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

Ph.D. Defense, 2022/04/15

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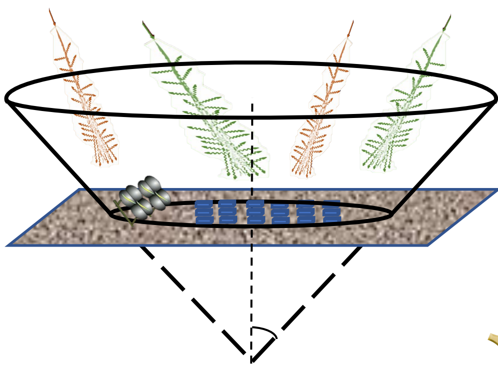
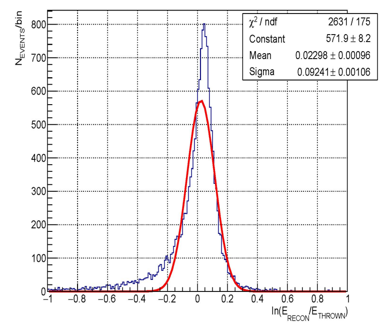
Outline

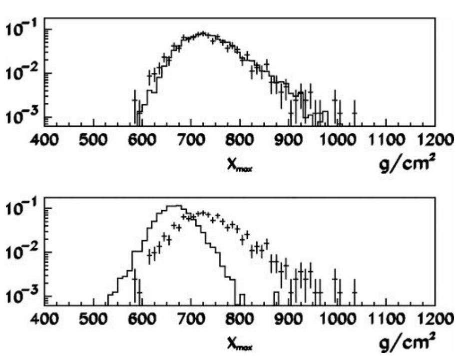
- Motivations
- Introduction to Cosmic Rays
- Detection of Cosmic Rays
  - Direct Detection
  - Indirect Detection
- Telescope Array (TA) Experiment
  - Status of TA Physics
  - Deployment of TAx4, the Expansion of TA
- Hybrid Detection Event Reconstruction
- TAx4 Energy Spectrum in Hybrid Mode

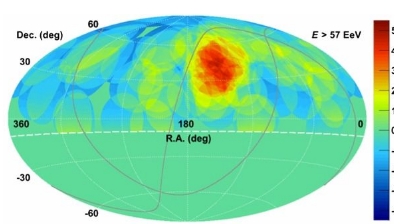
Motivations

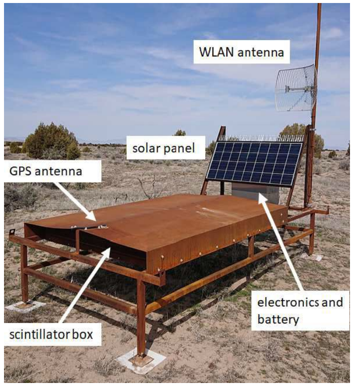
- Validate what we said in our proposals with TAx4
- Determine TAx4 resolutions
- Validate the hybrid MC process
- Calibrate the new TAx4 SDs
- Calculate energy spectrum (monocular and hybrid)
  - Spectrum not competitive but is preliminary to real physics
- Lay the groundwork for composition and anisotropy analyses



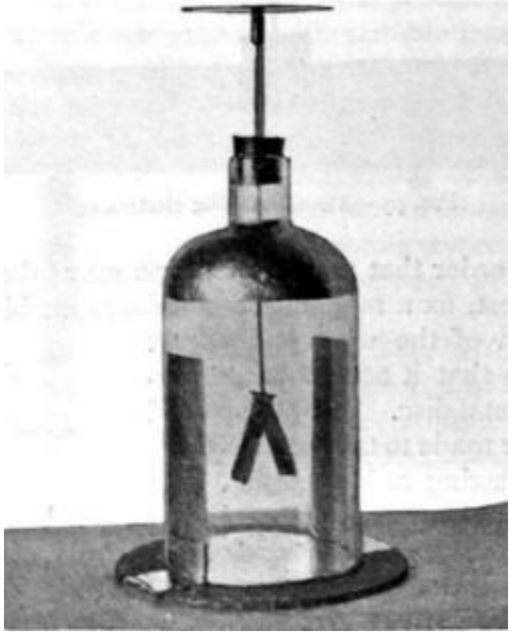


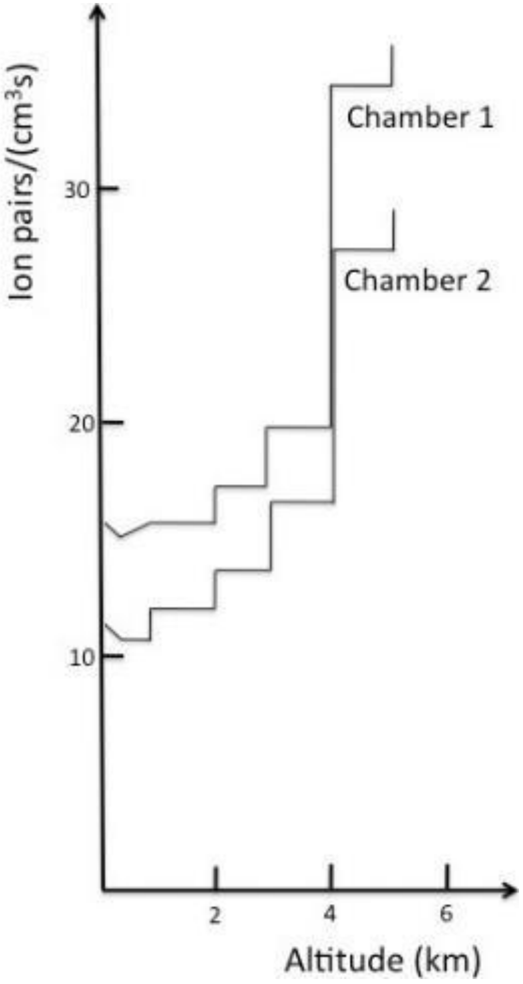






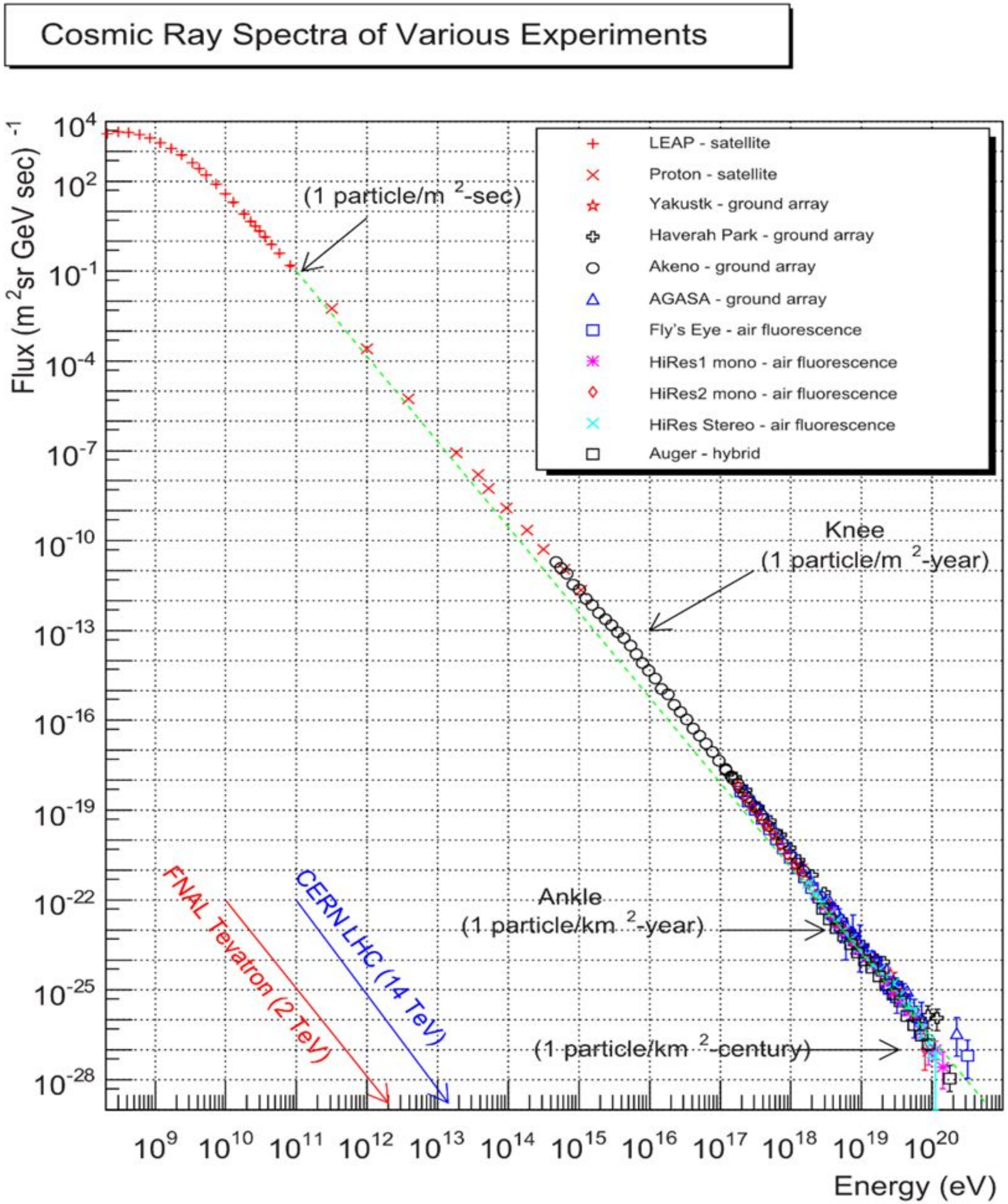
Introduction to Cosmic Rays





- 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

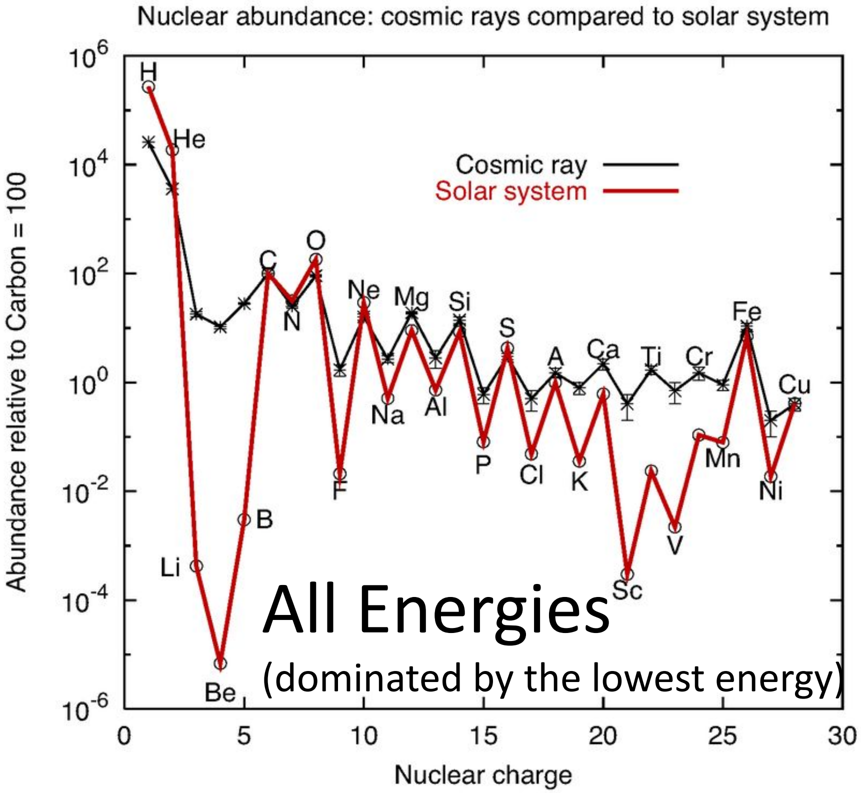


- Cosmic rays span more than 11 orders of magnitude
- 6×10^{18} eV ~ 1 joule
- Highest energy cosmic rays ~10,000,000 times more energetic than Large Hadron Collider (LHC) protons
- Flux falls rapidly:

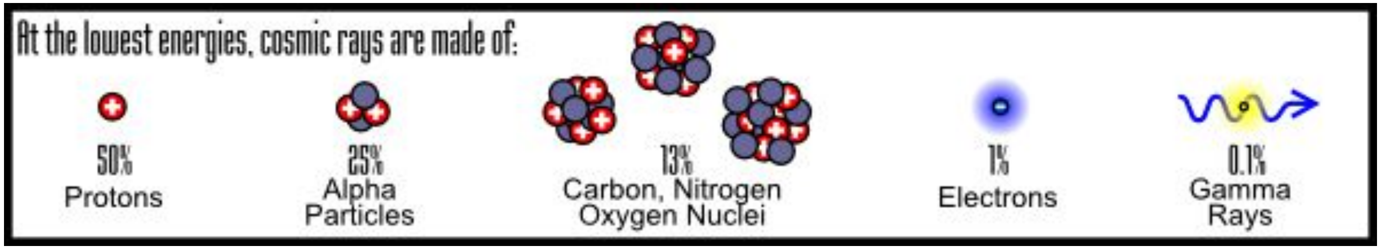
  $\propto E^{-3}$

  Mostly featureless except….

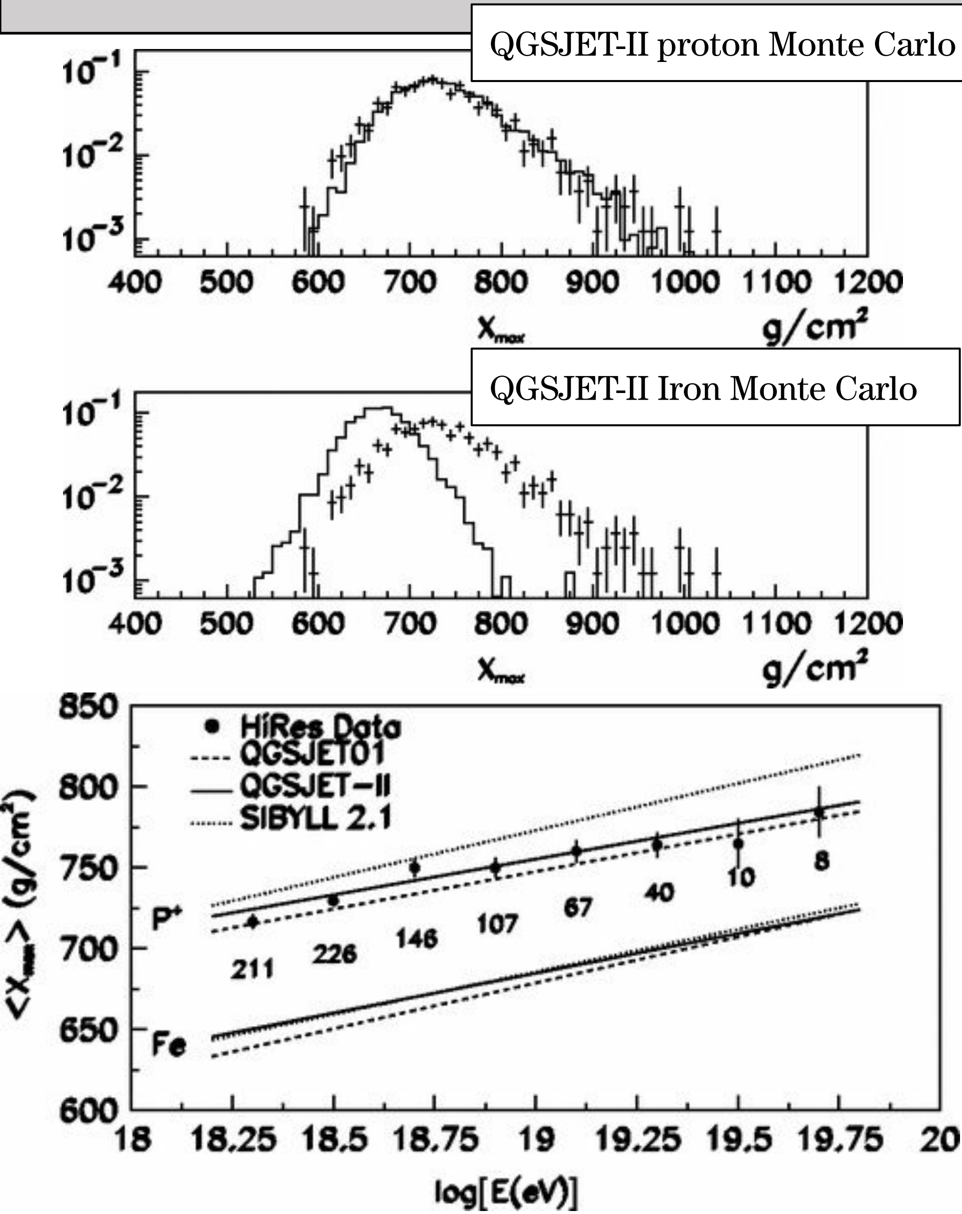
What are they? (1/2)



At low energies, ~10^{12} eV we think they are:



What are they? (2/2)



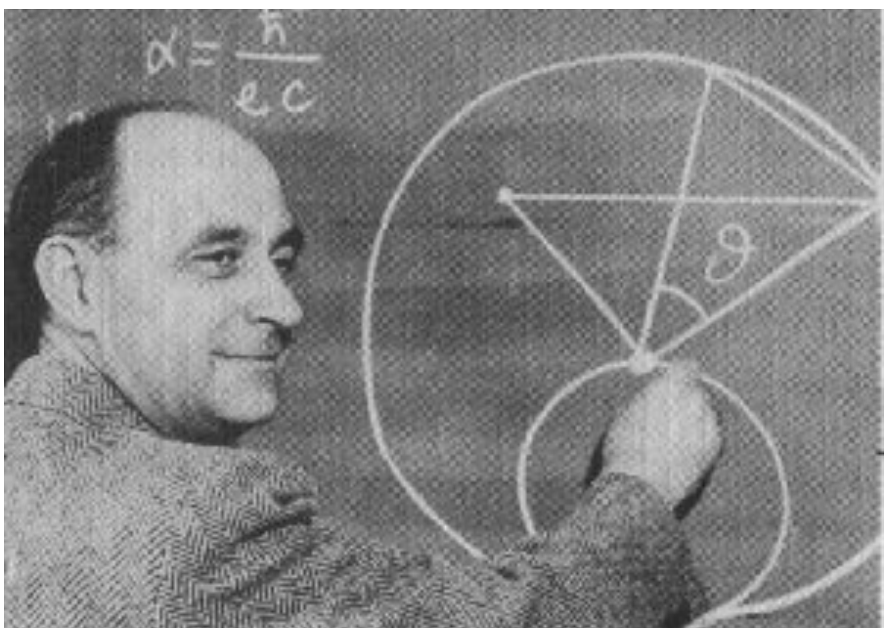
- Cosmic Rays > 10^{18} eV are referred to as "Ultra-High Energy (UHE) Cosmic Rays"
- HiRes was an experiment that operated from Dugway Proving Grounds in Utah from 1997 - 2006
- HiRes is consistent with a predominantly protonic composition [4]

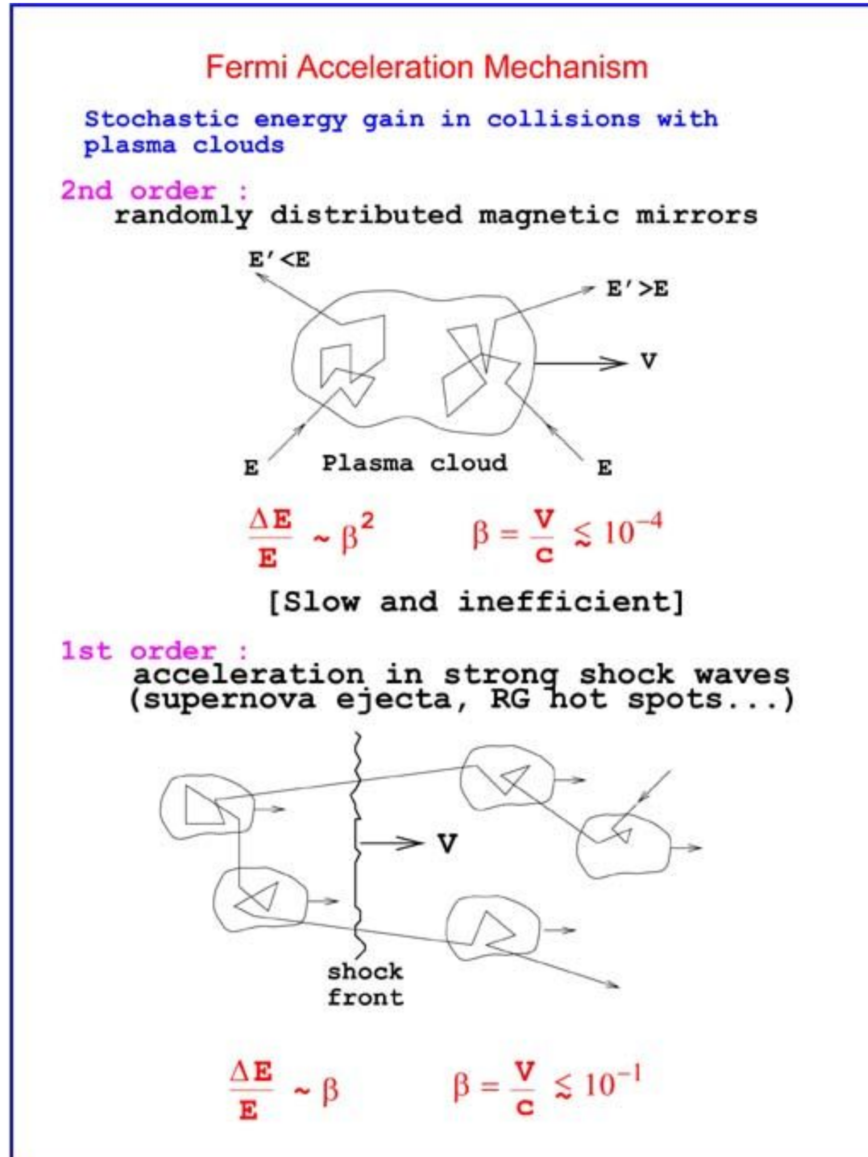
We think they are protons at the highest energy

How are they accelerated?

We're not sure…

Some plausible theories based on ideas of *Enrico Fermi*





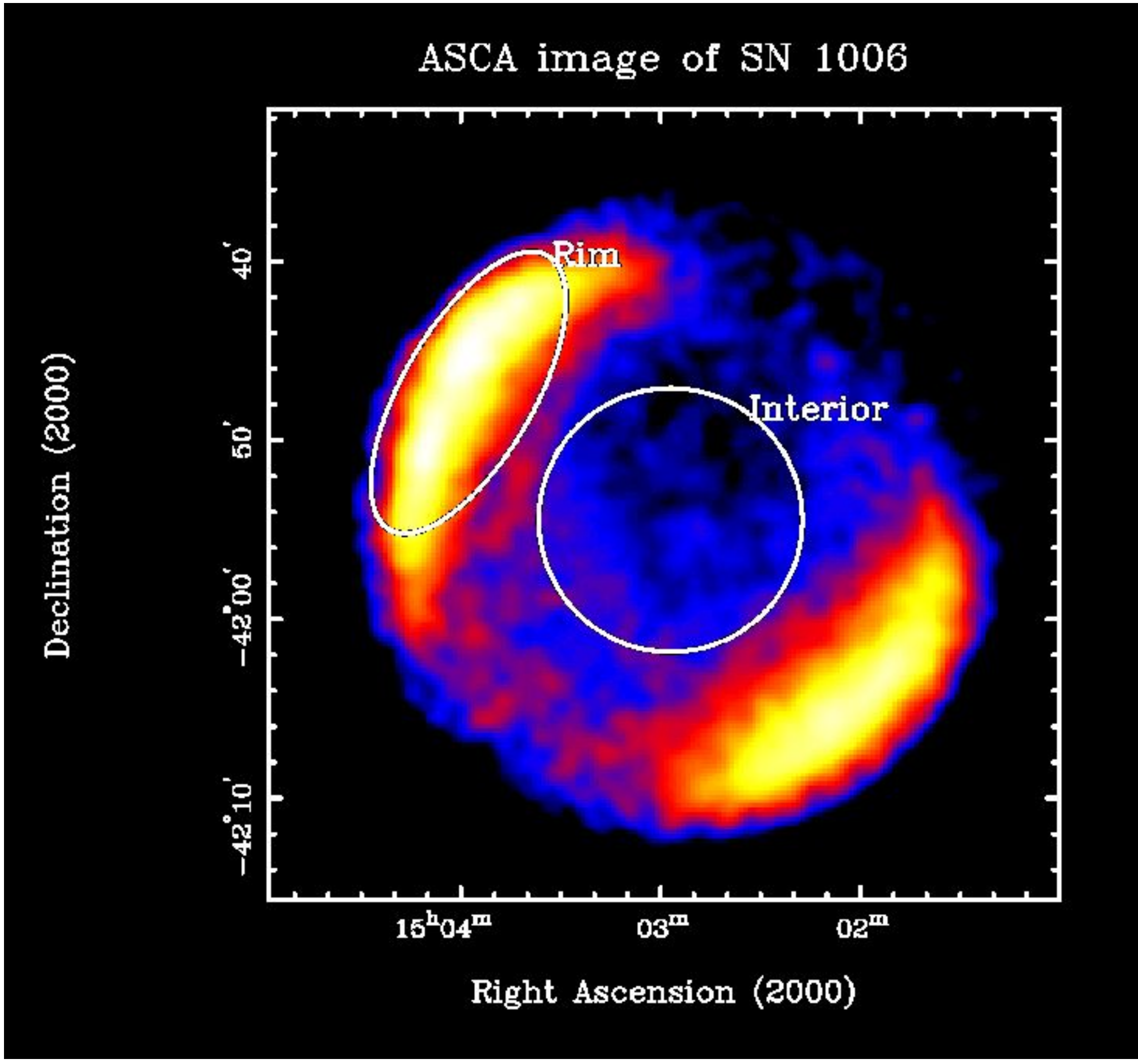
Where do they come from?

