Recent Results from Auger

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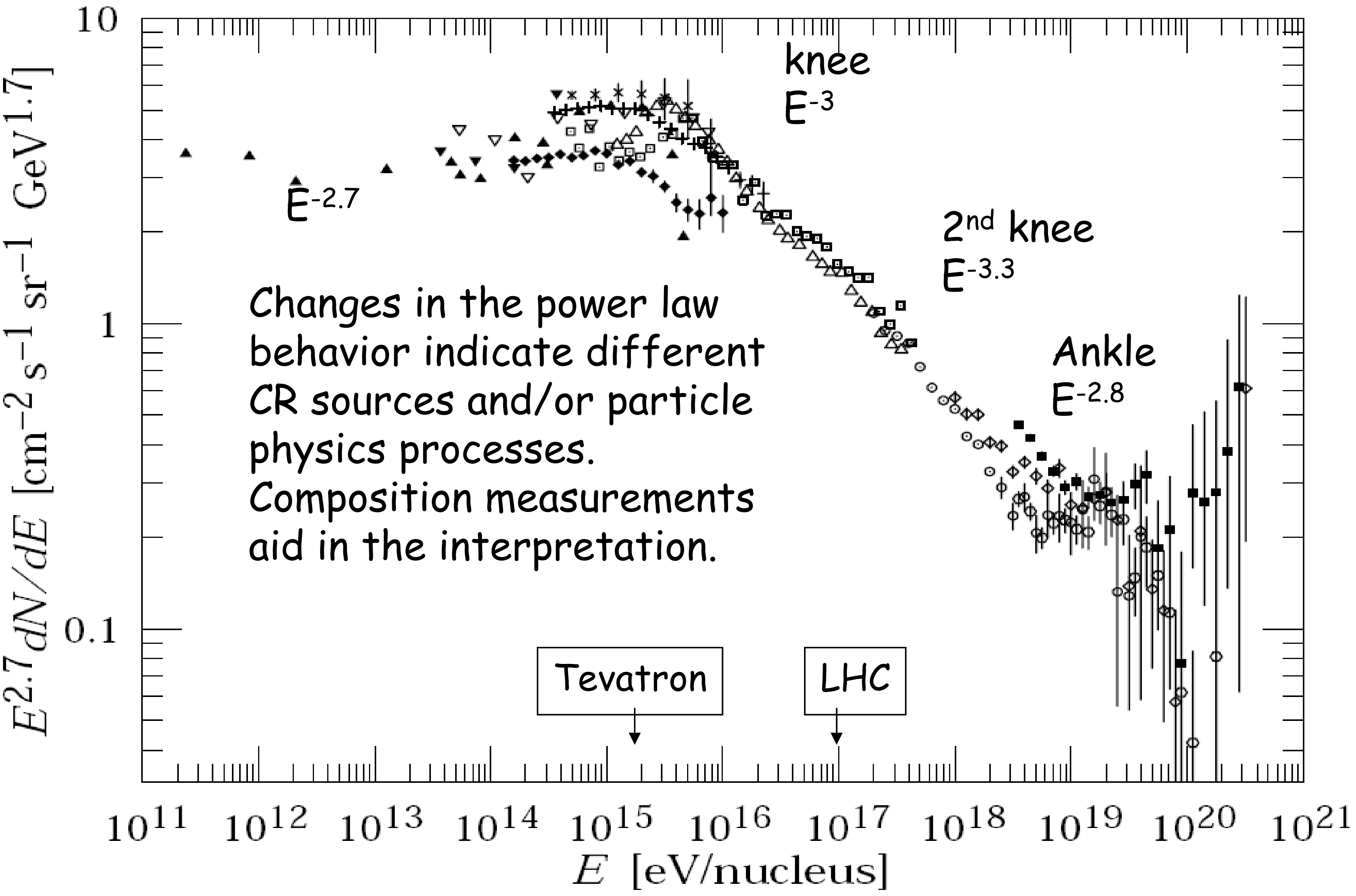
Cosmic ray all-particle spectrum (PDG2004)

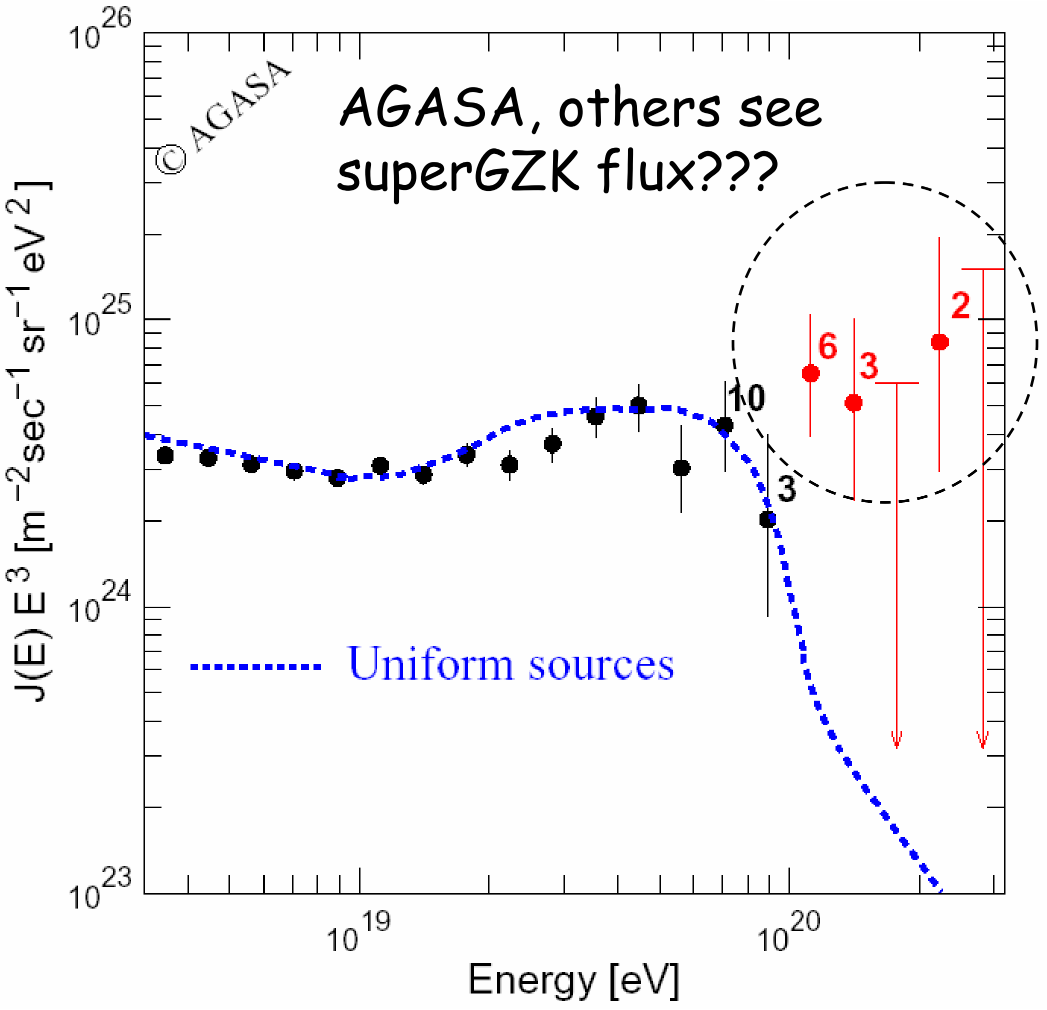


Changes in the power law behavior indicate different CR sources and/or particle physics processes. Composition measurements aid in the interpretation.

Greisen-Zatsepin-Kuzmin (GZK): Protons lose energy in collisions with the CMB above threshold energy

$$p+\gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p+\pi^{0} \rightarrow p\gamma\gamma$$

$$\rightarrow n+\pi^{+} \rightarrow pe^{-}\overline{\nu}_{e}+e^{+}\nu_{e}\overline{\nu}_{\mu}\nu_{\mu}$$



AGASA, others see superGZK flux???

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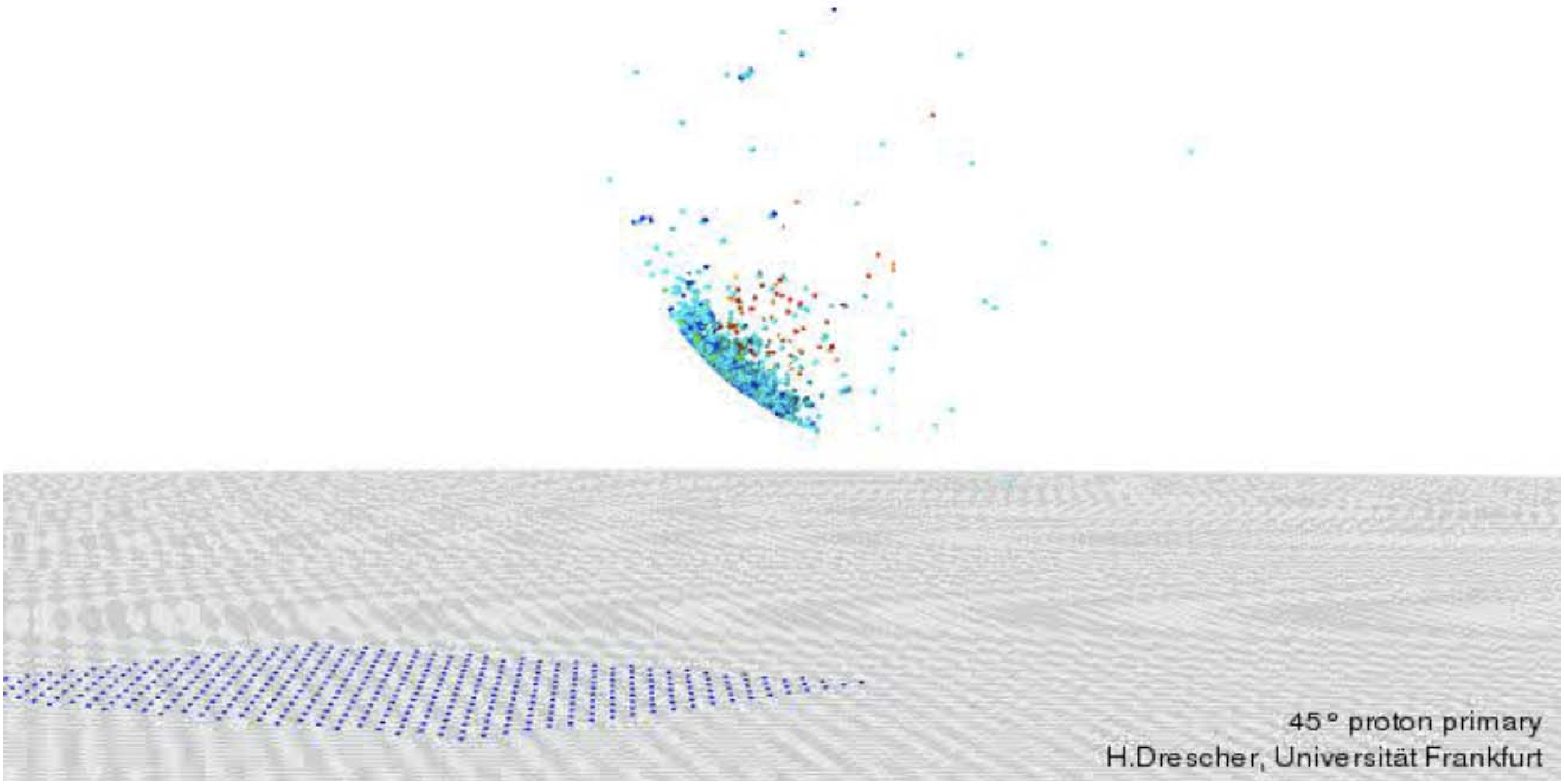
Possibilities:

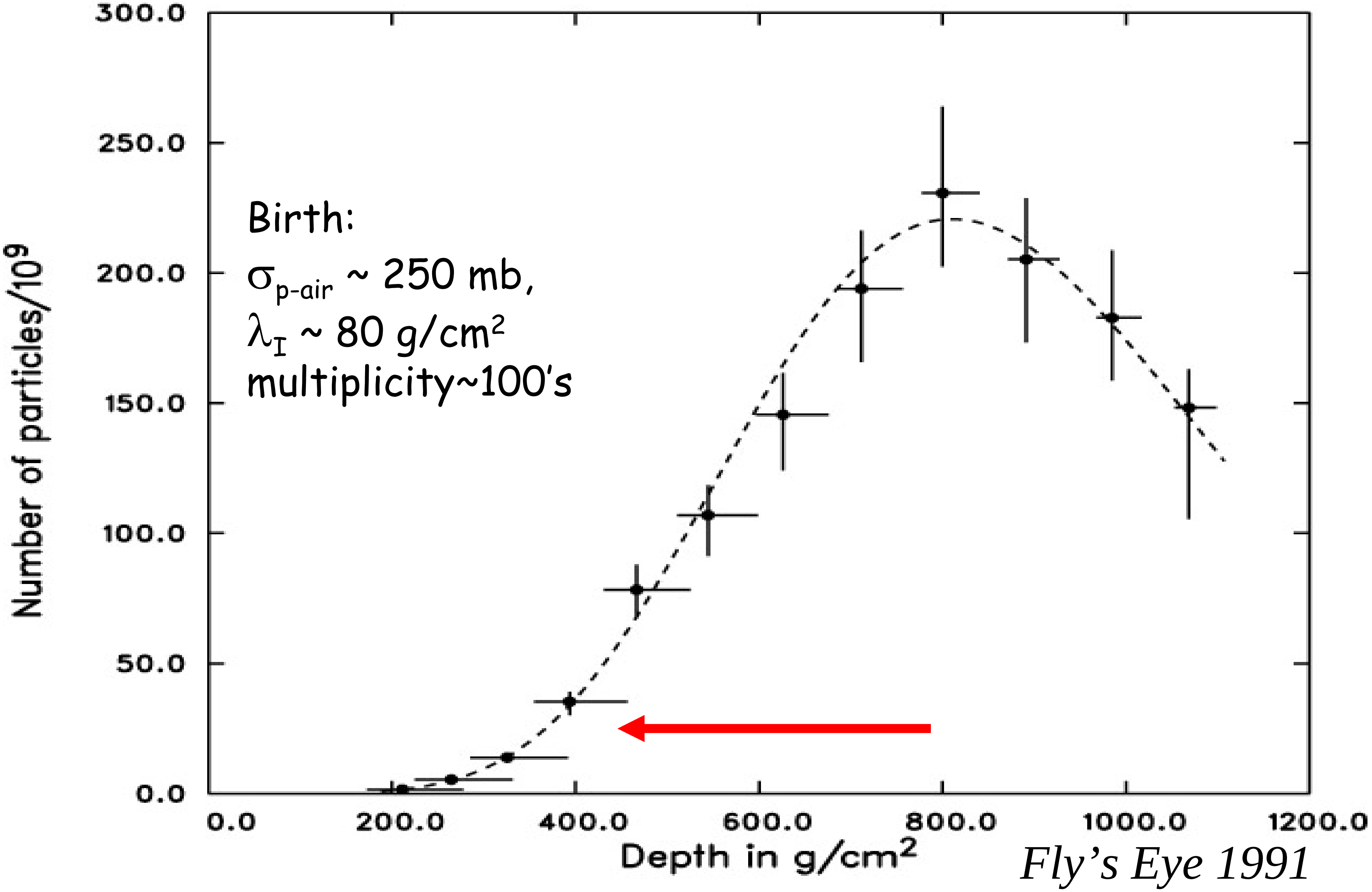
- The super-GZK sources are local (R<100Mpc) e.g. Super-heavy dark matter decay?
- Lorentz invariance is broken such that the interaction is kinematically forbidden
- $\sigma_{CR\text{-}\gamma}$ is suppressed (nuclei, shadrons, neutrinos, etc.)

