# The Pierre Auger Observatory

## astroparticle physics above ~$10^{18}$ eV

**Jeff Brack**

**Colorado State University**

*Northern observatory Colorado, USA (R&D underway)*

*Southern observatory Mendoza, Argentina (construction almost finished)*

# Outline

- Quick 100 year history of UHECR research
- Air shower detection basics
- Results from recent experiments
- Pierre Auger Observatory (PAO) description
- First results from Auger South: four selected publications
- Plans for Auger North

# UHECR research: historical high points

- 1912 – Victor Hess discovers cosmic rays

- 1938 – Pierre Auger discovers Extended Air Showers (EAS)

- 1963 – Linsley detects C.R. with energy ~$10^{20}$ eV at Volcano Ranch array, in Arizona

- 1965 – Penzias & Wilson discover 2.7 K Cosmic Microwave Background

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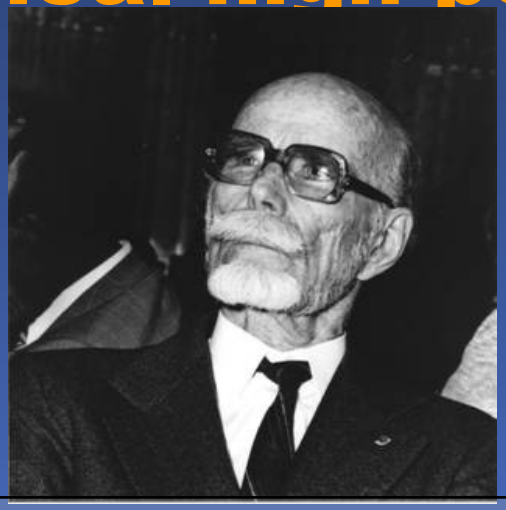

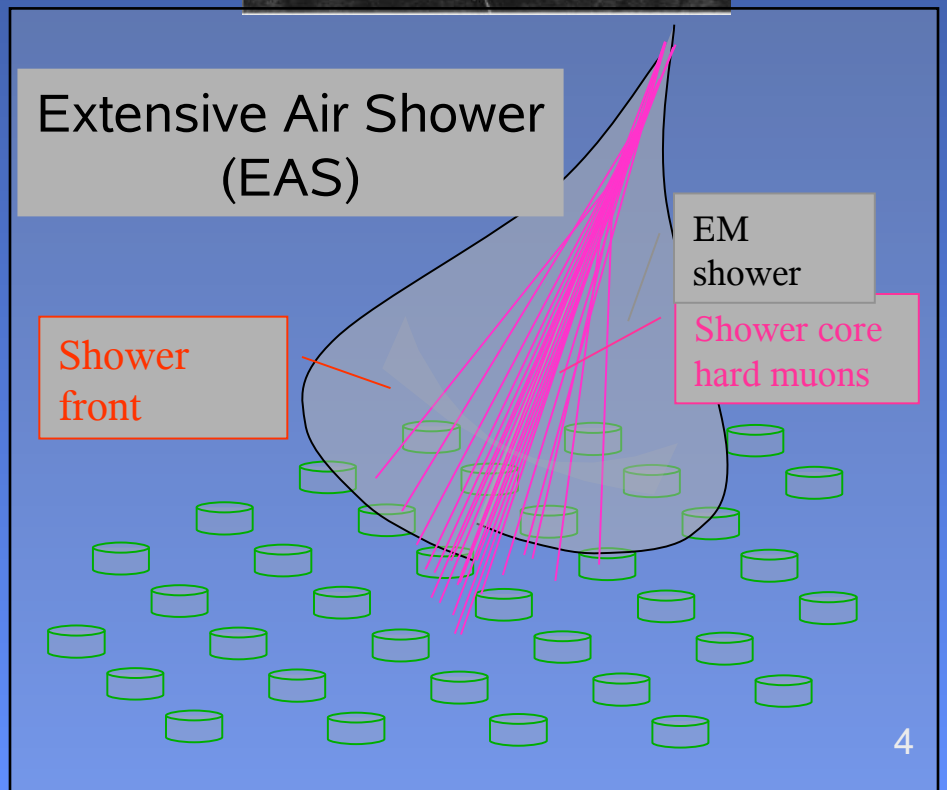

# UHECR research: historical high points

JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

## Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
*Paris, France*

### INTRODUCTION

IT is generally admitted that the soft group present at sea level is almost entirely due to the effects of mesotrons, that is to their decay electrons and their collision electrons. These electrons should then give rise in the lower atmosphere to local showers, the intensity of which should increase very slowly with the altitude, in the same way as the hard group (mesotrons).

But we know that the increase of the soft group with altitude is very rapid, so we must admit that electrons of another origin than that indicated above are adding their effects to those of the decay and collision electrons from mesotrons. It seems natural to suppose that they

number of coincidences decreases much more slowly, and for distances of the magnitude of ten meters, there remains a quite measurable effect, although small.[1, 3] In order to continue this study efficiently, it is then necessary to use a coincidence system with a very good resolving power, especially in the use of two counters. The apparatus employed in the present work registered only multiple kicks which happened within the time lag of $10^{-6}$ second.[4] The "background" or accidental coincidences can be calculated by the formula:*

$$N=\frac{n^x \tau^{(x-1)}}{60^{(x-2)}},$$

where $N$ is the number of accidental coincidences

Coincidences with 'fast counters' at up to 300 m separation

(Gieger counters; recent technical improvments in resolving time: 5μs)

Deduced: Primary particle E at least 10**15 eV at upper atmosphere,

10**6 particles in shower

Guessed: primary particles were electrons --- wrong!

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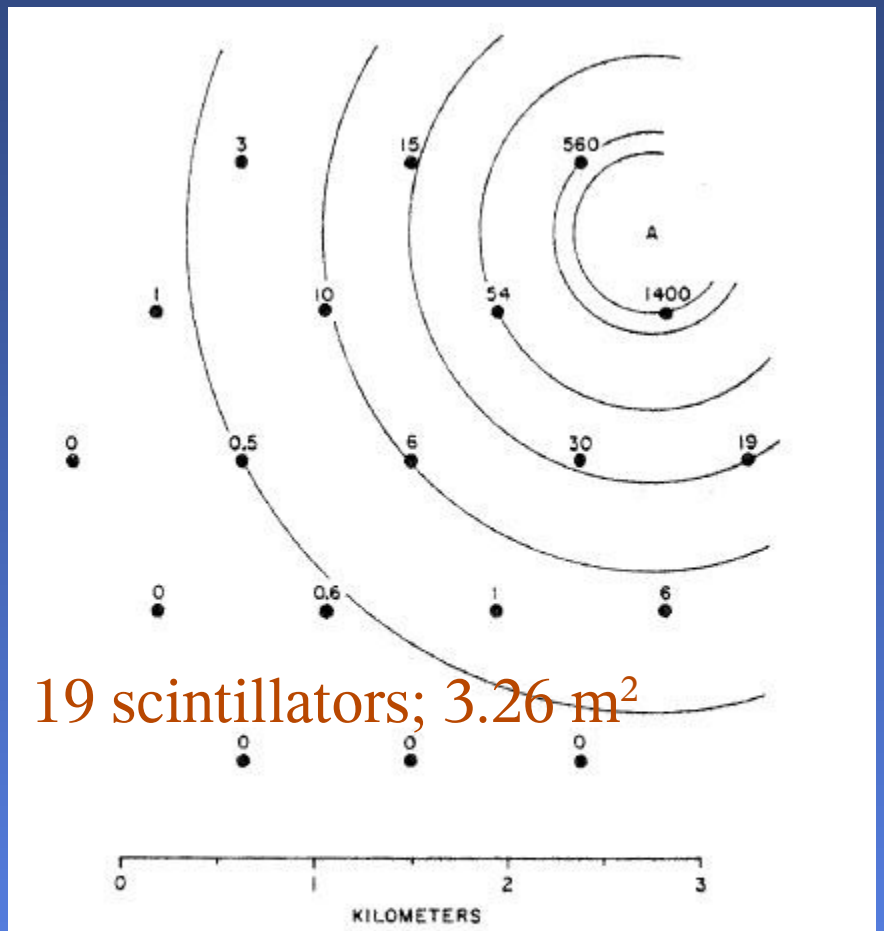


19 scintillators; 3.26 $m^2$

FIG. 8. The detector positions (dots) of the Volcano Ranch array, showing the density map of the first event exceeding $10^{20}$ eV. The number of particles observed by each detector is shown. The core is indicated by A. From Linsley, 1963a.

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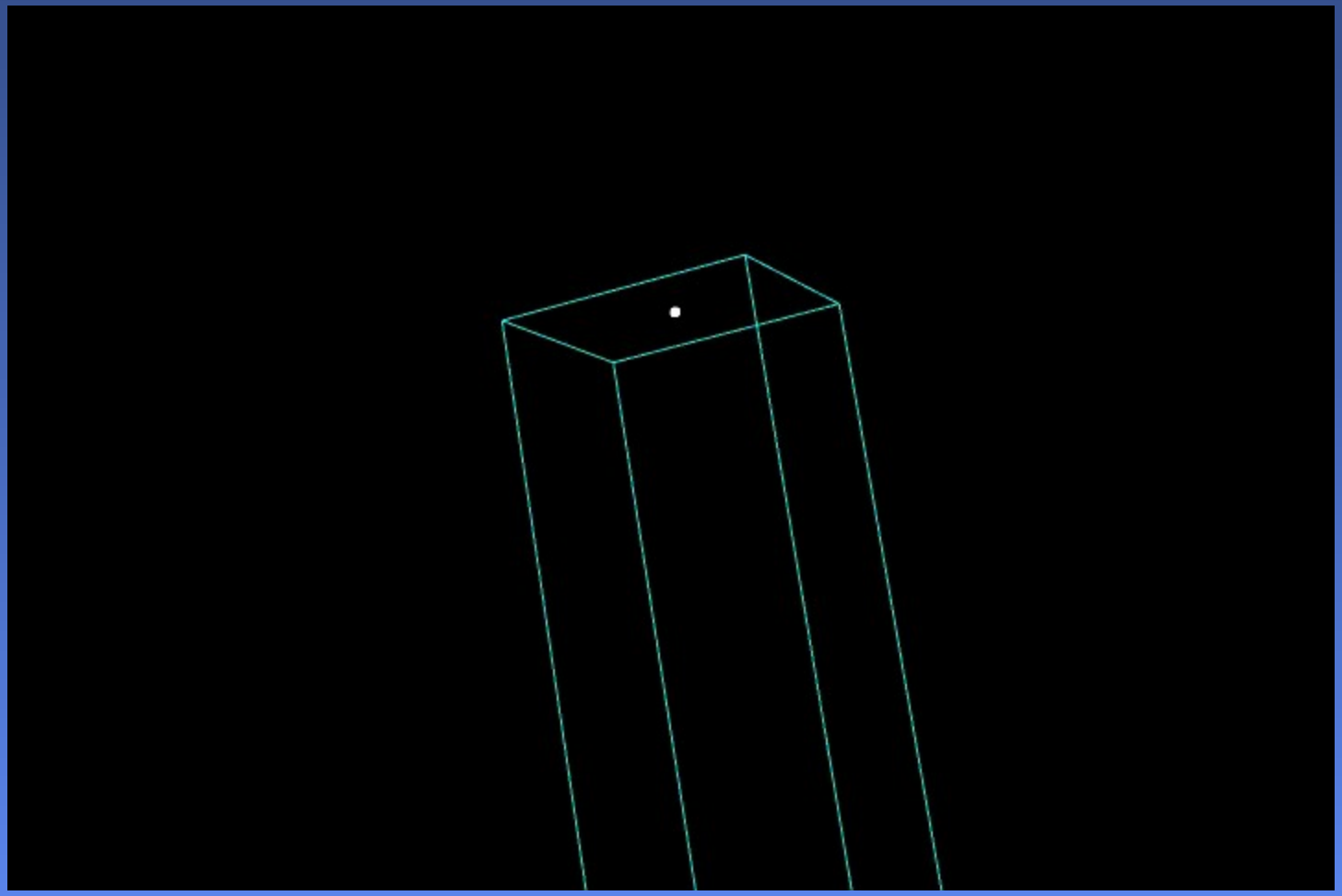
*Greisen '66, Zatsepin & Kuzmin '66*

pion production on CMB for protons > 5 * $10^{19}$ eV

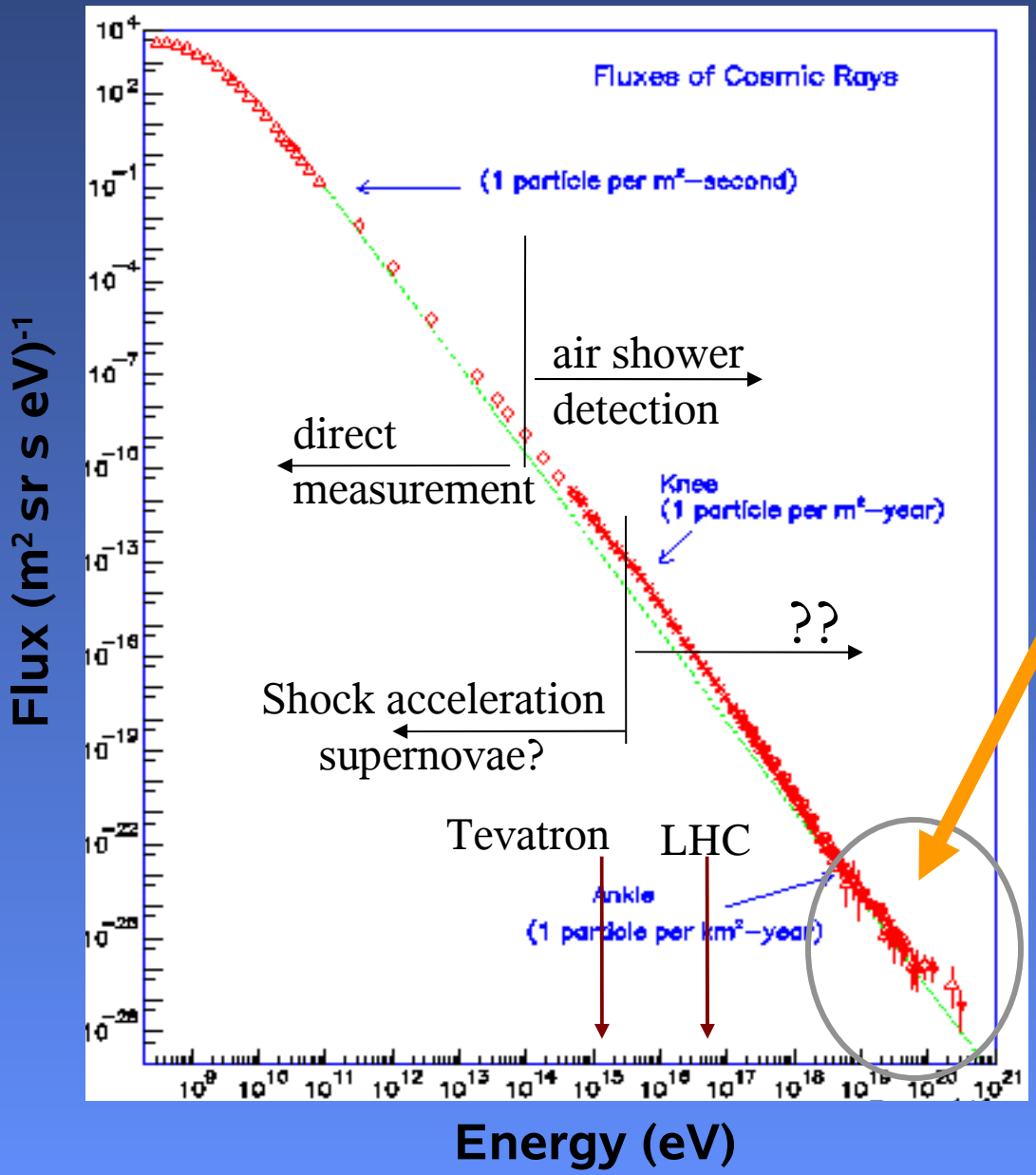
Sources must be < ~ 100 Mpc away

GZK effect

# Proton shower over Chicago



# Cosmic ray spectrum

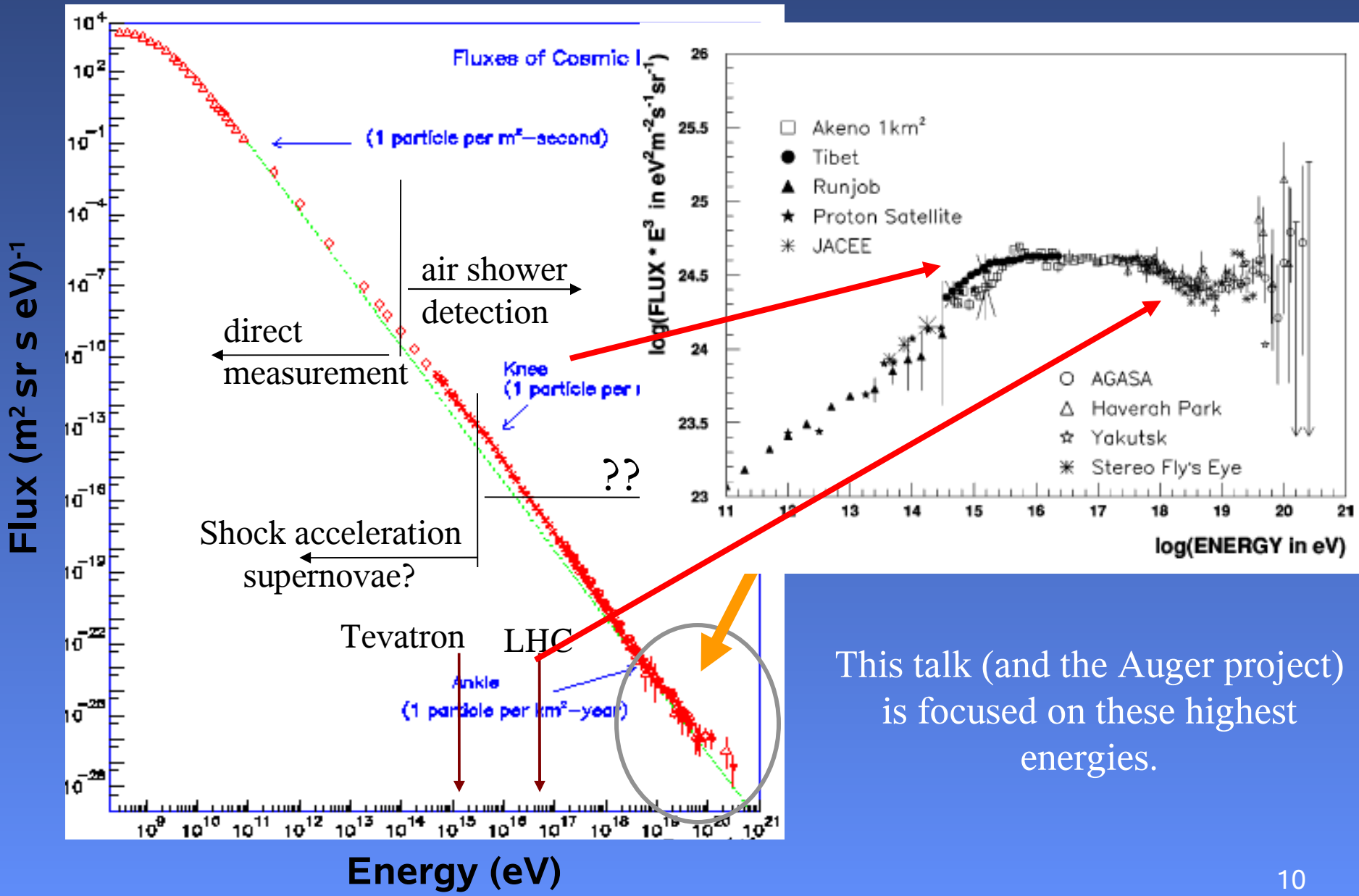



Highest energy particles known: ~$10^5$ x accelerator energies (fixed-target equivalent)

The flux at upper atm is low: a few / ($km^2$ x century)

This talk (and the Auger project) is focused on these highest energies.

# Cosmic ray spectrum

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# Possible sources

**Bottom up models:**

- particle acceleration
- assume R ~ Larmor radius in some B
- assume weak B (syncrotron Eloss < Egain)
  - difficult to find astrophysical regions with BxR big enough

**E~$10^{12}$ --> BxR = $10^{9}$ cm-g (Tevatron)**
**E~$10^{20}$ --> BxR = $10^{17}$ cm-g**

**Top down and exotic source models:**

- Super-heavy dark matter
- decay of super massive big bang relics
- Z-bursts
- topological defects (monopoles, strings)
- 'supersymmetric hadron' propogation
- Lorentz invariance breakdown

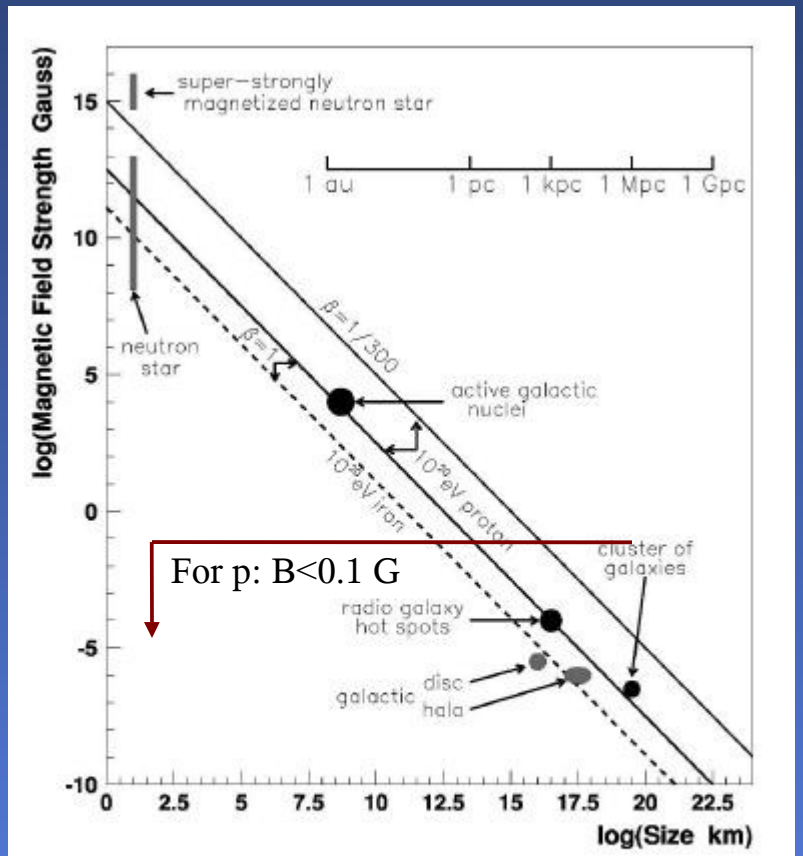
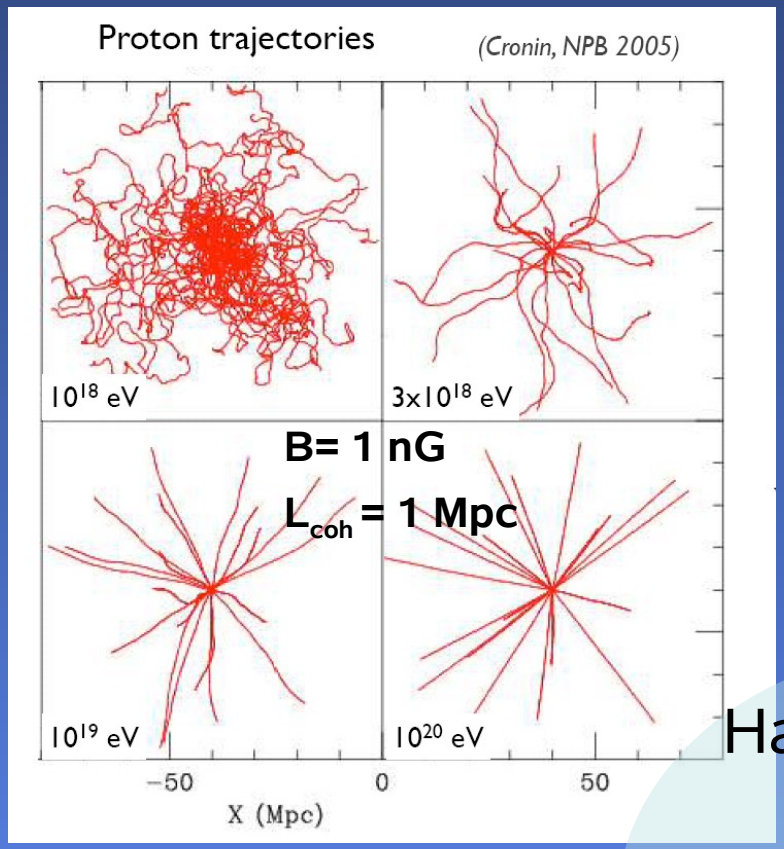
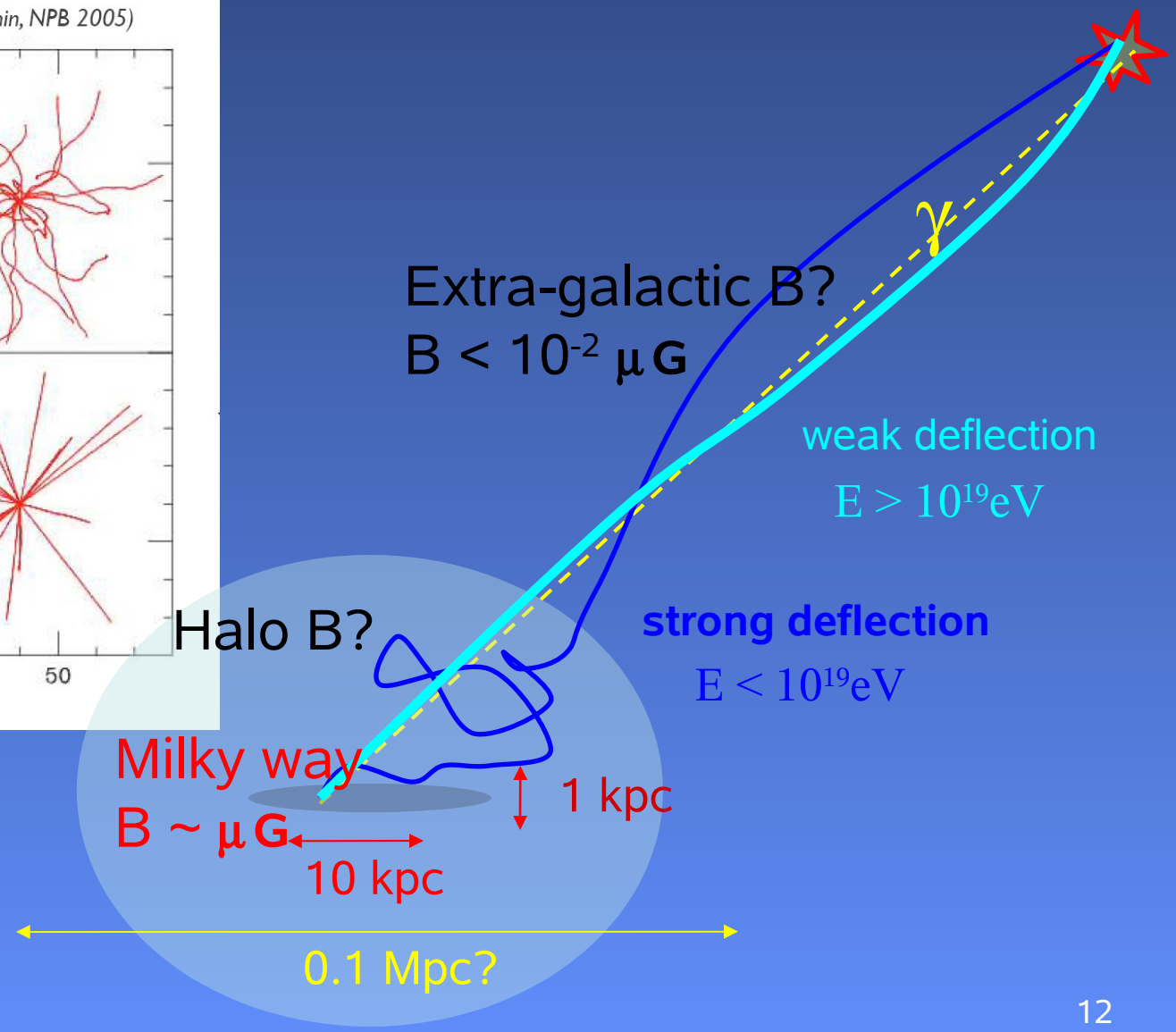



FIG. 2. The size and magnetic-field strength of possible astronomical objects that are particle source and acceleration candidates. $\beta$ is a characteristic velocity of scattering centers. Objects below the diagonal line cannot accelerate protons to $10^{20}$ eV. Modified from Hillas, 1984.

