

# Recent Results from Telescope Array

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- TA Detectors
- Shower analysis
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- Anisotropy
  - AGN correlation
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- New Projects

IKEDA Daisuke

ICRR, University of Tokyo  
for the Telescope Array Collaboration

# The Telescope Array Collaboration

International collaboration that consists of about 140 researchers,  
26 institutions from **Japan/US/Korea/Russia/Belgium**

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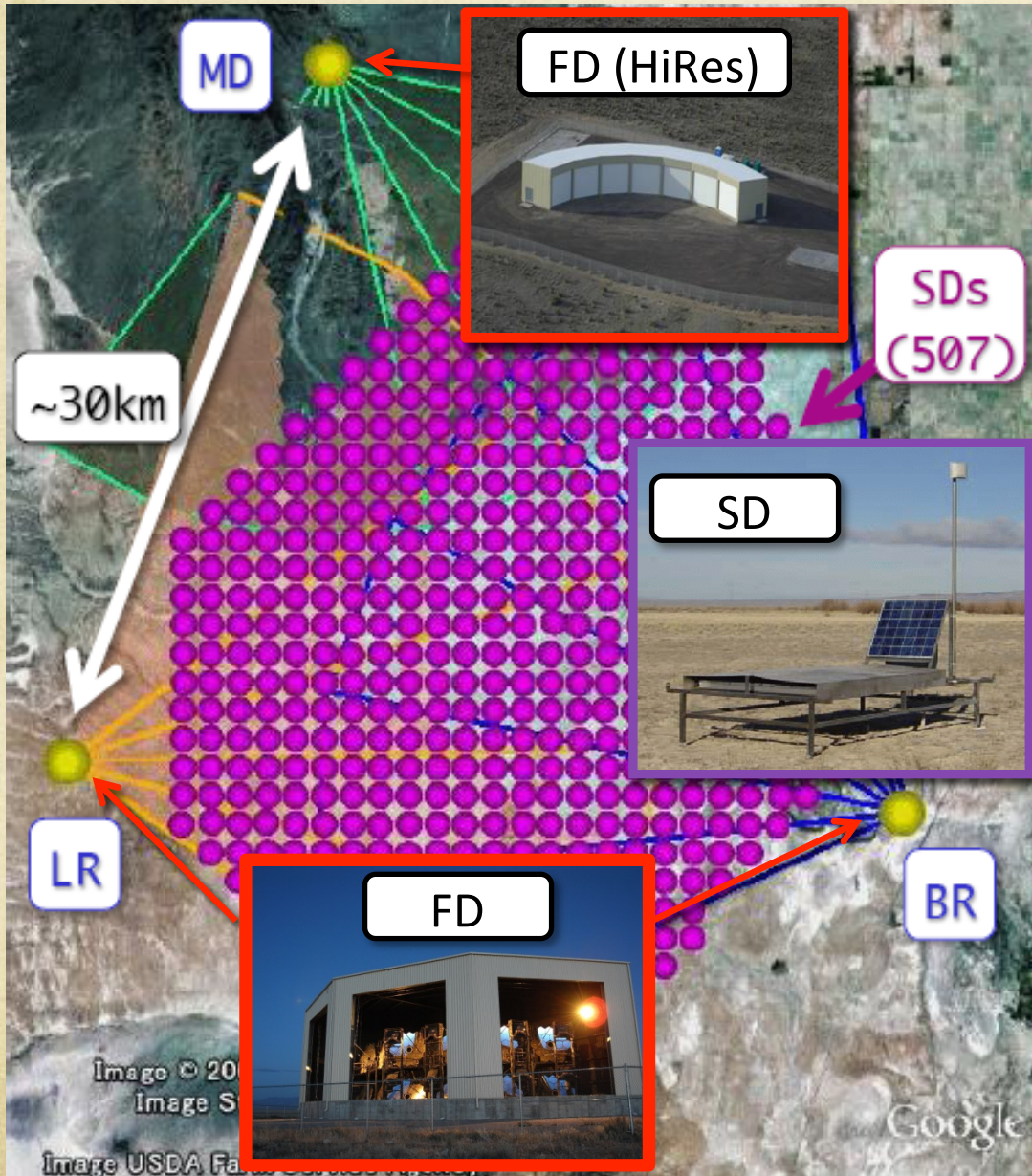
*23Kochi University, Kochi, Kochi, Japan*

*24Hiroshima City University, Hiroshima, Hiroshima, Japan*

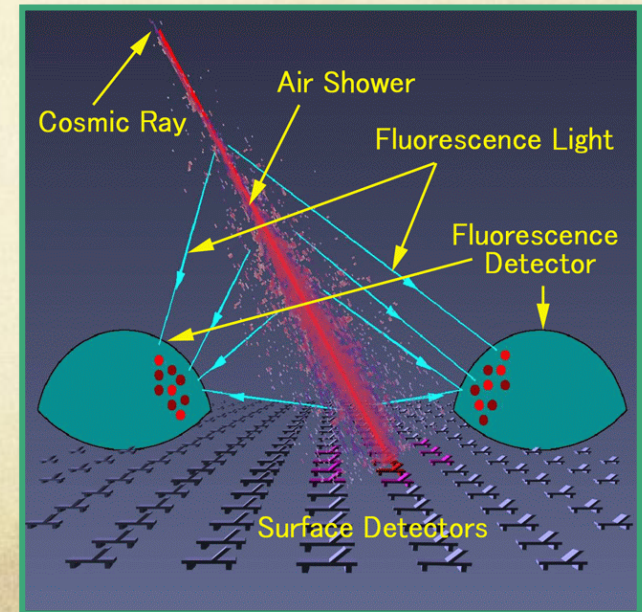
*25National Institute of Radiological Science, Chiba, Chiba, Japan*

*26Ehime University, Matsuyama, Ehime, Japan*

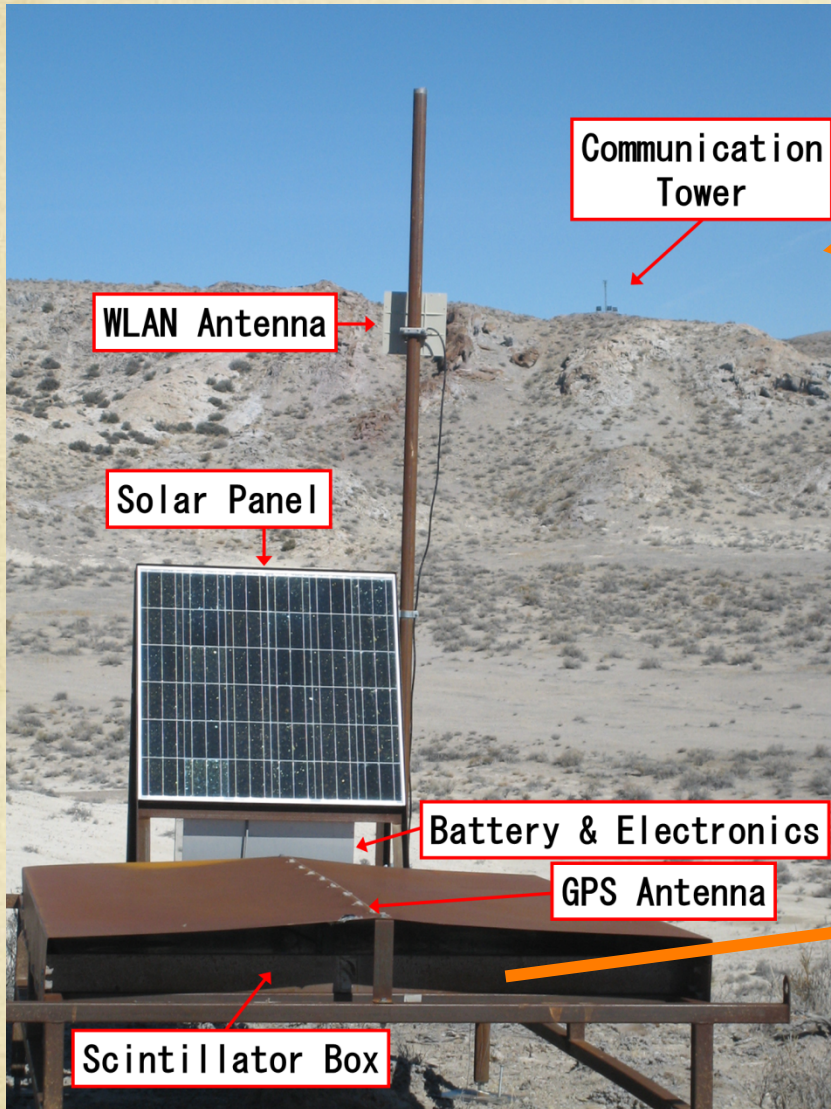
# Telescope Array Experiment



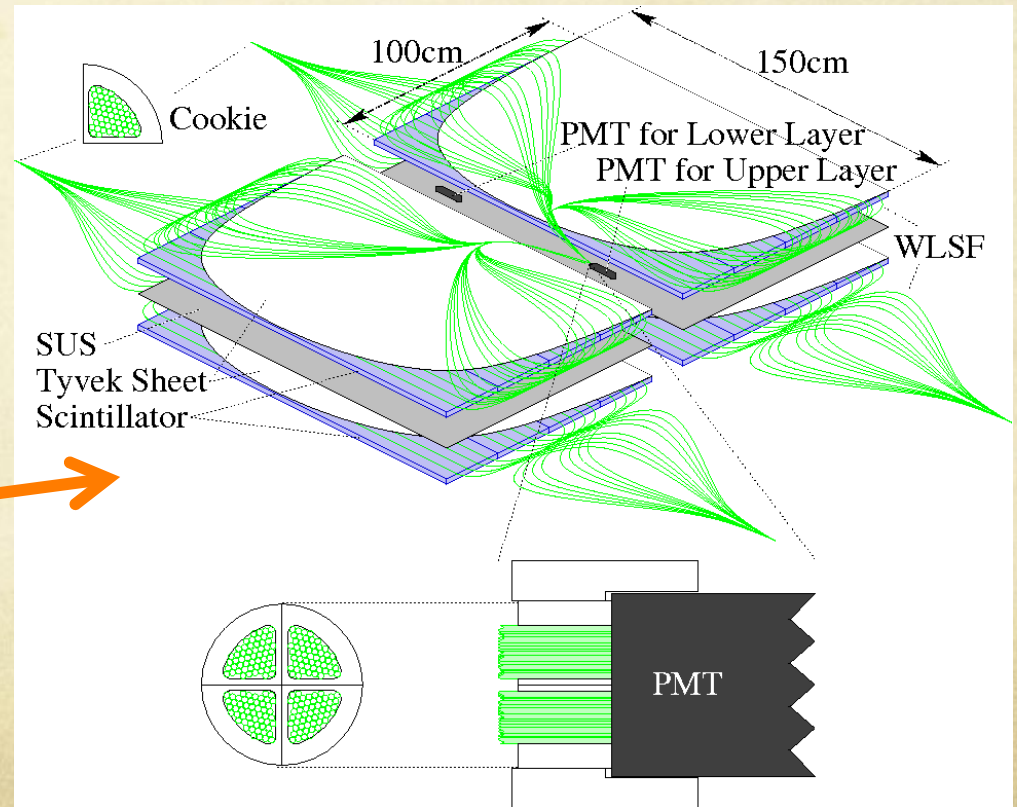
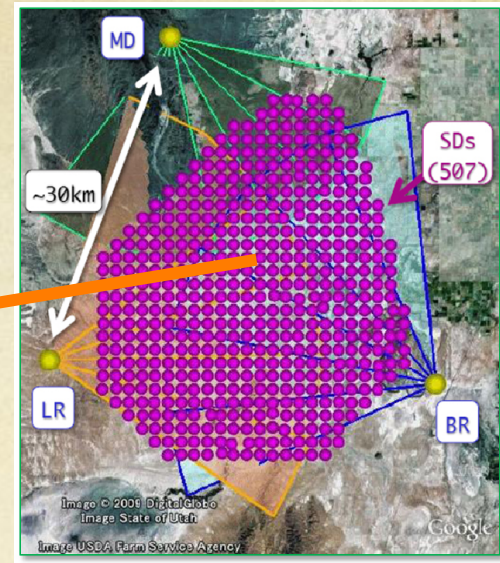
- Desert in Utah, US (1400m a.s.l.)
- 507 Surface Detectors (SDs)
  - 1.2km spacing
  - Two layer of plastic scintillator, 3m<sup>2</sup>, 1.2cm thickness
- 3 Fluorescence Detectors (FDs)
  - Middle Drum (MD) station is transferred from HiRes.
  - Black Rock (BR) and Long Ridge (LR) stations are newly built.
- FD observation : from Nov/2007
- SD observation : from Mar/2008



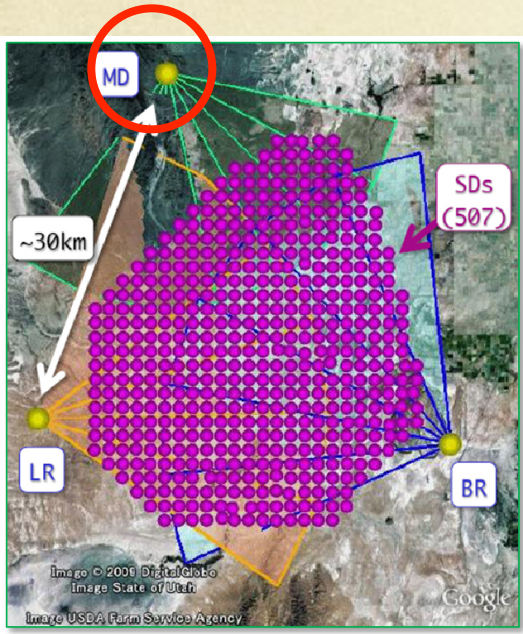
# Surface Detector array



- Two layers of the  $3\text{m}^2$  plastic scintillators



# Fluorescence Detector station at MD site

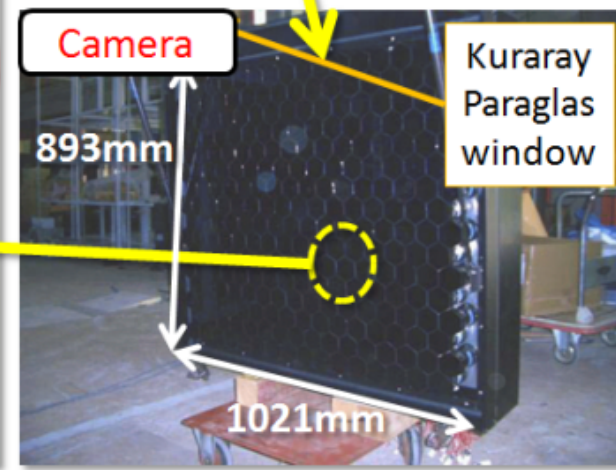
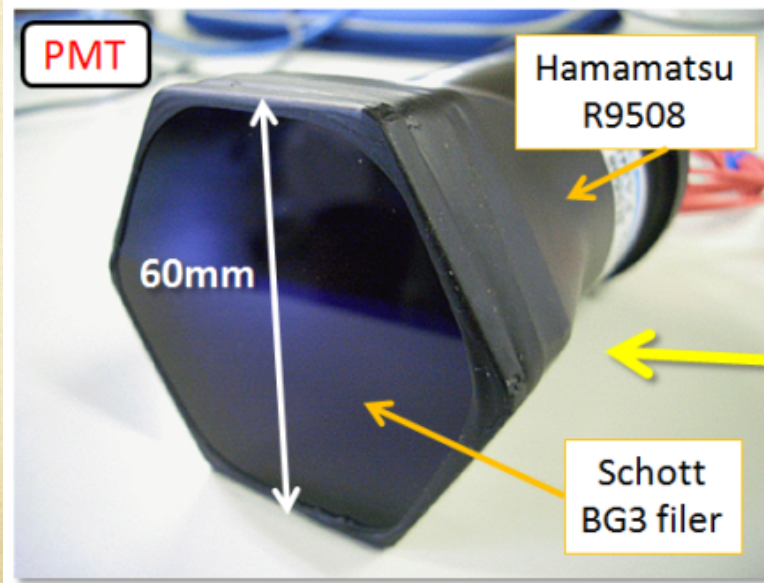
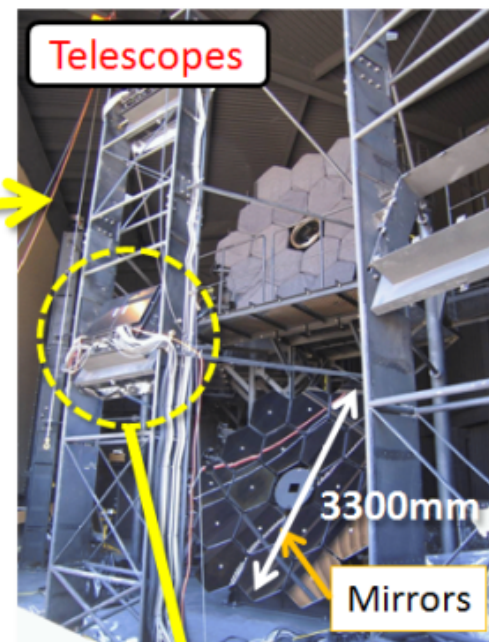
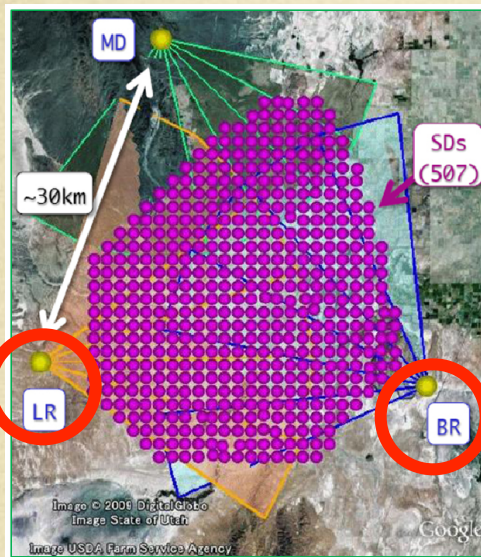


