Highlights from the Pierre Auger Observatory

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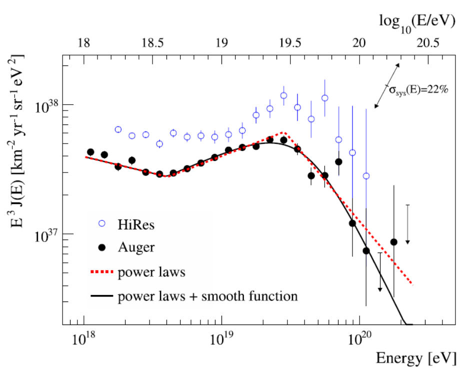
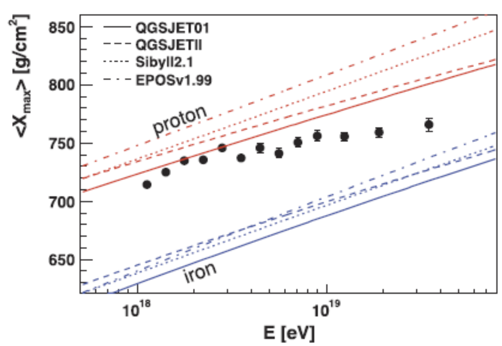
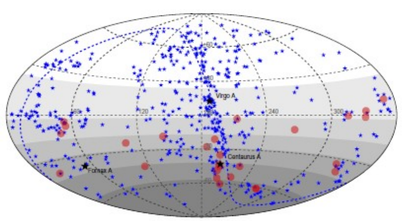
University of Adelaide
for the Pierre Auger Collaboration







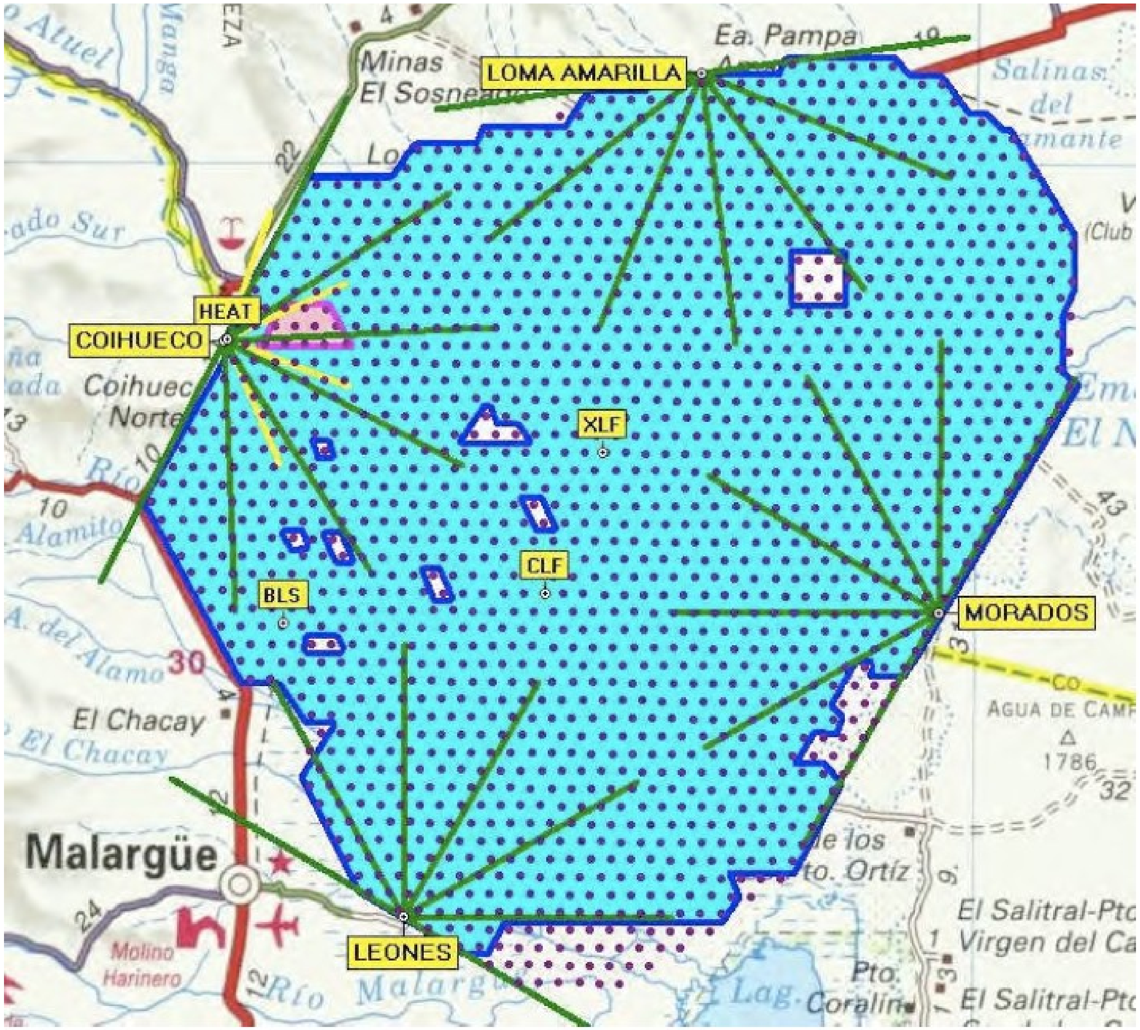
Nagoya, 10 December 2010

Outline

- The Observatory
  - description, philosophy, quality of the data
- The Astrophysics – understanding the origin of UHECR
  - spectrum, mass composition, anisotropy;
  - photon & neutrino limits; shower physics
- Summary

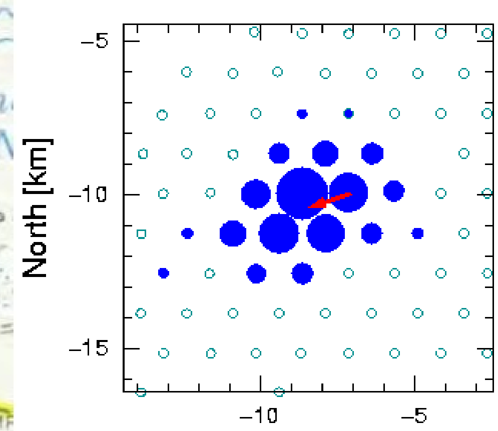
Surface detector (SD)

Over 1600 detectors in operation,
covering 3000 square kilometres



July 2009

ID 762238



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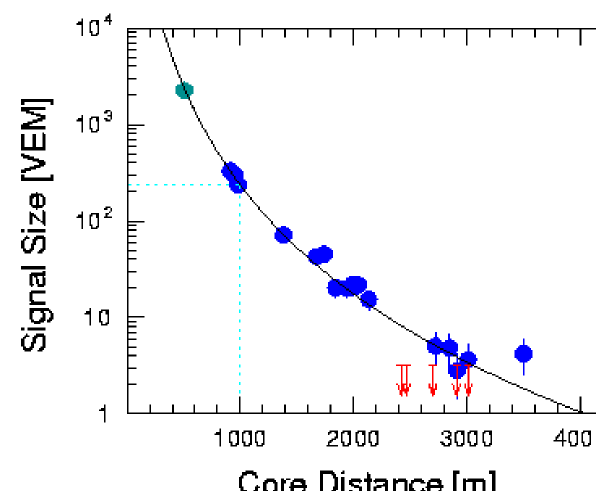
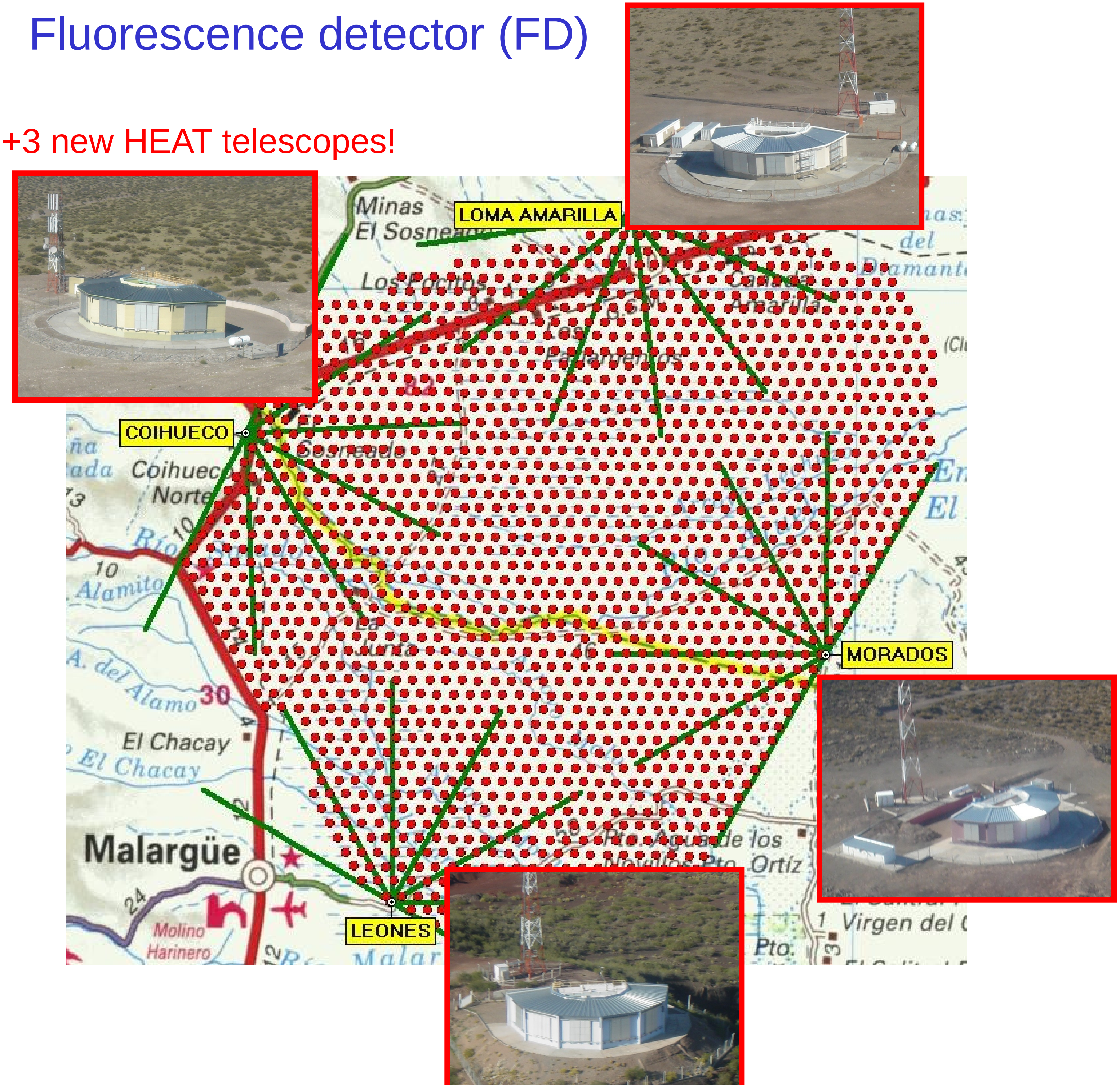
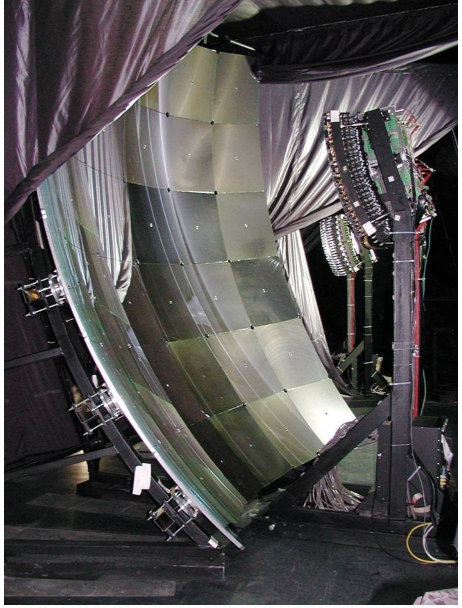
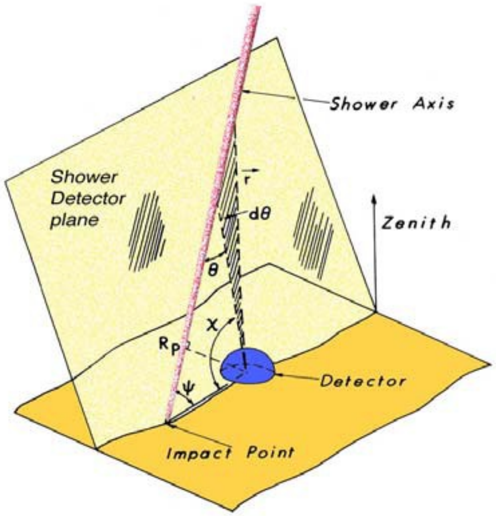


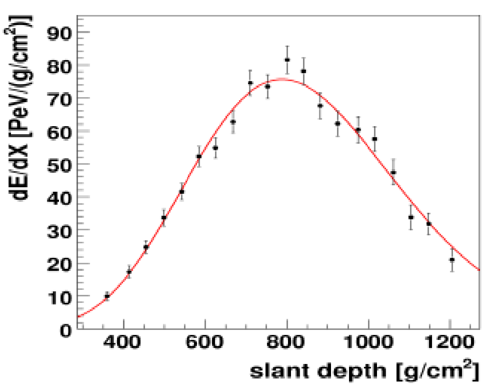
Fluorescence detector (FD)

+3 new HEAT telescopes!

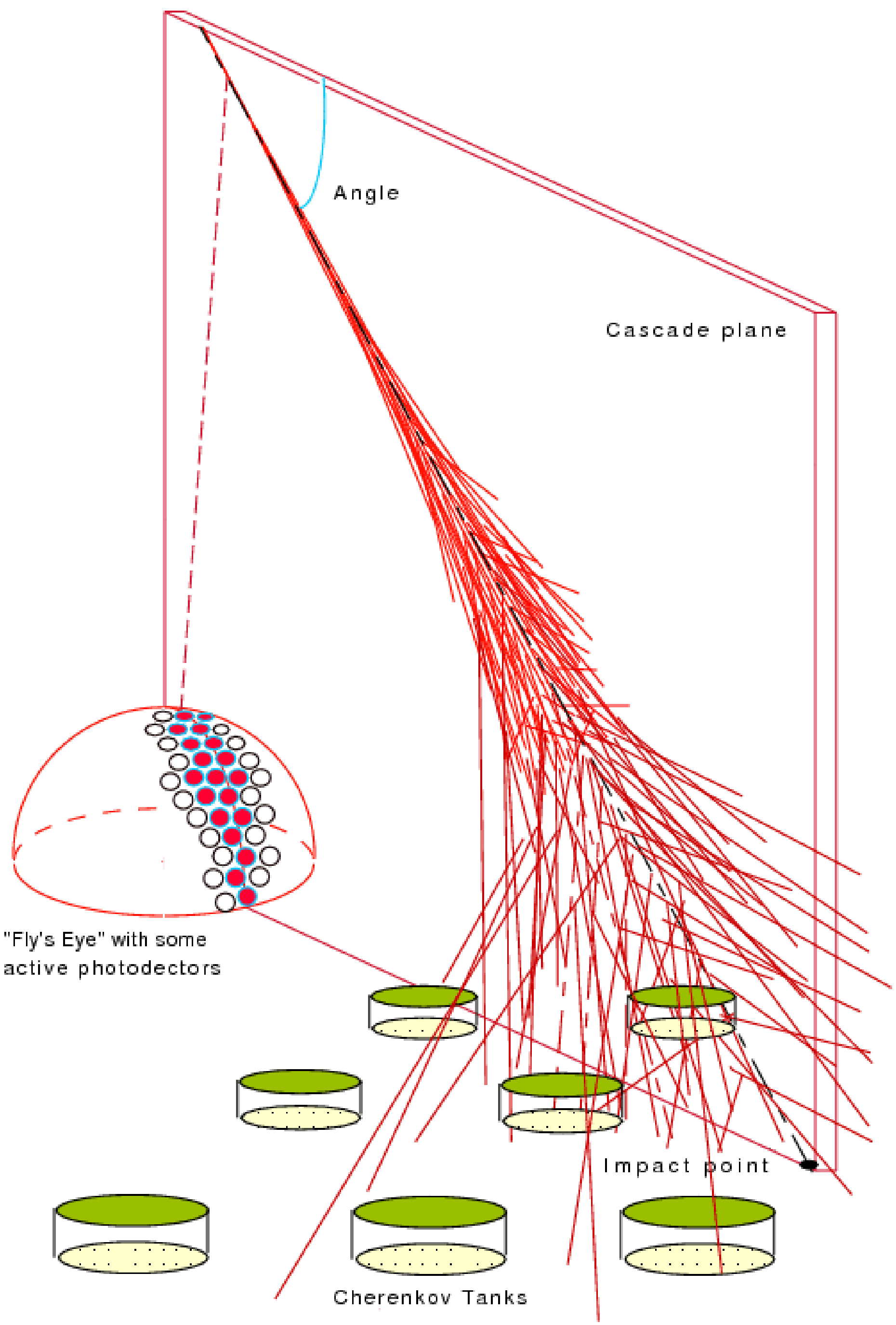








Auger is a Hybrid detector



- SD provides a huge aperture (easily calculable), with robust detectors. Good angular resolution, and promising mass composition indicators.

