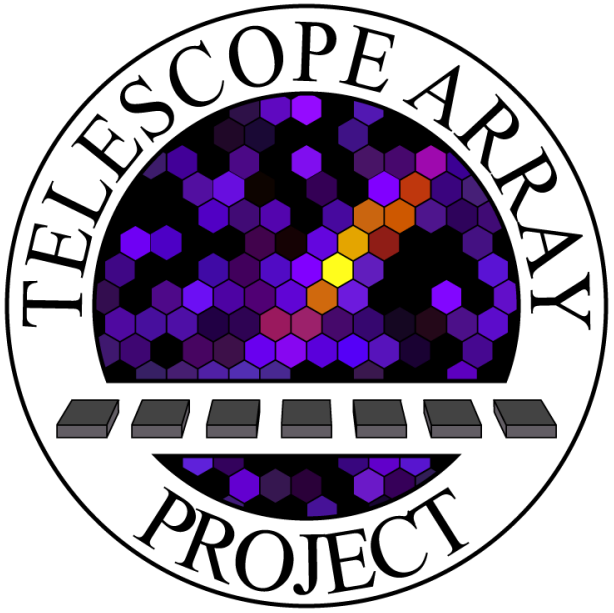
TA Spectrum Summary



Dmitri Ivanov
University of Utah
2016/10/11, Kyoto, JP

Outline

- Telescope Array (TA) Experiment
- TA Spectrum Measurements
  - Surface Detector (SD)
  - Fluorescence Detector (FD) Mono
  - TA Low Energy Extension (TALE) Fluorescence and Cherenkov
- Combined Spectrum
- Conclusions

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

Battery of Telescopes
Particle Detector
Communications Tower
CLF
0 1 2 4 Miles

Middle Drum, TALE (MD)

Middle Drum (MD) - CT

Smelter Knolls (SK) - CT

LR-CT

BR-CT

Long Ridge (LR)

Black Rock Mesa (BR)

R11W R11W R10W R10W R9W R9W R8W R8W
T15S T16S T17S T18S T19S

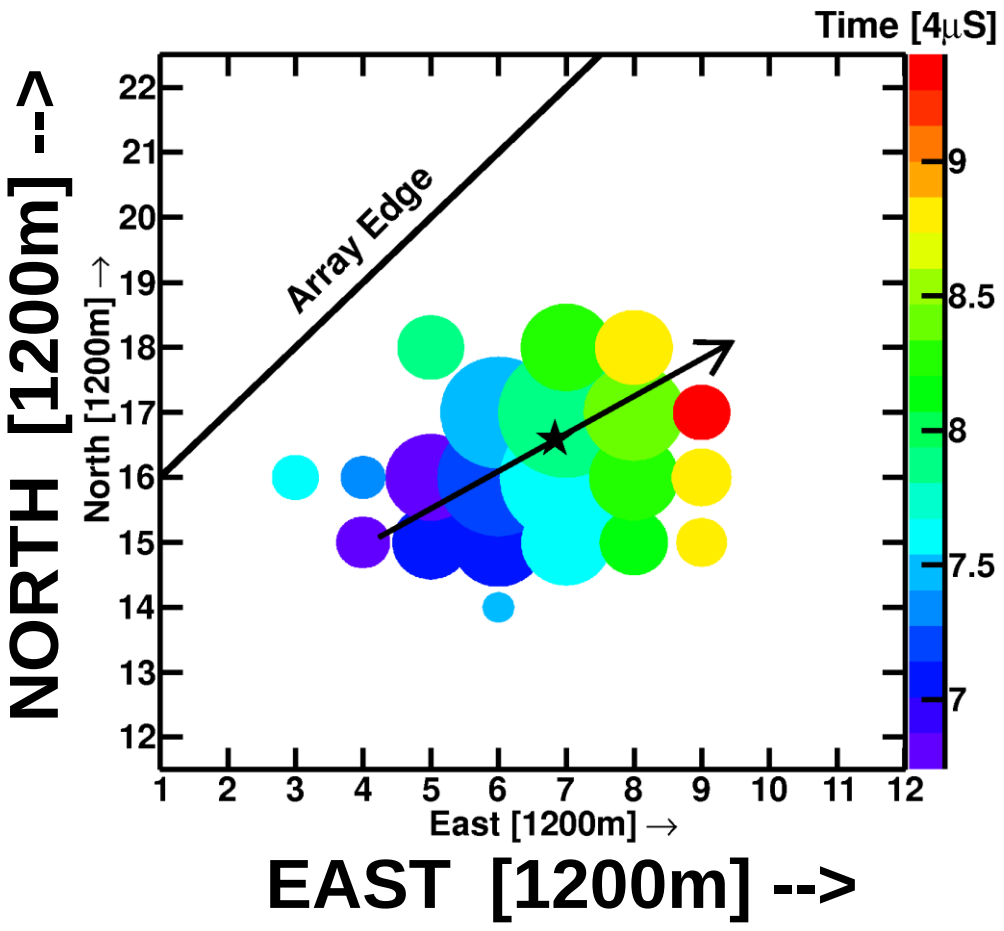
TA FD

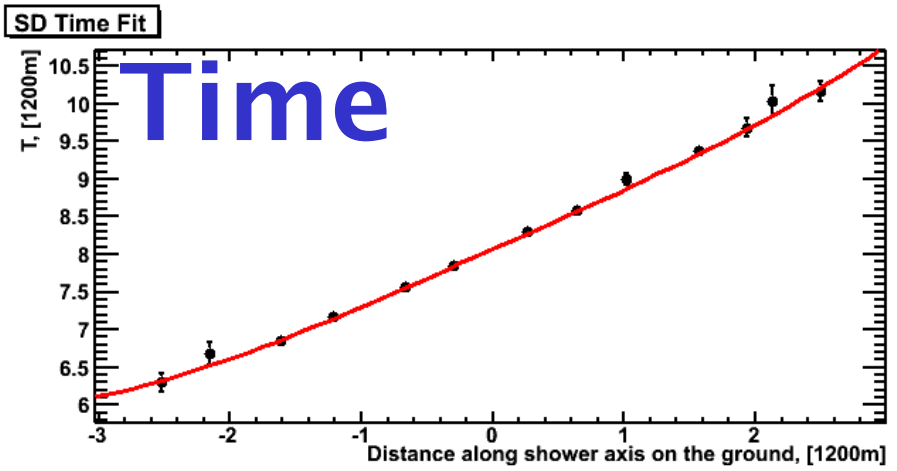

MD
LR
BRM
2013/03/29
© 2013 Google
Image USDA Farm Service Agency
Image State of Utah
Google earth

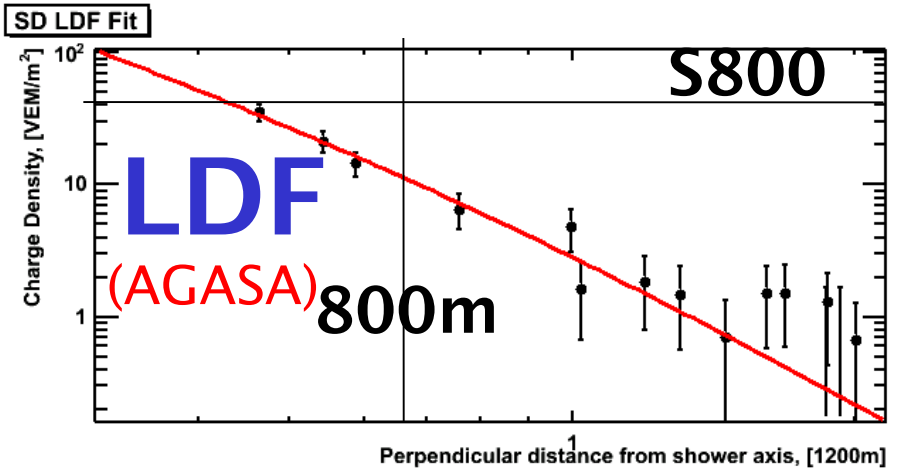
TA Surface Detector

- Powered by solar cells; radio readout.
- In operation since March, 2008.
- Self-calibration using single muons.
- Energy deposited by cosmic ray shower particles is measured in **VEM** units (**V**ertical **E**quivalent **M**uon = energy deposited by a vertical minimum ionizing muon)

