Ultra-High Energy Cosmic Ray Energy Spectrum using Hybrid Analysis with TAx4

LANL/SLAC Seminar
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10/22/2021

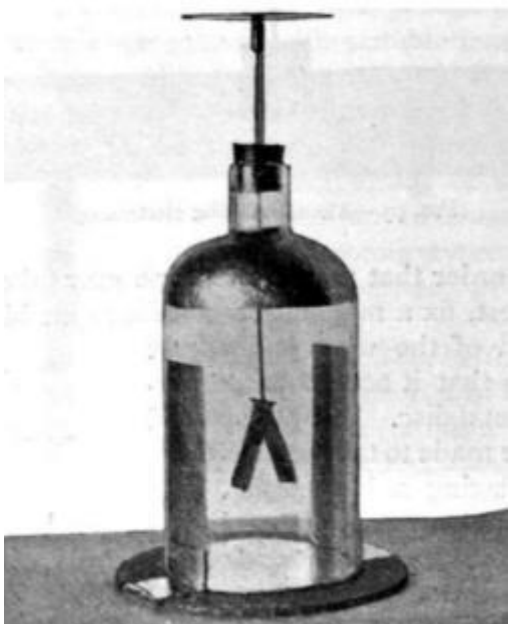
Abstract

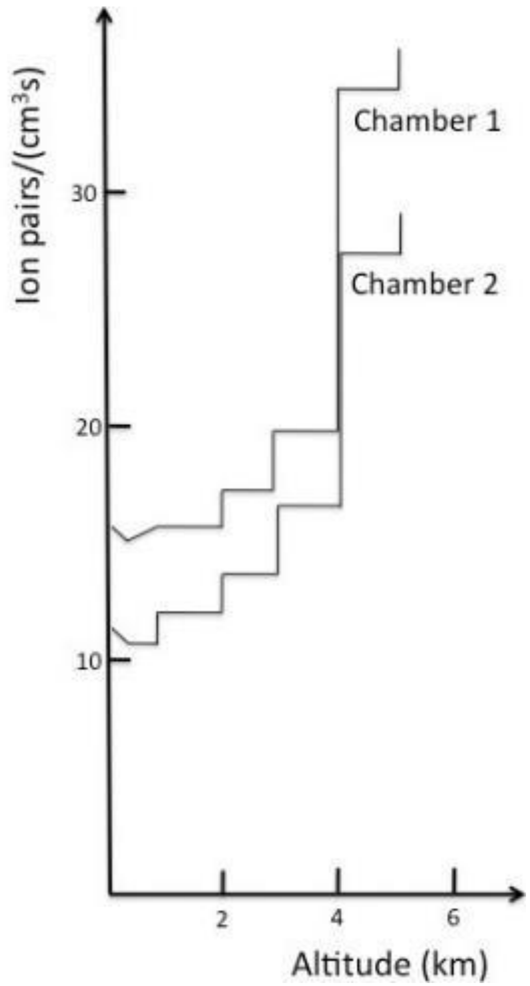
Cosmic rays are subatomic particles of extraterrestrial origin and at the highest energies, they are not well understood. The variation of the cosmic ray flux with energy is referred to as the "Energy Spectrum." The measurement of the cosmic ray energy spectrum is important because it may give a hint of where cosmic rays come from. The Telescope Array (TA) Cosmic Ray Observatory, located in Millard County Utah, is the largest cosmic ray detector in the Northern hemisphere. Following evidence for a hotspot in the arrival directions of the highest energy cosmic rays, TA underwent the TAx4 upgrade to expand the area of Surface Detectors (SD) by a factor of 4. The upgrade included new Fluorescence Detector (FD) stations to view over the expanded SD arrays. In this work, I will present a preliminary cosmic ray energy spectrum using hybrid events from TAx4, the hybrid resolutions of the detector, and data-MC comparisons. I will show this work's preliminary hybrid energy spectrum is in agreement with previous TA measurements, which is a key first step towards future composition and anisotropy studies.

Outline

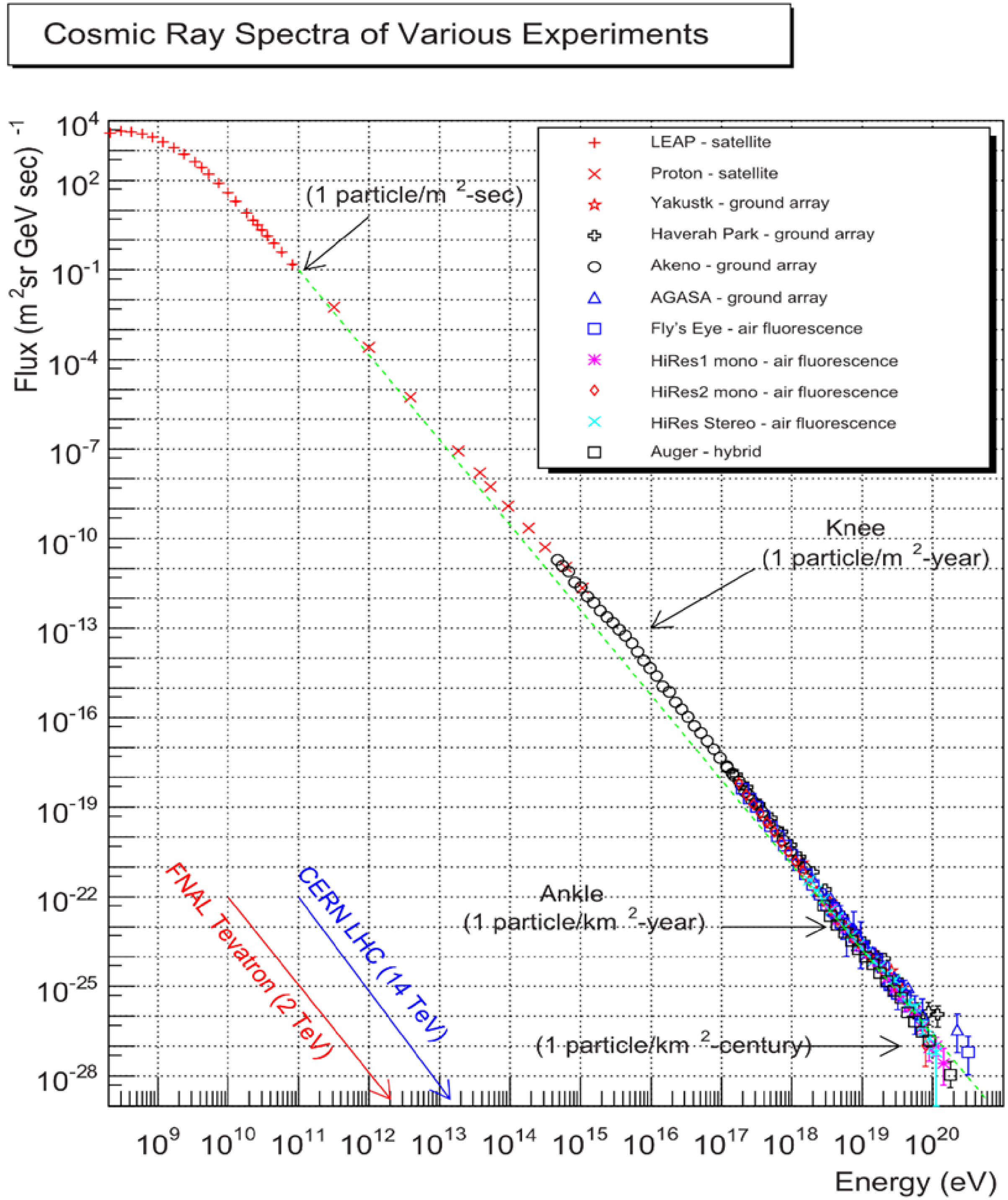
- Introduction to Cosmic Rays
- Physics Topics
- Detection of Cosmic Rays
- Telescope Array Experiment
- Status of TA Physics
- TAx4
- Hybrid Technique
- Energy Spectrum Calculation
- Conclusions
- What to do now?

Introduction to Cosmic Rays





- Cosmic Rays are subatomic particles of *extra-terrestrial* origin.
- First discovered in 1912 by Victor Hess
- In the 1920s, the term *cosmic rays* was coined by Robert Milikan
- Hess receives the Nobel Prize in 1936



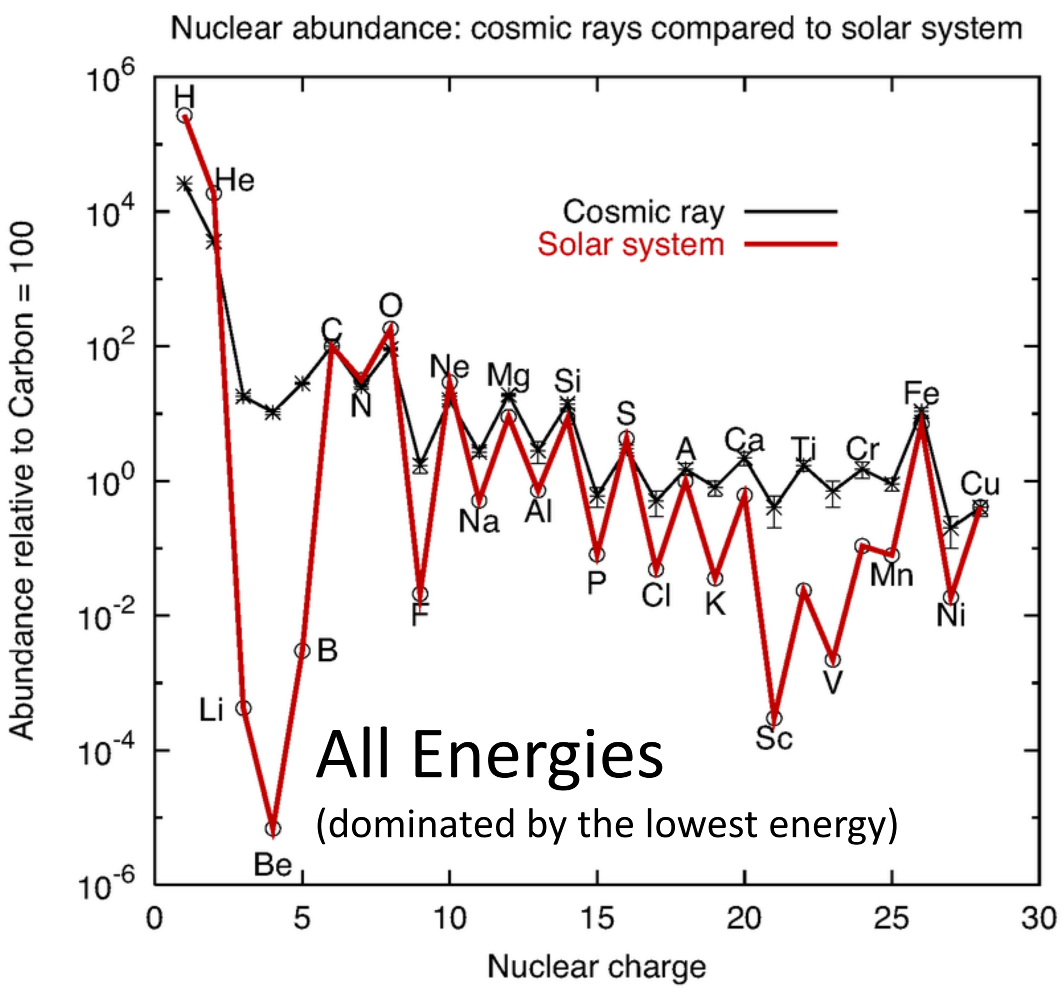
Energies of Cosmic Rays

- Cosmic ray energies span more than 11 orders of magnitude
- 6×10^{18}eV ~ 1 joule
- Highest energy cosmic rays ~ 10,000,000 times more energetic than Large Hadron Collider (LHC) protons
- Flux falls rapidly:

  $\propto E^{-3}$

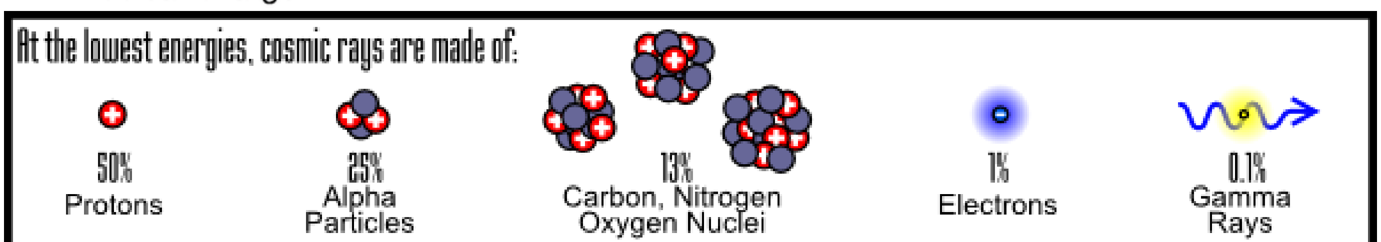
  Mostly Featureless except…

What are they?



Cosmic Rays > 10^{18}eV are referred to as "Ultra-High Energy (UHE) Cosmic Rays"

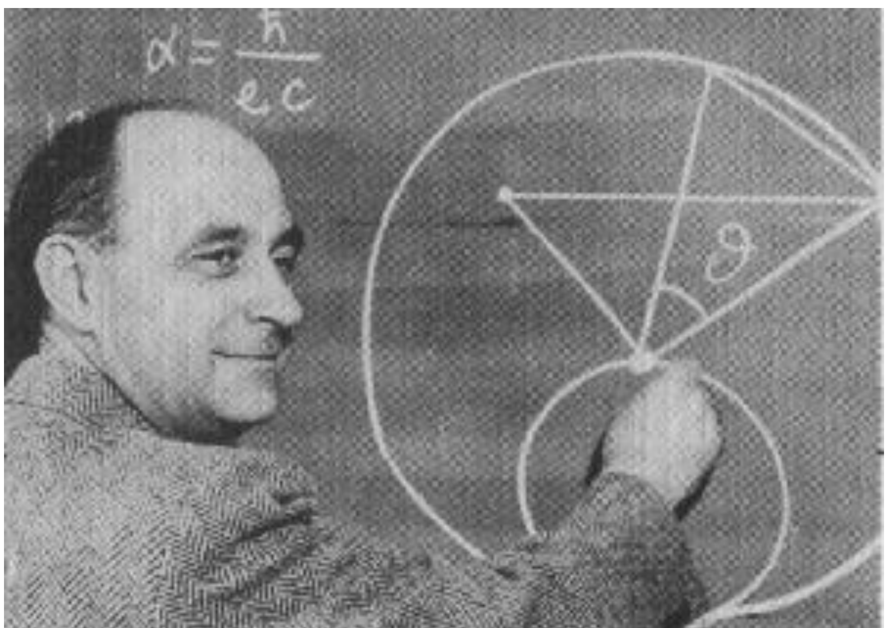
- We think they are protons at the highest energy

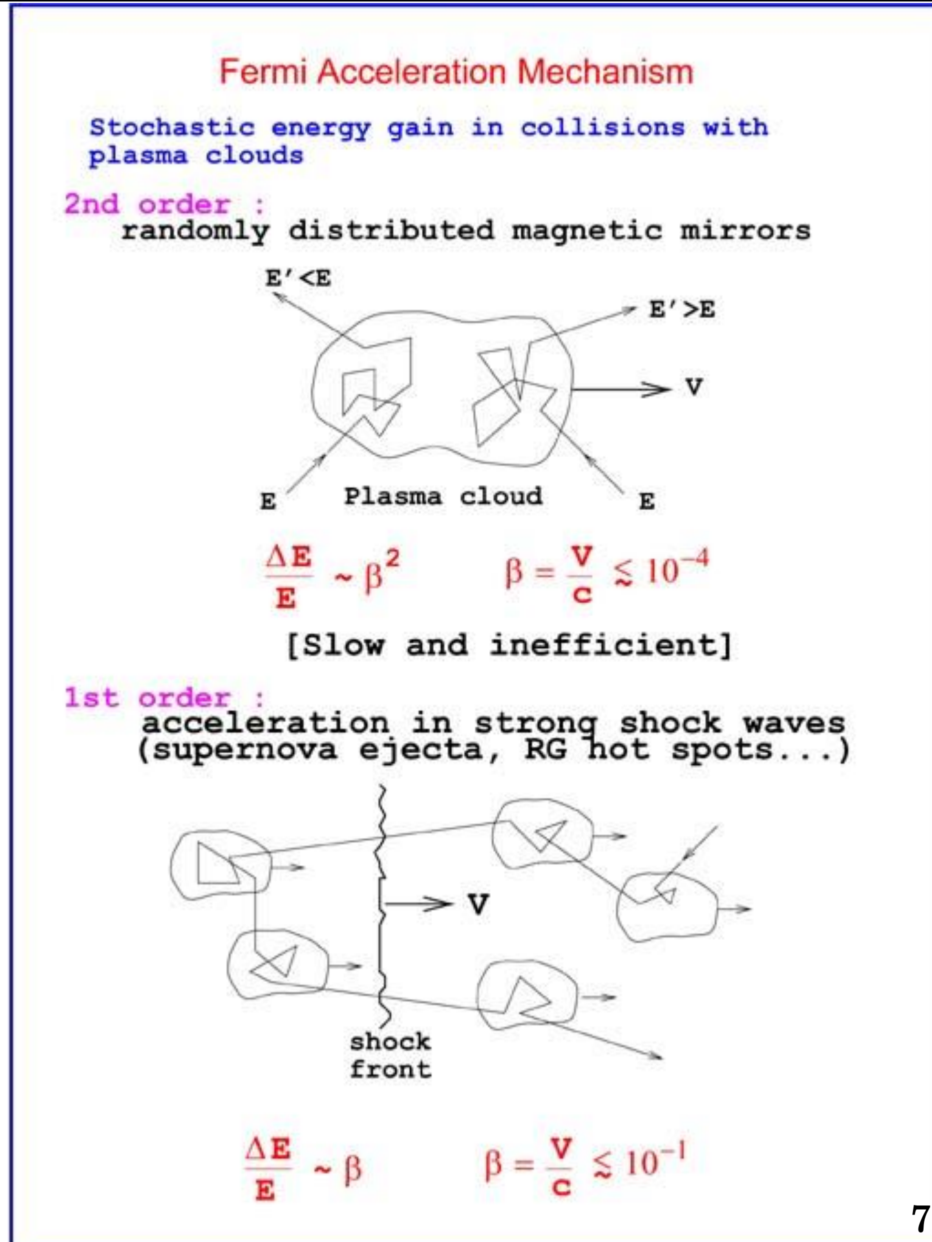


How are they accelerated?

We're not sure…

Some plausible theories based on ideas of *Enrico Fermi*





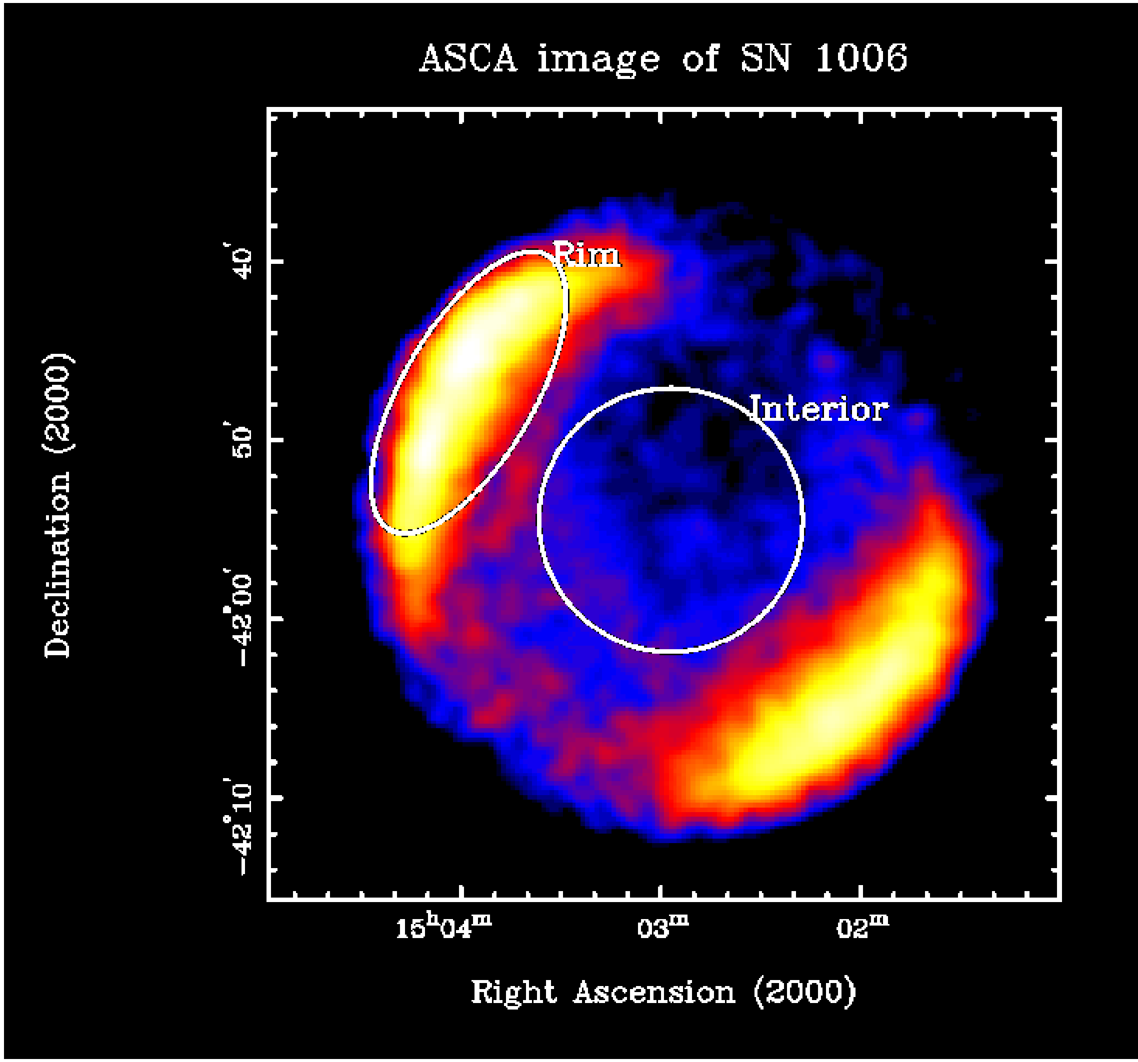
Where do they come from?

Suspected sources are large, energetic structures where strong shocks are found.

