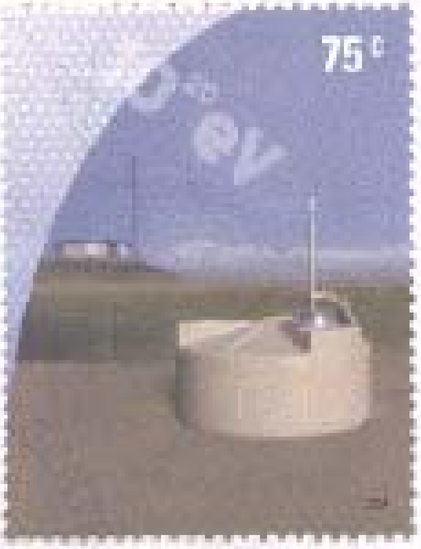
CORREO ARGENTINO

Imperial College: 13 February 2008



COSMOS CIENCIA

OBSERVATORIO PIERRE AUGER MALARGÜE MENDOZA

Sobre primer día 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

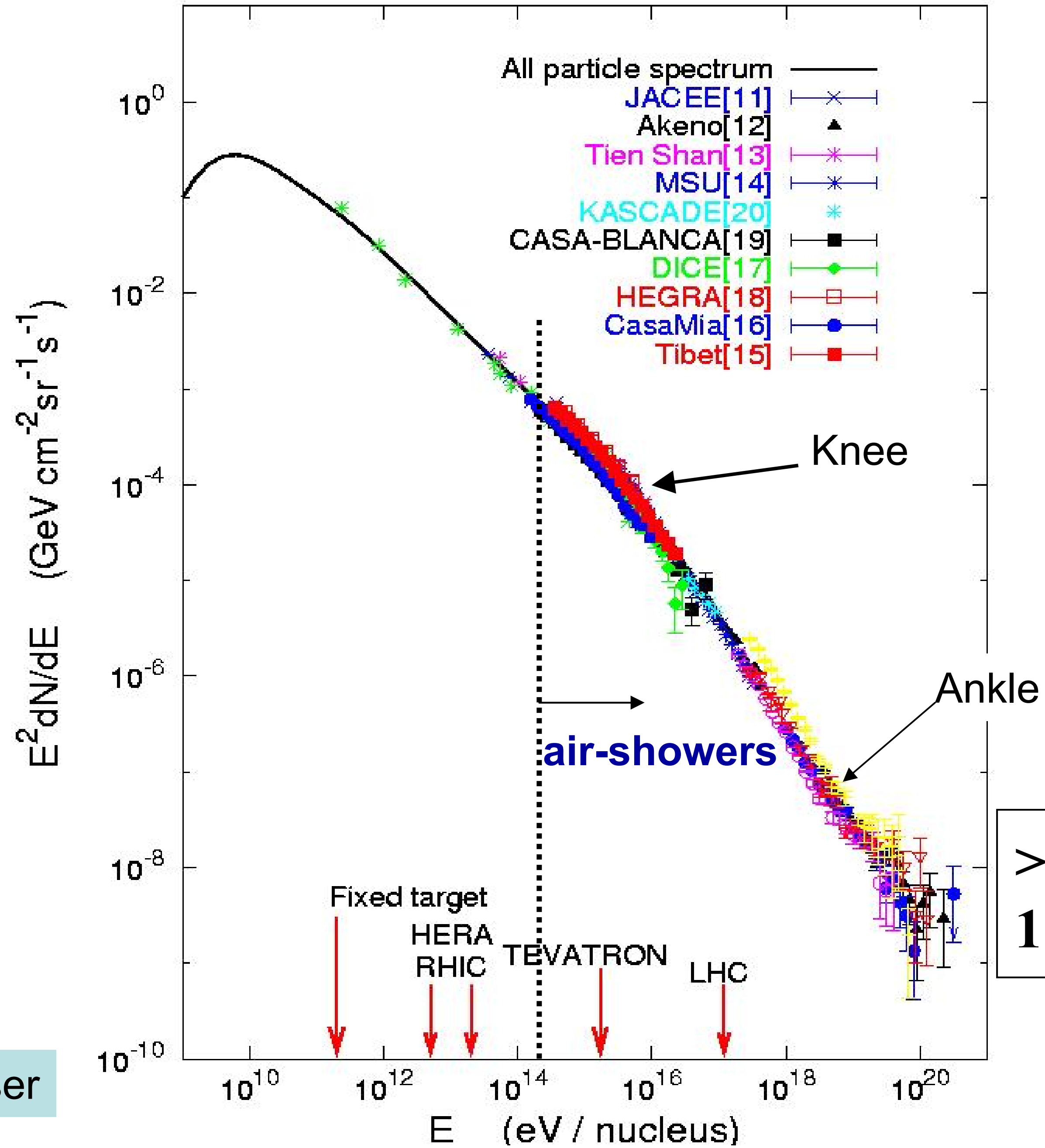
- Description and discussion of measurements:-

  Energy Spectrum

  Arrival Directions

  Primary Mass

- Prospects for the future



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

after Gaisser

Why the Interest?

(i) Can there be a cosmic ray astronomy?

Searches for Anisotropy (find the origin)

Deflections in magnetic fields:

at ~ 10^{19} eV: ~ 2 - 3° 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History of withdrawn or disproved claims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 ~ 3×10^{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)

(iii) How are the particles accelerated?

- **Synchrotron Acceleration** (as at CERN)

$$E_{max} = ZeBR\beta c$$

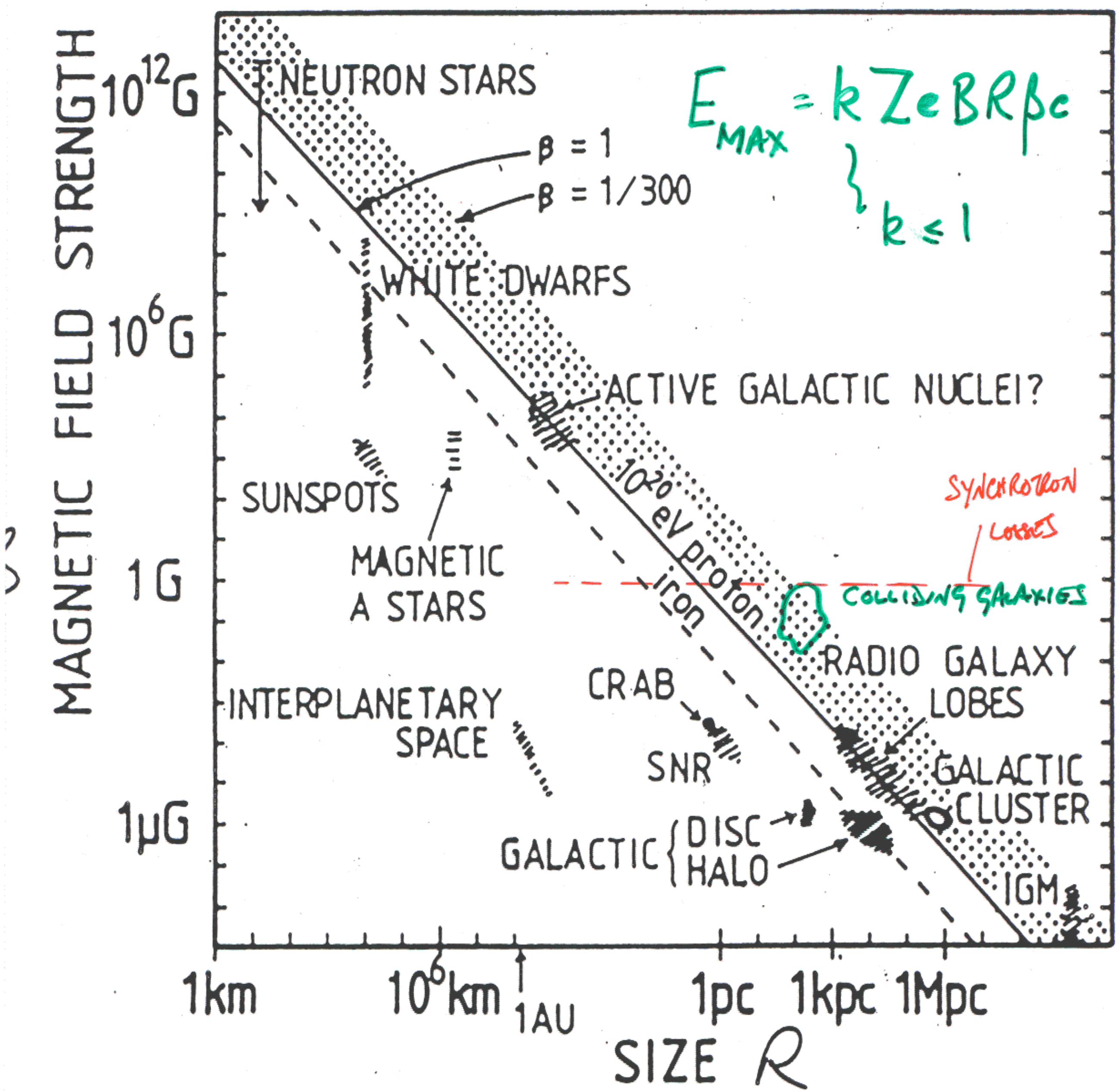
- **Single Shot Acceleration** (possibly in pulsars)

$$E_{max} = ZeBR\beta c$$

- **Diffusive Shock Acceleration at shocks**

$$E_{max} = kZeBR\beta c, \text{ with } k<1$$

Shocks in AGNs, near Black Holes, Colliding Galaxies ……



Hillas 1984
ARA&A
B vs R

Magnetars?

GRBs?