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

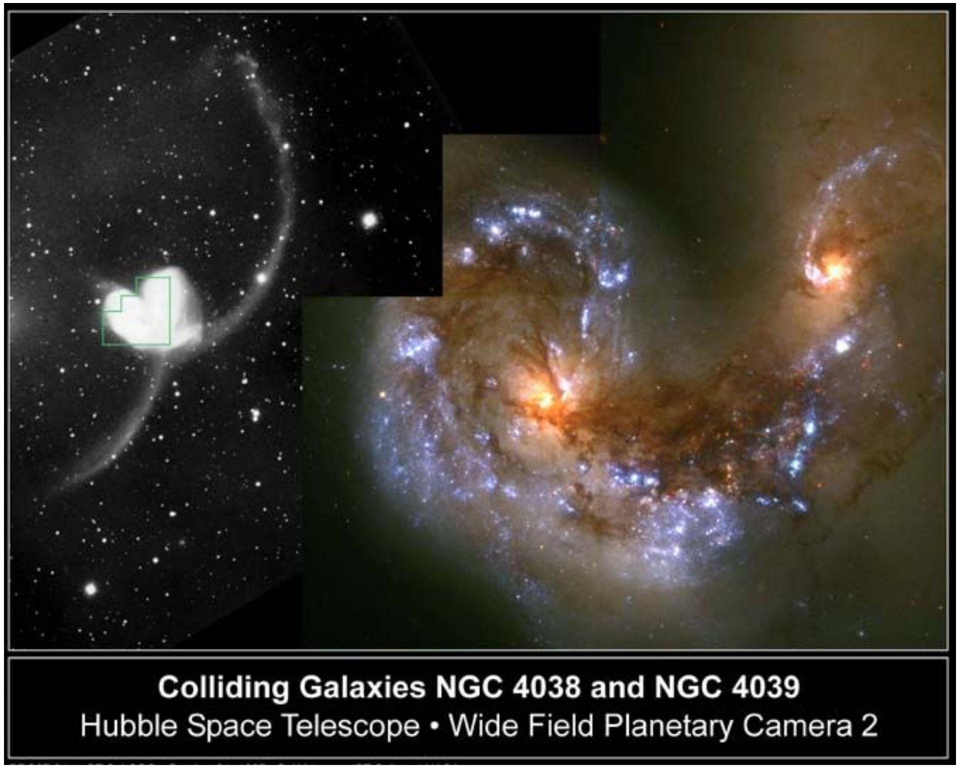
e.g., supernovae

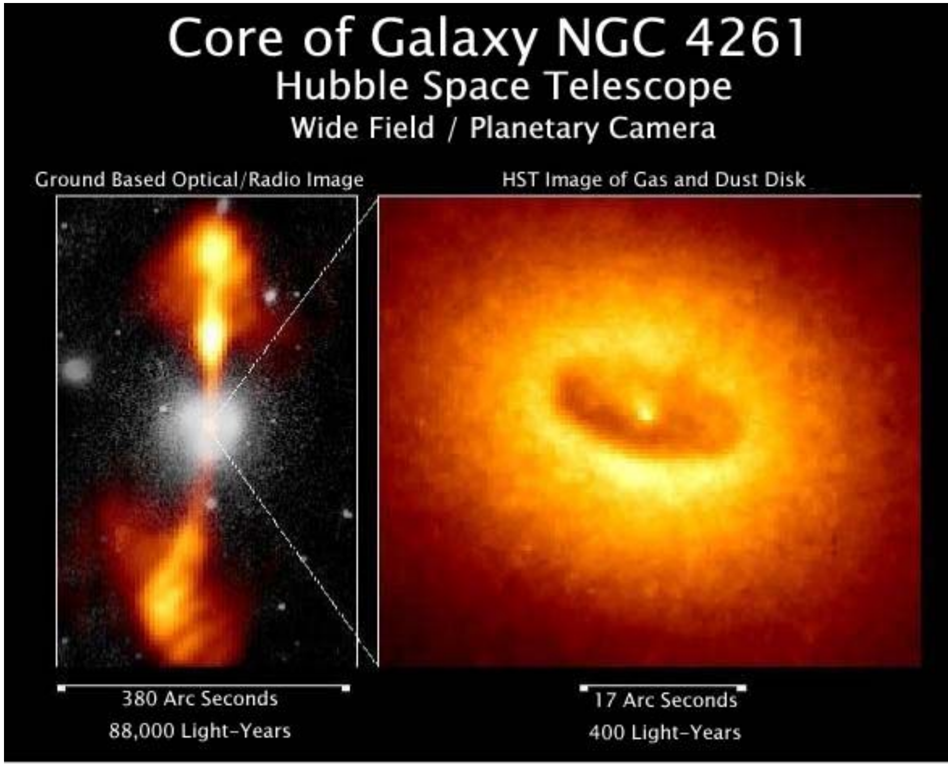
Problems:

- 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

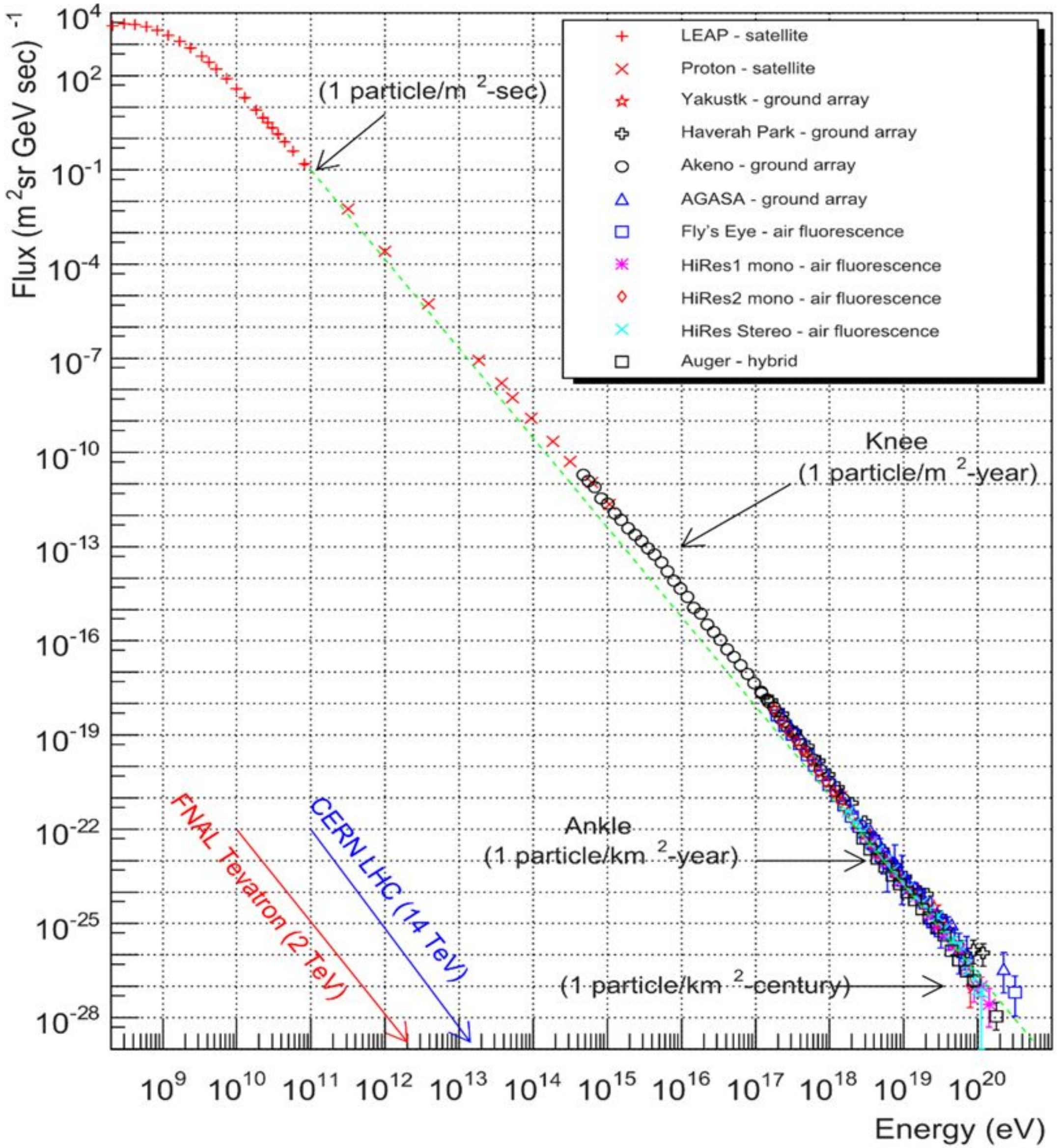




- Colliding galaxies, Active Galactic Nuclei (AGN), etc.
- Decay/annihilation of some unknown super-heavy particles or cosmological relics from the creation of the Universe?
- New physics?

Direct Measurement

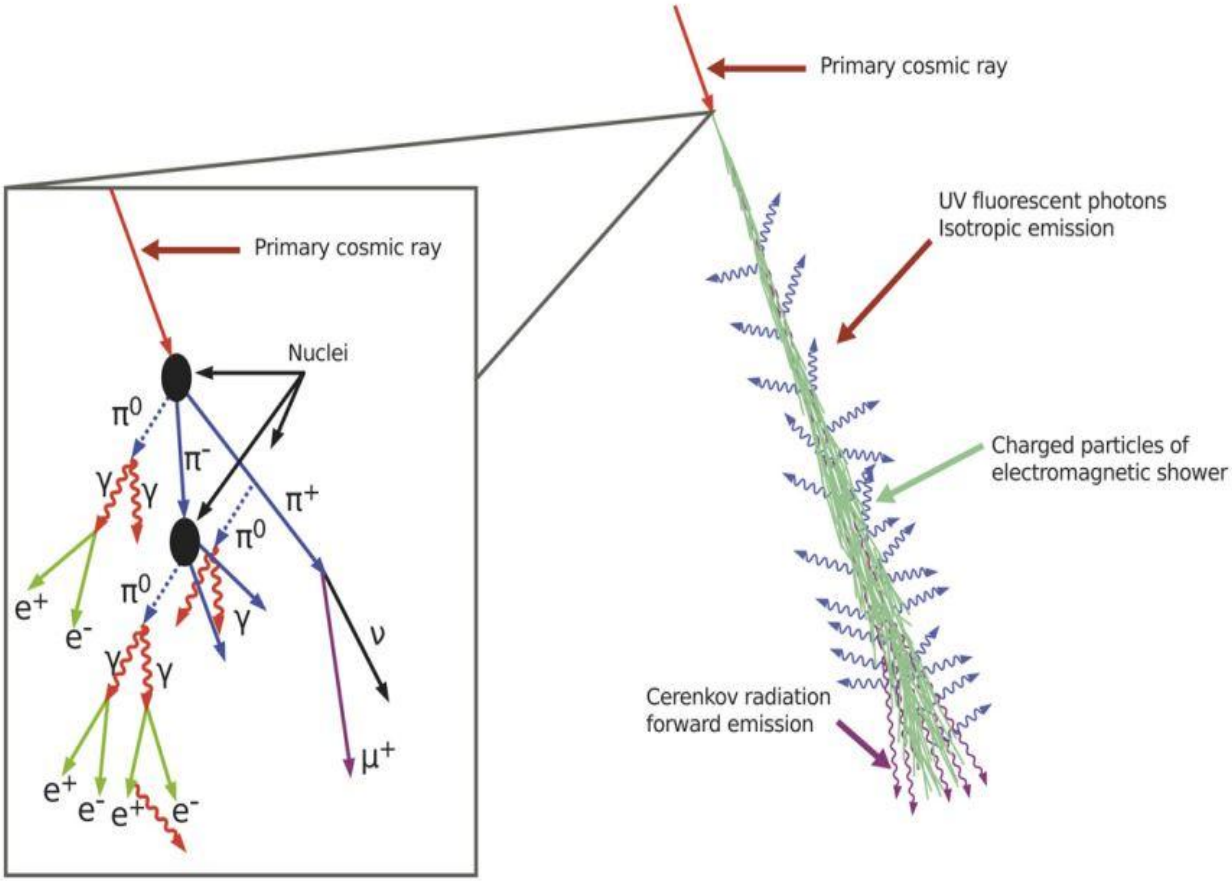
- E < 10^{14} eV flux is large enough to allow direct measurement on balloons, satellites, shuttle missions
- E > 10^{17} eV, we expect a flux < 10^{-10}/m^2 sr sec
- A 1 m^2, 2 sr detector sees < 1 event/50 years



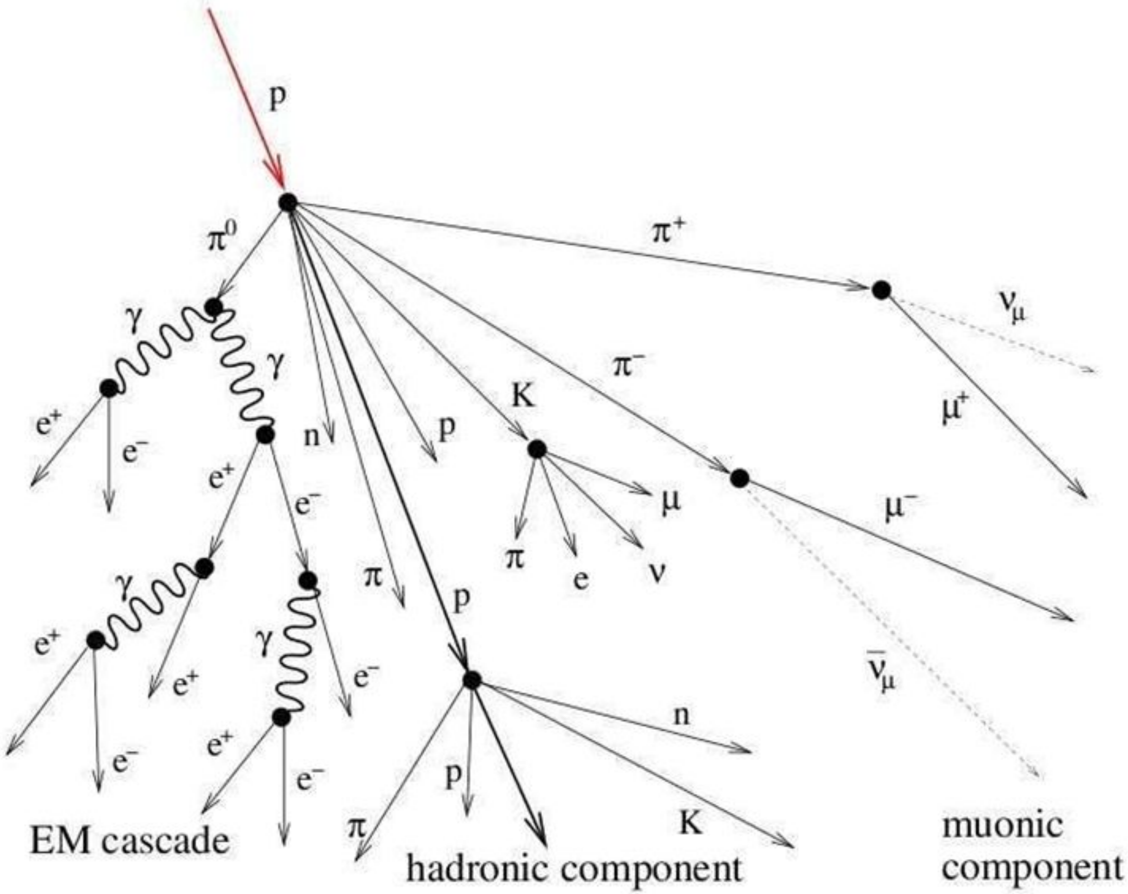
Direct measurement is impractical!!!

Indirect Measurement

- Use the Earth's atmosphere as your detector.
- Cosmic rays initiate Extensive Air Showers (EAS) high in the atmosphere
- Shower continues until the energy is spread over many particles
- EAS have three components

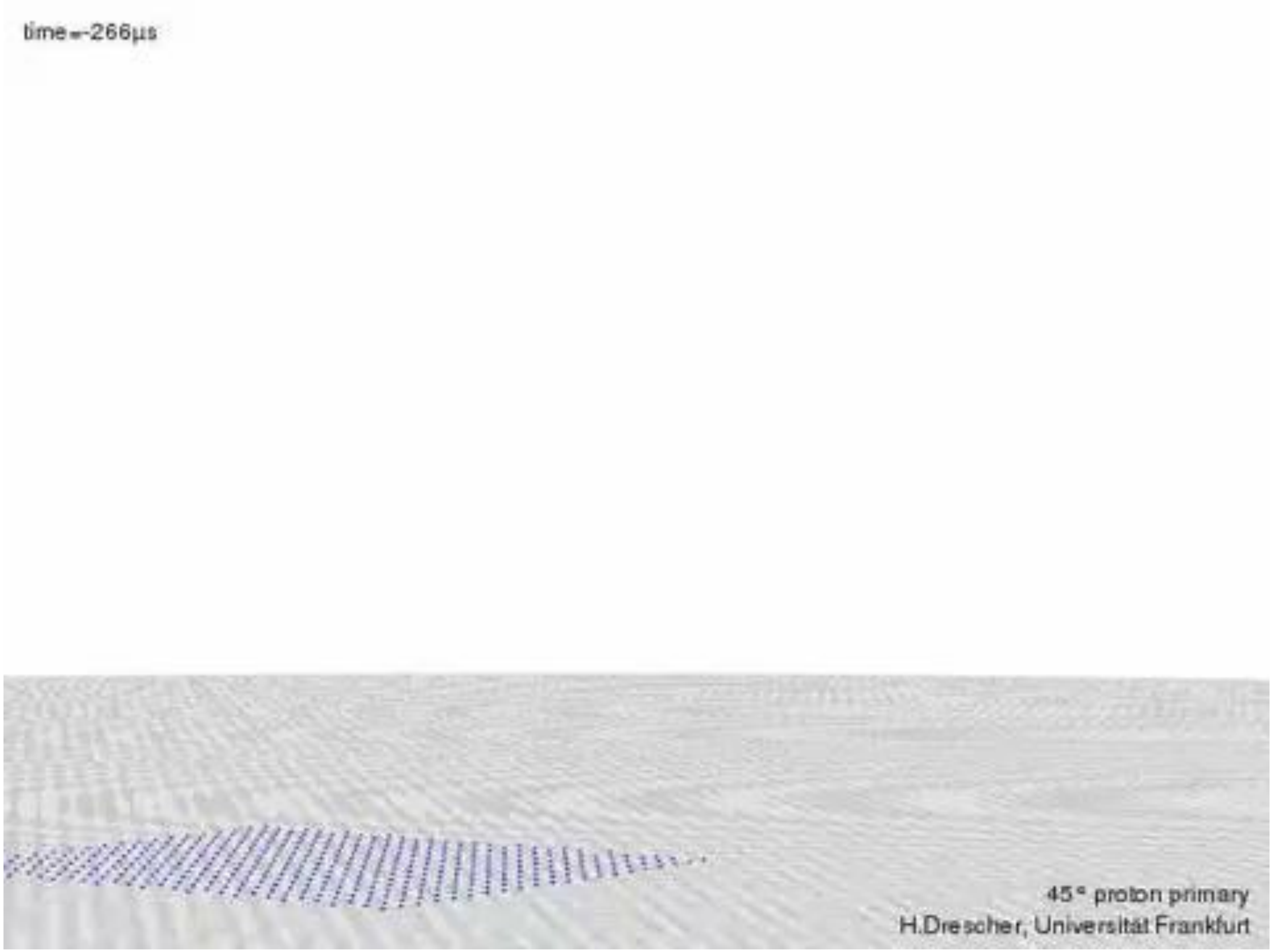


Extensive Air Shower Components



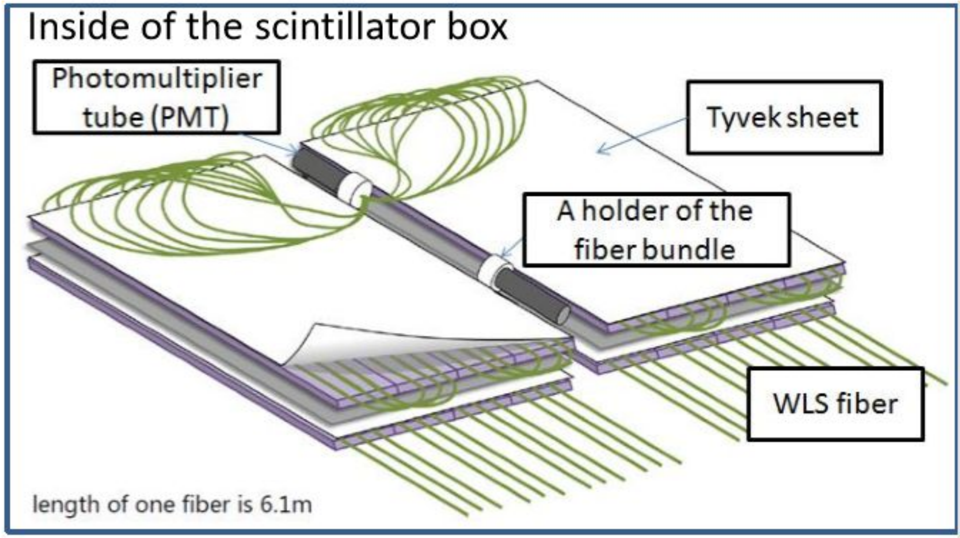
- Hadronic Component:
  - Core of the EAS
  - Feeds other components
- Electromagnetic (EM) Cascade:
  - Neutral Pions, π^0, decay into photons
    - Mean Lifetime: 8.05×10^{-17} s
  - Photons undergo pair-produce
  - Electrons undergo bremsstrahlung
- Muonic Component:
  - Charged Pions, $\pi^{\pm}$, decay into muons and neutrinos
    - Mean Lifetime: 2.6×10^{-8} s
  - Energy carried away from the EAS

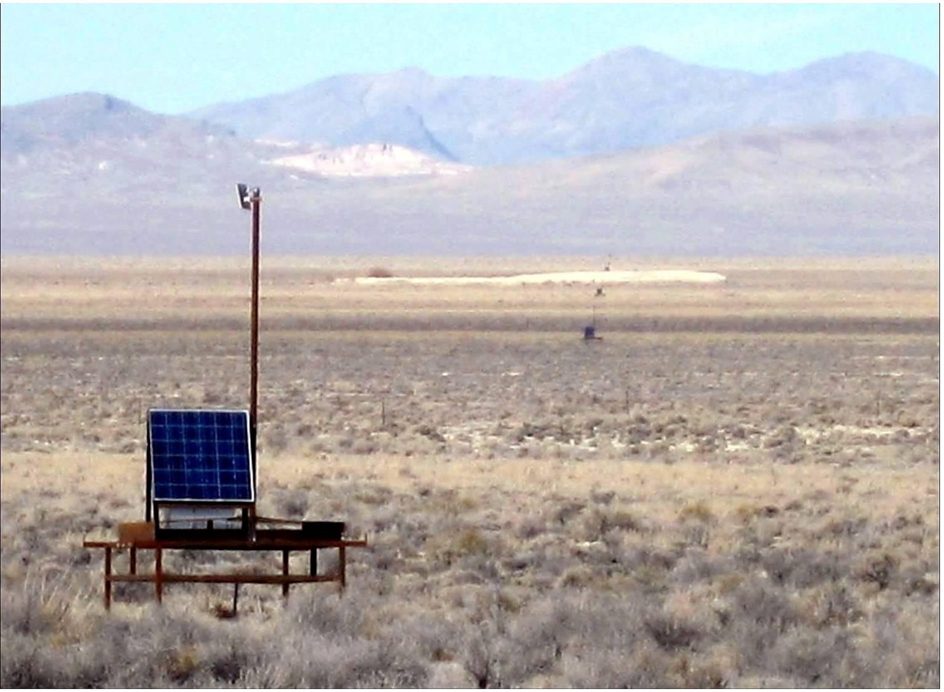
Extensive Air Shower (EAS)

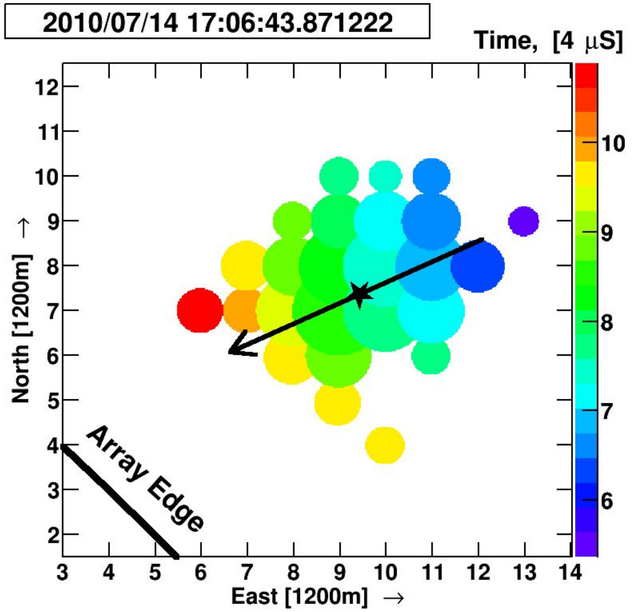


Surface Detectors (SDs)

- 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)

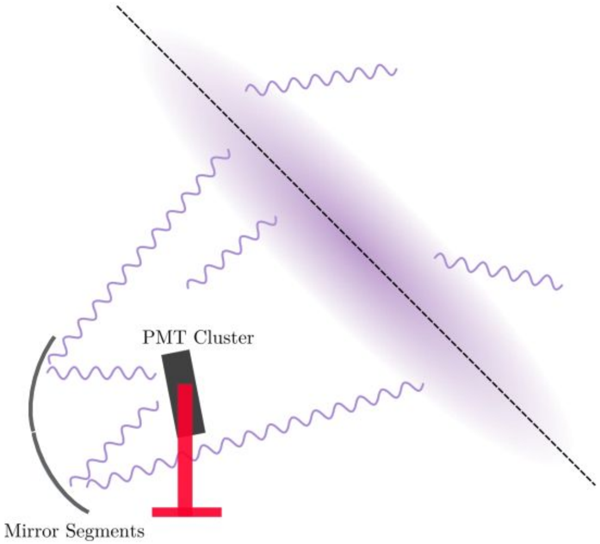




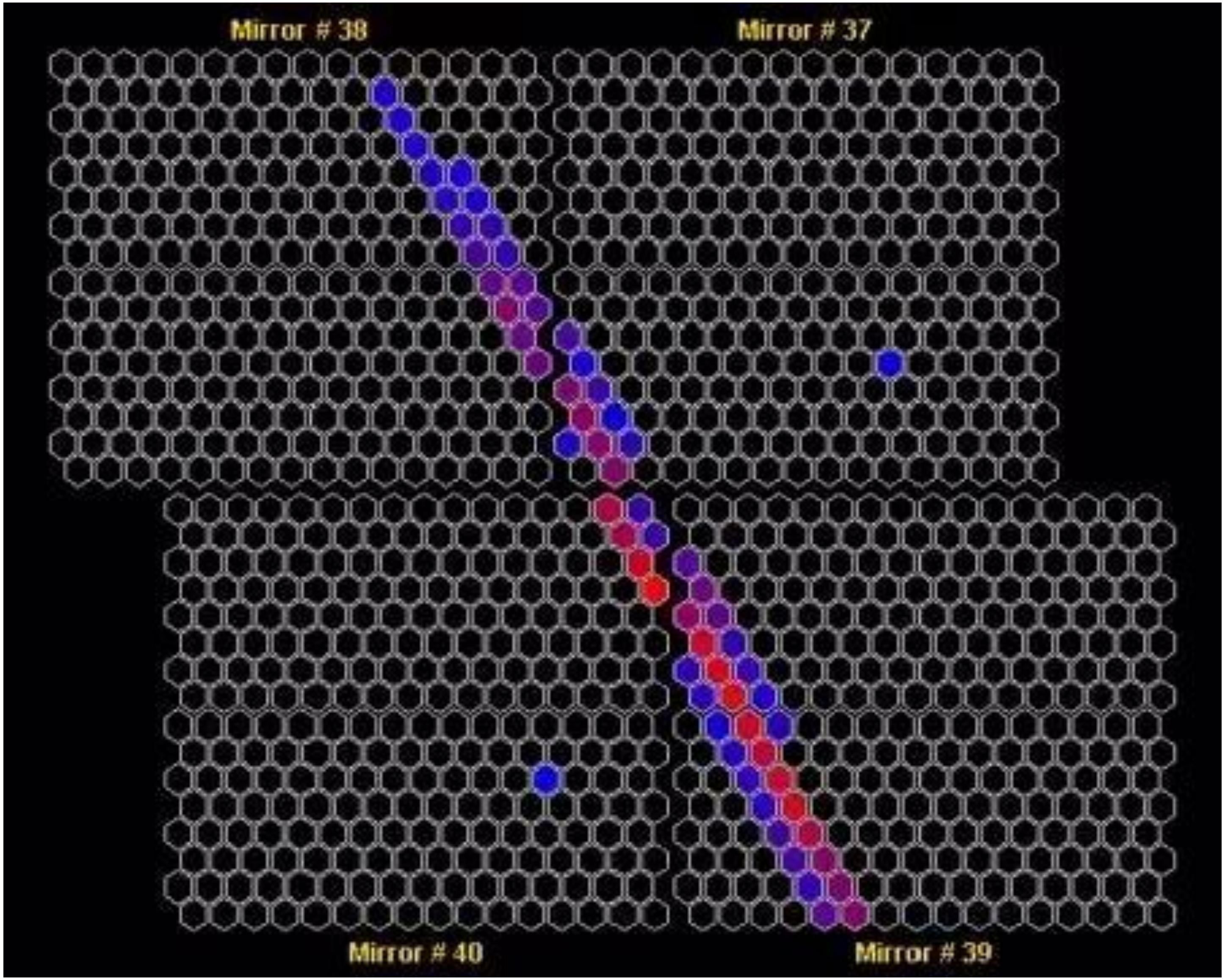


Fluorescence Detectors (FDs)

- Samples UV light emitted in the wake of the EAS
  - Excited molecular nitrogen in the atmosphere which emits light in the near UV (300-420 nm)
- Sensitive to cosmic rays >$10^{15.3}$ eV
- Operates on clear, moonless nights
- Intensity of the light signal along the EAS track allows for reconstruction of the EAS charged particle profile
  - Longitudinal shower development "chemical composition"
  - Energy estimation using fluorescence yield



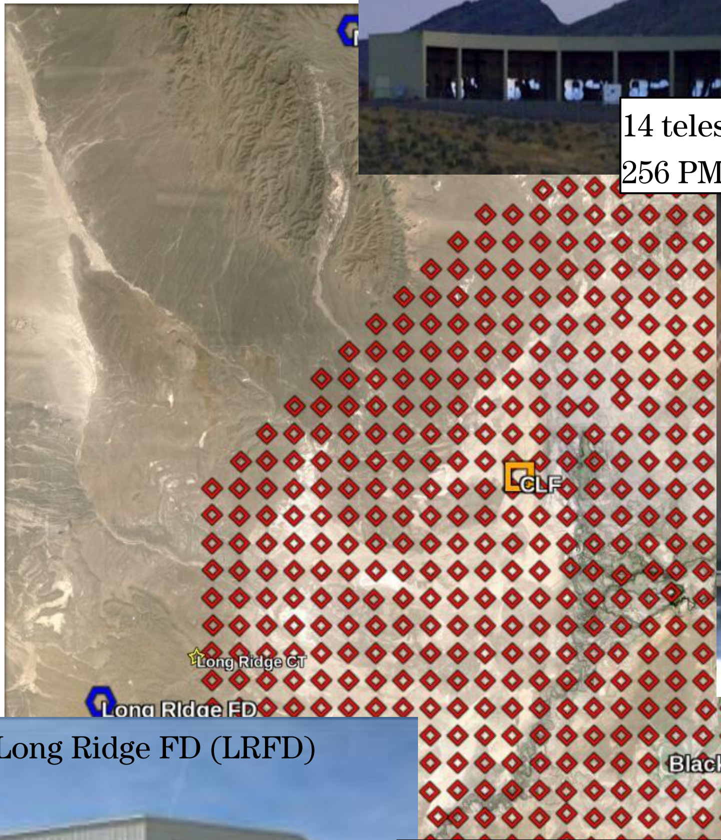
Example Animation of FD Event



- 1/500,000 playback speed
  - Each frame is 100 ns
- PMTs view 1^{0} full angle cone of the sky

