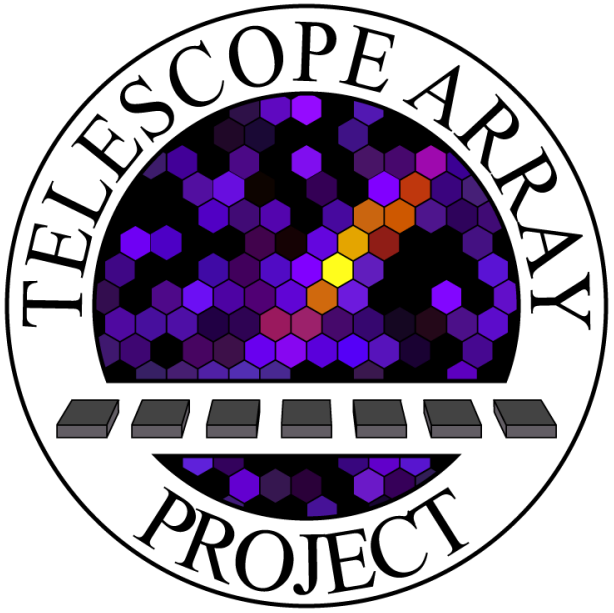
Telescope Array Experiment



Dmitri Ivanov
University of Utah
IPA 2017/05/09, 17:24-17:42

Outline

- Telescope Array (TA) Experiment
- Spectrum
- Anisotropy
- Composition
- Photon Search
- Summary

Telescope Array

Hybrid detector

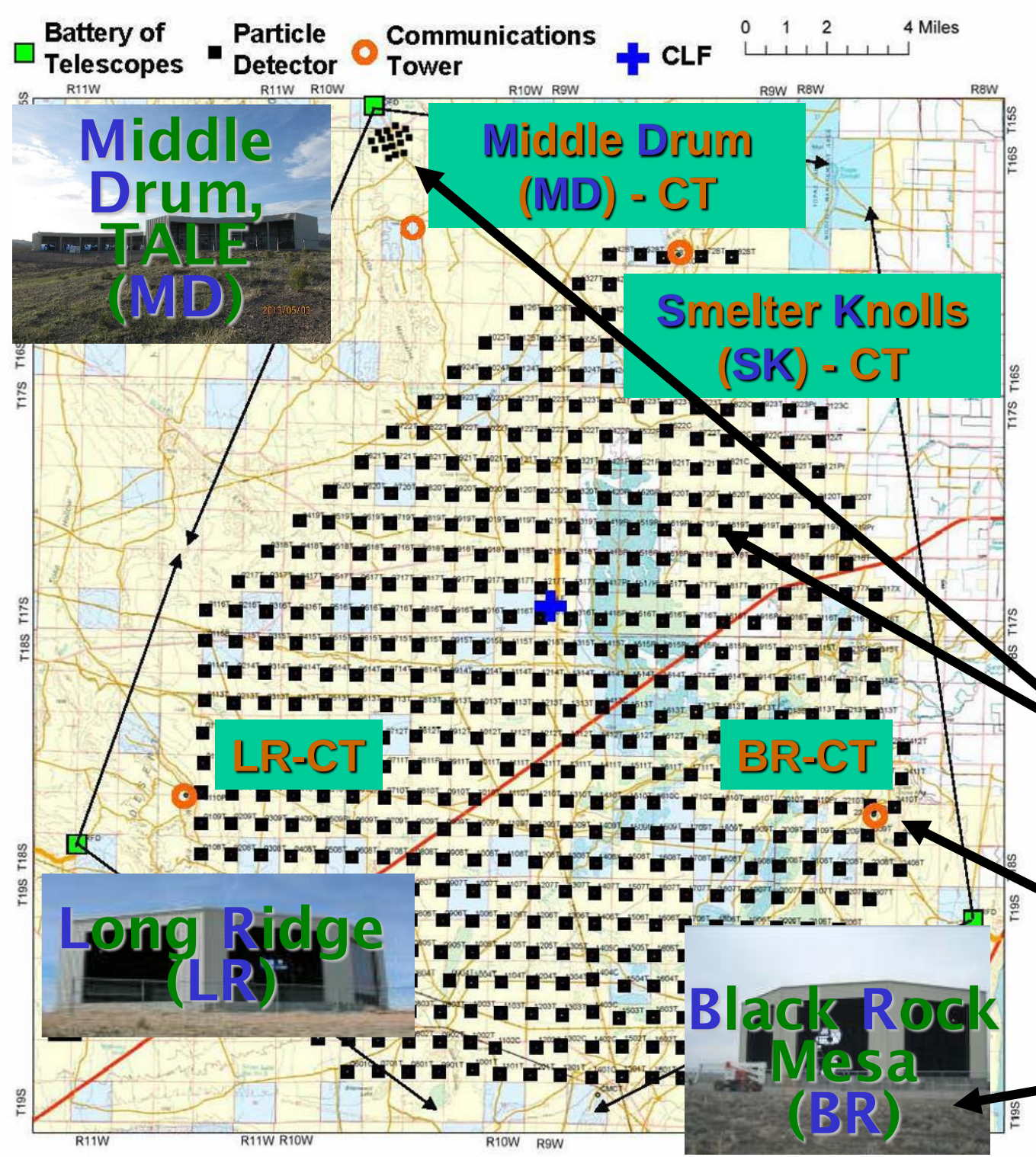
Millard County, UT
39.3˚ N , 112.9˚ W,
Alt. 1400m
~880g/cm²

507 Surface Detector (SD) counters, 1.2km apart

16 active TALE infill array counters, 400m spacing

4 Communication Towers(CT): BR,LR,SK,MD

3 Fluorescence Detector sites(FD): BR,LR,MD/TALE

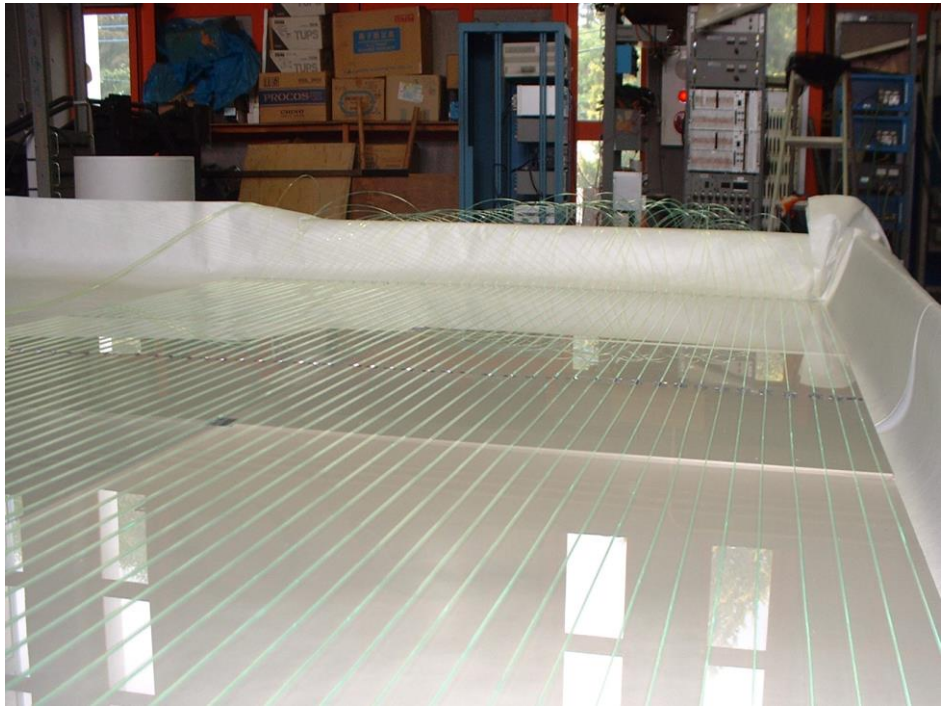


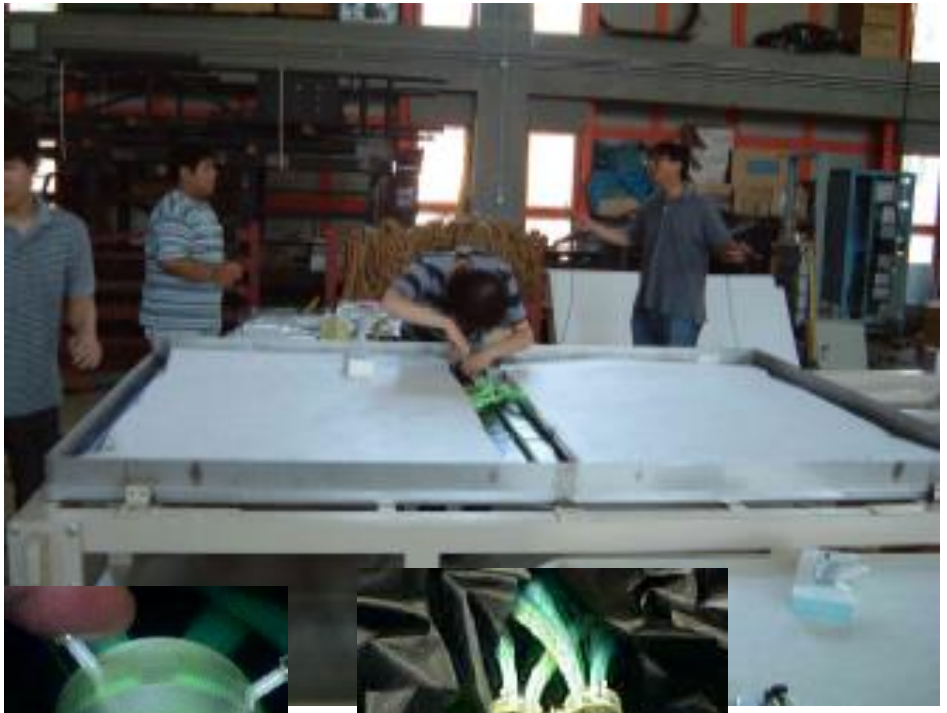
TA FD


MD
LR
BRM
2013/03/29
© 2013 Google
Image USDA Farm Service Agency
Image State of Utah
Google earth

TA Surface Detector

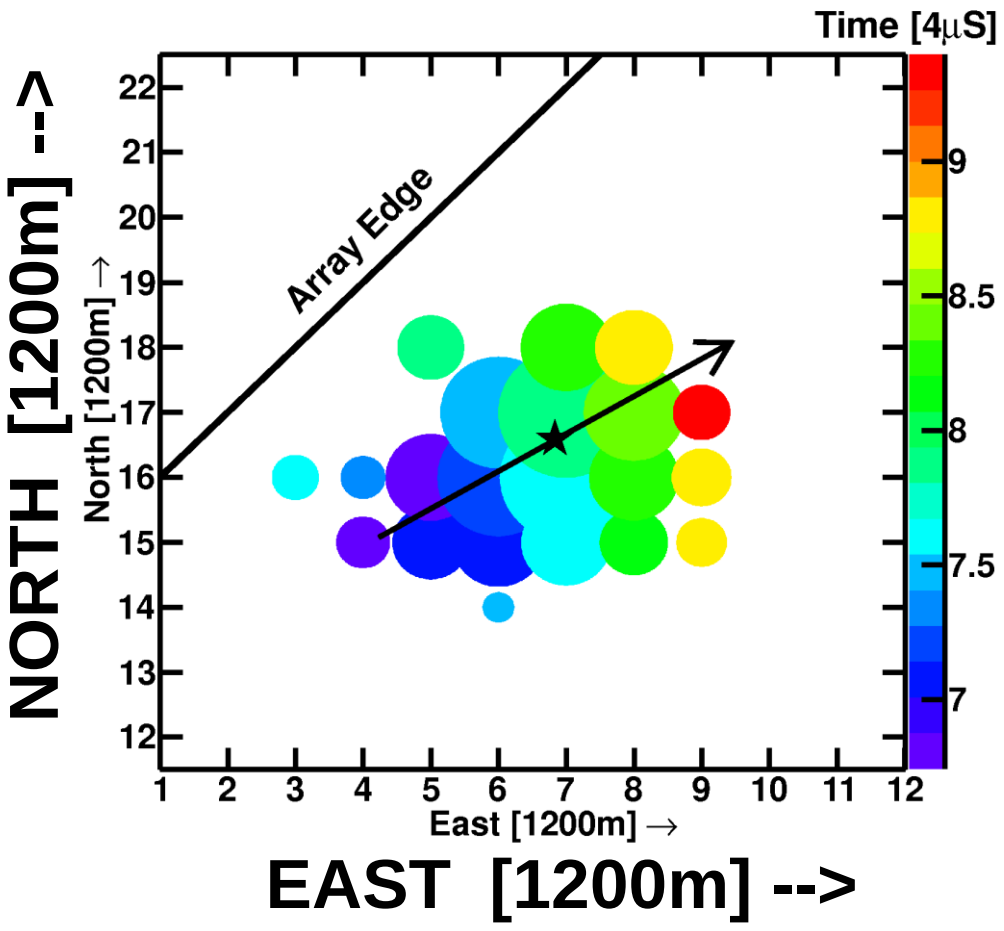
- Powered by solar cells; radio readout.
- In operation since March, 2008.
- Self-calibration using minimum ionizing atmospheric muons.

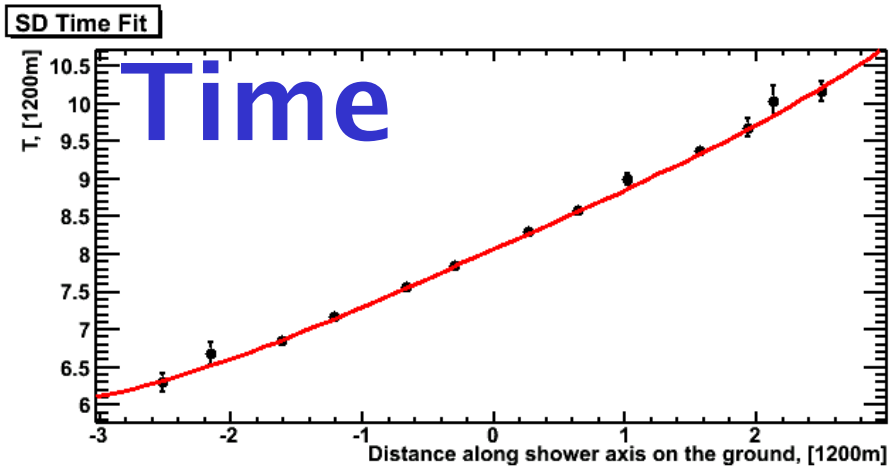


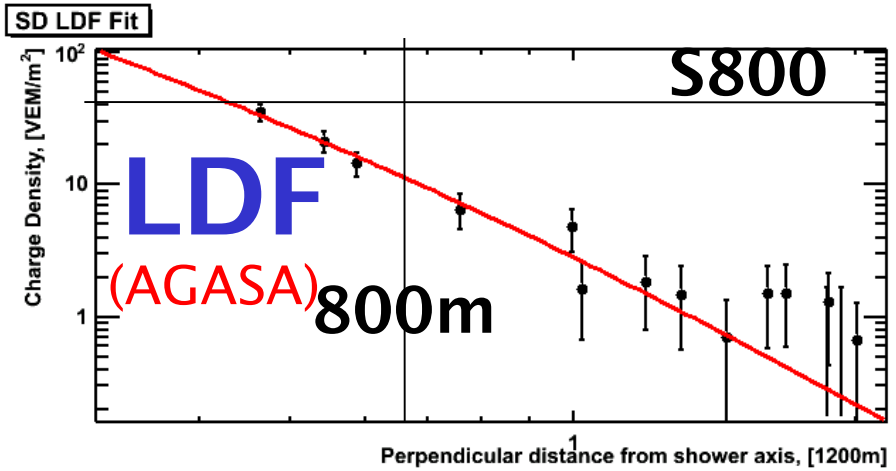


Pre-assembled in Japan, Final Assby/testing in Delta: **2 layers**, **1.25 cm** scintillator, **3m^2** area

