The Air Fluorescence Technique in UHECR: A History

Pierre Sokolsky

University of Utah

UHECR 2022

The History

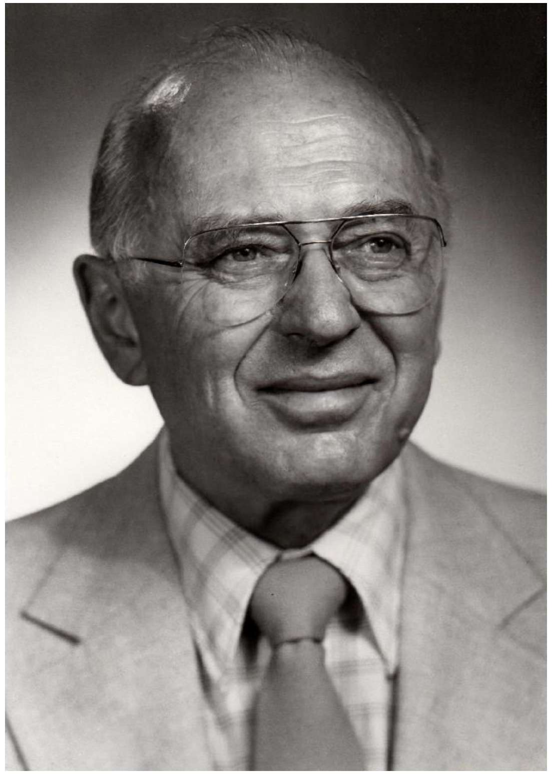
- Pre-history: first ideas
- Snakes in the haystack: Early attempts at detection
- Desert dreams: The Utah Fly's Eye
- Funding follies: The battle for high resolution
- Perseverence pays: The HiRes project
- Dances with Wolves: Snake Array, Northern Auger
- TA and Auger
- The unreasonable effectiveness of the fluorescence technique

Fathers of Fluorescence: Oda, Suga, Chudakov and Greisen

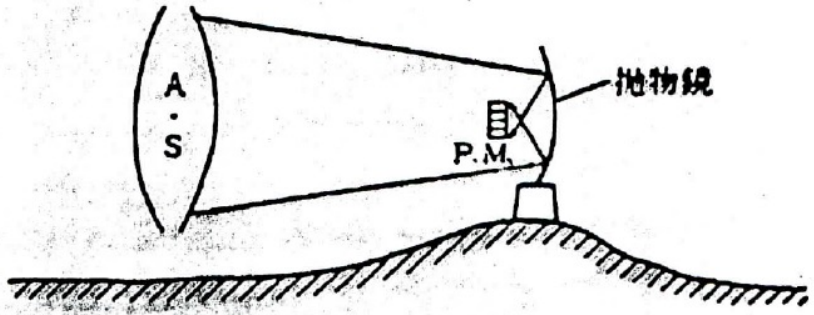
Oda

Suga

ALEKSANDR EVGENIEVICH CHUDAKOV



Greisen



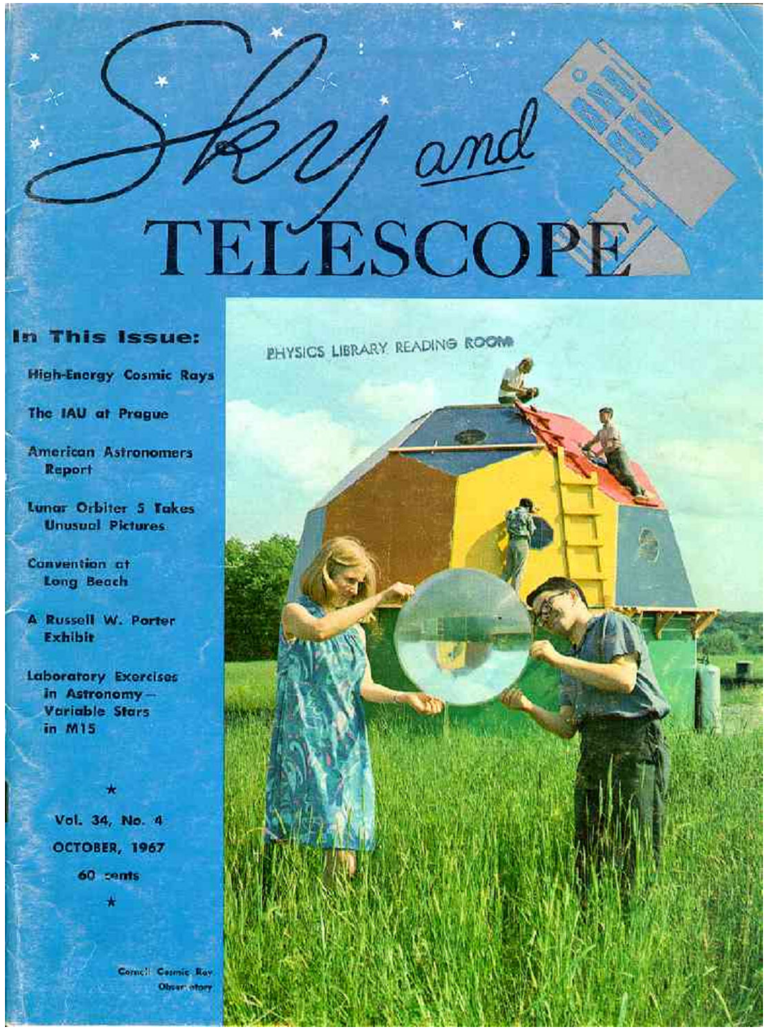
第3図　1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

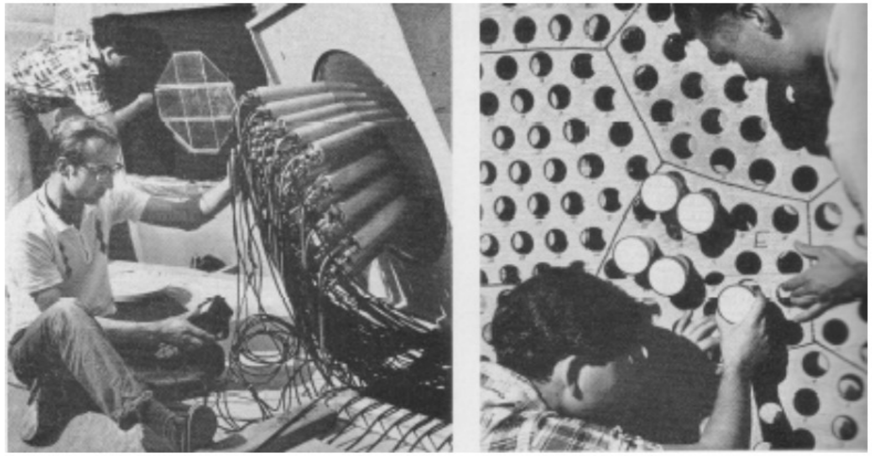
- *K. Greisen, Ann. Rev. Nucl. Sci 10, 63 (1960);*
- *J. Delvaille, F. Kendziorski, and K. Greisen, J. Phys. Soc. Jpn. 17 (Suppl. A-III), 76 (1962);*
- *K. Suga, in Proceedings of the 5th Interamerican Seminar on Cosmic Rays, La Paz, Bolivia (1962), Vol. 2, XLIX;*
- *A. E. Chudakov, in Proceedings of the 5th Interamerican Seminar on Cosmic Rays, La Paz, Bolivia (1962), Vol. 2, XLIX.*

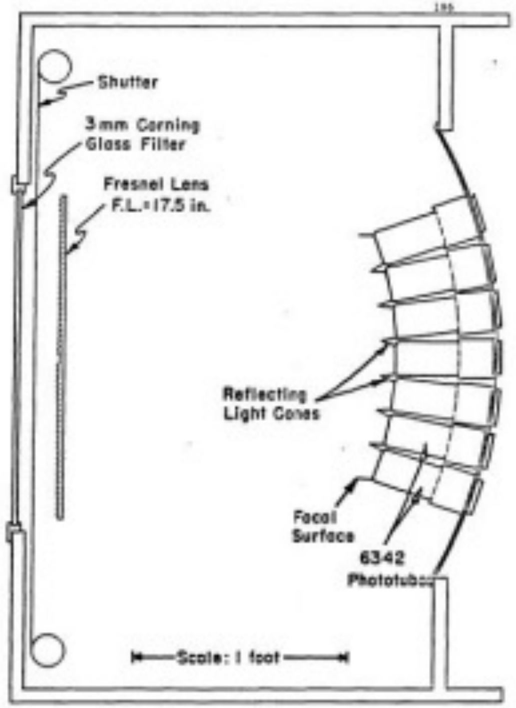
Air Fluorescence development

- K. Greissen – prototype “fly’s eye” detector at Cornell – 1965-70 – no events seen.
- T. Suga et al. – prototype “fly’s eye” at U. of Tokyo Dodairo Observatory – may have observed first such events (cf. B. Dawson)-1970
- G. Cassiday, H. Bergeson, E. Loh, J. Linsley –first coincident ground array/flourescence measurement Volcano ranch-1977
- G. Cassiday, E. Loh et al. First viable fluorescence detector – Fly’s Eye at Dugway, Utah 1981-1991

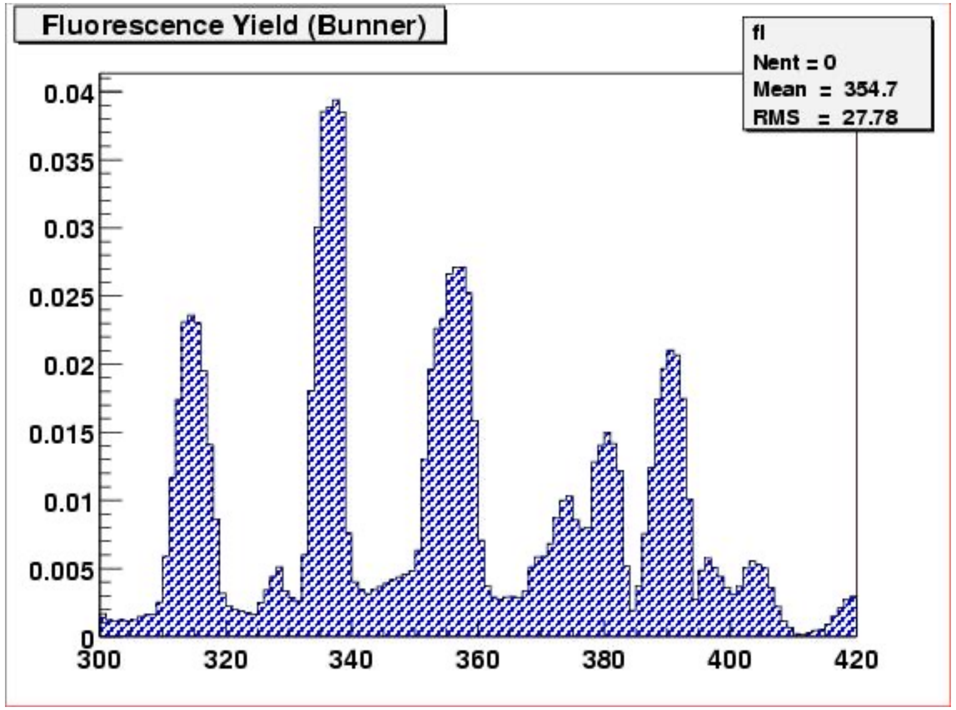
Fluorescence detector at Cornell



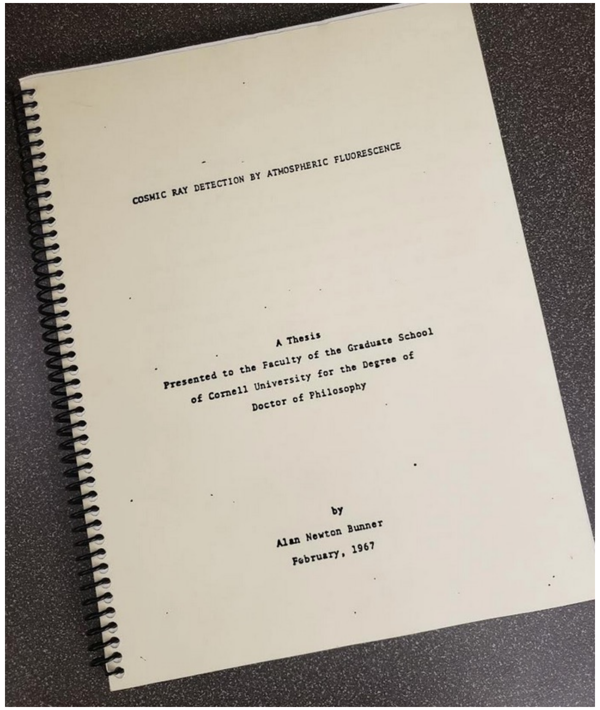




A prerequisite for detecting Air Fluorescence is knowledge of the AF efficiency – Bunner Thesis



Al Bunner and daughter
Visiting TA site



Prof Nagano with relic Japanese FD Prototype

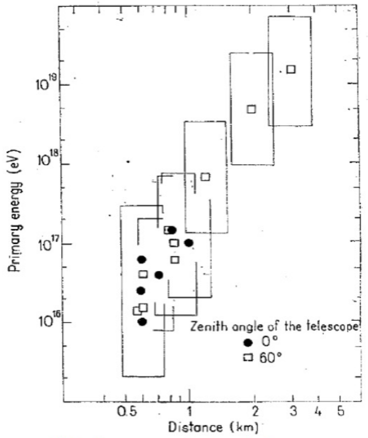
EAS—4/2 *Proc. 11th Int. Conf. on Cosmic Rays, Budapest 1969*

DETECTION OF THE ATMOSPHERIC SCINTILLATION LIGHT FROM AIR SHOWERS

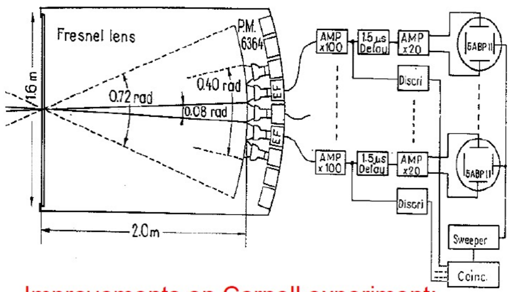
T. Hara, F. Ishikawa, S. Kawaguchi, Y. Miura, M. Nagano, K. Suga, G. Tanahashi

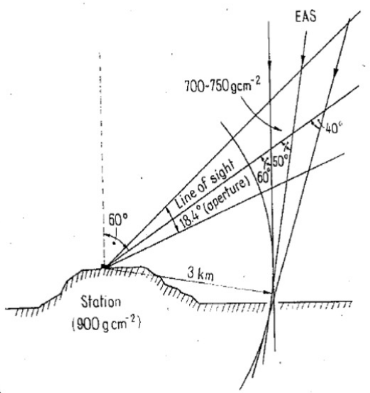
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo, Japan

A preliminary experiment to follow the development of air showers in the atmosphere and to estimate the interaction m.f.p. of the primary particles with energies of 10^{17} eV to 10^{19} eV is reported. A 160 cm telescope with 24 photomultipliers recorded light pulses from the showers. 15 events were identified as air showers at distances larger than 0.6 km from the low angular velocities of the incident light. One event is very likely due to the atmospheric scintillation light from an air shower whose primary energy and distance are about 10^{19} eV and 3 km, respectively.



15 showers detected at distances > 600m. One thought to be ~10^{19}eV





Improvements on Cornell experiment:
larger Fresnel lens (1.6m diam),
faster electronics (integration 0.1μs)

Acta Physica Academiae Scientiarum Hungaricae 29, Suppl. 3, pp. 369–376, 1970

Jack Keuffel

Student of Oppenheimer at Cal Tech.

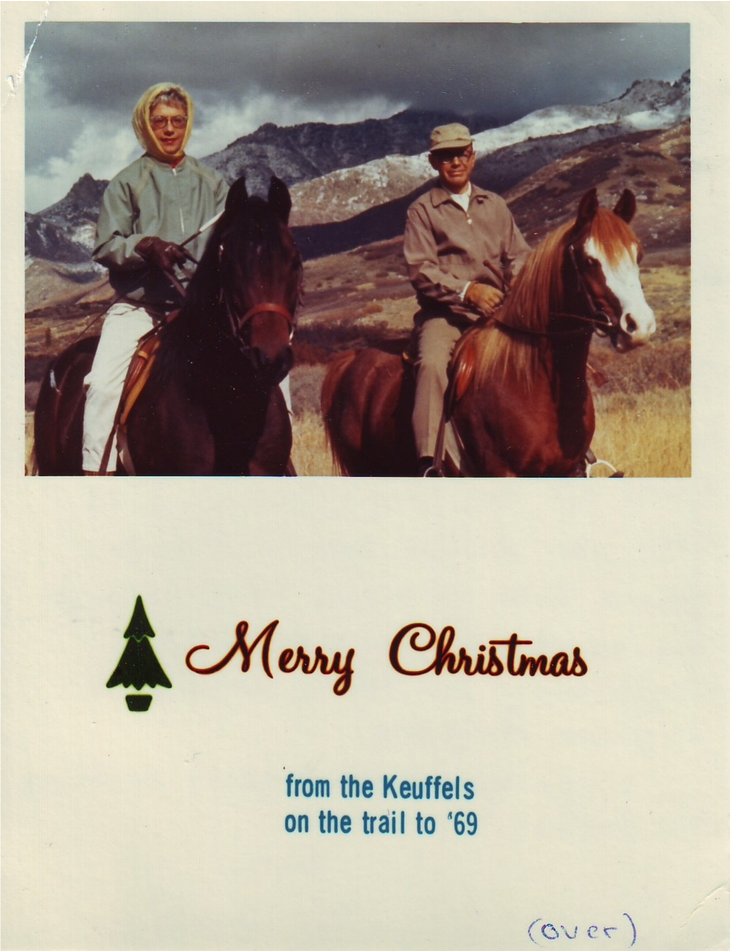
Worked on the development of radar in England and MIT during WWII

Hired as Professor in 1959 (from Princeton)

Developed (together with Haven Bergeson) the first significant underground detector to search for cosmic ray neutrinos In the Silver King Mine in Park City

While studying the atmospheric muon flux, observed an anomaly in the Muon zenith angle distribution → "The Utah Effect". Subsequently discovered error in analysis.

The torch is passed to Utah

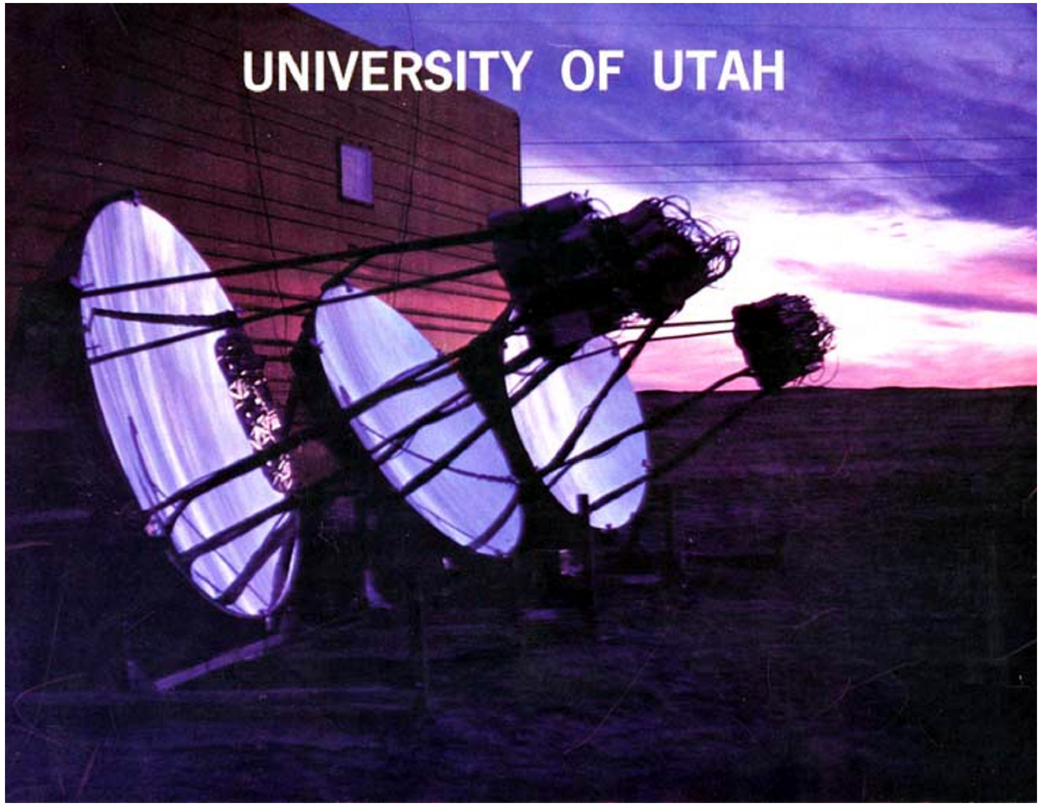


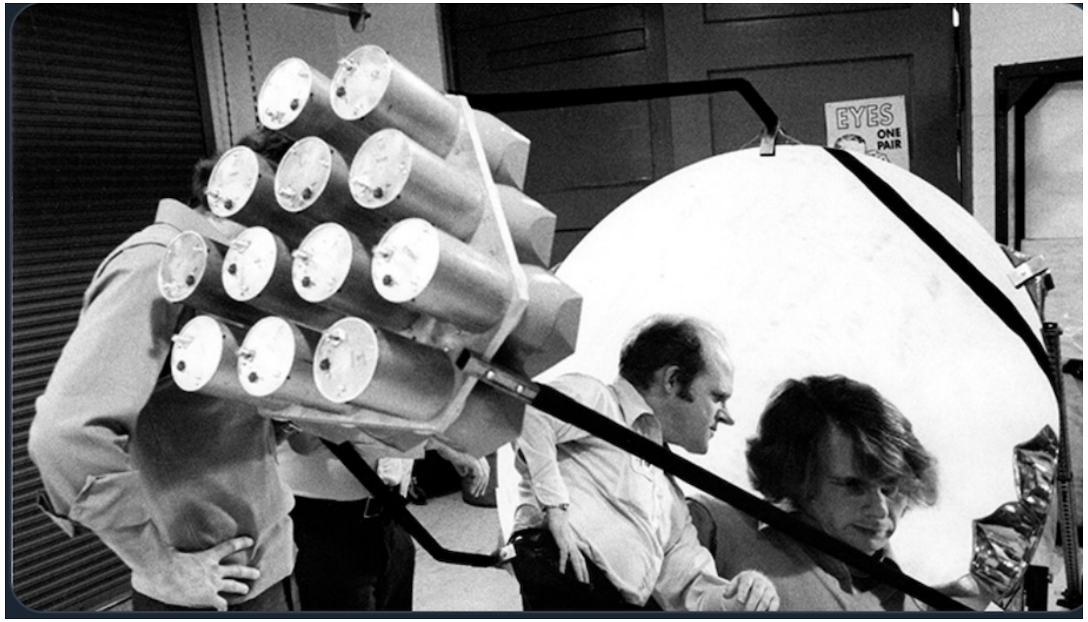
1971, page 17). At the XVI Conference on High-Energy Physics (held at both the University of Chicago and the National Accelerator Laboratory) in September the group, Haven E. Bergeson, Gary Carlson, Jack Keuffel and James Morrison announced what Keuffel called "the obituary of the Utah effect." Keuffel told us, "Alas, no W's. It was fun while it lasted!"

One leading experimenter remarked to us that usually a group works right up to the wire to announce a new discovery at a conference. This is probably the only example of a group rushing to announce an antidiscovery. As of the end of August the Utah group was still unable to say how the results of a repetition of the experiment were coming out. But in a paper dated 10 September and submitted to the conference, the group withdrew its earlier claim.

- Jack Keuffel was doing pioneering underground muon physics in Park City, Utah mines.
- Brought George Cassiday and later Gene Loh came from Cornell.
- After Keuffel's passing in 1974, Cassiday and Haven Bergeson built a 3 mirror prototype Fly's Eye detector and took it to John Linsley's Volcano Ranch array in New Mexico.
- First coincident observation of UHECR in FD and SD

First observations at Volcano Ranch with John Linsley





First clear demonstration of fluorescence technique – Utah group and Linsley at Volcano Ranch (1977)

VOLUME 39, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1977

Measurement of Light Emission from Remote Cosmic-Ray Air Showers

H. E. Bergeson, G. L. Cassiday, T.-W. Chiu, D. A. Cooper, J. W. Elbert, E. C. Loh, D. Steck, and W. J. West
Department of Physics, University of Utah, Salt Lake City, Utah 84112

and

J. Linsley
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131

and

G. W. Mason
Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602

(Received 28 June 1977)

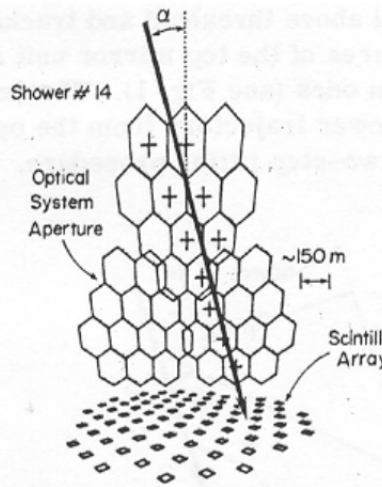


FIG. 1. Projection of the aperture of the optical detector onto a vertical plane above the center of the Volcano Ranch scintillator array. A reconstructed shower trajectory is indicated by the heavy line. Crosses denote phototube apertures in which a signal was detected.