Telescope Array (TA)

- Largest UHE cosmic ray detector in the Northern Hemisphere
  - Covers ~700 km^2
- 507 Surface detectors (red diamonds) coverage
  - 1.2 km spacing
- Three fluorescence stations overlooking SD array (blue hexagons)
  - Black Rock (BRFD)
  - Long Ridge (LRFD)
  - Middle Drum (MDFD)

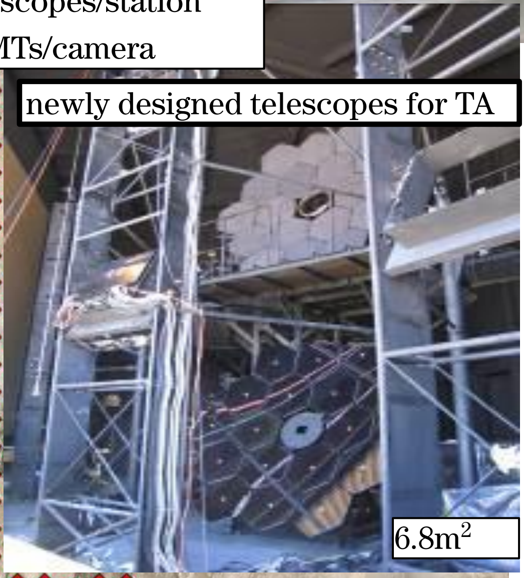


refurbished HiRes-I telescopes

5.2m^2

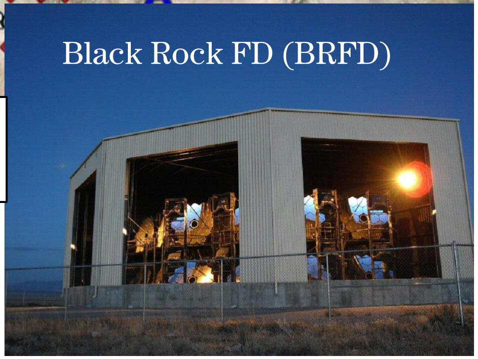
14 telescopes/station
256 PMTs/camera

newly designed telescopes for TA



6.8m^2

12 telescopes/station
256 PMTs/camera



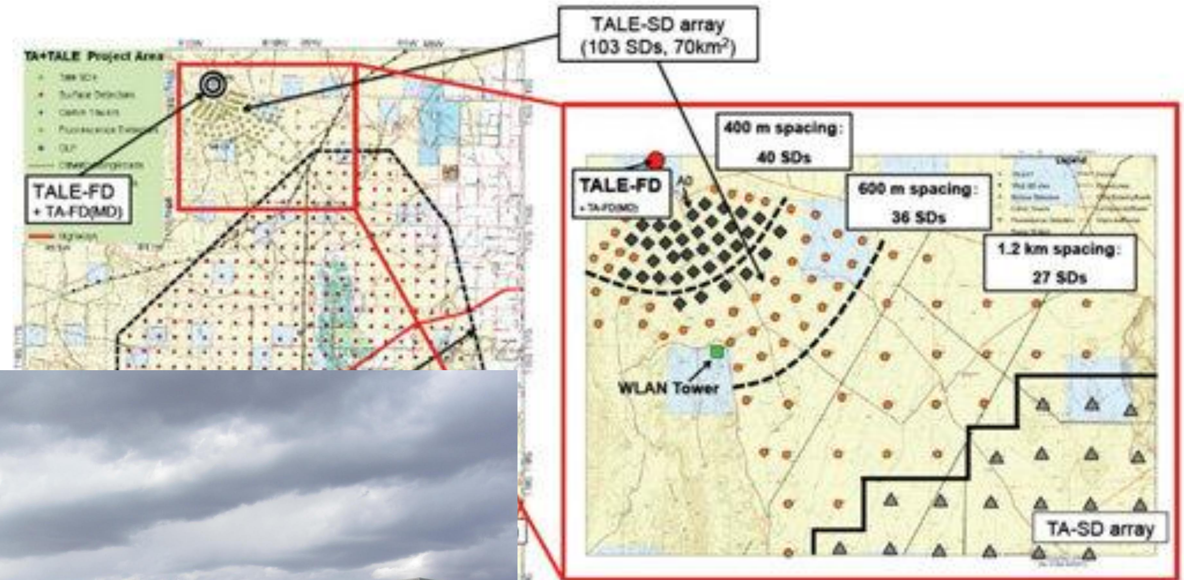
Telescope Array Low Energy extension (TALE)

- 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.

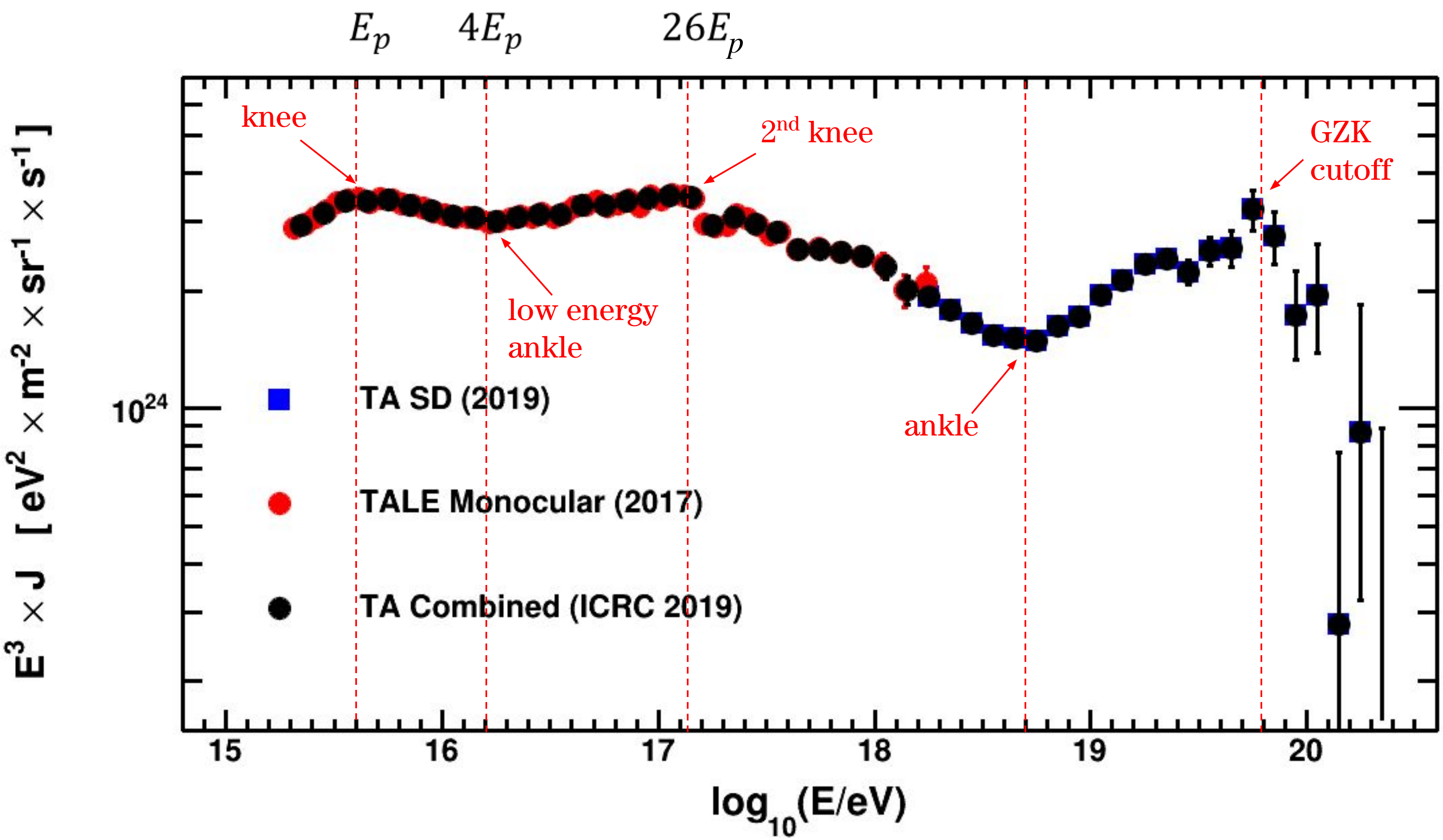
refurbished HiRes-II telscopes

5.2m^2

10 telescopes/station for higher elevation angles (31°–59°)

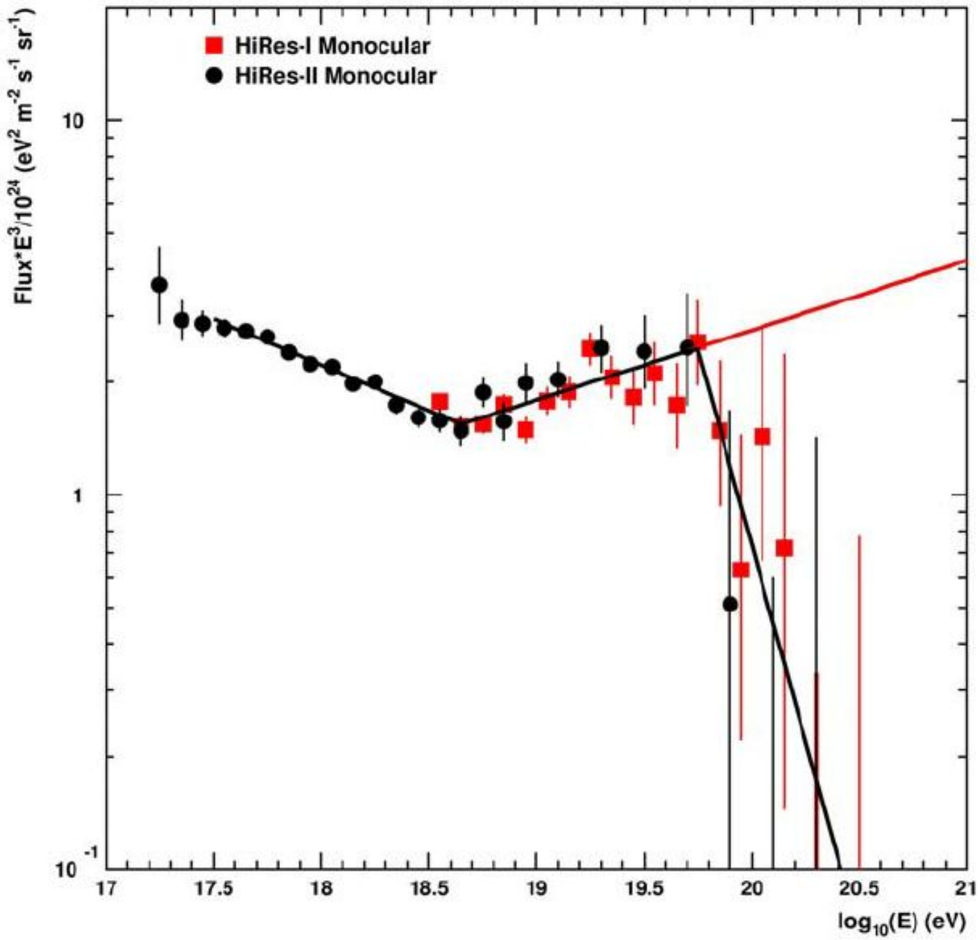


Status of TA Physics: Energy Spectrum



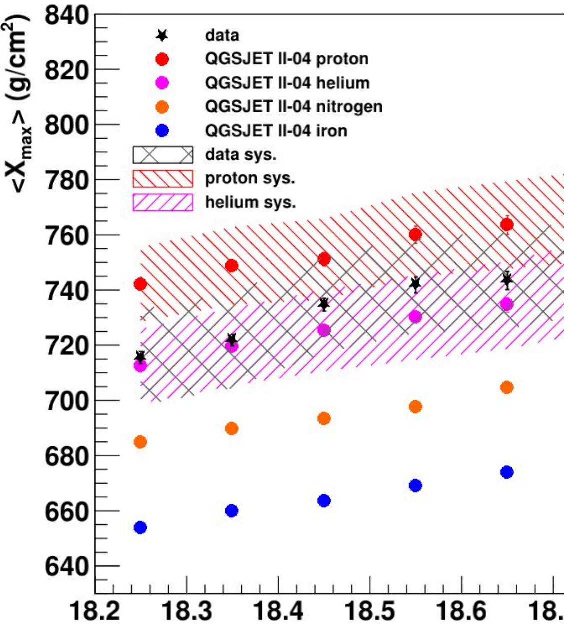
Status of TA Physics: Energy Spectrum

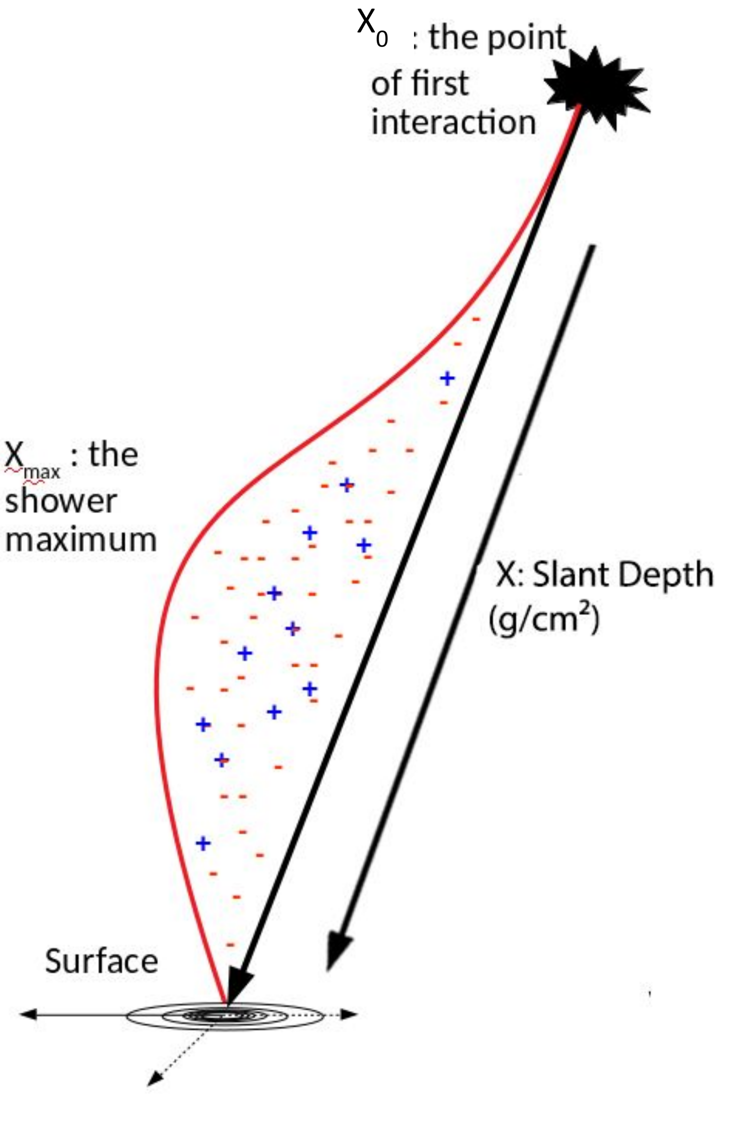
- Theoretical upper limit on the energy of cosmic ray protons traveling from other galaxies.
  - $\sim 5 \times 10^{19}\ eV$
  - The limit is set by interactions of the protons with the cosmic microwave background radiation (CMB)
    - $\gamma_{CMB} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$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



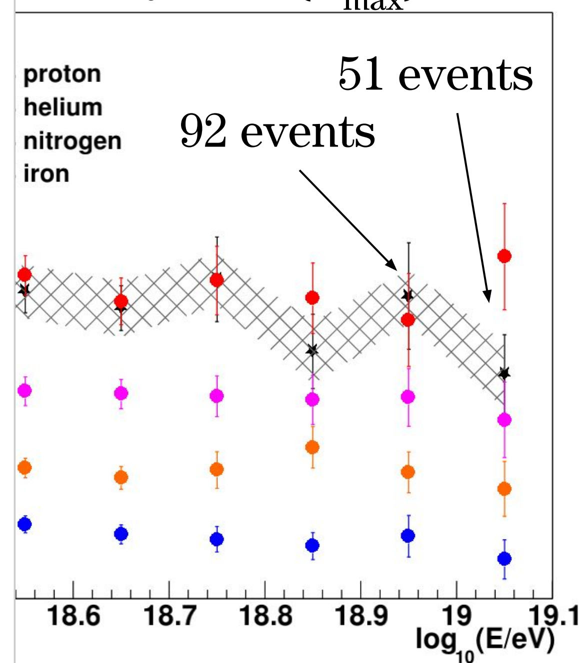
Status of TA Physics: Composition

10 year BR/LR hy





R/LR hybrid $\sigma(X_{max})$

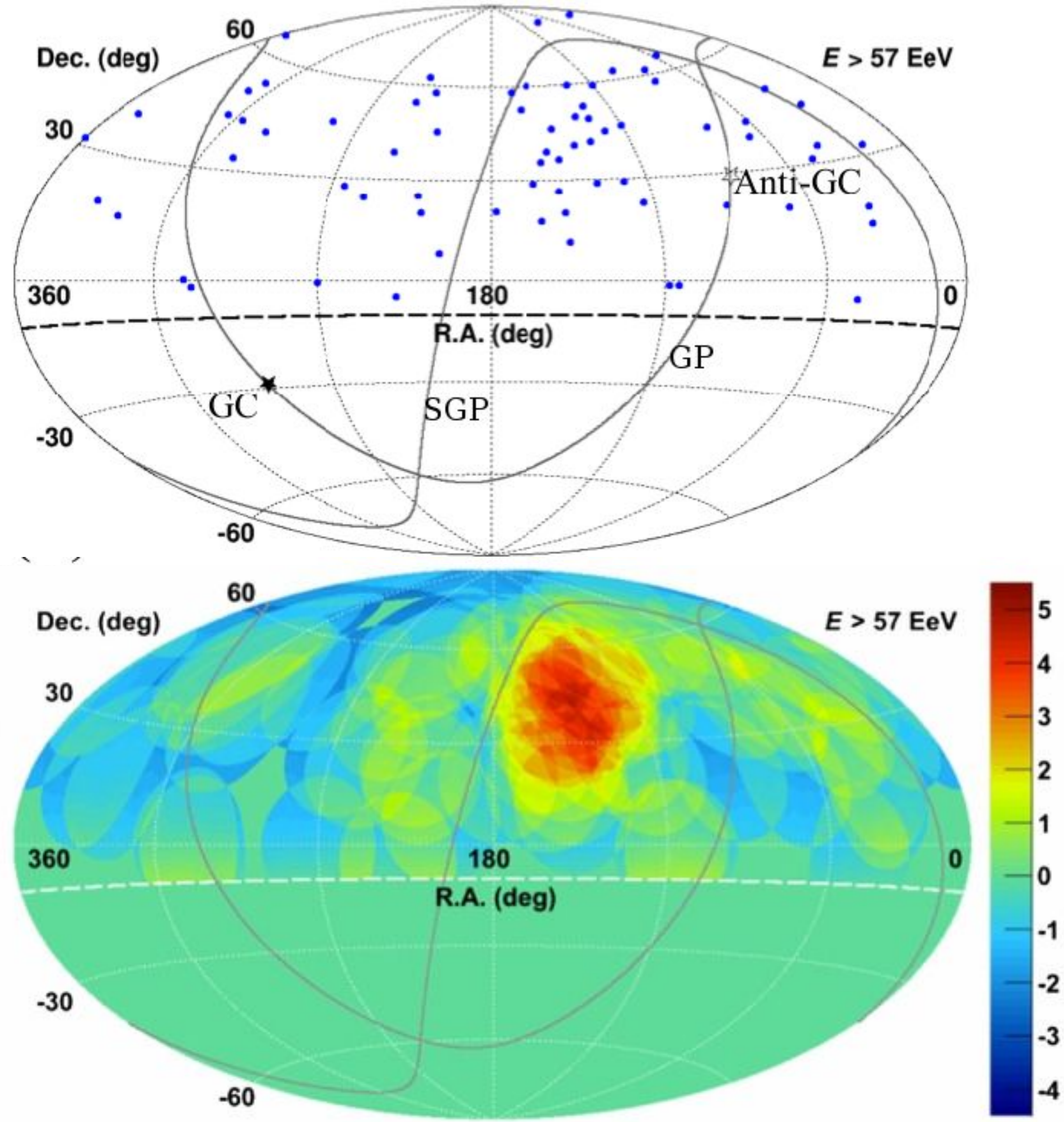


- Slant depth is … by a shower
- $\sigma(X_{max})$ is rela… e $\langle X_{max} \rangle$ which is model deper…
- Consistent wit… eV
- Insufficient st…
  - 96 events, …

Status of TA Physics: Hot Spot

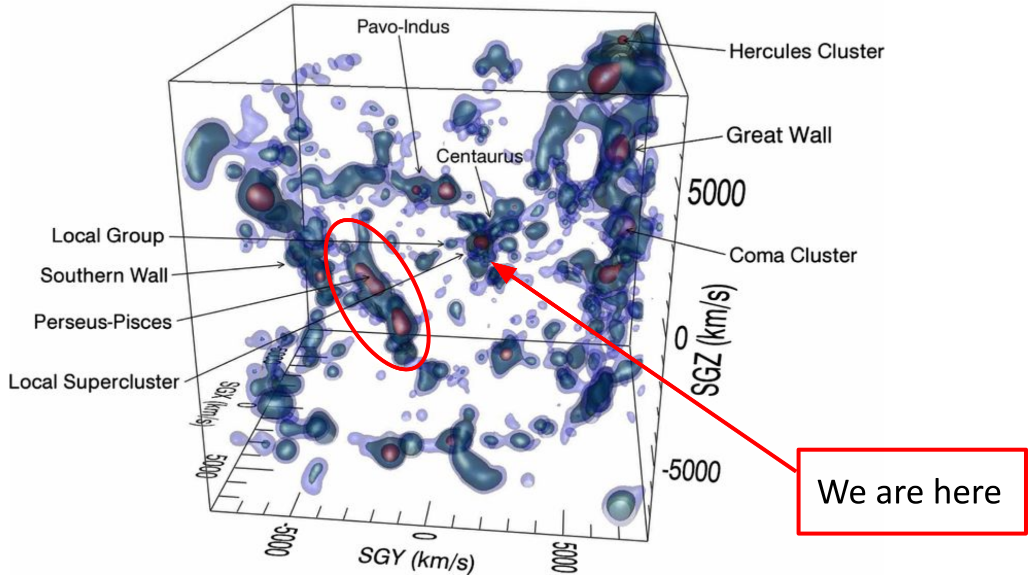
- TA has seen indication of possible *nearby* source of ultra high energy cosmic rays (UHECRs)
  - Local significance 5.1 σ
  - Global significance 3.4 σ

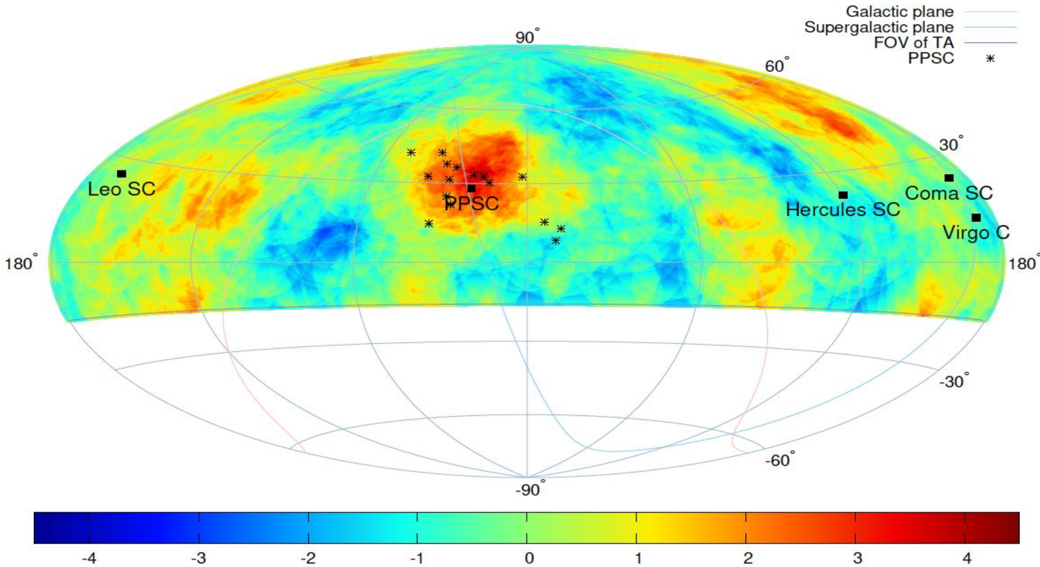
- 72 cosmic rays with E > 5.7×10^{19} eV can't have traveled much further than 100-300 million light years



Status of TA Physics: New "Blob"

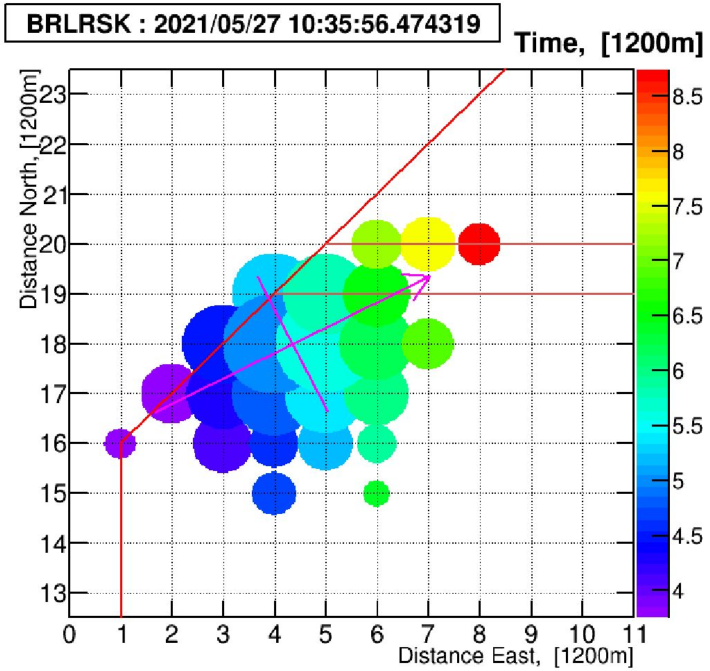
- The new "blob" is an excess of *relatively* low energy events
  - Near the Perseus-Pisces supercluster (PPSC)
  - Local significance ~4 σ
  - Global significance 3.5 σ
- PPSC is about 70 Mpc away
  - Closest supercluster in the Northern Hemisphere

