WALTA: School-Network Cosmic Ray Detectors

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Washington
Area
Large-scale
Time coincidence
Array

Quarknet: educational outreach program based at Fermilab

KEK, Dec 10, 2002

Overview

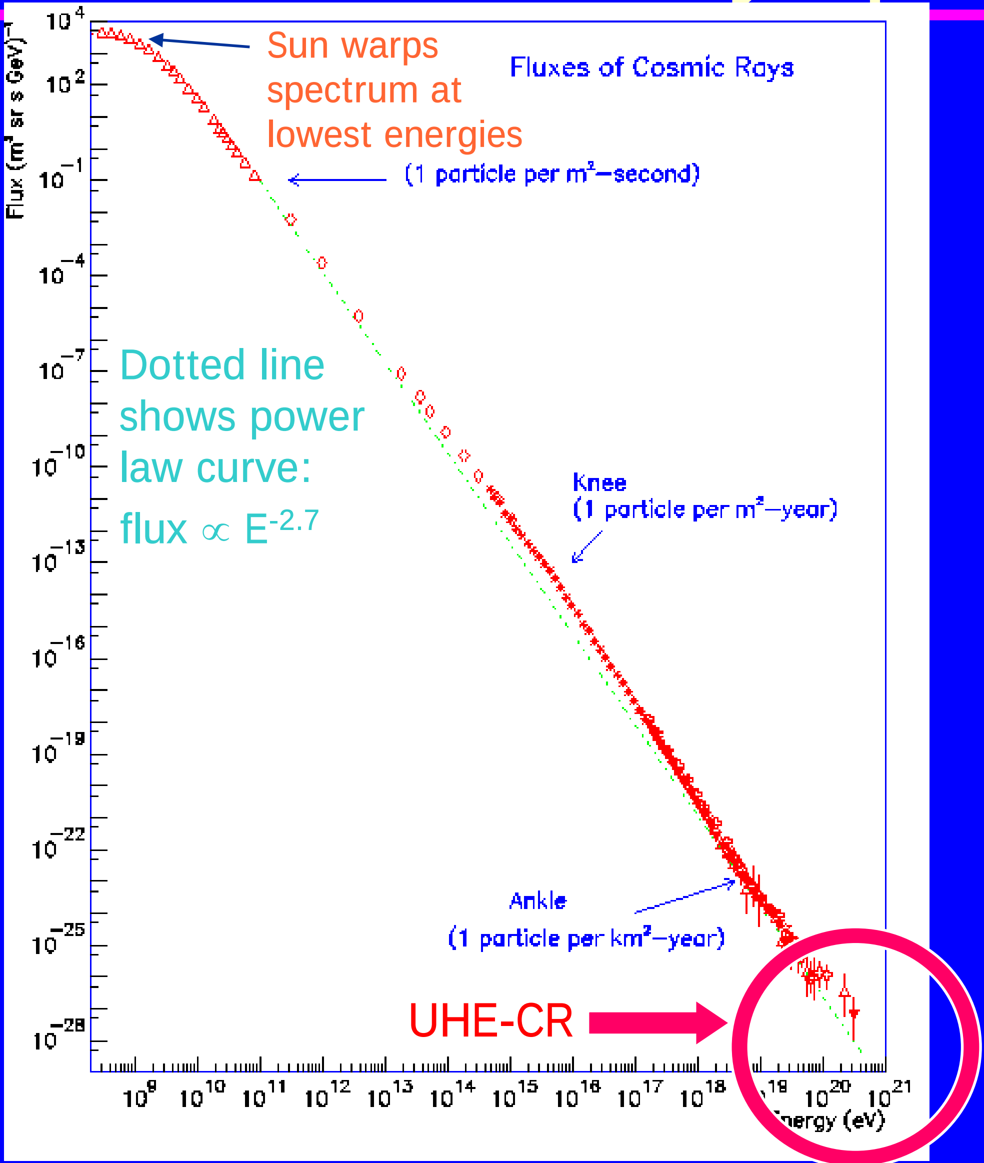
- What's WALTA?
- WALTA physics
- Detector development effort
- WALTA connections to high schools
- Other school-network projects in USA

For more information please see:
http://www.phys.washington.edu/~walta

Why put cosmic ray detectors in schools?

- Important open questions about extremely high energy (UHE) cosmic rays:
  - Where do cosmic rays with $E>10^{20}$ eV come from?
  - How can they be produced and accelerated?
  - How can they reach us through intergalactic space?
- UHE-CR research requires simple detectors, spread over a large area, with accurate time synchronization
- High cost for conventional physics experiment: new equipment, land use, data networks, and site support
  - Example: Auger Project: > US$ 10^8
- Solution: Physicists provide surplus HEP equipment, schools provide sites and Internet port

WALTA Physics: The cosmic ray spectrum

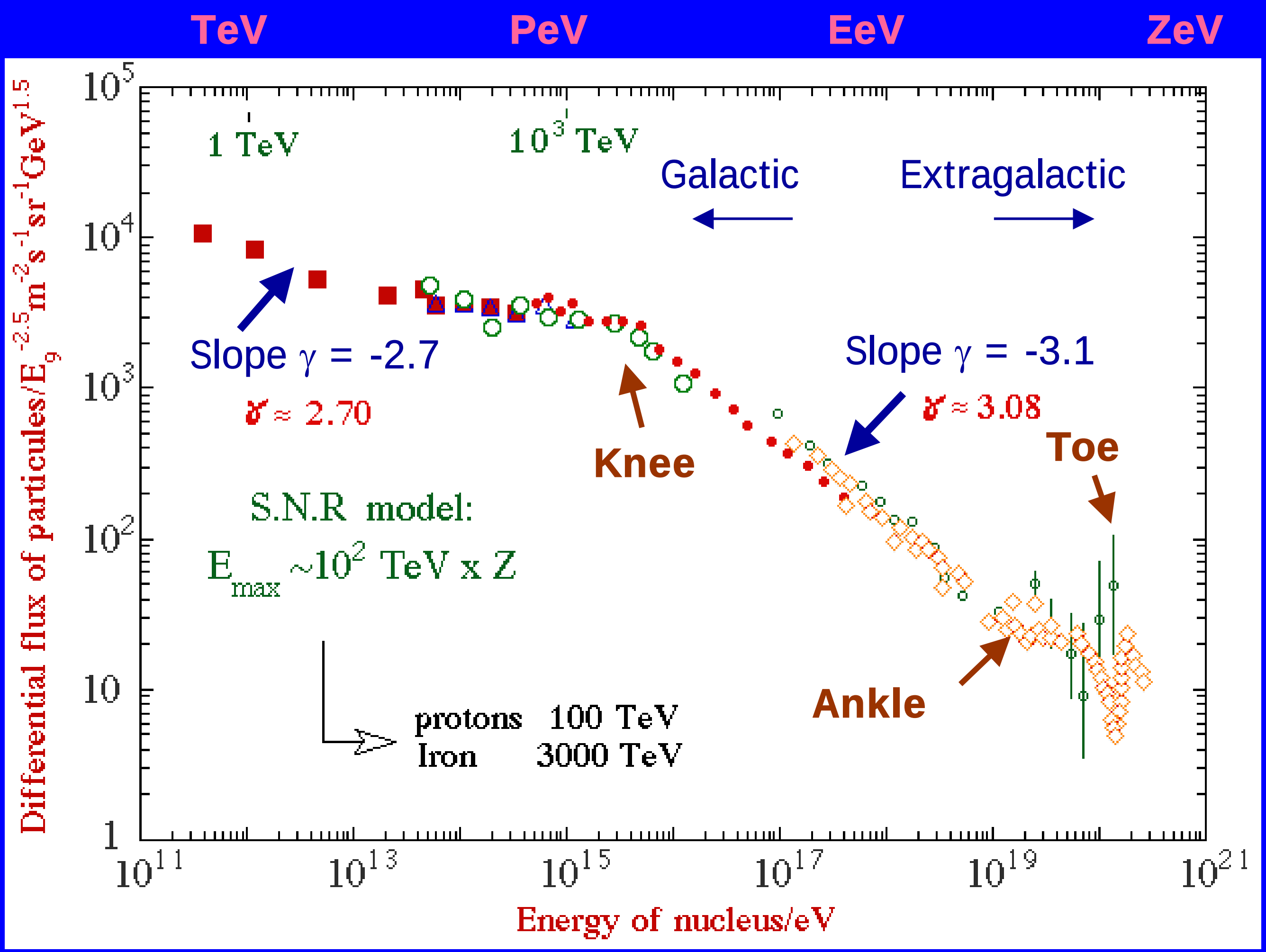


- Cosmic ray spectrum: intensity vs energy for primary cosmic rays
  - All charged particles (protons + nuclei)
  - At top of atmosphere
  - Note log-log scale
    - flux ranges over 30 orders of magnitude!
- Hard to see variations in behavior of spectrum on this type of plot…

Note: what to call them?

Some say EHE: prefer UHE

Spectrum (scaled for better viewing)



- Cosmic ray spectrum, multiplied by $E^{+2.5}$

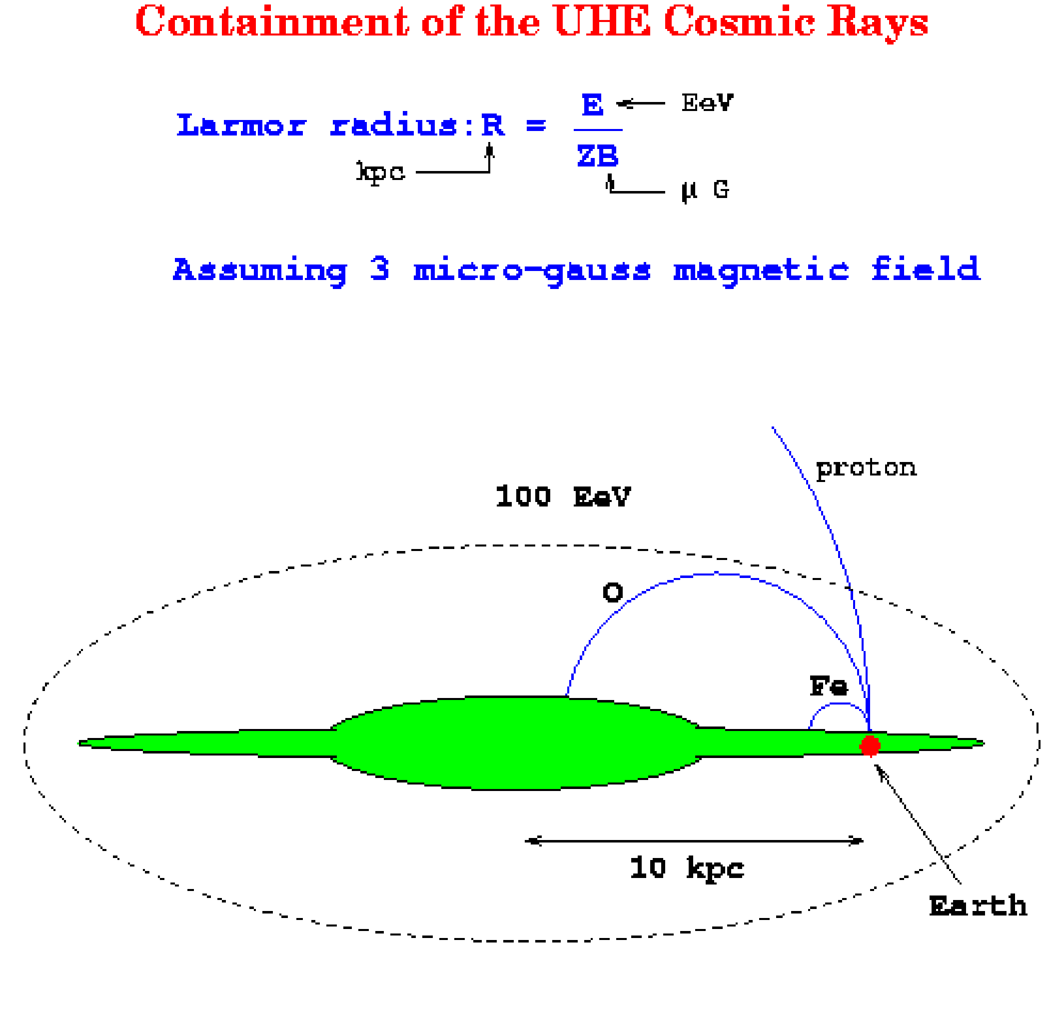
  If slope were ~$E^{-2.5}$ plot would be flat
- Changes in slope signal some change of regime…
  - knee
  - ankle
  - toe

Galactic and extra-galactic CRs

Galactic magnetic field cannot trap protons with $E > 10^{18\sim19}$ eV, so

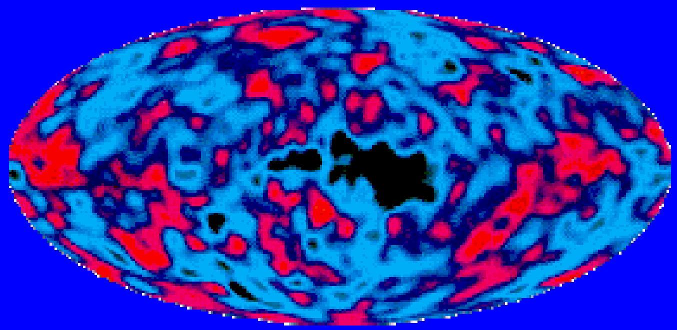
- Galactic EHE cosmic rays escape
- Observed EHE cosmic rays are mainly extragalactic

Q: Is there a significant intergalactic B?

