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Particle & Astroparticle Physics Spring Program

May 8, 2015

INFN Laboratori Nazionali del Gran Sasso

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Fluorescence detector Array of Single-pixel Telescopes

Development of a prototype for a Fluorescence detector Array of Single-pixel Telescopes (FAST)

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Outline

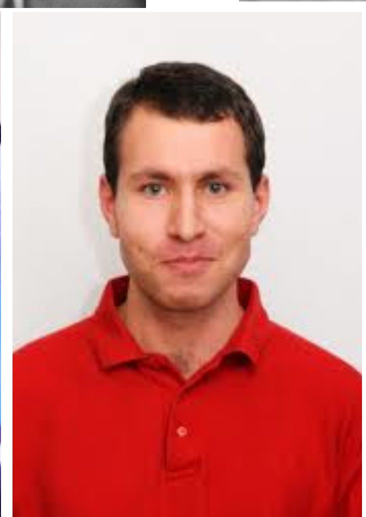
- Introduction and History of Cosmic Rays
- Detection
- Current Observation: Pierre Auger Observatory, TA, JEM-EUSO
- FAST Activity

Cosmic Ray Physics Timeline: University of Chicago



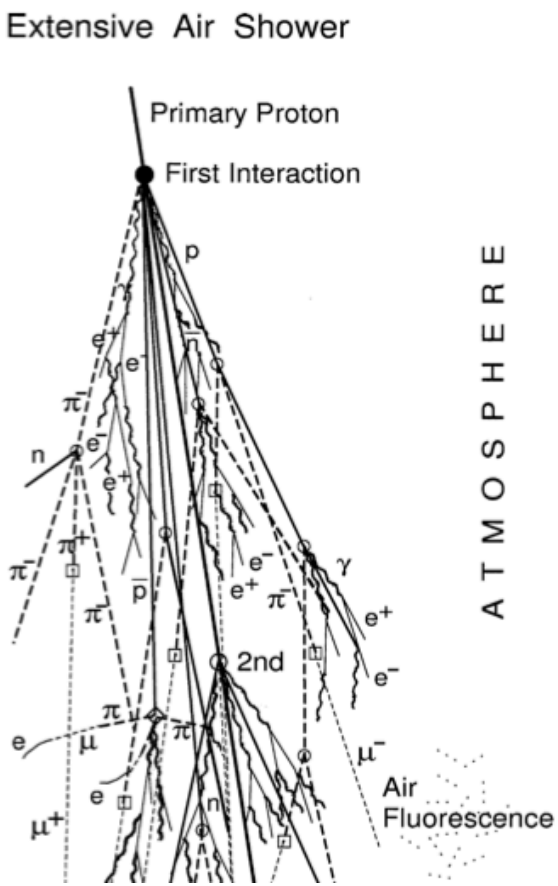






Fluorescence detector Array of Single-pixel Telescopes

Introduction to Cosmic Rays



- High energy primary cosmic ray hadron enters atmosphere isotropically
- Creates large number of secondaries from collisions within atmosphere (including with N2, O2, Ar)
- Cascade of particles creates an extensive air shower (EAS)

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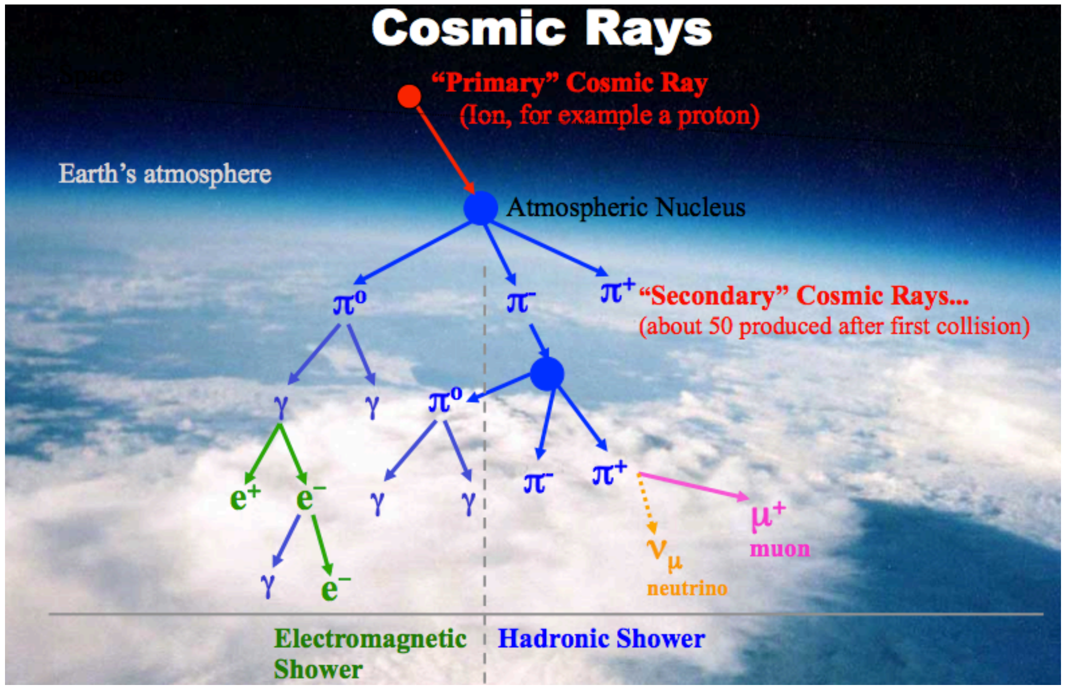
Introduction to Cosmic Rays

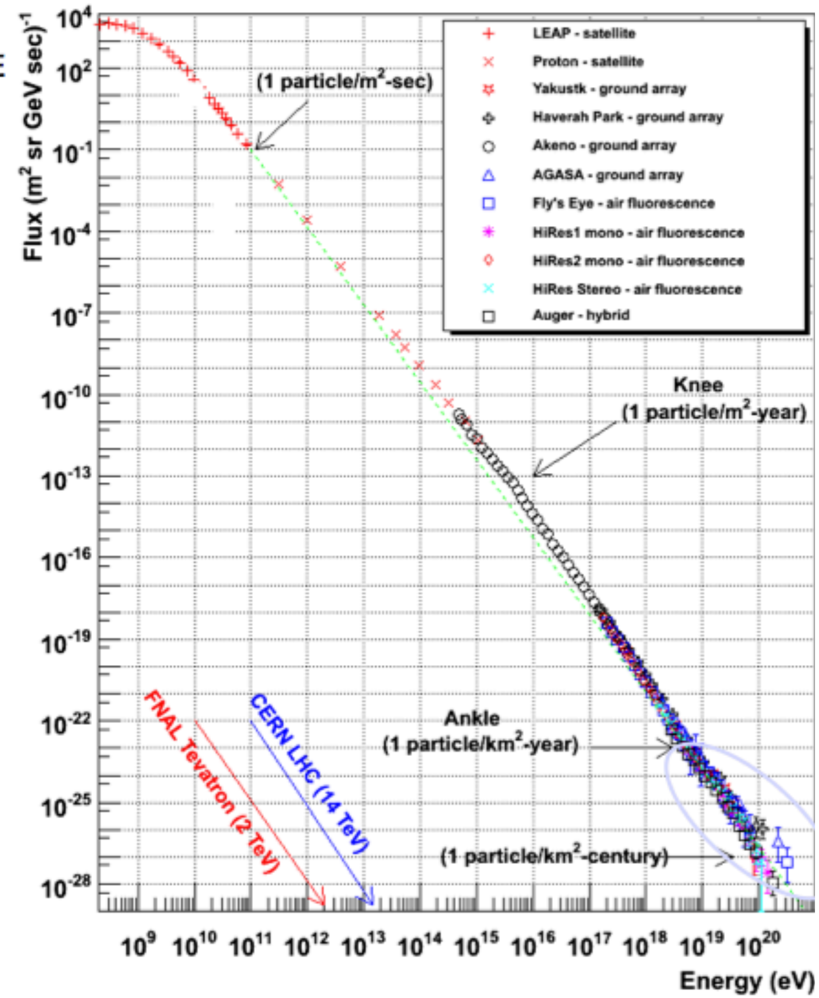


- Decay of charged pions forms a superimposed shower of muons and neutrinos -> *hadronic cascade*
- Neutral pions divert a lot of energy into gammas and electrons -> *electromagnetic cascade*

