PIERRE AUGER OBSERVATORY

ICRC 2007: Mérida, Mexico

Highlights from the Pierre Auger Observatory

- the birth of the Hybrid Era

Alan Watson

on behalf of the Pierre Auger Collaboration

"To make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side."

V.H.Hess, Nobel Lecture, December 1936

The Pierre Auger Collaboration

Czech Republic	Argentina
France	Austra
Germany	Bra
Italy	a*
Netherlands	exico
Poland	USA
Portugal	Vietnam*
Slovenia	
Spain	
Unit gdom	

*Associate Countries

~300 PhD scientists from

~70 Institutions and 17 countries

CINVESTAV

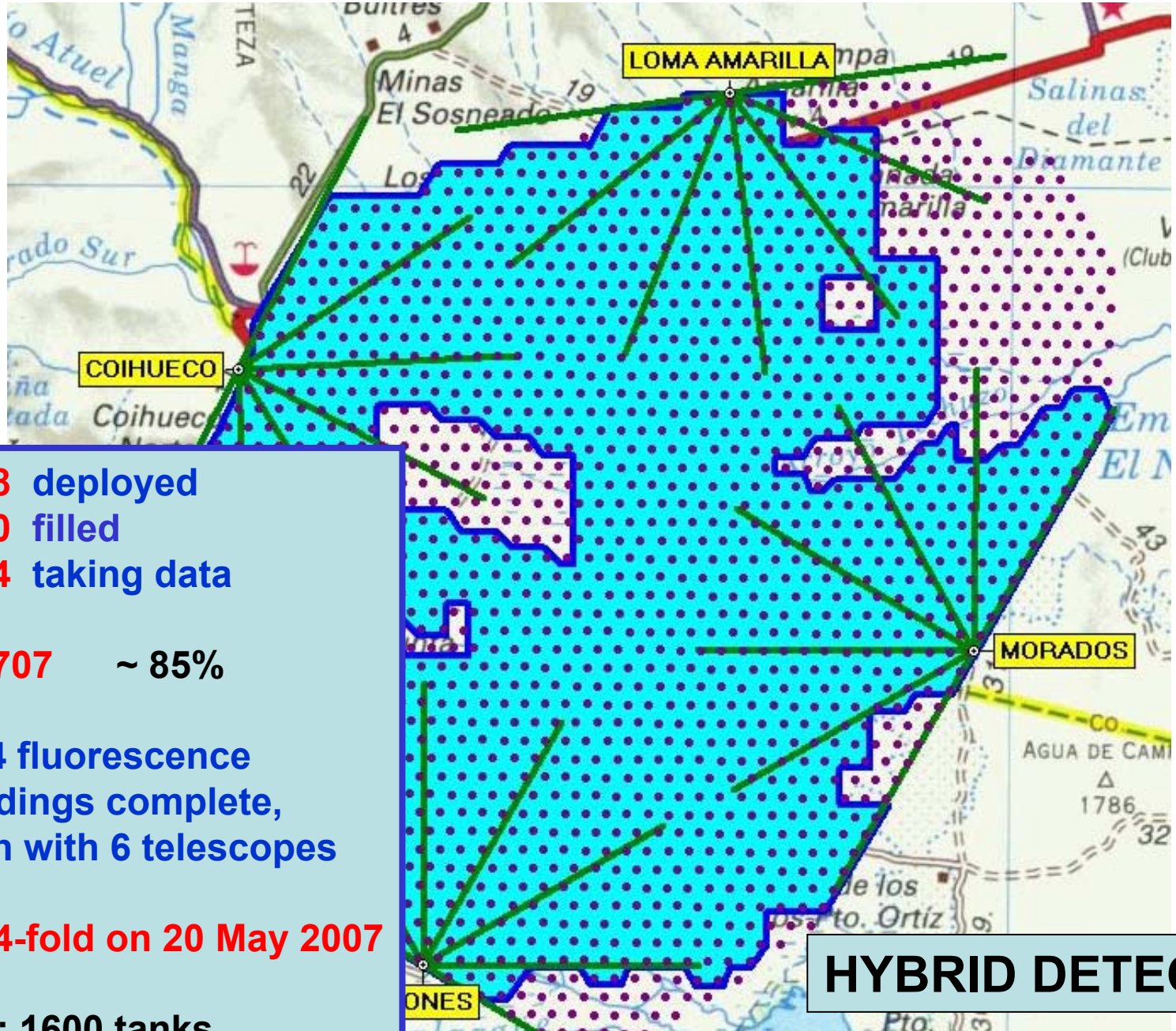
Michoacan

Puebla

UNAM

Thanks to all of my collaborators!!

Aim: To measure properties of UHECR with unprecedented statistics and precision – necessary even if no disagreement



1438 deployed
1400 filled
1364 taking data

090707 ~ 85%

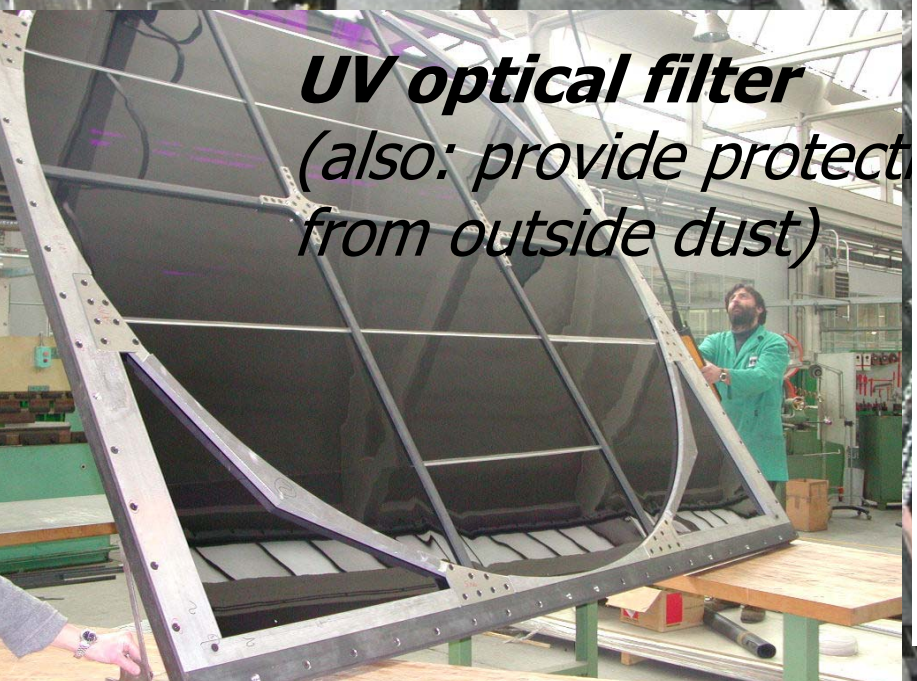
All 4 fluorescence buildings complete, each with 6 telescopes

1st 4-fold on 20 May 2007

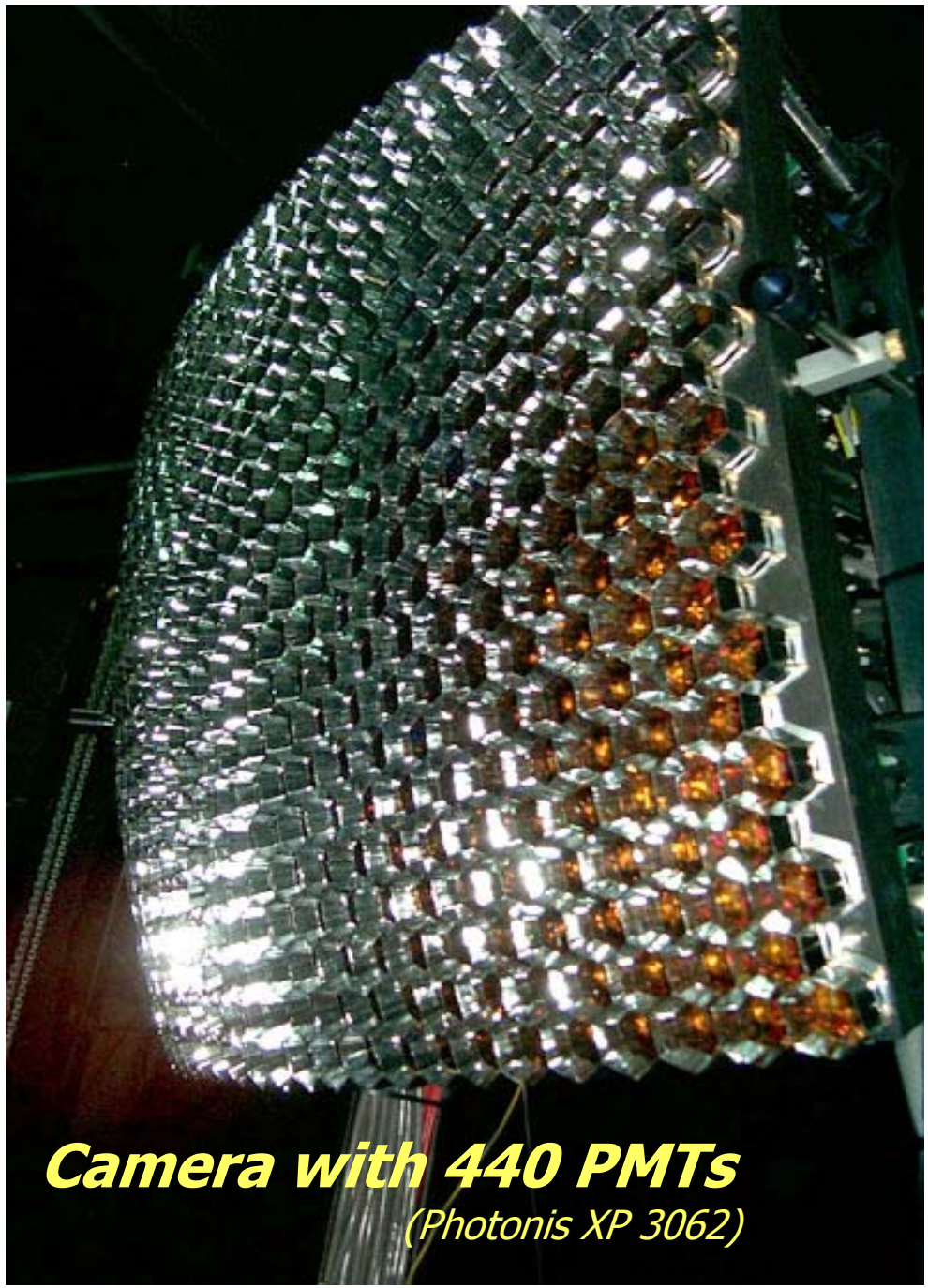
AIM: 1600 tanks


GPS Receiver
and radio transmission

Schmidt Telescope using 11 m² mirrors



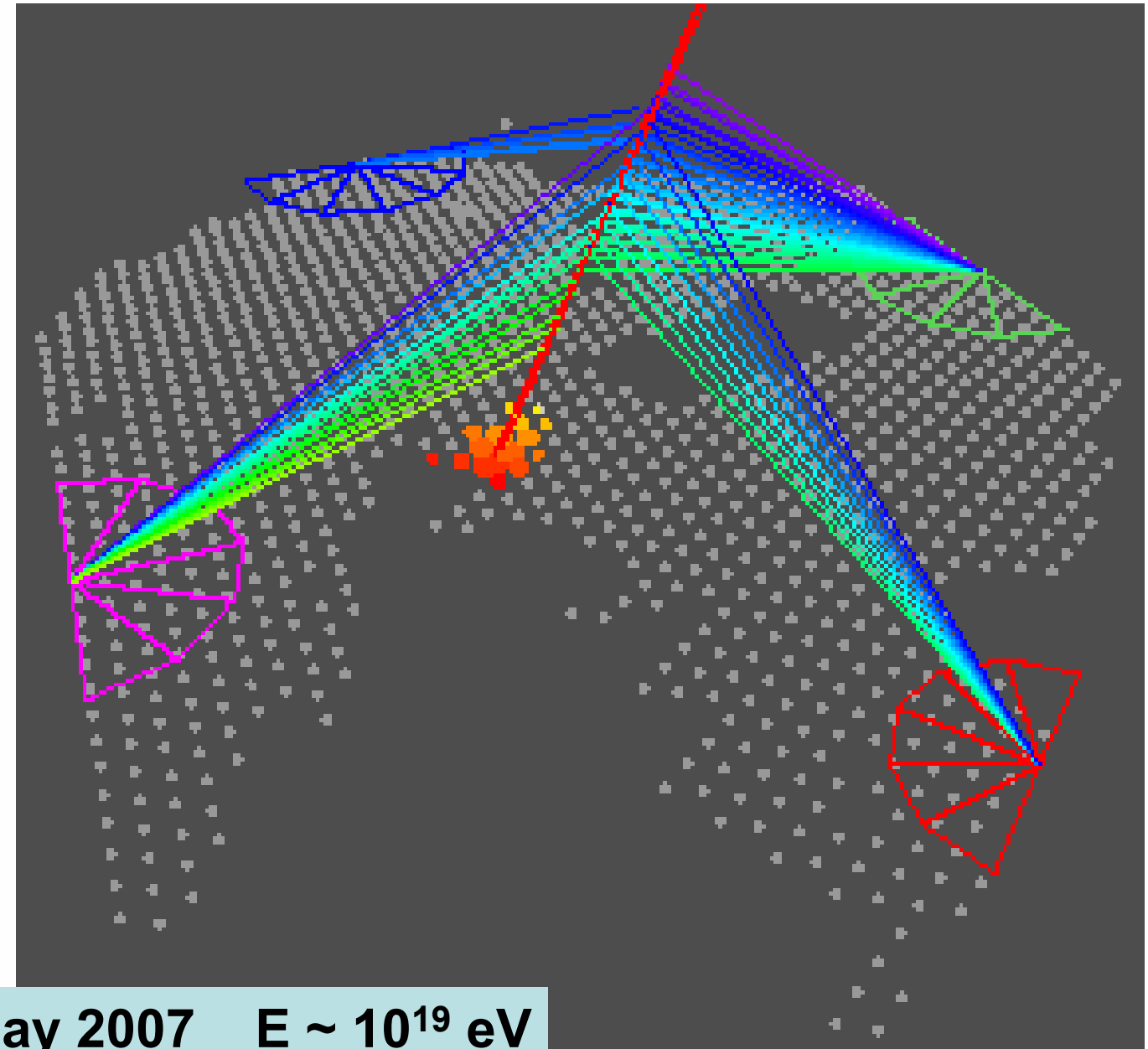
UV optical filter
(also: provide protect from outside dust)



Camera with 440 PMTs
(Photonis XP 3062)

The Hybrid Era

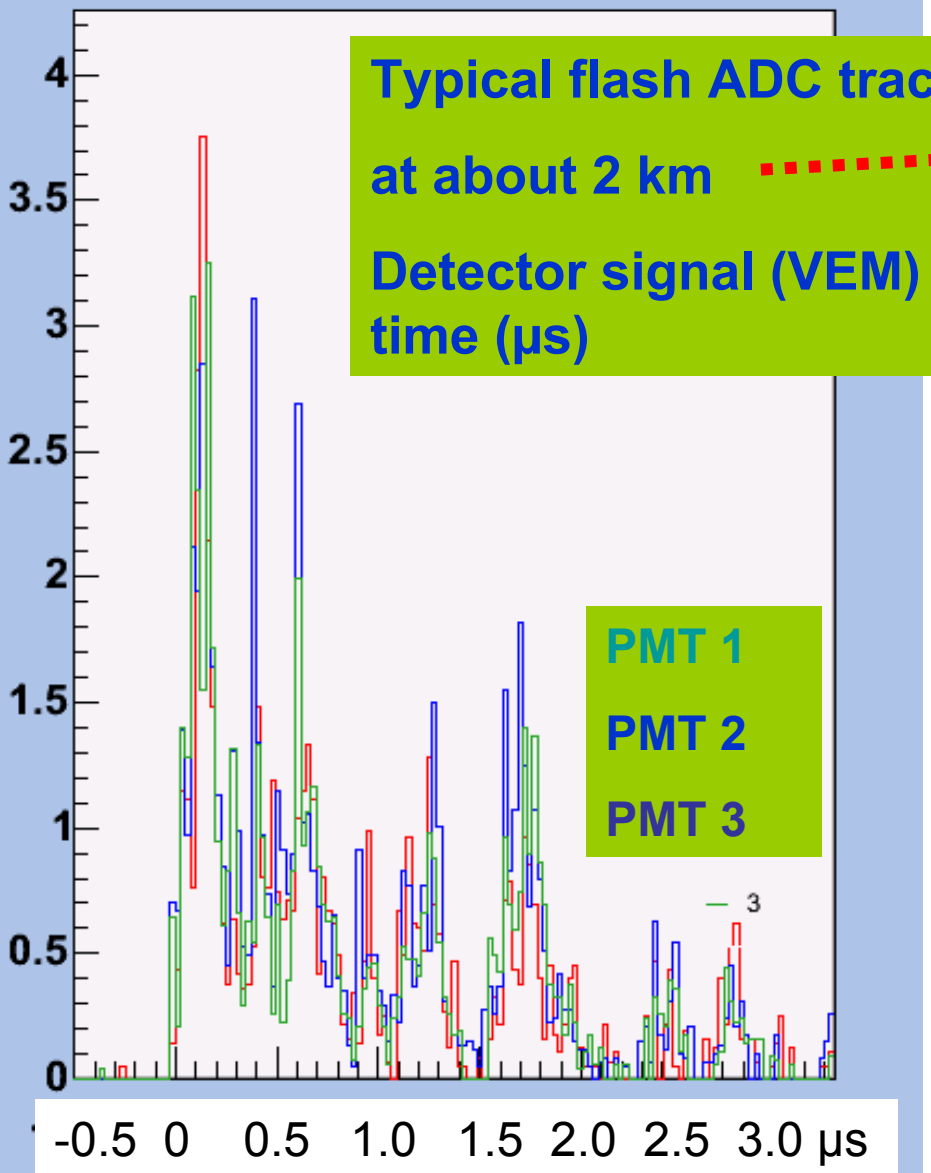
	Hybrid	SD-only	FD-only
			mono (stereo – low N)
Angular Resolution	**~ 0.2°**	**~ 1 - 2°**	**~ 3 - 5°**
Aperture	**Flat with energy AND mass and model (M) free**		**E, A, spectral slope and M dependent**
Energy	**A and M free**	**A and M dependent**	**A and M free**