Surface Detector Event



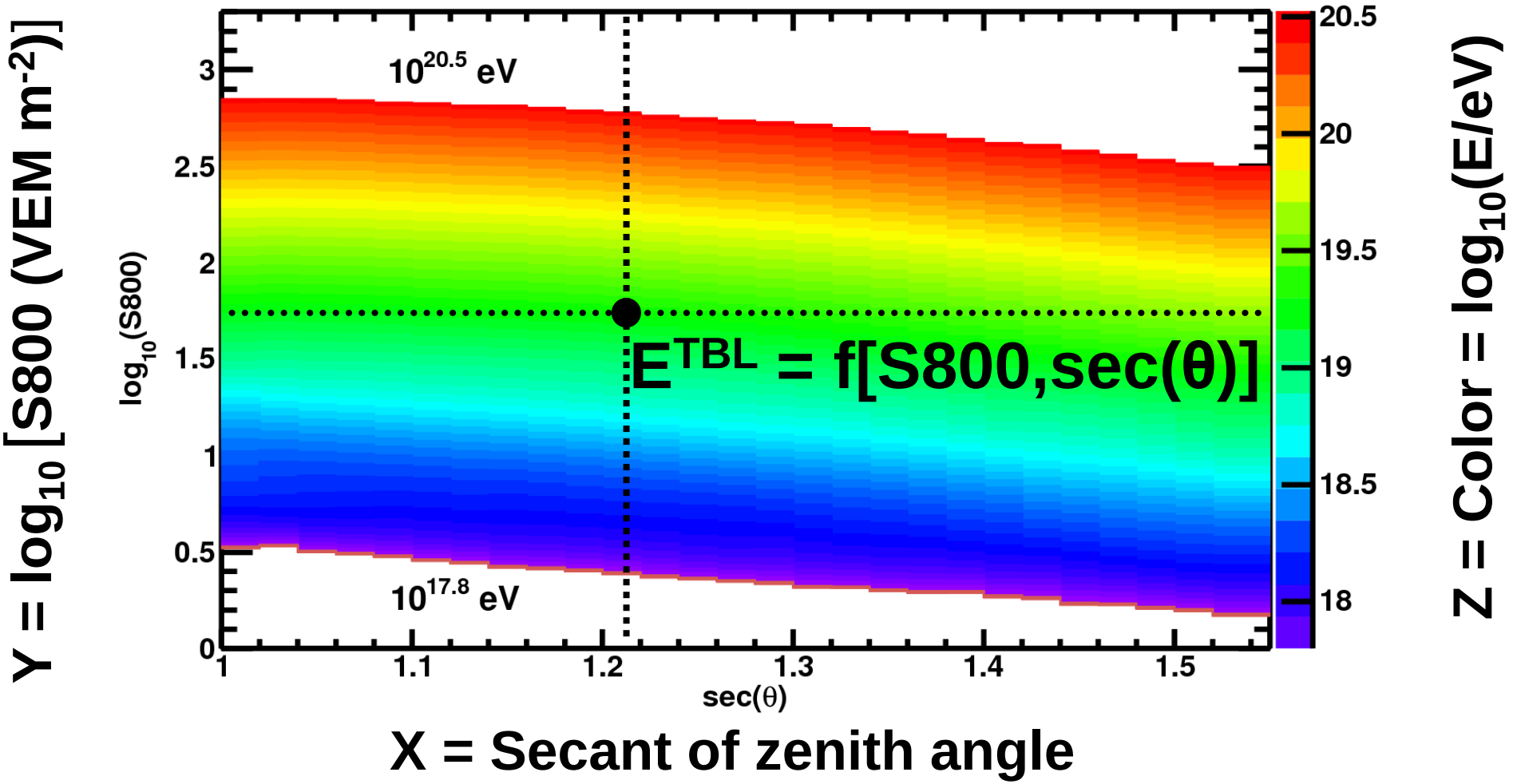




Time fit -> Event arrival Direction

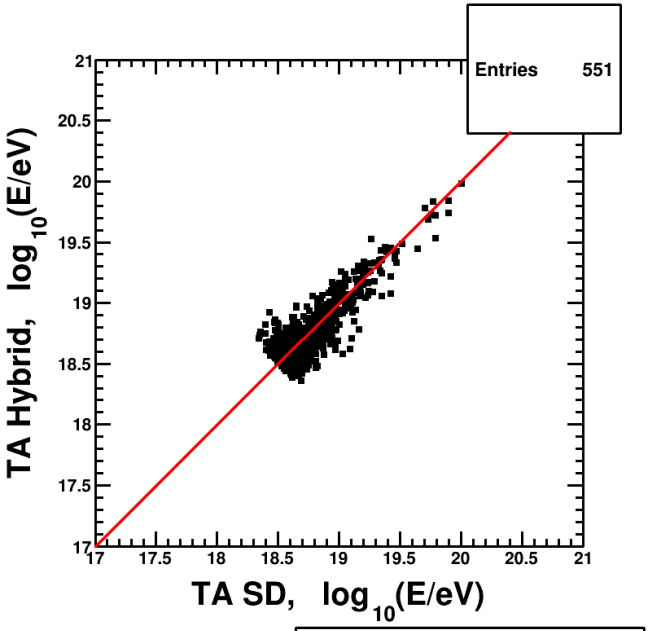
Lateral Distribution(LDF) fit -> S800 (signal size 800m from shower axis) -> **Event energy from SD Monte-Carlo and FD calibration using hybrid events**

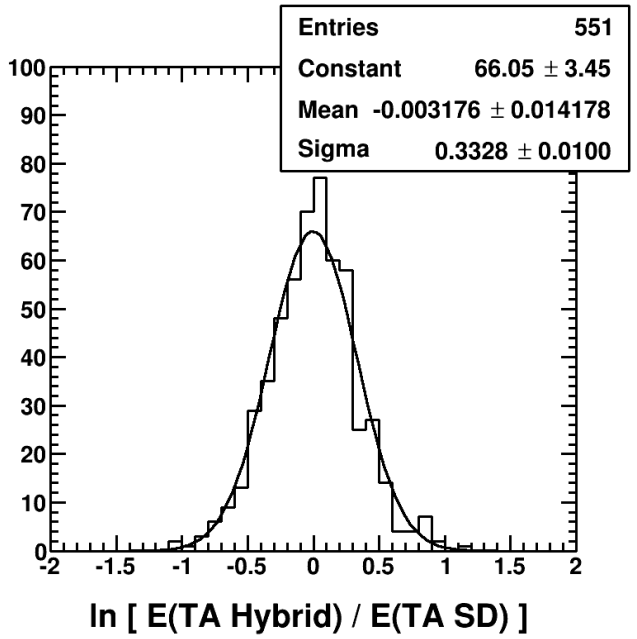
SD Energy 1/2



- First, a look-up table made from the Monte-Carlo
- Event energy (E^{TBL}) = function of *reconstructed* S800 and sec(θ)
- Energy reconstruction ←→ interpolation between S800 vs sec(θ) contours of constant values of E^{TBL}

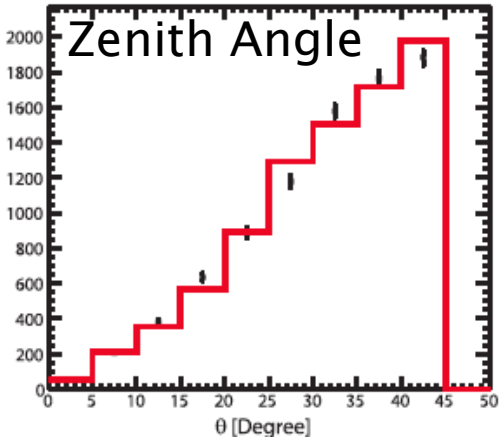
Then, the SD Energy Scale Set to FD using hybrid events

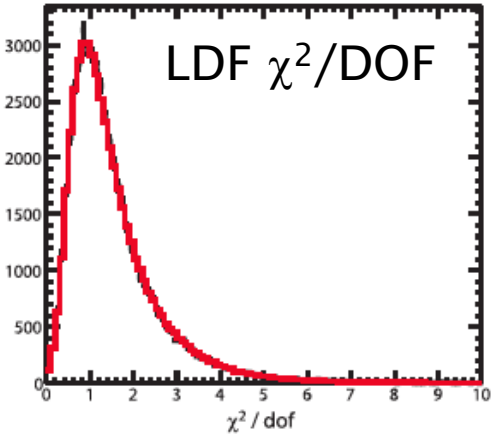


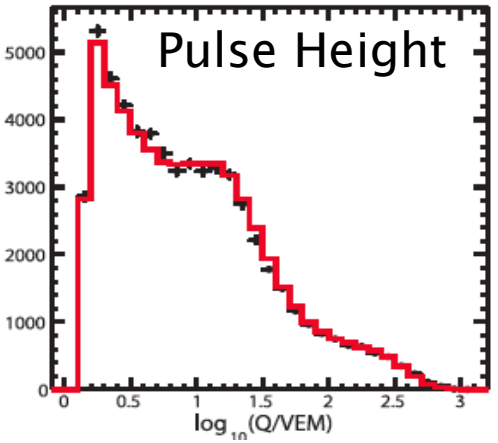


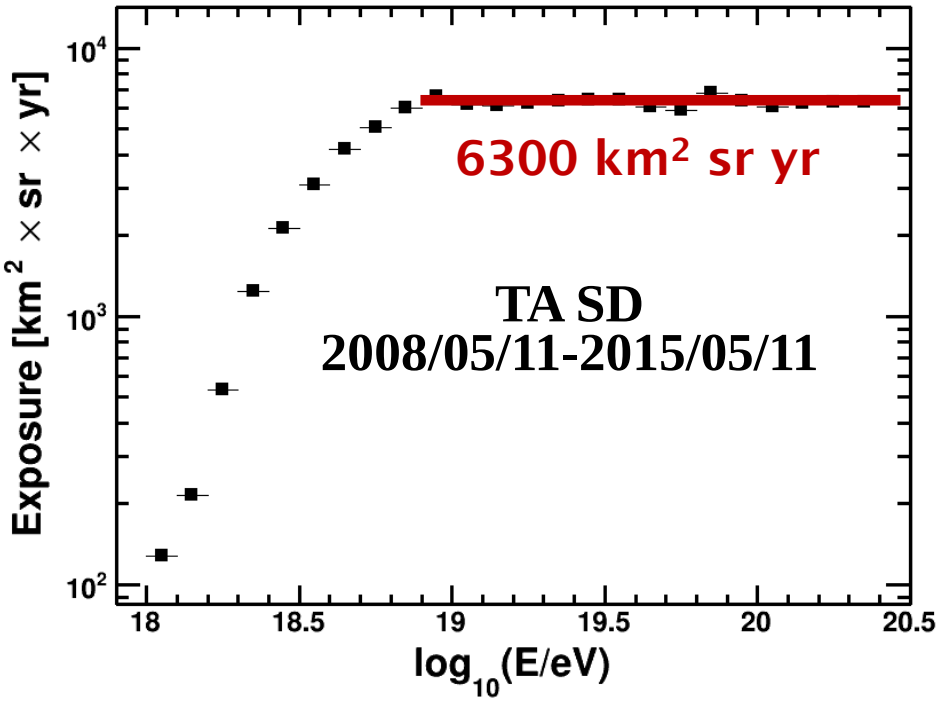
- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
- $E^{FINAL} = E^{TBL} / 1.27$
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD} ratio
- 2008/05/11-2013/05/04

Exposure Only from Monte Carlo







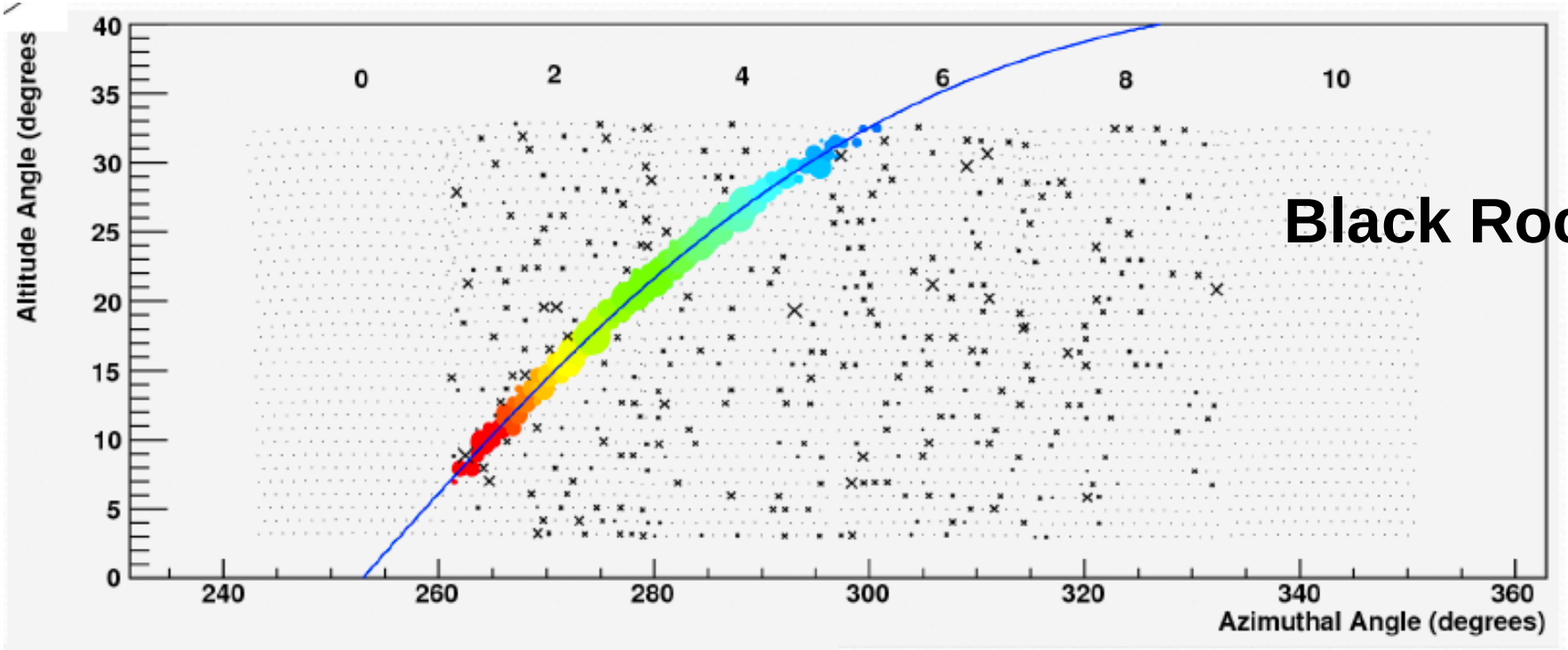


- Detailed Monte Carlo used for exposure calculation in all measurements of TA, down to 10% of the efficiency plateau
- Main uses of stand-alone SD analysis are energy spectrum and anisotropy measurements at high energies, where the detector has the best resolution, and a 100% duty cycle

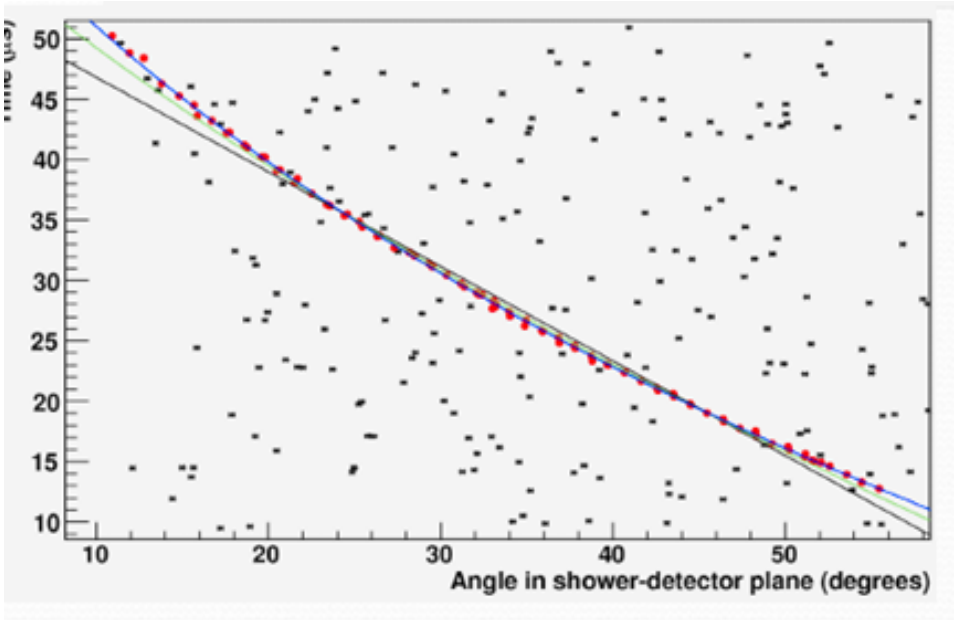
Air Fluorescence Analysis

- Stand alone fluorescence analysis (aka “Fluorescence mono”) provides best resolution and statistics for measuring spectrum at intermediate energies
- In combination with surface detector (the “hybrid analysis”) provides most accurate measurements of energy, arrival direction, and shower maximum.

