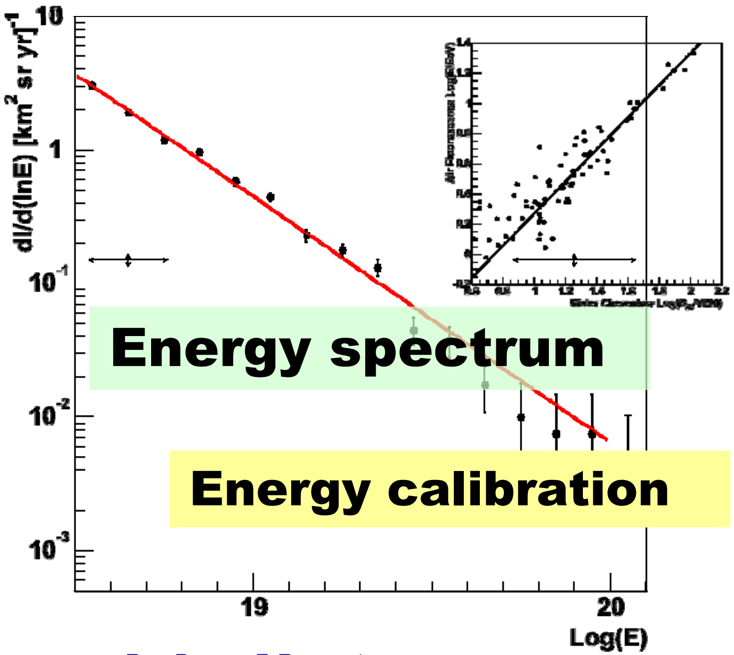
Results from the Pierre Auger Southern Observatory

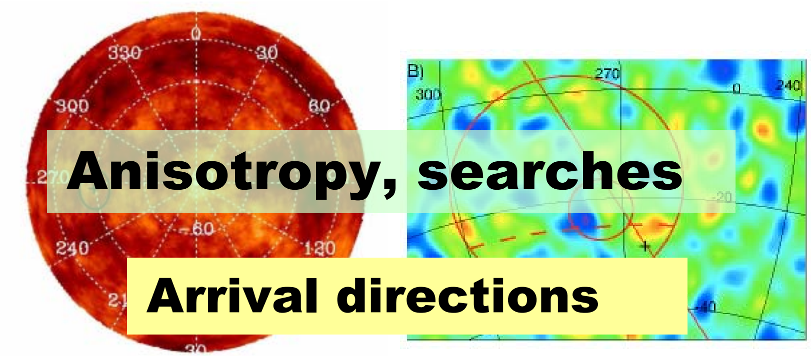
PIERRE AUGER OBSERVATORY

Outline



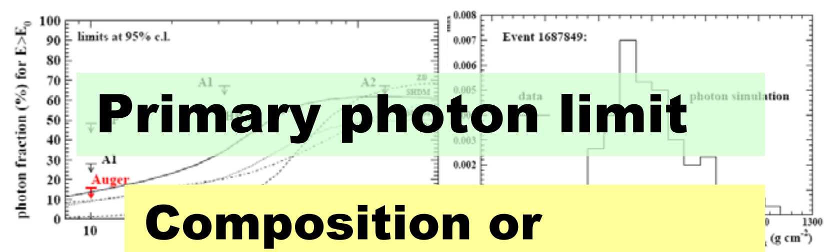
Energy spectrum

Energy calibration



Anisotropy, searches

Arrival directions



Primary photon limit

Composition or primary particle type

John Harton
Department of Physics
Colorado State University
Fort Collins, Colorado

SLAC Summer Institute
19 July 2006

Cosmic rays

Primary

Primaries are likely to be sub-atomic particles: γ, e, p, nuclei

Secondaries:
γ, e, p, n, π, μ...

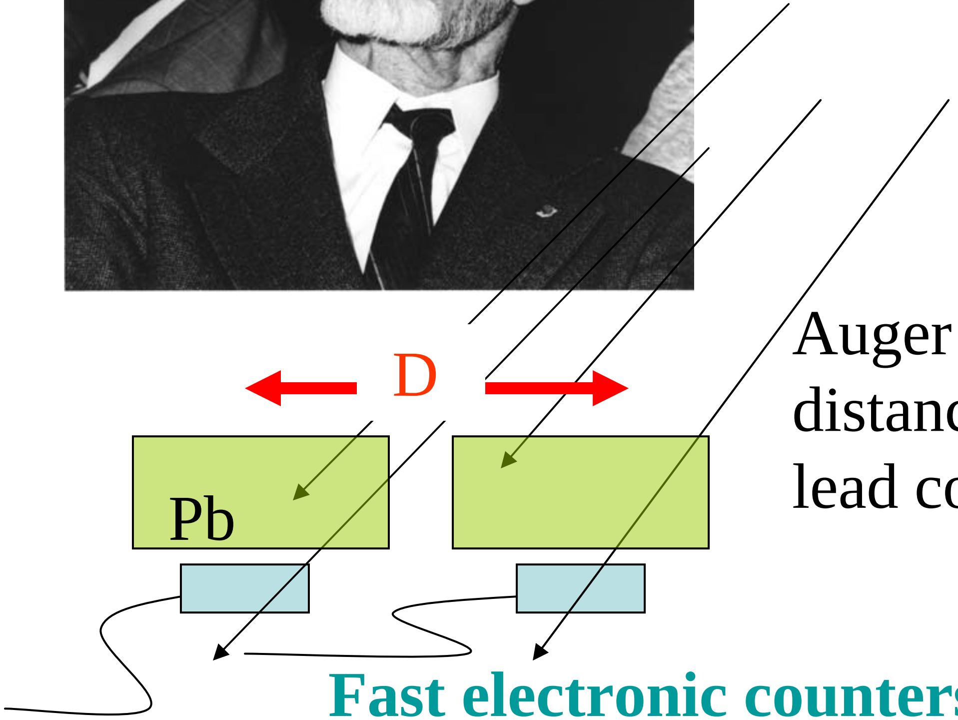
Low energy: few/hand/second.

High energy: Flux falls very steeply with energy.

Historical high points

1912
Victor Hess discovers "penetrating radiation" from space

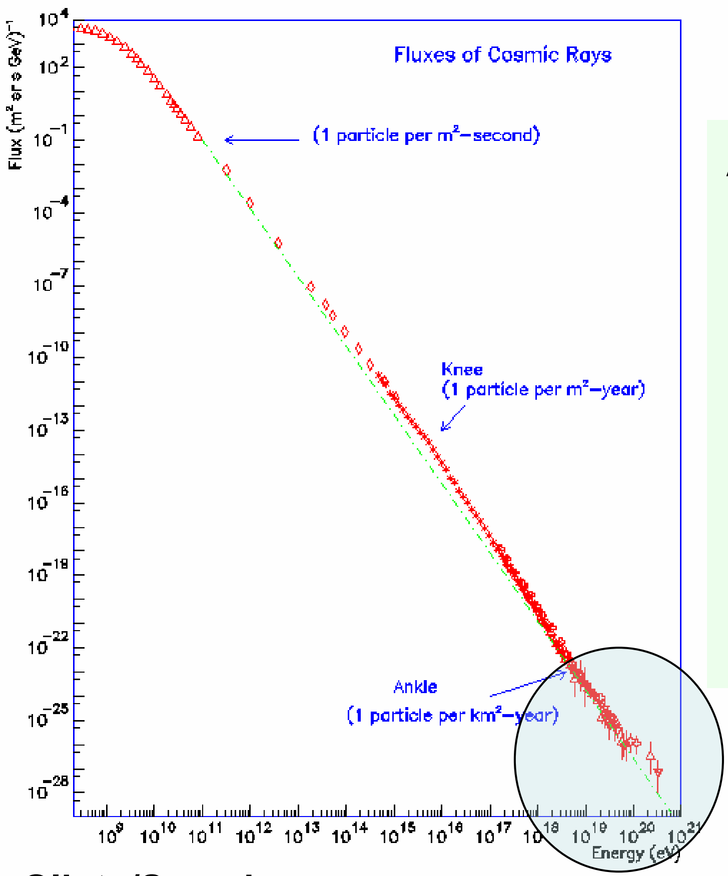
1938
Pierre Auger discovers Extensive air showers



Auger varied distance and lead covering

Fast electronic counters

The Auger Project studies the most energetic cosmic rays



Olinto/Swordy

Cosmic ray flux spans 32 orders of magnitude over 12 orders of magnitude in energy

Auger is focused on the high end: $E>10^{18}$ eV

Flux measured in # / km^2 / year

Sources, acceleration mechanism unknown

GZK feature starts around $5*10^{19}$ eV

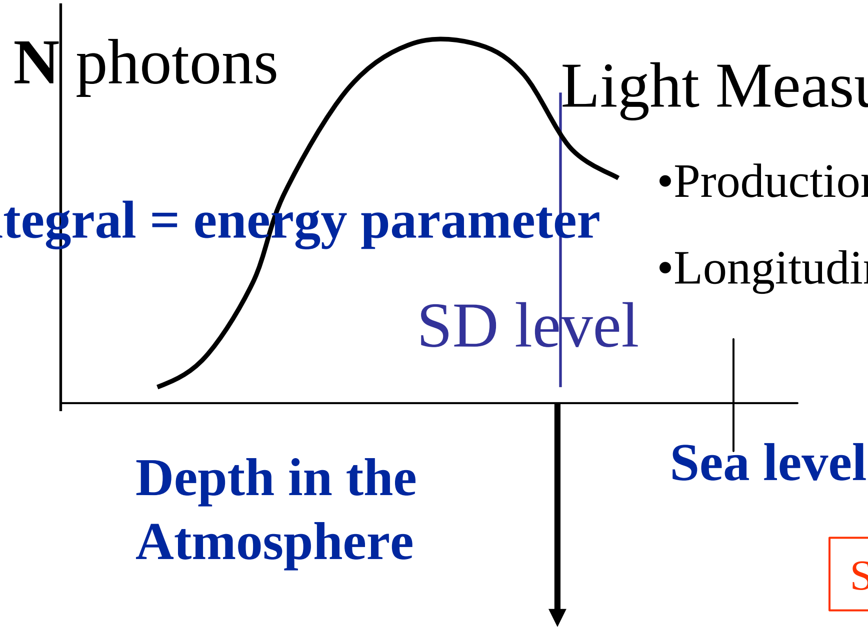
primary + CMB → primary + π
and primary loses energy

Length scale ≈ 50 Mpc

Macroscopic energies: $2*10^{20}$ eV = 30 Joules
= tennis ball at 75 mph
= laptop falling from shoulder height
= a person walking slowly

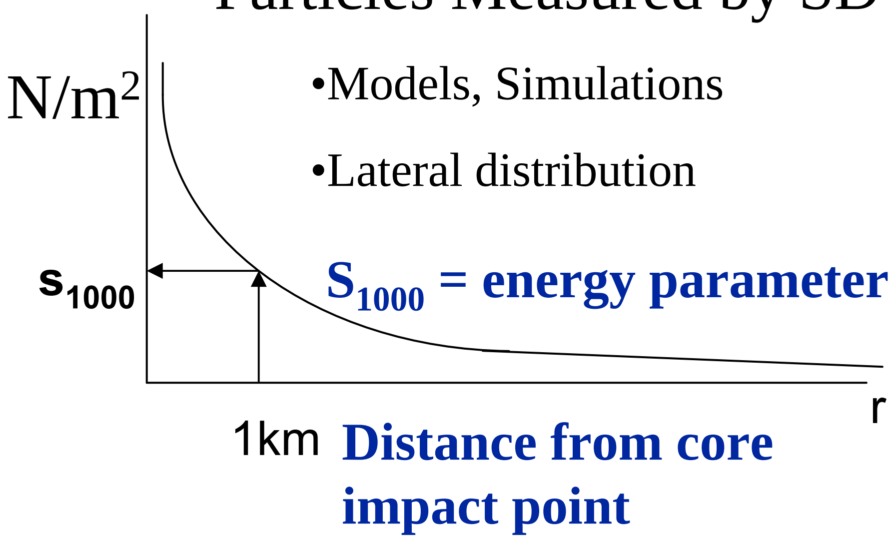
Light Measured by FD

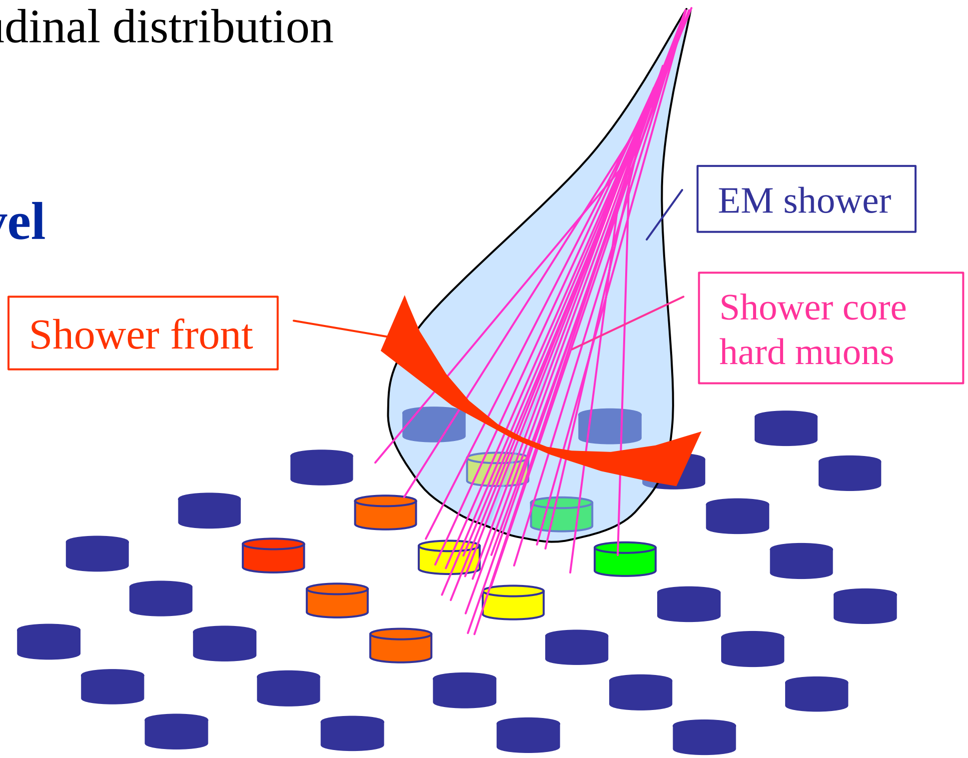
- Production, Propagation, Detection
- Longitudinal distribution



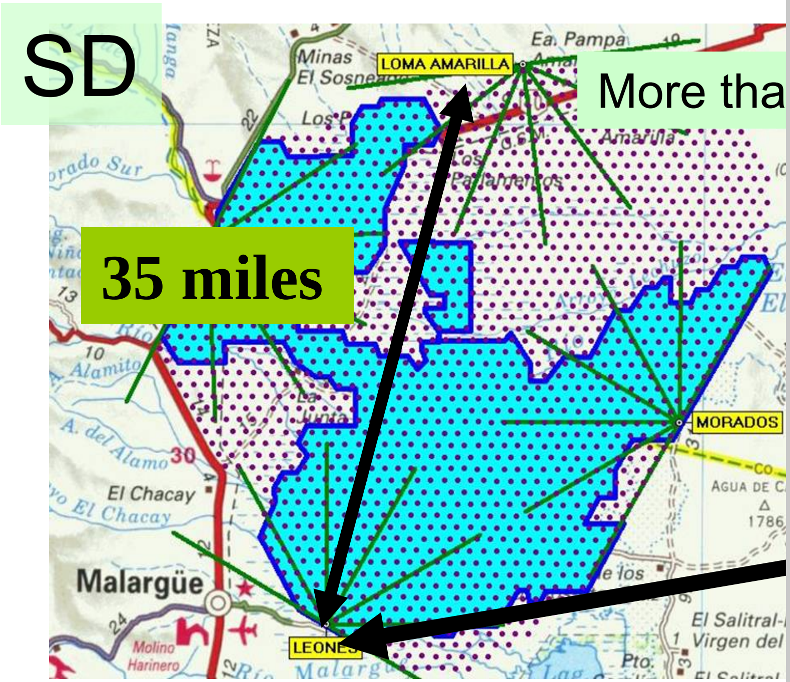
Particles Measured by SD

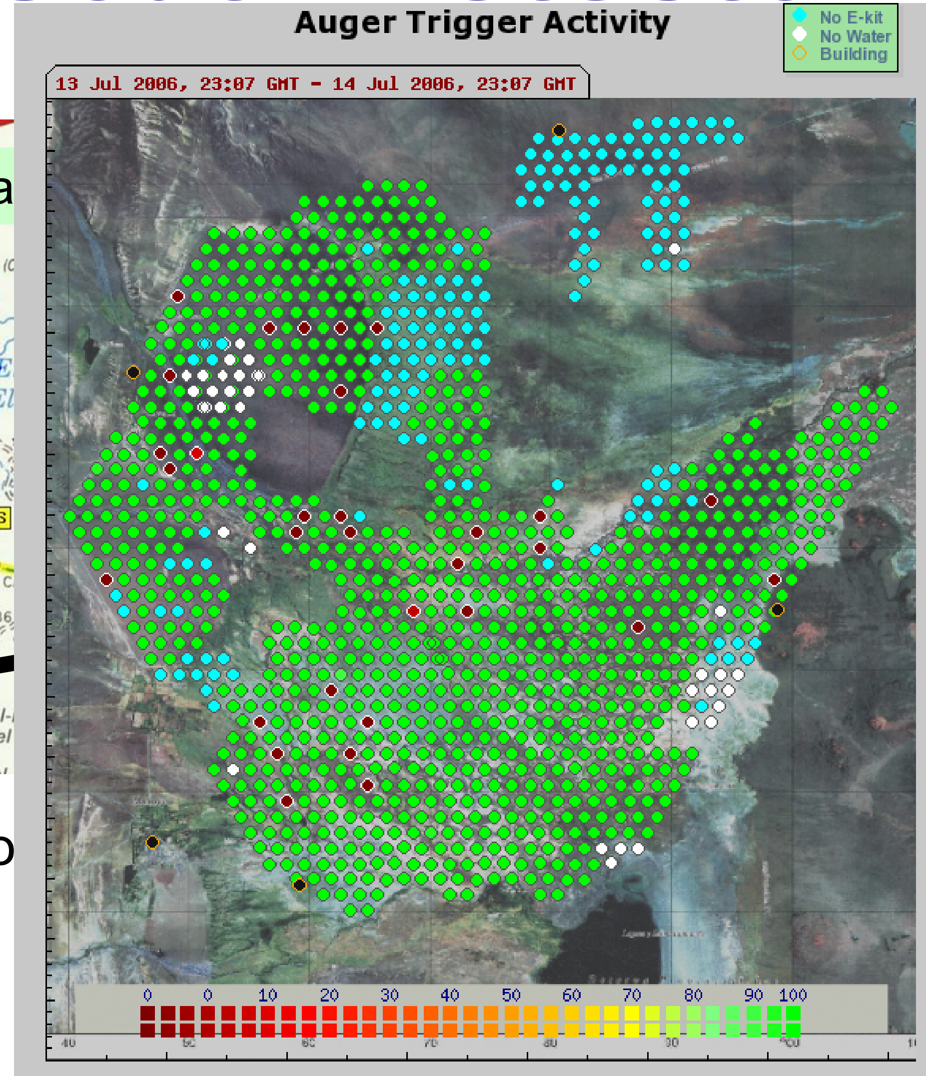
- Models, Simulations
- Lateral distribution





The Auger South Detector





3000 km², 1600 water Cerenko
tanks. Hex grid with 1.5 km spacing

About 1100 tanks deployed now.

