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 | Australia |
| Germany | Brasil |
| Italy | Bolivia* |
| Netherlands | Mexico |
| Poland | USA |
| Portugal | Vietnam* |
| Slovenia | |
| Spain | **Associate Countries* |
| United Kingdom | ~300 PhD scientists from ~70 Institutions and 17 countries |

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

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| Slovenia | |
| Spain | |
| United Kingdom | |

CINVESTAV
Michoacan
Puebla
UNAM

**Associate Countries*

~300 PhD scientists from
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| Spain | |
| Unit gdom | |

*Associate Countries

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CINVESTAV
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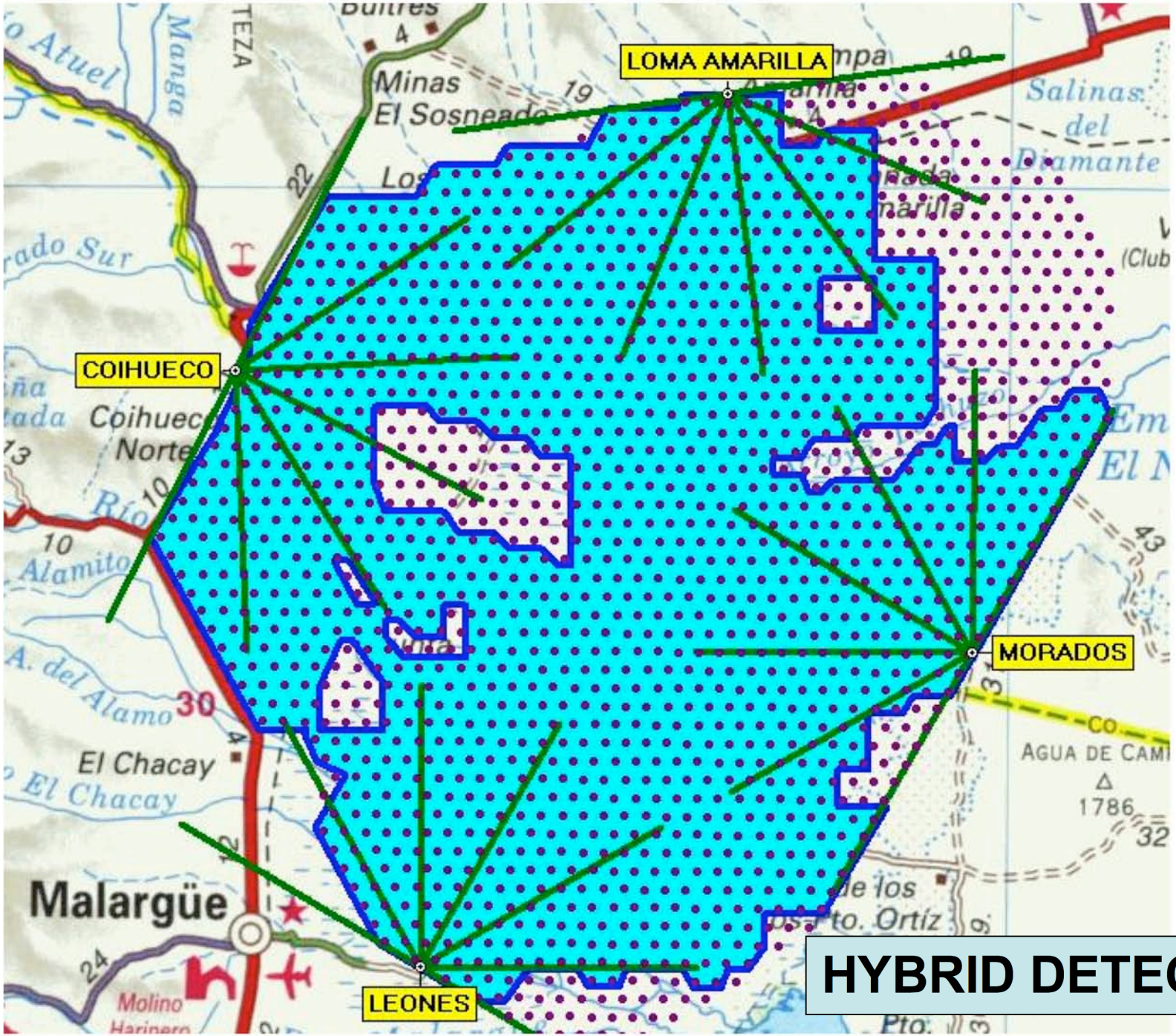
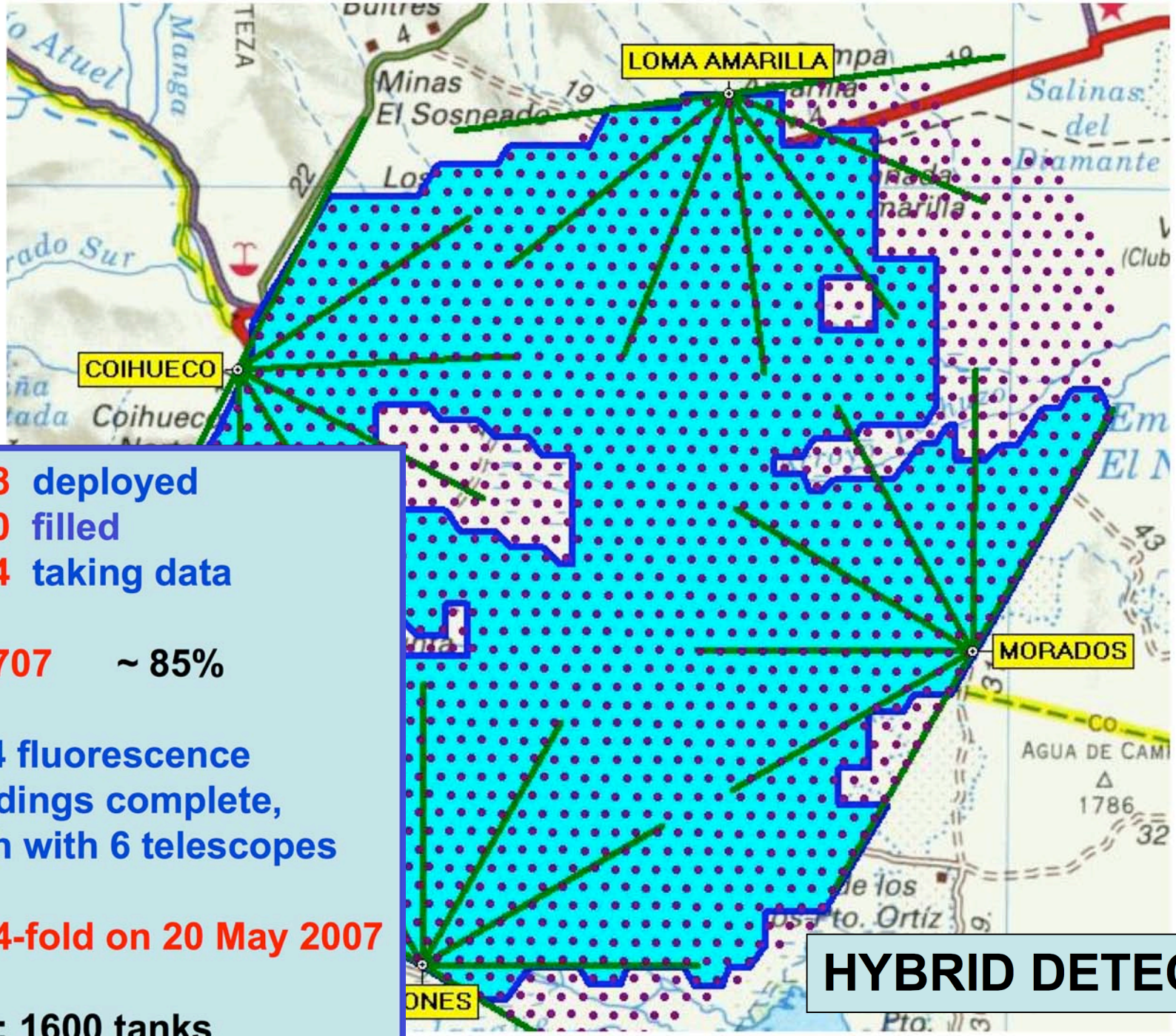
Puebla
UNAM

Thanks to all of my collaborators!!

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




**HYBRID DETECTOR**




1438 deployed
1400 filled
1364 taking data

090707 ~ 85%

All 4 fluorescence buildings complete, each with 6 telescopes

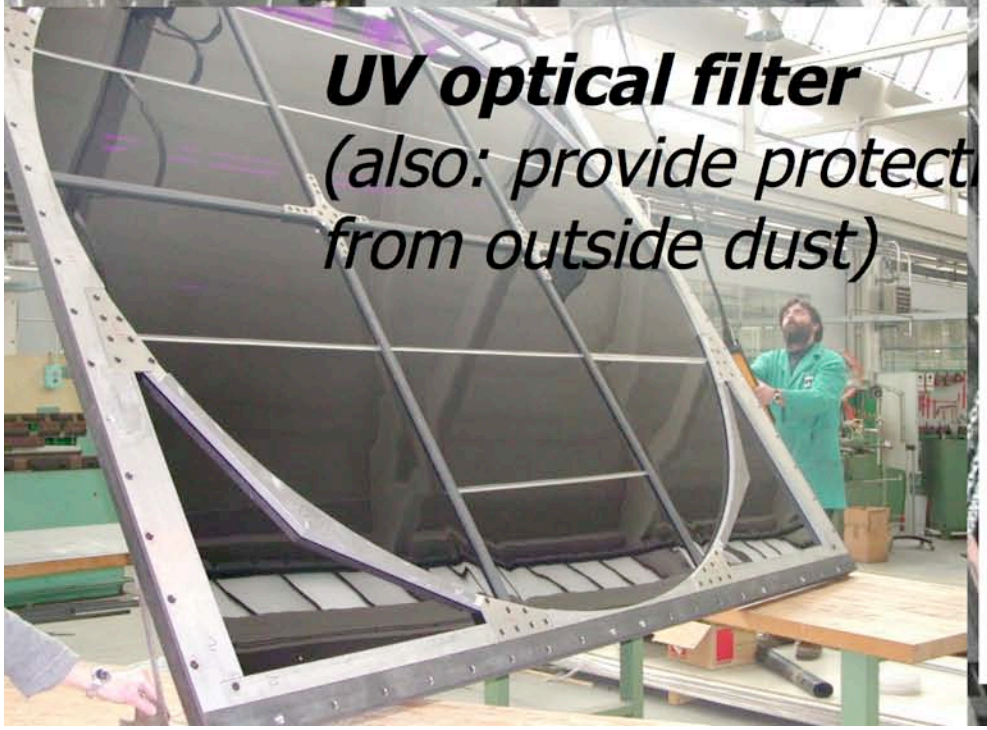
1st 4-fold on 20 May 2007

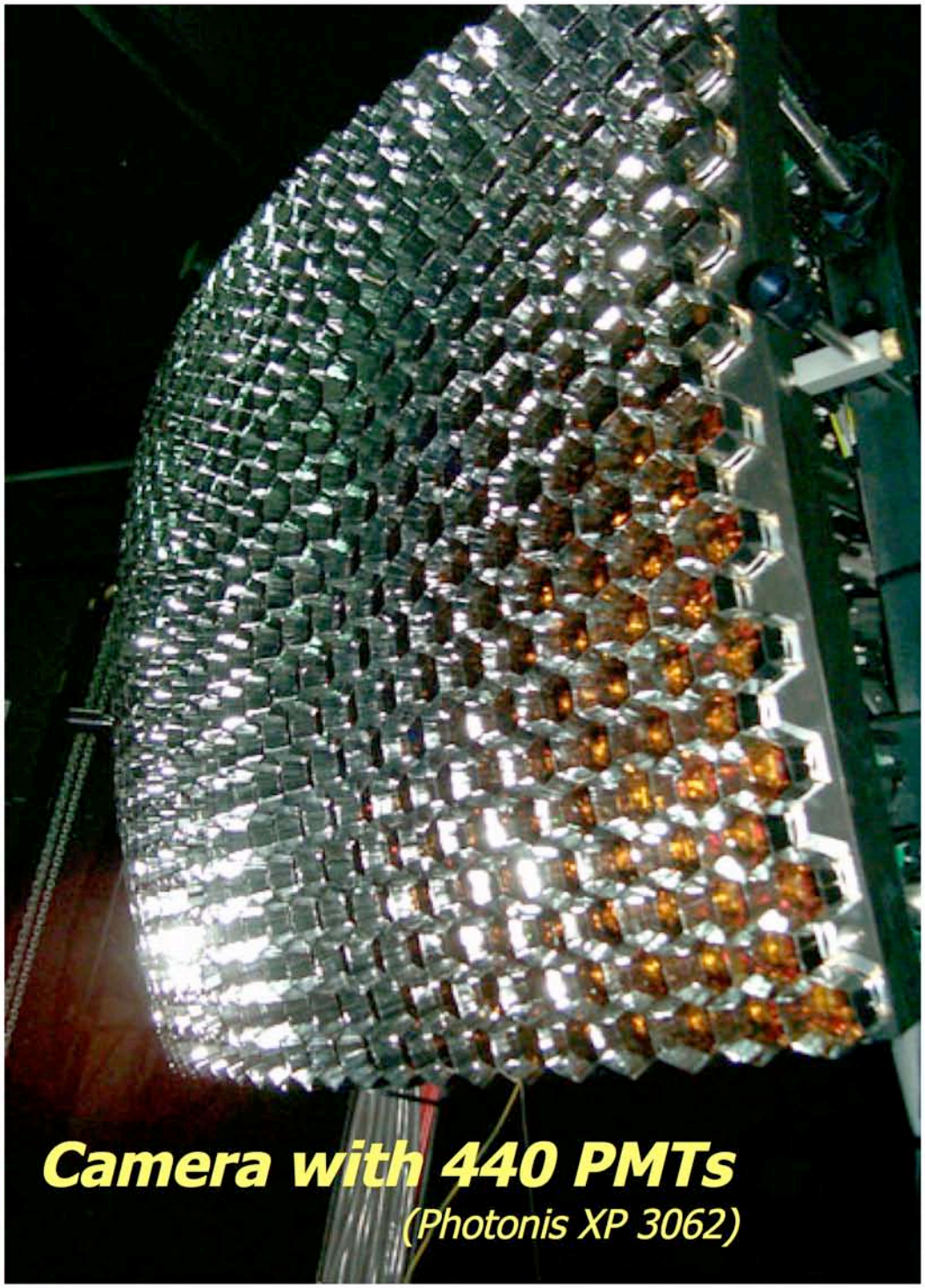
AIM: 1600 tanks

**HYBRID DETECTOR**


GPS Receiver
and radio transmission

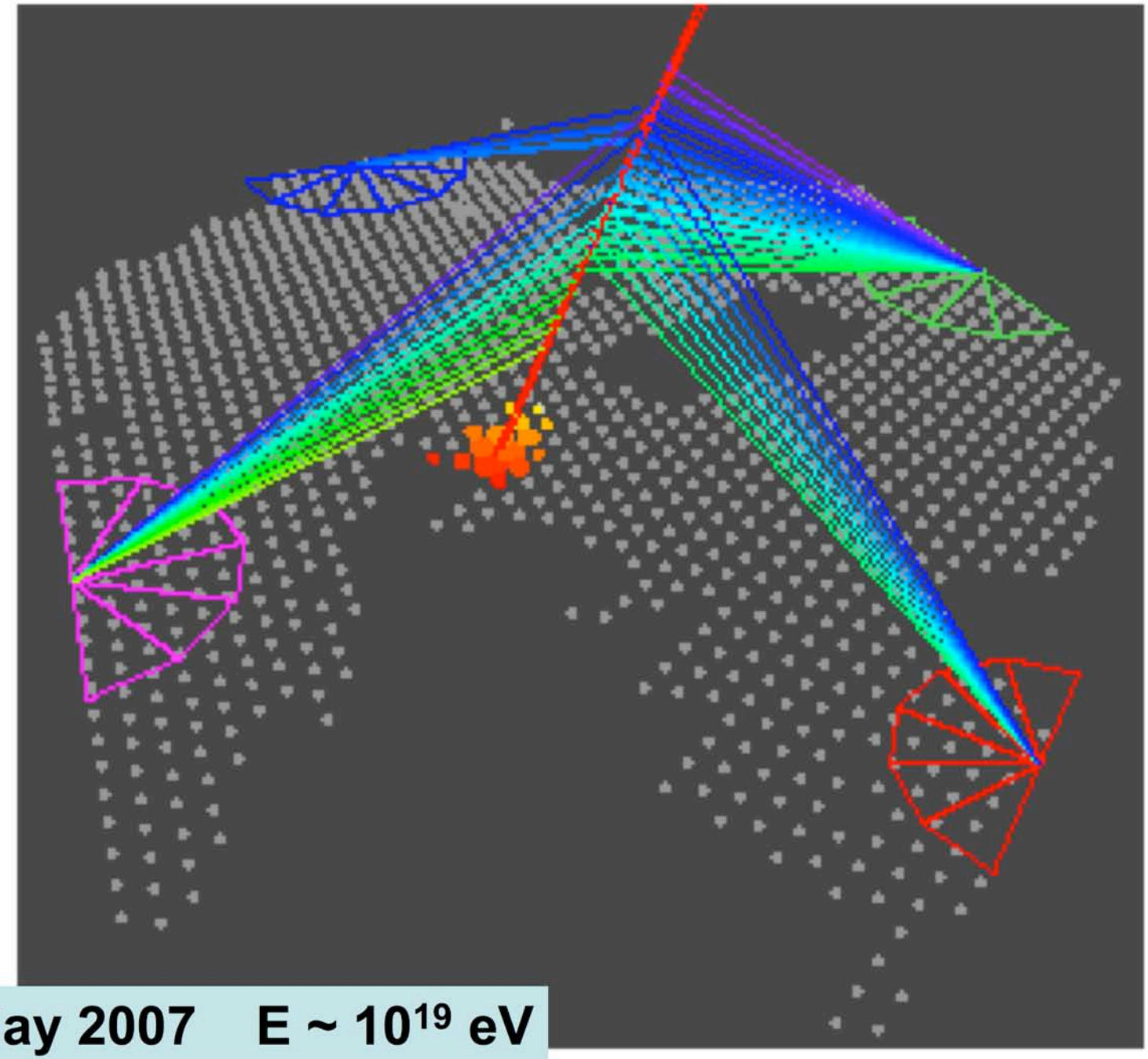

Schmidt Telescope
using 11 m² mirrors


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


Camera with 440 PMTs
(Photonis XP 3062)

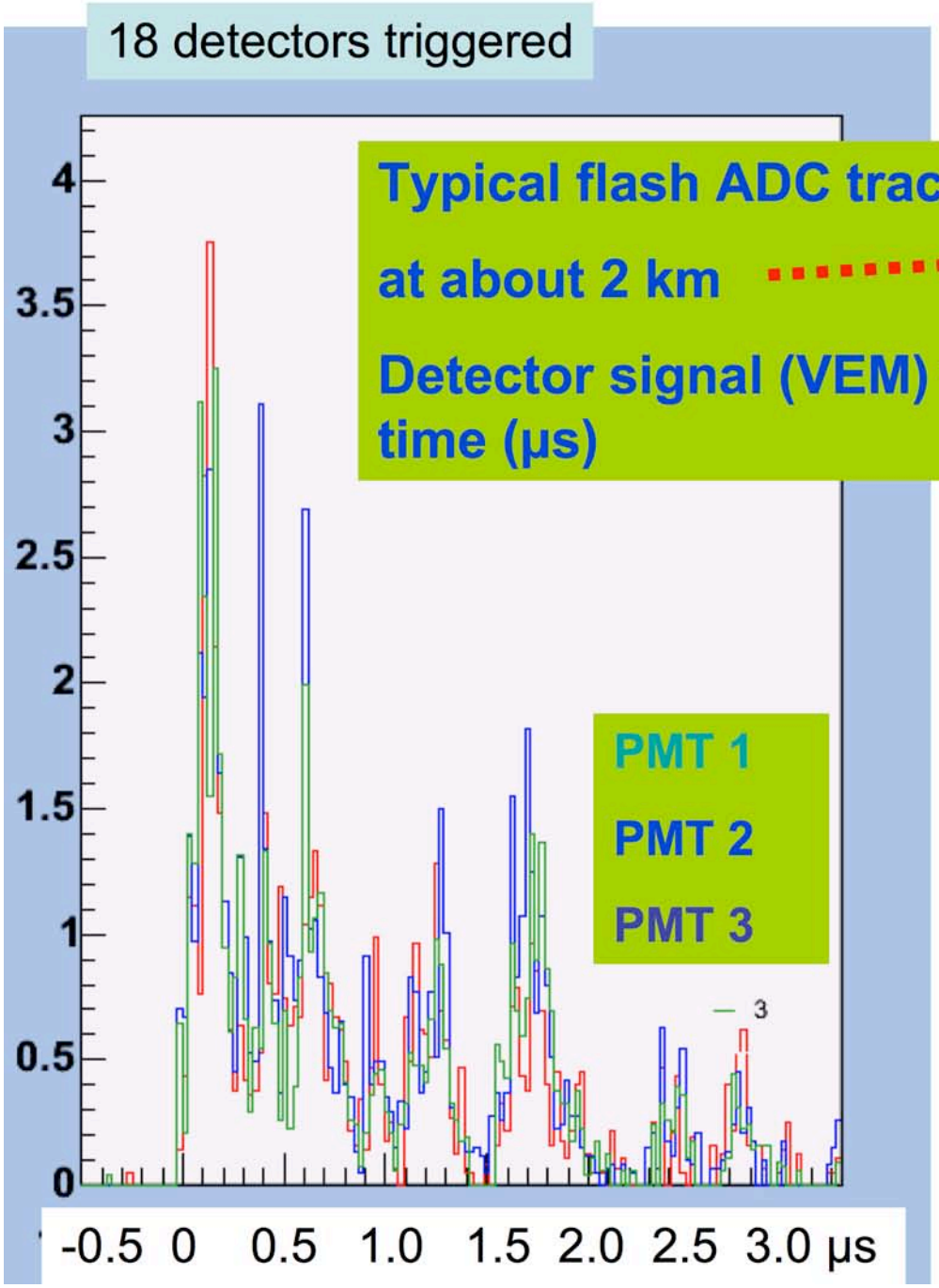
# The Hybrid Era

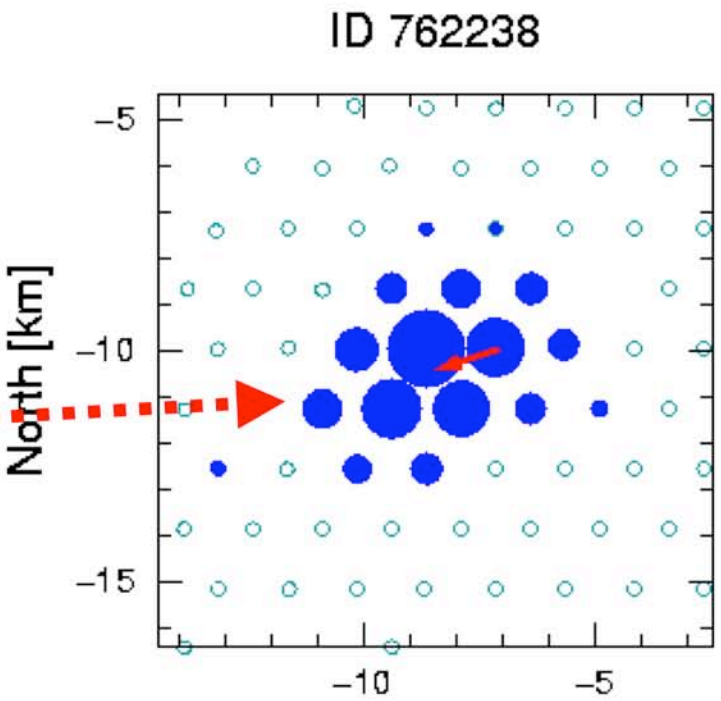
| | Hybrid | SD-only | FD-only |
|---|---|---|---|
| | | | **mono** (stereo – low N) |
| **Angular Resolution** | **~ 0.2°** | **~ 1 - 2°** | **~ 3 - 5°** |
| **Aperture** | **Flat with energy AND mass and model (M) free** | | **E, A, spectral slope and M dependent** |
| **Energy** | **A and M free**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

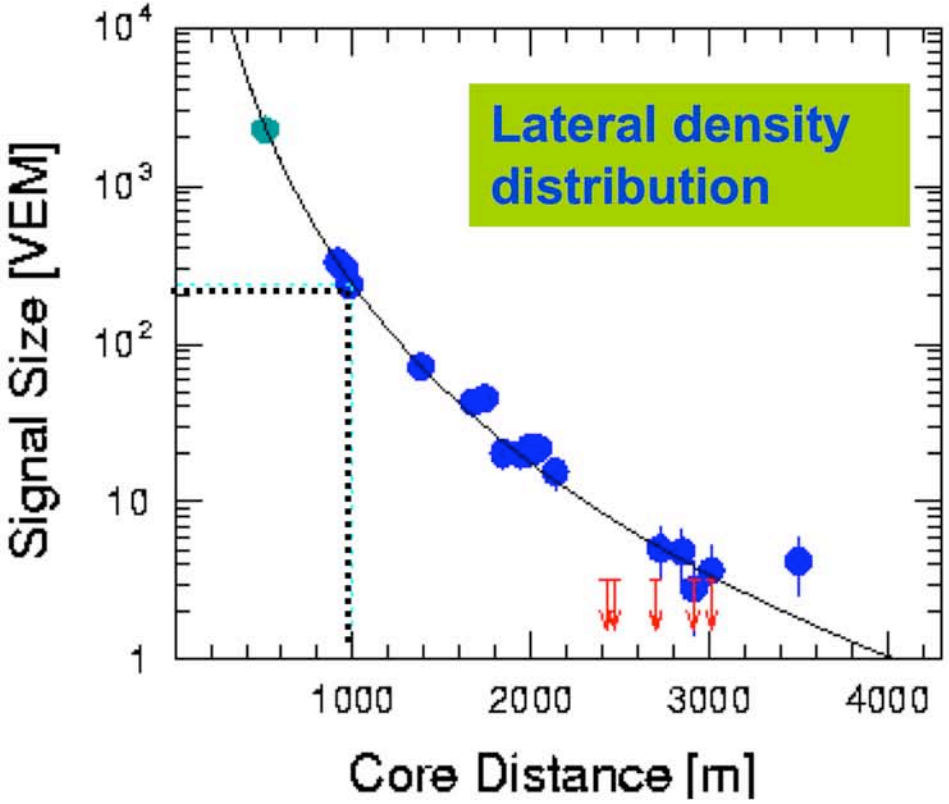


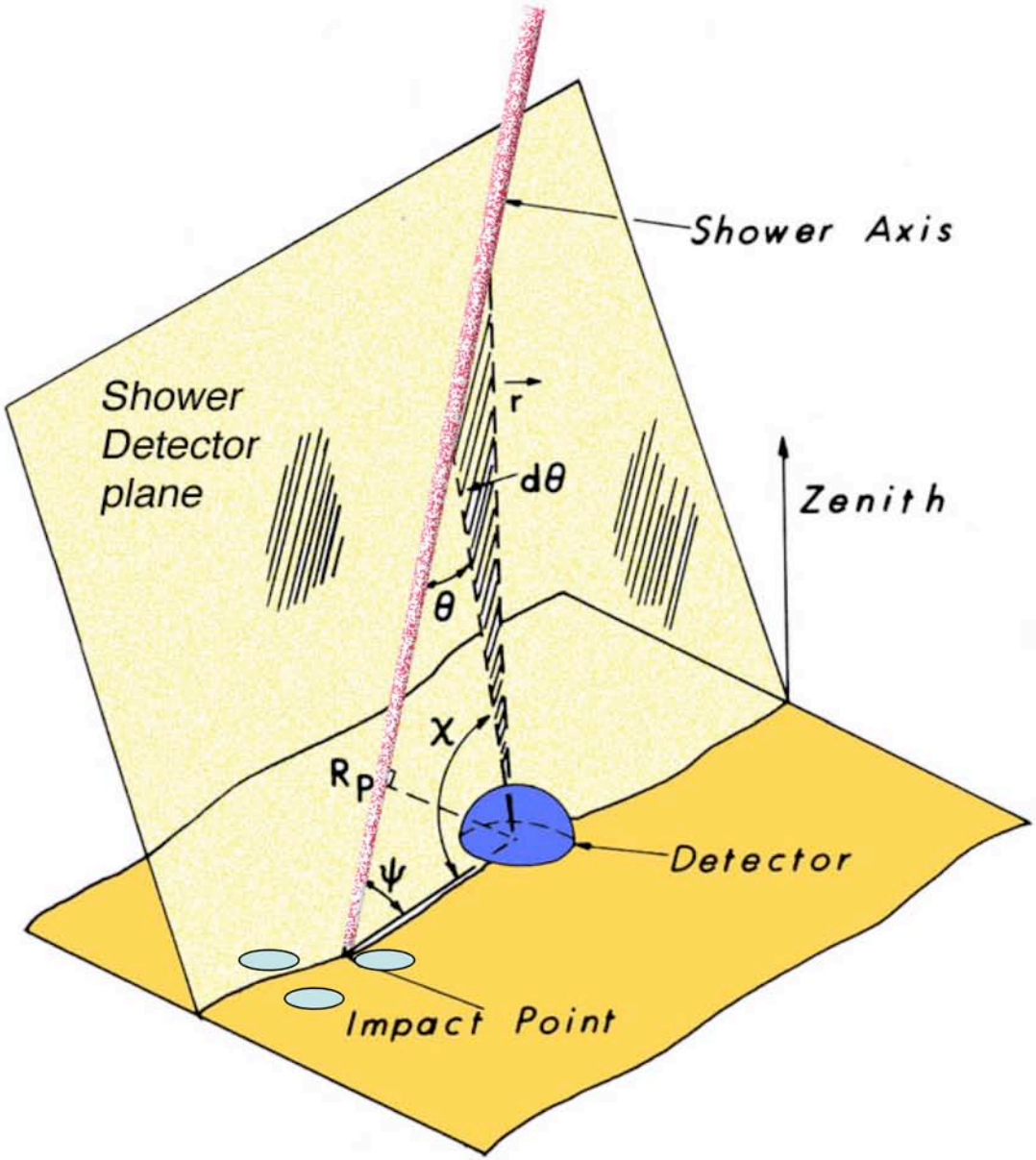
**20 May 2007 E ~ $10^{19}$ eV**

# θ~ 48º, ~ 70 EeV


18 detectors triggered
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]
10⁴
10³
10²
10
1
1000
2000
3000
4000
Core Distance [m]