Part 1: Air shower development



Important events in the life of a hadronic cosmic ray air shower

- **E=3 x 10^{20} eV**



Birth:

$\sigma_{p\text{-}air}$ ~ 250 mb,

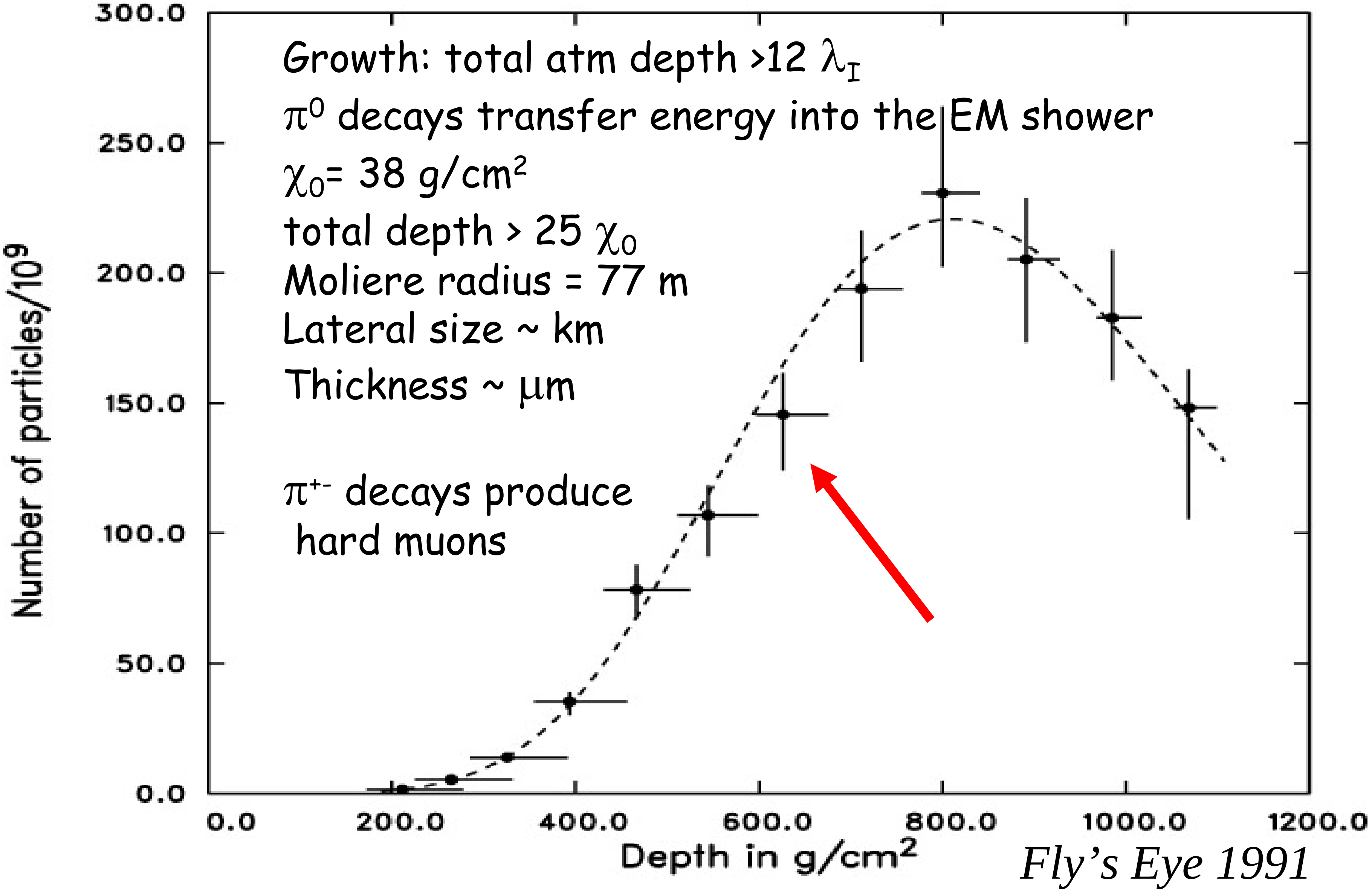
λ_I ~ 80 g/cm^2

multiplicity~100's

Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

- E=3 x 10^{20} eV



Growth: total atm depth >12 λ_I

π^0 decays transfer energy into the EM shower

χ_0= 38 g/cm^2

total depth > 25 χ_0

Moliere radius = 77 m

Lateral size ~ km

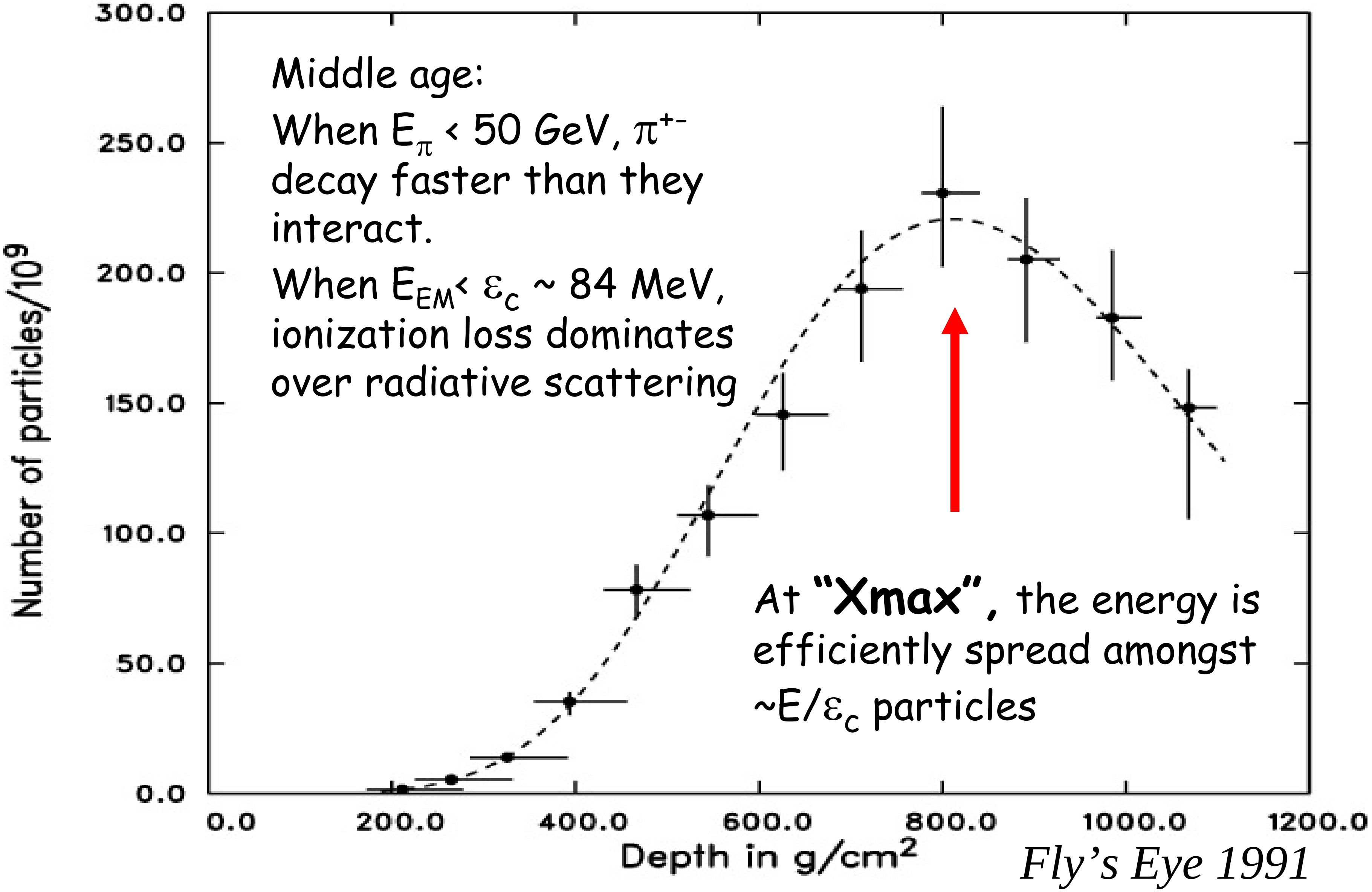
Thickness ~ µm

π^{+-} decays produce hard muons

Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

- $E = 3 \times 10^{20}$ eV



Middle age:

When E_π < 50 GeV, π^{+-} decay faster than they interact.

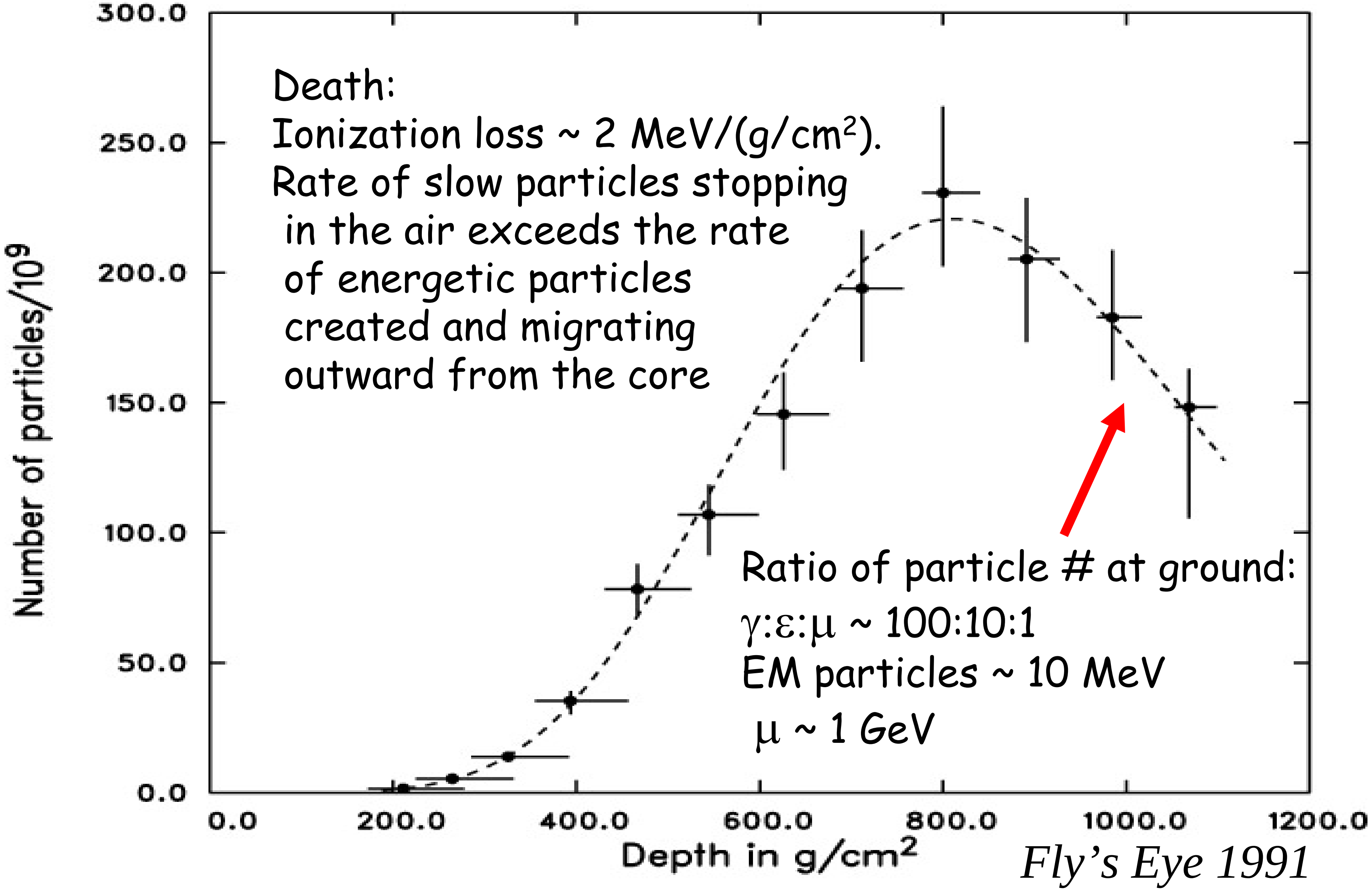
When $E_{EM} < \varepsilon_c \sim 84$ MeV, ionization loss dominates over radiative scattering

At **"Xmax"**, the energy is efficiently spread amongst $\sim E/\varepsilon_c$ particles

Fly's Eye 1991

Important events in the life of a hadronic cosmic ray air shower

- E=3 x 10^{20} eV



Death:
Ionization loss ~ 2 MeV/(g/cm^2).
Rate of slow particles stopping in the air exceeds the rate of energetic particles created and migrating outward from the core

Ratio of particle # at ground:
$\gamma:\varepsilon:\mu$ ~ 100:10:1
EM particles ~ 10 MeV
μ ~ 1 GeV

Fly's Eye 1991

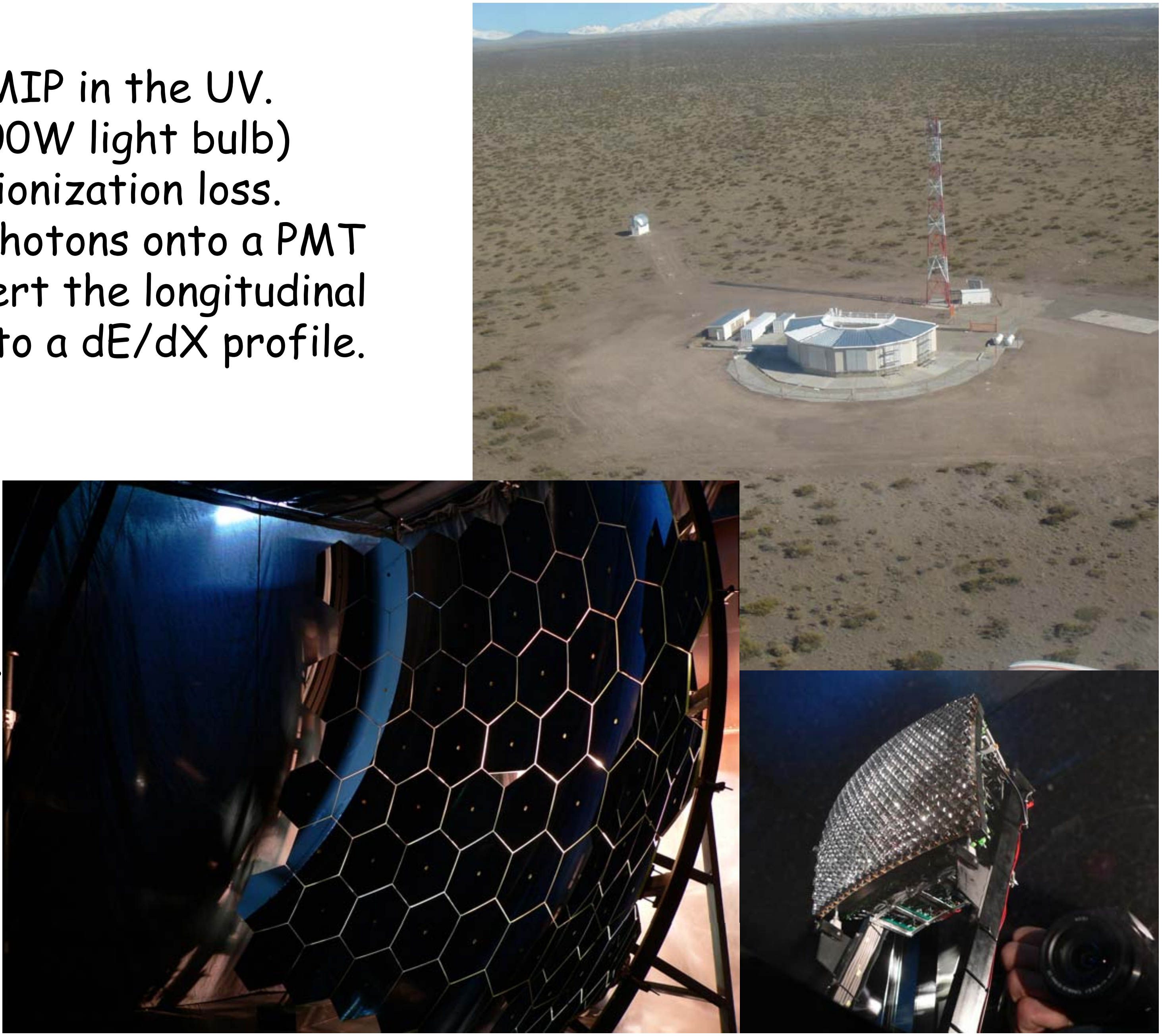
Part 2: Detection techniques

Calorimetry via air fluorescence

Fluorescence:
~4 photons/m/MIP in the UV.
(air shower ~ 100W light bulb)
Proportional to ionization loss.
Image the UV photons onto a PMT array, and convert the longitudinal signal profile into a dE/dX profile.

Integrate the dE/dX, and correct for invisible energy.

Fly's Eye,
HiRes,
Auger,
Telescope Array



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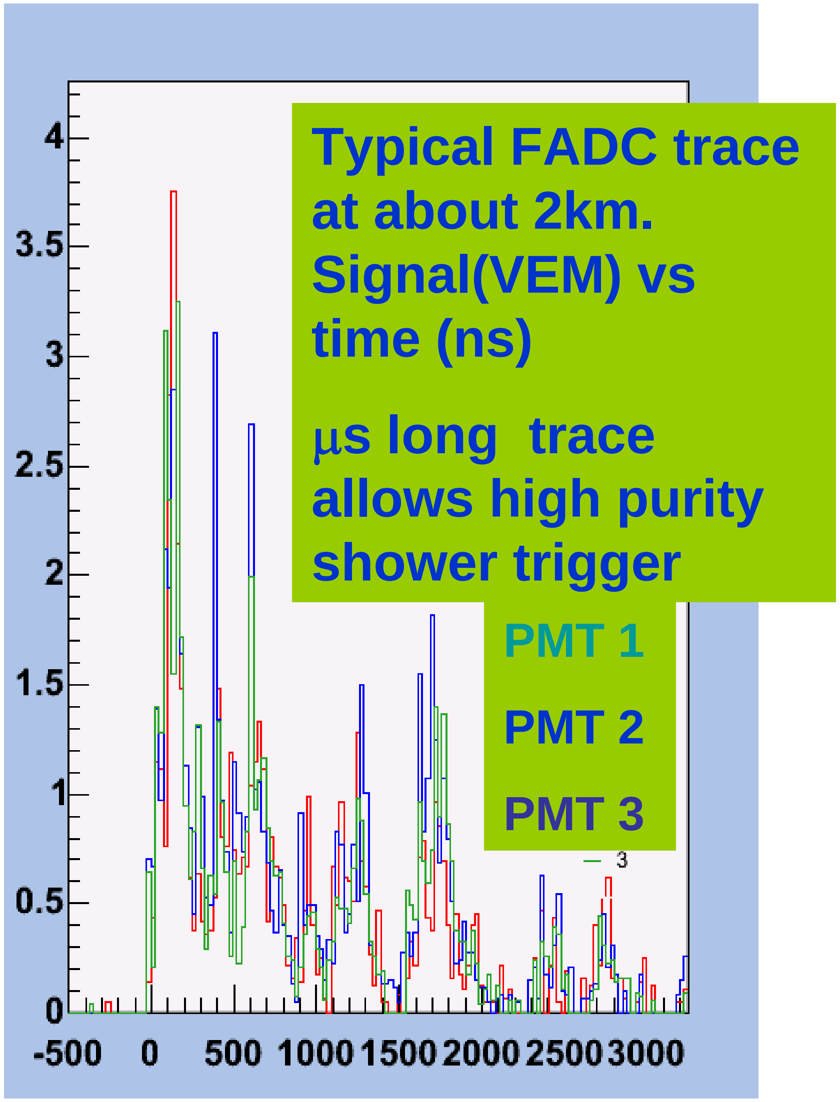
Surface detector arrays to sample the transverse air shower flux profile at ground

