The Pierre Auger Observatory
Recent results

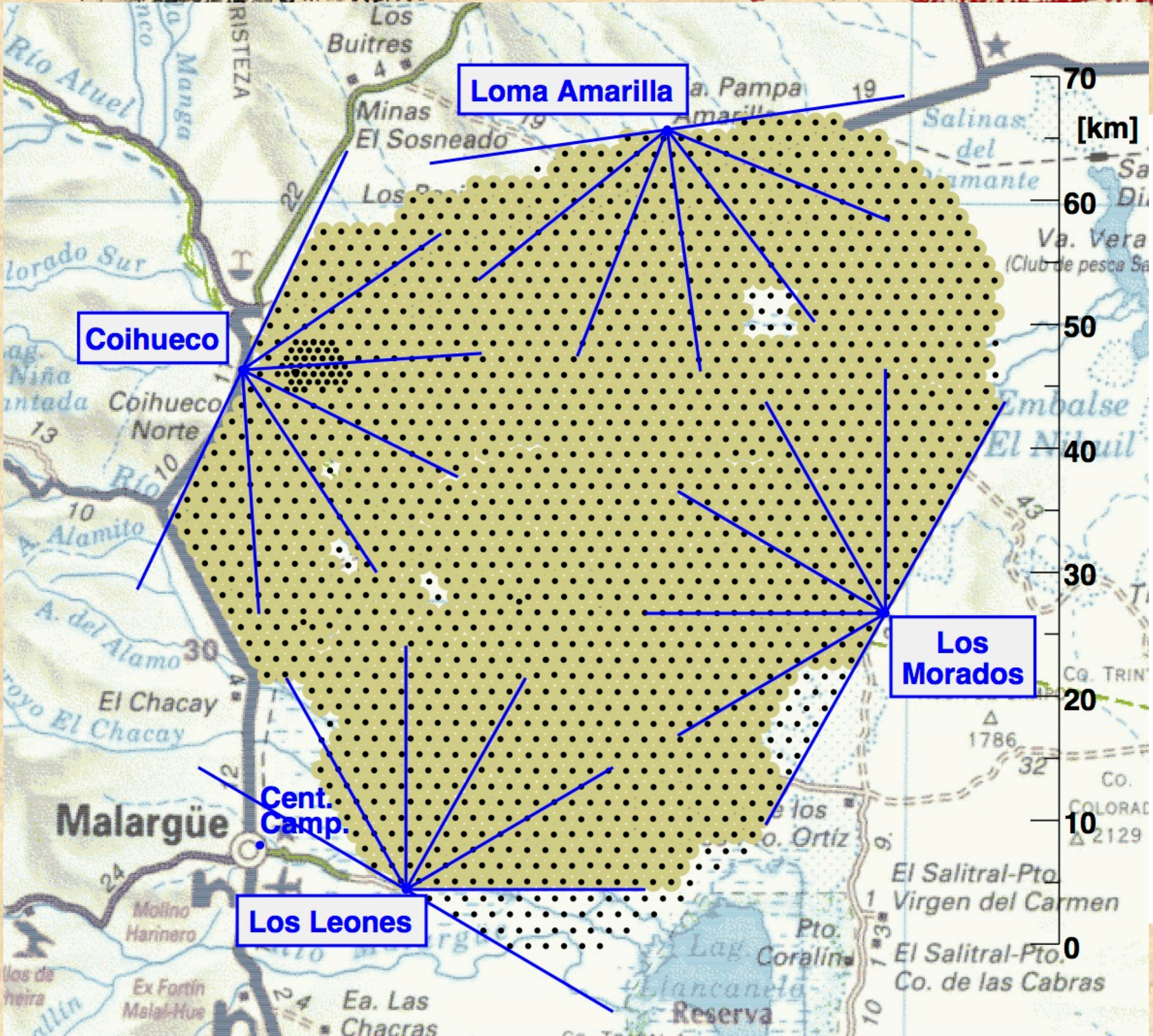
Ronald Cintra Shellard (CBPF)
On behalf of the
Pierre Auger Collaboration

Outline

- The Pierre Auger Observatory
- The spectrum
- Mass composition
- Cross section
- Neutrinos and Photons
- Neutron point sources
- Anisotropy
- Muon shower content
- Conclusions

The Pierre Auger Observatory

The Pierre Auger Observatory



1660 tanks installed

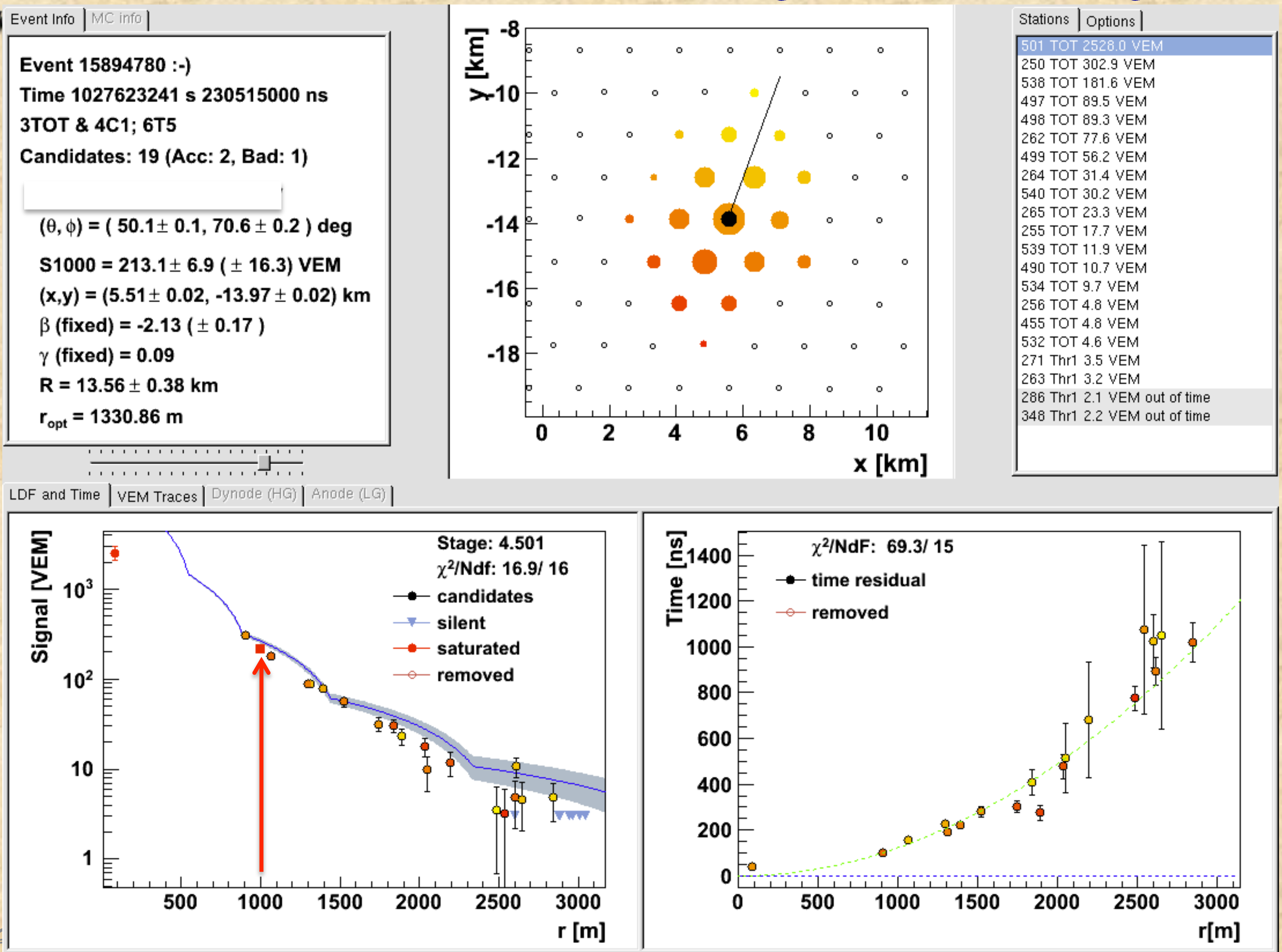
27 FD telescopes (4 locals)

