Progress in School-Network Cosmic Ray Detectors

Jeffrey Wilkes
Dept. of Physics
Univ. of Washington, Seattle
wilkes@u.washington.edu

KEK
22 Nov 2005

Washington
Area
Large-scale
Time coincidence
Array

Quarknet: educational outreach program based at Fermilab

Overview

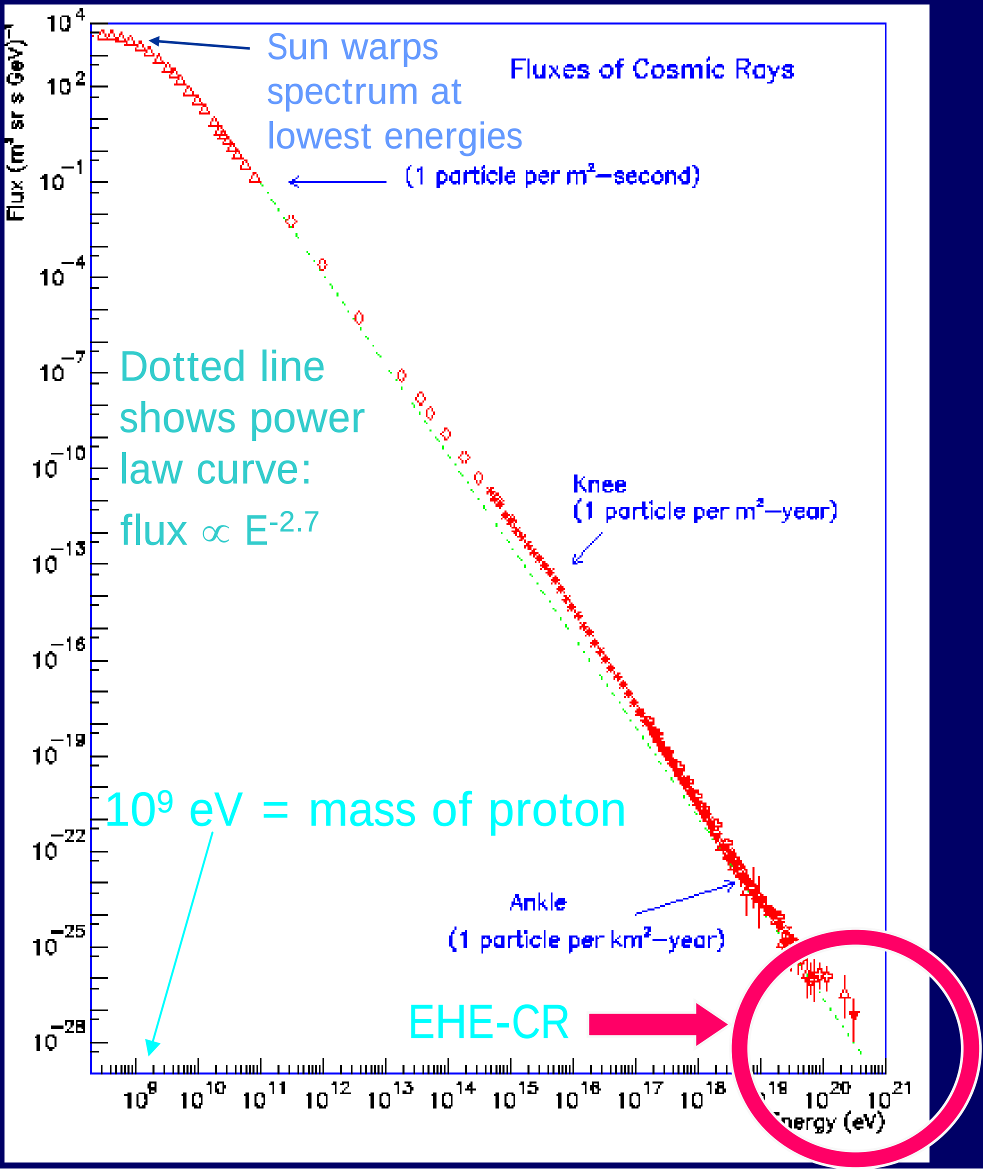
- What's WALTA?
- WALTA's physics
- WALTA's connections to high schools
- What does WALTA do for teachers and students?
- Other school-network projects in USA
- Current status of WALTA, and future plans

See: http://www.phys.washington.edu/~walta

Physics of WALTA: highest energy cosmic rays

- WALTA connects particle physics and astrophysics
  - Elementary particle physics (cosmic rays)
  - High energy astrophysics (where do they come from?)
- Puzzles to solve
  - We know how lower energy cosmic rays are produced (basically Fermi process), but that mechanism fails above about 10^{15} electron volts
    - Many competing ideas for higher energy CR acceleration
  - We know that if something *can* accelerate cosmic rays to $>10^{19}$ eV, they should be stopped (λ~50 Mpc) by the Cosmic Microwave Background (CMB) radiation
    - UHE CRs can't reach us from very far…
    - Nothing very near that can produce them!

WALTA Physics: the cosmic ray *spectrum*



- Cosmic ray spectrum: intensity vs energy for primary cosmic rays
  - All charged particles (protons and nuclei)
  - At top of atmosphere
  - Note log-log scale!
- WALTA focuses on the very highest energy cosmic rays
  - Kinetic energy of a thrown baseball in a single proton!
  - Only a few detected worldwide
  - Should be none!

Galactic and extra-galactic CRs

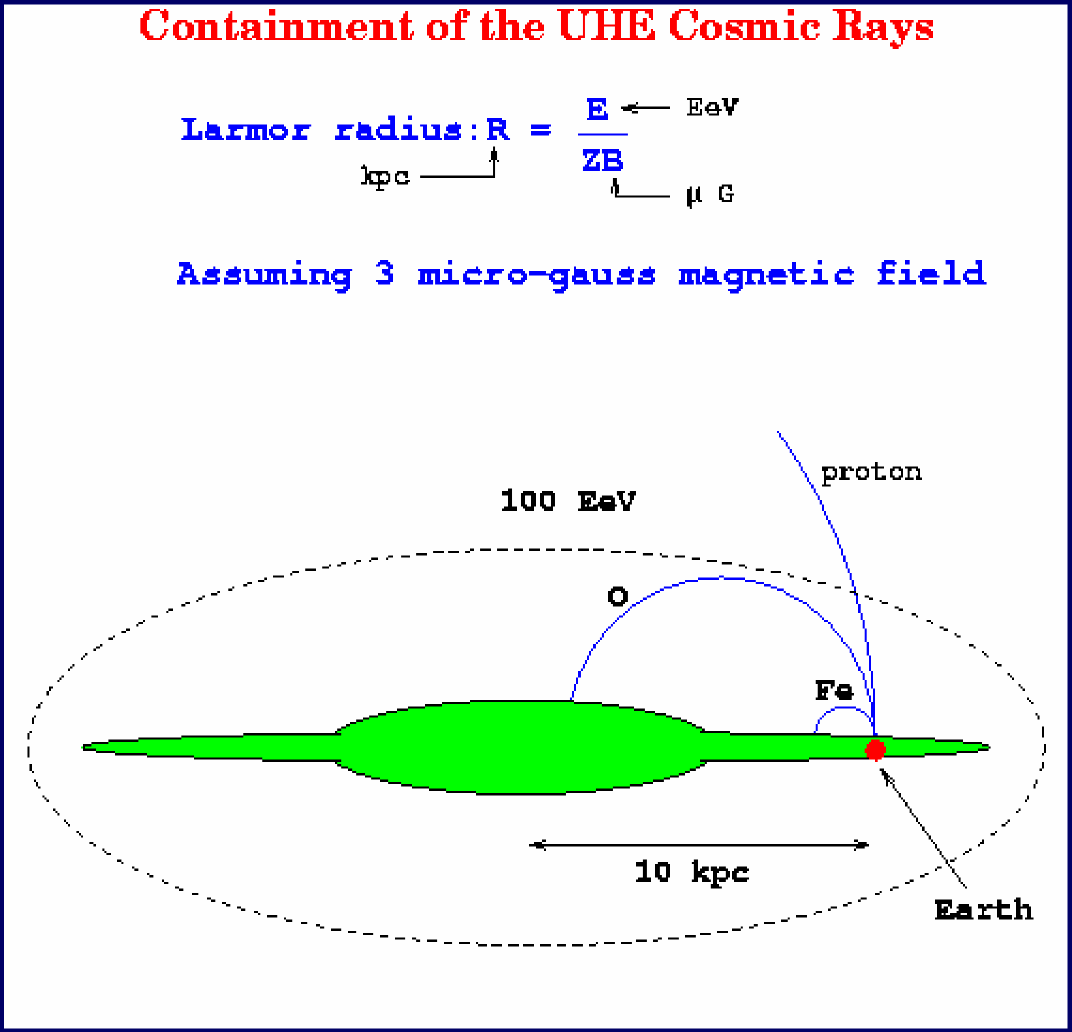
Our Galaxy's magnetic field can't trap protons with

E > $10^{18\sim19}$ eV, so

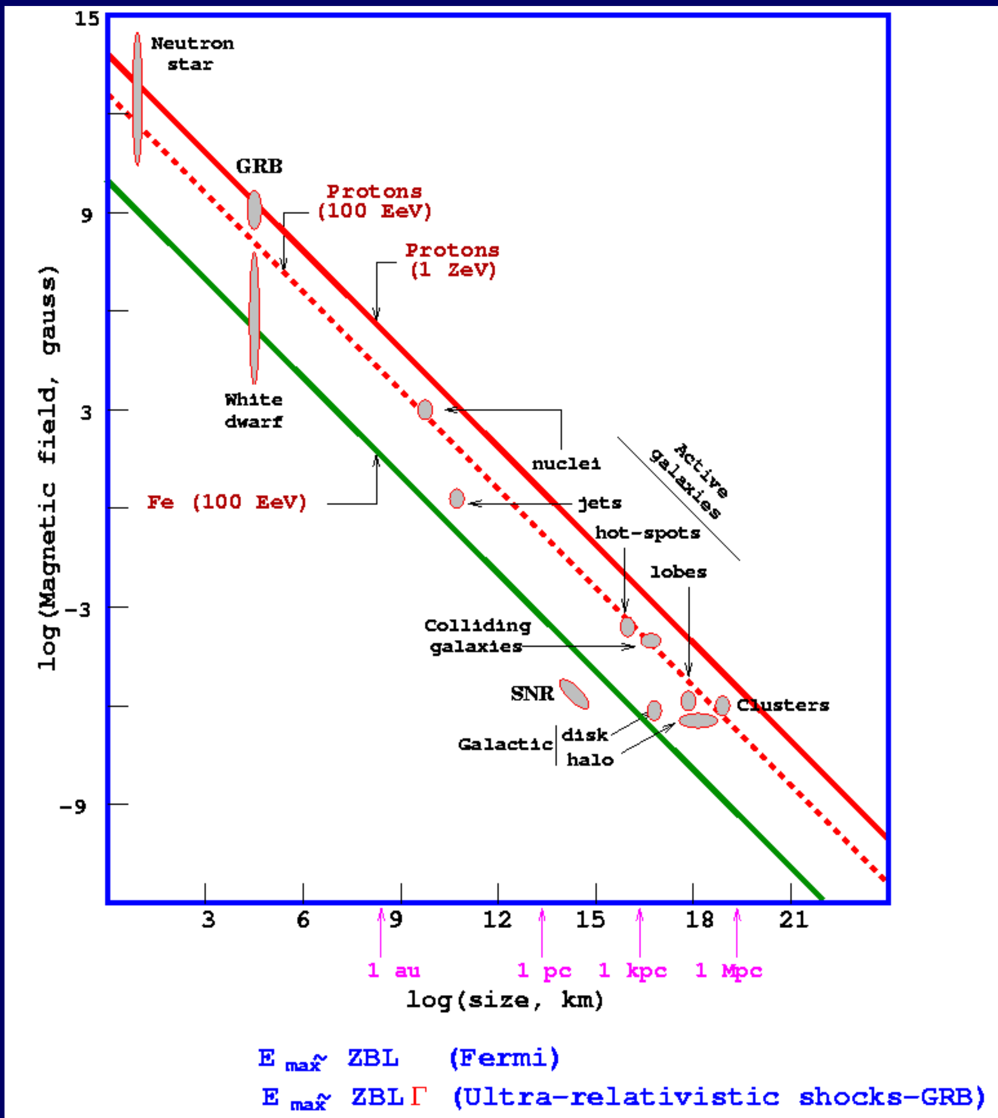
- Galactic EHE cosmic rays escape
- Observed EHE cosmic rays are mainly extragalactic

Q: Is there a significant intergalactic B field?

A: nobody knows...



"Hillas Plot": Magnetic field vs size of sources



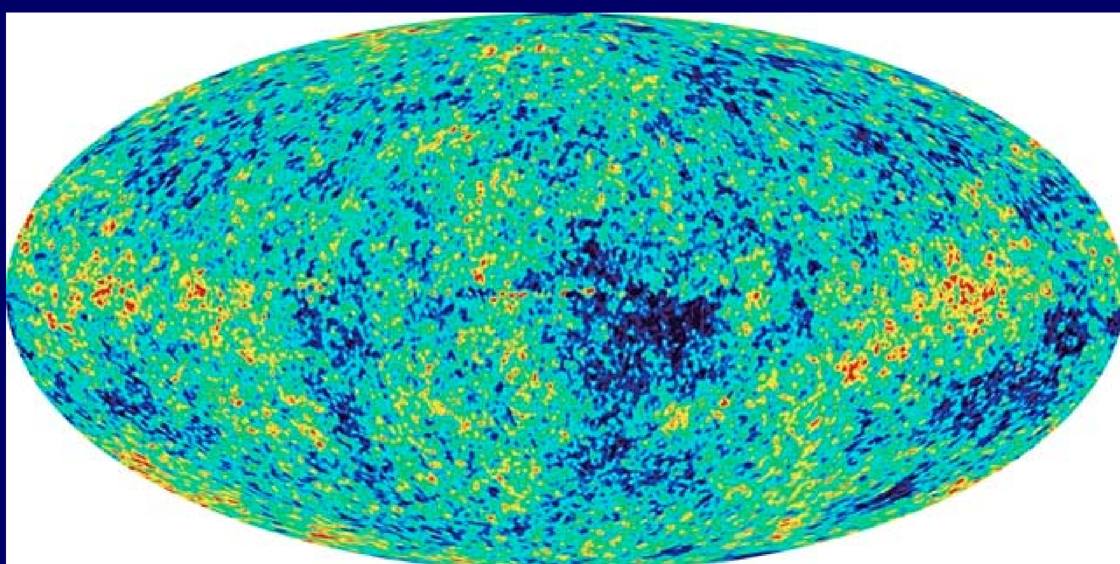
- Michael Hillas (1984) made this nice plot showing *acceleration limits* for possible cosmic ray sources
  - Must have large size or big magnetic (B) field – or both
  - Plot shows log <B> vs log <L> for known astrophysical objects

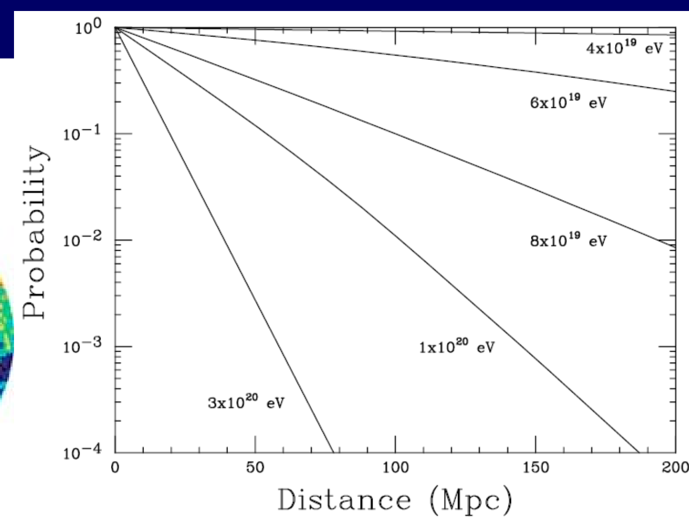
Very few objects can produce UHE-CR!