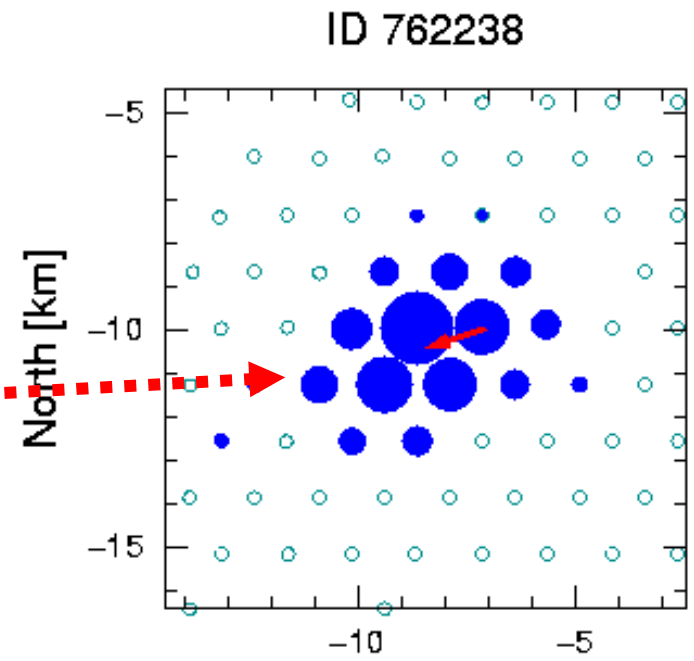


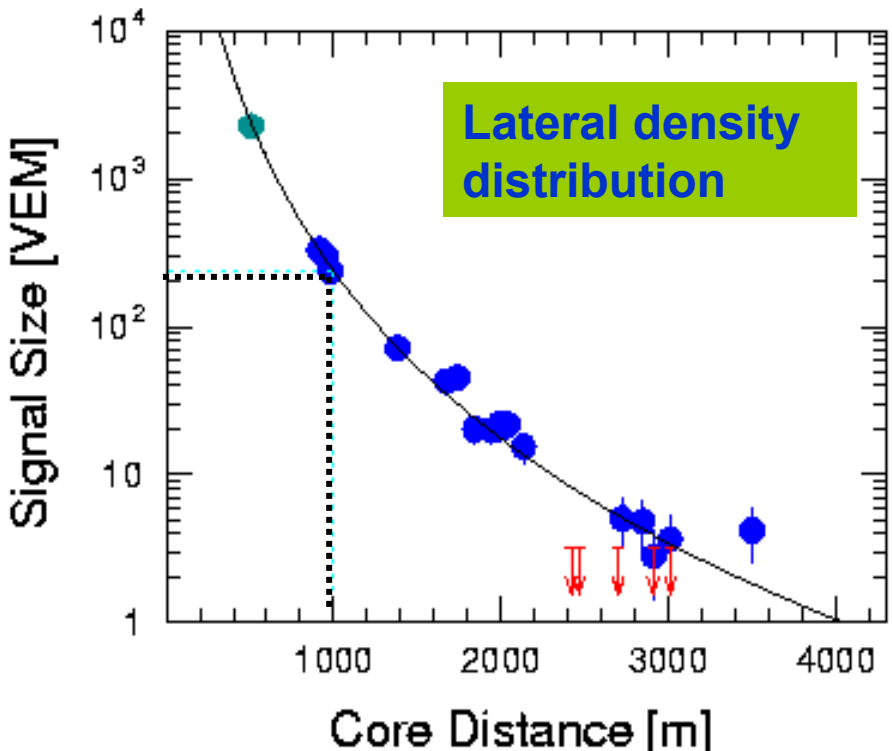
20 May 2007 E ~ 10^{19} eV

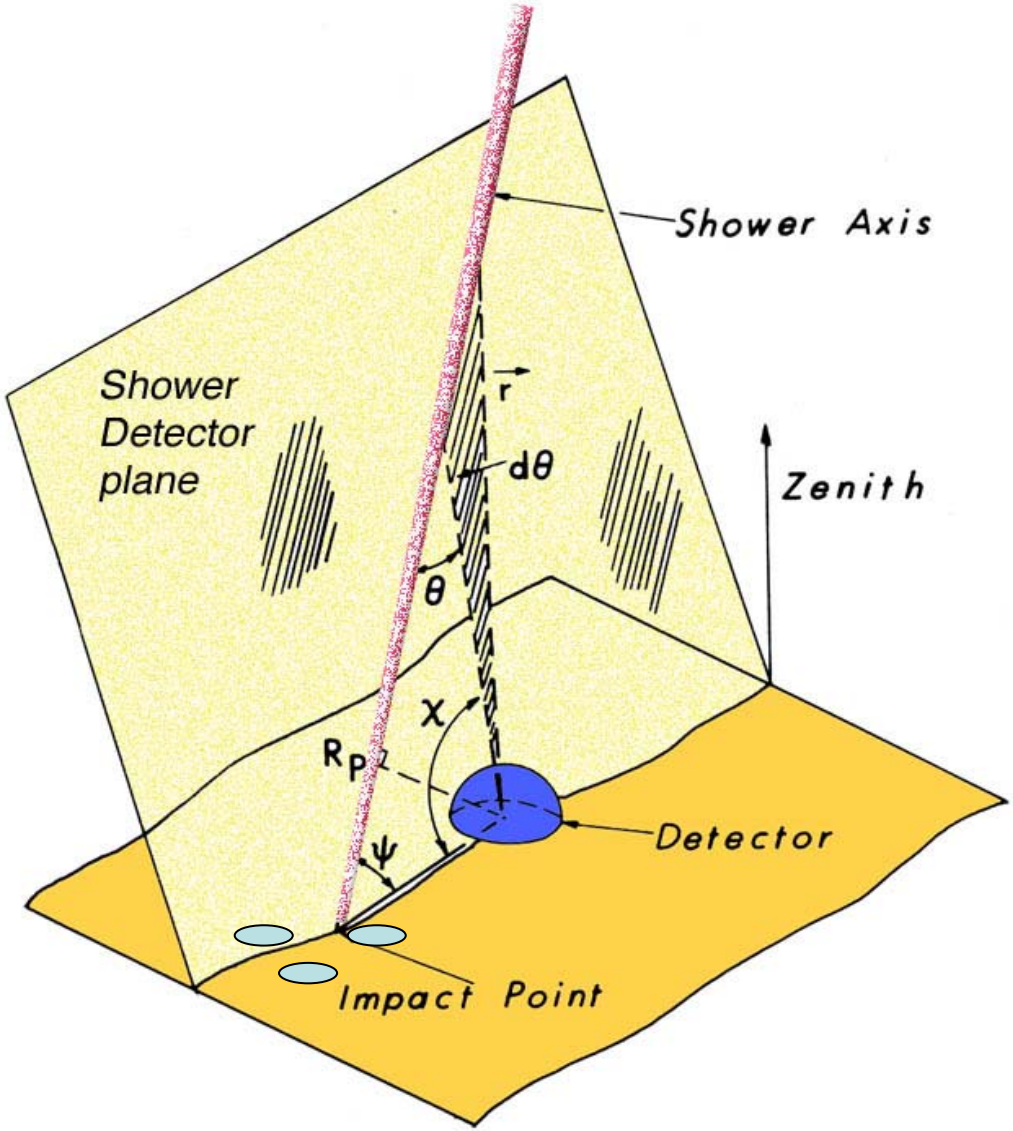
θ~ 48º, ~ 70 EeV

18 detectors triggered









The essence of the hybrid approach

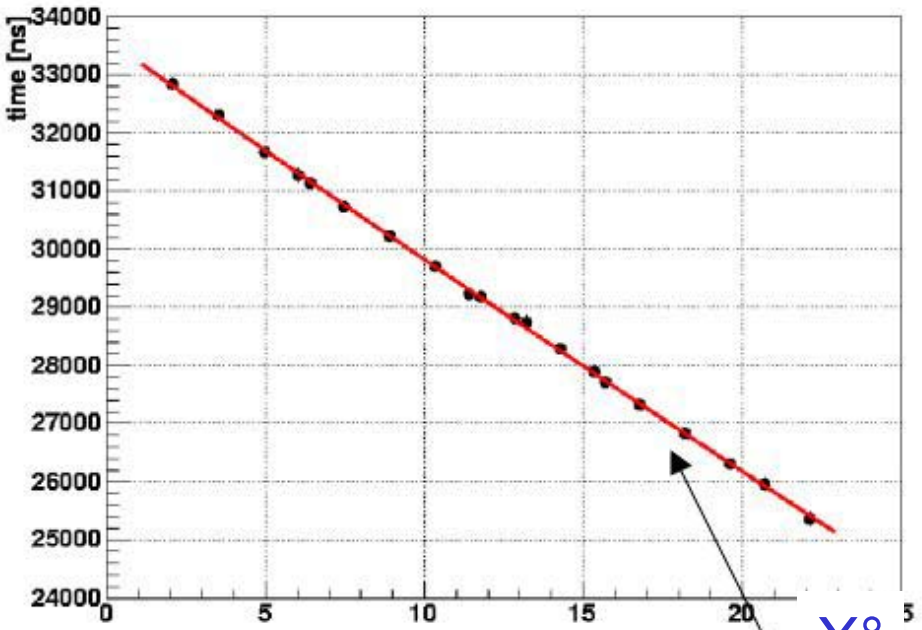
Precise shower geometry from degeneracy given by SD timing

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

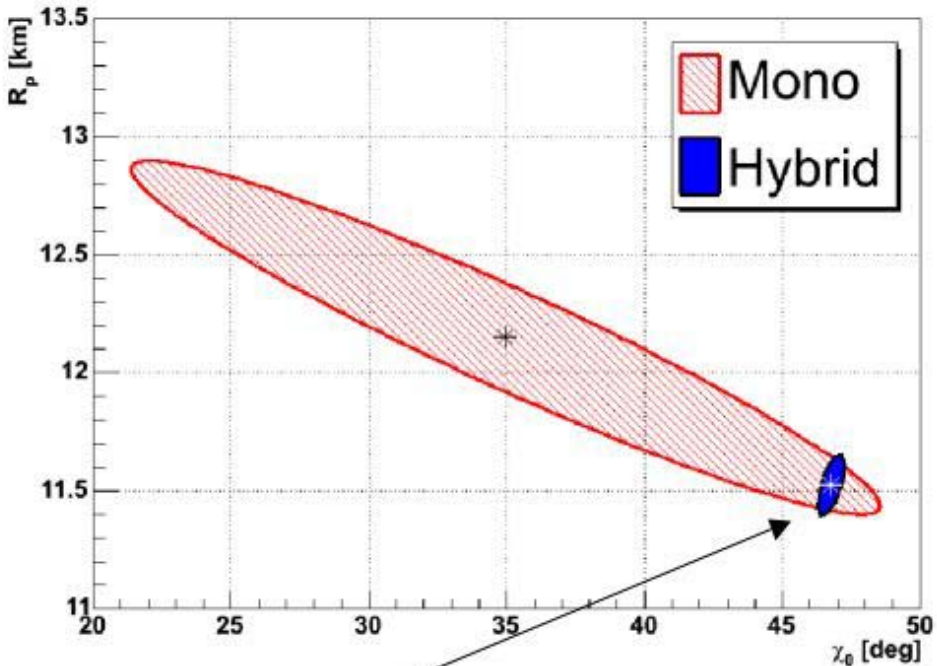
Times at angles,X, are key to finding R_p

Time, t

R_p km



X°



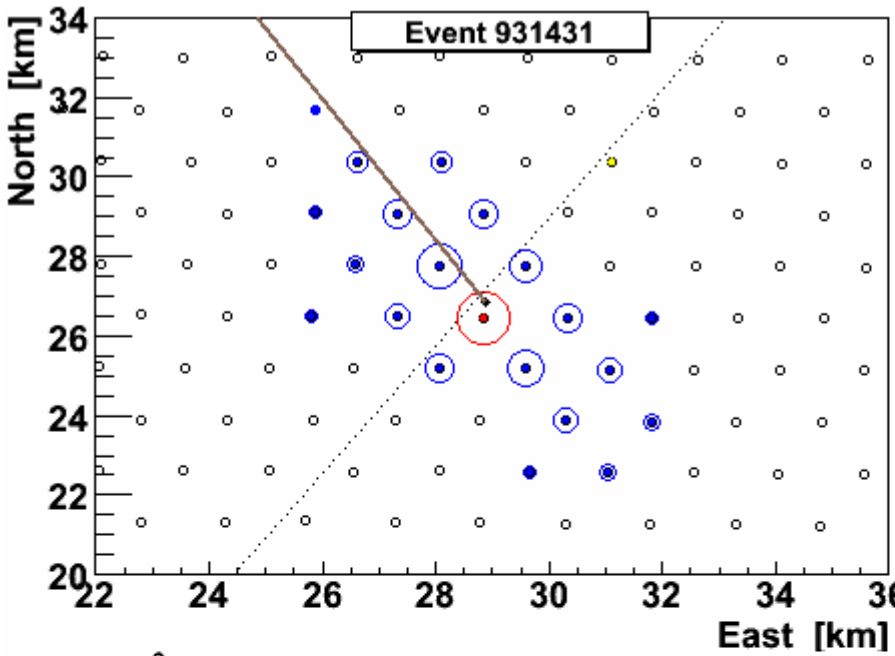
$\approx$ line but

3 free parameters

T_0 from tank!

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

Another Hybrid Event



Core location

Easting 468693 ± 59

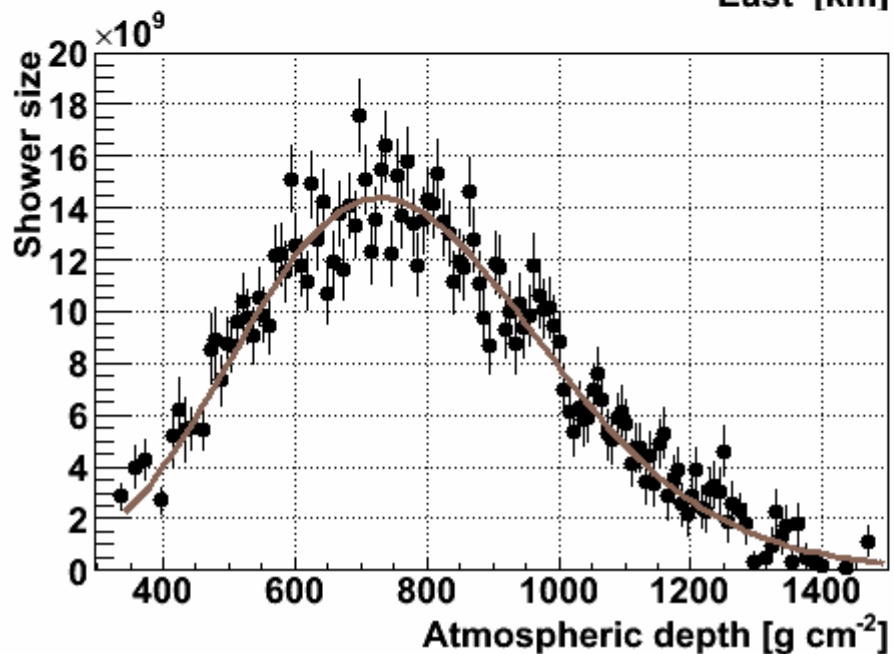
Northing 6087022 ± 80

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

ARRIVAL DIRECTION DISTRIBUTION

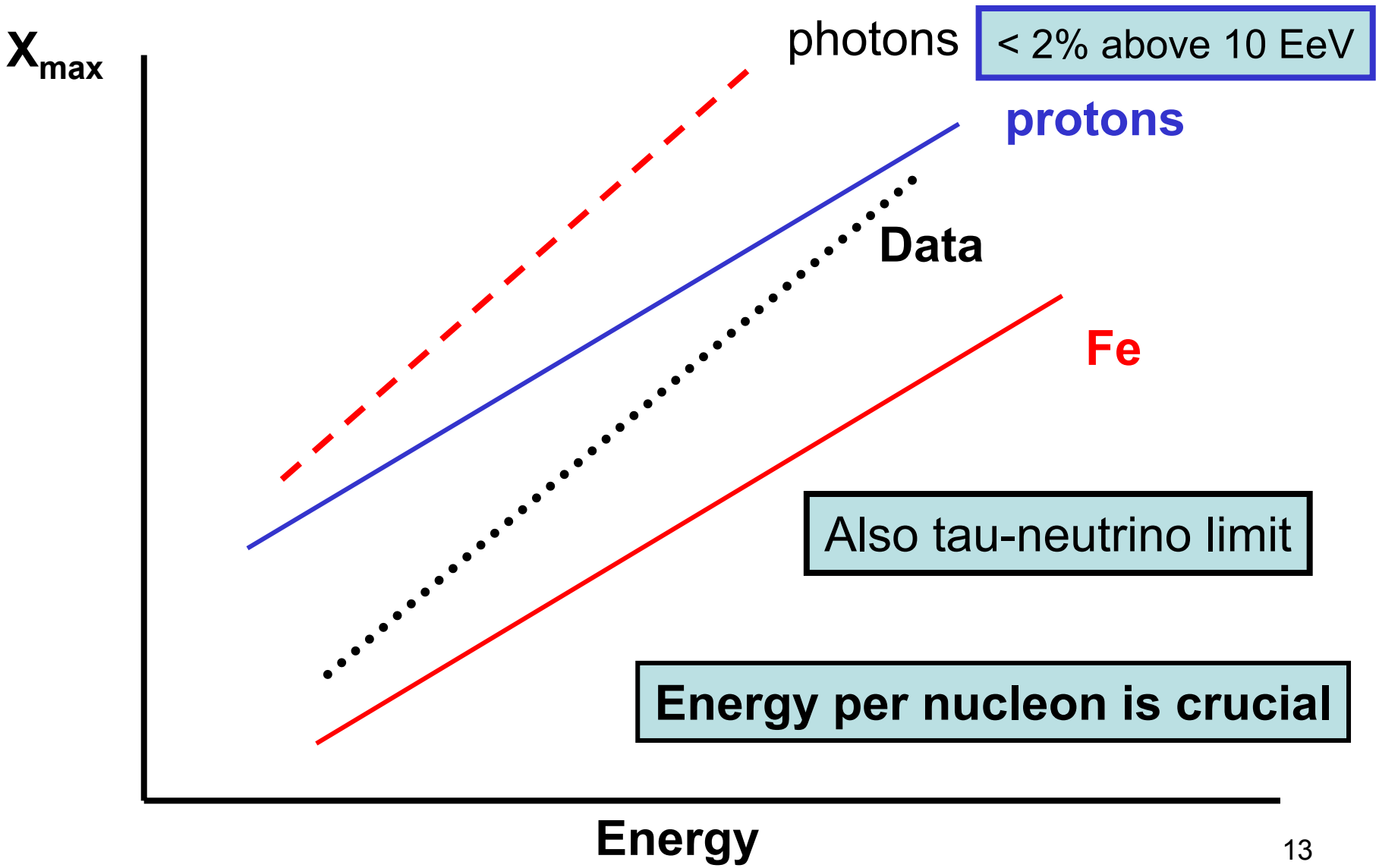
Typical accuracy of reconstruction <1°

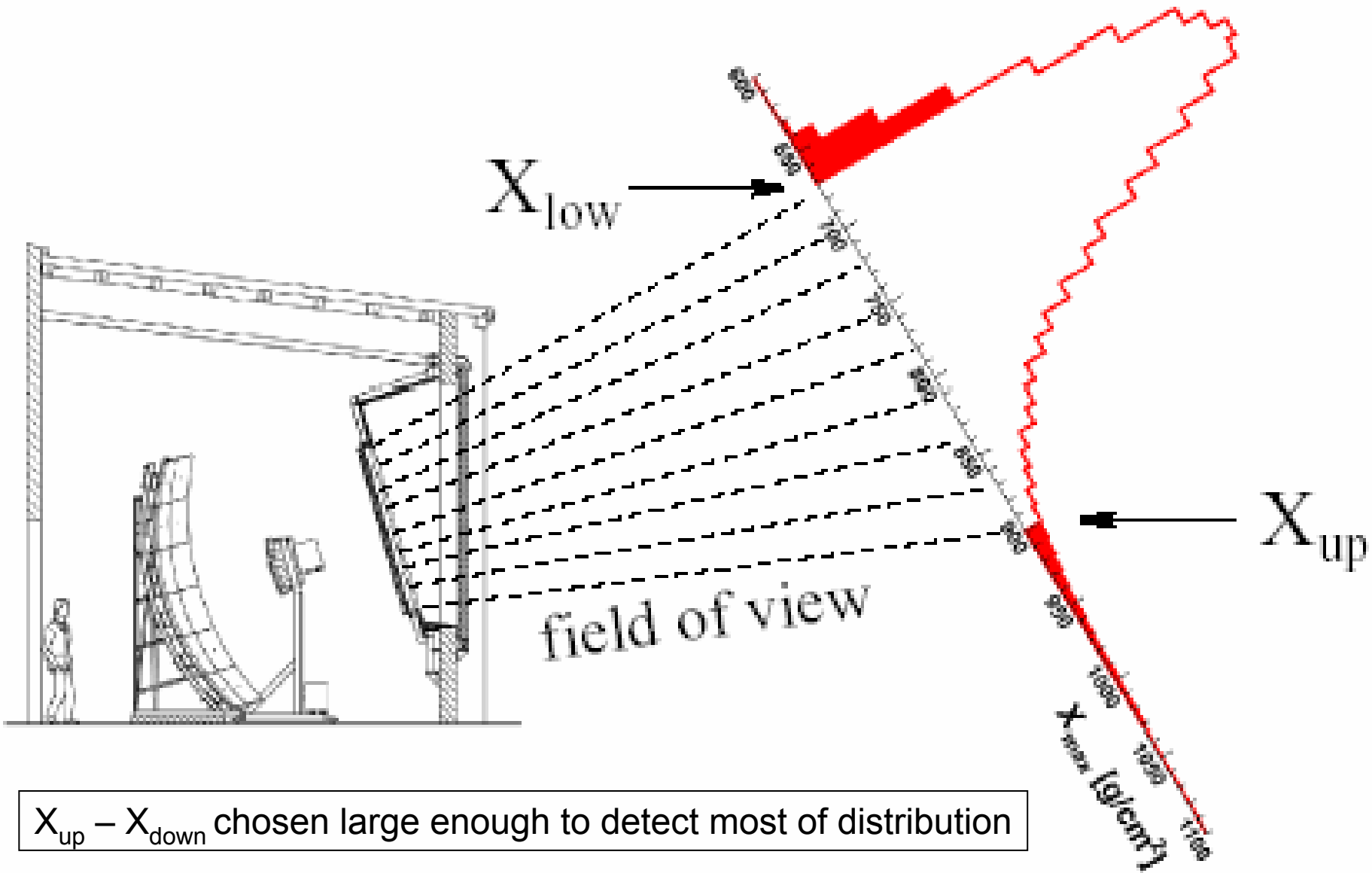
- No significant emission from Galactic Centre
- No broadband signals – e.g. Dipole – at any energy above 1 EeV
  e.g $1 < E < 3$ EeV, Amplitude < 0.7%
- No clustering of the type claimed by AGASA
- No signal from BL Lacs as possibly seen by HiRes

