Highest Energy Cosmic Rays: Probe of the Extreme Universe

Colloquium

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1. Background ... highest energy cosmic rays

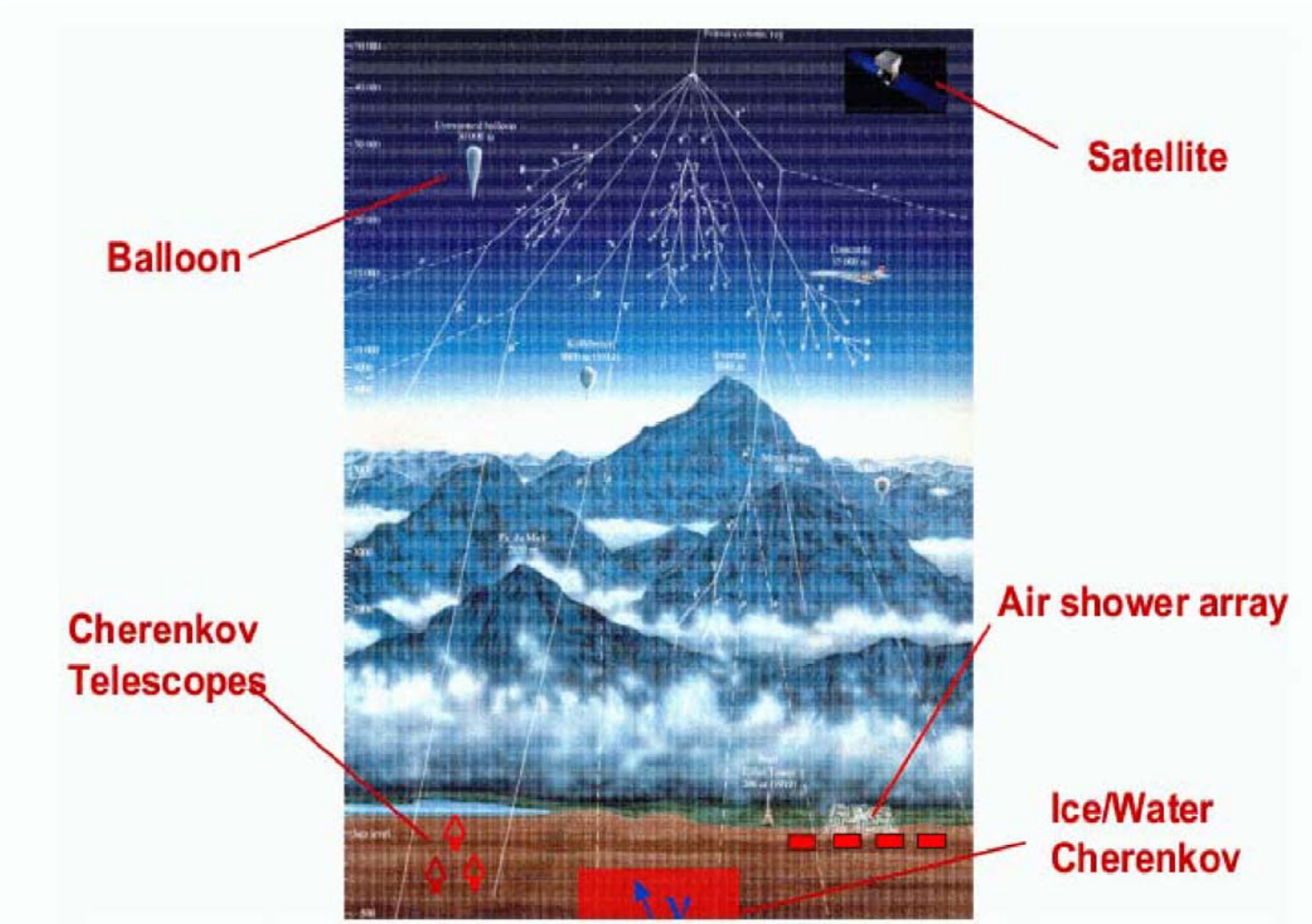
2. Status ...

3. Emerging model ...

4. Next (generation) experiments ...

5. Summary ...

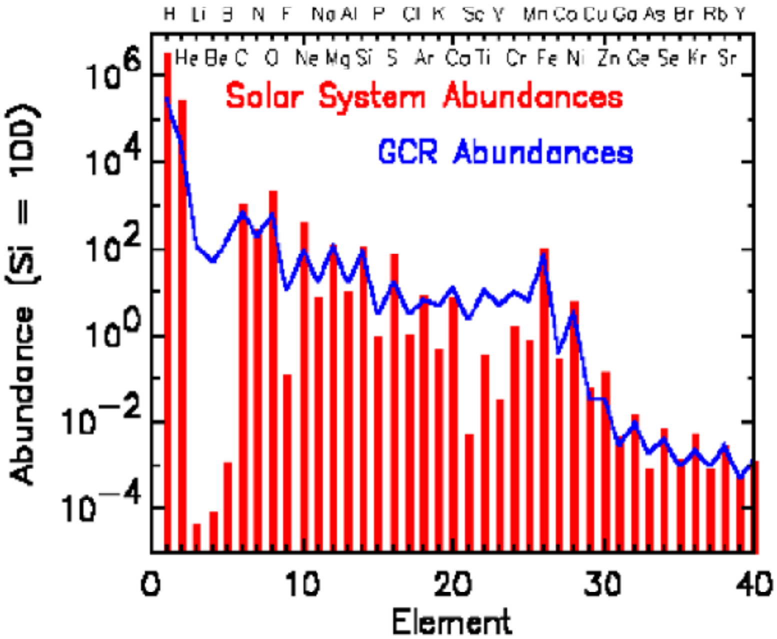
1. Background ... **what are cosmic rays?**



Cosmic ray detection depends on cosmic ray *type* **and** *energy*

- **Cosmic Rays (CRs)** ... *google Web definition*:
  1. Highly energetic sub-atomic particles, mostly protons and helium nuclei, which travel across space at close to the speed of light *and then rain down on the earth.*
  2. The lowest energy cosmic rays originate in the Sun; higher energy ones from supernovae and pulsars within the Galaxy, whilst those with the **highest energy of all may be extragalactic in origin, possibly from quasars and active galactic nuclei**.

1. Background ... **more than "p and He"!**



- Composition (at ~GeV):
  85% H (p)
  12% He (α)
  1% heavier nuclei
  2% $e^{\pm}$ (≥90% e^-)
  10^{-5}-10^{-4} antiprotons.

Cosmic ray abundance normalized to silicon

Source physics is best unraveled using many different observations *e.g. radio, visible, X-ray, ...*

Particle astrophysics experiments extend these measurements to include:

- "protons" (special case of *light* nuclei)
- "iron" (special case of *heavy* nuclei)
- **"gamma"-rays**
- **neutrinos**

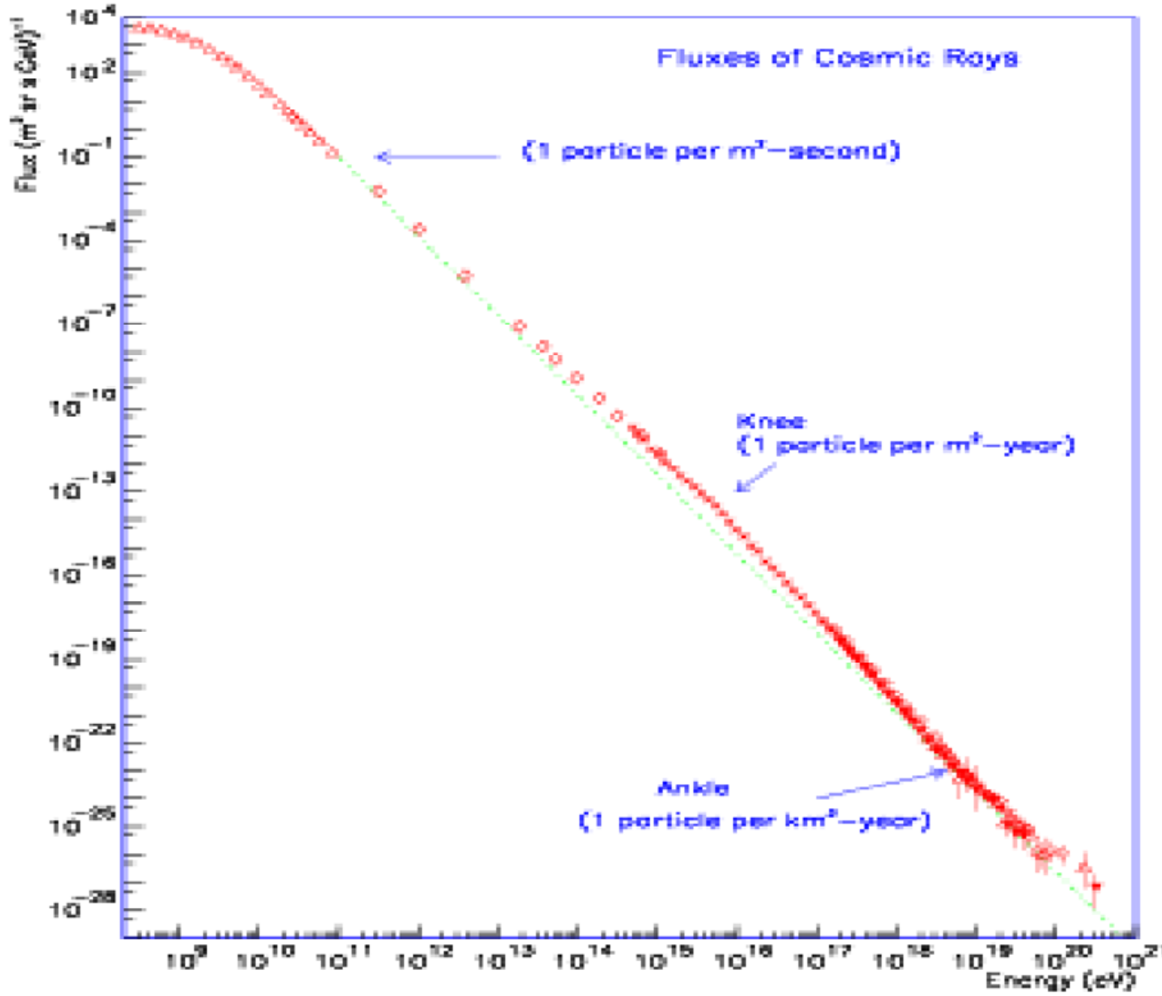
1. Background ... **the actual observables!**

- **Energy:**
  - the number of CR events *versus* energy is called the CR **spectrum**
  - the reconstructed energy of each primary CR has a precision $\sim 20\%$

- **Arrival direction:**
  - the reconstructed direction of each primary CR has a precision of $\sim 1^\circ$
  - as (conventional) CRs are charged, galactic and extra-galactic magnetic fields influence the CR arrival directions!

- **Particle type:**
  - the particle type, at a given CR energy, is called the CR **composition**
  - for (conventional) CRs this is the least well determined quantity because of: large shower-to-shower fluctuations and Monte Carlo (shower simulation) uncertainties ... more later!

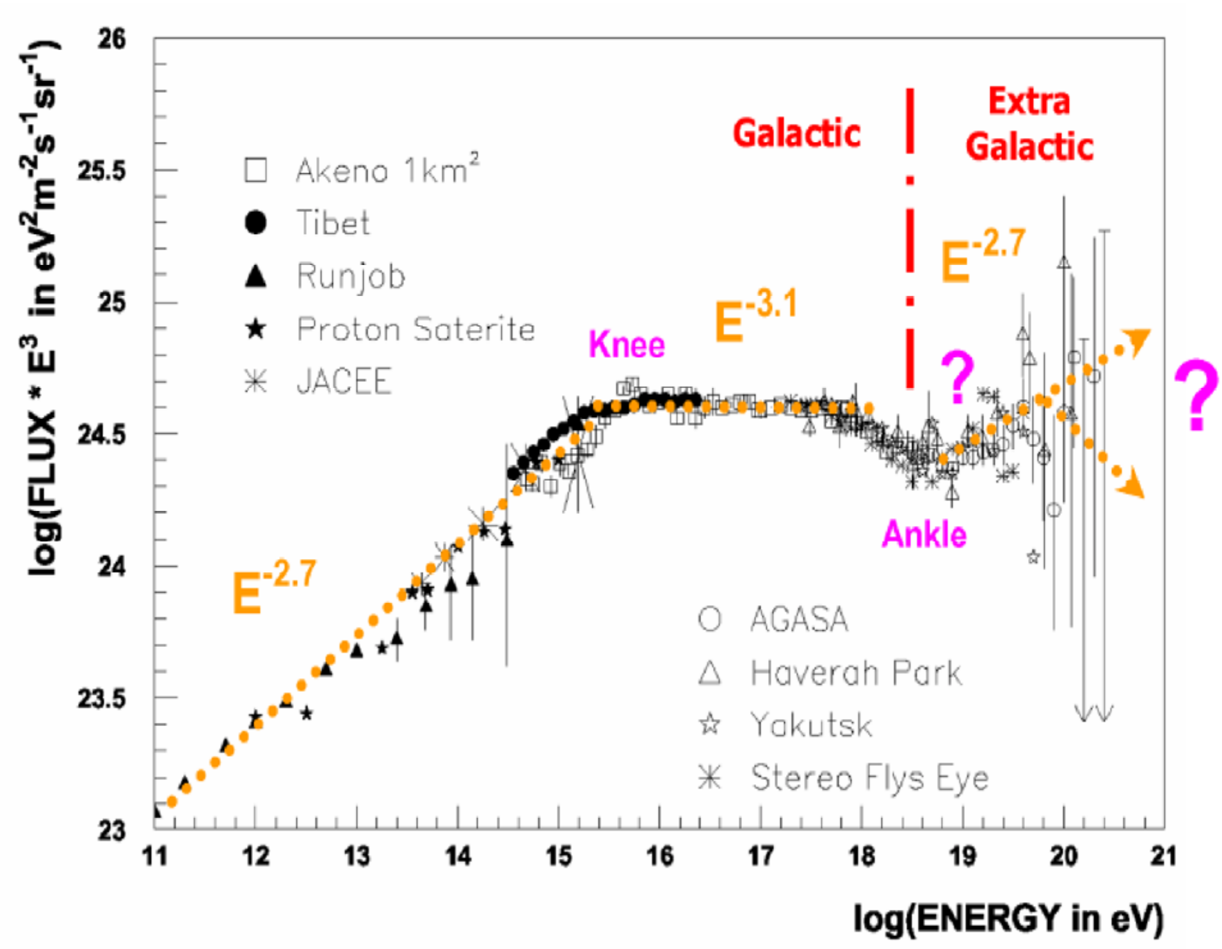
1. Background ... **end of the spectrum!**



Cosmic ray energy spectrum

- **Most interest at $\gtrsim 10^{20}$eV ... more later!**
- **Rate:** - low ($\sim 1/\mathrm{km}^2$/century) **...** so need large experiments ... about the area of Rhode Island! Fluorescence based experiments need dry (desert) air with good visibility.

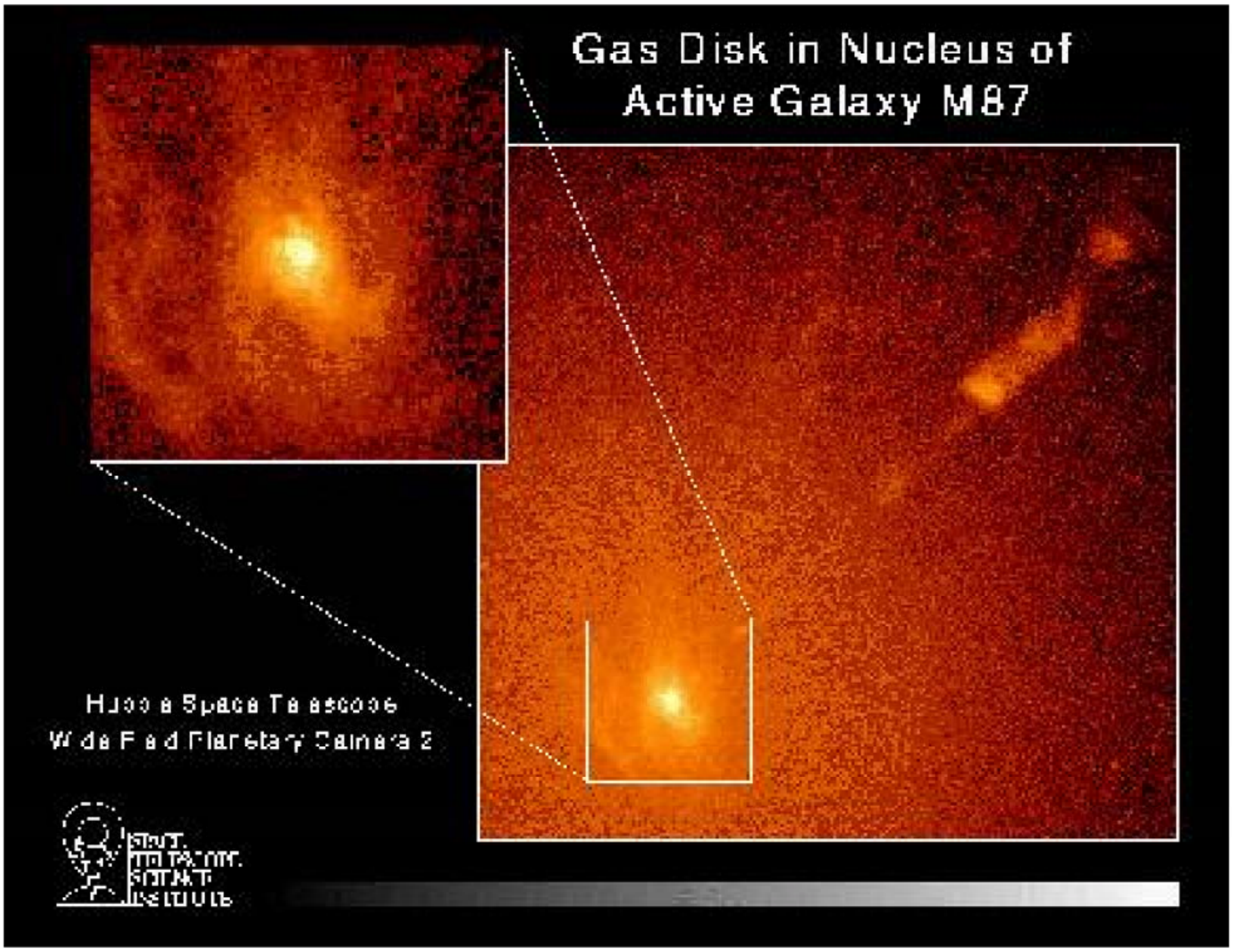
1. Background ... **not simple power law!**



Cosmic ray flux scaled by E^3

- **Structure in a power law spectrum:**
  1. *knee* at $\sim 4 \times 10^{15}$eV
  2. second *knee* at $\sim 4 \times 10^{17}$eV
  3. *ankle* $\sim 4 \times 10^{18}$eV
  4. *cutoff* **at** $\sim 10^{20}$**eV ... or not!**
- $10 \sim 20$ **events have been observed** $> 10^{20}$**eV!**

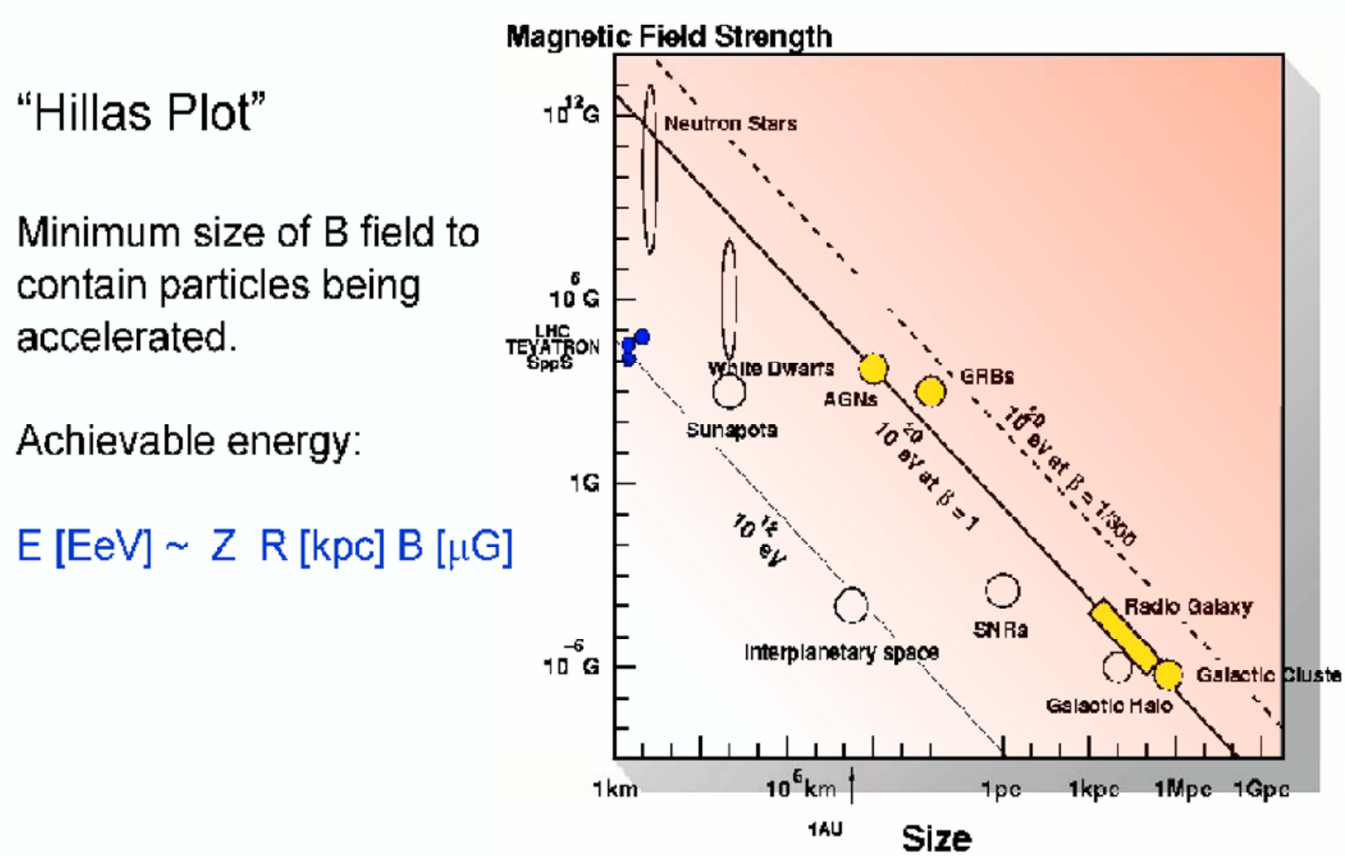
1. Background ... **more than "fine print"!**



(One) possible source of 10^{20}eV cosmic rays

- **Why do it? ... just a couple of reasons:**
  1. At these energies extra-galactic cosmic rays probably dominate local (galactic) sources.
  2. **At the same time the GZK cutoff** *predicts* **an end to the cosmic ray spectrum ... except for nearby ($\lesssim$50Mpc) sources.**

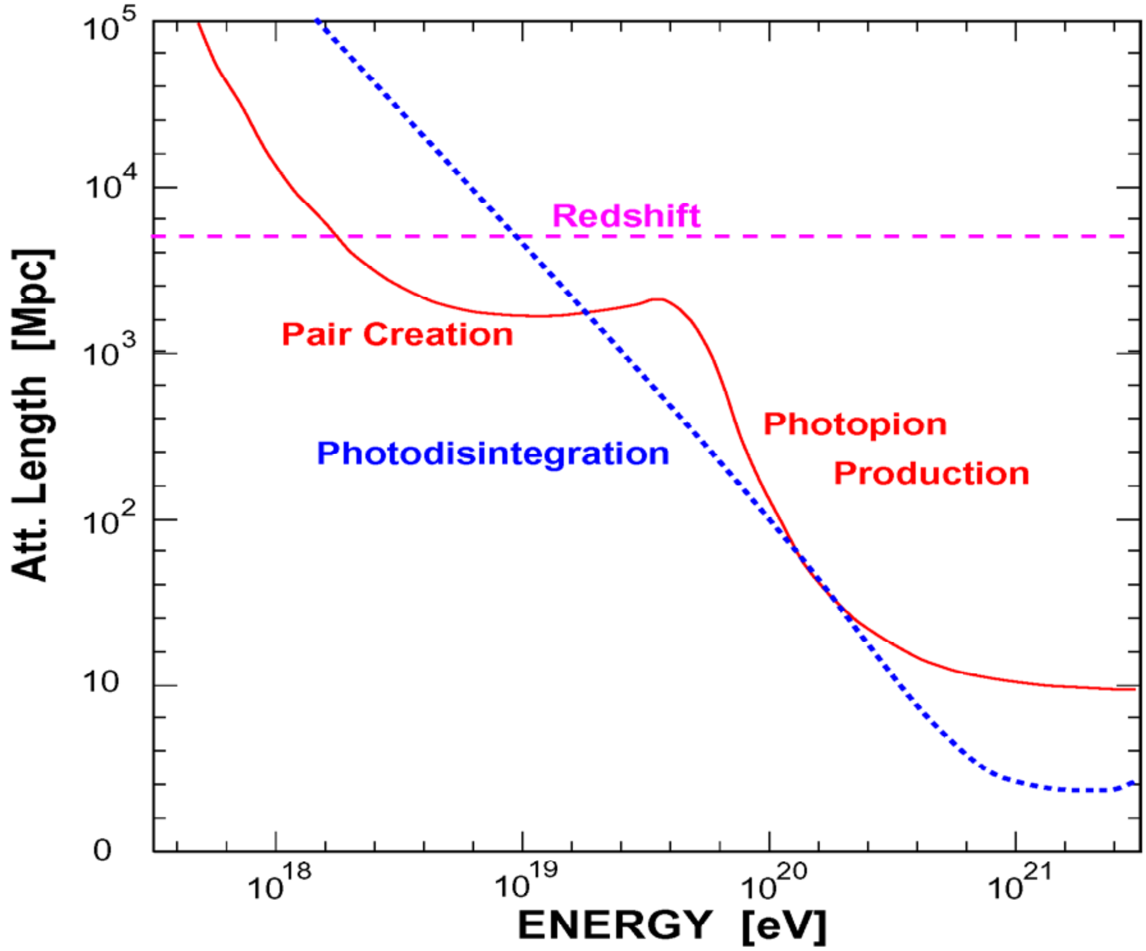
1. Background ... **only *ideas* at this time!**



Acceleration to 10^{20} eV is difficult ...

