David Schramm Symposium:

NEW VIEWS OF THE UNIVERSE

Recent Studies of Ultra High Energy Cosmic Rays

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Dave Schramm: 15 November 1997

Current Situation: (re- UHECR)

The "Conservative" AGN (Black Hole!) Bottom-Up scenario has observational Problems that are difficult to dismiss.

The Top-Down (Big Bang Relics) is also constrained but is still flexible enough to be quite viable.

NEED MORE DATA!!

Note: Top-Down(Big Bang Relics)
$\Rightarrow$ TOE (New Fundamental Physics)

Outline:

- **Present Status of Detectors - Auger**

- **The Issues:**

  i Changes to Hadronic Interaction Models

  - inferences for mass composition

  ii Energy Spectrum

  – is there a GZK-effect?

  iii Arrival Directions

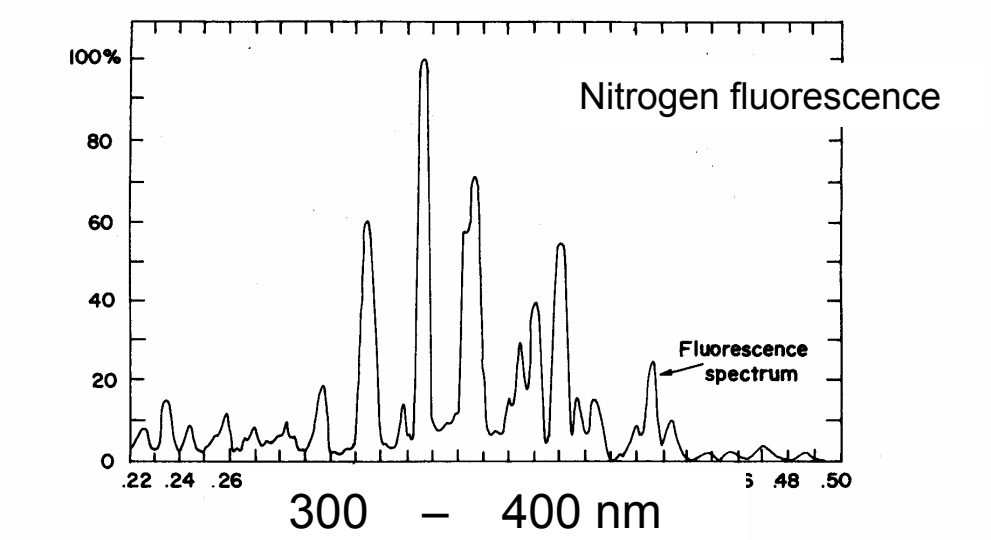
  - Clusters? BL Lac associations?

- **Summary**

Exposure and Event Numbers from various Instruments

	km² sr year	**Approximate rate > 10 EeV**	
			(km² sr year)$^{-1}$
	AΩt	N	rate
AGASA: closed in January 2004: Scintillator array	**1600**	**827**	**0.52**
HiRes I: monocular Fluorescence Detector	**~5000**	**403**	**0.08**
(HiRes II: monocular			
HiRes: stereo (**PRELIMINARY**)	**~2500**	**~500**	**0.20**
Yakutsk: Scintillator plus air-Cherenkov light	**~900**	**171**	**0.19**
Auger: data taking since Jan 2004 Fluorescence plus water-Cherenkov	**1750**	**444**	**0.25**

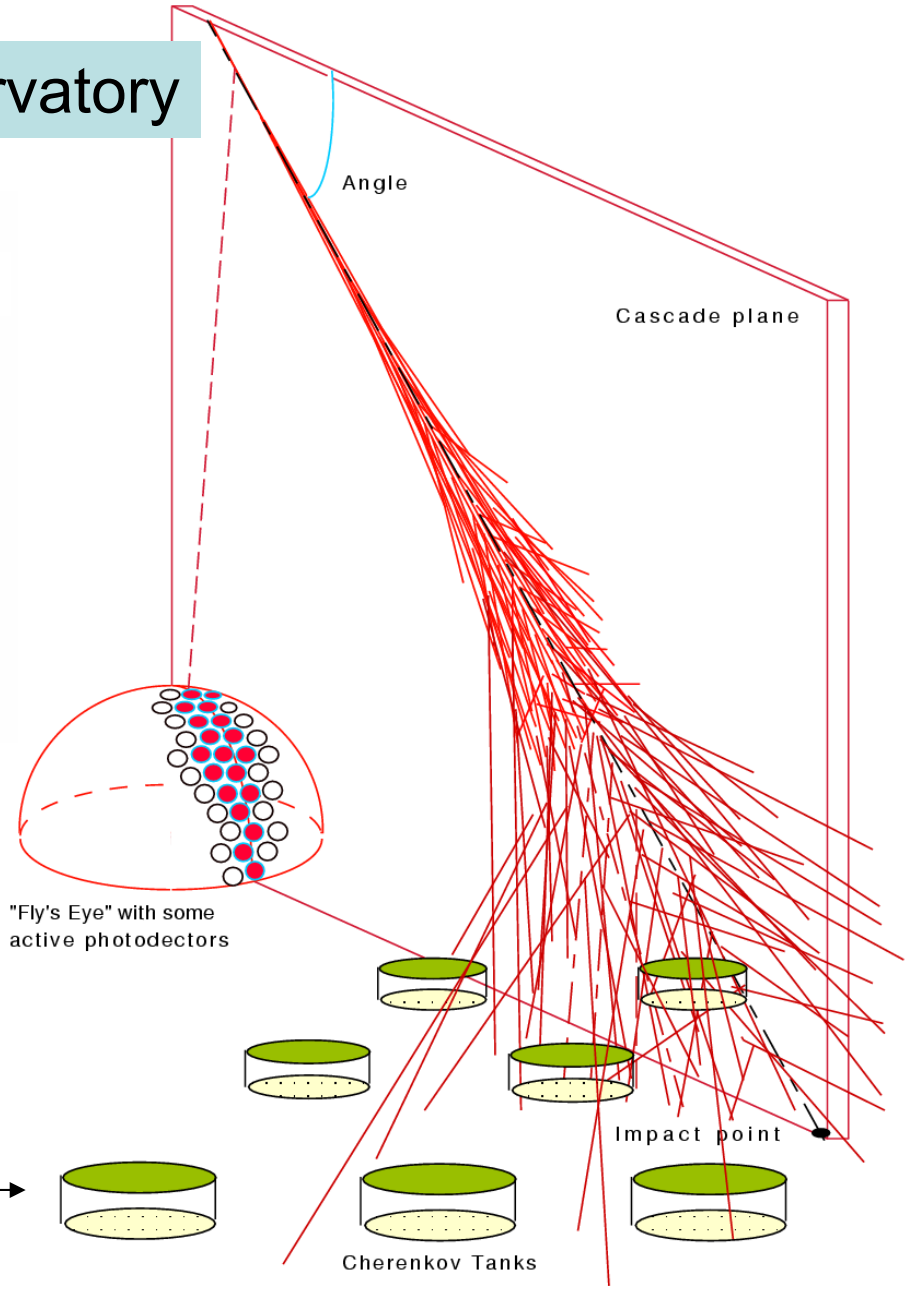
Hybrid Approach of Auger Observatory



Fluorescence in UV →

AND

Water-Cherenkov detectors respond to muons, $e^{\pm}$, γ →

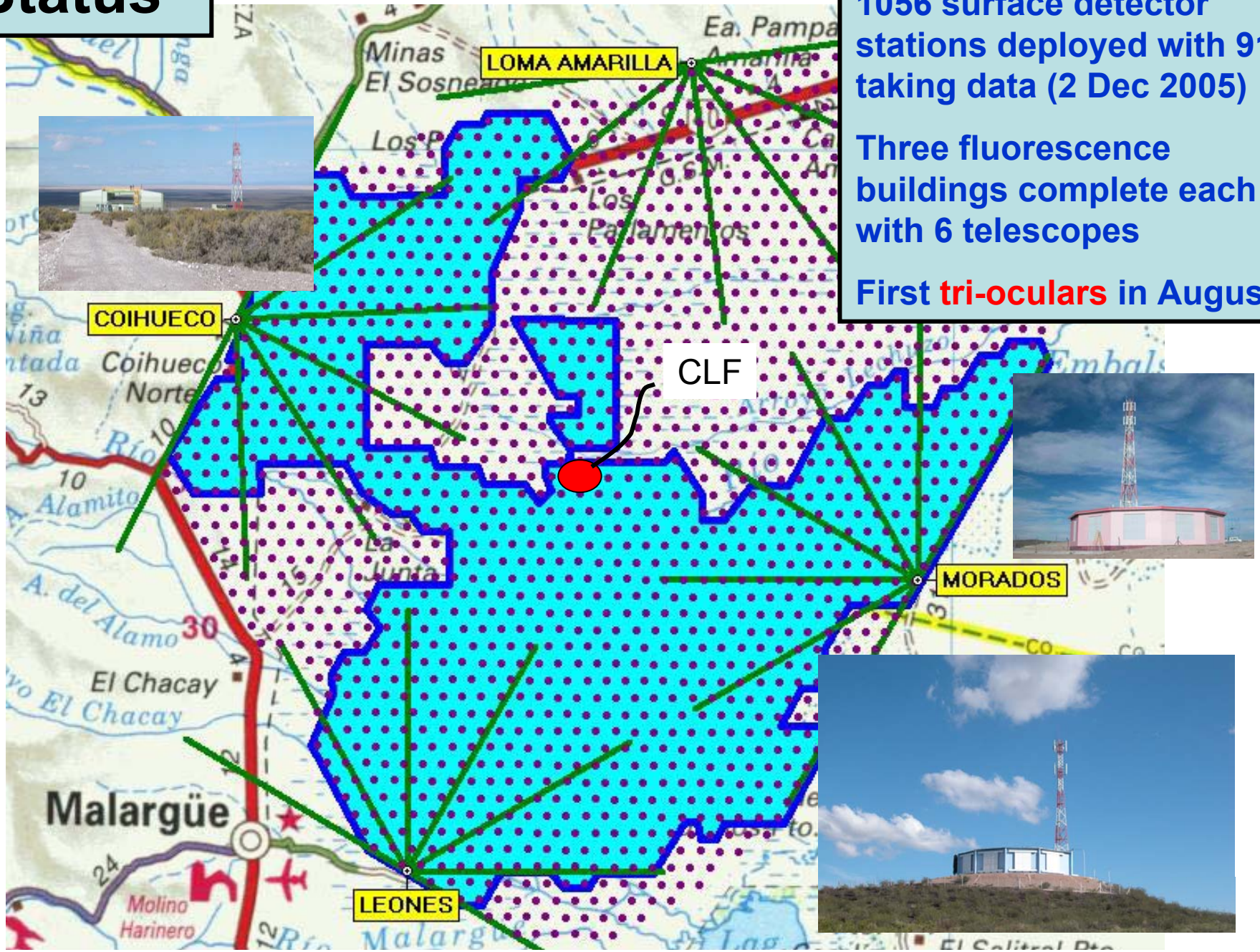


Status

1056 surface detector stations deployed with 919 taking data (2 Dec 2005)

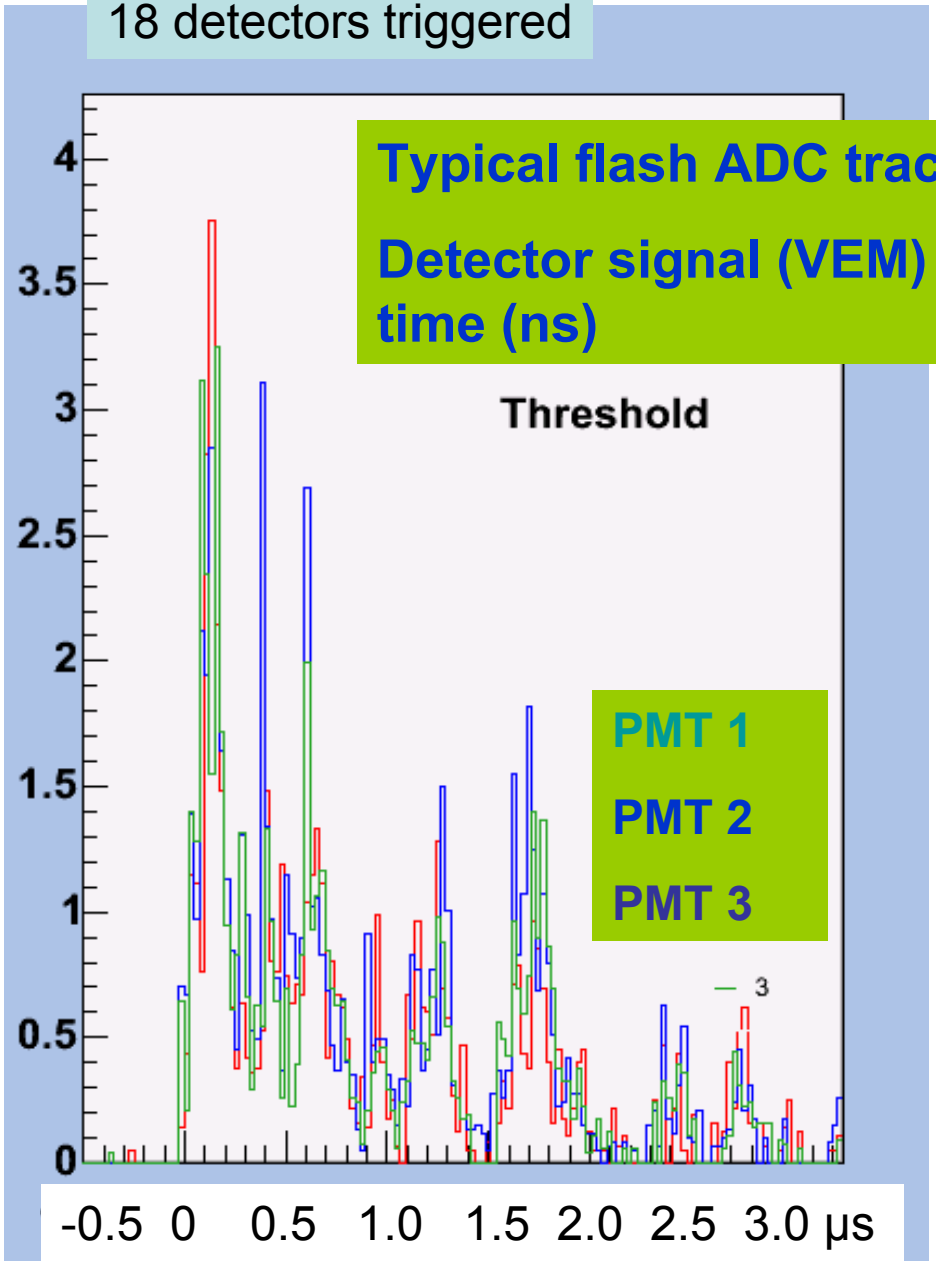
Three fluorescence buildings complete each with 6 telescopes