Completed in 2008

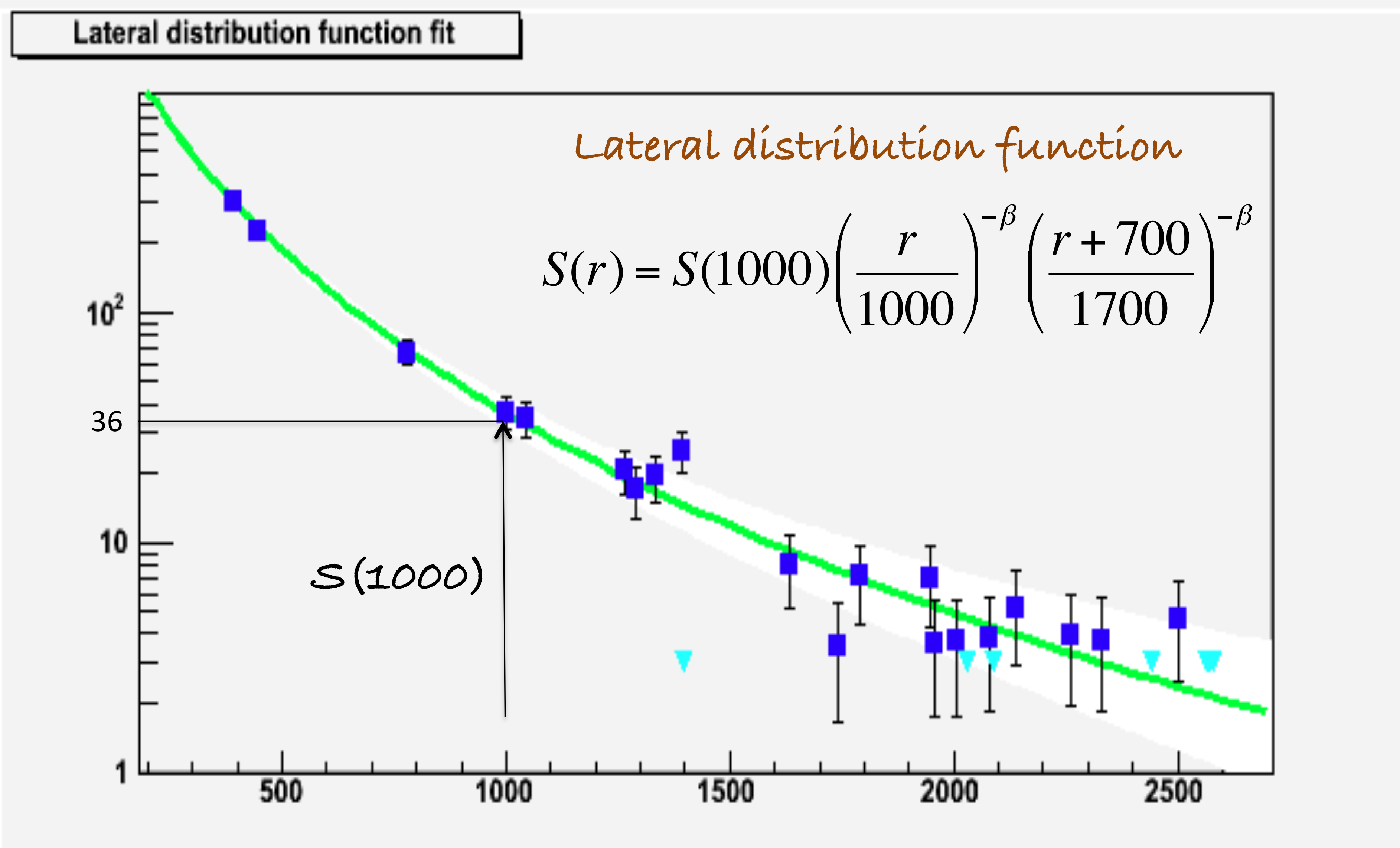
Taking data since 2004

SD event

29/07/2012 SD 15894780

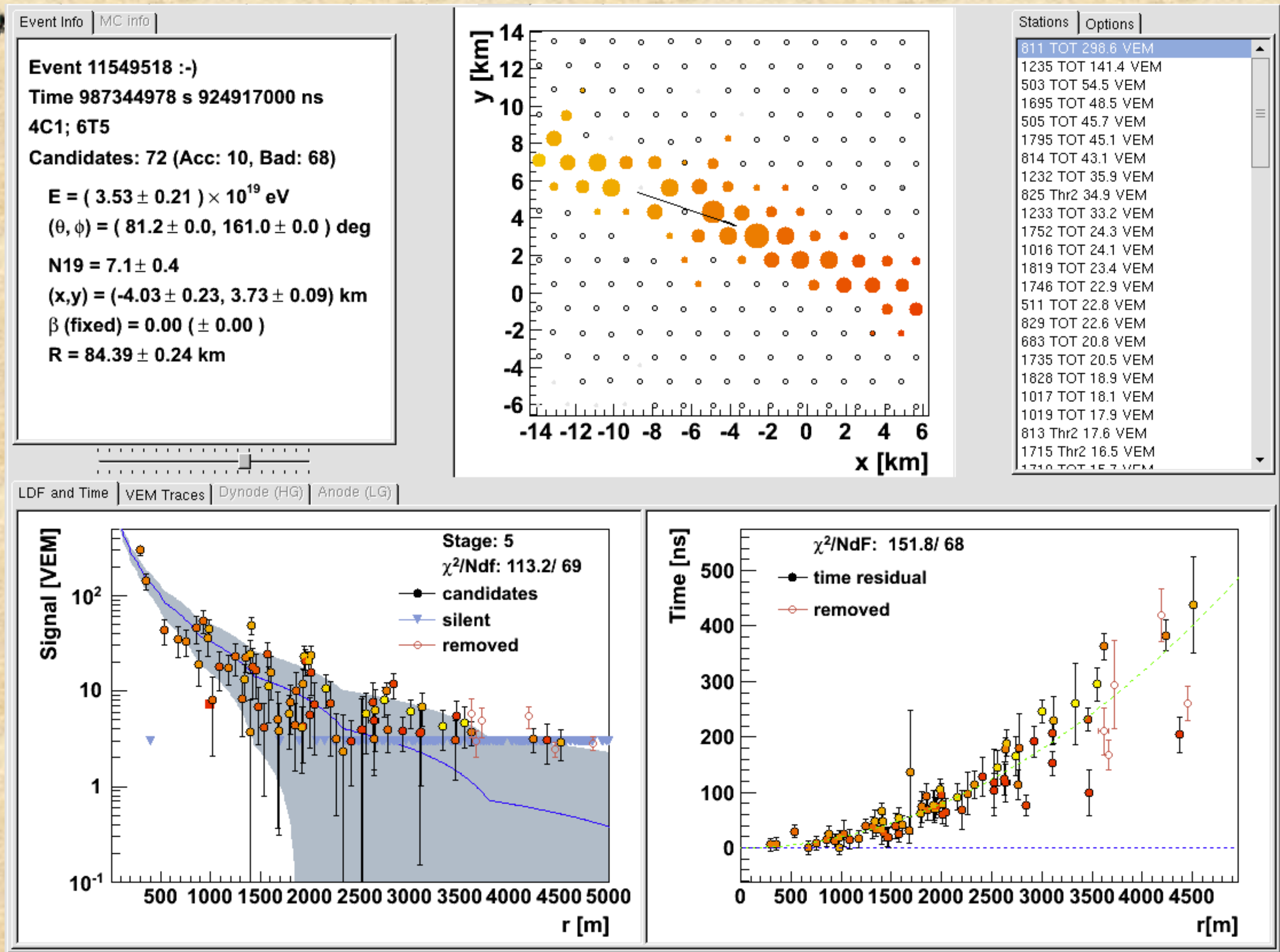


The Surface Detector



SD inclined event

20/4/2011 SD 11549518

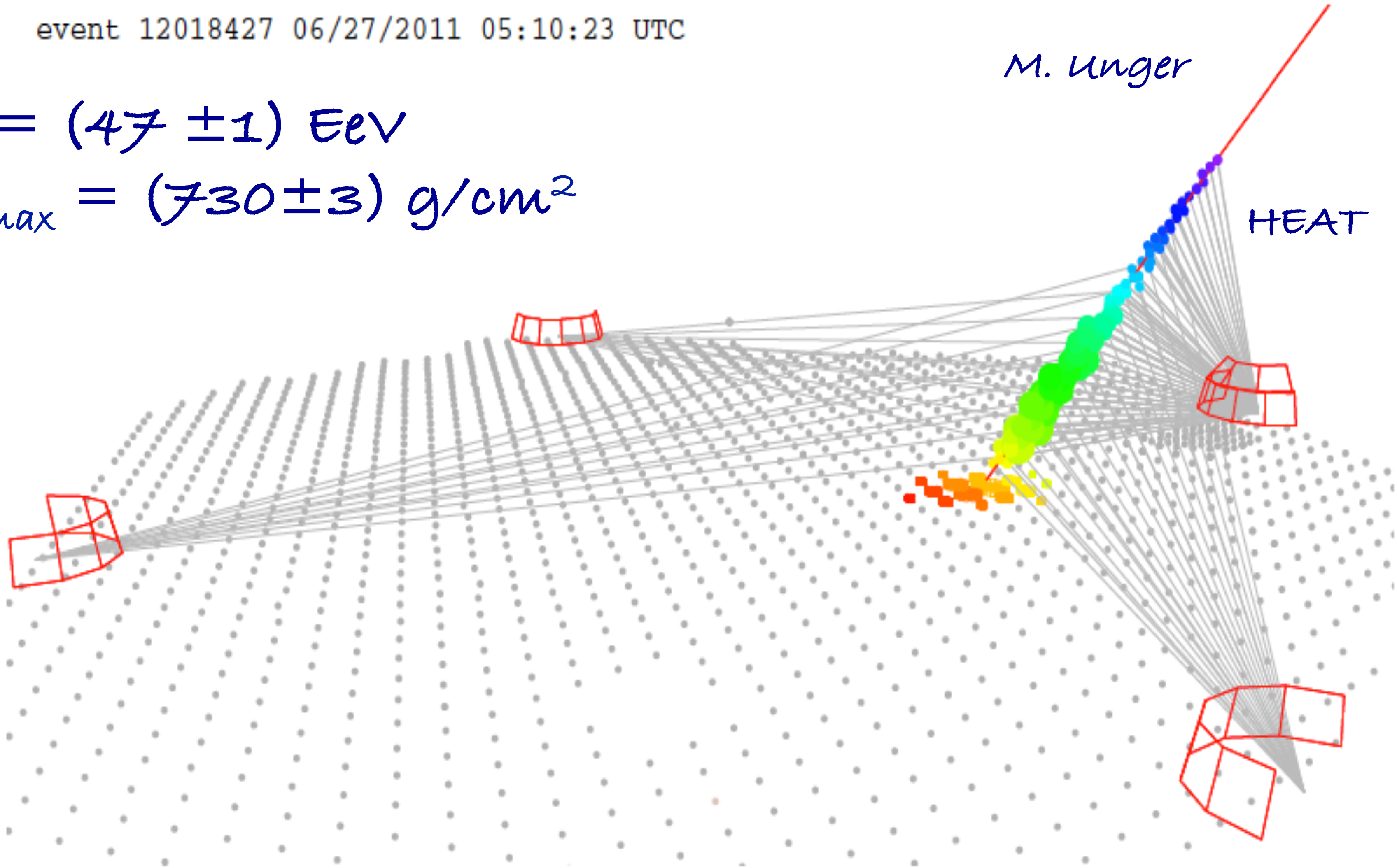