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

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

- and we don't know the relevant hadronic physics

Nuclear disintegrations with electronic elements 89

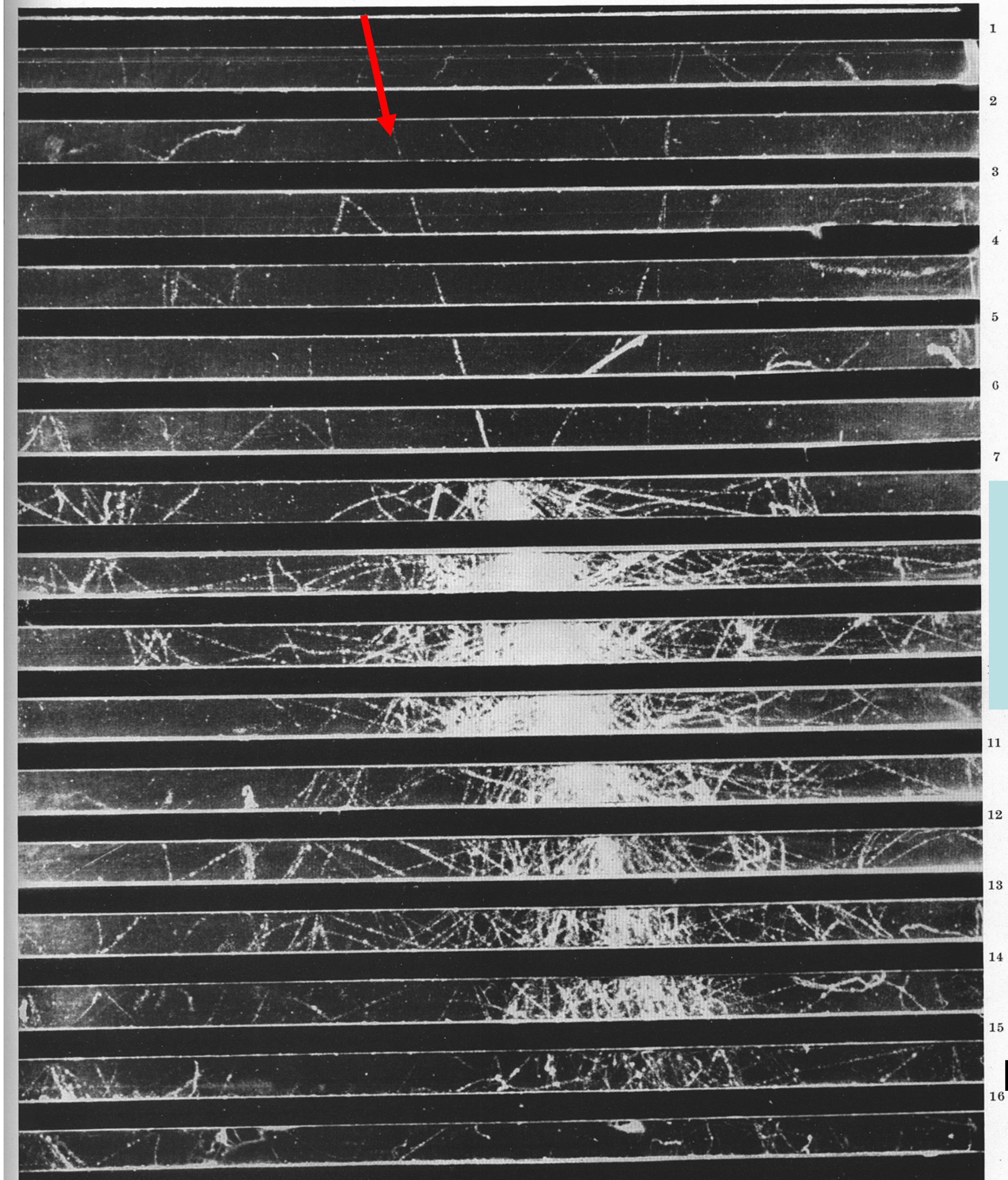


Plate 92

1.3 cm Pb

Shower initiated by proton in lead plates of cloud chamber

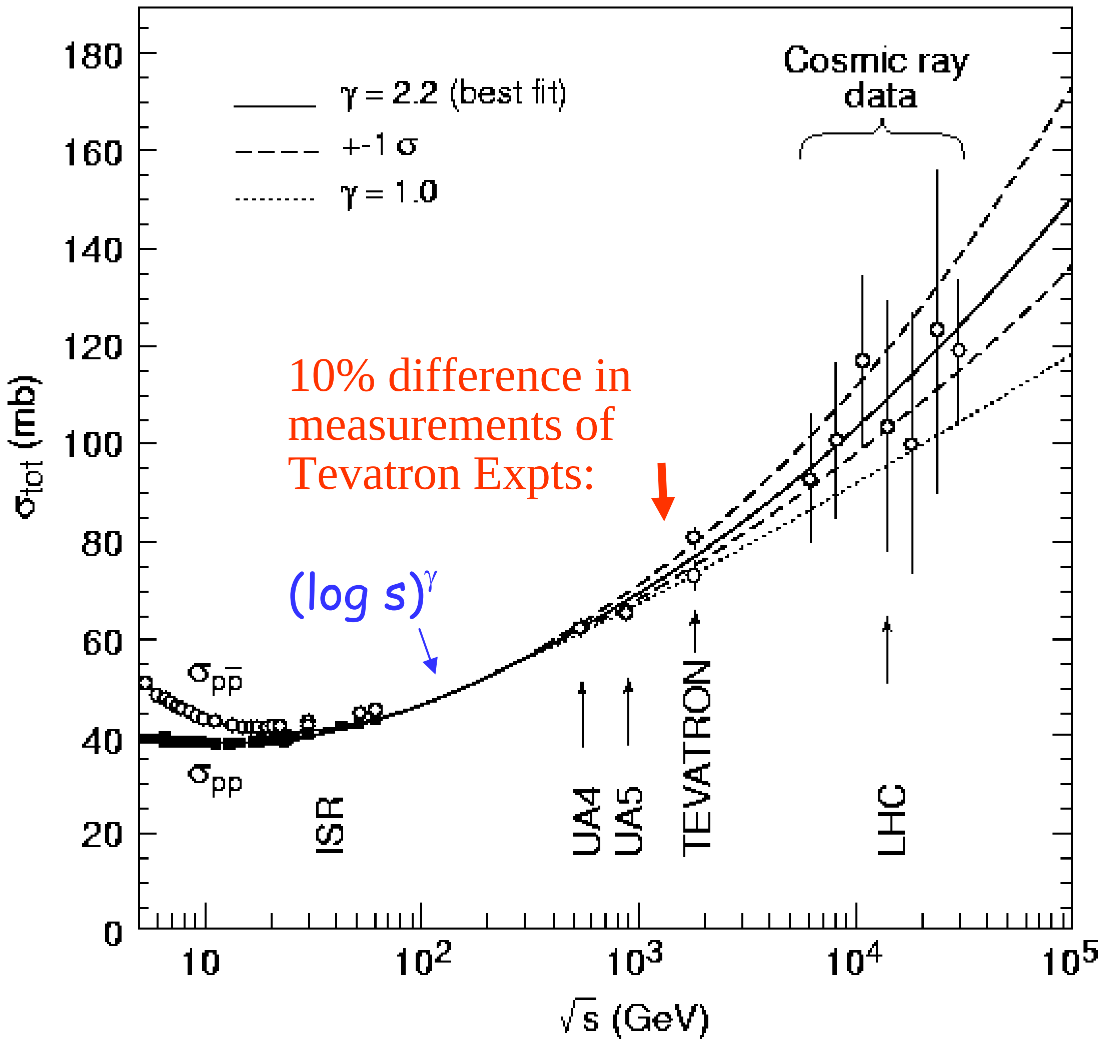
Fretter: Echo Lake, 1949

The p-p total cross-section

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

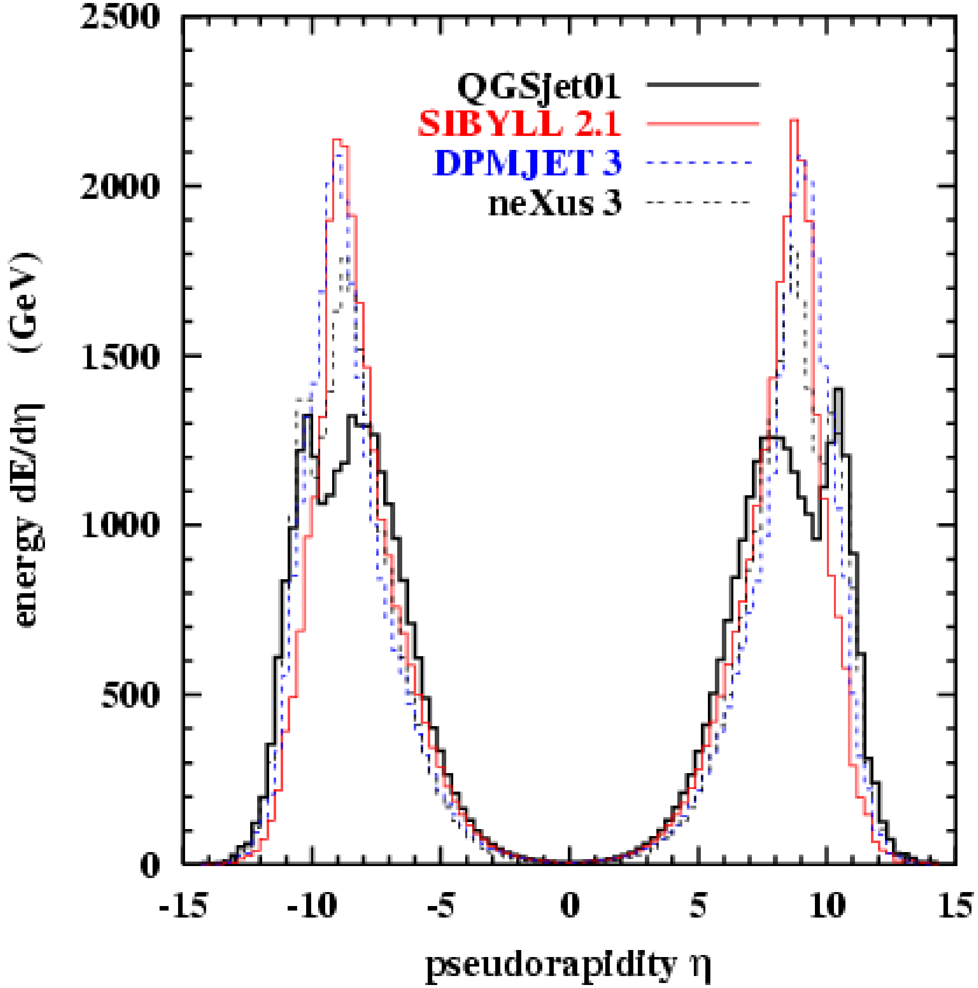
1% level

– very useful in the extrapolation up to UHECR energies

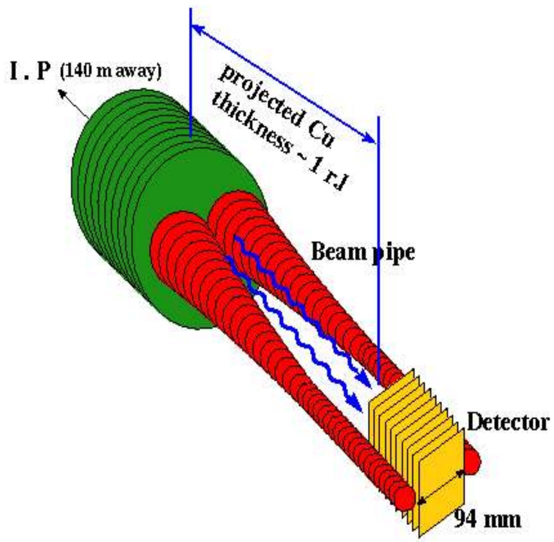


LHC Forward Physics & Cosmic Rays

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

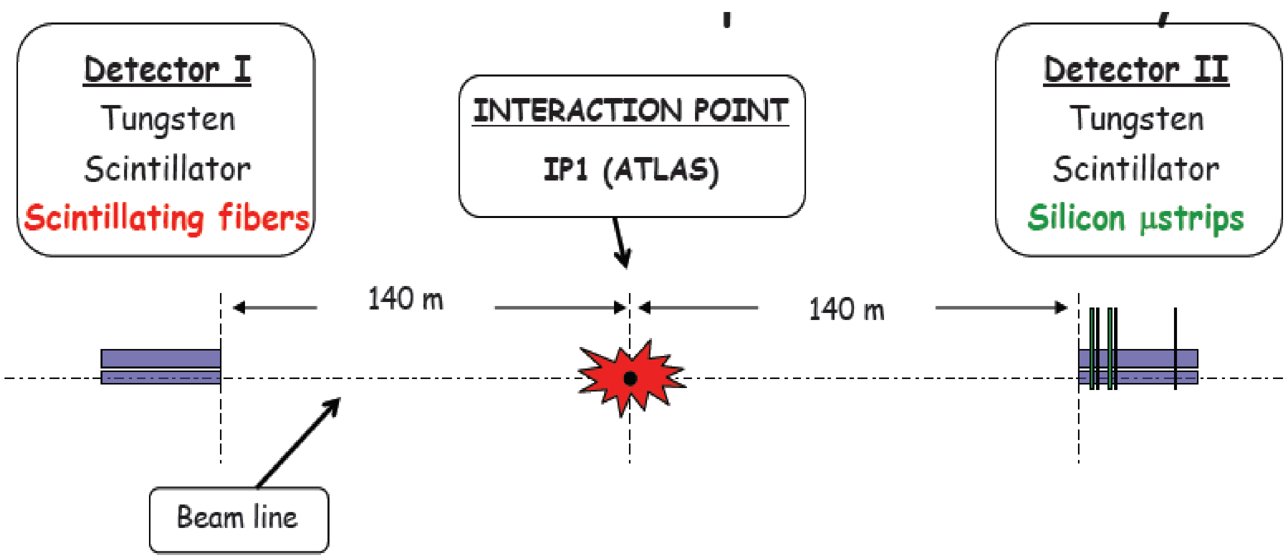


LHCf: an LHC Experiment for Astroparticle Physics



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



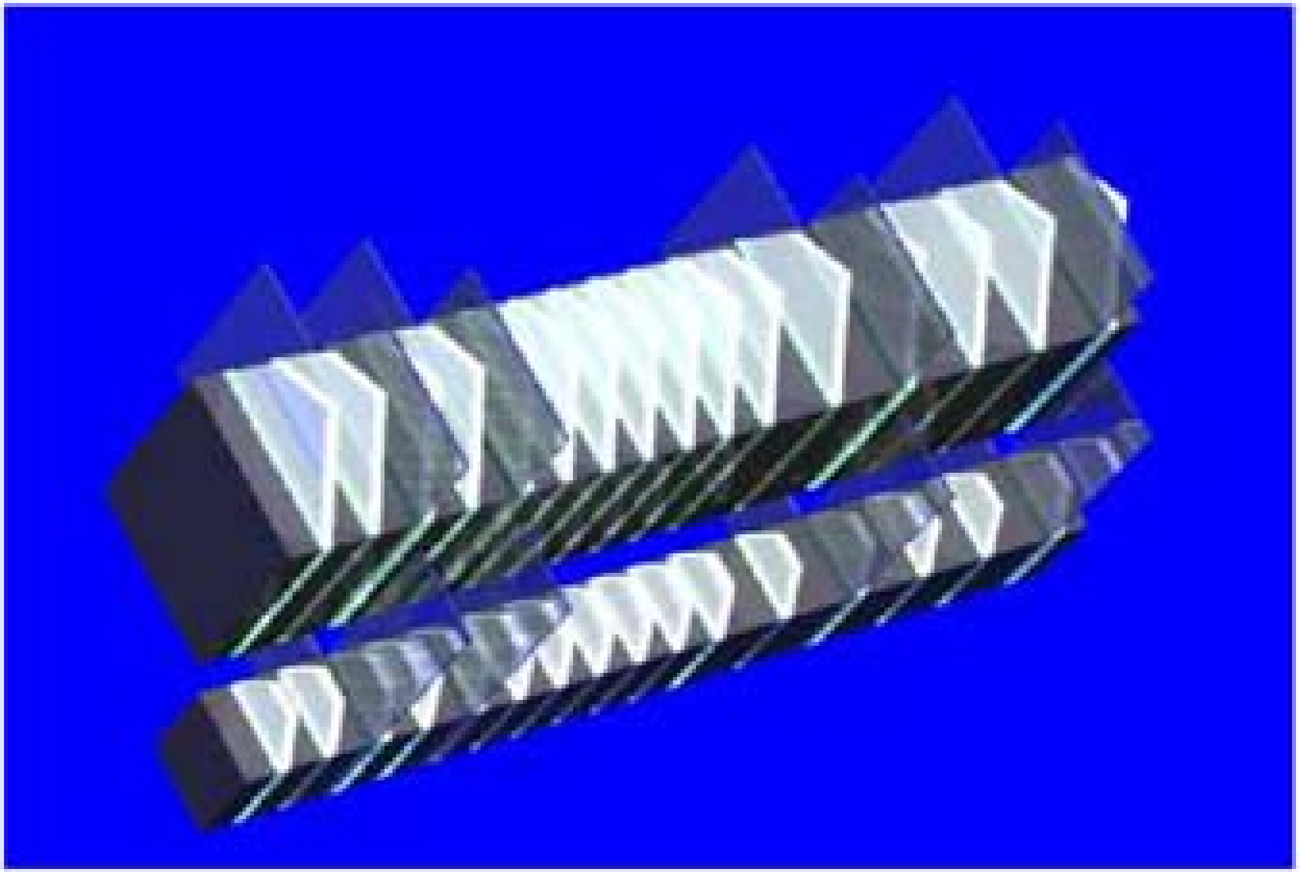
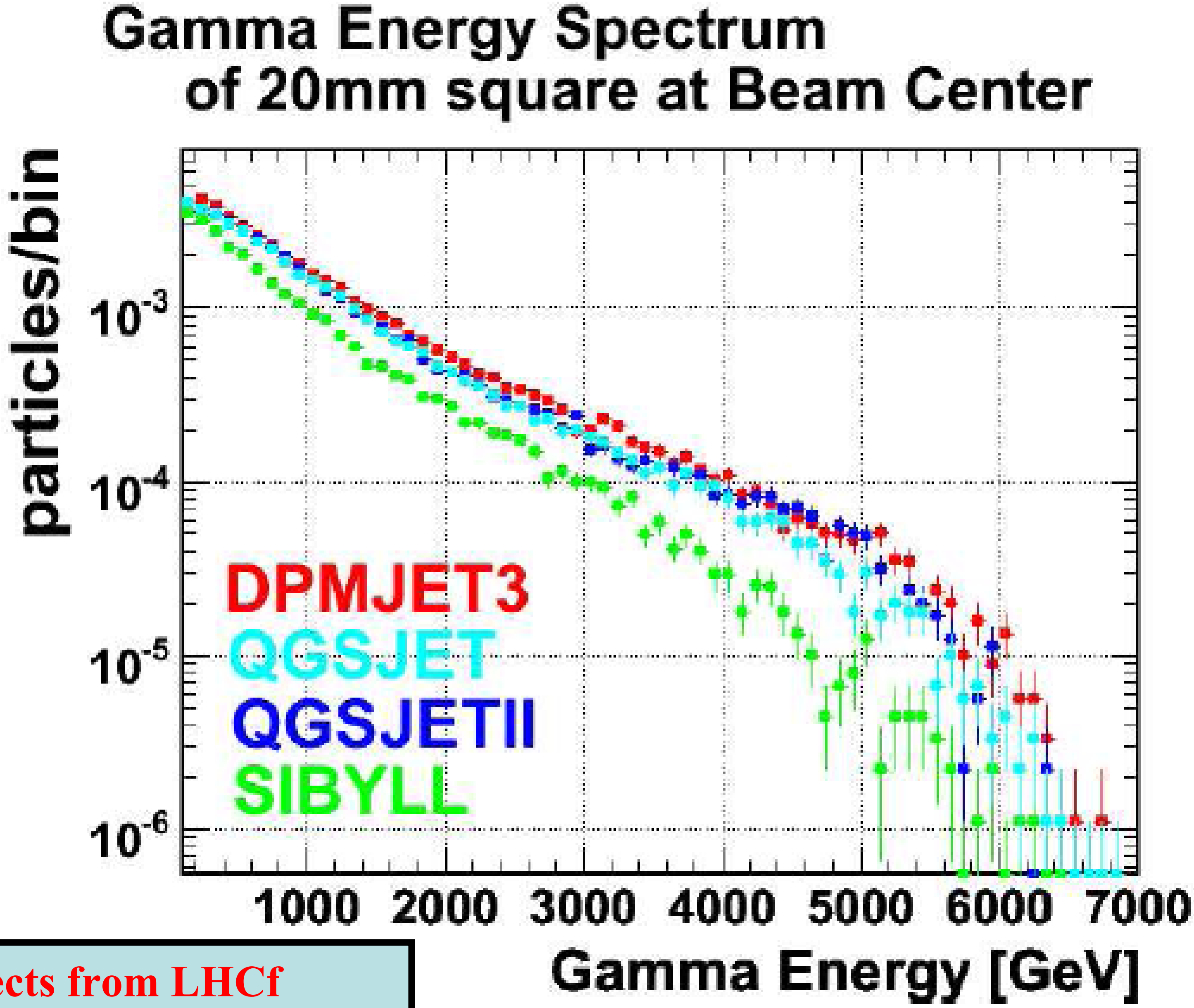


Figure 9: A schematic view of the Detector #1. It is composed of two individual tower of sampling calorimeters stacked vertically and diagonally.

28 x 9 x 60 cm^3



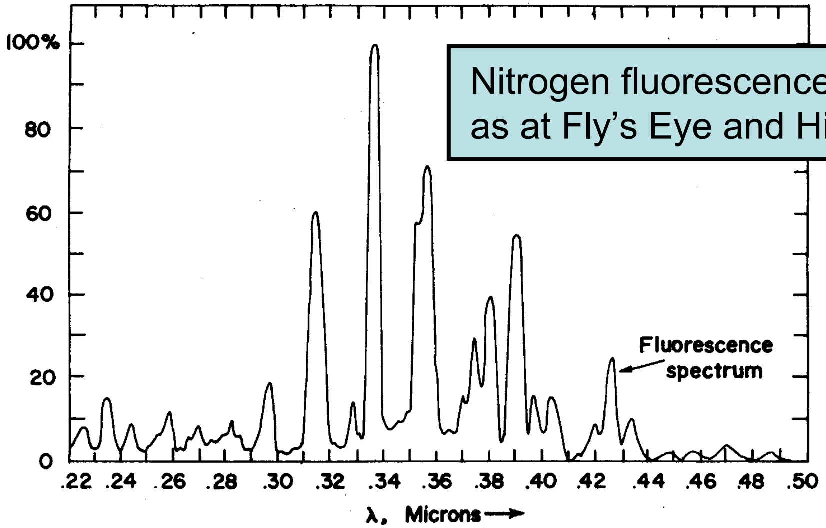
Prospects from LHCf

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



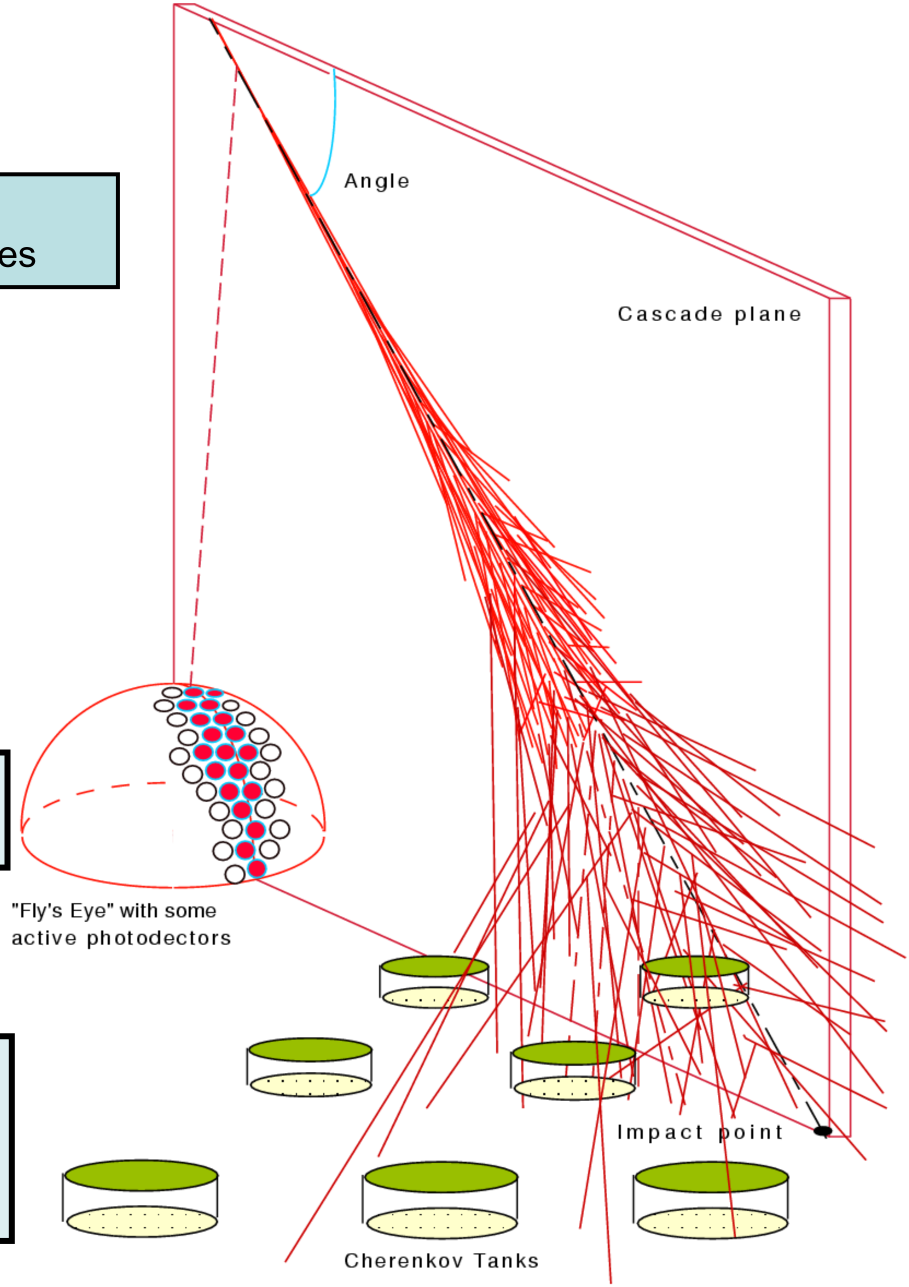
Nitrogen fluorescence
as at Fly's Eye and HiRes