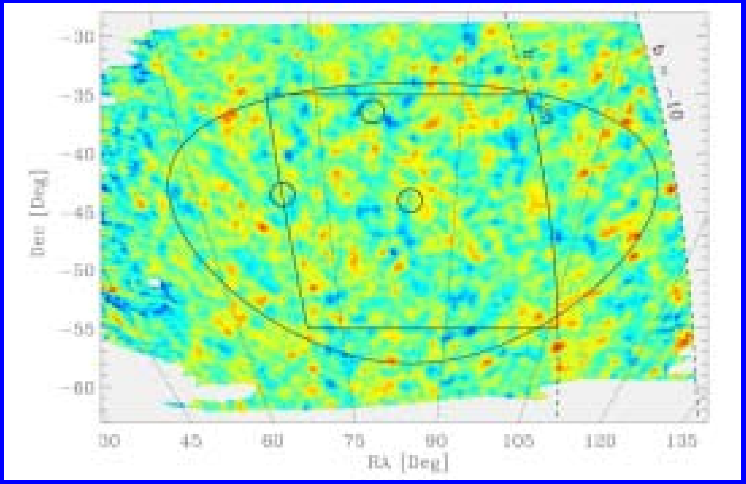


GZK cutoff mechanism

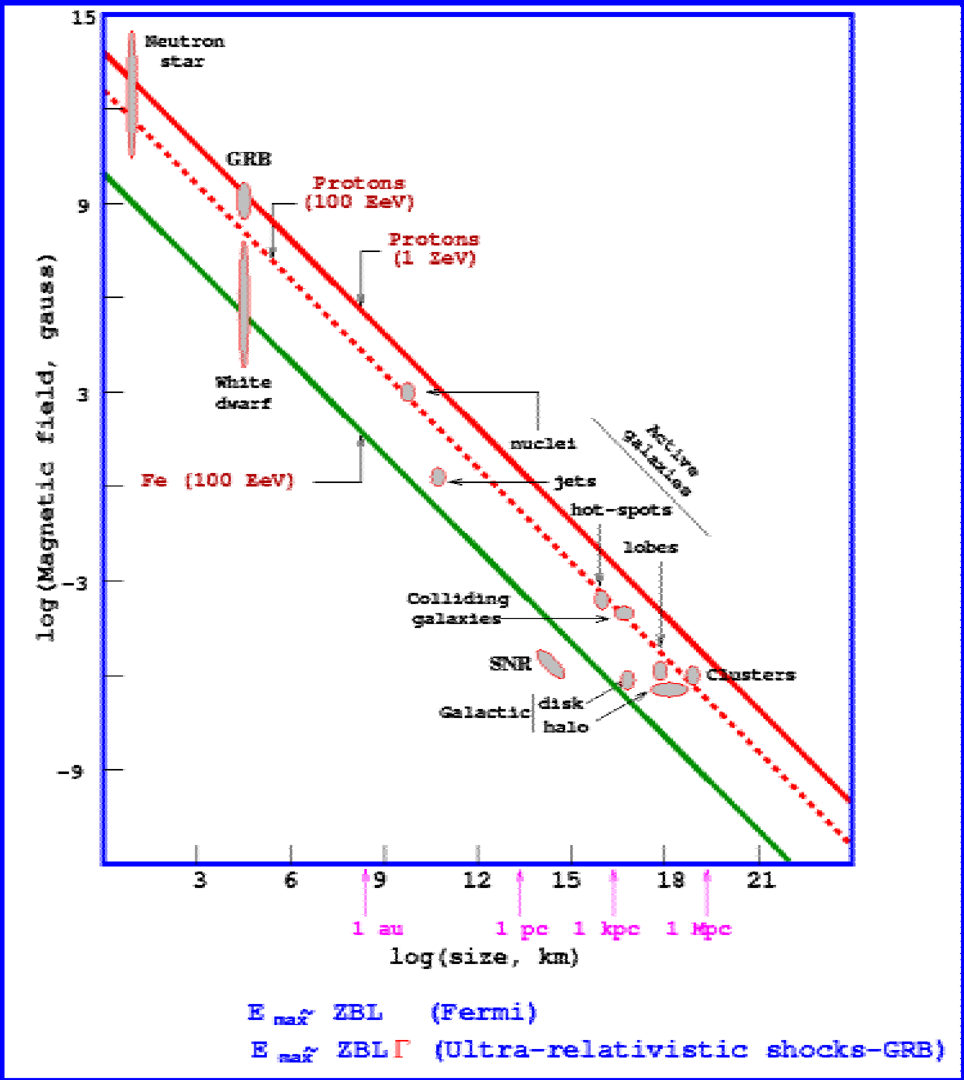
- Greisen, Zatsepin and Kuzmin (1960): expect a “cutoff” in the cosmic ray spectrum around 10^{20} eV (just at the toe):
  - CBR photons have energies in the ~0.001 eV (microwave) range
  - But in the *rest frame* of a 10^{19} eV proton, they look like high energy (>GeV) gamma rays
  - Large cross-section for photon-nucleon interaction above the pion production threshold
  - So ... >10^{19} eV protons from distant galaxies should not reach us!
- For galaxies more distant than 50~100 Mpc, CBR should block UHE cosmic rays
  - *if* they are protons or nuclei...



Maps of CBR: older, low-resolution (COBE satellite) and latest high-resolution (BOOMERANG Antarctic balloon flight)



“Hillas Plot”



- Michael Hillas (1984) made a nice plot showing acceleration limits for possible source objects
  - Need large size or high B field
  - Plot shows log <B> vs log <L> for known astrophysical objects

  Very few can produce UHE-CR!
- But UHE-CR *are* observed
  - Experiments with different techniques observed an excess above 10^{20} eV
    - AGASA (extensive air shower array in Japan)
    - Fly’s Eye (atmospheric fluorescence detector in USA)
      - (but now not so sure…)

So what can produce UHE-CR?

- Hillas plot says: only huge objects with intense B fields
- GZK: sources of UHE CR must be within ~50 Mpc of our Galaxy
- Only *O* (10) possible sources (AGNs, etc) are that close to us...
- Since we know so little, we may speculate!
  - New physics: perhaps fundamental laws of physics are different at extremely high energies, or exotic new particles exist
  - New astrophysics: perhaps there are objects capable of producing UHE-CR in distant galaxies
  - Clever tricks: no new physics (OK, not very much), just some way around GZK
    - » Example: UHE *neutrinos* from long ago and far away create the UHE cosmic rays *near* our galaxy
  - Or any combination of the above…

Scenarios to make UHE-CRs (I)

- I. Bottom-up models

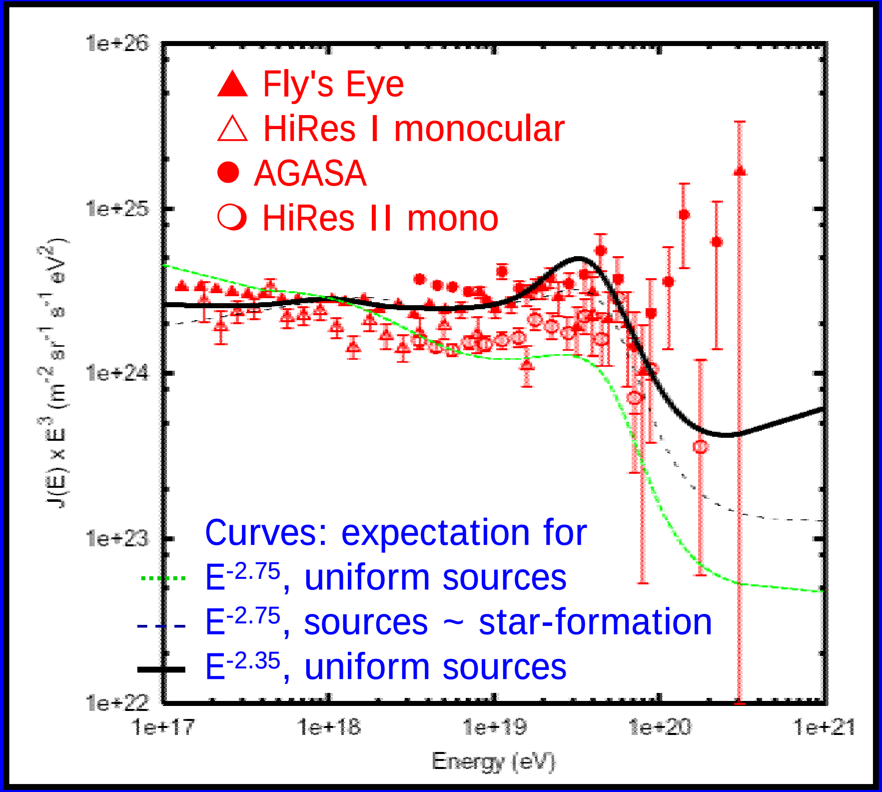
How to accelerate ordinary hadrons to ZeV energies?