24 hour operation

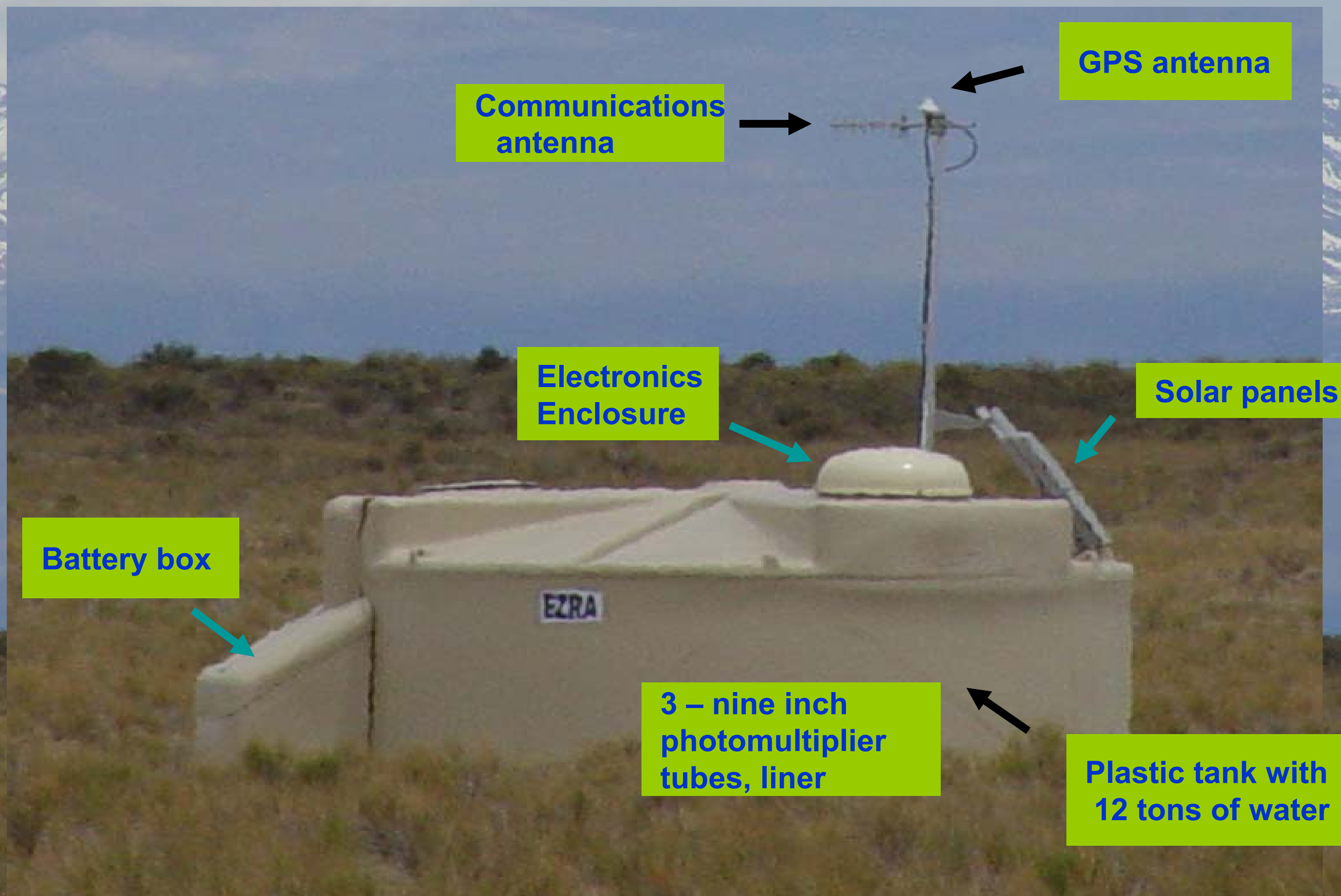
rror

ta.

Factor 10 lower duty factor than SD.

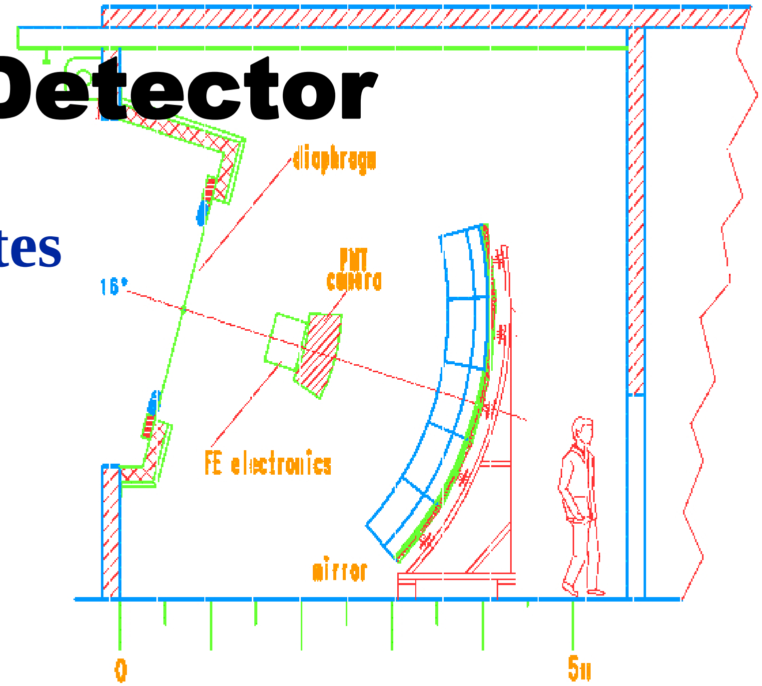
SD + FD = Hybrid. Key to present analyses.

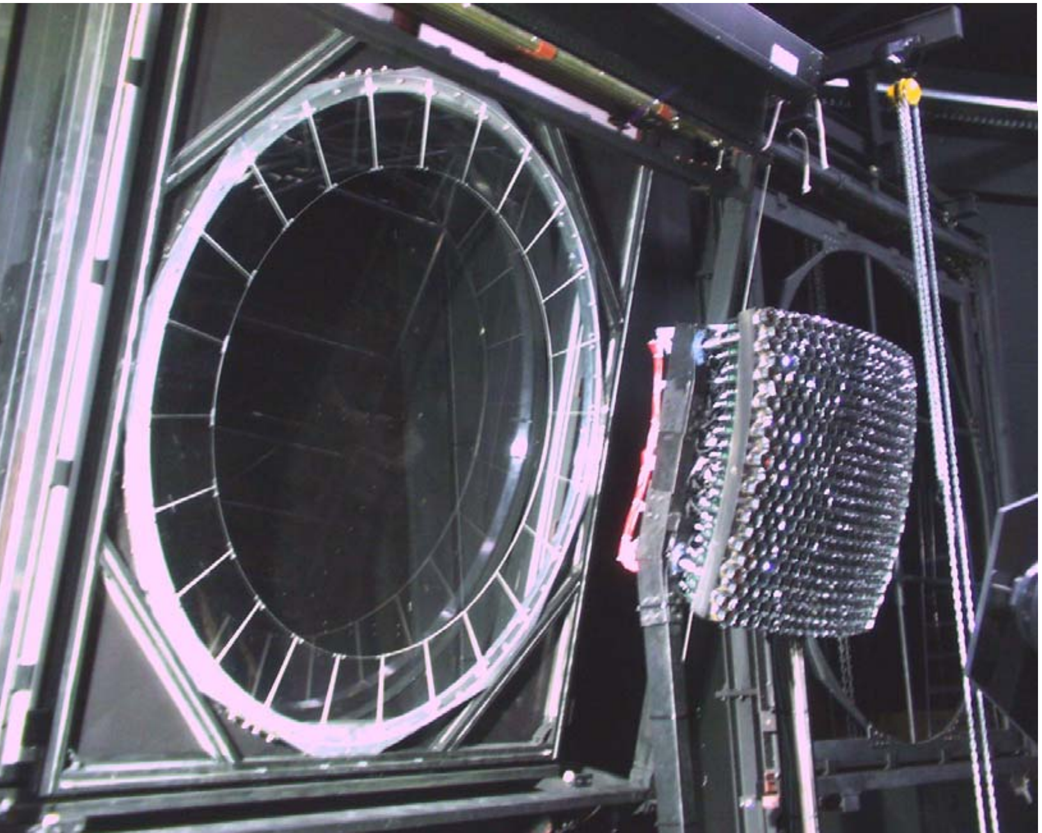
Auger surface detector unit

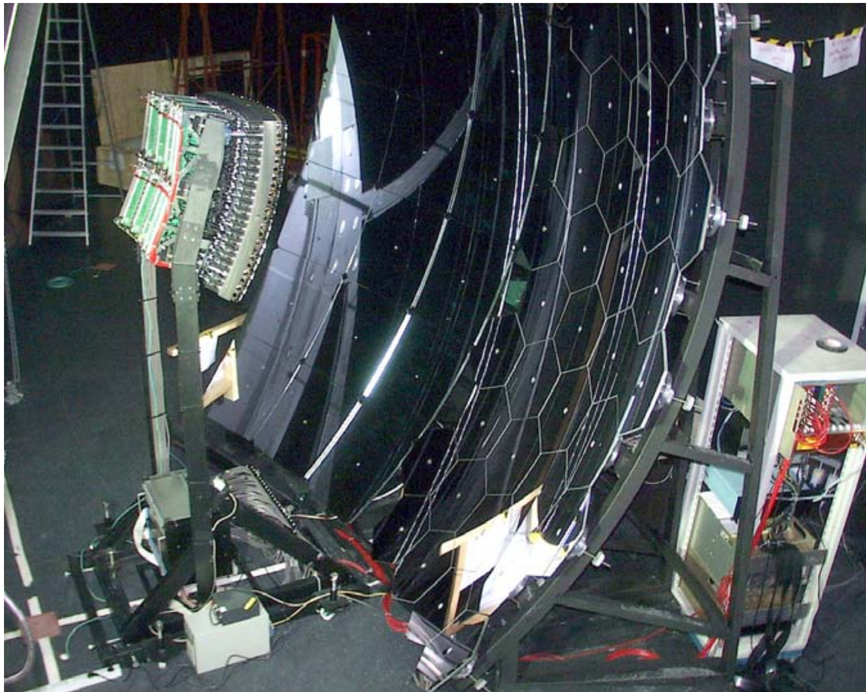


Auger Fluorescence Detector

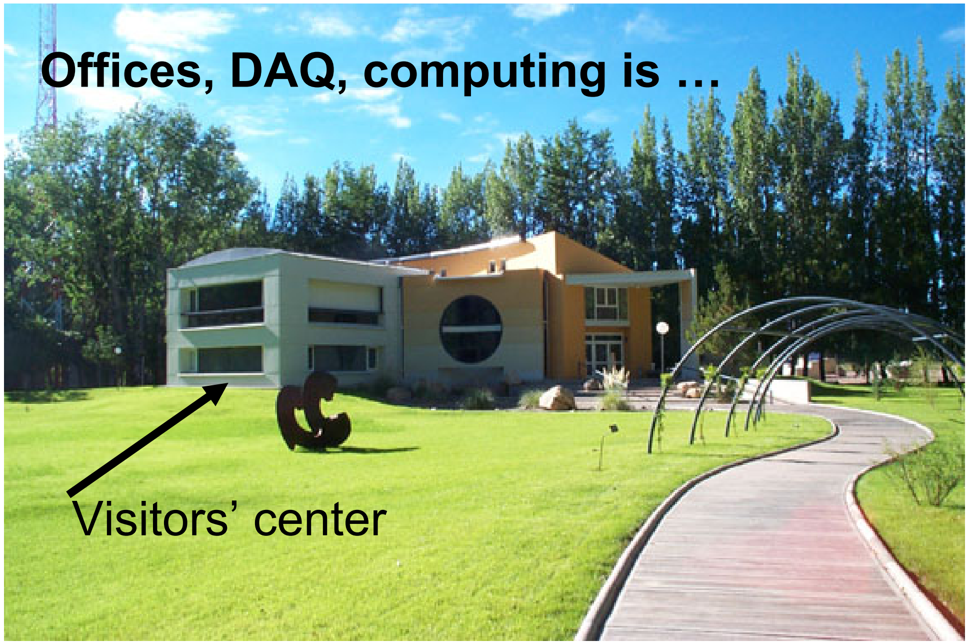
24 telescope units, six each at four sites
3.4 meter dia. mirrors
440 PMTs per camera







The Auger campus in Malargue, Mendoza Province, Argentina

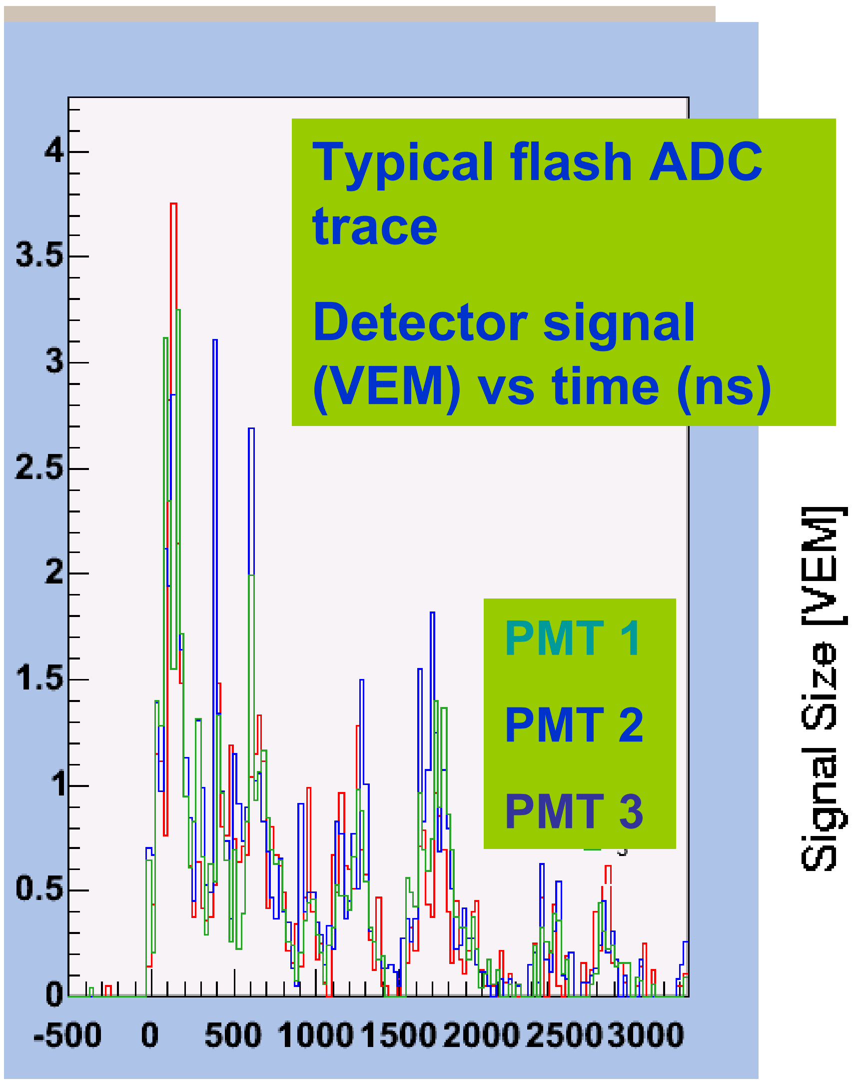


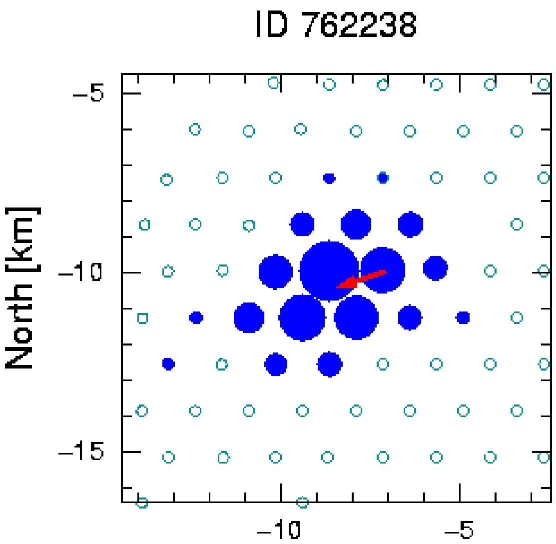
Auger Collaboration:
63 institutes, 370 collaborators

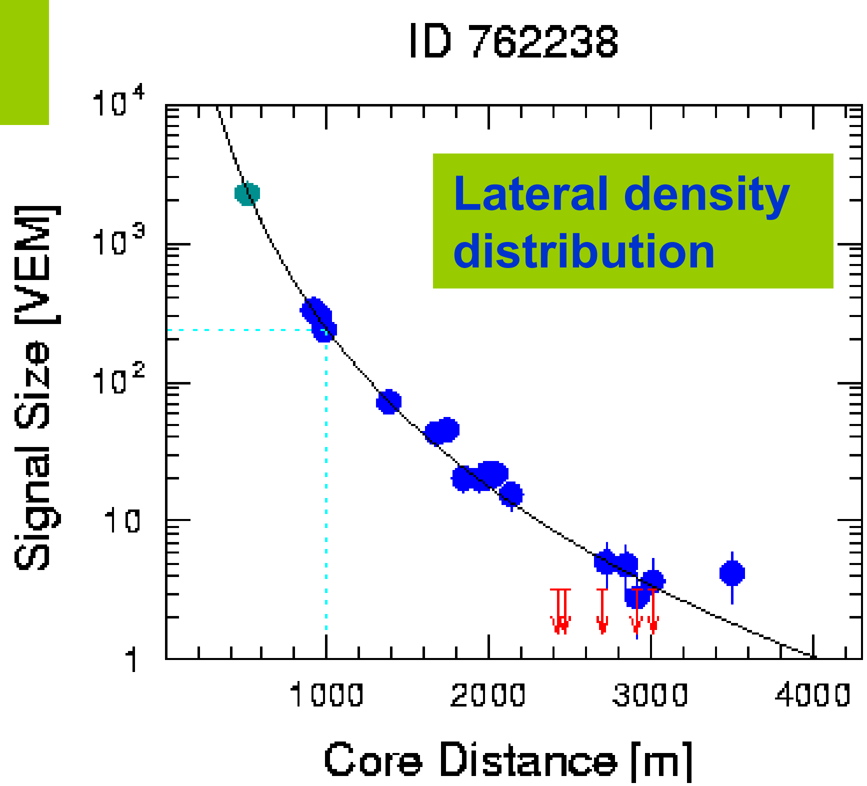
Argentina, Australia, Bolivia, Brazil, Czech Republic, France, UK, Germany, Italy, Mexico, Netherlands, Poland, Slovenia, Spain, USA, Vietnam