- **Classes of *possible* sources**:
  1. *Extreme* astrophysical sources: super-massive black holes, GRBs, colliding galaxies, ...
  2. *Particle physics* motivated: massive relic particles or relics of early universe
  3. **OR** new astrophysics
  4. **OR** new physics

1. Background ... **CMB *wall* at 10^{20}eV!**



Energy loss attenuation length, $\Lambda_{atten}(z=0)$

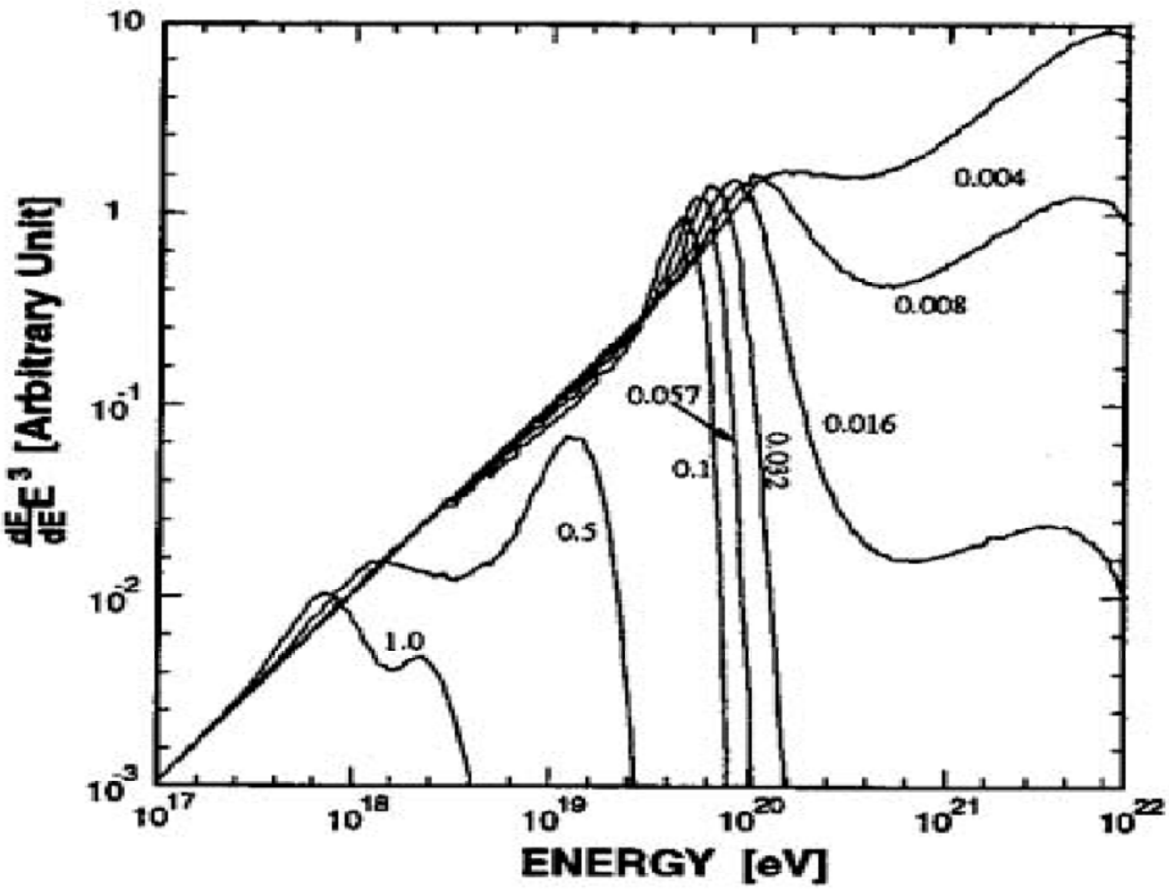
- **Greisen-Zatsepin-Kuz'min (GZK) cutoff:**

  1. Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, d:

  $$E = E_0 \cdot e^{-d/\Lambda_{atten}}$$

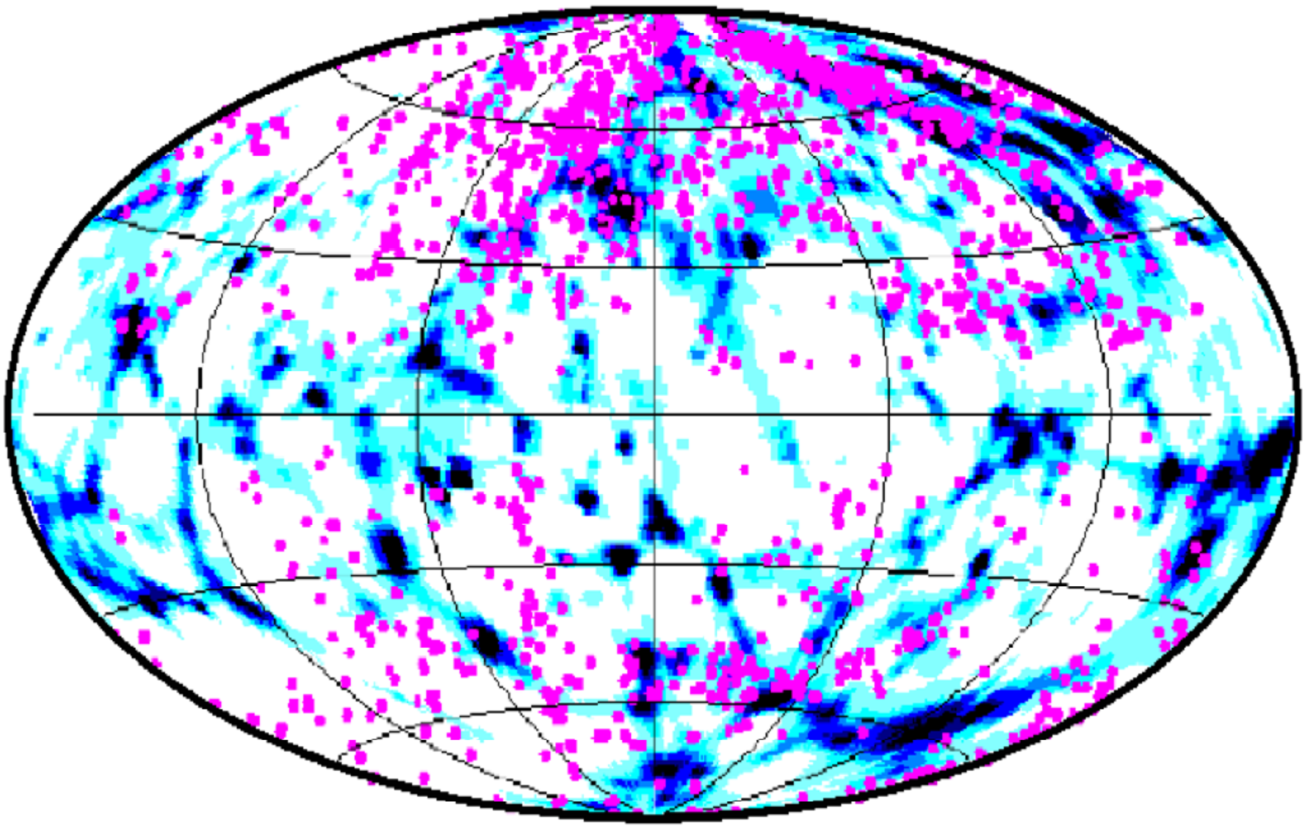
  2. Steep drop of Λ_{atten} near 10^{20}eV from the onset of π photo-production: $\gamma_{CMB}\, p \rightarrow \pi\, X$.

1. Background ... **p spectrum** *VS* $\mathbf{z}_{source}$!



- **GZK simulation (*proton* primary):**
  1. (Assumed) source spectrum: Flux(E) $\propto E^{-2}$
  2. *Observed* spectrum scaled by E^3 ...
  3. **Only sources with red-shift** $z \leq 0.03$ **(about 150Mpc) should have any flux above** $\sim 10^{20}$**eV.**
  4. *But cosmic rays with energies* $> 10^{20} eV$ *have been observed* ... **so sources should be nearby!**

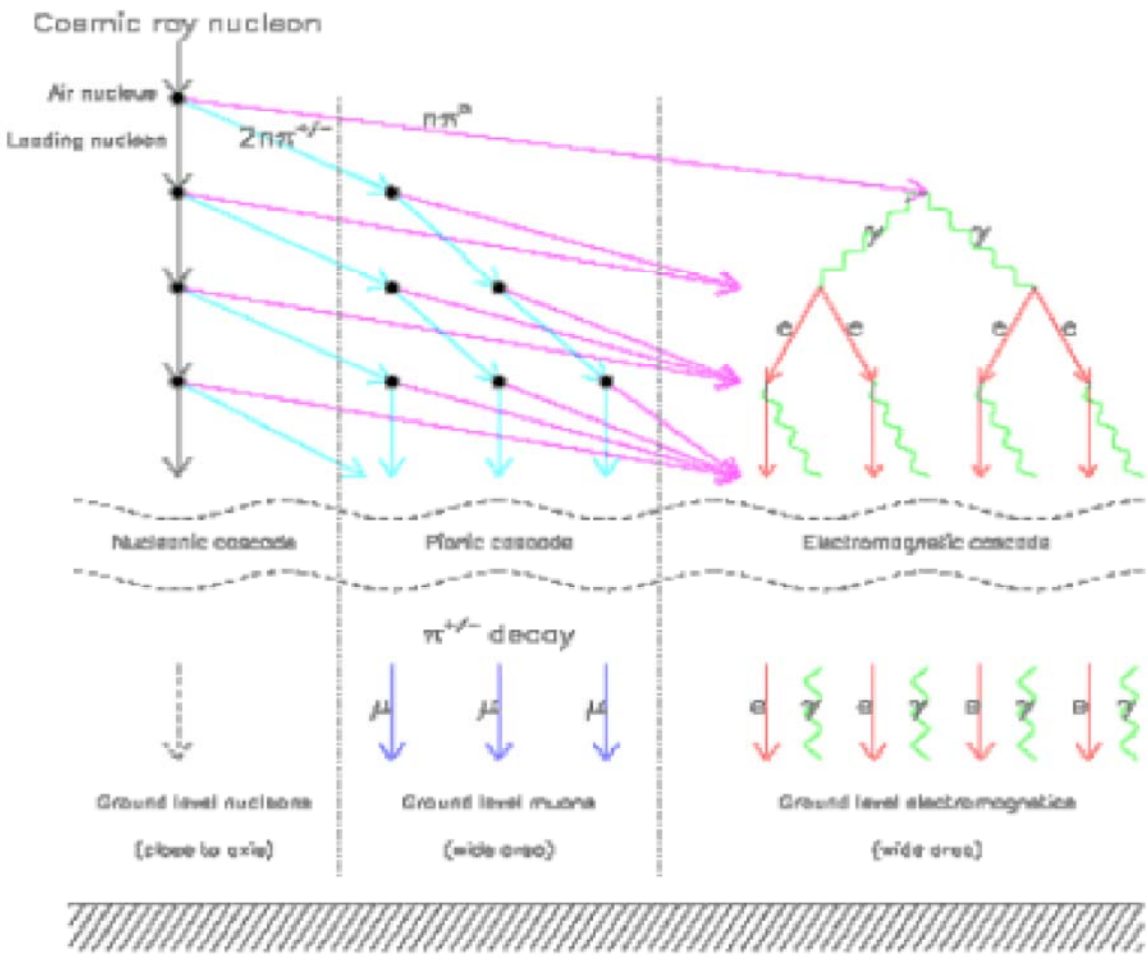
1. Background ... **will sources match?**



Galaxies (*pink*) and Dark Matter (*blue*) within 93Mpc
[courtesy A. Kravtsov]

- **For the highest energy ($> 10^{20}$eV) particles:**
  - High magnetic rigidity of primaries *if protons*
  - Nearby universe is not isotropic ... thus highest energy particles should not be isotropic
  - **Baring magnetic field surprises, arrival directions should *cluster* ... but will they and in which directions?**

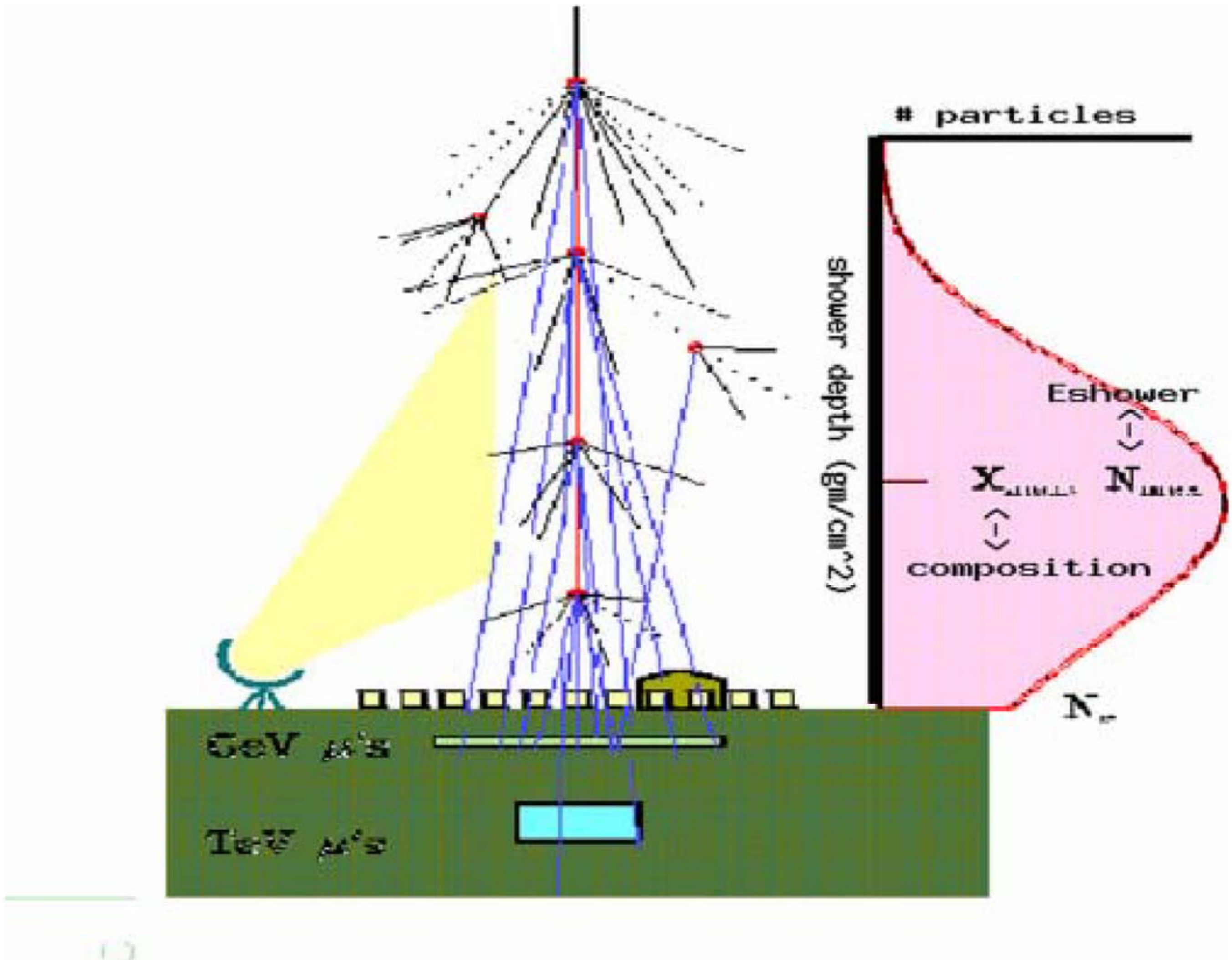
1. Background ... **experimental details!**



Schematic of extensive air shower cascade

- **Energy scale:** - 10^{20}eV = 16 Joules **...** <u>well</u> above future collider energies.
  1. cosmic rays are *observed* via the extensive air shower produced when they reach the earth's atmosphere
  2. 16Joules/$\sim$ 16μsec (typical shower time) $\approx$ 1 MW !

1. Background ... **atmosphere = detector!**

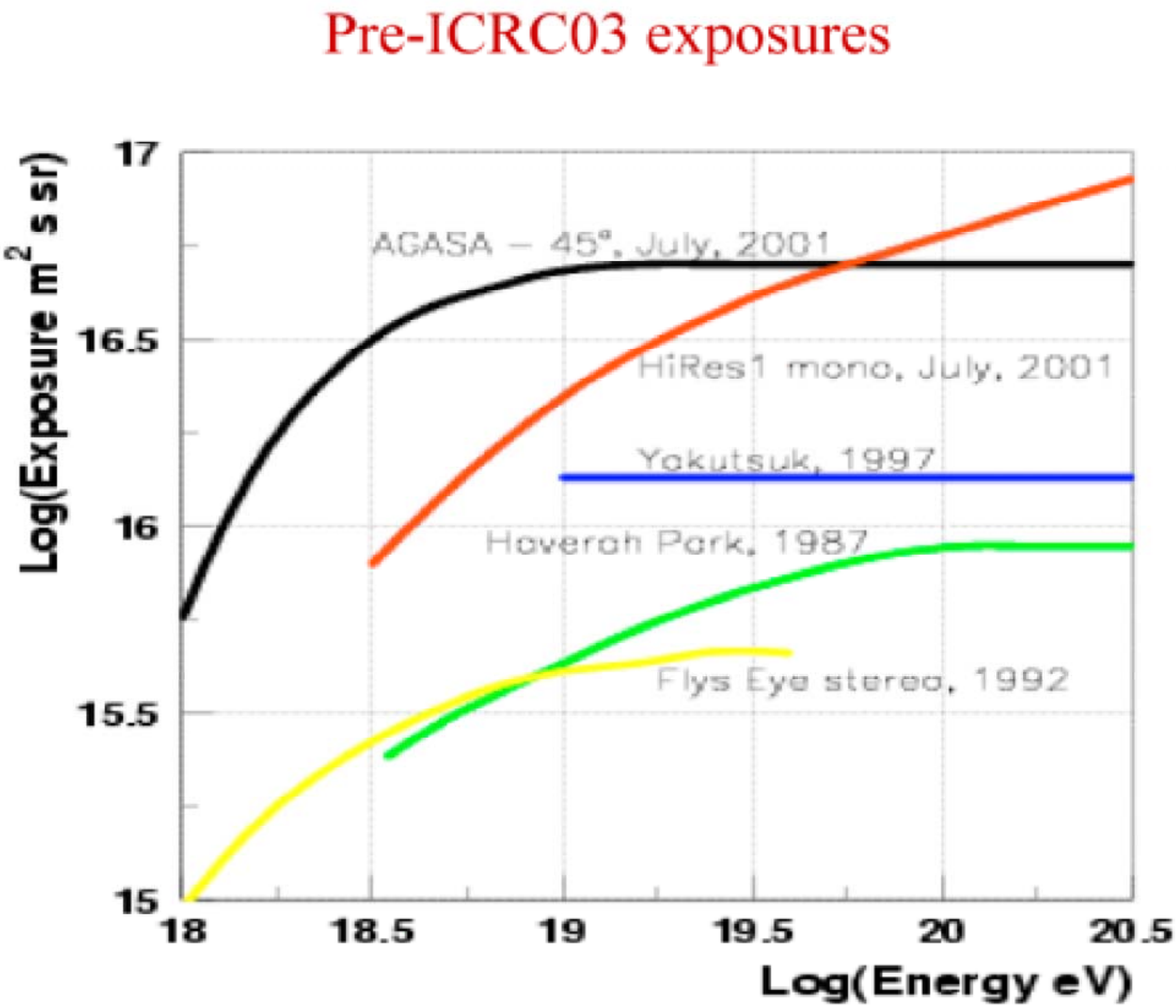


Schematic of air shower measurements

- **Measurement of 10^{20}eV air showers:**

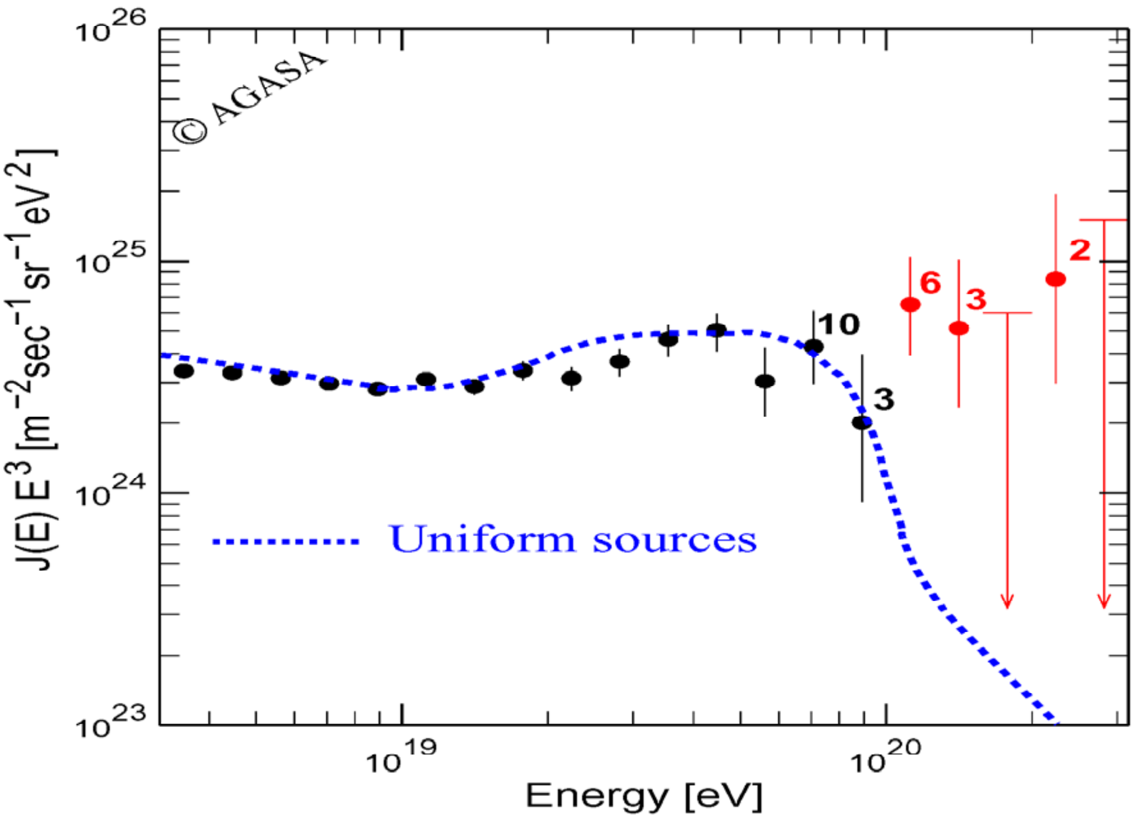
  1. km's *wide* at ground level ... sparse sampling OK!
  2. Composition of *primary* cosmic rays from depth of shower maximum, X_{max}, and/or from μ/e ratio.
  3. $\sim$ 50ppm of shower energy is re-emitted as nitrogen *fluorescence* light ($290 \sim 440$nm) ... thus a 1-MW shower appears as a 50W relativistic *light bulb*!