## Transferred from **HiRes**

- 14 cameras/station
- 256 PMTs/camera
- $3^{\circ}$ - $31^{\circ}$  elevation with  $1^{\circ}$  pixel
- $114^{\circ}$  in azimuth
- $5.2\text{m}^2$  mirror
- S/H electronics

# Fluorescence Detector station at BR/LR site

BR/LR site: **new** telescopes for TA



F.O.V of station:

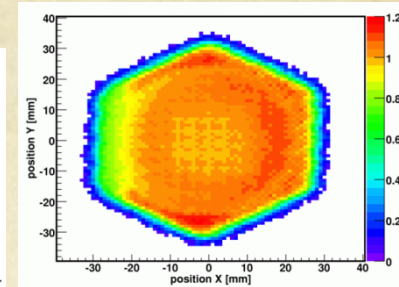
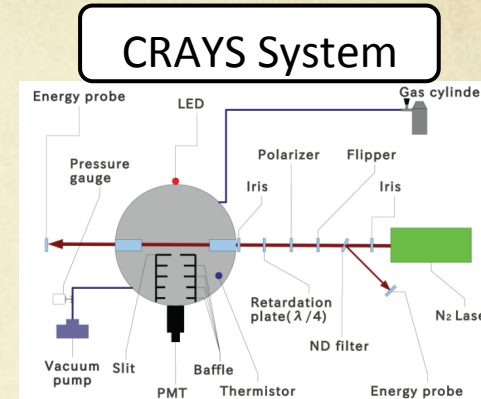
- Elevation:  $3 \sim 33^\circ$
- Azimuth:  $108^\circ$

# Calibrations for BR/LR

## Detector:

- Absolute gain : CRAYS (~8%)
- Aging : YAP pulsar
- Relative gain : Xe flusher
- PMT uniformity : XY-scanner
- Temperature dependence : incubator and LED
- Mirror reflectance : spectrometer

~10%

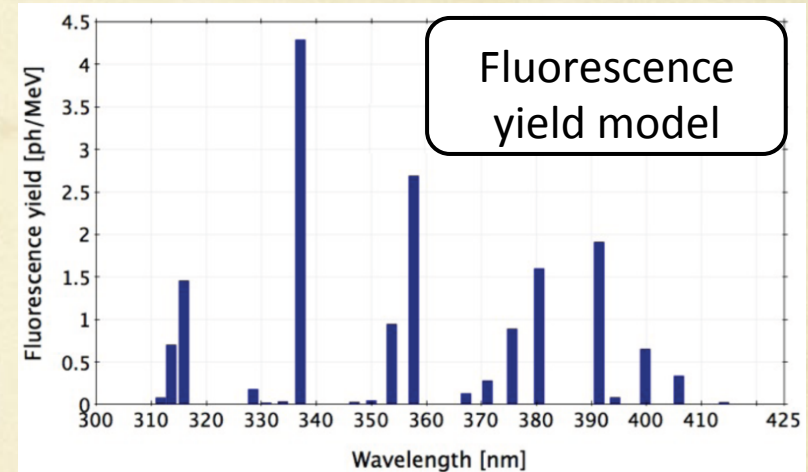


PMT Uniformity

## Air showers:

- Fluorescence yield:
  - Spectral lines: FLASH
  - Absolute values: Kakimoto
- If TA model applied to Auger analysis, the energy increases by ~9% (F. Arqueros).
- Cherenkov light: Nerling

~11%



Fluorescence yield model

## Atmosphere:

- Transparency : LIDAR
- Temp. , Pressure,... : Radiosonde
- Cloud : IR-Camera and Eye-check

~11%

See Talks by M.Fukushima (CRAYS)  
by T.Tomida (Atmosphere)

# Shower Analysis



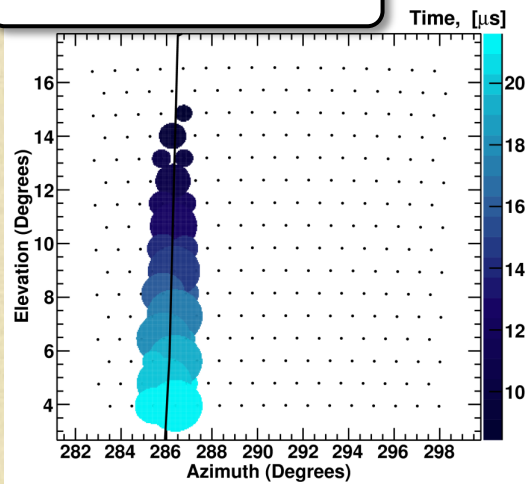
# Shower Analysis

## - FD Monocular -

Data set for MD monocular analysis:

- 16/Dec/2007 – 16/Dec/2010 (3 years)
- ~1/3 of HiRes-1 observation

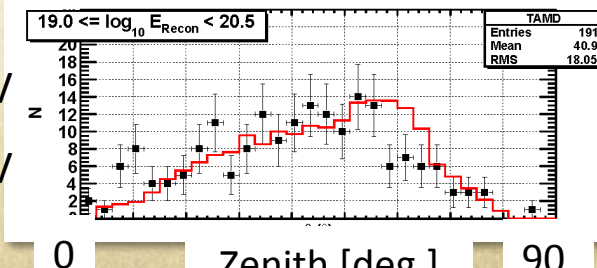
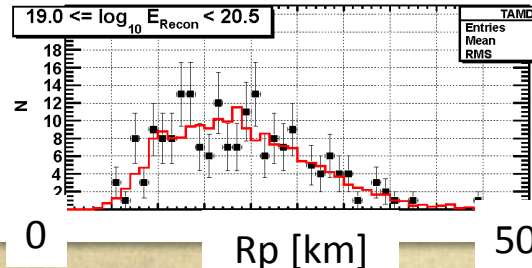
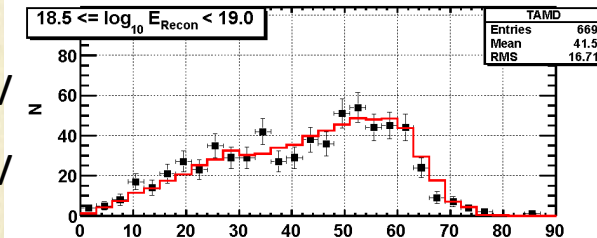
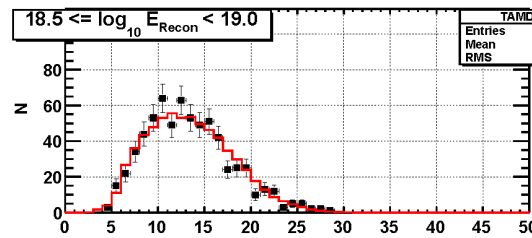
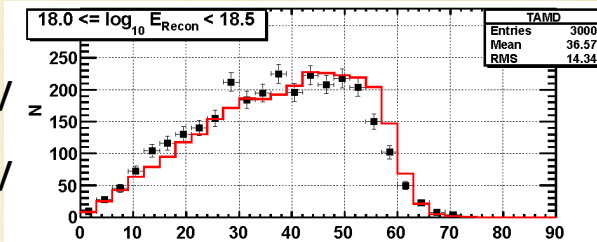
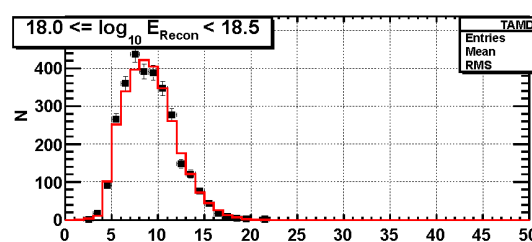
Mirror View



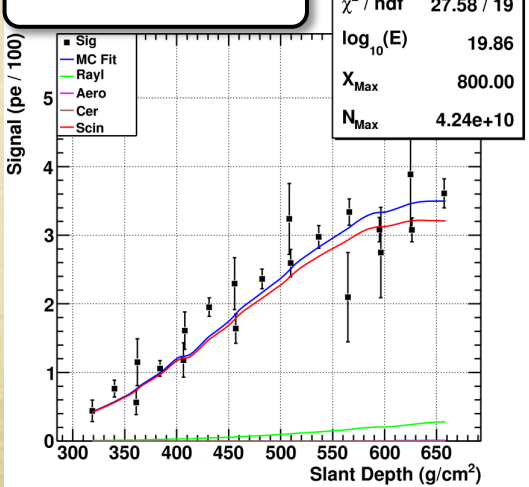
MD station: Transferred from HiRes-I

- Data analysis: Identical to HiRes-I monocular analysis
- Differences: Location, Direction, Trigger threshold...

Data/MC comparison with Coriska, Proton



Profile Fit



# Shower Analysis - Hybrid -

Data set for BR/LR Hybrid analysis:

• 27/May/2008 – 07/Sep/2010 (~2.3 years)

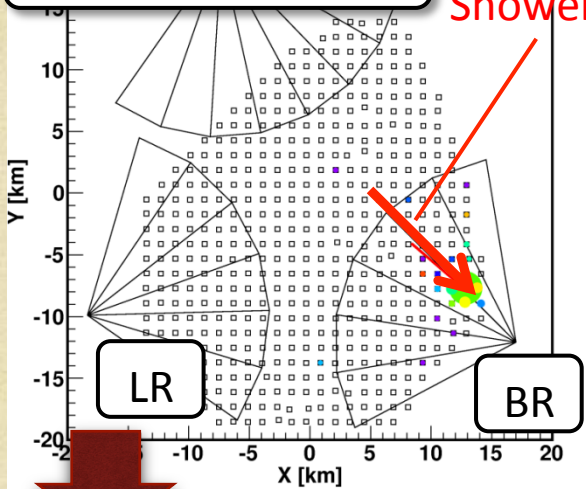
Geometry: FD+SD, Profile: FD

- Geometry: Traditional reconstruction of FD with timing of one SD (~0.9 deg.)
- Profile: Inverse Monte Carlo (~8%)

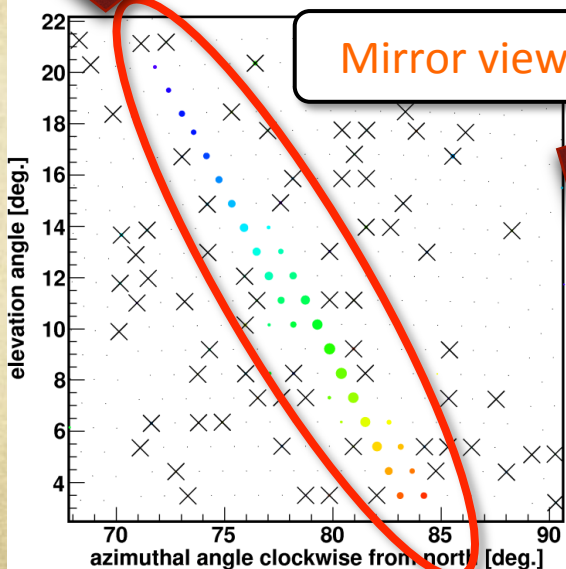
See Talk by T.Fujii (FD Analysis)

23/Dec/2008, 4:44

Shower axis

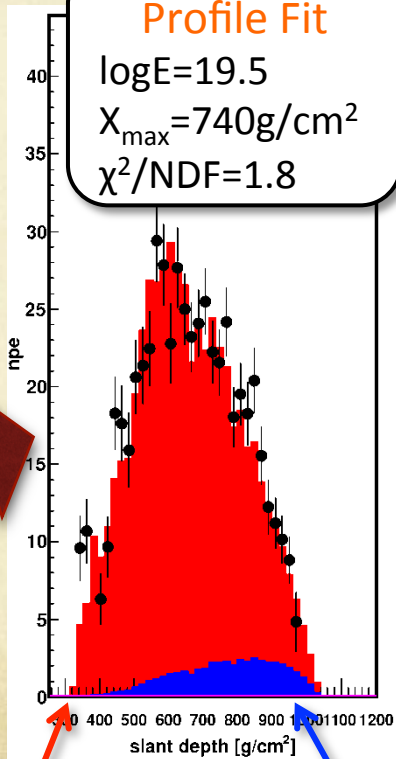


Mirror view

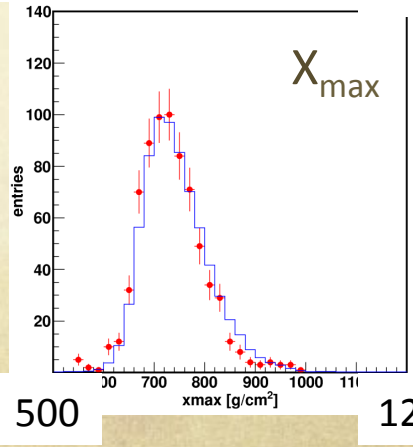
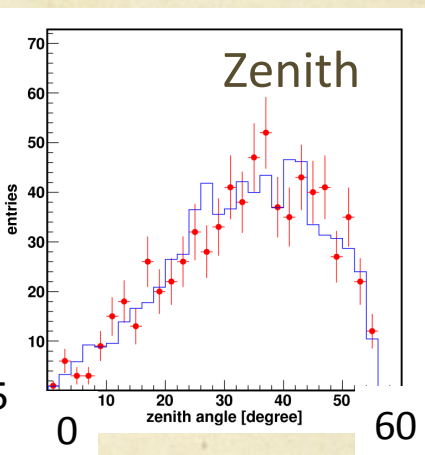
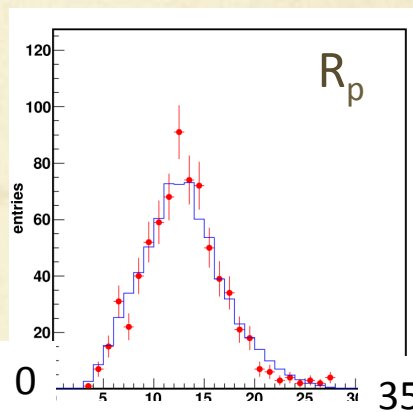


Profile Fit

$\log E = 19.5$   
 $X_{\max} = 740 \text{ g/cm}^2$   
 $\chi^2/\text{NDF} = 1.8$



Fluorescence  
Scattered Cherenkov



Data/MC comparison with Corsika, Proton

# Shower Analysis

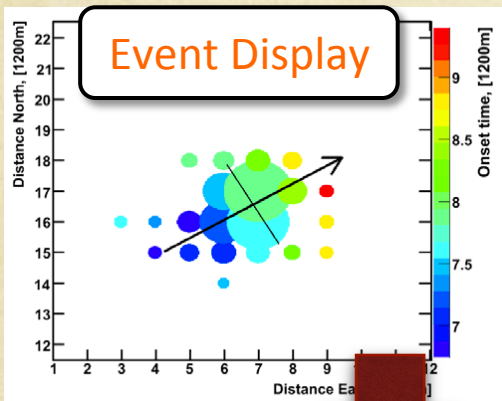
- SD -

Data set for SD analysis:

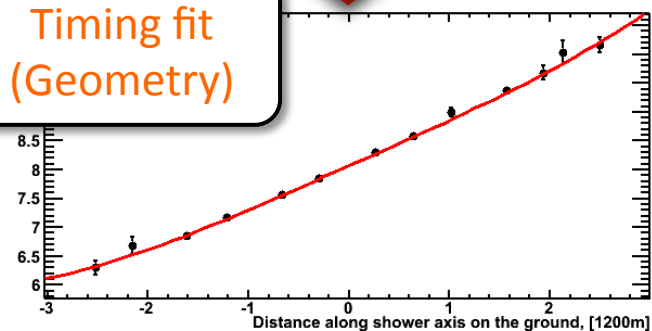
• 11/May/2008 – 01/May/2011 (3 years)

## Lateral distribution at the ground

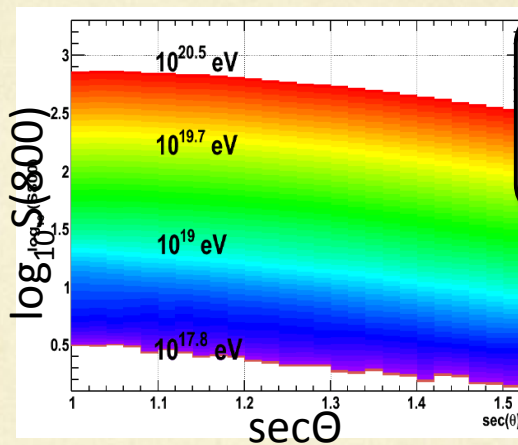
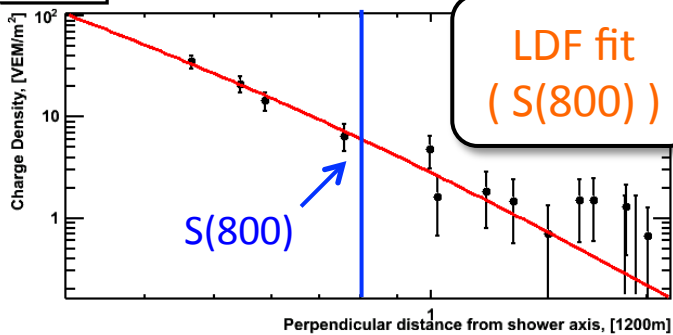
- Geometry: Time fit ( $\sim 1.5\text{deg.}$ )
- Energy  $E_{SD}(\text{MC})$ : Primary estimated by  $S(800)$  and Zenith angle by using MC ( $\sim 20\%$ )



Timing fit  
(Geometry)



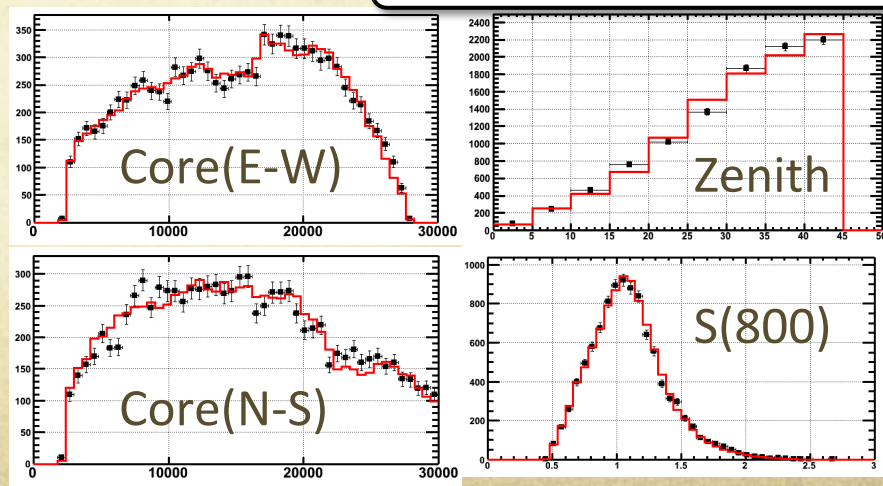
SD LDF Fit



Energy table  
Constructed from MC  
(Corsika, Proton)

$E_{SD}(\text{MC})$

Data/MC comparison

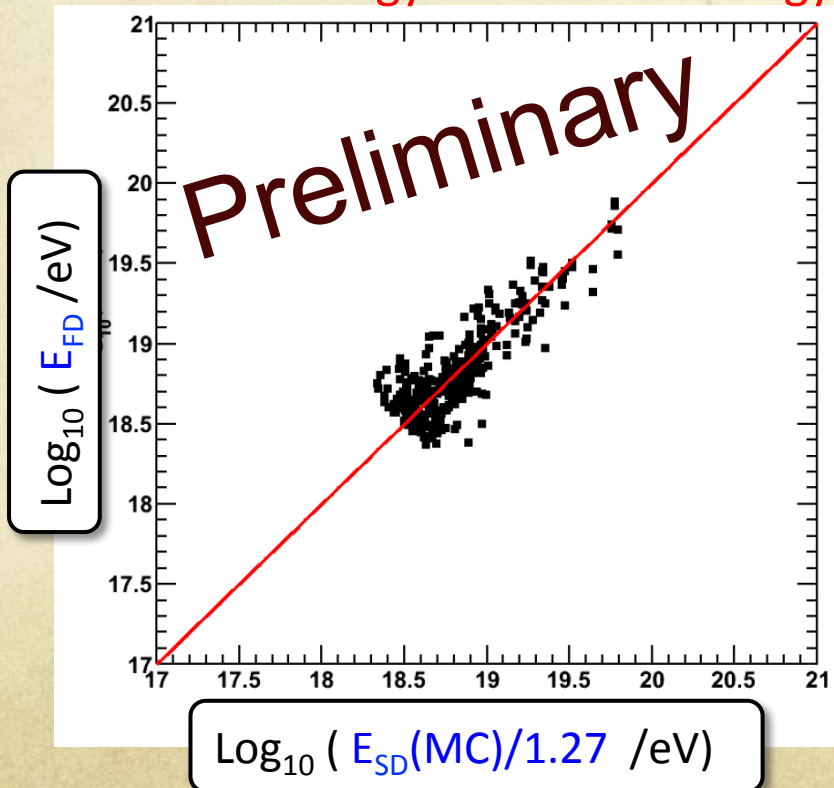


# FD-SD Energy Scale

- Energy scales from MD and BR/LR are consistent
- We use the MD + BR/LR as a calorimetrically determined energy by FD
- By using well-reconstructed events from MD, BR/LR hybrid analysis and SD, we obtained

$$E_{SD} = 1.27 \times E_{FD}$$

- Set SD energy scale to FD energy scale with 27% renormalization.

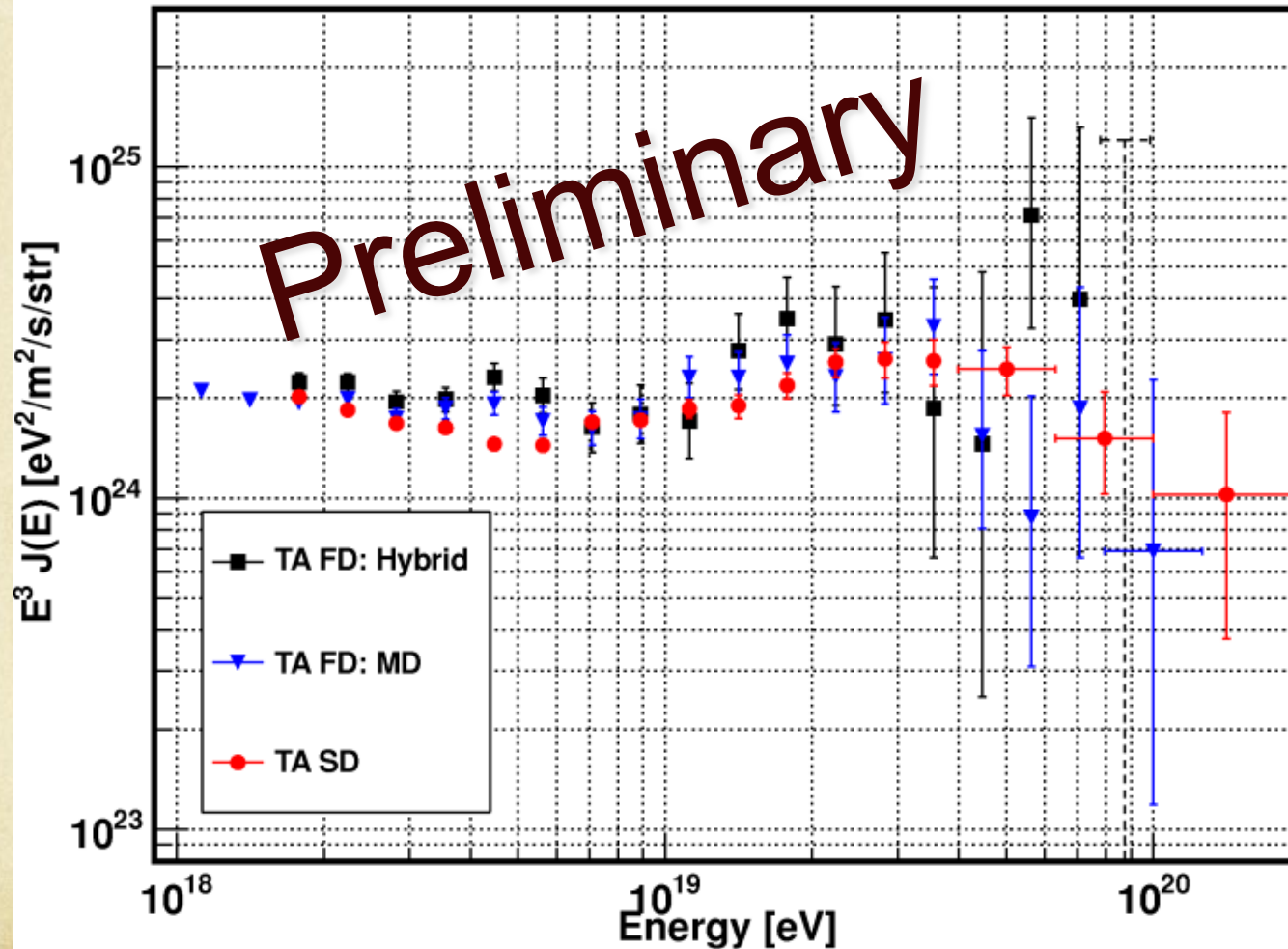


Systematic uncertainties  
for FD energy determination

Source	$\Delta E/E$
Fluorescence yield	11%
Detector	10%
Atmosphere	11%
Reconstruction	10%
Total	21%

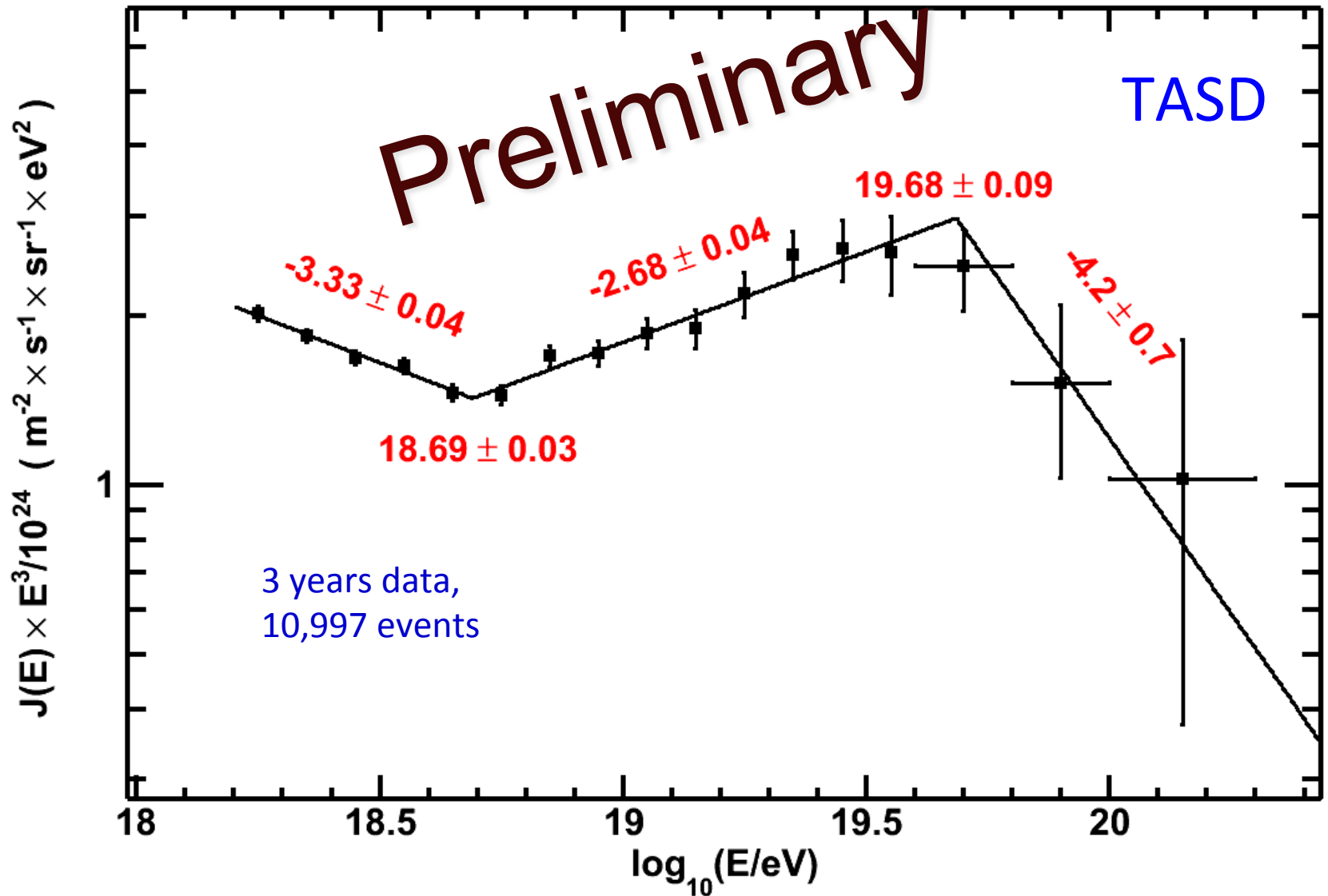
# Energy Spectra

# Energy spectra from TA

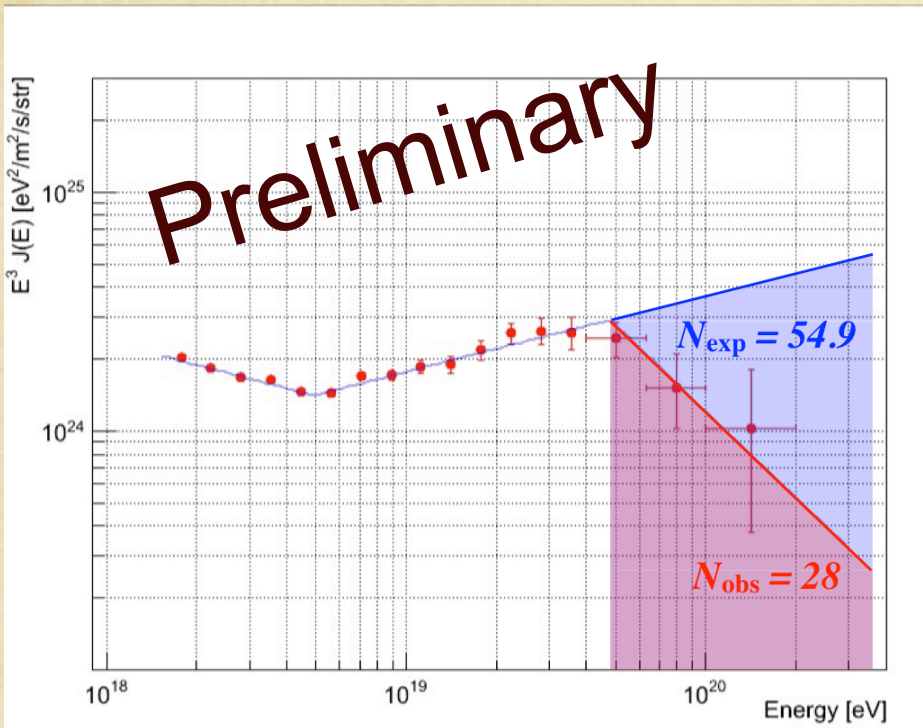


Three energy spectra from TA, MD monocular, BR/LR hybrid, and SD are in good agreement.