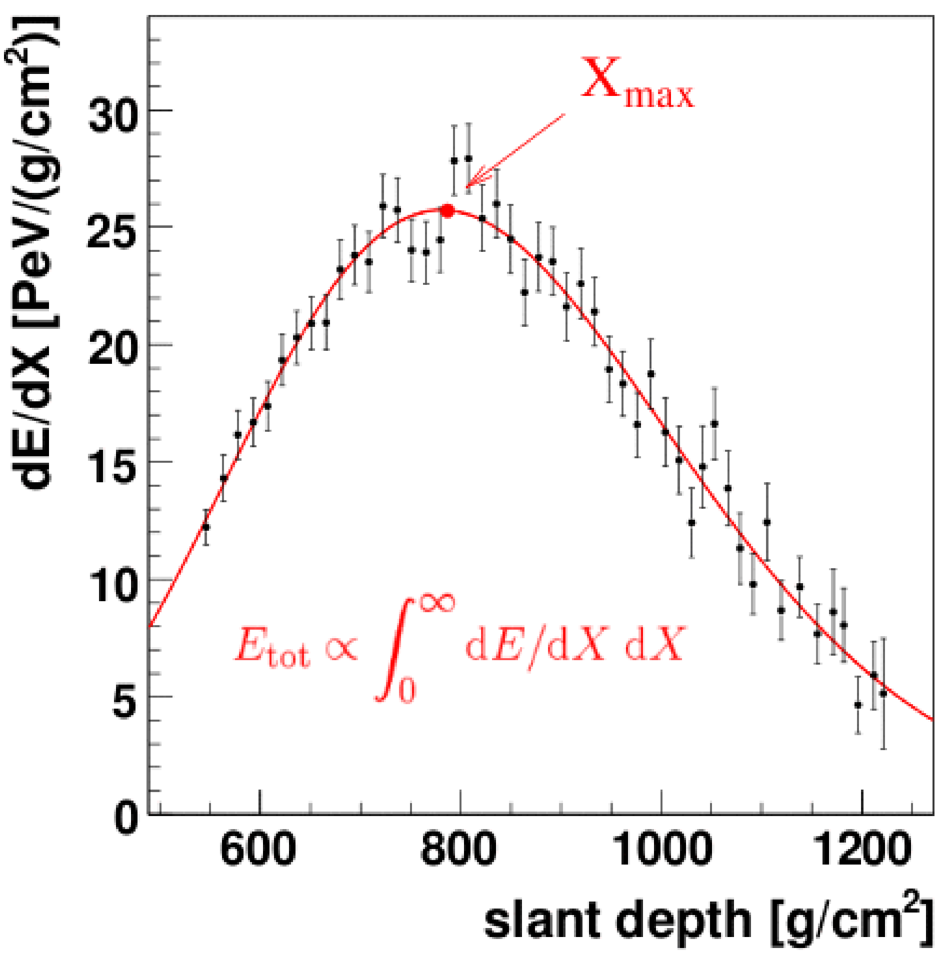
- FD can provide near calorimetric energy measurements, a direct view of shower maximum, and precise directions (hybrid method). But duty cycle is only 10-15%

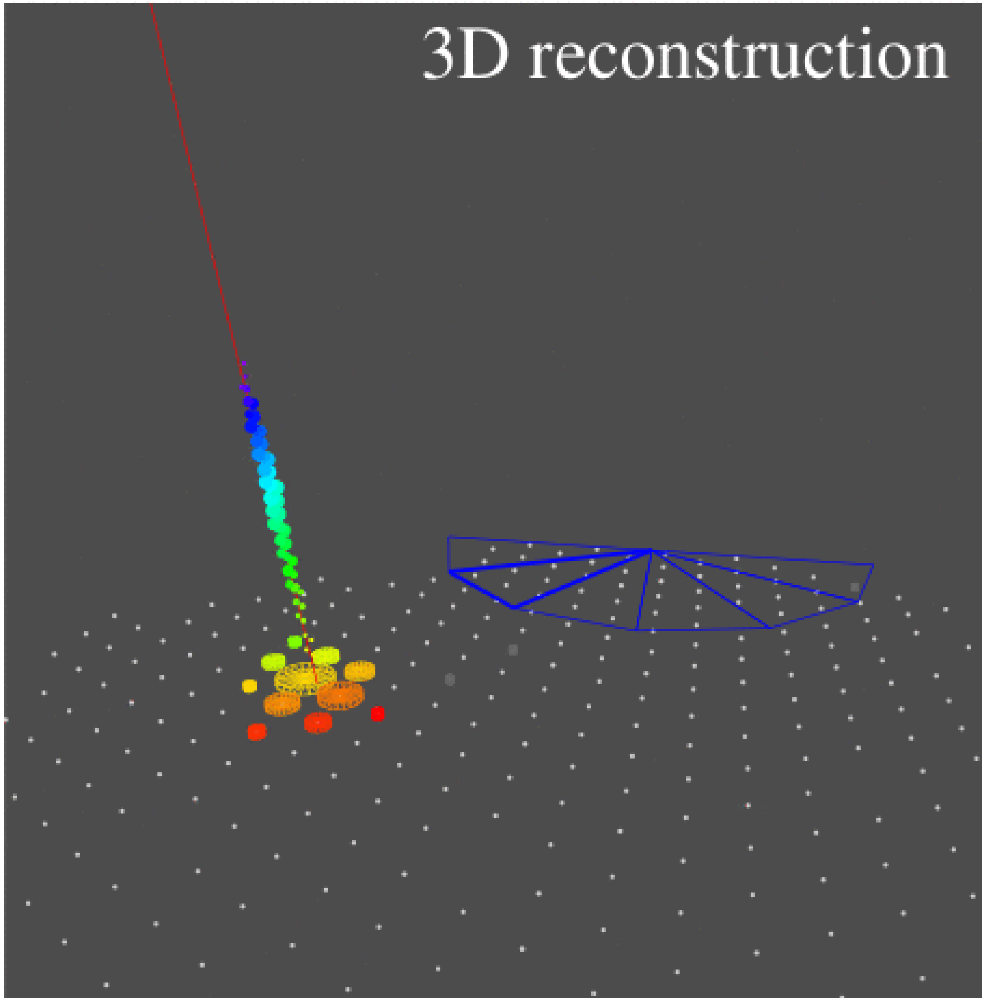
Two Key Aspects of the Auger Observatory Philosophy

- Where possible, minimise use of simulations in the production of key scientific outputs
  - e.g. SD energy spectrum, elongation rate (~ minimal use)
  - not always possible (e.g. hybrid spectrum)

- Take advantage of Auger's hybrid nature and other cross-checks, e.g.
  - FD calibrates SD energy scale
  - hybrid directions cross-check SD directions
  - SD cross-checks FD trigger efficiency
  - ....

“hybrid” reconstruction (FD + one SD station) $\rightarrow$ excellent geometrical reconstruction

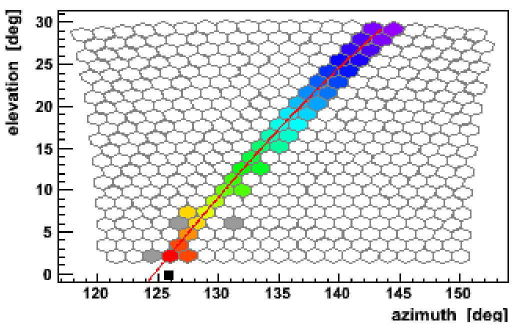


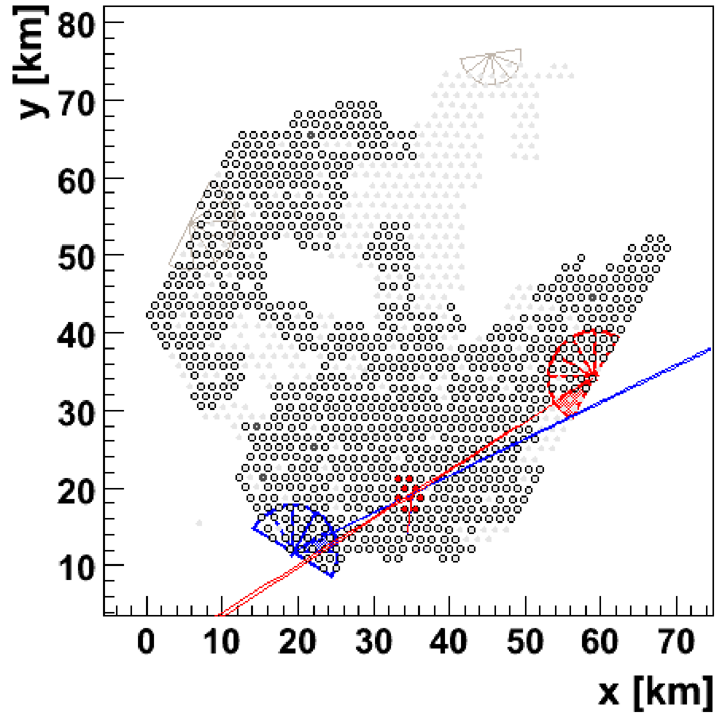


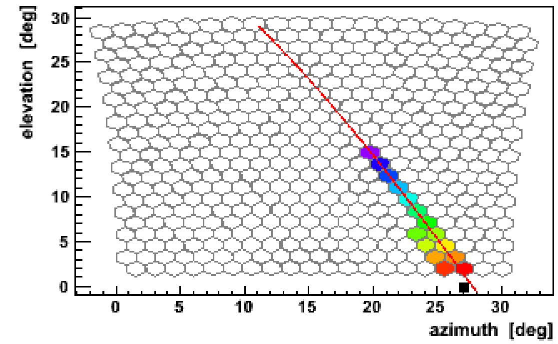
Hybrid event

-sometimes also “stereo”
- here independent hybrid
 reconstructions

E=(1.88±0.14) x 10^{19} eV

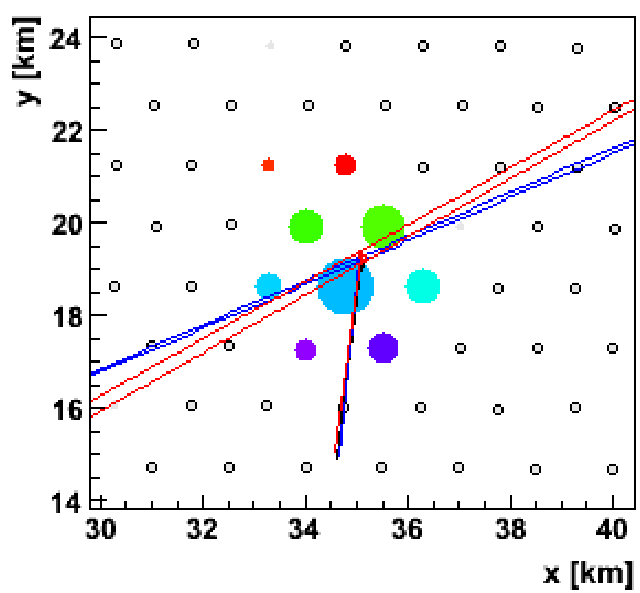


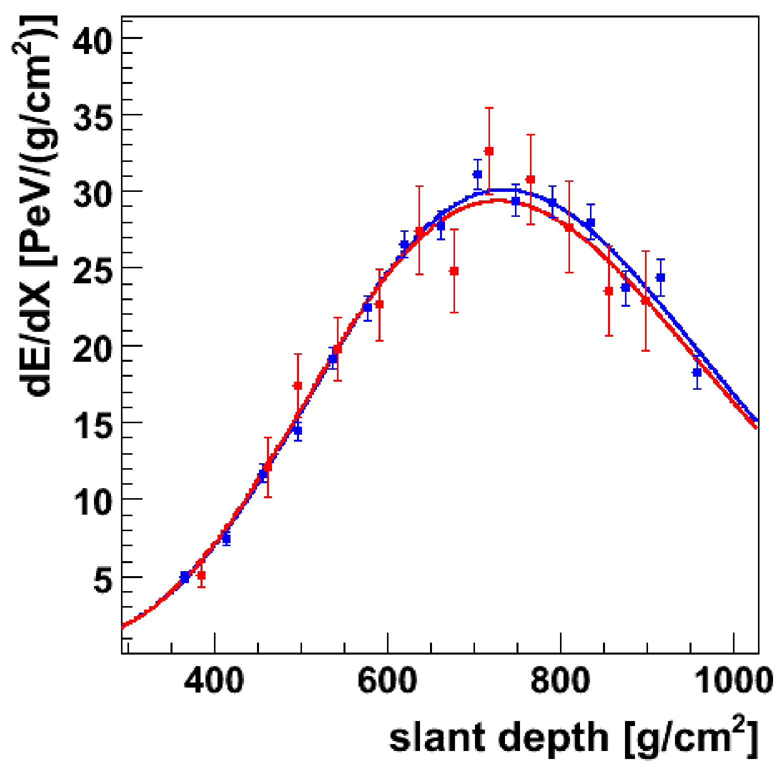




E=(1.85±0.19) x 10^{19} eV

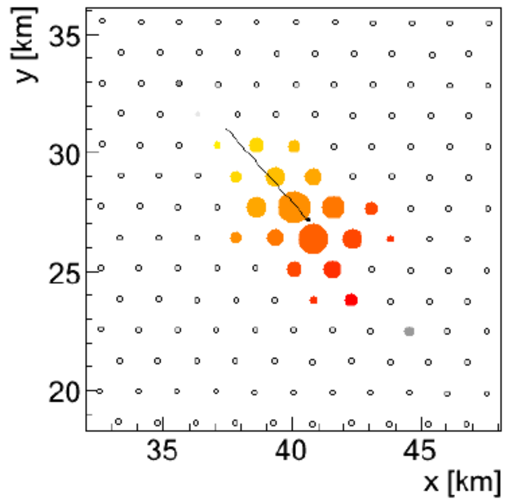
(Statistical error, including contributions from geometry, atmosphere)

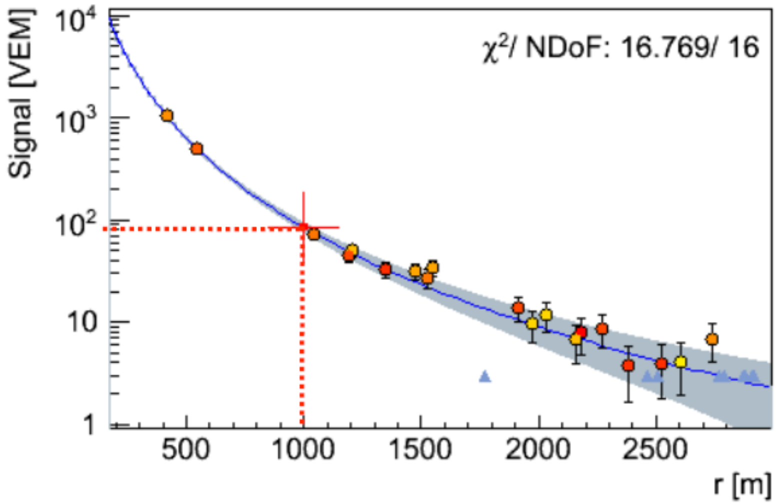


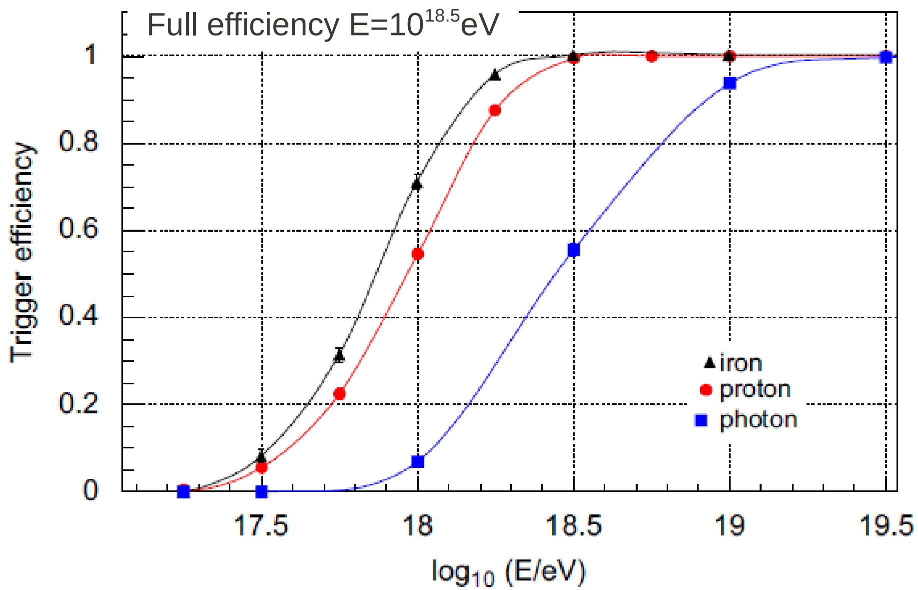


Event 2412881 30 June 2006

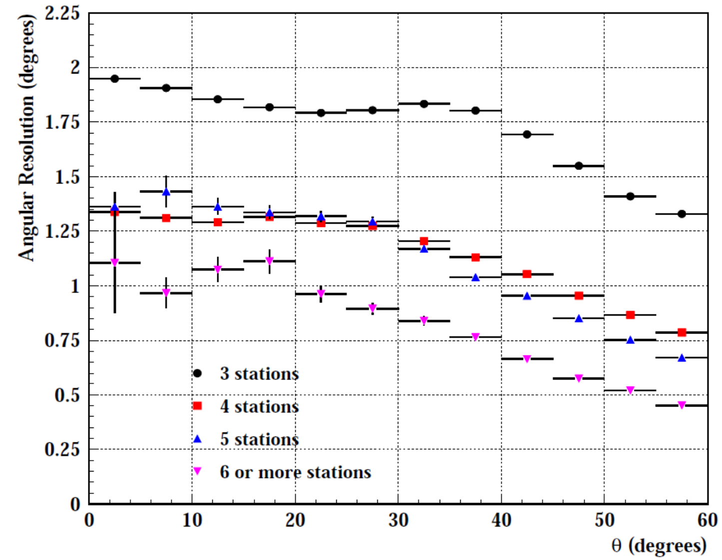
Surface Detector Quality







Abraham et al. NIM A613 (2010), 29



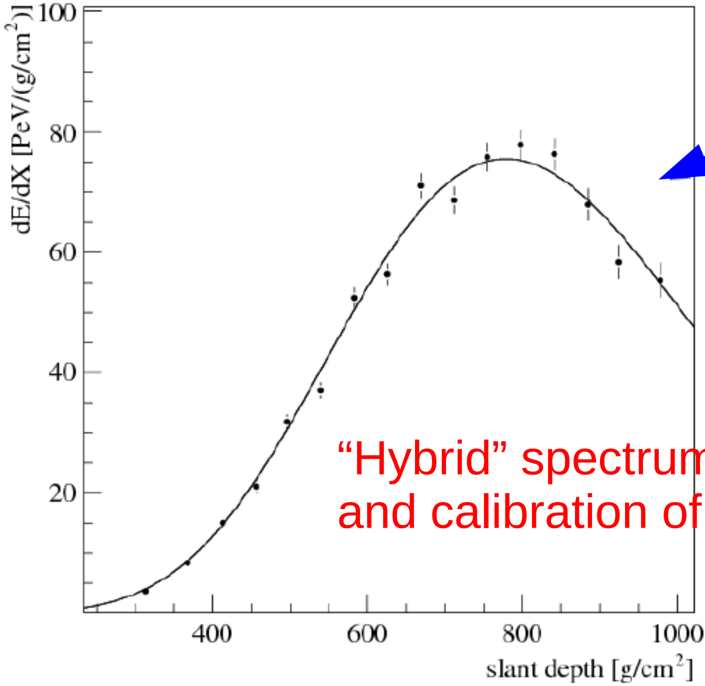
M.Ave et al. ICRC07 arXiv:0709.2125

Angular resolution: better than 1 degree for events with ≥6 tanks
(from timing uncertainties measured in dual-tank stations; verified by hybrid)