(or: $\beta$=accel efficiency)

# Propagation through space



# Propagation through space

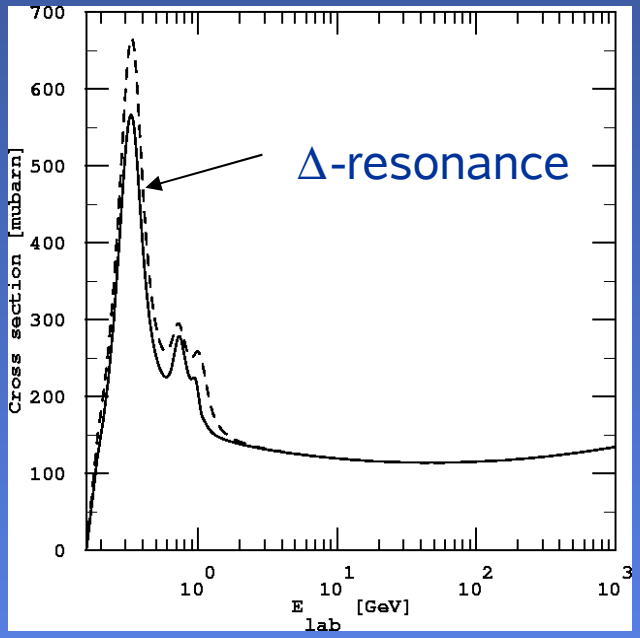
$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$
$$\rightarrow p + e^{+} + e^{-}$$

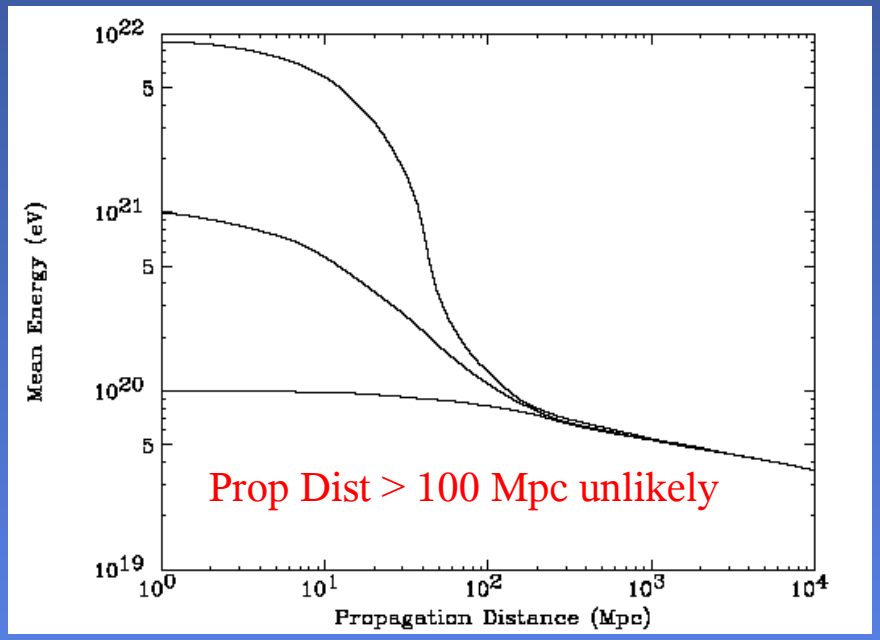
Pion production dominates E loss for proton:

E_thresh ~ $10^{19.6}$ eV

Mean free path ~6 Mpc

Eloss/interaction: ~20%




***The GZK effect,***
***Greisen '66, Zatsepin & Kuzmin '66***

(1 pc = 3.3 light years)

# Air shower detection techniques

- All use atmosphere as calorimeter
  - 12+ generations as shower propagates to ground
  - $10^8$ particles at maximum development (for proton at $10^{19}$ eV)
  - short-lived particles decay in flight
  - Low energy particles absorbed in atmosphere
  - Remainder: footprint ~ 15 $km^2$ at surface (for proton at $10^{19}$ eV)
- 1: Detect shower as it develops ← Precise energy determination ~10% duty factor
  - Secondary shower particles interact with nitrogen n atm.
  - Nitrogen fluorescence produces UV photons
  - View from distance with optical telescopes
- 2: Detect shower particles at surface ← Indirect energy determination ~100% duty factor
  - Sampling grid on surface: mostly muons from pion decay
  - use MC to reconstruct shower
    - *altitude of detection is important*
- 3: Cerenkov detection (different talk…)

# Previous UHECR experiments

M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays

TABLE I. The experimental sites used to study ultrahigh-energy cosmic rays.

| Experiment | Begin | End/status | Latitude | Longitude | Altitude m | Atmospheric depth g cm$^{-2}$ |
|---|---|---|---|---|---|---|
| Volcano Ranch | 1959 | 1963 | 35°09′ N | 106°47′ W | 1770 | 834 |
| SUGAR | 1968 | 1979 | 30°32′ S | 149°43′ E | 250 | 1015 |
| Haverah Park | 1968 | 1987 | 53°58′ N | 1°38′ W | 200 | 1016 |
| Yakutsk | 1974 | in operation with contracted area | 61°36′ N | 129°24′ E | 105 | 1020 |
| Fly's Eye | 1981 | 1992 | 40° N | 113° W | | 869 |
| AGASA | 1990 | in operation | 35°47′ N | 138°30′ E | 900 | 920 |

The only Fluorescence detector (HiRes fly's eye was under construction)

TABLE II. The types of surface arrays used to study ultrahigh-energy cosmic rays.

| Experiment | Detectors | Size | Number of detectors | Covered area km$^2$ | Notes |
|---|---|---|---|---|---|
| Volcano Ranch | scintillator | 3.3 m$^2$ | 19 | 8 | |
| | muon detector (>220 MeV) | 3.3 m$^2$ | 19 | | |
| SUGAR | muon detector (>0.75 GeV) | 2×6 m$^2$ | 54 | 60 | |
| Haverah Park | water Čerenkov | 34 m$^2$ | 4 | 12 | |
| | water Čerenkov | 2.25~54 m$^2$ | 28 | | |
| | water Čerenkov | 1 m$^2$ | 30 | 0.3 | close to the array center |
| Yakutsk | scintillator | 2~4 m$^2$ | 58 | 18 | up to 1995 |
| | muon detector (>1 GeV) | 20 m$^2$ | 5 | 10 | from 1996 |
| | muon detector (>0.5 GeV) | 192 m$^2$ | 1 | | |
| | air Čerenkov phototube | (1~3)×5″ | 45 | | |
| AGASA | scintillator | 2.2 m$^2$ | 111 | 100 | |
| | muon detector (>0.5 GeV) | 2.4~10 m$^2$ | 29 | 50 | |
| | scintillator | 1 m$^2$ | 159 | 1 | 1-km$^2$ array |
| | muon detector (>1.0 GeV) | 25 m$^2$ | 9 | 1 | |

# Previous UHECR experiments

TABLE IV. Exposure and number of events observed in each experiment.

| Experiment | Exposure ($\times 10^{16}$ m$^2$ sec sr) | | | No. of events | | | Expected number |
|---|---|---|---|---|---|---|---|
| | $\geqslant 10^{19}$ | $\geqslant 10^{19.6}$ | $\geqslant 10^{20}$ | $\geqslant 10^{19}$ | $\geqslant 10^{19.6}$ | $\geqslant 10^{20}$ | $\geqslant 10^{20}$ |
| Volcano Ranch | | 0.2 | 0.2 | | 6 | 1 | 0.52 |
| Haverah Park | 0.43 | 0.73 | 0.87 | 106 | 27 | 4 | 2.3 |
| Yakutsk | 1.35 | 1.35 | 1.35 | 230 | 12 | 0 | 3.5 |
| Fly's Eye (mono) | 1.3 | 2.6 | 2.6 | 297 | 22 | 1 | 6.8 |
| Fly's Eye (stereo) | 0.41 | 0.46 | 0.46 | 67 | 2 | 0 | 1.2 |
| AGASA (Aug. 1998) | 3.1 | 3.1 | 3.1 | 581 | 47 | 7 | 9.4 |

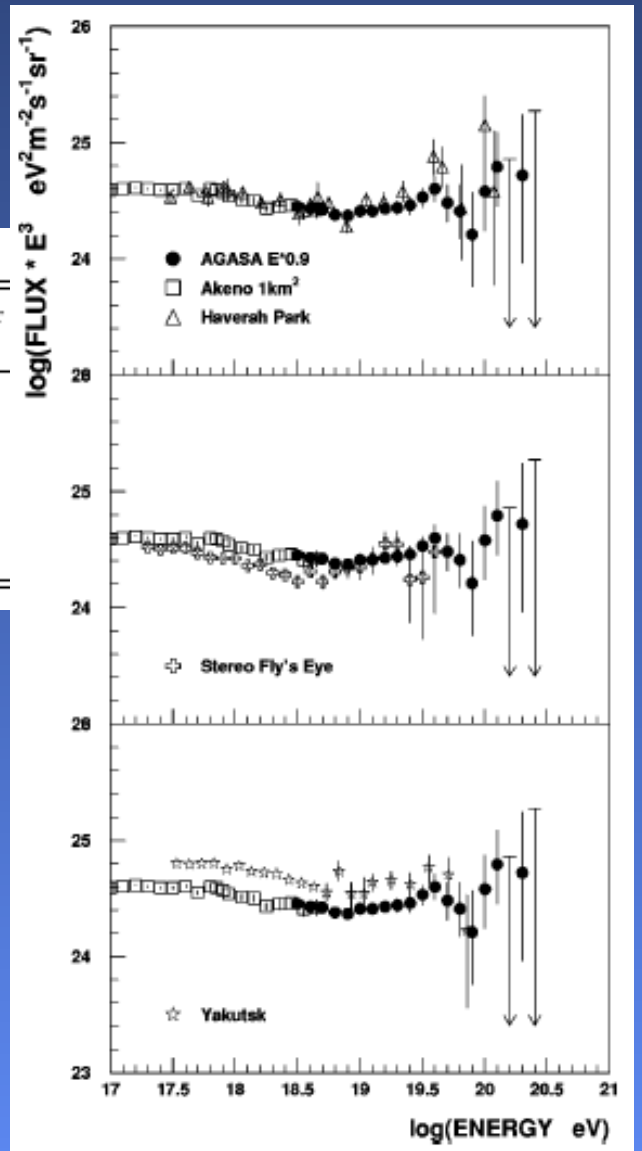



FIG. 23. Differential energy spectra determined by Haverah Park, Yakutsk, and Fly's Eye, compared with those determined by AGASA.

**Mid-1990s:**

**Only ~100 events above GZK energy**
**No conclusion on GZK or continuous spectrum**

# Open questions

- No convincing acceleration process for explaining particle energy > $10^{19}$ eV
- Sources of particles > $10^{19}$ eV must be closer than about 50-100 Mpc because of CMB, GZK effect

- Top down or bottom up acceleration?
- What are the masses?
- Is the 'GZK' effect real?
- Are the sources isotropically distributed?
- Point sources?
- Straight trajectories at highest energies?

# The Auger Collaboration

**65 Institutions, ~370 Collaborators,**
**17 Countries, 4 Continents**

***Participating Countries***

| | |
|---|---|
| Argentina | Mexico |
| Australia | Netherlands |
| Bolivia* | Poland |
| Brazil | Portugal |
| Czech Republic | Slovenia |
| France | Spain |
| Germany | United Kingdom |
| Italy | USA |
| | Vietnam* |

**Associate*

# The Auger Observatory

Full sky coverage:

Auger north is planned in Colorado for 2010..?

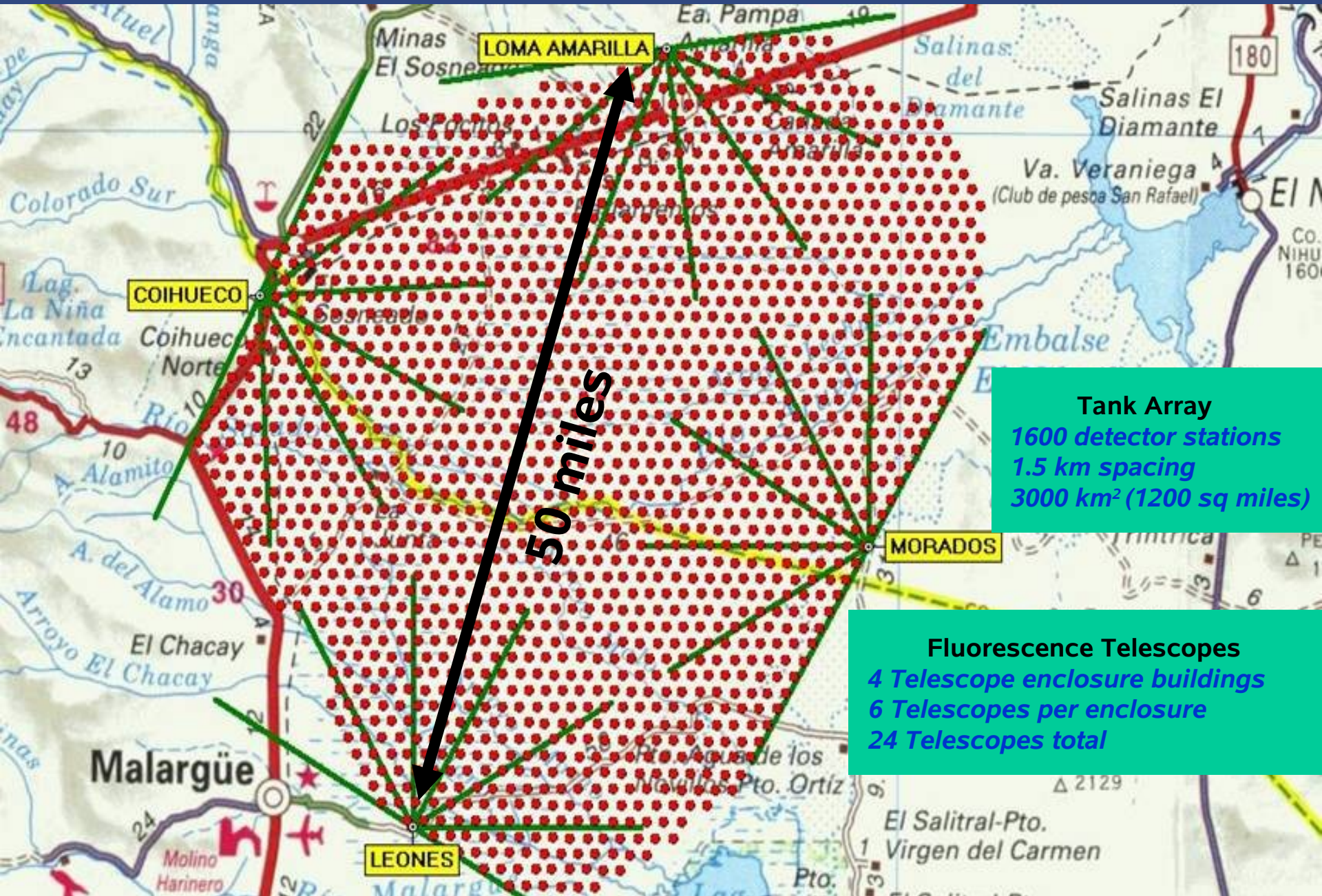
(R&D now)