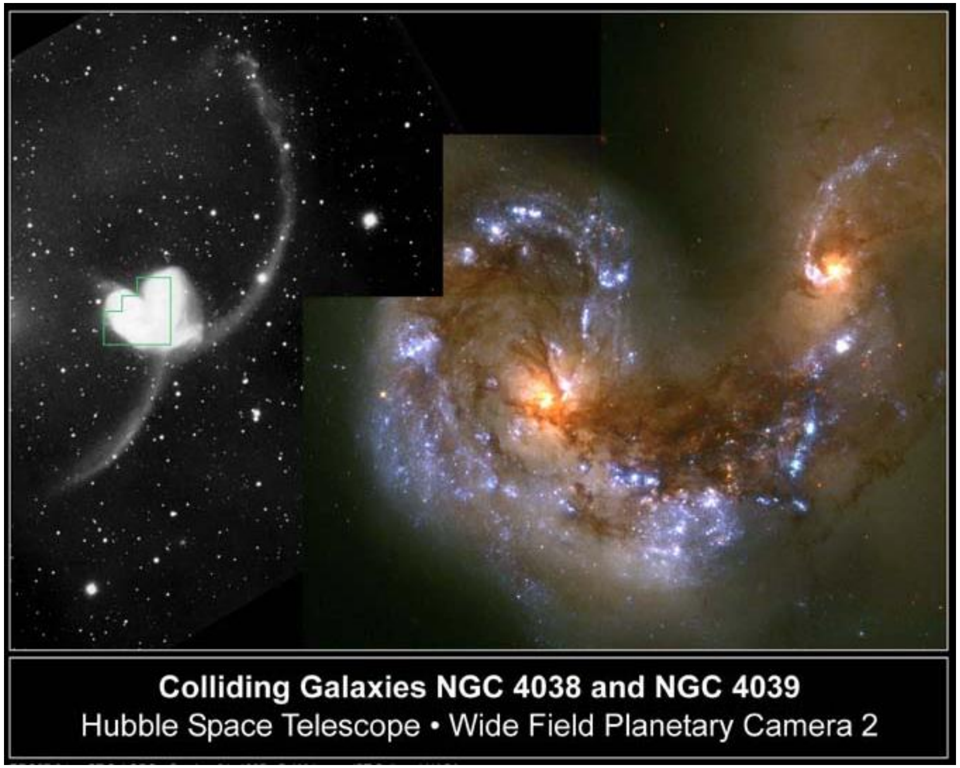
e.g., supernovae

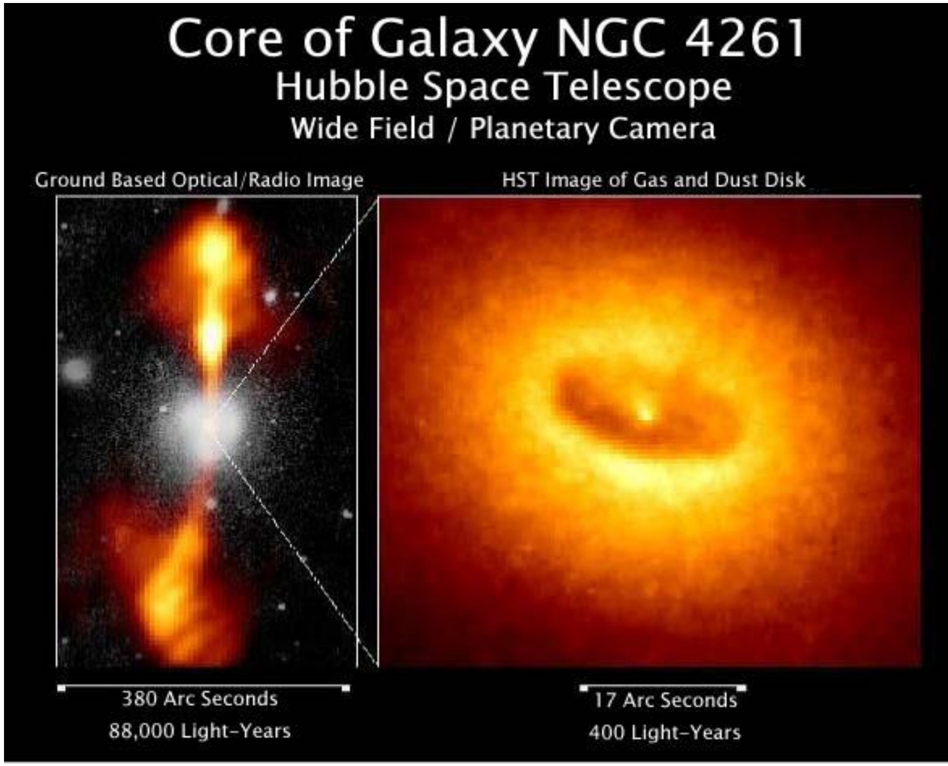
Problems:

- Difficult to explain > 10^{18} eV
- UHE cosmic rays do not point back to known supernovae in our galaxy



Other Possible Sources of UHE Cosmic Rays



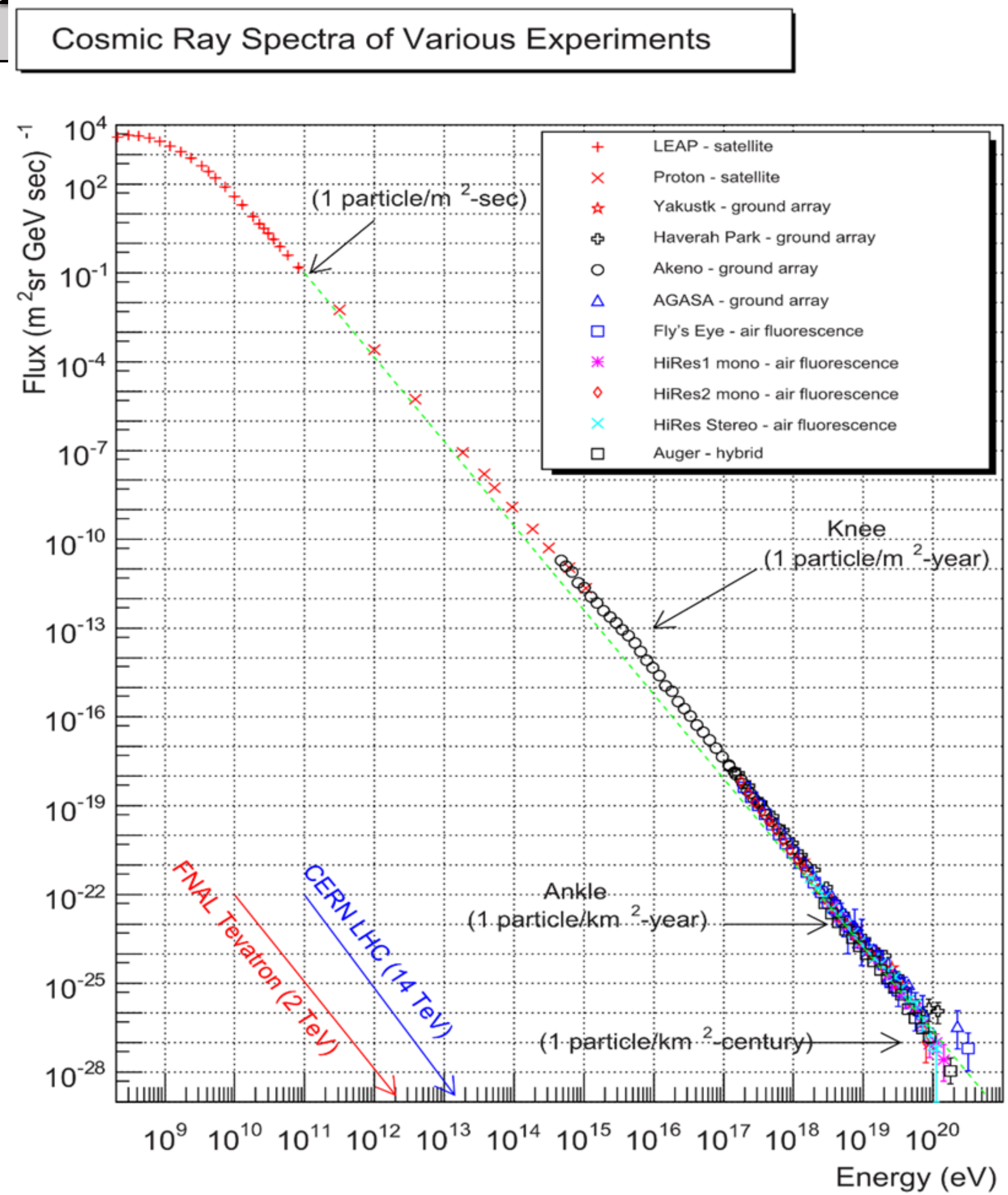


- Colliding galaxies, AGN, etc.
- Decay/annihilation of some unknown super-heavy particles or cosmological relics from the creation of the Universe?
- New physics?

Direct Measurement

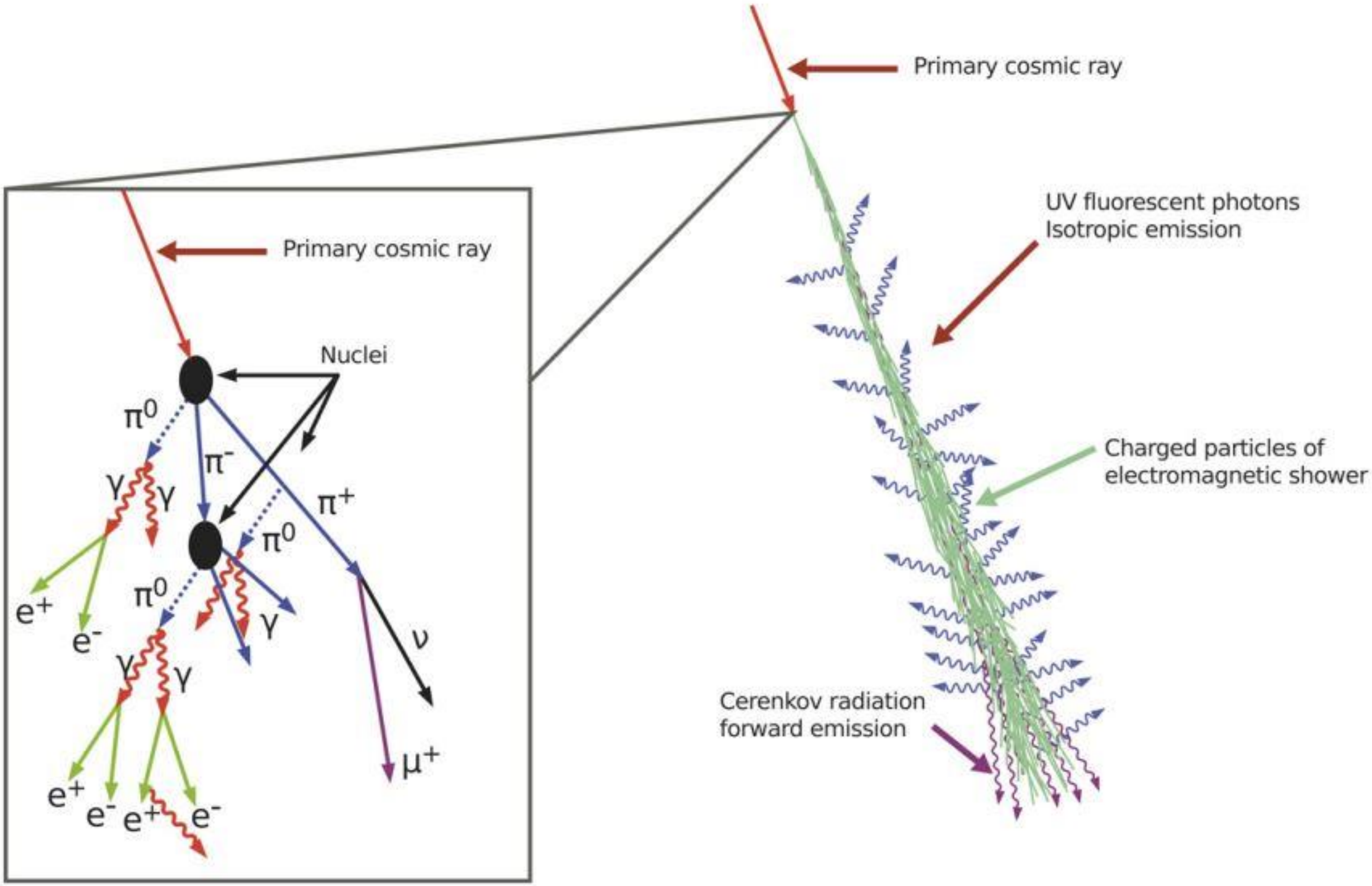
- E < 10^{14} eV: flux is large enough to allow direct measurement on balloons, satellites, shuttle missions.
- E > 10^{17} eV, we expect a flux < 10^{-10}/m^2 Sr s
- A 1 m^2, 2π Sr. detector sees < 1 event/50 yrs.

Direct measurement is impractical!!!

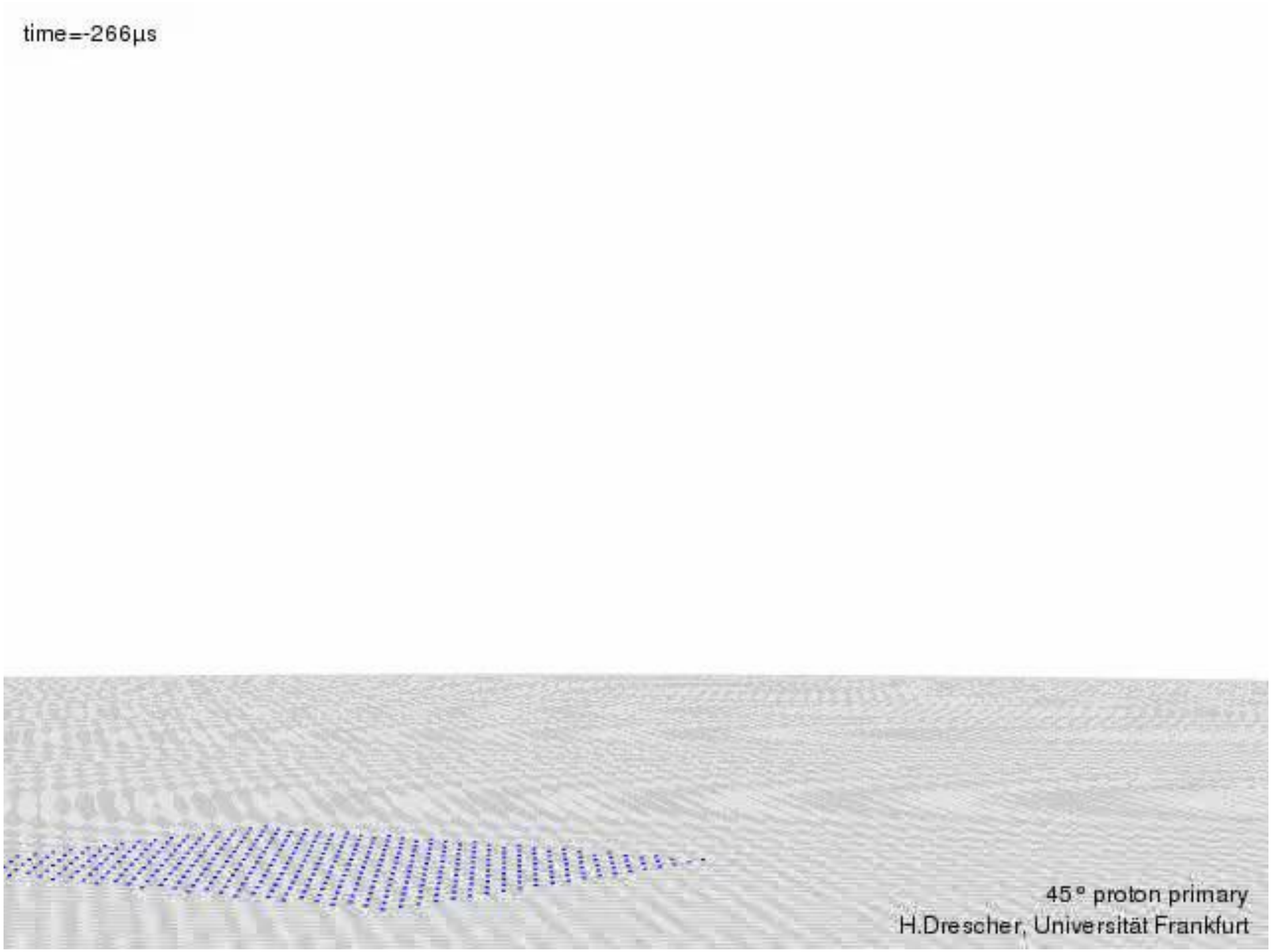


Indirect Measurement

- Use the Earth's atmosphere as your detector

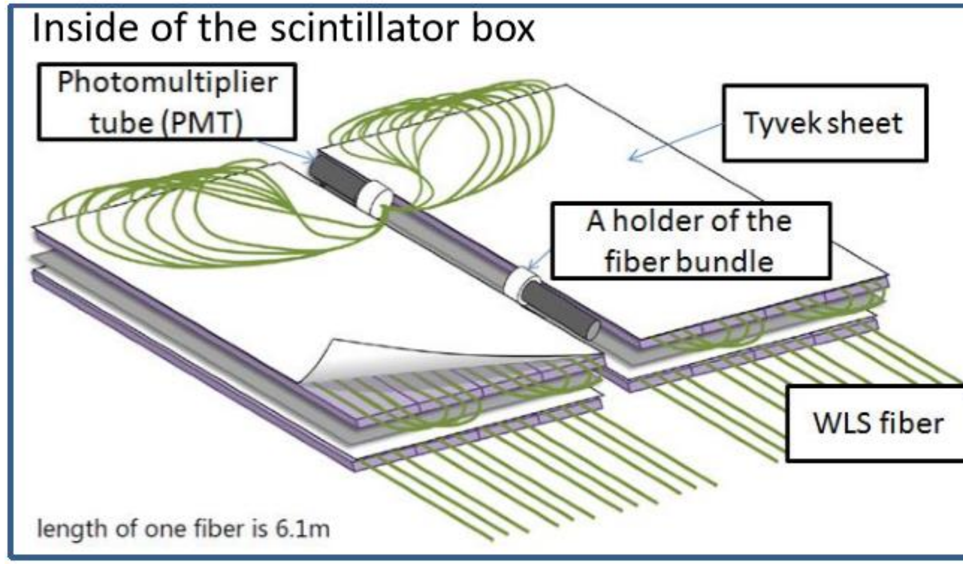


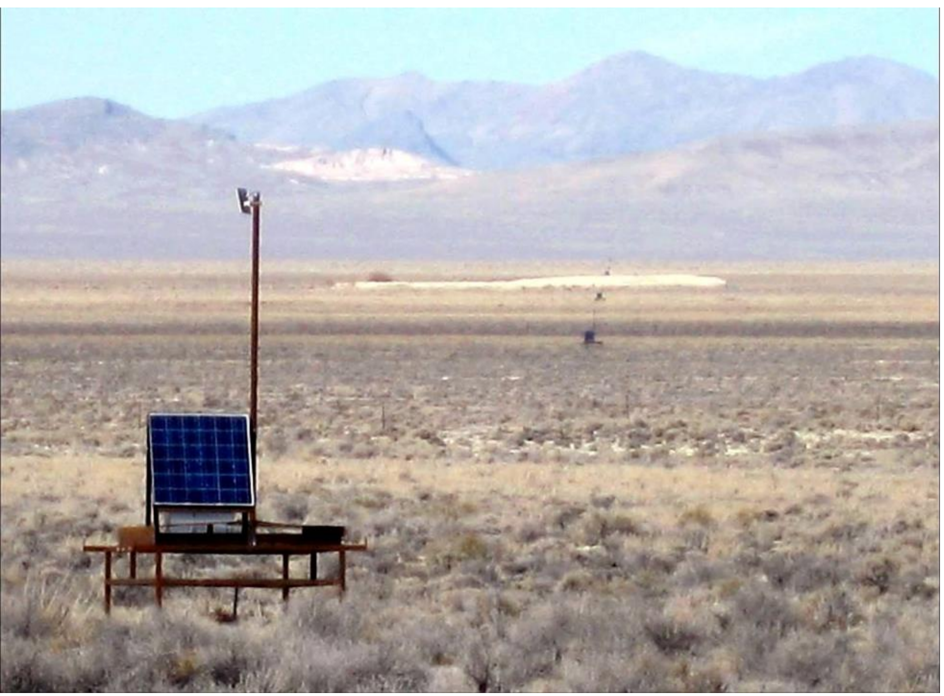
Extensive Air Shower

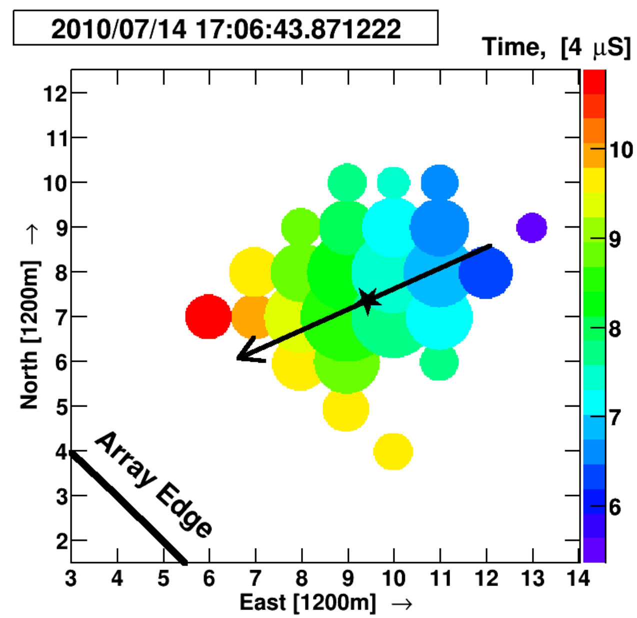


Surface Detectors (SD)

- Two 3m^2 organic plastic scintillation sheets detects secondary particles $(e^{\pm}, \gamma, \mu^{\pm}, \ldots)$
- Runs 24/7 → superior statistics at high energies ($E > 10^{18.0}$ eV)



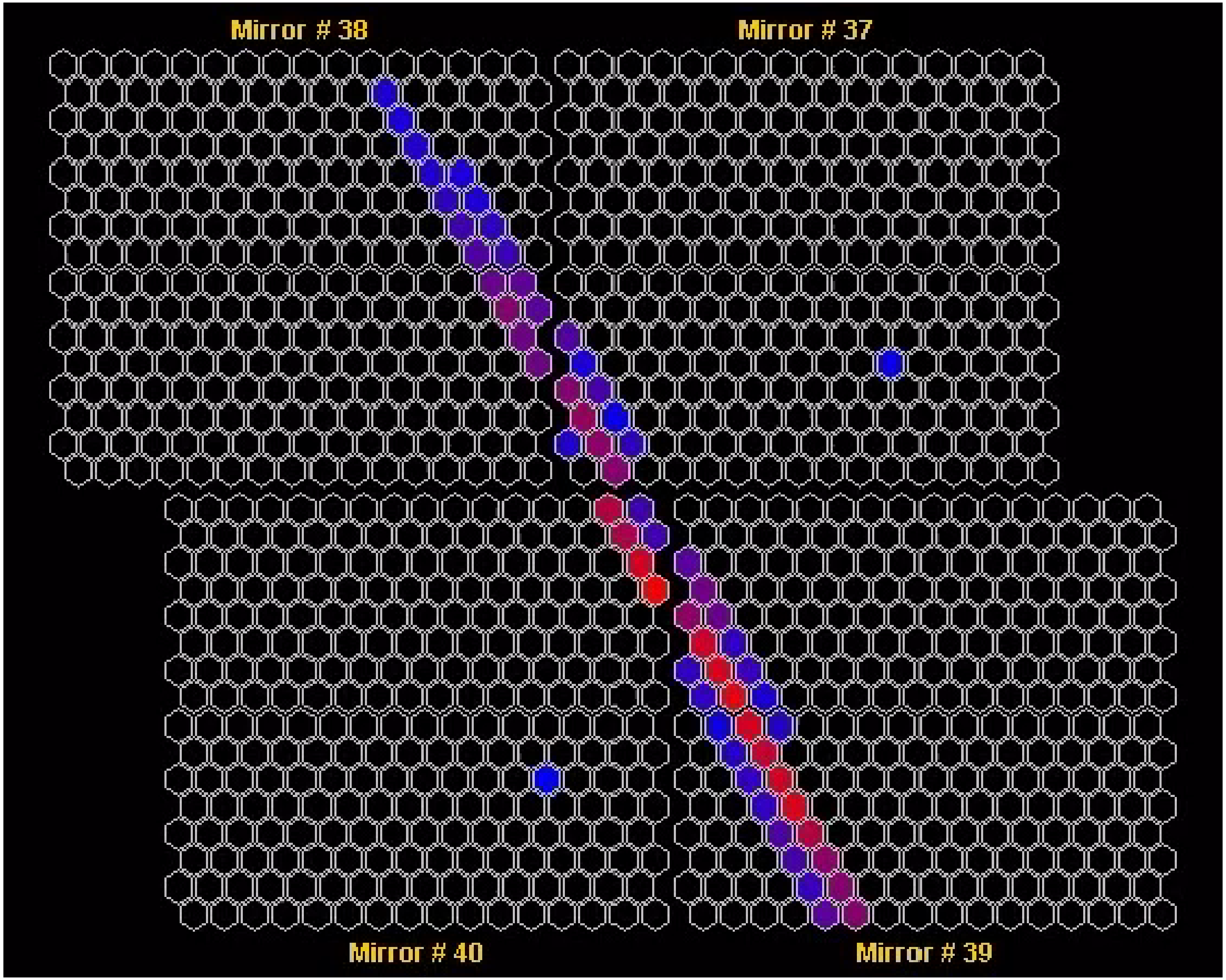




Fluorescence Detectors (FD)