Calibrated with atm muons
VEM = single muon signal

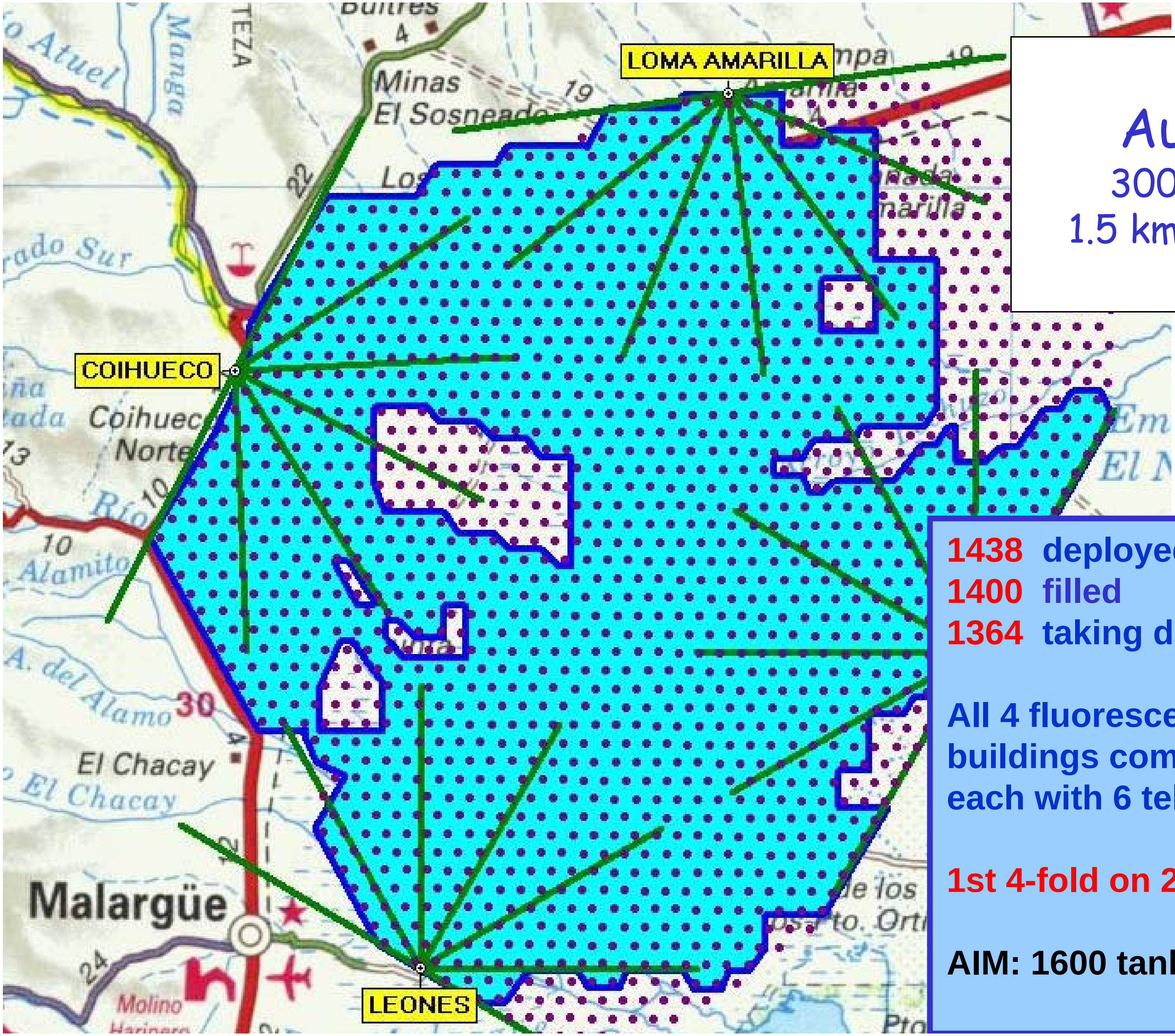


Typical FADC trace at about 2km. Signal(VEM) vs time (ns)

μs long trace allows high purity shower trigger

12 ton water Cherenkov tank
measures EM energy + muons.
Signal/muon ~25x Signal/gamma

Volcano Ranch, Yakutsk, Haverah Park, AGASA, SUGAR, Auger, Telescope Array



Auger

3000 km^2

1.5 km spacing

1438 deployed

1400 filled

1364 taking data

All 4 fluorescence buildings complete, each with 6 telescopes

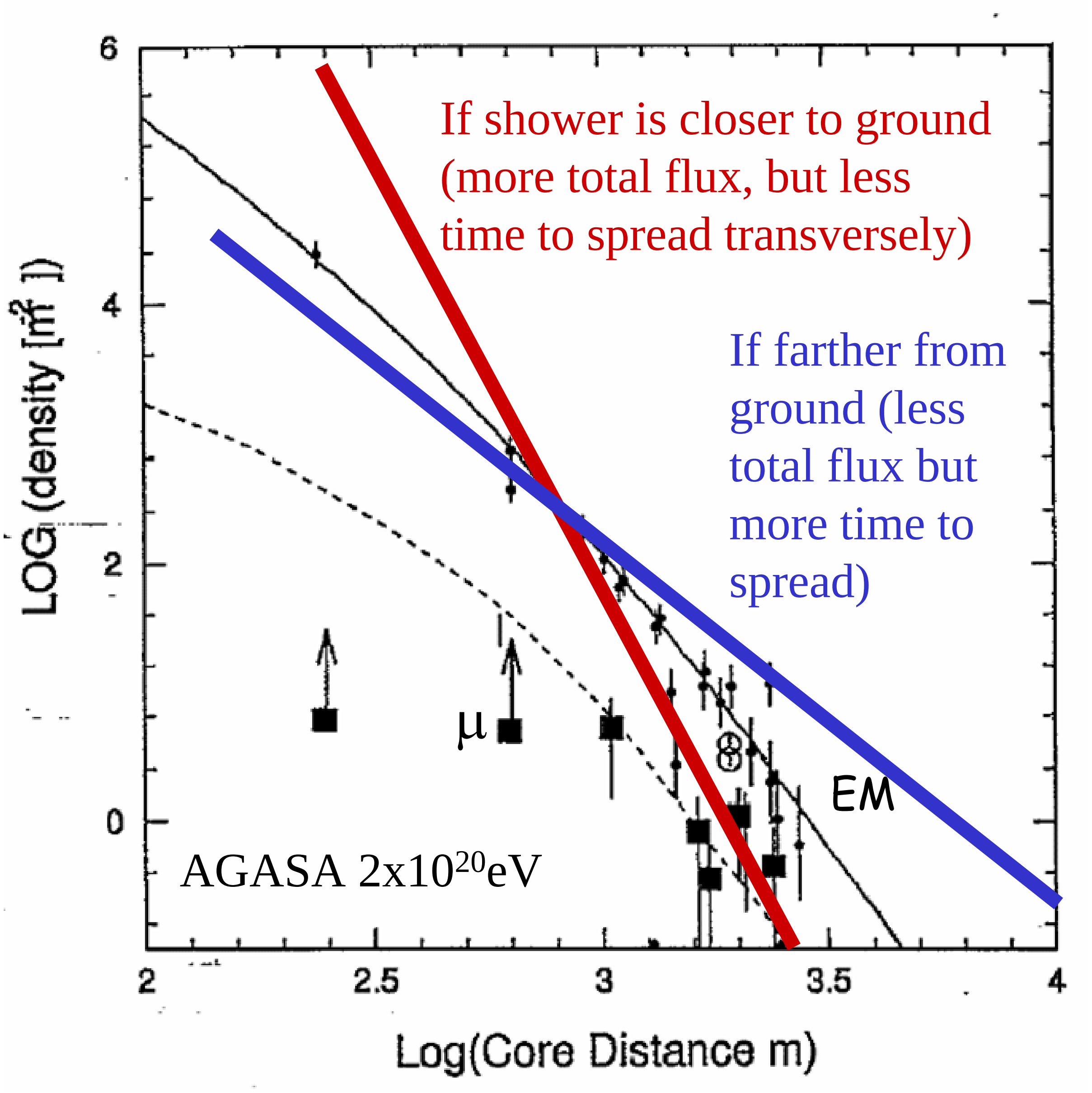
1st 4-fold on 20 May 2007

AIM: 1600 tanks

How can you do calorimetry with only one sampling plane? Surely you jest…..

While the total integrated ground flux is exponentially sensitive to event-by-event fluctuations in the shower penetration depth, **an interpolated flux parameter S(R) at finite core distance R is insensitive to this stochastic uncertainty.**

Previously: Need Monte Carlos to map S(R) onto CR energy.

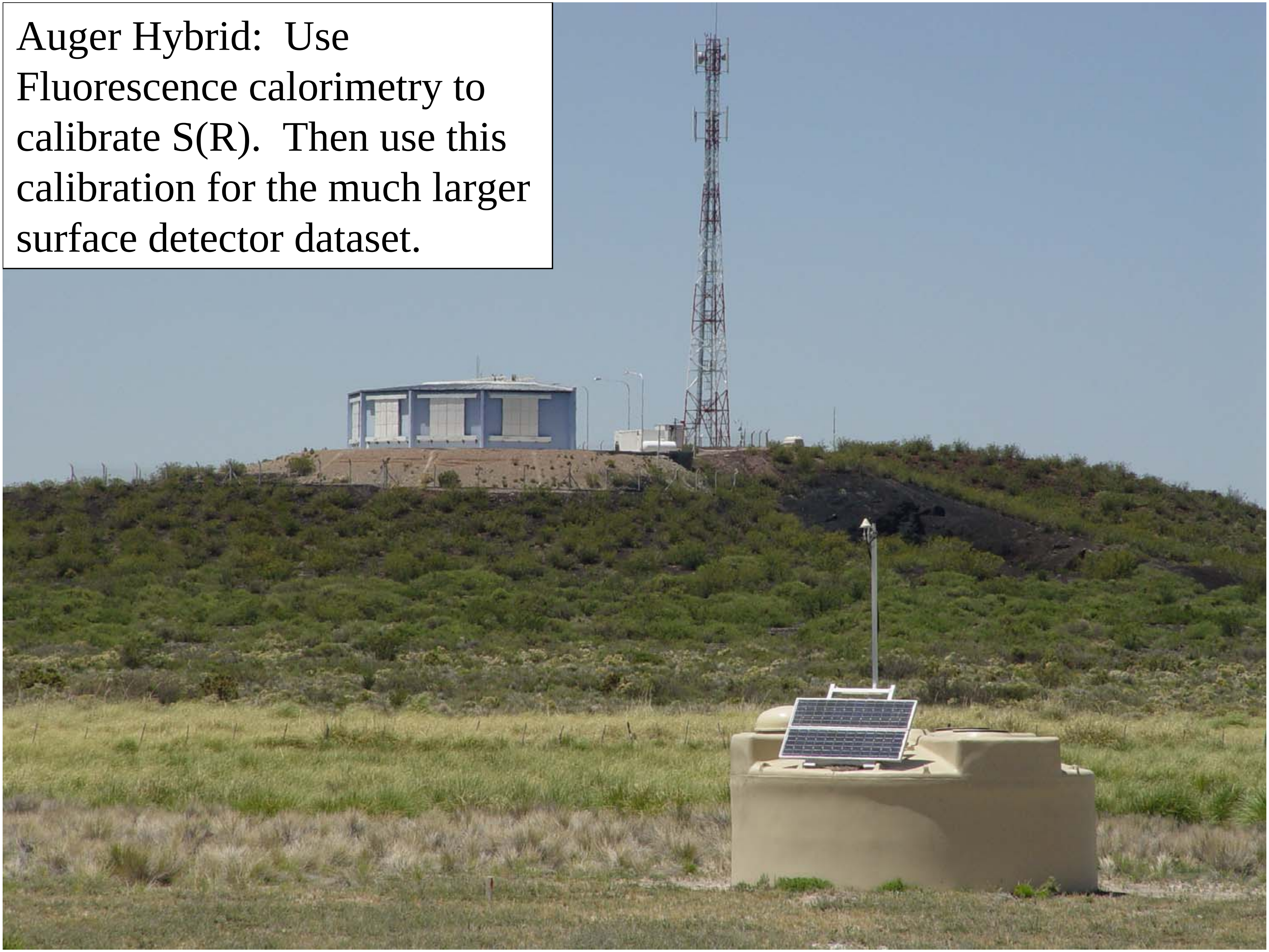


If shower is closer to ground (more total flux, but less time to spread transversely)

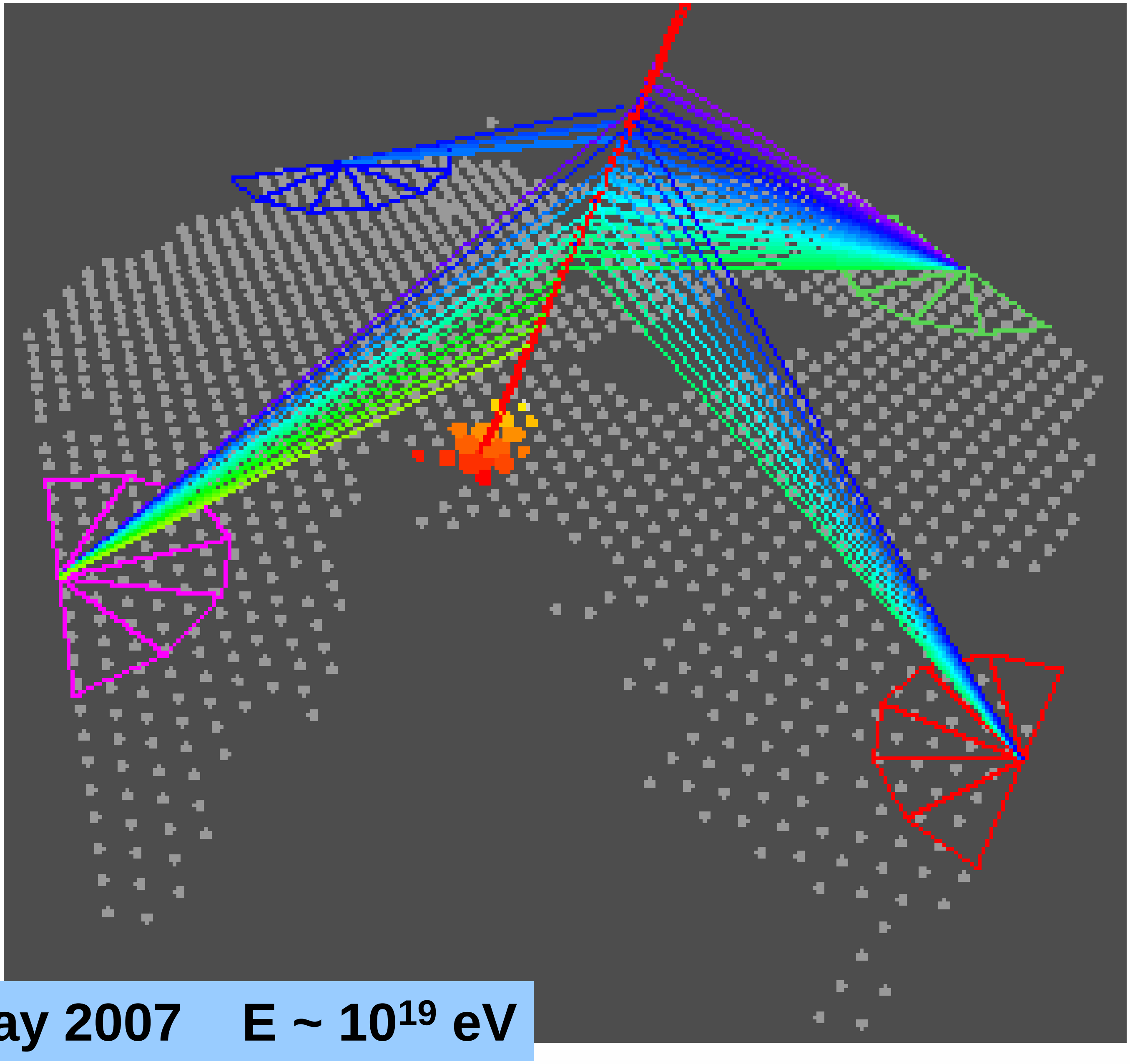
If farther from ground (less total flux but more time to spread)

AGASA 2x10^{20}eV

Auger Hybrid: Use Fluorescence calorimetry to calibrate S(R). Then use this calibration for the much larger surface detector dataset.