**The essence of the hybrid approach**

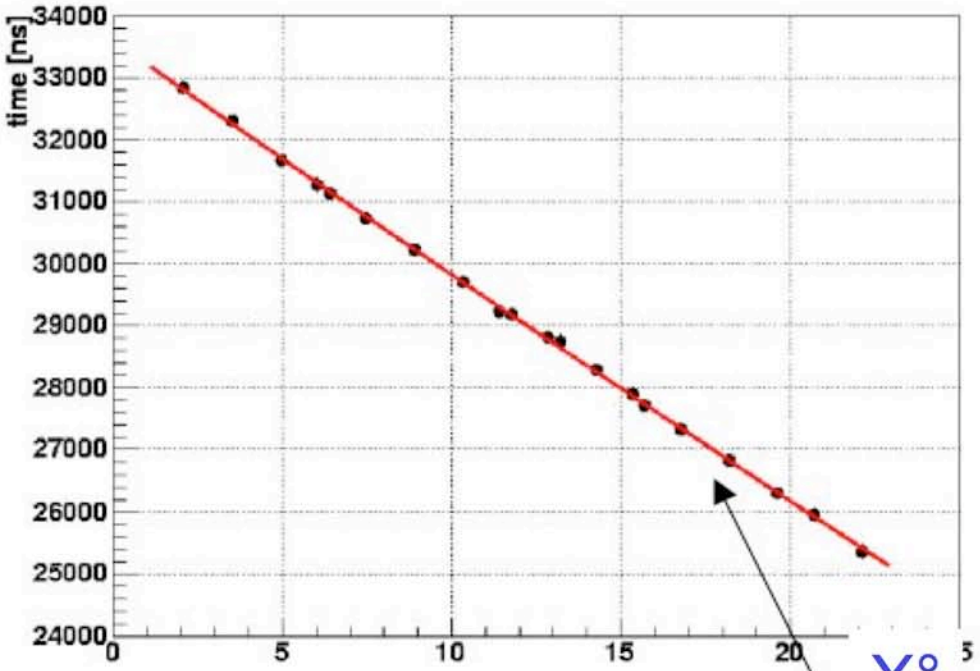
**Precise shower geometry from degeneracy given by SD timing**

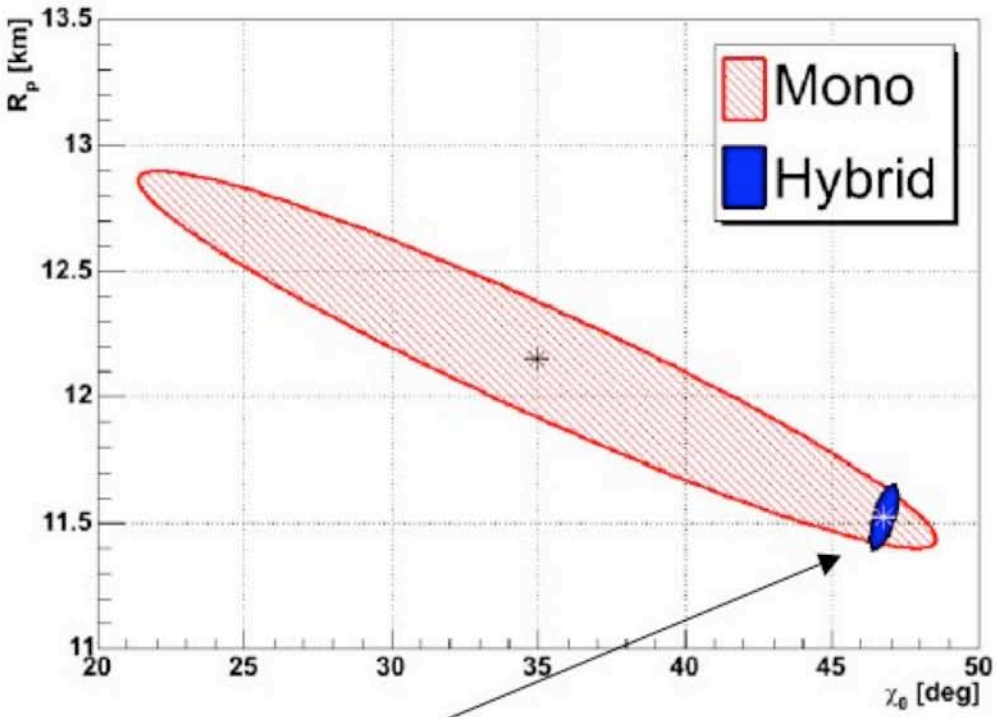
**Essential step towards high quality energy and $X_{max}$ resolution**

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

## Time, t

## $R_p$ km




X°

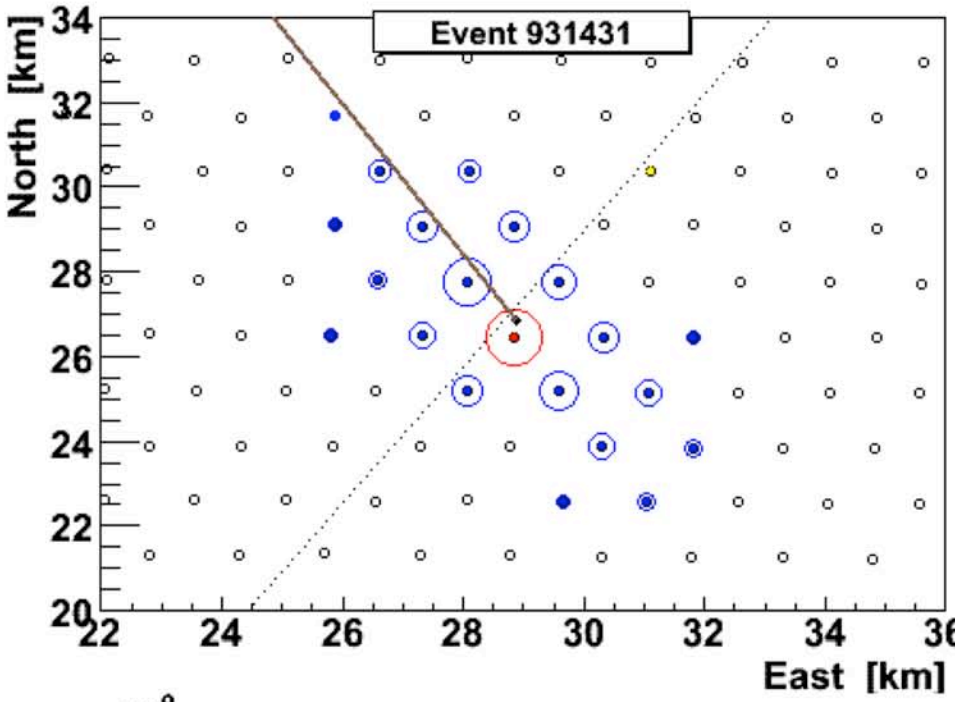
≈ line but

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

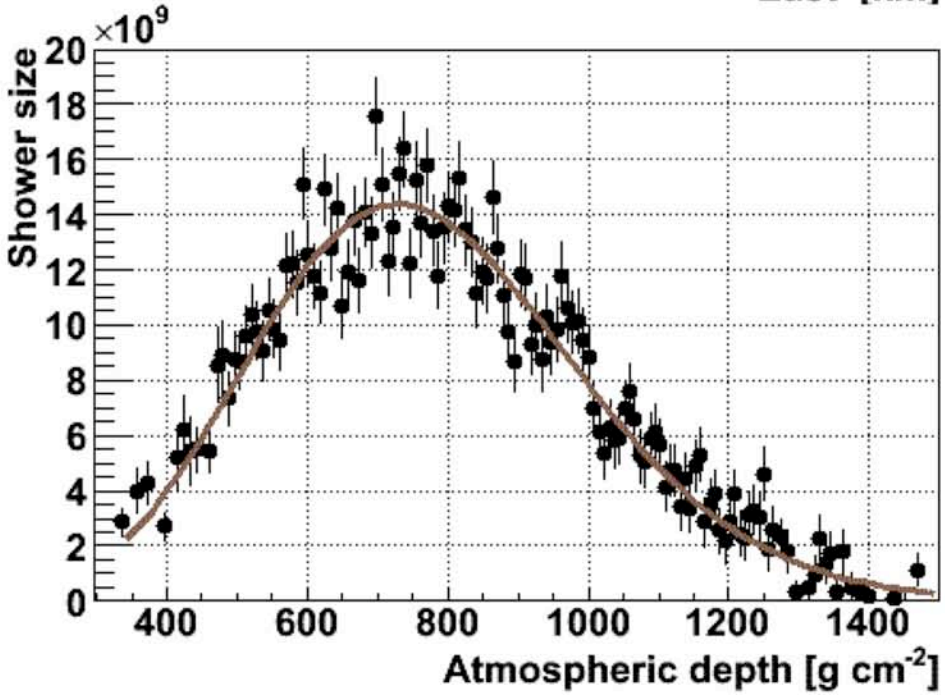
Northing 6087022 ± 80

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$^{-2}$

$\chi^2$/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

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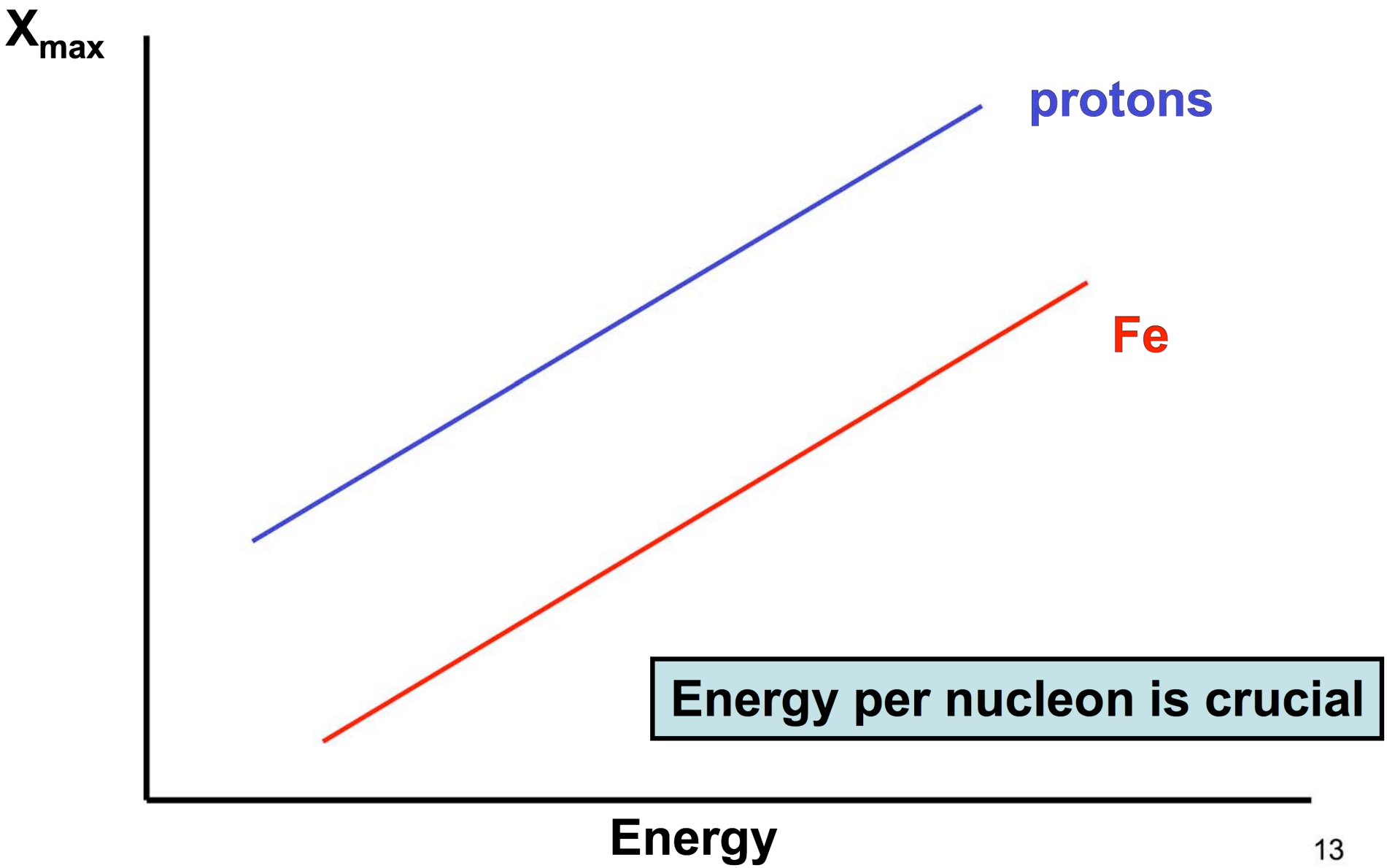
**Summary: Previous reports have not been confirmed**

**BUT,**
**two 'prescriptions' are currently being tested**

# How we try to infer the variation of mass with energy



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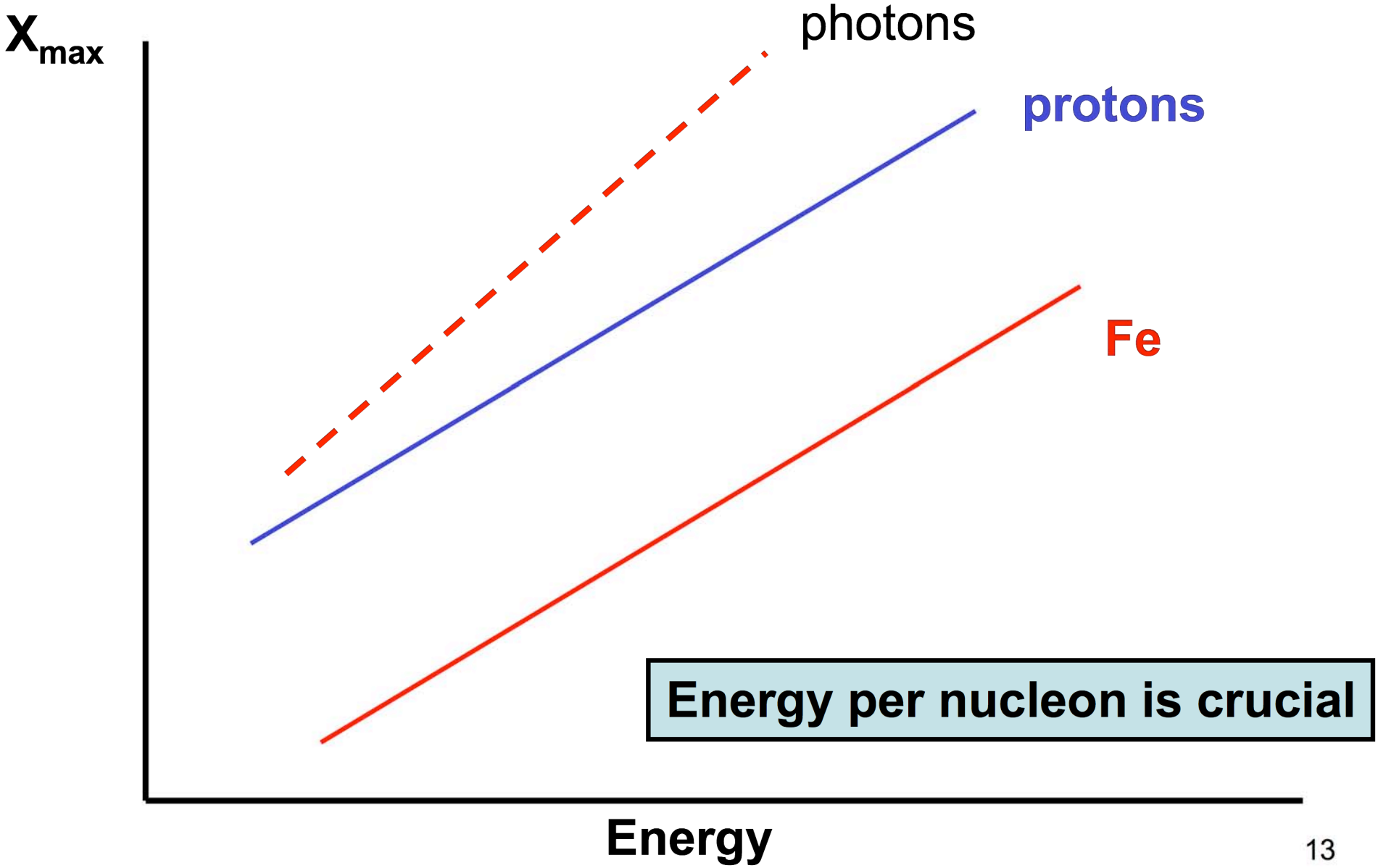

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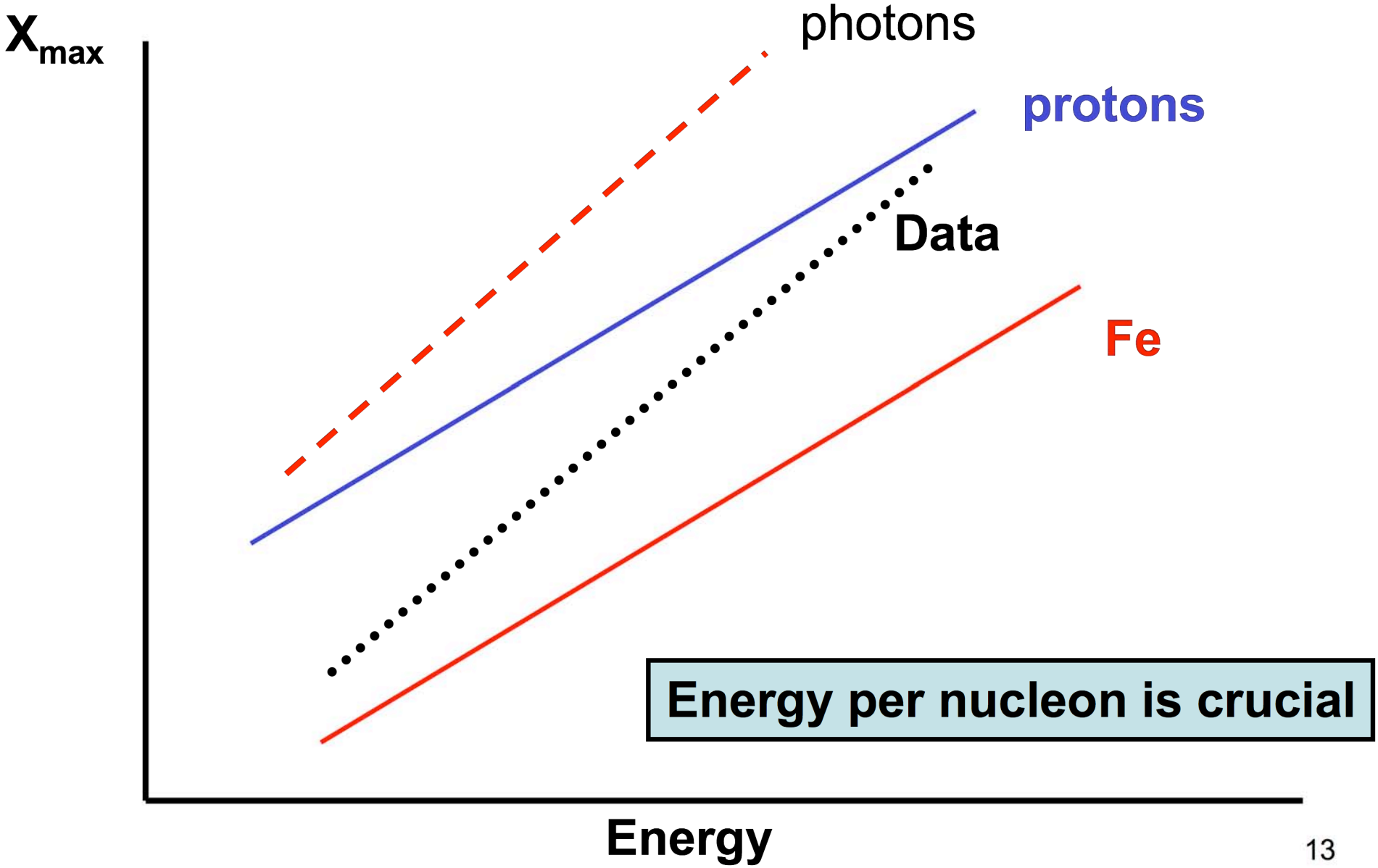

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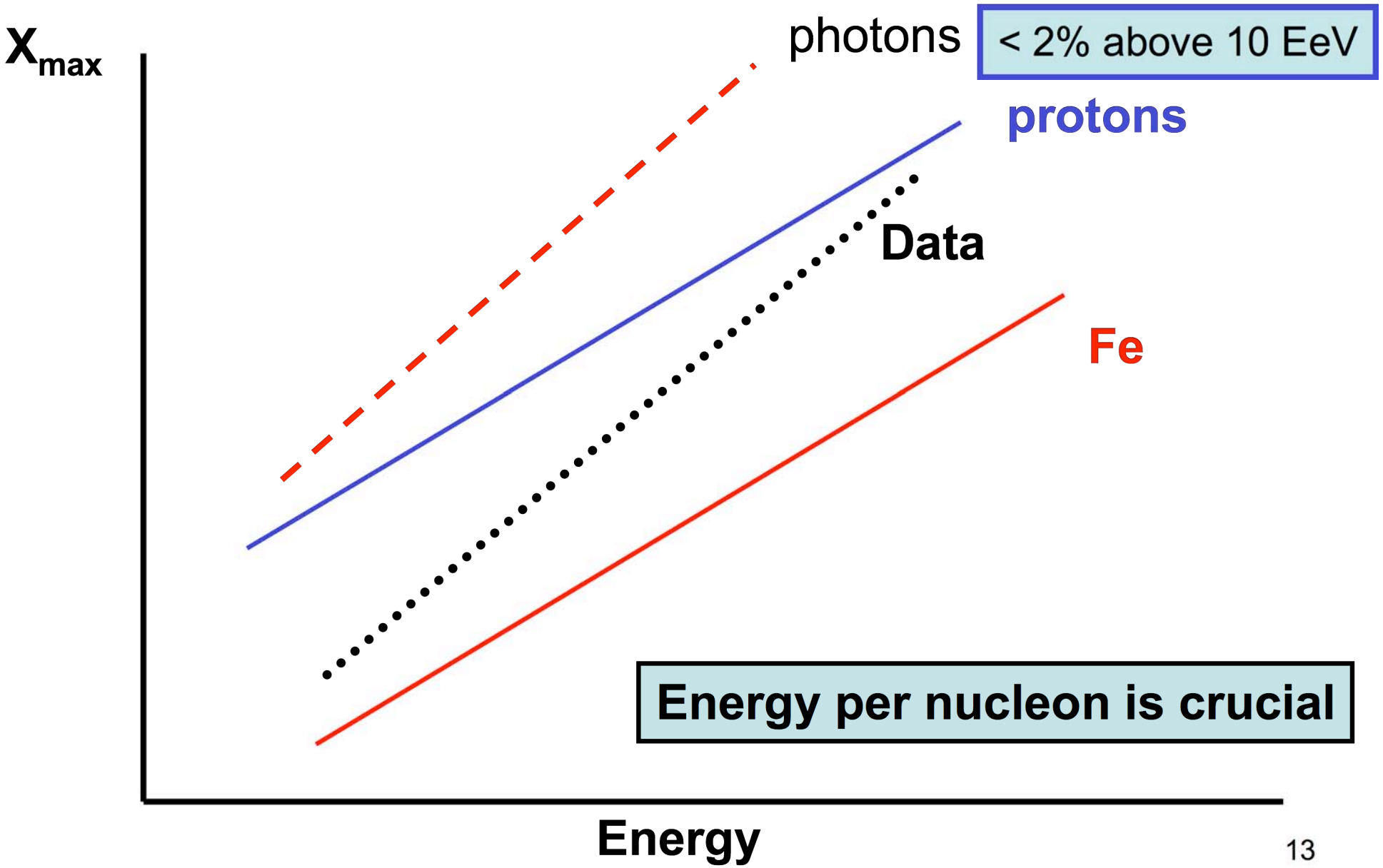