FD event

event 12018427 06/27/2011 05:10:23 UTC

$E = (47 \pm 1)$ EeV

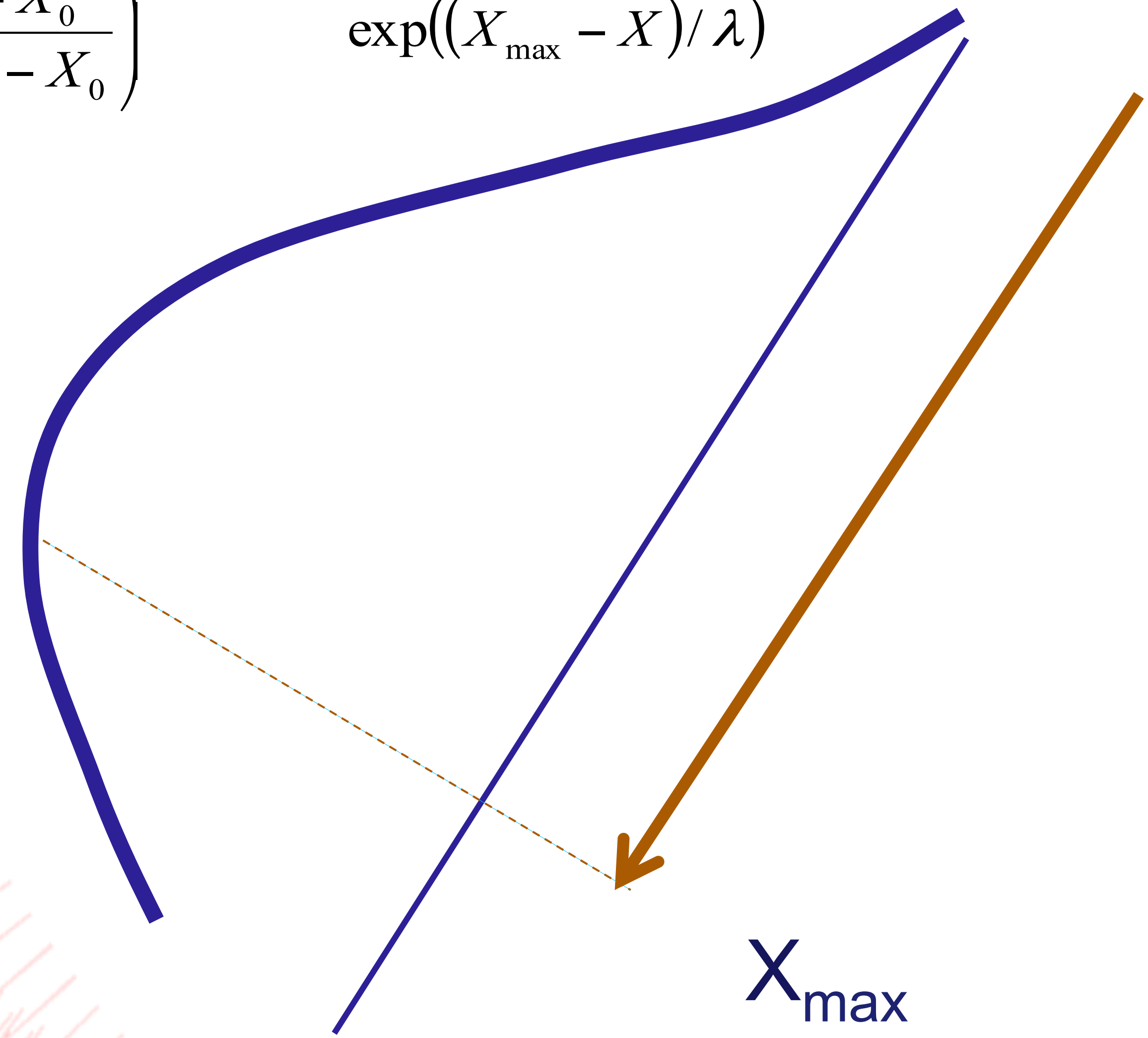
$X_{max} = (730 \pm 3)$ g/cm^2



Xmax

$$N_e(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{(X_{max} - X_0)/\lambda} \exp((X_{max} - X)/\lambda)$$