- But UHE-CR *are* observed (?)
  - Experiments with different techniques observed an excess above 10^{20} eV
    - AGASA (extensive air shower array in Japan)
    - Other experiments disagree

GZK cutoff: CMB blocks UHE cosmic rays

- Greisen, Zatsepin and Kuzmin (GZK, 1960): predict a “cutoff” in the cosmic ray spectrum around 10^{20} eV (just at the toe):
  - CMB 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 probability for photon-nucleon interaction at E ~ GeV
  - So … >10^{19} eV protons from distant galaxies should not reach us!
- For galaxies farther than 50~100 Mpc, CBR should block UHE cosmic rays
  - *if* they are protons or nuclei...





Survival probability vs distance for E>10^{19}eV (Cronin ‘04)

So what can produce UHE-CR?

- Hillas plot says: only *huge* objects with *intense B fields*
- GZK says: must be within ~50 Mpc of our Galaxy
- Only *a few* possible sources are that close to us…
- Experiments disagree on whether beyond-GZK particles have been observed
  - AGASA (surface air shower array) says yes
  - HiRes (atmospheric fluorescence detector) says no
  - Auger (both at the same site) says… we'll see
- It's fun to take high school students into current physics discussions like this!

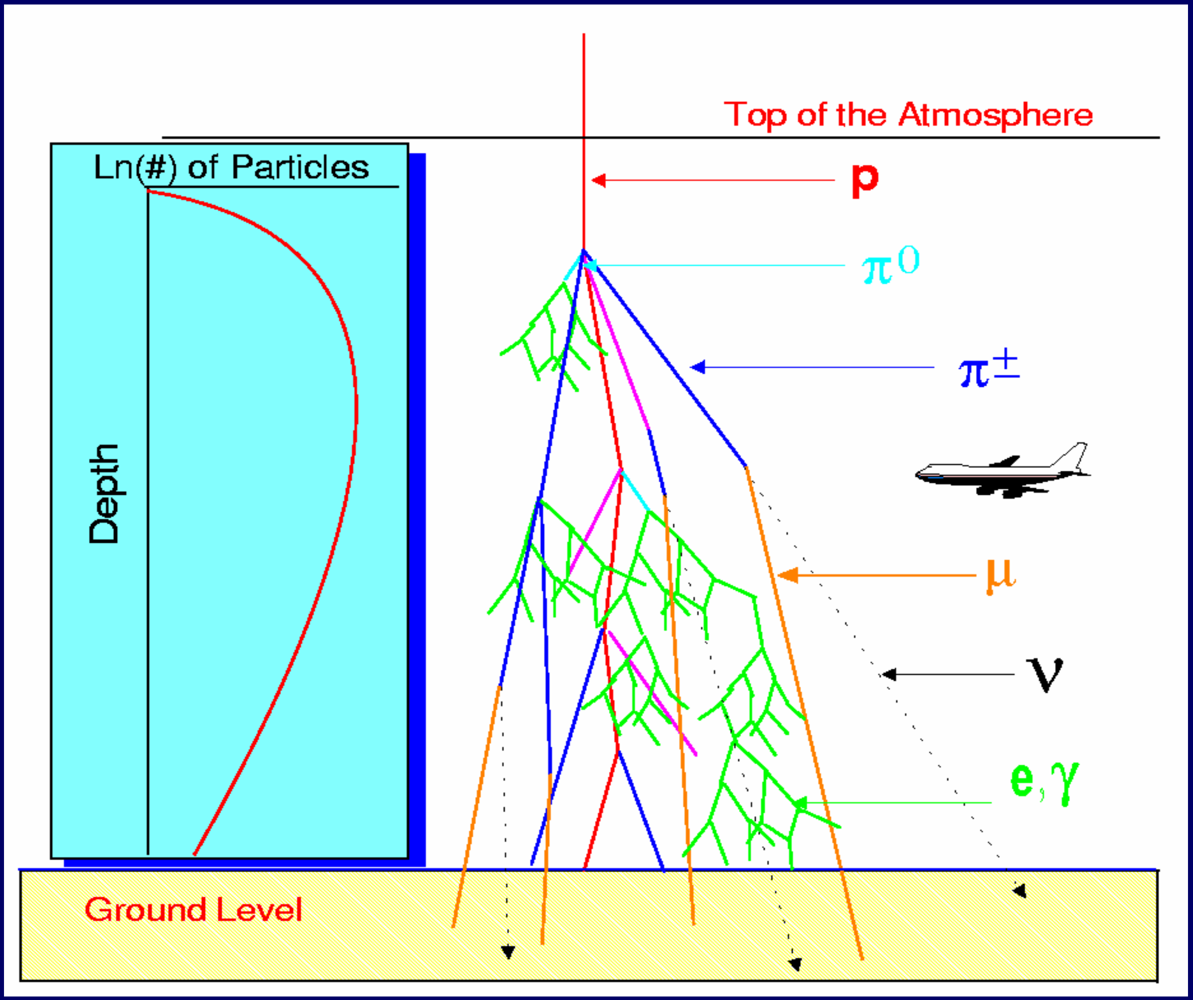
What are Extensive Air Showers ?

incoming cosmic ray proton

(from supernova in our Galaxy, or...?)

Plot of total number of particles vs depth in atmosphere

(We can only detect and count charged particles)

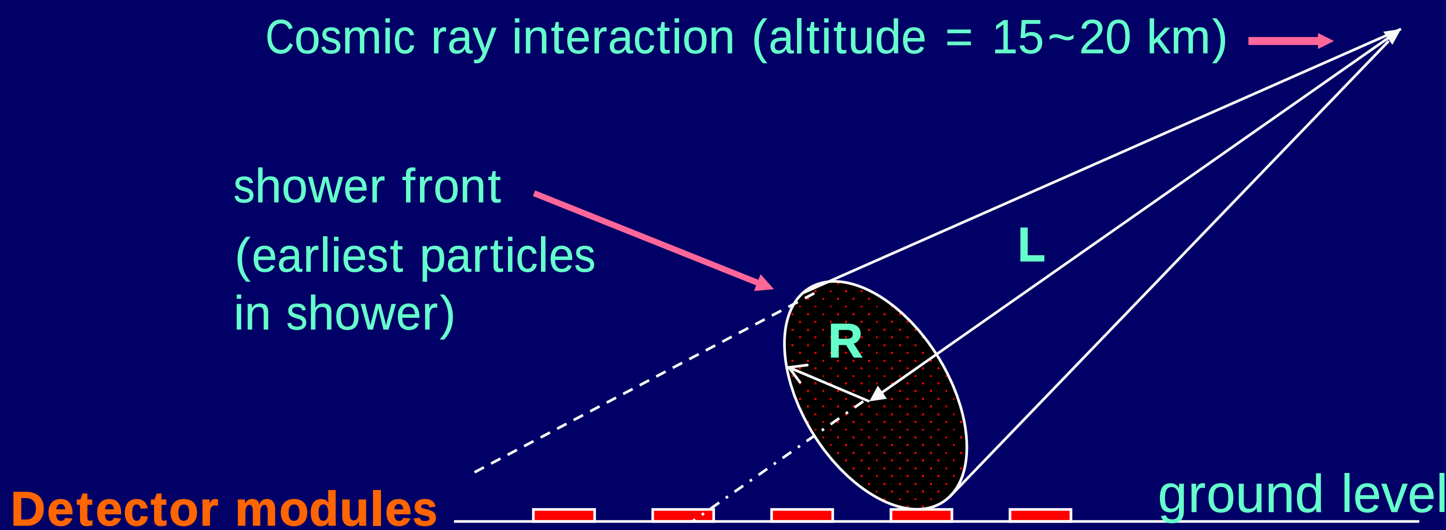


Secondary particles

Decay products

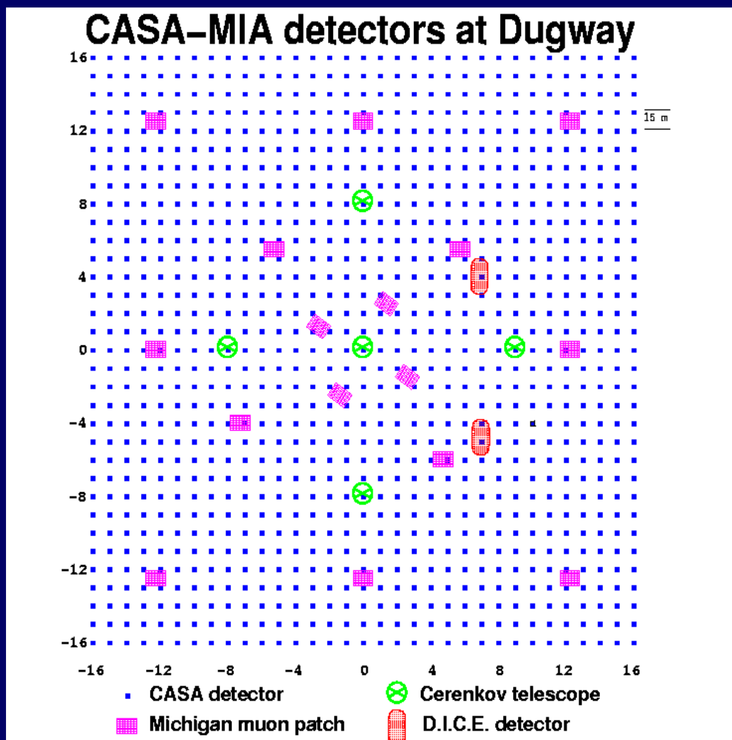
Electron cascades

How Air Shower detectors work



- Each detector module must report:
  - Time of hit (need better than microsecond accuracy)
  - Number of particles hitting detector module ($\propto$ pulse area or width)
- Time sequence of hits on detectors $\rightarrow$ shower direction
- Total number of particles $\rightarrow$ shower energy
- Lateral distribution of particles around shower axis $\rightarrow$ distance L
  - Needed for accurate energy calculation
  - Particle ID: proton-initiated showers start deeper than for nuclei

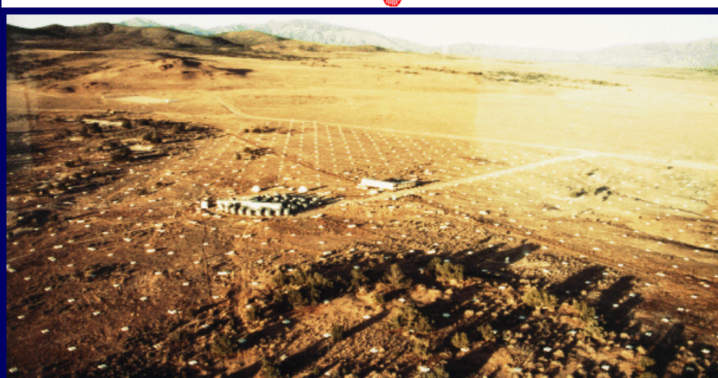
Example: CASA Experiment (1989-96)



0.5 km

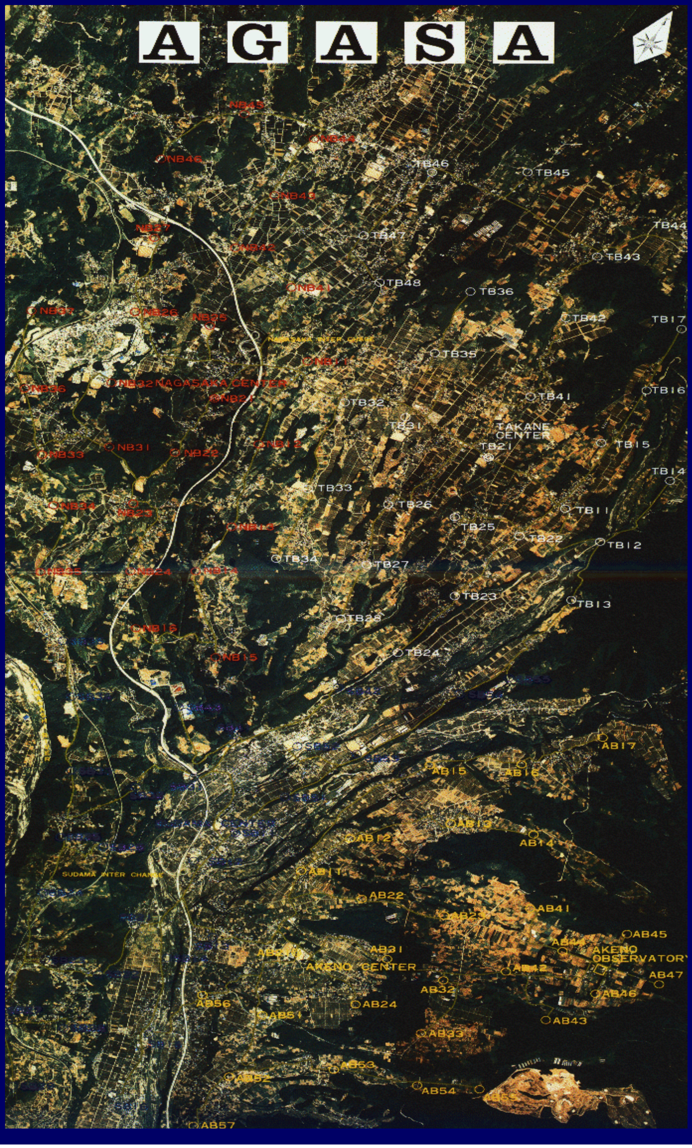
Chicago Air Shower Array, Michigan Muon Array, and Fly’s Eye detectors at Dugway, Utah

1024 CASA modules, 16 MIA modules

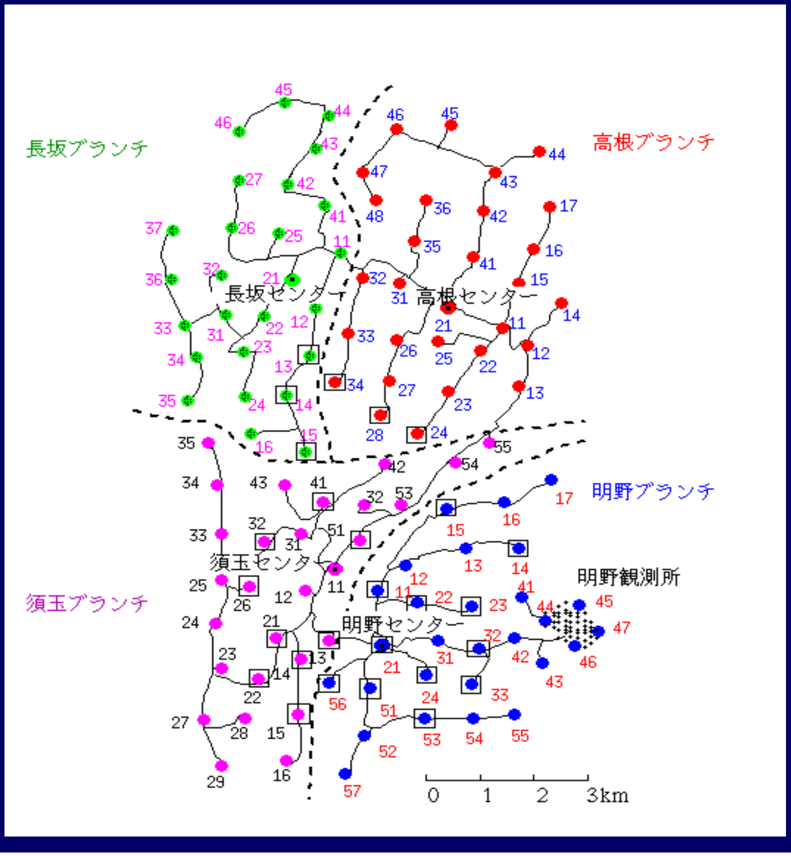


Aerial view of Dugway site

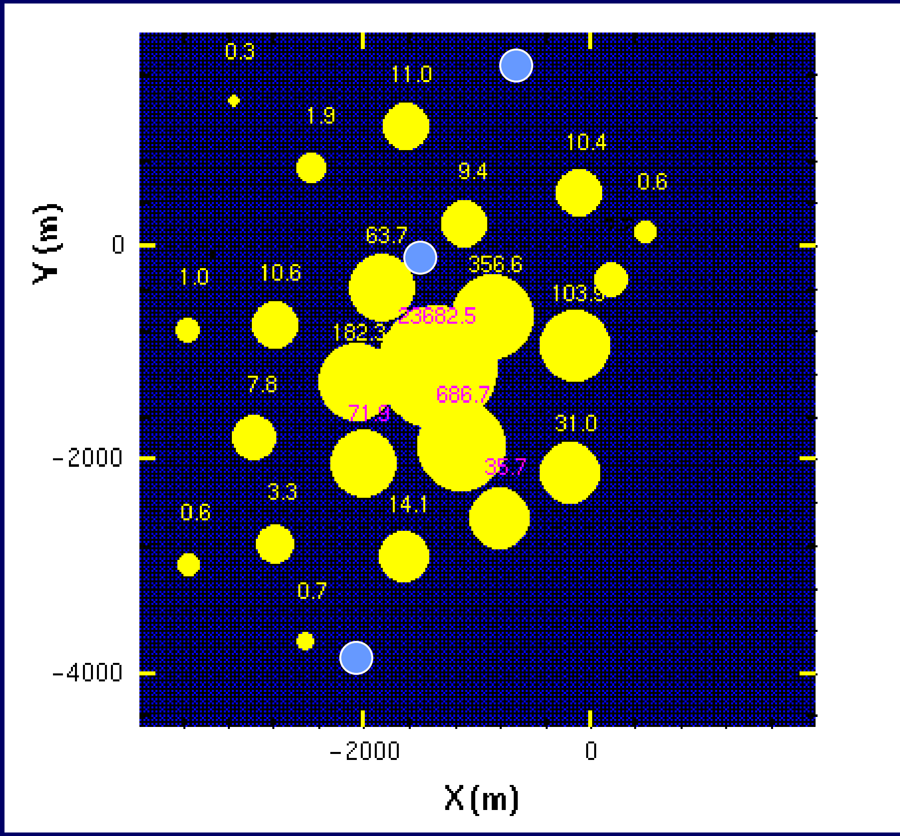
The Akeno Giant Air Shower Array (AGASA) in Japan