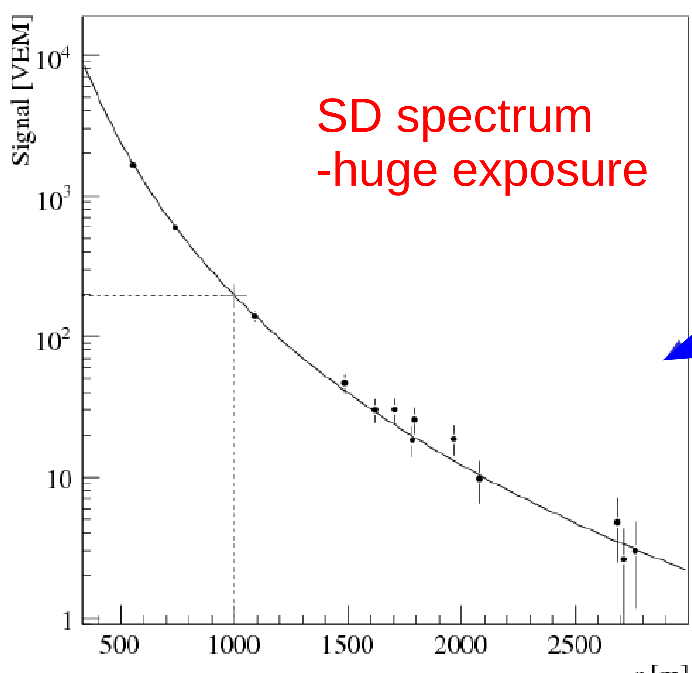
Resolution in S(1000): better than 10% above 10^{19}eV (stat+sys)
(verified by hybrid)

The Energy Spectrum

M. Roth, this afternoon

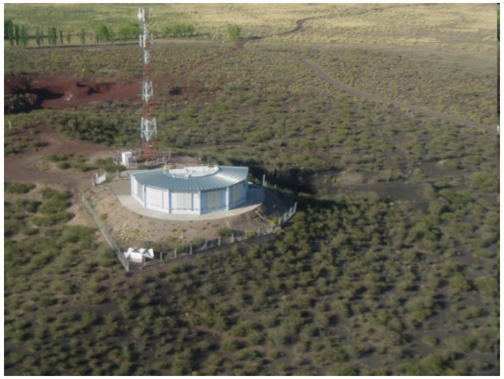


“Hybrid” spectrum
and calibration of SD spectrum



SD spectrum
-huge exposure

- Fluorescence Detector
  - fluorescence light emitted in proportion to energy deposit
  - atmosphere as calorimeter
  - near independent of mass and model



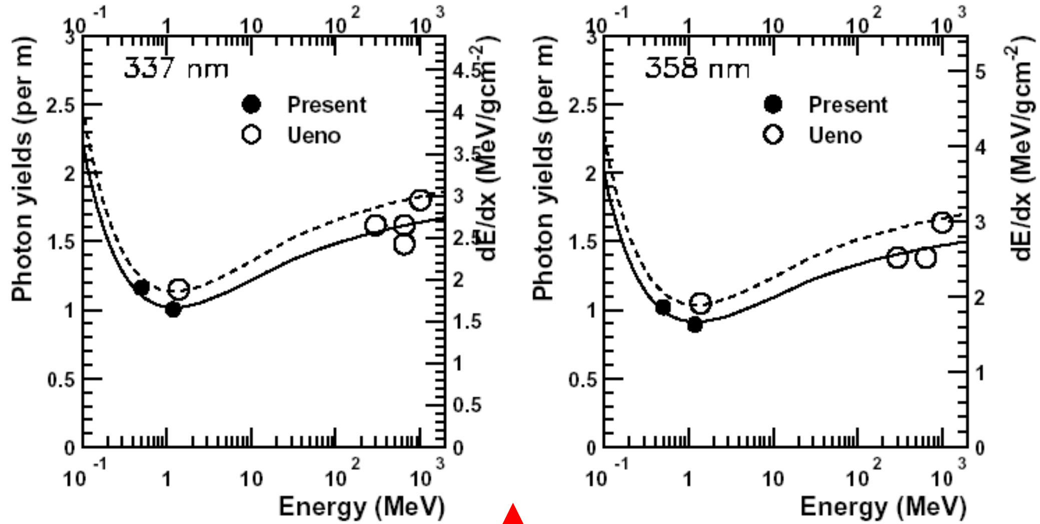
- Surface Detector
  - energy parameter is signal at 1000m from shower core S(1000)

Fluorescence Method – beautiful technique, but care required!

M. Nagano et al., Astropart. Physics 20 (2003) 293

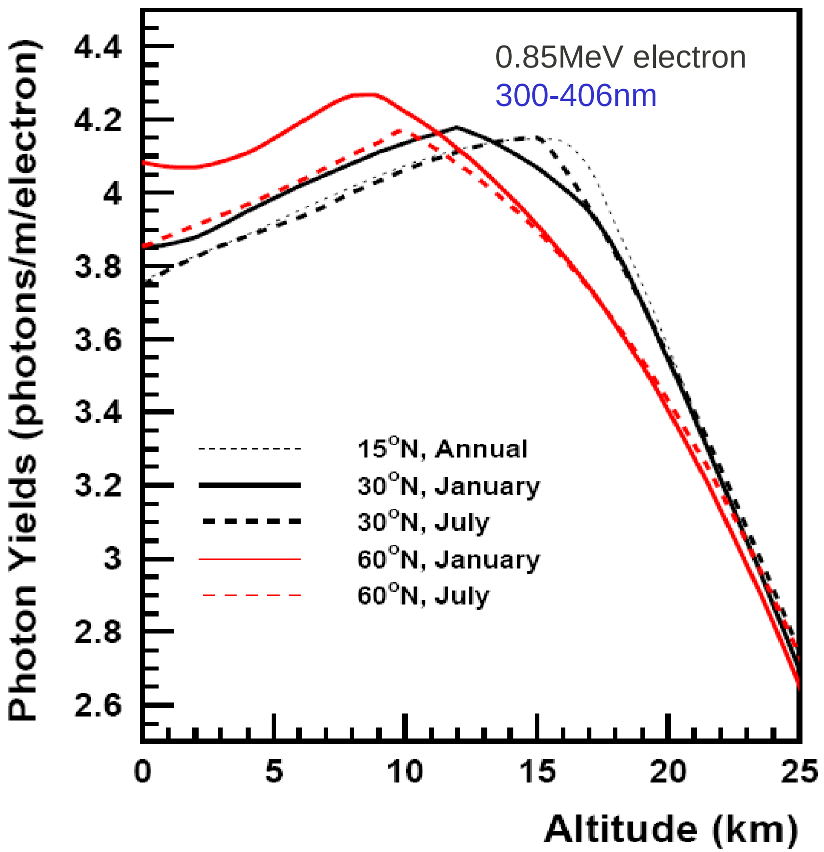
fluor. yield ~ 4 photons/ m /electron
-very moderate change in 0-10km region (the important region)

-because yield is the result of competition between excitation by air shower and collisional de-excitation

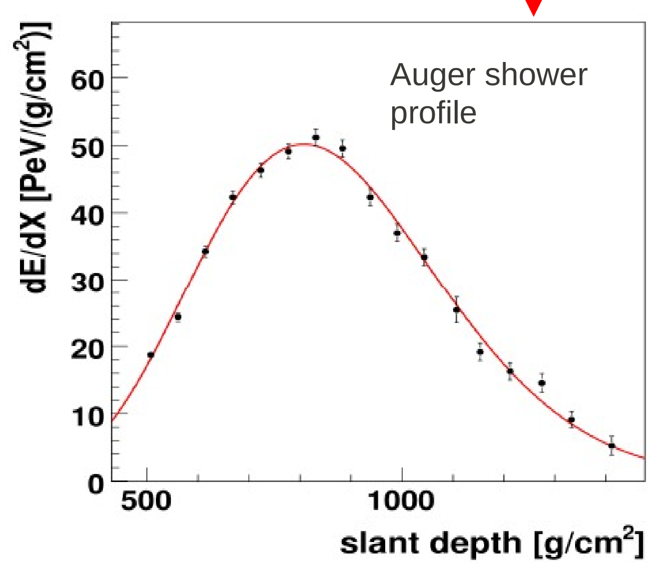


Yield vs electron energy – it scales like energy deposit dE/dX

M. Nagano et al., Astropart. Physics 22 (2004) 235



This means that fluorescence light is a DIRECT measure of energy deposited in the atmosphere by the shower



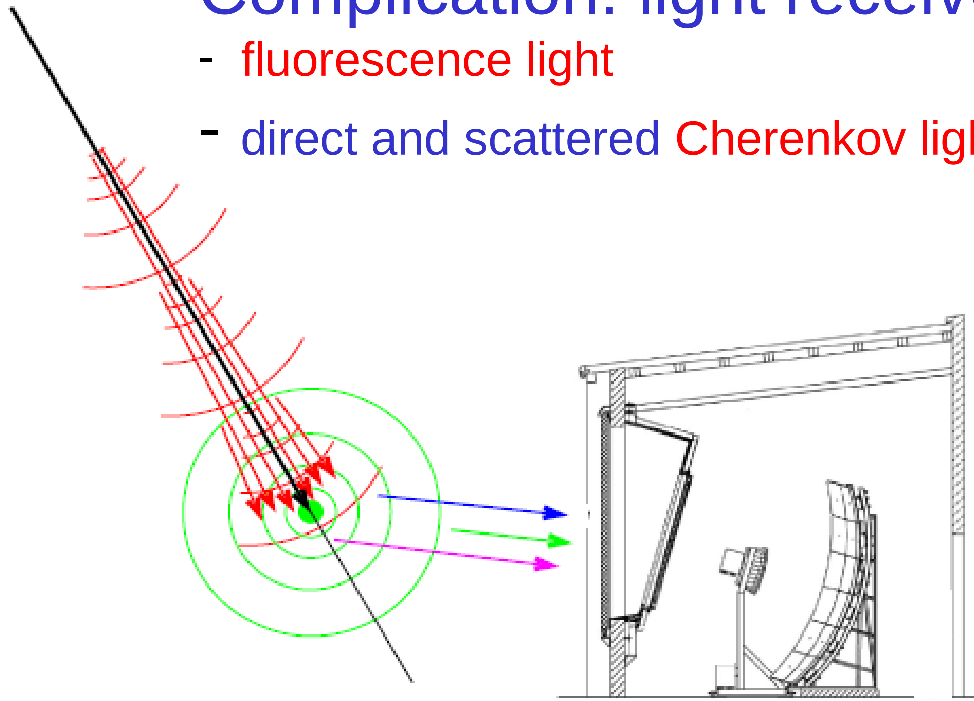
The atmosphere is a **calorimeter!**

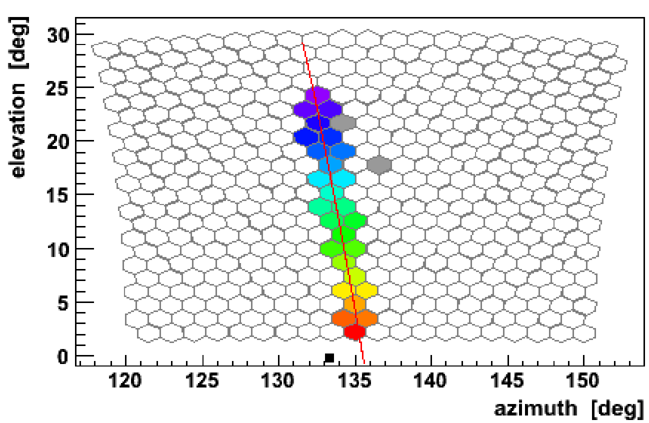
$$E = \int_0^\infty \frac{dE}{dX}\, dX$$

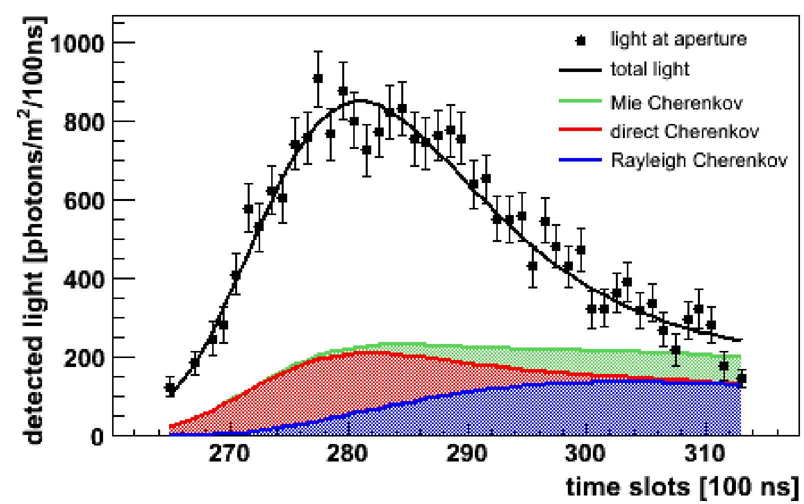
Complication: light received at detector is

- fluorescence light
- direct and scattered Cherenkov light

- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light







Unger, Dawson, Engel, Schuessler & Ulrich NIM A588 (2008) 443

The atmosphere

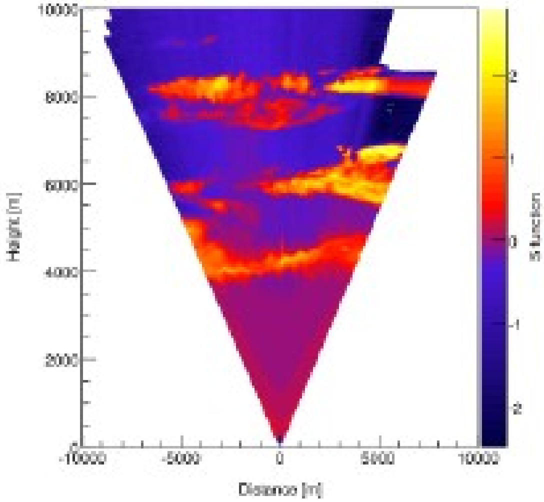
We must monitor the state of
- the molecular atmosphere
- aerosol distribution and
  scattering properties
- night-time cloud

lidars

UV lasers

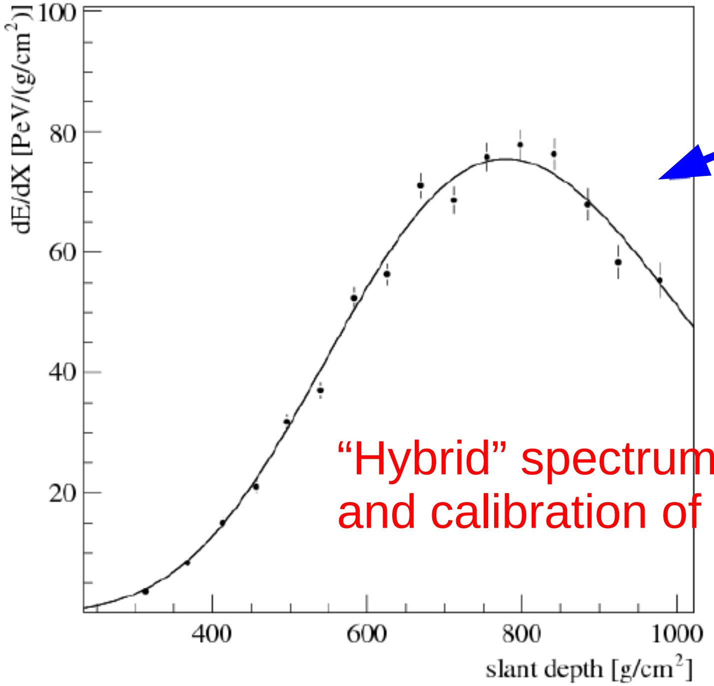
radiosondes

cloud detection



infra-red cameras and lidar

An example of Auger's philosophy...



"Hybrid" spectrum
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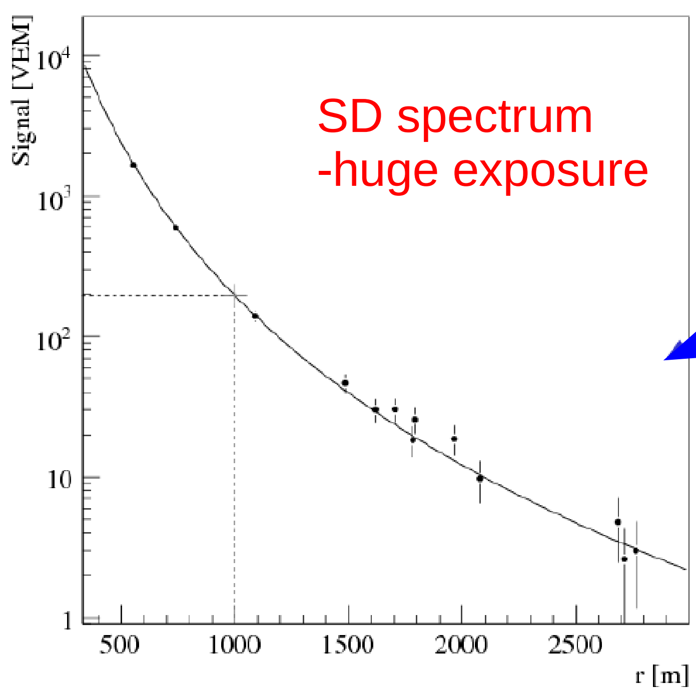

