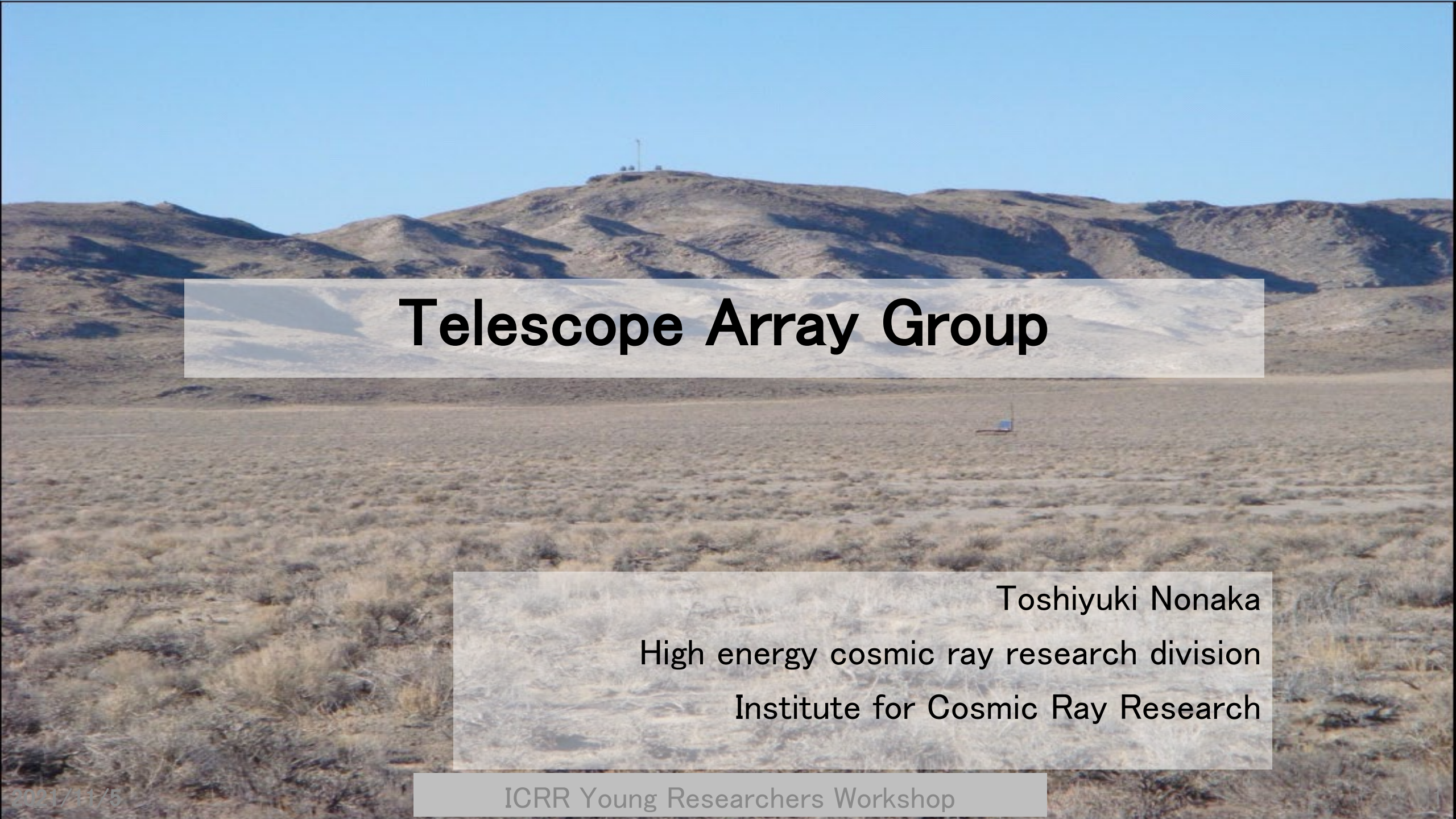
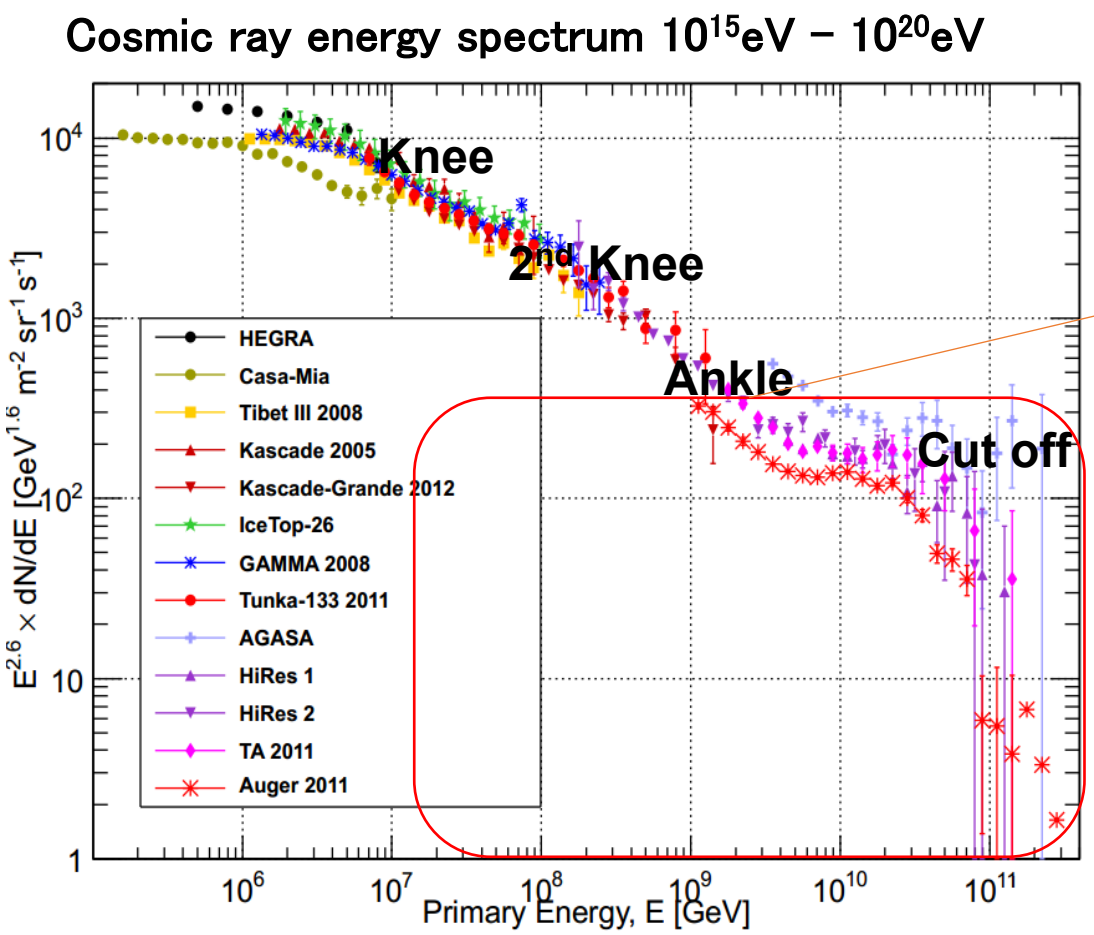


Telescope Array Group

Toshiyuki Nonaka
High energy cosmic ray research division
Institute for Cosmic Ray Research

Cosmic Ray Energy Spectrum



- Flux @ E 10^{18-19}eV
  - Small flux
  - Large area
  - Fluorescence telescope

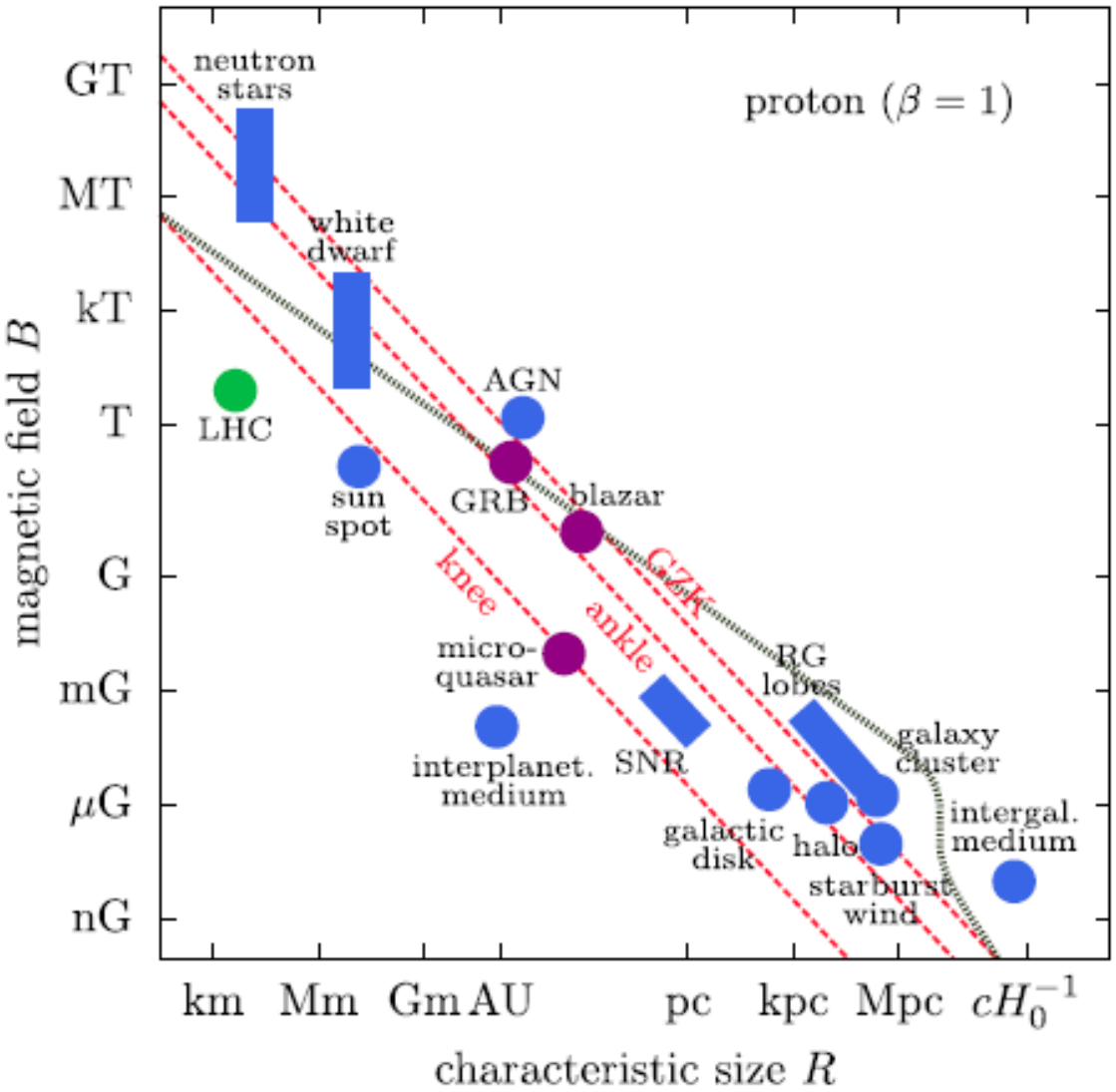
- @ E> 10^{19}eV
  - Higher rigidity
  - Short attenuation length
    - Anisotropy in spectrum/composition
    - Expect more correlation with matter distribution/objects

We are observing this energy region

- Northern hemisphere : TA
- Southern hemisphere : Auger

Candidates of UHECR sources

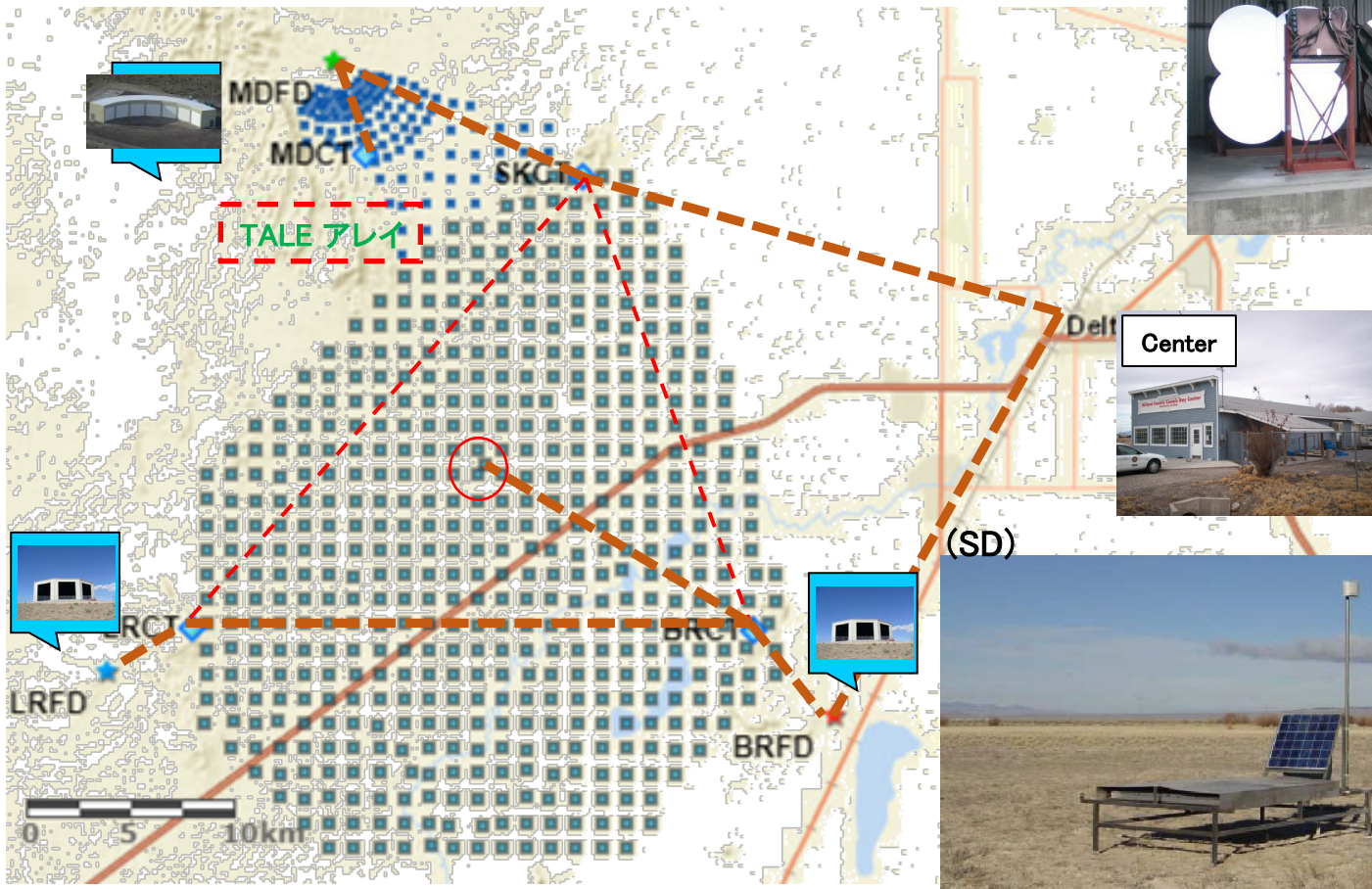
Hillas diagram



Advances in Space Research 62 (2018)

Telescope Array(TA)

- Fluorescence telescope (FD) x3site
- Surface detector (SD) x507, 1.2km grid (670km^2)



(FD)

(SD)

Present observation site

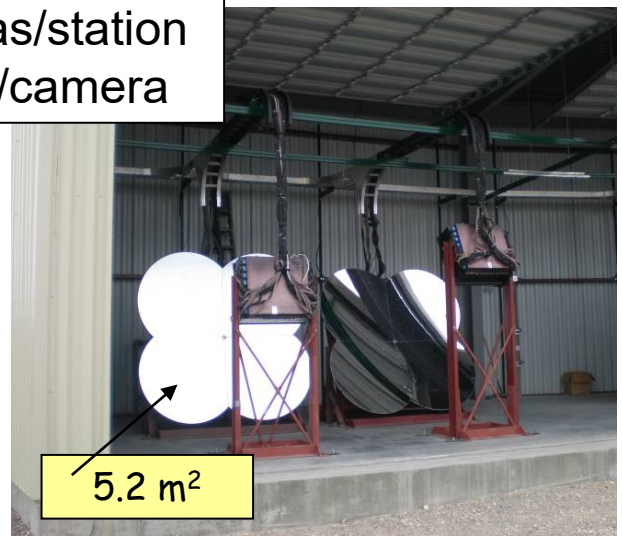
West of Delta City Utah state , USA
N39° W112° , ~1400 asl