"Zevatron" candidates:

- Diffusive shock acceleration
  - » Hillas plot makes it unlikely
- Gamma ray bursters (i.e., unknown mechanism!)
  - » viable if GRBs are uniformly distributed in Universe
  - » more likely: GRBs are associated with star-forming regions (higher redshifts) $\rightarrow$ does not fit observations
- UHE CRs = heavy nuclei ($\rightarrow$ higher GZK threshold)
  - » evidence supports mixed proton/nuclei CR composition, same as at lower energies

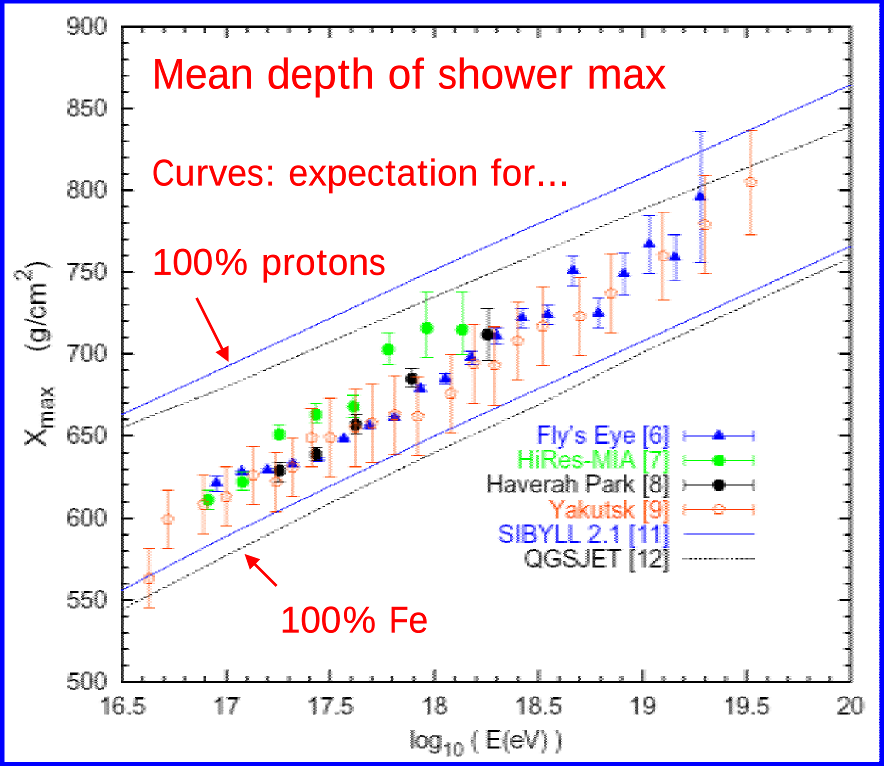
Collected Data on UHE-CRs

- Combined Spectrum (xE^3)



Note "pileup" effect expected for harder spectrum

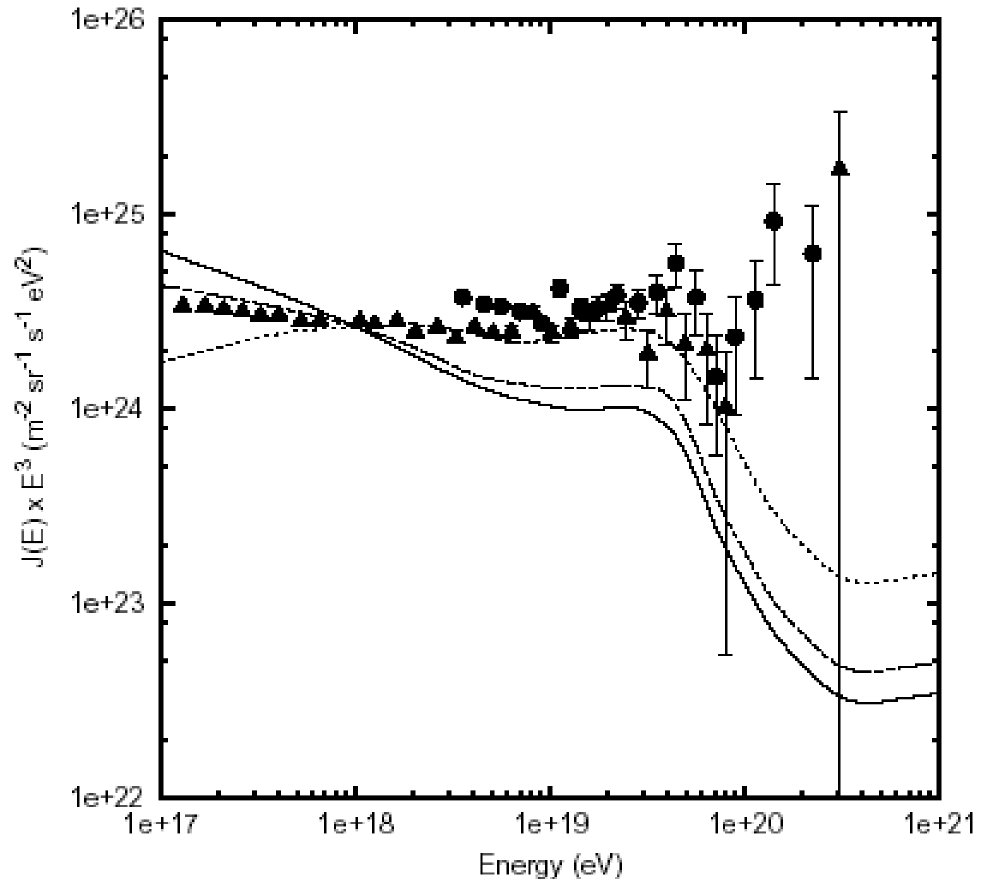
- Are they protons, or nuclei?



Composition seems mixed…

GRB sources?

- Predicted UHE fluxes from GRBs
  - solid line: strong z dependence: $(1+z)^{3.6}$
  - dashed: GRB ~ z distribution of star-forming regions
  - dotted: uniform GRB distribution, no z dependence
- Note the GZK effect is present for all…



UHECR fluxes from GRB [Scully and Stecker 2000].

Scenarios to make UHE-CRs (II)

◆ II. Top-down models

Bypass Hillas plot: assume UHE-CRs are born energetic

- UHE-CRs = decay products of objects predicted by GUTs, SUSY or String Theory
  - » Great advantage: untestable!!
    - ◆ Fun for theorists: >500 papers cited in recent review
- Examples:
  - » Topological defects
  - » Z-bursts from UHE neutrinos
    - ◆ can come from very far away - interact with 1.9K CBR neutrinos to make UHE-CR nearby: $\nu + \nu \rightarrow Z^0 \rightarrow$ jets$\rightarrow$ hadrons
  - » Wimpzillas (Waimupu-jira?)
    - ◆ non-thermal production of super-heavy wimps at end of inflationary period: survive and decay to make UHE-CR
      - – if so, UHE-CR should come from our Galaxy's halo

Scenarios to make UHE-CRs (III)

- III. New Physics

Ignore Hillas plot by assuming the rules change at UHE

– Examples:

» Increase in ν-N cross section to mb level at UHE

- Must be clever: most models ruled out by accelerator data
- Extra-dimensions models may still be viable

» New very heavy particles ($\rightarrow$ higher GZK cutoff energy)

- Unlikely given existing accelerator data

» Violation of Lorentz Invariance

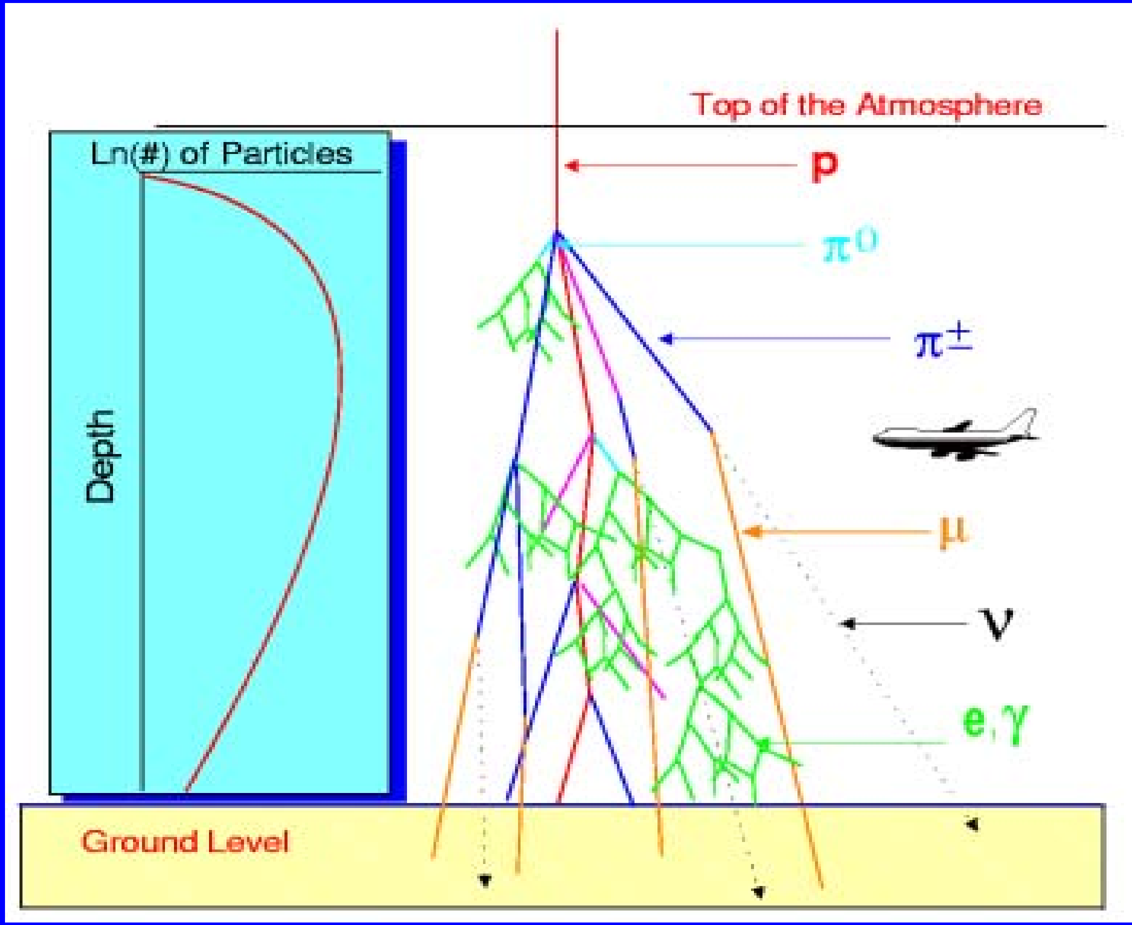
- may come as part of a theory of quantum gravity
- only a tiny violation is required (Glashow, 1999)
  - $O(10^{-23})$ change in difference between speed of photon and electron would push GZK out of range

Detecting UHE-CR: Extensive Air Showers (EAS)

cosmic ray proton
(or nucleus)

Total number of particles vs depth in atmosphere

(We can only detect and count charged particles)

