CORREO ARGENTINO

Colloquium, University of Virginia: 18 April 2008

COSMOS CIENCIA

OBSERVATORIO PIERRE AUGER
MALARGÜE MENDOZA

Sobre primer dia oficial

Is the search for the origin of the Highest Energy Cosmic Rays over?

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OVERVIEW

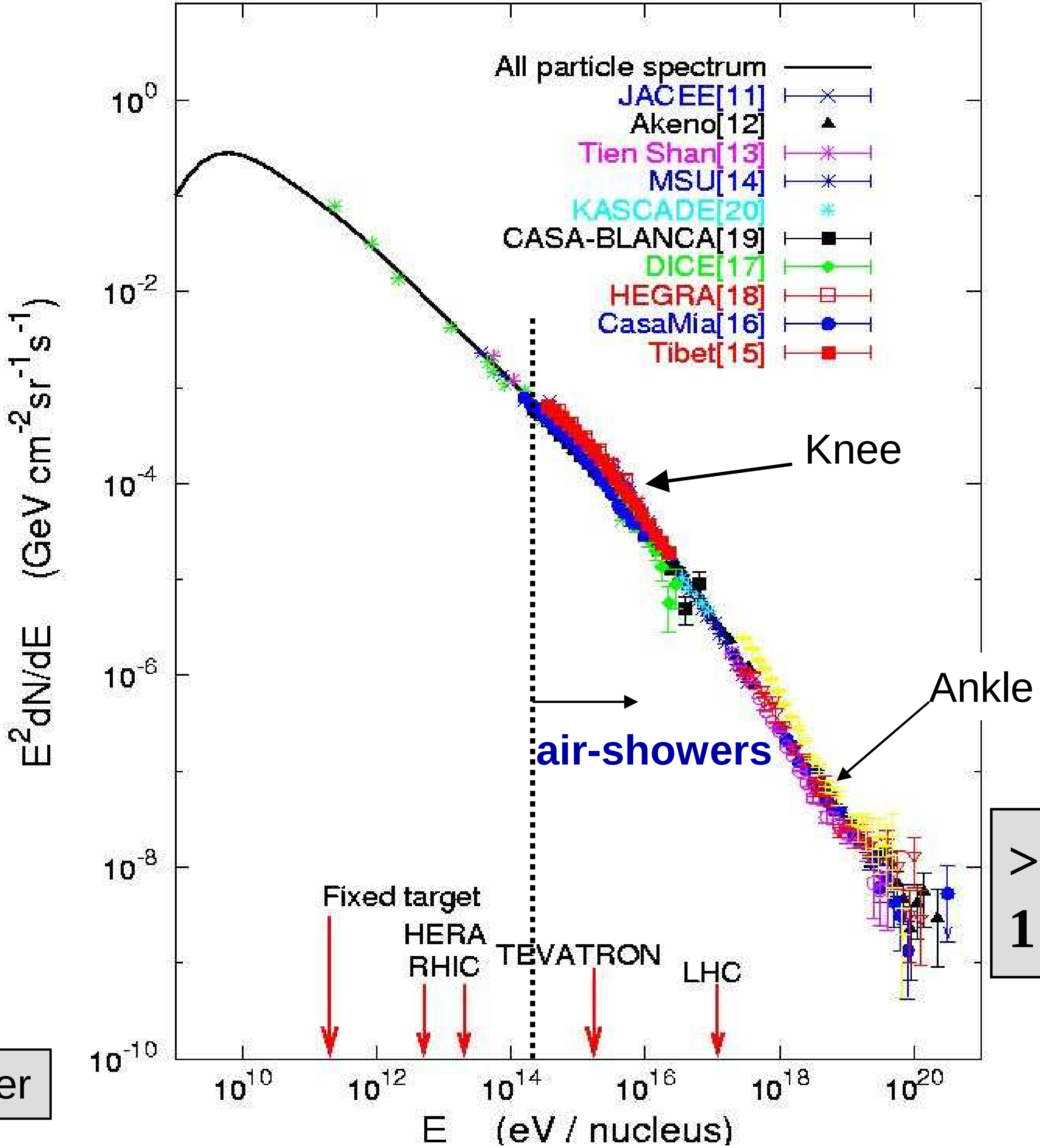
- **Why there is interest in cosmic rays > 10^{19} eV**
- **The Auger Observatory**
- **Description and discussion of measurements:-**

Energy Spectrum

Arrival Directions

Primary Mass (not photons or neutrinos)

- **Prospects for the future**



$>10^{19}$ eV
1 km^{-2} sr^{-1} year^{-1}

after Gaisser

Why the Interest in UHECR?

(i) Can there be a cosmic ray astronomy?

Searches for Anisotropy (find the origin)

Deflections in magnetic fields:

at ~ 10^{19} eV: ~ 10° in Galactic magnetic field for protons - depending on the direction

For interpretation, and to deduce B-fields, ideally we need to know Z - hard enough to find A!

History of withdrawn or disproved claims

(ii) What can be learned from the spectrum shape?

- 'ankle' at ~ $3x10^{18}$ eV

  - galactic/extra-galactic transition?

- Steepening above 5×10^{19} eV because of energy losses?

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

$$\gamma_{2.7\,K} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \text{ or } p + \pi^o$$

(sources of photons and neutrinos)

or

$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

(IR background more uncertain)

Existence of particles above GZK-steepening would imply that sources are nearby, 70 – 100 Mpc, depending on energy.

Essentially the CMB acts as a shield against cosmic rays from distant sources reaching earth.

IF particles are protons, the deflections are small enough above ~ 5 x 10^{19} eV that point sources might be seen.

So, measure:

- **energy spectrum**
- **arrival direction distribution**
- **mass composition**

But rate at 10^{20} eV is < 1 per km^2 per century

Nuclear disintegrations with electronic elements 89

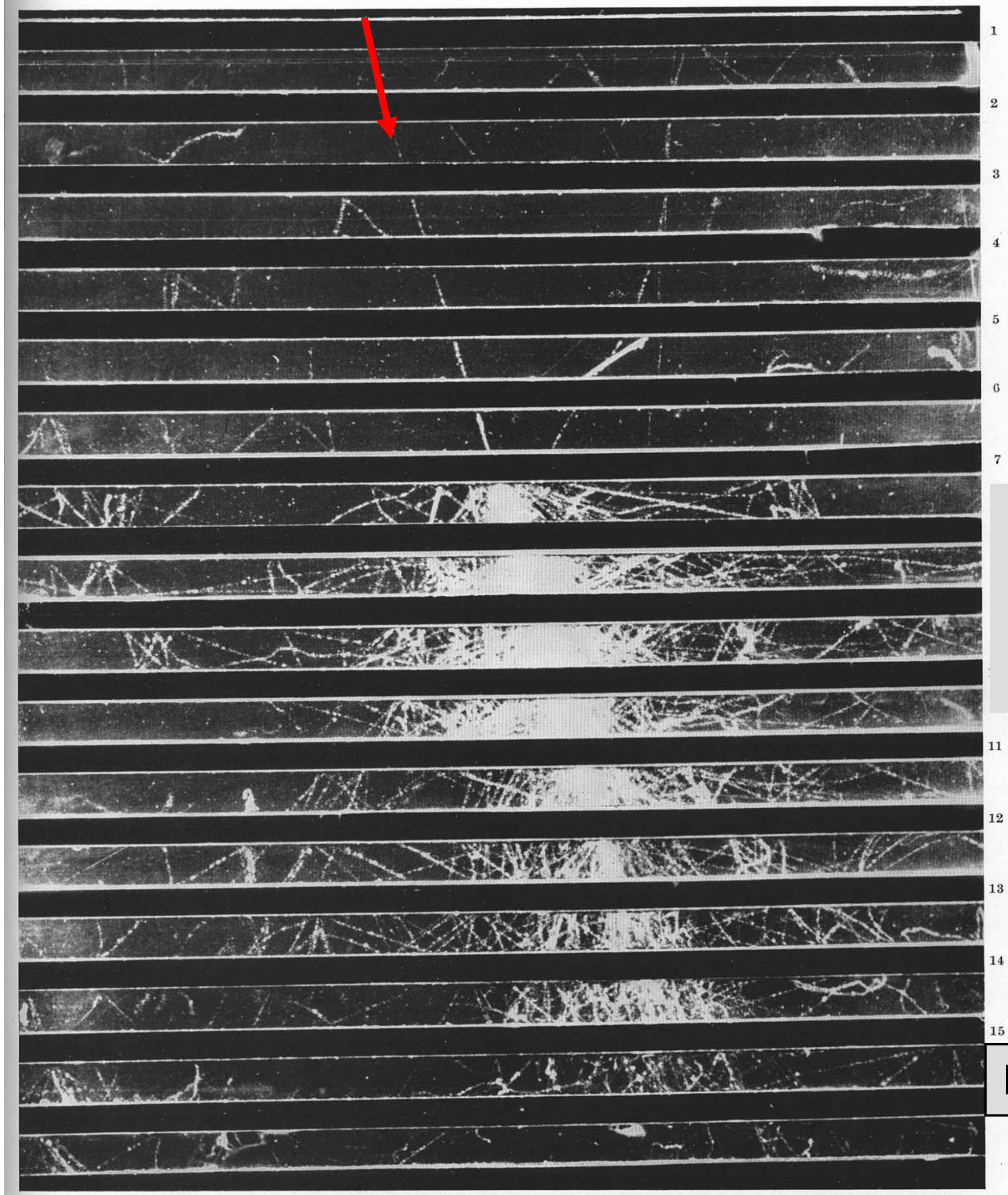


Plate 92

1.3 cm Pb

Shower initiated by proton in lead plates of cloud chamber

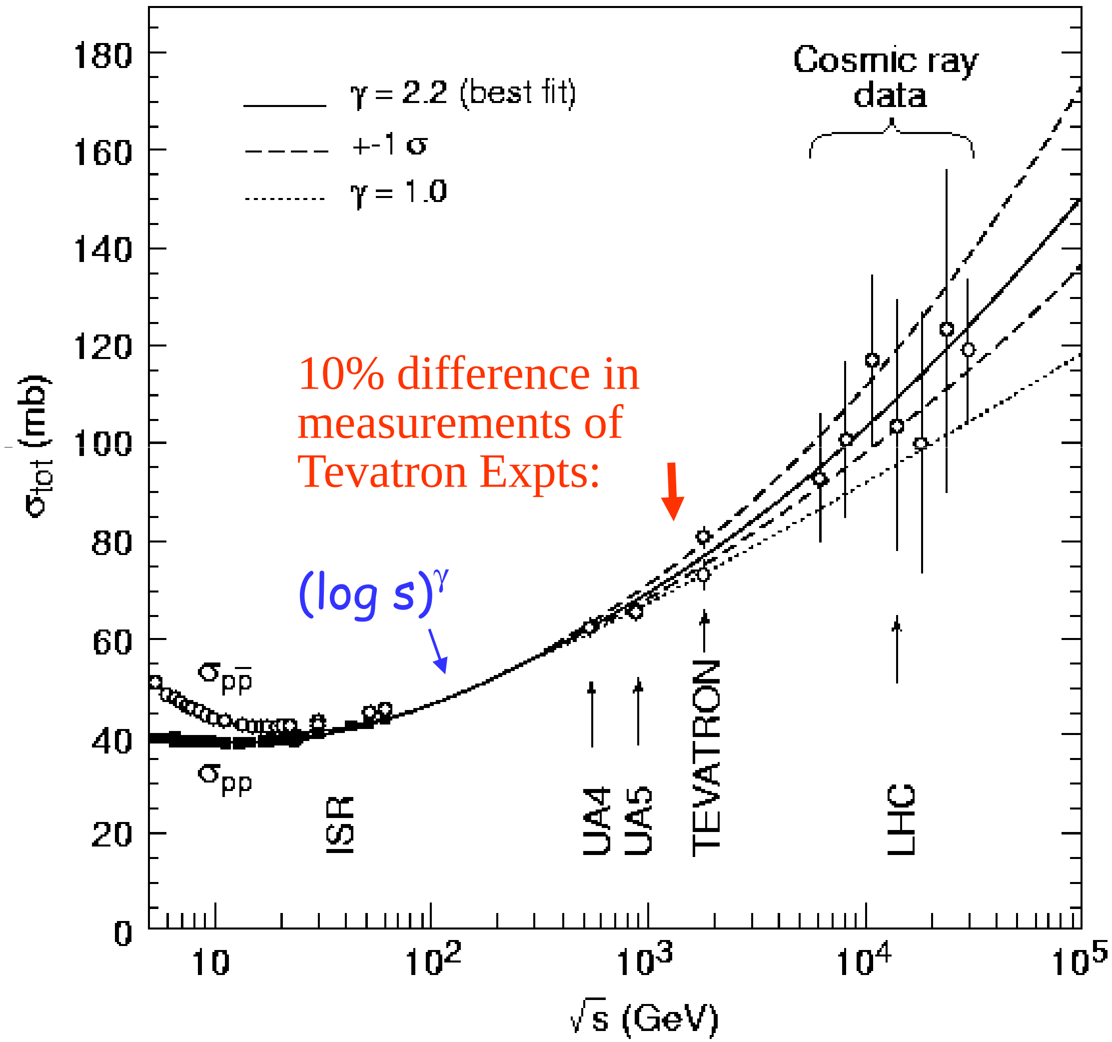
Fretter: Echo Lake, 1949

The p-p total cross-section

LHC measurement of σ_{TOT} expected to be at the

1% level

– very useful in the extrapolation up to UHECR energies



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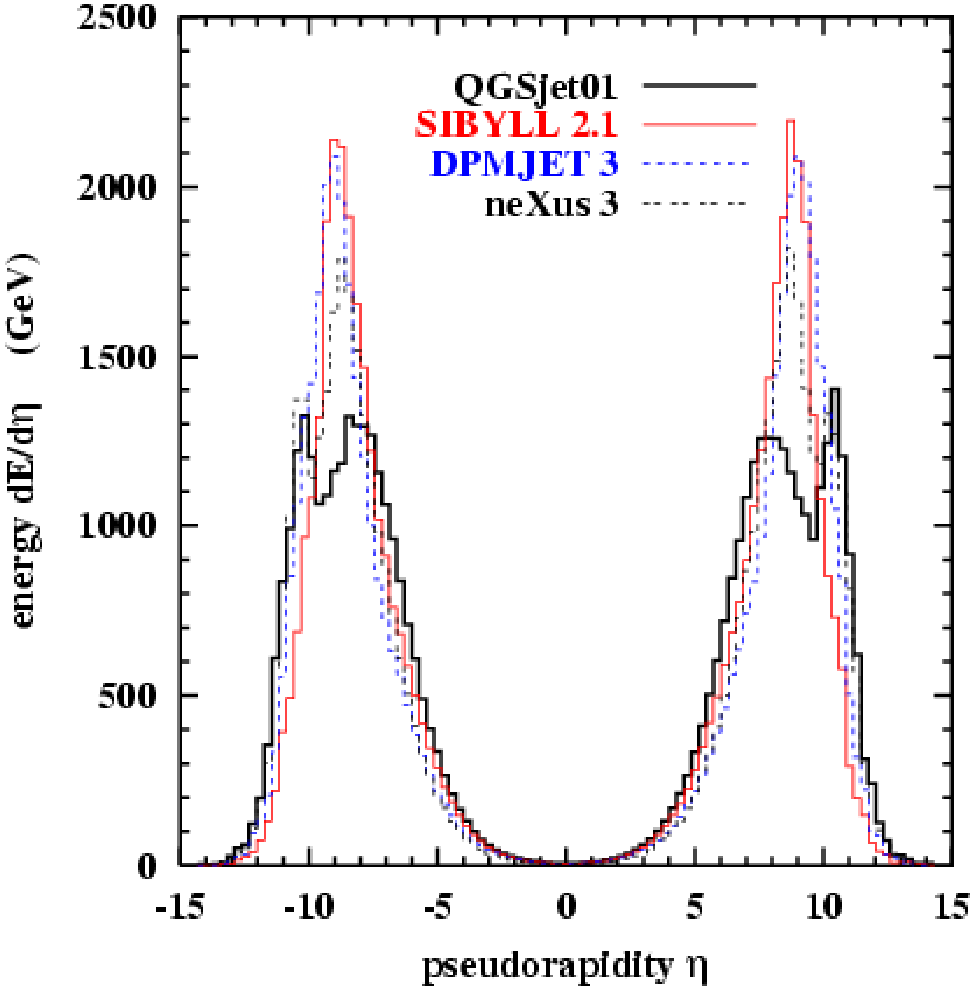
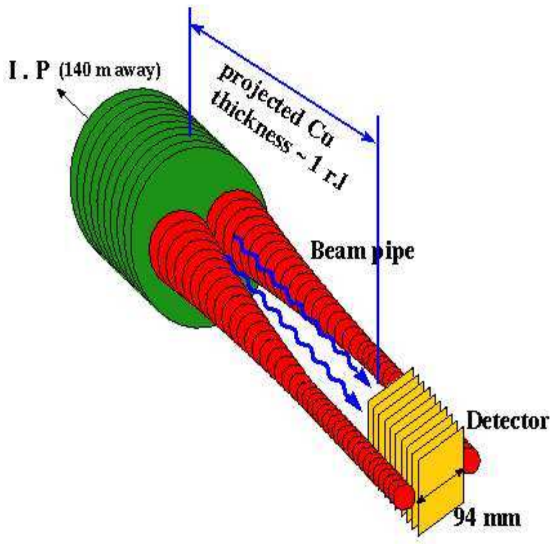
LHC Forward Physics & Cosmic Rays

Models describe Tevatron data well - but LHC model predictions reveal large discrepancies in extrapolation.