Malargue

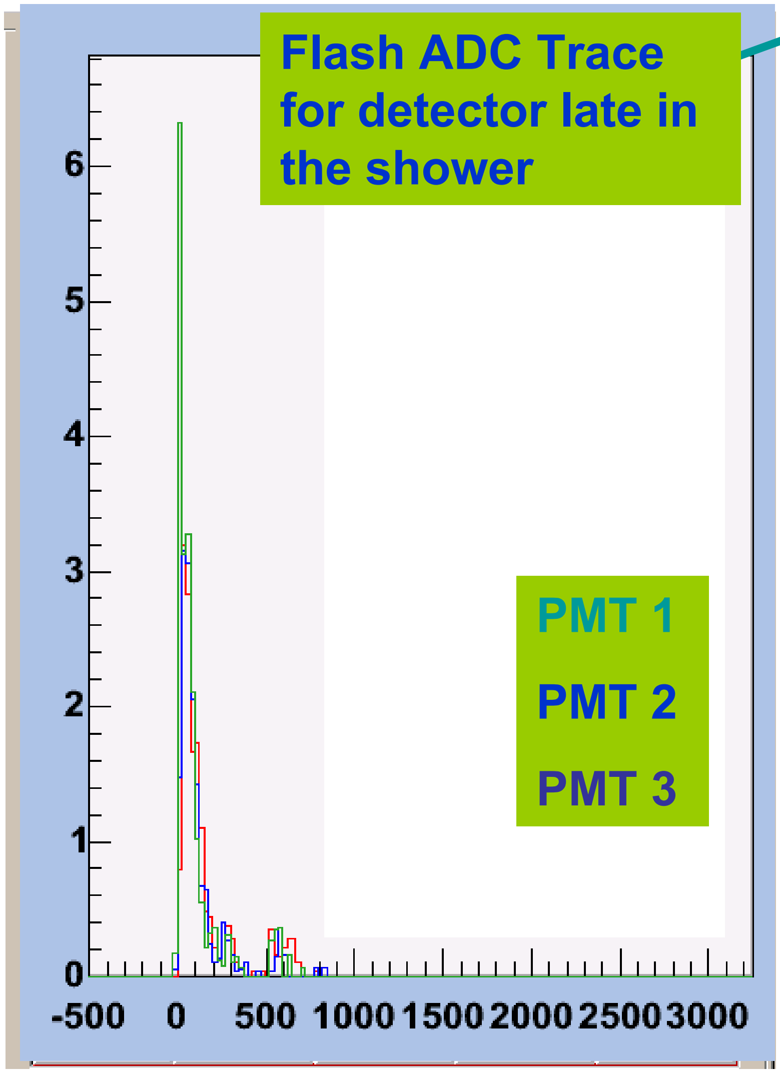
Example event
Θ~ 48º, ~ 70 EeV

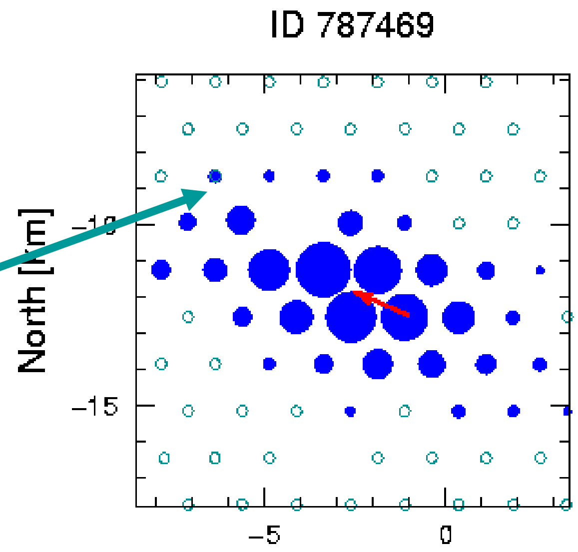


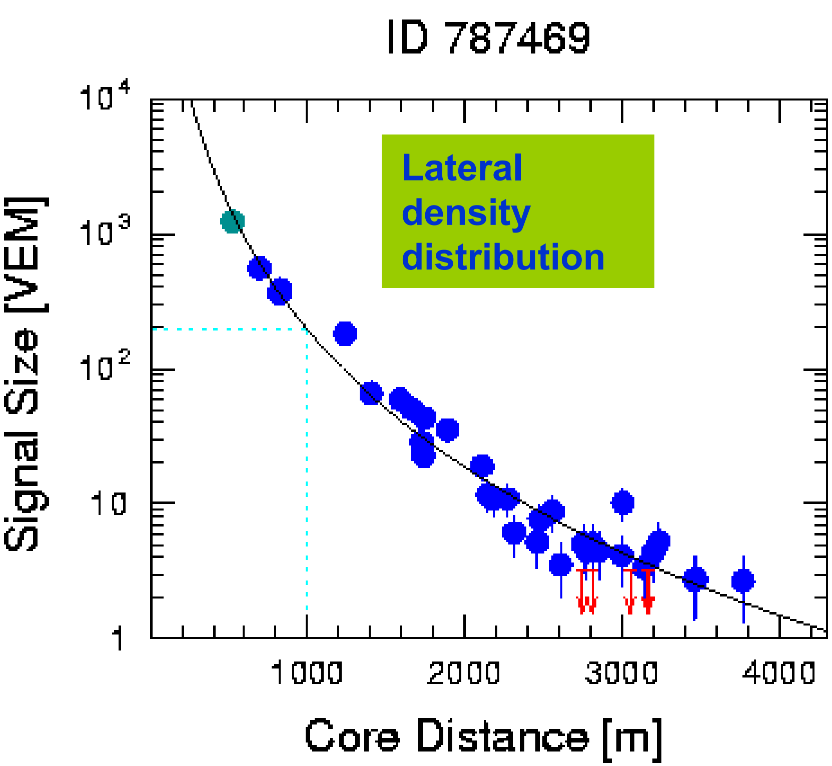




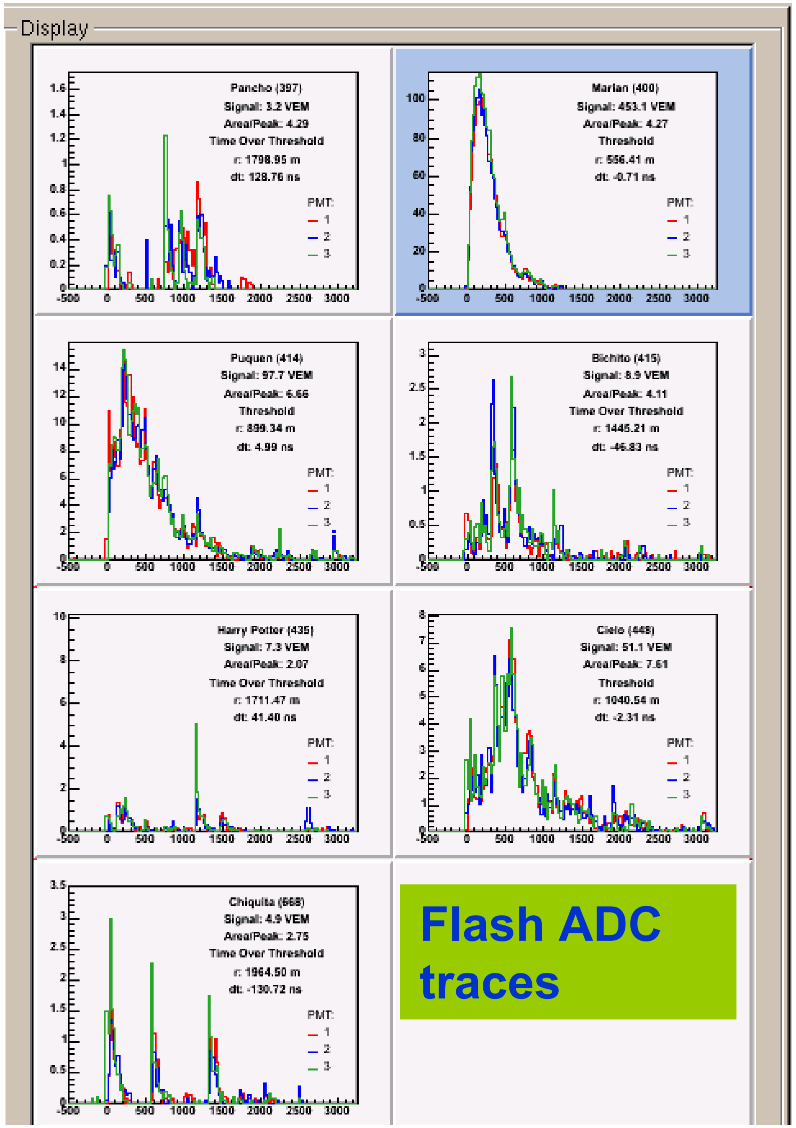
Surface Detector Event
Θ~ 60º, ~ 86 EeV

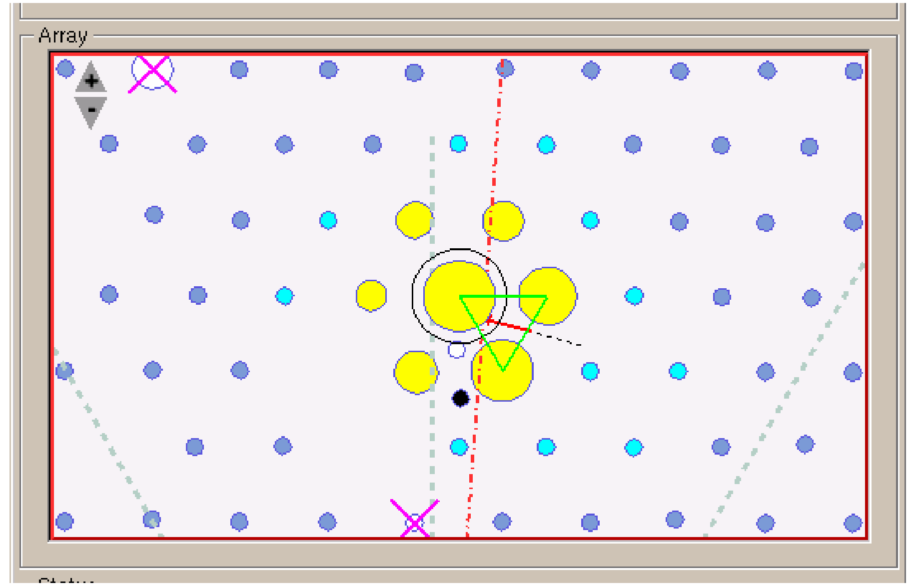


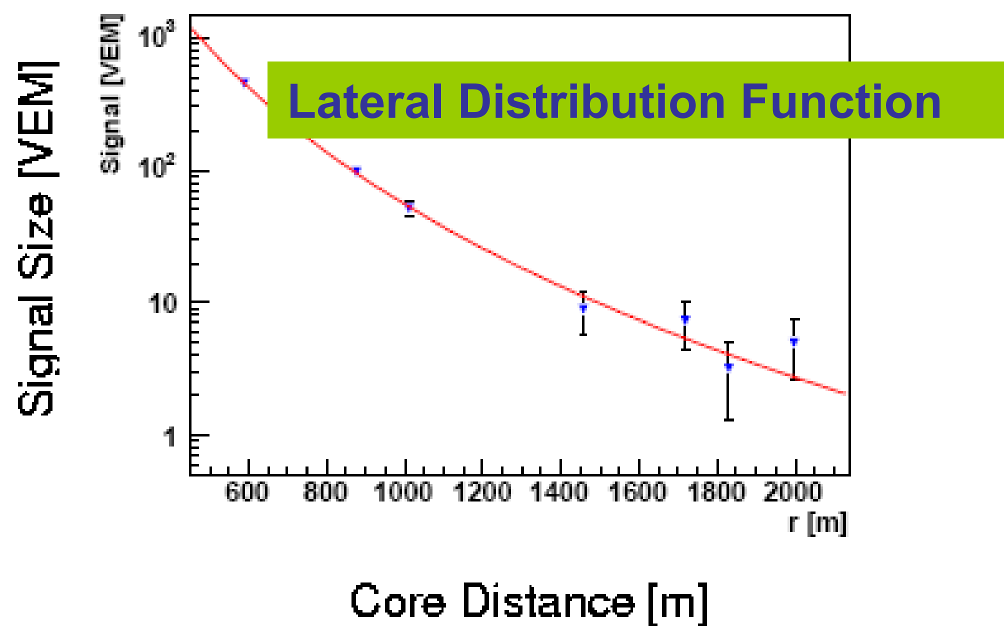




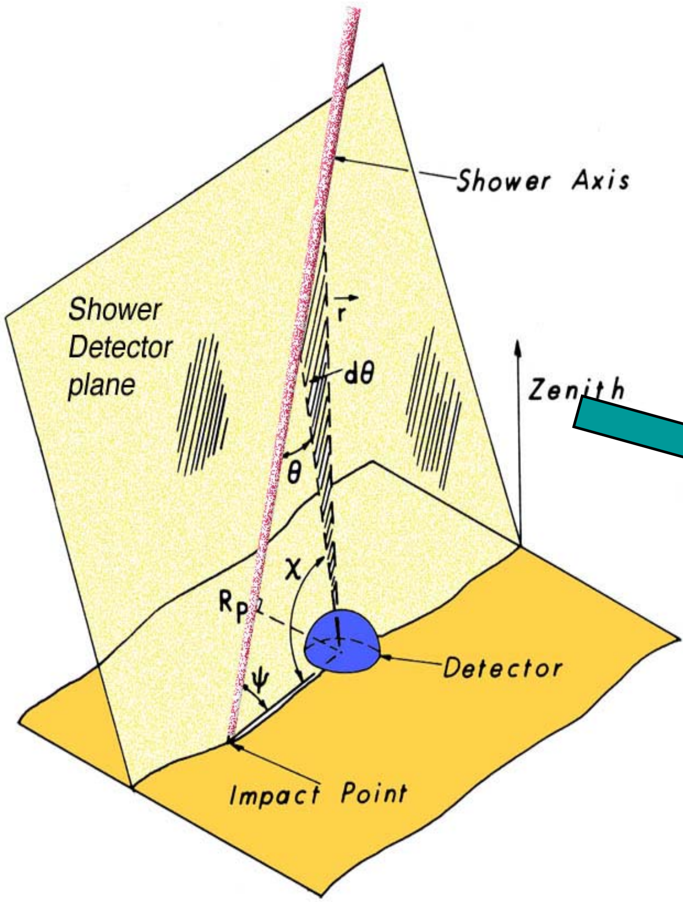
Hybrid Event
Θ~ 30º, ~ 8 EeV

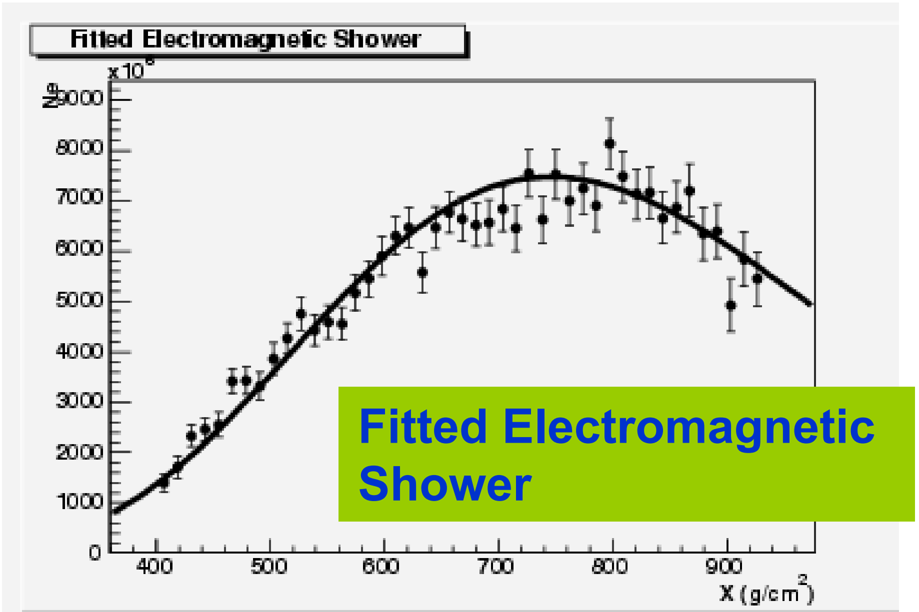


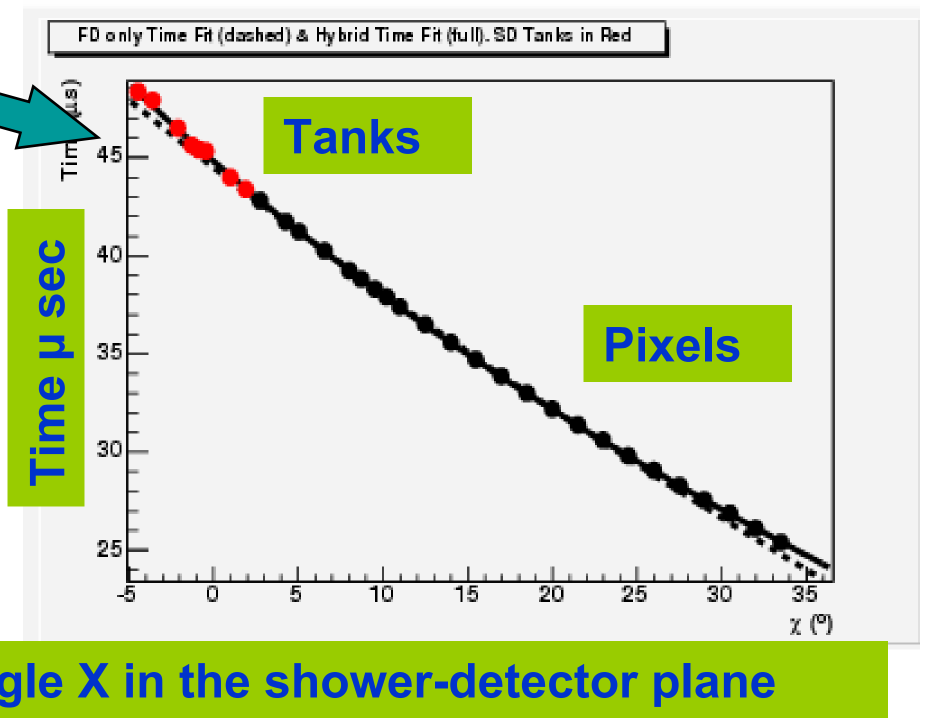




Same Hybrid Event
Θ~ 30º, ~ 8 EeV







Substantial improvement in geometry compared to monocular.

…and that ends the introduction.