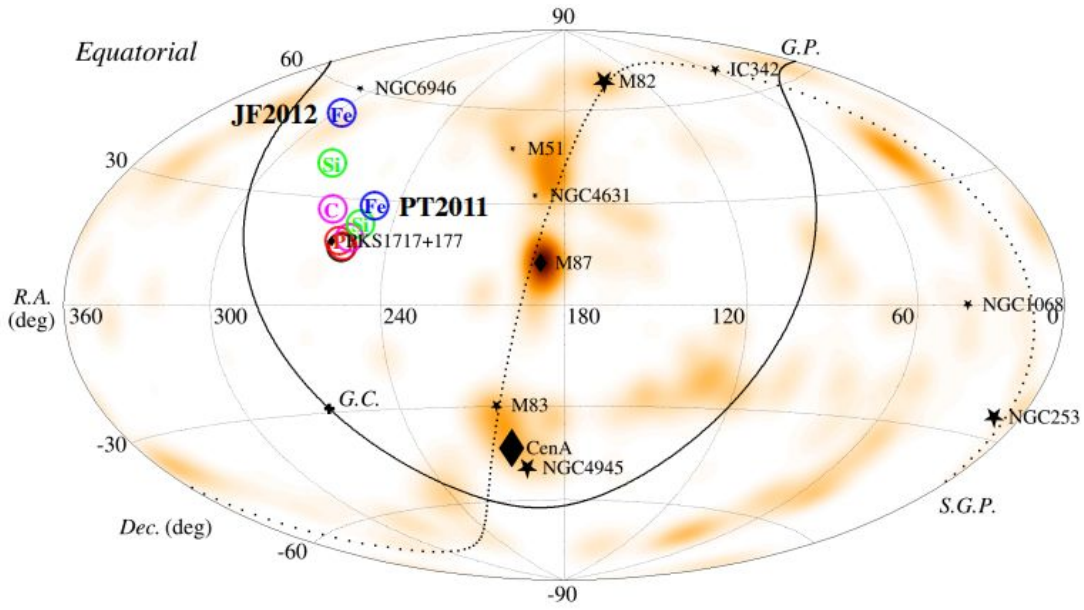




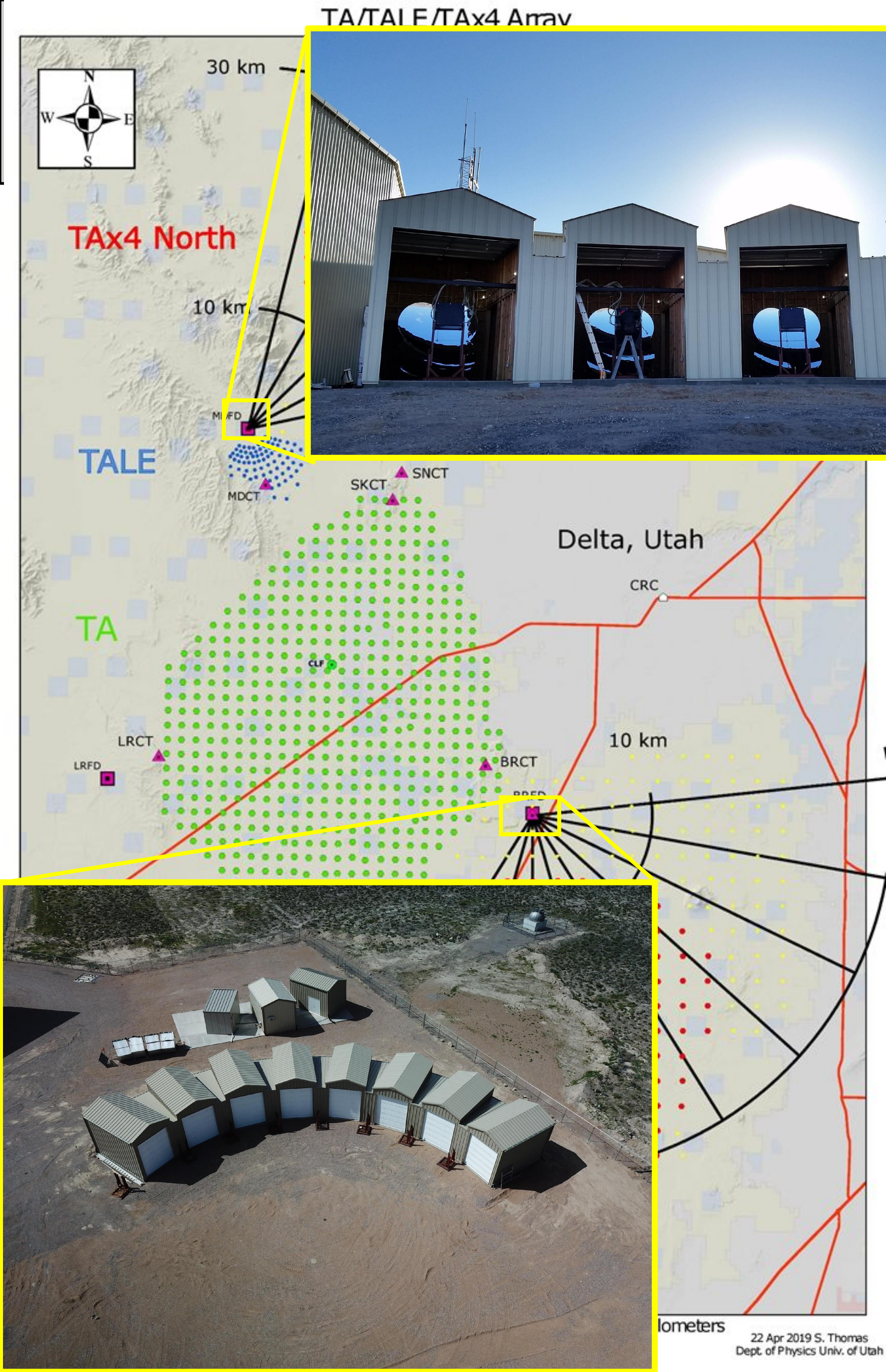
Status of TA Physics: Highest Energy Event

- Highest energy event in the recent 30 years detected by TA SDs!
  - Detected on May 27, 2021
  - $(2.44 \pm 0.11\ (\text{stat.}) \pm 0.51\ (\text{syst.})) \times 10^{20}$ eV
- Other high energy events
  - 1991 Fly's Eye (OMG particle): $(3.20 \pm 0.38\ (\text{stat.}) \pm 0.85\ (\text{syst.})) \times 10^{20}$ eV
  - 1993 AGASA: 2.13×10^{20} eV





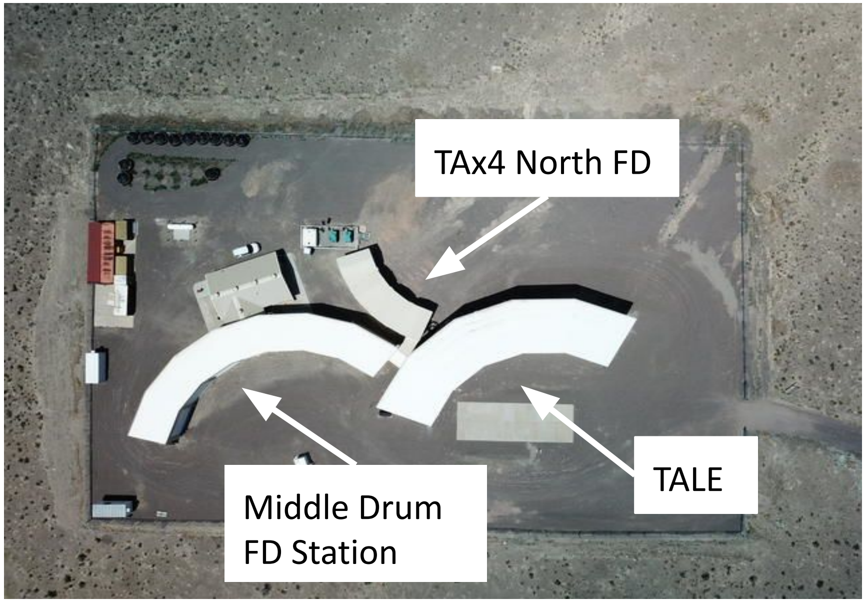
TAx4



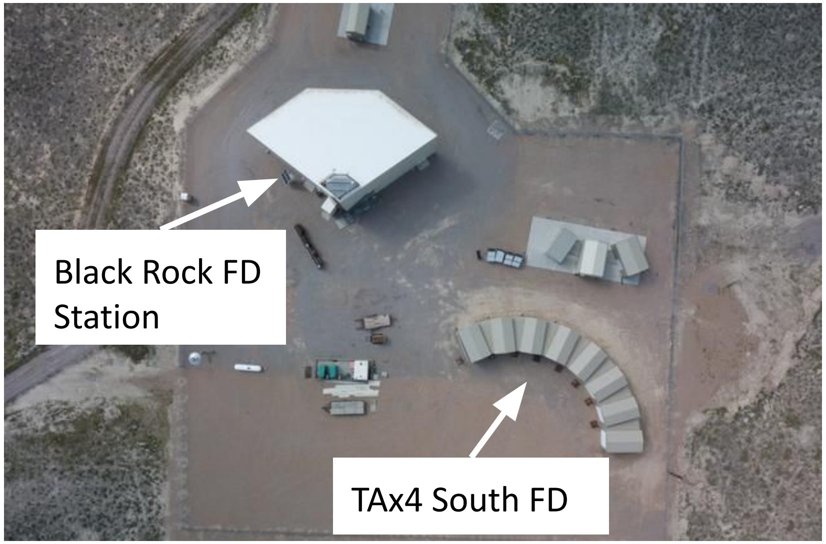
- rfold increase in size of TA SD array
  - Plan to add 500 scintillators SDs at 2.08 km spacing
  - 257 SDs deployed
- The goal of TAx4 is to increase the statistics for the highest energy range (E > 20 EeV)
  - In ~5 years of collecting data it will triple the TA data set
- Added 2 FD stations, 12 refurbished HiRes-II telescopes spread over two sites (TAx4 North FD, TAx4 South FD)
  - Calibrate SDs
  - Improve TA's hybrid composition statistics at the highest energies

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



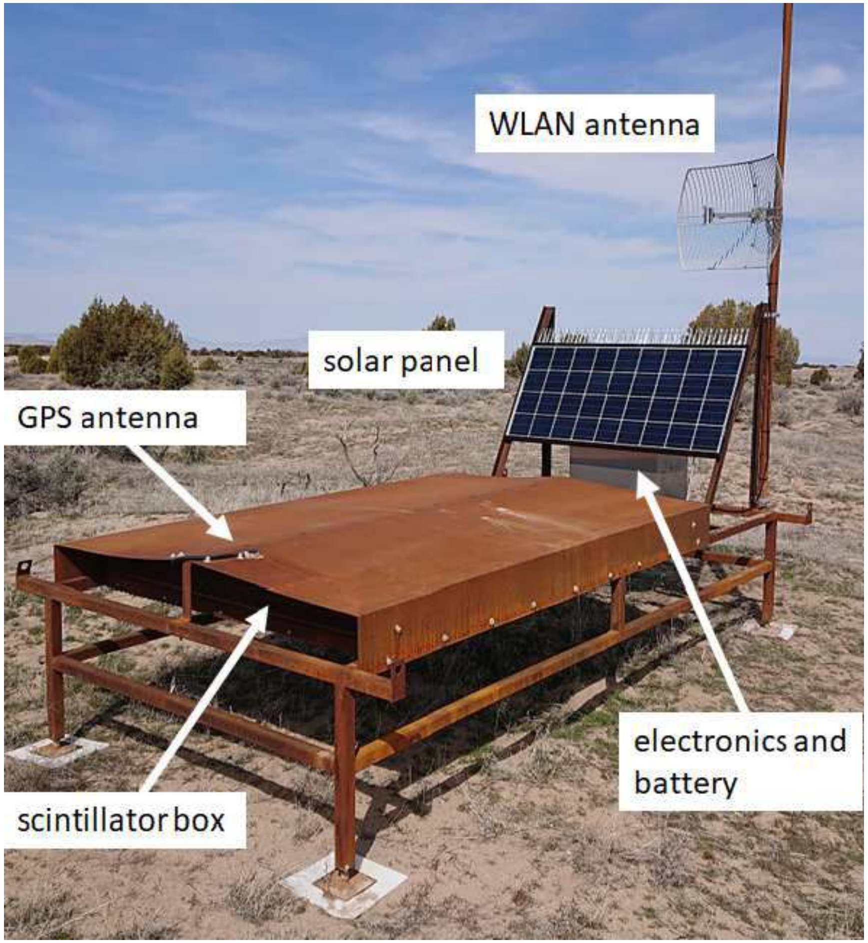
Status of TAx4 South FDs



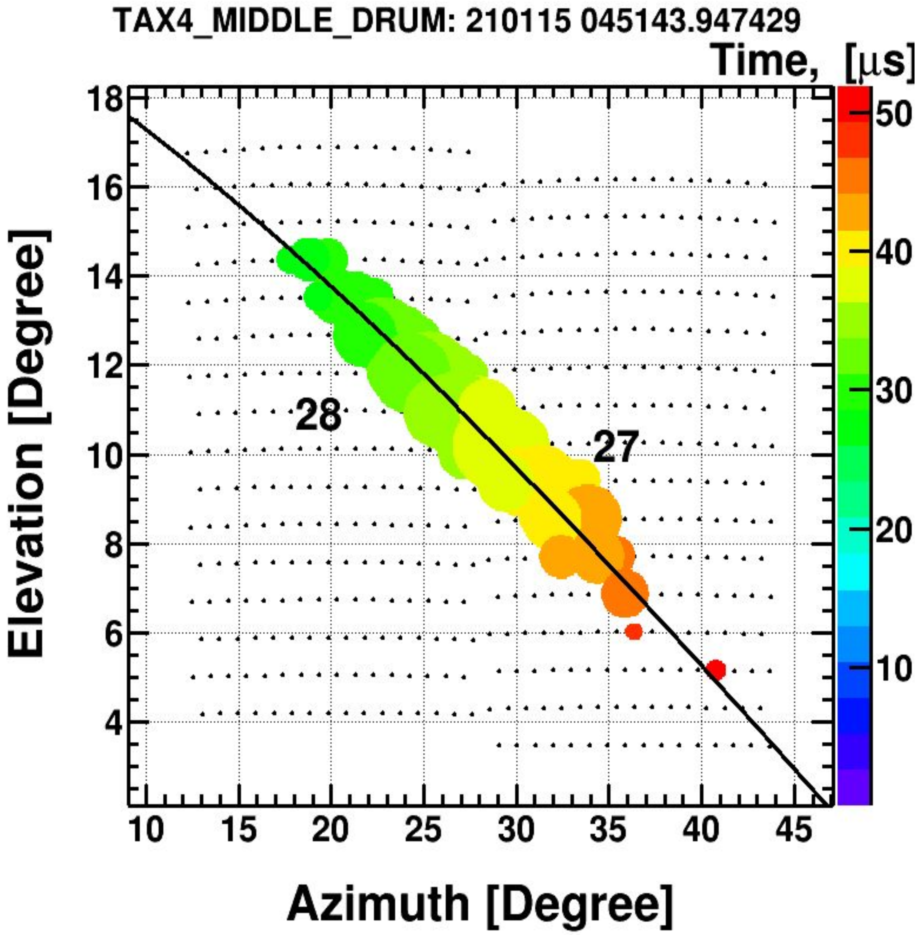
- Construction completed in July 2019
- First night of observation October 21st, 2019. Commissioning of the detector began
- Remote data collection started in July 2020

Status of TAx4 SDs

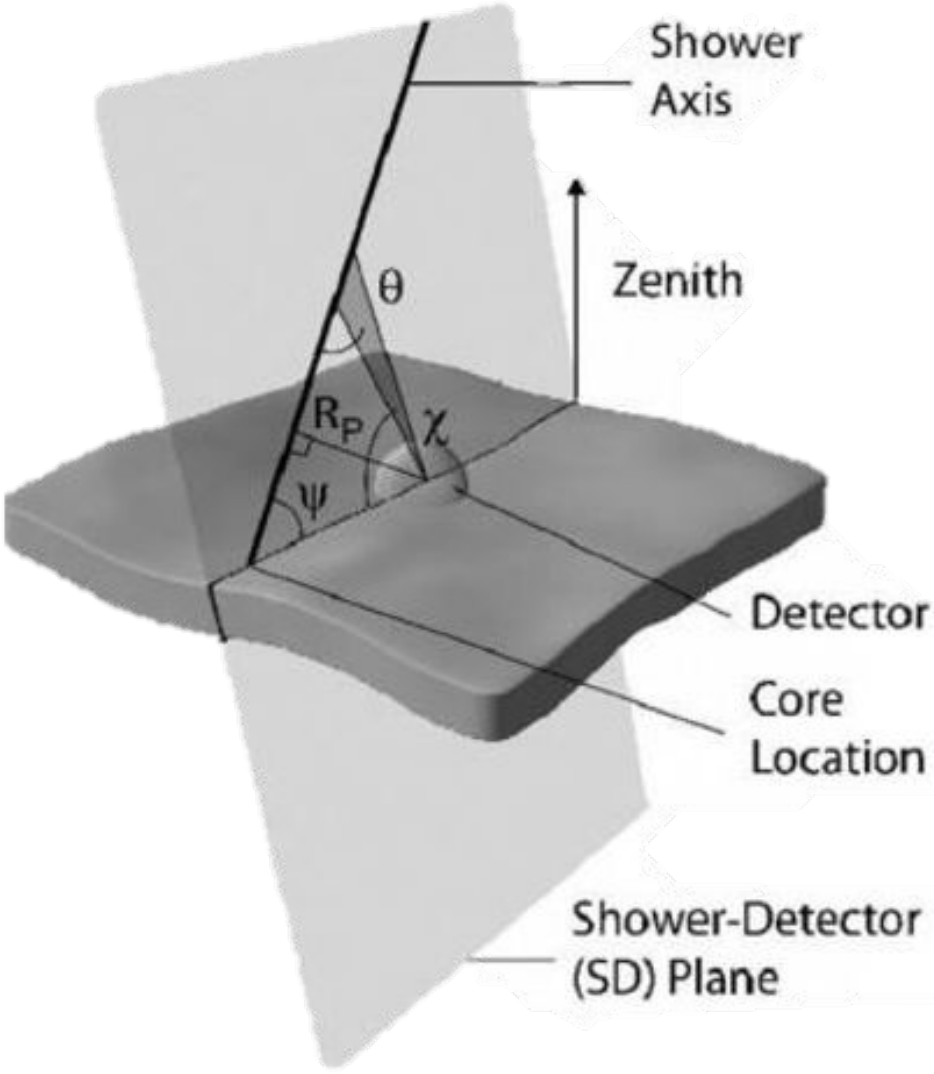
- February and March of 2019 half of all SDs deployed (257 SDs)
- Location optimized for hybrid events E > 10^{19} eV
  - 2.08 km SD spacing
- Mostly the same as TA SDs
- DAQ started in April 2019



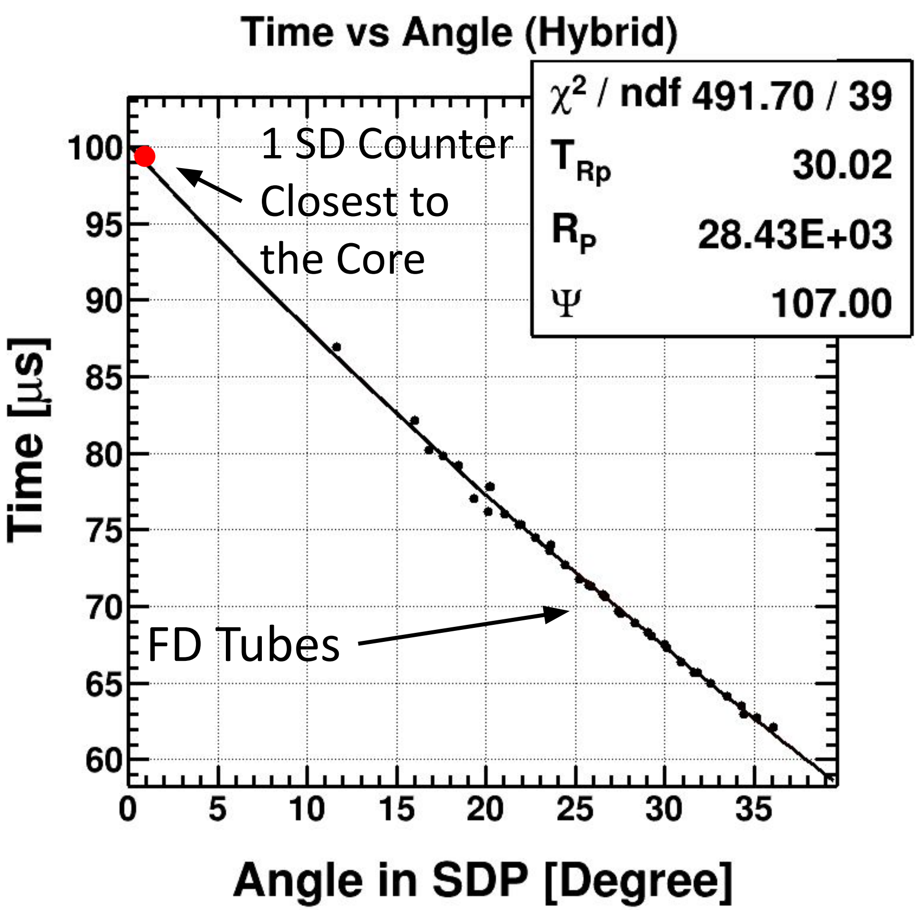
TAx4 Hybrid Reconstruction - PMT Selection

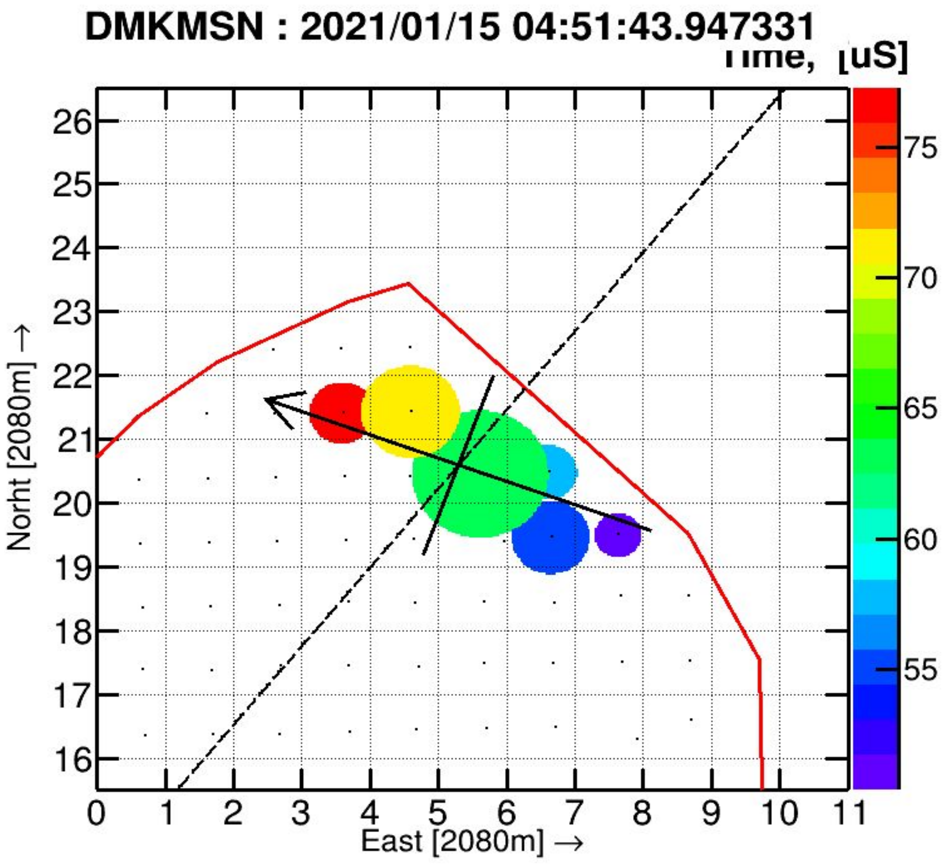


Event Display showing pattern of hit pixels



TAx4 Hybrid Reconstruction - Hybrid Timing Fit

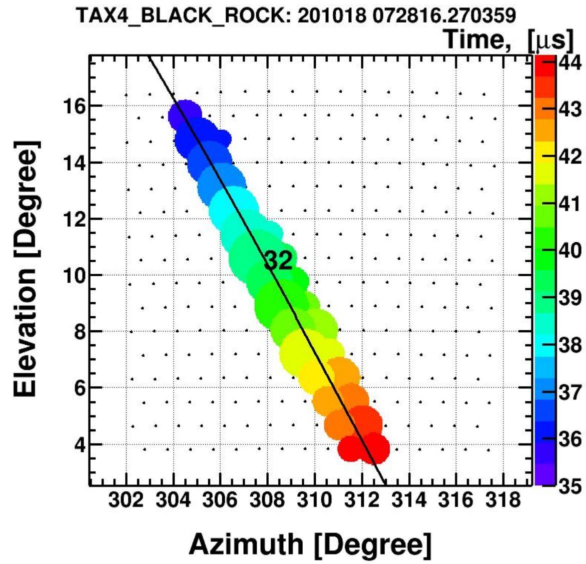


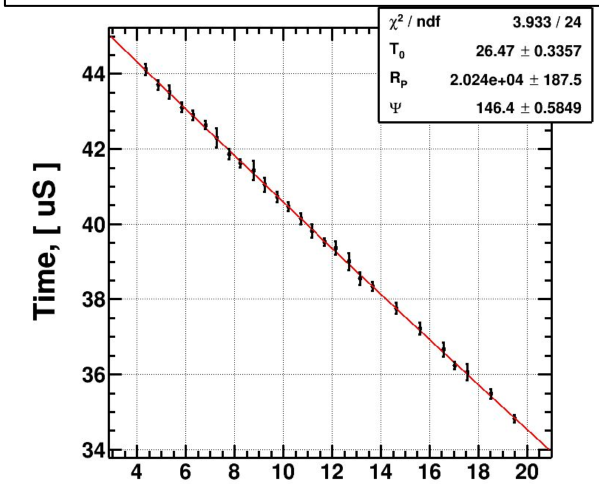


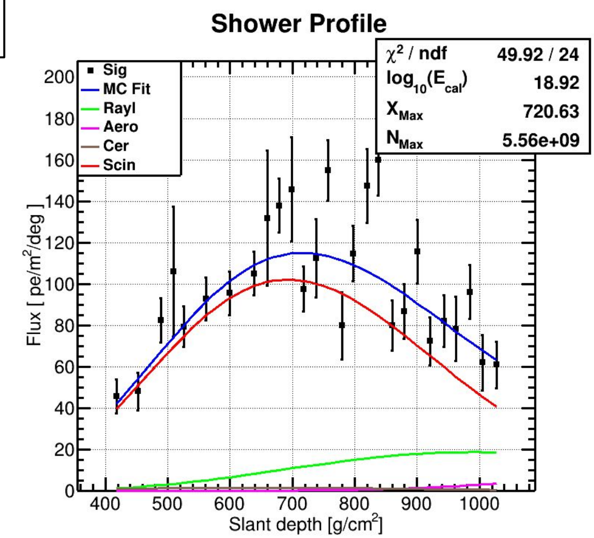
Arrival times of signal light in each PMT/SD is fitted as a function of the SDP angles: **Gives direction of primary cosmic ray**