Introduction to Cosmic Rays: Energy Spectrum

- Energy spectrum goes by power law of about E^-3
- At ~10^20 eV, expect 1 particle/km^2-century (close to GZK cutoff)
- We therefore need large ground arrays to detect secondary particles

$$\Phi \equiv \frac{\Delta N}{\Delta S \Delta t \Delta \Omega \, \Delta E}$$



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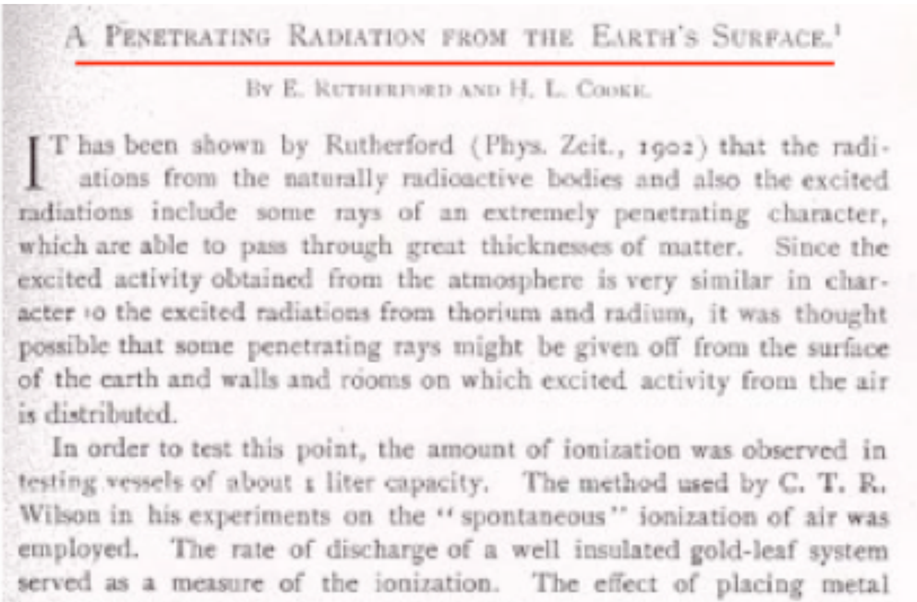
History of Cosmic Rays: Discovery

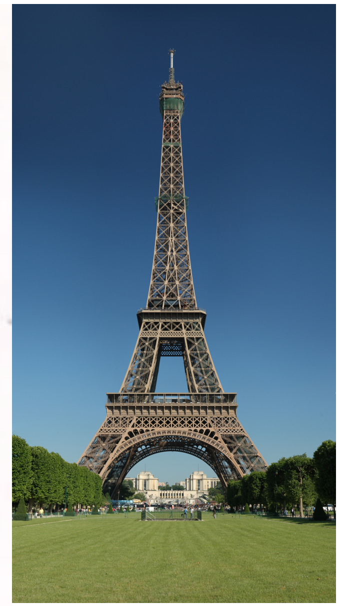


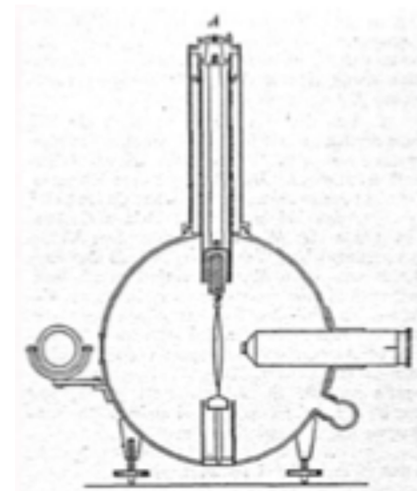
A Penetrating Radiation from the Earth's Surface.[1]

By E. Rutherford and H. L. Cooke.

It has been shown by Rutherford (Phys. Zeit., 1902) that the radiations from the naturally radioactive bodies and also the excited radiations include some rays of an extremely penetrating character, which are able to pass through great thicknesses of matter. Since the excited activity obtained from the atmosphere is very similar in character to the excited radiations from thorium and radium, it was thought possible that some penetrating rays might be given off from the surface of the earth and walls and rooms on which excited activity from the air is distributed.

In order to test this point, the amount of ionization was observed in testing vessels of about 1 liter capacity. The method used by C. T. R. Wilson in his experiments on the "spontaneous" ionization of air was employed. The rate of discharge of a well insulated gold-leaf system served as a measure of the ionization. The effect of placing metal



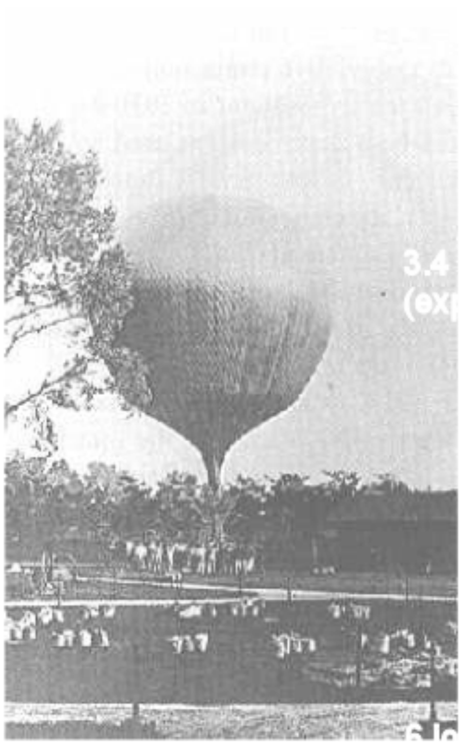


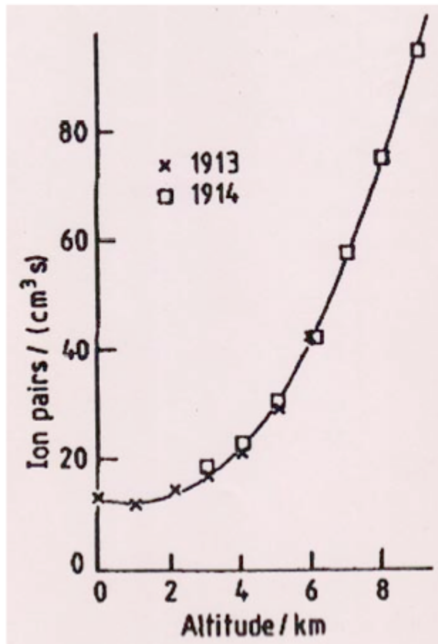
Electroscope

- Detected ionization from natural radioactivity
- If source is from Earth, radiation should decrease with increased height above surface
- 1910: Father Theodore Wulf performed studies from the Eiffel tower

Fluorescence detector Array of Single-pixel Telescopes

History of Cosmic Rays: Discovery





- Left: Victor Hess reaches 5km (1912)
- Right: Werner, Kolholster reach 9km! (1914)

- Unknown ionizing radiation with extraterrestrial origin -> “Cosmic Rays” (Millikan)

Fluorescence detector Array of Single-pixel Telescopes

History of Cosmic Rays: Clashes and Media

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

In an atmosphere surcharged with drama, in which the human element was by no means lacking, the two protagonists presented their views with the vehemence and fervor of those theoretical debates of bigone days when learned men clashed over the number of angels that could dance on the point of a needle. Dr. Millikan particularly sprinkled his talk with remarks directly aimed at his antagonist's scientific acumen. There was obvious coolness between the two men when they met after the debate was over.

MILLIKAN DENIES 'CLASH' ON THEORY

Scientist Protests That the Word 'Incautious' Was Not Aimed at Compton.

DISCLAIMS ANY COOLNESS

Holds The Times Report Stated "Exactly the Opposite" of the Findings He Presented.

- Millikan: photons
- Compton: charged particles

History of Cosmic Rays: Clashes Decided

Fig. 8. Compton with the special ionization chamber which he designed and used for his world-wide cosmic-ray survey during 1931–33, which proved that cosmic rays are charged particles.

MILLIKAN'S DATA CONFIRM COMPTON

Results of Cosmic Ray Study at Panama Tend to Back Rival's Ideas.

RAY INTENSITY VARIES

Strength Is Greater at the Poles —Equatorial Tests Are Now Projected.

PASADENA, Cal., Feb. 4 (UP).—The stratosphere above equatorial regions of the earth should be the next scene of exploration in the quest of the secrets of the cosmic ray, Dr. Robert A. Millikan said here today.

Announcing that observations of his co-workers at Panama confirmed the earlier reports of Dr. Arthur H. Compton of Chicago that the rays from interstellar space showed latitude effects, Dr. Millikan disclosed that the variance was as high as 8 per cent.