Gaisser-Hillas

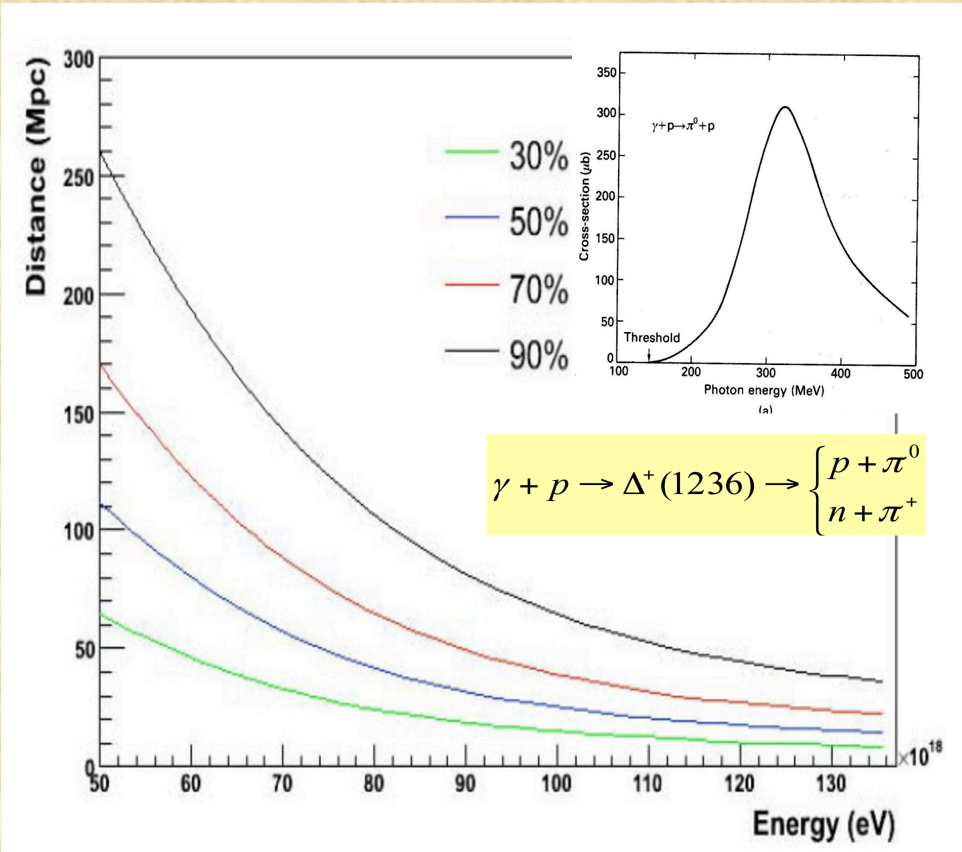


The cosmic rays spectrum

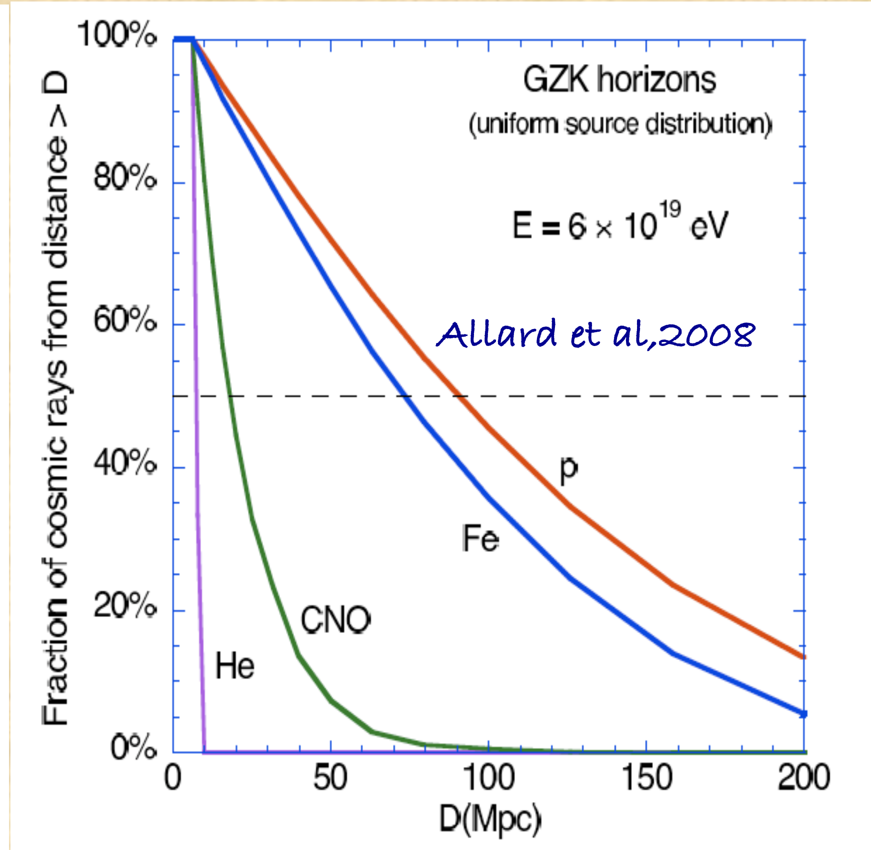
The cosmic ray spectrum

- Auger is sensitive to energies > 1 EeV (10^{18} eV)
- Greisen-Zatsepin-Kuzmin (GZK) prediction (supression of Flux above ~ 40 EeV due to Δ(1236) ressonance in interaction between proton and CMB)
- Energy and exposure determination
- Good measurement of the spectrum is essential to discriminate between different models for the transition

GZK limit

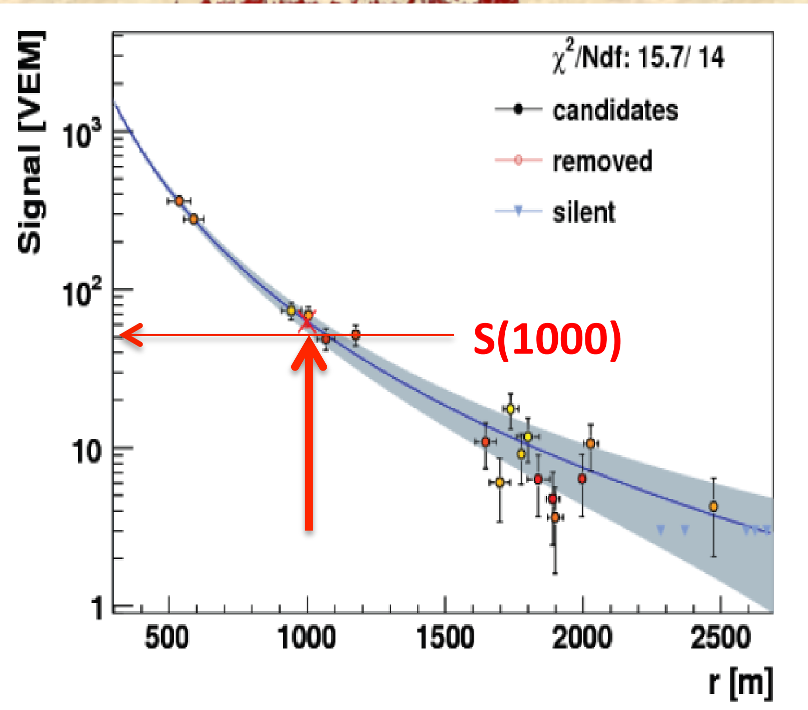


$$\gamma + p \longrightarrow \Delta^{+}(1236) \longrightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$