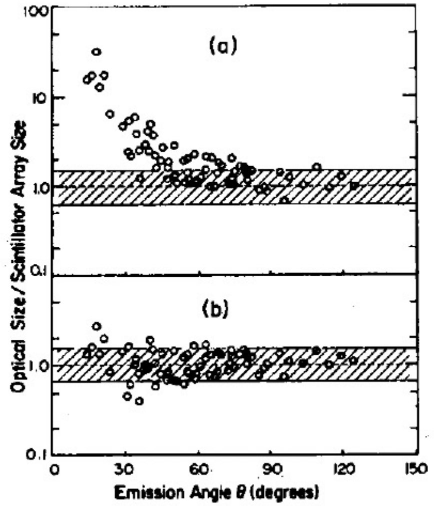
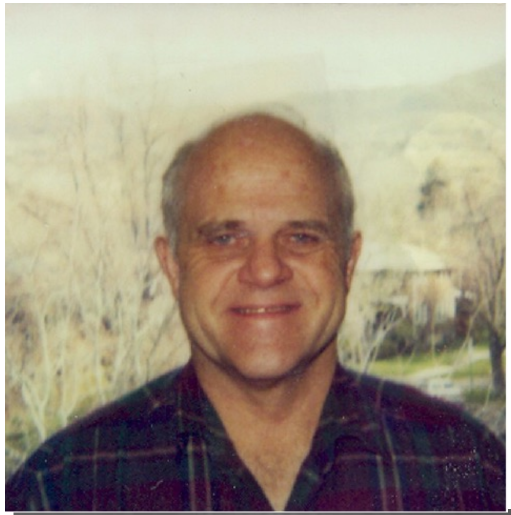
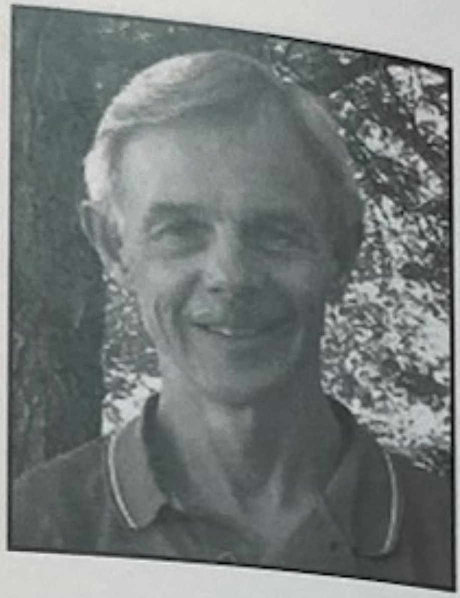


FIG. 4. Ratios of sizes obtained from the optical data to sizes measured by the Volcano Ranch array using (a) computed scintillation light only and (b) estimated light from all sources. Data are plotted for each phototube in all fifteen reconstructed showers. The shaded bands display the uncertainty due to systematic effects in both size measurements.



2008 W.K.H. Panofsky Prize in Experimental Particle Physics



George Cassiday
University of Utah

For the pioneering development of the atmospheric fluorescence technique as a method for exploring the highest energy cosmic rays.

George Cassiday received his A.B. in 1963 from the University of Pennsylvania and his Ph.D. in 1968 from Cornell University. Since 1970 he has been a professor at the University of Utah.

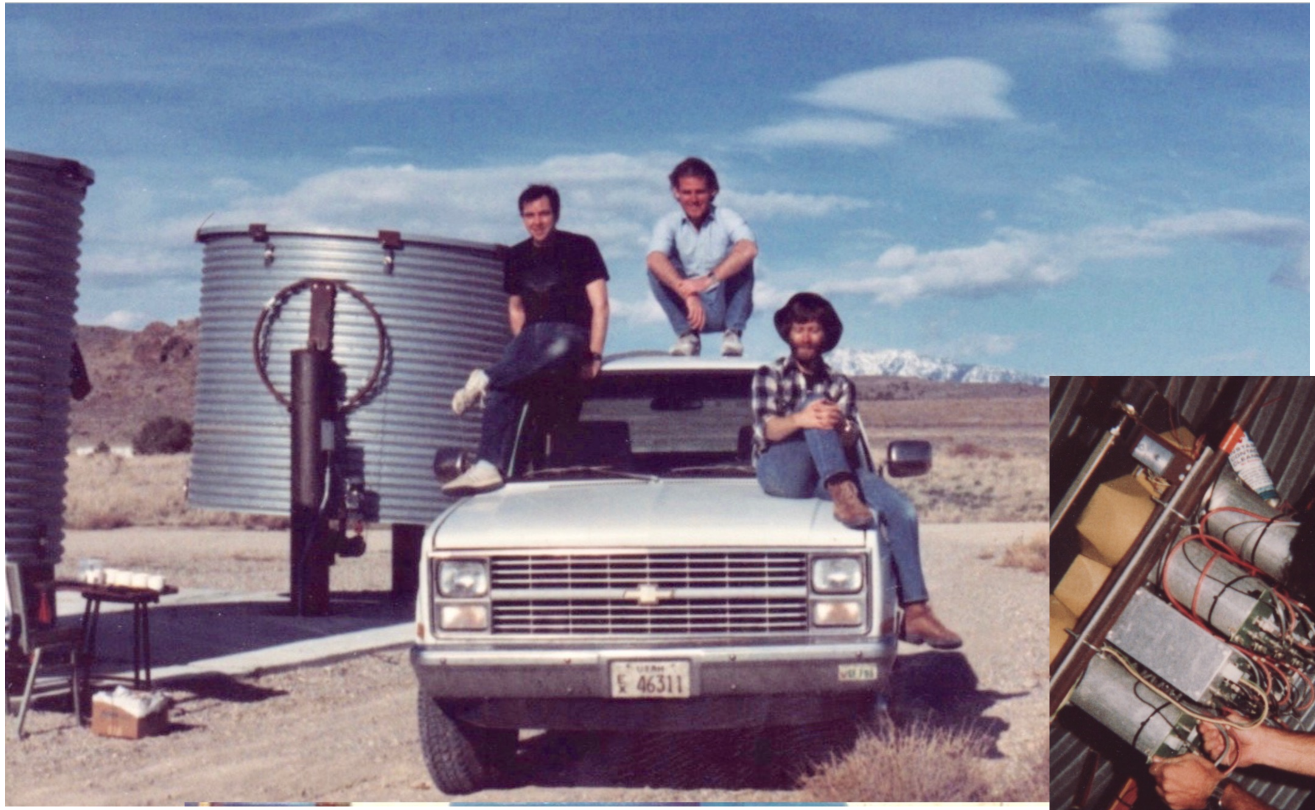
Among many significant accomplishments, Cassiday developed the 2nd generation large tank Cherenkov light detectors deployed in the deep underground Utah Neutrino detector. He also built a cosmic ray telescope that was used to measure the bulk density of 2000 feet of mountainous rock overburden of the Utah neutrino detector. Cassiday designed and built the world's first working air fluorescence cosmic ray detector that conclusively demonstrated the feasibility of the technique. He designed and built the first

Construction of Fly's Eye 1 1978-1981

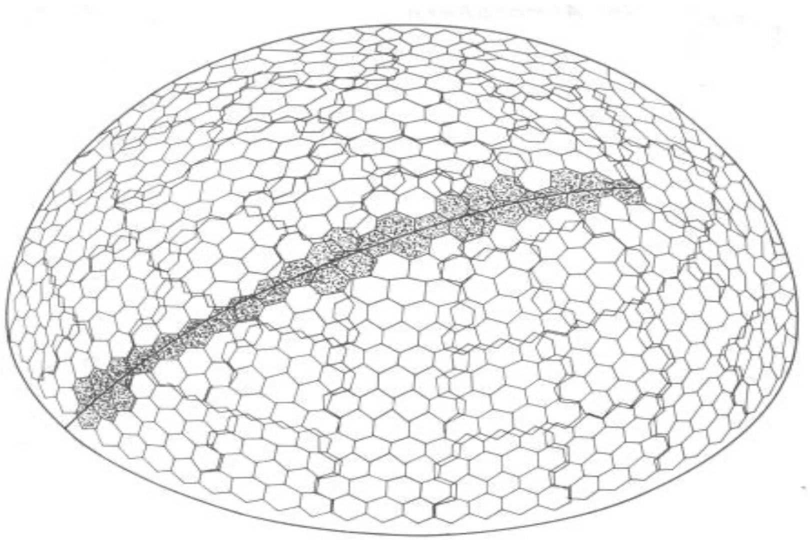
George at the PDP-11 terminal

Typical operating conditions at Dugway PG

F.E. 1 was built and run by an extraordinary group of Postdocs from U. of Adelaide: Peter Gerhardy, Bruce Dawson, Dave Liebeing and Dave Bird. And Brian Fick and others from Utah

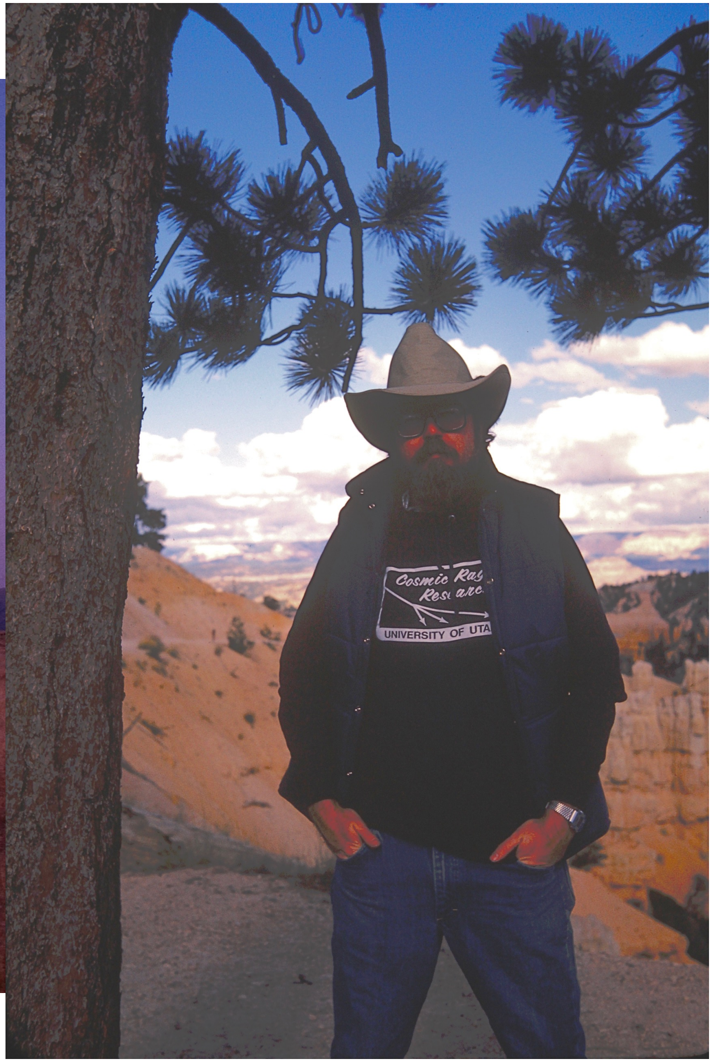


FE 1 Field of View – only FD with full-sky coverage



67 mirrors were turned down during daylight hours

Stereo FD arrived with F.E. 2 3.5 km distant.
First Seven Mirrors at FE 2 (1985)



First significant papers: 1983-1985

LIMITS ON ASTROPHYSICAL ν_e FLUX AT $E_\nu > 10^{19}$ eV

R. BALTRUSAITIS, R. CADY, G. CASSIDAY, J. W. ELBERT, P. GERHARDY, E. LOH, Y. MIZUMOTO, P. SOKOLSKY, AND D. STECK
Physics Department, University of Utah
Received 1983 November 28; accepted 1984 February 16

ABSTRACT

We report on a search for upward-going extensive air showers using the University of Utah Fly's Eye detector. No events have been found in 3.9×10^6 s of running time. The resultant ν flux limit at 10^{20} eV varies from 5.8×10^{-16} ν cm^{-2} s^{-1} sr^{-1} to 3.0×10^{-14} ν cm^{-2} s^{-1} sr^{-1} for σ_ν between 10^{-33} cm^2 and 10^{-32} cm^2. We also present flux limits for larger σ_ν using near-horizontal events originating in the atmosphere. The implications of the flux limits at $E_\nu > 10^{20}$ eV are discussed.

Subject headings: cosmic background radiation — cosmology — early universe — neutrinos

Total Proton Proton Cross-Section at s**(1/2) = 30-TeV

R.M. Baltrusaitis (Utah U.), G.L. Cassiday (Utah U.), J.W. Elbert (Utah U.), P.R. Gerhardy (Utah U.), S. Ko (Utah U.)
Show All(9)
1984

4 pages
Published in: *Phys.Rev.Lett.* 52 (1984) 1380-1383
DOI: 10.1103/PhysRevLett.52.1380
View in: OSTI Information Bridge Server, ADS Abstract Service

Evidence of a High-Energy Cosmic Ray Spectrum Cutoff

R.M. Baltrusaitis (Utah U.), R. Cady (Utah U.), G.L. Cassiday (Utah U.), R. Cooper (Utah U.), J.W. Elbert (Utah U.)
Show All(12)
1985

3 pages
Published in: *Phys.Rev.Lett.* 54 (1985) 1875-1877
DOI: 10.1103/PhysRevLett.54.1875
View in: OSTI Information Bridge Server, ADS Abstract Service

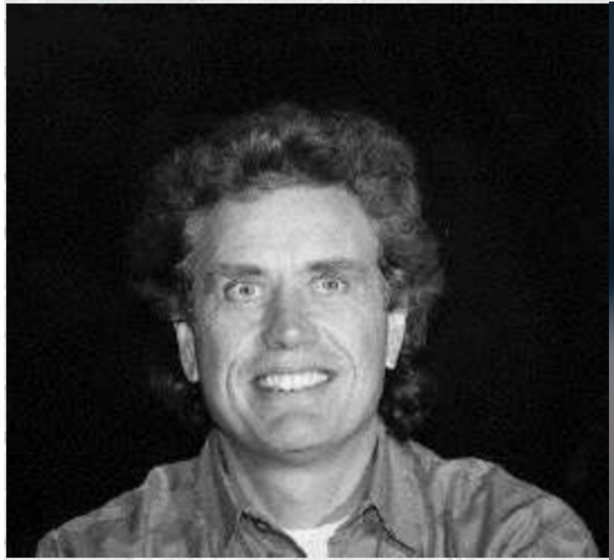
The “Oh My God” Particle (1991)

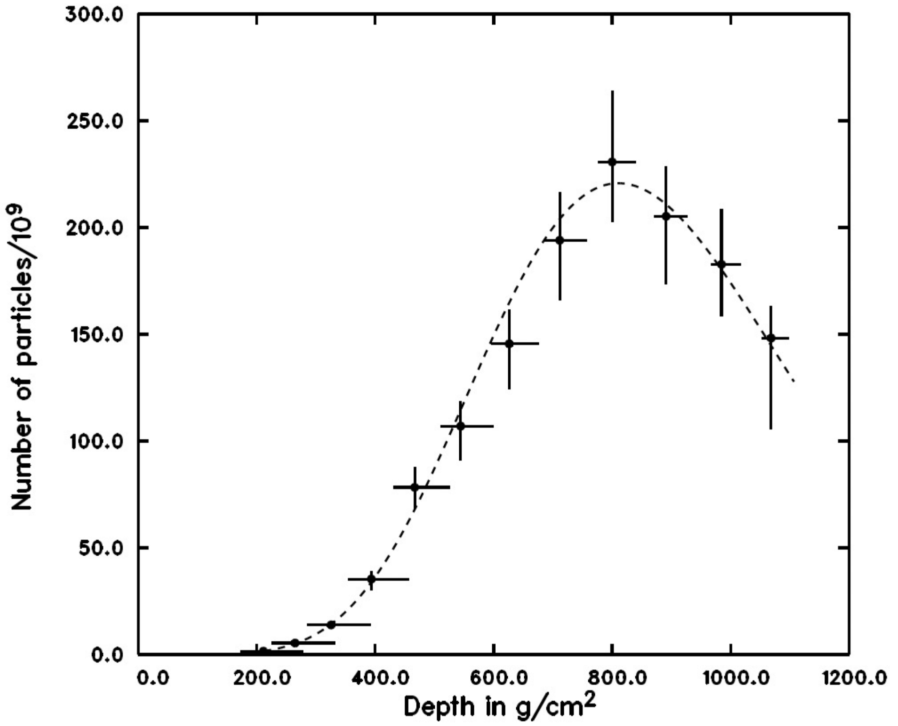
Detection of a Cosmic Ray with Measured Energy Well Beyond the Expected Spectral Cutoff due to Cosmic Microwave Radiation

D. J. Bird et al. (Utah)

We report the detection of a 51-joule (320 +/- 90 EeV) cosmic ray by the Fly's Eye air shower detector in Utah. This is substantially greater than the energy of any previously reported cosmic ray. A Greisen-Zatsepin-Kuz'min cutoff of the energy spectrum (due to pion photoproduction energy losses) should occur below this energy unless the highest energy cosmic rays have traveled less than about 30 Mpc. The error box for the arrival direction in galactic coordinates is centered on b=9.6 deg, l=163.4 deg. The particle cascade reached a maximum size near a depth of 815 g/cm^2 in the atmosphere, a depth which does not uniquely identify the type of primary particle.

Comments: uuencoded compressed postscript, 20 pages, to appear in ApJ (3/1/95)
Subjects: **Astrophysics (astro-ph)**
Cite as: arXiv:astro-ph/9410067
(or arXiv:astro-ph/9410067v1 for this version)
https://doi.org/10.48550/arXiv.astro-ph/9410067





Event discovered and analyzed by Paul Sommers and Hungye Dai.

Fly’s Eye data -> need better resolution and larger aperture -> HiRes

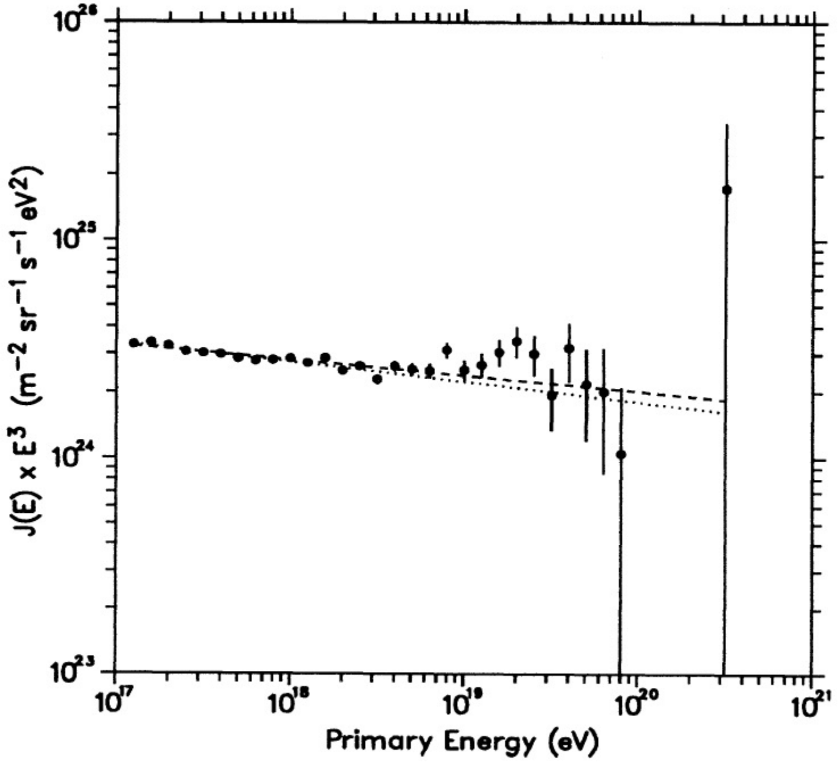


FIG. 2. Fly’s Eye monocular differential energy spectrum multiplied by E^3. Points: data. Dashed line: best fit of the total spectrum. Dotted line: best fit up to $10^{18.5}$ eV.

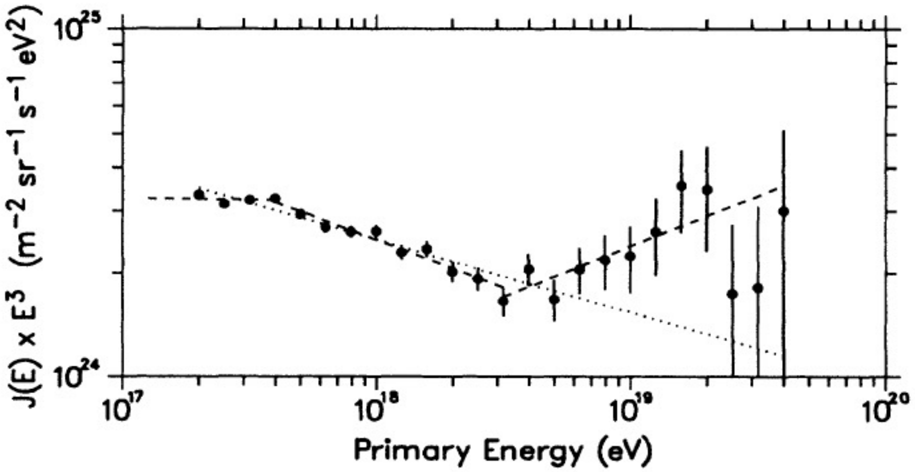


FIG. 1. Fly’s Eye stereo differential energy spectrum multiplied by E^3. Points: data. Dashed line: best fit in each region. Dotted line: best fit up to $10^{18.5}$ eV.

Report of the HEPAP Subpanel on Major Detectors in Non-Accelerator Particle Physics

Robert Adair (Chairman), Yale University
Thomas Fields, Argonne National Laboratory
William F. Fry, University of Wisconsin
Thomas Gaisser, Bartol Research Institute
Howard Gordon, Brookhaven National Laboratory
Robert Lanou, Brown University
Adrian Melissinos, University of Rochester
Bernard Sadoulet, University of California, Berkeley
Mark Strovink, University of California, Berkeley
Trevor Weekes, Smithsonian Astrophysical Observatory
Louis Voyvodic (Executive Secretary), Department of Energy

Germantown, March 20-21, 1989

The Subpanel feels that the magnitude of the proposed Fly's Eye Upgrade construction project is large in proportion to the amount of qualitatively new information likely to be gained. Hence, the Subpanel recommends unanimously that the High Resolution Eye proposal not be approved. However, the Subpanel encourages the exploitation of the high resolution technique on a smaller scale.

The Subpanel does favor the possibility of more modest improvements of the resolution and/or other aspects of the detector at a level of about one or two million dollars. The group is small and does not include any outside collaborators. We suggest that any large expansion of this project will require a broadening of the group.