Auger south in Malargue, Ar
Now >99% complete

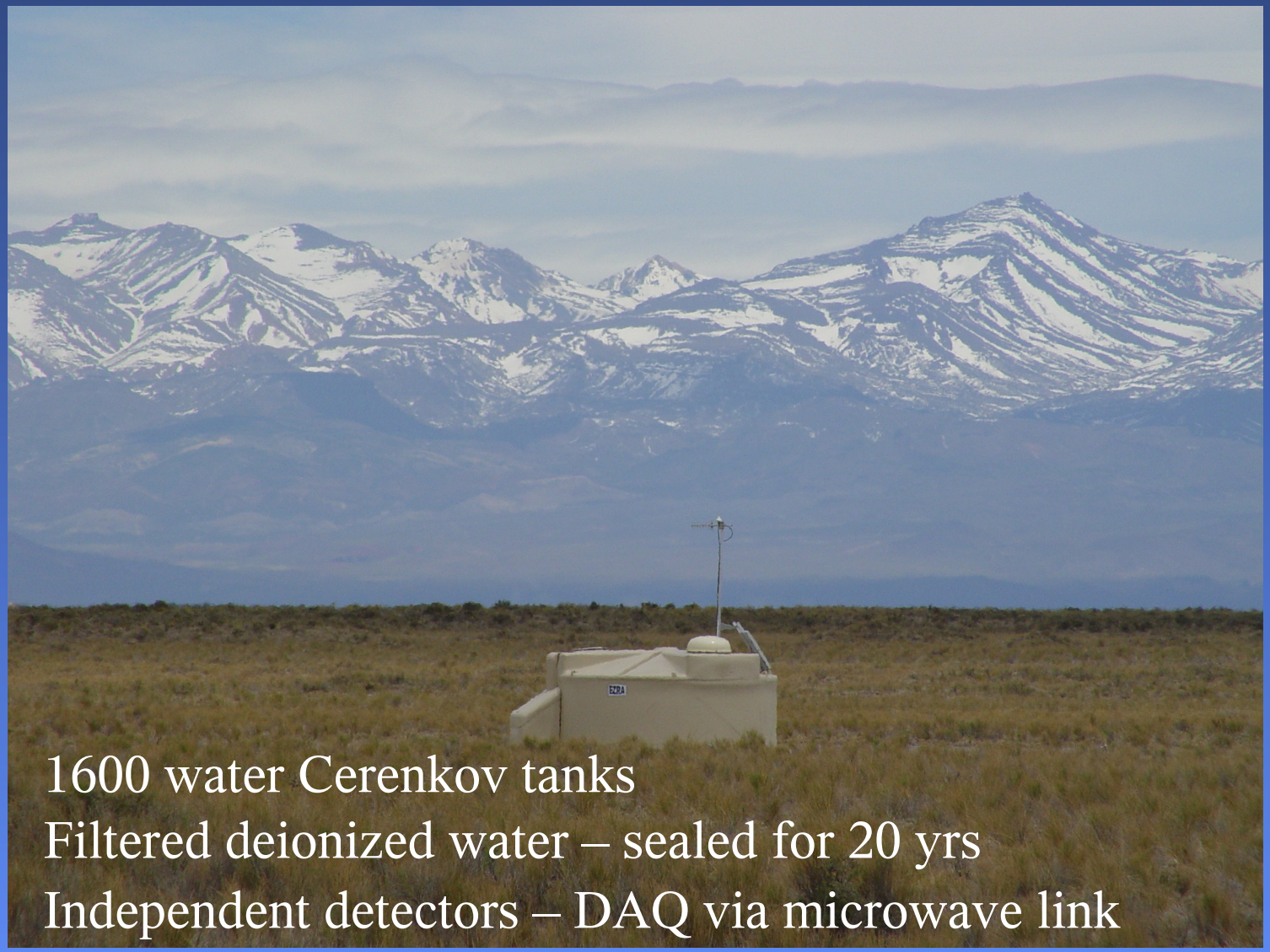
Lamar: 38 deg north

Malargue: 31 deg south

# Auger Observatory – Southern Array

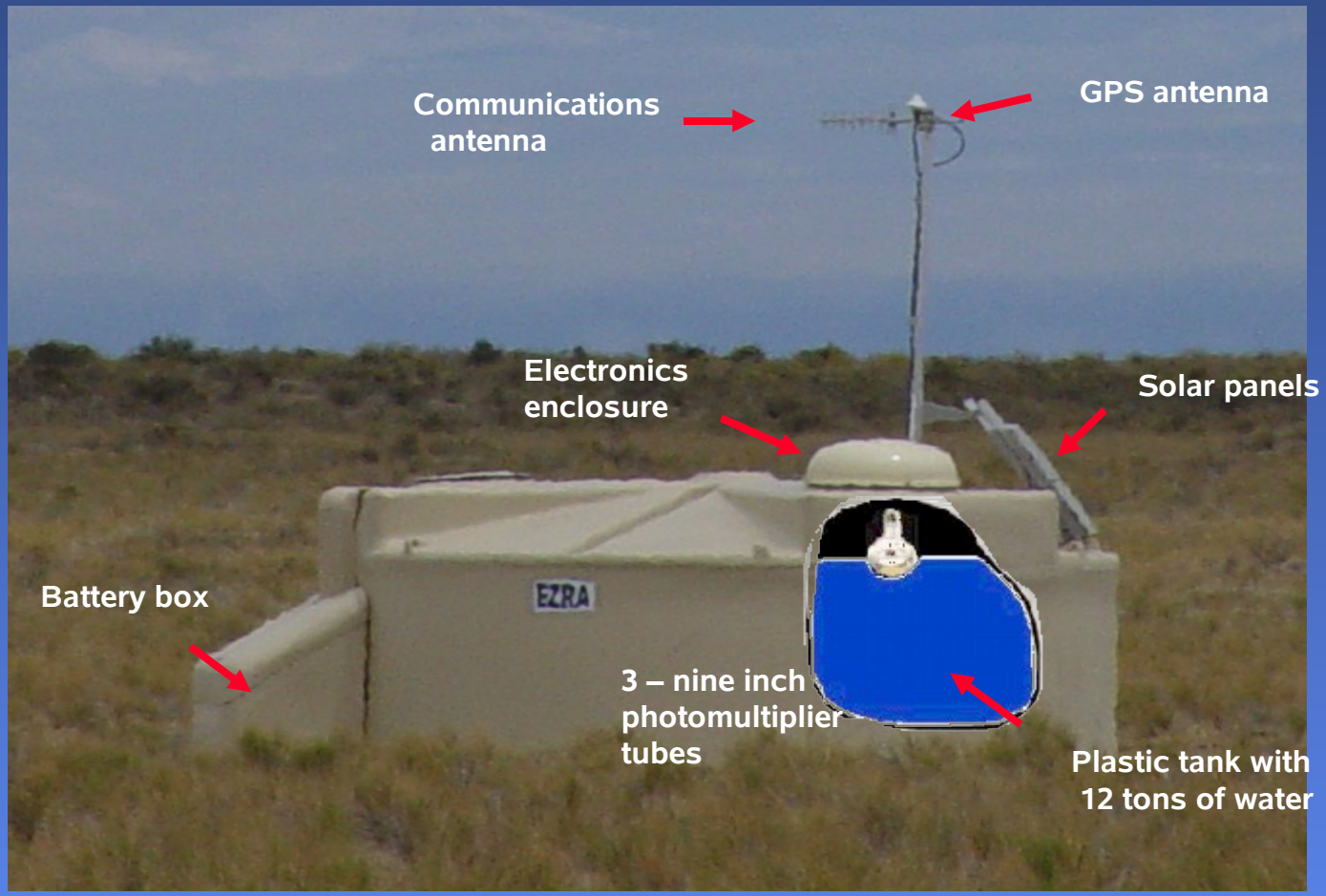


# Surface detector: Tank Array

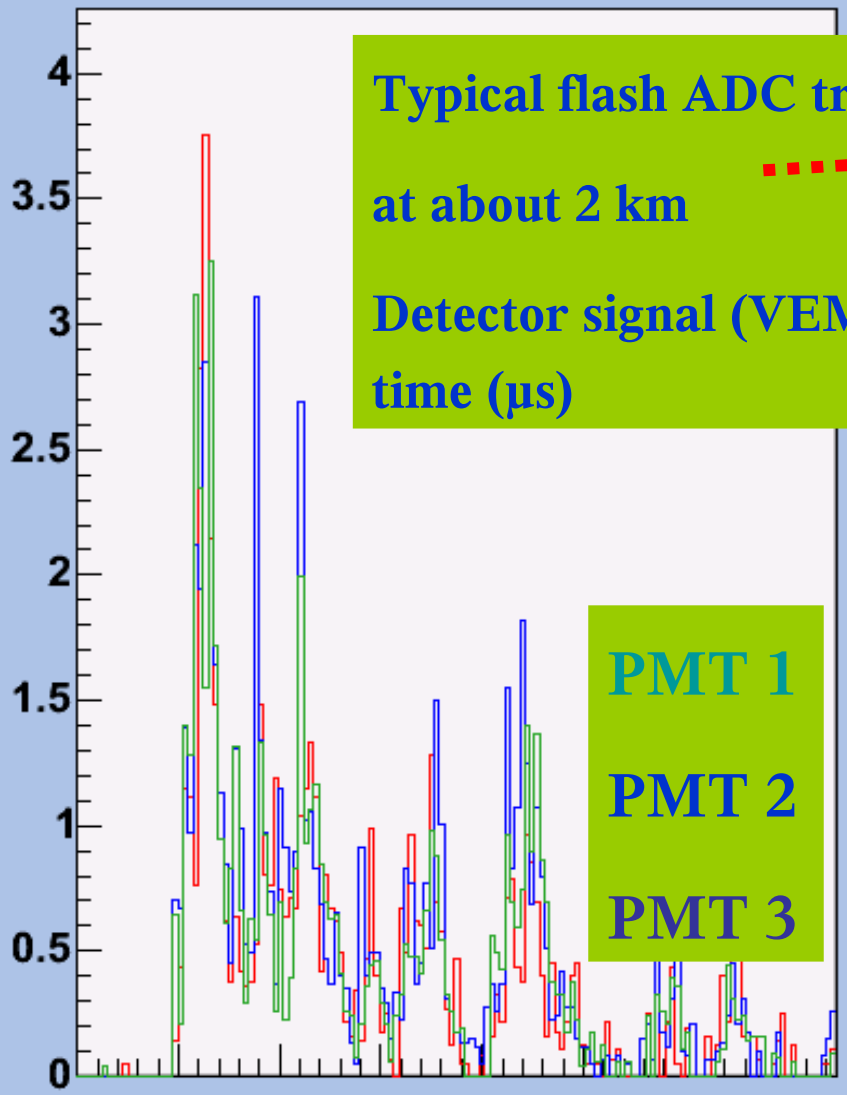


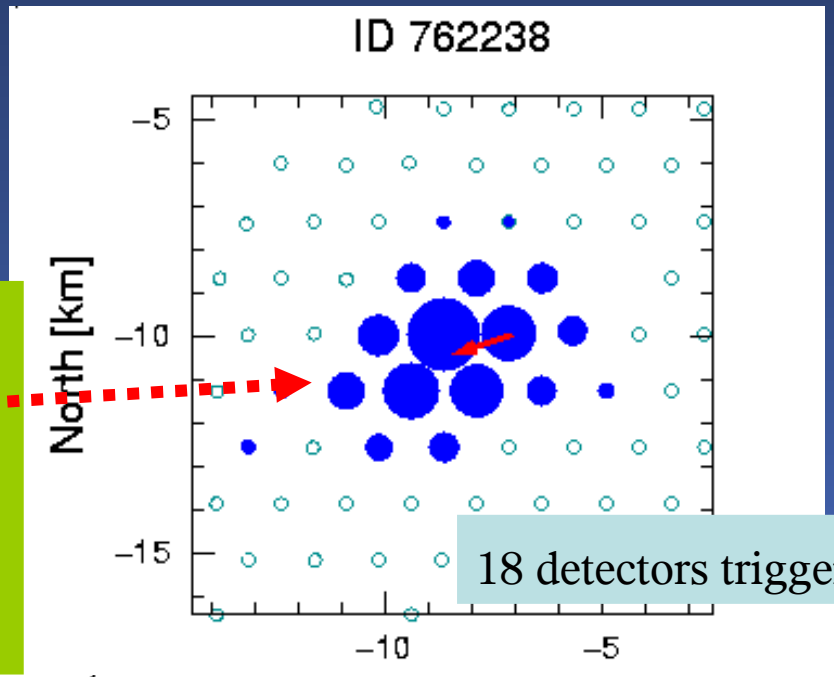

1600 water Cerenkov tanks
Filtered deionized water – sealed for 20 yrs
Independent detectors – DAQ via microwave link
Solar panels point north!

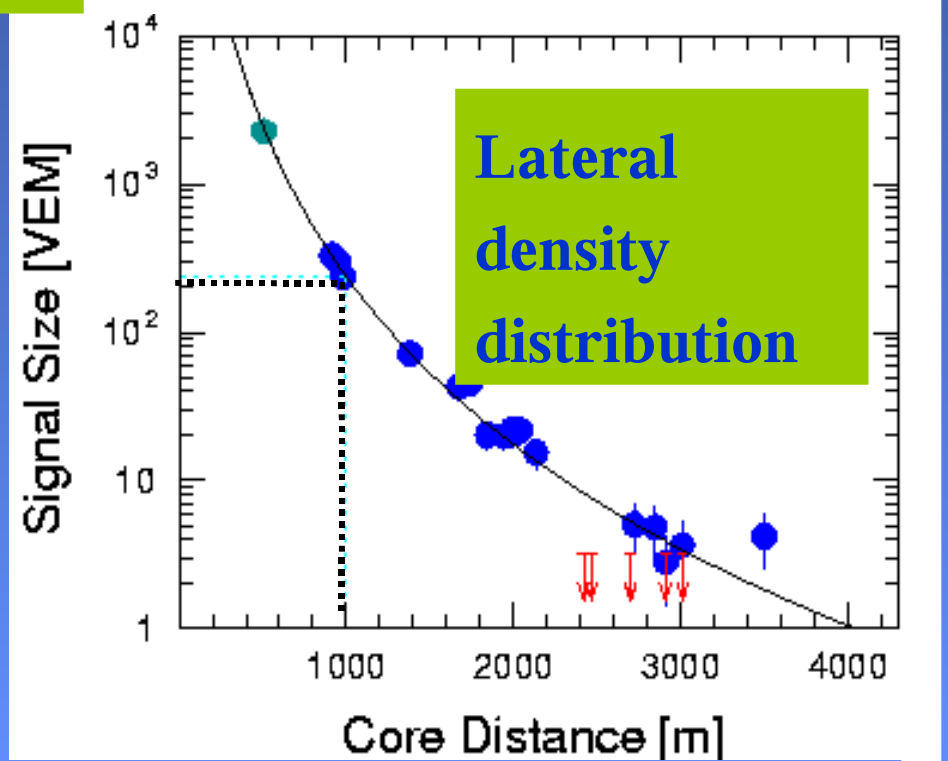
# Surface detector: Tank Array



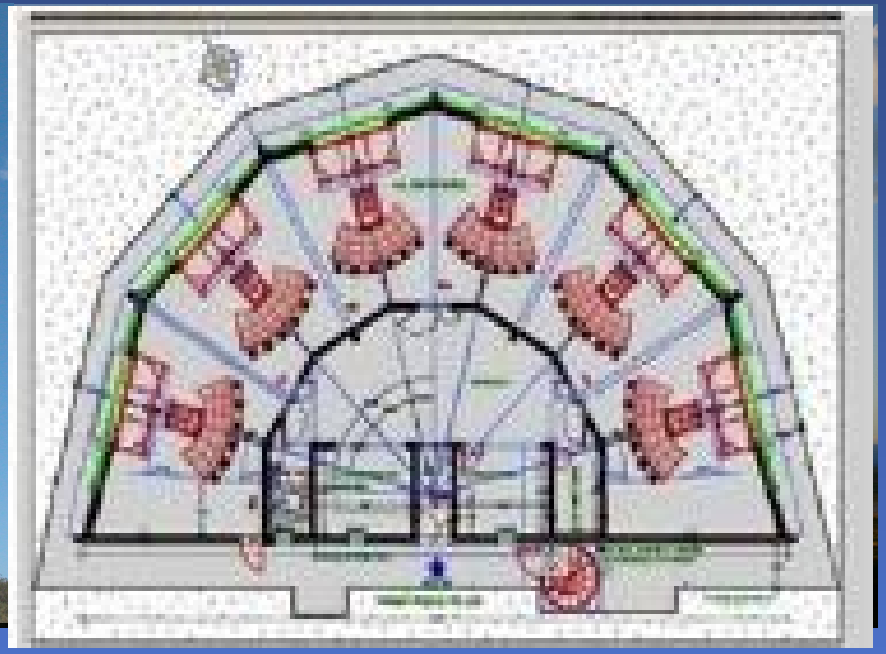
# θ~ 48º, ~ 70 EeV

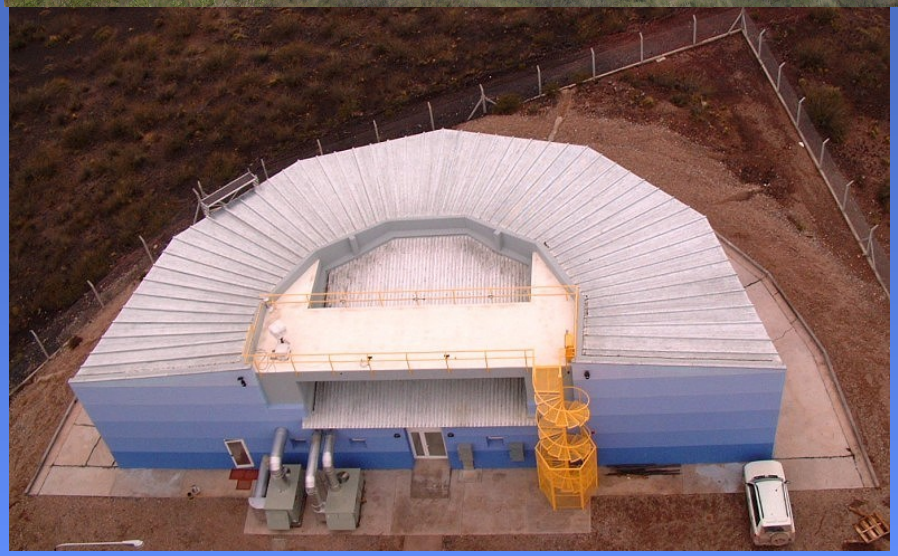

Typical flash ADC trace
at about 2 km
Detector signal (VEM) vs time (µs)
PMT 1
PMT 2
PMT 3
0
0.5
1
1.5
2
2.5
3
3.5
4
-0.5 0 0.5 1.0 1.5 2.0 2.5 3.0 µs


ID 762238
North [km]
−5
−10
−15
−10
−5
18 detectors triggered


Lateral density distribution
Signal Size [VEM]
Core Distance [m]
1
10
10²
10³
10⁴
1000
2000
3000
4000

# Fluorescence detector: UV telescopes





24 telescopes

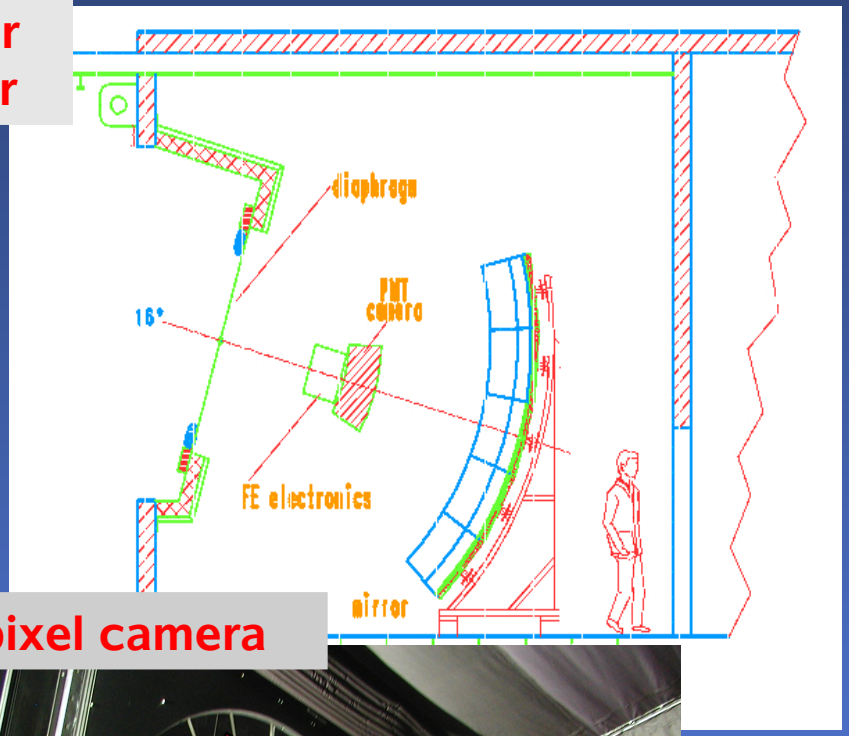
Each views ~30x30 deg solid angle

View ~15 km of atmosphere above ground array

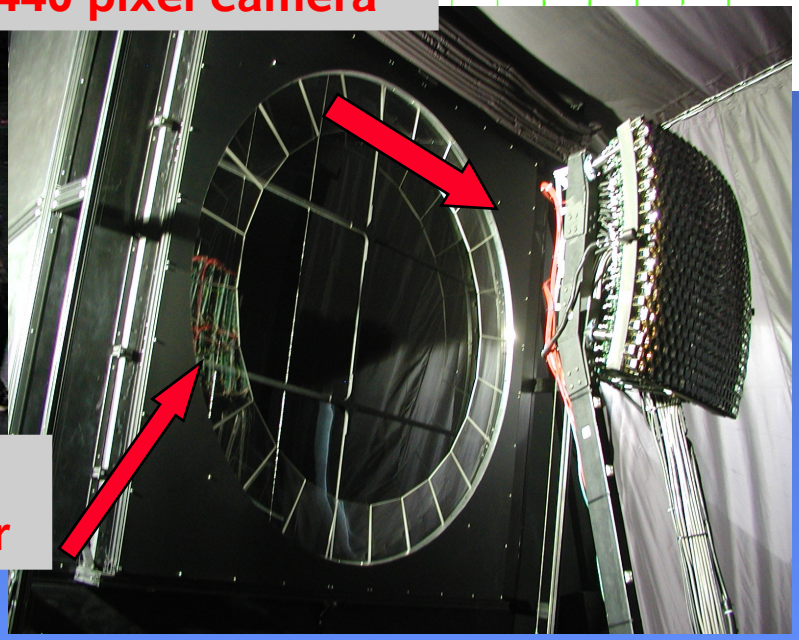
Total of 10,560 PMTs

# Fluorescence detector: UV telescopes

3.4 meter diameter segmented mirror

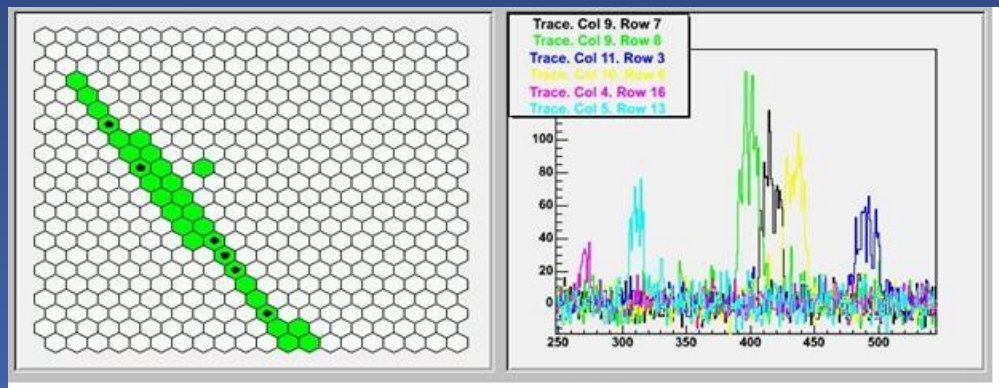



440 pixel camera



Aperture stop and optical filter

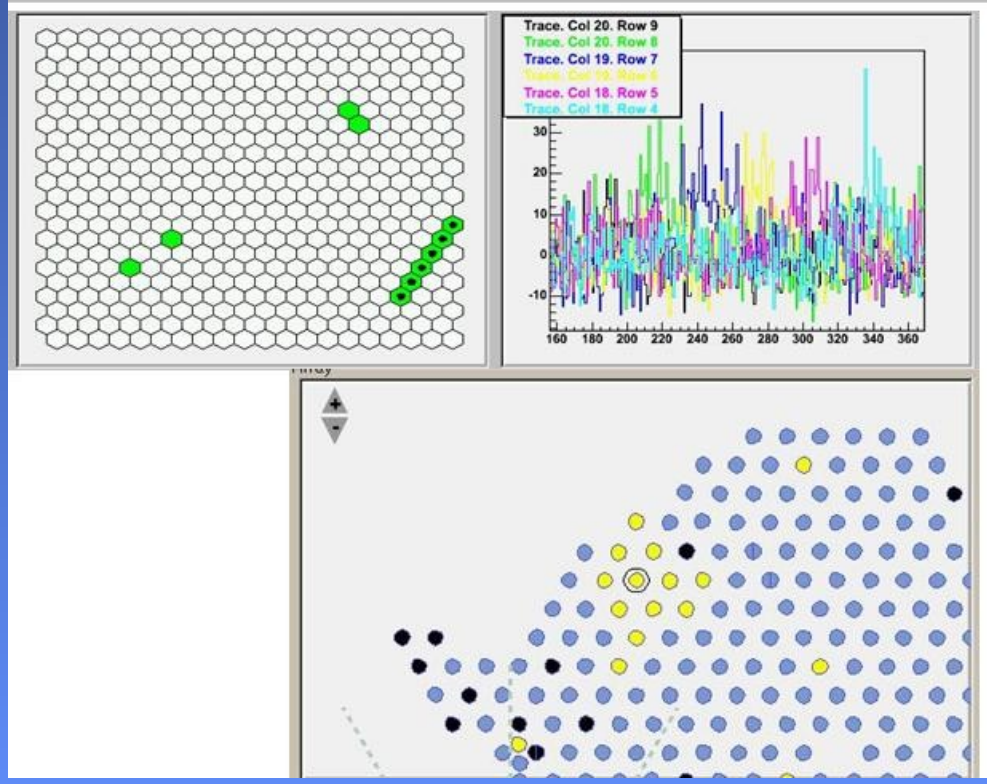
# FD and Hybrid event detection

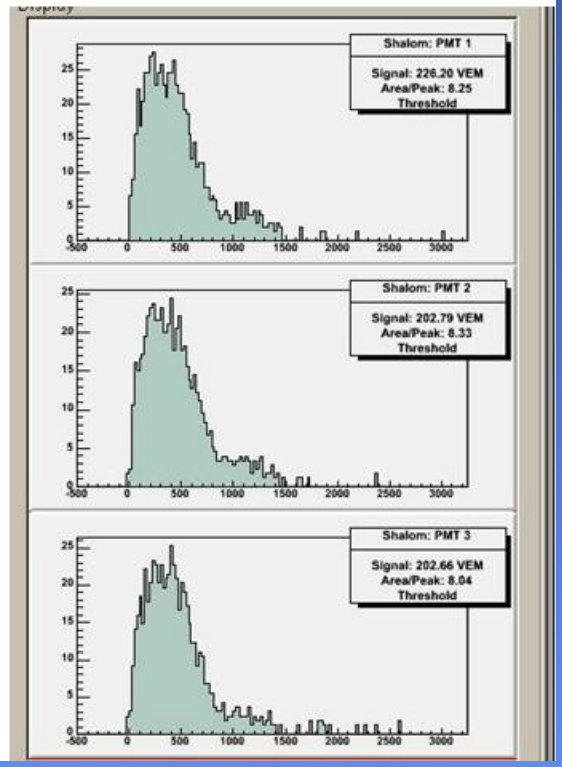



Platinum Event

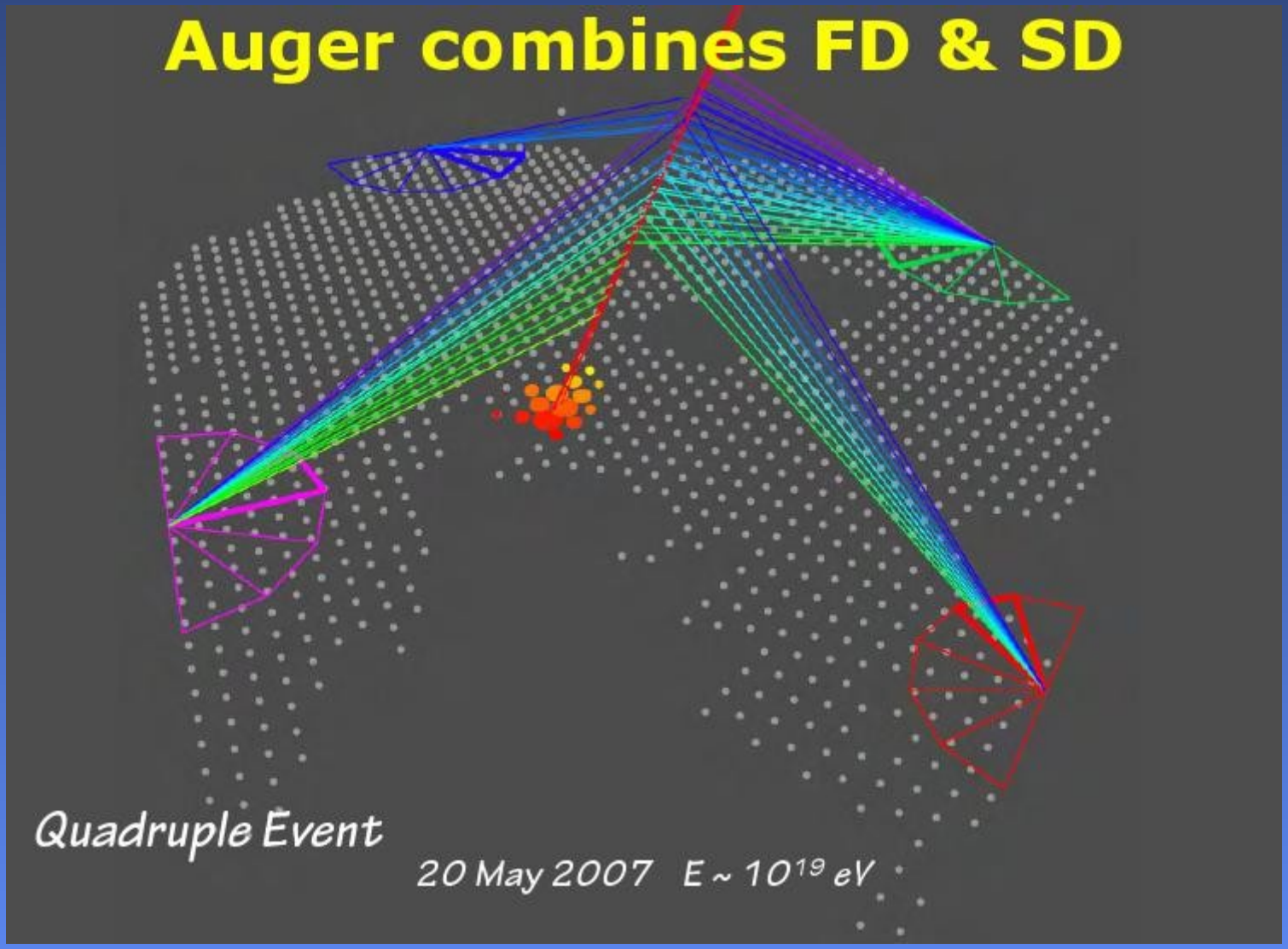
#673411

(10 tanks in fit)