# Broken Power Low Fit



# GZK suppression



## Significance of GZK suppression

Comparison with the expectation from the extended power law fit beyond the break point and data:

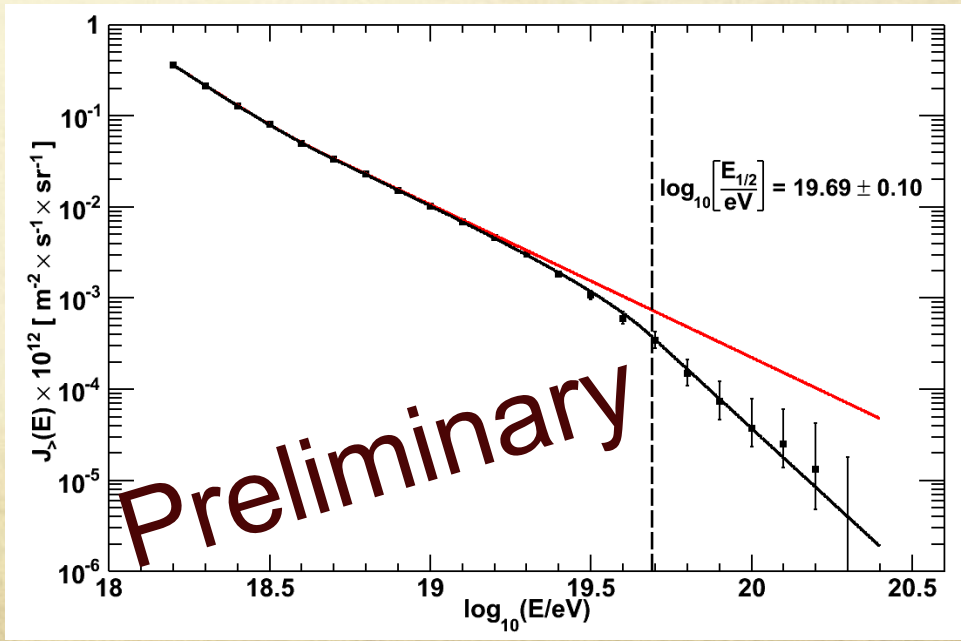
- # of expected events: **54.9**
- # of observed events: **28**

$$\sum_{i=0}^{28} \text{Poisson}(\mu = 54.9; i) = 4.75 \times 10^{-5}$$

**3.9σ**

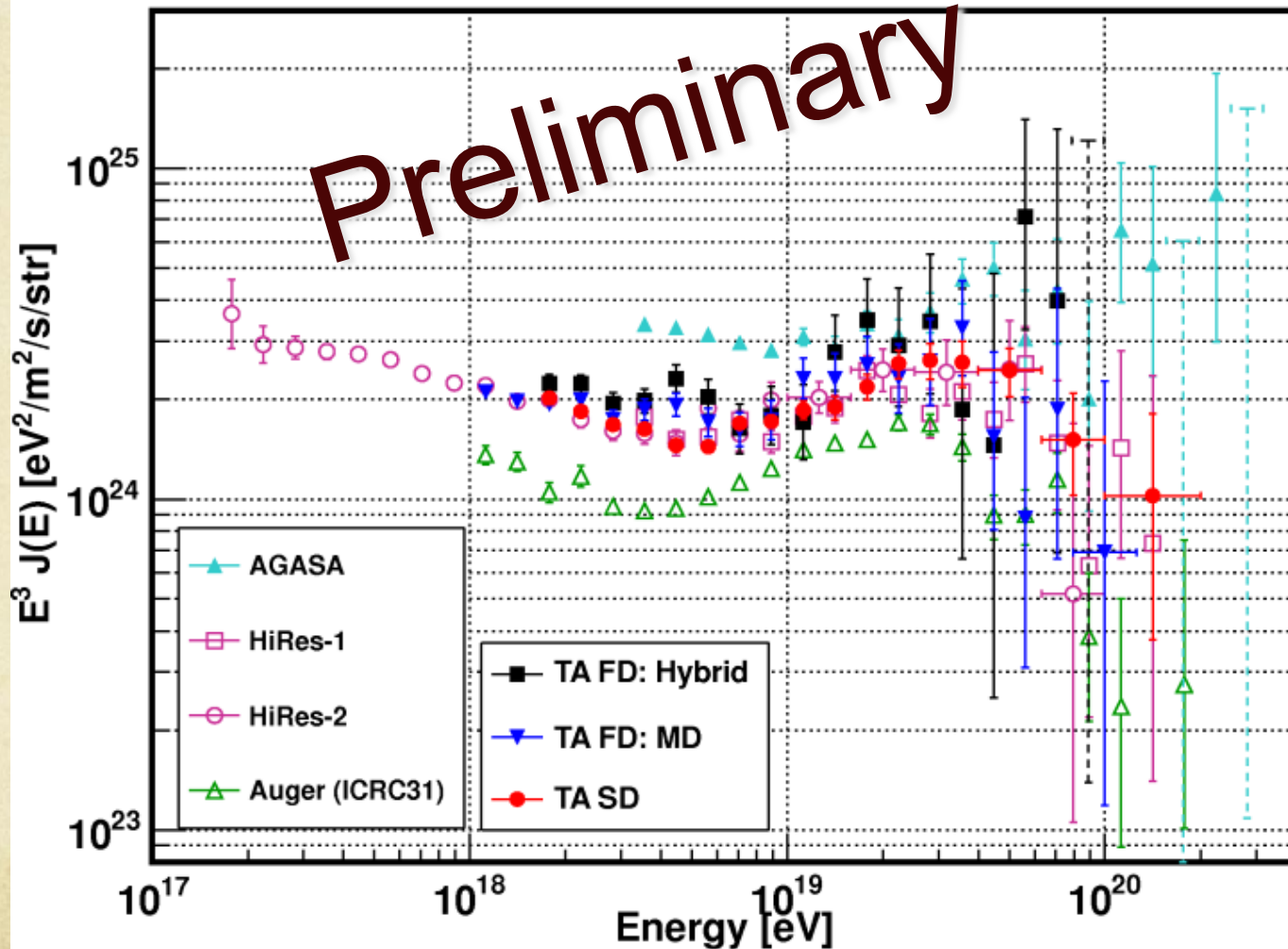
## Integral Flux $E_{1/2}$

- $E_{1/2} = 10^{19.69} \text{eV}$
- Berezhinsky et al. predict  $10^{19.72} \text{eV}$



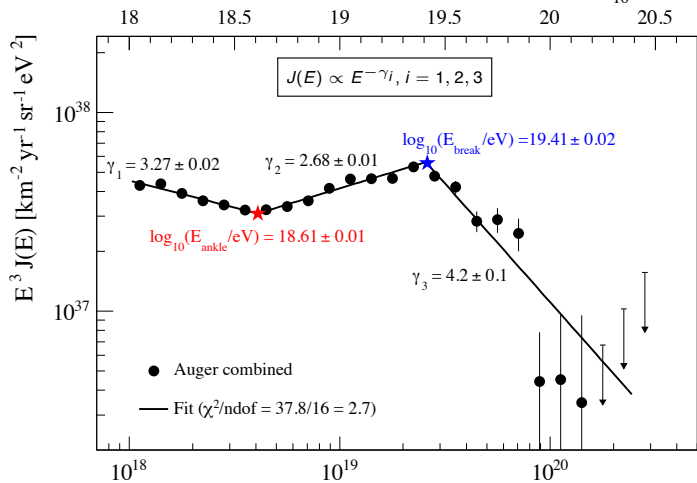
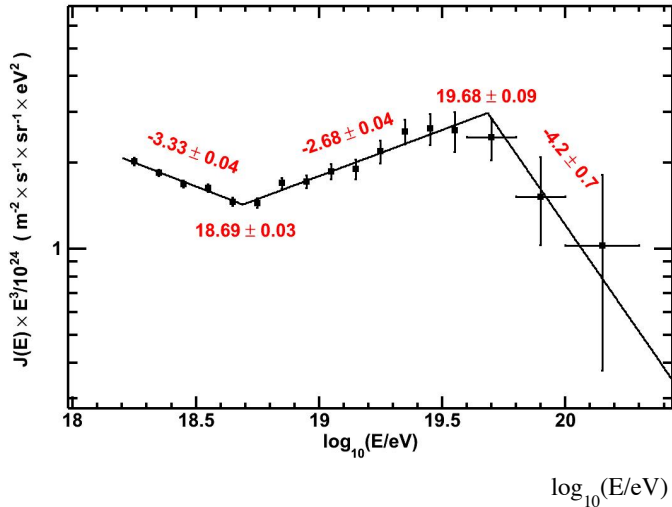


# AGASA, HiRes, Auger, TA



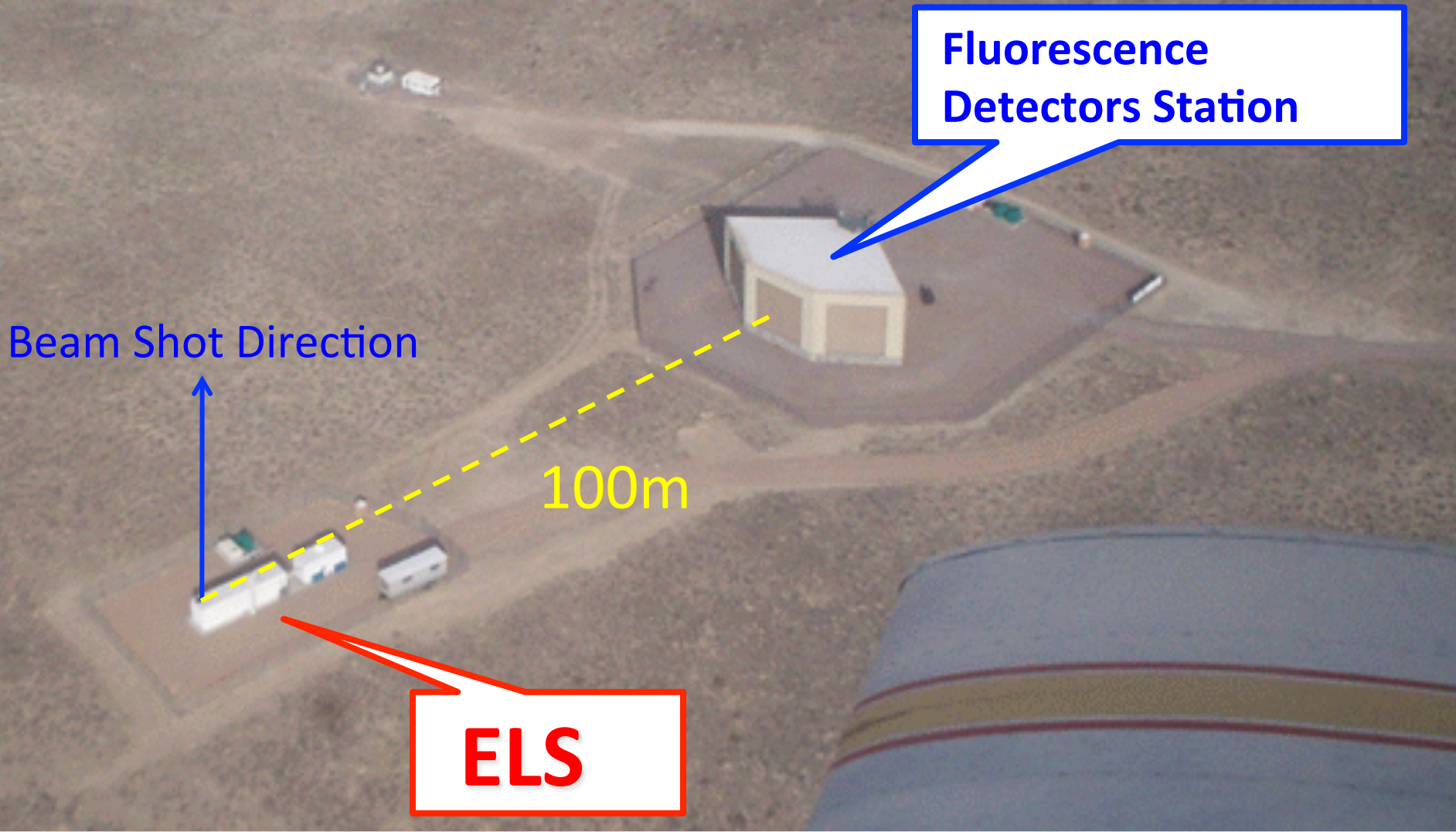
TA spectra are consistent with HiRes. (-20% AGASA, +20% Auger)

# Energy scale and Spectrum in TA, PAO

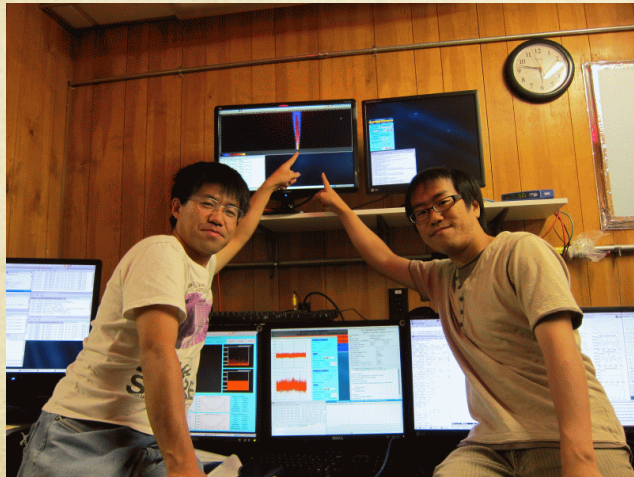
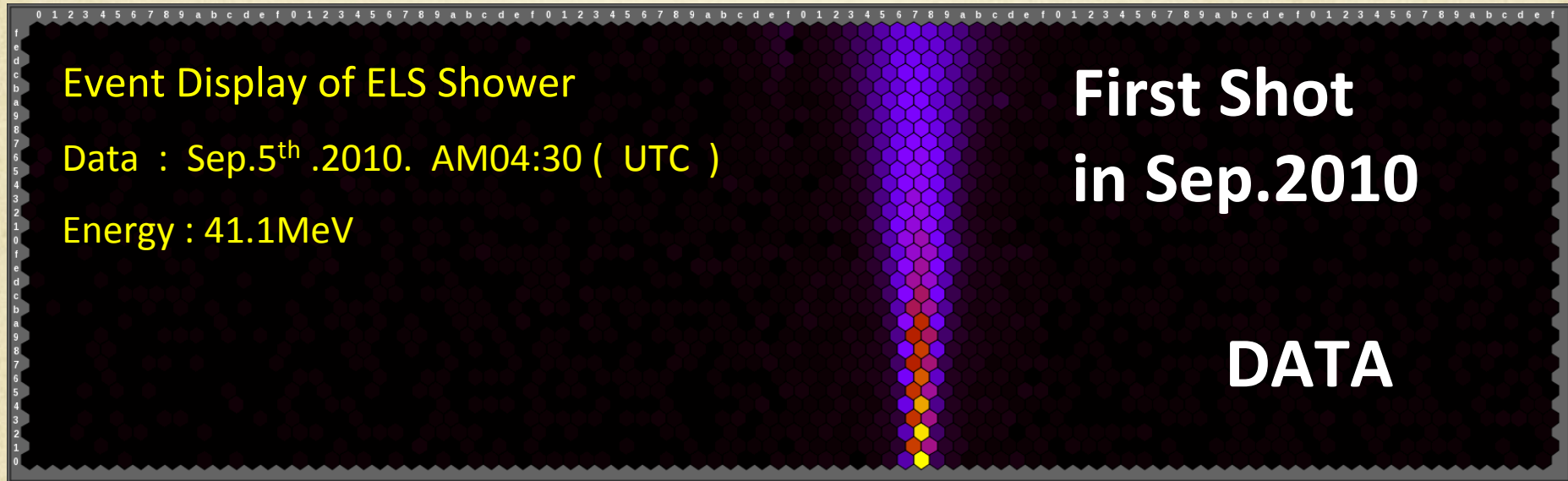


	<b>TA</b>	<b>Auger</b>
$\gamma_1$	$3.33 \pm 0.04$	$3.27 \pm 0.02$
$\gamma_2$	$2.68 \pm 0.04$	$2.68 \pm 0.01$
$\gamma_3$	$4.2 \pm 0.7$	$4.2 \pm 0.1$
$\lg(E_1/\text{eV})$	$18.69 \pm 0.03$	$18.61 \pm 0.01$
$\lg(E_2/\text{eV})$	$19.68 \pm 0.09$	$19.41 \pm 0.02$