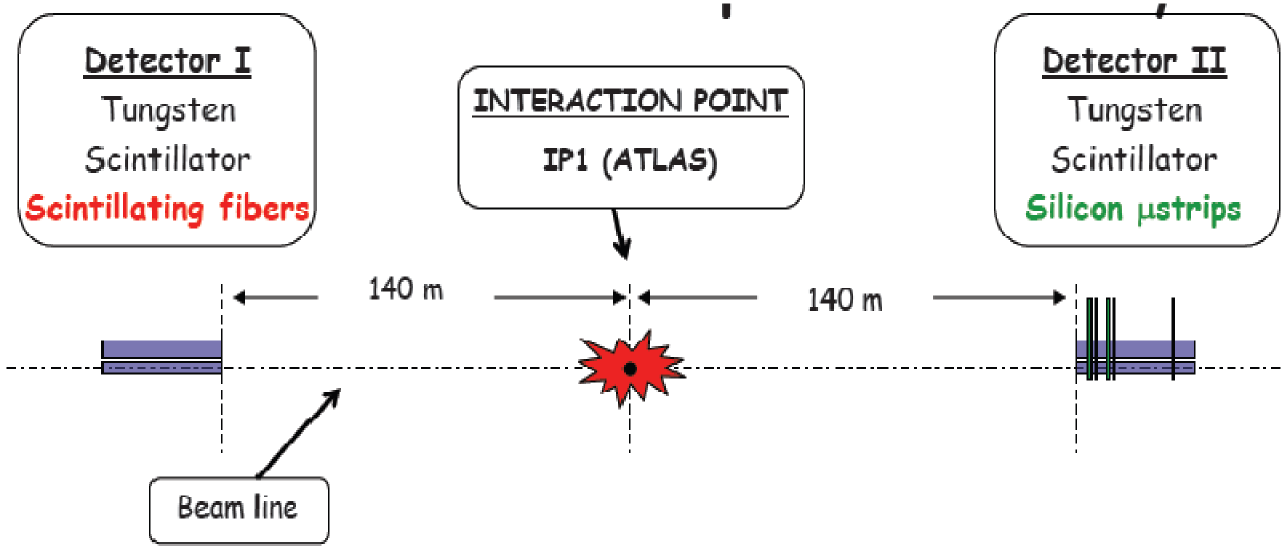


LHCf: an LHC Experiment for Astroparticle Physics



LHCf: measurement of photons and neutral pions and neutrons in the very forward region of LHC

Add an EM calorimeter at 140 m from the Interaction Point (IP1 ATLAS)
For low luminosity running



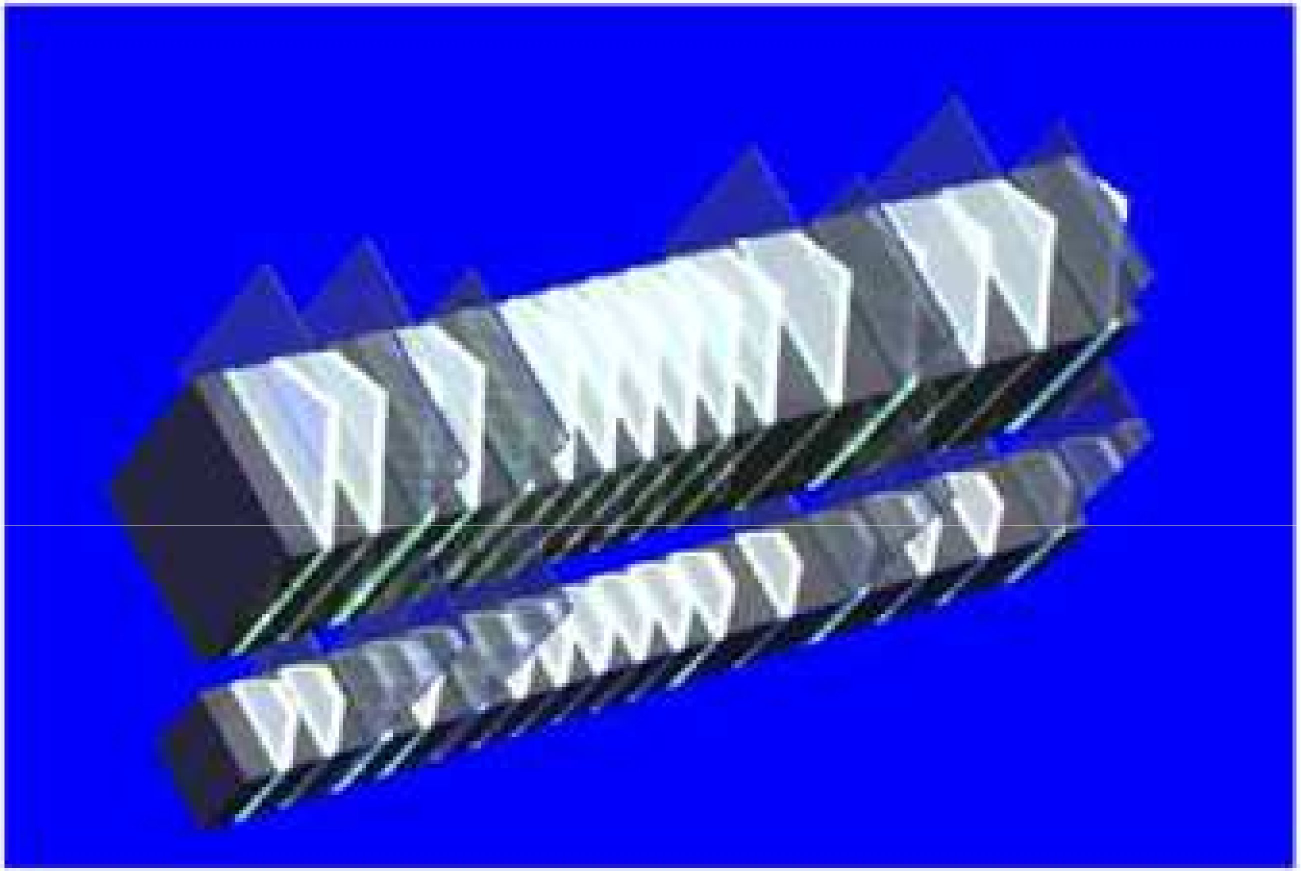
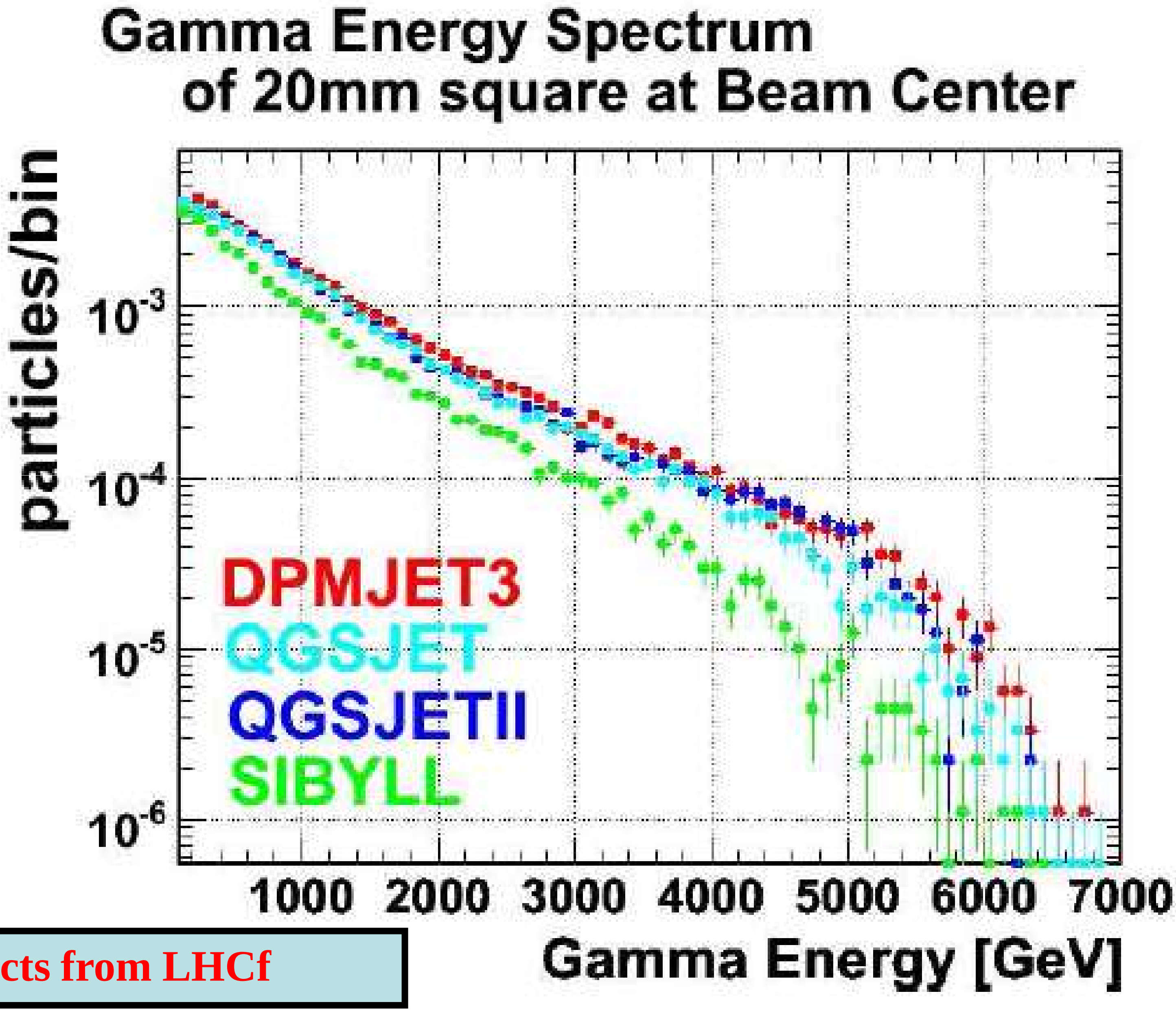


Figure 9: A schematic view of the Detector #1. It is composed of two individual tower of sampling calorimeters stacked vertically and diagonally.

28 x 9 x 60 cm^3



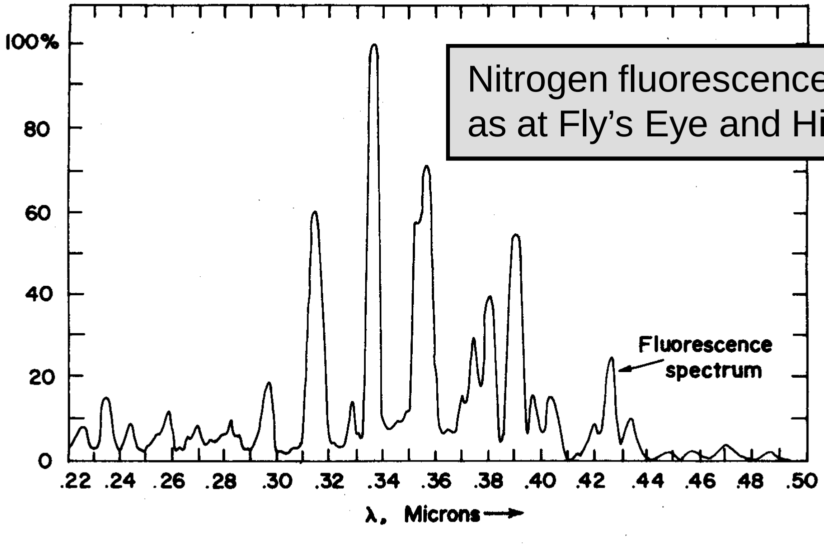
Prospects from LHCf

The Pierre Auger Collaboration

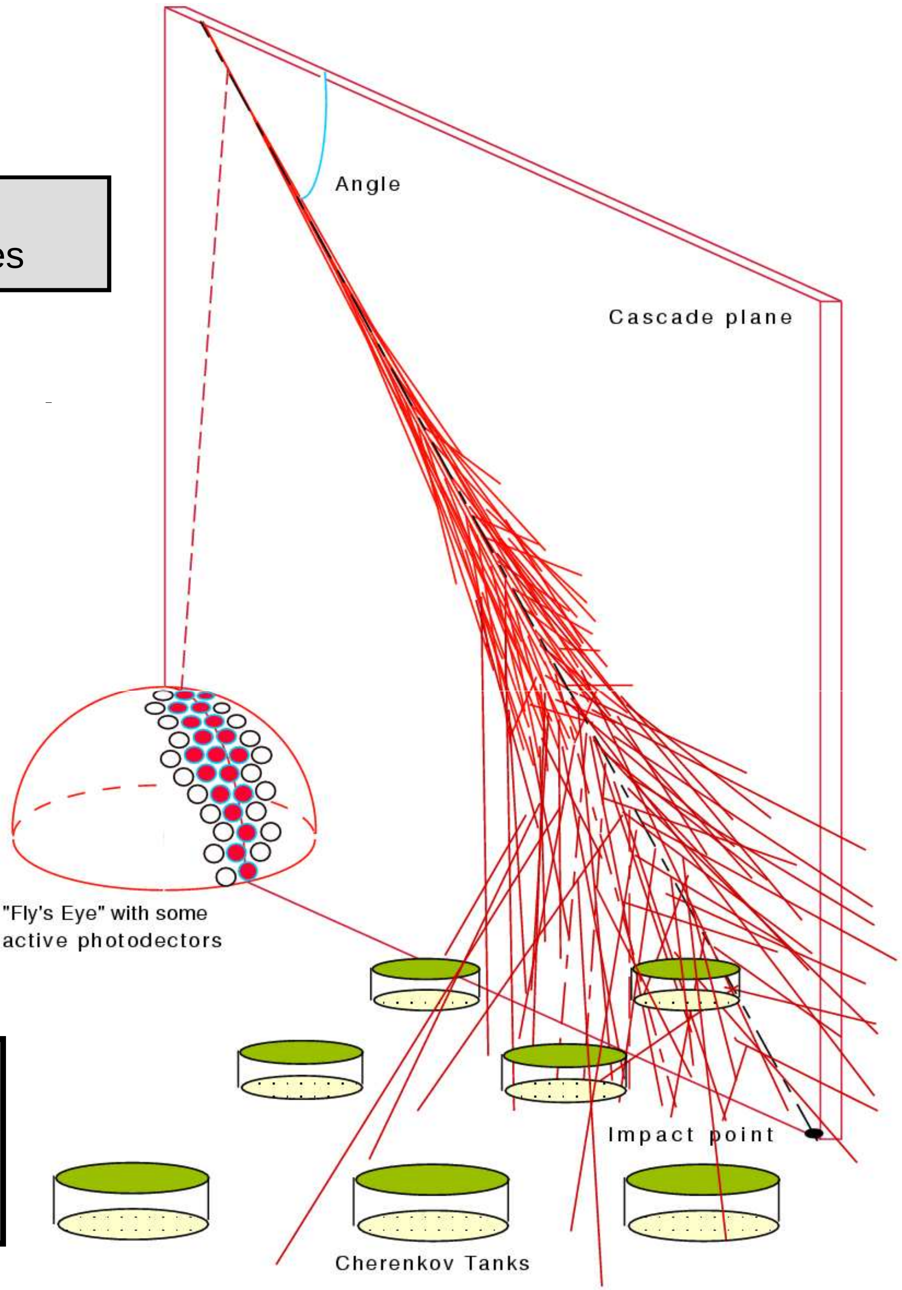
Czech Republic	Argentina
France	Australia
Germany	Brasil
Italy	Bolivia*
Netherlands	Mexico
Poland	USA
Portugal	Vietnam*
Slovenia	**Associate Countries*
Spain	
United Kingdom	~330 PhD scientists from ~90 Institutions and 17 countries

Aim: To measure properties of UHECR with unprecedented statistics and precision – first discussions in 1991

Shower Detection Methods



Nitrogen fluorescence as at Fly's Eye and HiRes



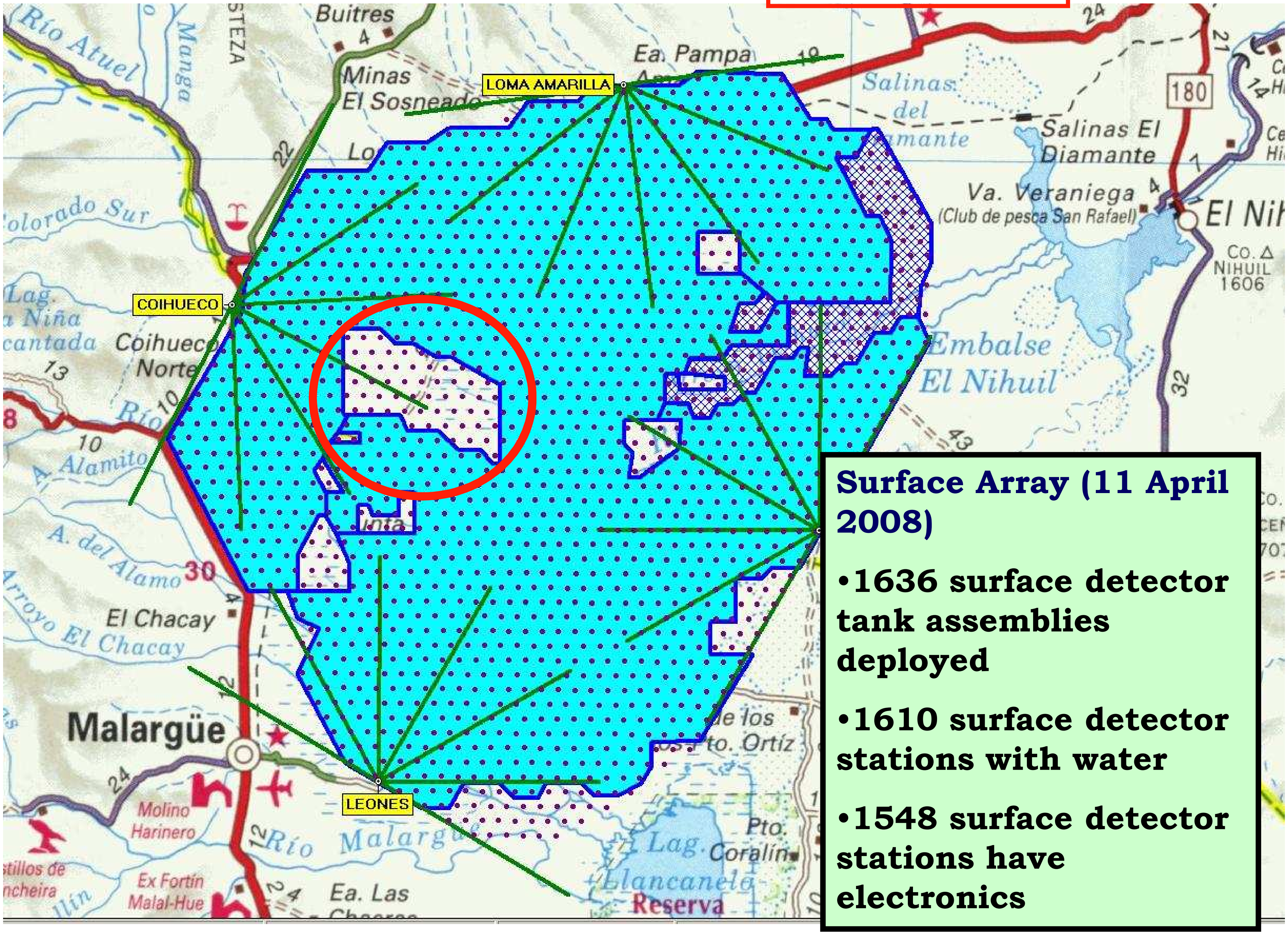
Fluorescence →

OR AND

Arrays of water-Cherenkov detectors →

or Scintillation Counters

26 February 2008

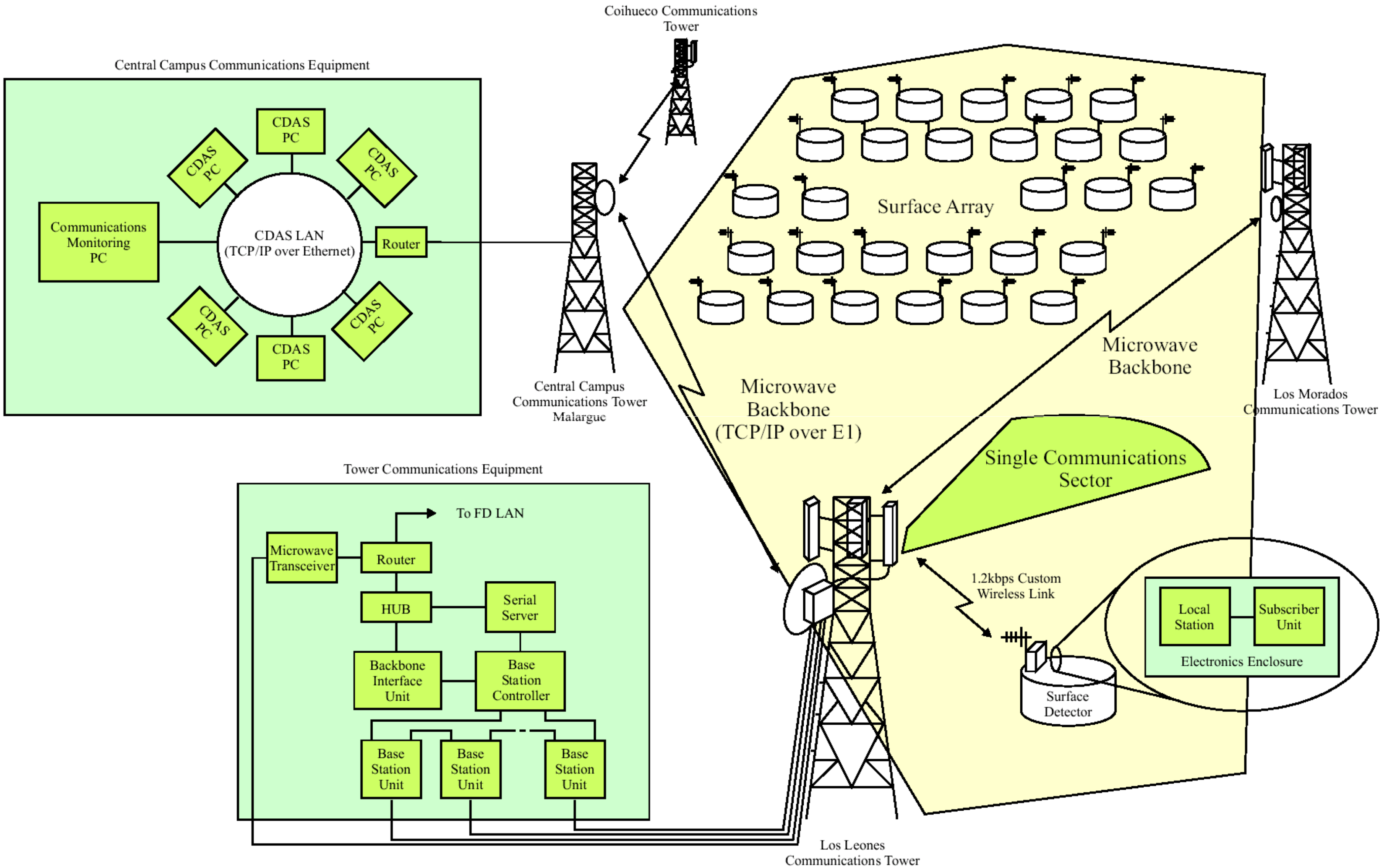


Surface Array (11 April 2008)