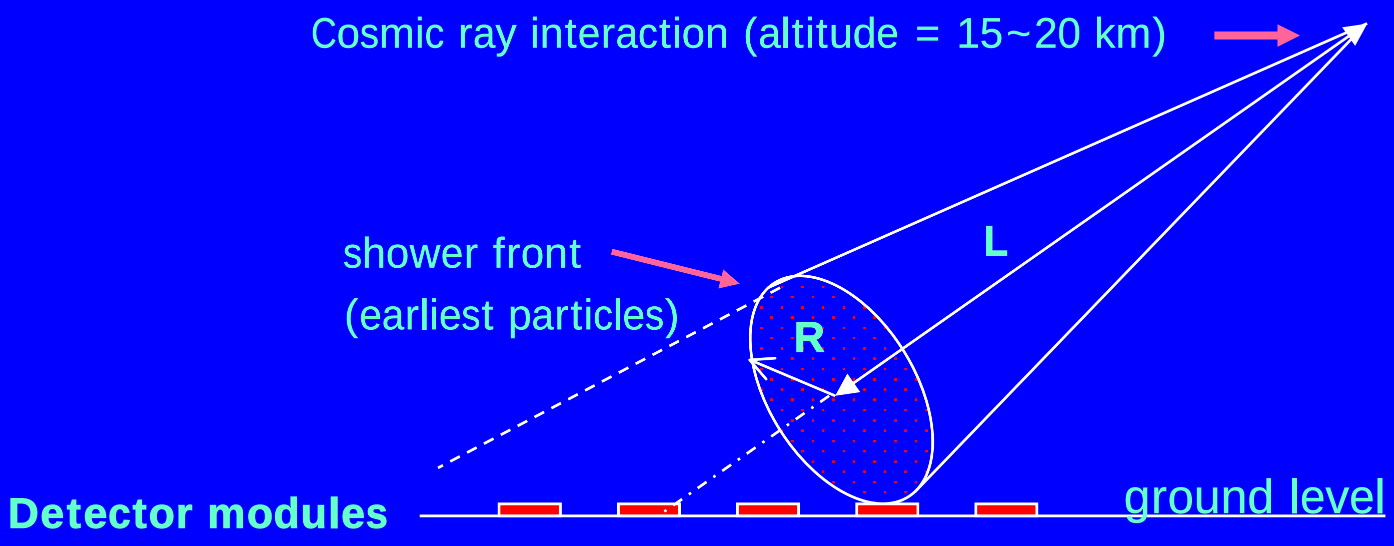


Secondary particles

Decay products

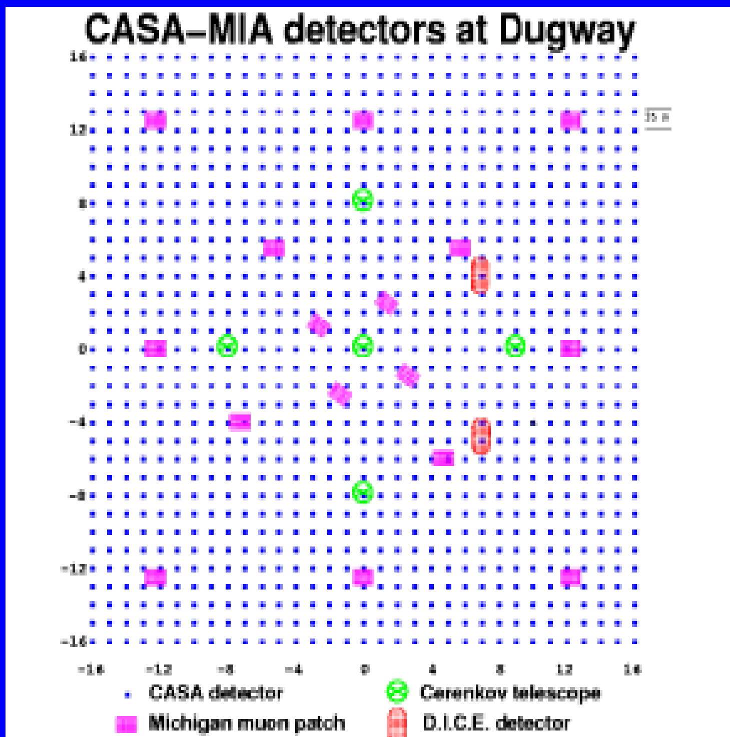
Electron-photon cascades

EAS : ground-based detector observations



- Each detector module reports:
  - Time of hit (better than μsec accuracy)
  - Number of particles hitting detector module
- Time sequence of hit detectors → shower direction
- Total number of particles → shower energy
- Distribution of particles → distance L

Example: CASA Experiment (1989-96)



0.5 km

Chicago Air Shower Array, Michigan Muon Array, and Fly's Eye detectors at Dugway, Utah

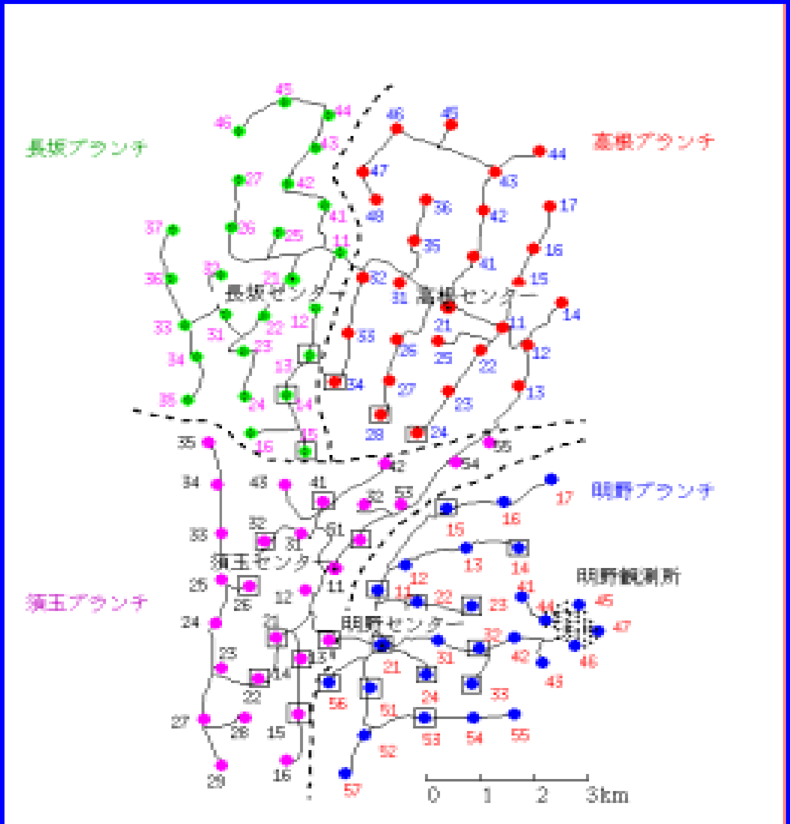
1024 CASA modules, 16 MIA modules

Source of parts for WALTA!

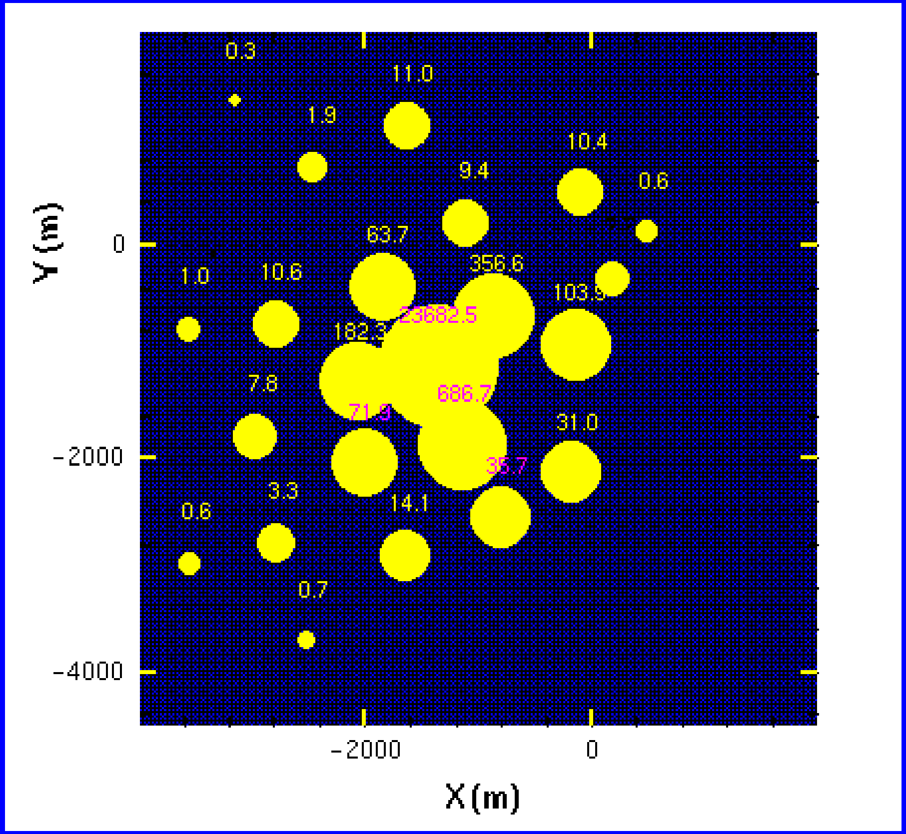
Aerial view of Dugway site

The Akeno Giant Air Shower Array (AGASA) in Japan

- >100 detector sites using scintillation counters
- Approx. 1 km spacing between sites
- Covers about 100 square km



The Akeno Giant Air Shower Array (AGASA) in Japan

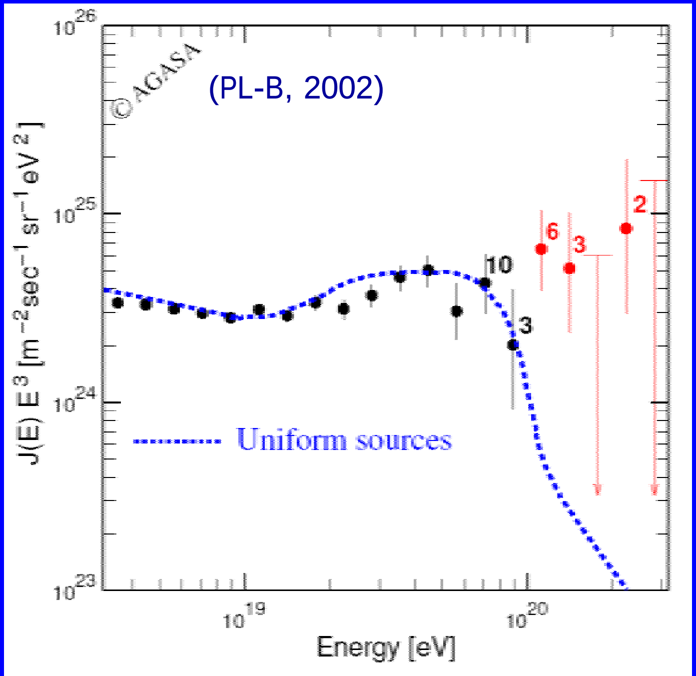


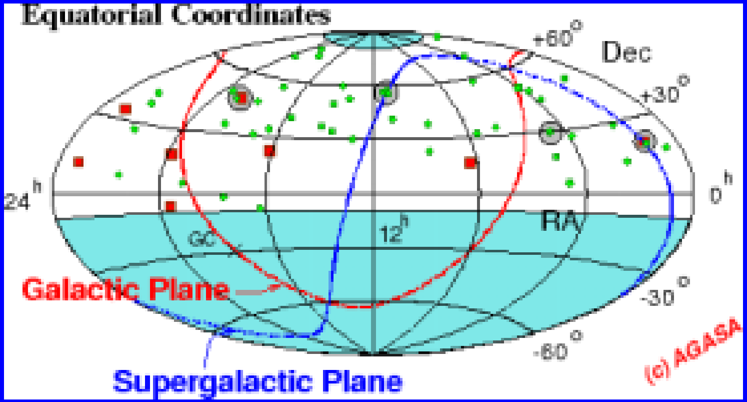
Primary
energy
2×10^{20} eV

- One of the world's highest energy cosmic ray events
- Recorded December 3, 1993
- Particles covered 4 km × 4 km area
- 23 detector modules recorded coincident hits
- Plot indicates particle density at each location
  - Radius of yellow disk = logarithm of number of particles recorded

AGASA highest-energy events

- Energy Spectrum:
  - significantly above expectation even for realistic source distribution (previous plot)

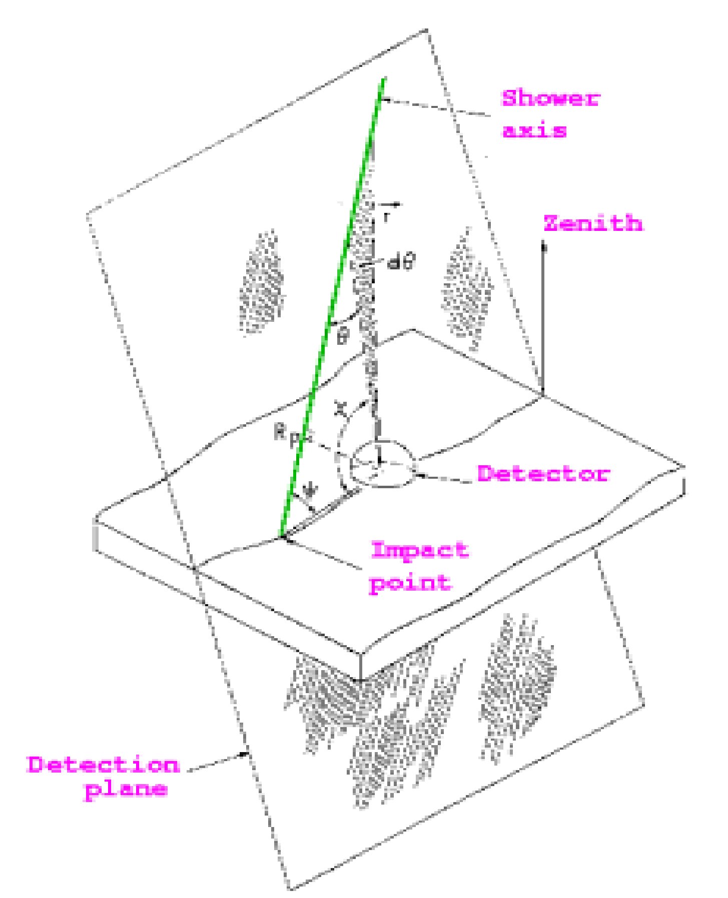




- Sky map of UHE events:
  - no apparent correlations with candidate source regions