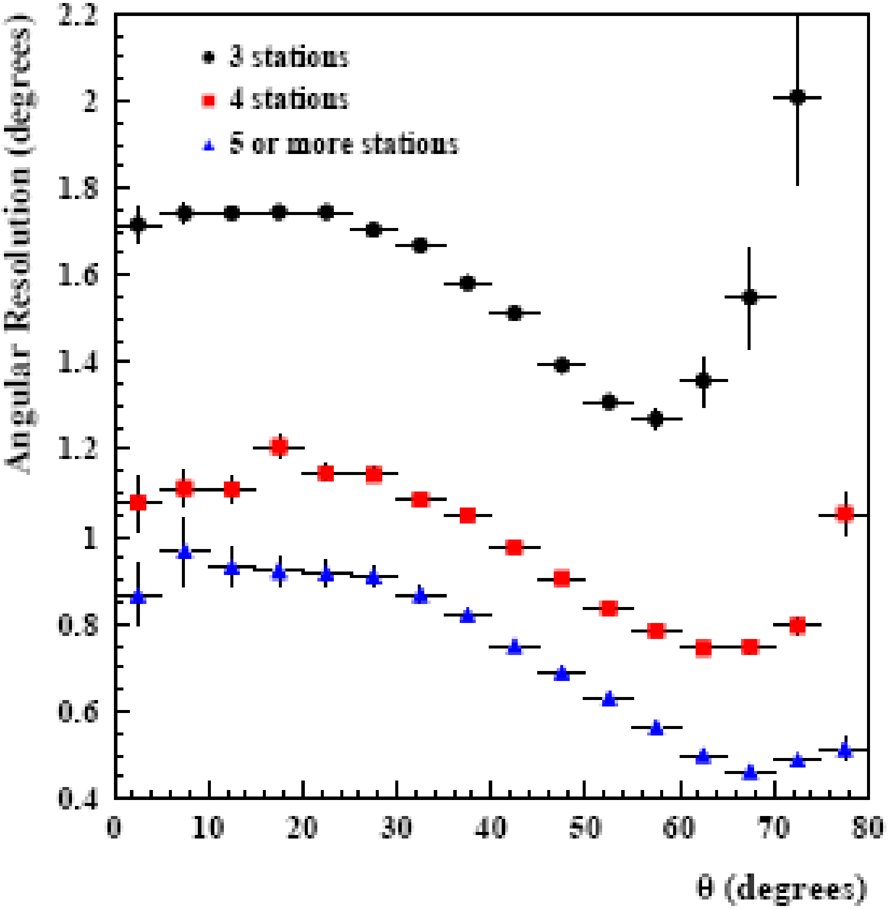
Next:

<u>Detector resolutions, performance, monitoring</u>

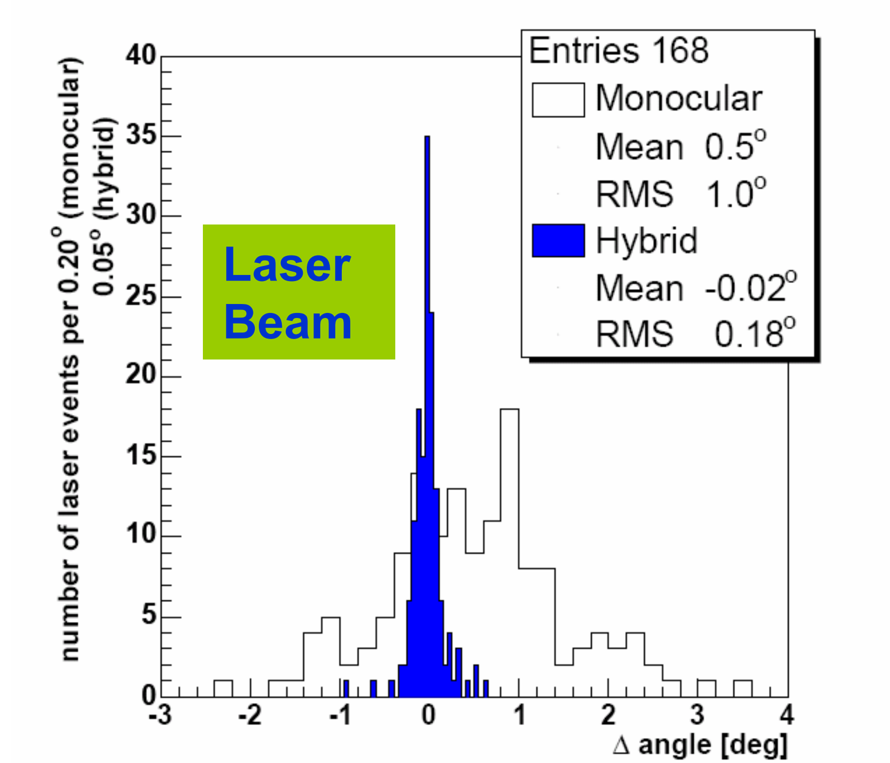
- **Angular resolution**
- **SD calibration – "VEM", uniform trigger and response (SD energy scale provided by FD)**
- **SD signal resolution and tank trigger efficiency**
- **FD absolute calibration**
- **Atmospheric measurements and monitors**

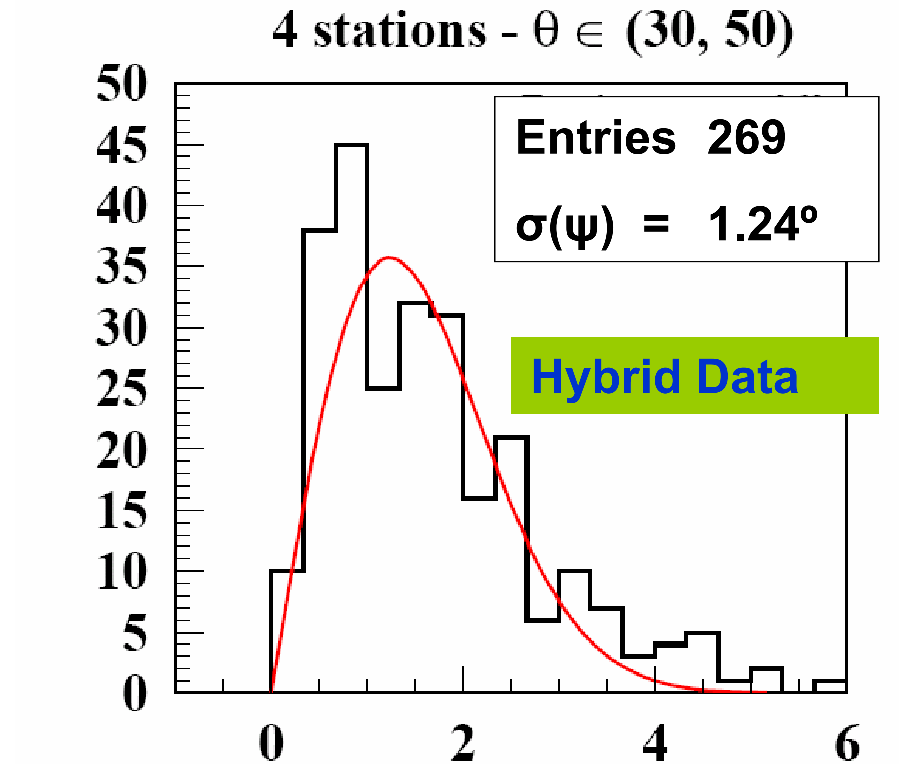
Angular resolution on Arrival Direction

Surface Detector angular resolution depends on number of tanks and arrival zenith angle.



Angular Resolution is improved by hybrid detector





Angle in laser beam /FD detector plane

Hybrid-SD only space angle difference

Hybrid (68% CL)

0.6 degrees (mean)

Surface array (68% CL)

< 2.2º for 3 station events (E< 3EeV, θ < 60º)

< 1.7º for 4 station events (3<E<10 EeV)

< 1.4º for 5 or more station events (E>10 EeV)

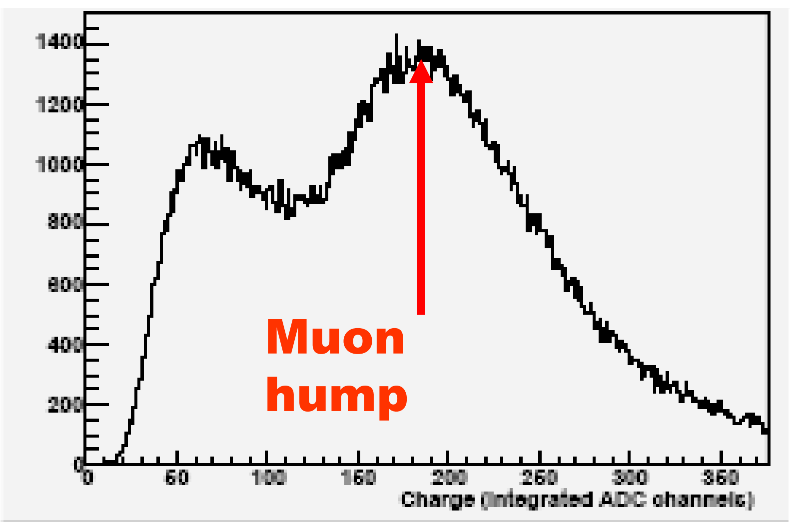
SD tank calibration in terms of :VEM” = Vertical Equivalent Muon

First take measures in a test tank with external paddle trigger

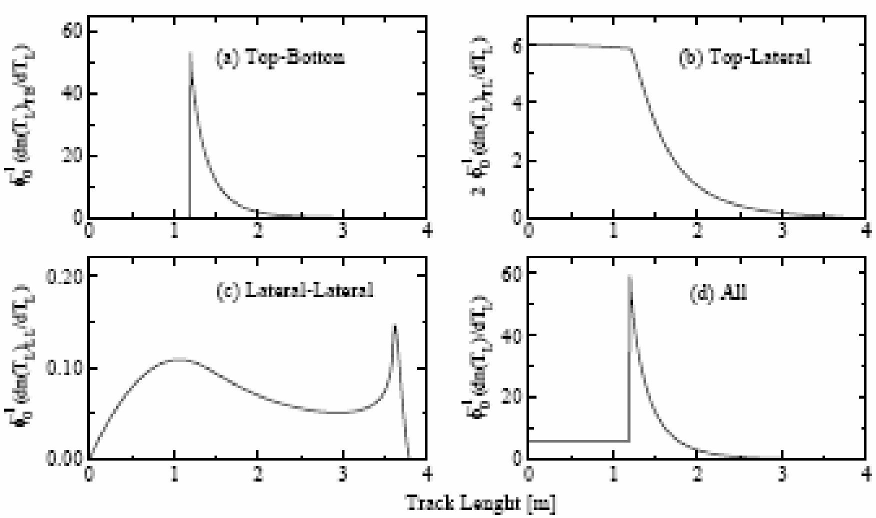
For each tank:

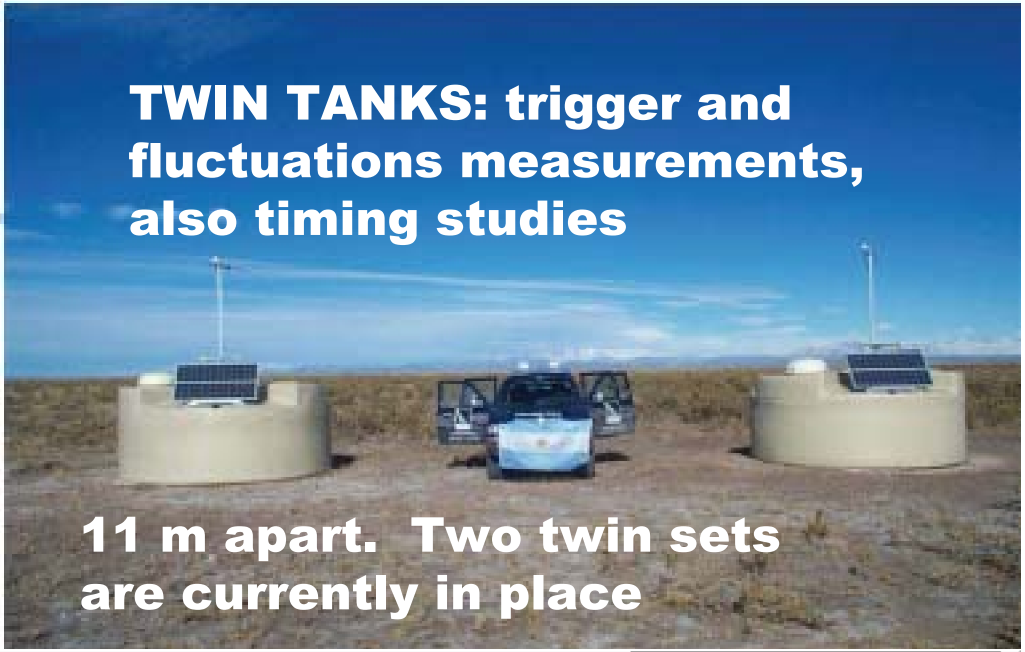
- Adjust HV to give rate for each PMT = 100Hz in channel 50 FADC (balances gains)
- Then continually adjust PMT trigger thresholds to give 100 Hz 3-fold coincidence/tank (uniform trigger across array, compensates drifts)
- Relate muon “hump” to the VEM found using a test tank.

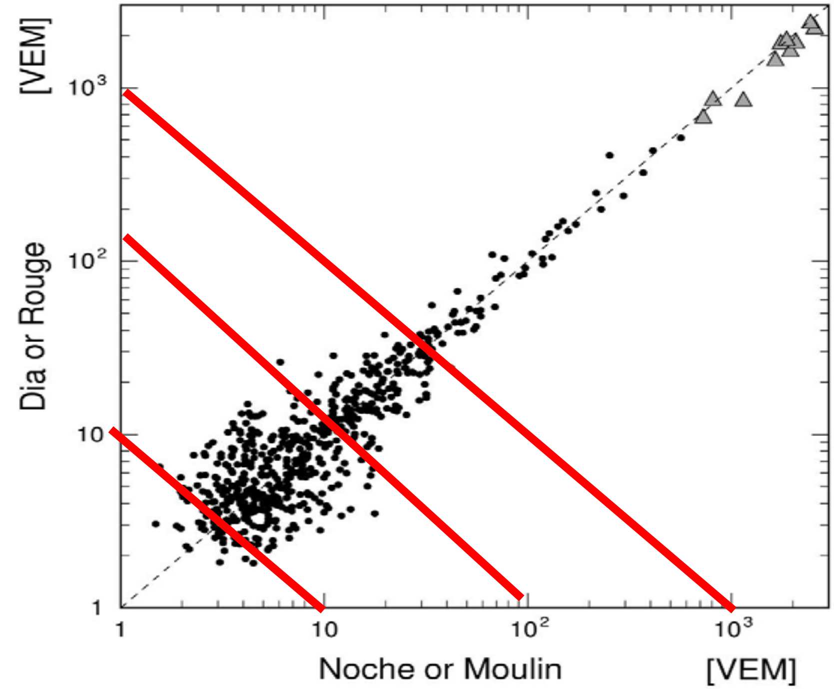
Charge distribution in tank

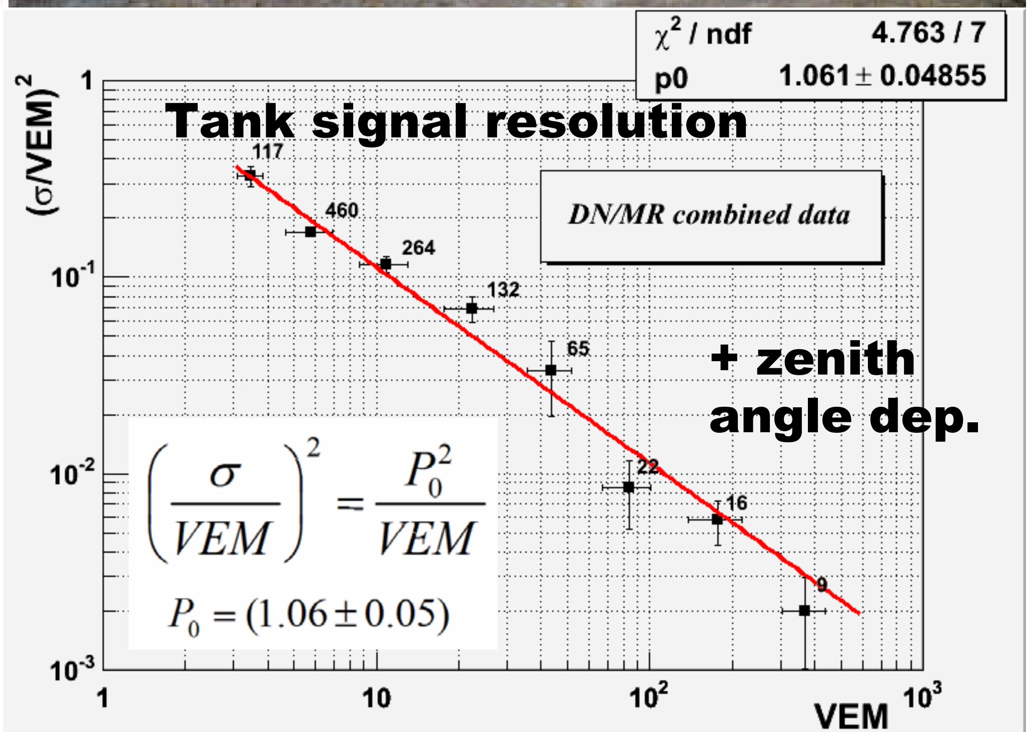


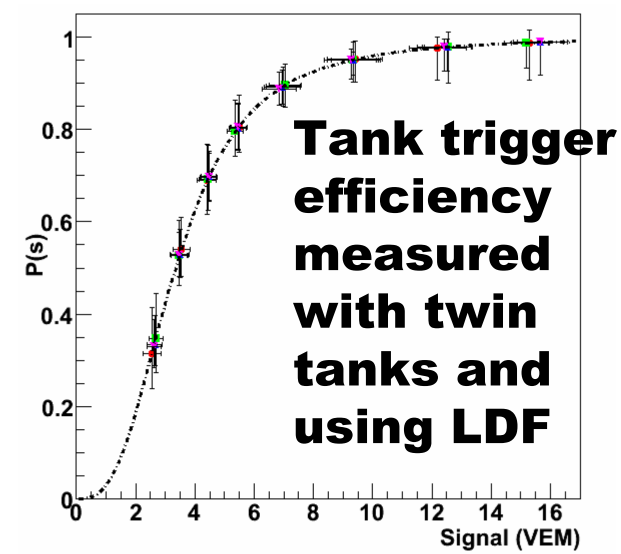
Track lengths in tank




TWIN TANKS: trigger and fluctuations measurements, also timing studies
11 m apart. Two twin sets are currently in place