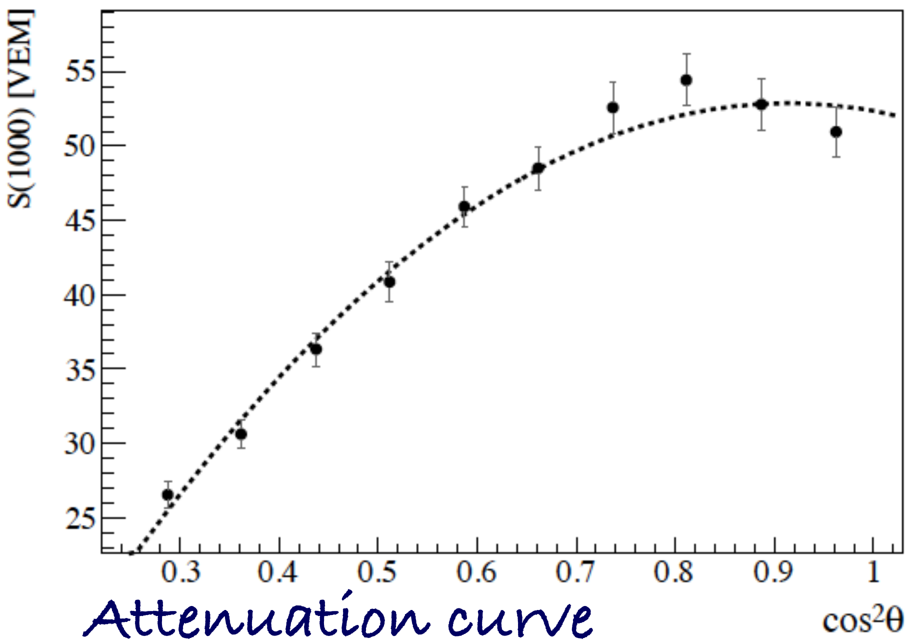
The spectrum (a note on Energy calibration)

- SD Energy calibration
  - Energy extracted from lateral distribution function [S(1000)]
  - Global fitting



- FD Energy calibration
  - Energy deposited proportional to fluorescence light emitted. Light converted into energy deposited using absolute fluorescence yield in 337nm band (5.05±0.71) photons/MeV.
  - Corrected for environmental factors

The spectrum (a note on Energy calibration)



Attenuation curve

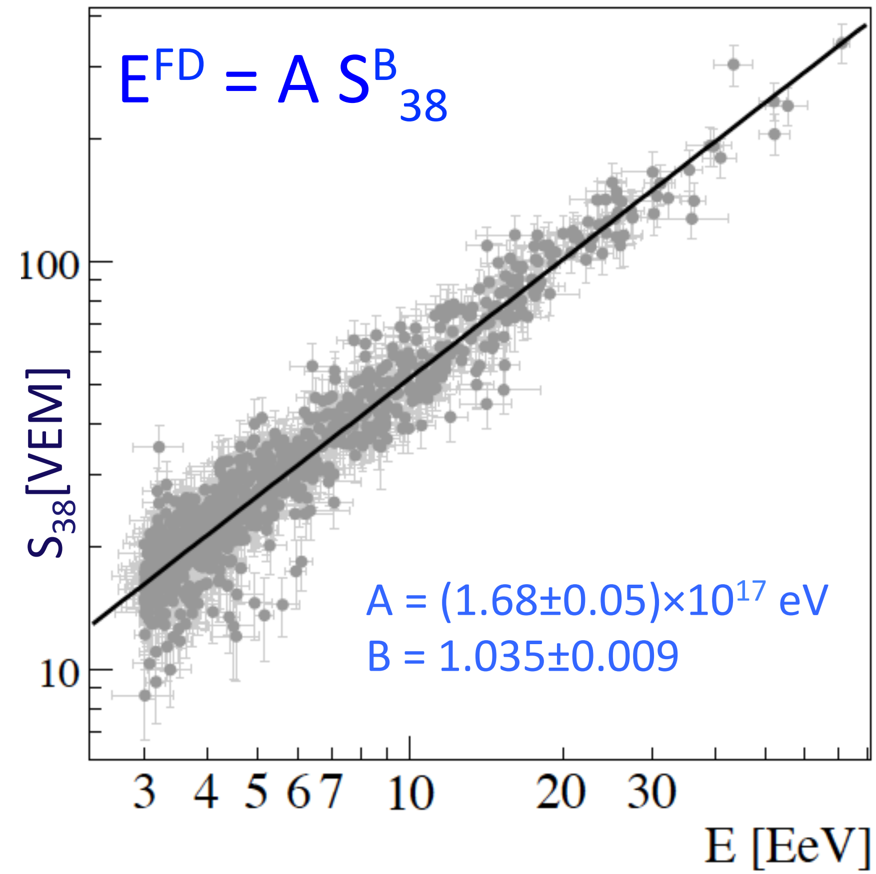
FD energies are used to calibrate SD energy parameter (839 Golden hybrid events here)

$$CIC(\theta) = 1 + ax + bx^2$$

$$x = \cos^2\theta - \cos^2 38^\circ$$

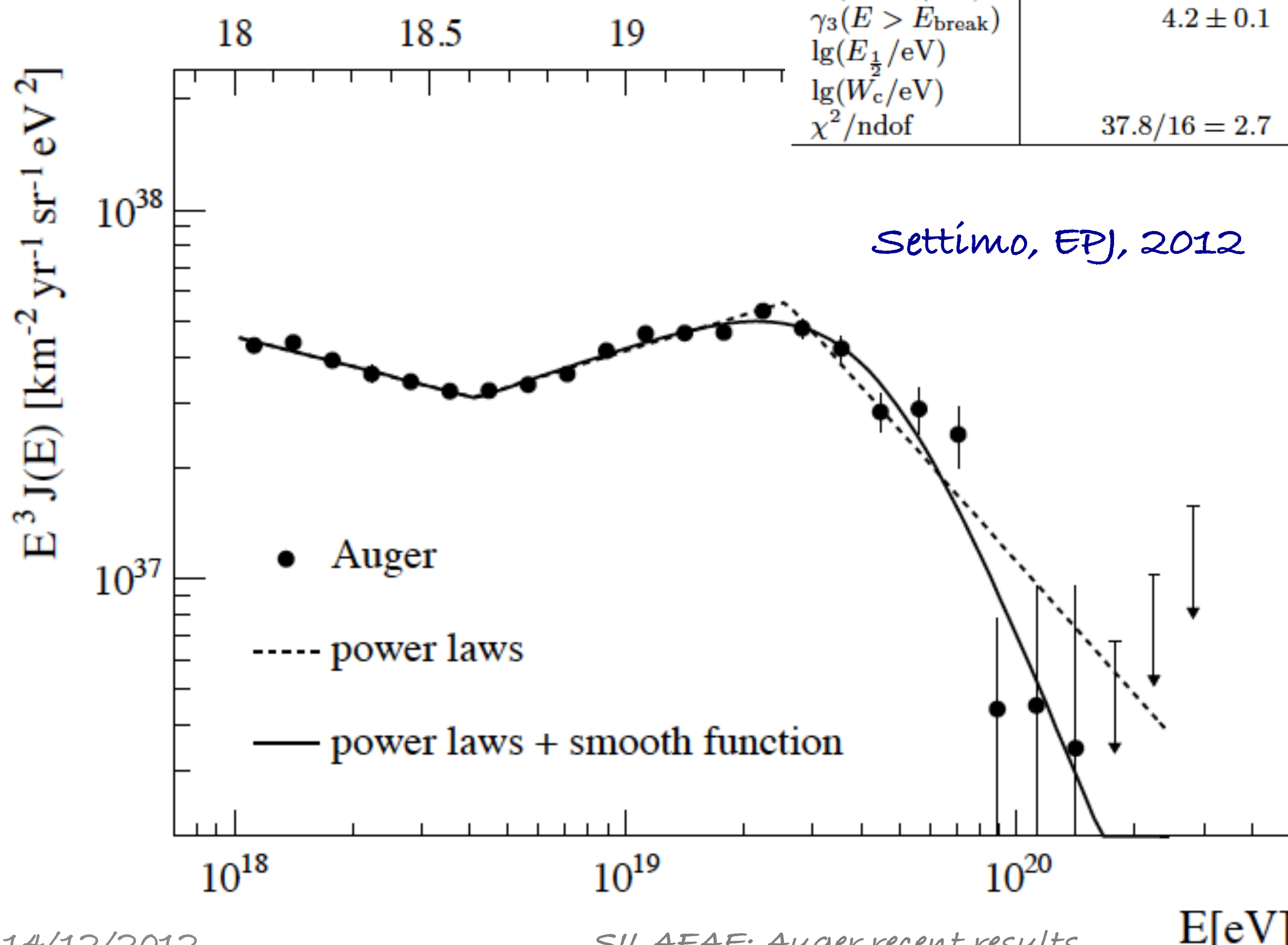
$$S_{38^\circ} \equiv S(1000) / CIC(\theta)$$