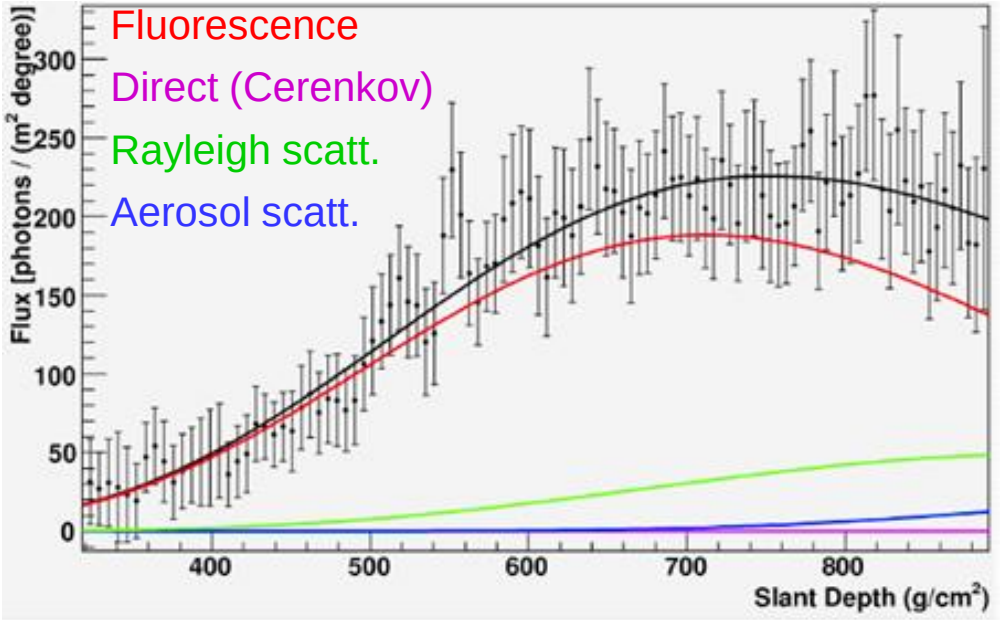
Fluorescence Mono Analysis



Black Rock Mesa

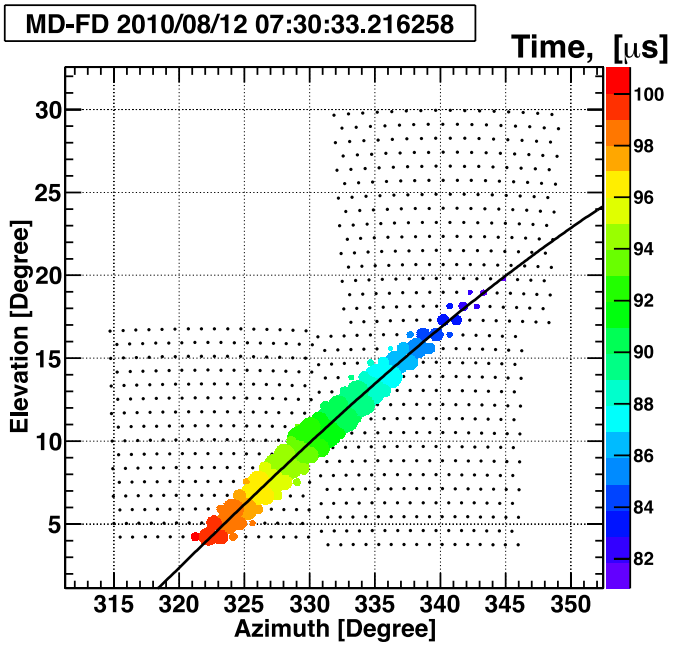


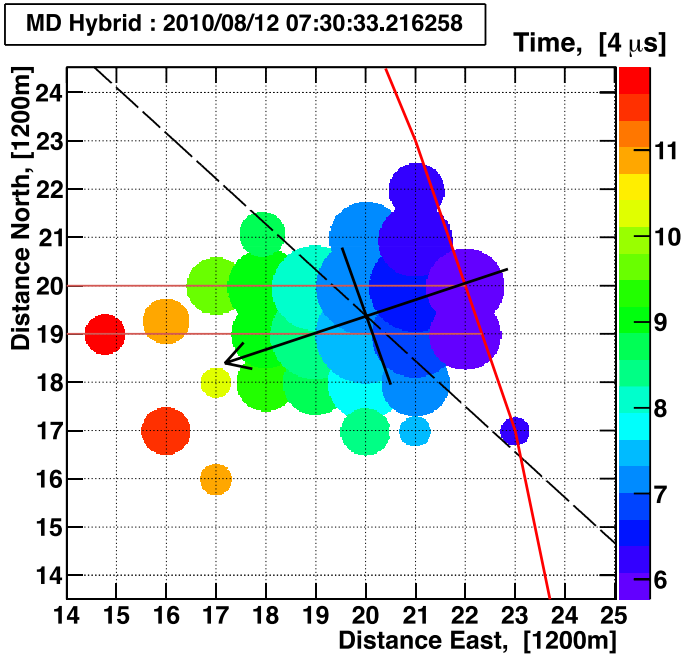
Time fit

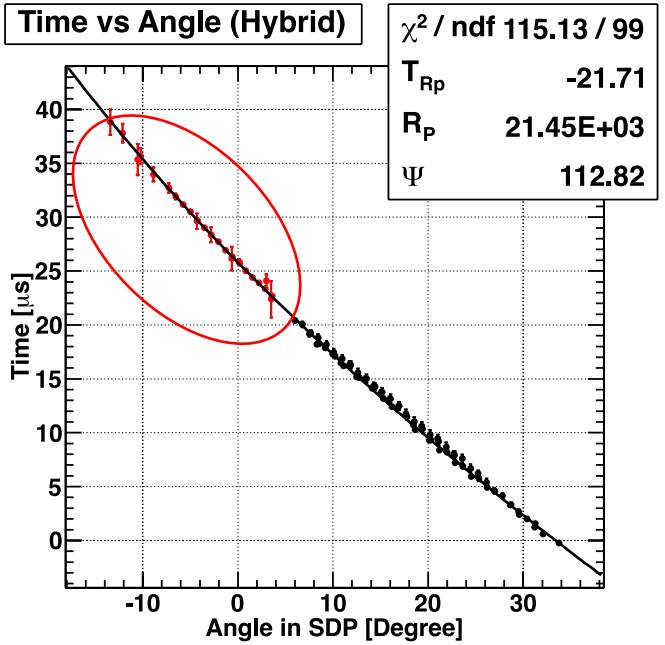


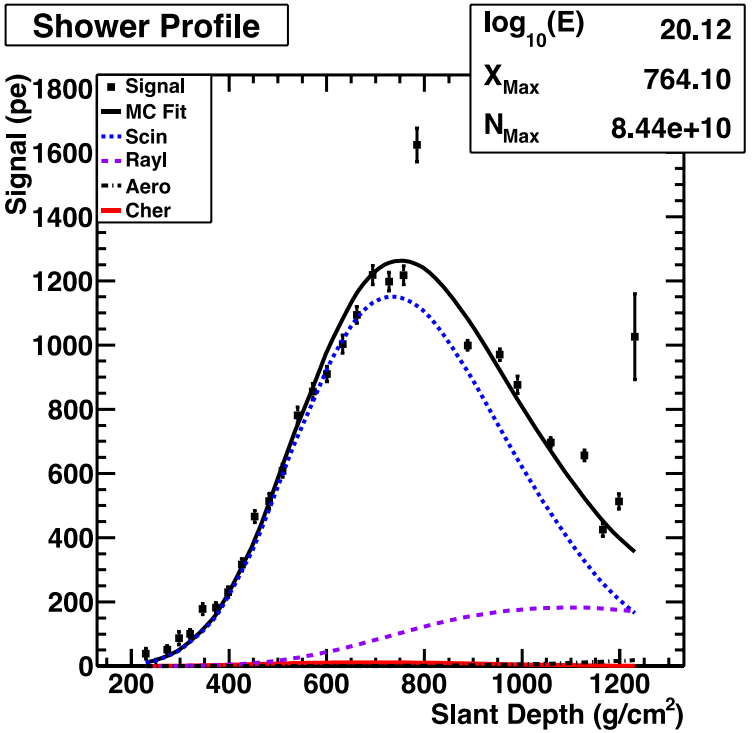
Profile fit

Hybrid Analysis









Surface array constrains geometry fit via extra timing & core information

Hybrid analysis provides best resolution and statistics for composition studies using shower maximum X_{max}

Also, TA SD energy scale is calibrated using results of hybrid reconstruction.

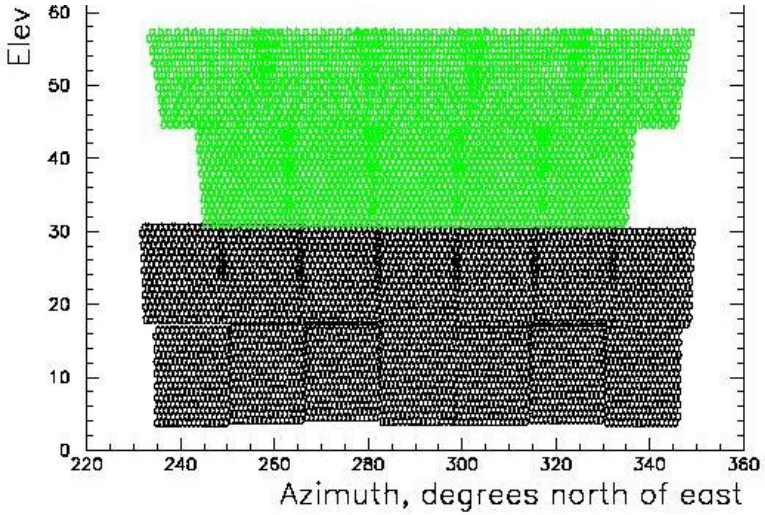
TA Low Energy Extension (TALE)

- Study the 10^{16} and 10^{17} eV decades with a hybrid detector.
  - End of the rigidity-dependent cutoff that starts with the knee (at 3×10^{15} eV).
  - The second knee
  - The galactic-extragalactic transition
- High energy physics measurements:
  - σ(p-air) and σ(p-p) from LHC energy (10^{17}) to 10^{19} eV.
- Now we observe cosmic rays from 3×10^{16} eV to 3×10^{20} eV using one experiment (TA + TALE)

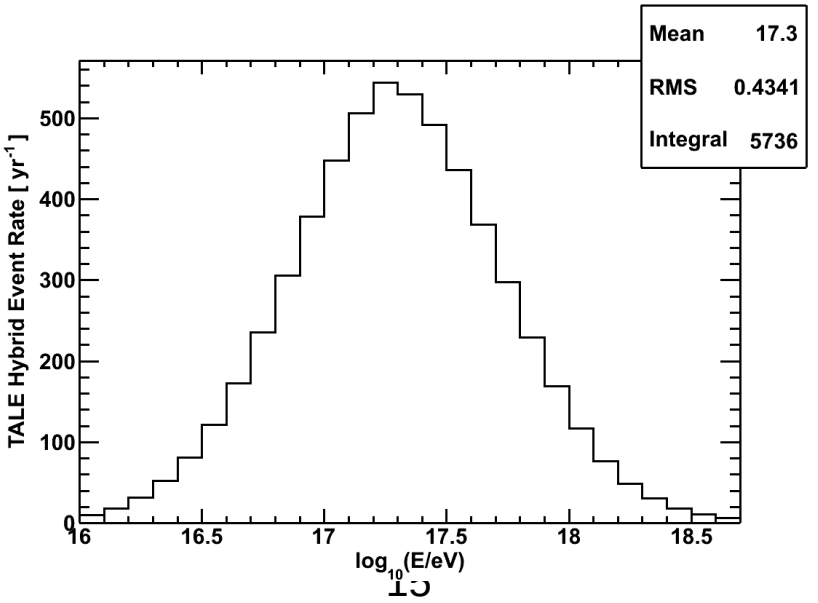
TALE Detector

- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operate in conjunction with the TA Middle Drum FD.
- Add infill array (400m and 600m spacing) for hybrid and stand-alone observation
  - 105 counters in all, now beginning taking data

