



# Telescope Array Group

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High energy cosmic ray research division

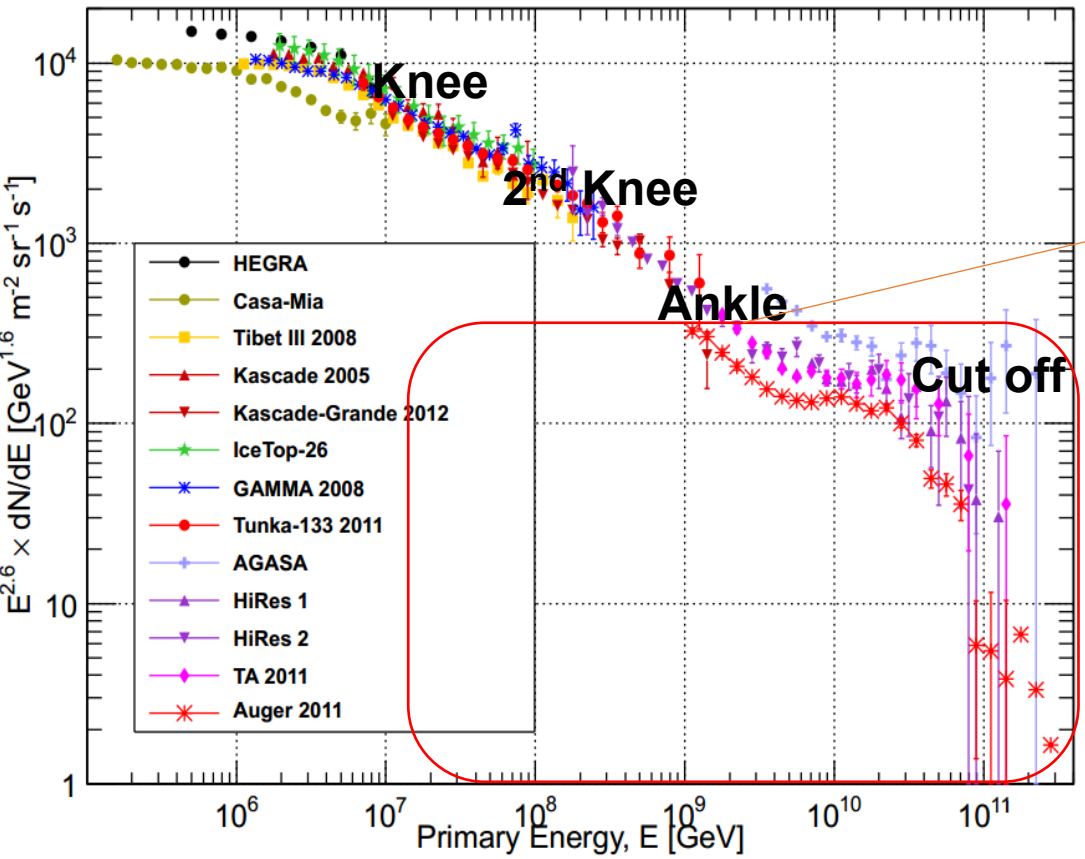
Institute for Cosmic Ray Research

ICRR Young Researchers

Workshop

# Cosmic Ray Energy Spectrum

Cosmic ray energy spectrum  $10^{15}\text{eV} - 10^{20}\text{eV}$



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

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

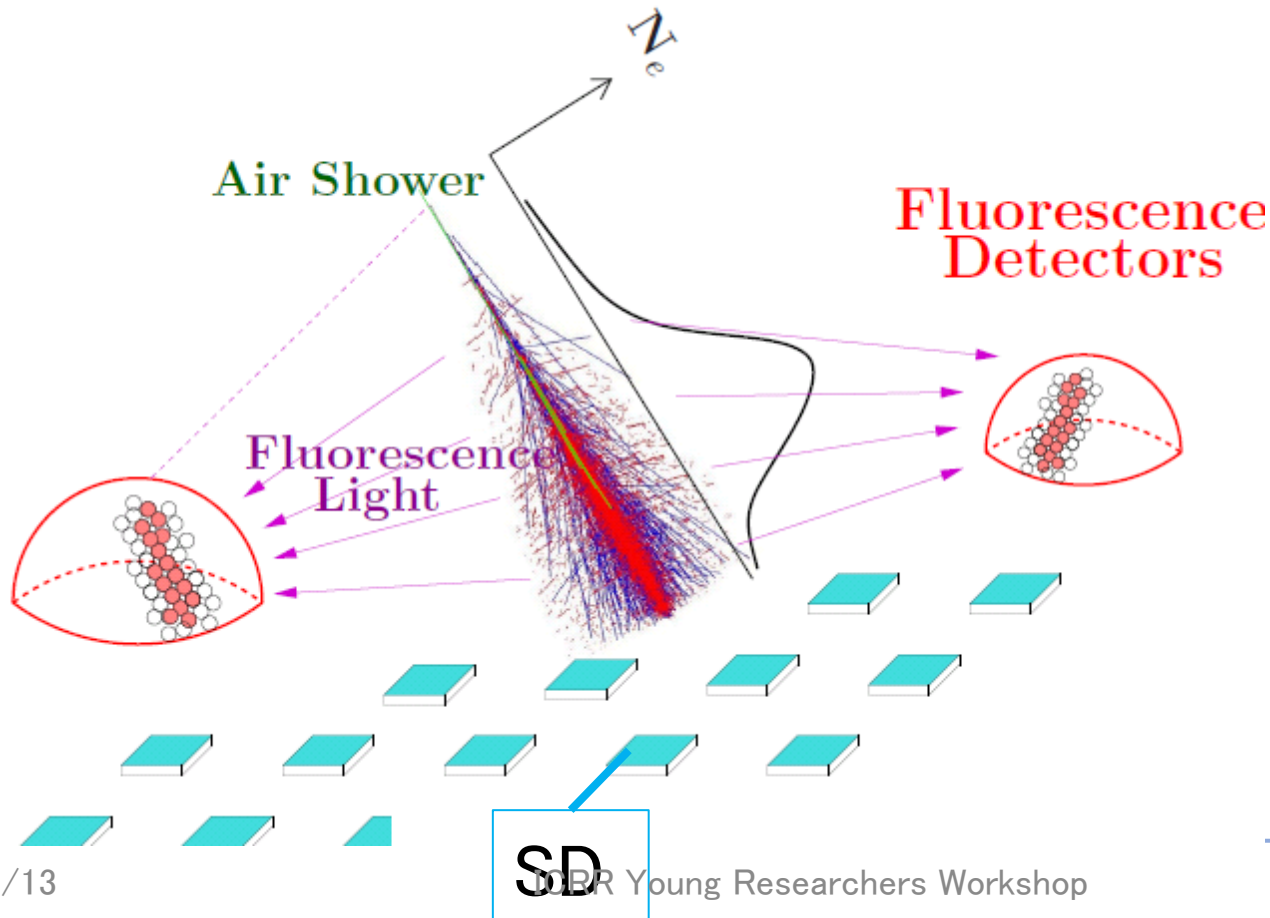
We are observing this energy region

- Northern hemisphere : TA
- Southern hemisphere : Auger

# Hybrid observation

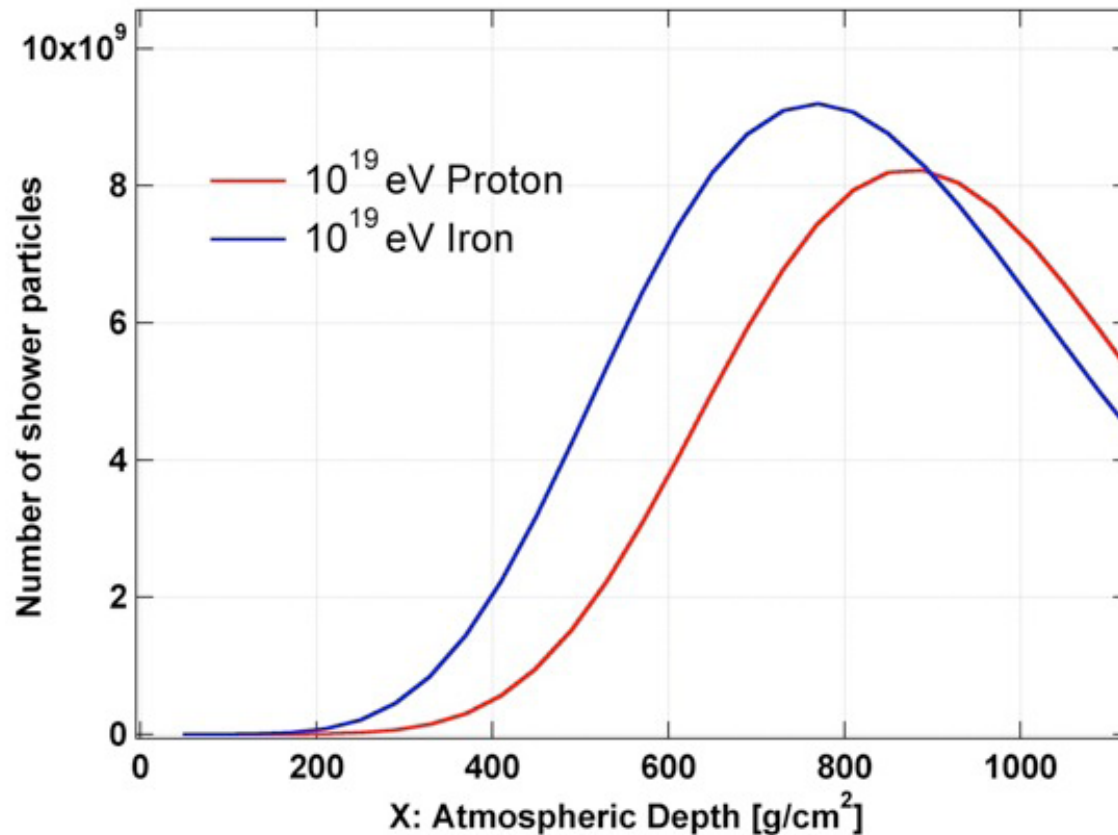
Fluorescence light from air shower (emitted light all direction).

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



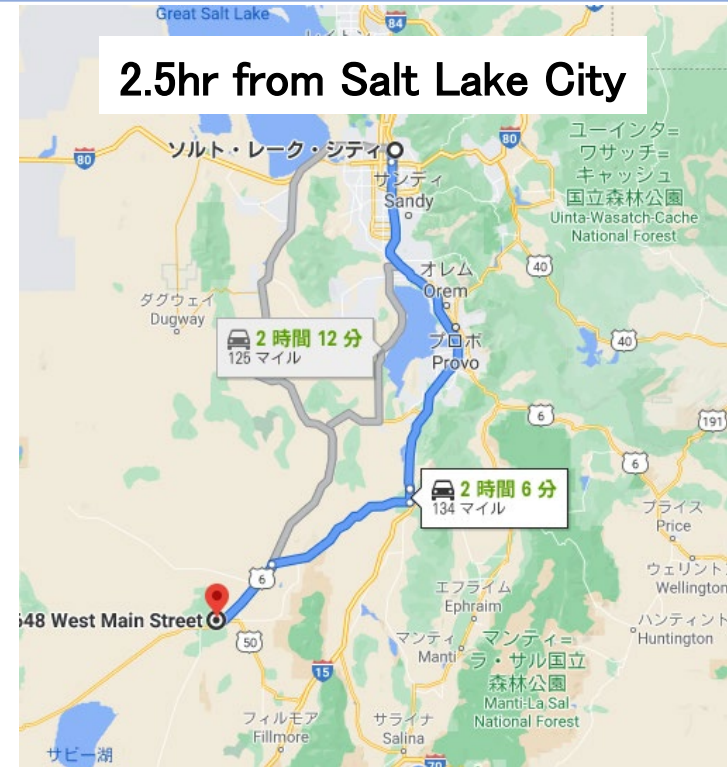
# X<sub>max</sub>, chemical composition

The depth at maximum development (X<sub>max</sub>) of shower depends on the type of primary cosmic rays.