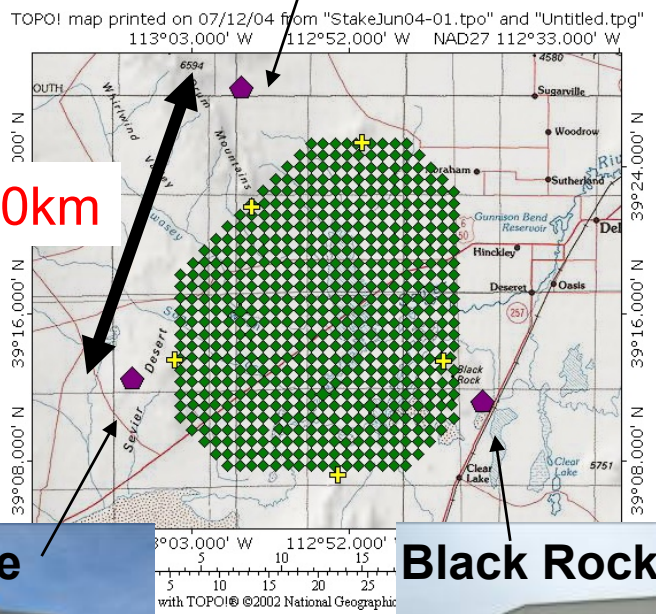
Telescope Array Fluorecence Detector

From HiRes

Middle Drum

14 cameras/station
256 PMTs/camera



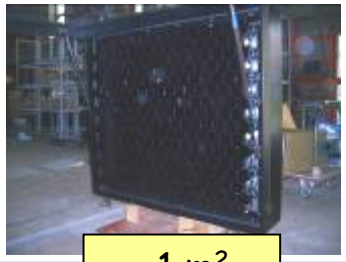


~30km

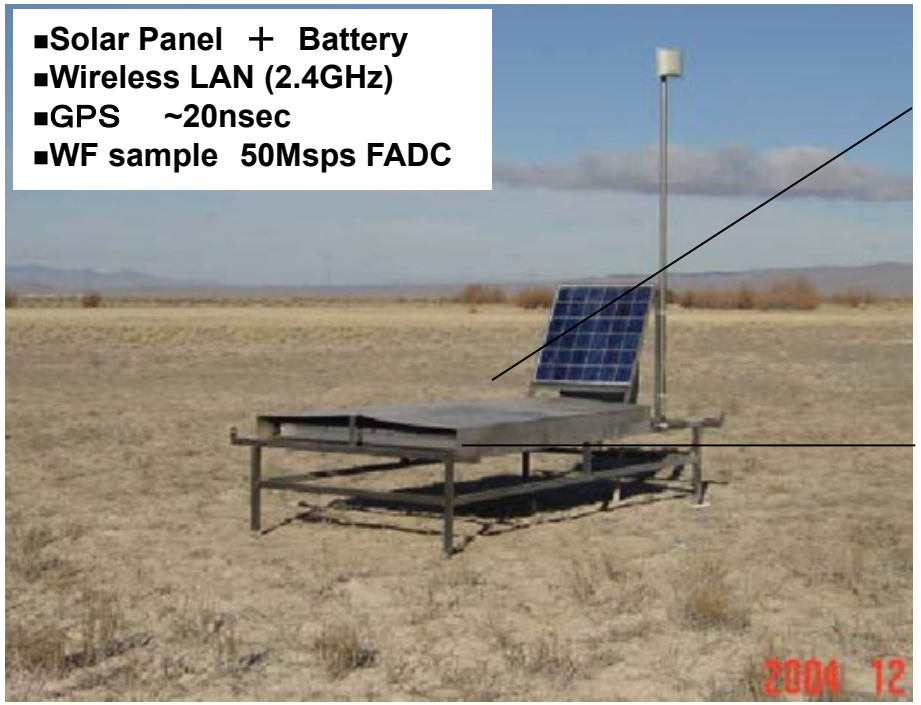
256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

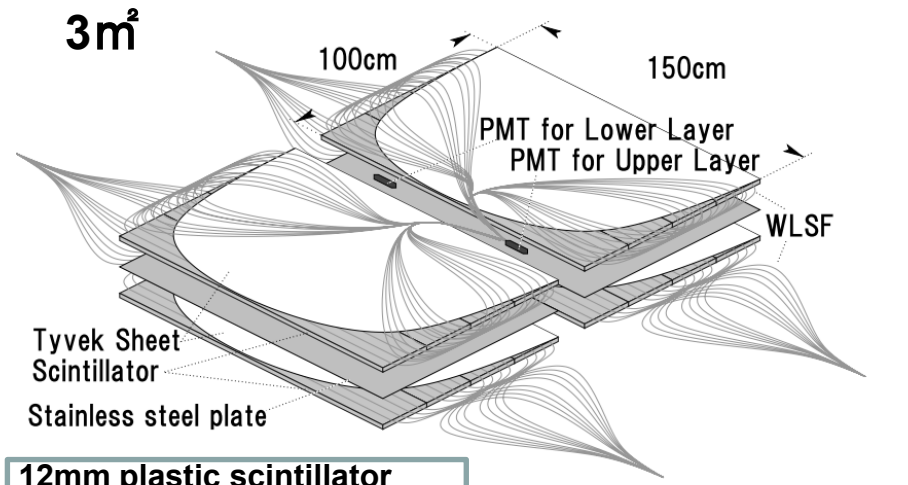
Long Ridge

Black Rock Mesa



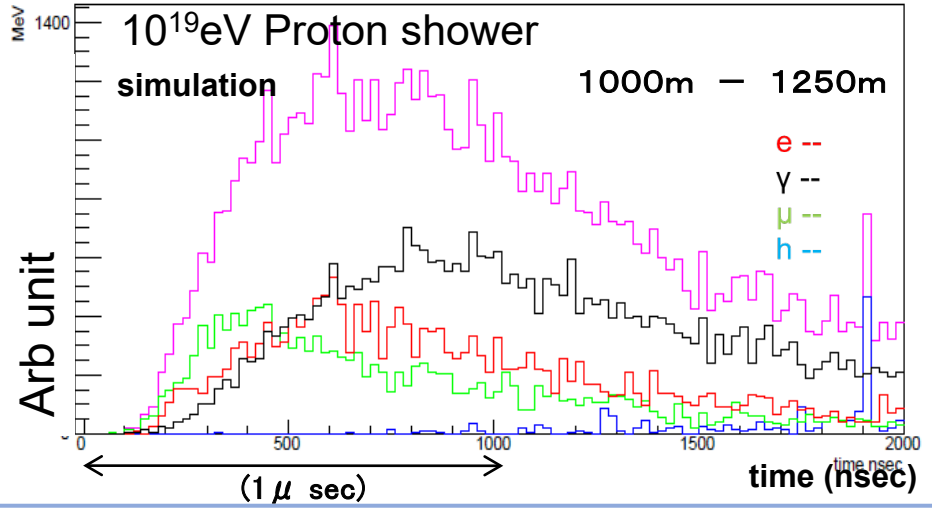
Telescope Array Surface Detector





12mm plastic scintillator
-----1mm SUS-----
12mm plastic scintillator → 2 independent layer

WLSF (475nm) x5m PMT ETL9124SA

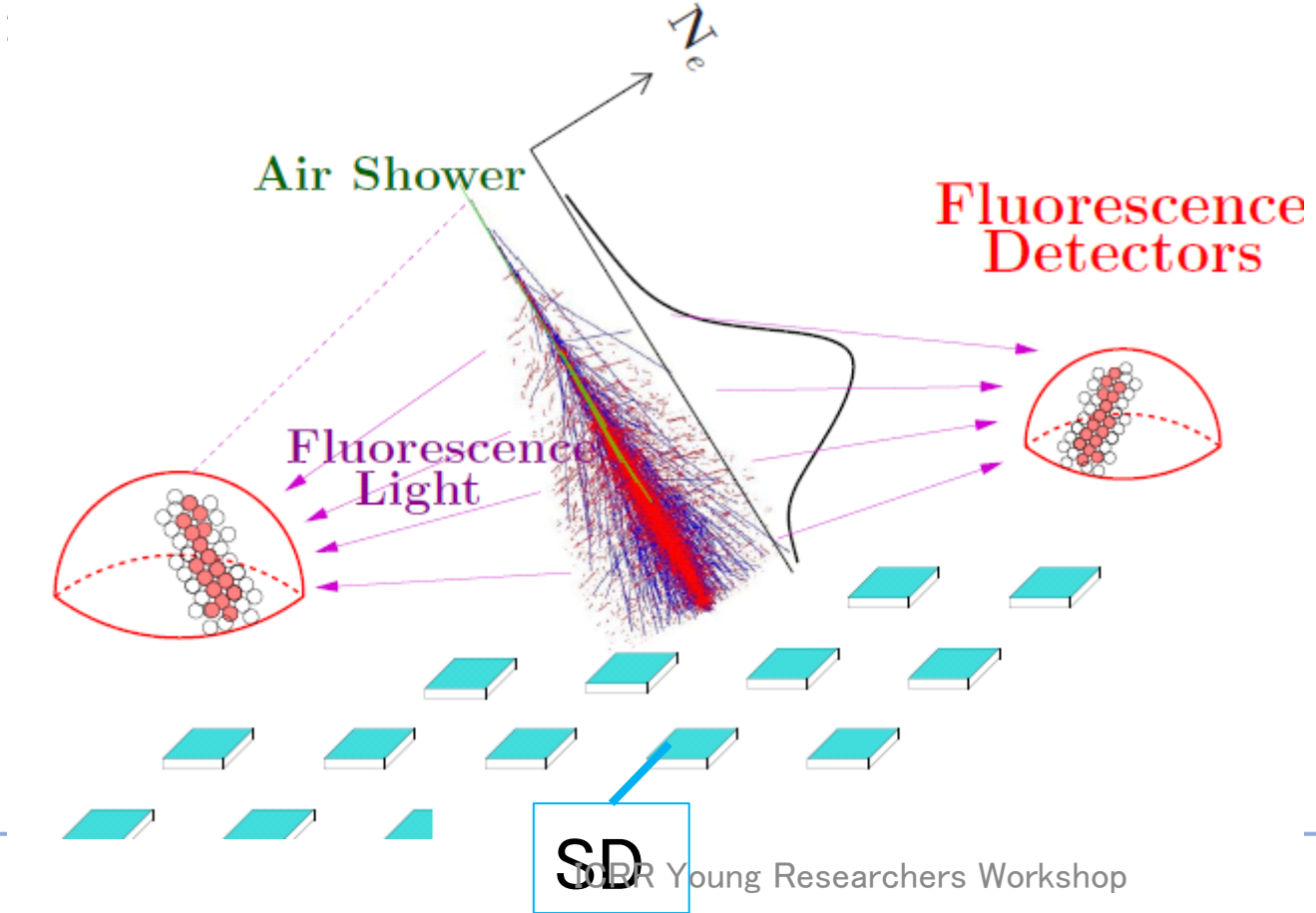


TASD:
- ◇Signal = Scintillation light in detector
- ◇photons collected by WLSFs and guided to PMT
- ◇Thin scintillator = Low threshold EM component sensitive.

Hybrid observation

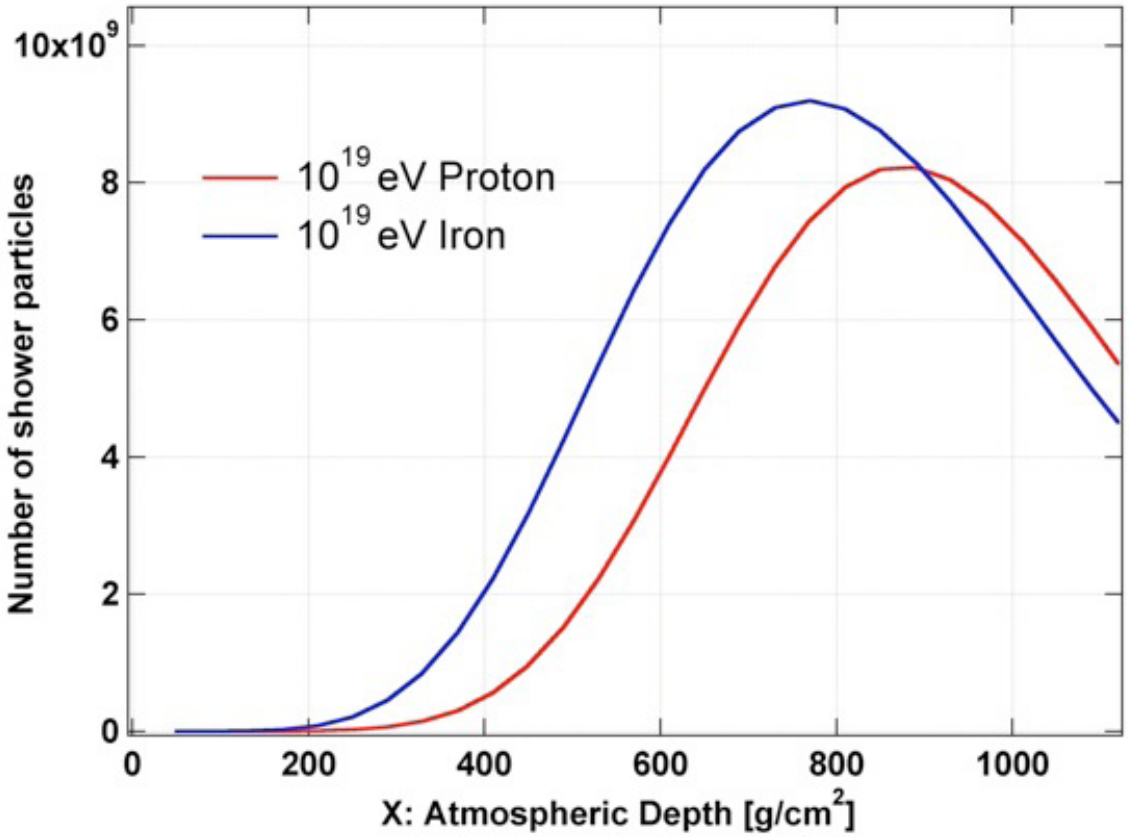
Fluorescence light from air shower (emitted light all direction).

- Fluorescence Telescopes (FD)
  - Observe shower track from side
  - Observe shower development
- Surface detector (SD)
  - Observe particles density and timing at ground level.



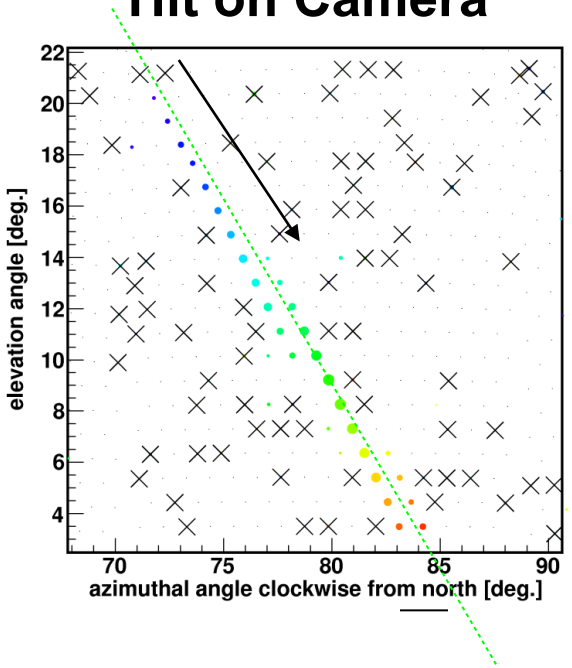
Xmax, chemical composition

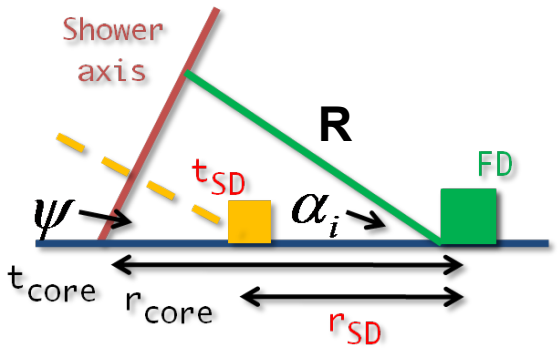
The depth at maximum development(X_max) of shower depends on the type of primary cosmic rays.