First 4-fold Event



20 May 2007 E ~ 10^{19} eV

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QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

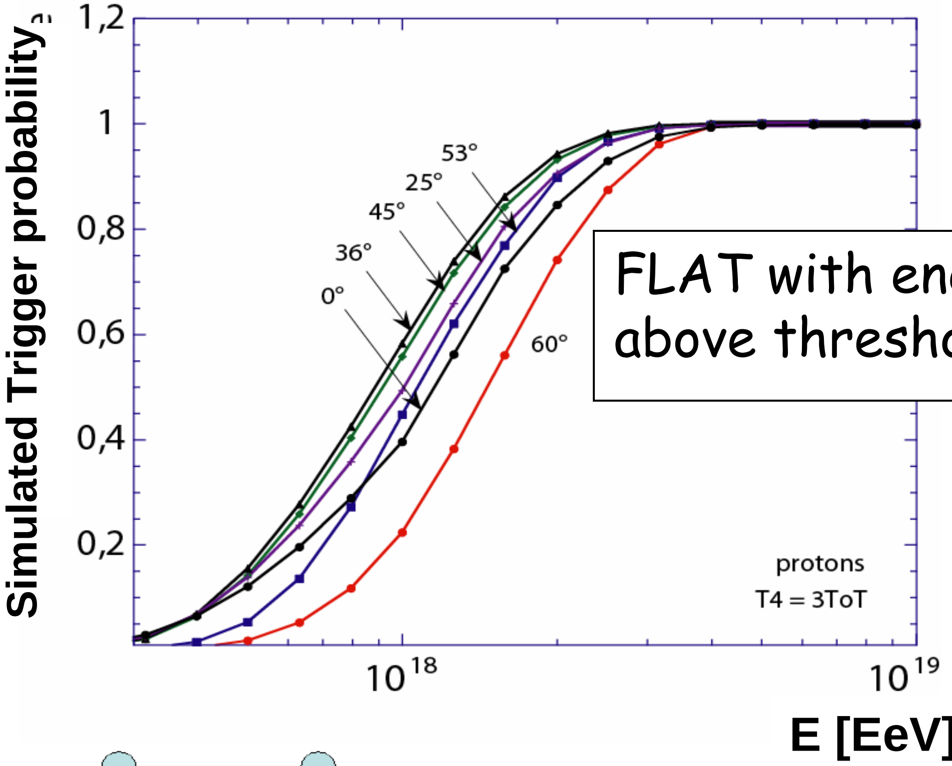
After correcting for Cherenkov contamination

The Hybrid Era

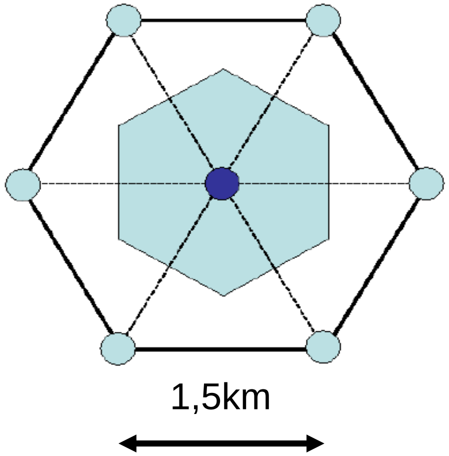
	Hybrid	SD-only	FD-only mono
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5° (correlated with impact parameter)
Aperture	Flat with energy AND mass (A) and model (M) free		E, A, and M dependent (strongly E-dependent)
Energy	A and M free	A and M dependent	A and M free

SD [0,60°] event selection and acceptance

- **Physics trigger:**
  3 stations (equilateral, ToTs)
- **100% efficiency:**
  E > 3×10^{18} eV
- **Event quality selection:**
  Hottest tank surrounded by 6 active stations
- **1/1/2004 – 2/28/2007**
- **Exposure: 5165 km^2 sr yr**
  ~3x AGASA
  (uncertainty 3%)



FLAT with energy,
above threshold

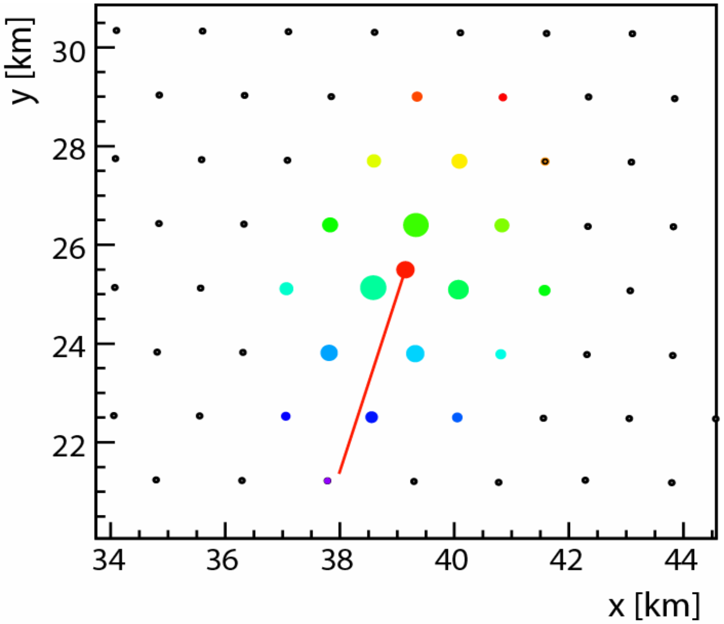


Aperture:
# of active cells;
A_C=1.95 km^2

Exposure:
Integr. of array evolution

Auger SD Event reconstruction

Reconstruction procedure:

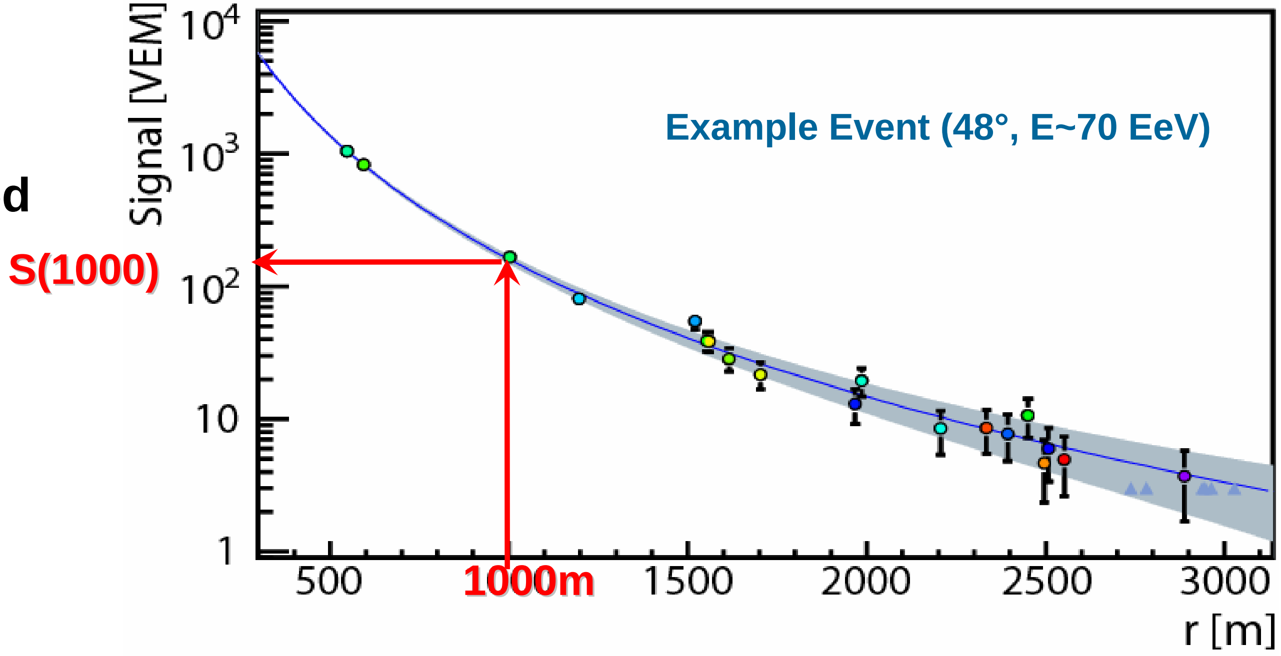


- **χ^2-method to fit angles (θ,ϕ) based on 25 ns FADC trigger timing**

- **Likelihood method to fit a NKG-type LDF with fixed slope β**

- **Simultaneous fit for**
  - **core position**
  - **S(1000)**

- **Interpolated signal at 1000m is well-measured**



Simulated measurement uncertainty on S(1000)

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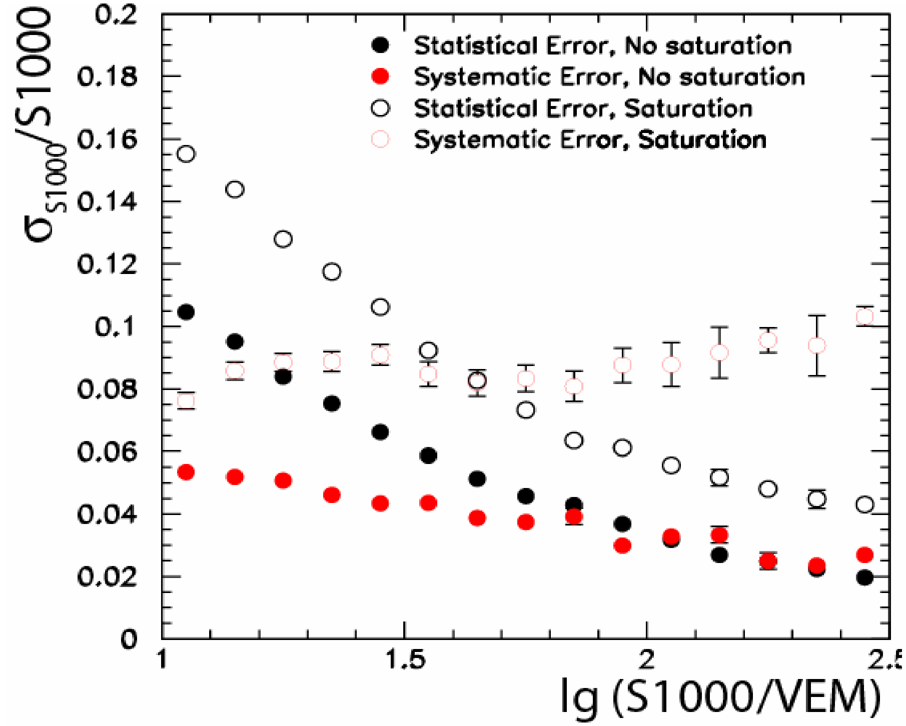
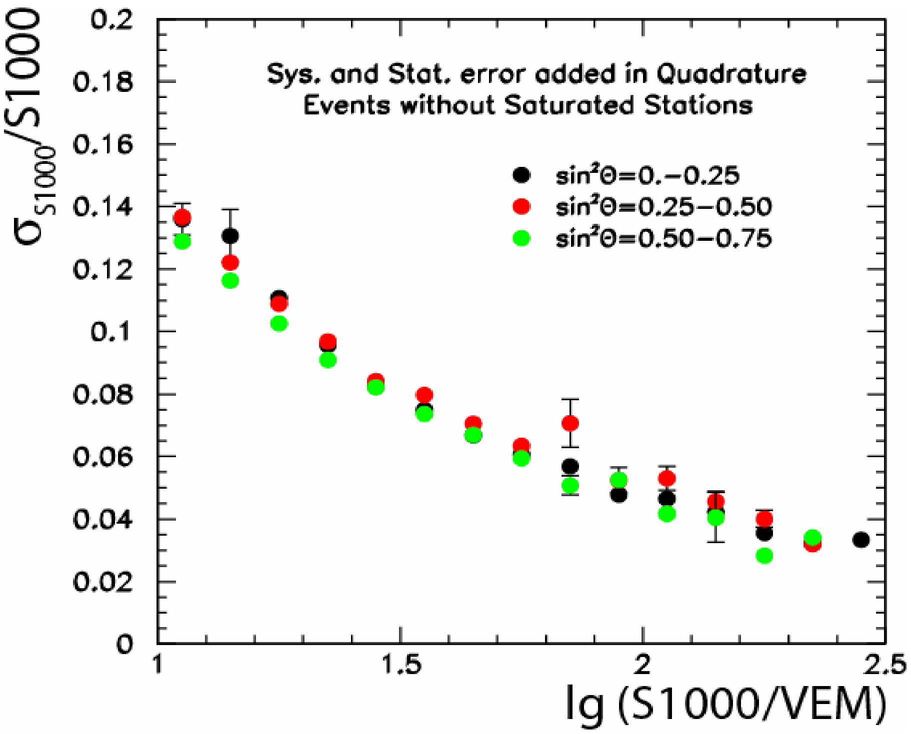




Statistical uncertainty from

- **finite size of the detectors**
- **Shower-to-shower fluctuations**
- **limited dynamic range**
  - **Saturation at 600 VEM**

Systematic uncertainty from

- **shape (slope) of the LDF**

Other effects like T,P dependency of less importance ($\Delta S(1000) = 0.3\%/K$)

Errors are propagated

$\sigma_{S(1000)}$ well under control
No zenith angle dependency

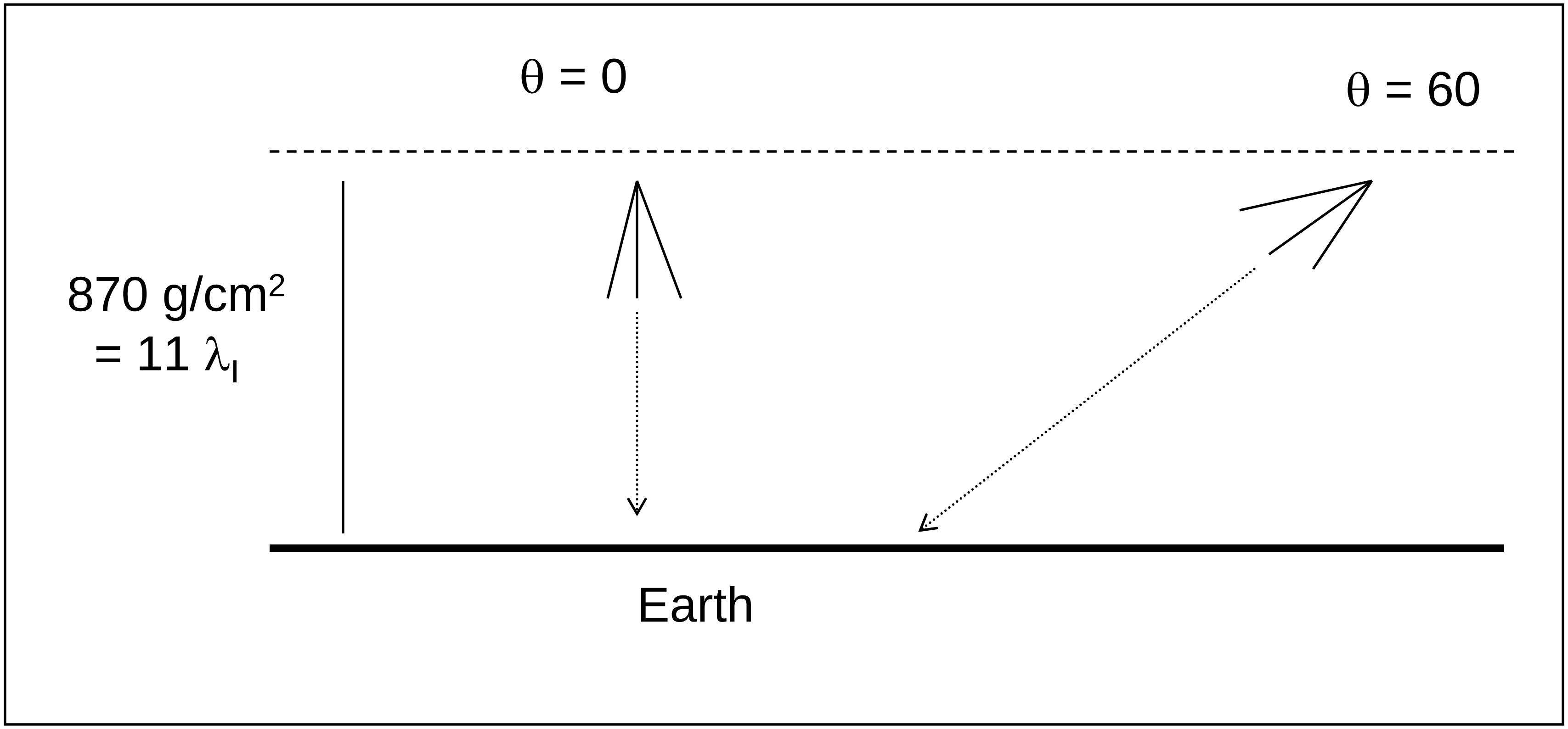
We have now measured the ground flux parameter S(1000).

How do we convert this to primary energy?

Auger does this all empirically!
No Monte Carlo

1. Zenith angle correction:

Showers coming from different zenith angles give very different signals at ground due to flux attenuation in the atmosphere.



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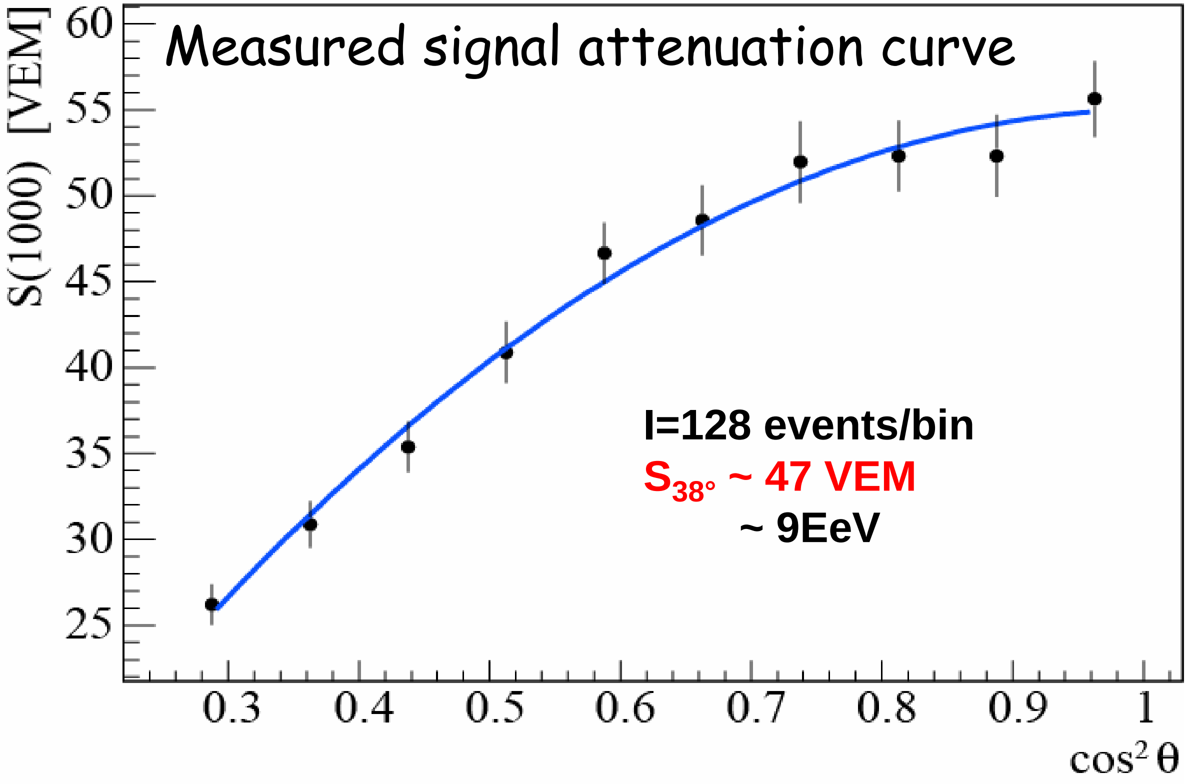
The "slant depth" is $870 \mathrm{g/cm}^2 * \sec(\theta)$

Constant Intensity Method to empirically determine the atmospheric attenuation curve for the air shower flux

- CR flux is isotropic and should be the same in any bin of solid angle centered at any zenith angle: $I(E>E_0,\theta_1) = I(E>E_0,\theta_2)$
- Measure the integral flux dN/dS(1000) at different θ bins, and adjust the lower bound $S(1000)_{min}$ until the integral flux is equal in each bin.