# Present observation site

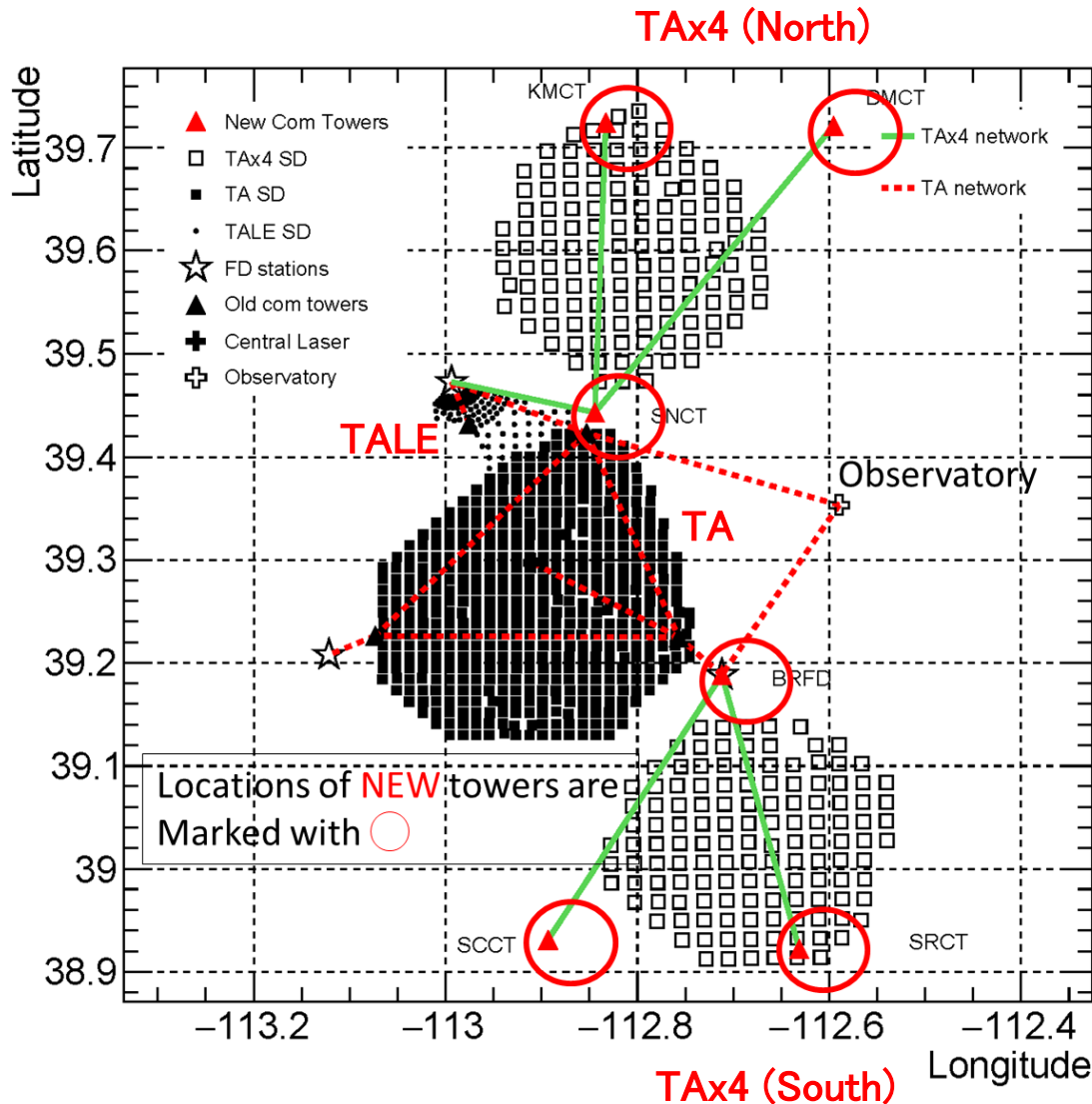
West of Delta City Utah state , USA  
N39° W112° , ~1400 asl



observatory



# Ongoing experiments



## Three observations of different energies

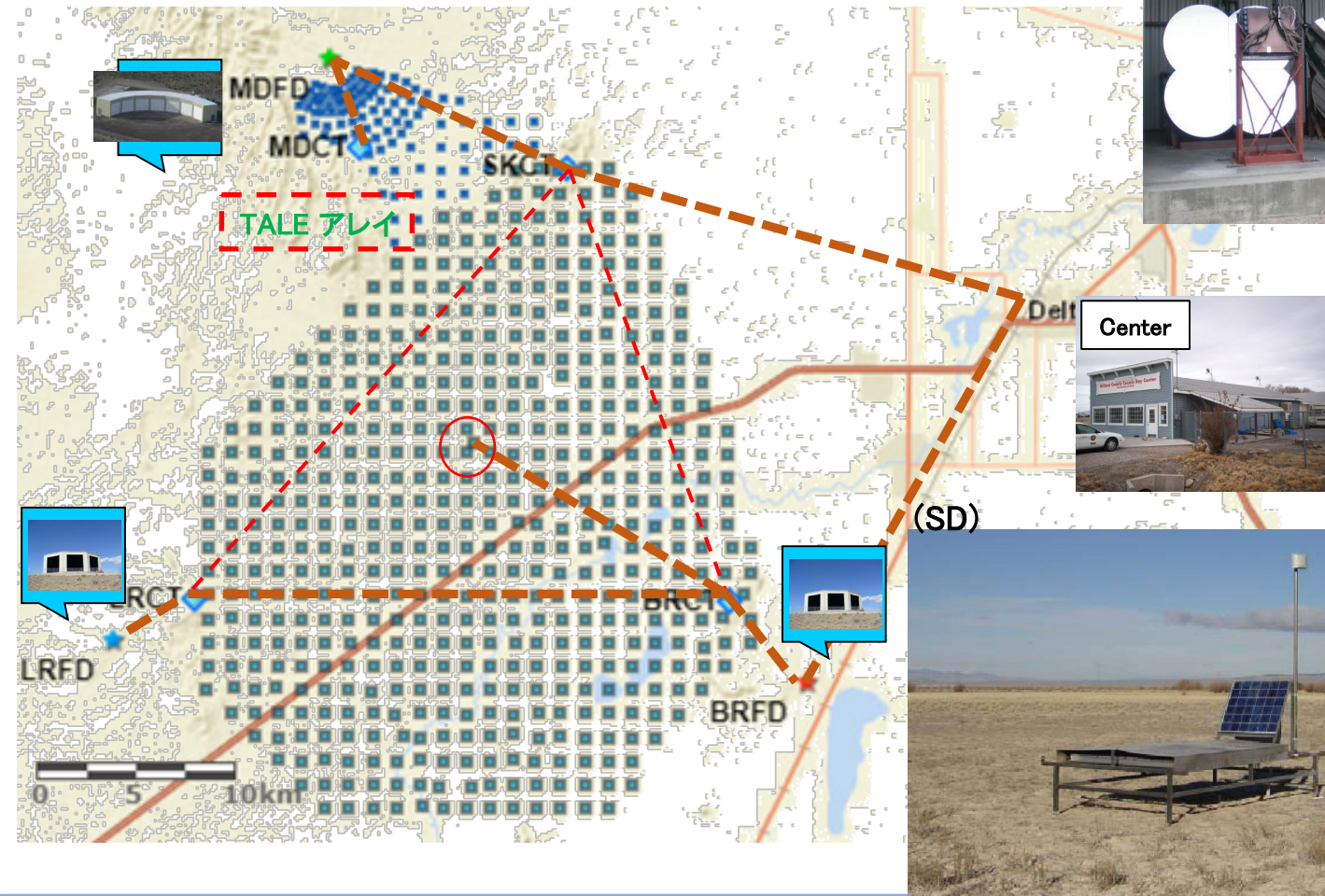
- TA
  - $10^{18} eV \sim 10^{20} eV$
- TALE
  - $10^{16} eV \sim 10^{18.5} eV$
- TAx4
  - $10^{19.7} eV \sim 10^{20} eV$

100km x 60 km

# Telescope Array (TA)

- Fluorescence telescope (FD) x3site
- Surface detector (SD) x507, 1.2km grid (670km<sup>2</sup>)

(FD)



(SD)

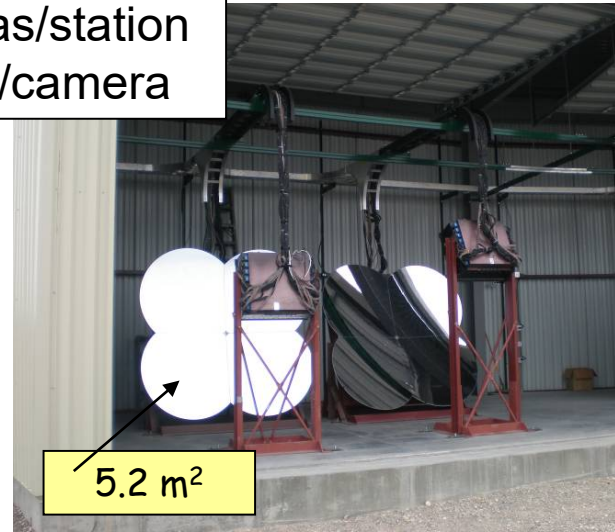


# Telescope Array Fluorescence Detector

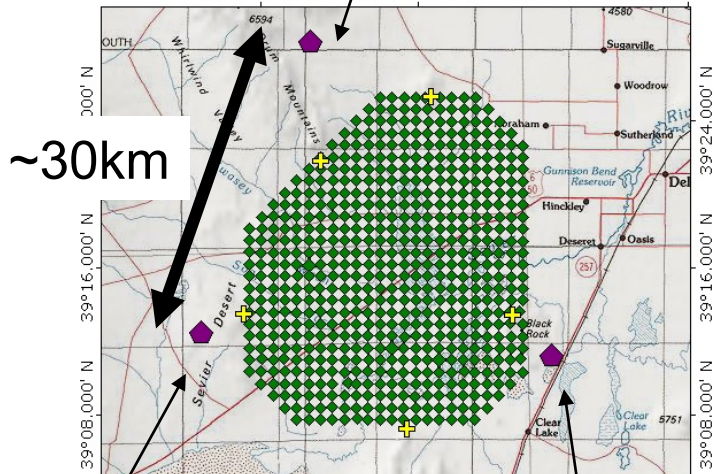
From HiRes

Middle Drum

14 cameras/station  
256 PMTs/camera



TOPO! map printed on 07/12/04 from "StakeJun04-01.tpo" and "Untitled.tpg"  
113°03.000' W 112°52.000' W NAD27 112°33.000' W

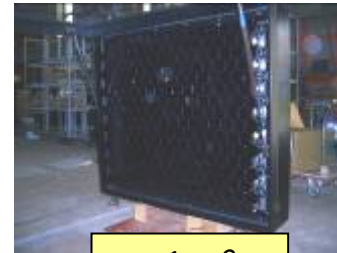


256 PMTs/camera  
HAMAMATSU R9508  
FOV~15x18deg  
12 cameras/station



Long Ridge

Black Rock Mesa



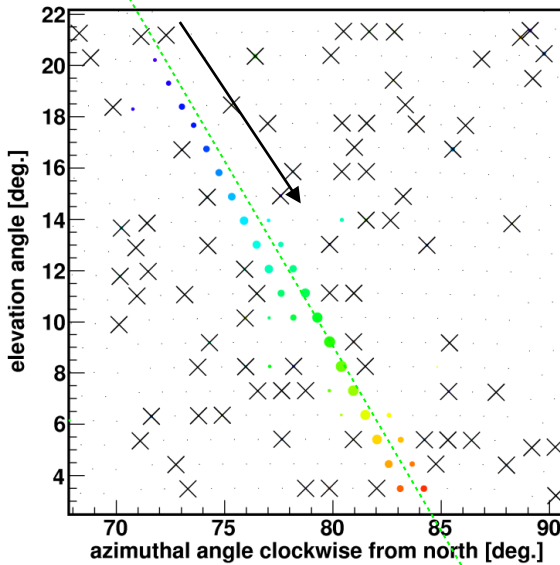
6.8 m²

~1 m²

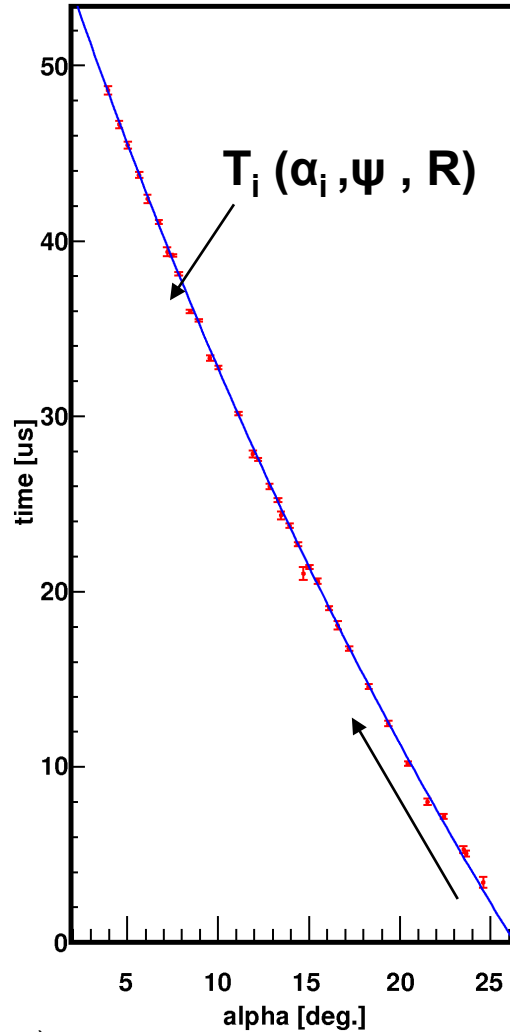


# Telescope Array Fluorescence Detector

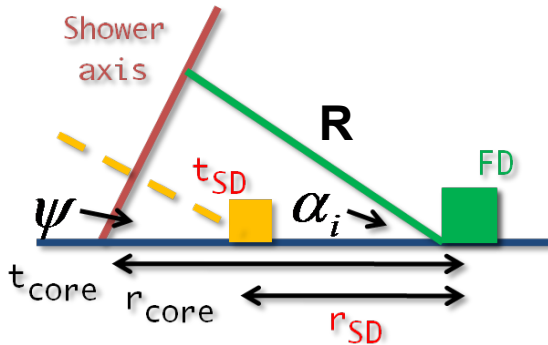
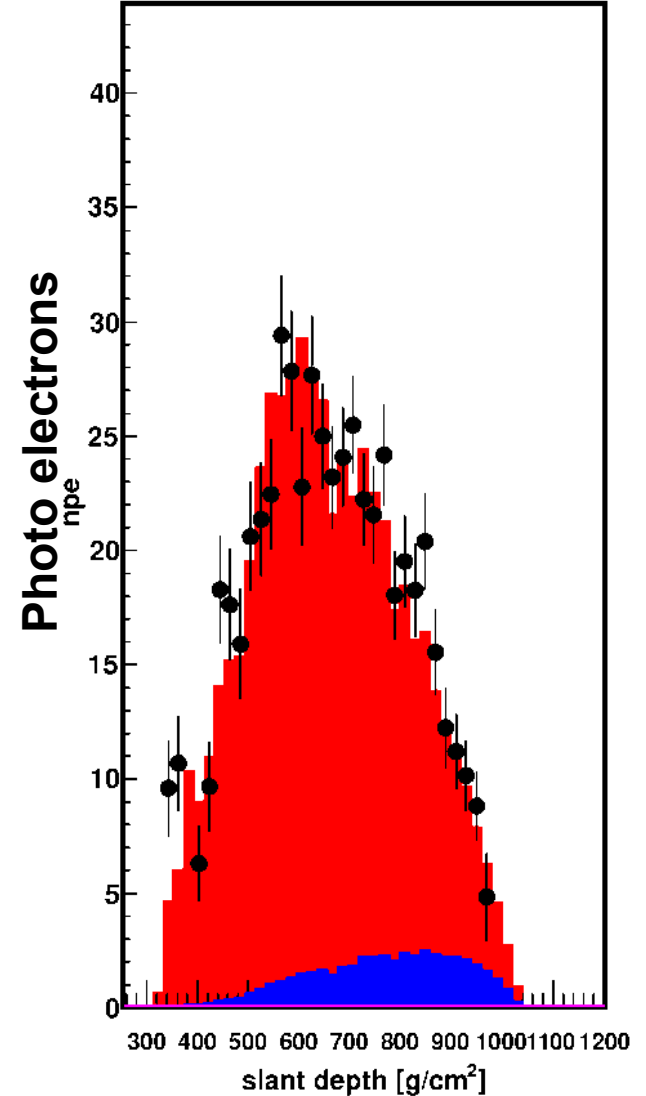
## Hit on Camera