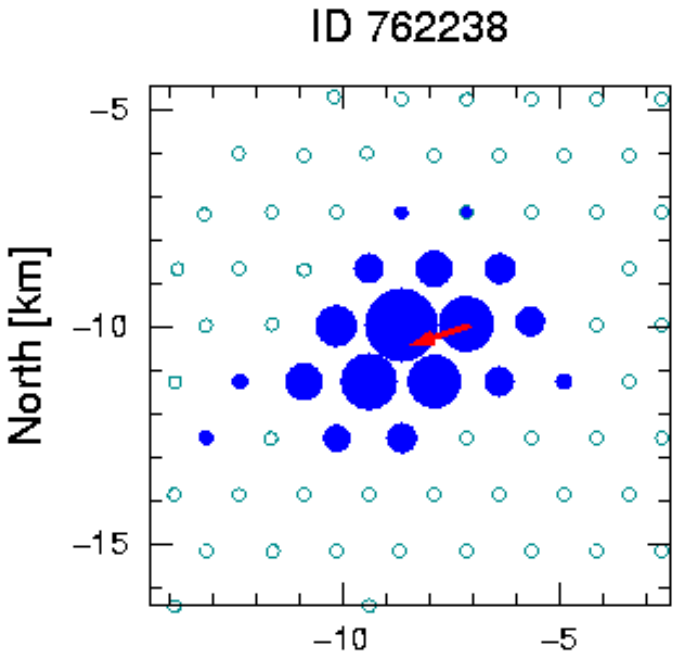
First tri-oculars in August

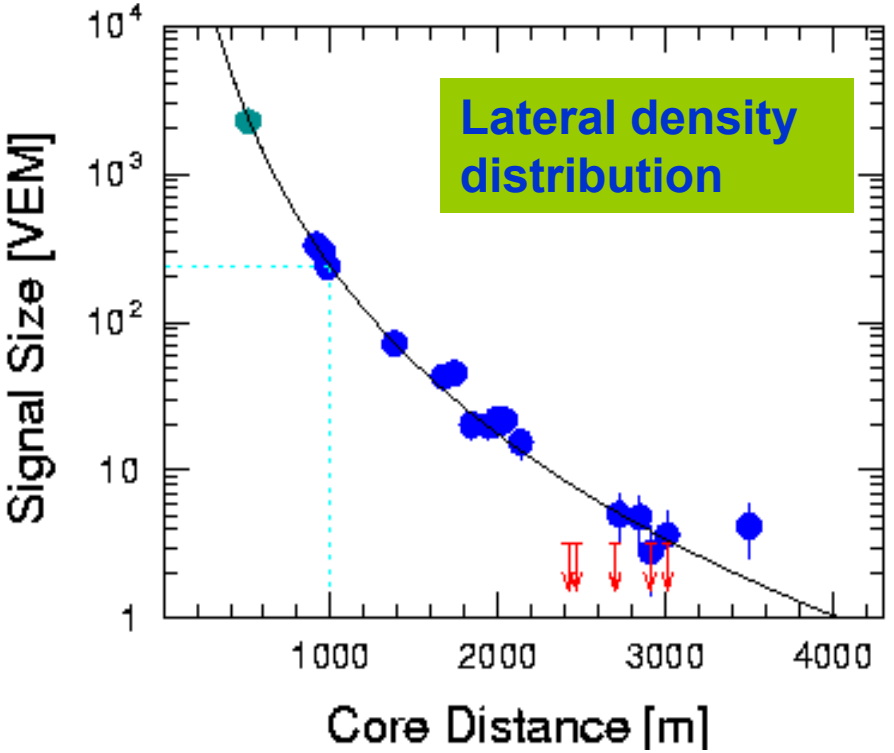


θ~ 48º, ~ 70 EeV

18 detectors triggered

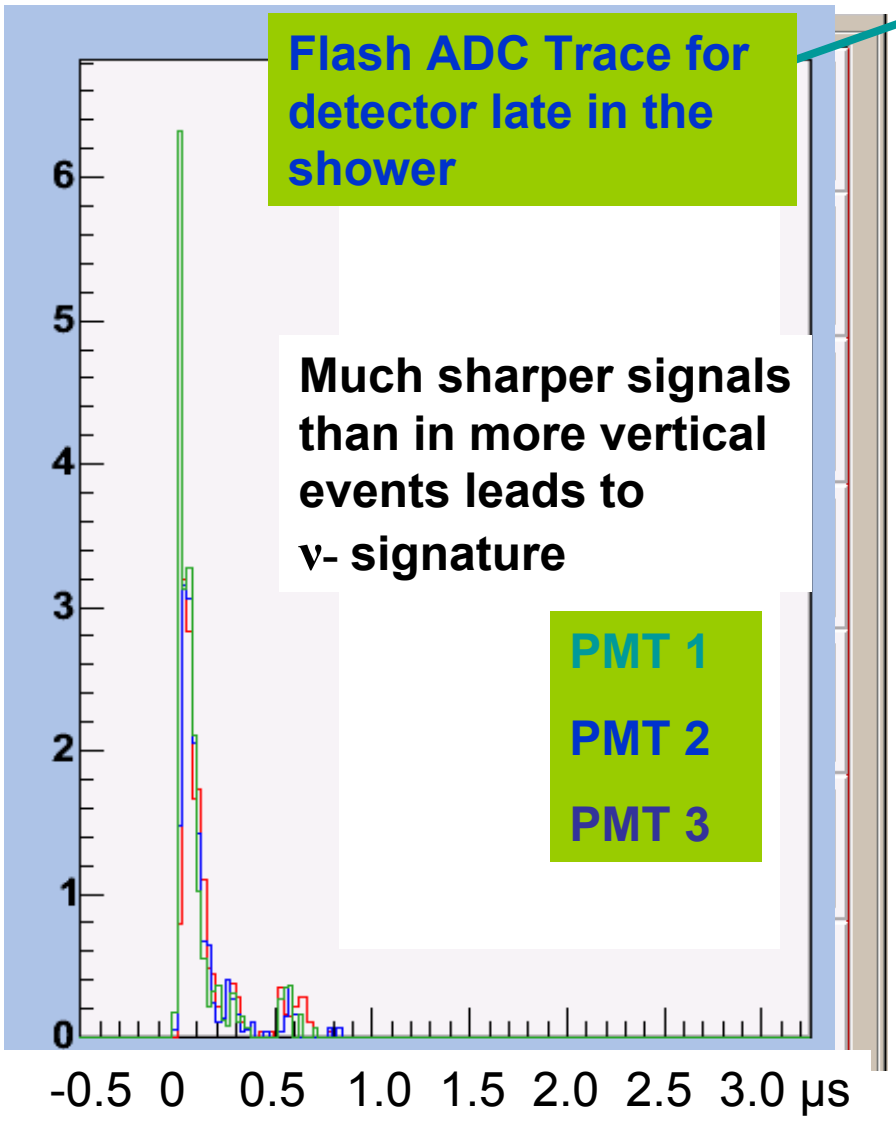


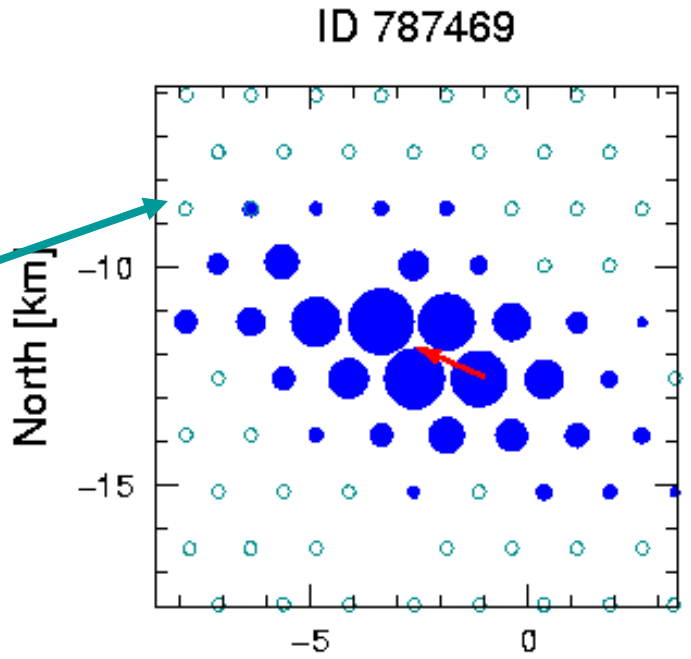


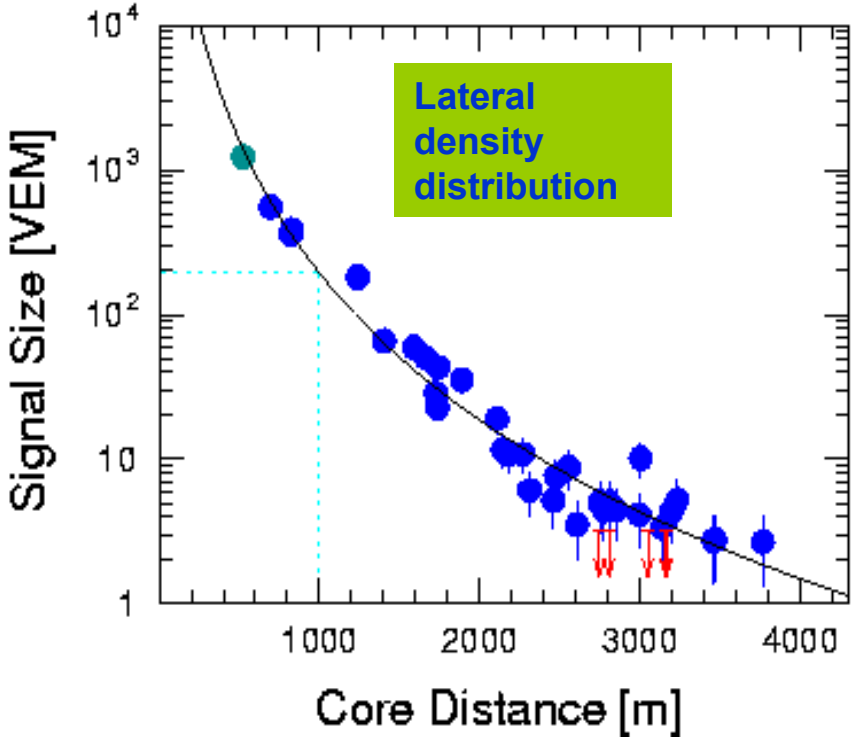


θ~ 60º, ~ 86 EeV

35 detectors triggered

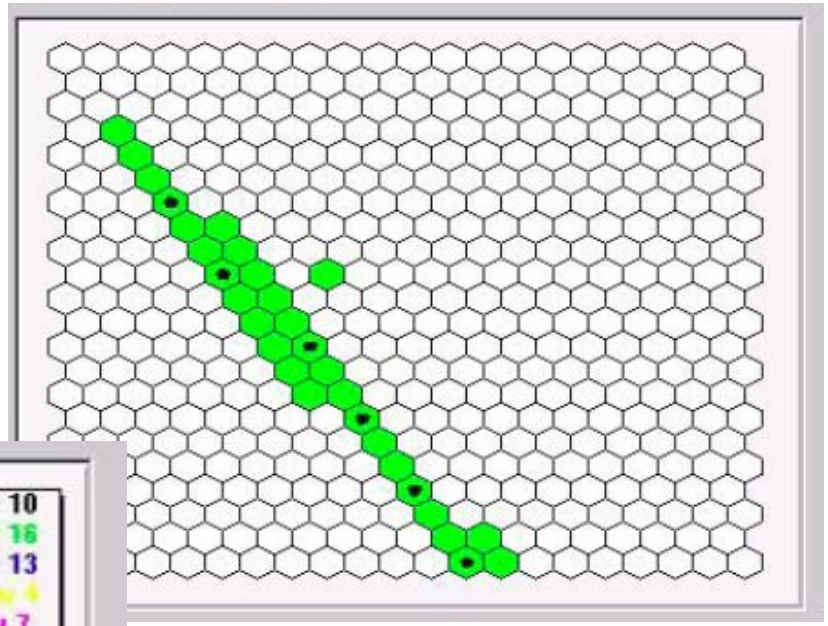


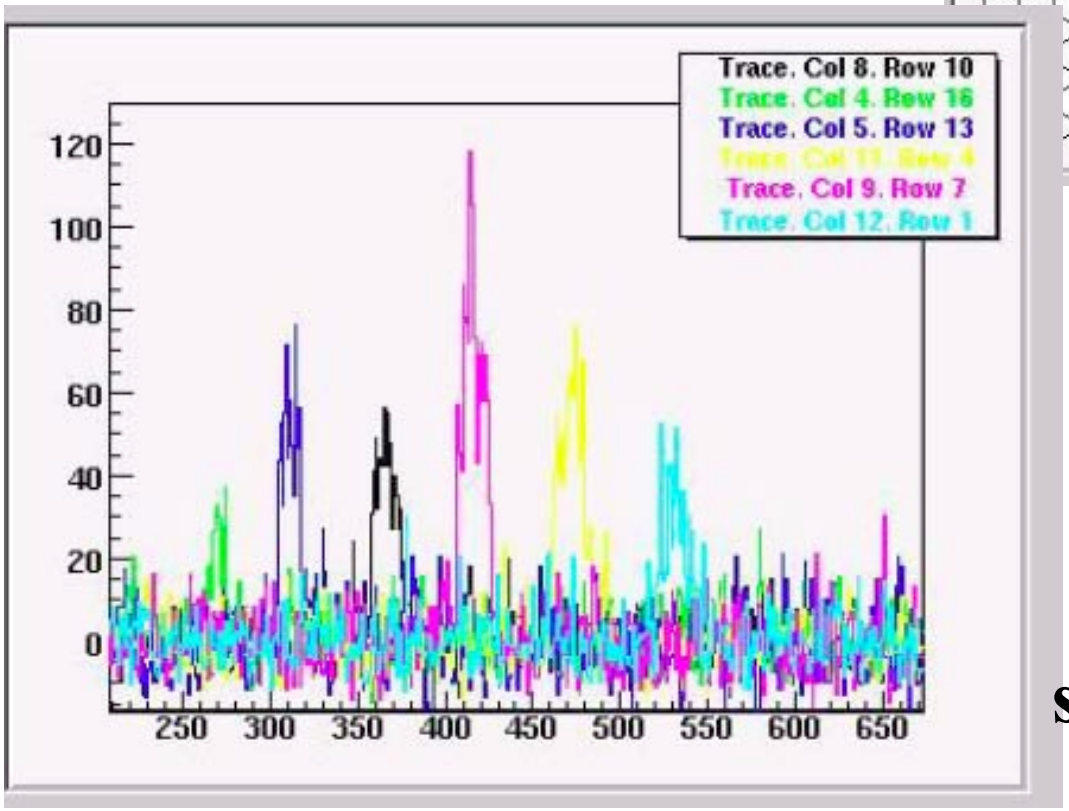




FD reconstruction

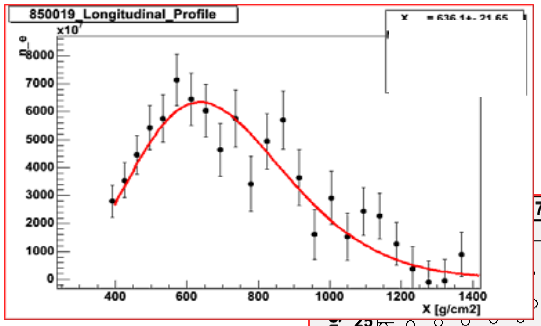
Signal and timing
Direction & energy

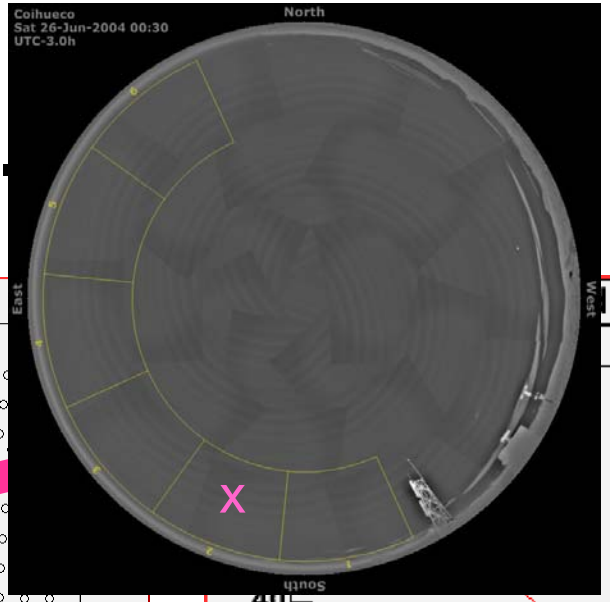


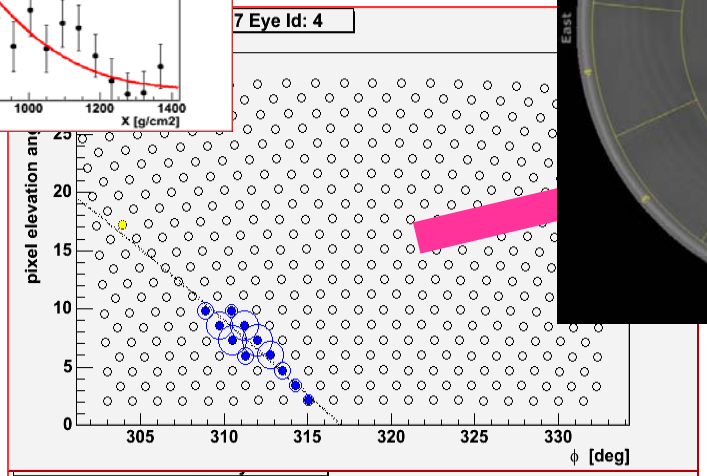


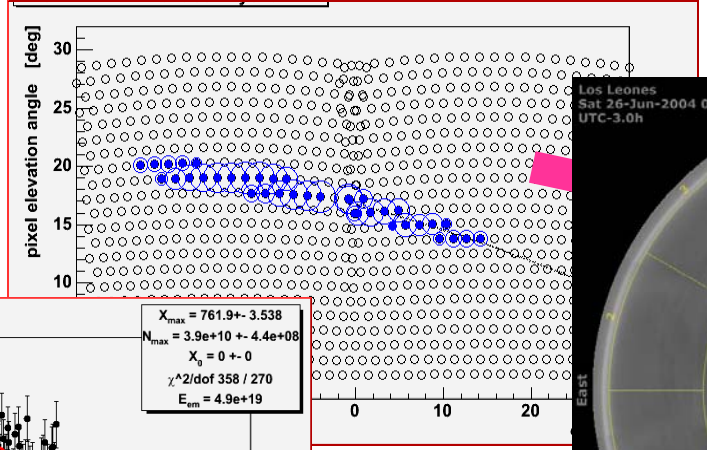
Pixel geometry
shower-detector plane

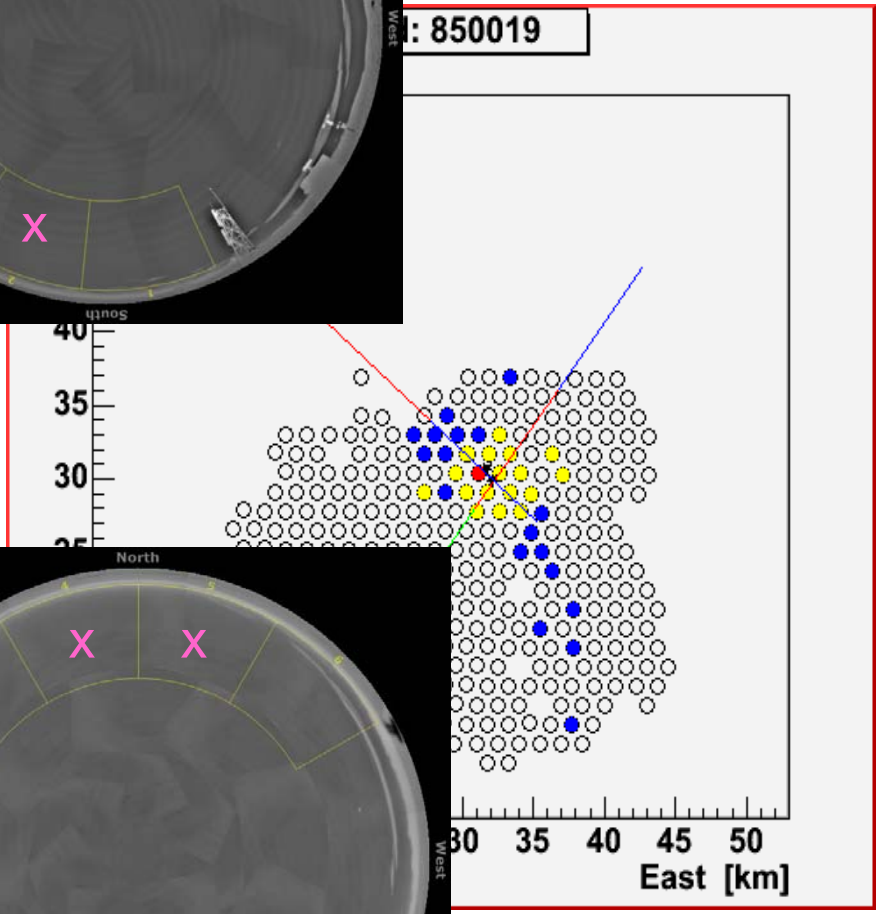
Stereo-

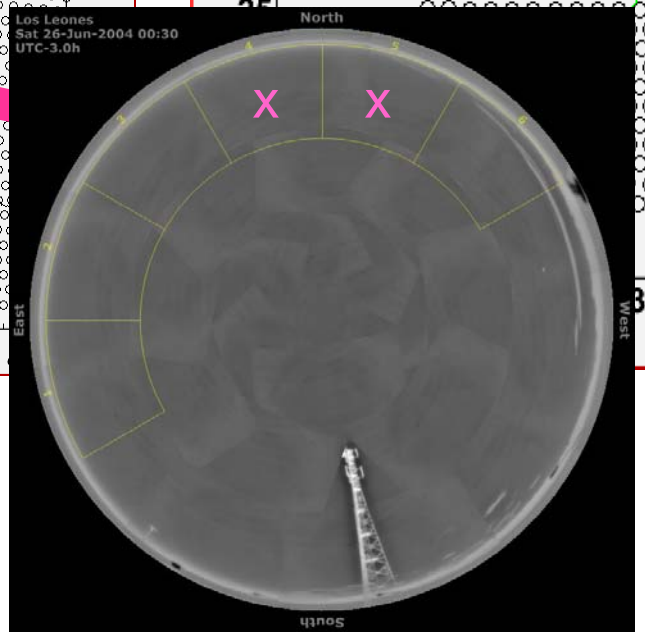

850019_Longitudinal_Profile
X [g/cm2]

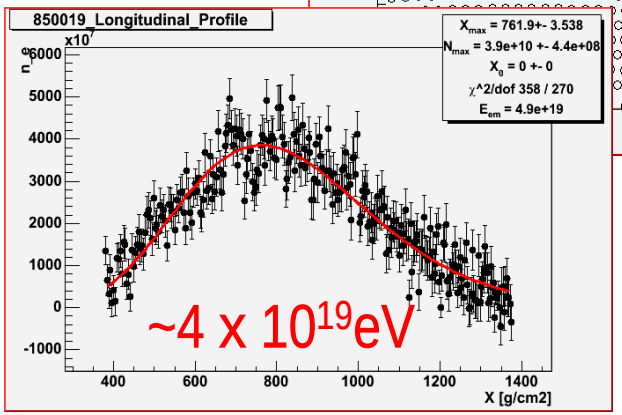

Coihueco
Sat 26-Jun-2004 00:30
UTC-3.0h
North
East
West
South


7 Eye Id: 4
pixel elevation
ϕ [deg]


pixel elevation angle [deg]


l: 850019
East [km]

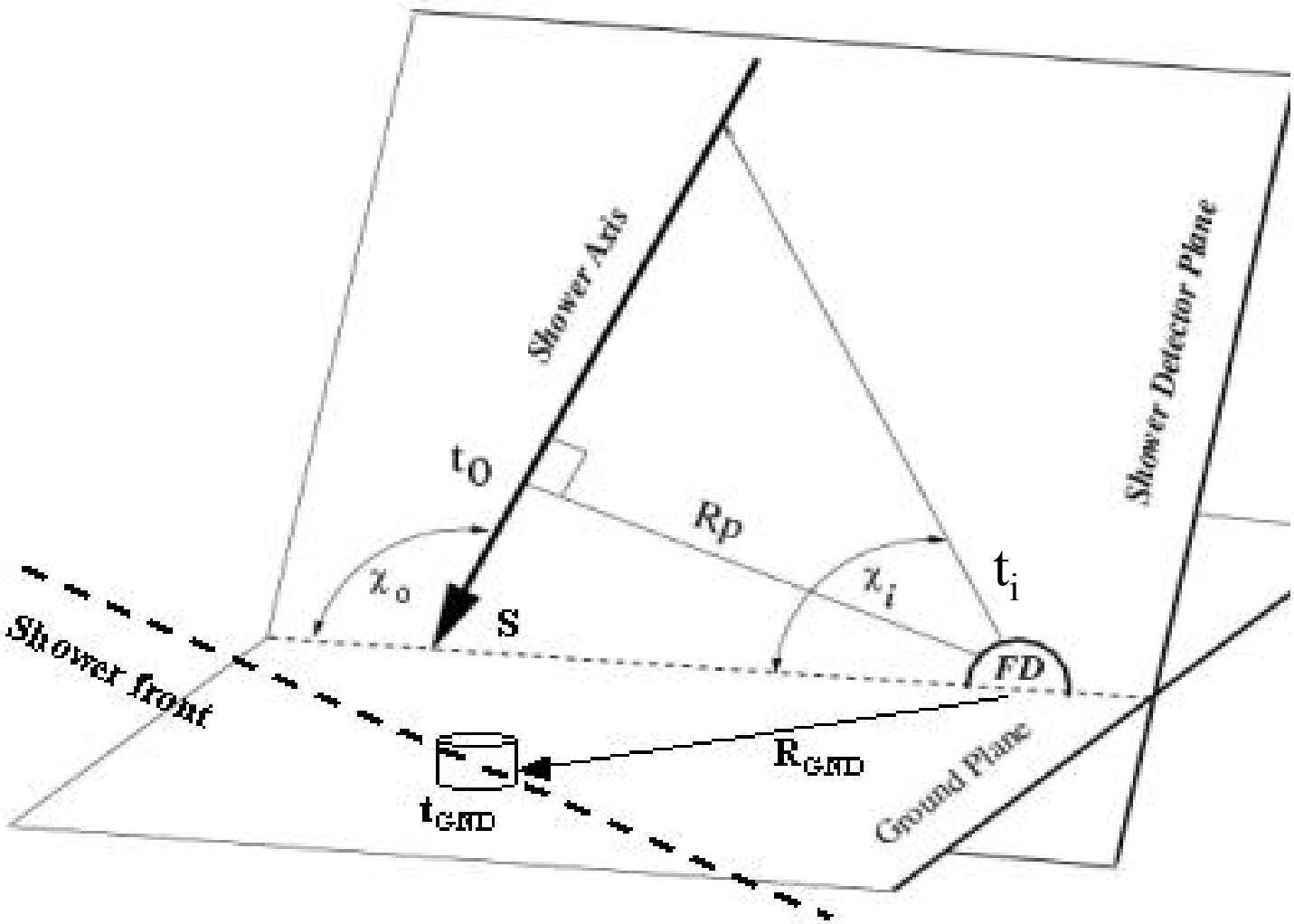

Los Leones
Sat 26-Jun-2004 00:30
UTC-3.0h
North
East
West
South


850019_Longitudinal_Profile
X_max = 761.9+- 3.538
N_max = 3.9e+10 +- 4.4e+08
X_0 = 0 +- 0
χ^2/dof 358 / 270
E_em = 4.9e+19
~4 x 10^19eV
X [g/cm2]

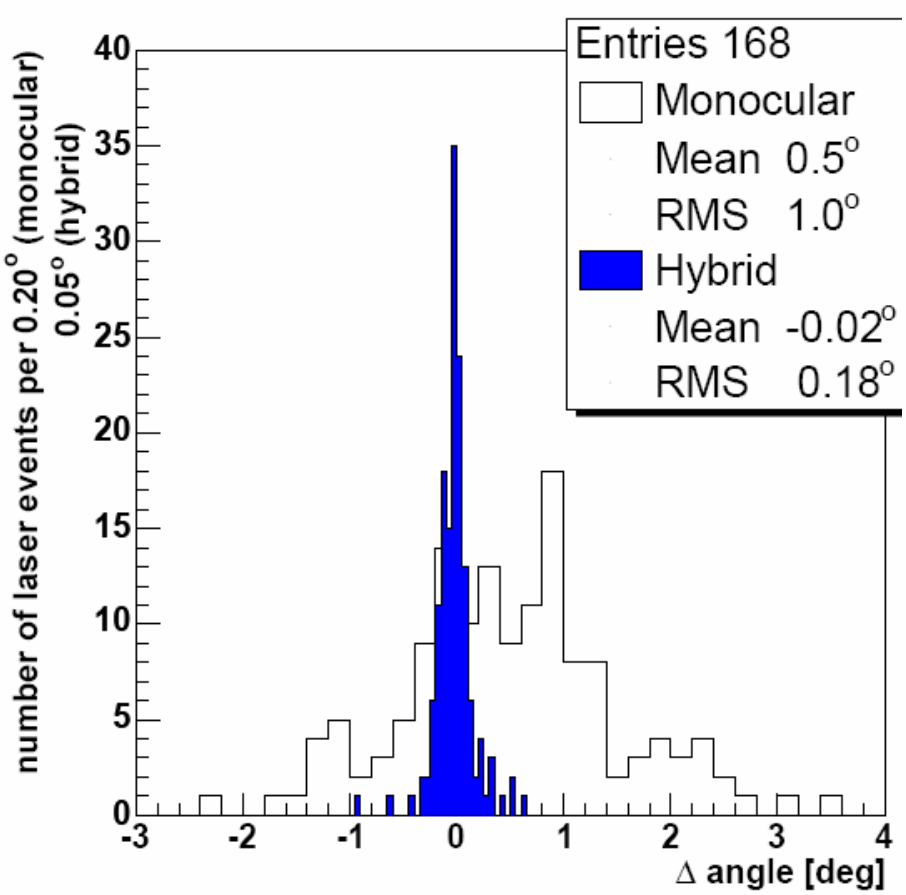
The Central Laser Facility of the Pierre Auger Observatory

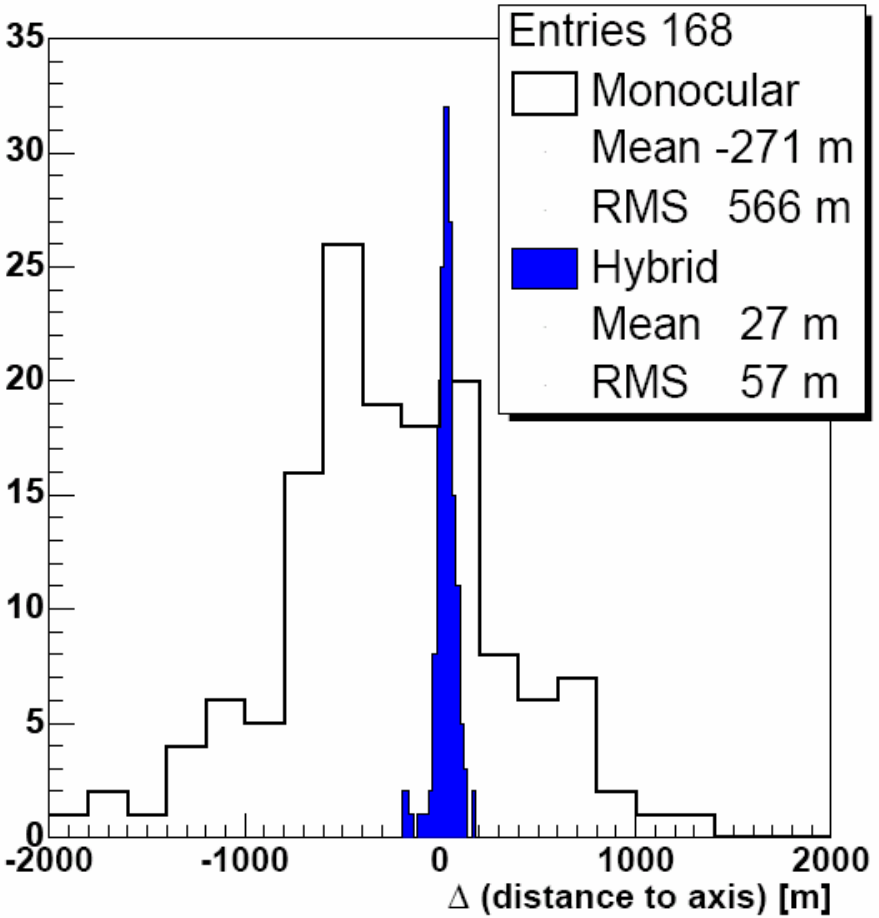
355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

Geometrical Reconstruction



Angular and Spatial Resolution from Central Laser Facility





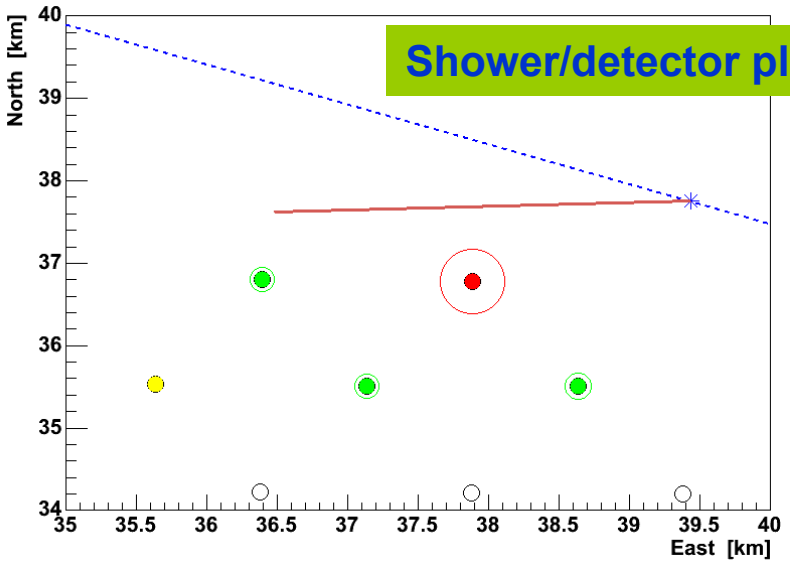
Angle in laser beam /FD detector plane

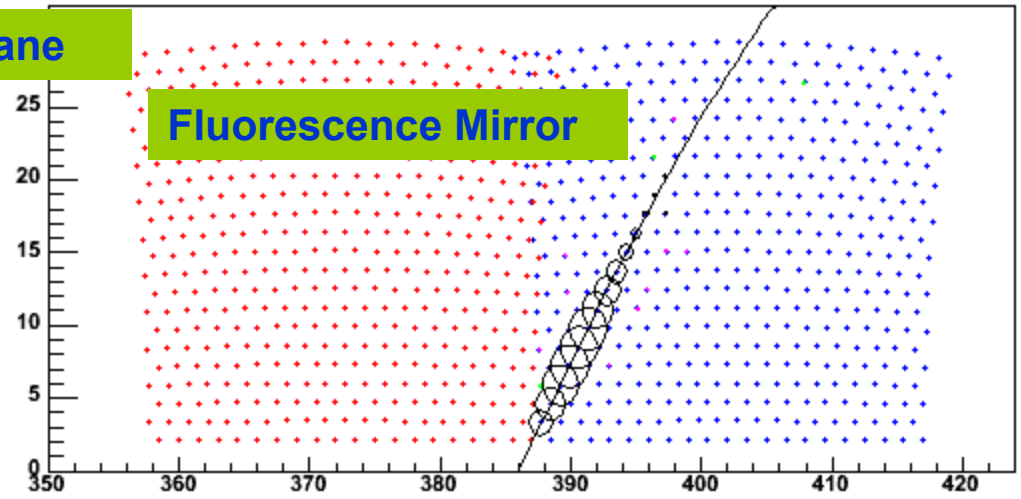
Laser position – Hybrid and FD only (m)