Fluorescence →

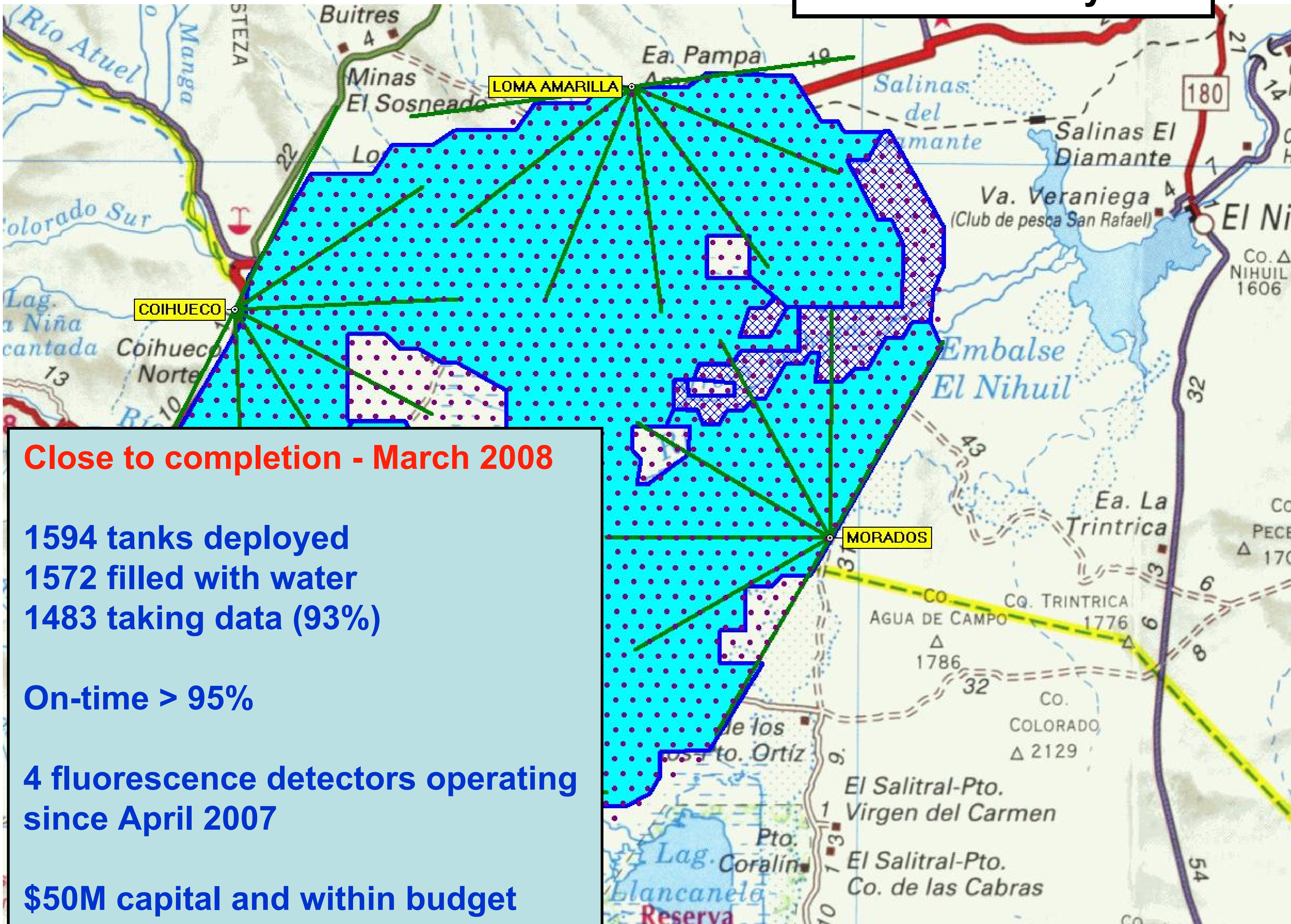
OR AND

Array of water-Cherenkov detectors →

or Scintillation Counters



As at 31 January 2008



Close to completion - March 2008

1594 tanks deployed
1572 filled with water
1483 taking data (93%)