- The vector of $S(1000)_{min}[\theta]$ are the relative attenuation values.

Apply the θ correction to get S_{38}, the equivalent signal for a shower at $\theta=38$ degrees.

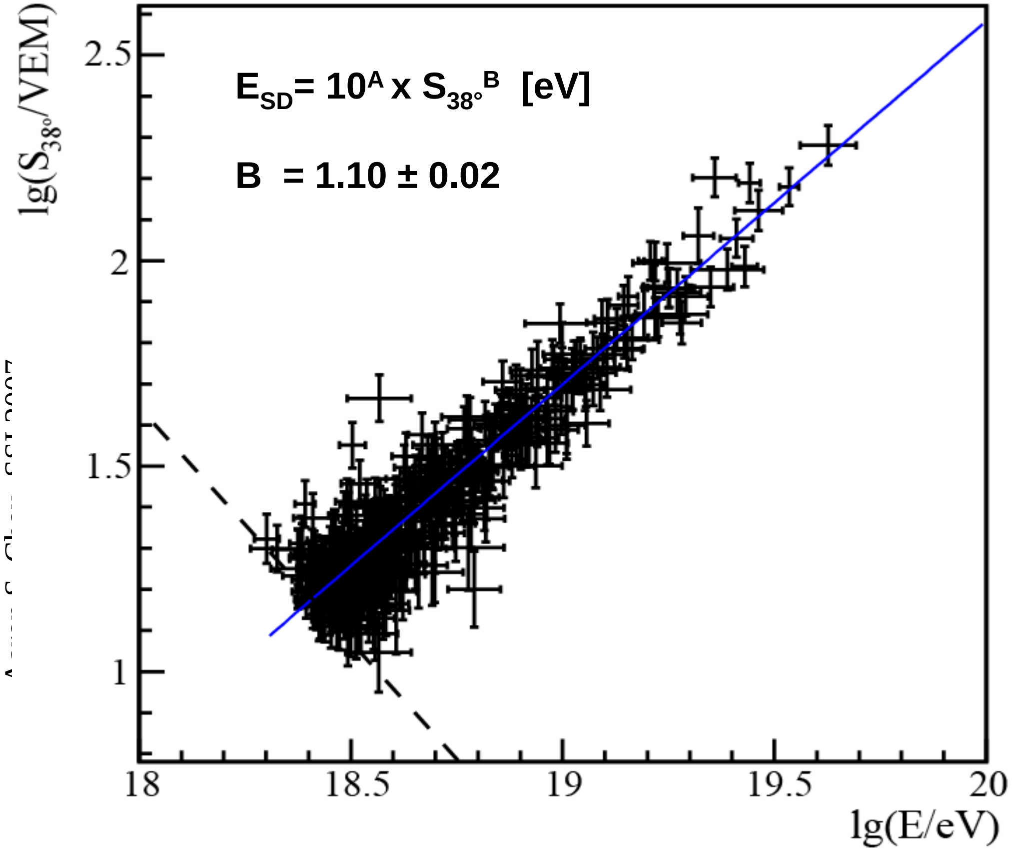


I=128 events/bin

$S_{38^\circ} \sim 47$ VEM

~ 9EeV

2. Correlate S_{38} to FD energy with hybrid dataset



Selection of high quality hybrid data without introducing Xmax biases

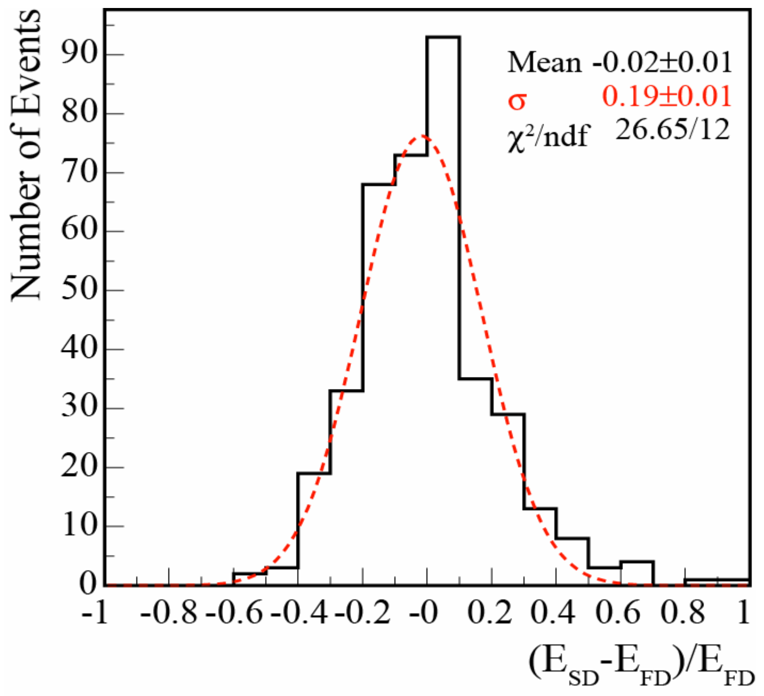
387 events

$$\frac{\sigma_E}{E} = \frac{\sigma_{E_{SD}}(\sigma_{S_{38°}})}{E_{SD}} \otimes \frac{\sigma_{E_{FD}}}{E_{FD}} = 18\%$$

16%

8%

Energy resolution



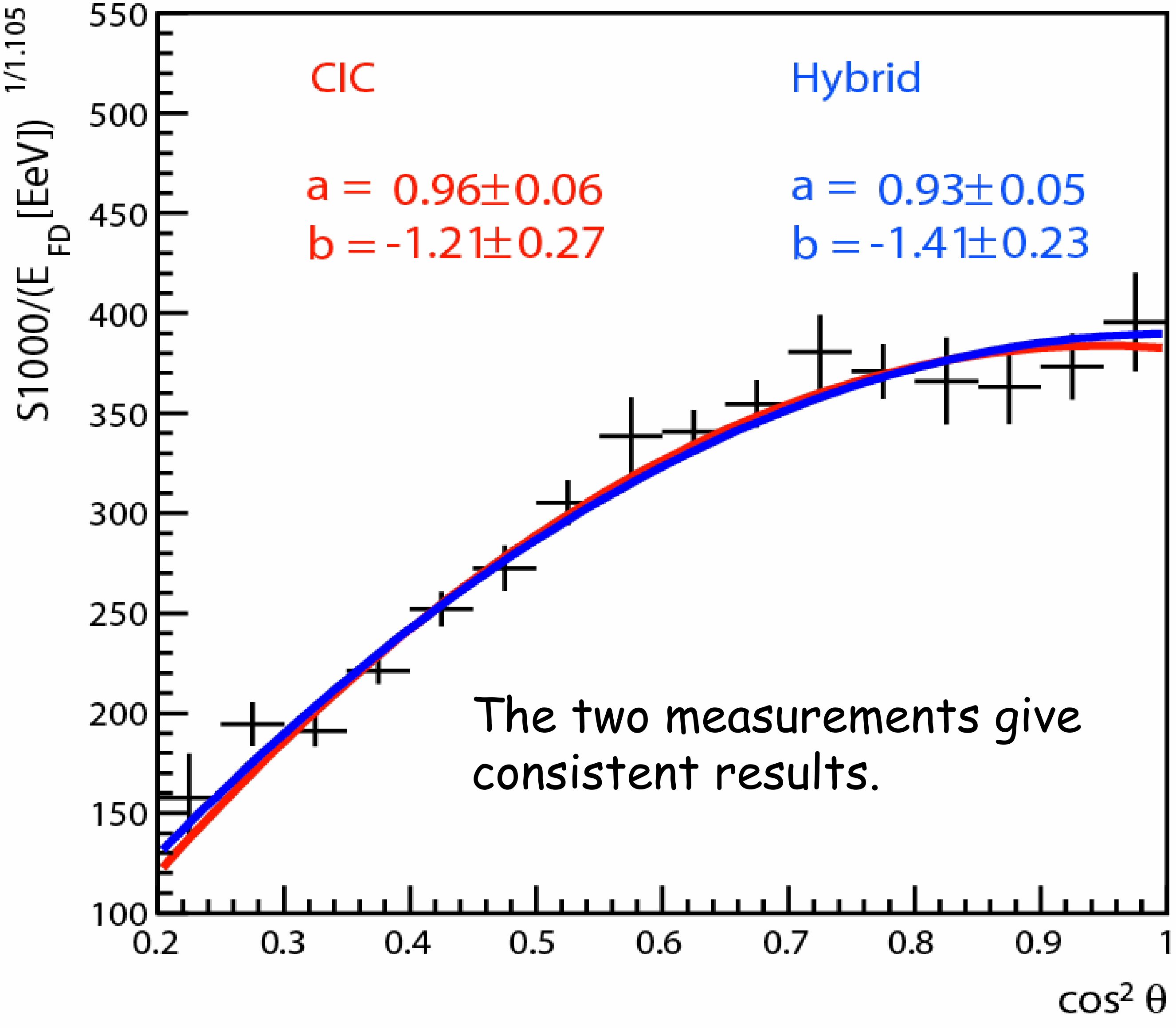
Summary of systematic uncertainties in the energy measurement

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

Double-check the measured constant intensity attenuation curve with hybrid events



The two measurements give consistent results.

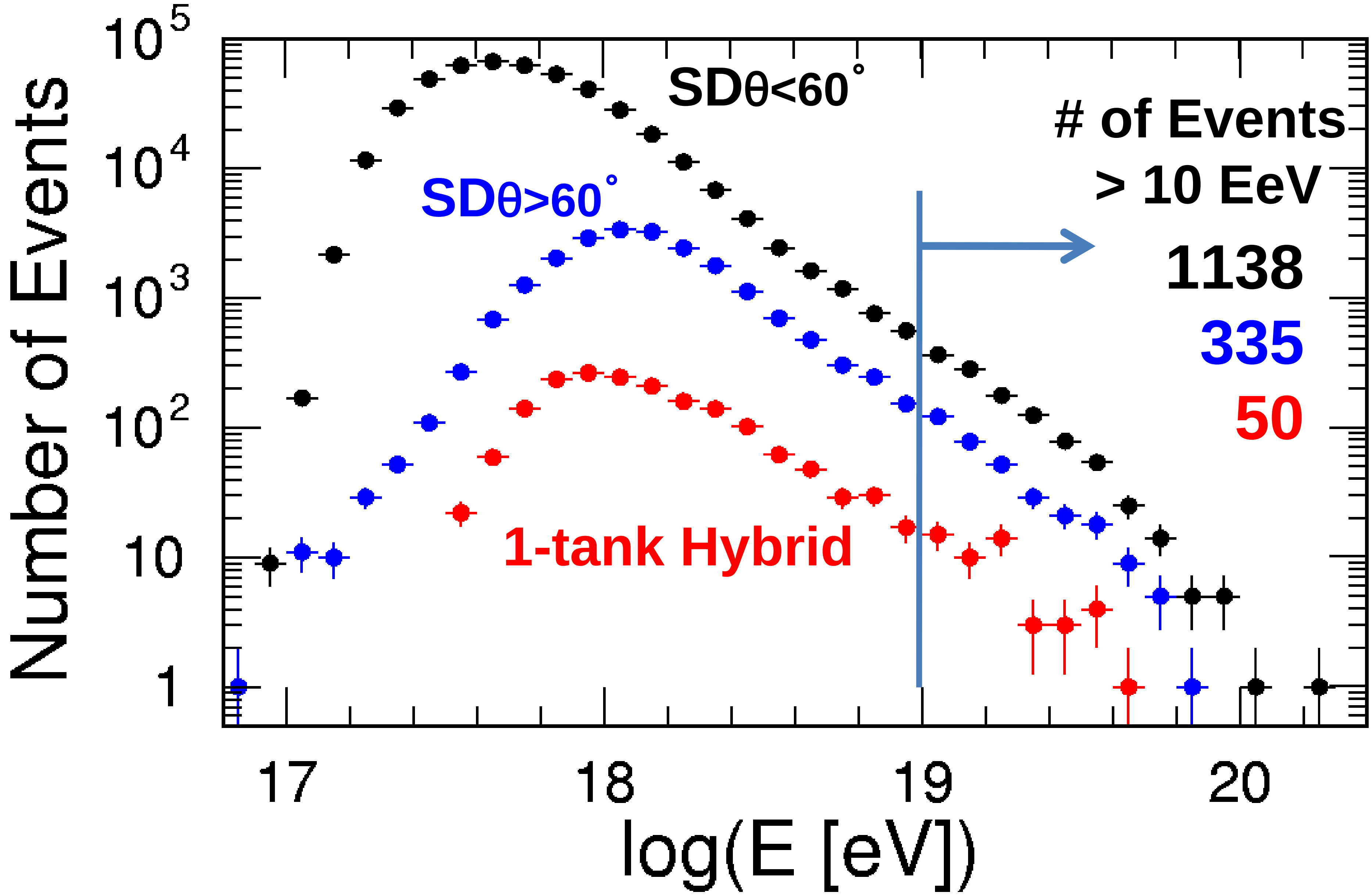
Do the same calibration for inclined ($60<\theta<80$) showers for muon flux measurements

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Must treat this event sample separately because inclined muons are deflected by the geomagnetic field.

The resulting asymmetric transverse distribution of muon flux must be simulated, but is nearly model-independent.

Raw event energy histograms



Spectrum = Energy histogram/Exposure

SD exposure is flat:

above 3 EeV for $\theta<60$ and above 6.8 EeV for $60<\theta<80$

Known to 3% uncertainty just by counting livetime.

The hybrid exposure grows as log(E) as expected from Rayleigh attenuation of the fluorescence light.

By requiring only 1 tank to constrain the geometry, the hybrid energy threshold for quality events is much lower than that of SD →

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

16% uncertainty

Auger SD Energy spectrum (2007)

Cross-checks:

- Different reconst. methods
- $\cos^2\theta$
- Different portions of the array
- Different time periods
- Temperature

⇨ **All compatible within uncert. (few %)**

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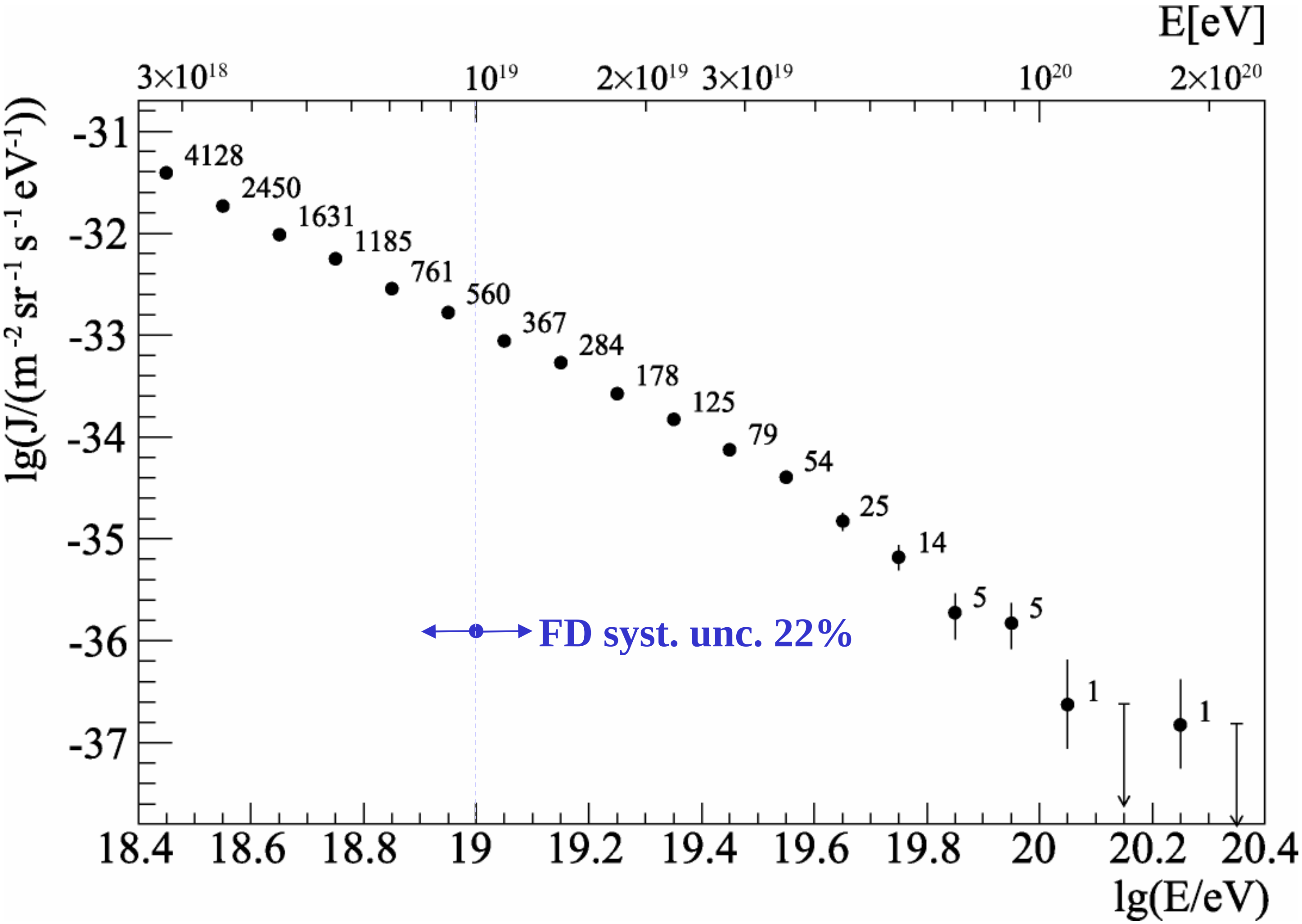
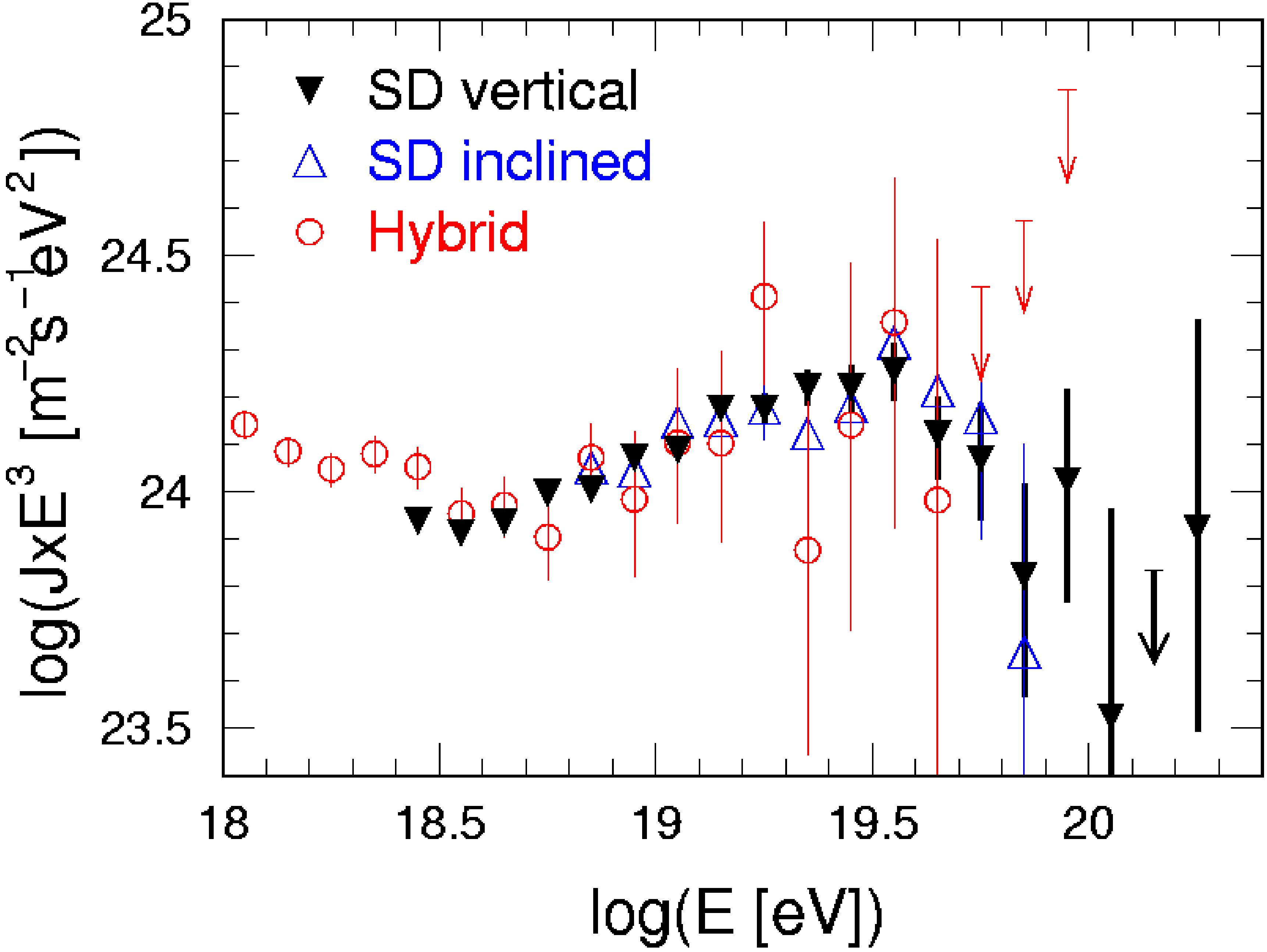