- Technique originally developed in the 1950's as a way to estimate the yield from atmospheric nuclear tests
- Samples UV light emitted in the wake of the charged particles
- Sensitive to cosmic rays $>10^{15.3}$ eV
- Measures the central portion of the shower:
  - Longitudinal shower development → "chemical composition"
  - Energy estimation using fluorescence yield

Example FD Event



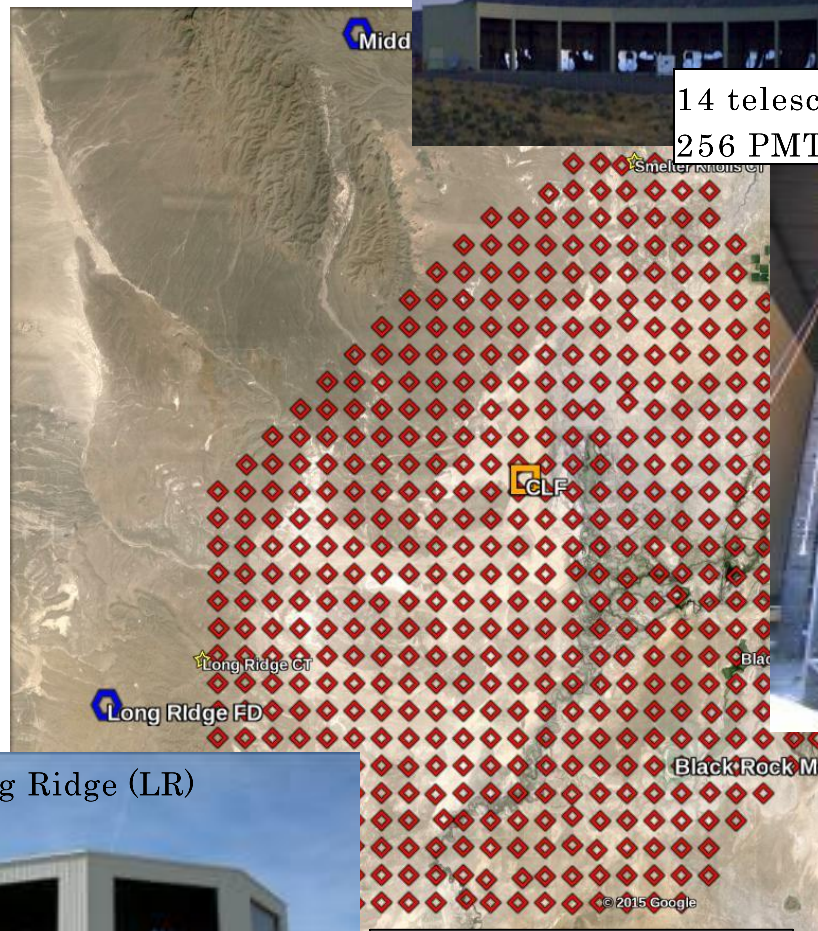
- 1/500,000 playback speed
  - Each frame is 100 ns
- PMTs view 1° full angle cone of the sky

Telescope Array (TA)

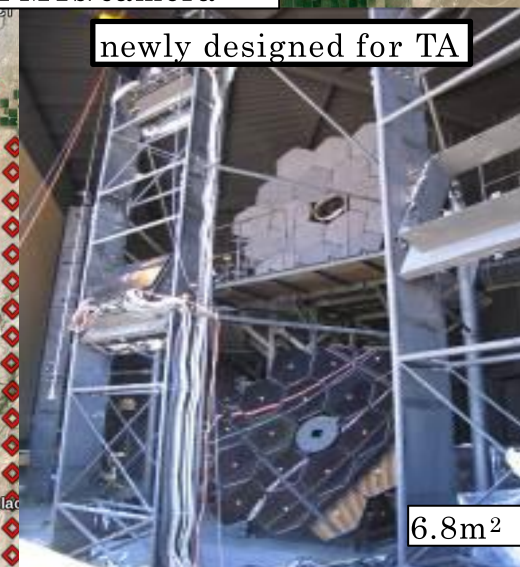
- Largest UHE cosmic ray detector in the Northern Hemisphere
  - 1 of 2 UHECR detectors in the world, the other is in Argentina
- Surface detectors (red diamonds) coverage: ~700 km^2 with 1.2 km spacing.
- Three fluorescence stations (blue octagons)
  - Black Rock Mes (BRM), Long Ri (LR), Middle Di (MD)

14 telescopes/station
256 PMTs/camera

refurbished HiRes-I



newly designed for TA



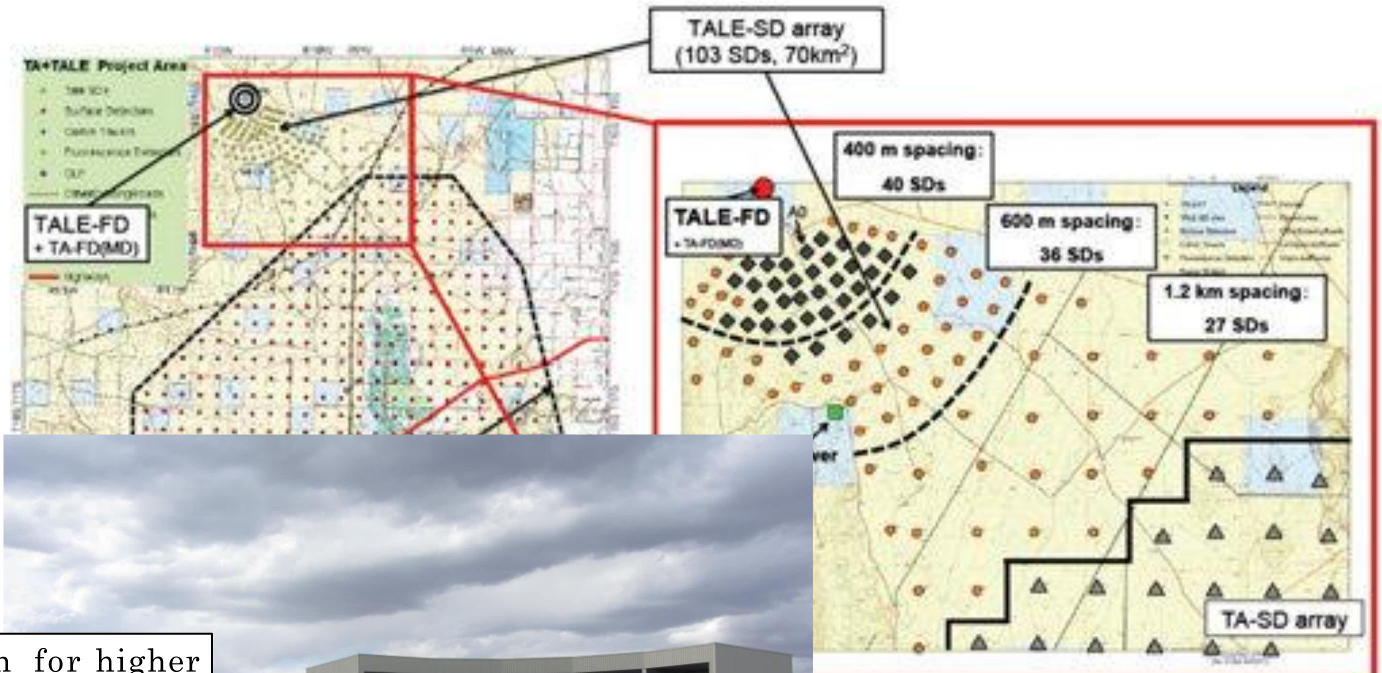
12 telescopes/station
256 PMTs/camera

Telescope Array Low Energy extension (TALE)

- In-fill SD array of 103 counters arranged with spacings that grow with distance from the TALE FD
- Optimal coverage at energies 10^{16}-10^{18} eV.

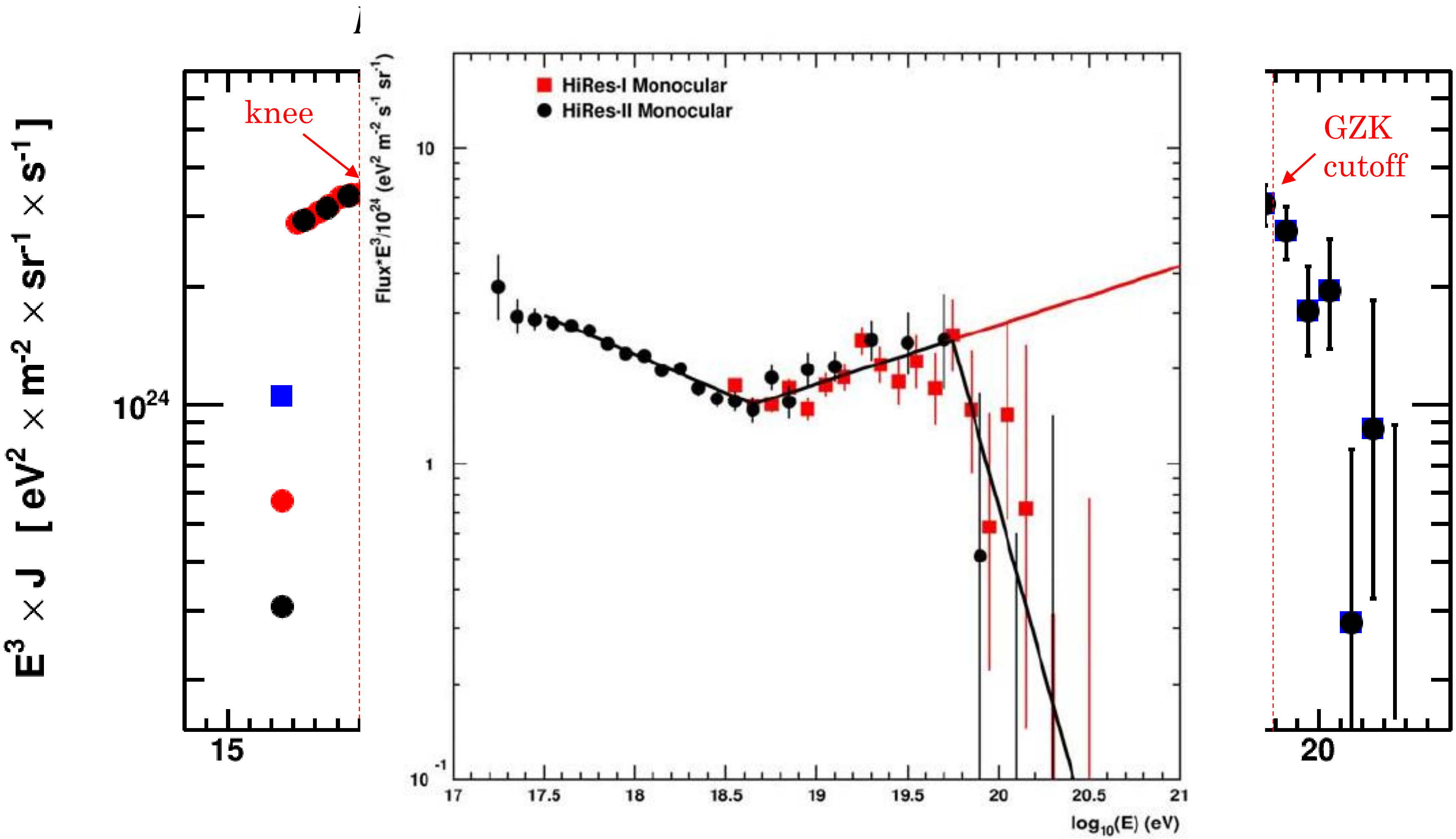
refurbished HiRes-II

$5.2 m^2$



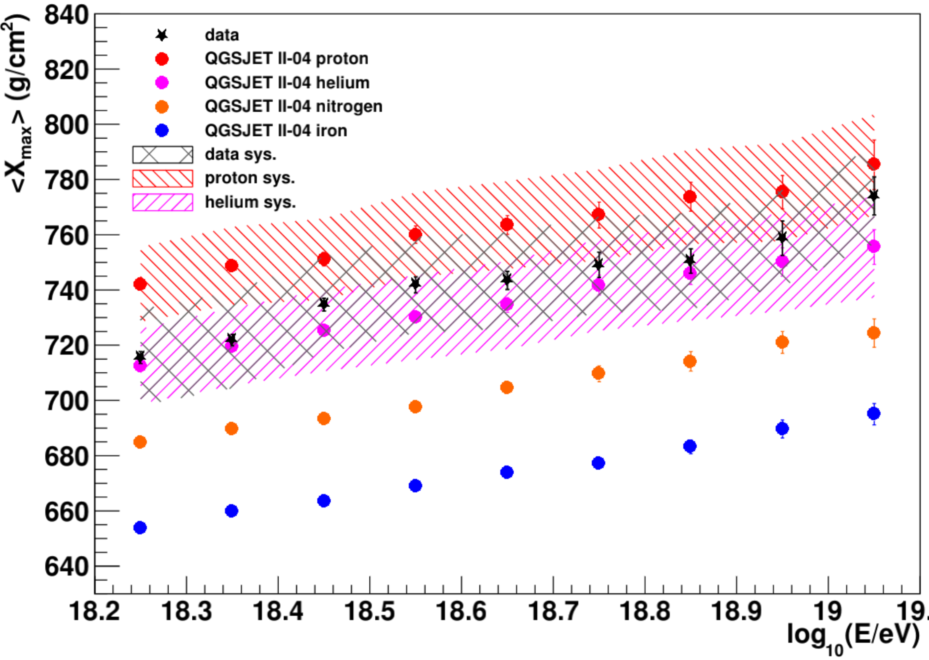
10 telescopes/station for higher elevation angles (31^{o}–59^{o})

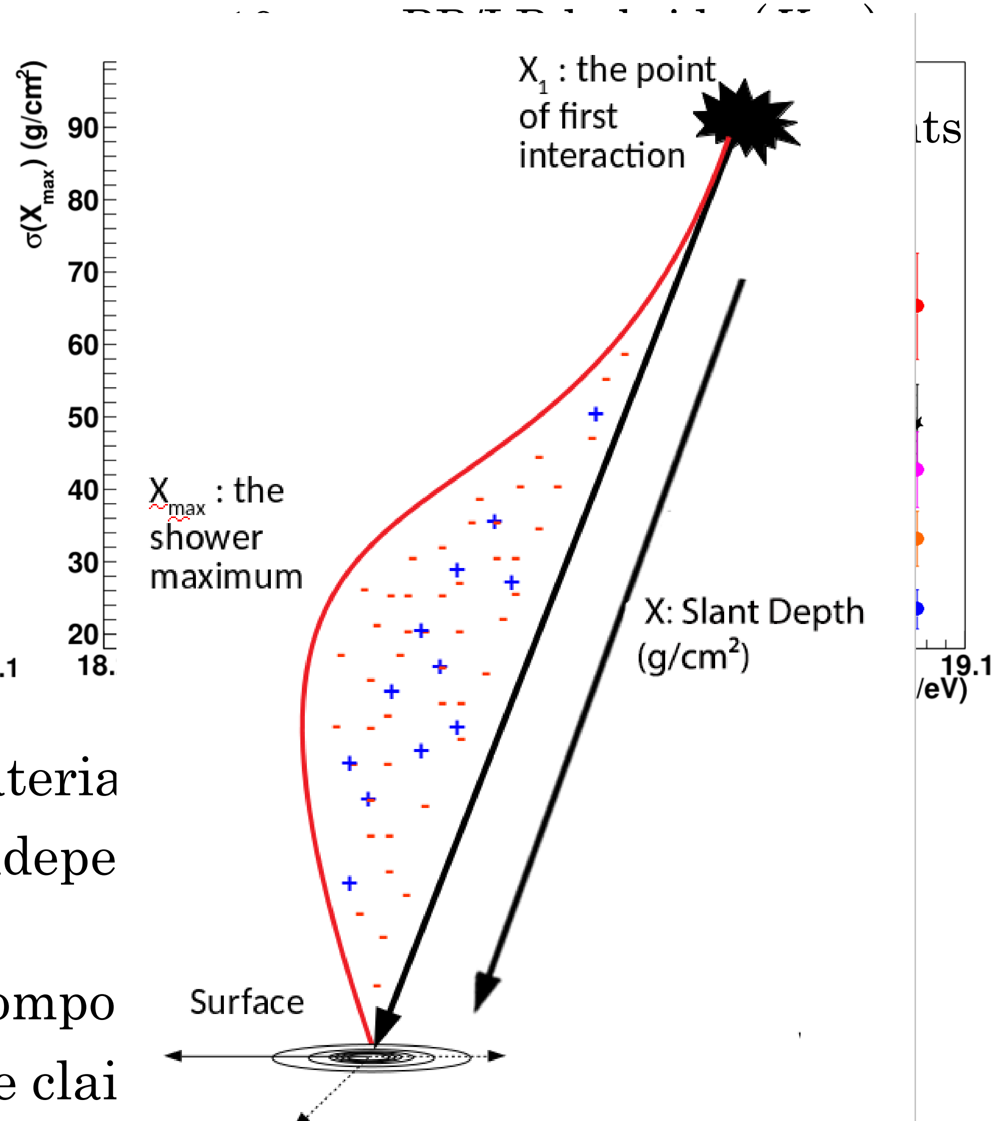
Status of TA Physics: Energy Spectrum



Status of TA Physics: Composition

10 year BR/LR hybrid $\langle X_{max} \rangle$

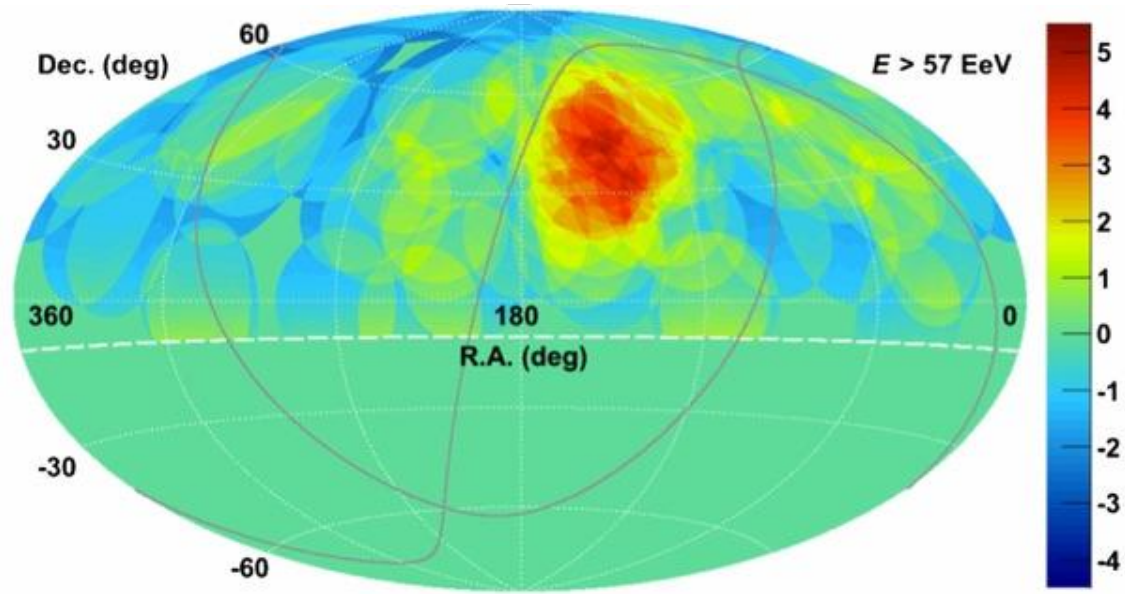


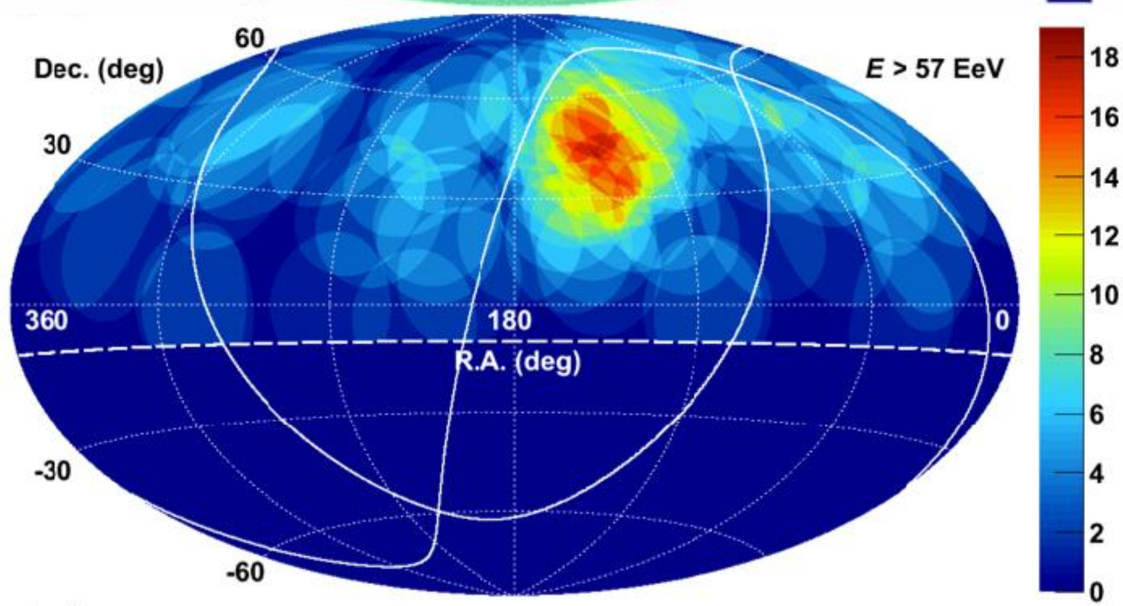


- Slant depth is measure of materia
- $\sigma(X_{max})$ is relatively model indepe is model dependent.
- Consistent with light mass compo
- Insufficient statistics to make clai
  - 96 events, $19.1 \leq \log_{10}(E/eV) <$