SD spectrum
-huge exposure

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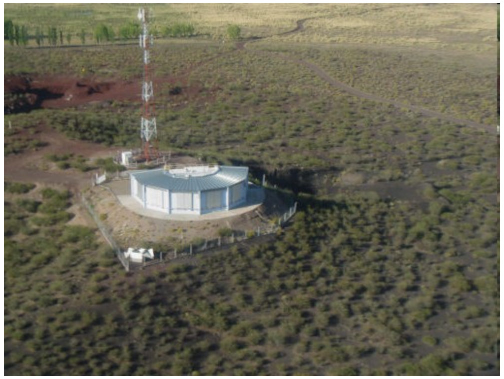
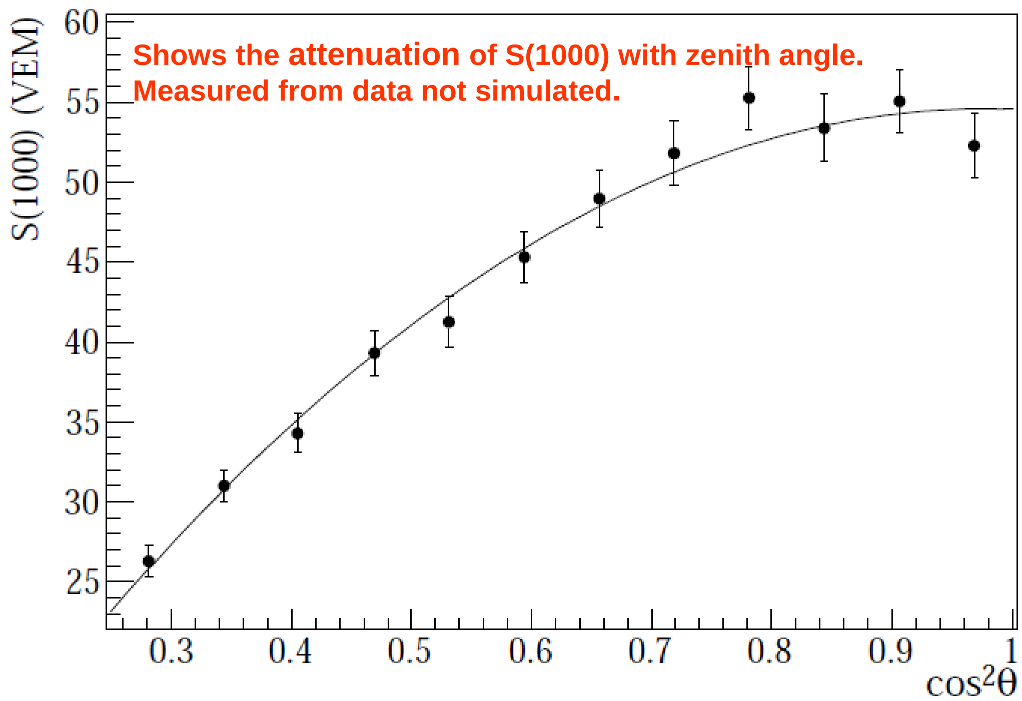
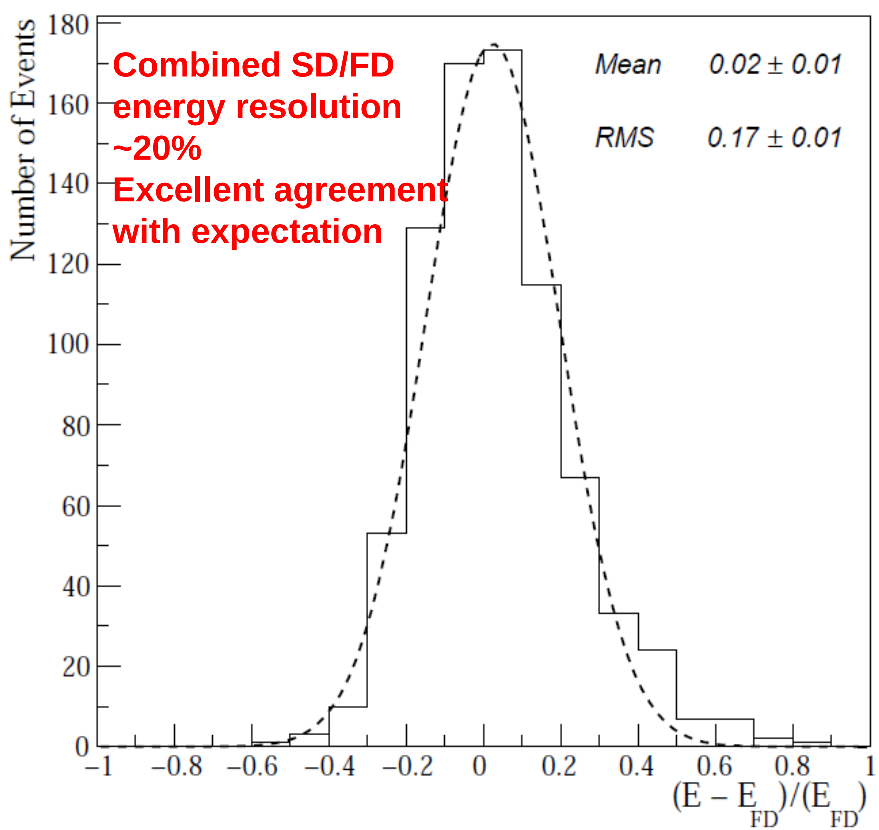


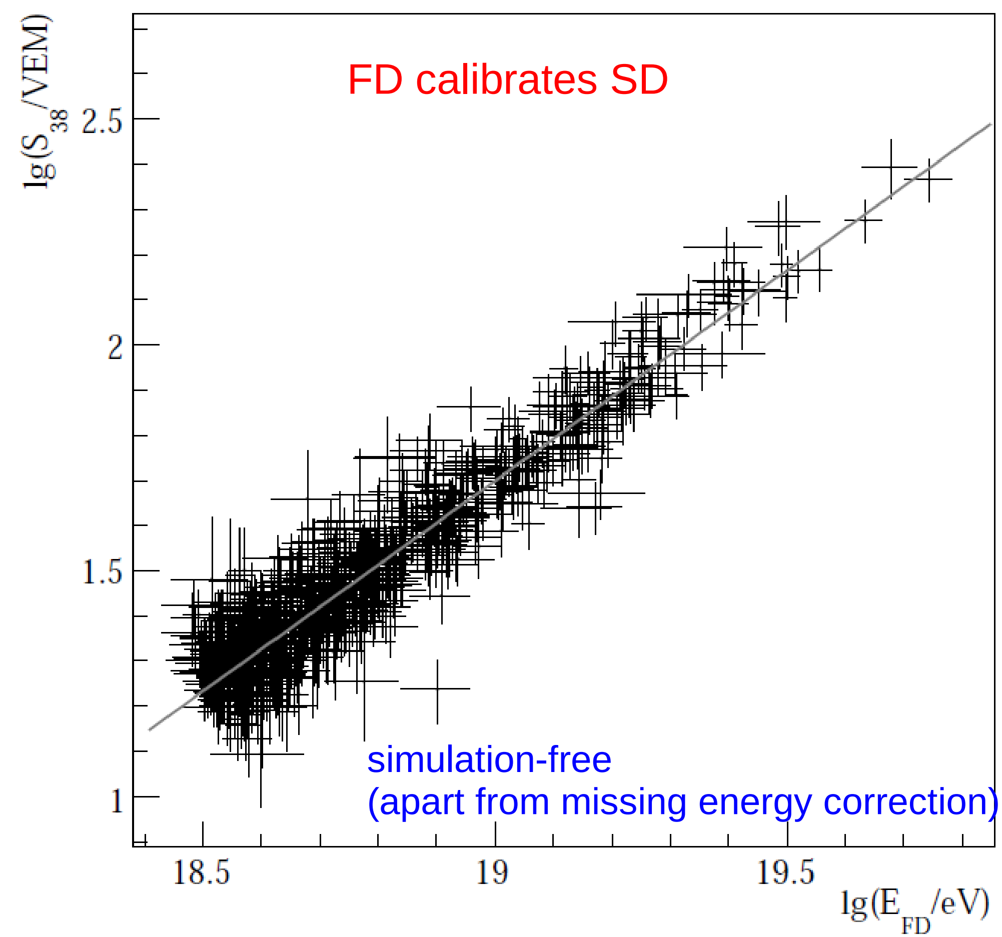
- Surface Detector
  - energy parameter is signal at 1000m from shower core S(1000)

C. DI GIULIO *et al.* PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009



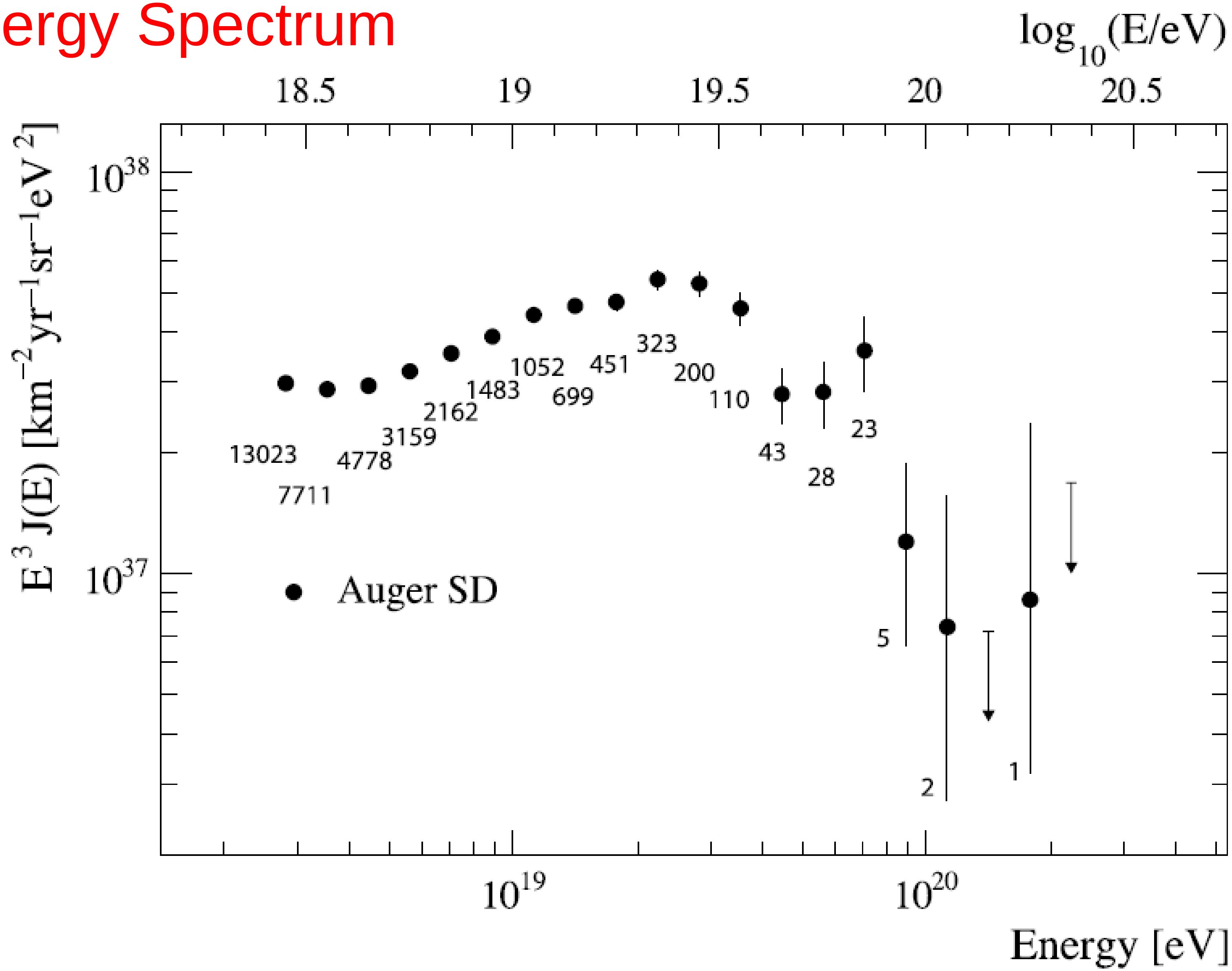
convert all S(1000) to S_{38} – the S(1000) expected at θ=38 deg





SD Energy Spectrum

Pierre Auger Collaboration / Physics Letters B 685 (2010) 239–246



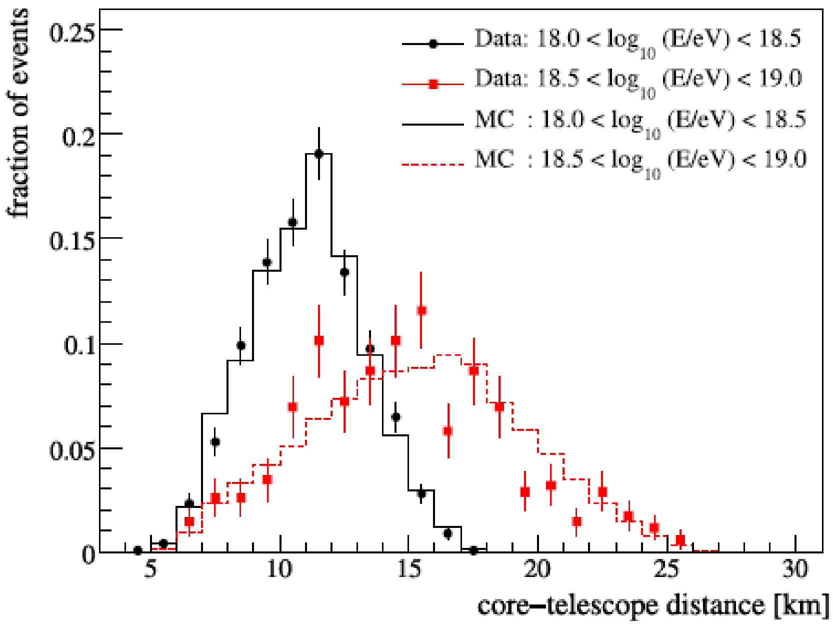
- data up to end December 2008. Exposure 12,790 km^2 sr y.
- spectrum corrected for resolution effects (~15% resolution at lower energy, improving to ~10%).
- compared with power law extrapolation, flux drops to 50% at logE=19.6. Significance ~20σ. Consistent with GZK suppression.

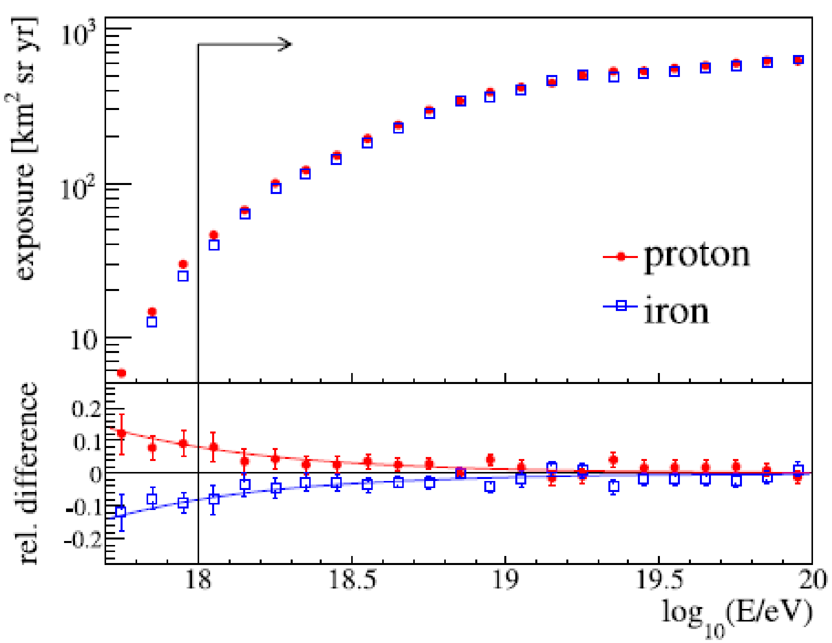
Pierre Auger Collaboration / Physics Letters B 685 (2010) 239–246

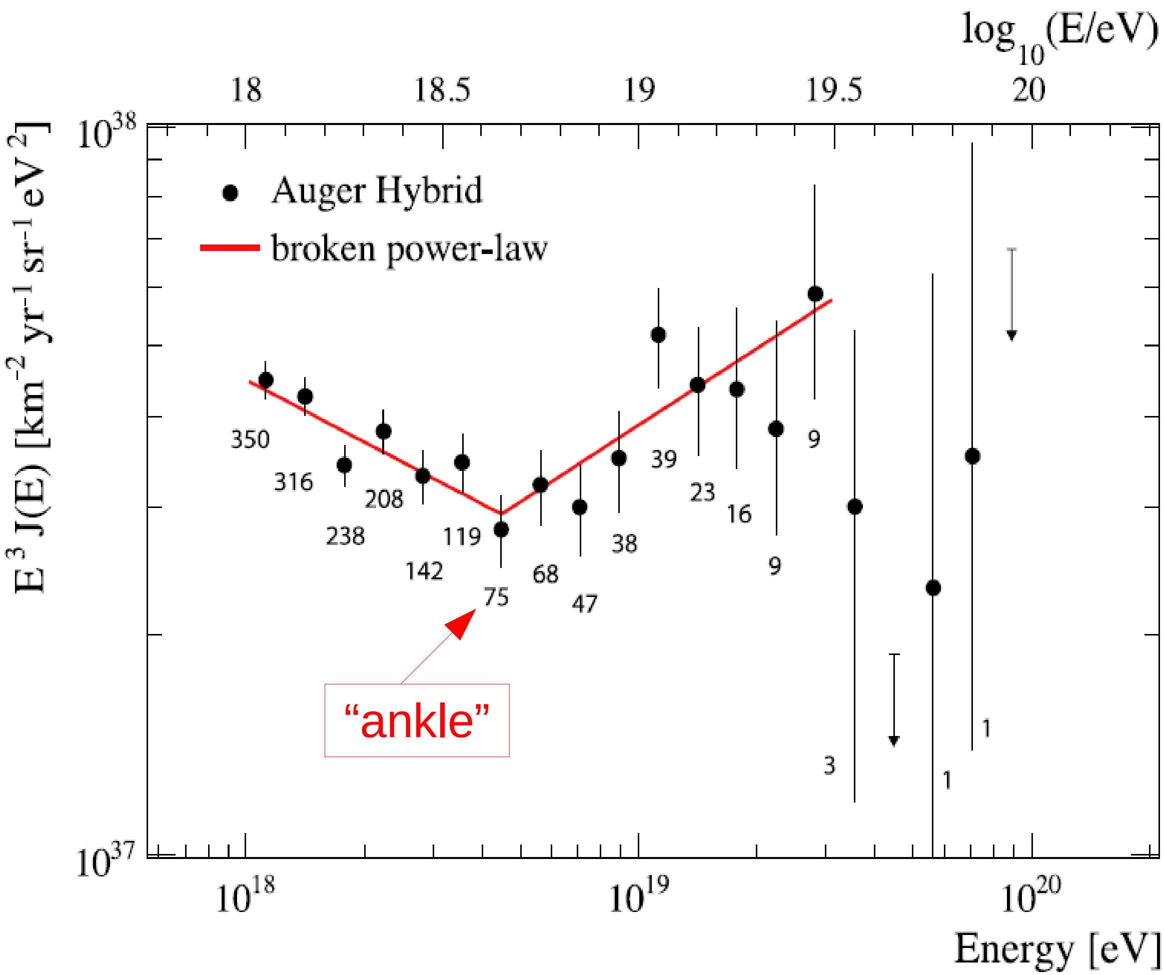
“Hybrid” Spectrum

allows spectrum measurement at lower energies

Data to May 2008. Requires
- careful MC evaluation of exposure, including measured atmospheric and detector conditions
- quality cuts and anti-bias cuts to minimise influence of mass composition on exposure