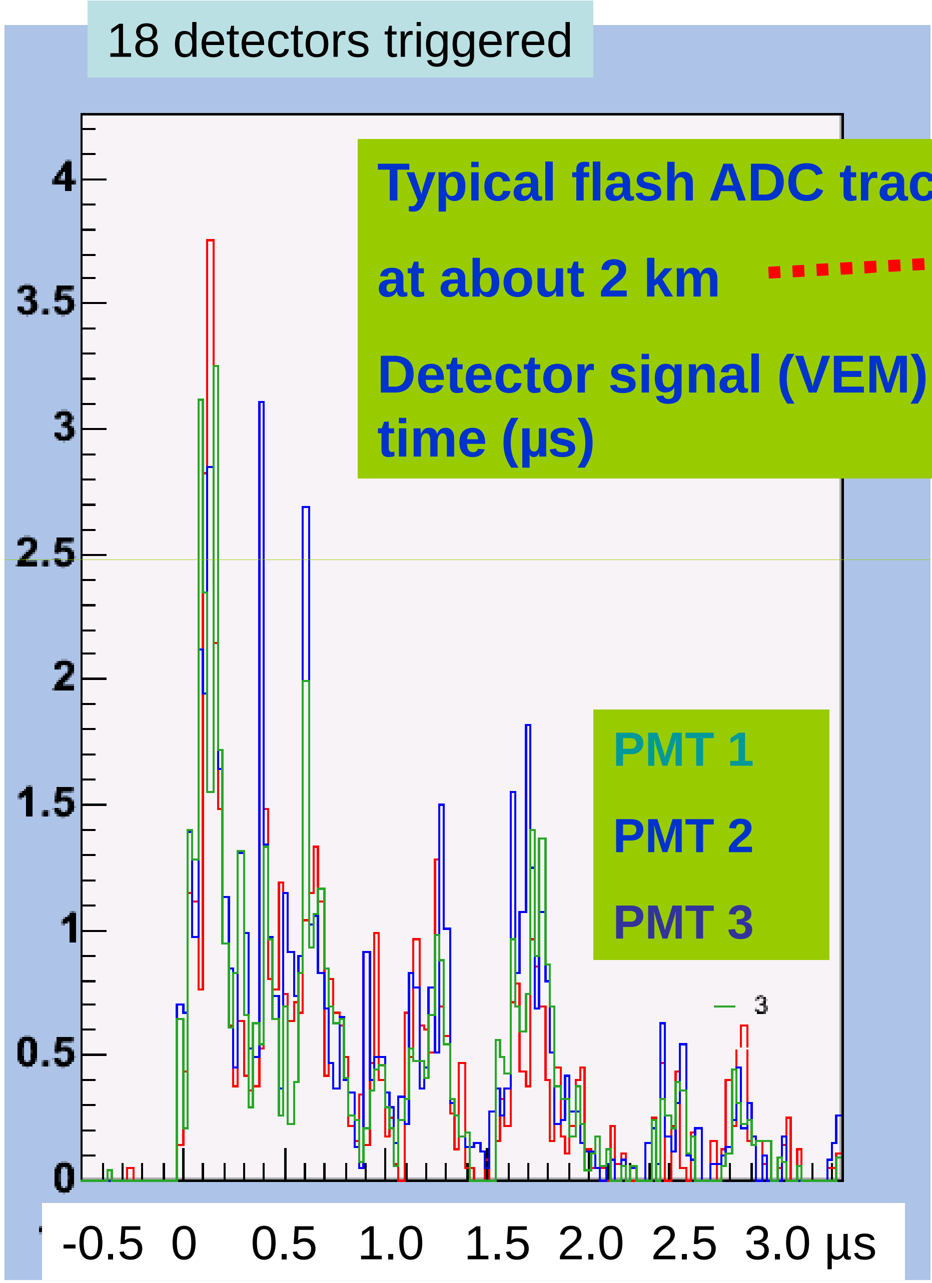
- 1636 surface detector tank assemblies deployed
- 1610 surface detector stations with water
- 1548 surface detector stations have electronics


GPS Receiver
and radio transmission

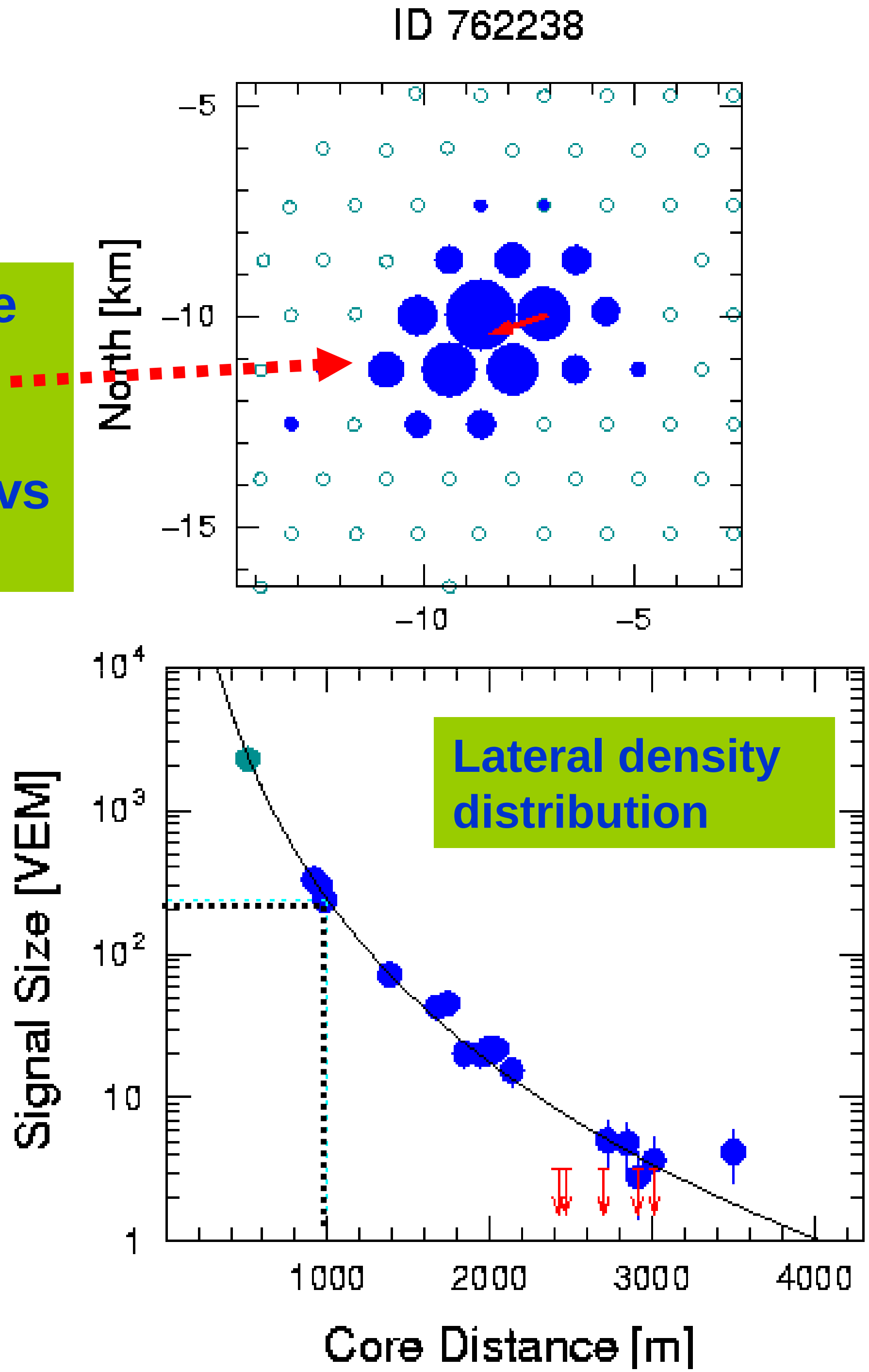
Telecommunication system



θ~ 48°, ~ 70 EeV

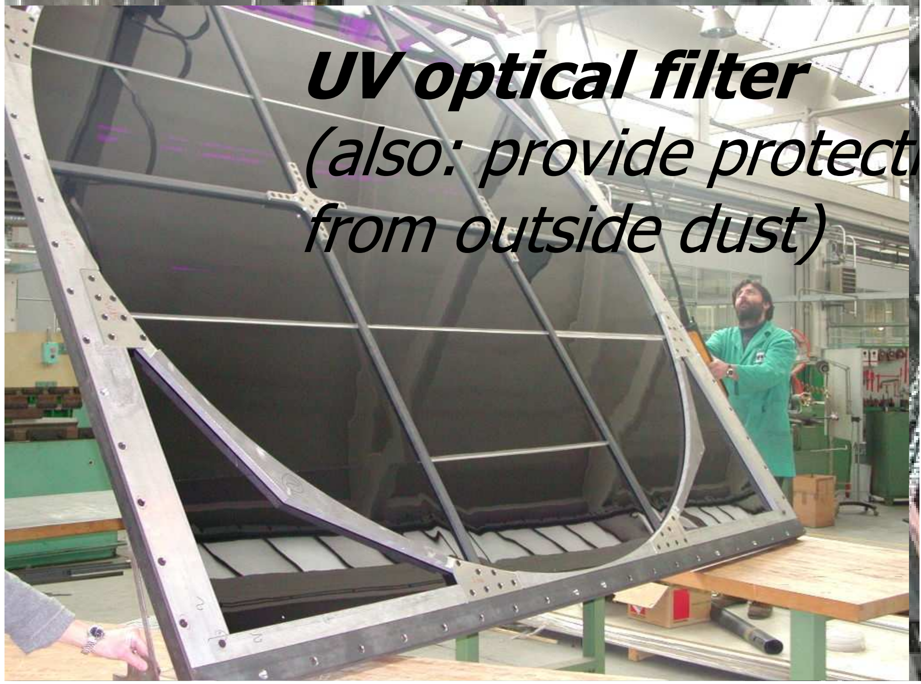


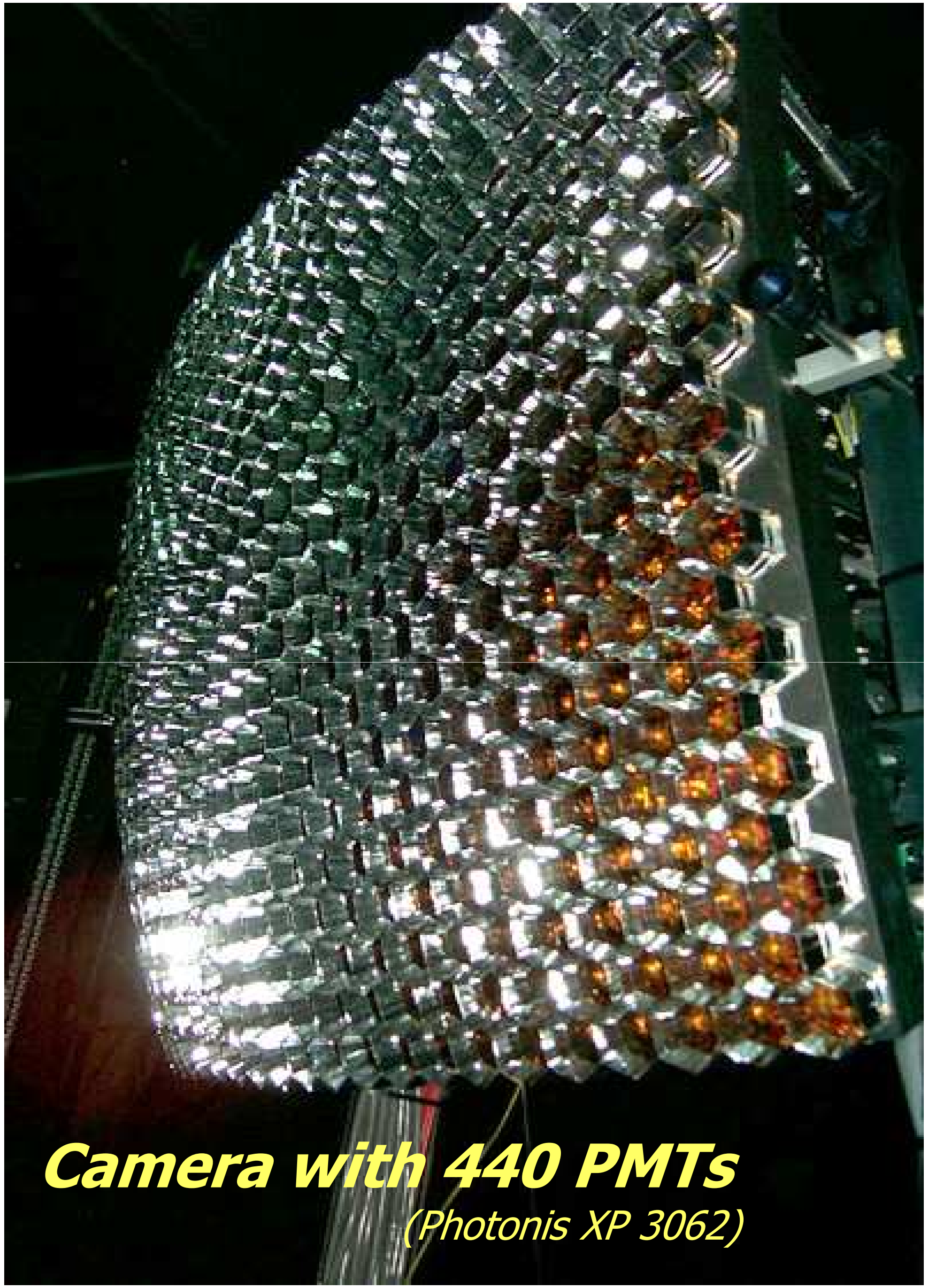
18 detectors triggered
Typical flash ADC trace
at about 2 km
Detector signal (VEM) vs time (μs)
PMT 1
PMT 2
PMT 3
0
0.5
1
1.5
2
2.5
3
3.5
4
-0.5 0 0.5 1.0 1.5 2.0 2.5 3.0 μs



ID 762238
North [km]
−5
−10
−15
−10
−5
Lateral density distribution
Signal Size [VEM]
Core Distance [m]
1
10
10^2
10^3
10^4
1000
2000
3000
4000

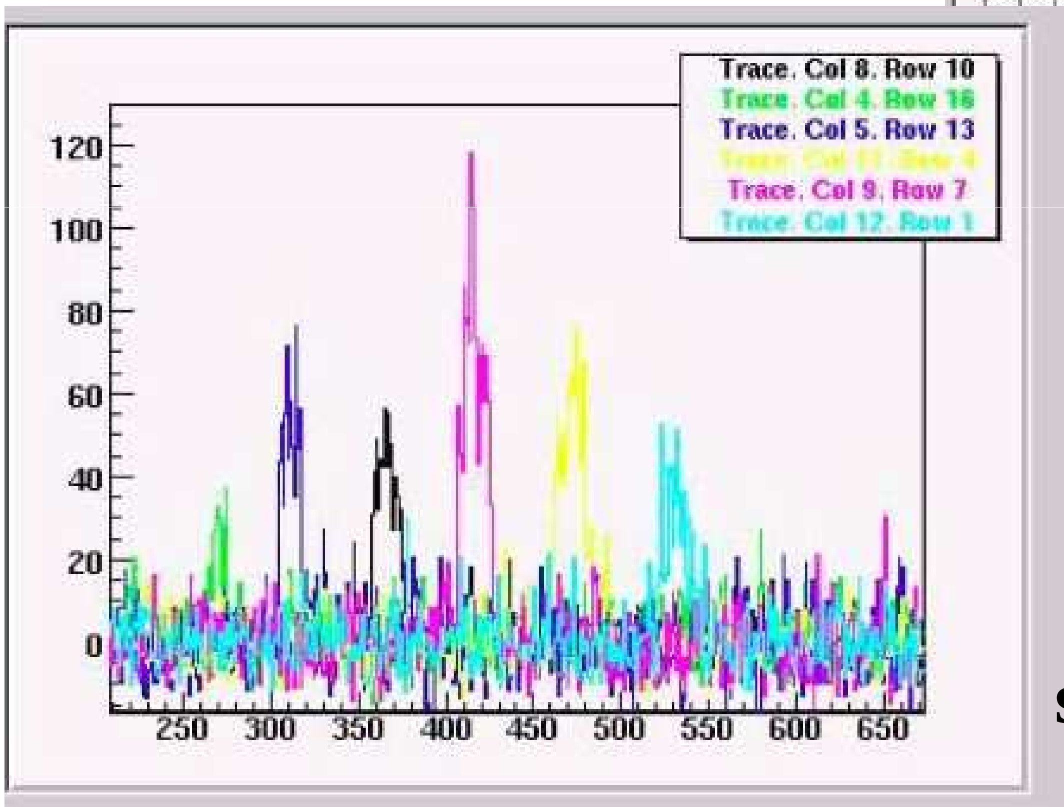

Schmidt Telescope
using 11 m^2 mirrors

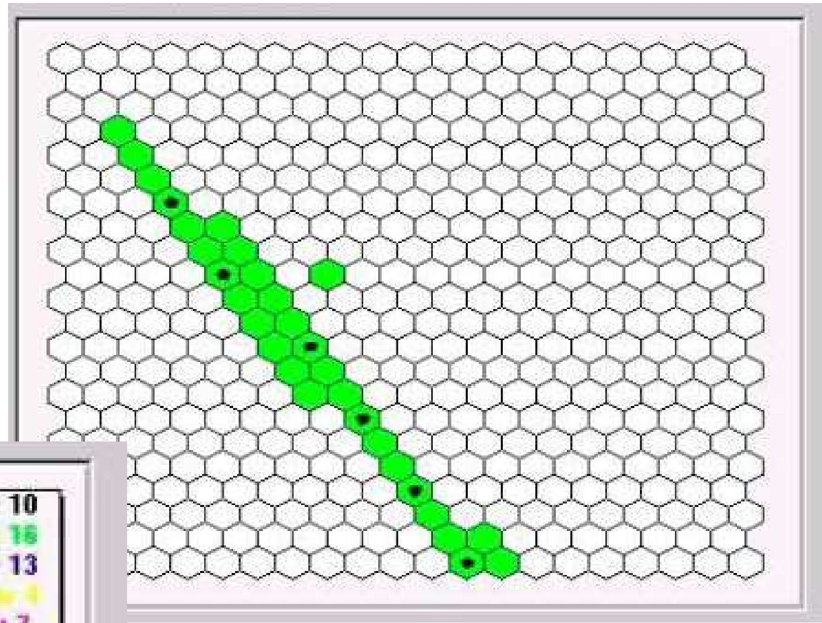

UV optical filter
(also: provide protecti
from outside dust)


Camera with 440 PMTs
(Photonis XP 3062)