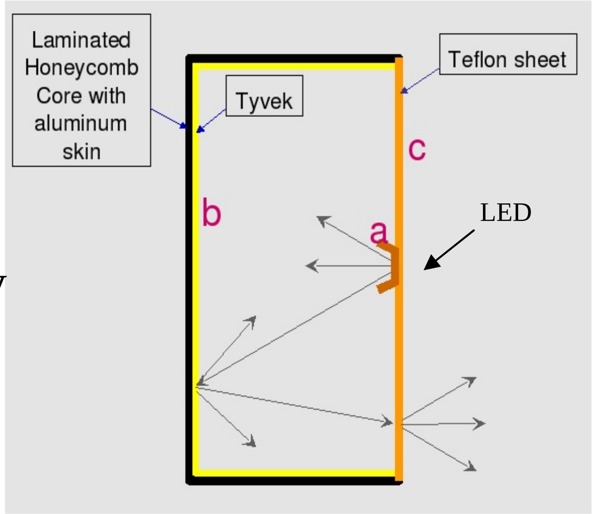

Dia or Rouge [VEM]
Noche or Moulin [VEM]
1
10
10²
10³


Tank signal resolution
χ² / ndf 4.763 / 7
p0 1.061 ± 0.04855
DN/MR combined data
(σ/VEM)²
VEM
117
460
264
132
65
22
16
9
+ zenith angle dep.
$\left(\frac{\sigma}{VEM}\right)^2 = \frac{P_0^2}{VEM}$
$P_0 = (1.06 \pm 0.05)$

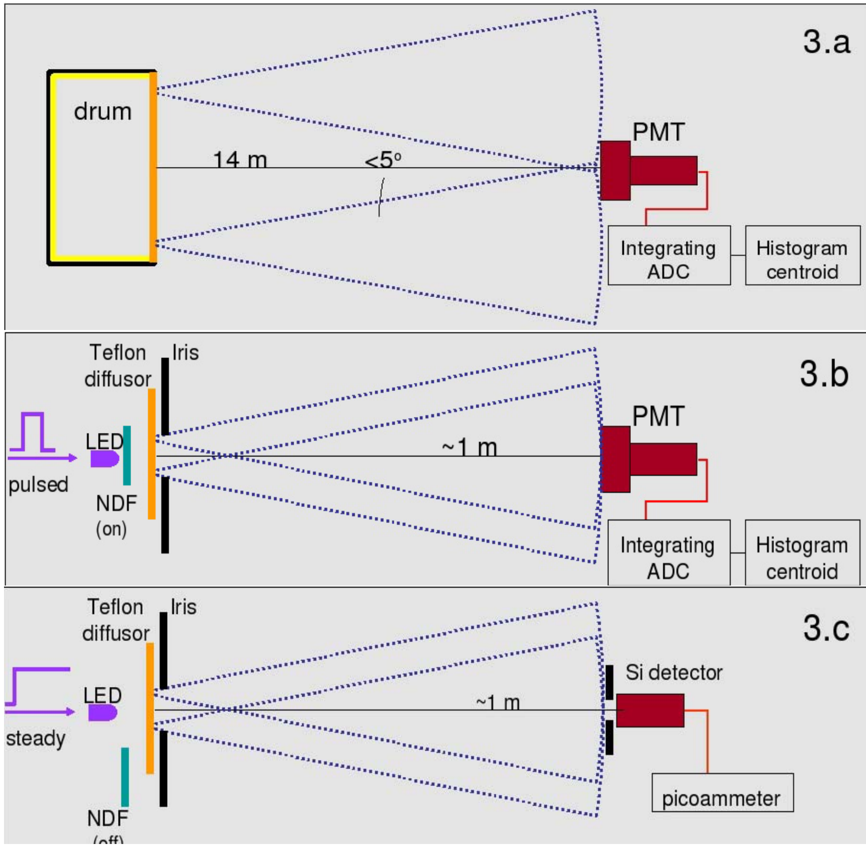

Tank trigger efficiency measured with twin tanks and using LDF
P(s)
Signal (VEM)

FD Absolute Calibration Drum

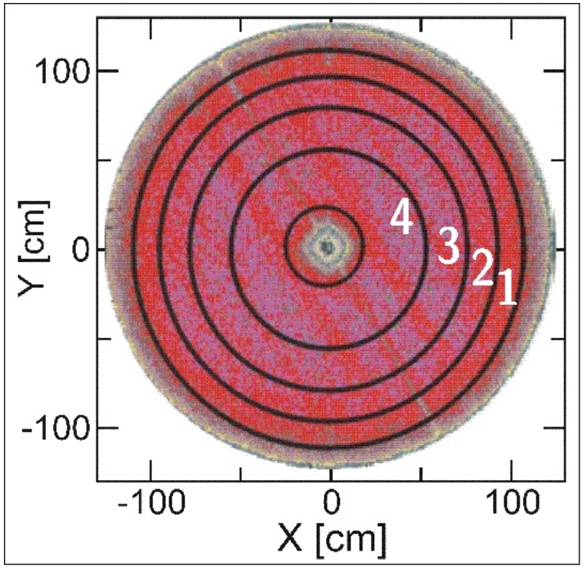
Construction uses diffusively reflecting materials to enhance uniformity of illumination at output surface

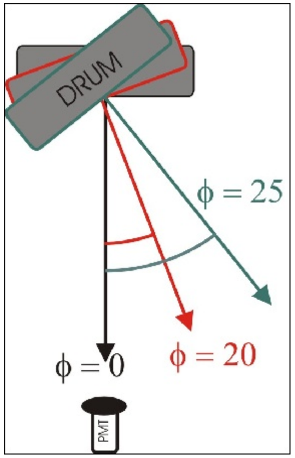


Absolute intensity measurement is based on NIST-calibrated photodiode at 375nm.



Surface uniformity is measured using CCD imaging techniques

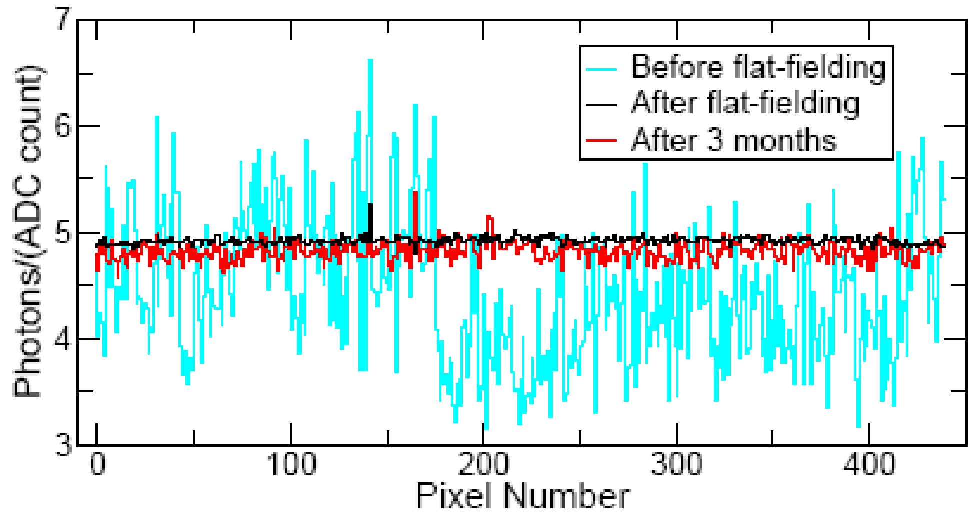




Theta

Started multi-wavelength calibrations with Xe flasher+filters and lower wavelength UV LEDs.

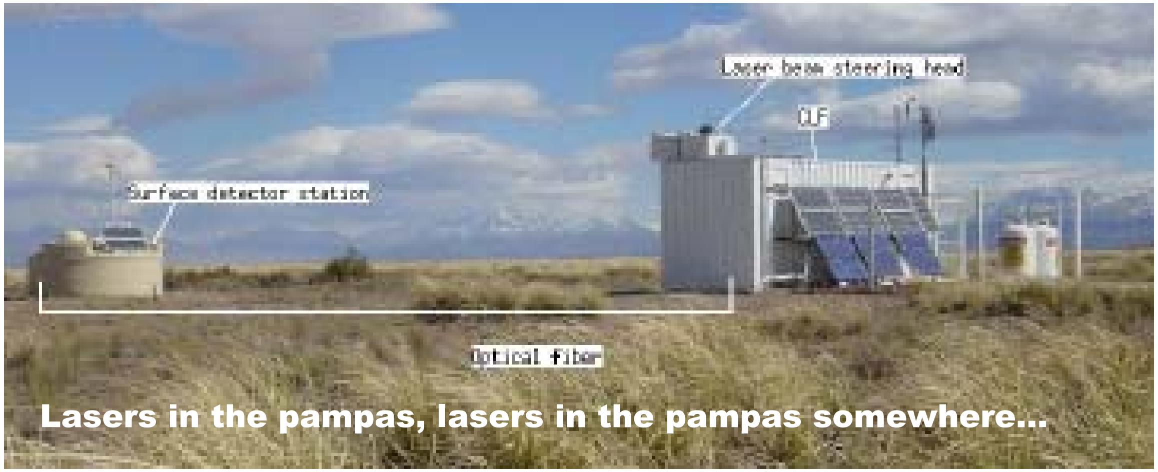
Flat-fielding brings uniformity to the camera response.



FD absolute calibration drum fills the aperture with a known, uniform flux of photons.

August 2006: Campaign with roving laser at 4km and drum, both at 337nm, same night.

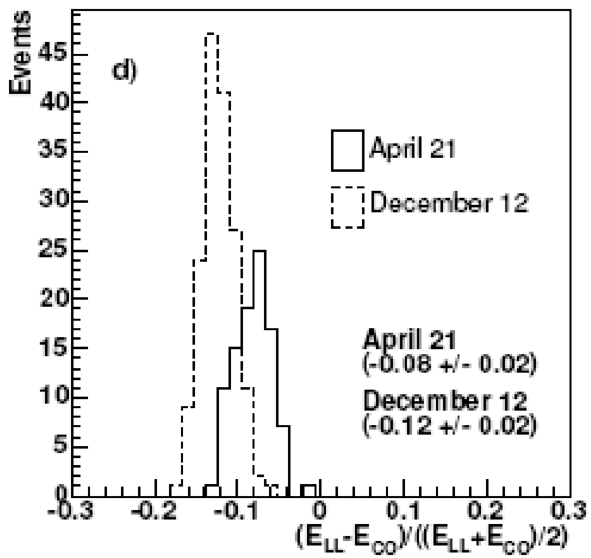
Atmospheric monitoring is also key to understanding the response of the FD…and hence the SD



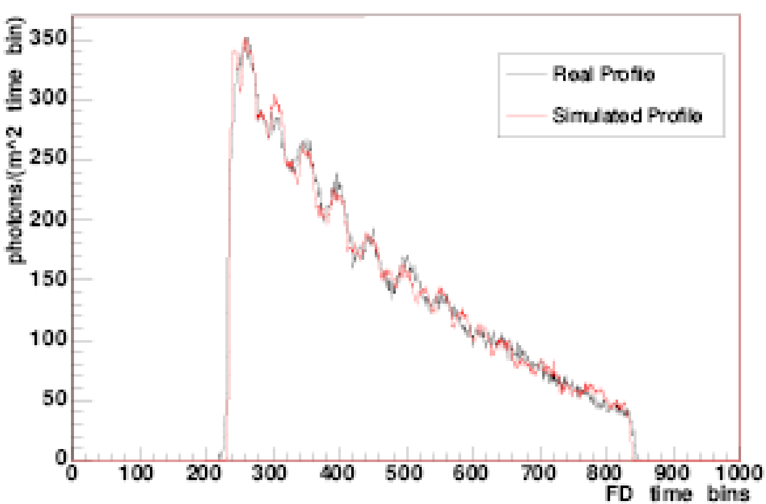
Central laser facility has several uses:

- **Timing studies**
- **Angular resolution**
- **Aerosol measurements**

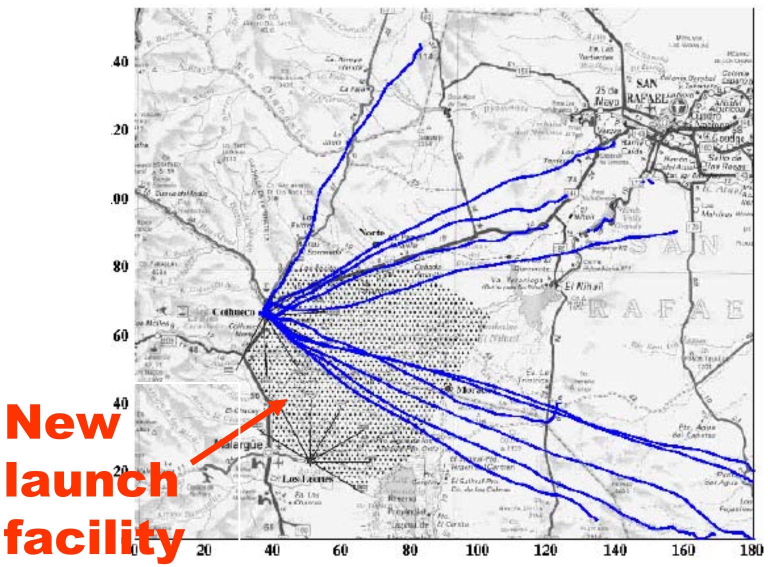
Laser energy from two FD buildings

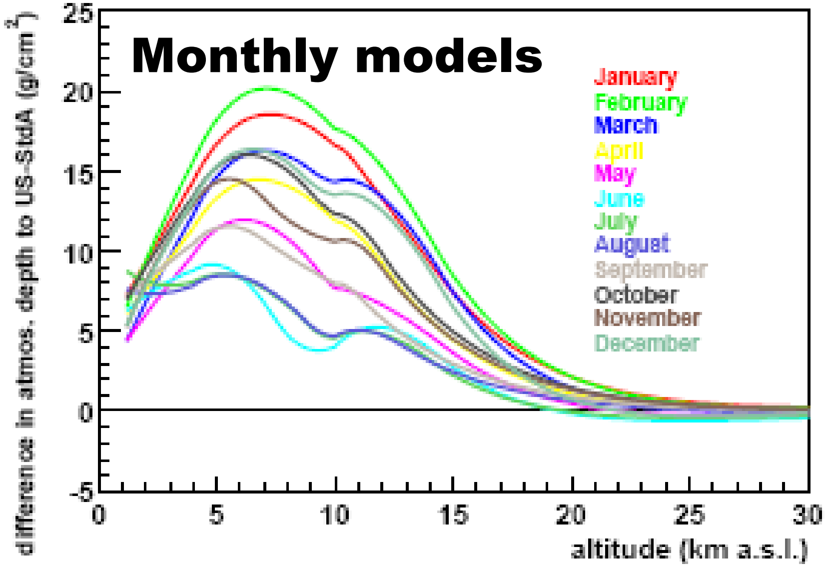


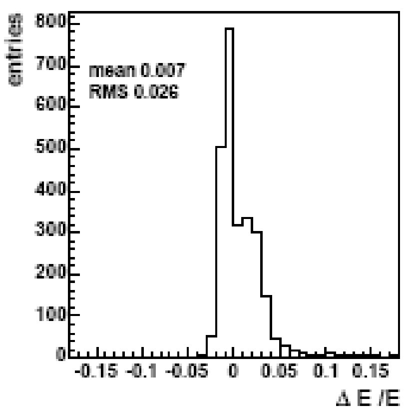
Extracting aerosols from laser shots

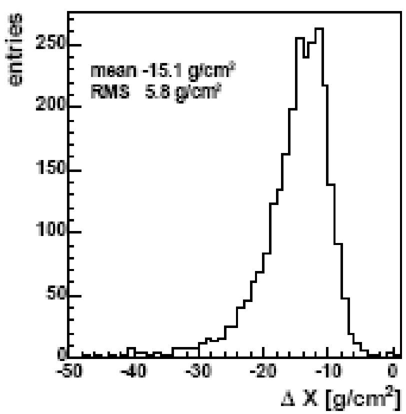


And the molecular atmosphere is measured by a systematic series of balloon launches.





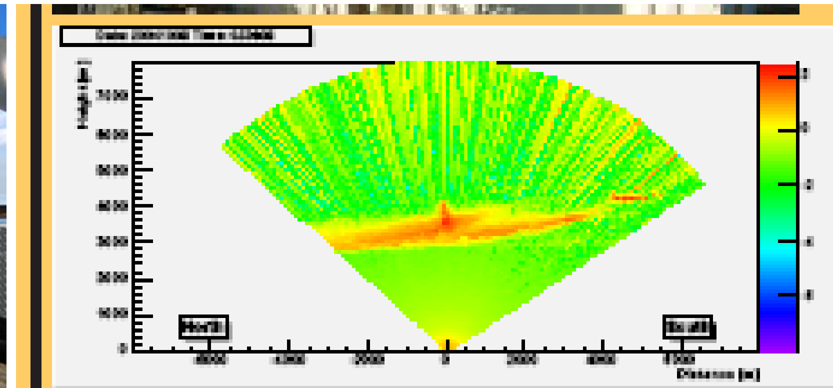




Reconstructed energy is not drastically effected, but Xmax can shift systematically, and possibly by a significant amount if standard atmosphere is assumed.

Additional sky monitoring...

LIDARs at each FD "shoot the shower" for large events looking for clouds.



Cloud cameras at each FD continually monitor the sky and take snapshots for cloud cover.