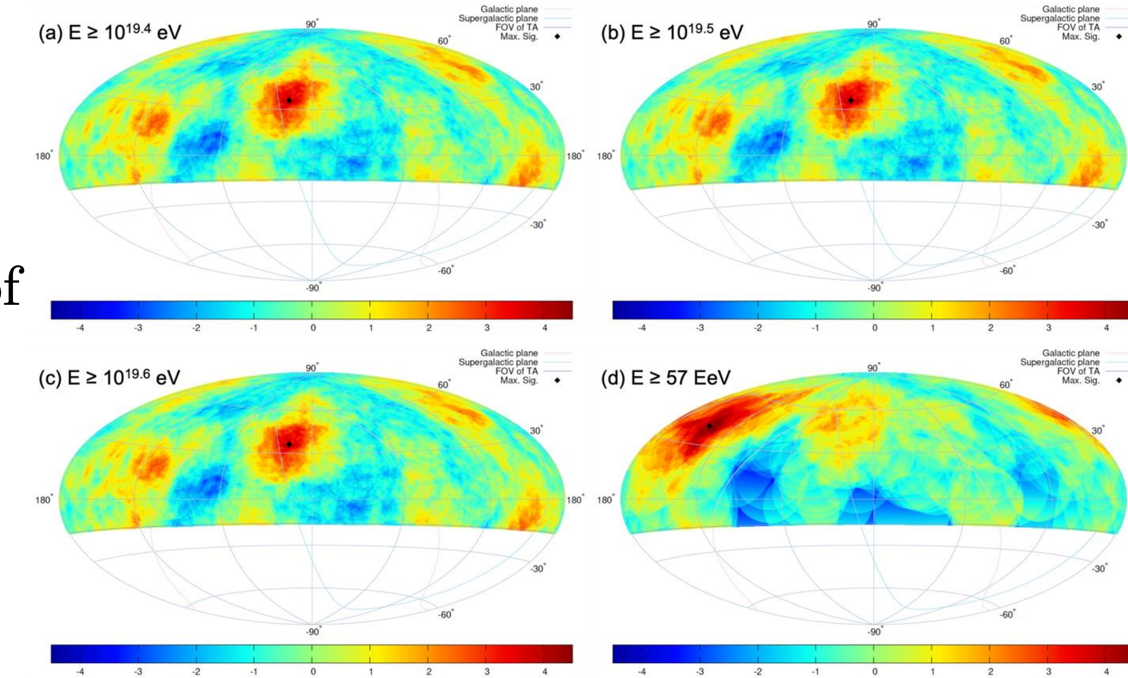
Status of TA Physics: Hot Spot

- TA has seen indication of possible *nearby* source of ultrahigh energy cosmic rays
- Cosmic Rays with E > $5.7\text{x}10^{19}$ eV can't have traveled much further than 100-300 million light years



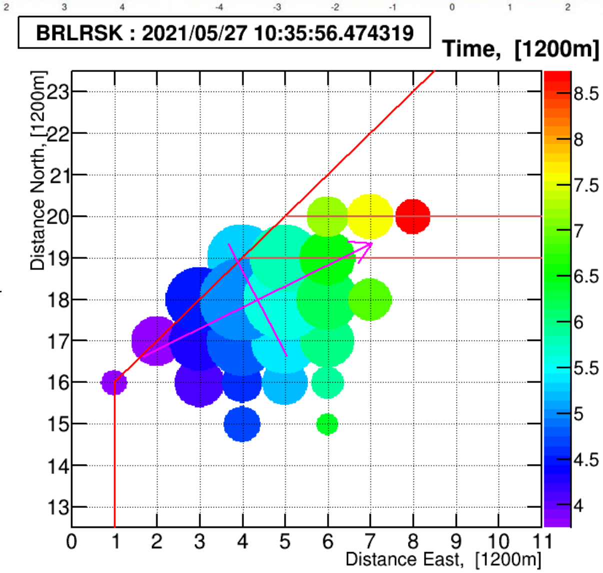


Status of TA Physics: New Stuff

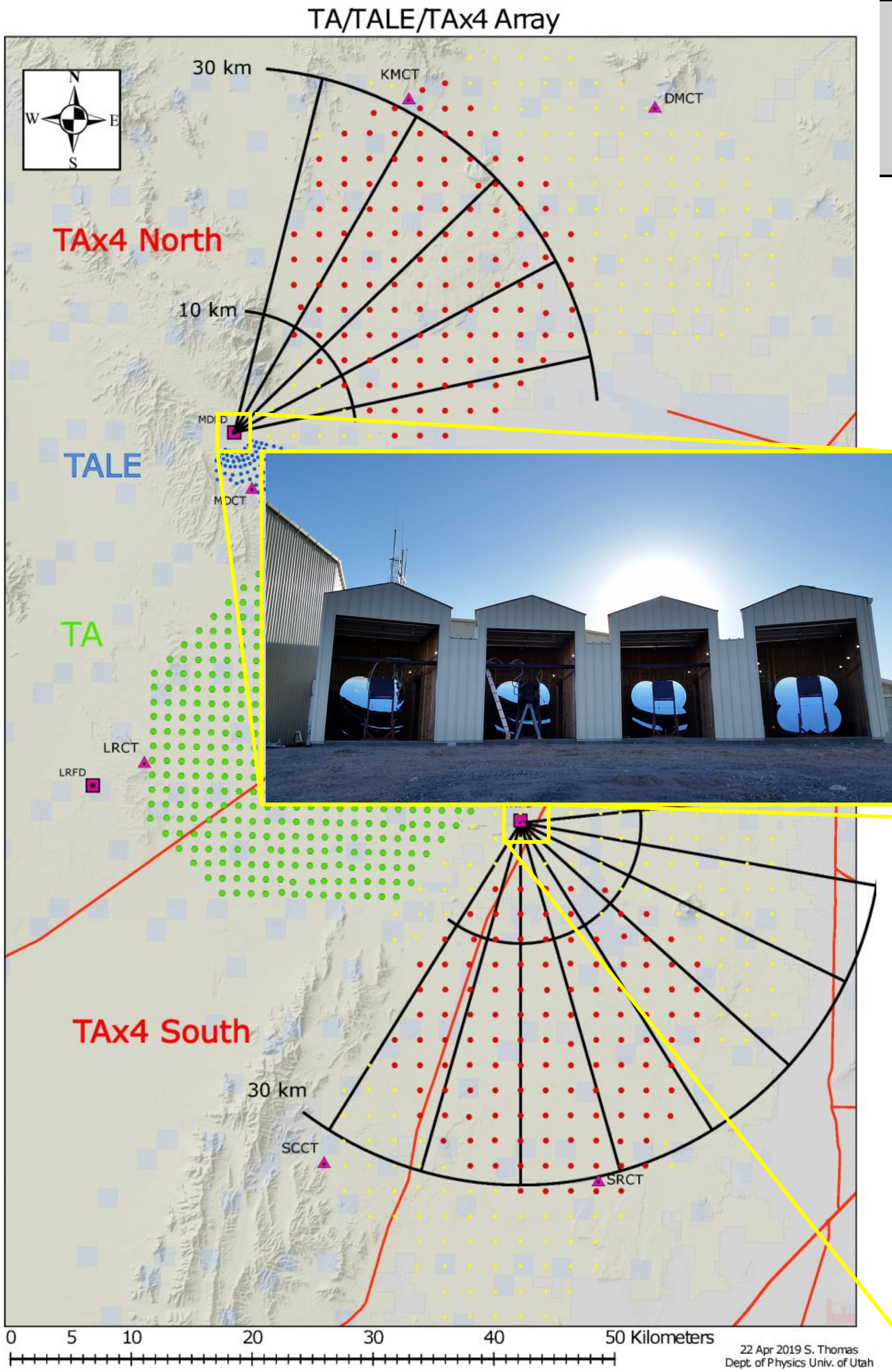


- The new "blob" is an excess of *relatively* low energy events
  - Perseus-Pisces supercluster

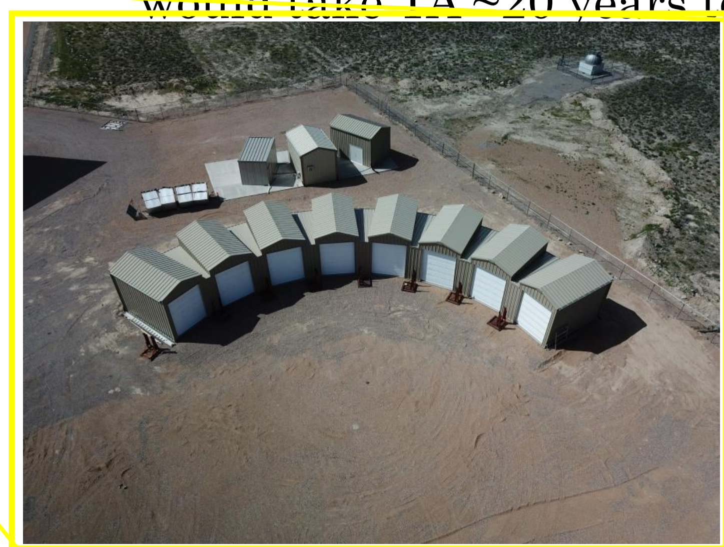
- May 27th 2021 by TA SDs: $(2.44 \pm 0.11\ \text{(stat.)} \pm 0.51\ \text{(syst.)}) \times 10^{20}$ eV
  - The highest energy shower in recent 30 years
    - 1991 Fly's Eye: $(3.20 \pm 0.38\ \text{(stat.)} \pm 0.85\ \text{(syst.)}) \times 10^{20}$ eV
    - 1993 AGASA: 2.13×10^{20} eV



TAx4



- Fourfold increase in size of TA SD array.
  - 257 of a planned 500 SDs are deployed at 2.08 km spacing
  - Added 2 FD station, 12 telescopes
- The goal of TAx4 is to increase the statistics for the highest energy range ($E > 2 \times 10^{19}$ eV)
  - In ~5 years collect data that it would take TA ~20 years to



Status of TAx4 North FD's

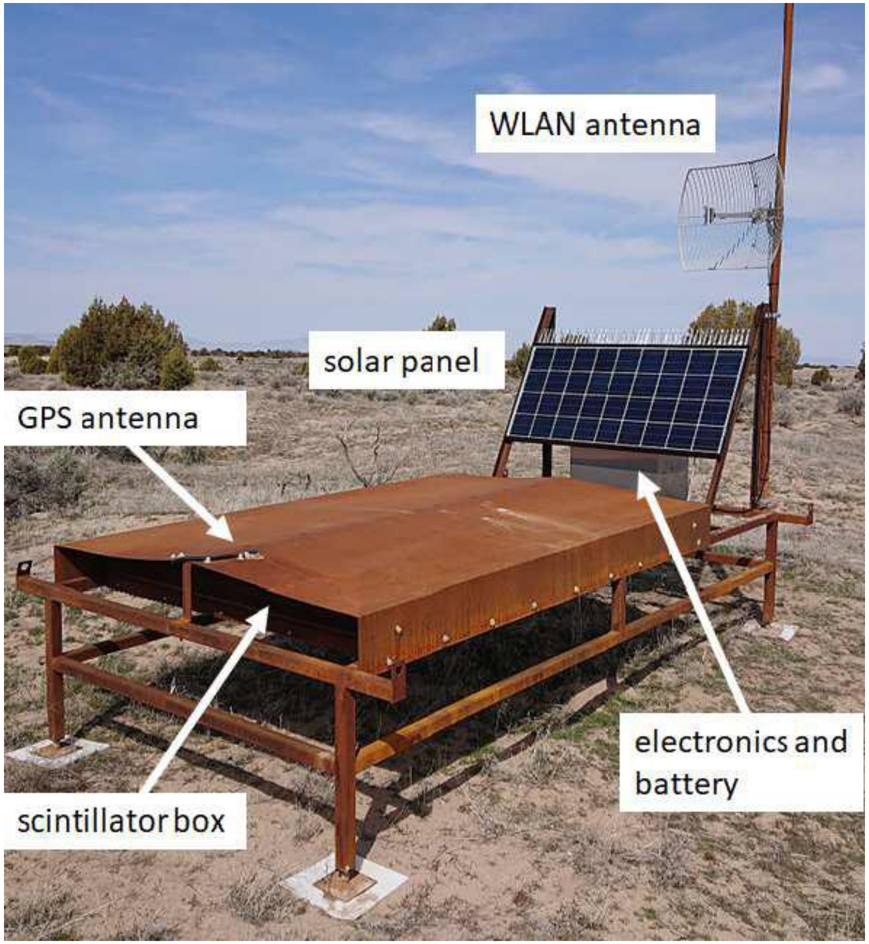
- Construction completed in February 2018, started commissioning detector
- Data collection started in July 2018
- Vertical shower trigger enhancement in May 2019
- Nearest neighbor trigger upgrade in June 2019

Status of TAx4 South FD's

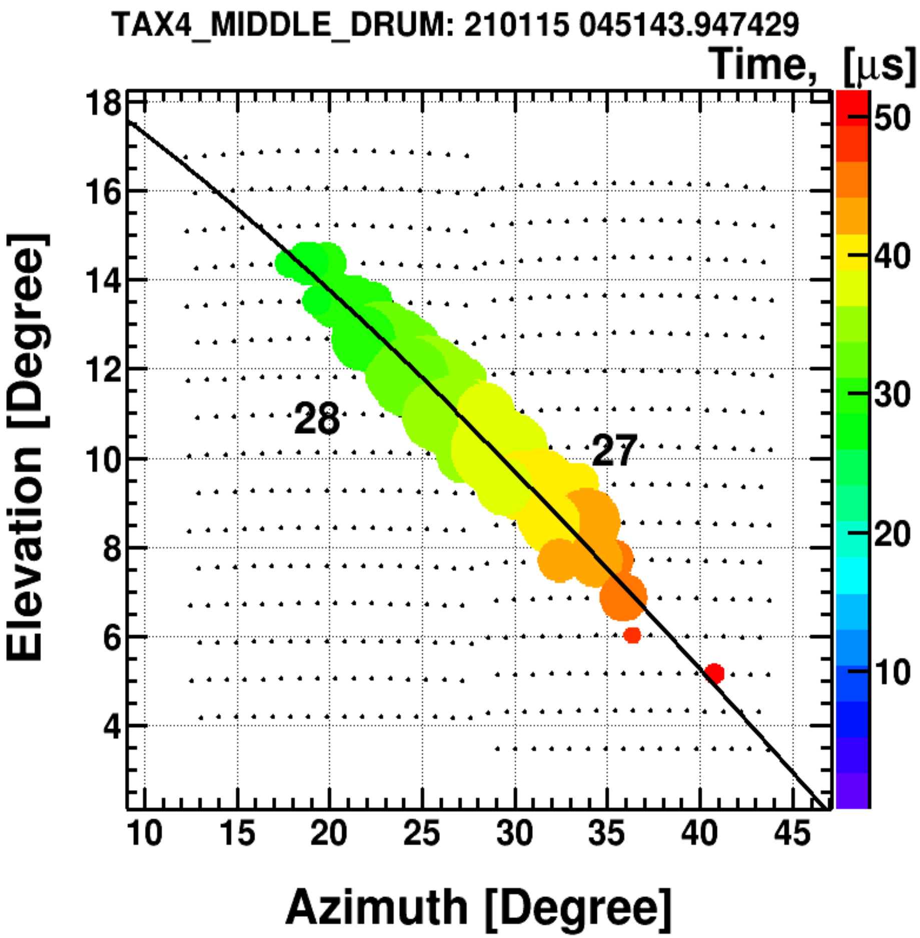
- Construction completed in July 2019
- First night of observation October 21st, 2019. Commissioning of the detector began
- Data collection started in July 2020

TAx4 SDs

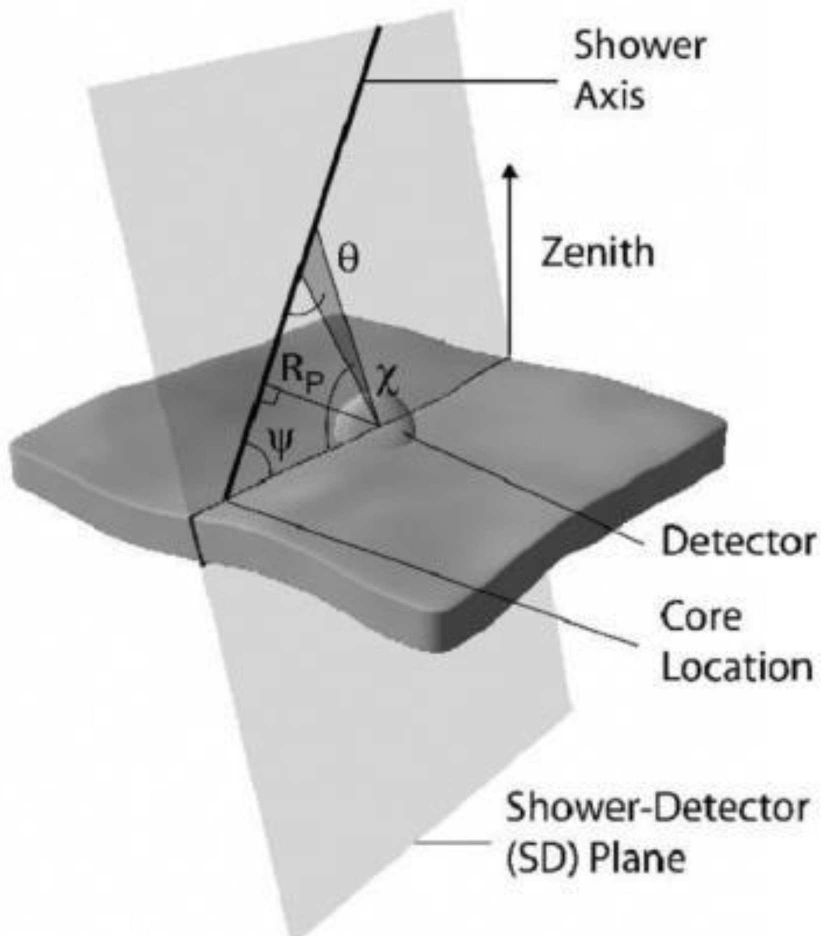
- February and March of 2019 half of all SDs deployed (257 SDs)
- Location optimized for hybrid events E > 10^{19} eV
  - 2.08 km SD spacing
- Mostly the same as TA SDs
- DAQ started in April 2019



TAx4 Hybrid Reconstruction - PMT Selection

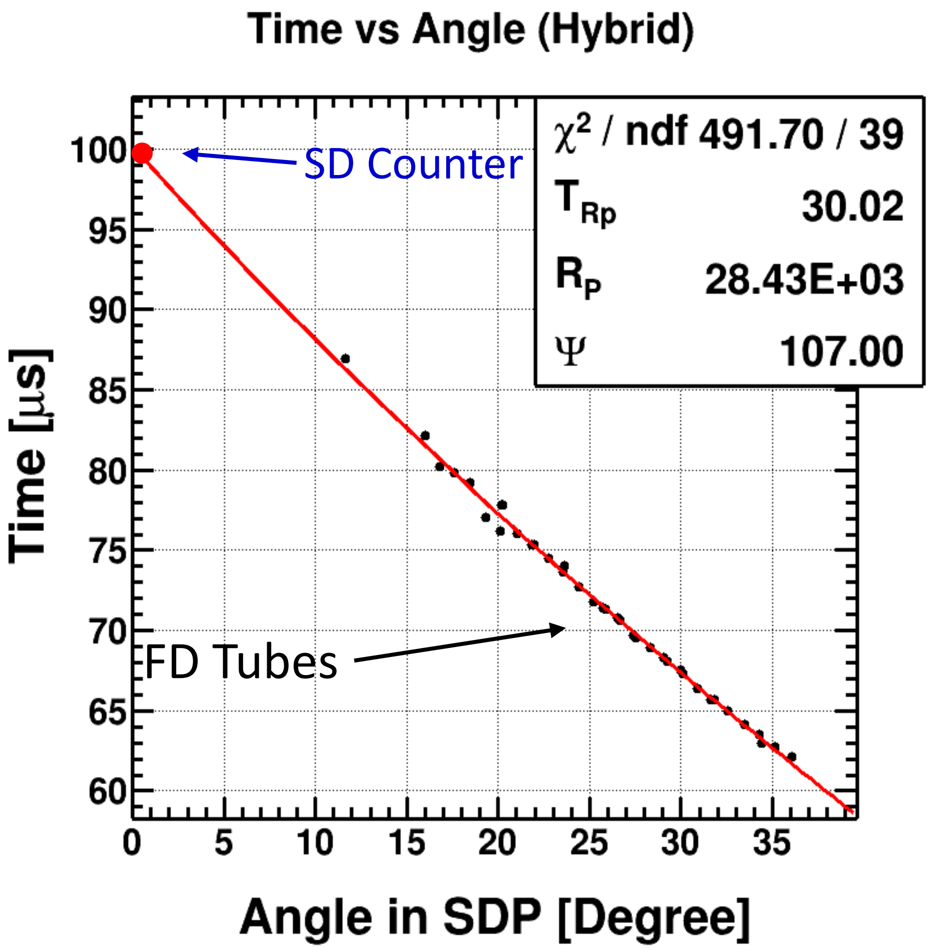


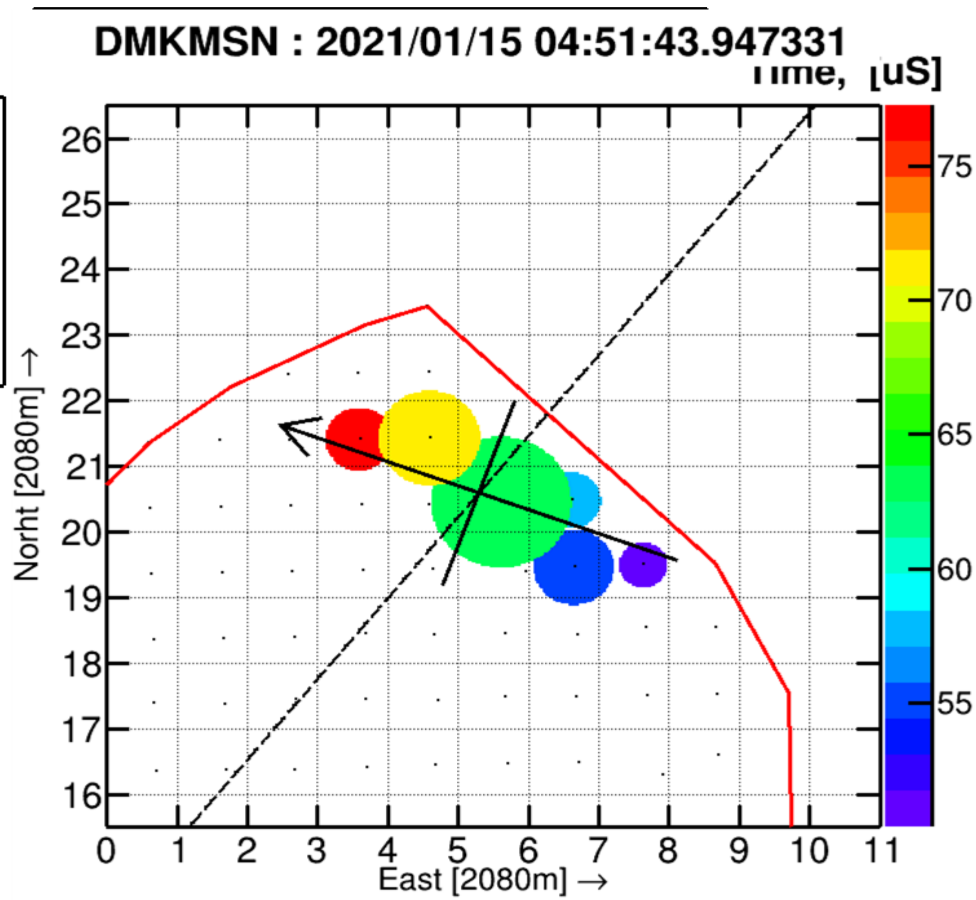
Event Display showing pattern of hit pixels



Direction of hit pixels fitted to a shower-detector plane (SDP)