- Compton organized first international collaboration in 1931 utilizing standardized ionization chambers calibrated with a radium gamma ray source

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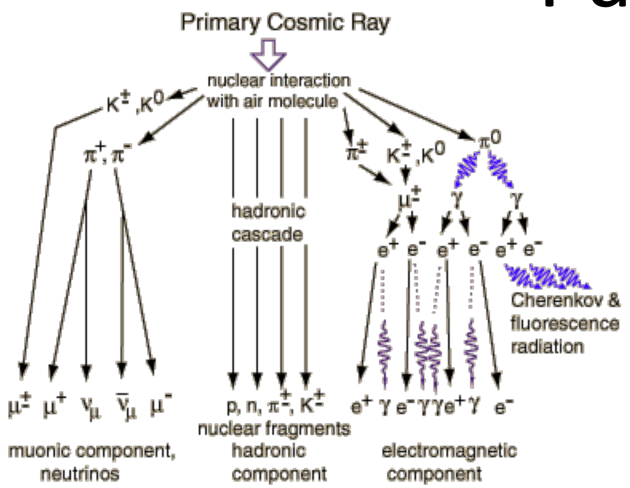
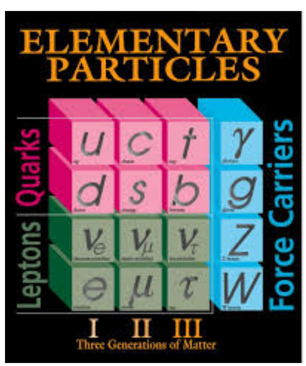
Fluorescence detector Array of Single-pixel Telescopes

History of Cosmic Rays: Discovery of Particles





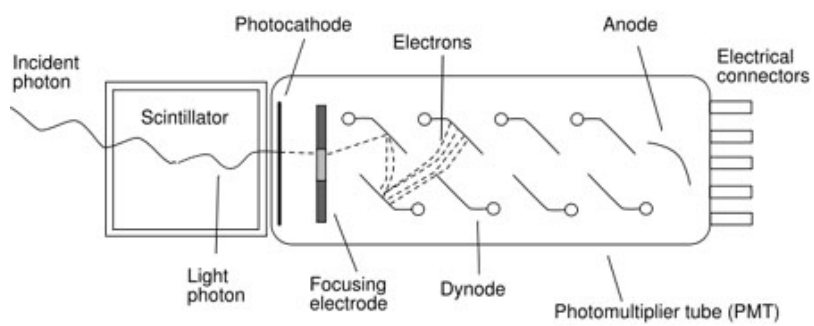
- Studies of cosmic rays in the 1930s and 1940s saw the discovery of particles including: positron, muon, pion, kaon, lambda

Cosmic Rays: Detection

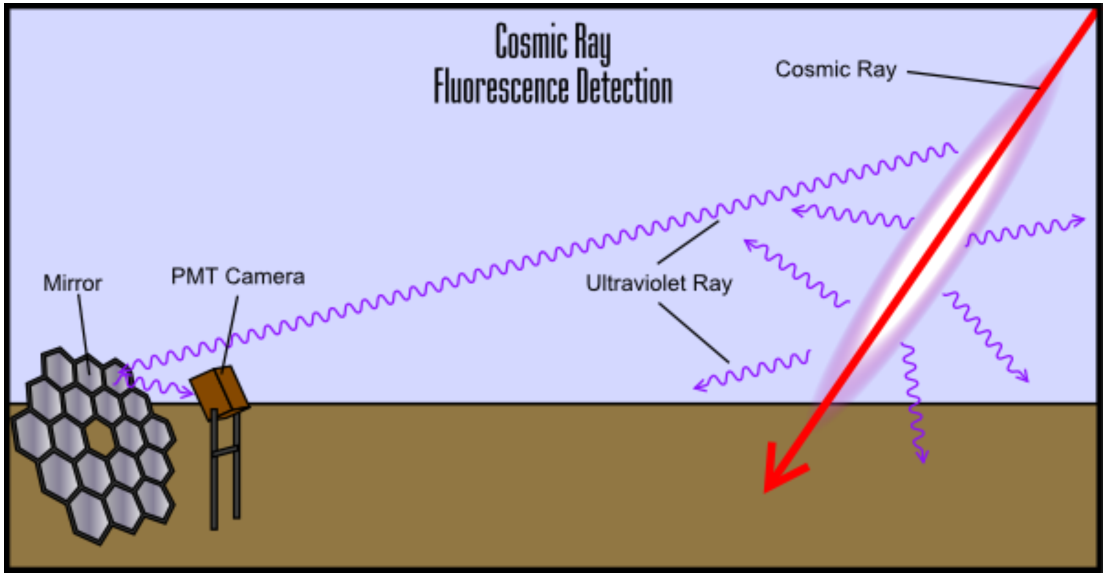
- Energy of low flux, ultra-high energy cosmic rays (UHECRs) not detected directly: must be inferred from energy, arrival direction, and mass composition of secondary showers
- Use of ground based detectors:

  - plastic scintillators, water-Cherenkov tanks, etc.

  - use of *fluorescence light* emitted by excited nitrogen as UHECR particles pass through the atmosphere

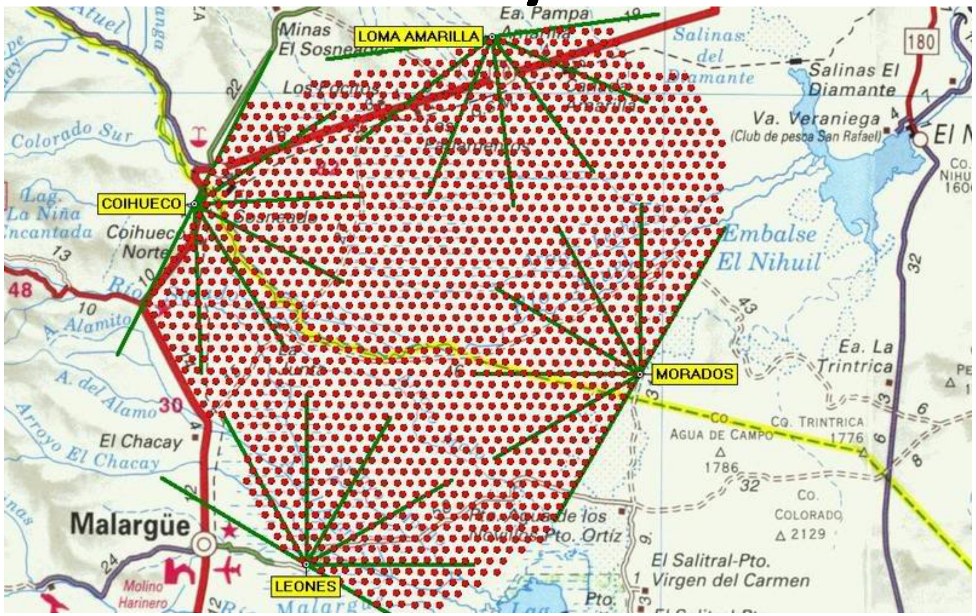


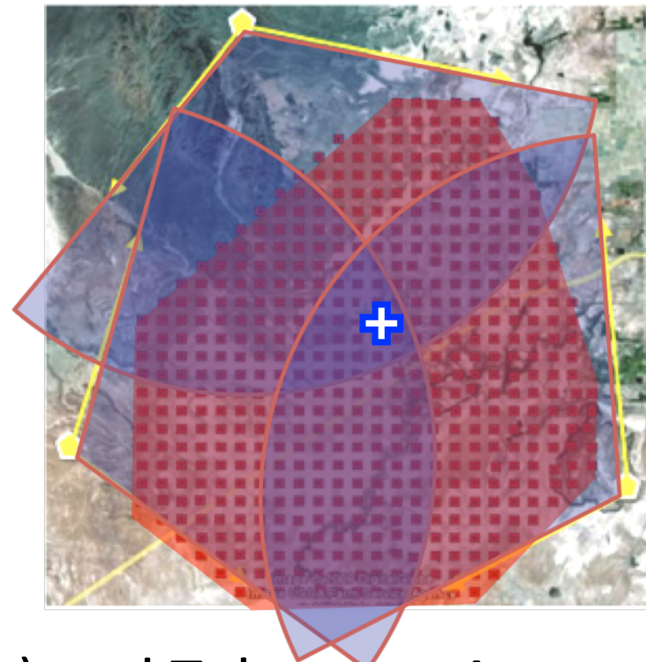
Cosmic Rays: Detection



- Fluorescence telescopes observe EAS through the atmosphere: large, curved mirrors focus light onto PMTs which convert the light to an electric signal