Auger Physics results:

- **Energy spectrum (astro-ph/0507150   ICRC ’05)**
- **Photon fraction upper limit (astro-ph/0606619   26 June 2006)**
- **Galactic center anisotropy (astro-ph/0607382   17 July 2006)**
- **Highest energy events (ICRC 2005)**

PIERRE AUGER OBSERVATORY

First Estimate of the Primary Energy Spectrum

- **Measurement is from the southern sky**
- **24/7 SD measurement for greater statistics…**
- **…calibrated by the FD for a sample of events**
- **Does *not* depend on air-shower models, interaction models, or assumptions on the primary particle type**

Data set: 1 Jan 2004 – 1 June 2005 (ICRC 2005 analysis)

Array size = ½*full size = ½ * 3000 km^2 (time average = 22%)

Exposure = 1750 km^2 str yr (about equal to AGASA, below HiRes)

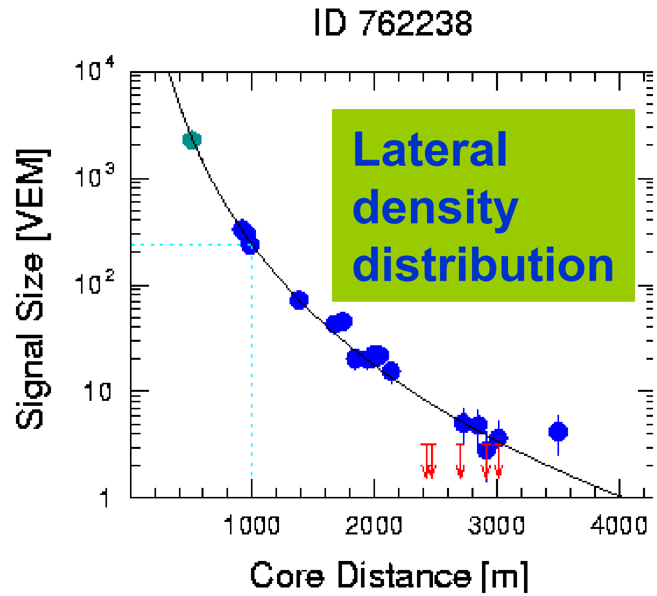
3525 events above $10^{18.5}$ eV; full efficiency above $3*10^{18}$ eV

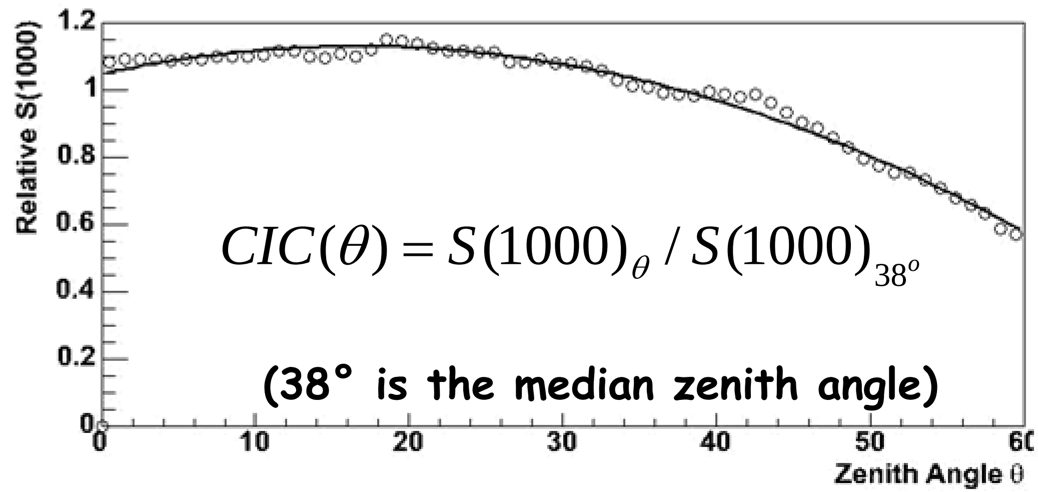
Selection: core surrounded by working triangle; hottest tank has 5 working nearest neighbors. Zenith angle < 60º

Model independent "CIC"

SD signal is attenuated for steeper showers…

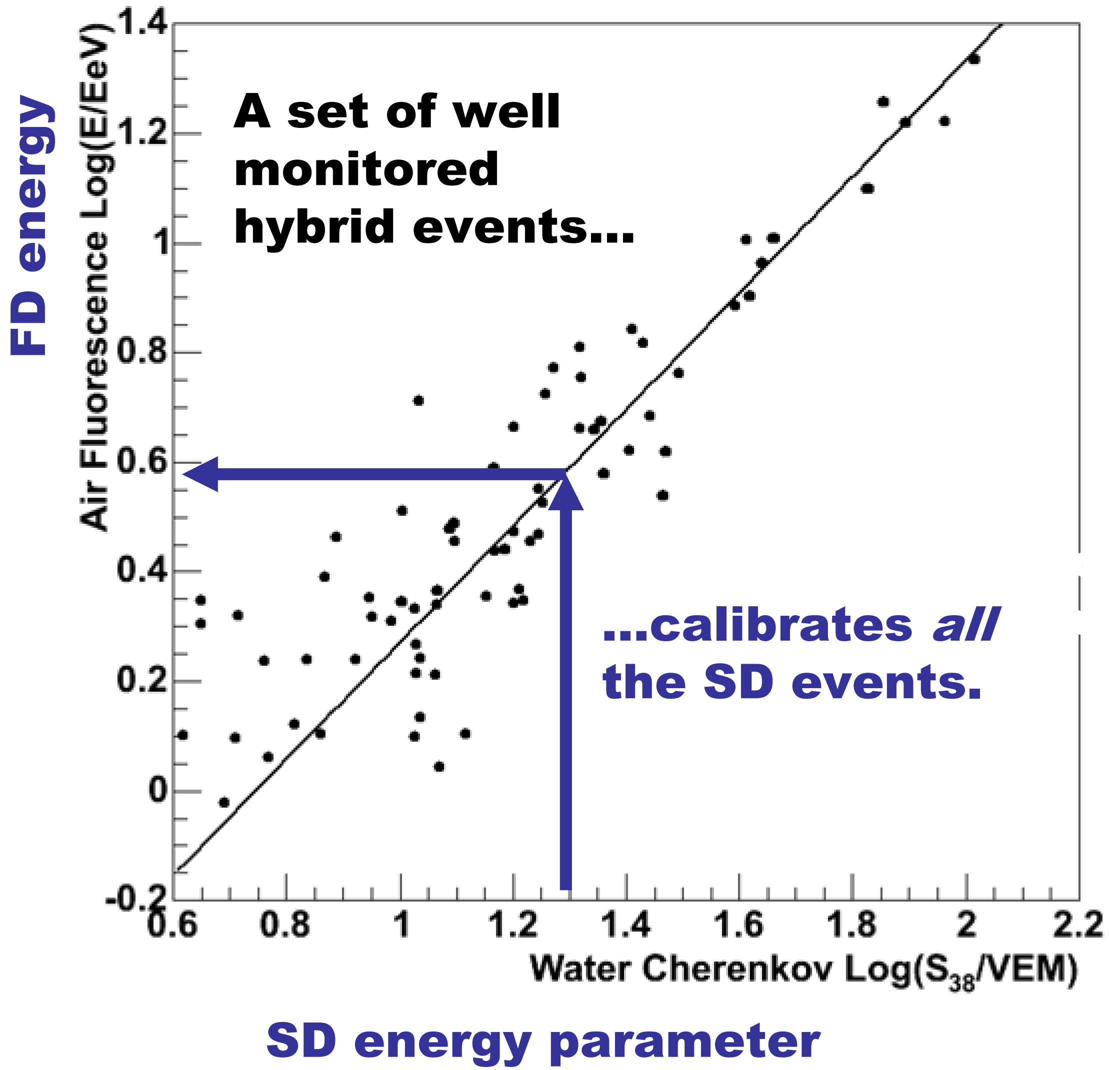
…attenuation is measured from data by assuming near isotropy of cosmic rays





Pick a zenith angle bin and measure S(1000) distribution. Number of events above some cut on S(1000) is I_0 events. Other zenith angle bins should have same number of events above another value of S(1000). Slid a cut on S(1000) in this new bin of zenith angle until number events above cut is I_0 events. ➔ Find S(1000) attenuation with zenith angle.

FD calibrates SD

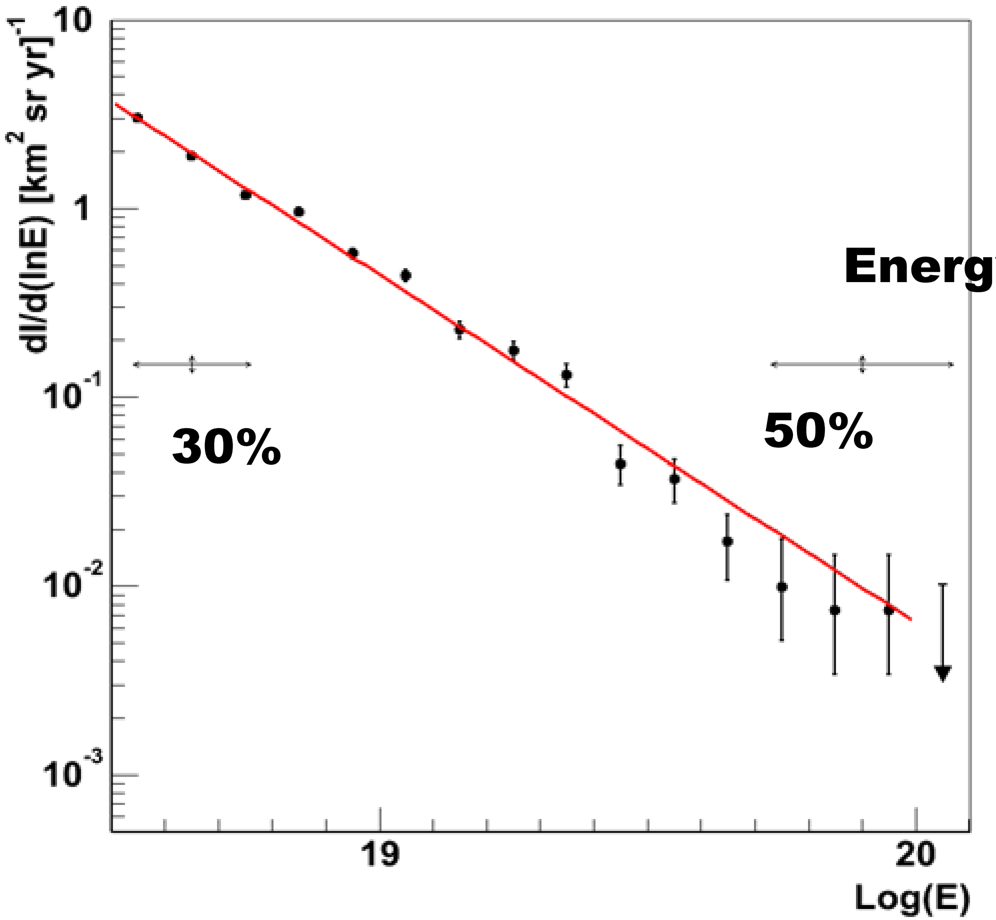


First Auger Energy Spectrum

$$\frac{dI}{d\ln(E)} \equiv E\frac{dI}{dE}$$

vs.

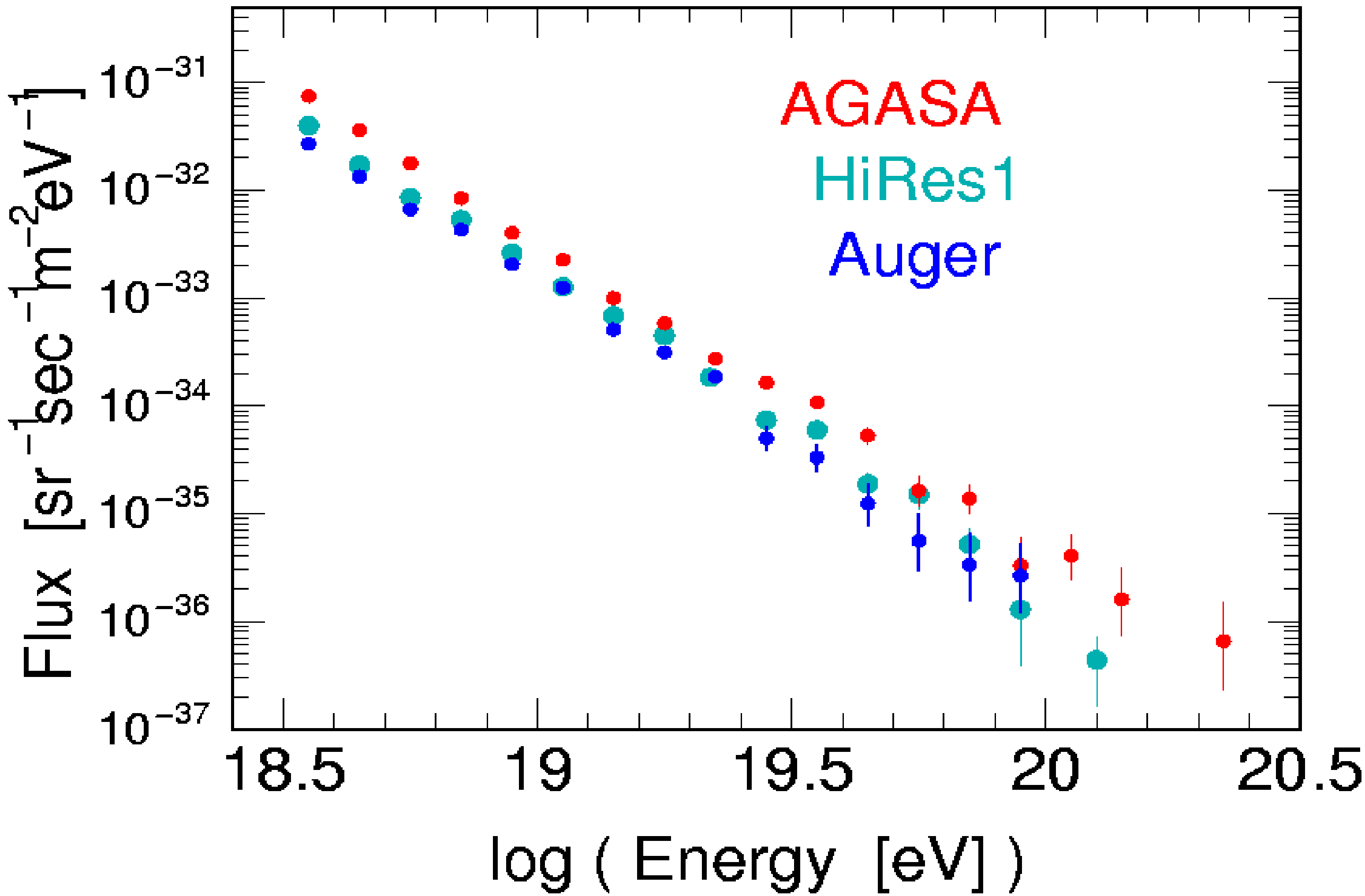
Log(E)



Energy systematic

- **N_2 yield 15%**
- **FD abs cal 12 %**
- **total FD 25%**
- **Stats of FD→SD correlation**
- **Total: 30% to 50%, low to high energy**

...and other measurements

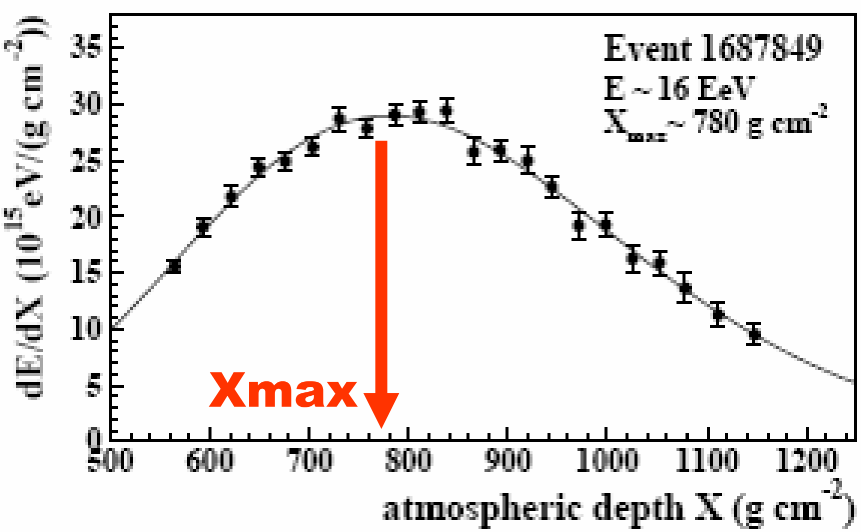


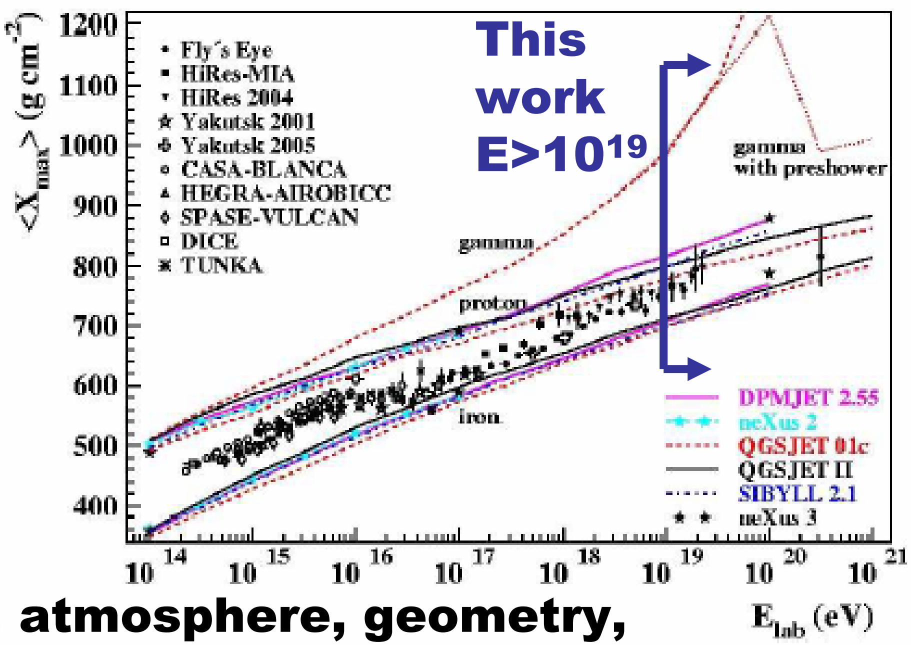
1) M. Takeda *et al.* Astroparticle Physics 19, 447 (2003)

2) R.U. Abbasi *et al.* Phys Lett B (to be published)

Primary photons

- "Top down" models predict large fraction of primaries are photons (TD, SHDM, ZB) at high energies
- Photons result in deep X_{max} position (SD: muon poor)
- Present Auger measurement based on sample of 29 hybrid events – direct measurement of X_{max}

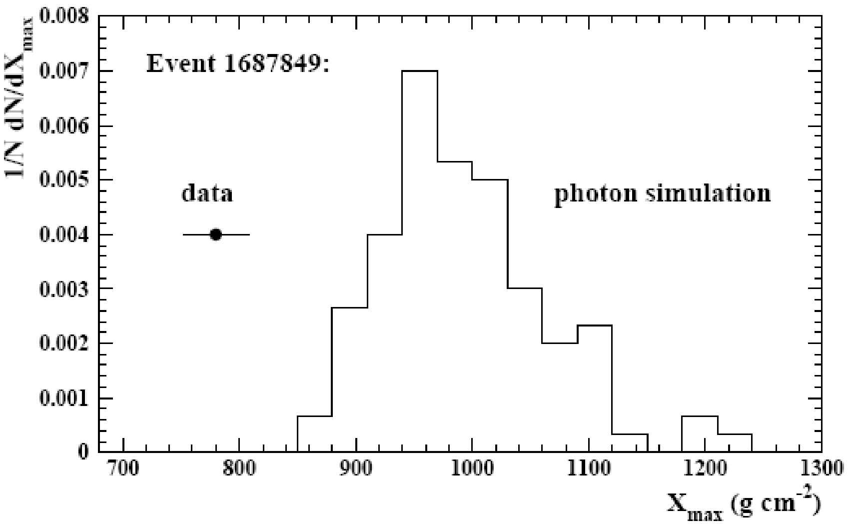




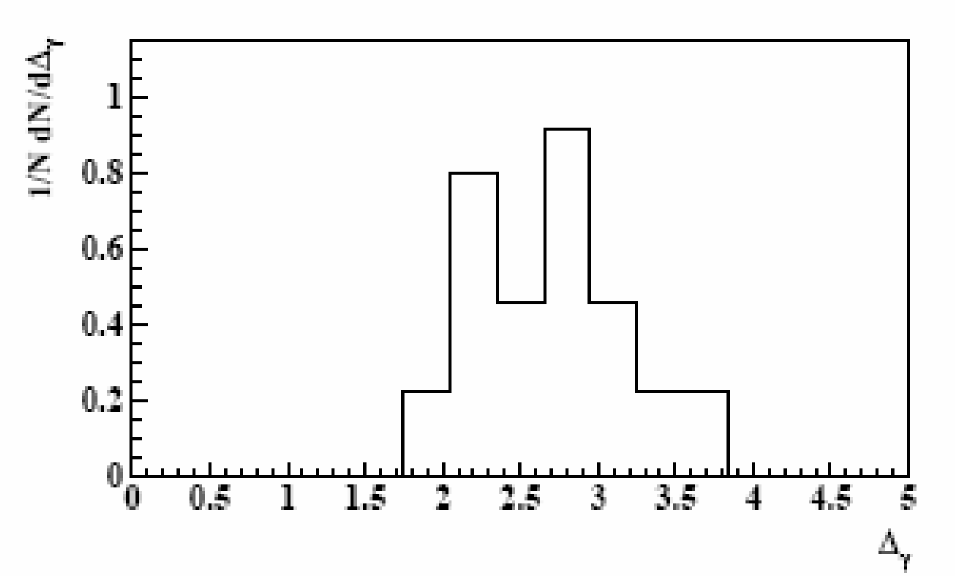
ΔXmax uncertainties: profile fit, atmosphere, geometry, cross section... Total = 28 (stat)+23(syst) g/cm²

