keitaro Fujita
ICRR, University of Tokyo

Contents:
1. Introduction
2. Recent results
3. Recent progress of extension/expansion projects

Telescope Array:
Largest cosmic ray observatory in northern hemisphere with Hybrid Detectors

Telescope Array collaboration

140 collaborators from 32 institutions in 7 countries

R.U. Abbasi[1], T. Abu-Zayyad[1,2], M. Allen[2], Y. Arai[3], R. Arimura[3], E. Barcikowski[2], J.W. Belz[2], D.R. Bergman[2], S.A. Blake[2], I. Buckland[2], B.G. Cheon[4], M. Chikawa[5], T. Fujii[6], K. Fujisue[5], K. Fujita[3], R. Fujiwara[3], M. Fukushima[5], G. Furlich[2], N. Globus[7*], R. Gonzalez[2], W. Hanlon[2], N. Hayashida[8], H. He[7], K. Hibino[8], R. Higuchi[5], K. Honda[9], D. Ikeda[8], N. Inoue[10], T. Ishii[9], H. Ito[7], D. Ivanov[2], H. Iwakura[11], A. Iwasaki[3], H.M. Jeong[12], S. Jeong[12], C.C.H. Jui[2], K. Kadota[13], F. Kakimoto[8], O. Kalashev[14], K. Kasahara[15], S. Kasami[16], S. Kawakami[3], K. Kawata[5], I. Kharuk[14], E. Kido[7], H.B. Kim[4], J.H. Kim[2†], J.H. Kim[2], S.W. Kim[12], Y. Kimura[3], I. Komae[3], Y. Kubota[11], V. Kuzmin[14‡], M. Kuznetsov[14,17], Y.J. Kwon[18], K.H. Lee[12], B. Lubsandorzhiev[14], J.P. Lundquist[2,19], H. Matsumiya[3], T. Matsuyama[3], J.N. Matthews[2], R. Mayta[3], I. Myers[2], S. Nagataki[7], K. Nakai[3], R. Nakamura[11], T. Nakamura[20], T. Nakamura[11], Y. Nakamura[11], A. Nakazawa[11], E. Nishio[16], T. Nonaka[5], H. Oda[3], S. Ogio[5], M. Ohnishi[5], H. Ohoka[5], Y. Oku[16], T. Okuda[21], Y. Omura[3], M. Ono[7], A. Oshima[22], S. Ozawa[23], I.H. Park[12], M. Potts[2§], M.S. Pshirkov[14,24], J. Remington[2], D.C. Rodriguez[2], C. Rott[2,12], G.I. Rubtsov[14], D. Ryu[25], H. Sagawa[5], N. Sakaki[5], T. Sako[5], N. Sakurai[3], K. Sato[3], T. Seki[11], K. Sekino[5], P.D. Shah[2], Y. Shibasaki[11], N. Shibata[16], T. Shibata[5], J. Shikita[3], H. Shimodaira[5], B.K. Shin[25], H.S. Shin[5], D. Shinto[16], J.D. Smith[2], P. Sokolsky[2], B.T. Stokes[2], T.A. Stroman[2], K. Takahashi[5], M. Takamura[26], M. Takeda[5], R. Takeishi[5], A. Taketa[27], M. Takita[5], Y. Tameda[16], K. Tanaka[28], M. Tanaka[29], Y. Tanoue[3], S.B. Thomas[2], G.B. Thomson[2], P. Tinyakov[14,17], I. Tkachev[14], H. Tokuno[30], T. Tomida[11], S. Troitsky[14], R. Tsuda[3], Y. Tsunesada[3,31], S. Udo[8], T. Uehama[11], F. Urban[32], D. Warren[7], T. Wong[2], M. Yamamoto[11], K. Yamazaki[22], K. Yashiro[26], F. Yoshida[16], Y. Zhezher[5,14], and Z. Zundel[2]

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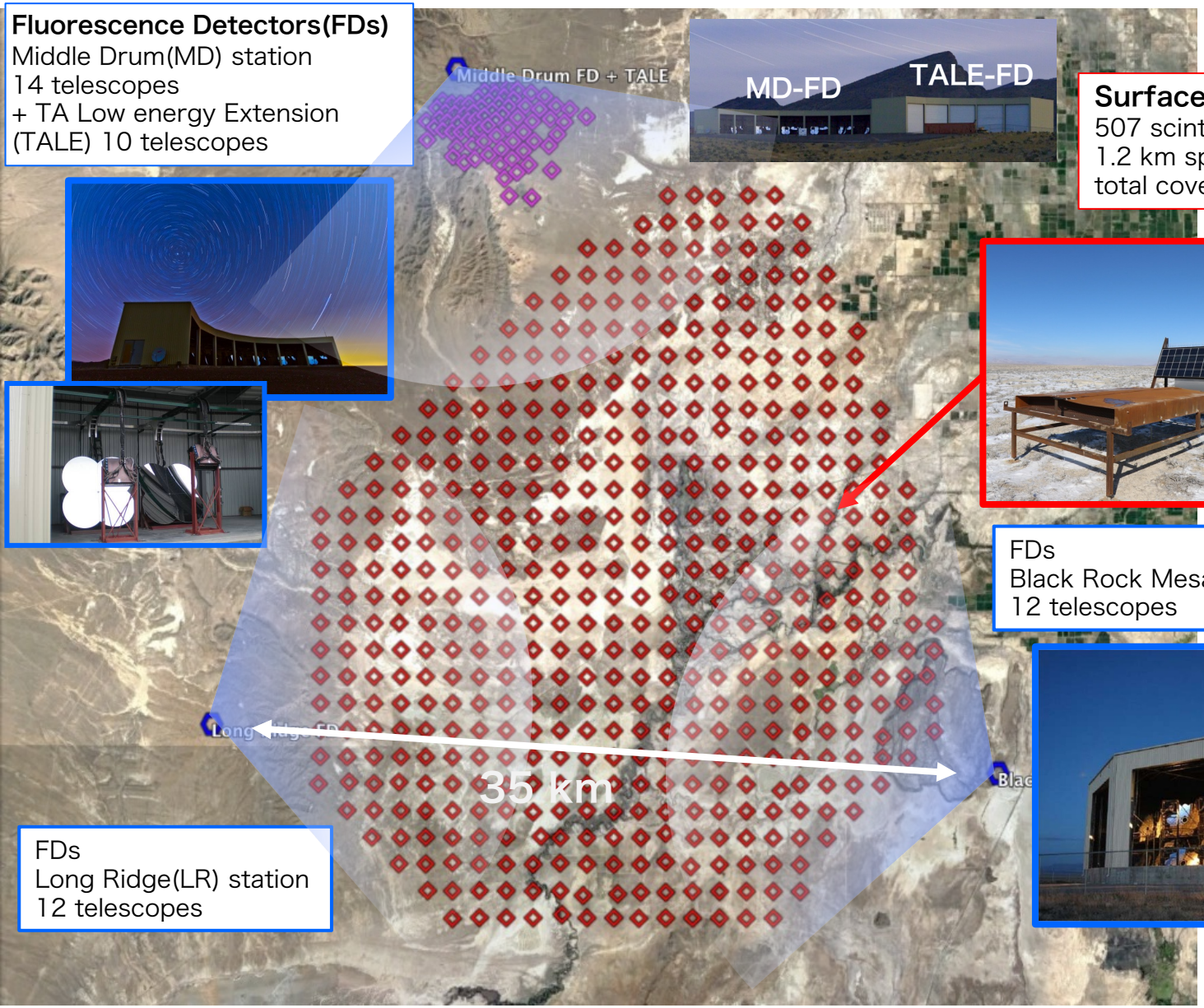
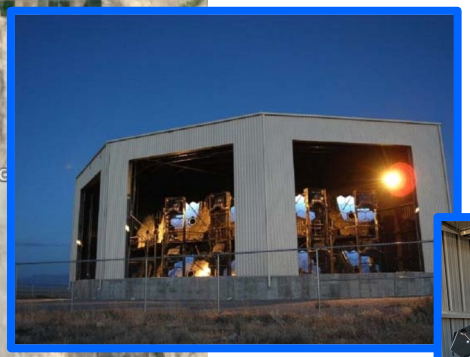
Telescope Array Detectors

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



Surface Detector(SD) array
507 scintillation detectors, each 3m^2
1.2 km spacing
total coverage ~ 700km^2

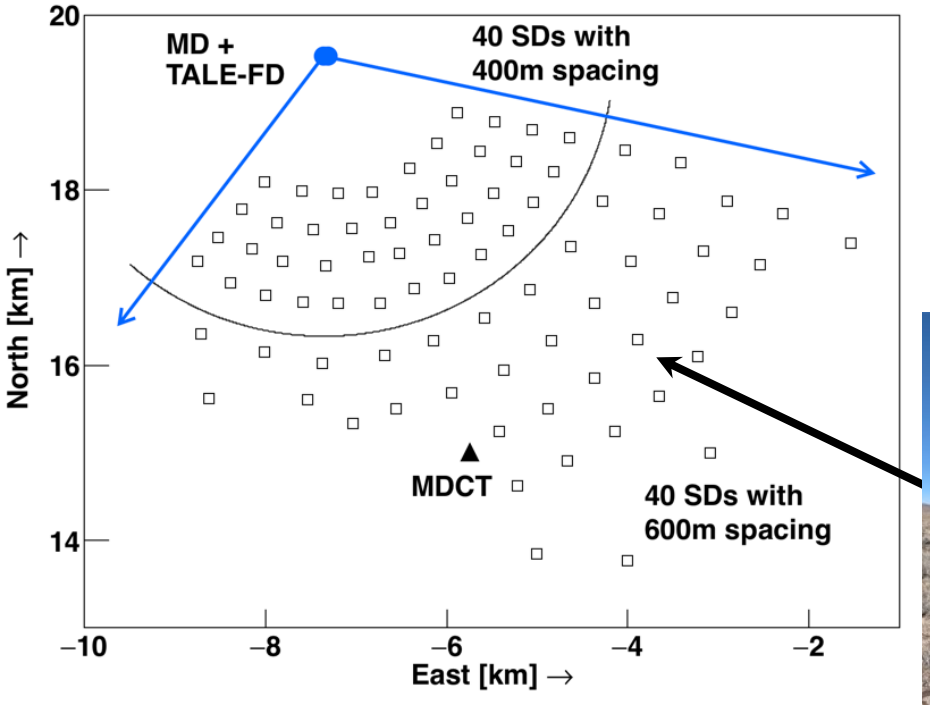
FDs
Black Rock Mesa(BRM) station
12 telescopes



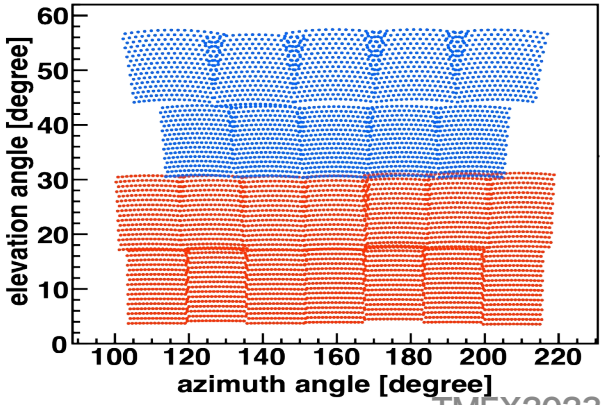
FDs
Long Ridge(LR) station
12 telescopes

TA Low energy Extension(TALE)

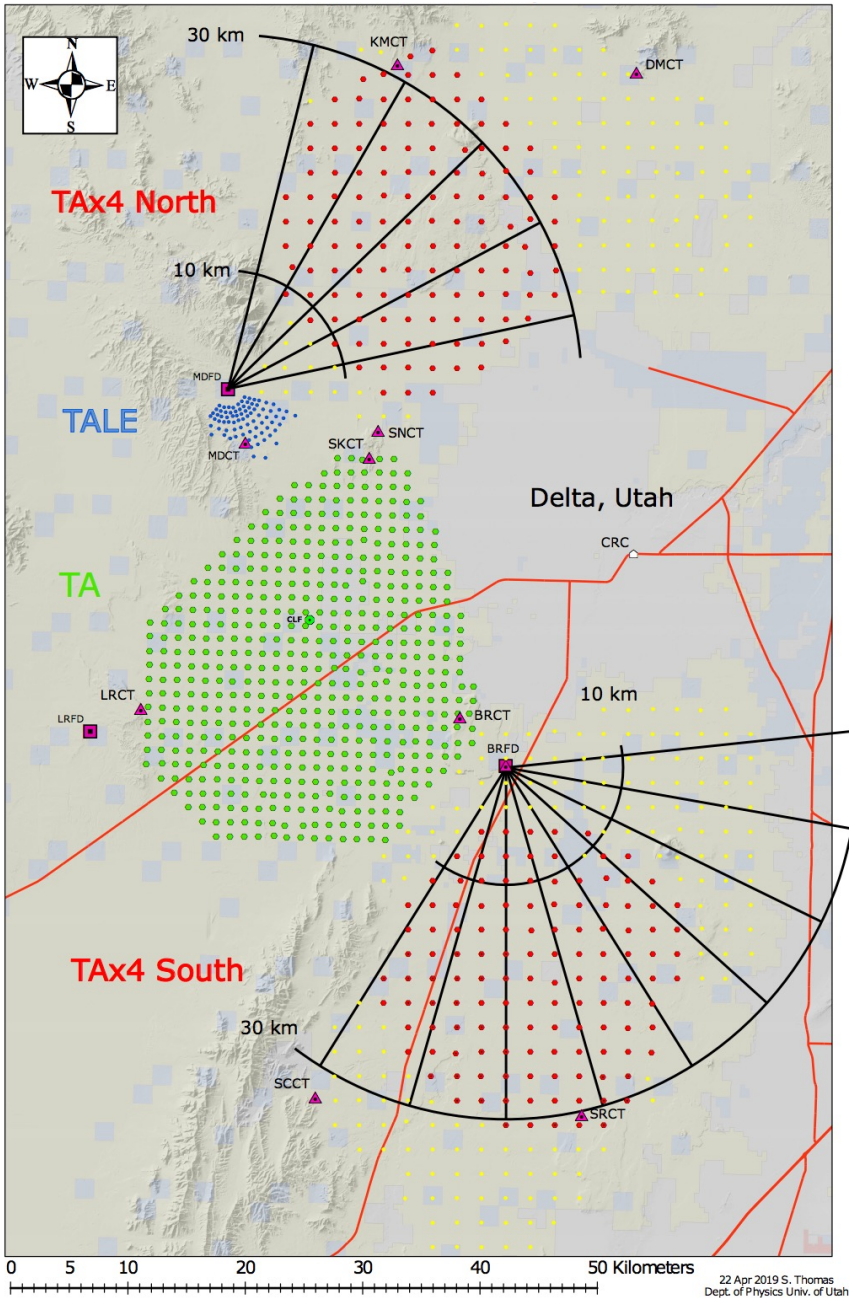
- Low energy CRs-induced shower
  - Not so bright, higher $X_{\max}$ → high elevation telescope
  - compact shower size → dense SD array
- Constructed in north part of TA site
- Same concept as TA detector
  - 10 Fluorescence Telescopes
  - 80 Surface Detectors, 20 km²
- Low energy target: E > 10^{16} eV
- Operation: FD since Sep. 2013
  SD since Nov. 2017