On-time > 95%

4 fluorescence detectors operating since April 2007

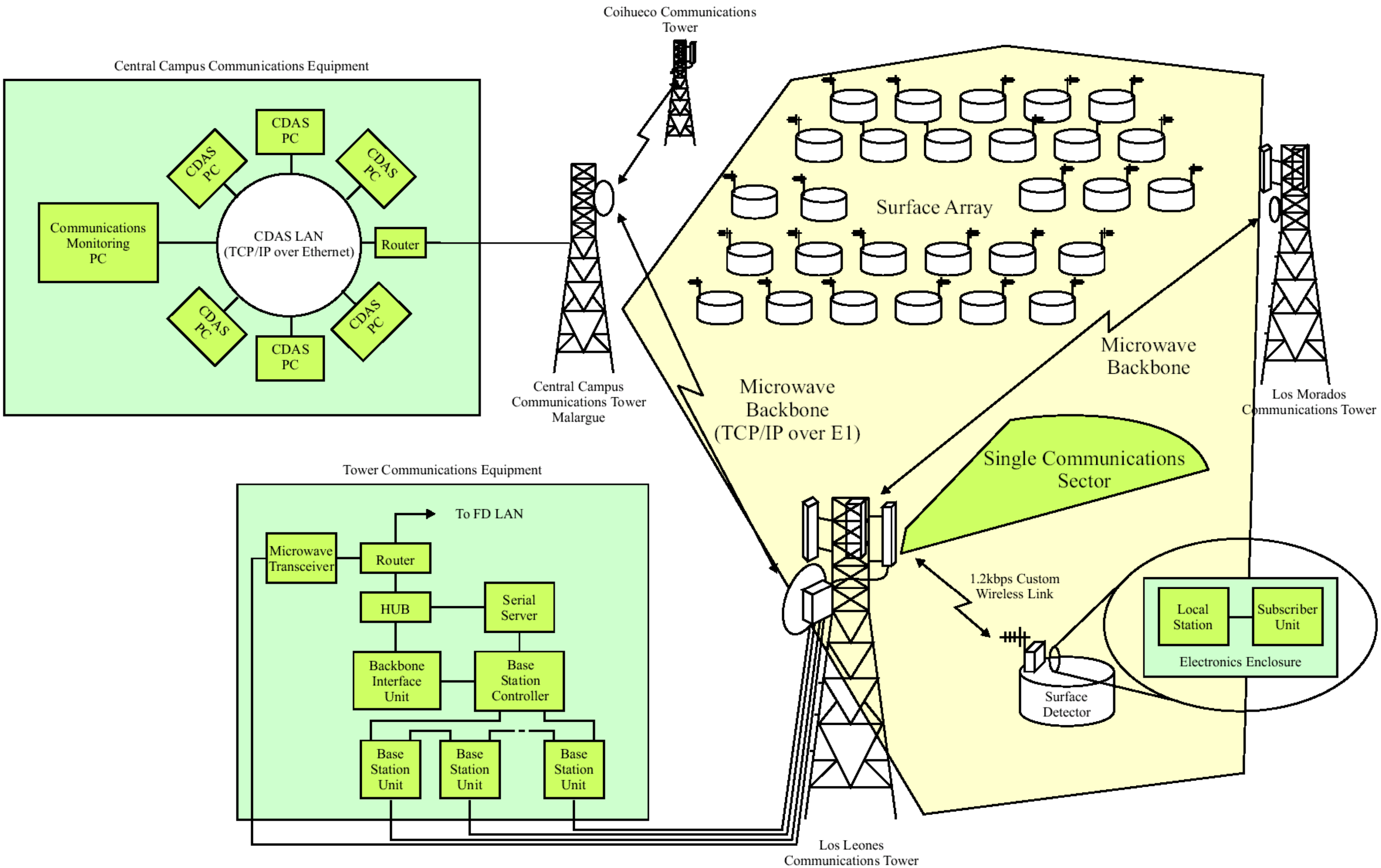
$50M capital and within budget


GPS Receiver
and radio transmission


28. 6. 1999


29. 6. 1999

Telecommunication system

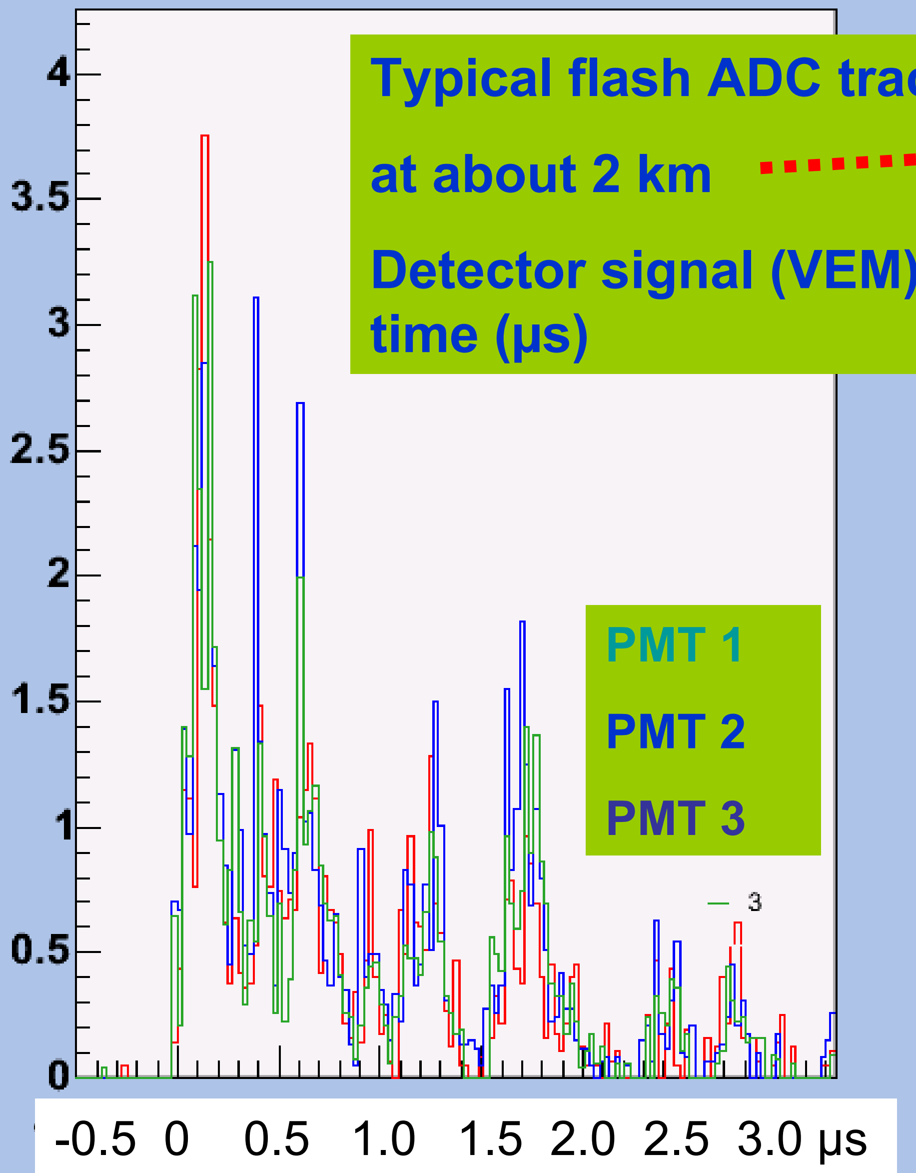


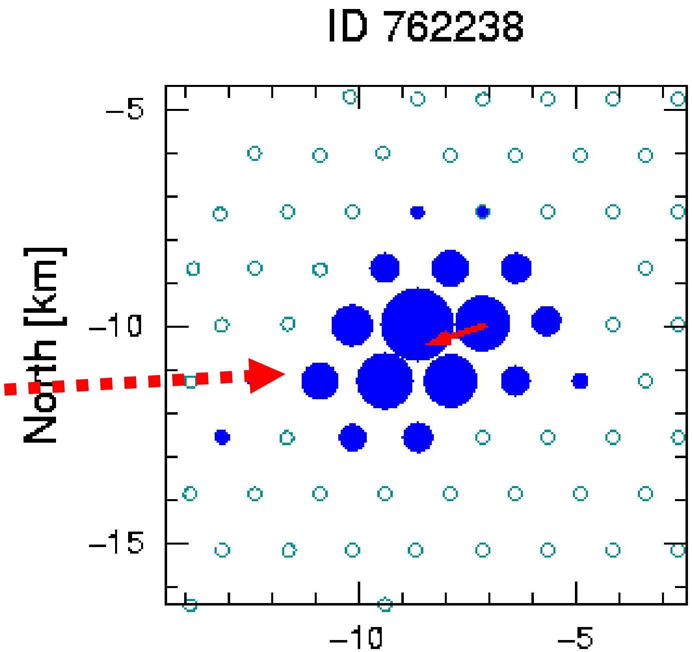
θ~ 48º, ~ 70 EeV

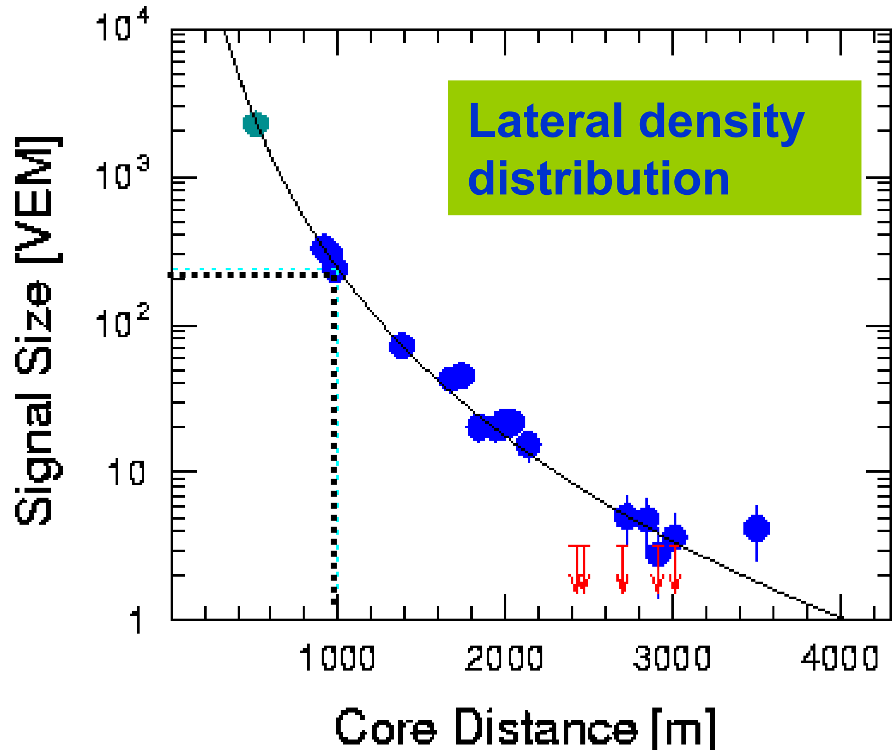
18 detectors triggered

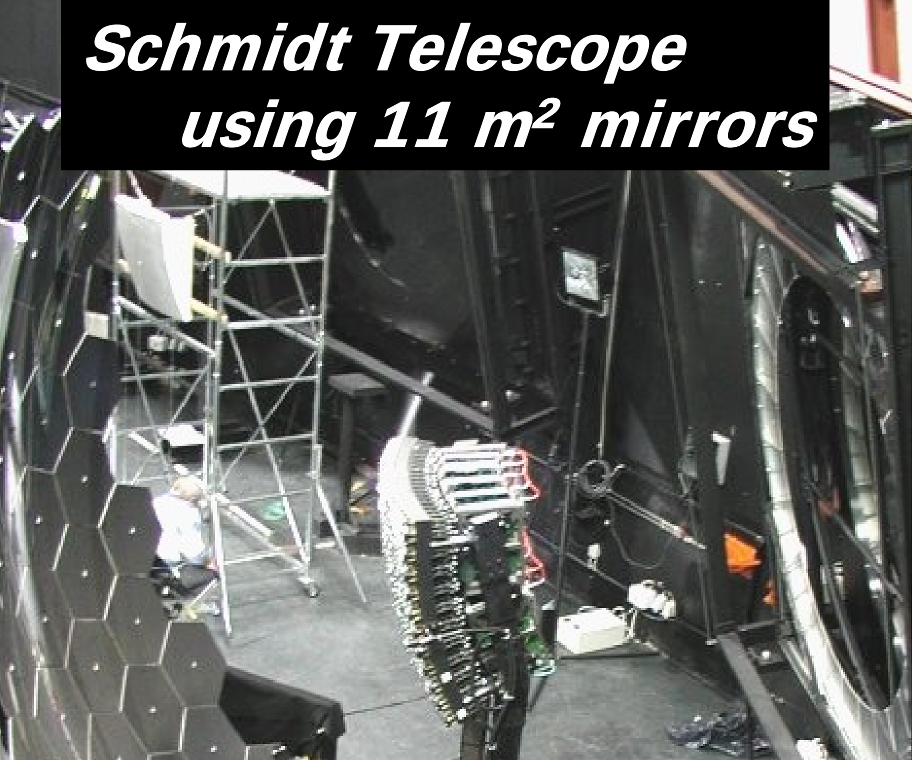
Typical flash ADC trace at about 2 km

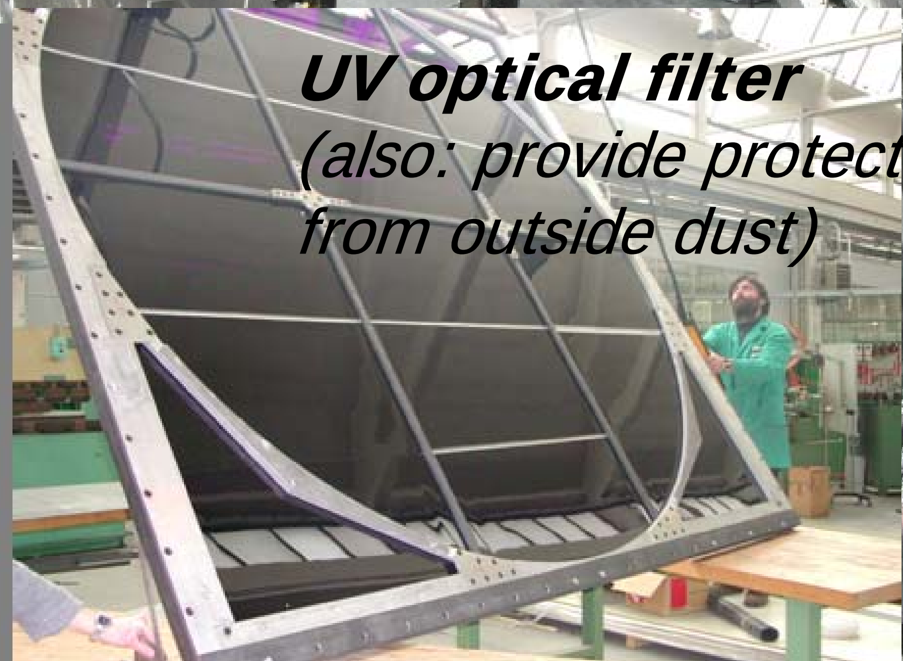
Detector signal (VEM) vs time (μs)

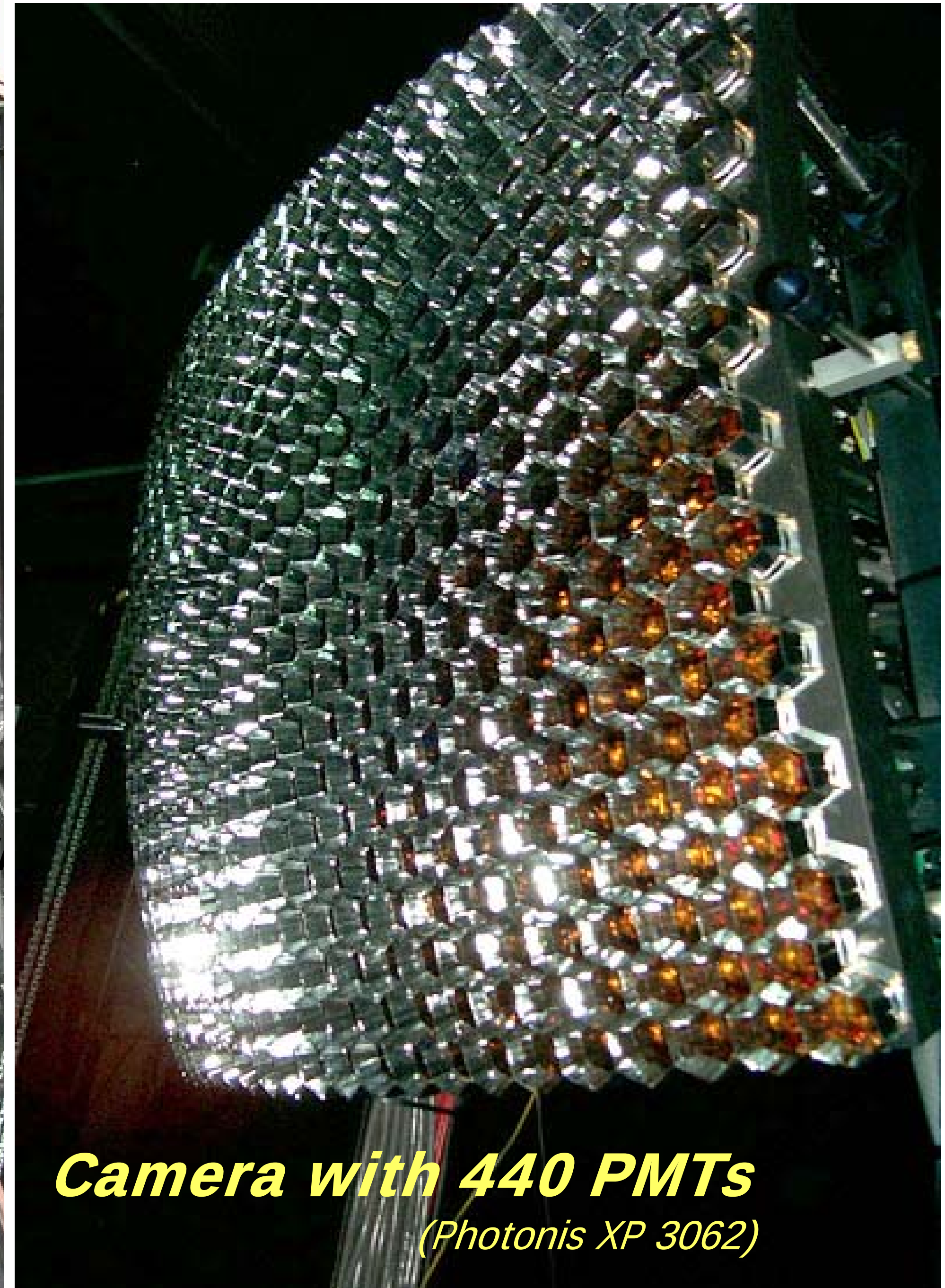






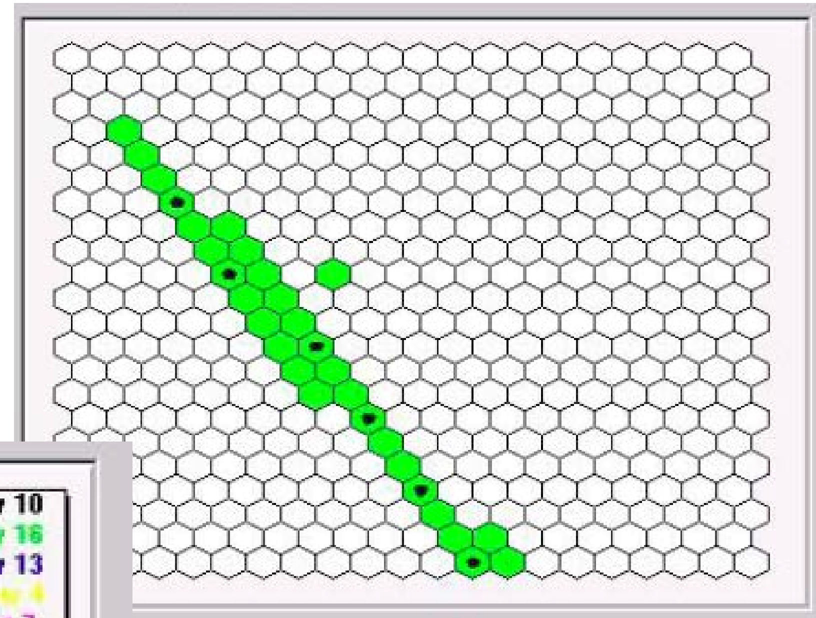

Schmidt Telescope
using 11 m² mirrors

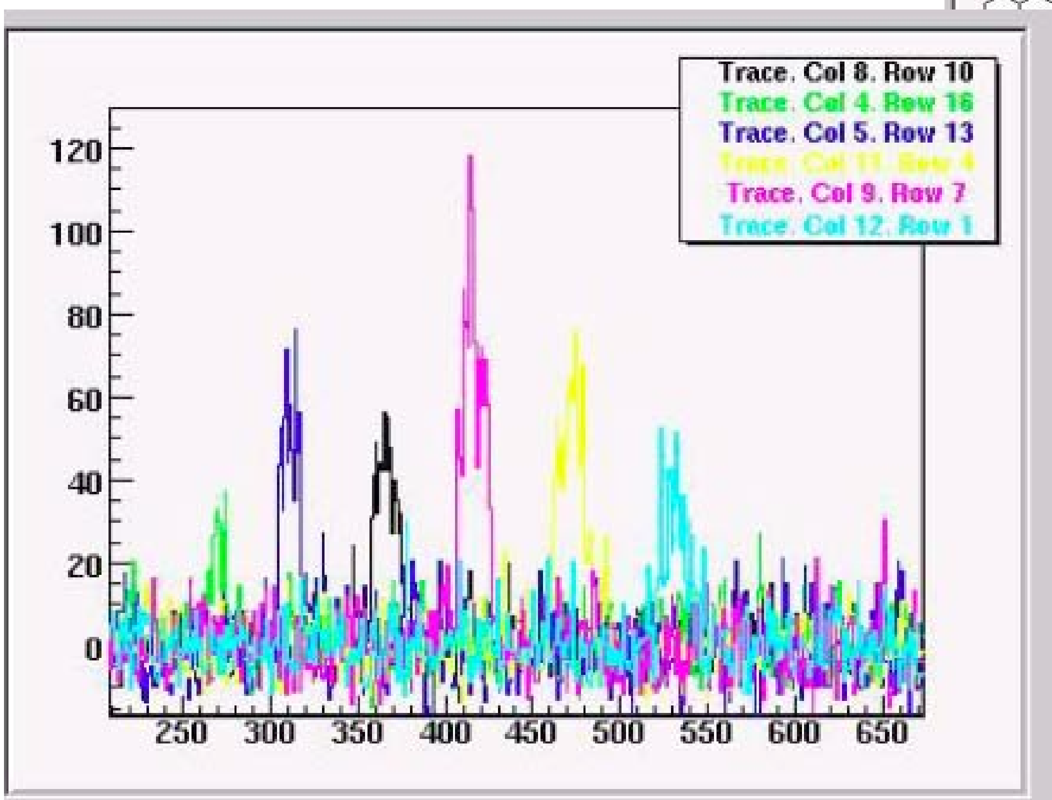

UV optical filter
(also: provide protect
from outside dust)


Camera with 440 PMTs
(Photonis XP 3062)