- 111 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

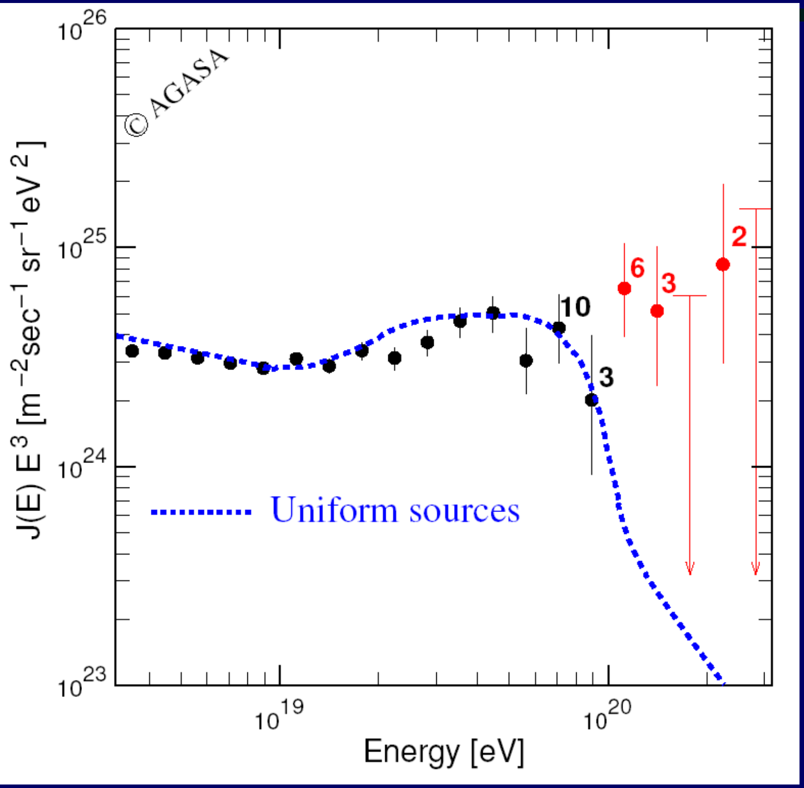


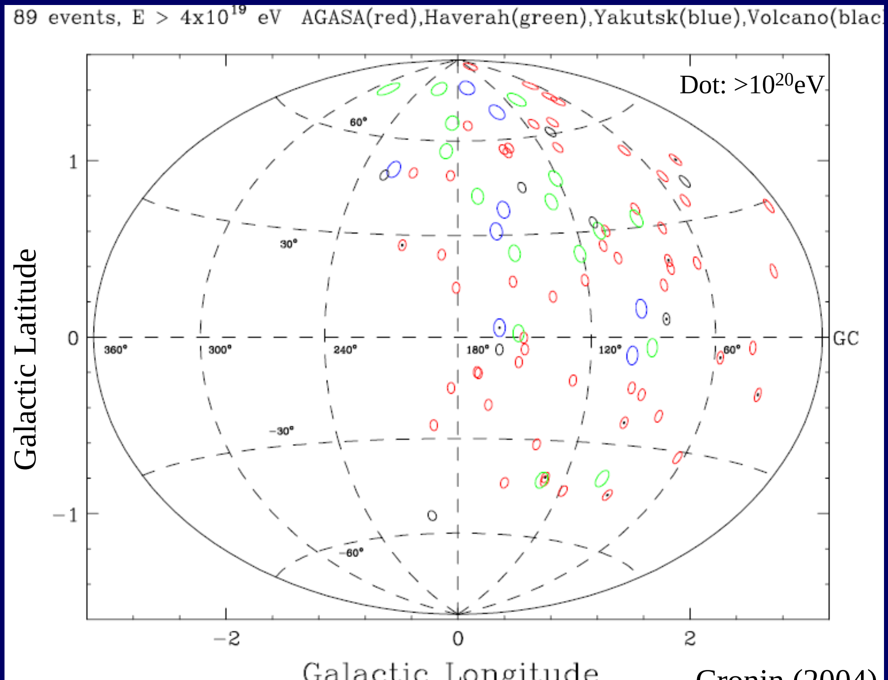
Primary energy 2×10^{20} eV

- Local sites superimposed to show you size of shower!
- One of the world's highest energy cosmic ray events
- Particles covered 4 km $\times$ 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

- AGASA UHE Energy Spectrum:
  - significantly above expectation
- Directions of arrival
  - No anisotropy or special sources



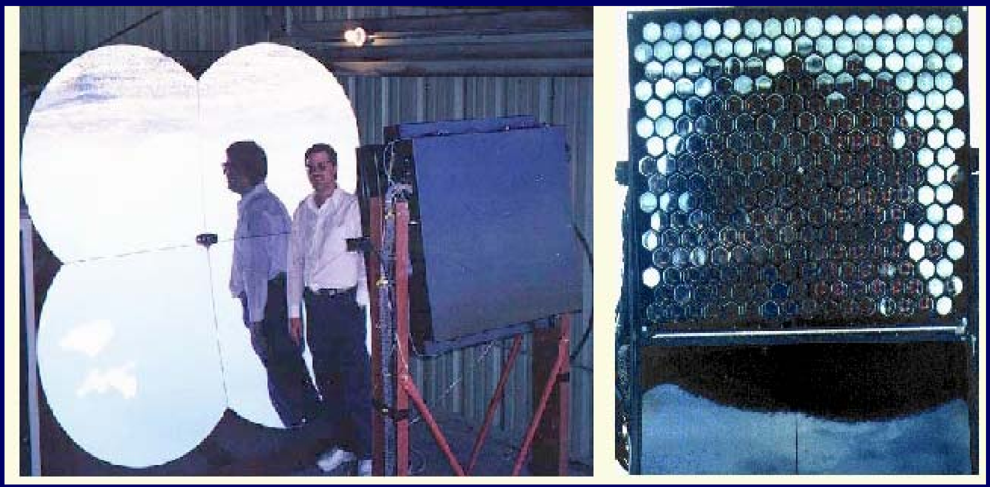


Cronin (2004)

"Based on the energy spectrum from $10^{14.5}$eV to a few times 10^{20}eV determined at Akeno, there are surely events above 10^{20}eV and the energy spectrum extends up to a few times 10^{20}eV without a GZK-cutoff."

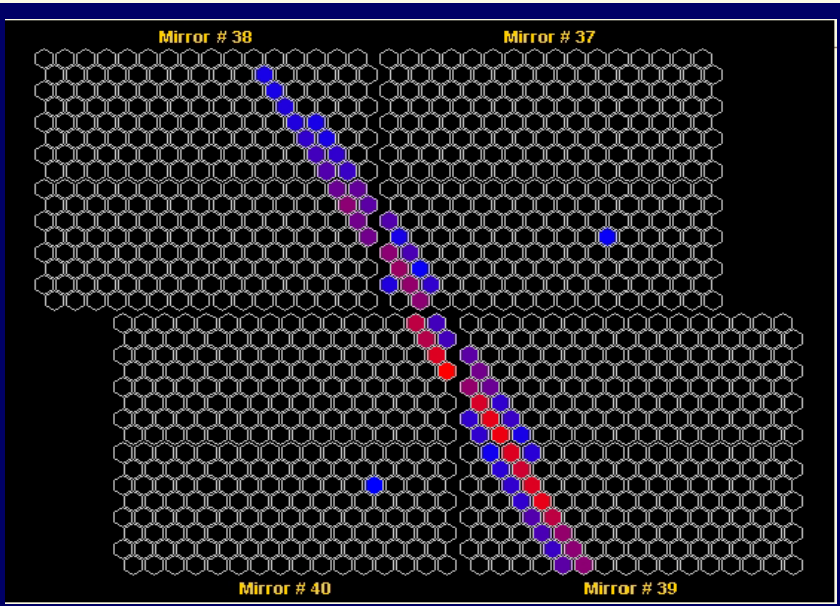
- AGASA, *Astropart. Phys.* 19:447 ('03)

HiRes detector: Son of Fly's Eye



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

HiRes detector module: mirrors and PMT array

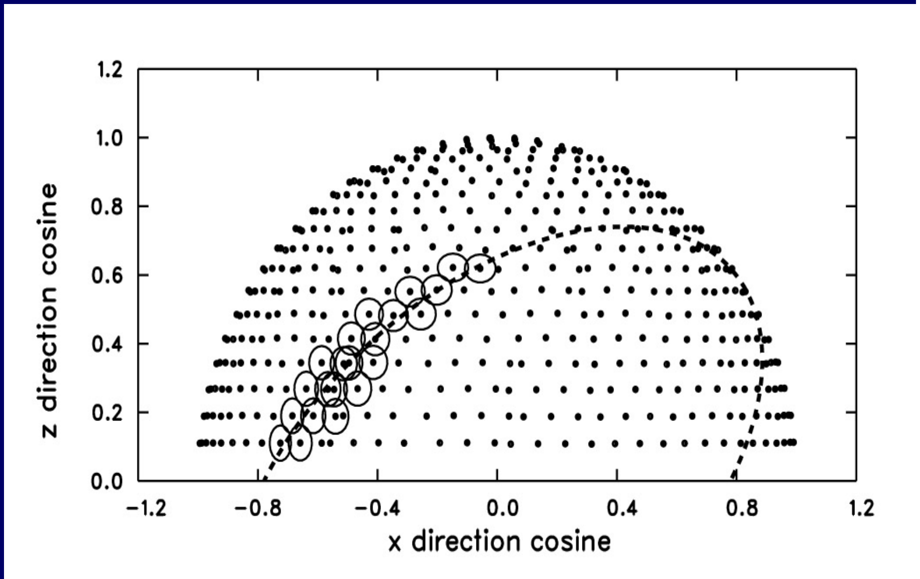


HiRes event display, showing cosmic ray shower's scintillation trail detected by several HiRes modules

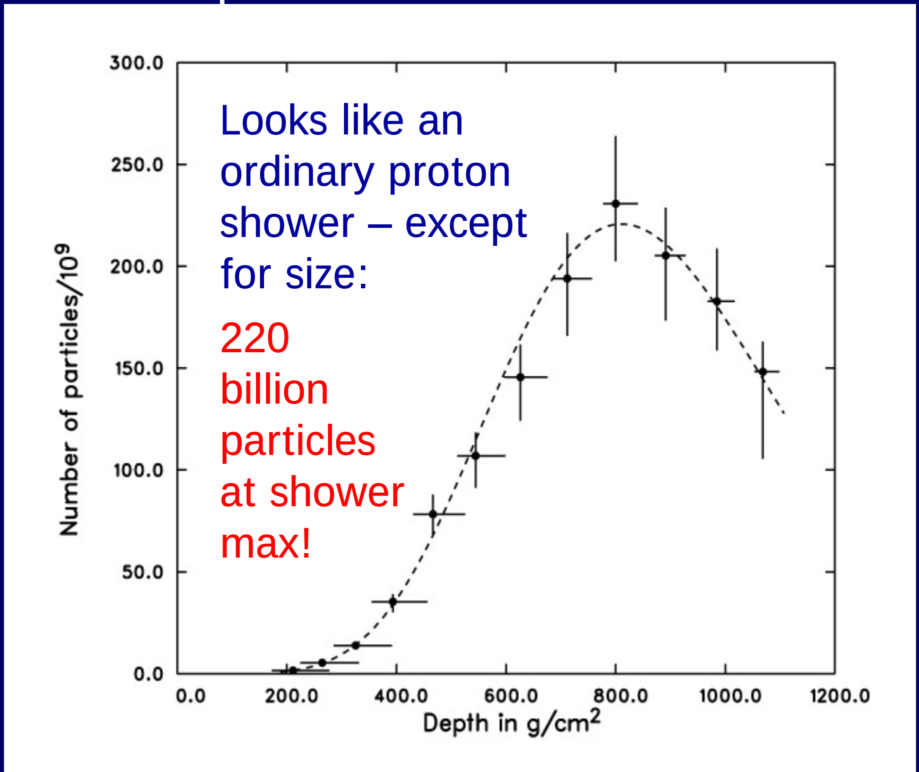
Fly’s Eye 1991 event – highest-E cosmic ray?

3.2x10^{20} eV (but now retracted…)

- Event display, showing detectors illuminated:



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



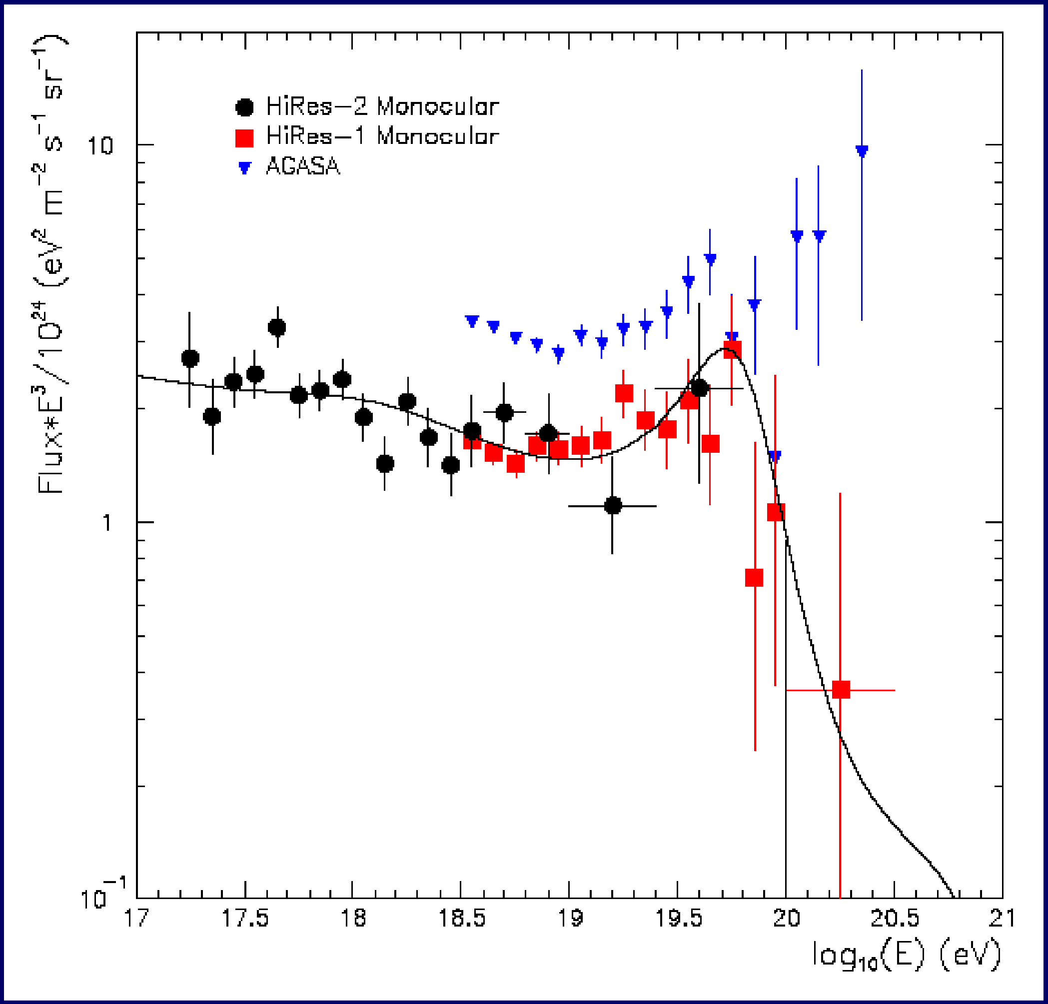
- Utah group says systematic error in analysis of fluorescence (now corrected) pushes event energies below GZK cutoff

Utah spectra - re-visited

- Good example for students: how competition and controversy advance science!