TAx4 Hybrid Reconstruction - Hybrid Timing Fit

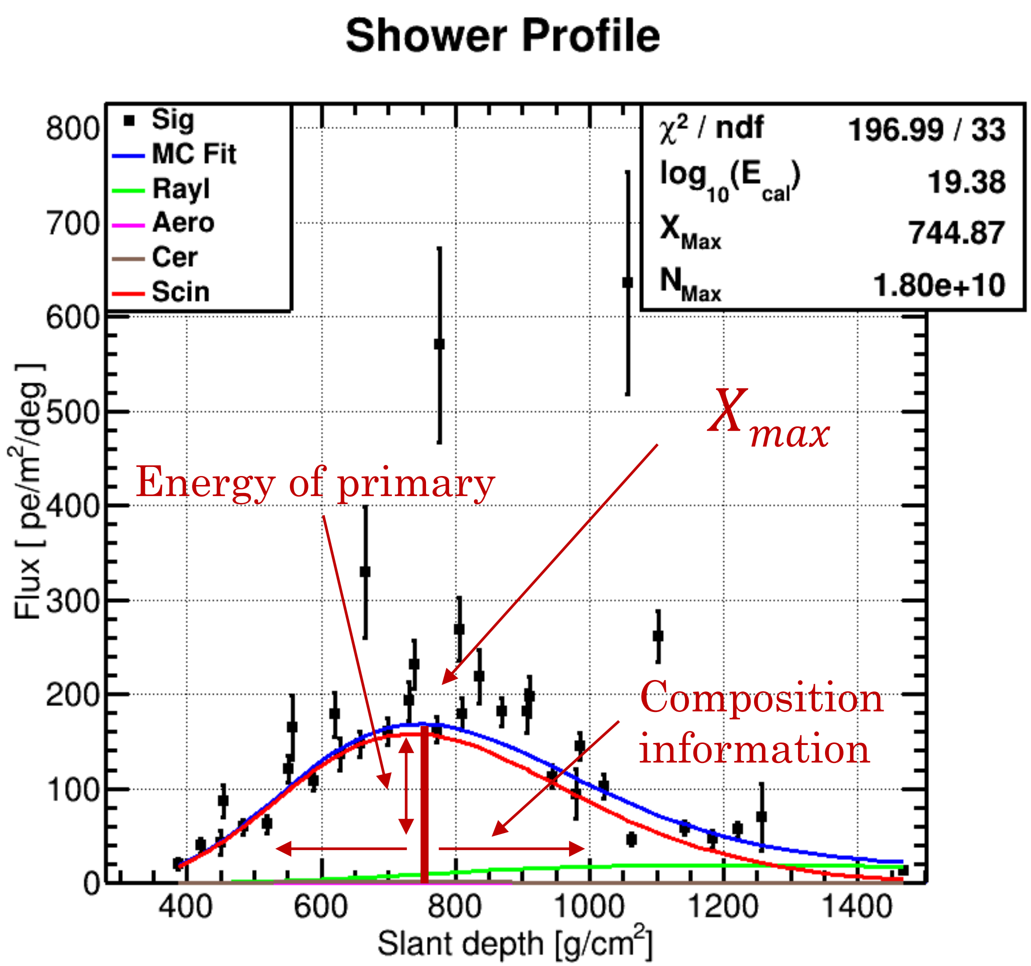


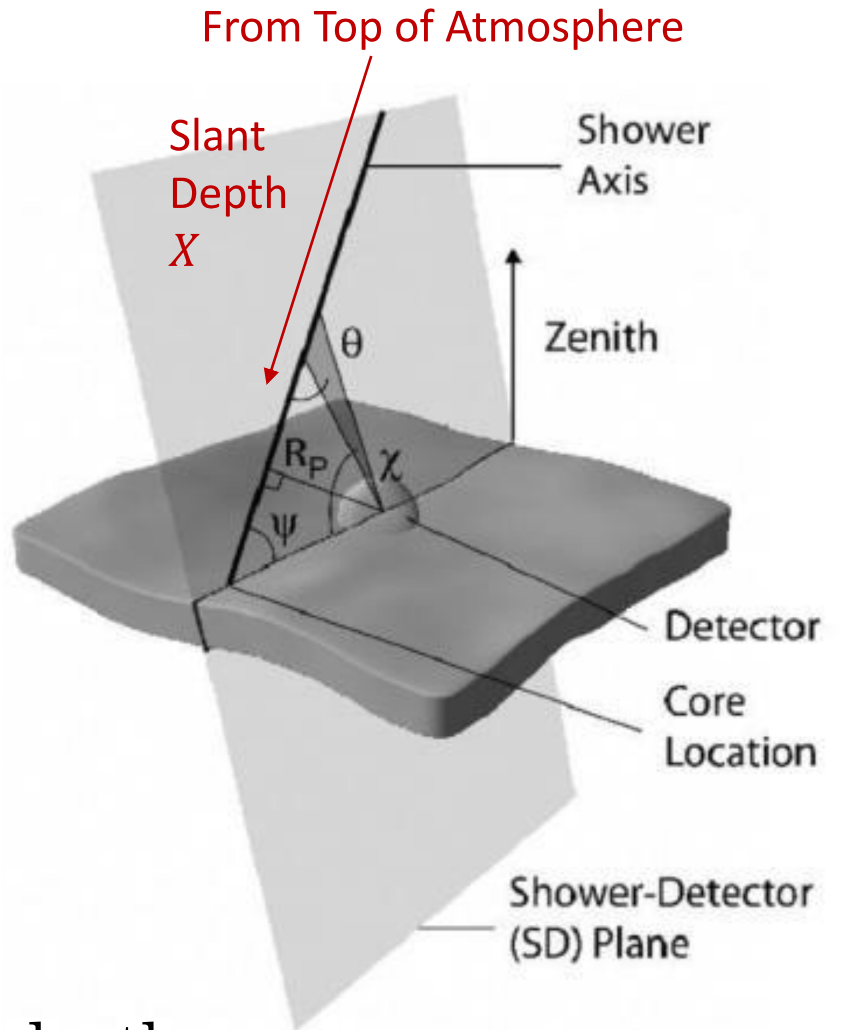


Arrival times of signal light in each pixel is fitted as a function of the SDP angles: **Gives direction of primary cosmic ray**

$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

TAx4 Hybrid Reconstruction - Shower Profile Fit





SDP angles are converted to slant depth.
Light signal fitted to depth to give
energy E and X_{max} (depth of maximum)

Hybrid Event - TAx4 North

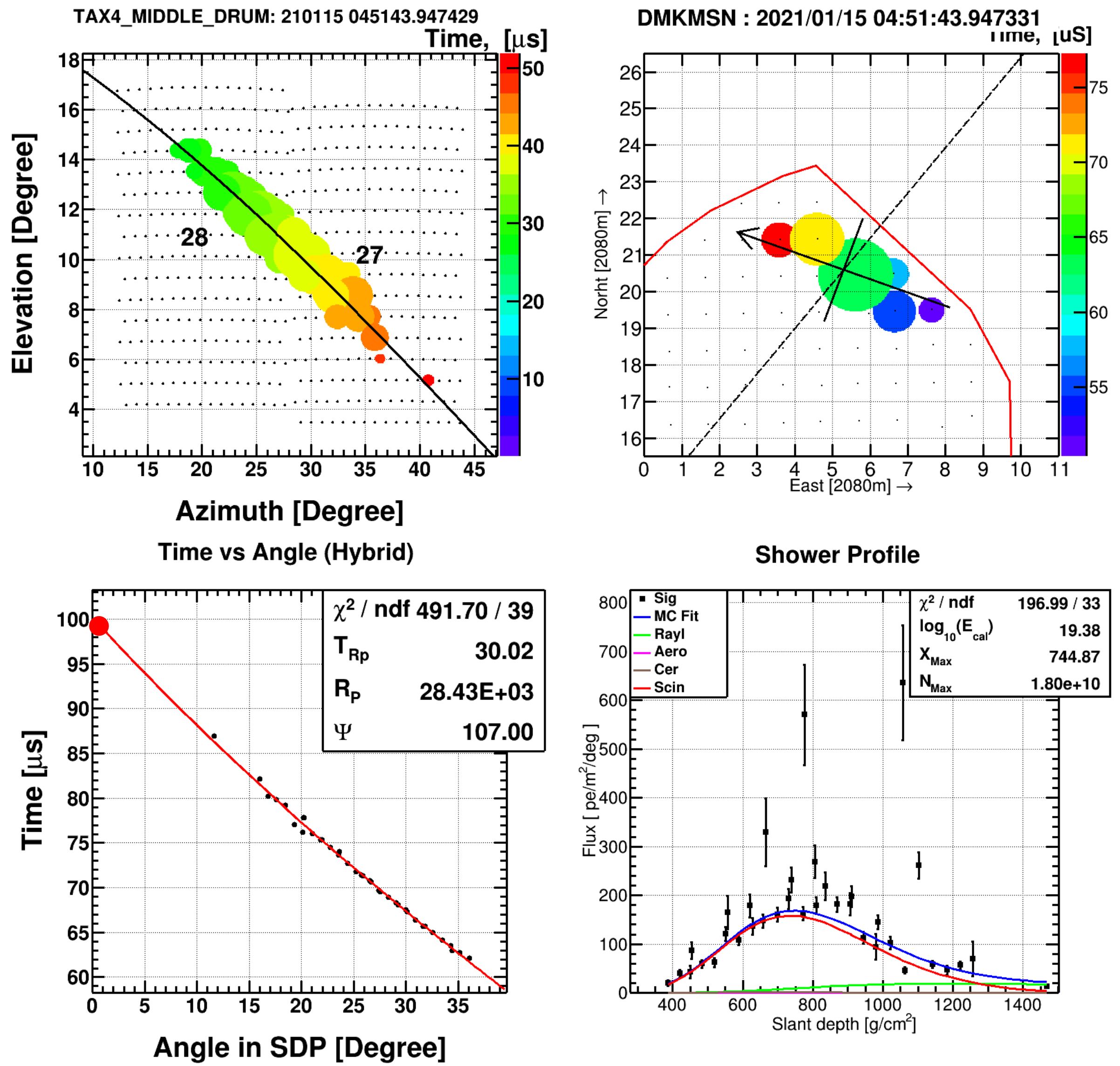
$E = 2.4 \times 10^{19}$ eV

$R_p = 28.43$ km

$\Psi = 107°$ N of E

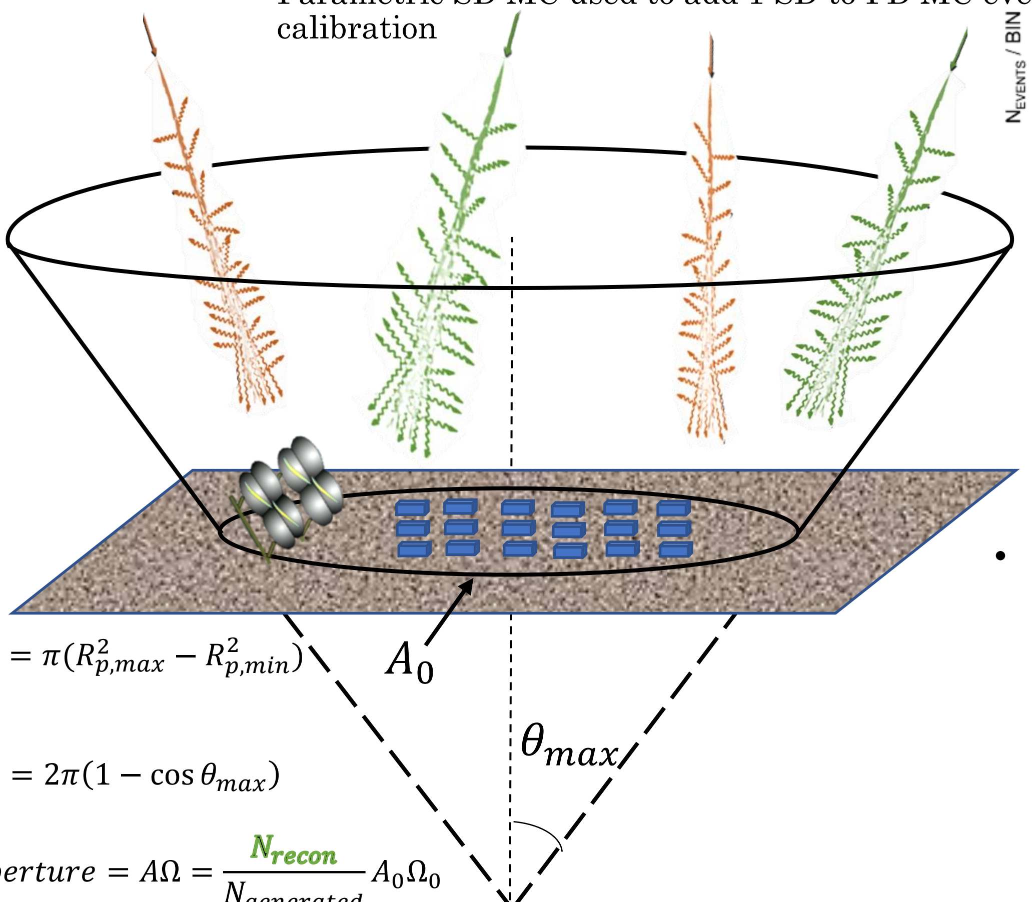
$\chi_{max} = 744.87$ g/cm^2

$N_{max} = 1.80 \times 10^{10}$ particles



Monte-Carlo Simulations

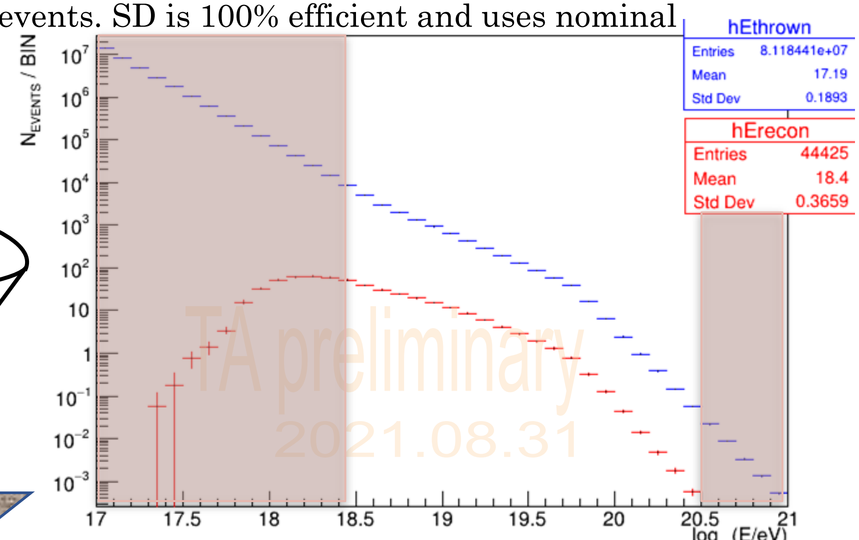
- Performance of our detectors, reconstruction programs, and the aperture are evaluated using a Monte-Carlo (MC) simulations.
  - CORSIKA shower library used for shower simulation
    - User able to change how a EAS develops
  - Detector simulation
    - Parametric SD MC used to add 1 SD to FD MC events. SD is 100% efficient and uses nominal calibration



$A_0 = \pi(R_{p,max}^2 - R_{p,min}^2)$

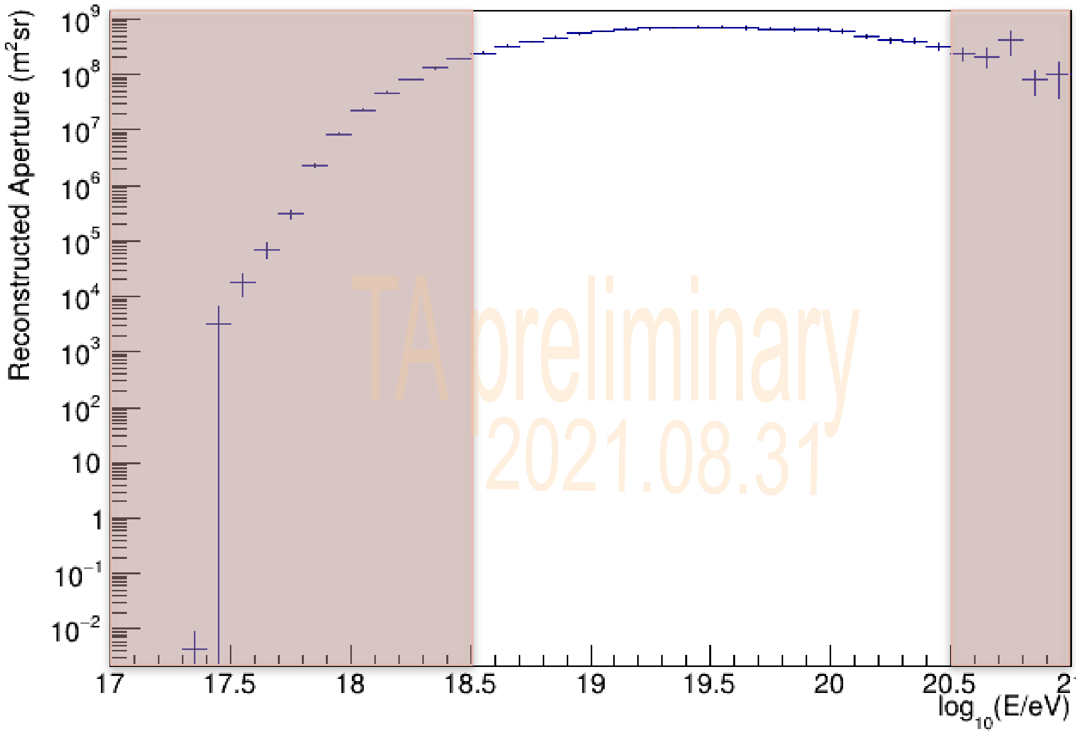
$\Omega_0 = 2\pi(1 - \cos\theta_{max})$

$Aperture = A\Omega = \frac{N_{recon}}{N_{generated}} A_0\Omega_0$



- 80 million QGSJetII-03 protons simulated at E^{-2} power law spectrum
  - Events are reweighted with spectral indices reported in the TA ICRC 2019 spectrum.
  - Reconstructed MC has quality cuts and a protonic missing energy correction applied.

Monte-Carlo Simulations



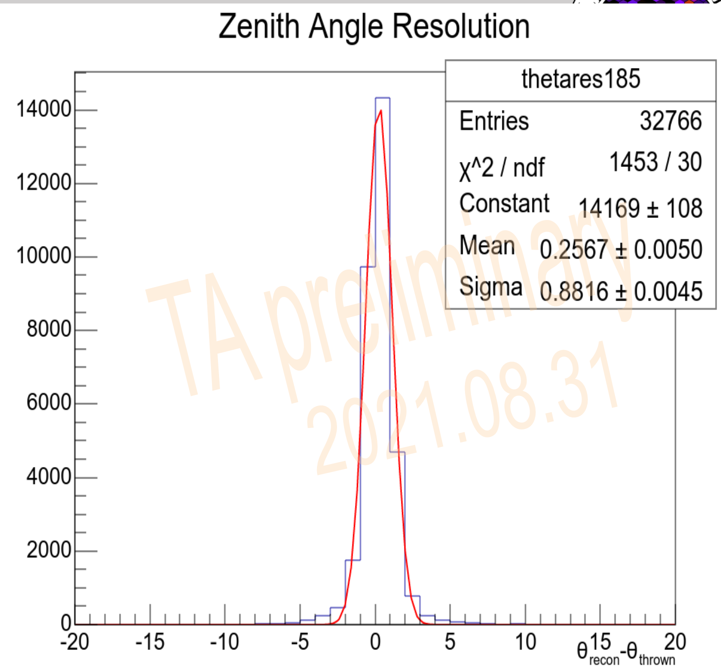
$$\Omega_0 = 2\pi(1 - \cos\theta_{max})$$

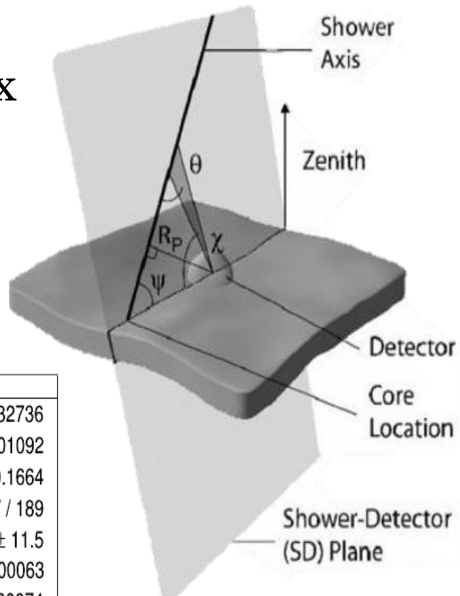
$$A_0 = \pi(R_{p,max}^2 - R_{p,min}^2)$$

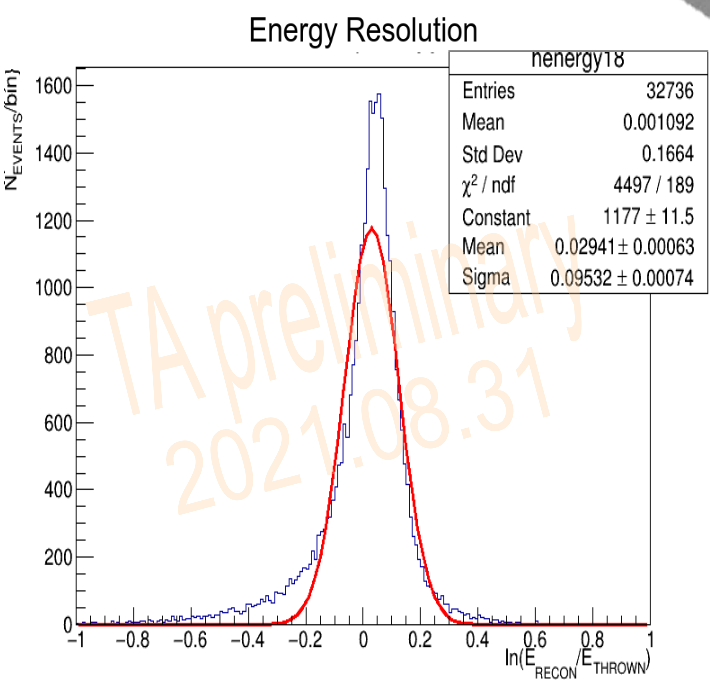
$$Aperture = A\Omega(E) = \frac{N_{recon}(E)}{N_{generated}(E)} A_0\Omega_0$$

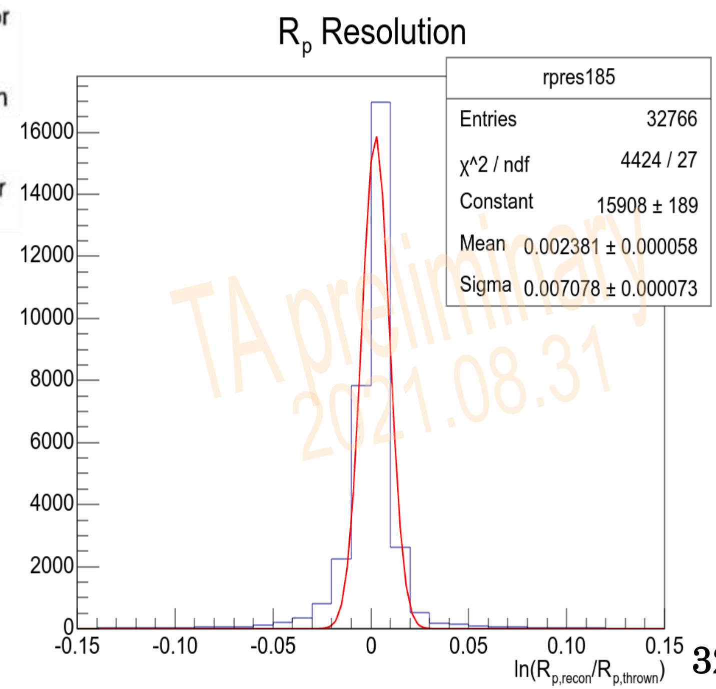
Resolutions

- Energy Resolution: ~10%
- Zenith Angle Resolution: ~1°
- Rp Resolution: ~0.7%
- These resolutions are ~2x MD hybrid resolutions