## Geometry



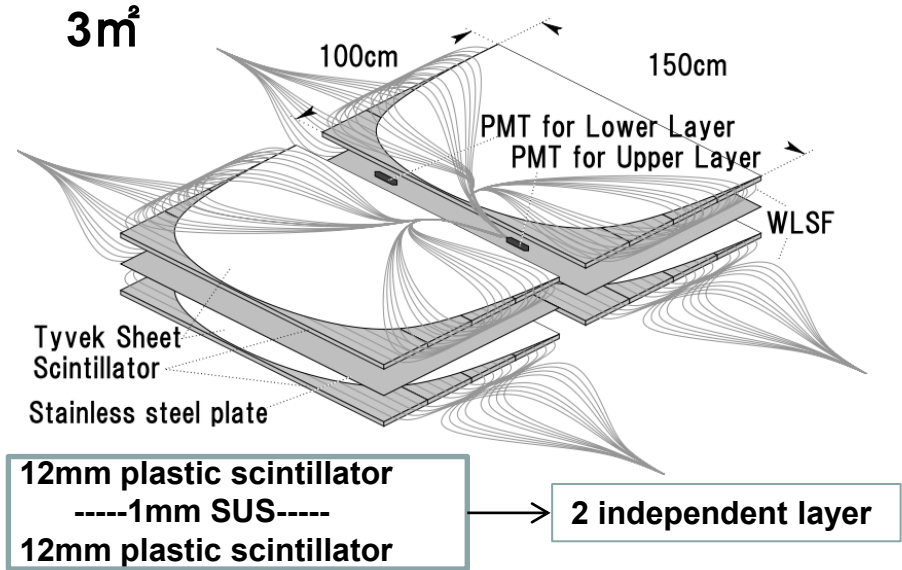
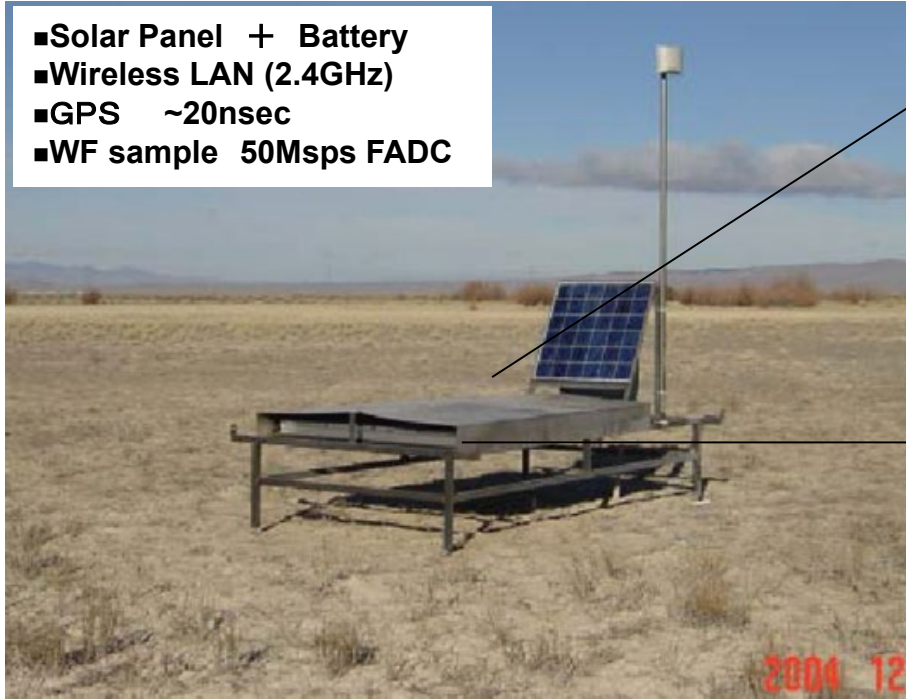
## Energy



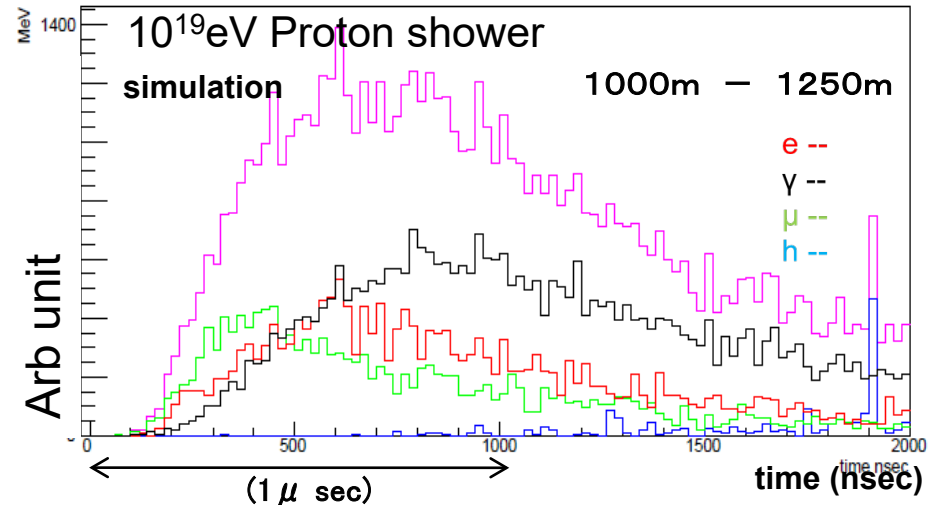
Use SD timing information  $\rightarrow$   
 $\Psi$ ,  $R$  resolution improve (Hybrid analysis)

# Telescope Array Surface Detector

- Solar Panel + Battery
- Wireless LAN (2.4GHz)
- GPS ~20nsec
- WF sample 50Msps FADC



WLSF (475nm) x5m PMT ETL9124SA

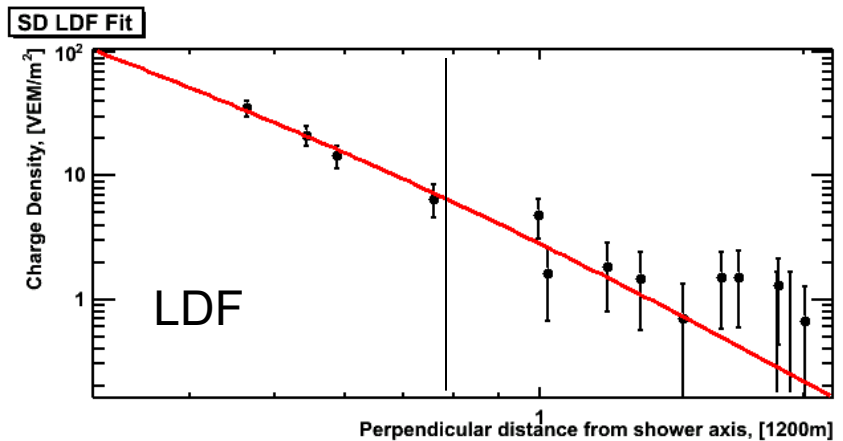
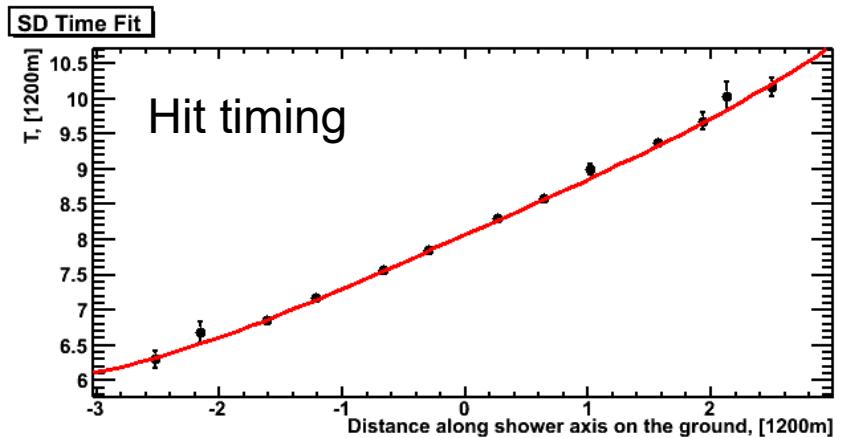
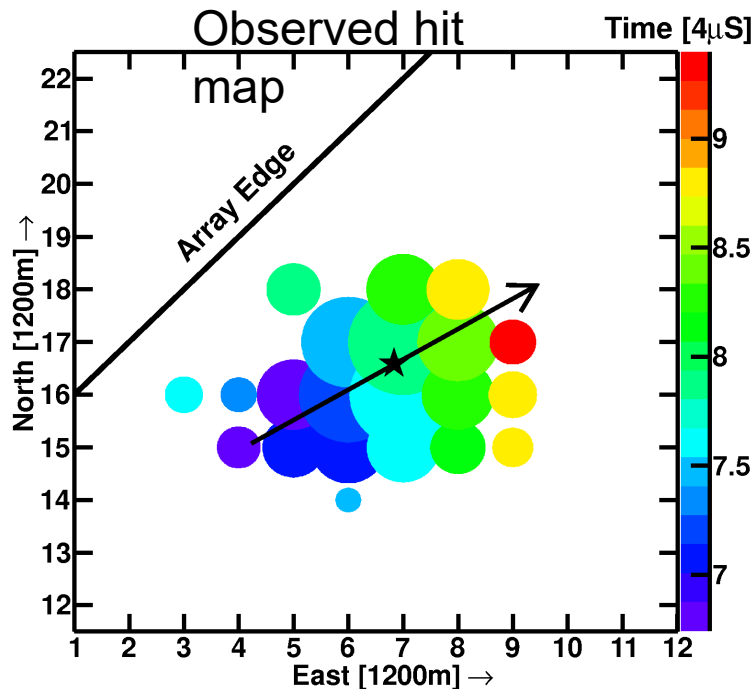


## TASD:

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

# Telescope Array Surface Detector

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



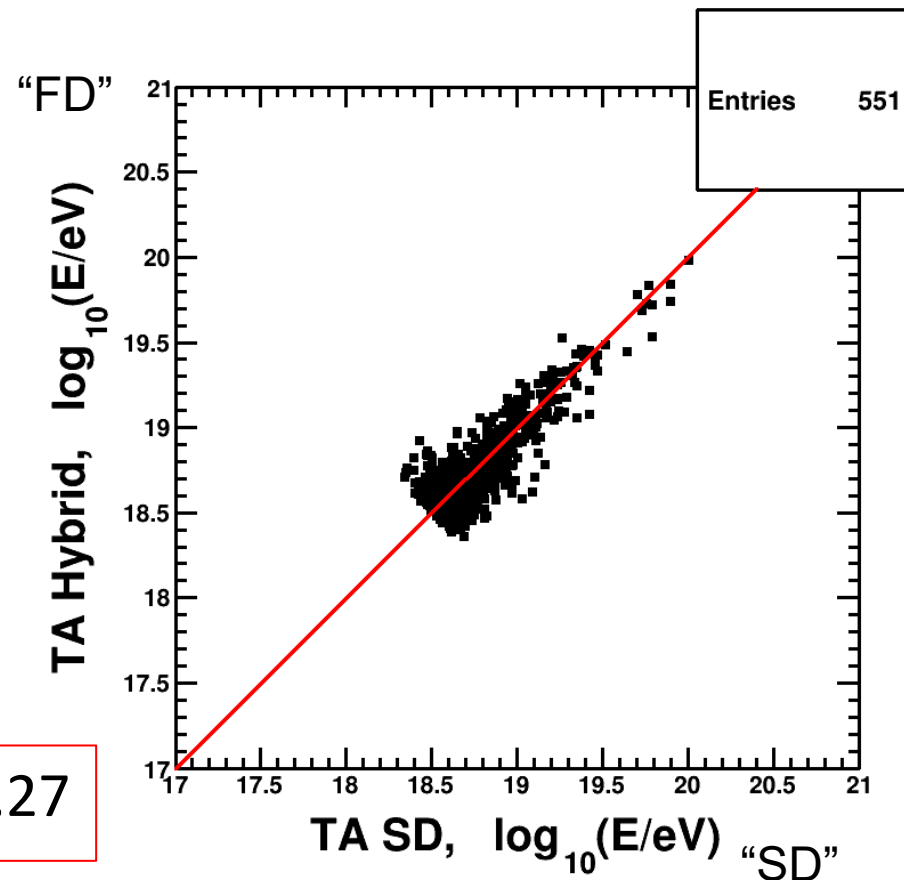
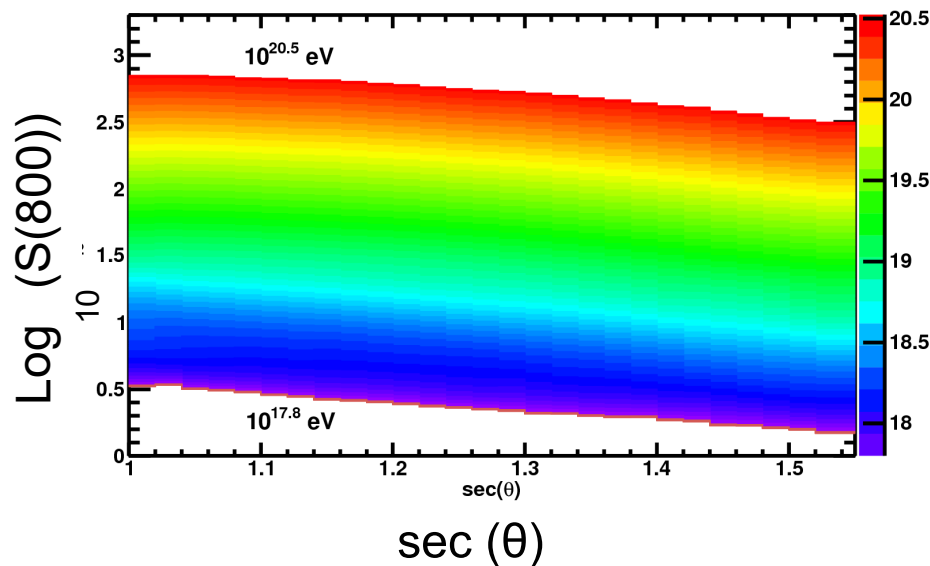
Hit timing :  $\rightarrow$  Arrival direction