Event by event simulation

Data and many photon simulations for one of the 29 hybrid events selected



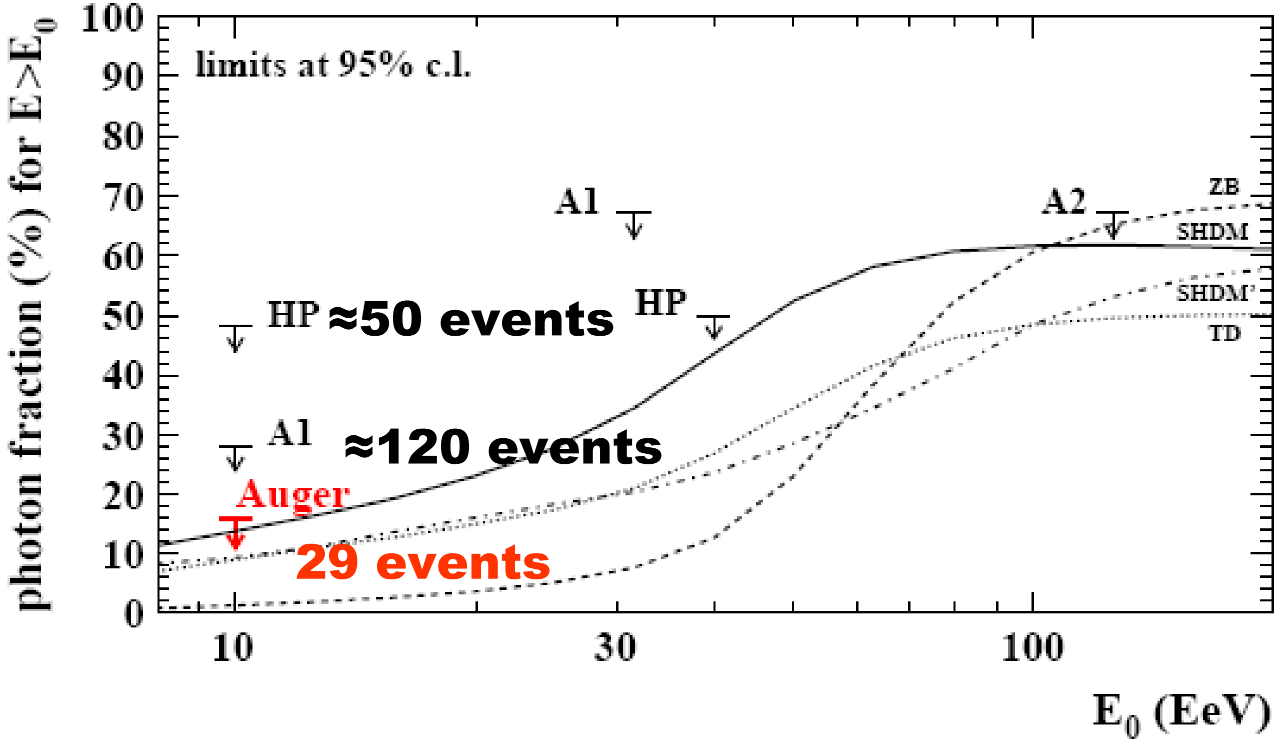
Standard deviations from photon expectation for 29 events



Each event is compared to the distribution expected for photons.

Event sample consists of 29 hybrid events: E>10^{19} eV with strict quality cuts, geometry ***(Update to ICRC 2005, which had 16 events).***

Auger Upper Limit on Primary Photon flux

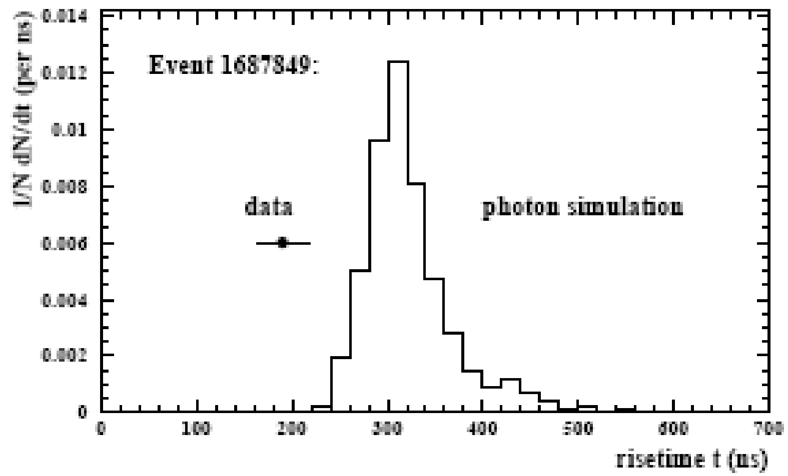


16% upper limit (95%CL) on primary photon flux **above 10^{19} eV.**

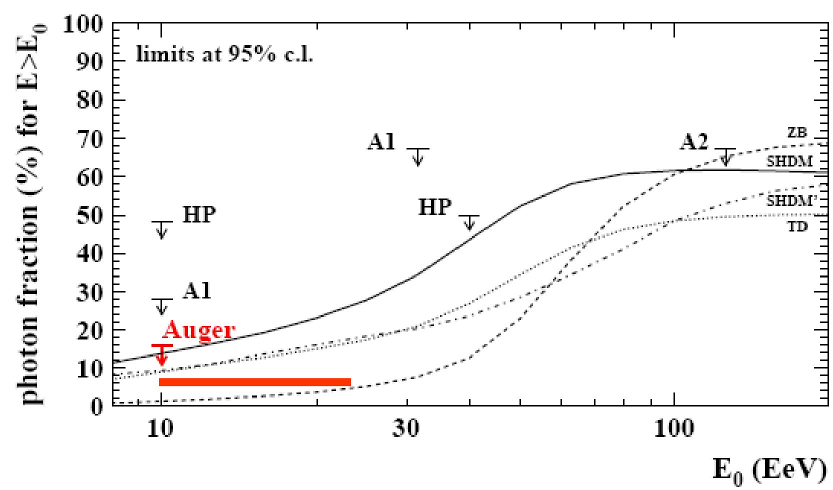
Confirms and improves previous limits by ground arrays

Outlook for Limit on Primary Photon flux

Use of SD measurements, such as the 10-50% rise time at 1000 m core distance, will help

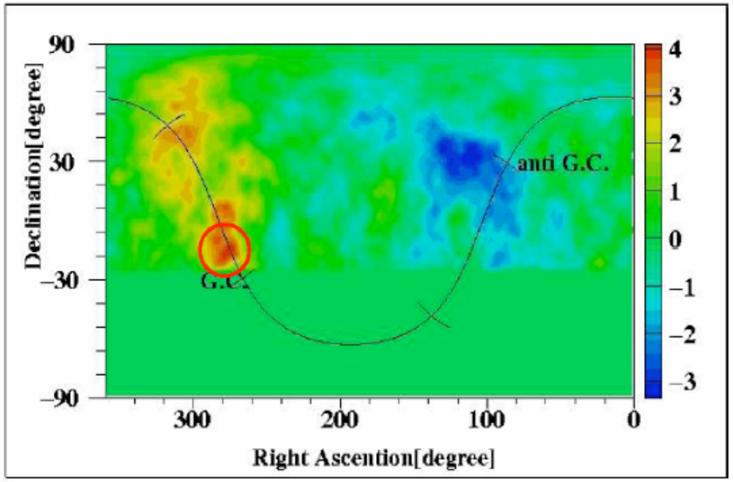


Current analysis extrapolated to 10 times more data, as expected in a couple of years ➔ ≈5% above 10^{19}, and a good limit at few* 10^{19}

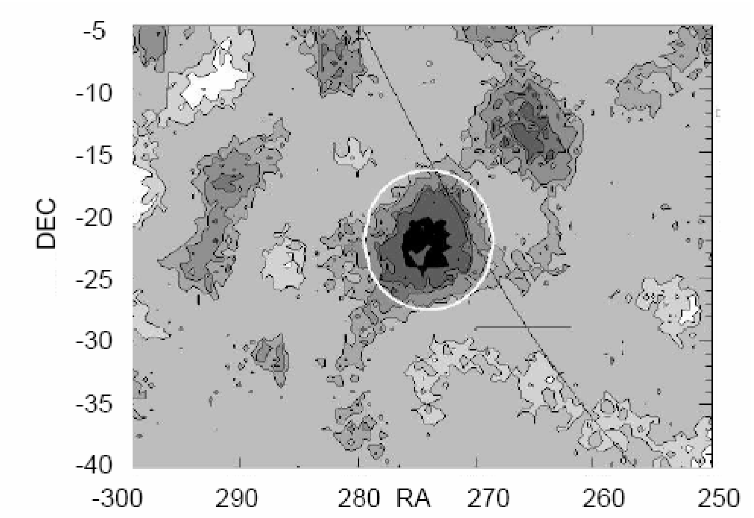


Anisotropy Studies Around the Galactic Center at EeV Energies

Previous measurements of excesses near galactic center



AGASA 4.5 σ, 22% excess

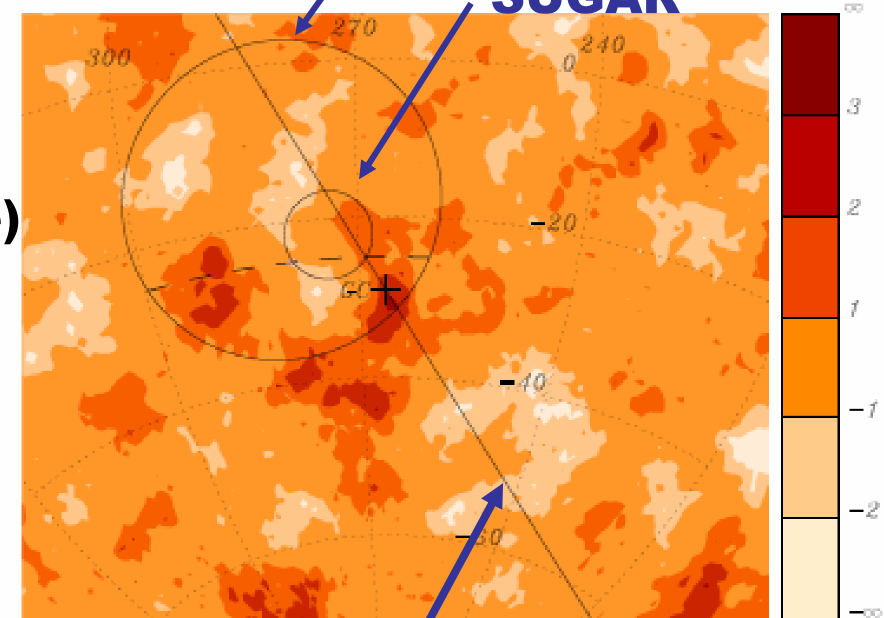


SUGAR 2.9 σ, 85% excess

Data from 1/04 to 3/06.

- 5º circle windows (about SUGAR window size)
- $10^{17.9} < E < 10^{18.5}$ eV (SUGAR range, slightly larger than AGASA energy range)

Auger over densities are consistent with statistical fluctuations of a uniform distribution.



Do not confirm AGASA: we see 2116 expecting 2160 with AGASA selection (more than 4 times number of events seen by AGASA). Also scaling energy do not see excess.

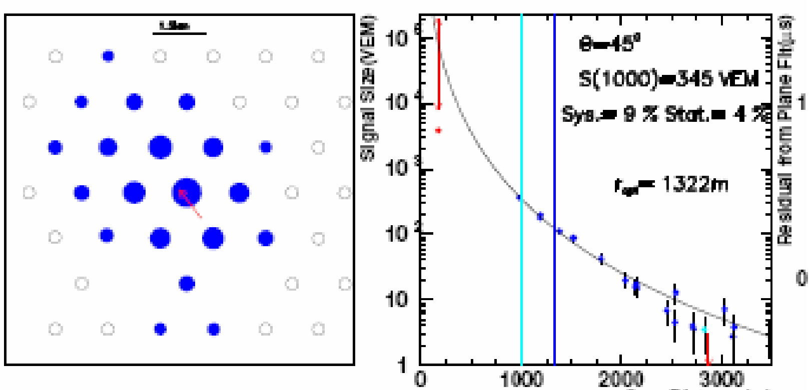
Do not confirm Sugar: we see 286 expecting 290.

Do not see excess in galactic plane or super-galactic plane.

The highest energy events in Auger data from 1/2004 – 6/2005 (ICRC ’05 data set)

Event Id	θ	S(1000)	Multiplicity	r_{opt}	β	E(EeV)
1096757	45.1 ± 0.2	$344 \pm 15 \pm 33$	21	1322	—	86 ± 9
1225537	34.4 ± 0.2	$364 \pm 10 \pm 13$	14	909	2.48 ± 0.06	79 ± 4
787469	59.7 ± 0.2	$204 \pm 8 \pm 11$	31	1173	2.03 ± 0.06	76 ± 5
762238	47.3 ± 0.2	$248 \pm 11 \pm 12$	18	1135	2.22 ± 0.07	64 ± 4
1102721	23.8 ± 0.2	$318 \pm 22 \pm 52$	12	1467	—	63 ± 11
1233429	54.3 ± 0.2	$201 \pm 9 \pm 16$	21	1261	—	63 ± 6
1018639	26.9 ± 0.2	$294 \pm 19 \pm 26$	10	1196	2.93 ± 0.13	59 ± 6
1264145	16.3 ± 0.2	$289 \pm 12 \pm 11$	11	910	2.65 ± 0.11	56 ± 3
1263529	20.7 ± 0.2	$264 \pm 20 \pm 34$	7	1470	—	51 ± 8
634746	51.6 ± 0.2	$174 \pm 9 \pm 12$	14	1203	—	48 ± 4

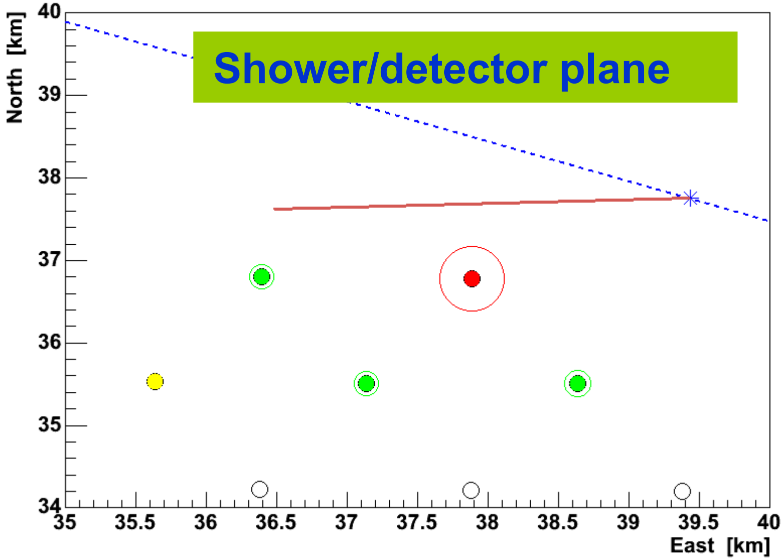
Energy scale set by FD

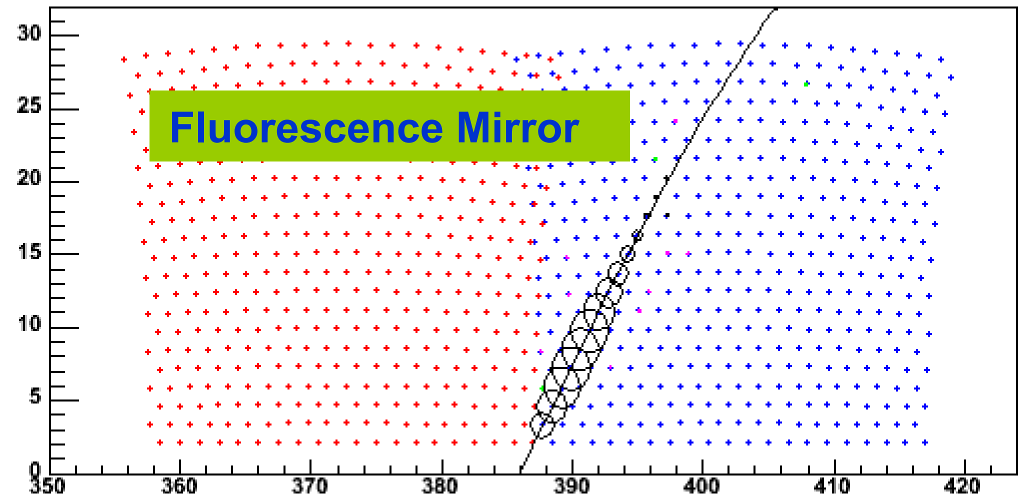


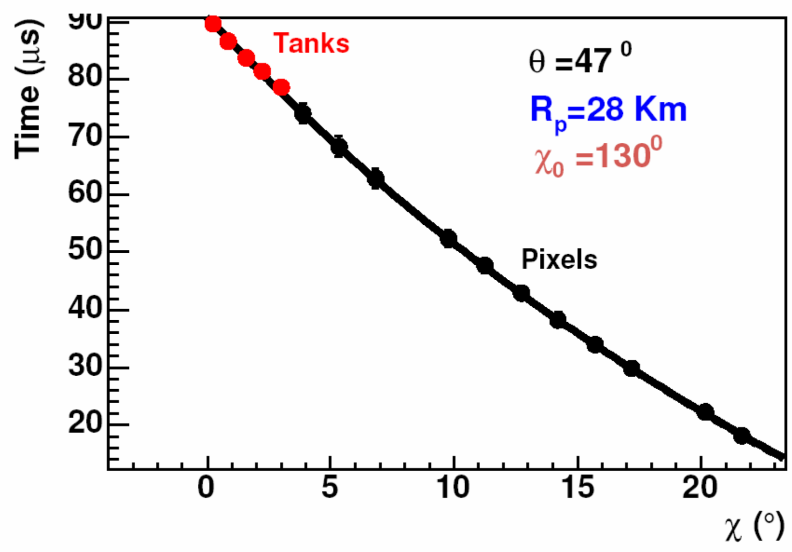
$$S(r) = A \left(\frac{r}{r_s}\right)^{-\beta} \left(1 + \frac{r}{r_s}\right)^{-\beta},$$

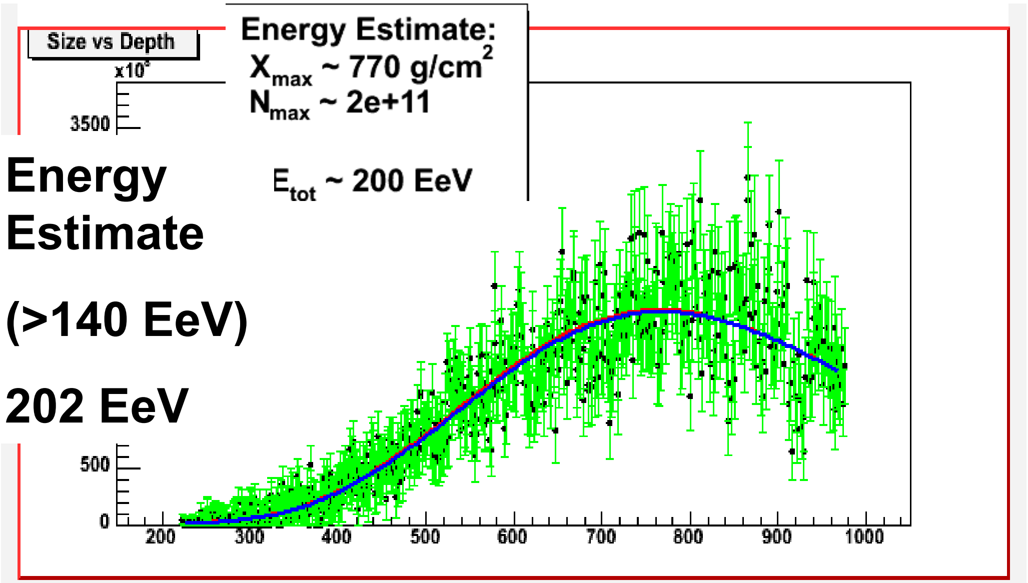
LDF form

Our largest event hit outside the array...and had some other isues.