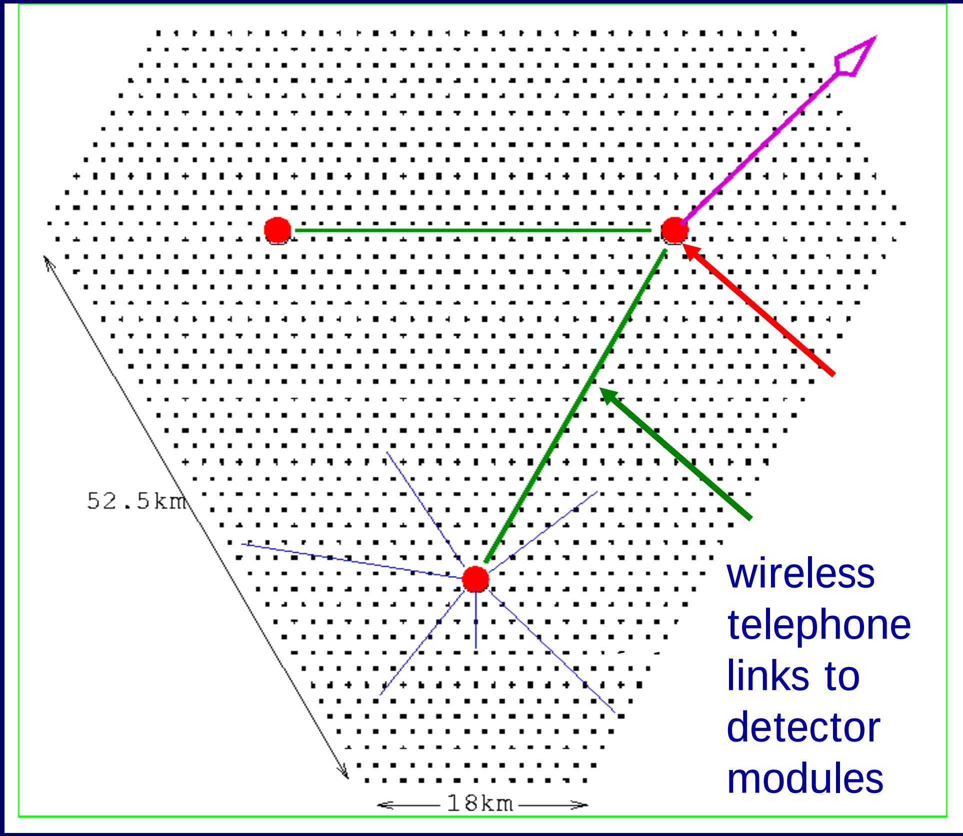
HiRes data (1997-2001)

- Claim GZK cutoff seen!
  - See no excess events
  - Published data are only for "monocular" events (observed in only 1 of the 2 detectors)
- AGASA group sticks to their guns
  - HiRes may have energy determination wrong?
- Auger will settle this!
  - Has both types of detector



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 Seattle metro area
- Will (hopefully) determine whether trans-GZK events exist

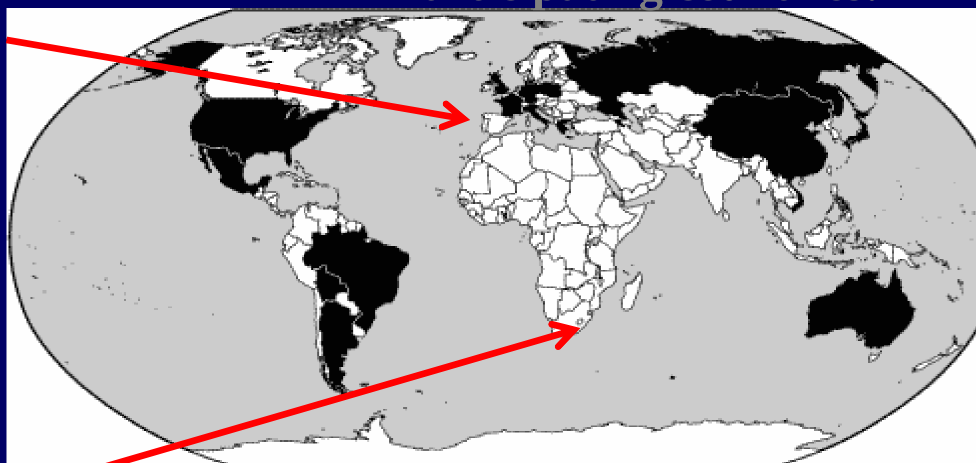


Pierre Auger Observatory

Detector Sites:

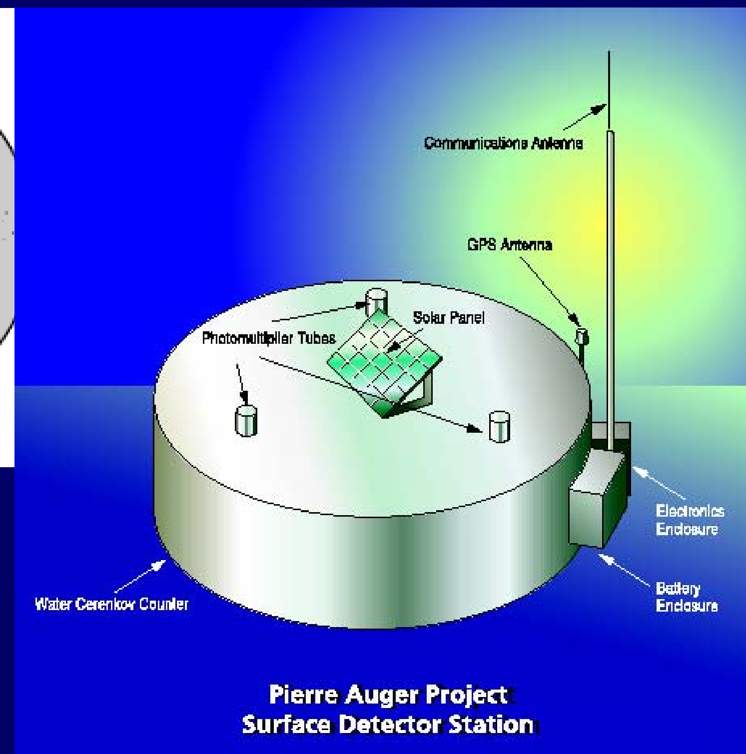
Utah

Participating countries:



Argentina

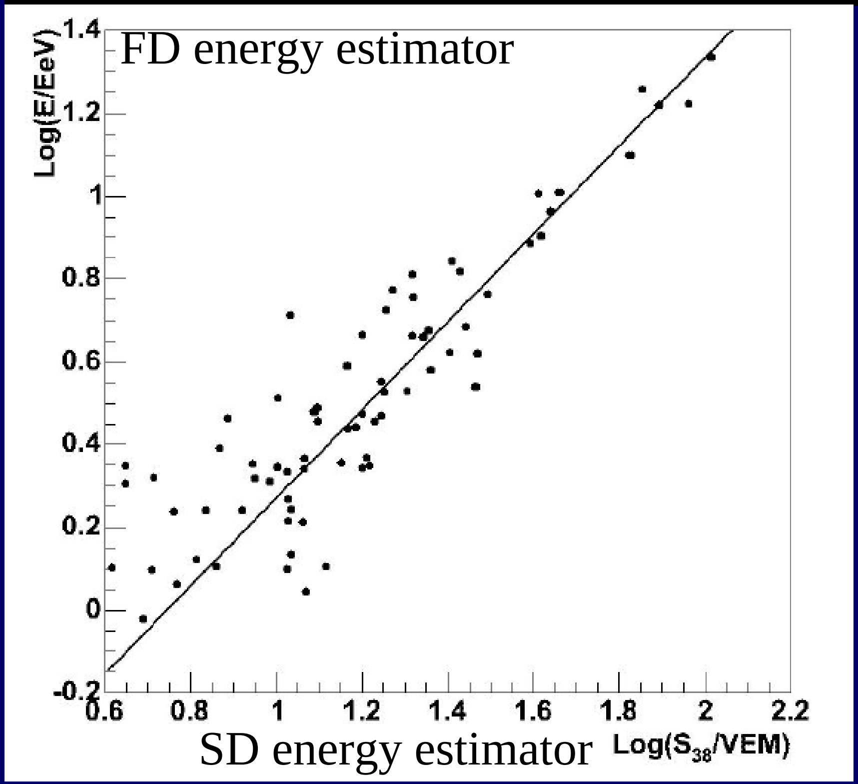
Water Cherenkov detector for Auger



Report from Auger (ICRC, 2005)

- Data taken with *both* fluorescence detectors and surface detectors (EAS array) from 1/2004 to 6/2005
  - Already more exposure than AGASA
  - FD data gives model-independent connection to energy deposition
  - SD has easily calculated exposure/livetime factor
- Conclusion:
  - Systematic differences exist between FD and SD
  - More study is needed!

"In metaphorical terms the fluorescence technique resembles a beautiful prima donna who needs constant pampering. Then she will sing with such beauty that shivers run up and down your spine. By contrast the surface array technique reminds one of a chanteuse in a smoky bar who sings with the same passion, no matter how she feels or how she is treated."
-J. Cronin (2004)



School-network approach

- University joins secondary schools
  - use <u>existing</u> resources in the community, and surplus equipment
- Schools provide detector sites
  - Schools' existing Internet connections link 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

Educational Goals

- Learn about cosmic rays and particle physics
  - Single particles can be detected
  - Events at the top of the atmosphere can be observed from sea level
- Learn about astronomy and astrophysics
  - Where in our galaxy do cosmic rays come from?
  - supernovae, CMB, other galaxies – what do these terms mean?
- Learn the craft of experimental science
  - Basic electronics, particle detection devices, and oscilloscopes
  - Counting, statistics, fitting, simulations
  - Global positioning system: how does it work?
  - Use computers for more than games and chat groups
    - LabView is used widely in US industry
    - Students become Linux sysadmins !
- Our not-so-hidden agenda: lure a few students into physics!
  - Many others are attracted to engineering, serious computing, etc

The Quarknet connection

- *Quarknet* : US national particle physics education / outreach program based at Fermi National Laboratory

  See http://quarknet.fnal.gov/

  – Goal: to make secondary school teachers and students (and their parents) aware of particle physics research and its impact on society

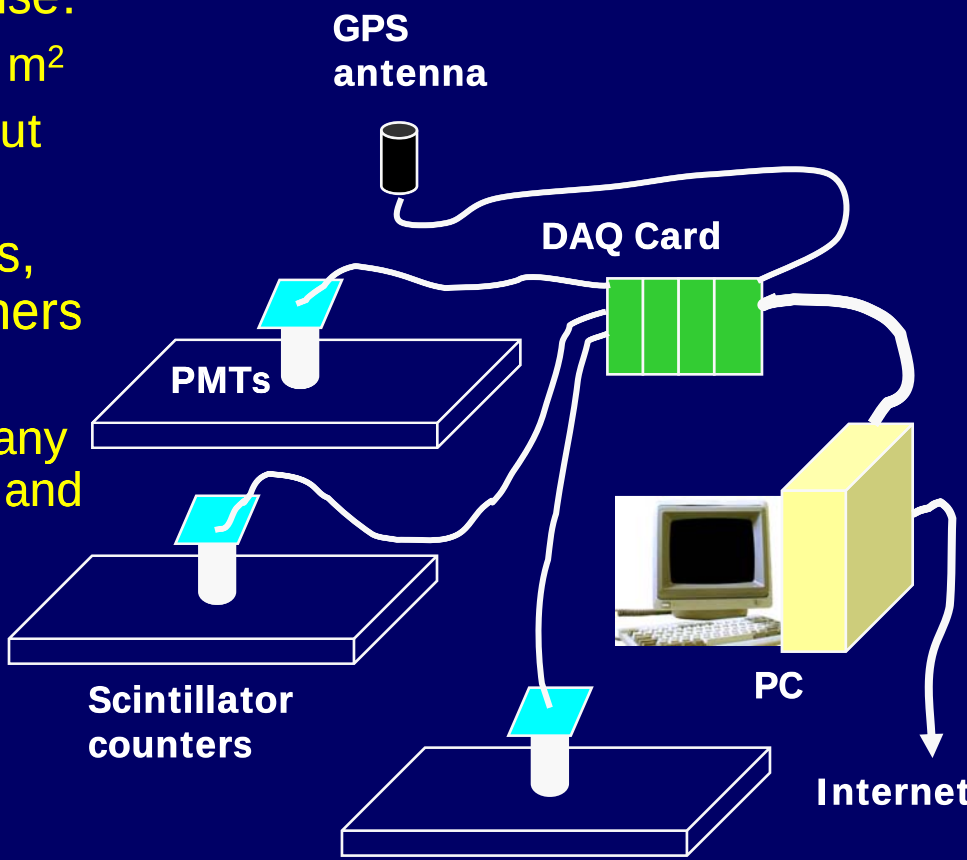
- Quarknet funding supports WALTA's work with local schools
  – All WALTA teachers are Quarknet members
    - Expenses paid to visit Fermilab, attend professional conferences
    - Stipends for attending local workshops, materials

- Quarknet operates a GRID site which we hope to use for data analysis and cross-country collaboration

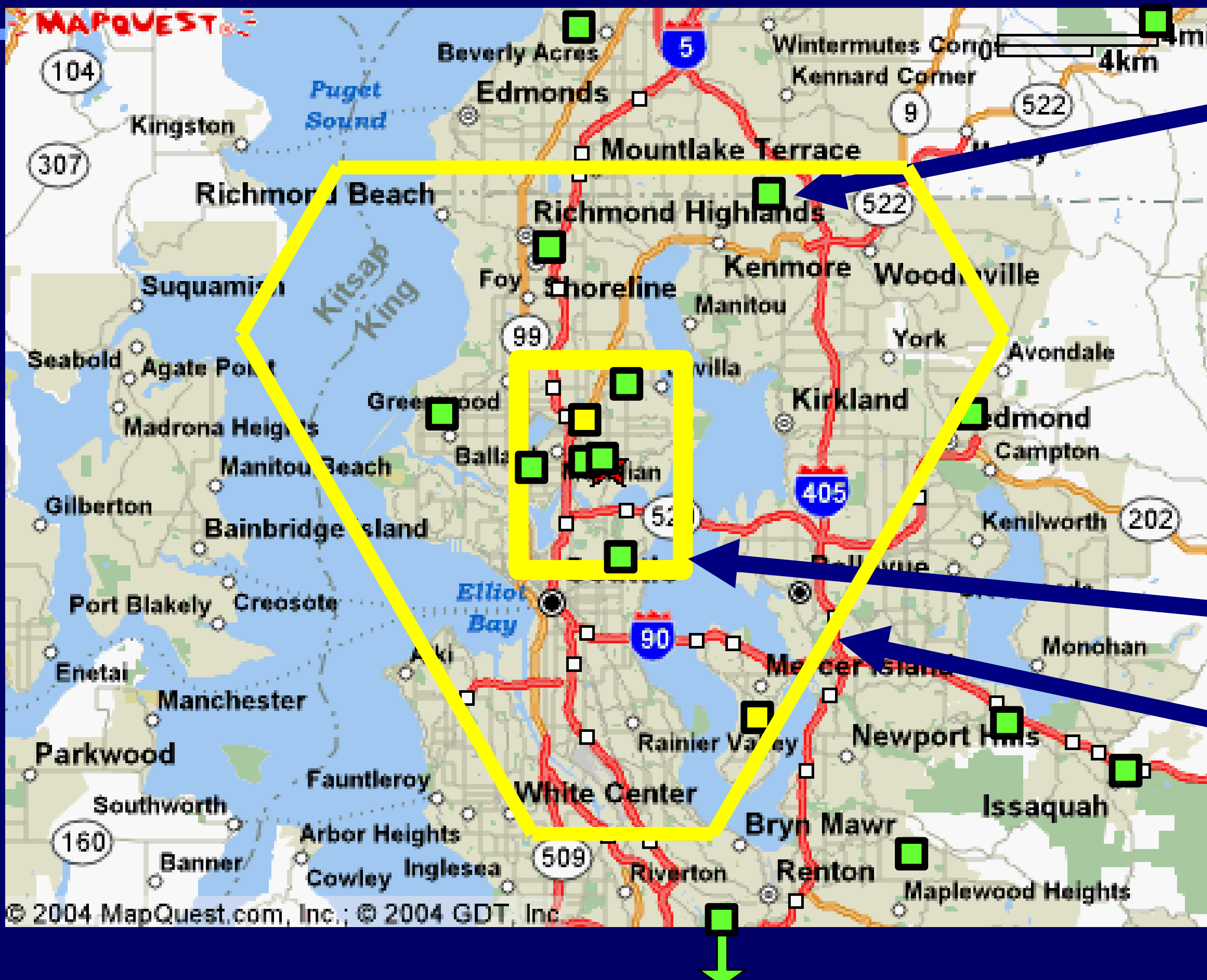
  See http://quarknet.uchicago.edu/elab/cosmic/project.jsp