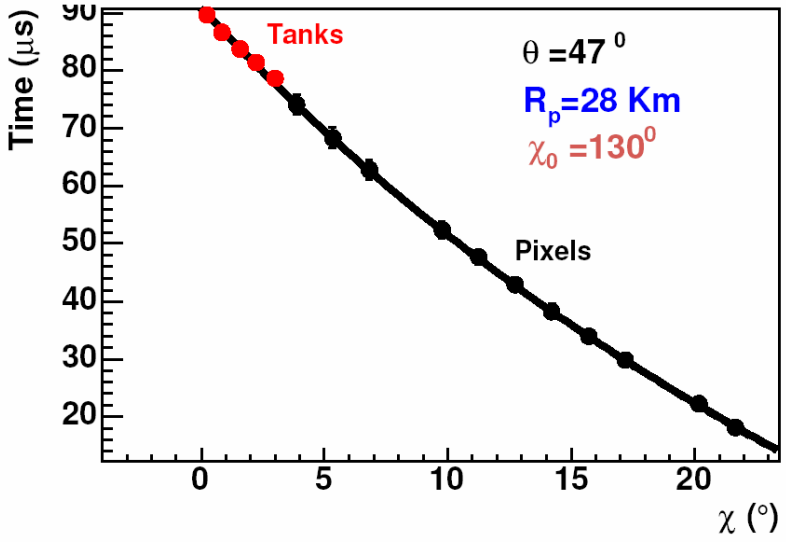
Mono/hybrid rms 1.0°/0.18°

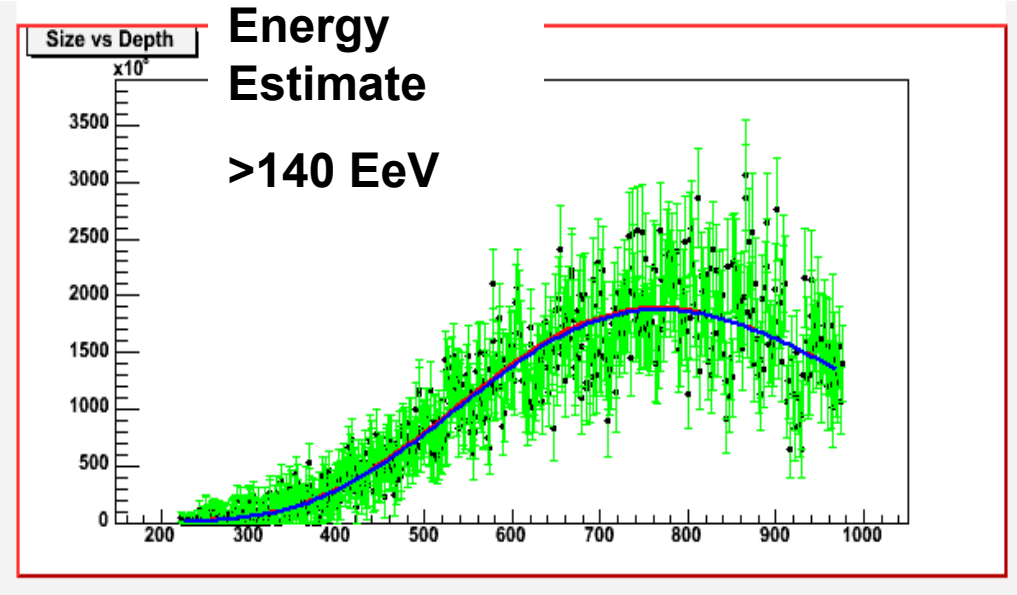
Mono/hybrid rms 566 m/57 m

A Big Event - *One that got away!*





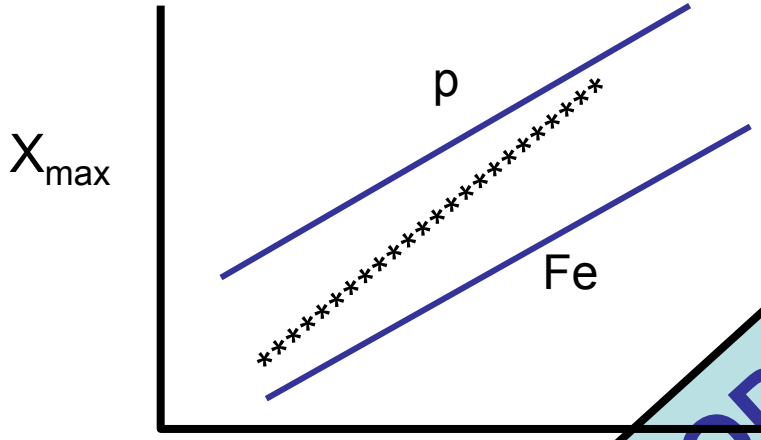




19 April 2004

Methods of Inferring the Primary Mass

(i) Variation of Depth of Maximum with



Limiting bound = 2.3 X_0 g cm^{-2} per decade
(Linsley 1977)

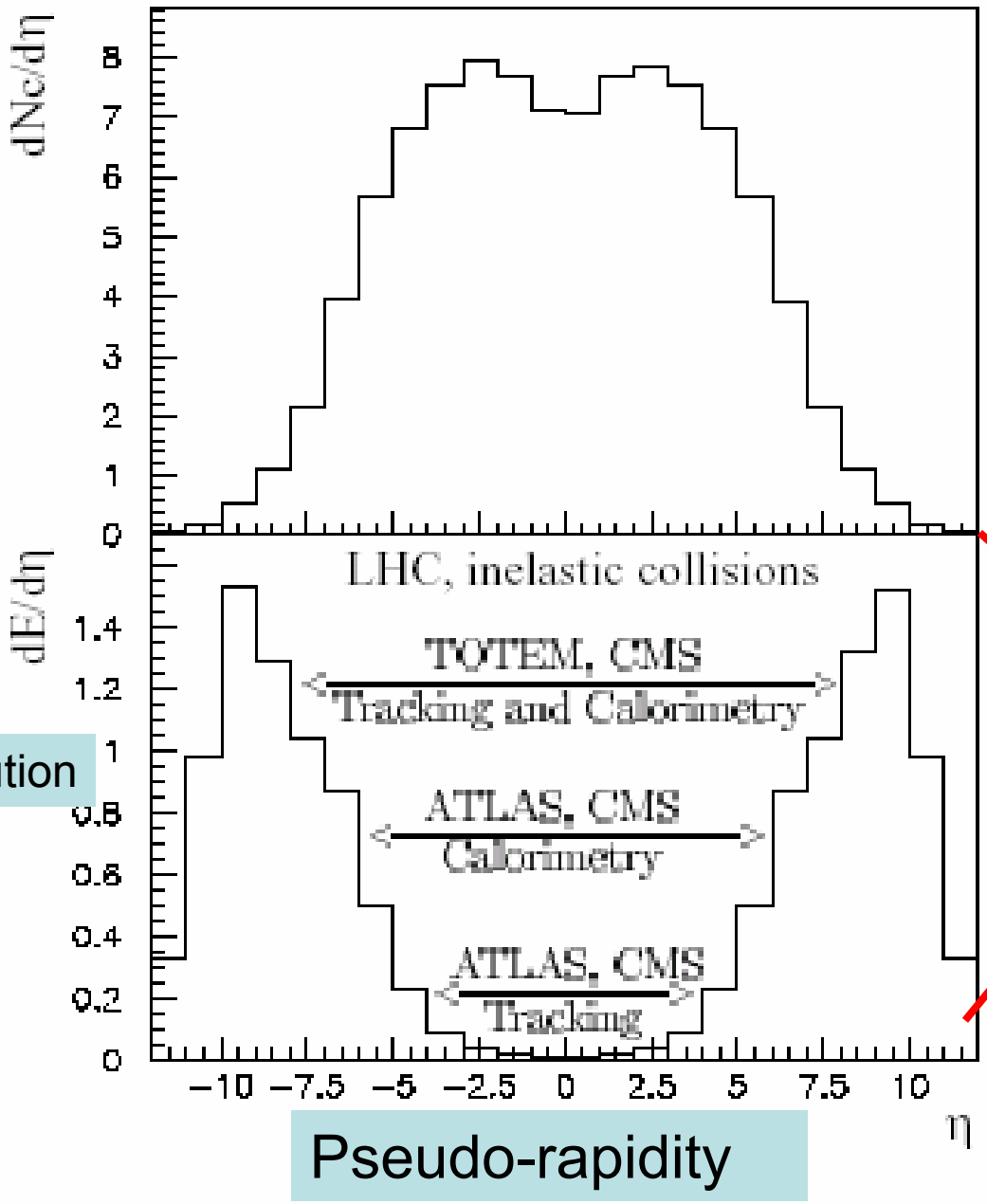
(ii) Muon Conte

Nμ (>1 Ge
(dep and model)

Nμ(>1 $\sim A^{0.14}$

So, more Fe showers

HADRONIC MODELS REQUIRED FOR INTERPRETATION – New model, QGSJET II, discussed at ICRC



Multiplicity

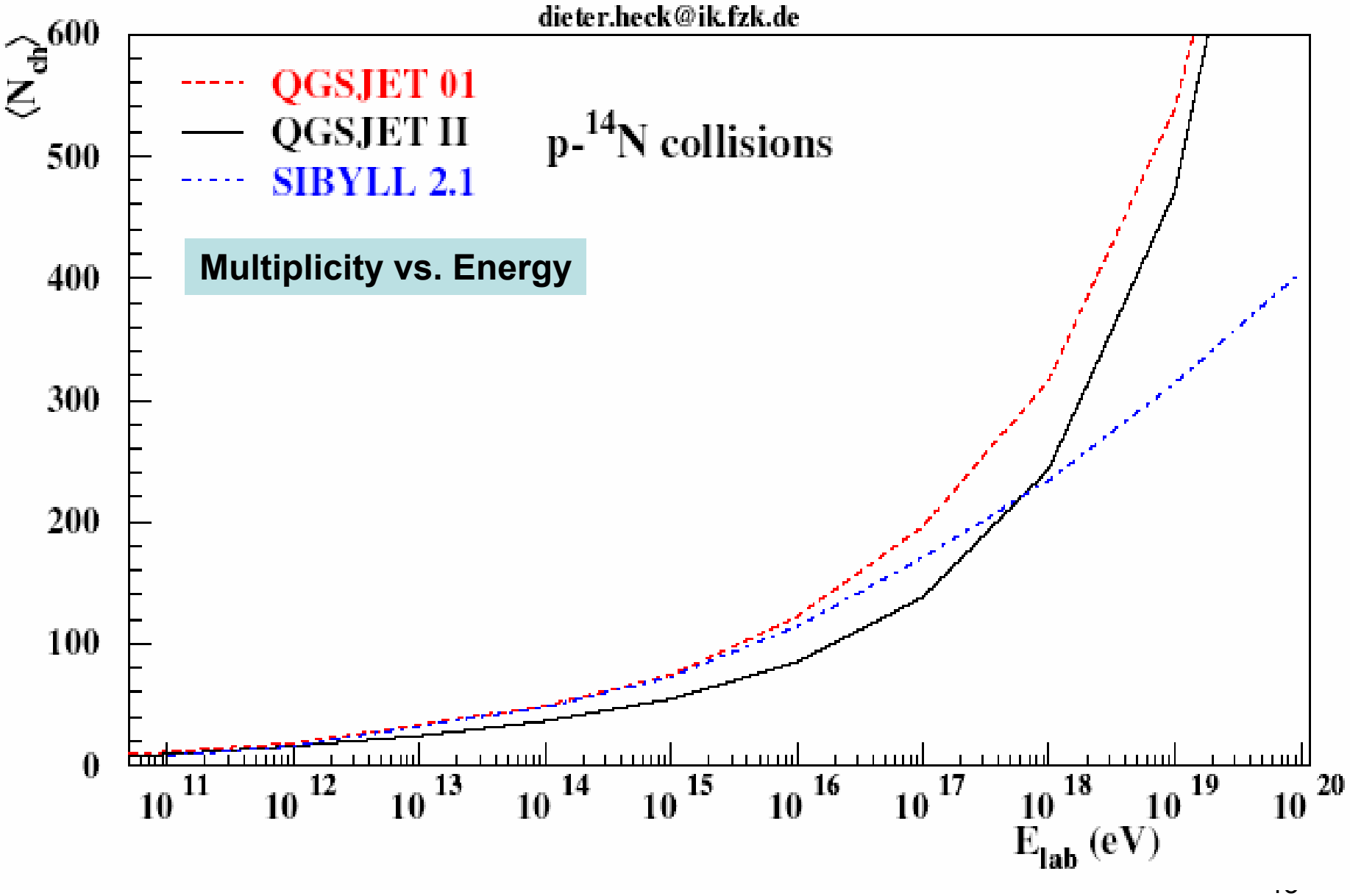
Energy distribution

Regions of most interest for shower modelling

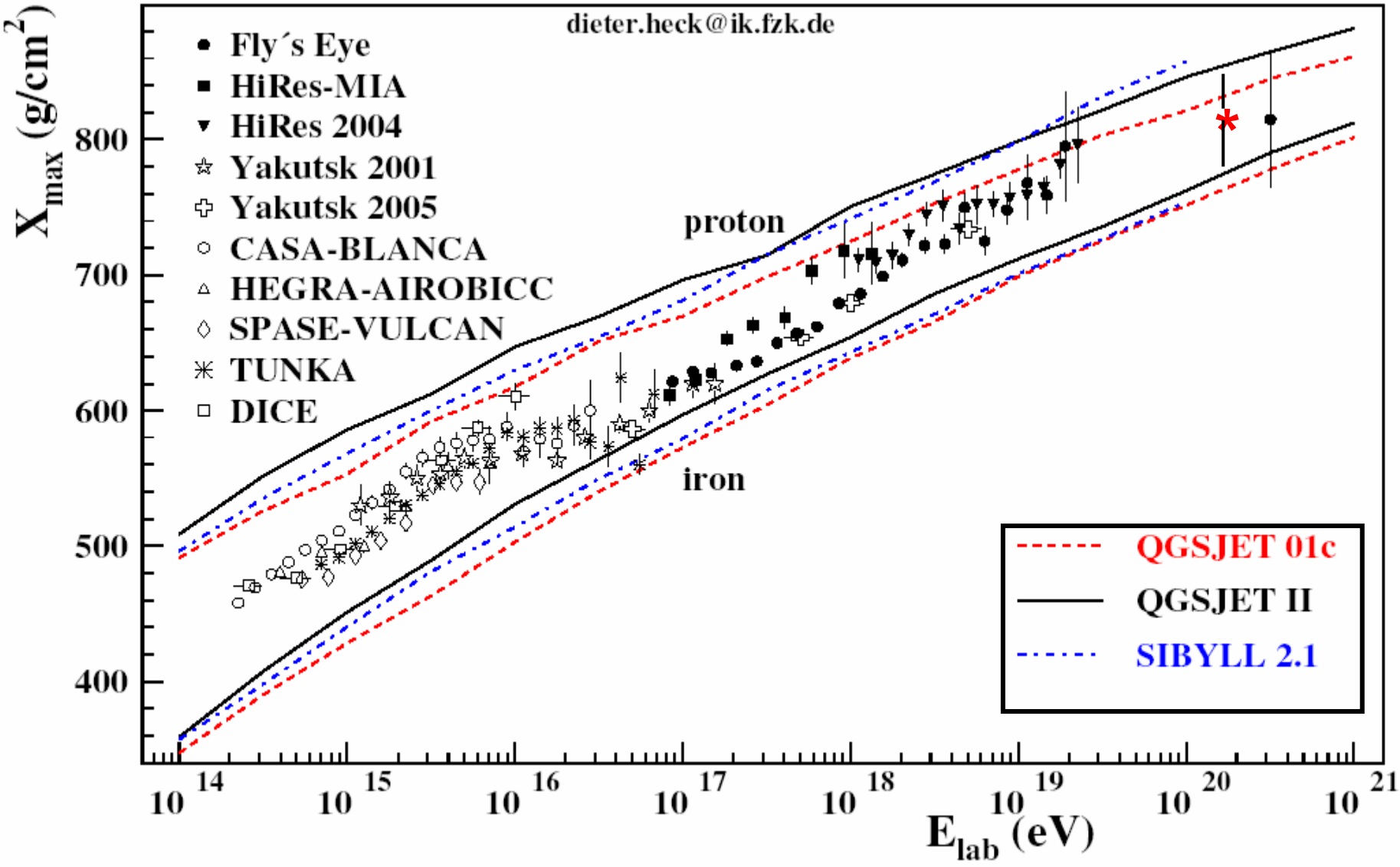
Pseudo-rapidity

FIG. 7: Pseudorapidity distributions of charged particles (upper panel) and of the energy flow (lower panel) for pp collisions at LHC [121].

New hadronic model: QGSJETII Heck and Ostapchenko ICR 2005



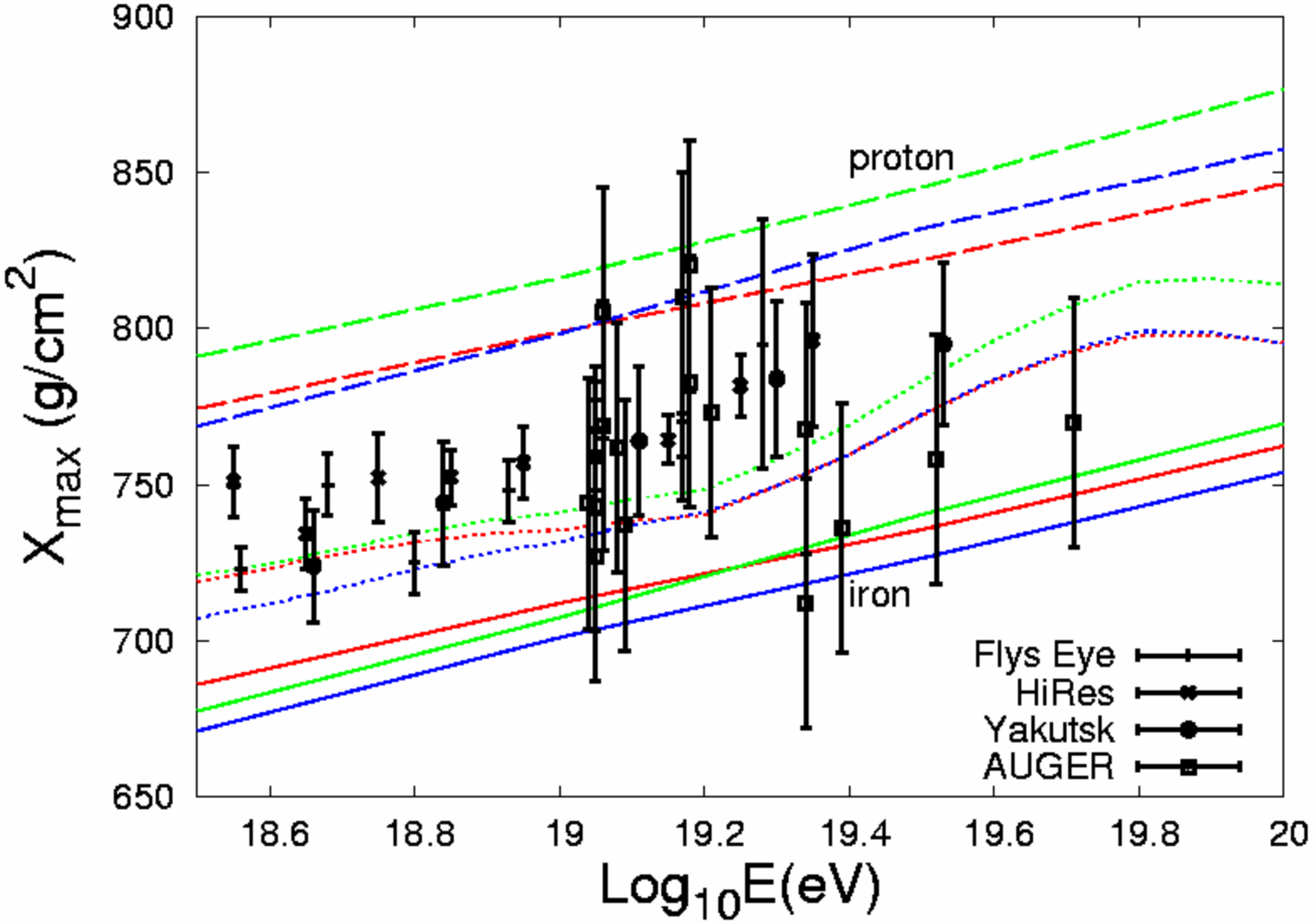
X_{max} vs. Energy for different models compared with data



Heck and Ostapchenko: ICRC 2005

Hooper, Sarkar and Taylor 2005

Assumption: Fe with E^{-2} with sharp cut-off at 10^{22} eV



Spectrum measurements: Issues of concern

1: SURFACE DETECTOR ARRAYS (e.g. AGASA, Yakutsk)

APERTURE:

- relatively easy to determine

ESTIMATION OF PRIMARY ENERGY:

- mass assumption required

- hadronic interaction model must be assumed for which systematic uncertainty in **UNKNOWABLE**

- QGSJETII model will lead to revisions

2. FLUORESCENCE DETECTOR (e.g. HiRes):

ENERGY ESTIMATES depend only weakly on assumptions about models and mass

BUT determination of energy requires
- atmospheric corrections for each event
- Cherenkov light subtraction (< 25% used)

APERTURE is difficult to measure
- does not saturate
- depends on atmosphere
- mass of primary
- models
- spectral shape

so, aperture can be systematically uncertain

3. Hybrid Detectors (e.g. Auger)

ENERGY CALIBRATION of size parameter measured by surface detectors is made with fluorescence detectors on carefully selected sample of events:

- **long tracks in atmosphere: > 350 g cm^{-2}**

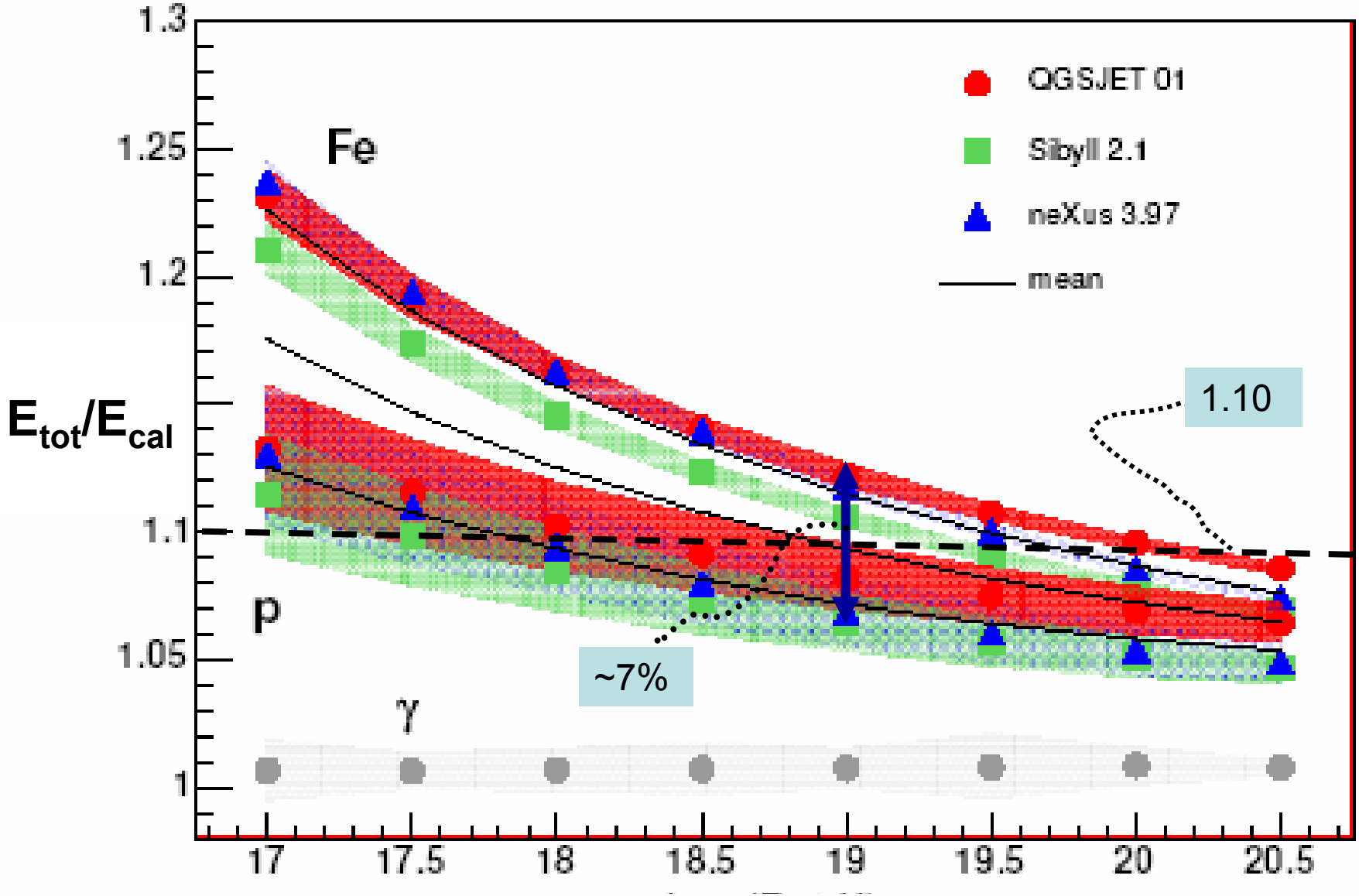
- **Cherenkov light contamination: < 10%**

(Auger criteria)