Air-fluorescence detectors in Utah

Fly's Eye II
Dugway, Utah

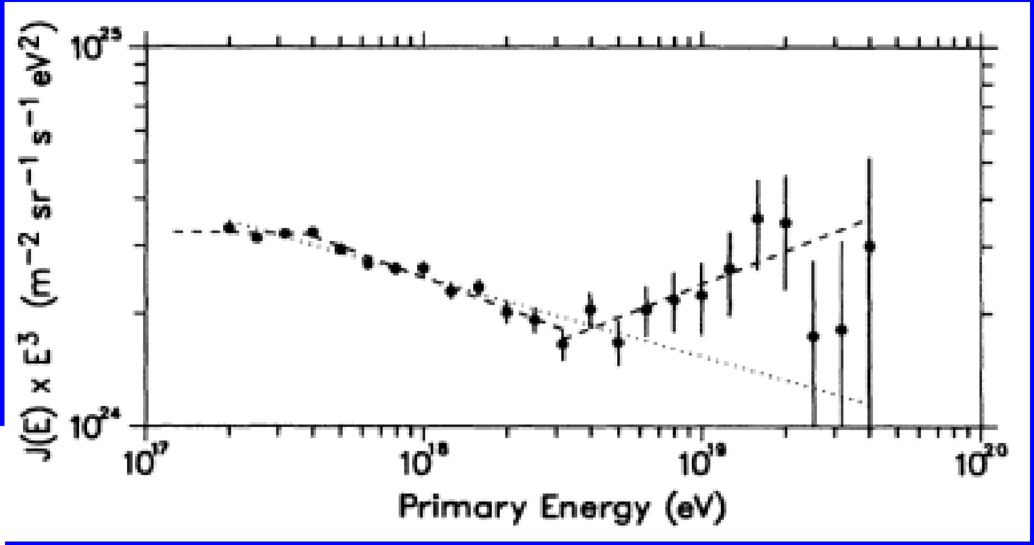


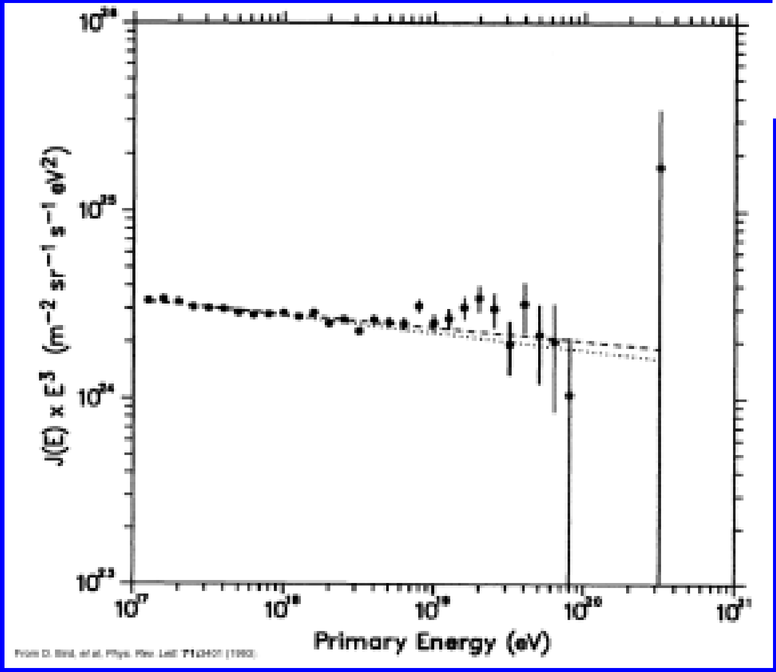
Detection of an EAS with a "Fly's Eye"

Utah spectra (1993 PRL article)

- Stereo data (events seen by both FE-I and II)
  - – distinct rise above $10^{18.5}$ eV

  ...but no data above 10^{20} eV





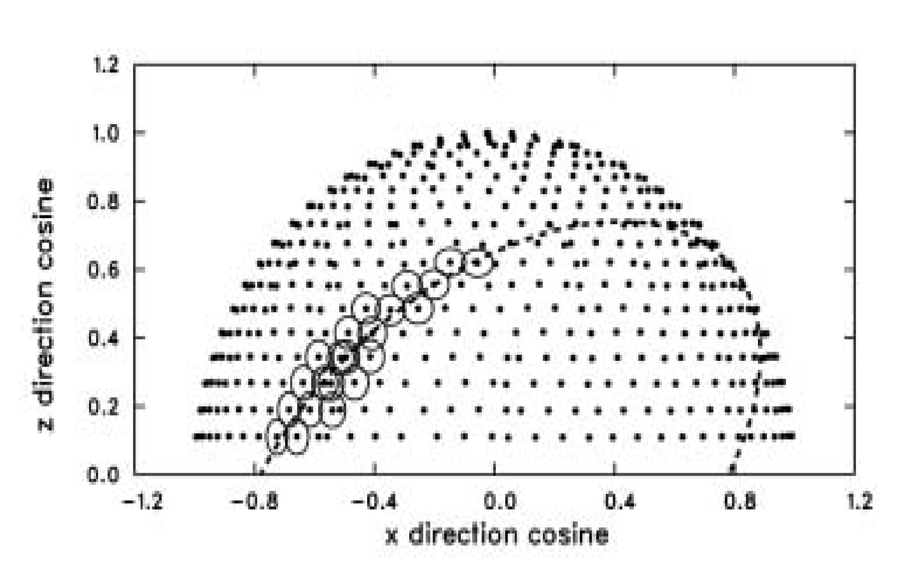
- Monocular events (observed in only 1 of the 2 detectors)
  - – ambiguous about rise

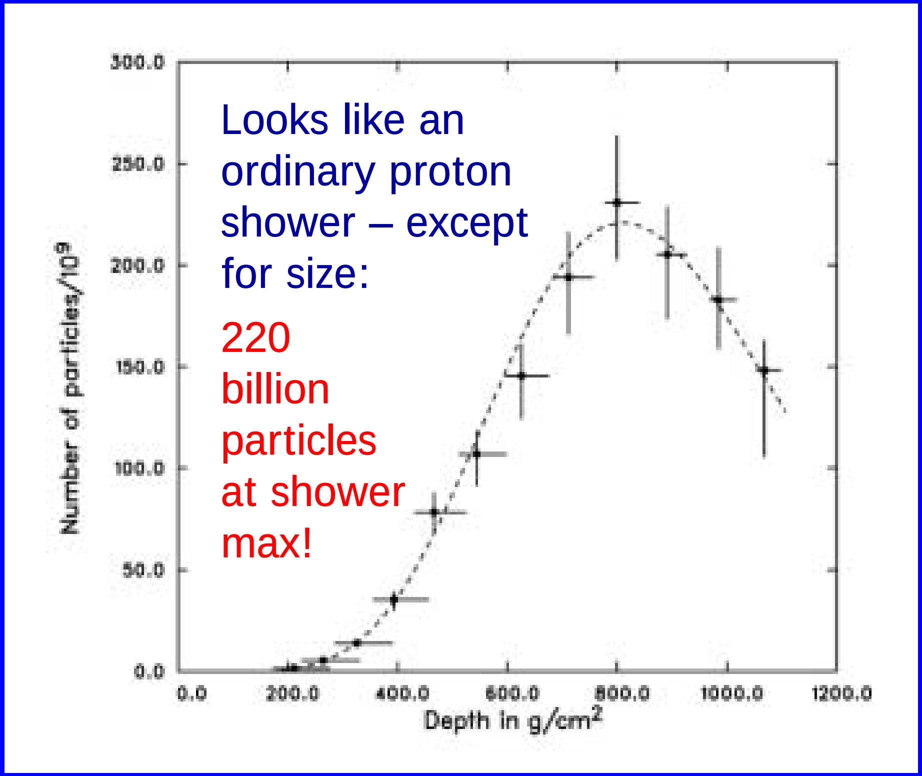
  ... but includes the highest-energy event at 320 EeV

Fly’s Eye 1991 event – highest-E cosmic ray

3.2×10^{20} eV (but now not so certain…)

- Event display, showing detectors illuminated:





Looks like an ordinary proton shower – except for size:

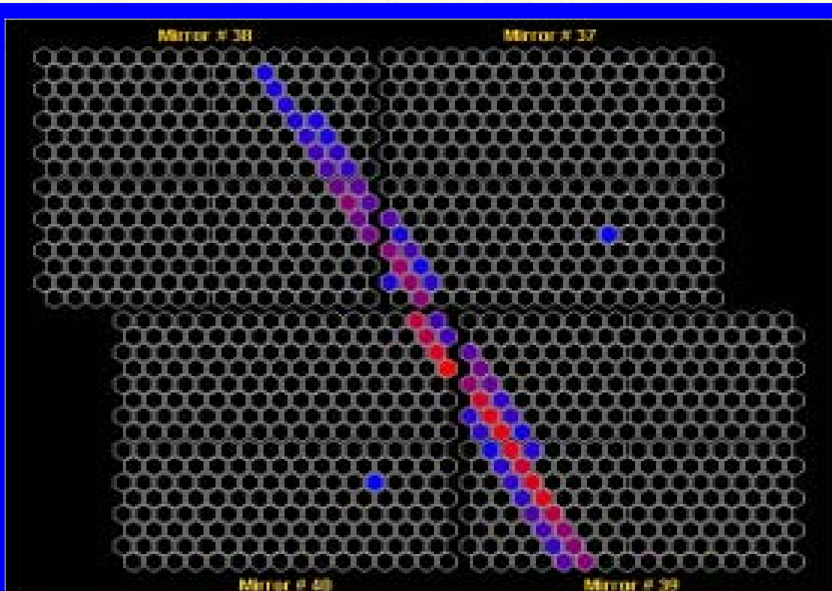
220 billion particles at shower max!