Lateral distribution of energy deposit  $\rightarrow$  Energy estimator "S(800)"  
(Energy deposit at 800m)

# Telescope Array Surface Detector

## Energy determination at SD

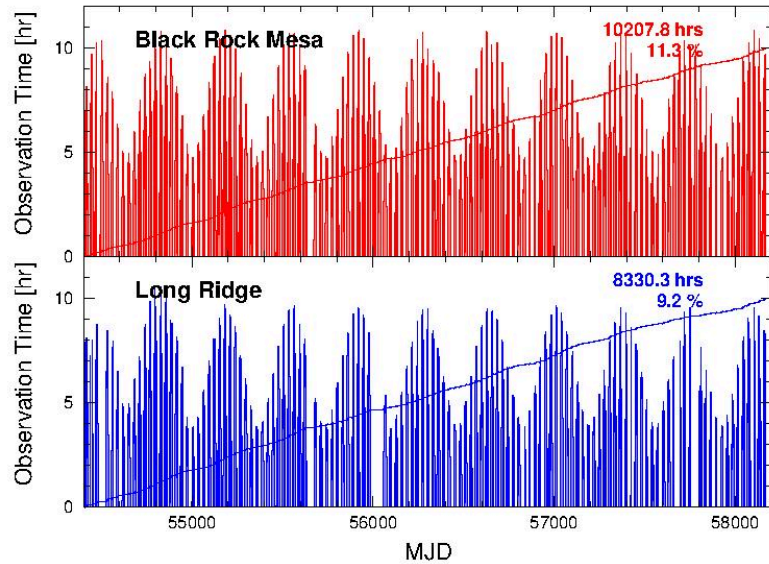
- Look up table generated by “MC”
- FD gives calorimetric energy.
- SD energy obtained by “MC” is calibrated with FD energy obtained at hybrid events.



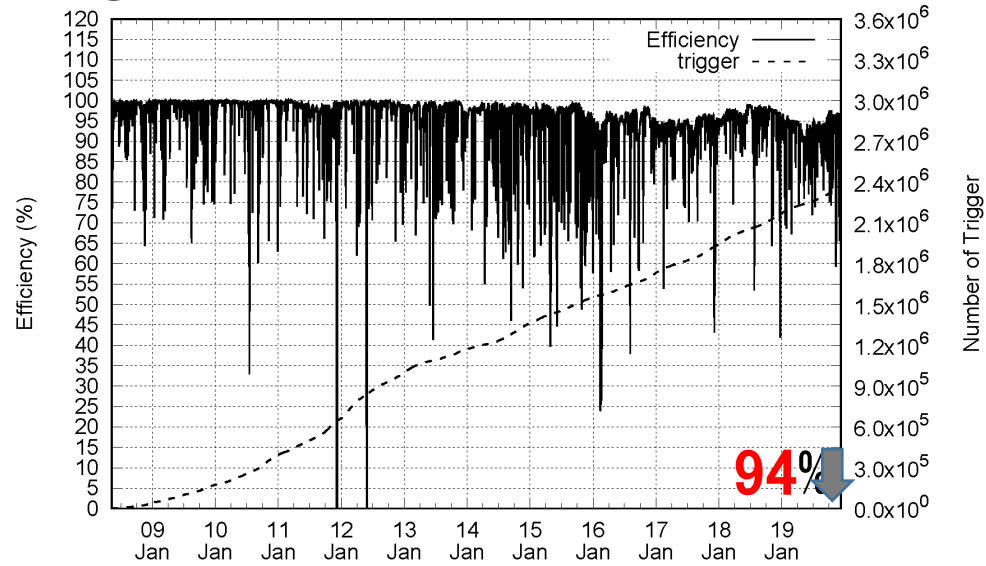
$$E_{\text{FD}} = E_{\text{SDMC}}/1.27$$

# TA operation

FD



SD



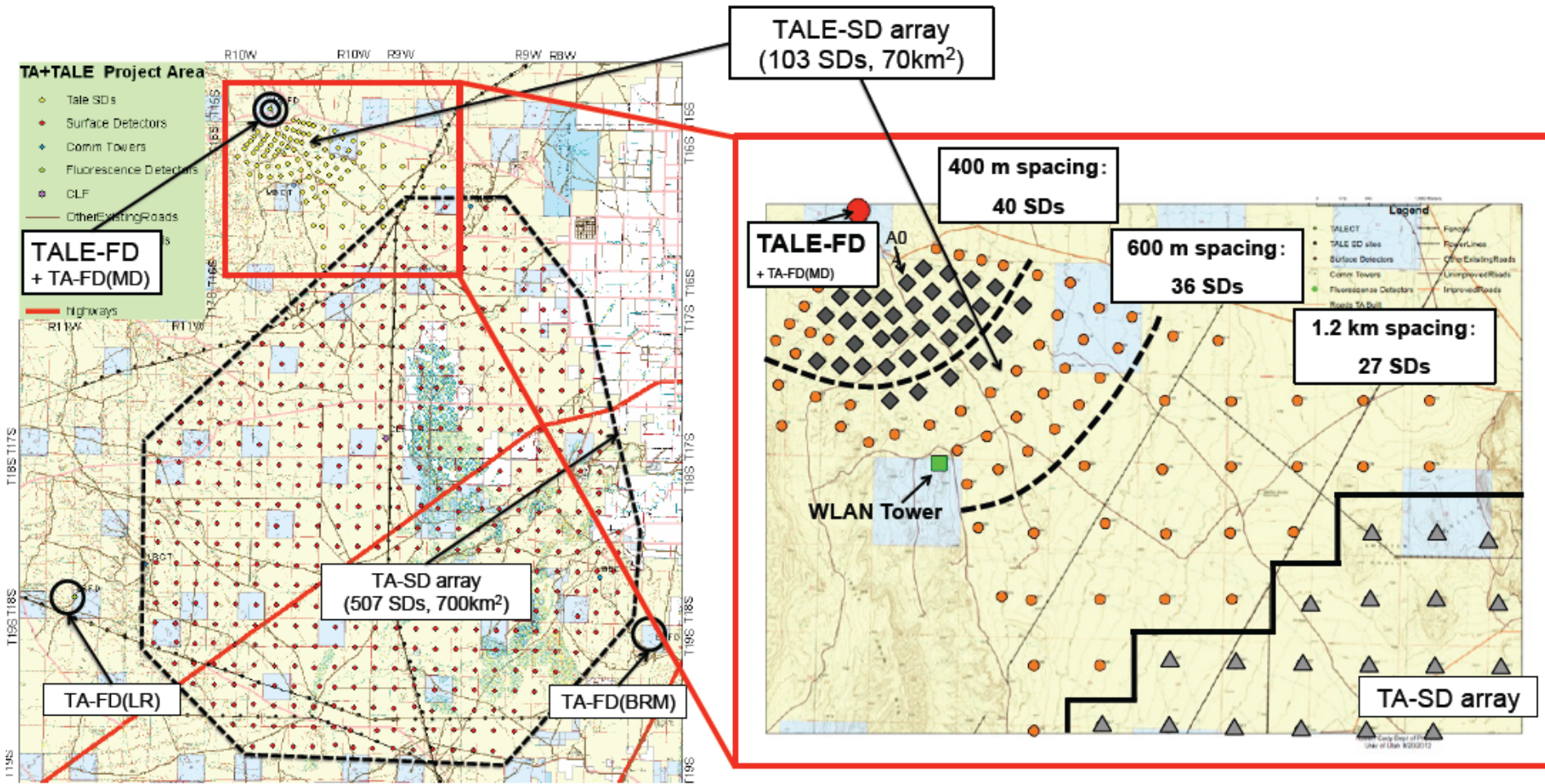
- 2008/05~SD+FD Hybrid observation
- 12 years of data.



# TA Low Energy extension (TALE)

10 new telescopes to look higher in the sky ( $31-59^\circ$ ) 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 ( $31\text{-}59^\circ$ )



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

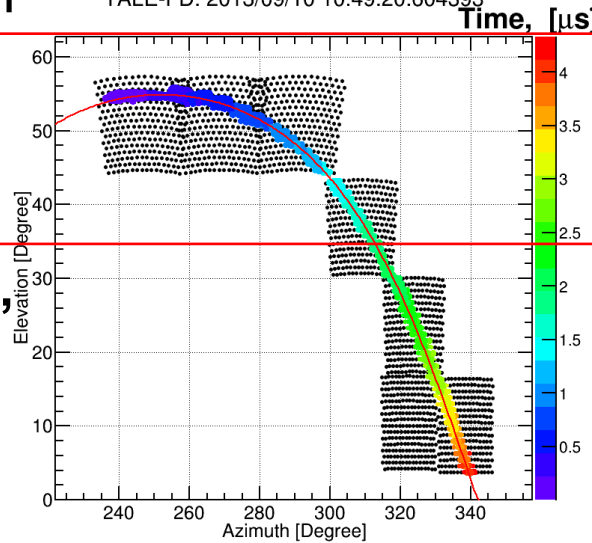
## TALEハイブリッド実験の基本性能

エネルギーしきい値  $\log E = 16.0$   
イベントレート  $\sim 5,000$  事象/年  
← 50,000 事象/年 (SD単体)  
 $\Delta\theta = 1.0^\circ \leftarrow 5.3^\circ$  (FD単眼)  
 $\Delta X_{\max} = 20 \text{ g/cm}^2 \leftarrow 60 \text{ g/cm}^2$  (FD単眼)