Proposal to Construct a

High Resolution EYE

(HiRes)

Detector

University of Utah
Physics Department, Salt Lake City, Utah

University of Illinois at Urbana-Champaign
Physics Department, 1110 W. Green St., Urbana, Illinois

Columbia University
Nevis Laboratories, Irvington, New York

HiRes Collaboration Members

(Principal investigators denoted by underlining)

University of Utah

G.L. Cassiday, R. Cooper, S.C. Corbató, H.Y. Dai, J.W. Elbert, D.B. Kieda, S. Ko, E.C. Loh, M.H. Salamon, J.D. Smith, P.V. Sokolsky, P. Sommers, J. Tang, S.B. Thomas

University of Illinois

R. Downing, T.A. O'Halloran, V. Simaitis

Columbia University

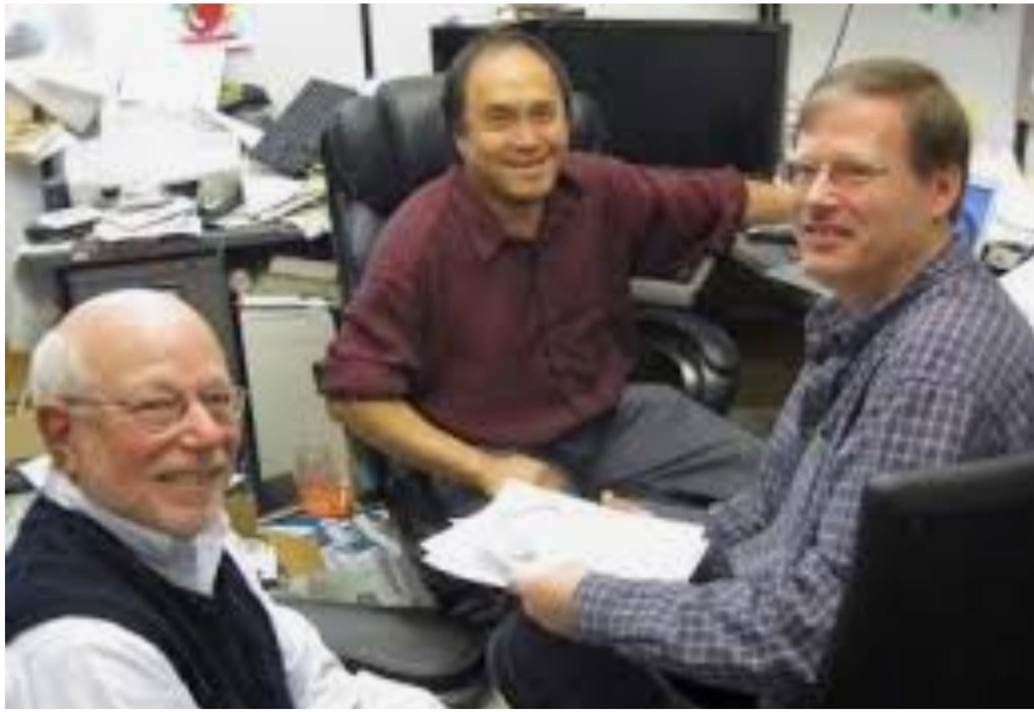
L. Borodovsky, J. Boyer, C.Y. Chi, Y. Ho, W. Lee, J. Mechalakos

Wonyong Lee

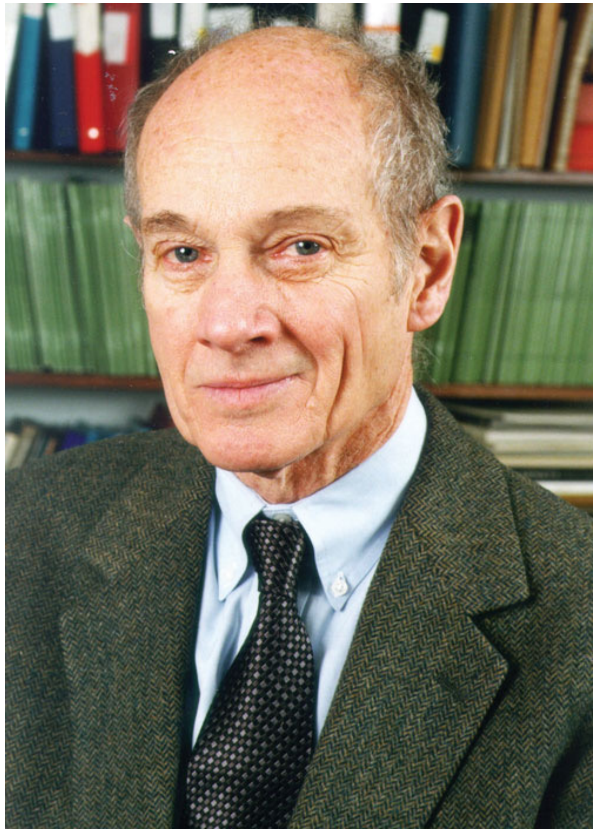
Tom O'Halloran

HiRes History

- Initial HiRes (Utah) proposal was turned down by subpanel of HEPAP - 1991
- HiRes prototype (Utah, Illinois) was funded by NSF-1992 - Dave Berley was program director. HiRes prototype/CASA/MIA experiment begins
- W. Chinowsky took over as our program director at NSF-1993 - revised HiRes proposal (Utah, Illinois, Columbia).
- NSB threshold for consideration moves up - 1994
- Willie approves HiRes - 1994
- HiRes construction begins - 1995
- HiRes I begins taking data - 1996
- HiRes II begins taking data - 1999
- HiRes goes off the air - 2006



Sig X-3 Mania:The U. of Chicago/U. of Michigan Connection: Jim Cronin and John Van der Velde: CASA/MIA



And, importantly, Jim Matthews

Negative Results Can Be Important

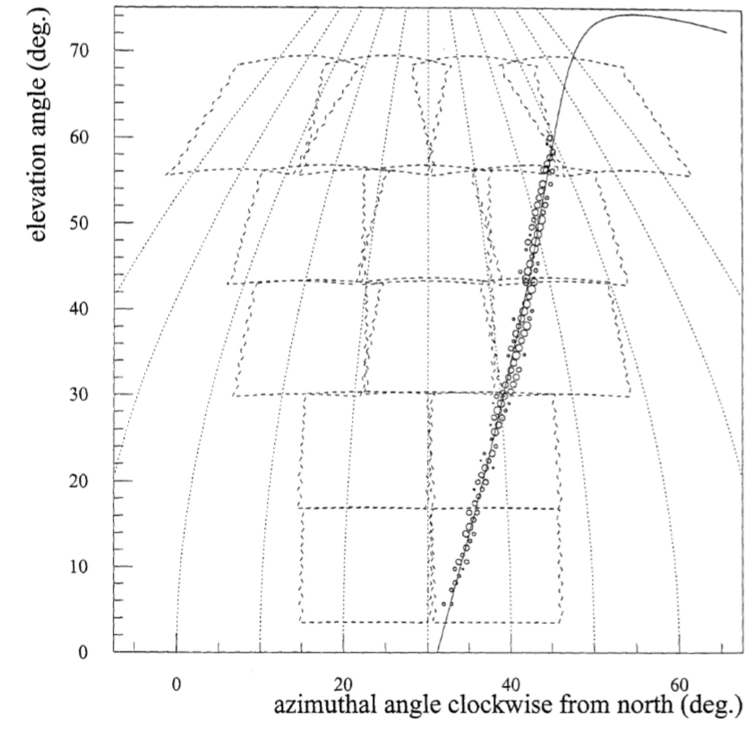
- Cyg X-3 searches sparked a wide interest among High Energy Physicists, some of whom moved to establish “Particle Astrophysics”
- Gene Loh moved to the NSF where he established a sub-directorate in “Particle and Nuclear Astrophysics”. Funding became available for large-scale projects (including eventually ICE CUBE)
- The CASA/MIA detector could also study hadronic cosmic rays and was in the field of view of the Fly’s Eye.

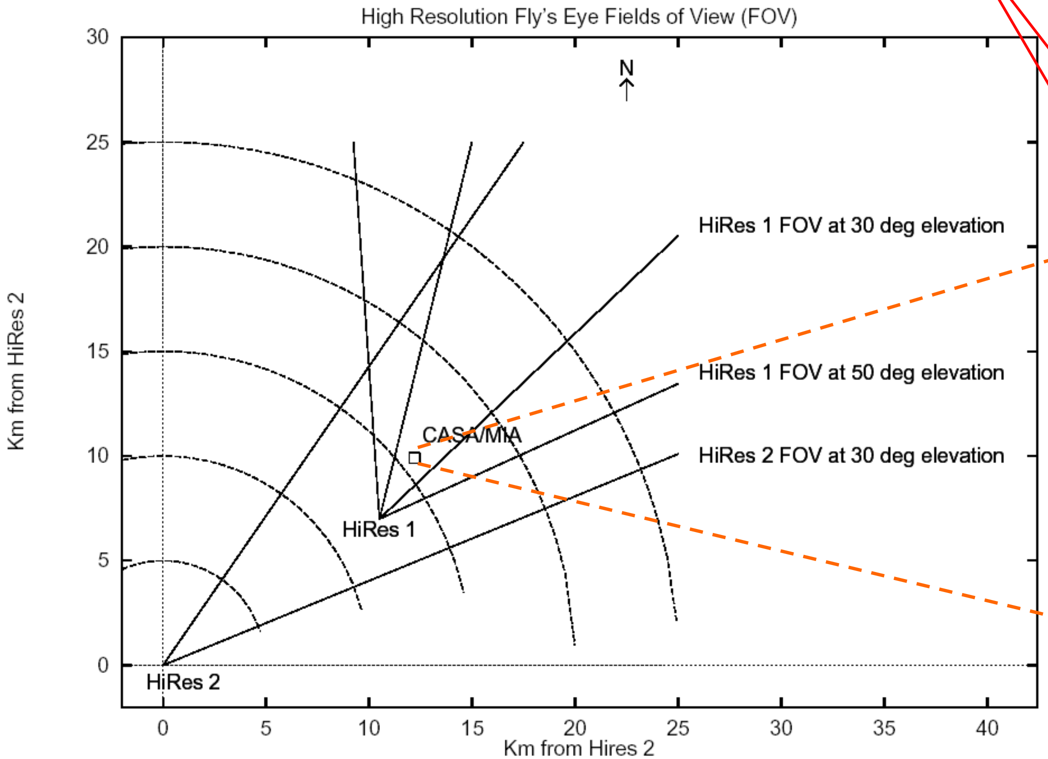
HiRes Prototype (14 mirrors)

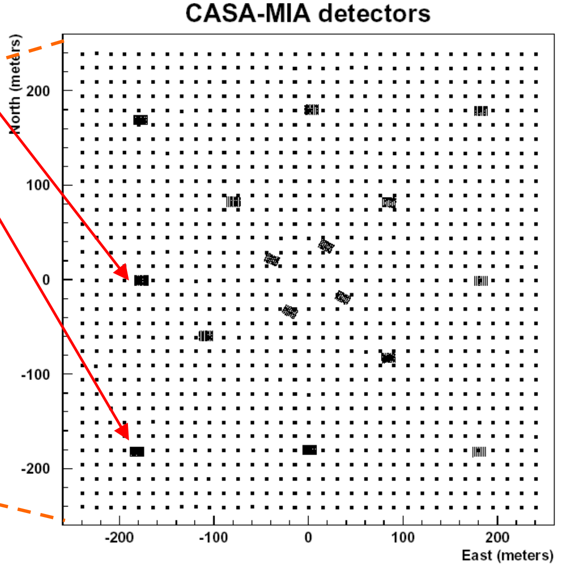
CASA/MIA and Fly’s Eye 2

1992-1996: HiRes Prototype

- 14 (HiRes-1) + 4 (HiRes-2) mirror prototype detector operated between 1992 and 1996
- HiRes-1 field of view up to ~70°.
- HiRes-1 operated in hybrid mode with the MIA muon array (16 patches×64 underground scintillation counters each):







Coincident Observation of Air Showers by the HiRes Prototype and CASA/MIA Experiments

D.J. Bird,[1] A. Borione,[2] J. Boyer,[3] M. Catanese,[4] R.W. Clays,[5] S.C. Corbato,[6] C.E. Covauft,[2] J.W. Cronin,[2] H.Y. Dai,[6] B.R. Dawson,[5] R.W. Downing,[1] J.W. Elbert,[6] B.E. Fick,[2] K.G. Gibbs,[2] K.D. Green ,[4] M.A. Huang,[6] M.J. Kidd,[1] D.B. Kieda,[6] S. Ko,[6] C.G. Larsen,[6] W. Lee,[3] E.C. Loh,[6] TA. McKay,[2†] E. Mannel,[3] J. Matthews,[4] B.J. Newport,[2] D. Nitz,[4] TA. O'Halloran,[1] R.A. Ong,[2] M.H. Salamon,[6] L.J Rosenberg,[2‡] J.D. Smiths,[6] D. Sinclair,[4] P. Sokolsky,[6] P. Sommers,[6] J.K.K. Tang,[6] S.B. Thomas,[6] and J.C. van der Velde [4]

[1] Dept. of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA
[2] Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA
[3] Nevis Laboratories, Columbia University, Irvington NY 10533 USA
[4] Dept. of Physics, University of Michigan, Ann Arbor, MI 48109 USA
[5] Dept. of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5001 Australia
[6] High Energy Astrophysics Institute, Dept of Physics, University of Utah, Salt Lake City UT 84112 USA

[†] now at Fermi National Accelerator Laboratory, Batavia IL 60510 USA
[‡] now at Dept. of Physics, M. I. T, Cambridge, MA 02139 USA

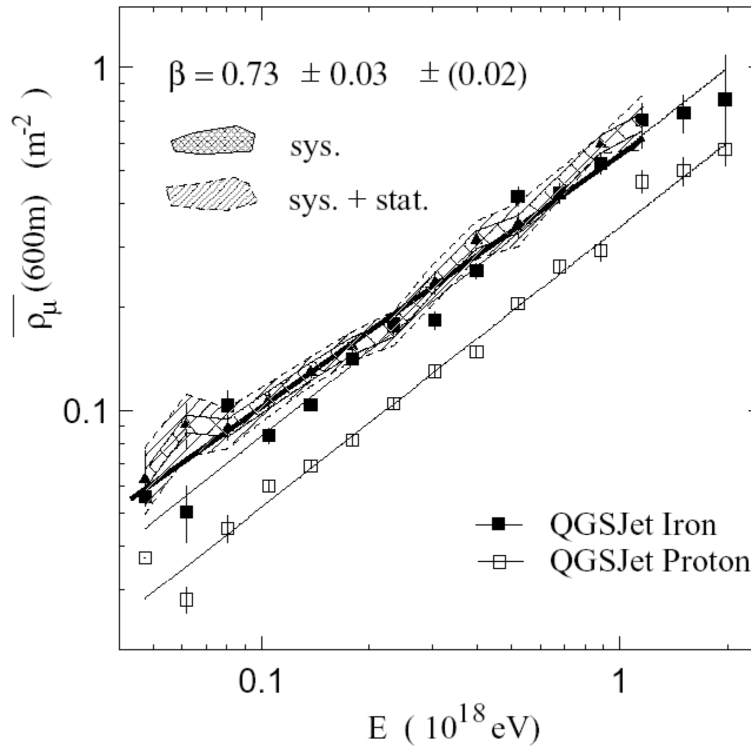


FIG. 2. Average Muon density at 600 m from the shower core. Same as FIG 1

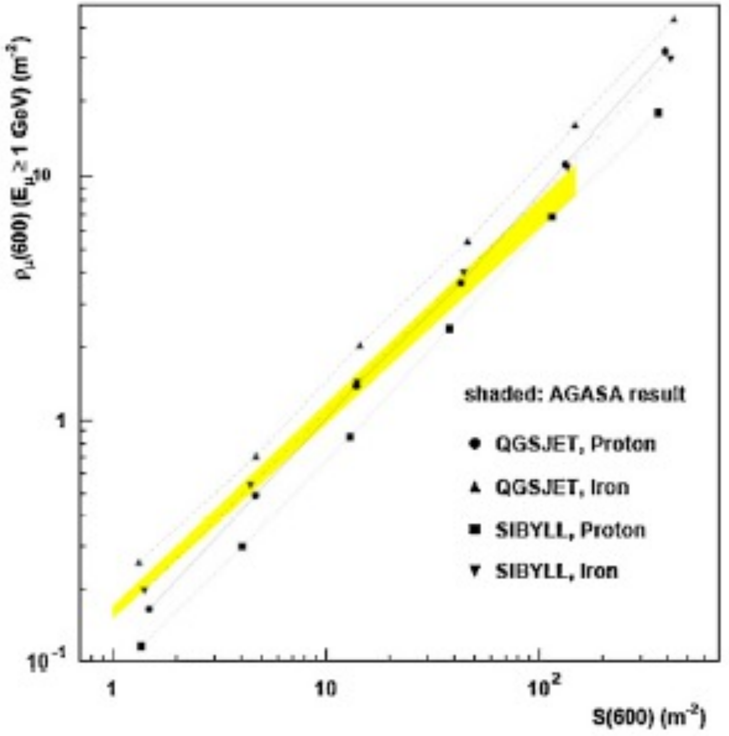
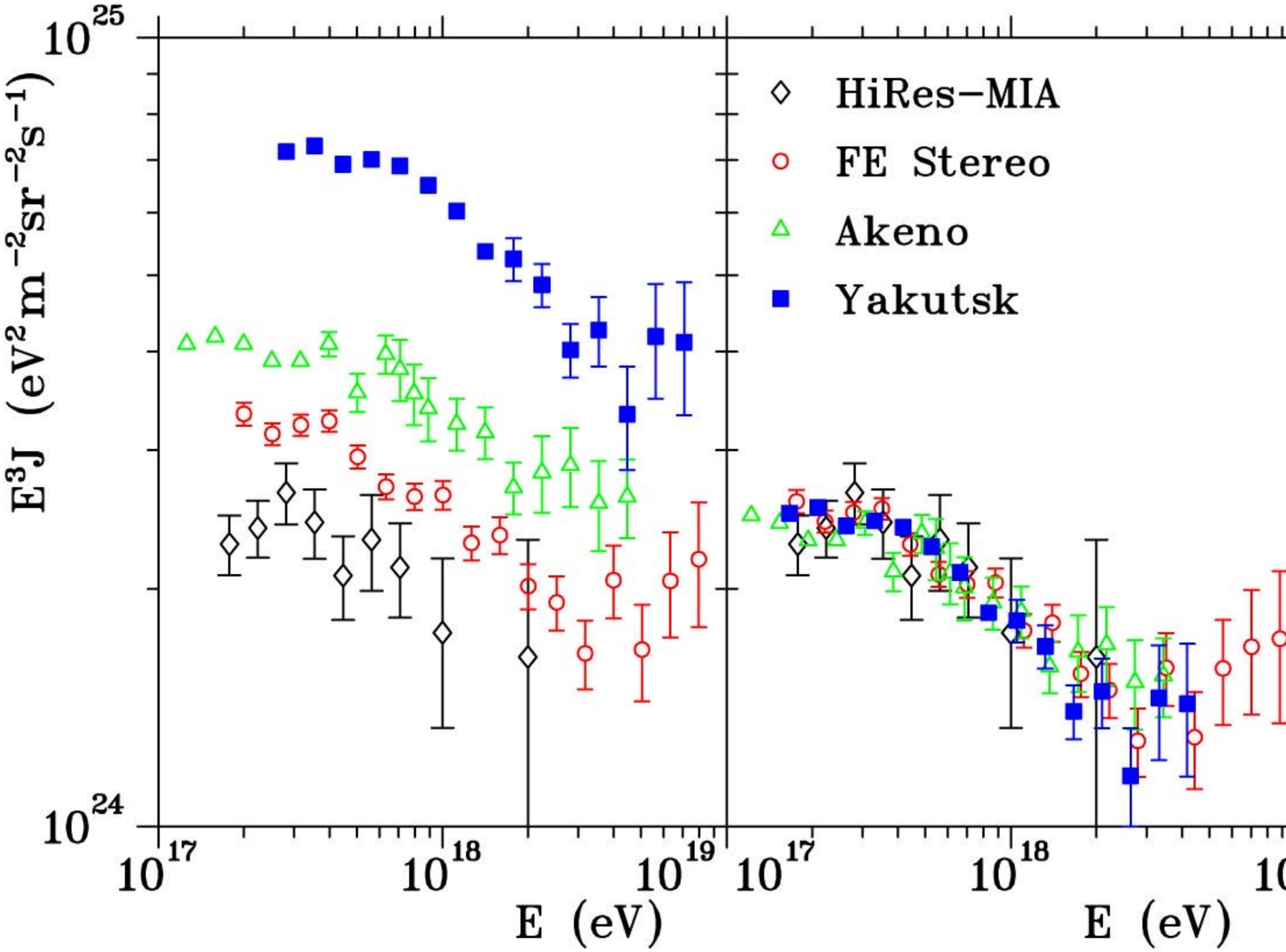


Figure 13. AGASA data on muon density as a function of energy estimator S(600) and comparison with predictions.

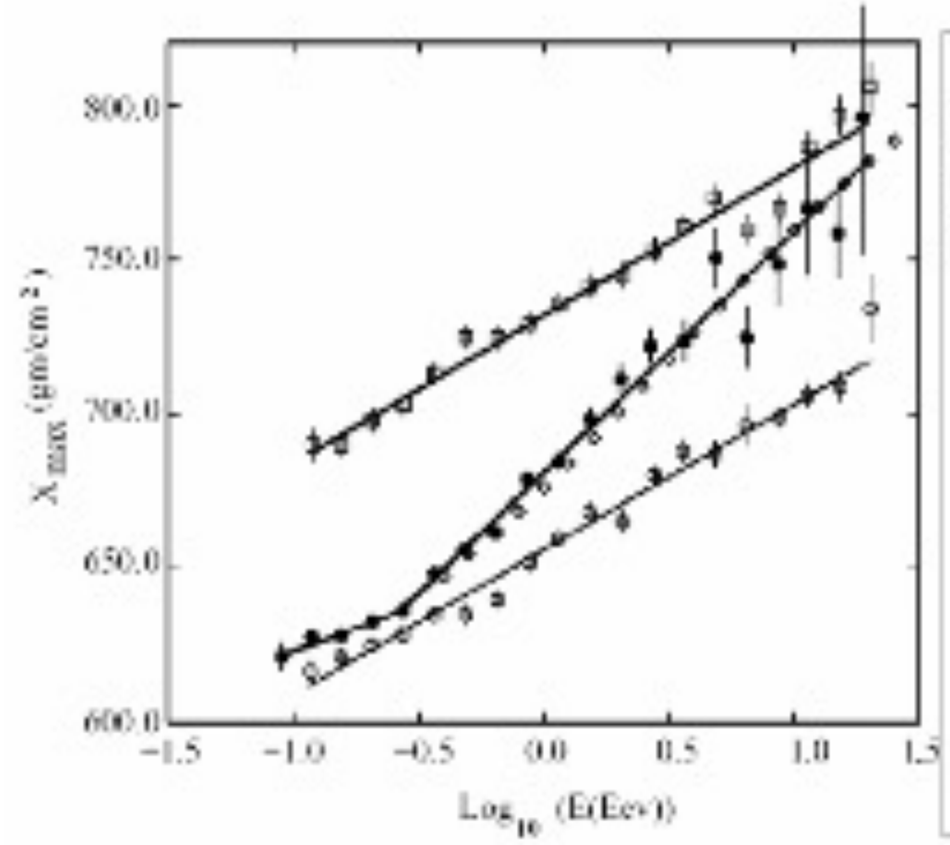
Muon content of showers in HiRes/MIA higher than expected!

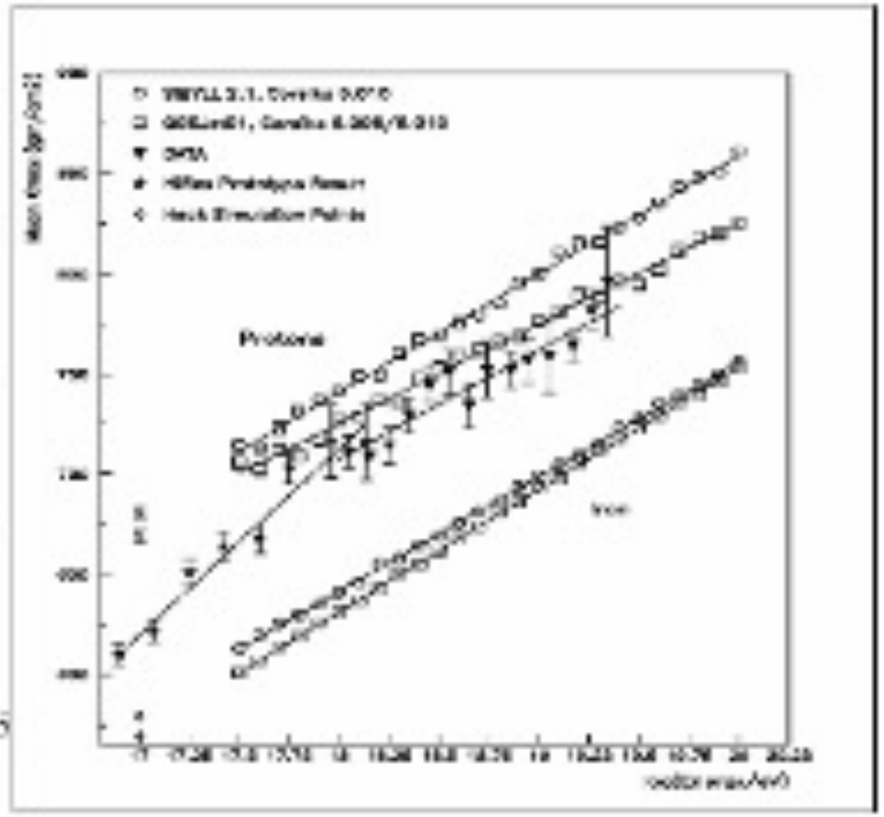
Zhen Cao



Evidence for Second Knee between 10^{17} and 10^{18} eV ?

Stereo Fly's Eye, Prototype HiRes/MIA and HiRes Elongation Rate





The HiRes Collaboration

- Next gen Fly's Eye: smaller pixels, full stereo coverage. ~ 10x larger aperture, better resolution.
- Collaboration between Utah, Columbia University, University of Illinois, Rutgers, University of New Mexico,LANL, U. of Tokyo.
- M. Teshima (U. of Tokyo) built first CTA prototype on an adjacent site. Original idea for Cosmic Ray and Gamma Ray Astronomy detector.




High Resolution Fly's Eye Collaboration:

S. BenZvi, J. Boyer, B. Connolly, C.B. Finley, B. Knapp, E.J. Mannel, A. O'Neill, M. Seman, S. Westerhoff

Columbia University

J.F.Amman, M.D.Cooper, C.M.Hoffman, M.H. Holzscheiter, C.A.Painter, J.S.Sarracino, G.Sinnis, T.N.Thompson, D.Tupa

Los Alamos National Laboratory

J. Belz, M. Kirn

University of Montana

J.A.J. Matthews, M. Roberts

University of New Mexico

D.R. Bergman, G. Hughes, D. Ivanov, S.R. Schnetzer, L. Scott, S. Stratton, G.B. Thomson, A. Zech

Rutgers University

N. Manago, M. Sasaki

University of Tokyo

R.U.Abbasi, T.Abu-Zayyad, G.Archbold, K.Belov, O.Brusova, S.A..Blake, Z.Cao, W.Deng, R.C.Gray, W.Hanlon, Y.Fedorova, P.Huentemeyer, B.F Jones, C.C.H.Jui, **E.C.Loh**, M.M.Maestas, K.Martens, J.N.Matthews, S.A.Moore, K.Reil, D.Rodriguez,,P.Shen, J.Smith, P.Sokolsky, R.W.Springer, B.T.Stokes, J.R.Thomas, S.B.Thomas, L.Wiencke

University of Utah

HiRes Design Based on Fly's Eye
Goal: Increase Sensitivity by 10x

- Reduce pmt aperture to increase signal to noise
- Observe significant fraction of events in stereo
- Optimize stereo aperture for > 10^{19} eV events
- Improve Xmax resolution by 2x
- Increase instantaneous aperture ~ order of magnitude above Fly's Eye detector
- Optimal solution: 1 x 1 deg pixels, 12.5 km separation between eyes.