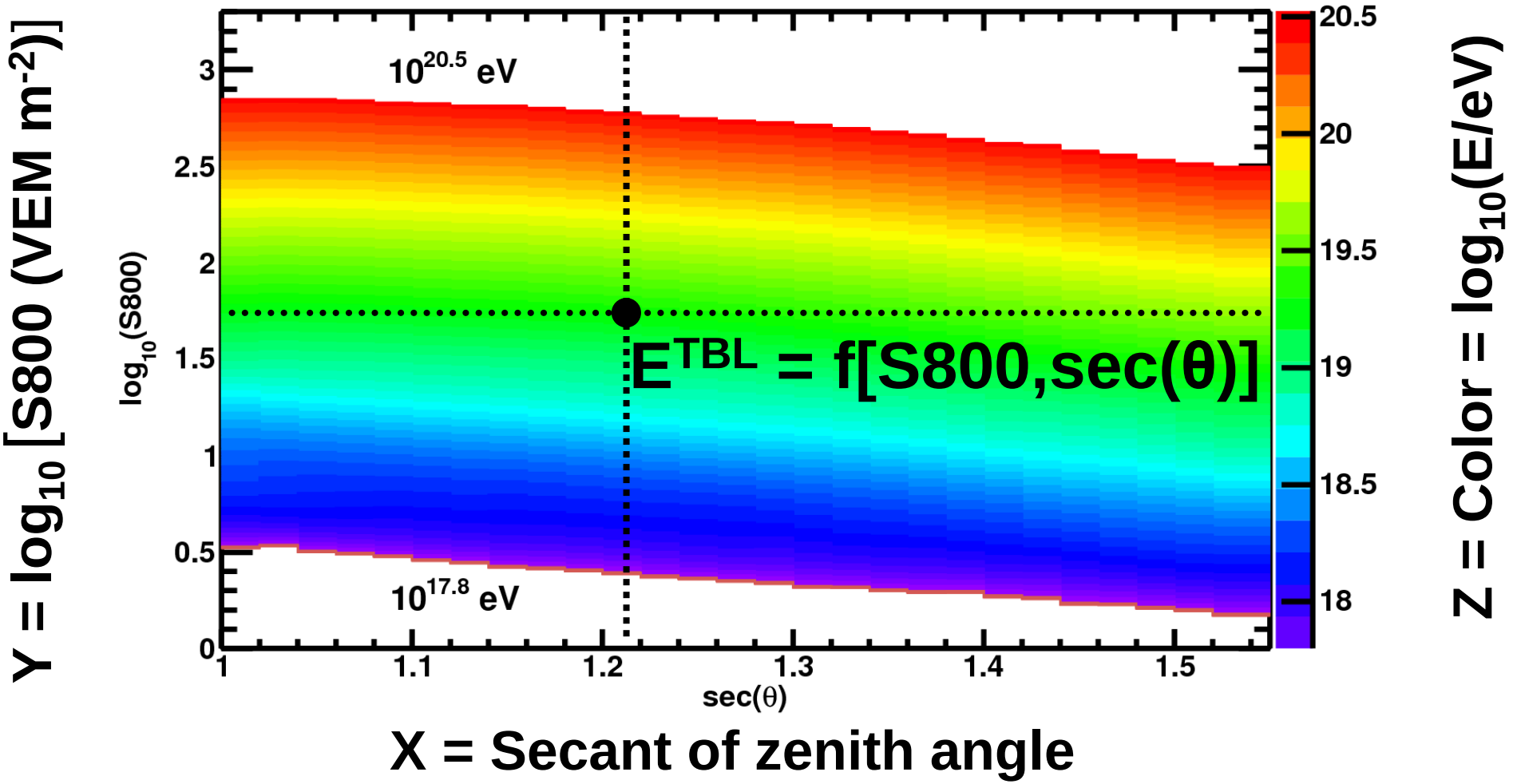
Surface Detector Event





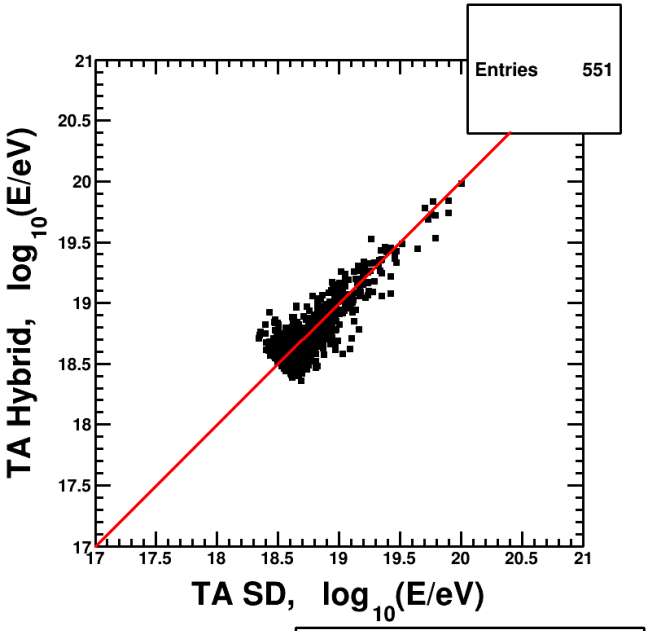


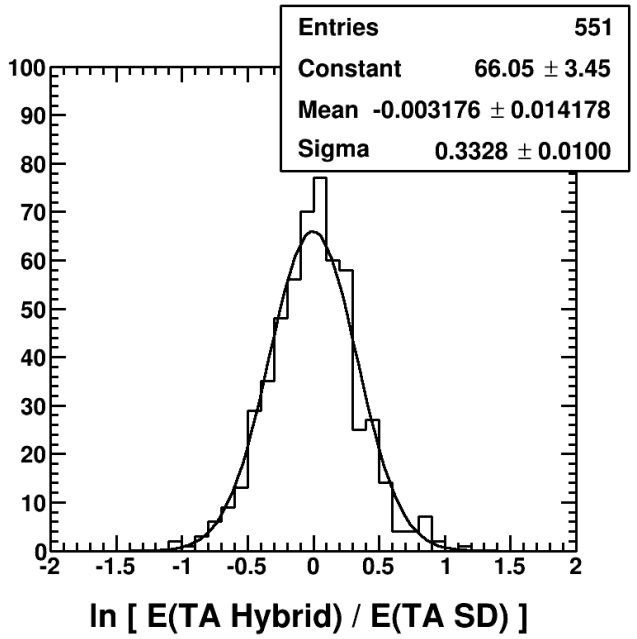
SD Energy 1/2



- 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}
- The overall energy scale locked to the fluorescence detector

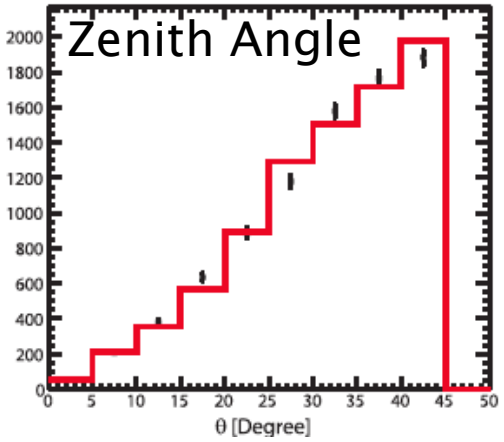
SD Energy 2/2: Energy Scale Set to FD

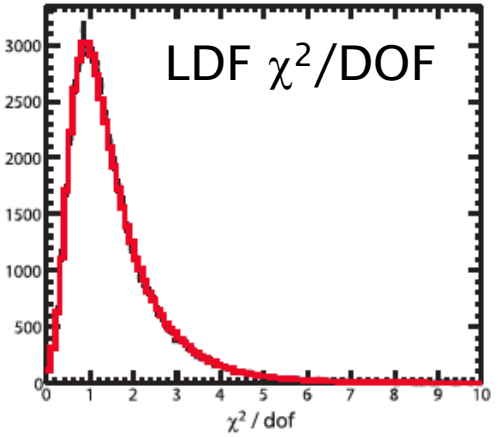


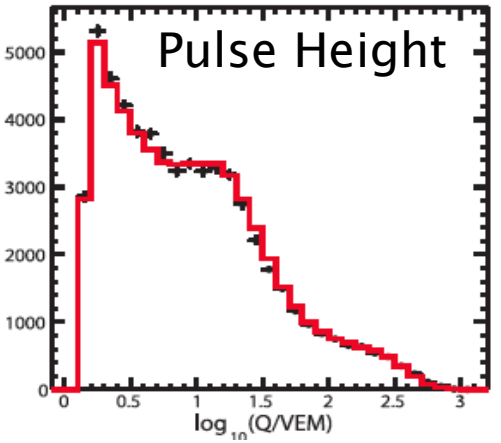


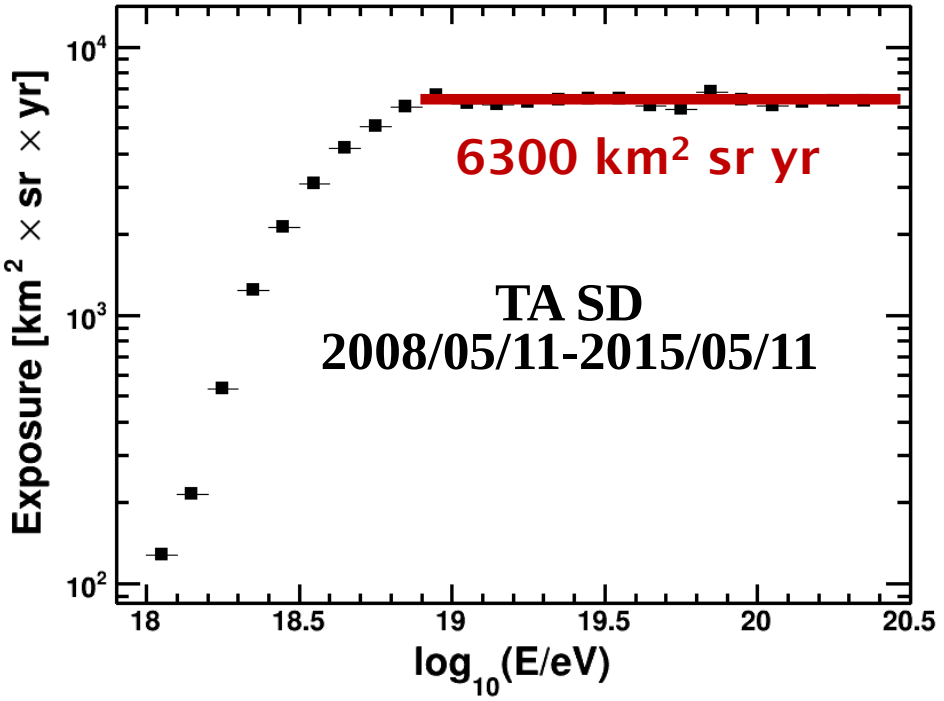
- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
- $E^{FINAL} = E^{TBL} / 1.27$
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD}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