Cosmic Rays: Current Observation





- Pierre Auger Observatory (Argentina) and Telescope Array (TA) Project (Utah) are the two largest UHECR experiments currently in operation
- Both consist of an array of ground based particle detectors overlooked by a number of Fluorescence Detectors

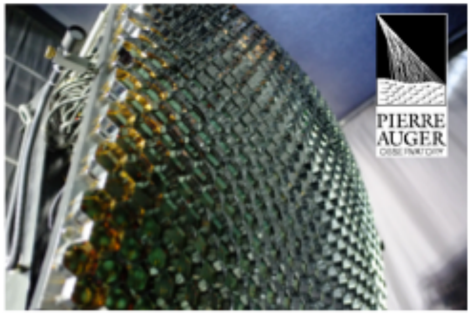
Fluorescence detector Array of Single-pixel Telescopes

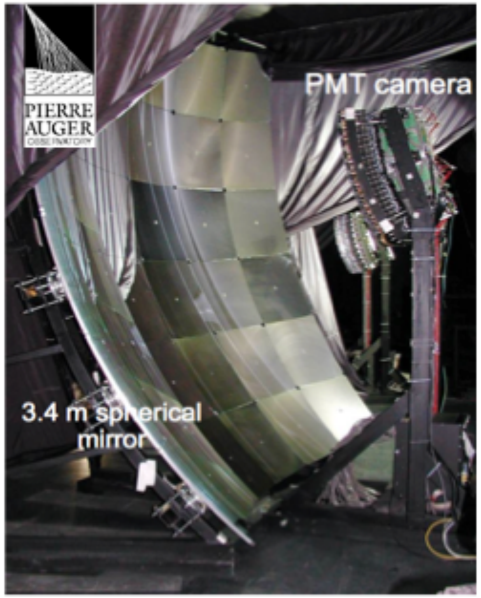
Cosmic Rays: Current Observation

- Pierre Auger Observatory: 3000 km^2, data collection since 2004
- Telescope Array Project: 700 km^2 (largest in northern hemisphere), data collection since 2008
- JEM-EUSO: “Extreme Universe Space Observatory”, use fluorescence techniques to observe EAS through Earth’s atmosphere from the International Space Station (ISS); launch (hopefully) in 2017

Cosmic Rays: Current Observation

- Current generation detectors have given us many important clues to the possible origins of UHECRs
- Next generation experiment is required to increase statistics at the highest energies
- Will require a huge ground area coverage an order of magnitude larger than the current Pierre Auger coverage
- Costly to cover such an area with the current generation fluorescence detectors



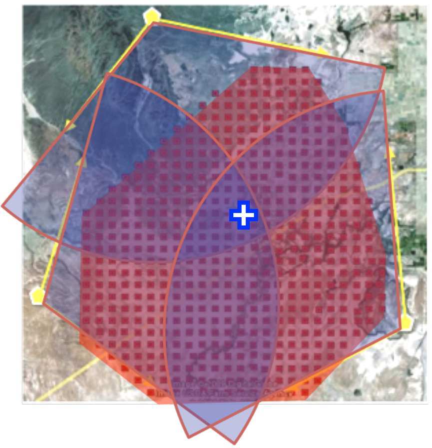


FAST: Fluorescence detector Array of Single-pixel Telescopes

- Research & Development for future detectors
- Simplified and cost effective next generation fluorescence telescope allowing for coverage of a huge ground area
- Single 8-inch PMT at focus of Fresnel lens (15º x 15º FOV)

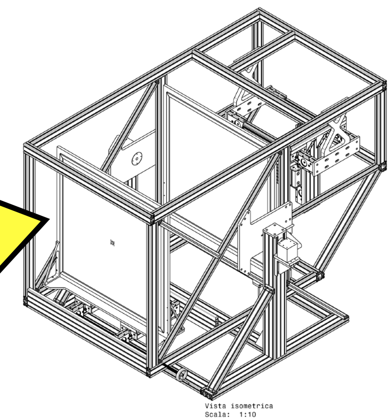
Window of Opportunity at TA-EUSO

Telescope Array, Utah, USA



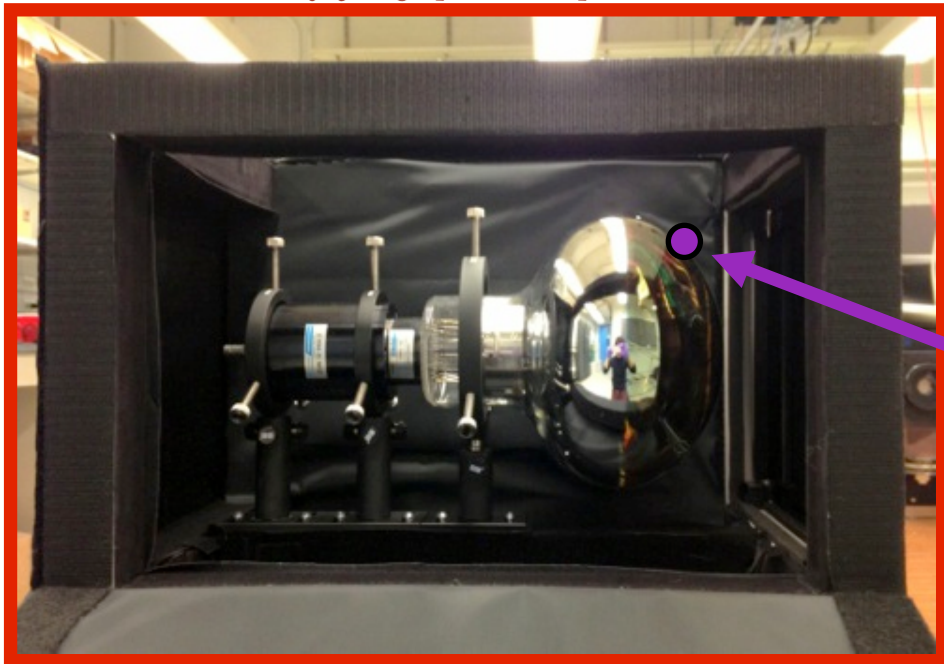
Black Rock Mesa site

JEM-EUSO optics

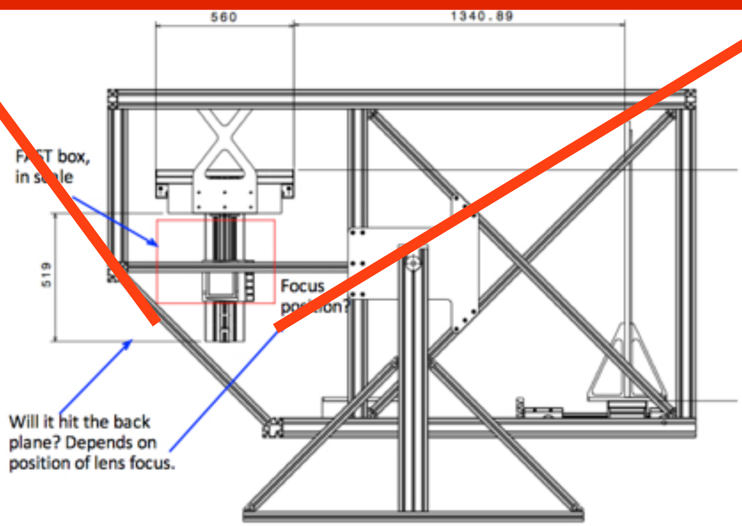


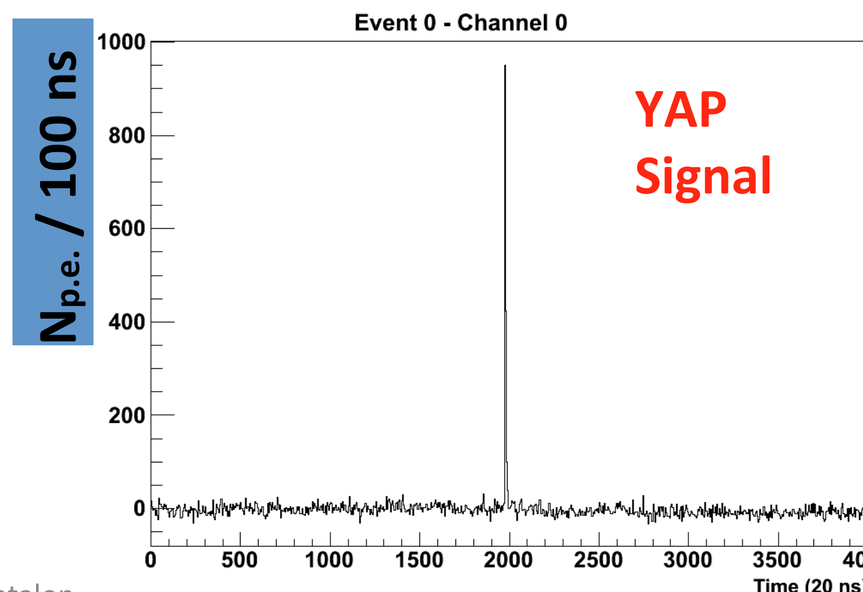
- Temporally borrow the EUSO optics in the TA site.
  - Two Fresnel lenses (+ 1 UV acrylic plate in front for protection)
- Installation in February 2014, initial test measurements in April and June 2014
- Collaboration between Pierre Auger, TA and JEM-EUSO.