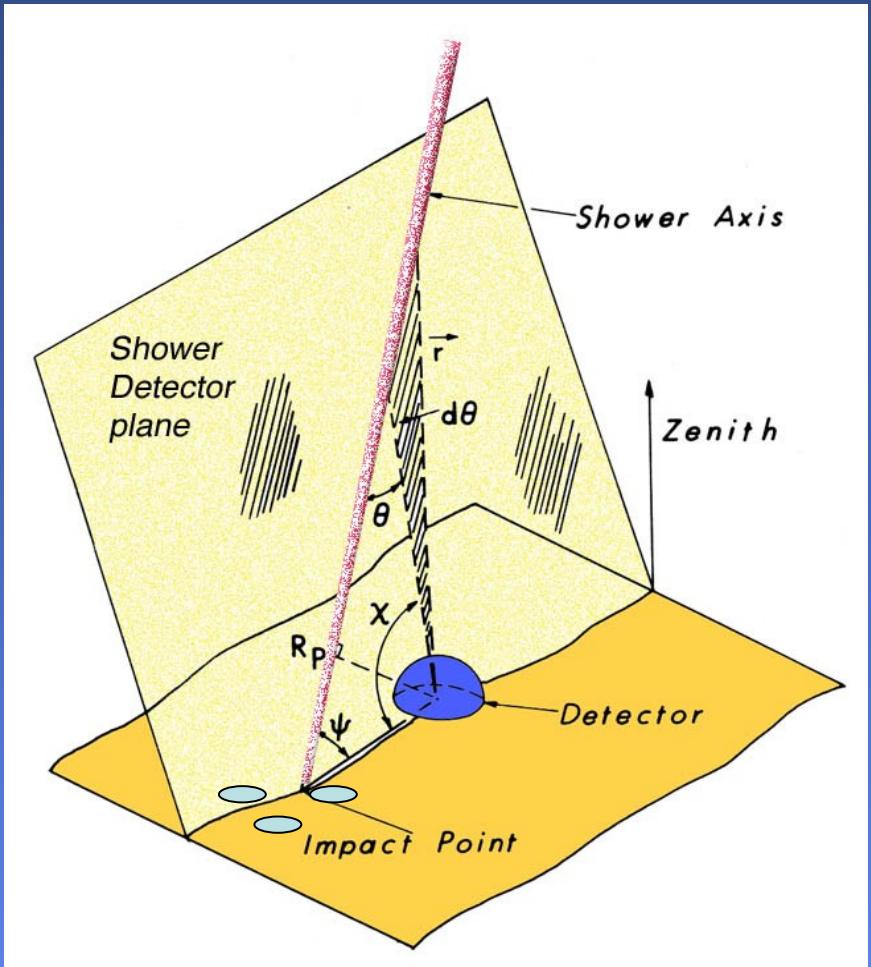


# Auger combines FD & SD



# Hybrid event detection




Shower-detector plane is well determined by FD

Times at angles,X, are key to finding $R_p$

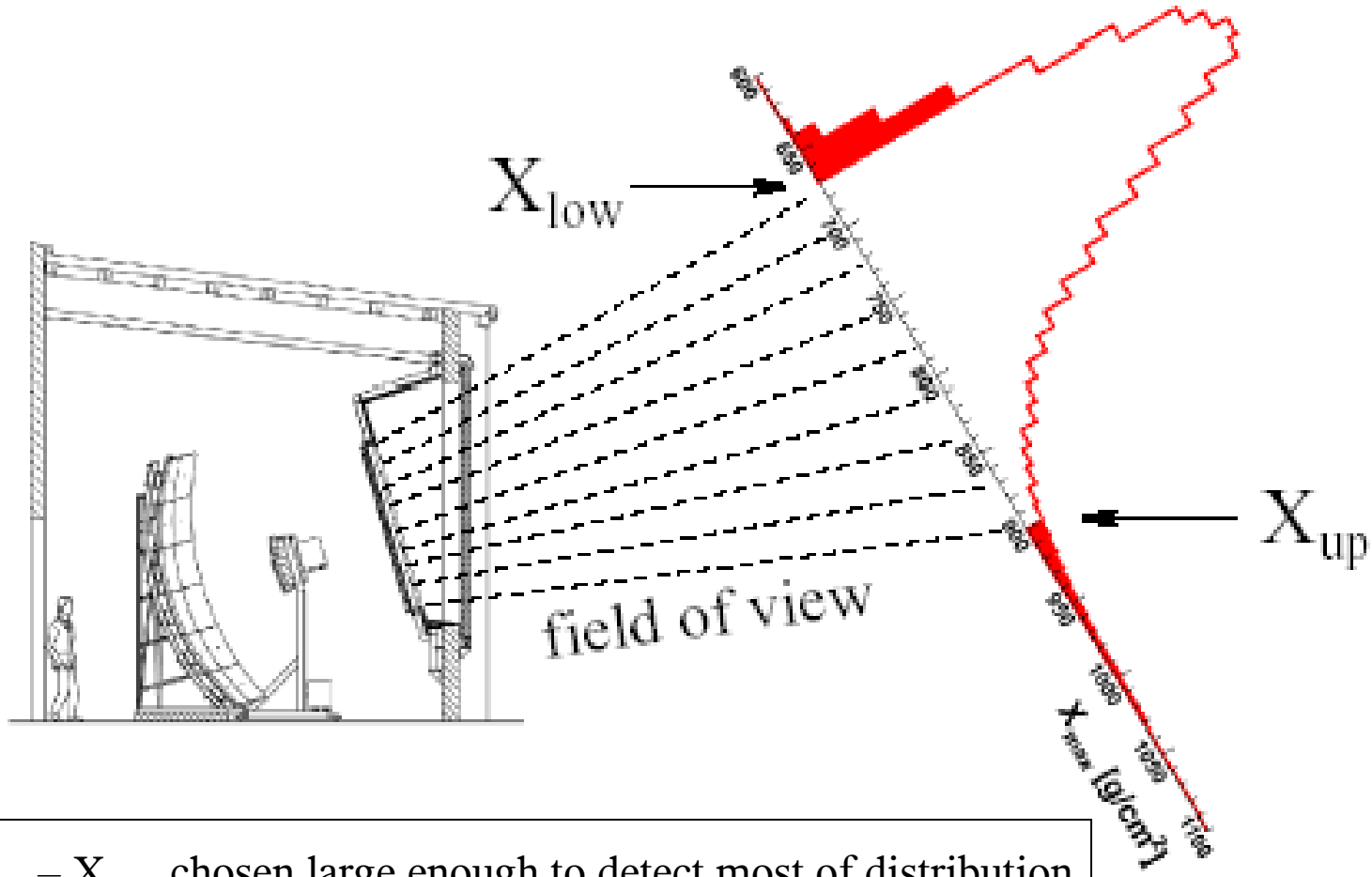
FD impact point measurement less precise

Precise shower geometry from degeneracy given
by SD timing, and core location

# Hybrid event detection

| | Hybrid | SD-only | FD-only |
|---|---|---|---|
| | | | mono<br>(stereo – low stat) |
| Angular Resolution | ~ 0.2° | ~ 1 - 2° | ~ 3 - 5° |
| Aperture | Flat with energy AND mass and model (M) free | | E, A and M dependent |
| Energy | A and M free | A and M dependent | A and M free |

# Detecting shower development




$X_{up} - X_{down}$ chosen large enough to detect most of distribution

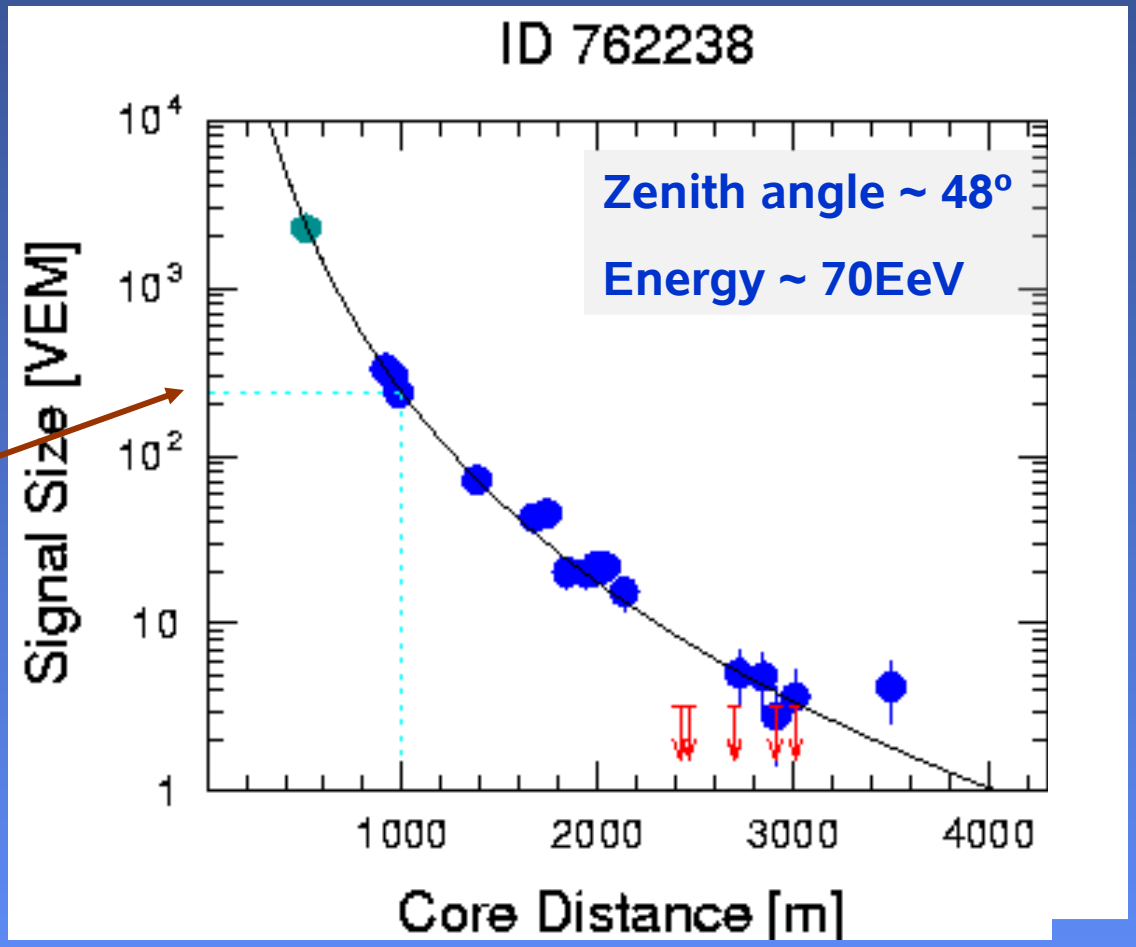
# Energy Determination and the spectrum

First step:

Statistics for the energy spectrum come from Surface Detector

Lateral density function LDF:

- Density of particles as fn of tank distance from shower axis int. w/ ground (core location)
- LDF at 1000 m is stable
  - MC studies
- Choose s(1000) as SD energy indicator, proportional to primary particle energy
- Adjust s(1000) to s(1000) at average angle of 38 deg



# Energy Determination and the Spectrum

Second step:

The SD energy scale is based on fluorescence detector absolute calibration via hybrid events

Establish relationship of FD energy to s(1000) using selection of clean hybrid events

Use this relationship for each SD event

Result: get full SD statistics without reliance on a specific interaction model or assumptions about the composition, as required for pure SD experiment

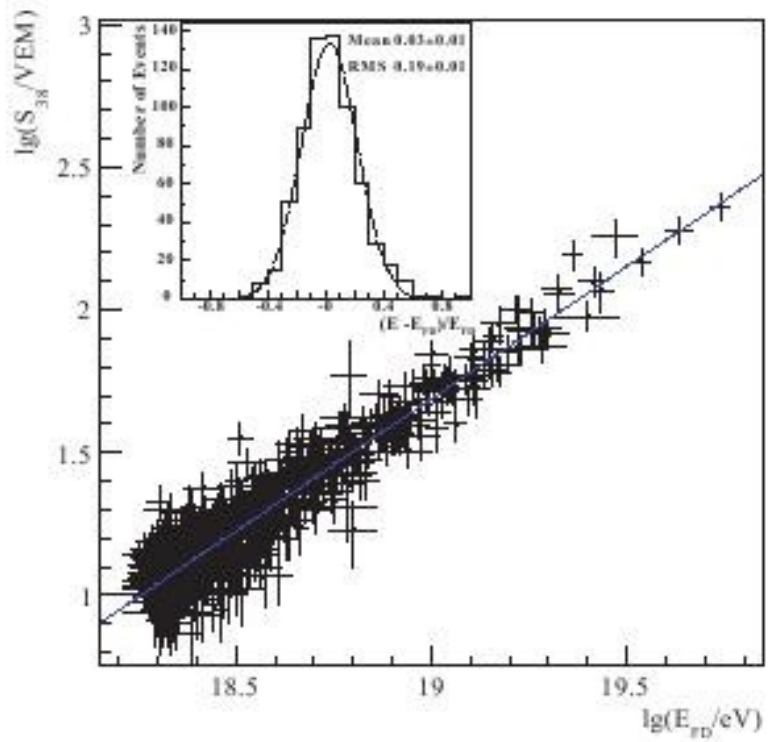



FIG. 1: Correlation between lg $S_{38^\circ}$ and lg $E_{FD}$ for the 661 hybrid events used in the fit. The full line is the best fit to the data. The fractional differences between the two energy estimators are inset.

# PAO Recent Results

## (After 1 year equivalent accumulated running time)

36 scientific and technical papers currently published or in prep

- Cosmic ray primary mass analysis
- Particle physics at ~300 TeV
- Galactic and extragalactic magnetic fields
- NIM articles on SD, FD…

Major scientific papers published, accepted or submitted:

Evidence for suppression of flux of cosmic rays above $4 \times 10^{19}$ eV *(submitted, PRL, April 08)*

Anisotropy studies around the galactic center at EeV energies *(Astroparticle Physics 27 2007)*

Correlation of highest-energy CRs with nearby extra-galactic objects *(Science 318 2007)*

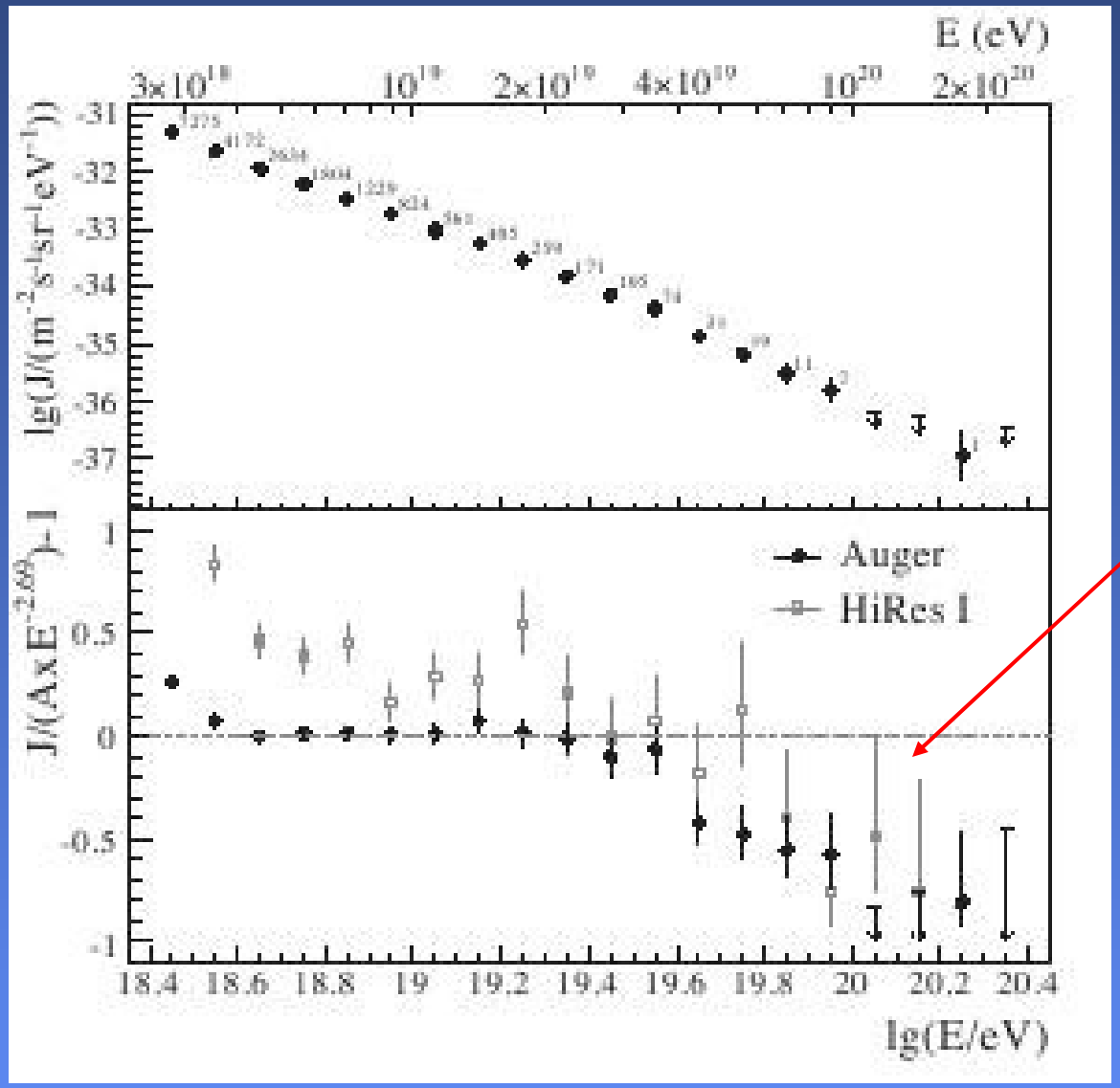
Correlation of highest energy CRs with positions of nearby AG*N* *(Astroparticle Physics 29, 2008)*

Upper limit on the photon fraction in CRs above $10^{19}$ eV *(Astroparticle Physics 27, 2007)*

Upper limit on CR photon flux above $10^{19}$ eV using the SD *(accepted Astroparticle Physics 08)*

Upper limit on the diffuse flux of UHE tau neutrinos *(accepted, PRL, 08)*

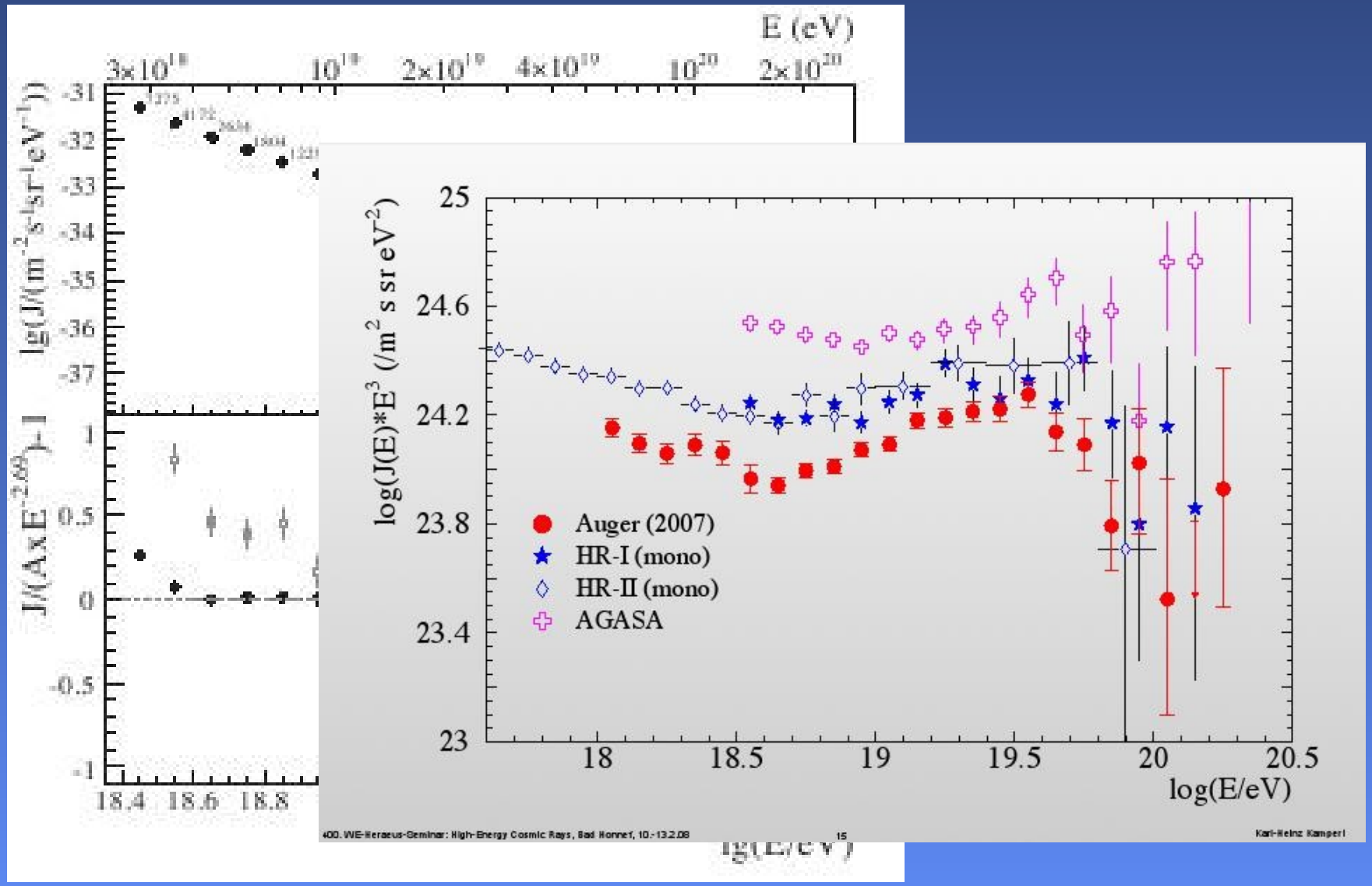
# Energy Spectrum comparison




Spectrum as published

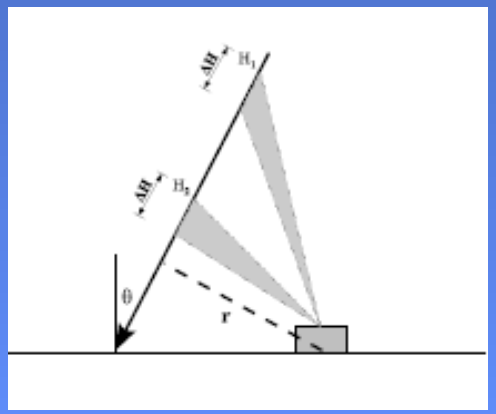
Evidence for GZK suppression

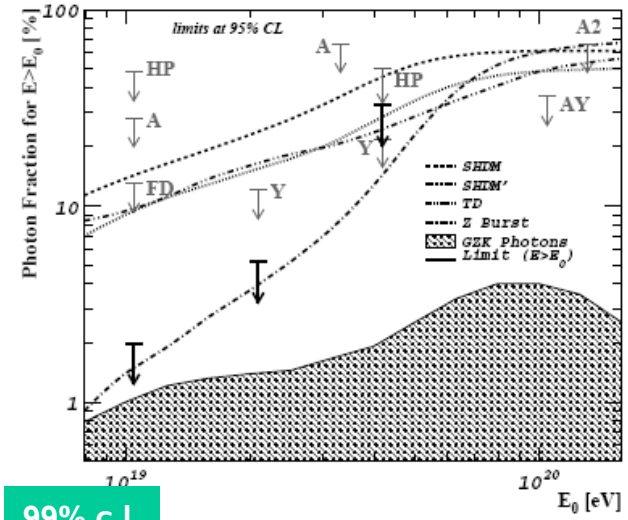
# Energy Spectrum comparison



# Primary photon fraction and flux

- "Top down" models predict large fraction of primaries are photons.
- Photon showers develop deep in atm (EM, not hadronic)
- Identify photon primaries using SD timing data by:
  - Slow signal rise time at r=1000m
  - Large curvature of shower front
    - Large H → more planar
- We see NONE
- Best limit on photon fraction of CRs
- First direct bounds on flux of UHECRs
- Most top-down models excluded




99% c.l.

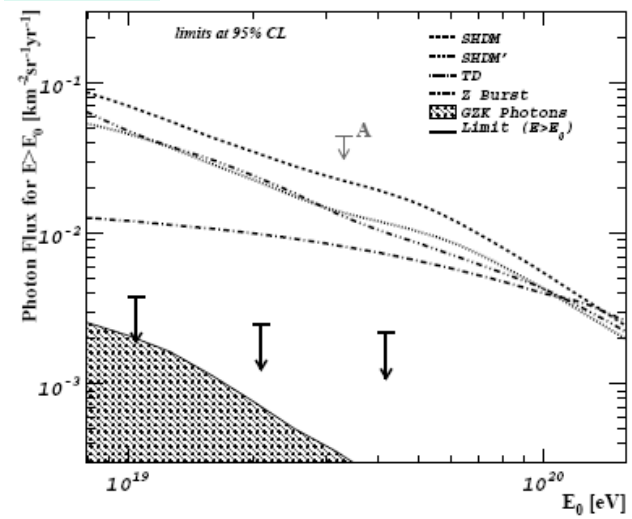
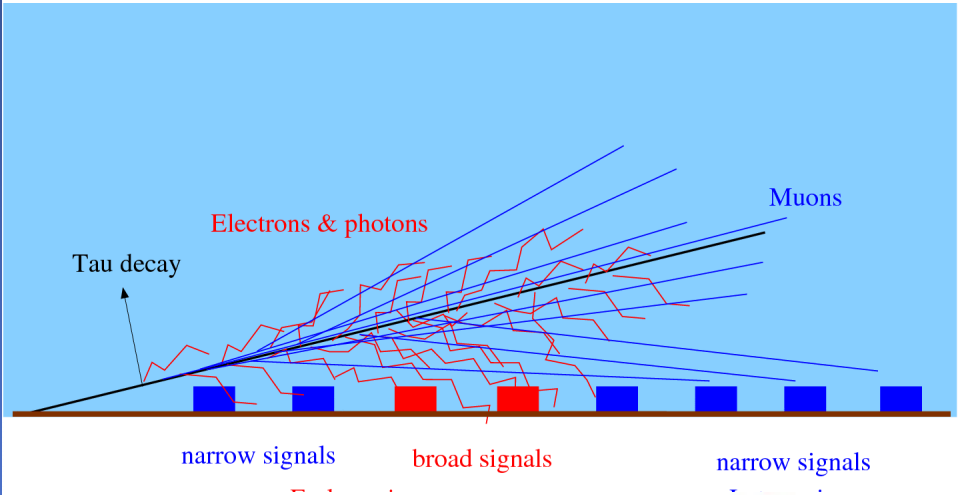
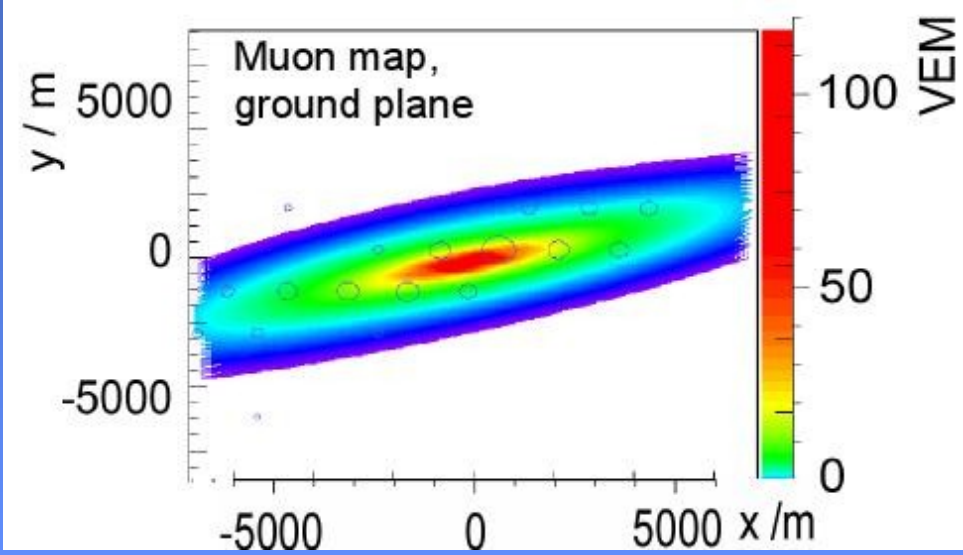



Fig. 8. The upper limits on the integral flux of photons derived in this work (black arrows) along with predictions from top-down models (SHDM, TD and ZB from Ref. [21], SHDM' from Ref. [12]) and with predictions of the GZK photon flux [21]. A flux limit derived indirectly by AGASA ("A") is shown for comparison [29].