- Plot of number of particles in shower vs depth in atmosphere

HiRes detector: Son of Fly's Eye

- Higher resolution
- Advanced electronics
- Direct laser calibration of PMTs and air scattering properties

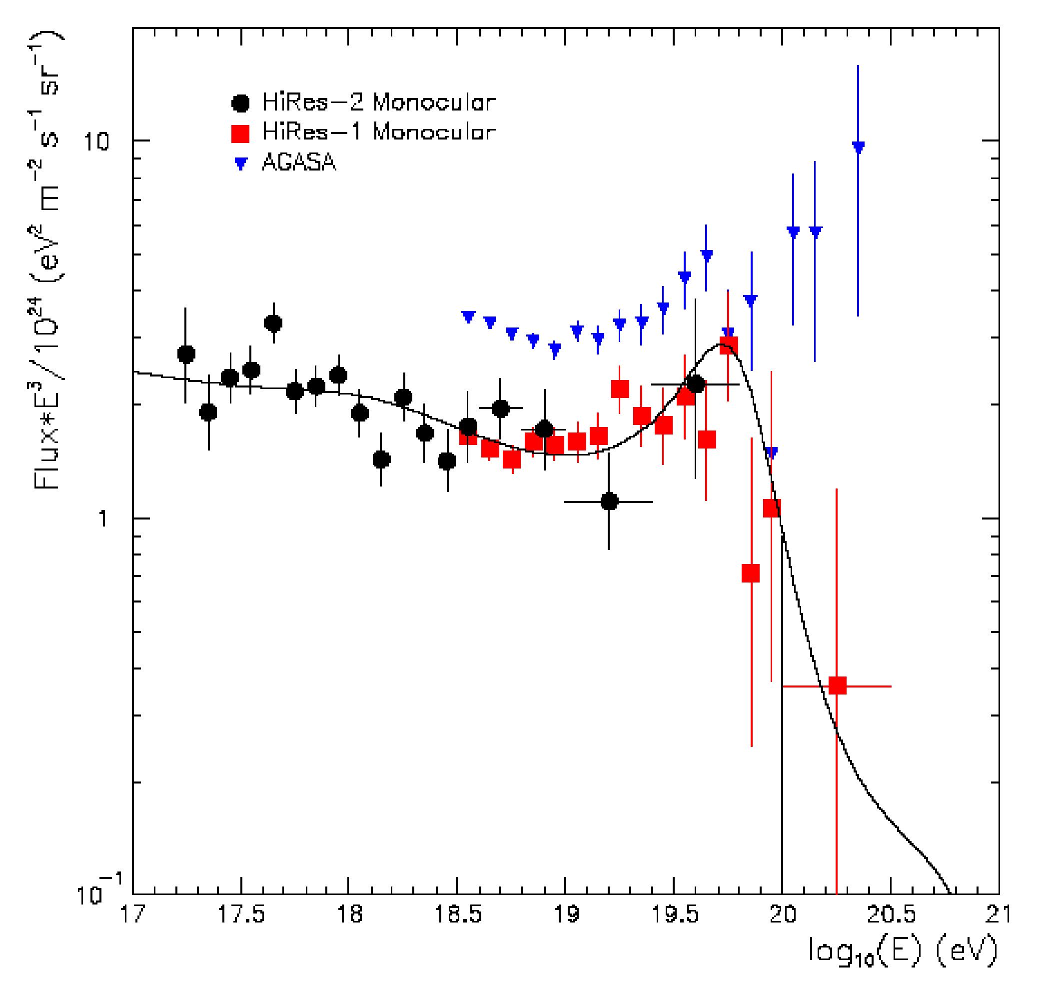
HiRes detector module: mirrors and PMT array



HiRes event display,
showing cosmic ray shower's scintillation trail detected by several HiRes modules

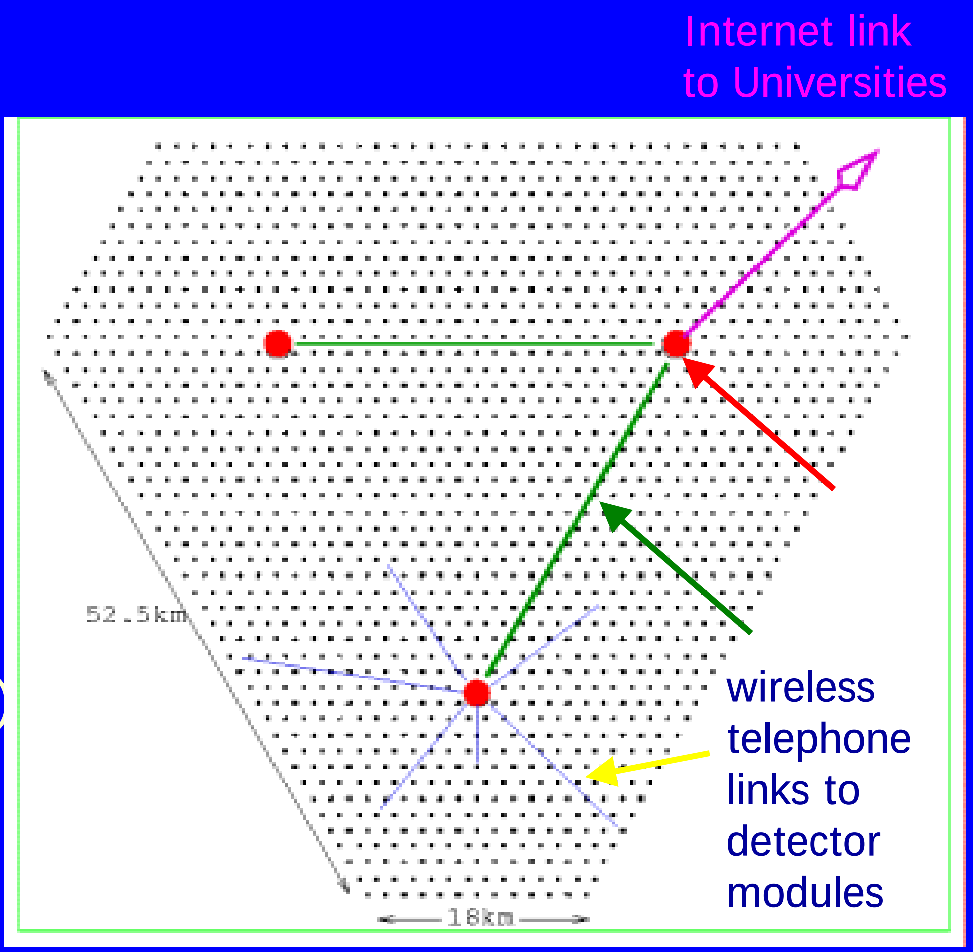
Utah spectra - re-visited

- HiRes I (1997-2001) and II (1999-2000)
  - Published data are only for "monocular" events (observed in only 1 of the 2 detectors)
- GZK cutoff seen!
  - no excess events



Next-generation EAS detector: The Auger Project

- International collaboration proposes to build huge arrays at 2 sites (Utah and Argentina), each:
- 1600 detector modules with 1.5 km separation
- 3000 km^2 area - size of King County
- Cost: $100 million (1996 estimate)
- Will (hopefully) determine whether trans-GZK events exist

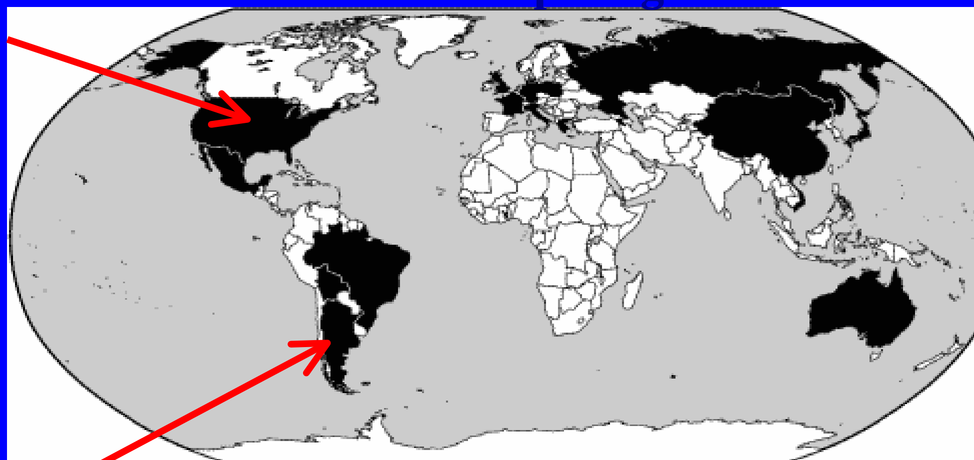


Pierre Auger Observatory

Detector Sites:

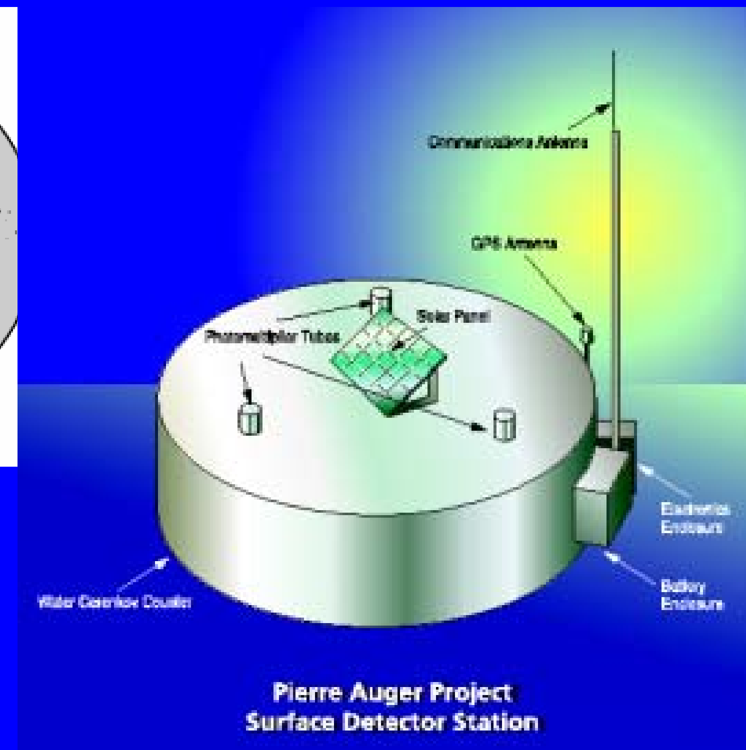
Participating countries:

Utah



Argentina

Water Cherenkov detector for Auger



School-network approach

- Pioneered by U. of Alberta in Canada (ALTA) and U. of Nebraska in USA (CROP)
- University joins secondary schools to build a very large detector array at low cost, using existing resources in the community, and surplus equipment
- Use schools' existing Internet access to link the sites
- Students and teachers participate in forefront research
  - More than a one-time field trip or term paper
  - *Doing*, not watching
  - Research is ongoing, in the school *every day*
  - Students help monitor detectors and analyze data
  - *Long-term relationship* between school and University

Potential WALTA sites in Seattle

Shows all public and private middle schools, high schools, and colleges in Seattle.

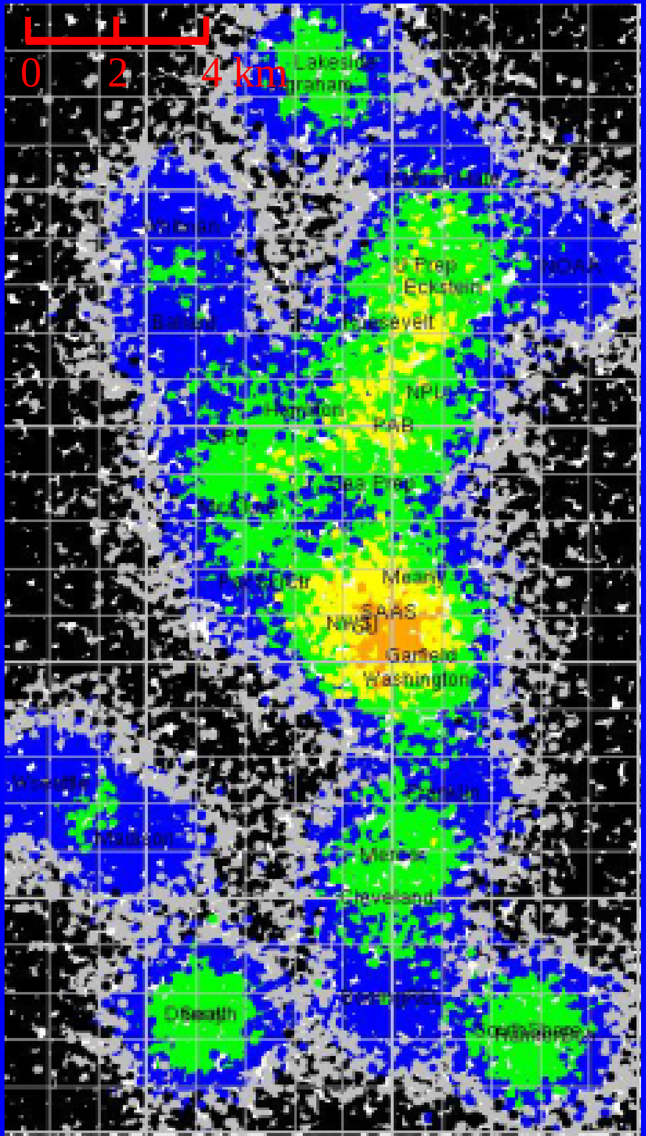
Mean spacing is 1.5~2 km: ideal!