2. Status ... **the bigger the better!**



- **Experiments probing** 10^{20}**eV cosmic rays:**
  1. Fly's Eye, Utah, $\sim 30\text{km}^2$ (equivalent)
  2. Haverah Park, UK, 12km^2 ground array area
  3. Yakutsk, Russia, $7 \sim 16\text{km}^2$ ground array area
  4. **AGASA**, Japan, 100km^2 ground array area
  5. **HiRes**, Utah, $\sim 300\text{km}^2$ (equivalent)
  6. **Pierre Auger**, Argentina, 3000km^2 (building)

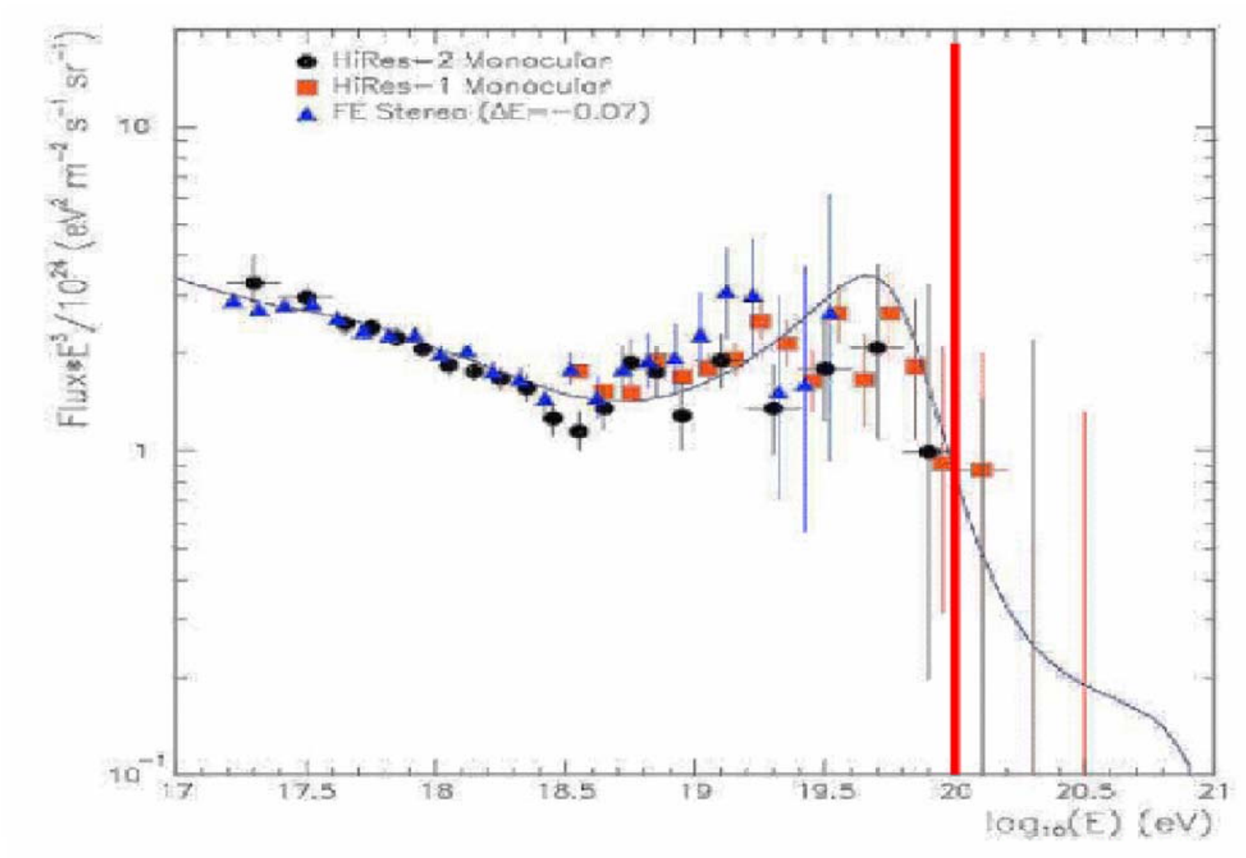
2. Status ... **AGASA** *above* **GZK curve!**



AGASA spectrum above 10^{18}eV

- **AGASA flux** *versus* **energy:**
  1. (Published) experiment with the largest *exposure*
  2. *GZK* model: uniform distribution of extra-galactic sources, proton primary, source flux $\mathrm{J}(E) \propto E^{-2}$, plus detector resolution
  3. 11 events above 10^{20}eV and 2 well above 10^{20}eV!
  4. Number of events above 10^{20}eV **inconsistent with the curve**!

2. Status ... **HiRes consistent with GZK!**

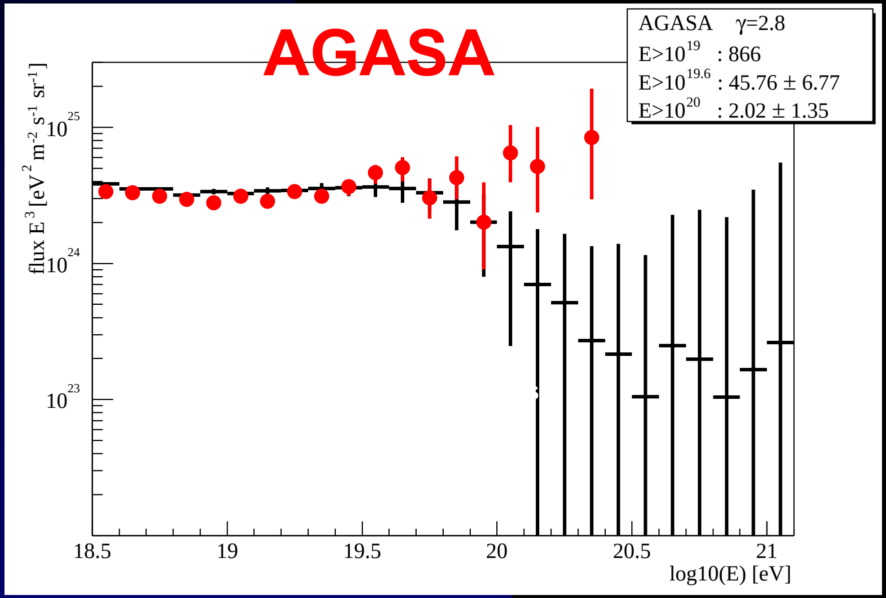


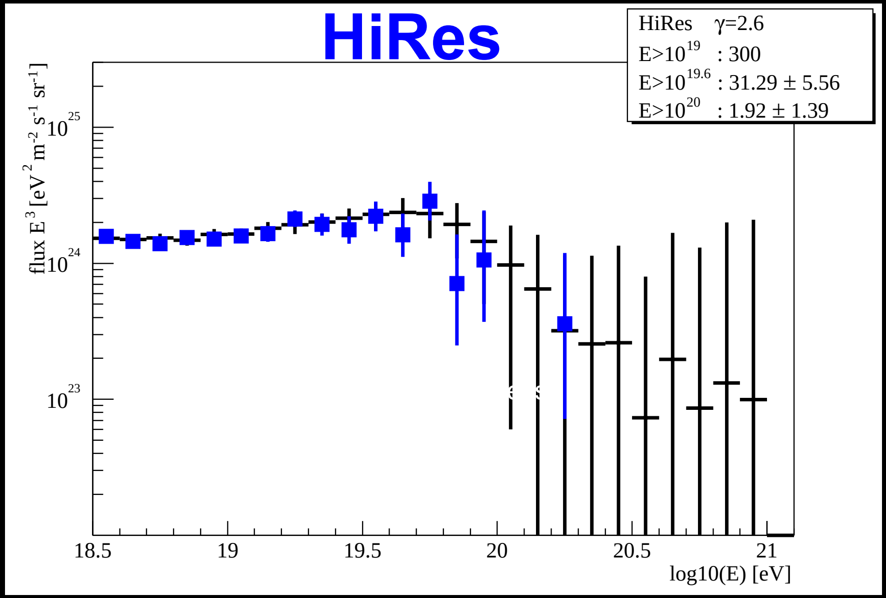
Combined HiRes I and II *monocular* **spectra**

- **HiRes flux** *versus* **energy:**
  1. Most recent data as of the ICRC 2003 conference
  2. Only one event $> 10^{20}$eV ... but exposure $\geq$ AGASA!
  3. HiRes I and II *monocular* spectra consistent with "old" Fly's Eye stereo spectrum.
  4. Something **may be** happening that is GZK-like ... but we can not be sure!

Too Low Statistics for clear GZK or no-GZK determination

$E_{max}=10^{21.5}$ eV



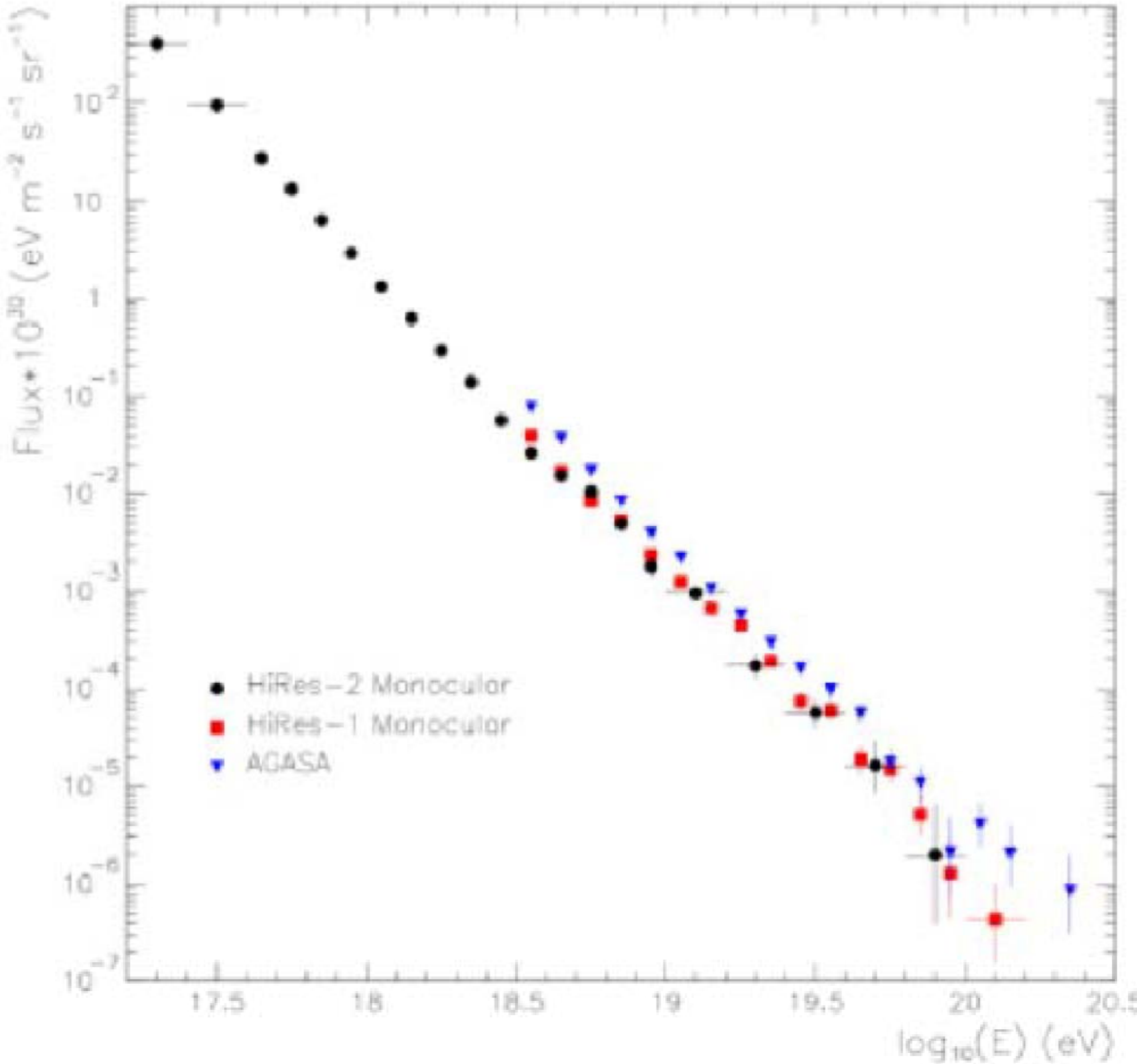


number of events above 10^{20}eV:
no GZK @ 2.5 sigma

number of events above 10^{20}eV:
GZK cutoff

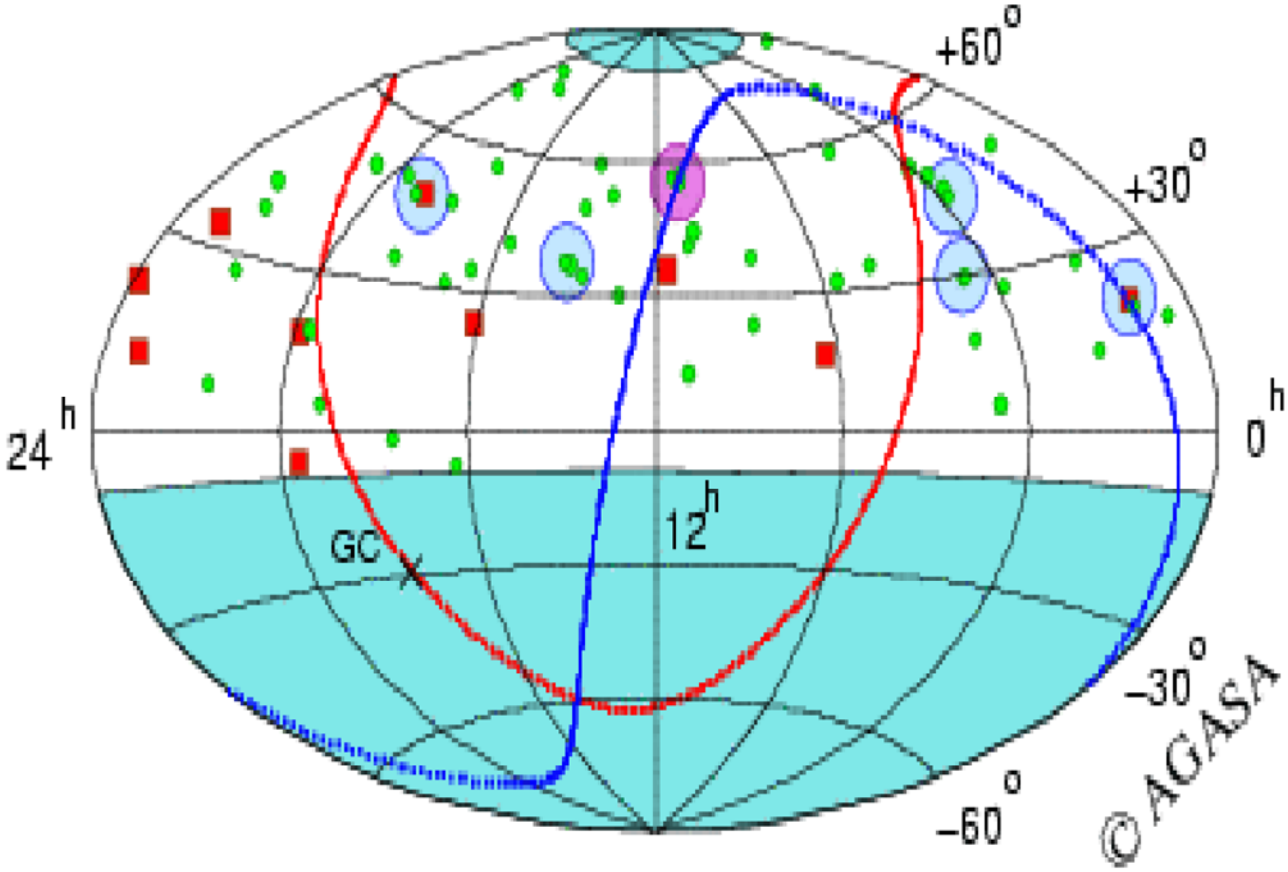
DeMarco et al (ICRC03)

2. Status ... **look at the RAW data!**



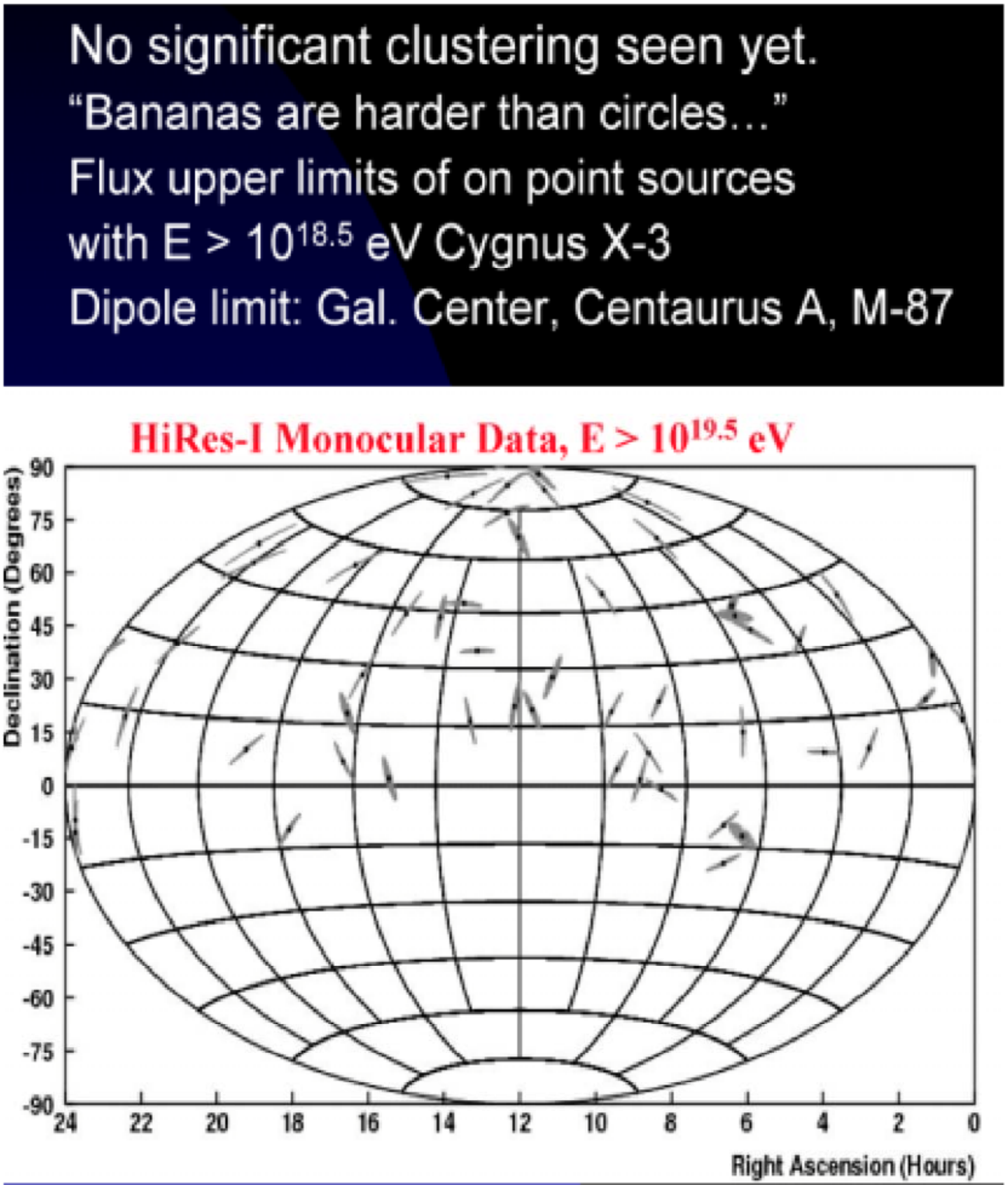
- Data consistent with 20 $\sim$ 30% systematic energy difference between AGASA and HiRes ... in agreement with experimental energy-scale uncertainties.
- **Confirmation of GZK-*structure*, or not, requires significantly reduced statistical errors!**

2. Status ... **AGASA arrival directions**



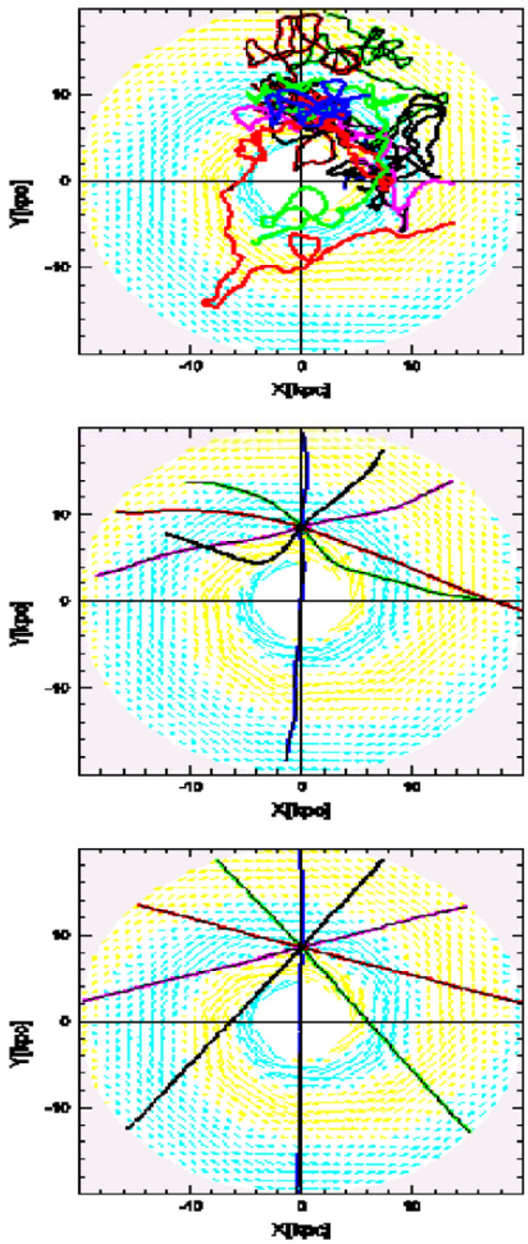
- **AGASA arrival directions above** 4×10^{19}**eV**
  1. Primary cosmic ray direction measured to $\sim 1°$
  2. *red* squares (events $> 10^{20}$eV) and *green* dots ($4 - 10 \times 10^{19}$eV) are **consistent with large-scale source uniformity**
  3. Six *2.5° clusters* of events: 5 doublets and 1 triplet
  4. Two of the clusters lie *in* the super-galactic plane (blue line)

2. Status ... **HiRes arrival directions**



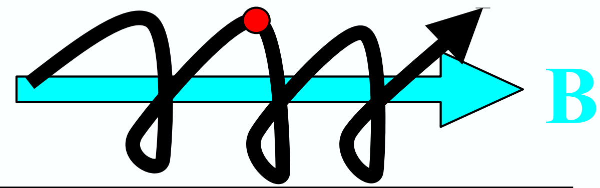
- *Monocular* data have asymmetrical pointing errors ...
- No "exact" match with AGASA ... but some clusters are close!
- **Significantly more events are needed ... !**

2. Status ... **B-field alters CR trajectories!**



- **Simulated** *proton* **trajectories:** $10^{18}, 10^{19}$ **and** 10^{20}**eV in** 2μ**G fields** ... $\geq 4 \times 10^{19}$eV protons are deviated little by local (galactic) magnetic fields.
- **But what if the fields are more extensive or stronger?**

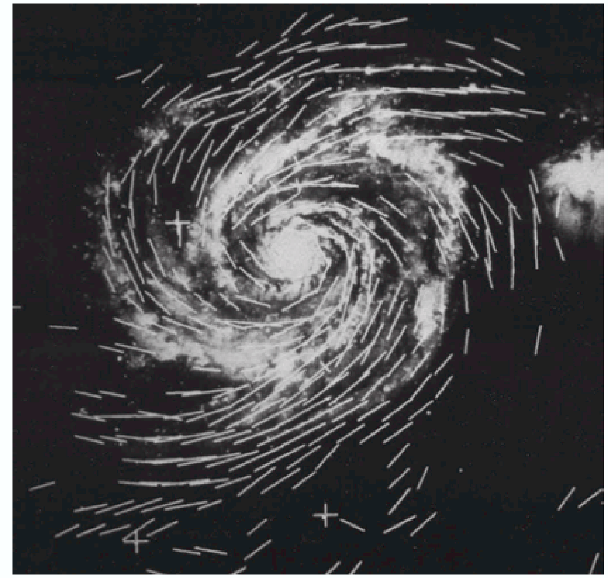
Magnetic Fields



1. Galaxies have magnetic fields.
   - Protons and nuclei will be deflected by the B ~ 5 μG galactic field.

     Larmor radius r = R/cB

R	r	
10^{15} eV	0.3 pc	
10^{20} eV	30 kpc	← size of galaxy

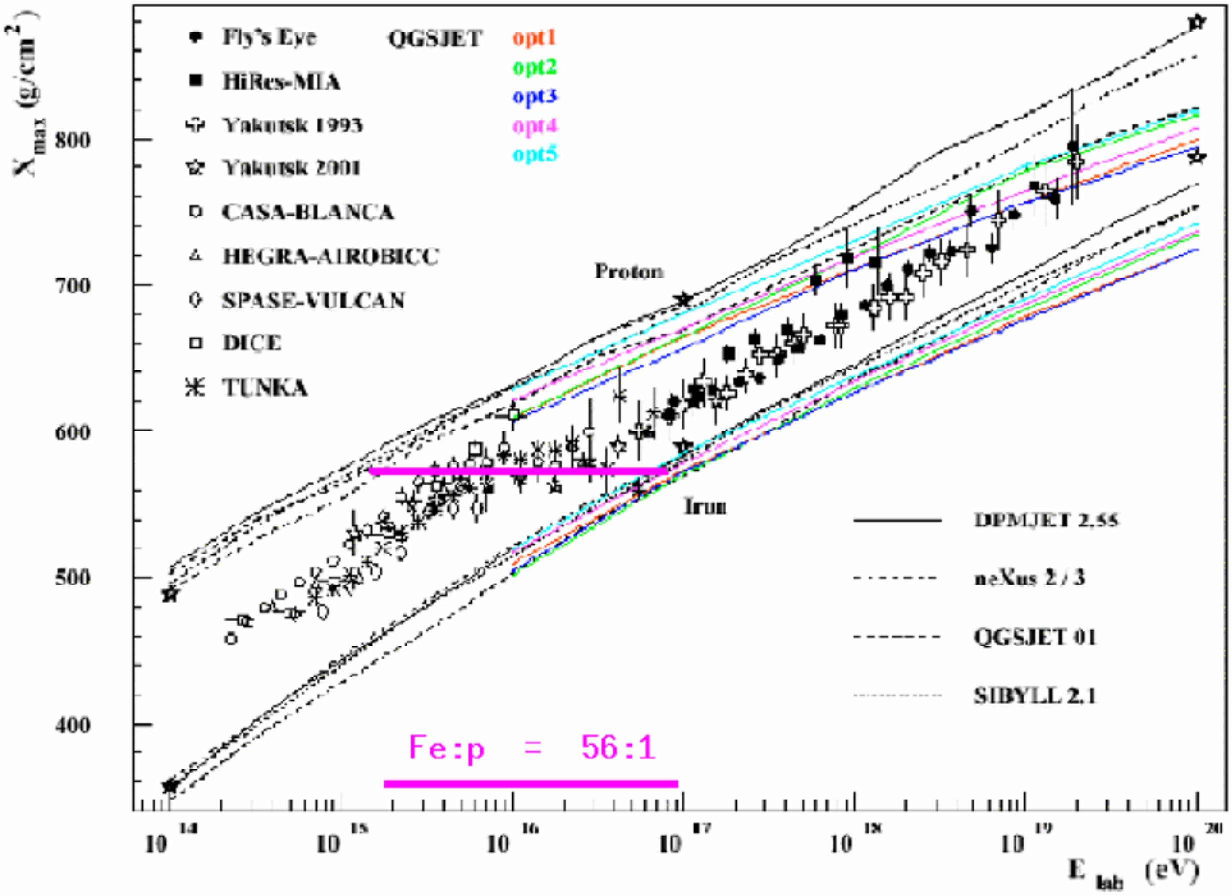


M51

2. Intergalactic fields may also be significant
   - Clusters (e.g. Coma) have field strengths B ~ 0.1 – 2 μG, perhaps extending out along sheets and filaments.