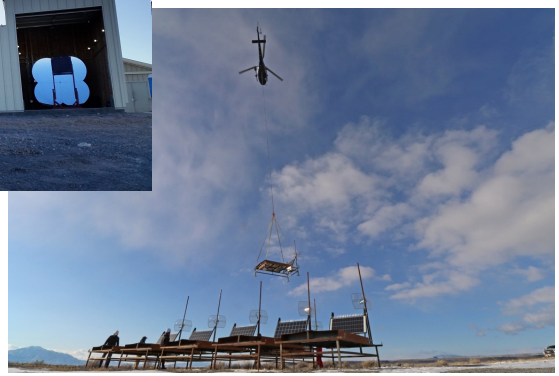
TA/TALE FD FoV



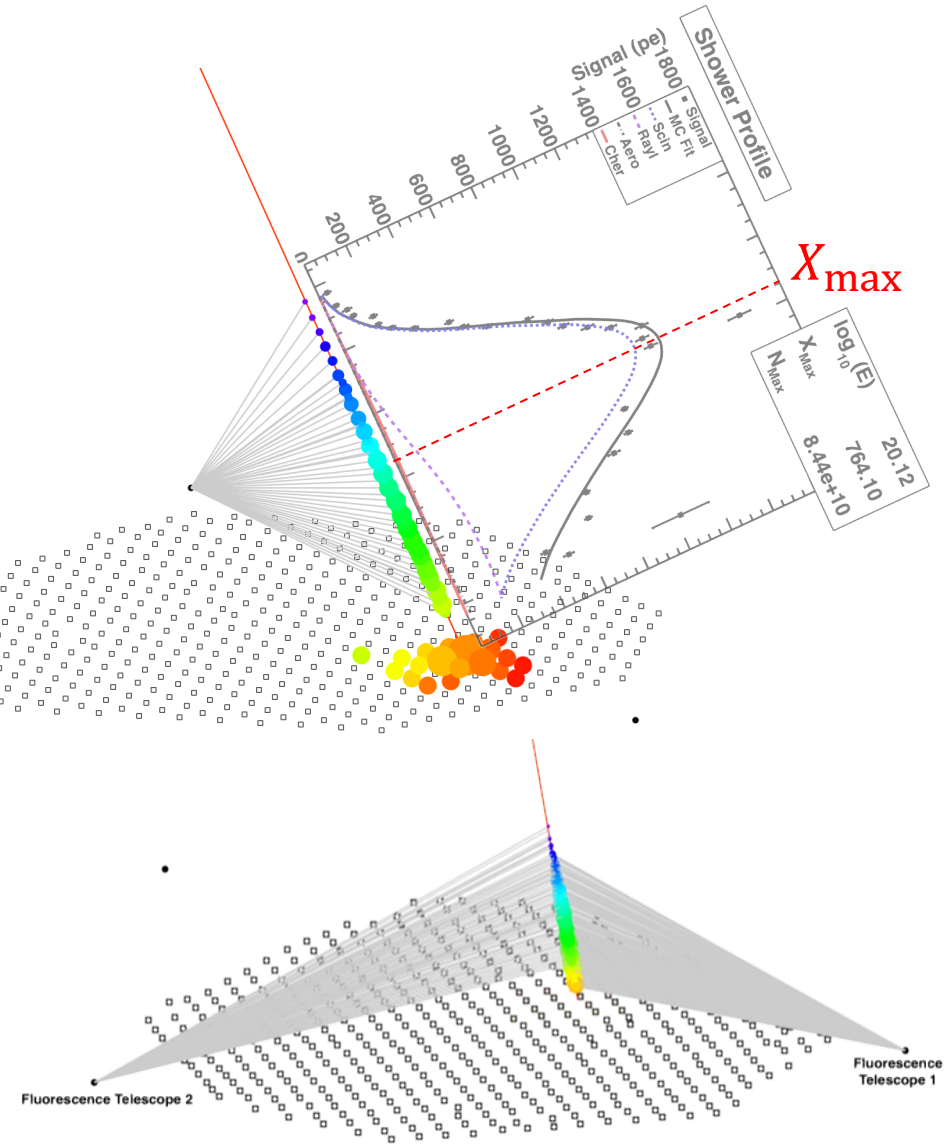
TAx4 Detectors



- Focus on highest energies
  - $E > 10^{19.5}$ eV
- New Northern and Southern SD array
  - expand TA SD area by factor 4 ~3000 km^2
  - 2.08 km spacing (TA: 1.2km)
- New 4 + 8 FDs
- In operation both detectors
  - over 3 yrs data taking



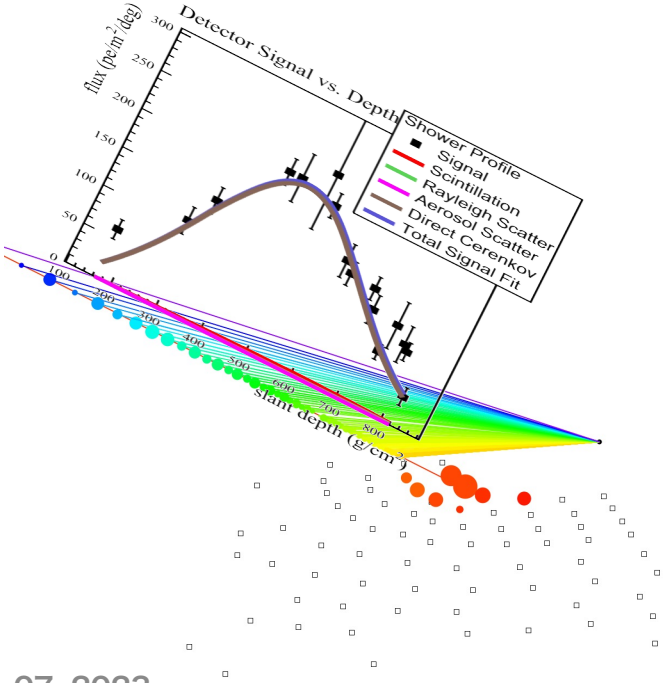
Event Reconstruction, Hybrid/Stereo



- time vs. angle fit to obtain shower geometry
  - in hybrid: add SD info.
    → most precise shower geometry
- stereo case: 2FDs observe same shower
  → intersect shower image
- shower profile reconstruction using signal intensities
- Integral of $\boldsymbol{dE/dX}$ to obtain energy
  - $E \propto \int_0^\infty \frac{dE}{dX} dX$
- Achieve ~8% E resolution

Event Reconstruction, FD
Low energy event

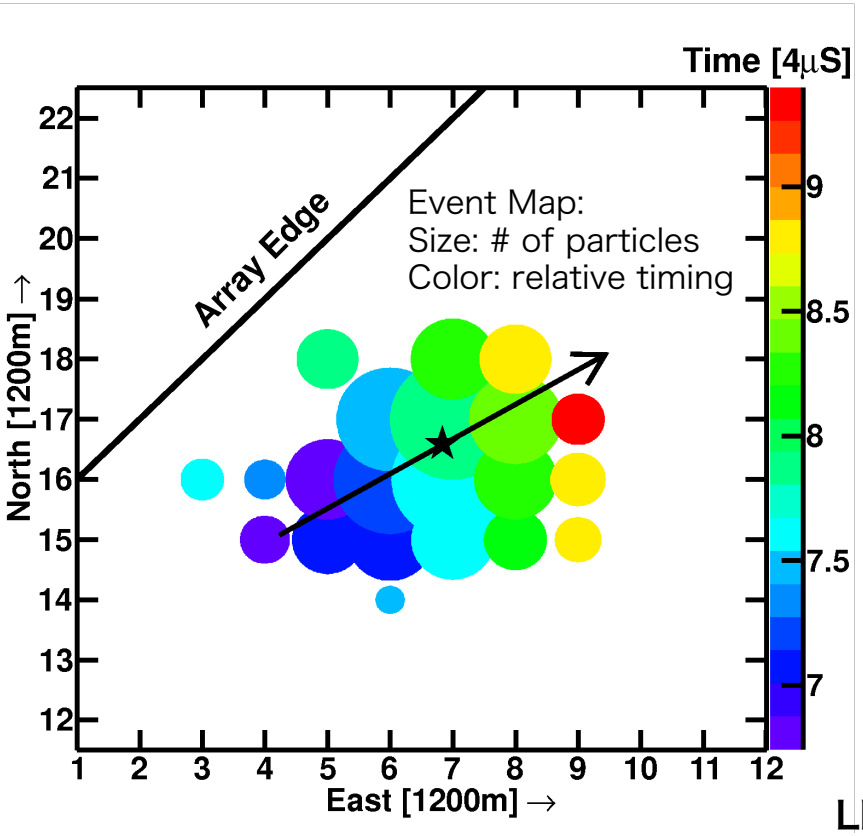
- detect Cherenkov light like IACT
  → achieve low energy threshold
- simultaneous reconstruction for shower geometry and shower profile
  - constrained shower geometry by shower profile because of Cherenkov light directivity

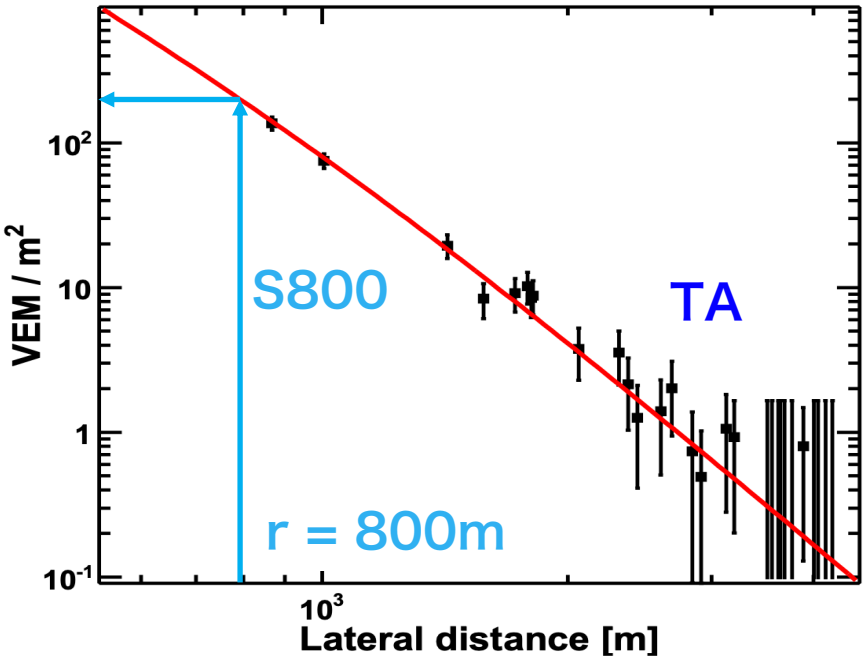


- Integral of dE/dX to obtain energy
  - $E \propto \int_0^\infty \frac{dE}{dX} dX$
  - same way as high energies
- Achieve ~1° angular resolution
  ~10% E resolution @10PeV

Event Reconstruction, SD

- Measured footprint
- Arrival direction reconstructed using relative timing differences
- LDF fit has done to obtain energy estimator