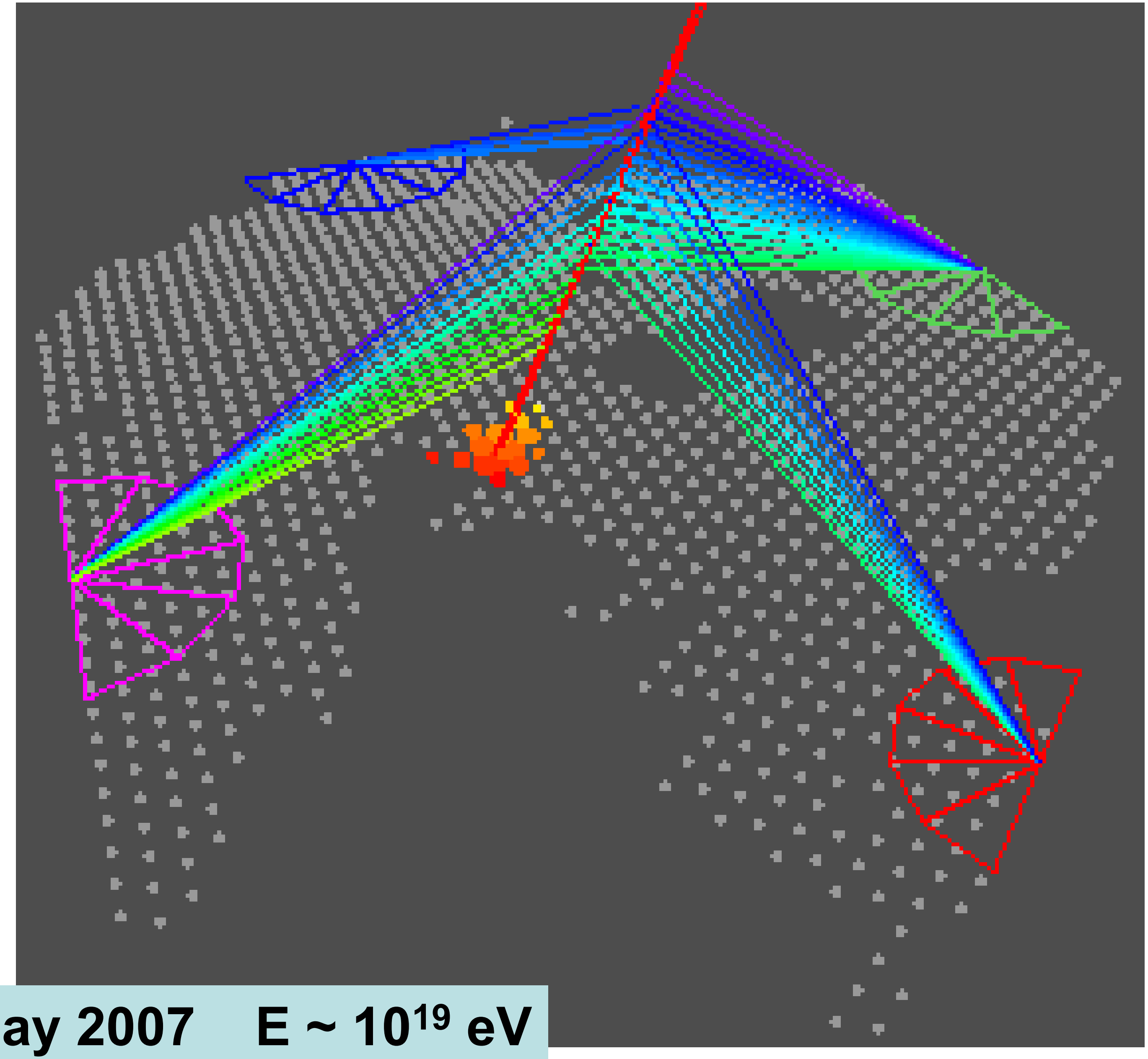
FD reconstruction

Signal and timing
Direction & energy

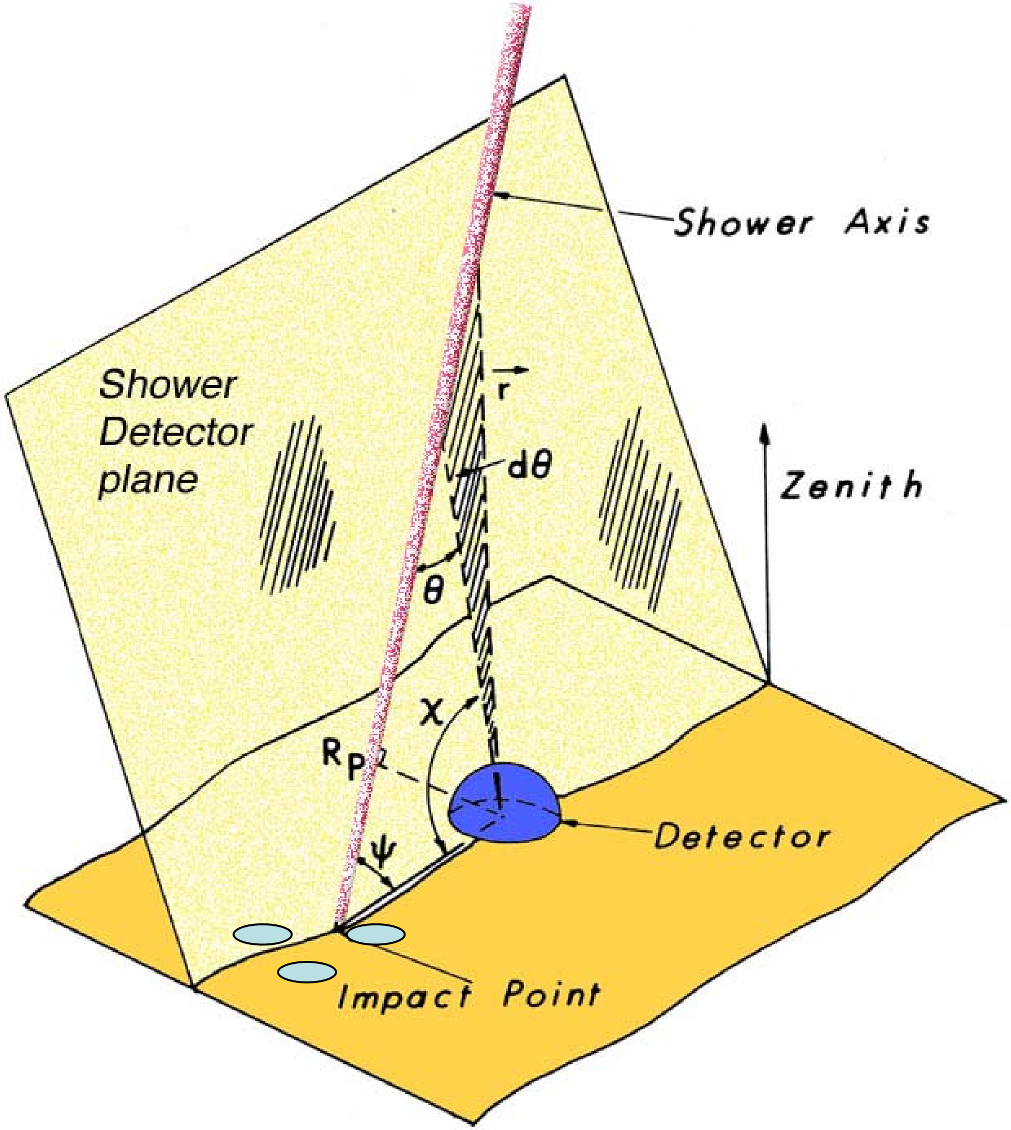




Pixel geometry
shower-detector plane



20 May 2007 E ~ 10^{19} eV



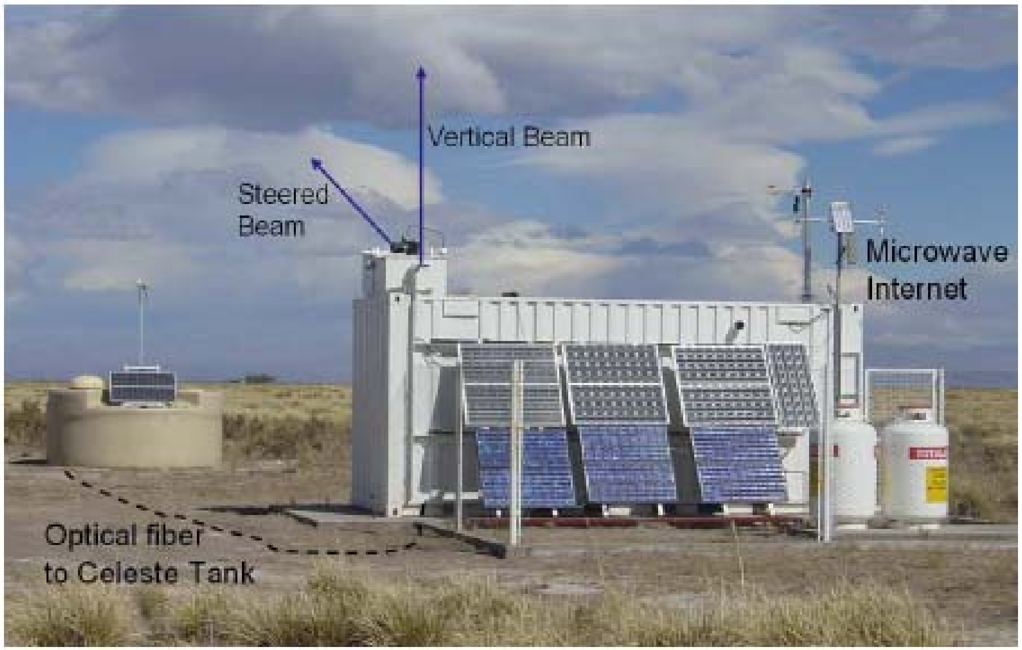
The essence of the hybrid approach

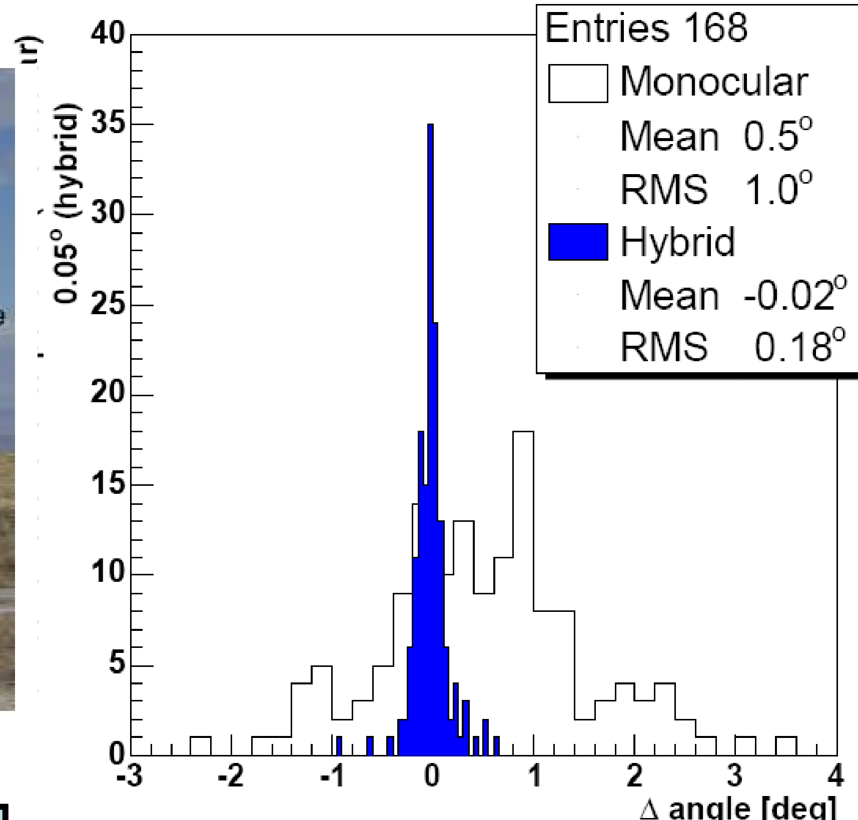
Precise shower geometry from degeneracy given by SD timing

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

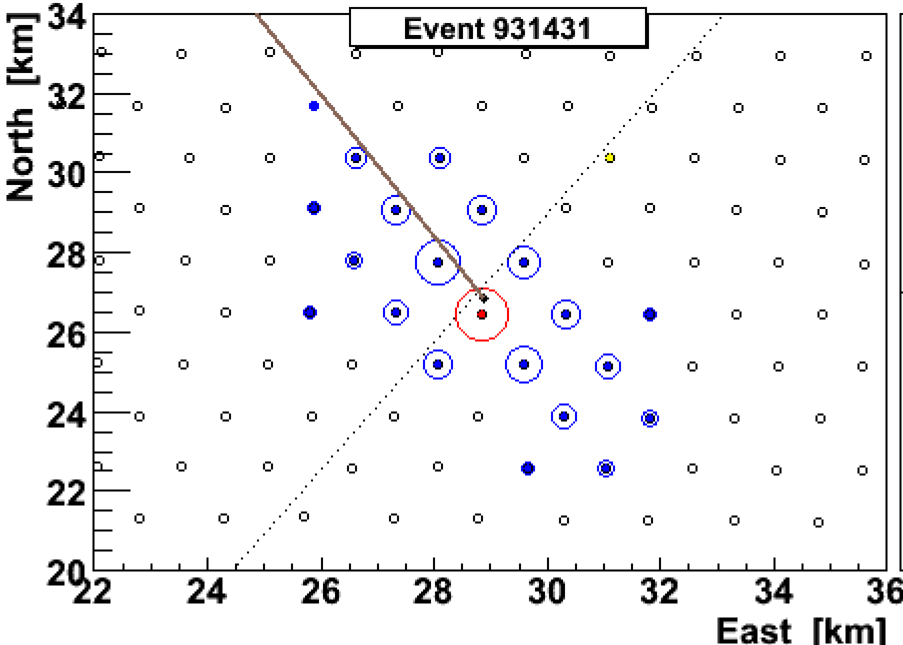




355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Mono/hybrid rms 1.0°/0.18°

A Hybrid Event



Core location

Easting 468693 ± 59

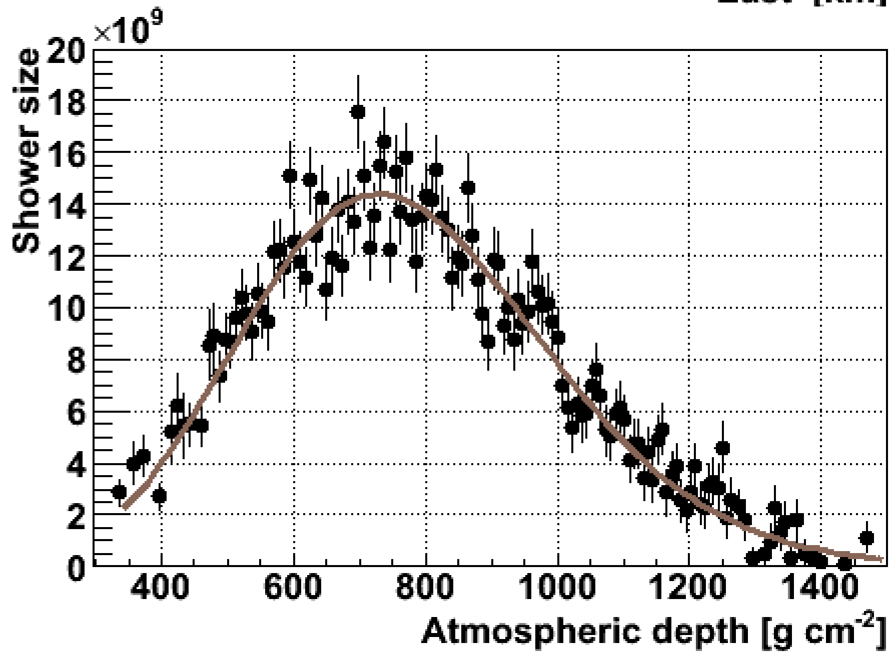
Northing 6087022 ± 80

Altitude = 1390 m a.s.l.

Shower Axis

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

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



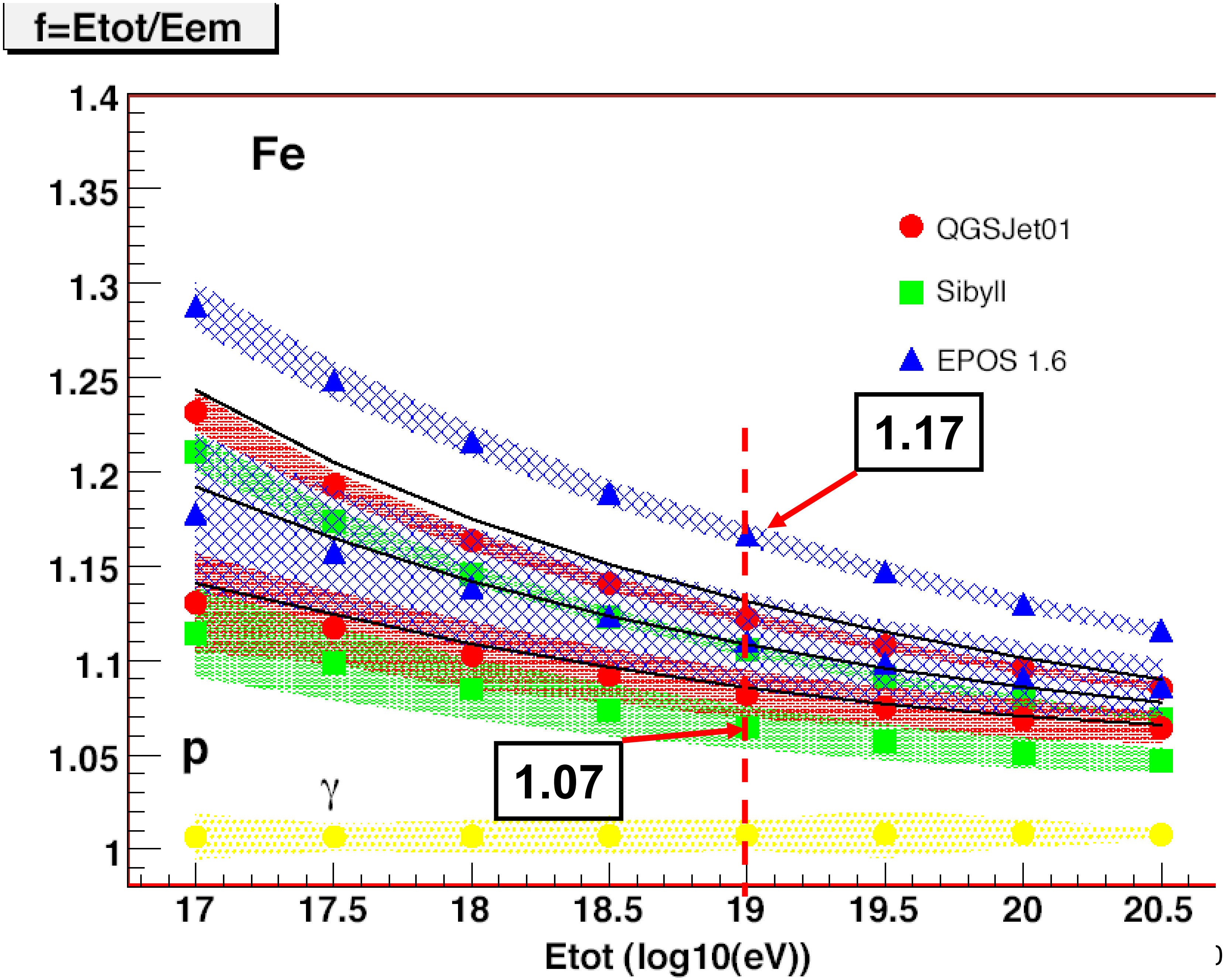
Energy Estimate:

$X_{max} = (728 \pm 20)$ 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

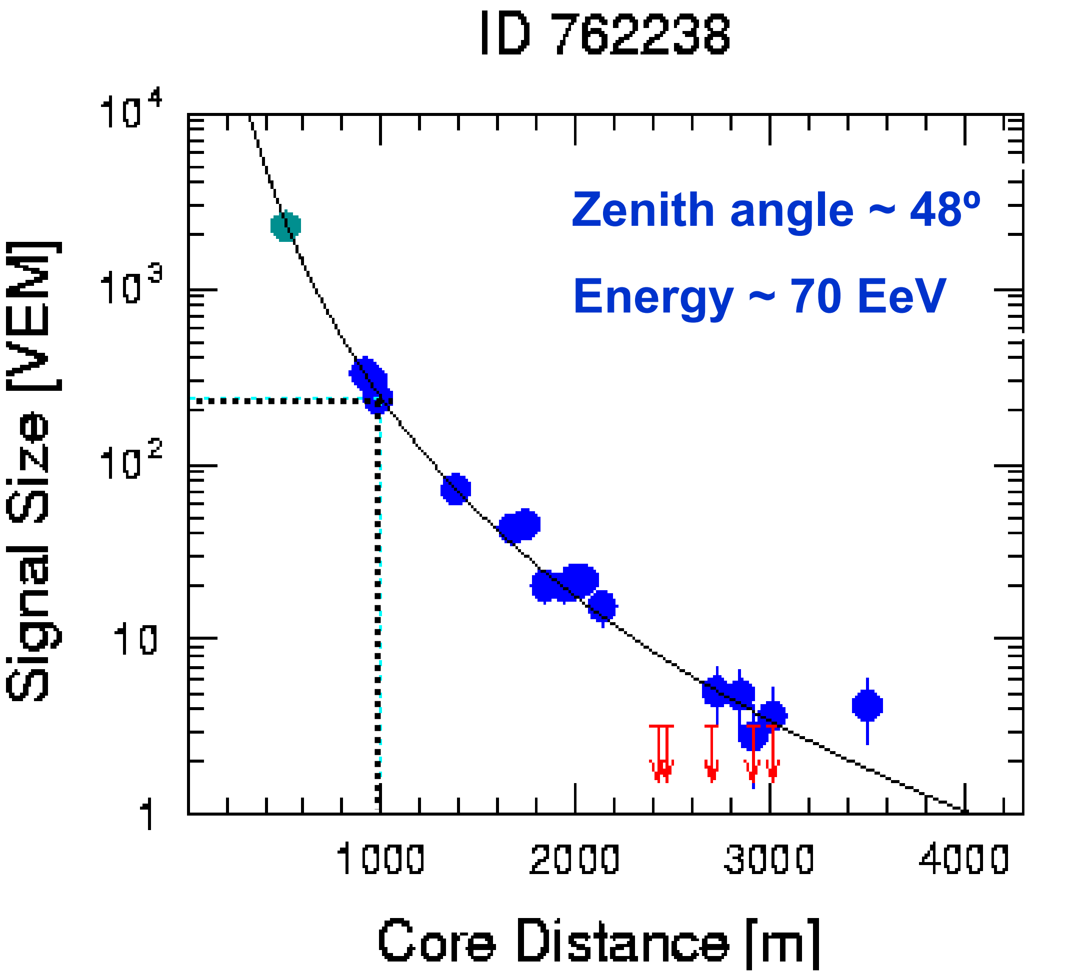
The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