How WALTA works

- University group provides all hardware and specialized expertise:
  - Particle detectors, each about 1 m^2
  - Specialized electronics to read out detectors
- Schools provide site for detectors, Internet link, and eager researchers (students and teachers)
  - Each school's own data gives many opportunities for teaching math and science *by example*
  - University staff visit classrooms regularly
  - Students and teachers access project database @ UW and participate in data analysis



WALTA Sites around Seattle



WALTA sites

Now running

Up soon

(Total 16:

12 schools +

2 @ UW +

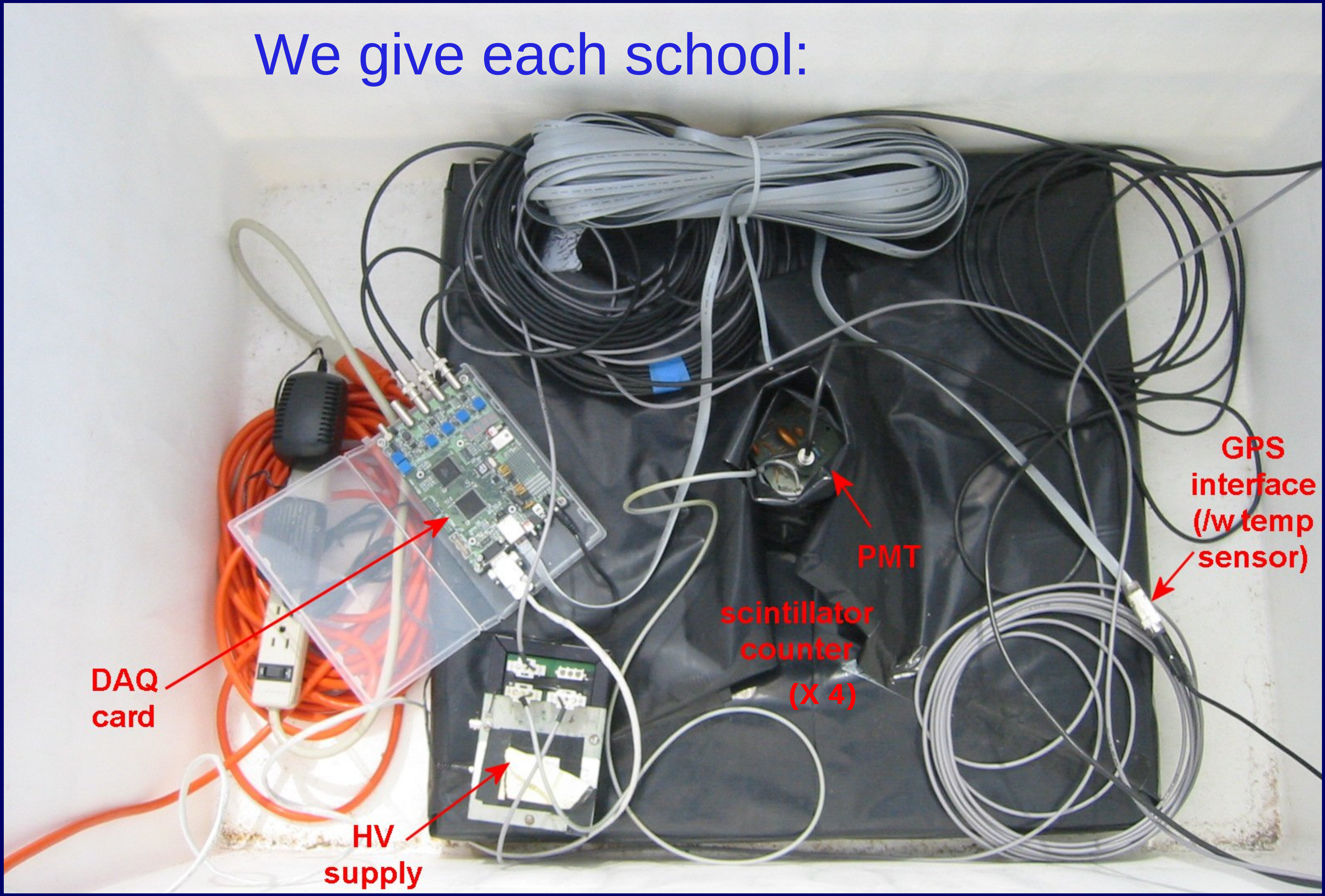
2 homes)

6 more schools have equipment and training but are not yet ready to set up an array

Size of AGASA

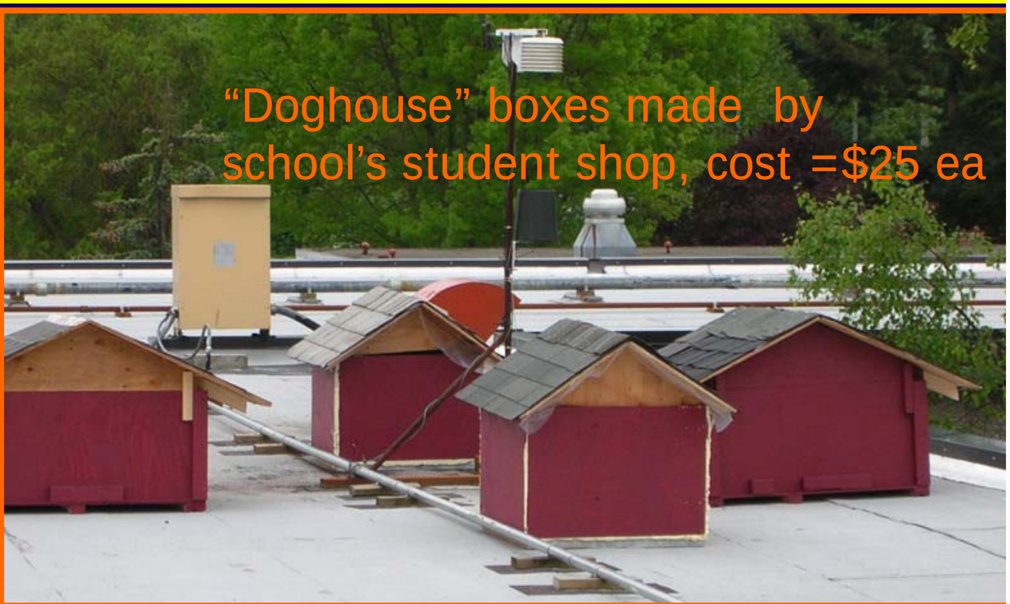
Size of Auger

School contributes: students, Internet, PC, space, boxes



Example sites: UW-APL and Nathan Hale H.S.

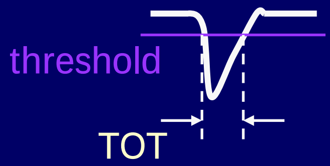
Plastic boxes for food storage,
cost = $100 ea



"Doghouse" boxes made by
school's student shop, cost =$25 ea

WALTA/CROP/Quarknet Custom DAQ board

- Design requirements:
  - Handle 4 channels of PMT input with adjustable thresholds
  - Selectable 1- to 4-fold majority trigger logic
  - Relative arrival times of pulses with < nanosecond precision
    - Uses KEK/ATLAS TMC chips and CPLDs
    - Can estimate pulse area via time over threshold:



  - Onboard scalers for singles and trigger rates
  - Trigger times stamped with GPS time to ~20 nsec
  - Simple digital interface to any PC via serial port
  - Low cost (under US$500 per board for parts)
  - Reliable and robust
  - Simple enough so high school students can use it

“Low-Cost Data Acquisition Card for School-Network Cosmic Ray Detectors”, S. Hansen, T. Jordan, T. Kiper, D. Claes, G. Snow, H. Berns, T. H. Burnett, R. Gran, and R. J. Wilkes, IEEE Trans. On Nucl. Sci. 51, 926 (2004).

QuarkNet DAQ Board

CPLD
(Programmable fast logic)

Time-to-digital converter (KEK TMC)

Discriminator threshold trimpots

Serial port (output to PC)

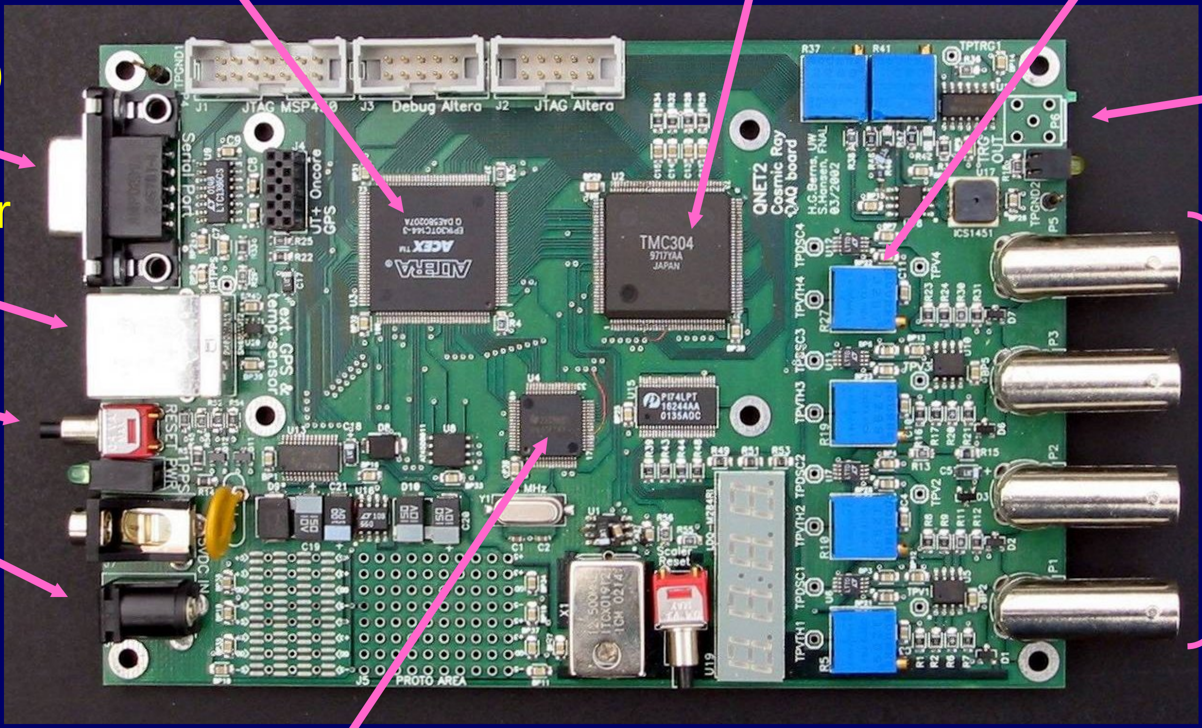
GPS connector

Reset switch

5V-DC input

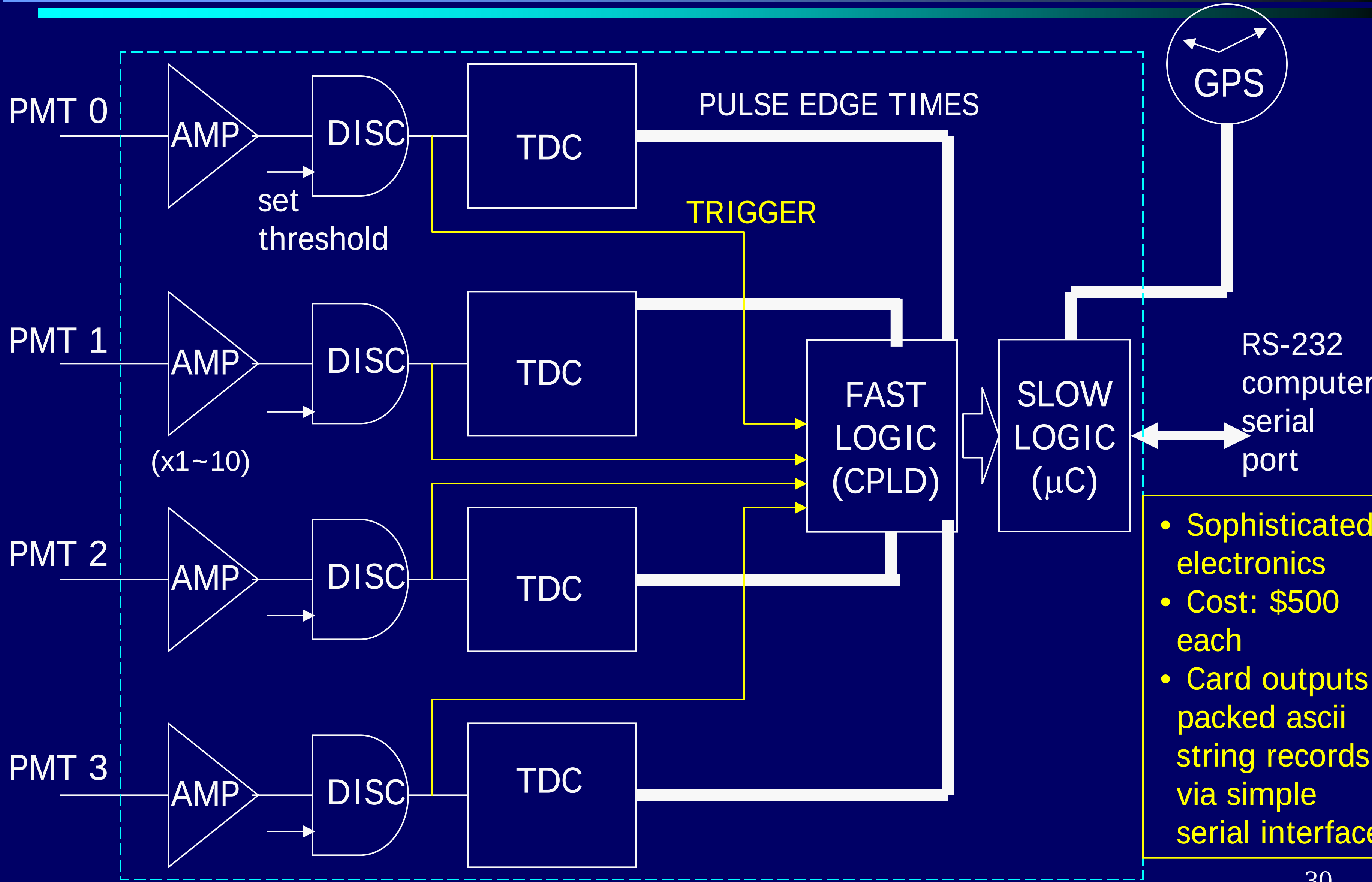
Trigger output

Inputs for 4 PMT channels



Microcontroller (Programmable slow logic / interface)

Quarknet Data Acquisition Card (supplied by Fermilab)