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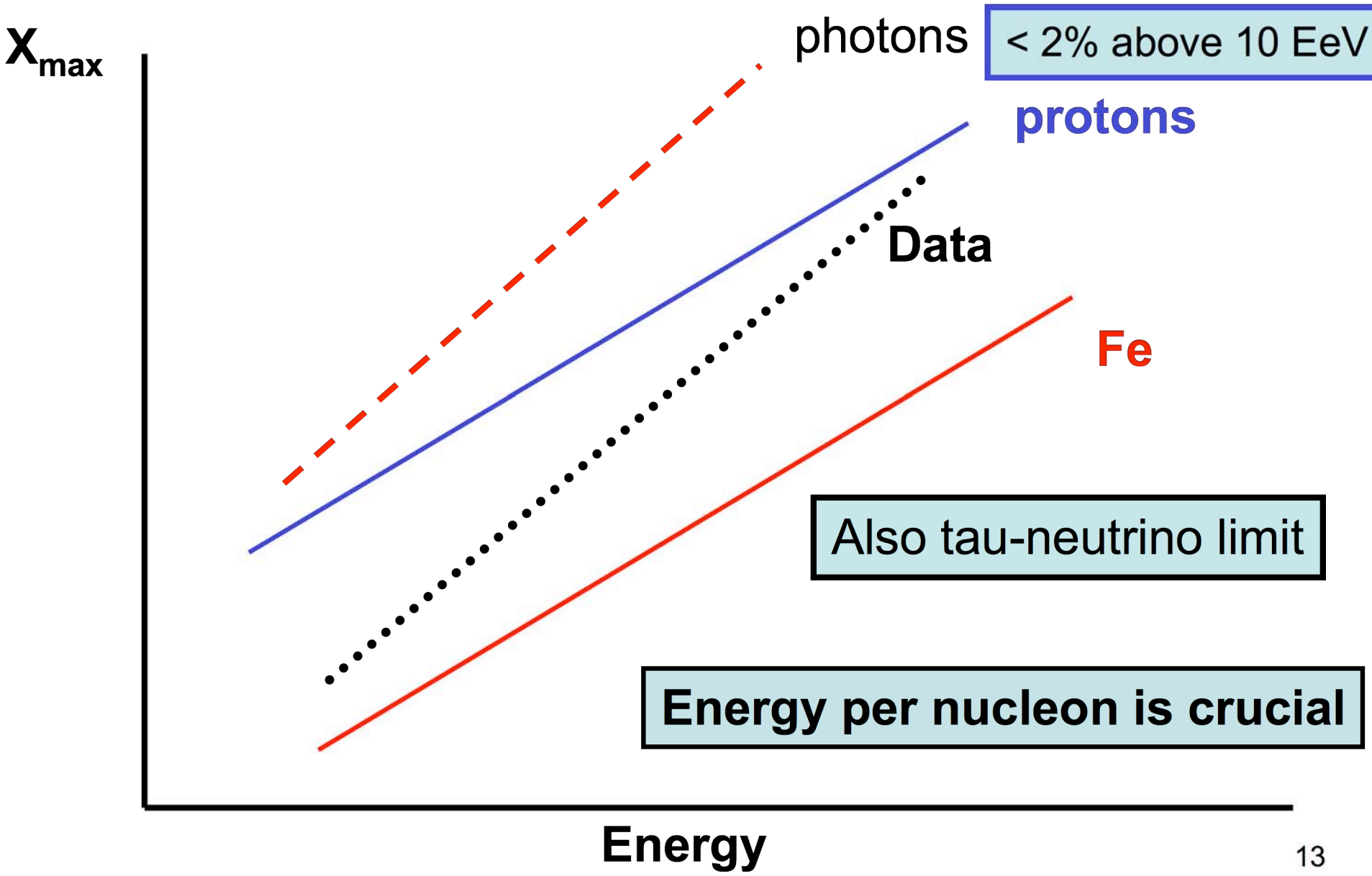
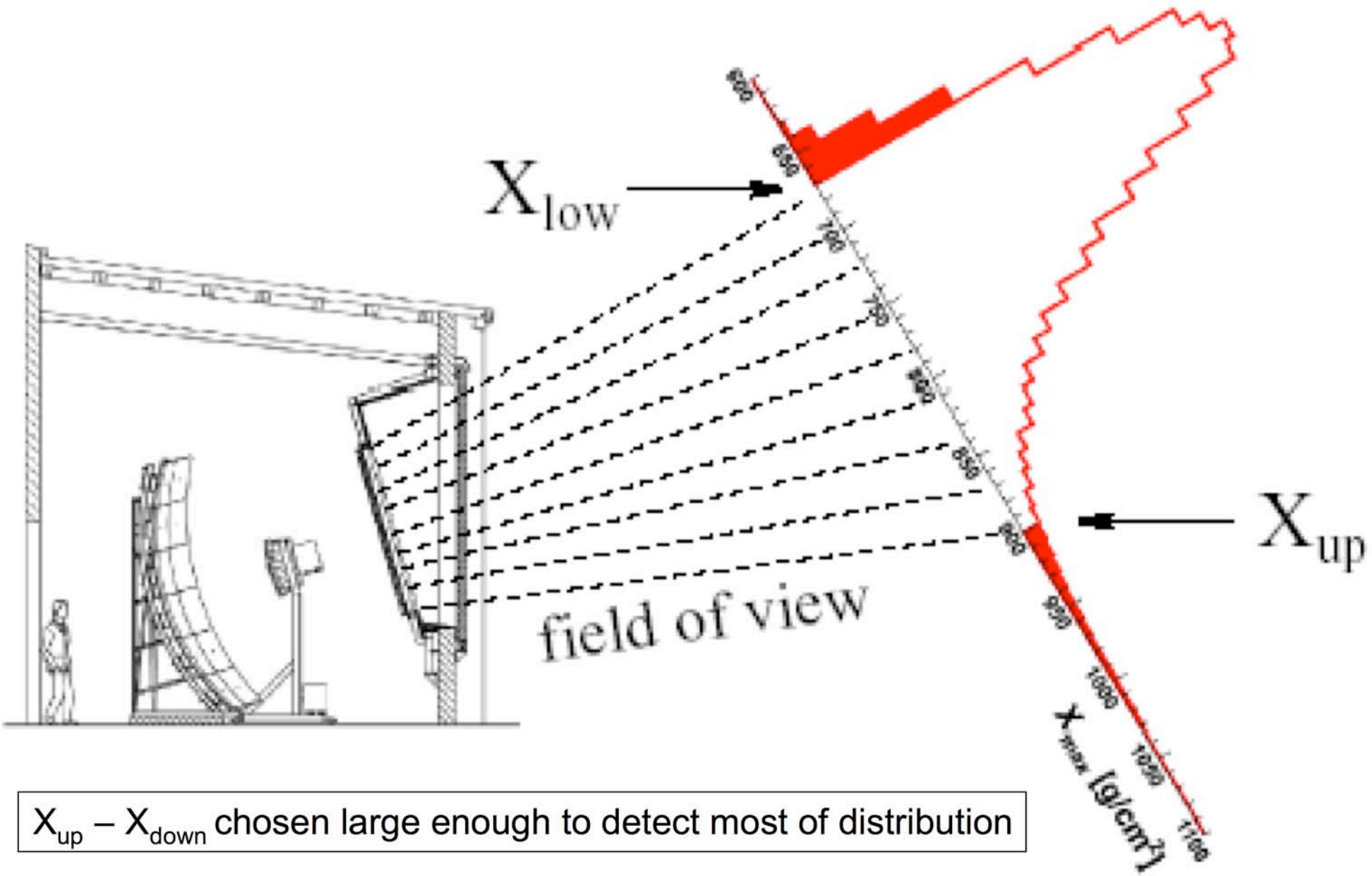
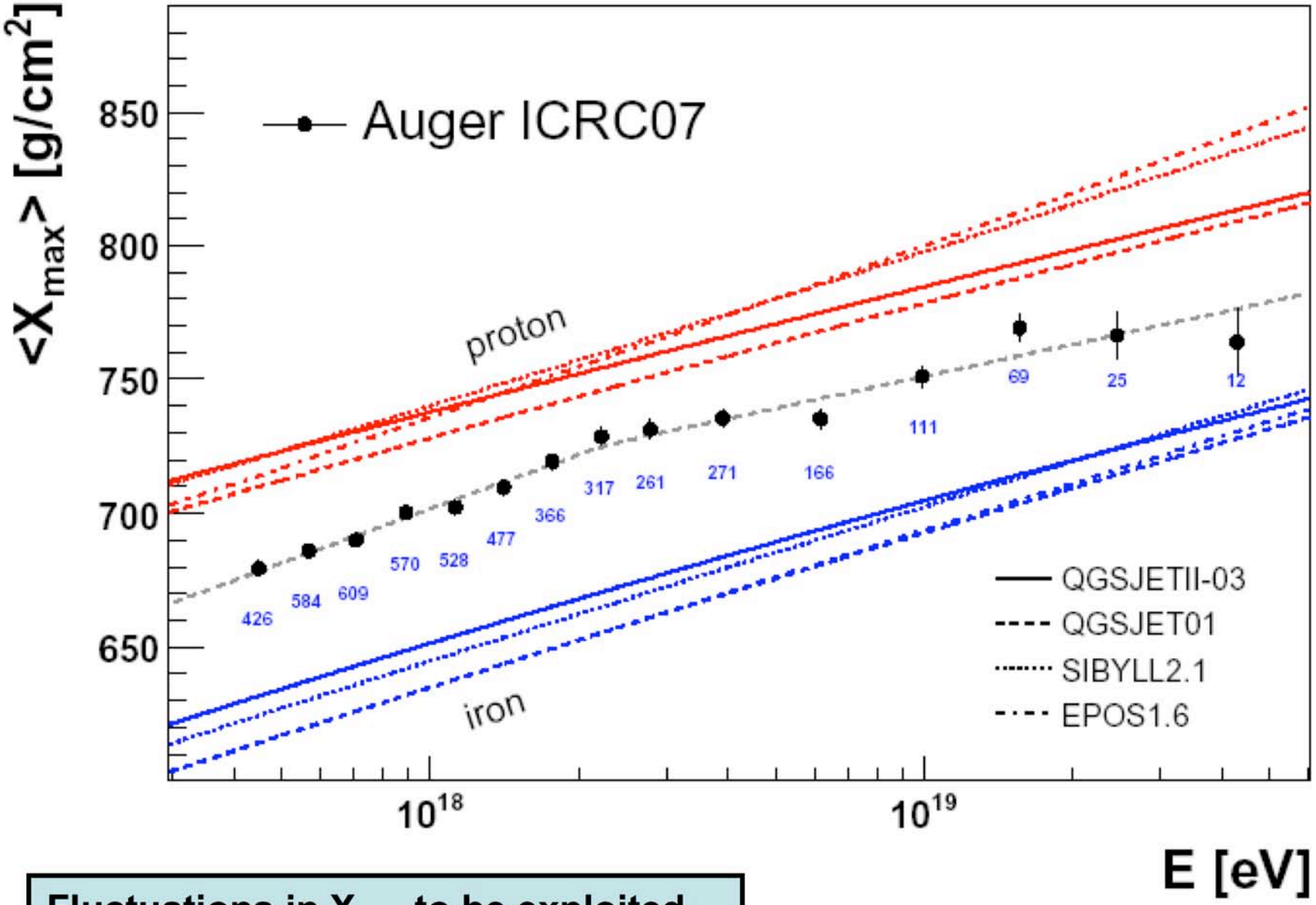


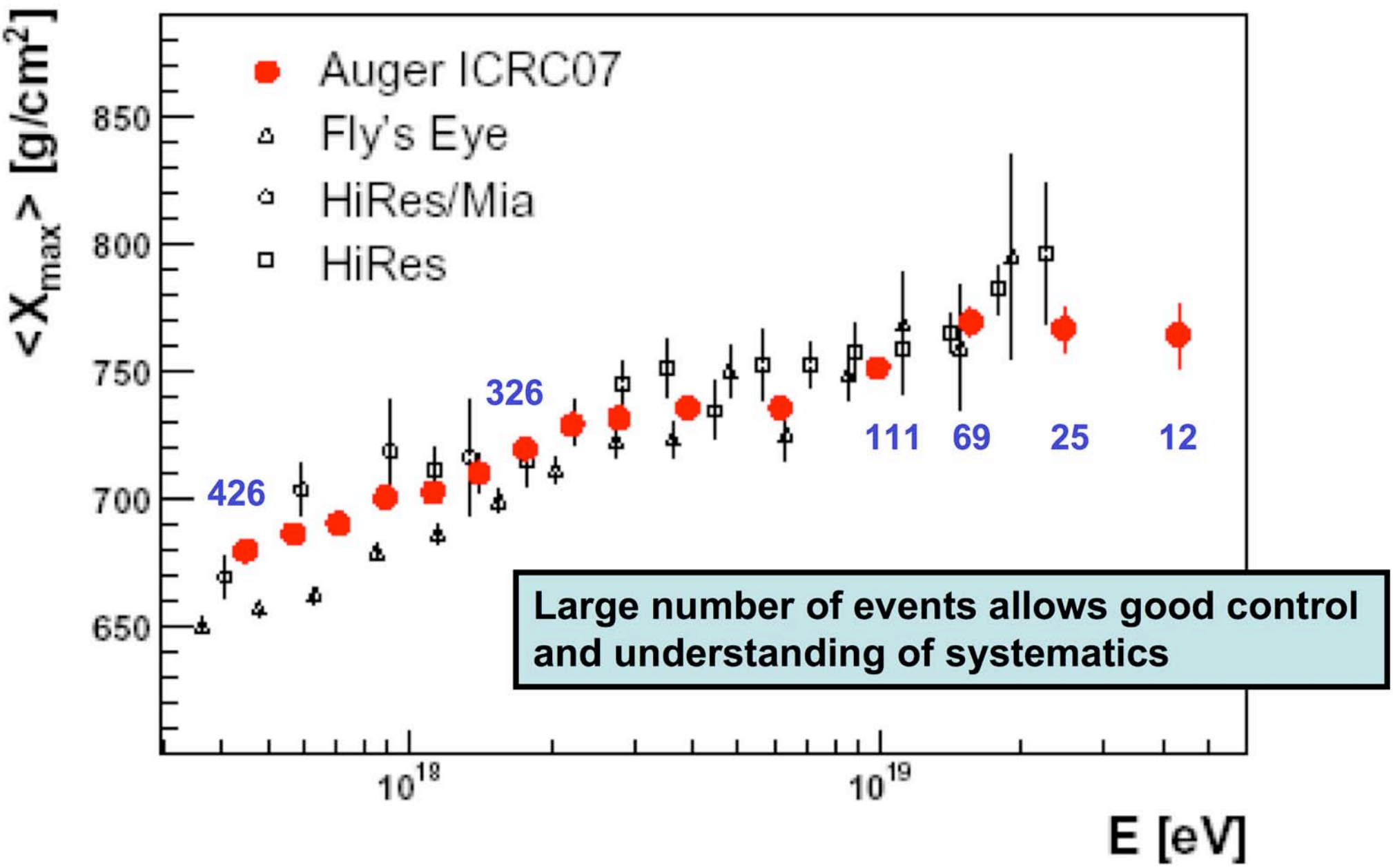



$X_{up} - X_{down}$ chosen large enough to detect most of distribution

# Elongation Rate measured over two decades of energy




**Fluctuations in $X_{max}$ to be exploited**


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

# Energy Determination with Auger

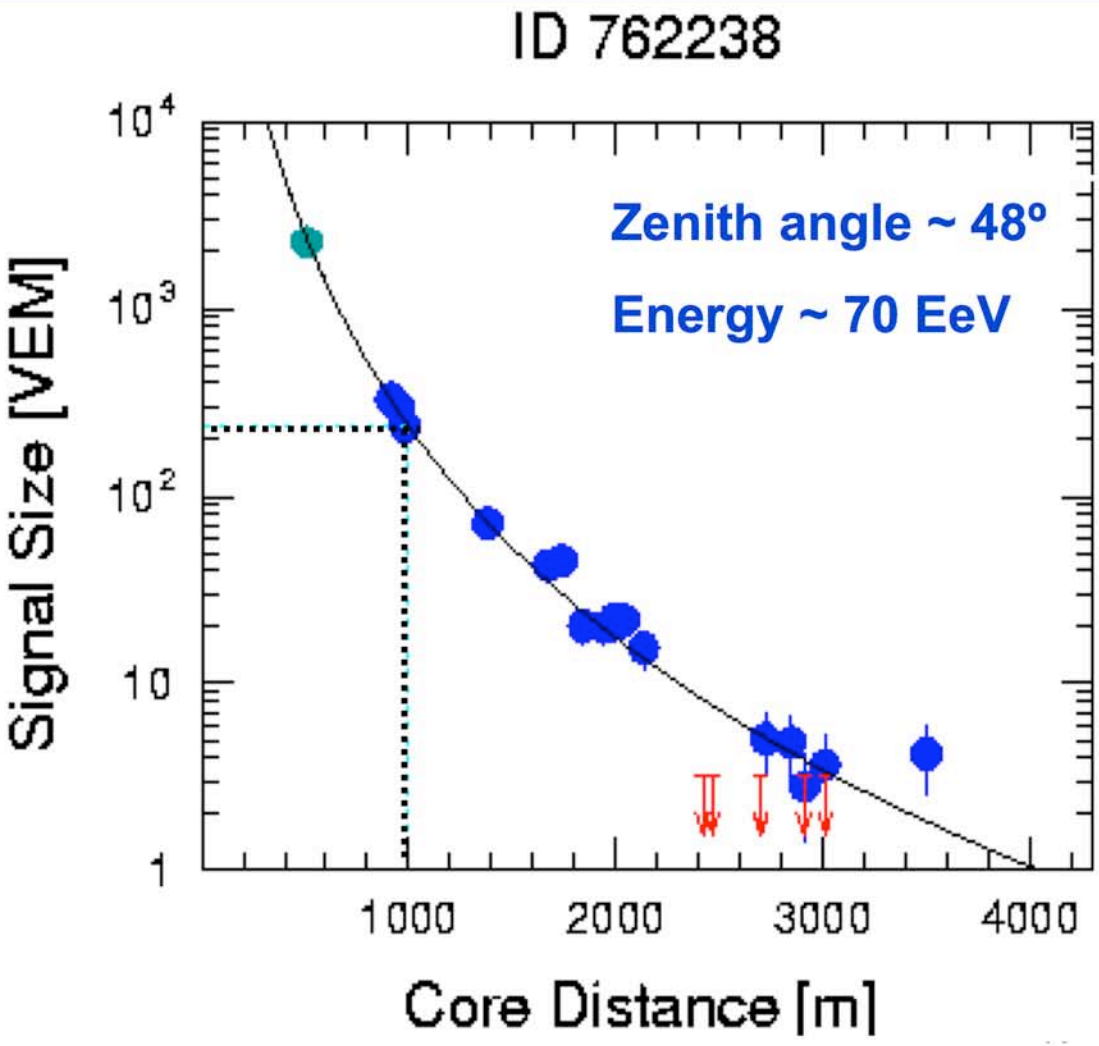
***The energy scale is determined from the data***
***The dependence on knowledge of interaction models or of the primary composition is at level of a few %.***

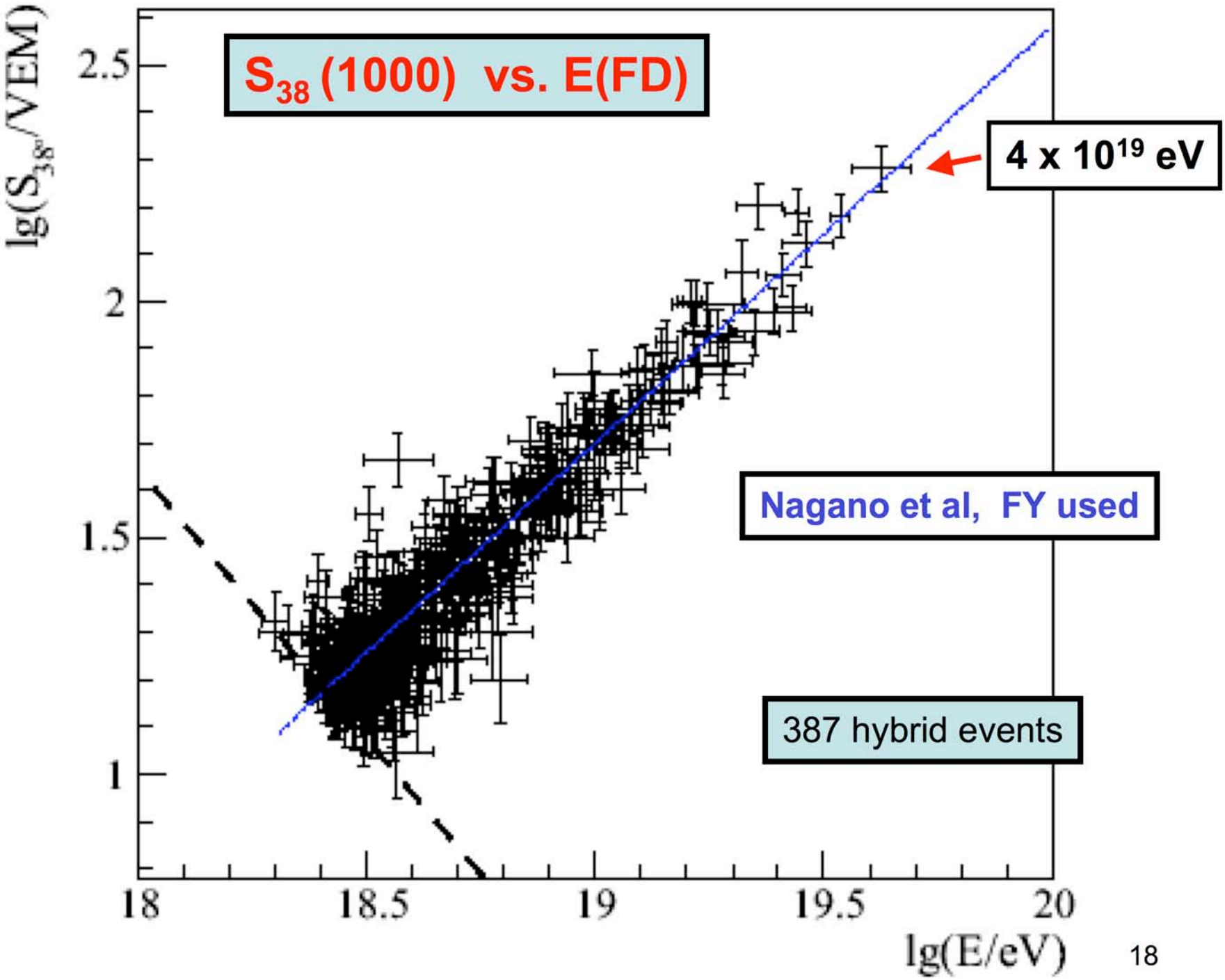
**The detector signal at 1000 m from the shower core**

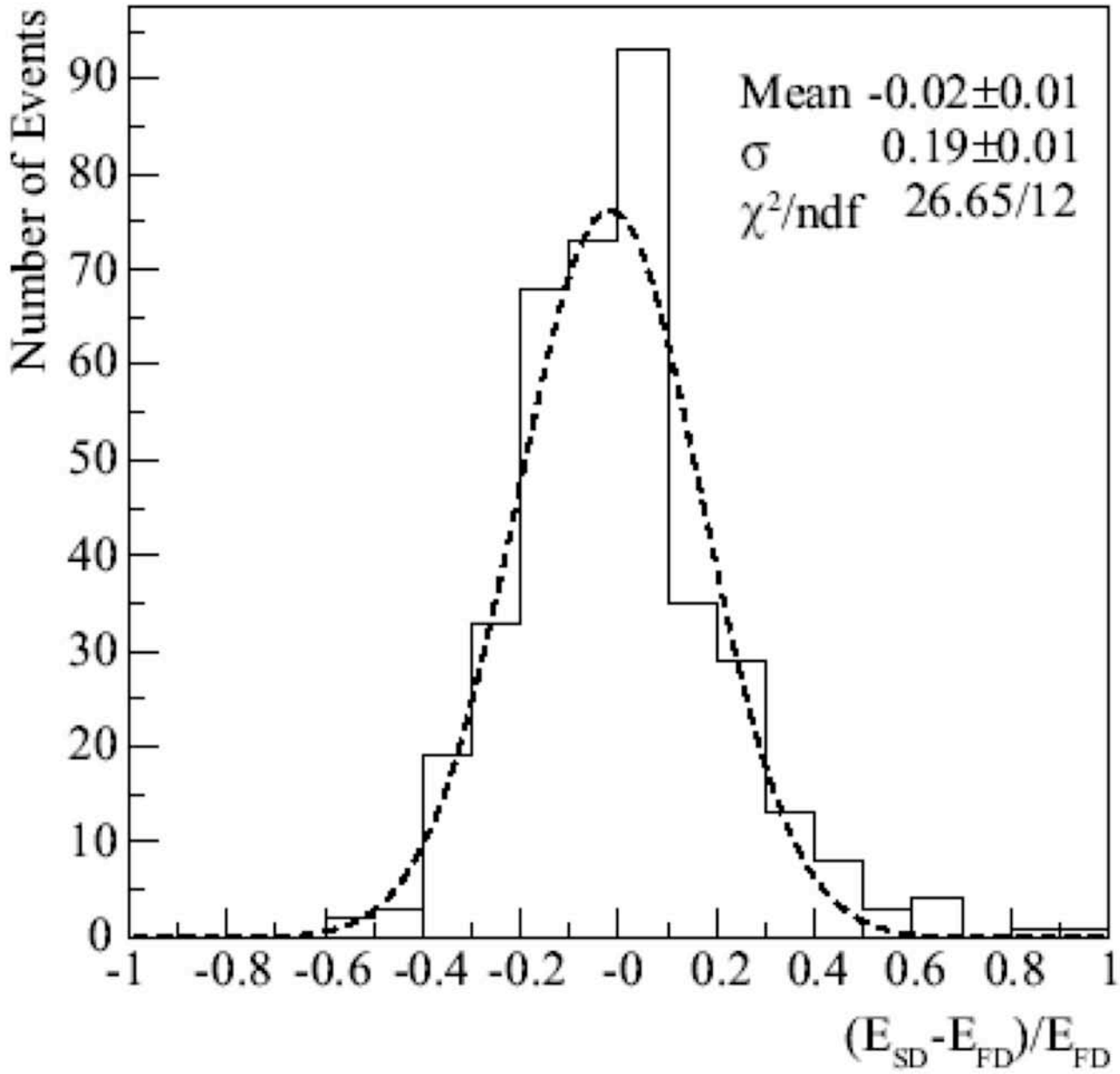
– **S(1000)**

- determined for each surface detector event

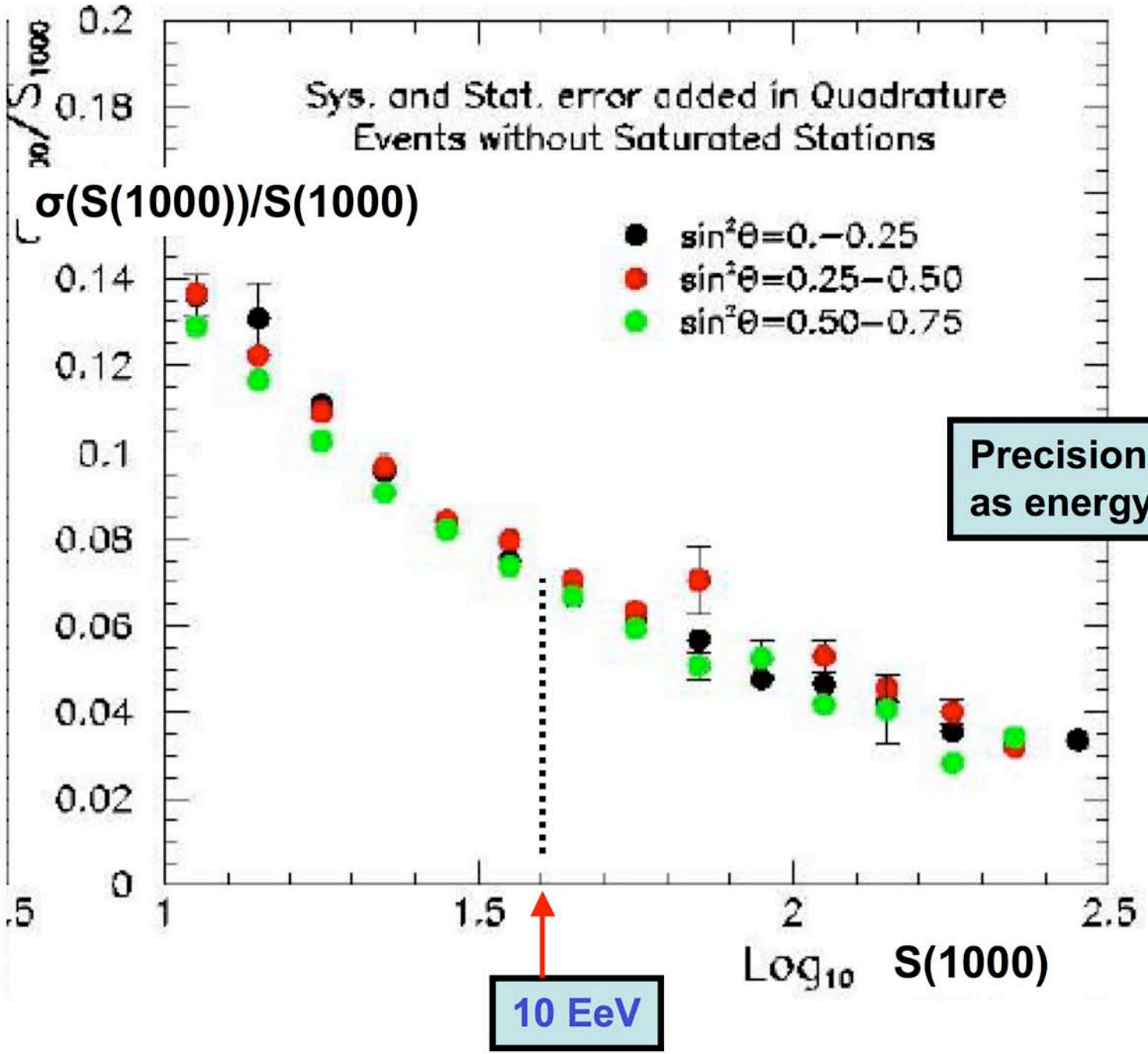
**S(1000) is proportional to the primary energy**




$S_{38}$ (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



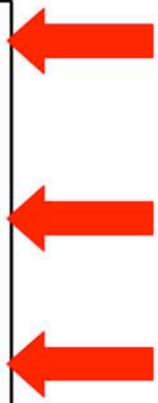

Fractional difference between the FD and SD energy for the 387 selected hybrid events.