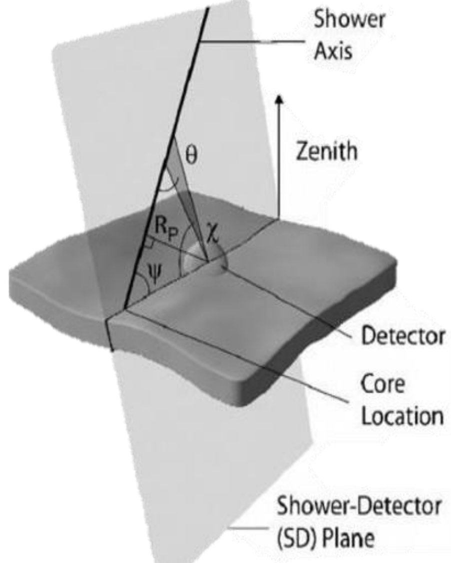


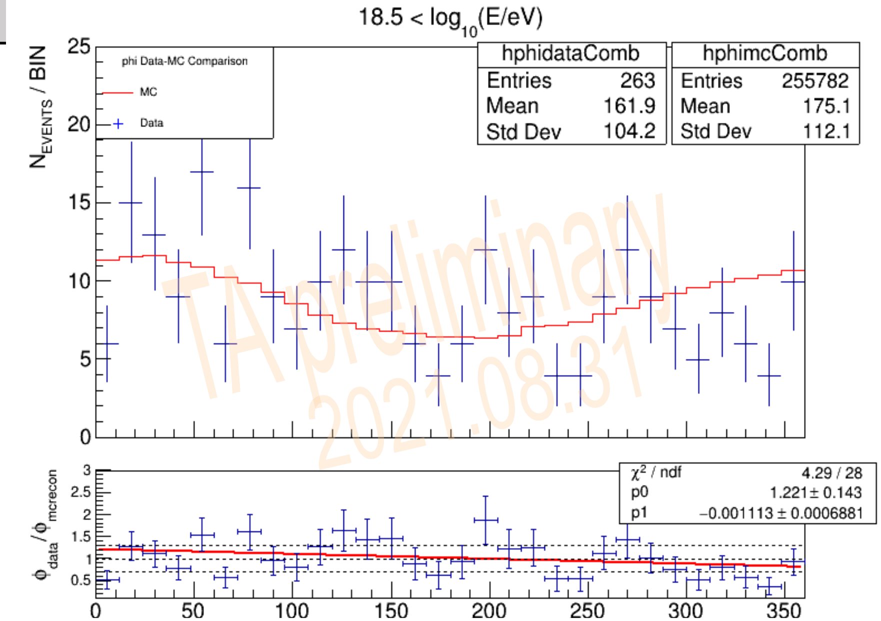


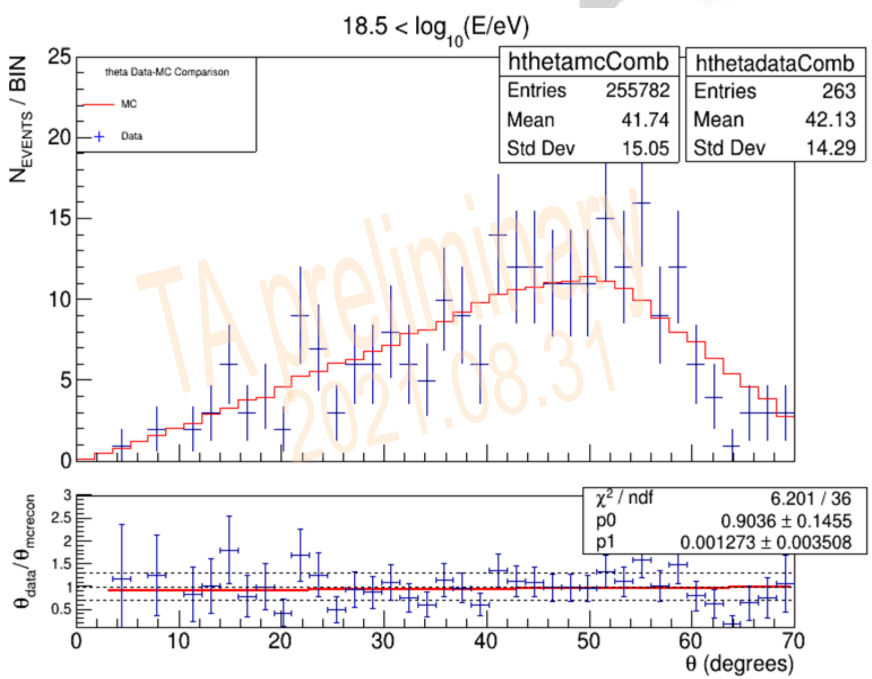


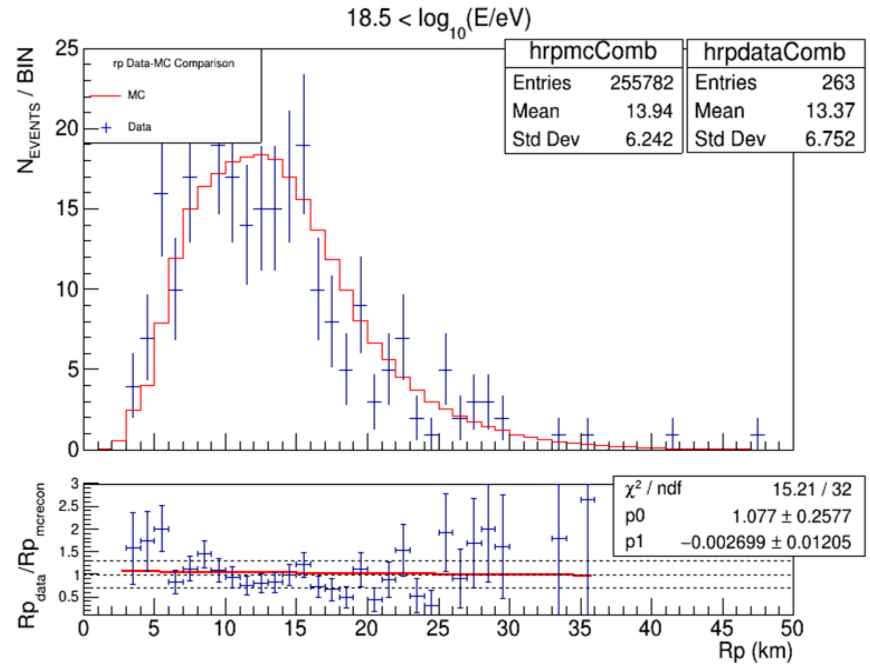
Data-MC Comparisons

- Blue points are data, the red line is the MC
- All geometrical parameters appear to be in reasonable agreement with the MC

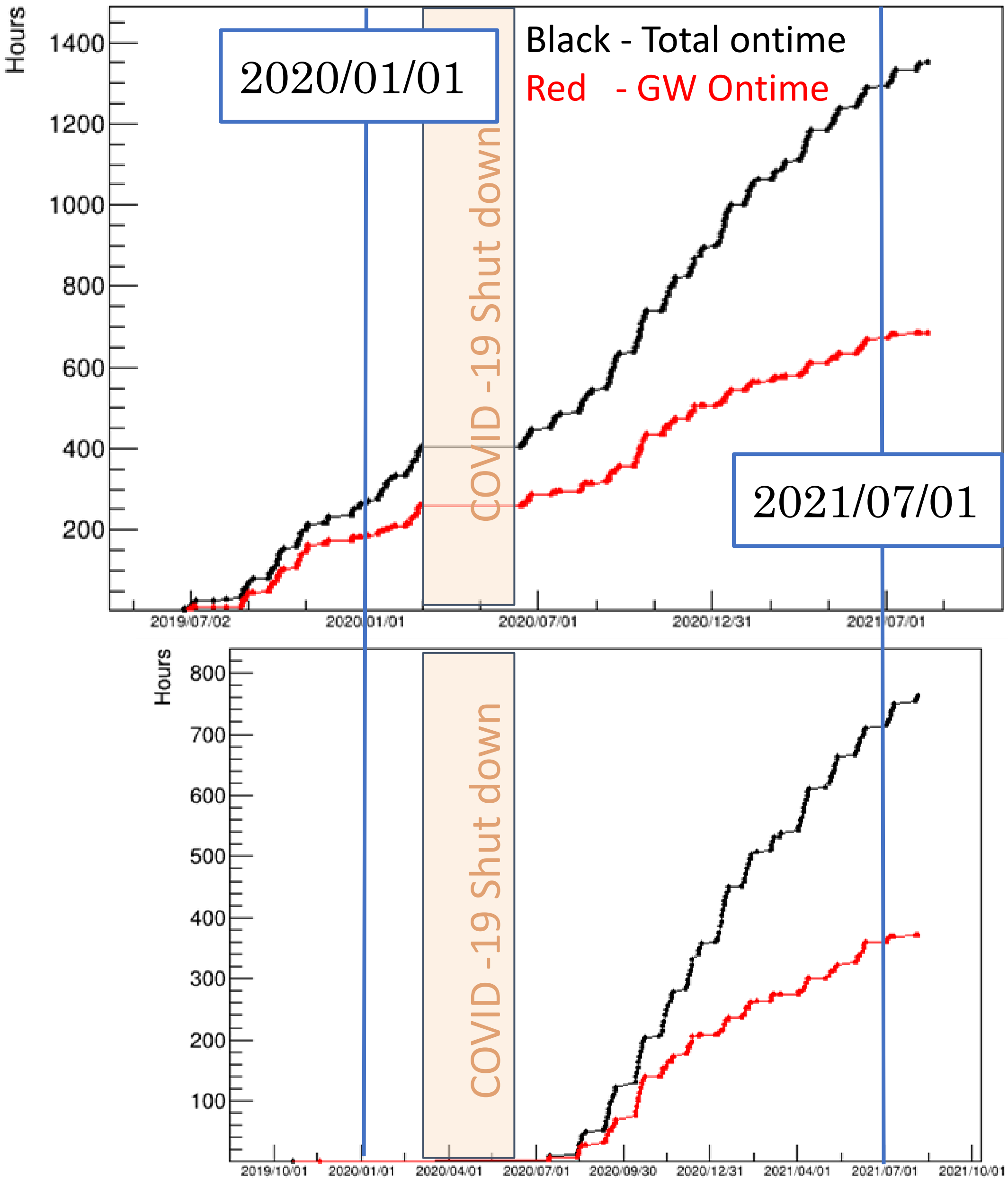






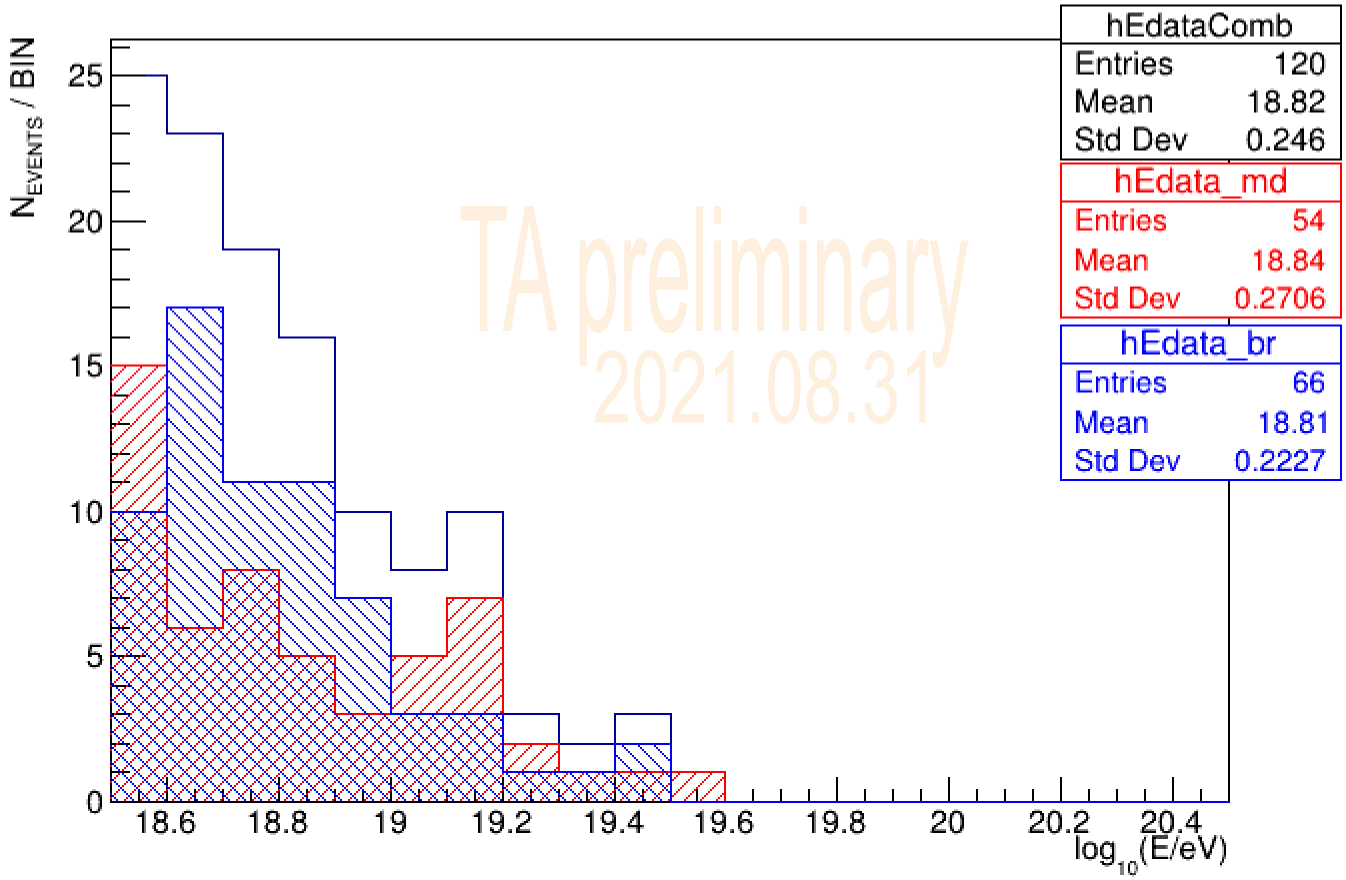


TAx4 Ontime (2019/06/26-2021/08/31)



- **TAx4 Detector total ontime: 2120.0527 hrs**
  - GW on-time：1058.8825 hrs
- **TAx4 North total ontime: 1353.4808 hrs**
  - on-time for m25 ：1314.6569 hrs
  - on-time for m26 ：1323.2869 hrs
  - on-time for m27 ：1272.9378hrs
  - on-time for m28 ：1292.1548 hrs
  - GW on-time： 685.3675 hrs
    - No clouds overhead, no horizon clouds to the north and east, and no haze
- **TAx4 South total ontime: 766.5719 hrs**
  - on-time for m29 ：757.7142 hrs
  - on-time for m30 ：756.4706 hrs
  - on-time for m31 ：761.0536 hrs
  - on-time for m32 ：692.3671 hrs
  - on-time for m33 ：757.8402 hrs
  - on-time for m34 ：728.4909 hrs
  - on-time for m35 ：751.5253 hrs
  - on-time for m36 ：708.6107 hrs
  - GW on-time：373.5150 hrs
    - No clouds overhead, no horizon clouds to the south and east, and no haze

Hybrid Data Distribution



- Total events 120
- TAx4 North events 54
- TAx4 South events 66

TAx4 Energy Spectrum

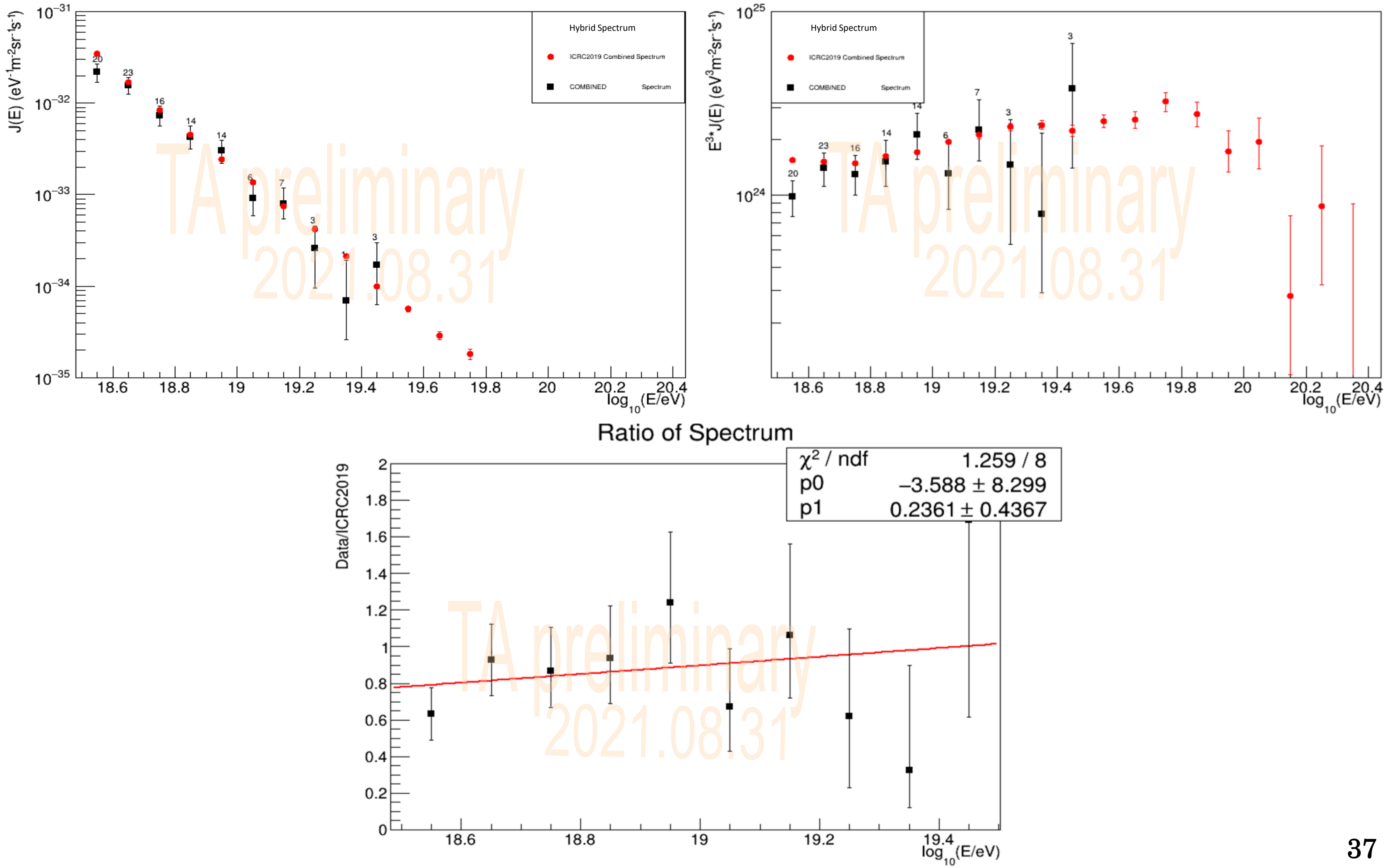
$$N_{\mathrm{TAx4}}\left(E_i\right) = N_N\left(E_i\right) + N_S\left(E_i\right),$$

$$\epsilon_{\mathrm{TAx4}} = A\Omega_N T_N + A\Omega_S T_S,$$

$$J_{\mathrm{TAx4}}\left(E_i\right) = \frac{N_{\mathrm{TAx4}}\left(E_i\right)}{\Delta E_i \cdot \epsilon_{\mathrm{TAx4}}\left(E_i\right)},$$

- The TAx4 total number of events and combined exposure simplify to sums
  - No overlap of the detector's FOVs

TAx4 Hybrid Energy Spectrum

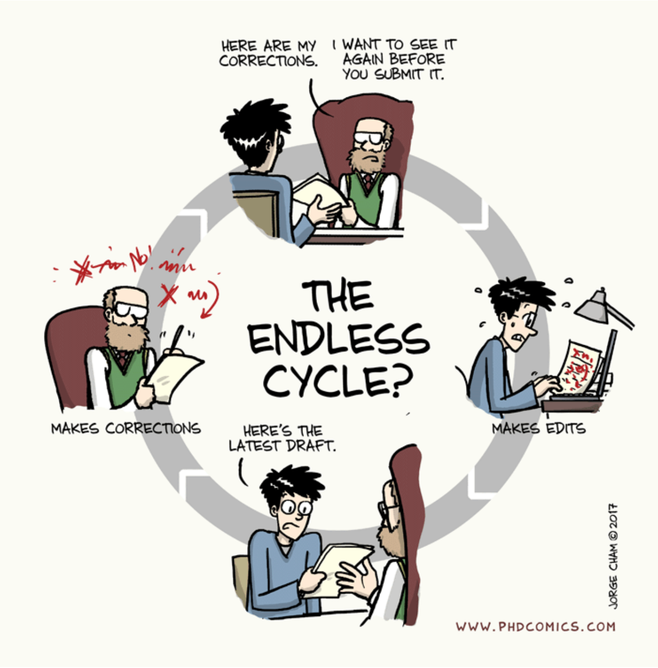


Conclusions

- Cosmic rays are subatomic particles of extraterrestrial origin that pose many interesting questions.
- Evidence of anisotropy and need for greater statistics at higher energies pushed TA to expand and create TAx4.
- The TAx4 North and TAx4 South FD sites were completed in 2018 and 2019, respectively. Both sites are now taking data continuously on clear moonless nights.
- 257 of a planned 500 TAx4 SDs were deployed in early 2019 and began regular DAQ by April 2019.
- The hybrid resolutions are consistent with a single ring detector.
- The MC and data appear to be in agreement.
- This work's hybrid energy spectrum using TAx4 is in agreement with the TA ICRC2019 combined spectrum.
- **The energy spectrum paves the way for composition and anisotropy analyses for a future graduate student.**

Where to go from here?