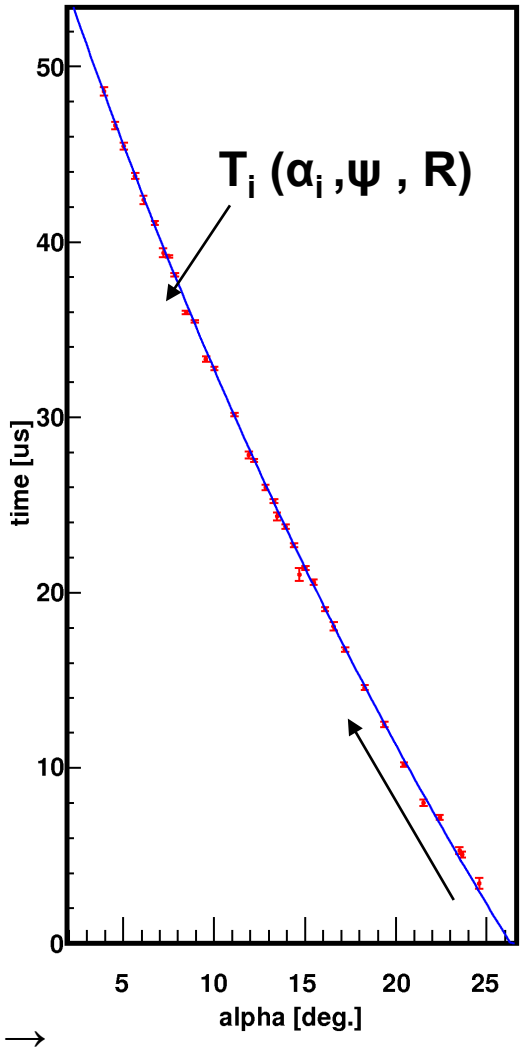
Telescope Array Fluorecence Detector

Hit on Camera

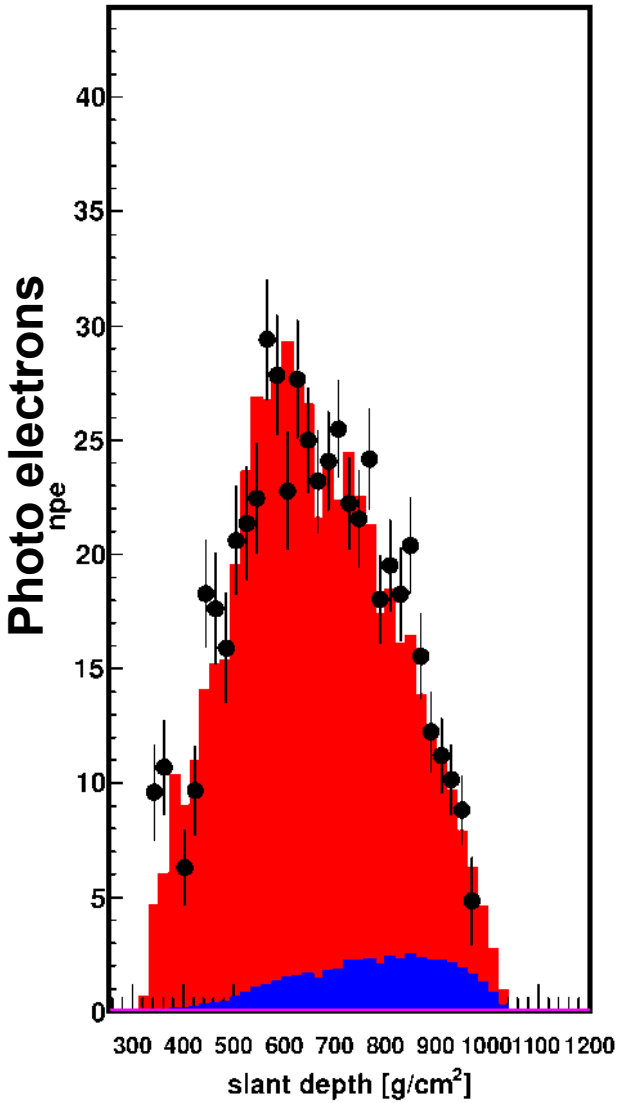




Geometry



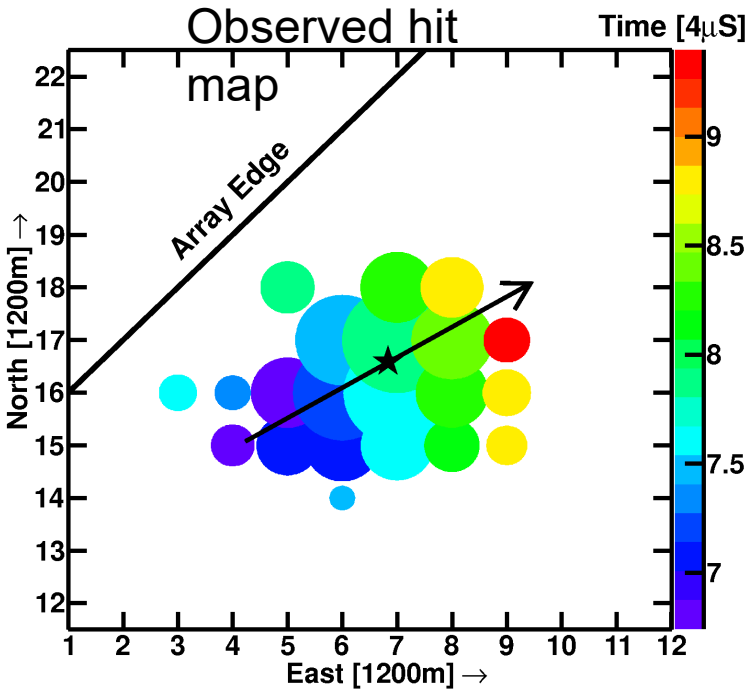
Energy

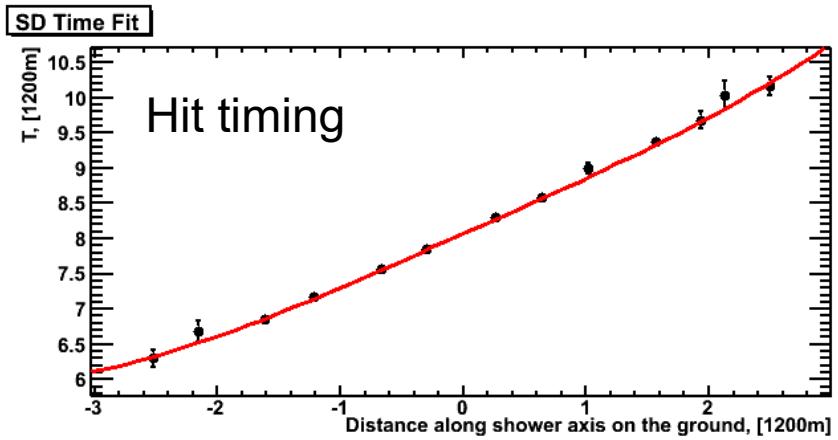


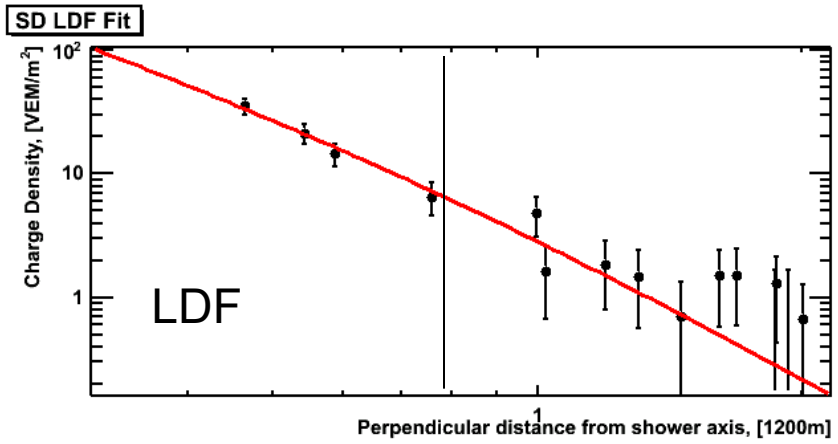
Use SD timing information →
Ψ、R resolution improve (Hybrid analysis)

Telescope Array Surface Detector

- An event hit map are shown
- Geometrical and LDF reconstruction fit is shown for this event.





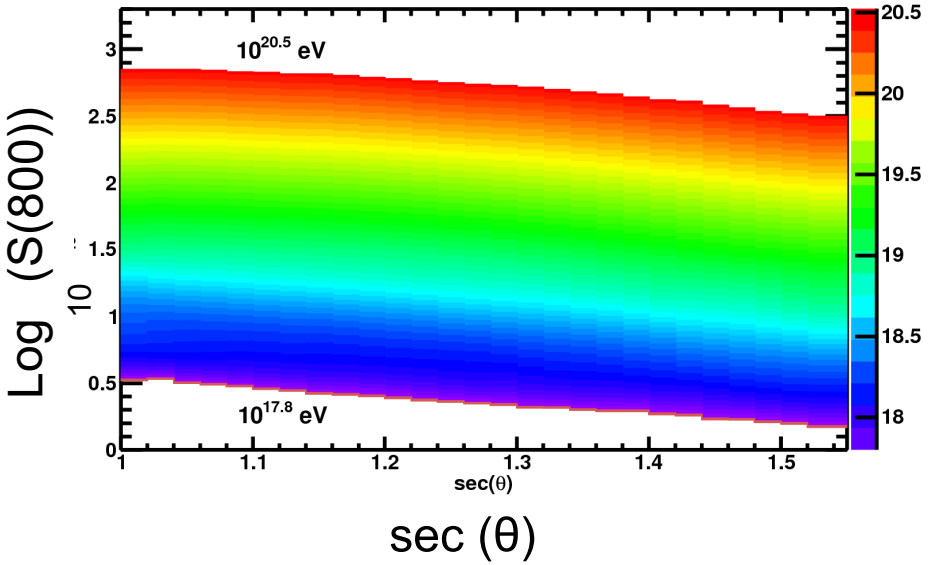


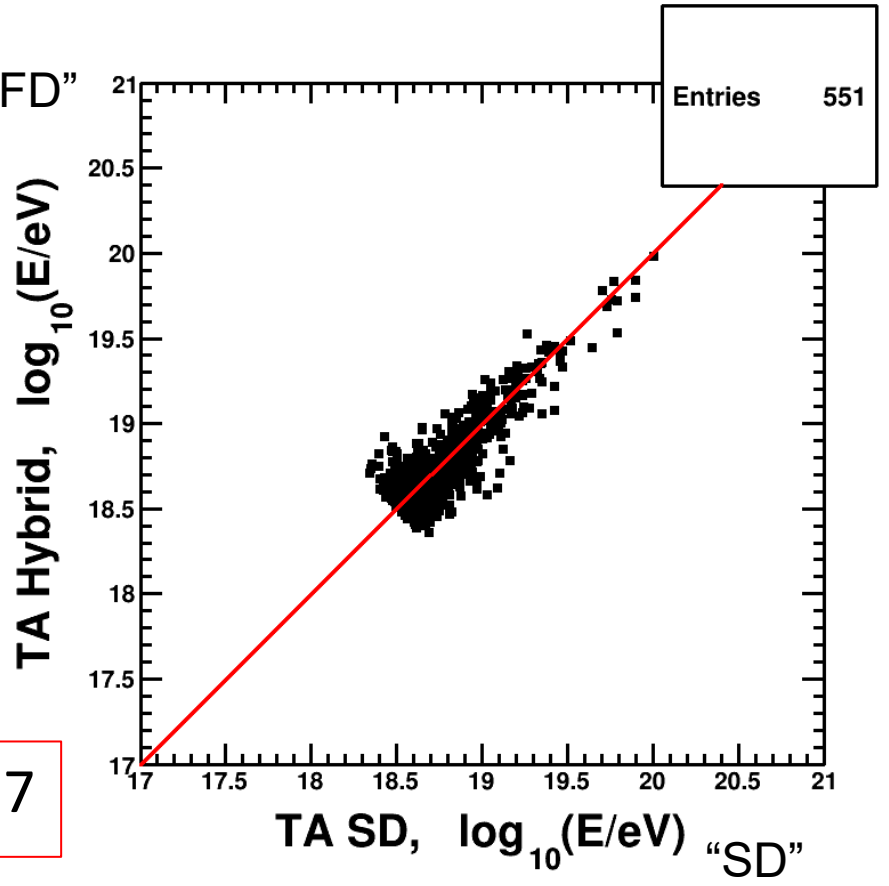
Hit timing : → Arrival direction
Lateral distribution of energy deposit → <u>Energy estimator "S(800)"</u>
(Energy deposit at 800m)

Telescope Array Surface Detector

Energy determination at SD

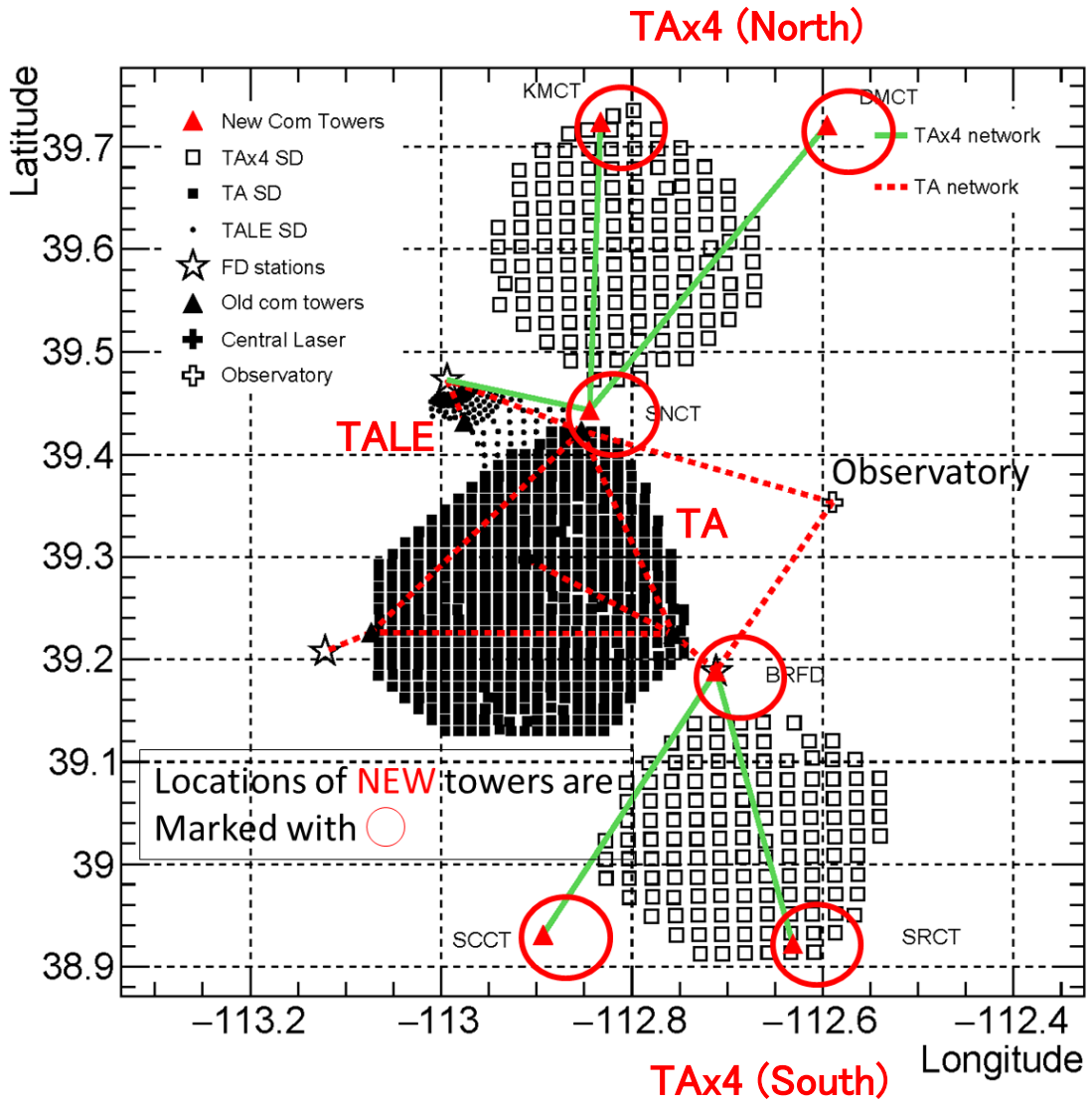
- Look up table generated by “MC”
- FD gives calorimetric energy.
- SD energy obtained by “MC” is calibrated with FD energy obtained at hybrid events.





$$E_{FD} = E_{SDMC}/1.27$$

Ongoing experiments



Three observations of different energies

- TA
  - $10^{18}eV \sim 10^{20}eV$
- TALE
  - $10^{16}eV \sim 10^{18.5}eV$
- TAx4
  - $10^{19.7}eV \sim 10^{20}eV$