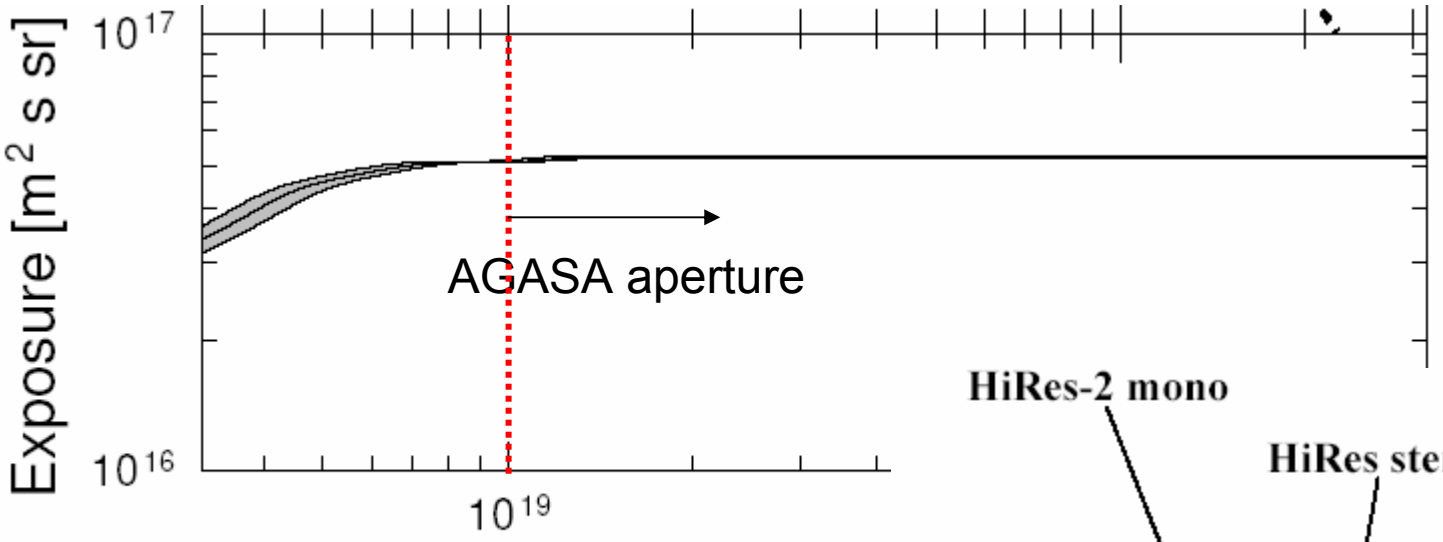
HIGH STATISTICS from surface array

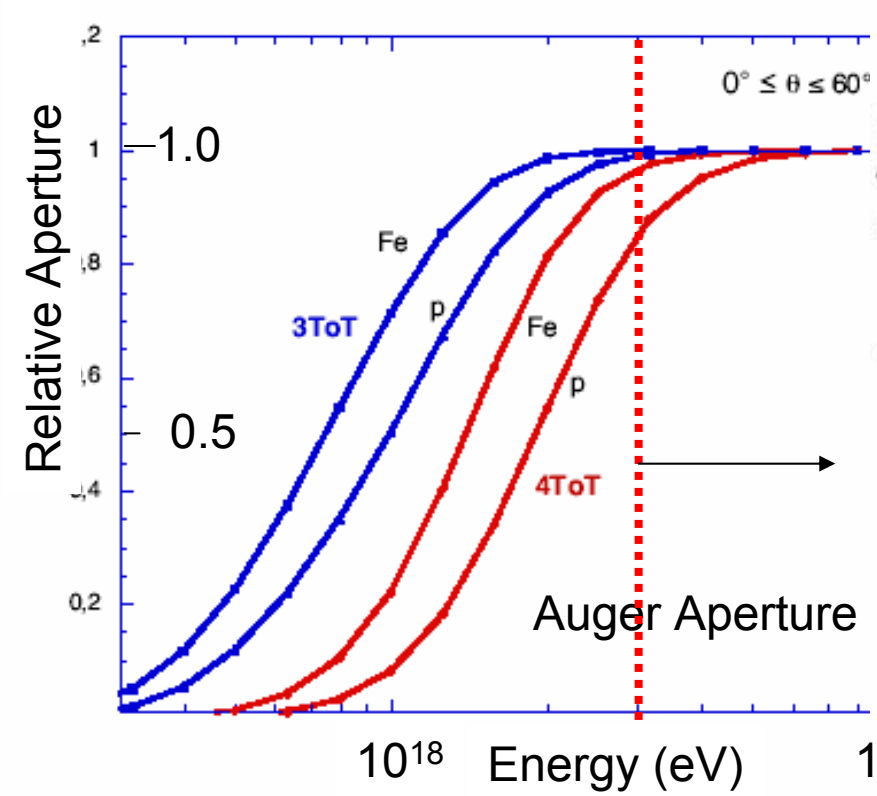
APERTURE: well-defined

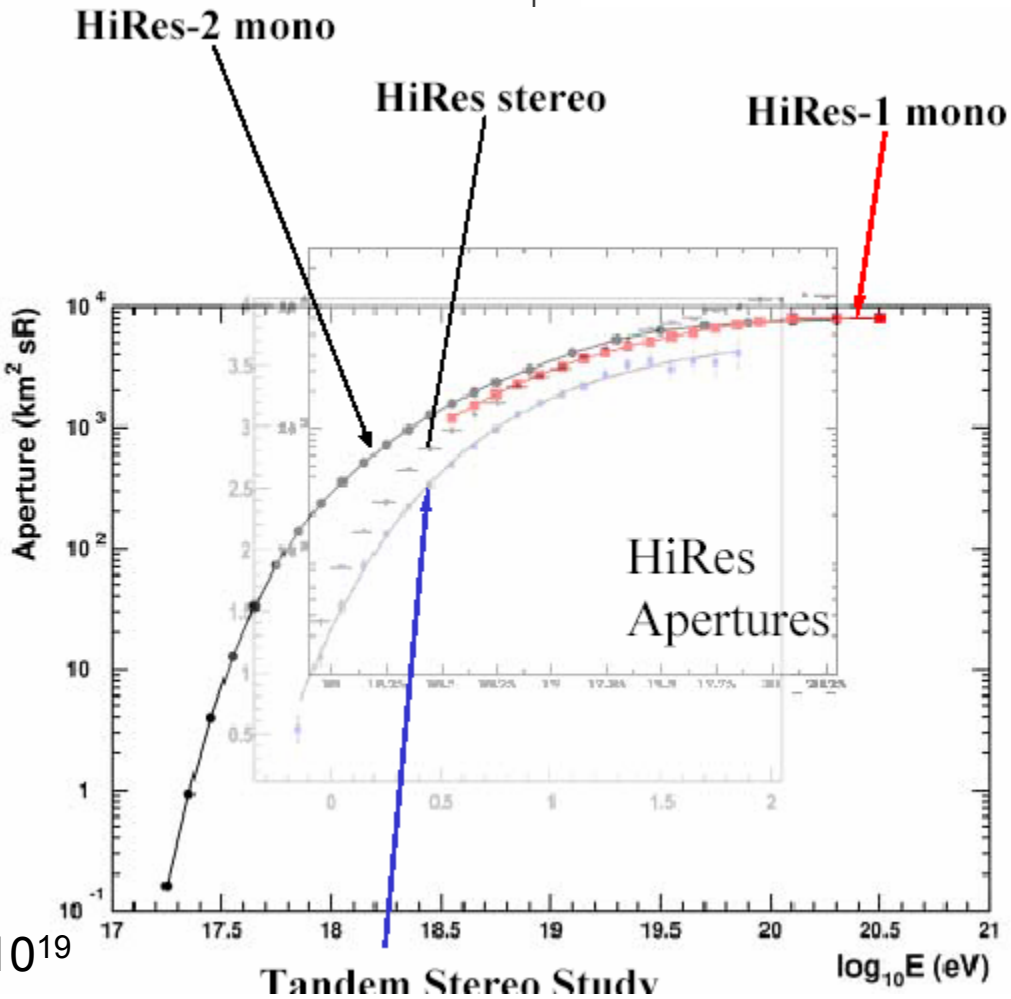
Ratio of total energy to electromagnetic energy for fluorescence detector



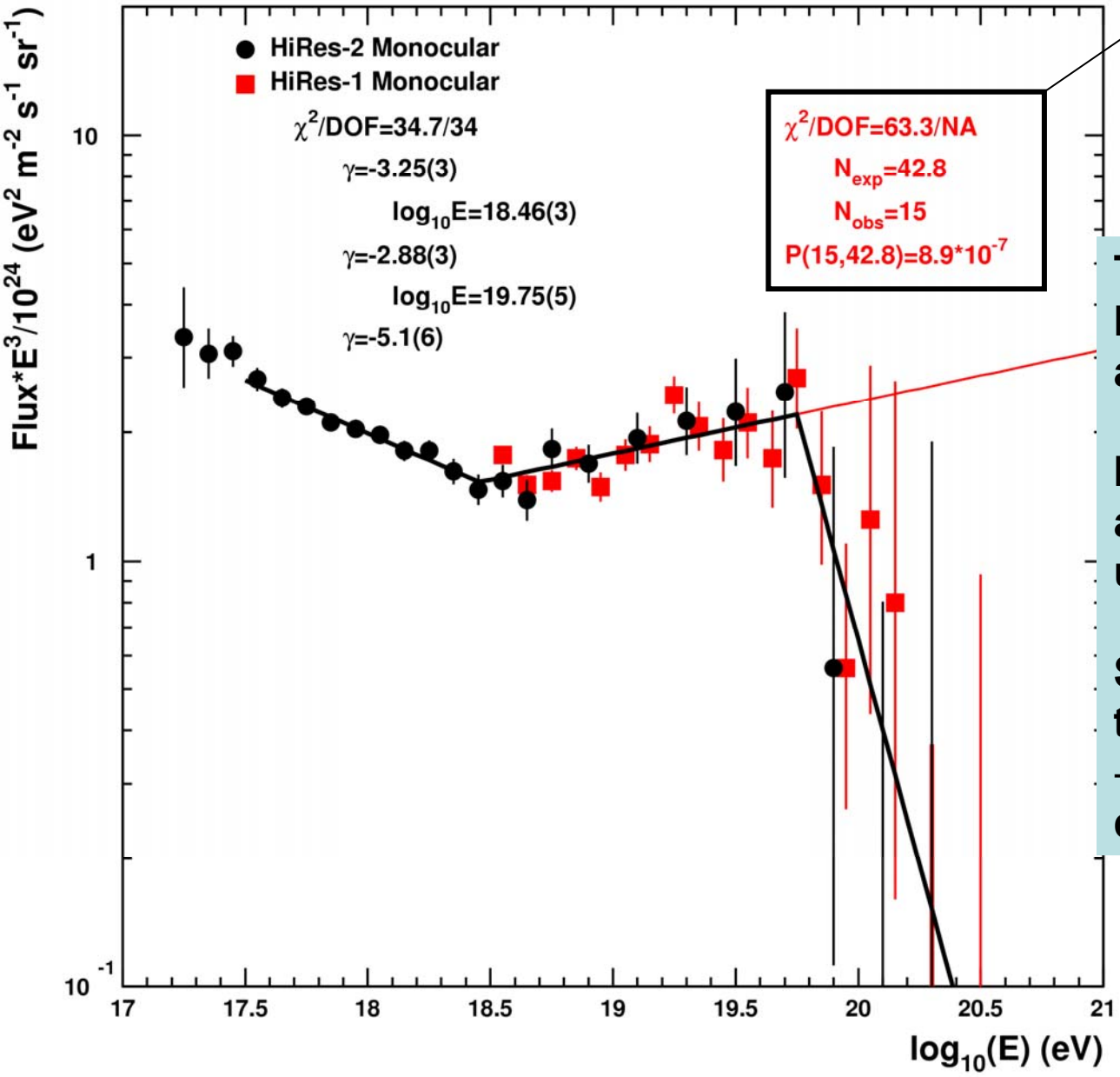
Pierog et al. ICRC 2005


Exposure [m^2 s sr]
10^{17}
10^{16}
10^{19}
AGASA aperture


Relative Aperture
1.0
0.5
0° ≤ θ ≤ 60°
Fe
p
3ToT
Fe
p
4ToT
Auger Aperture
10^{18}
Energy (eV)
10^{19}


HiRes-2 mono
HiRes stereo
HiRes-1 mono
Aperture (km^2 sR)
HiRes
Apertures
Tandem Stereo Study
log$_{10}$E (eV)

HiRes Monocular Spectra: ICRC



Choice of data used in the fit is entirely subjective and no propagation of E errors into y-direction

The HiRes group have yet to release a stereo spectrum.

It will have hour-by-hour atmospheric corrections using monitoring data

Should also help to resolve the aperture uncertainties - at least at small distances

Auger Energy Determination: Step 1

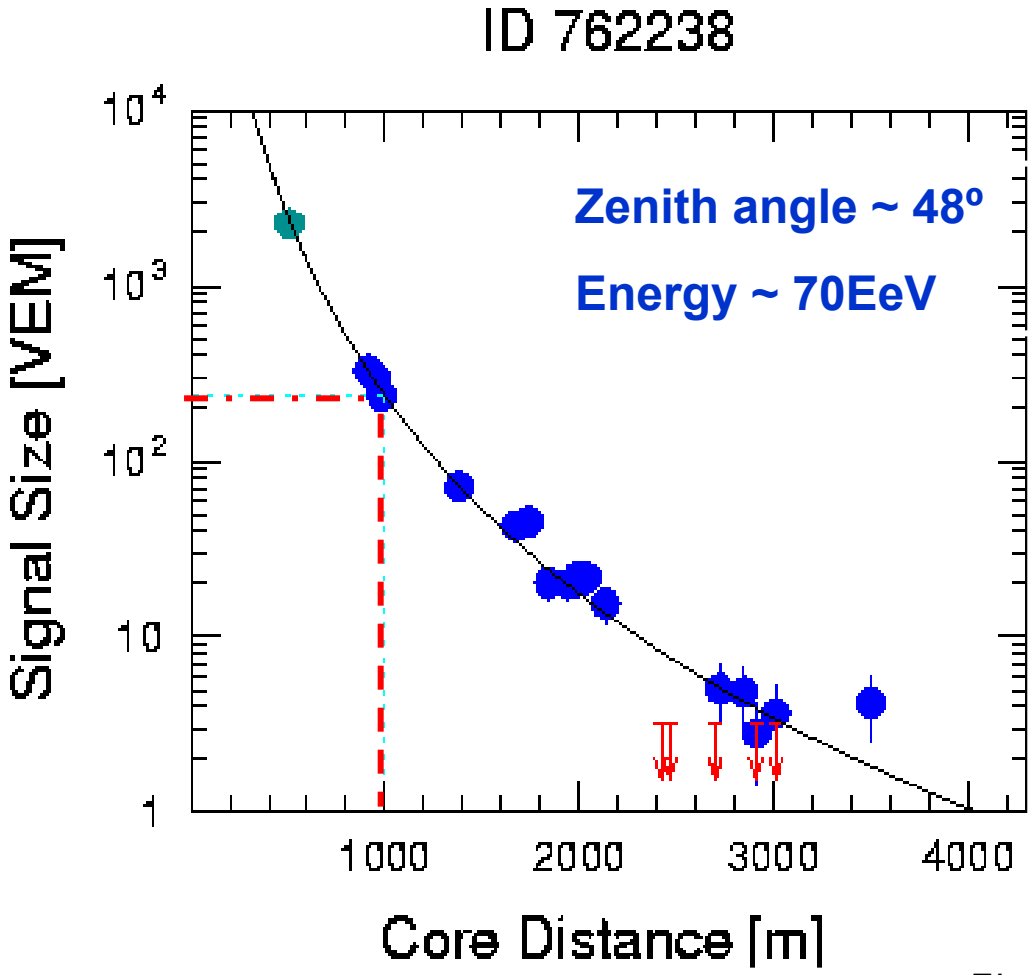
The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

The detector signal at 1000 m from the shower core

– called the ground parameter or S(1000)

- is determined for each surface detector event using the lateral density function.

S(1000) is **proportional to the primary energy.**



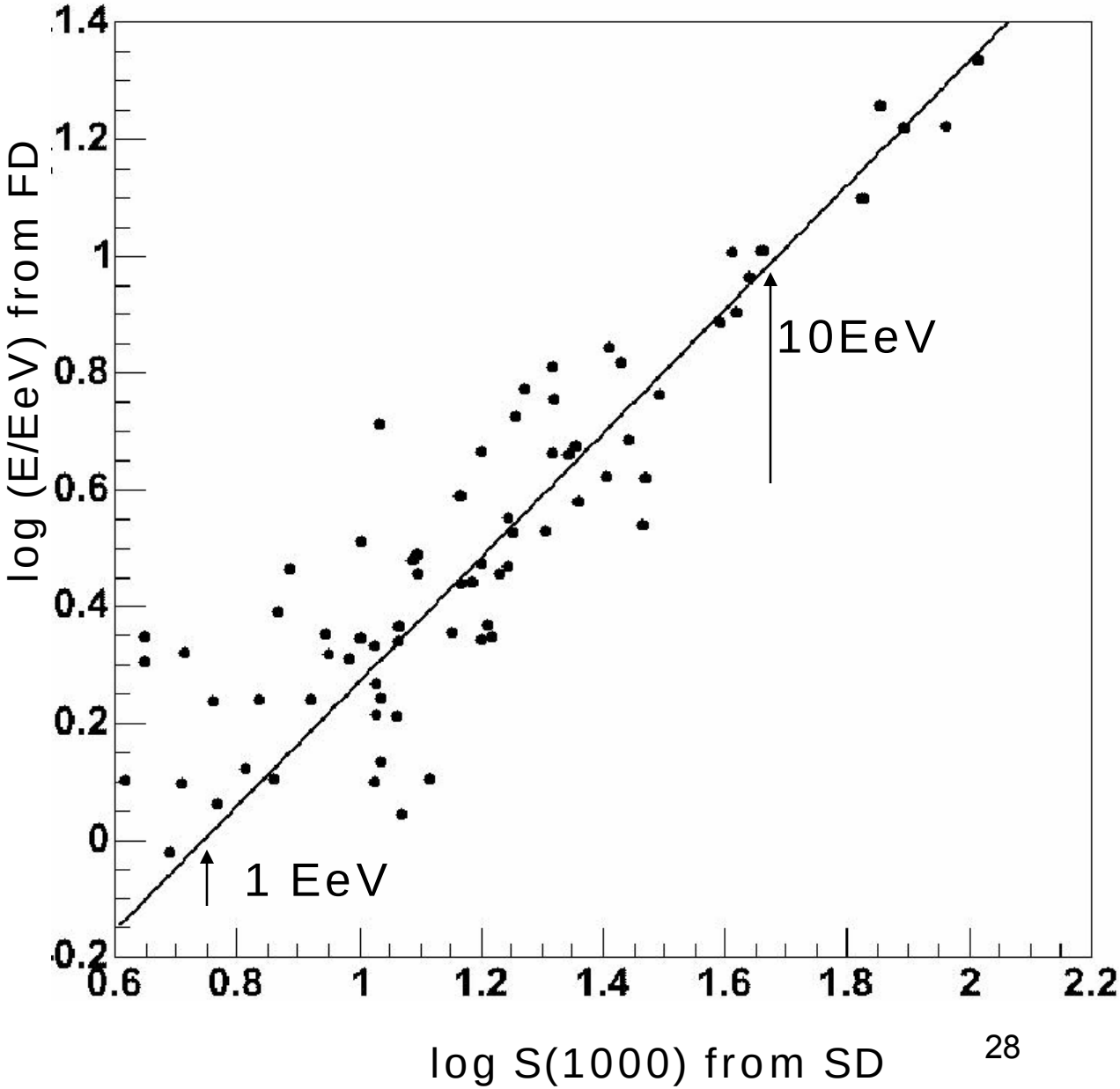
Auger Energy Determination: step 2

Hybrid Events with STRICT event selection:

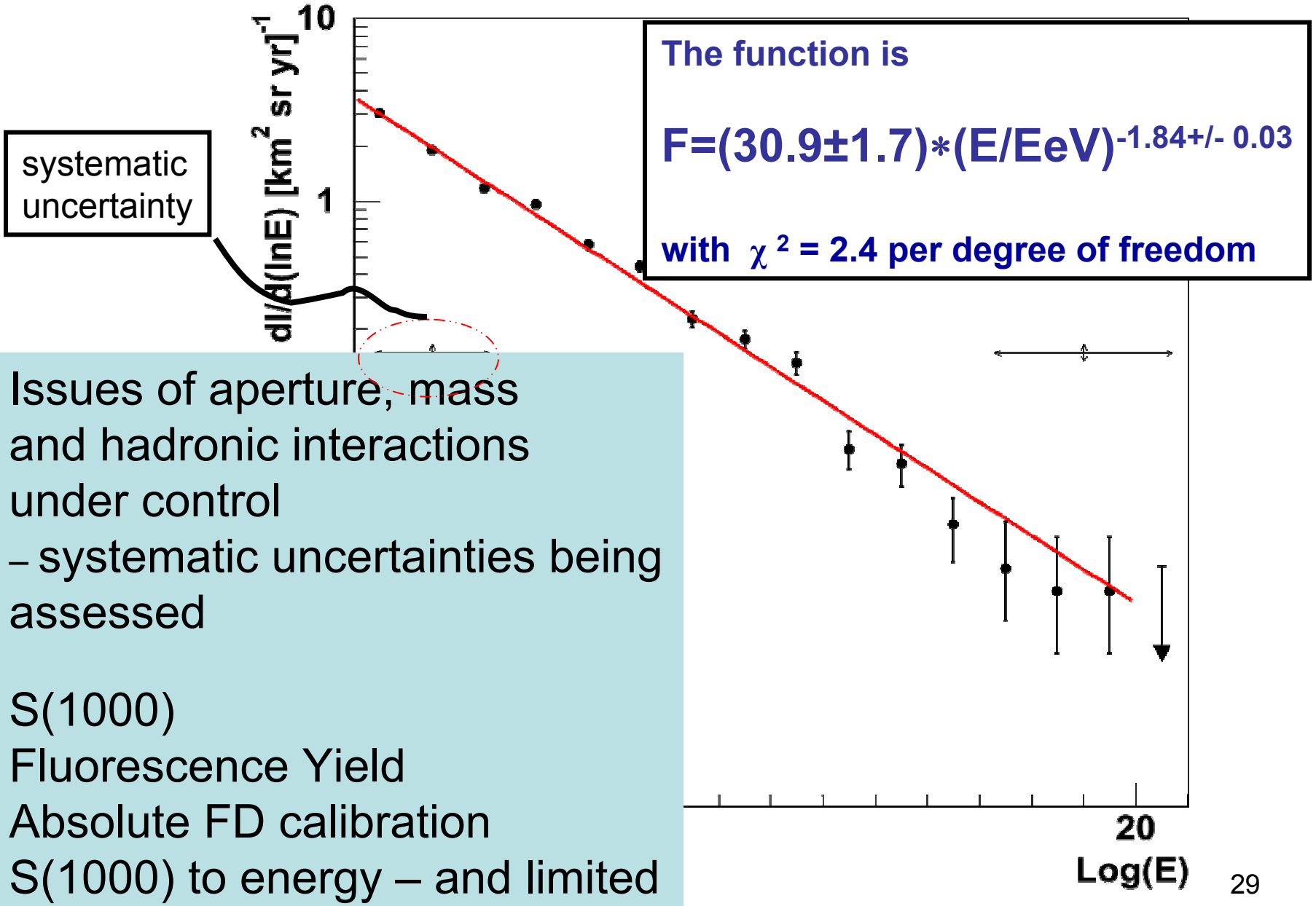
aerosol content measured

track length
> 350 g cm^{-2}

Cherenkov contamination
<10%



Spectrum measured with Auger Observatory



The function is

$$F=(30.9\pm1.7)*(E/EeV)^{-1.84+/-\ 0.03}$$

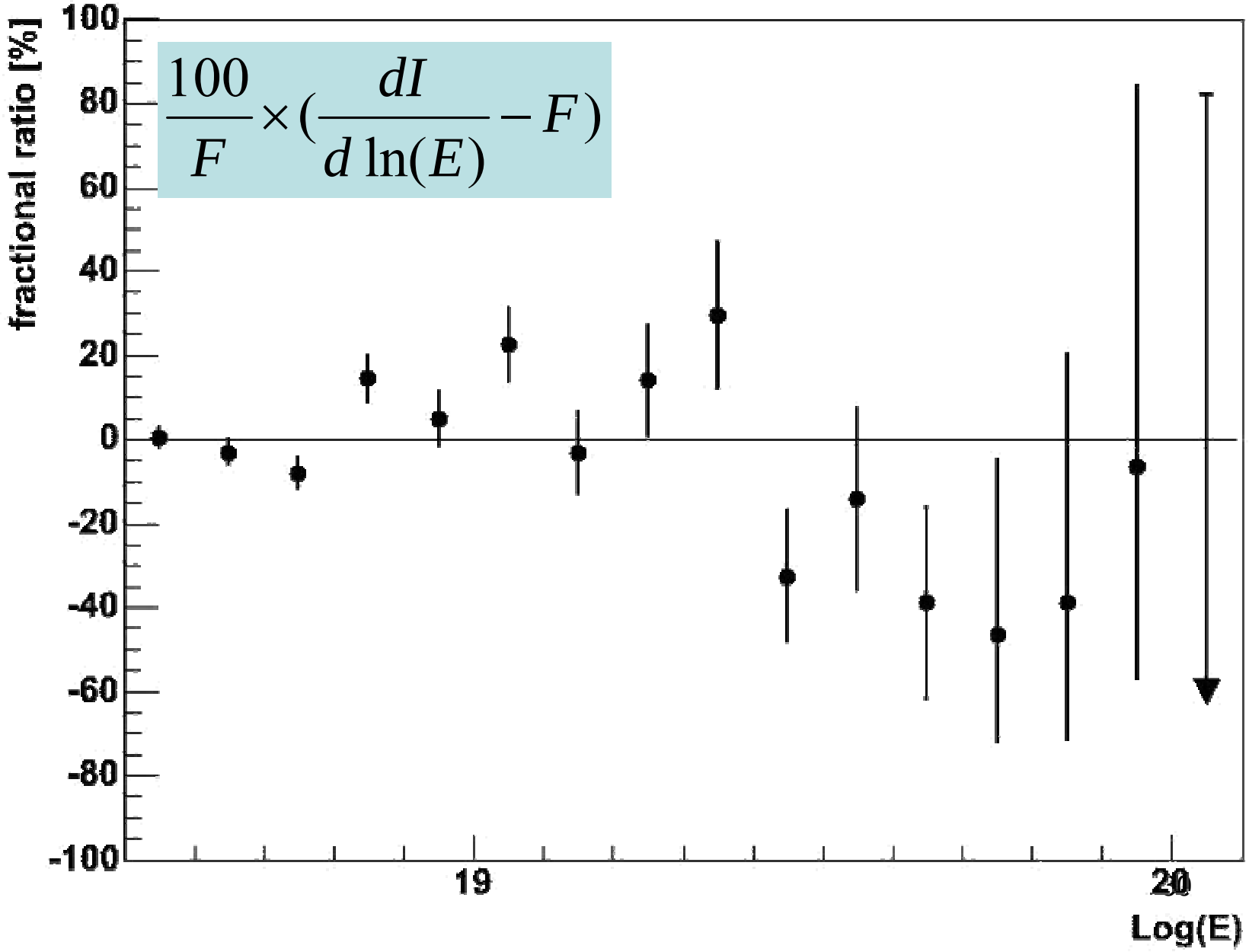
with χ^2 = 2.4 per degree of freedom

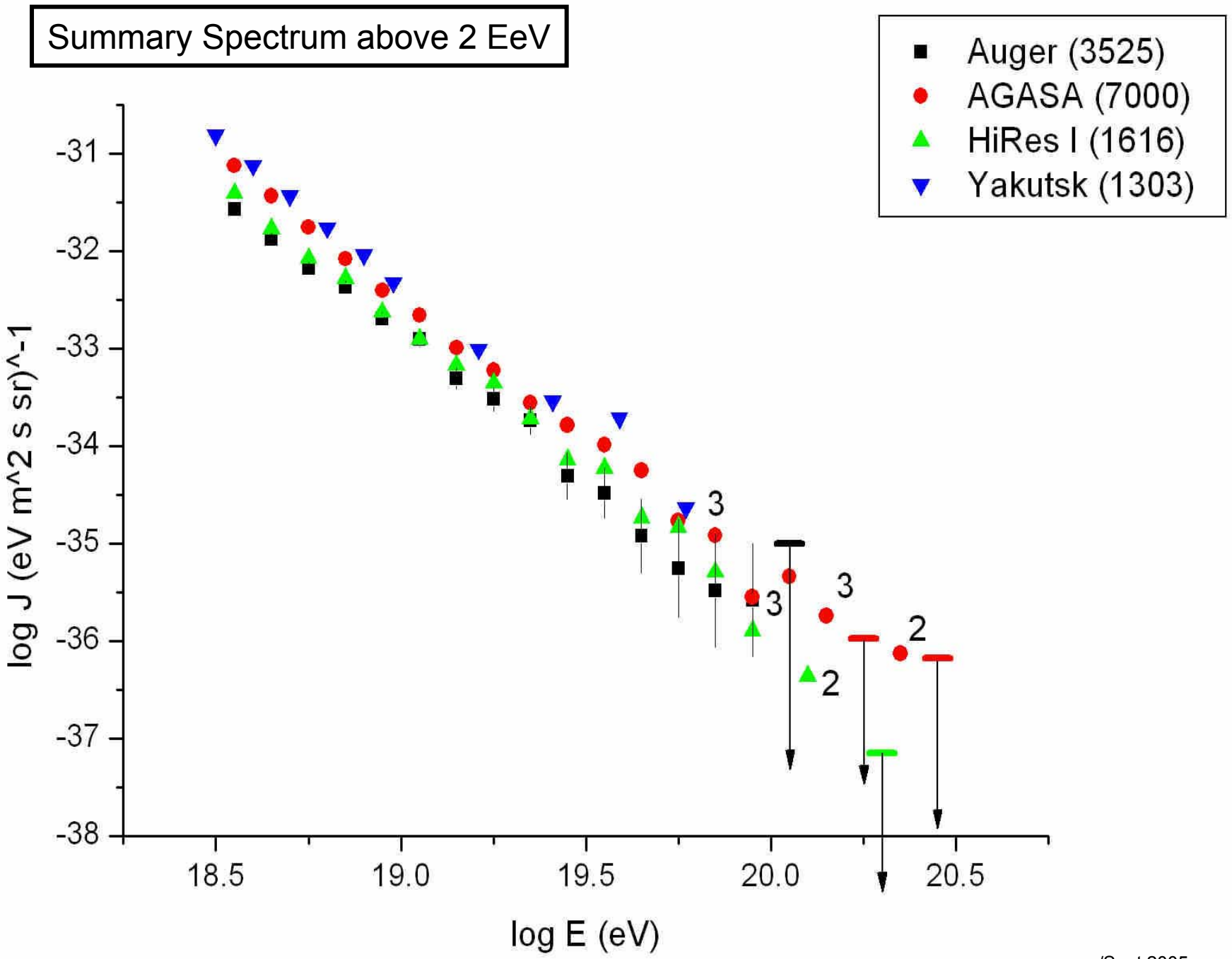
Issues of aperture, mass and hadronic interactions under control

– systematic uncertainties being assessed

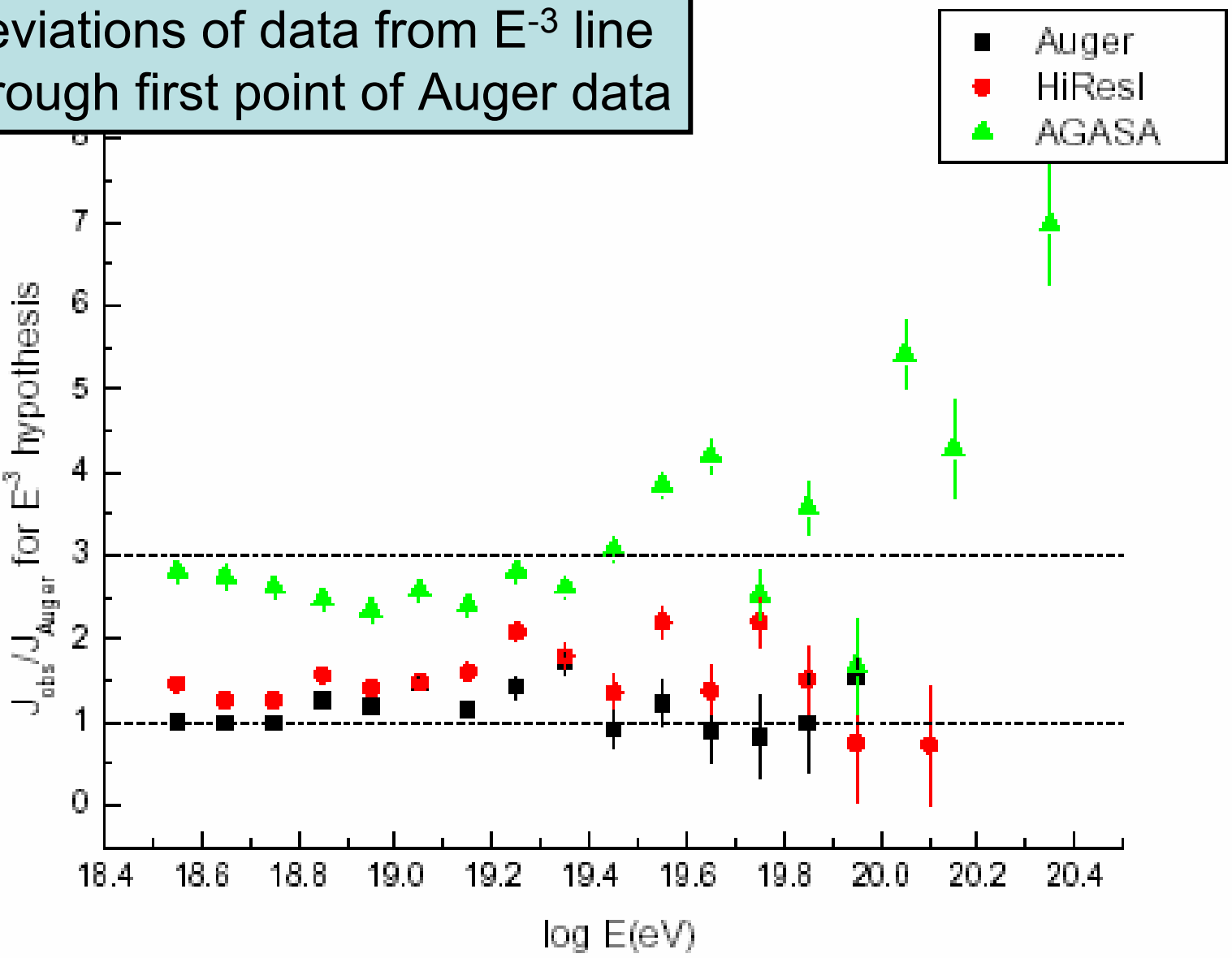
S(1000)
Fluorescence Yield
Absolute FD calibration
S(1000) to energy – and limited statistics

Percentage Deviation from the Power-Law Fit

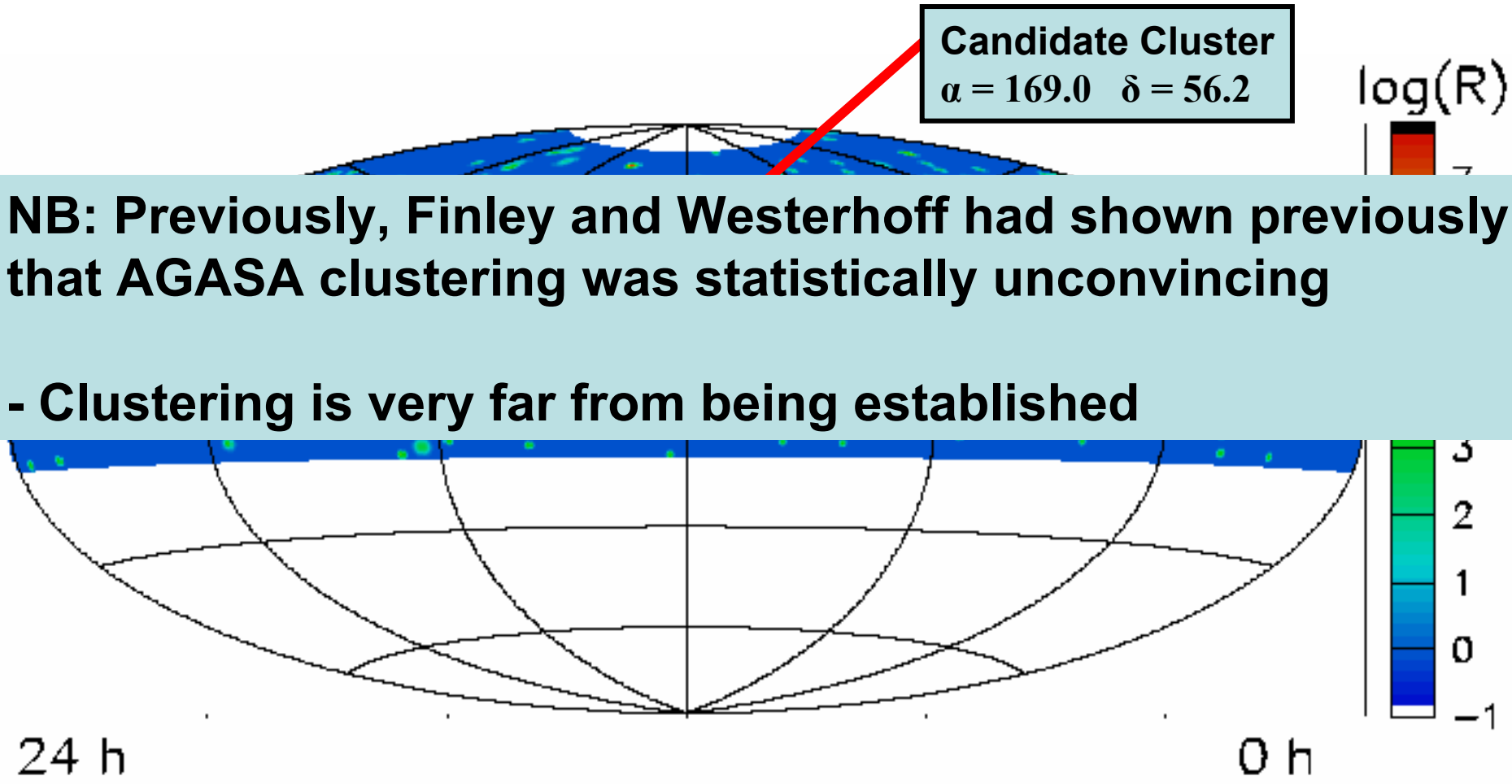



Summary Spectrum above 2 EeV
Auger (3525)
AGASA (7000)
HiRes I (1616)
Yakutsk (1303)
log J (eV m^2 s sr)^-1
-31
-32
-33
-34
-35
-36
-37
-38
18.5
19.0
19.5
20.0
20.5
log E (eV)
3
3
3
2
2
aaw/Sept 2005

Deviations of data from E^{-3} line through first point of Auger data



HiRes stereo events > 10 EeV plus AGASA events above 40 EeV



NB: Previously, Finley and Westerhoff had shown previously that AGASA clustering was statistically unconvincing

- Clustering is very far from being established

Analysis uses likelihood ratio method:

p = 43% for 271 HiRes and 47 AGASA events

HiRes Collaboration: ICRC 2005: Westerhoff et al.

HiRes does see

correlations with BL Lacs:

Veron 11th Catalogue:

178 objects with magnitude < 18

Claim: excess number of BL Lacs seen near HiRes events > 10^{10} GeV, consistent with the HiRes angular resolution ~ 0.6º

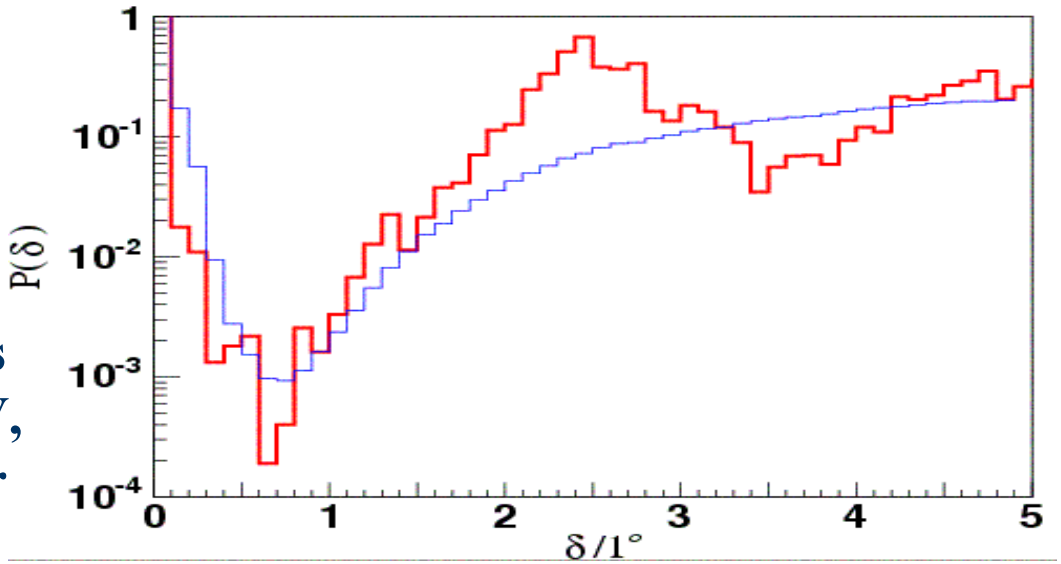
GOOD ANGULAR RESOLUTION

see 11 pairs < 0.8º and expect ~ 3,

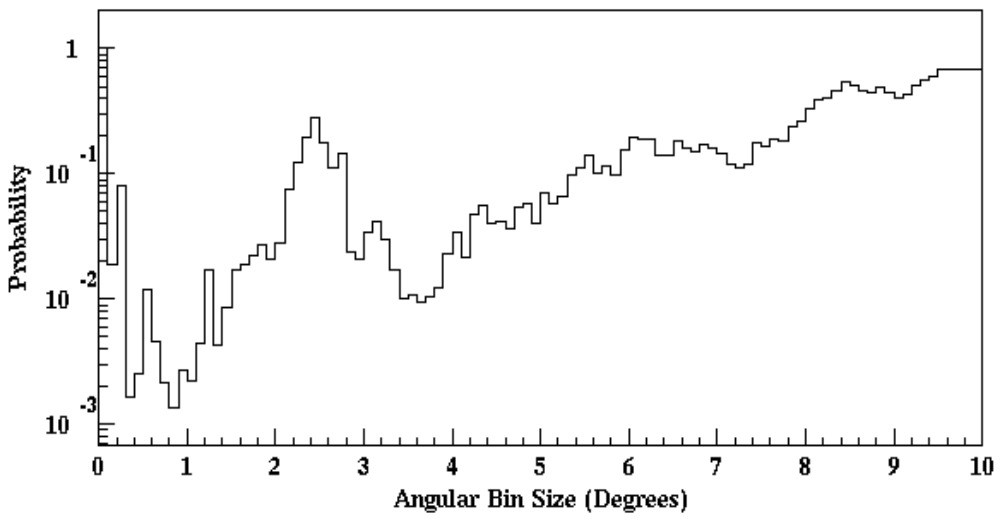
⇒ probability ~ 5×10^{-4}

But these BL Lacs are hundreds of Mpc distant!

Few % of primaries must be neutral @ 10^{10} GeV!!



Gorbunov *et al* (2004)



Westerhoff *et al* (2005)

Summary of BL Lac Searches

Source Sample (# Obj.)	All Energies	$E > 10$ EeV
"BL" (157)	2×10^{-4}	2×10^{-4}
"BL"+"HP" (204)	5×10^{-4}	10^{-5}
TeV Blazars (6)	10^{-3}	2×10^{-4}

Table 2. Combined HiRes — BL Lac Correlations: Fraction $\mathcal{F}$ of simulated HiRes sets with stronger correlation signal. All samples include the $m < 18$ cut. The samples overlap and are *not* independent.

Finley and Westerhoff ICRC 2005

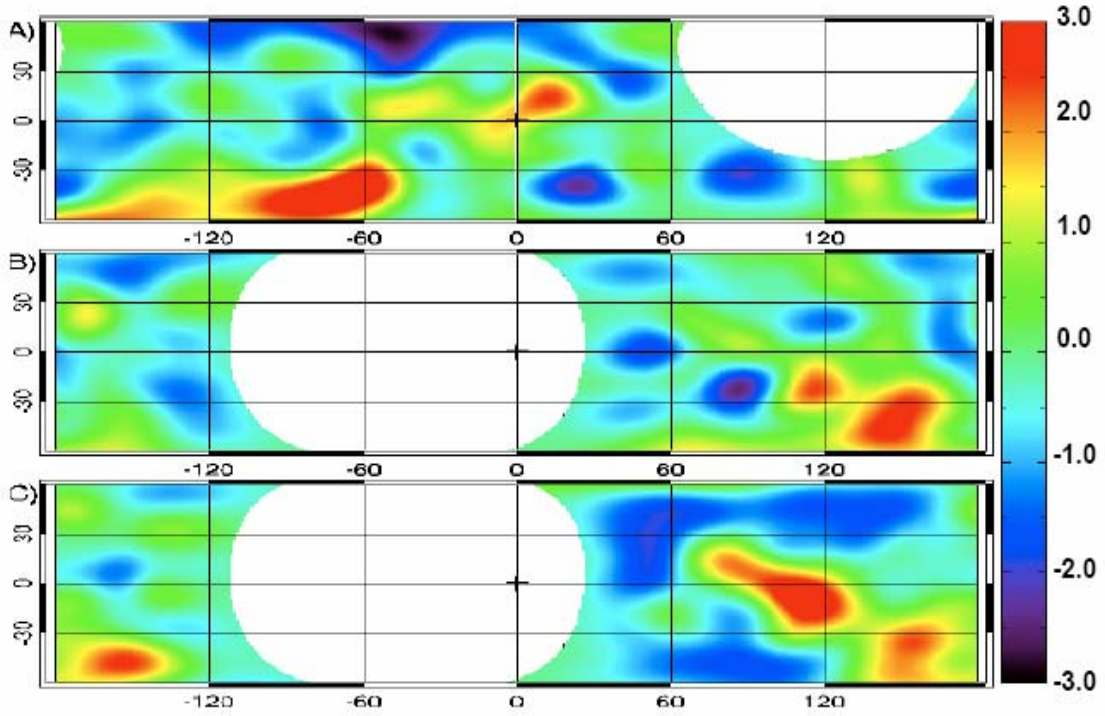
Group is awaiting independent data set recorded post January 2004 up to closure in March 2006 before making any claims.
They have concerns about 'over tuning'

Auger Observations show NO concentration of events along Galactic or Super-Galactic Plane

A: 1 – 5 EeV: Galactic Plane

B: > 5 EeV: SGP

C: > 10 EeV: SGP



A) GP 1 - 5 EeV (L ± 10°) 5077 / 5083.3

B) SGP > 5 EeV (L ± 10°) 241 / 232.8

C) SGP > 10 EeV (L ± 10°) 68 /67.4

(Antoine Letessier-Selvon, ICRC 2005)

If highest energy particles were protons, and there is no anisotropy, exotic origin ideas have to be invoked

- **Decay of super-heavy relics from early Universe (or top down mechanisms)**

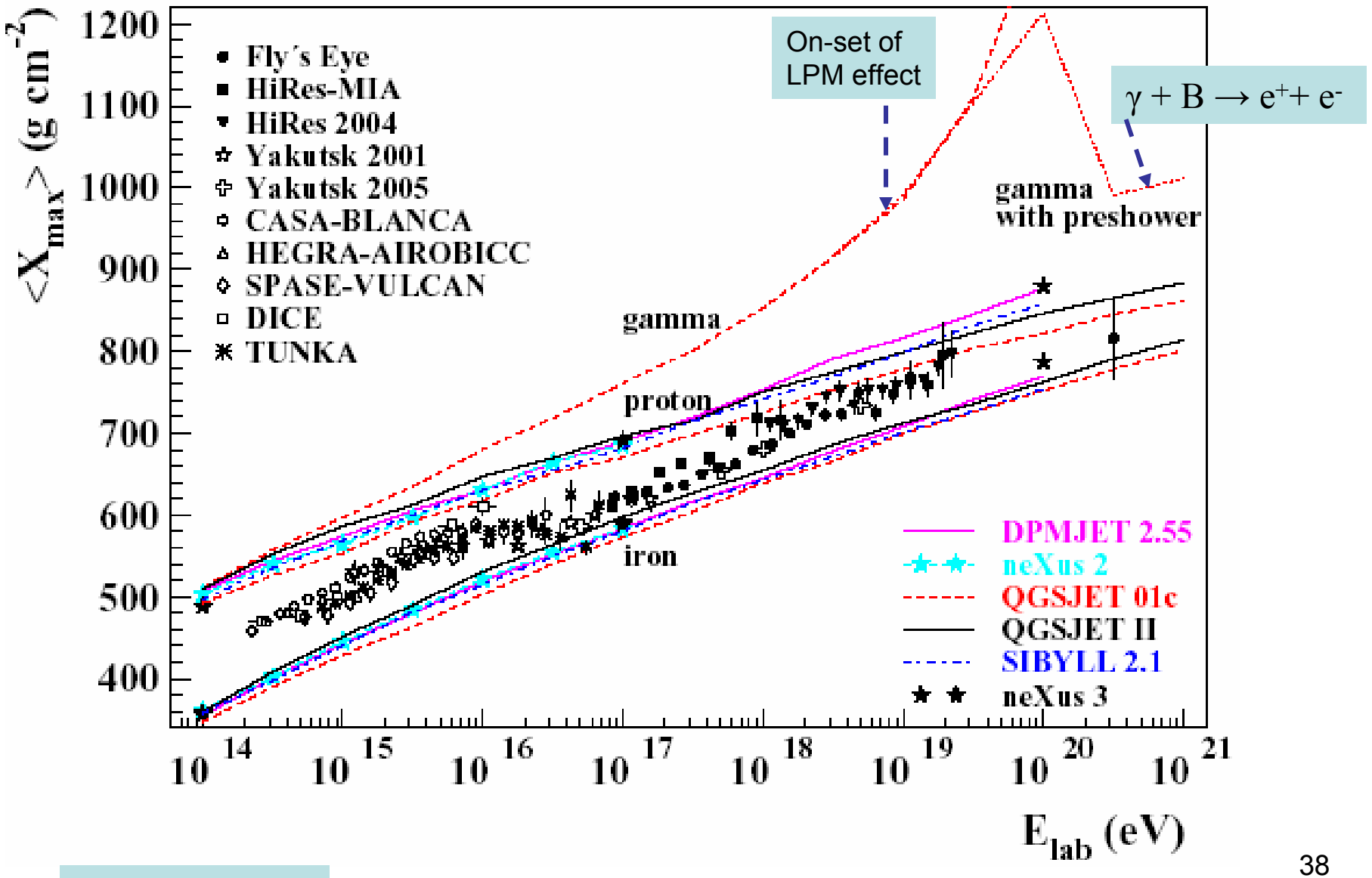
  Wimpzillas/Cryptons/Vortons

Predictions:

dominance of neutrinos and photons

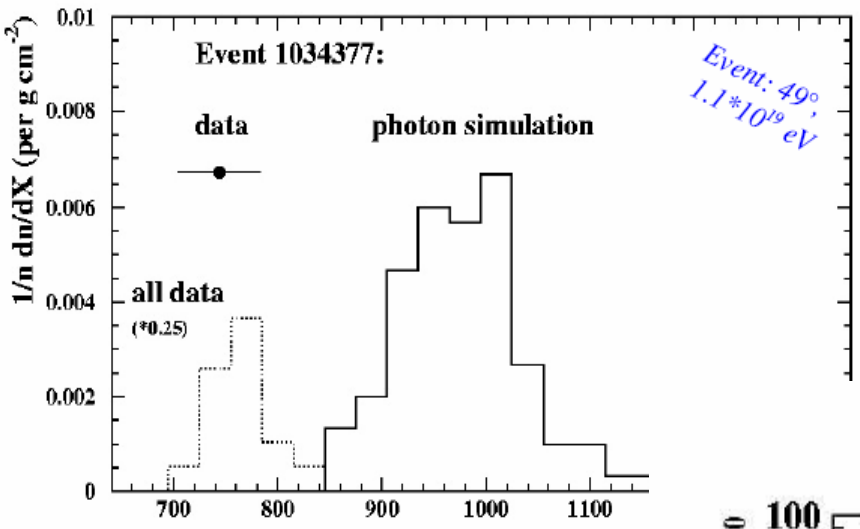
- **New properties of old particles or new particles**

- **Breakdown of Lorentz Invariance**



Picture by Dieter Heck

Example



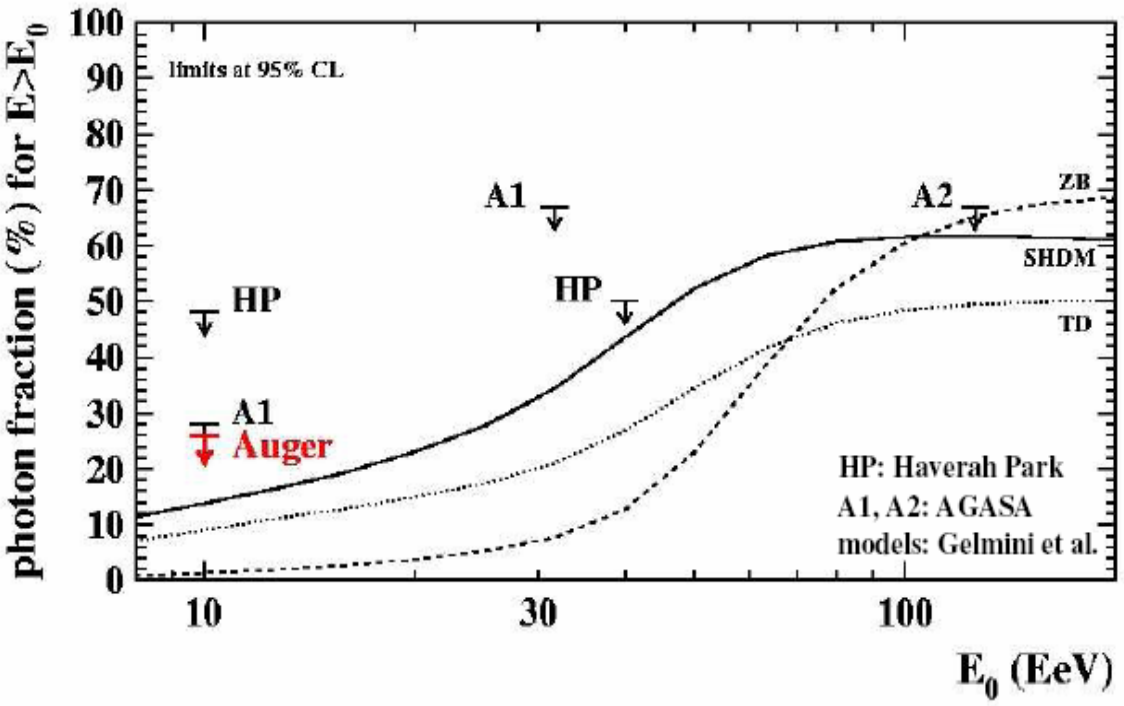
- event: $X_{max} = 744 \pm 40$ g cm^{-2}
- photons: $\langle X_{max} \rangle = 1020$ g cm^{-2} , rms = 8
- → observed X_{max} well below photon expec

... the highest energy particles seem NOT to be dominantly photons

Photon limit from Auger observations

Constrains (but does not yet rule out) 'top-down' models of UHECR origin

New upper limit



(Risse for Auger Collaboration, ICRC 2005) **26% upper limit** (95% CL) on cosmic-ray photon fraction

Ideas to explain the Enigma

- **Decay of super heavy relics from early Universe (or top down mechanisms)**

Wimpzillas/Cryptons/Vortons

Few photons: <26% at 10^{19} eV (Auger claim)

Model predictions have changed

Is there need for exotic explanations?

or is it 'simple'?