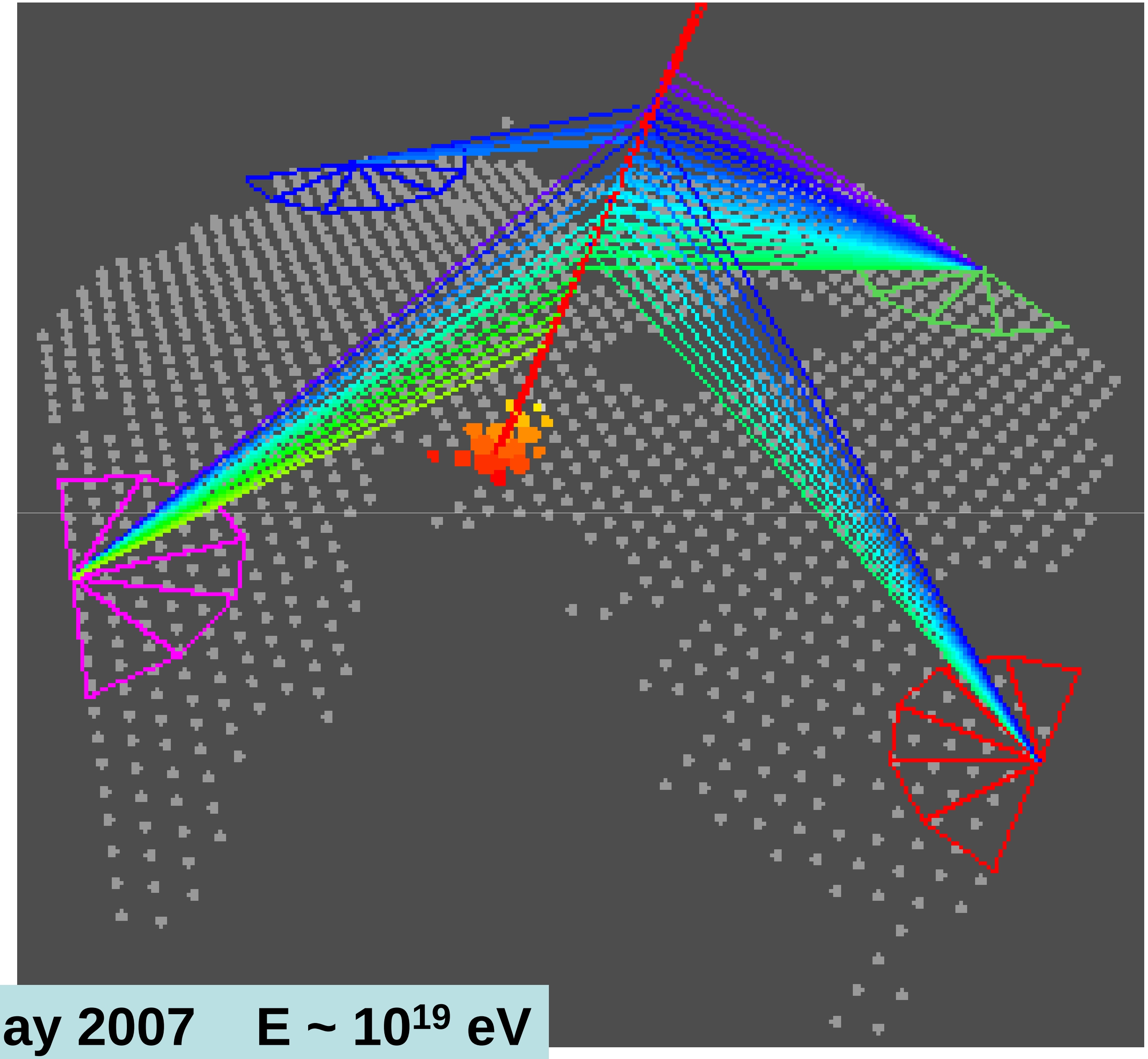
FD reconstruction

Signal and timing
Direction & energy

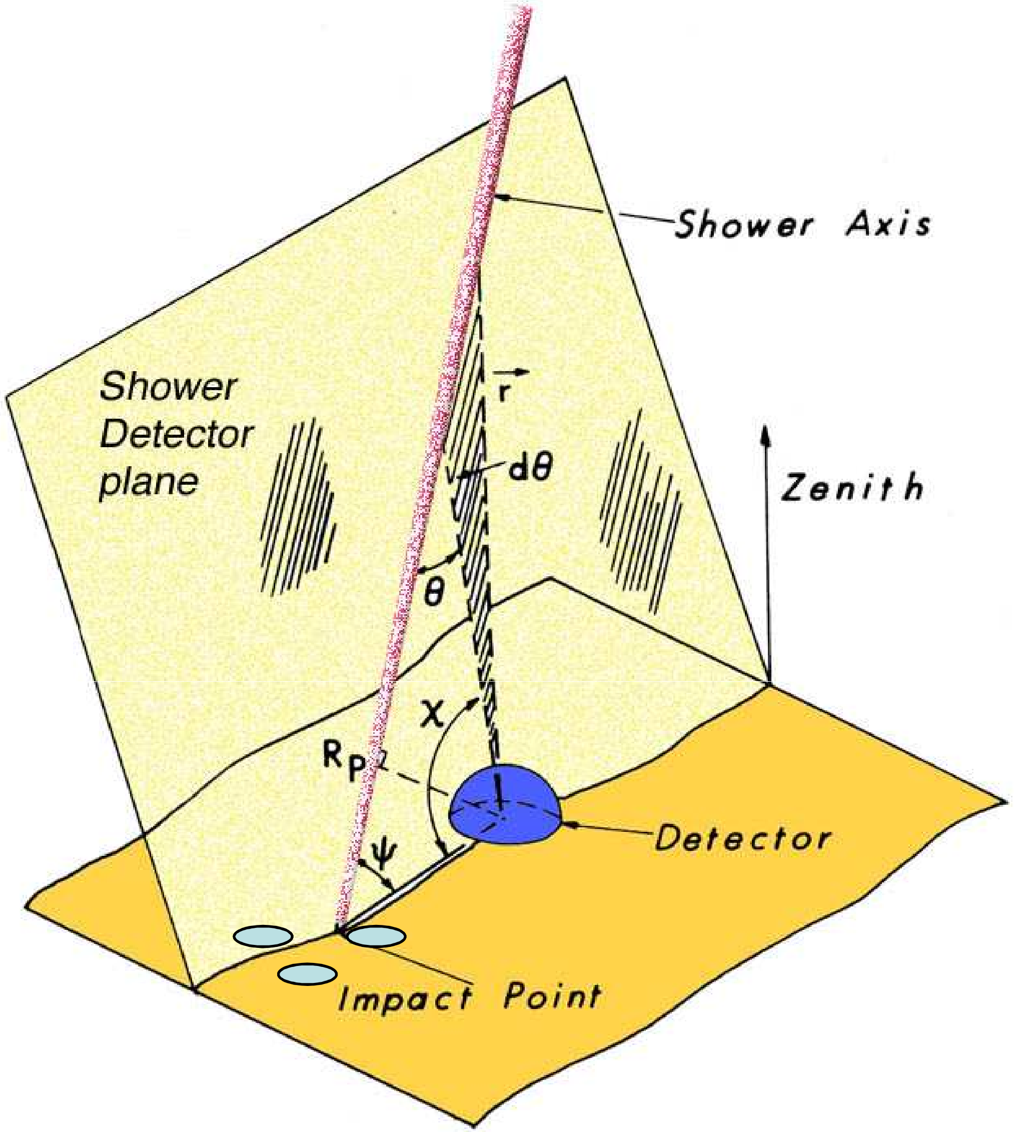




Pixel geometry
shower-detector plane



20 May 2007   E ~ 10^{19} eV



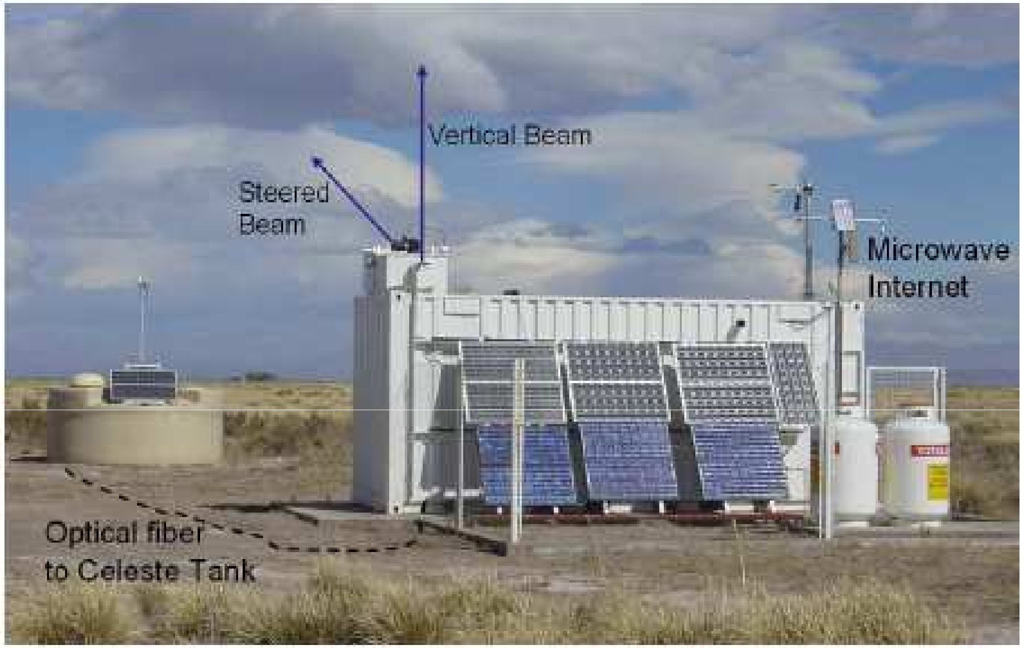
The essence of the hybrid approach

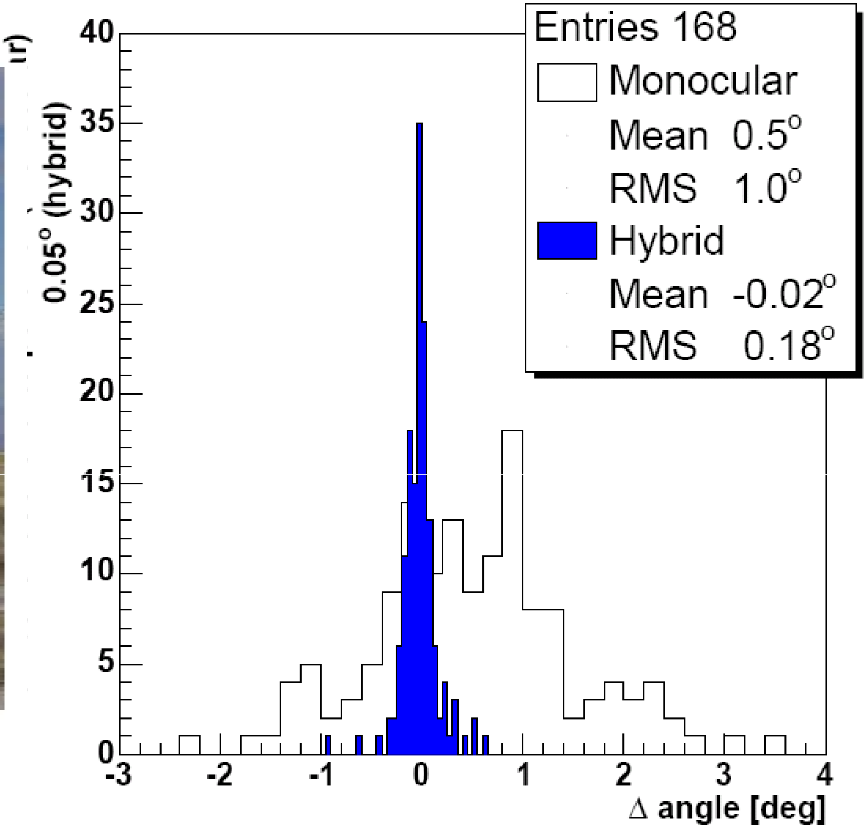
Precise shower geometry from degeneracy given by SD timing

Essential step towards high quality energy and X_{max} resolution

Times at angles, χ , are key to finding R_p

Angular Resolution from Central Laser Facility



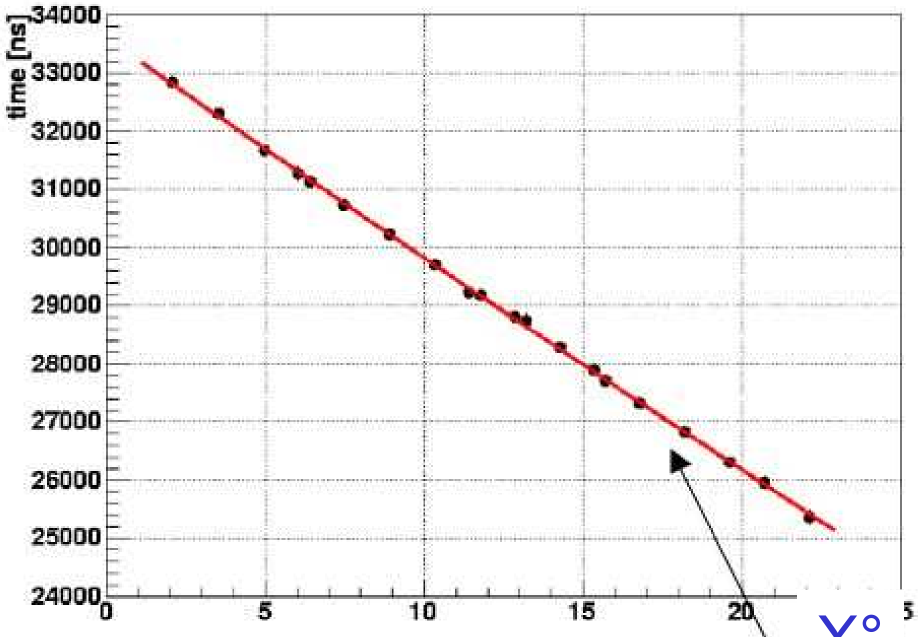


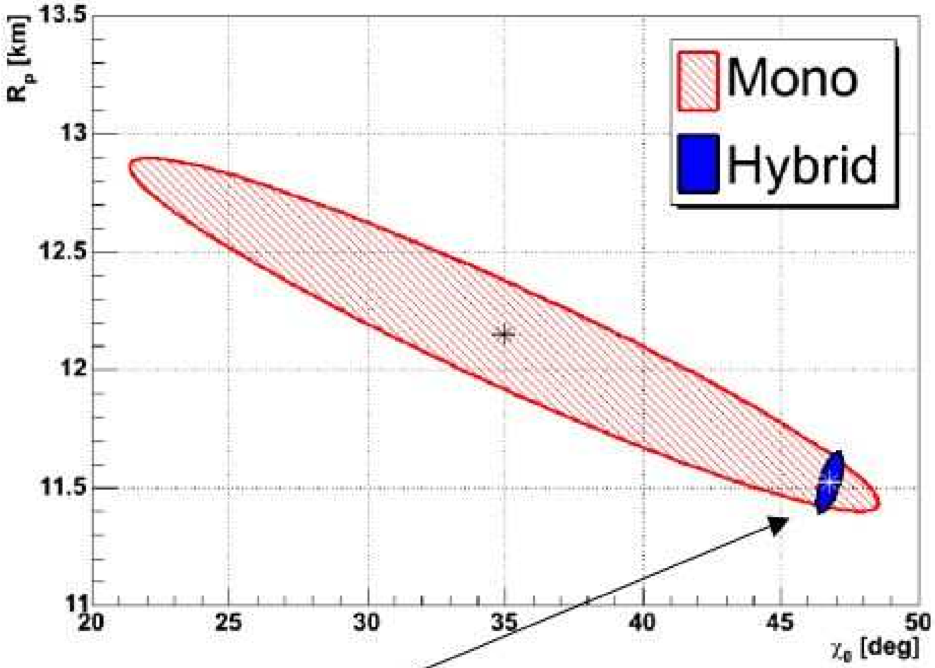
355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Mono/hybrid rms 1.0°/0.18°

Time, t

R_p km





X°

≈ line but

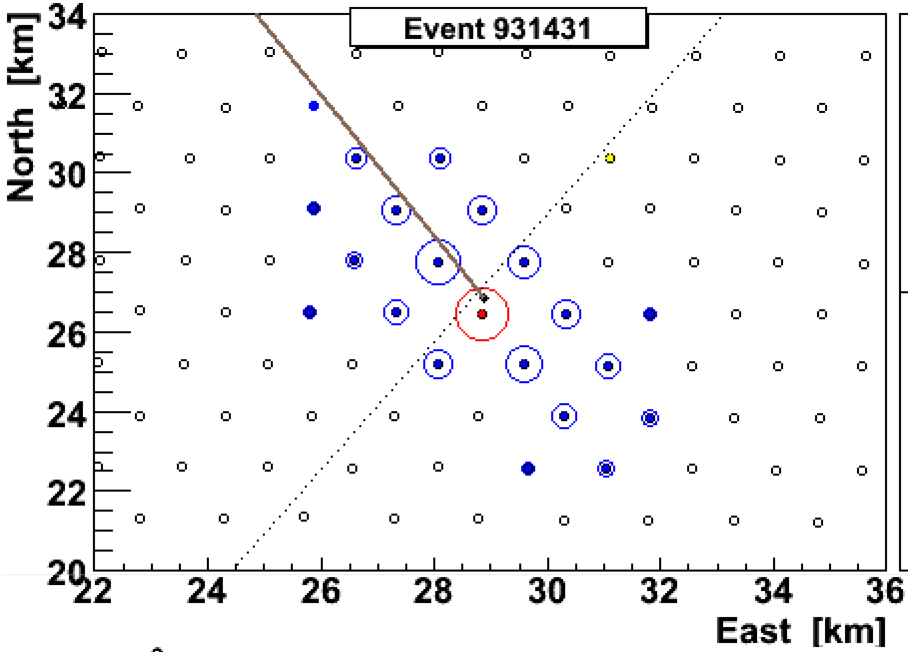
3 free parameters

T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

7 tank event

A Hybrid Event



Core location

Easting 468693 $\pm$ 59

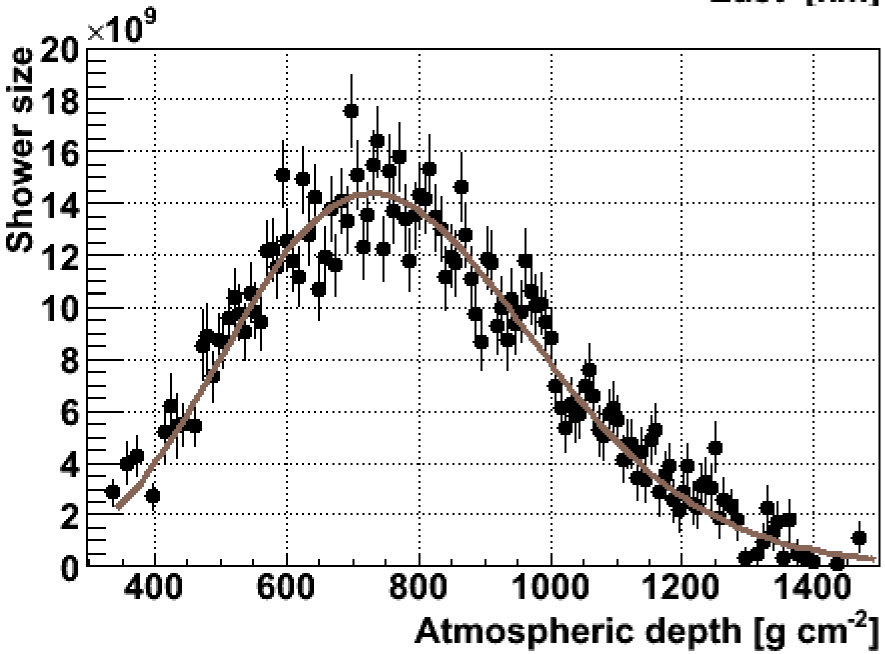
Northing 6087022 $\pm$ 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^\circ$