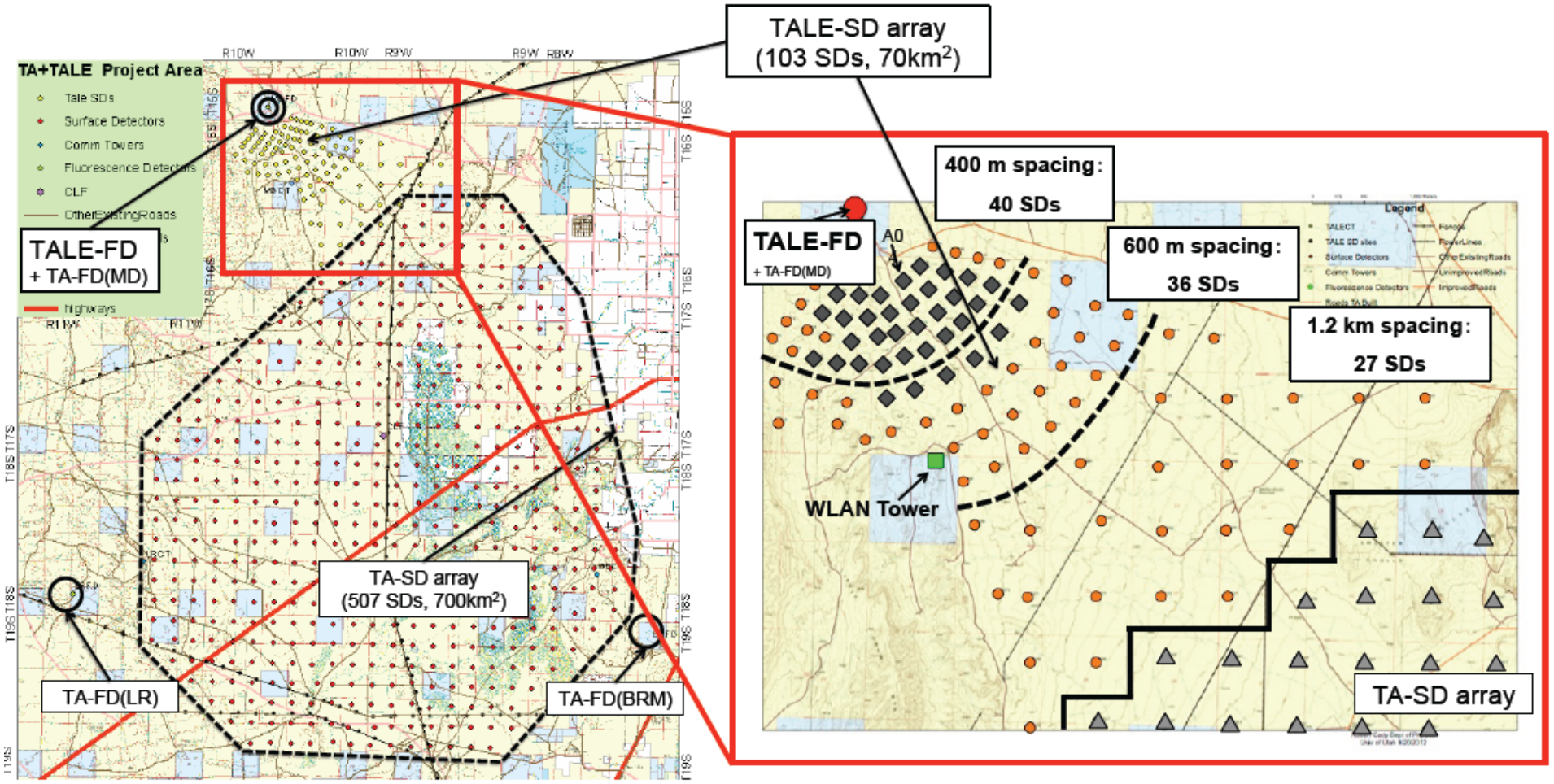
100km x 60 km

TA Low Energy extension (TALE)

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

+

Infill surface detector array of more densely packed surface detectors (lower energy threshold)



TALE telescopes

Telescopes for
high elevation angle (31-59°)

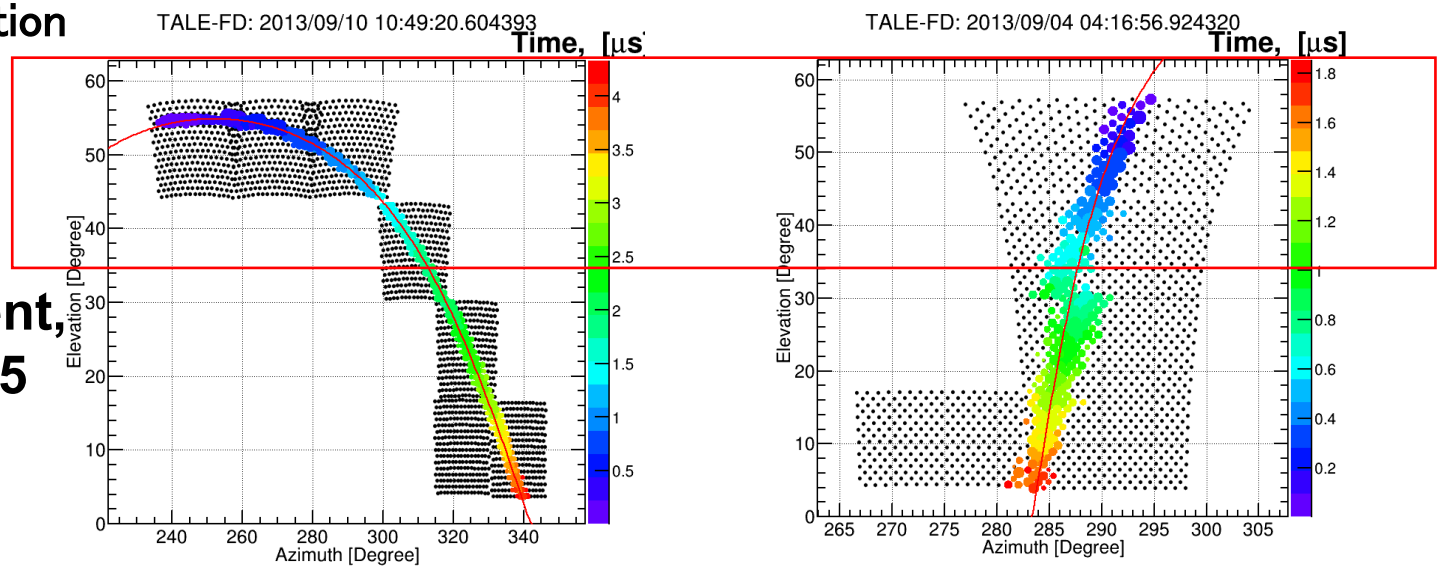
- 2013- Telescope operation
- 2017- 80 SDs deployed and hybrid observation started.
  - Upgraded DAQ system from original TA

TALEハイブリッド実験の基本性能

エネルギーしきい値 logE=16.0
イベントレート ~5,000 事象／年
← 50,000 事象／年 (SD単体)
Δθ = 1.0° ← 5.3°(FD単眼)
ΔXmax = 20 g/cm² ← 60g/cm²(FD単眼)

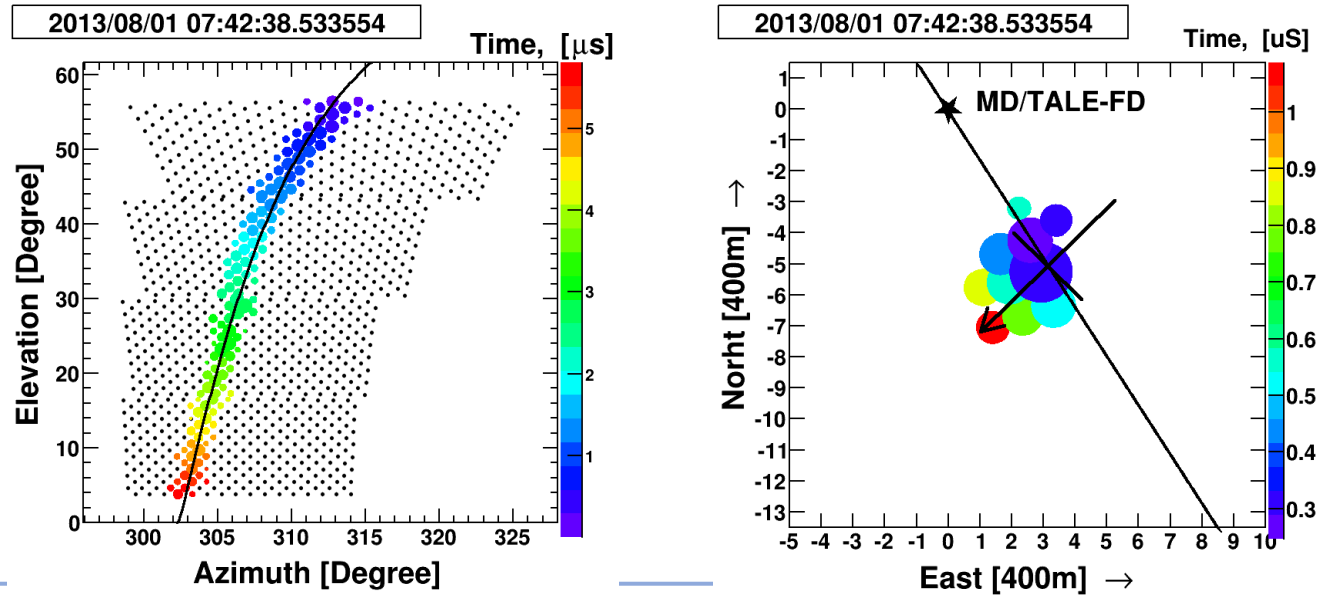
TALE event display

High elevation telescopes

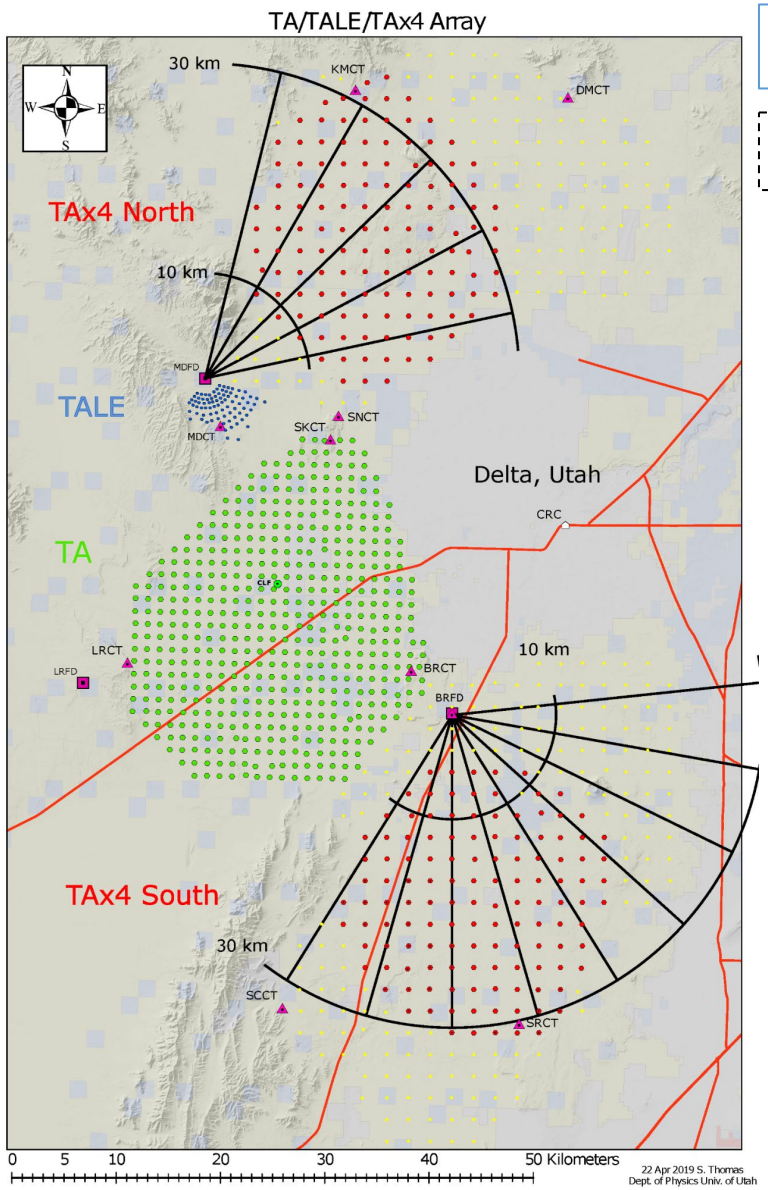


7 mirror event, log(E) = 16.5

Hybrid event



TAx4



Observation for higher energy part $E>10^{19.5}$

Red marker : Deployed at 2019/03

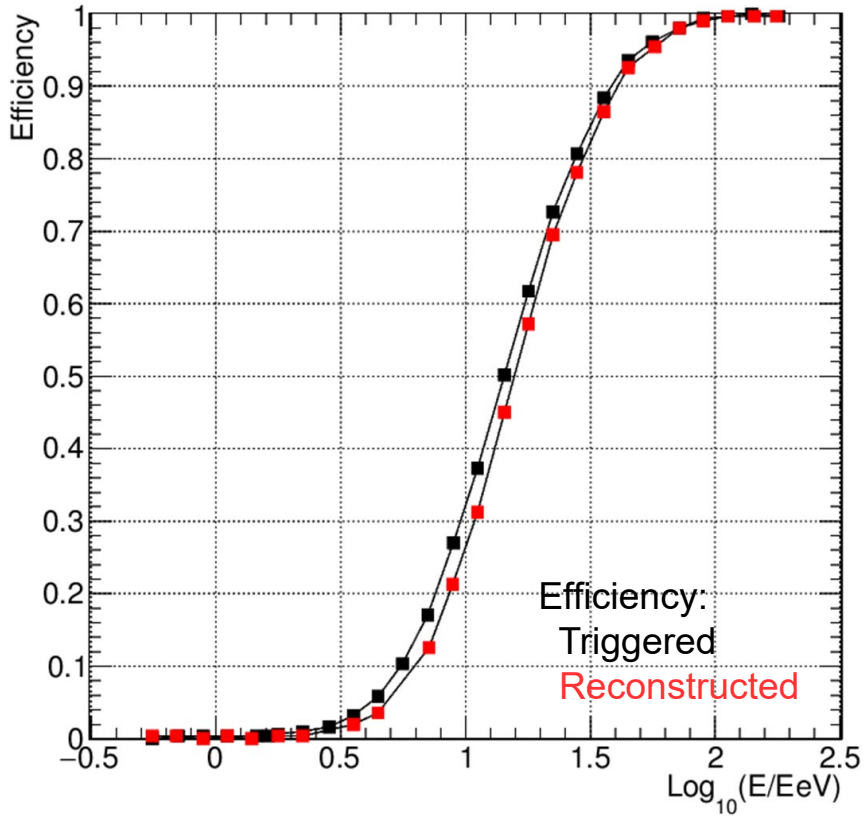
- 2 divided SD array
- North 130 SDs 2.08 km grid
- South 127 SDs 2.08 km grid

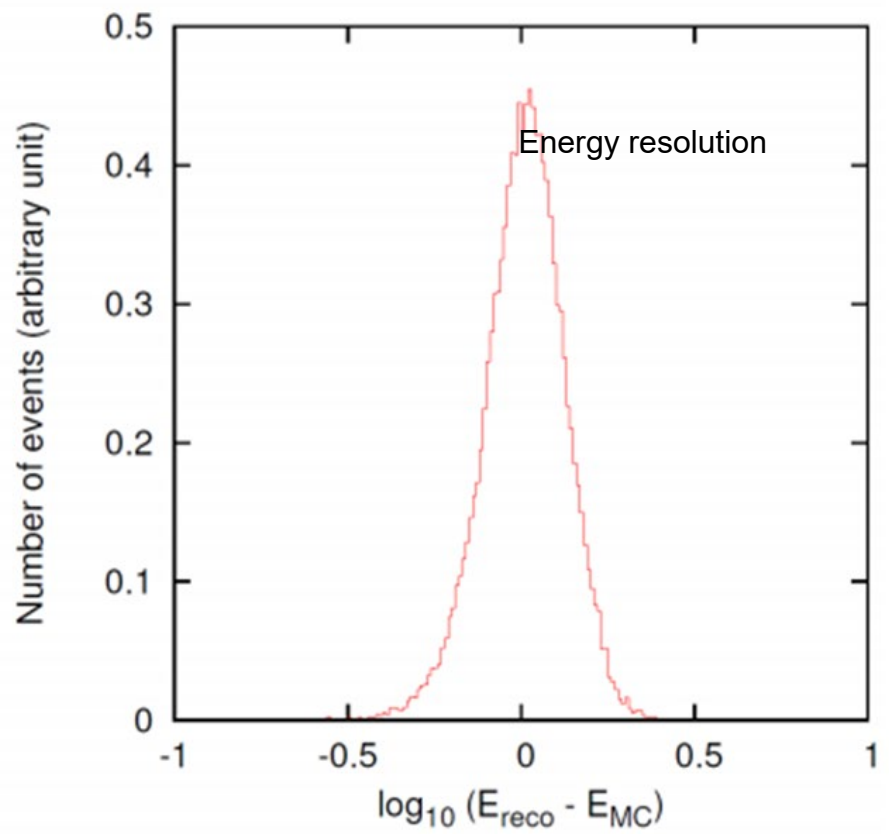
More robust detector than TA

TAx4 Experiment

- Array grid is 2.0km.
- Trigger efficiency ~95% at 57 EeV
- Energy resolution < -29% +22 %
- Angular resolution < 2.2 deg