- Finish writing my dissertation
  - Defending next semester
- Working on getting SD calibration files for a full hybrid MC that includes SD efficiencies
- Work towards a matrix based correction to X_{max} and energy can remove the bias introduced in reconstruction
  - Performed a similar analysis on TALE



TA Collaborators

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- 愛媛大学 Ehime University
- Rutgers The State University of New Jersey
- Yonsei University
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- ICRR Institute for Cosmic Ray Research University of Tokyo
- 東京大学 The University of Tokyo
- 千葉大学 Chiba University
- WASEDA University
- Hanyang University
- 東京都市大学 Tokyo City University
- CNU 충남대학교 Chungnam National University
- University of Yamanashi
- Vrije Universiteit Brussel
- Kanagawa University
- KEK - Institute of Particle And Nuclear Studies
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- Институт ядерных исследований Российской академии наук / Institute for Nuclear Research of Russian Academy of Sciences
- Tokyo University of Science
- Shibaura Institute of Technology
- Kinki University
- National University Corporation Kochi University
- Saitama University
- NIRS National Institute of Radiological Sciences 独立行政法人 放射線医学総合研究所

Telescope Array Project

Backup Slides

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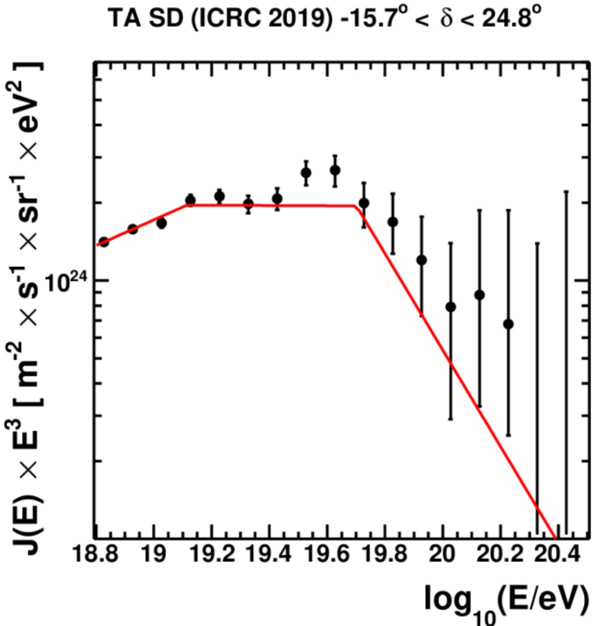
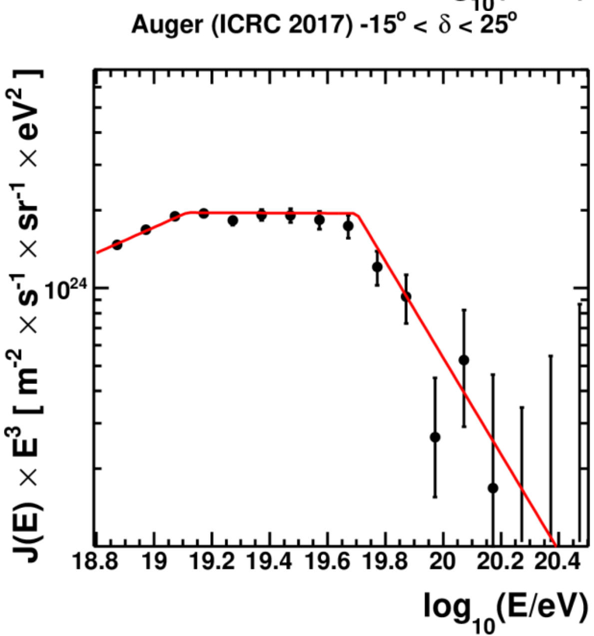
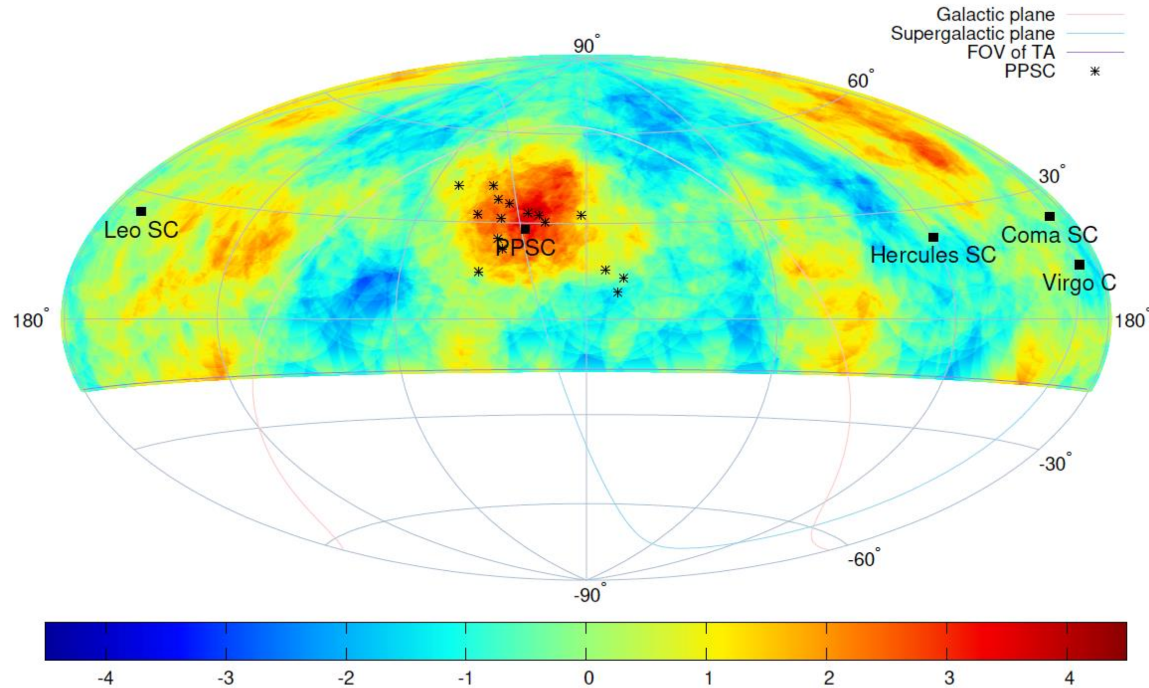
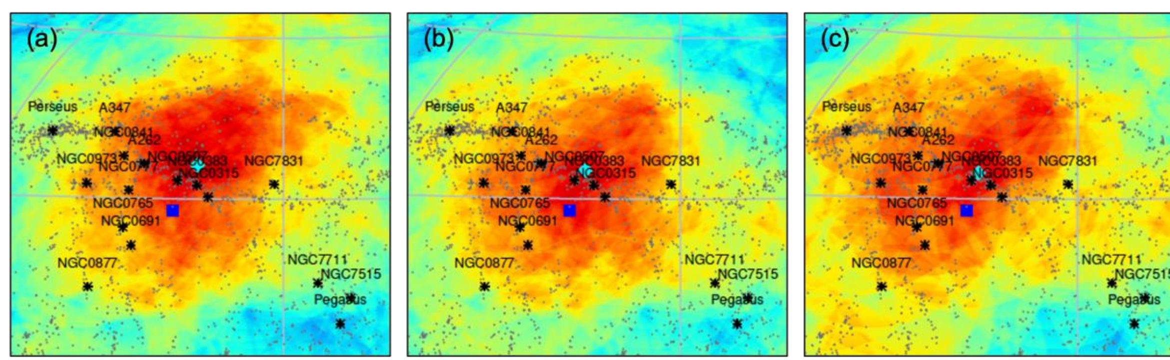
New Blob


TA SD (ICRC 2019) -15.7° < δ < 24.8°
J(E) × E³ [m⁻² × s⁻¹ × sr⁻¹ × eV²]
10²⁴
18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
log10(E/eV)

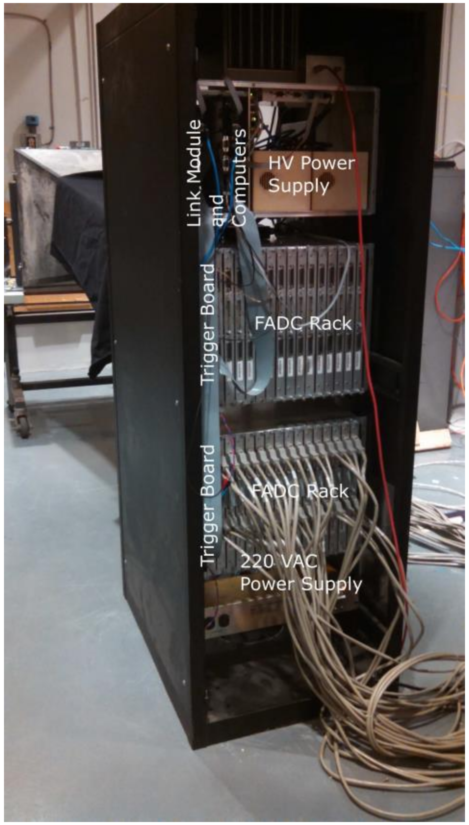

Auger (ICRC 2017) -15° < δ < 25°
J(E) × E³ [m⁻² × s⁻¹ × sr⁻¹ × eV²]
10²⁴
18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
log10(E/eV)


Galactic plane
Supergalactic plane
FOV of TA
PPSC
90°
60°
30°
180°
180°
-30°
-60°
-90°
Leo SC
PPSC
Hercules SC
Coma SC
Virgo C
-4 -3 -2 -1 0 1 2 3 4

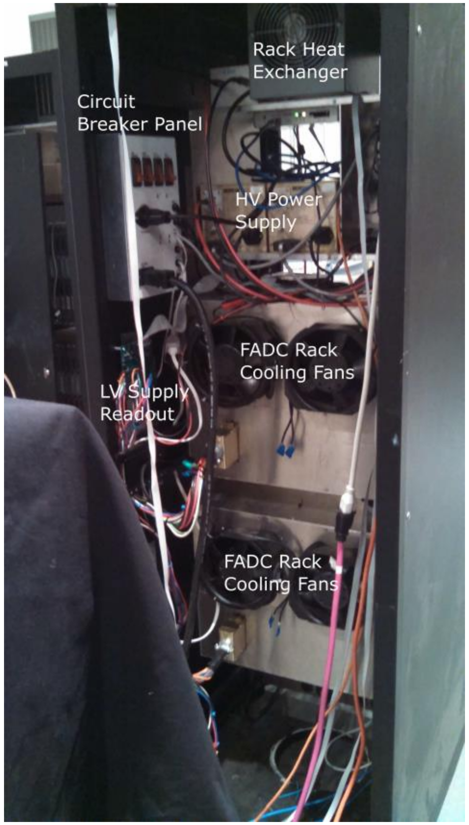

(a)
(b)
(c)
Perseus
A347
A262
NGC7831
NGC0315
NGC0765
NGC0691
NGC0877
NGC7711
NGC7515
Pegasus

TAx4 FD Electronics and FADC readout

- Fast Analog Digital Converters (FADCs) are employed to read out the signal from the PMTs.
    - 10 MHz sampling rate
    - 16 FADC boards
    - Each FADC rack has 20 channels
- The TAx4 trigger condition for EAS tracks are the same for that of TALE.
- The trigger-host board contains four Programmable Logic Devices (PLDs) and a Digital Signal Processor (DSP)



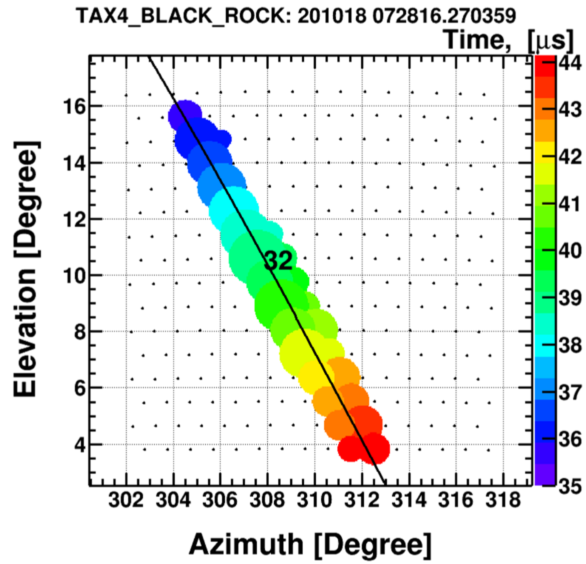
Front of Rack

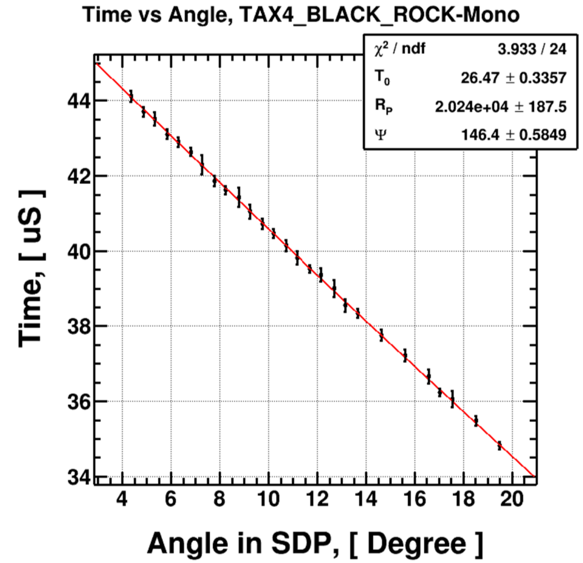


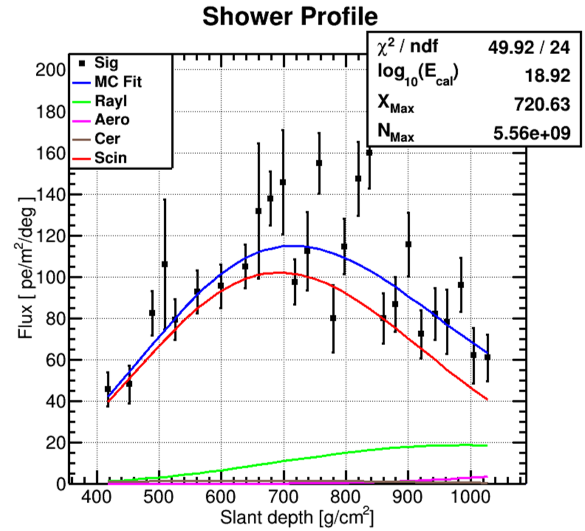
Back of Rack

Monocular vs. Hybrid Event

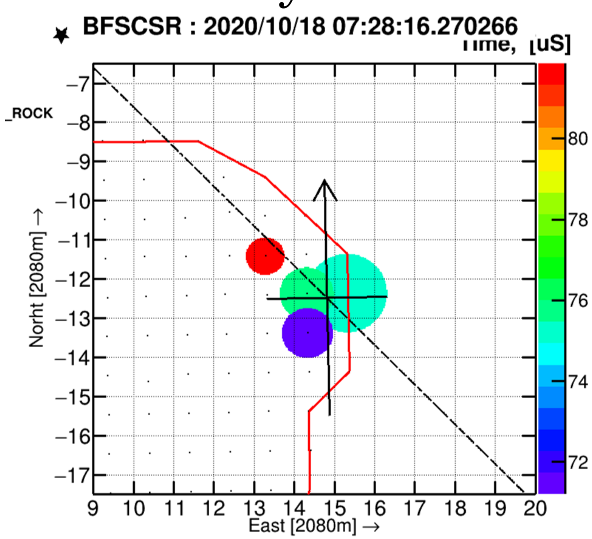
TAx4 South Monocular

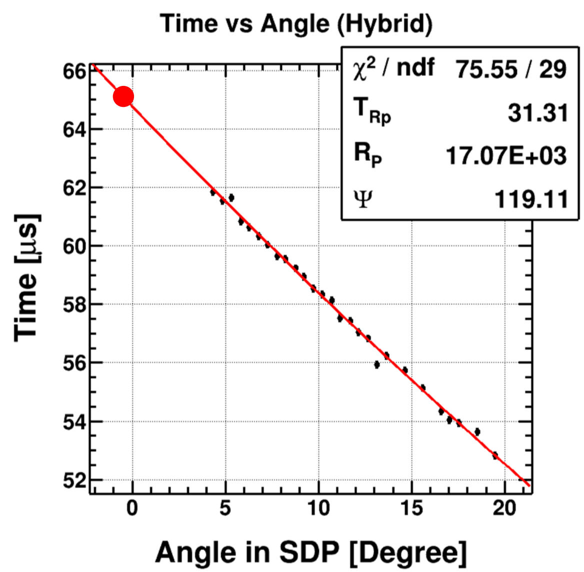


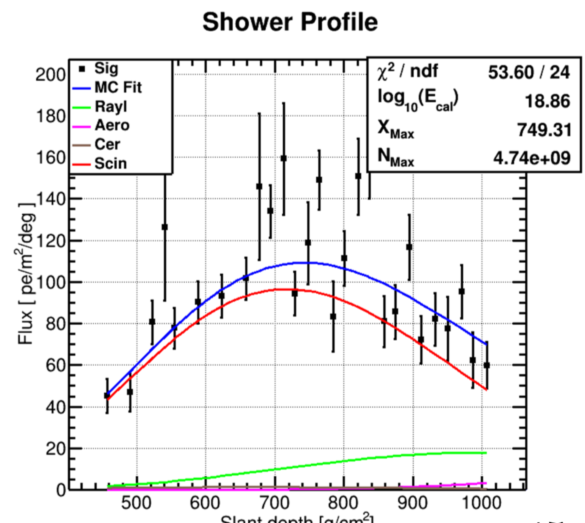




TAx4 South Hybrid

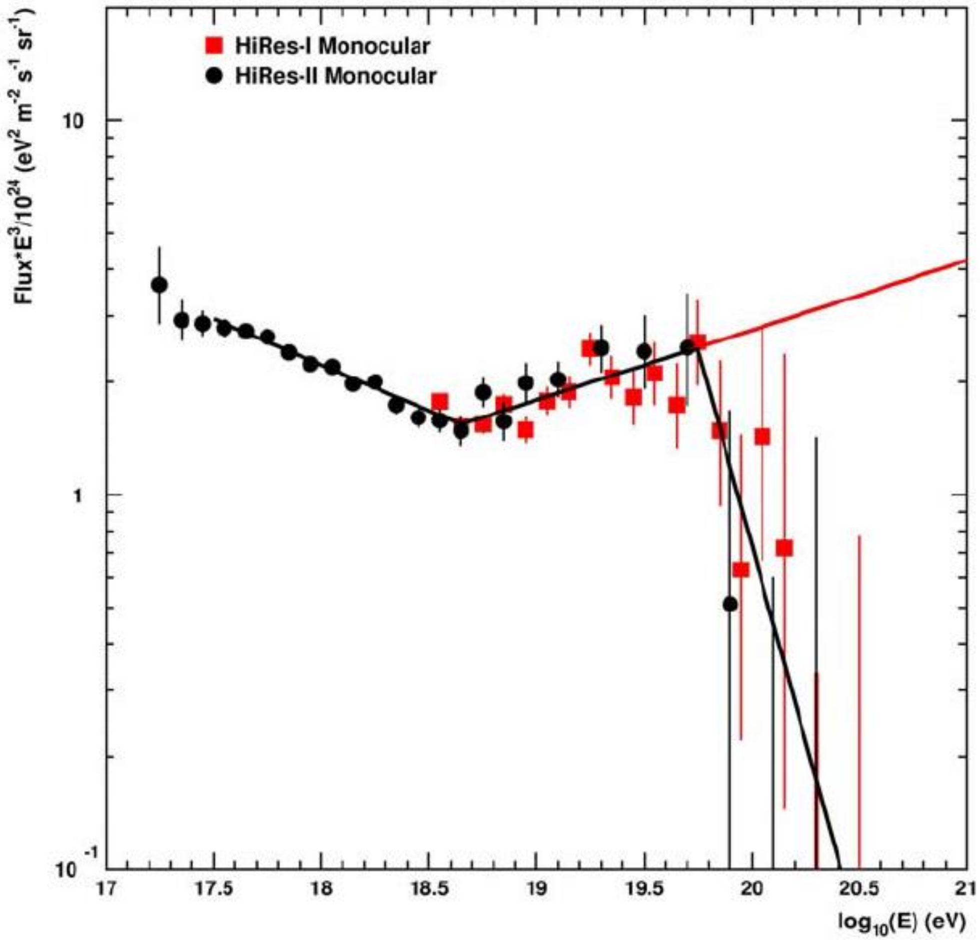






Greisen-Zatsepin-Kuzmin limit (GZK limit)

- Theoretical upper limit on the energy of cosmic ray protons traveling from other galaxies.
  - $\sim 5 \times 10^{19}\ eV$
  - The limit is set by interactions of the protons with the cosmic microwave background radiation (CMB)
    - $\gamma_{CMB} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$
    - $\gamma_{CMB} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$

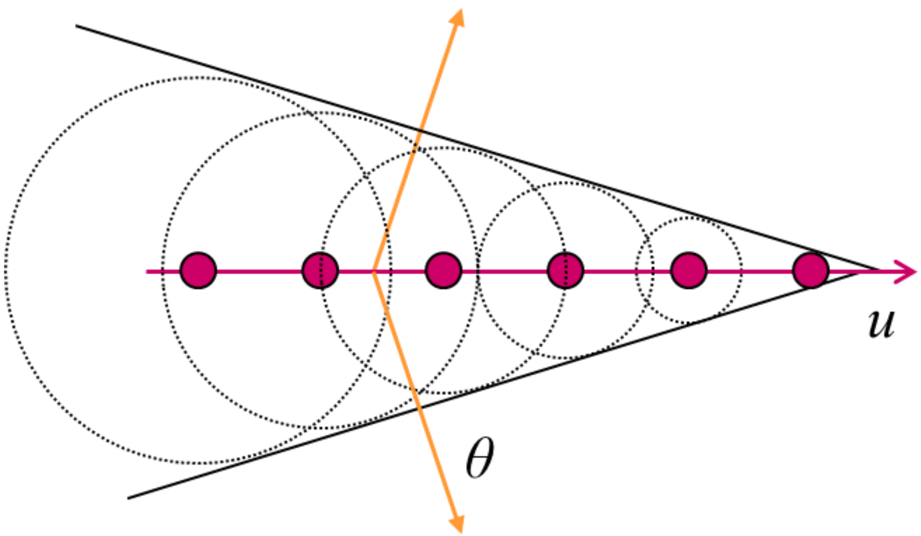


TAx4 FD Calibration

- TAx4 uses a Ultra-Violet Light Emitting Diode (UV LED) for the photometric calibration of the PMTs
- Temperature stabilized to 45°C
- Pulsed at a wavelength of 355 nm
- The calibration is performed at the beginning and end of each night of observation to record the drift of the gain balance.