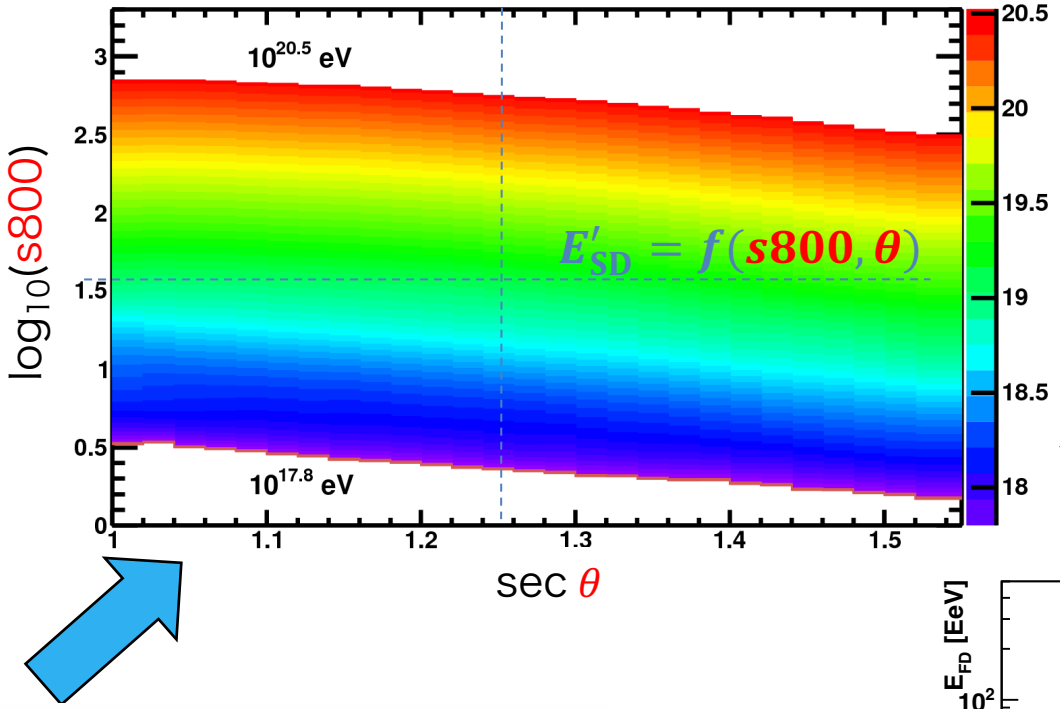




LDF: $S(r) = A\left(\frac{r}{91.6\text{m}}\right)^{-1.2}\left(1+\frac{r}{91.6\text{m}}\right)^{-\{\eta(\theta)-1.2\}}\left(1+\left[\frac{r}{1000\text{m}}\right]^2\right)^{-0.6}$

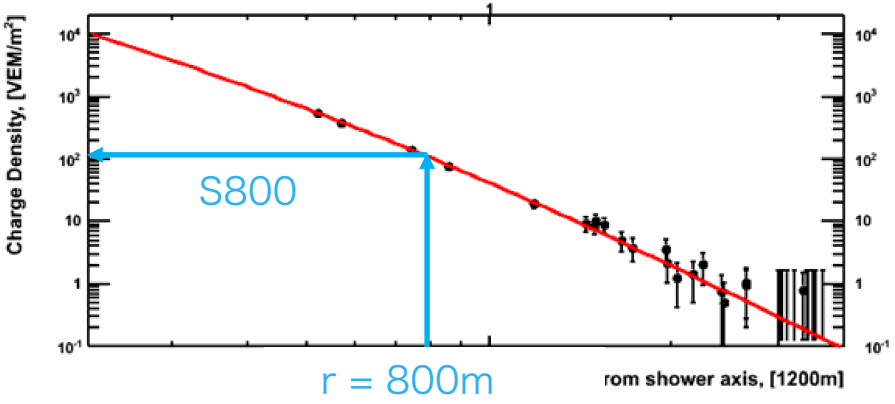
Primary Energy determination, SD

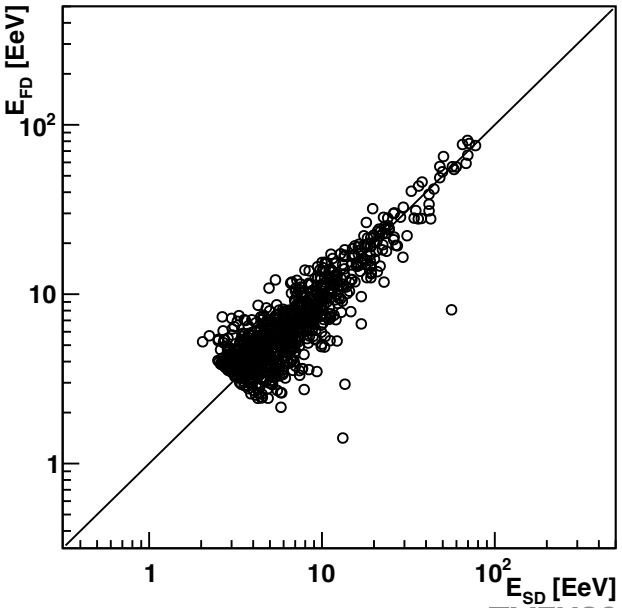
→ Energy look-up table (S800, θ)



Scale to FD(Hybrid) energy

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

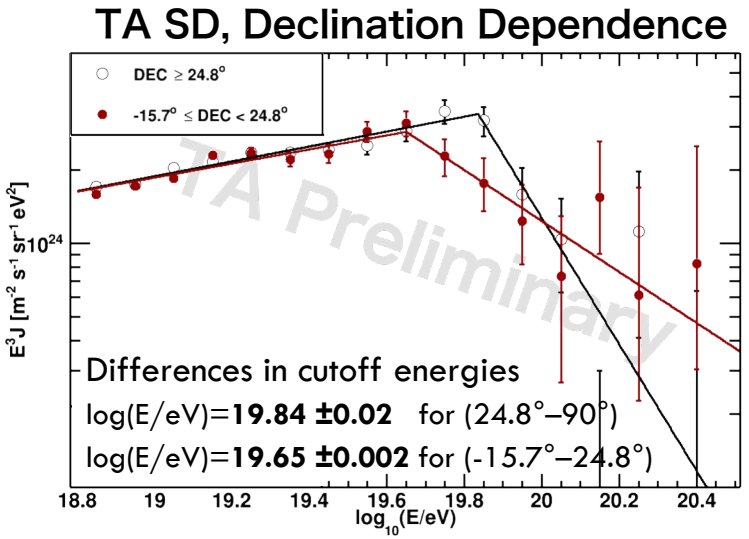


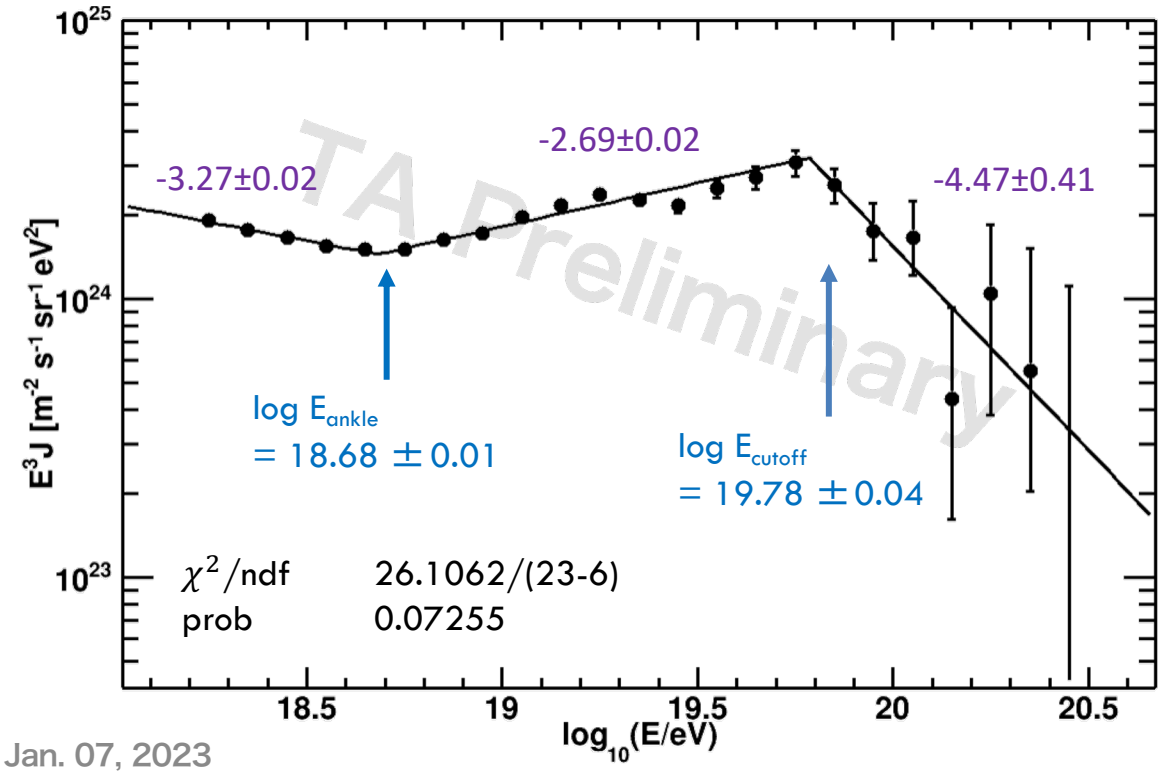


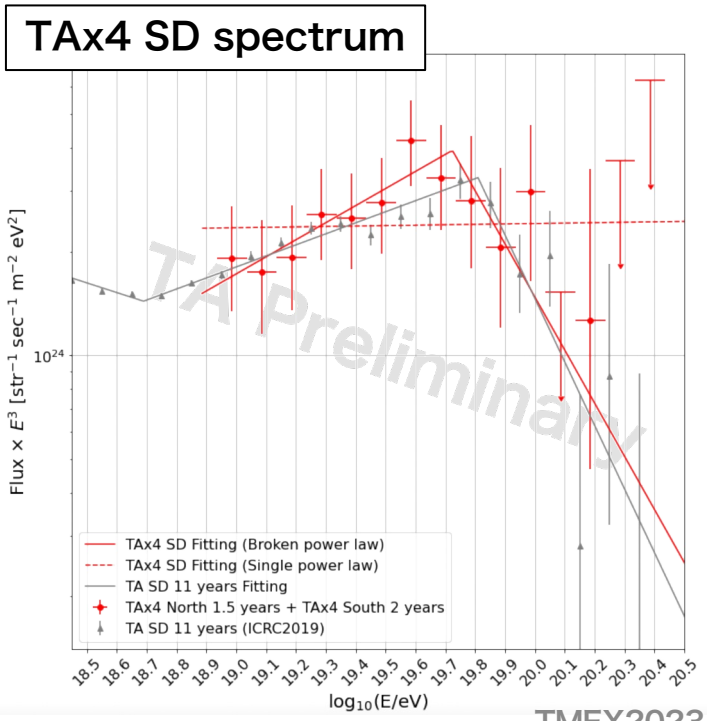
Energy Spectrum

Energy Spectrum in UHE

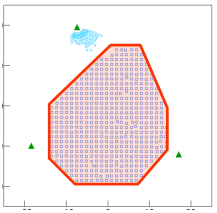
- Energy spectrum ($E > 10^{18}$eV)
  - 14 yrs TA SD
    - declination dependence
  - 2yrs TAx4 SD ($E > 10^{19}$eV)







New feature in energy spectrum

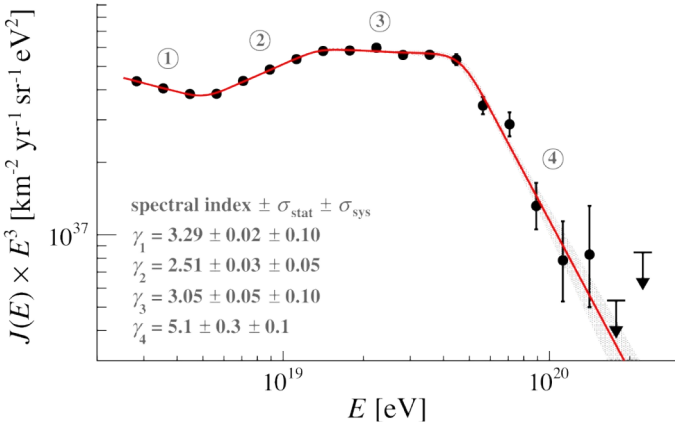


Pierre Auger found a spectrum hardening in 10^{19} – $10^{19.5}$ eV range

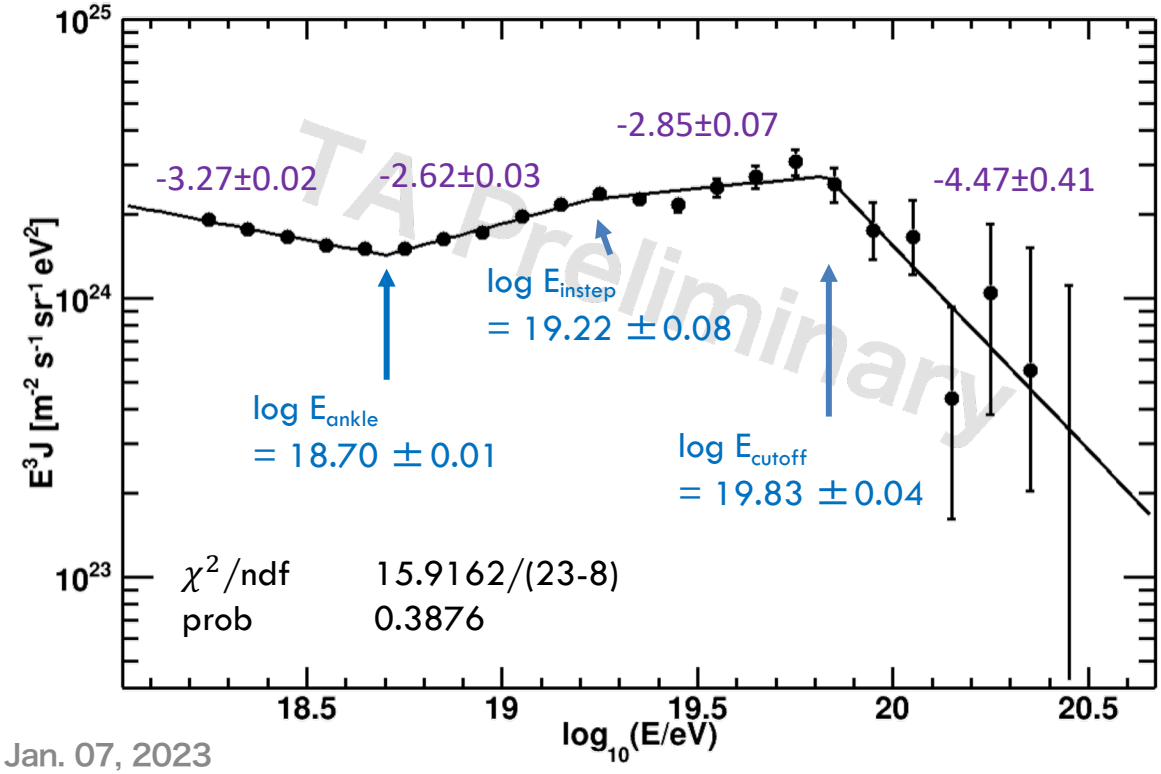
- 2-step softening after the ankle

Two-step softening exists in TA SD spectrum

- 4.0σ deficit above $10^{19.22}$ eV from an assumption of no breaks before the high-energy steepening