Exposure from Monte Carlo



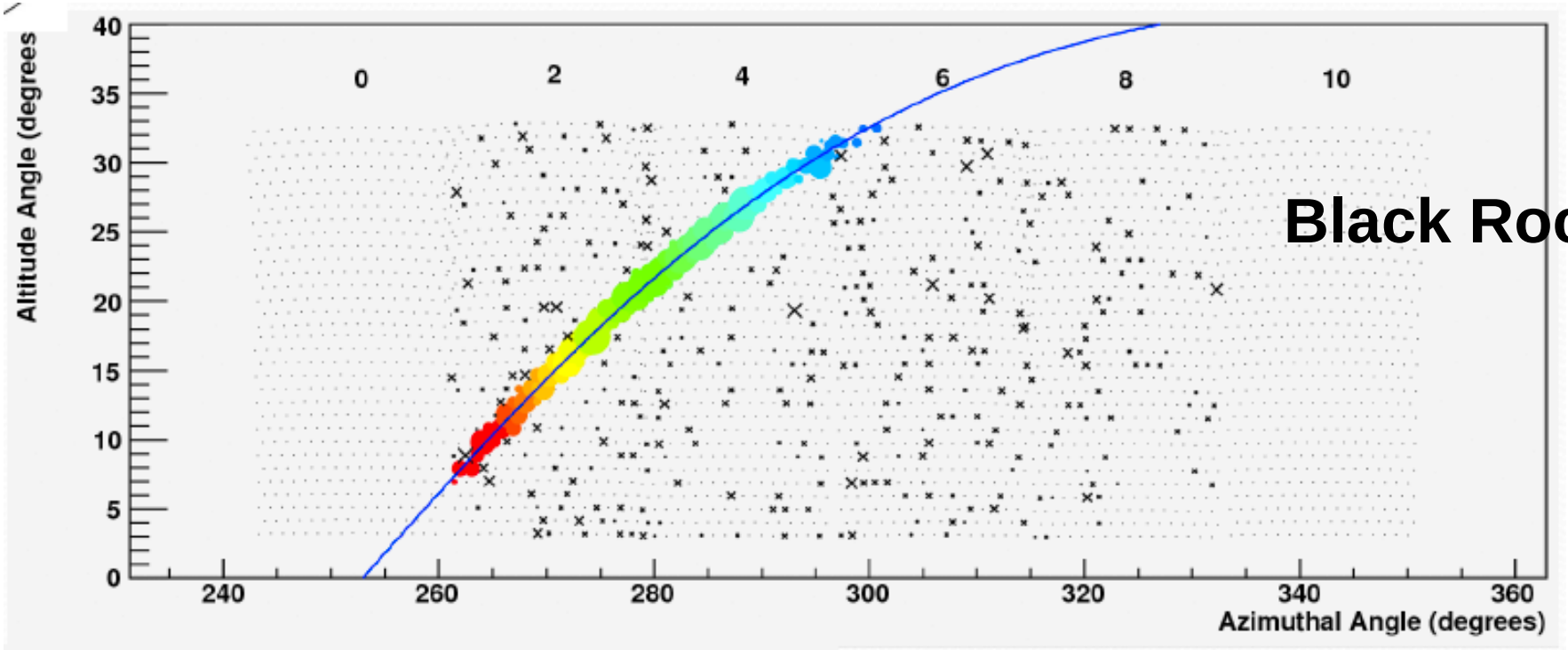




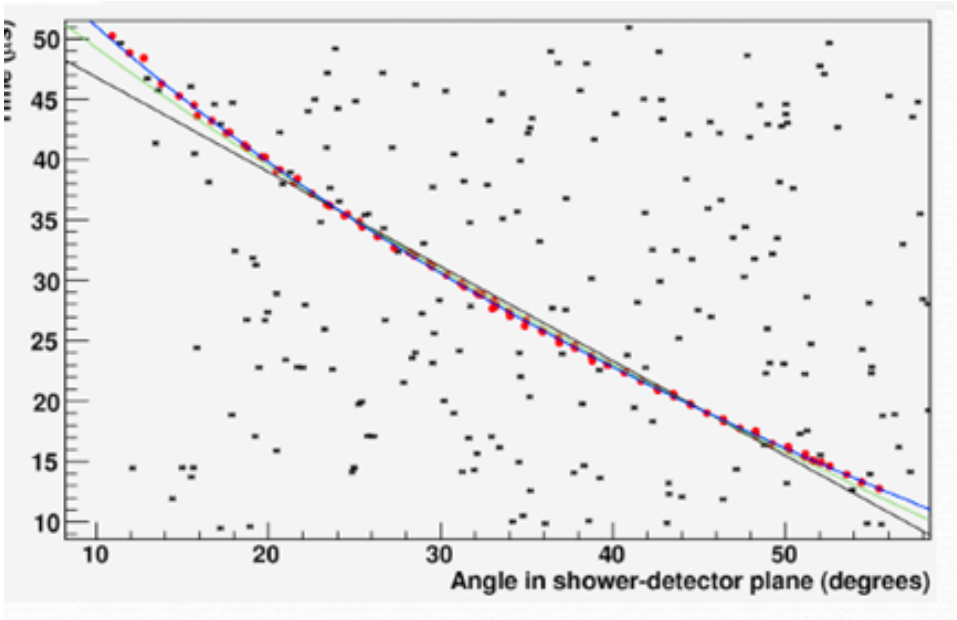


- Detailed Monte Carlo used for exposure calculation in all measurements of TA

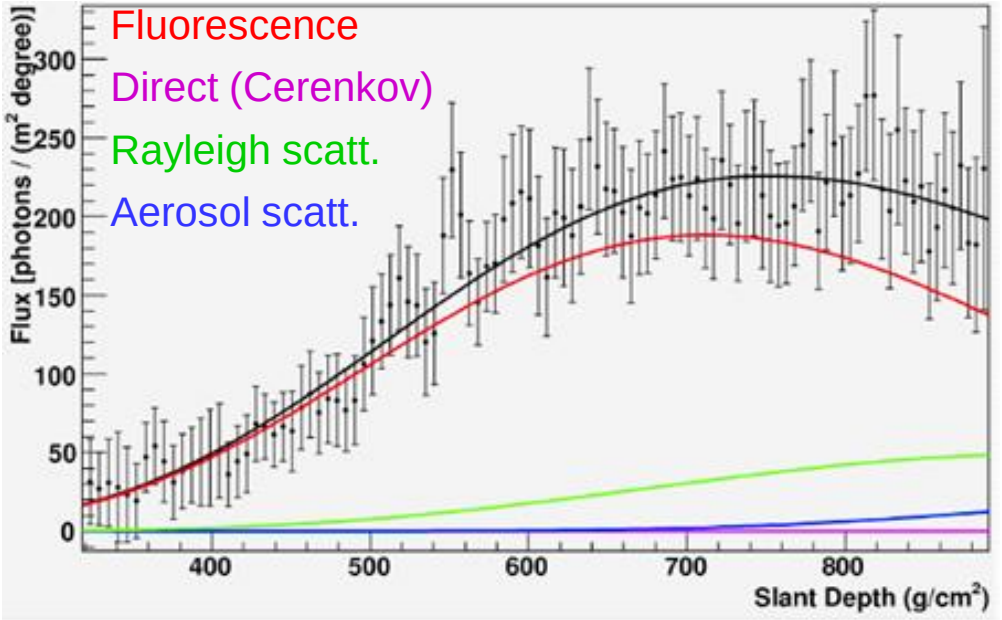
Fluorescence Mono Analysis



Black Rock Mesa



Time fit



Profile fit

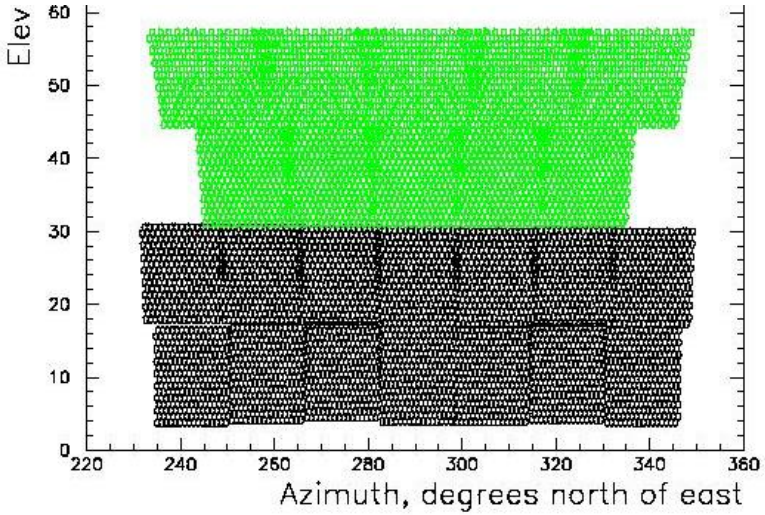
TA Low Energy Extension (TALE)

- 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.
- Need to observe from 3×10^{16} eV to 3×10^{20} eV all in one experiment. That is TA and TALE.

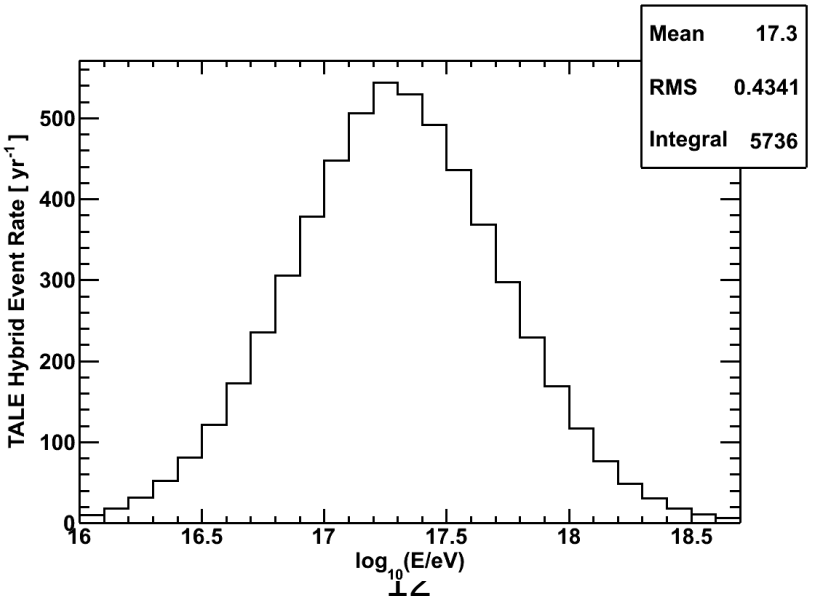
TALE FD

- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operate in conjunction with the TA Middle Drum FD.

TALE telescopes



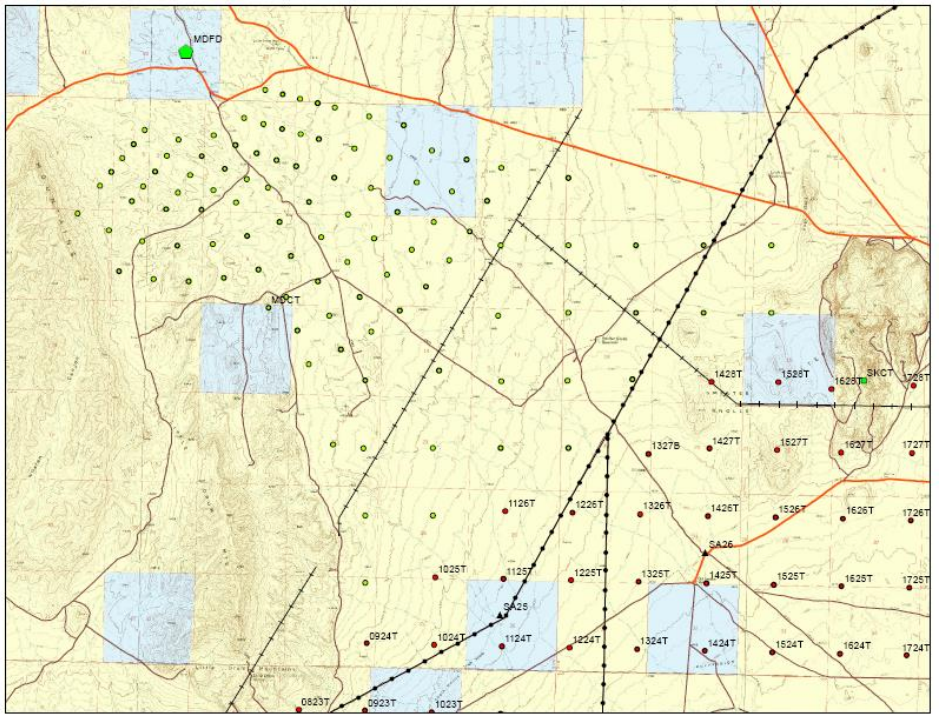
TA MD telescopes

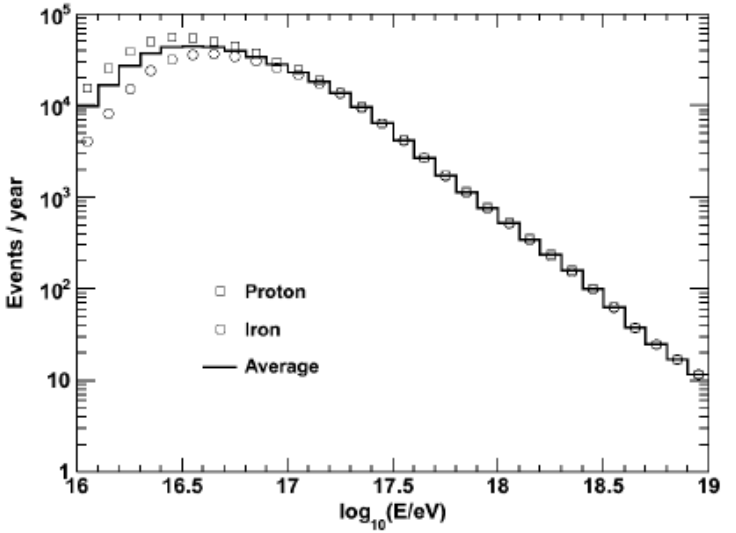


TALE hybrid events per year

TALE Infill Array

- Add infill array (400m and 600m spacing) for hybrid and stand-alone observation.
- Also add counters to build out main TA SD array (1200m separation).
- 105 counters in all, 16 are now taking data which is currently being analyzed