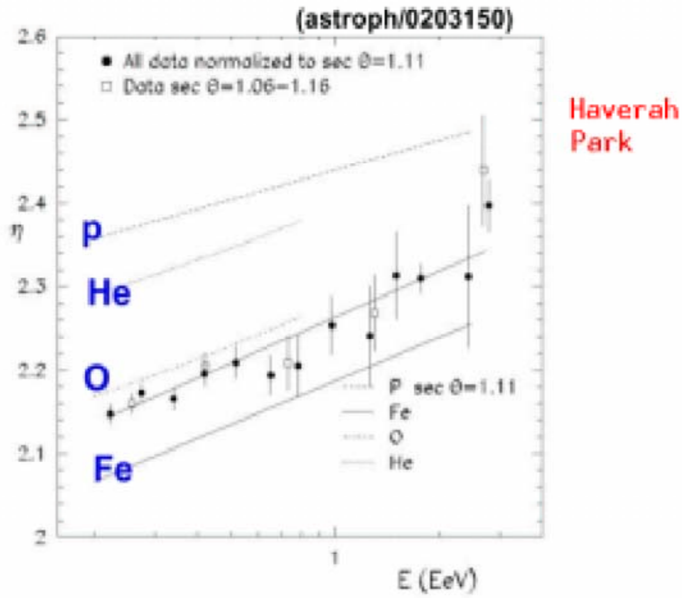
Charged CR directions will be scrambled by B fields.
But we can still learn a lot from their <u>composition</u>.

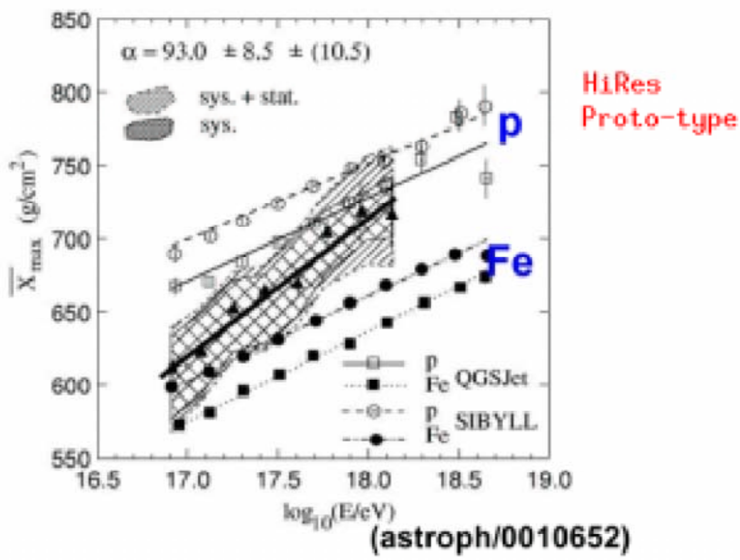
2. Status ... **CR** *average* **composition**



- **Average depth of shower maximum (X_{max}) is sensitive to primary cosmic ray** *composition*:
  - Interpretation clouded by shower simulation (different *curves*) uncertainties!
  - To first approximation: nucleus of atomic number A and energy E results in A sub-showers each with average energy E/A. **As** $X_{max} \propto log(E)$**, thus** $X^{Fe}_{max} < X^{p}_{max}$**!**
  - **Data trends:** *intermediate-to-heavy* **at** $\sim 4 \times 10^{16}$**eV to** *light* = *proton* **at** $10^{18} \sim 10^{19}$**eV**!

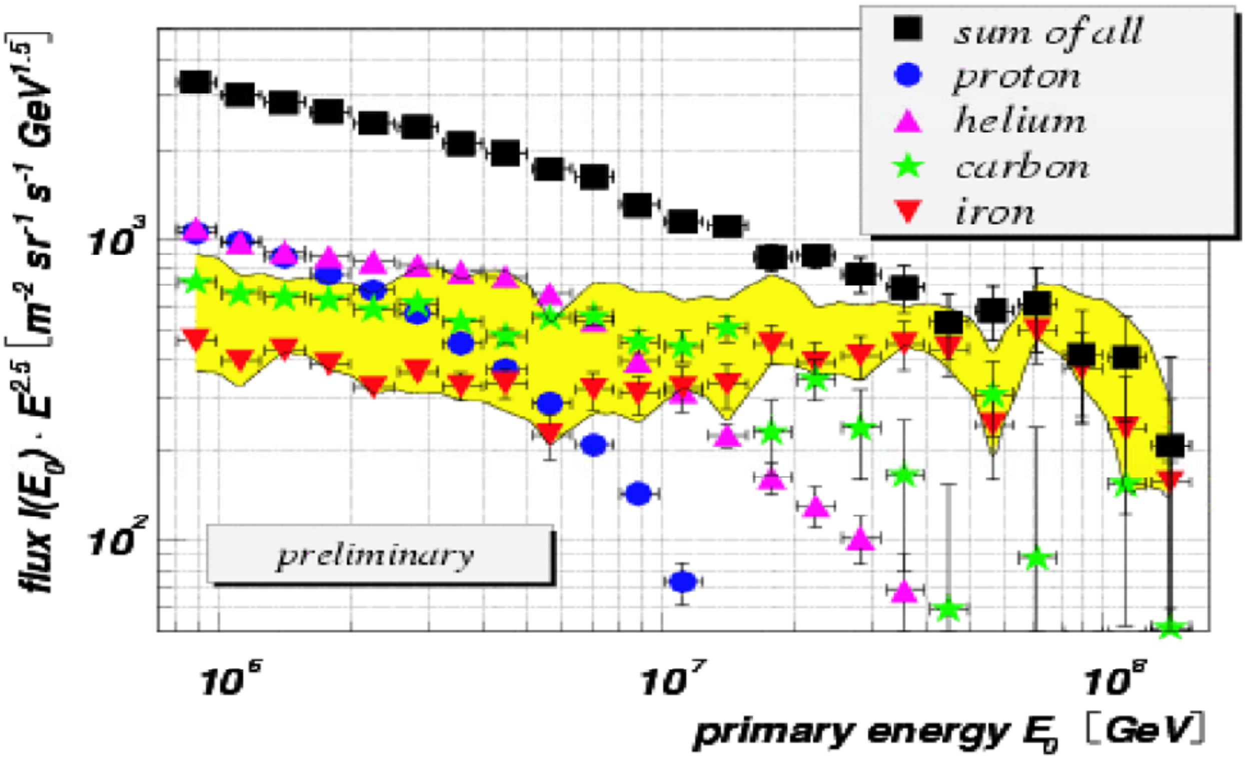
2. Status ... **when <u>do</u>** *protons* **dominate?**





- ... on average consensus
- **in detail experiments disagree:** *e.g.* at 1 Eev = 10^{18}eV Haverah Park measures *intermediate-to-heavy* composition and HiRes measures *light* = *proton* composition!

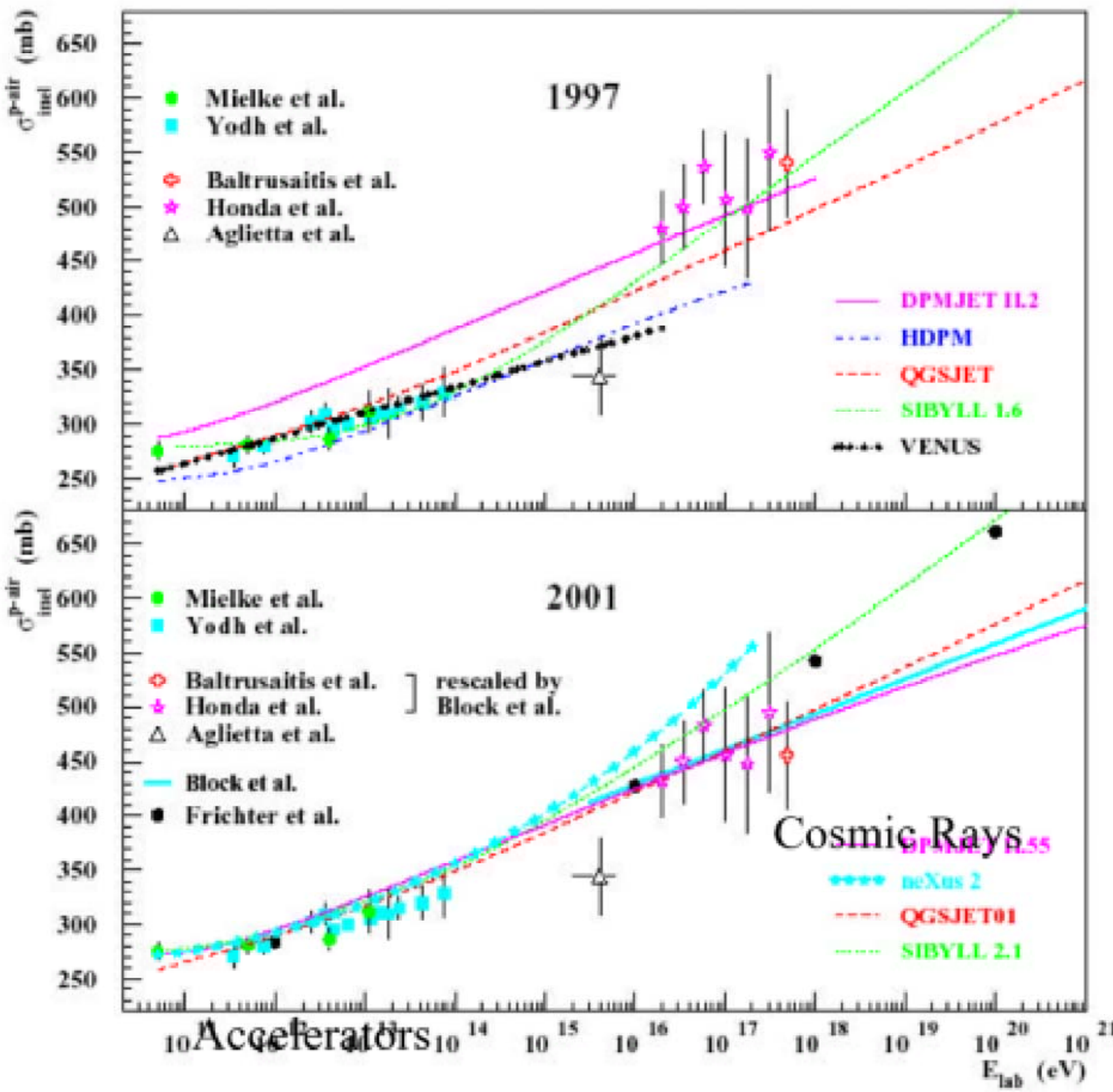
2. Status ... **new analysis developments!**



Unfolding of cosmic ray spectra near the *knee*
Note: horizontal-axis units are GeV where 1 GeV = 10^9eV

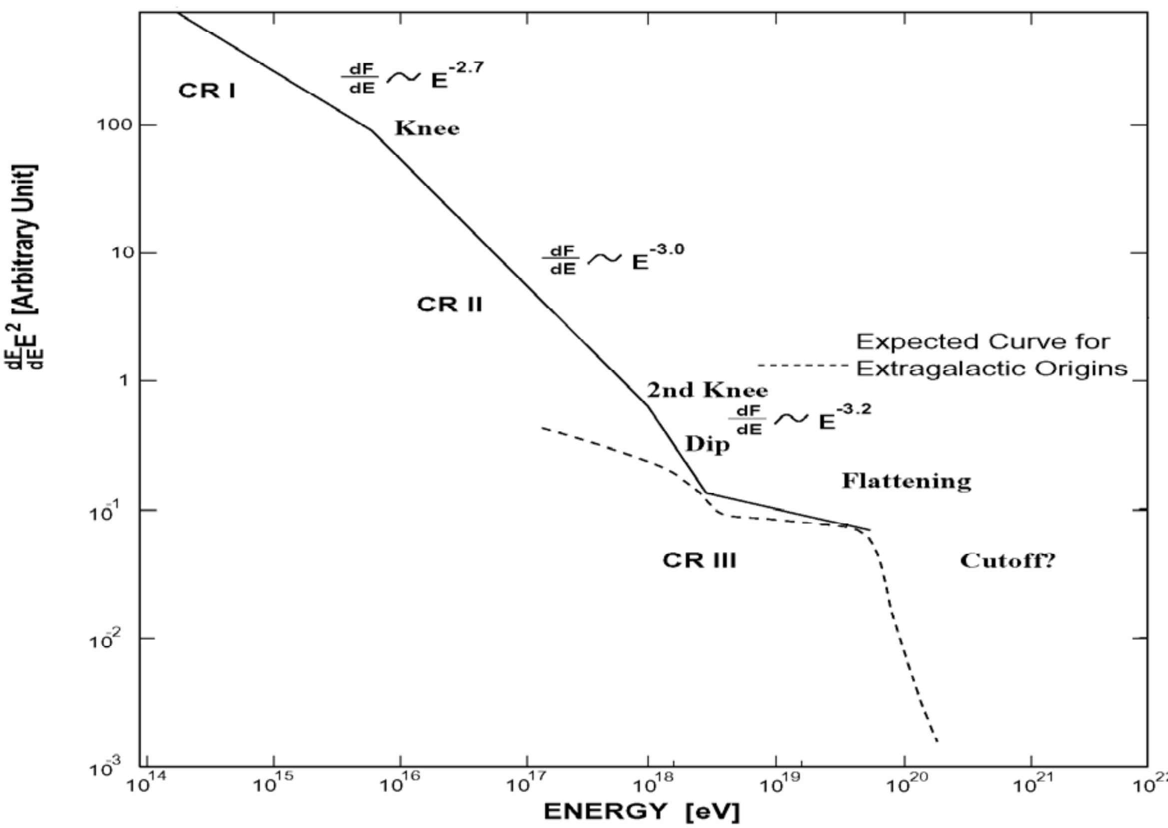
- **KASKADE results ...** *astro-ph/0201109*:
  1. **With more sophisticated experiments more detailed analyses are possible.**
  2. One KASKADE analysis has attempted to extract individual element-group fluxes *versus* energy.
  3. **The results are consistent with** *rigidity-dependent* **breaks in flux for different element-groups.**
  4. Rigidity-dependent *breaks* would be consistent with CR lifetime/retention limitations in the galaxy.

2. Status ... **simulations also improve!**



- **Simulations are needed to link** *e.g.* **depth of shower maximum (X_{max}) with** *composition***:**
  1. Several Monte Carlo (hadronic interaction) models are under development to interpret the data.
  2. **(Systematic) uncertainties remain ...**

3. Emerging model ... **listen to the data!**



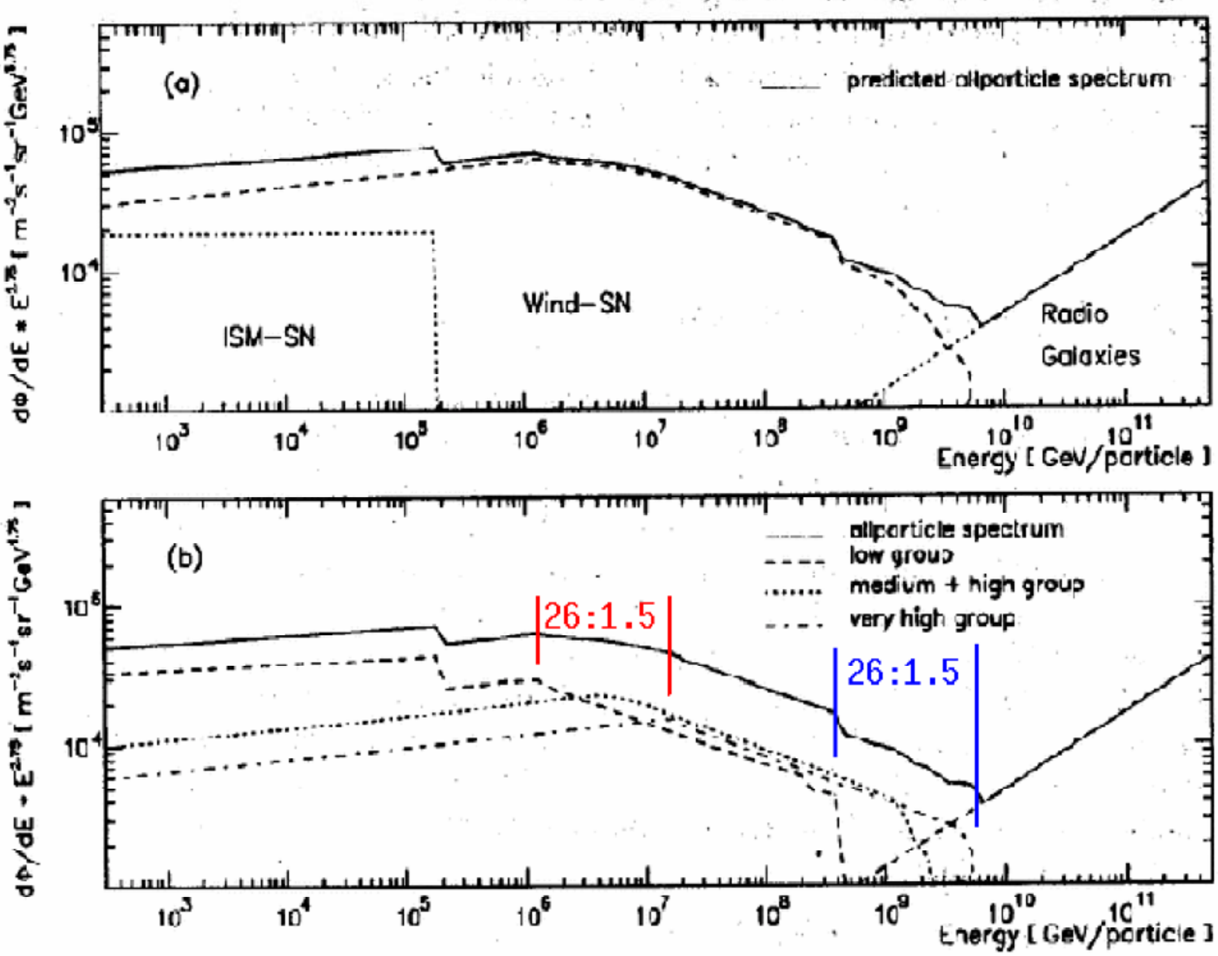
Conceptual model for cosmic ray flux ...

S. Yoshida and H. Dai, astro-ph/9802294

- **Consider a 2-component model:**

  1. KASKADE data consistent with *one* component for CR-I and CR-II (*e.g.* galactic super-novas ...)
  2. **Spectrum steepening**, at 1^{st} and 2^{nd} knee, from acceleration or lifetime/retention limitations
  3. **Spectrum flattening**, at the ankle, consistent with a new, CR-III, (2^{nd}) component

3. Emerging model ... **"theory" guidance!**



Theoretical model for cosmic ray flux ...

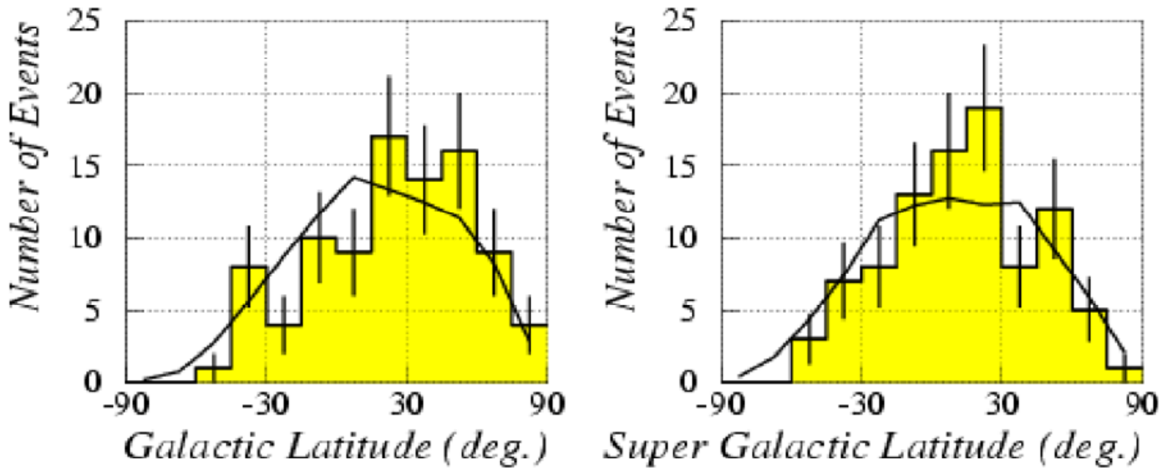
B. Wiebel-Sooth and P. Biermann, Springer Verlag, Sept 1998

Note: horizontal-axis units are GeV where 1 GeV = 10^9eV

1. Slope *breaks* at the 1^{st} and 2^{nd} knee follow constant *rigidity* physics observed by KASKADE ... *i.e.* energy features scale in nuclear charge: $E_{Fe} \equiv 26 \times E_p$.

2. 2^{nd} break, $E_p \approx 4 \times 10^{17}$eV, proton Larmor-radius: $(\frac{R_p}{1kpc}) \approx (\frac{E_p}{10^{18}eV}) \cdot (\frac{1\mu G}{B}) \approx$ galaxy thickness.

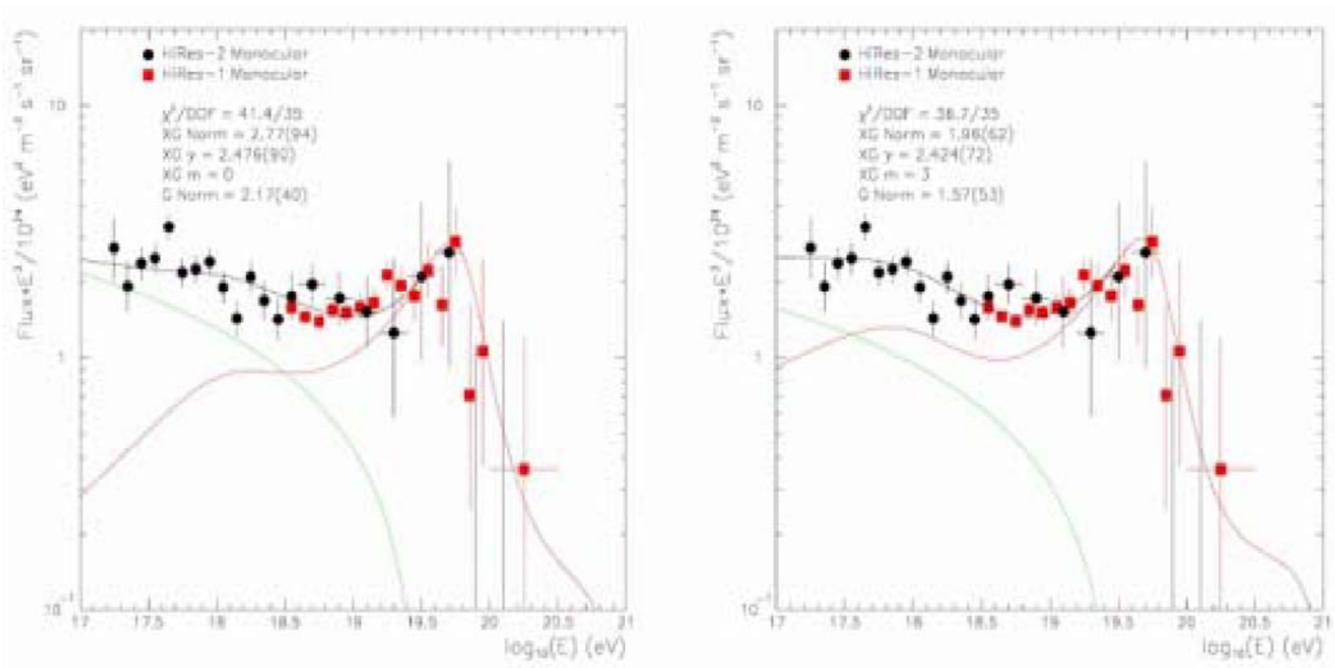
3. Emerging model ... **initial summary!**



Cosmic ray ($> 4 \times 10^{19}$eV) arrival directions ...