The detector signal at 1000 m from the shower core

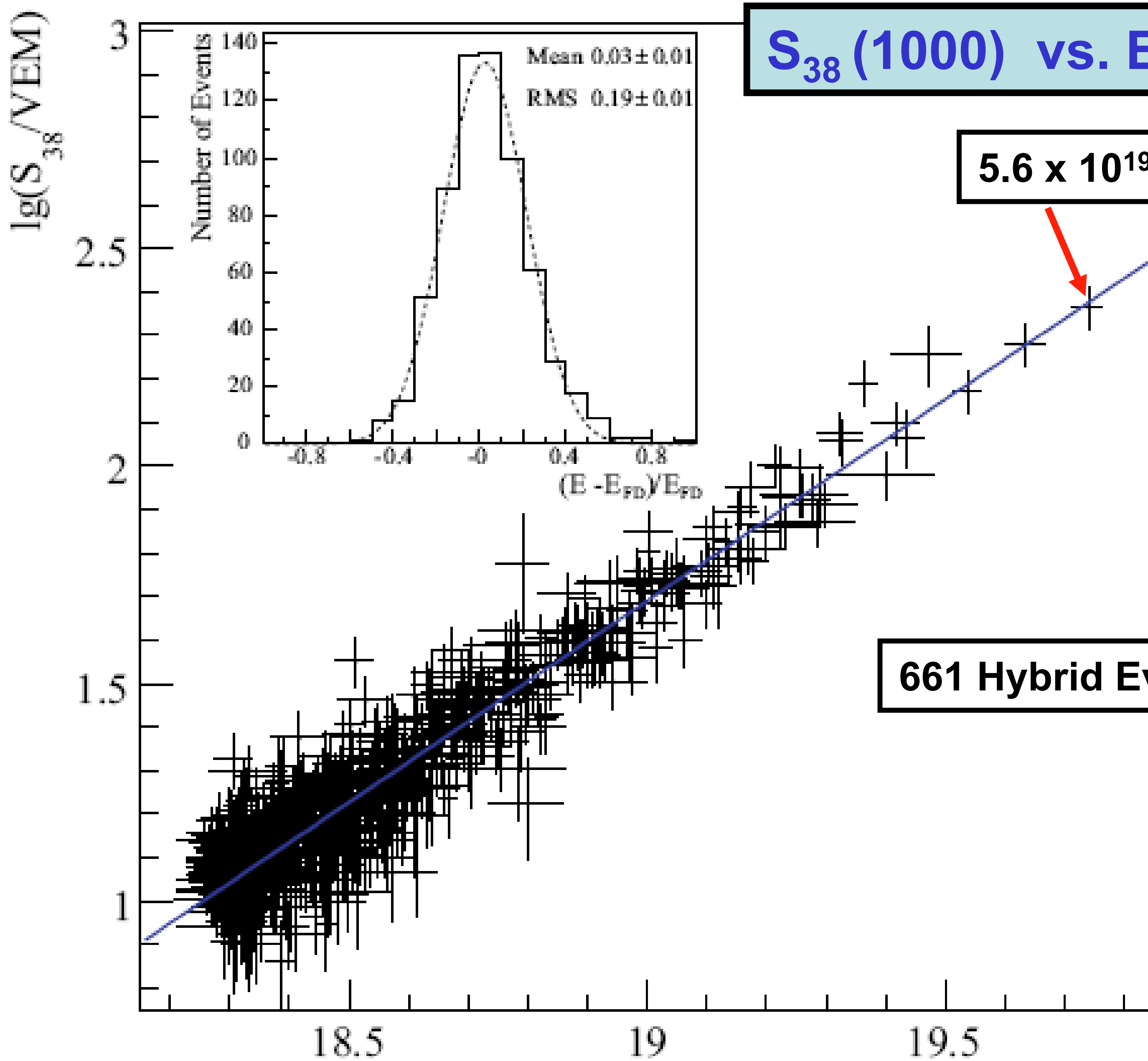
– S(1000)

- determined for each surface detector event

S(1000) is proportional to the primary energy



S_{38} (1000) vs. E(FD)



Energy from Fluorescence Detector

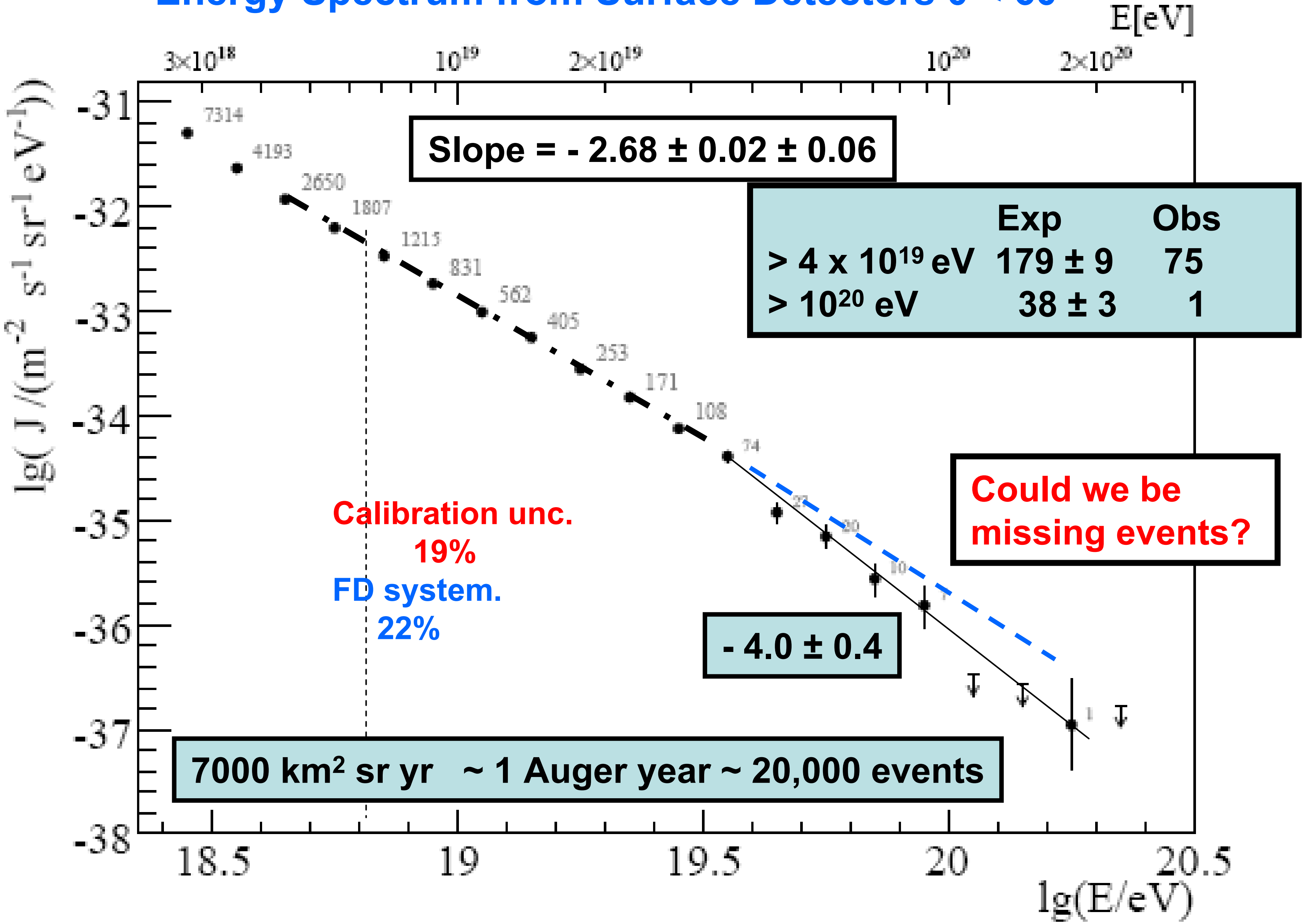
Summary of systematic uncertainties

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%

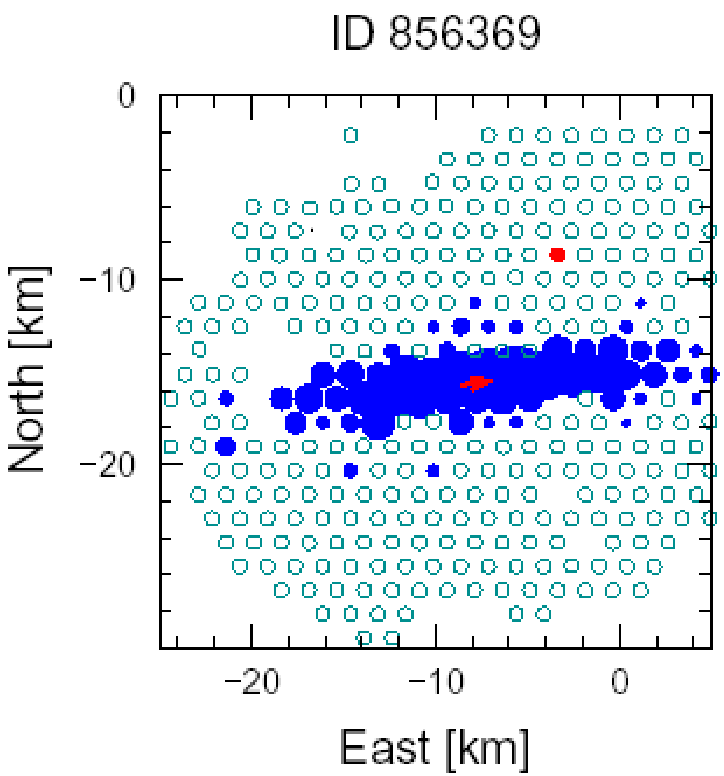
Note: Activity on several fronts to reduce these uncertainties

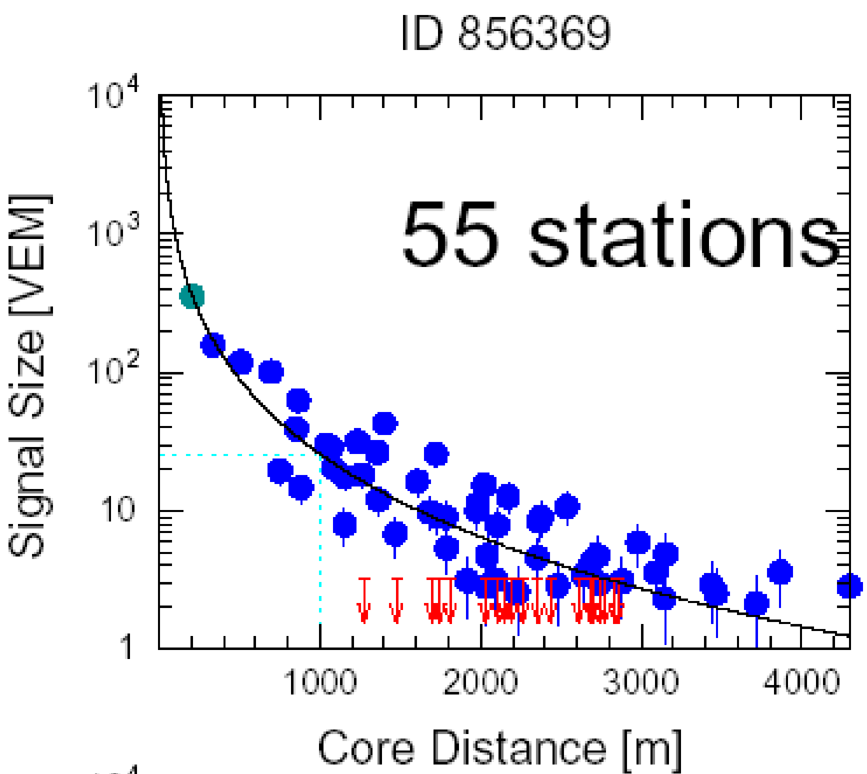
Fluorescence Detector Uncertainties Dominate