FAST Camera



- PMT 8 inch R5912-03
- E7694-01(AC coupling) for base
- MUG6 UV band pass filter
- YAP (YAlO3: Ce) scintillator with ^{241}Am (50 Hz, ~1000 p.e.) to monitor stability.





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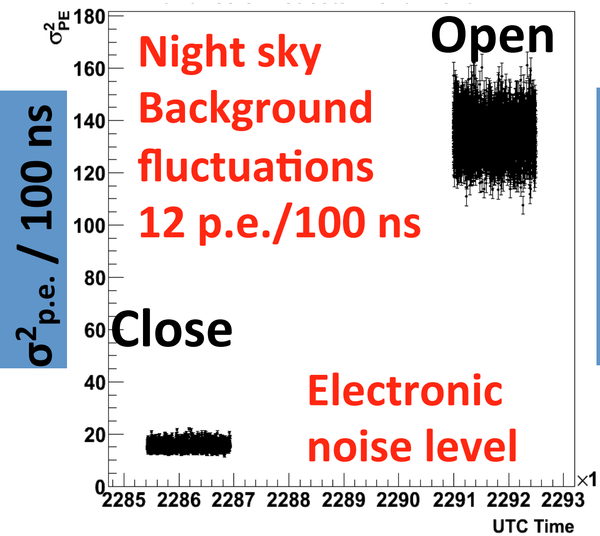
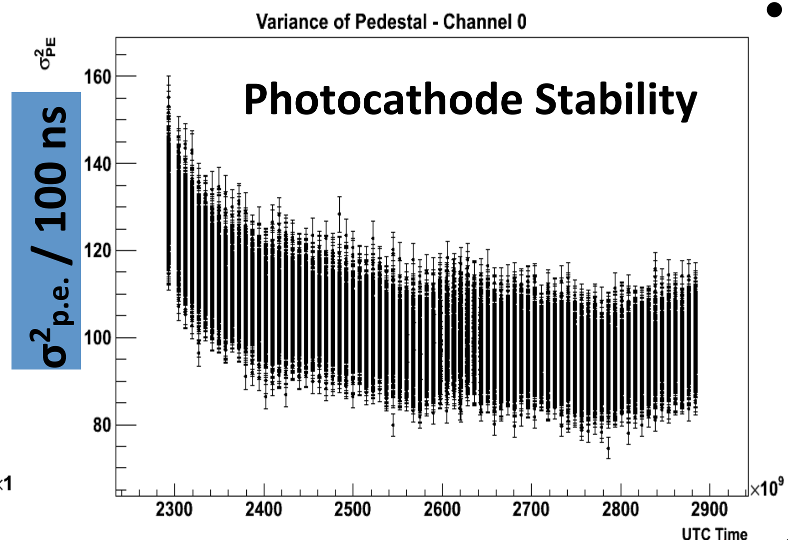
Installation in February 2014

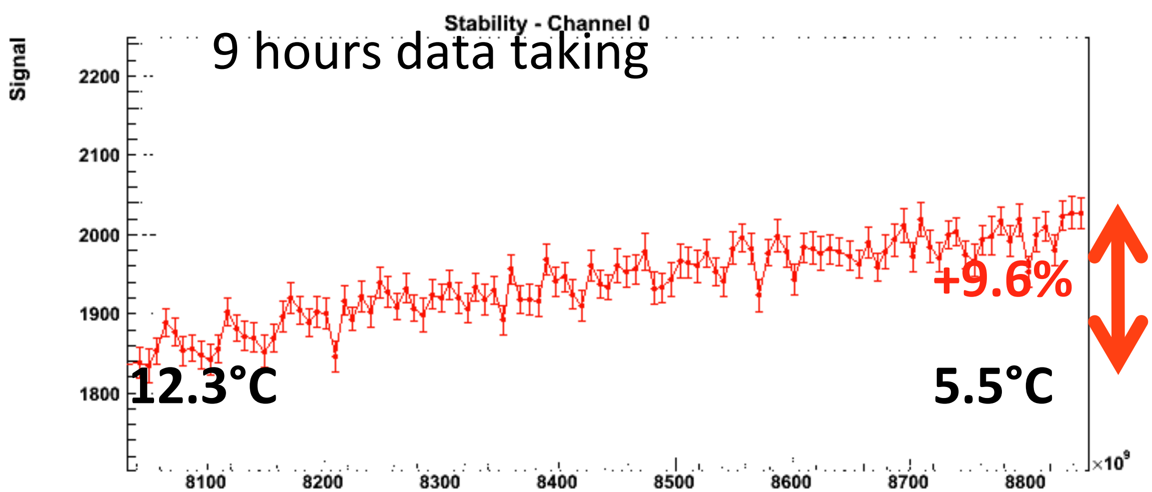
Fluorescence detector Array of Single-pixel Telescopes

Operation in Clear Night





- Variance proportional to PMT current. Electronic noise is negligible with regard to night sky background.



- Good gain stability during data taking, consistent with PMT gain temperature dependence of -1.4%/°C

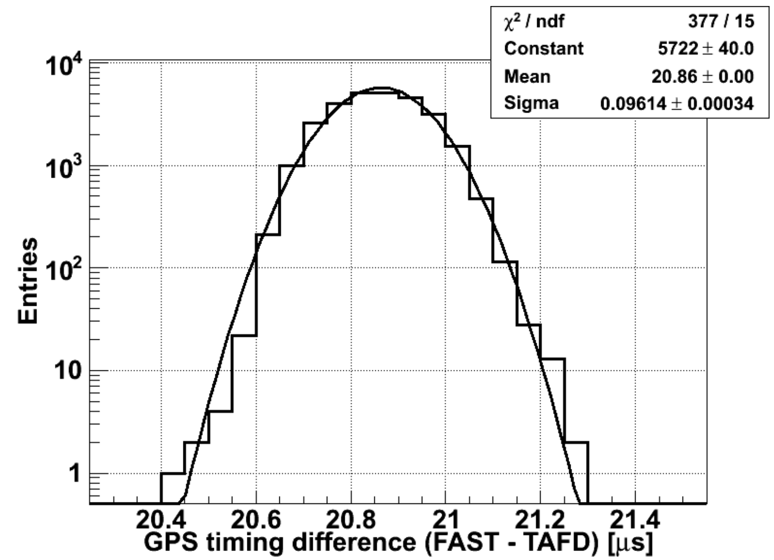
FAST

Fluorescence detector Array of Single-pixel Telescopes

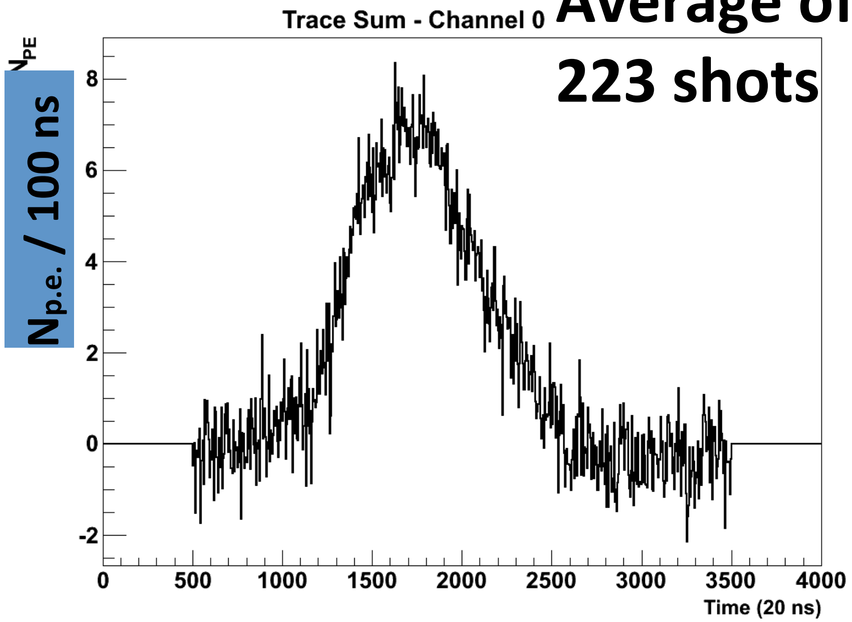
Timing and CLF Signal

Central Laser Facility

Vertical UV laser shooting every 30 minutes, **21 km from FAST**, 10 Hz, 2.2 mJ, 300 shots