1. 1^{st} component: broad *composition* light (p,He) to heavy (Si,Fe,..); may extend to energies $\sim 10^{19}$eV
2. 2^{nd} component: lighter (significant proton) composition; possibly measurable implications to below 10^{18}eV
3. **Primary motivations for the** 2^{nd} **component**: **flattening** of the flux above the ankle ($\sim 4 \times 10^{18}$eV) and a **change to lower mass composition** at the highest cosmic ray energies: above $\sim 10^{18}$eV
4. The primary motivation for identifying the 2^{nd} component as **extra-galactic** is the **isotropy of the highest energy cosmic rays** (strengthened if *light* (p,He))

3. Emerging model ... **testable implications!**



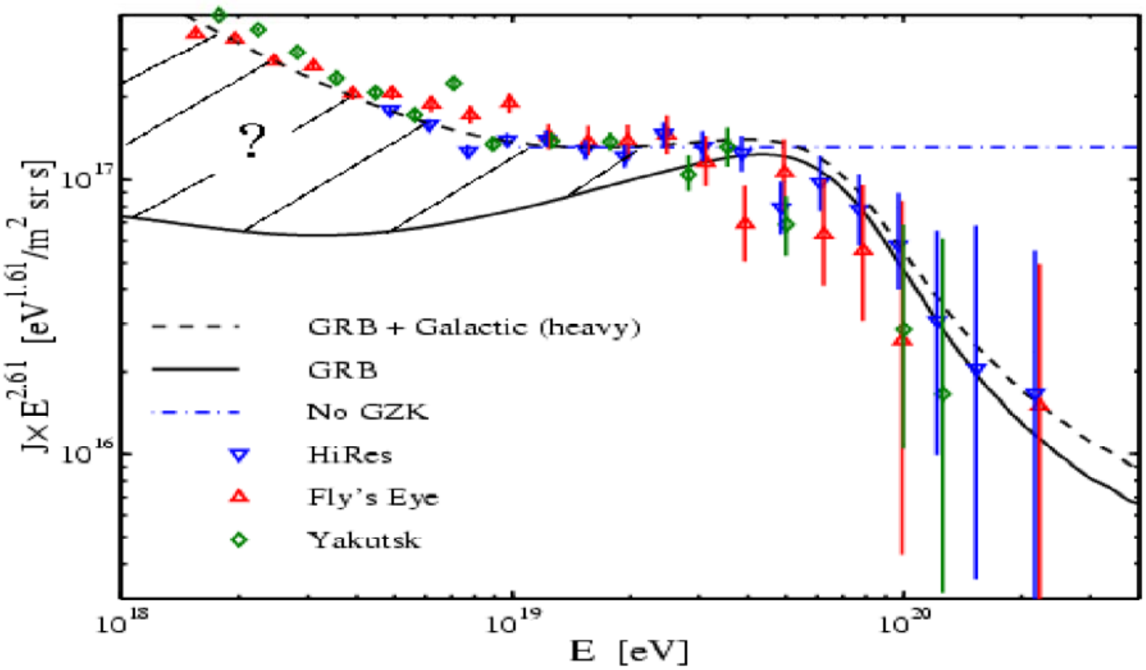
D. Bergman *GZK*-model fits to HiRes Flux(E) data

The green curve simulates the galactic flux

The red curve simulates the extra-galactic (proton) flux

- **Propose a model (*e.g.* like Biermann model):**
  - Particle composition, above $\sim 10^{18}$eV should have two components: *heavy*$\geq$**Fe** from galactic sources and *light*=**p** from extra-galactic sources.
  - If *light* is truly protons, then the data should show the GZK structure.
  - Measure fraction of light (protons) primaries, $f_p(E)$, *versus* energy.
  - **Then GZK model predictions can be meaningfully compared to $f_p(E)\times$Flux(E).**

3. Emerging model ... **don't skip the fun!**

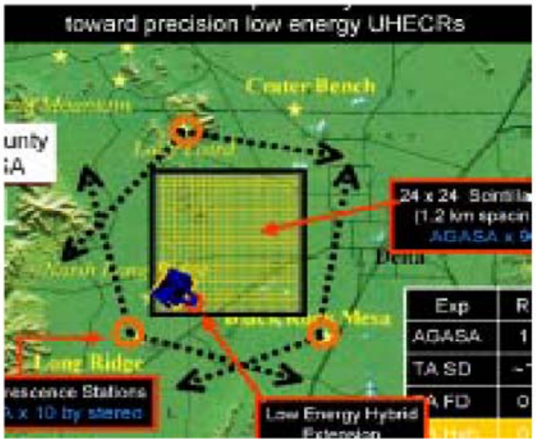


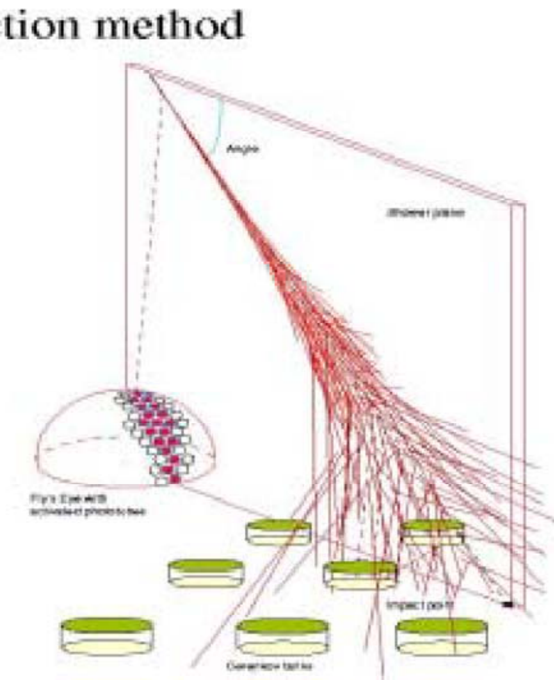
Bachall et al GRB model *showing* **GZK-cutoff, hep-ph/0206217**

Even though we would like to ... there is simply not enough data to answer the issues of 10^{20}**eV CRs!**

- AGASA, Fly's Eye and HiRes have observed (a few) events above 10^{20}eV **... but:**
  - What is the detailed shape of the spectrum?
  - What is the *composition* versus energy?
  - Are there arrival direction anisotropies and are there *point source clusters*?

4. Next step ... **need bigger and better!**



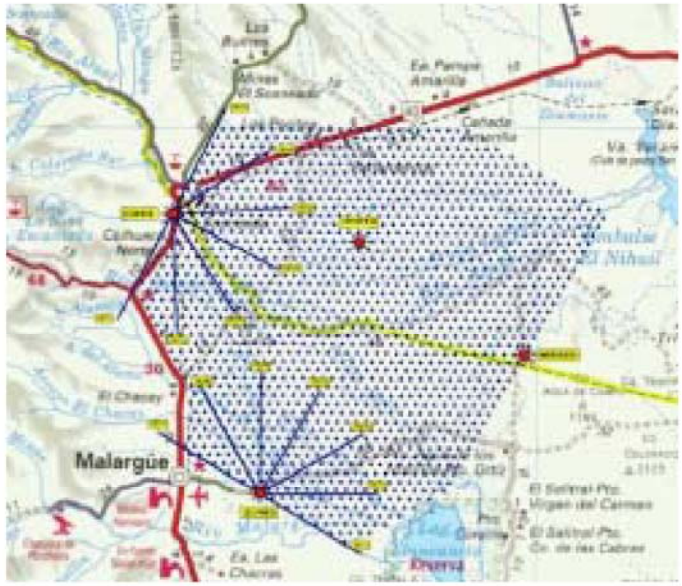


Hybrid Fluorescence + Ground Array

precision measurements

- **The next step ...** <u>high quality data</u> are needed from $\lesssim 10^{17}$eV to several $\times 10^{20}$eV:
  1. need to link with galactic source(s) measurements
  2. need to tune the Monte Carlo (hadronic interaction) models
  3. need to constrain the models with much reduced error bars ... especially above 6×10^{19}eV
  4. In a post-GZK cutoff era, need to look carefully where we expect *no* signal

4. Next step ... **SW U.S. and Argentina!**

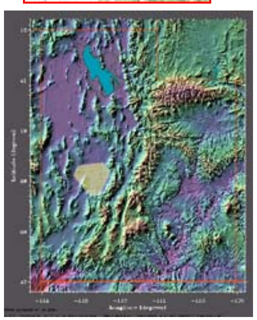


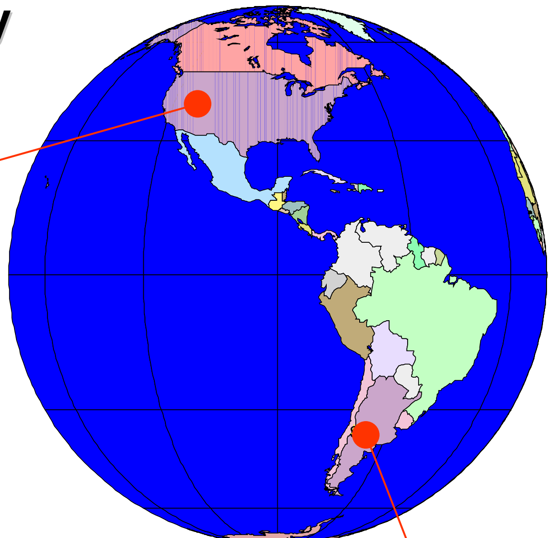
HiRes **Dugway, Utah or** *Auger Southern Observatory* **Malargue, Argentina**

- **HiRes** ... (now):
  1. 2 fluorescence detector sites separated by 12.6km
  2. Will run for a few more years
- **Telescope Array (TA)** ... (in a few years):
  1. 25km × 25km surface detector (SD) array
  2. Overlooked by 3 fluorescence detectors (FDs) ... to *resolve* AGASA-HiRes "controversy"
- **Auger** ... (now):
  1. 55km × 55km SD array overlooked by 4 FDs
  2. Construction of the full experiment is well underway
  3. Data taking simultaneous with construction ... **already biggest running experiment!**

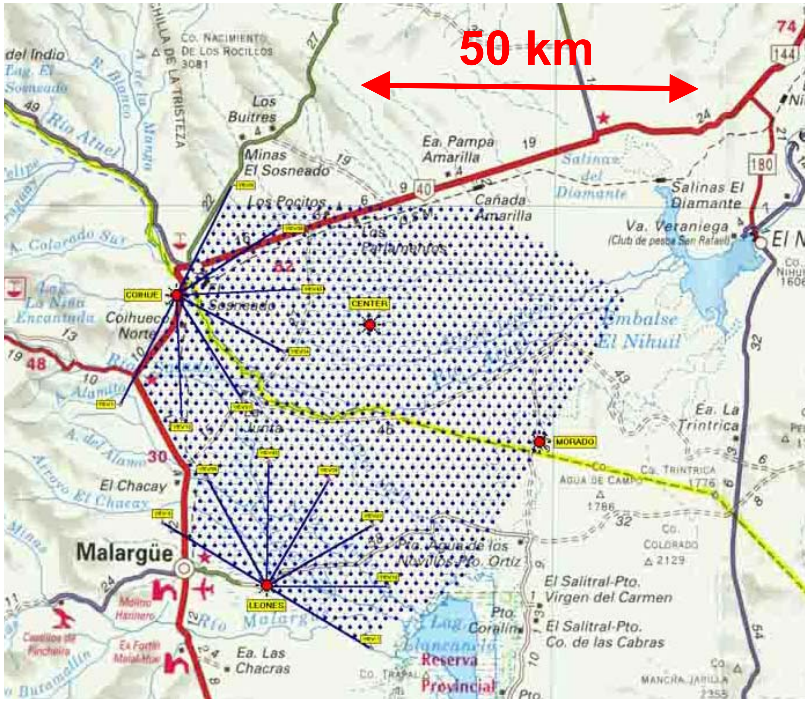
Auger Sites

Northern site
Millard County
Utah, USA



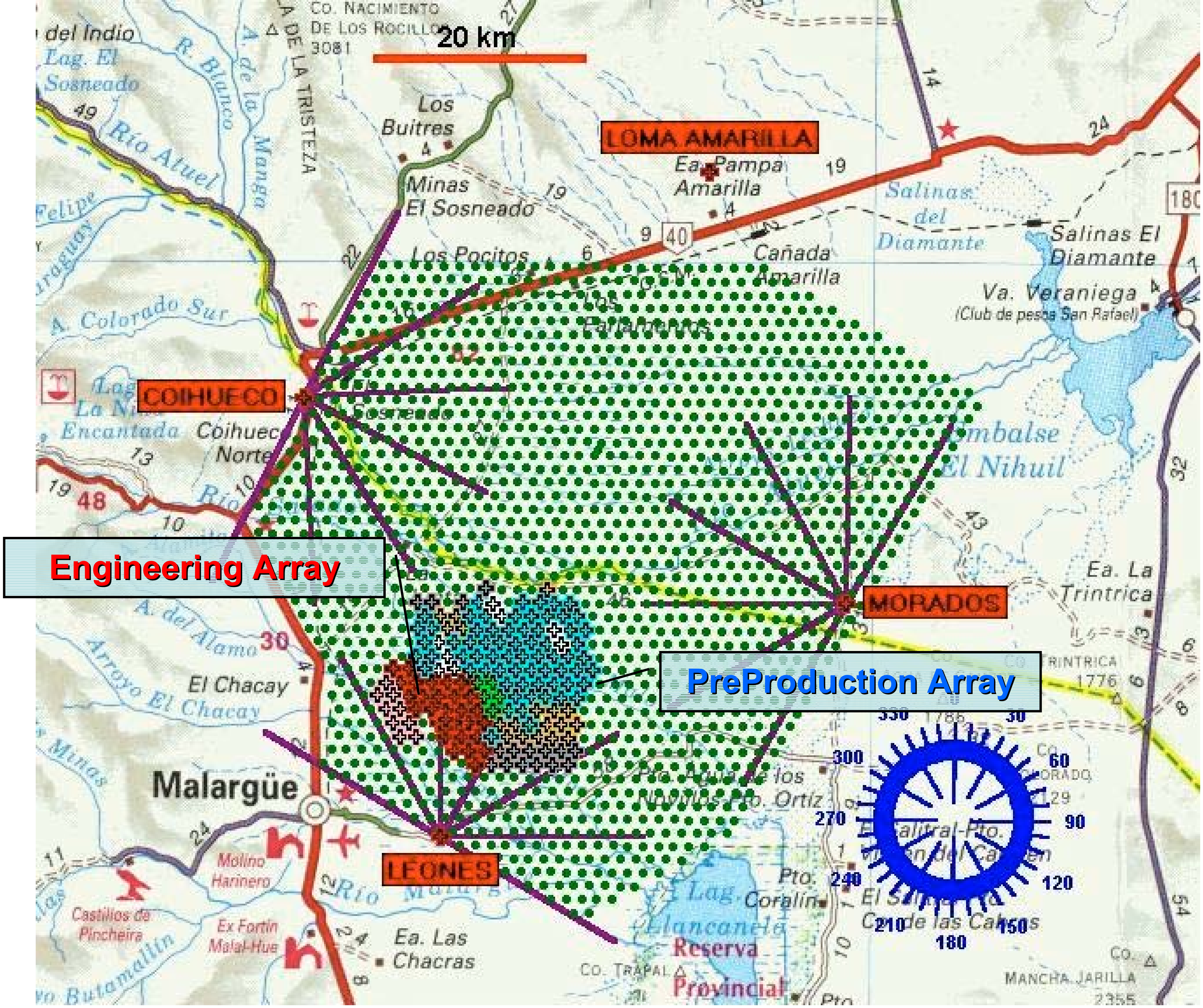


Auger Project



Surface detector in place.

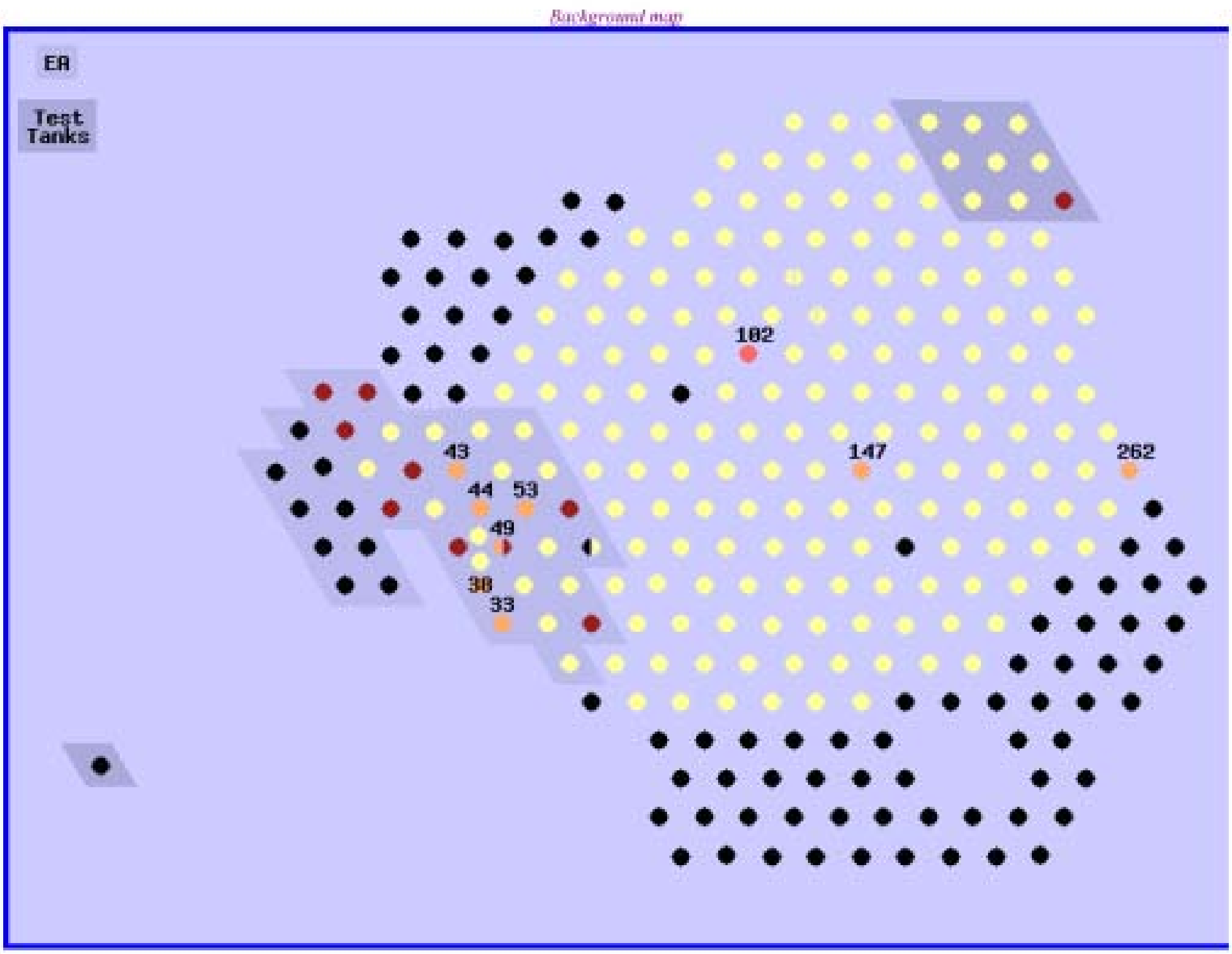
- Southern site in Argentina
- 1600 water detect., 4 fluorescence.
- > 3,000 km^2.
- Construction complete in 2006.



20 km
LOMA AMARILLA
COIHUECO
MORADOS
LEONES
Engineering Array
PreProduction Array
330
30
300
60
270
90
240
120
210
150
180
Malargüe
Los Buitres
Minas El Sosneado
Los Pocitos
Ea. Pampa Amarilla
Cañada Amarilla
Salinas del Diamante
Salinas El Diamante
Va. Veraniega
(Club de pesca San Rafael)
Coihueco Norte
A. Colorado Sur
Río Atuel
El Chacay
Arroyo El Chacay
A. del Alamo
Embalse El Nihuil
Ea. La Trintrica
Molino Harinero
Castillos de Pincheira
Ex Fortín Malal-Hue
Ea. Las Chacras
Lag. Llancanelo
Reserva Provincial
Co. Trapal
Mancha Jarilla
Co. Nacimiento De Los Rocillos
3081

Current Status of the Array January 23, 2004

199 detectors with electronics out of 287 deployed.



No kit - No data - Alarm - Warning - Running well | Acquisition (100%)

The Hybrid Detector Concept

- **Surface Array**

  Simple and reliable detectors
  100% duty cycle
  Energy Determination relies on simulation

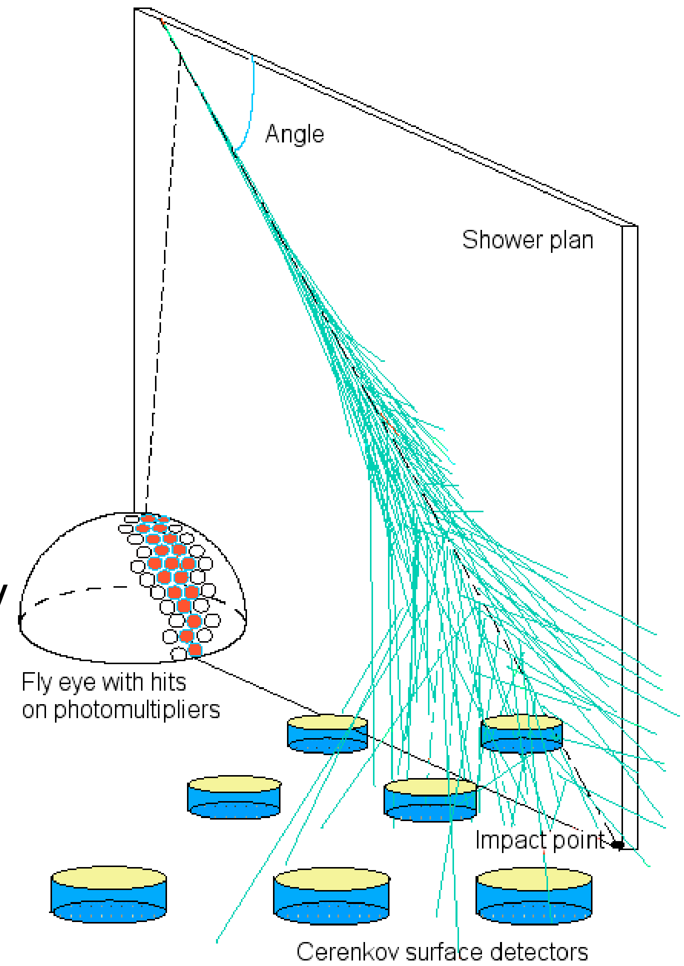
- **Fluorescence Detector**

  Quasi calorimetric energy measurement
  Tracks directly shower developement
  10-15 % duty cycle
  Sistematics from atmospheric transparency

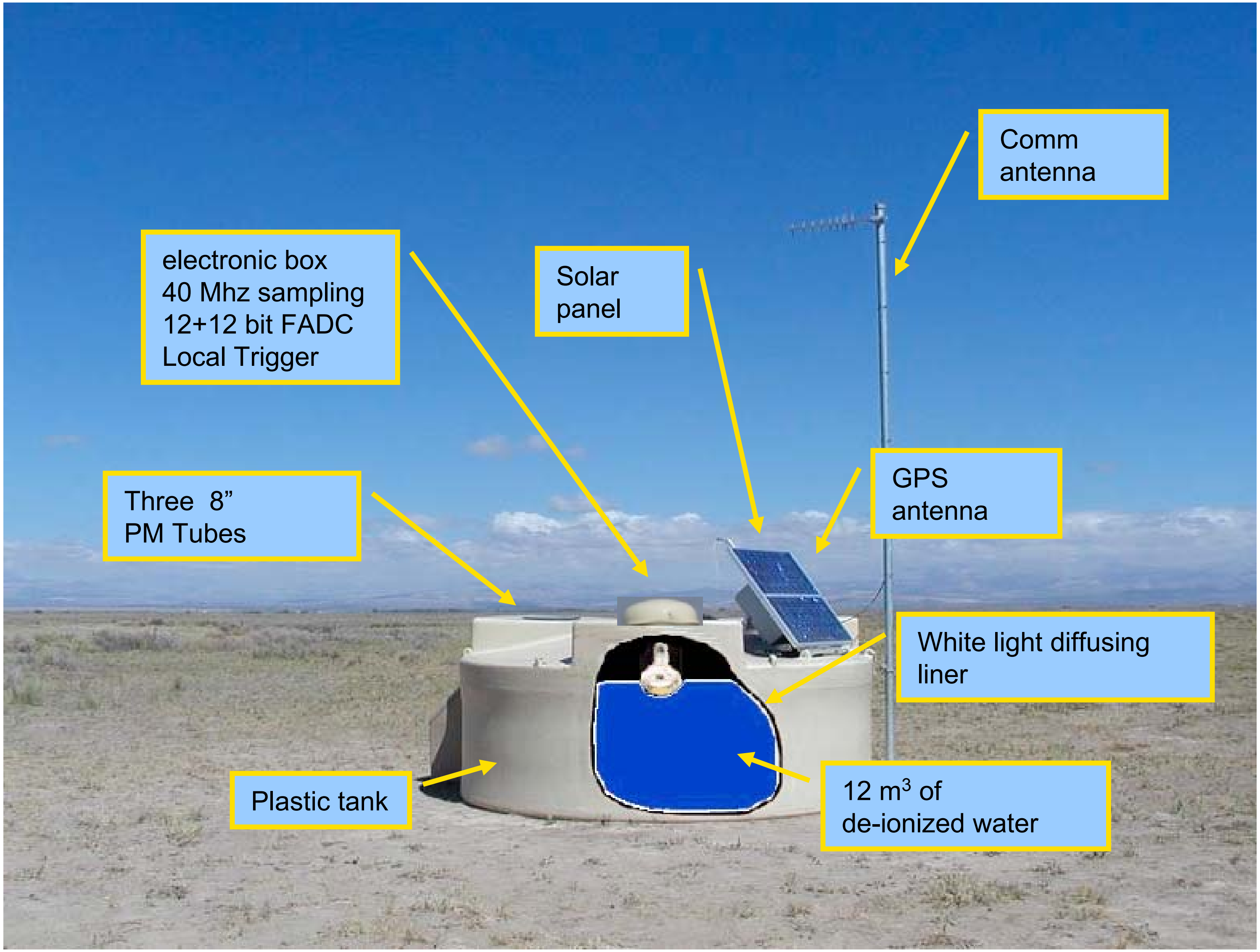
- **Combination**

  Cross Calibration
  Better control of systematics
  Superior Angular resolution
  Independent measurement of