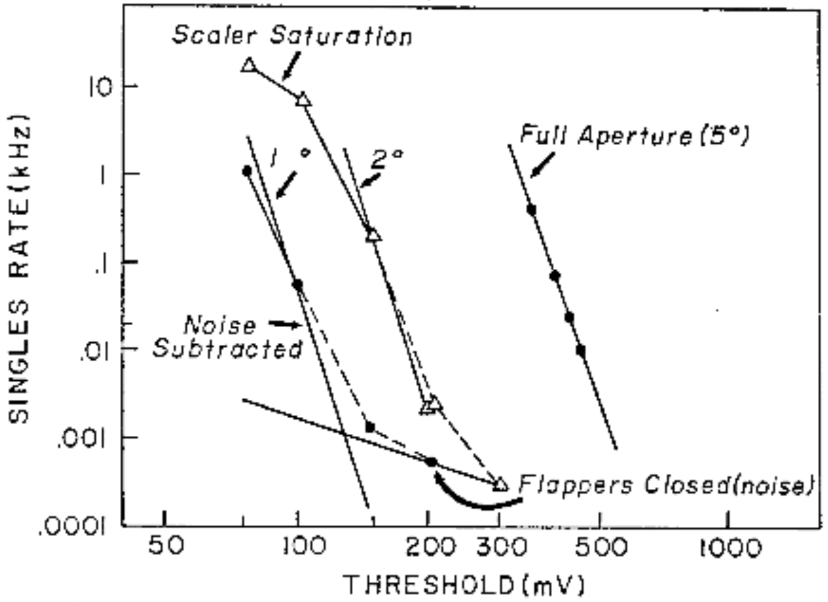


Figure C.2: Singles rate vs threshold and tube aperture for filter RC constant of 700 nsec. This was measured at the F.E. 1 detector by masking phototubes. After subtraction of system noise (the rate with flappers closed), the threshold for fixed singles rate scales as expected with tube aperture.

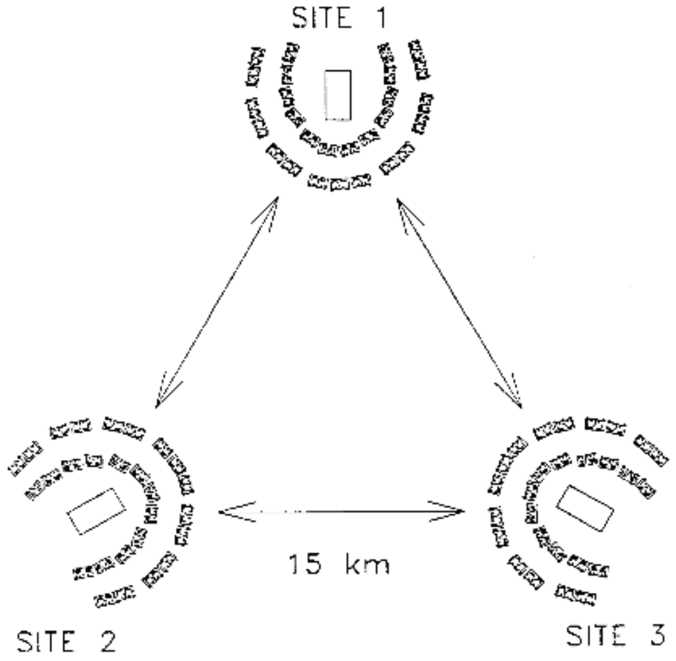
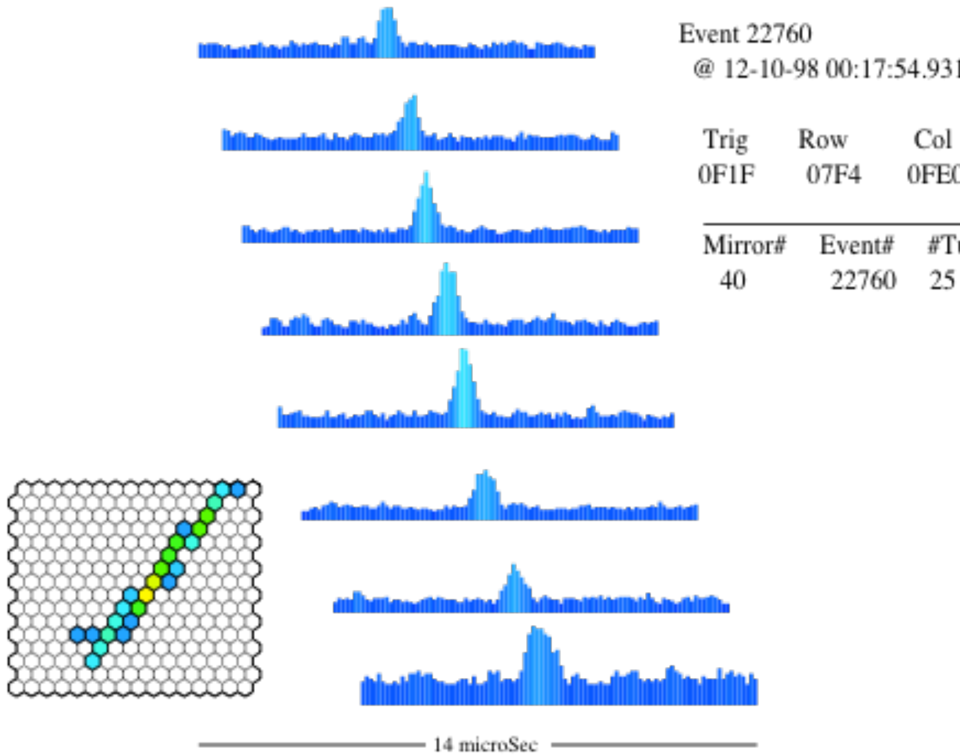


Figure 4.5: Schematic layout of HiRes detectors (not to scale). Three identical sites are located on the vertices fo a 15 km equilateral triangle.

Effective collecting area ~ 1000 sq km !!

Camel's Back Site

Bruce Knapp

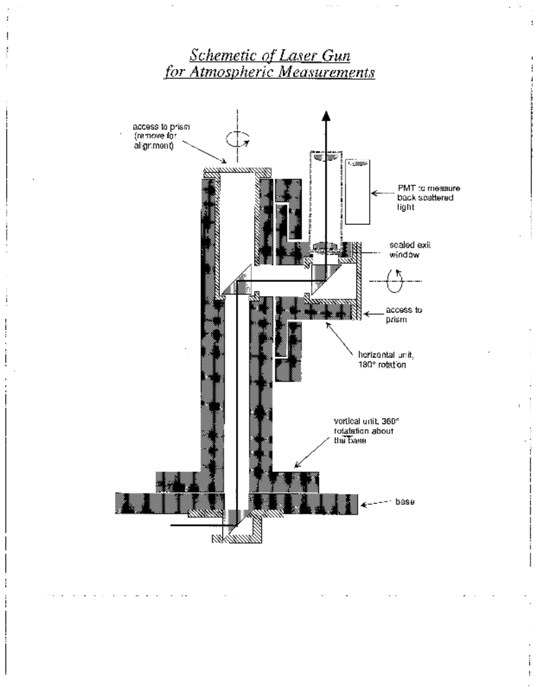


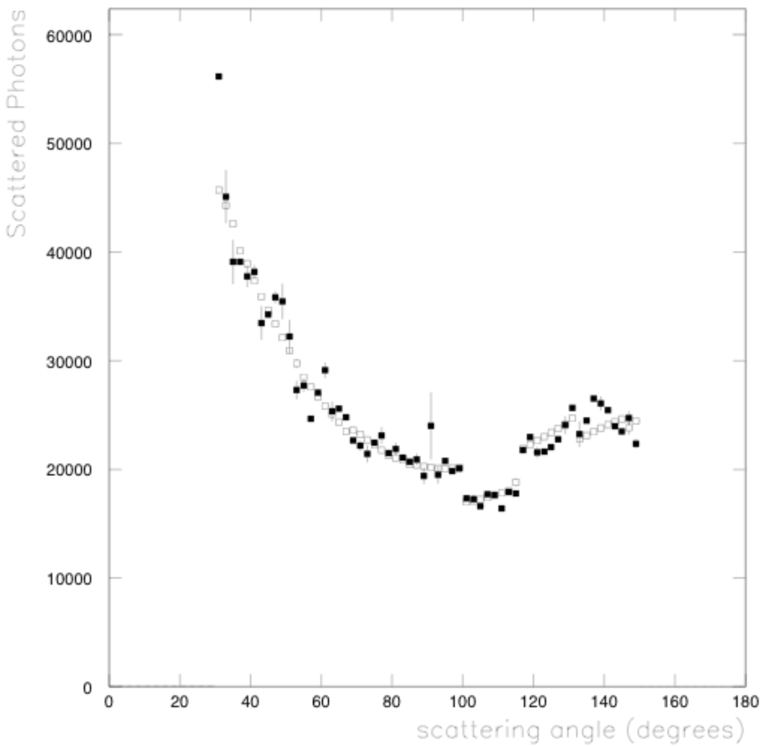
First FADC traces of EAS development

High Resolution Fly's Eye at Dugway Proving Grounds

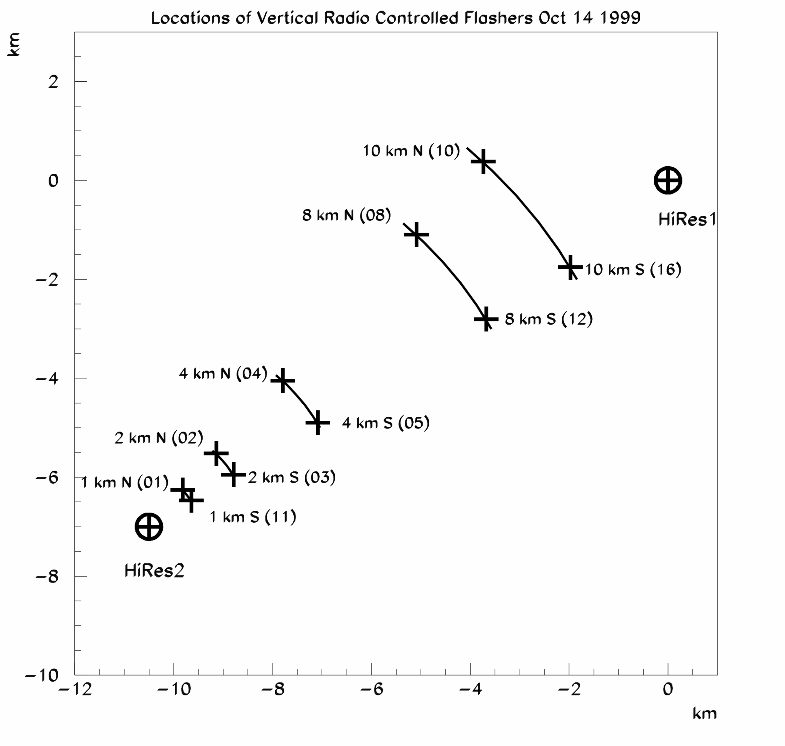
Calibration and Atmospheric Monitoring

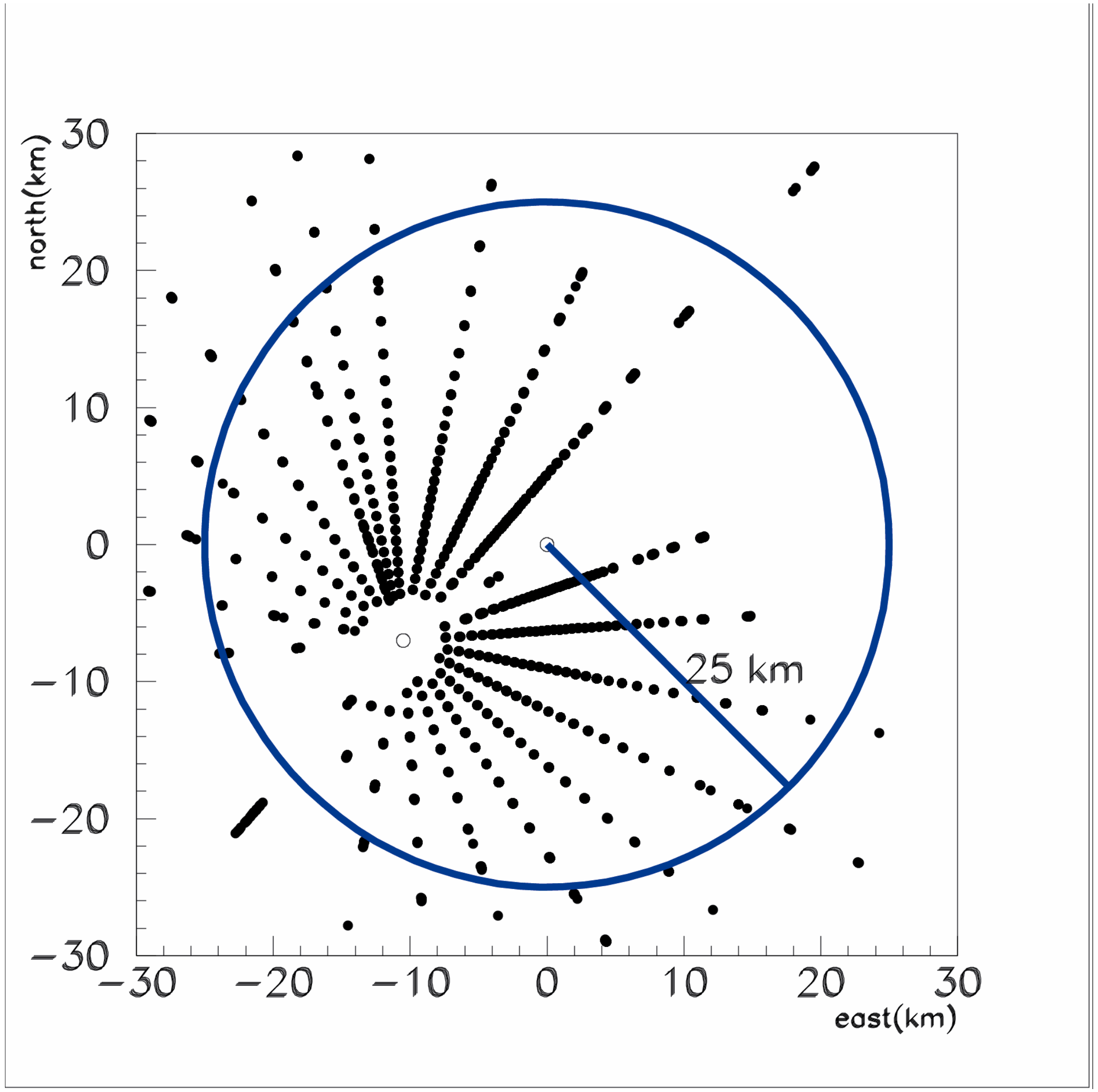
- Fly’s Eye and HiRes pioneered calibration and atmospheric monitoring techniques now used by PAO and TA experiments
- Pioneered use of lasers and lidar systems to understand aerosols.
- Pioneered use of IR sensors to monitor clouds.





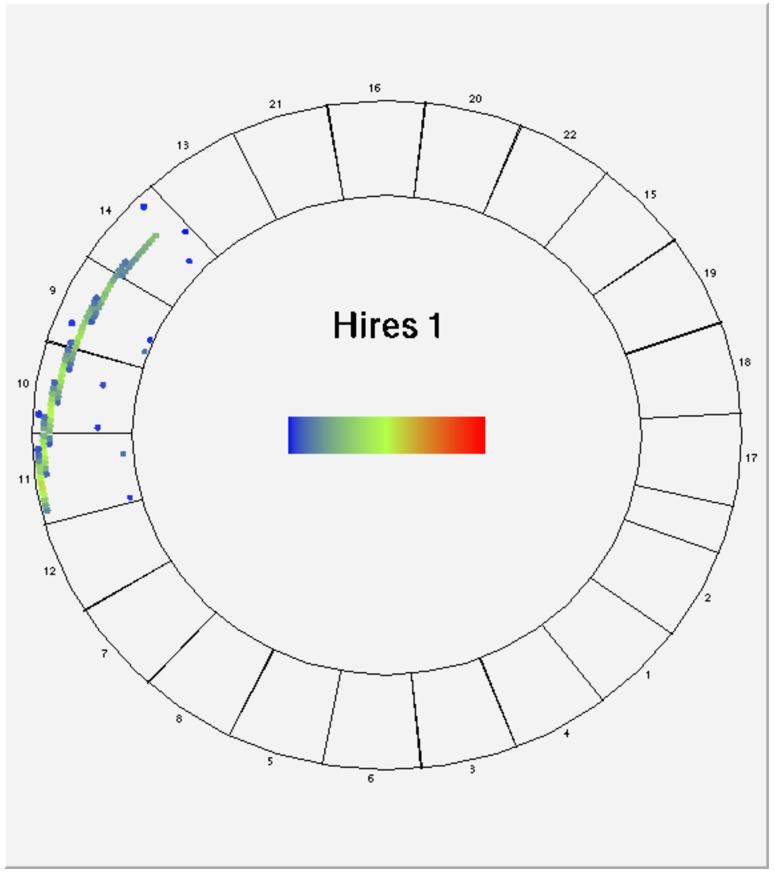
Atmospheric Monitoring: Vertical Xenon Flashers



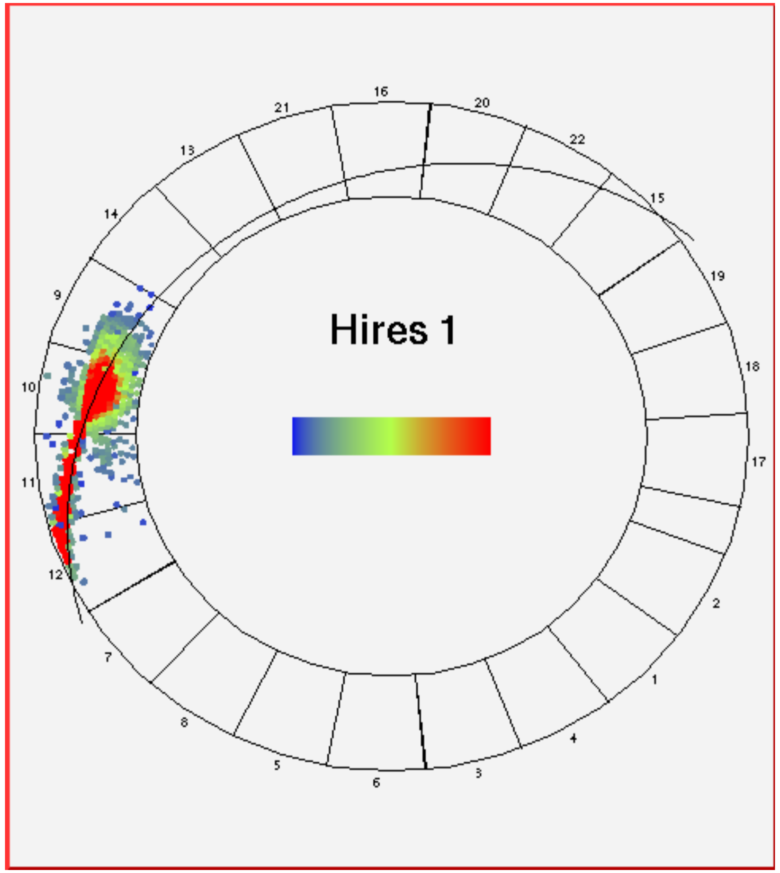


Steerable laser can sweep through most of our aperture and provide hourly corrections

Finding Clouds with the Steerable Lasers

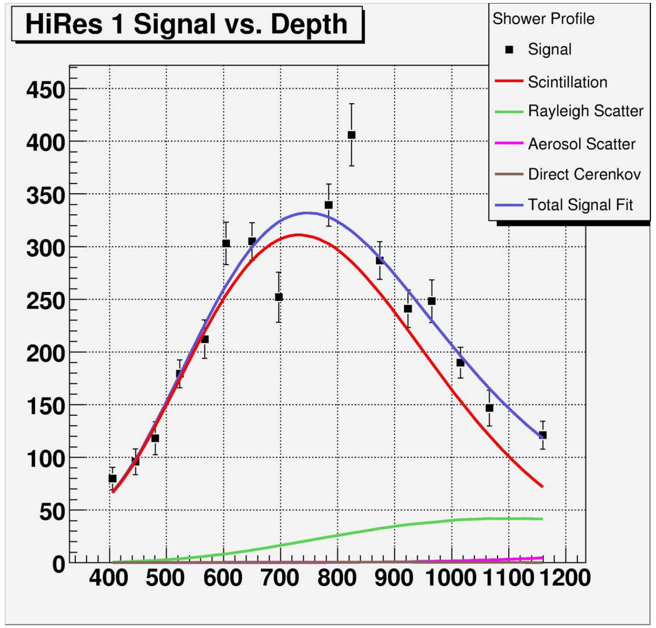


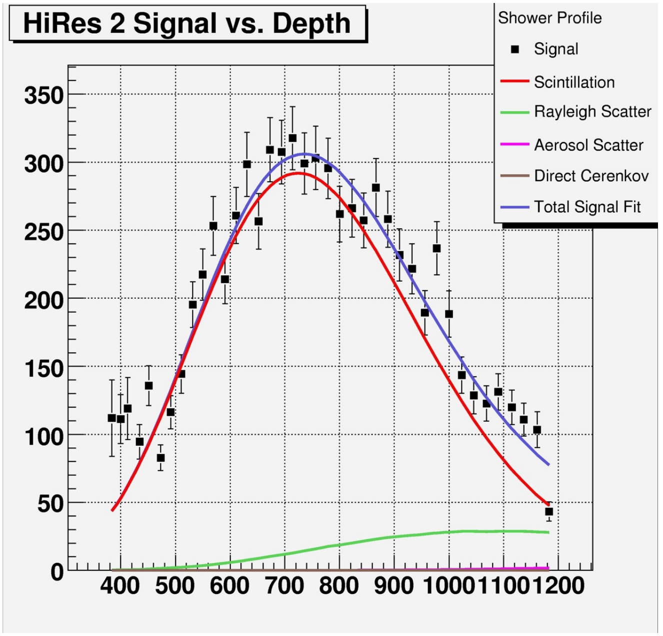
Typical Laser Shot



Laser Strikes a Cloud

Measured Shower Profile





Measured shower parameters.

Event by event:

- X_{max} in g/cm^2; →
- Total energy of the primary particle:
- Arrival direction

Statistically:

- Mass composition
- *p*-air inelastic cross-section

Stereo Geometrical Resolution

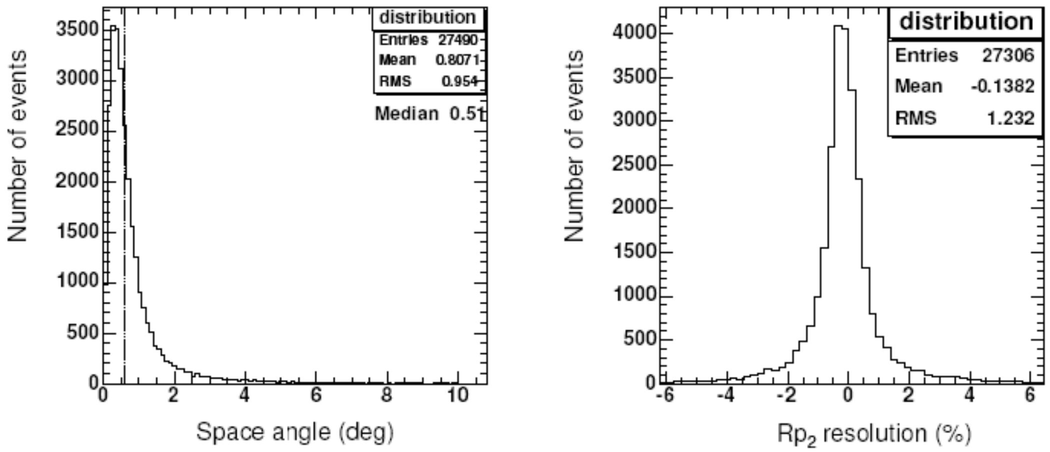
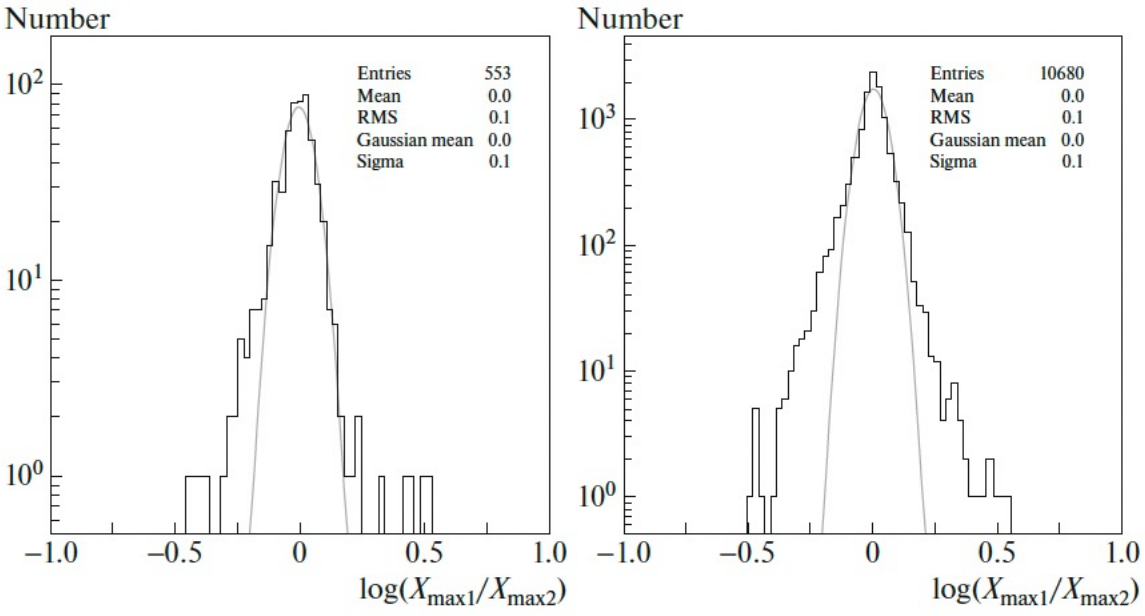


FIG. 5: Resolution functions of geometrical parameters. Left panel is the arrival direction resolution presented as the space angle between the reconstructed and known shower directions. The vertical dashed line indicates the median value of the distribution. Right panel is the R_p resolution showing a reconstruction accuracy of about 1.2%.