TALE telescopes



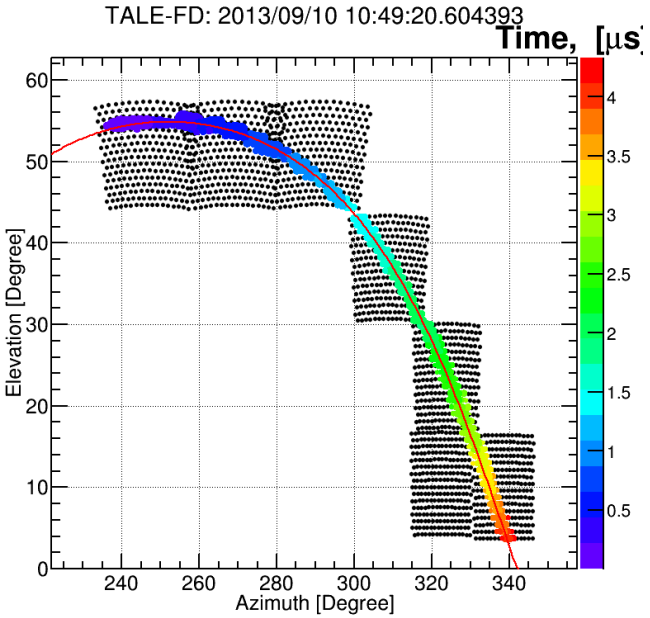
TA MD telescopes

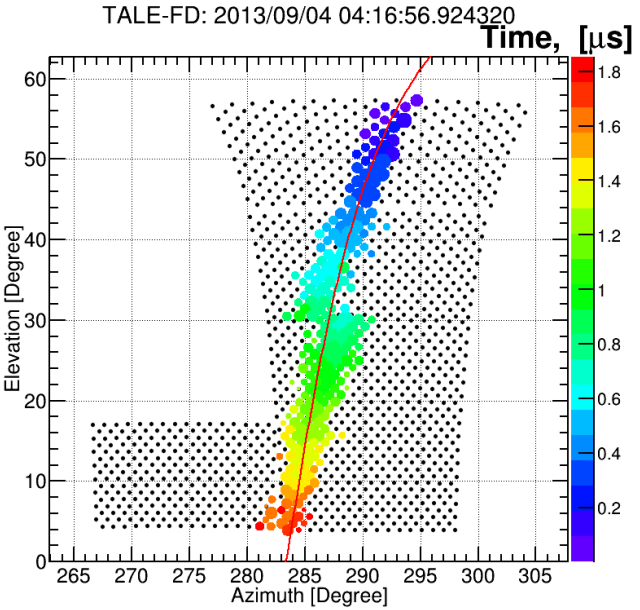


TALE hybrid events per year

TALE Events

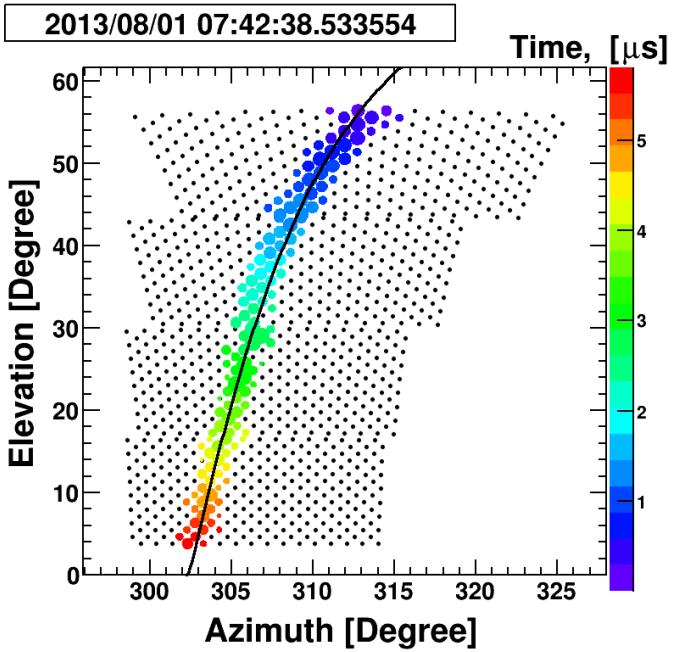
7 mirror event, log(E) = 16.5

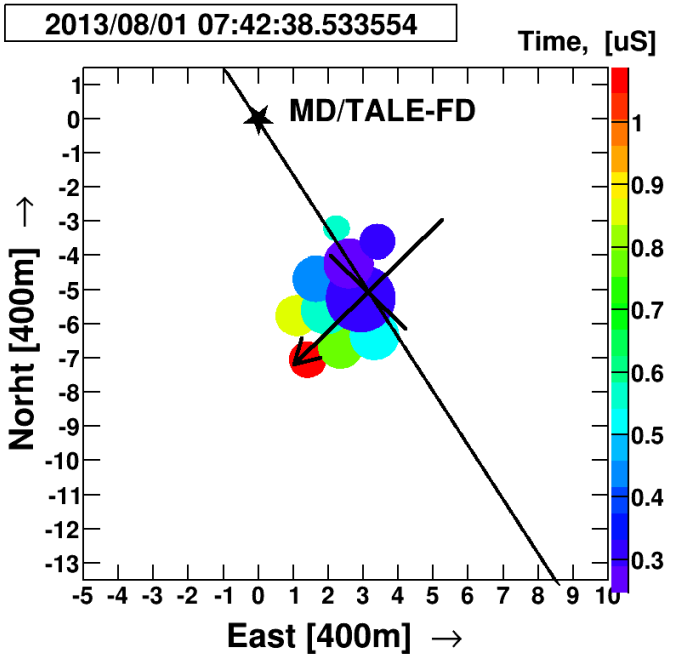




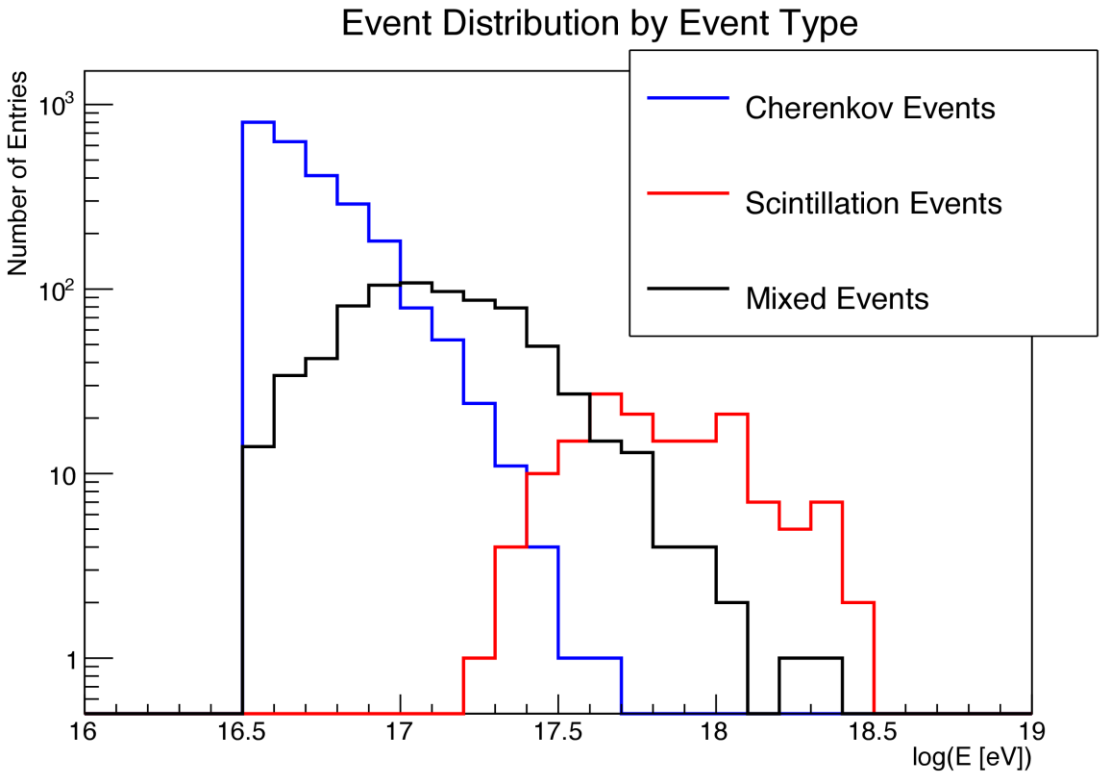
Parallax event, R_p=800m

Hybrid event





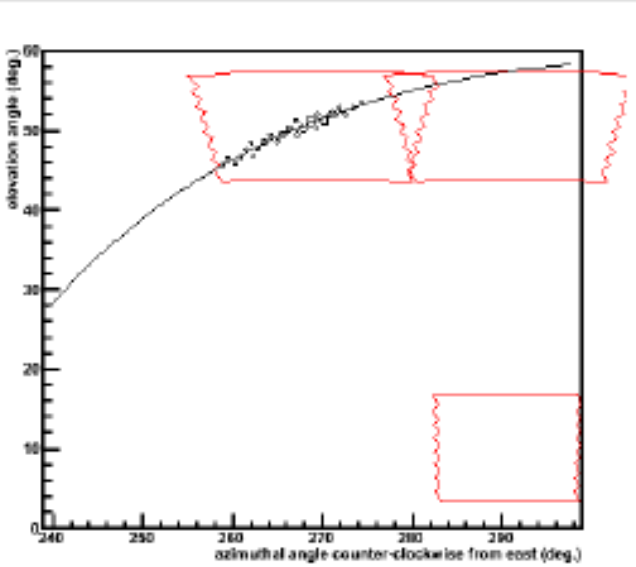
TALE Cherenkov vs. Fluorescence

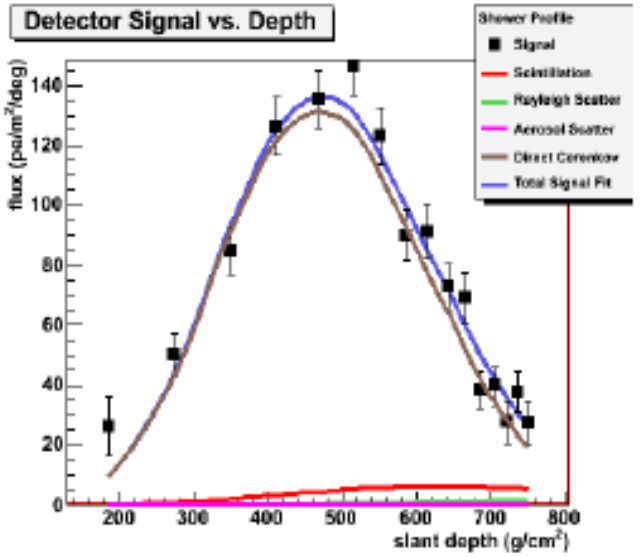


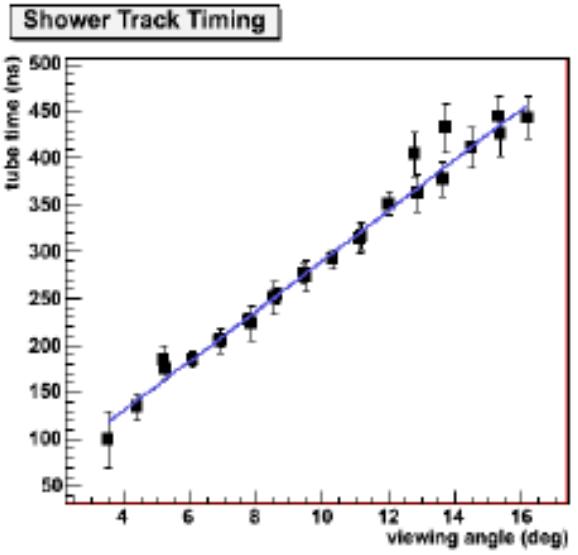
Unexpected: many Cherenkov events are seen as tracks (most land ~0.5 km from FD).
Use profile constrained reconstruction.
Cherenkov light is bright ➔ **can go much lower in energy than originally expected**.

TALE Cherenkov Event

- Most C'kov events are single telescope
- Event duration ~100ns - ~600 ns
- Short angular extent
- Unlikely to trigger surface detector
- Threshold ~3e15 eV







TALE event data

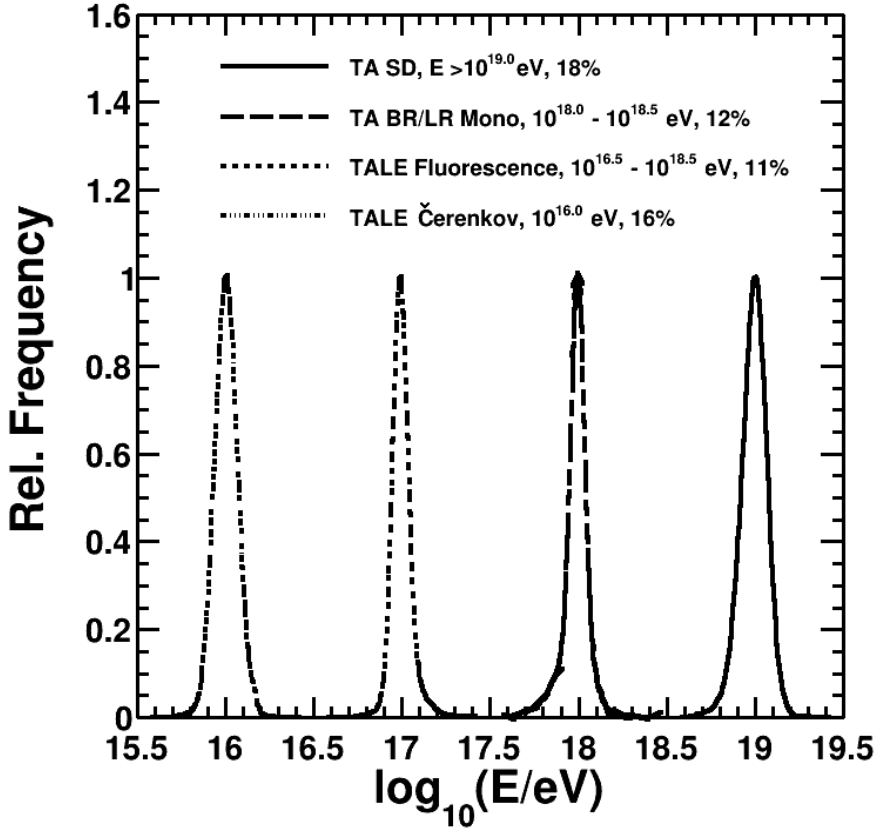
Event Starting: 0: 0:0.139663747441801

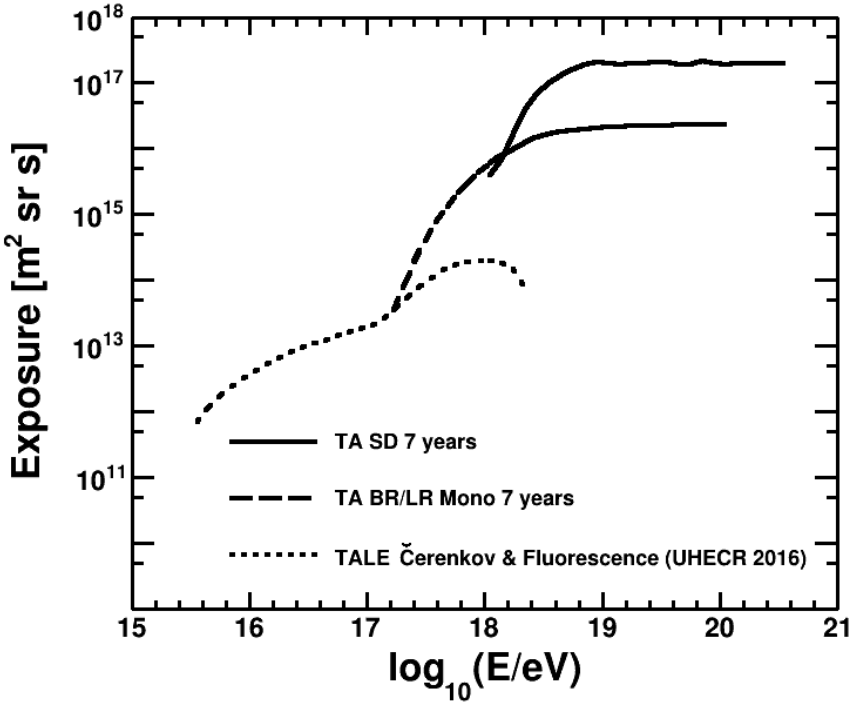
Energy:	9.241 PeV
Shower max size:	6.143e+06 particles
Shower max depth:	605.810 g/cm²
Profile Fit χ^2/ndf:	0.7362

Rp Magnitude: 0.912 km
ψ angle: 106.9 degrees

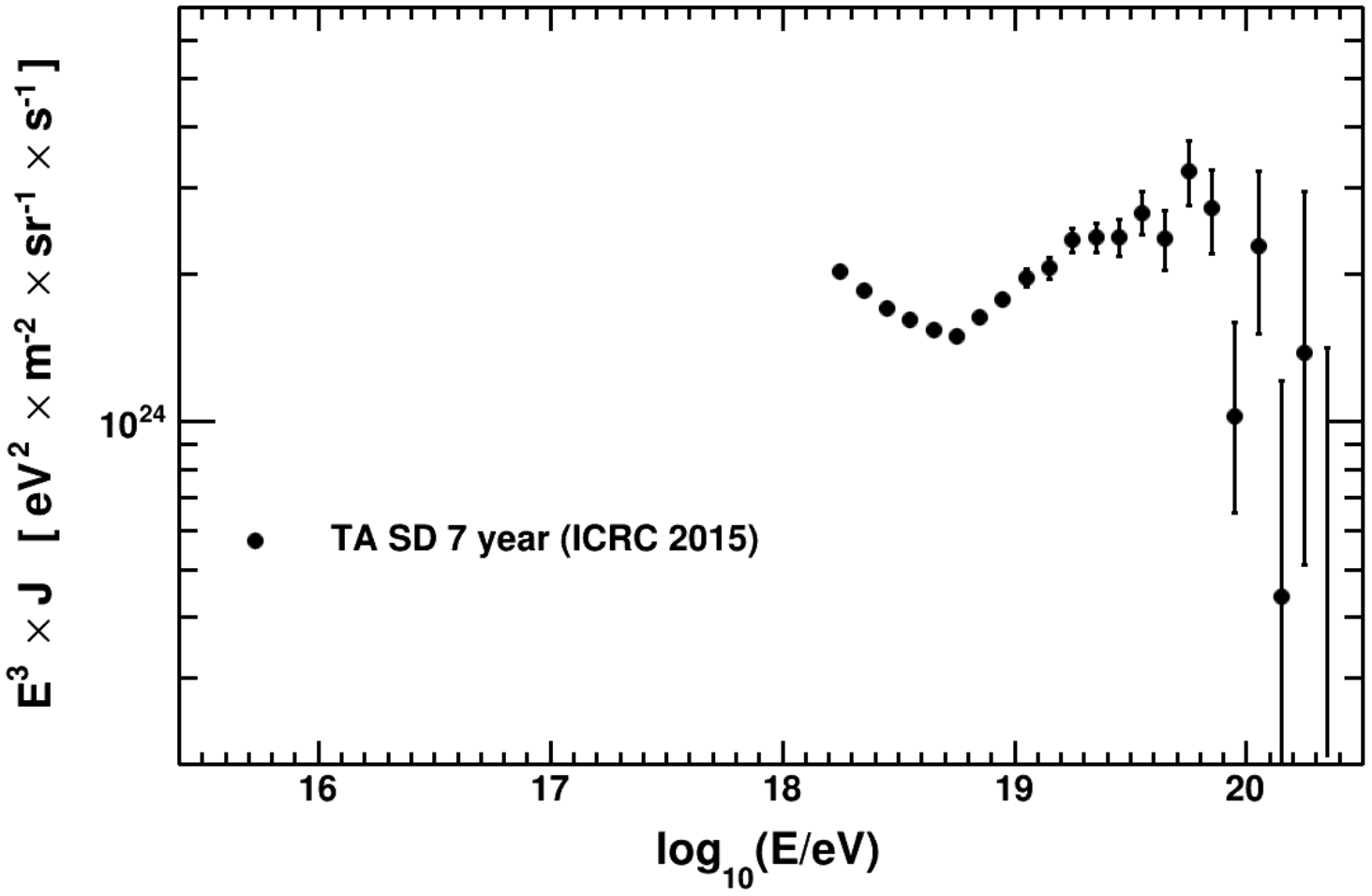
Shower azimuthal angle: -80.1 degrees
Shower zenith angle: 35.0 degrees