Triggering efficiency

Simulation study by E. Zager:

Used FLUKA for interaction model, GEANT for atmospheric and detector effects.

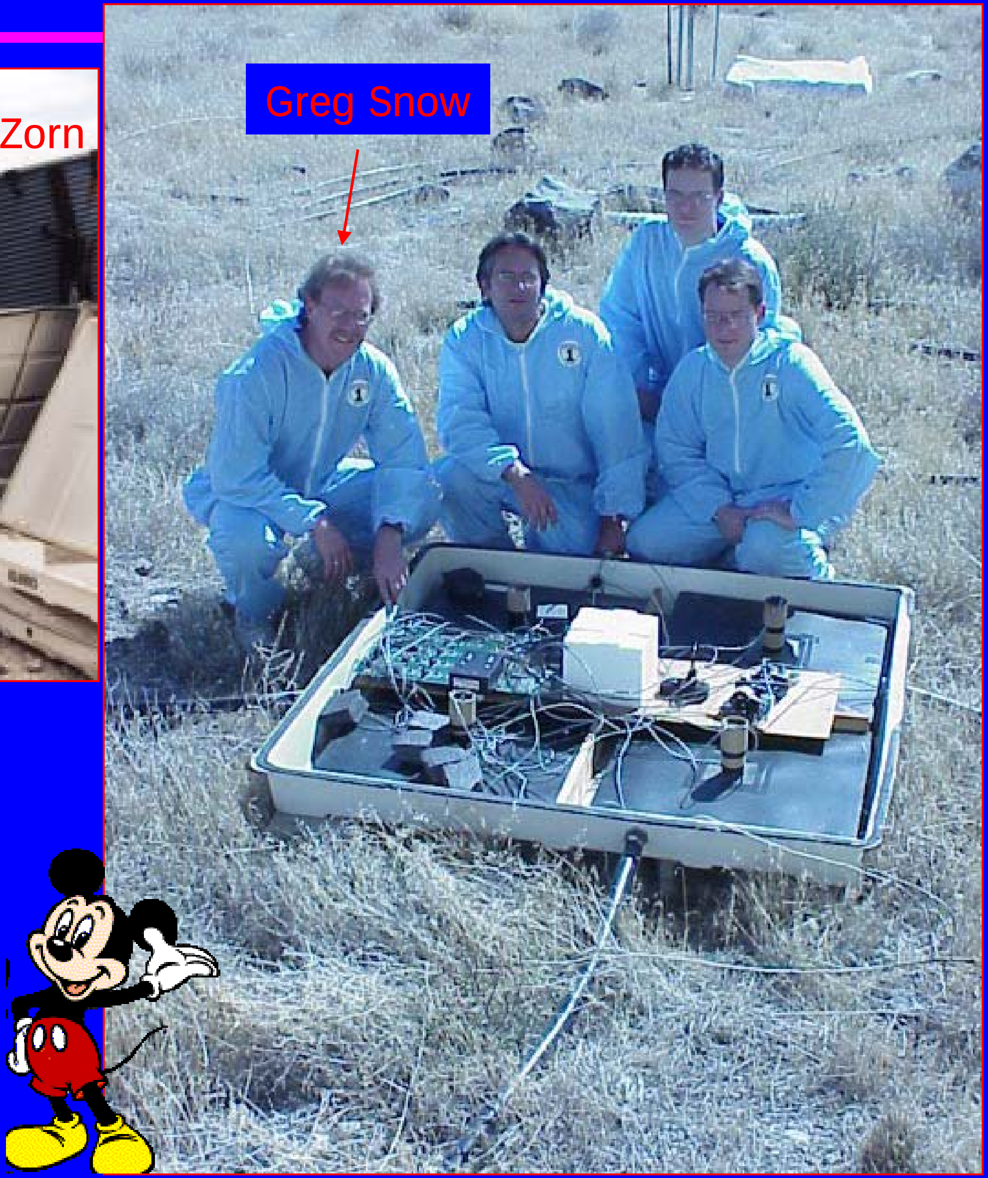
Assumes 4 modules spaced 10m apart at each school in Seattle.



Number of detector modules hit by a 10^{19} eV event arriving vertically at the location shown:

- 15-20
- 10-14
- 6-9
- 3-5
- 1-2
- 0

Recovering CASA counters



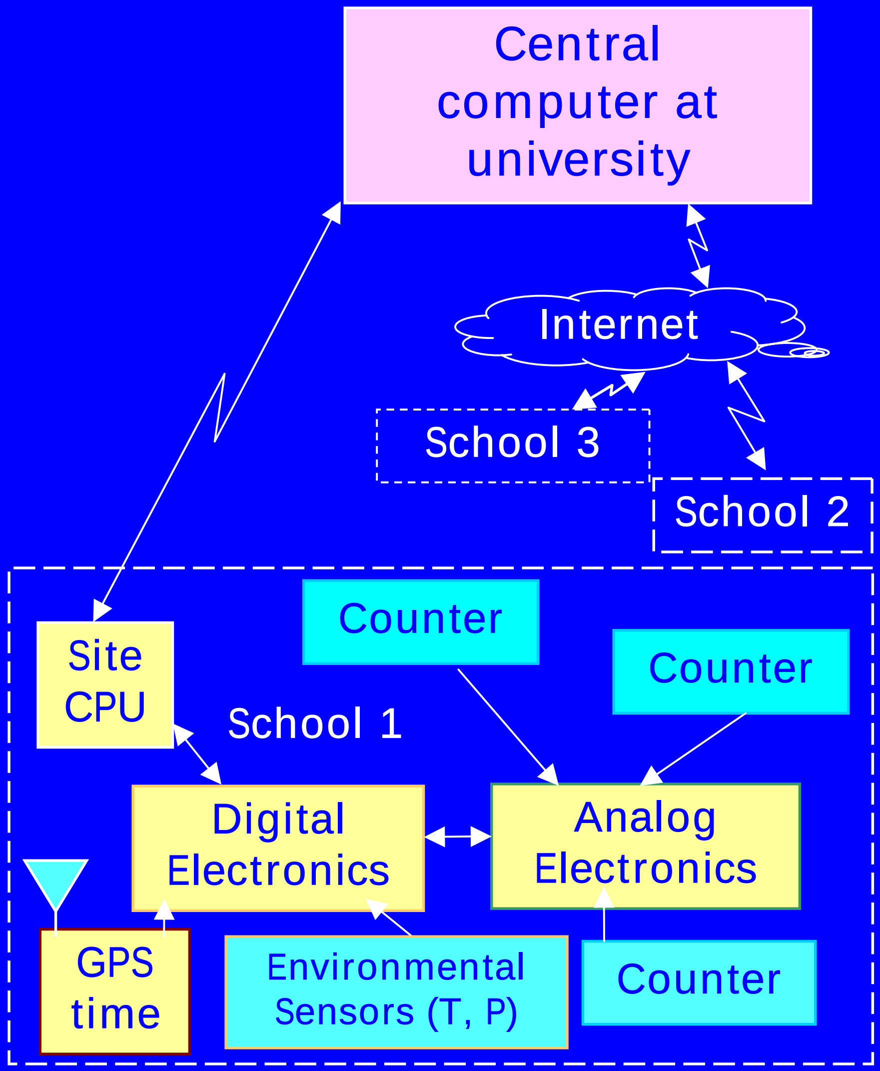
CROP/WALTA expedition to Utah to recover abandoned CASA modules (before US Army destroys them!), May 2001.

(Danger of Hanta Virus in mouse droppings: moon suits required until counters are cleaned)

School Site Installations

Each school site has:

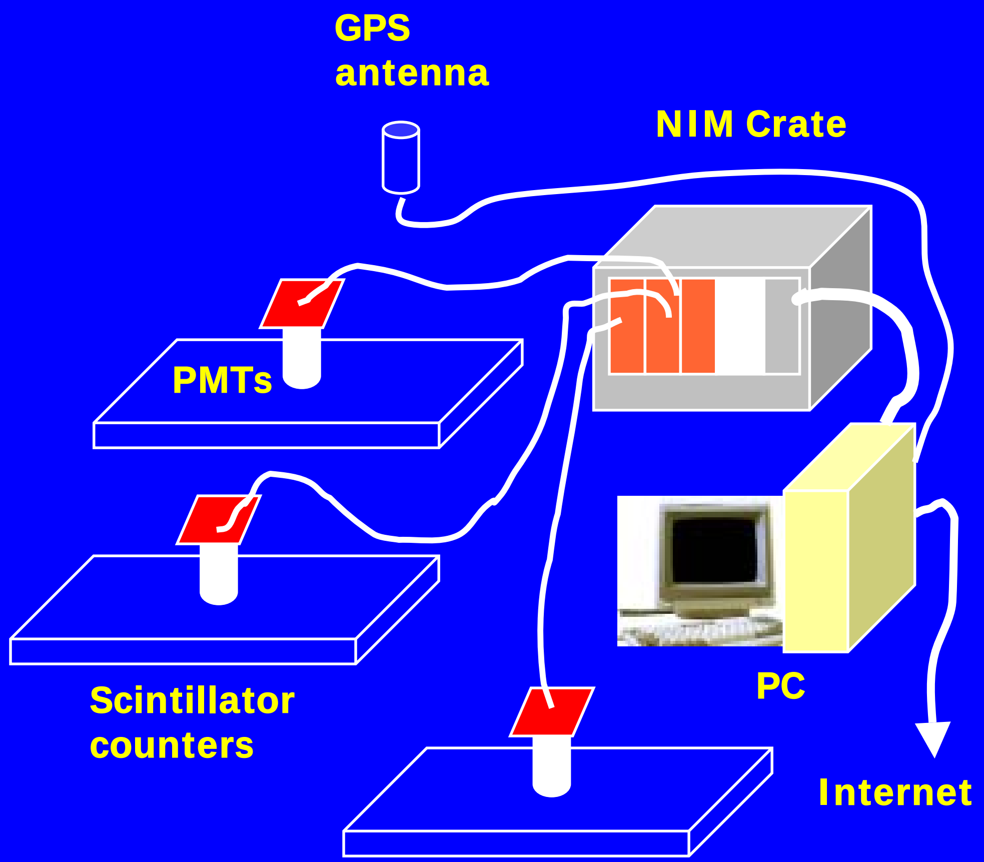
- 3~4 scintillation counters
- Data Acquisition electronics
  - Detects local coincidences
  - Digitize counter pulses and arrival times
- GPS clock system
  - Time synch between sites with ~10 nanosec precision.
- Desktop PC + Internet connection (*only* items supplied by school)
  - Students and teachers use PC to monitor detector status and data flow, and participate in data analysis.
  - Plenty of spare CPU capacity for ordinary use also



WALTA school stations

Strategy:

- At first, use standard NIM particle physics electronics modules borrowed from Fermilab
- Teachers learn to prepare counters and check their operation at WALTA Workshop
- Later: custom electronics board replaces high-cost NIM modules