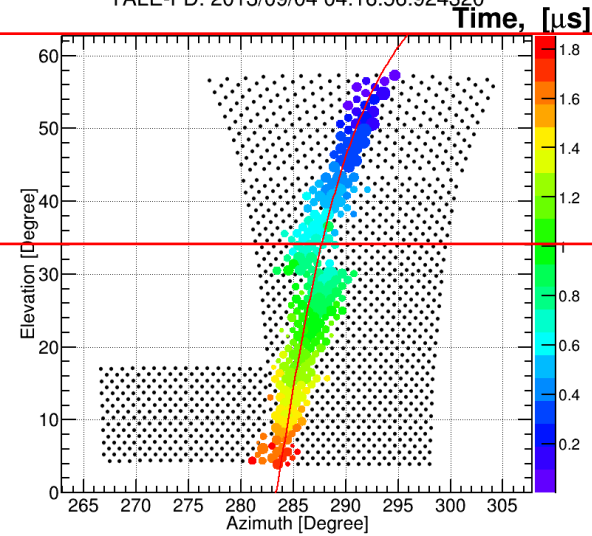
# TALE event display

High elevation  
telescopes

TALE-FD: 2013/09/10 10:49:20.604393

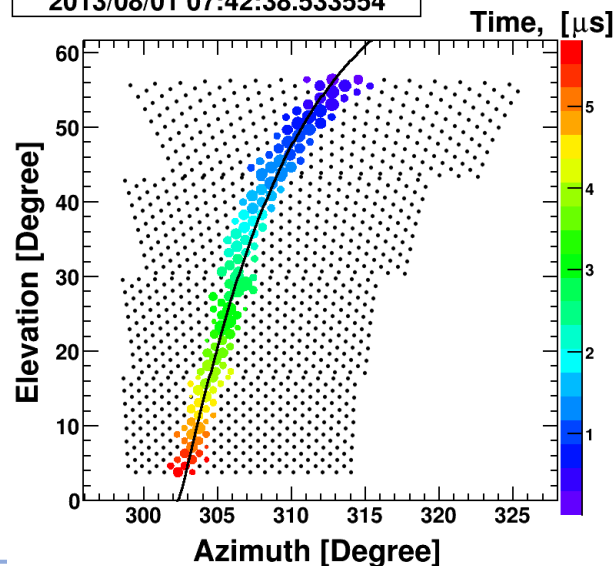


TALE-FD: 2013/09/04 04:16:56.924320



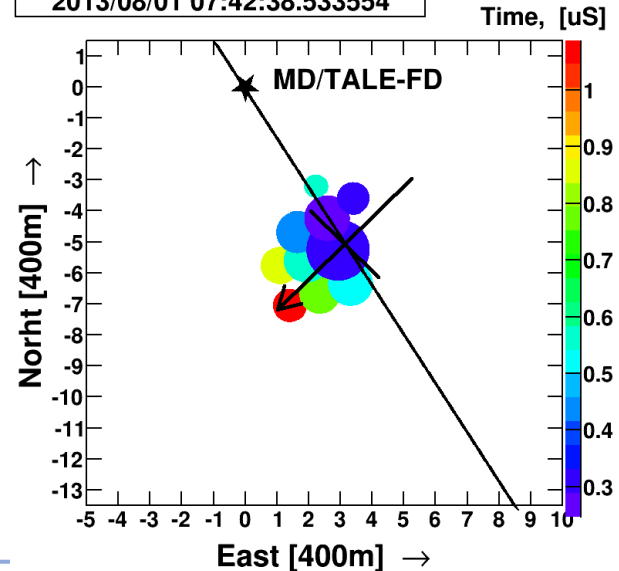
7 mirror event,  
 $\log(E) = 16.5$

2013/08/01 07:42:38.533554

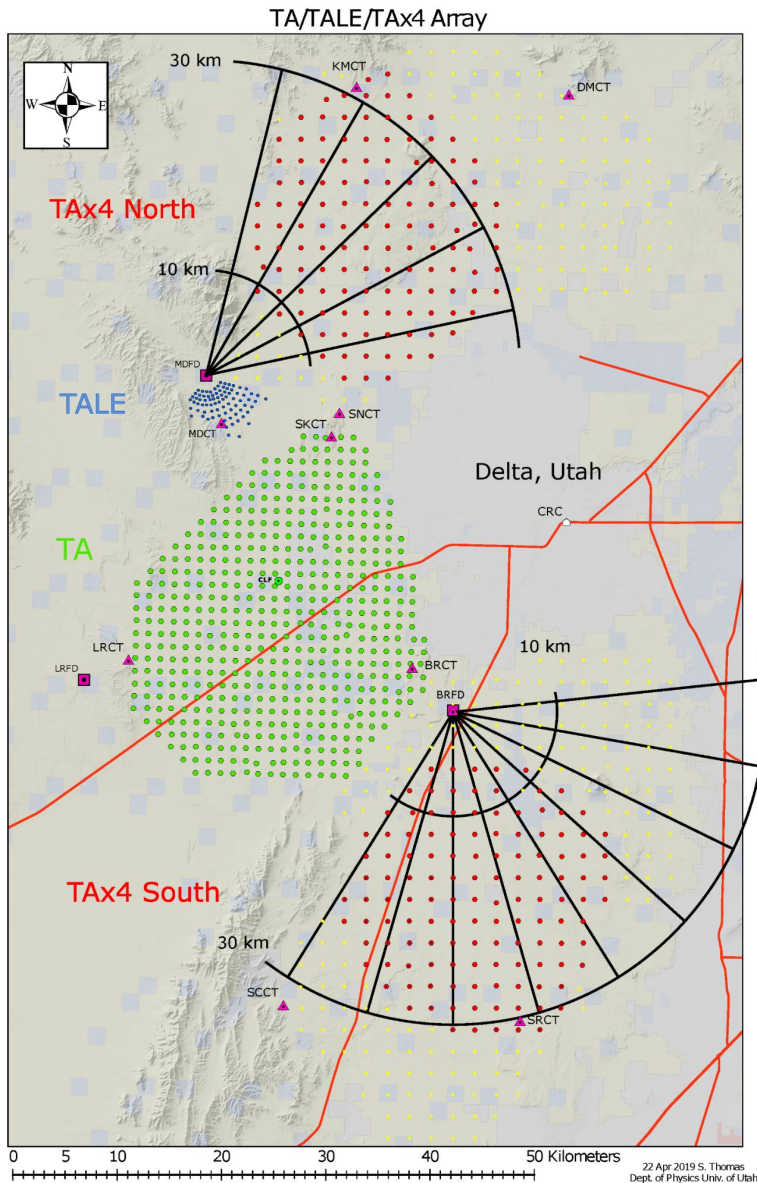


Hybrid event

2013/08/01 07:42:38.533554







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

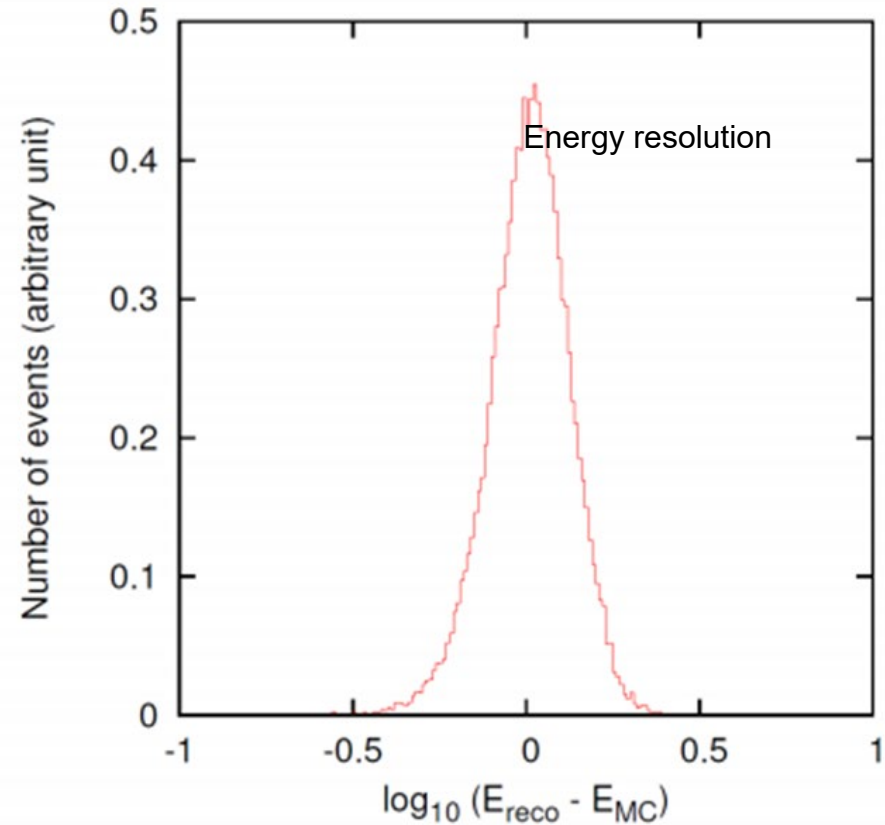
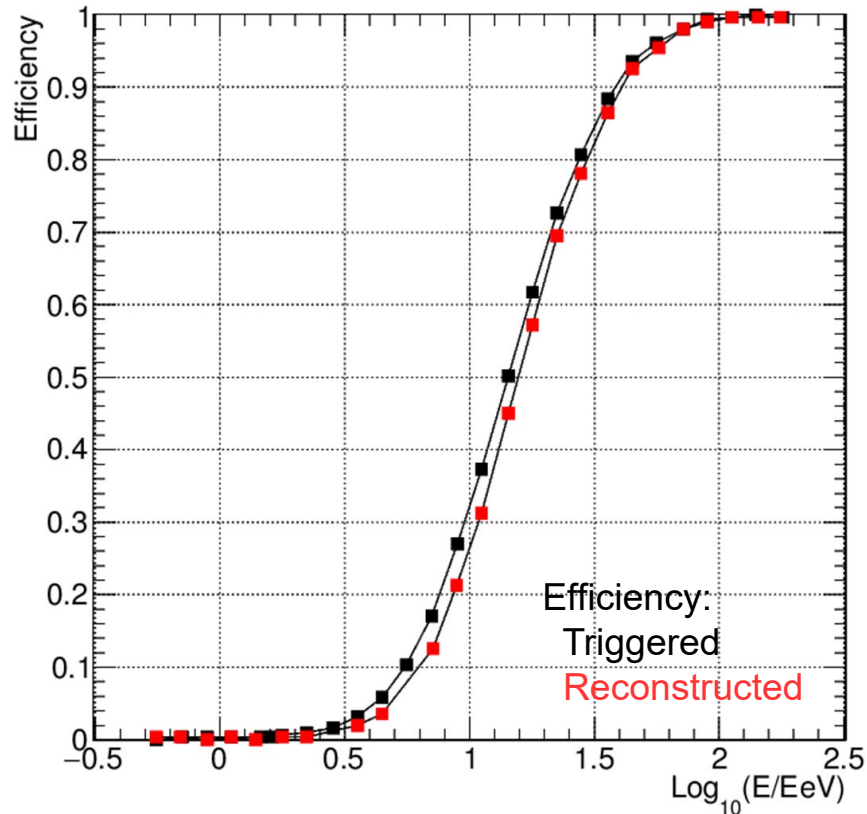
Red marker : Deployed at 2019/03

- 2 divided SD array
  - North 130 SDs 2.08 km grid
  - South 127 SDs 2.08 km grid
- More robust detector than TA



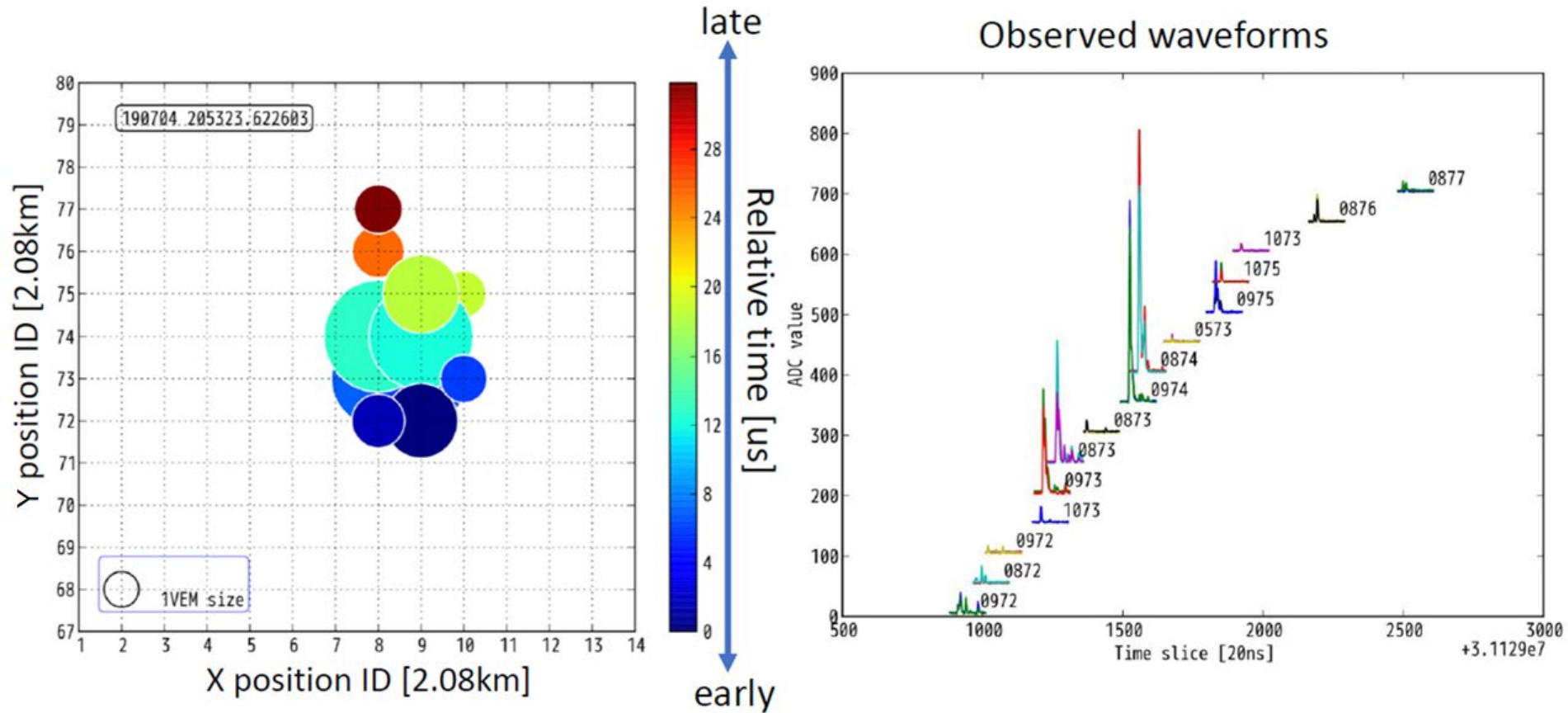
# TAx4 Experiment

- Array grid is 2.0km.
  - Trigger efficiency  $\sim 95\%$  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.