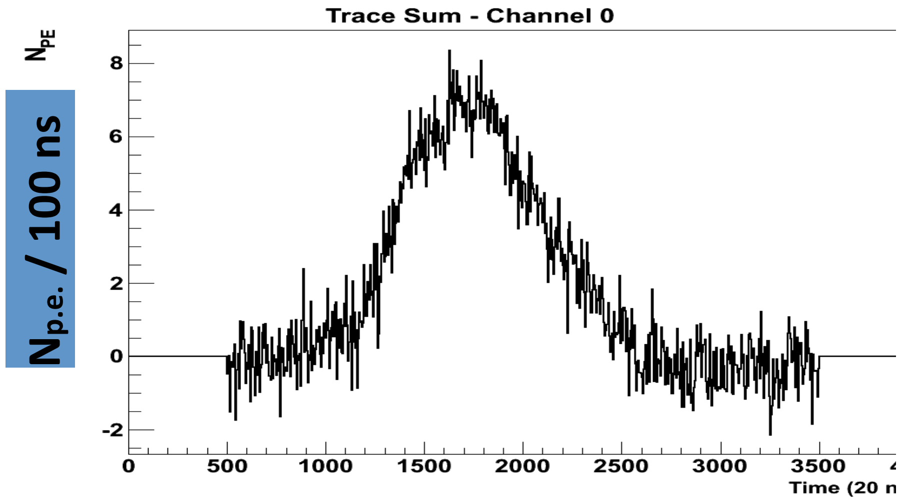
Average of 223 shots

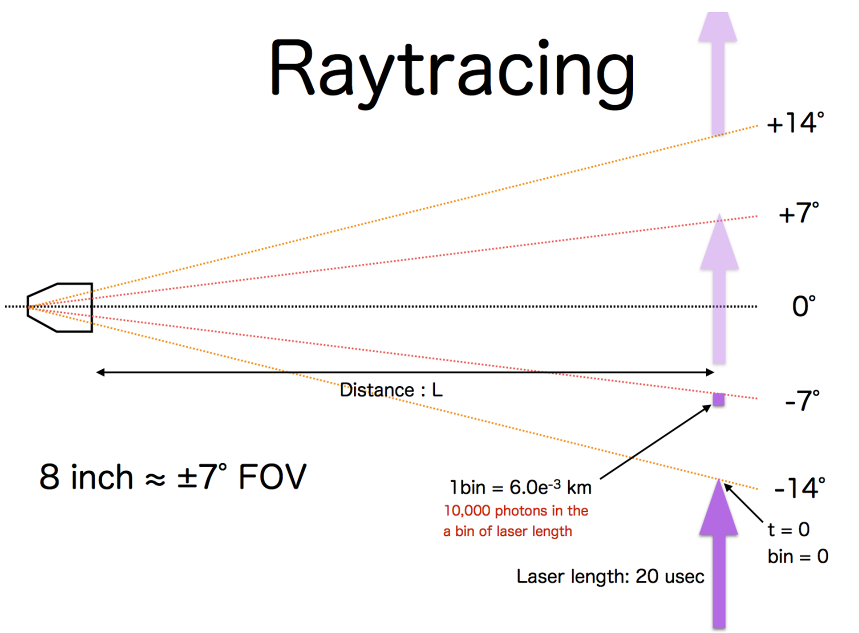


- FAST- TAFD timing resolution, 100 ns. (20.9 μs is the TAFD trigger processing time.)
- laser signal ~ $10^{19.5}$ eV at 21 km
- peak signal ~ 7 p.e. / 100 ns ($\sigma_{p.e.}$ = 12 p.e.) at the limit of detectability

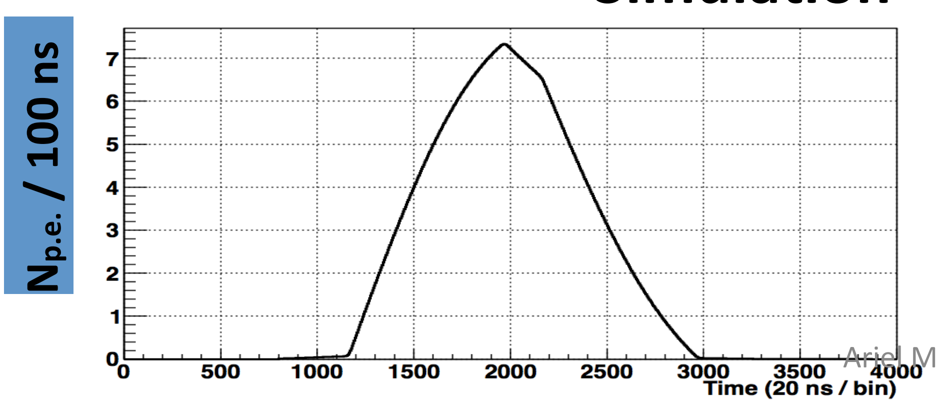
Preliminary CLF Simulation

Data





Simulation



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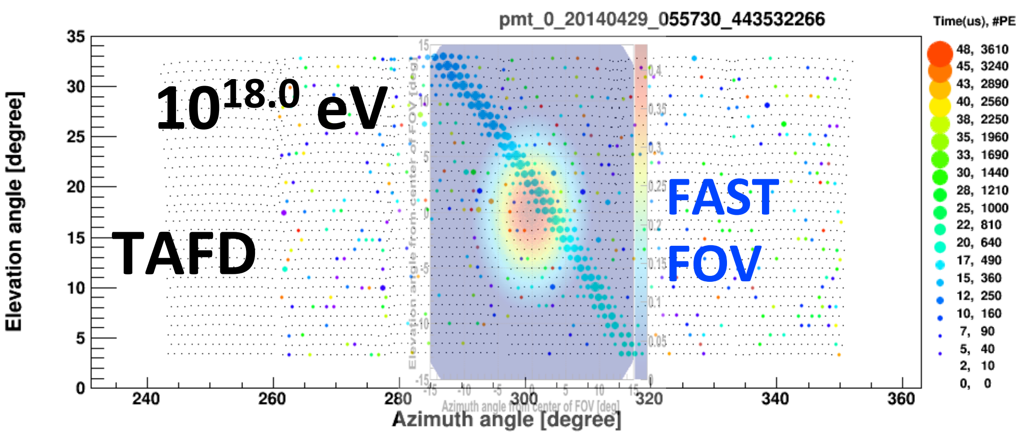
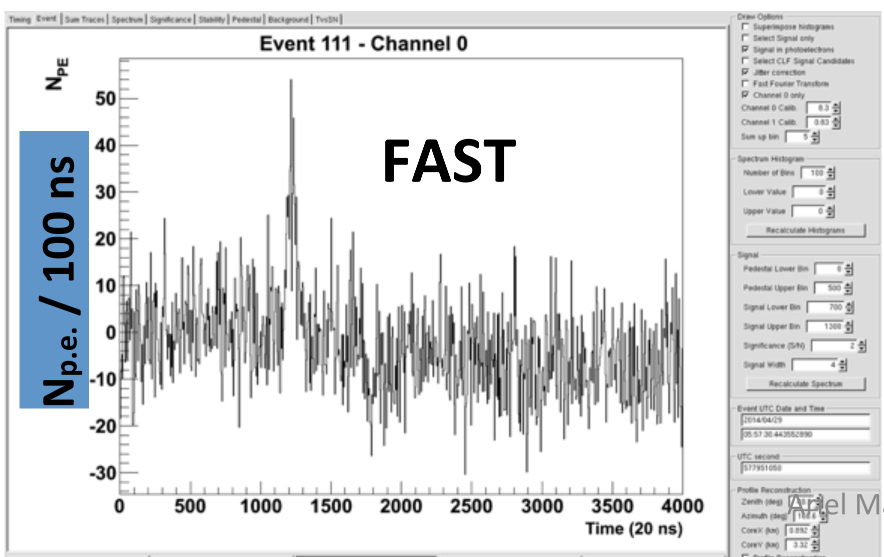
- Evaluate simulated signals observed by the CLF and the Portable UV Laser System (PLS)