a= 0.87±0.04
b=-1.49±0.20



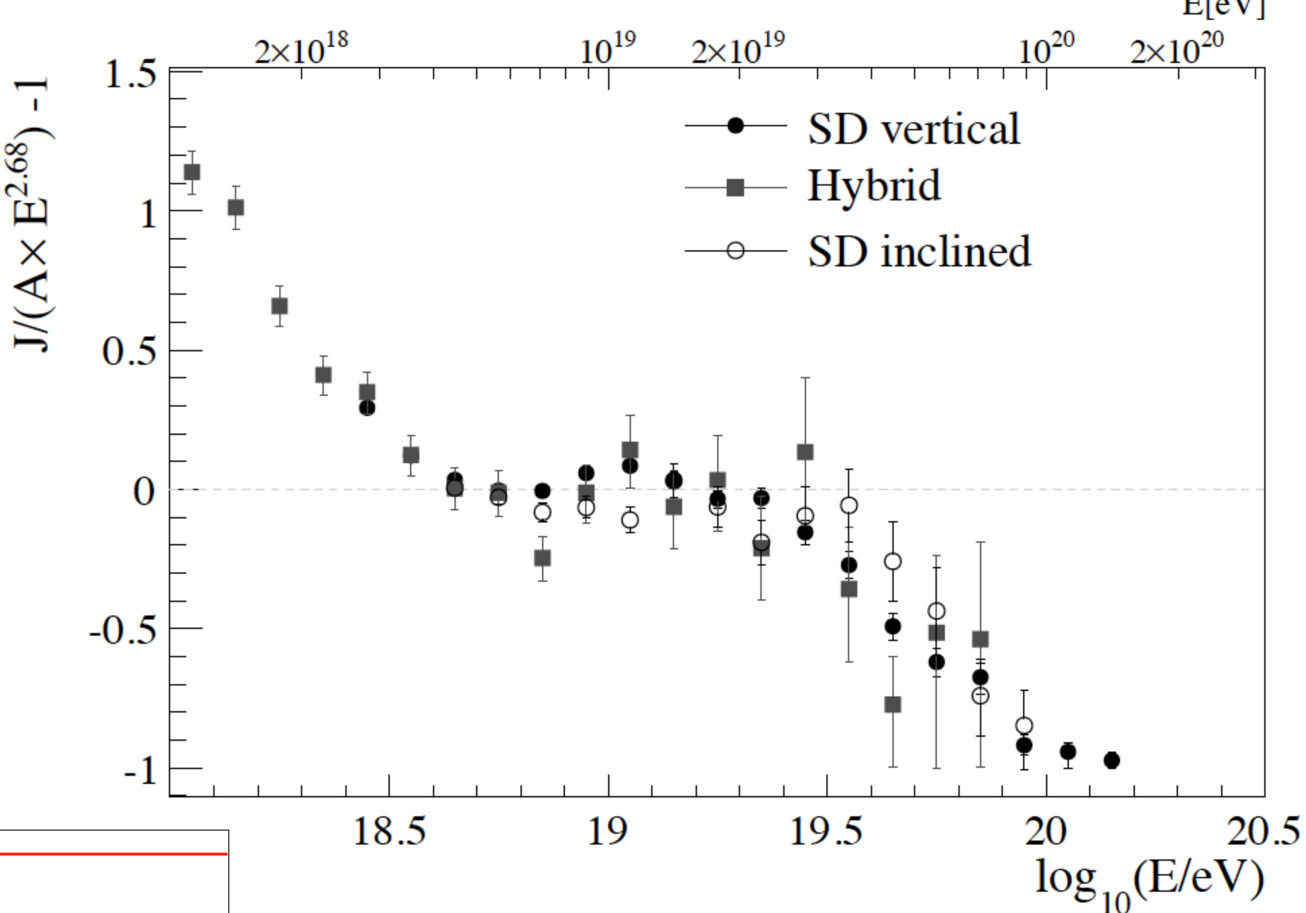
The Spectrum

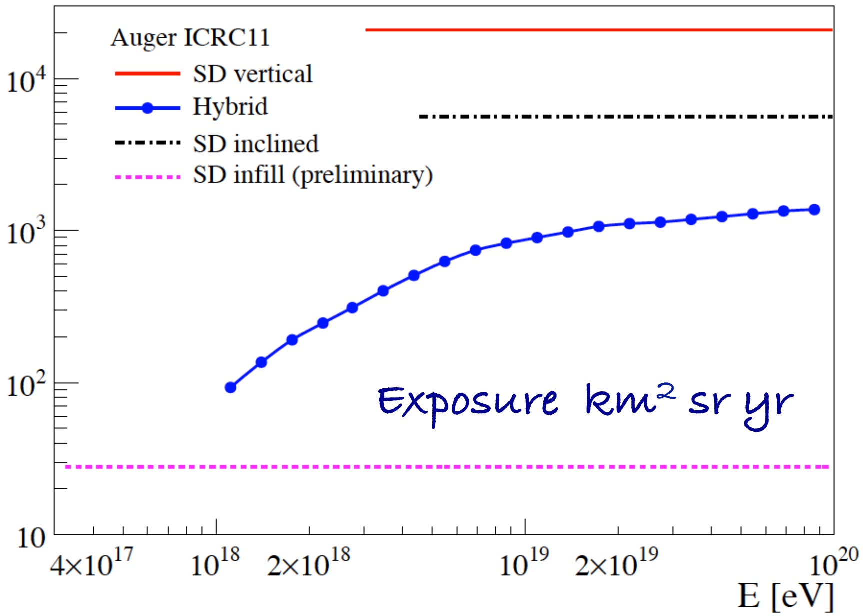
parameter	broken power laws	power laws + smooth function
$\gamma_1(E < E_{\rm ankle})$	3.27 ± 0.02	3.27 ± 0.01
$\lg(E_{\rm ankle}/{\rm eV})$	18.61 ± 0.01	18.62 ± 0.01
$\gamma_2(E > E_{\rm ankle})$	2.68 ± 0.01	2.63 ± 0.02
$\lg(E_{\rm break}/{\rm eV})$	19.41 ± 0.02	
$\gamma_3(E > E_{\rm break})$	4.2 ± 0.1	
$\lg(E_{\frac{1}{2}}/{\rm eV})$		19.63 ± 0.02
$\lg(W_c/{\rm eV})$		0.15 ± 0.02
$\chi^2/{\rm ndof}$	$37.8/16 = 2.7$	$33.7/16 = 2.3$