**Precision of S(1000) improves as energy increases**

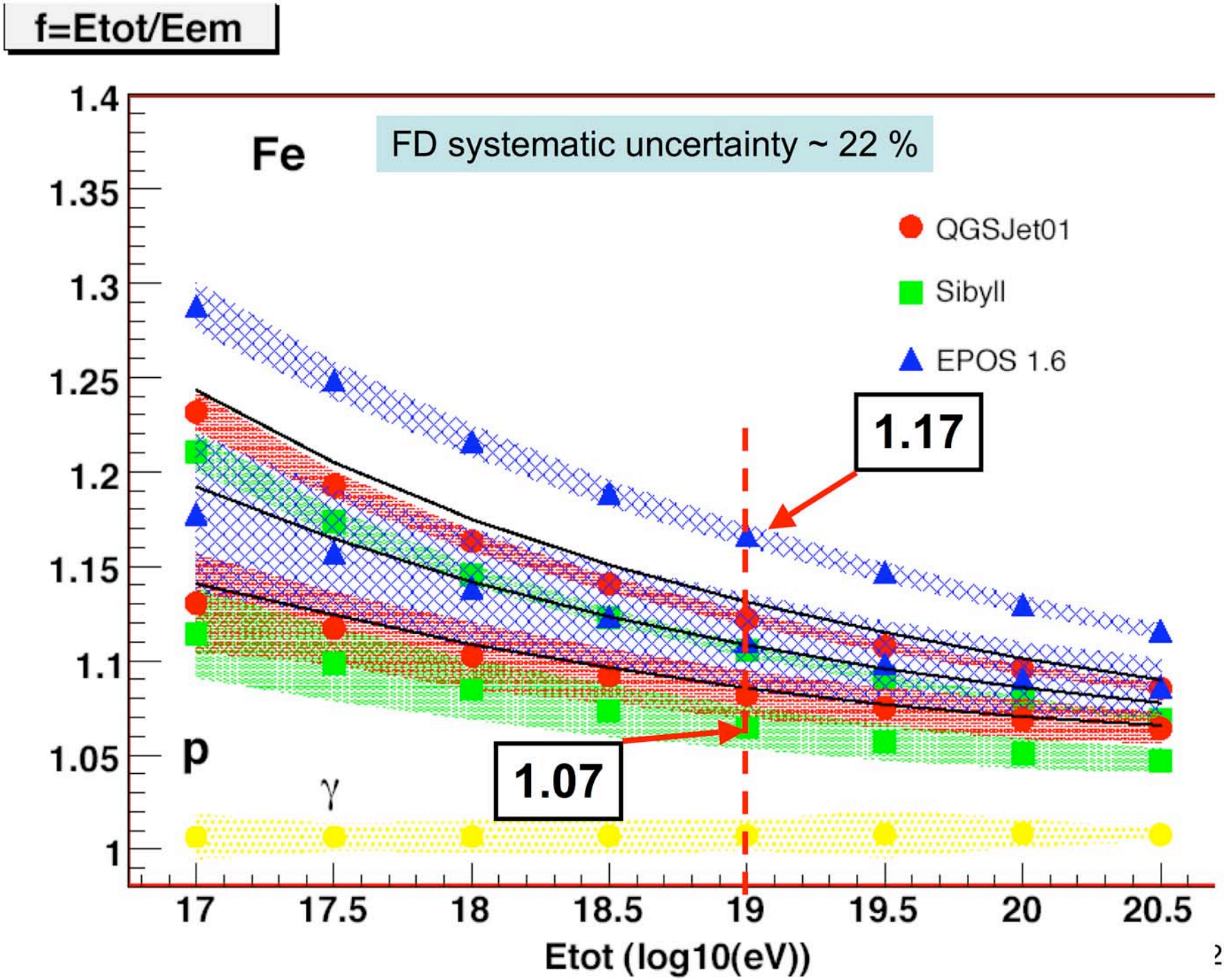
# Summary of systematic uncertainties

| 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% |

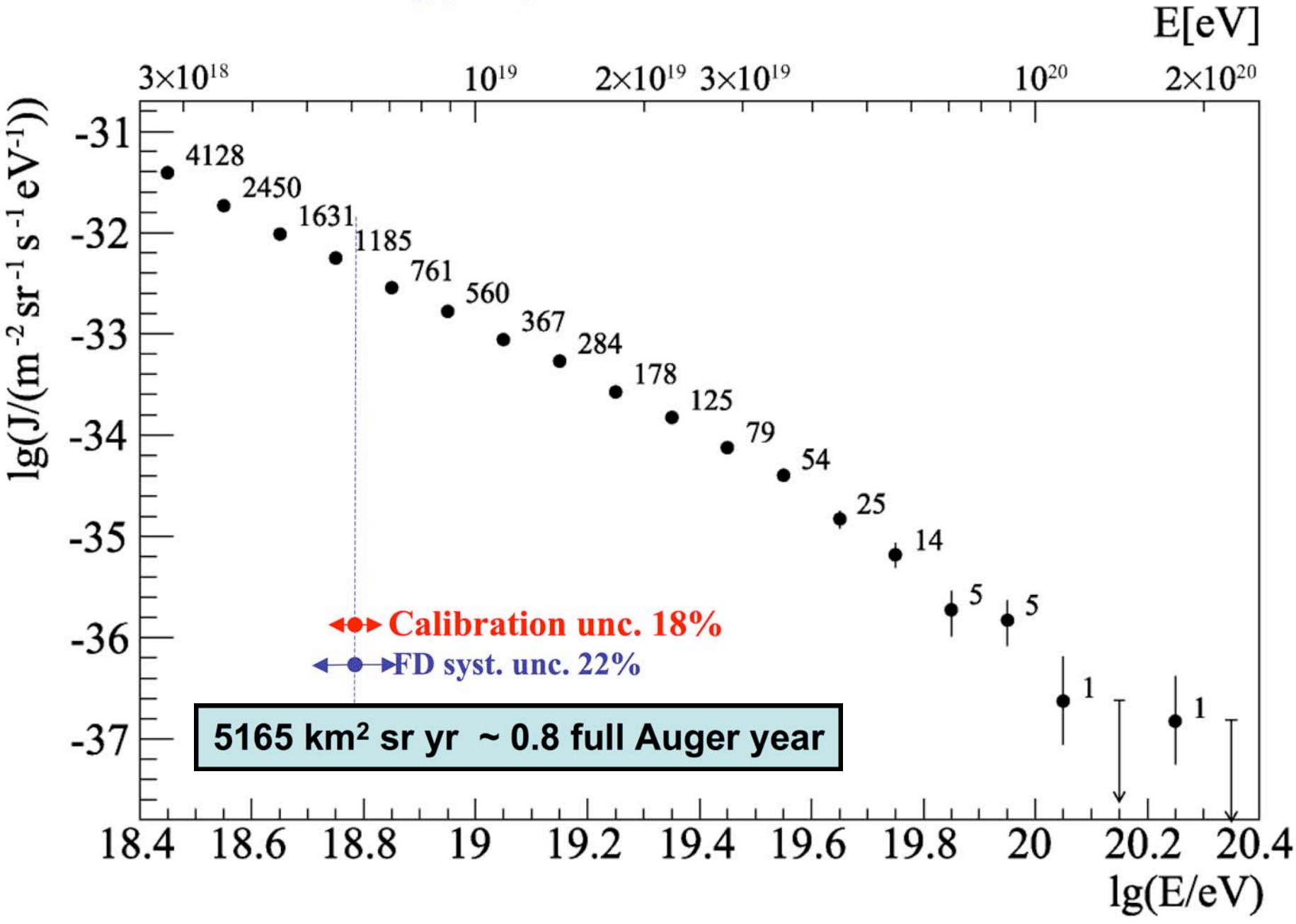


Note: Activity on several fronts to reduce these uncertainties

**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°



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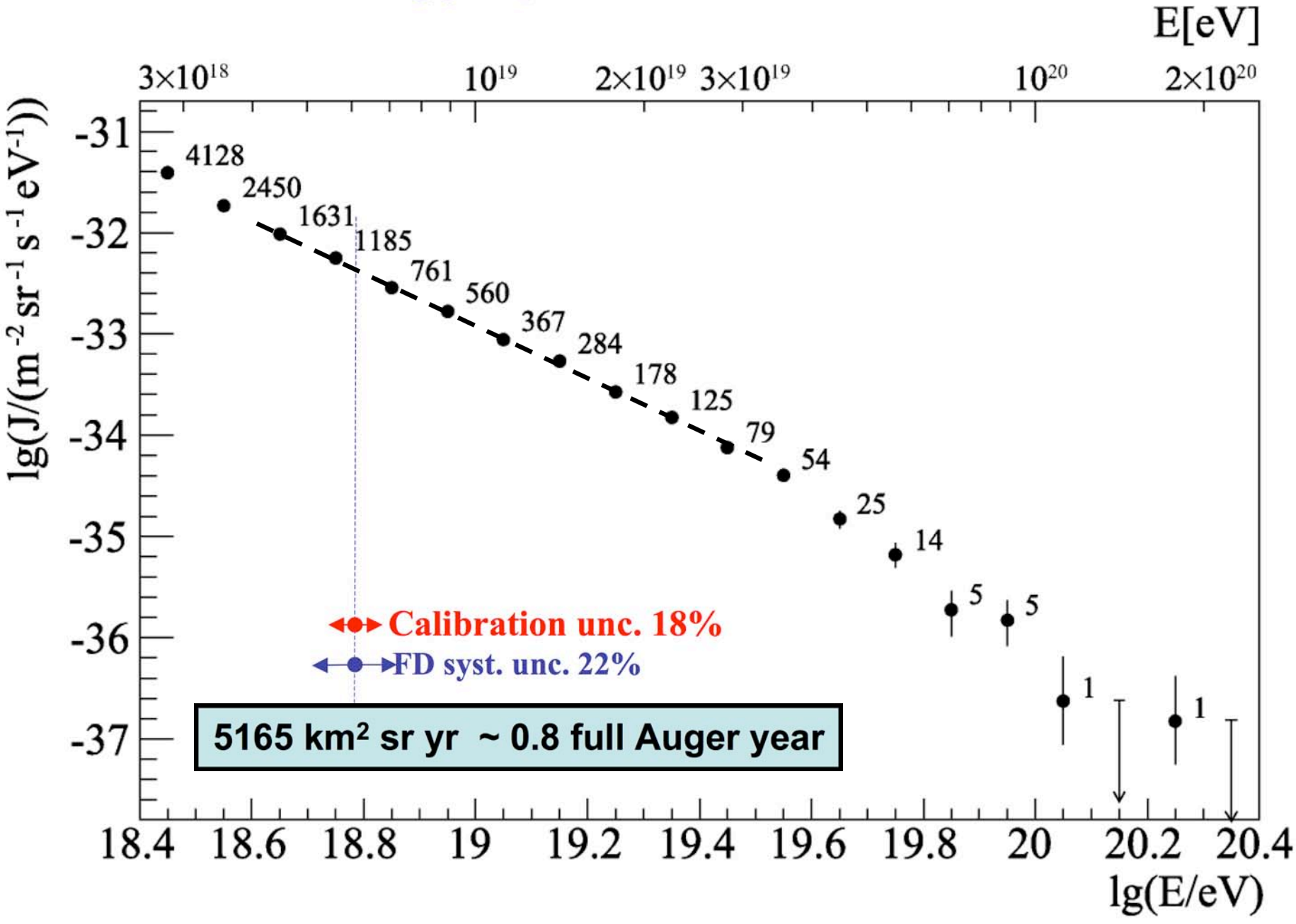

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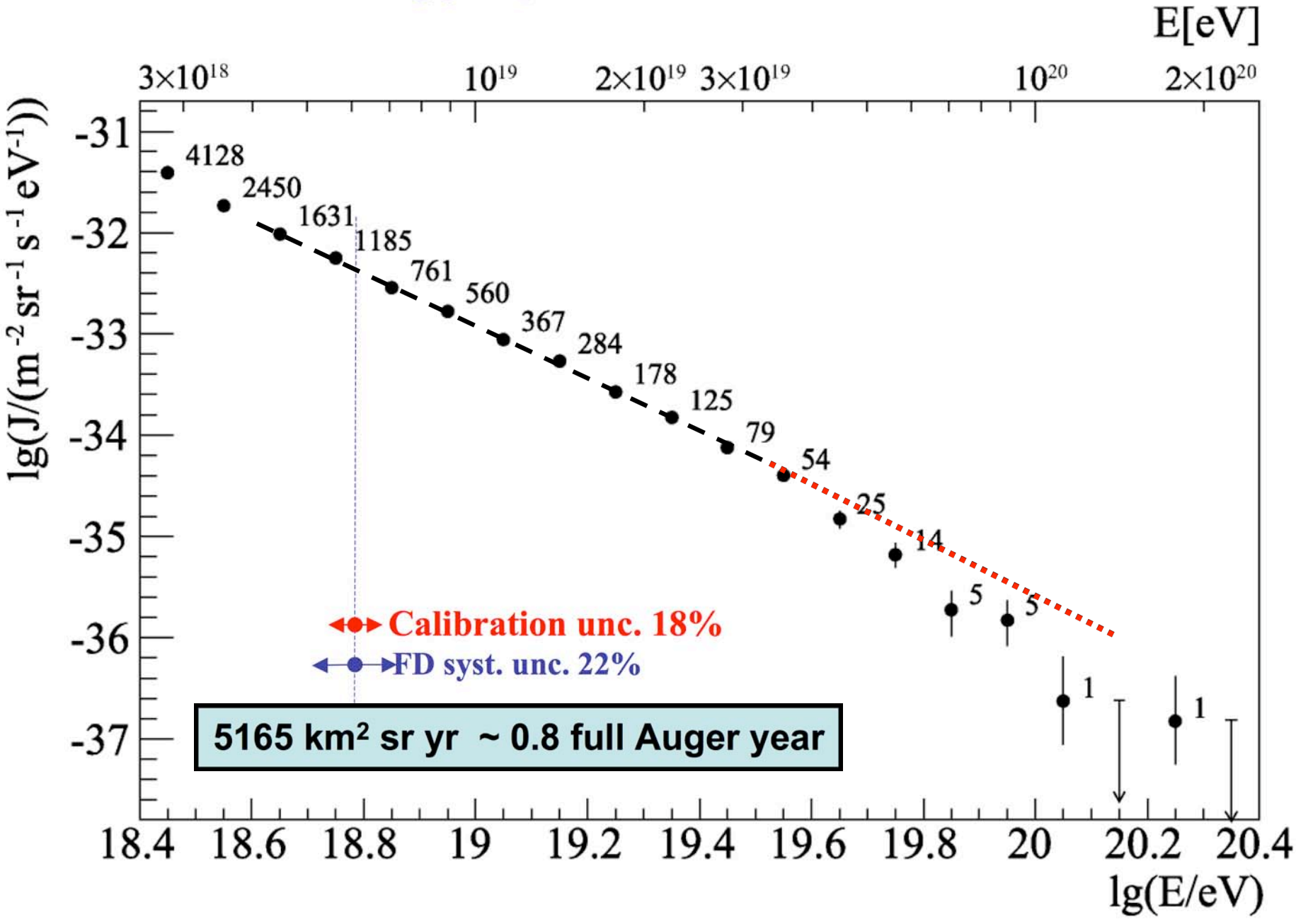

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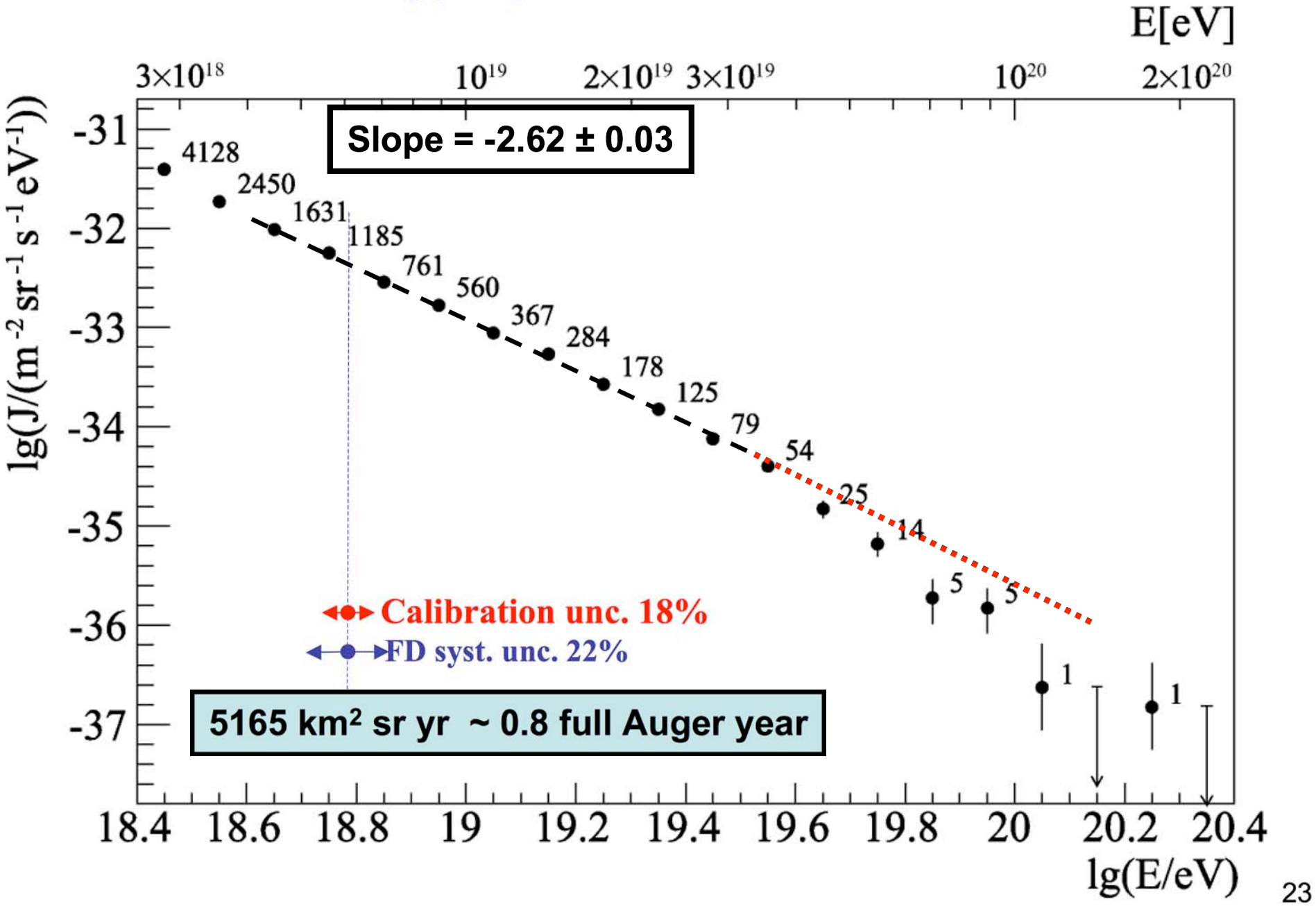

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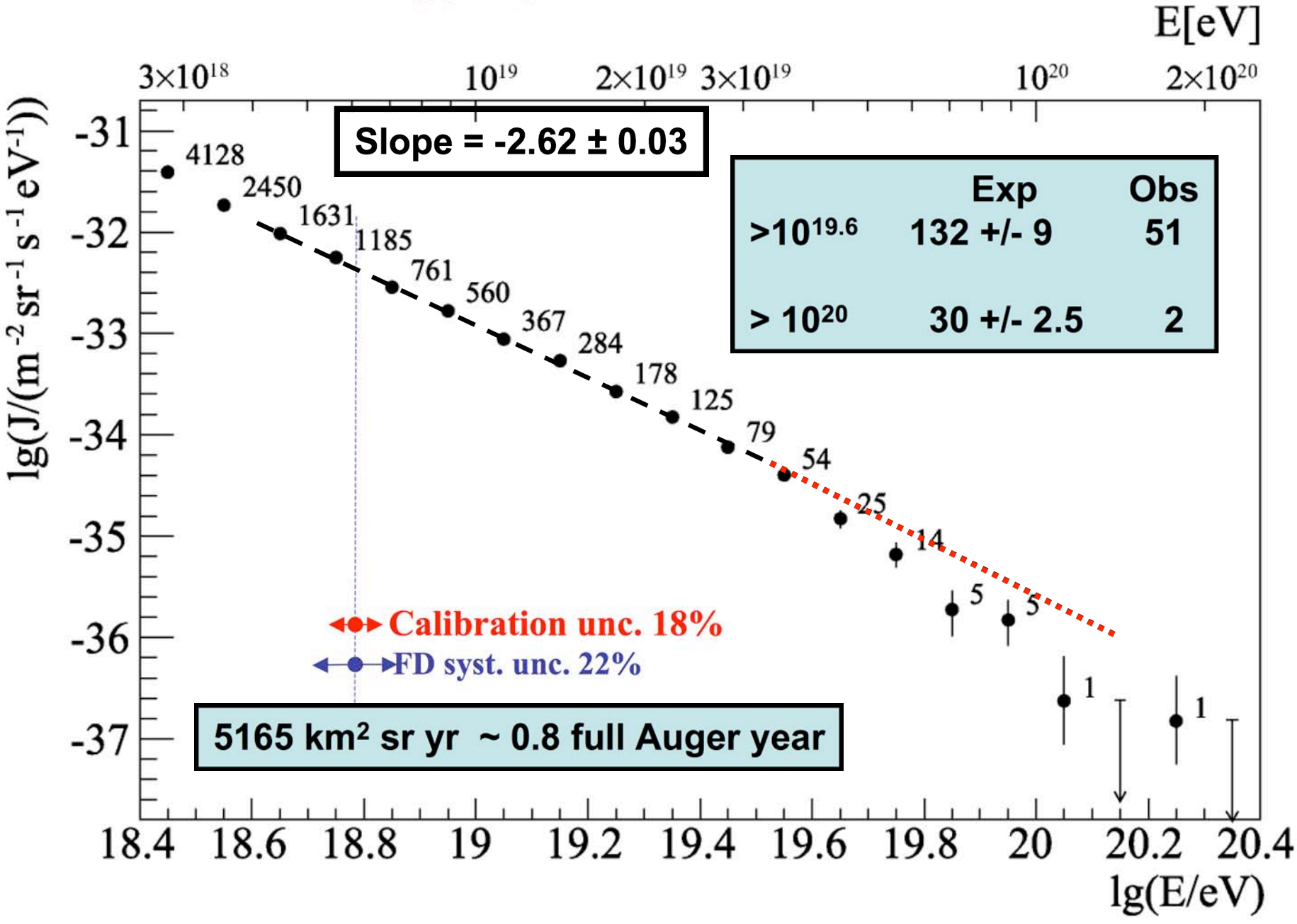
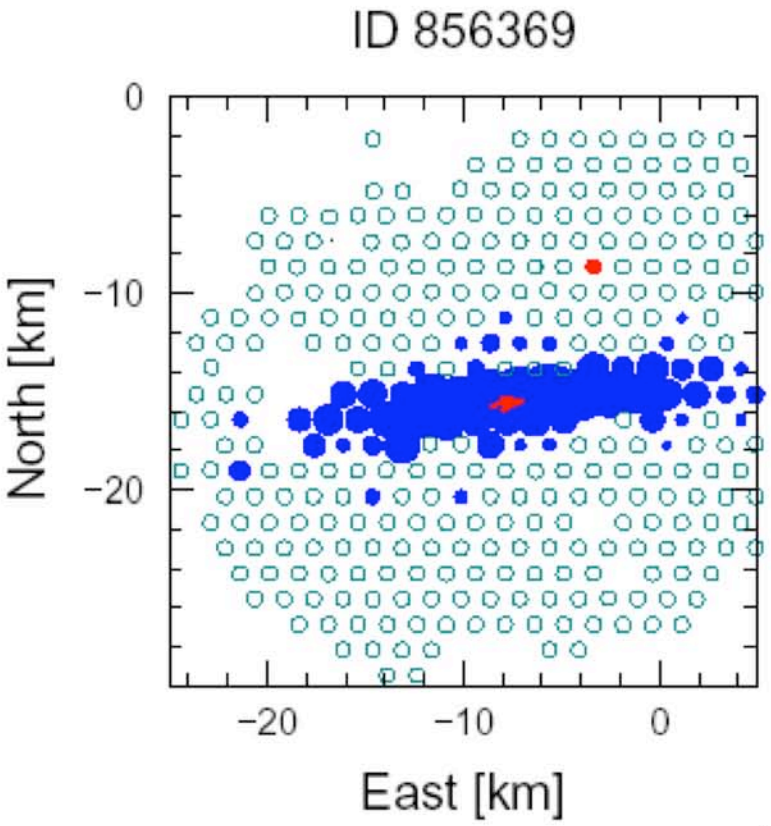
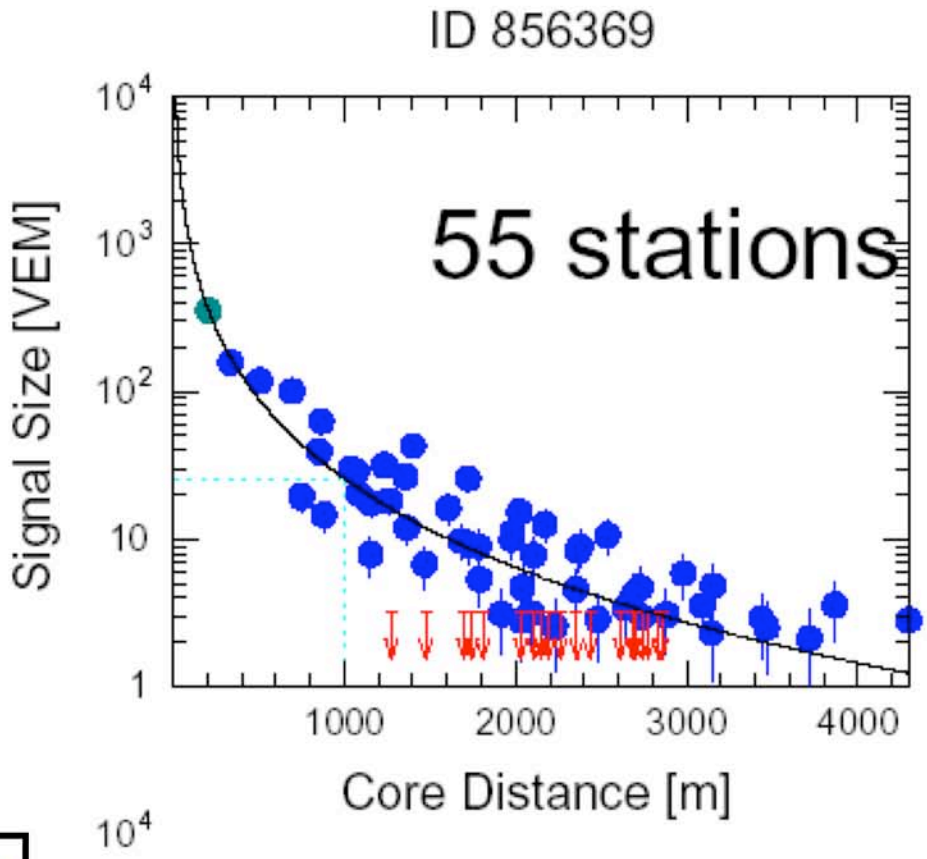


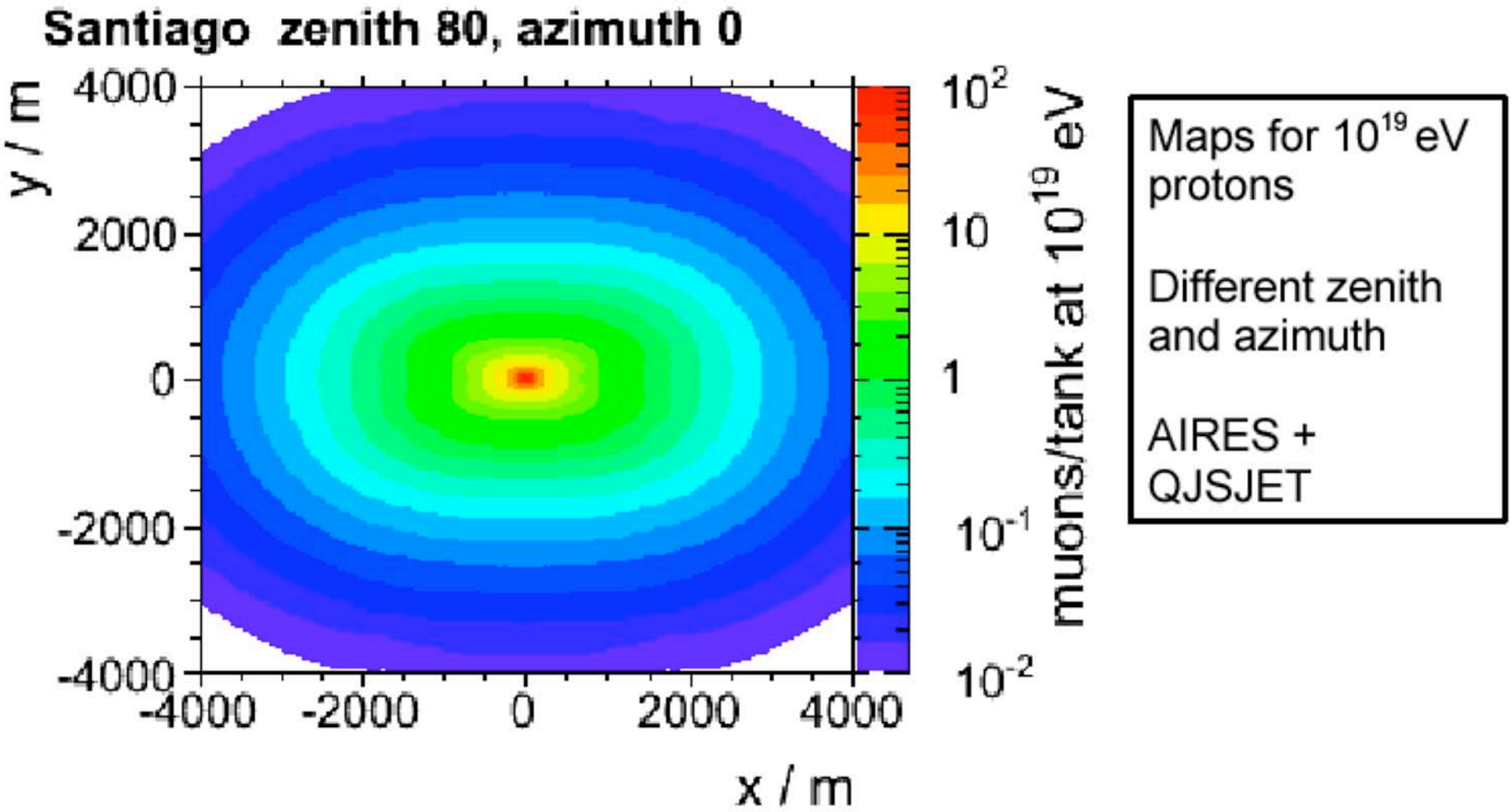
# Inclined Events offer additional aperture