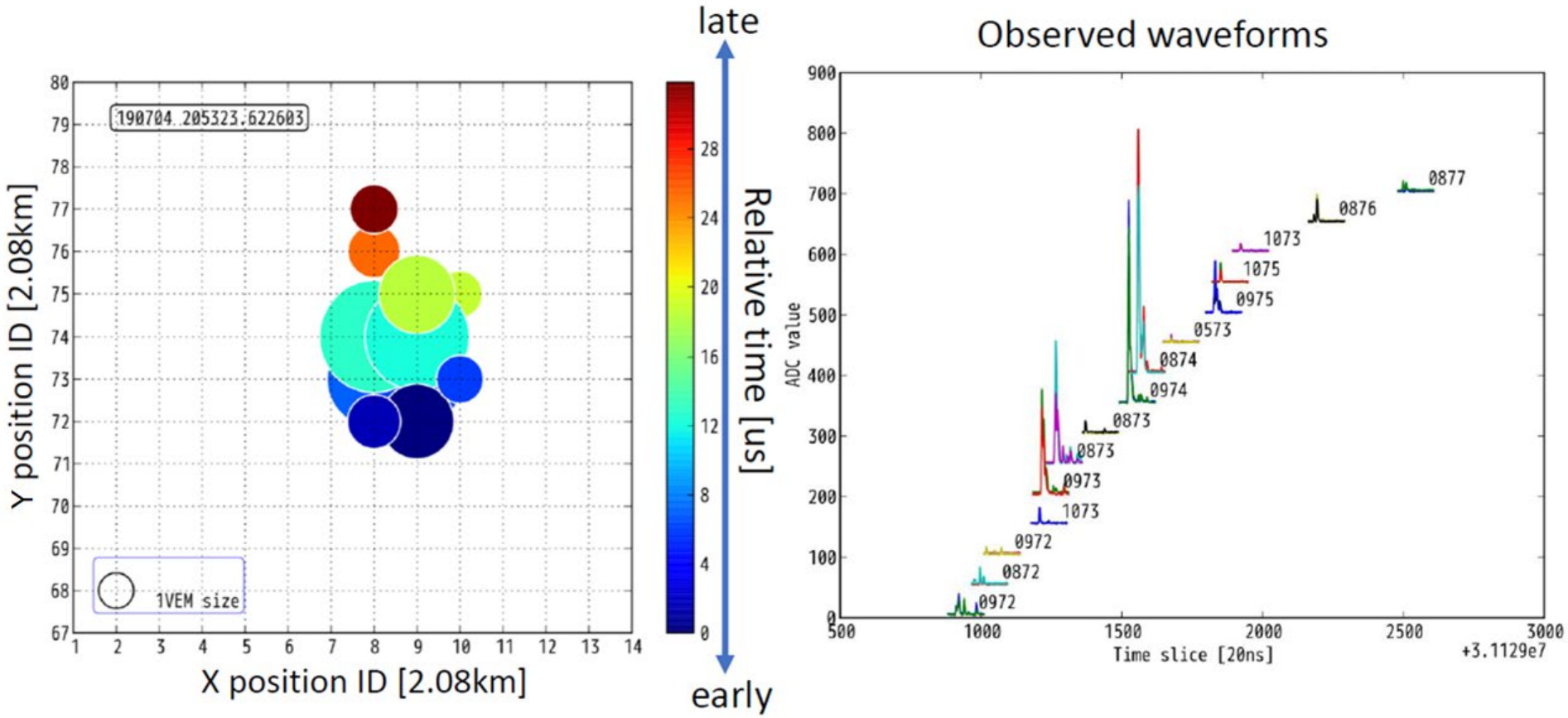
- Study of reconstruction have been updated





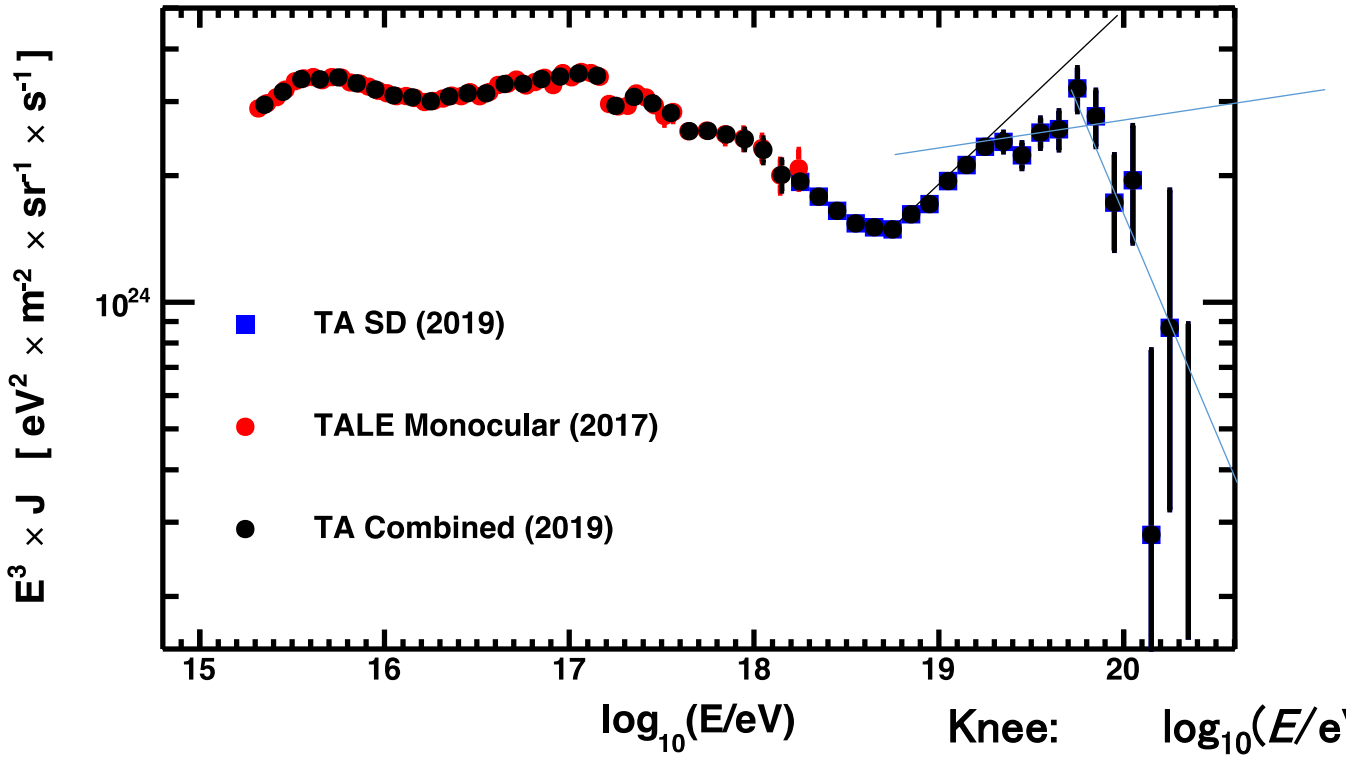
TAx4 SD

Stable operation started in the fall of 2019
already 1 yr of data.



Energy spectrum

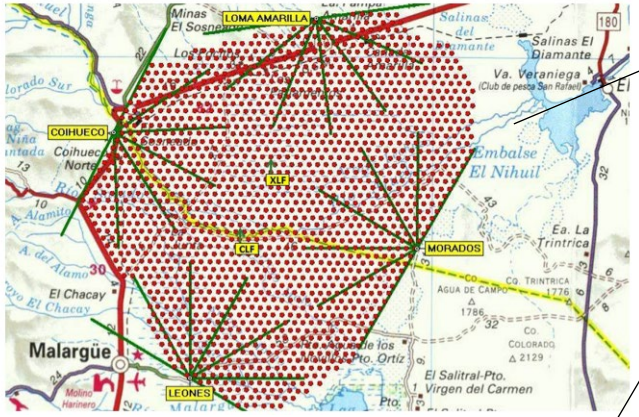
- Combine TA spectrum (11 years)
  - Statistics is dominated by SD data while combining.



Knee: $\log_{10}(E/eV) \sim 15.5$
LE ankle: $\log_{10}(E/eV) = 16.22(2)$
2nd Knee: $\log_{10}(E/eV) = 17.04(4)$
Ankle: $\log_{10}(E/eV) = 18.69(1)$
Cutoff: $\log_{10}(E/eV) = 19.81(3)$

Comparison with other experiment

◆ Auger observatory
◆ Southern hemisphere 3000km²



SD 10m² (120cm WCD)
1.5km grid x1500 unit

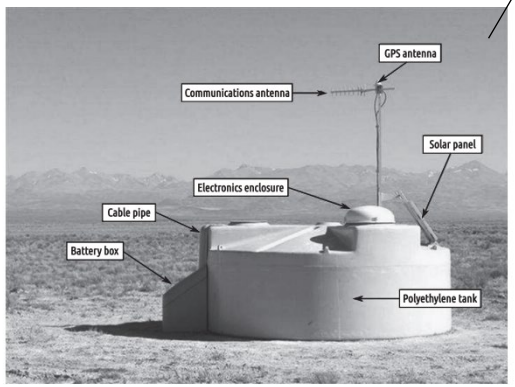
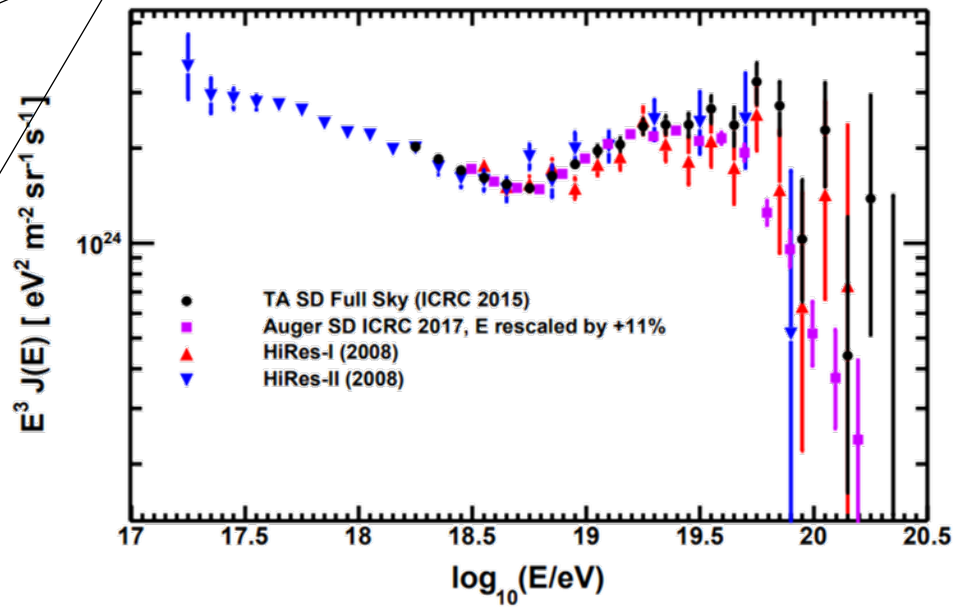


Fig. 3. A schematic view of a surface detector station in the field, showing its main

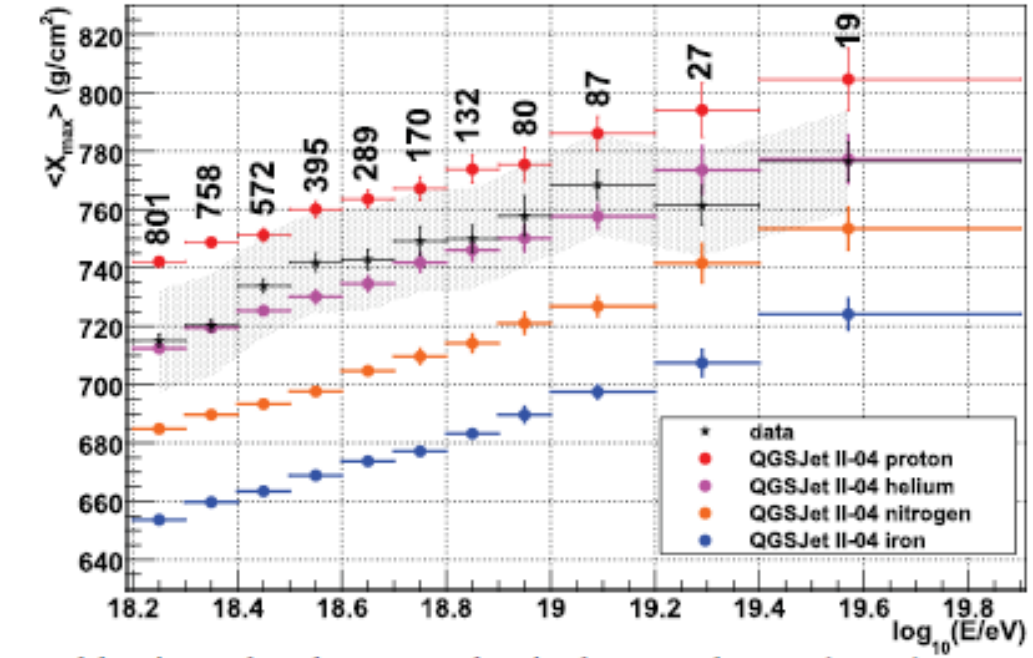
◆ Auger/ TA

R.U Abbasi et.al arXiv:1801.07820

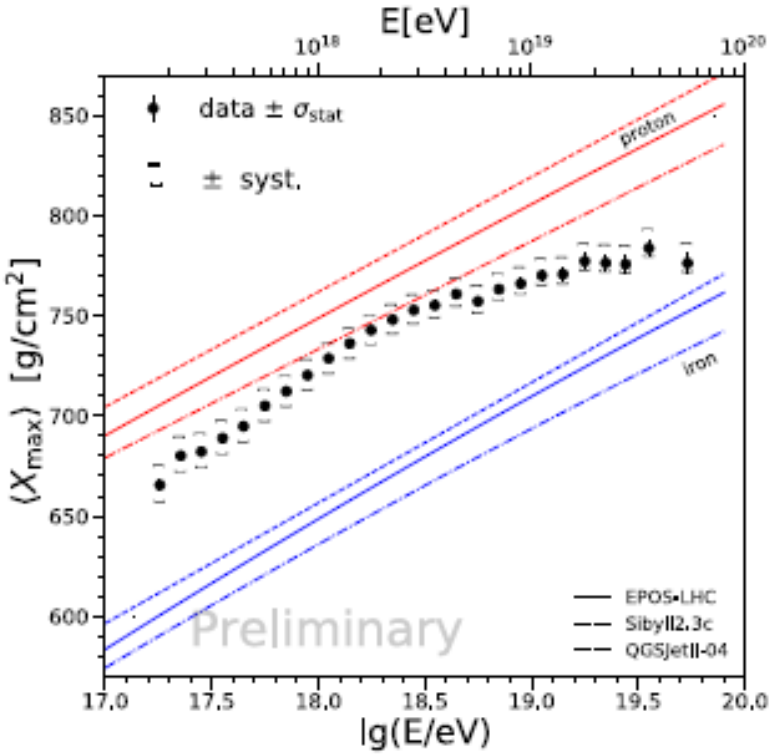


◆ TA (ICRC2015)
◆ Auge (ICRC2017)
(E+11%)
◆ Discrepancy at E～$10^{19.5}$ eV

Composition study using FD



U. Abbasi, et al., The Astrophysical Journal, 858 (2018) 76



A. Yushkov, et al., PoS ICRC2019 (2020)

Composition study using SD

Composition study using BDT multivariate classifier based on particles arrival timing and lateral distribution.

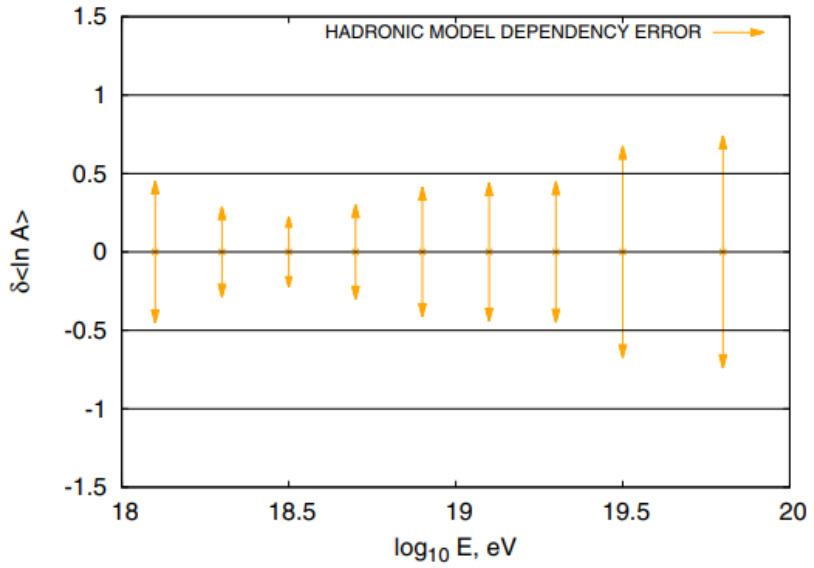


FIG. 6. Hadronic model dependency error of the method as a function of energy, based on a comparison with QGSJETII-04 hadronic interaction model.