Monocular vs. Hybrid Event Reconstruction

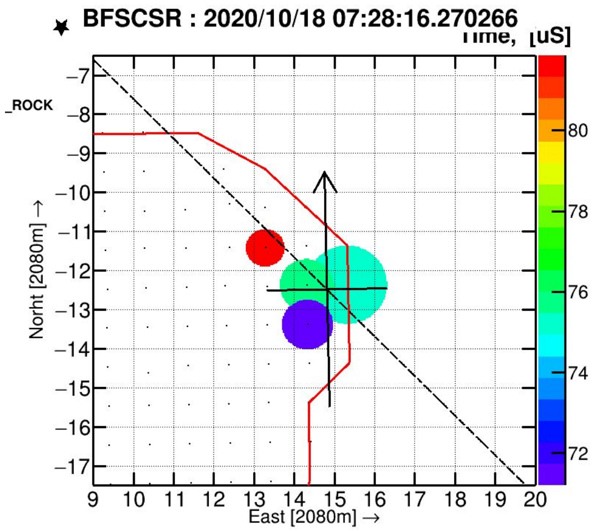
TAx4 South - Monocular

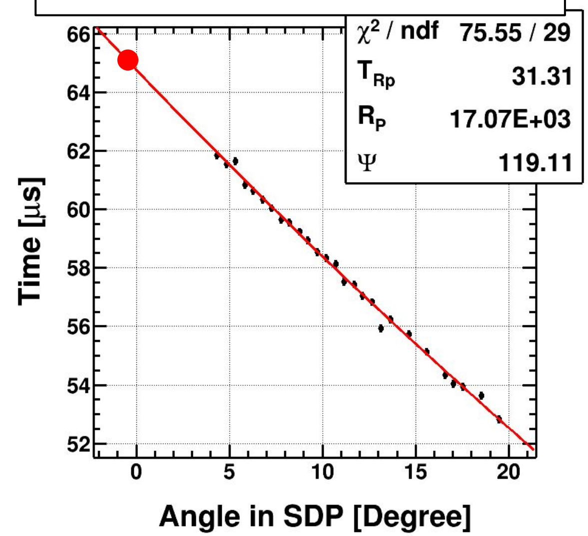


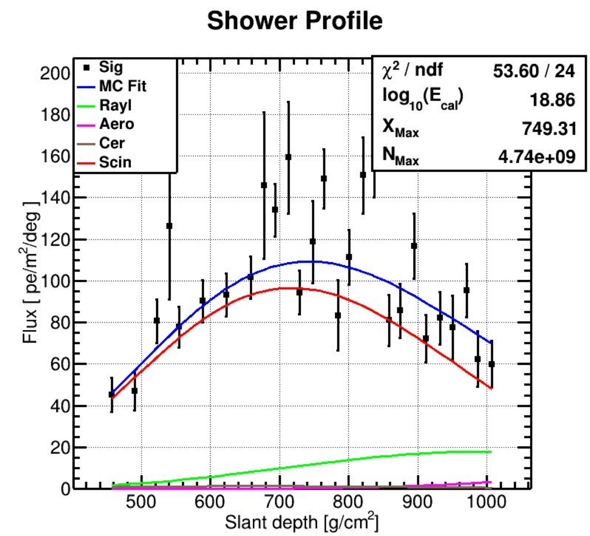




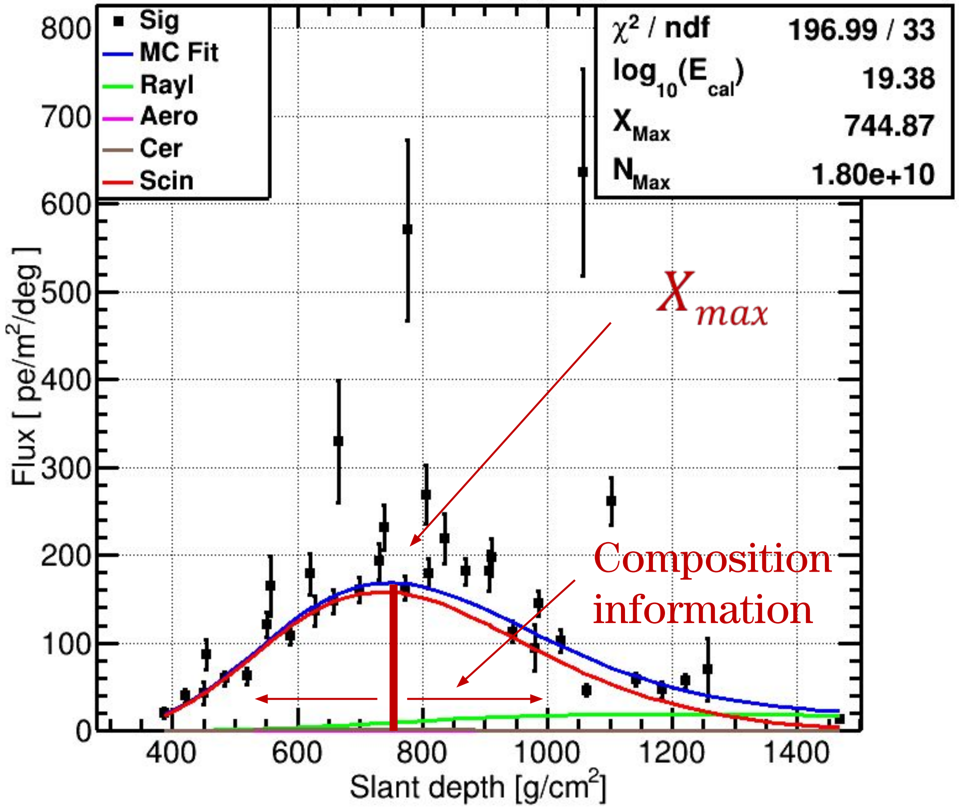
TAx4 South - Hybrid

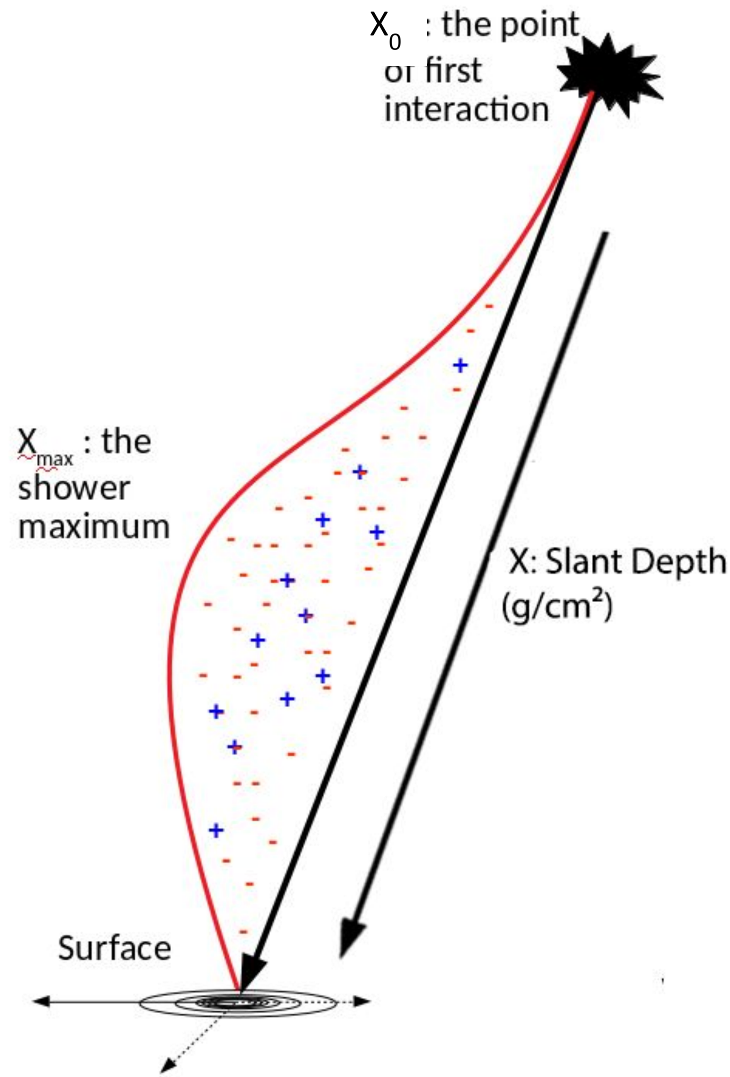






TAx4 Hybrid Reconstruction - Shower Profile Fit





SDP angle are converted to slant depth. Light signal fitted to depth to give energy E and X_{max}

TAx4 Hybrid Reconstruction - Calorimetric Energy

Phenomenological Parametric Fit (Gaisser-Hillas) Function:

$$N(X) = N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X_0}{\lambda}} \exp \left(\frac{X_{max} - X}{\lambda} \right)$$

N : Charged Particles in EAS at depth X

N_{max} : maximum number of particles the shower creates

X_{max} : depth of shower maximum

X_0 : approximate start of the shower

λ : shower decay length

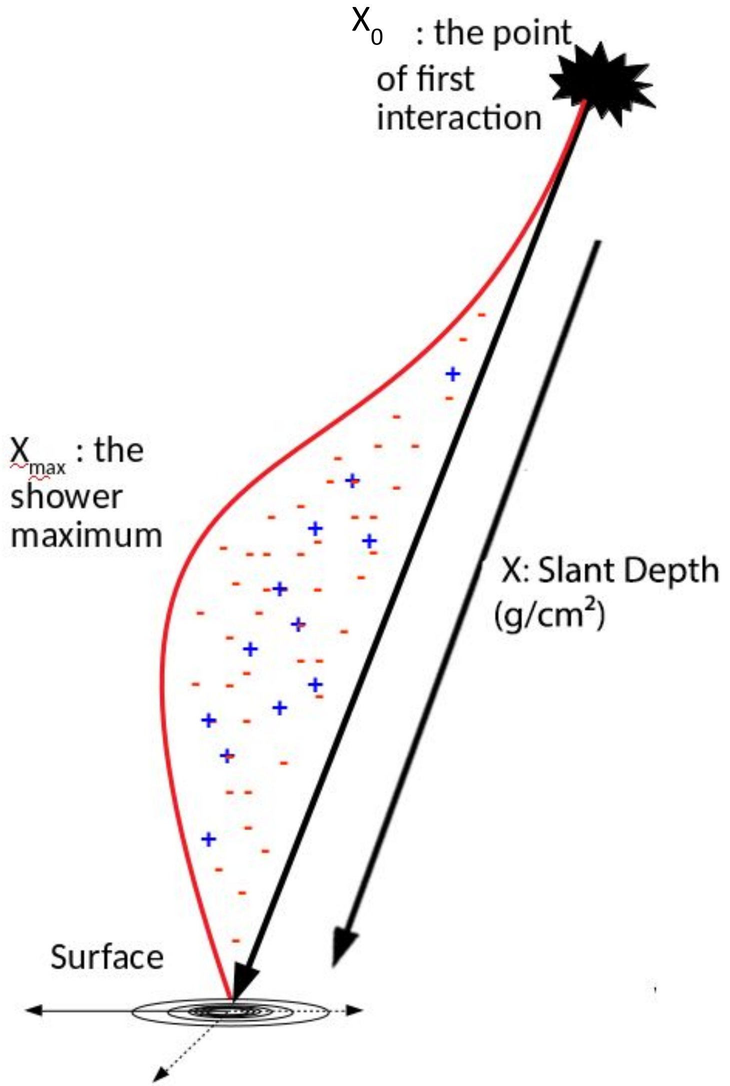
Calorimetric Energy:

$$\frac{dE_{dep}(X)}{dX} = \alpha_{\text{eff}}(X) N(X)$$

$\alpha_{eff}(X)$: mean ionization energy loss of the charged particles to the atmosphere

Shower Energy Deposition:

$$E_{cal} = \int_{X_0}^{\infty} \frac{dE_{dep}(X)}{dX} dX$$



Hybrid Event - TAx4 North

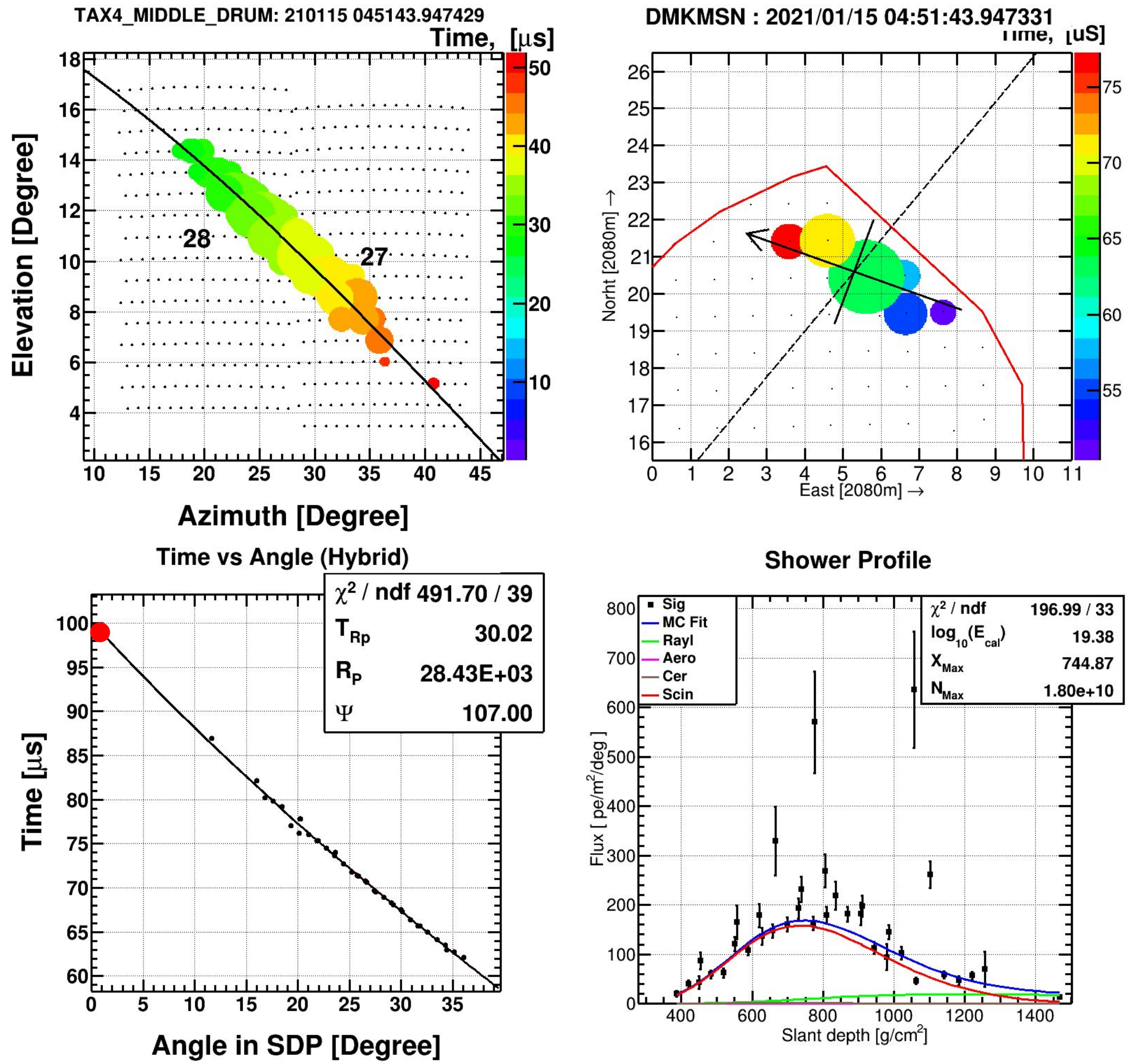
$E = 2.4 \times 10^{19}$ eV

$R_p = 28.43$ km

$\phi = 107°$ N of E

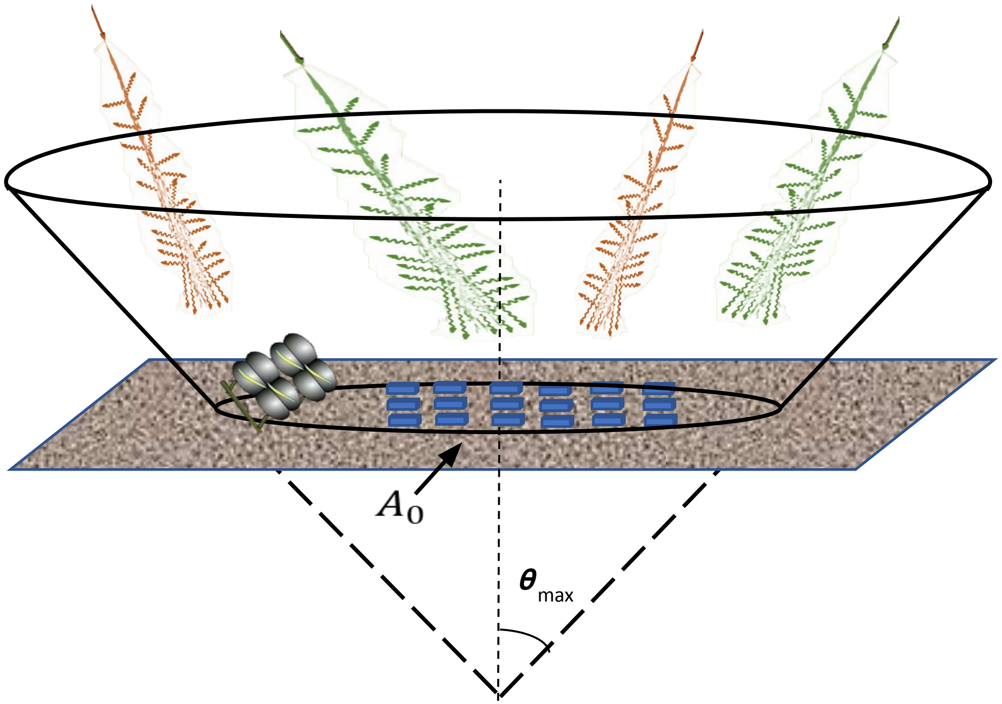
$X_{max} = 744.87$ g/cm^2

$N_{max} = 1.80 \times 10^{10}$ 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 fully efficient at energies above $10^{18.5}$
  - 90 million QGSJetII-03 protons simulated at E^{-2} power law spectrum
    - Events are reweighted with spectral indices reported in the TA spectrum. [2]
    - Quality cuts are applied to the reconstructed MC.



MC input parameter	Value
$R_{p,min}$	100 m
$R_{p,max}$	50 km
θ_{max}	70°
E_{min}	10^{17} eV
E_{max}	10^{21} eV
Spectral index, γ	2
Hadronic Model	QGSJetII-03, proton

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
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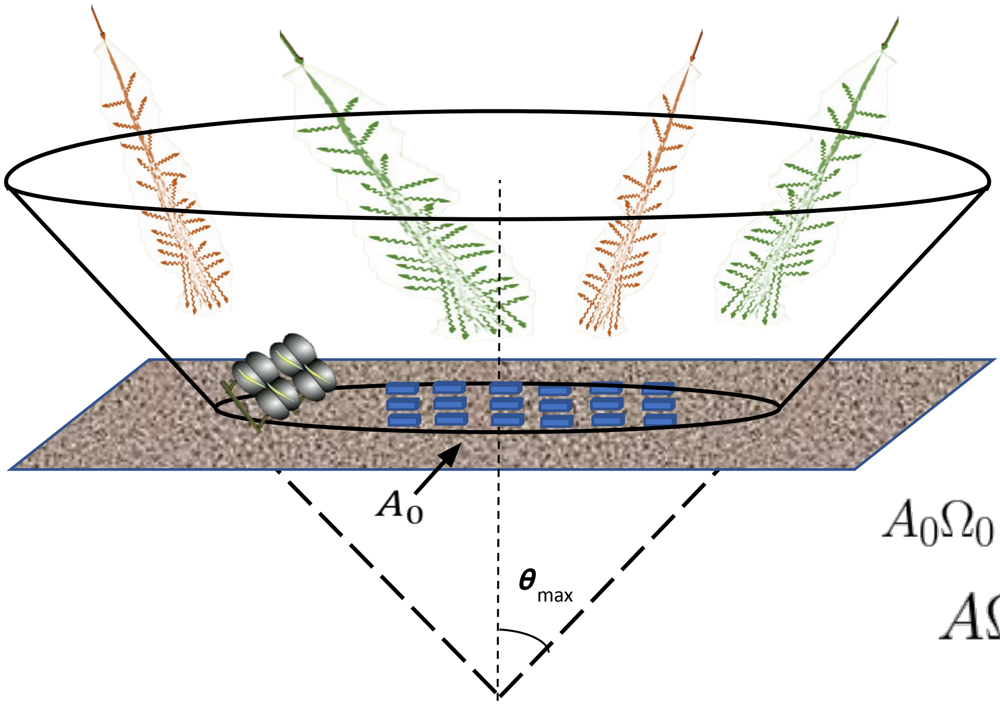
    - Quality cuts are applied to the reconstructed MC.



Acceptance:

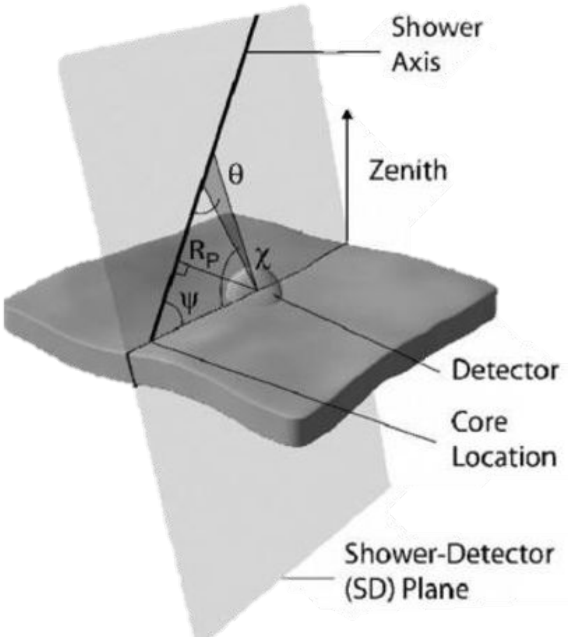
$$\text{Acceptance}(E_i) = \frac{N_{recon}(E_i)}{N_{thrown}(E_i)}$$

Aperture:

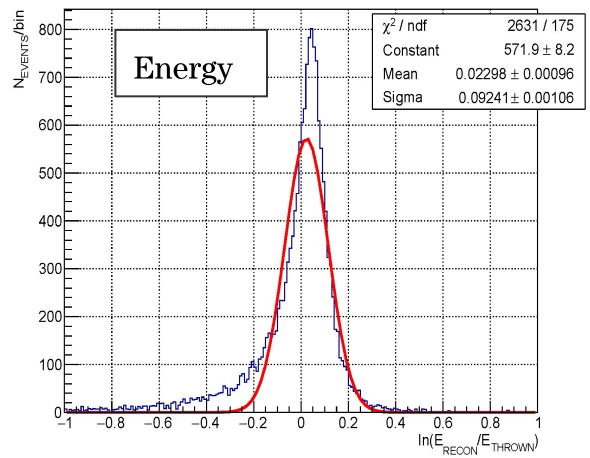
$$A_0\Omega_0 = 2\pi^2 \left(R^2_{p,\text{max}} - R^2_{p,\text{min}}\right)\left(1 - \cos\left(\theta_{\text{max}}\right)\right)$$

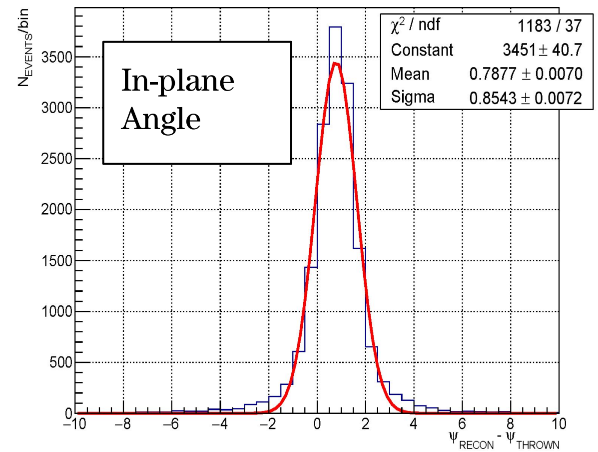
$$A\Omega(E_i) = A_0\Omega_0 \times \text{Acceptance}(E_i)$$

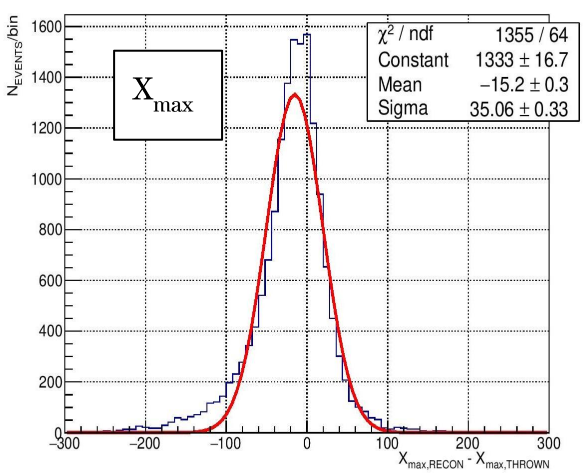
Resolutions

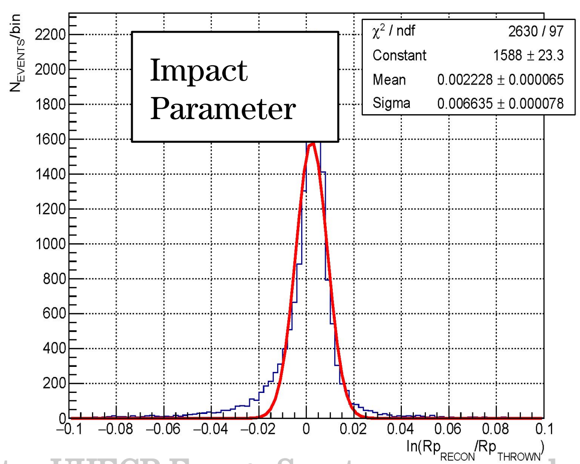


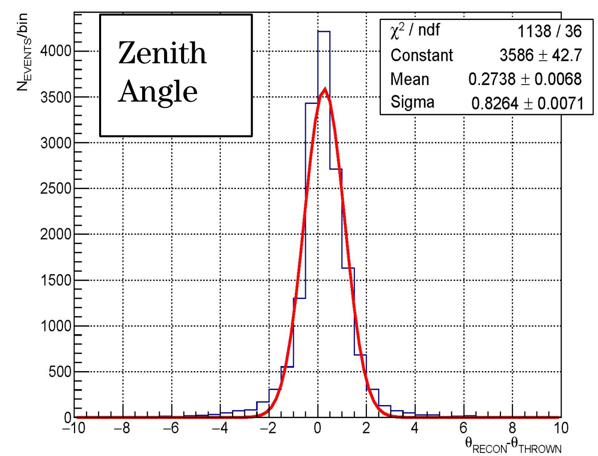
Parameter	Monocular Resolution	Hybrid Resolution
Energy, *E*	19.93%	9.2%
Zenith Angle, θ	3.03°	0.8°
In-plane Angle, ψ	6.98°	0.9°
Impact Parameter, R_p	10.68%	0.7%
Depth of Shower Maximum, X_{max}	85.56 g/cm^2	35 g/cm^2







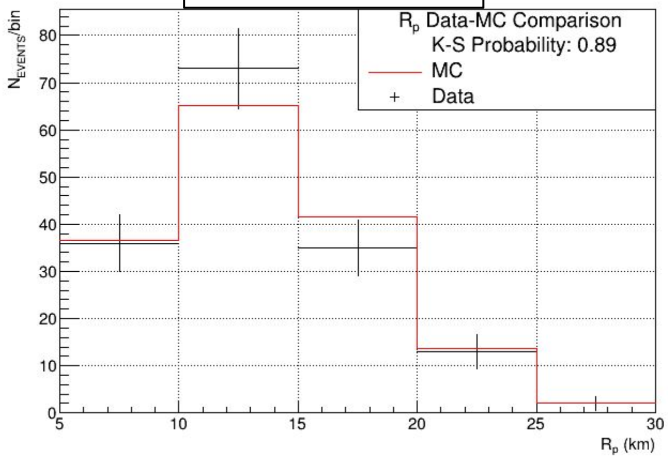




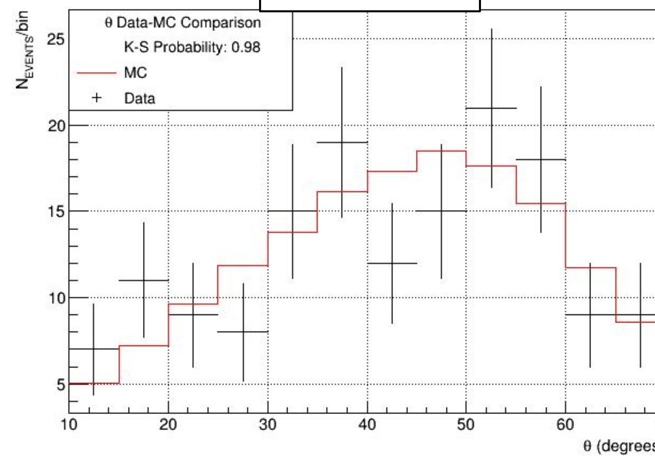
Data-MC Comparisons (1/2)

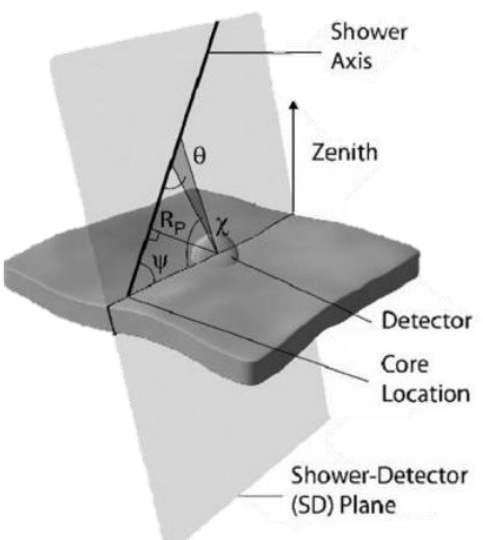
- **Black points** are data, the red line is MC
- Kolmogorov–Smirnov tests compare the MC and data distributions to determine agreement
- **Impact parameter and zenith angle are in reasonable agreement with the MC**

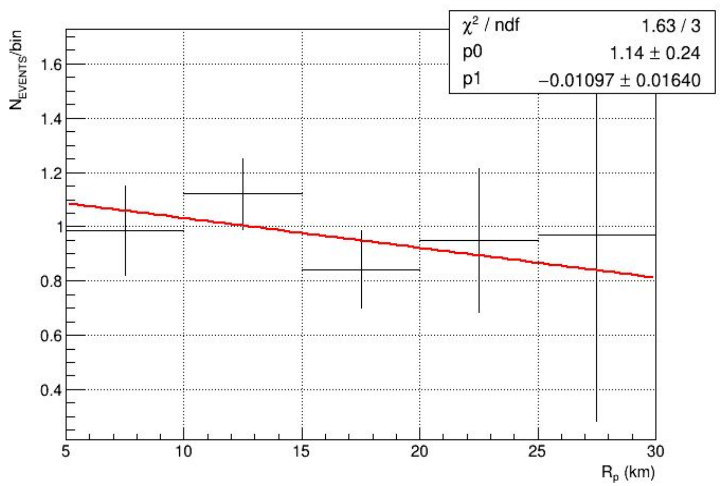
Impact Parameter

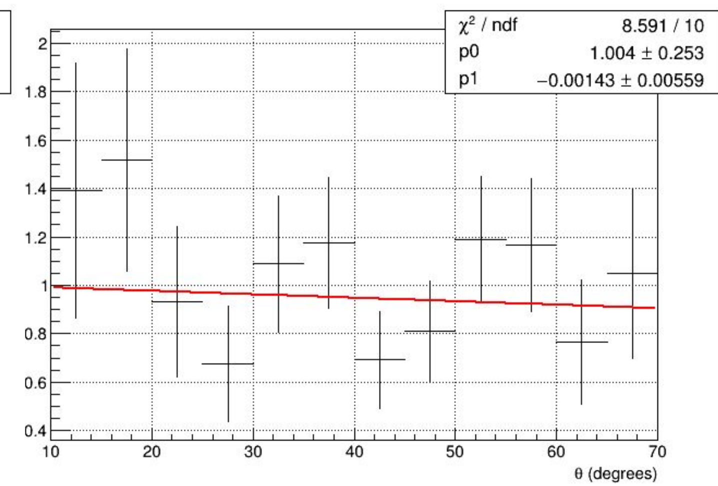


Zenith Angle







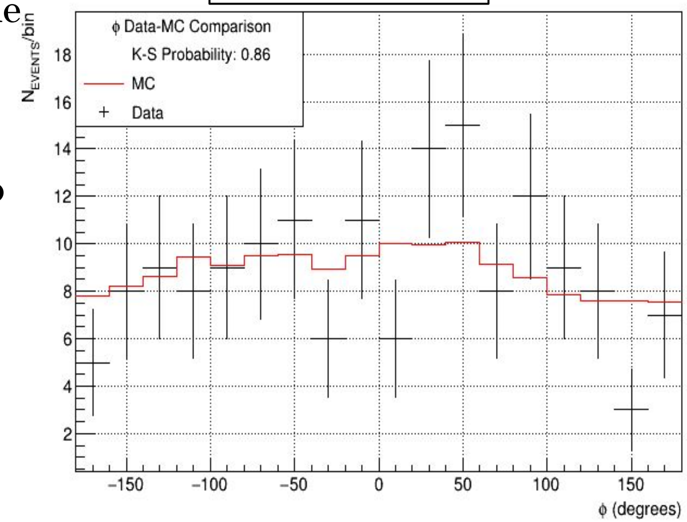


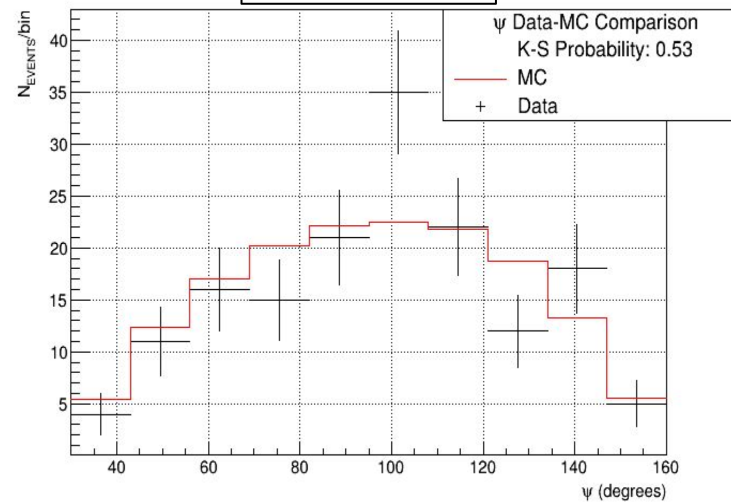
Data-MC Comparisons (2/2)