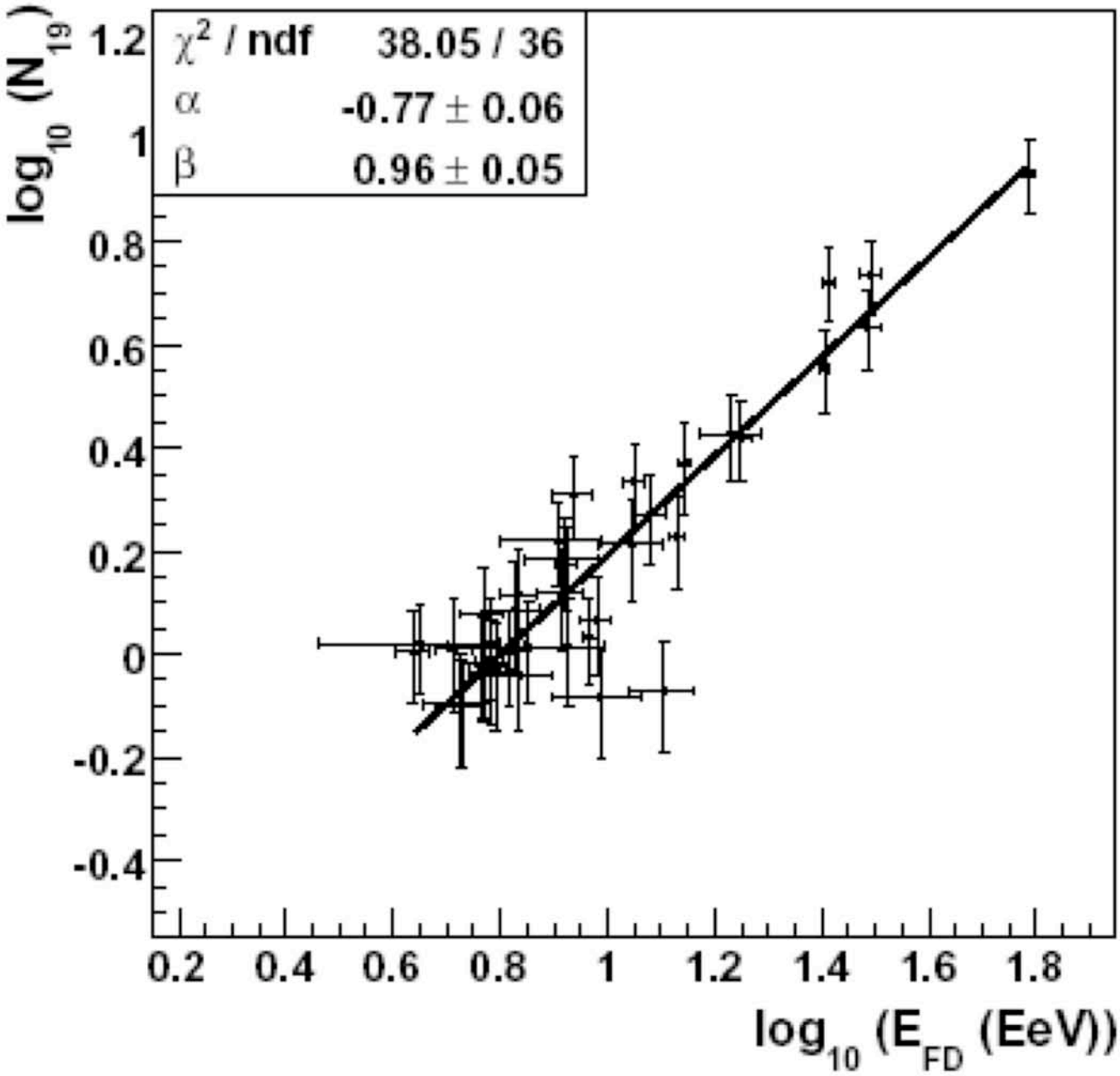




**θ = 79 °**

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

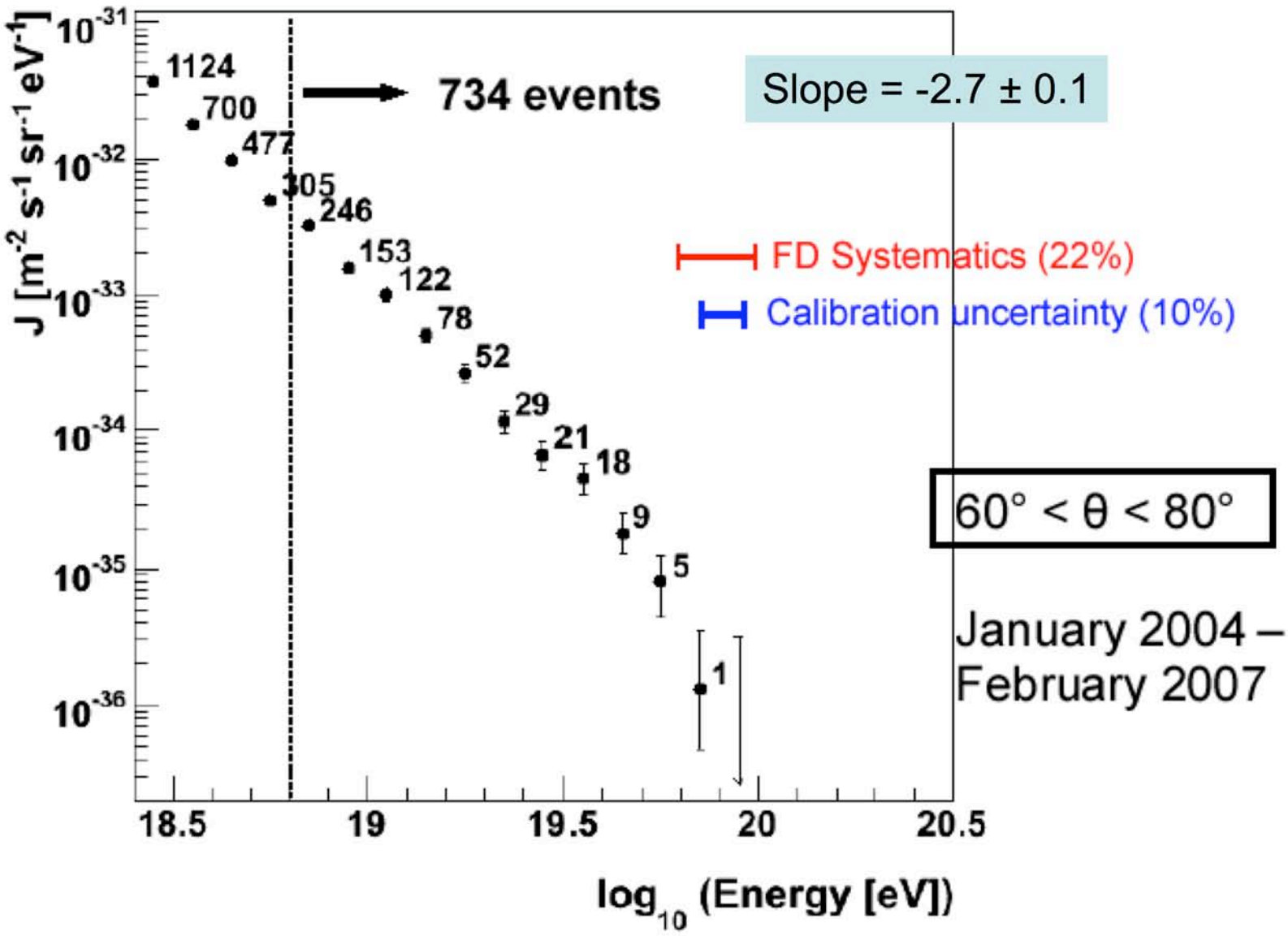



**The shape of the map is mass and model independent**

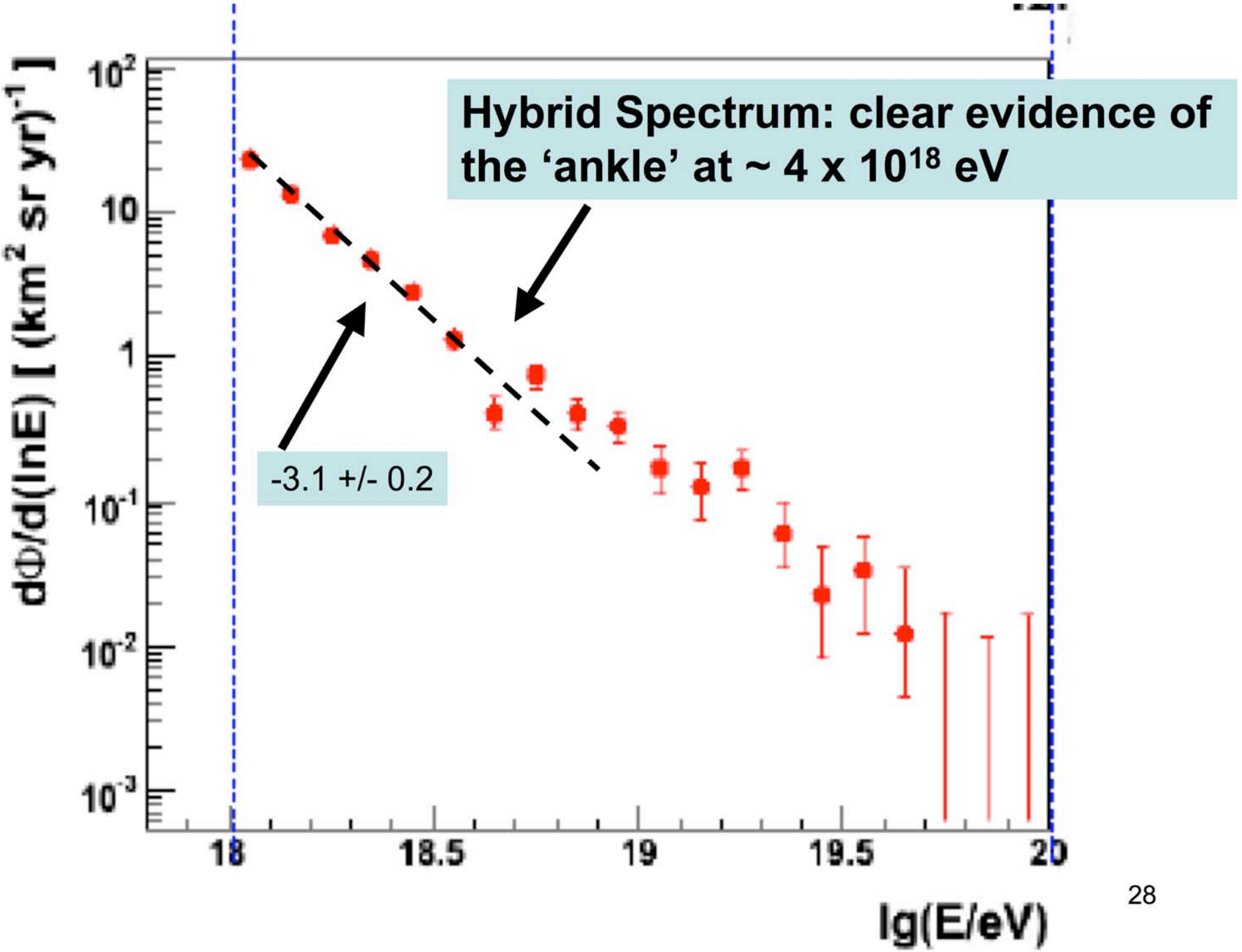


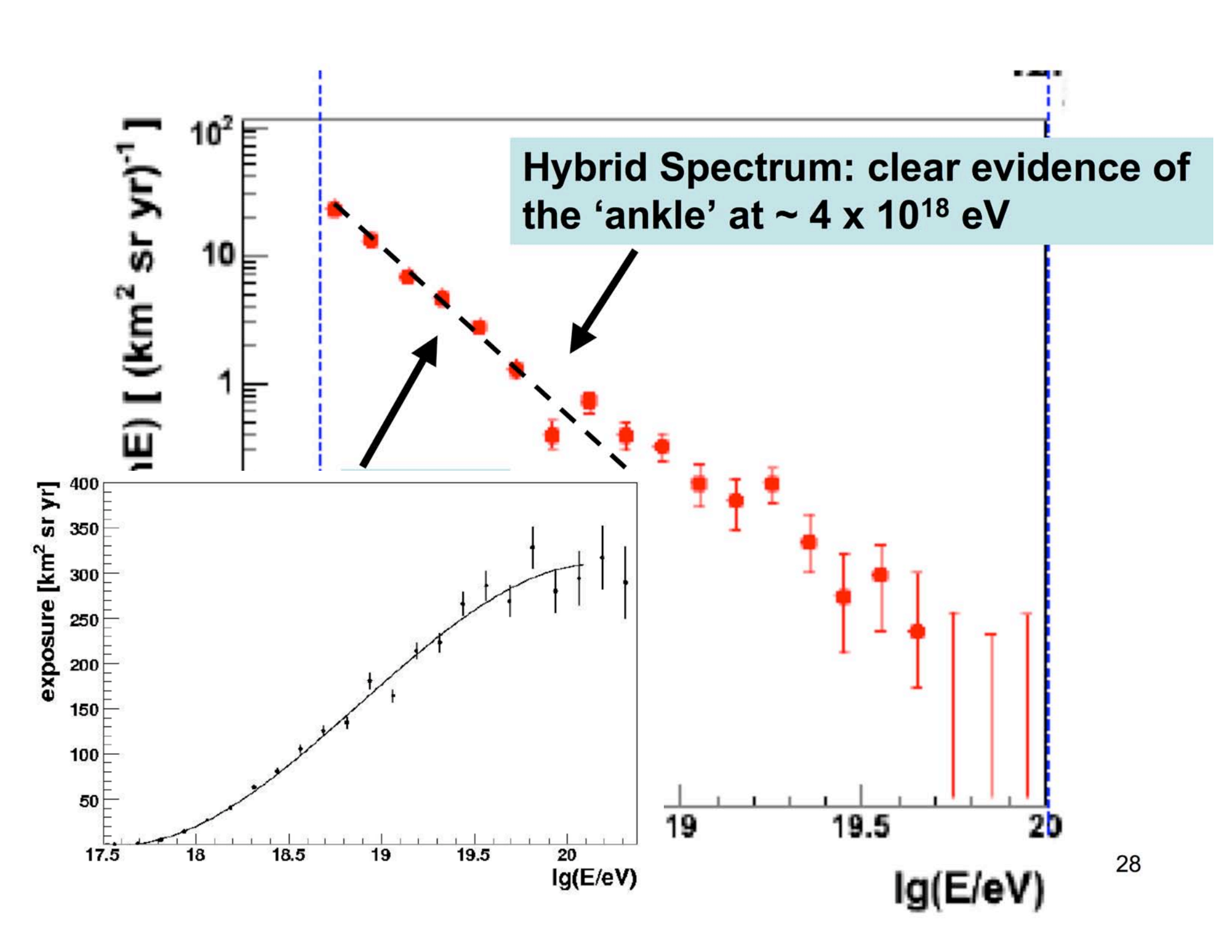

**Calibration curve for inclined showers**

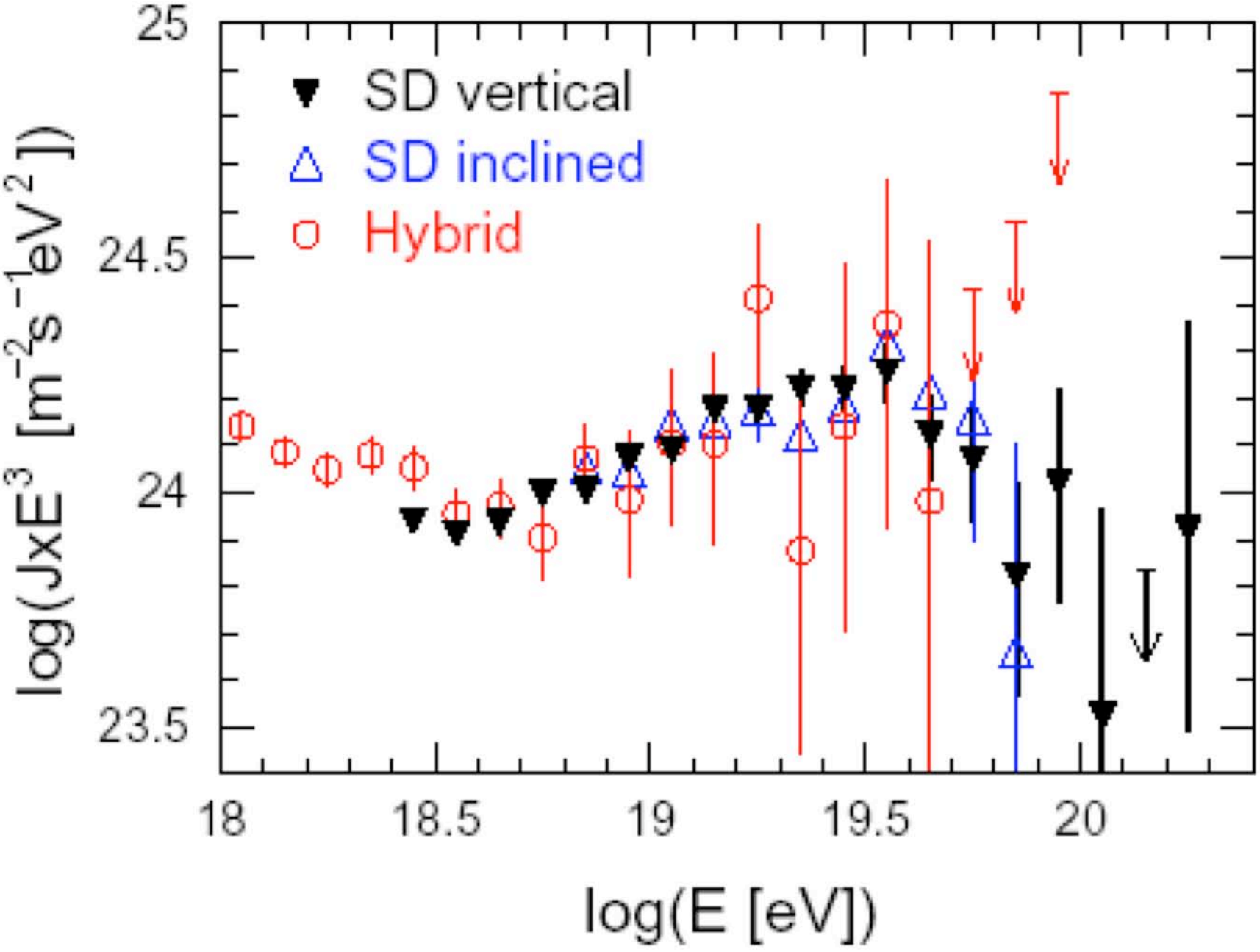
# Inclined events energy spectrum

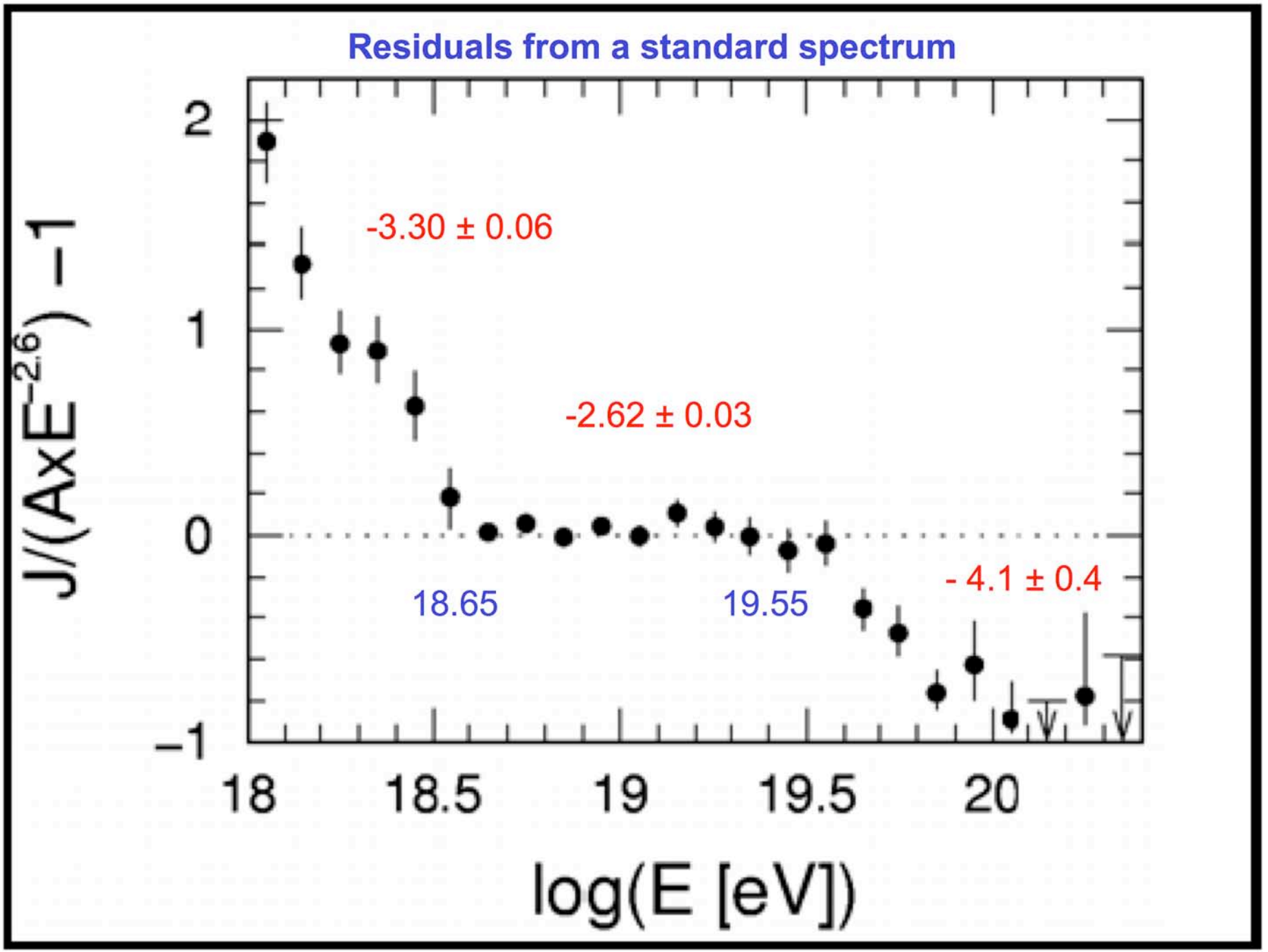


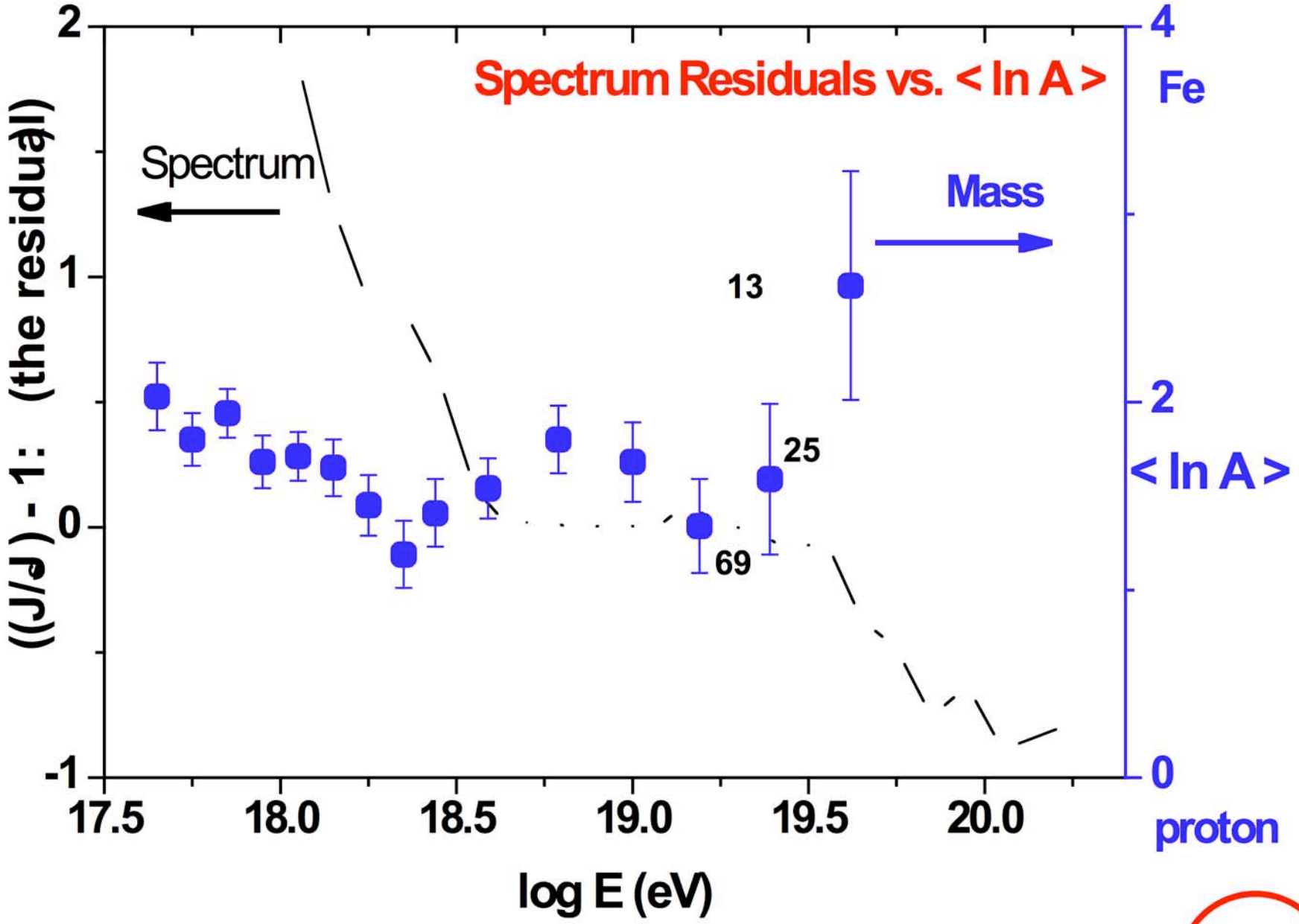

**Exposure 1510 km$^2$ yr sr (29% of θ<60°)**


Hybrid Spectrum: clear evidence of the 'ankle' at ~ 4 x 10^18 eV
-3.1 +/- 0.2
dΦ/d(lnE) [ (km^2 sr yr)^-1 ]
10^2
10
1
10^-1
10^-2
10^-3
18
18.5
19
19.5
20
lg(E/eV)

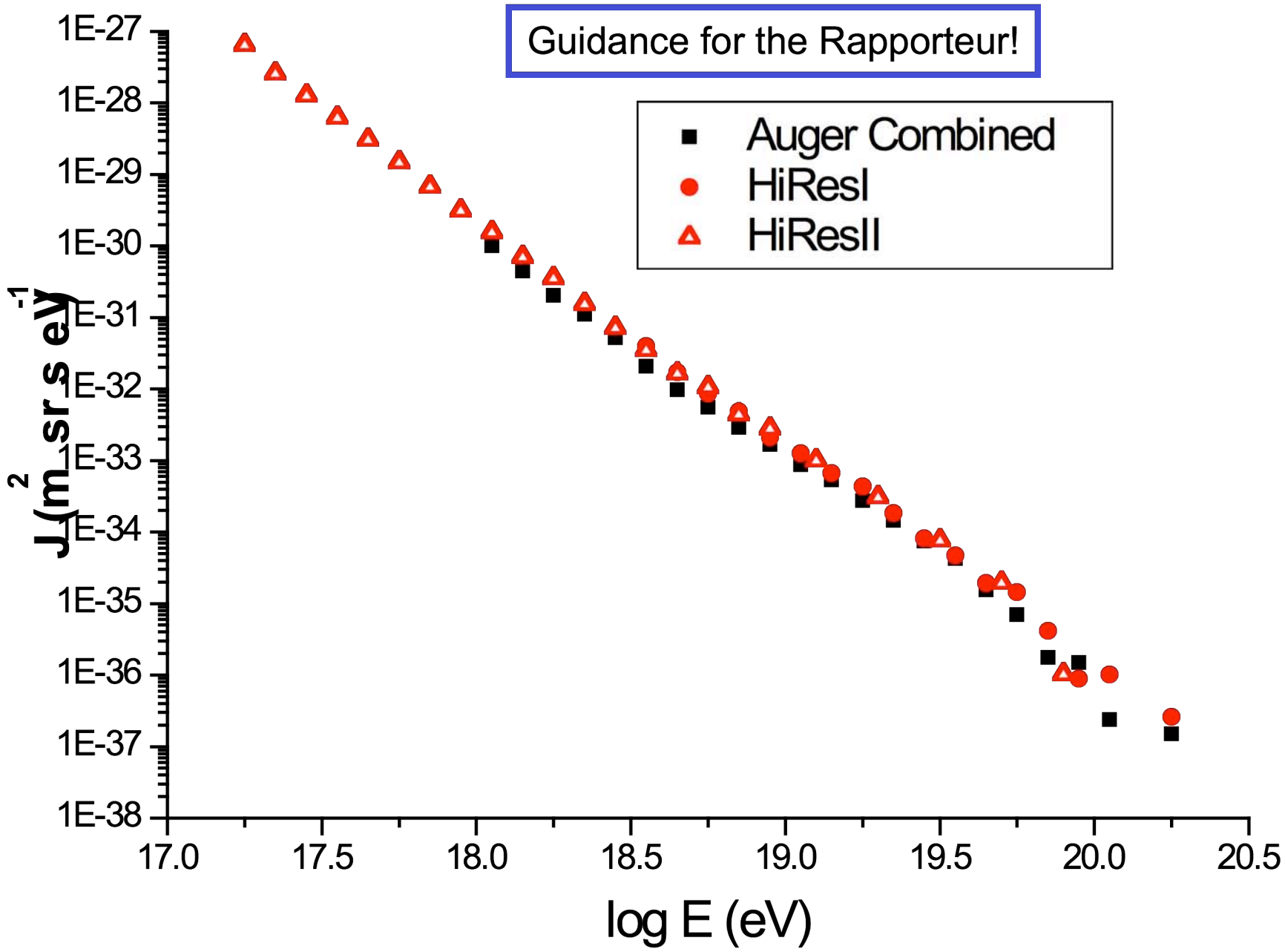

Hybrid Spectrum: clear evidence of the 'ankle' at ~ 4 x 10^18 eV
exposure [km^2 sr yr]
lg(E/eV)
lg(E/eV)

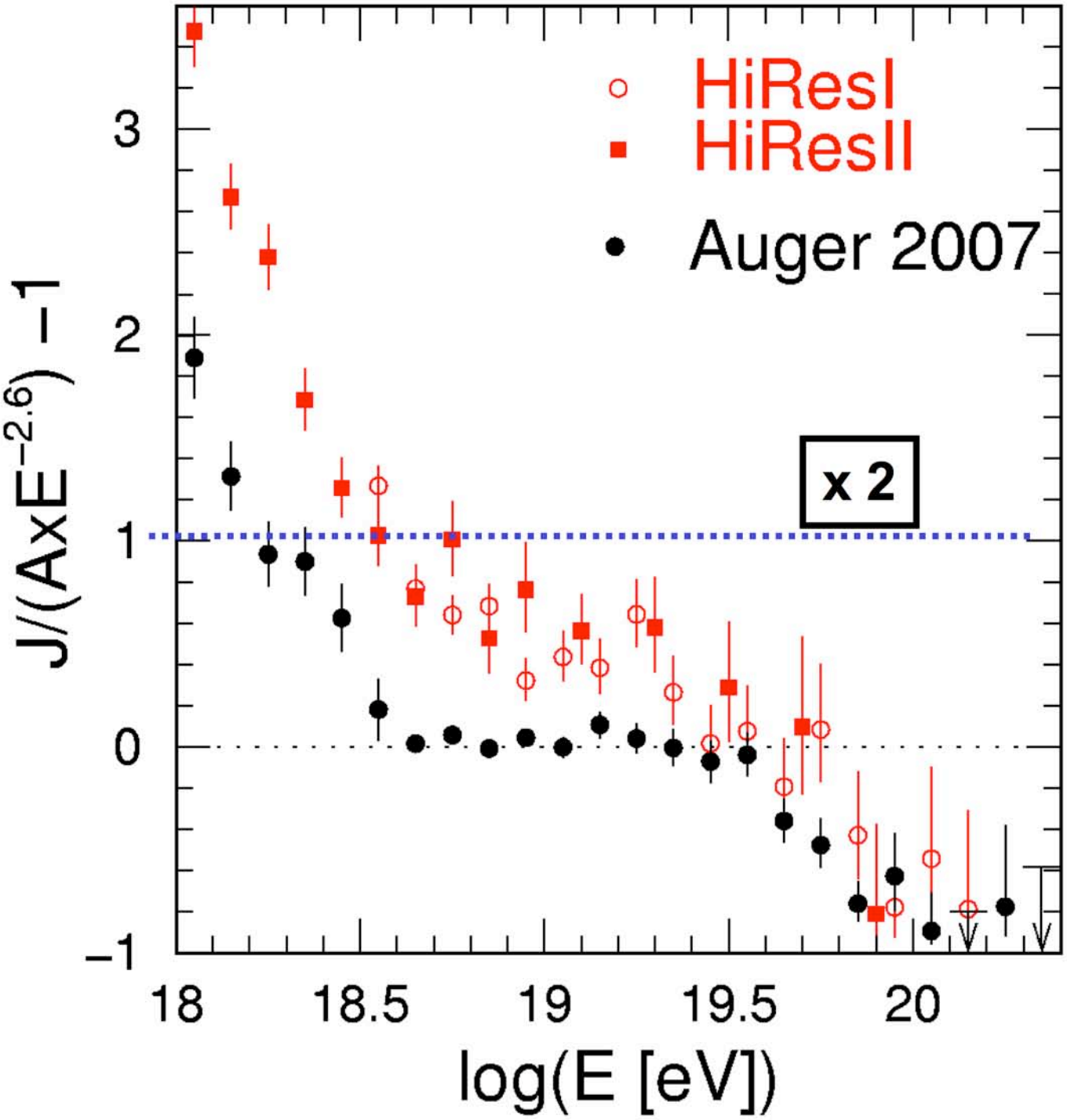

SD vertical
SD inclined
Hybrid
log(JxE^3 [m^-2 s^-1 eV^2])
log(E [eV])
25
24.5
24
23.5
18
18.5
19
19.5
20