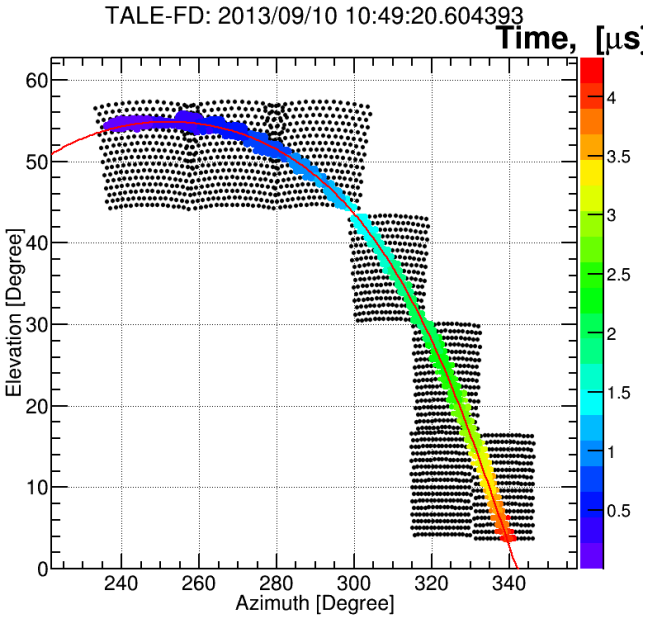


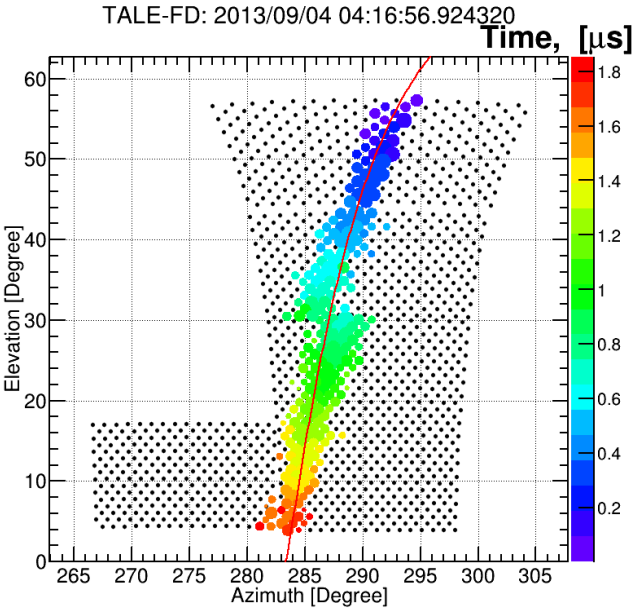


Events per year

TALE Events

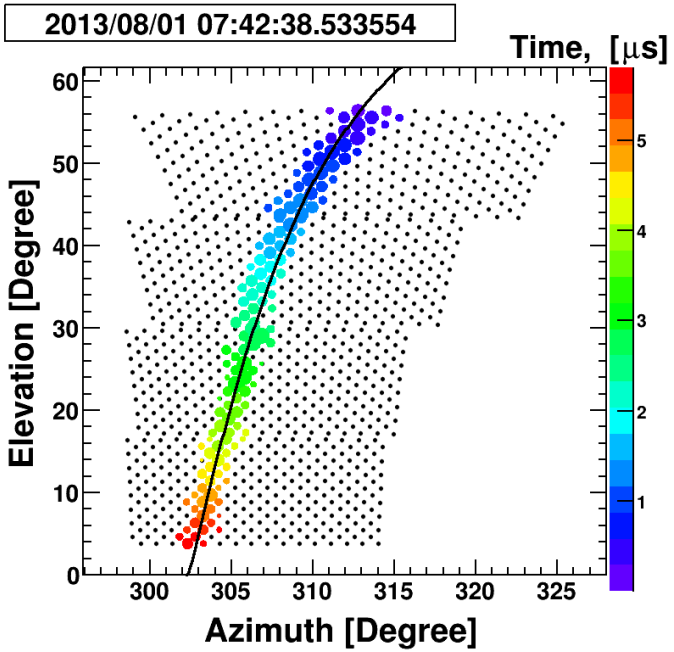
7 mirror event, log(E) = 16.5

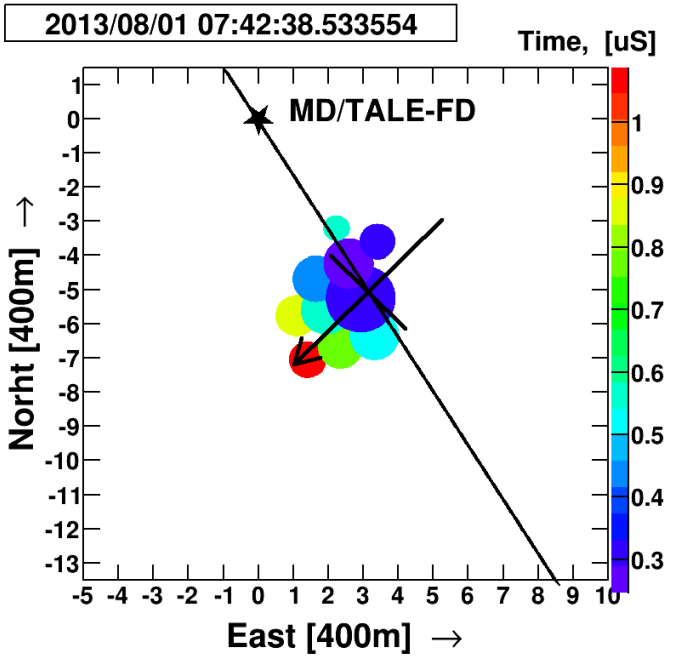




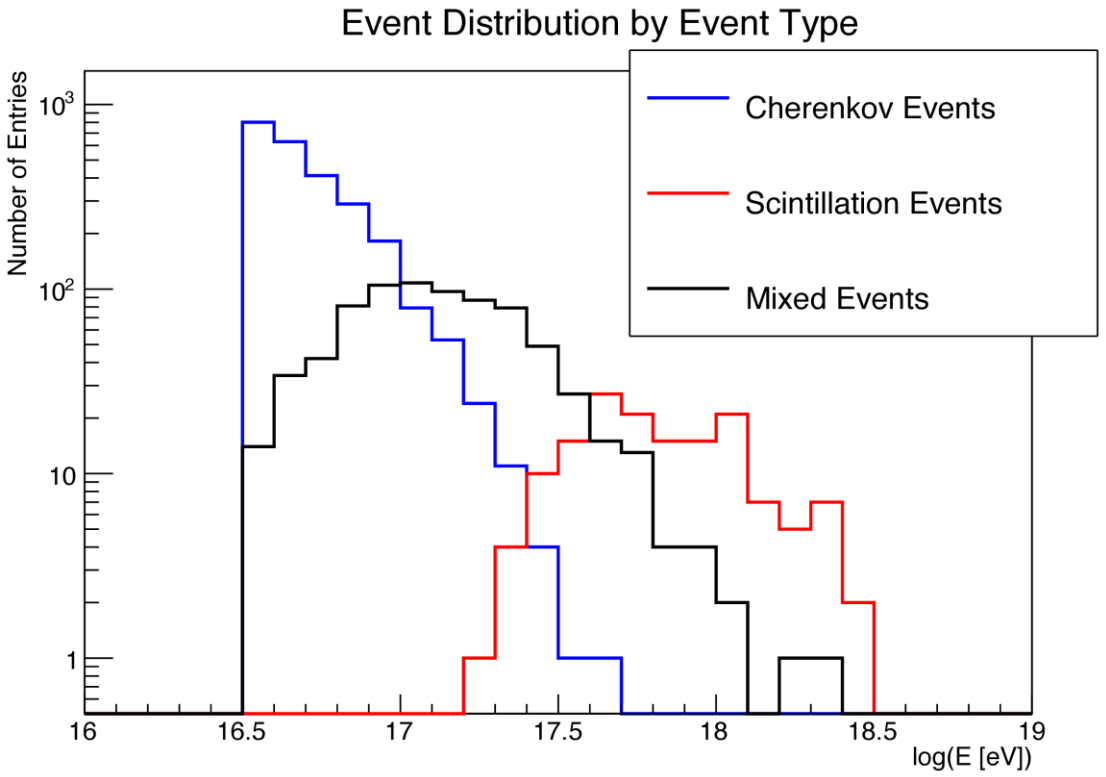
Parallax event, R_p=800m

Hybrid event



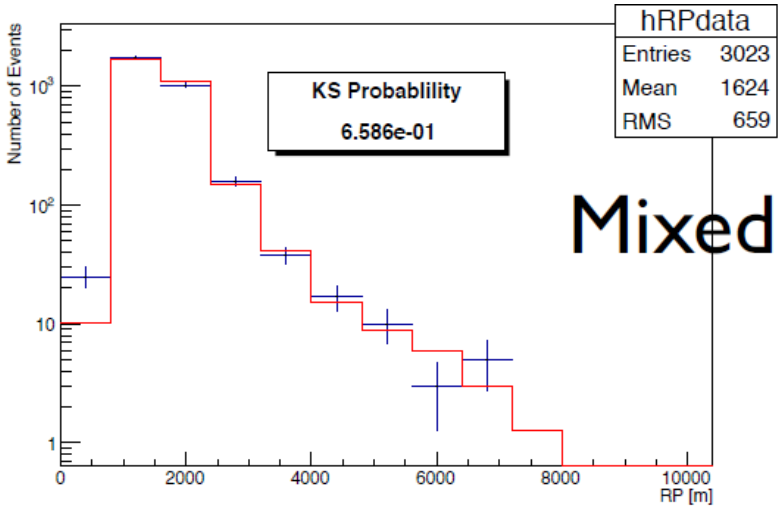


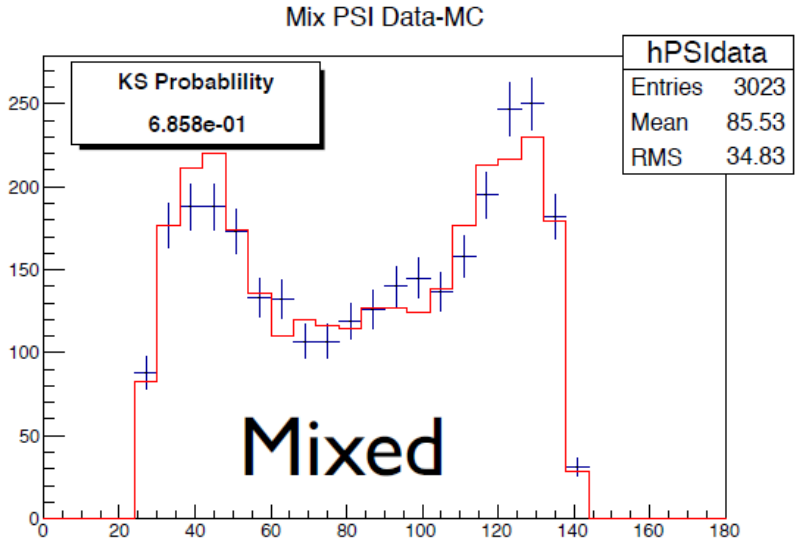
TALE Cherenkov vs. Fluorescence

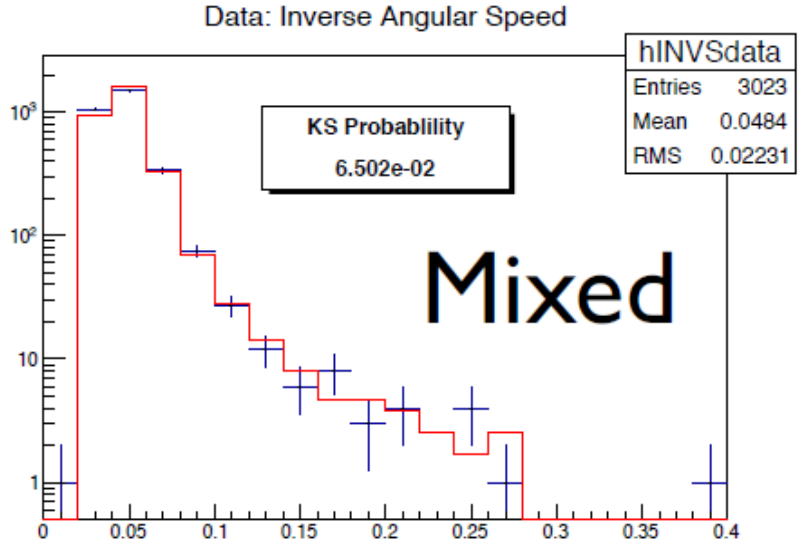


Unexpected result: many Cherenkov events are seen as tracks (most land ~0.5 km from FD).