Summary: Previous reports have not been confirmed

BUT,
two 'prescriptions' are currently being tested

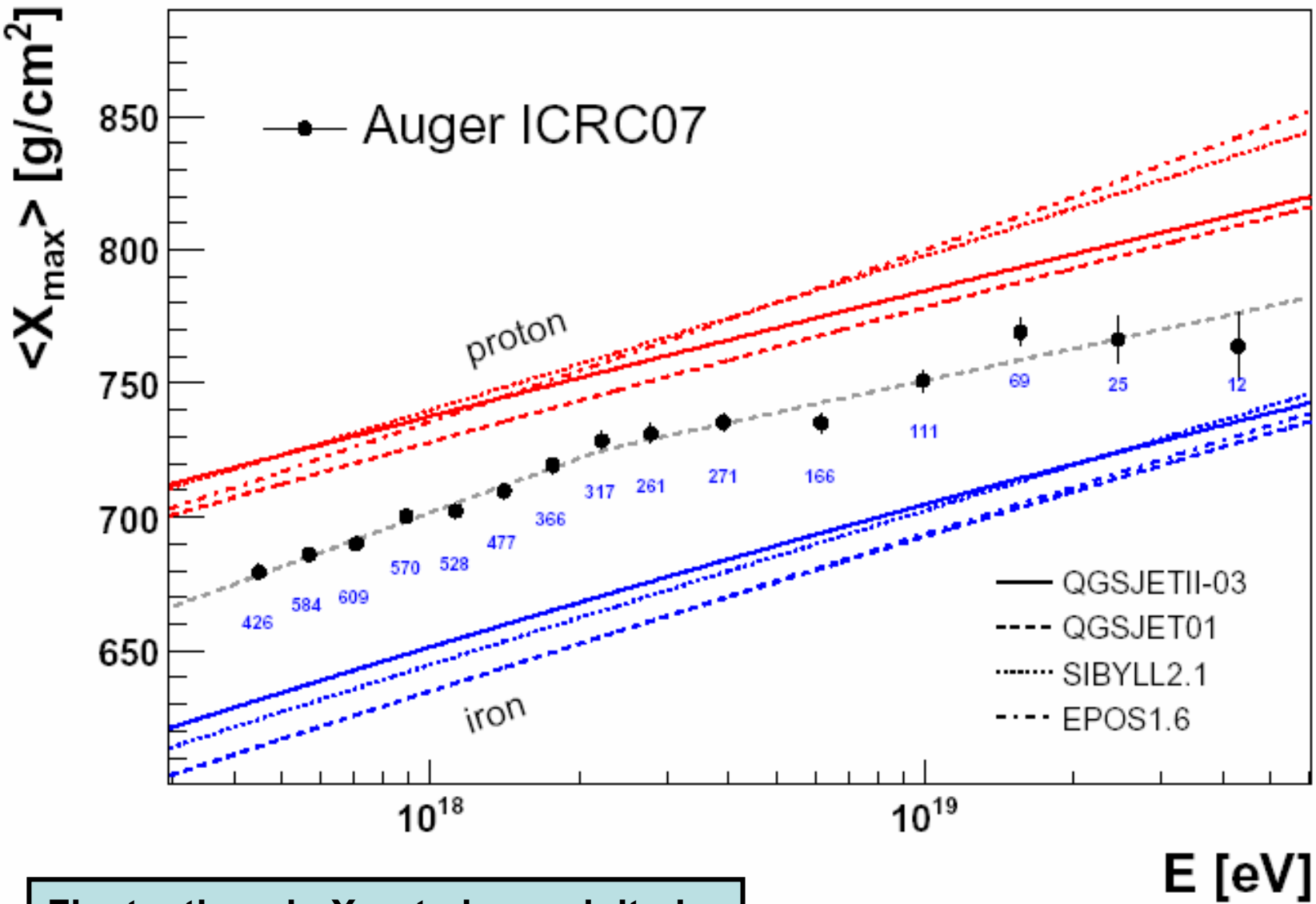
How we try to infer the variation of mass with energy



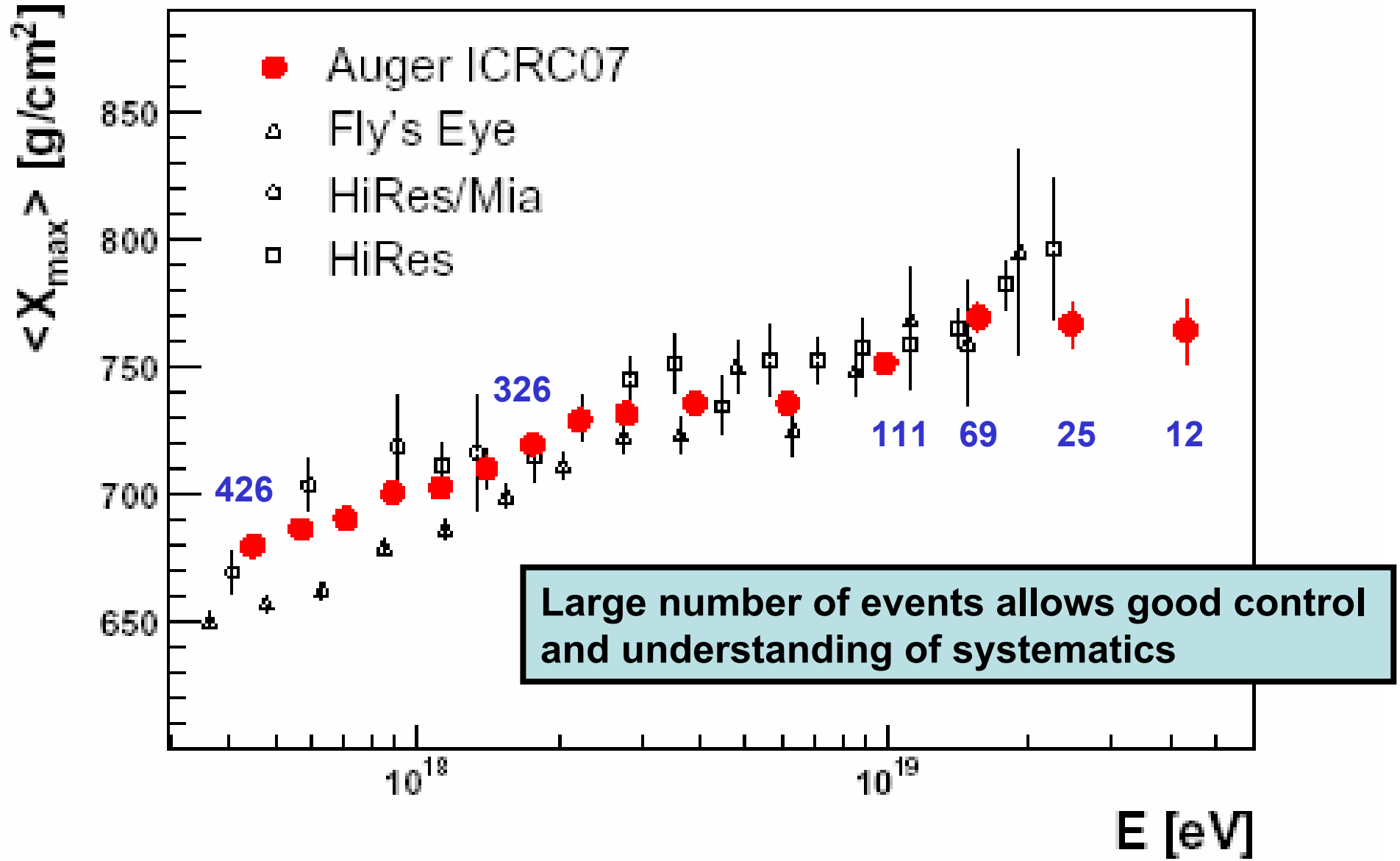


$X_{up} - X_{down}$ chosen large enough to detect most of distribution

Elongation Rate measured over two decades of energy



Fluctuations in X_{max} to be exploited



Large number of events allows good control and understanding of systematics

Energy Determination with Auger

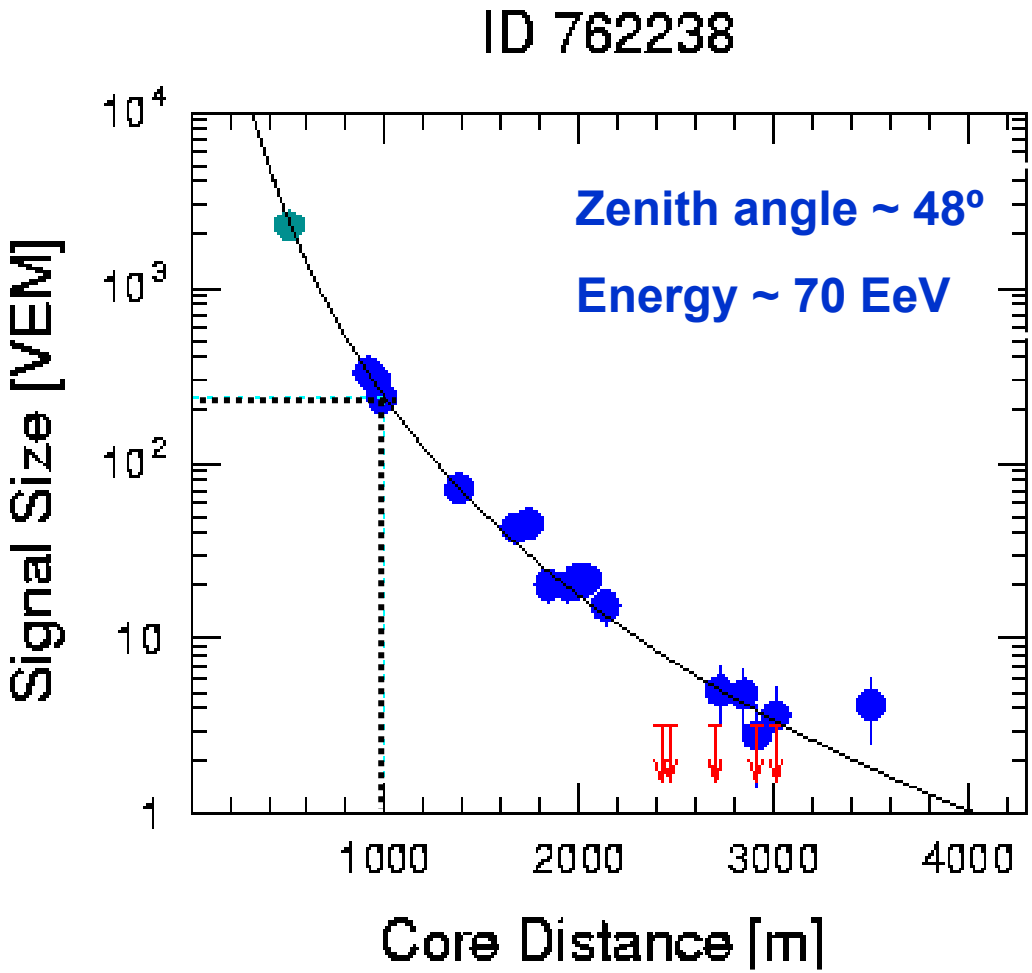
The energy scale is determined from the data
The dependence on knowledge of interaction models or of the primary composition is at level of a few %.

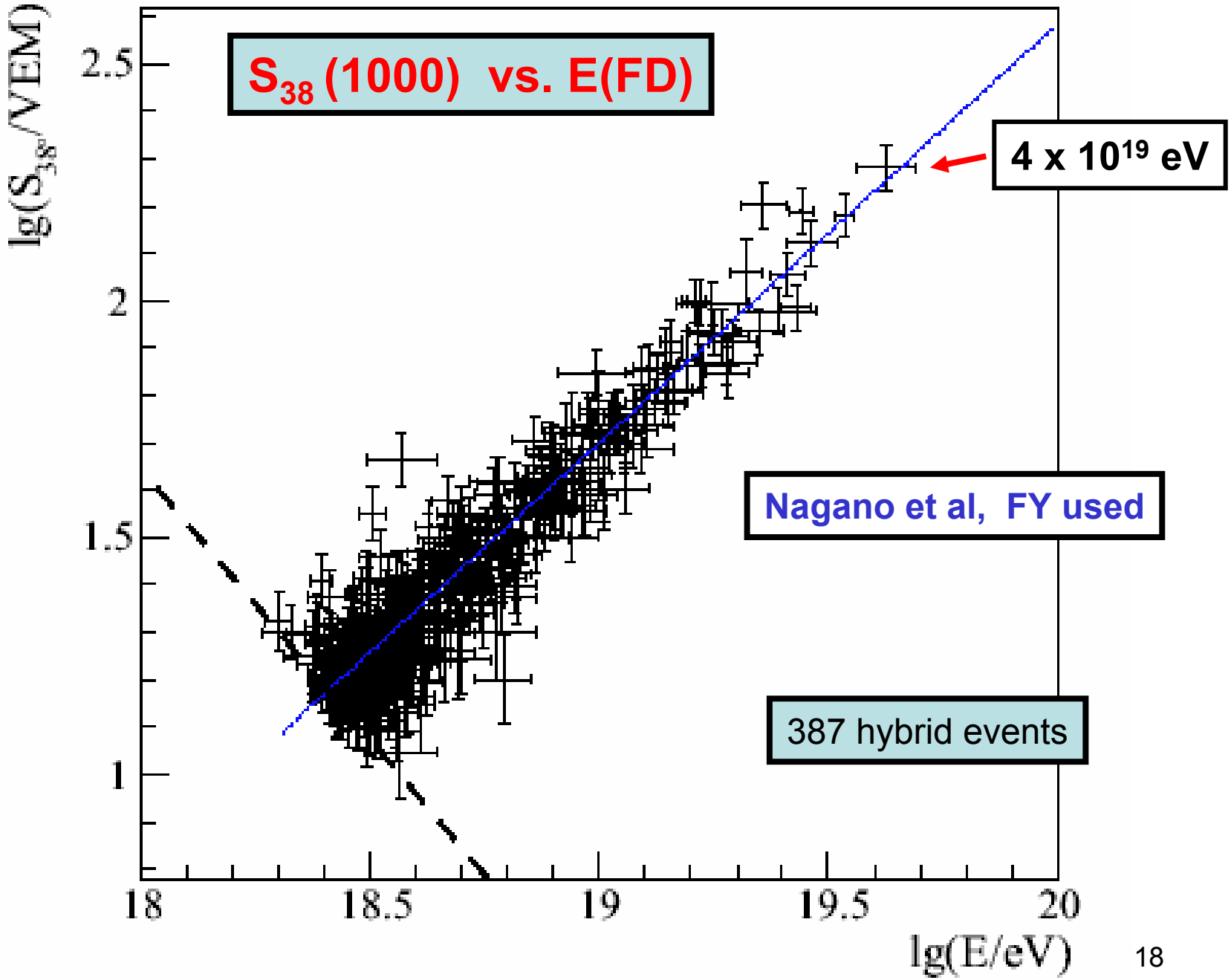
The detector signal at 1000 m from the shower core

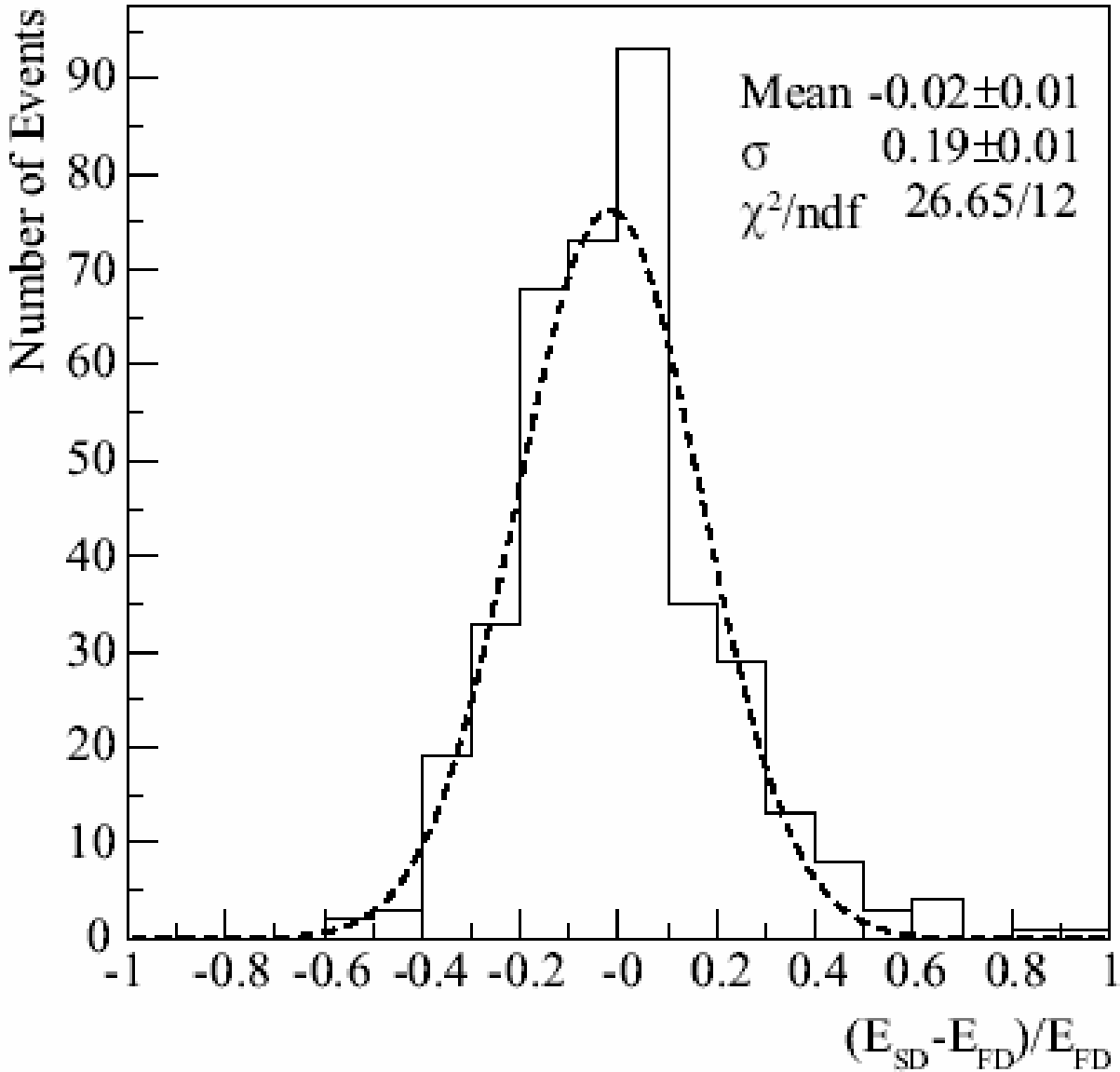
– **S(1000)**

- determined for each surface detector event

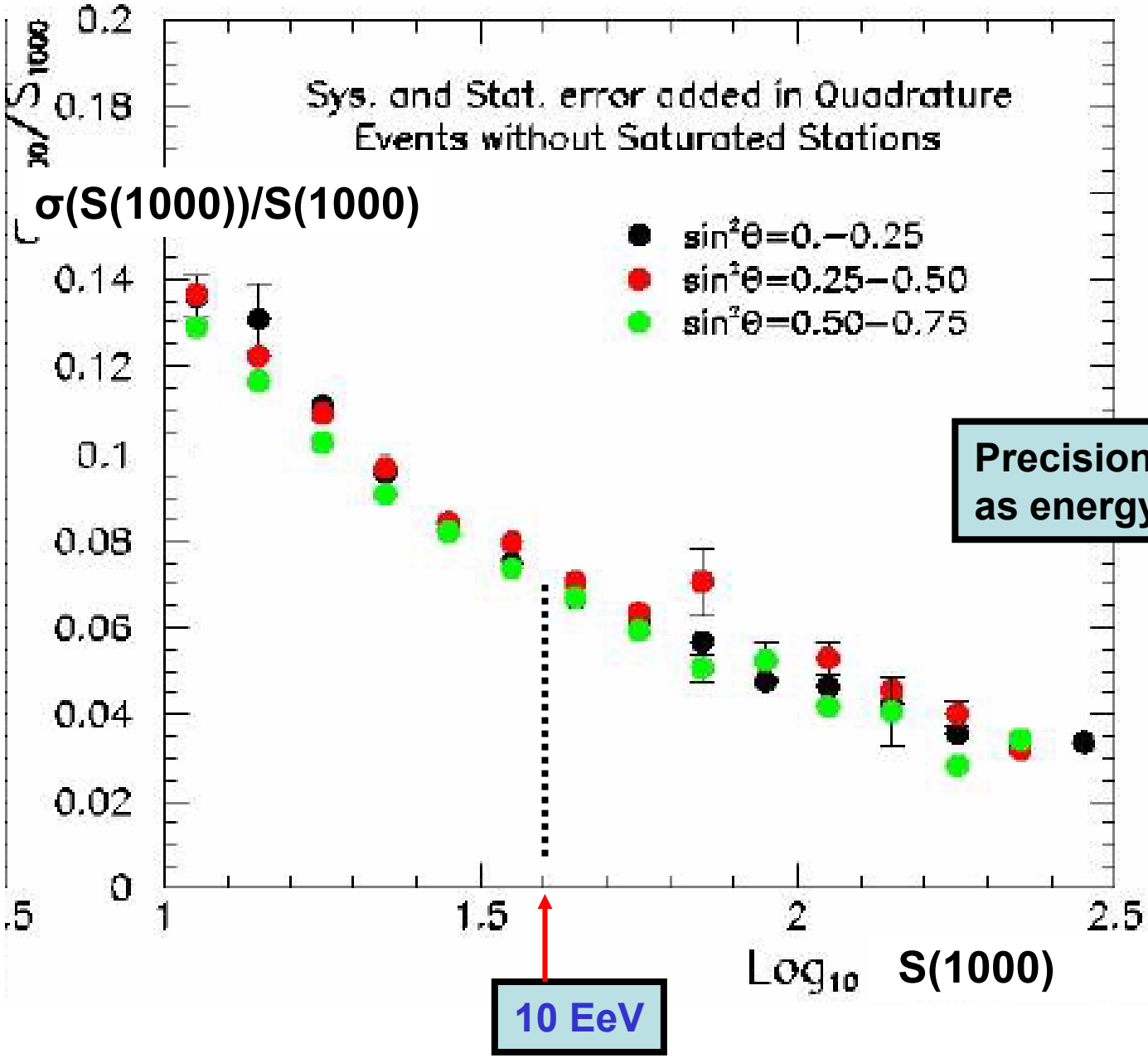
S(1000) is proportional to the primary energy




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



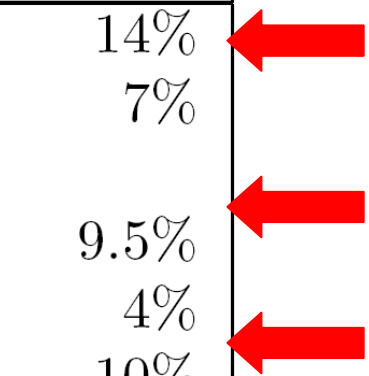
Fractional difference between the FD and SD energy for the 387 selected hybrid events.