Cherenkov Light

- According to the Huygens principle, the emitted waves move out spherically at the phase velocity of the medium.
- If the particle motion is slow, the radiated waves bunch up slightly in the direction of motion, but they do not cross.
- However if the particle moves faster than the light speed, the emitted waves add up constructively leading to a coherent radiation at angle θ with respect to the particle direction, known as Cherenkov radiation. The signature of the effect is a cone of emission in the direction of particle motion

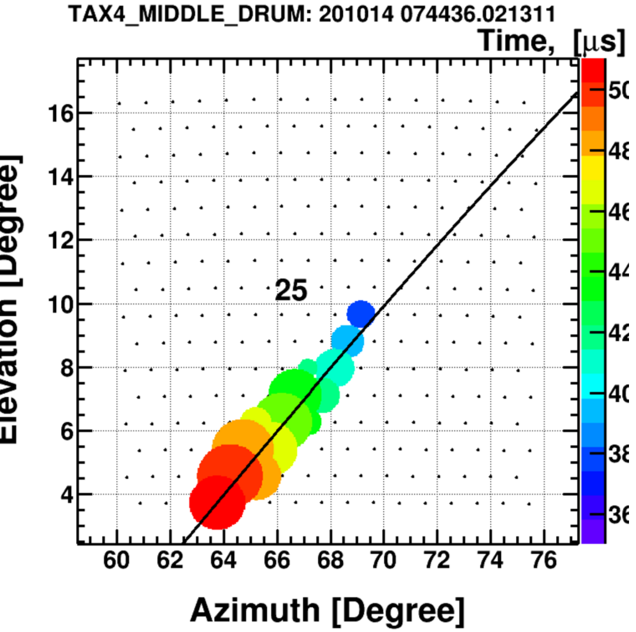


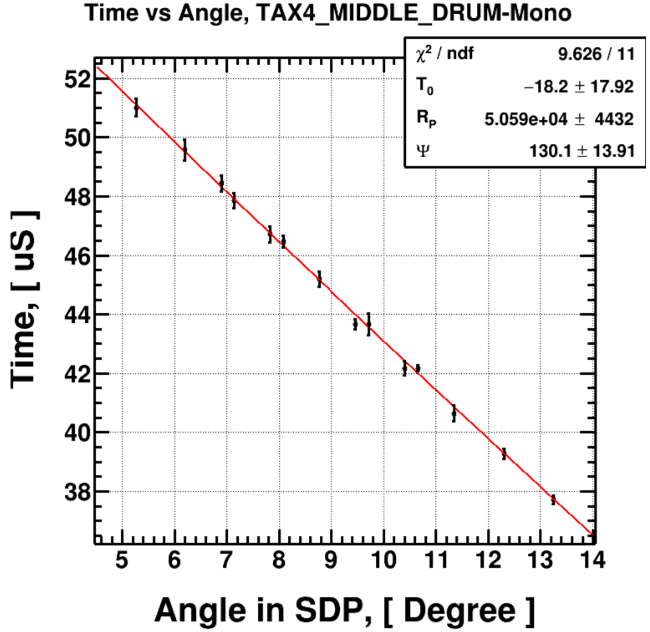
Quality Cuts

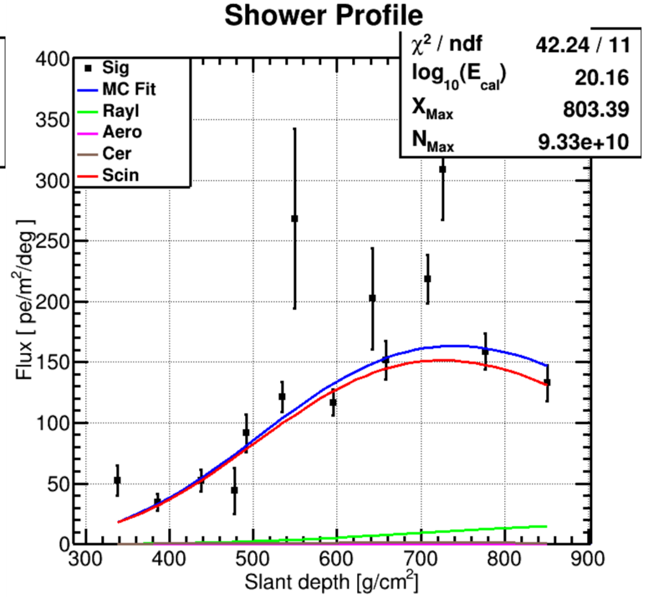
To ensure reconstruction quality, we only accept events that satisfy the following criteria:

- The number of PMTs used in the reconstruction is greater than 20.
- The zenith angle of the reconstructed shower axis is less than 55 degrees.
- The shower core is inside the edges of the SD array.
- The angle between the reconstructed shower axis and the telescope is greater than 20 degrees
- X_{max} is observed in the field of view of the telescopes.

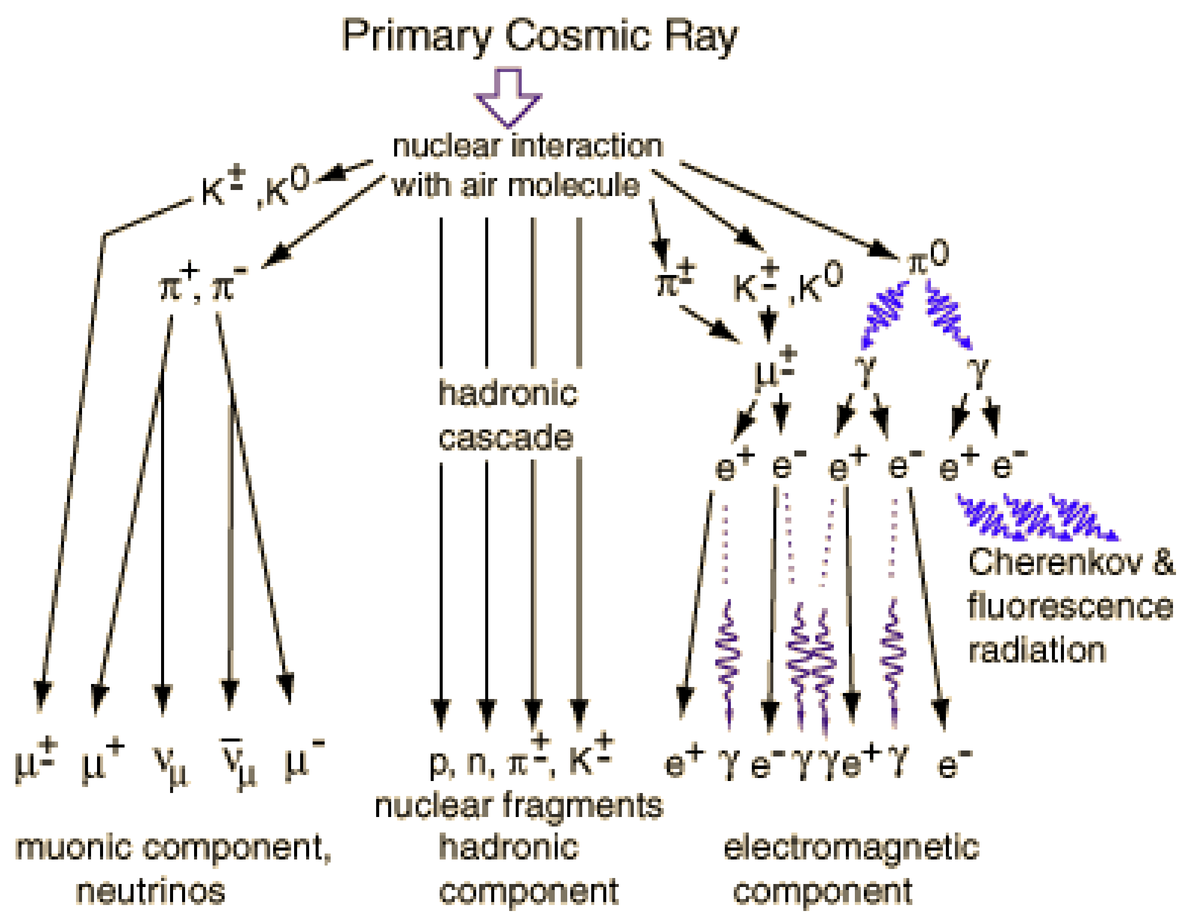
TAx4 North - $10^{20.1}$ eV mono event







Extensive Air Shower

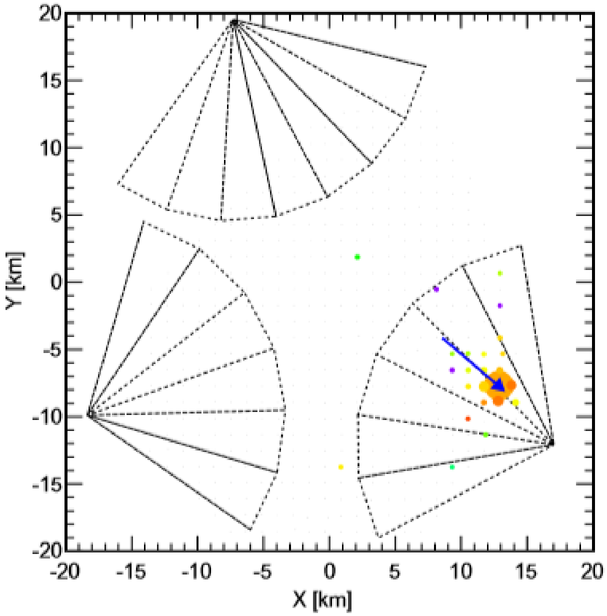


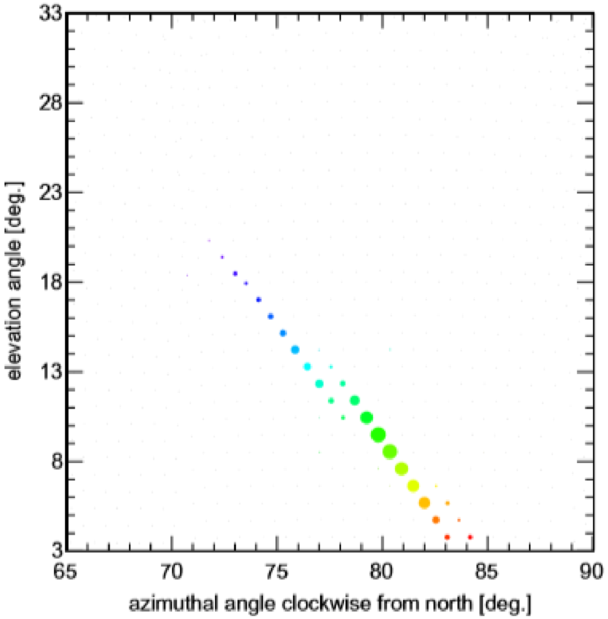
Scintillation

- Scintillation is a flash of light produced in a transparent material by the passage of a particle (an electron, an alpha particle, an ion, or a high-energy photon).
- An incoming particle can excite either an electron level or a vibrational level
- The singlet excitations immediately decay (< 10 ps) to the S* state without the emission of radiation (internal degradation). The S* state then decays to the ground state S0 (typically to one of the vibrational levels above S0) by emitting a scintillation photon.
- When one of the triplet states gets excited, it immediately decays to the T0 state with no emission of radiation (internal degradation). Since the T0 → S0 transition is very improbable, the T0 state instead decays by interacting with another T0 molecule and leaves one of the molecules in the S* state, which then decays to S0 with the release of a scintillation photon.

PMT Selection

- Signals greater than 3σ above the background fluctuations are selected.
- PMTs that are spatially and temporally isolated are rejected.
- The pointing direction vectors of the PMTs selected defines the SDP





Photomultiplier Tubes (PMTs)

- Photons that strikes photocathode emits electrons due to photoelectric effect
- The electrons are accelerated towards a series of dynodes
  - Each dynode is maintained at a more positive potential
  - Additional electrons are generated at each dynode

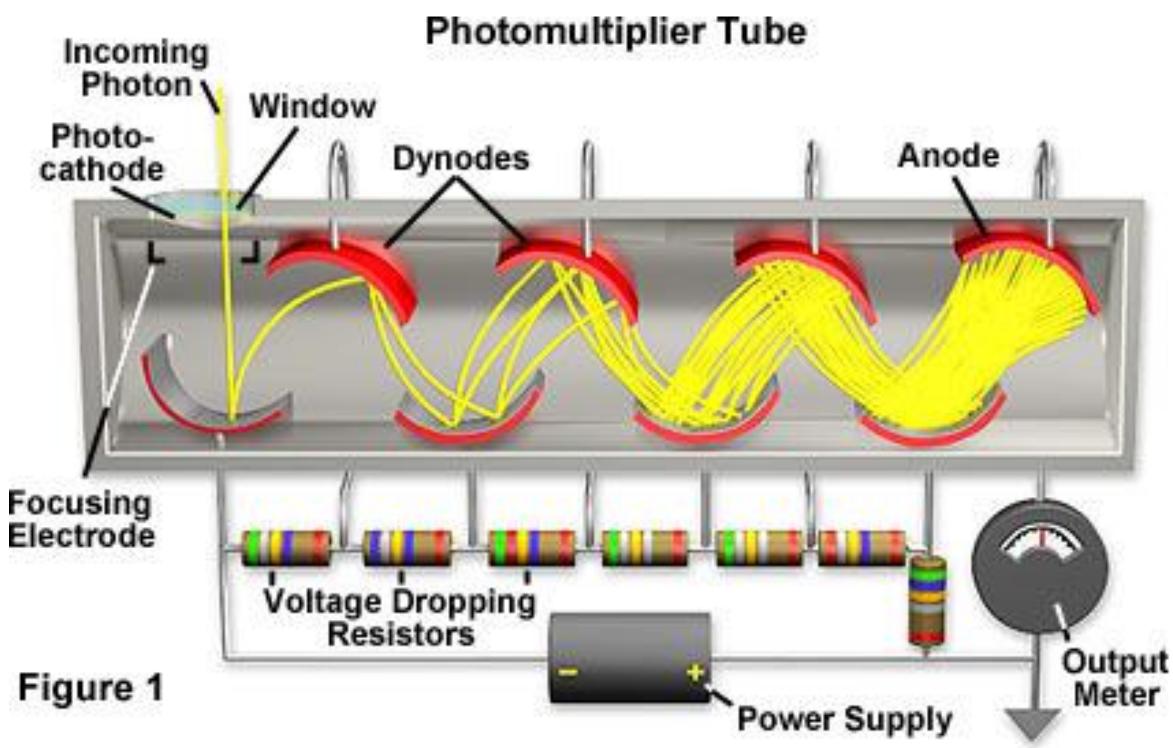
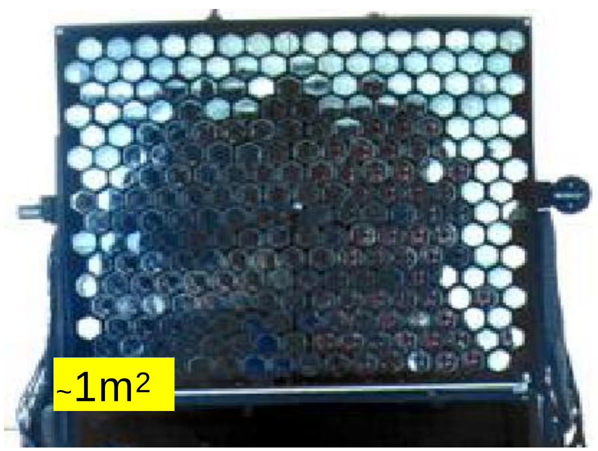
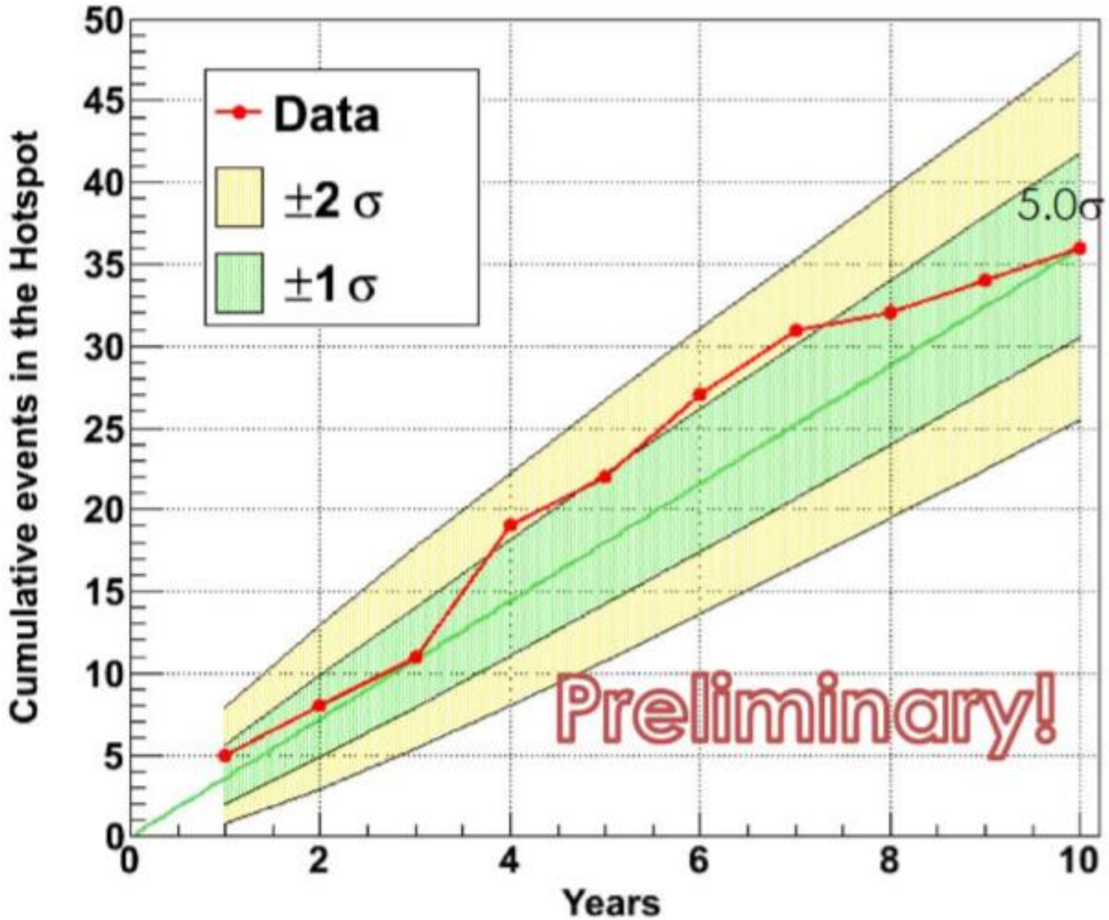


Figure 1

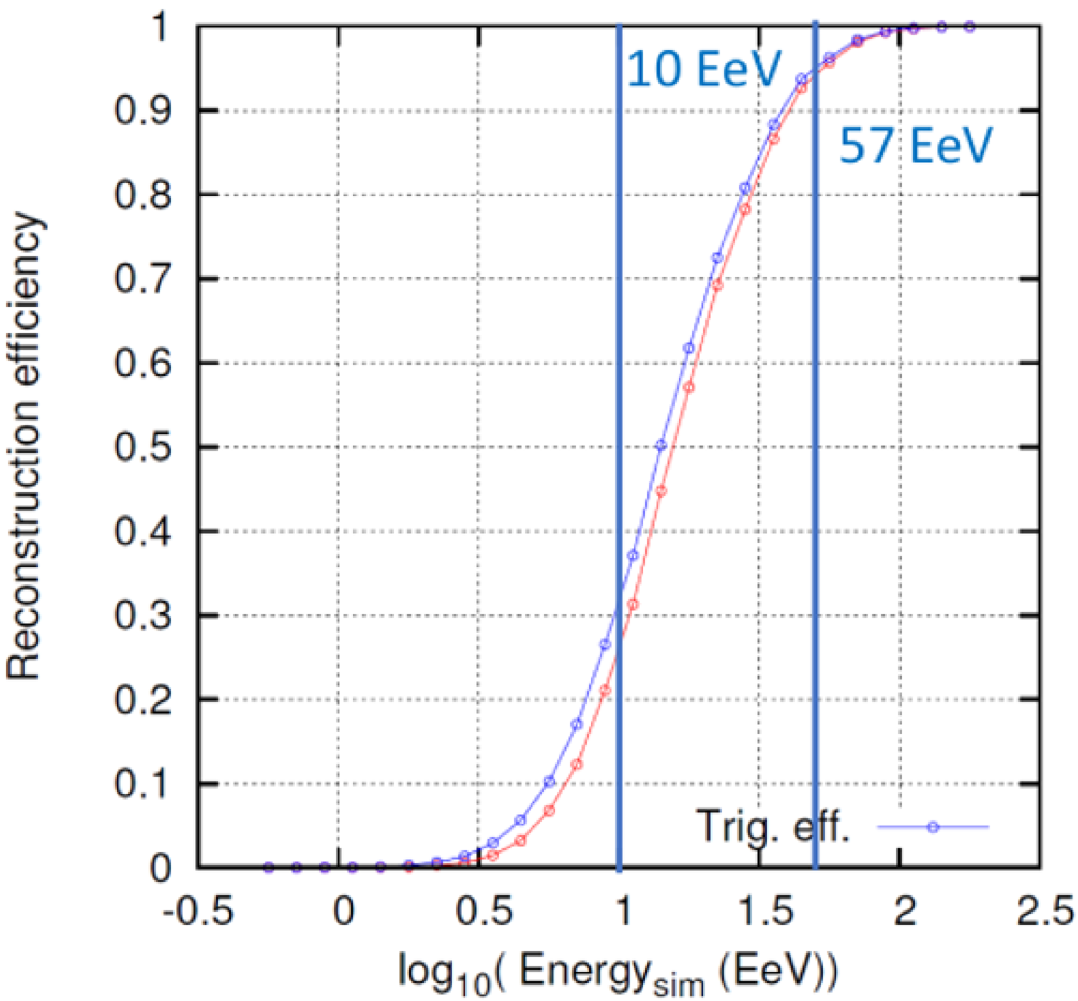


Goals of TAx4 Program

- The primary goal is to get more events with E > 57 EeV in the hotspot
  - ~40 events are expected in ~2.5 years of full operation
- Fill out the composition at E > 10 EeV
- First step is the energy spectrum



Expected Performance of TAx4 SDs

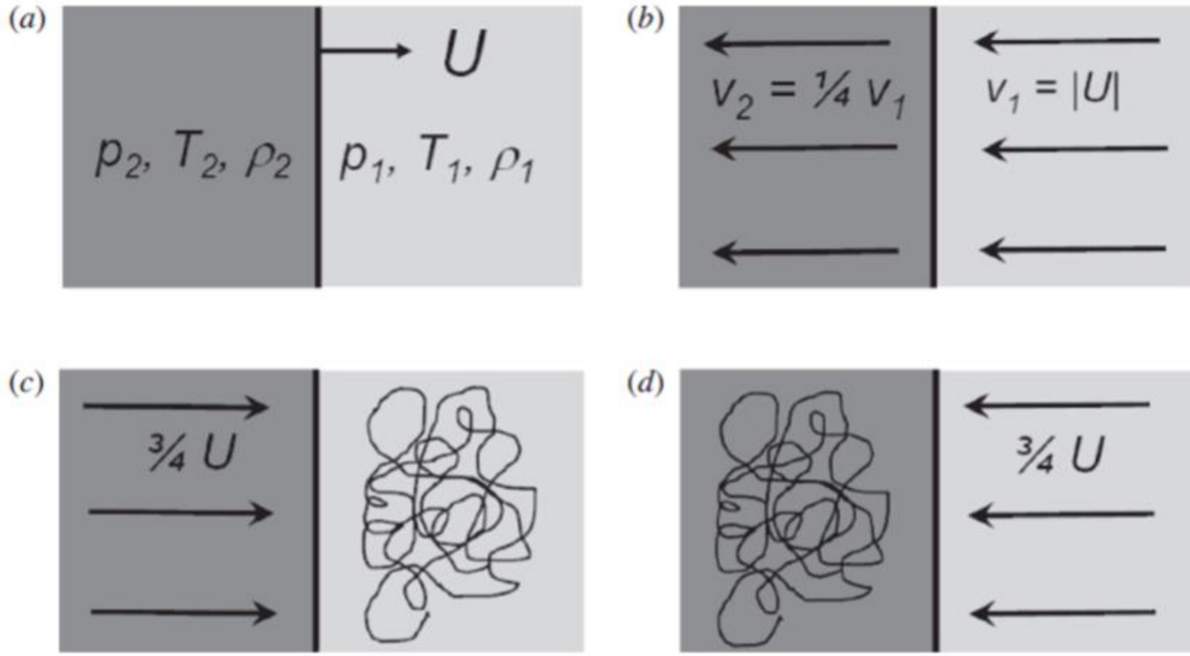


Trigger condition: adjacent 3 SDs with 14μs

E > 57 EeV:

- Reconstruction efficiency > 95%
- Angular resolution: 2.2°
- Energy resolution: ~25%

1st Order Fermi Acceleration



- (a) Observer's frame, (b) reference frame of shock, (c) upstream frame, (d) downstream frame
- When crossing the shock from either side the particle sees plasma moving towards it at V= ¾ U.

Peters Cycle

- The acceleration depends on the interaction of the particles being accelerated with the moving magnetic fields and hence on rigidity. For both acceleration and propagation, therefore, if there is a feature characterized by a critical rigidity R*, then the corresponding critical energy per particle is
$$E_{max} = Z \times R^*$$
  - Protons will cut off first at $E_{max} = eR^*$
  - Helium at $E_{max} = 2eR^*$, etc for CNO, Fe
- Peters, 1961 described this cycle of composition change and pointed out the consequences for composition. Since the abundant elements from protons to iron group cover a factor of 30 in Z, the "Peters cycle" should occupy a similar range of total energy

Status of TA Physics: Composition