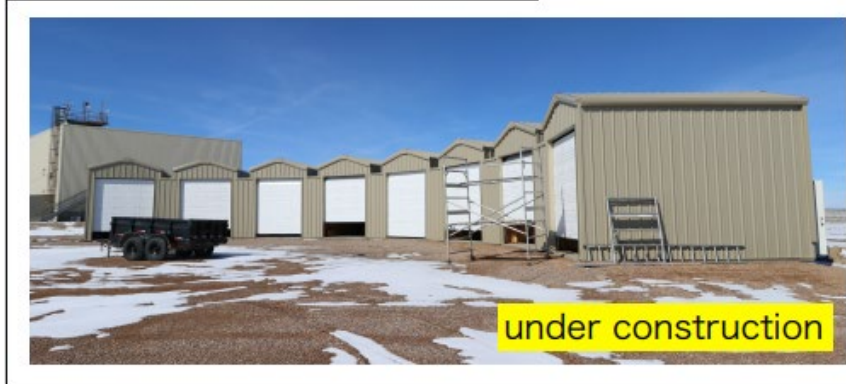


# TAx4 FD

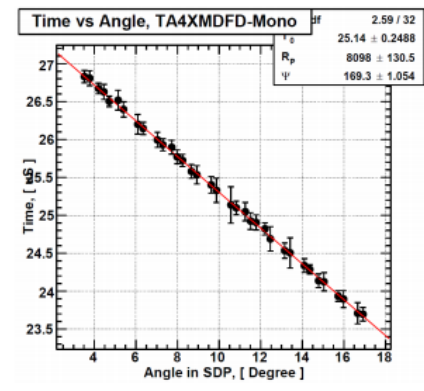
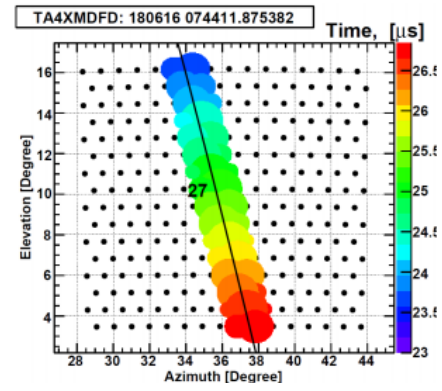
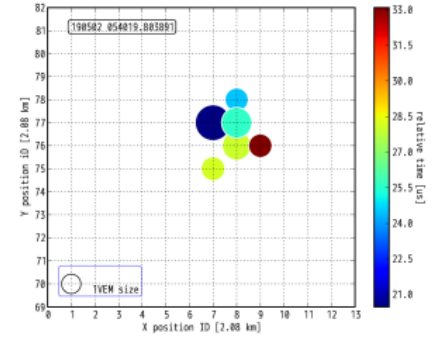
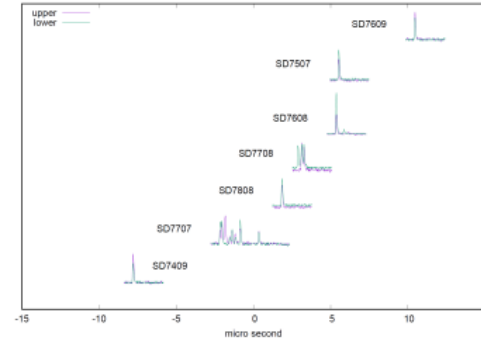
## TAx4 northern FD station



## TAx4 southern FD station

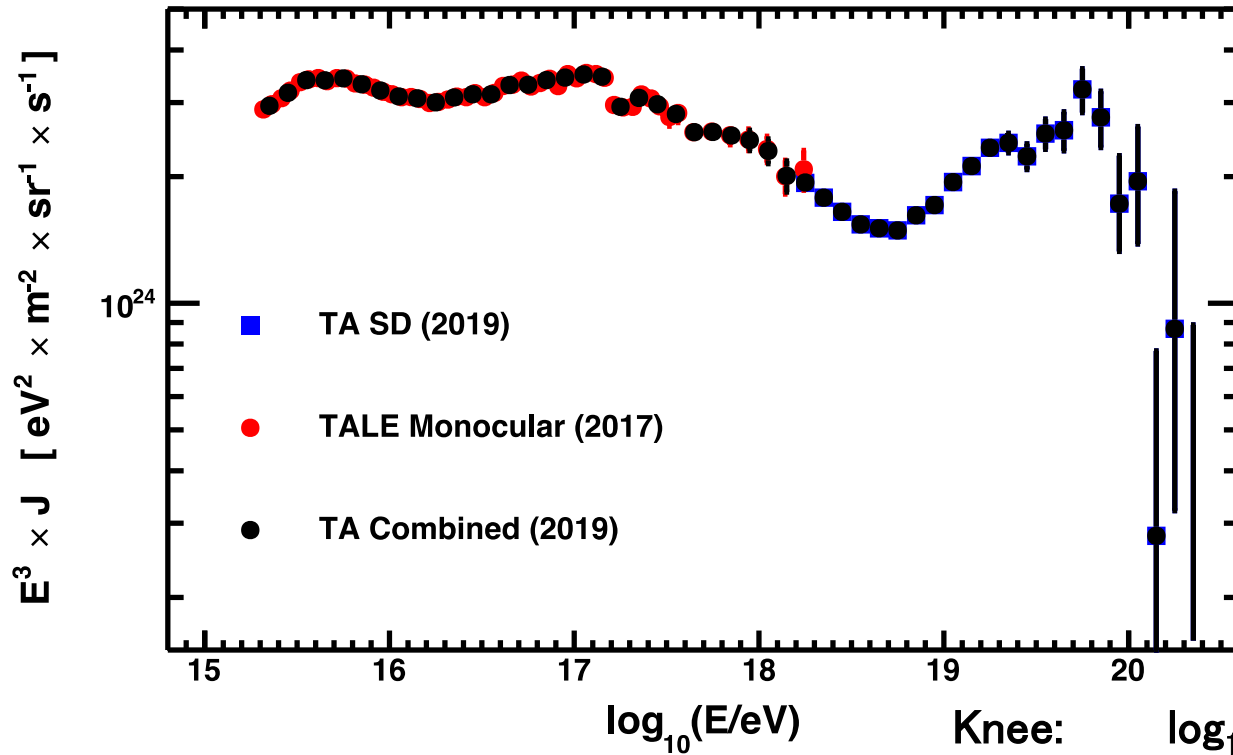


## Hybrid event



# Energy spectrum

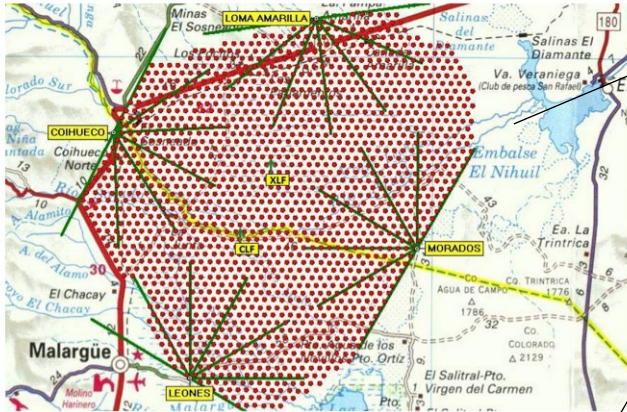
- Combine TA spectrum (11 years)
  - Statistics is dominated by SD data while combining.



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

# Comparison with other experiment

- ◆ Auger observatory
- ◆ Southern hemisphere 3000km<sup>2</sup>



SD 10m<sup>2</sup> (120cm WCD)  
1.5km grid x1500 unit

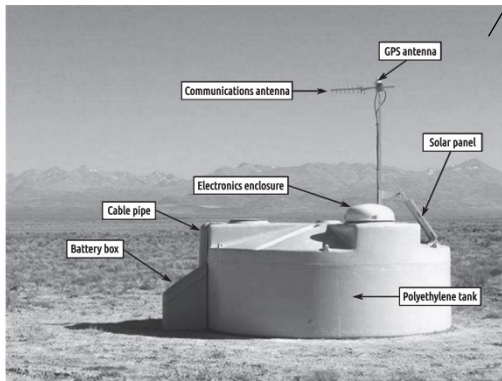
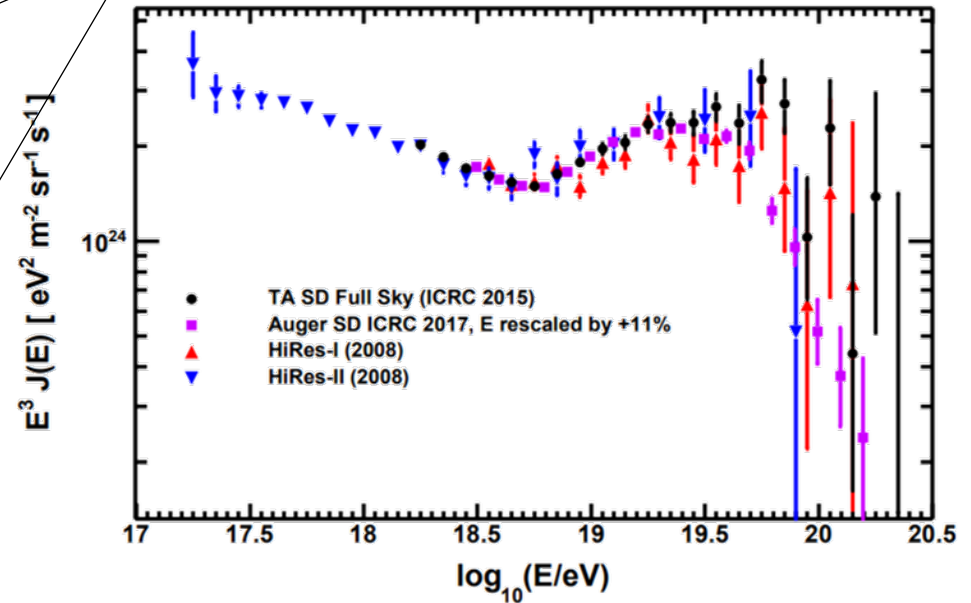


Fig. 3. A schematic view of a surface detector station in the field, showing its main

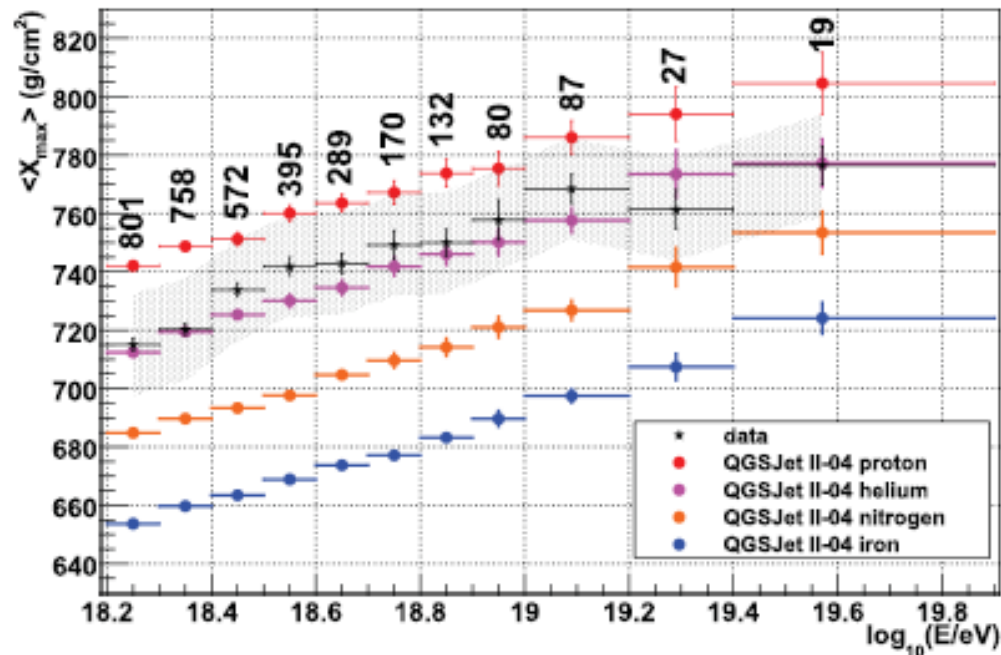
- ◆ Auger/ TA

R.U Abbasi et.al arXiv:1801.07820

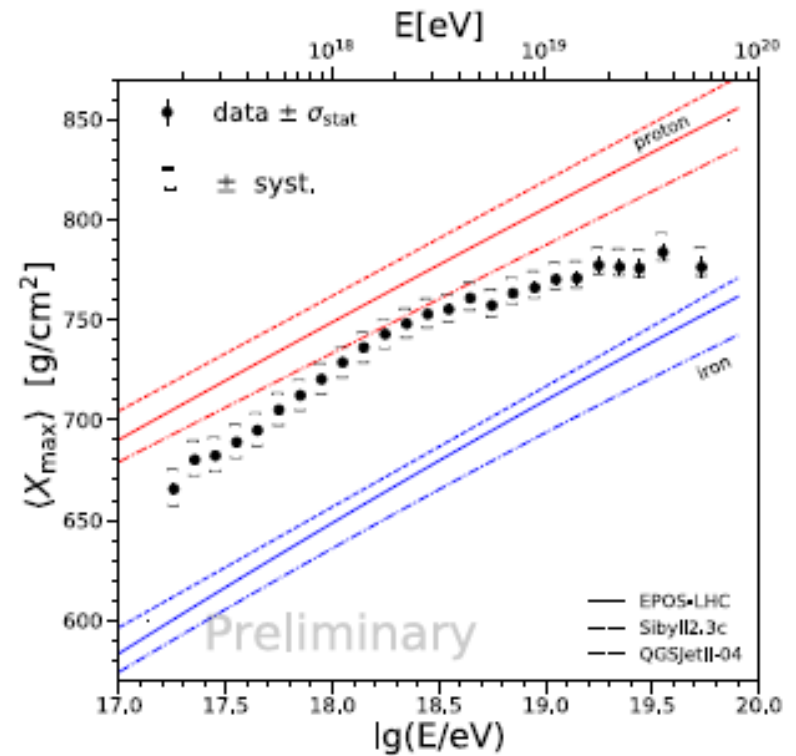


- ◆ TA (ICRC2015)
- ◆ Auger (ICRC2017)  
( E+11% )
- ◆ Discrepancy at  $E \sim 10^{19.5}$  eV

# 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.

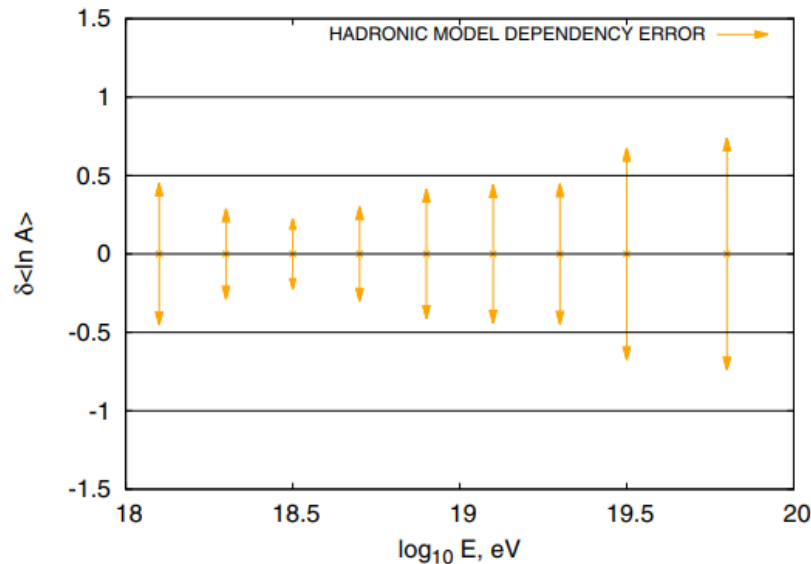


FIG. 6. Hadronic model dependency error of the method as a function of energy, based on a comparison with QGSJETII-04 hadronic interaction model.