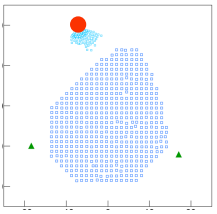


A. Aab et al. (The Pierre Auger Collaboration) Phys. Rev. Lett. 125, 121106 (2020)

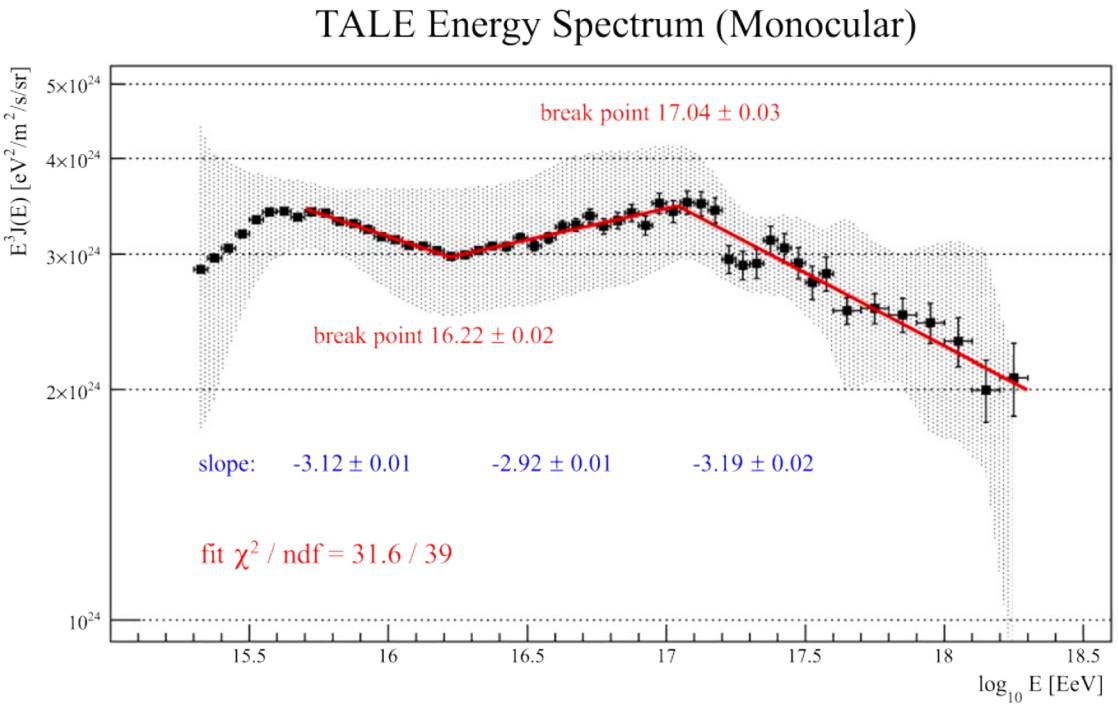


	Auger	TA
γ_1	-3.29 ± 0.02	-3.23 ± 0.02
γ_2	-2.51 ± 0.03	-2.63 ± 0.03
γ_3	-3.05 ± 0.05	-2.85 ± 0.07
γ_4	-5.1 ± 0.3	-4.47 ± 0.41
E_{ankle} / EeV	5.0 ± 0.1	5.0 ± 0.1
E_{instep} / EeV	13 ± 1	17 ± 3
E_{cutoff} / EeV	46 ± 3	68 ± 7

Energy Spectrum in lower energy



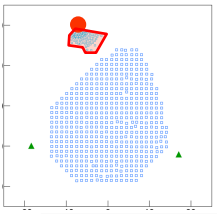
- TALE FD monocular mode measurement
  - Cherenkov dominated spectrum



Energy	Source	Value	Contribution to Flux
$<10^{17}$ eV	photonic scale	10%	20%
$<10^{17}$ eV	missing energy	10%	20%
$<10^{17}$ eV	atmosphere	0	0
$<10^{17}$ eV	Cherenkov model	5%	10%
$<10^{17}$ eV	fluorescence yield	0	0
$<10^{17}$ eV	composition (X_{max})	3%	6%
10^{18} eV	photonic scale	10%	20%
10^{18} eV	missing energy	5%	10%
10^{18} eV	atmosphere	2%	4%
10^{18} eV	Cherenkov model	0	0
10^{18} eV	fluorescence yield	10%	20%
10^{18} eV	composition (X_{max})	3%	6%
$<10^{17}$ eV	total	15%	31%
10^{18} eV	total	15%	31%

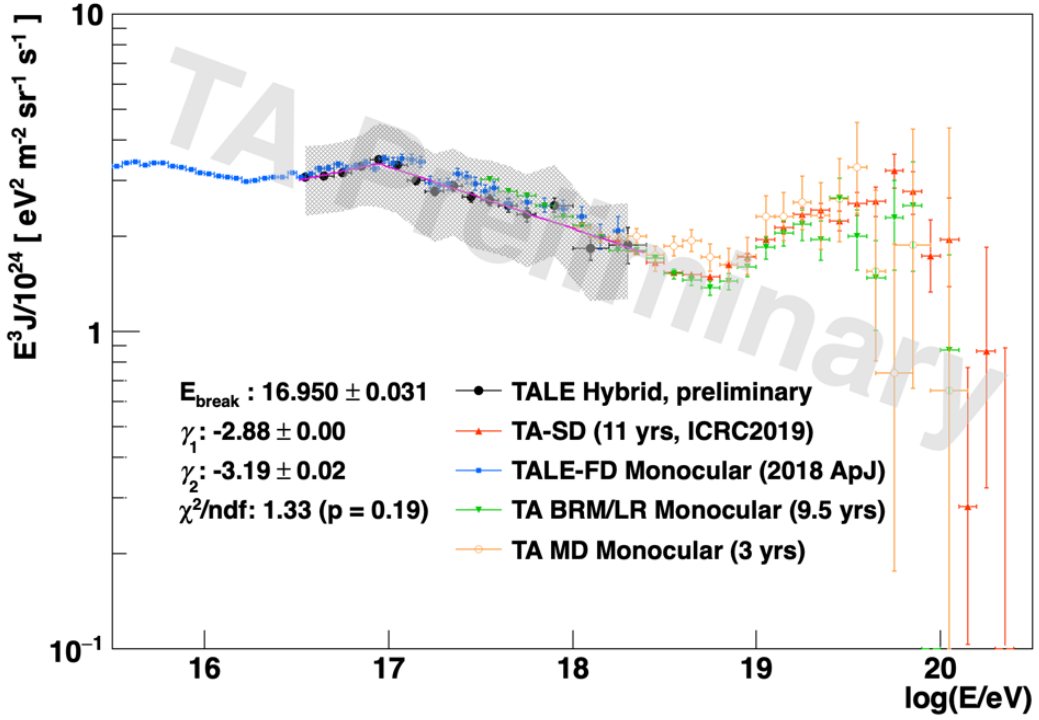
Down to 2 PeV with FD measurement
Energy resolution at 2 PeV : 20%
at 6 PeV : 15%
at 100 PeV: 10%

Energy Spectrum in lower energy



- TALE Hybrid measurement
  - 4yrs data

TALE Hybrid Spectrum with TA spectra



	γ_1	$\log_{10}(E_{break}/eV)$	γ_2
TALE Hybrid	-2.88 ± 0.003	16.95 ± 0.03	-3.19 ± 0.02
TALE Monocular	-2.92 ± 0.01	17.04 ± 0.04	-3.19 ± 0.02
TA SD	-	-	-3.28 ± 0.02
TA BRM / LR FDs	-	-	-3.29 ± 0.01

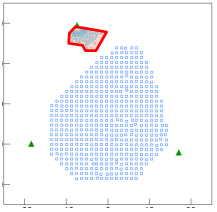
Summary of systematic uncertainties in energy, X_{max}

Sources	Energy
Photonic Scale	10 %
Relative Time of FD and SD	0
Fluorescence yield	3 to 10%
Cherenkov model	5 to 1 %
Atmosphere	$^{+2.7}_{-1.8}$ %
Missing energy	6 %
Total	12.6 to 15.7 %

Down to $10^{16.5}$ eV
with Hybrid measurement
Energy resolution
at $10^{16.5}$ eV: <10%

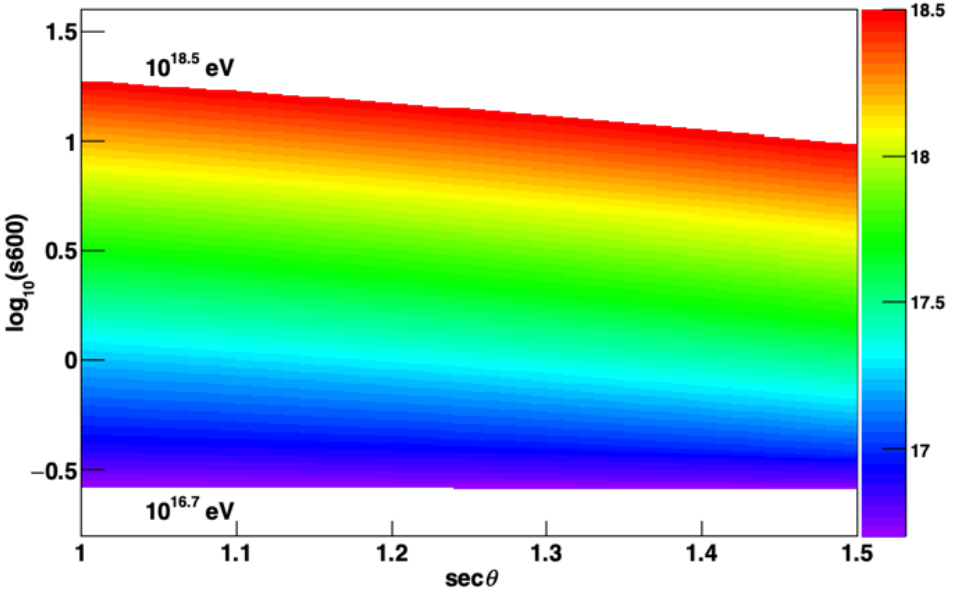
Clearly shows break feature
at 10^{17} eV