- **Are the UHE cosmic rays iron nuclei at source?**
- **Are magnetic field strengths really well known?**

Summary: I

- **Arrival Directions:**

  No convincing evidence for anisotropy
  Possibility of BL Lac associations could be clarified in ~ 2 years

- **New Hadronic Interaction Model:**

  suggests that there could be a heavier mass > 10 EeV than has been supposed by many in the past

  Heavier mass would ease acceleration, isotropy and spectrum issues

BUT – Nature may have surprises to show at the LHC

Summary: II

Energy Spectrum:

Auger: ~ 5 to 7 X AGASA by 2007
Spectrum that is largely mass and model independent

AGASA/HiRes/Auger differences could – *possibly* – be understood through combination of improved understanding of HiRes aperture (composition/spectrum/ hadronic model and stereo data) AND different models and mass assumptions by AGASA

ALL GROUPS HAVE REPORTED EVENTS ABOVE 100 EeV

QUESTION: WHAT IS THE DETAILED SHAPE OF THE SPECTRUM?

Thanks to all of my Auger colleagues

Czech Republic
France
Germany
Italy
Netherlands
Poland
Slovenia
Spain
United Kingdom

Argentina
Australia
Brasil
Bolivia*
Mexico
USA
Vietnam*

~250 PhD scientists from 63 Institutions and 15 countries

**Associate Countries*

Electromagnetic Acceleration

- **Synchrotron Acceleration**

  $E_{max} = ZeBR\beta c$

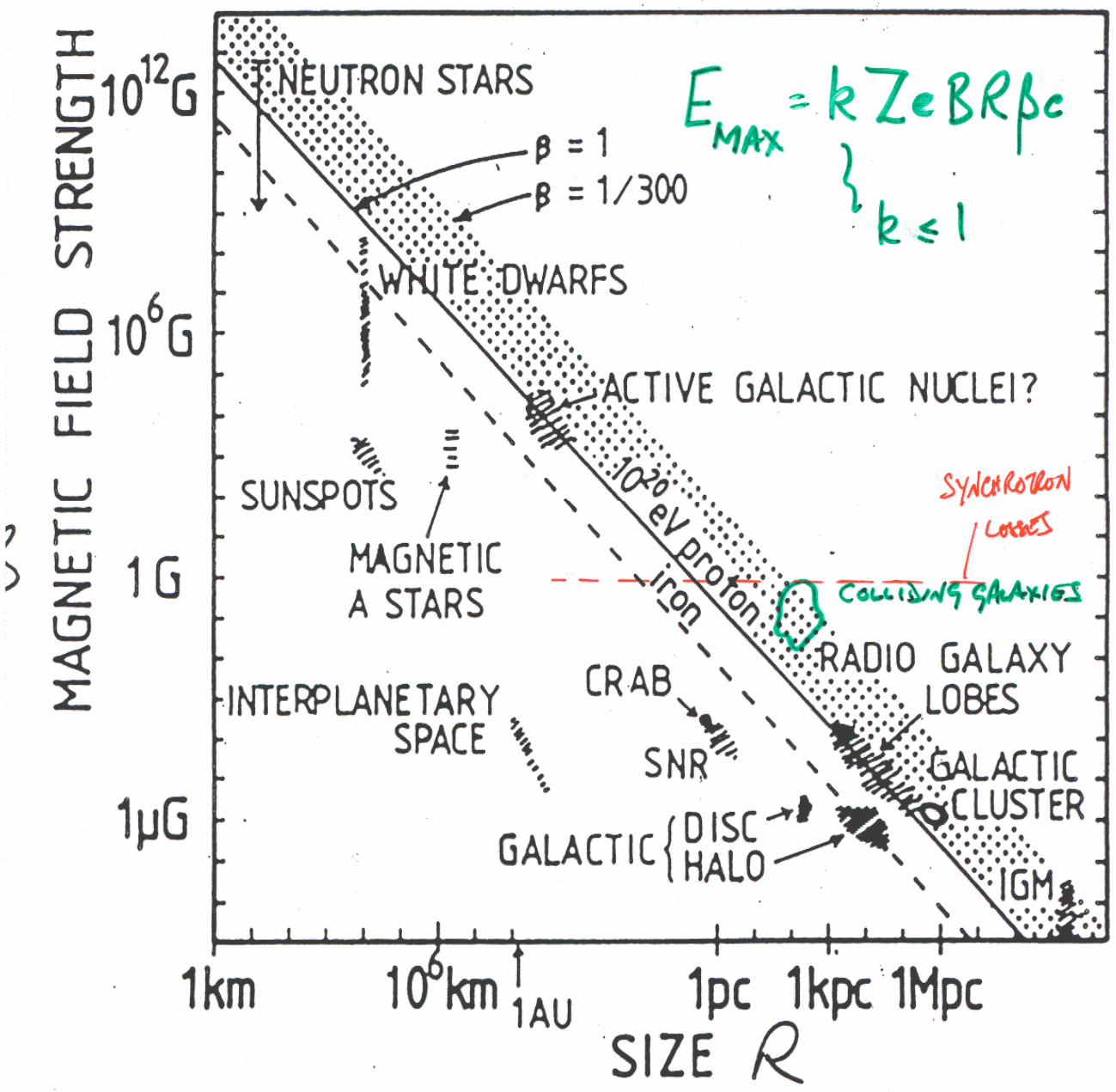
- **Single Shot Acceleration**

  $E_{max} = ZeBR\beta c$

- **Diffusive Shock Acceleration**

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

Shocks in AGNs, near Black Holes……

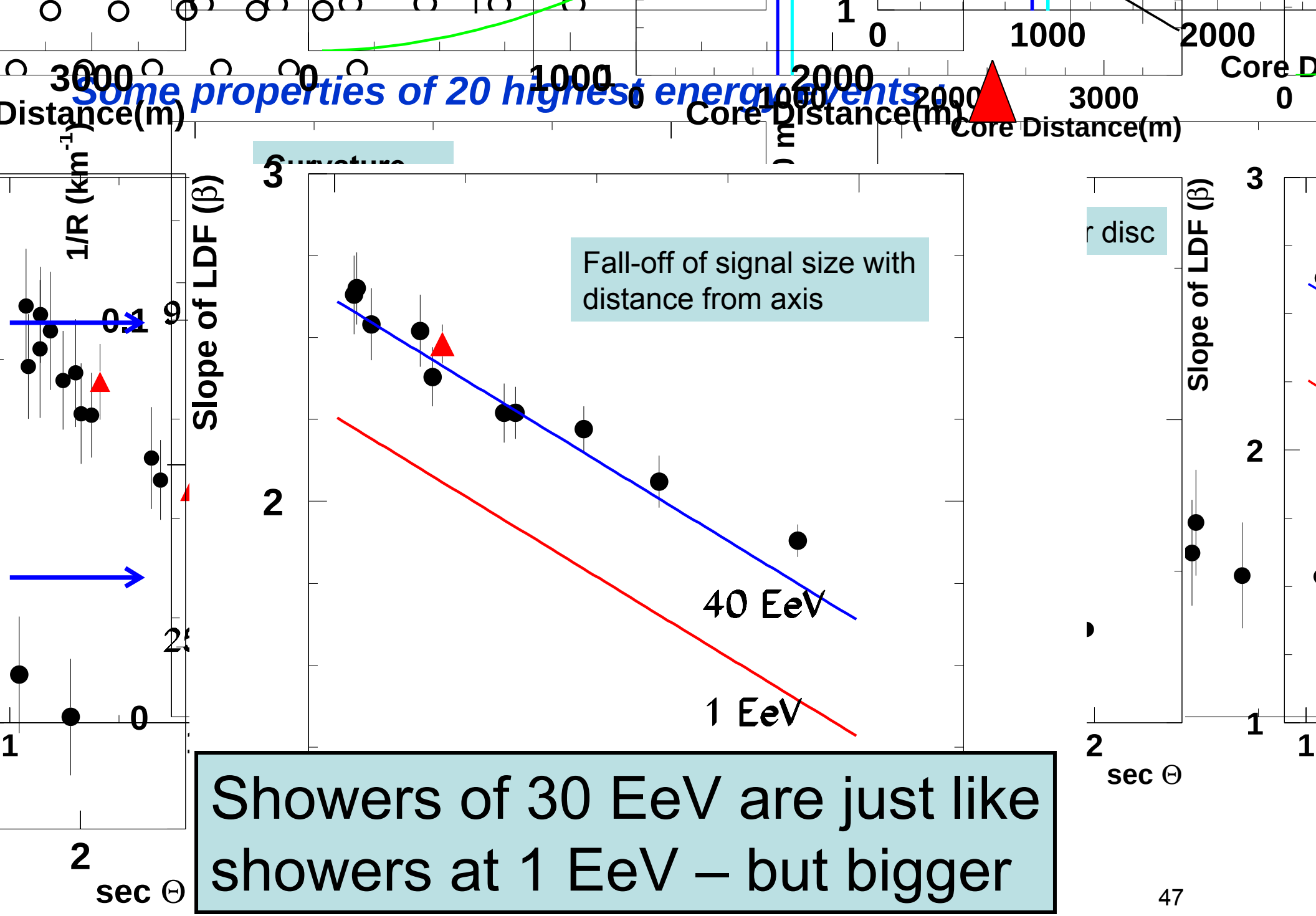


Hillas 1984
ARA&A
B vs R

Magnetars?

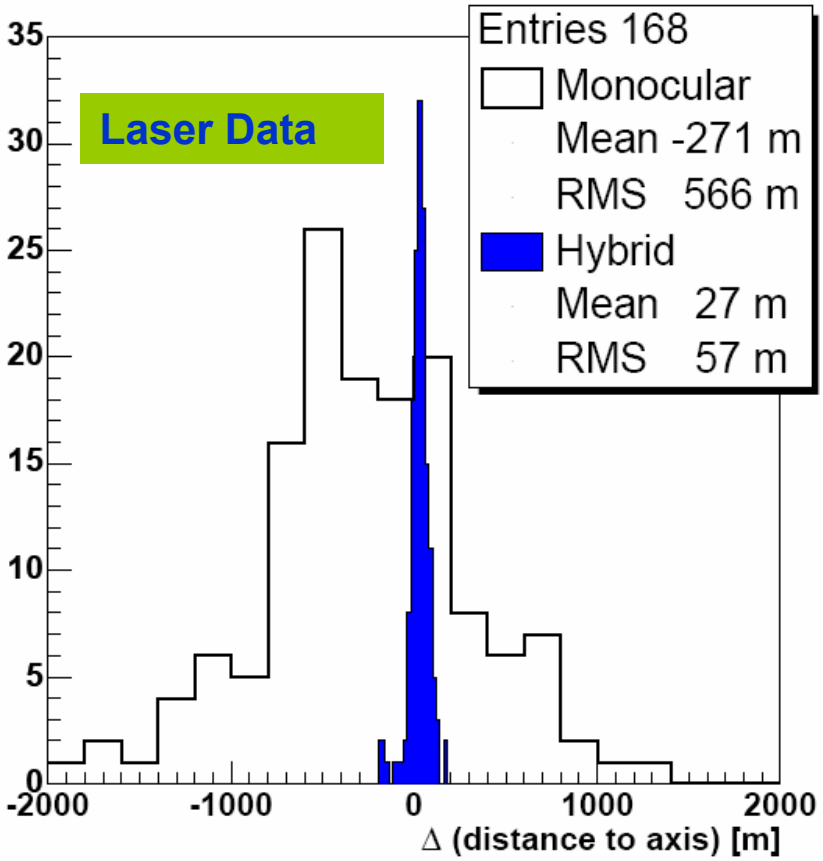
GRBs?

Some properties of 20 highest energy events



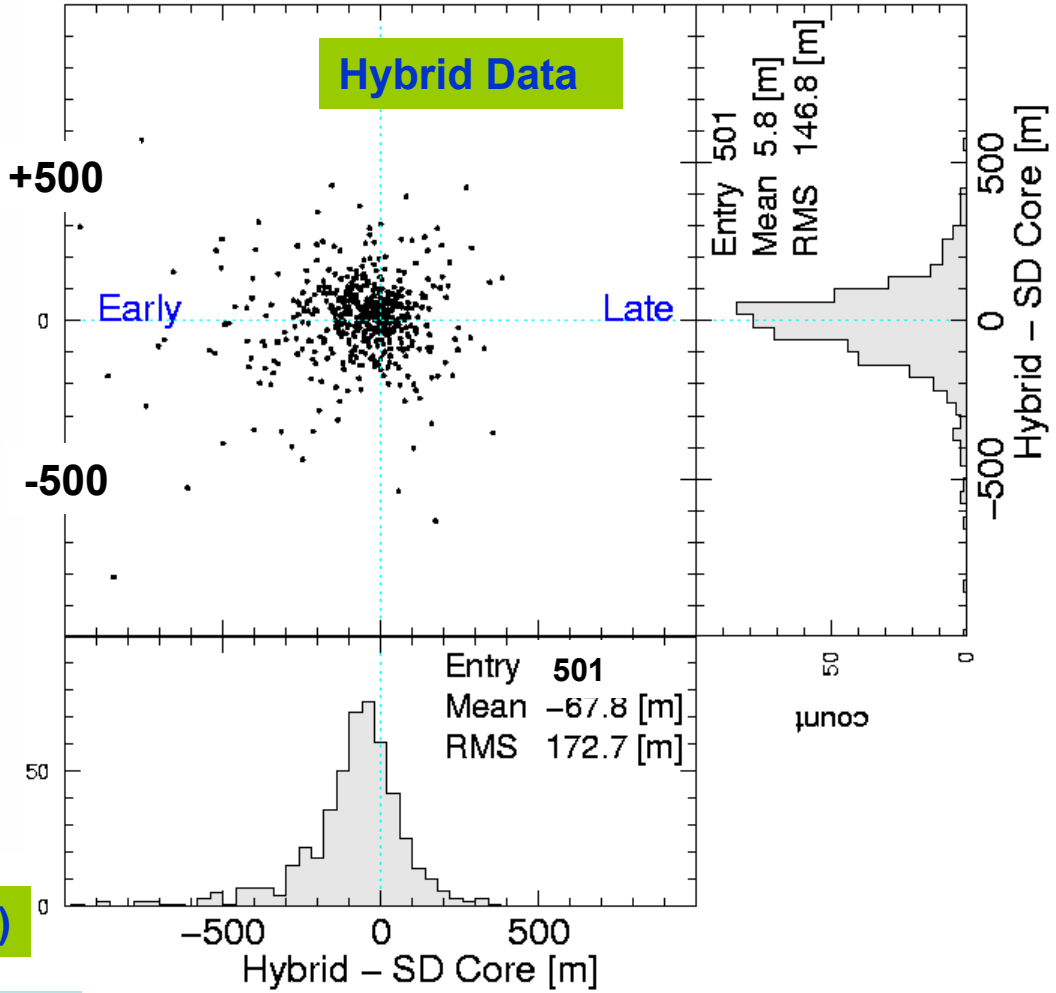
Showers of 30 EeV are just like showers at 1 EeV – but bigger

Resolution of Core Position



Laser position – Hybrid and FD only (m)

rms spread ~ 570 m for monocular fit

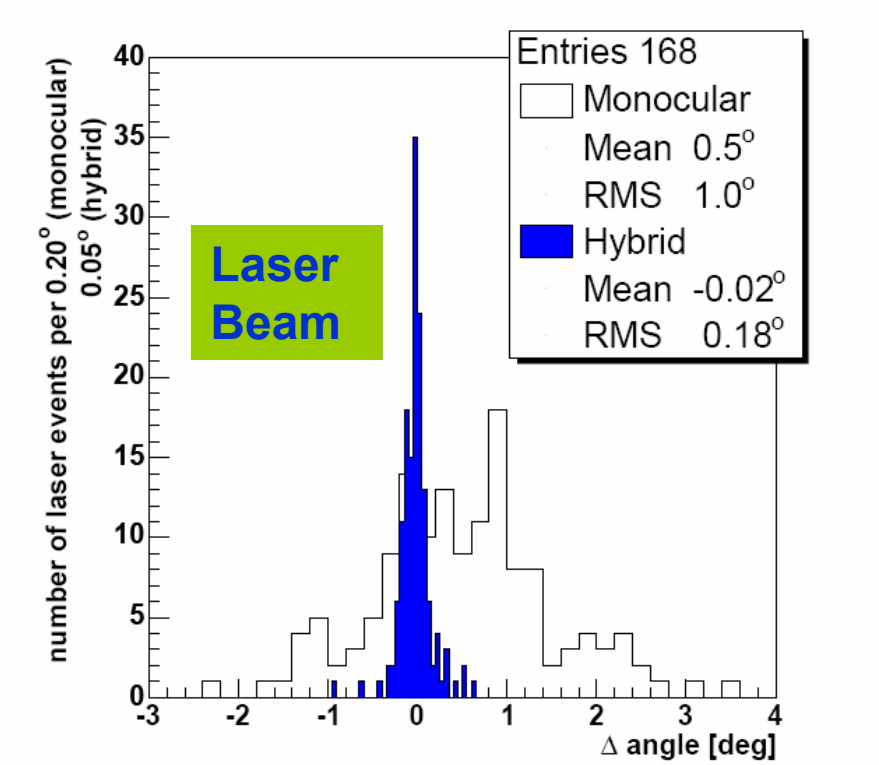


Hybrid – SD only core position

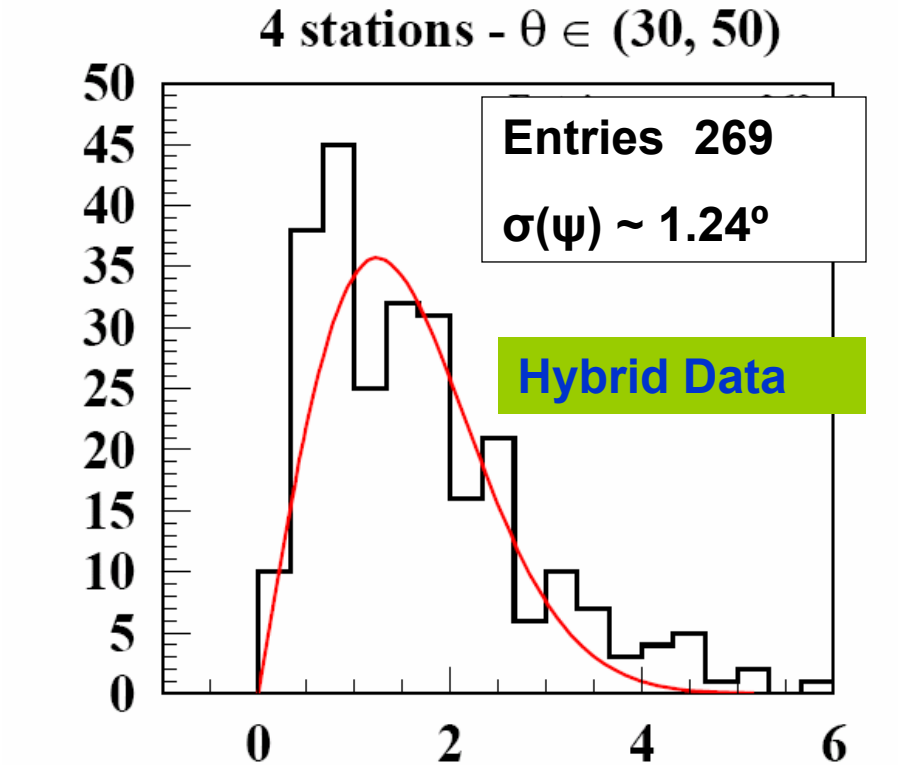
Core position resolution:

Hybrid: < 60 *m* **Surface array: < *200 m***

Angular Resolution



Angle in laser beam /FD detector plane



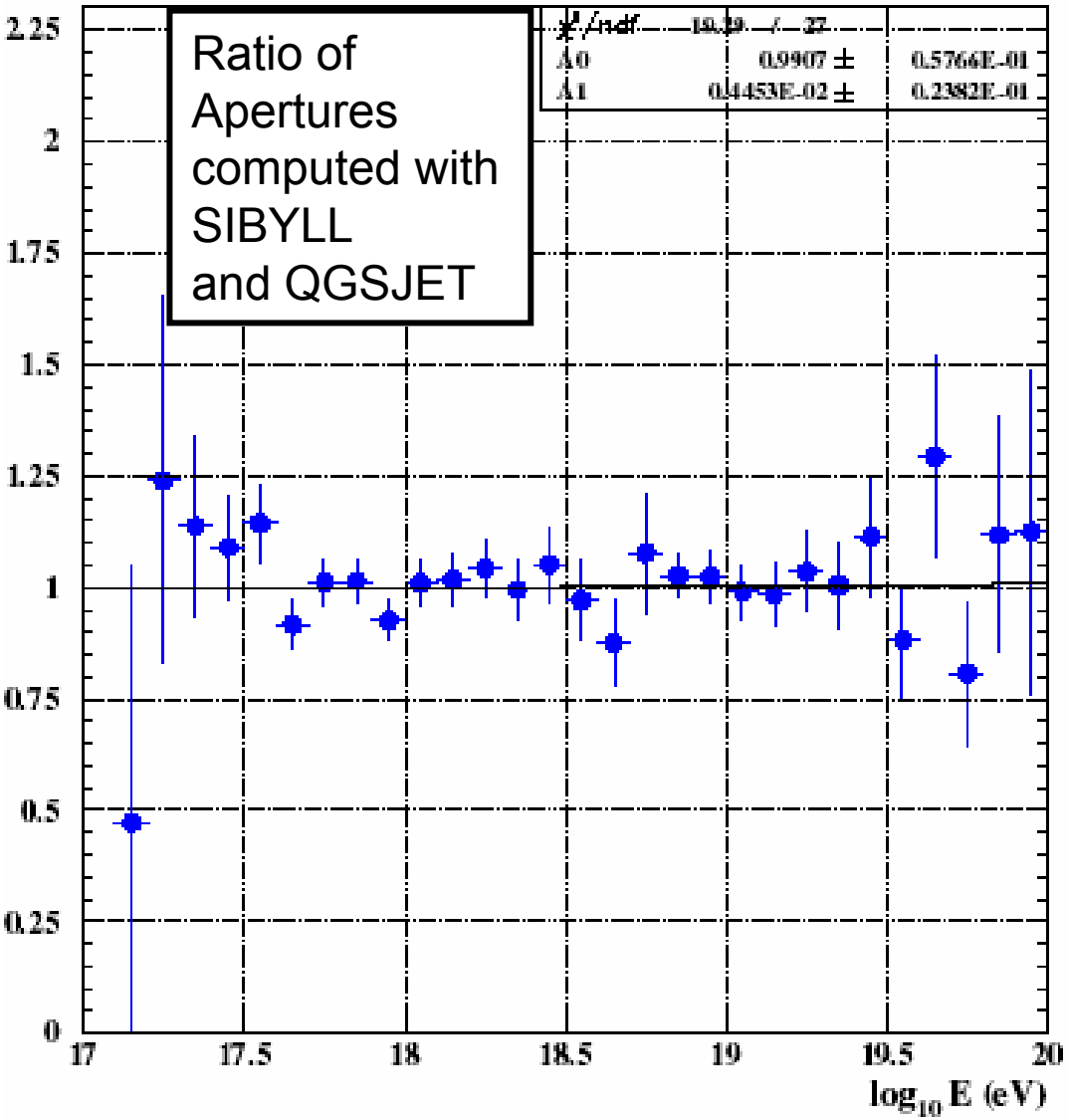
Hybrid-SD only space angle difference

Resolution using a centrally positioned laser

Hybrid Angular resolution
(68% CL)
0.6 degrees (mean)

Surface array Angular resolution (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)

Sensitivity of HiRes II aperture to shower model



More statistics needed and up-dated model needs to be used.