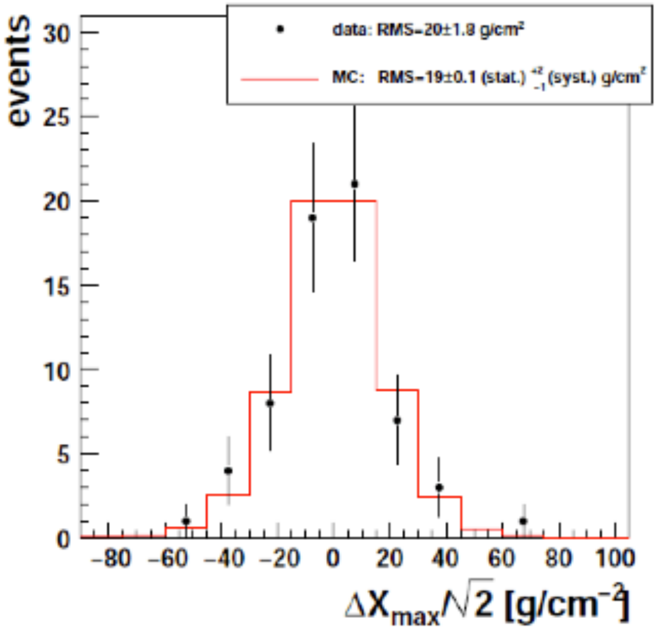
Stereo Xmax Resolution can be tested with data

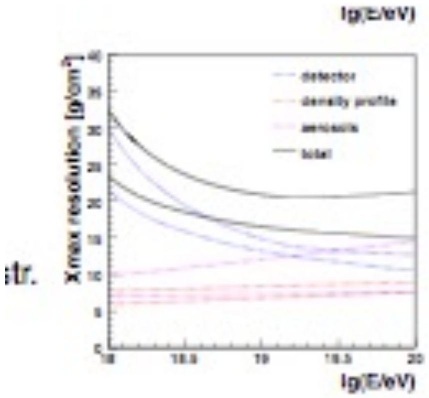


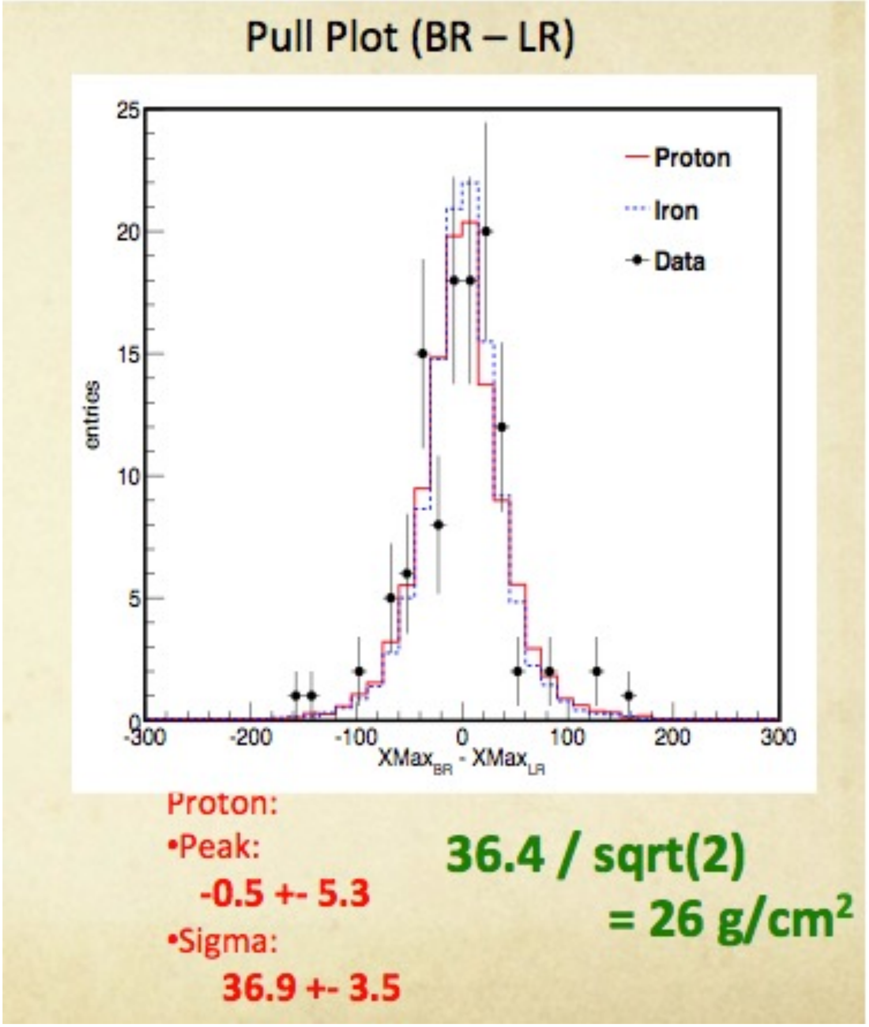
Data

Simulation

Important cross-check for Auger and TA to evaluate atmospheric effects.







Calculated and measured Xmax resolutions for PAO and TA stereo hybrid events appear to be very similar

First Observation of the Greisen-Zatsepin-Kuzmin Suppression

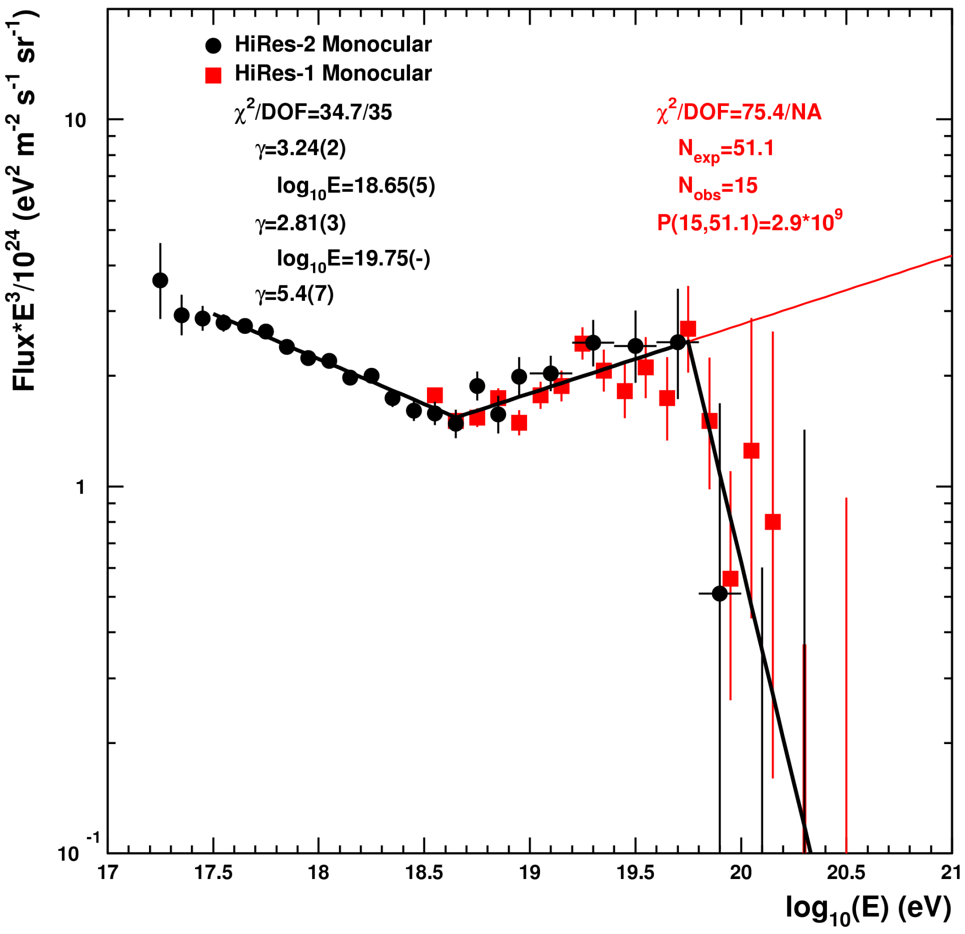
R.U. Abbasi,[1] T. Abu-Zayyad,[1] M. Allen,[1] J.F. Amman,[2] G. Archbold,[1] K. Belov,[1] J.W. Belz,[1] S.Y. Ben Zvi,[3] D.R. Bergman,[4,*] S.A. Blake,[1] O.A. Brusova,[1] G.W. Burt,[1] C. Cannon,[1] Z. Cao,[1] B.C. Connolly,[3] W. Deng,[1] Y. Fedorova,[1] C.B. Finley,[3] R.C. Gray,[1] W.F. Hanlon,[1] C.M. Hoffman,[2] M.H. Holzscheiter,[2] G. Hughes,[4] P. Hüntemeyer,[1] B.F Jones,[1] C.C.H. Jui,[1] K. Kim,[1] M.A. Kirn,[5] E.C. Loh,[1] M.M. Maestas,[1] N. Manago,[6] L.J. Marek,[2] K. Martens,[1] J.A.J. Matthews,[7] J.N. Matthews,[1] S.A. Moore,[1] A. O'Neill,[3] C.A. Painter,[2] L. Perera,[4] K. Reil,[1] R. Riehle,[1] M. Roberts,[7] D. Rodriguez,[1] N. Sasaki,[6] S.R. Schnetzer,[4] L.M. Scott,[4] G. Sinnis,[2] J.D. Smith,[1] P. Sokolsky,[1] C. Song,[3] R.W. Springer,[1] B.T. Stokes,[1] S.B. Thomas,[1] J.R. Thomas,[1] G.B. Thomson,[4] D. Tupa,[2] S. Westerhoff,[3] L.R. Wiencke,[1] X. Zhang,[3] and A. Zech[4]

(The High Resolution Fly's Eye Collaboration)

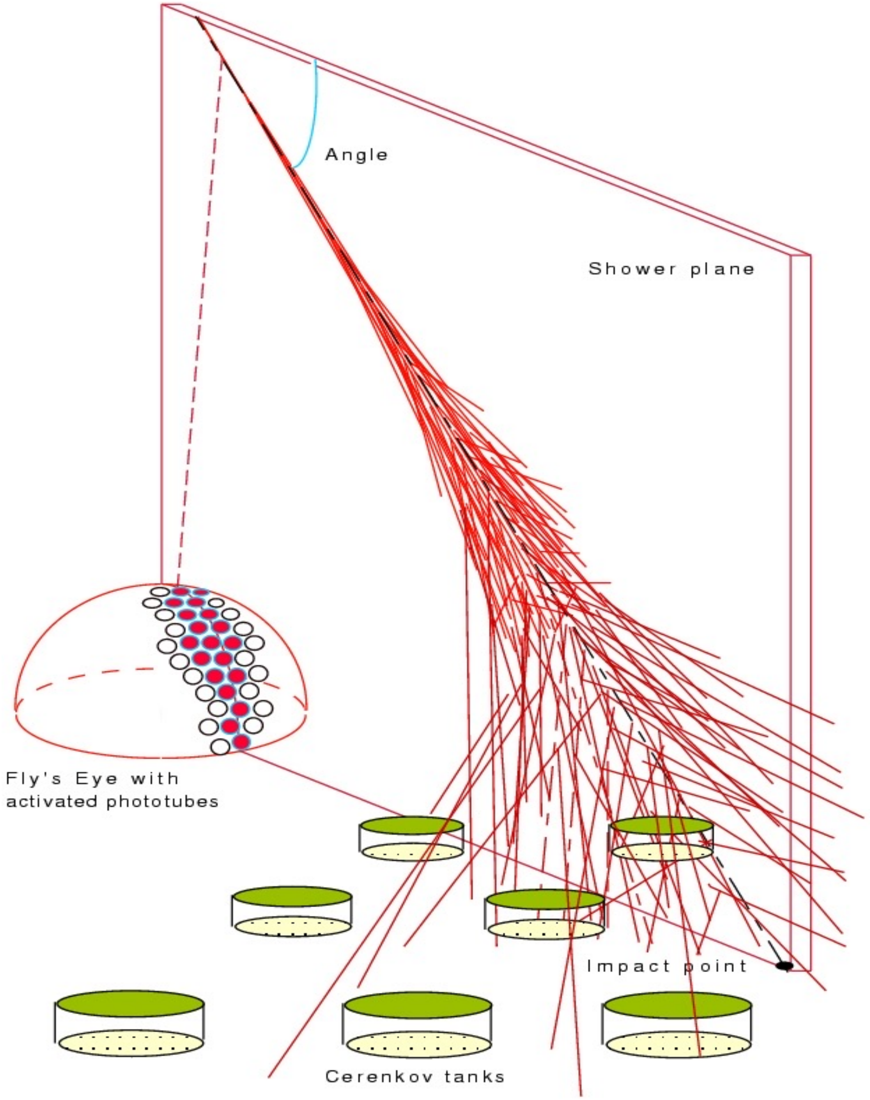
[1] *University of Utah, Department of Physics, Salt Lake City, UT, USA*
[2] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[3] *Columbia University, Department of Physics and Nevis Laboratory, New York, New York, USA*
[4] *Rutgers University — The State University of New Jersey, Department of Physics and Astronomy, Piscataway, NJ, USA*
[5] *Montana State University, Department of Physics, Bozeman, MT , USA*
[6] *University of Tokyo, Institute for Cosmic Ray Research, Kashiwa, Japan*
[7] *University of New Mexico, Department of Physics and Astronomy, Albuquerque, NM, USA*

The High Resolution Fly's Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes' measurement of the flux of ultrahigh energy (UHE) cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, consistent with the expected cutoff energy. We observe the "ankle" of the cosmic-ray energy spectrum as well, at an energy of 4×10^{18} eV. We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of the statistical significance of our observation is described.

PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd



Surface and Fluorescence Detectors can work together



Development of "Hybrid" detectors

-HiRes/MIA – 10 sq km
--Pierre Auger Observatory
-3000 sq km surface detector
--Telescope Array Experiment
-700 sq km surface detector

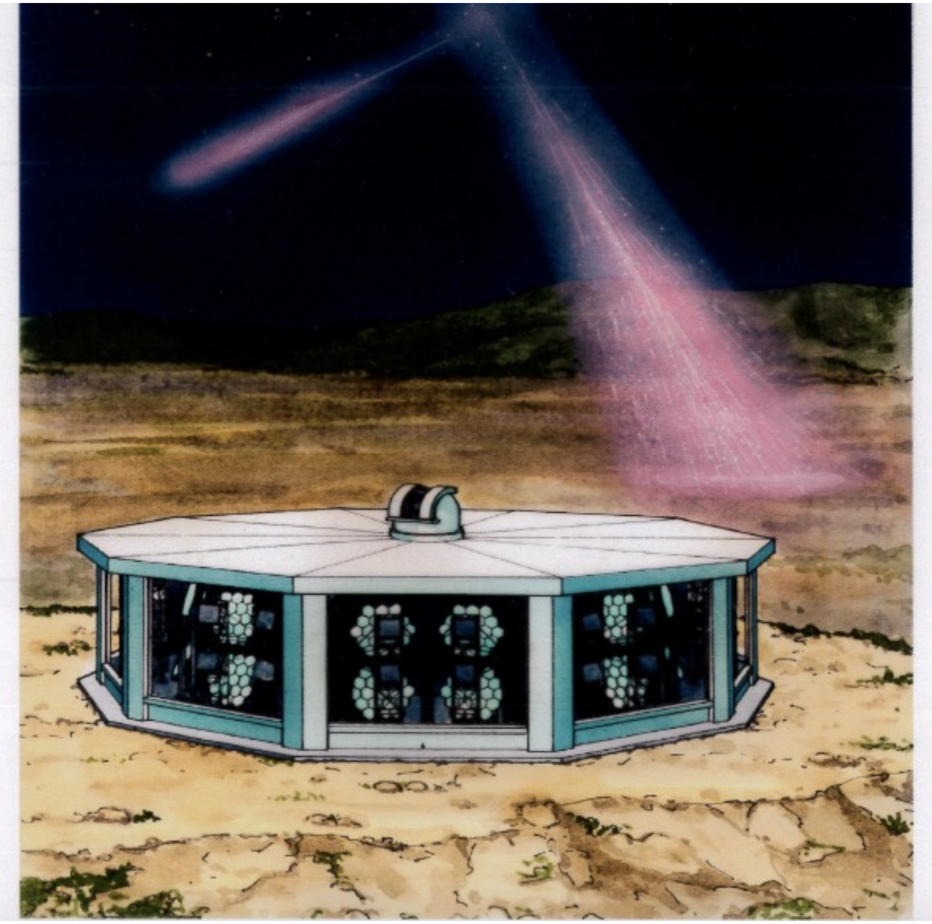
HiRes and AGASA groups come together

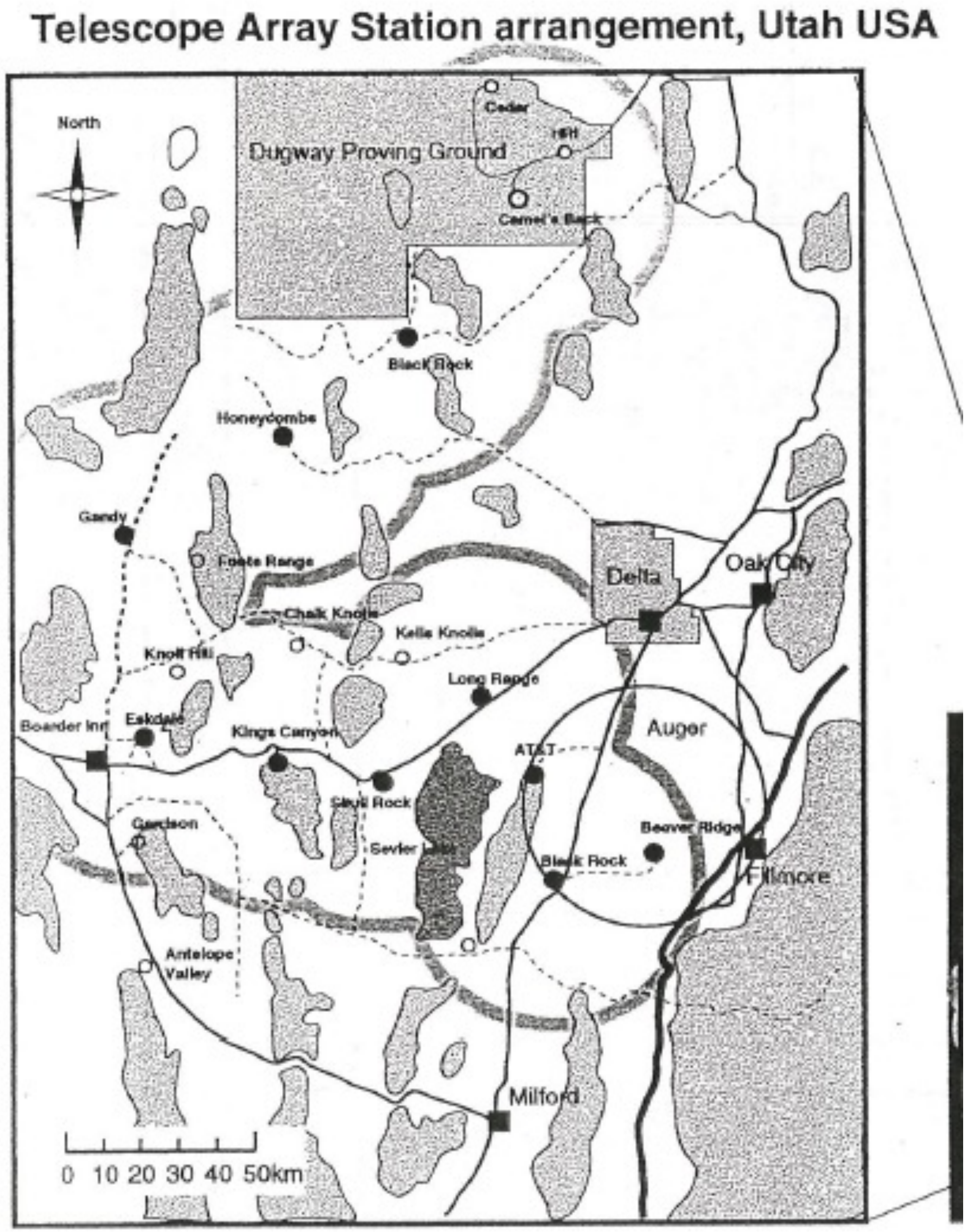
- In 1999 serious discussions between Teshima, Loh and Sokolsky to form a new collaboration
- Pure fluorescence (Snake Array) or mixed Cherenkov/fluorescence telescope arrays discussed
- Vision of a hybrid detector using AGASA style surface detectors and HiRes style fluorescence technique prevailed.
- TA began taking data in 2008 with Fukushima and Sokolsky as co-spokespersons.

But before TA there was the Snake Array

- Discussions between Gene Loh, M. Teshima and myself with L. Wiencke and S. Yoshida doing extensive field survey.
- Maximize FD Stereo, no SD.
- Optimization -> minimize redundancy – only 2 detector stereo -> linear array of detectors.
- Site survey was done and > 10 sites found
- ~ 30-40 km apart.

Survey of sites for Snake Array in Utah





Auger and the acceptance of FD’s

1991 - Cronin proposed building at 5000km2 SD array. Dublin meeting

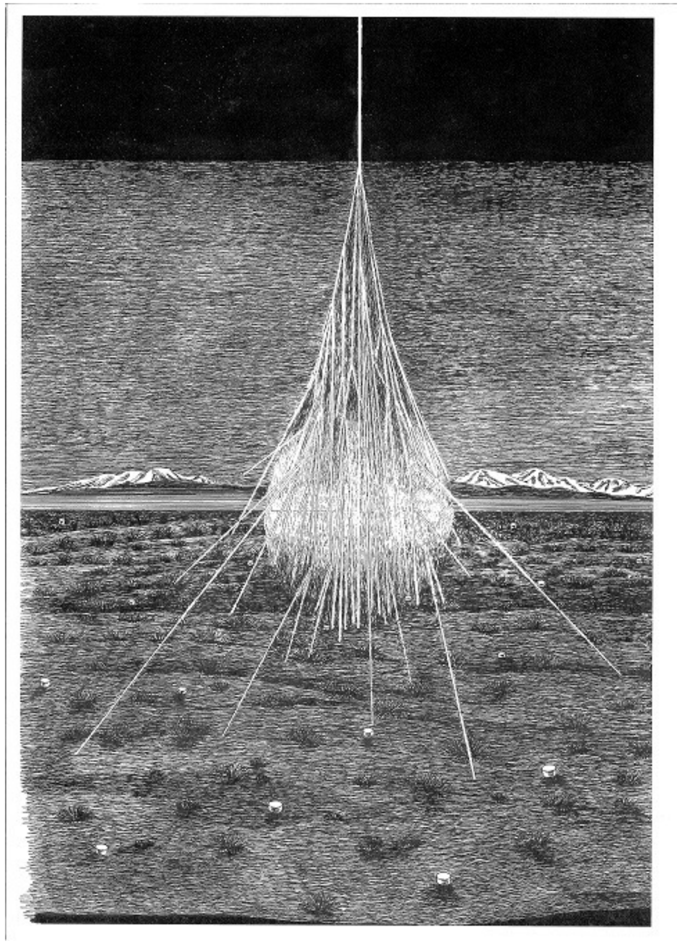
1995 – Fermilab six-month workshop to design the next observatory “Let a thousand flowers bloom”. Selection of water tanks for SD and addition of an FD detector (Paul Sommers).

1998-1999 – Jim Cronin comes to University of Utah to push for large array and collaboration with HiRes group and Japanese TA group for Northern Auger. Idea of North and South observatories. Northern Auger sites narrowed to Utah and Colorado.

2000 – Colorado chosen for Auger North.