Energy Spectrum in lower energy

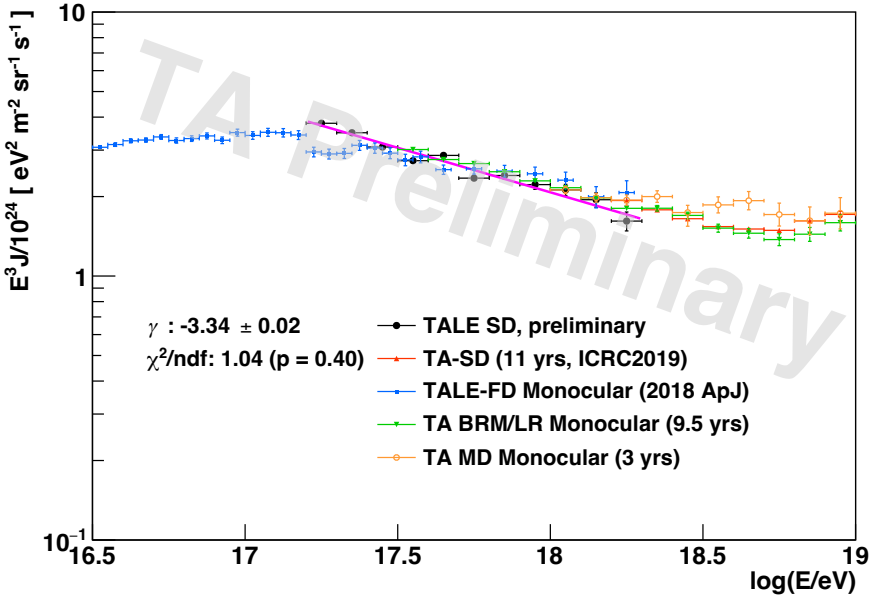


- TALE SD measurement
  - 2.5yrs data

TALE SD energy table



TALE SD Spectrum



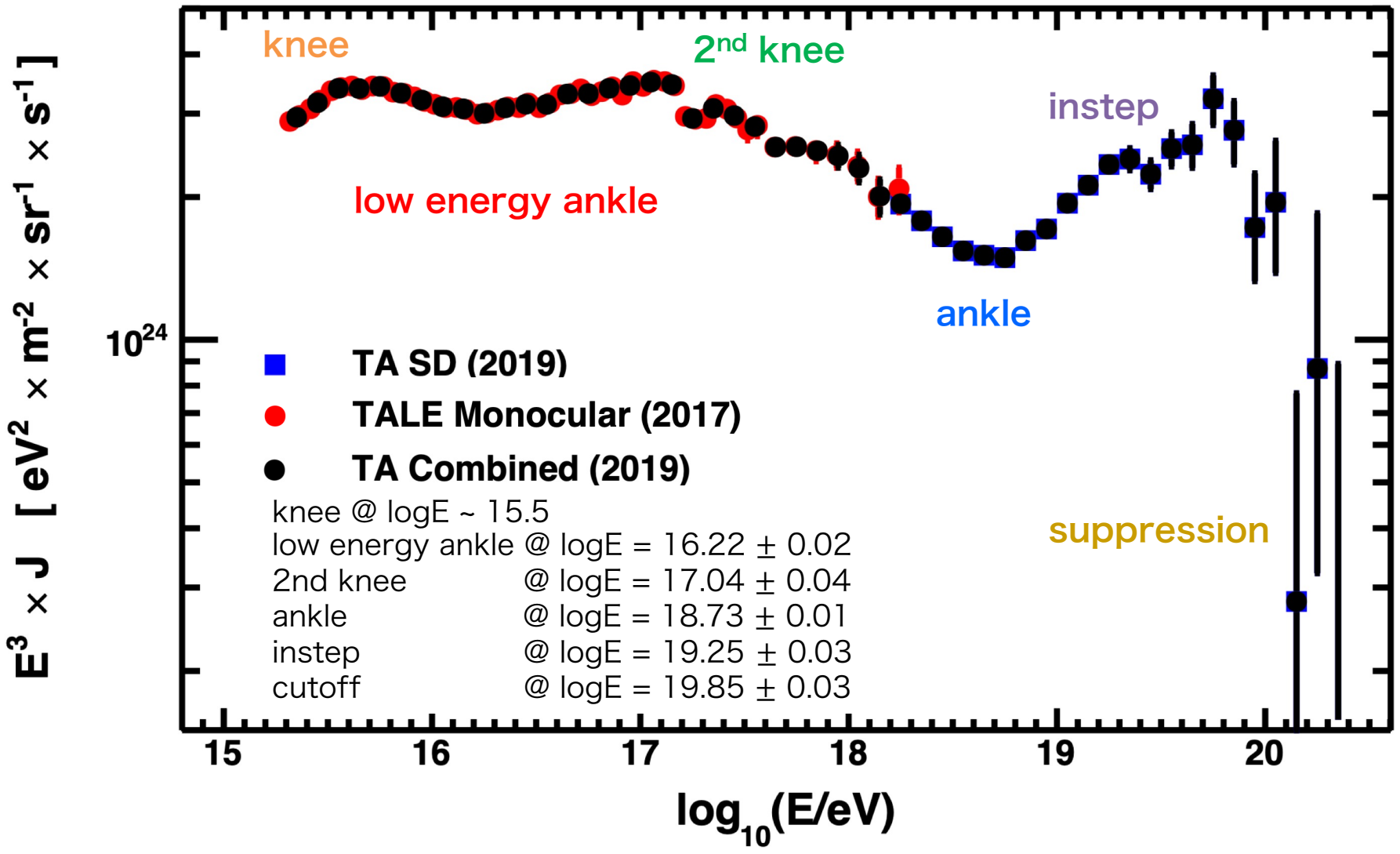
Down to ~10^{17} eV with only SD array
Energy estimator: s600
look up table was made
- same way as TA SD
- reconstructed θ and s600 is used

Finally scaled to FD energy

Energy resolution
E > 10^{17} eV: ~20%

Consistent with TA results

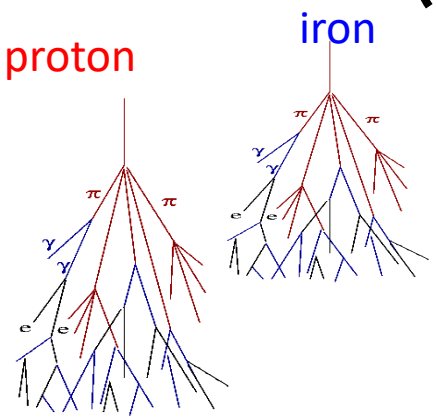
TA energy spectrum
All energy range



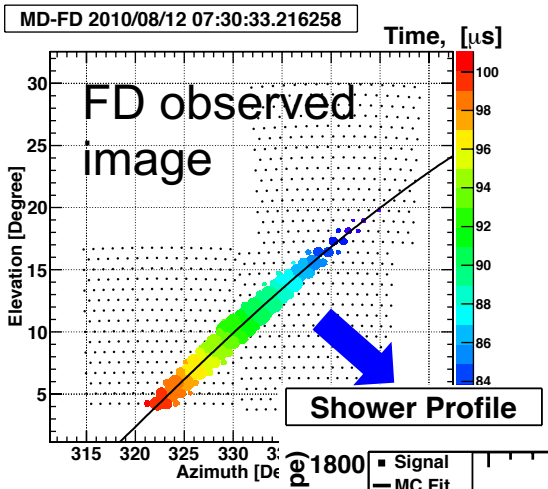
Mass Composition

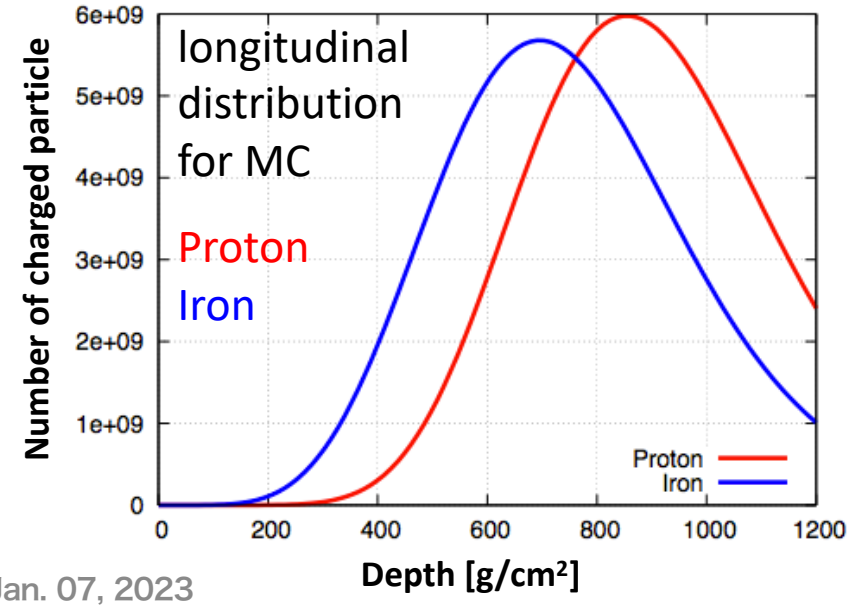
Mass composition analysis

Estimate primary cosmic ray mass composition from the depth of the air shower maximum (X_{max})

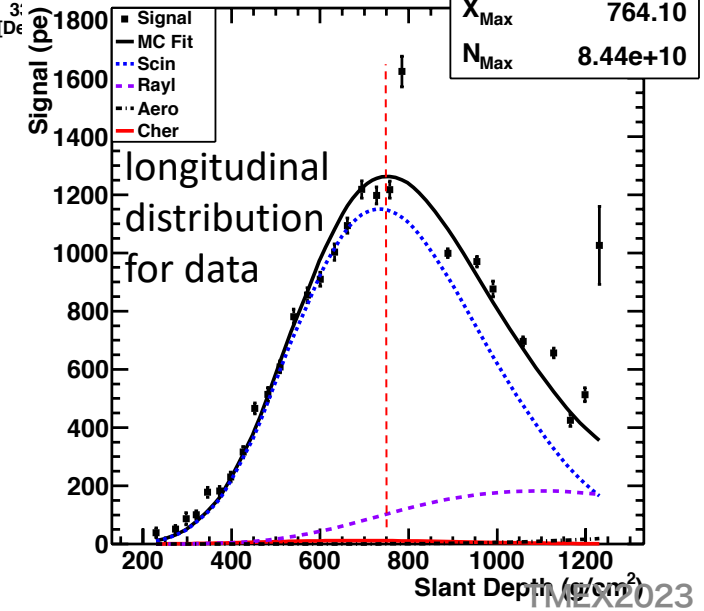


Lighter composition propagates deeper at same energy

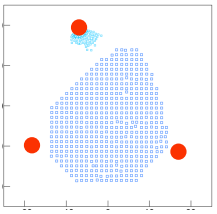


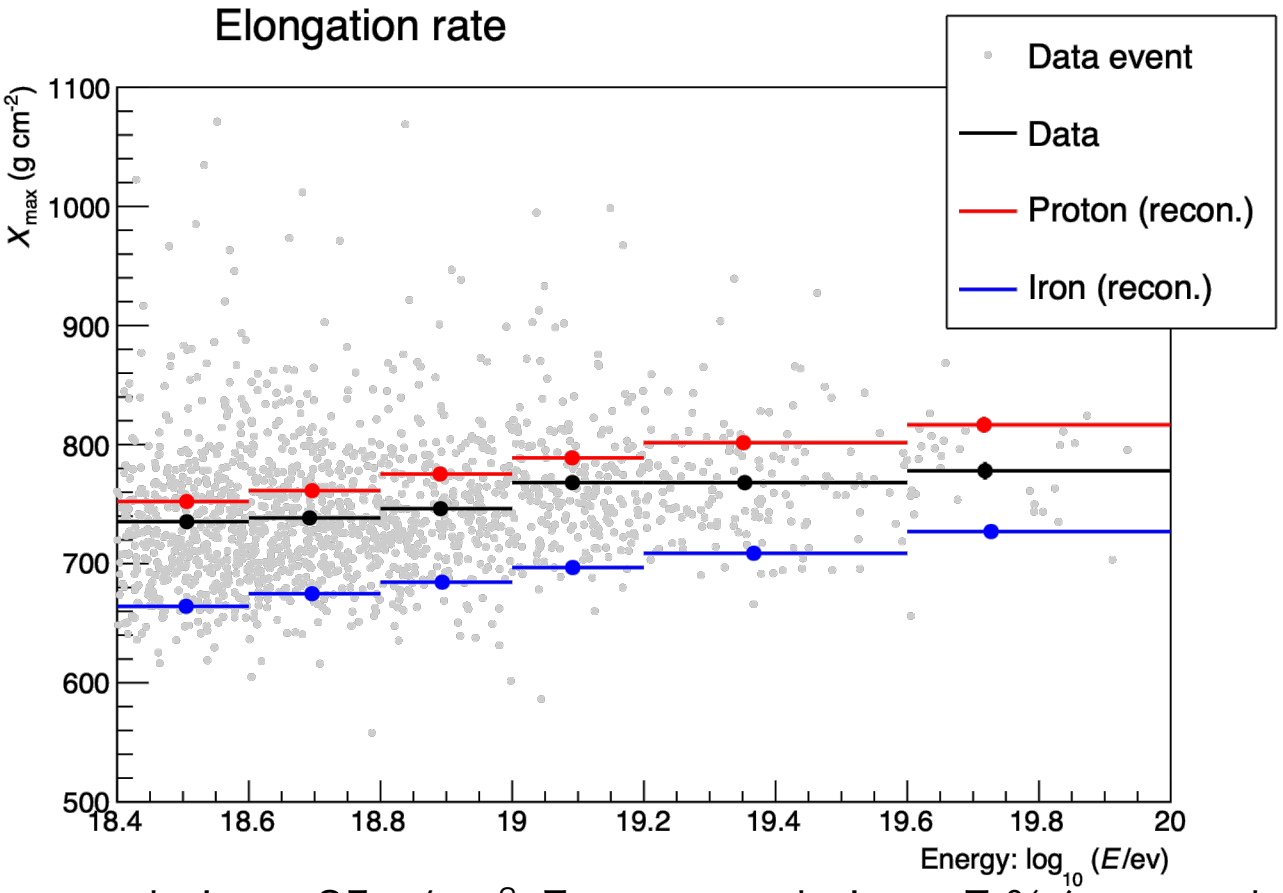


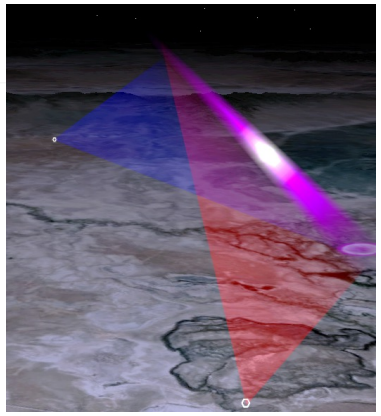
X_{max}



TA Stereo measurement





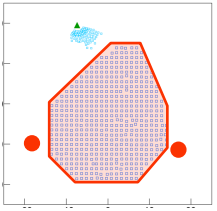


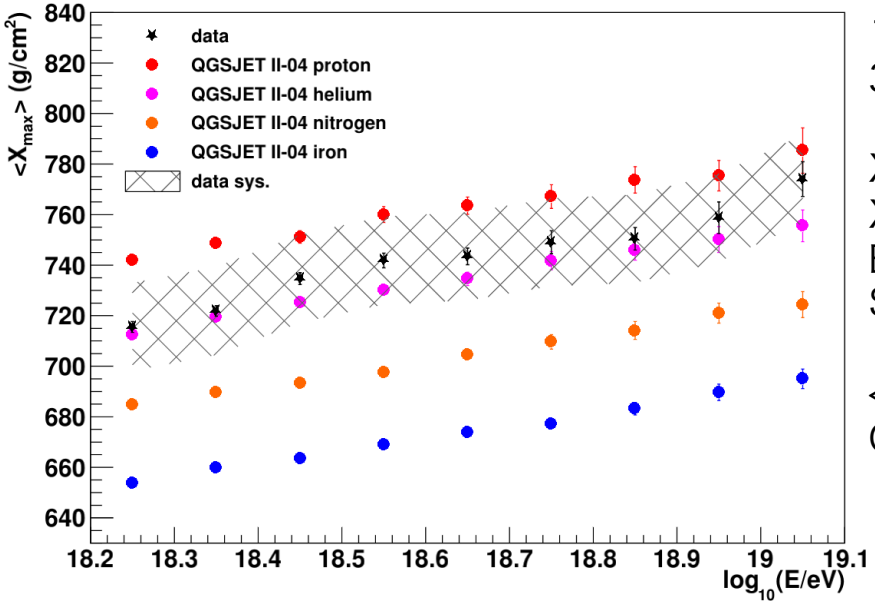
stereo image

Xmax resolution < 25 g/cm^2, Energy resolution < 7 % (energy dependent)
Systematic uncertainty on is 15 g/cm^2
Scatter plot of Xmax vs energy.
Measured data and from QGSJET II-04 MC predictions (proton and iron)
Data support a light component at any energy