$\phi = (119.7 \pm 0.1)^\circ$



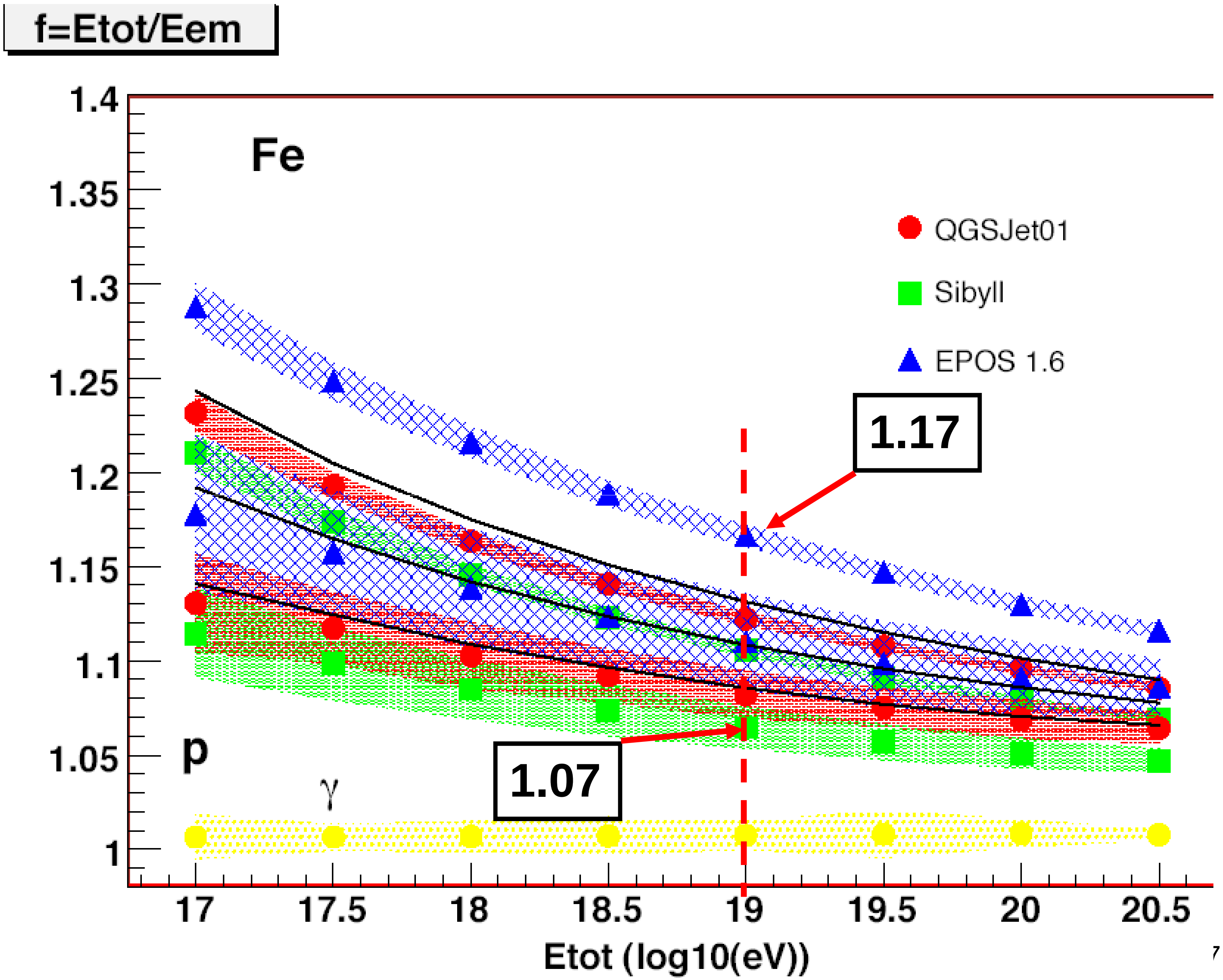
Energy Estimate:

X_{max} = (728 $\pm$ 20) g cm^{-2}

χ^2/dof = 258 / 134

E_{em} = (21 $\pm$ 5) EeV

E_{tot} = (23 $\pm$ 6) EeV


f=Etot/Eem
Fe
p
γ
QGSJet01
Sibyll
EPOS 1.6
1.17
1.07
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
17
17.5
18
18.5
19
19.5
20
20.5
Etot (log10(eV))

Results from Pierre Auger Observatory

Data-taking started on 1 January 2004 with

125 (of 1600) water tanks

6 (of 24) fluorescence detectors

more or less continuous since then

~ 1.3 Auger years to 31 Aug 2007 for anisotropy

~ 1 Auger year for spectrum analysis

Energy Determination with Auger

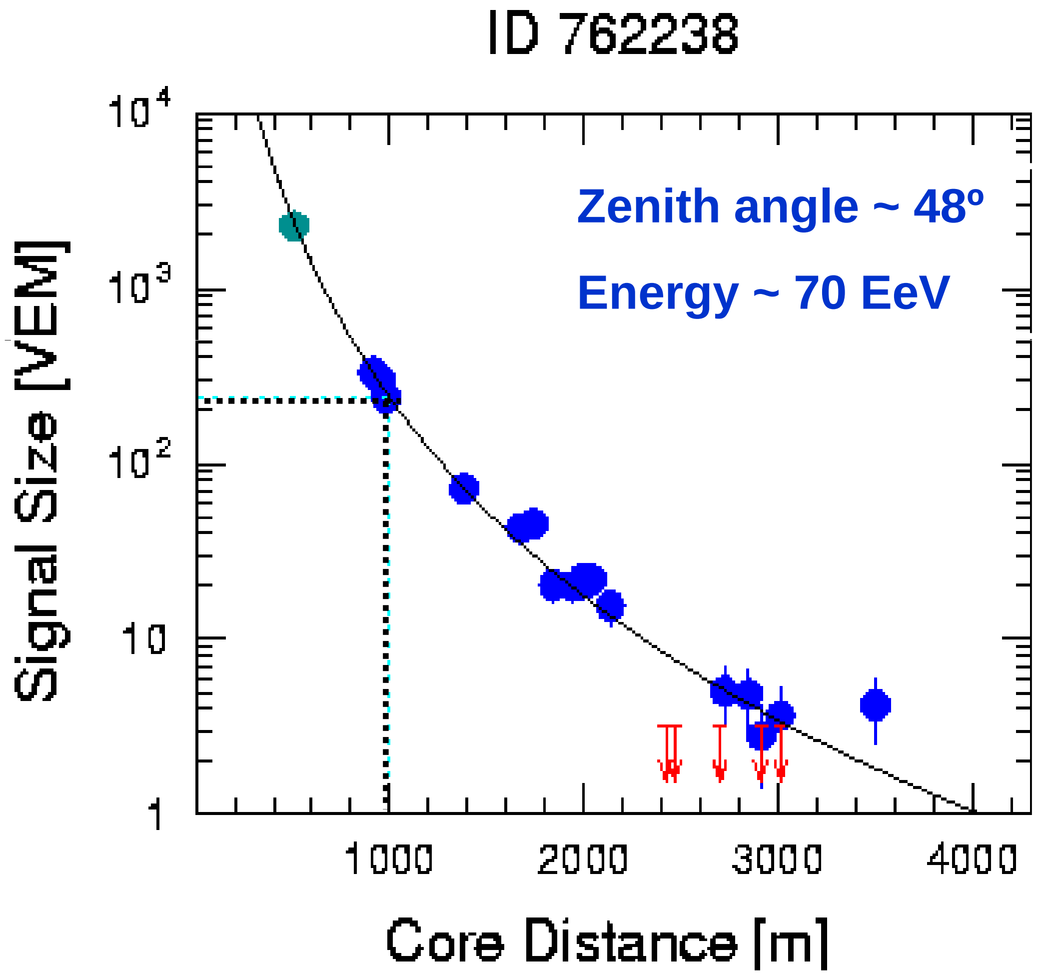
The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

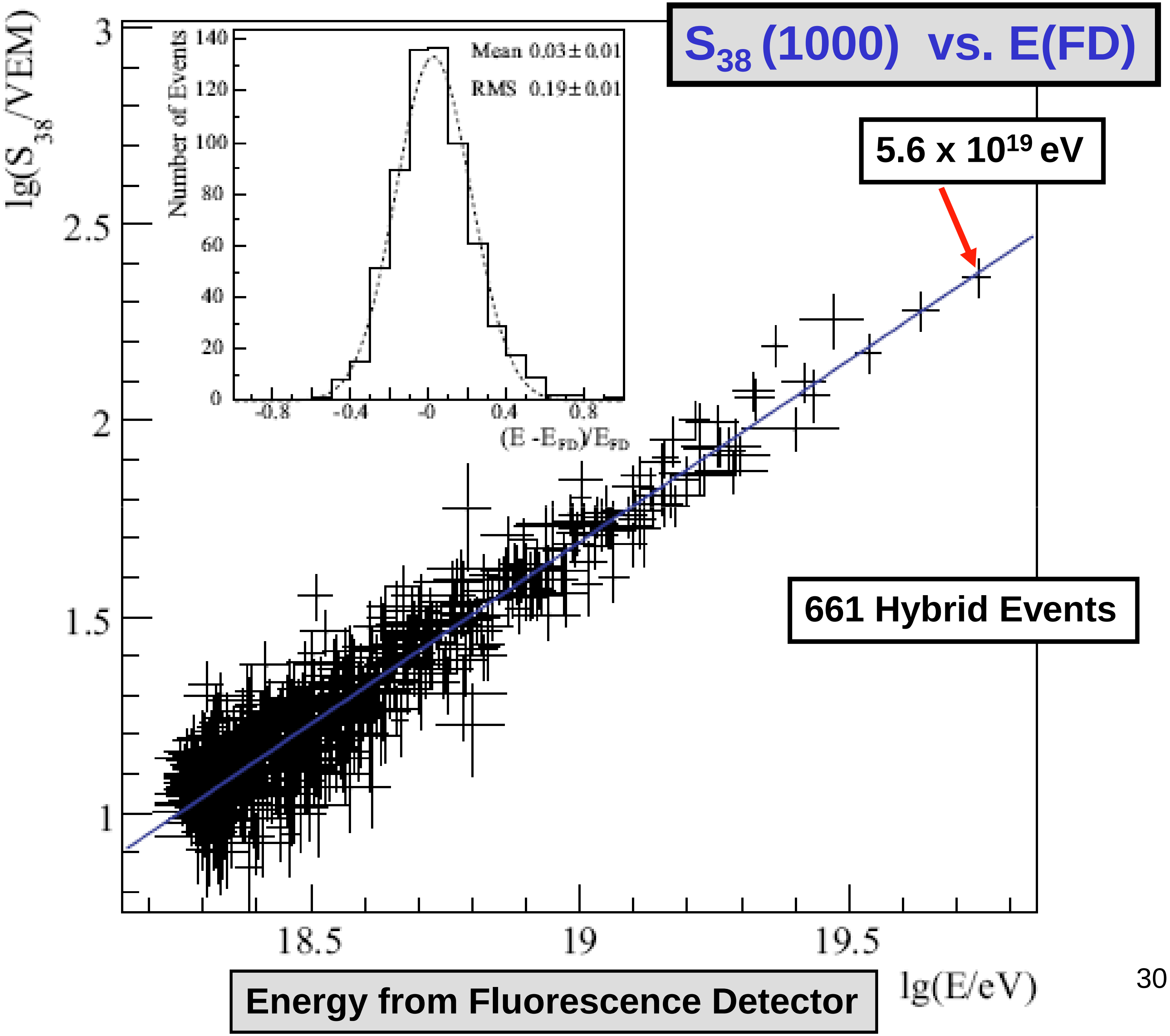
The detector signal at 1000 m from the shower core

– S(1000)

- determined for each surface detector event

S(1000) is proportional to the primary energy




S38 (1000) vs. E(FD)
5.6 x 10^19 eV
661 Hybrid Events
Energy from Fluorescence Detector
lg(S38/VEM)
lg(E/eV)
Number of Events
Mean 0.03±0.01
RMS 0.19±0.01
(E -EFD)/EFD

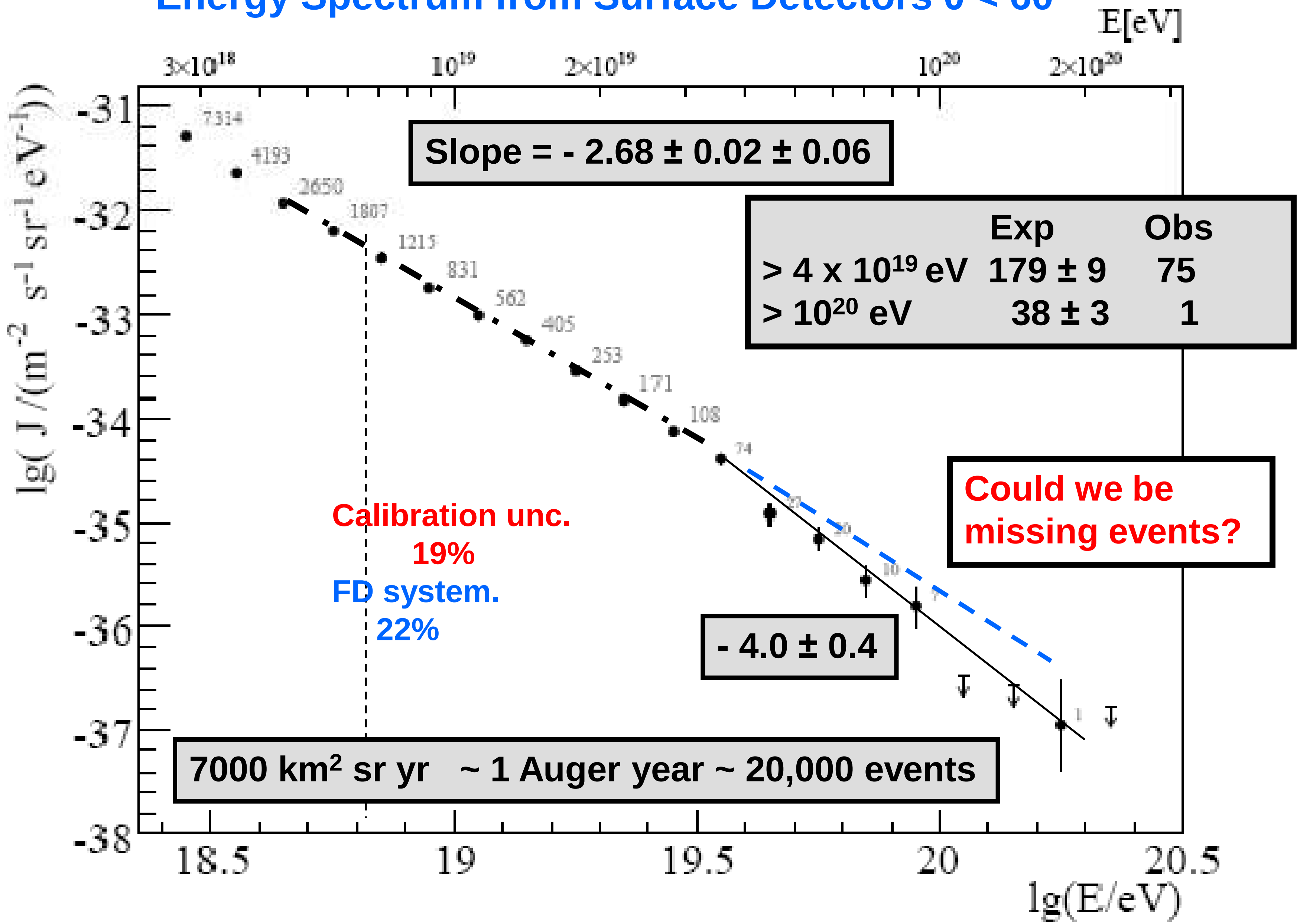
Summary of systematic uncertainties

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%

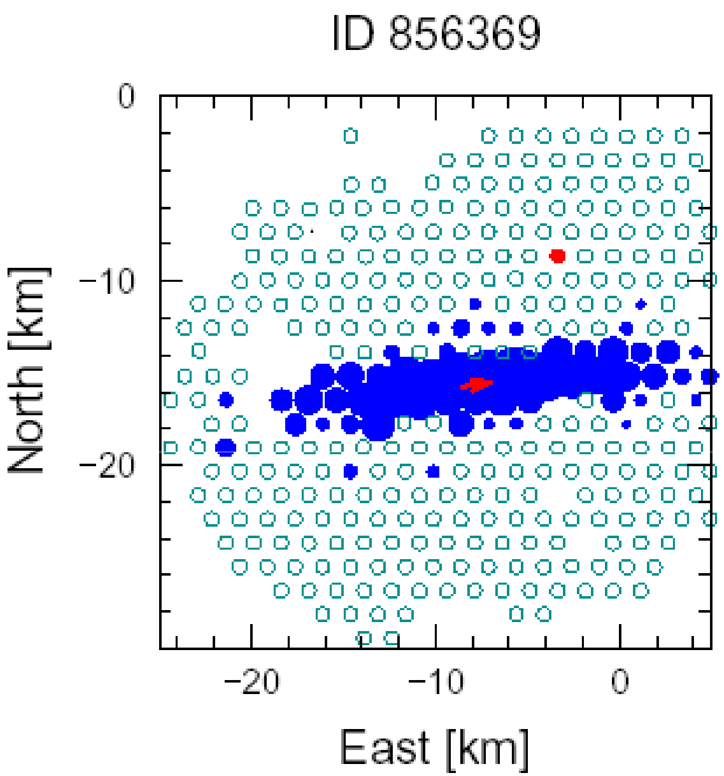
Note: Activity on several fronts to reduce these uncertainties

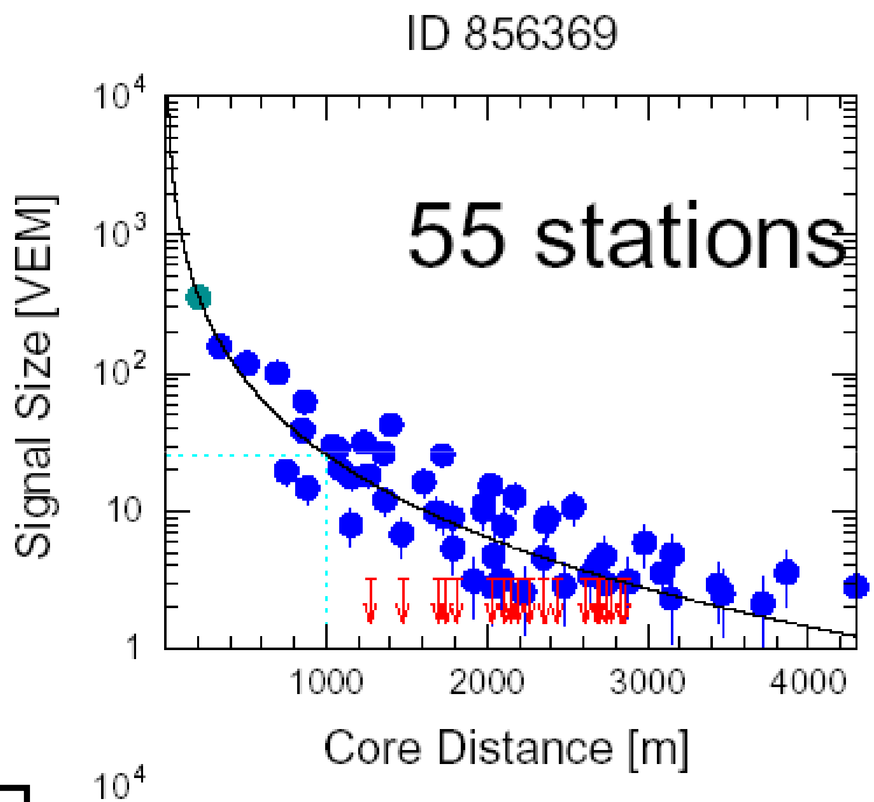
Fluorescence Detector Uncertainties Dominate