Use profile constrained reconstruction.
Cherenkov light is bright ➔ can go lower in energy than expected.

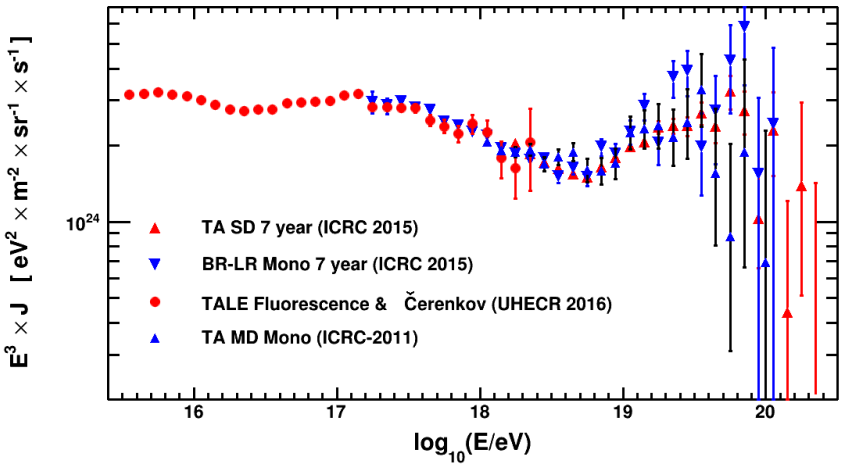
TALE DATA/MC Comparisons





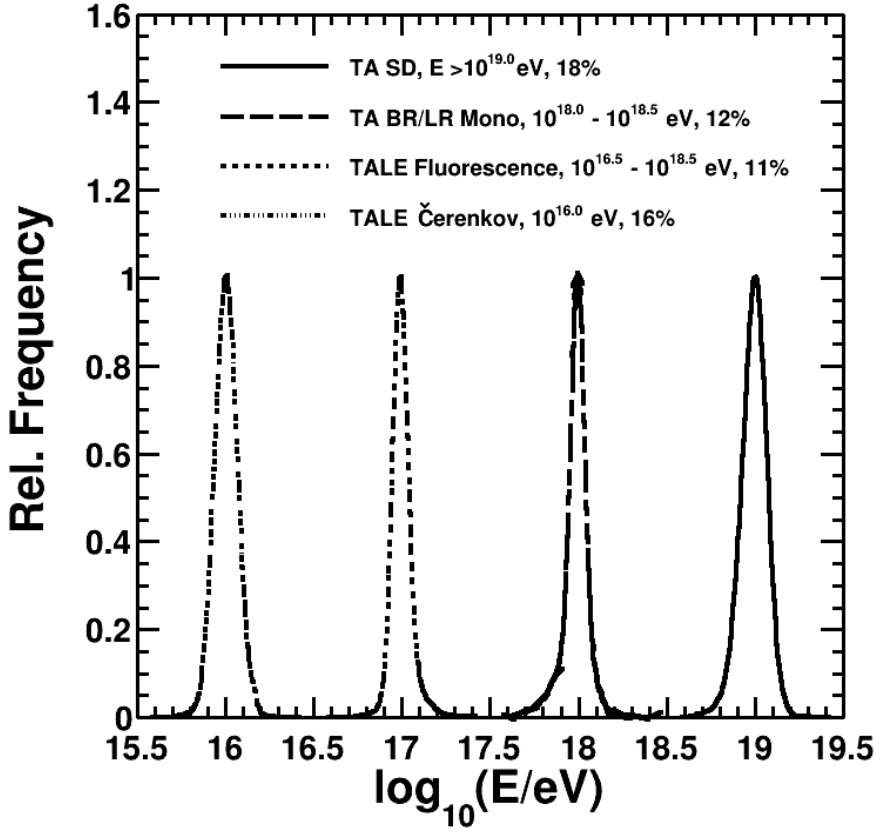


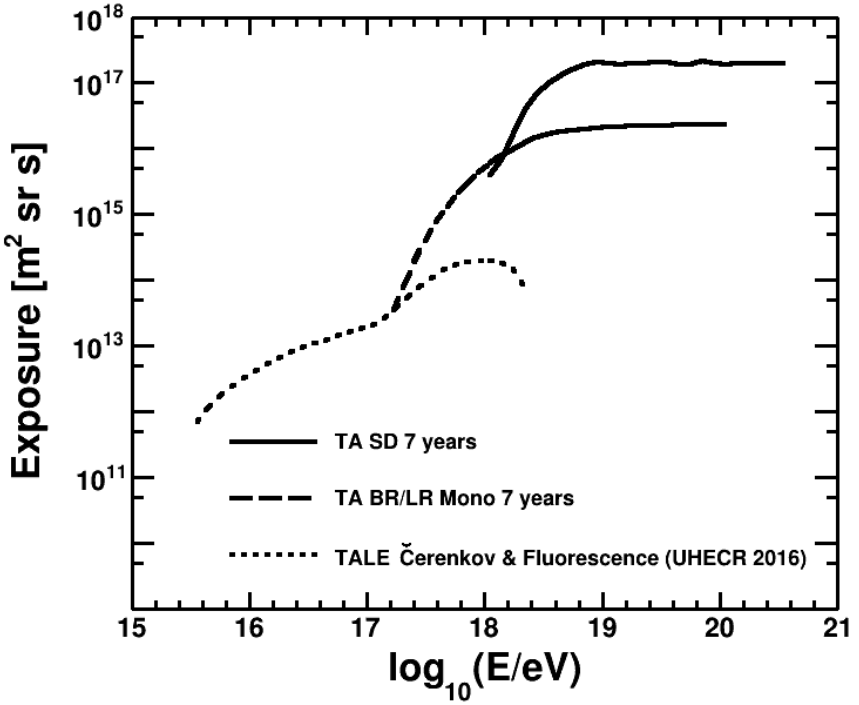
TA Spectra



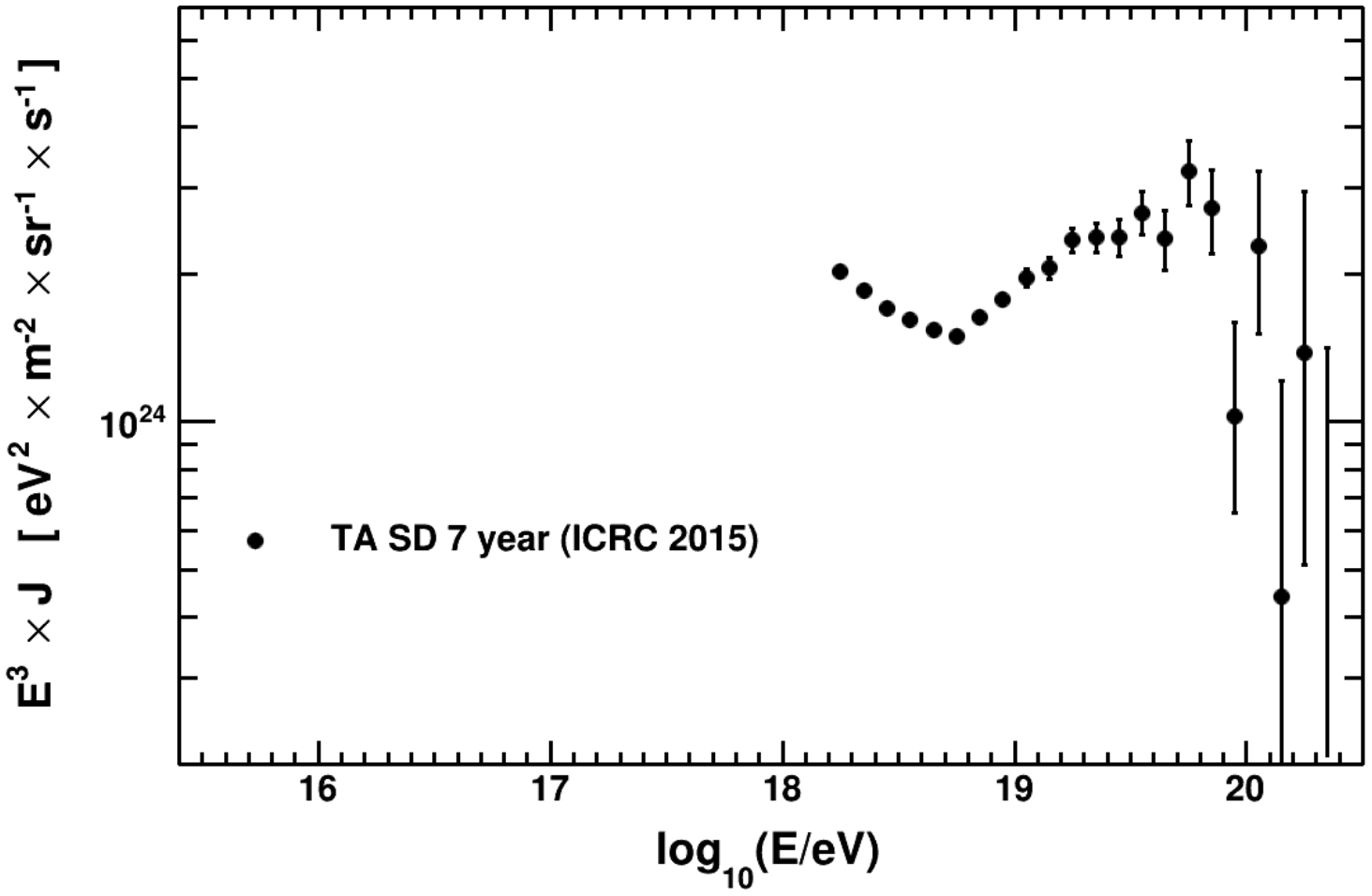
- Energy spectrum measurements available in TA for each type of detection technique
  - Often, more than one analysis exists
- To form a combined spectrum, we choose analyses with best statistics and energy resolution for their respective energy ranges