Quality cuts: Coincidence FDs within 2 ms, Downward-going, SDP angle < 170^o , track length ≧ 6^o, duration ≧ 2 μs, Xmax in FOV

TA Hybrid measurement

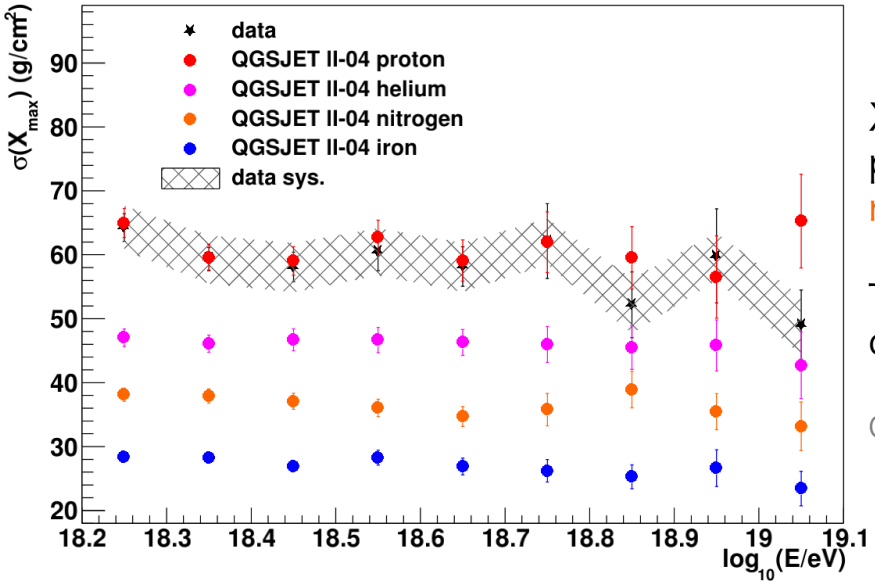




10yrs TA-Hybrid data $10^{18.2}$ to $10^{19.1}$ eV
3560 events after the quality cuts

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

<Xmax> along with predictions of QGSJETII-04 proton, helium, nitrogen, iron

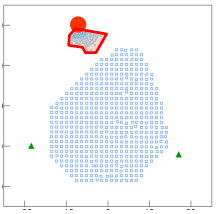


Xmax dist. width(σ_{Xmax}) along with predictions of QGSJETII-04 proton, helium, nitrogen, iron

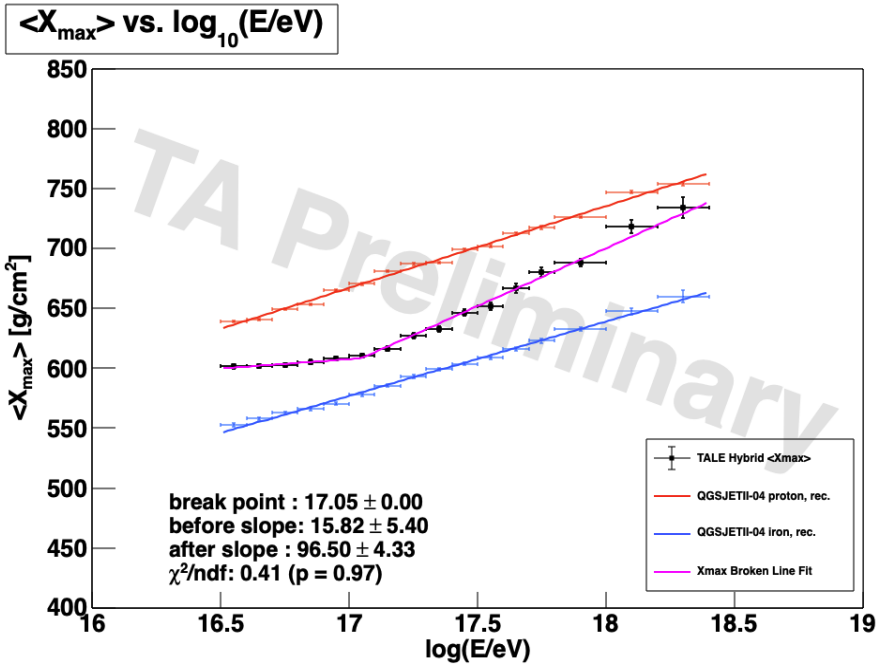
TA data are compatible with the light component below 10^{19} eV

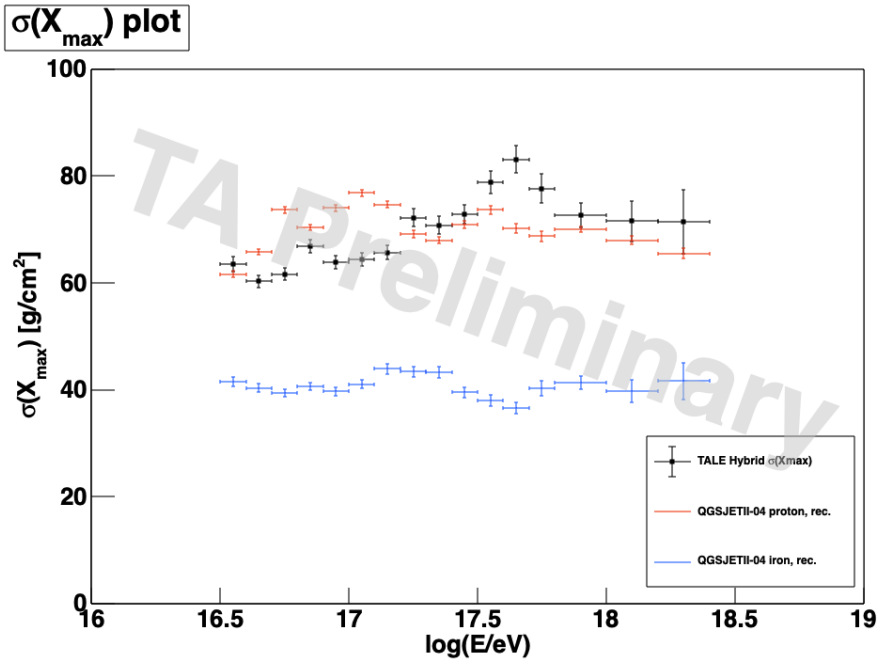
Quality Cuts:
D_{border} > 100m, tracklength > 10^o ,# of PMT > 11
SDP angle < 130^o, duration > 7μs, zenith angle < 55^o
Xmax in F.O.V, good weather

TALE Hybrid X_{max} measurement



- Measured reconstructed $\langle X_{max} \rangle / \sigma(X_{max})$ vs. energy
  - Nov. 2017 - May. 2022 (4 yrs, 1880 hours)





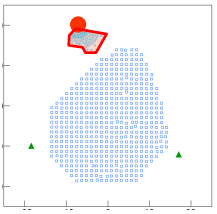
D_{10}^{before} = 16 ± 5 g/cm²/decade
D_{10}^{after} = 97 ± 4 g/cm²/decade
$\log_{10}(E_{break}/eV)$ = 17.1

Suggest light to heavy below 10^{17} eV, then getting lighter above

MC elongation rate [g/cm²/decade]

	proton	iron
D_{10}^{MC}	68 ± 2	62 ± 2

TALE Hybrid X_{max} measurement



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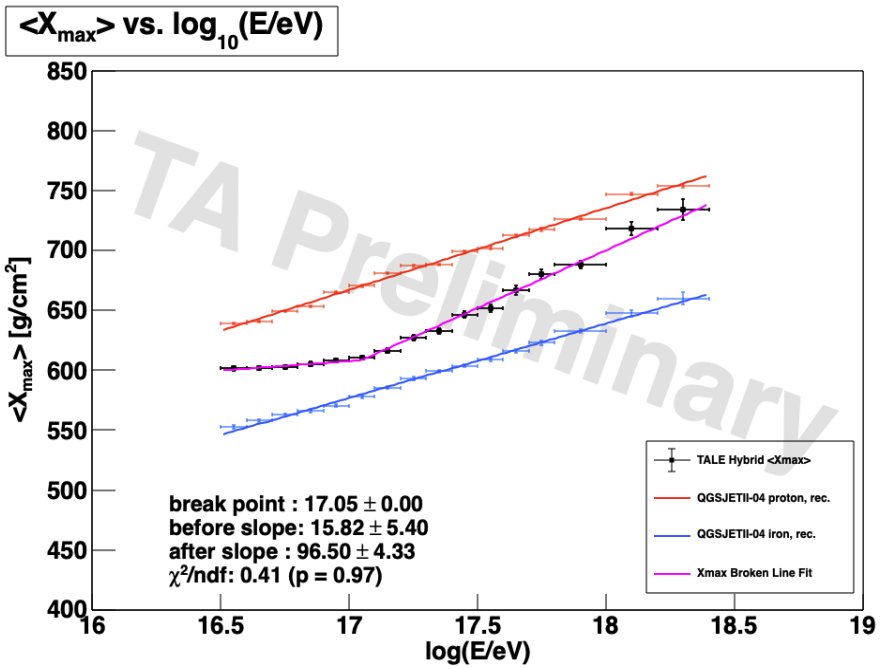

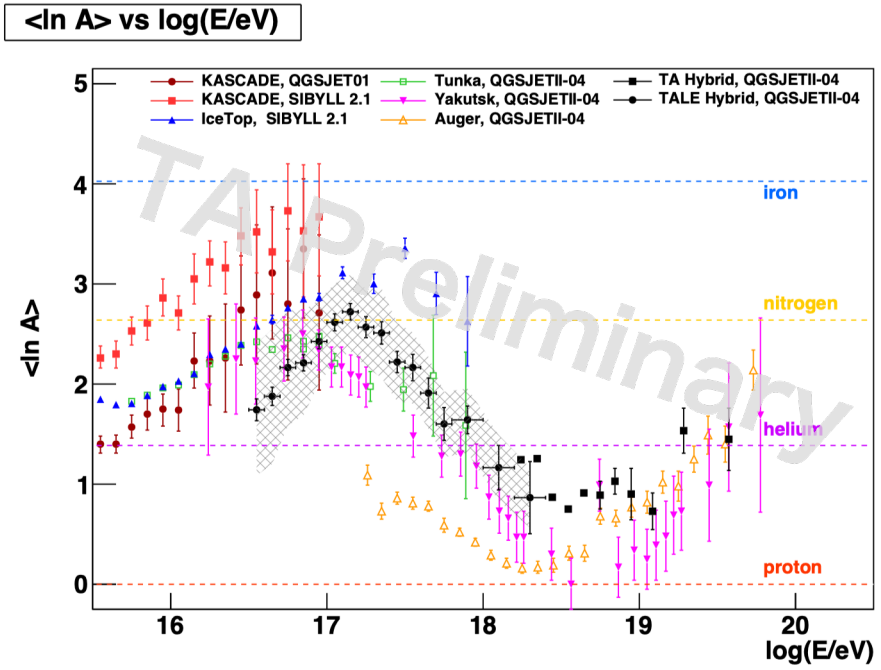

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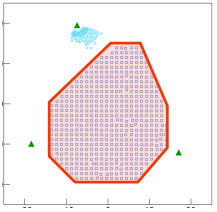
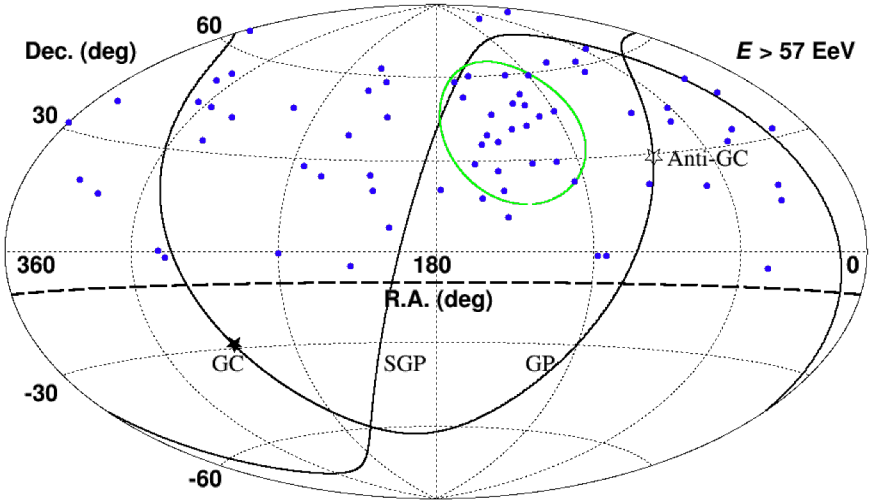
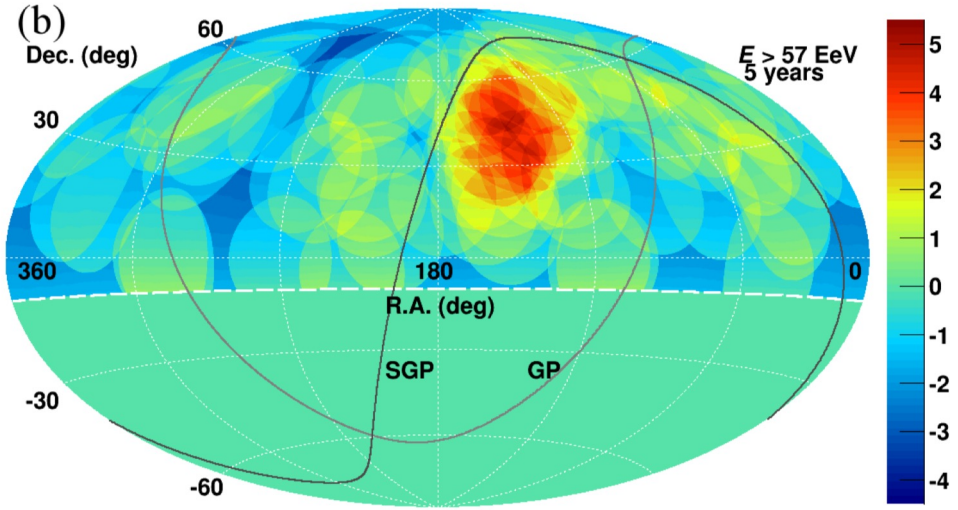
Anisotropy