# Primary neutrino flux

- "Top down" models predict large fraction of primaries are neutrinos.
- Tau neuts suppressed at production, but oscillation 1:1:1 ratio at cosmological distances
- Earth-skimming tau neutrinos interact in earth to produce taus
- Tau decay produces 'young' horizontal shower just above array
- Identify event by:
  - Signal – mostly electrons and photons, few muons
  - footprint on array - length/width
  - speed of propagation across array ~ c



# Primary neutrino flux

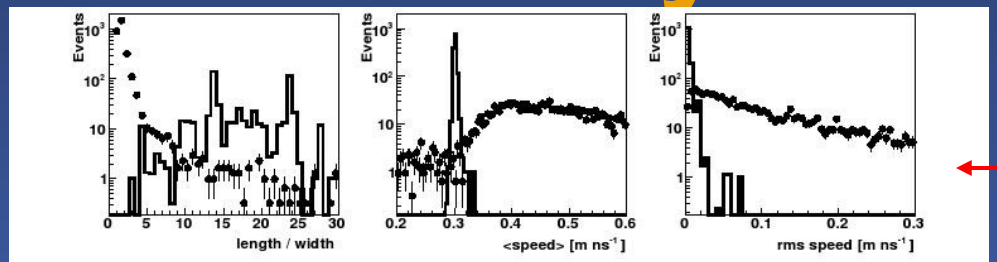



FIG. 2: Distribution of discriminating variables for showers initiated by $\tau$s decaying in the atmosphere, generated by $\nu_\tau$s with energies sampled from an $E_\nu^{-2}$ flux (histogram), and for real events passing the "young shower" selection (points). Left: length/width ratio of the footprint of the shower on the ground; middle: average speed between pairs of stations; right: r.m.s. scatter of the speeds. See text for details.

We see NONE

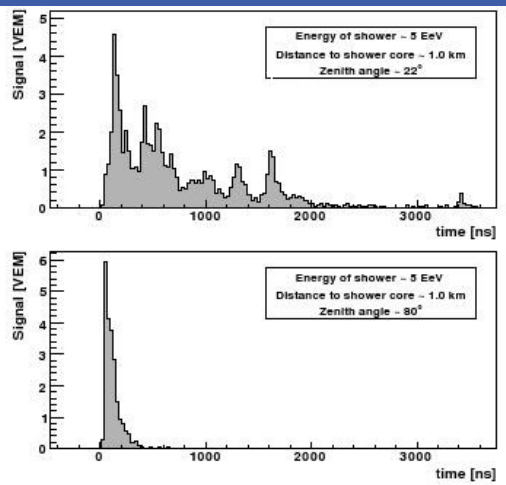



FIG. 1: FADC traces of stations at 1 km from the shower core for two real showers of 5 EeV. Top panel: electromagnetic component ($\theta \sim 22$ °); bottom: muonic signal ($\theta \sim 80$ °).

90% c.l.

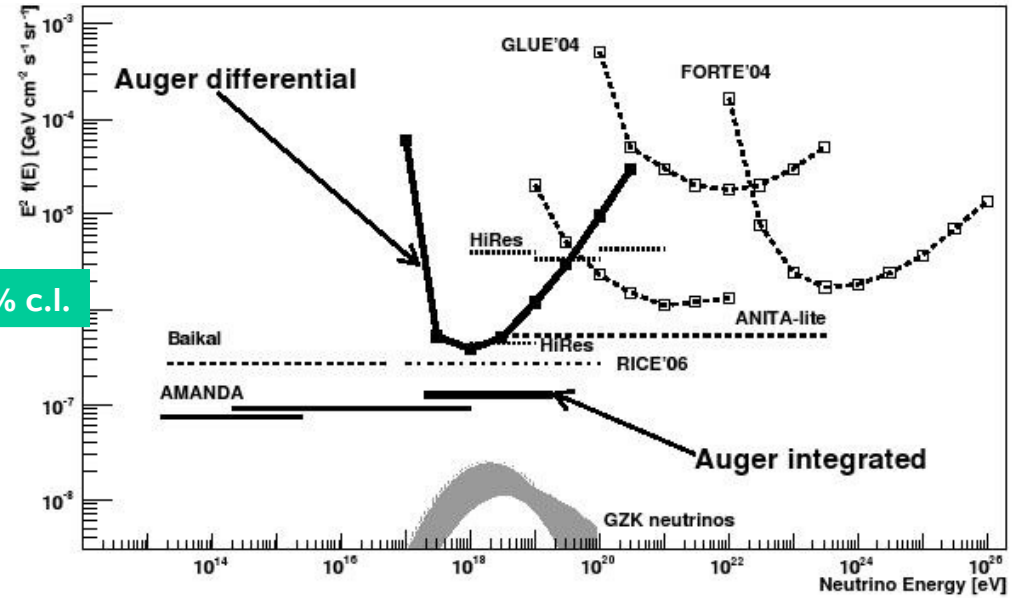



FIG. 3: Limits at 90% C.L. for a diffuse flux of $\nu_\tau$ from the Pierre Auger Observatory. Limits from other experiments [36–43] are converted to a single flavour assuming a 1 : 1 : 1 ratio of the 3 neutrino flavours and scaled to 90% C.L. where needed. Two different formats are used: differential (squares) and integrated (constant lines). The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [10, 11], although predictions almost 1 order of magnitude lower and higher exist.

# Anisotropy search

Know:

- Photon, neutrino limits:
  - top-down models unlikely
  - Then increased probability of point sources
- At highest energies, trajectories should be straight
- GZK effect probably exists
  - then point sources must be near

➔Search for correlations of pointing directions of highest energy events with nearby sources

AGNs are possible source – remember B*R plot

- Use 12th Edition Veron-Cetty Catalog of AGN and quasars
- Scan distances within GZK horizon (around 75 Mpc; z=0.018)
- Scan correlation angles beginning at instrumental resolution
- Start with highest energy events

# Anisotropy search

Initial scan found statistical correlation:

- 12 of 15 highest energy events correlated with directions to AGNs
  Chance probability = 0.21, expect 3.2 correlations by chance
  - Used SD data from 1 Jan 2004 – 27 May 2006
  - Considered all events E > 40 EeV
  - Zenith angles < 60 degrees (best event reconstruction)
  - Strict quality cuts
    - *5 nearest-neighbor tanks in trigger*
    - *Core contained inside active part of tank array…*

Know:

- Low statistics data sets often contain 3-sigma fluctuations, and scanning in multiple variables is sure to find them.
- Difficult to assess statistical scanning penalties

Establish prescription:

- Establish energy, angular, distance criteria
- Include statistical precision for success (99%)
- Use only post-prescription data – after 27 May 06
- Wait until accumulated events satisfy prescription

Astroparticle Phys, **29**, 188 (2008)

# Anisotropy search

25 May 07: 6 of 8 events correlated

➔prescription satisfied

1 Jan 2004 to 31 Aug 2007 : 8 of 13

P = 1.7x10**-3 (2.7 expected by chance)

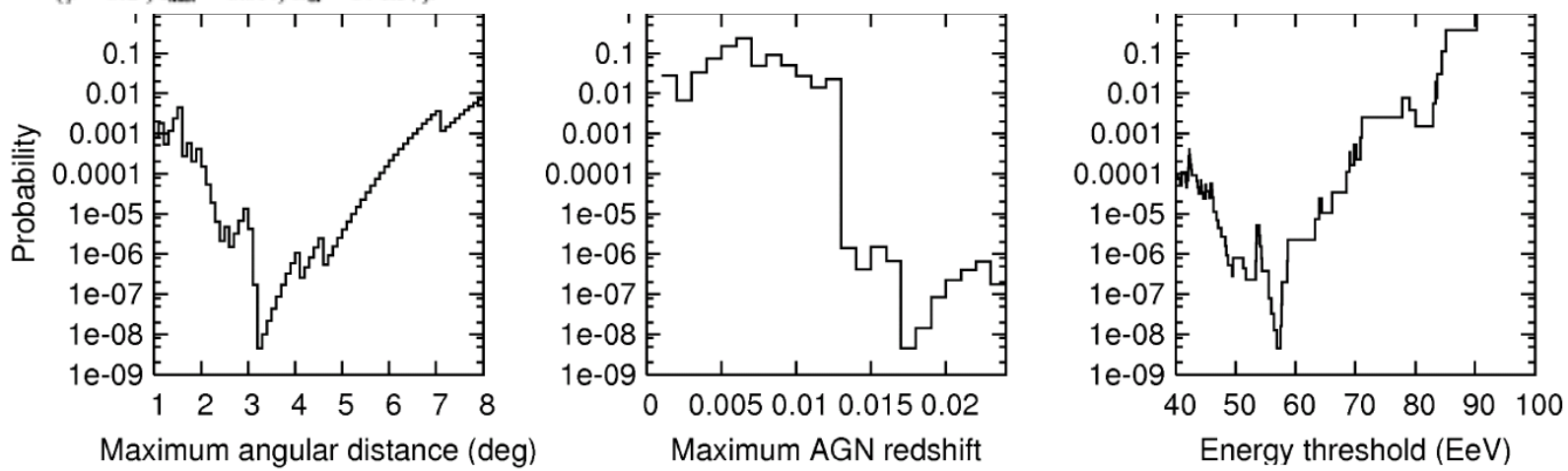
1 Jan 2004 to 31 Aug 2007: Total of 20 of 27 w/ 292 AGN in FOV

(Array grew from 154 to 1388 tanks in this time)

The probability $P$ that $k$ or more out of a total of $N$ events from an isotropic flux are correlated by chance with the selected objects at the chosen angular scale is given by the cumulative binomial distribution

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}. \quad (2)$$

Fig. 3. Probability for the null hypothesis (isotropic distribution) vs. maximum angular distance $\psi$ (left), maximum AGN redshift $z_{max}$ (centre), and threshold cosmic-ray energy $E_{th}$ (right). In each case the other two parameters are held fixed at the values that lead to the absolute minimum probability ($\psi = 3.2°$, $z_{max} = 0.017$, $E_{th} = 57$ EeV).




**$\psi < 3.1^0$** **Z<0.018 (D<75 Mpc)** **Energy>56 EeV**

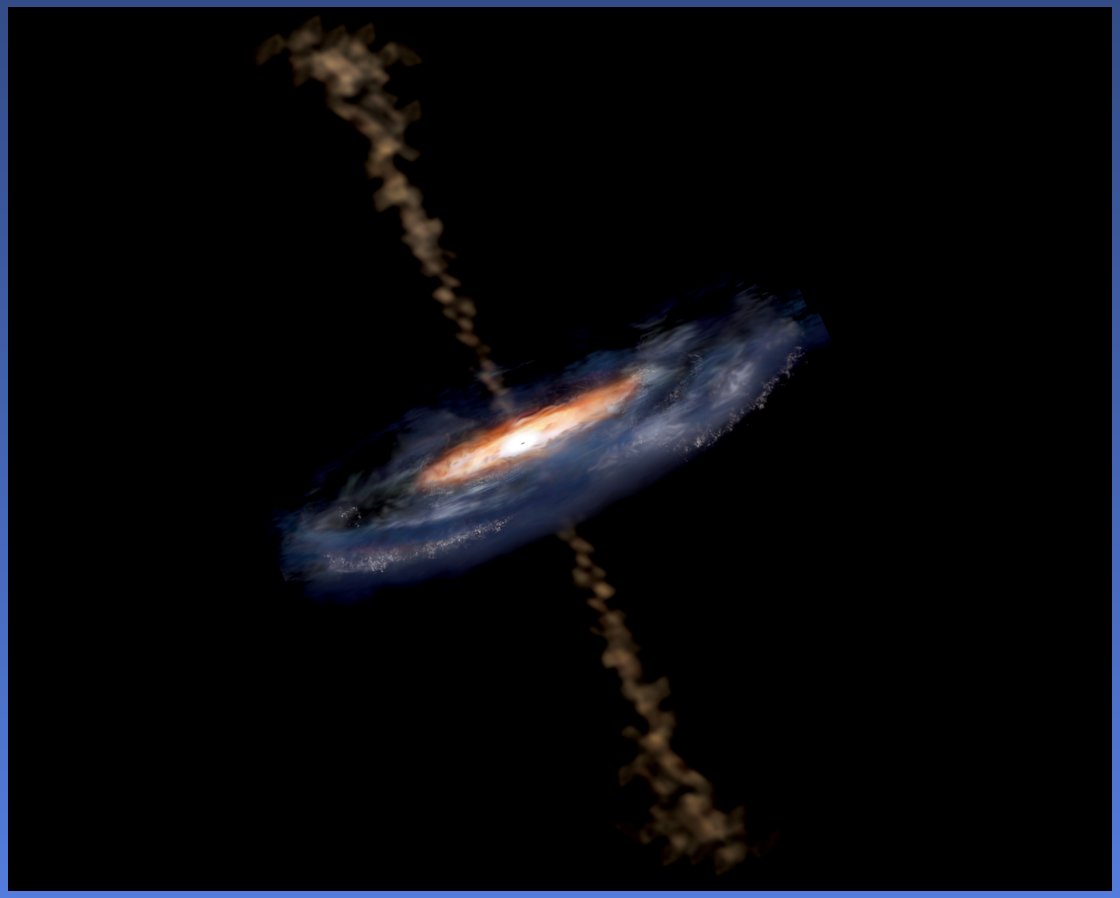
# "Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

**Comments on this Pierre Auger Publication:**

- **Nature:**
  A top 10 story of 2007
- **Science:**
  A top 3 discovery in 2007
- **American Physical Society:**
  A top 2 discovery in 2007

Science, **318**, p.938, 2007; also Astroparticle Physics 29 (2008) 188-204

# Active Galactic Nuclei



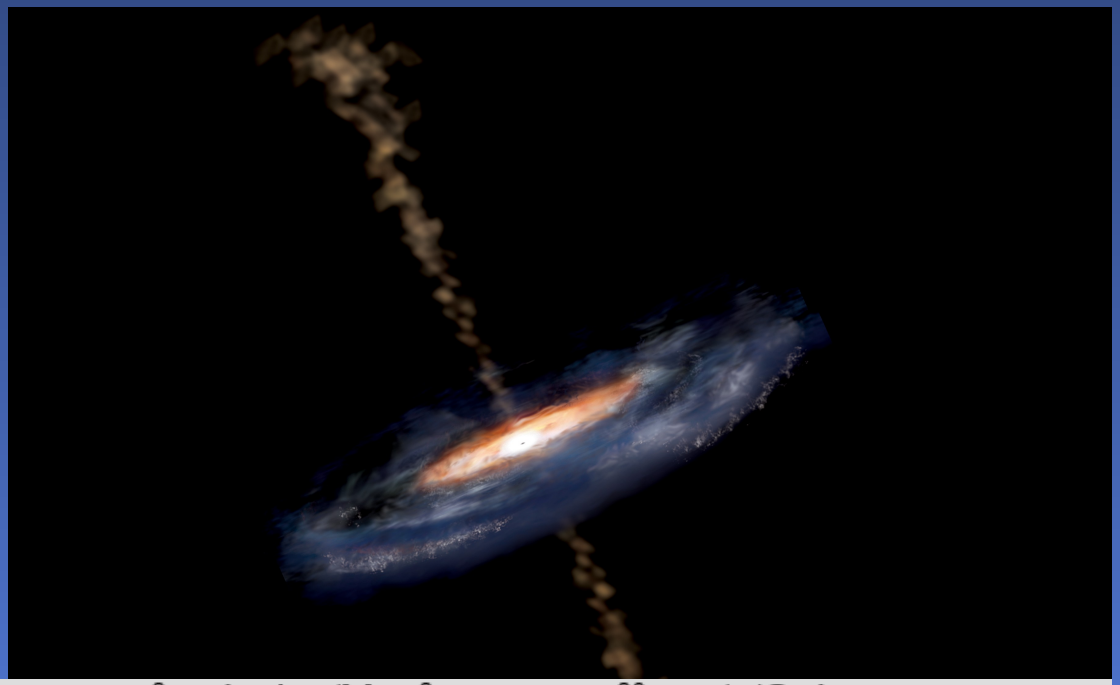
- Active Galactic Nuclei or AGNs
- Powered by acretion into massive black hole at center of galaxy
- Compact and highly luminous:

  $10^{44}$ ergs/s

  Jets are typical
- Low luminosity AGNs also exist

- **Emission in X-Ray, Gamma Ray, visible, etc**
- **Jets associated with acretion disk rotation axis**
- **Depending on jet orientation and spectra could be called: Blazar, Quasar, Seyfert, etc**

# Active Galactic Nuclei



| | |
|---|---|
| – $3 \times 10^{-3}$ galaxies/Mpc$^3$ | $5 \times 10^{39}$ erg/s/Galaxy |
| – $3 \times 10^{-6}$ clusters/Mpc$^3$ | $4 \times 10^{42}$ erg/s/Galaxy Cluster |
| – $10^{-7}$ AGN/Mpc$^3$ | $10^{44}$ erg/s/AGN |
| – ~1000 GRB/yr | $3 \times 10^{52}$ erg/GRB |

- Active Galactic Nuclei or AGNs
- Powered by acretion into massive black hole at center of galaxy
- Compact and highly luminous:

  $10^{44}$ ergs/s

  Jets are typical
- Low luminosity AGNs also exist

- **Emission in X-Ray, Gamma Ray, visible, etc**
- **Jets associated with acretion disk rotation axis**
- **Depending on jet orientation and spectra could be called: Blazar, Quasar, Seyfert, etc**

# Correlation Map

**Correlation confirmed with > 99.9% confidence limit**

**It does NOT mean AGNs are the actual sources!**

**Mass clumps;**
**AGNs could just be tracers for…?**

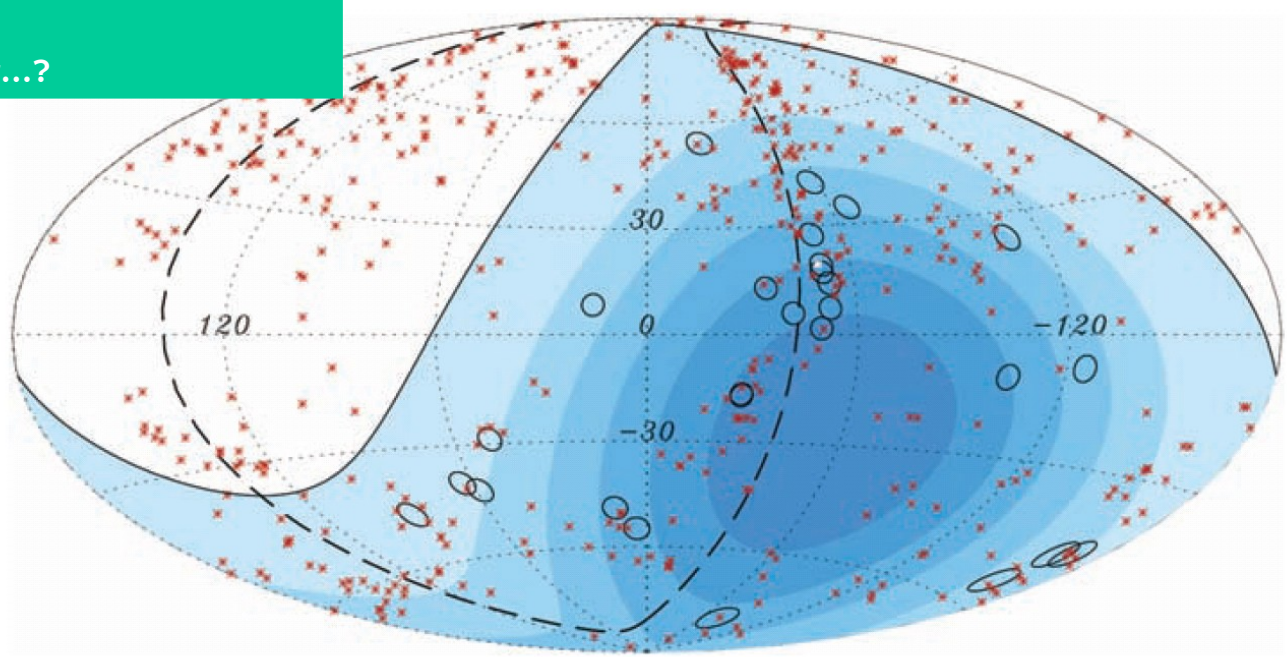
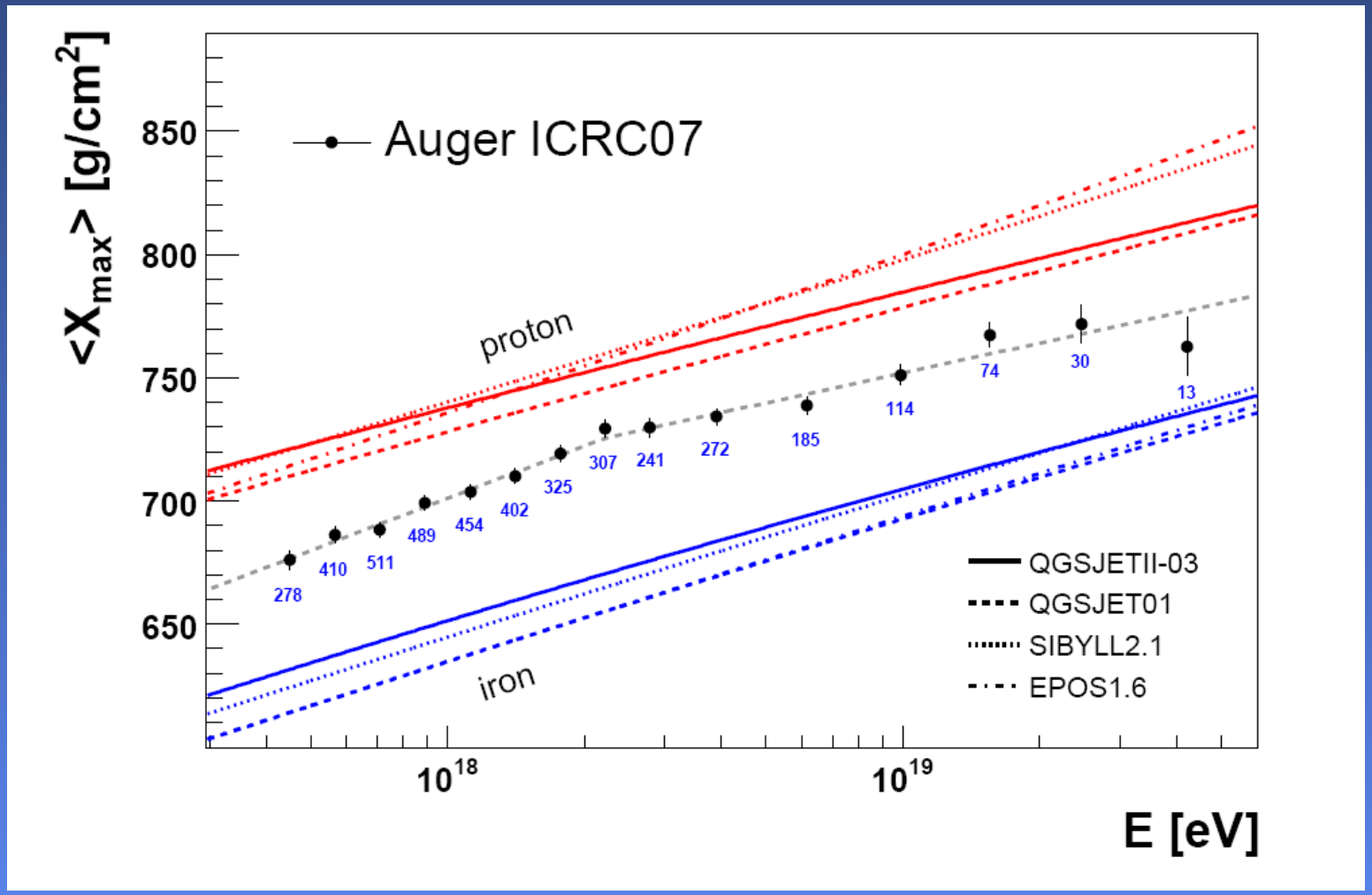



**Fig. 2.** Aitoff projection of the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018$ ($D < 75$ Mpc) from the 12th edition of the catalog of quasars and active nuclei (*12*) are indicated by red asterisks. The solid line represents the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is the supergalactic plane. Centaurus A, one of our closest AGN, is marked in white.