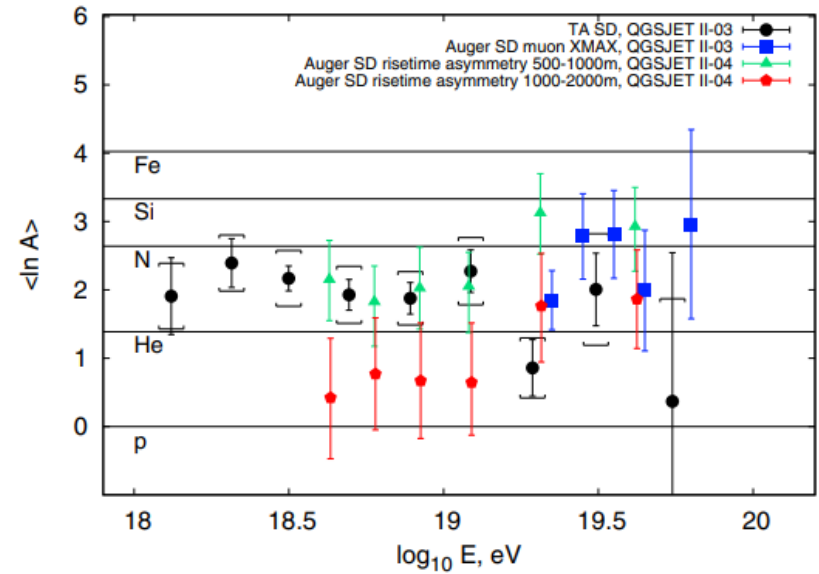


FIG. 8. Average atomic mass  $\langle \ln A \rangle$  in comparison with the Pierre Auger Observatory  $X_{MAX}^{\mu}$  and risetime asymmetry results [18,52]; statistical error is shown with error bars, systematic error is shown with brackets.

Phys. Rev. D 99, 022002 (2019)

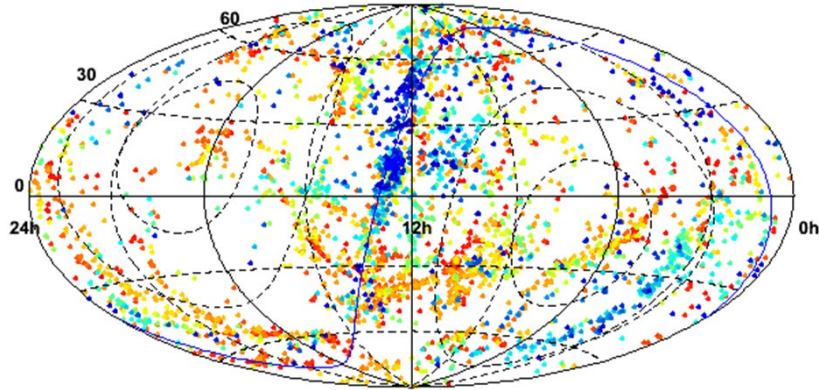
The technique extends energy range for composition study.

Also it can be adopted to anisotropy study (by selecting proton like events . etc)

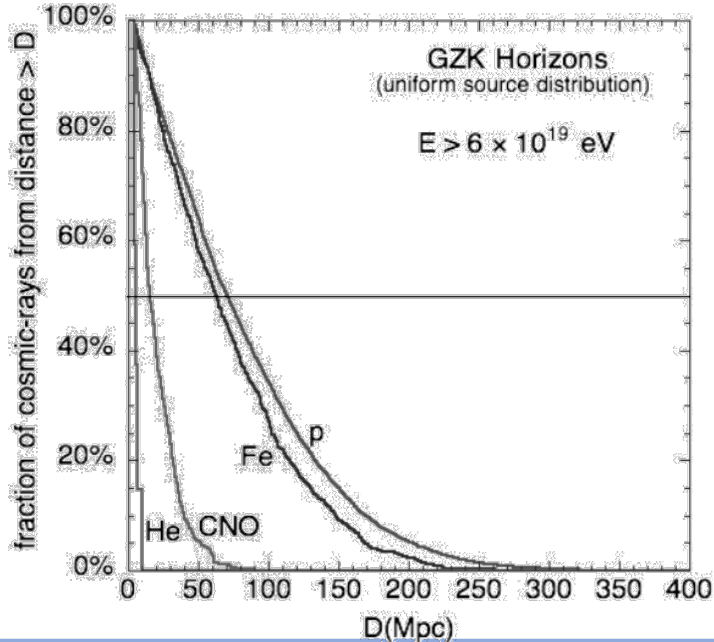
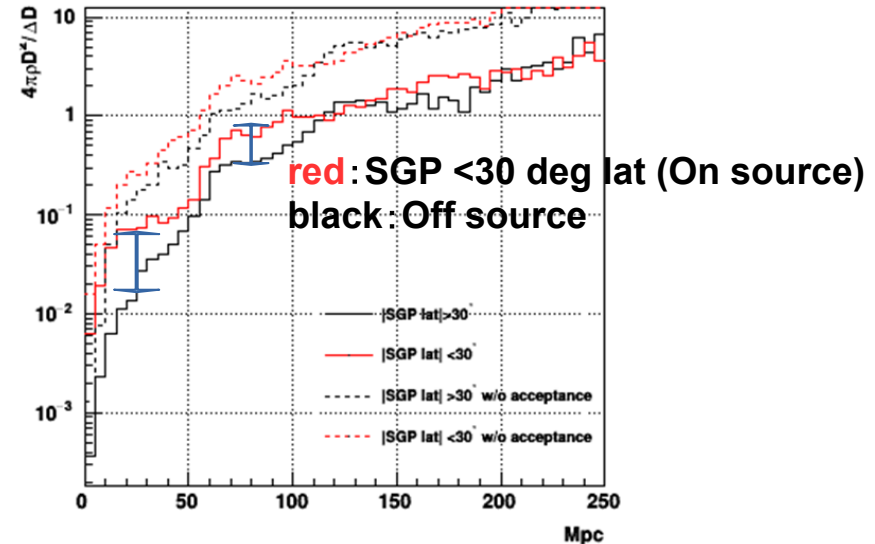


# Anisotropy

2MRS catalogue  $D < 75 \text{ Mpc}$   
 Blue ~ Red corresponds to  $0 \sim 75 \text{ Mpc}$

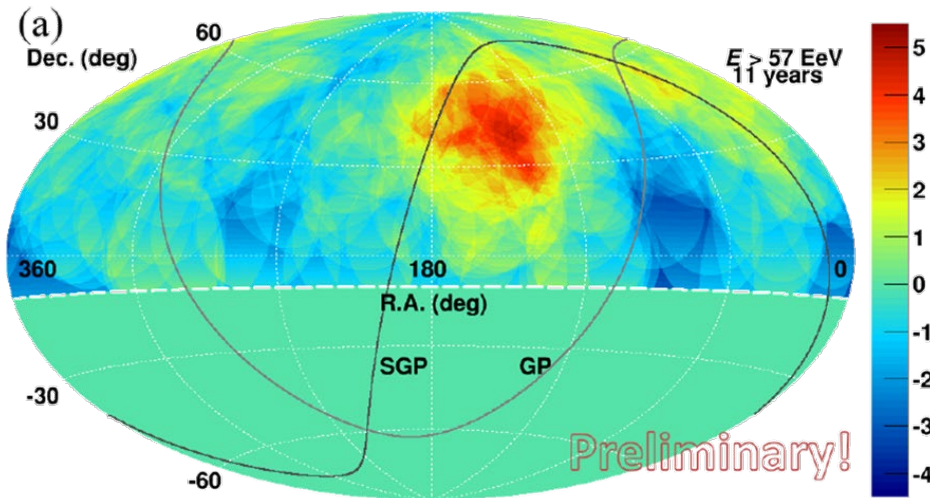


Relative amount of objects  
 (in 2MRS, efficiency corrected)



- 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

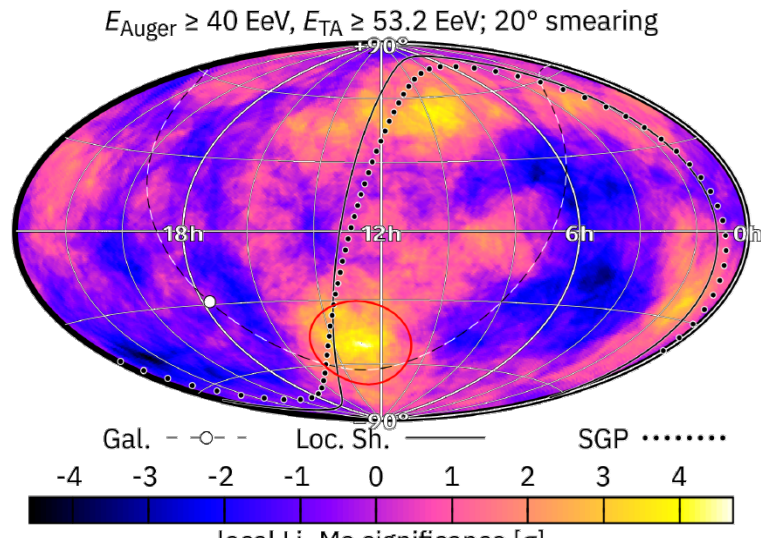
# Anisotropy $E > 10^{19.7}$



K. Kawata, PoS ICRC2019 (2020) 310

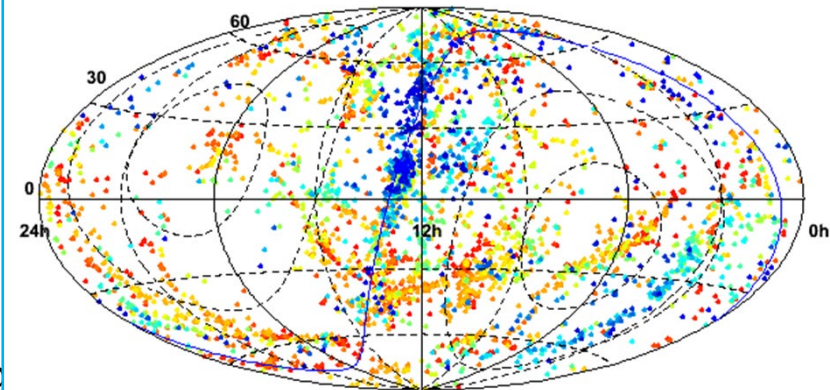
## TASD 11yr data

- 168 events with  $E > 57 \text{ EeV}$
- 38 events in hot-spot  $25^\circ$  radius (expect 14.2 events),
- local  $5.1 \sigma$  significance (Li-Ma)
- $2.9 \sigma$  global



- Joint analysis with Auger group

2MRS catalogue  $D < 75 \text{ Mpc}$   
Blue ~ Red corresponds to  $0 \sim 75 \text{ Mpc}$

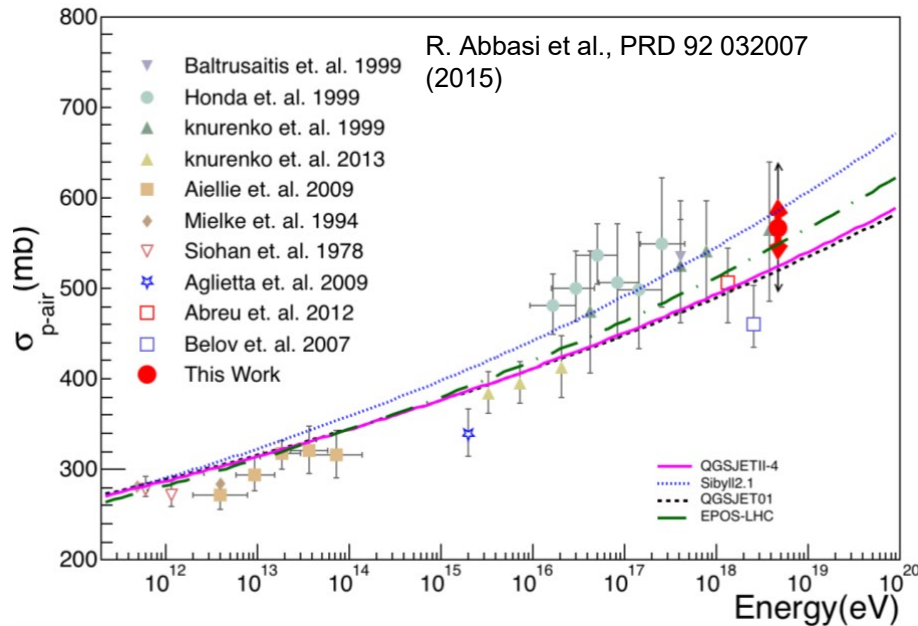
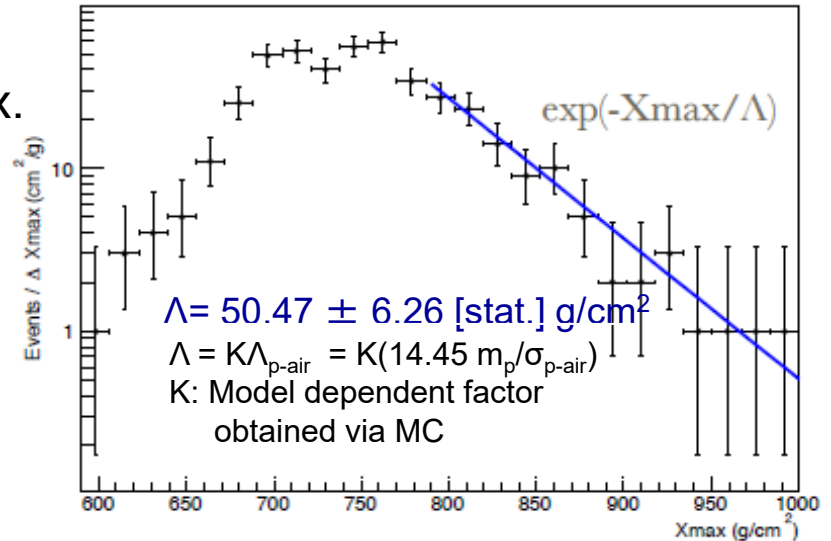