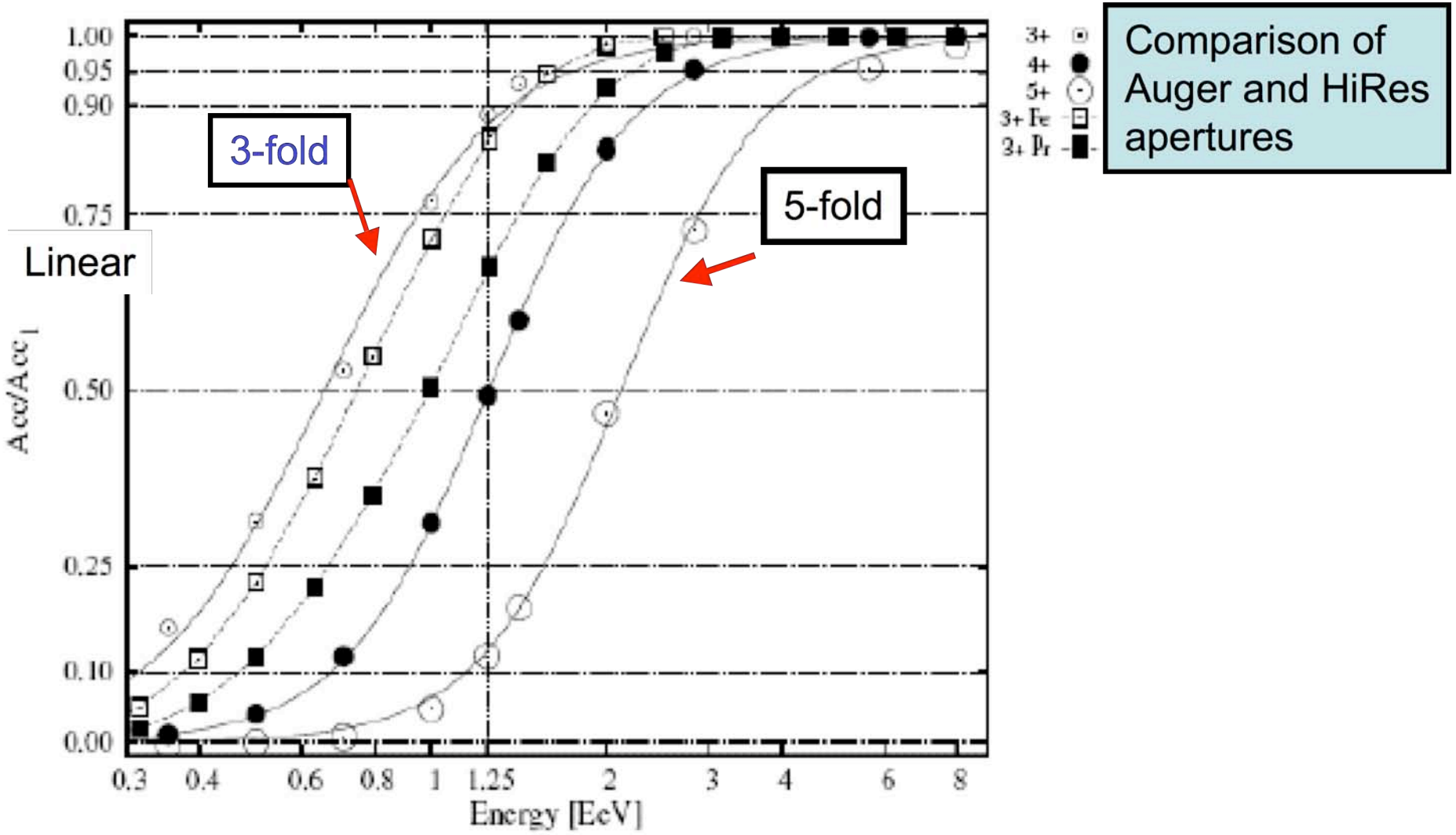

Residuals from a standard spectrum
2
1
0
−1
J/(AxE^-2.6) −1
-3.30 ± 0.06
-2.62 ± 0.03
- 4.1 ± 0.4
18.65
19.55
18
18.5
19
19.5
20
log(E [eV])

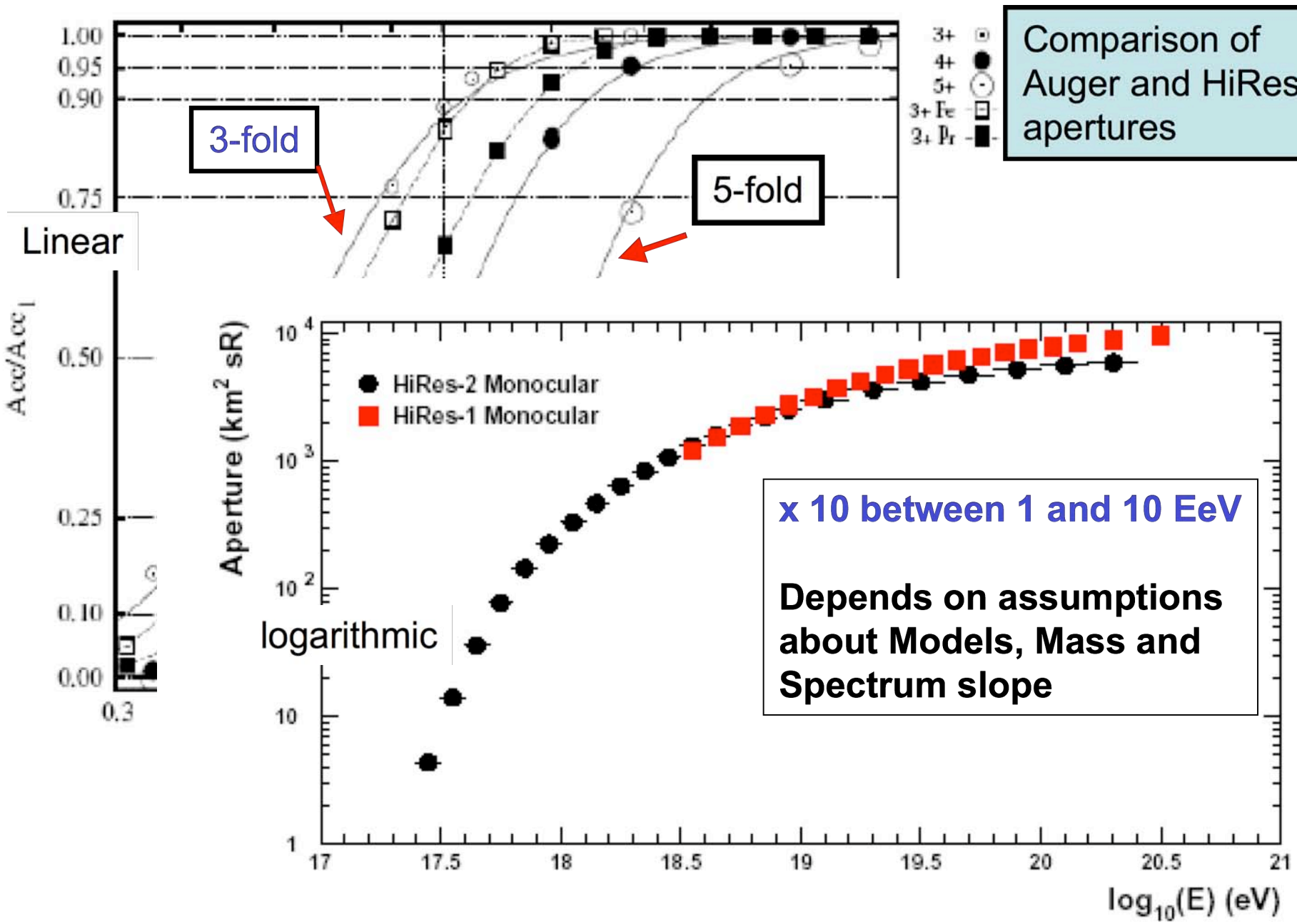

Spectrum Residuals vs. < ln A >
Spectrum
Mass
13
25
69
((J/J) - 1: (the residual)
log E (eV)
< ln A >
Fe
proton
2
1
0
-1
4
2
0
17.5
18.0
18.5
19.0
19.5
20.0

Guidance for the Rapporteur!

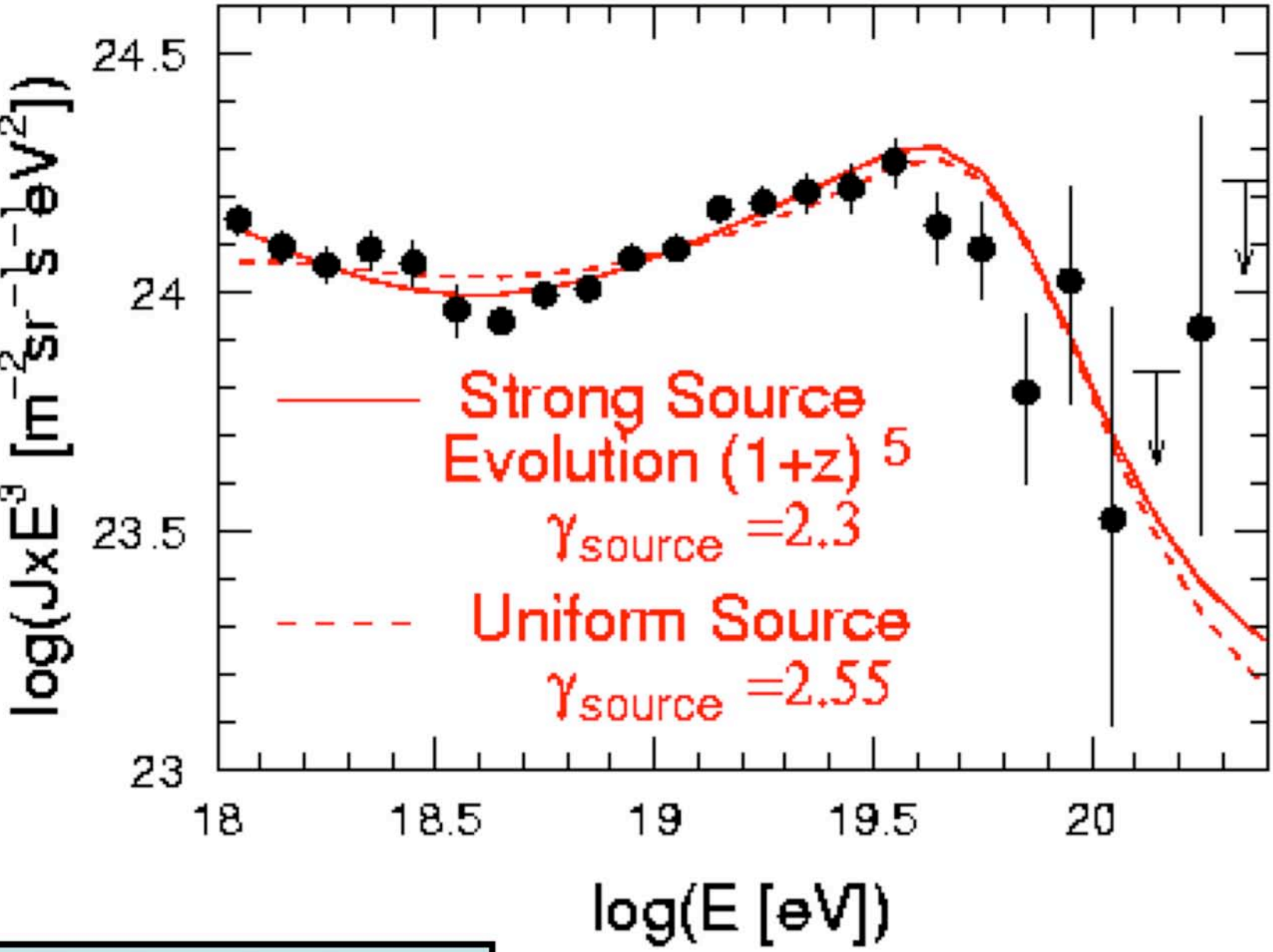

Guidance for the Rapporteur!
Auger Combined
HiResI
HiResII
J (m^-2 sr^-1 s^-1 eV)
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
1E-33
1E-34
1E-35
1E-36
1E-37
1E-38
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log E (eV)


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


Comparison of Auger and HiRes apertures
3-fold
5-fold
Linear
Acc/Acc$_1$
Energy [EeV]
1.00
0.95
0.90
0.75
0.50
0.25
0.10
0.00
0.3
0.4
0.6
0.8
1
1.25
2
3
4
6
8
3+
4+
5+
3+ Fe
3+ P$_r$


Comparison of Auger and HiRes apertures
3-fold
5-fold
3+
4+
5+
3+ Fe
3+ Pr
1.00
0.95
0.90
0.75
Linear
Acc/Acc$_1$
0.50
0.25
0.10
0.00
0.3
Aperture (km$^2$ sR)
$10^4$
$10^3$
$10^2$
10
1
HiRes-2 Monocular
HiRes-1 Monocular
logarithmic
17
17.5
18
18.5
19
19.5
20
20.5
21
log$_{10}$(E) (eV)
x 10 between 1 and 10 EeV
Depends on assumptions about Models, Mass and Spectrum slope

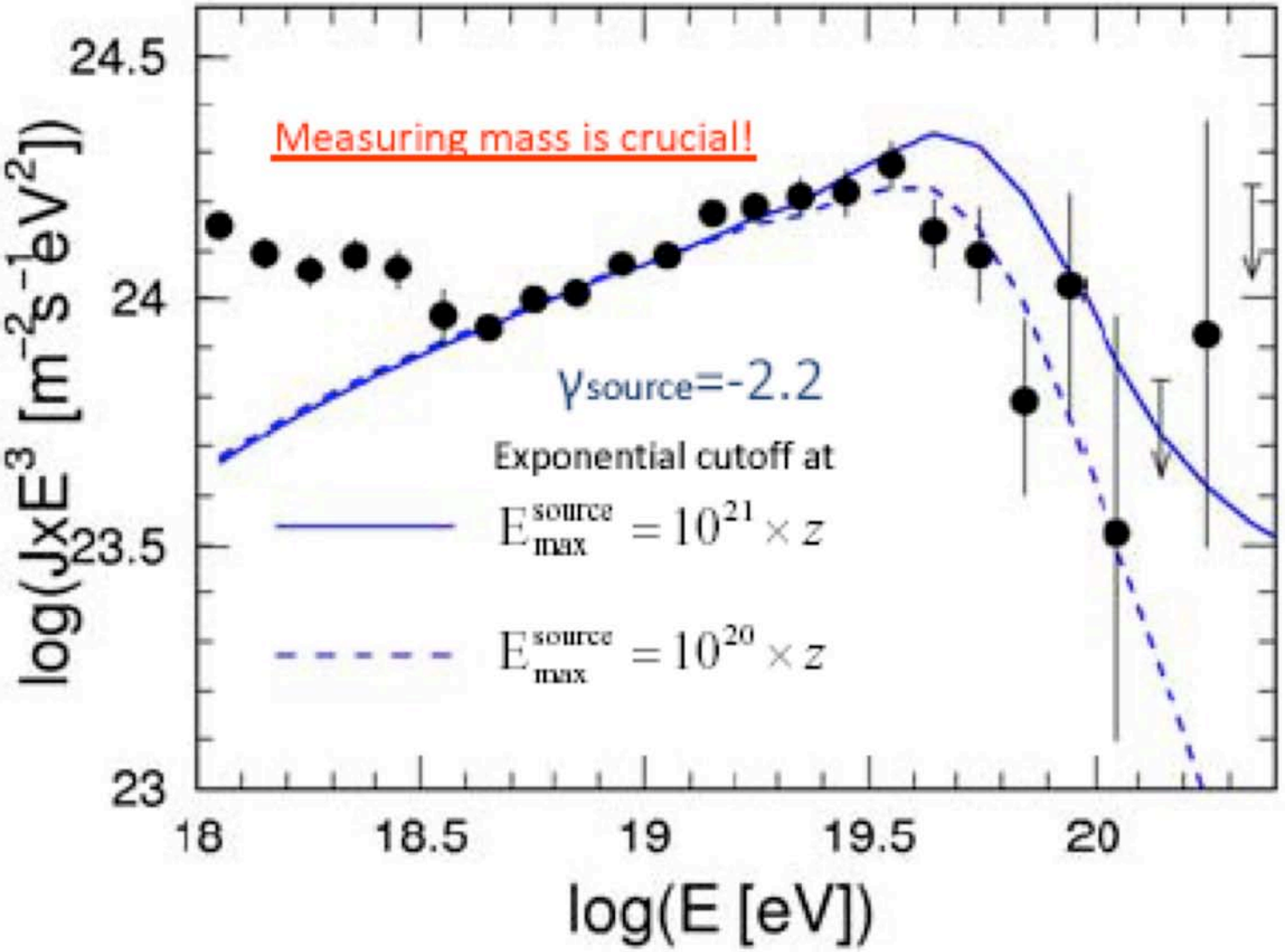
## Test of Berezinsky's $e^+e^-$ model




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 1600$^{th}$ 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

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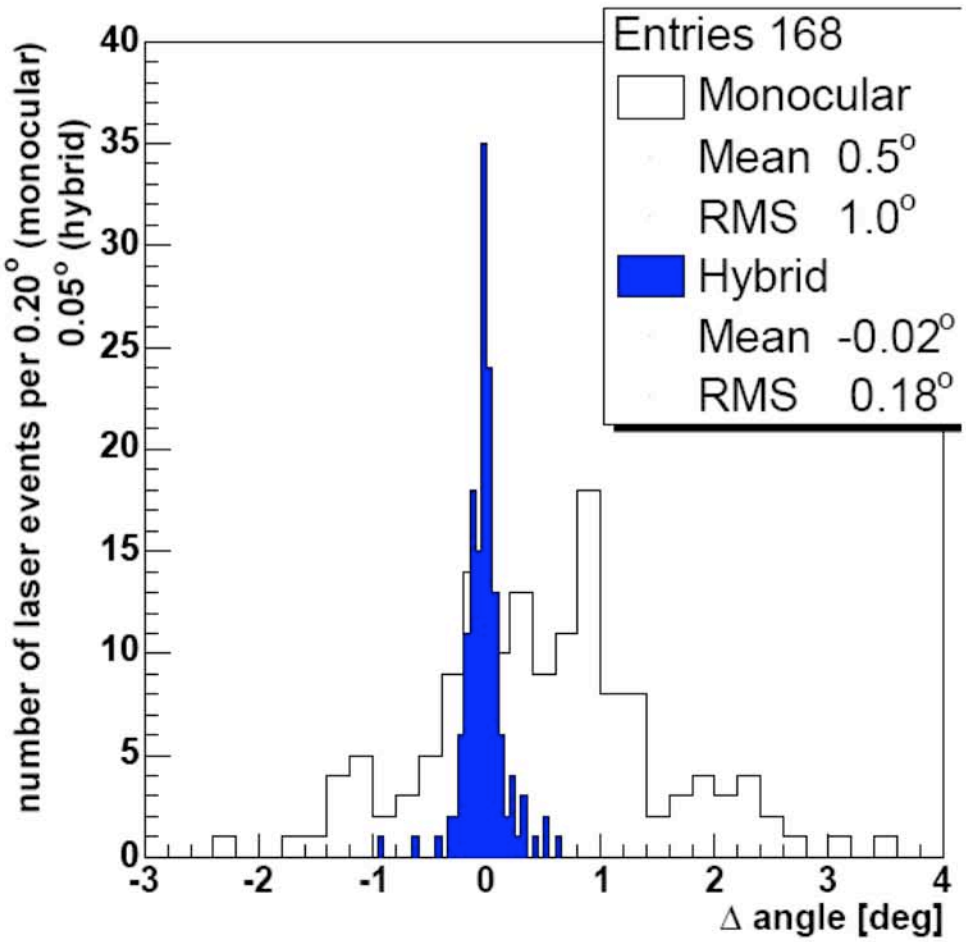
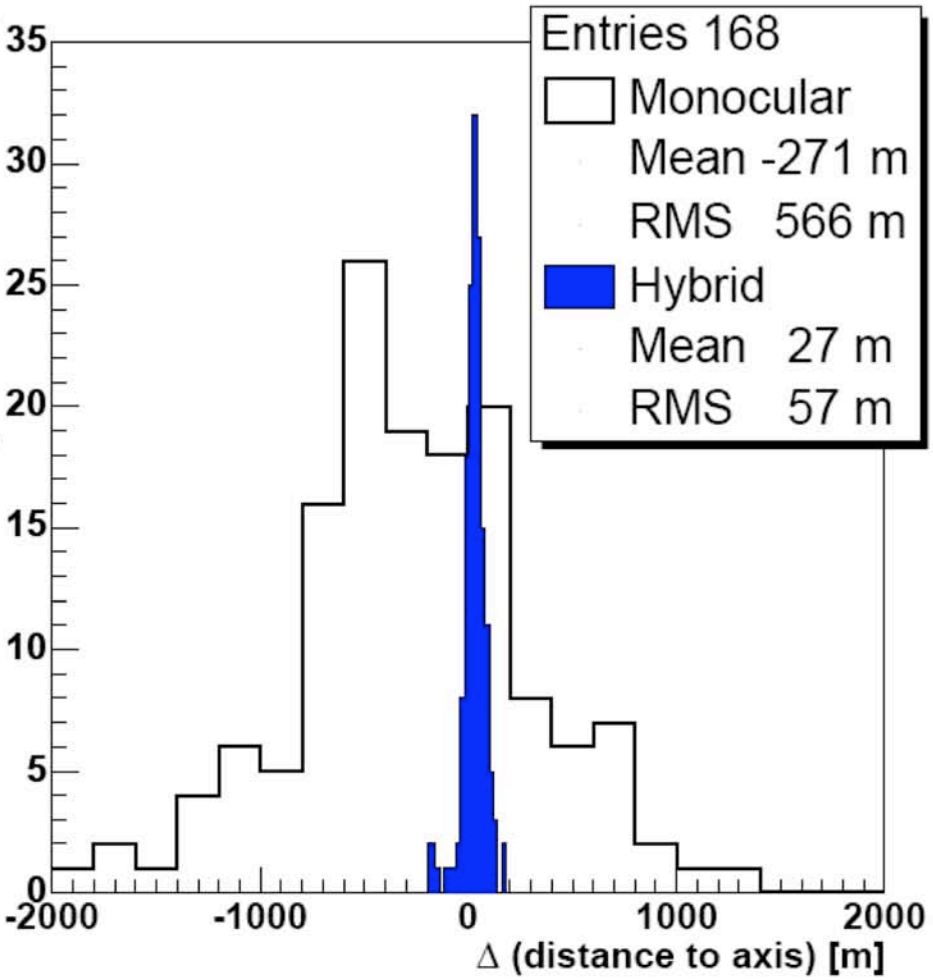
**"I have an idea in the morning. I have lunch, I write it up and send it to PRL in the late afternoon.**