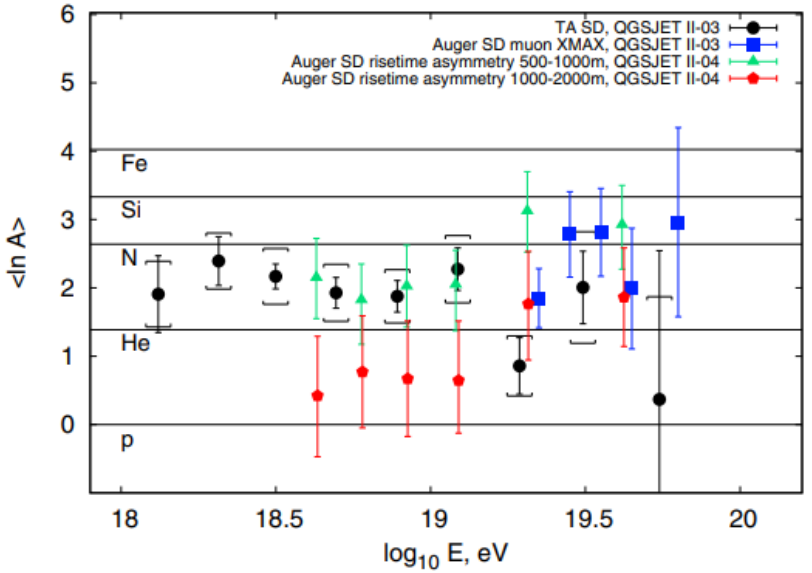


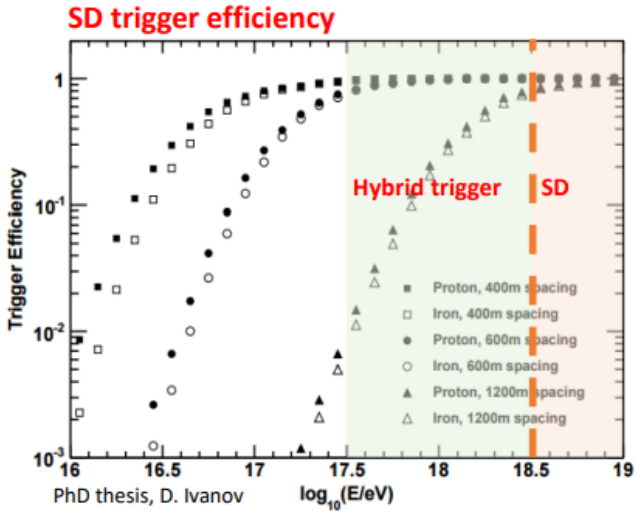
FIG. 8. Average atomic mass $\langle \ln A \rangle$ in comparison with the Pierre Auger Observatory X^{μ}_{MAX} and risetime asymmetry results [18,52]; statistical error is shown with error bars, systematic error is shown with brackets.

Phys. Rev. D 99, 022002 (2019)

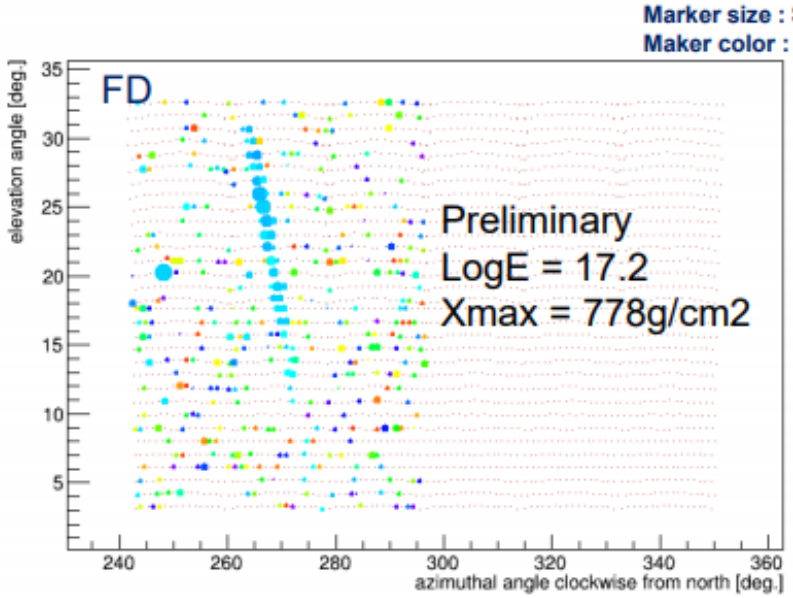
The technique extends energy range for composition study.
Also it can be adopted to anisotropy study (by selecting proton like events . etc)

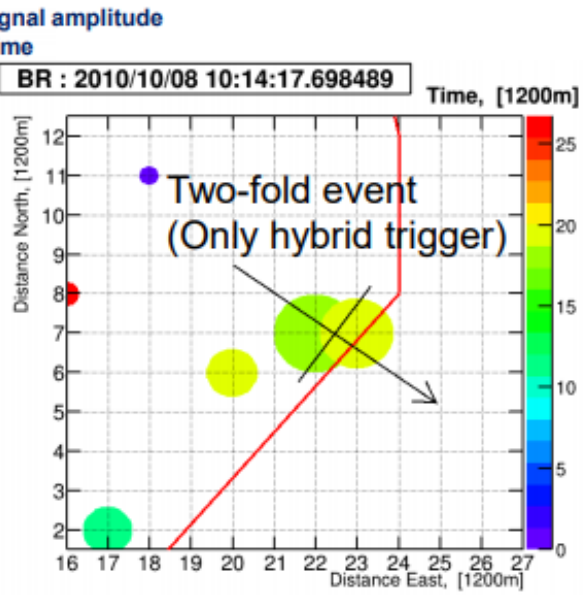
Hybrid Trigger data

H. Shin



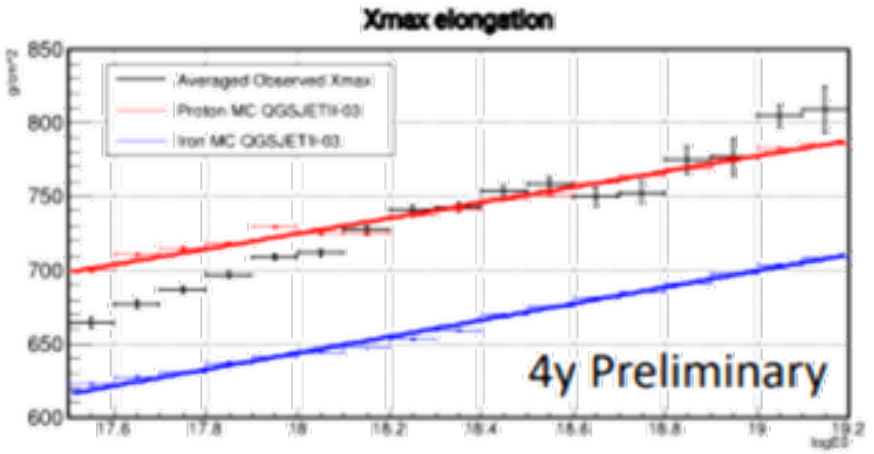
- Extend hybrid study
- More statistics for composition study.
- Cross check of each telescopes.
- Improvements have been attempted, including consideration of meteorological conditions





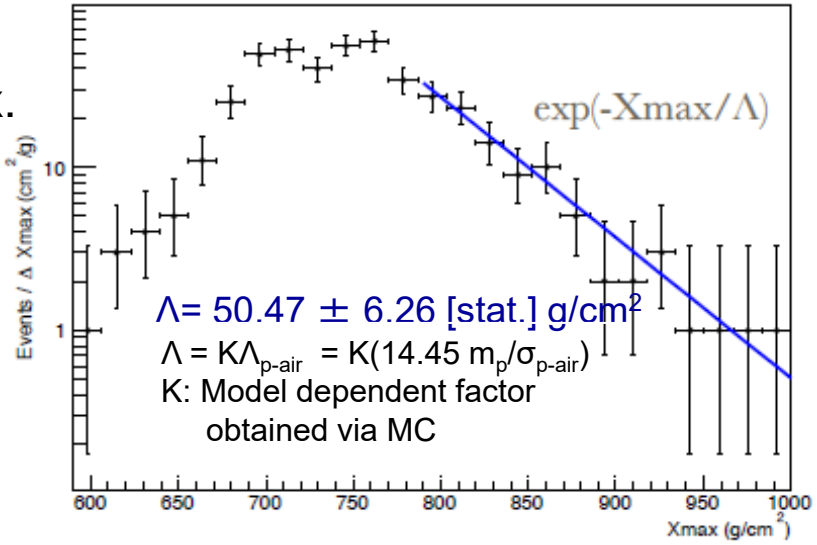
Elongation rate

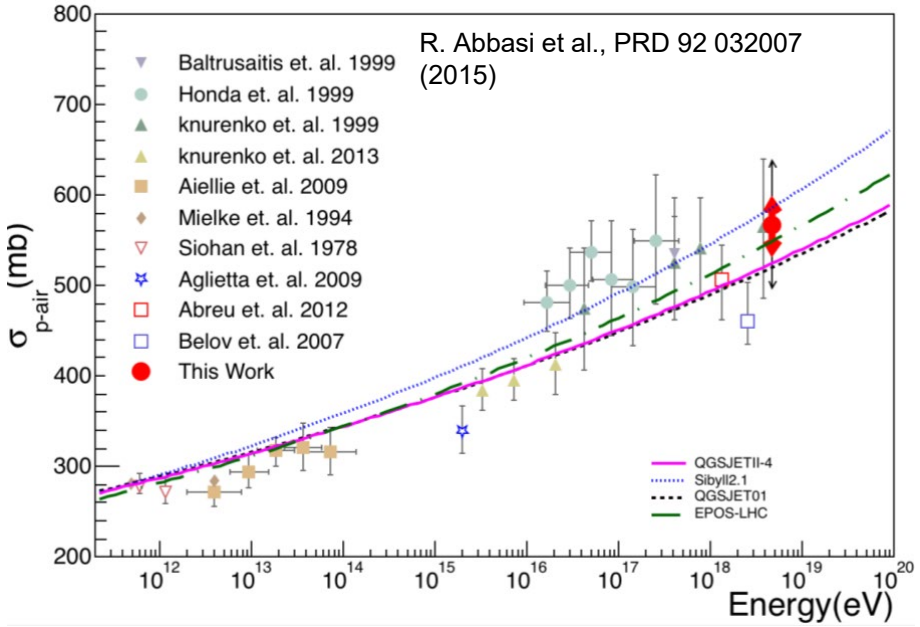
ICRC2021



P-air Inelastic Cross section

- Using deep penetrating shower (proton),
- Mean free path(Λ) is extracted from Xmax.
- The factor k between ratio extracted Λ and true mean free path $\Lambda_{p\text{-}air}$ is estimated with MC.
- k's systematic is considered while error estimation



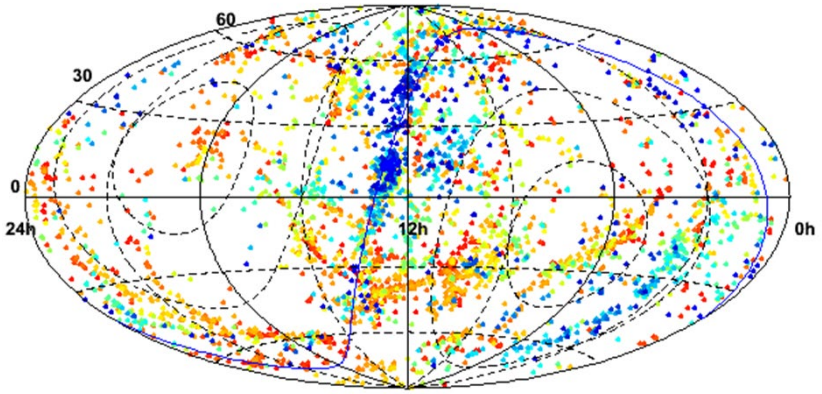


Model	+- 17
20% He	+18
Gamma < 1%	-23
Total	(+25, -29)

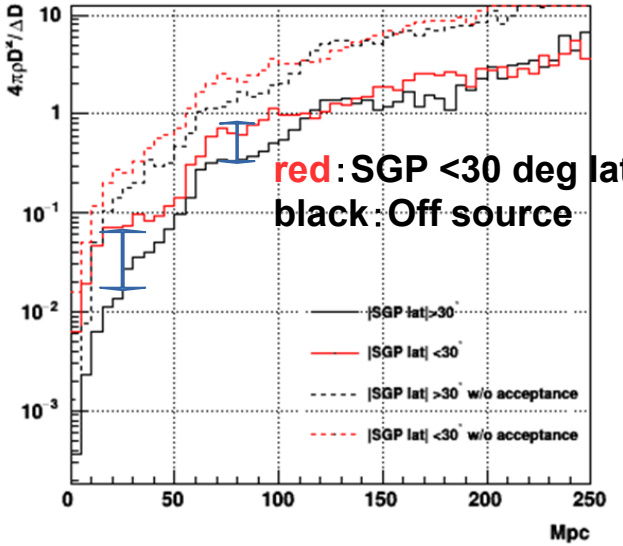
- $\sigma_{p\text{-}air}$(inelast.) @ 95TeV of √S is 567.0±70.5[Stat.] (+25,-29)[Sys.] mb
- The value observed is between EPOS-LHC and Sibyl2.1.

Anisotropy

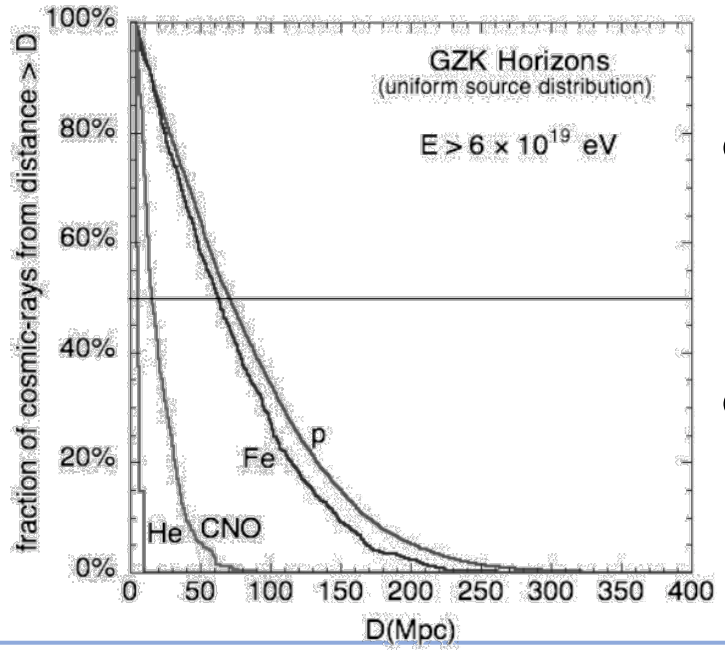
2MRS catalogue D<75Mpc
Blue～Red corresponds to 0～75Mpc



Relative amount of objects
(in 2MRS , efficiency corrected)