Precision of S(1000) improves as energy increases

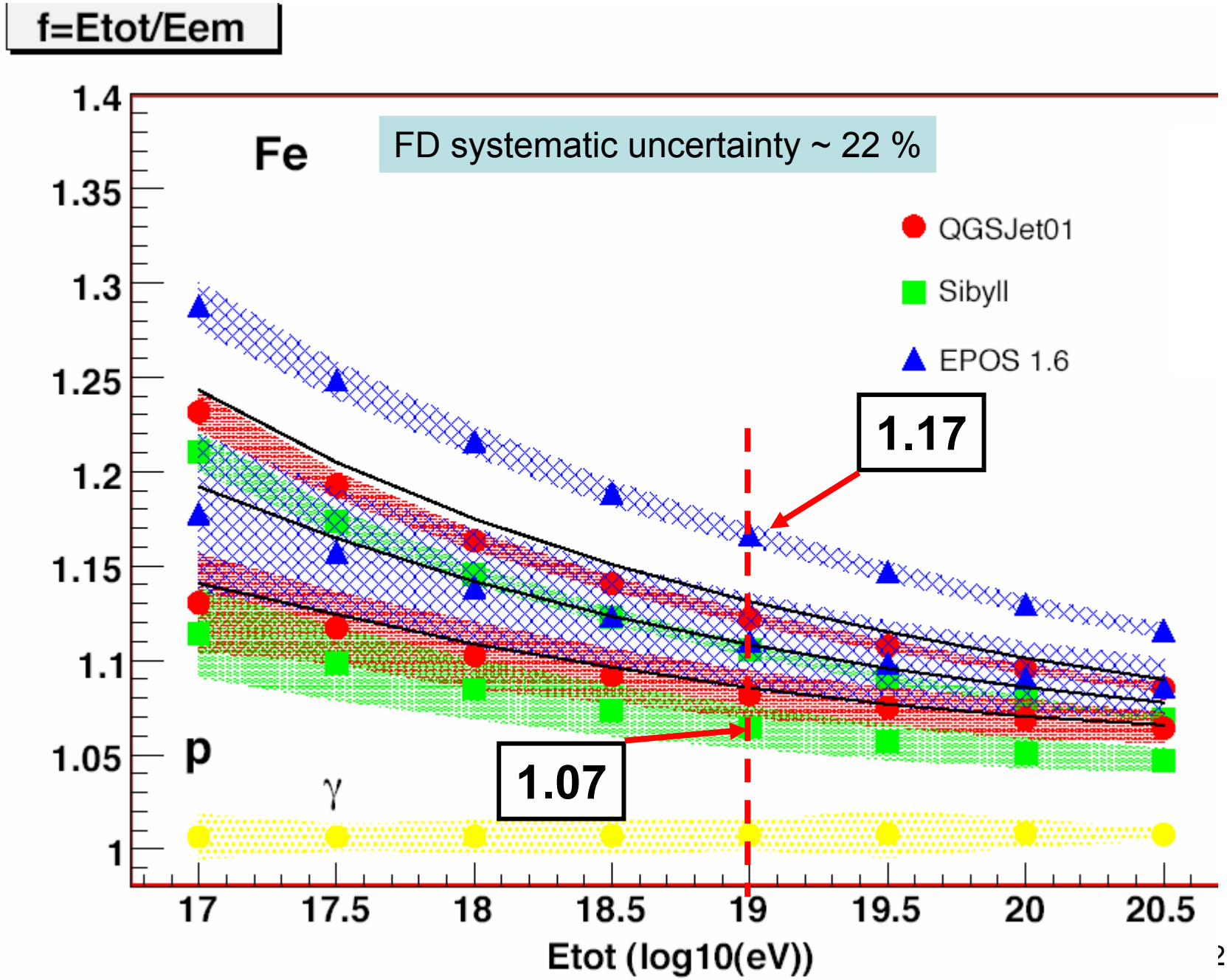
Summary of systematic uncertainties

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%

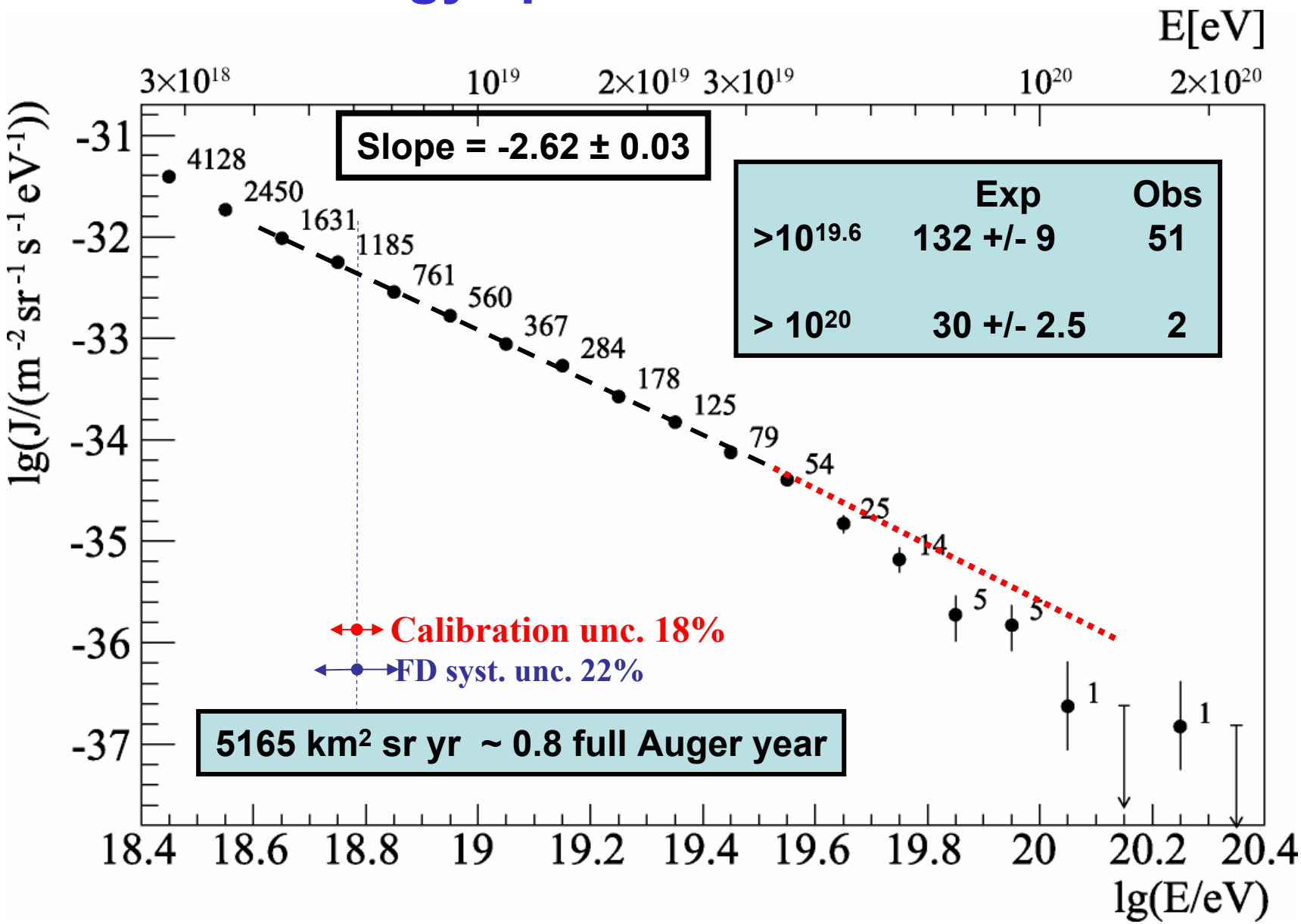


Note: Activity on several fronts to reduce these uncertainties

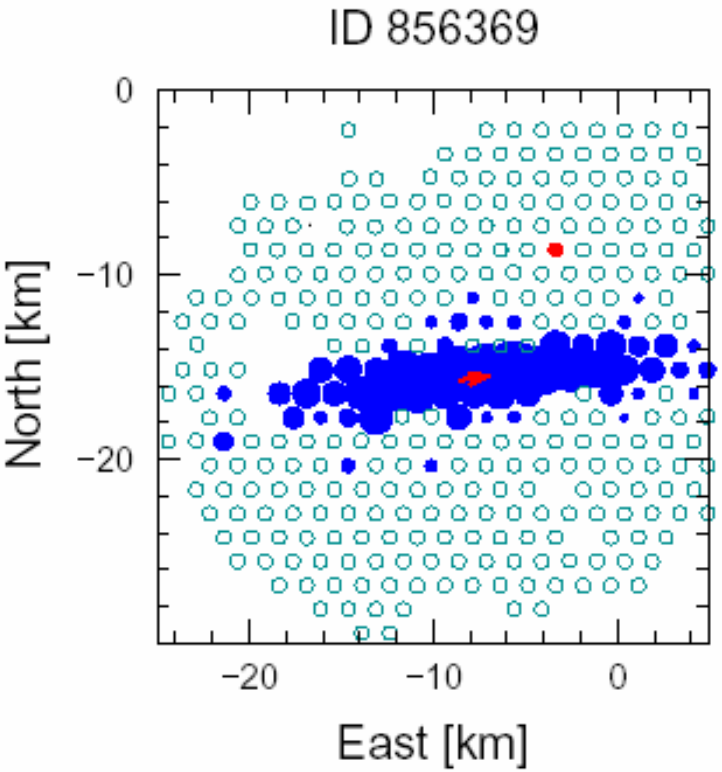
Fluorescence Detector Uncertainties Dominate

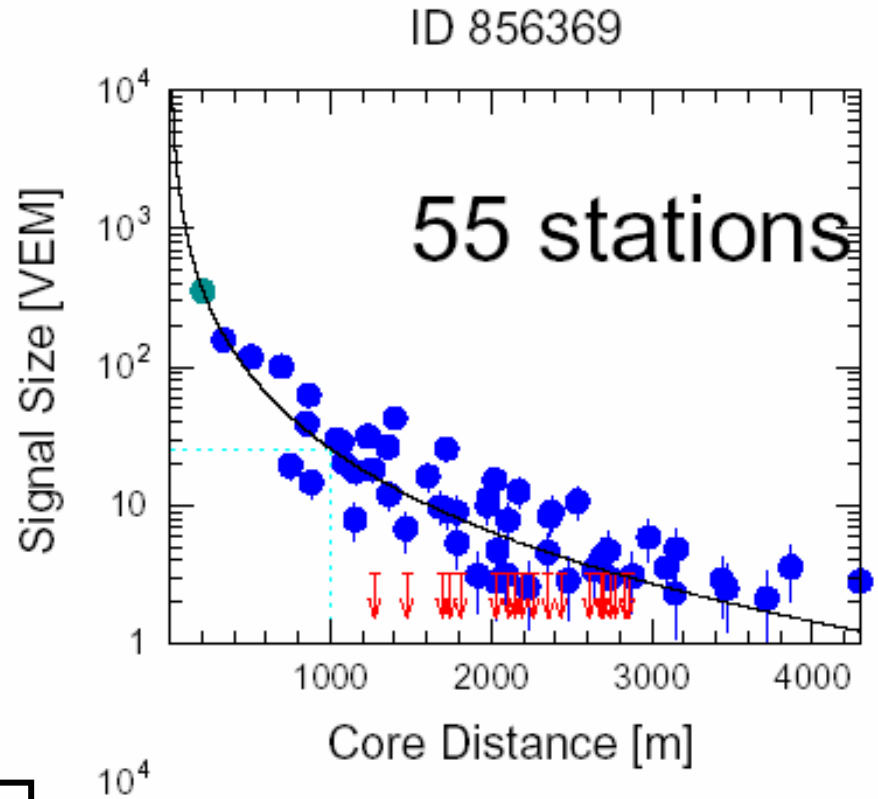

f=Etot/Eem
Fe
FD systematic uncertainty ~ 22 %
QGSJet01
Sibyll
EPOS 1.6
1.17
1.07
p
γ
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
17
17.5
18
18.5
19
19.5
20
20.5
Etot (log10(eV))

Energy spectrum from SD < 60°



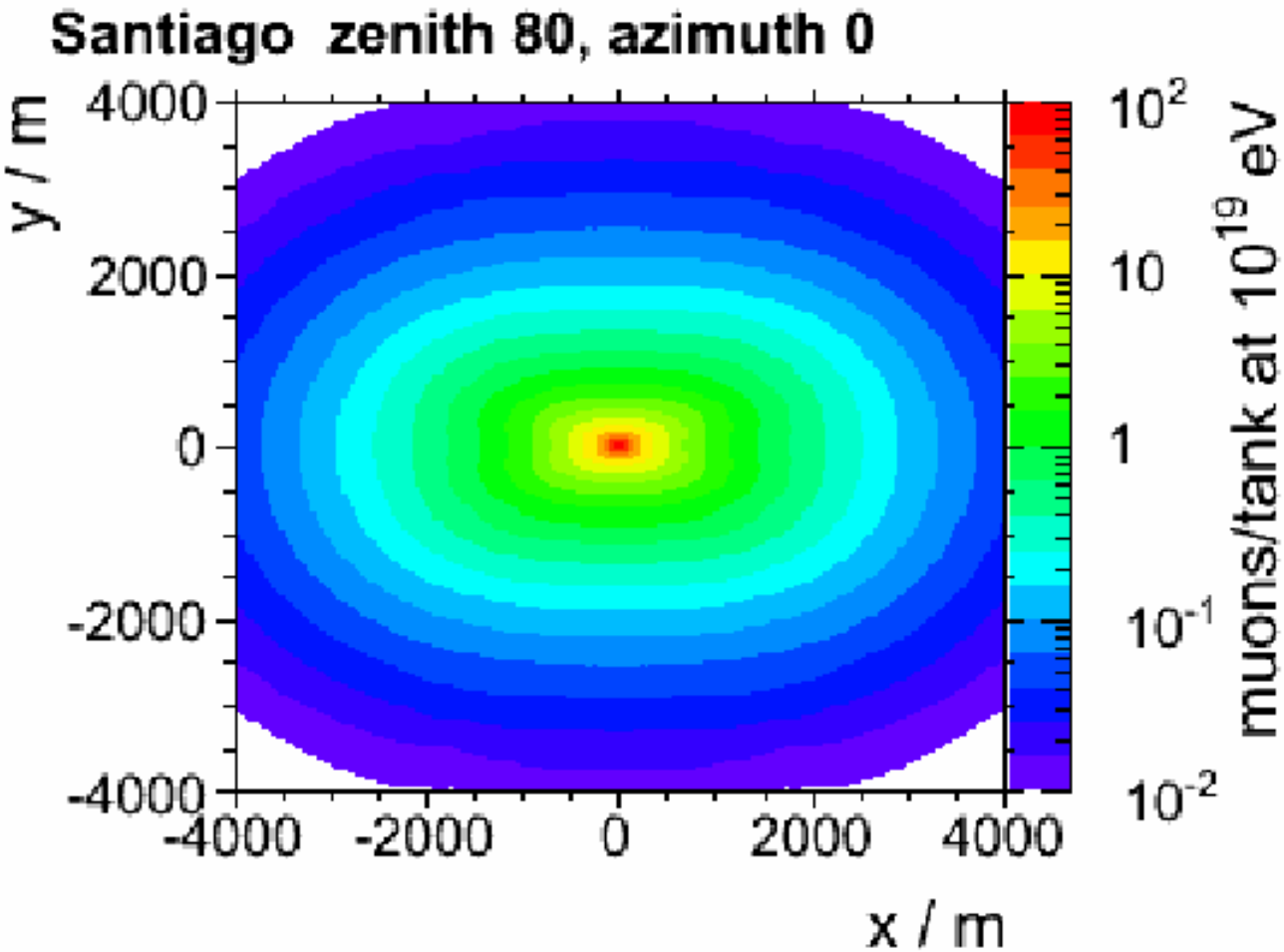
Inclined Events offer additional aperture