TA Resolution and Exposure as Function of Energy

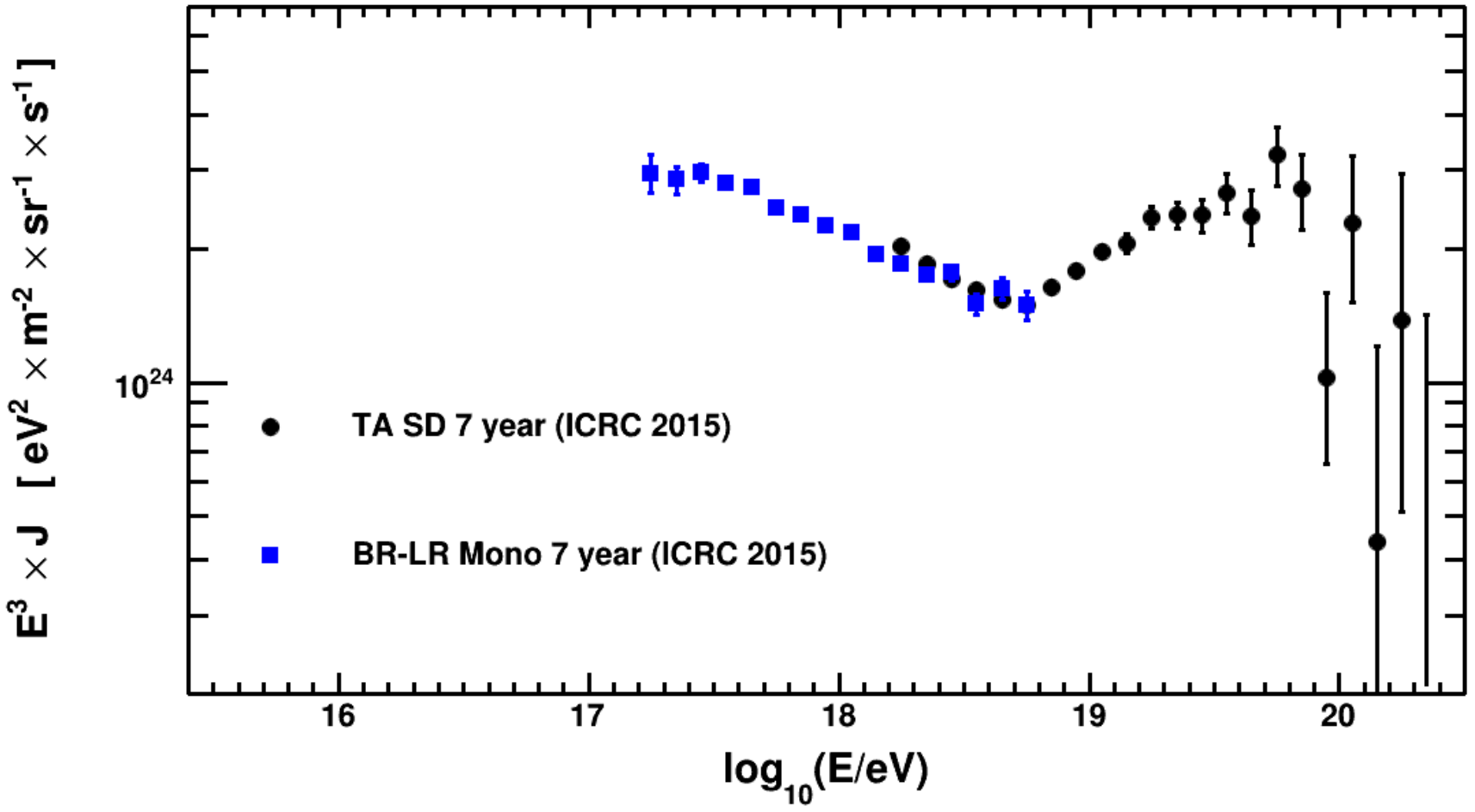




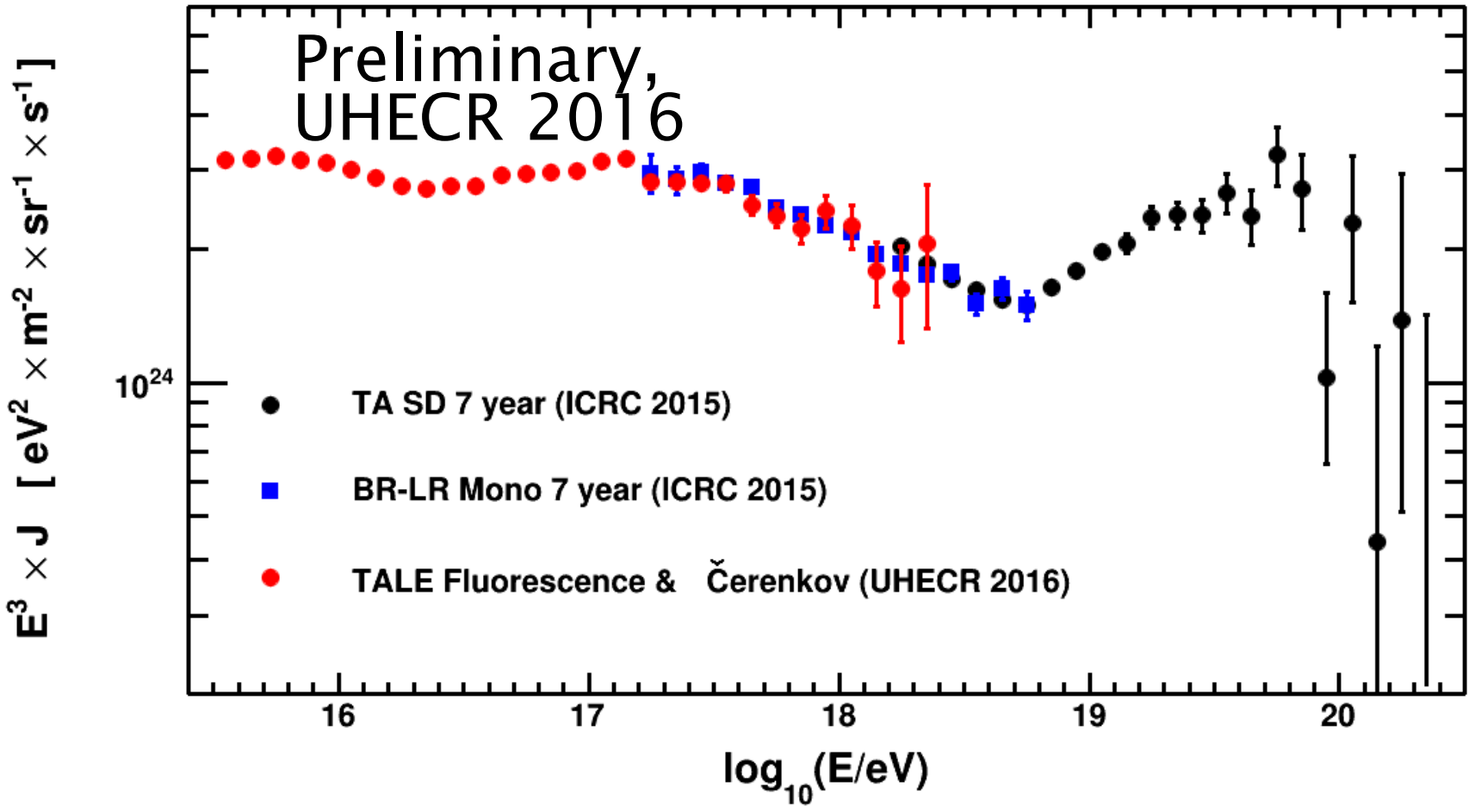
TA SD, E > $10^{18.2}$ eV



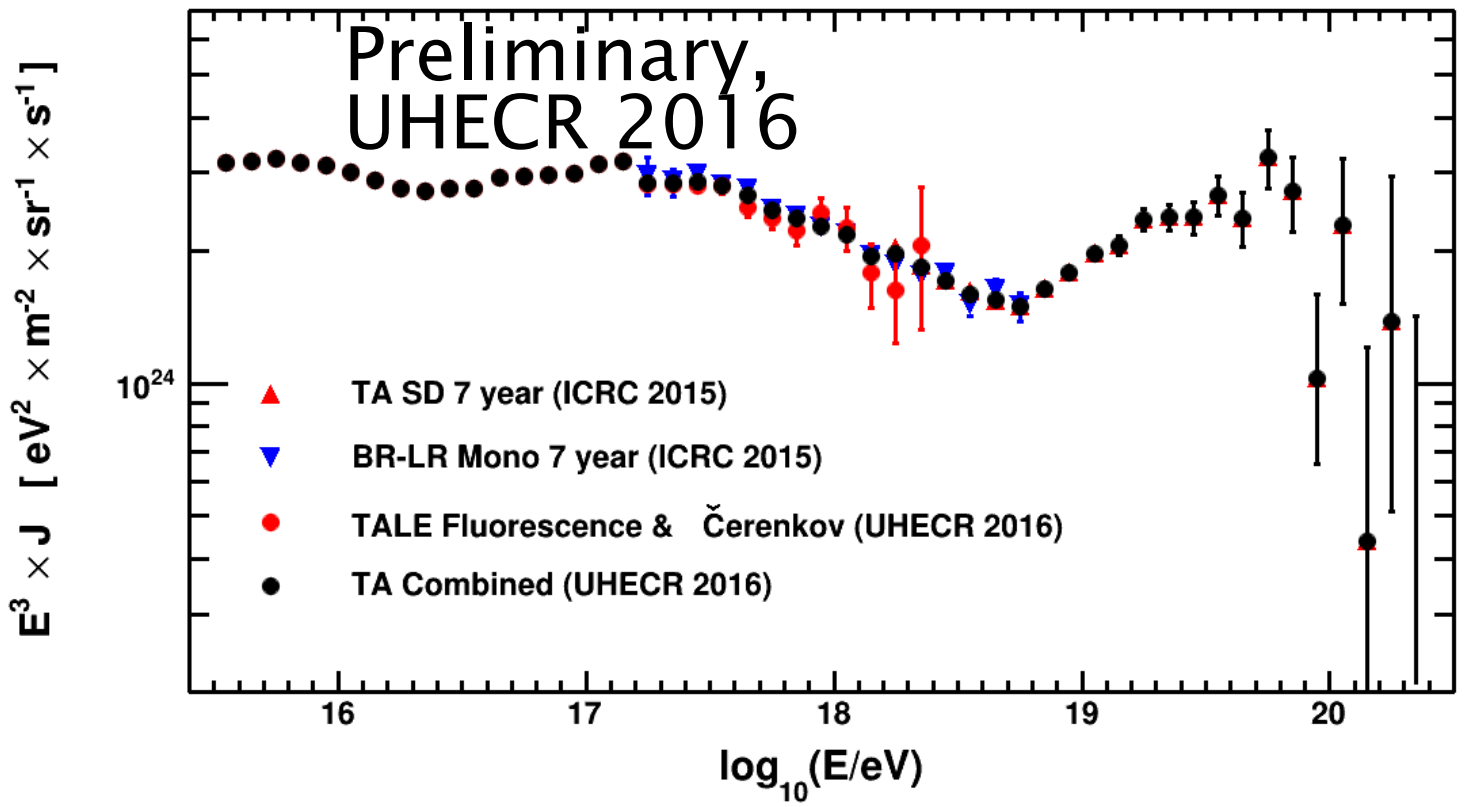
Add TA BR/LR Mono, $10^{17.2}$ eV< E < 18.8 eV



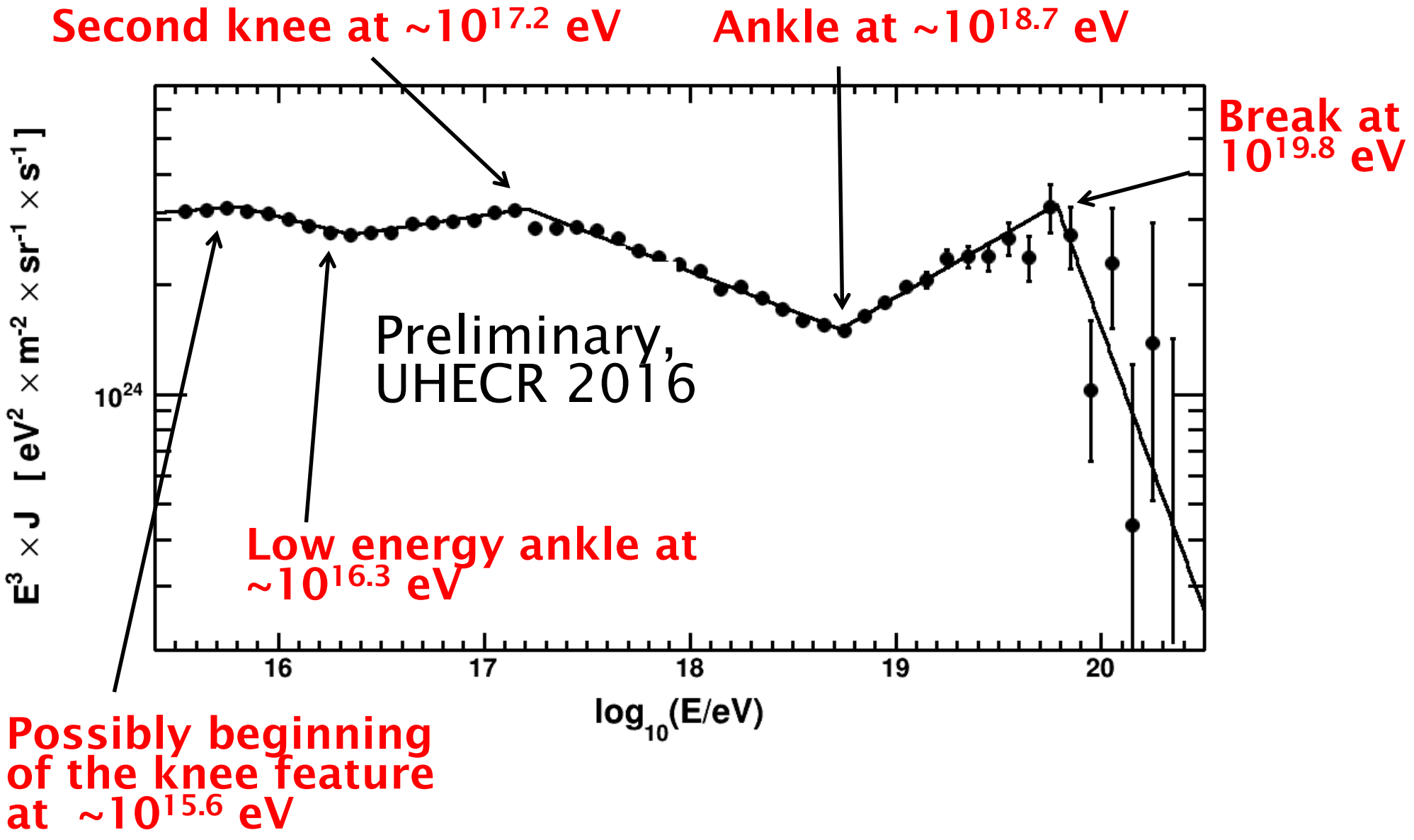
Add TALE Fluorescence and Cherenkov, $10^{15.5}$ eV< E < 18.3 eV