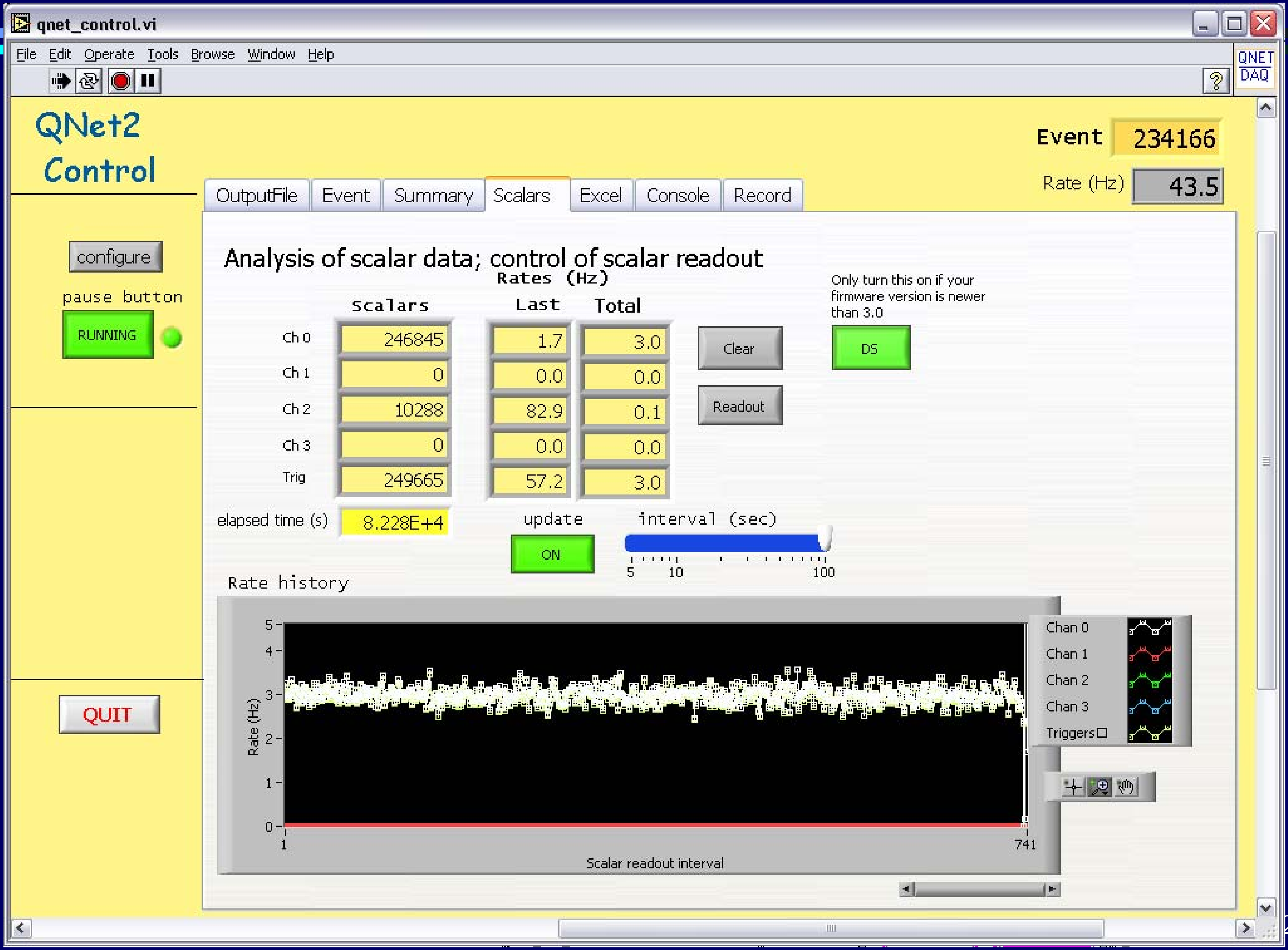
- Sophisticated electronics
- Cost: $500 each
- Card outputs packed ascii string records, via simple serial interface

Tools for reading out DAQ card

- Physicist-written C++ software to unpack ascii strings
  - Typically difficult to modify!
  - or
- UW student-written GUI (help from T. Burnett) in LabView
  - LabView = National Instruments ® product
    - visual programming environment
    - easy to create GUIs for unique applications
  - Widely distributed at very low cost to schools and colleges
  - Widely used in industry
    - Stable and well supported by National Instruments
    - Many users -- many help and source code websites
    - Learning LabView is a useful job skill!

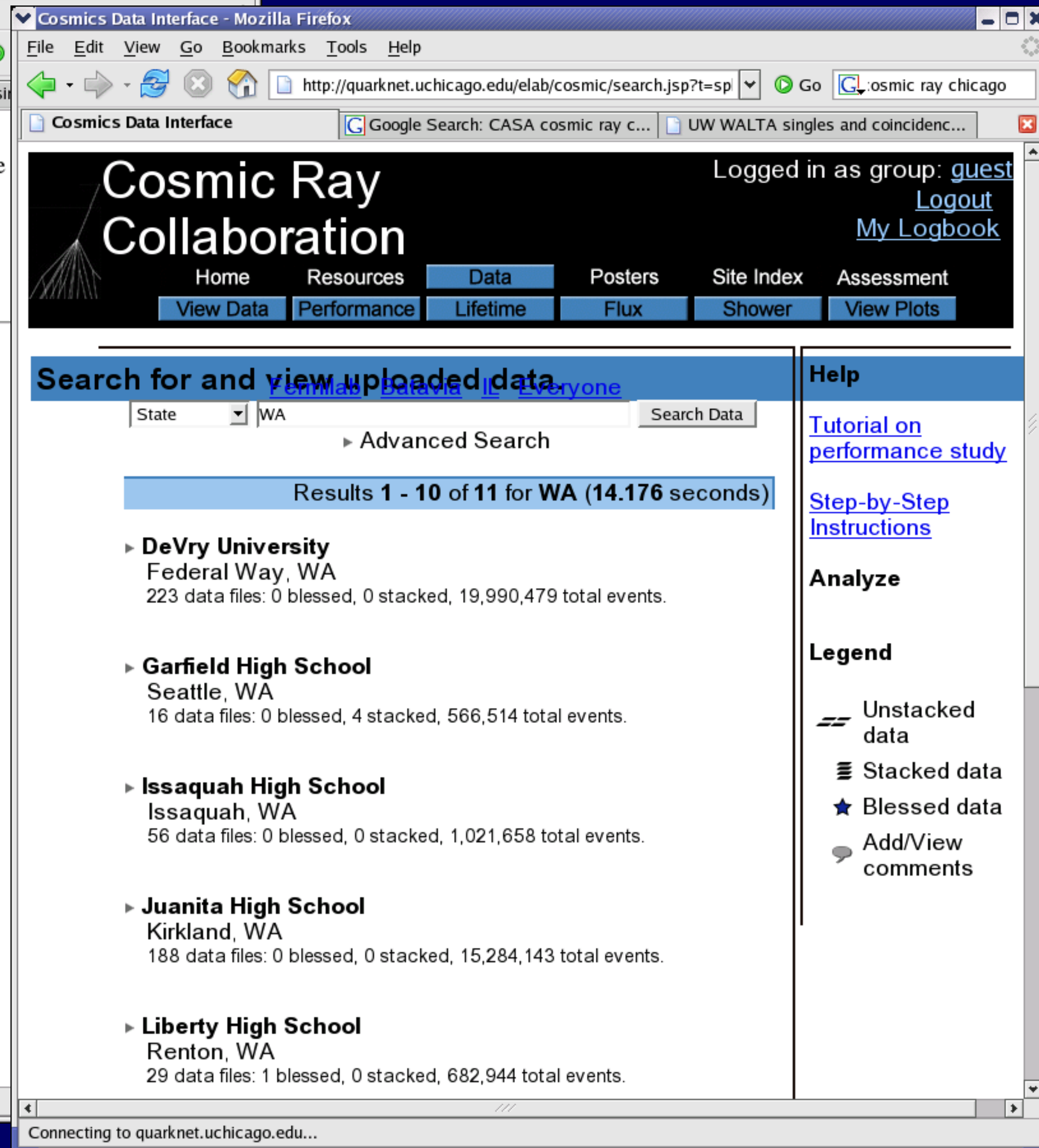
Labview software

J.Wilkes, 11/22/05



Websites: WALTA and QuarkNet (Fermilab)

Simple data upload, help with analysis and posting data



WALTA Web resources

- WIKI board, sample how-to

RecentChanges | FindPage | LikePages | BackLinks

Walta Message Board

We are ready to set the thresholds, but I have some questions. What should the HV suppl
summer we set it at 1900 V, but I believe at the winter meeting 2500 volts was recommend

After the power supply, we need to adjust the threshold to different mV levels. Where do
probes to read this? (Positive probe goes where? Negative probe goes where?) Is there a r
between the multimeter reading (regular digital multimeter with regular probes)and the mV?

If there is any other hint to setting the thresholds, please pass it on. The students are finally
sports but the year is drawing to a close. I would like to have this group of students finish
nim crates before we begin next year with the new software.

Thanks.

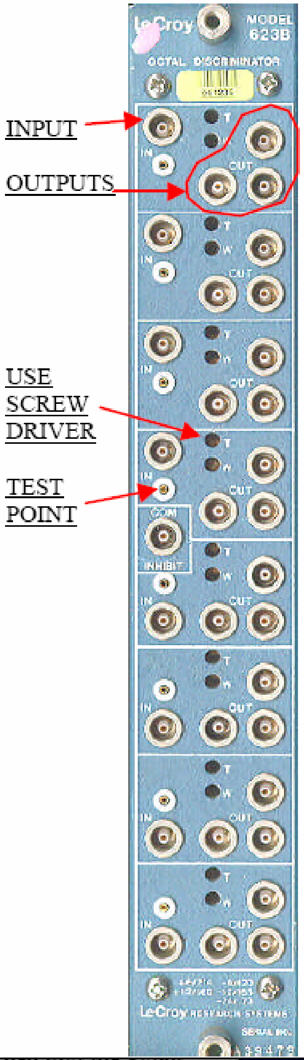
Monroe High

Okay, you should set your HV supply between 1900V and 2100V. The 2500V that was m
was for when you do the muon telescope.

As for the multimeter probes. There should be a white circle with a metal thing in it for eac
ports. This is the sense for the discriminator, it will be easy to find it is the smallest hole, b
threshold holes. This is where you put the positive end of the probe. Now you can do one
ground. The first thing you can do is put the ground on the side of the discriminator case,
ground port in the NIM crate (it should be next to the on/off switch). All the voltages that
multiplied by 10 from their real value, so divide by 10 (i.e. if you read 1000mV on your m
is really at 100mV).

In order to actually set the thresholds go in increments of 100mV on the multimeter scale.
rate you get for each threshold on a graph and then log both sides. Then look for the kink in the graph and that is

Octal Discriminator



General

Discriminator serves to eliminate signals with amplitude less than threshold. Each of 8 channels provides three identical and independent standard outputs.

To use

Turn the crate off. Push the discriminator along crate's guide rails until it plugs in. Turn the power on. Use LEMO connectors for input and output channels.

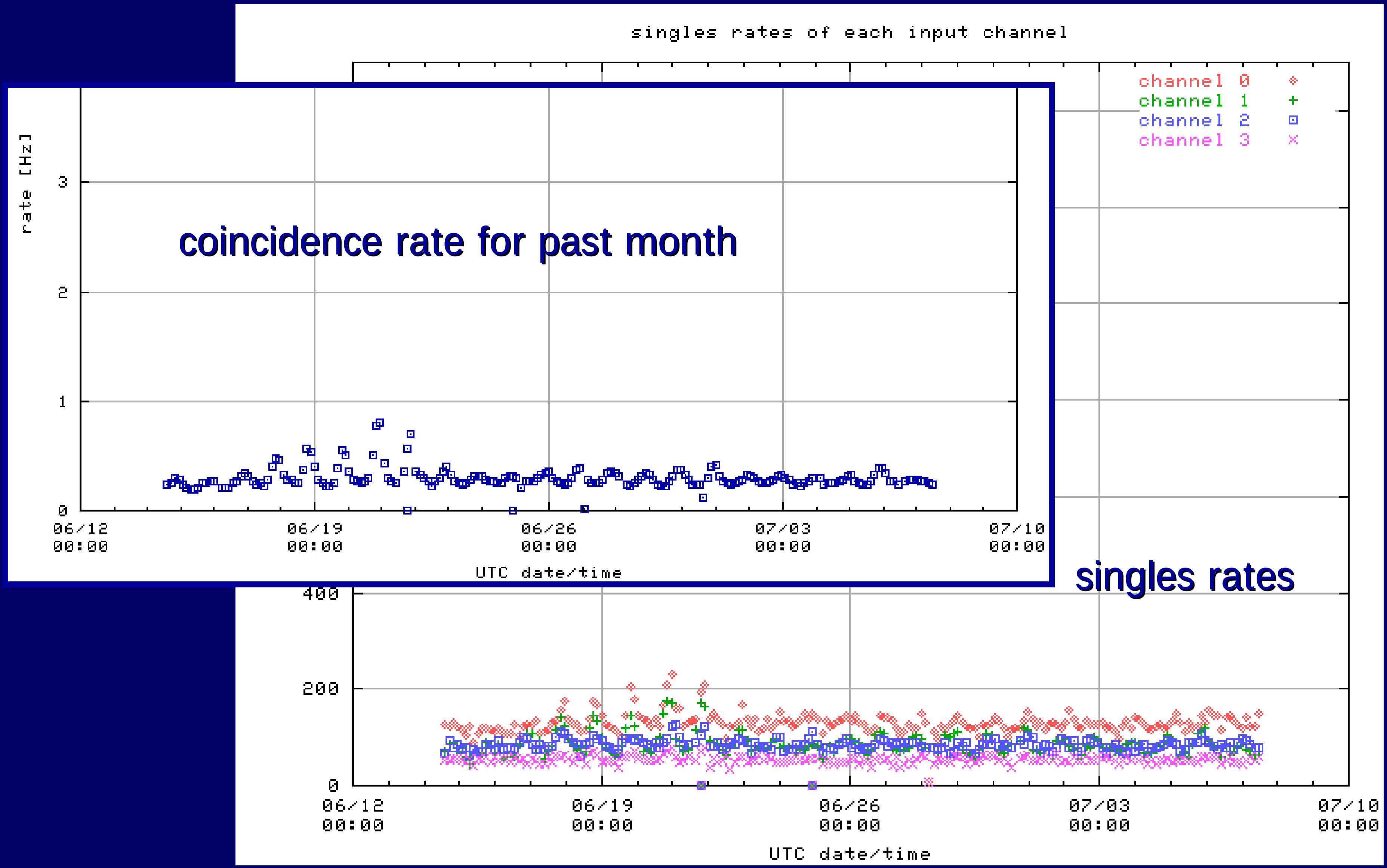
To adjust a threshold

Use an external DC voltmeter to monitor threshold setting by touching a test point. Voltmeter's reading will be 10x the threshold setting (e.g. 300mV reading means 30mV threshold setting). Use jeweler's screwdriver to adjust a threshold. The screw is delicate and recessed 1.5 cm. You may need to gently feel around to engage the screw head.

To adjust the width of the output pulse

Use a scope to monitor the with of the pulse. Again, use a jeweler's screwdriver to adjust the width (marked "w").