Combined Hybrid and SD Spectra

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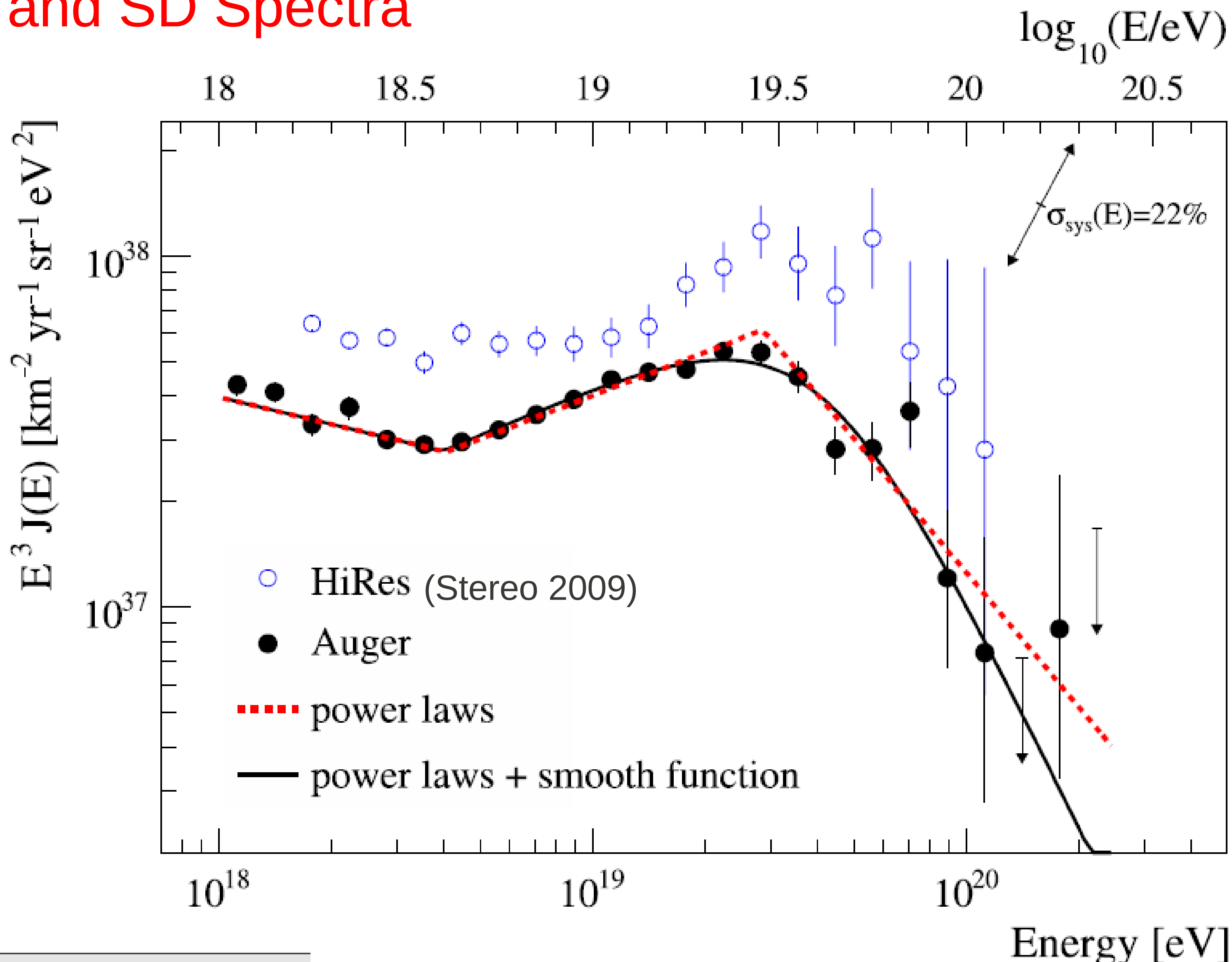


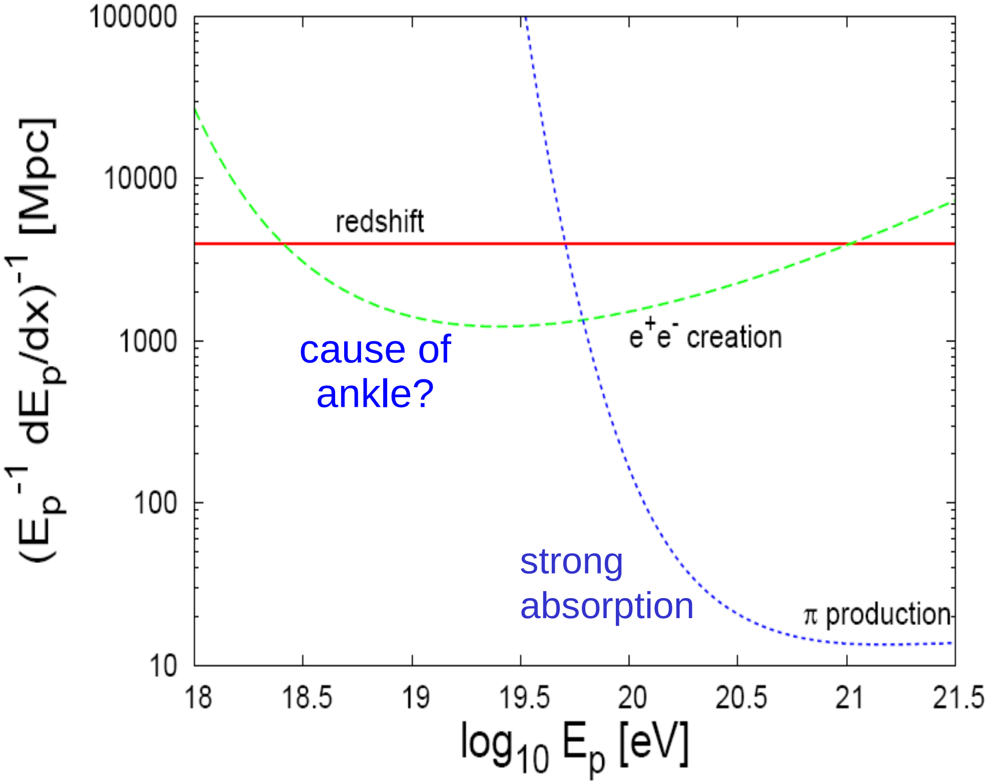
Parameter	Power laws	Power laws + smooth function
$\gamma_1(E < E_{ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\log_{10}(E_{ankle}/eV)$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\log_{10}(E_{break}/eV)$	19.46 ± 0.03	
$\gamma_3(E > E_{break})$	4.3 ± 0.2	
$\log_{10}(E_{1/2}/eV)$		19.61 ± 0.03
$\log_{10}(W_c/eV)$		0.16 ± 0.03
χ^2/ndof	38.5/16	29.1/16

Auger and HiRes spectra consistent within systematic errors (22% and 17% respectively)

Nature of suppression?

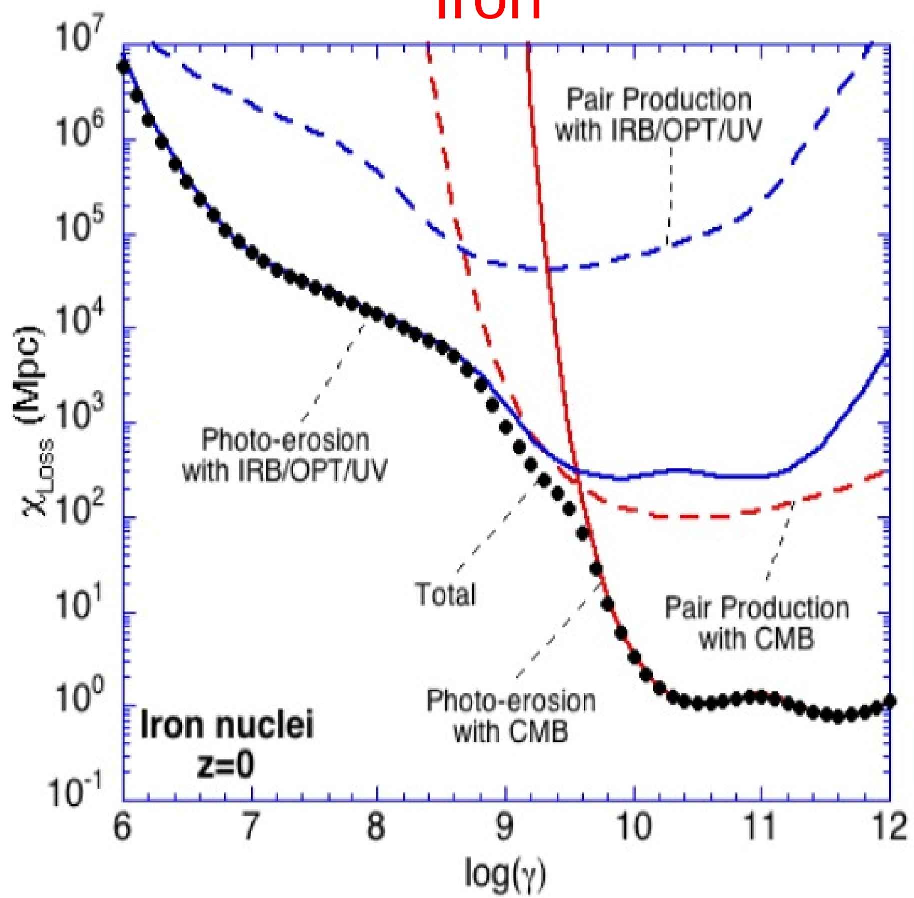
Energy loss lengths in Cosmic Microwave Background $\frac{E_p}{dE_p/dX}$

Protons



Taylor & Aharonian PRD arXiv:0811.0396

Iron



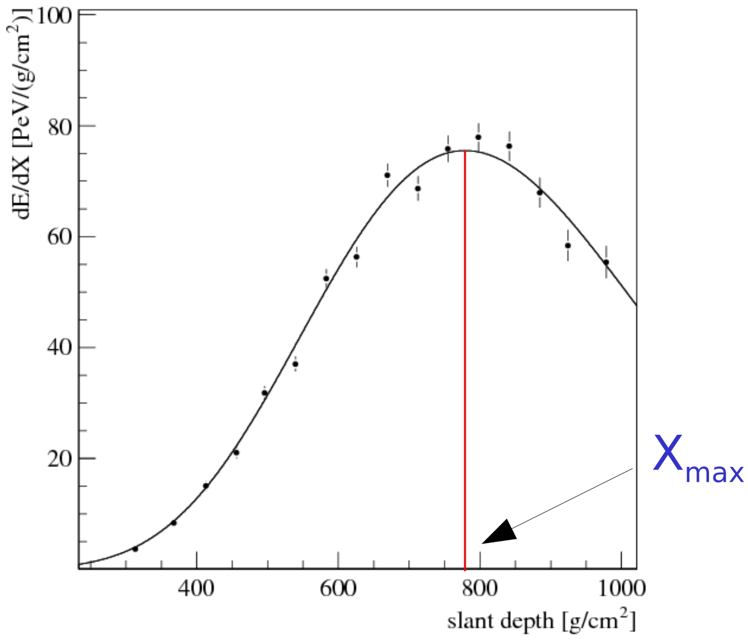
D.Allard, Proc. Rencontres de Moriond 2009, arXiv:0906.3156

Protons and iron nuclei have very similar energy loss lengths, which both become <100Mpc beyond logE ~ 19.5. Could both produce a spectral suppression at Earth.

The observed spectral suppression may also be due to the average injection spectrum at the sources.

Mass Composition

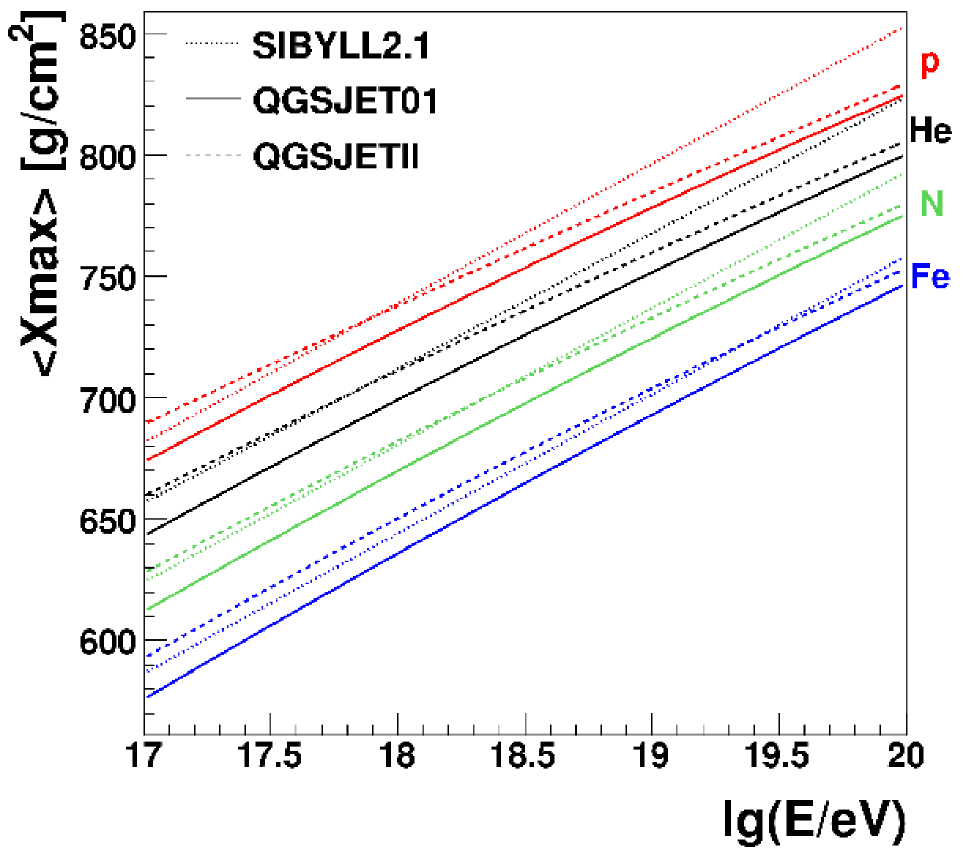
M. Unger (tomorrow)

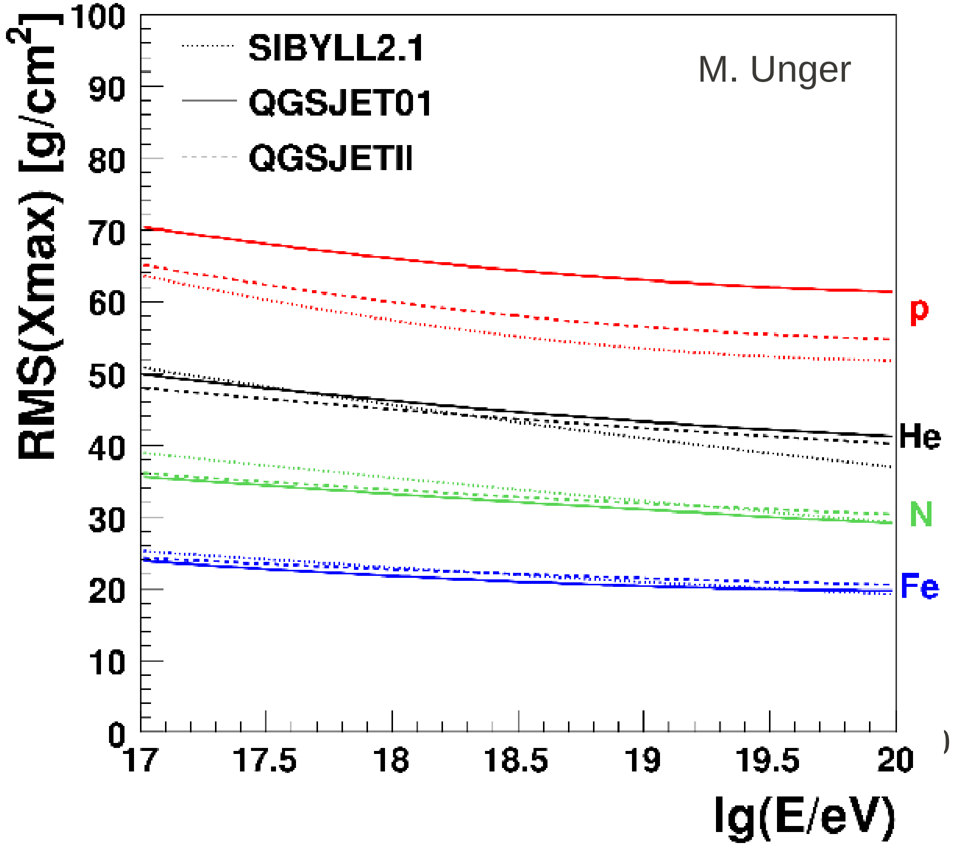


Fluorescence detector measurements of Xmax.

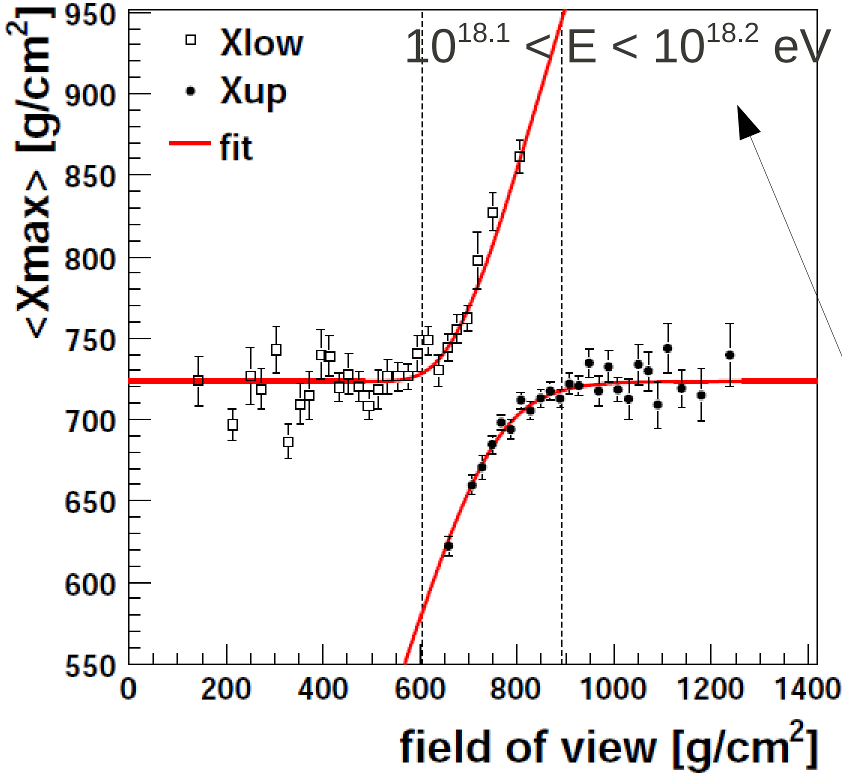
SD measurements (e.g. asymmetry) coming soon.