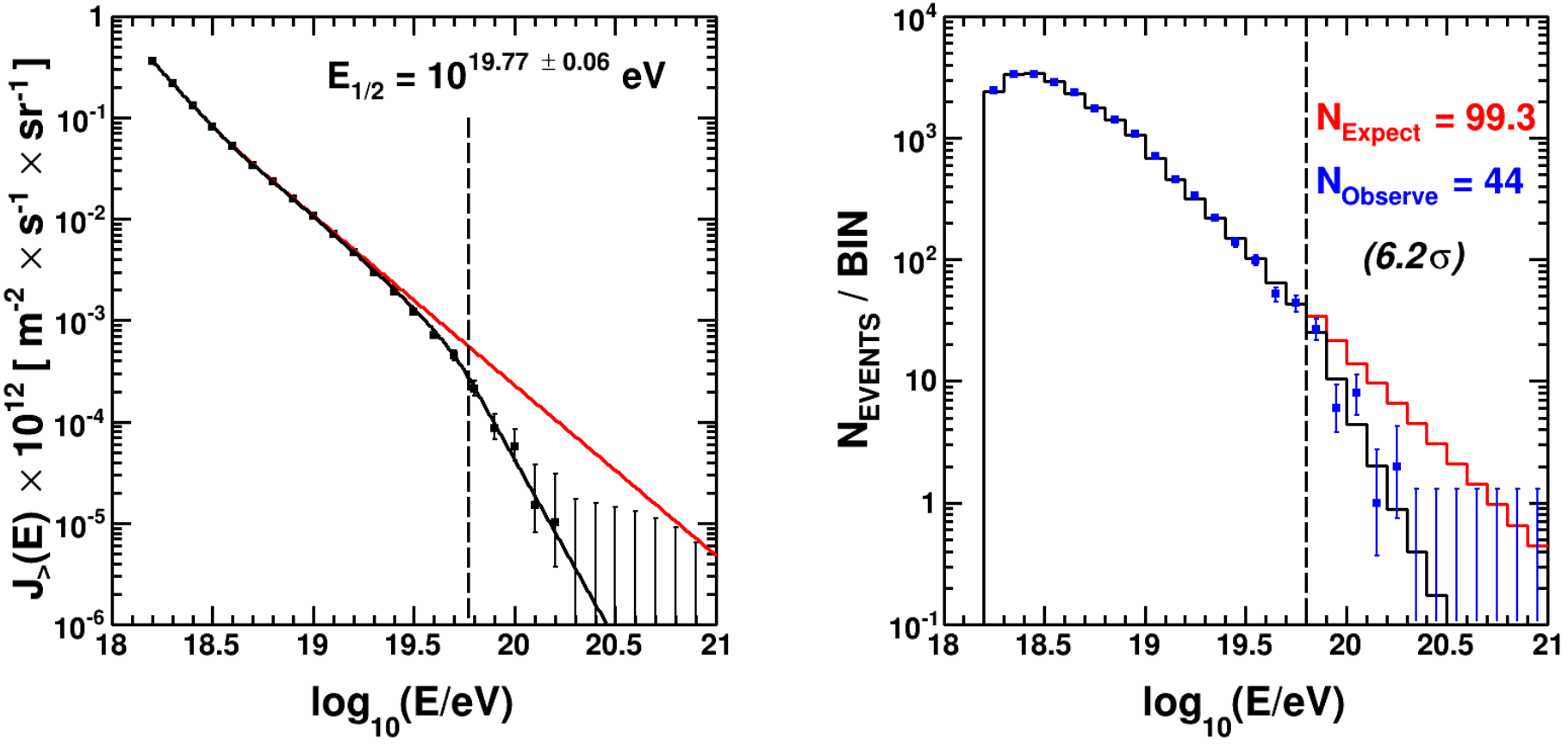
Combine the TA spectrum



4 to 5 features, over nearly 5 orders of magnitude in energy



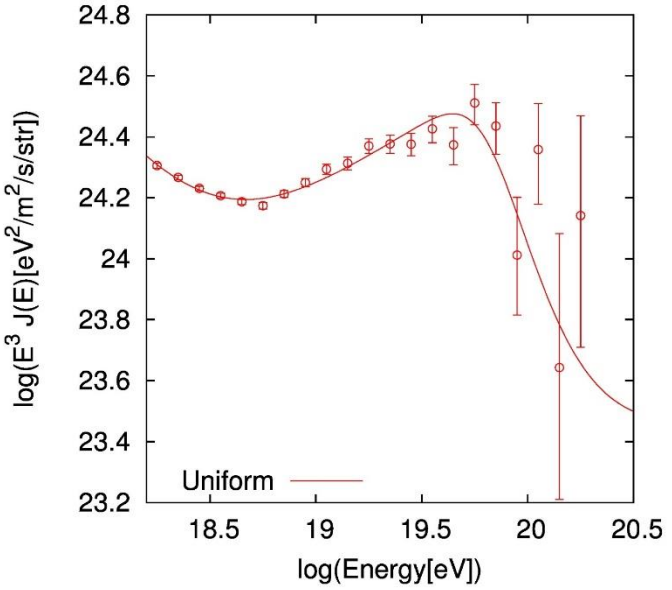
Berezinsky $E_{1/2}$ and GZK Cutoff

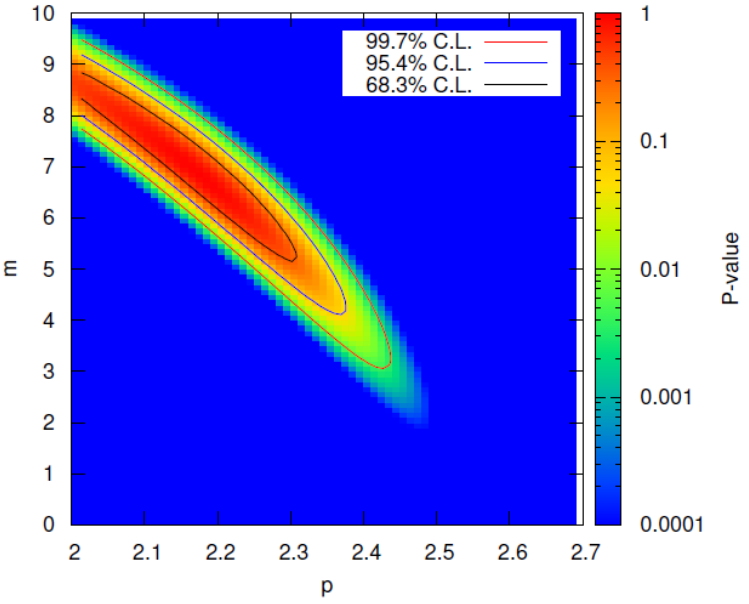


Consistent with proton propagation on CMB

Fit spectrum to an energy loss model

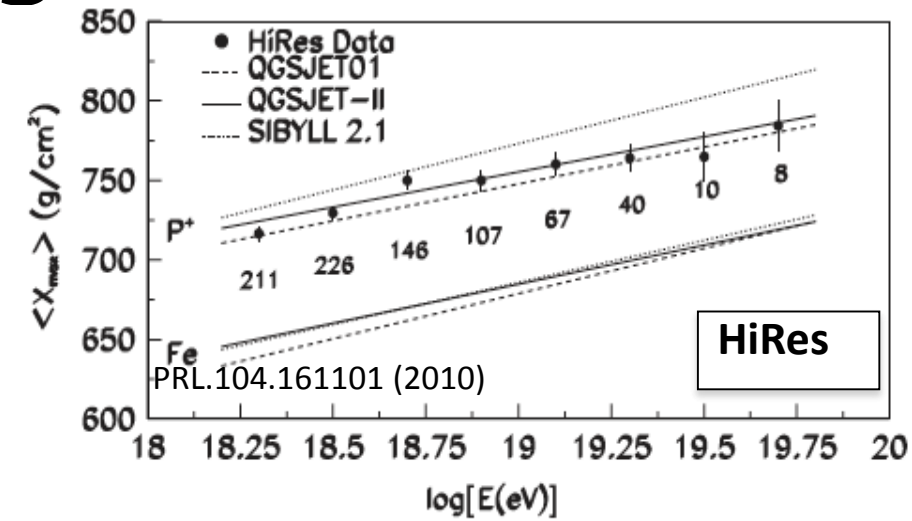
- Inputs:
  - Pion photoproduction
  - e+/e- pair production
  - Hubble expansion
- Fitting parameters:
  - Power law at the source, E^{-p}
  - Evolution of the sources, $(1+z)^{m}$



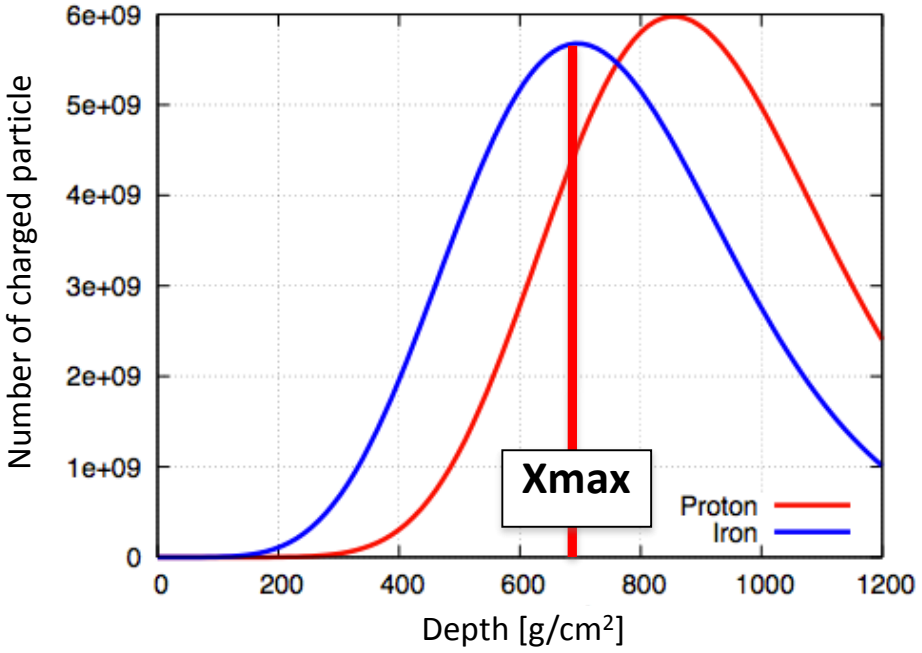


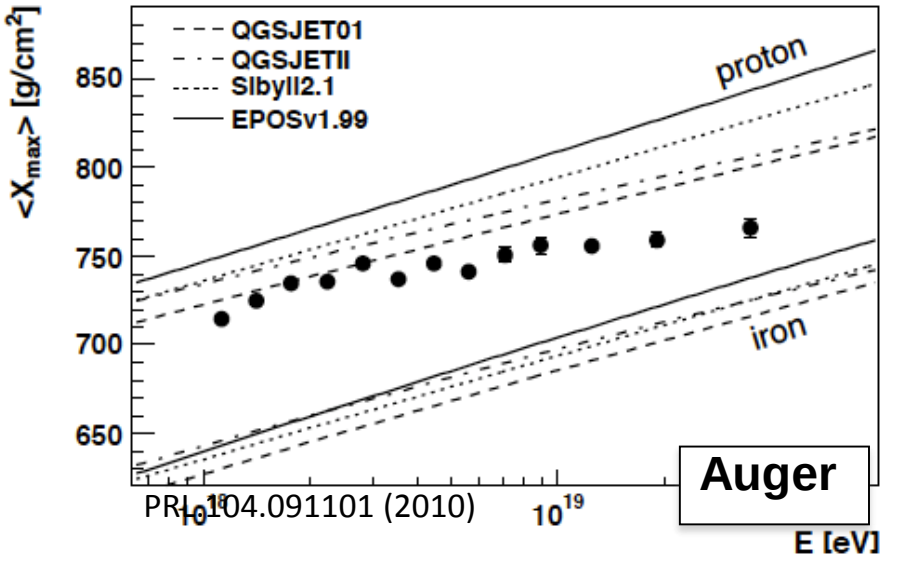
Composition from Xmax - HiRes and Auger

- **Shower longitudinal development depends on primary particle type.**
- **FD observes shower development directly.**
- **Xmax is the most efficient parameter for determining primary particle type.**



PRL.104.161101 (2010)





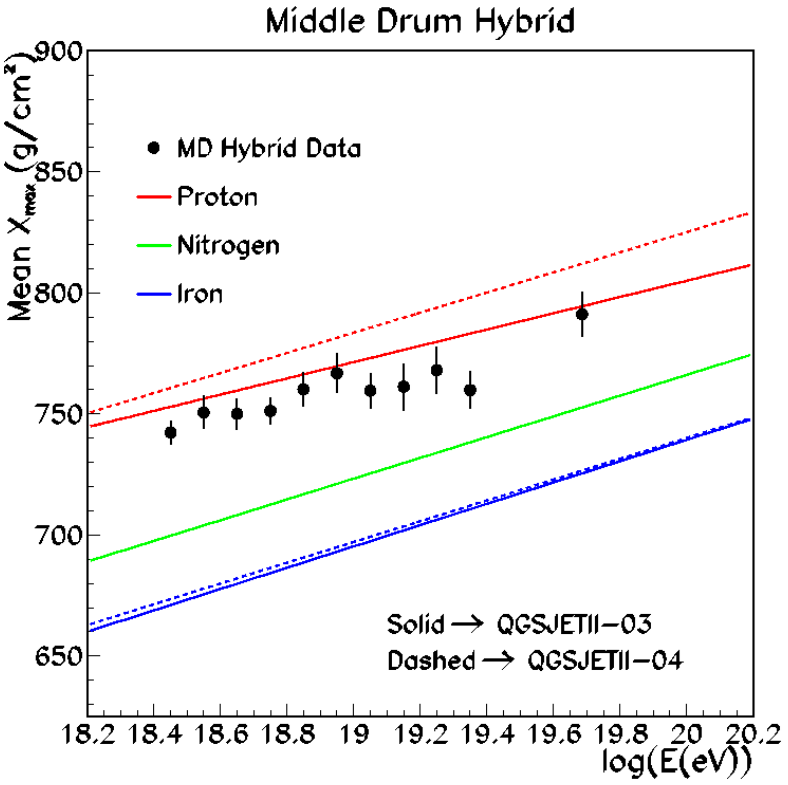
PRL.104.091101 (2010)

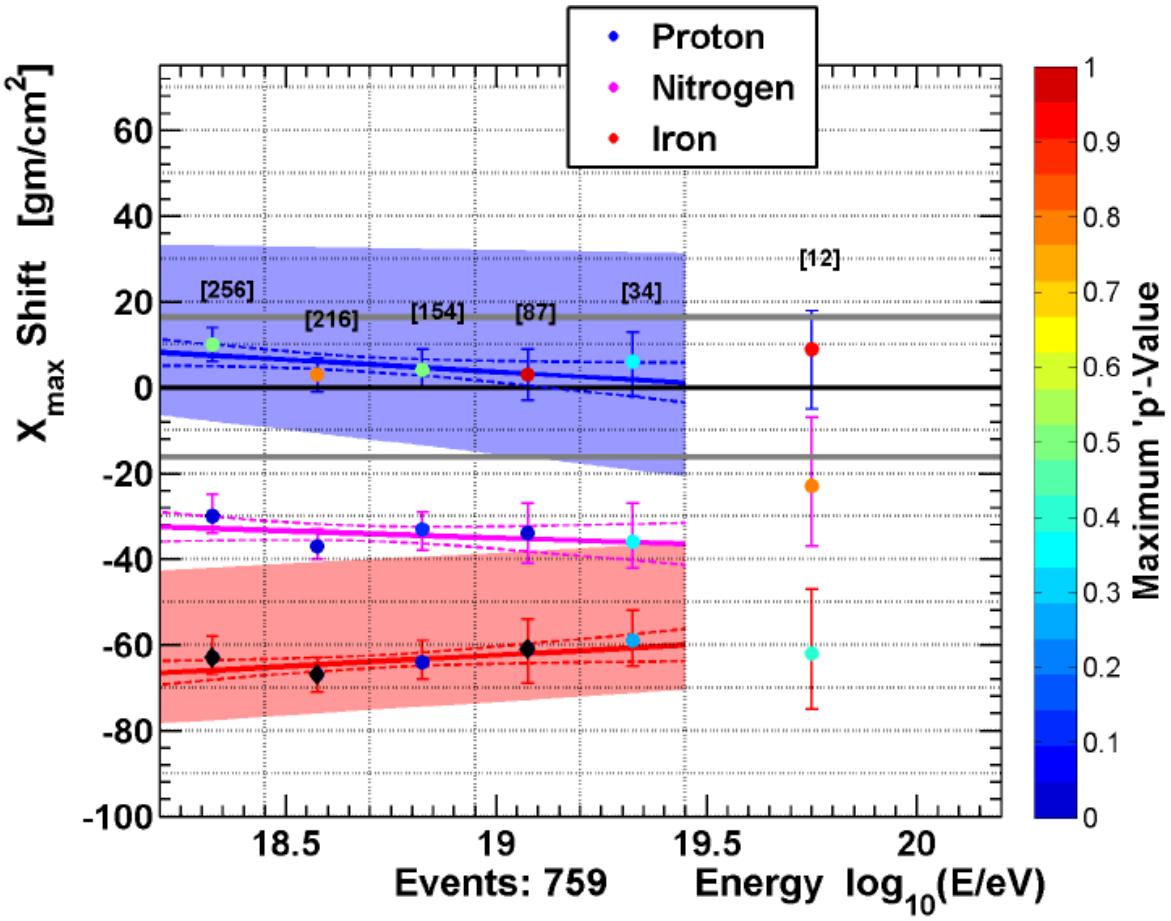
Published HiRes and Auger composition results do not agree above $10^{18.5}$ eV

TA Composition

MD Hybrid X_{Max}

Standard mean vs log(E) plot





"Shift Plot"

Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

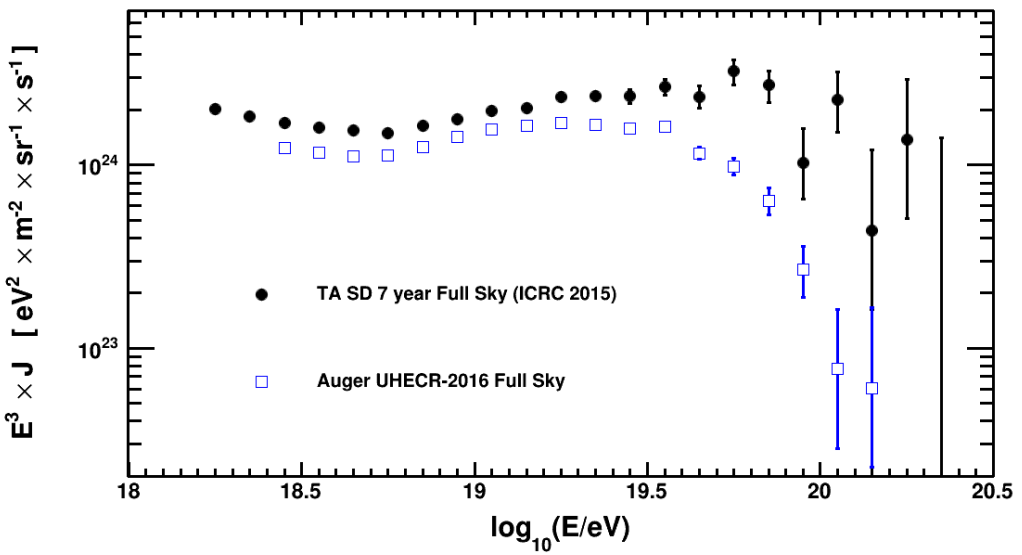
Pink, blue bands for other hadronic models

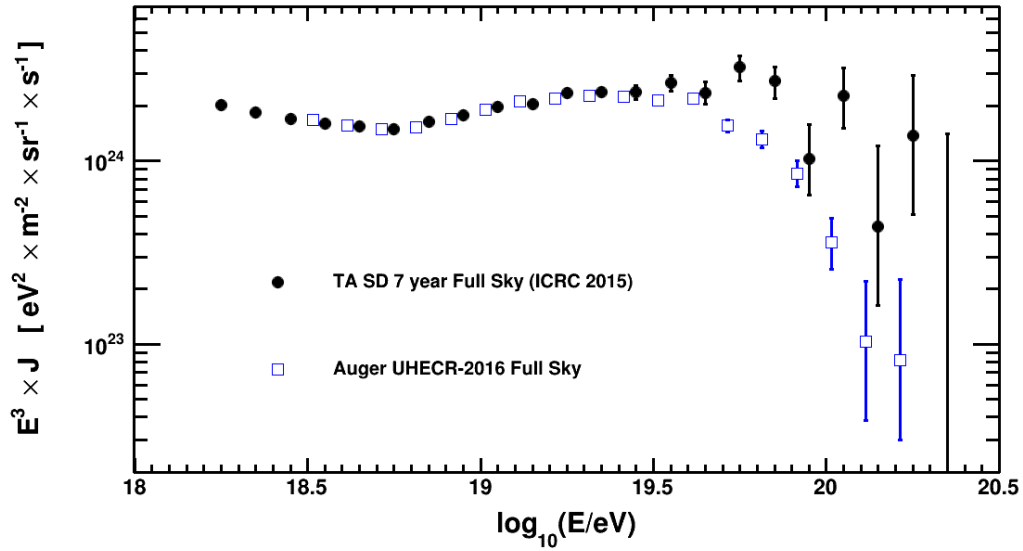
16 g/cm^2 systematic uncertainty.