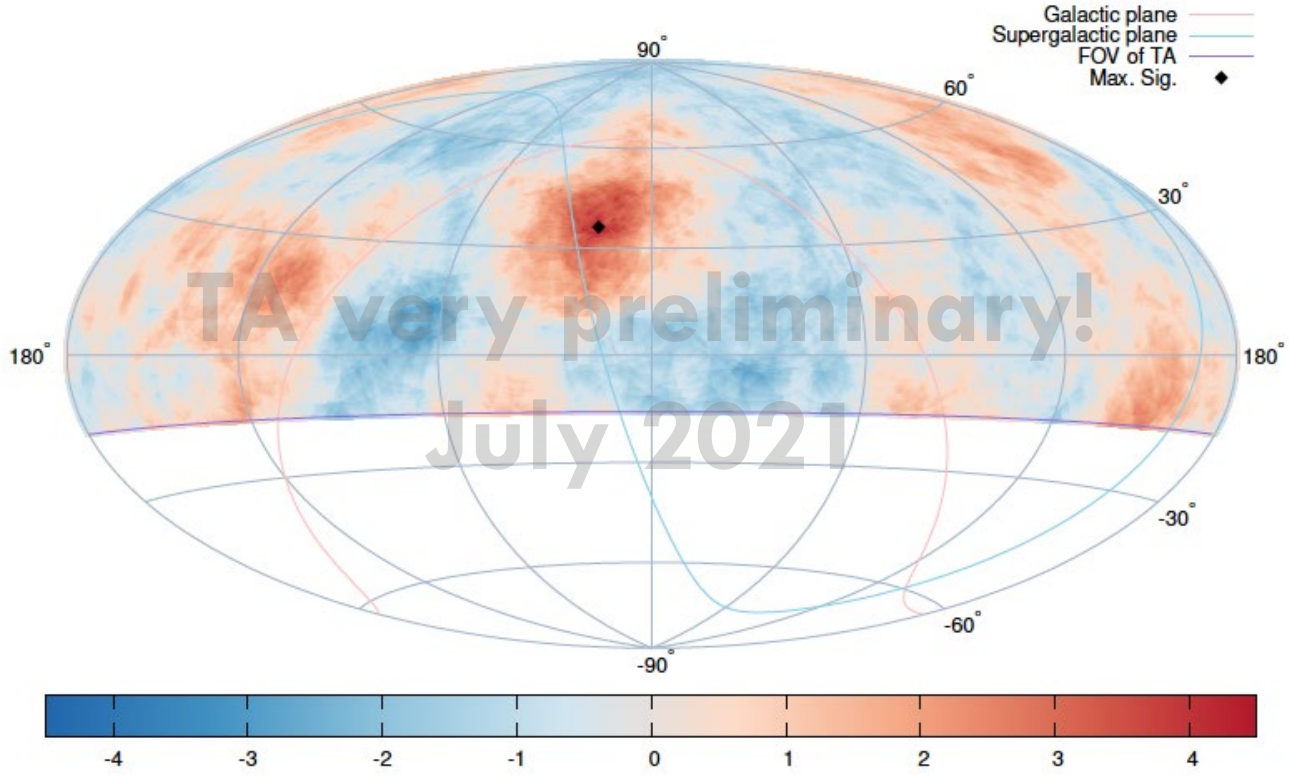


red : SGP <30 deg lat (On source)
black : Off source



- Matter distribution within 100Mpc differ between direction of SGP and other.
  - Spectrum modulation differ due to different matter distribution.
- The attenuation depends on composition.
  - Anisotropy in energy spectrum
  - Anisotropy in composition

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



Skymaps in the equatorial coordinates

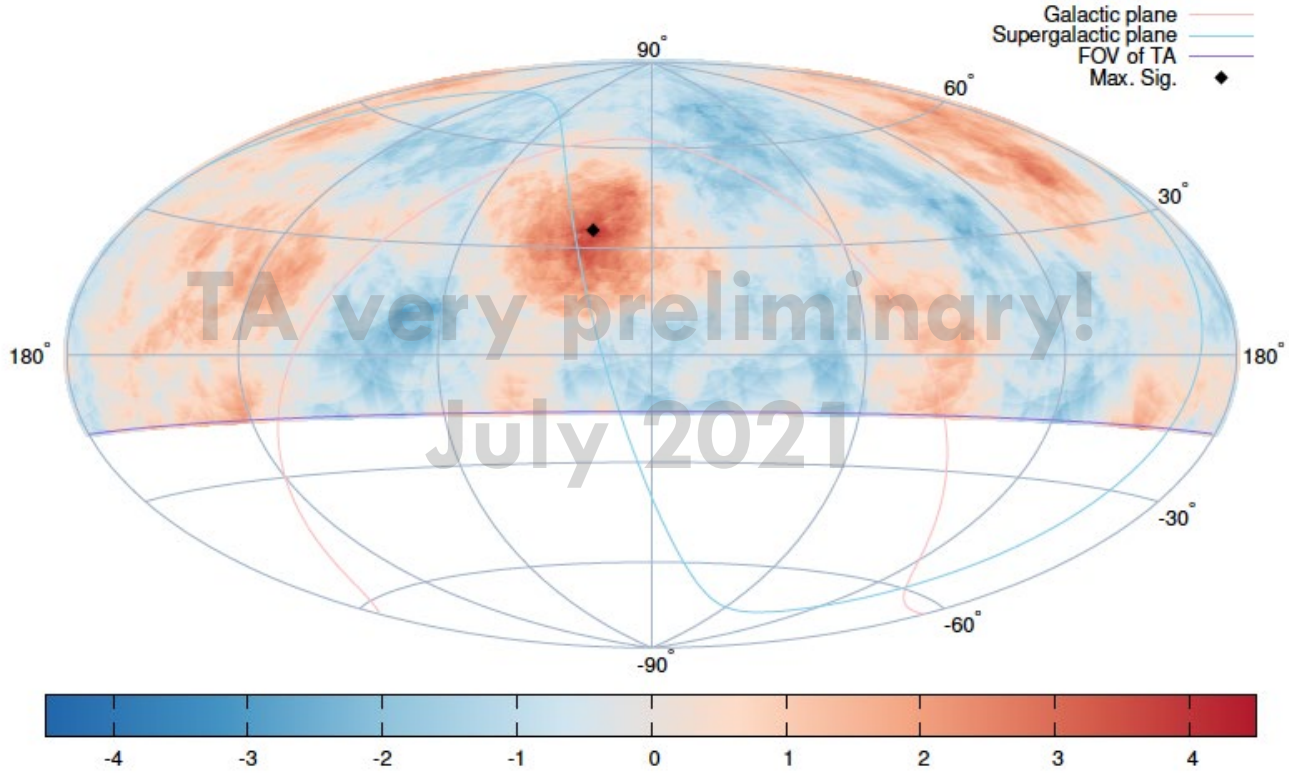
- 864 events with E ≥ $10^{19.4}$ eV (11-year TA SD data)
- Maximum local significance: 4.4σ at (17.4°, 36.0°)

  Observed: 85 events

  Expected from isotropy: 49.5 events

  } ~72% excess to the isotropy

New excess of events with E ≥$10^{19.5}$ eV



Skymaps in the equatorial coordinates

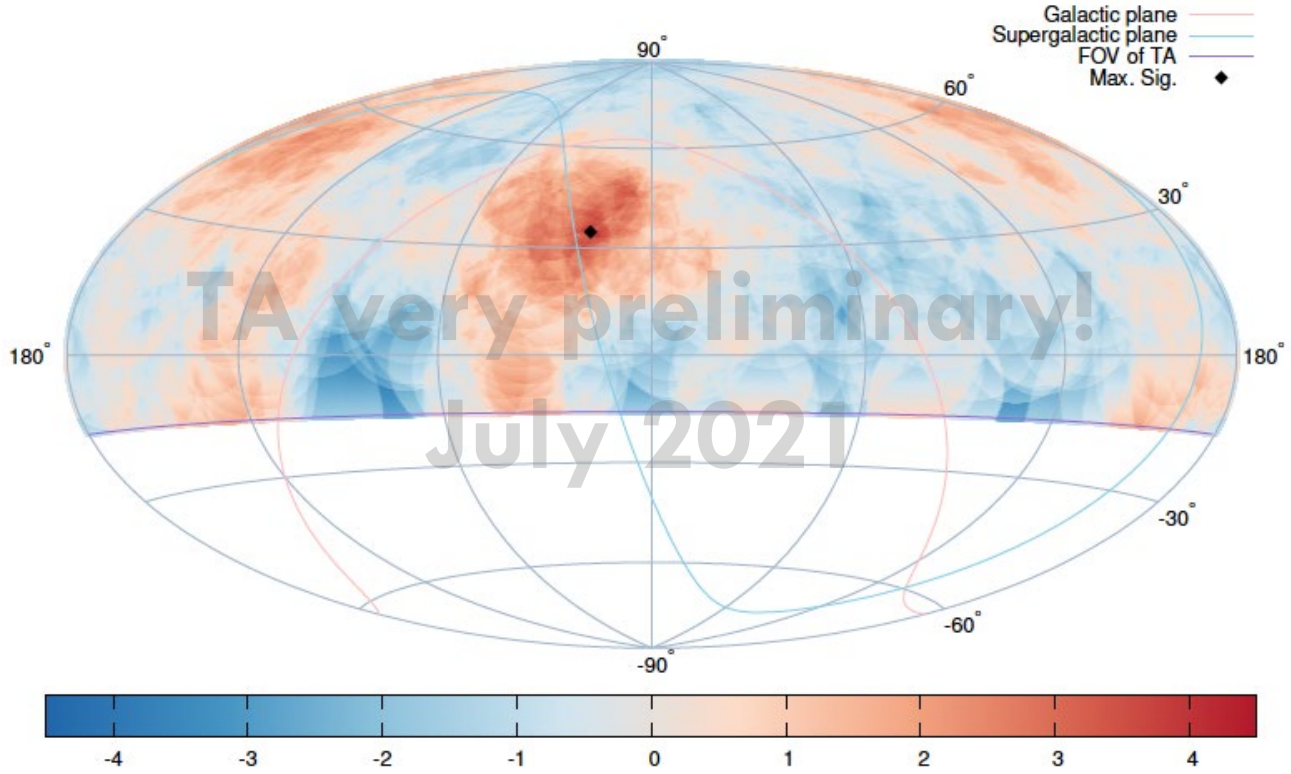
- 558 events with E ≥ $10^{19.5}$ eV (11-year TA SD data)
- Maximum local significance: 4.2σ at (19.0°, 35.1°)

  Observed: 59 events

  Expected from isotropy: 31.5 events

  } ~87% excess to the isotropy

New excess of events with E ≥$10^{19.6}$ eV



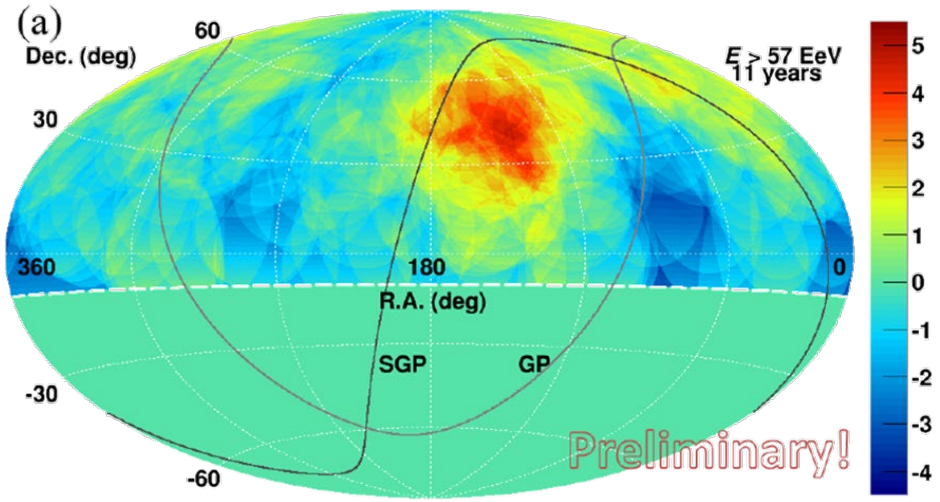
Skymaps in the equatorial coordinates

- 335 events with E ≥ $10^{19.6}$ eV (11-year TA SD data)
- Maximum local significance: 4.0σ at (19.7°, 34.6°)

  Observed: 39 events

  Expected from isotropy: 18.6 events } ~110% excess to the isotropy

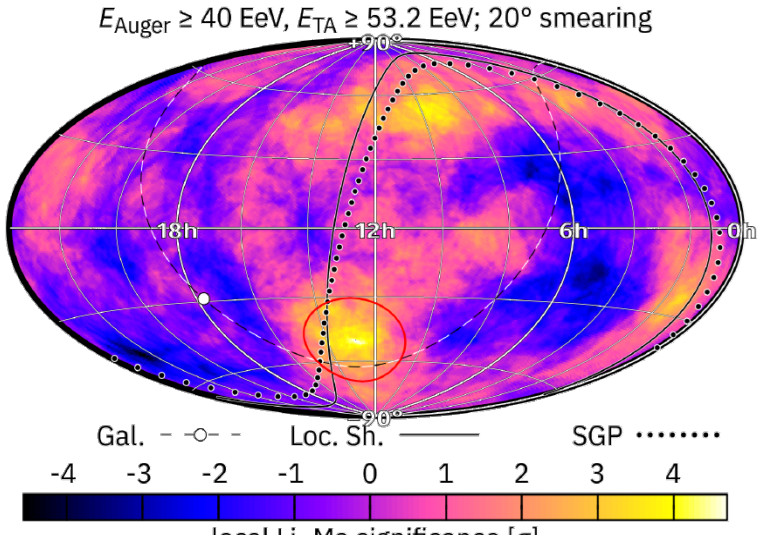
Anisotropy $E>10^{19.7}$



K. Kawata, PoS ICRC2019 (2020) 310

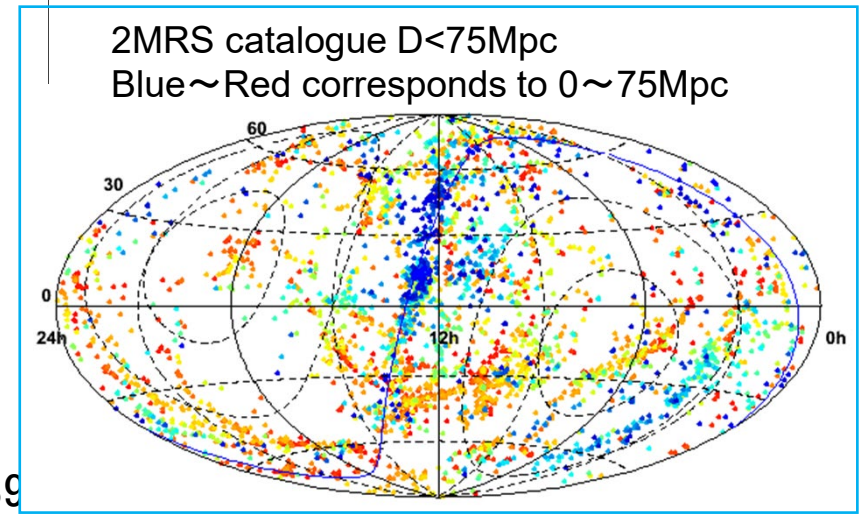
TASD 11yr data

- 168 events with E > 57 EeV
- 38 events in hot-spot 25° radius (expect 14.2 events),
- local 5.1σ significance(Li-Ma)
- 2.9σ global



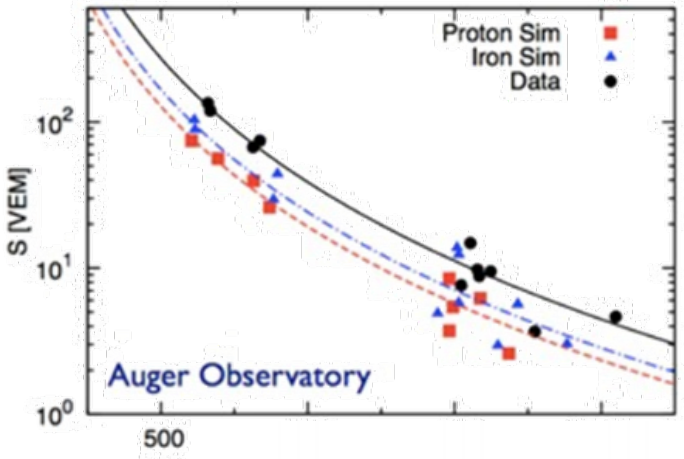
Anisotropy working group, PoS ICRC2019 (2020) 439

- Joint analysis with Auger group



Muon excess

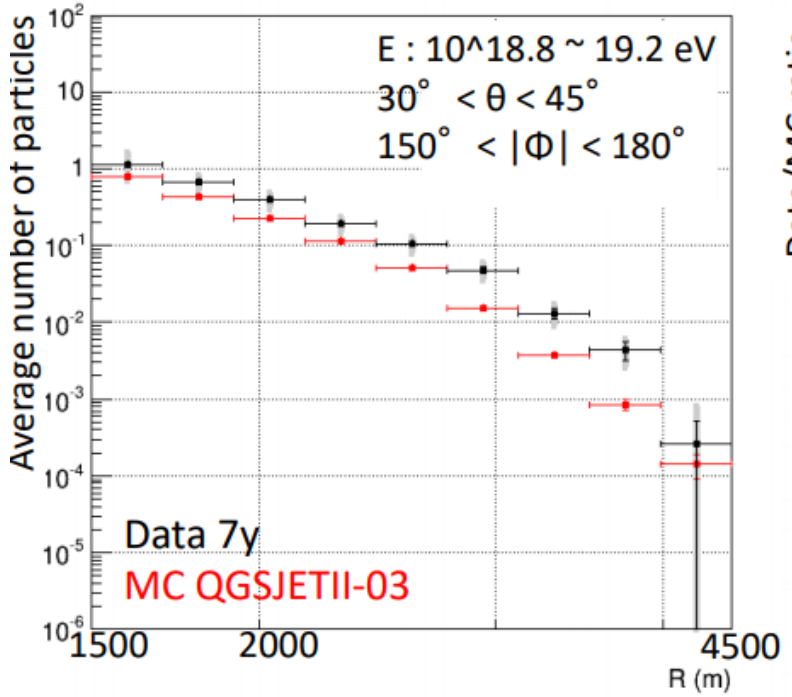
R. Takeishi

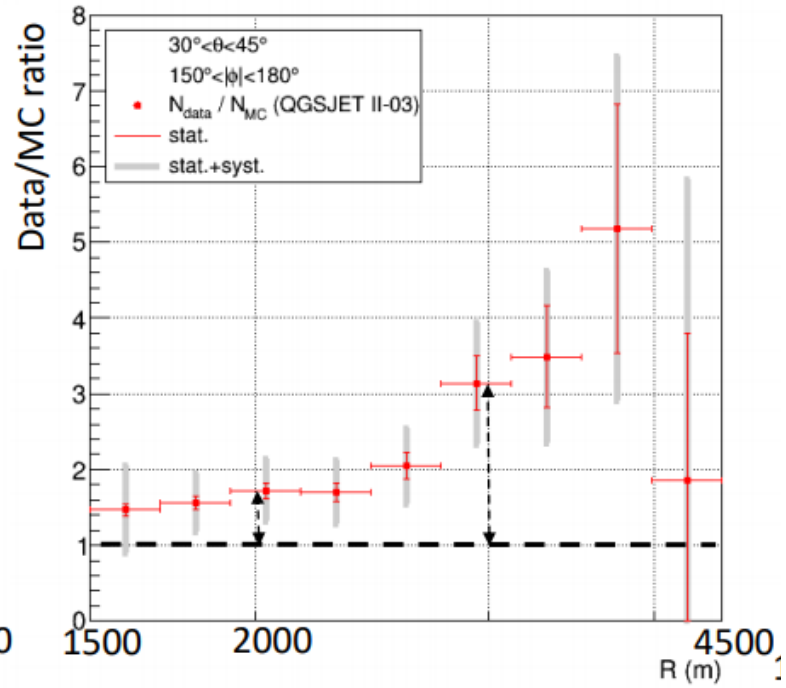


- Lateral distribution on condition μ purity 60~70% and data/MC ratio
- Data is larger than MC by more than 1.5 times, with R dependence.