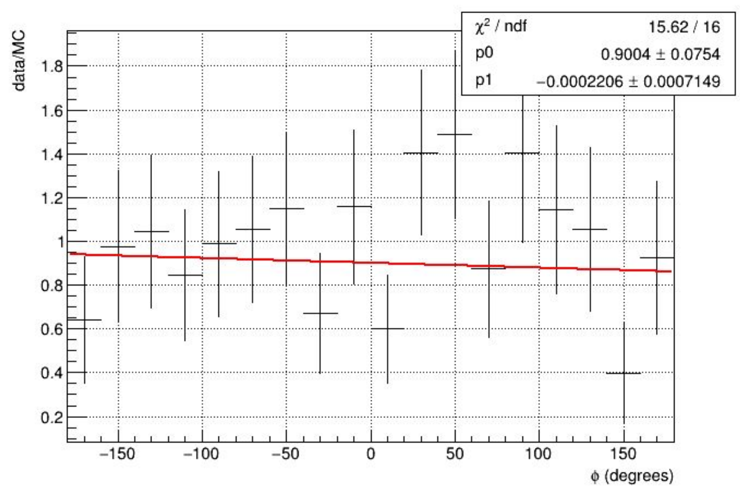
Azimuthal Angle

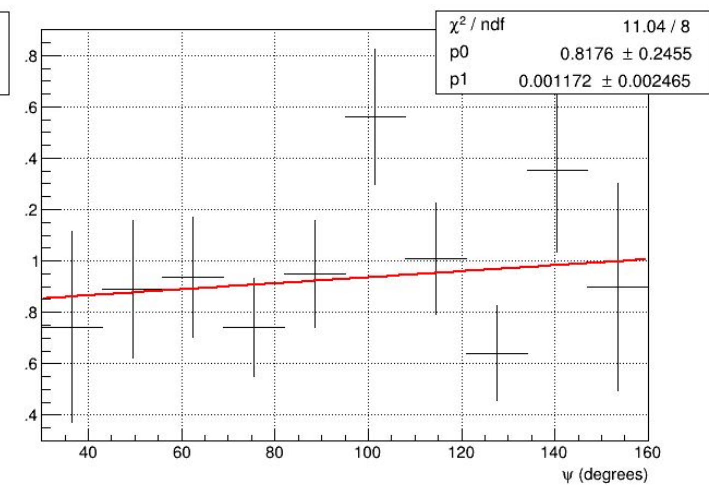
In-plane Angle

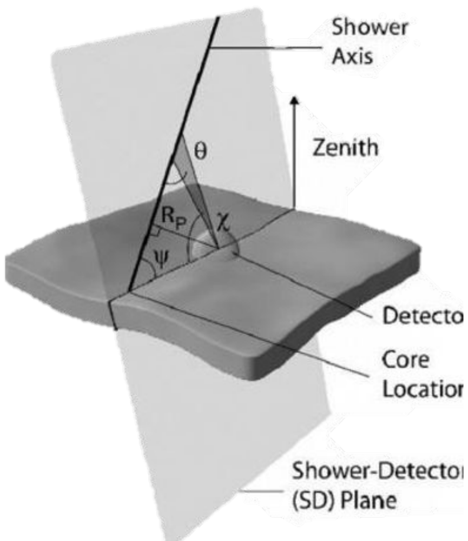
- **Black points** are data, the red line is MC
- Kolmogorov–Smirnov tests compare the MC and data distributions to determine agreement
- **Azimuthal angle and in-plane angle are in reasonable agreement with the MC**











TAx4 Energy Spectrum (1/2)

- Differential flux of particles as a function of energy
- Represents the energy density of cosmic rays in the universe
- Features in the spectrum are insights into cosmic ray populations

$$J(E_i) = \frac{N(E_i)}{\Delta E_i A\Omega(E_i) T}$$

$N(E_i)$: Event Distribution

ΔE_i : Bin Size

$A\Omega(E_i)$: Detector Aperture

$\epsilon(E_i) = A\Omega(E_i)T$: Detector Exposure

T : Detector Ontime

TAx4 Energy Spectrum (2/2)

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

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

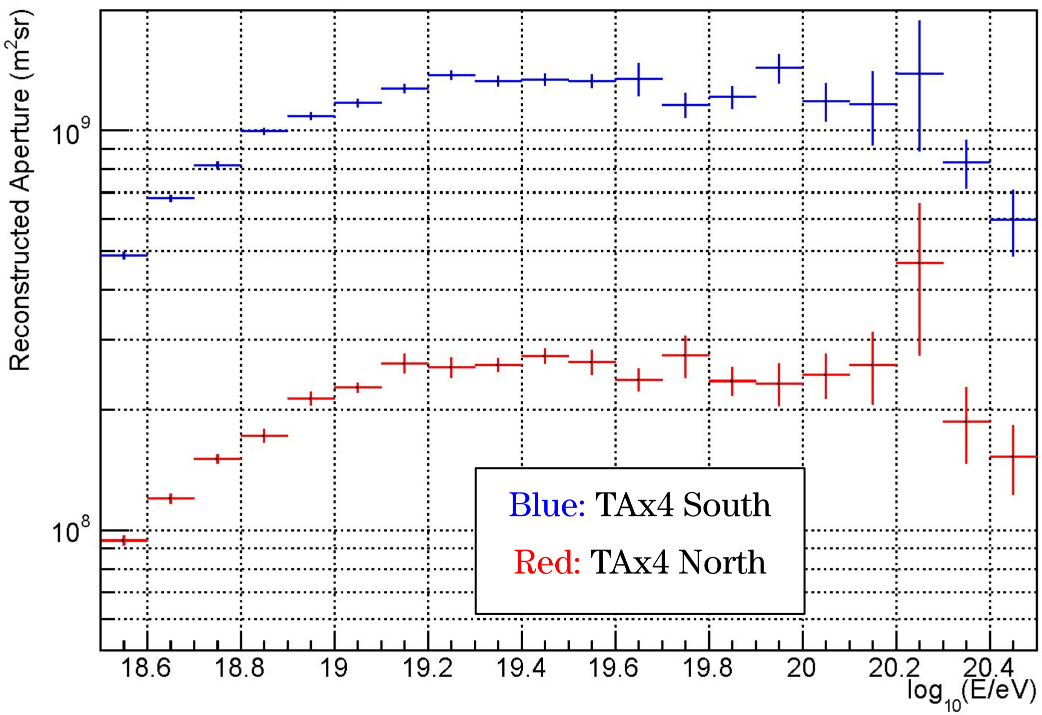
$$\epsilon_{\mathrm{TAx4}} = A\Omega_N T_N + A\Omega_S T_S,$$

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

TAx4 Hybrid Aperture

$$A_0\Omega_0 = 2\pi^2\left(R^2_{p,\max} - R^2_{p,\min}\right)(1-\cos(\theta_{\max}))$$

$$A\Omega(E_i) = A_0\Omega_0 \times \mathrm{Acceptance}(E_i)$$

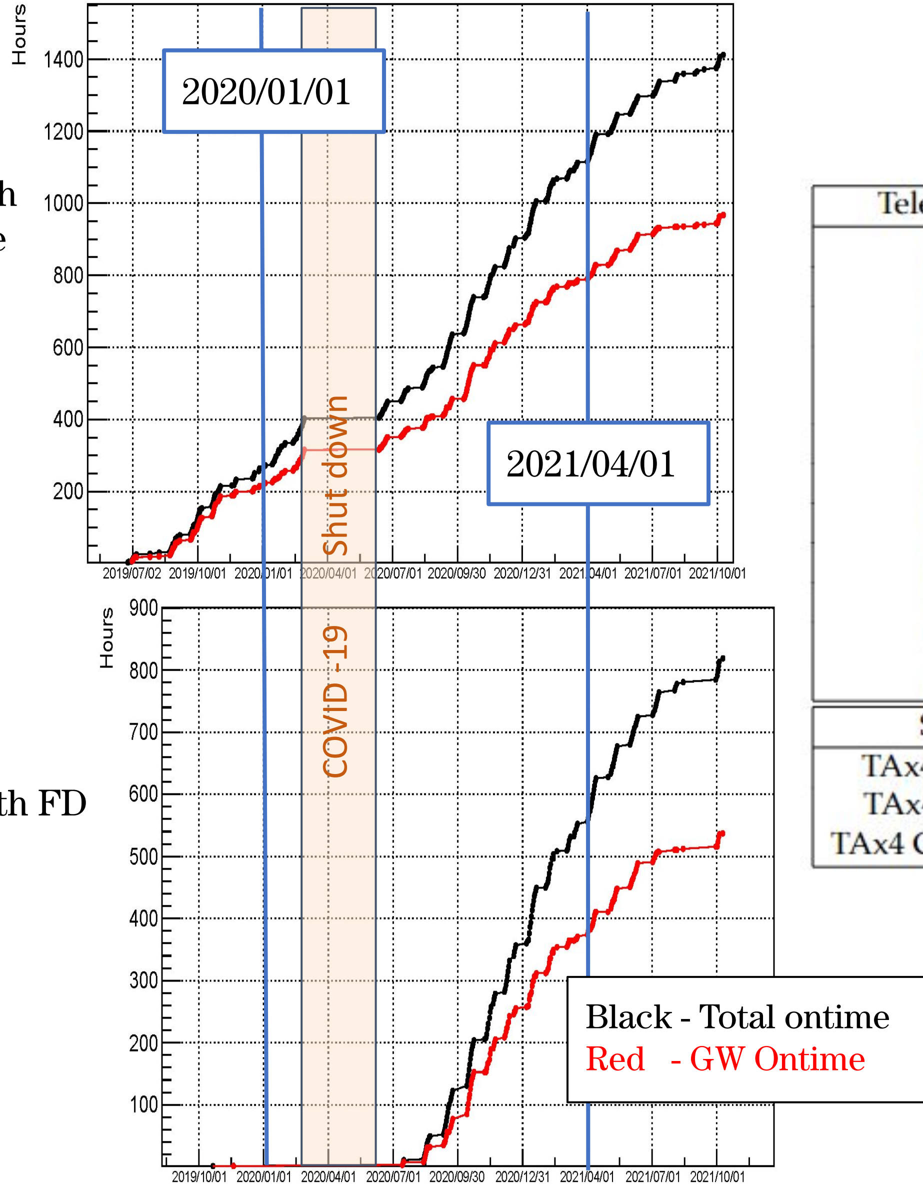


$\log_{10}(E/eV)$	TAx4 N Aperture (m^2sr)	TAx4 S Aperture (m^2sr)
18.5	9.424×10^7	4.875×10^8
18.6	1.199×10^8	6.773×10^8
18.7	1.508×10^8	8.198×10^8
18.8	1.722×10^8	9.963×10^8
18.9	2.135×10^8	1.089×10^9
19.0	2.274×10^8	1.173×10^9
19.1	2.613×10^8	1.275×10^9
19.2	2.561×10^8	1.376×10^9
19.3	2.589×10^8	1.329×10^9
19.4	2.727×10^8	1.343×10^9
19.5	2.635×10^8	1.332×10^9
19.6	2.381×10^8	1.346×10^9
19.7	2.736×10^8	1.160×10^9
19.8	2.362×10^8	1.214×10^9
19.9	2.326×10^8	1.435×10^9
20.0	2.447×10^8	1.183×10^9
20.1	2.595×10^8	1.163×10^9
20.2	4.661×10^8	1.387×10^9
20.3	1.870×10^8	8.312×10^8
20.4	1.527×10^8	5.982×10^8

TAx4 Ontime (2019/06/26 - 2021/10/28)

TAx4 North FD Ontime

TAx4 South FD Ontime

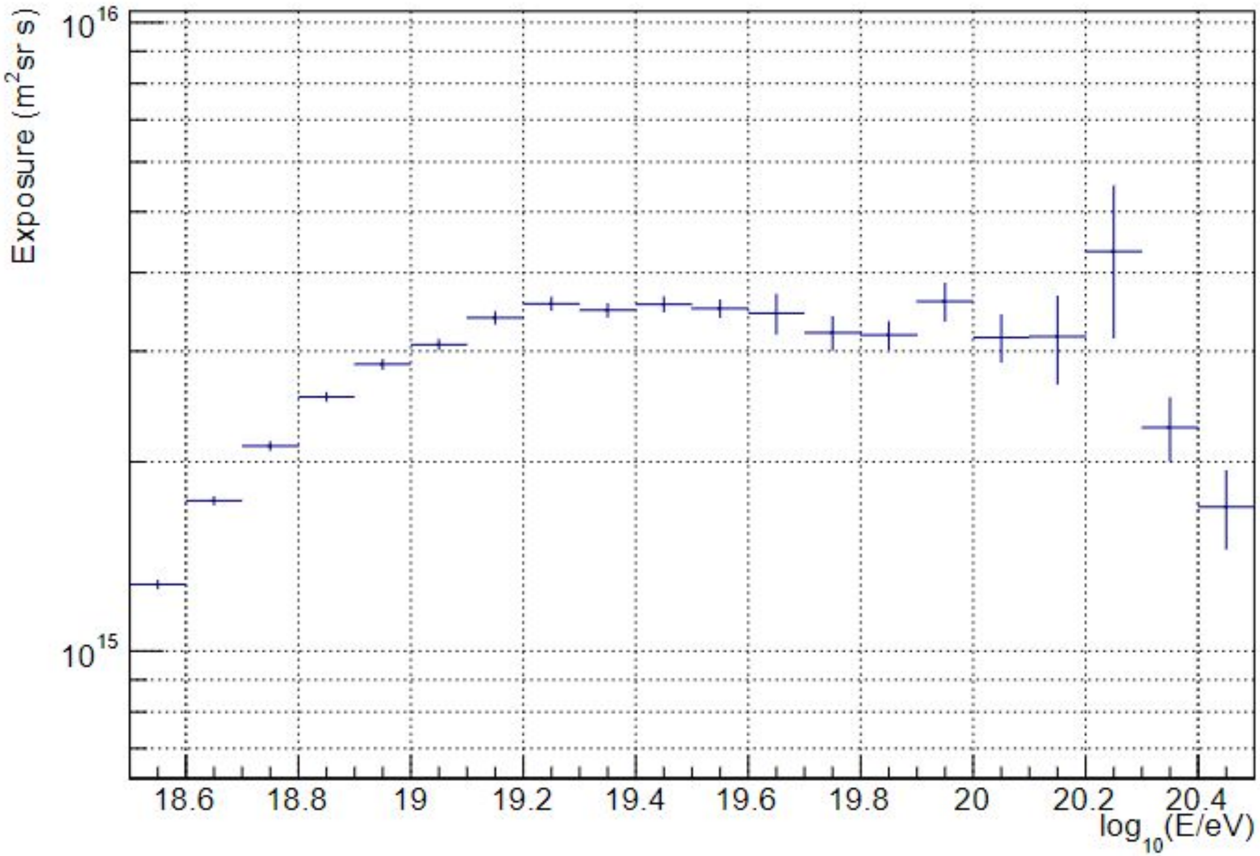


Telescope	Total Ontime (hours)
25	1366.6284
26	1381.0281
27	1339.3858
28	1352.4767
29	818.6036
30	817.3898
31	821.9800
32	753.3116
33	818.8213
34	788.7251
35	811.7769
36	768.8446

Site	Total Ontime (hours)	GW Ontime (hours)
TAx4 North	1420.1697	969.9144
TAx4 South	827.5822	539.7292
TAx4 Combined	2247.7492	1509.6436

TAx4 Hybrid Exposure

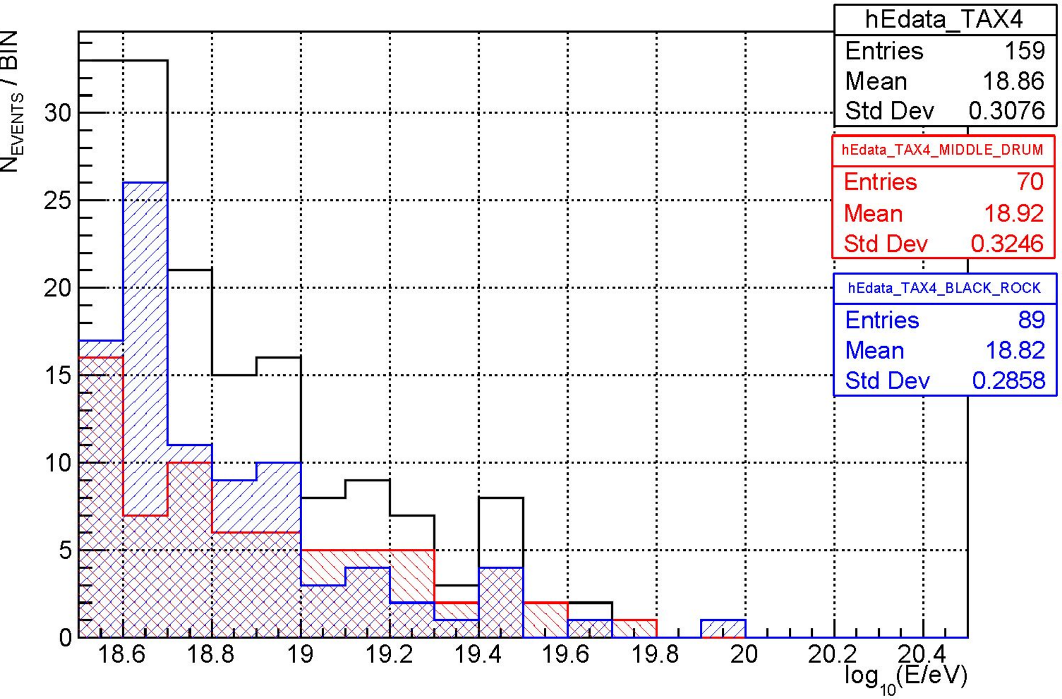
$$\epsilon_{\text{TAx4}} = A\Omega_N T_N + A\Omega_S T_S,$$



$\log_{10}(E/eV)$	TAx4 Exposure $(m^2 \text{sr s})$
18.55	1.276×10^{15}
18.65	1.735×10^{15}
18.75	2.119×10^{15}
18.85	2.537×10^{15}
18.95	2.861×10^{15}
19.05	3.072×10^{15}
19.15	3.391×10^{15}
19.25	3.568×10^{15}
19.35	3.487×10^{15}
19.45	3.562×10^{15}
19.55	3.508×10^{15}
19.65	3.447×10^{15}
19.75	3.210×10^{15}
19.85	3.184×10^{15}
19.95	3.600×10^{15}
20.05	3.154×10^{15}
20.15	3.165×10^{15}
20.25	4.322×10^{15}
20.35	2.268×10^{15}
20.45	1.696×10^{15}

Hybrid Data Distribution

- 159 TAx4 hybrid events with E ≥ $10^{18.5}$ eV
  - 70 TAx4 North events
  - 89 TAx4 South events

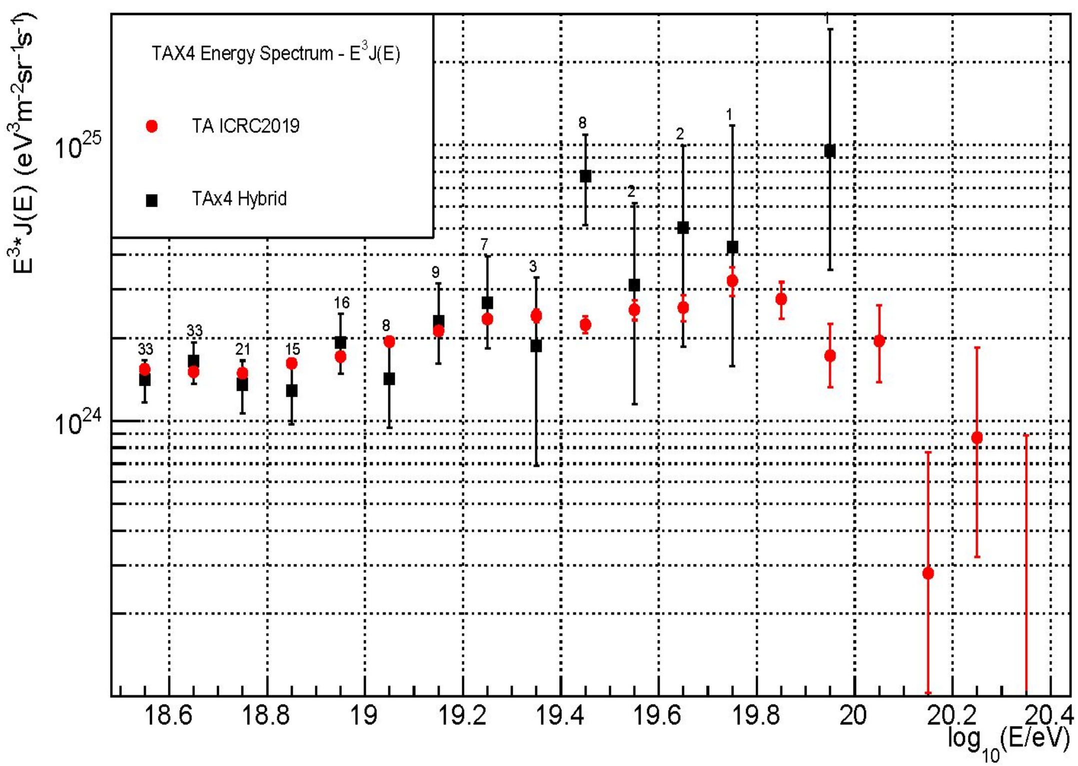


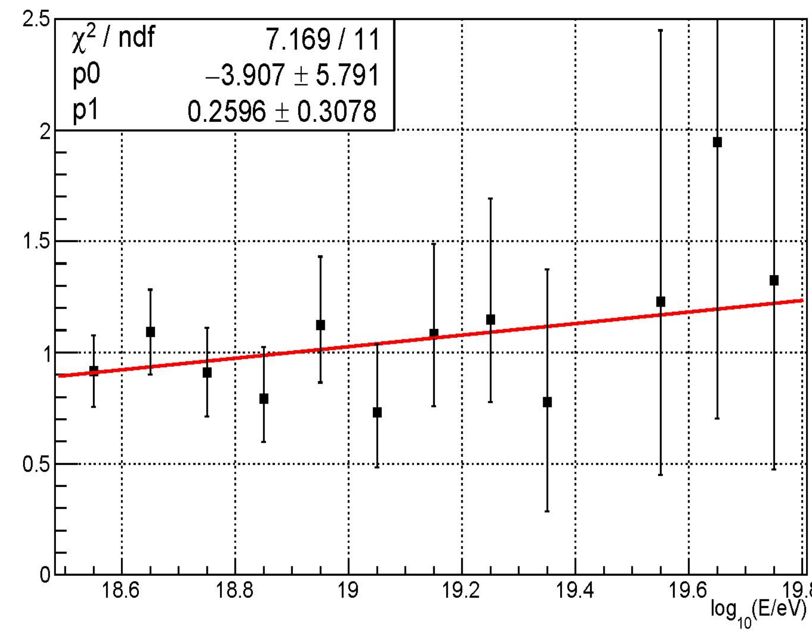
$\log_{10}(E/eV)$	TAx4 North N(E)	TAx4 South N(E)	Total N(E)
18.5	16	17	33
18.6	7	26	33
18.7	10	11	21
18.8	6	9	15
18.9	6	10	16
19.0	5	3	8
19.1	5	4	9
19.2	5	2	7
19.3	2	1	3
19.4	4	4	8
19.5	2	0	2
19.6	1	1	2
19.7	1	0	1
19.8	0	0	0
19.9	0	1	1
Total Events	70	89	159

TAx4 Hybrid Energy Spectrum

- The slope is relatively flat, indicating reasonable agreement between this works energy spectrum and TA's energy spectrum.

$\log_{10}(E/eV)$	J(E)	J(E) Lower Error	J(E) Upper Error
18.55	3.158×10^{-32}	5.497×10^{-33}	5.497×10^{-33}
18.65	1.846×10^{-32}	1.846×10^{-33}	1.846×10^{-33}
18.75	7.635×10^{-33}	1.666×10^{-33}	1.666×10^{-33}
18.85	3.619×10^{-33}	8.878×10^{-34}	1.043×10^{-33}
18.95	2.719×10^{-33}	6.229×10^{-34}	7.368×10^{-34}
19.05	1.006×10^{-33}	3.388×10^{-34}	4.174×10^{-34}
19.15	8.143×10^{-34}	2.411×10^{-34}	3.018×10^{-34}
19.25	4.781×10^{-34}	1.530×10^{-34}	2.257×10^{-34}
19.35	1.665×10^{-34}	1.052×10^{-34}	1.279×10^{-34}
19.45	3.453×10^{-34}	1.163×10^{-34}	1.433×10^{-34}
19.55	6.964×10^{-35}	4.387×10^{-35}	6.876×10^{-35}
19.65	5.629×10^{-35}	3.546×10^{-35}	5.559×10^{-35}
19.75	2.401×10^{-35}	1.513×10^{-35}	4.214×10^{-35}
19.85	0	0	0
19.95	1.351×10^{-35}	8.509×10^{-36}	2.370×10^{-35}
20.05	0	0	0





Conclusions (1/2)

- 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 TAx4 SDs were deployed in early 2019 and began regular DAQ by April 2019. We hope to complete as soon as conditions permit.

Conclusions (2/2)

- The TAx4 hybrid resolutions are consistent other TA results.
- The TAx4 MC and data appear to be in reasonable agreement.
- This work's hybrid energy spectrum using TAx4 is in agreement with the TA' energy spectrum.
- **The energy spectrum paves the way for composition and anisotropy analyses for a future graduate student.**

Acknowledgements

- My Advisor, Charlie Jui
- My Thesis Committee: Tareq AbuZayyad, Steve Wasserbaech, Michael Vershinin, Yue Zhao
- Members of the Telescope Array Collaboration: Charlie Jui,, John Matthews, Frank Misak, Stan Thomas, Jeremy Smith, Robert Cady, Perrie Sokolsky, Gordon Thomson, Dmitri Ivanov, Doug Bergman, Jihyun Kim, JiHee Kim, Greg Furlich, Yoshiki Tsunesada, Toshihiro Fujii, Eiji Kido, Nonaka Toshiyuki, and many many more!
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- Undergrads: Anna Christopherson, Samantha Roberts
- My Family: Keith, Shelley, Kayla, Clinton, Brianna, Jake, Bob, in memory of Marilyn, and the rest of my extended family.
- My Friends: entire Fankhauser family, Chad Jackson, DJ Braken, Danny Reyes, Devon Lee, Utah (my dog), and many more.