# Absolute energy calibration : ELS



# First light of e- beam from ELS



Beam Operation : Sep.2<sup>nd</sup> -4<sup>th</sup>

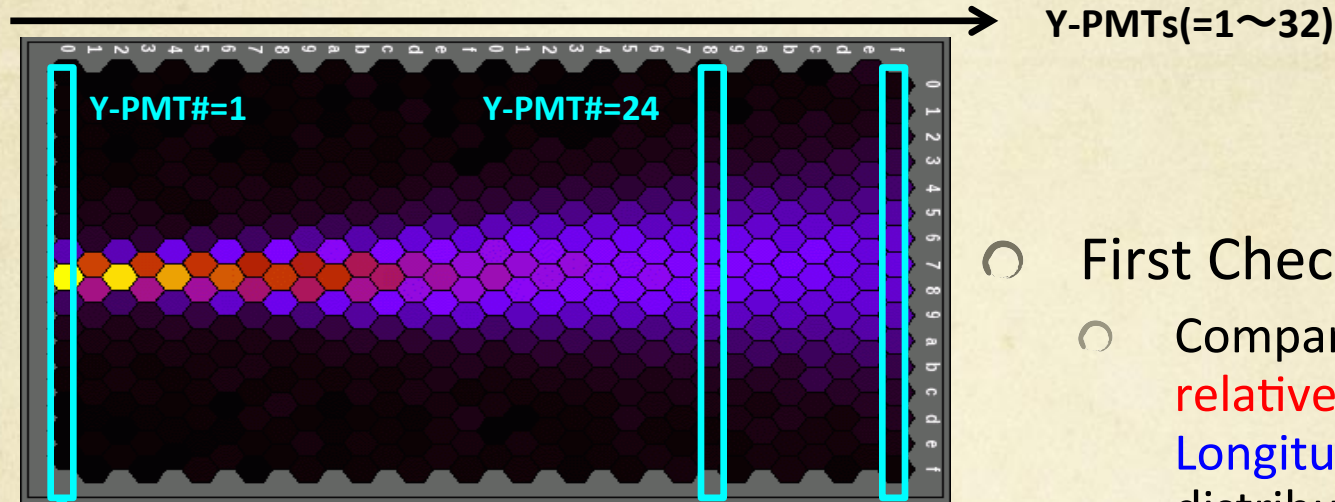
Beam shot into the Sky : Sep. 3<sup>rd</sup> and 4<sup>th</sup>

# of shot into the Sky: ~1800 pulses

Output power =  $41.1\text{MeV} \times 40 \sim 140\text{pC/pulse} \times 0.5\text{Hz}$

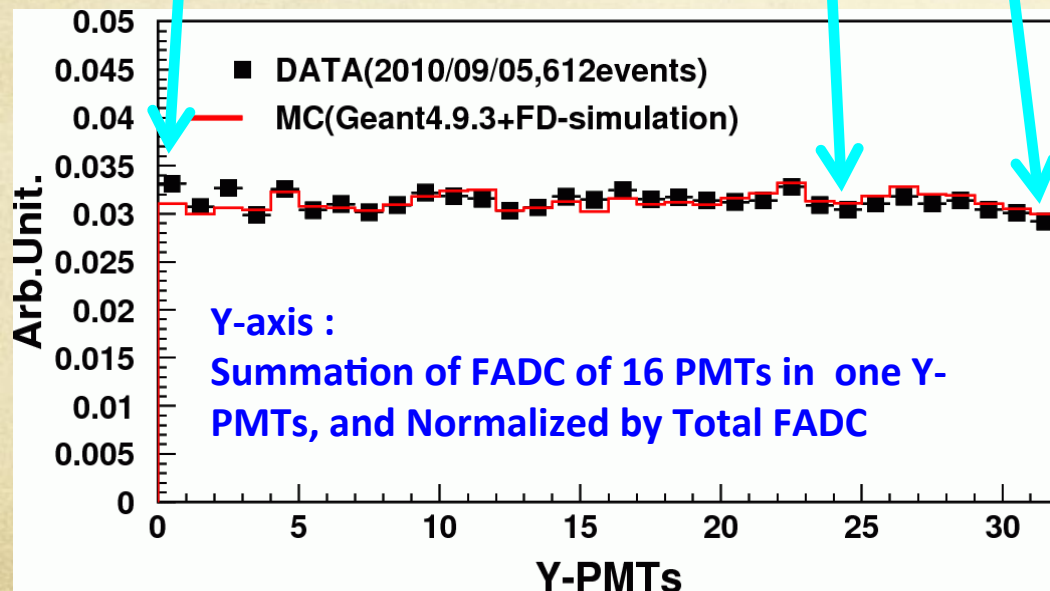
# ELS Analysis

## - Longitudinal distribution-



- First Check:
  - Comparison with the **relative values** on **Longitudinal/Lateral** distributions

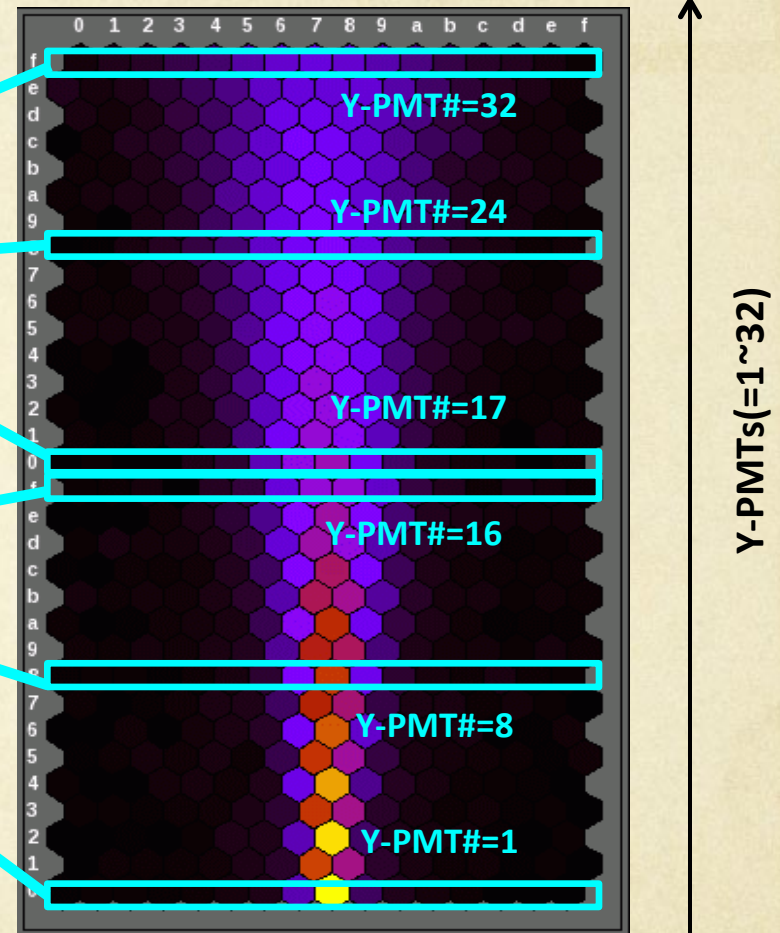
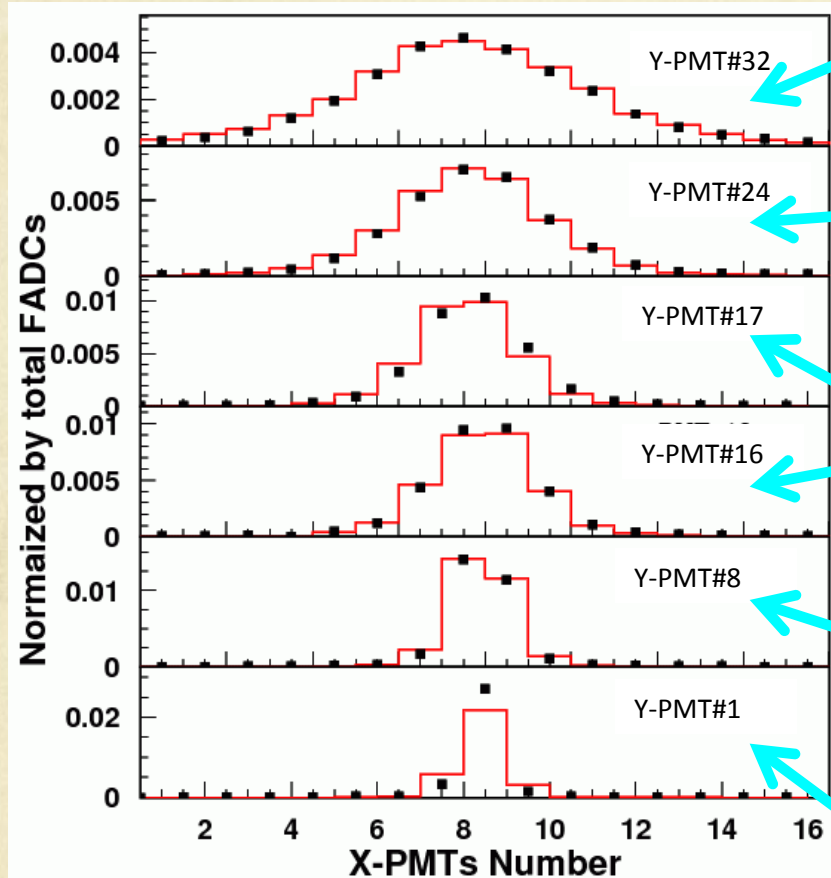
- Data:
  - **612** events (Sep/2010)
  - Beam Energy: **41.1 MeV**



# ELS Analysis

## - Lateral distribution -

■ DATA  
- MC



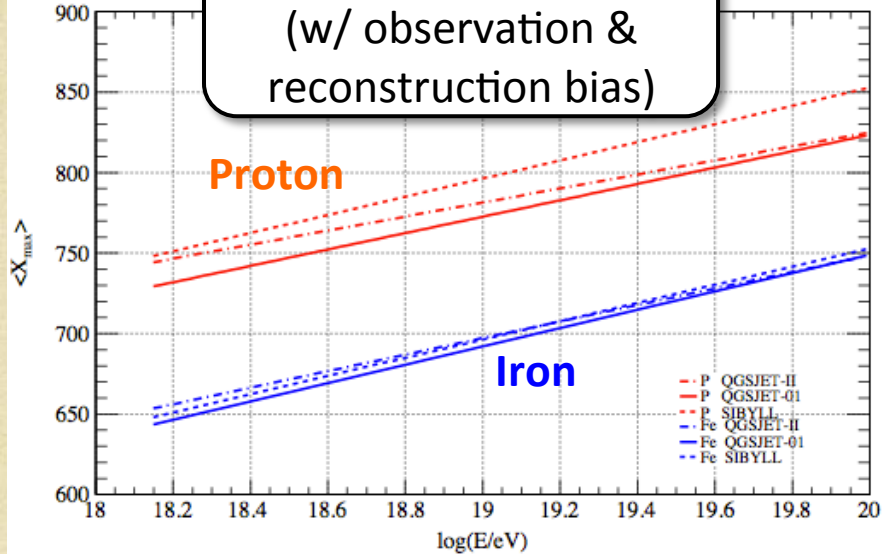
Data/MC are in good agreement !!

➔ Go to absolute calibration...

# Mass Composition

# $X_{\max}$ analysis

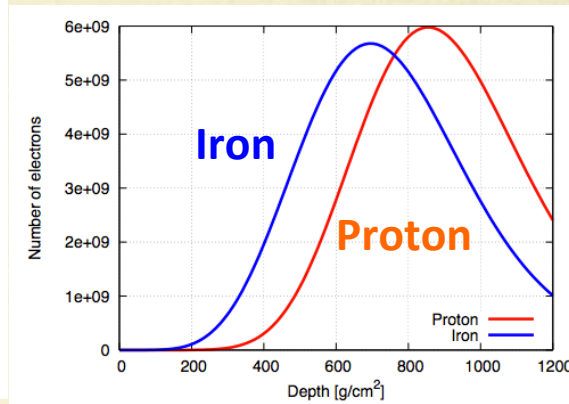
Expected  $\langle X_{\max} \rangle$   
(w/ observation & reconstruction bias)



Shower longitudinal development depends on primary particles

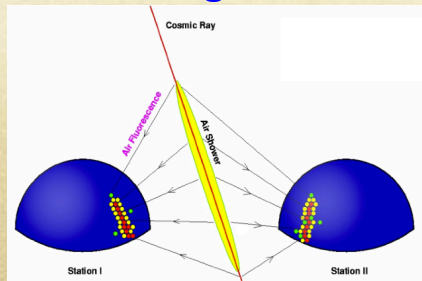
- $X_{\max}$  is the most efficient parameter
- $\langle X_{\max} \rangle$  and that's distribution are compared with Model prediction.

See Talk by Y.Tameda

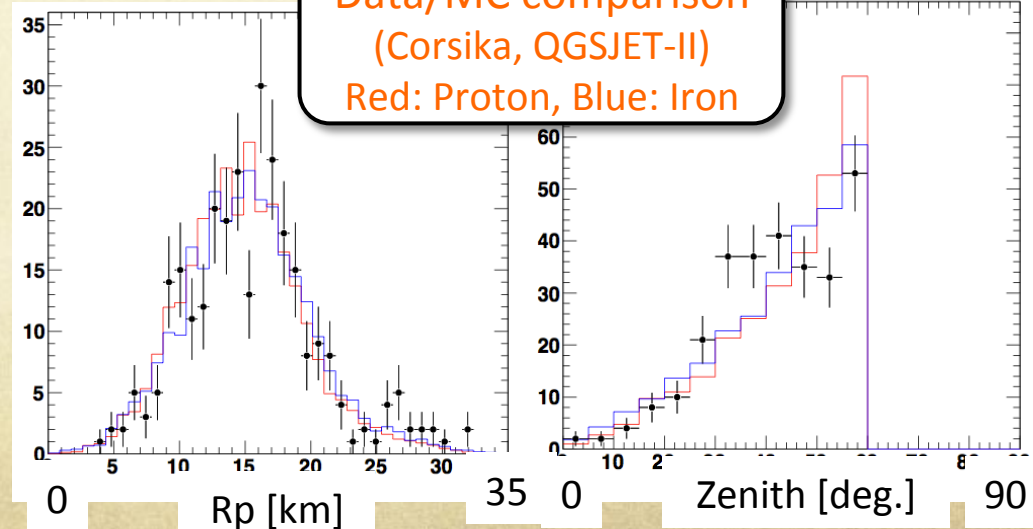


## Stereo analysis on BR/LR

- Axis: Intersection of two Shower-Detector Plane
- Profile: Inverse Monte Carlo
  - $X_{\max}$  resolution:  $\sim 22 \text{ g/cm}^2$