Sample of online monitoring plots (on UW website)



We have data (at the “first light” stage)

For all data, all sites:
~400 two-site events
0 three-site events
Consistent with accidentals (excluding UW sites):

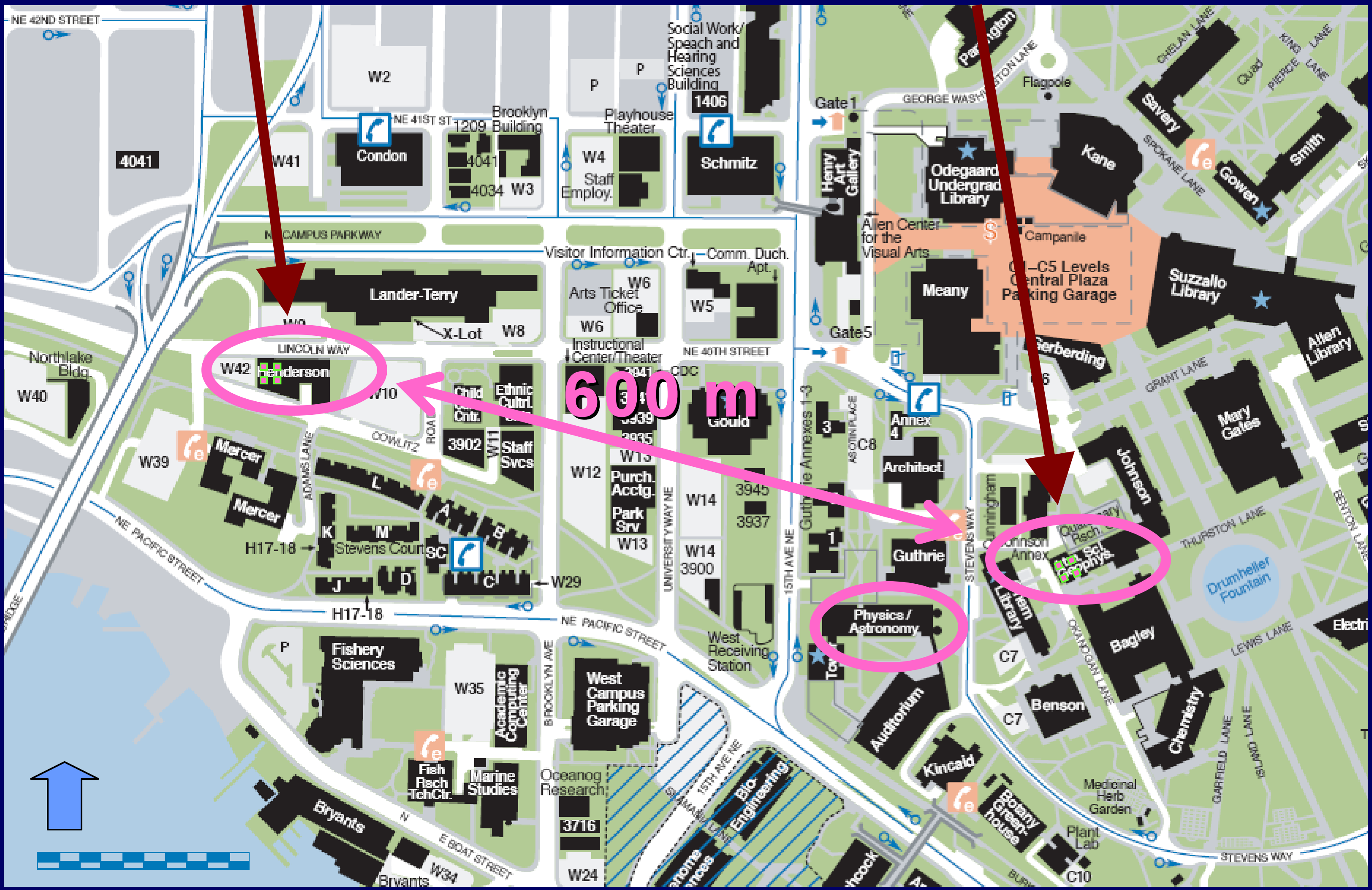
Check the 2 *closest* sites (on UW campus, δx = 600 meters)
Overlap livetime = 185 days, expect about 5 accidentals
Find 205 events
So about ~ 1 coincidence per day for real air showers
(Consistent with expectation from CR flux)

Conclusion: We see real air showers, and big 1-site events,
but so far no real + big air showers

Locations of UW campus arrays

Applied Physics Lab

Atmospheric Sciences



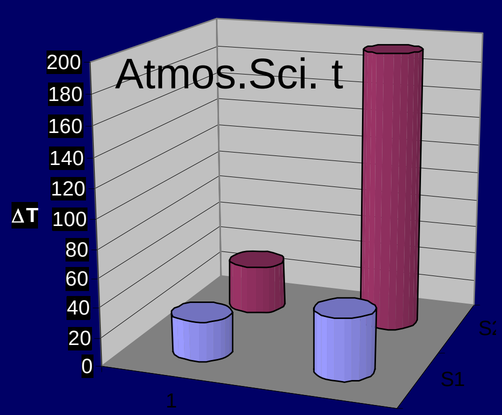
Data examples:

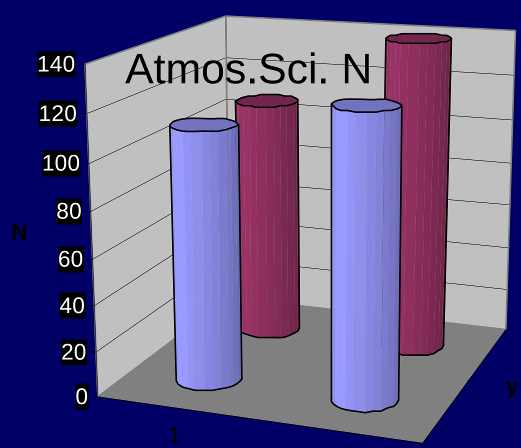
- Likely "real" event:
  - Δt between site triggers = 336 ns

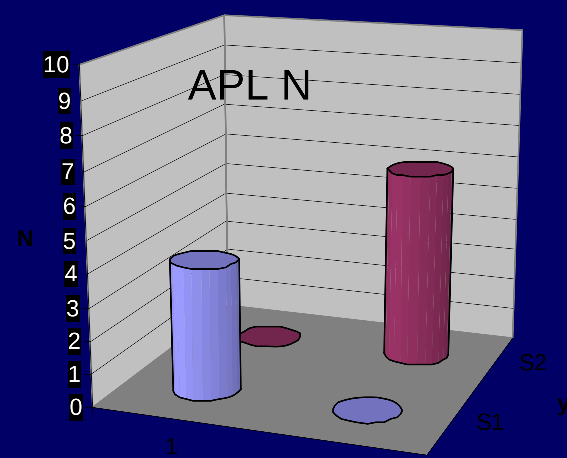
Number of particles in counter:	N_1	N_2	N_3	N_4
Applied Physics Lab:	4	3	6	0
Atmospheric Sciences	30	34	46	53

- Biggest event at one site:
  - Δt between site triggers = 864 ns

Number of particles in counter:	N_1	N_2	N_3	N_4
Applied Physics Lab:	6	0	0	4
Atmospheric Sciences	111	124	108	140

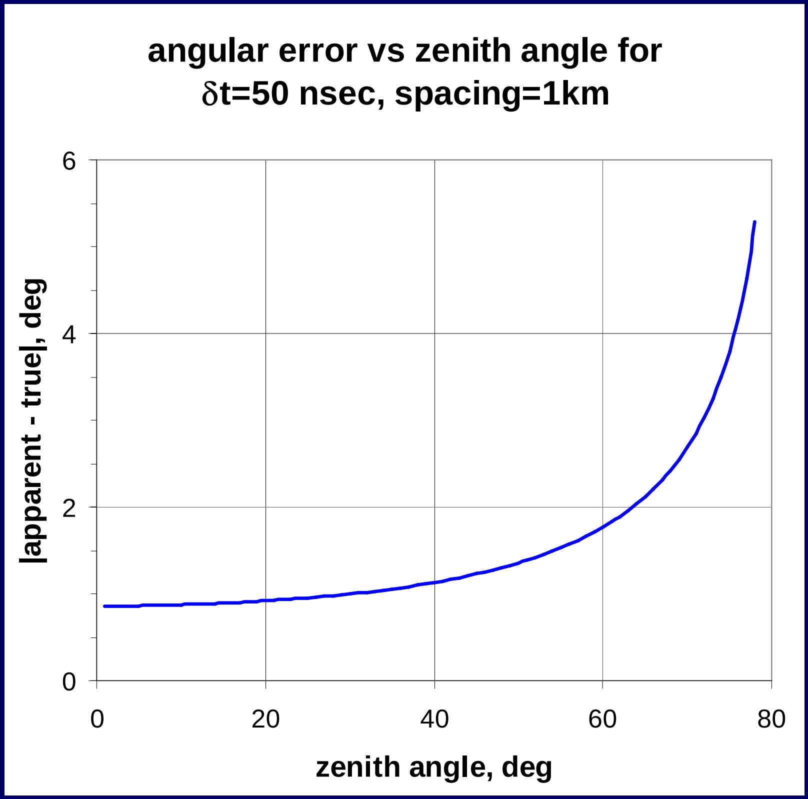




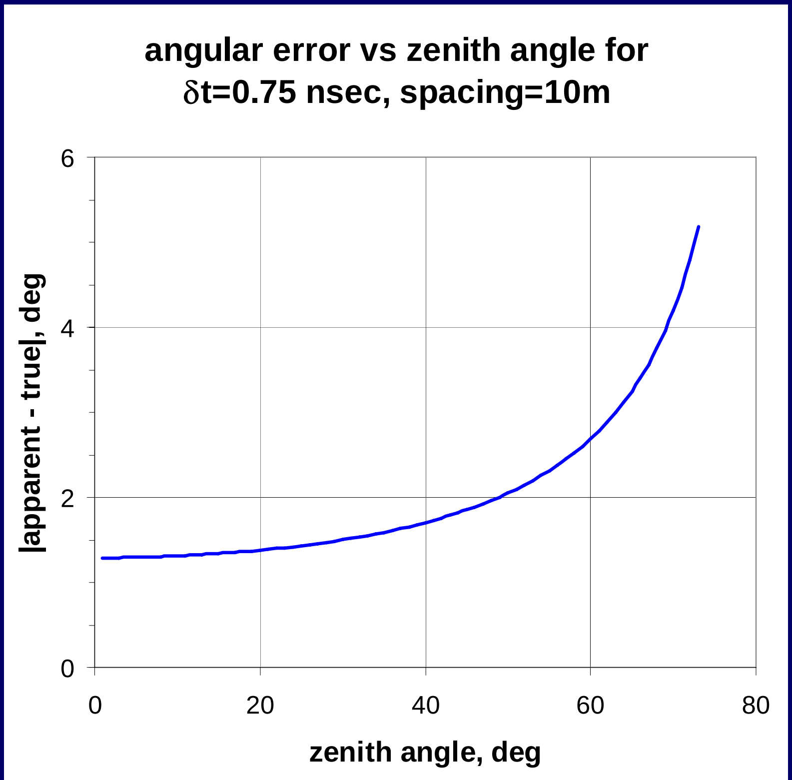


Can we find shower directions?

- Between different sites, we have 50 ns GPS time accuracy
  - For sites spaced 1km apart



- Within one site, δt ~ 1 ns
  - For counters spaced 10 m:



Summer Workshop for Teachers
Step 1: polishing counters

Salvaged 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

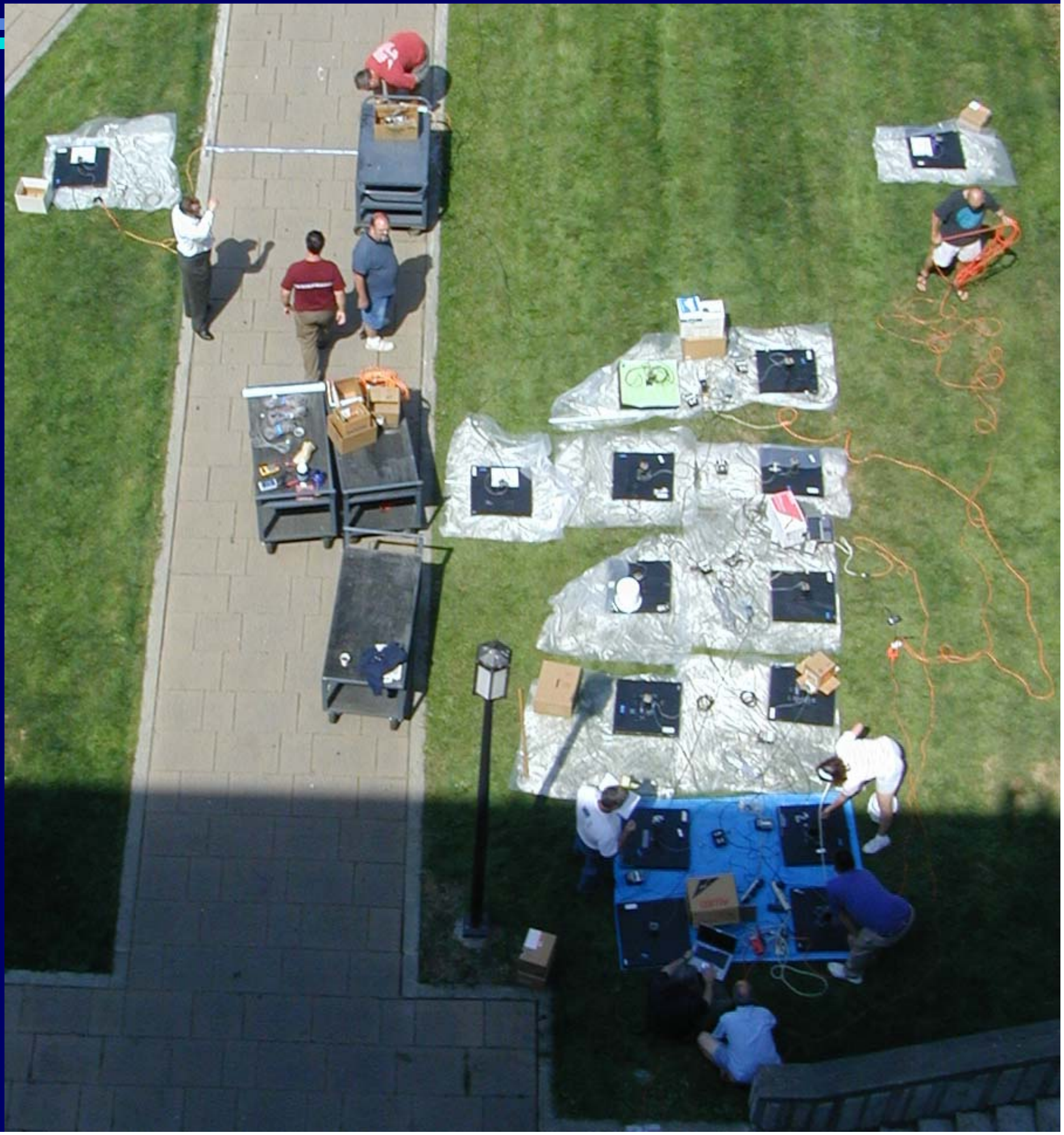
- Welcome to the world of experimental physics! Teachers wonder why the counting rate is not as expected...

- Making a 2-layer cosmic ray telescope

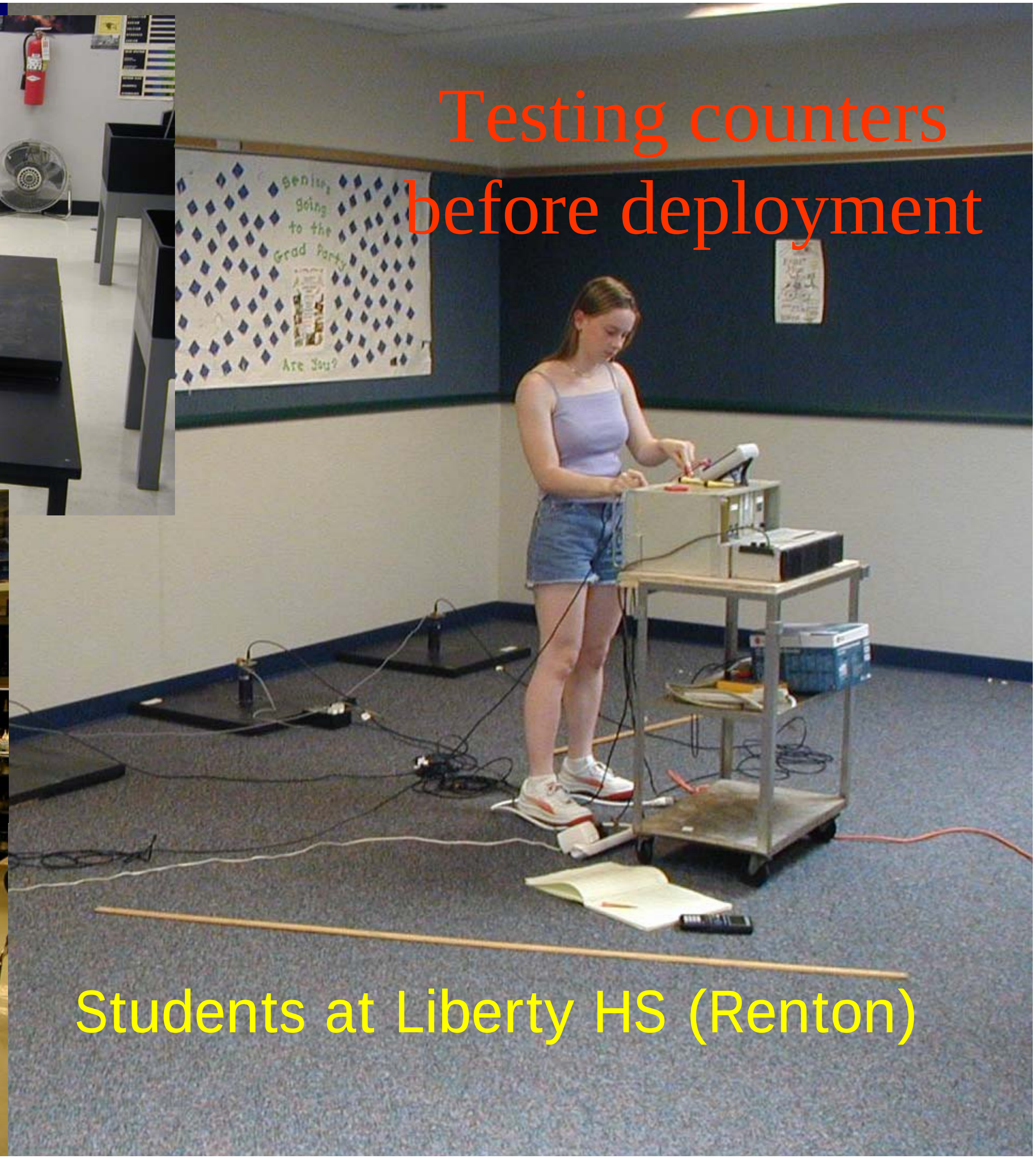
- Next: teachers take what they learned into their classrooms...