  1.72±0.10(stat.)±0.40(syst.) (1910 m < R < 2160m) (1.8σ)

  3.14±0.36(stat.)±0.72(syst.) (2760 m < R < 3120m) (2.7σ)
- Larger difference at larger R





Anisotropy study w magnetic field

R.Higuchi , ICRC2021

UHECR anisotropy

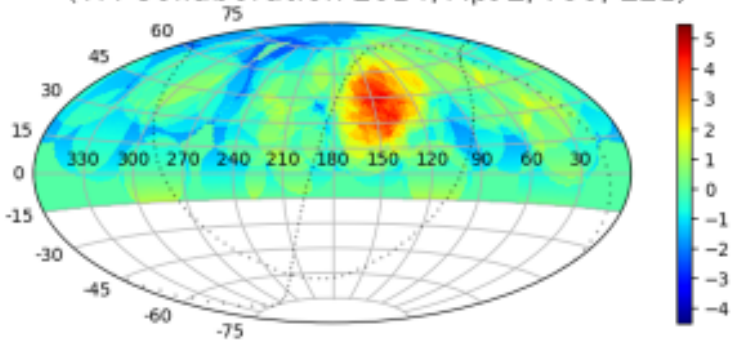
- Anisotropy of UHECR arrival direction
  - Hotspot (TA)
  - Warm spot (Auger)

  => Correlation with the UHECR source distribution?
- Possible candidates
  - Starburst galaxies (SBG)
  - Active galactic nuclei (AGN), etc…
- Correlation studies (Auger/TA collaborations 2018)
  - Observed UHECR arrival directions
  - CR flux model of possible candidates

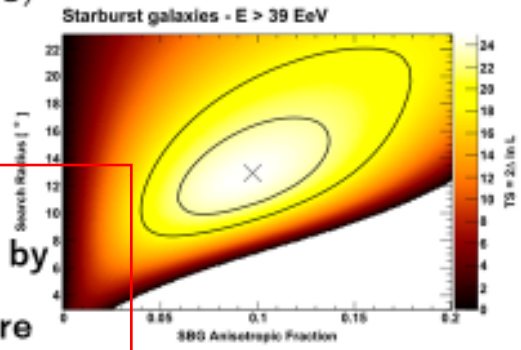
  =>Nearby SBGs contribute 10% of anisotropy ?

- **Items discussed in this study:**
  - **Rigidity ($R = E/Ze$) dependent coherent deflection by GMF**
  - **Rigidity spectrum of UHECRs (here only proton pure case)**
- **Questions:**
  1. **How much bias in the parameter estimation w/ and w/o GMF, North and South?**
  2. **Can we reduce the bias by considering GMF effect in the analysis?**

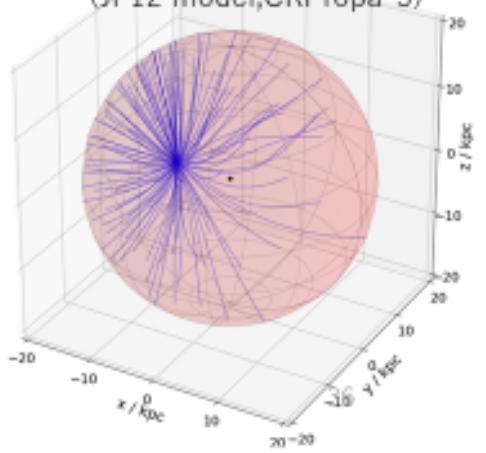
Significance map of TA 5yr data (>57EeV)
(TA Collaboration 2014, ApJL, 790, L21)



TS distribution (Auger 2018)



Trajectory of 10 EeV proton in GMF
(JF12 model,CRPropa 3)



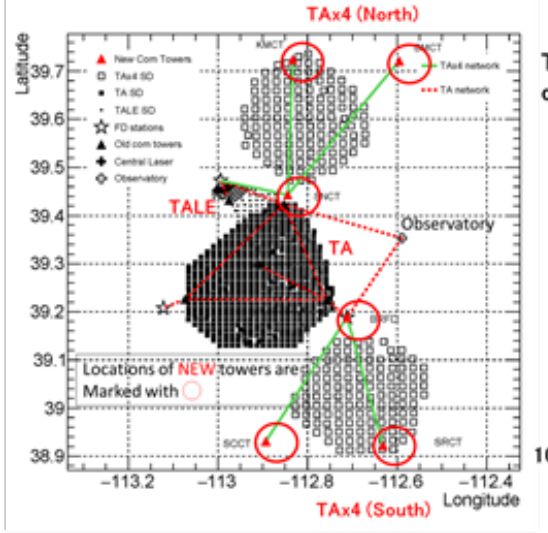
Study on the cosmic ray intensity variation using scintillation counters for air shower observation

T.Nonaka[1], A.Oshima[2], K.Yamazaki[2] for The Telescope Array Collaboration , for The GRAPES-3 Collaboration

1: Institute for Cosmic Ray Research, University of Tokyo 5-1-5 Kashiwanoha Kashiwa Chiba 277-8582 Japan 2: College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan

Telescope Array Detectors

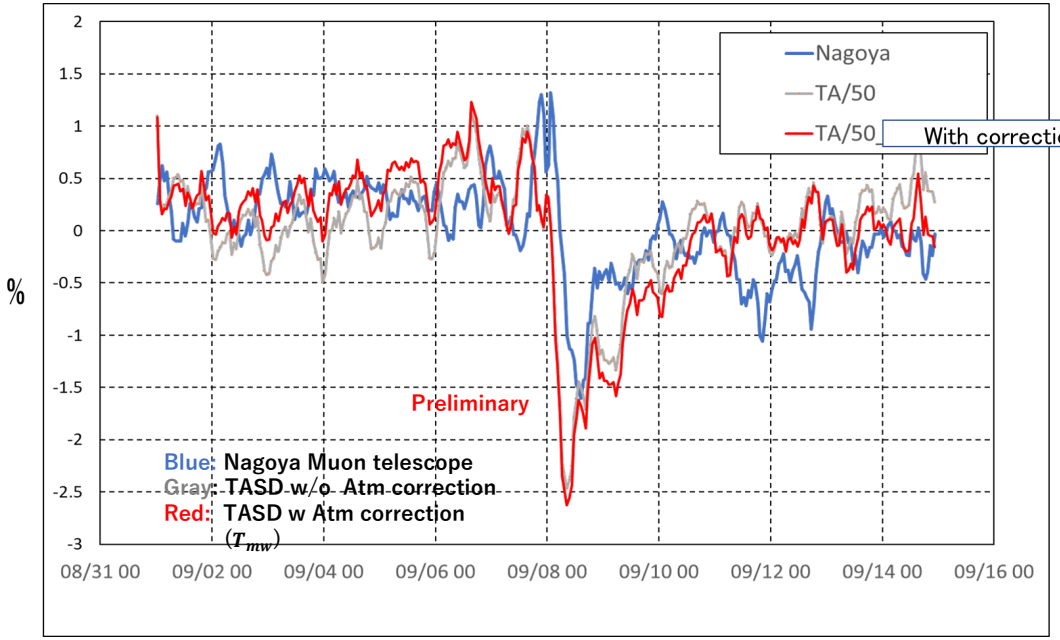
Total detector area for atmospheric muon : 1500 m^{2+}



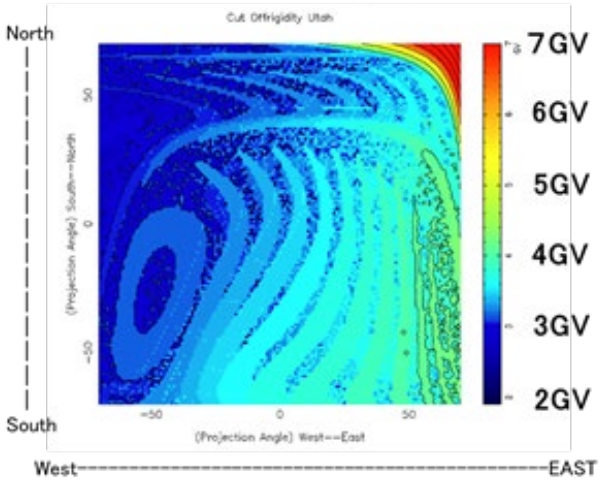
Three observations of different energies

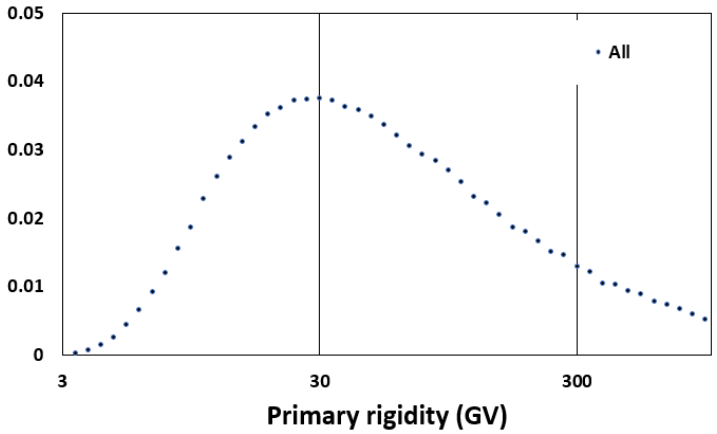
- TA
  - $10^{18}eV \sim 10^{20}eV$
- TALE
  - $10^{16}eV \sim 10^{18.5}eV$
- TAx4
  - $10^{19.7}eV \sim 10^{20}eV$

TASD:
- Large area surface → collect scintillation light with WLS fiber
- Thin schinchlator →Low threashold. (~30MeV)
- Sensitive to EM / Mu



Geomaginetic Cutoff : 3GV @vertical



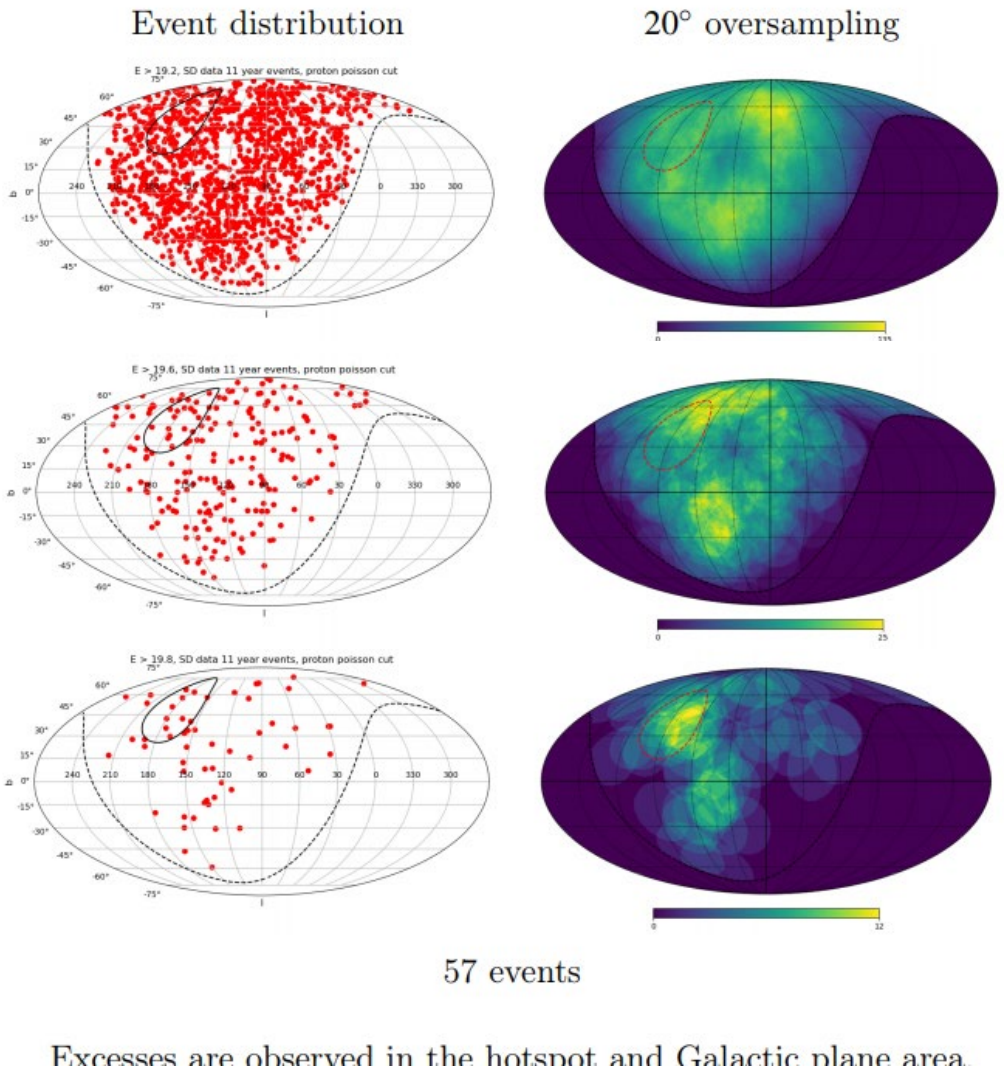


Summary

Using Telescope Array Surface Detector , we obtained data comparable with other observations.

- ✓ Total detector area 1500m^2
- ✓ Maximum time resolution 1min
- ✓ Count rate $\sim \frac{750\text{Hz}}{3m^2}$
- ✓ Trigger threshold : $\sim 20 - 30Mev\ for\ electron, muon$
- ✓ Geomagnetic cut off $3GV@vertical$
- ✓ MedianRigidity: 40GV

Anisotropy in composition

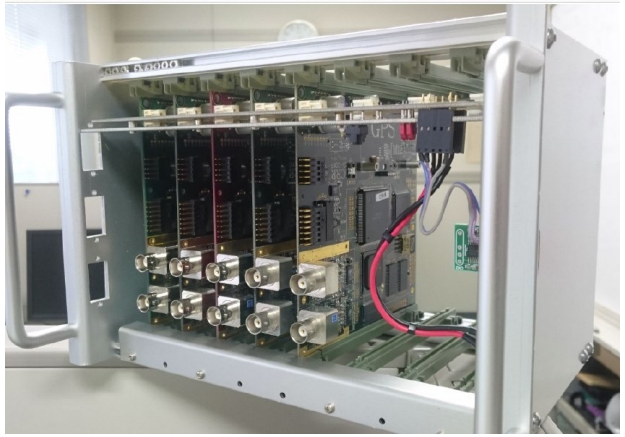


- Proton-like events were selected with ξ parameter used for composition study.(Phys. Rev. D 99, 022002 (2019))
- GMF is considered
- Left panel is selected events. Right panel is significance of excess from expectation of uniform distribution.

R and D studies for new detector

T. Nonaka +TA collaboration
+ F. Saraddin , Carload School of Mine

- **Simultaneous observation by Auger SD and TA SD**
- **Upgrade of Firmware DAQ software.**



Summary

- TelescopeArray Experiment
  - Northrn hemisphere , Energy range $10^{16.5}$–10^{20}
  - Hybrid observation since 2008
  - TAx4 array started observation from 2019. (K.Fujisue)
- Spectrum , Composition (Xmax), (H. Shin)
- Anisotropy, GMF effect in Anisotropy (R. Higuchi)
- Anisotropy in spectrum
  - Solar activity, E-field effect