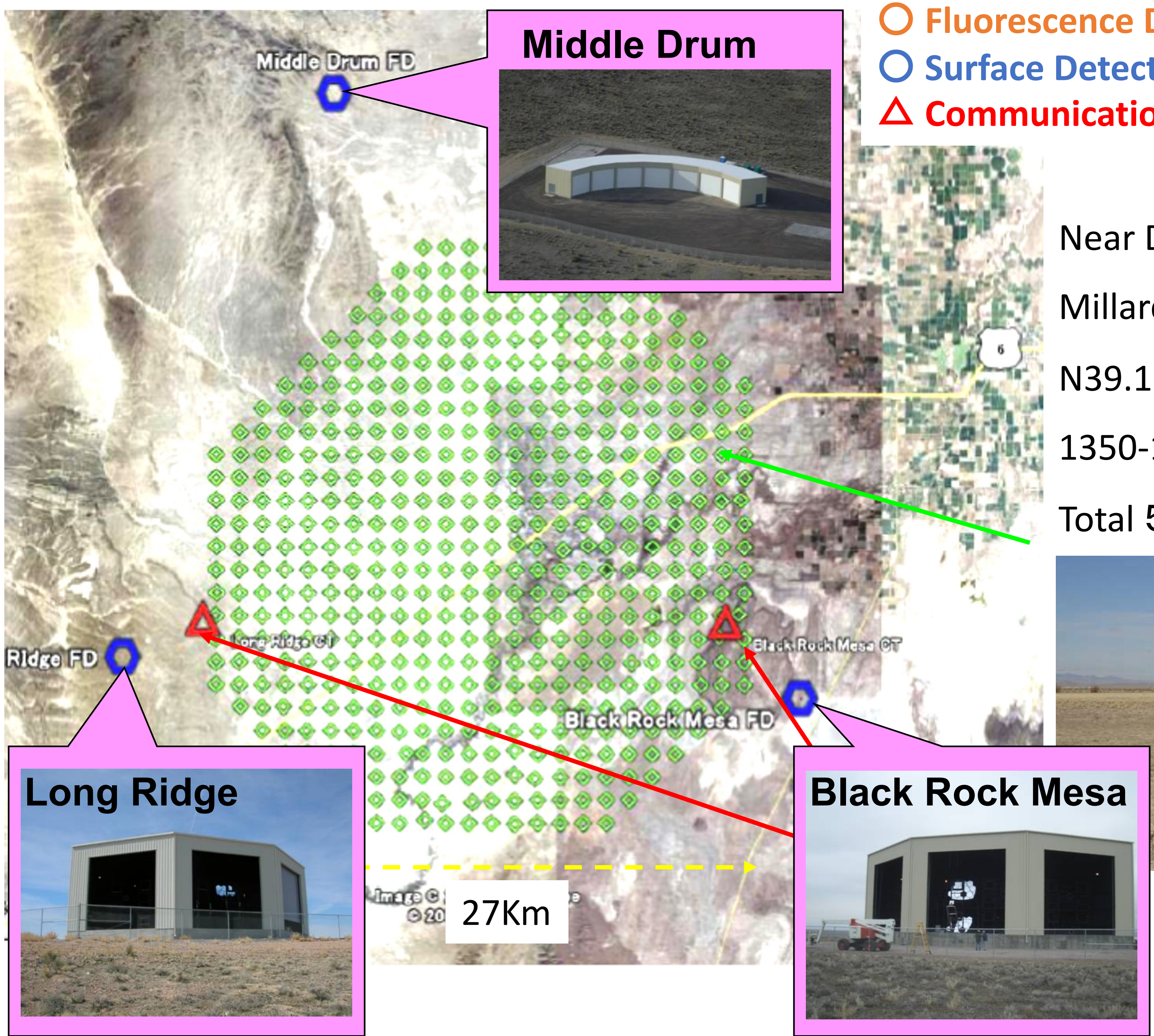
2002 – Construction begins on Auger in Argentina.

2009 – Proposal for N. Auger in Colorado to funding agencies – not funded.



Transition to TA
New fluorescence telescopes and leadership from Japan – M. Fukushima ICRR Tokyo

Telescope Array Detector



○ Fluorescence Detector
○ Surface Detector
△ Communication Tower

Near Delta, Utah

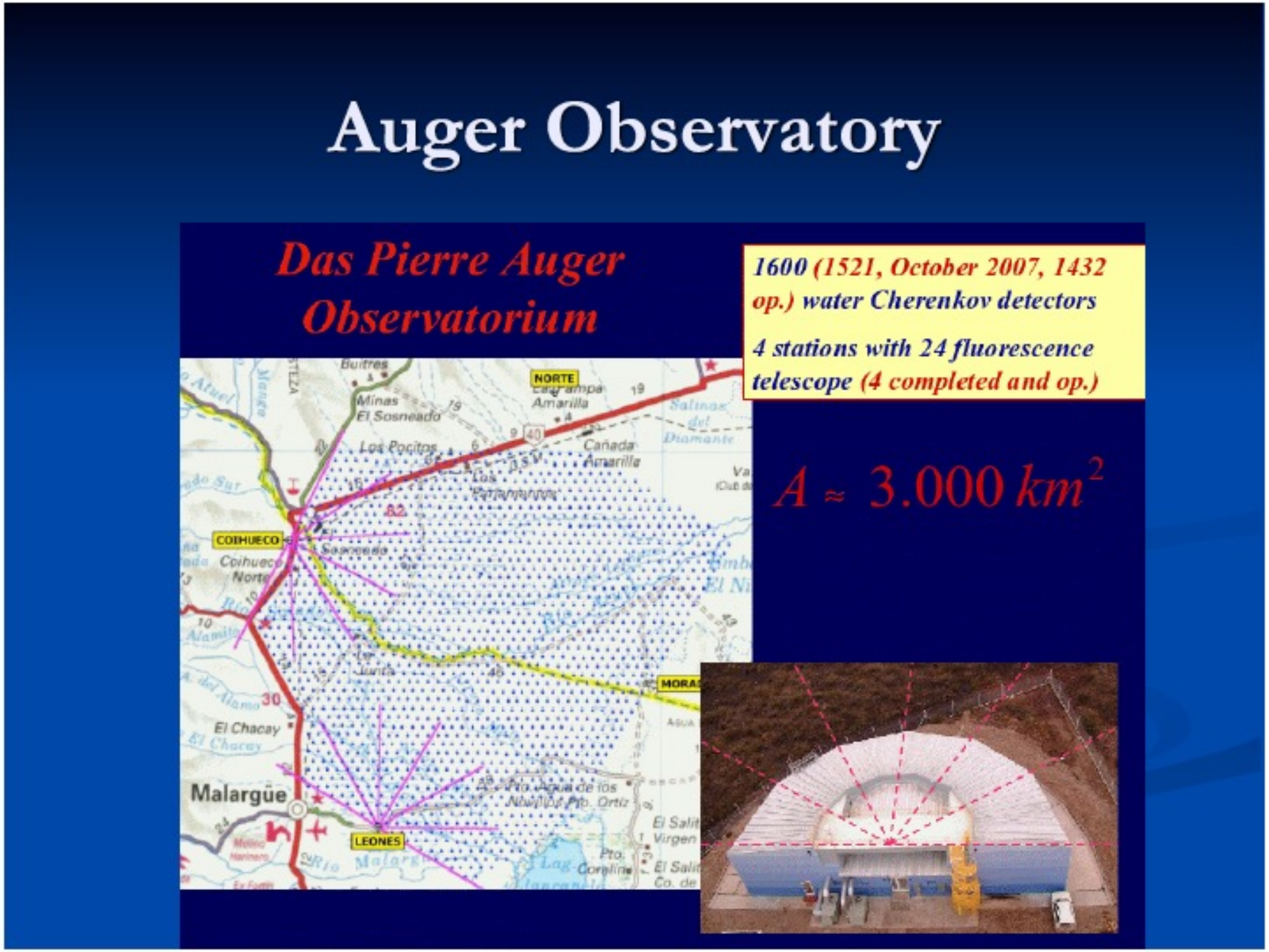
Millard county Utah USA

N39.1° W122.9°

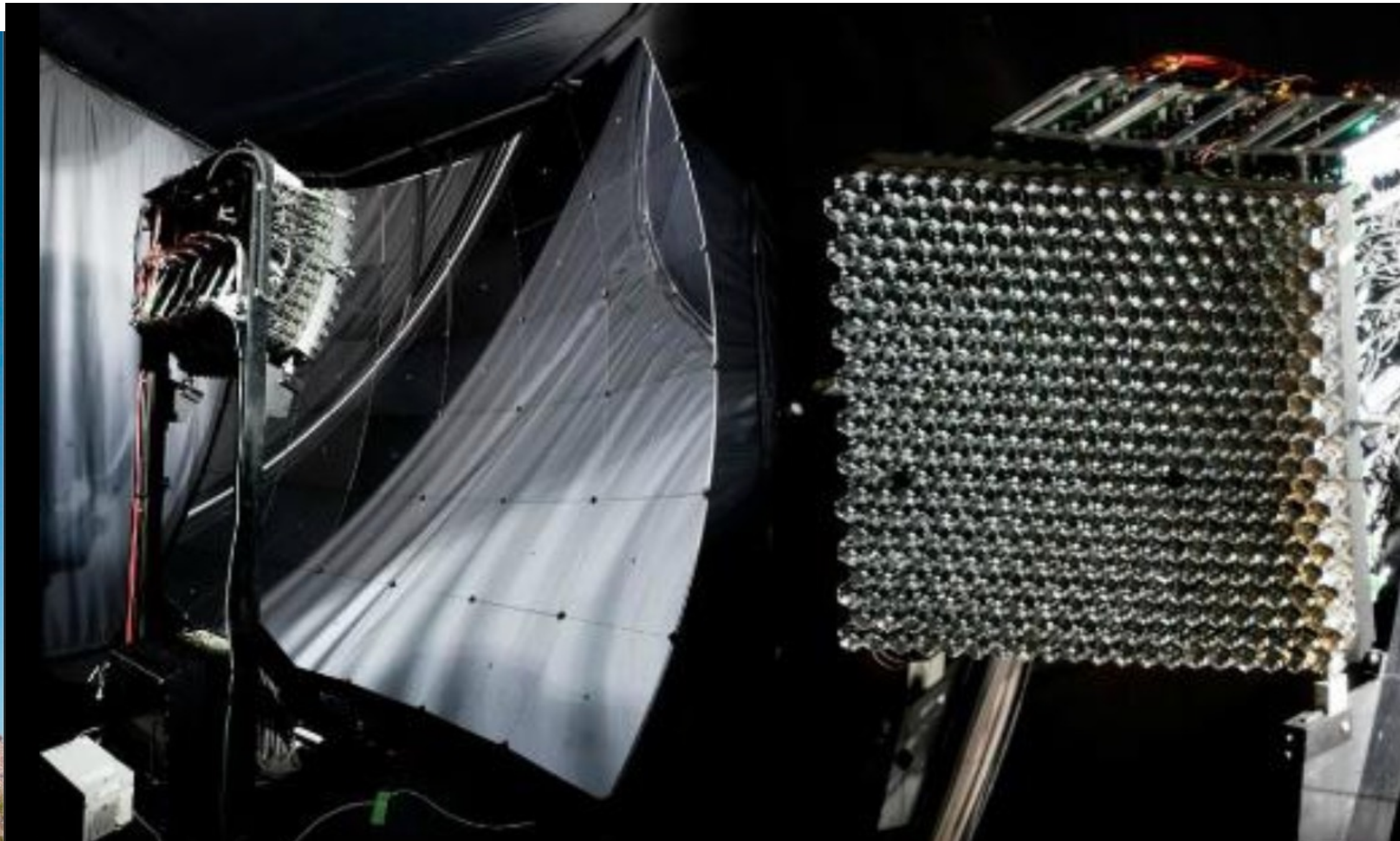
1350-1500m asl

Total 503SD(2007/12-)

Au


Auger Observatory
Das Pierre Auger Observatorium
1600 (1521, October 2007, 1432 op.) water Cherenkov detectors
4 stations with 24 fluorescence telescope (4 completed and op.)
A ≈ 3.000 km²
NORTE
COIHUECO
LEONES
Malargüe
El Sosneado
Los Pocitos
Cañada Amarilla
Coihueco Norte
El Chacay
Minas
Buitres
Salinas del Diamante

Auger state of the art FD detectors and sophisticated atmospheric monitoring -> good EAS reconstruction and resolution. Large aperture -> tighter cuts on data.



And yet !

The Unreasonable Effectiveness of the Air-Fluorescence Technique in Determining the EAS Shower Maximum

P. Sokolsky[a,*] and R. D'Avignon[a]
[a] *Department of Physics and Astronomy University of Utah, Salt Lake City, 84112 Utah, United States*
**e-mail: ps.protopop@gmail.com*
Received September 13, 2021; revised December 2, 2021; accepted December 2, 2021

Abstract—We review all existing air-fluorescence measurements of the elongation rate of extensive air showers (slope of mean EAS shower maximum X_{max} vs. log of shower energy E) above 10^{17} eV. We find remarkable agreement for all current and historic experiments over a 30 yr period for the energy range from 10^{17} to 3×10^{18} eV. The mean elongation rate in this energy interval is near 80 g/cm^2/decade. Above this energy, experiments in the Northern hemisphere are in good agreement with an average elongation rate of 48 ± 10 g/cm^2/decade while Southern hemisphere experiments have a flatter elongation rate of 26 ± 2 g/cm^2/decade. We point out that, given the agreement at lower energies, possible systematic reasons for this difference are unlikely. Given this, the world elongation rate data alone may indicate a composition difference of UHECR in the Northern and Southern hemisphere and thus a diversity of UHECR sources in the Northern and Southern sky.

DOI: 10.1134/S1063776122040100

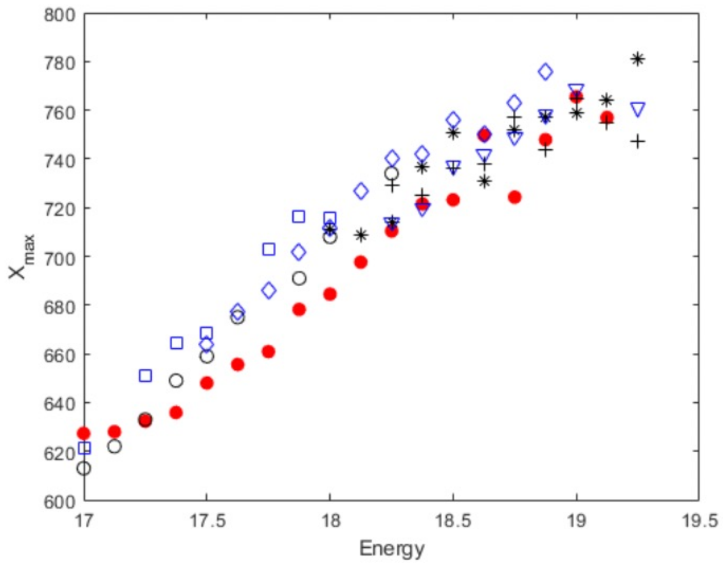


Fig. 5 Mean Xmax as function of energy for Northern hemisphere measurements. Statistical error bars have been suppressed for clarity.
Key: red circles – Fly's Eye Stereo; open circle-TALE hybrid; diamonds-TA hybrid trigger; square-HiRes-MIA; star-HiRes stereo; triangle-TA BR-LR hybrid; cross-TA-MD-hybrid;

Remarkable agreement between all FD experiments on the Evolution of shower maximum with energy.

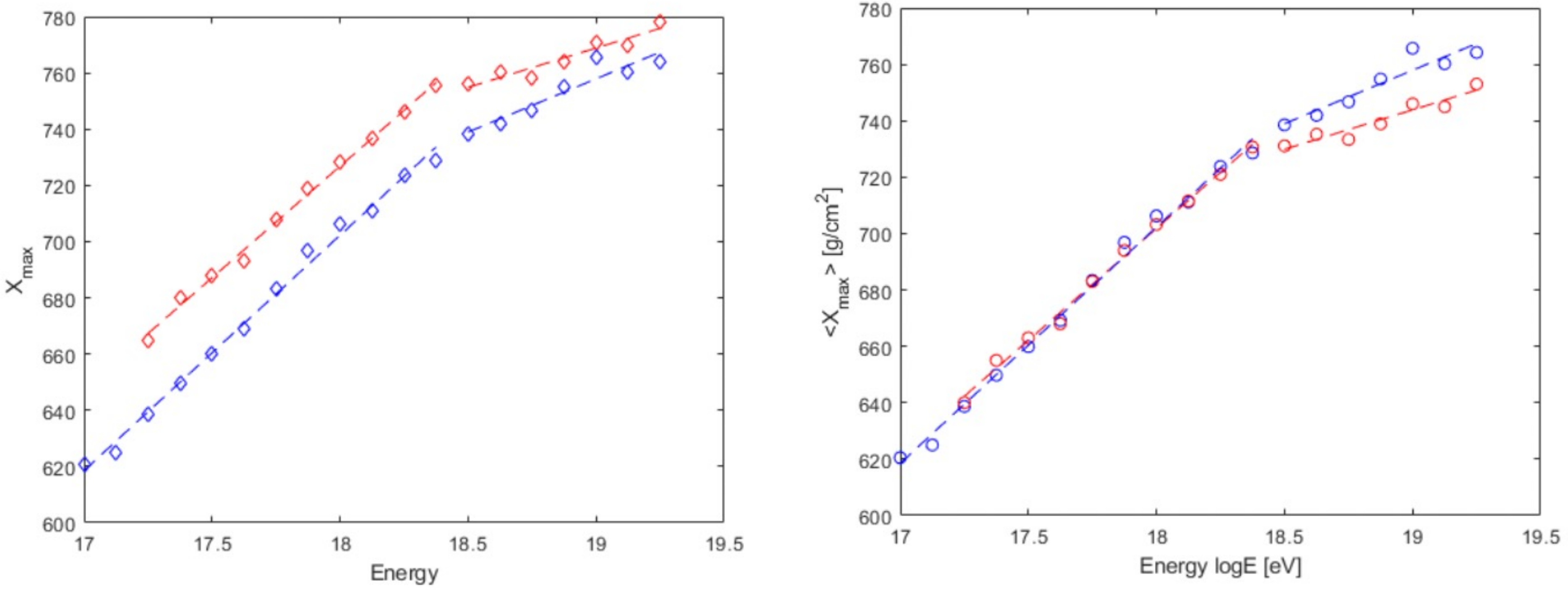


Fig. 7 North and South Elongation Rates. Red points are Auger data. Blue points are the mean Northern data. Dashed lines are linear fits with an assumed break at 3 x 10^{18} eV. Error bars have been suppressed for clarity but are smaller than the ~20g/cm^2 systematic errors. Auger data points have been slightly interpolated in energy to correspond to the binning used here.

25 gm/cm2 shift

After 40 years, Air Fluorescence is a well-understood technique. Remaining issues

- Air Fluorescence Efficiency

 - Large number of laboratory measurements but room for improvement. Translating single particle measurements to EAS

- Possible hints of energy dependence within EAS development (sFLASH)

- Atmospheric corrections –GDAS, Lidar etc – major improvement.
- Most importantly: Independent measurements by competing groups.

- Auger/TA comparisons are crucial in understanding details of remaining FD systematics.

The History of the (Fluorescent) Future?

- Faster, Cheaper, “Better”?
- Cadillac Desert?
- Space Poetry?

The next generation will have to decide

Stan Thomas, Senior Engineer
35 years with FD development

Bob Cady, First Ph.D
Student on Fly's Eye.
TA deployment chief

Proposals for collaborative studies…

May 14, 1997

Professor Pierre Sokolsky
University of Utah

Dear Pierre,

During the Auger Collaboration meeting at Utah we discussed the similarities and differences of the scientific goals of the HiRes and Auger projects. The Auger Collaboration Board decided to invite you and your collaborators to consider joining the Auger Observatory with the purpose of a single enhanced scientific program. We would like to proceed in this direction as fast as possible.

We recognize that our groups have chosen to emphasize different techniques. HiRes and its preceding experiments have pioneered atmospheric fluorescence detectors. These detectors are also an important component of the hybrid technique chosen for the Auger Observatory. Working together we will significantly strengthen both our projects.

We believe that a small discussion group may be the right forum for the conversations leading to a joint scientific statement and the detailed planning of our collaboration. We have asked Carlos Hojvat to convene this group for Auger.

We propose that, starting immediately, the characterization of the atmosphere at the Auger Northern Site be undertaken as a joint effort of HiRes, Telescope Array and Auger. We propose that Dr. Fick, the Auger Northern Acting Site Manager coordinates the activities at the site and continues to be the contact person with the State and Local authorities.

We look forward to productive conversations and a successful collaboration,

J. W. Cronin A. A. Watson
University of Chicago University of Leeds

May 14, 1997

Professor M. Teshima
ICRR
University of Tokyo

Dear Professor Teshima,

During the Auger Collaboration meeting at Utah, May 9-14, 1997, we were impressed by the continued interest of the Telescope Array group in the Auger Observatory. The Auger Collaboration has discussed the relationship between our two projects and possibilities for the future. We invite you and your collaborators to engage in discussions leading to a possible scientific collaboration.

The scientific goal of both our experiments is the study of the EHE Cosmic rays. We recognize that both our groups have chosen to emphasize different techniques. We believe that our proposals could eventually work together to enhance the scientific potential of our experiments.

The Telescope Array proposal, as presented by Professor Yoshida at the Auger meeting, appears to be compatible with the Auger hybrid design. The Auger Collaboration would like to support a free exchange of ideas to explore the advantages of a collaboration. We believe the discussion group we have formed with HiRes may be the right forum for these discussions.

The Pierre Auger Collaboration supports the Telescope Array proposal.

We propose that, starting immediately, the characterization of the atmosphere at the Auger Northern Site be undertaken as a joint effort of HiRes, Telescope Array and Auger. We propose that Dr. B. Fick, the Auger Northern Acting Site Manager coordinates the activities at the site and continues to be the contact person with the State and Local authorities.