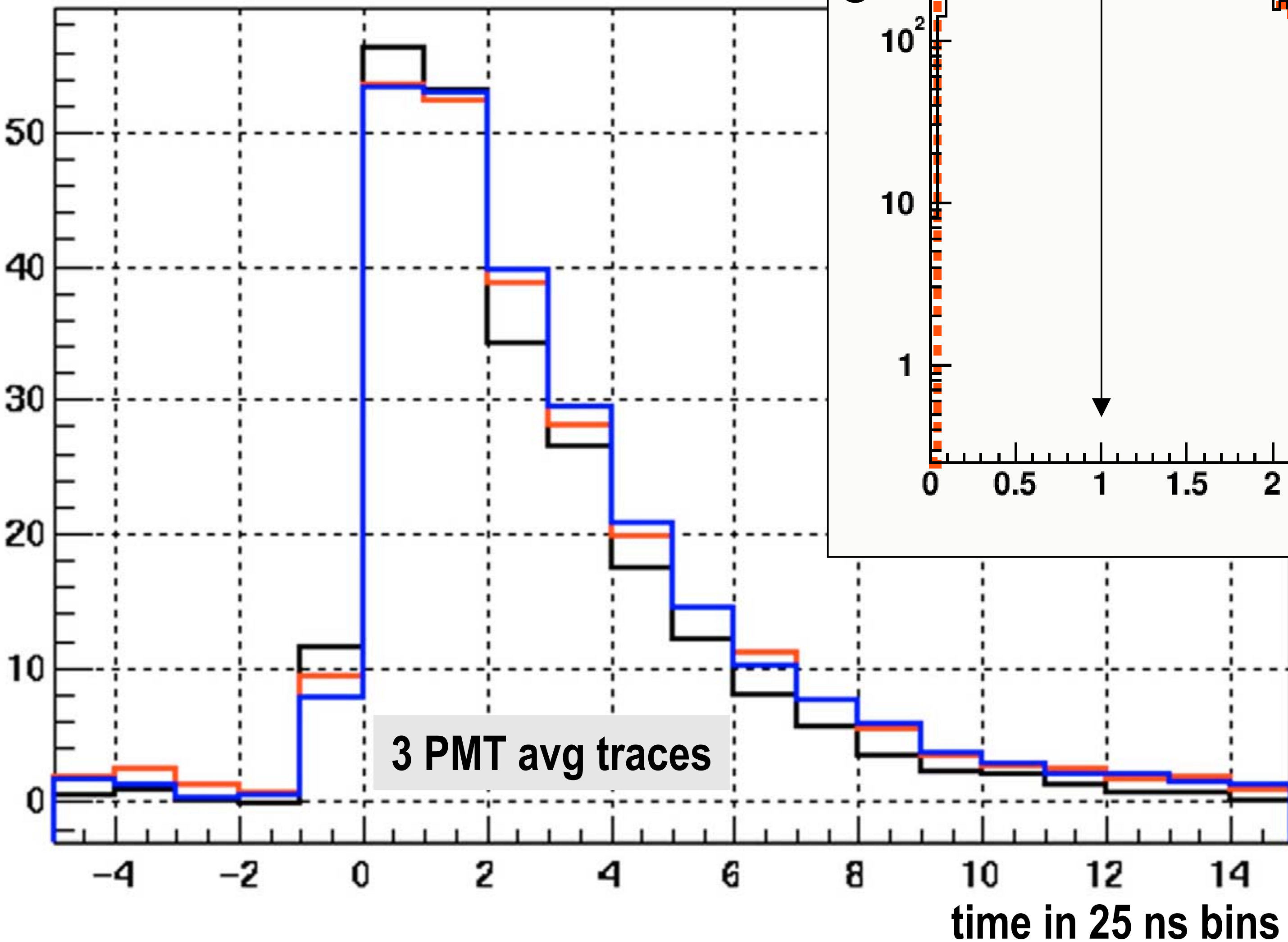
  Energy
  Composition: ρ_{μ}/ρ_{e} , X_{max}

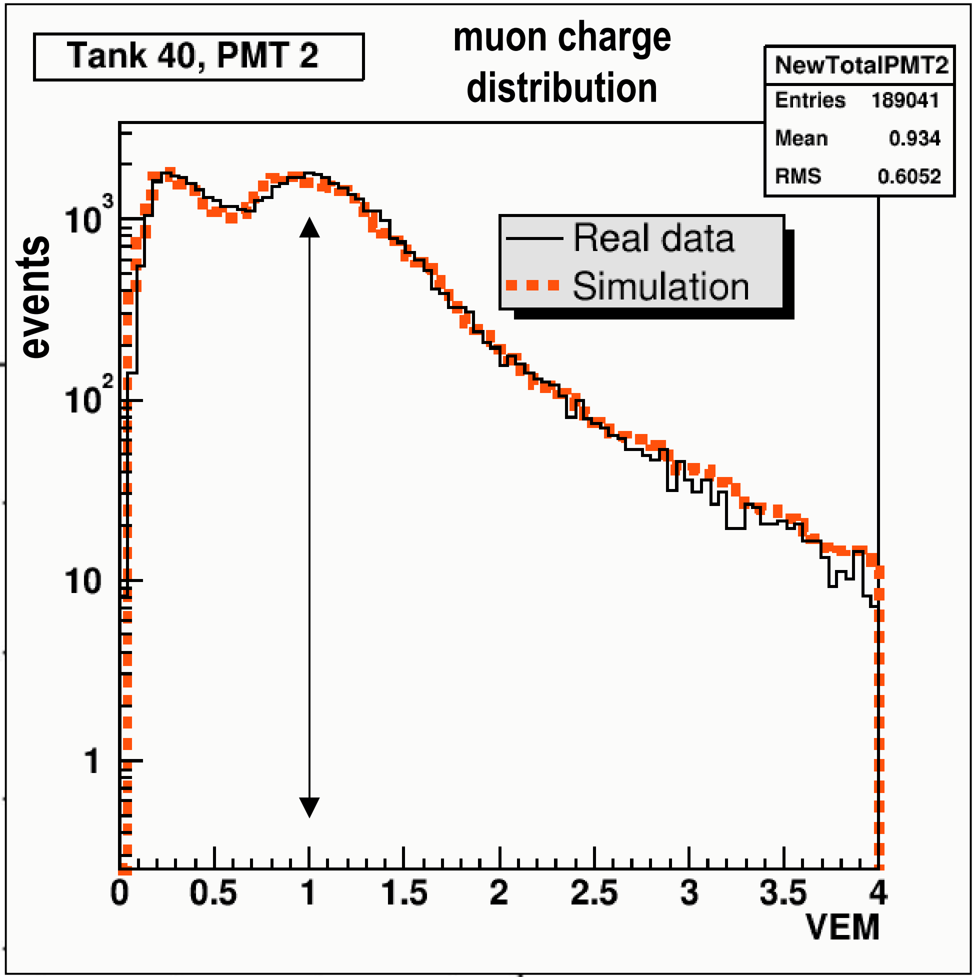


The Surface Detector



self-calibrating detectors...





PIERRE
AUGER
OBSERVATORY

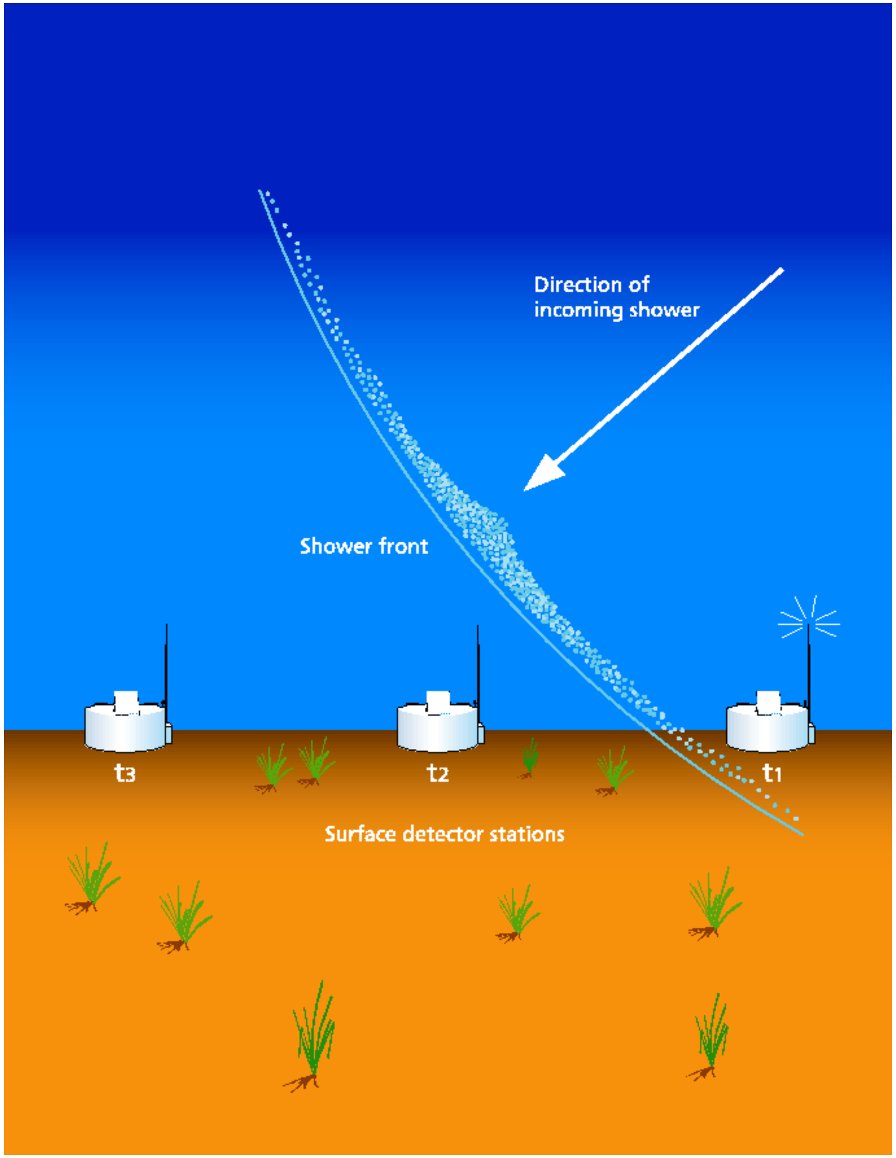
Air Shower Detectors - Surface Detector Array

Shower timing → **Shower angle**

Particle density → **Shower energy**

Muon number
Pulse rise time → **Measure of primary mass**

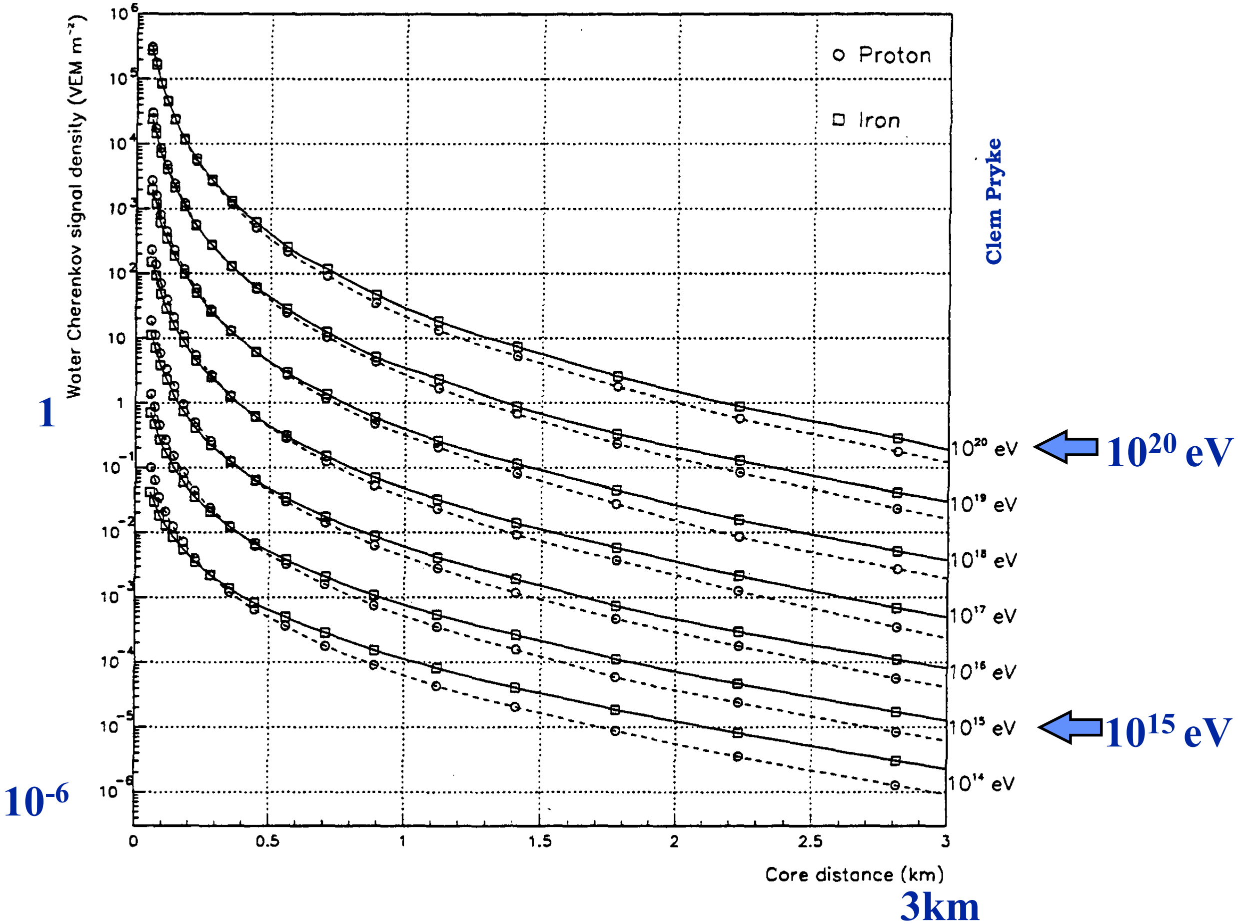
Event timing and direction determination



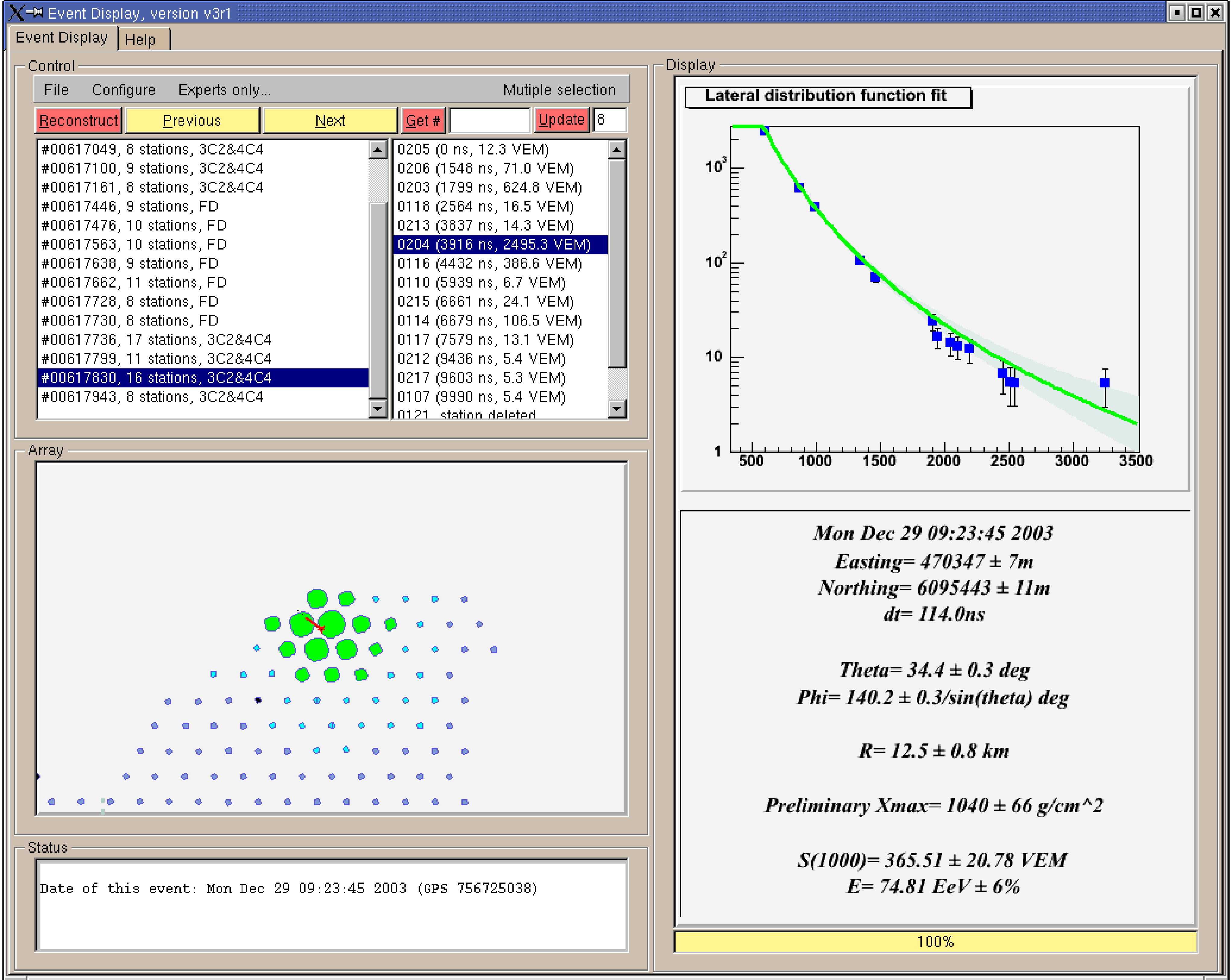
Shower Density Lateral Distribution (simulation)

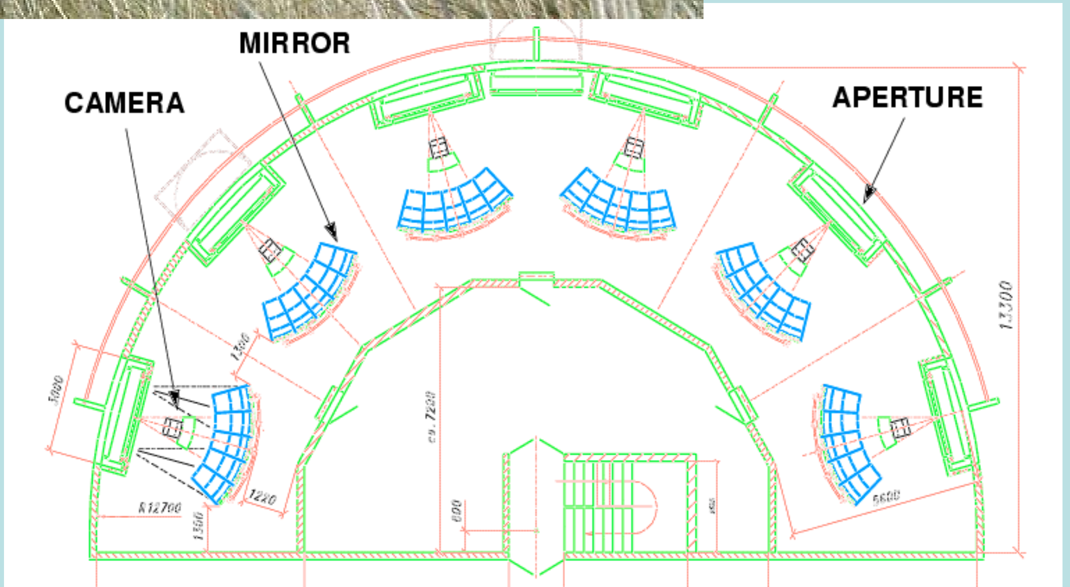
Detector Signal Density

(equiv. muons/m²)



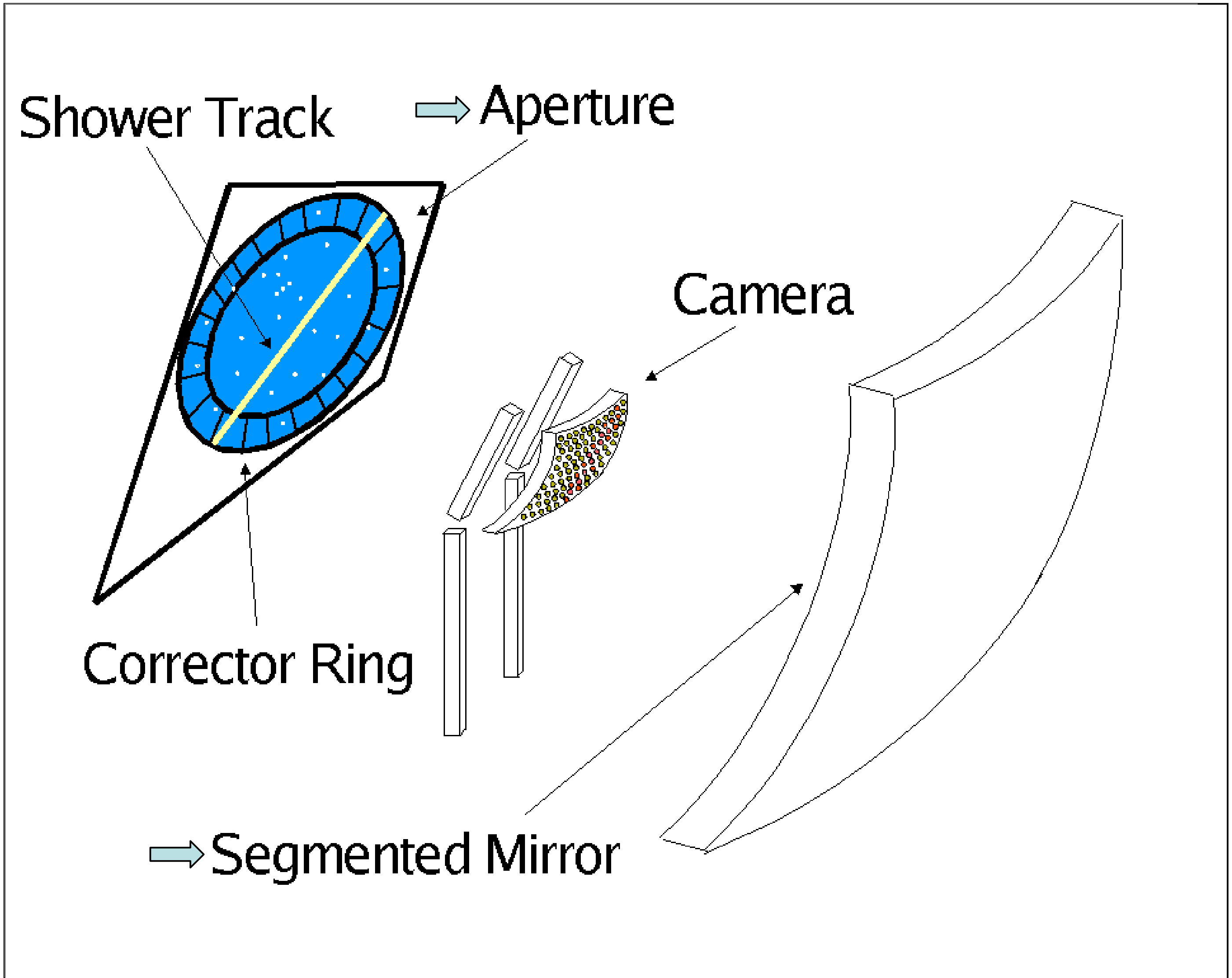
Core Distance (km)


Event Display, version v3r1
Event Display
Help
Control
File
Configure
Experts only...
Mutiple selection
Reconstruct
Previous
Next
Get #
Update
8
#00617049, 8 stations, 3C2&4C4
#00617100, 9 stations, 3C2&4C4
#00617161, 8 stations, 3C2&4C4
#00617446, 9 stations, FD
#00617476, 10 stations, FD
#00617563, 10 stations, FD
#00617638, 9 stations, FD
#00617662, 11 stations, FD
#00617728, 8 stations, FD
#00617730, 8 stations, FD
#00617736, 17 stations, 3C2&4C4
#00617799, 11 stations, 3C2&4C4
#00617830, 16 stations, 3C2&4C4
#00617943, 8 stations, 3C2&4C4
0205 (0 ns, 12.3 VEM)
0206 (1548 ns, 71.0 VEM)
0203 (1799 ns, 624.8 VEM)
0118 (2564 ns, 16.5 VEM)
0213 (3837 ns, 14.3 VEM)
0204 (3916 ns, 2495.3 VEM)
0116 (4432 ns, 386.6 VEM)
0110 (5939 ns, 6.7 VEM)
0215 (6661 ns, 24.1 VEM)
0114 (6679 ns, 106.5 VEM)
0117 (7579 ns, 13.1 VEM)
0212 (9436 ns, 5.4 VEM)
0217 (9603 ns, 5.3 VEM)
0107 (9990 ns, 5.4 VEM)
0121 station deleted
Array
Status
Date of this event: Mon Dec 29 09:23:45 2003 (GPS 756725038)
Display
Lateral distribution function fit
10^3
10^2
10
1
500
1000
1500
2000
2500
3000
3500
Mon Dec 29 09:23:45 2003
Easting= 470347 ± 7m
Northing= 6095443 ± 11m
dt= 114.0ns
Theta= 34.4 ± 0.3 deg
Phi= 140.2 ± 0.3/sin(theta) deg
R= 12.5 ± 0.8 km
Preliminary Xmax= 1040 ± 66 g/cm^2
S(1000)= 365.51 ± 20.78 VEM
E= 74.81 EeV ± 6%
100%