Anisotropy working group, PoS ICRC2019 (2020) 439

Anisotropy working group, PoS ICRC2019 (2020) 439

# P-air Inelastic Cross section

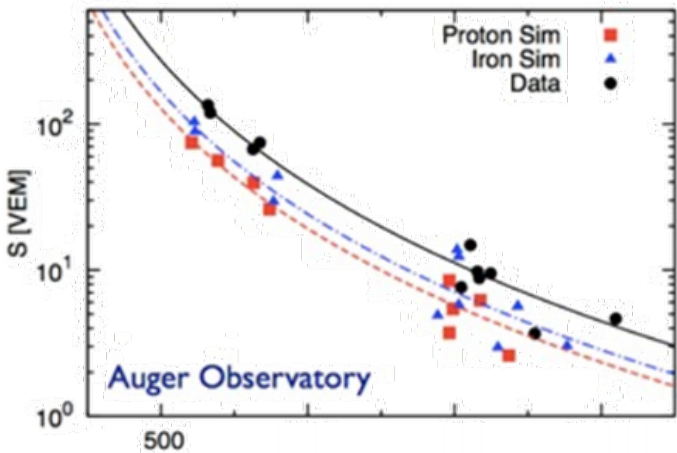
- Using deep penetrating shower (proton),
- Mean free path( $\Lambda$ ) is extracted from  $X_{max}$ .
- The factor k between ratio extracted  $\Lambda$  and true mean free path  $\Lambda_{p-air}$  is estimated with MC.
- k's systematic is considered while error estimation



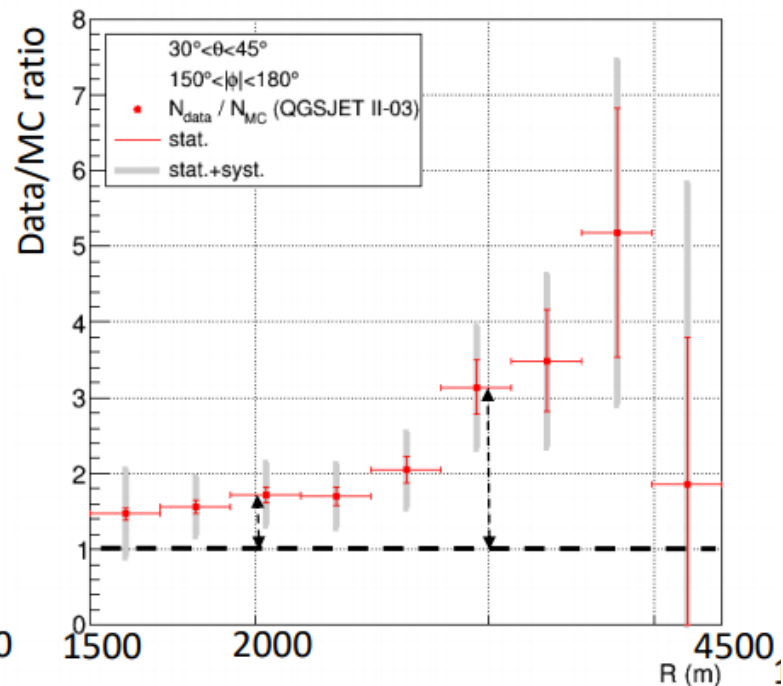
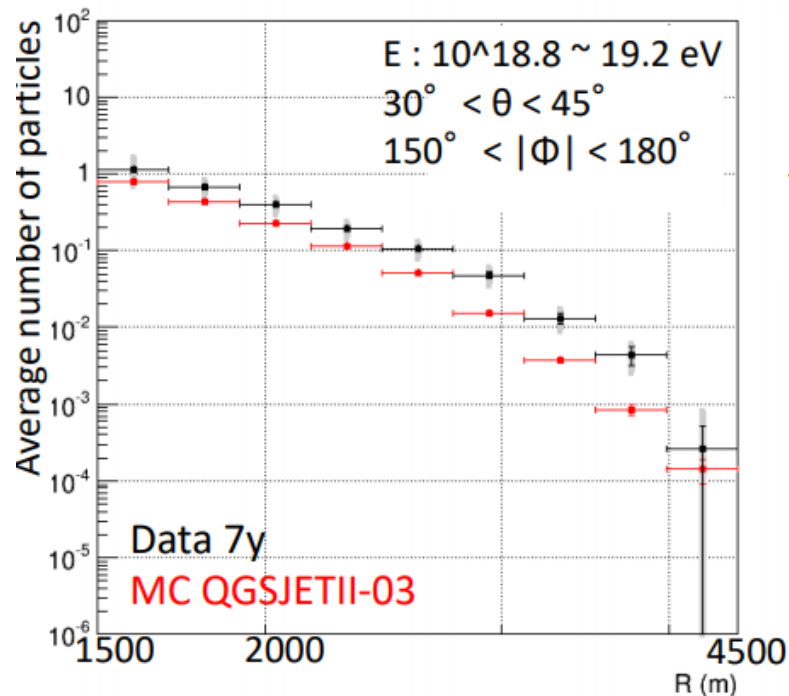
Model	+ - 17
20% He	+18
Gamma < 1%	-23
Total	(+25, -29)

- ◇  $\sigma_{p-air}(\text{inelast.}) @ 95\text{TeV}$  of  $\sqrt{S}$  is  $567.0 \pm 70.5[\text{Stat.}] (+25, -29)[\text{Sys.}] \text{ mb}$
- ◇ The value observed is between EPOS-LHC and Sibyll2.1.

# Muon excess



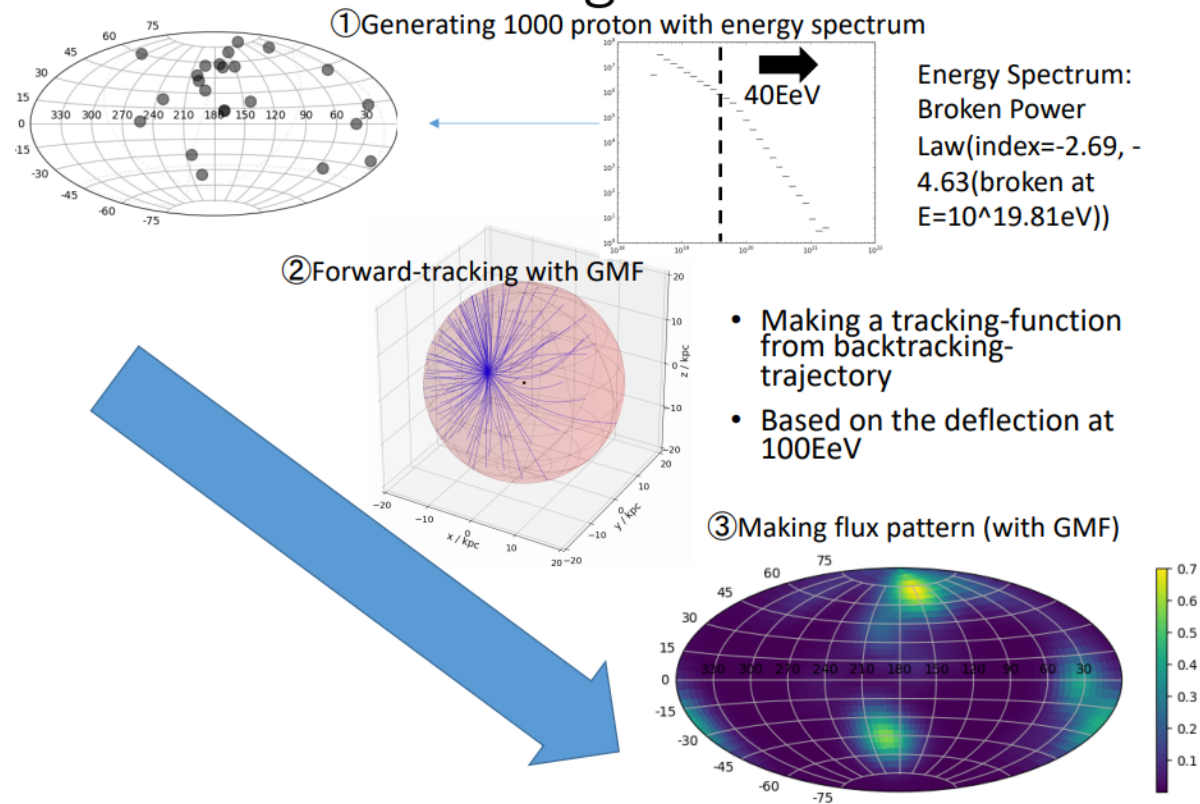
- Lateral distribution on condition  $\mu$  purity 60~70% and data/MC ratio
- Data is larger than MC by more than 1.5 times, with R dependence.
  - $1.72 \pm 0.10(\text{stat.}) \pm 0.40(\text{syst.})$  ( $1910 \text{ m} < R < 2160 \text{ m}$ ) ( $1.8\sigma$ )
  - $3.14 \pm 0.36(\text{stat.}) \pm 0.72(\text{syst.})$  ( $2760 \text{ m} < R < 3120 \text{ m}$ ) ( $2.7\sigma$ )
- Larger difference at larger R



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# Ongoing analysis and development

# Anisotropy study w magnetic field



R.Higuchi , JPS meeting Sep. 2020

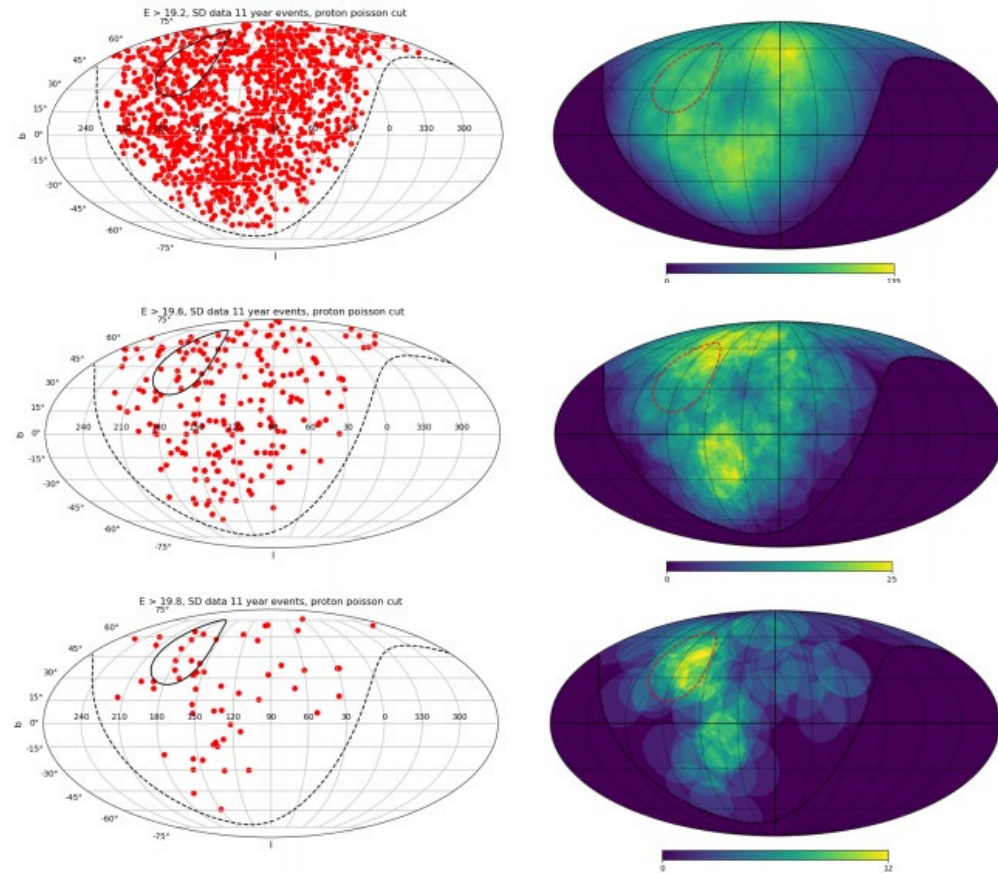
Flux pattern of cosmic ray is generated using galactic magnetic field models.  
Then study compatibility with flux pattern of observed data.

# Anisotropy in composition

Event distribution

20° oversampling

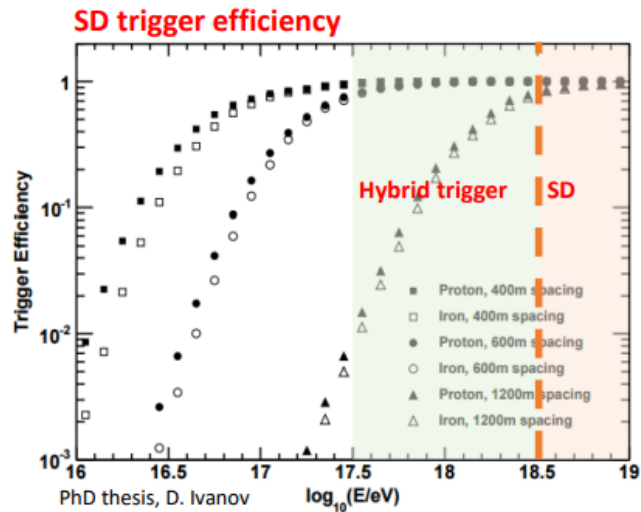
- Proton-like events were selected with  $\xi$  parameter used for composition study. (Phys. Rev. D 99, 022002 (2019))
- GMF is considered
- Left panel is selected events. Right panel is significance of excess from expectation of uniform distribution.



57 events

Excesses are observed in the hotspot and Galactic plane area.

# Update of hybrid event analysis



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