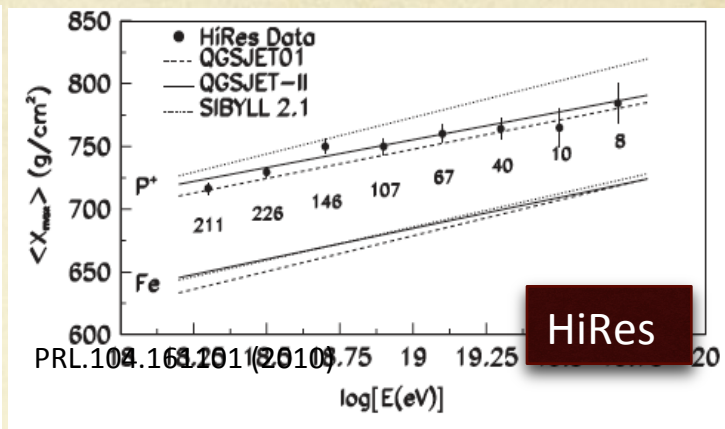
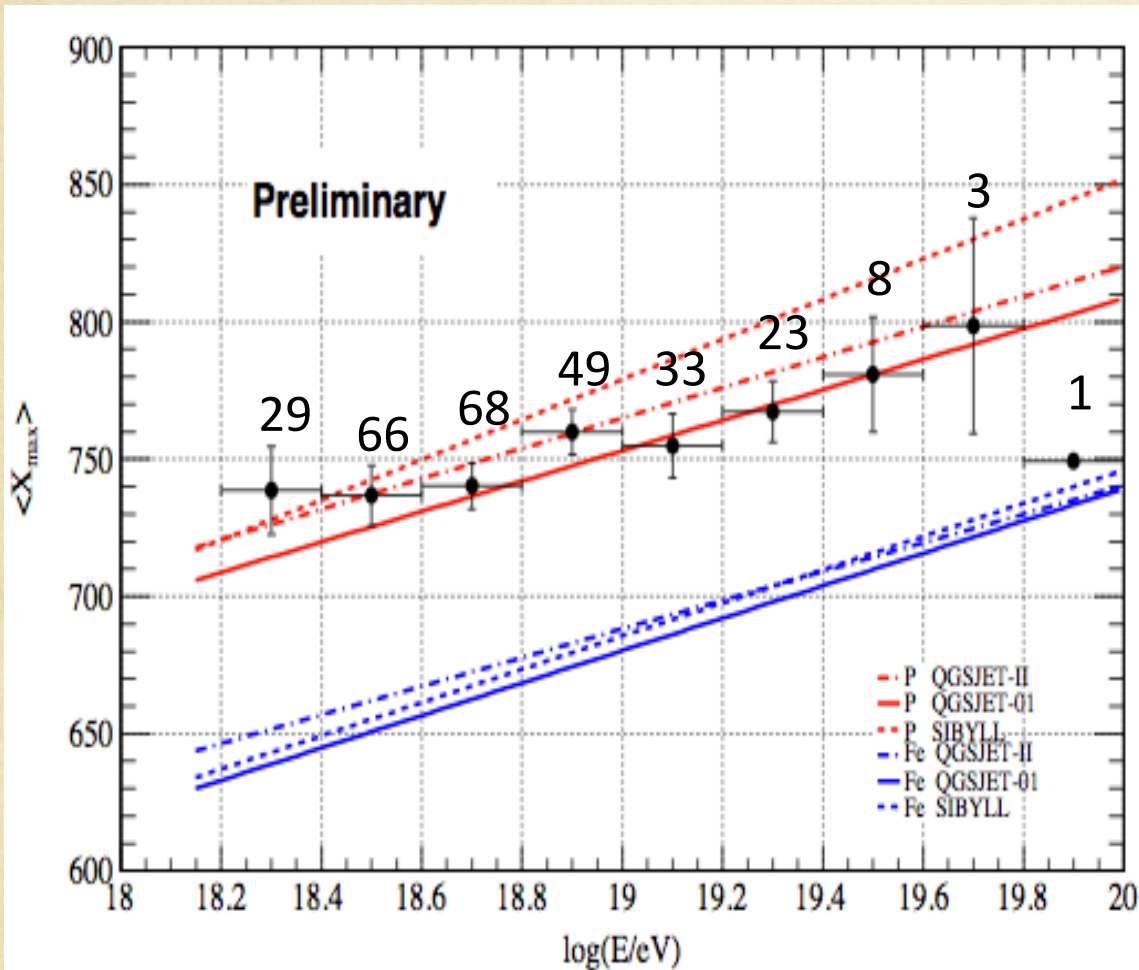


Data/MC comparison  
(Corsika, QGSJET-II)  
Red: Proton, Blue: Iron

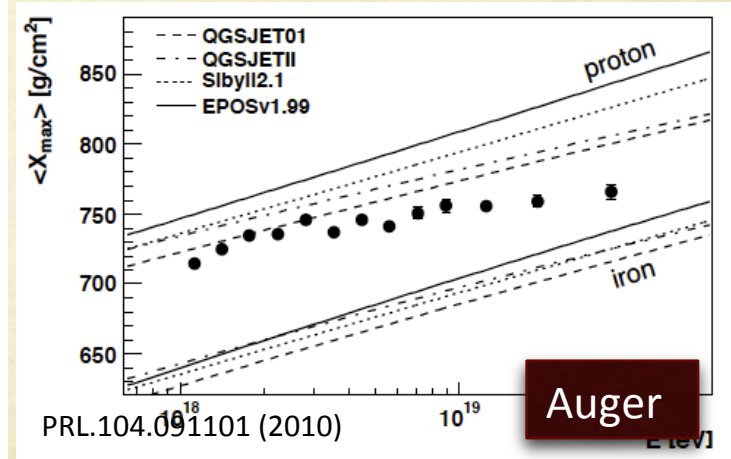




# Energy - $\langle X_{\max} \rangle$



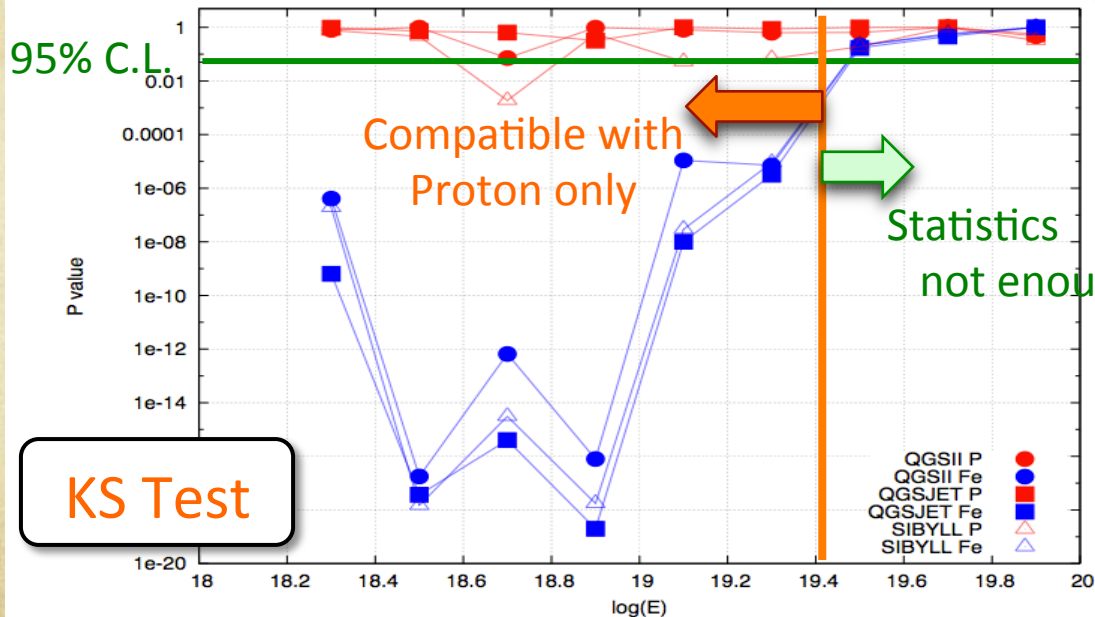
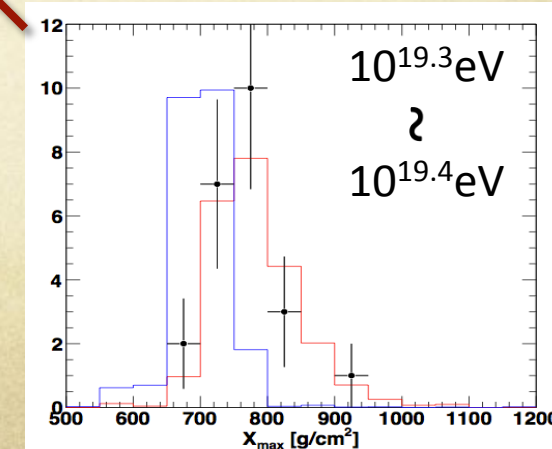
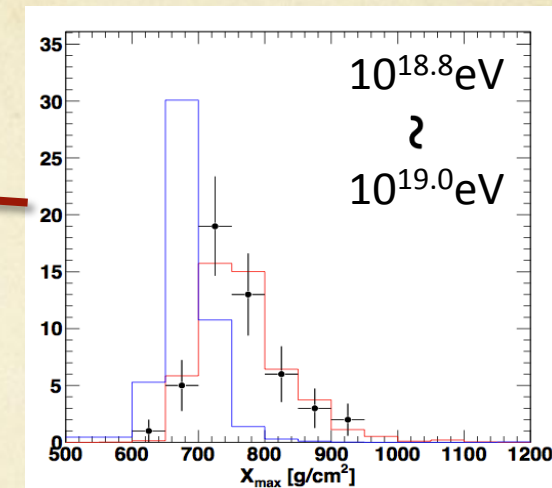
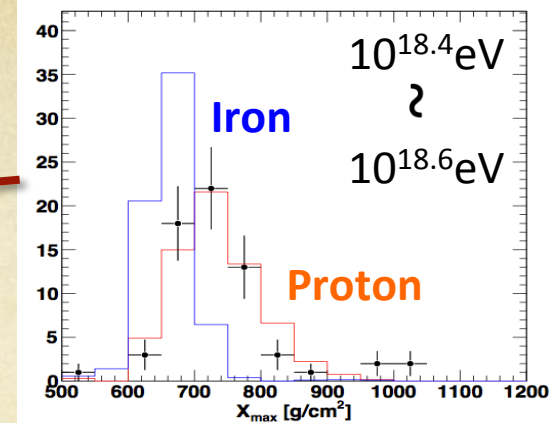
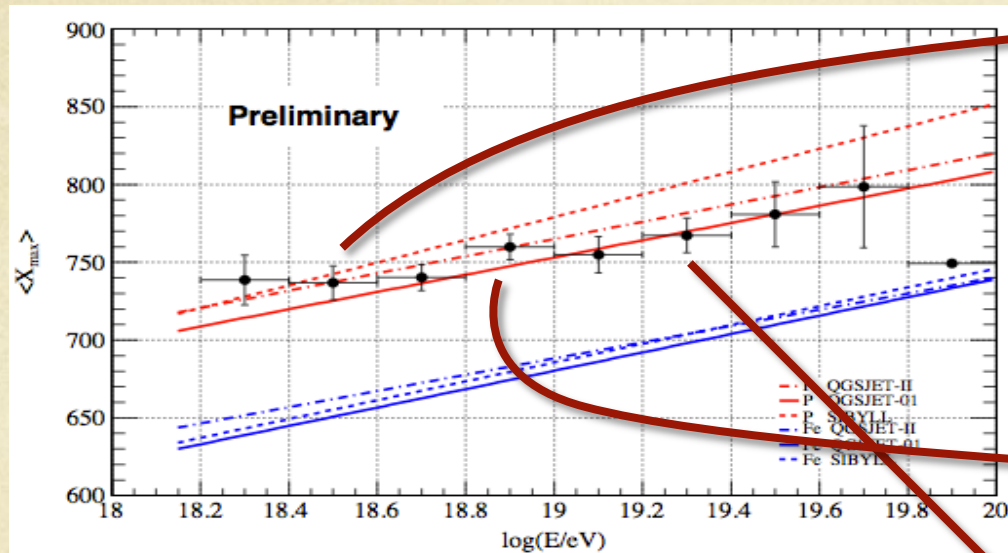
HiRes



Auger

Data set : 2007/Nov – 2010/Sep

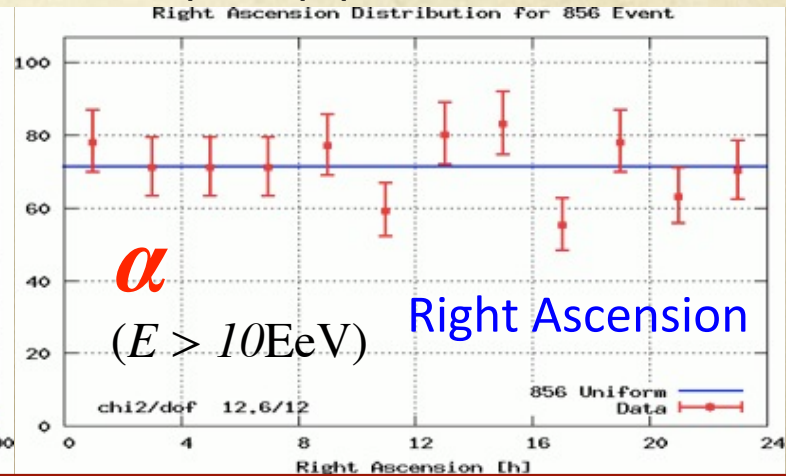
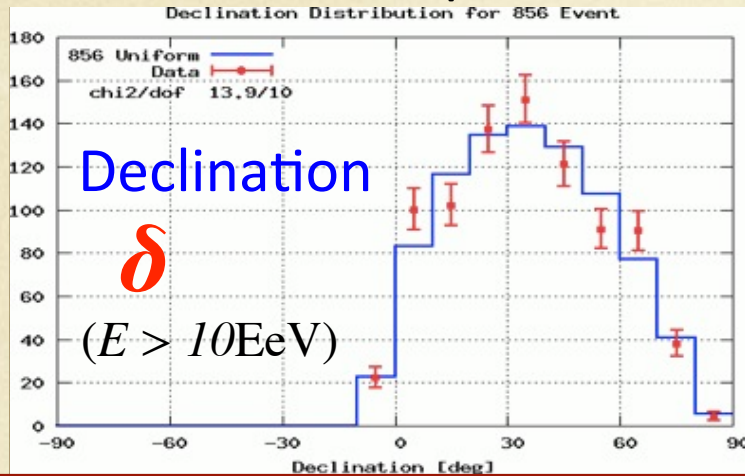
# Distribution of $X_{\max}$ , KS Test



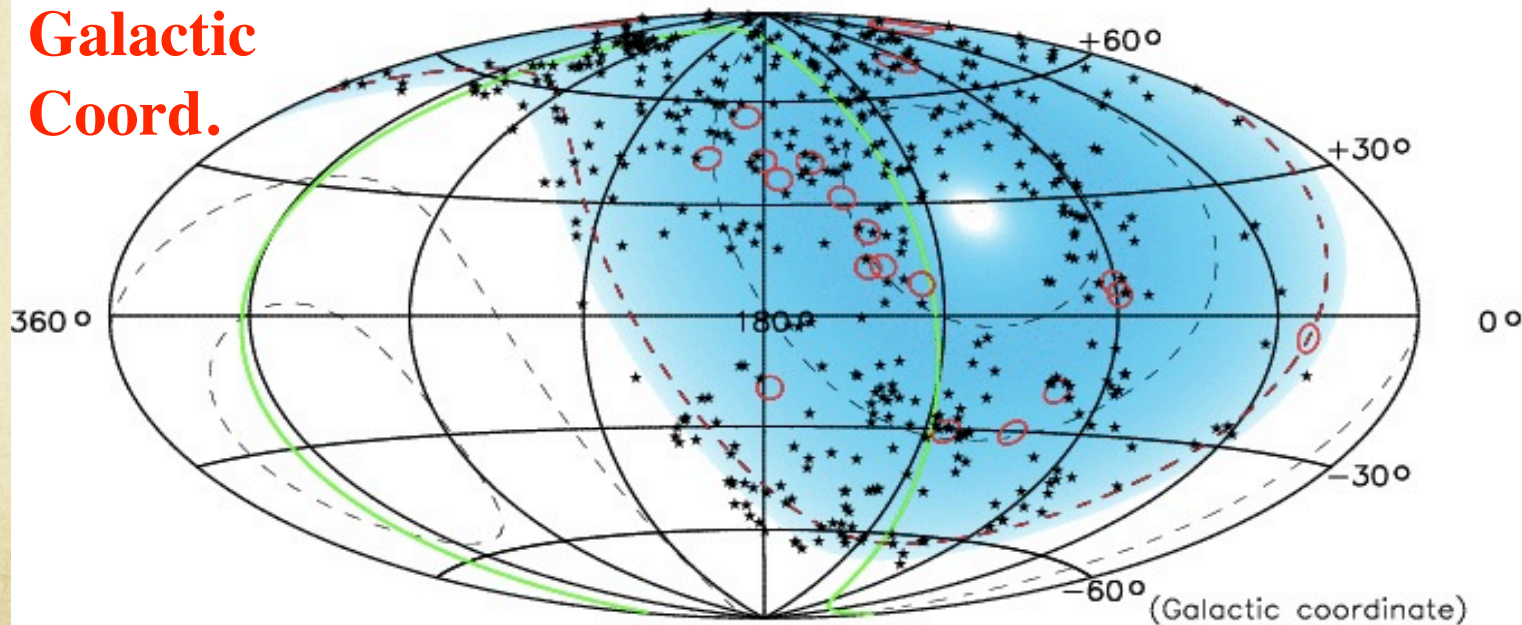
Anisotropy

# Event map

- Consistent w/ Isotropic distribution in  $(\delta, \alpha)$  (854 events,  $E > 10$  EeV)



Galactic  
Coord.