$\theta = 79\ °$

Muon map normalization fitted to the data -> N_{19}

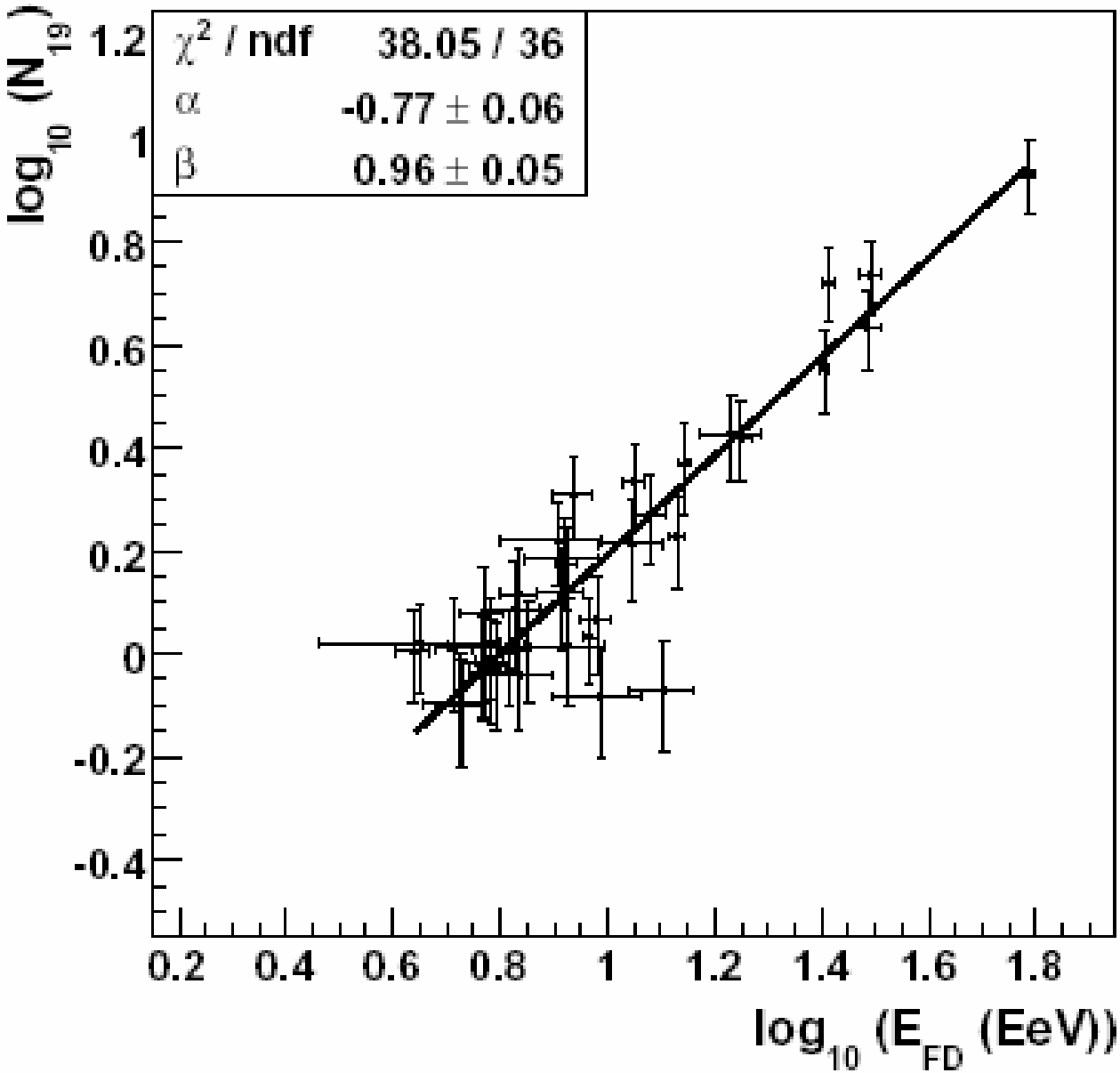


Maps for 10^{19} eV protons

Different zenith and azimuth

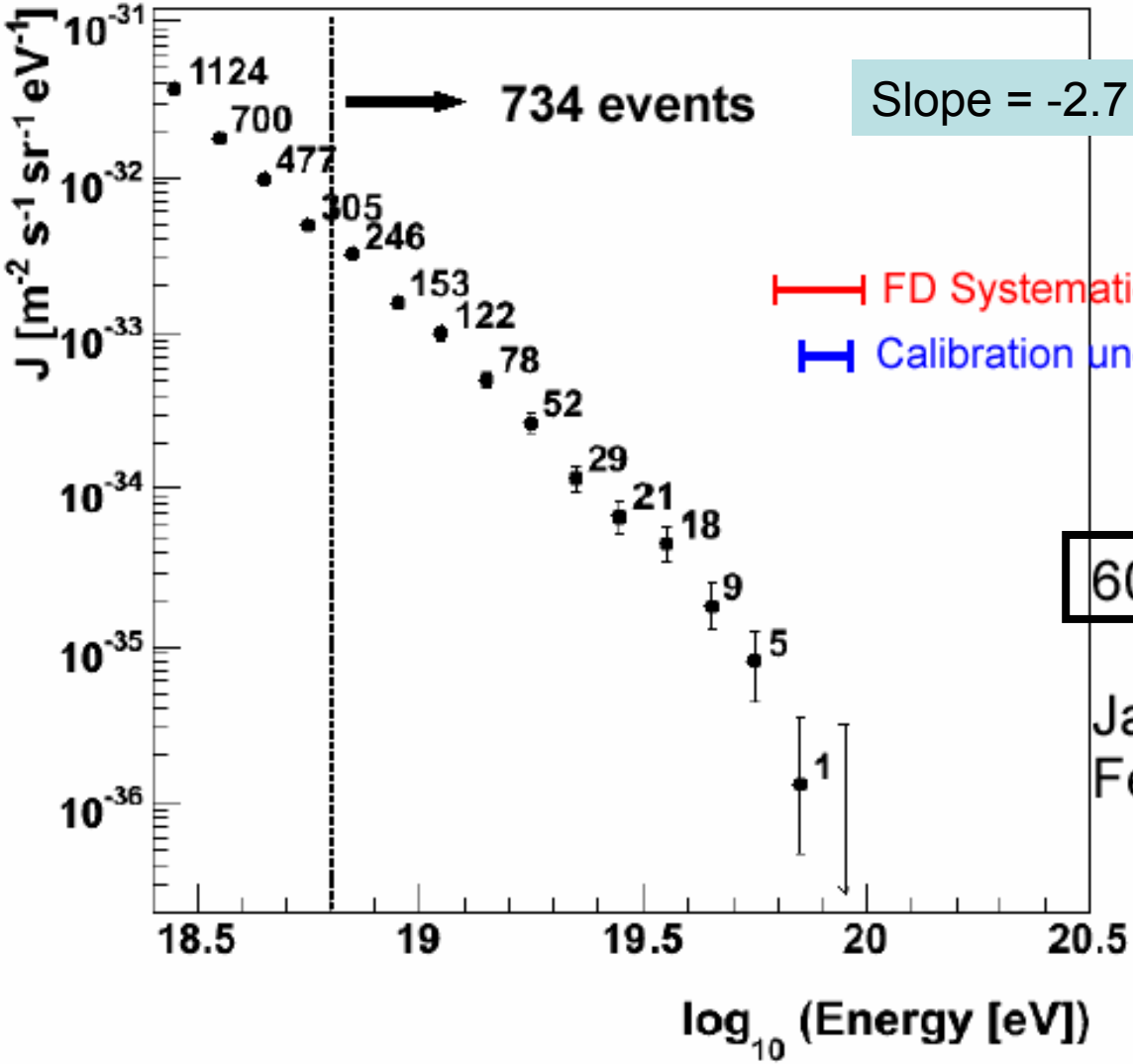
AIRES + QJSJET

The shape of the map is mass and model independent



Calibration curve for inclined showers

Inclined events energy spectrum



Slope = -2.7 ± 0.1

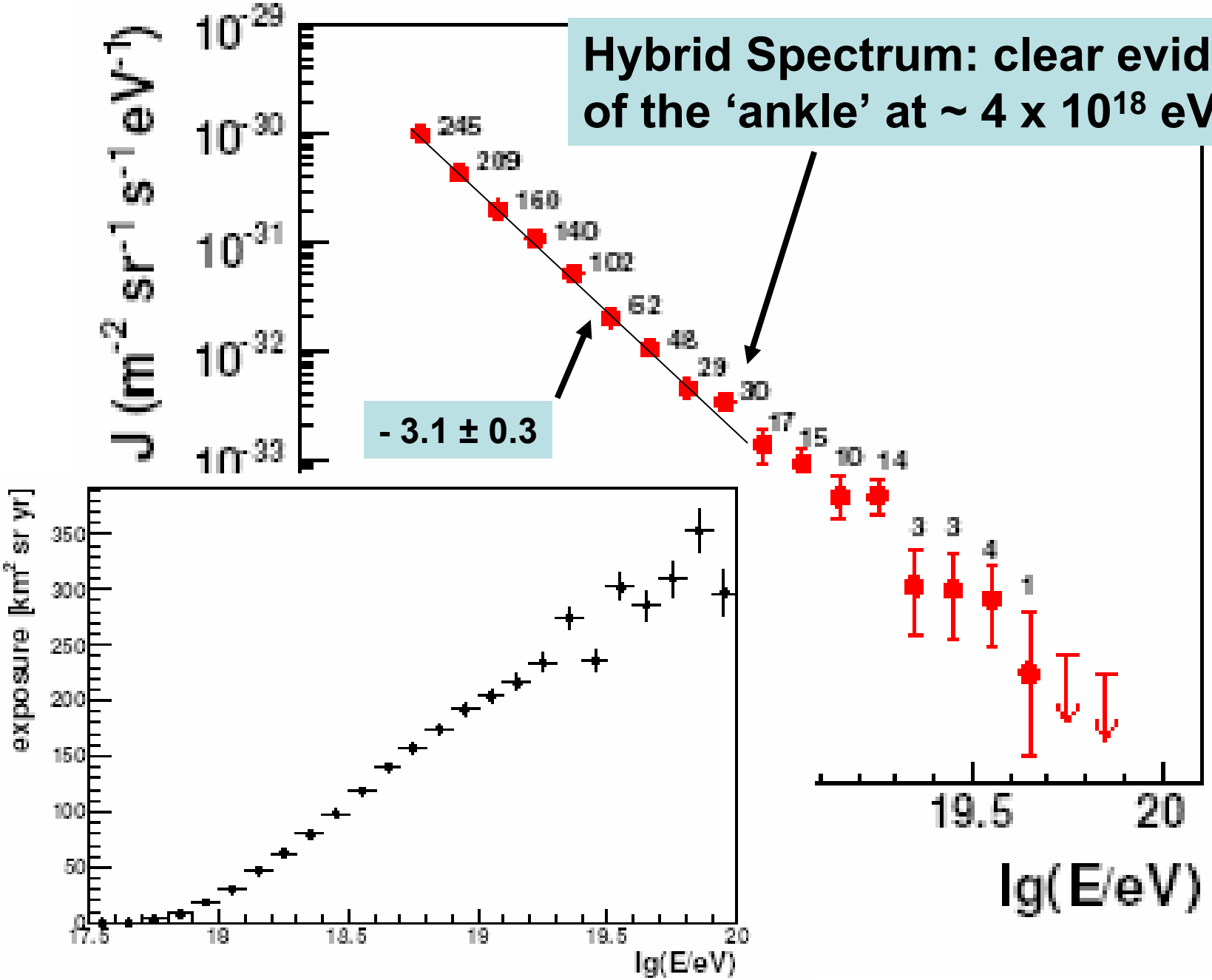
FD Systematics (22%)

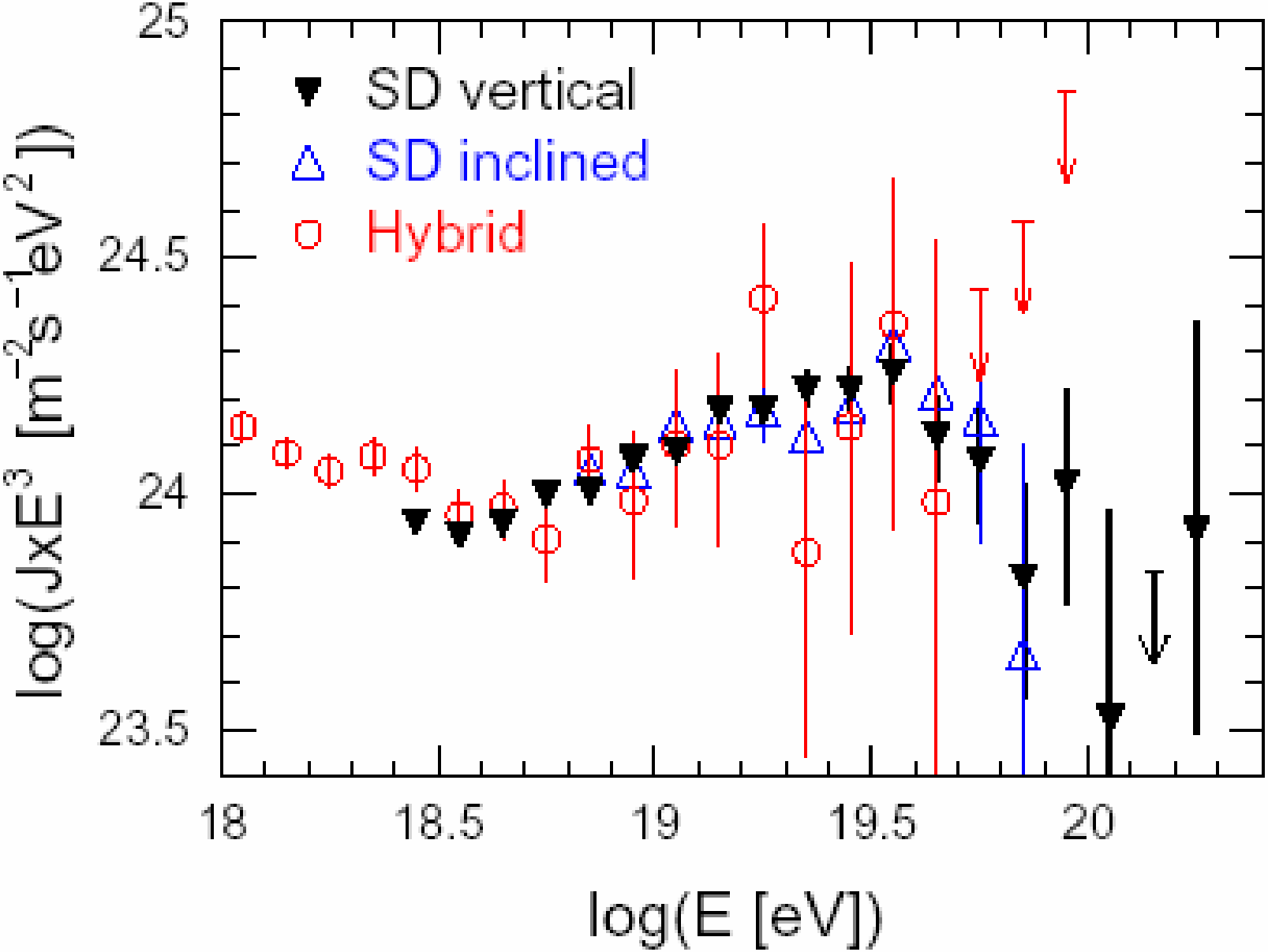
Calibration uncertainty (10%)

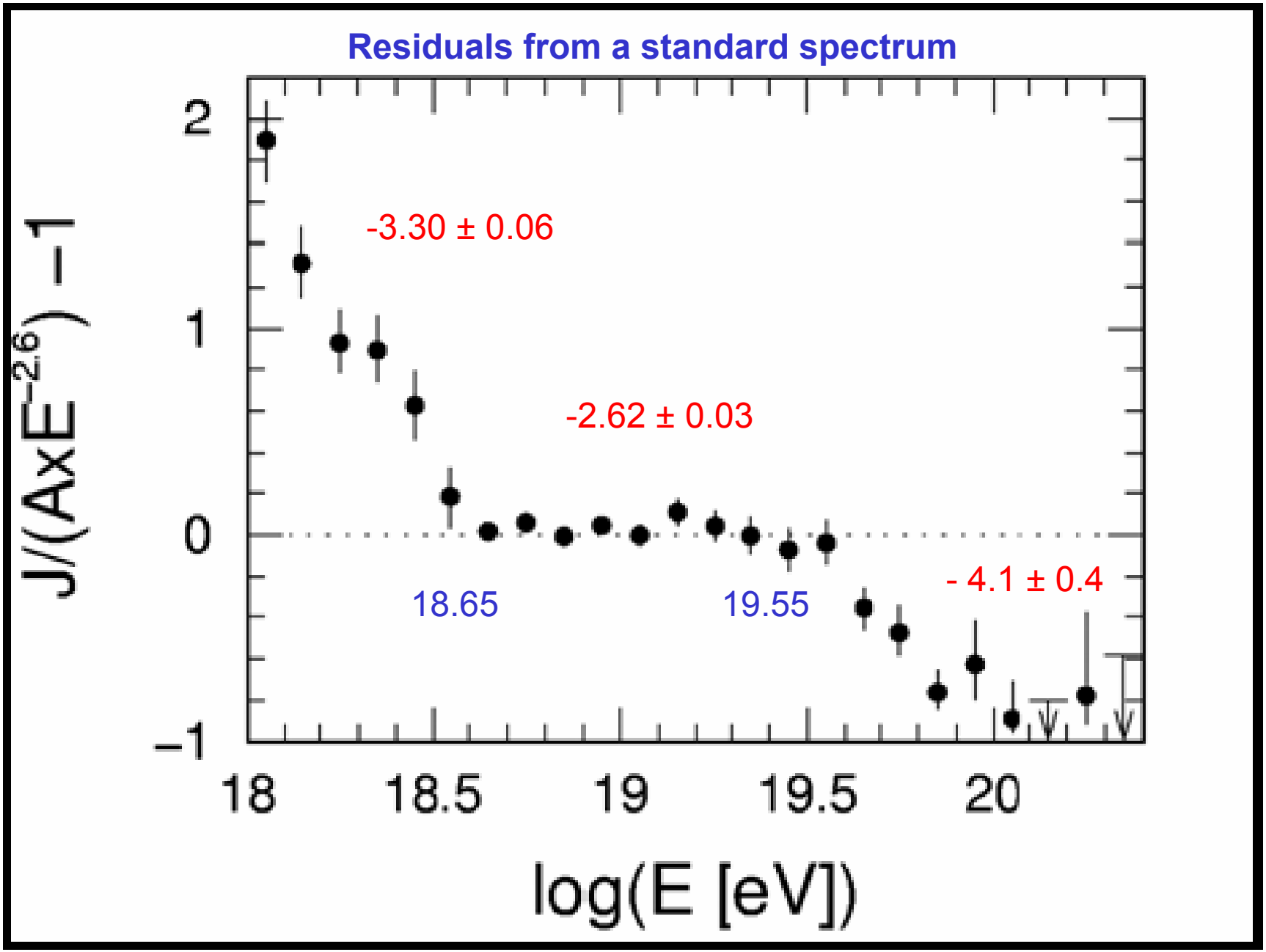
$60° < \theta < 80°$

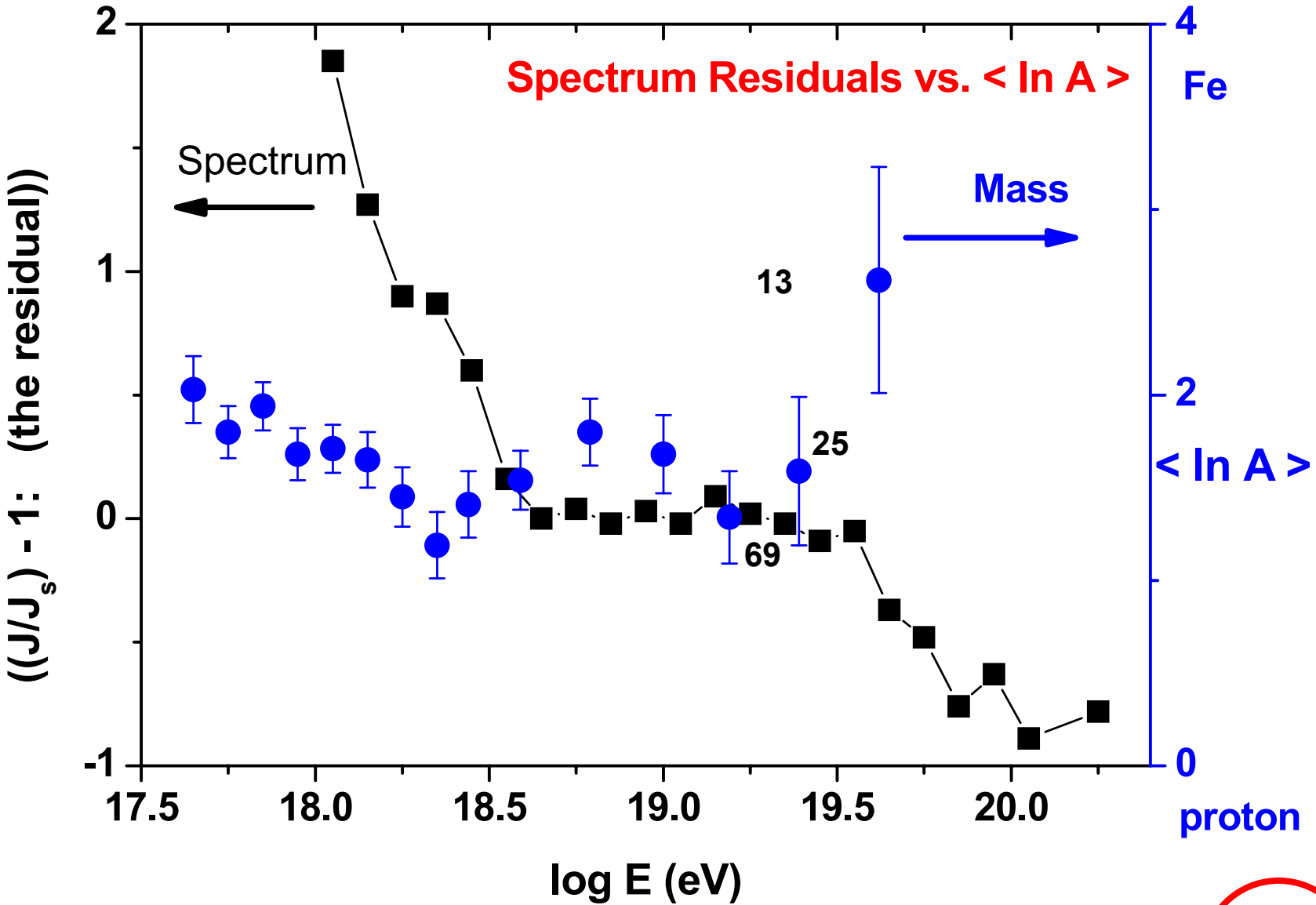
January 2004 – February 2007

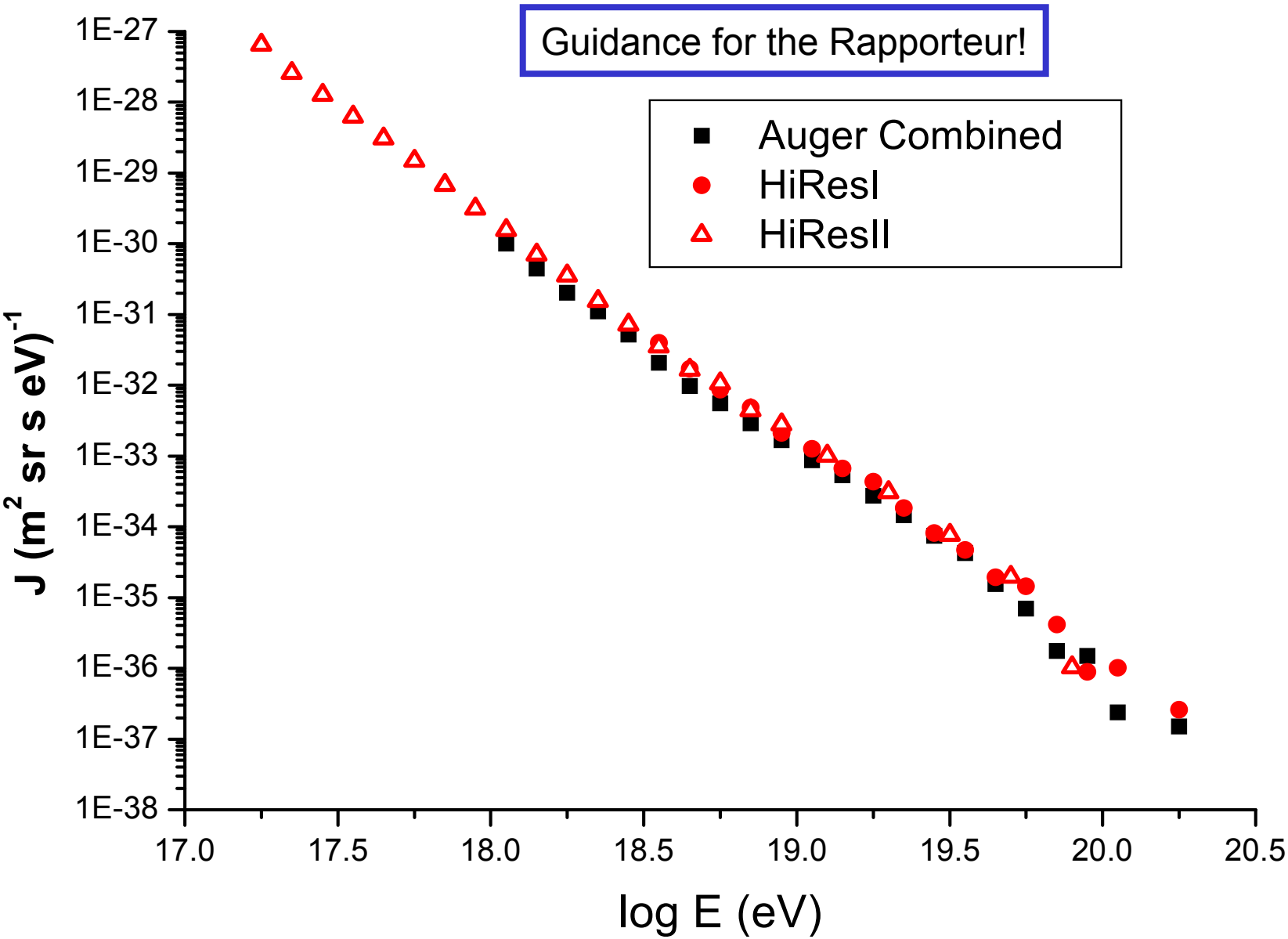
Exposure 1510 km^2 yr sr (29% of θ<60°)