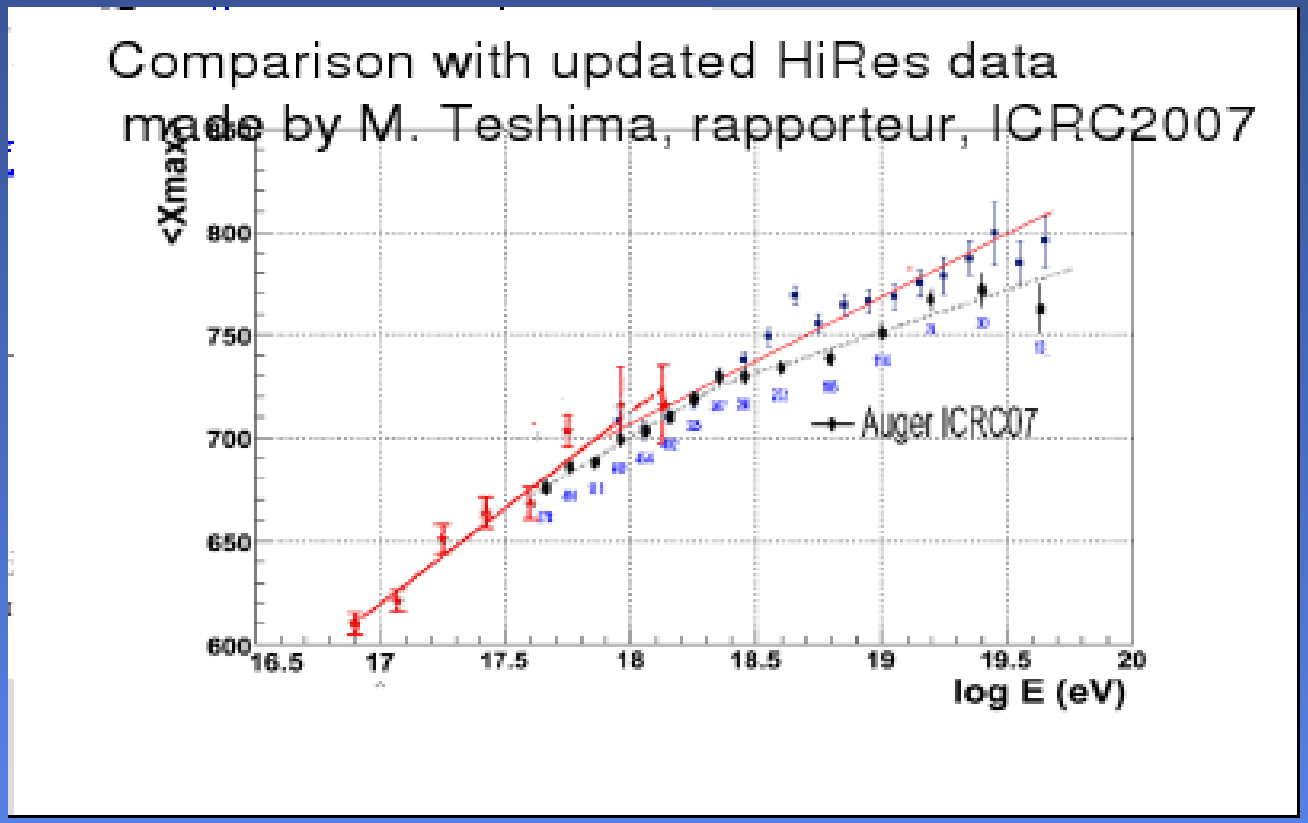
Proceedings 30th ICRC, 594, 2007

# Elongation Rate (Primary Mass)




**Shower penetration depth depends of primary mass**

# Unresolved questions



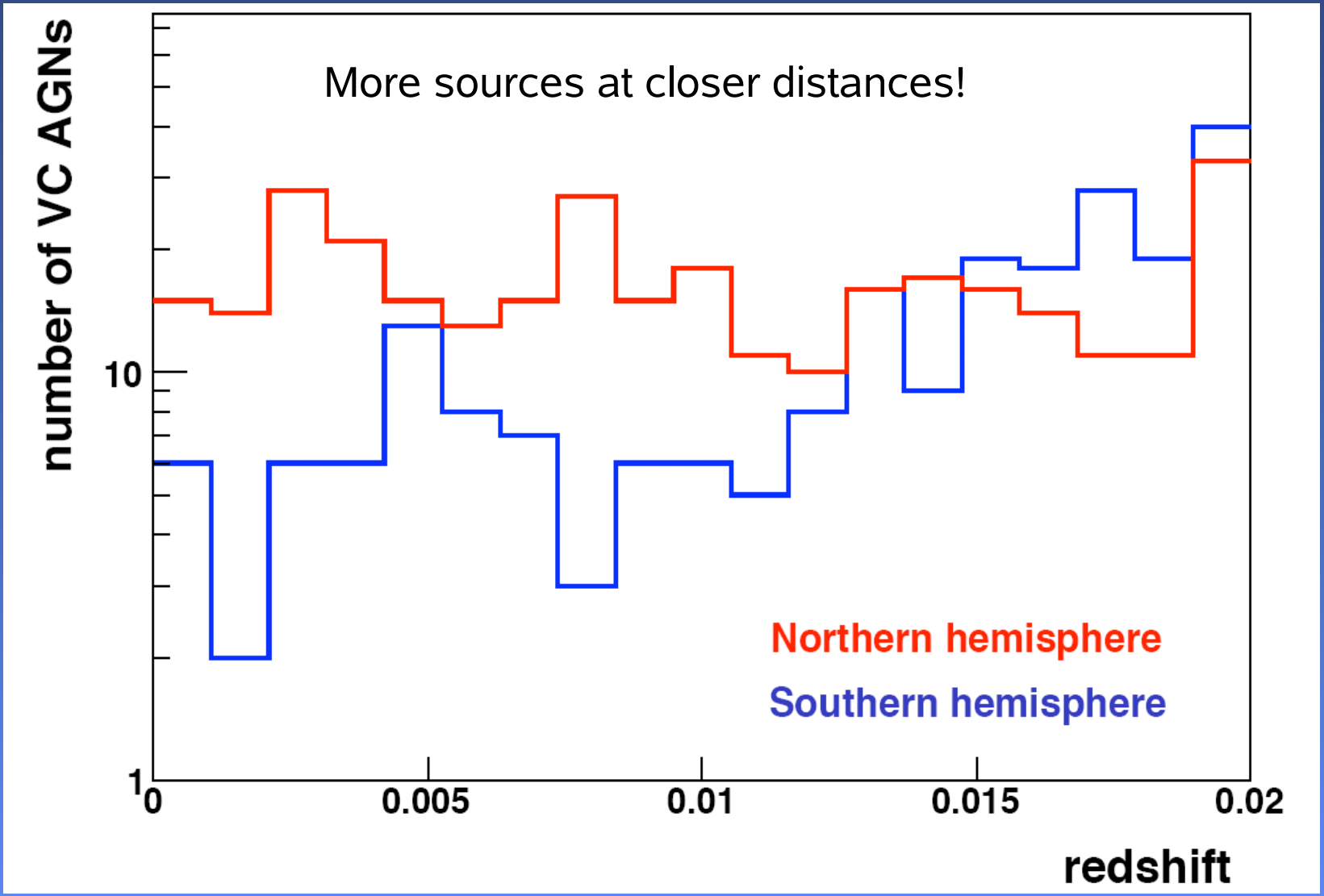
# Unresolved questions

- Are highest energy CRs protons or heavier?
  - if heavy, how do they point back through B fields?
  - if not, what's up with X_max?  (And MC hadronic evnt gen?)
- AGN correlation seems real
  - still doesn't explain acceleration mechanism
    - *B*R seems too large near AGN*
- P-air cross section (p,p) at highest energies
- Excess muon generation in MC

# Unresolved questions 2

- HiRes experiment does not confirm AGN correlation in northern hemisphere
  - is it real?
  - more AGNs in northern sky, but dominated by low luminosity AGNs (Ho et al)
  - experiments differ
    - *in energy calibration / scale / exposure*
    - *Hires is fluorescence only – no ground array*
- HiRes experiment also does not confirm
  - Energy spectrum details
  - Heavy mass ID at highest energies

# Auger North


More sources at closer distances!
number of VC AGNs
10
1
0
0.005
0.01
0.015
0.02
redshift
Northern hemisphere
Southern hemisphere

# The Auger North site: southeast corner of Colorado, near Lamar

- Goal: statistical study of UHECR sources
  - Highest energies, as in AGN correlation: ~56 EeV and up
  - will propose **10x area of Auger South!**
- R&D in progress
  - changes in communications
  - tank design (thermal insulation)
- Test array running end 2009?
  (10 tanks, 20 comms stations)
- Full proposal in prep
  (submit early 2009)

- Site:
  - Large flat area
  - Good atmospheric clarity
  - Correct Altitude & Latitude
  - Infrastructure

# Auger North

# The Future

- Complete Auger South this year
- Use rapidly expanding data set to enable
  - Improved statistics in photon, neutrino limits
  - High statistical study of the spectrum in the GZK region
  - Refined anisotropy studies and point source searches
  - Mass composition studies at ~300 TeV (Particle physics)

- Begin Auger North in Colorado
  - R&D funding this year
  - 20-tank R&D array running in 18 months?
  - Full proposal in 09

# Backup slides

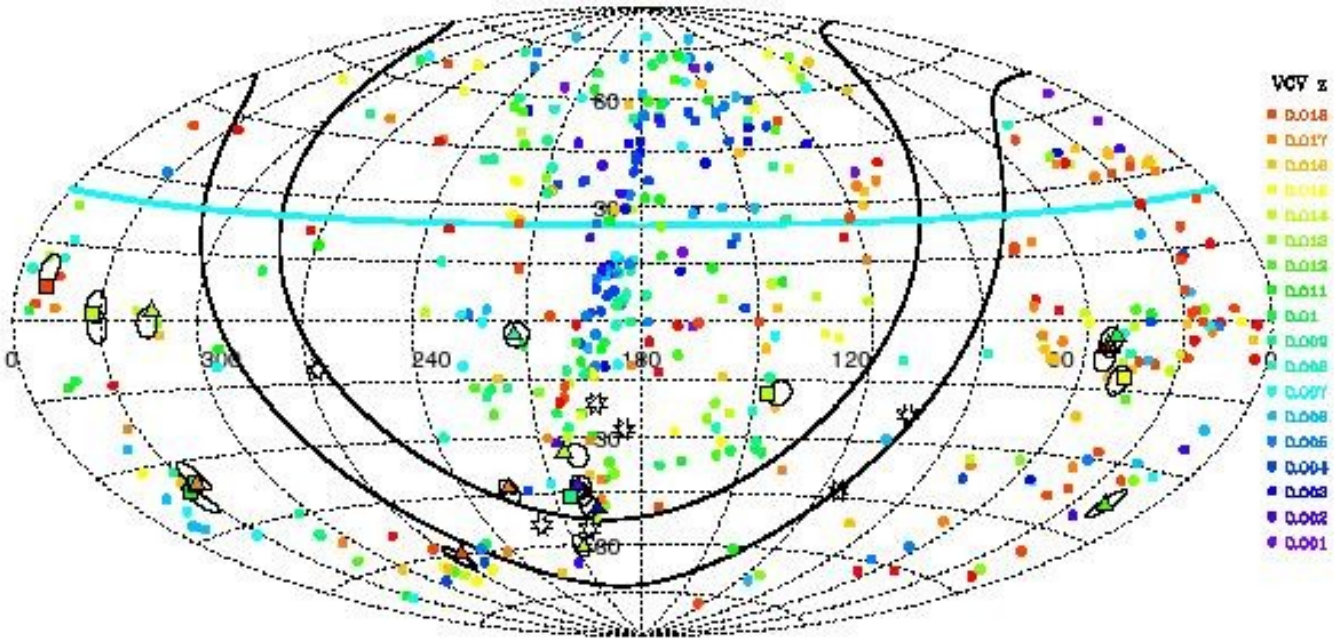
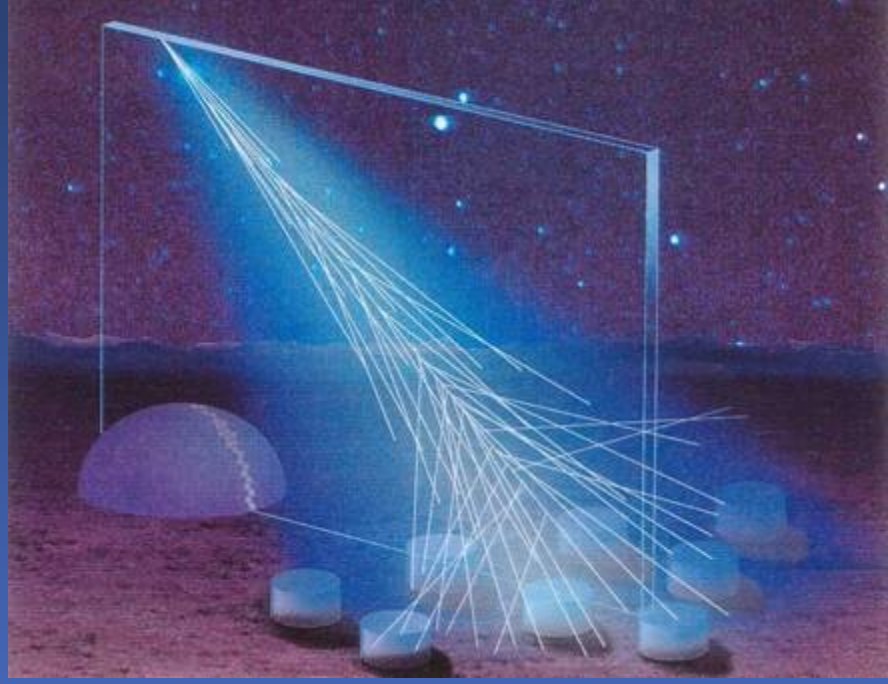


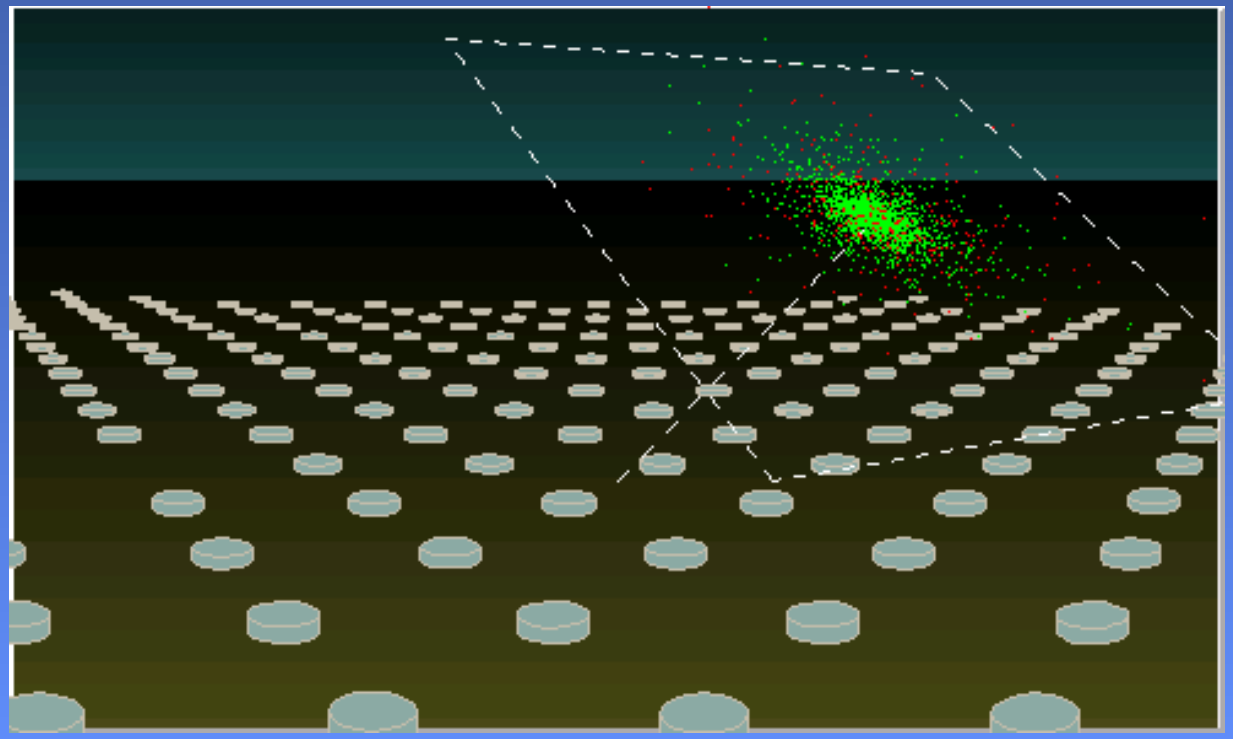

FIG. 2.— Sky plot in equatorial coordinates showing Auger's 27 highest energy cosmic rays and VCV galaxies. The UHECRs correlating with an AGN are indicated with open 3.2° circles and those that do not are indicated with an 8-point star. The 14 true AGN from the correlated VCV galaxies are shown as triangles. The 7 other correlating VCV galaxies are shown as squares. The rest of the VCV galaxies with $z \leq 0.018$ are shown as points color-coded by redshift. The Galactic plane band ($|b| = 10°$) where the VCV catalog is most incomplete is indicated by the solid black lines. Auger's exposure cutoff at $\delta < 25°$ is indicated by the cyan line.

# Extracting information from an EAS

- Tank timing
  - Arrival direction
- Number of particles in tanks
  - Total Energy
- Telescope image (digital camera like)
  - Arrival direction
- Light detected
  - Total Energy

**Redundant measurement for cross-checks**





Animation of an event measured in Argentina

# Detector performance



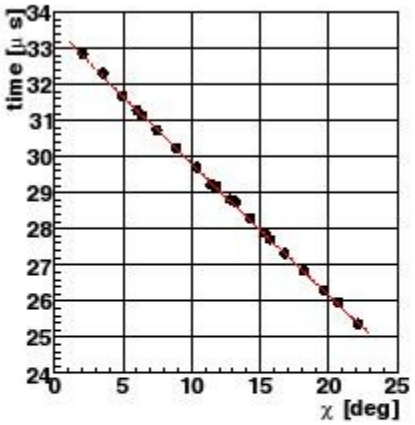



Figure 3. Functional form that correlates the time of arrival of the light at each pixel with the angle between the pointing direction of that particular pixel and the horizontal line within the shower-detector plane.

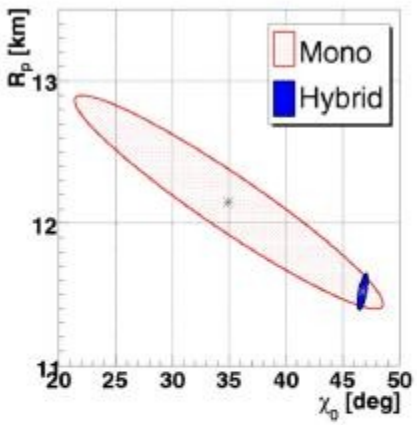



Figure 4. Solutions (and 1σ regions) for the axis fit shown in Fig. 3. The large uncertainty (and strong correlation) of the monocular reconstruction is broken using the timing information from the surface detectors (hybrid). The stars mark the solutions that minimize the $\chi^2$ for the axis reconstruction. (Following the notation of this paper, $\chi_0 = 180° - \psi$.)



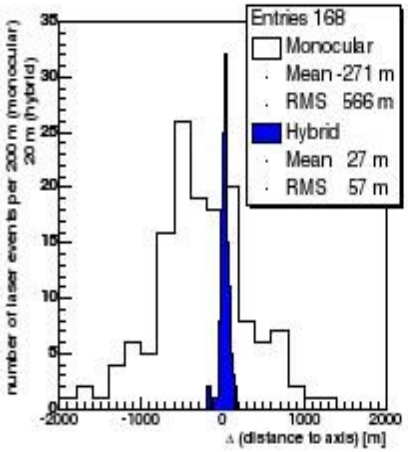



Figure 5. Difference between the reconstructed and true distance from the eye to the vertical laser beam using the monocular and hybrid techniques. The location of the laser is known to 5 m.

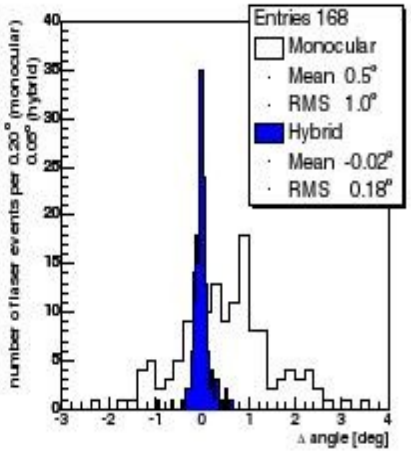



Figure 6. Angular difference between reconstructed and true direction of the laser beam using the monocular and hybrid techniques. The laser beam is vertical within 0.01°.

# Detector performance

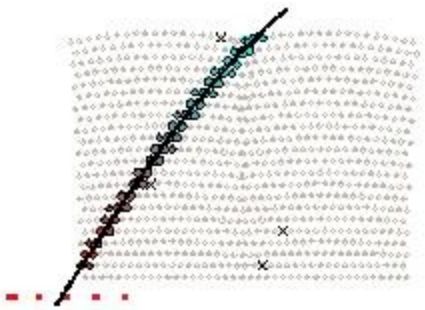


Figure 1. Light track of a hybrid event as seen by two adjacent fluorescence telescopes. The different colors indicate the timing sequence of the triggered pixels. The full line is the fitted shower-detector plane. The red squares represent the surface detectors that also triggered in this event.

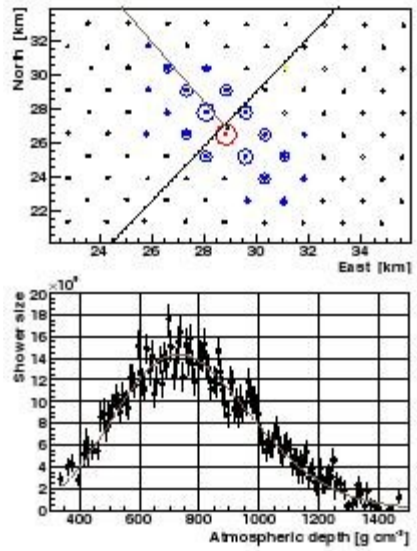



Figure 8. An air-shower event detected both water tanks (*top:* array view), and in a fluorescence detector (*bottom:* longitudinal profile).

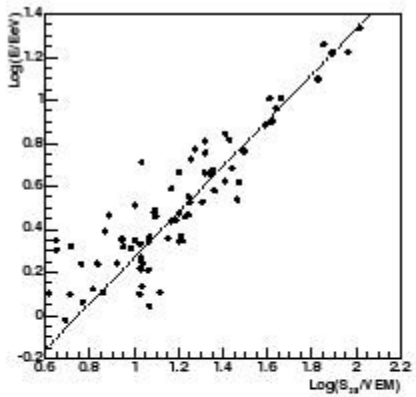



Figure 10. Shower energy (measured from the longitudinal profile) as a function of the ground parameter $S_{38}$. Each point is a hybrid event recorded when there were contemporaneous aerosol measurements, whose longitudinal profile included shower maximum in a measured range of at least 350 g cm$^{-2}$, and in which there was less than 10% Cherenkov contamination. The fitted line is $\log(E) = -0.79 + 1.06\ \log(S_{38})$.

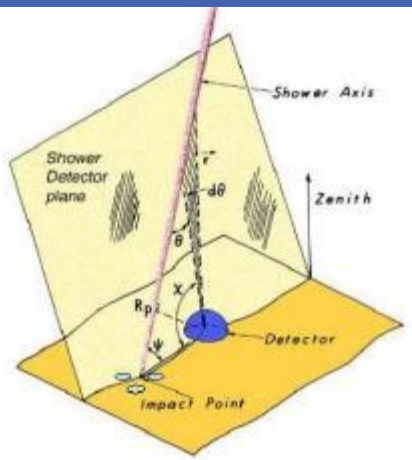
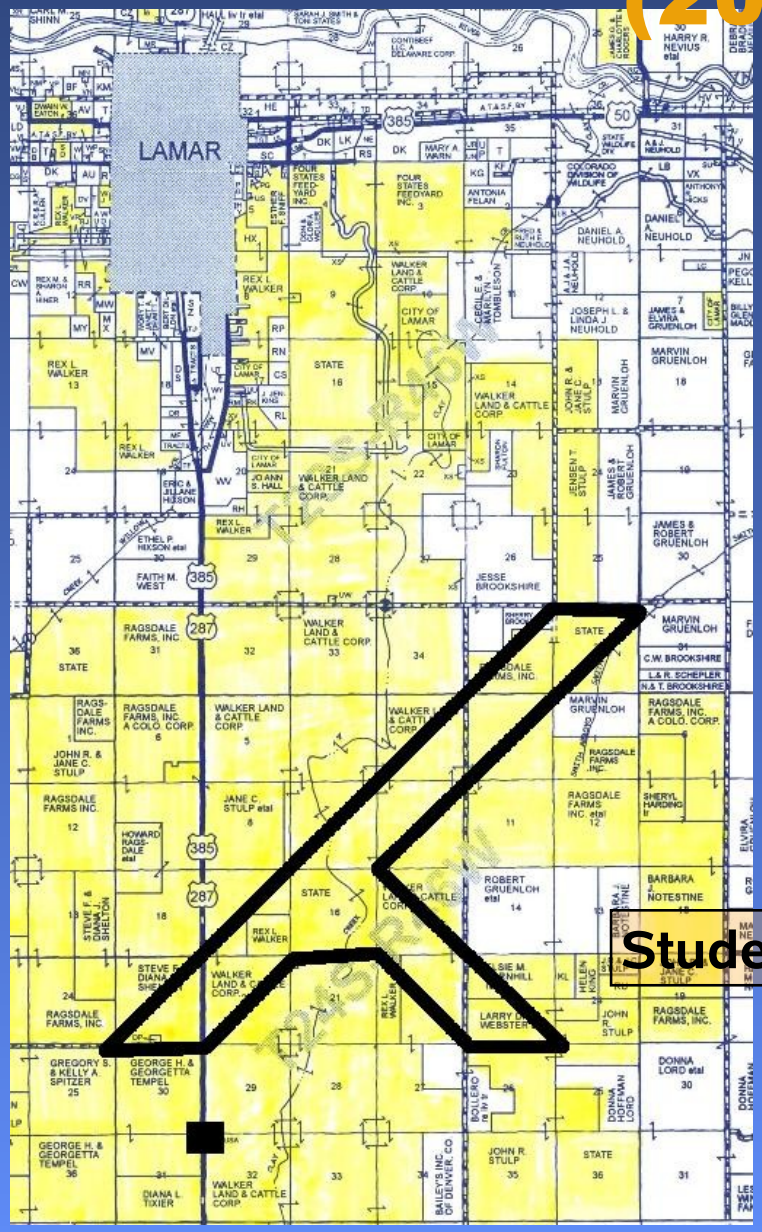



Figure 2. Illustration of the geometrical shower reconstruction from the observables of the fluorescence detector.