Energy Spectrum from Surface Detectors θ < 60°



Evidence that we do not miss events with high multiplicity

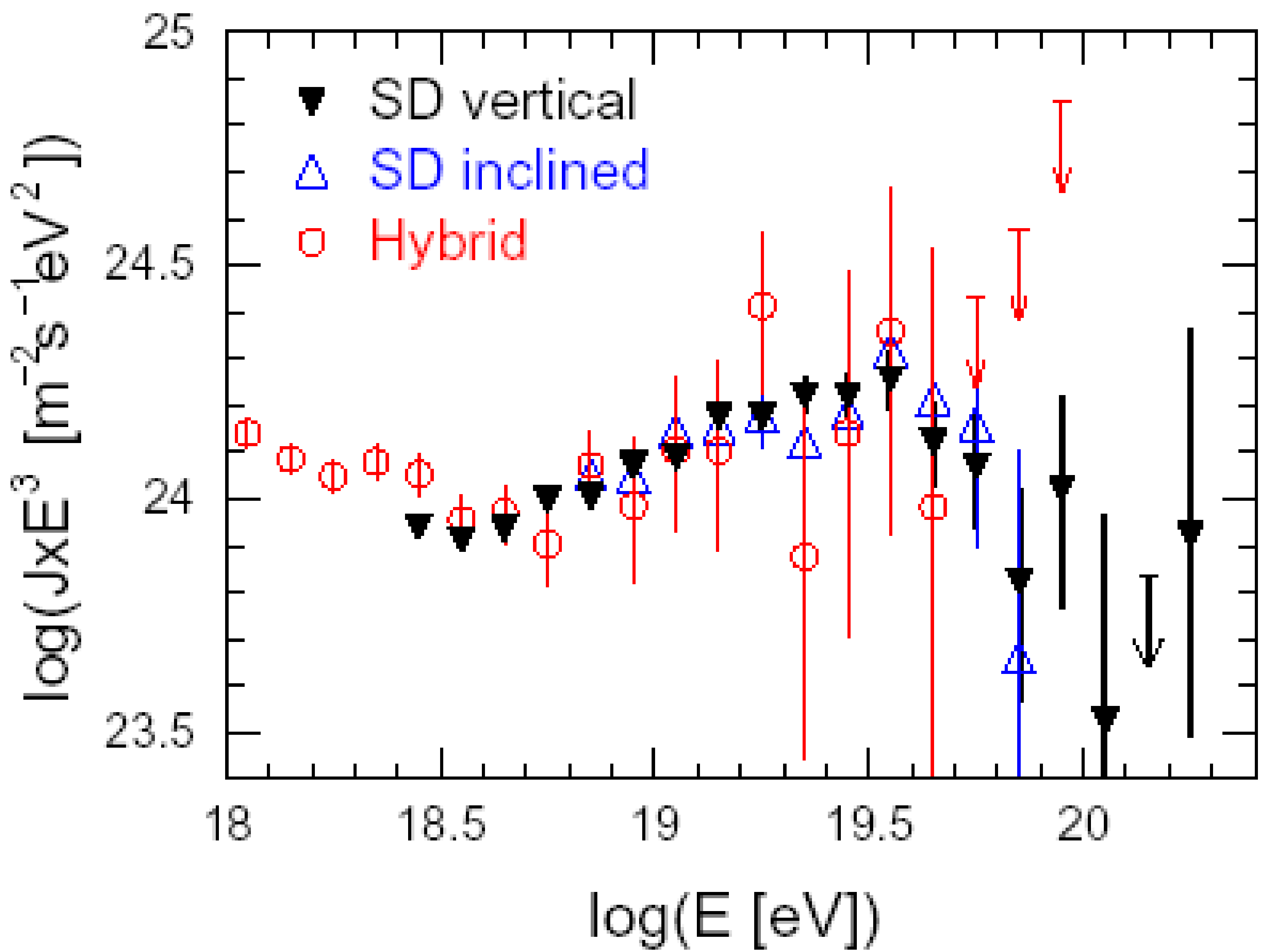




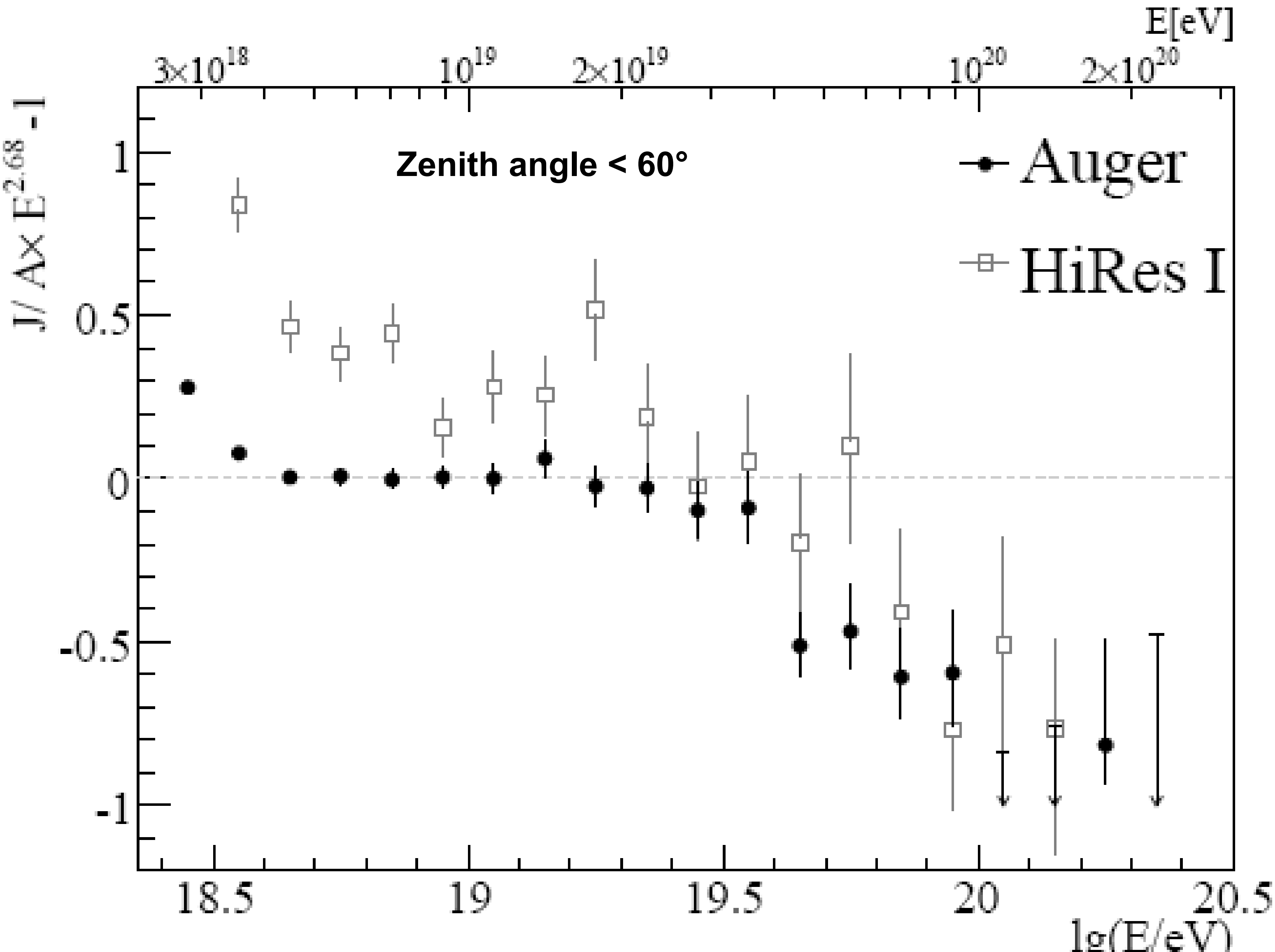
10^4

θ = 79 °

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



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



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

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 – but few (~1 with Auger) - events 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

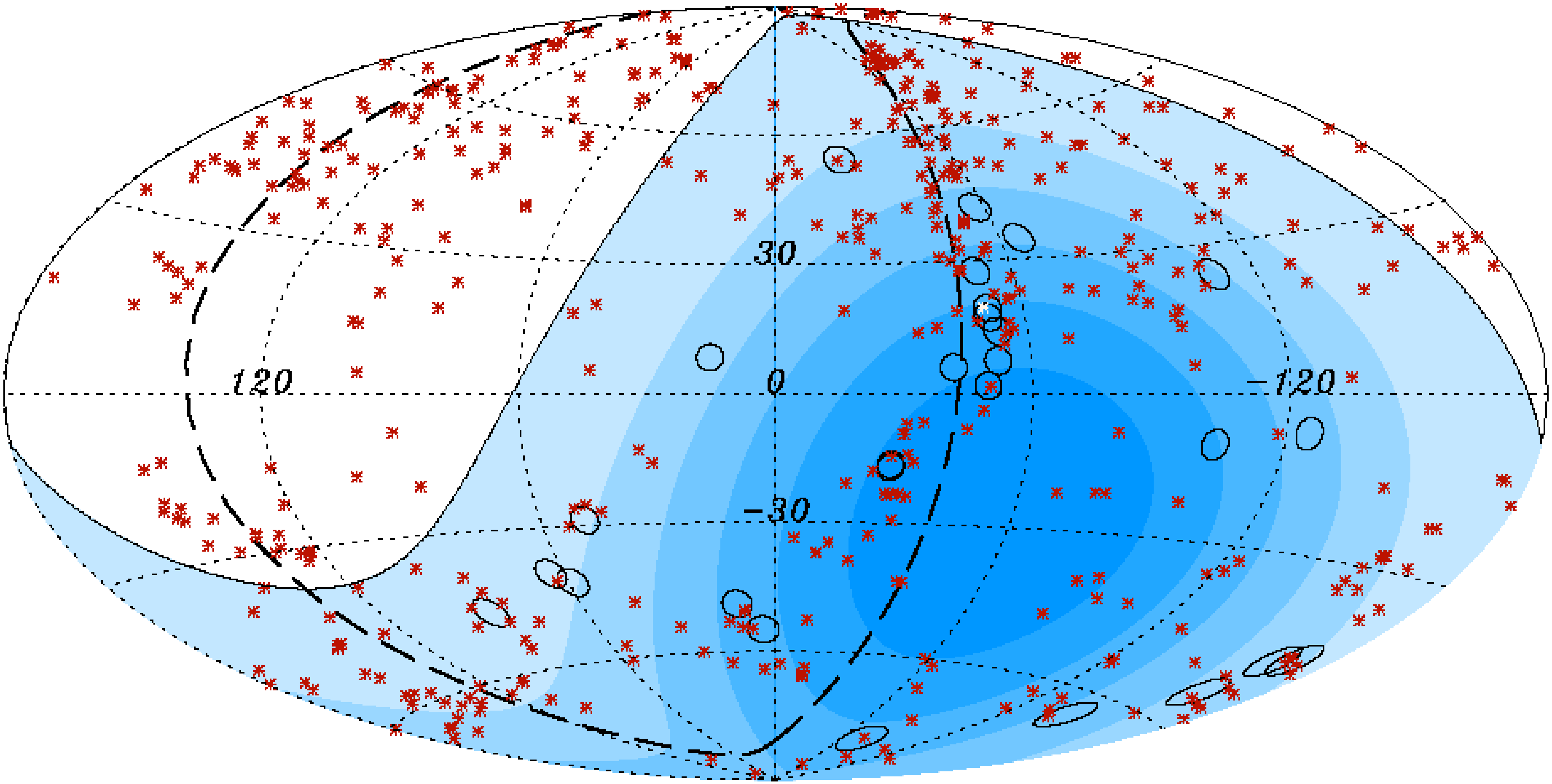
Using Veron-Cetty AGN catalogue

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

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

6 of 8 ‘misses’ are with 12° of galactic plane

Science: 9 November 2007



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

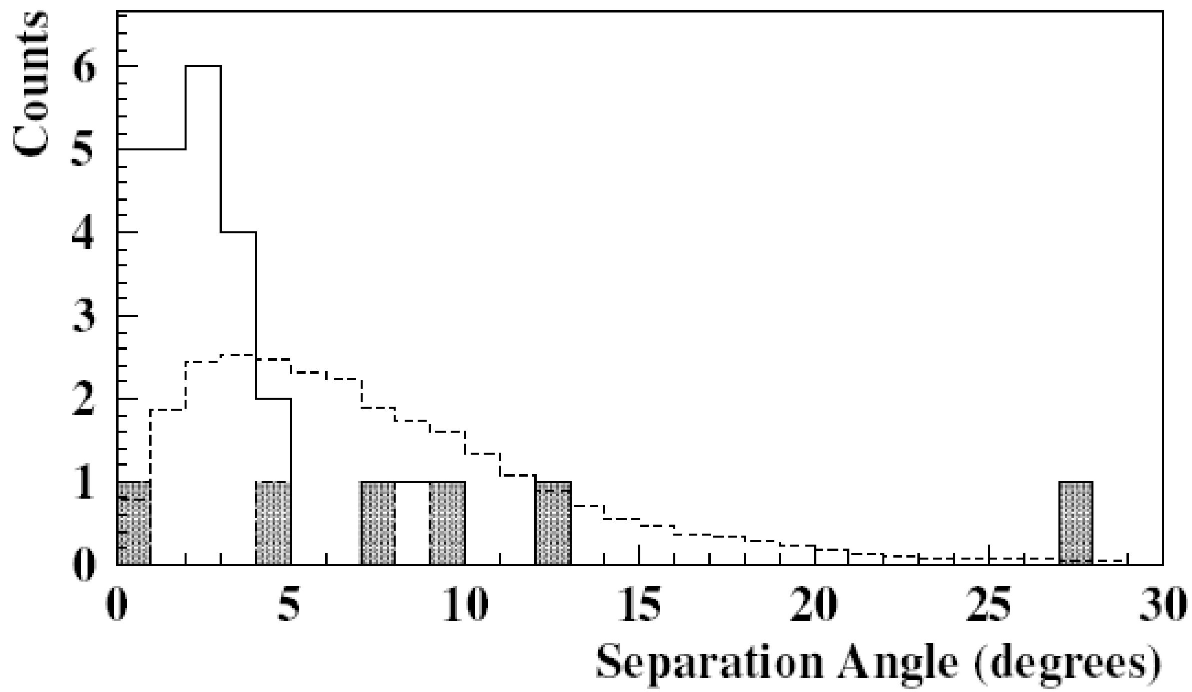


Fig. 4. Distribution of angular separations to the closest AGN within 71 Mpc. The 6 events with $|b| \leq 12°$ have been colored in grey. The average expectation for an isotropic flux is shown as the dashed line histogram.

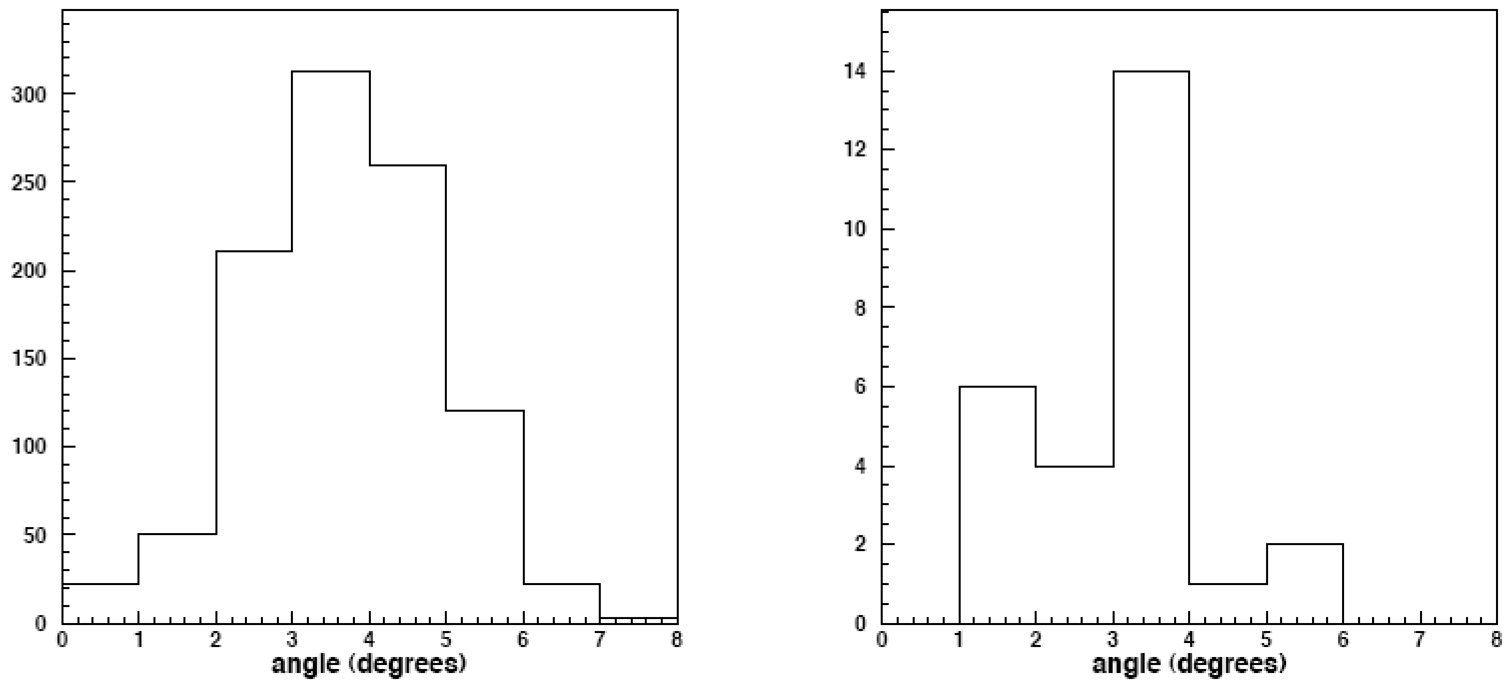


Fig. 8. Distribution of the deflections for protons in the BSS-S model of the galactic magnetic field. Left panel: 1000 directions drawn from an isotropic flux in proportion to the exposure of the Observatory, for $E = 60$ EeV. Right panel: deflections of the 27 arrival directions of the observed events with $E > 57$ EeV .

Support for BSS-S model from Han, Lyne, Manchester et al (2006)

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

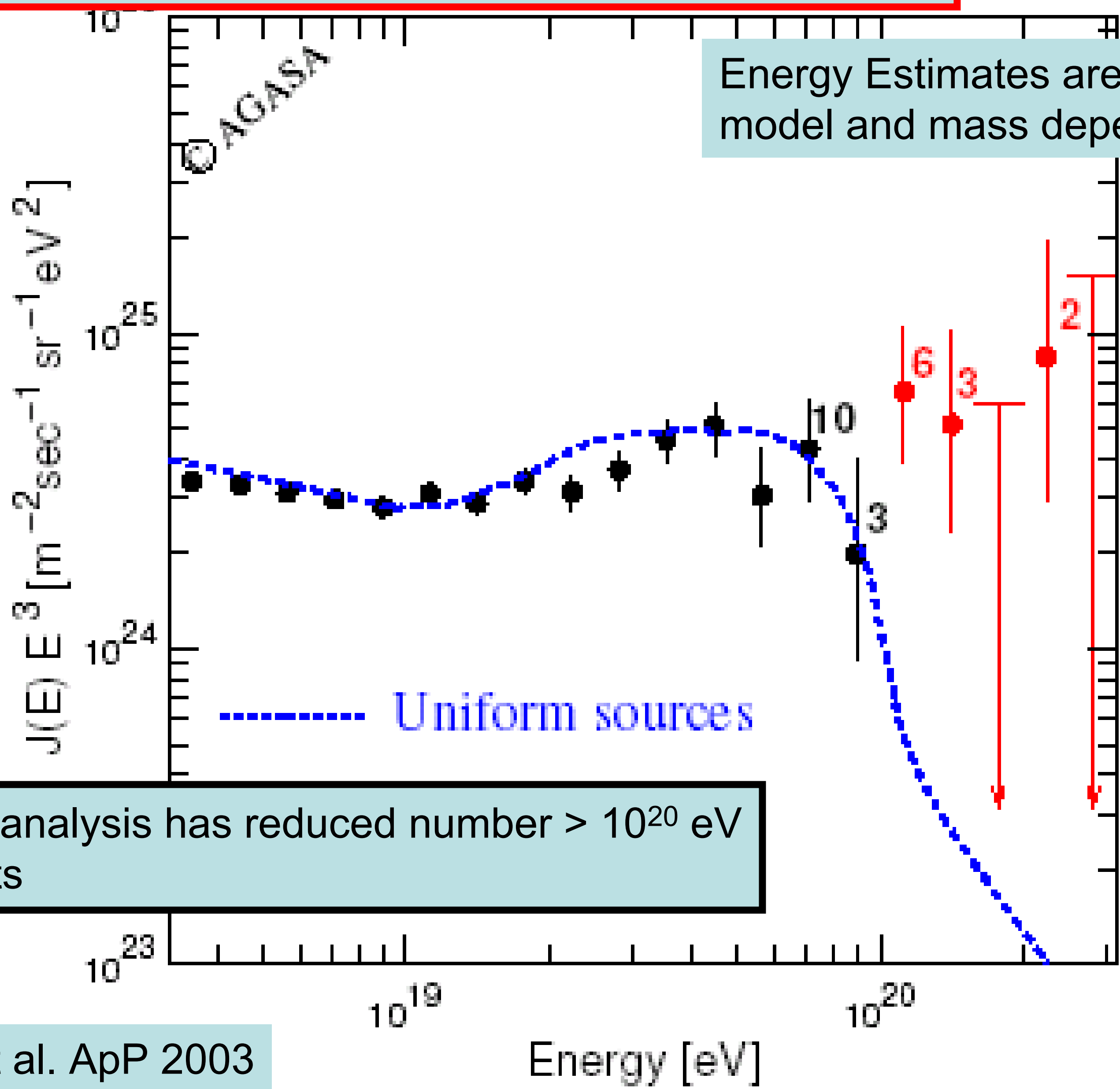
3. Events are associated with AGNs, from the Veron-Cetty catalogue, within 3.1° and 75 Mpc. This association has been demonstrated using an independent set of data with a probability of $\sim 1.7 \times 10^{-3}$ that it arises by chance (~1/600)