Anisotropy, in higher energy(E>57EeV)



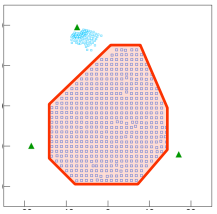
Search for Intermediate-scale anisotropy
in the UHECR arrival directions



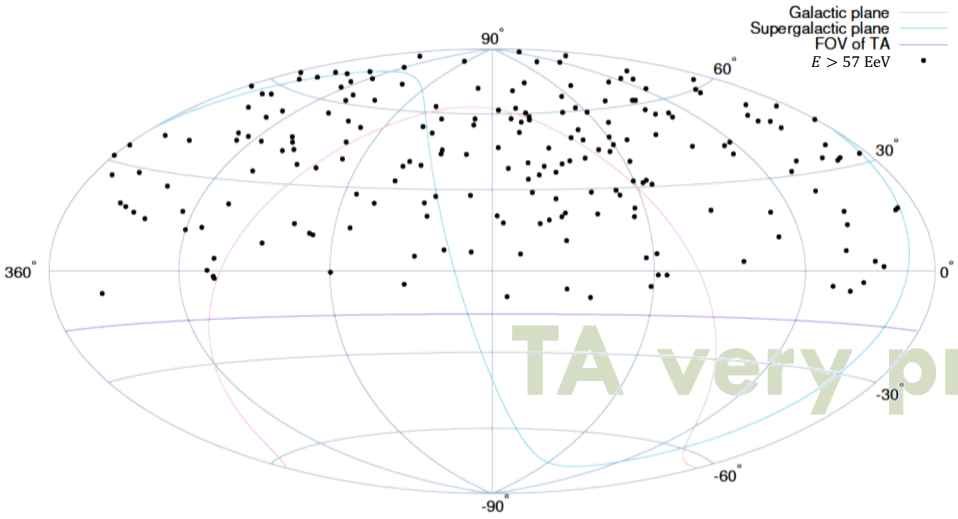


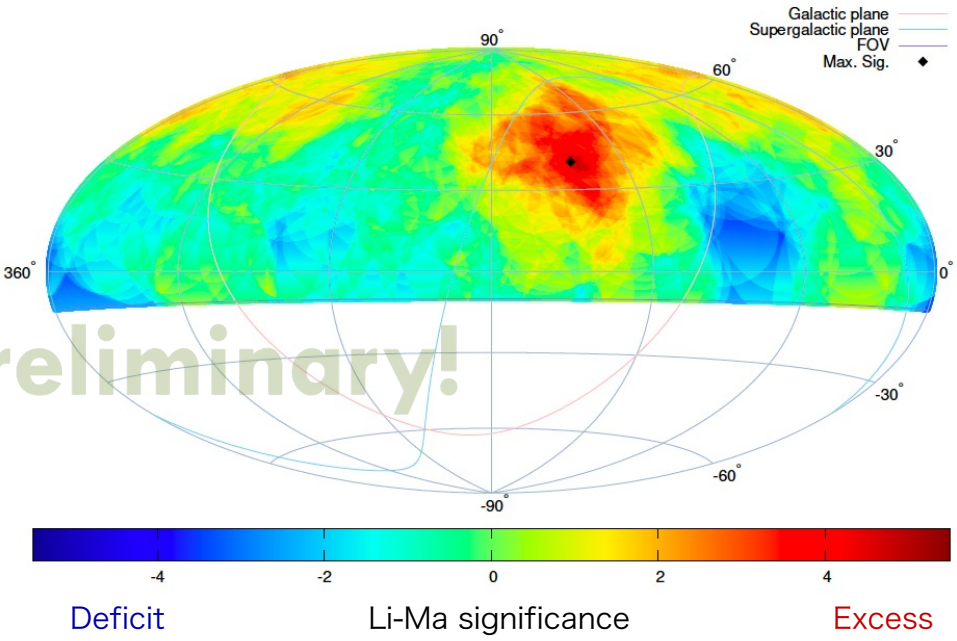
Original hotspot reported in 2014, from 5 years of data
Ap. J., 790, L21(2014)
E > 57 EeV (Observed 72 events)
20° over-sampling circle
19 events fall in “Hotspot” centered at (146.7°, 43.2°)
(Expected = 4.5 events) local significance 5.1 σ
post trial significance 3.4 σ

Anisotropy, in higher energy(E>57EeV)



Search for Intermediate-scale anisotropy
in the UHECR arrival directions

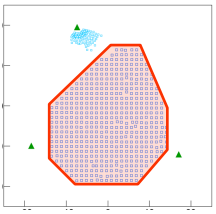


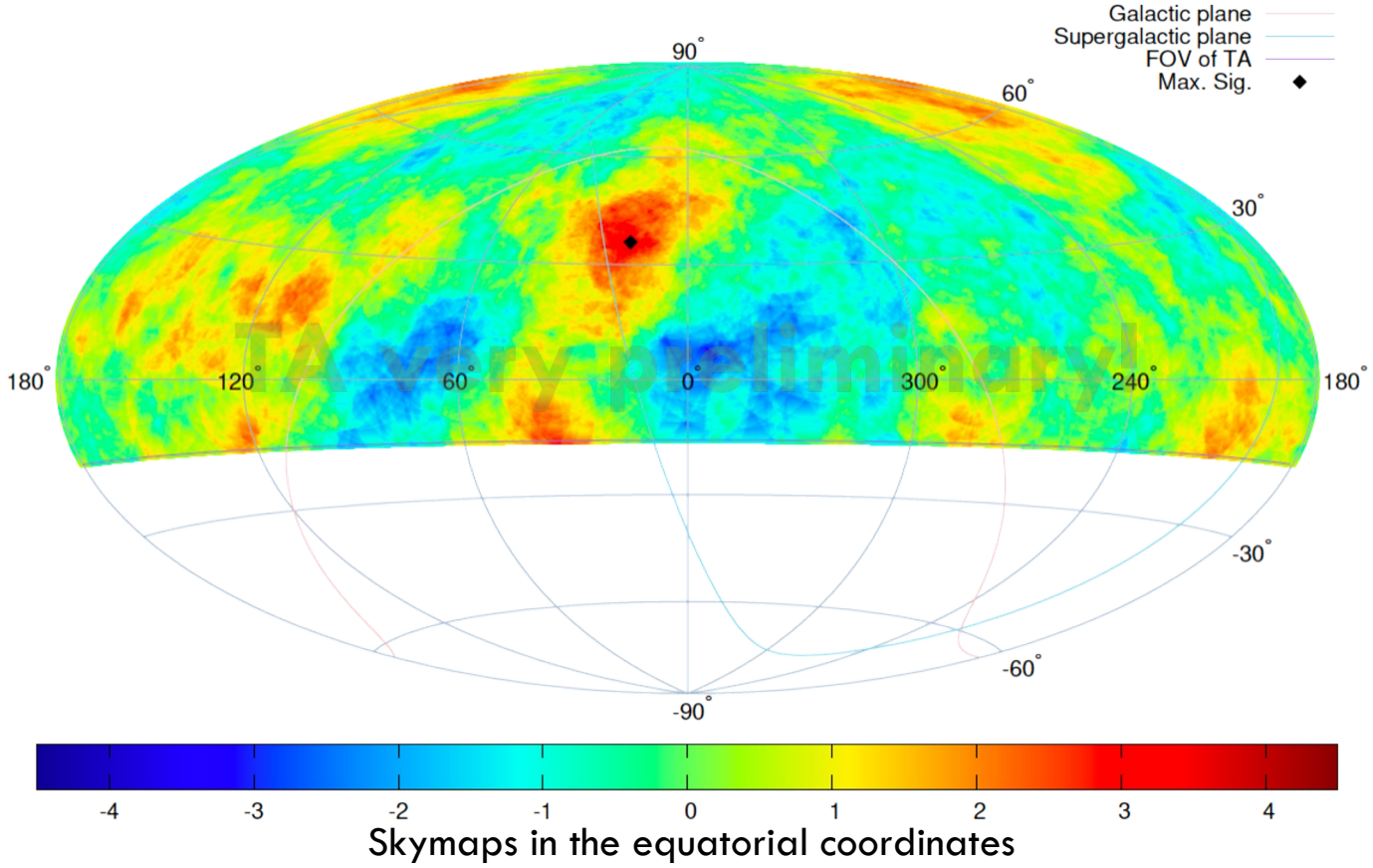


using 14yrs TA-SD dataset

E > 57 EeV, in total 205 events
44 events fall in Hotspot (α=144.0°, δ=40.5°, 25° radius, 22° from SGP)
expected=16.9 events
local significance: 5.1σ, chance probability: 3.2σ
25° over-sampling radius shows the highest local significance
(scanned 15° to 35° with 5° step)

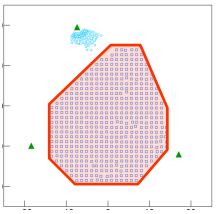
New excess of events with E ≥$10^{19.4}$ eV

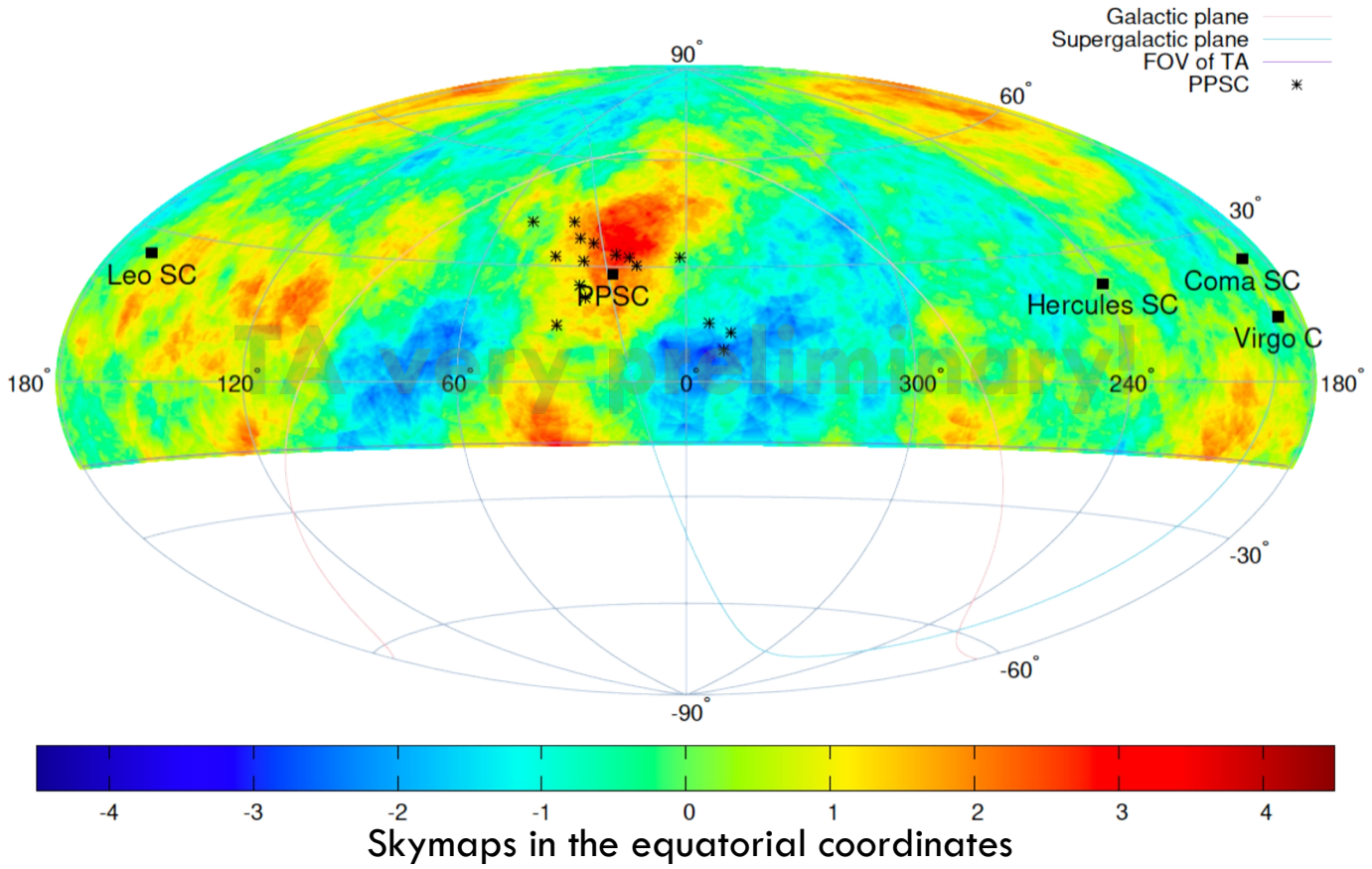




- 1060 events with E ≥ $10^{19.4}$ eV (14yrs TA SD data)
- Maximum local significance: 3.8σ at (17.4°, 36.0°)
  - Observed: 95 events
  - Expected from isotropy: 61 events
- post trial : 3.1σ