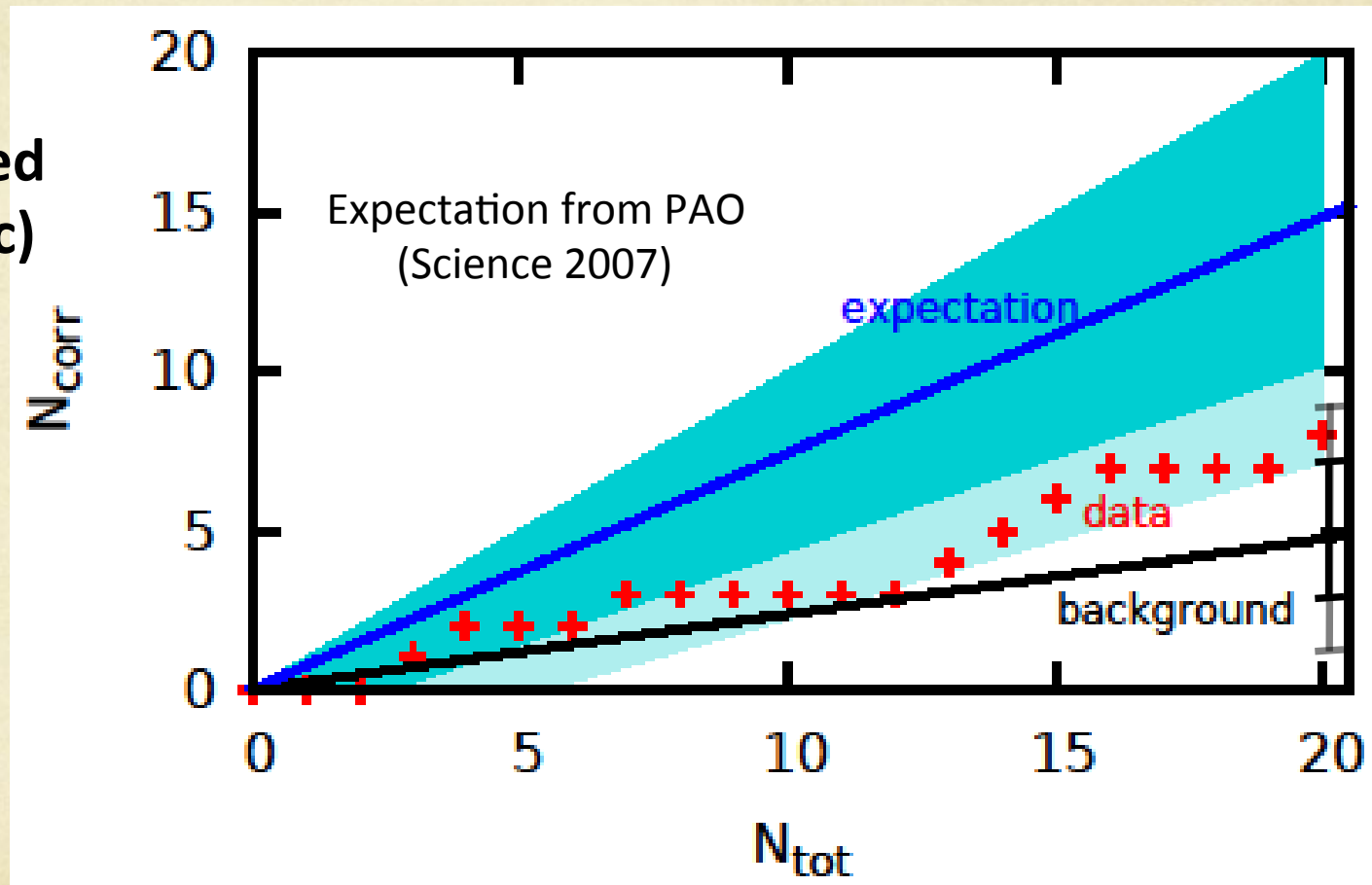
AGN and SD events (20 events,  $>57$  EeV, 3.1 radii)

# AGN correlation

Binomial correlation of SD events ( $>57\text{EeV}$ )

with AGNs in VCV catalog ( $Z < 0.018$ ,  $3.1\text{deg.}$ )

**8 of 20 correlated**  
**(4.8 for isotropic)**

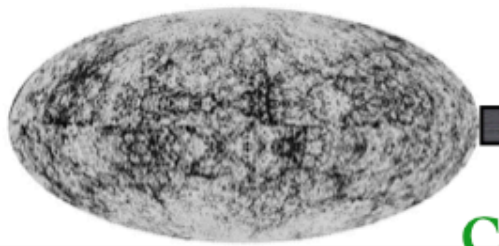


TASD data is consistent with Isotropic distribution

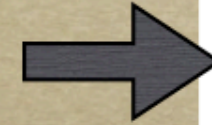
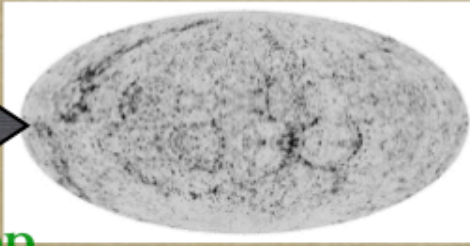
# Large-Scale Anisotropy

2MASS catalog (5-250Mpc)  
& uniform intensity (>250Mpc)

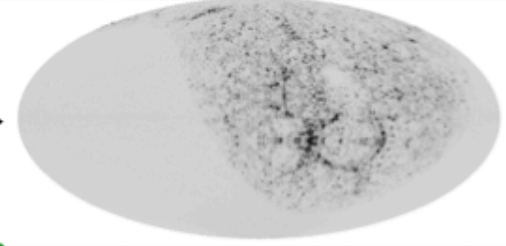
Proton ( $E^{-2.2}$ )  
Interactions/redshift



CR Prop.



TA Exp.



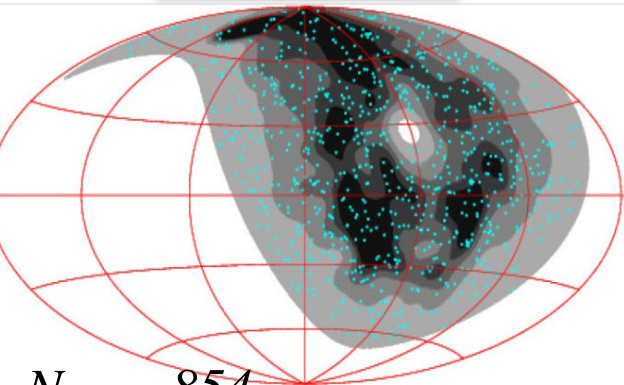
Smearing angle: Free parameter  
GC region excluded  
( $|b| < 10\text{deg}$ ,  $||l|| < 90\text{deg}$ )

Smearing

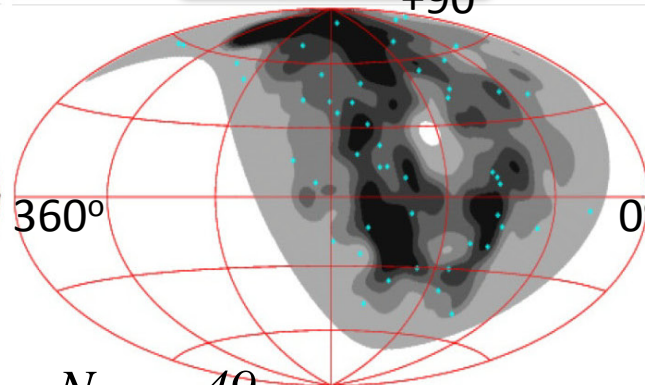
$E > 10 \text{ EeV}$

$E > 40 \text{ EeV}$

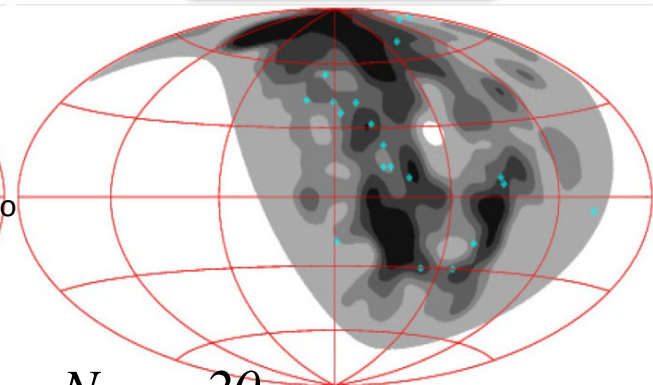
$E > 57 \text{ EeV}$



$N_{\text{evt}} = 854$



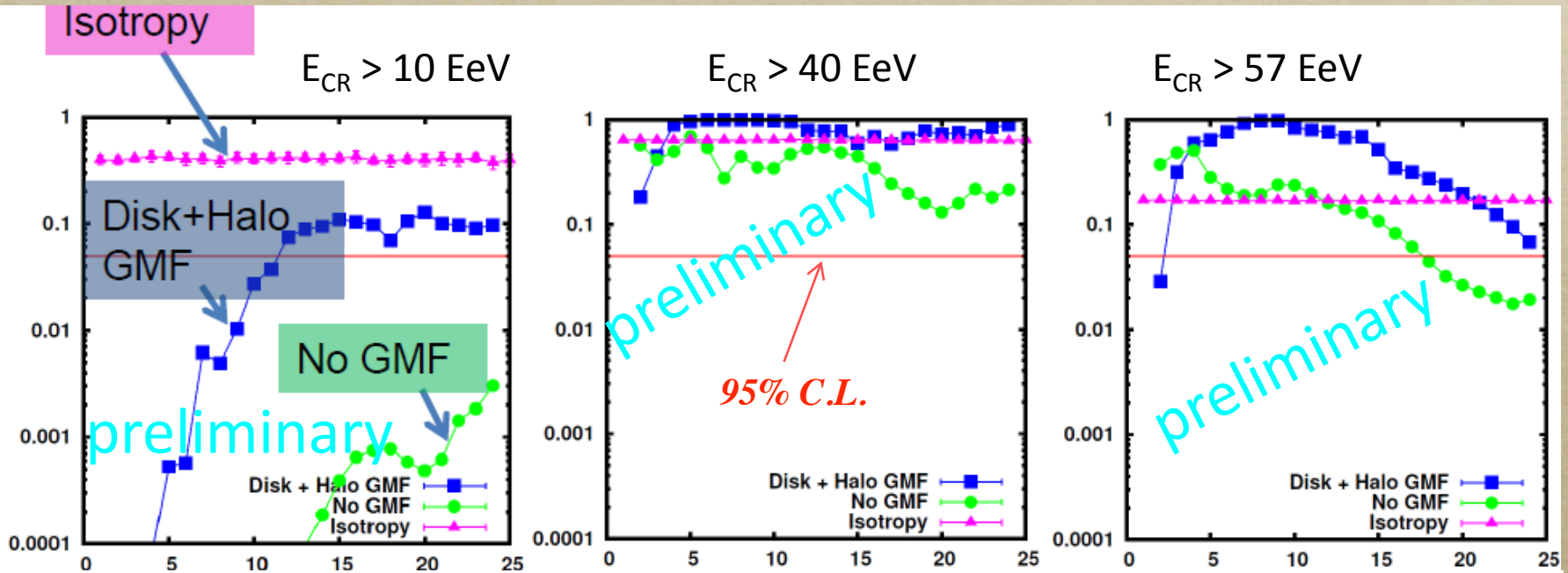
$N_{\text{evt}} = 49$



$N_{\text{evt}} = 20$

# TASD and LSS - KS Test -

Probability



Smearing angle  $\theta \sim 25^\circ$

- Compatible with isotropy for all energy regions
- Compatible with the LSS hypothesis at  $40/57$  EeV w/ or w/o GMF
- NOT compatible with LSS for  $E > 10$  EeV,  
w/o strong/extended halo field

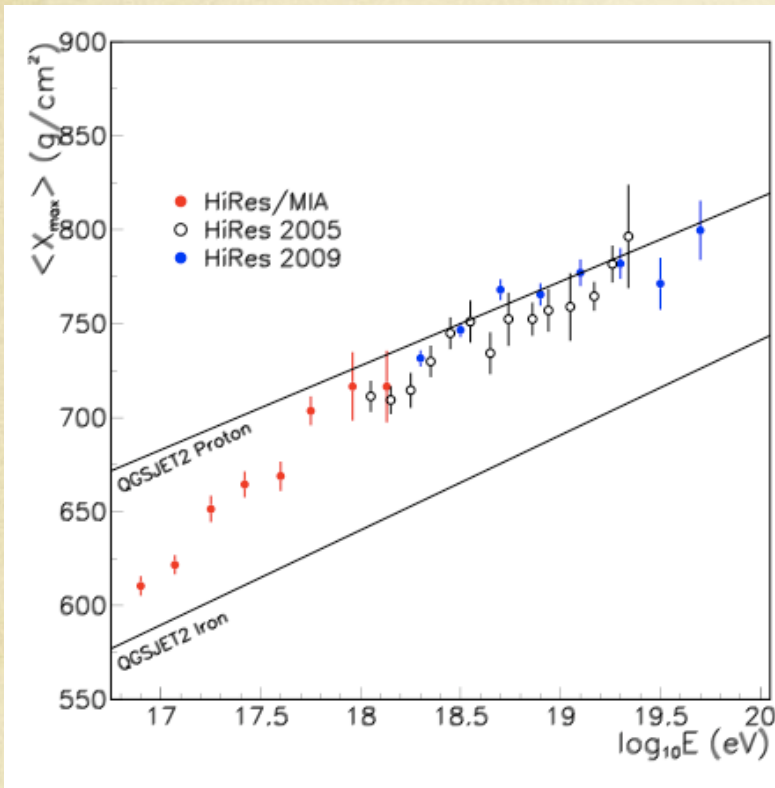
# New Projects



# New Projects at the Telescope Array

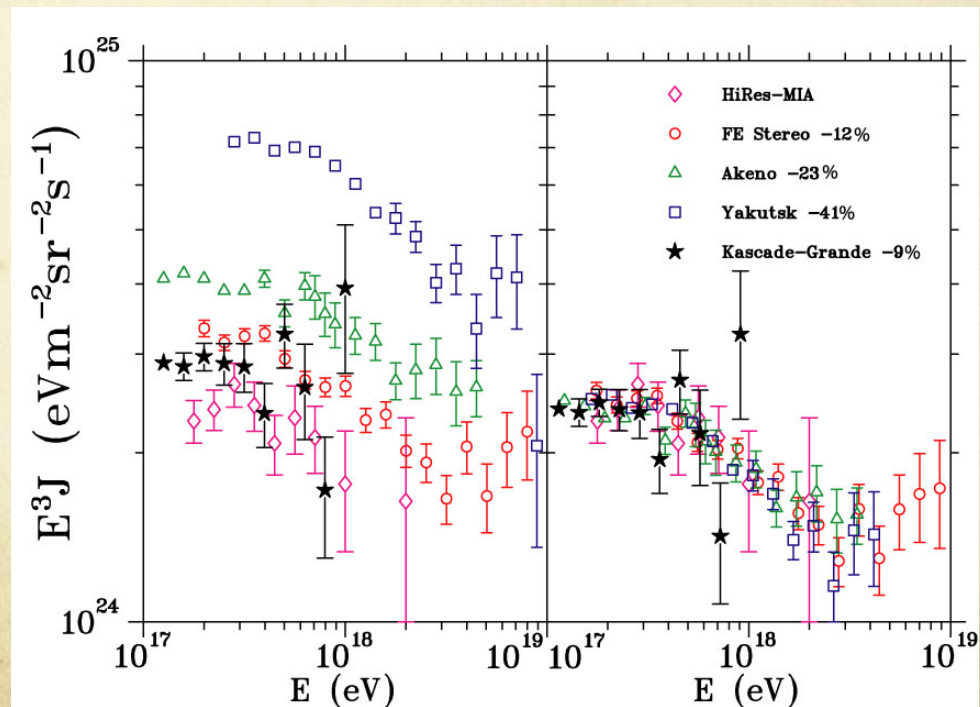
- **Telescope Array Low Energy Extension : TALE**
  - Study CR spectrum, composition, anisotropy from  $10^{16.5}$  eV to  $10^{18}$  eV with hybrid detectors
  
- **Detection of  $> 10^{18}$  eV CR using bi-static radar**
  - R/D project to use 50MHz TV carrier waves to detect plasma produced by EAS in the atmosphere

# TALE physics



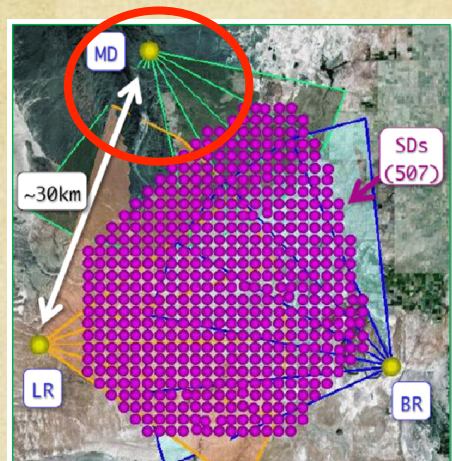
- Study reported but poorly known spectral features – “iron knee”, “second knee”, “galactic-extragalactic transition”

- Study EAS physics at same energy as LHC ( $10^{16.5-17}$  eV)
  - Compare LHC validated proton MC with experimental EAS determination

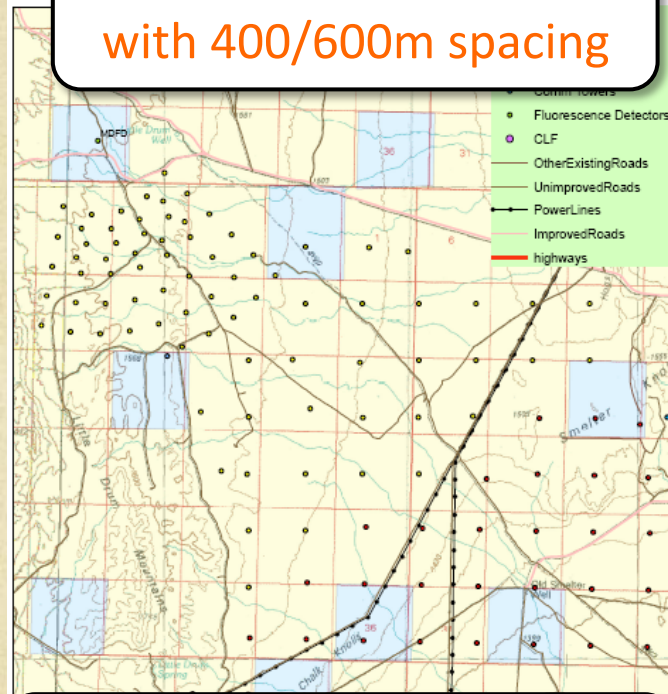


# TALE Detectors

F.O.V of TALE FD (~60deg.)