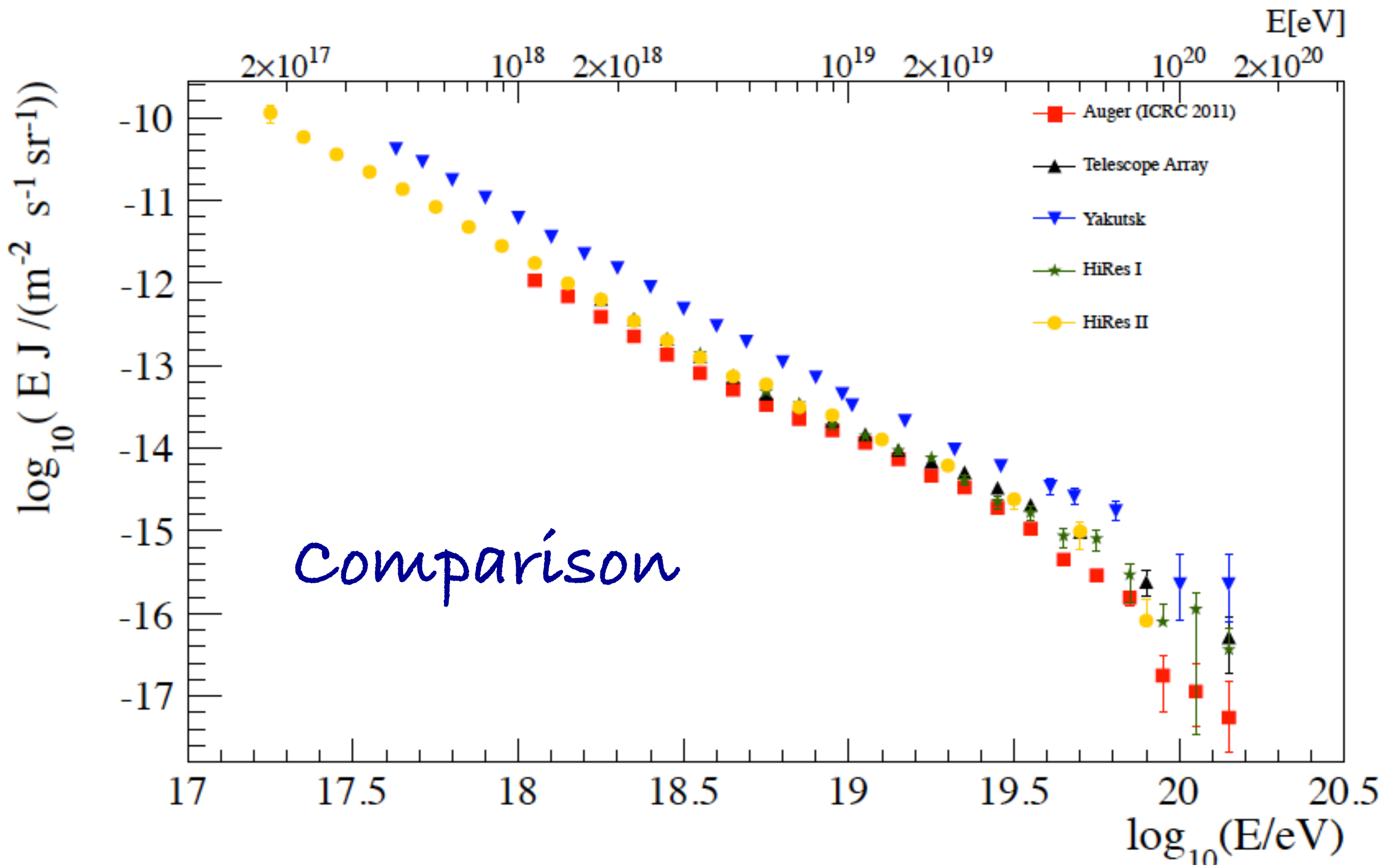
Settimo, EPJ, 2012

The Spectrum





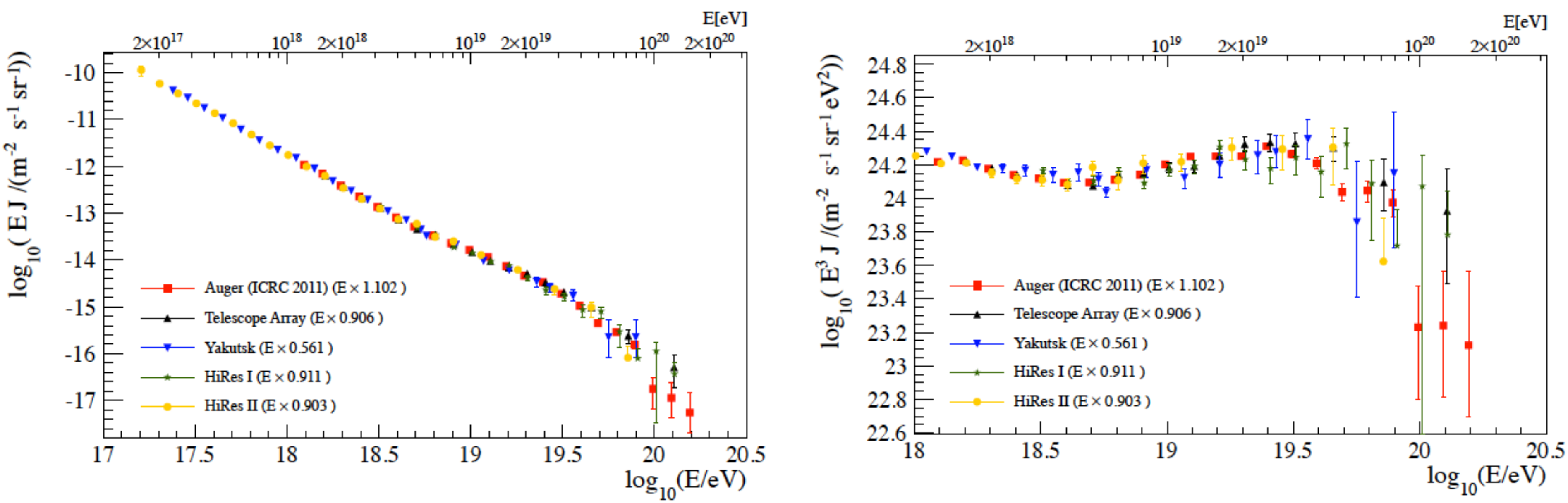
The cosmic rays spectrum



	γ_1	γ_2	γ_3	$\log_{10} E_A$	$\log_{10} E_S$
AGASA	3.16 ± 0.08	2.78 ± 0.3	-	19.01	
Yakutsk	3.29 ± 0.17	2.74 ± 0.20	-	19.01 ± 0.01	-
HiRes	3.25 ± 0.01	2.81 ± 0.03	5.1 ± 0.7	18.65 ± 0.05	19.75 ± 0.04
Auger	3.27 ± 0.02	2.68 ± 0.01	4.2 ± 0.1	18.61 ± 0.01	19.41 ± 0.02
TA	3.33 ± 0.04	2.68 ± 0.04	4.2 ± 0.7	18.69 ± 0.03	19.68 ± 0.09