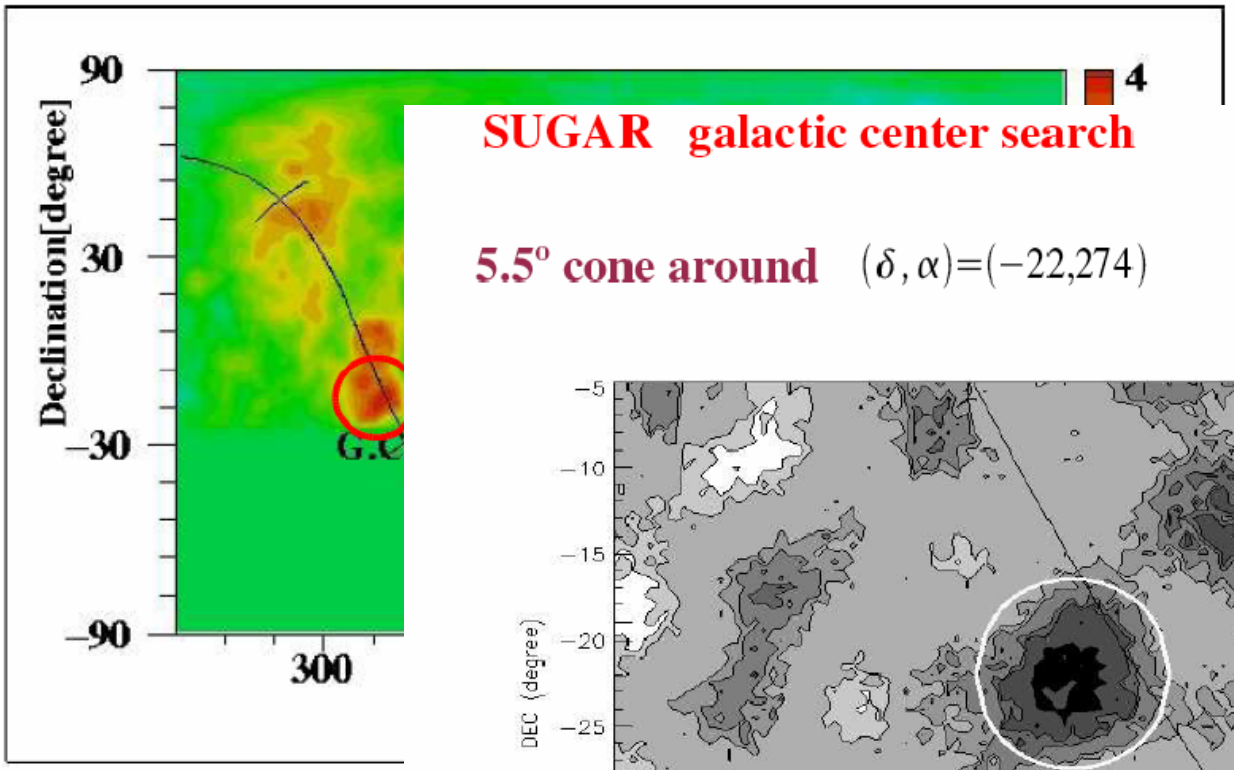
Mass assumption has only been explored at ± 5% of an assumed proton fraction

Zech et al. HiRes Collaboration: ICRC 2005

Arrival Direction Studies

AGASA ANISOTROPIES ON 20° SCALES (10^{18} – $10^{18.4}$ eV)

$$\frac{observed}{expected}=\frac{506}{413.6}\quad(+4.5\sigma)$$ **(22% excess)** **at** $(\delta,\alpha)=(-15,280)$

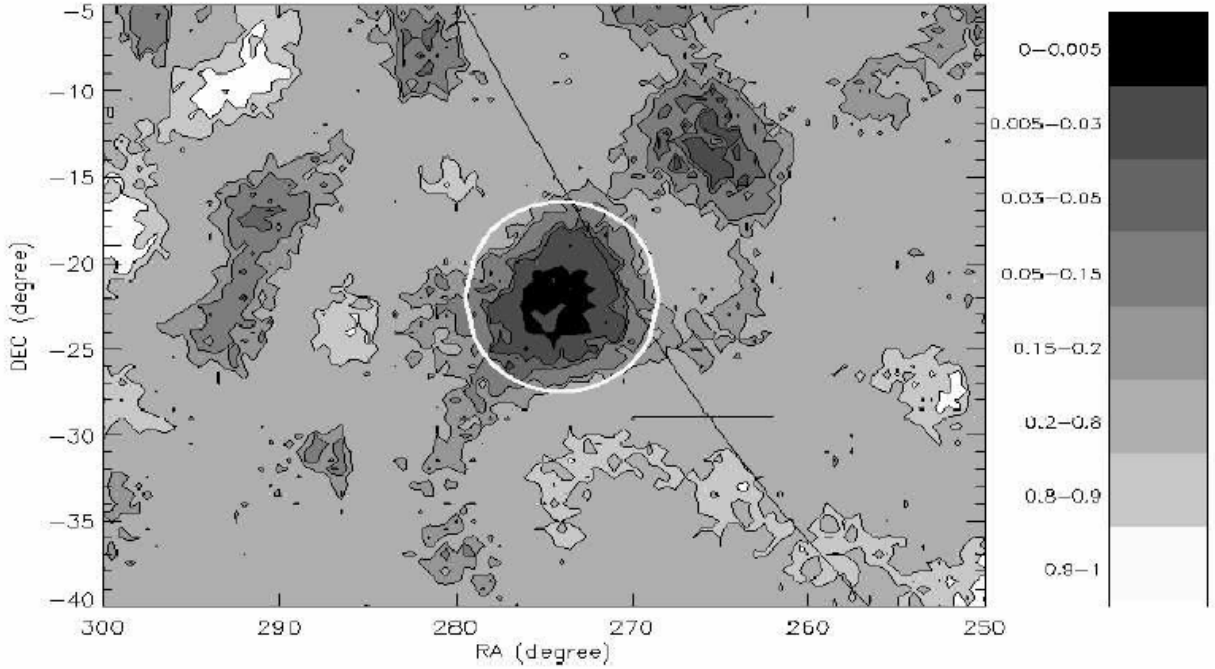


SUGAR galactic center search ($10^{17.9}$ – $10^{18.5}$ eV)

5.5° cone around $(\delta,\alpha)=(-22,274)$

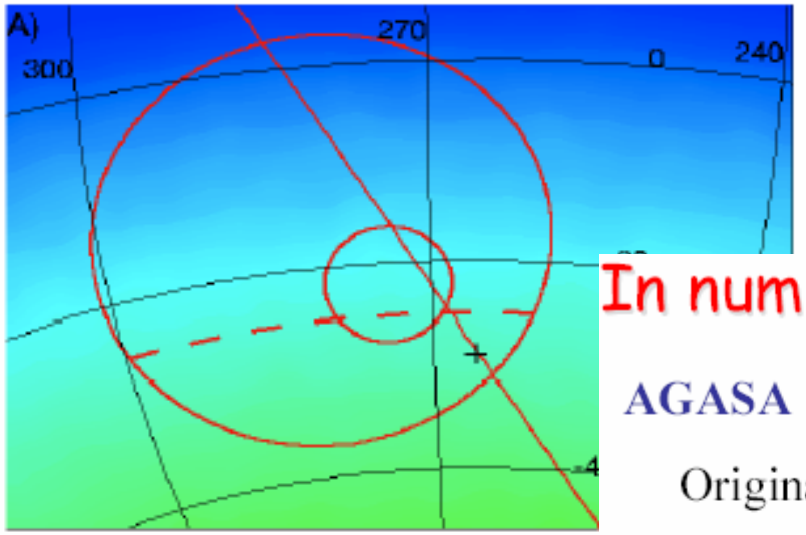
$$\frac{observed}{expected}=\frac{21.8}{11.8}\quad(+2.9\sigma)$$

(85% excess)

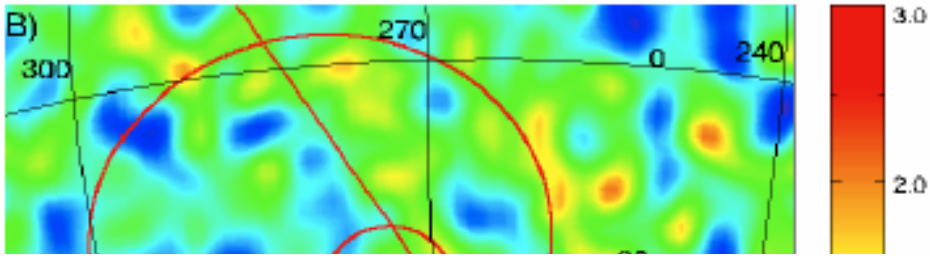


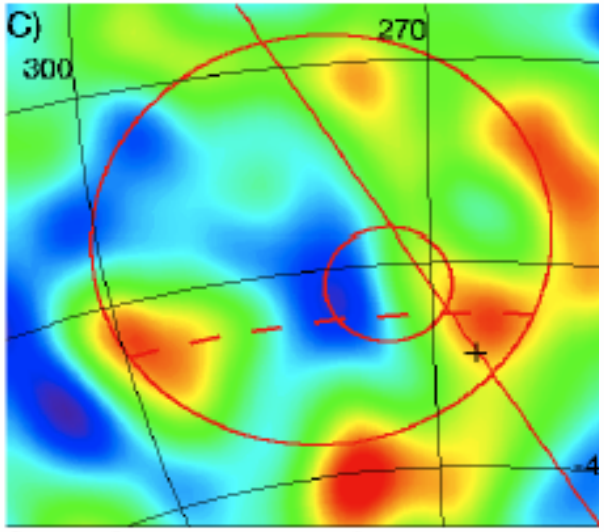
Galactic center seen by Auger :

Coverage



Significance (1.5°)





Significance (3.7°)

In numbers :

AGASA

Original Cuts (1.0 – 2.5 EeV)

top hat 20° 1155 / 1160.7 ratio = 1.00 ± 0.03

(22% excess would give 1415 and a 7.5 σ excess)

Enlarge energy range (0.8 – 3.2 EeV)

top hat 20° 1896 / 1853.06

SUGAR (0.8 – 3.2 EeV)

top hat 5° 144 / 150.9 ratio = 0.95 ± 0.08

(85% excess would give 279 and a 10.5 σ excess)

Also looked for as a point source, no signal.

Galactic center search (point source)

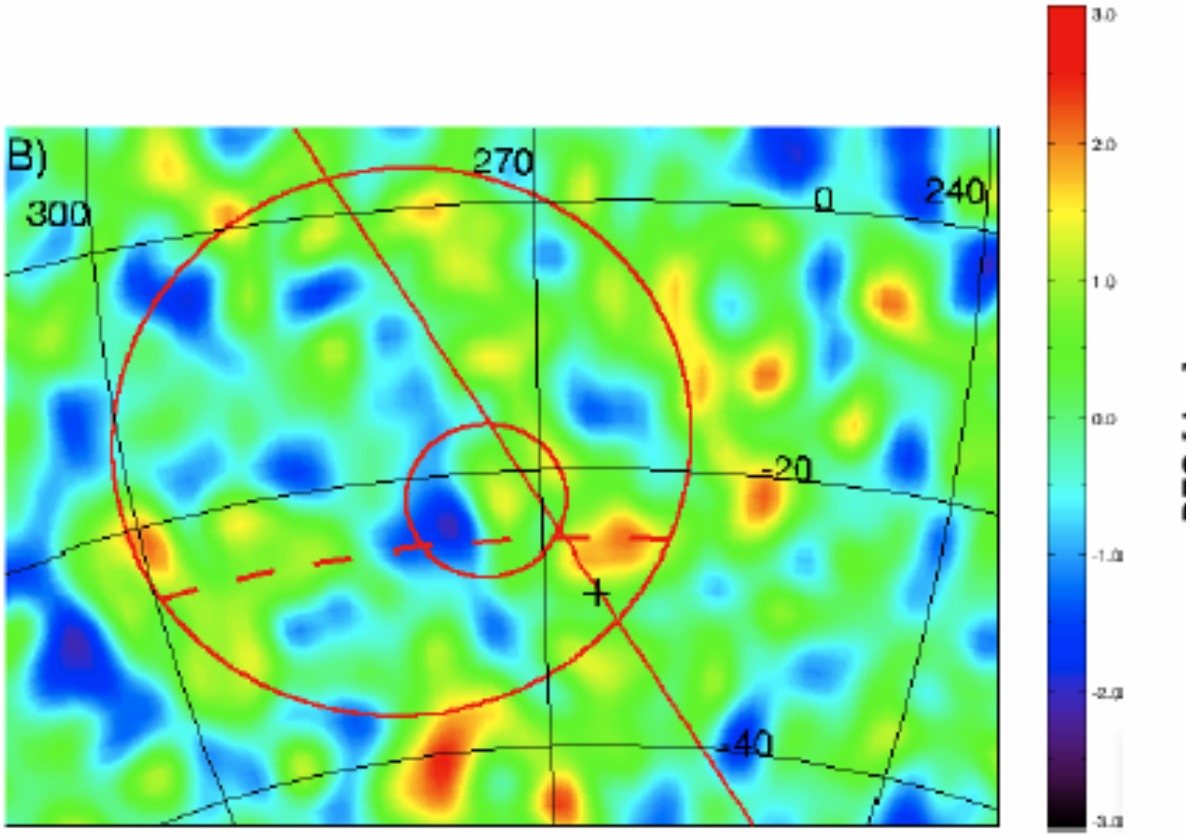
SD only:

Gaussian filtering 1.5 degree

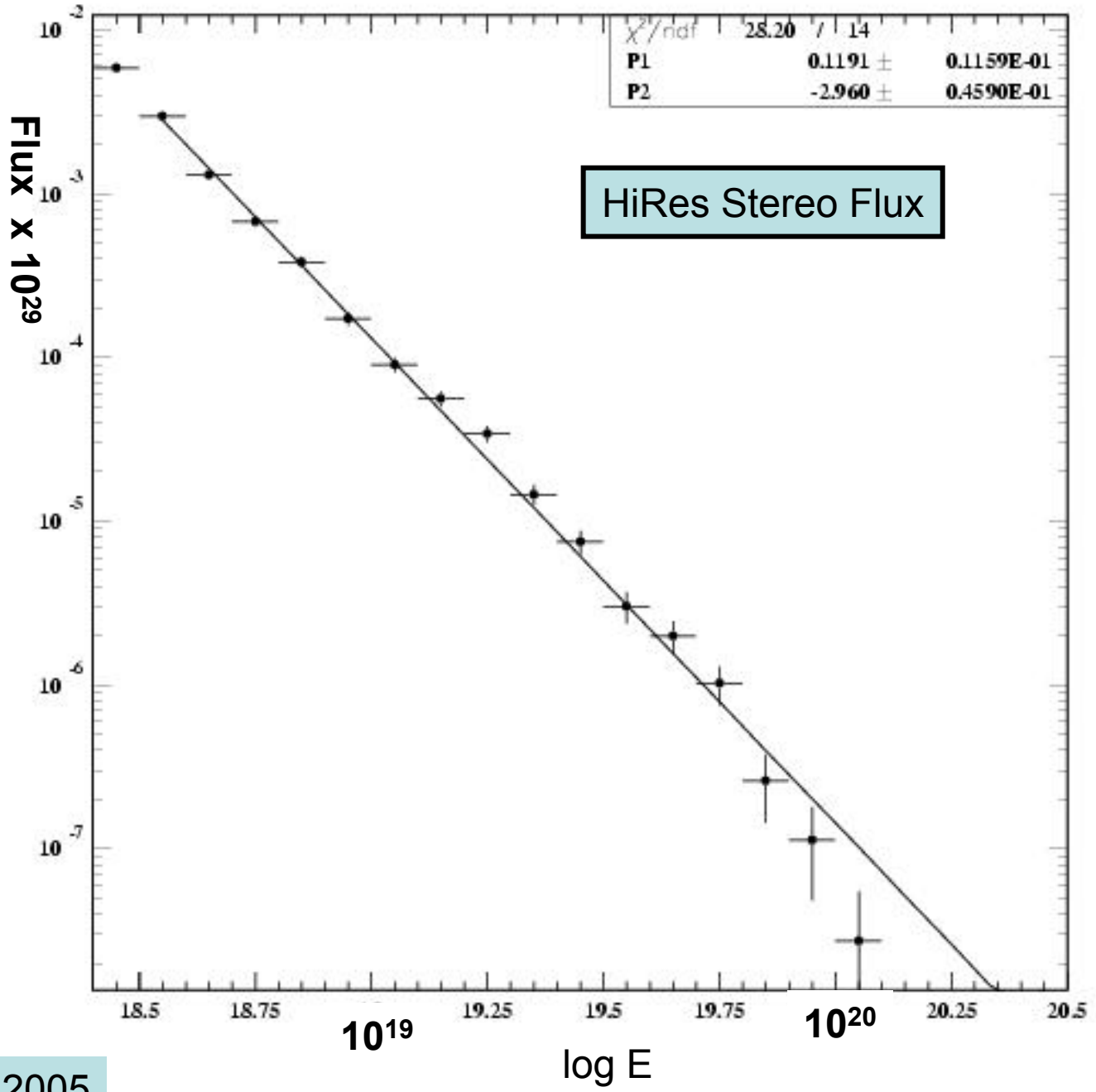
exp/obs 24.3/23.9

if $\phi_S \propto \phi_{CR}$ then for 0.8 EeV < E < 3.2 EeV :

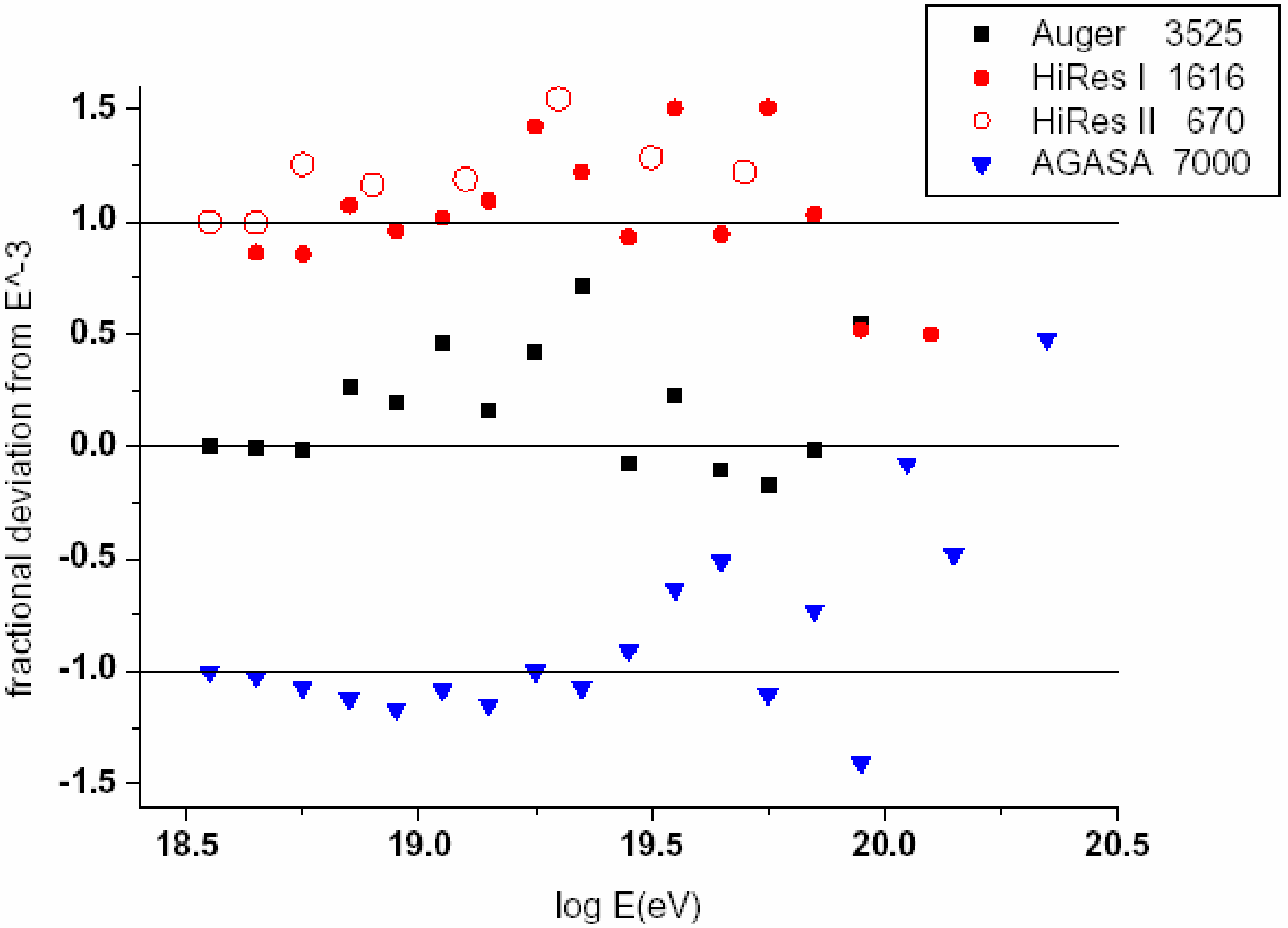
$\phi_S < 2.5\ \xi\ \varepsilon \times 10^{-15}\ \mathrm{m^{-2}\ s^{-1}}$ @ 95 %



- Fit to power law.
- Single index gives poor χ^2
- Evidence for changing index



Springer et al. ICRC 2005


Auger 3525
HiRes I 1616
HiRes II 670
AGASA 7000
fractional deviation from E^-3
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
18.5
19.0
19.5
20.0
20.5
log E(eV)

Association with BL Lacs?

Initial claims by Tinyakov et al.
– but disputed by Evans et al and others

217 HiRes Stereo events above 10 EeV

$\sigma = 0.4$ deg, so that 68% of events would lie within $\theta = 1.52\ \sigma$

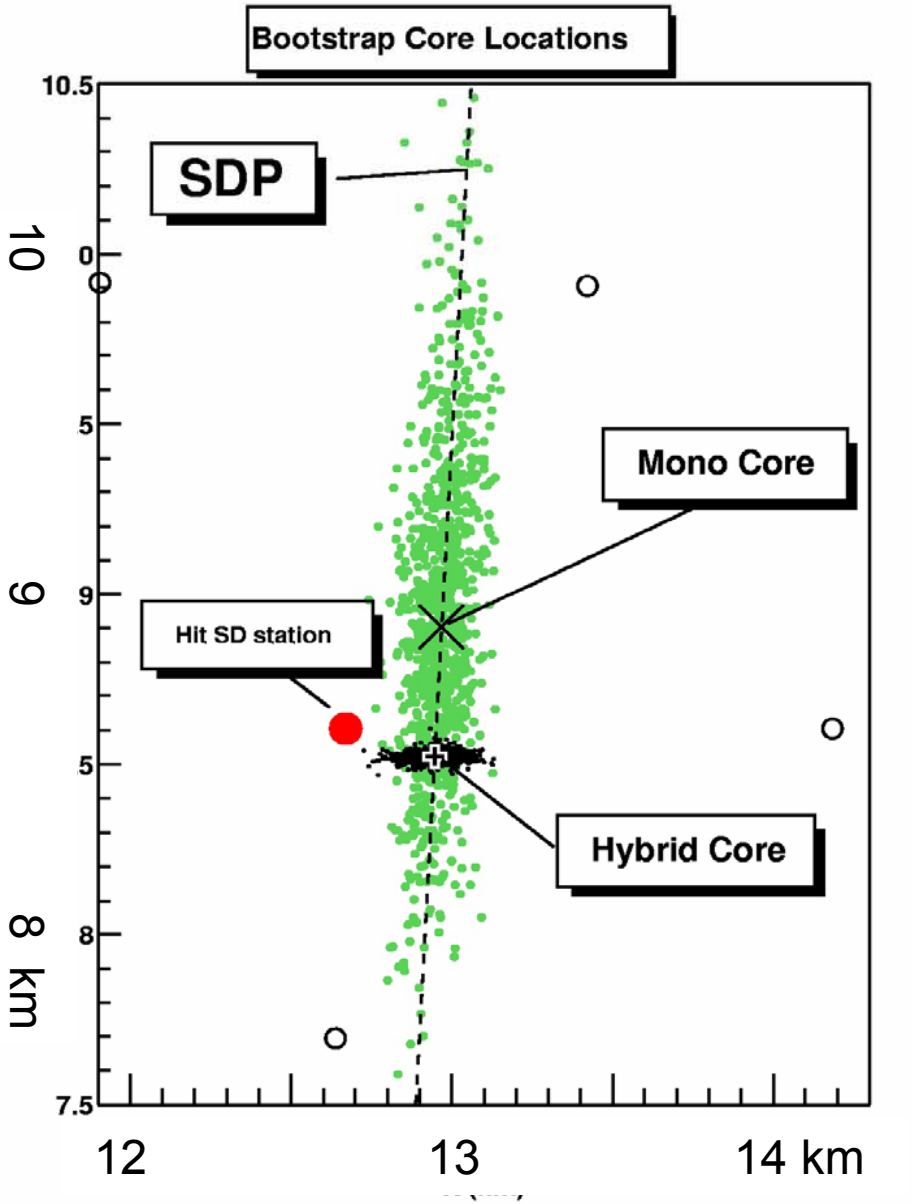
This is an impressive angular accuracy

Tinyakov et al. conclusion for m<18 confirmed
– but same data set of events and same 157 BL Lacs

BUT for E> 40 EeV, HiRes shows a deficit in the correlation

Presumably primaries are neutral because of anticipated magnetic field deflections – worth looking at lower energies.