Energy Spectrum from Surface Detectors θ < 60°



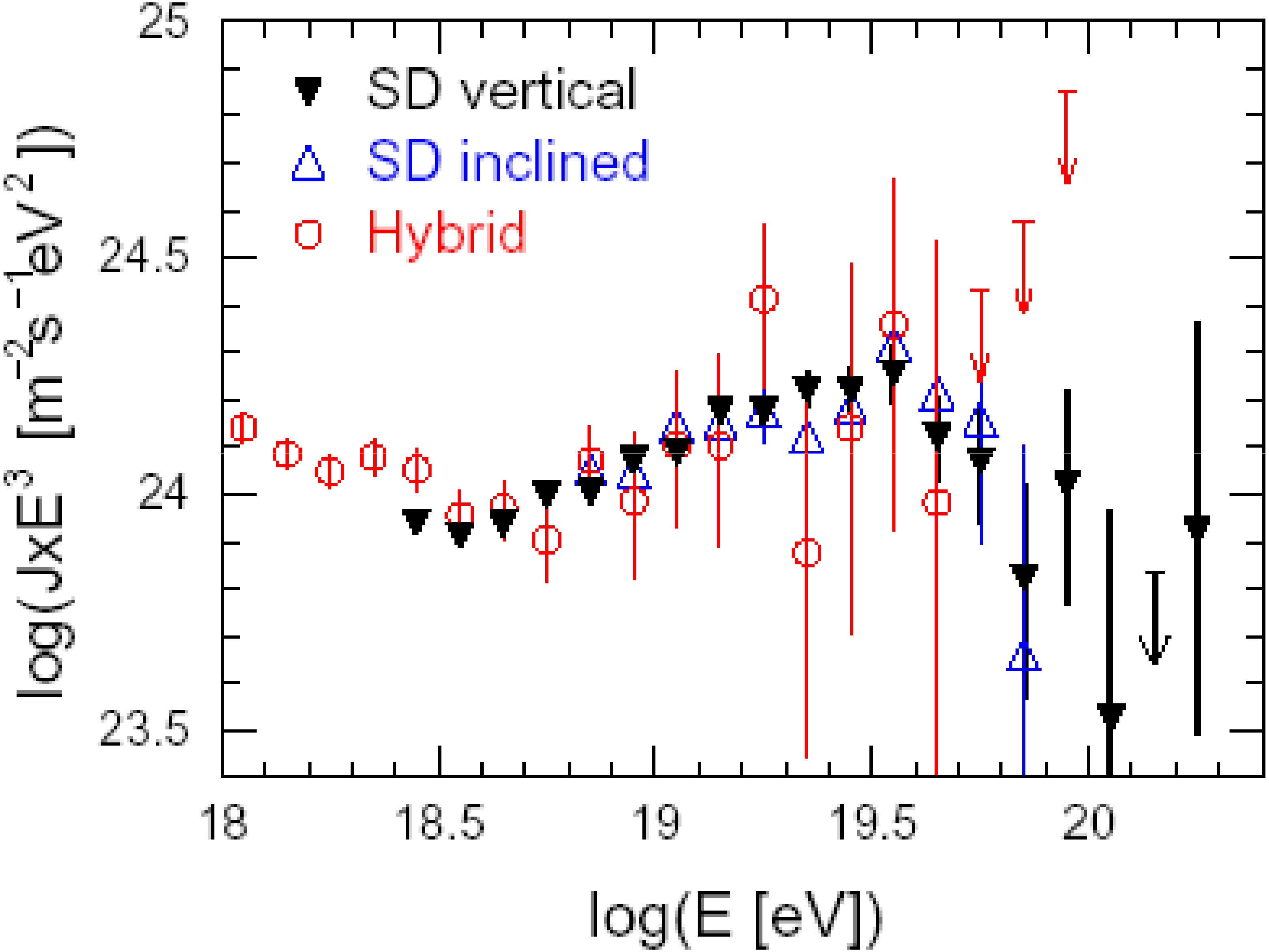
Evidence that we do not miss events with high multiplicity



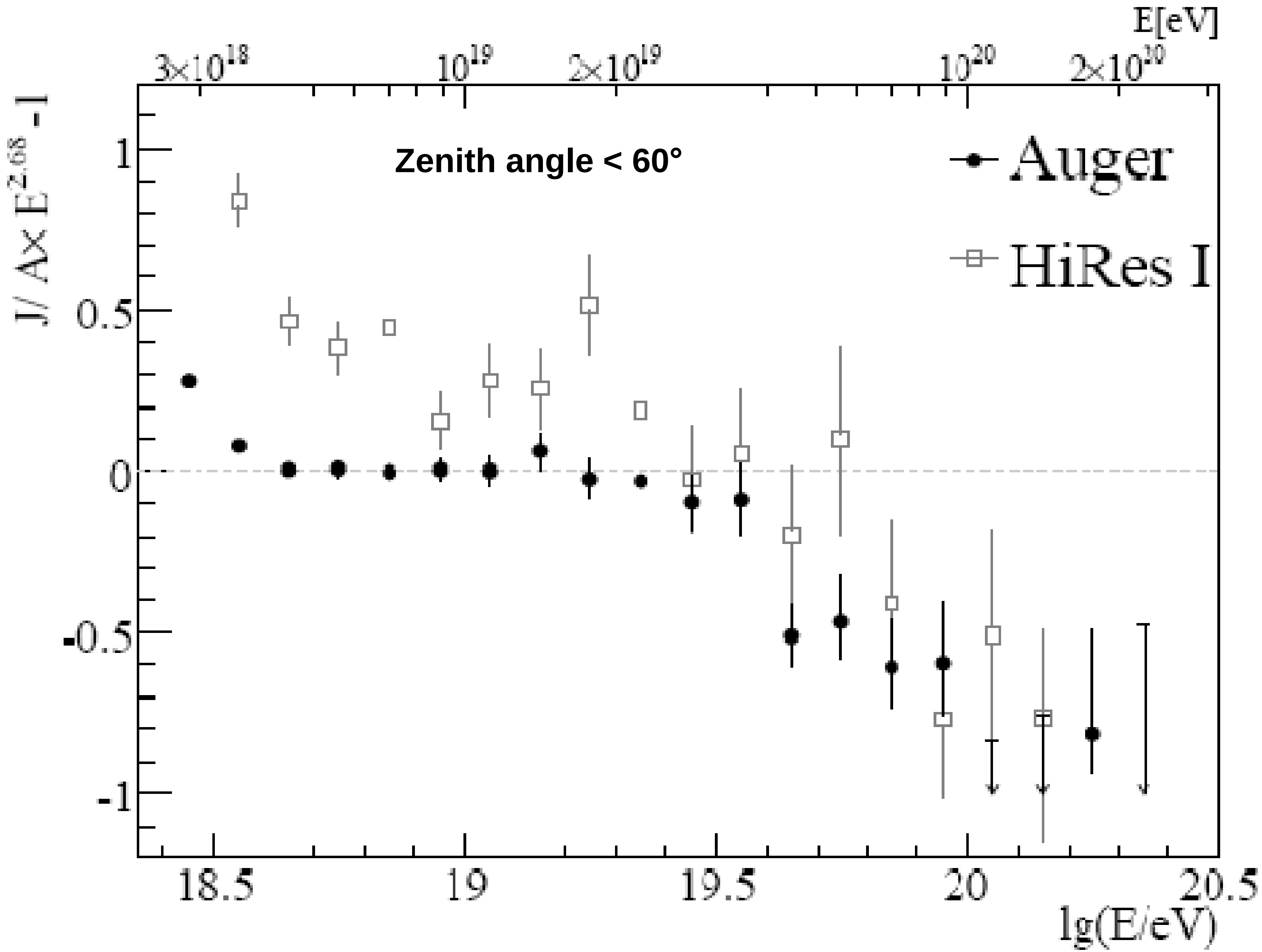


$\theta = 79°$

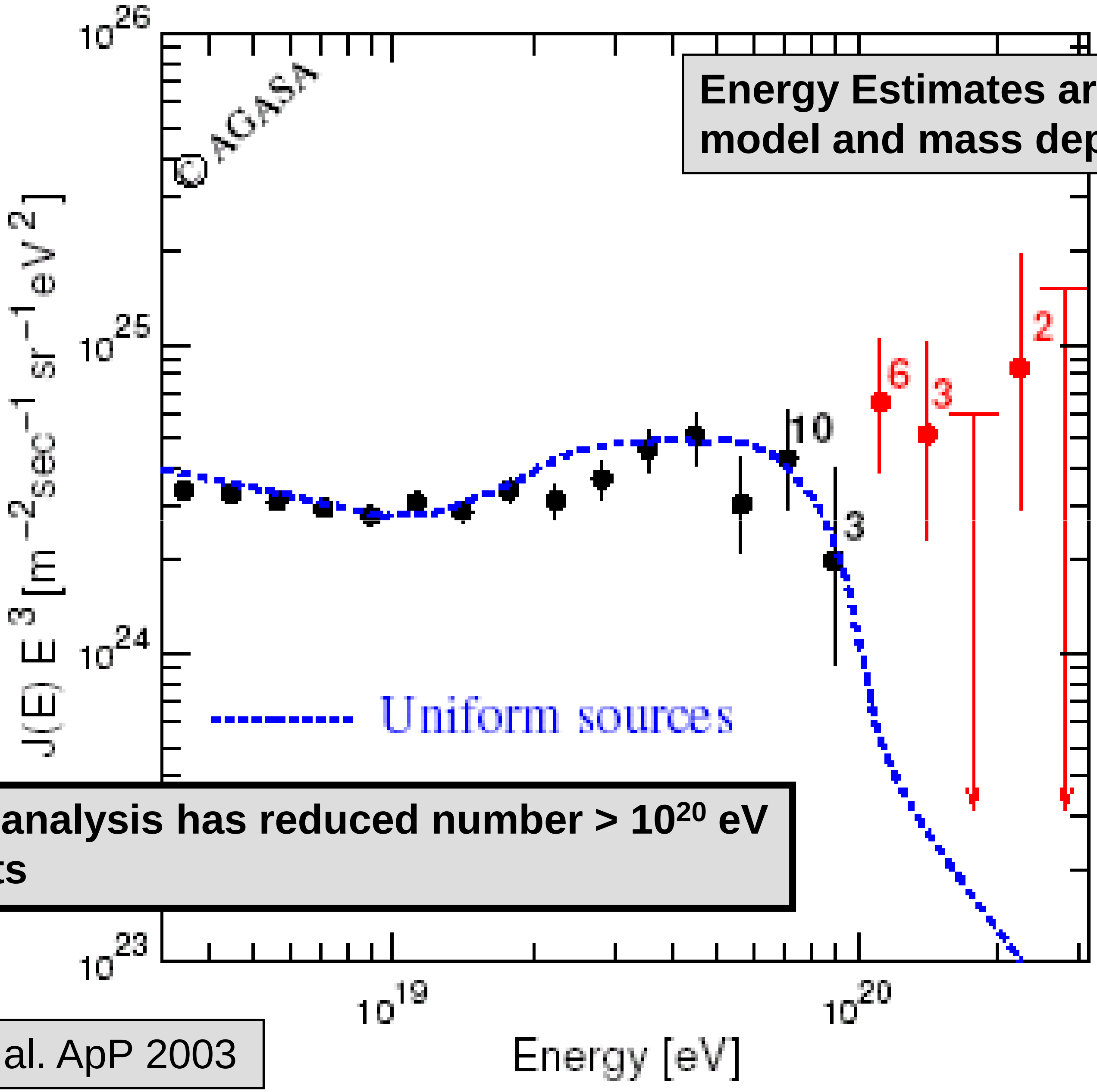
Inclined Events offer additional aperture of ~ 29% to 80°



SD vertical
SD inclined
Hybrid
25
24.5
24
23.5
18
18.5
19
19.5
20
log(JxE^3 [m^{-2}s^{-1}eV^2])
log(E [eV])


Zenith angle < 60°
Auger
HiRes I
E[eV]
3×10^18
10^19
2×10^19
10^20
2×10^20
J/ A× E^2.68 -1
lg(E/eV)
1
0.5
0
-0.5
-1
18.5
19
19.5
20
20.5

AGASA: Surface Detectors: Scintillators over 100 km^2



Energy Estimates are model and mass dependent

Recent reanalysis has reduced number > 10^{20} eV to 6 events

Takeda et al. ApP 2003

Summary of Inferences on Spectrum

- **Clear Evidence of Suppression of Flux > 4 x 10^{19} eV**

- **Rough agreement with HiRes at highest energies**
- **Auger statistics are superior**

  - but is it the GZK-effect (mass, recovery)?

- **AGASA result not confirmed**

  AGASA flux higher by about 2.5 at 10^{19} eV

  Excess over GZK above 10^{20} eV not found

- **Some events (~1 with Auger) above 10^{20} eV**

Only a few per millenium per km^2 above 10^{20} eV

Searching for Anisotropies

We have made targeted searches of claims by others

- no confirmations (Galactic Centre, BL Lacs)

- **There are no strong predictions of sources**

(though there have been very many)

So:-

- **Take given set of data and search exhaustively**
- **Seal the ‘prescription’ and look with new data**

At the highest energies we think we have observed a significant signal

Using Veron-Cetty AGN catalogue

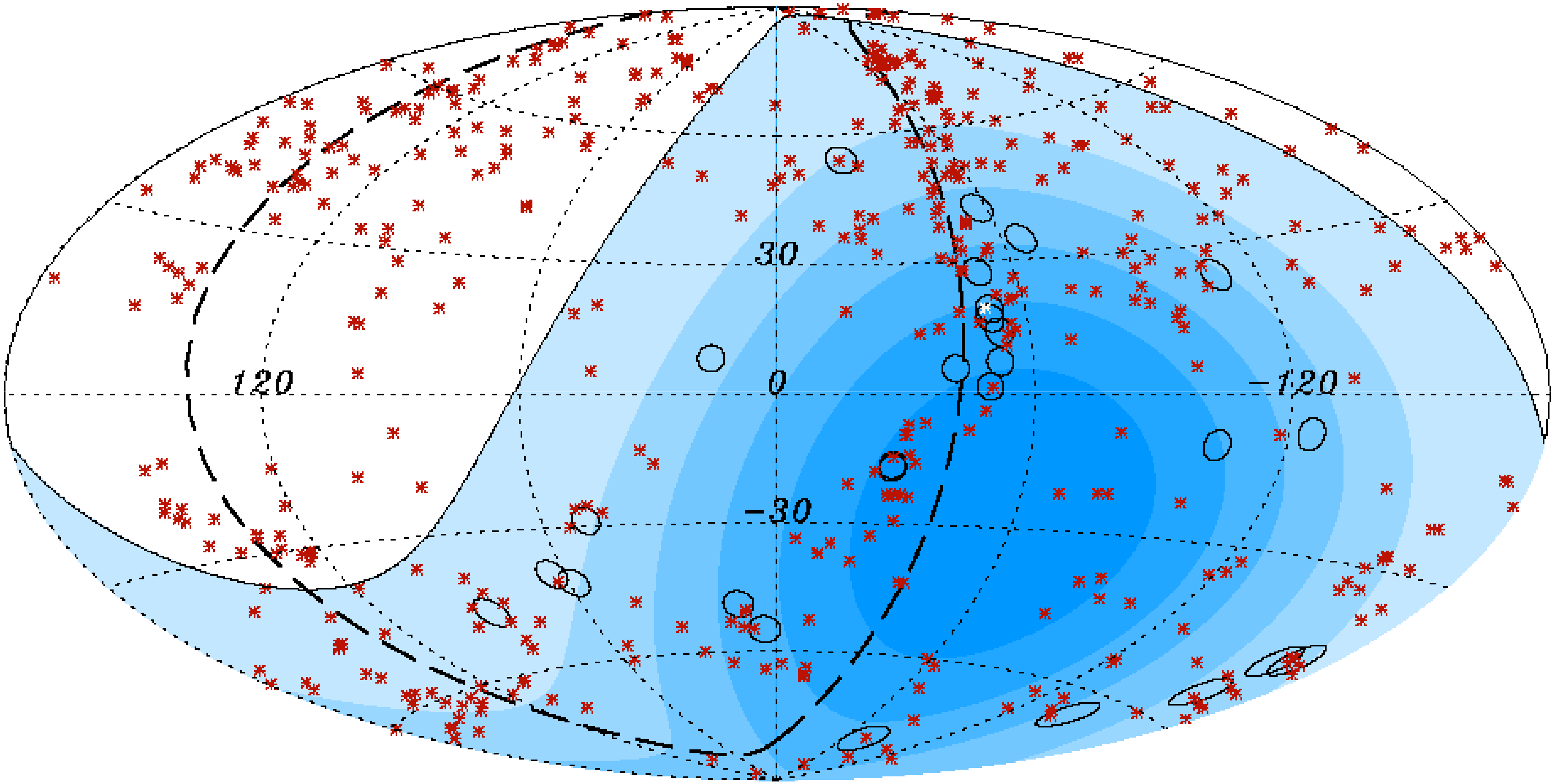
First scan gave ψ < 3.1°, z < 0.018 (75 Mpc) and E > 56 EeV

Period	total	AGN hits	Chance hits	Probability
1 Jan 04 - 26 May 2006	15	12	3.2	1^{st} Scan
27 May 06 – 31 August 2007	13	8	2.7	1.7×10^{-3}