Interpretation requires simulations, significant model dependence

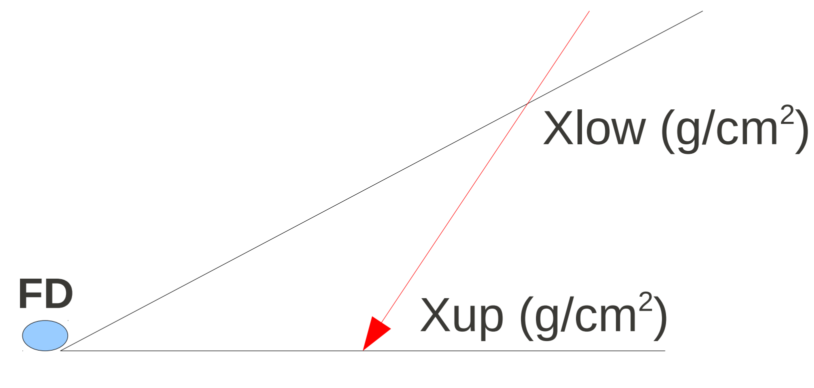




Event Selection for X_{max} - avoid composition bias

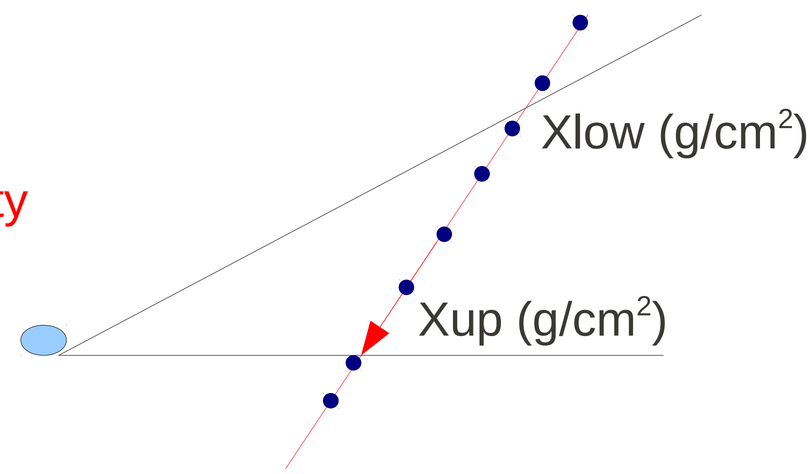


Q: At a given energy, what range of depths must be visible for an unbiased estimate of Xmax?



A: at this energy, Xlow<600g/cm^2, Xup>900g/cm^2

For every real shower, simulate a range of Xmax for its true energy and geometry. Determine uncertainty in reconstructed Xmax for every realization.

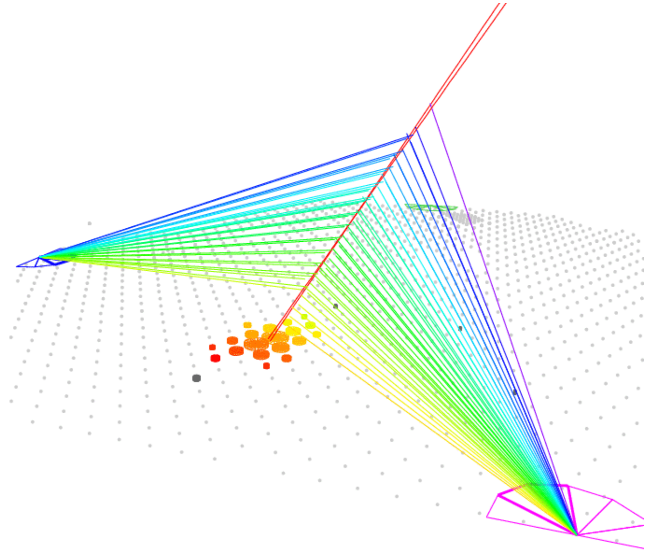


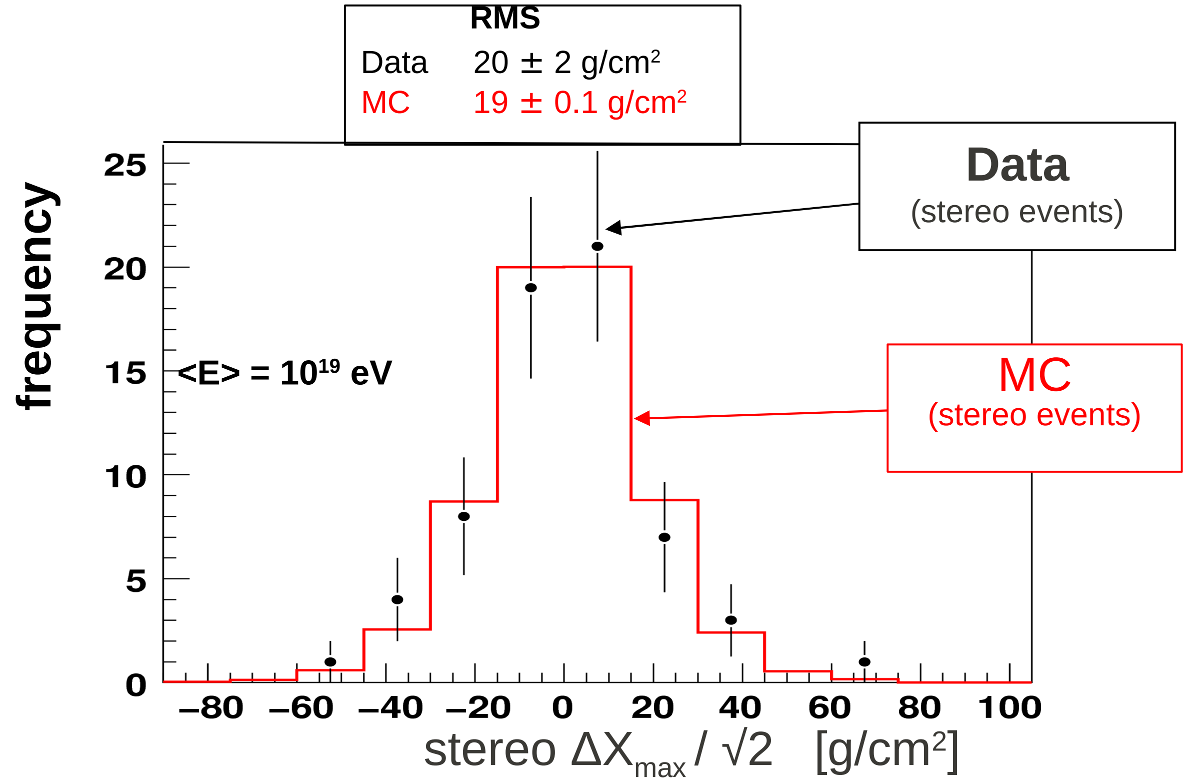
Require that Xmax uncertainty be less than 40 g/cm^2 between Xlow and Xup.
If so, event is accepted as having an unbiased measurement of Xmax

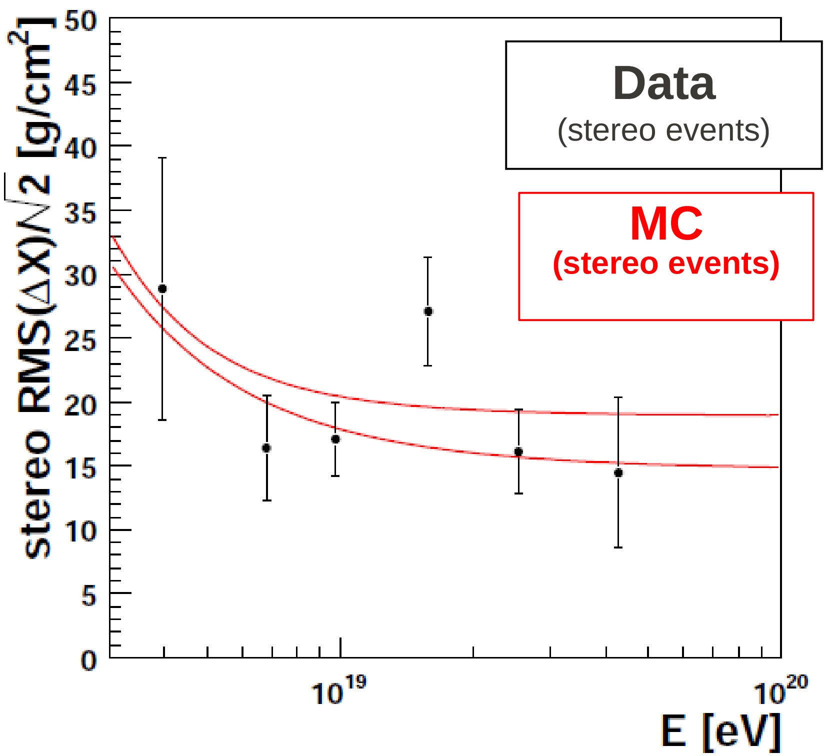
Resolution of the reconstructed X_{max}

The detector resolution of the reconstructed X_{max} is estimated using MC simulations.

This resolution is validated by comparing X_{max} measurements from two independent FD detectors.







Pierre Auger Collaboration, PRL 104, 091101 (2010)

Auger's X_{max} results

PIERRE AUGER OBSERVATORY

The data favor a break in the X_{max} vs energy curve at :

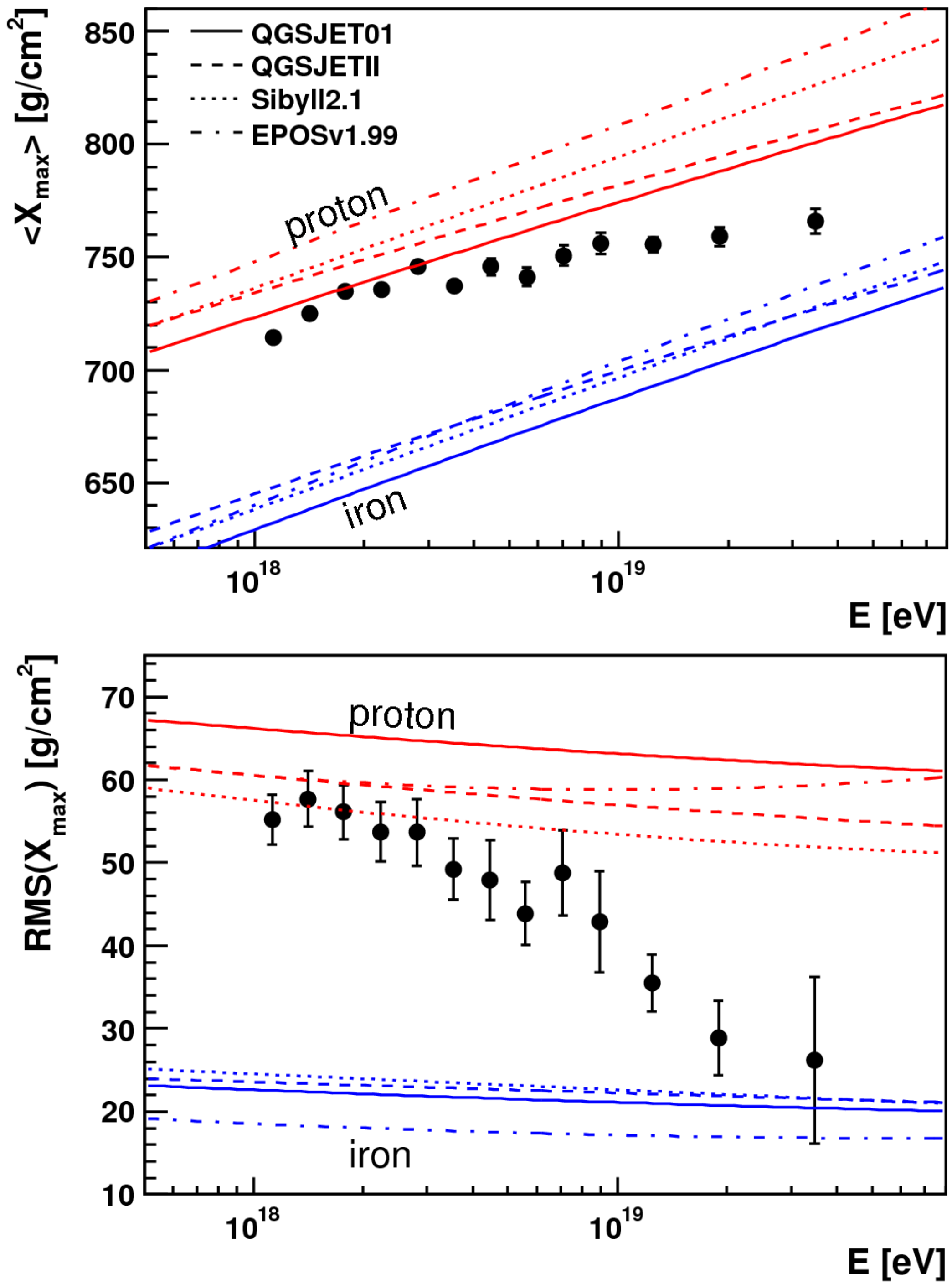
$E_b = 10^{18.25\pm0.05}$ eV

an energy close to the ankle in the energy spectrum.

At energies above $E=2 \times 10^{18}$ eV the small elongation rate,

$D_{10}=24\pm3$ g cm^{-2} / decade

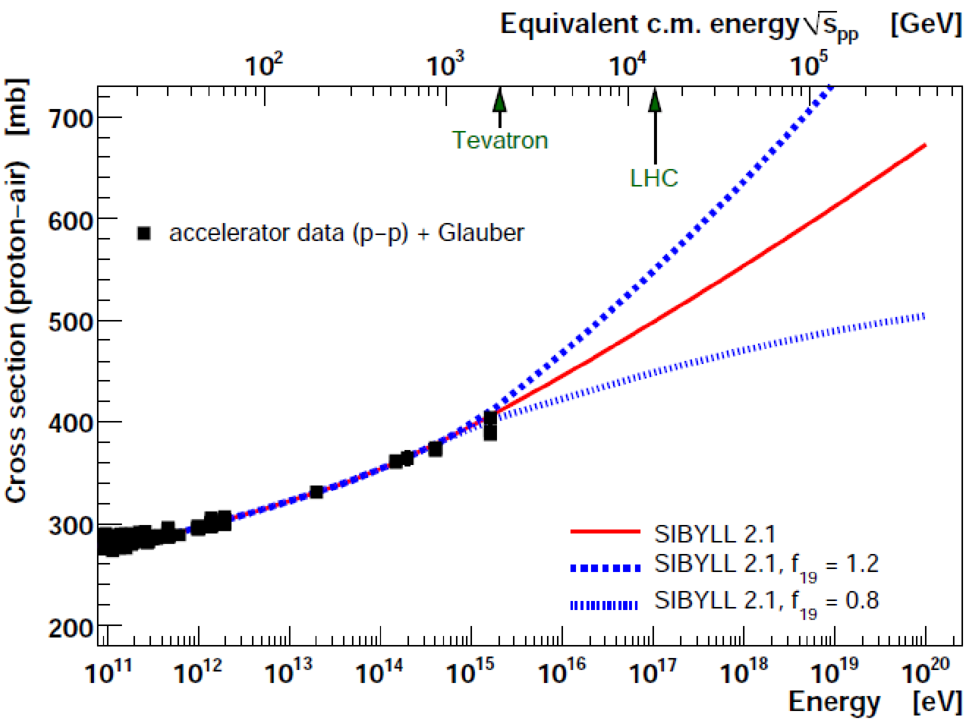
and the decreasing trend of the RMS(X_{max}) suggest a composition change towards a heavier composition



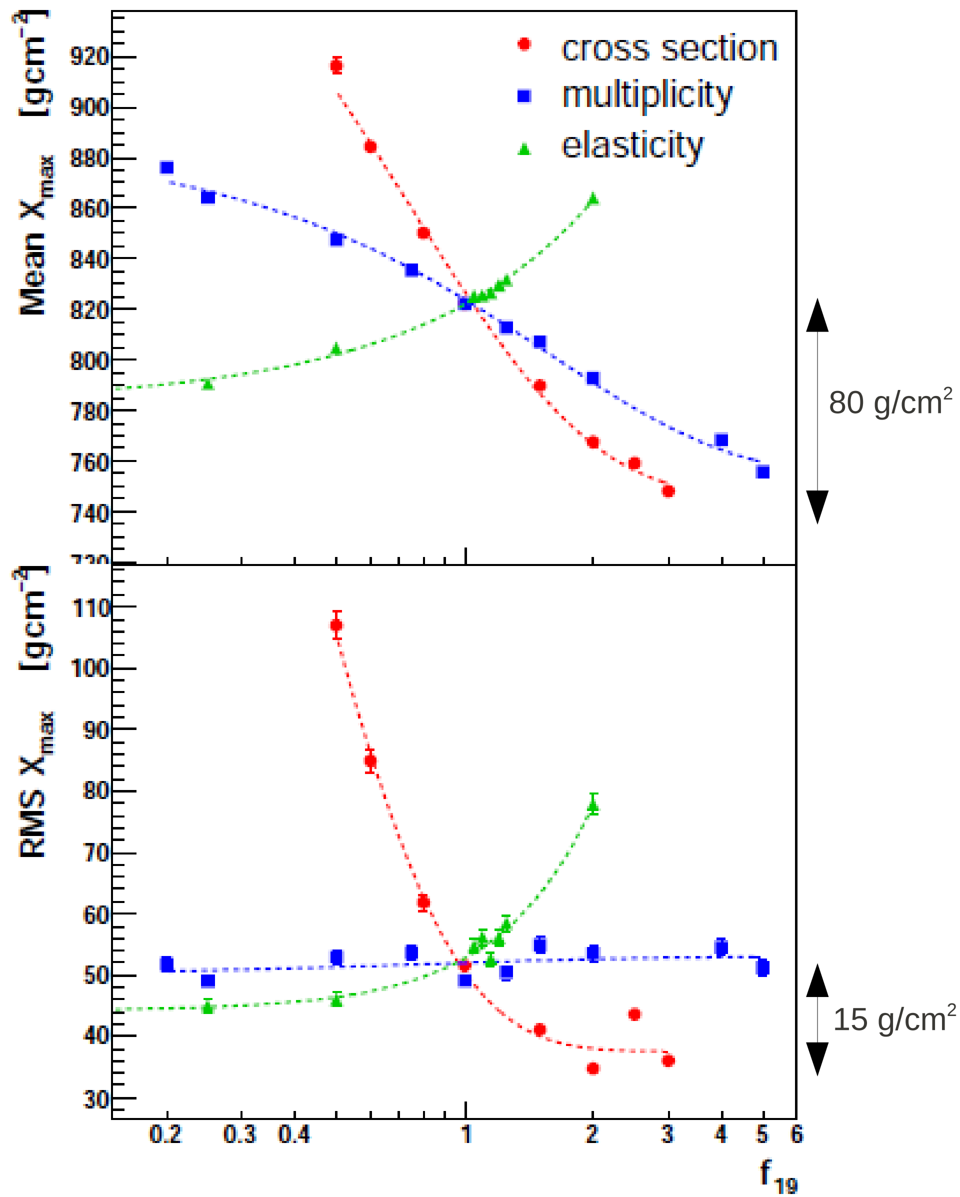
Pierre Auger Collaboration, PRL 104, 091101 (2010)

Are Changes to Hadronic Physics Responsible?