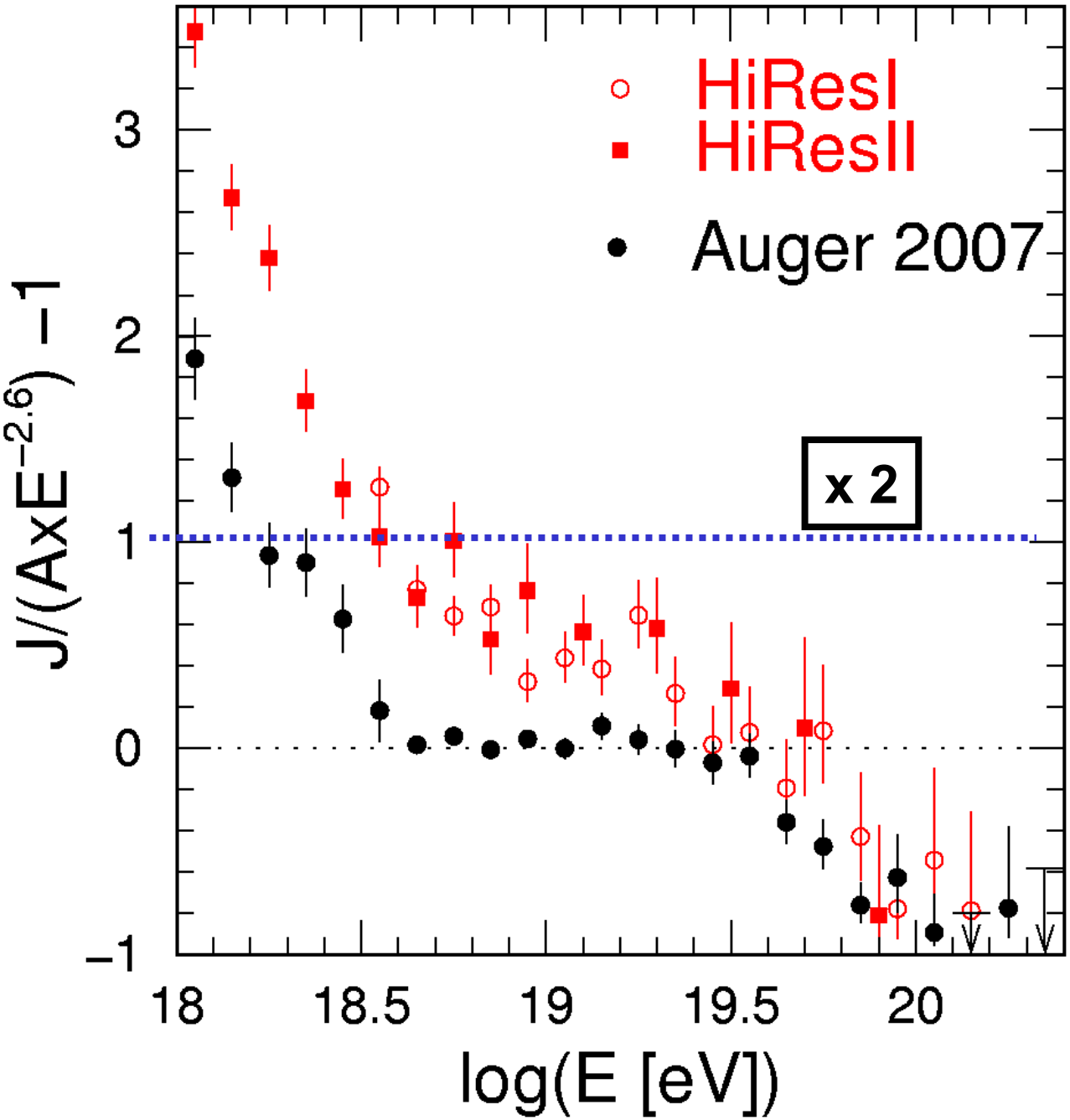

Hybrid Spectrum: clear evidence of the 'ankle' at ~ 4 x 10^18 eV
- 3.1 ± 0.3
J (m^-2 sr^-1 s^-1 eV^-1)
10^-29
10^-30
10^-31
10^-32
245
209
160
140
102
62
48
29
30
17
15
10
14
3
3
4
1
19.5
20
lg(E/eV)
exposure [km^2 sr yr]
350
300
250
200
150
100
50
0
17.5
18
18.5
19
19.5
20
lg(E/eV)

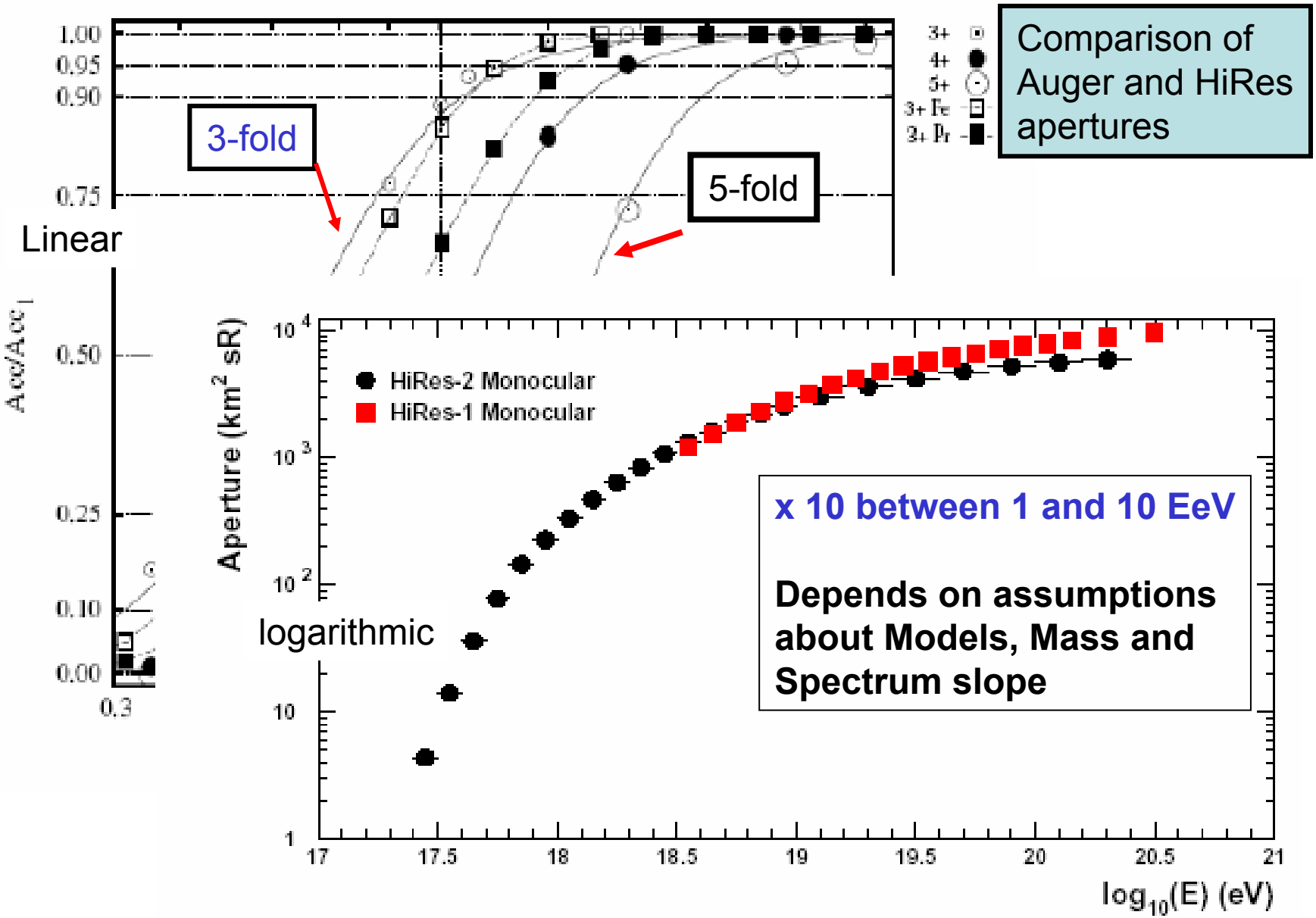

SD vertical
SD inclined
Hybrid
log(JxE^3 [m^-2 s^-1 eV^2])
log(E [eV])
25
24.5
24
23.5
18
18.5
19
19.5
20


Residuals from a standard spectrum
J/(AxE^-2.6) -1
2
1
0
−1
-3.30 ± 0.06
-2.62 ± 0.03
- 4.1 ± 0.4
18.65
19.55
18
18.5
19
19.5
20
log(E [eV])

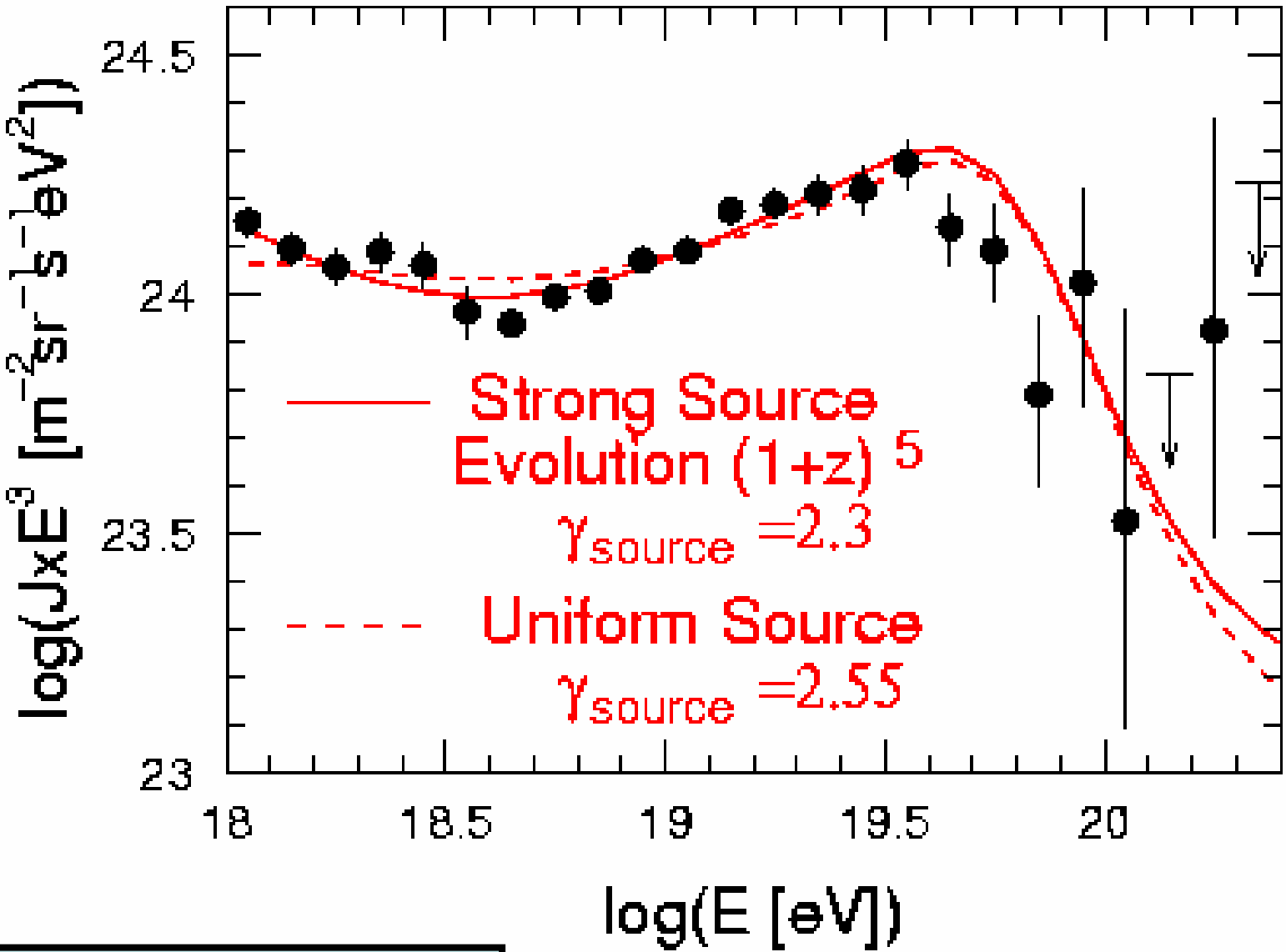

Spectrum Residuals vs. < ln A >
Spectrum
Mass
13
25
69
((J/J$_s$) - 1: (the residual))
log E (eV)
< ln A >
Fe
proton
2
1
0
-1
17.5
18.0
18.5
19.0
19.5
20.0
4
2
0


Guidance for the Rapporteur!
Auger Combined
HiResI
HiResII
J (m^2 sr s eV)$^{-1}$
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
1E-33
1E-34
1E-35
1E-36
1E-37
1E-38
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log E (eV)


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


Comparison of Auger and HiRes apertures
3-fold
5-fold
Linear
logarithmic
HiRes-2 Monocular
HiRes-1 Monocular
Aperture (km² sR)
log10(E) (eV)
x 10 between 1 and 10 EeV
Depends on assumptions about Models, Mass and Spectrum slope

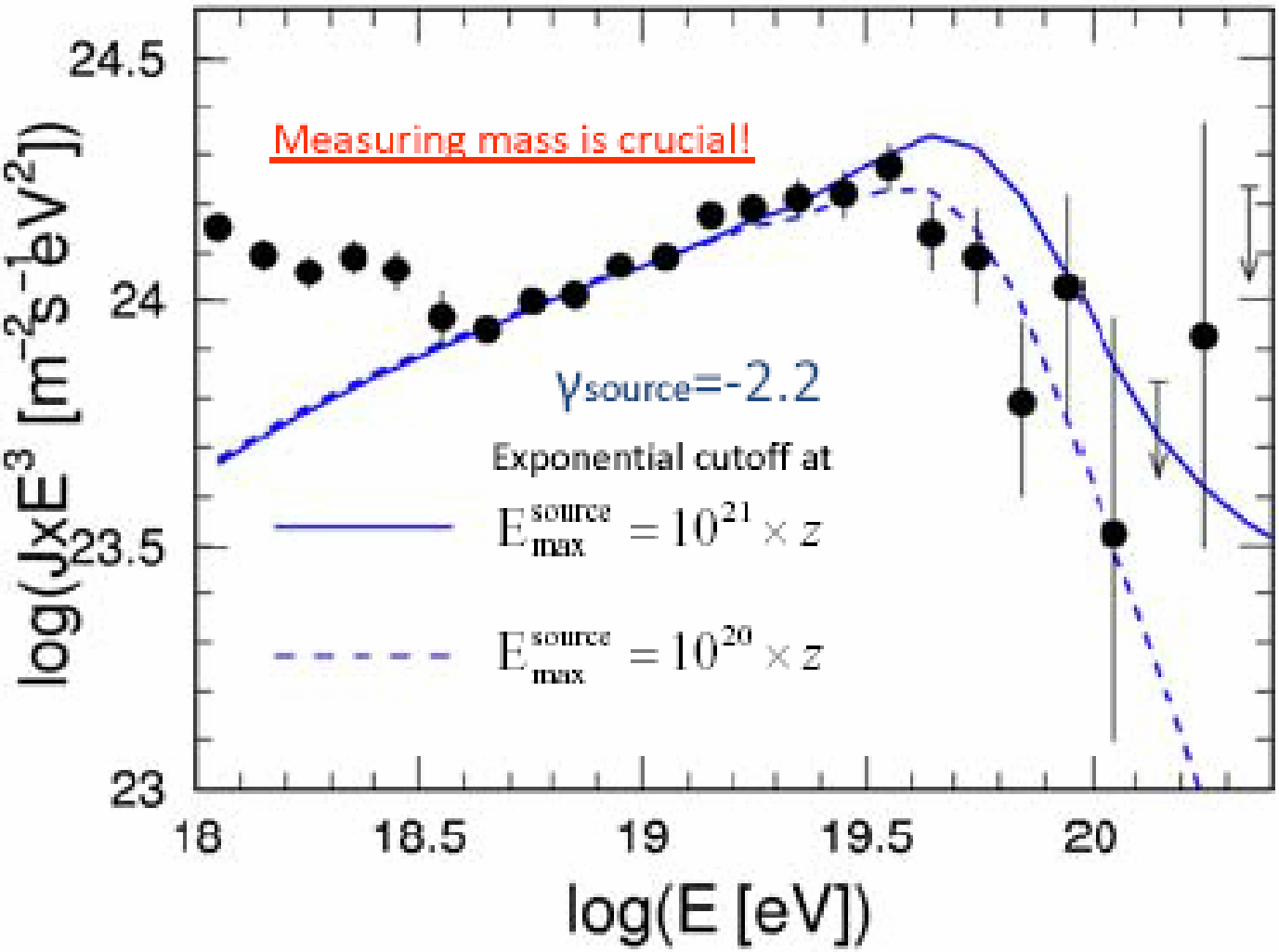
Test of Berezinsky's e^+e^- model



Work within Auger Collaboration

Nucleus Model

CR abundance is same as low energy Galactic components



D.Allard, *et al.* Astropart.Phys., **27**, 61, (2007); astro-ph/0512345

Summary of Auger Highlights:

- **More events > 10 EeV than from AGASA or HiRes and close to more than their total AND with superior angular and energy resolution**

- **Auger-South more than 80% complete**

- **Arrival Directions:**

  No evidence of point sources – but relatively few events at the very highest energies: Auger is just starting

- **Spectrum: ankle and steepening seen - with model-independent measurement and analysis at ~ 4.5 x 10^{18} and ~ 3.55 x 10^{19} eV**

But what does this all mean?

Is the ankle marking a galactic/extra-galactic change?

Have we seen the GZK effect?

Is it a 'bump' from a more local effect?

Are the accelerators just 'tired'?

What can we deduce from propagation models?

Deducing the MASS is crucial: mixed at highest energy?

Certainly not expected – do hadronic models need modification?

Larger cross-section and/or more muons (EPOS?)