**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)**

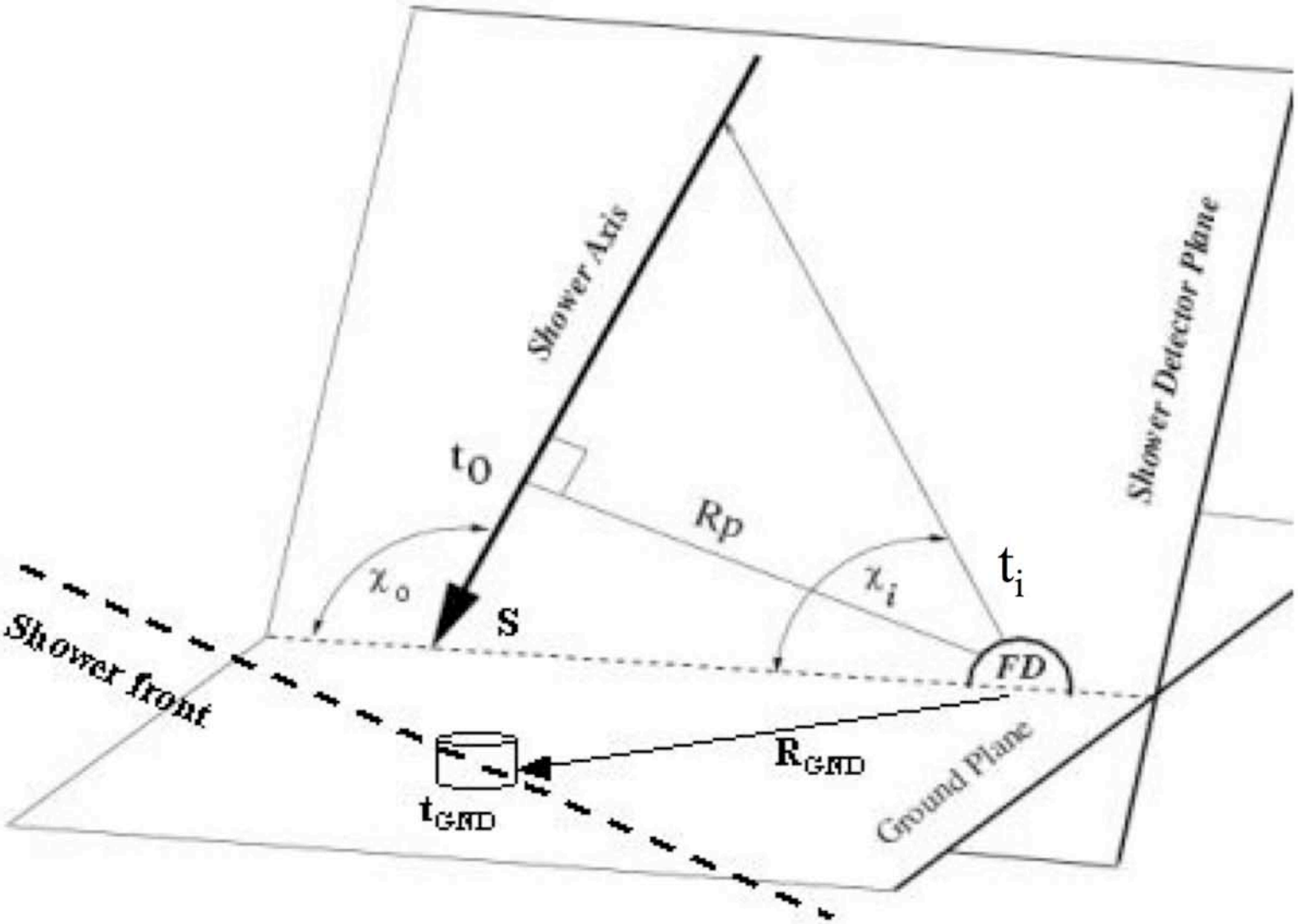
**Mono/hybrid rms 1.0°/0.18°**

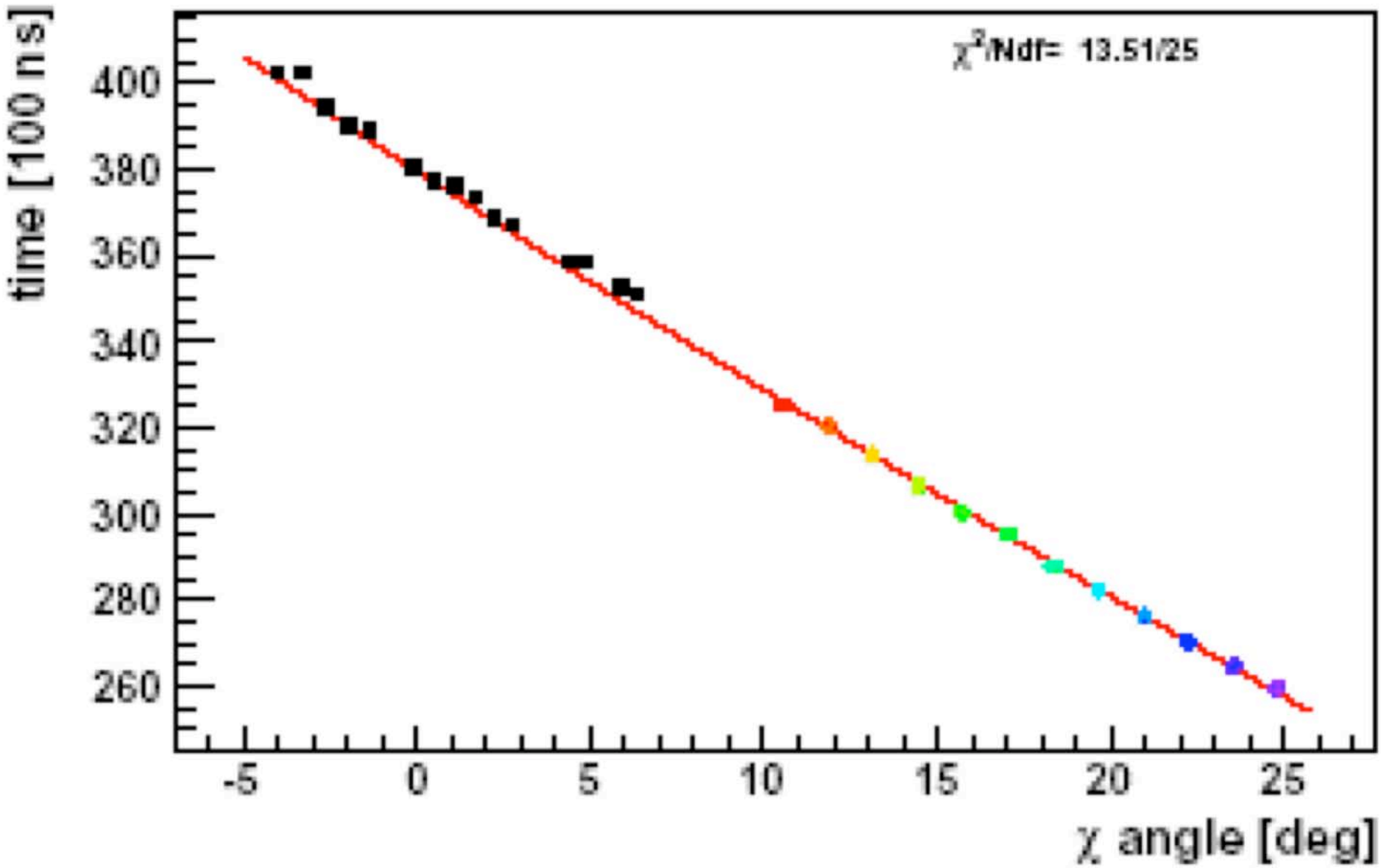
**Mono/hybrid rms 570 m/60 m**

# Number of Events

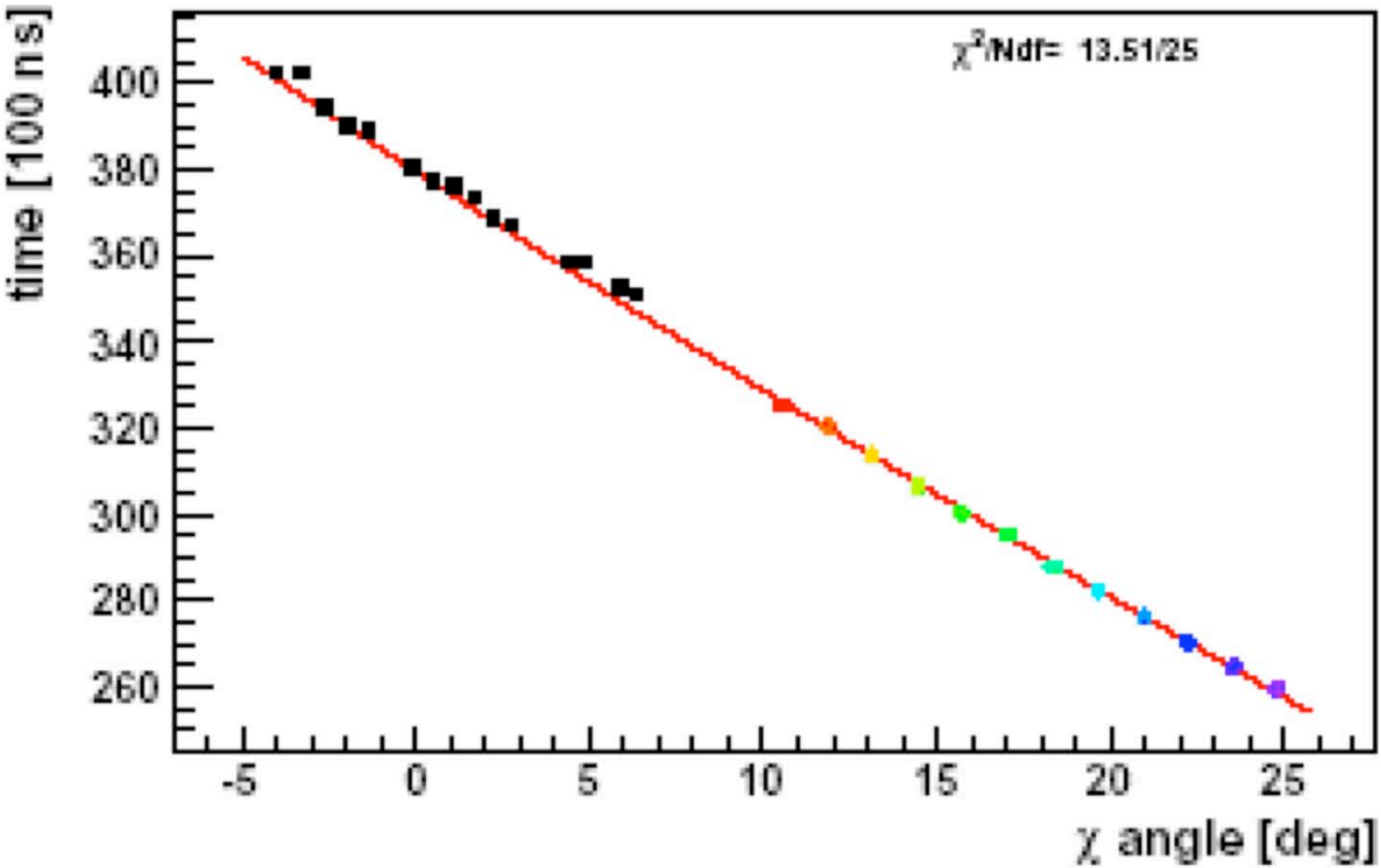
| | HiRes I (HiRes II) | AGASA'02 (P+SYBILL '06) (Fe+QGSJet '06) | Auger |
|---|---|---|---|
| $>10^{19}$ eV | 564 (180) | 945 (726) (639) | 1473 |
| $>6\times10^{19}$ eV | 49 (12) | 31 (23) (20) | 66 |
| $>7\times10^{19}$ eV | 31 | 25 (15) (14) | 31 |
| $>10^{20}$ eV | 4 (0) | 11 (6) (5) | 2 |

# The ‘hybrid’ spectrum

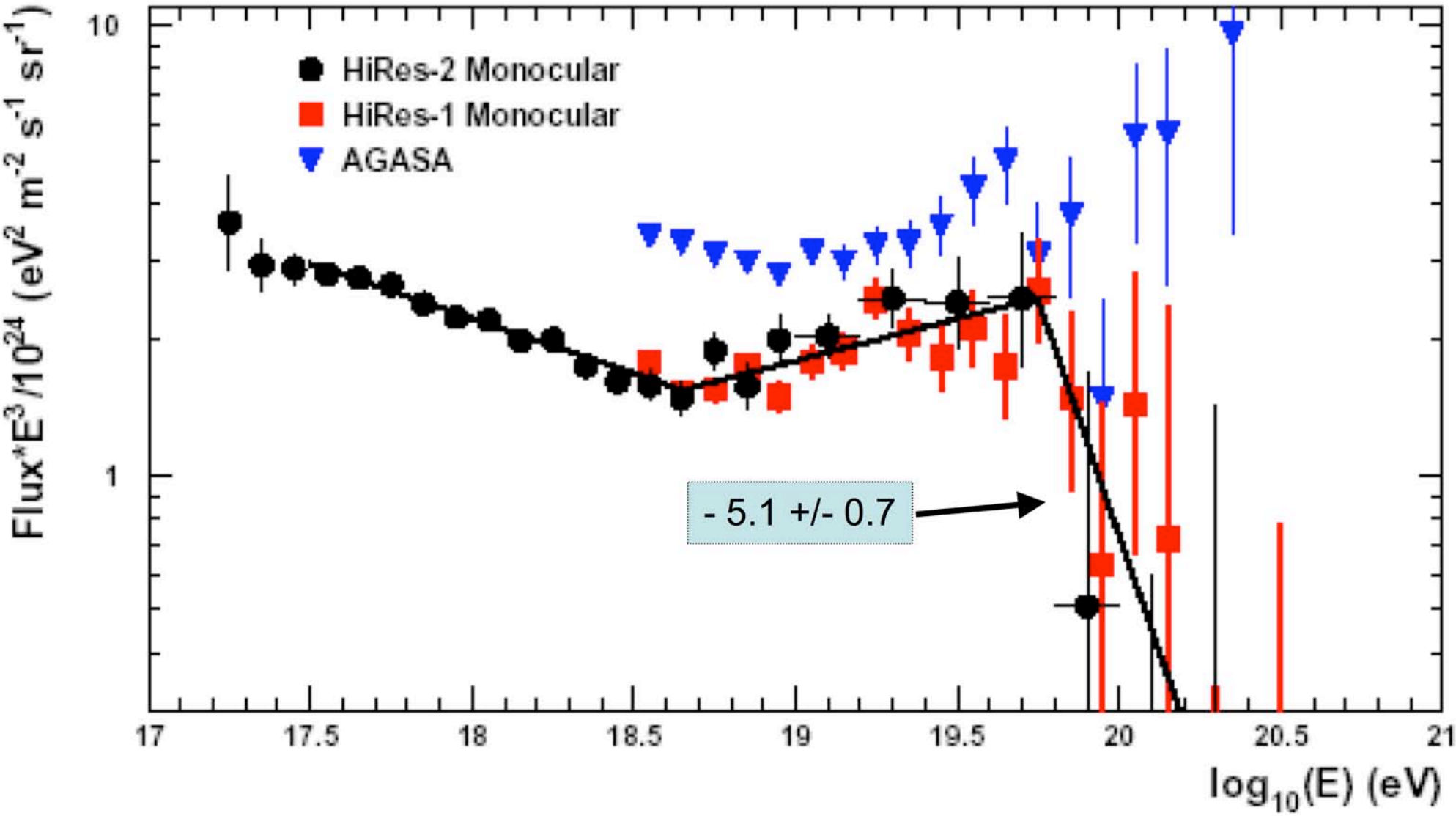



time [100 ns]
400
380
360
340
320
300
280
260
-5
0
5
10
15
20
25
χ angle [deg]
χ²/Ndf= 13.51/25

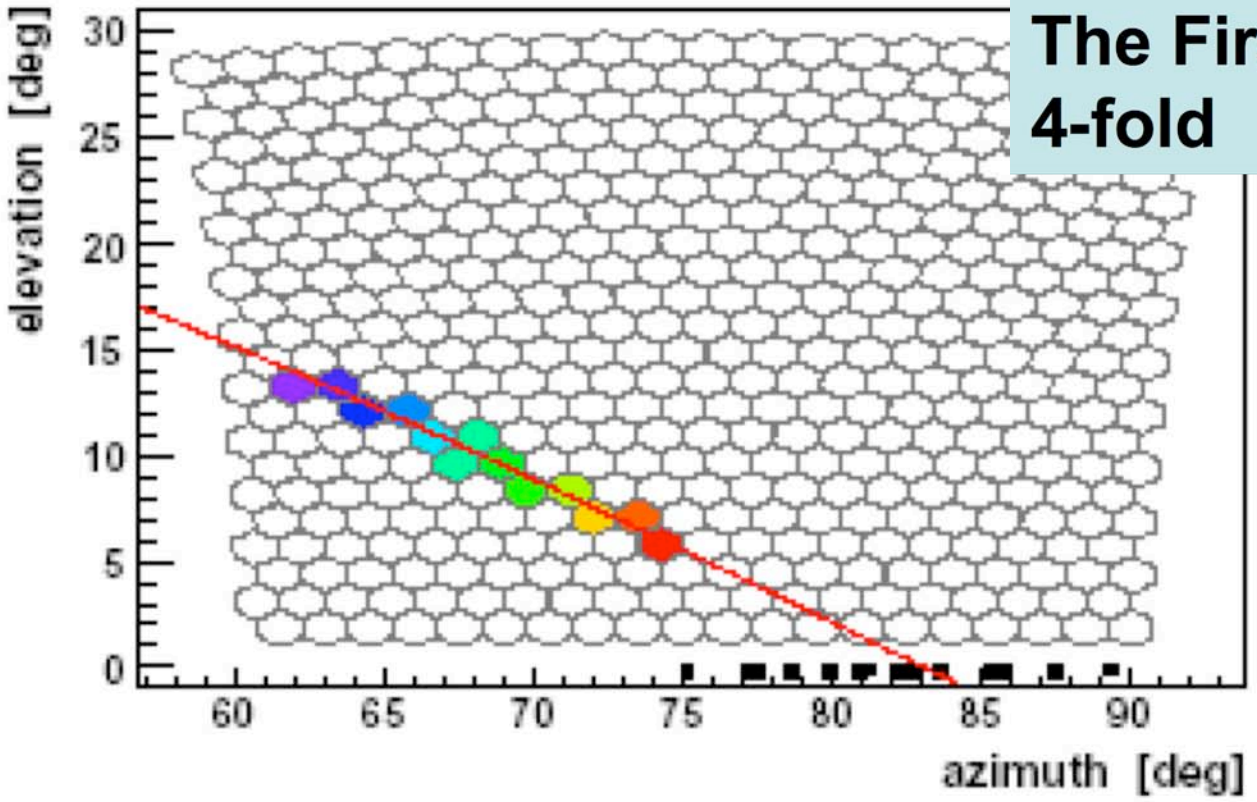

t_GND




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

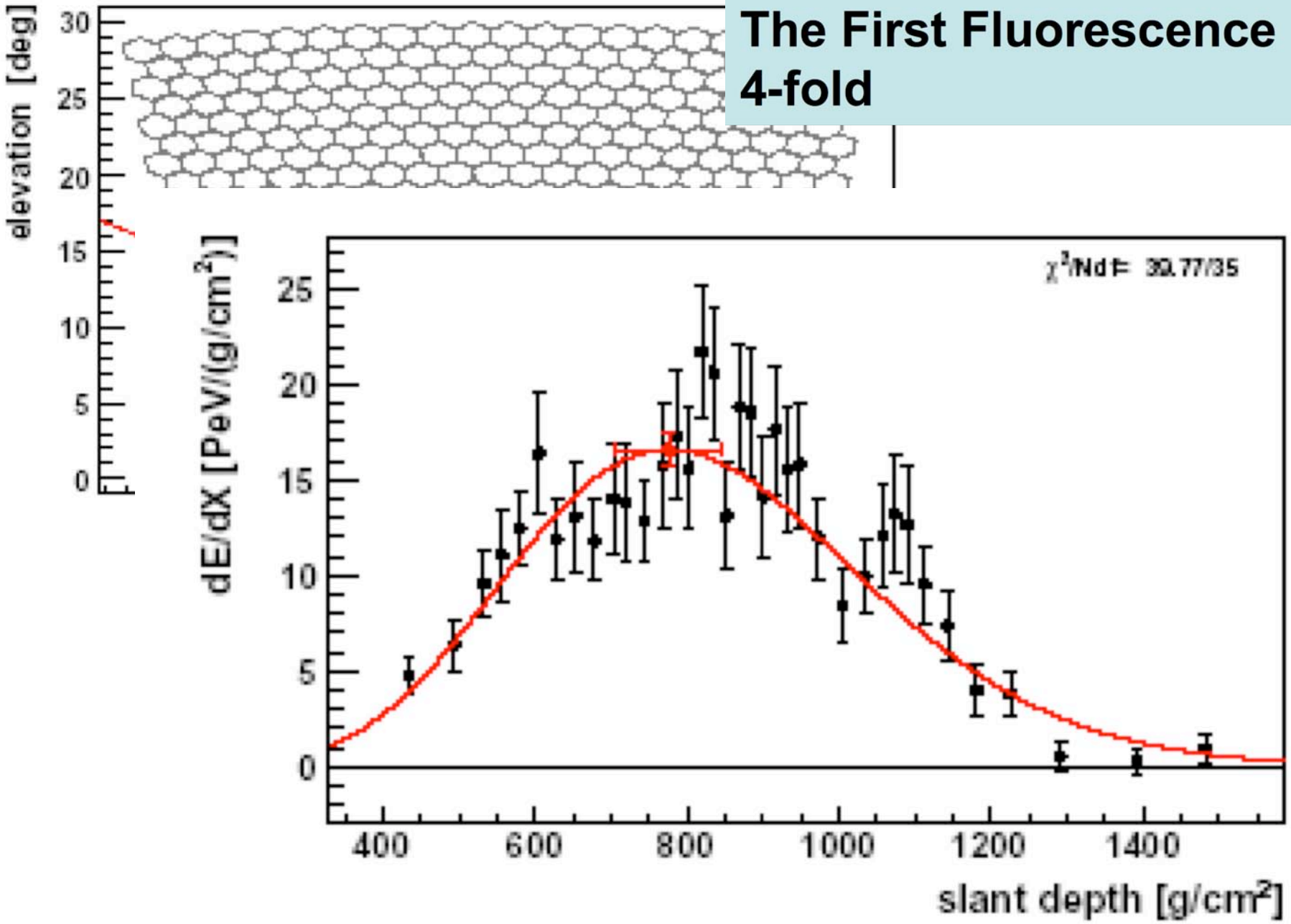



**HiRes Group: astro-ph/0703099**

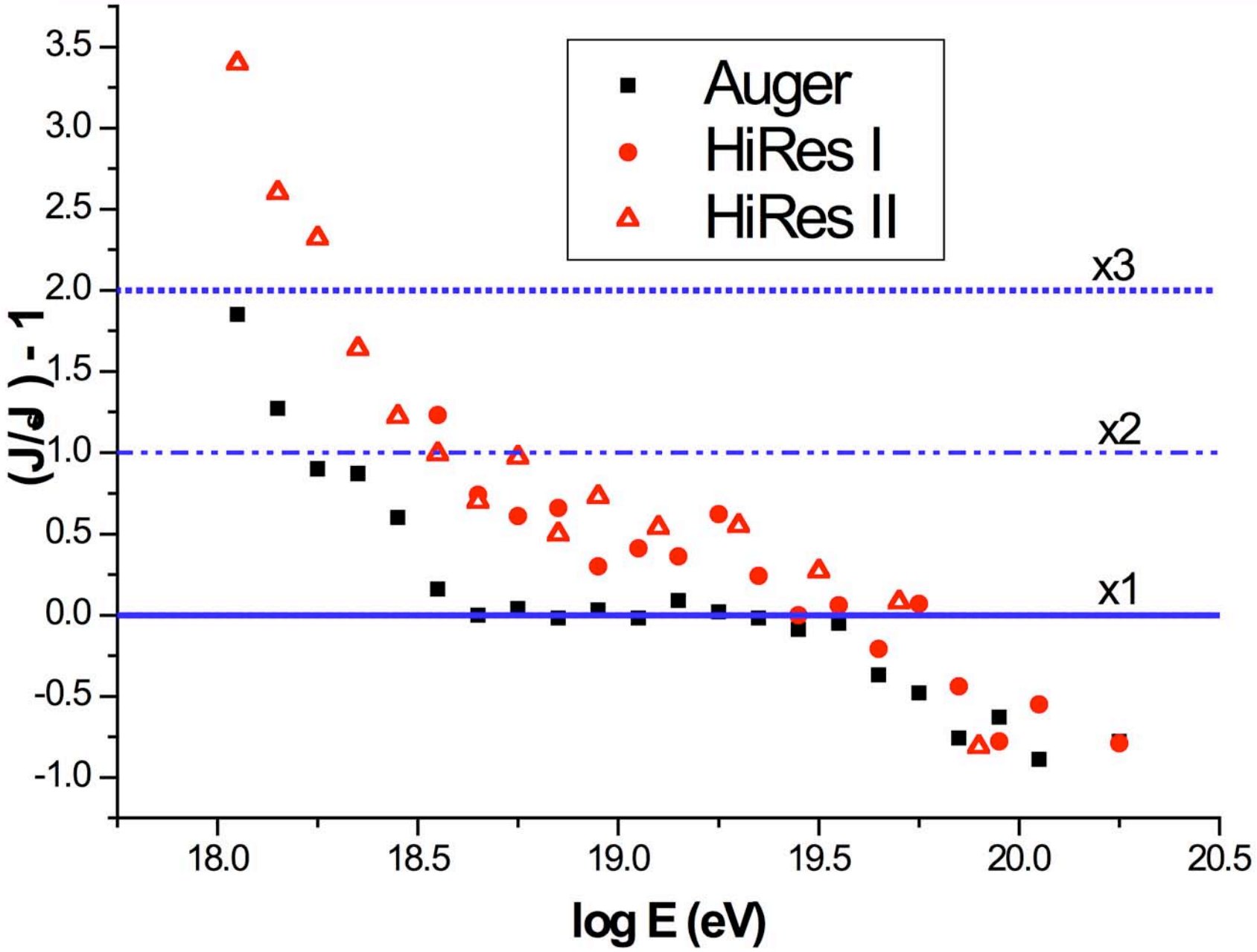



# The First Fluorescence 4-fold

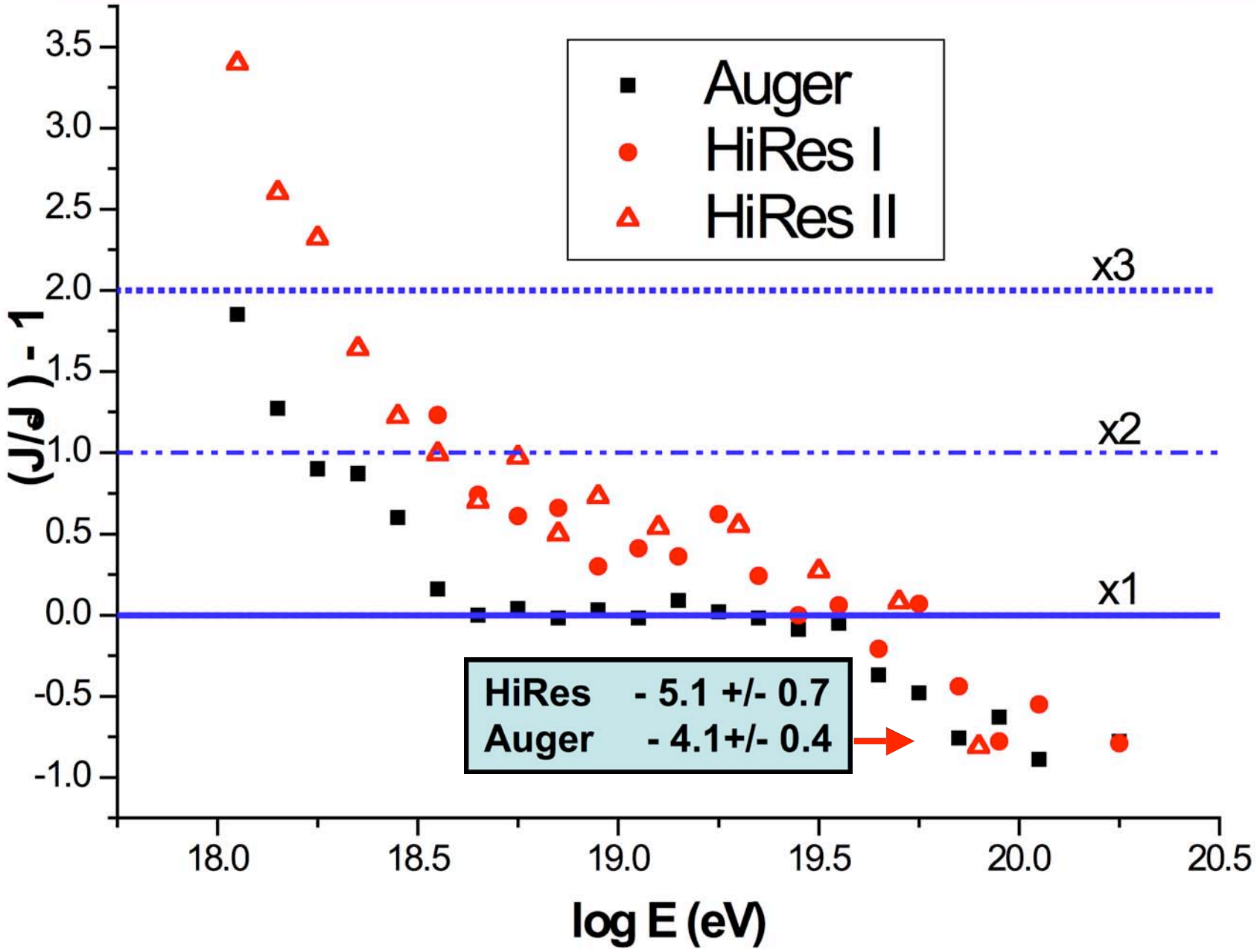
# The First Fluorescence 4-fold



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



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



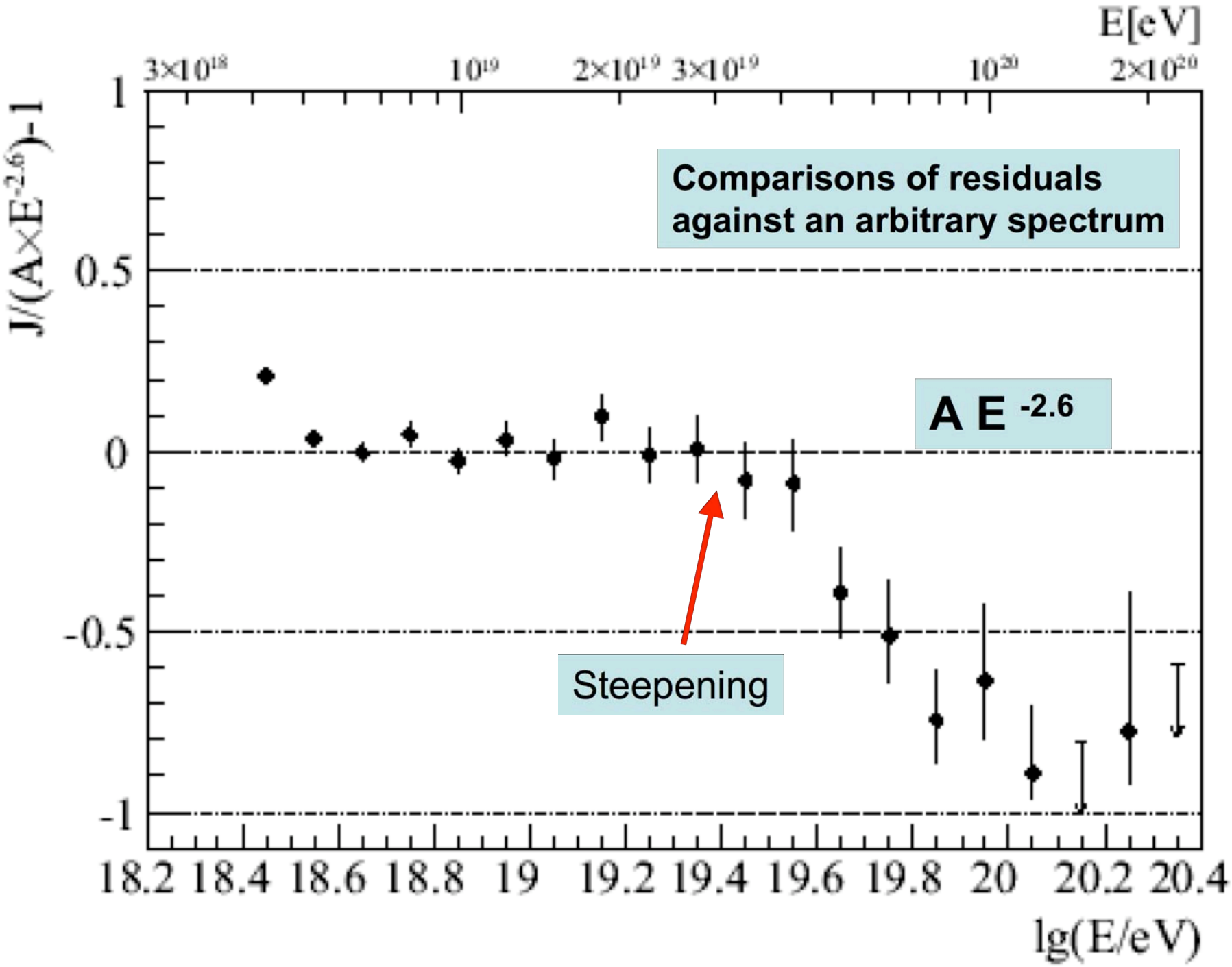
Immensely important IF it was to be established that slopes at highest energy are different in