- Protons at highest energies?
- Can vary assumptions about hadronic interaction models
- Find that mean Xmax is easier to influence than the RMS
- extreme changes to proton-air cross-section required to explain RMS



1000 proton showers at $10^{19.5}$eV

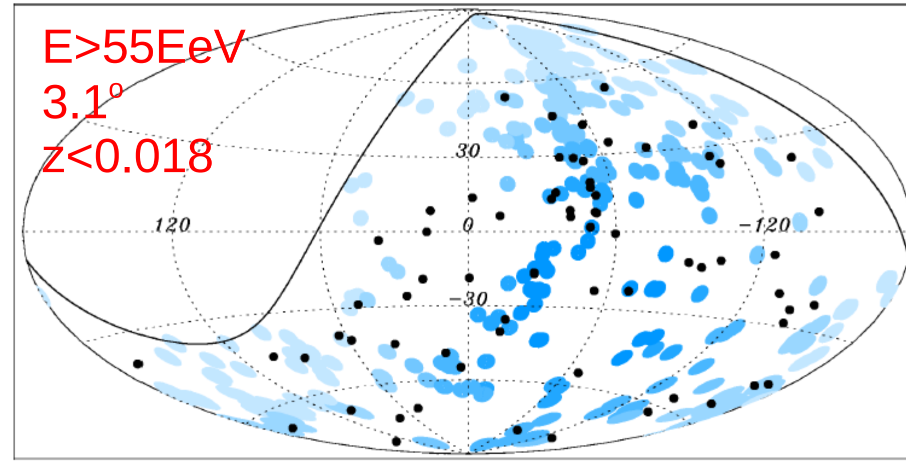


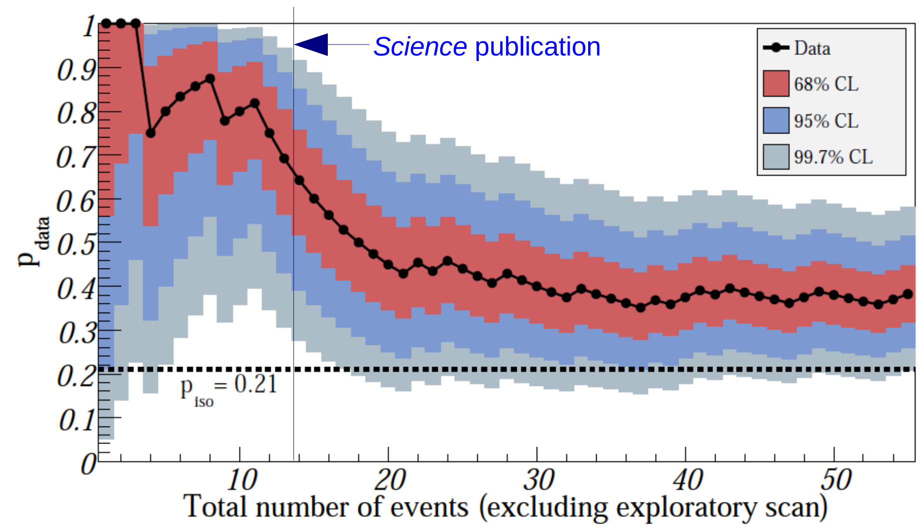
R. Ulrich et al. ICRC09 arXiv:09060418

Anisotropy

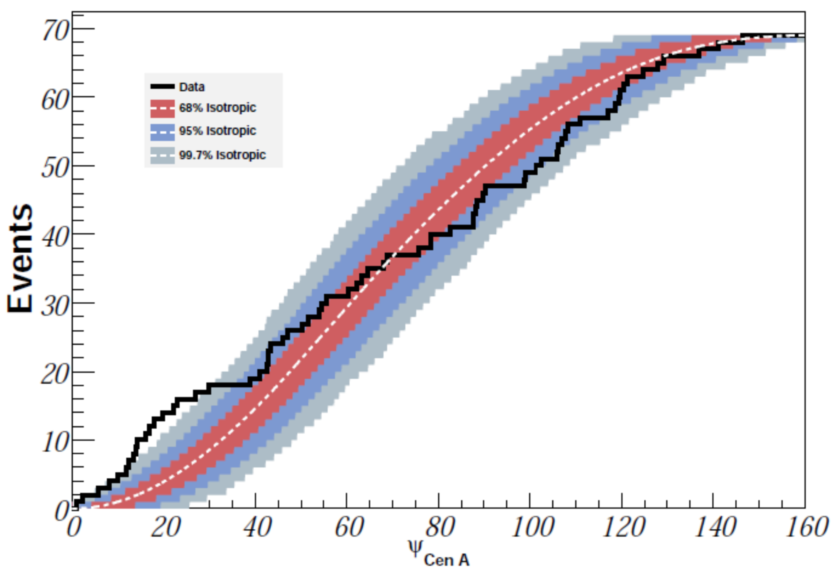
A. Letessier-Selvon tomorrow

- Prescription: used early dataset to define energy cut, catalog and redshift cut, angle. First published November 2007, *Science*
- AGN correlation now weaker than first indicated, but is apparently still present (38 +/- 6 % compared with 21% for isotropy).
- Tension with mass composition result?
- Interesting feature is the clustering (20° scale) around direction of Cen A





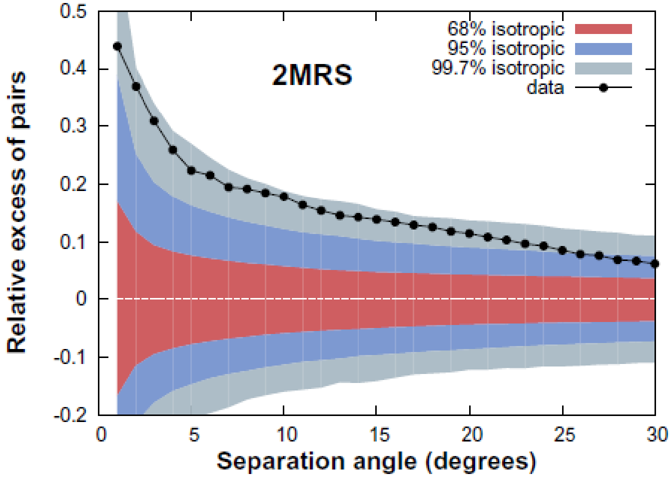
degree of correlation P_{data}=k/N
21/55 events now correlate
0.3% chance of finding this degree of correlation from an isotropic distribution.



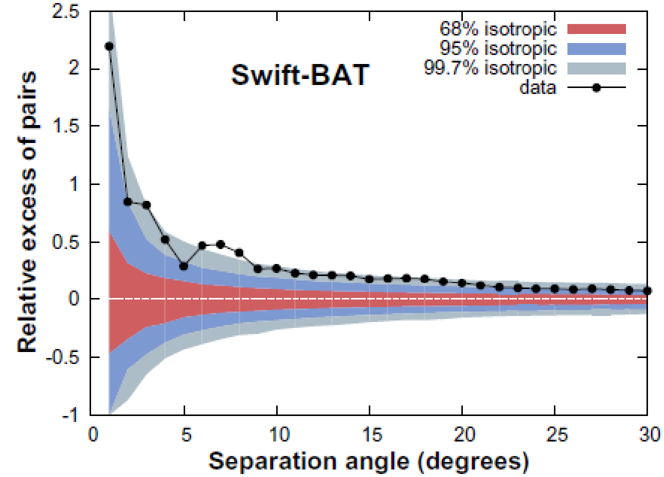
Update on the correlation of the HECR with nearby extragalactic matter, PA Collab., Astropart. Phys. 34 (2010) 314

Cross-Correlation analysis E > 55 EeV.

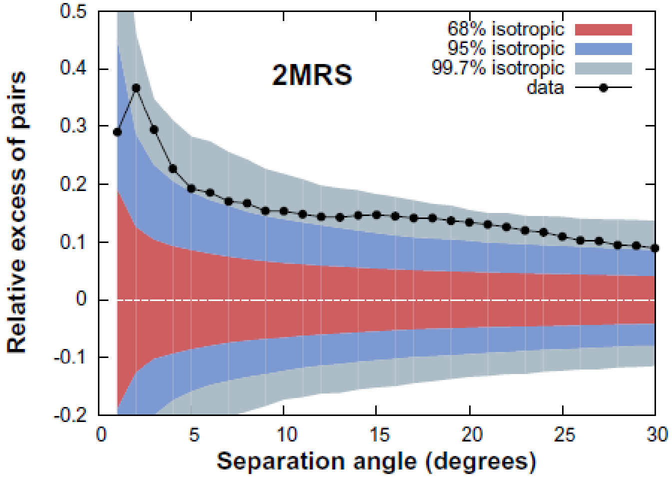
22,000 “normal” galaxies within 200Mpc

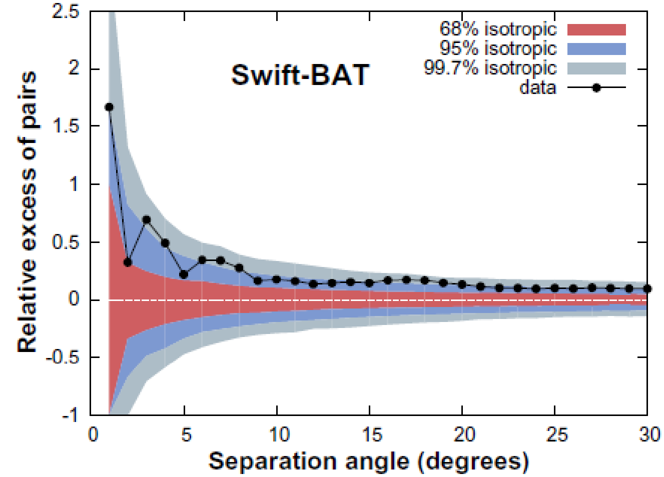


373 x-ray galaxies within 200Mpc



All events since 1/2004



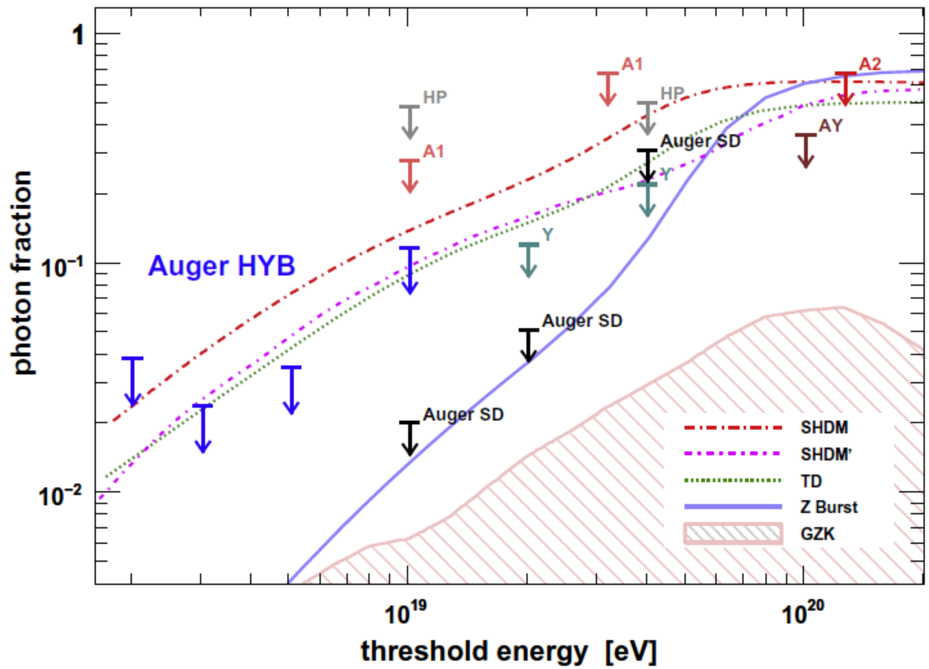


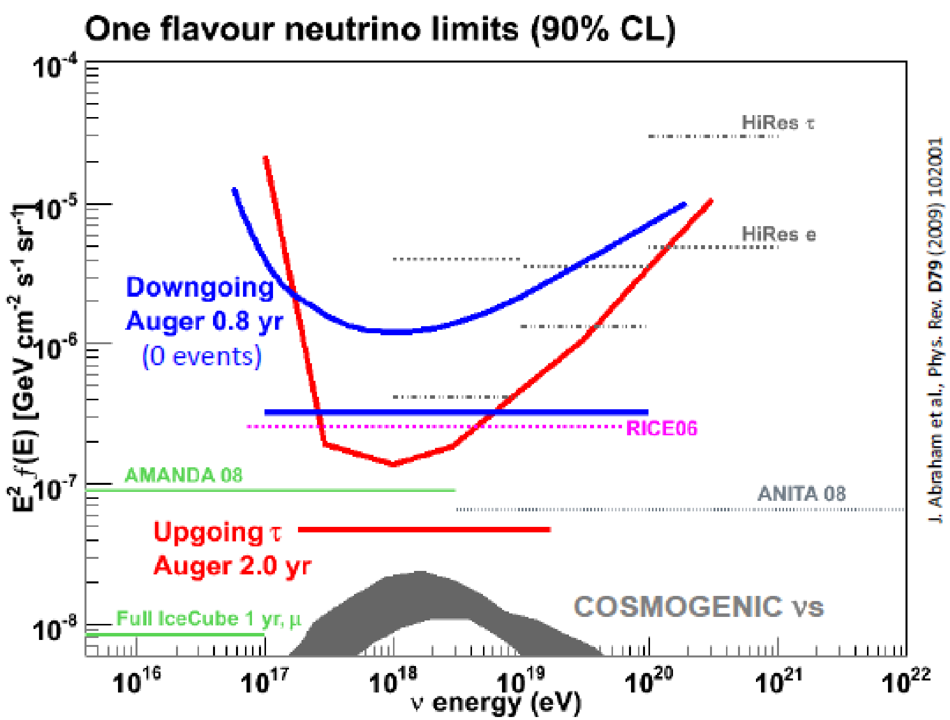
excluding early events used to formulate AGN prescription, particularly the energy cut

- “a posteriori” analysis, but interesting
- excess of correlating pairs (event+catalog object) within separation angle above isotropic expectation
- there is an excess of pairs, but significance is difficult to evaluate

PA Collab., Astropart. Phys. 34 (2010) 314

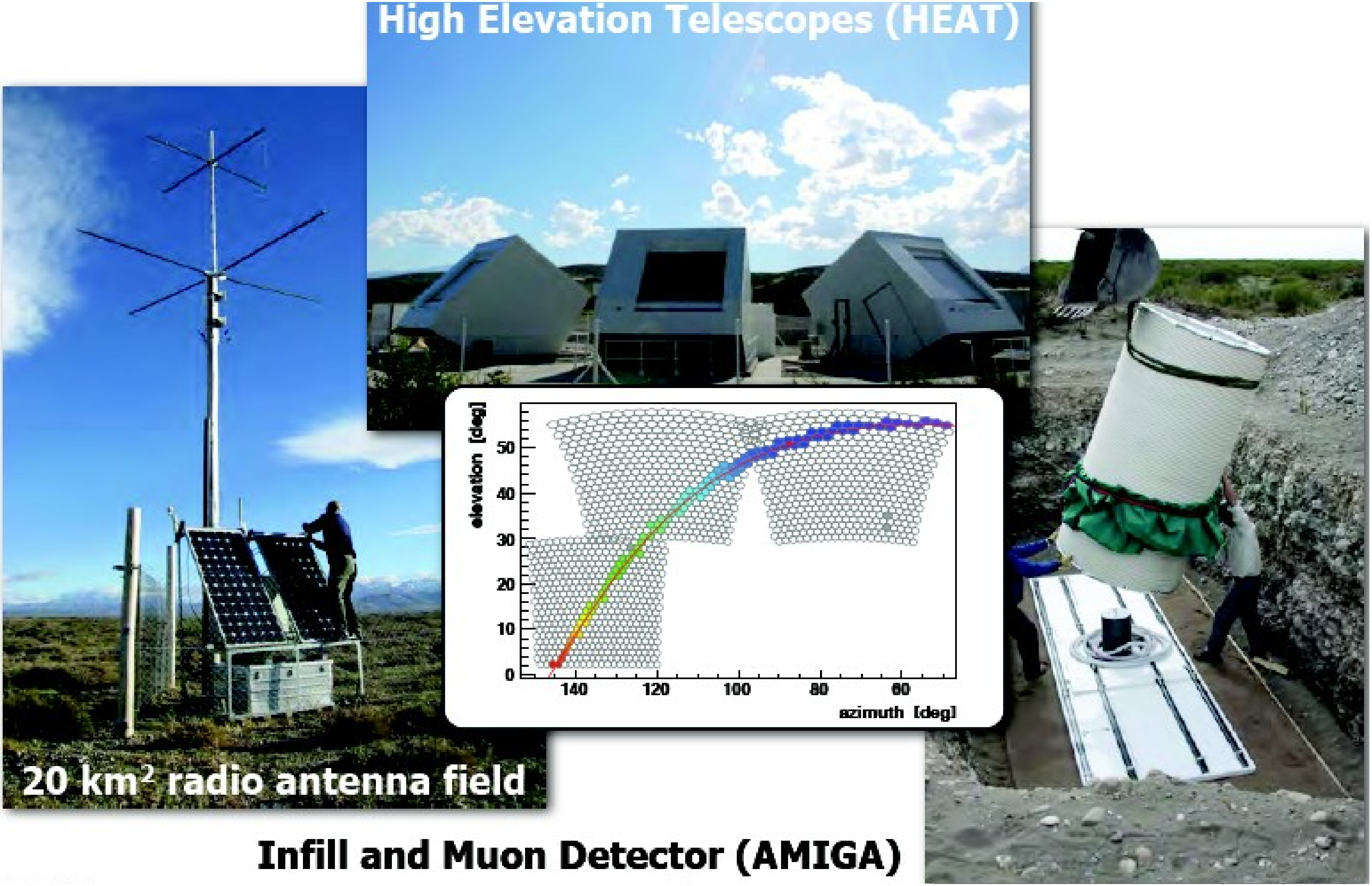
Photon and Neutrino Limits



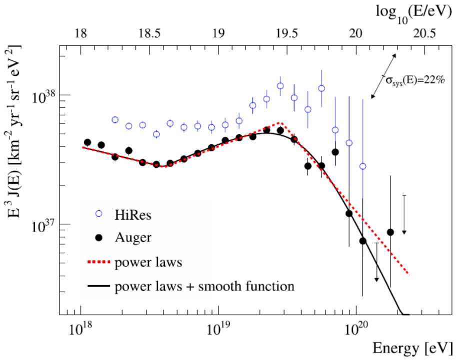


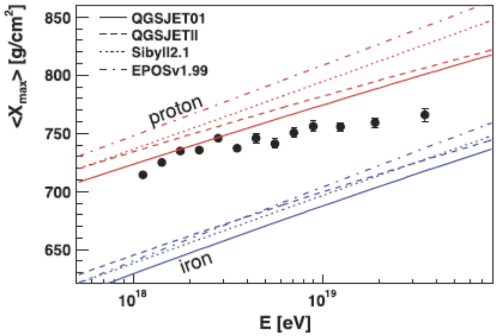
- Photons
  - FD and SD techniques
  - top-down models highly constrained
  - GZK photons ~ within reach (but 20 years for current aperture)
- Neutrinos
  - SD limits from "young" inclined showers
  - up-going (tau) and down-going (all flavours)
  - cosmogenic neutrinos within reach within lifetime of Auger south, if they exist.