TA Resolution and Exposure as Function of Energy

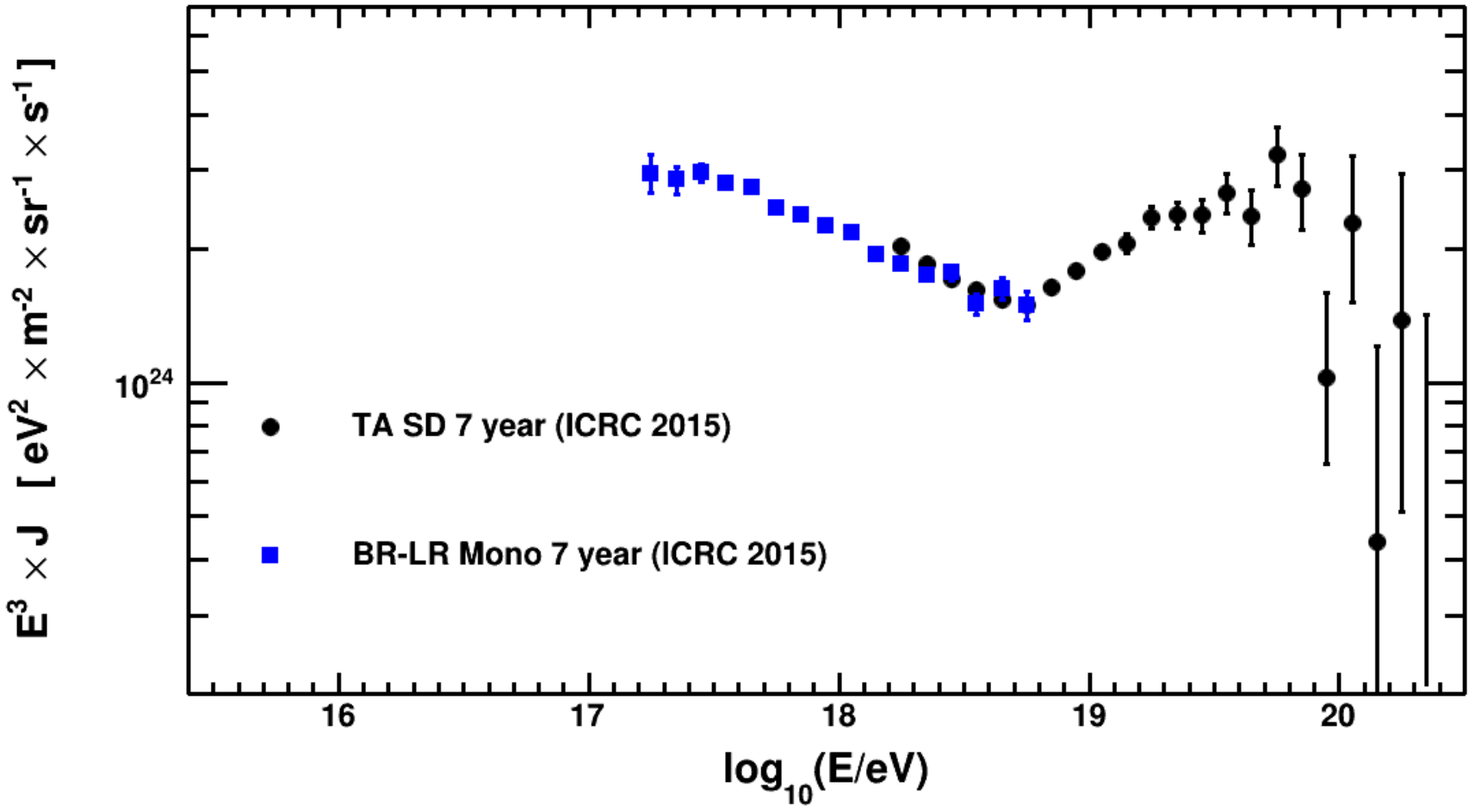




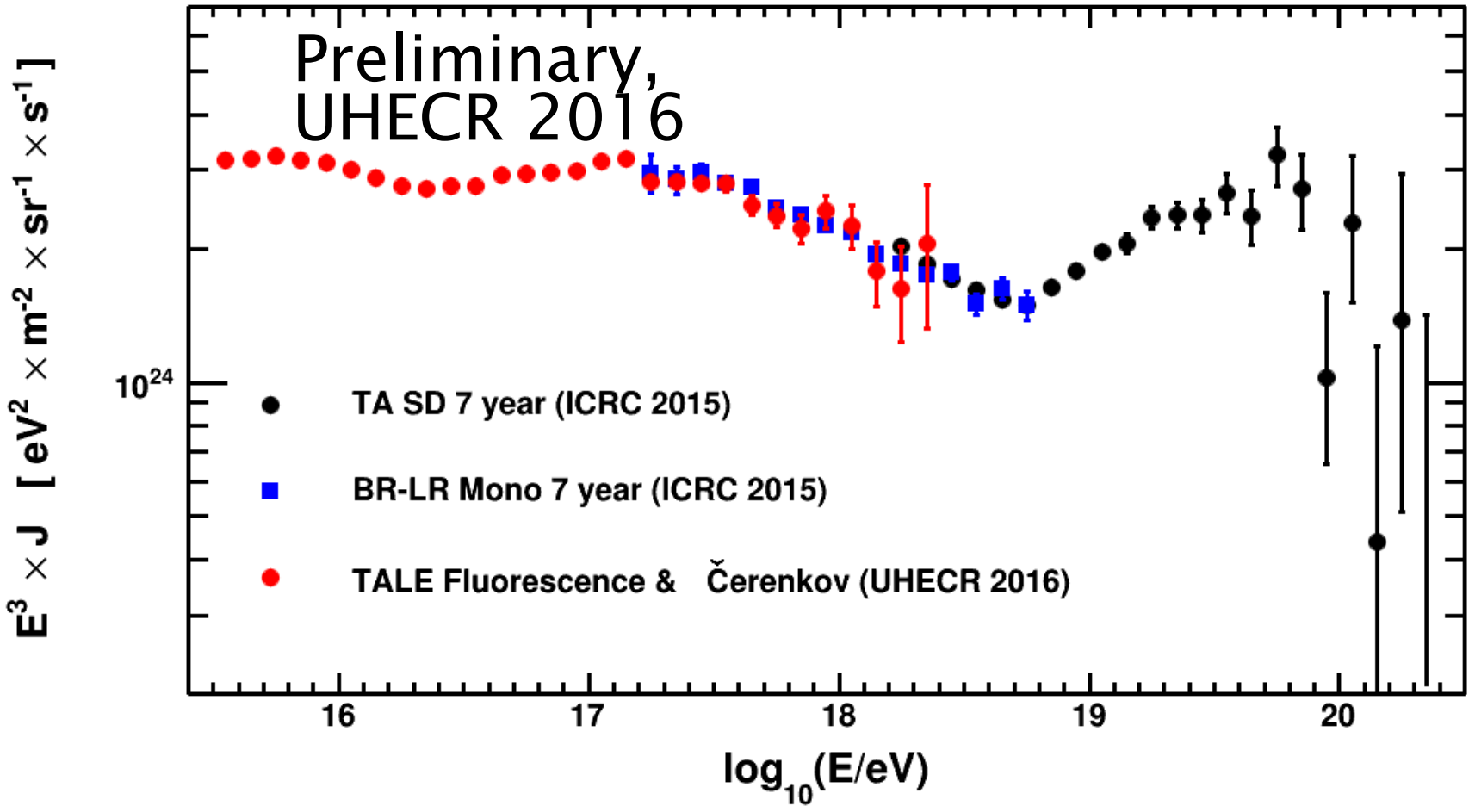
TA SD, E > $10^{18.2}$ eV



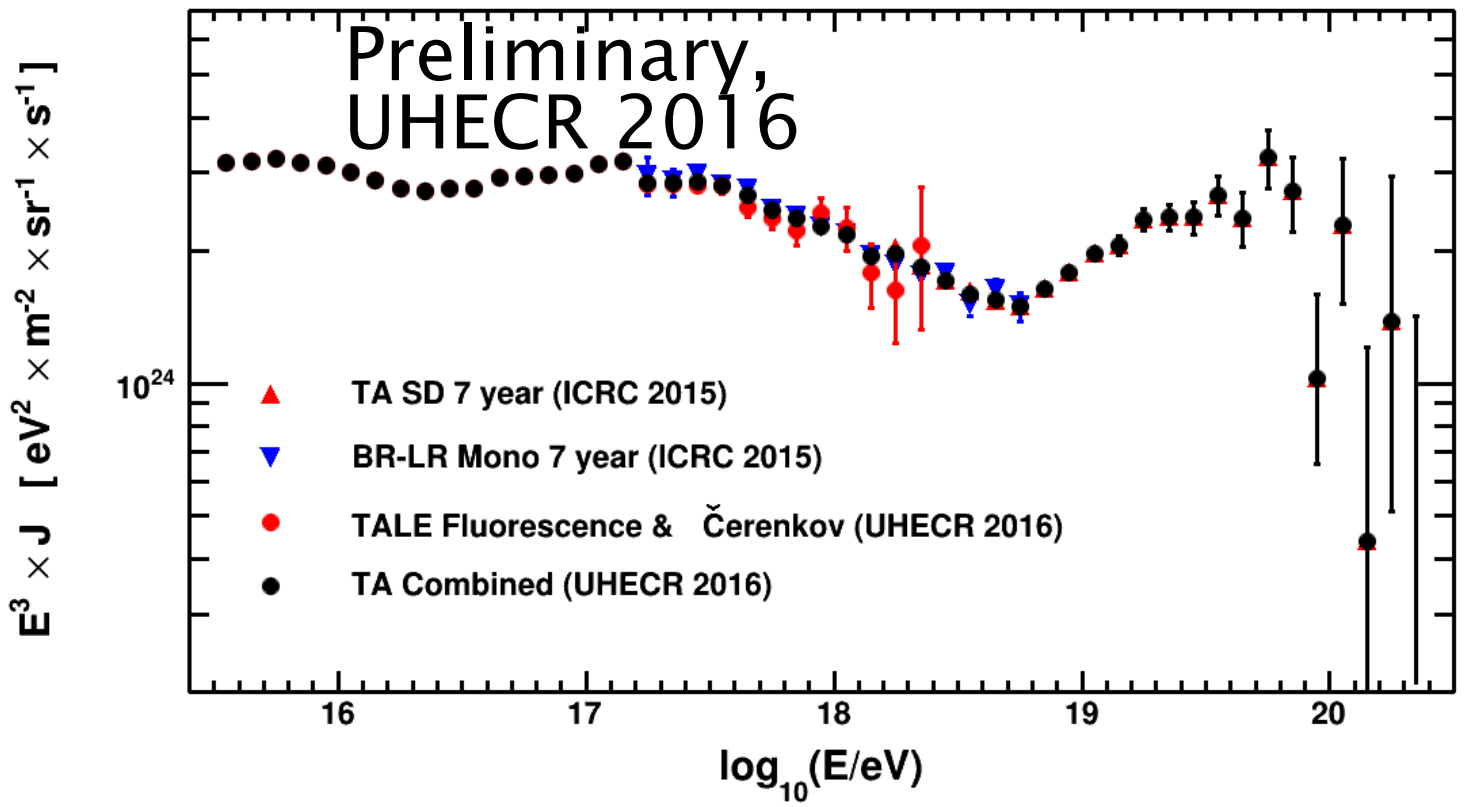
Add TA BR/LR Mono, $10^{17.2}$ eV< E < 18.8 eV