Interpretation:

BUT

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

AGASA: Surface Detectors: Scintillators over 100 km²

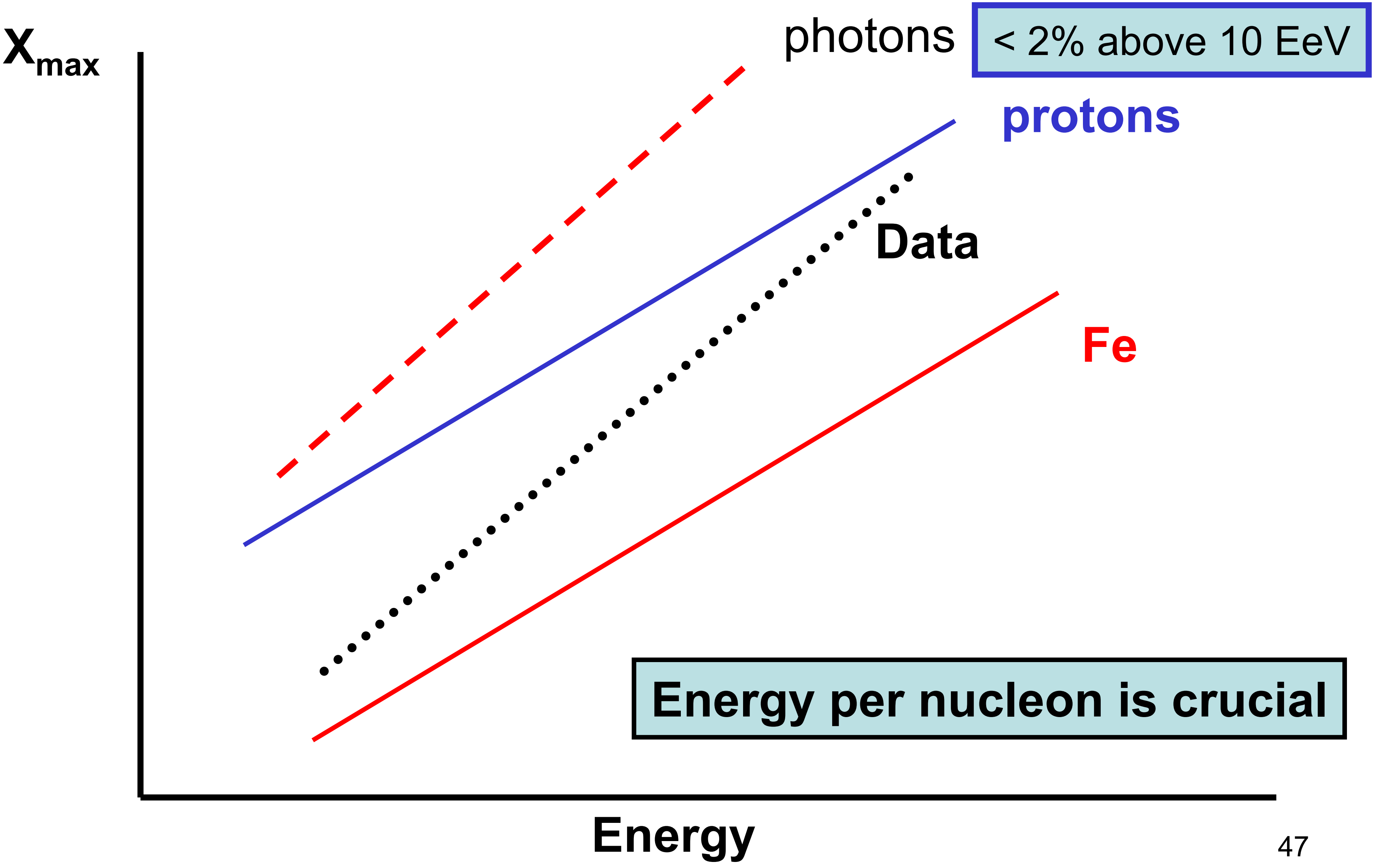


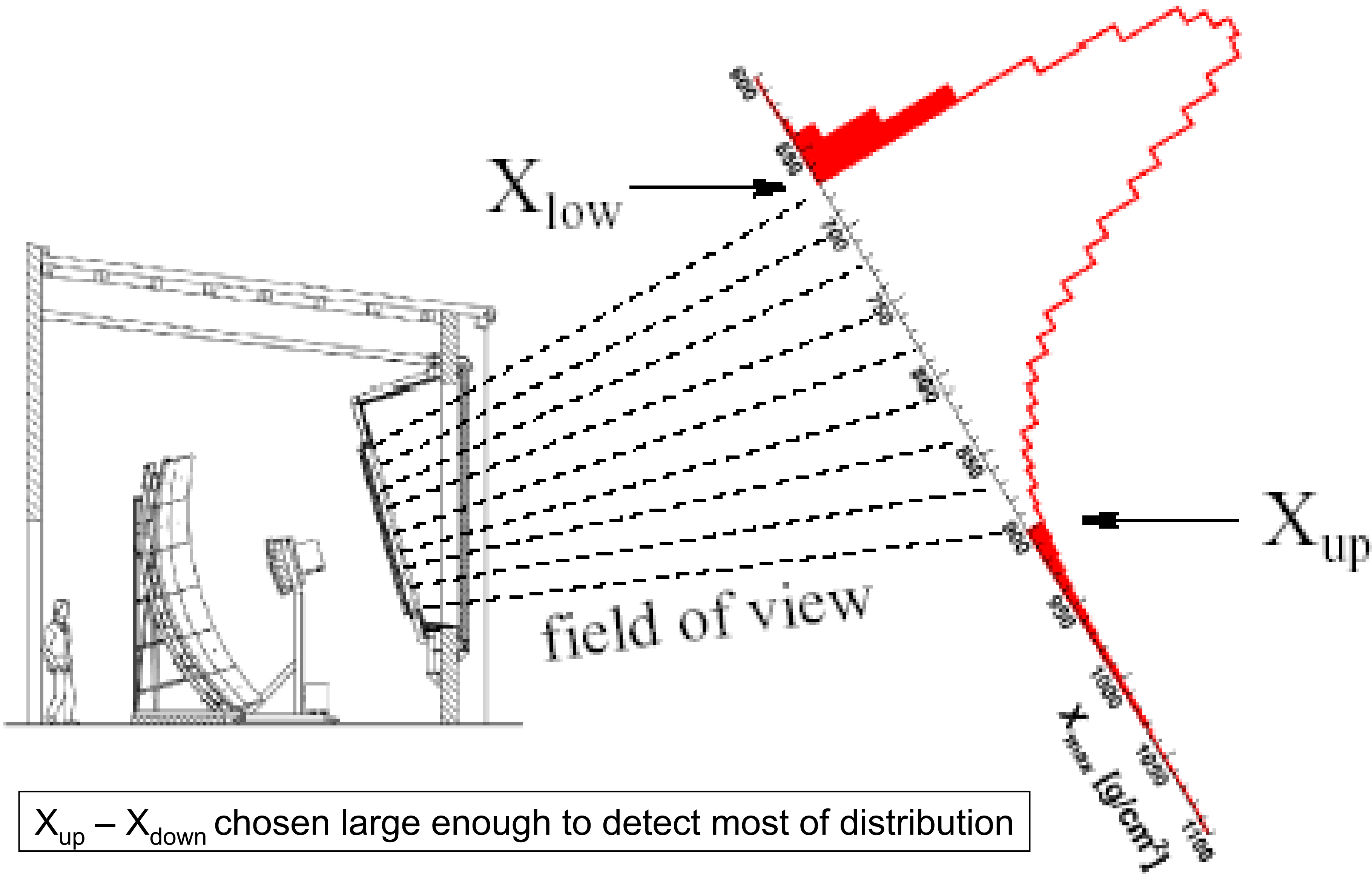
Energy Estimates are model and mass dependent

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

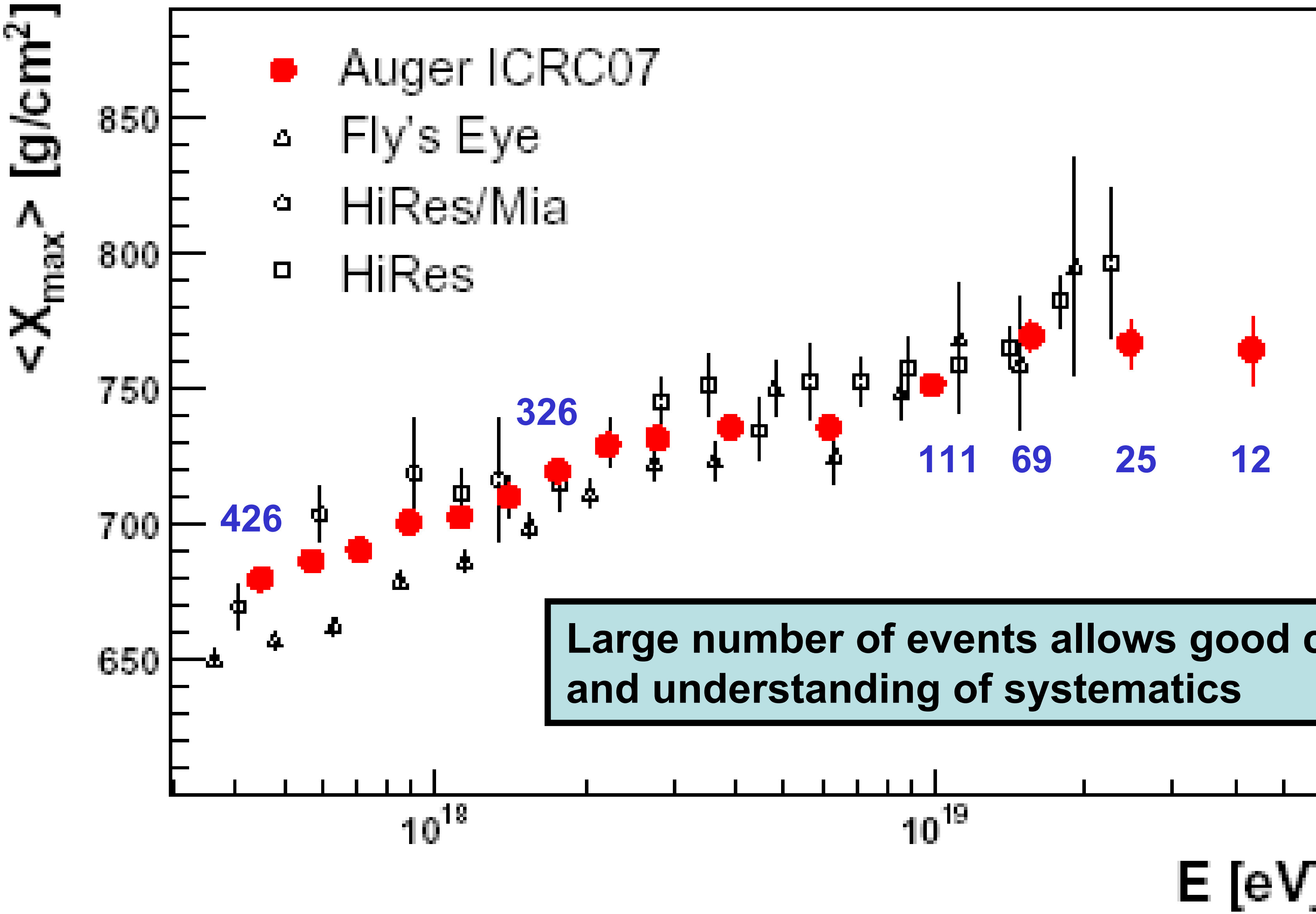
Takeda et al. ApP 2003

How we try to infer the variation of mass with energy

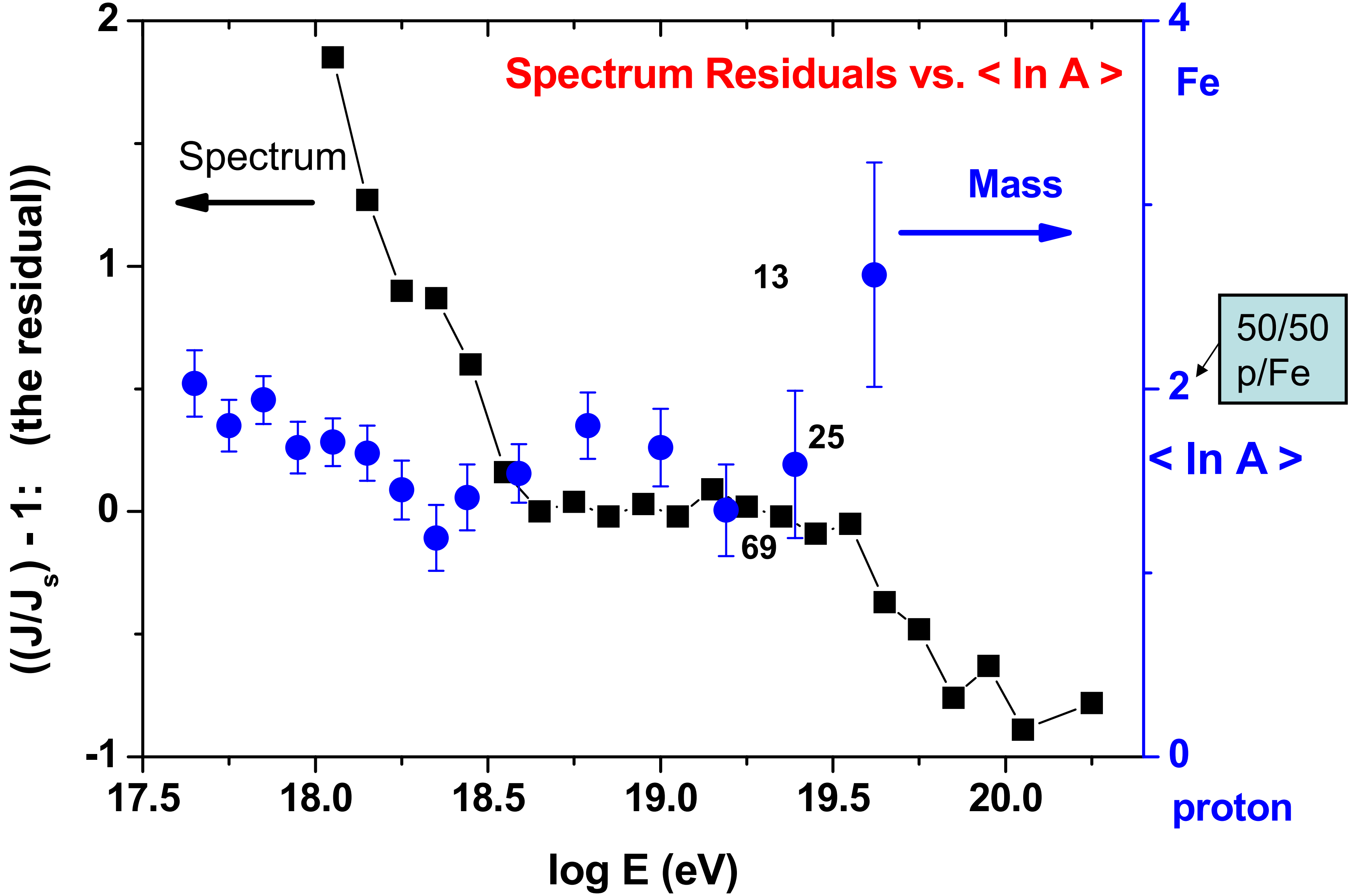




$X_{up} - X_{down}$ chosen large enough to detect most of distribution



Large number of events allows good control and understanding of systematics


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 comments:-

We were careful NOT to say (at least we thought we were)

- that AGNs are the sources of UHECR
- that Cen A is a particularly favoured source

- Gorbunov et al and Wibig and Wolfendale have developed discussions of the anisotropy result on the assumption that the sources are AGNs – the latter suggesting that the mass of the primaries is mixed.

- Cuoco and Hannestad assume that there are 2 events from Cen A and deduce a rate of 100 TeV neutrinos of about 0.5 yr^{-1} in IceCube

- De Angelis et al derived an Intergalactic Magnetic Field of 0.3- 0.9 nG

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 are 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?
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 ~ 3 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, 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