New excess of events with E ≥$10^{19.4}$ eV



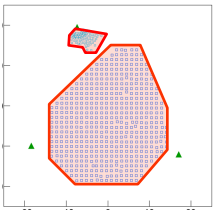


Compare new excess with the major structures within 150 Mpc

- Virgo cluster (17 Mpc)
- PPSC (70 Mpc)
- Coma supercluster (90 Mpc)
- Leo supercluster (135 Mpc)
- Hercules supercluster (135 Mpc)

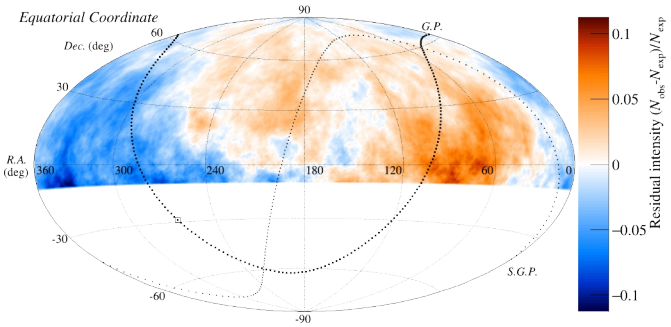
Result indicates that a CRs source may exist in the direction of PPSC

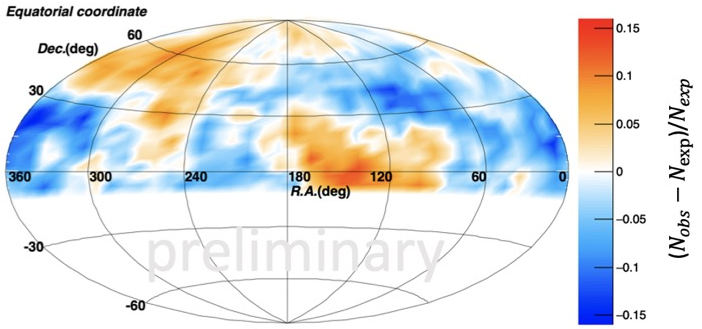
Large scale anisotropy



- Dipole anisotropy search with SD data
  - 11yrs TA SD and 2yrs TALE SD

Residual intensity sky-map with
45-degrees oversampling

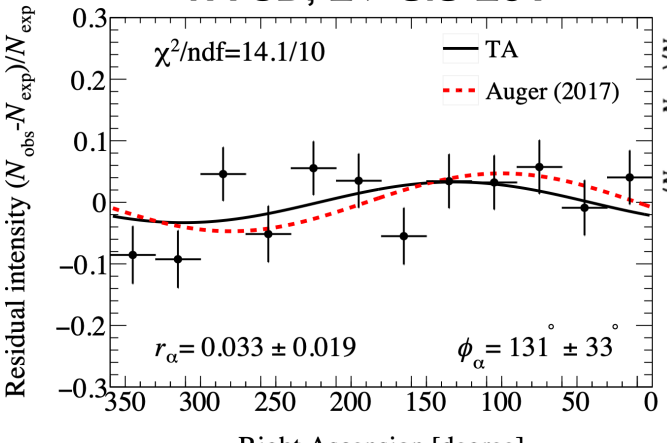


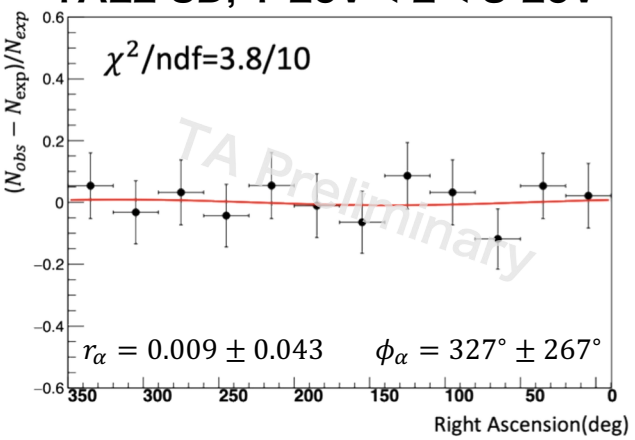


TA SD 11years data
6032 events observed
above 8.8 EeV

TALE SD 2years data
1122 events observed
in 1 EeV < E < 3 EeV

ApJL, 898, L28 (2020)





E > 8.8 EeV
- Consistent with both isotropic and Auger reported dipole

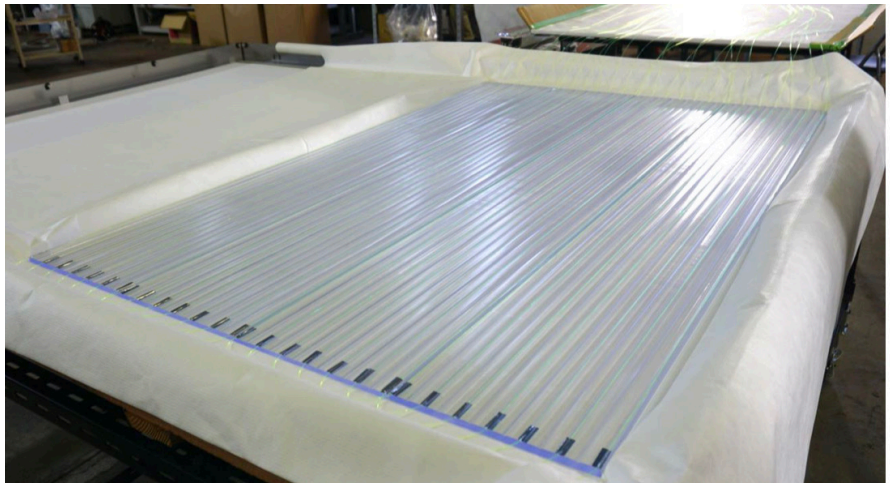
1 EeV < E < 3 EeV
- Consistent with isotropic

Need more statistics

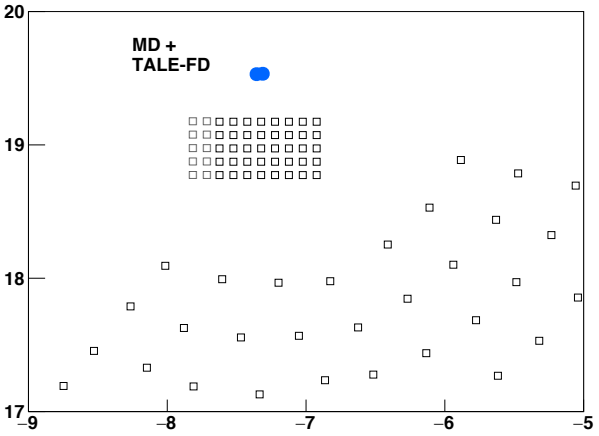
Recent progress of extension project

Future prospect

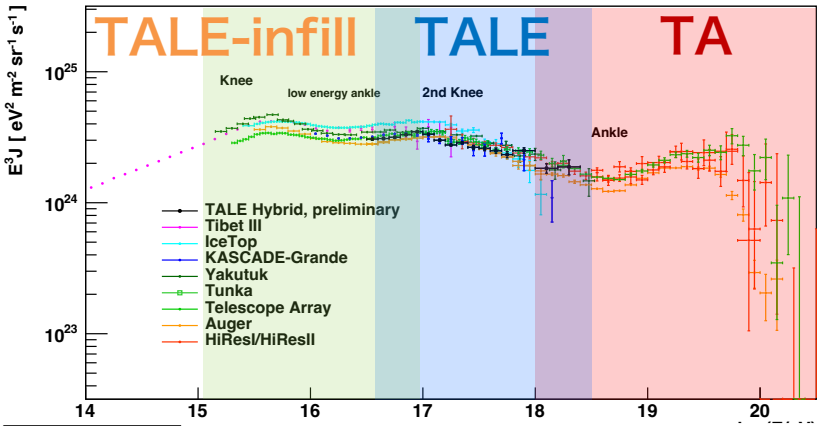
- Farther low energy extension with Hybrid mode
  - 50 SDs with 100m spacing
- Target energy: E > 10^{15} eV
- SD production on Oct. 2021
  - same design as TA/TALE SD



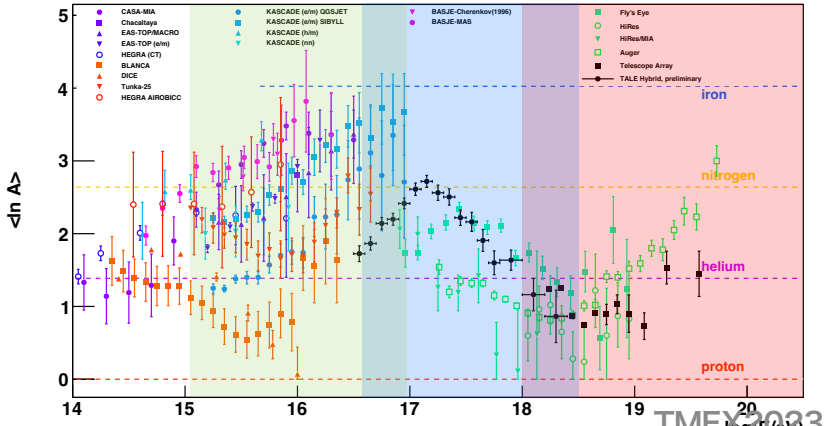
- plan to start data taking on 2023
- MC study is ongoing also



TALE Hybrid Spectrum with recent measurements



<ln A> vs log E

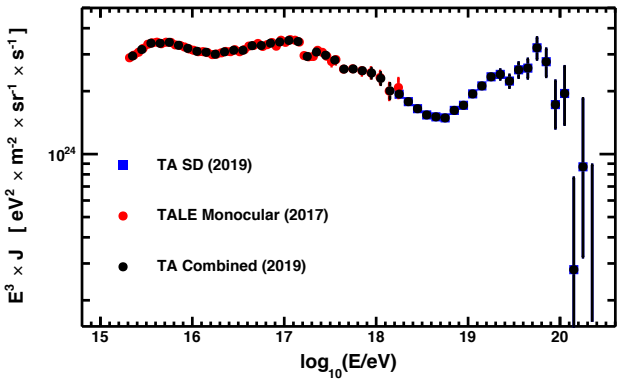


Summary

Telescope Array is UHECR observatory in the northern hemisphere

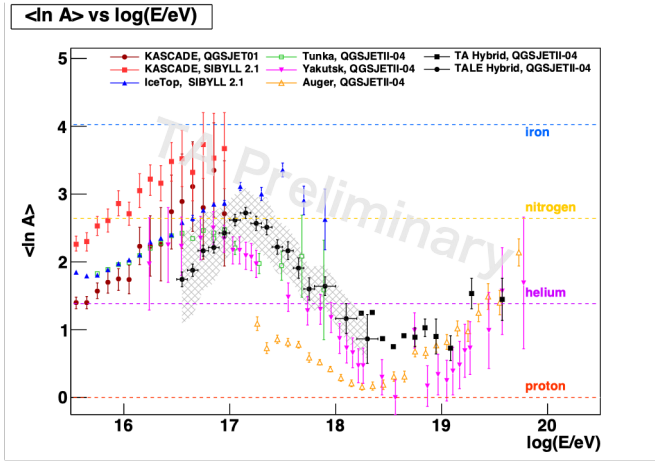
Spectrum

- 5 orders of spectrum are observed
- new feature above ankle



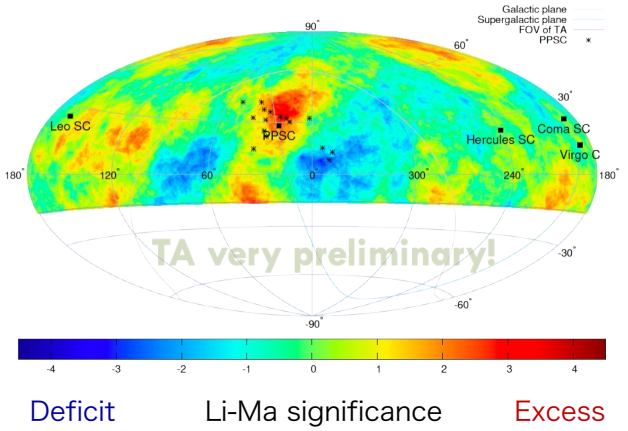
Mass composition

- heavy to light above 2nd knee
- Compatible with a light component in higher energies



Anisotropy search

- new excess above $10^{19.4}$ eV
- PPSC is behind



We need much more data at highest energy

-> TAx4 is in operation!