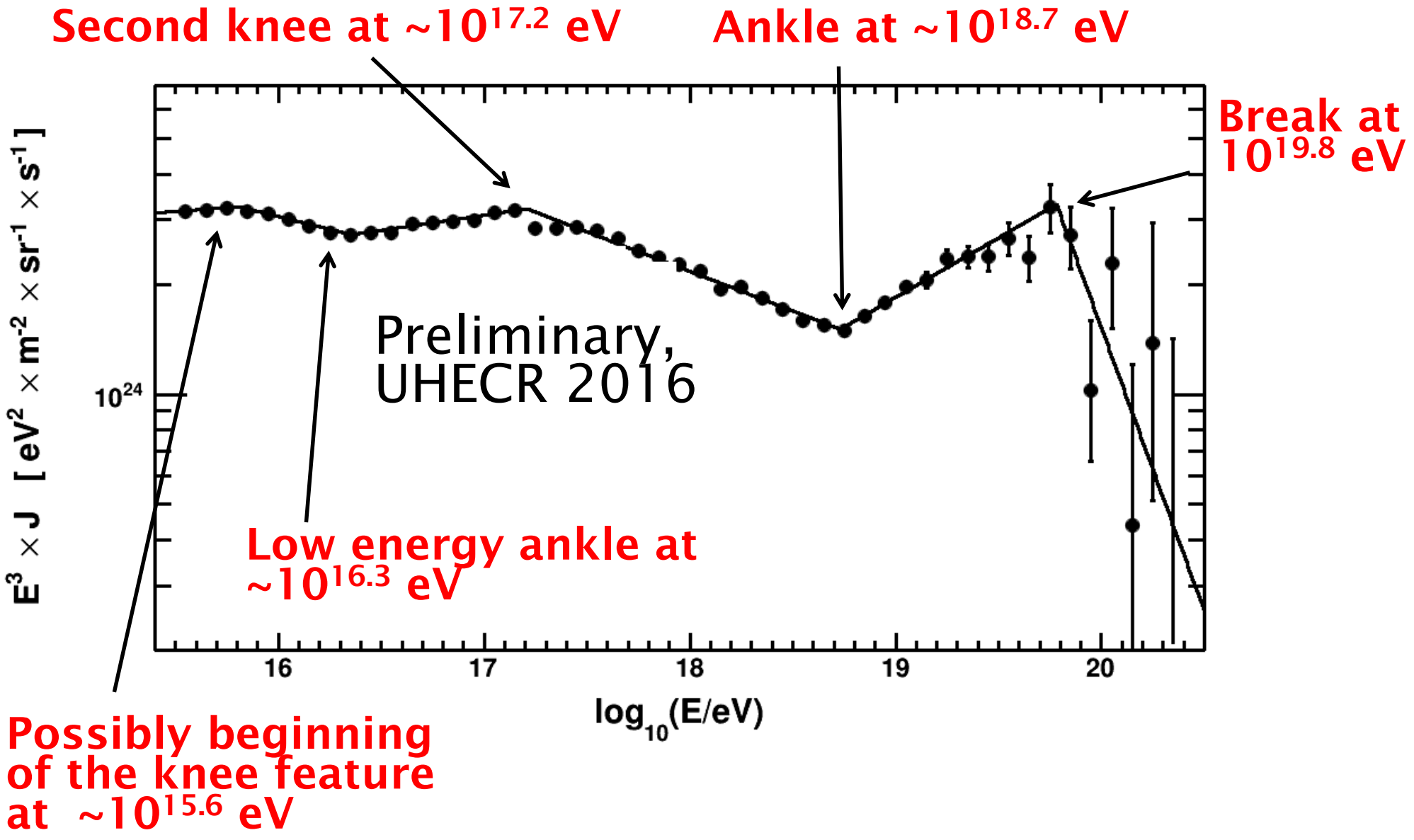
Add TALE Fluorescence and Cherenkov, $10^{15.5}$ eV< E < 18.3 eV



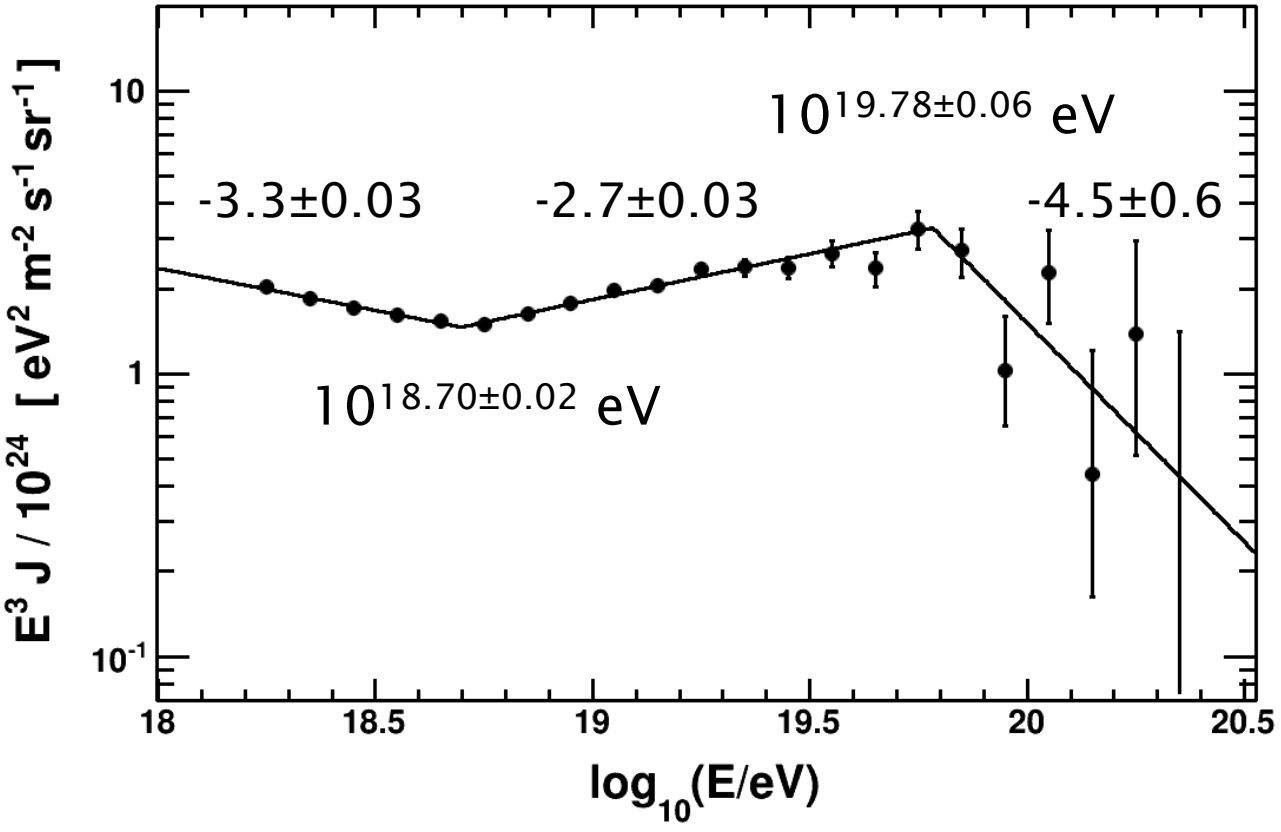
Combine the TA spectrum



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



Standard SD spectrum analysis

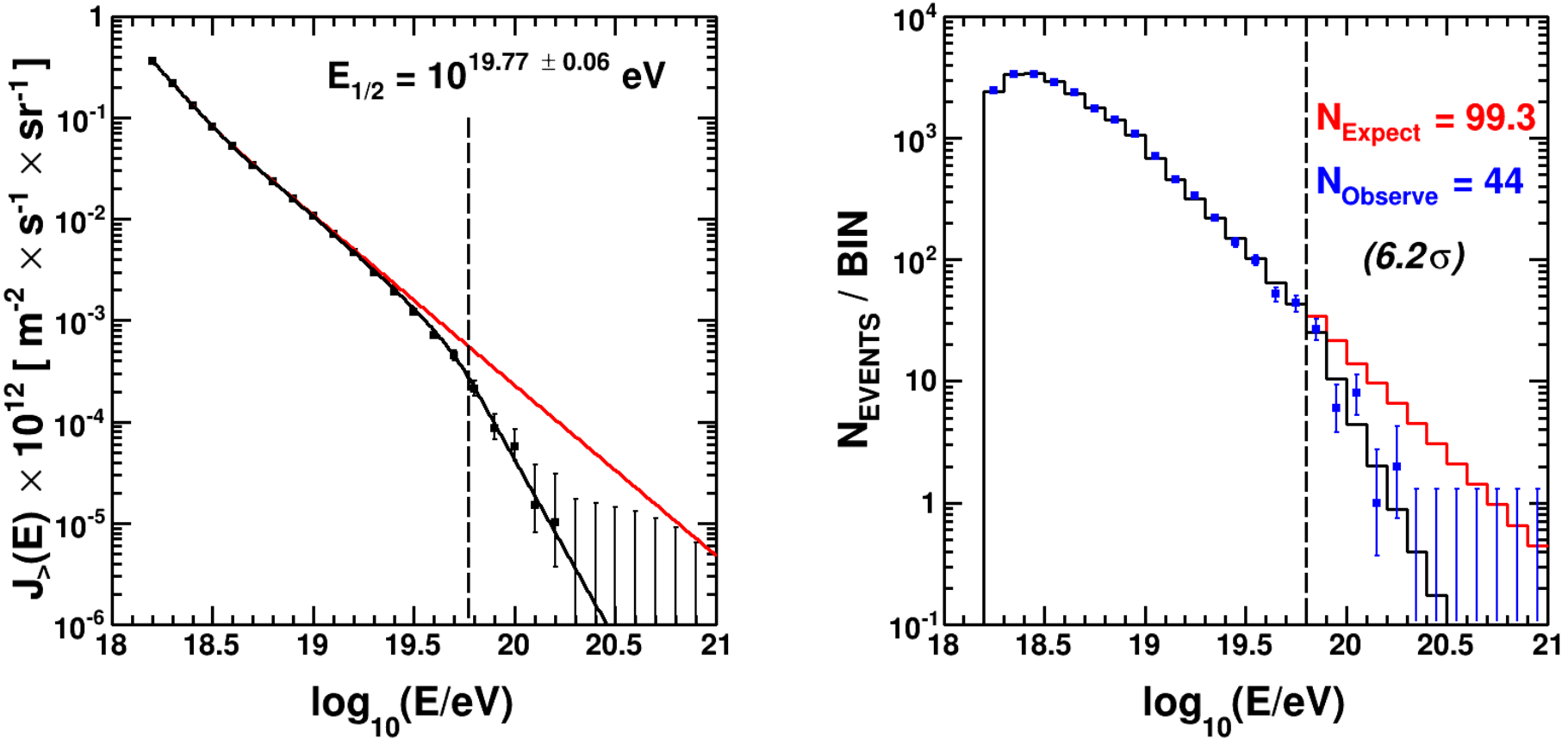


For details on BR/LR Mono spectrum, see Astropart. Phys. 80 (2016) 131-140

For details on TALE Combined spectrum see T. AbyZayyad presentation at this conference