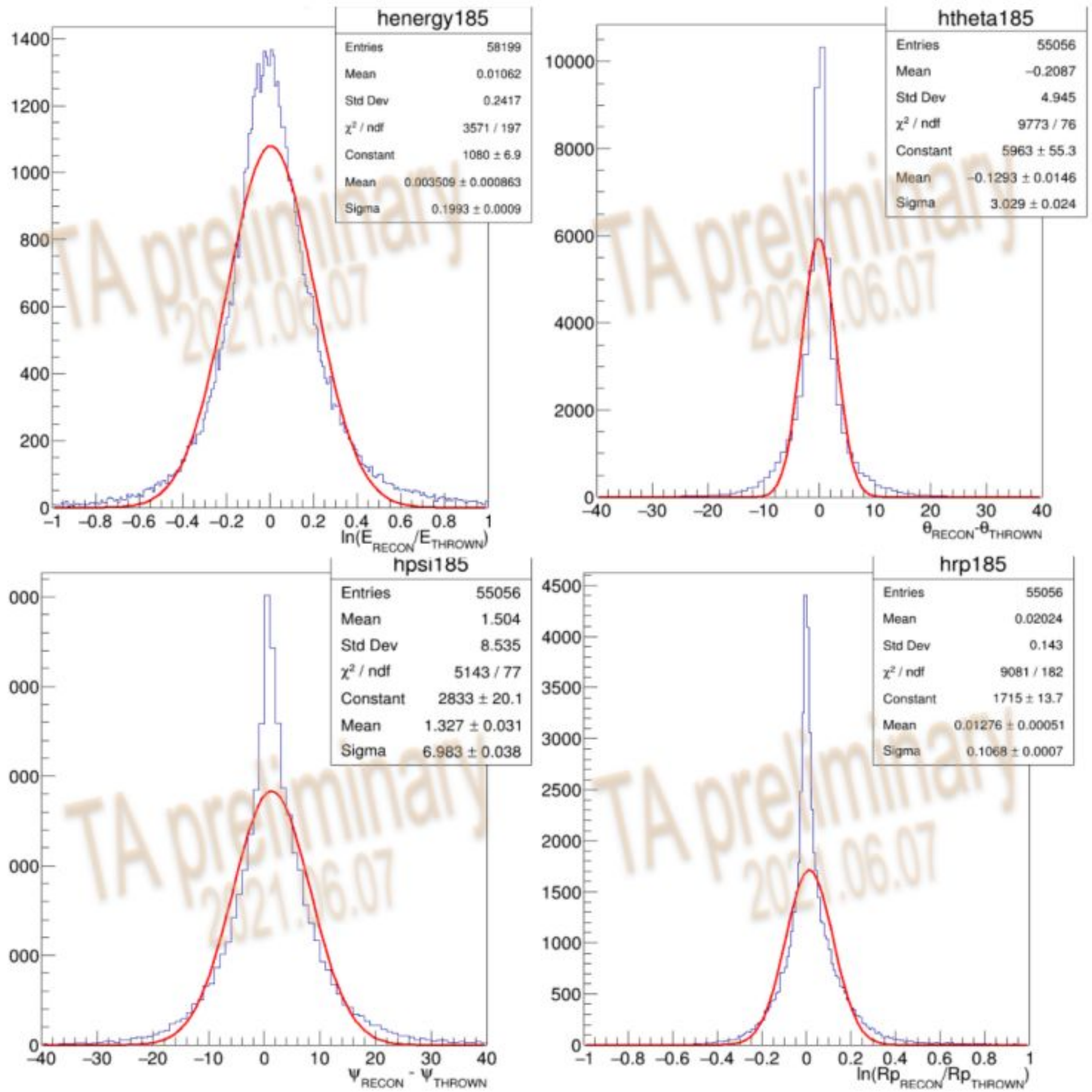
Thank you!

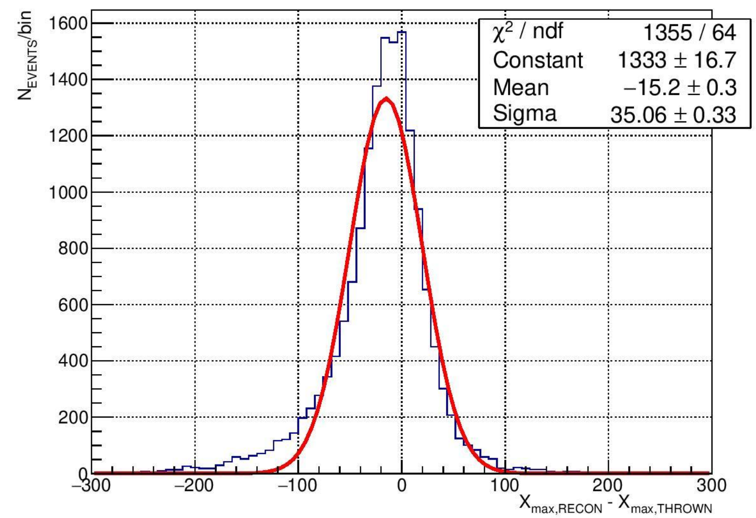
Questions?

Backup Slides

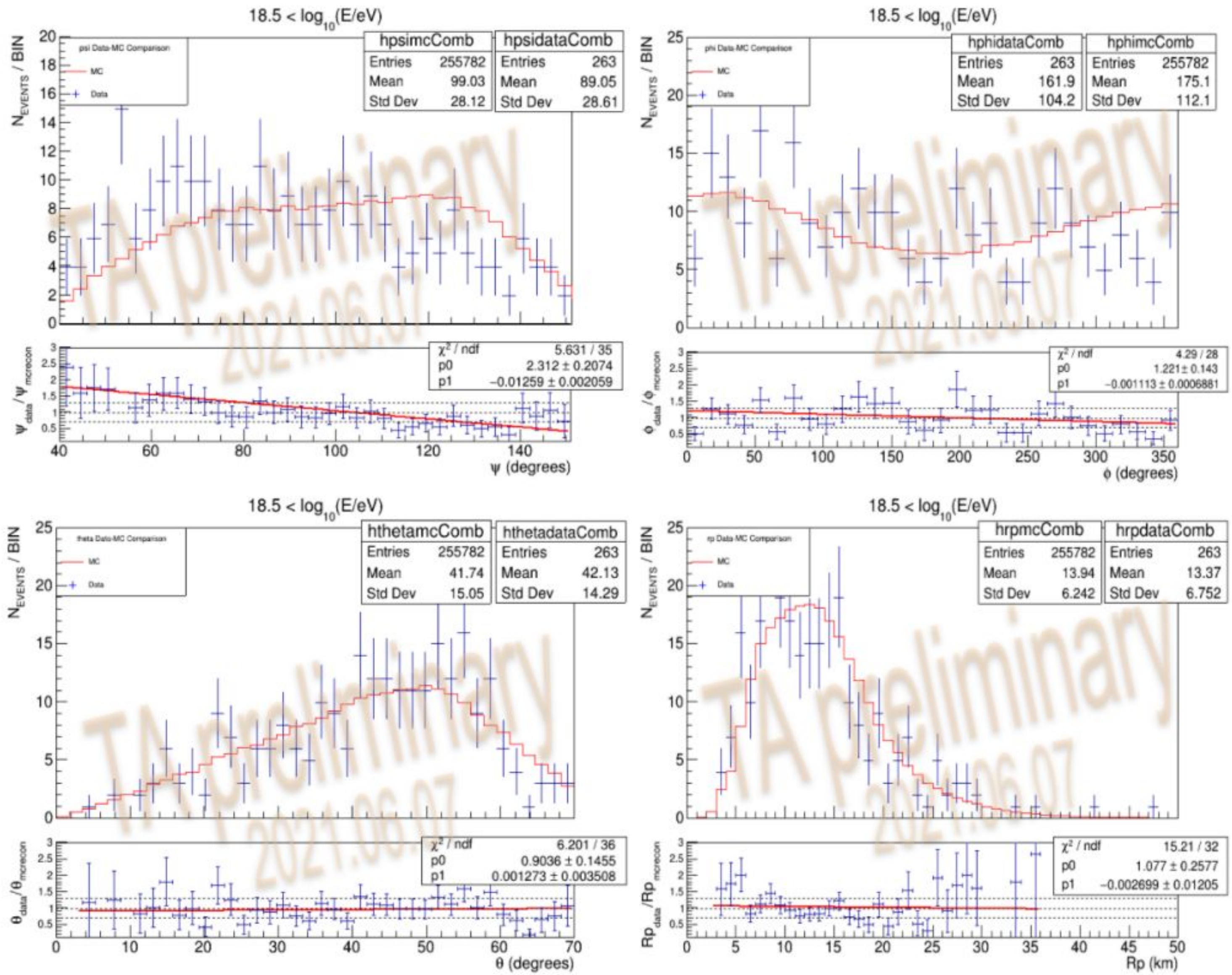
Telescope Array (TA) Collaborators

TAx4 Monocular Resolutions

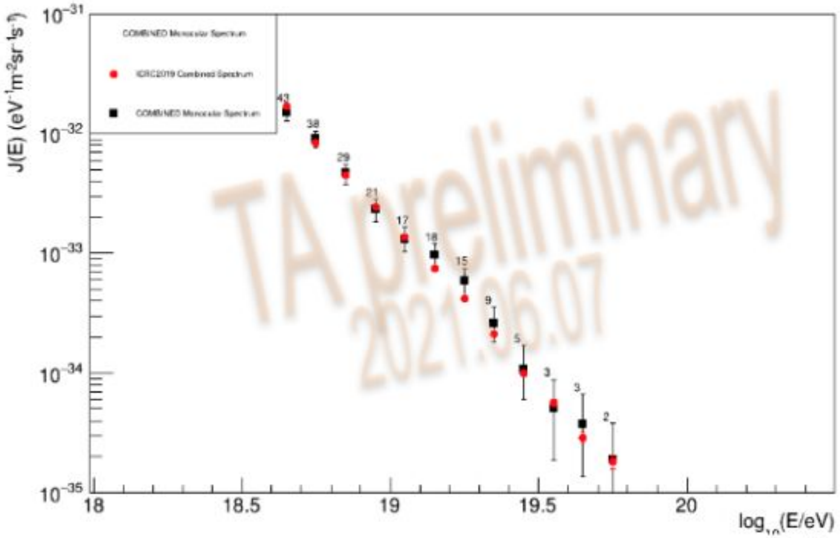


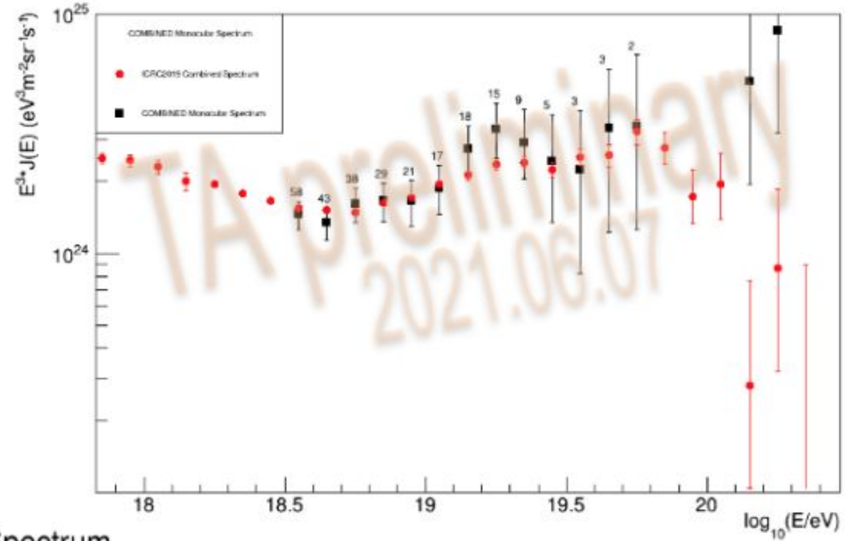


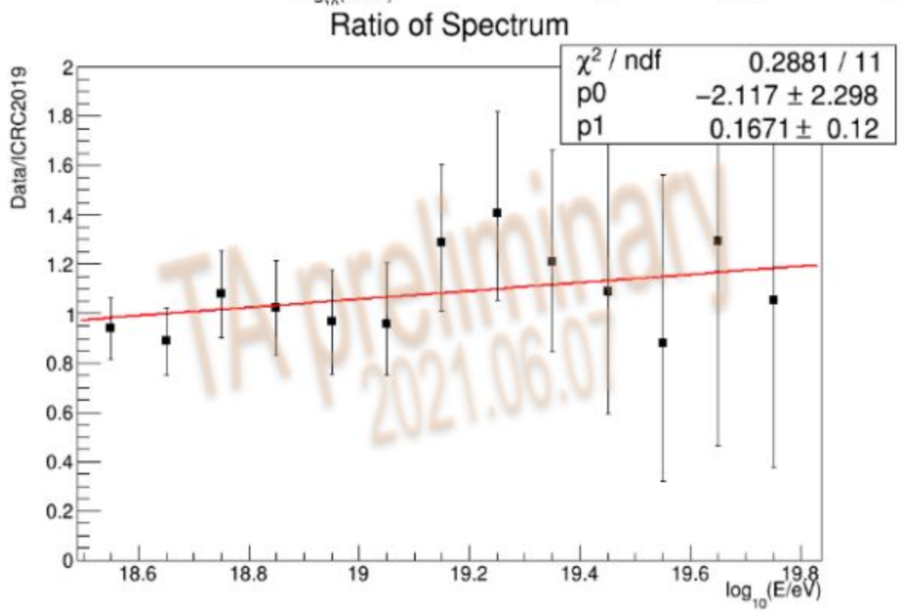
TAx4 Monocular Data-MC Comparisons



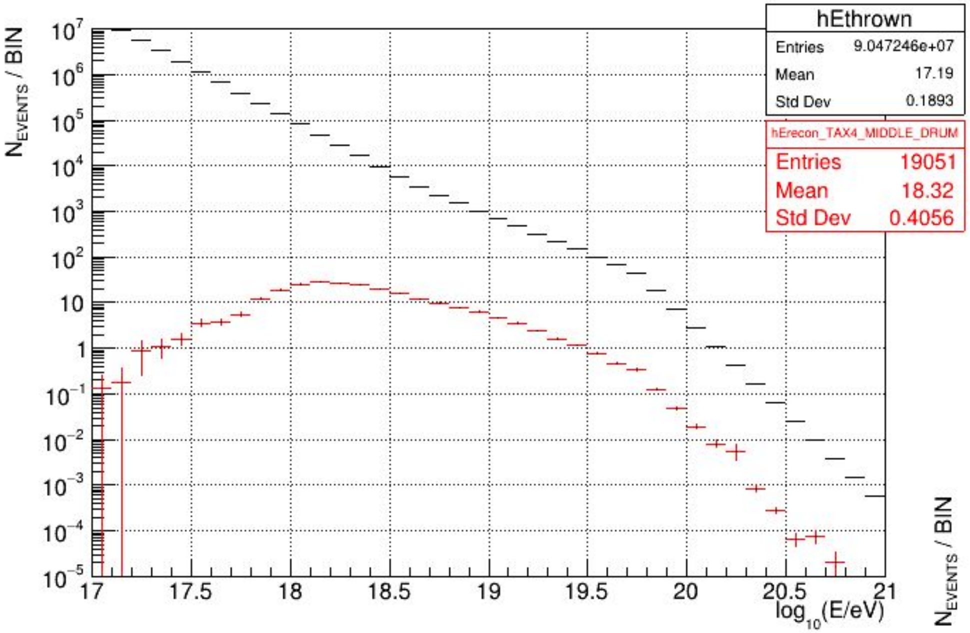
TAx4 Monocular Energy Spectrum

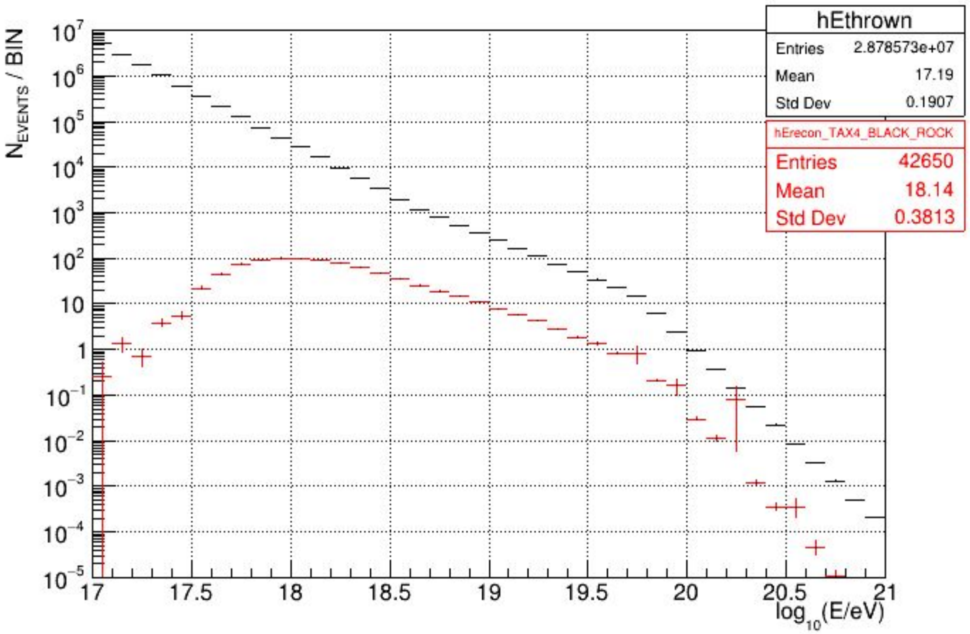






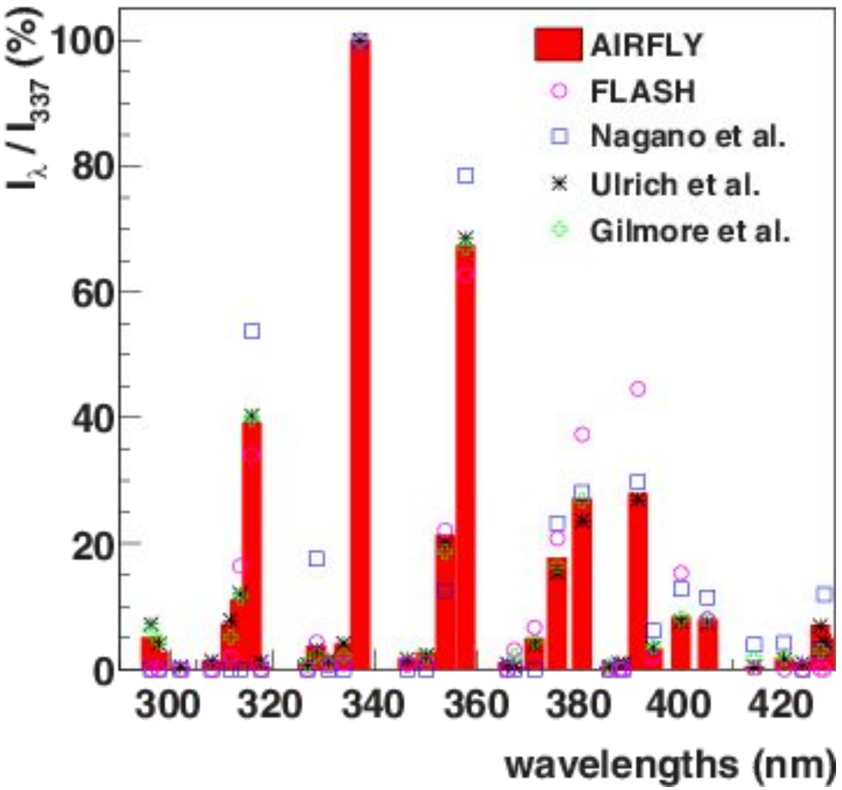
Monte Carlo Distributions





EAS “Fluorescence” Photons

- The “fluorescence” light initiated by EAS is mainly produced by the energy deposit of e^-/e^+ from the air shower in inelastic collisions with air molecules
  - *Fluorescence* refers to the process by which atoms absorb photons of one wavelength and emits photons at a longer wavelength
  - More accurate to refer to it as "luminescence" or "scintillation"



TAx4 Epochs

- **Epoch 0 (2018/06/08 - 2019/04/24):** The initial TAx4 FD epoch when it became operational and started collecting data every night.
- **Epoch I (2019/04/24 - 2019/06/08):** The column thickener daughter board was added to the trigger-host board for the four TAx4 telescopes at Middle Drum. The column thickener was set to the thicken all mode.
- **Epoch II (2019/06/26 - Present):** The current TAx4 FD epoch. The inter-mirror trigger was enabled in the TAx4 operations software.
  - 2020/03/03 : Hybrid trigger trigger Gate Width SN and KM
  - 2020/03/30 : Hybrid trigger corrected for 1 integer second offset fix
  - 2020/06/06 : Hybrid trigger Gate Width widened rest of SD sub arrays
  - 2020/11/07 : 1 integer second offset fix enabled for FD timing

Hybrid Trigger

The FD FADC event scans are analyzed to find the number of good PMTs, track length, and crossing time to determine if an event passes a set of conditions.

- Event must be downward going (i.e., no upward going events from lasers, flashers, etc.).
- The number of good PMTs is >= 5.
- The number of good PMTs per degree < 5.0.
- All events that have a crossing time >= 500 ns, every 20th event if the crossing time is >= 200 ns, and every 200th event if the crossing time is < 200 ns.

When these minimum conditions are met a trigger packet is sent to the TAx4 SD sub-arrays to capture the footprint of the event.

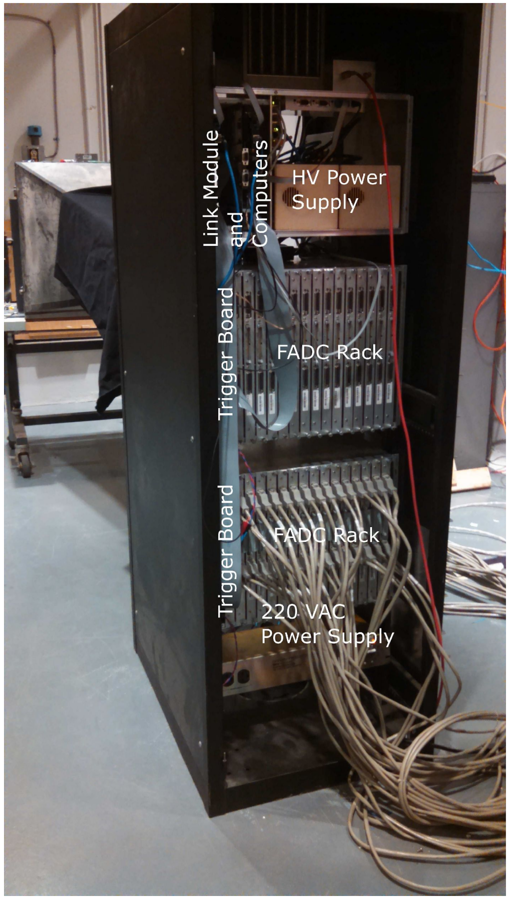
TAx4 Hybrid Quality Cuts

- These cuts ensure quality while being loose enough to have decent event statistics above $10^{18.5}$ eV.

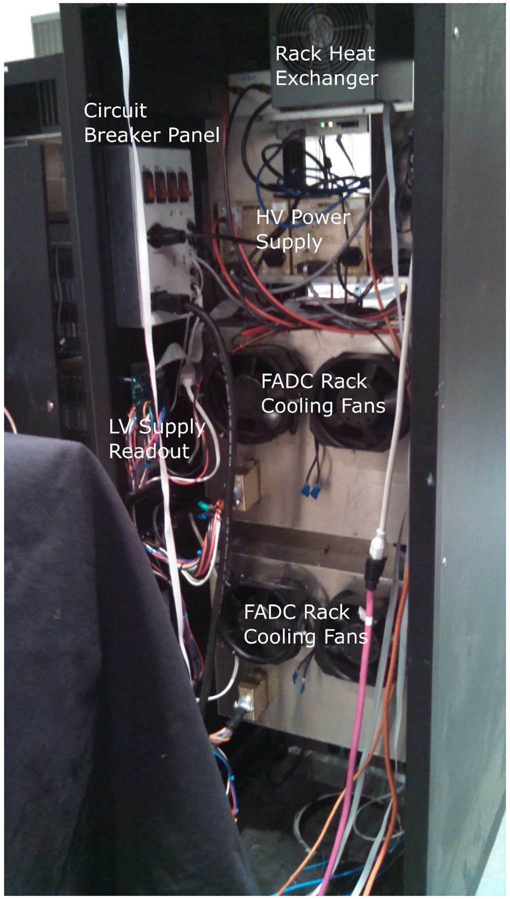
Name	Description
Energy Cut	$E \geq 10^{18.5}$ eV
Weather Cut	No overhead clouds and good seeing conditions
Hybrid Trigger Cut	Discard hybrid trigger events between March 2020 and October 2020 for the TAx4 North site
Core Position Cut	The hybrid core position is within 5 km of the core position calculated by SD only.
Border Cut	The shower core must be within the SD array
χ^2/ndf Cut	Profile and geometry $\chi^2/\mathrm{ndf} \leq 50$

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



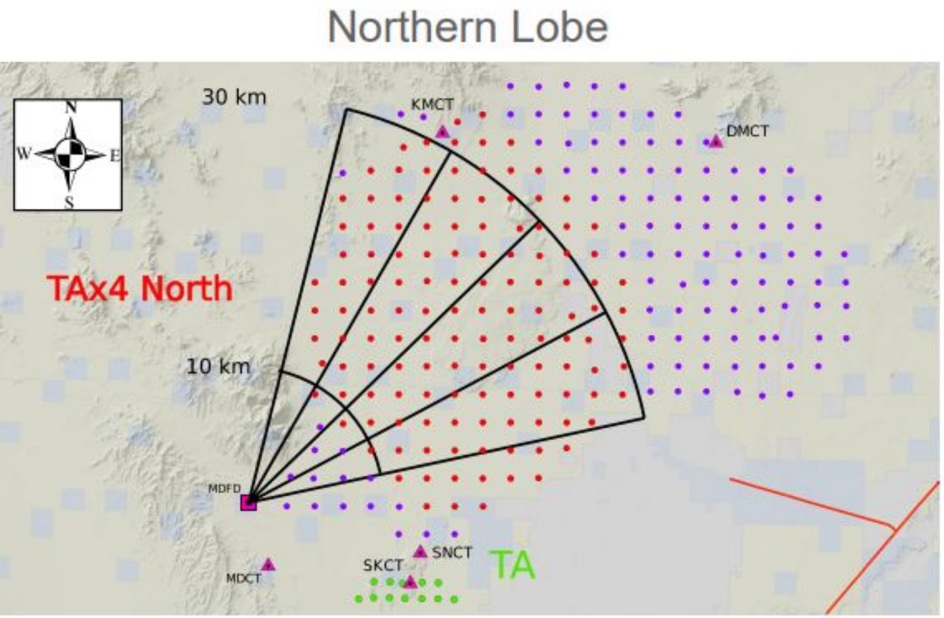
Back of Rack

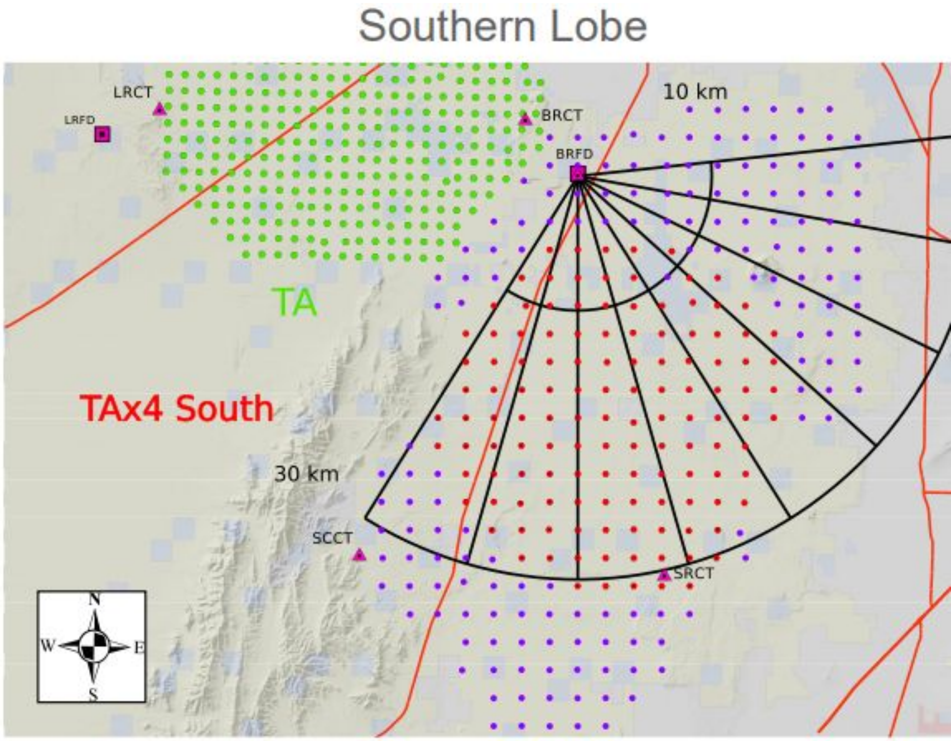
TAx4 Fluorescence Telescope

HiRes Ring-1 “Clover-leaf” Primary Mirror

HiRes 16x16 PMT Cluster Camera

TAx4 SD Array Expansion



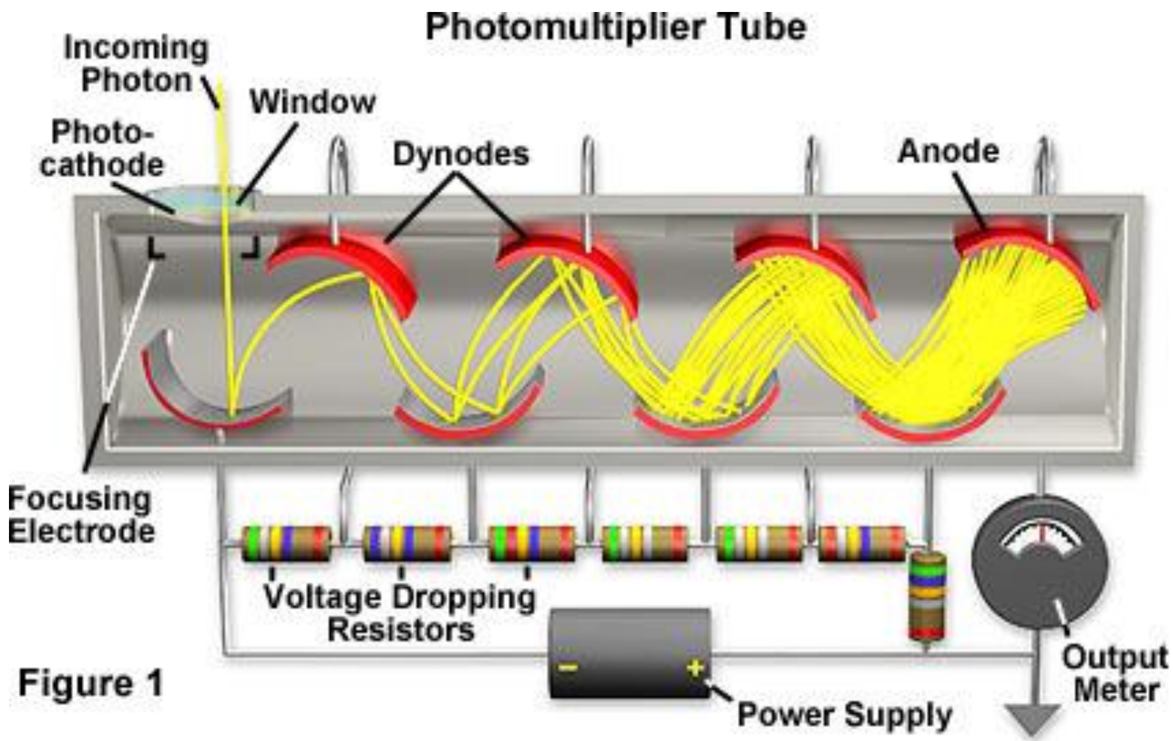


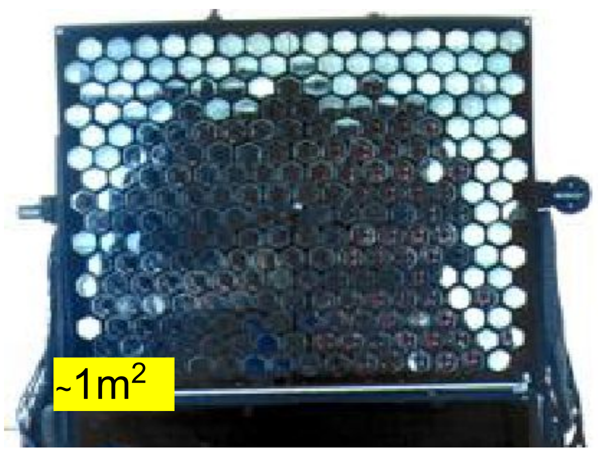
TAx4 FD Calibration

- 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.