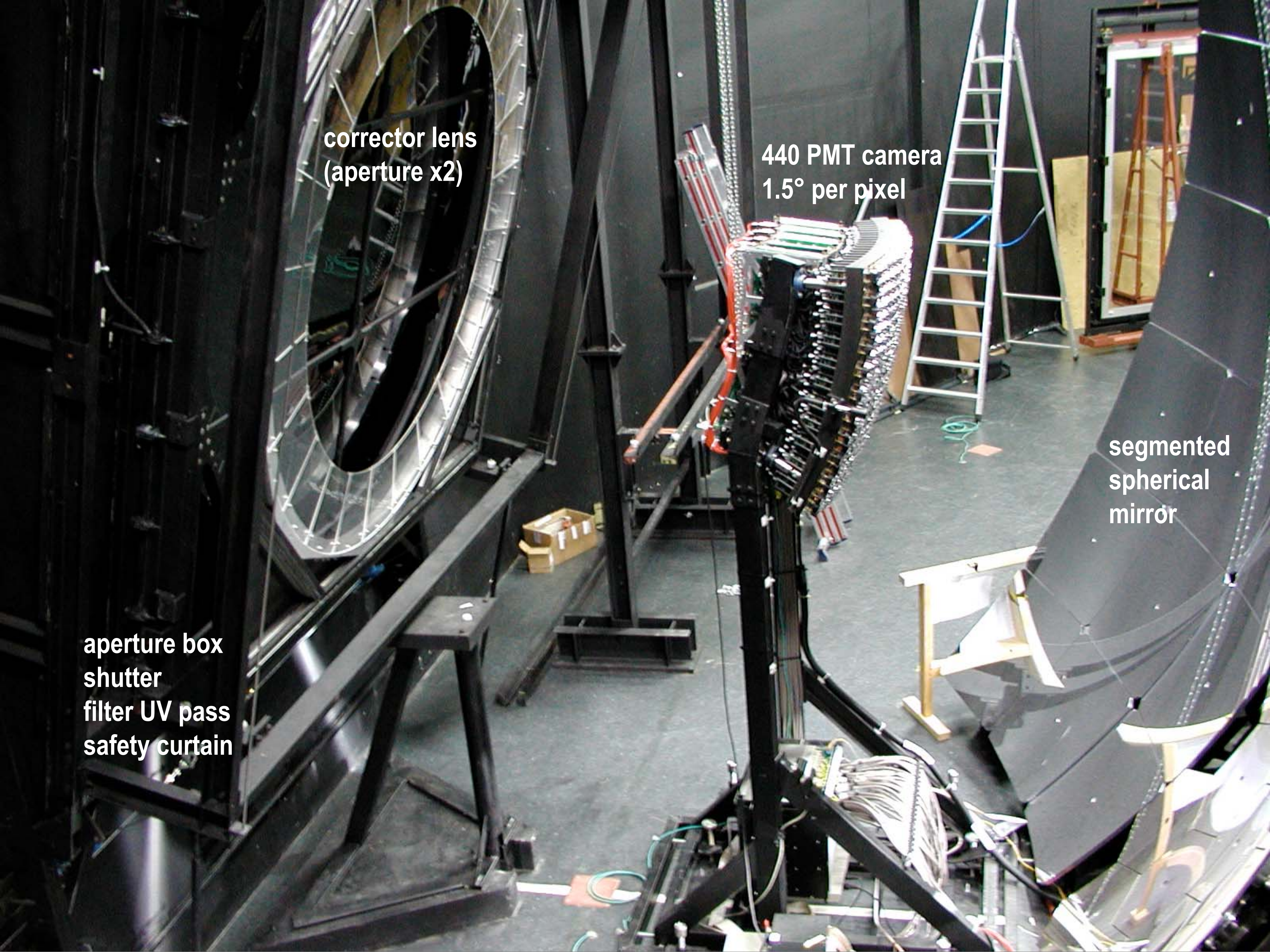


Stefano Argirò, “Status ... of the Pierre Auger Observatory”

Fluorescence Detector



- 30° x 30 ° fov
- Schmidt optics
- 440 pixels
- 1.5 ° Ø pixel
- 12 bit FADC
  10 Mhz f_s ⇨
  < 4 g/cm^2
- Digital trigger

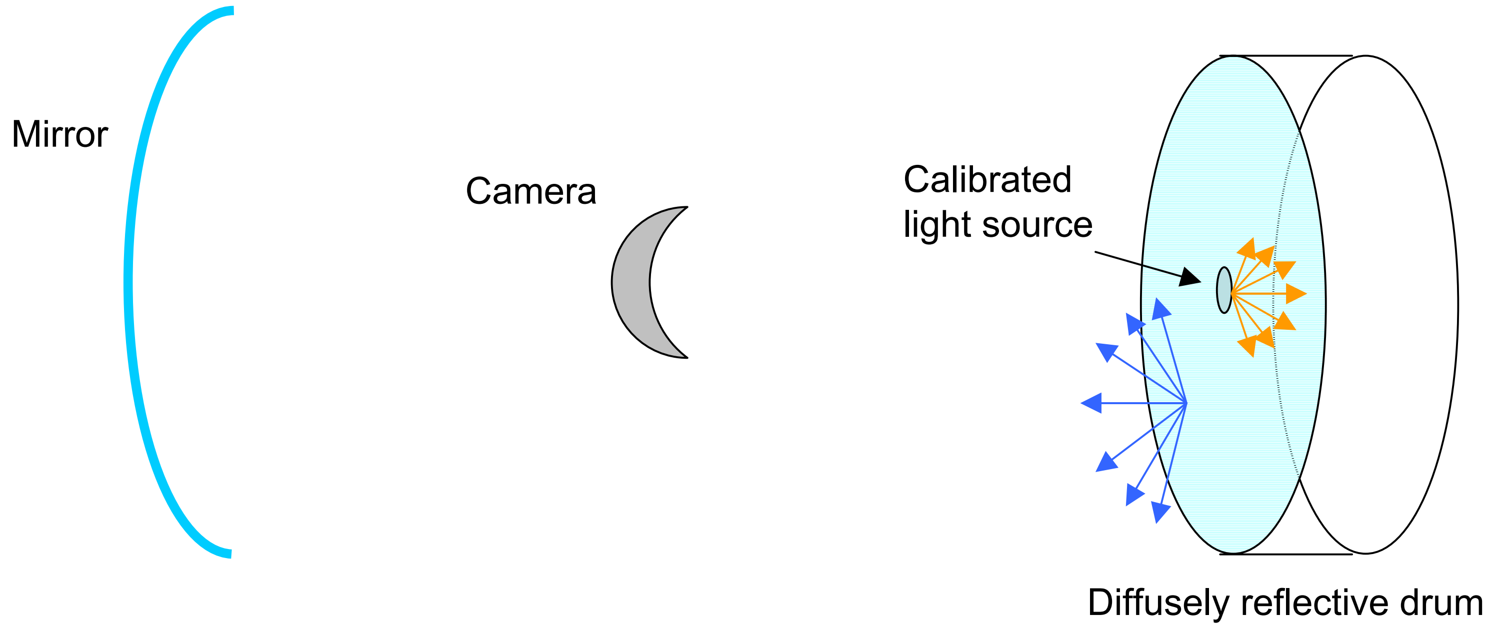

corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

FD Calibration

- **Absolute**: End to End Calibration

N Photons at diaphragm → FADC counts

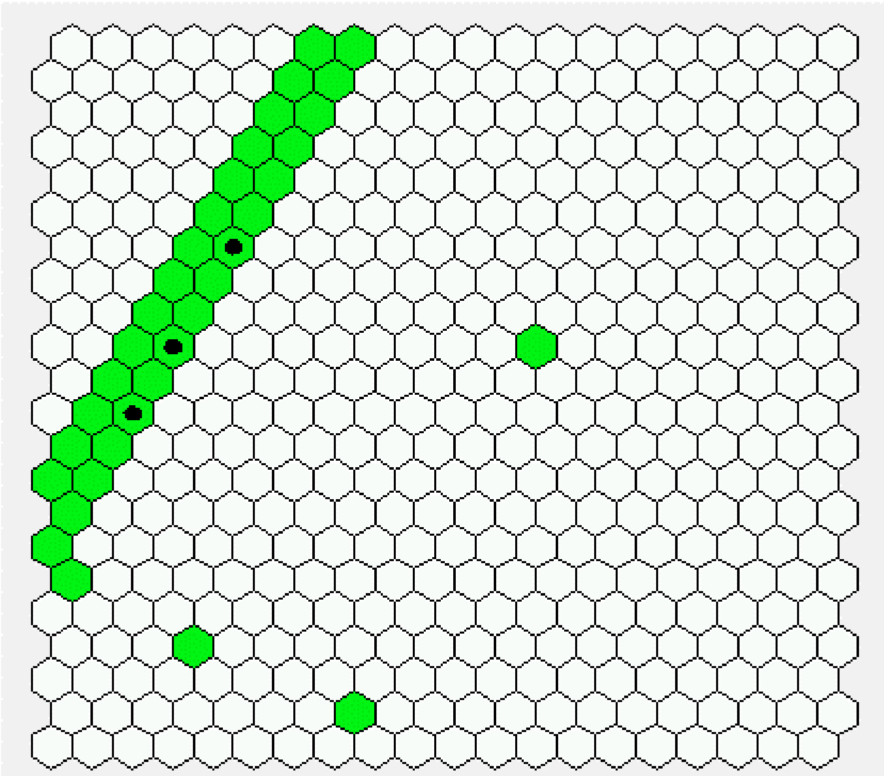
The **Drum** device installed at the aperture uniformly illuminates the camera with light from a calibrated source (1/month)

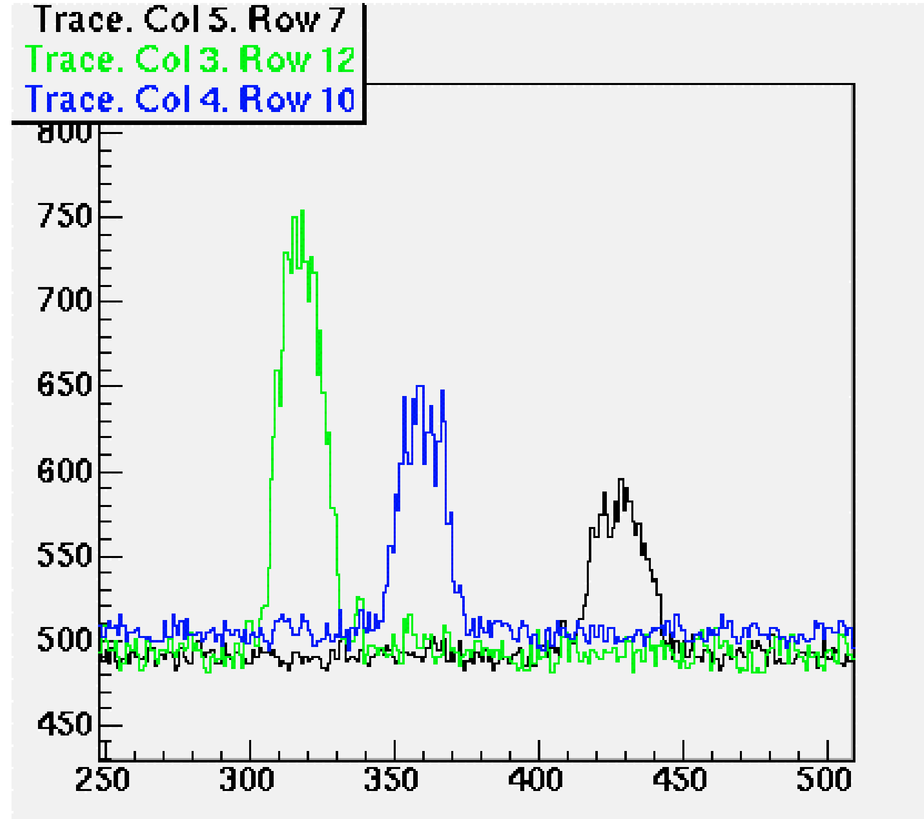


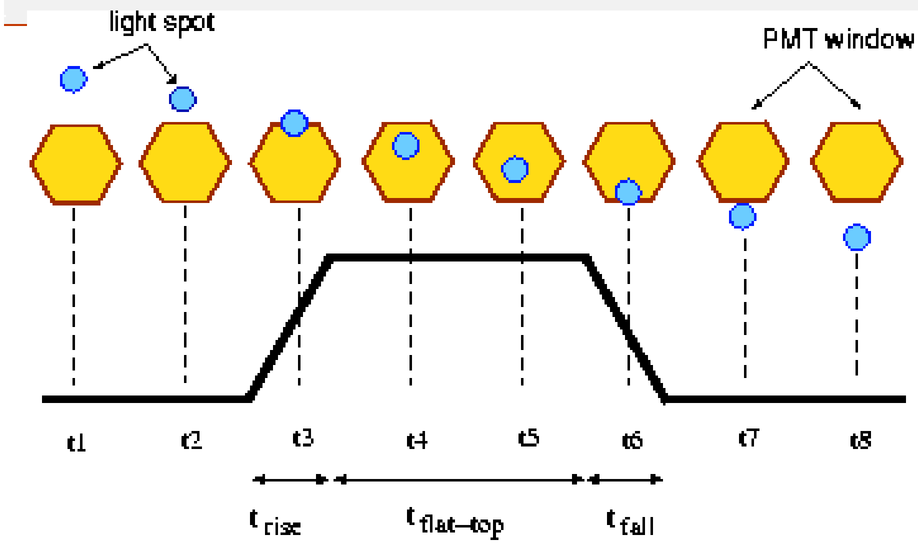
- Relative: UV LED + optical fibers (1/night)
- Alternative techniques for cross checks
    - Scattered light from laser beam
    - Statistical

⇨ All agreed within 10% for the EA

FD Event Display



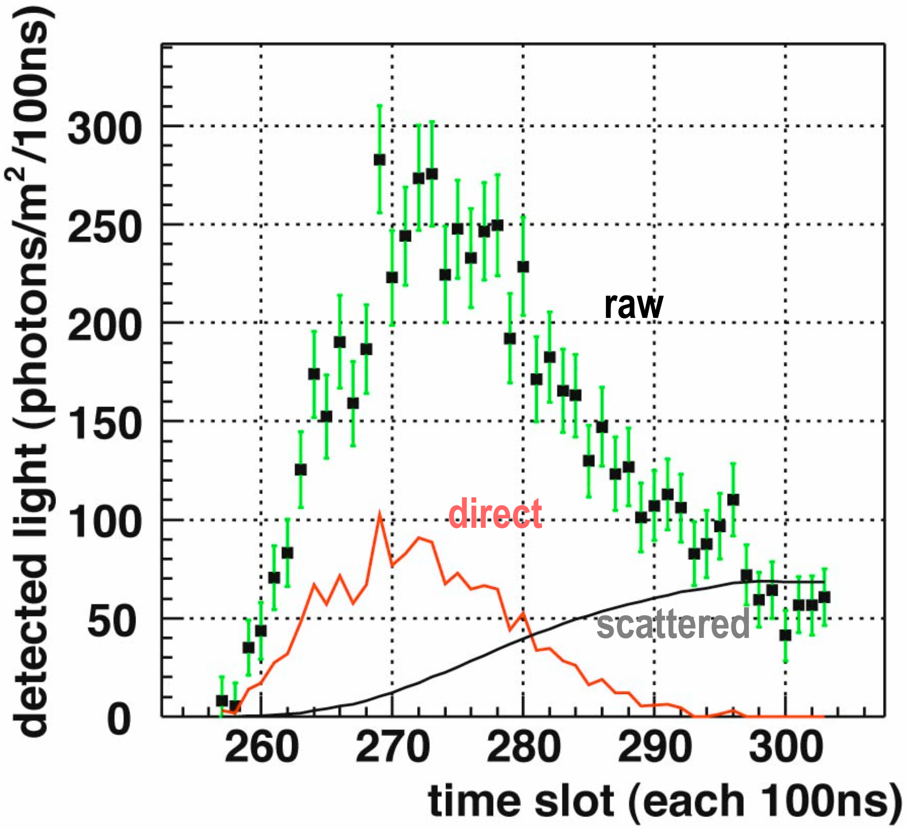


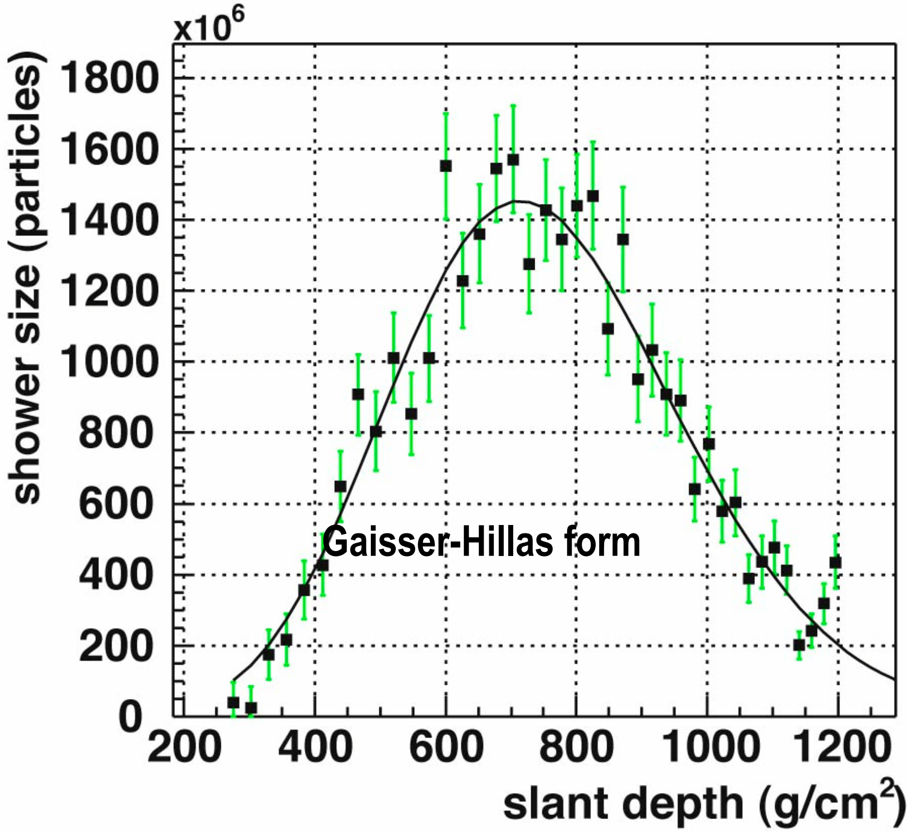


Stefano Argirò, "Status ... of the Pierre Auger Observatory"

Analysis procedures with the FD

this event: initial viewing angle 15°, i.e. large direct Cherenkov contribution
iterative procedure, converges in <4 steps; suggested energy here 2e18 eV





Atmosphere

calibrated (movable) light sources

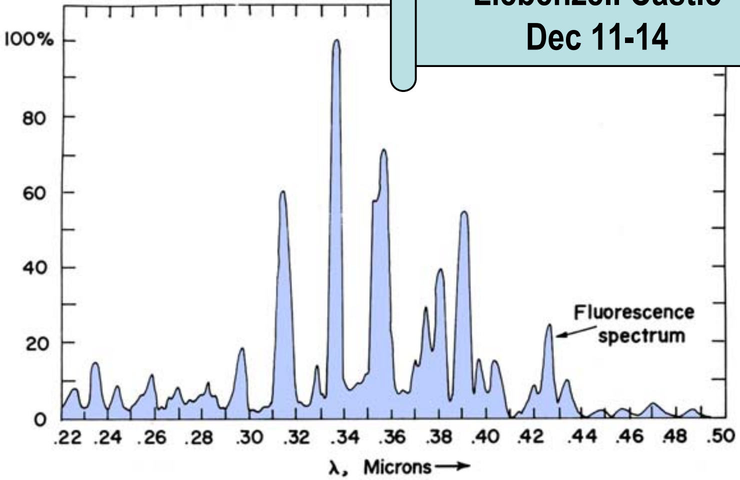
cloud monitors

LIDAR

lasers

balloon sondes

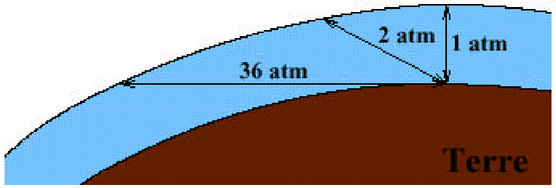
2. Intl Workshop
Liebenzell Castle
Dec 11-14



Using Horizontal Air Showers

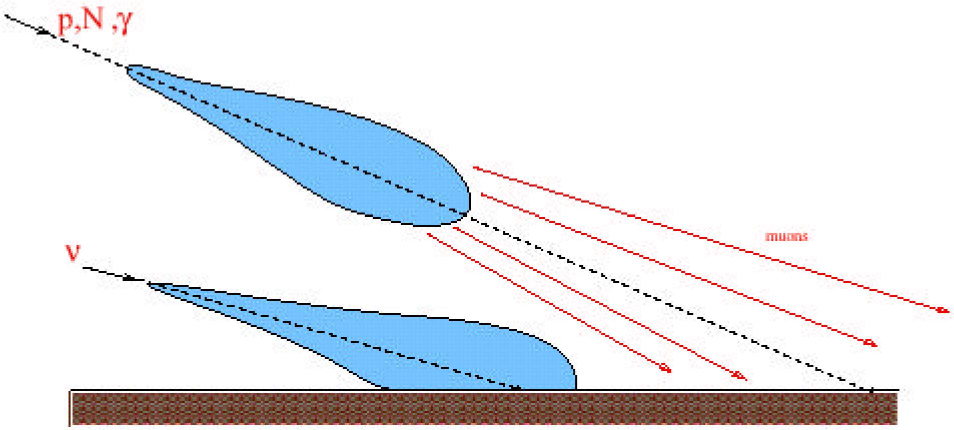
Atmosphere: $1000 g/cm^2$ thick vertically

$36000 g/cm^2$ thick horizontally



$\Rightarrow$ Look for interactions at deep column densities

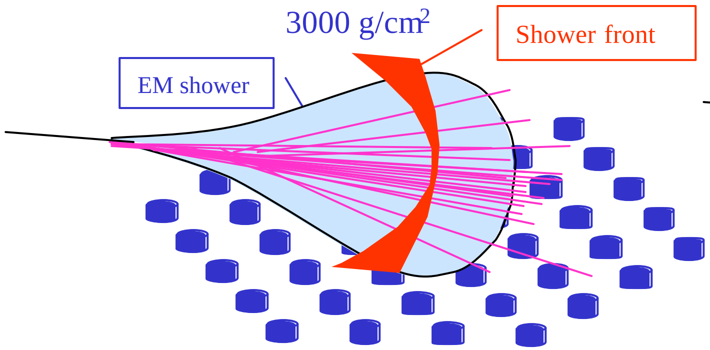
i.e. large zenith angles: $75° < \theta < 90°$