Each exposure was 4500 km^2 sr yr

6 of 8 'misses' are with 12° of galactic plane

Science: 9 November 2007



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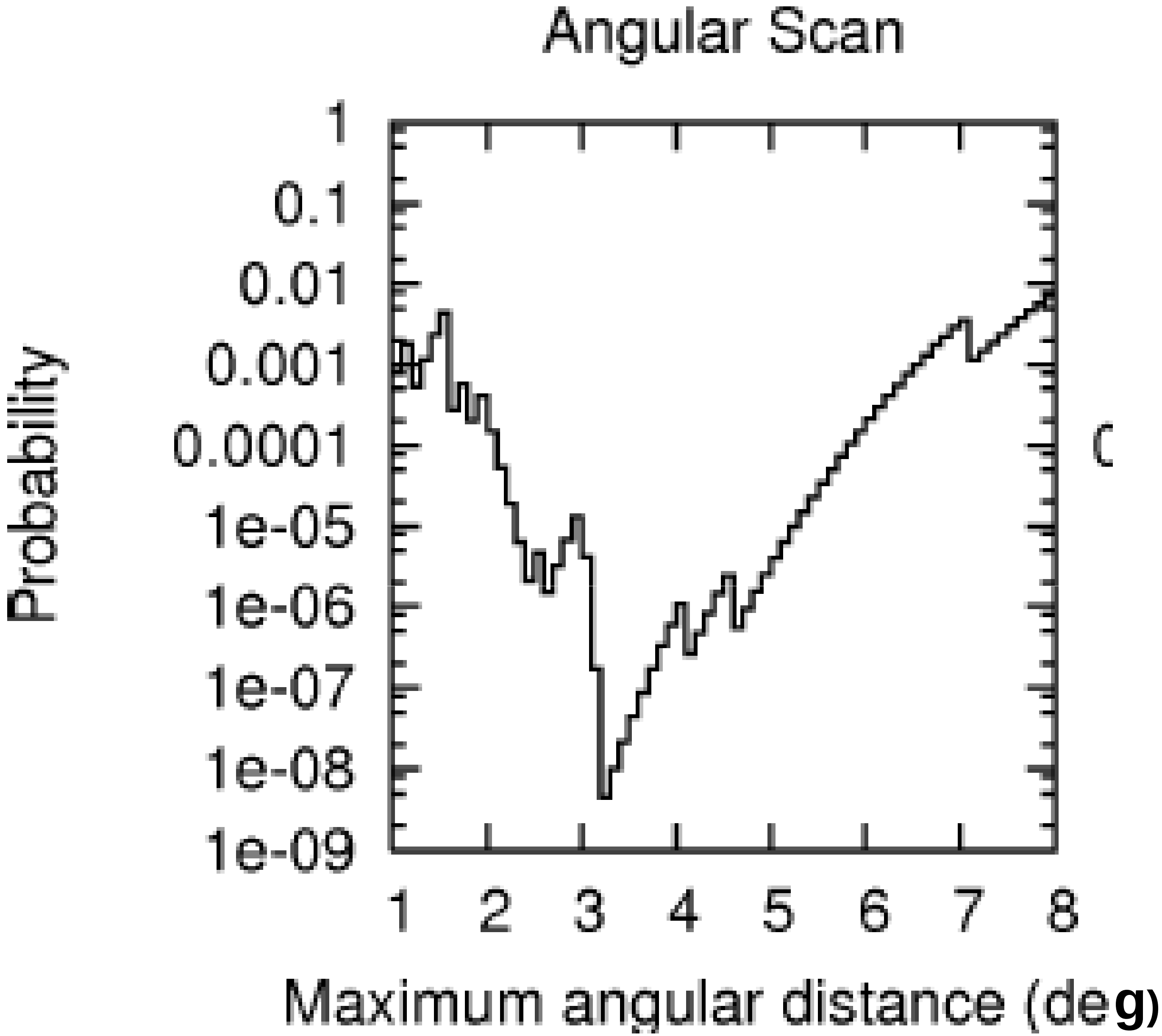
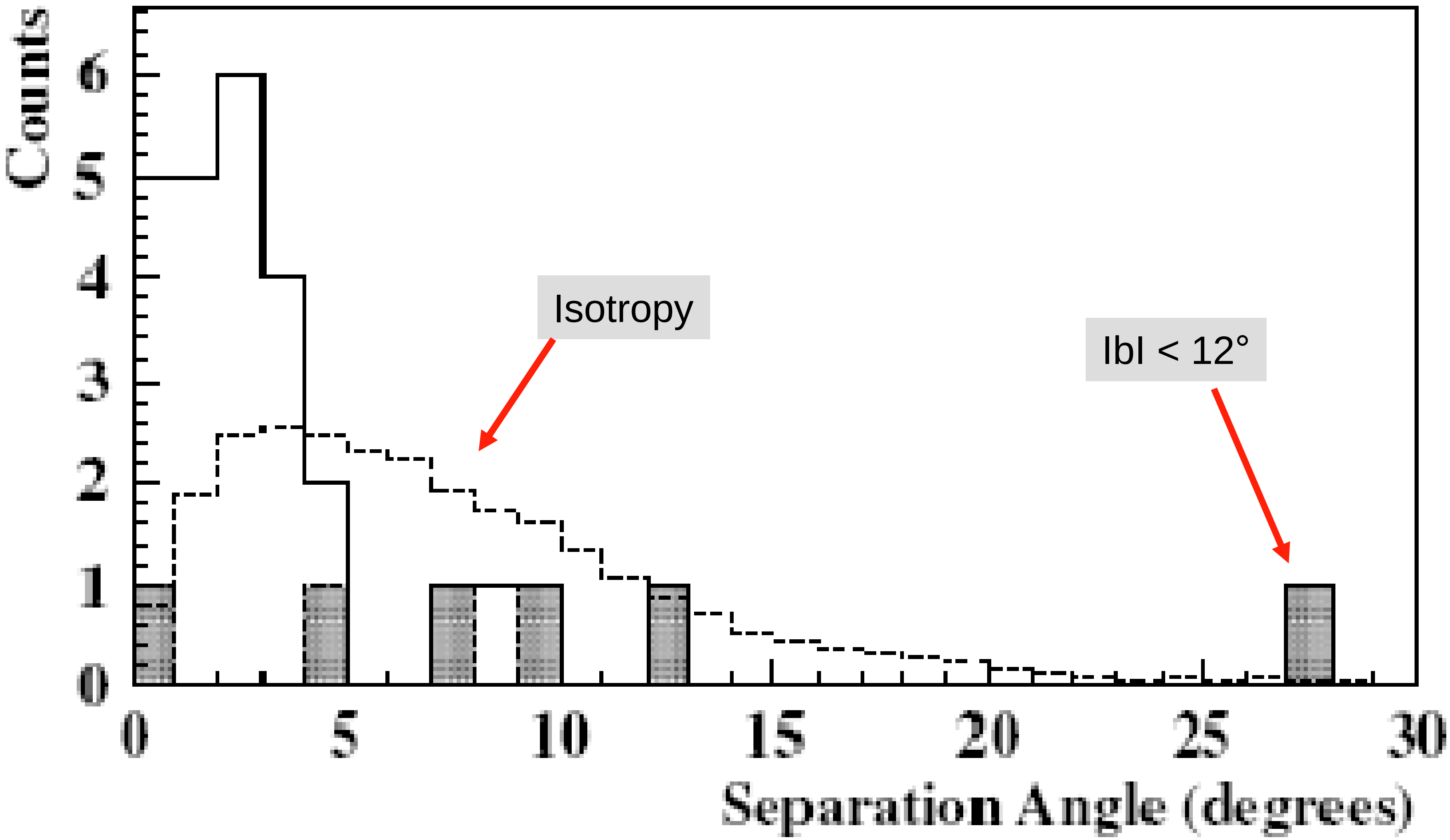
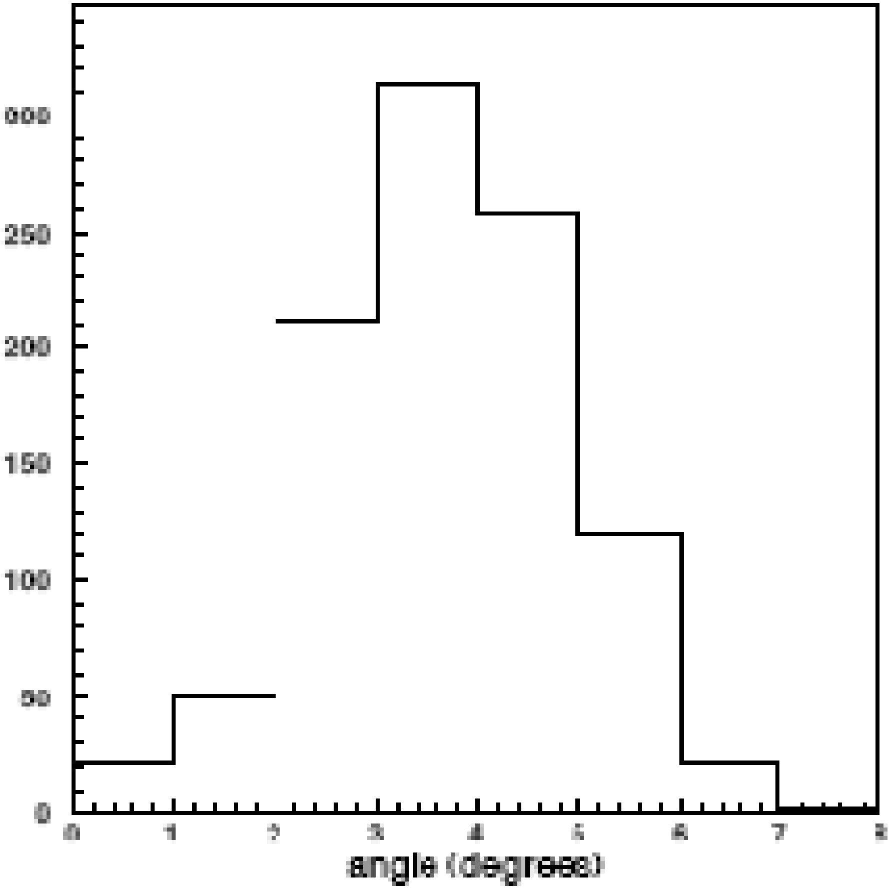
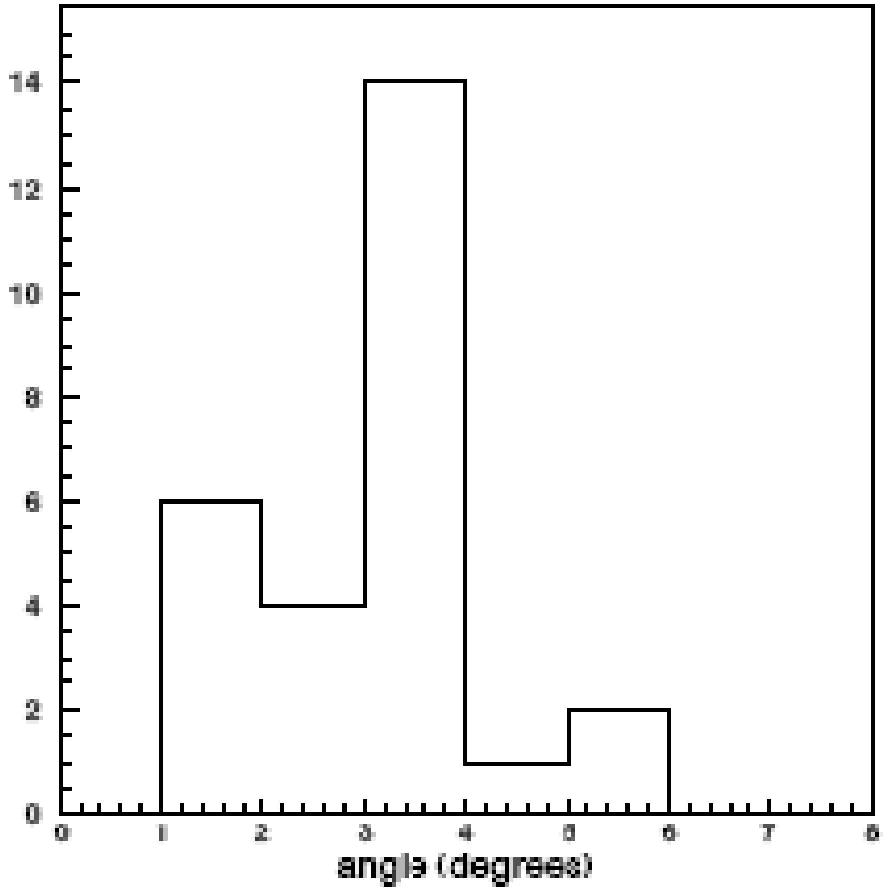


Angular scan with E > 57 EeV and z < 0.017



Distribution of angular separations to closest AGN within 71 Mpc





1000 isotropic protons

27 events with E > 57 EeV

B-SSS model of Galactic Field: some support from Han, Manchester and Lyne

Conclusions from ~ 1 year of data (as if full instrument)

1. There is a suppression of the CR flux above 4×10^{19} eV

2. The 27 events above 57 EeV are not uniformly distributed

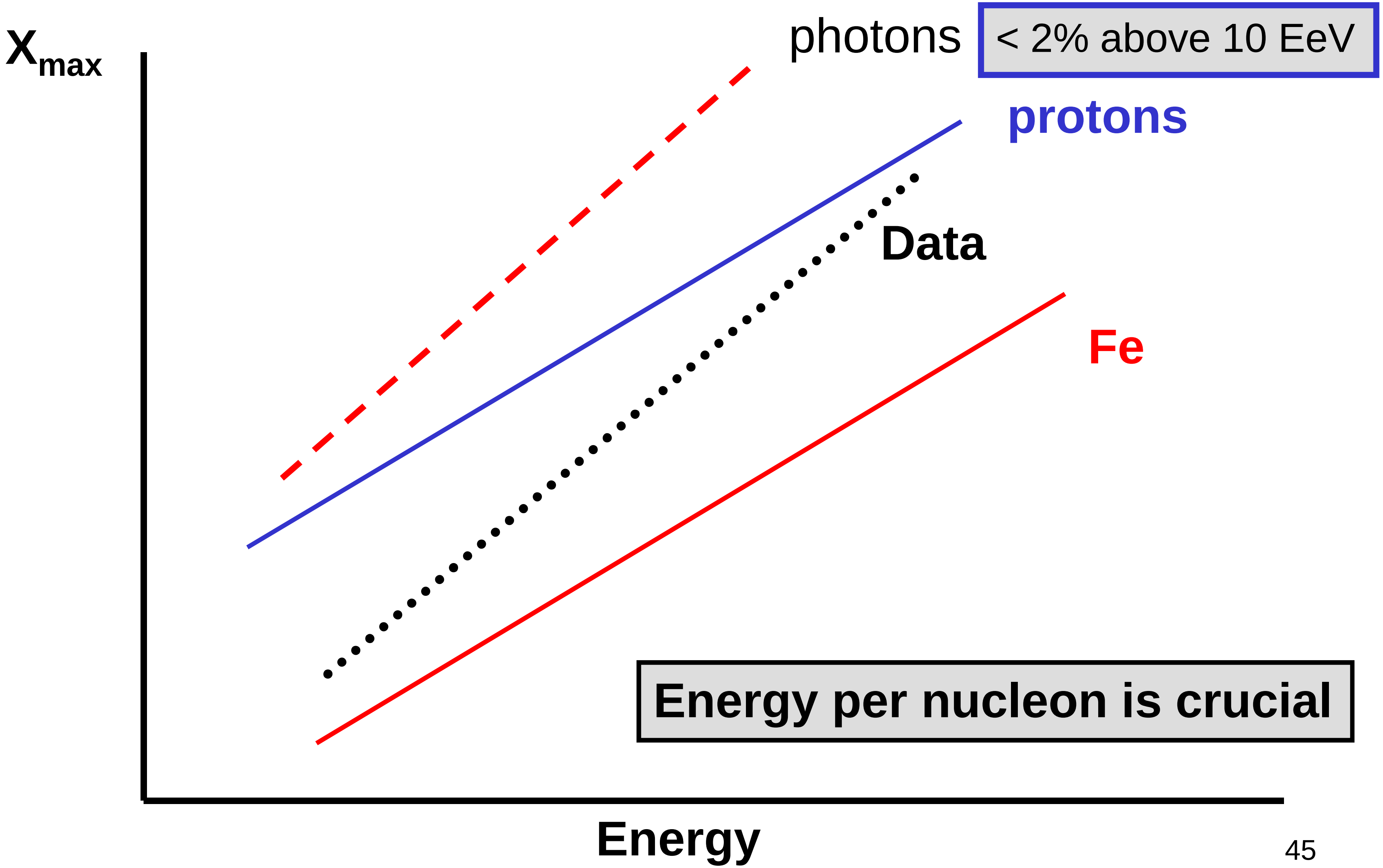
3. Events are associated with AGNs, from the Veron-Cetty catalogue, within 3.1° and 75 Mpc. This association has been demonstrated using an independent set of data with a probability of $\sim 1.7 \times 10^{-3}$ that it arises by chance (~1/600)

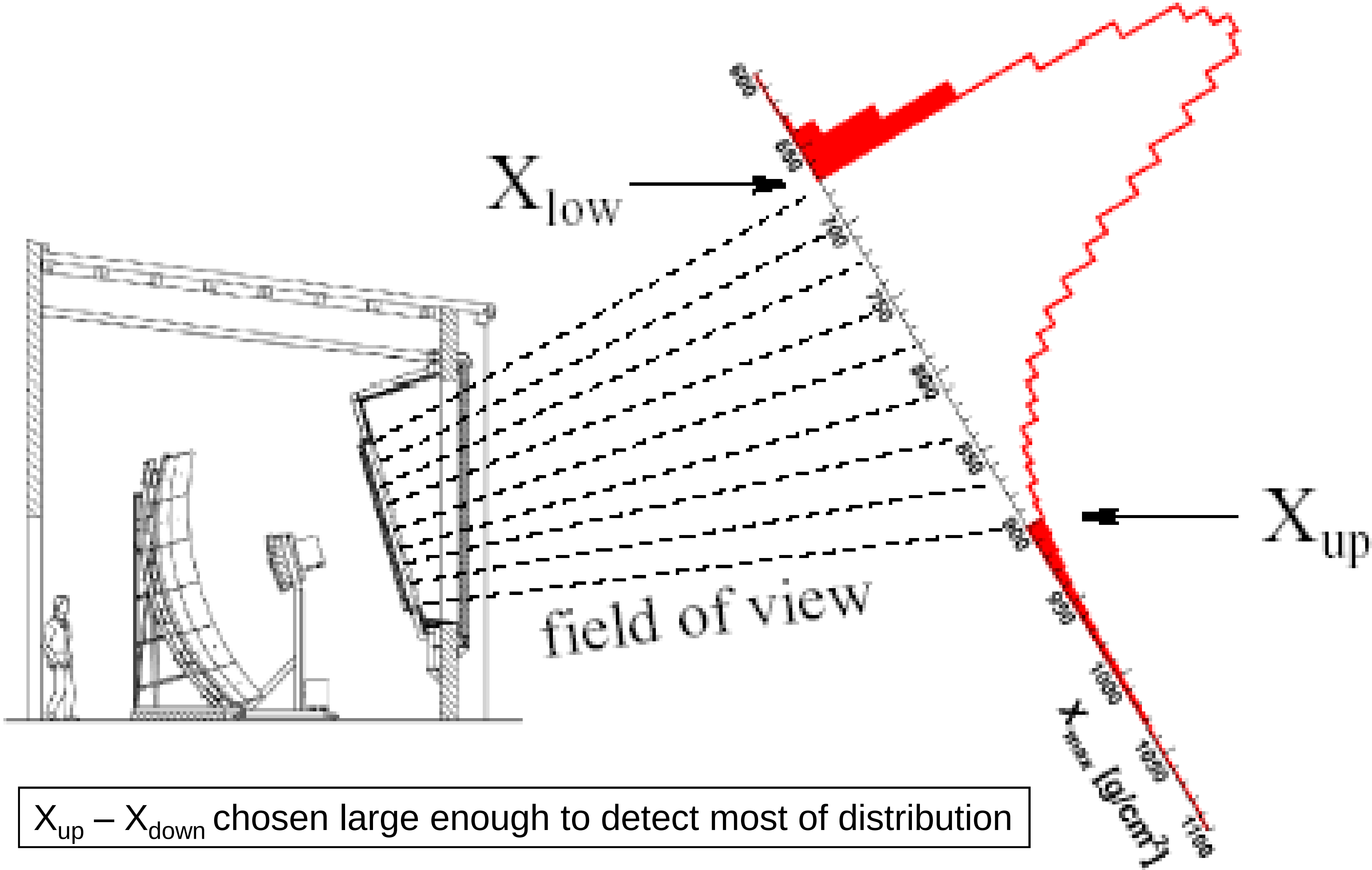
Interpretation:

BUT

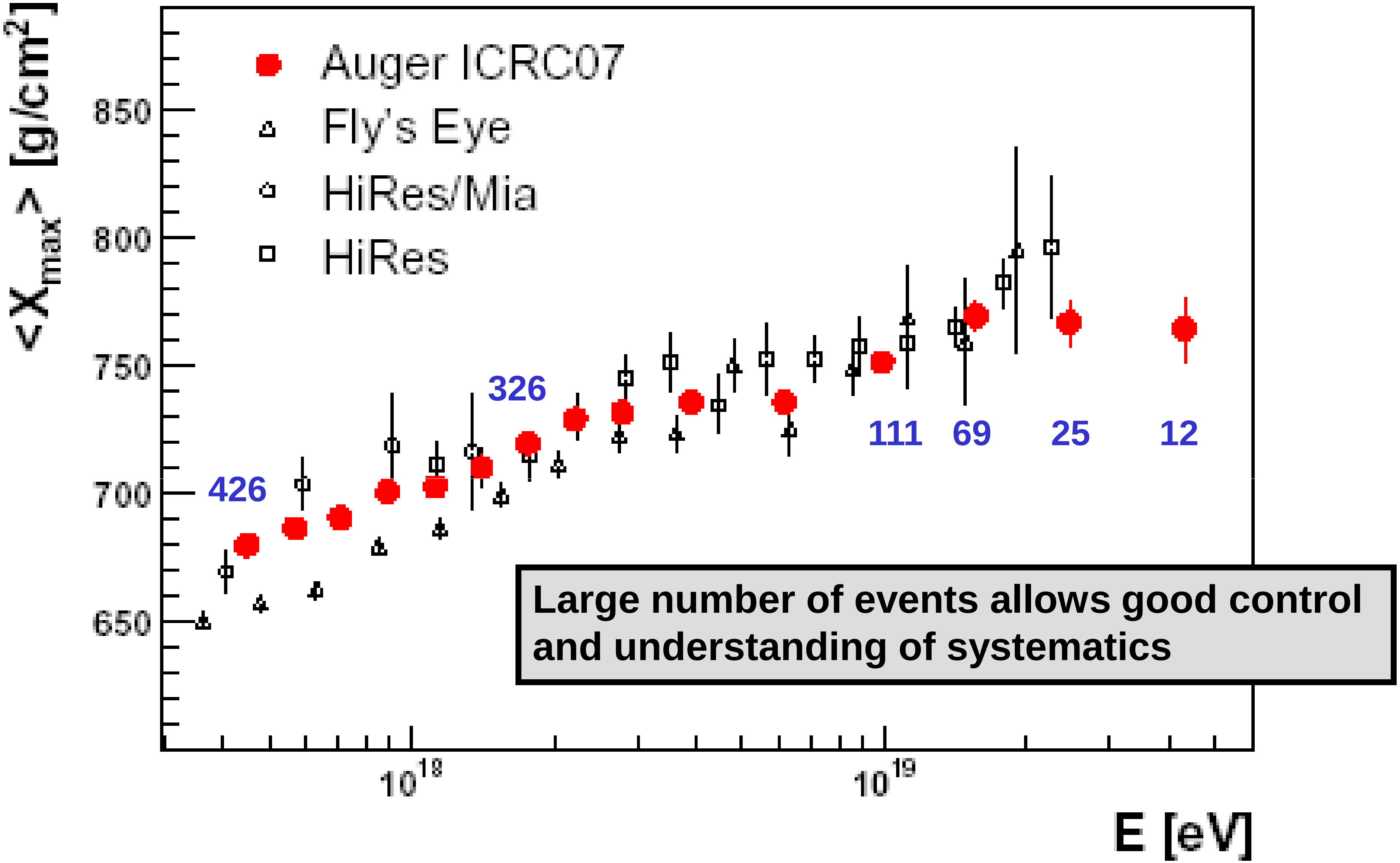
- The highest energy cosmic rays are extra-galactic
- The GZK-effect has probably been demonstrated
- There are > 60 sources (from doubles $\sim 4 \times 10^{-5}$ Mpc^{-3})
- The primaries are possibly proton-dominated with energies ~ 30 CMS-energy at LHC.