Light composition favored, iron strongly disfavored. Cannot disprove nitrogen with current statistics but it is also disfavored by the TA data.

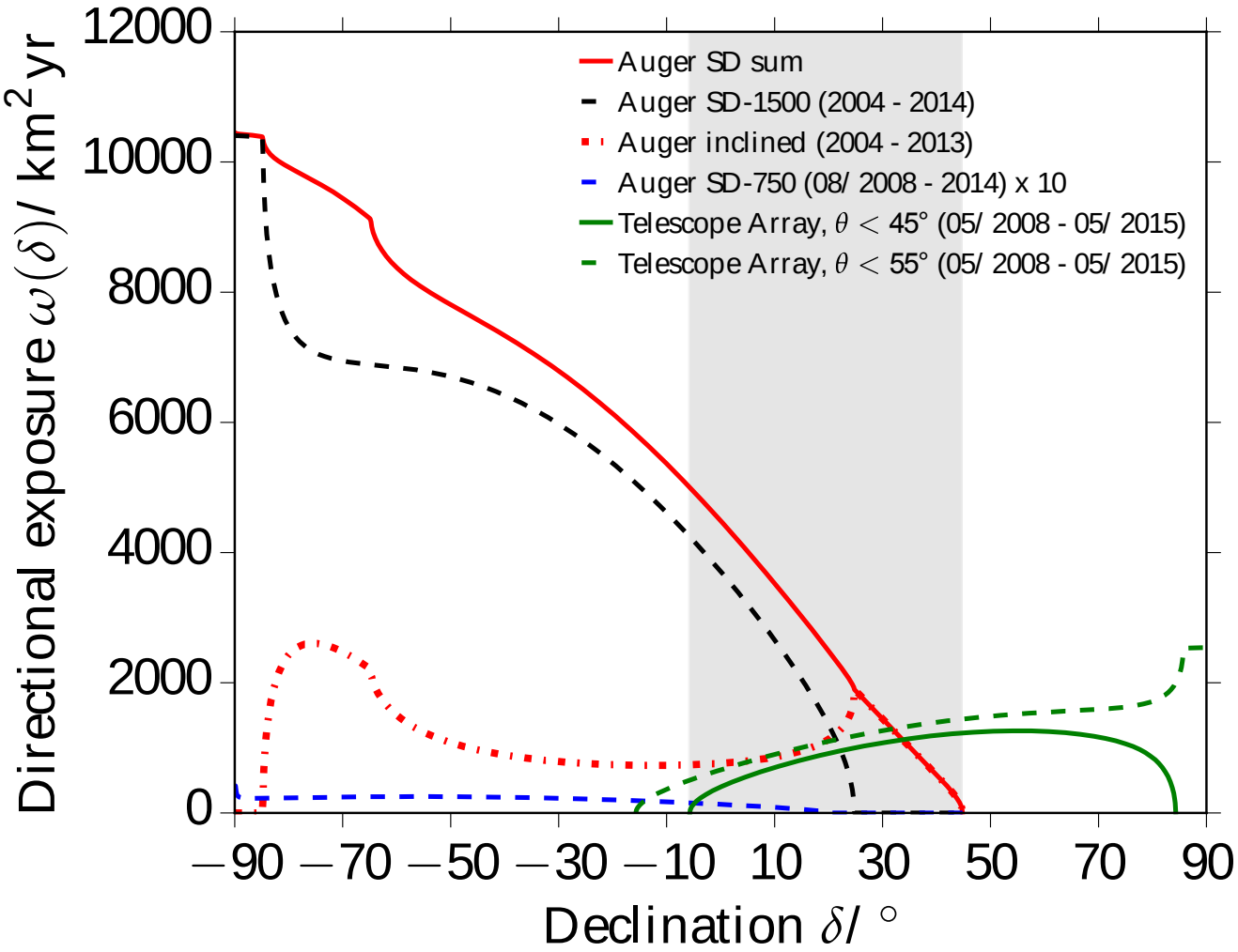
Now Compare Telescope Array and Pierre Auger Observatory Spectrum Results

- Compare Auger and TA spectra
- Rescaling Auger by 16% aligns the ankle region, excellent agreement up to $10^{19.4}$ eV
- **Significant difference above $10^{19.4}$ eV**
- UHECR-2016 spectrum working group: a joint TA-Auger report will be published in the UHECR-2016 proceedings





TA/Auger Common Declination Band



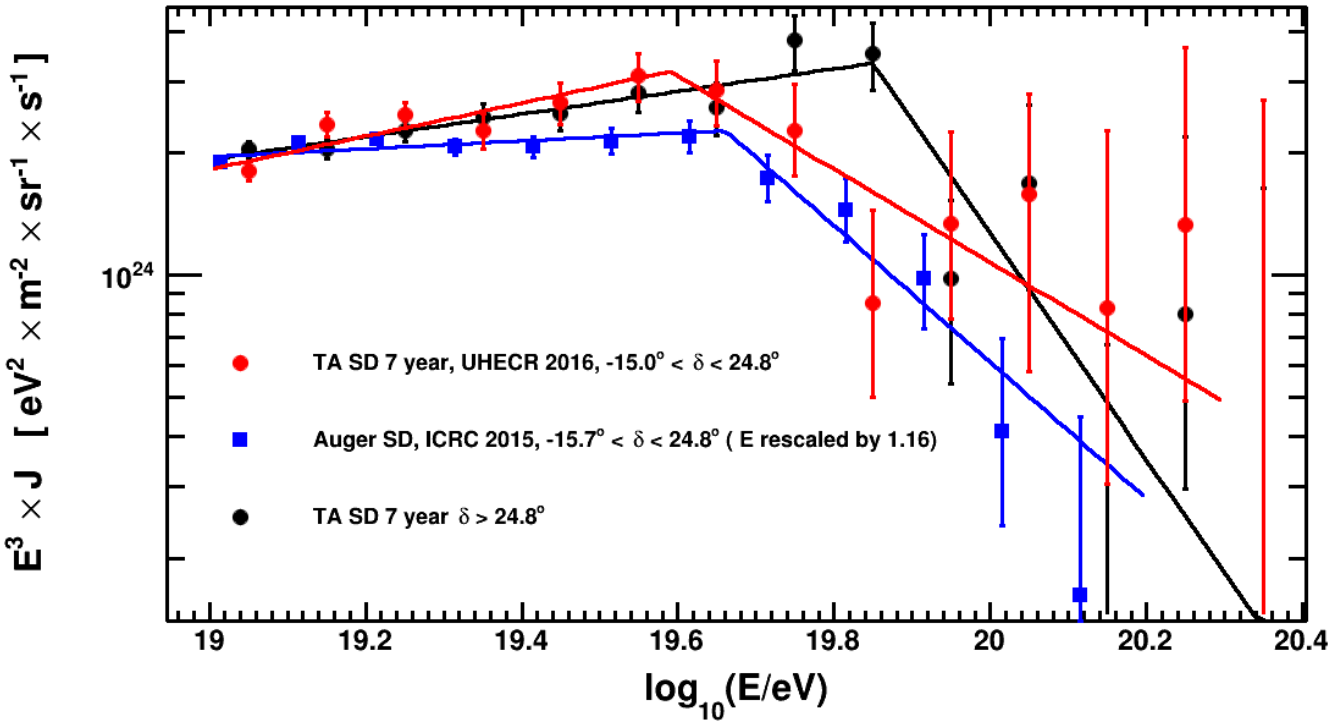
UHECR Spectrum WG

TA and Auger WG members compared spectra in the common declination band: $-15^\circ < \delta < 25^\circ$

TA, $\delta > 25^\circ$, high energy break at 19.85±0.03

TA, $-15 < \delta < 25^\circ$, 19.59±0.06; **TA difference: 3.9 σ**

Auger, $-15 < \delta < 25^\circ$, 19.66±0.04; **TA-Auger difference: 1 σ**



High Energy Anisotropy Analysis

SD data from period **12.05.2008 — 11.05.2015 (full 7 years)**

Zenith angle up to 55°

Geometrical acceptance; exposure 8600 km² yr sr

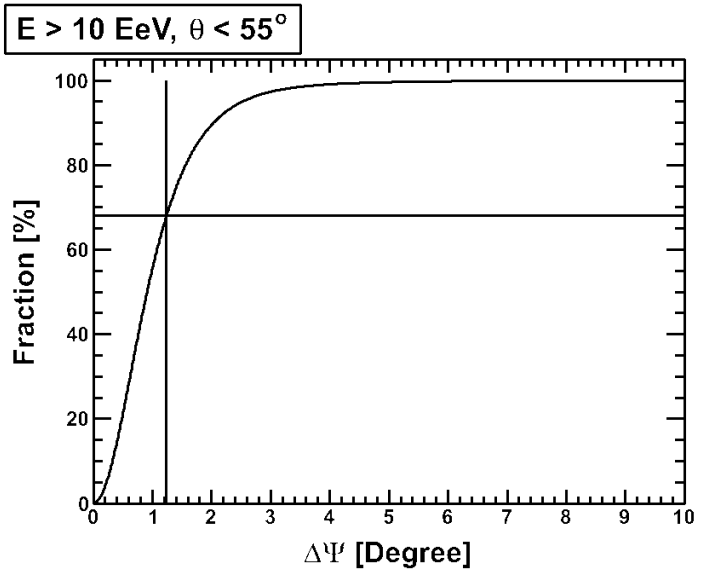
2996 above **10 EeV**

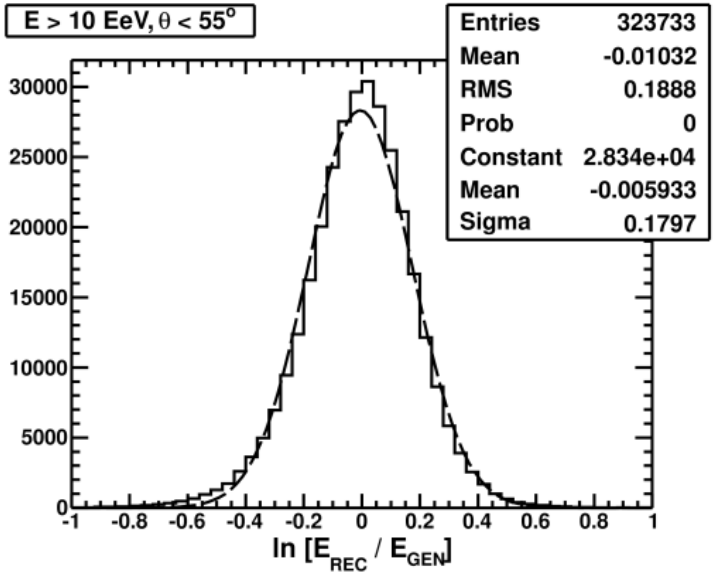
210 above **40 EeV**

83 above **57 EeV**

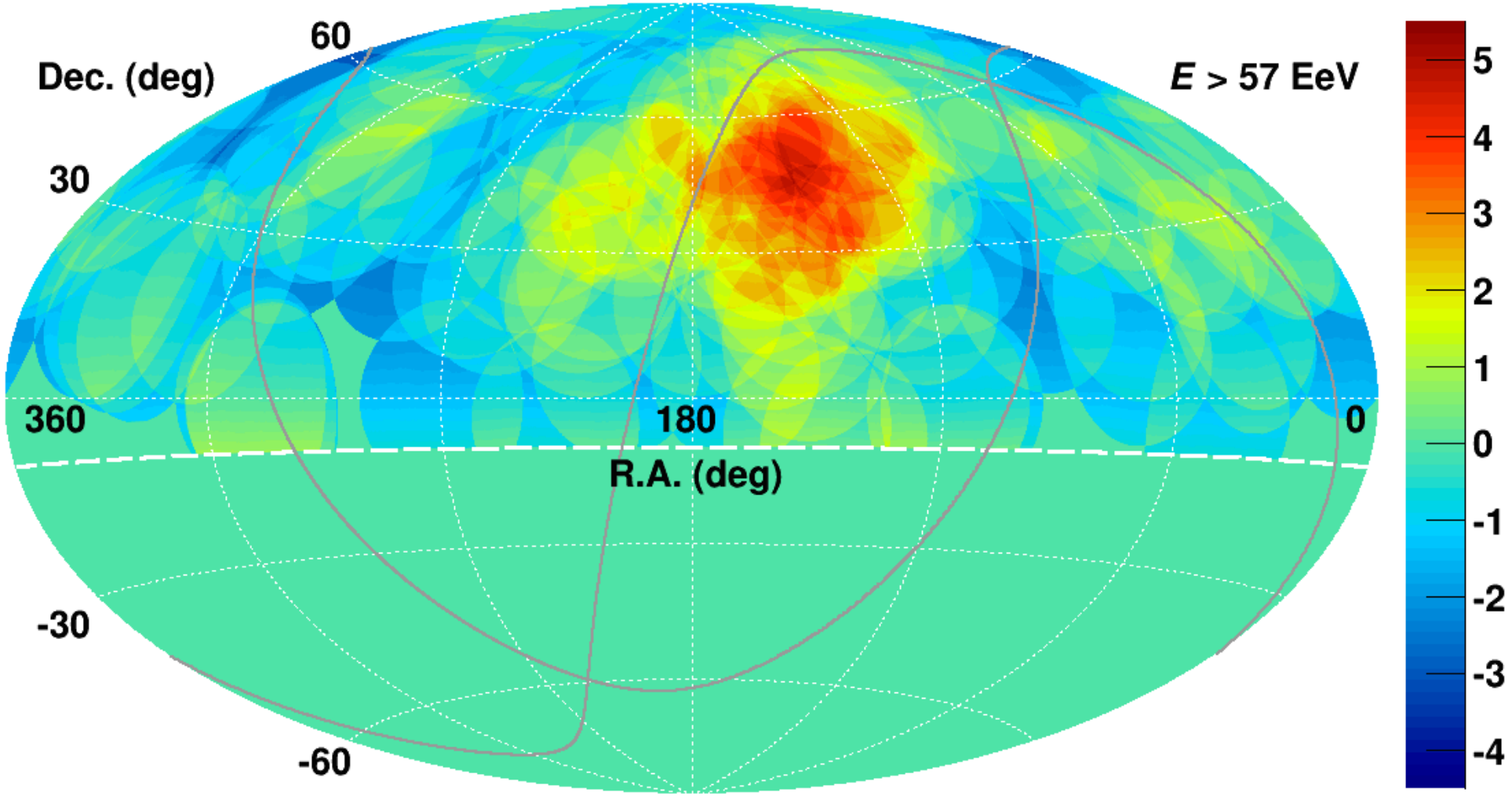
Angular resolution: better than 1.5°

Energy resolution: 20%





7 Year Excess Map (ICRC-2015)



Max Li & Ma significance **5.1**σ (N_{SIG} = 24, N_{BG}=6.88) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Global Excess Chance Probability: 3.7×10^{-4} : 3.4σ (~ same as first 5 years). **Addition of last 2 years of data is work in progress.**