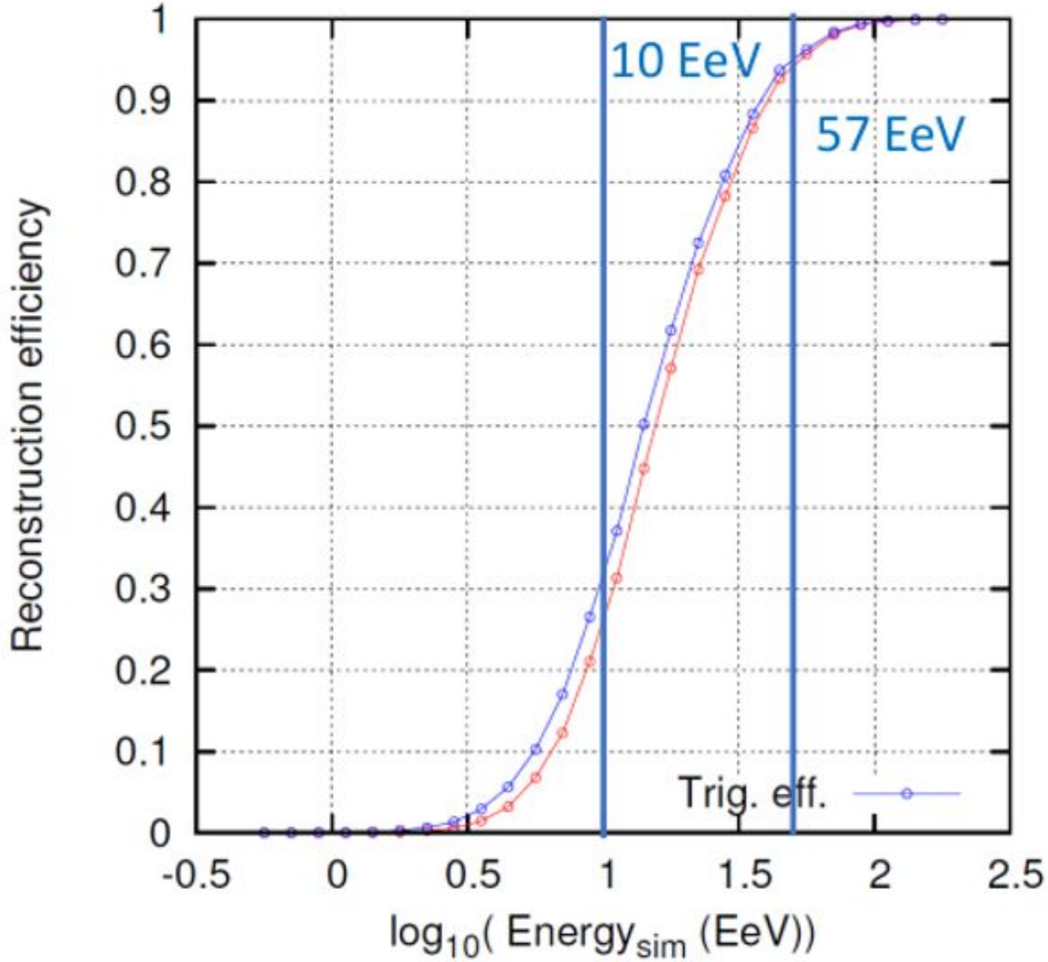
Photomultiplier Tubes (PMTs)

- 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





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%

Peter 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 “Peter cycle” should occupy a similar range of total energy

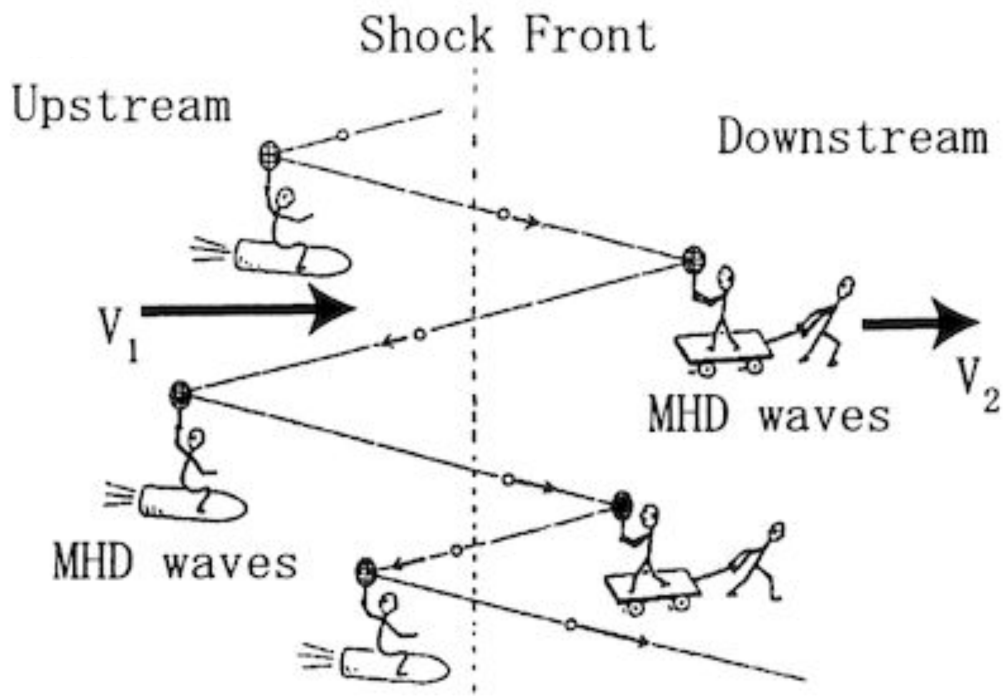
1st Order Fermi Acceleration

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\beta \cong \frac{V_1}{C}$$

$$\frac{dN(E)}{dE} \propto E^{-p}$$

Here the spectral index, $p \gtrsim 2$, depends, for non-relativistic shocks, only on the compression ratio of the shock

Predicts a value of spectral index which is not too different from the observed value of ~2.7



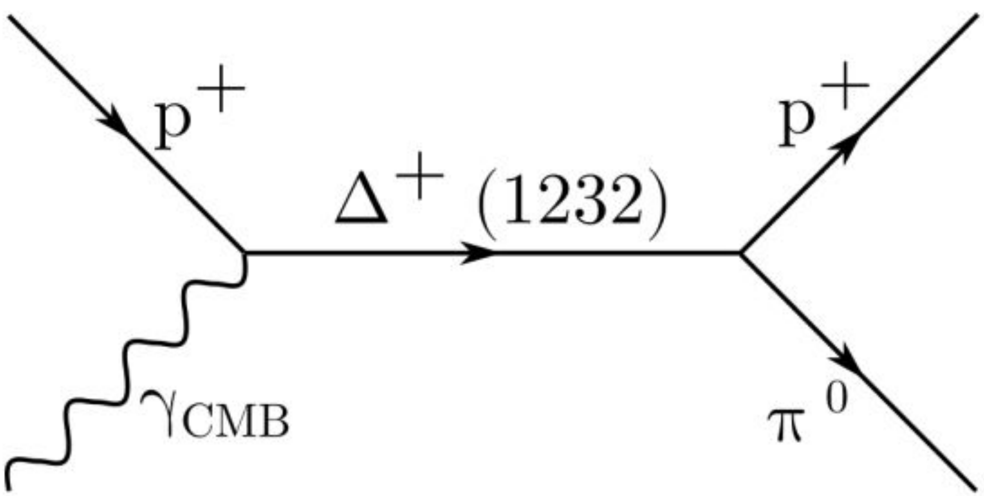
Delta Resonance, $\Delta^{+}(1232)$

Composition: uud

Mass: 1232 MeV/c^2

Mean Lifetime: 5.63×10^{-24} s

Decay Type: Strong Force



Particle Interactions :

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

Neutral Pions, π^0

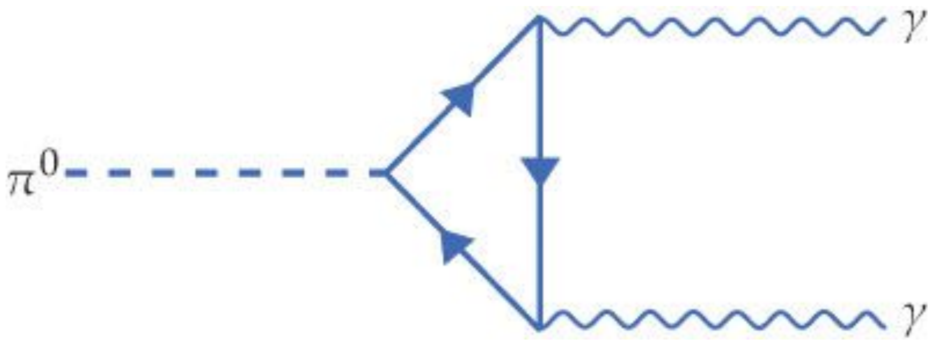
Composition: uu^* or dd^*

Mass: 135.0 MeV/c^2

Mean Lifetime: 8.05×10^{-17} s

Decay Type: Electromagnetic force

Dominate Decay mode ($BR_{2\gamma}$ = 0.98823):



Other Decay modes:

- $\pi^0 \rightarrow \gamma + e^+ + e^-$ ($BR_{\gamma ee} = 0.01174$)
- $\pi^0 \rightarrow e^+ + e^- + e^+ + e^-$ ($BR_{2e2e} = 3.34\times10^{-5}$)
- $\pi^0 \rightarrow e^+ + e^-$ ($BR_{ee} = 6.46\times10^{-8}$) (helicity-suppressed)

Charged Pions, $\pi^{\pm}$

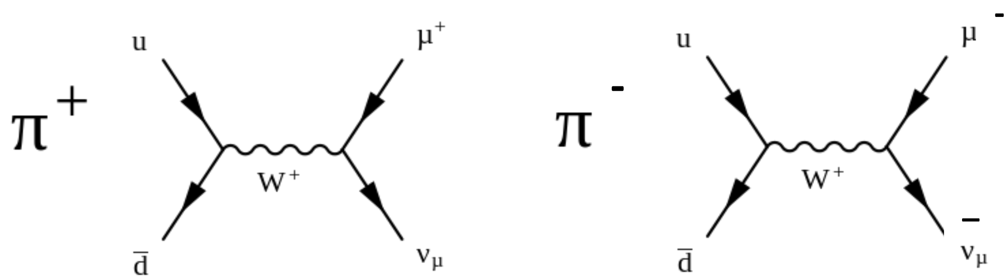
Composition: ud^* (π^+), du^* (π^-)

Mass: 139.6 MeV/c^2

Mean Lifetime: 2.6033×10^{-8} s

Decay Type: Weak Interaction

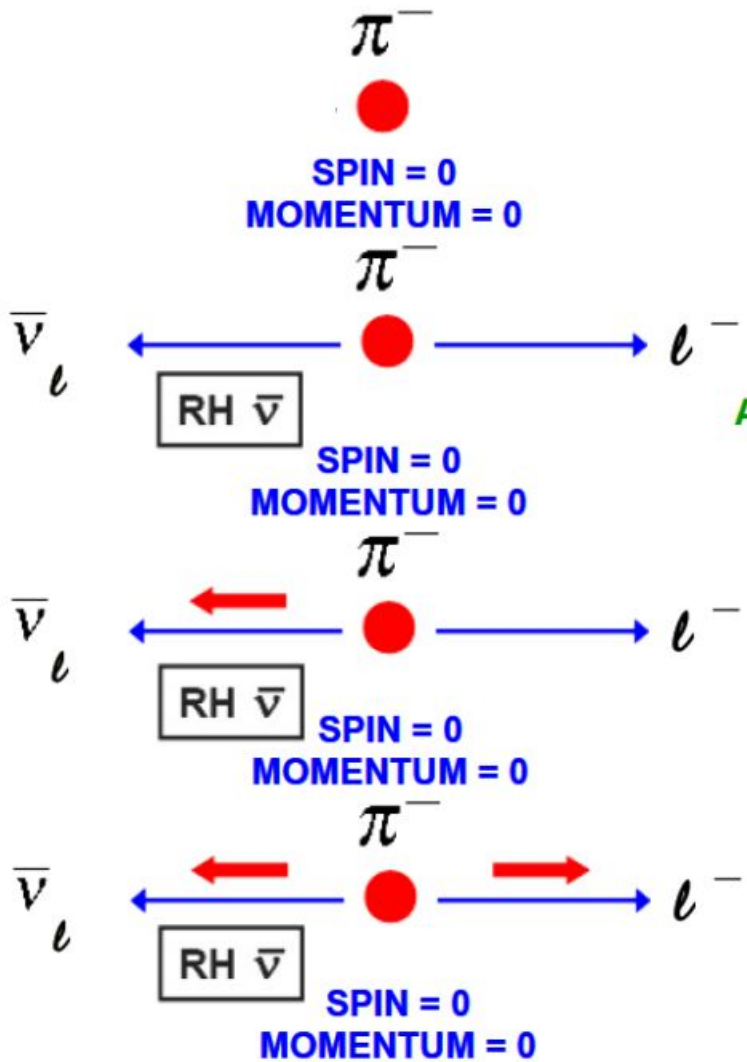
Dominate Decay mode ($BR_{\mu\nu}$=0.999877):



Other Decay modes:

- $\pi^+\rightarrow e^+ + \nu_e$, $\pi^-\rightarrow e^- + \nu_e^*$ ($BR_{e\nu}$=0.000123)(helicity-suppressed)
- $\pi^+\rightarrow \pi^0 + e^+ + \nu_e$, $\pi^-\rightarrow \pi^0 + e^- + \nu_e^*$ ($BR_{\pi e\nu}\sim10^{-8}$)

Helicity suppression



PION REST FRAME

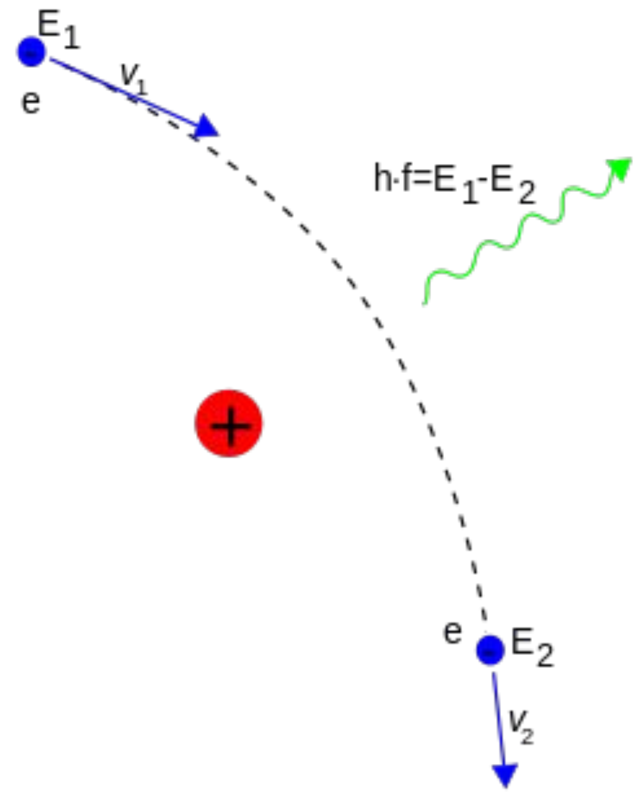
MOMENTUM CONSERVATION
ANTINEUTRINO AND LEPTON LEAVE IN OPPOSITE DIRECTIONS
AND SAME MOMENTUM

ANTINEUTRINOS ALWAYS RIGHTHANDED
FOR NEUTRINOS CHIRALITY= HELICITY

ANGULAR MOMENTUM CONSERVATION
ANTINEUTRINO AND LEPTON HAVE SAME HELICITY

Bremsstrahlung

- AKA "Braking Radiation" is produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus
- Includes synchrotron radiation (i.e., photon emission by a relativistic particle), cyclotron radiation (i.e., photon emission by a non-relativistic particle), and the emission of electrons and positrons during beta decay
- Continuous spectrum, which becomes more intense and whose peak intensity shifts toward higher frequencies as the change of the energy of the decelerated particles increases



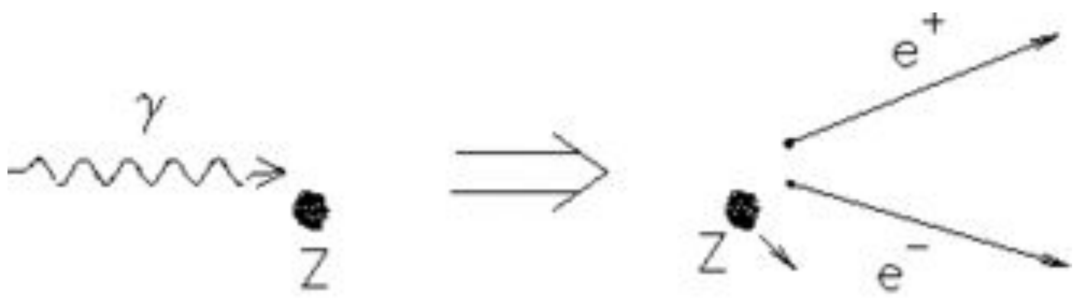
Pair Production

- It is the creation of a subatomic particle and its antiparticle from a neutral boson

- Momentum and energy is conserved
  - The incoming energy of the photon must be above a threshold of at least the total rest mass energy of the two particles created

- All other conserved quantum numbers (angular momentum, electric charge, lepton number) of the produced particles must sum to zero

- The probability of pair production in photon–matter interactions increases with photon energy and also increases approximately as the square of atomic number of (hence, number of protons in) the nearby atom



Photoelectric Effect

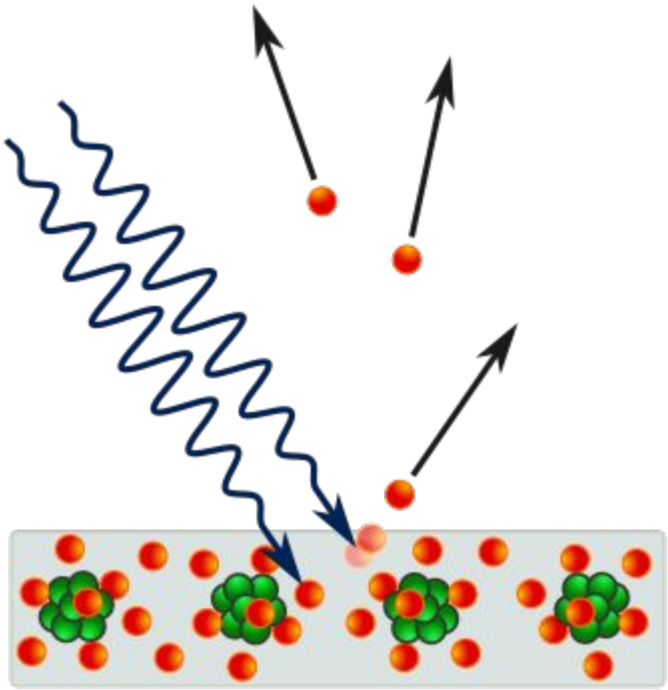
$$K_{\text{max}} = h\,\nu - W$$

$$W = h\,\nu_o$$

$$K_{\text{max}} = h\,(\nu - \nu_o)$$

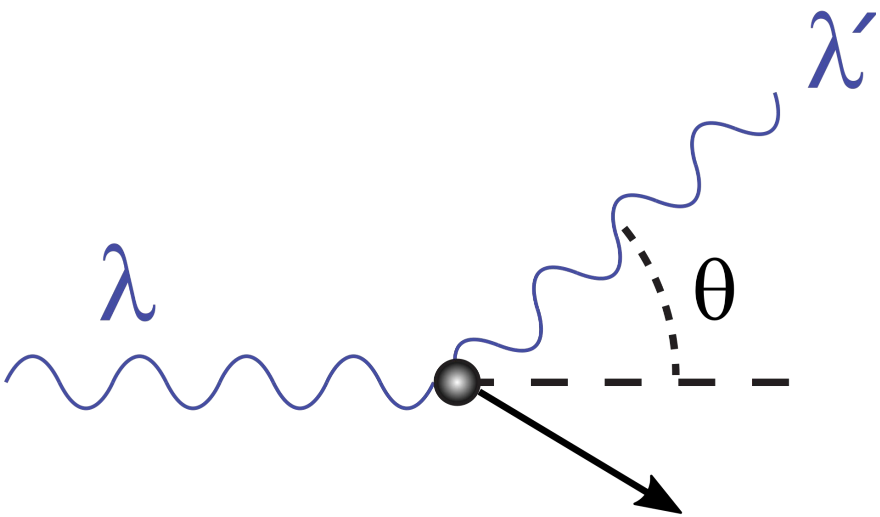
- Emission of electrons when electromagnetic radiation, such as light, hits a material

- Electrons emitted in this manner are called photoelectrons (pe)



Compton Scattering

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

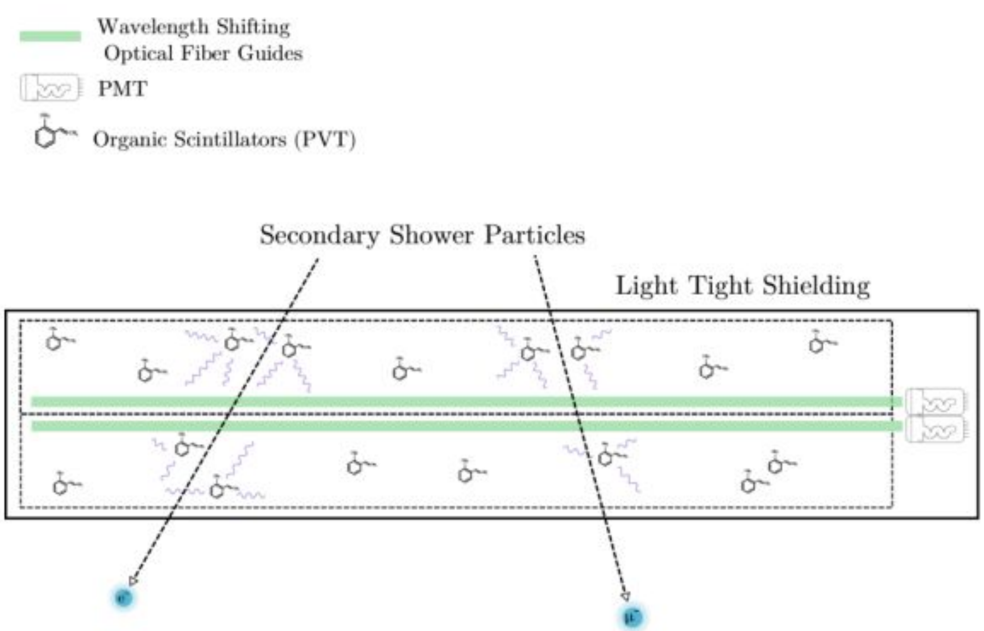


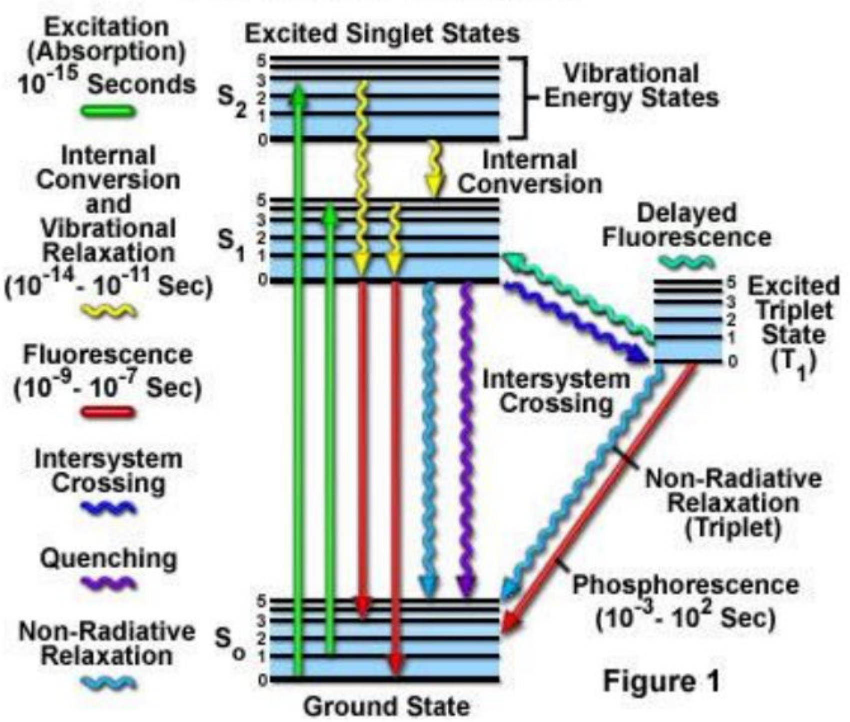
Compton scattering: Scattering of a photon after an interaction with a charged particle, usually an electron. If it results in a decrease in energy (increase in wavelength) of the photon

Inverse Compton scattering: occurs when a charged particle transfers part of its energy to a photon

Scintillation

- In organic molecules scintillation is a product of π-orbitals. These π-orbitals are out-of-plane; the π electrons overlap and are completely delocalized
- Scintillation light is produced from the de-excitation of the molecule





http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html

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.

References

[1] R. U. Abbasi et al. Indications of Intermediate-Scale Anisotropy of Cosmic Rays with Energy Greater than 57 EeV in the Northern Sky measured with the Surface Detector of the Telescope Array Experiment. The Astrophysical Journal, 790(2):L21, July 2014

[2] D. Ivanov. Energy Spectrum Measured by the Telescope Array Experiment. In Proceedings of the International Cosmic Ray Conference (ICRC2019), Madison, USA, 2019.

[3] M. Allen. Ultra High Energy Cosmic Ray Energy Spectrum and Composition using Hybrid Analysis with Telescope Array. Ph.D. Thesis, University of Utah, Salt Lake City, UT, USA, 2012.

[4] R. U. Abbasi et al. (The High Resolution Fly's Eye Collaboration). Indications of Proton-Dominated Cosmic-Ray Composition above 1.6 EeV. Phys. Rev. Lett. 104, 161101. 2010.