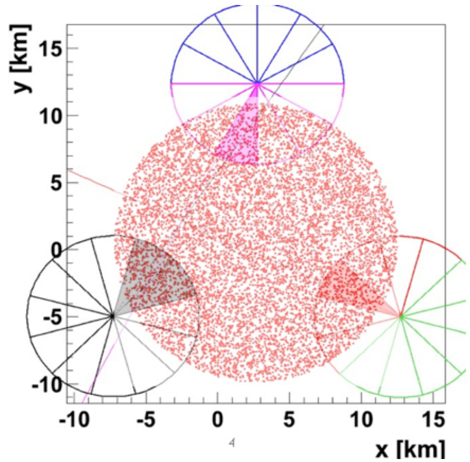
Shower Signal Search





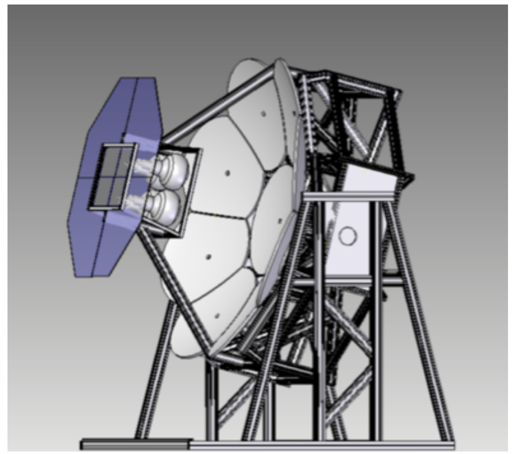
- We searched for FAST signals in coincidence with TAFD showers in the FAST field of view.
- Data set: April and June observation, 19 days, 83 hours.
- **16 candidates found.**
- Low energy showers as expected.

Simulation Study



- FAST with 20 km spacing

- 4 PMTs Telescope



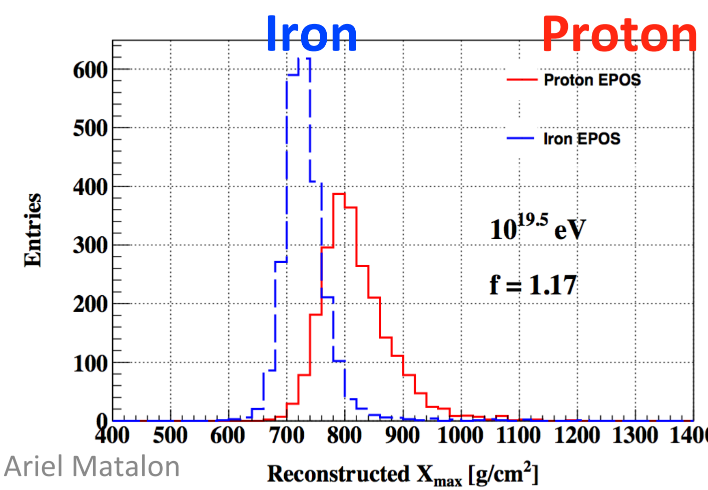
- Reconstruction efficiency

logE	Proton	Iron
18.5	0.65	0.56
19.0	0.88	0.89
19.5	0.99	1.00

- 100% efficiency at $10^{19.5}$ eV

- With smearing SD accuracy of geometry, Xmax resolution of FAST is 30 g/cm^2 at $10^{19.5}$ eV.

- Under implementing a reconstruction by only FAST.

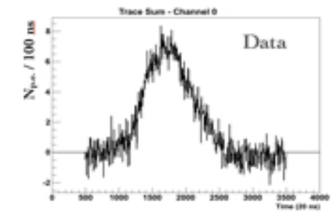


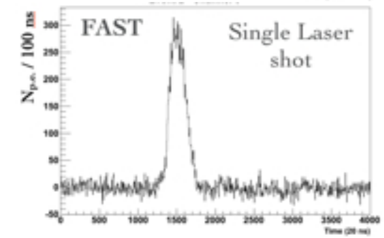
Including Xmax resolution

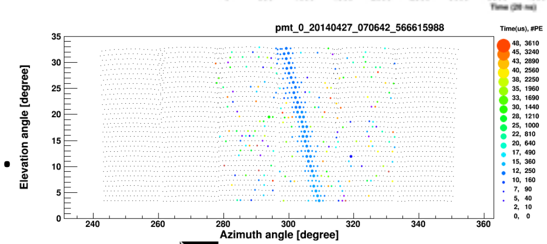
FAST
Fluorescence detector Array of Single-pixel Telescopes

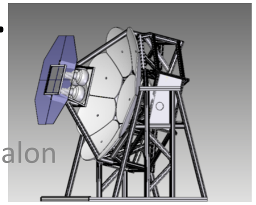
Summary and Future Plans

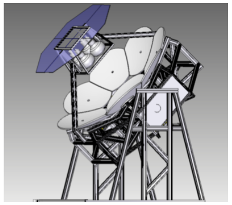
- Promising results from the first field test of FAST concept:
  - very stable and simple operation
  - robust behavior under NSB (gain stability, a single bright star does not matter when integrating over the large FAST FOV)
  - laser shots and shower candidates detected
  - sensitivity is consistent with simulated expectation
- Very successful example of Auger-TA-EUSO collaboration.
- Several improvements possible, e.g. high Q.E. PMT, narrow UV pass filter, mirror design, etc.
- Next step: full 30°×30° prototype.

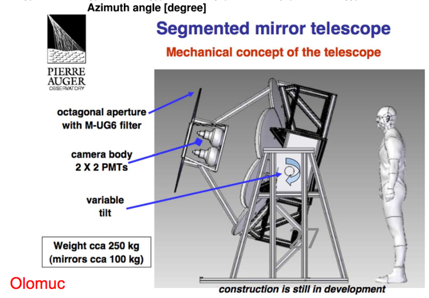




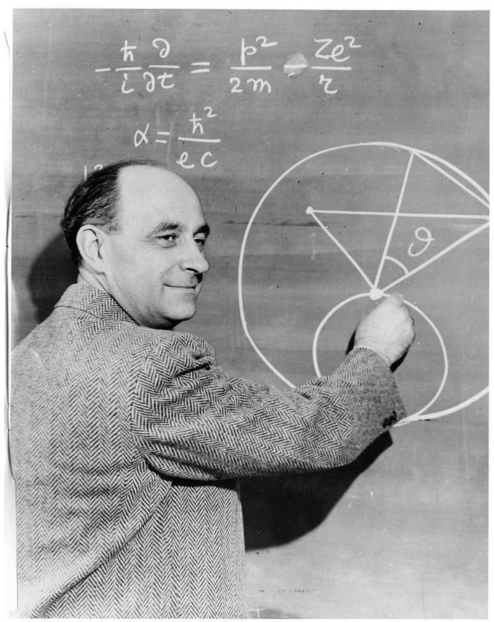


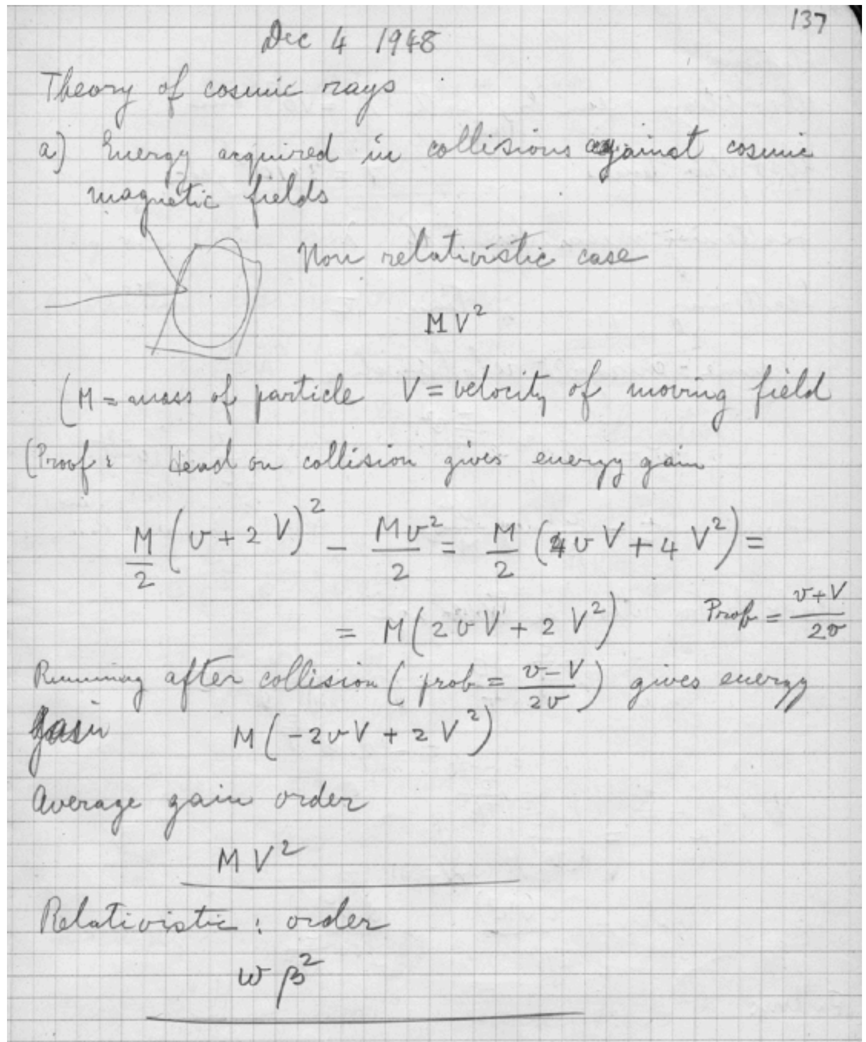






Origin of Ultra-High Energy Cosmic Rays: Fermi's Perspective

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Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Prob: Head on collision gives energy gain