The 3 measured spectra



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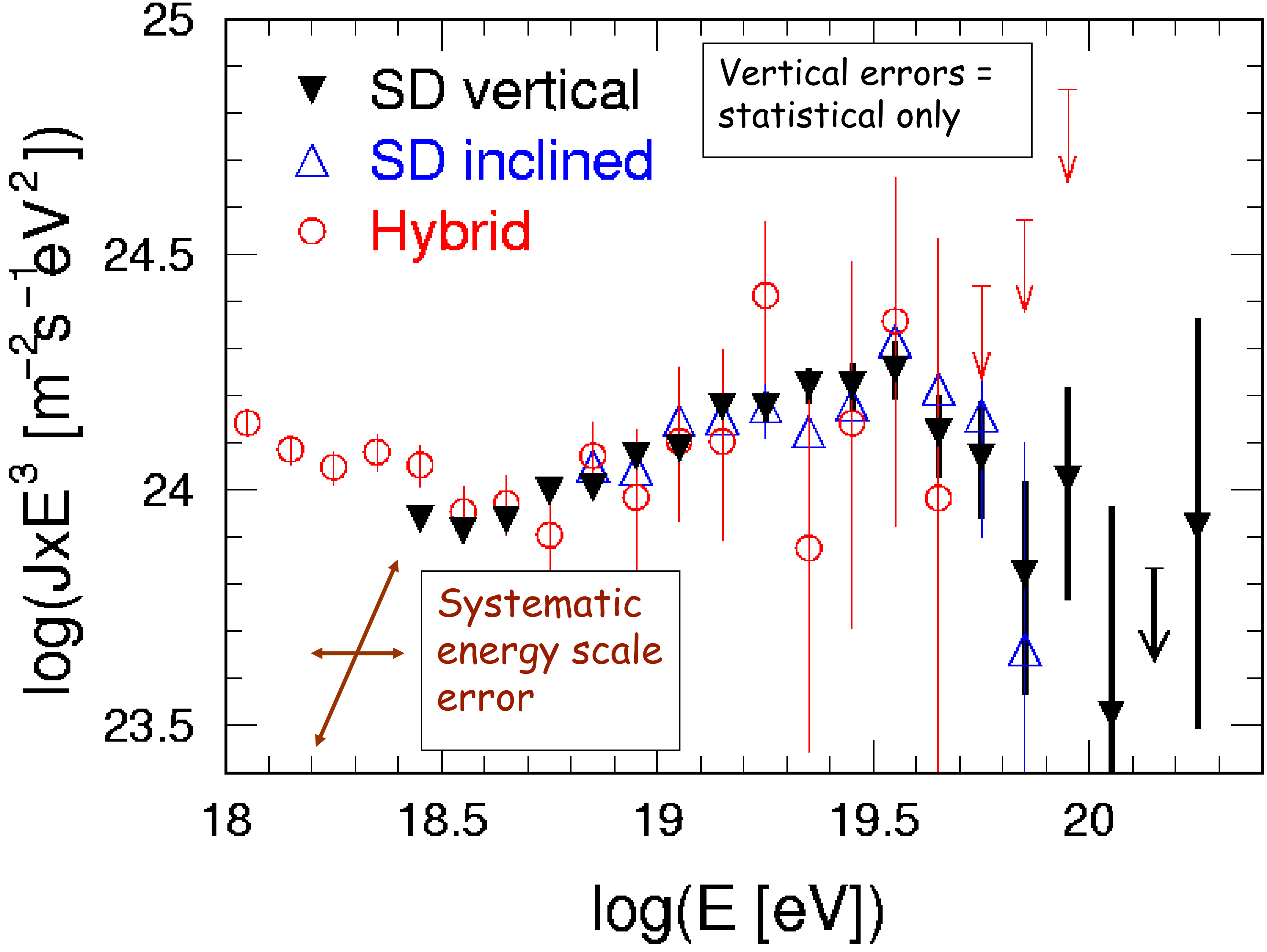
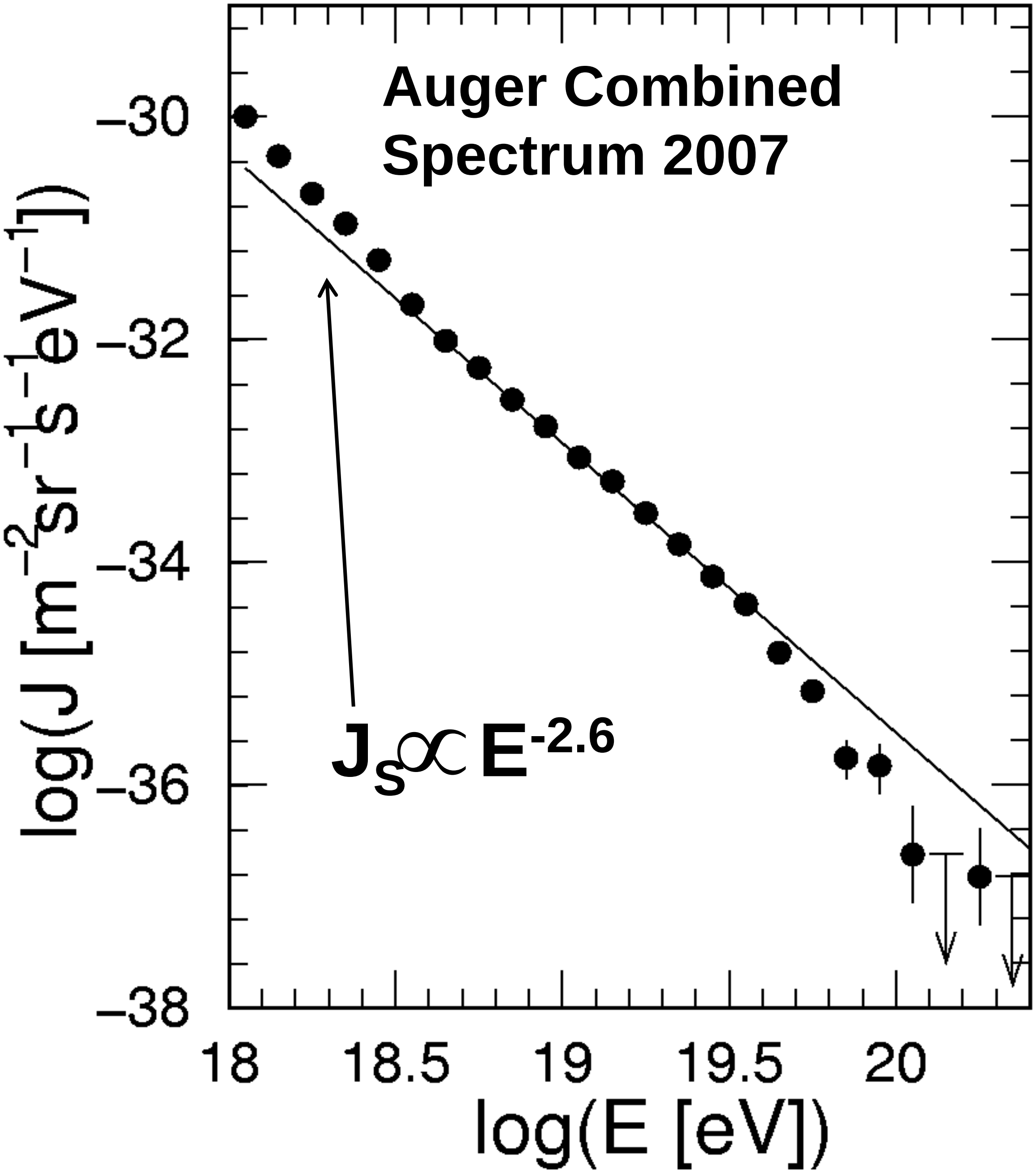
The 3 measured spectra

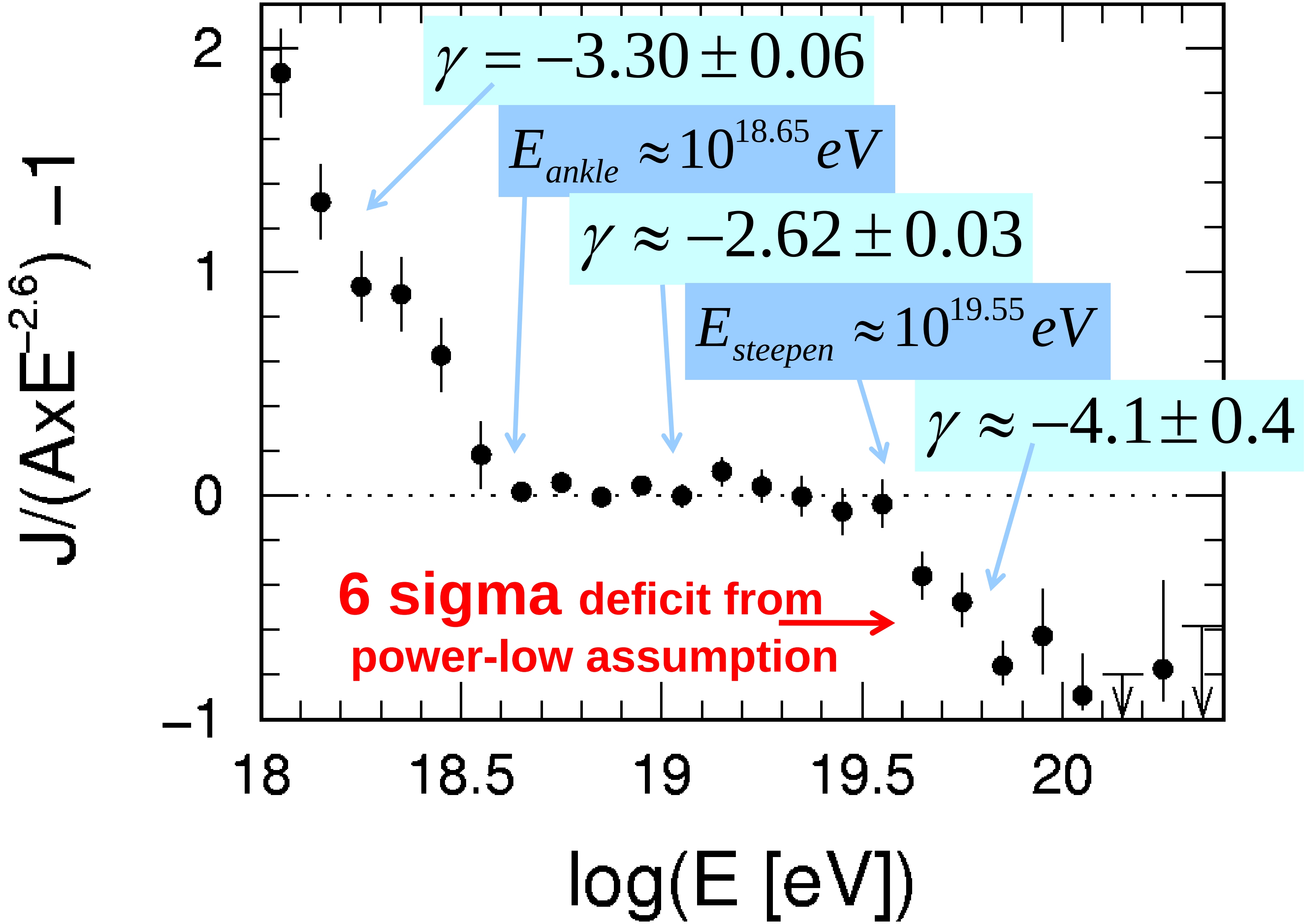




Three spectra combined weighting statistical error in each energy bin (some double counting).

Low energy from Hybrid observation, High energy from SD.

‘ankle’ and ‘steepening’ seen in (nearly) model and mass-independent measurement .