We look forward to having productive conversations with you,

Early Work on Lidar Systems

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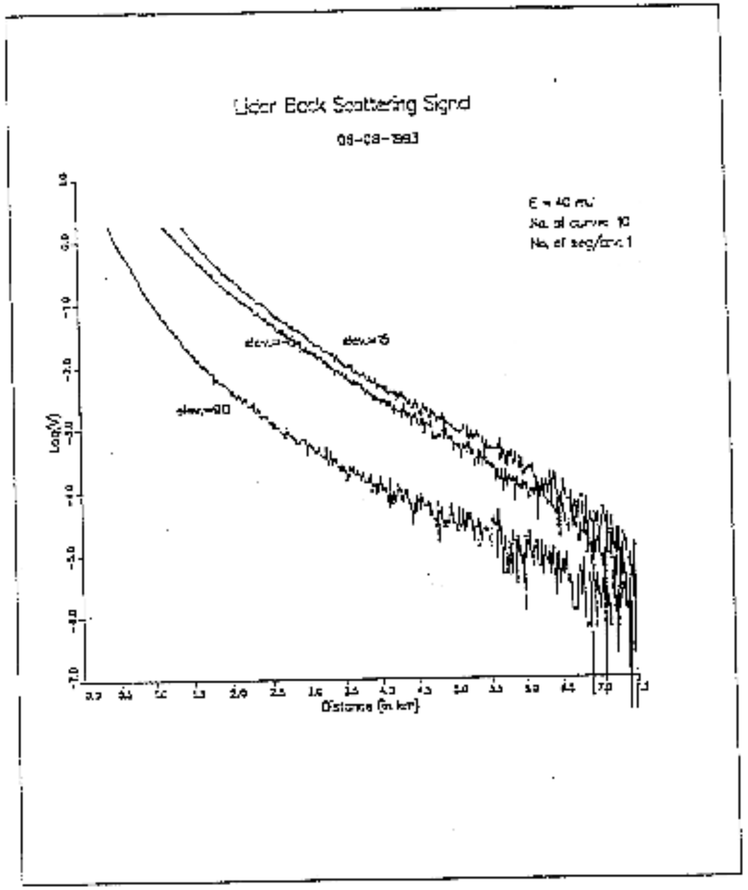
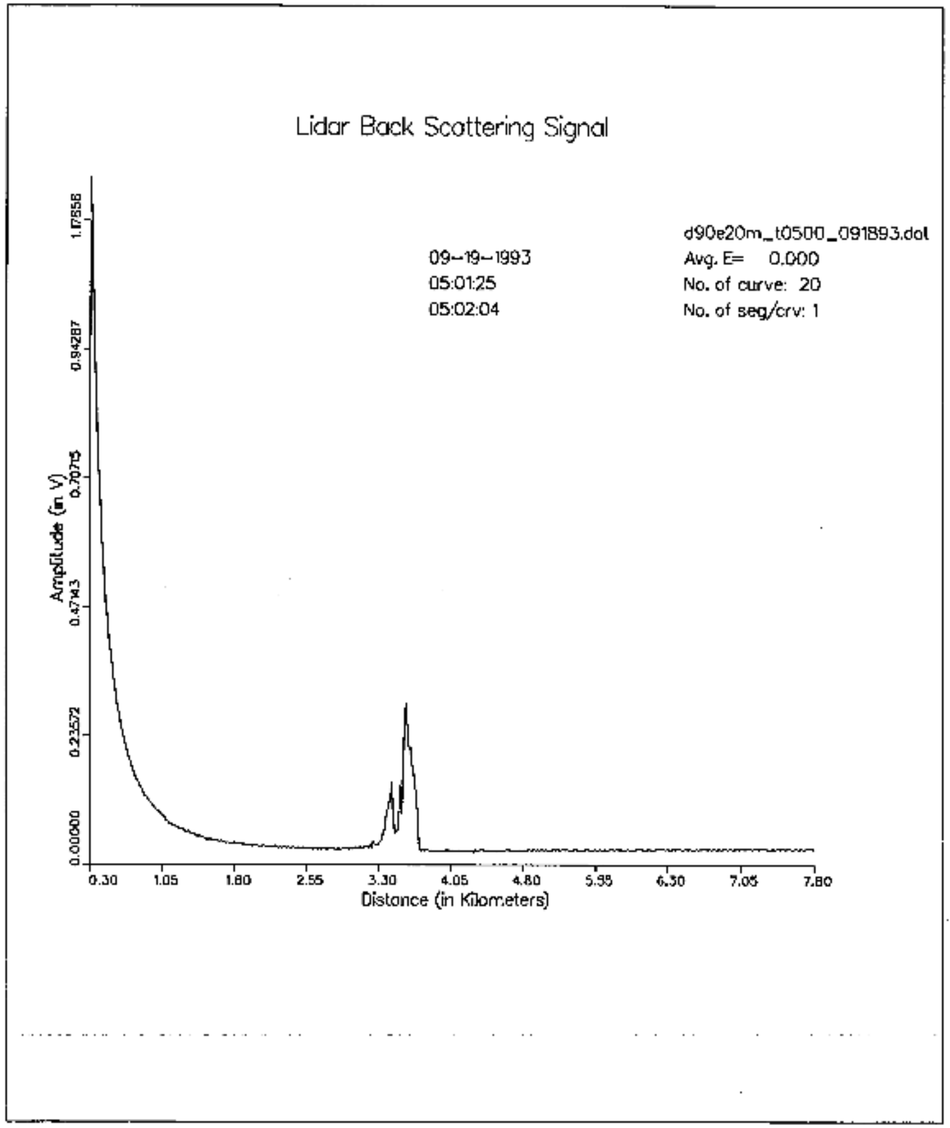
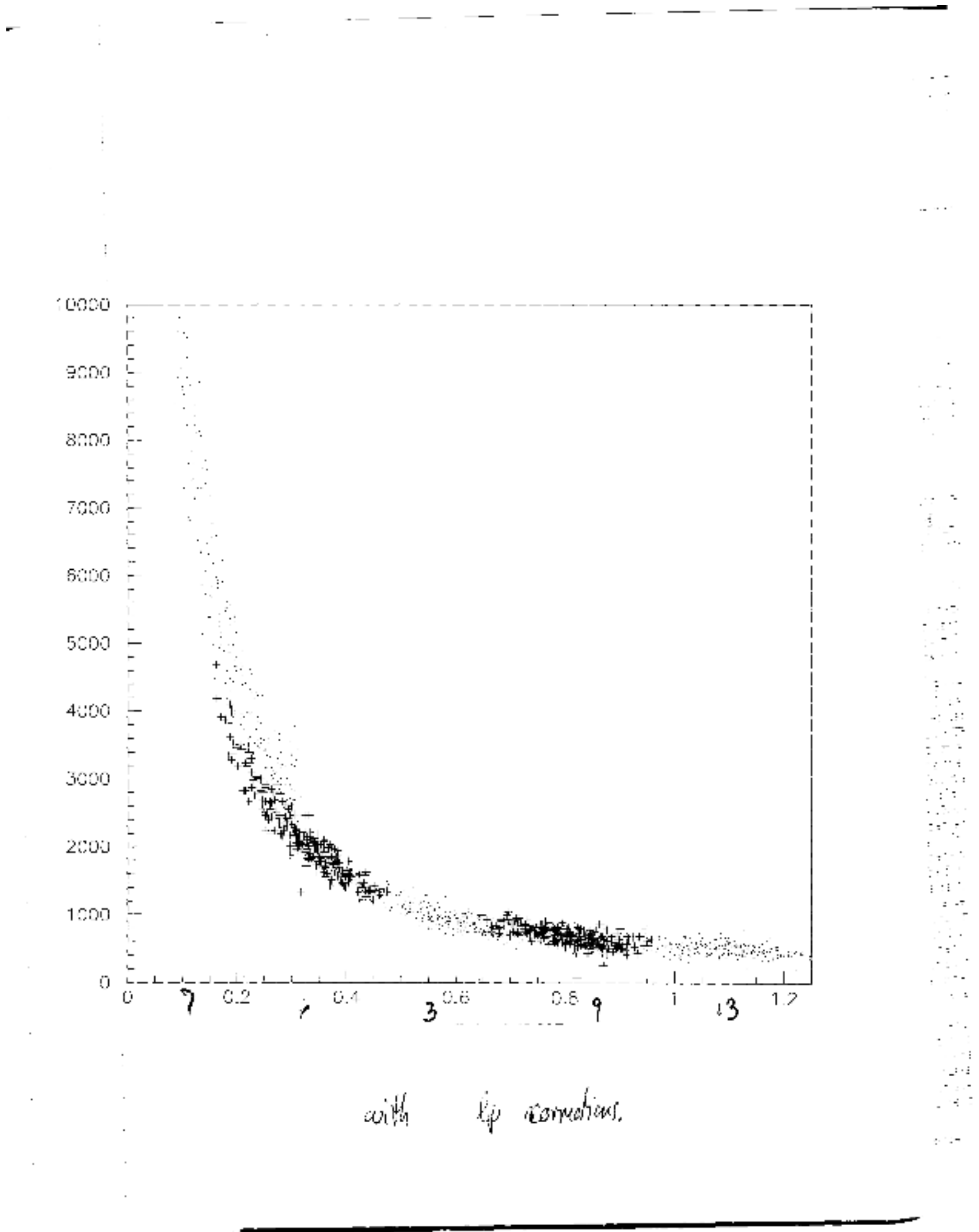


Figure E.3: Lidar Backscattered Signal measured by test Lidar system at the F.E. II site. Horizontal Axis: distance to scattering volume (km); Vertical Axis: Photomultiplier Tube Signal (proportional to backscattered light intensity) ($\log_{10}$ V (Volts)). Three traces are plotted corresponding to elevation angles of 15°, 45°, and 90°.





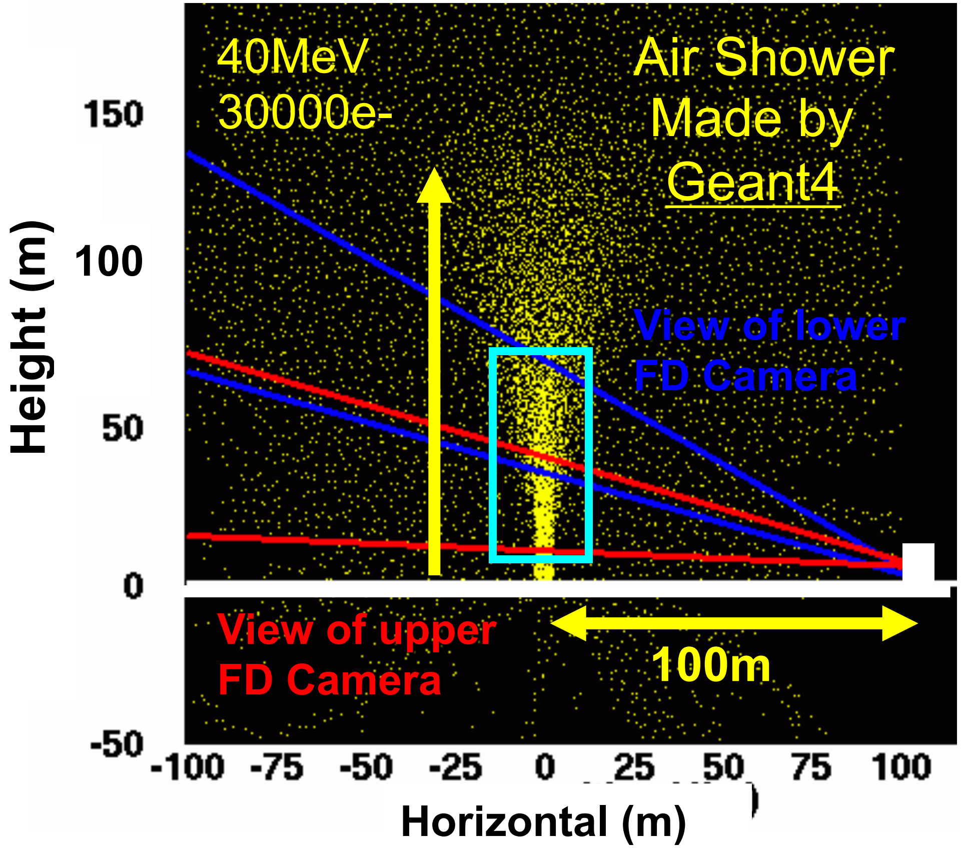
Study of multiple scattering of
Light in atmosphere - Aureole
Of point source.

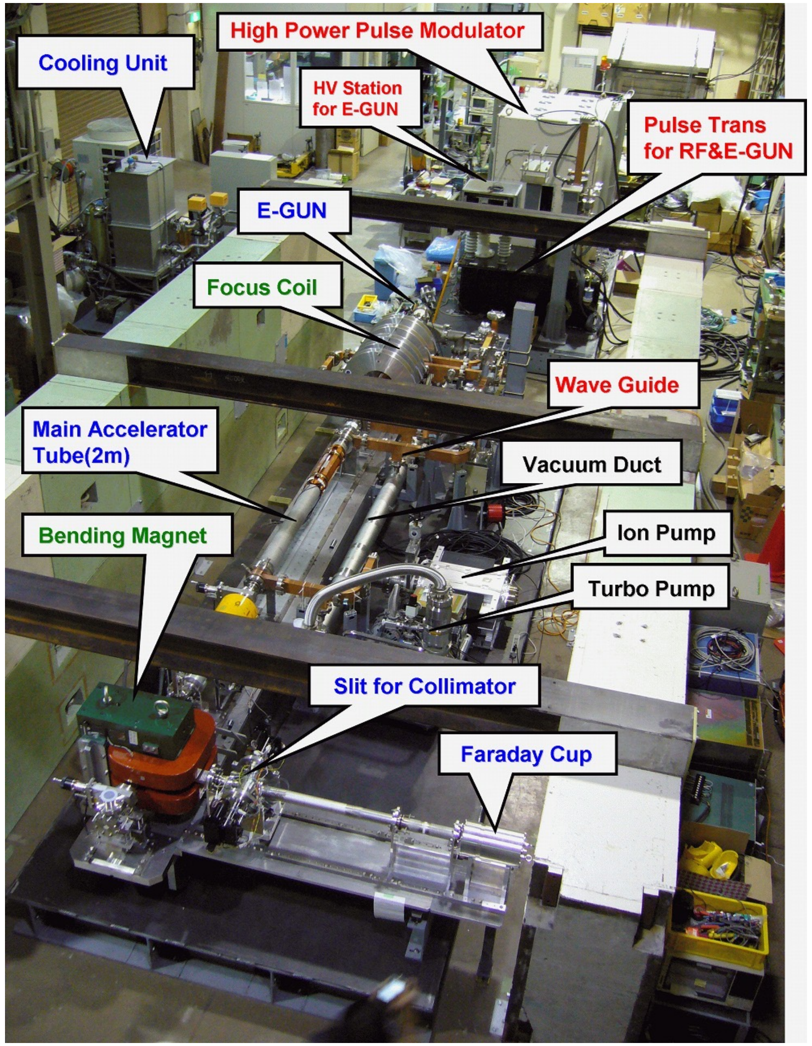
Hot-air balloon mounted point
light source (collaboration with
Air Force -

HiRes mirrors pick up scattered
Light over wide angular range

Study dependence on aerosol
properties

Energy Calibration using by LINAC





Energy: Max40MeV (Continuous adjust)

Repetition : 1Hz(Max)

Beam power: 6.4mJ/pulse ($=10^9 e^-$/pulse)

Pulse width: 1 µsec (typical value)

@KEK Japan.

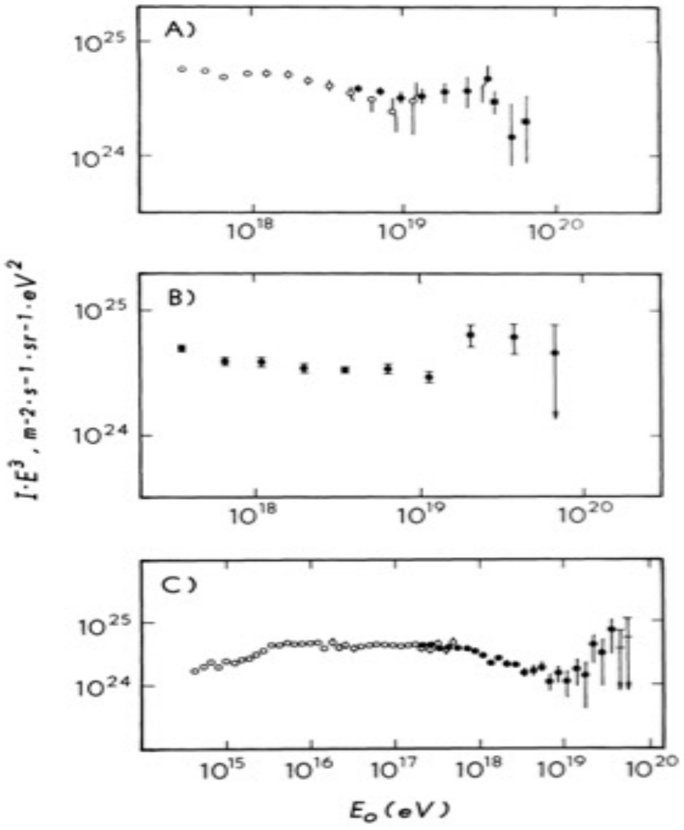
Shipping : → this Autumn.

The race for the GZK – mid 80’s

Yakutsk

Fly’s Eye

Akeno

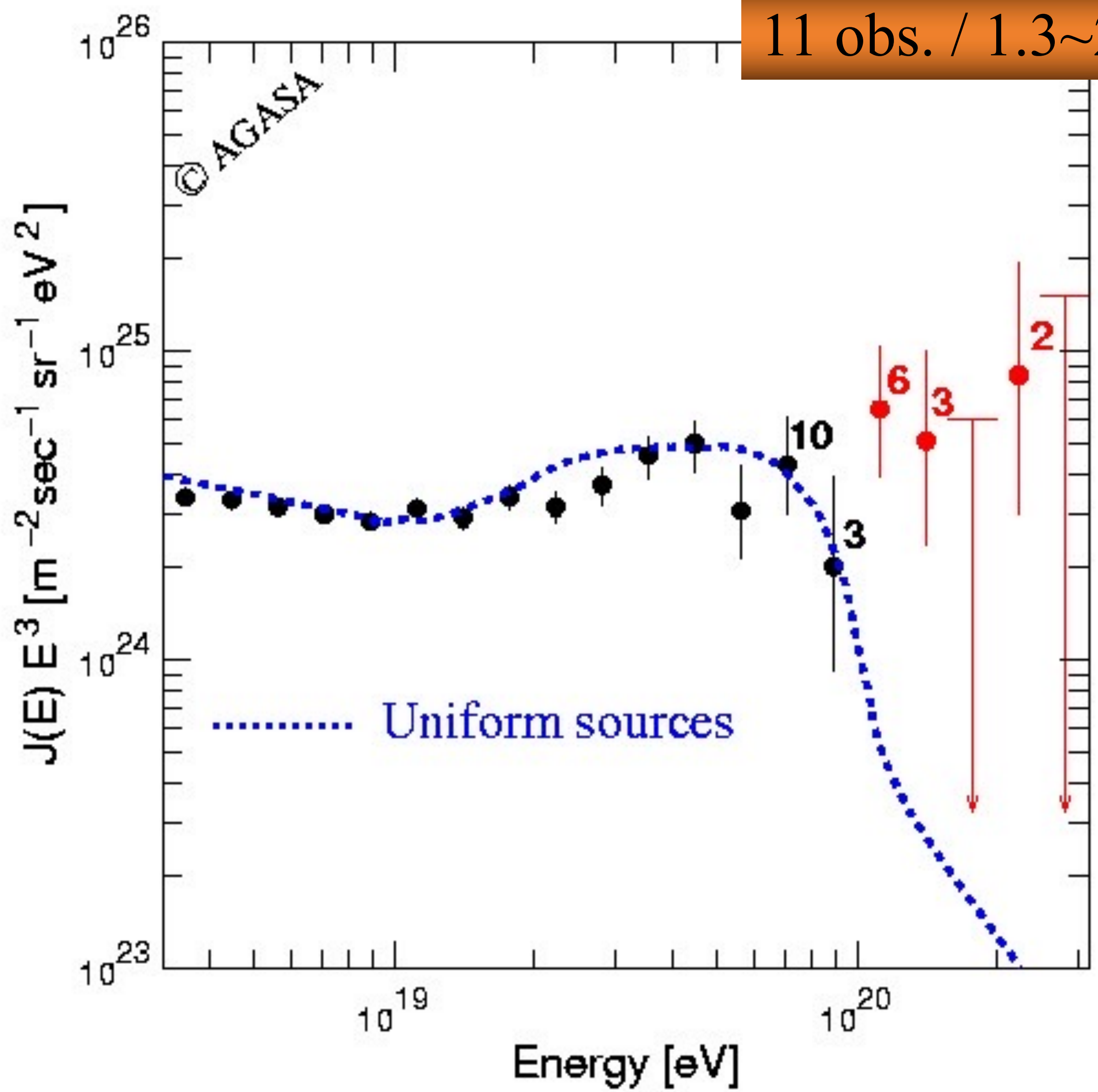


AGASA and the GZK crisis

- AGASA- first ~100 km^2 surface array – successor to Akeno.
- No evidence for GZK
- No evidence for anisotropy
- How can this be reconciled with universality of microwave background?
- Possible ‘New Physics”?? A thousand theory papers followed…

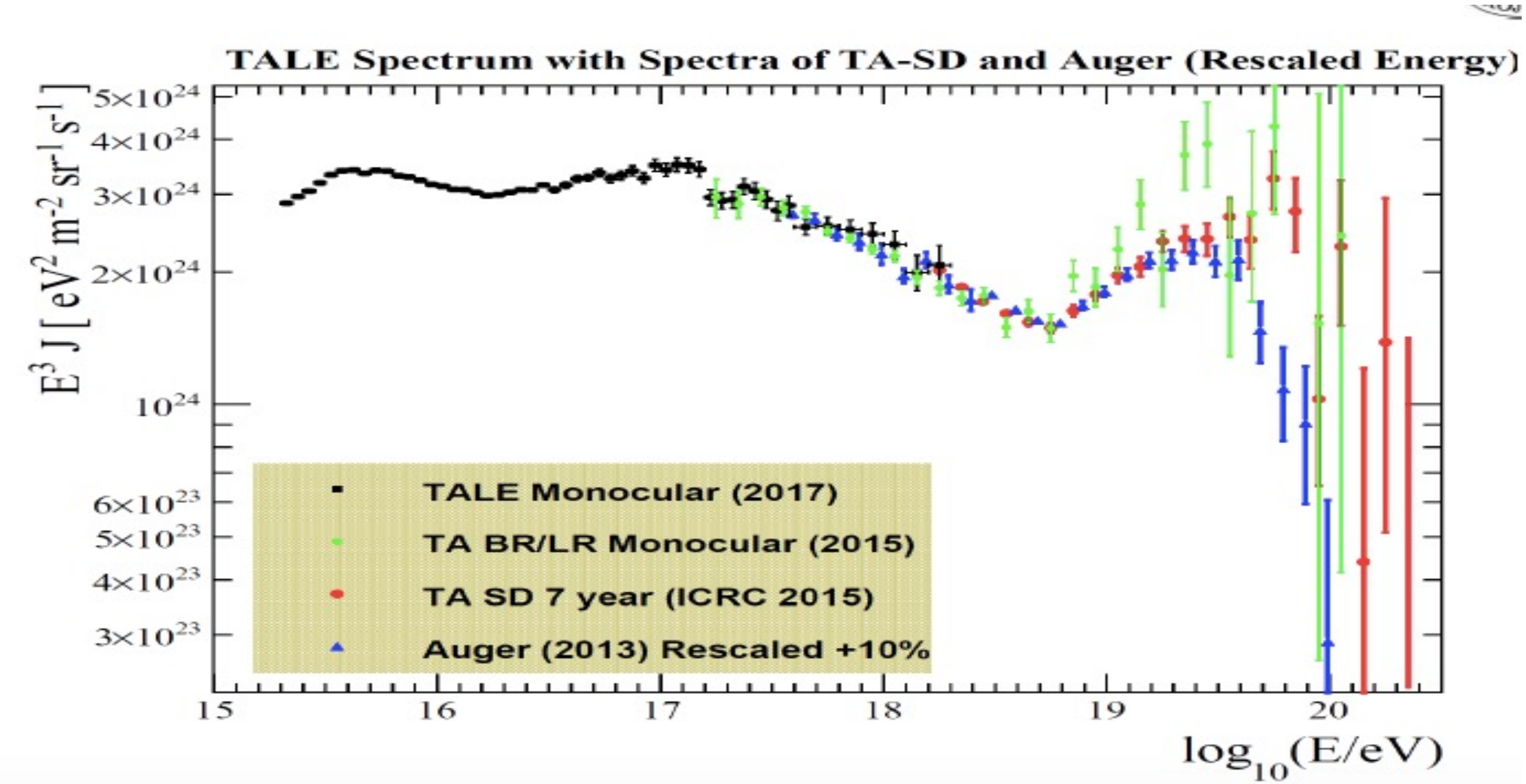
Nagano and Teshima led the development of AGASA (ICRR Tokyo)

11 obs. / 1.3~2.6 exp.



5.1×10^{16} m^2 s sr

Five Decade Spectrum showing five spectral features. Energy scale determined by AF

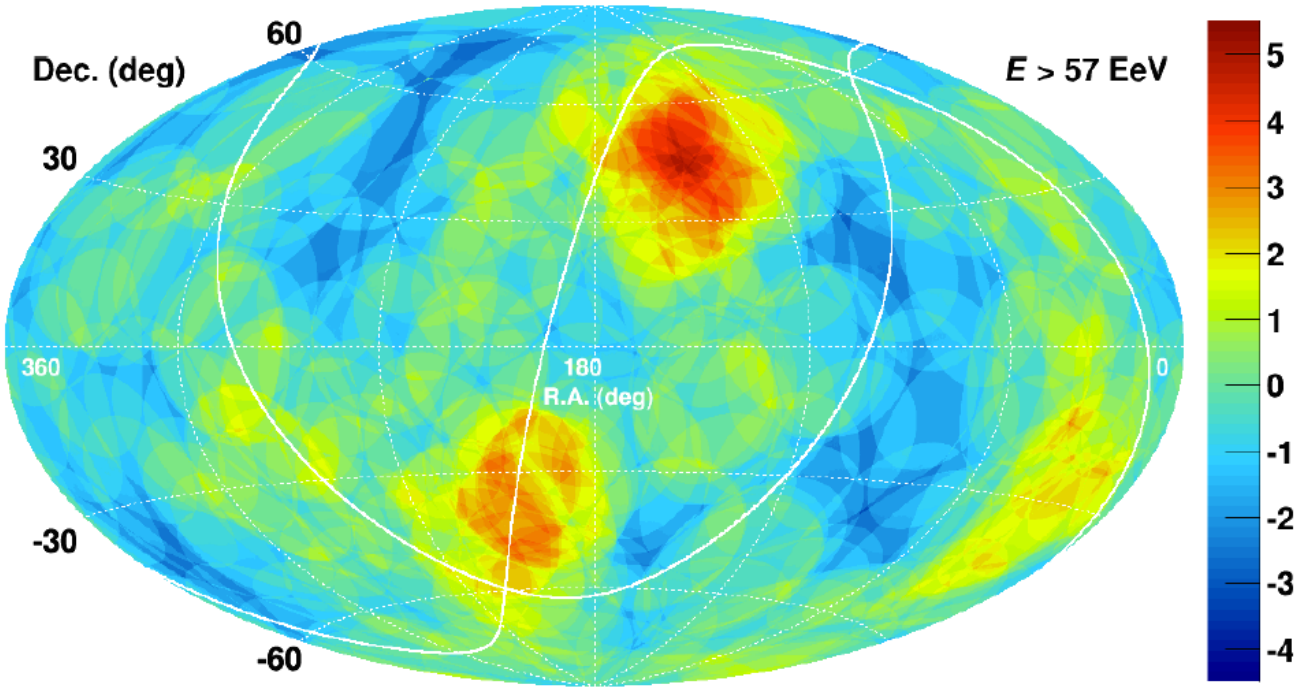


The Birth of the Auger Observatory

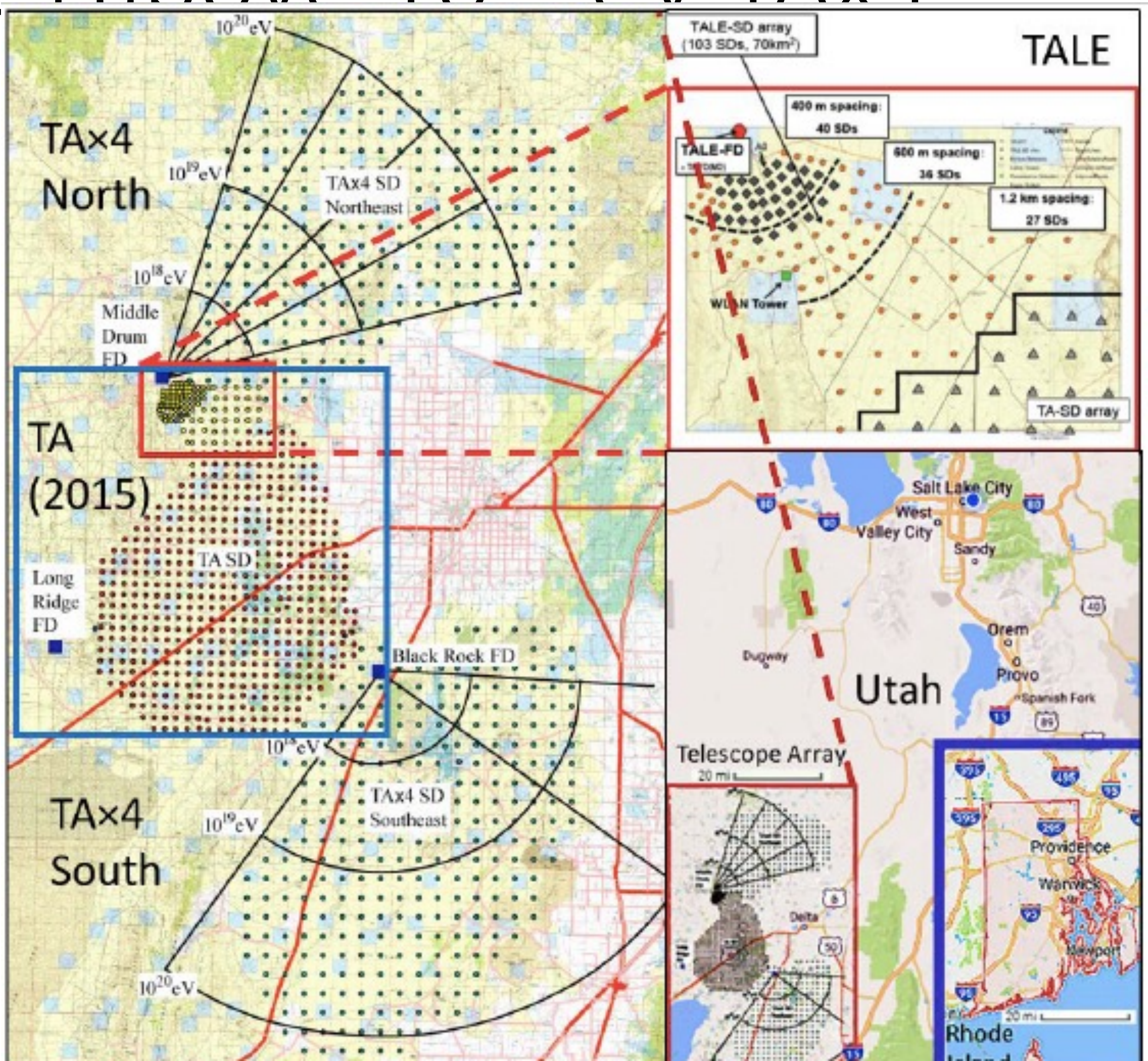
- Jim Cronin came to Utah for several years 1998-2001.
- Proposed next gen ground array ~1000 sq km scale; one in each hemisphere.
- Southern array near Malargue, Argentina
- Northern array – Utah near Delta or Colorado
- Only southern site was funded. Added air-flurescence to make a hybrid detector.
- TA became the Northern UHECR observatory.