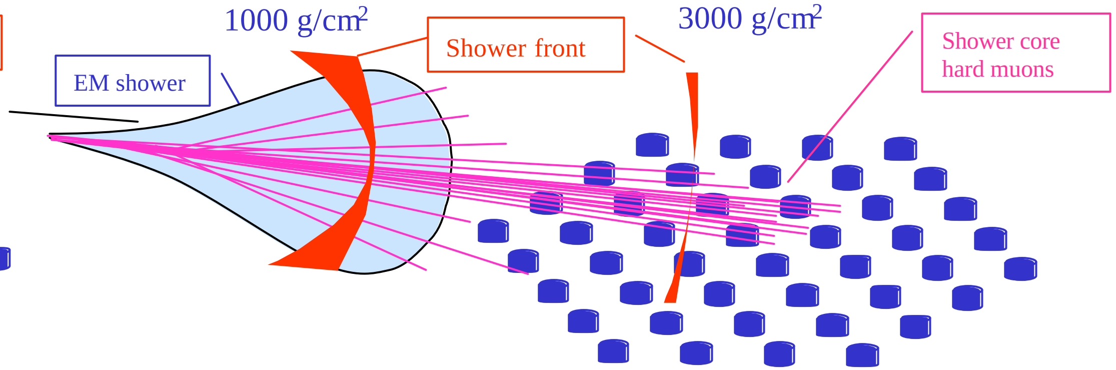


Neutrino Air Showers / Hadron Air Showers

ν : “new” showers

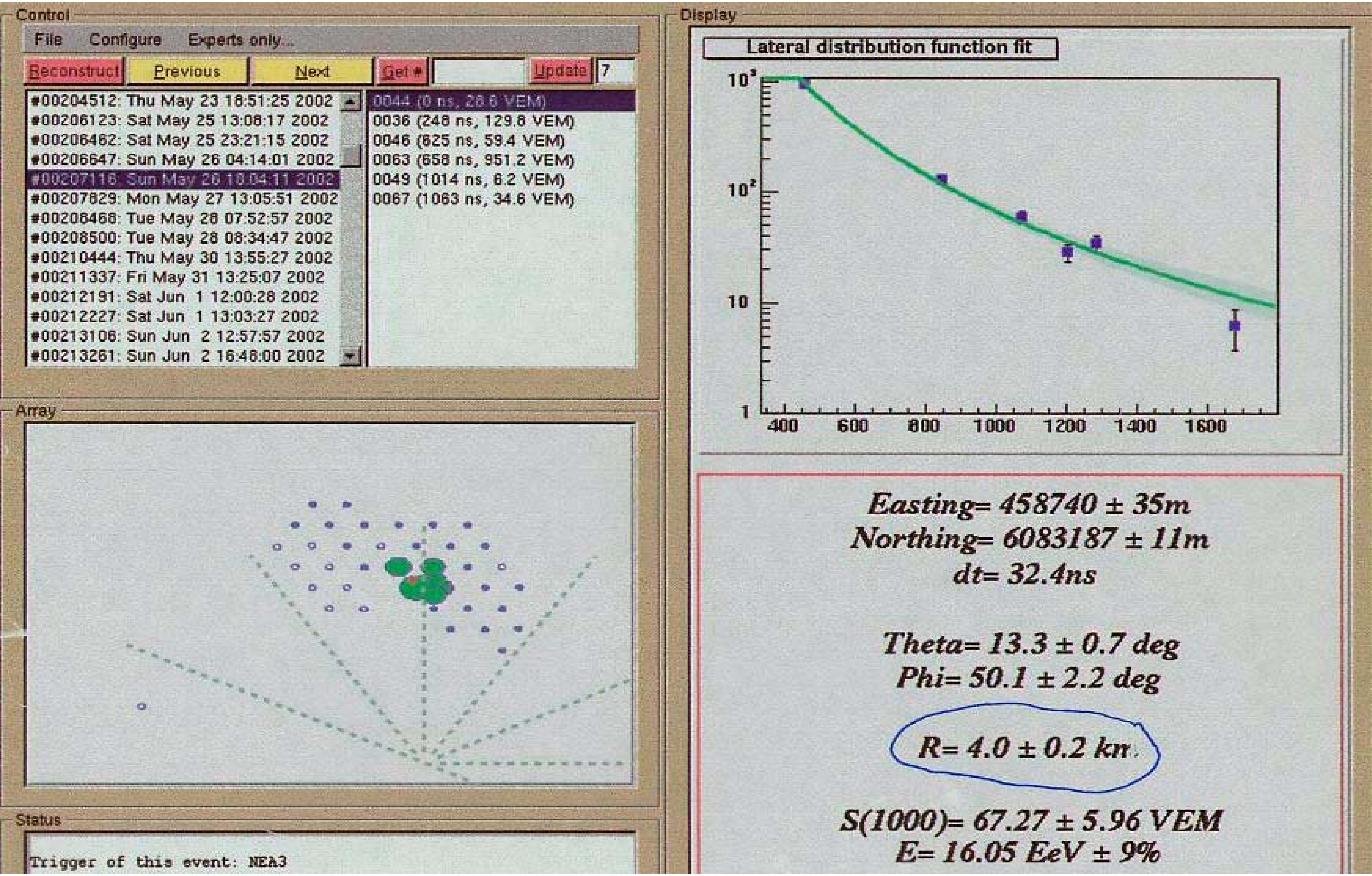
hadrons: “old” showers



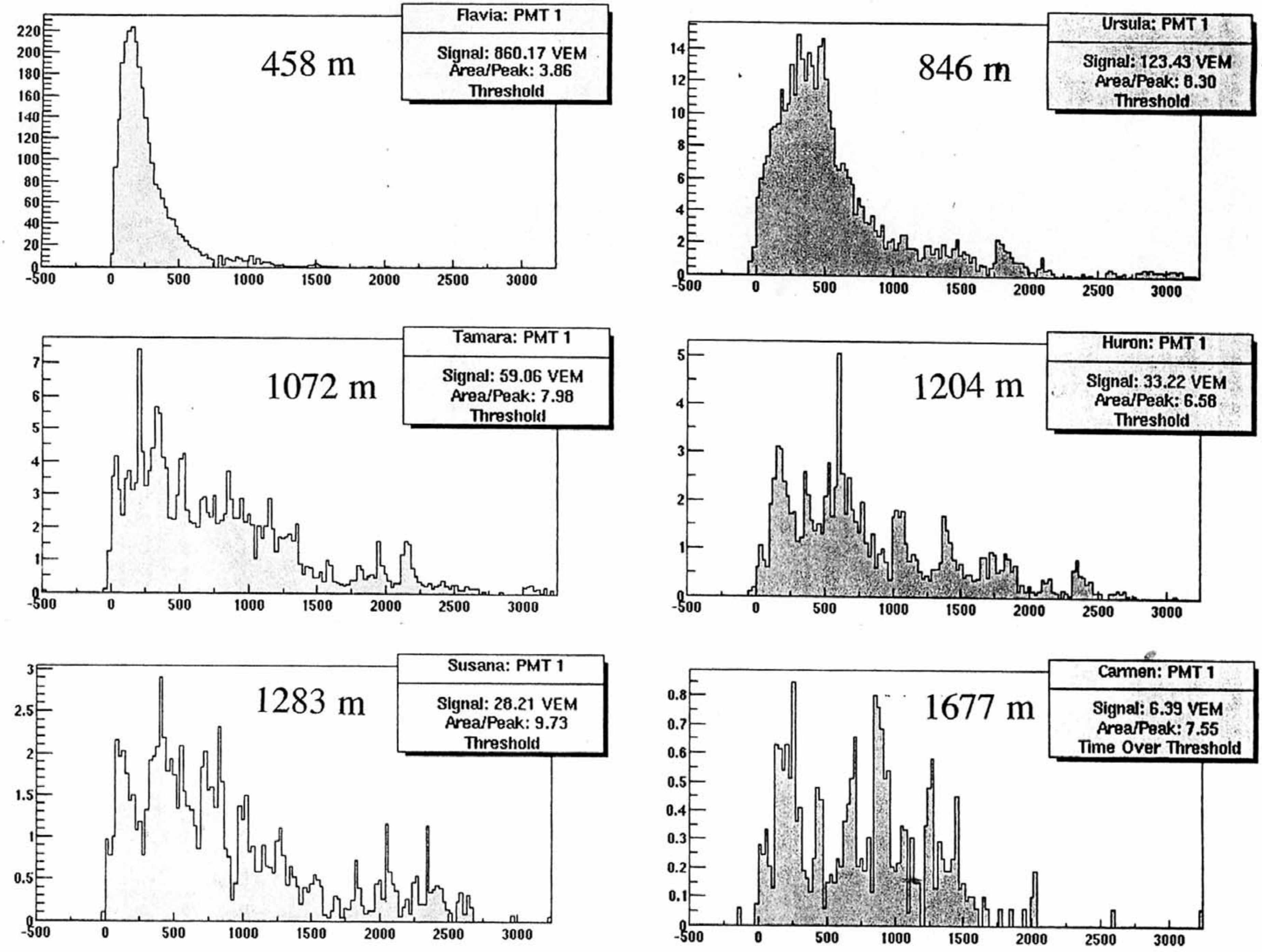


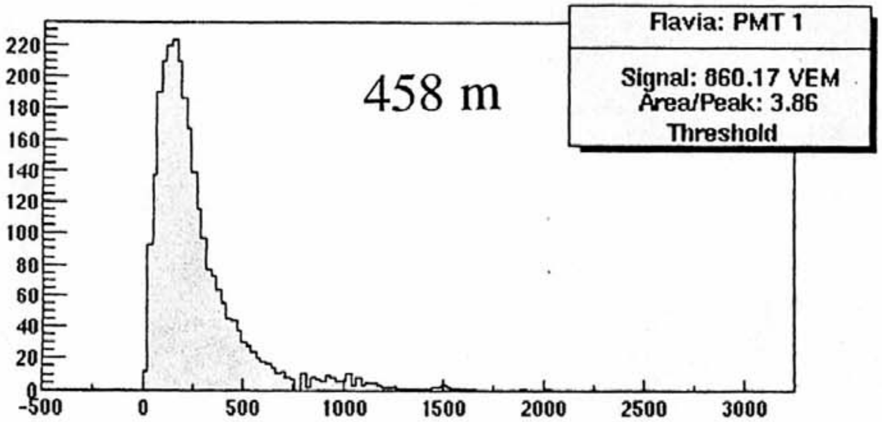
Signal is:
- Few events per year
- EM rich, curved and thick front
- Broad signals

Background is:
- Thousands events per year
- EM poor, muon rich, flat and thin front
- Prompt signal



Control
File
Configure
Experts only...
Reconstruct
Previous
Next
Get #
Update
7
#00204512: Thu May 23 16:51:25 2002
#00206123: Sat May 25 13:08:17 2002
#00206462: Sat May 25 23:21:15 2002
#00206647: Sun May 26 04:14:01 2002
#00207116: Sun May 26 18:04:11 2002
#00207829: Mon May 27 13:05:51 2002
#00208468: Tue May 28 07:52:57 2002
#00208500: Tue May 28 08:34:47 2002
#00210444: Thu May 30 13:55:27 2002
#00211337: Fri May 31 13:25:07 2002
#00212191: Sat Jun 1 12:00:28 2002
#00212227: Sat Jun 1 13:03:27 2002
#00213106: Sun Jun 2 12:57:57 2002
#00213261: Sun Jun 2 16:48:00 2002
0044 (0 ns, 28.6 VEM)
0036 (248 ns, 129.8 VEM)
0046 (625 ns, 59.4 VEM)
0063 (658 ns, 951.2 VEM)
0049 (1014 ns, 6.2 VEM)
0067 (1063 ns, 34.6 VEM)
Array
Status
Trigger of this event: NEA3
Display
Lateral distribution function fit
10³
10²
10
1
400
600
800
1000
1200
1400
1600
Easting= 458740 ± 35m
Northing= 6083187 ± 11m
dt= 32.4ns
Theta= 13.3 ± 0.7 deg
Phi= 50.1 ± 2.2 deg
R= 4.0 ± 0.2 km
S(1000)= 67.27 ± 5.96 VEM
E= 16.05 EeV ± 9%


Flavia: PMT 1
Signal: 860.17 VEM
Area/Peak: 3.86
Threshold
458 m
Ursula: PMT 1
Signal: 123.43 VEM
Area/Peak: 8.30
Threshold
846 m
Tamara: PMT 1
Signal: 59.06 VEM
Area/Peak: 7.98
Threshold
1072 m
Huron: PMT 1
Signal: 33.22 VEM
Area/Peak: 6.58
Threshold
1204 m
Susana: PMT 1
Signal: 28.21 VEM
Area/Peak: 9.73
Threshold
1283 m
Carmen: PMT 1
Signal: 6.39 VEM
Area/Peak: 7.55
Time Over Threshold
1677 m

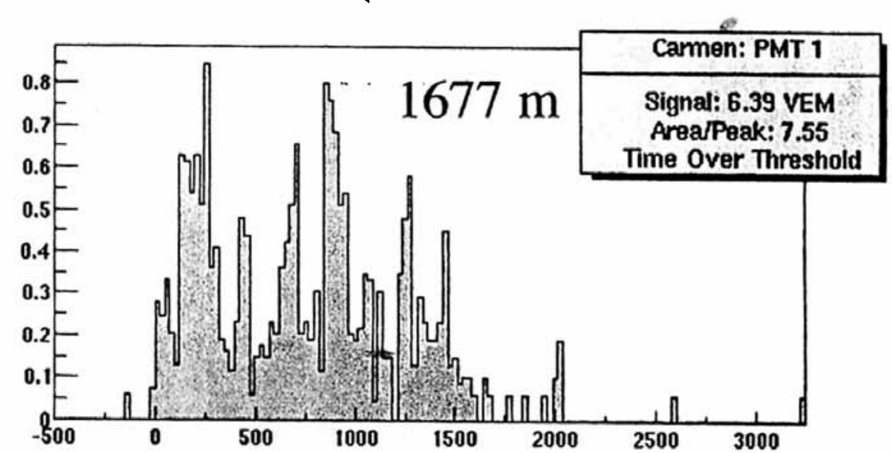


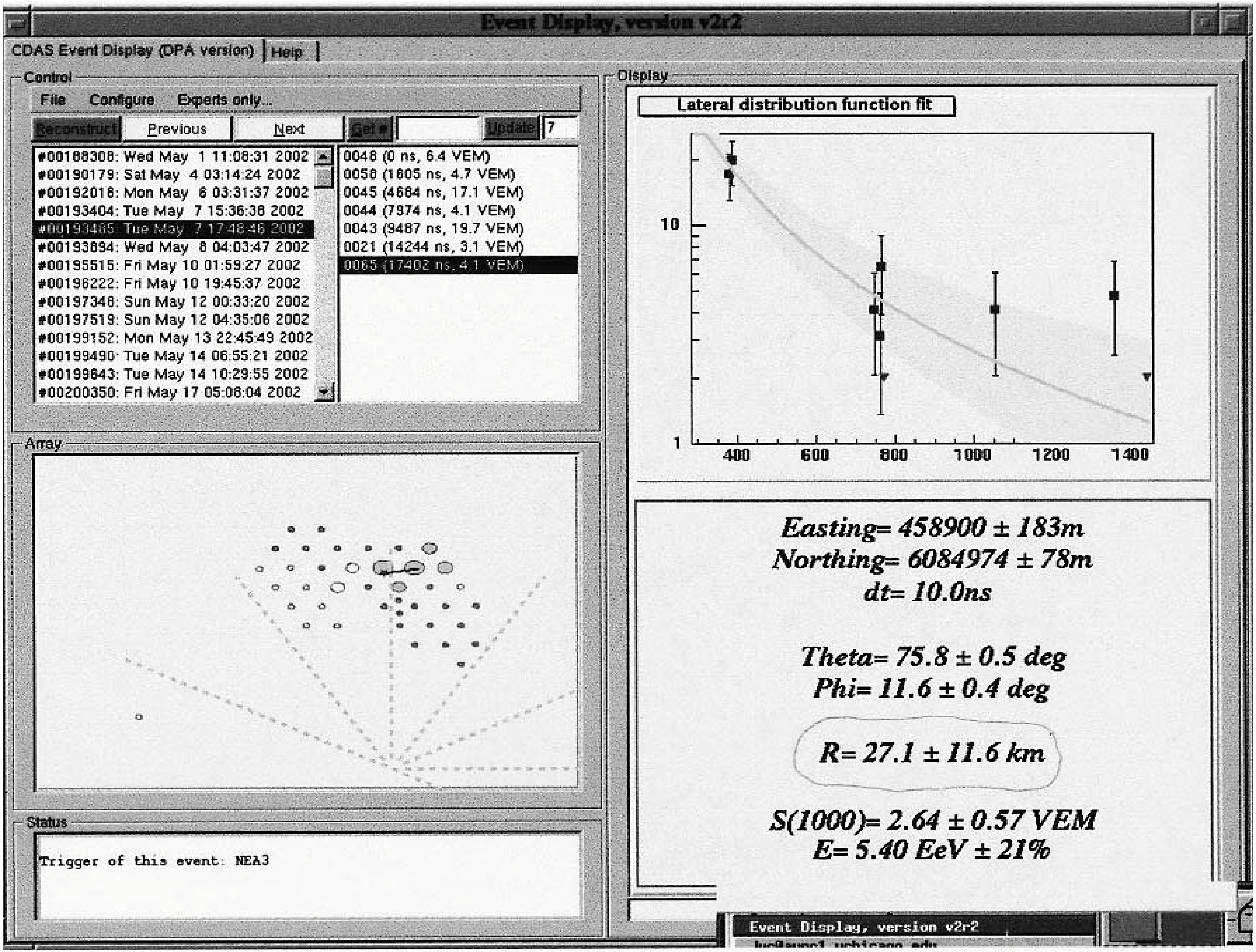
Near PMT

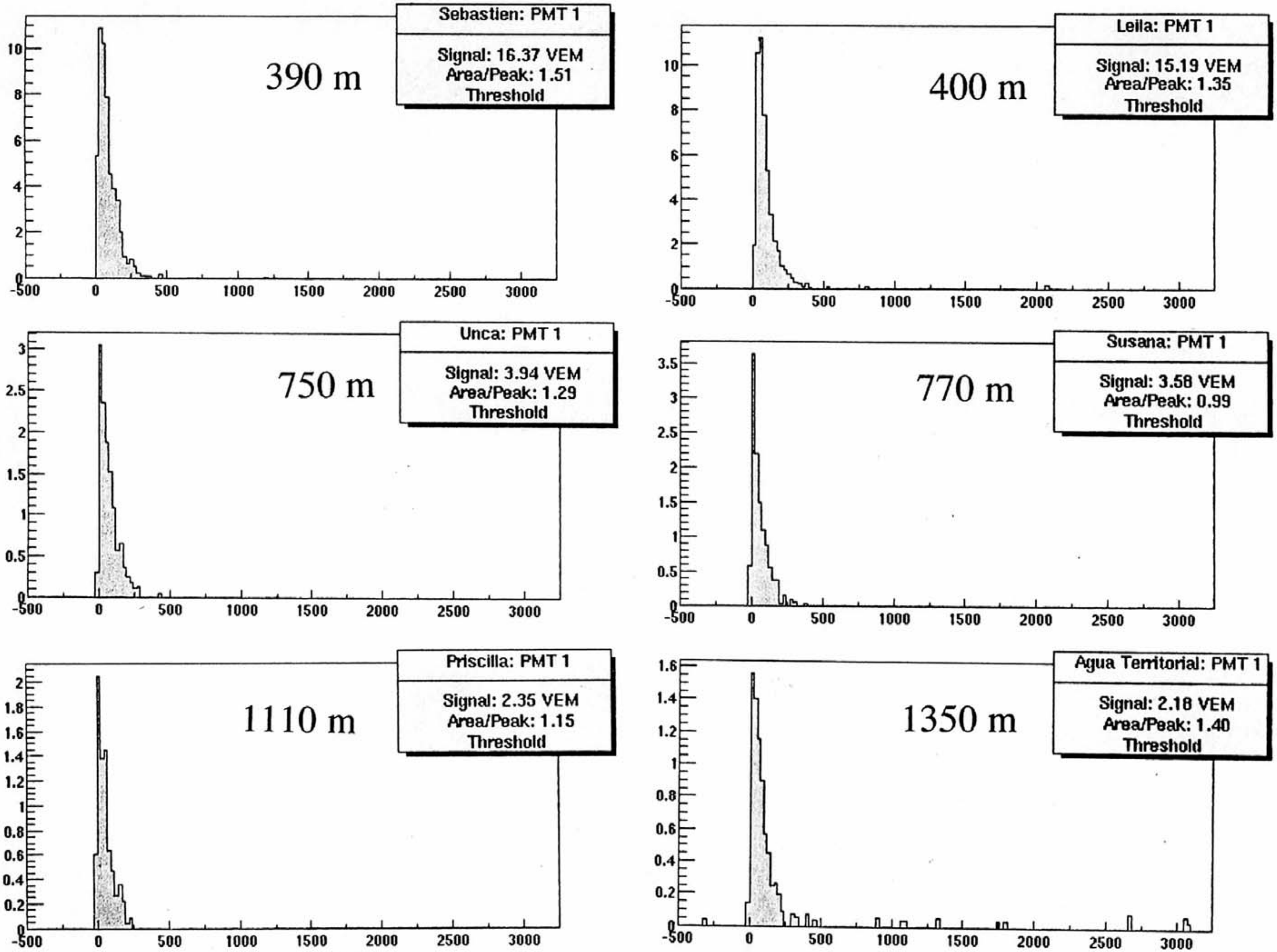
Distance ratio = 3.7 Density ratio = 134

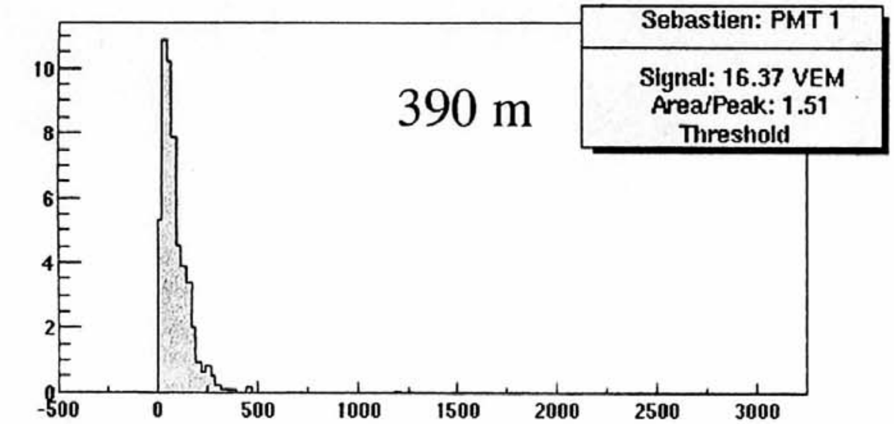
this is a 'young shower', lots of electrons

Far PMT




Event Display, version v2r2
CDAS Event Display (DPA version)
Help
Control
File
Configure
Experts only...
Reconstruct
Previous
Next
Get #
Update
7
#00188308: Wed May 1 11:08:31 2002
#00190179: Sat May 4 03:14:24 2002
#00192018: Mon May 6 03:31:37 2002
#00193404: Tue May 7 15:36:38 2002
#00193465: Tue May 7 17:48:46 2002
#00193694: Wed May 8 04:03:47 2002
#00195515: Fri May 10 01:59:27 2002
#00196222: Fri May 10 19:45:37 2002
#00197348: Sun May 12 00:33:20 2002
#00197519: Sun May 12 04:35:06 2002
#00199152: Mon May 13 22:45:49 2002
#00199490: Tue May 14 06:55:21 2002
#00199643: Tue May 14 10:29:55 2002
#00200350: Fri May 17 05:08:04 2002
0048 (0 ns, 6.4 VEM)
0058 (1605 ns, 4.7 VEM)
0045 (4684 ns, 17.1 VEM)
0044 (7374 ns, 4.1 VEM)
0043 (9487 ns, 19.7 VEM)
0021 (14244 ns, 3.1 VEM)
0065 (17402 ns, 4.1 VEM)
Array
Status
Trigger of this event: NEA3
Display
Lateral distribution function fit
10
1
400
600
800
1000
1200
1400
Easting= 458900 ± 183m
Northing= 6084974 ± 78m
dt= 10.0ns
Theta= 75.8 ± 0.5 deg
Phi= 11.6 ± 0.4 deg
R= 27.1 ± 11.6 km
S(1000)= 2.64 ± 0.57 VEM
E= 5.40 EeV ± 21%
Event Display, version v2r2


Sebastien: PMT 1
Signal: 16.37 VEM
Area/Peak: 1.51
Threshold
390 m
Leila: PMT 1
Signal: 15.19 VEM
Area/Peak: 1.35
Threshold
400 m
Unca: PMT 1
Signal: 3.94 VEM
Area/Peak: 1.29
Threshold
750 m
Susana: PMT 1
Signal: 3.58 VEM
Area/Peak: 0.99
Threshold
770 m
Priscilla: PMT 1
Signal: 2.35 VEM
Area/Peak: 1.15
Threshold
1110 m
Agua Territorial: PMT 1
Signal: 2.18 VEM
Area/Peak: 1.40
Threshold
1350 m

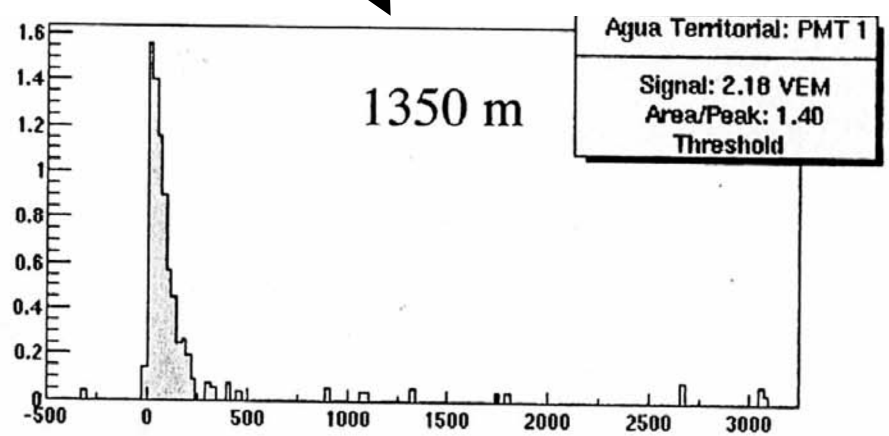


Near PMT

Distance ratio = 3.5   Density ratio = 7.5

this is an old shower', mostly muons

Far PMT



Tau Neutrino Detection

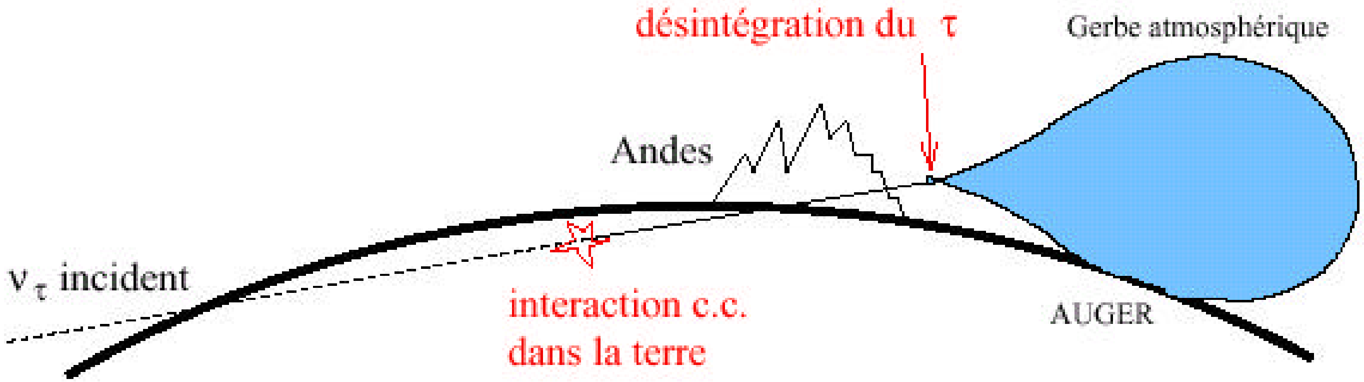
- Principle:
  - Interaction length in the earth ~ 300 km at 10^{18} eV
  - Tau time of flight ~ 50 km at 10^{18} eV
  - 1° below horizon $\Rightarrow$ 200 km of rock
  - Shower maximum ~10 km after decay

  In practice $85° < \theta_z < 95°$

  AUGER window: 10^{17} to 10^{20} eV

X.Bertou, P.Billoir, O.Deligny, A.Letessier-Selvon

astro-ph/0104452v4
Accepted in Astropart. Phys.



5. Summary ... highest energy cosmic rays

- Cosmic rays are observed by AGASA and HiRes to energies above 10^{20}eV. **Low statistics permit interpretation of the spectrum shape as *GZK-like* ... but we can not say for sure**.
- AGASA energy scale may be 20 $\sim$ 30% higher than Fly's Eye, Haverah Park and HiRes. **IF AGASA energies scaled down then fewer events $> 10^{20}$eV but *biggest* events remain.**
- Arrival directions of events $> 4 \times 10^{19}$eV are isotropic supporting the extra-galactic source of these cosmic rays. AGASA *clusters* interesting ... but could be a statistical fluctuation.
- **Sources of the events above the cosmic microwave background *GZK cutoff* "must" be (relatively) nearby ... but are not yet identified. More data are essential!**
- **New data are consistent with light (p,He) primaries at the highest energies.** What is needed to make this firm ... *e.g.* can better data and data analyses circumvent hadronic interaction uncertainties?
- **Much larger and more sophisticated *hybrid* experiments are being built! Auger is already running ... and has plans for a Northern observatory to provide essential** *full sky coverage.* So stay tuned!