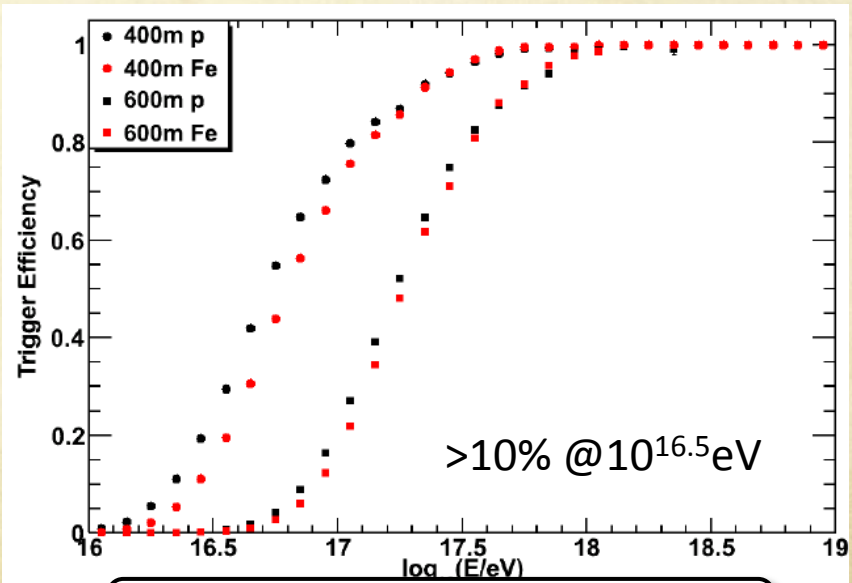
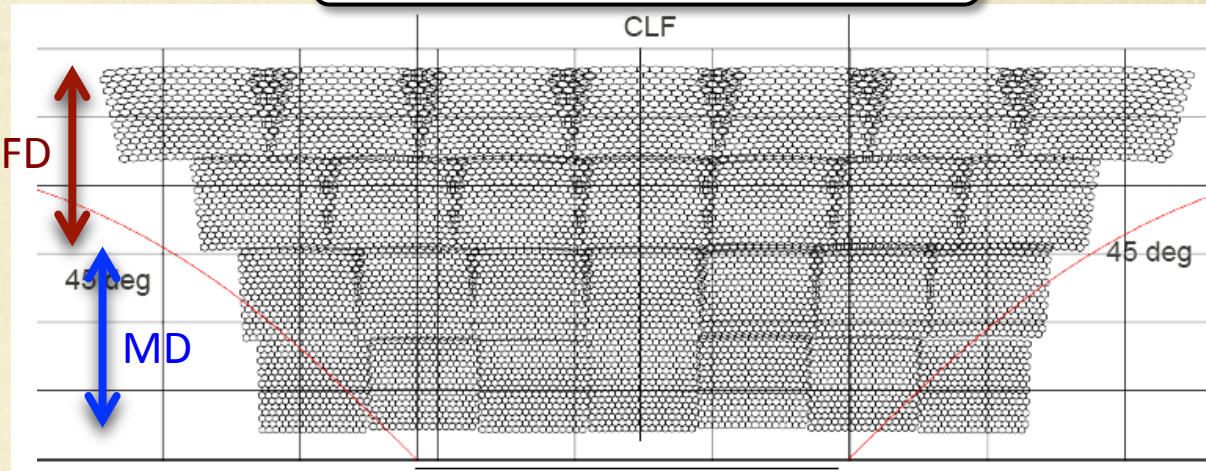


50 scintillator counters with 400/600m spacing



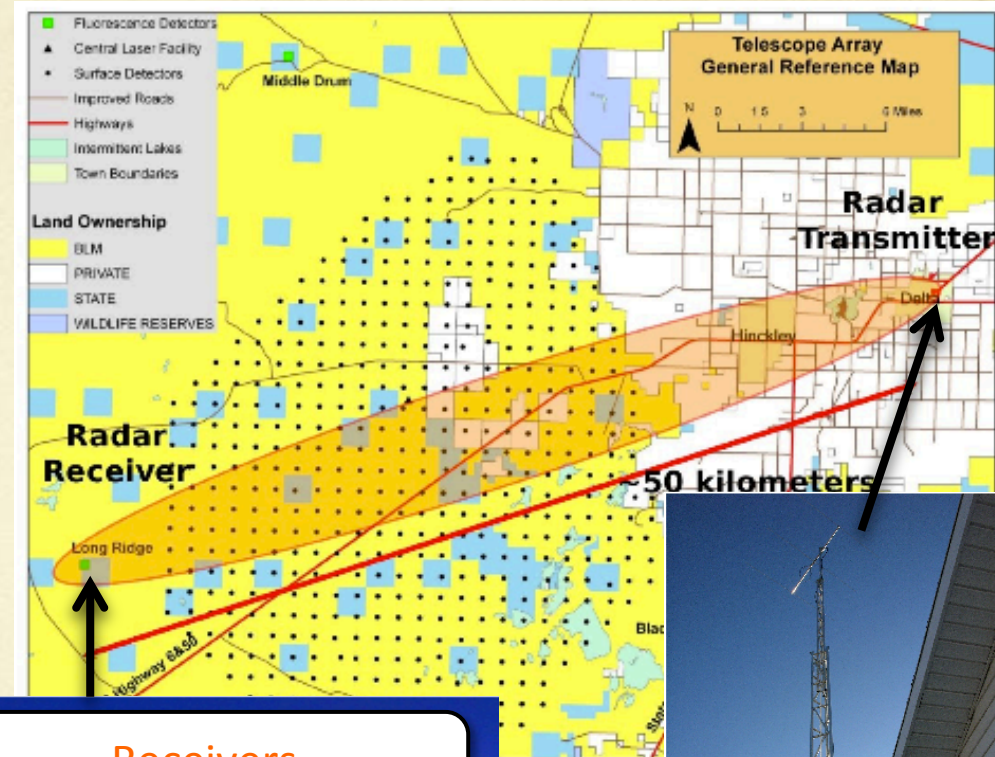
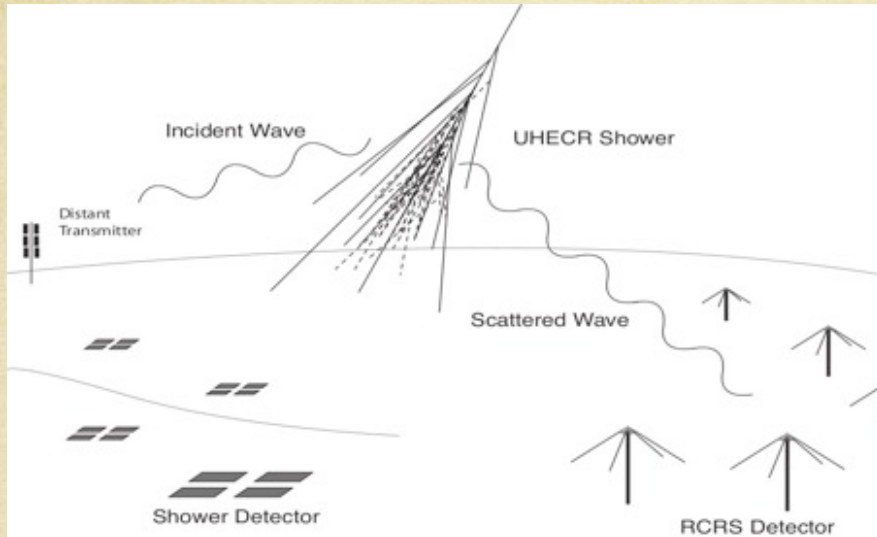
30 counters with 1.2km spacing link infill with T ASD

TALE FD

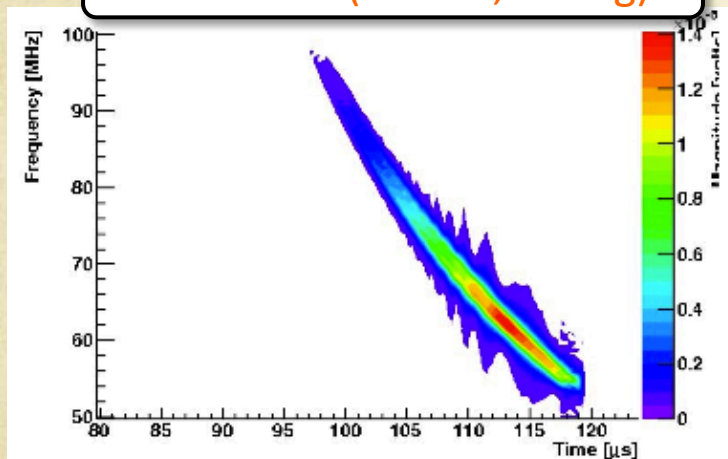


Trigger efficiency of TALE SD

# Bistatic Radar at Telescope Array

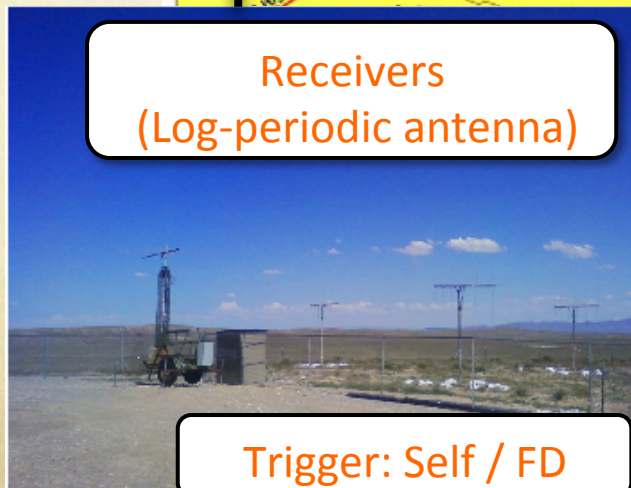


Prediction ( $10^{19}$ eV, 30deg)



“Chirp” : Unique signature for EAS  
(Rapid movement of “target” produces Doppler-like shift)

Receivers  
(Log-periodic antenna)



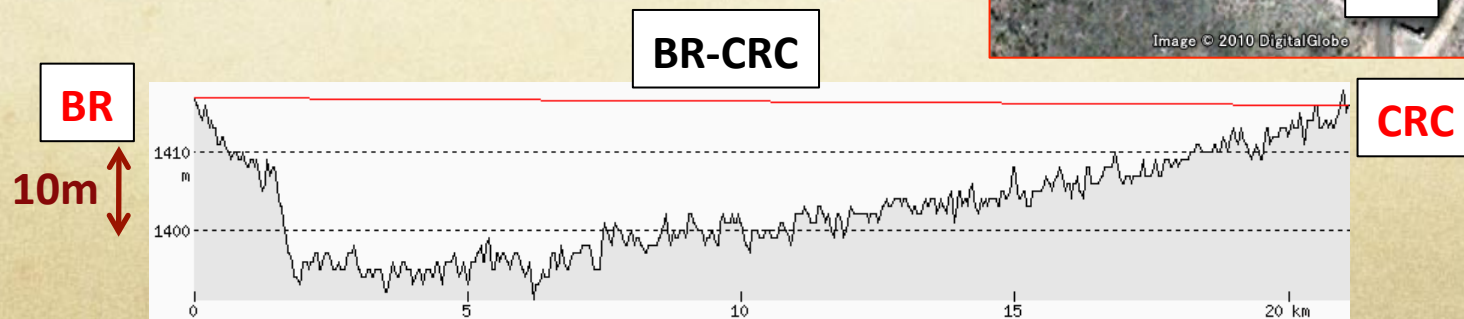
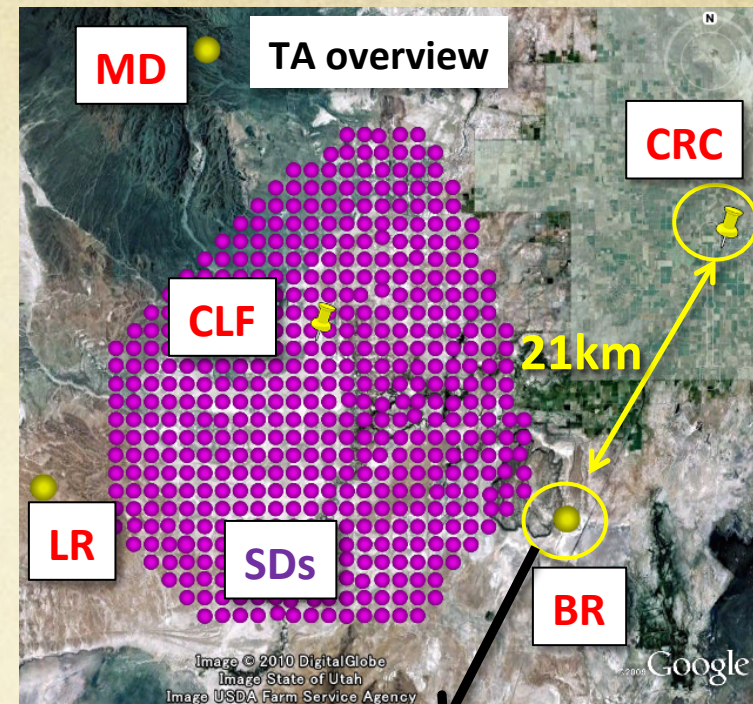
Trigger: Self / FD



Transmitter (6m Yagi)  
Power: 2kW -> 40kW

# Calibration by ELS

- Radio path: CRC - ELS – BR
- E-plane of trans. wave is vertical
- Confirmation of the technique
- Ratio of detected power to received power gives **cross-section**
- Duration of signal gives **free electron lifetime** in air
- Expected S/N:  $\sim 30 / 1000$ shots (30min)



# Conclusion

- Three years TA full operation
- Energy Spectrum:
  - MD, BR/LR, SD spectra are in good agreement
  - Consistent with HiRes
  - Suppression:  $3.9 \sigma$  away from continued spectrum
- Composition: Proton dominant up to GZK break point
- Anisotropy: Compatible with both isotropy and AGN/LSS correlation hypothesis
  - Need more statistics
- New projects: TALE, bistatic radar...

Other four talks from TA:

FD analysis (T.Fujii), Composition (Y.Tameda)

CRAYS (M.Fukushima), Atmosphere (T.Tomida)