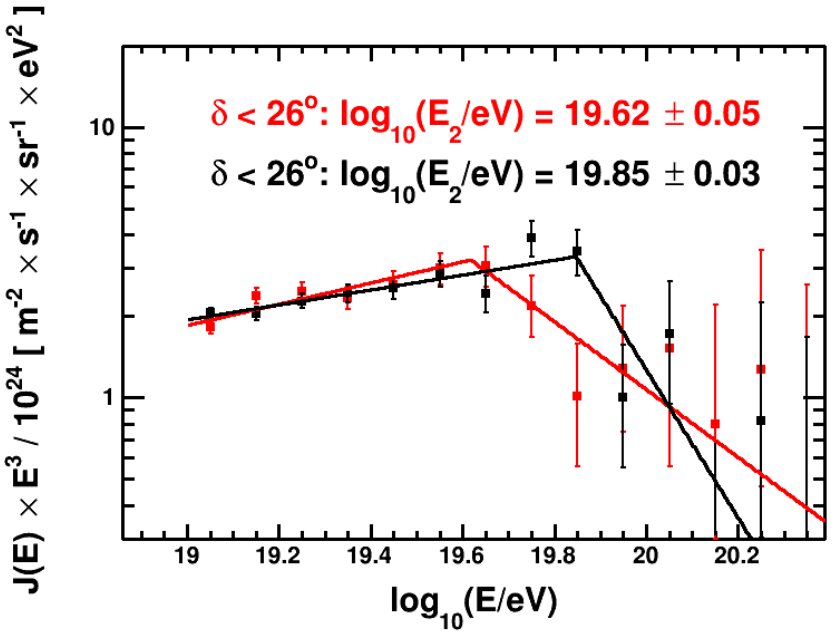
- From 2008/05/11 to 2015/05/11
- Cuts
  - Zenith angle < 45 degrees
  - N_{SD} >= 5
  - Distance of the shower core from the border of the array > 1200m
  - Geometry, LDF Chi2 / d.o.f. < 4
  - Pointing direction uncertainty < 5 degrees
  - S800 fractional uncertainty < 25%
  - E > $10^{18.2}$ eV
- ~6300 km^2 sr yr exposure above $10^{19.0}$ eV

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



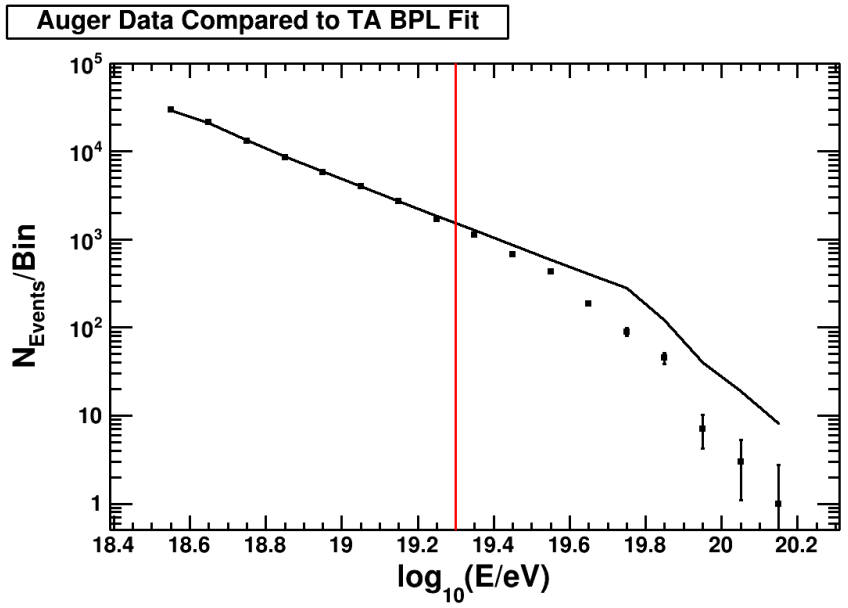
Consistent with proton propagation on CMB

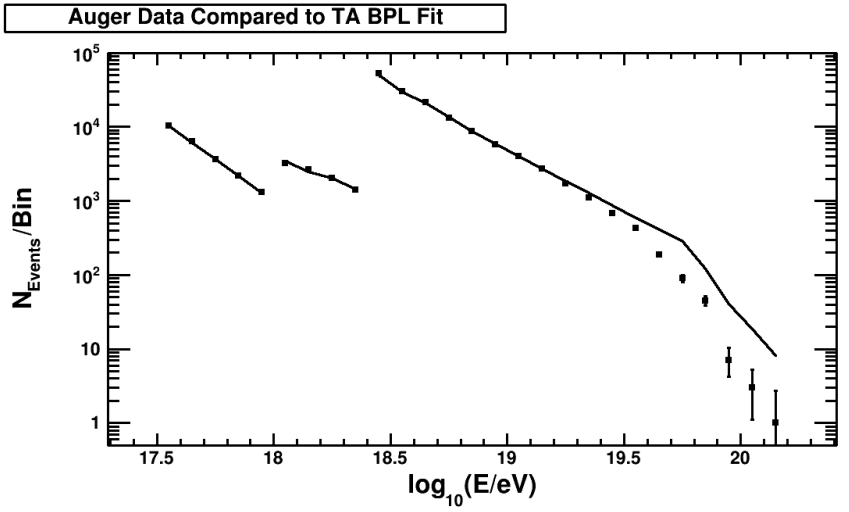
Declination dependence of SD spectrum



- Position of the 2'nd break point appears to be dependent on the declination band
  - ~3.9σ effect
- This result uses events up to 55 degrees in zenith angle
- See TA/Auger working group report for comparisons with Pierre Auger in different declination bands

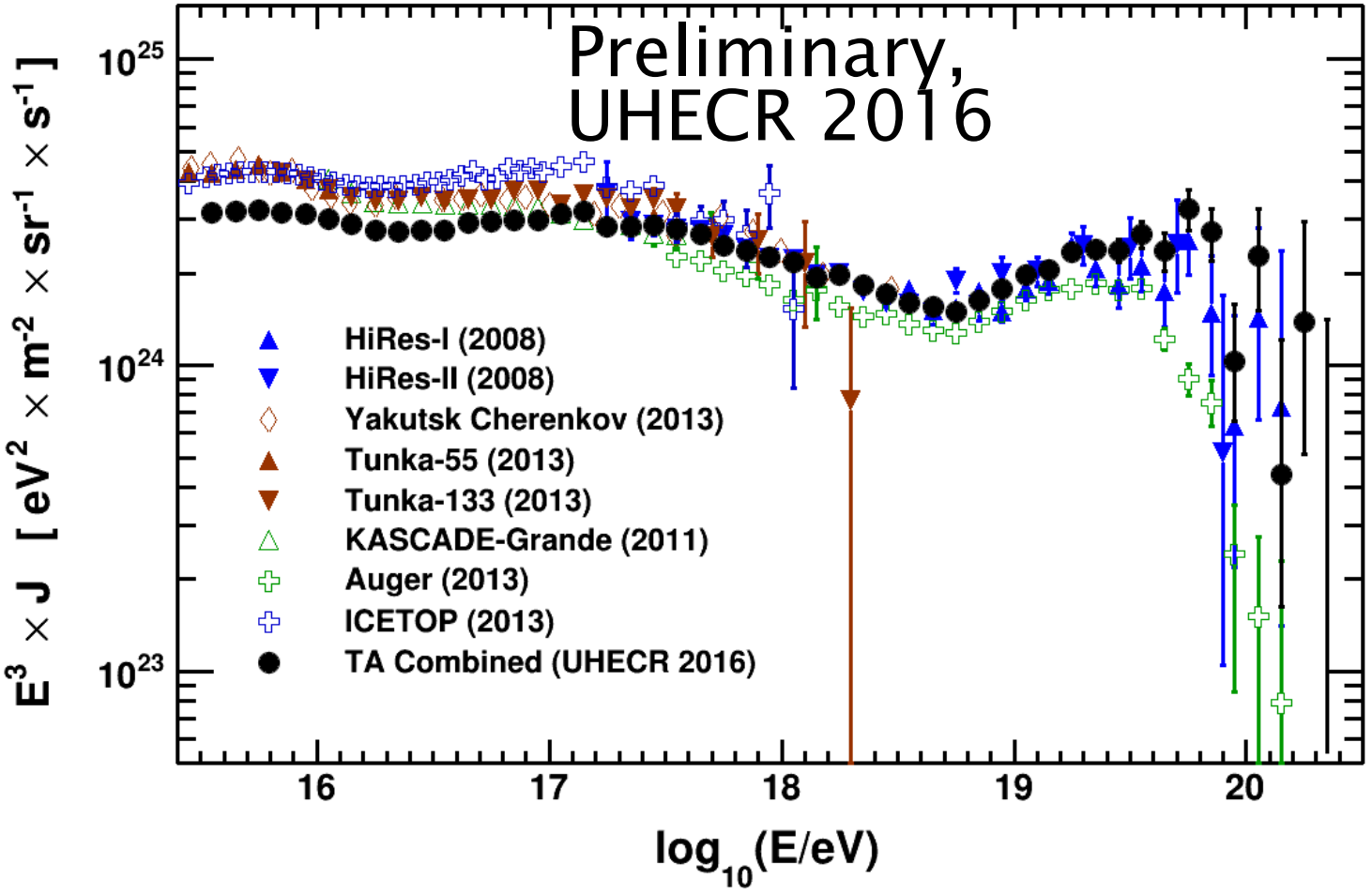
Auger / TA (as of ICRC-2015)





- Significant discrepancy with Pierre Auger above ~25 EeV
- Good agreement everywhere else, down to $10^{17.5}$ eV, after Auger energies were rescaled by 10%
- For current status, see TA/Auger spectrum working group report

Combined TA with Other Experiments



Conclusions

- We measured spectrum over ~5 orders of magnitude in energy, starting at $10^{15.5}$ eV
- One experiment, one energy scale, consistent with proton composition at highest energies
- 4 Features:
  - Low Energy Ankle at ~$10^{16.3}$ eV
  - 2nd knee at ~$10^{17.2}$ eV
  - Ankle at ~$10^{18.7}$ eV
  - GZK Break at ~$10^{19.8}$ eV
- Evidence of TA spectrum declination dependence at highest energies
- Good agreement with HiRes, but discrepancy with Pierre Auger at ~25 EeV (energy rescaling doesn't help)