Summer Workshop for Teachers
Step 1: polishing counters

CASA counters are unwrapped, and edges scraped, sanded and polished

Polishing edges with auto-body plastic polish

Step 2: glue PMTs on counters and rewrap

Tom Jordan (Quarknet Director from Fermilab) helps tape a counter

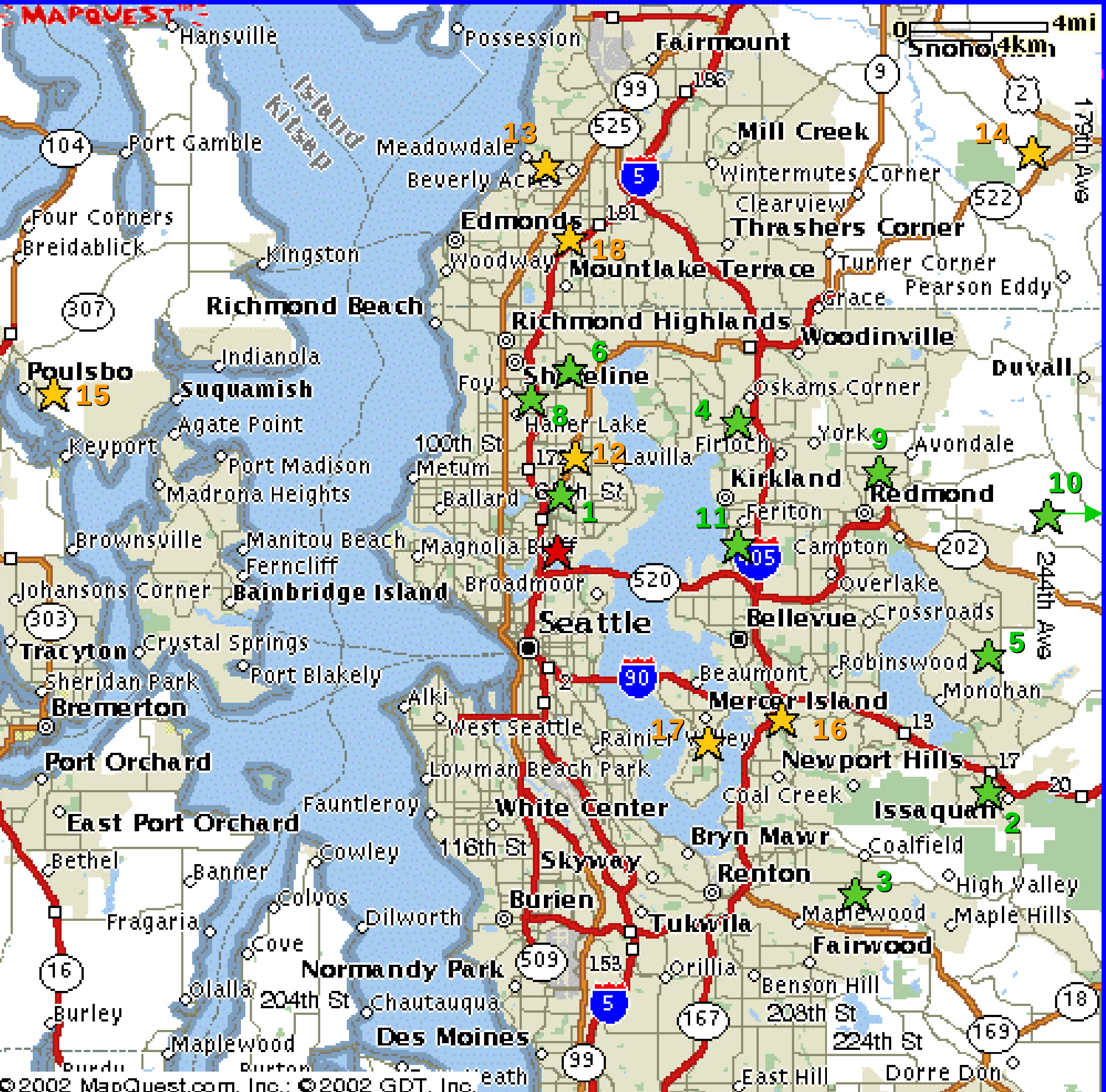
Step 3: test and calibrate counters

- Welcome to the world of experimental physics! Teachers wonder why the counting rate is not as expected...

- Making a 2-layer cosmic ray telescope

WALTA: participating schools

(as of 8/2002)



UW Physics Dept.

WALTA-2001

1. Roosevelt HS
2. Issaquah HS
3. Liberty HS
4. Juanita HS
5. Skyline HS
6. Shorecrest HS
7. Tiger Mt. Comm. Sch.
8. Lakeside School
9. Redmond HS
10. Tolt MS
11. Puget Sound Adventist

WALTA-2002

12. Nathan Hale HS
13. Meadowdale HS
14. Monroe HS
15. N. Kitsap HS
16. Newport HS
17. NW Yeshiva
18. Scriber Lake HS

The Quarknet connection

- *Quarknet* : National educational outreach program based at Fermi National Laboratory

  See http://quarknet.fnal.gov/

  – Goal: to make high school teachers and students aware of particle physics research and its impact on society

- Quarknet funding supports WALTA work with local schools

- WALTA, CROP and Quarknet are collaborating to build a *low-cost*, robust, custom DAQ board for school networks

WALTA/CROP/Quarknet Custom DAQ board

Engineers Sten Hansen (FNAL) and Hans Berns (UW) designed a custom electronics board:

- Input = pulses from CASA PMTs
- Output = data needed for WALTA
  - 4 channels (number of counters at one school)
  - Relative arrival times of pulses with < nanosecond precision
    - » KEK ATLAS TMC chip used
  - Estimates of pulse sizes
  - Arrival times synchronized with GPS time to 100 nsec
  - Simple digital interface to any PC via serial port
- Low cost (under US$500 per board for parts)
  - Replaces expensive (borrowed) NIM electronics
- Reliable and robust
  - Simple enough so students can assemble it and use it

Prototype Q'Net DAQ Board

Programmable logic

Time-to-digital
converter (KEK Atlas TMC)

Serial port
(output to PC)

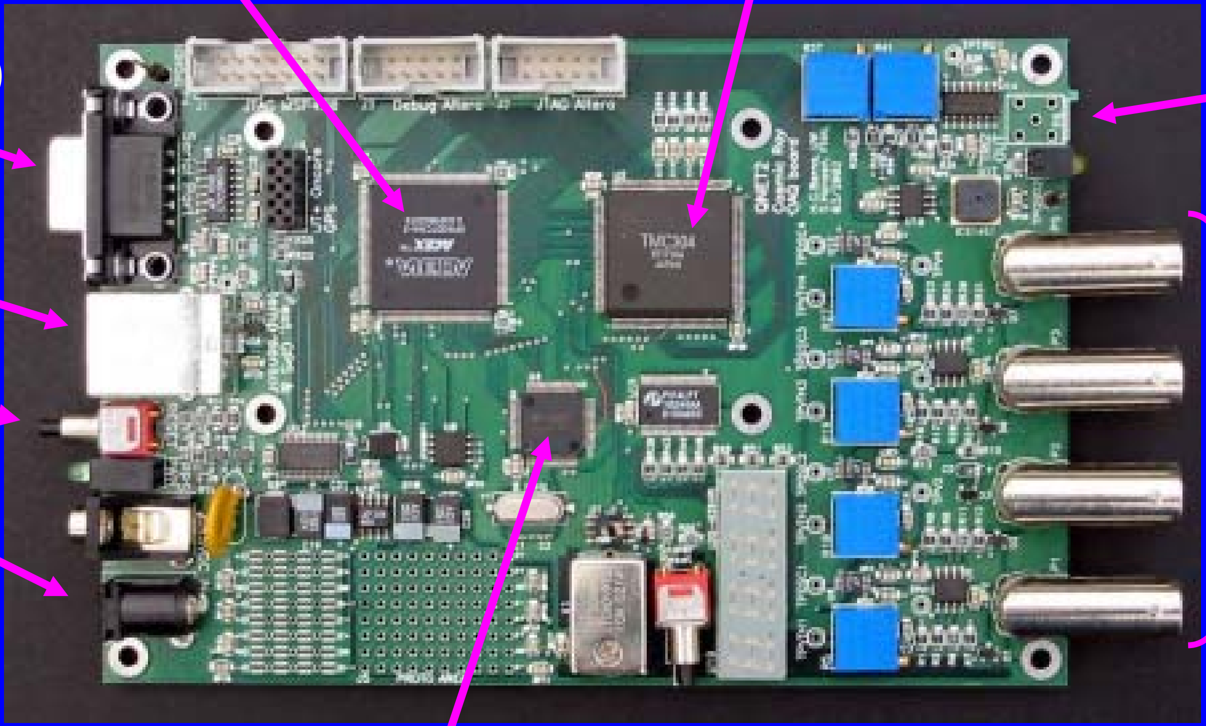
Trigger
output

GPS input

Reset switch

Inputs for
4 counter
signals

5V-DC input



Microcontroller

Next steps

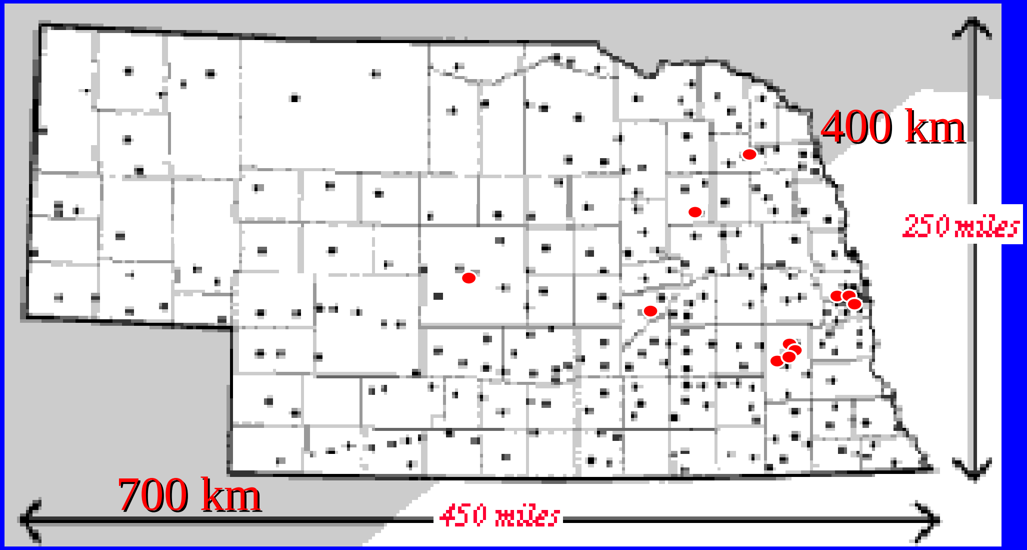
- Testing and debugging prototype boards at UW, and at Fermilab and U. Nebraska
- Revise and make version 2
- Hope to get boards in WALTA-2001 schools before end of January

Active school-network cosmic ray projects in North America

North American LTA consortium:
http://csr.phys.ualberta.ca/nalta/

HiRes and Pierre Auger northern hemisphere site in Utah

Schools participating in CROP



CROP detector sites at Nebraska high schools

Participating schools marked in red

(Map shows ALL high schools in the state of Nebraska!)

Curriculum Topics Available in CROP

Classroom Curriculum

- History of cosmic rays
- Charged particles in matter
- Scintillators & photomultiplier tubes
- Cosmic ray energy spectrum
- Julian calendar, UTM, galactic coordinates
- Global positioning system
- Ionizing particle detectors
- Calorimeters and showering
- Particle zoo and Standard Model
- Tour of particle accelerators
- Random events, probability
- Monte Carlo simulations
- Lightning protection

Lab Curriculum

- Polishing, cleaning scintillator
- Gluing PMT and wrapping scintillator
- Assembling high-voltage supply
- Oscilloscope lesson
- Turning on counters, source tests, finding/fixing light leaks
- Measure counter efficiency, high voltage plateau

Other active projects

CHICOS, run by Caltech in the Los Angeles area: uses old CYGNUS detectors

ALTA, run by the University of Alberta in the Edmonton area

Conclusion

- School network cosmic ray detector projects are under way in several places in USA and Canada
- May make a significant contribution to physics
- Certain to help motivate students to study physics