$\gamma = -3.30 \pm 0.06$

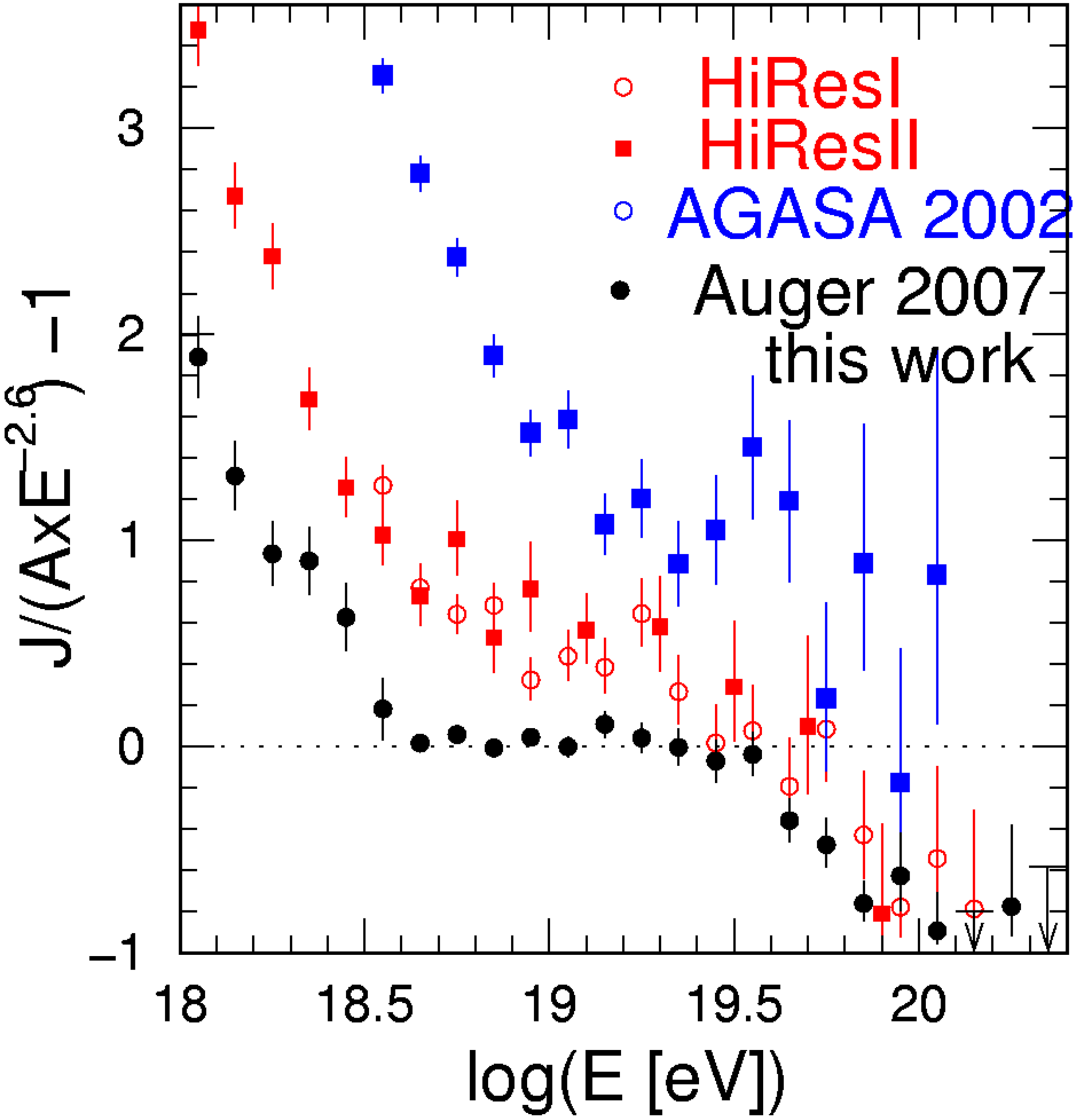
$E_{ankle} \approx 10^{18.65} eV$

$\gamma \approx -2.62 \pm 0.03$

$E_{steepen} \approx 10^{19.55} eV$

$\gamma \approx -4.1 \pm 0.4$

6 sigma deficit from power-low assumption



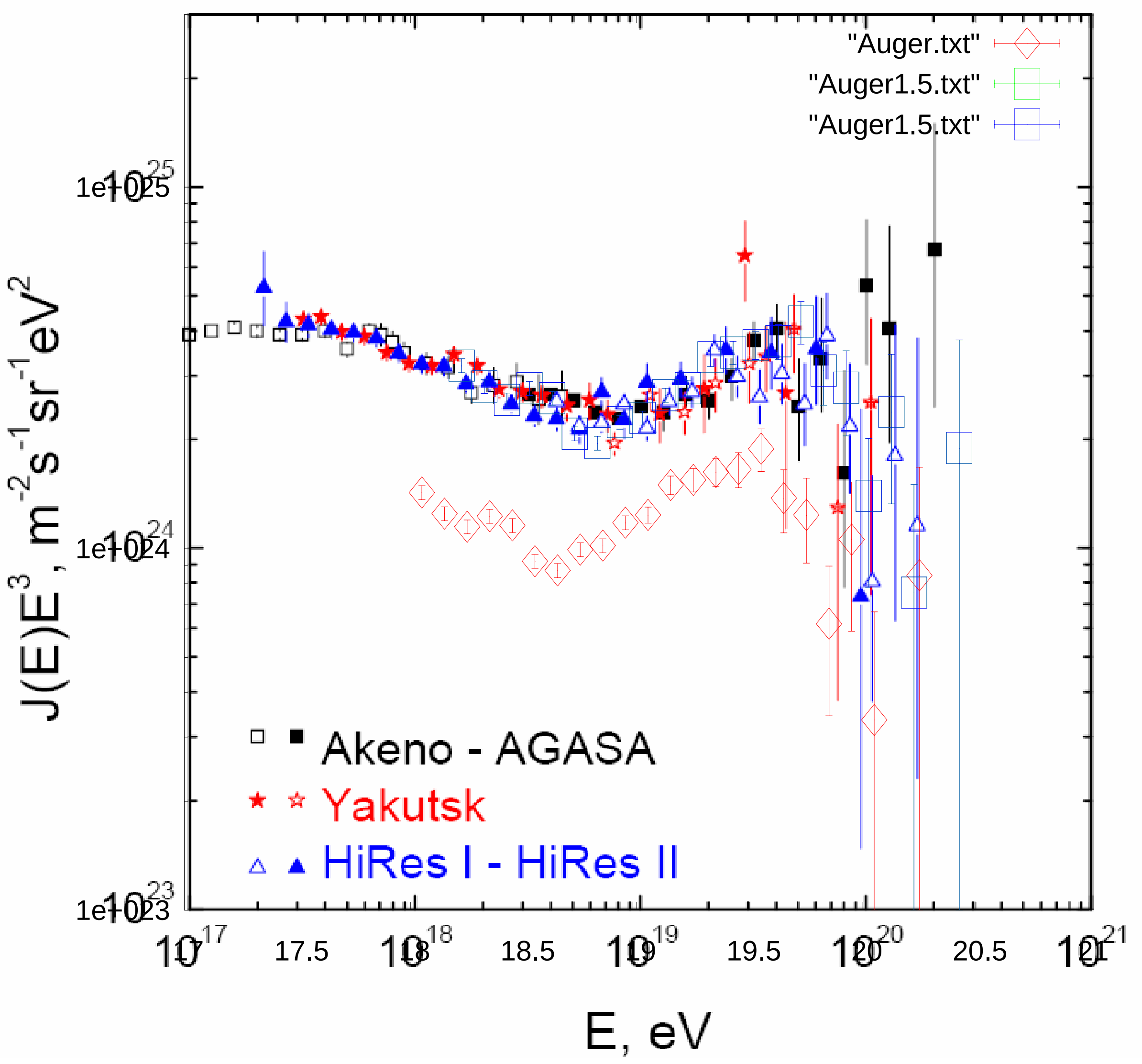
There is a significant difference from HiRes spectra both in shape and in normalization (despite common systematics….)

AGASA energies were revised downward ~15% in 2006 due to updates to hadron interaction models. This is not enough to account for the difference

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
>6×10^{19} eV	49 (12)	31 (23) (20)	66
>7×10^{19} eV	31	25 (15) (14)	31
>10^{20} eV	4 (0)	11 (6) (5)	2

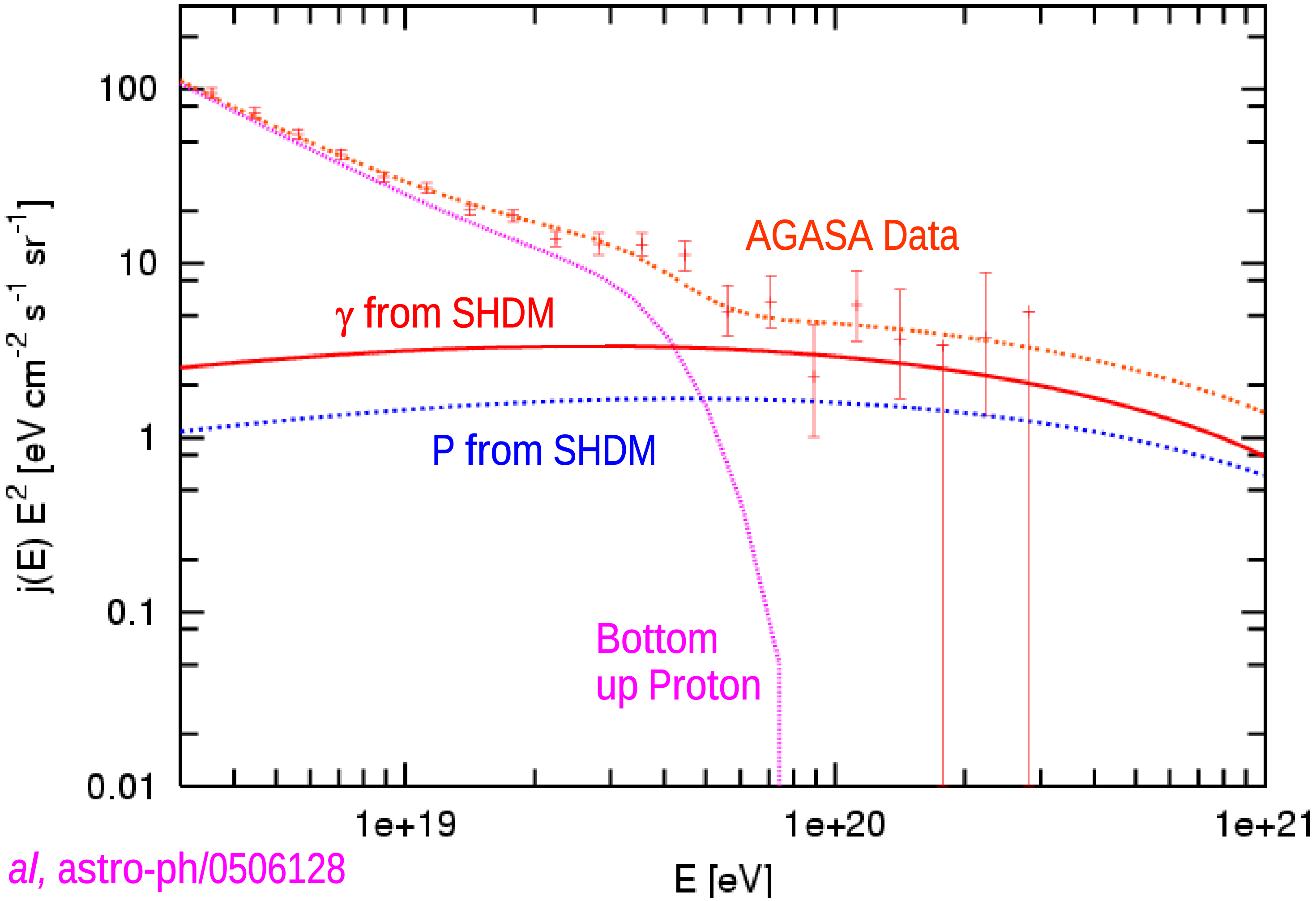
If all spectra are normalized to AGASA:
Auger energies need to be increased by 50%
(Plot from M. Teshima, AGASA spokesperson)



Photon primaries?

- In top-down models, UHECR are produced with extremely high energies from decays of super-massive objects like superheavy dark matter, or topological defects
- If these objects decay to hadrons at all, then they produce far more pions than protons. The UHE flux is then expected to be dominated by UHE photon primaries from pi0 decay.
- Limits on the photon fraction in the measured flux can therefore constrain top-down models.

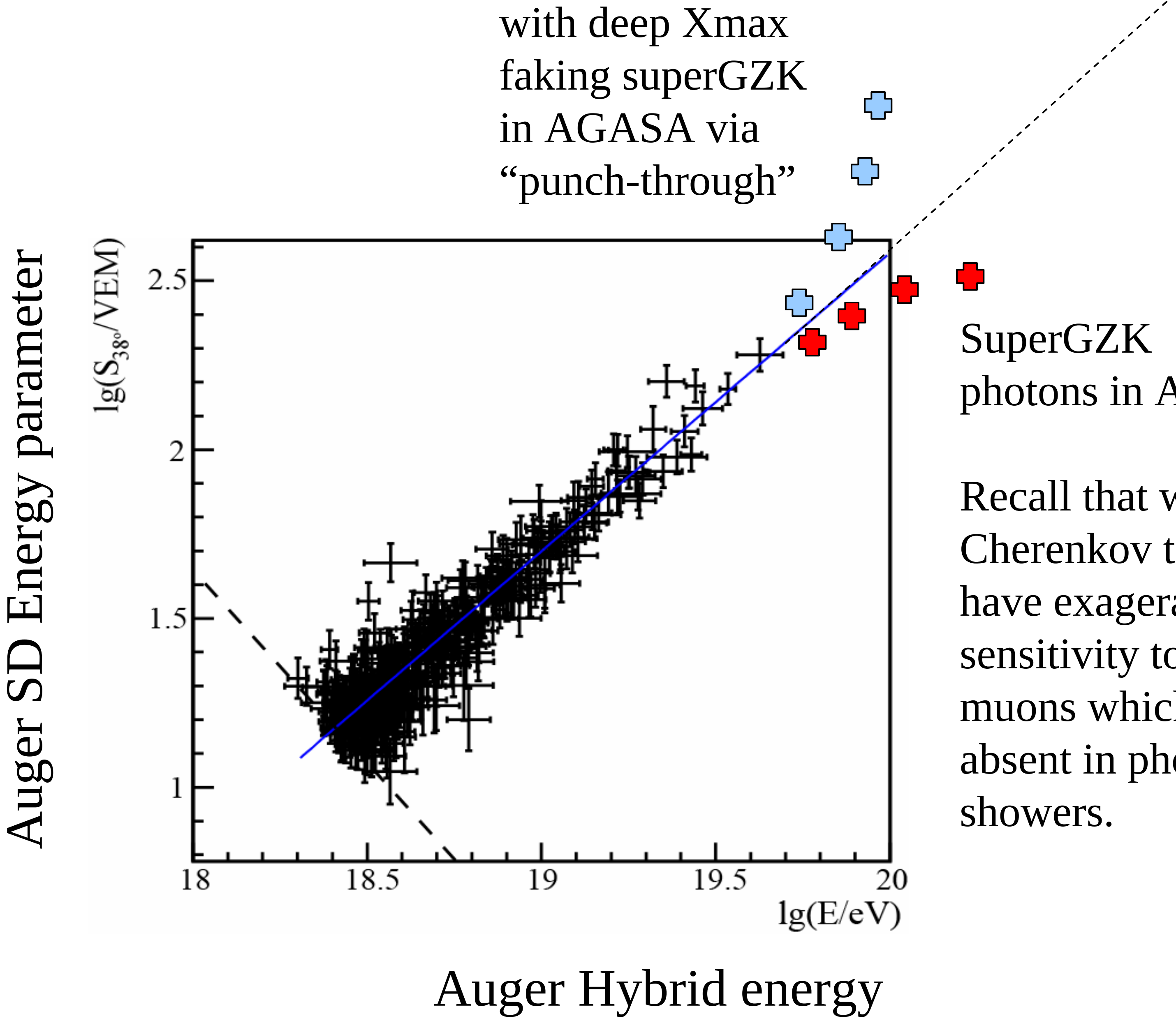
Super Heavy Dark Matter fit to AGASA2002



Gelmini, *et al*, astro-ph/0506128

What if….

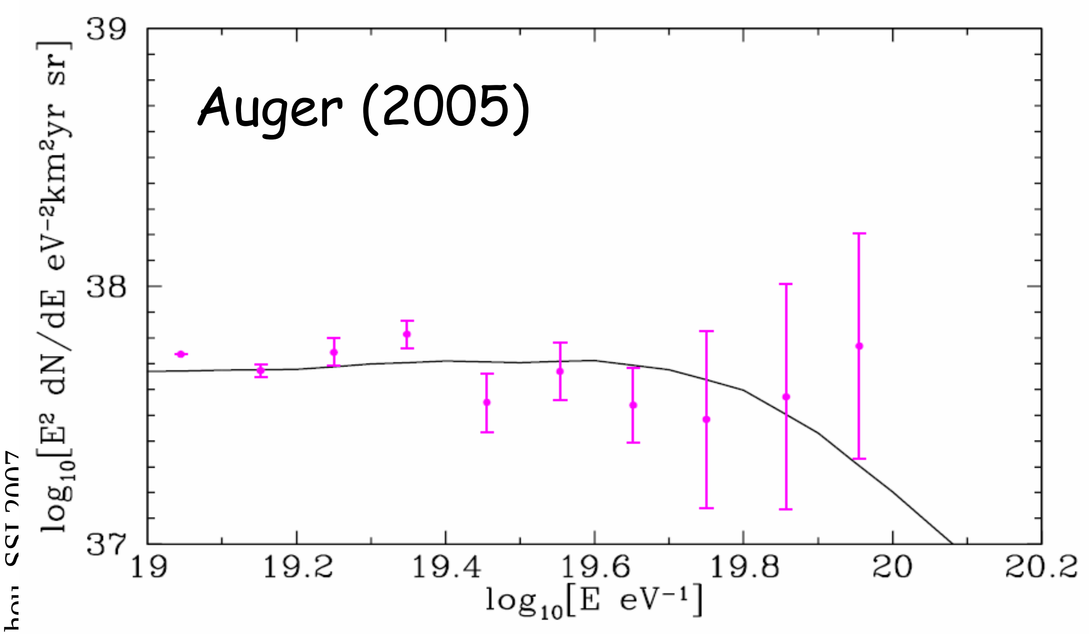
SubGZK exotics
with deep Xmax
faking superGZK
in AGASA via
"punch-through"

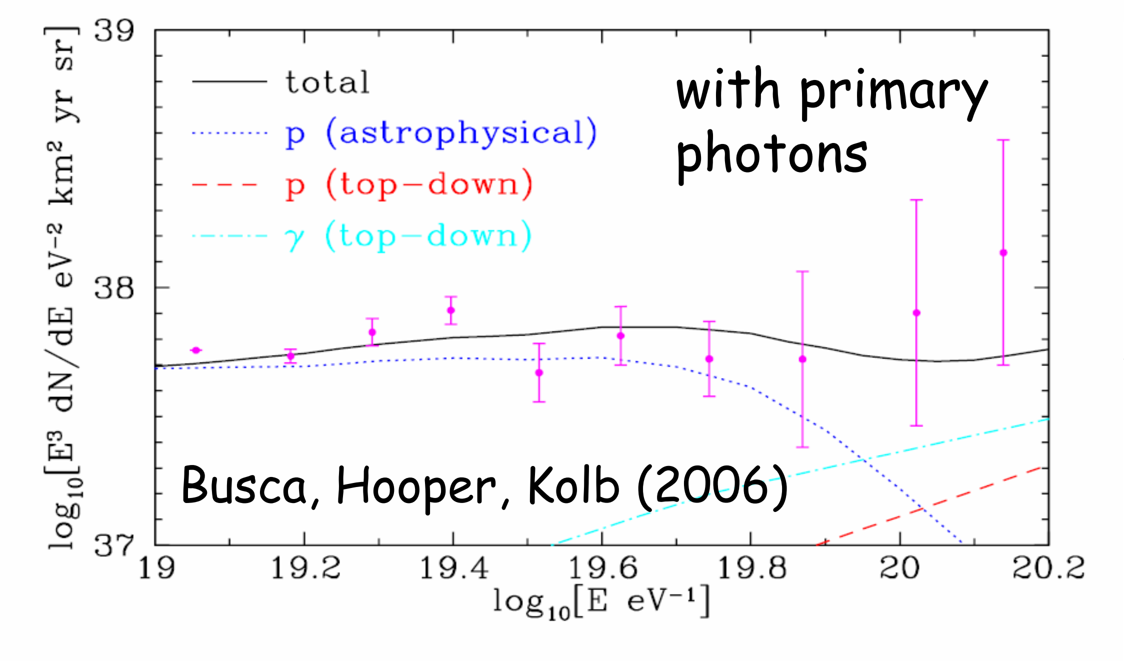


SuperGZK
photons in Auger

Recall that water
Cherenkov tanks
have exagerated
sensitivity to
muons which are
absent in photon
showers.