# Research and Development Array (2008-09)




Assemble and commission 20 tanks :

- Test communication scheme
- Test electronics
- Decision low/high gain channels
- Mechanical test of components
- Tank deployment procedure
- Procurement of GPS (timing)
- Procurement of water
- Tank design & Insulation
- Power system (solar panels)
- Integration of systems

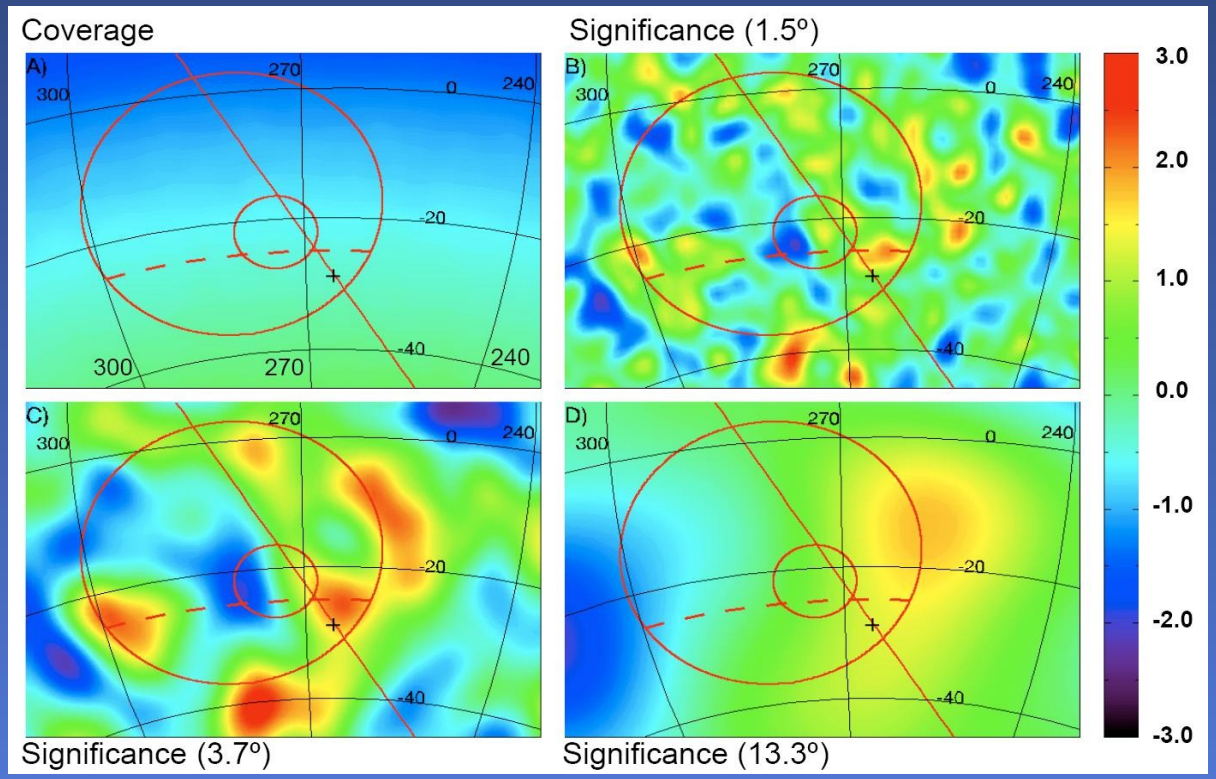
**Students**

- New set of twin-tanks
  - Trigger studies
  - Signal accuracy studies
  - Timing studies

# Galactic Center & Anisotropies

AGASA claim*
+4.5 σ
(large circle)

SUGAR claim**
+2.9 σ
(small circle)



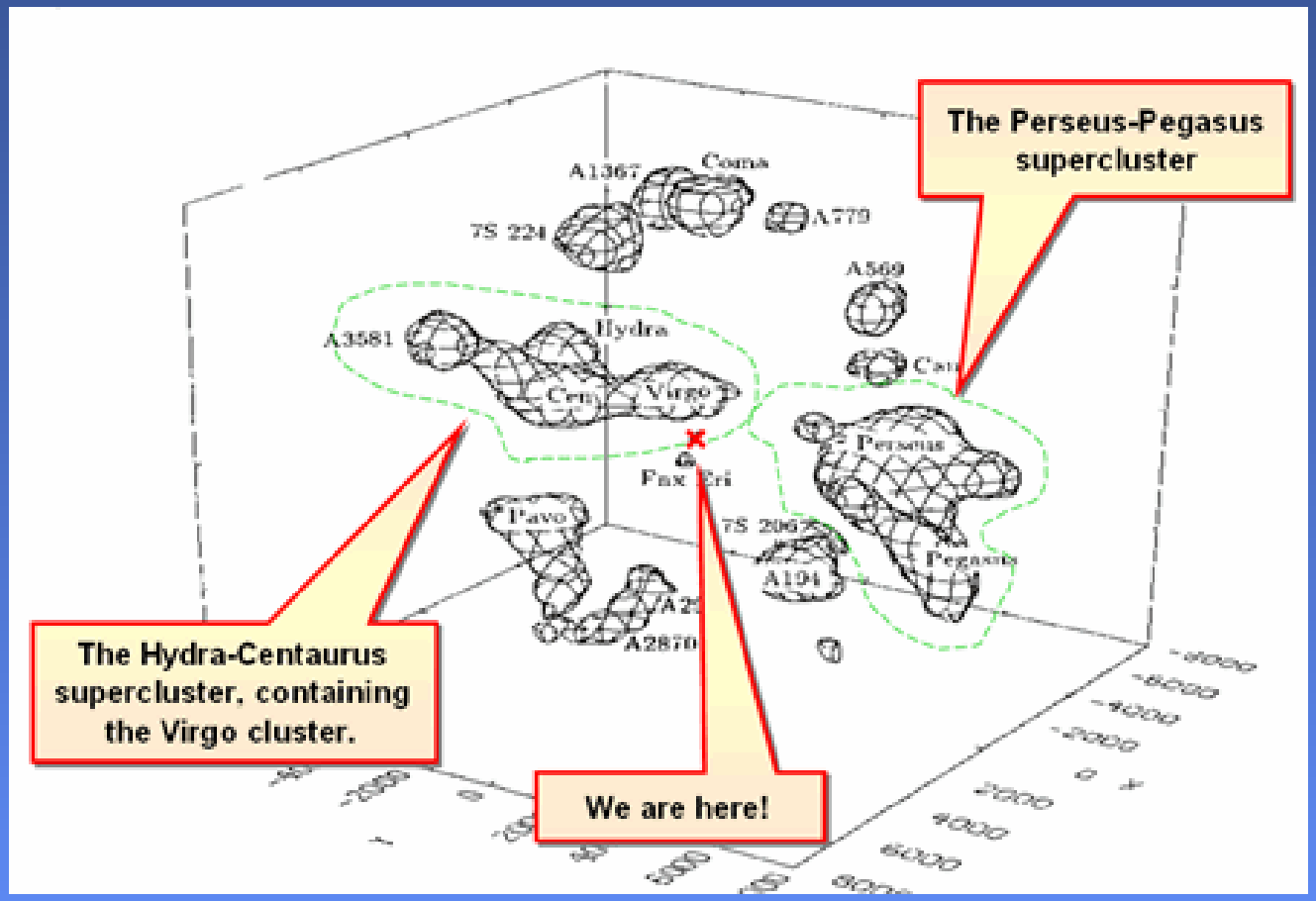

- Auger sees no excess from the Galactic Center (Did it turn it off?)
  - -0.15 σ for AGASA claim
  - -0.5 σ for SUGAR claim

* AGASA Coll, Astrop. Phys 10 (1999)

** SUGAR Coll, Astrop Phys 15 (2001)

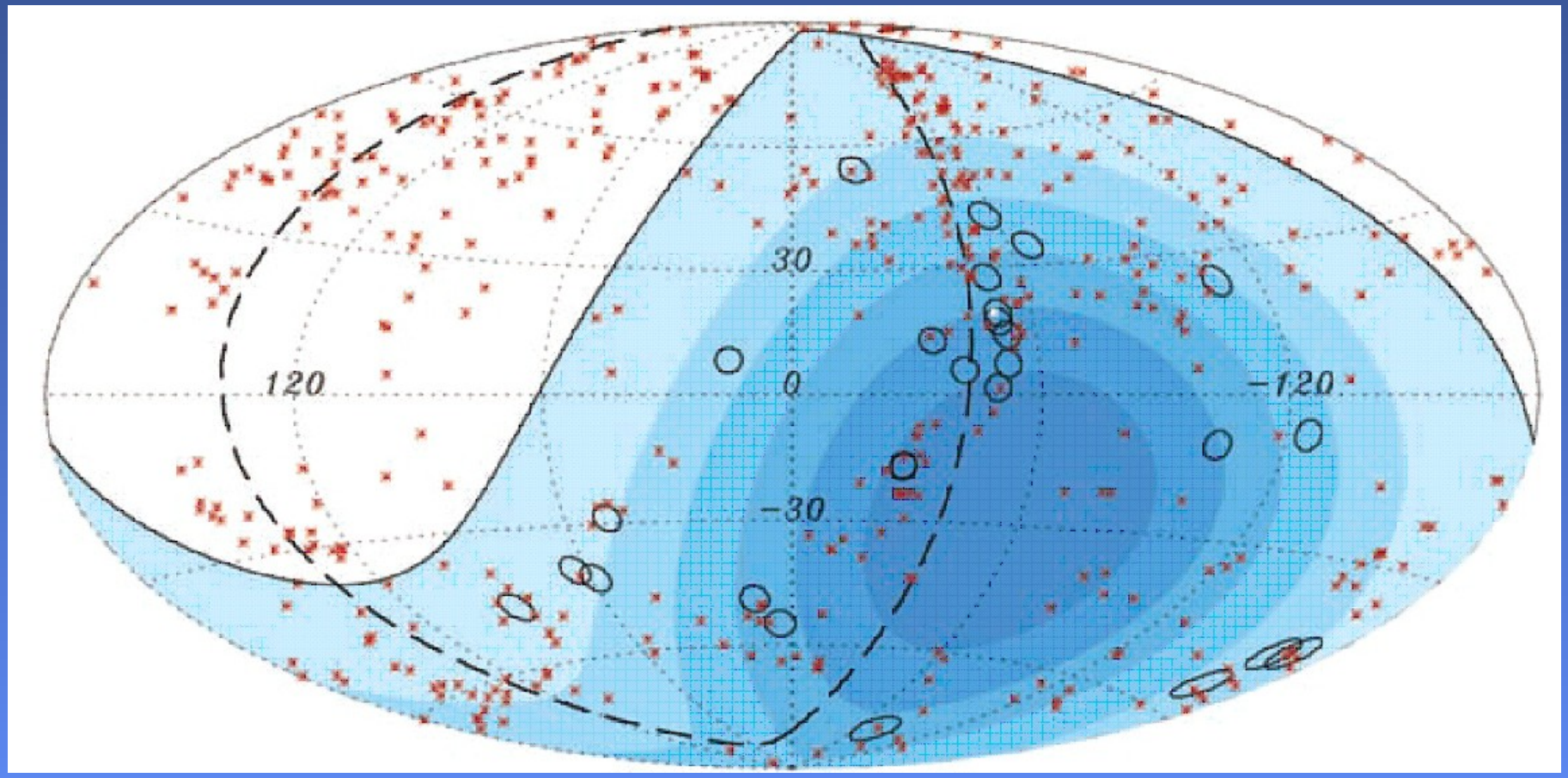
# What does the correlation mean? (1)

- Are AGN definitely the sources?
  - Any other objects with the same spatial distribution could be the source



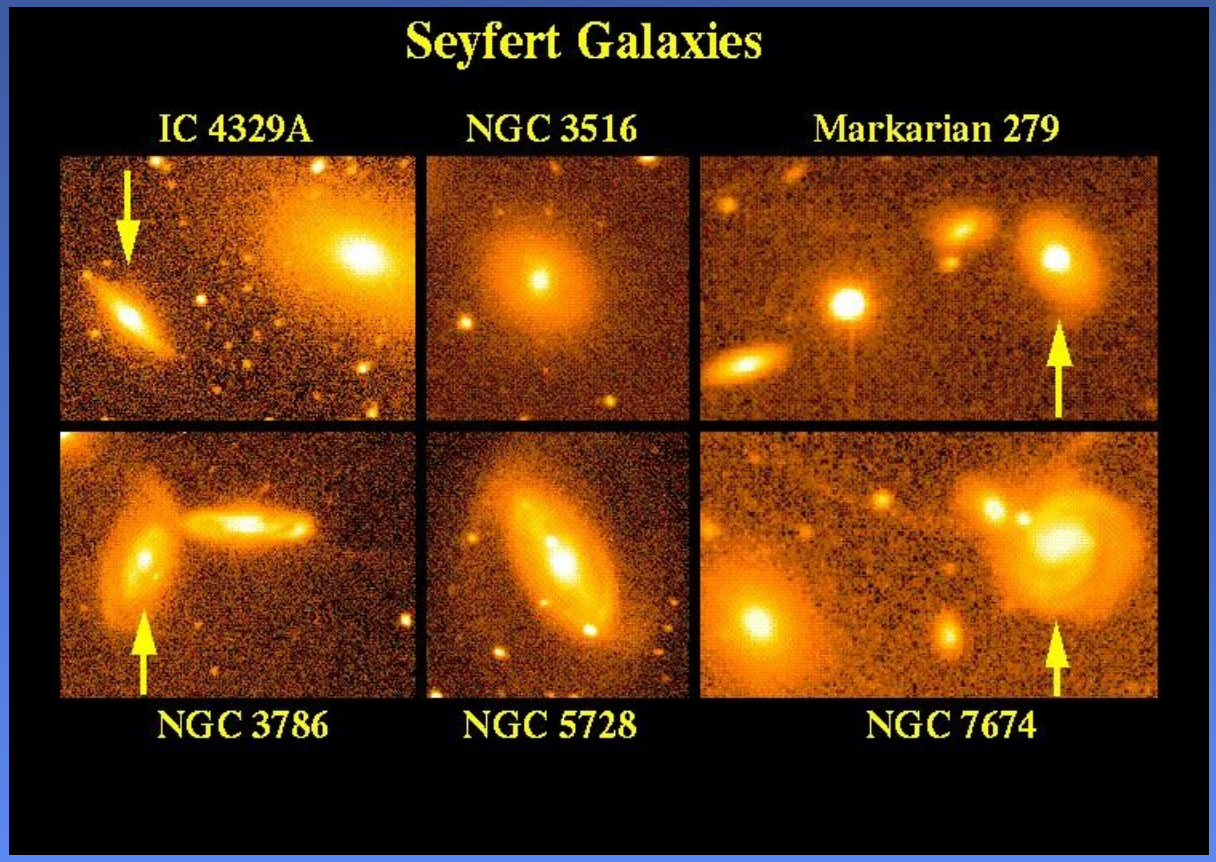
# What does the correlation mean? (2)

- Supergalactic plane seems to be associated with cosmic rays sources

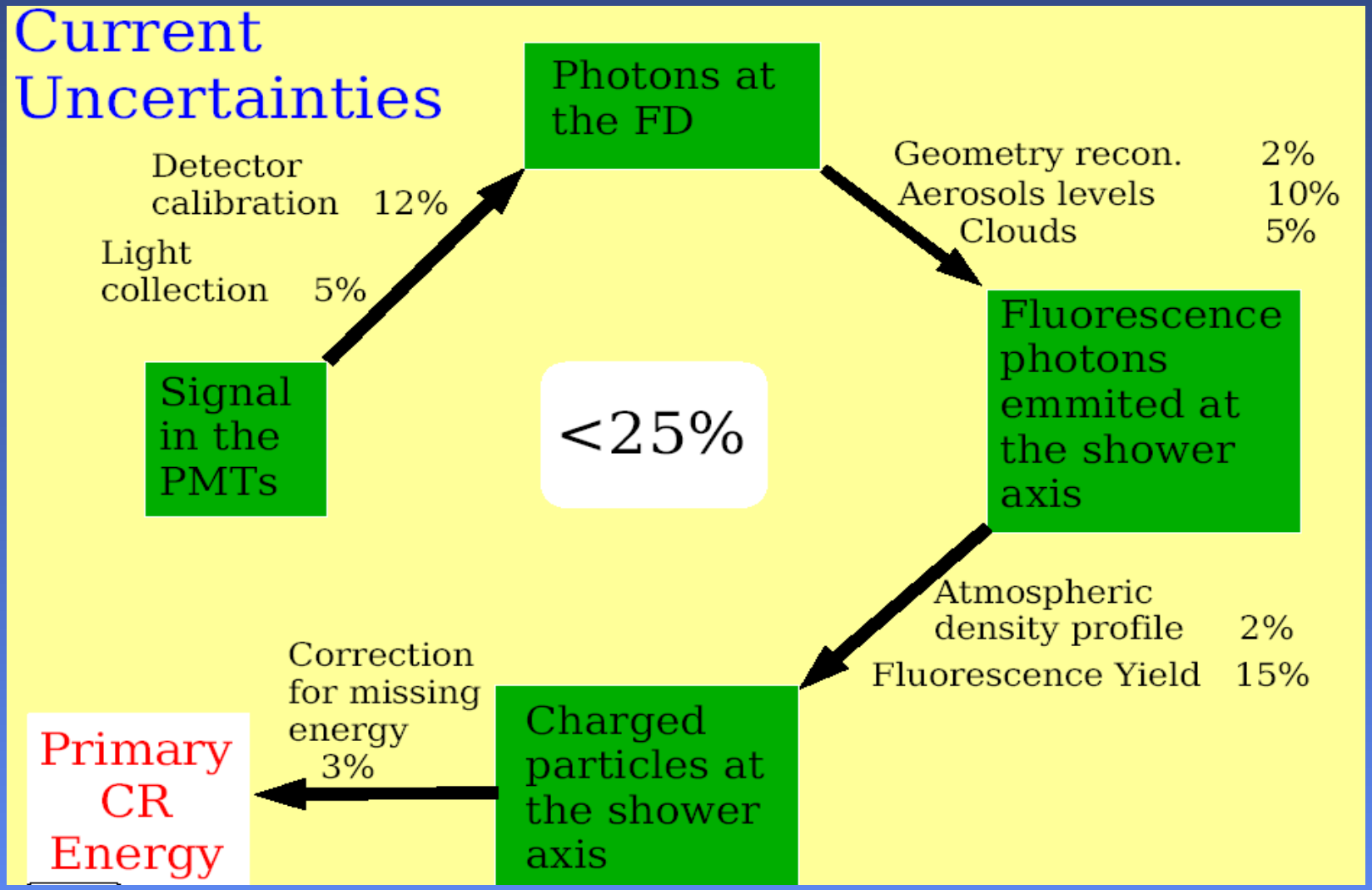


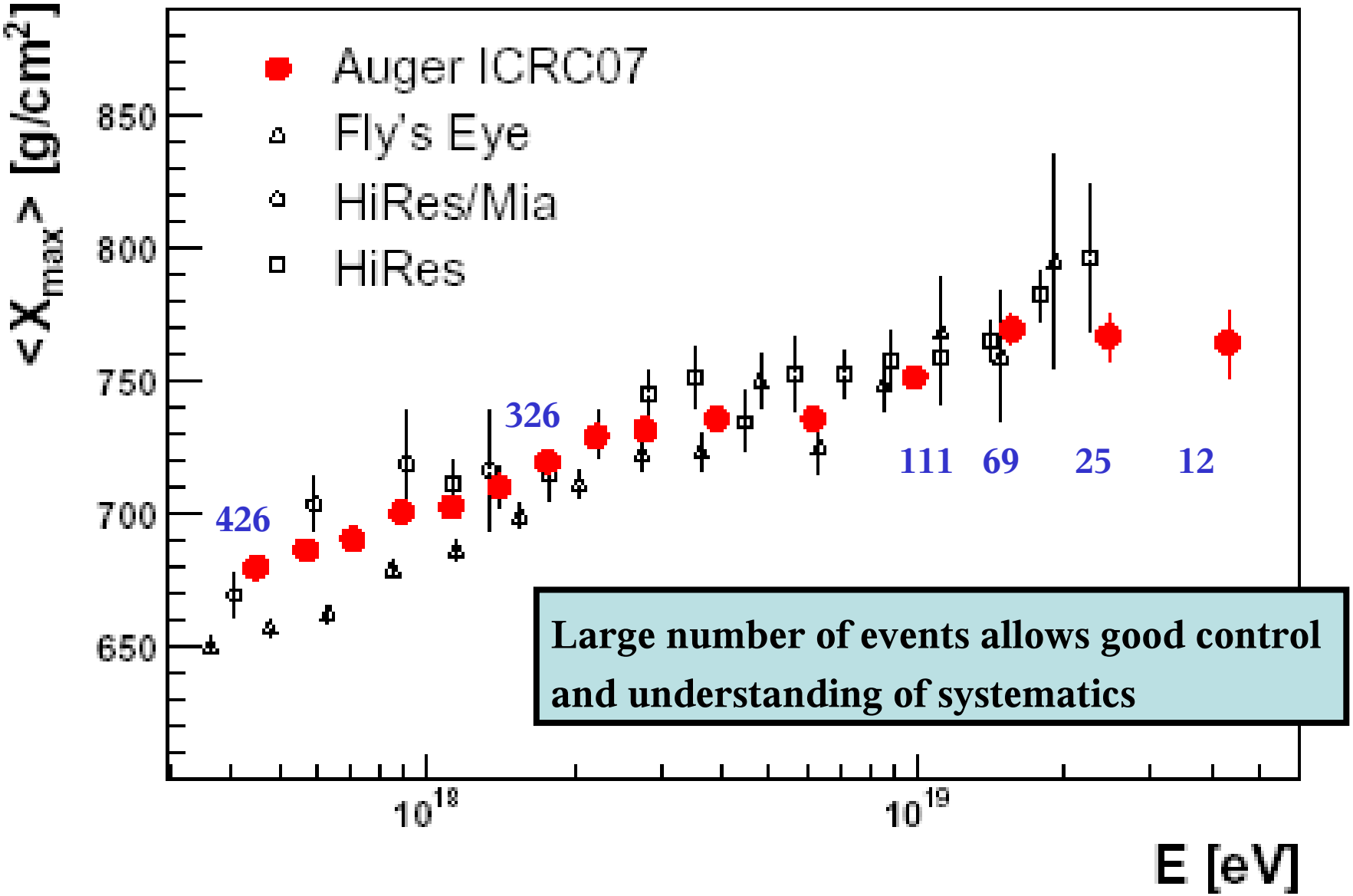
# What does the correlation mean? (3)

- What kind of AGN correlates with cosmic rays?
  - 15 out of 24 events seems to be coming from Seyfert galaxies, however still is not statistically significant



# Systematic Errors in the FD (Hybrid) Energy Normalization






**Large number of events allows good control and understanding of systematics**

# Energy Determination With Auger

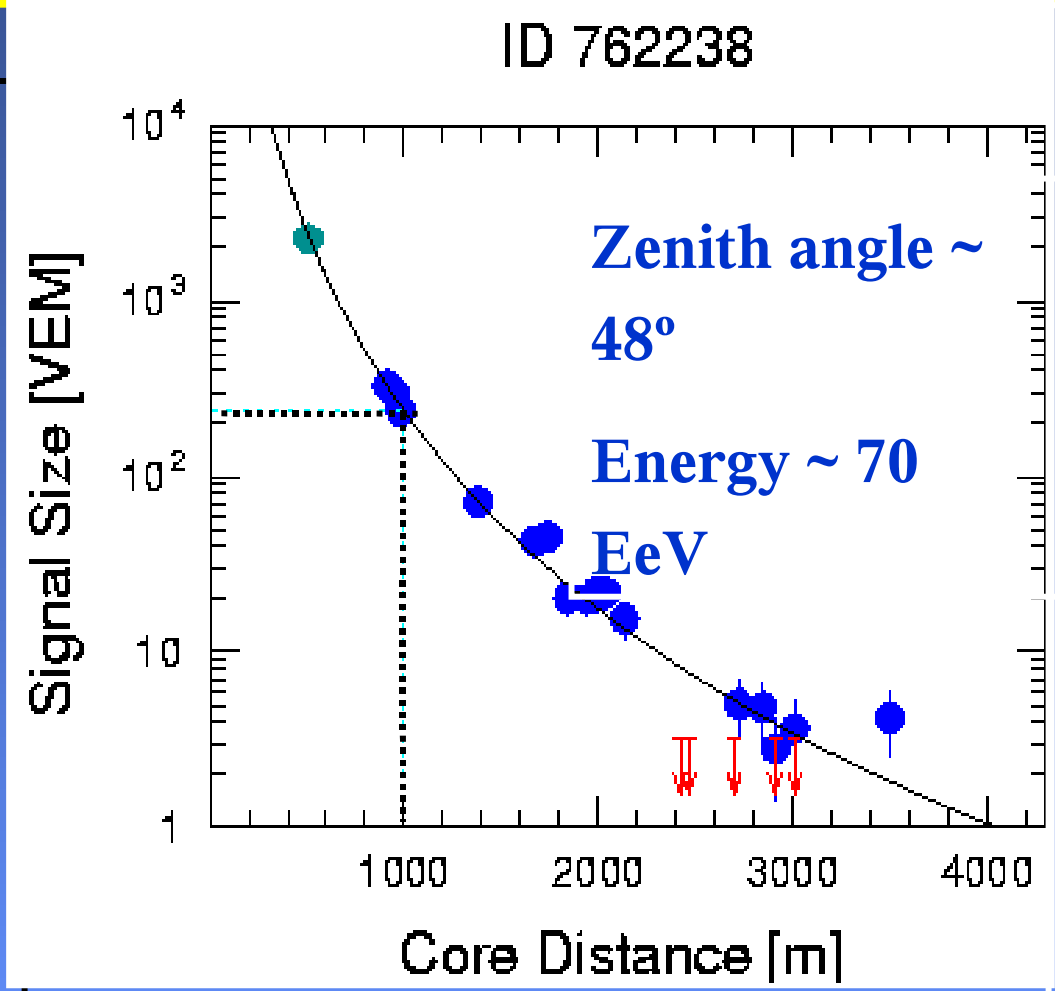
***The energy scale is determined from the data*** ***The dependence on knowledge of interaction models or of the primary composition is at level of a few %.***