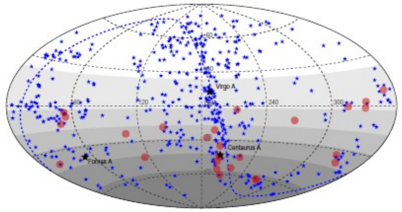
Auger Enhancements/New Techniques



… and several experiments testing feasibility of molecular bremsstrahlung detection (Sunday)







Summary

- This is what we see:
  - a significant spectral suppression above $10^{19.6}$eV
  - a weaker AGN correlation, but with interesting future targets
  - a change in shower development with E – mass increase, or hadronic physics? RMS results are striking. Tension with anisotropy?
  - no photons and neutrinos so far, several exotic models ruled out
- What must we do next? (J. Bluemer, Sunday)
  - continue accumulating 7000 km^{2}sr exposure <u>every year</u>
  - continue to develop new analysis (e.g. SD mass composition)
  - extend energy reach downwards
  - work with other experiments to understand differences
  - strive for larger area, longer exposure, new cheaper techniques
- UHECR physics is rich
  - clues are more puzzling than some would have expected, but not “disappointing”
  - anisotropy is a key measurement, but mass and energy information is crucial!

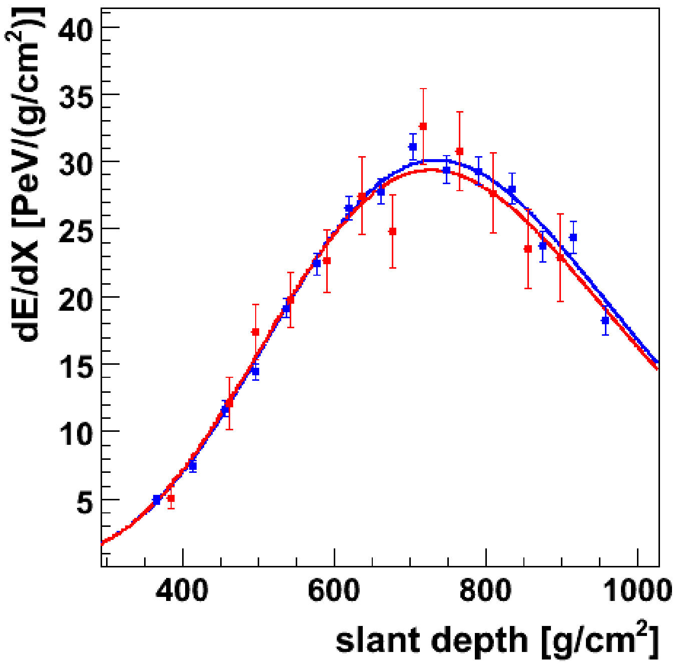
Backup Slides

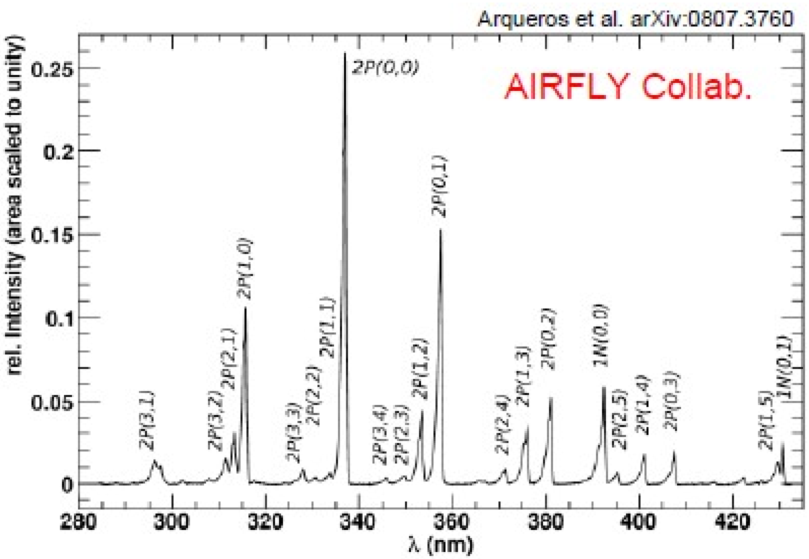
Systematic Uncertainties in FD Energies

(typically much larger than statistical errors on individual events)

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%

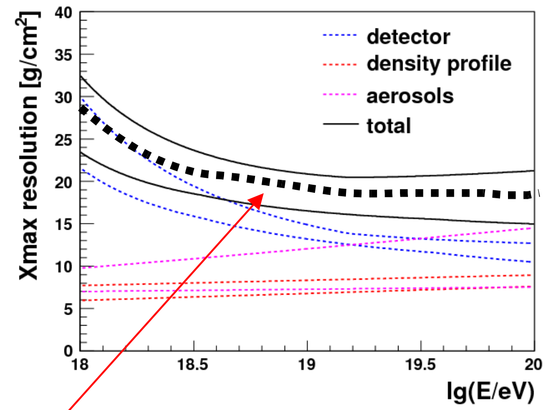
(significant work underway to reduce these uncertainties)



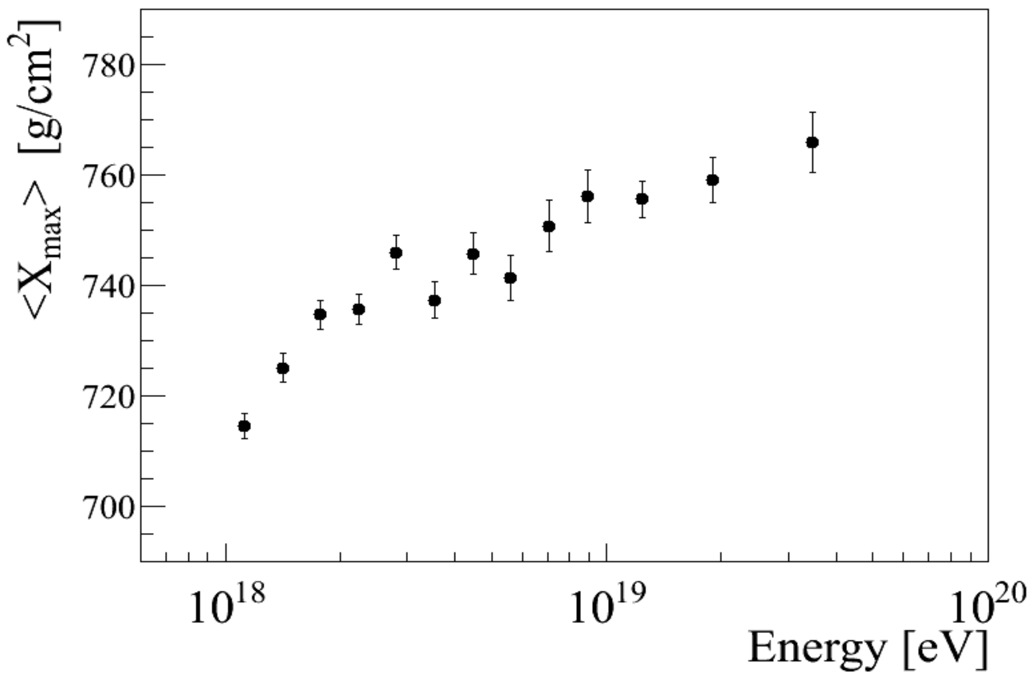


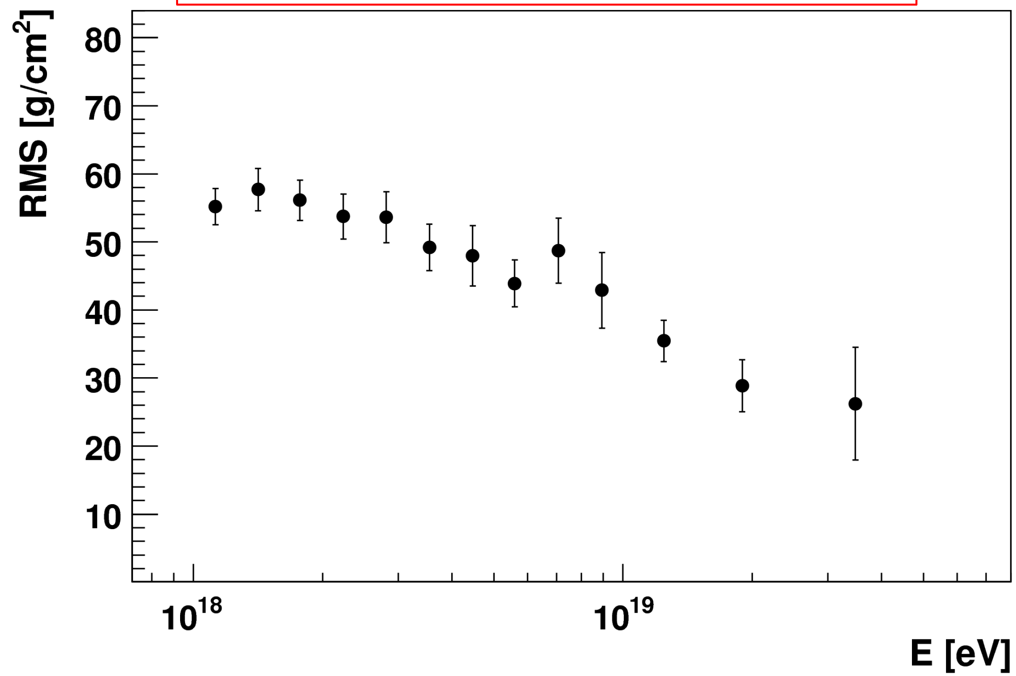
Results (total number of events 3764)

Mean X_{max} and RMS(X_{max}) Vs energy



after correcting the RMS for resolution





A reduction in the elongation rate (left) accompanied by a reduction in the RMS of the Xmax distribution (right).
Indication of an increase in the mean mass of cosmic rays?

Pierre Auger Collaboration, PRL 104, 091101 (2010)

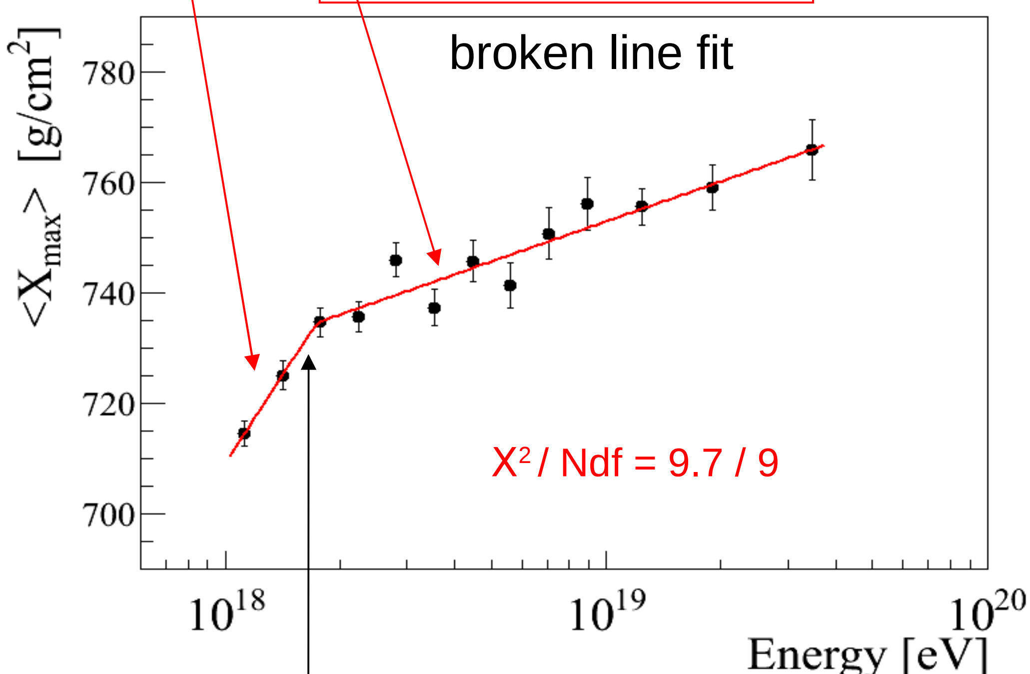
The data suggest a break in the $\langle X_{max} \rangle$ vs energy curve

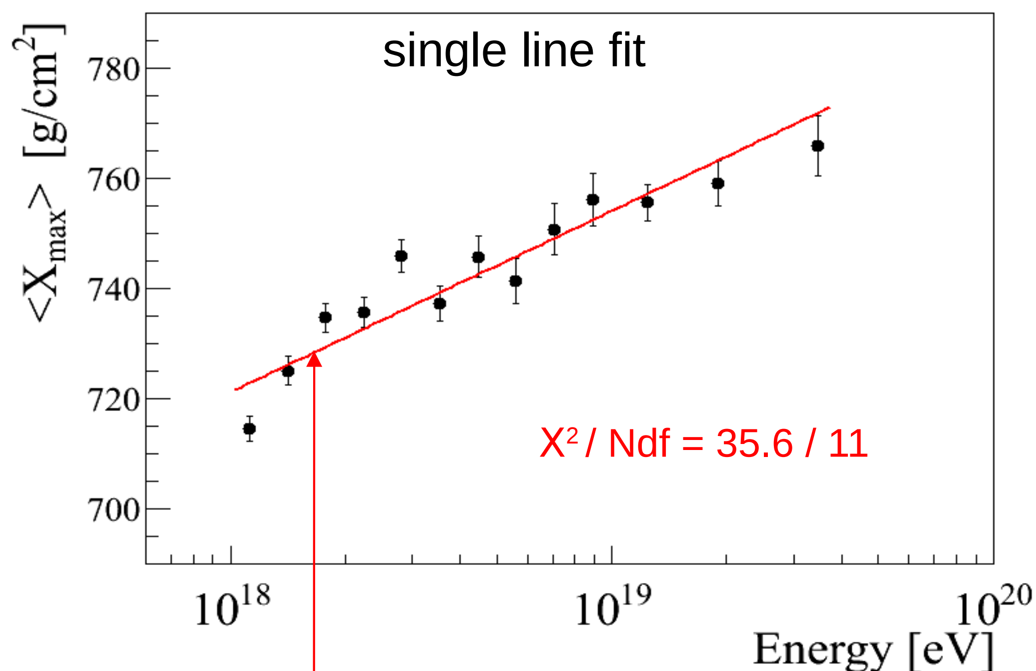
PIERRE AUGER OBSERVATORY

uncertain, but rapid elongation interesting!

$D_{10}=106\ ^{+35}_{-21}$ g/cm^2 per decade

$D_{10}= 24\pm 3$ g/cm^2 per decade very slow elongation



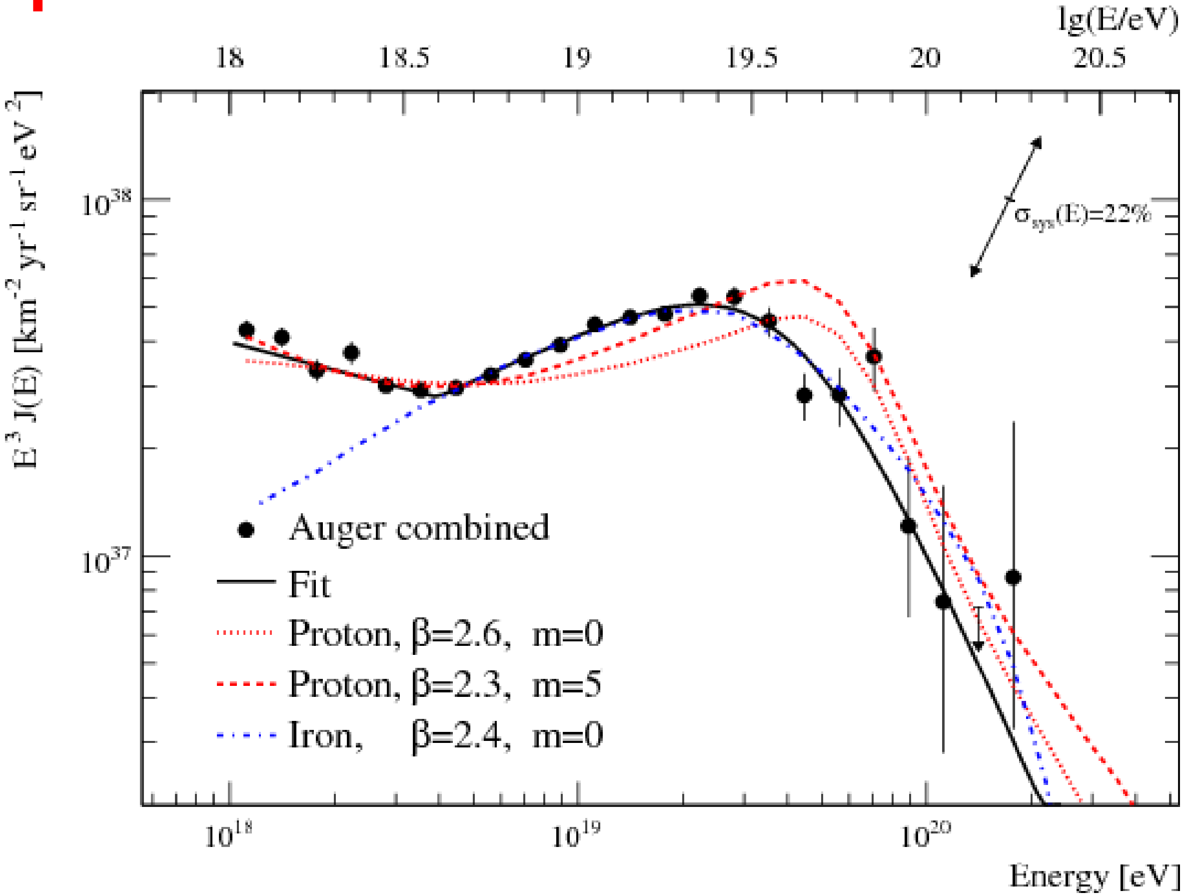


$E_b=10^{18.25\pm0.05}$ eV

$D_{10}=33\pm2$ g cm^{-2} / decade

J. Bellido et al. 31[st] ICRC Lodz (2009)

Some simple models



- Uniform distribution of sources
- cosmological evolution of source luminosity $(1+z)^m$, source spectrum $E^{-\beta}$. $E_{max}=10^{20.5}$eV
- No serious attempt at modelling, but better agreement with data with
  - protons and rapid evolution of sources m=5, or
  - iron and no evolution (galactic source required for ankle)
- Simple examples now, promise of future capabilities