Energy Estimate

(>140 EeV)

202 EeV

Auger physics results

1. First Estimate of the Primary Cosmic Ray Energy Spectrum above 3 EeV from the Pierre Auger Observatory
2. Upper limit on the primary photon fraction from the Pierre Auger Observatory

Bodes well for neutrino detection

3. Detection of very Inclined Showers with the Auger Observatory
4. A Description of some ultra-high energy cosmic rays observed with the Pierre Auger Observatory
5. Anisotropy Studies Around the Galactic Center at EeV Energies with Auger Data

See no 'hot spots', no previous source confirmed, no positive prescription result

6. Search for localized excess fluxes in Auger sky maps and prescription results

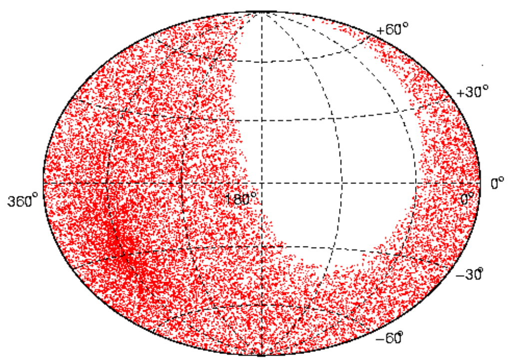

OBSERVATORIO DE RAYOS COSMICOS PIERRE AUGER
Malargüe, Provincia de Mendoza, Argentina
PIERRE
AUGER
OBSERVATORY

The future...

Twenty years of taking data in Malargue will turn up things we have not yet imagined.

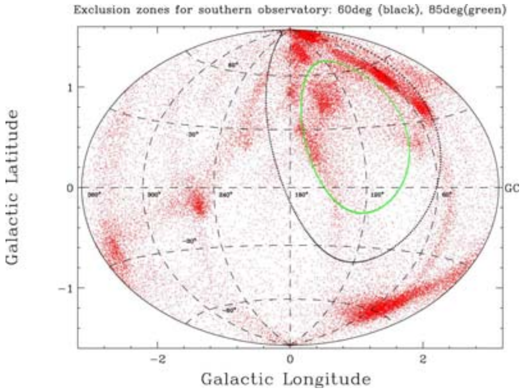
Data sets will be orders of magnitude larger than any existing (By ICRC 2007 factor of 7 larger than ICRC 2005).

The southern detector accepts more than half the sky, but that isn't enough.



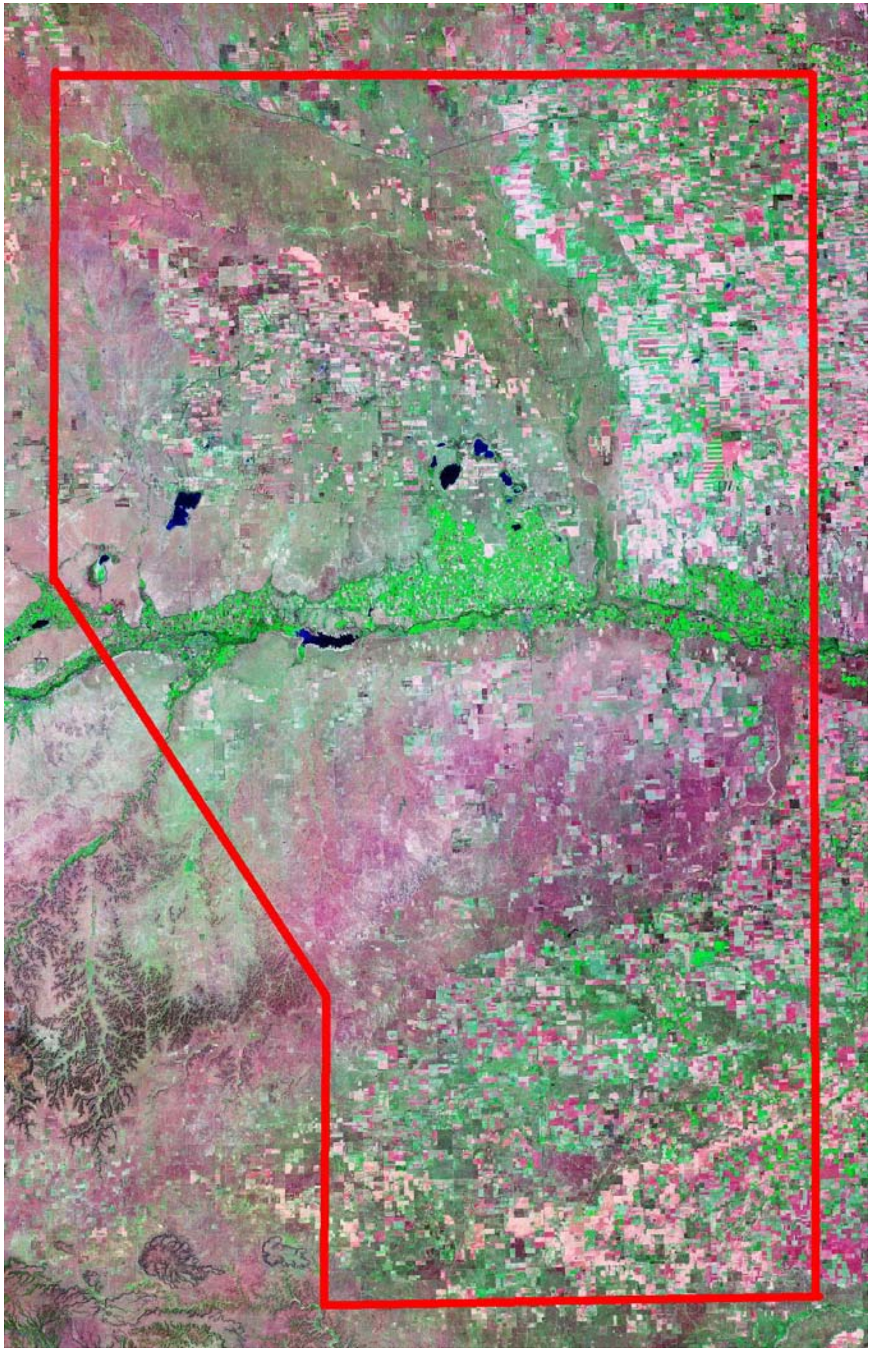
Auger south data (to 60°) miss much of northern sky

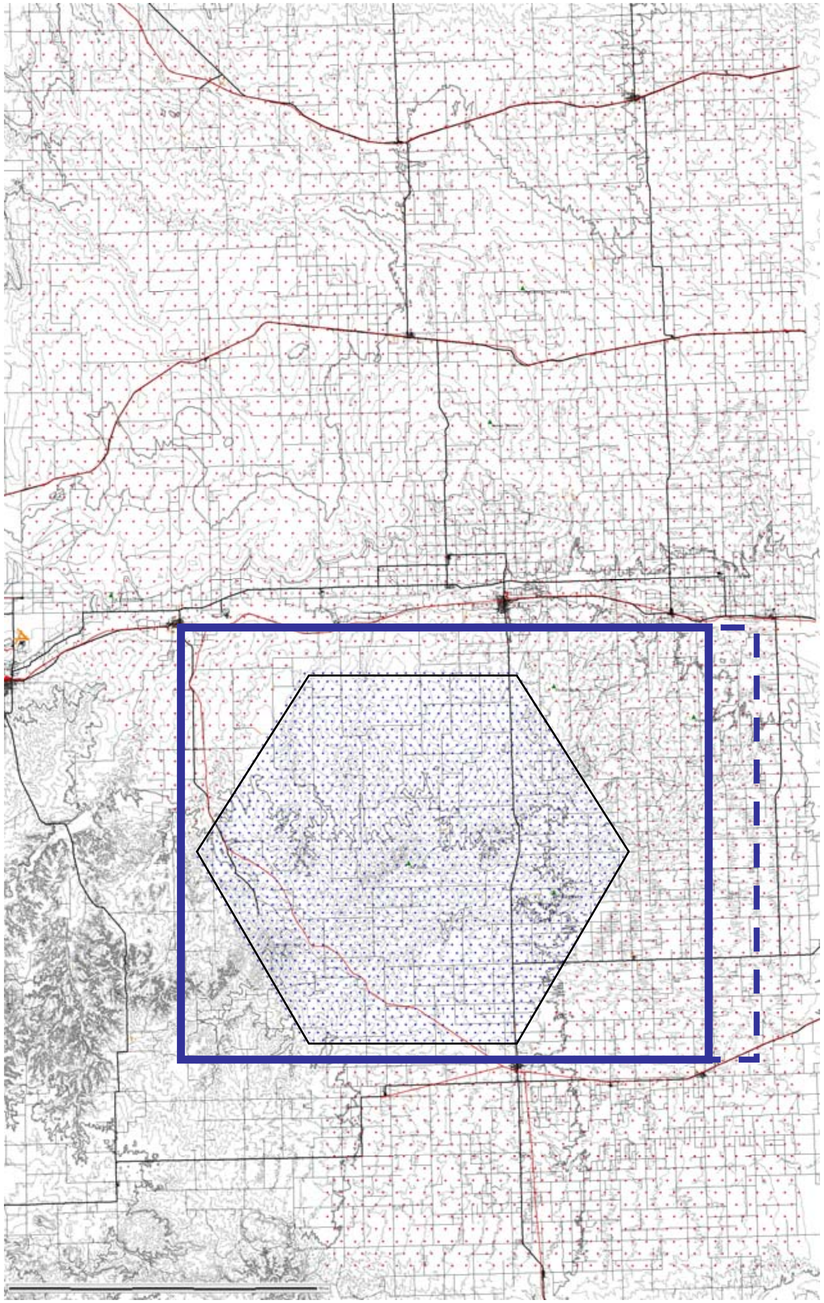
Galaxy distribution 7-21 Mpc



For full-sky coverage we need Auger North

Southeast corner of Colorado, near small cities of Lamar and Springfield





Lamar Community College

LCC will make approx. 5 acres of land available for central campus.

Same size as fenced area of main campus in Malargue.

Location is southern edge of Lamar on highway 287, just north of proposed array.

Atmospheric Monitoring at Colorado Auger North Site

Auger and the CSU-UVB Monitoring and Research Group

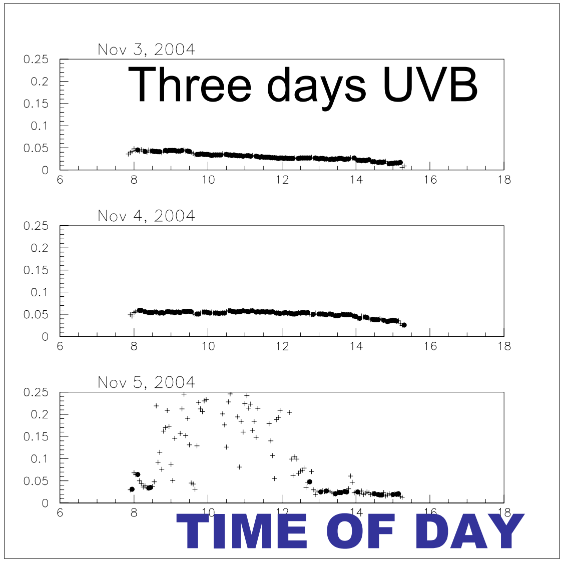
UVB radiometer at 332 nm, 368 nm and other UV and visible wavelengths.

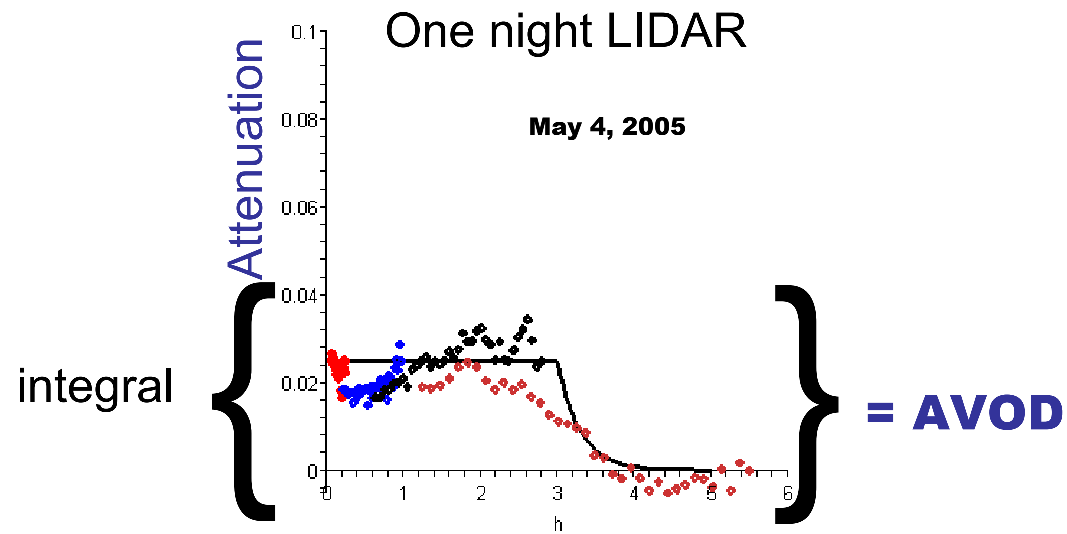
18 months of daytime data since December 2003.

Group operates 34 sites across North America since 1993. Installed at Lamar CC Dec 2003

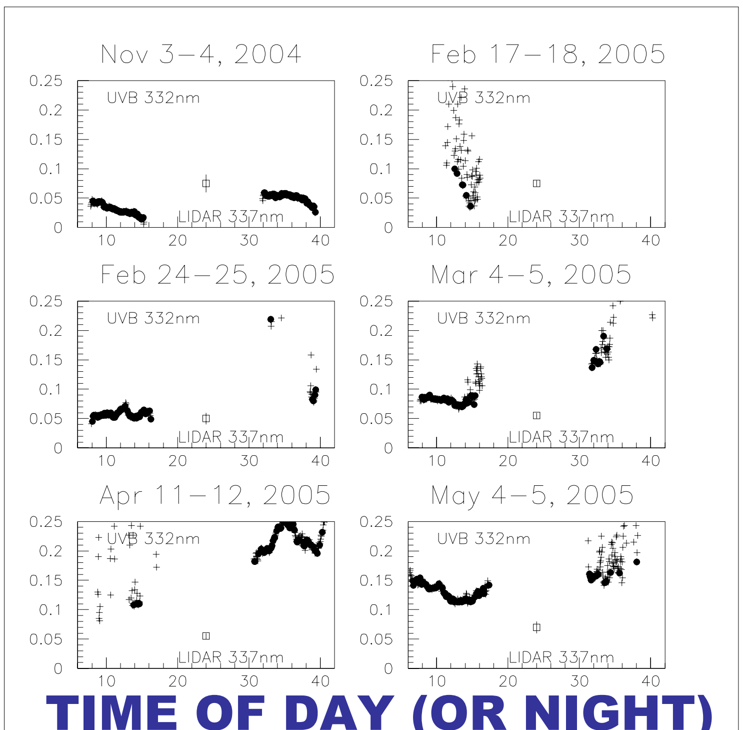
Prowers county buildings provide temporary home for Auger

AVOD

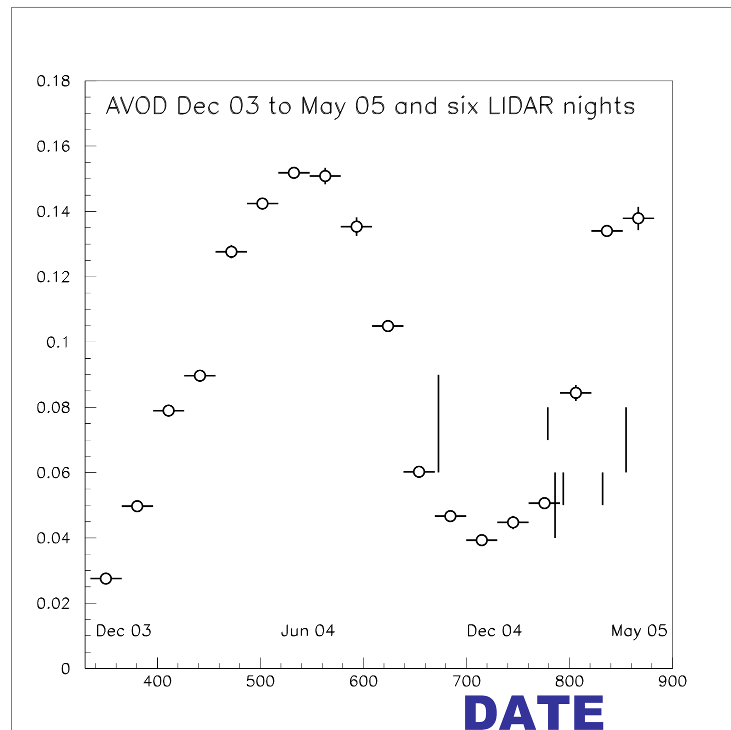




AVOD



AVOD



- Auger Observatory results have been presented from the first running period, which has been during the construction.
- Auger South is over 3/4 finished.
- Aim to complete the southern observatory soon.
- Plans and a proposal for the Northern Auger Observatory are moving forward.