Would help to reconcile AGASA with HiRes and Auger at the highest energies

Auger statistics will totally dominate after another year

Future for Auger Collaboration

- **Complete Auger-South in ~ 6 months and provide reliable and extensive experimental data for many years**

- **Commence construction of high elevation FD (to 60°), dense SD array plus muon detectors, the day 1600th tank is deployed (designed and fully funded) for hybrid work to 10^{17} eV**

- **Submit Auger-North proposal within a year**

Rocky Kolb (ICRC2001, Hamburg)

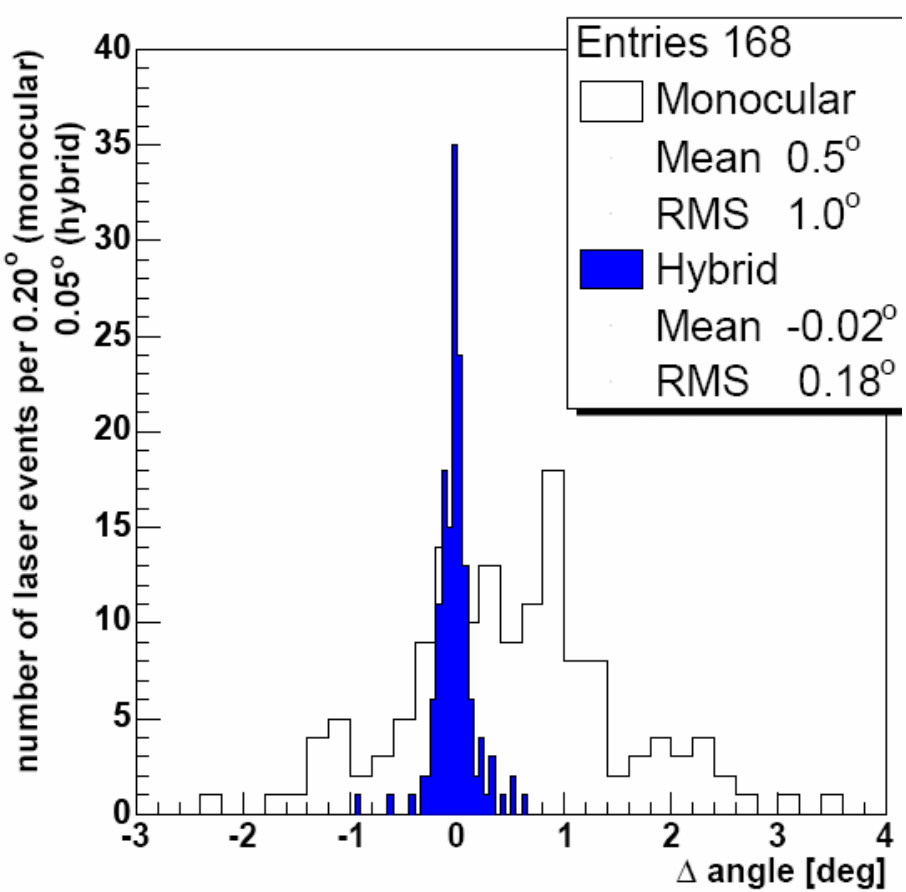
on the life of a theoretician

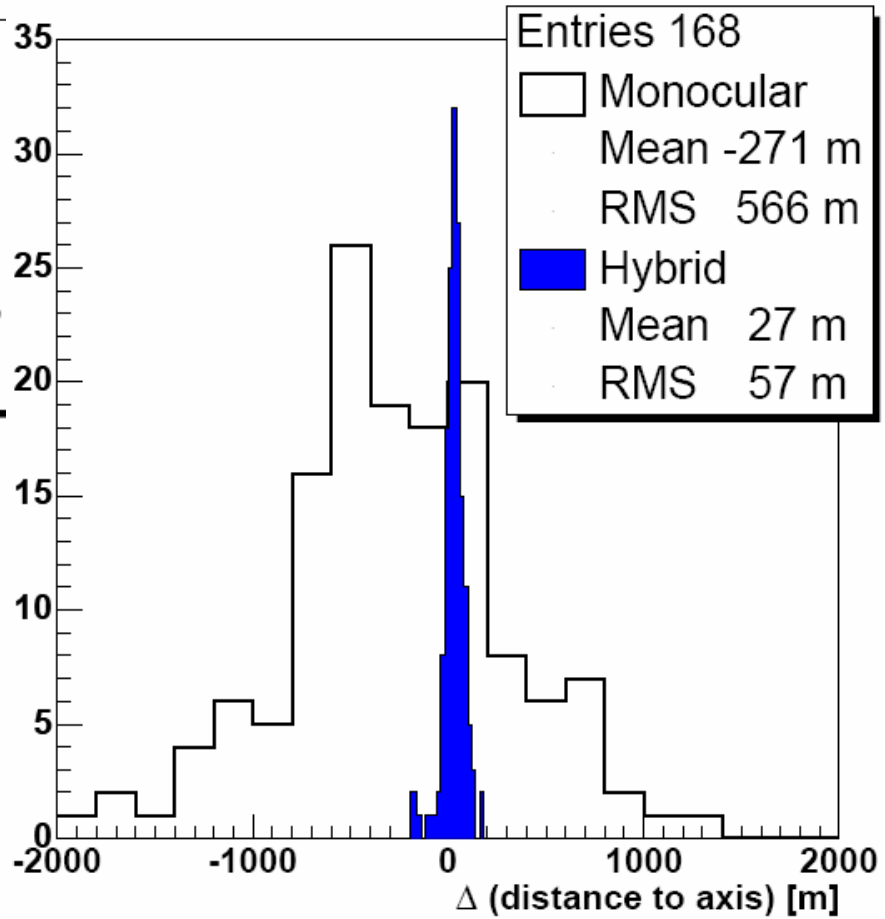
"I have an idea in the morning. I have lunch, I write it up and send it to PRL in the late afternoon.

Then, many years later, some experimentalist disproves my theory: it's so unfair!"

Back Up Slides

Angular and Spatial Resolution from Central Laser Facility





Angle in laser beam /FD detector plane

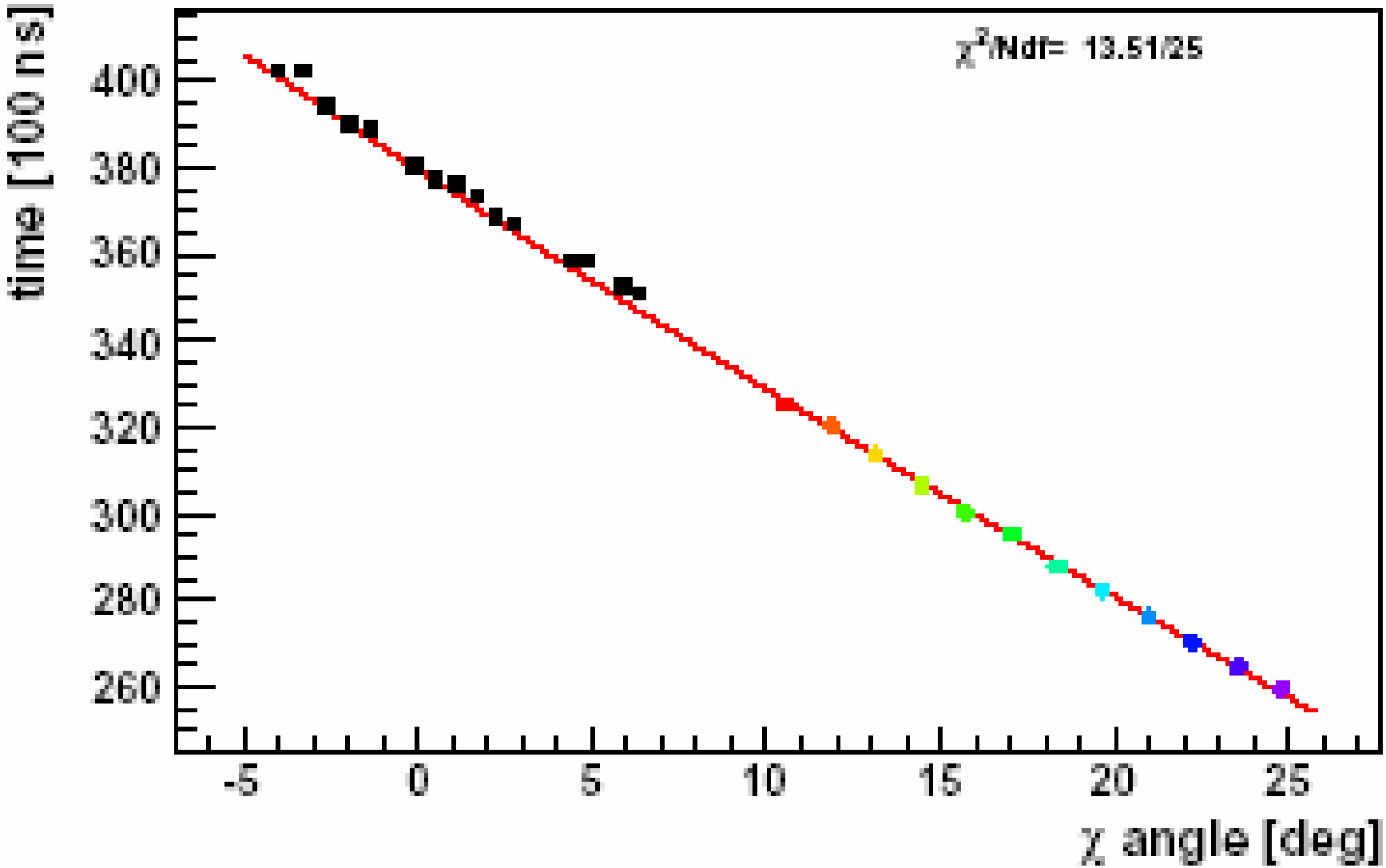
Laser position – Hybrid and FD only (m)

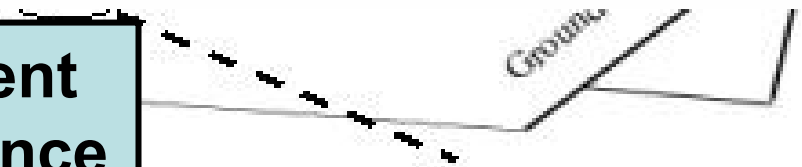
Mono/hybrid rms 1.0°/0.18°

Mono/hybrid rms 570 m/60 m

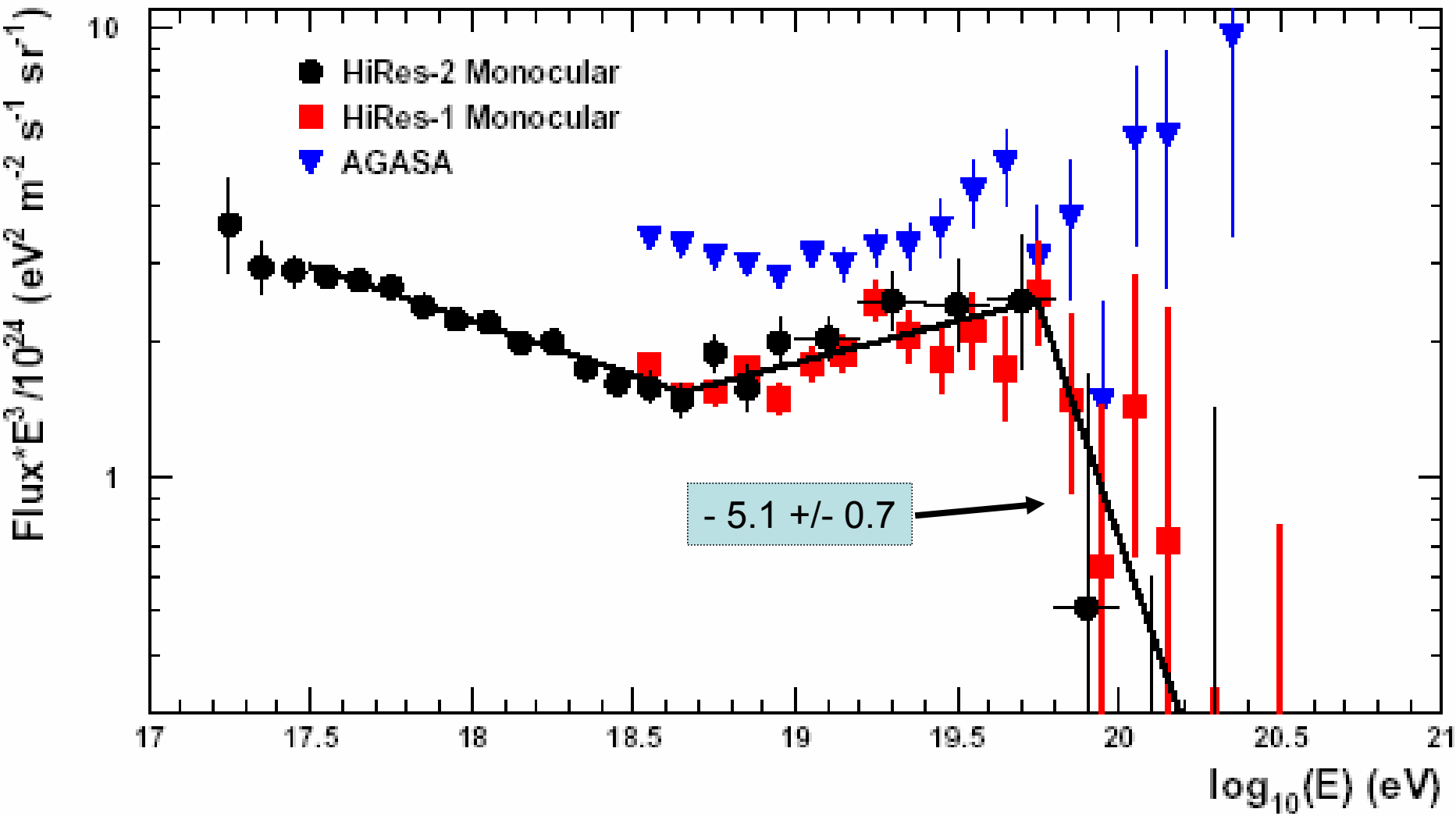
Number of Events

	HiRes I (HiRes II)	AGASA'02 (P+SYBILL '06) (Fe+QGSJet '06)	Auger
$>10^{19}$ eV	564 (180)	945 (726) (639)	1473
$>6\times10^{19}$ eV	49 (12)	31 (23) (20)	66
$>7\times10^{19}$ eV	31	25 (15) (14)	31
$>10^{20}$ eV	4 (0)	11 (6) (5)	2



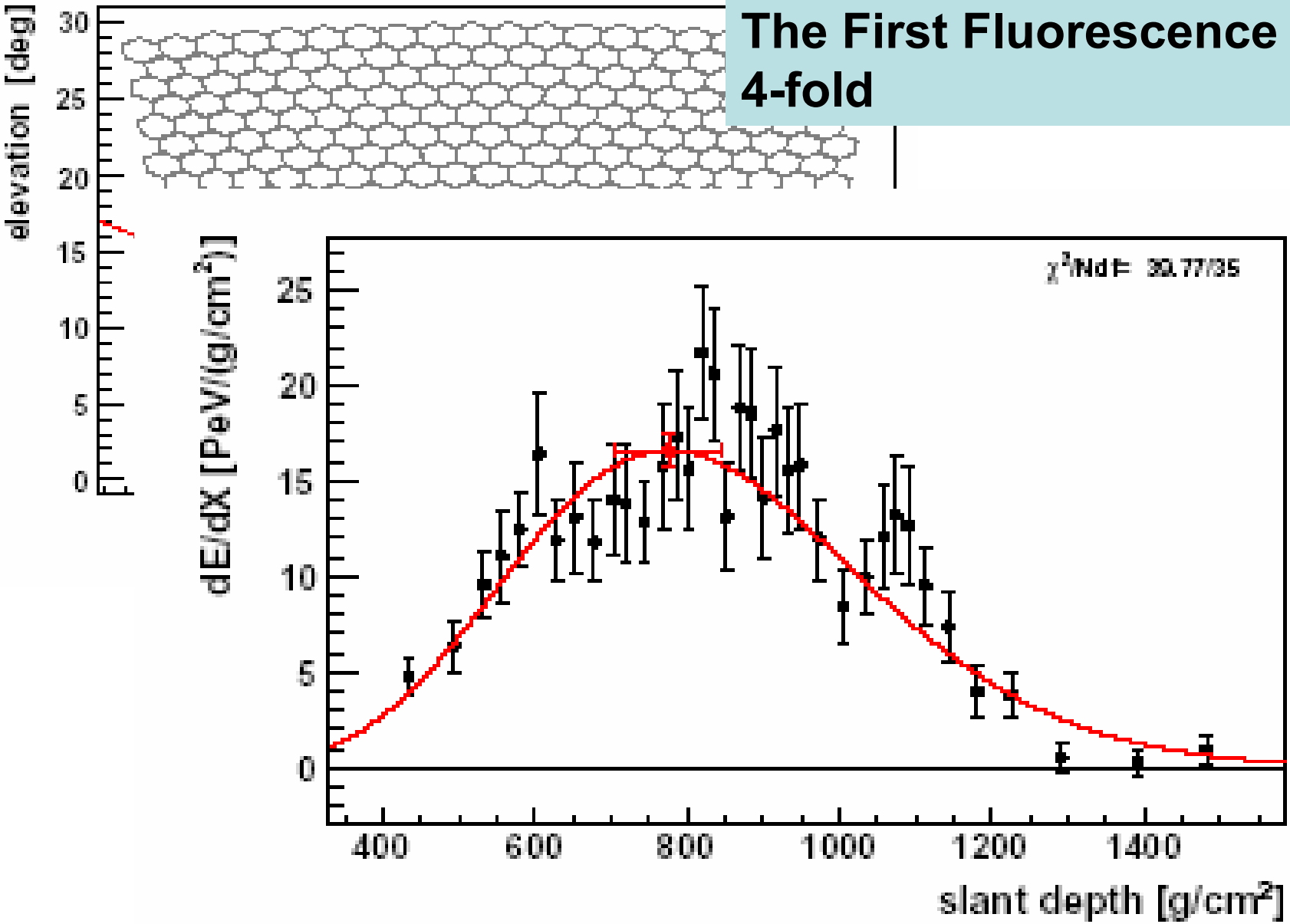


~ X 10 improvement in angle and distance as checked with laser

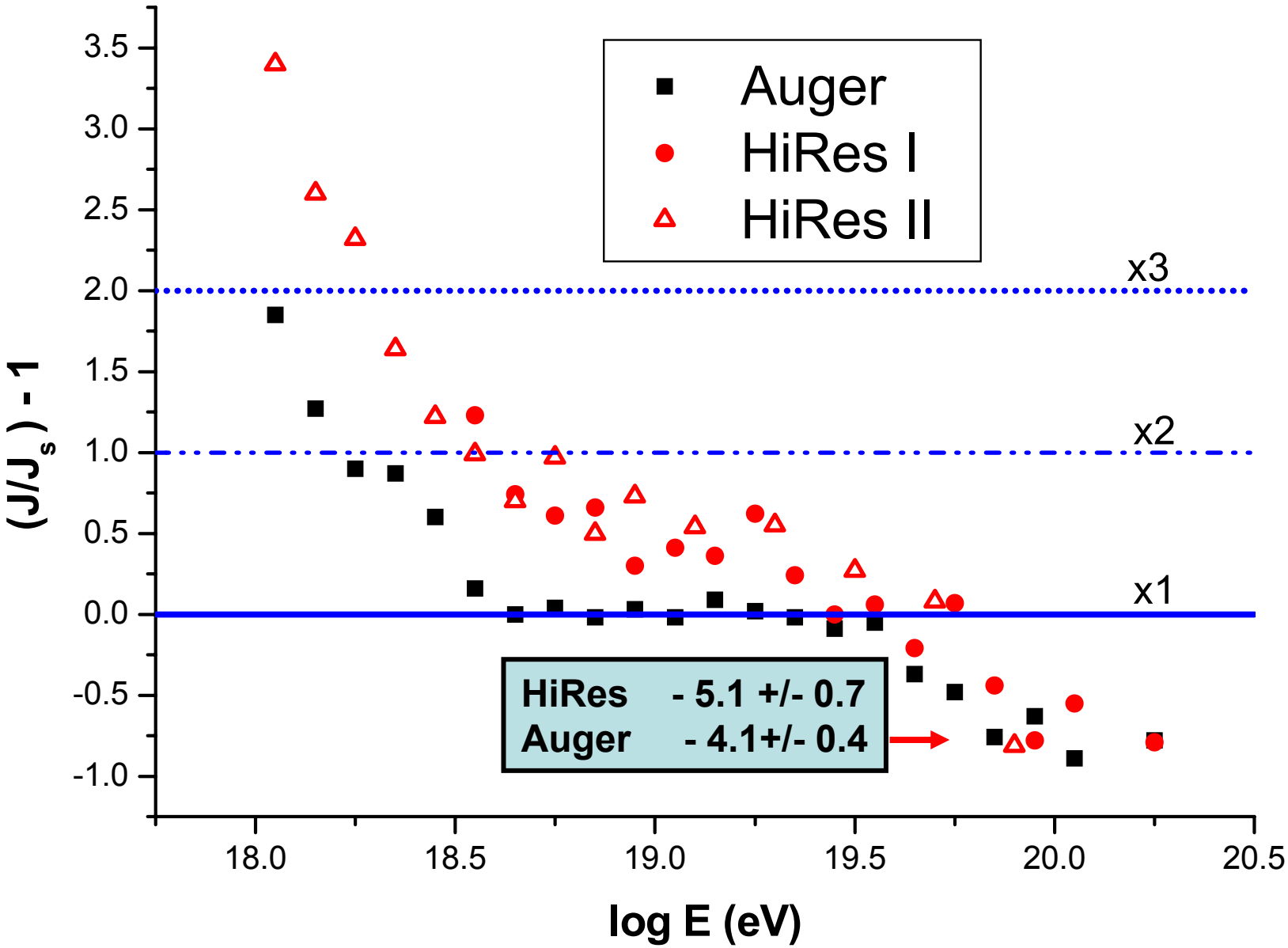


HiRes Group: astro-ph/0703099

The First Fluorescence 4-fold



Plot of residuals of individual spectra compared to standard, $J_s = A\ E^{-2.6}$



Immensely important IF it was to be established that slopes at highest energy are different in

northern (- 5.1+/- 0.7) and
southern hemispheres (- 4.1 +/- 0.4)