The spectra all have composition systematics!





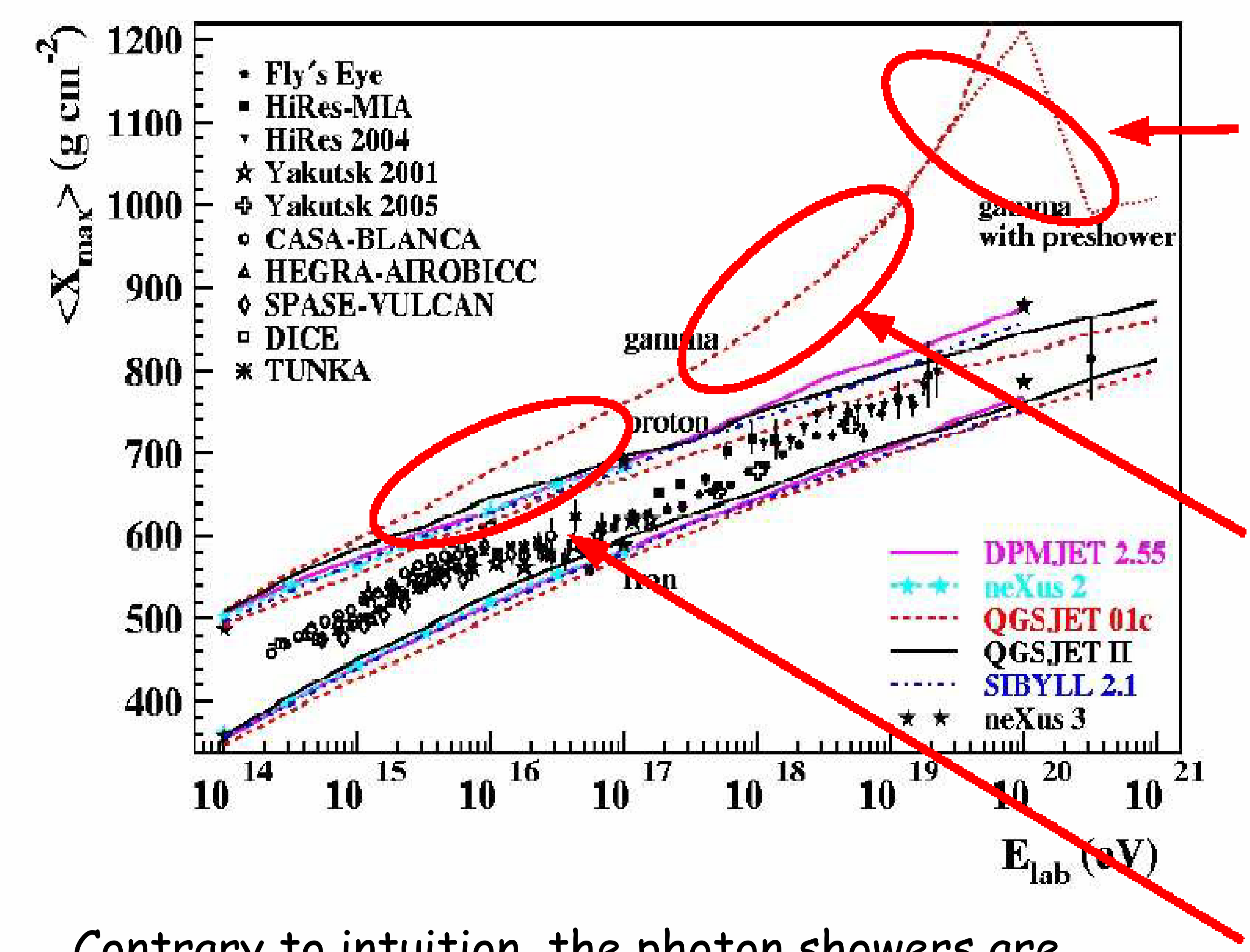
HiRes1 must assume that all particles are protons in order to reconstruct

AGASA must assume all particles are protons in order to assign MC energies

Auger must assume that all particles behave like the typical particle in order to assign calibrated energies.

CR composition must be studied separately in dedicated analyses.

Use ‹Xmax›(E) to detect composition changes



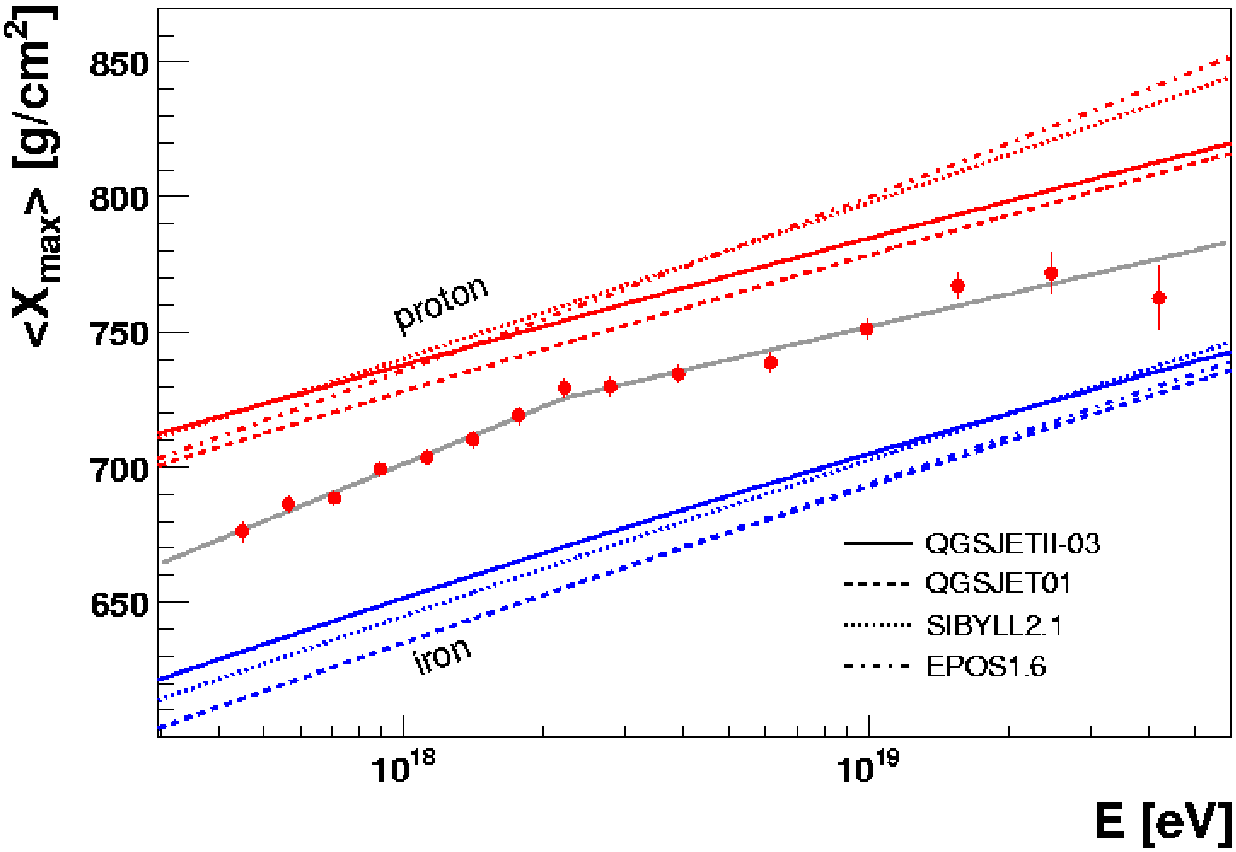
Preshower

LPM

“Standard“

Contrary to intuition, the photon showers are deeper than hadron showers. This is due to slow development of EM shower, and LPM suppression.

Mean Hybrid Xmax vs energy Auger2007 and model predictions



If models can be believed, then this implies a mixed heavy primary composition even at the highest energies. This implies astrophysical **bottom-up sources** for most UHE cosmic rays, though acceleration models are difficult. Also the “steepening” seen the spectrum is then not at the correct GZK threshold energy….

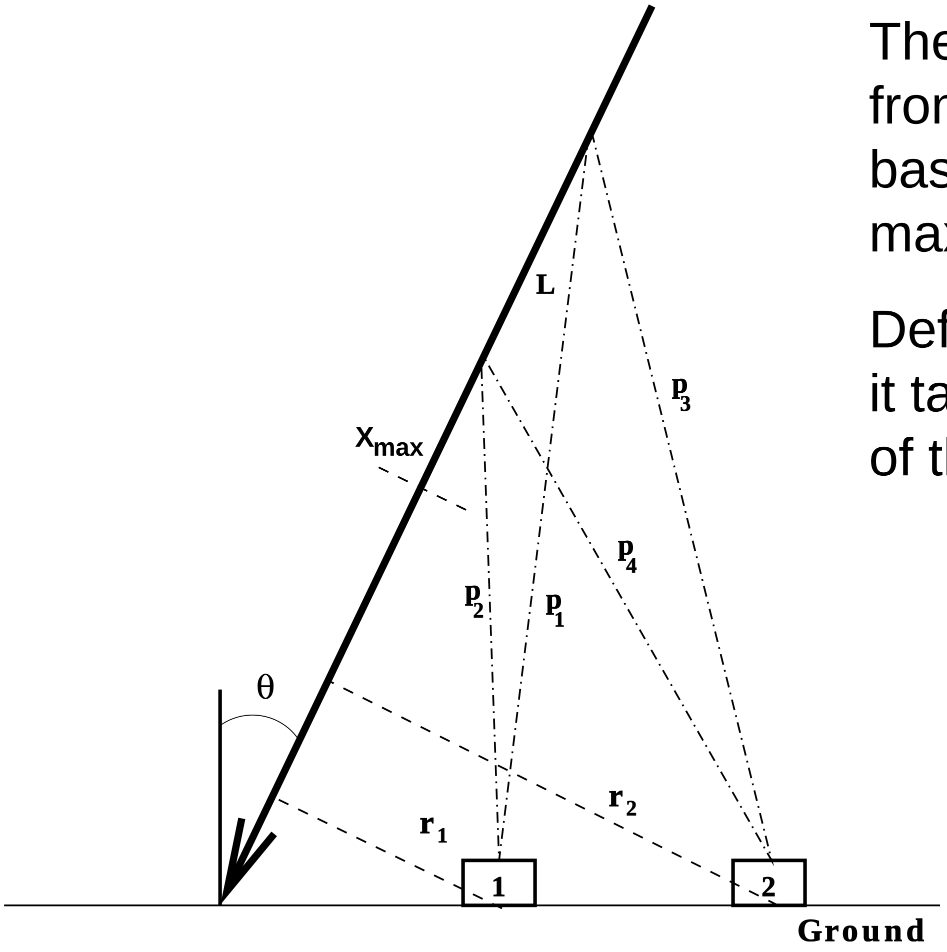
No obvious photon events in the tails of the hybrid Xmax distribution (58 quality events with unbiased fiducial event selection)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Photon simulation

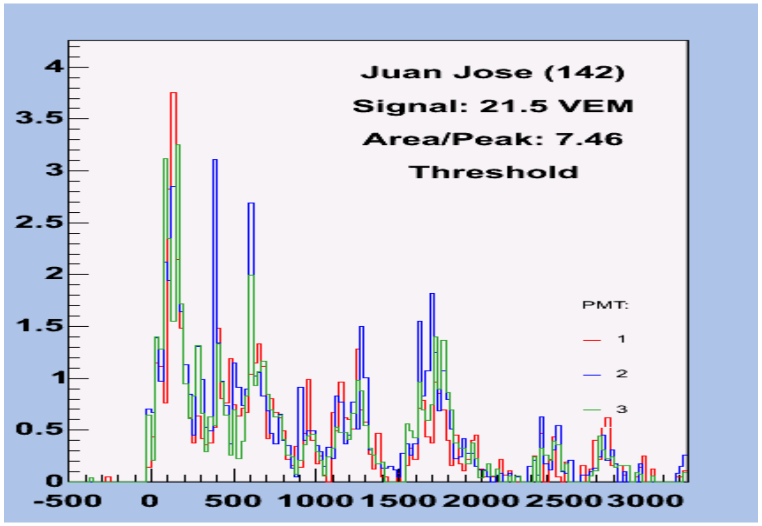
data

SD signal risetime is also sensitive to Xmax



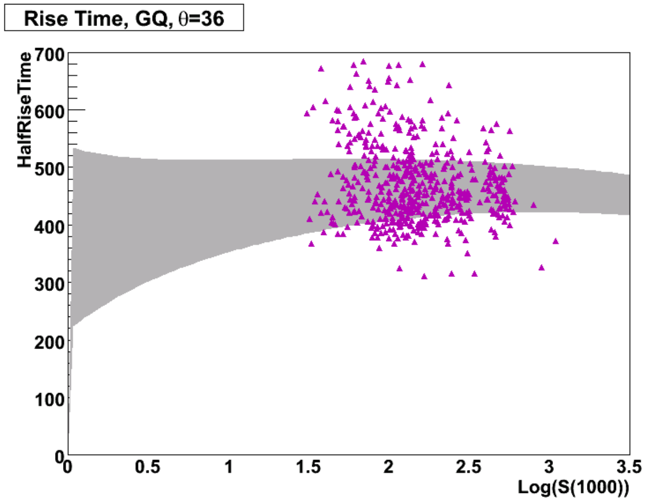
The path lengths to detectors from the point of creation differ based on how close the shower maximum is to the ground.

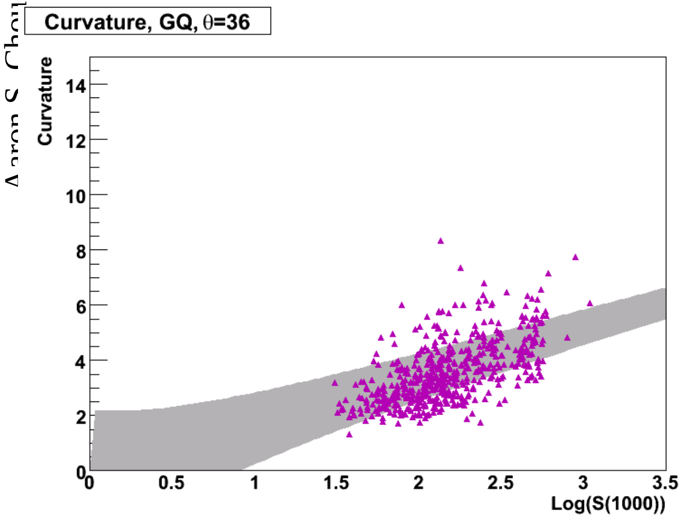
Define signal risetime as the time it takes to get from 10% to 50% of the total integrated signal



Also, the radius curvature of the shower front is geometrically related to the physical location of shower maximum, and hence Xmax.

Use Fisher principle component analysis in the space of (risetime,curvature)





QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Particle flux time-distributions look hadronic rather than like deeper gamma-induced EM showers.

Auger SD photon fraction limits after applying unbiased fiducial cuts (hi E, large θ).

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

These models are all disfavored. (Z-burst was ruled out by ANITA). Because of the specific fiducial cuts, it is unclear to what extent these limits rule out exotic non-photon deep showers.

Empirical studies of hadronic models

- There is a 50% energy scale difference between Auger and AGASA. AGASA has reduced their energy scale by 15% after updating their hadronic interaction simulations. Is this enough?
- Could Auger energies still be underestimated by 35% despite our careful calibration to fluorescence energies?
  - Alternatively, if the problem is fluorescence yield, could HiRes also be underestimating their energies by 25%?
- Let's do some empirical checks of the hadronic models.

Next, look at Monte Carlo predicted muon and EM fluxes in the air shower

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$X_{ground}\ \sec(\theta)\text{-}X_{max}$

Muon signal normalization is model dependent.
EM signal profile (measured rel to Xmax) is nearly model-independent.
The profiles have very different dependences on sec(θ).

Using a simulation-inspired S38-to-Energy converter, adjust the muon flux normalization to produce constant flux intensity in each bin of θ. **This requires 1.63 times more muon flux than predicted in proton/QGSJETII/FLUKA simulations**

With both the mean Xmax and the muon flux normalization now **measured**, we can make a **model-independent** prediction for S38

- $S38 = S38_{EM}(\langle Xmax \rangle) + N_m \, S38_m(\langle Xmax \rangle)$
- $S38(10^{19}$ eV) [VEM] = 37.5 +- 1.7(stat) +-2.2(syst)
- This energy scale is 30% higher than the FD calibrated energy scale ~50 VEM!
- Also seen in AGASA-HiRes discrepancy (AGASA signals are EM dominated and hence also largely model-independent)
- Perhaps all simulations are consistently wrong and hence model-independence is not necessarily a good thing....

Aaron S. Chou, SSI 2007

Can this be right? Let's double-check with golden hybrid events where we can now measure the muon flux directly:

$$S_m(\theta) = N_m^{rel}\, S_m^{pred} = S_{total} - S_{EM}^{pred}(Xmax,\theta)$$

Consistent result:

With this interpretation, UHECR are heavier than iron, in contradiction to the Xmax results….

Summary

- Auger is still growing, but is now alreadythe UHECR statistics champion!
- The energy spectrum is measured with an empirical calibration to the FD energy scale, and with an unambiguous flat exposure.
- **Sharp deviations are seen from a power-law spectrum.**
- Discrepancies remain between Auger, HiRes, and AGASA in both the shape of these features, and in the energy scales.
- **Composition measurements strongly disfavor top-down mechanisms for UHECR production such has superheavy dark matter.** These measurements depend on simulations of hadronic interactions at energies and rapidities beyond where we have collider data
- Preliminary indications are that these same simulations still have serious problems, but also that the FD energy scale may still be systematically offset.

2007 Earth-skimming Tau neutrino limit

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Select using consistency of SD triggers with speed of light, other discriminators.

Exposure has factor of 3 uncertainty.