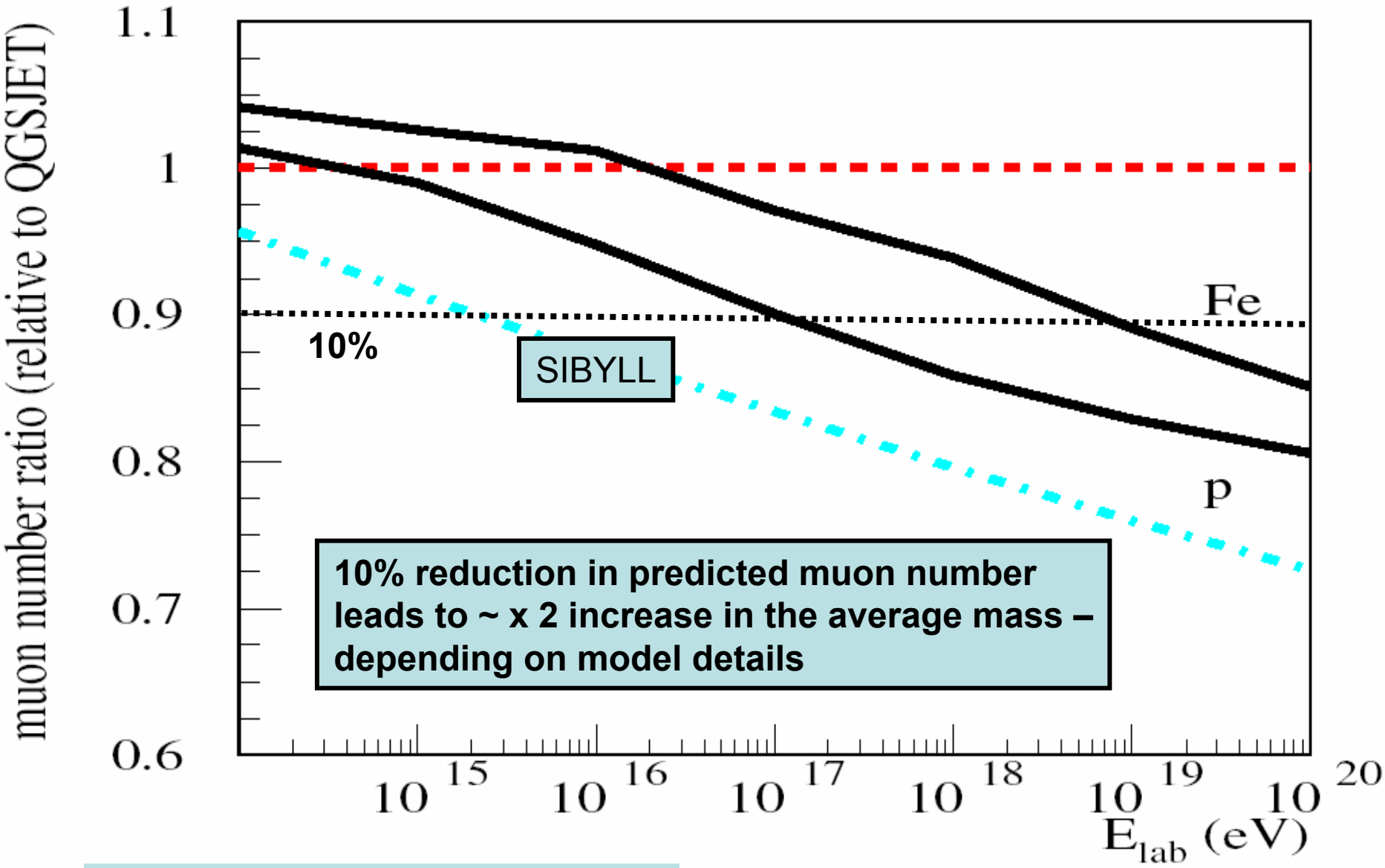
105573



Hybrid events are equivalent to stereo-events and superior to monocular events

Observations with real showers confirm the results from Central Laser Facility

Muon Number Ratio for different models and masses



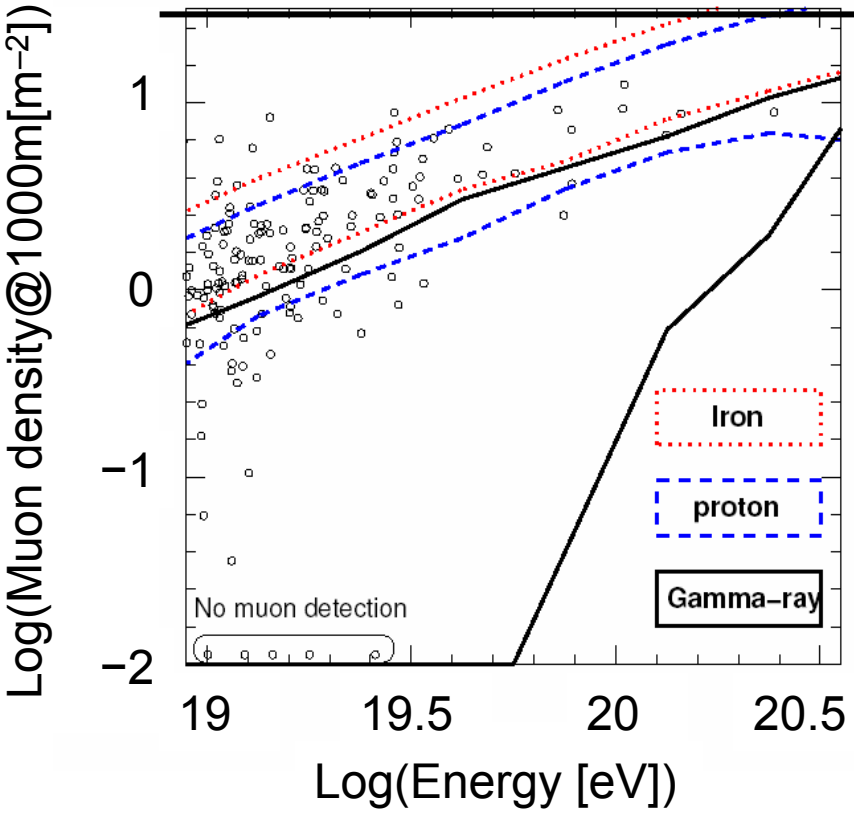
Heck and Ostapchenko: ICRC 2005

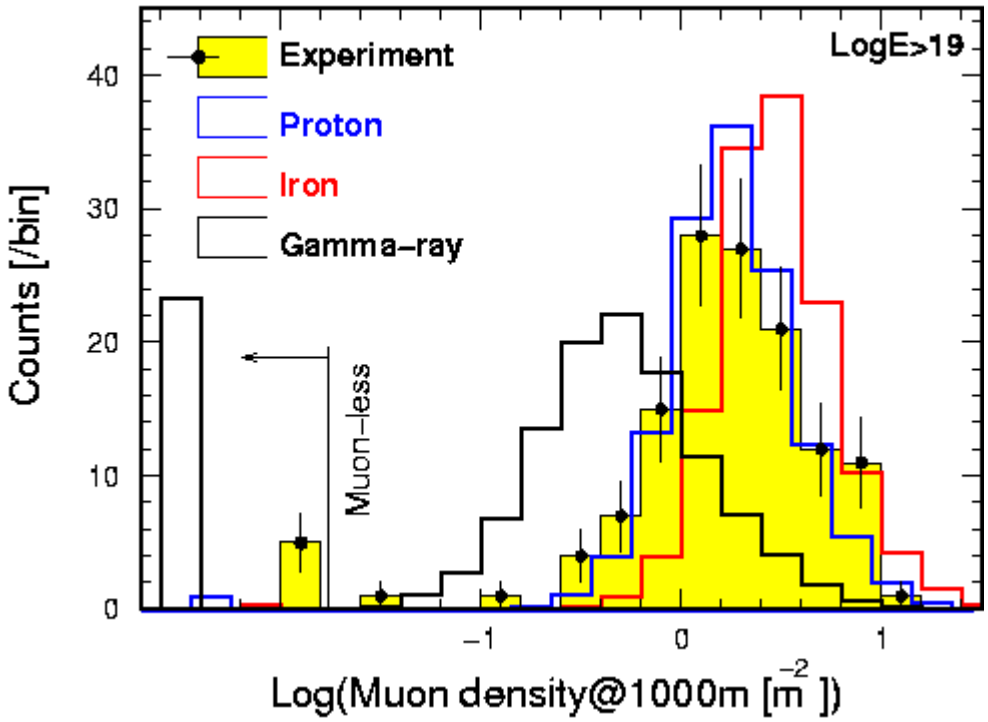
Muon measurements with the AGASA array

Original Claim (2003):

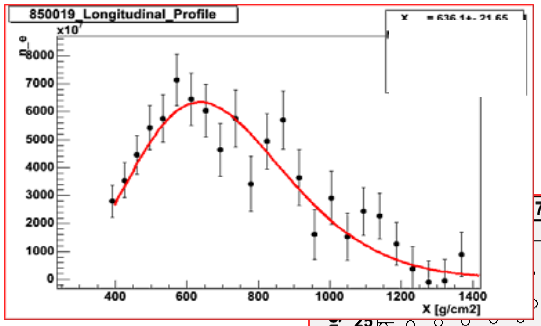
"Consistent with proton dominant component" –

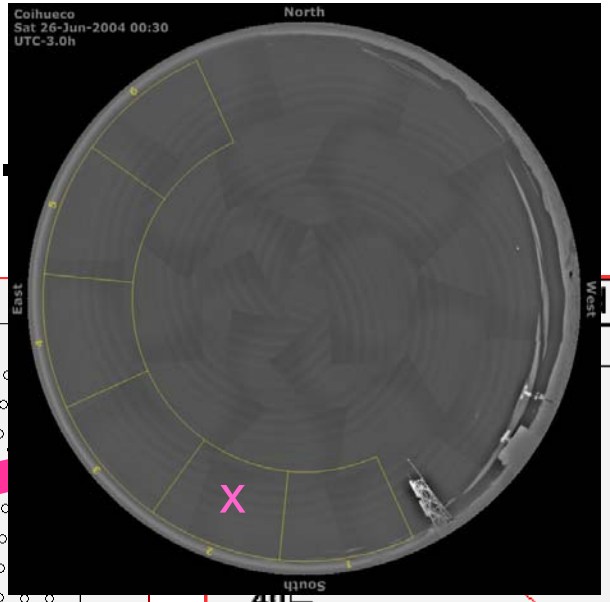
must be revised

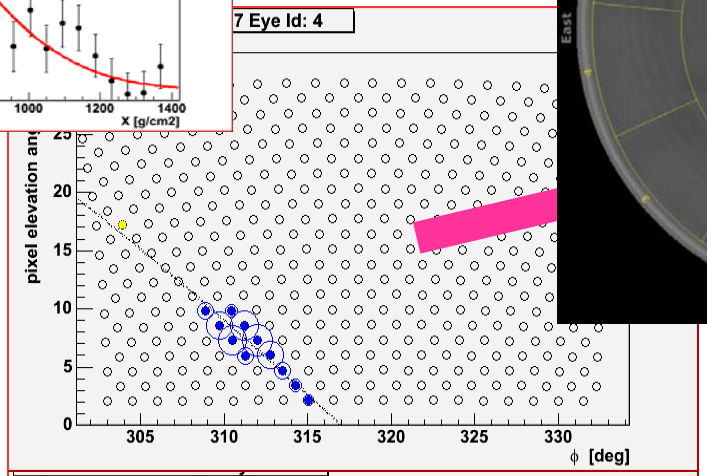


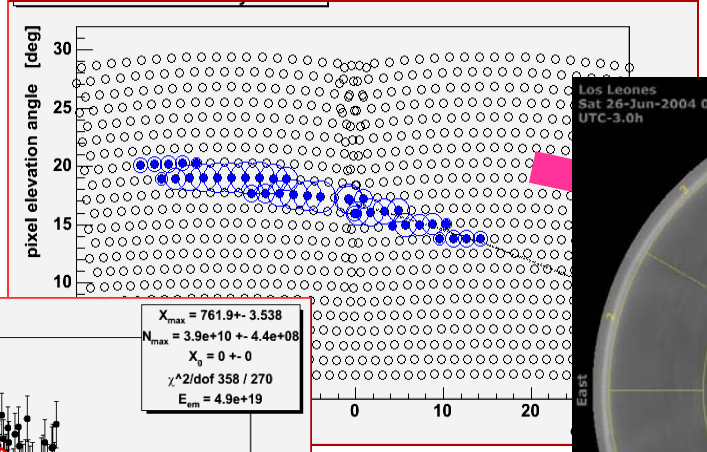


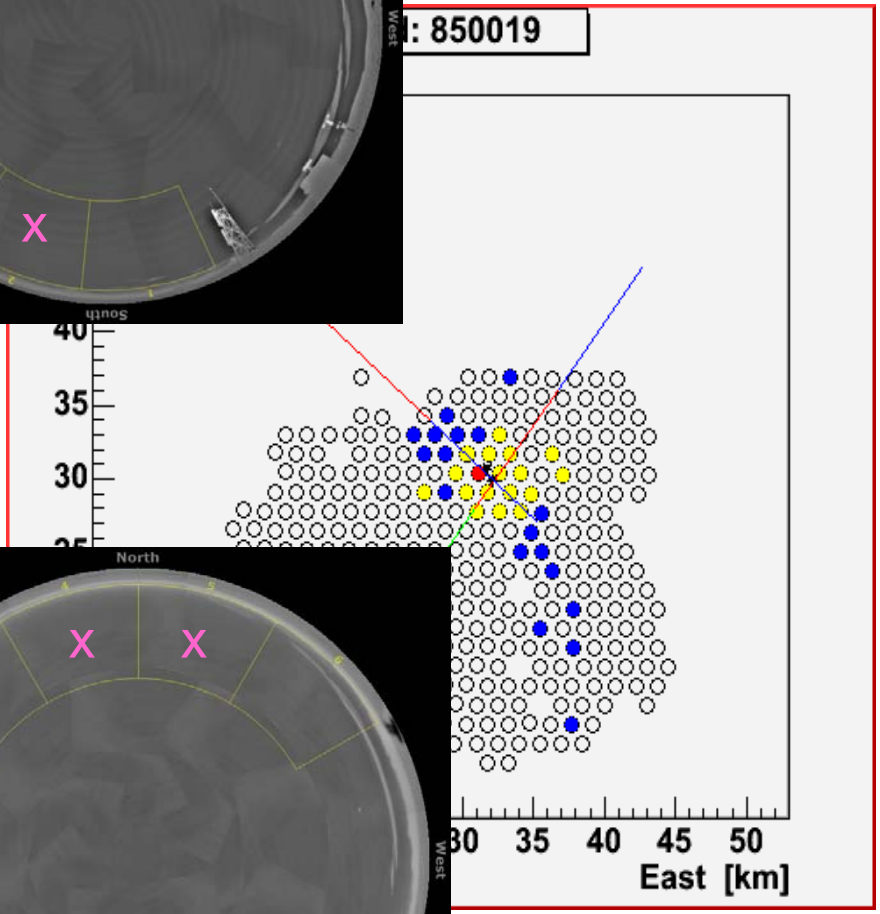
Stereo-

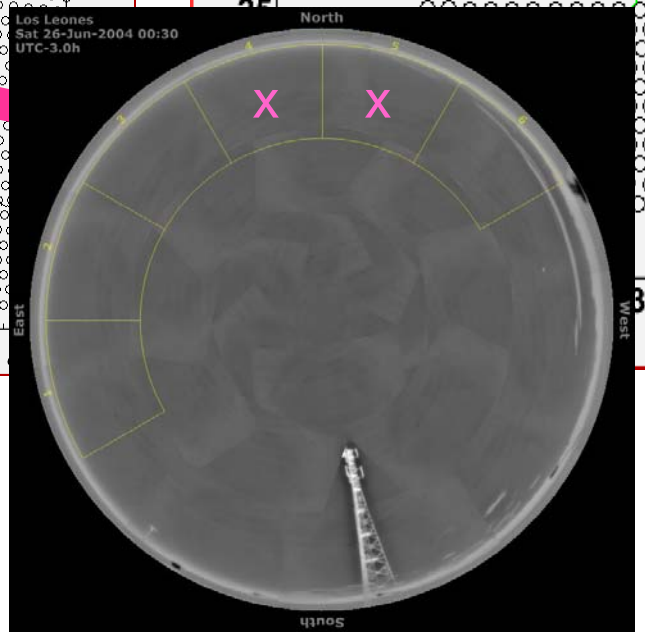

850019_Longitudinal_Profile
X [g/cm2]

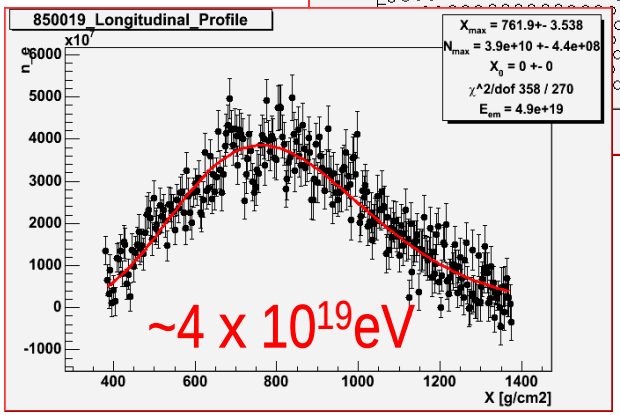

Coihueco
Sat 26-Jun-2004 00:30
UTC-3.0h
North
East
West
South

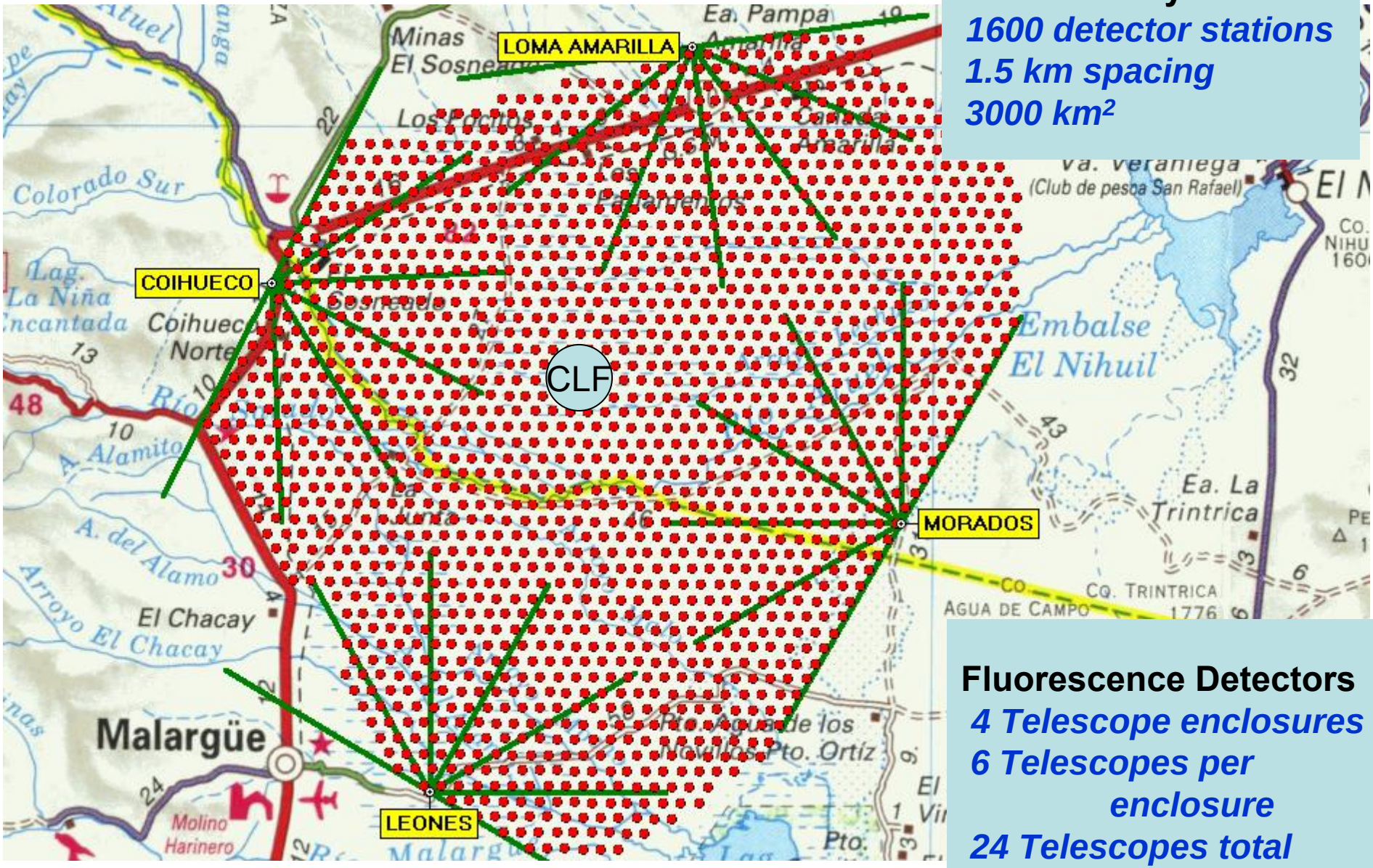

7 Eye Id: 4
pixel elevation
ϕ [deg]


pixel elevation angle [deg]


l: 850019
East [km]


Los Leones
Sat 26-Jun-2004 00:30
UTC-3.0h
North
East
West
South


850019_Longitudinal_Profile
X [g/cm2]
~4 x 10^19eV

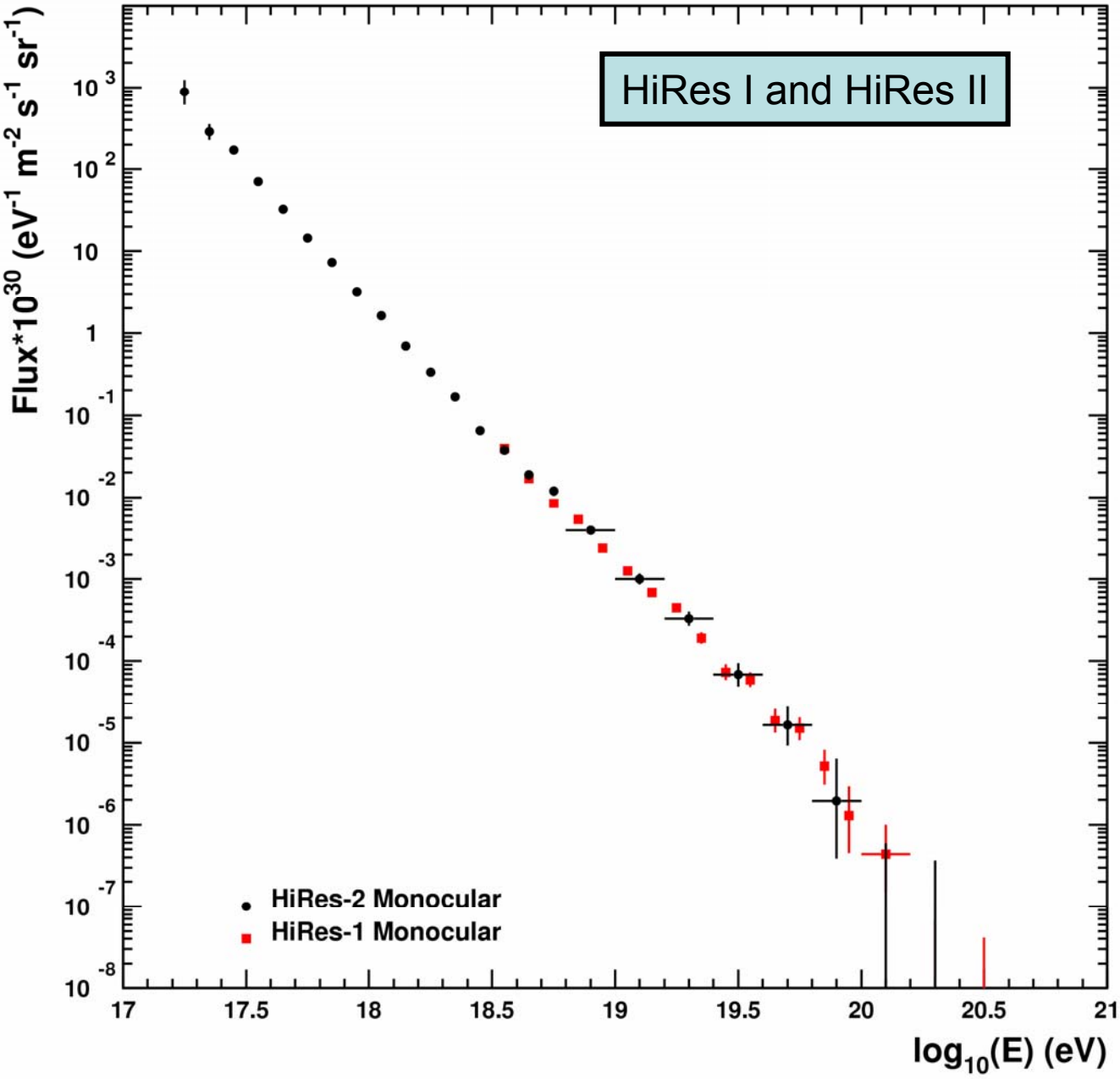


Surface Array

1600 detector stations
1.5 km spacing
3000 km^2

Fluorescence Detectors

4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total


HiRes I and HiRes II
Flux*10^30 (eV^-1 m^-2 s^-1 sr^-1)
log10(E) (eV)
HiRes-2 Monocular
HiRes-1 Monocular

Geometrical Reconstruction