TA×4 Project

Quadruple TA SD (~3000 km^2)

- **500** scintillator SDs
- **2.08 km** spacing

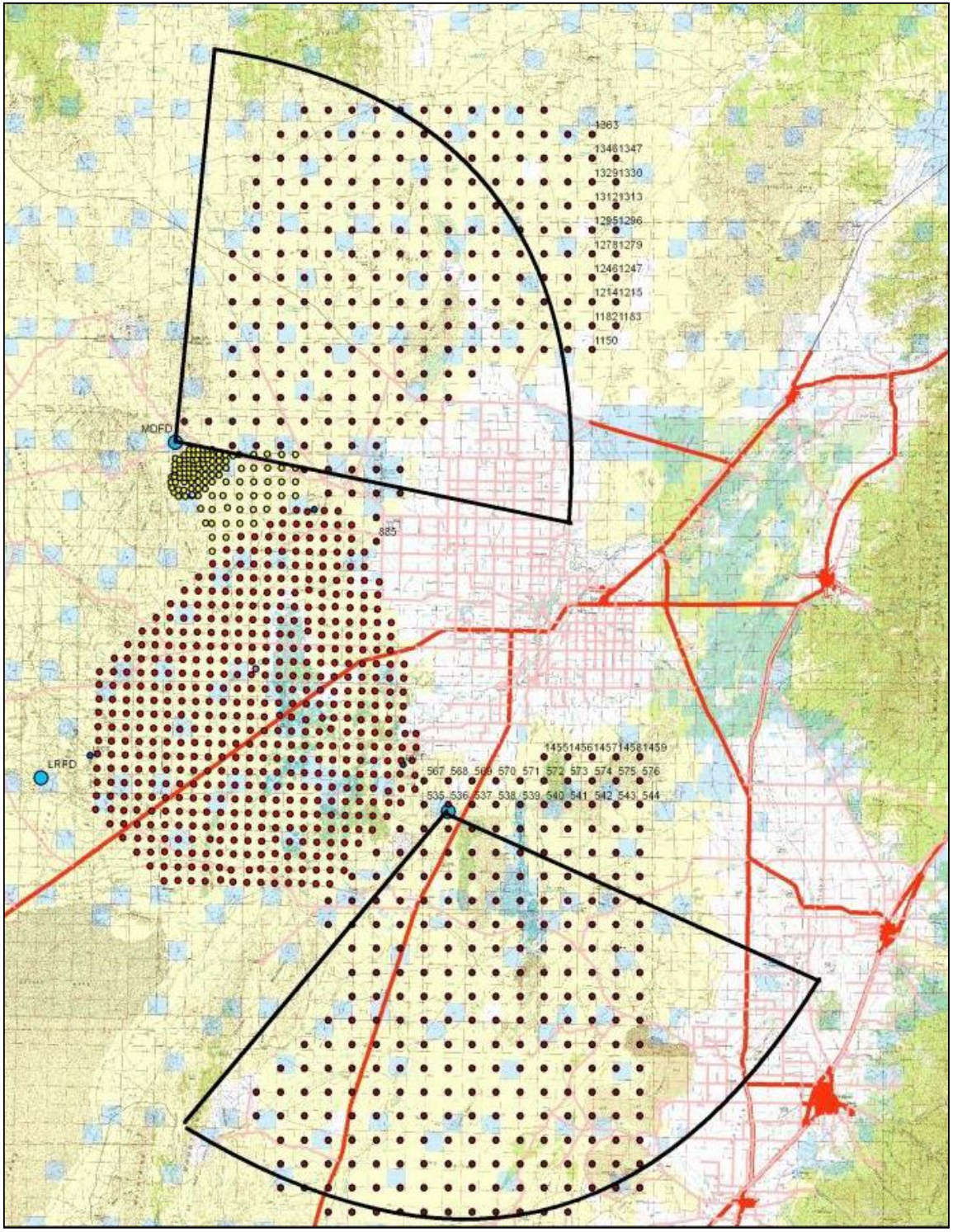
2 FD stations

Proposals

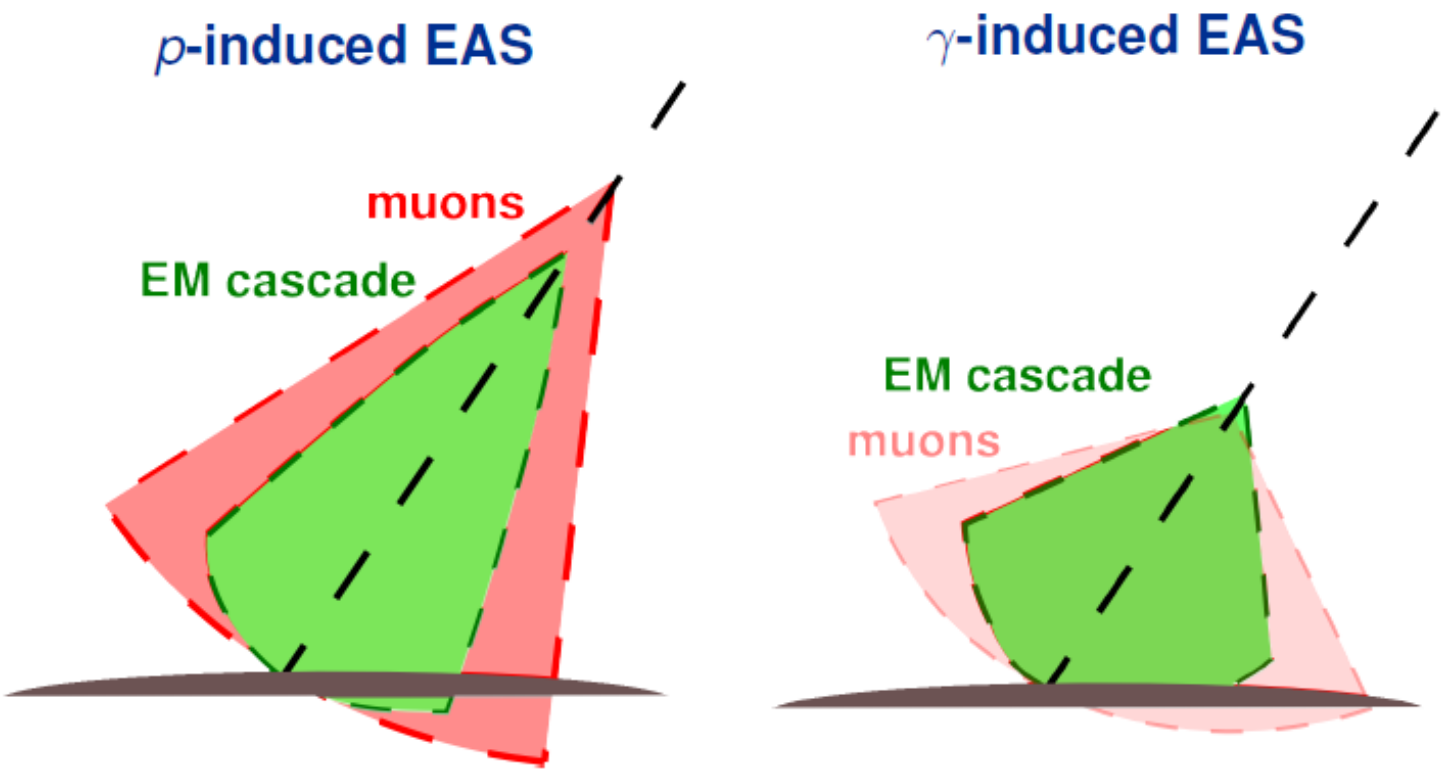
- **SD: approved** in Japan in April 2015
- **FD: recently approved** in US

Get 19 TA years of SD data by 2020

- Get 16.3 (current) TA years of hybrid data



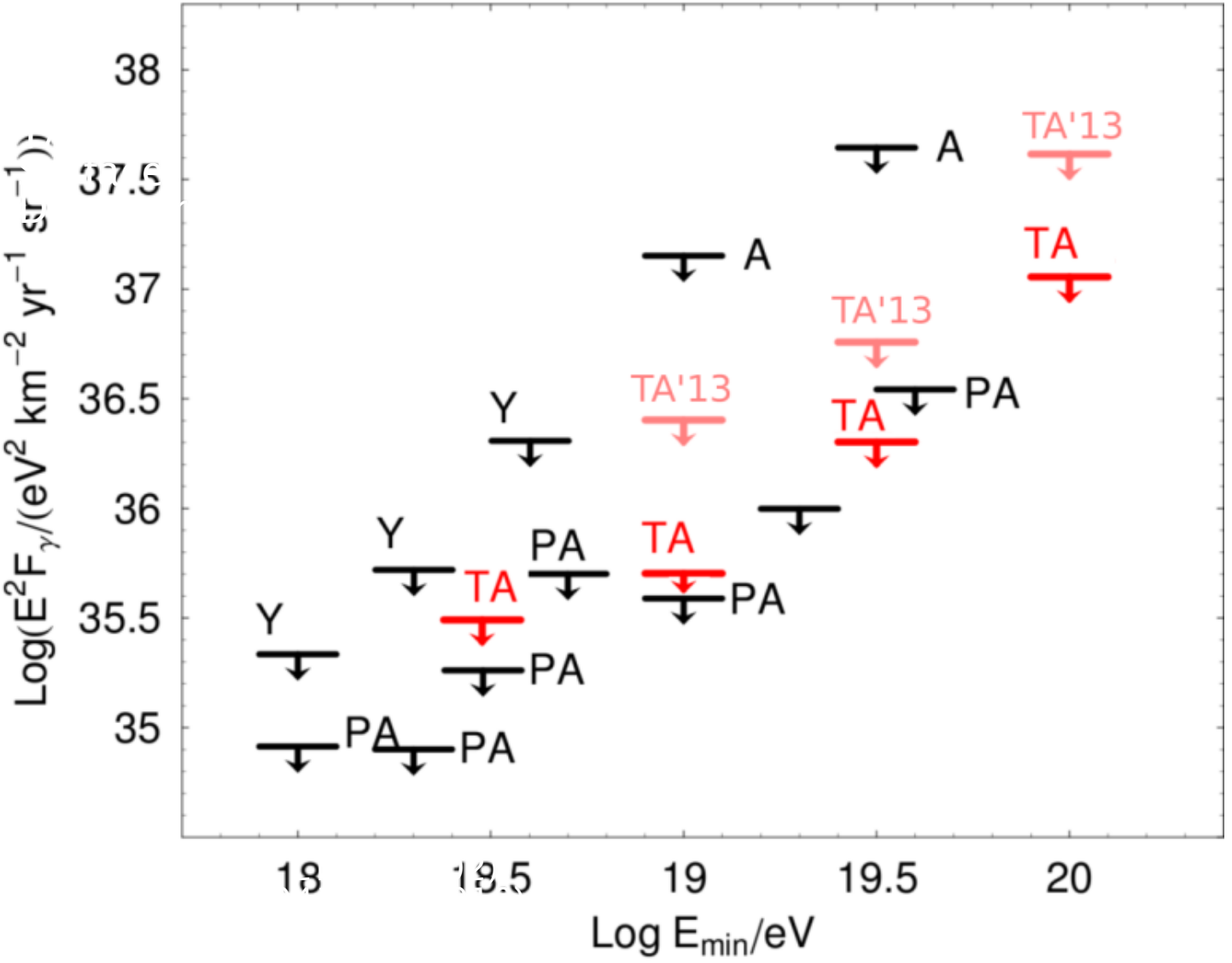
Photon Search using TA SD Data



Photon-induced showers:

- arrive younger
- contain less muons
- $\Rightarrow$ multiple SD observables affected:
  - **front curvature, Area-over-peak, number of FADC signal peaks, $\chi^2/d.o.f.$, S_b**

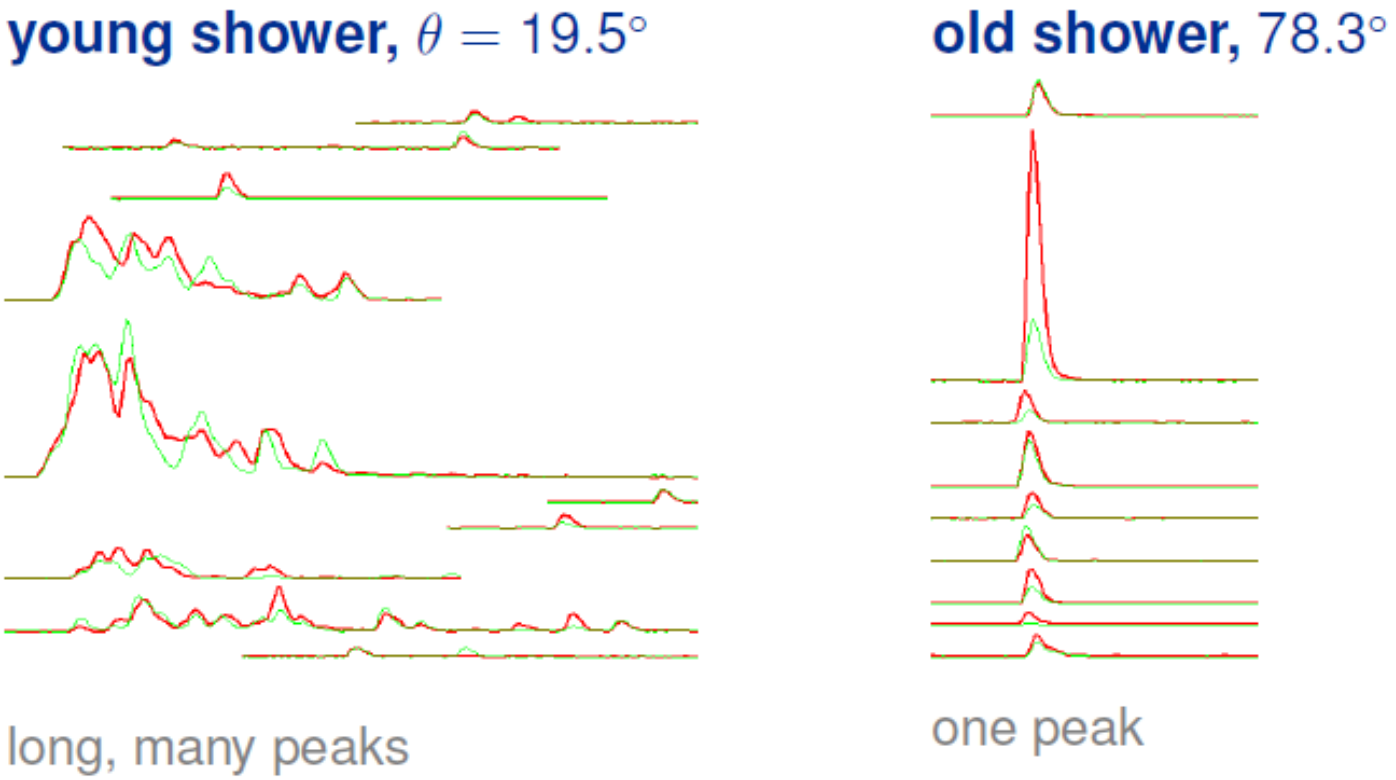
TA Gamma Ray Limit Result (ICRC-2015)



Search for Neutrinos

- New technique based on multivariate analysis may be applied for searching for downward going neutrinos in the TA SD data:

  - Neutrino produces very inclined young shower



  - Down-going ν search based on MVA is in progress

*(**M**ulti Variate Analysis approach)

Summary

- We measured CR energy spectrum over 5 orders of magnitude of energy, 4 features seen, using a common energy scale in all measurements
- TA X_{Max} data is consistent with the light composition below $10^{19.5}$ eV and TA energy spectrum fits proton composition above $10^{18.2}$ eV. Not enough statistics above $10^{19.5}$ eV yet.
- A 3.4σ localized deviation from isotropy above 57 EeV seen in 7 years of TA SD data. Also, second break point in the energy spectrum (GZK cutoff) appears to be dependent on the declination band. Better Agreement with Pierre Auger Observatory spectrum results is achieved when we use a common declination band.
  - More data needed to measure composition, anisotropy, and spectrum at the highest energies
  - TAX4 is being constructed to do that
- Studies of neutrino and high energy photon fluxes in TA are in progress