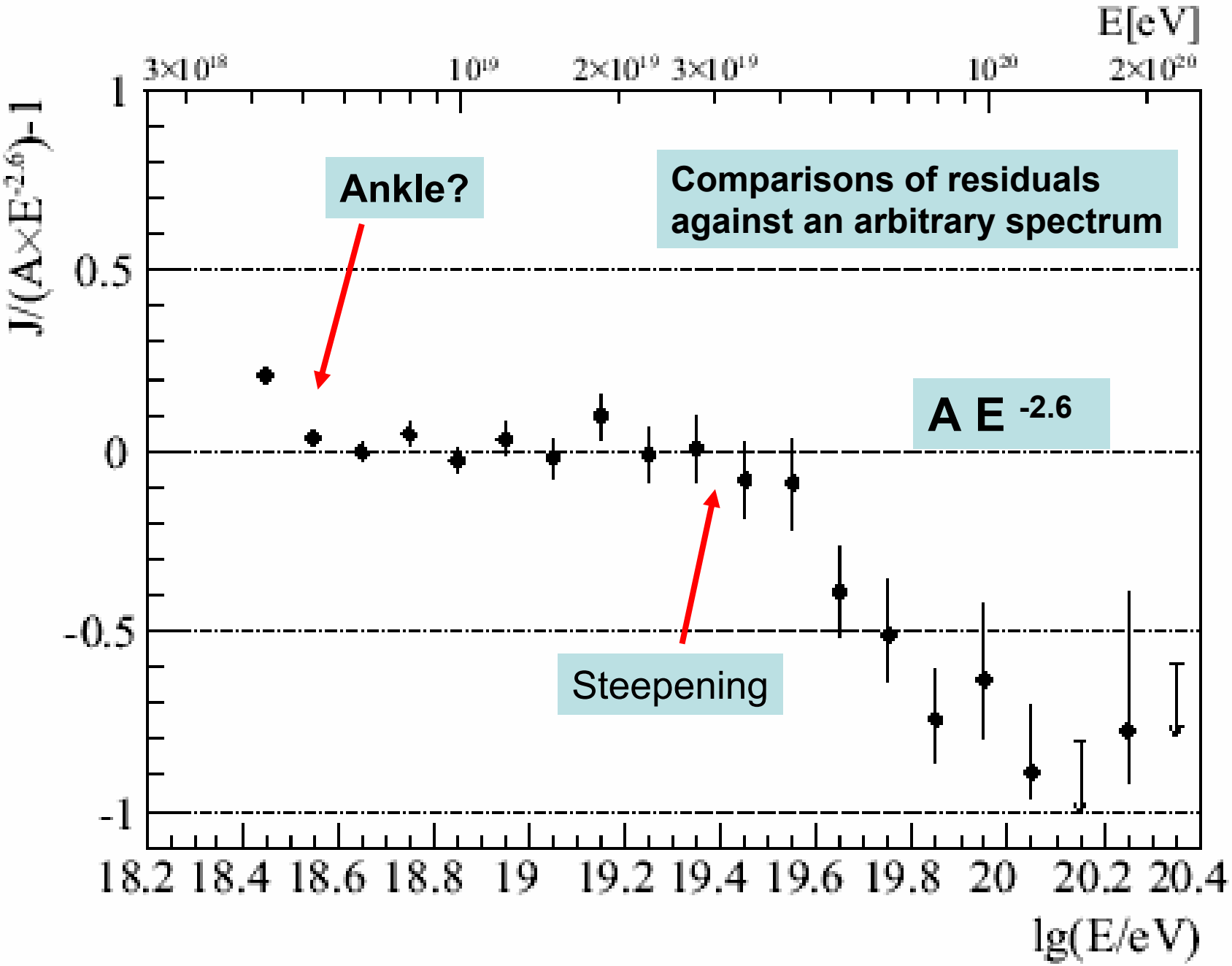
But, MUCH TOO EARLY TO DRAW CONCLUSIONS

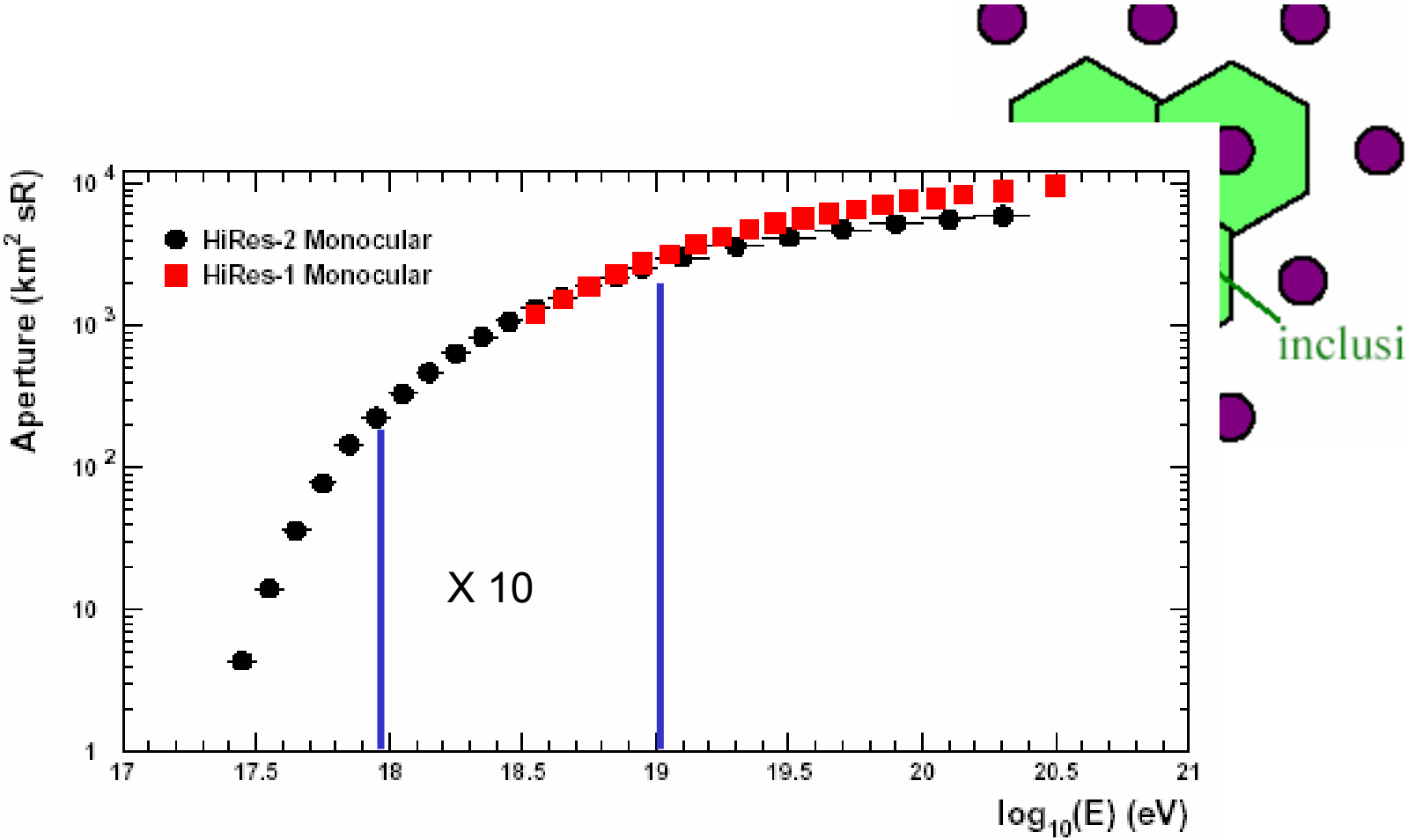
- **Uncertainties about HiRes aperture**

- **Poorer energy and angular resolution in HiRes than Auger**

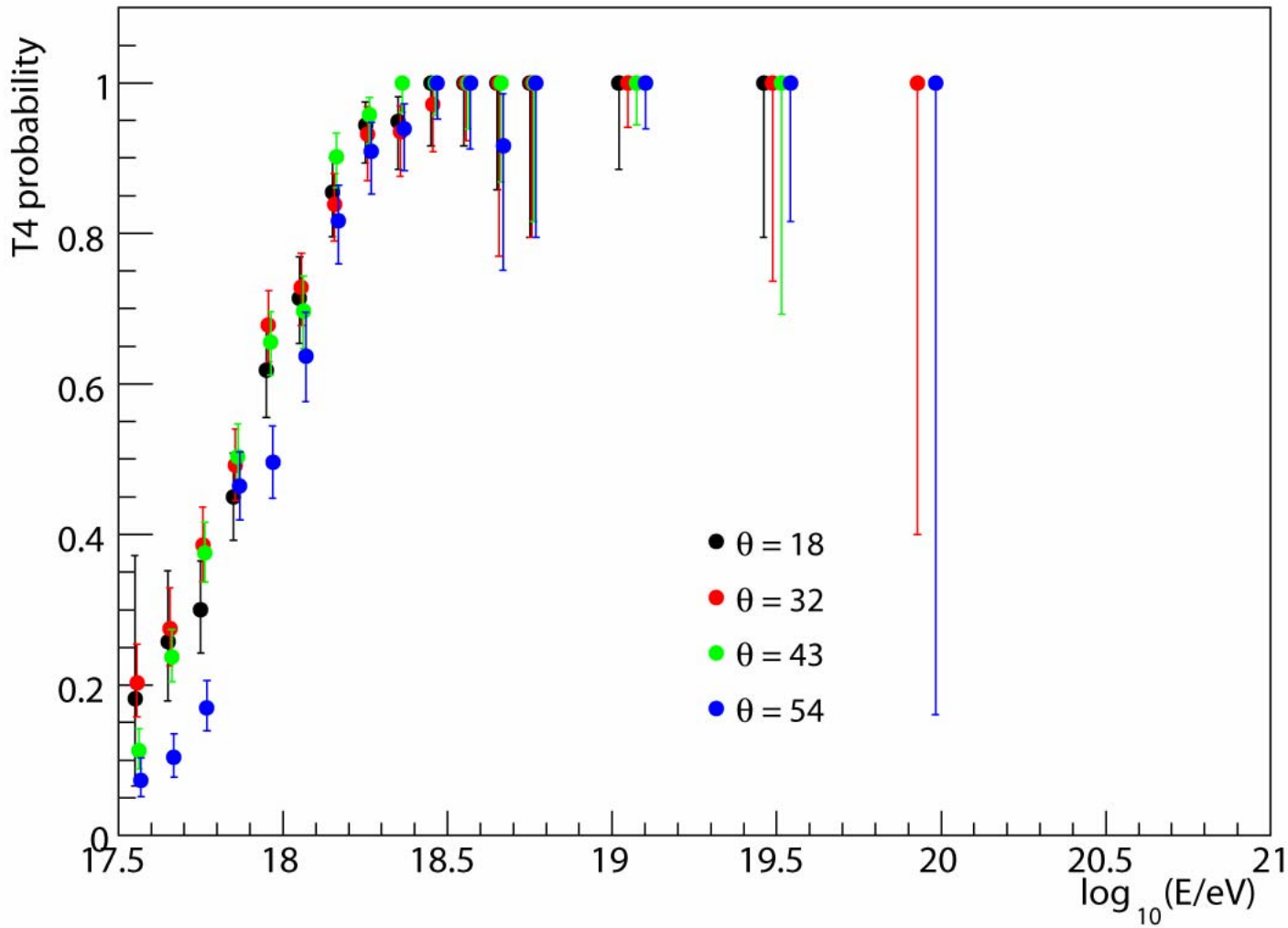
- **Low number of events – and no more to come to from HiRes**

- **Issue will be addressed with more Auger data**

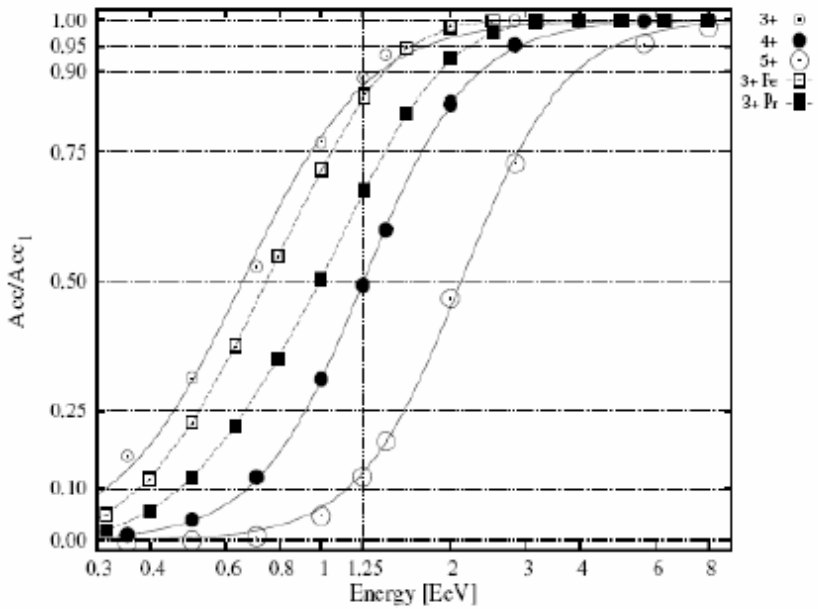

E[eV]
3×10^18
10^19
2×10^19
3×10^19
10^20
2×10^20
J/(A×E^-2.6)-1
1
0.5
0
-0.5
-1
Ankle?
Comparisons of residuals against an arbitrary spectrum
A E -2.6
Steepening
18.2 18.4 18.6 18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
lg(E/eV)

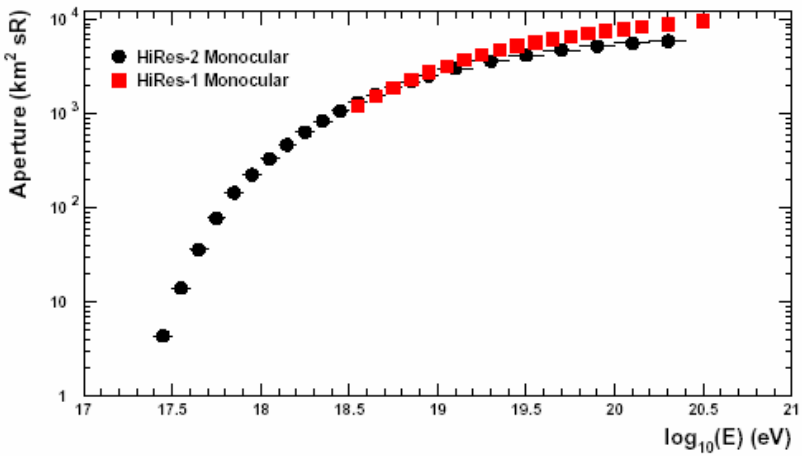


HiRes aperture depends on assumptions about spectrum slope, mass and hadronic models


T4 probability
1
0.8
0.6
0.4
0.2
0
17.5
18
18.5
19
19.5
20
20.5
21
log 10 (E/eV)
θ = 18
θ = 32
θ = 43
θ = 54

Energy Dependence of Aperture for Auger and HiRes





• Serious discrepancies between HiRes and Auger in the LOW energy region (small numbers at top end)

• Auger Aperture is INDEPENDENT of models, mass or assumptions about spectral slope

• This is NOT the case for HiRes

Problem with HiRes aperture?

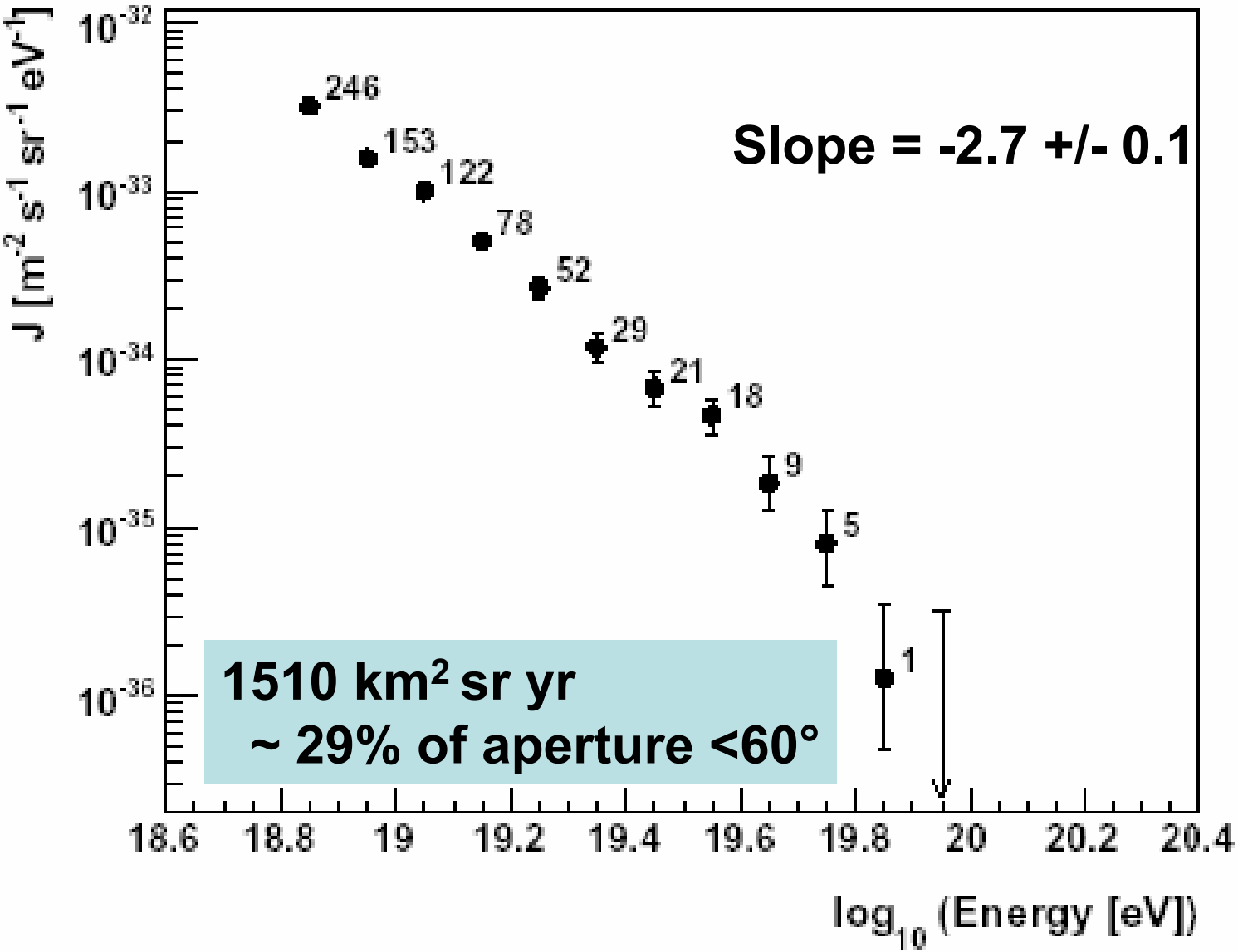
The HiRes aperture estimate requires assumptions about primary mass, spectrum slope and hadronic model

• Cannot be FY or hemisphere differences

Highlights:

- **The Collaboration works well**
- **Observatory Status**
- **First 4-fold Fluorescence Event**
- **Remarkable Isotropy**
- **Studies relating to Nucleonic Composition**
- **Primary Energy Spectrum**
- **Comparisons, Conclusions and Future Prospects**

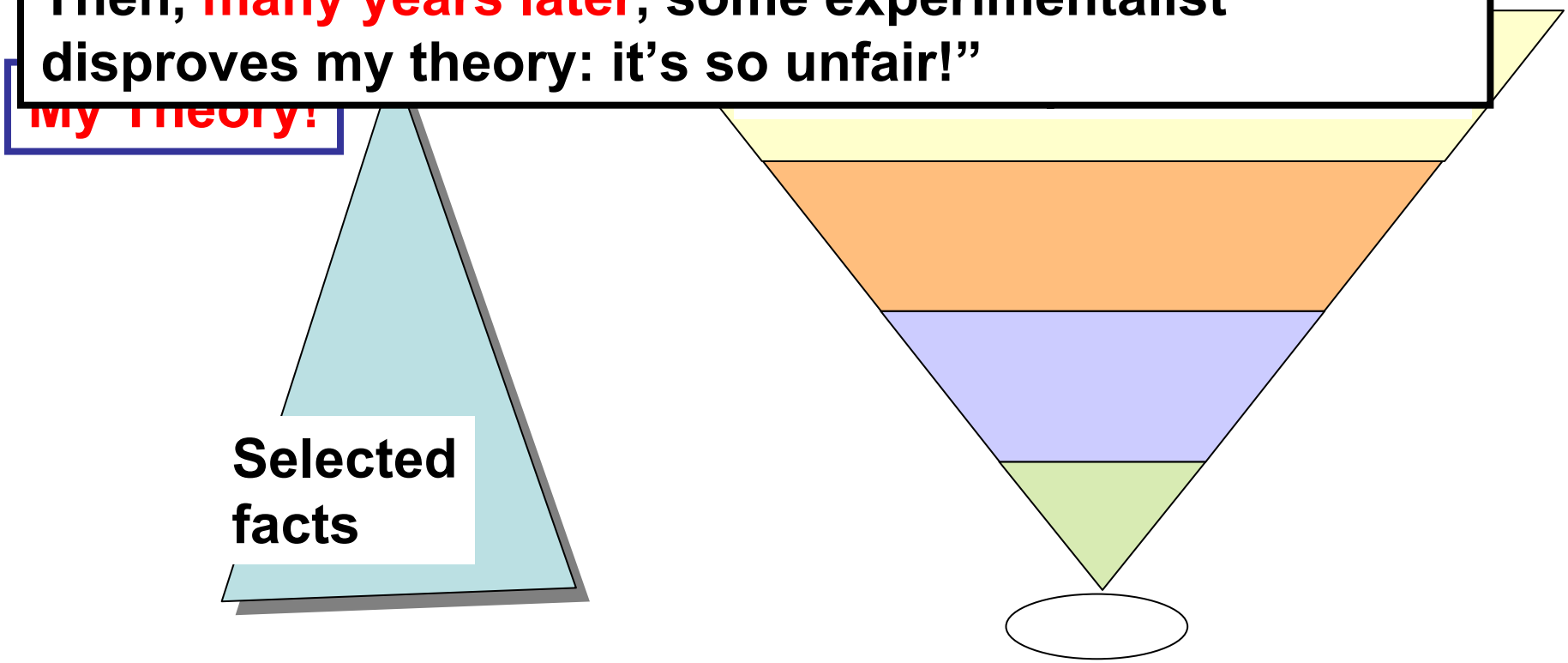
Energy Spectrum from 60 °< θ < 80°: 734 events



Rocky Kolb (ICRC2001)

"I have an idea in the morning: I send it to PRL in the afternoon.

Then, many years later, some experimentalist disproves my theory: it's so unfair!"



Theorist's view

Experimentalist's view