$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV + 4V^2) =$

$= M(2vV + 2V^2)$ Prob $= \frac{v+V}{2v}$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain $M(-2vV + 2V^2)$

Average gain order

MV^2

Relativistic: order

$w\beta^2$

Two interesting things
in each photo:
can you
spot them?

Acknowledgements

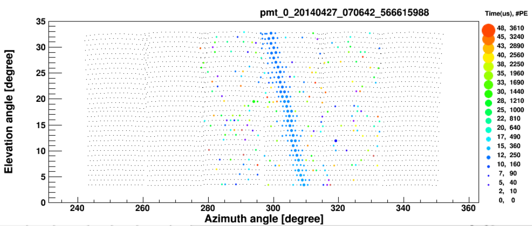
- Everyone involved in the organization, support, and activities of this program (IAPS, LNGS, GSSI, etc.)
- The Dean's Fund for Student Life at the University of Chicago
- The astroparticle physics group at the Kavli Institute for Cosmological Physics

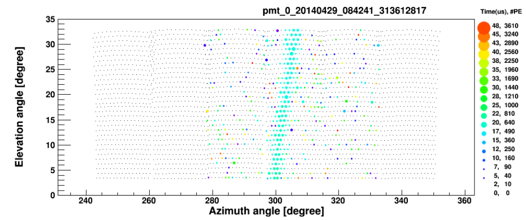
Thanks for your attention!

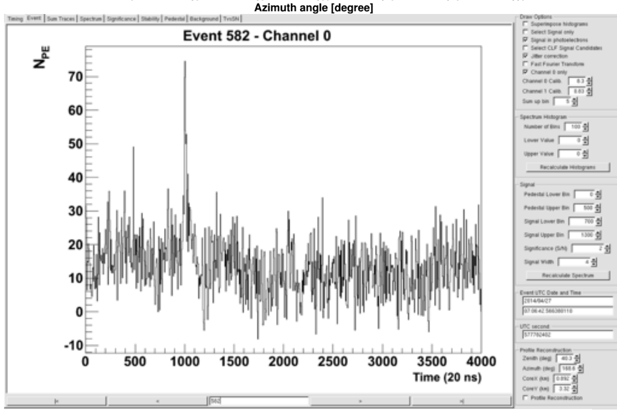
Questions?

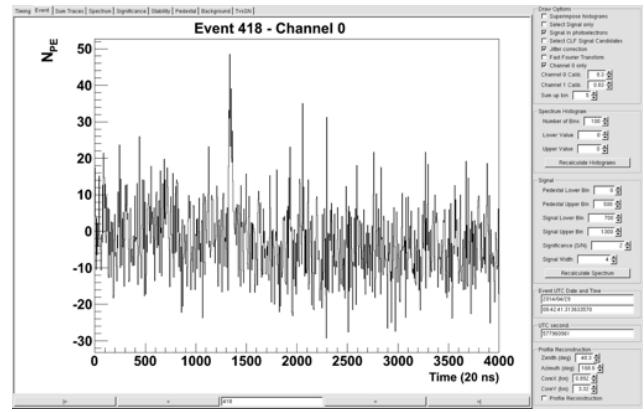
Paper: http://arxiv.org/abs/1504.00692

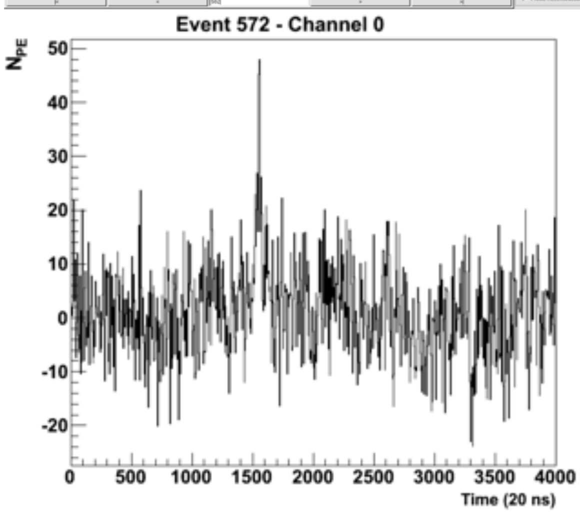
Shower Canadidate

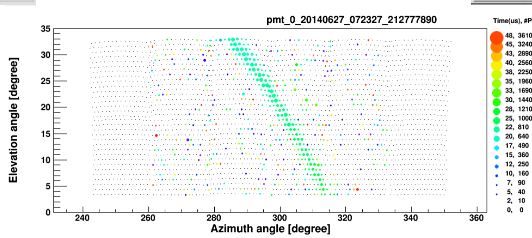


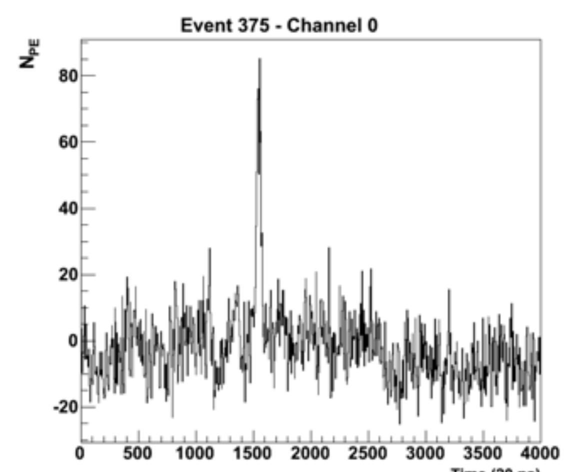


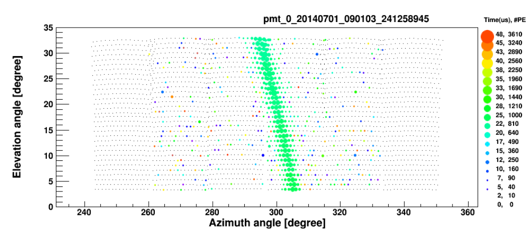












DAQ System

TAFD external trigger, 3~5 Hz

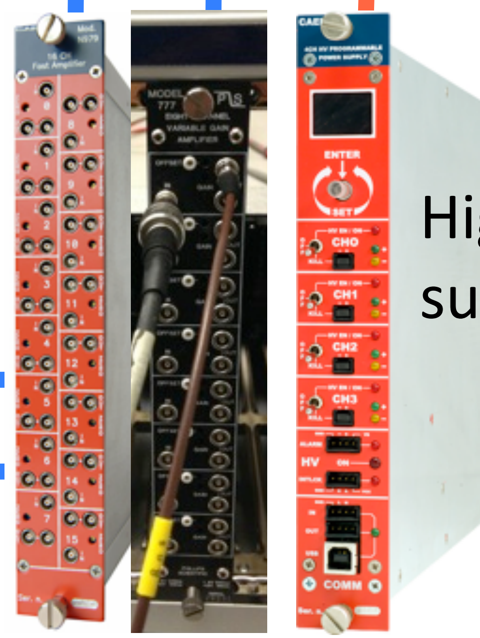
Anode & dynode Signal

Camera of FAST

15 MHz low pass filter

Portable VME Electronics

- Struck FADC 50 MHz sampling, SIS3350
- GPS board, HytecGPS2092



High Voltage power supply, N1419 CAEN

All modules are remotely controlled though wireless network.

Amplifiers R979 CAEN Signal×10

Phillips scientific Signal×50