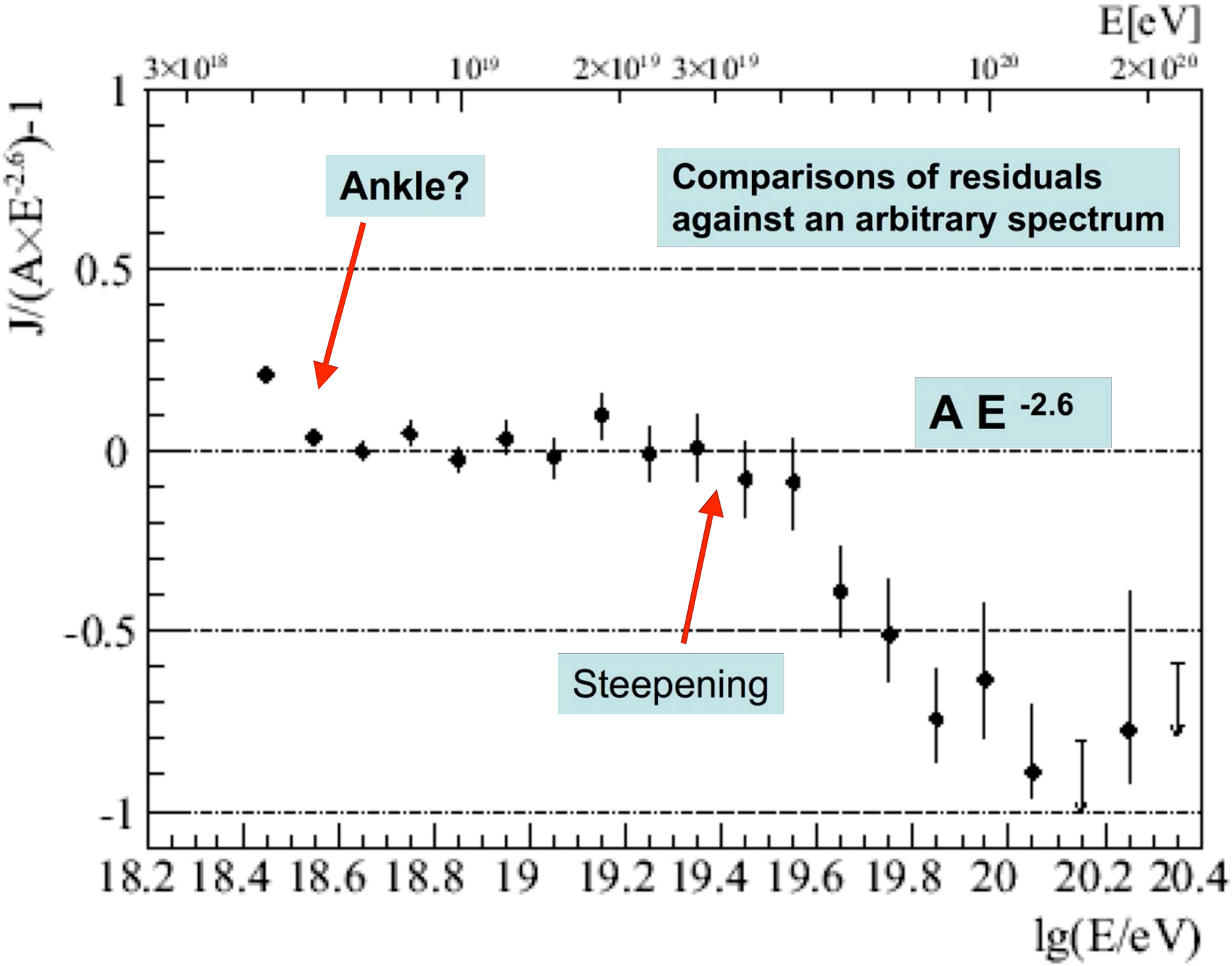
northern (- 5.1+/- 0.7) and

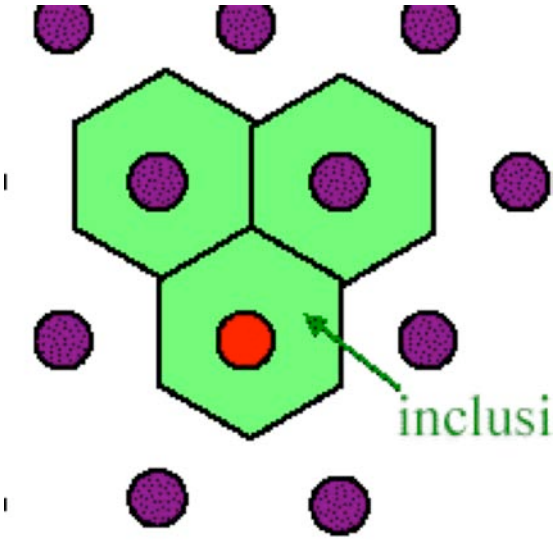
southern hemispheres (- 4.1 +/- 0.4)

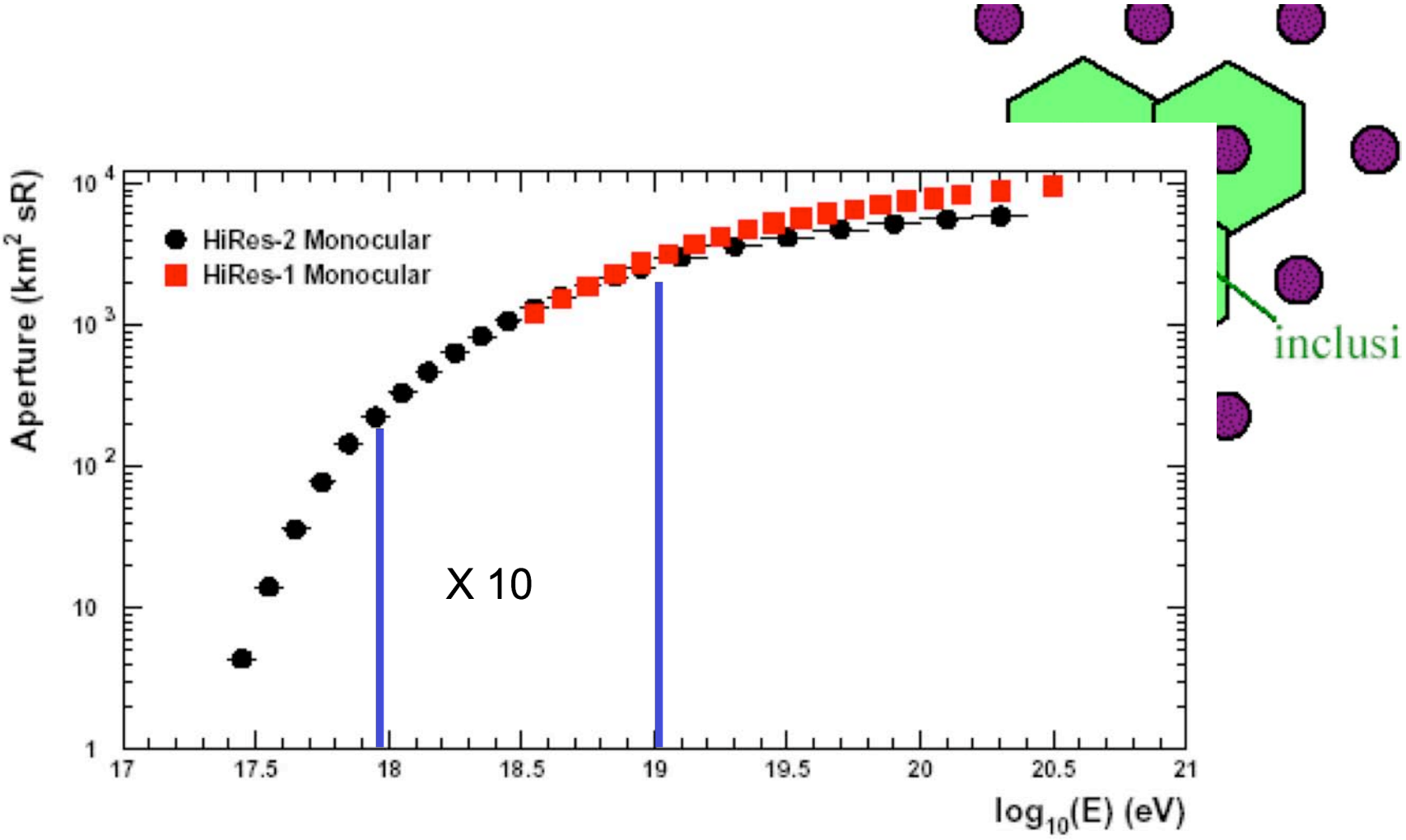
But, MUCH TOO EARLY TO DRAW CONCLUSIONS

- 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

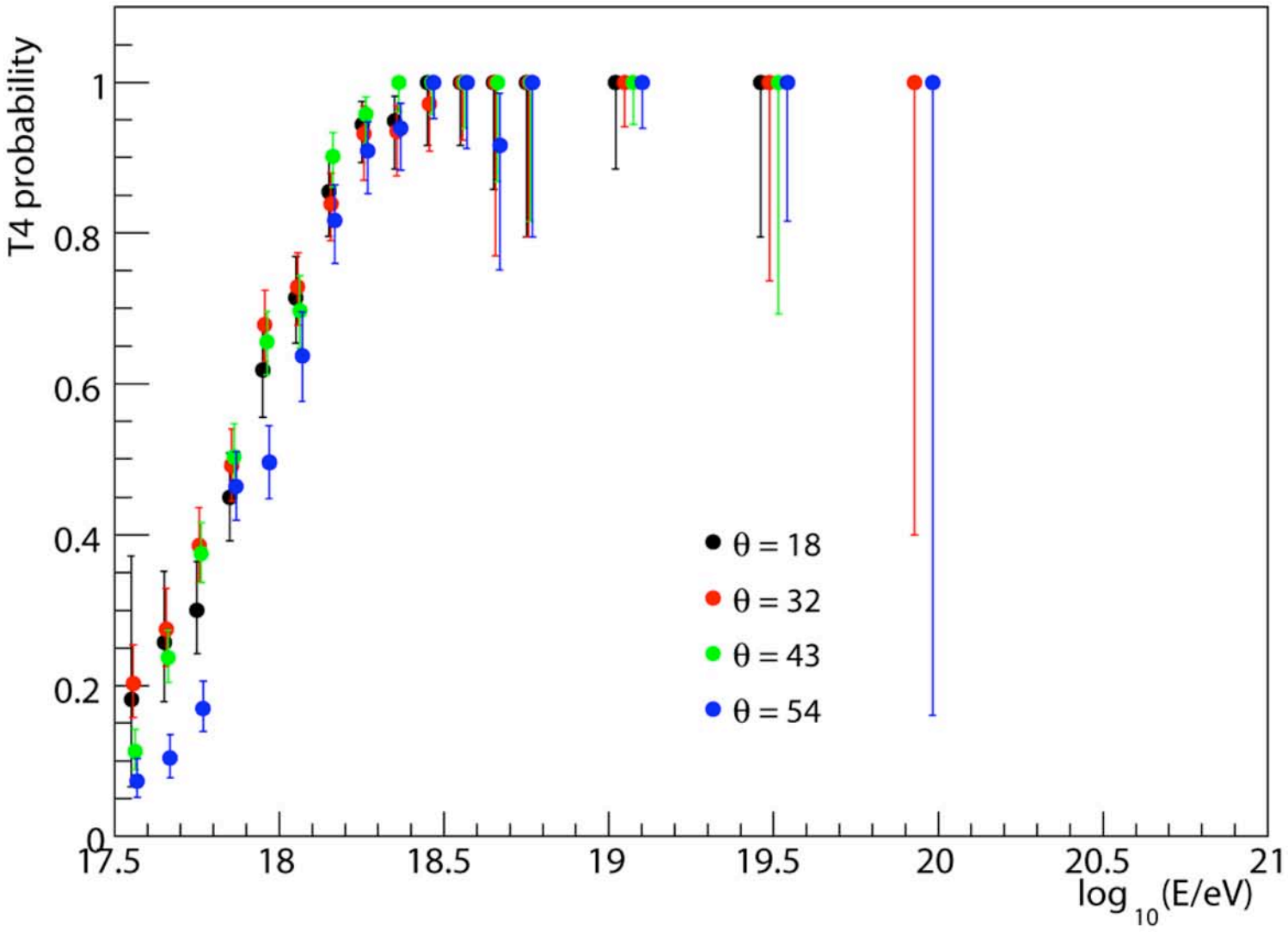

E[eV]
3×10^18
10^19
2×10^19
3×10^19
10^20
2×10^20
J/(A×E^-2.6)-1
1
0.5
0
-0.5
-1
Comparisons of residuals against an arbitrary spectrum
A E -2.6
Steepening
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
20.2
20.4
lg(E/eV)


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)

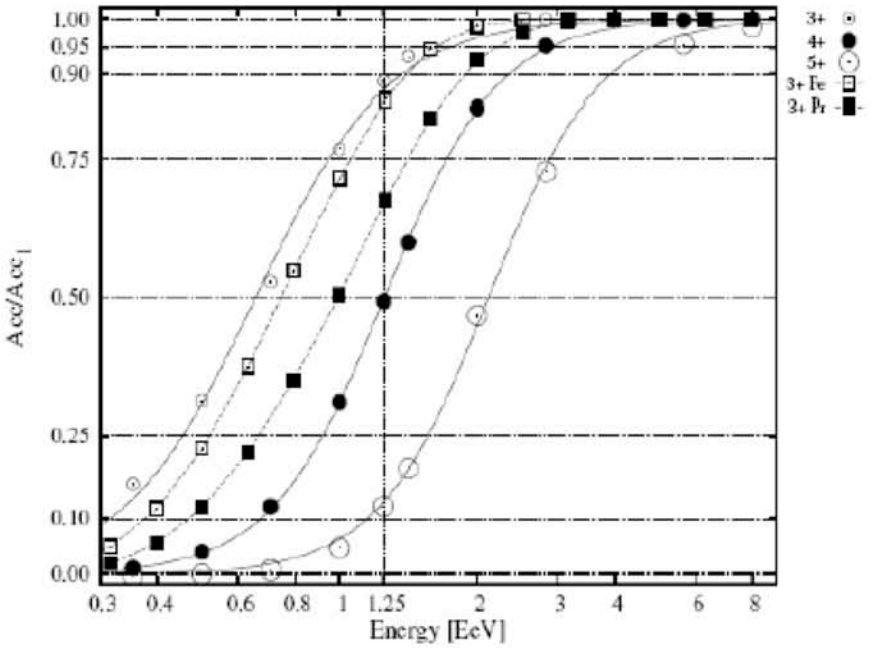

inclusi



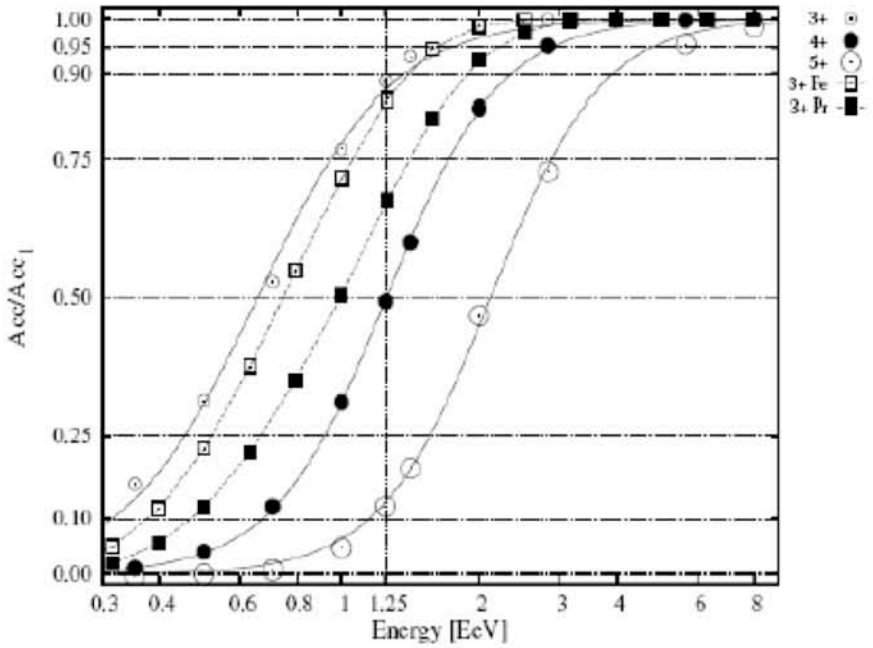

HiRes aperture depends on assumptions about spectrum slope, mass and hadronic models

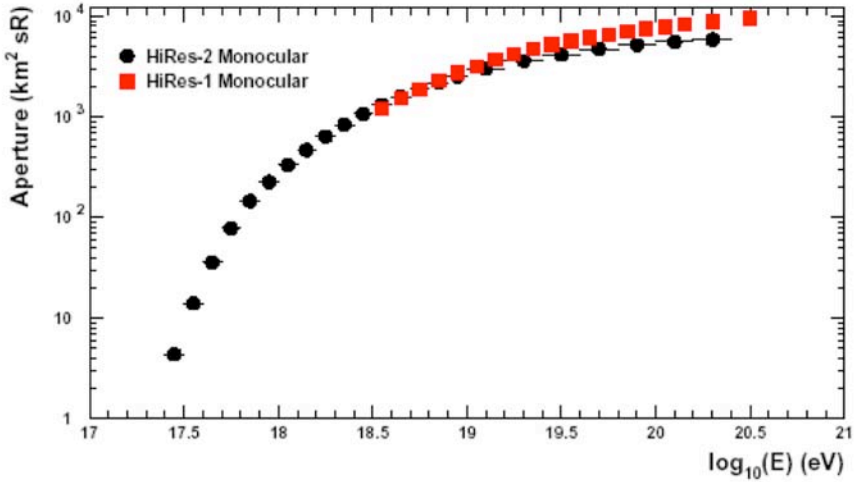

T4 probability
1
0.8
0.6
0.4
0.2
0
17.5
18
18.5
19
19.5
20
20.5
21
log 10(E/eV)
θ = 18
θ = 32
θ = 43
θ = 54

# Energy Dependence of Aperture for Auger and HiRes



# 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?

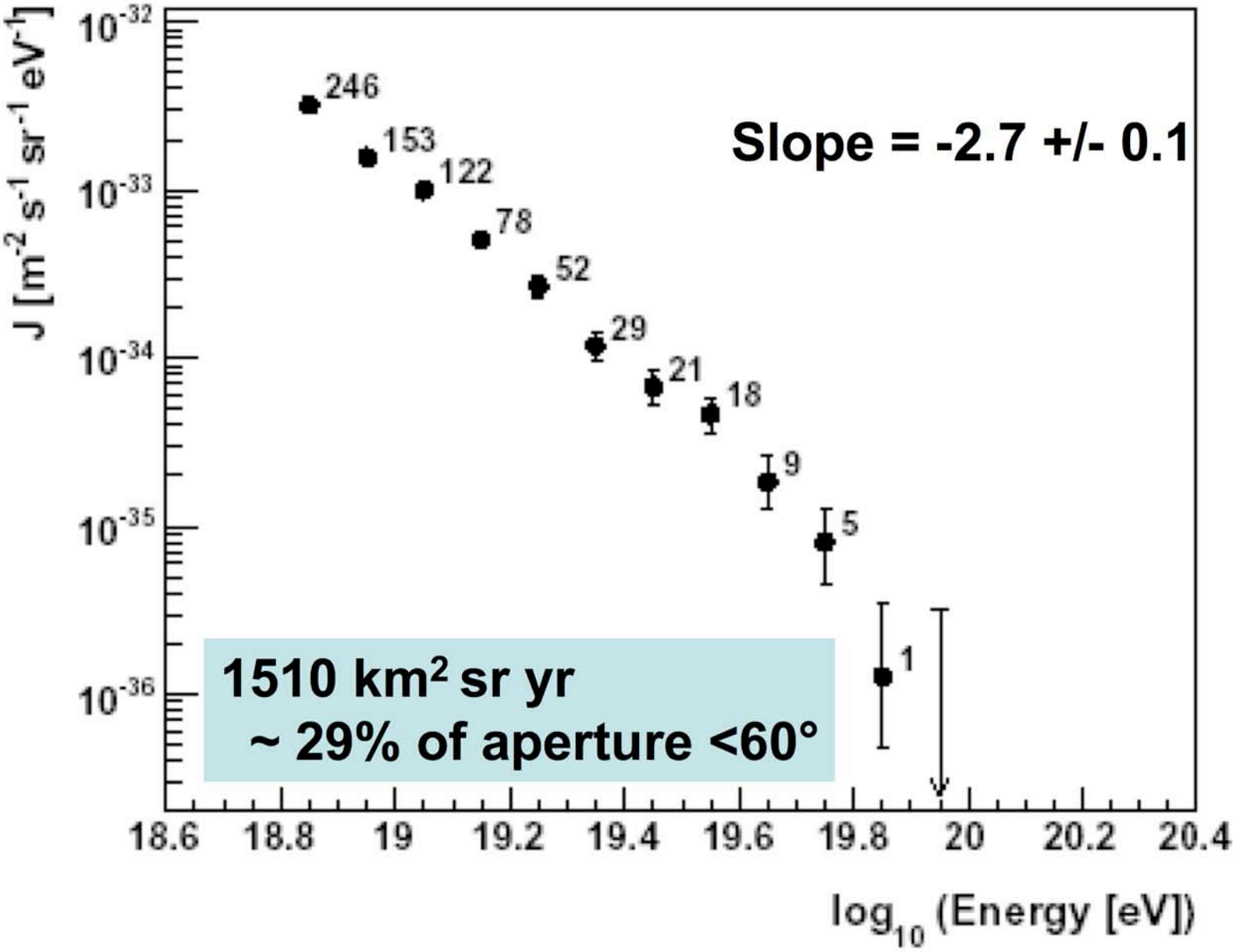
The HiRes aperture estimate requires assumptions about primary mass, spectrum slope and hadronic model

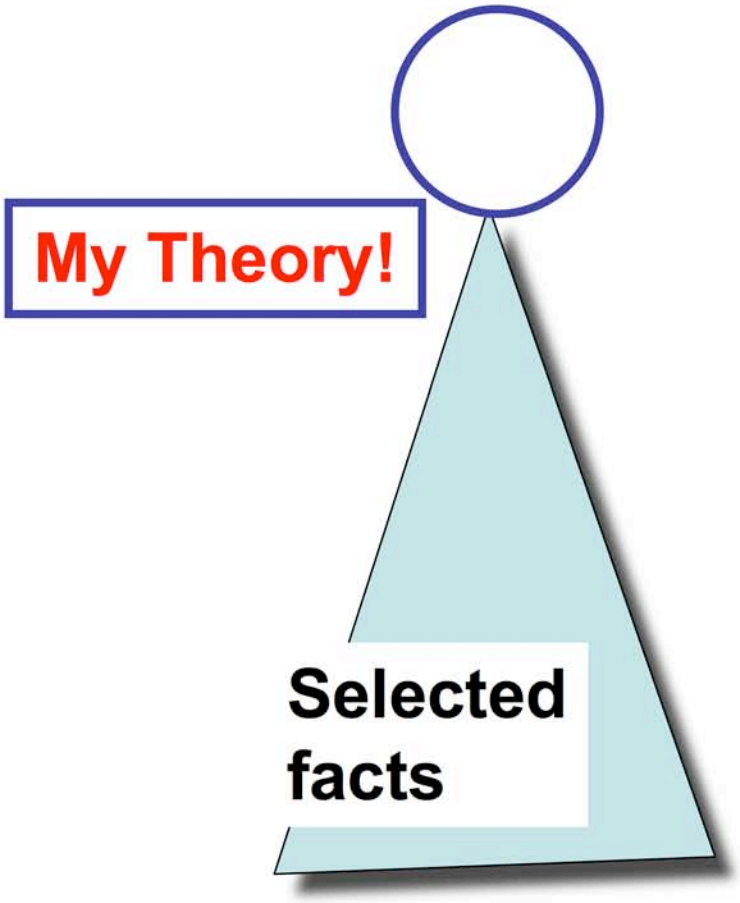
• Cannot be FY or hemisphere differences

## Highlights:

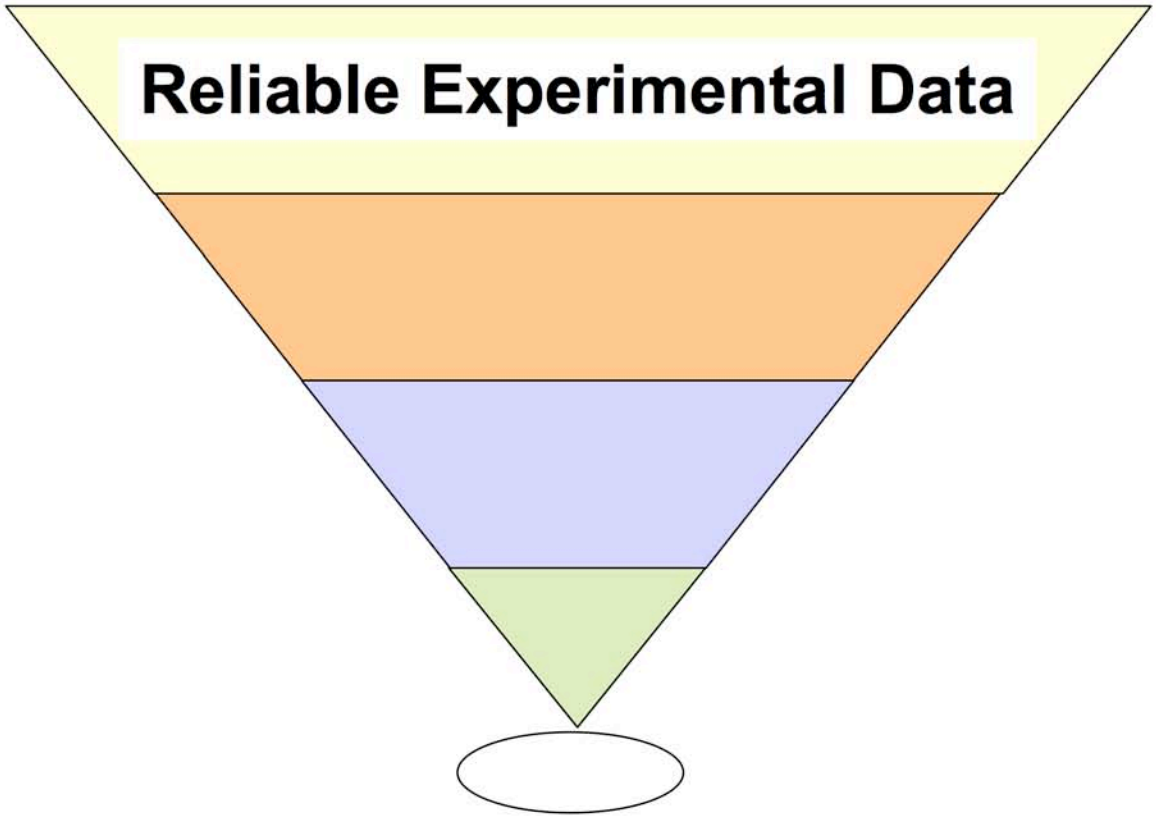
- The Collaboration works well
- Observatory Status
- First 4-fold Fluorescence Event
- Remarkable Isotropy
- Studies relating to Nucleonic Composition
- Primary Energy Spectrum
- Comparisons, Conclusions and Future Prospects

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






Theorist's view




Experimentalist's view

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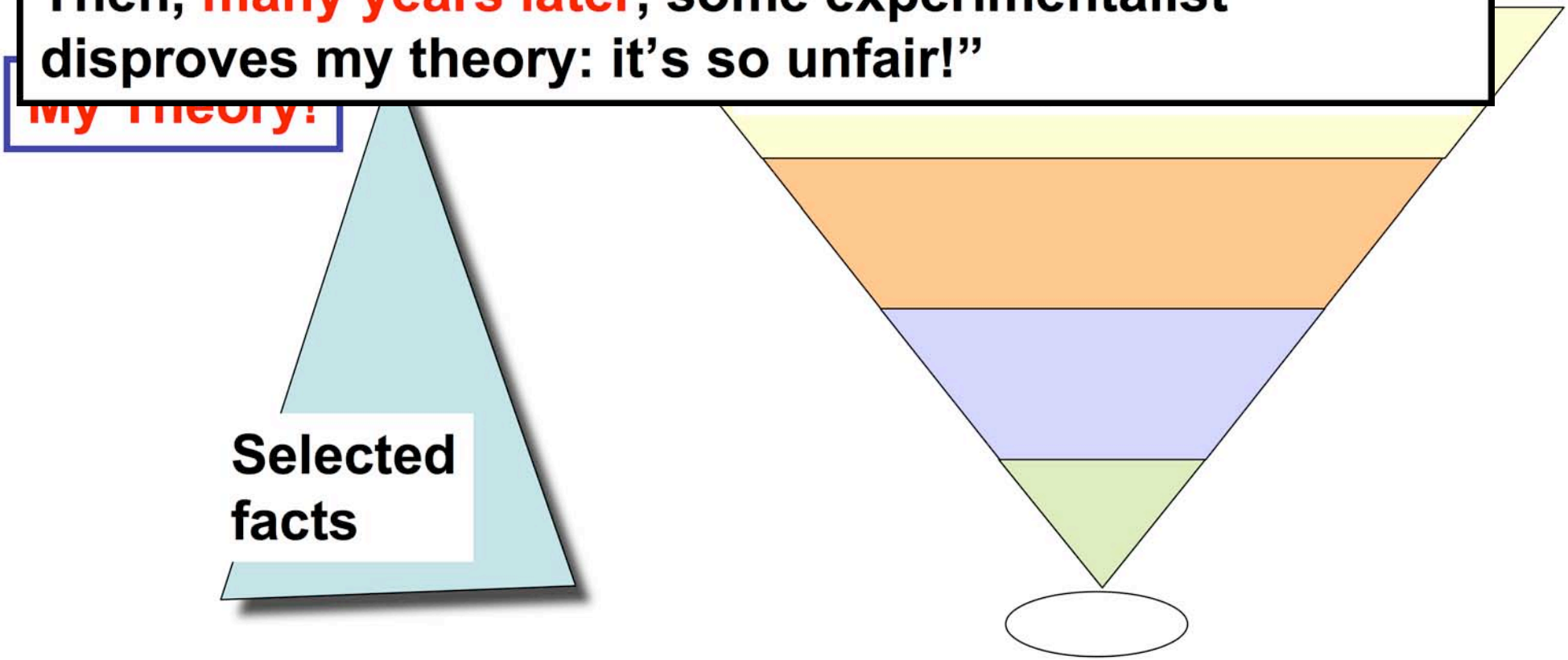
**Then, many years later, some experimentalist disproves my theory: it's so unfair!"**




**Theorist's view**

**Experimentalist's view**