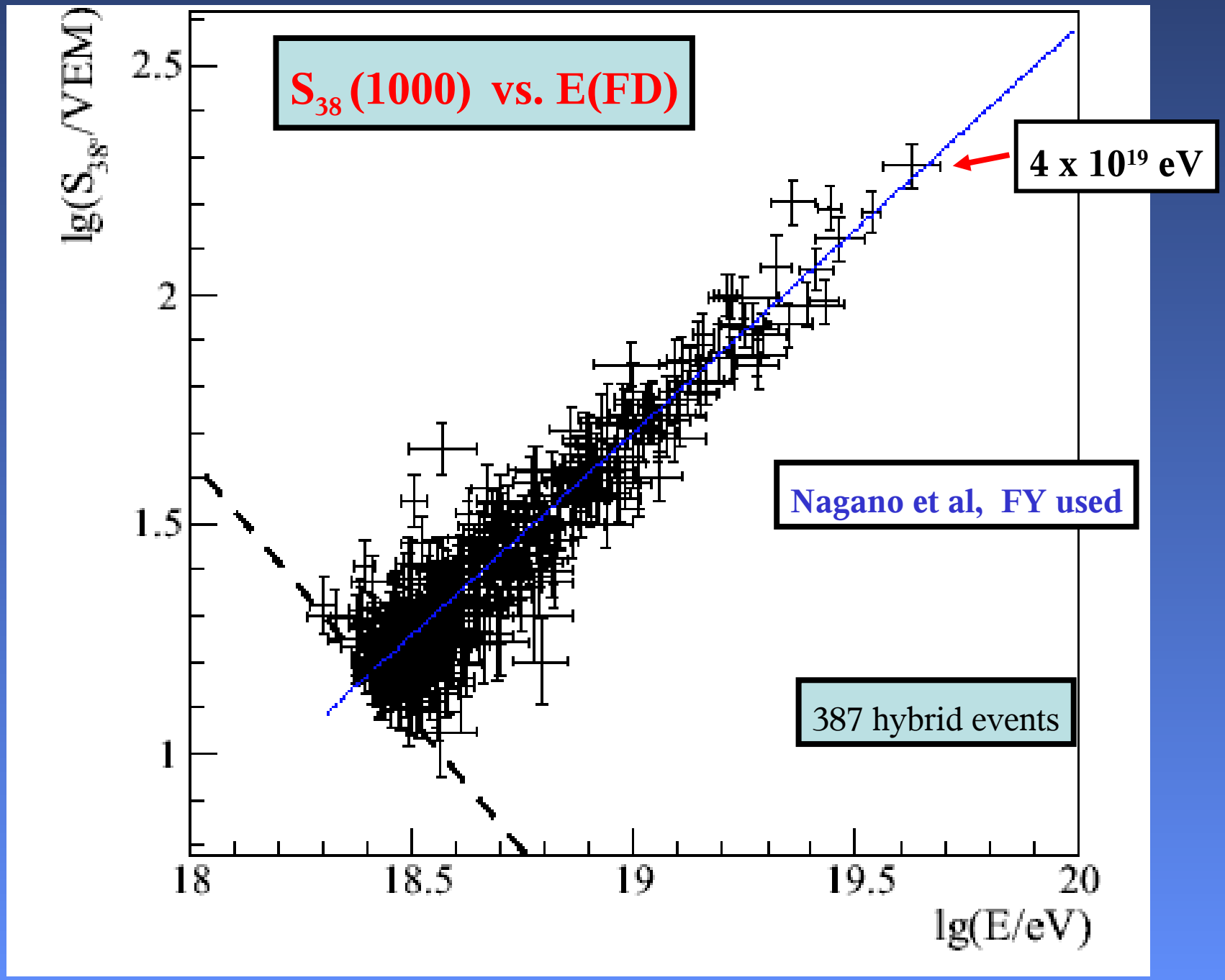
The detector signal at 1000 m from the shower core

– S(1000)

- **determined for each surface detector event**

S(1000) is proportional to the primary energy



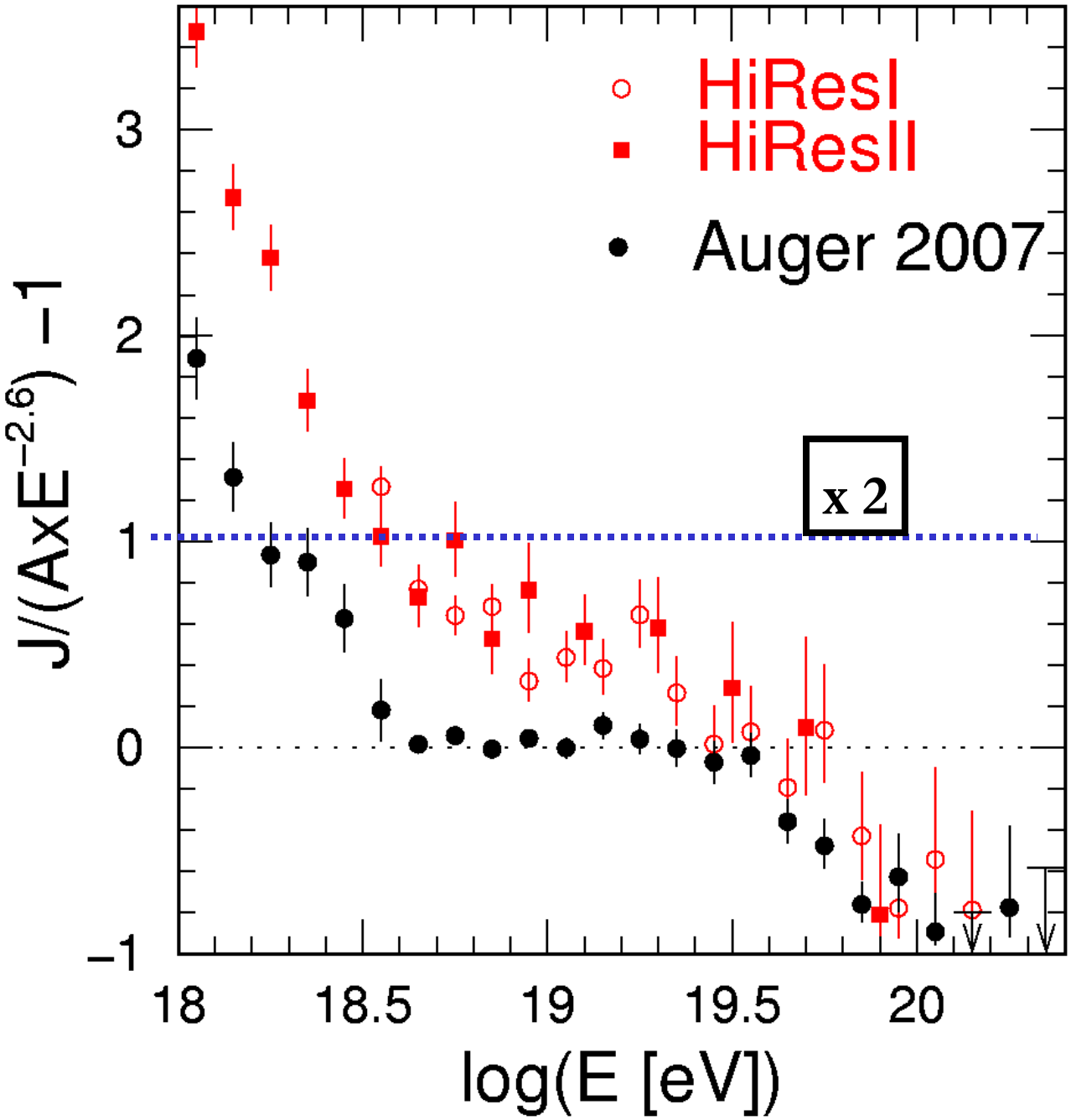

$S_{38}$ (1000) vs. E(FD)
4 x $10^{19}$ eV
Nagano et al, FY used
387 hybrid events
lg($S_{38}$/VEM)
lg(E/eV)
2.5
2
1.5
1
18
18.5
19
19.5
20

# Summary of systematic uncertainties

| Source | Systematic uncertainty |
|---|---|
| Fluorescence yield | 14% |
| P,T and humidity effects on yield | 7% |
| Calibration | 9.5% |
| Atmosphere | 4% |
| Reconstruction | 10% |
| Invisible energy | 4% |
| TOTAL | 22% |

Note: Activity on several fronts to reduce these uncertainties

**Fluorescence Detector Uncertainties Dominate**


HiResI
HiResII
Auger 2007
x 2
J/(AxE^-2.6) -1
log(E [eV])
3
2
1
0
-1
18
18.5
19
19.5
20

Event Display, version v3r1

Event Display | Help

**Control**

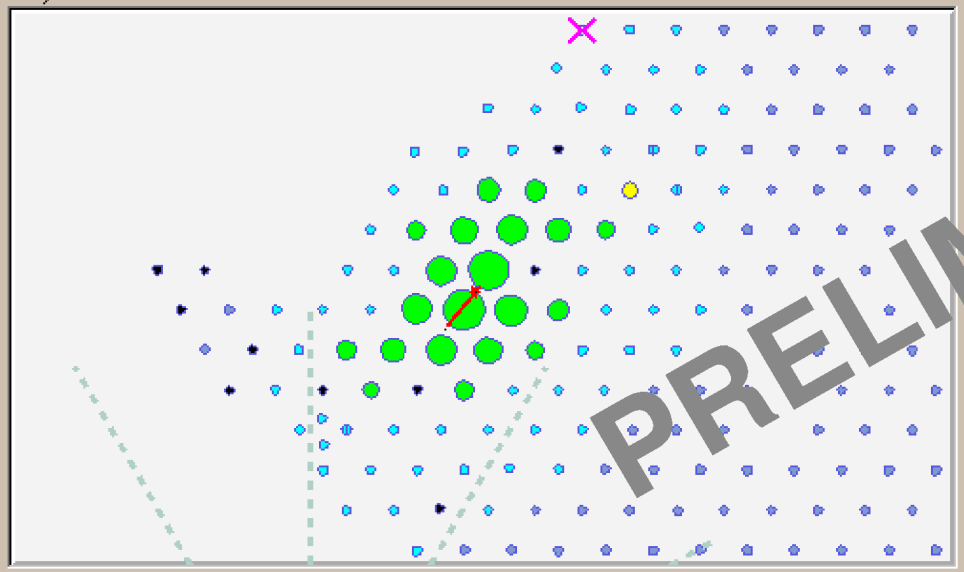
File | Configure | Experts only... | Mutiple selection

Reconstruct | Previous | Next | Get # 648728 | Update 0

#00648728, 22 stations, 3C2&4C4

0157 (14051 ns, 700.9 VEM)
0166 (15418 ns, 21.2 VEM)
0148 (15776 ns, 6.9 VEM)
0156 (18087 ns, 38.4 VEM)
0172 (19749 ns, 10.0 VEM)
0151 (20737 ns, 12.8 VEM)
0173 (22278 ns, 9.2 VEM)
0102 (24435 ns, 4.2 VEM)
0138 (28369 ns, 2.8 VEM)
0205, station deleted

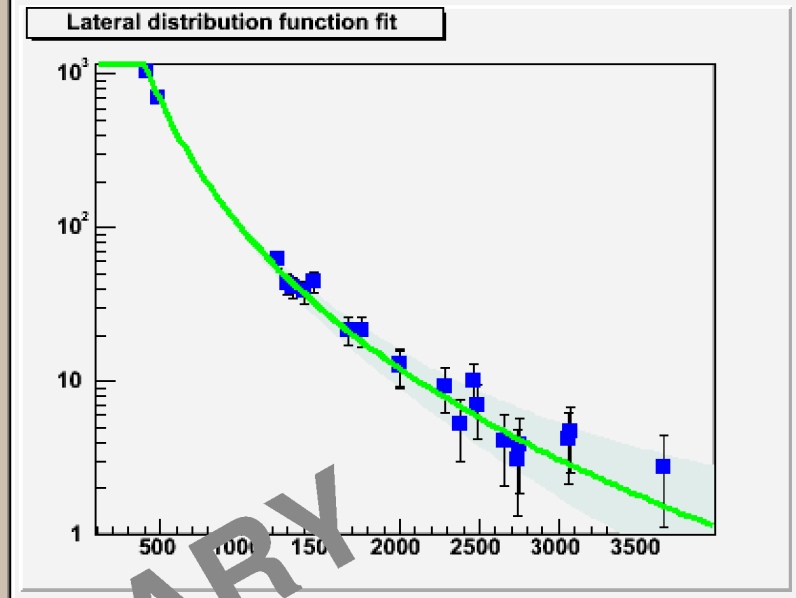
**Array**



**Status**

```
file selected: sd_2004_02_02_01h07.root
Minimum number of triggered stations: 0
Trigger selected: all of them
Date of this event: Mon Feb  2 06:02:44 2004 (GPS 759736977)
```

**Display**




*Mon Feb 2 06:02:44 2004*
*Easting= 464513 ± 36m*
*Northing= 6087246 ± 12m*
*dt= 120.3ns*

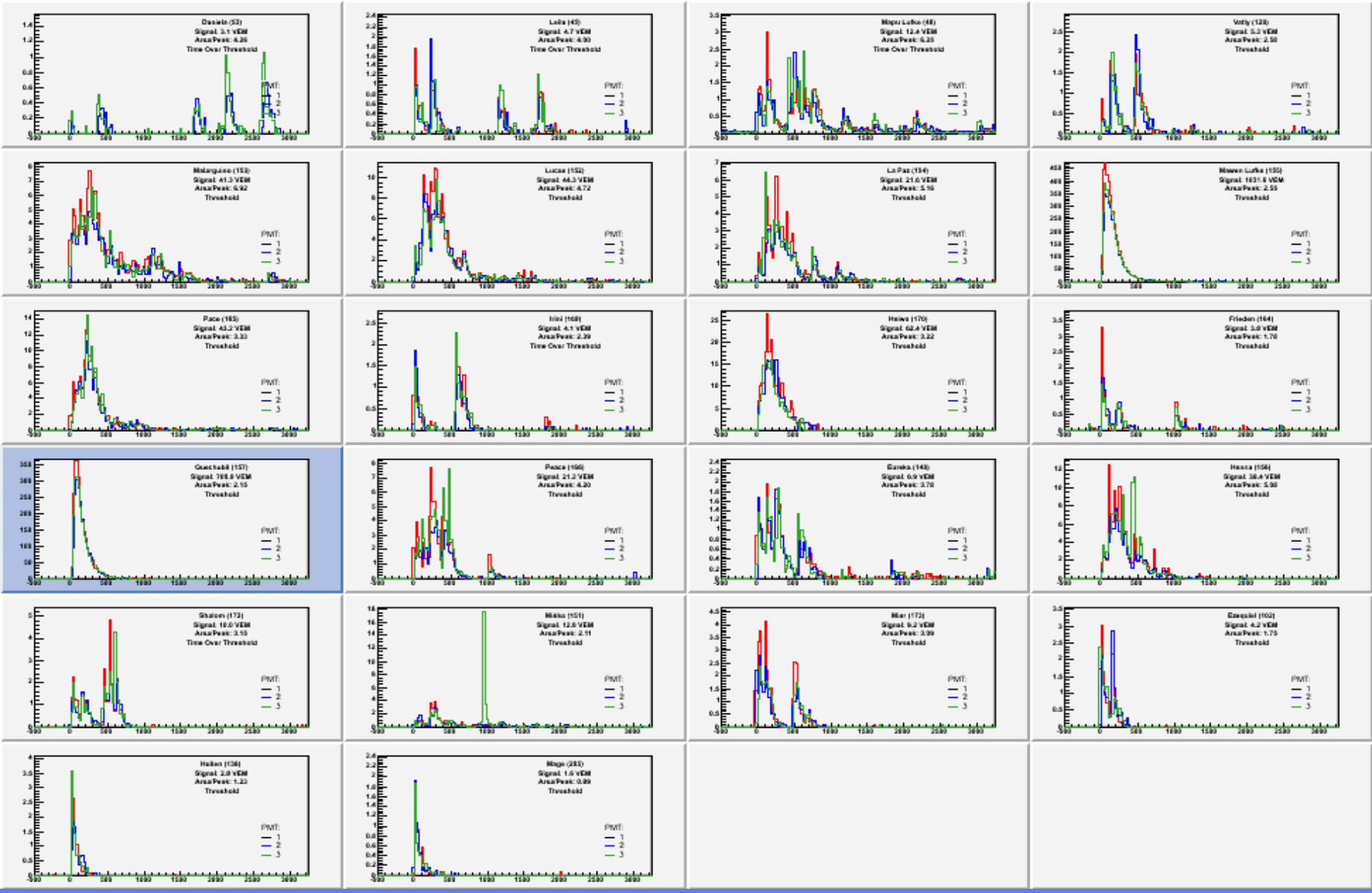
*Theta= 54.2 ± 0.2 deg*
*Phi= -130.6 ± 0.2/sin(theta) deg*

*R= 18.4 ± 1.1 km*

*S(1000)= 101.88 ± 2.77 VEM*
*E= 43.58 EeV ± 3%* *(statr. error only)*

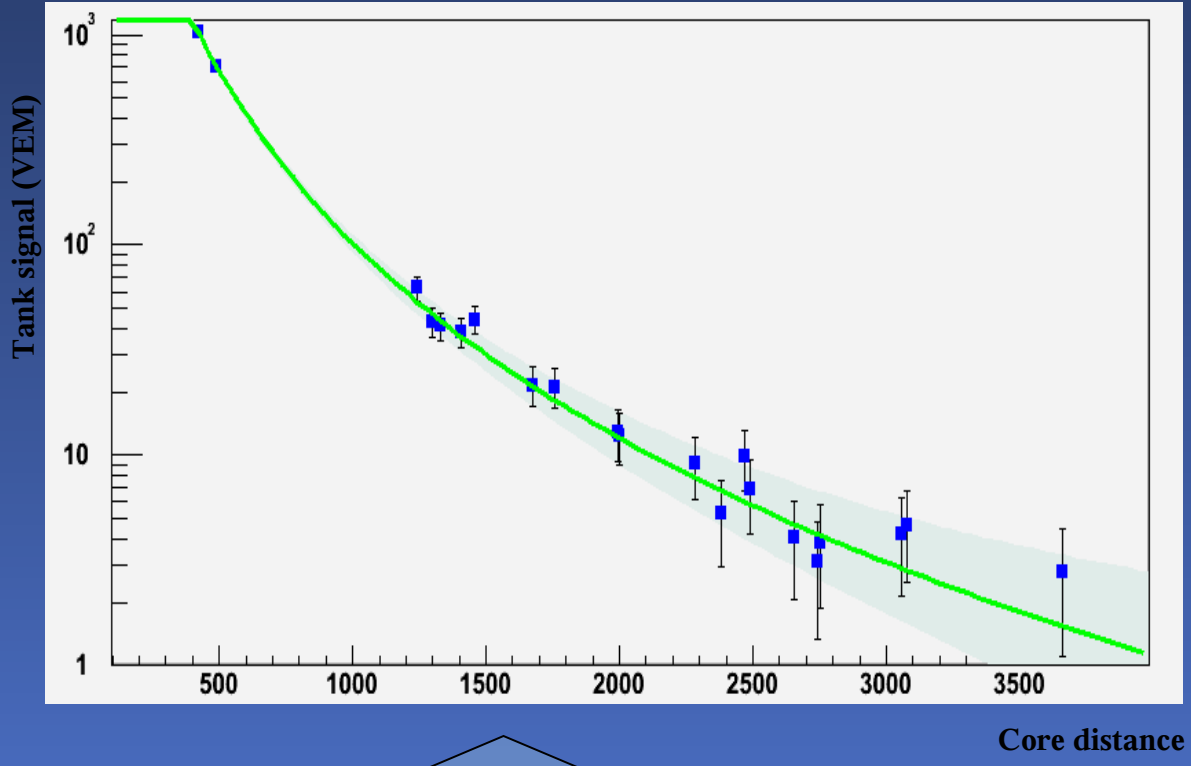
100%

PRELIMINARY



PRELIMINARY analysis shows

zenith angle 54º, energy 44 EeV




*Mon Feb 2 06:02:44 2004*
*Easting = 454513 ± 36 m*
*Northing = 6087246 ± 12m*
*dt = 120.3ns*

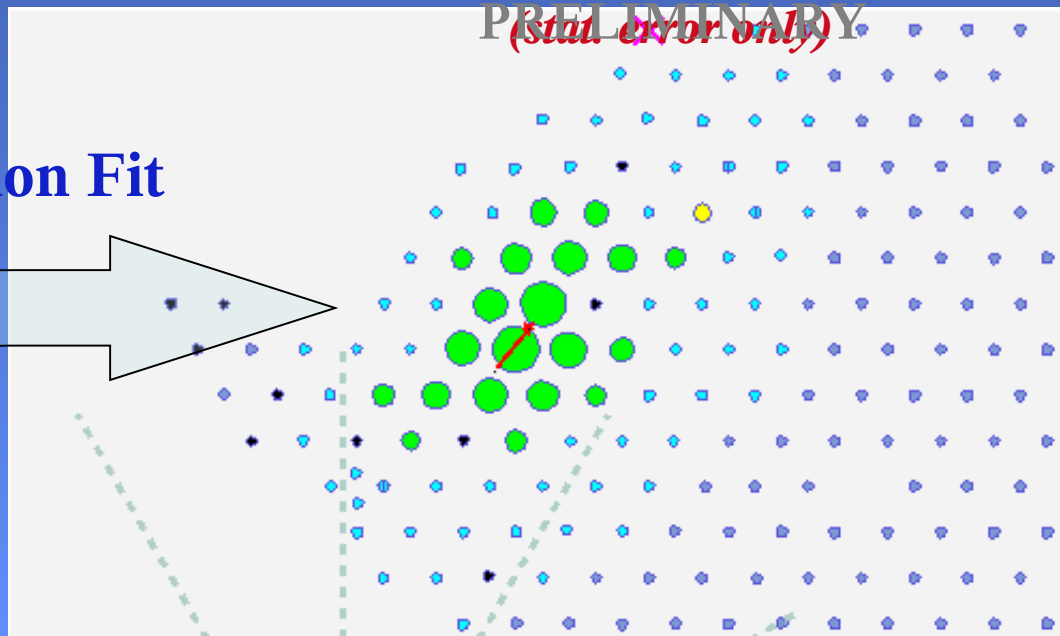
*Theta = 54.2 ± 0.2 deg*
*Phi =-130.6 ± 0.2/sin(Theta) deg*

*R = 18.4 ± 1.1 km*

*S(1000) = 101.88 ± 2.77 VEM*
*E = 43.58 EeV ± 3%*
*(stat. error only)*

PRELIMINARY

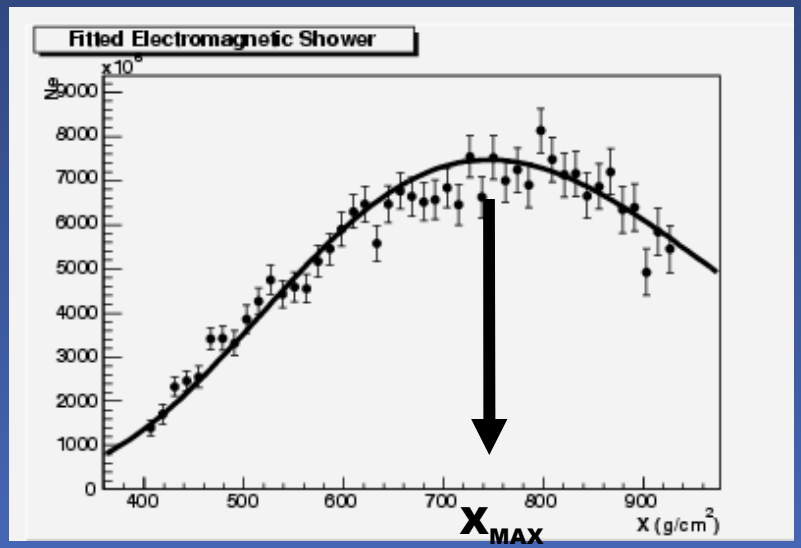
**Lateral Distribution Function Fit**

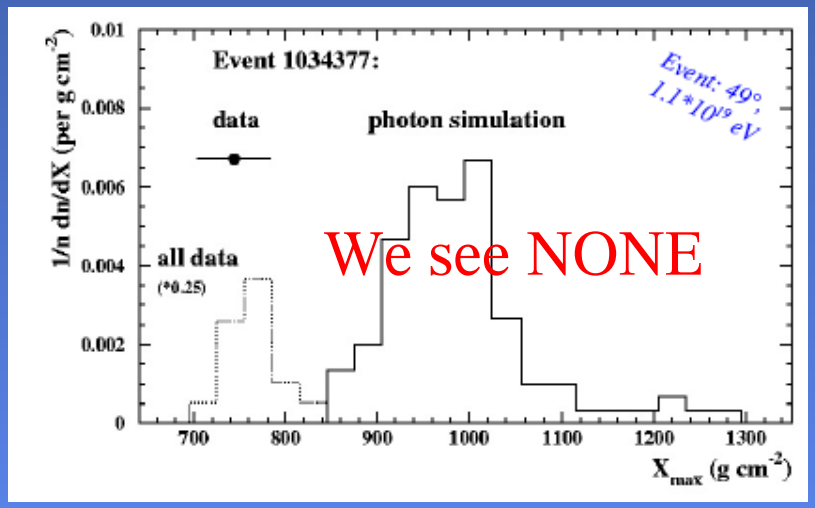


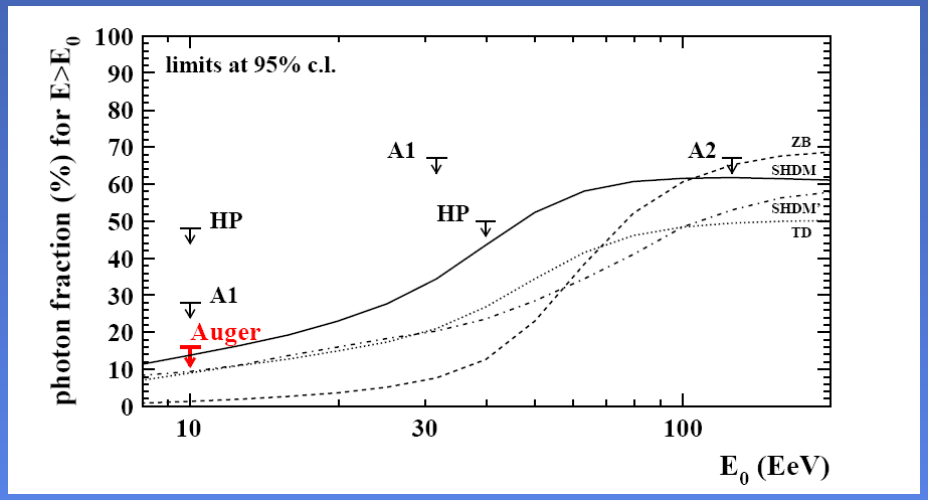
**Surface Array view**

# Primary photon fraction

- "Top down" models predict large fraction of primaries are photons.
- Photons result in deep $X_{max}$ position (SD: muon poor)
- Present measurement based on sample of hybrid events – direct measurement of $X_{max}$




**16% upper limit on primary photon fraction near $10^{19}$ eV.**

**Confirms and improves previous limits by ground arrays**