Auger sees weak excess from Cen A (also 3.8 Mpc)

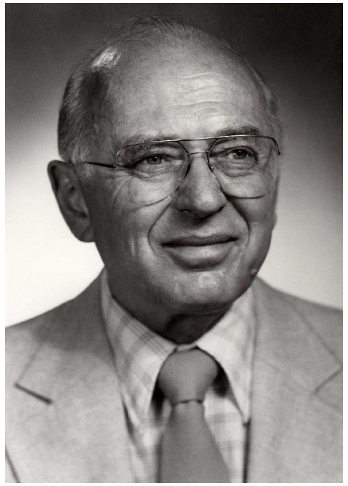
- E > 57EeV
- r = 20°



Composition and Anisotropy requires more statistics above 10^{19} eV:TAx4



TAx4 under construction:



- Predicted in 1966 by K. Greisen, G. Zatsepin, and V. Kuzmin.
- Photons of CMBR interact with cosmic ray protons of extragalactic origin.
- Photoproduction of pions; Δ resonance.
- Pion carries away 20% of proton's energy ➔ strong energy-loss mechanism for protons that travel > 50 Mpc.
- Causes a strong break in the spectrum if sources are distant.
- Should occur at about 6×10^{19} eV (10J) if

Sources ~ universally distributed

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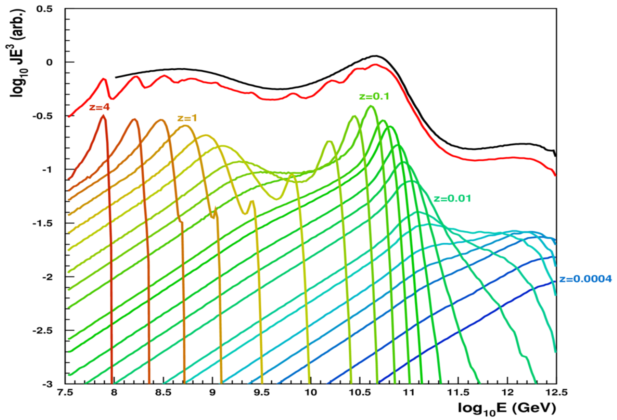
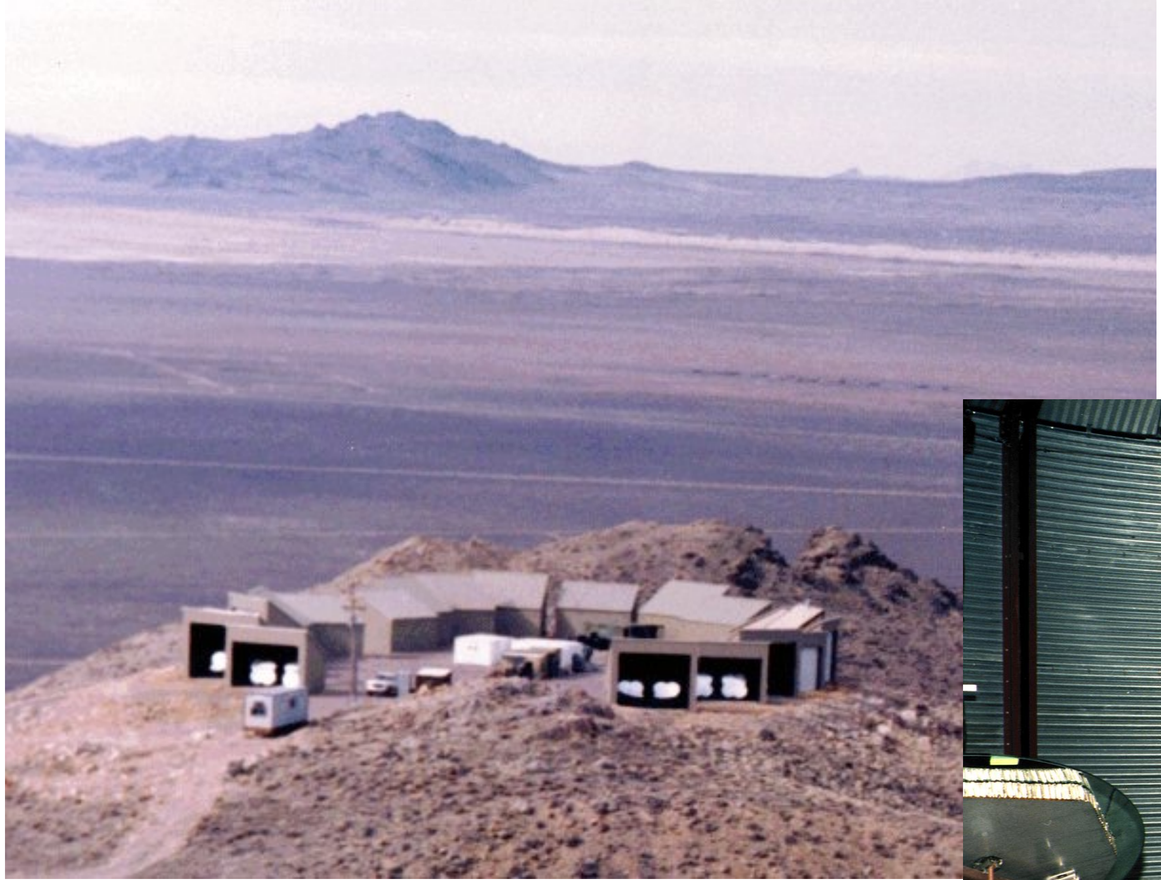
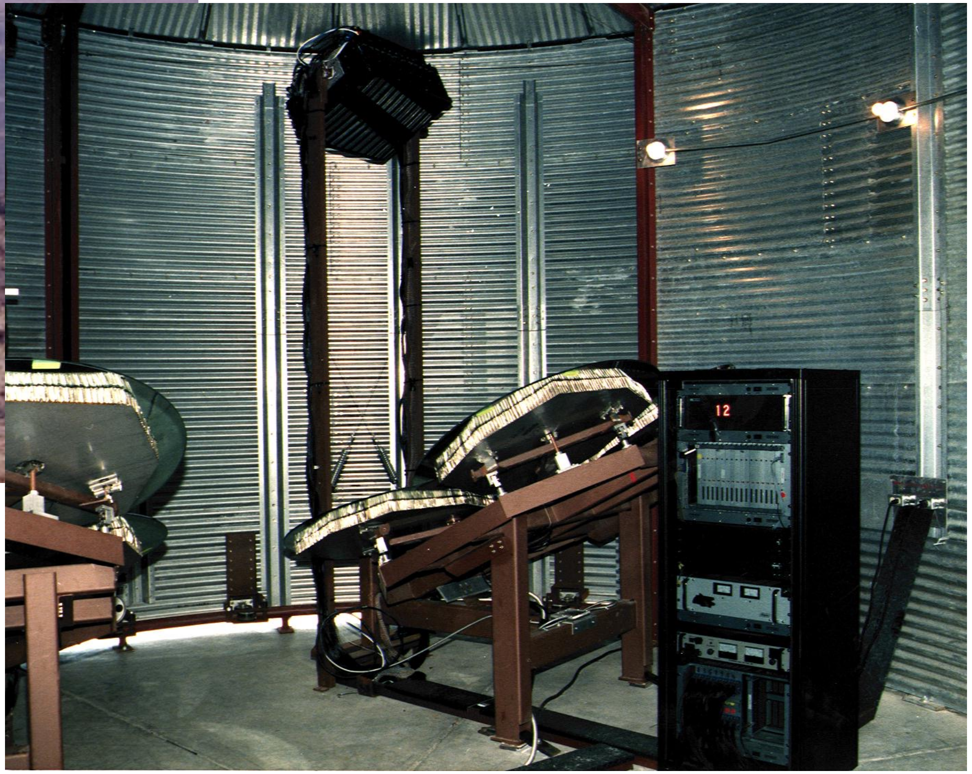
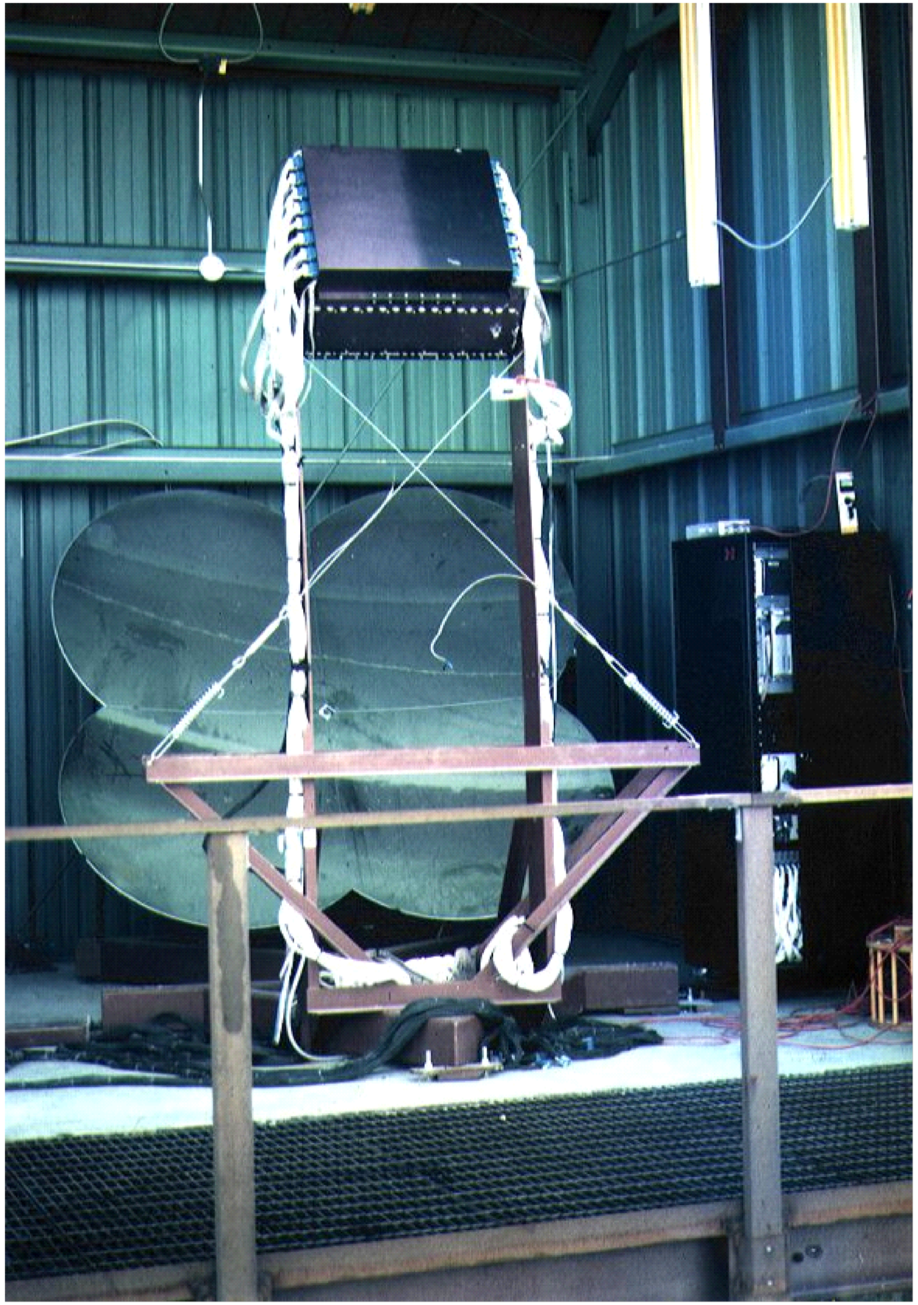




Effective collecting area ~ 1000 sq km !!



High Resolution Fly’s Eye at Dugway Proving Grounds



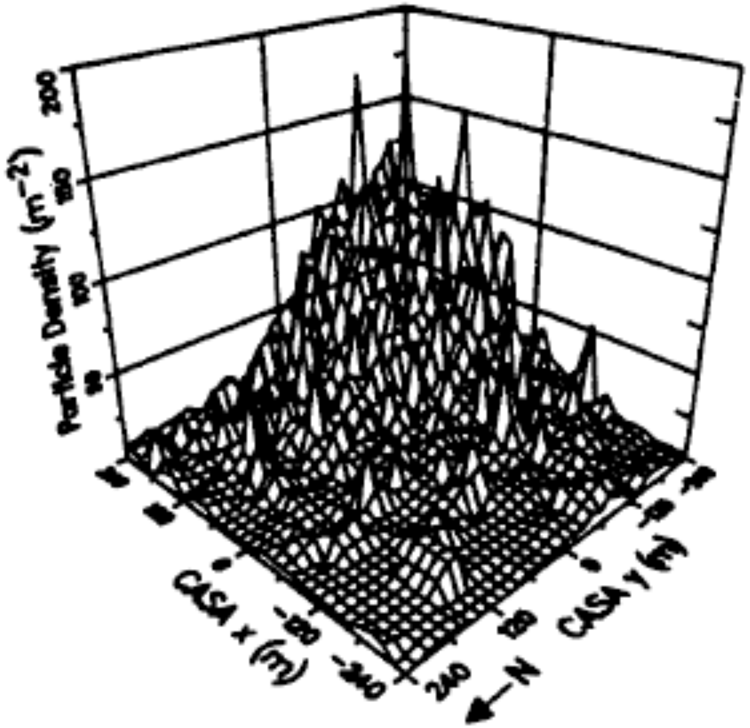
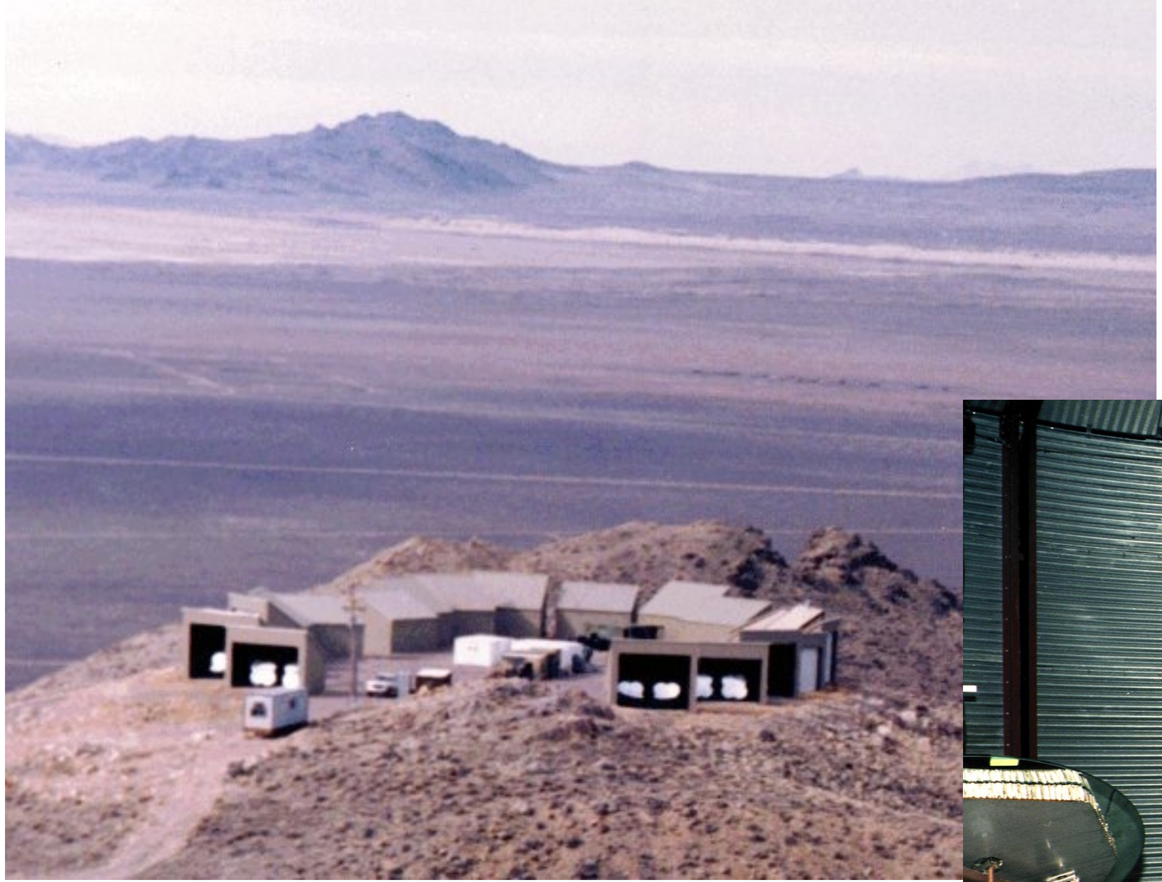
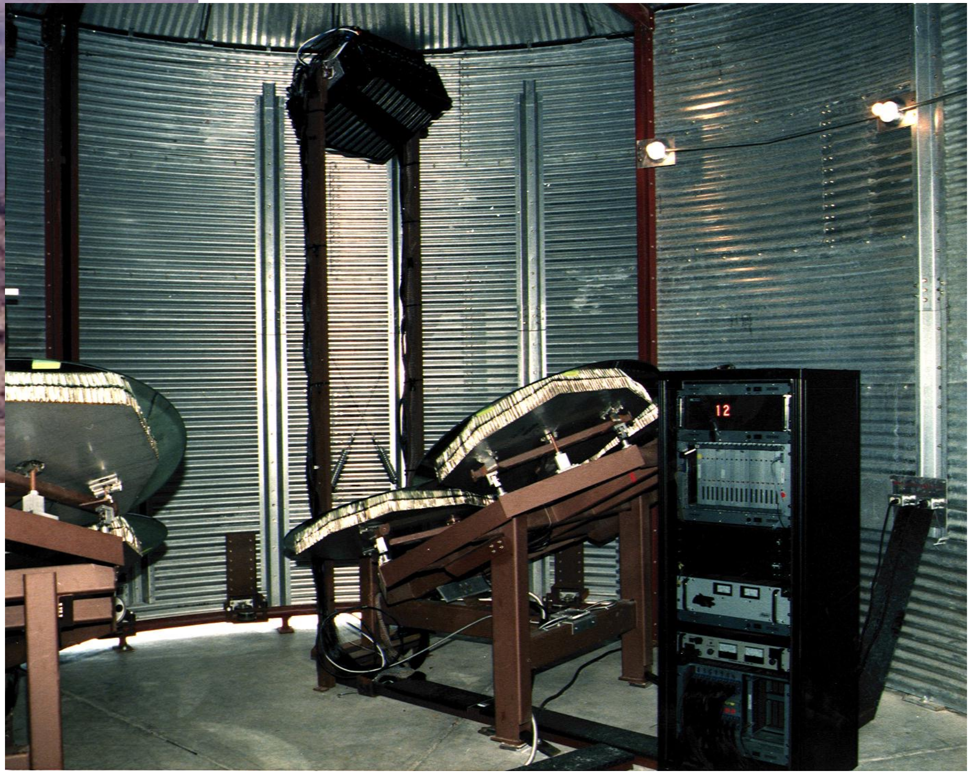


Figure 3: CASA particle density distribution for coincident event at 08:27:45.280 UT, 27 Sep 1992. The shower saturated the ADC's in the CASA Stations near the core, which fell beyond the far southeastern comer of the array.

Figure 4: HiRes prototype triggered tube pattern for the same event as in Figure 3.

Effective collecting area ~ 1000 sq km !!

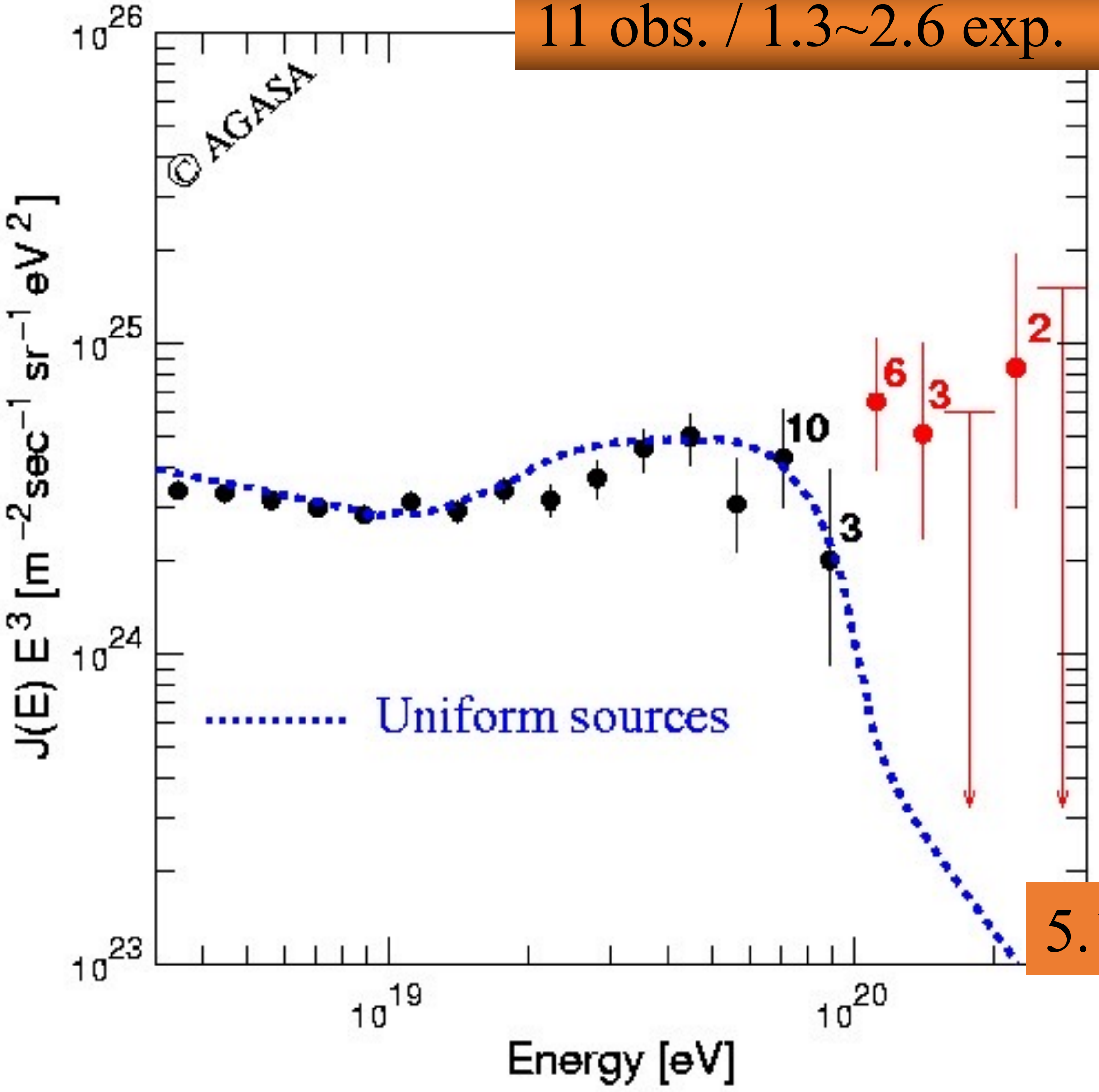




High Resolution Fly’s Eye at Dugway Proving Grounds

Energy Spectrum by AGASA (θ<45)

11 obs. / 1.3~2.6 exp.



5.1×10^{16} m^2 s sr