Summer '03 Workshop

- WALTA teachers at work setting up array at UW Physics Dept.
- M. Buchli helped organize and run the workshop



Testing counters before deployment



Students at Liberty HS (Renton)

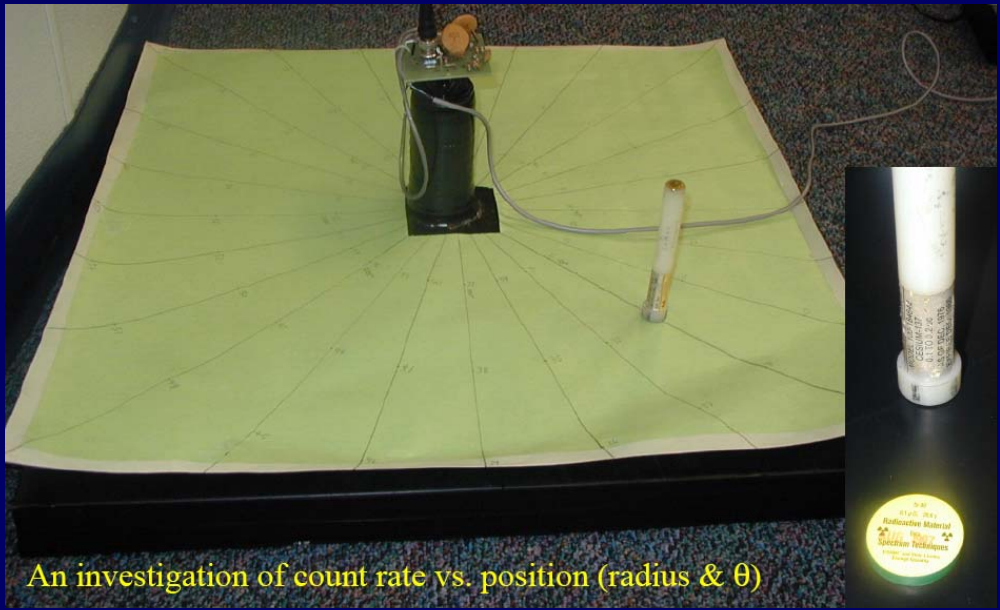
WALTA June '05 "collaboration meeting"

Half-day of presentations from the schools and UW.
Different approaches:
In some schools WALTA = "physics club" activity
Other schools WALTA = class activity

...also yearly 1-week summer workshop for teachers

Classroom examples: simple counting experiments

- Using standard lab radioactive source
  - Students measured efficiency of counter vs position
- Using living source!
  - Teacher had to ingest radioisotope for a medical test.
  - Students measured the counting rate from their teacher to get isotope lifetime
  - Counts taken several times during day following test



An investigation of count rate vs. position (radius & θ)

Mr. Tom Haff =
Source for 2nd experiment

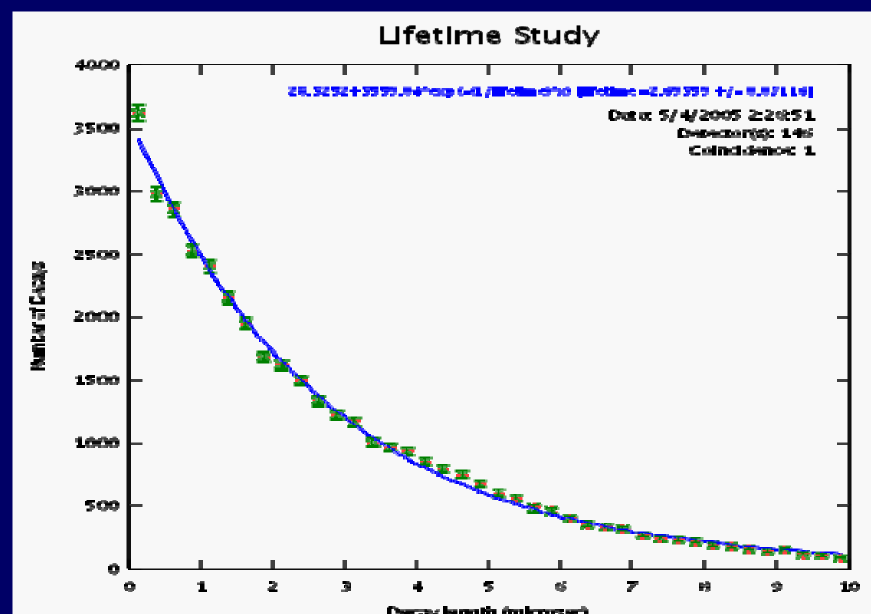
Classroom project: Muon telescope

- Stack three or four counters vertically
- Look for downward-going muons passing through all of them.
- Check timing:
  - Are they really downward moving?
  - How fast are they going?

  (Set up in stairway for LONG Δz)

- Also: look for stopping muon decays and measure muon lifetime.
  - DAQ card allows 1 channel to be used in anticoincidence

(Plot produced with QuarkNet web tools)



Decay time (microseconds)

Class project: Beowulf computer cluster

"Whenever you have a computer question, just ask a 16-year old!"
- J. Wilkes

Liberty High School
built a computing cluster from surplus PC's, using Beowulf software
(see http://www.beowulf.org/)

Students did most of the work themselves

We can use this resource to run WALTA air-shower simulations

Challenge: “imperfect” equipment

- Most of our equipment spent 10 years in the Utah desert
- Other parts were designed, built, debugged, redesigned…
  - DAQ board is a “work in progress”
  - LabView User Interface was built by students and faculty, not by GUI design experts
- All of this for use by non-expert teachers and students!
  - Enormous challenge to make hard/software robust and reliable
  - Physicists think “It’s OK when I check carefully, so it’s just good enough” (Fermi’s criterion for hardware)
  - High school teachers and students think “it’s broken!”

    (or worse, “I'm too dumb to figure it out - better not study science!”

Challenge: maintaining student/teacher interest

- These are long timescale projects
  - Schools get a new group of students every year
  - Often new teachers too! Must be rewarding for teachers to join
    - Quarknet gives them stipends, Fermilab visits, etc

Strategy:

- Repeat short-term in-classroom experiments every school year to ‘train’ students
- Make sure teachers and students can set up easily using web resources
  - University people can’t come fix every time!
- Provide good classroom and web materials
  - Worldwide interest group

Lessons learned

- Hands-on element is important
  - demystifies "ultra-high energy cosmic rays"
  - Teachers jump at a chance to work on projects like Super-K and K2K
    - Can make significant contributions by supervising teams of undergrads!
- Hard to involve schools in large cities: too many bureaucrats!
  - Currently only 2 Seattle schools, all others are suburban or private
- Need new ways to support teachers
  - Many teachers want to spend summers working on WALTA
  - Longer-term support is critically needed
    - Every funding agency loves 'startups', nobody wants to 'sustain'
    - Fact of life in America: school districts/states have no money!
- Avoid being too fancy
  - Teachers don't need to learn SUSY to contribute (and benefit)
    - We can *never* give a full development that satisfies fellow professors
    - It's fun and useful to learn bits and pieces of physics

Byproduct: HS physics teacher helped at Super-K

Mark Buchli
(Liberty HS)

- Spent summer ‘02 at Super-Kamiokande helping rebuild the detector (funded by Murdock Fouondation grant)
- Supervised teams of student workers (very expert managing young people!)

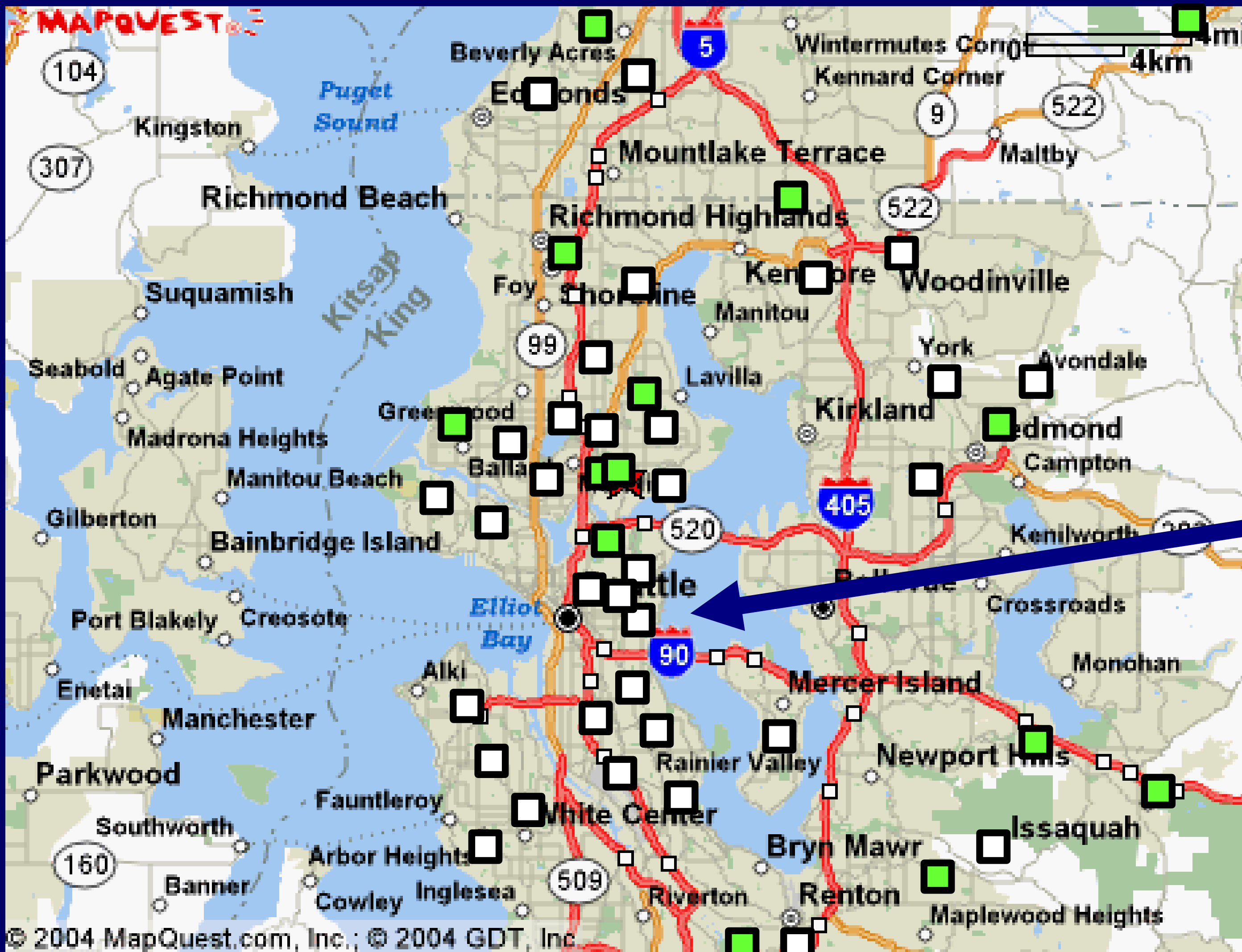
US students prepping PMTs for installation

WALTA Progress

- Add 2-year college sites (Green River CC, DeVry Univ.)
  - Students have tech skills, can mentor HS groups
- Involve undergrads and MS degree students at UW
  - Undergrad majors are required to do 'independent study' research
    - enthusiastic undergrads are a mainstay of the program
  - Evening MS degree program includes many teachers and industrial/government R&D techies who are interested in education
    - Two high school teachers currently writing WALTA materials for their MS degree projects
- Get experienced teachers to mentor new members
  - University faculty cannot lead a full-size WALTA array (~30 sites)
    - Probably will never have funds for full-time staff
    - Enthusiastic lead teachers can help less-confident new members
  - Developing web-based resources for trouble-shooting, exchanging tips and tricks, networking between school districts

"Real" science goals require expansion

Need 5X current WALTA sites to really see 10^{20} eV cosmic rays



High schools are densely spaced in city center

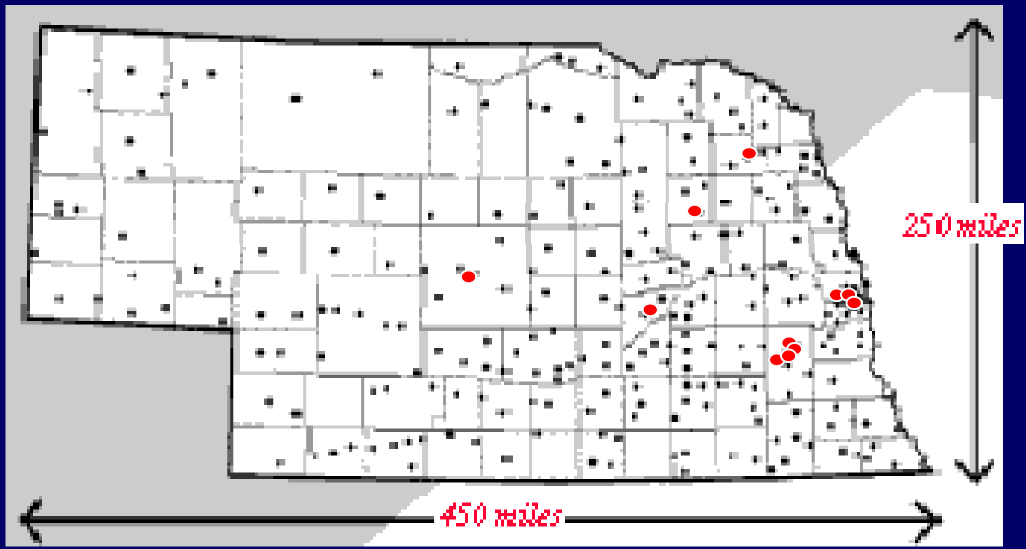
Also: we could add many middle schools

WALTA is part of a worldwide effort

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

Similar projects in
- Argentina
- Australia
- EU (England, Holland, Italy)
- Japan

Schools participating in CROP



CROP detector sites at Nebraska high schools

Joined CROP summer 2000

- Lincoln Science Focus Program
- Lincoln Northeast High School
- Mt. Michael Benedictine H.S.
- Marian High School
- Norfolk High School

Joined CROP summer 2001

- Lincoln Lutheran H.S.
- Lincoln High School
- Omaha Westside High School
- Anselmo-Merna High School
- Osceola Public High School
- Wayne State College

Curriculum Topics Available in CROP

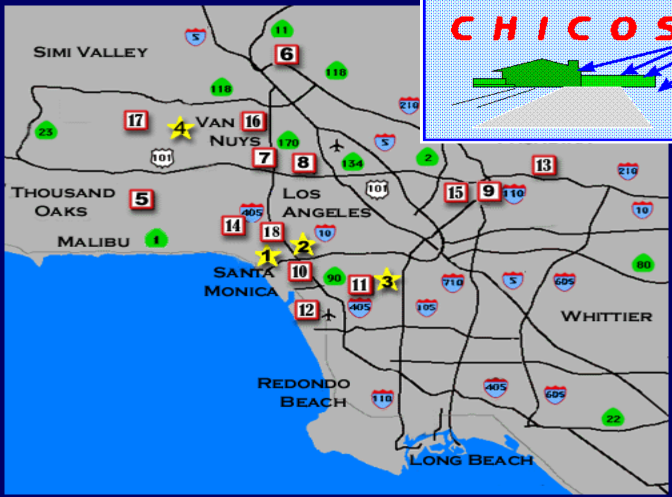
Classroom Curriculum

- 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 in N. America



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