How we try to infer the variation of mass with energy

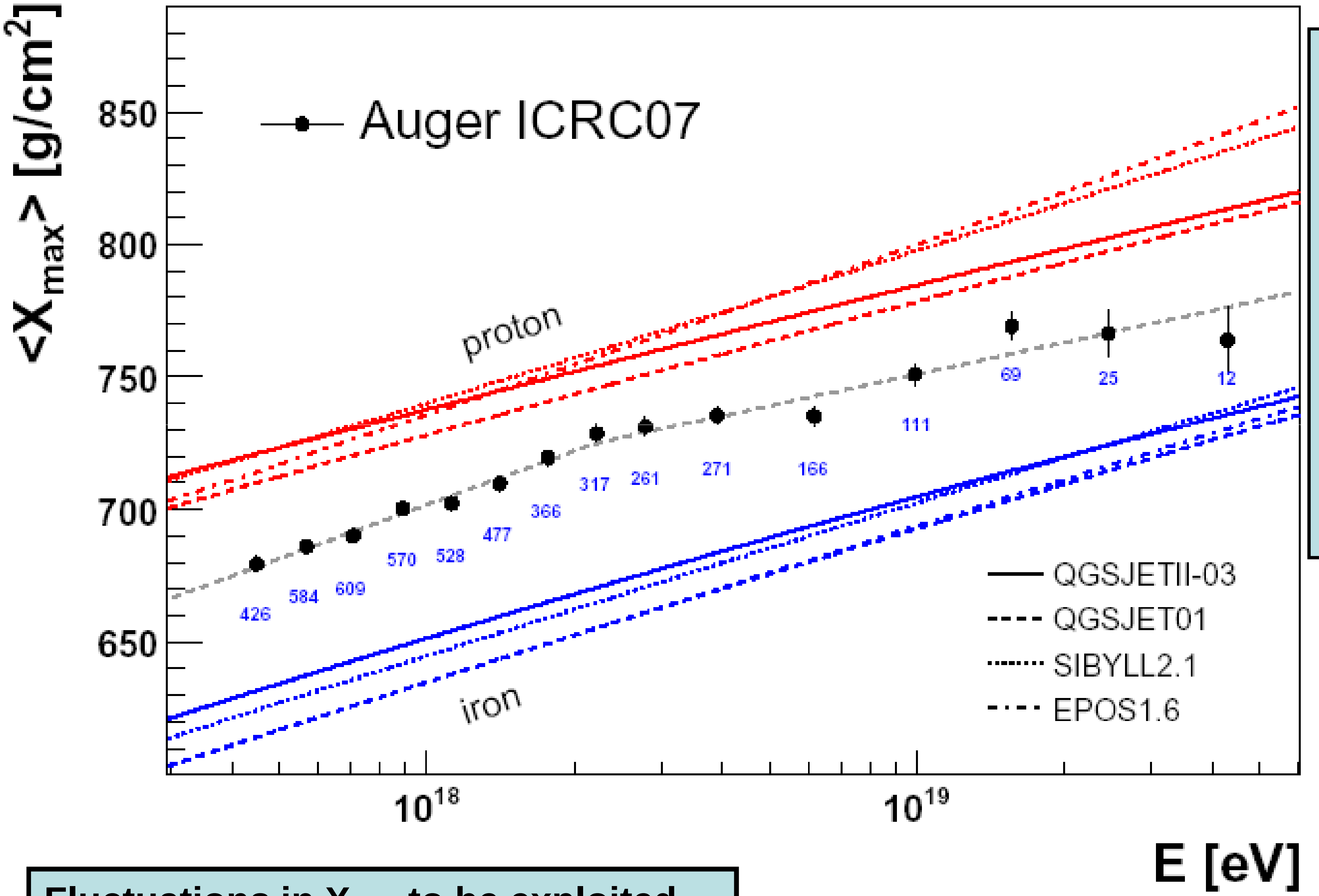




$X_{up} - X_{down}$ chosen large enough to detect most of distribution

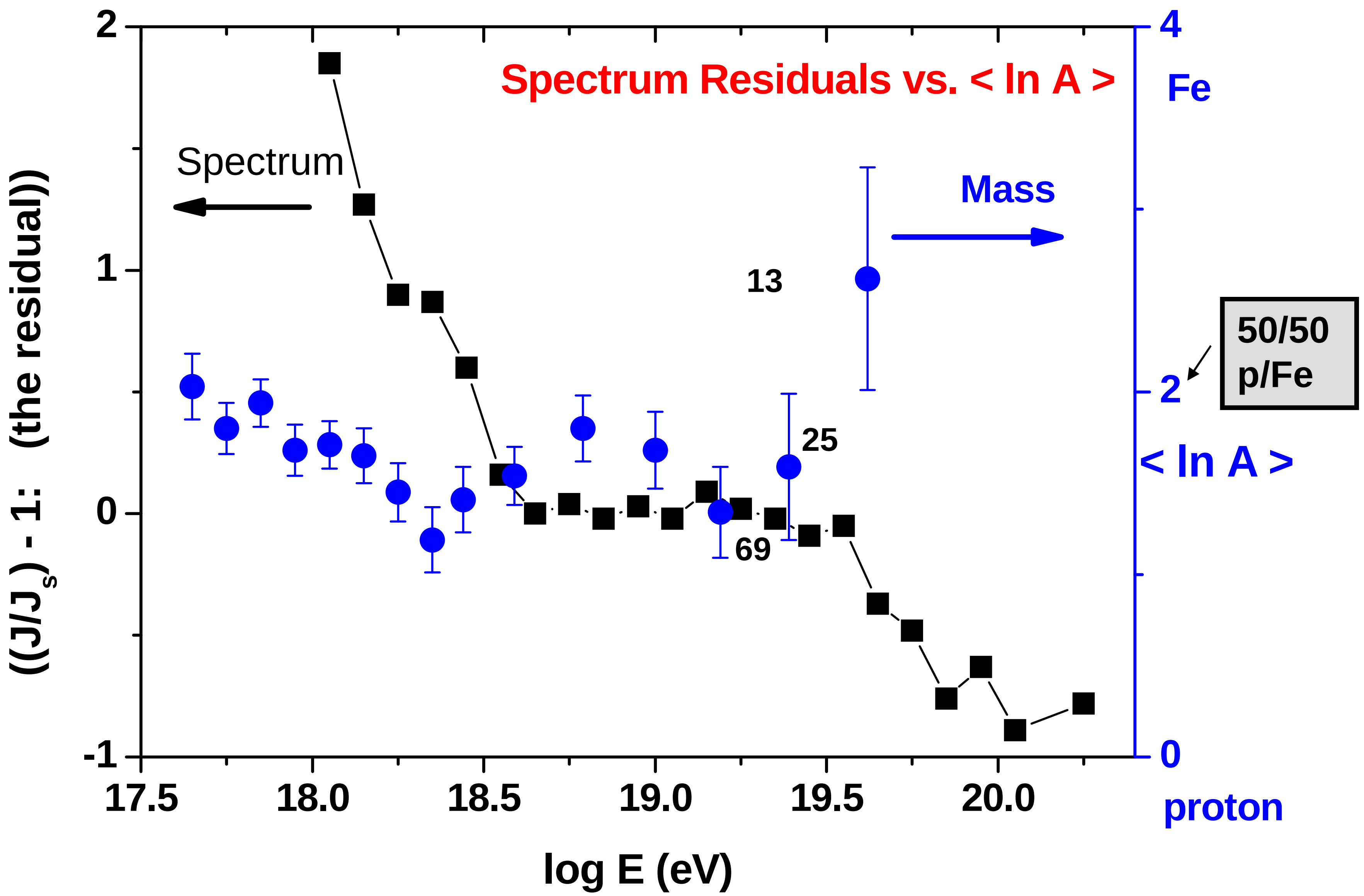

Auger ICRC07
Fly's Eye
HiRes/Mia
HiRes
$<X_{max}>$ [g/cm^2]
850
800
750
700
650
10^{18}
10^{19}
E [eV]
426
326
111
69
25
12
Large number of events allows good control and understanding of systematics

Elongation Rate measured over two decades of energy



Partilce Physics Correct?

Fluctuations in X_{max} to be exploited


Spectrum Residuals vs. < ln A >
Spectrum
Mass
13
25
69
50/50 p/Fe
Fe
proton
< ln A >
((J/J_s) - 1:   (the residual))
log E (eV)
2
1
0
-1
4
2
0
17.5
18.0
18.5
19.0
19.5
20.0

Follow-up work by others

HiRes Search for AGN correlation: arXiv:0804.0382vr1

Stereo data only

Claim angular accuracy of 0.8°

13 events > 56 EeV (‘after energy decreased by about 10%’)

Only 2 of these 13 events are within 3.1° of AGN

Possible that angular accuracy is poorer and/or that energy alignment is not correct.

There are some puzzling features about the stereo aperture

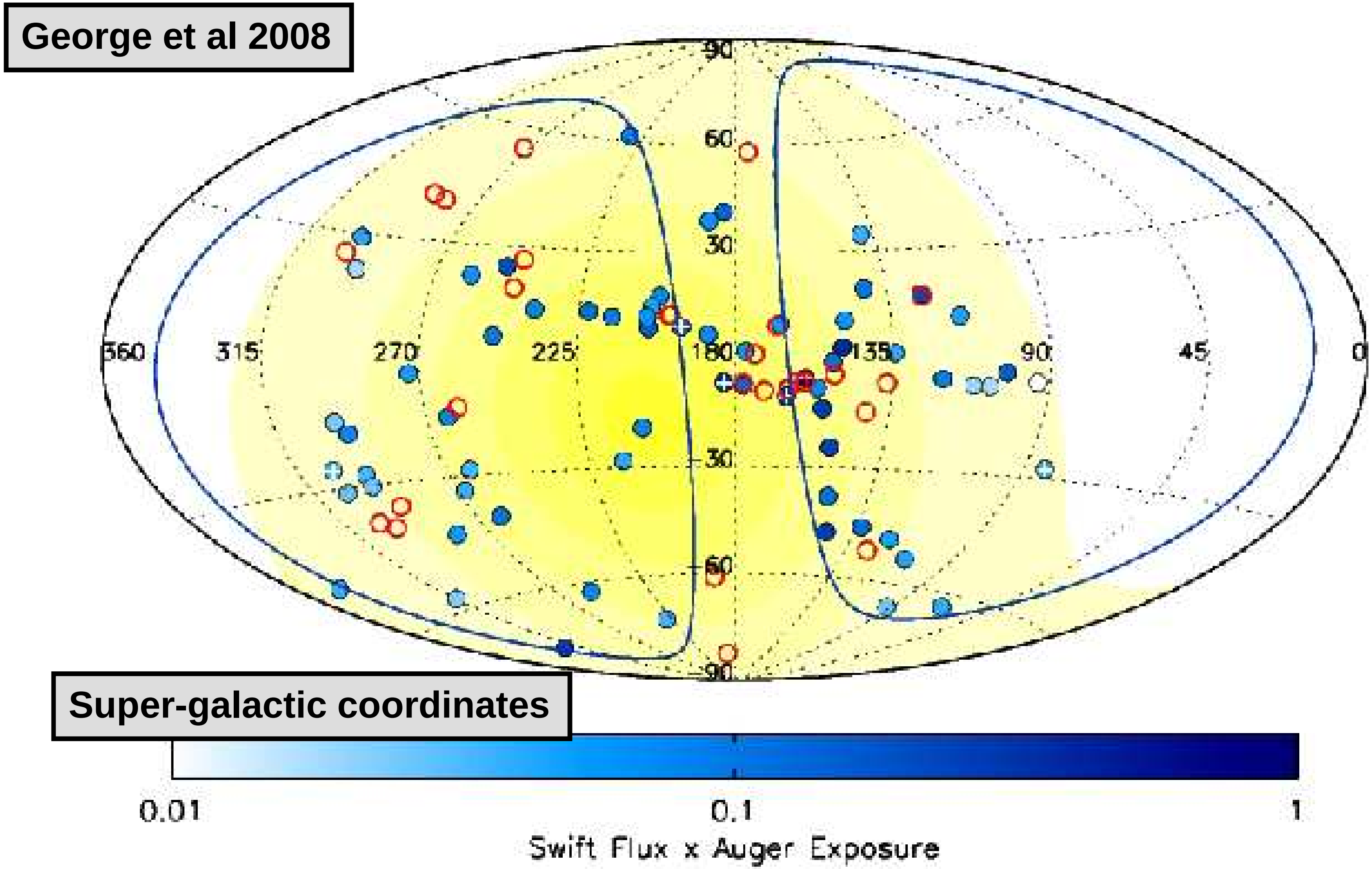
Confirmation of claim using a Complete Catalogue

George, Fabian, Baumgartner, Mushotsky and Tueller
MNRAS submitted (April 2008)

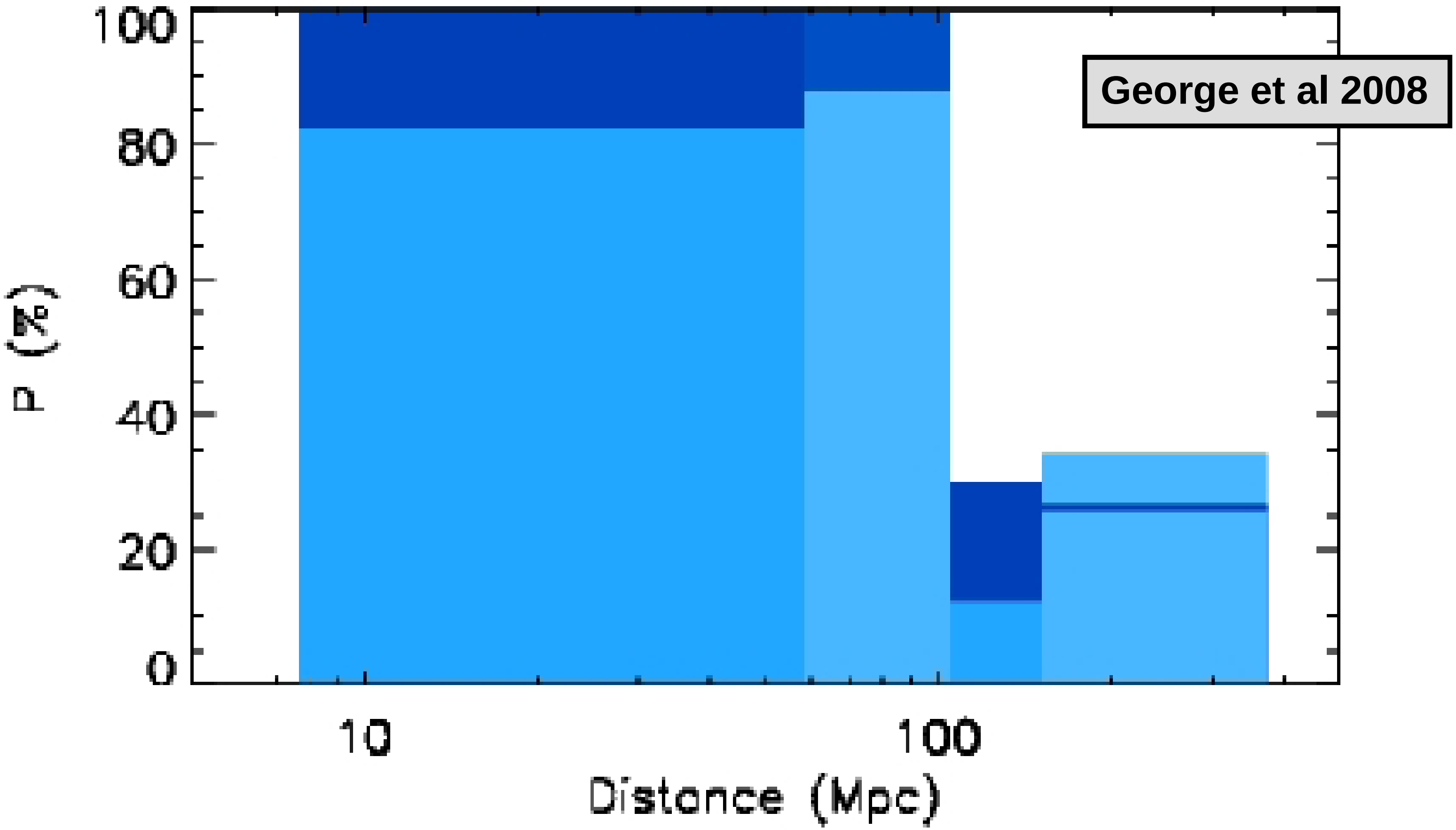
Swift BAT (14 – 195 keV) catalogue of AGNs
First 22 months:
254 objects have known red-shifts and 138 AGNs are in the field of view of Auger (> few x 10^{-11} erg cm^{-2} s^{-1})
- with 19 Auger events in BAT field of view

1. When weighted by hard X-ray flux, AGNs within 100 Mpc are correlated at 98% significance level (2-D KS)

2. Correlation decreases sharply beyond ~ 100 Mpc, suggesting GZK suppression



Auger: **open red**, **BAT AGN** within 100 Mpc: **filled blue**, scaled by X-ray flux and Auger Exposure. **6 AGN within 20 Mpc and 6° marked with x.**



Correlation dependence with distance

Light (dark) blue for unweighted (weighted) flux values

Summary of Results from Auger Observatory

• **Spectrum:** **suppression of highest energy flux seen - with model independent measurements and analyses at ~ 3.55 x 10^{19} eV**

• **Arrival Directions:** **At highest energies there is an anisotropy associated with nearby objects (< 75 Mpc)**

• **Mass Composition:** **Getting heavier as energy increases – if extrapolations of particle physics are correct**

The statistics and precision that are being achieved with will improve our understanding of UHECR dramatically.

What new astrophysics and physics could be learned?

- Magnetic field models can be tested
- Source spectra will come – rather slowly
- Map sources such as Cen A – if it is a source
- Deducing the MASS is crucial:

  mixed at highest energy? Fluctuation studies key
  and independent analysis using SD variables

  Certainly not expected – do hadronic models
  need modification?

  - Larger cross-section? Higher multiplicities?
  LHC results will be very important

- Particle Physics at extreme energies?

What next?

- Complete Auger-South and work hard on analysis
- Build Auger-North to give all-sky coverage:
  plan is for ~ 2 x 10^4 km^2 in South-East Colorado

~€100M

- Fluorescence Detector in Space:

  - JEM-EUSO (2013)

  - LoI to ESA in response to Cosmic Vision
    - SSAC ‘support technology’ for S-EUSO

Is the search for the origin of the highest energy cosmic rays over?

No - certainly not yet!

Indeed we are only at 'the end of the beginning'. There is much still to be done. We need

Exposure, Exposure, Exposure

to exploit several exciting opportunities in astrophysics and particle physics