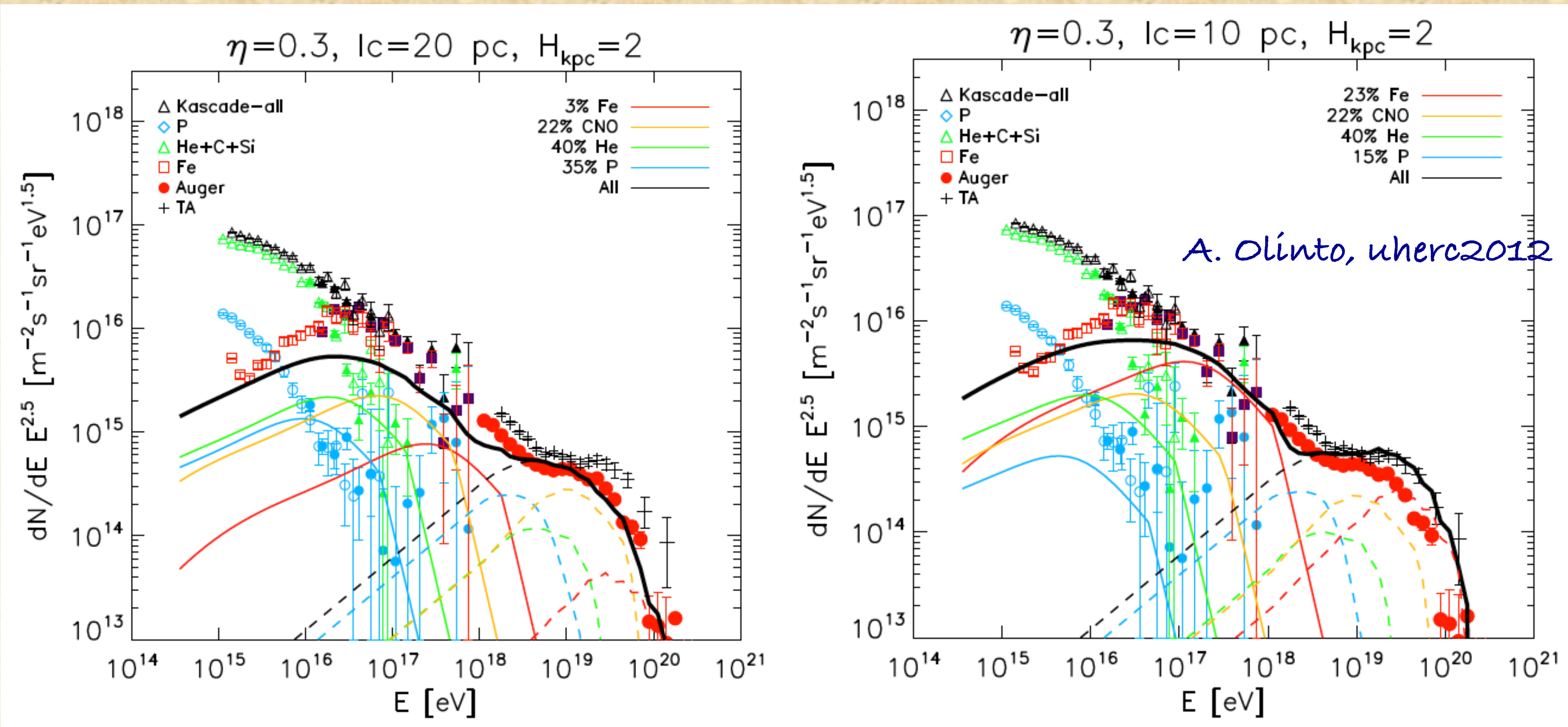
The cosmic rays spectrum: comparison

After Energy re-scaling



The cosmic rays spectrum

Exaustion of sources?

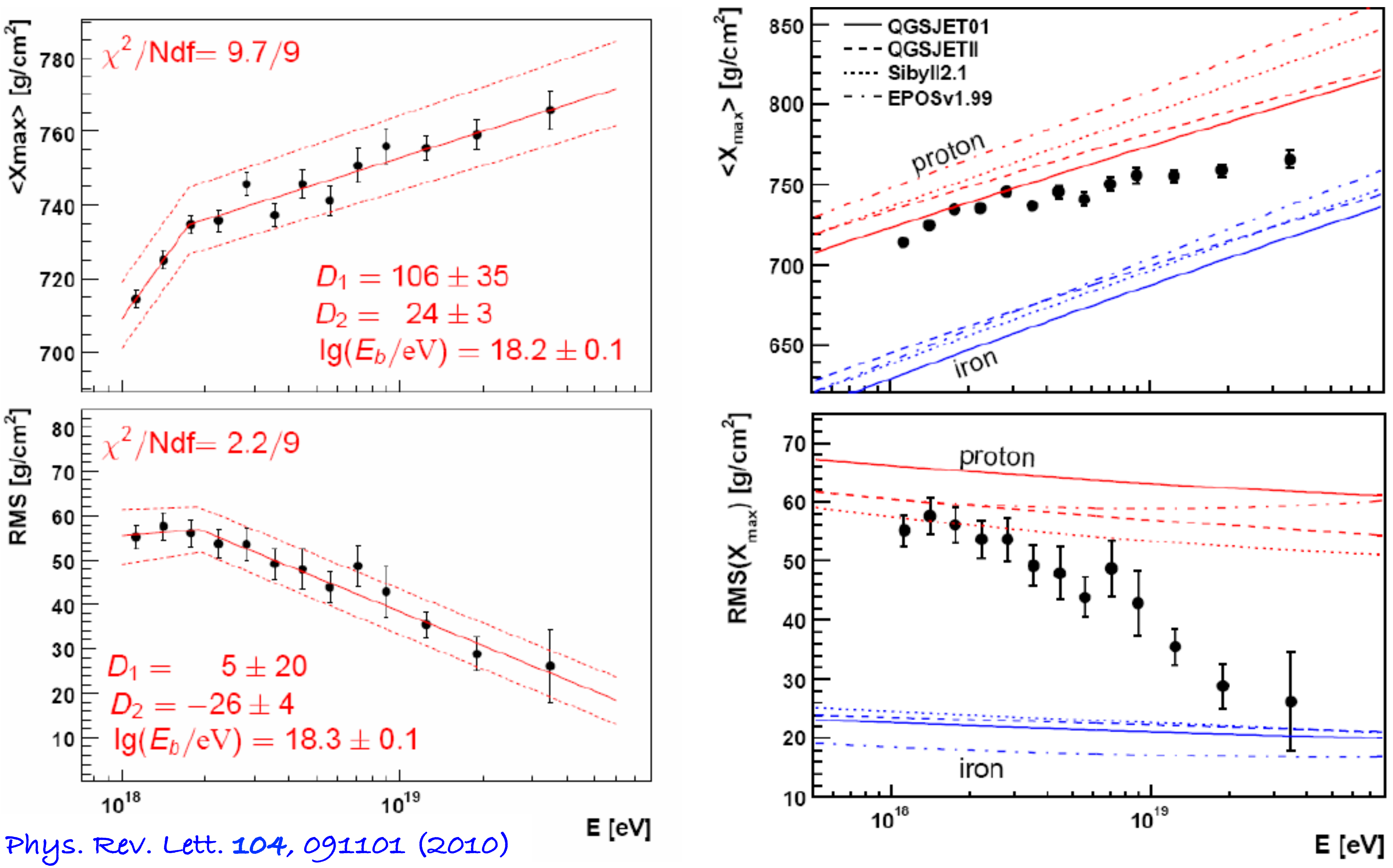


Mass composition

Mass Composition

- UHECR: observatories detect induced showers in the atmosphere
- Nature of primary: look for differences in the shower development
- Showers from **heavier** nuclei develop **earlier** in the atm with **smaller** fluctuations
- They reach their maximum development higher in the atmosphere (lower cumulated grammage, X_{max})
- X_{max} is increasing with energy (more energetic showers can develop longer before being quenched by atmospheric losses)

Mass Composition



Phys. Rev. Lett. 104, 091101 (2010)

pp Cross Section

pp Cross section (Phys. Rev. Lett. 109, 062002 (2012))

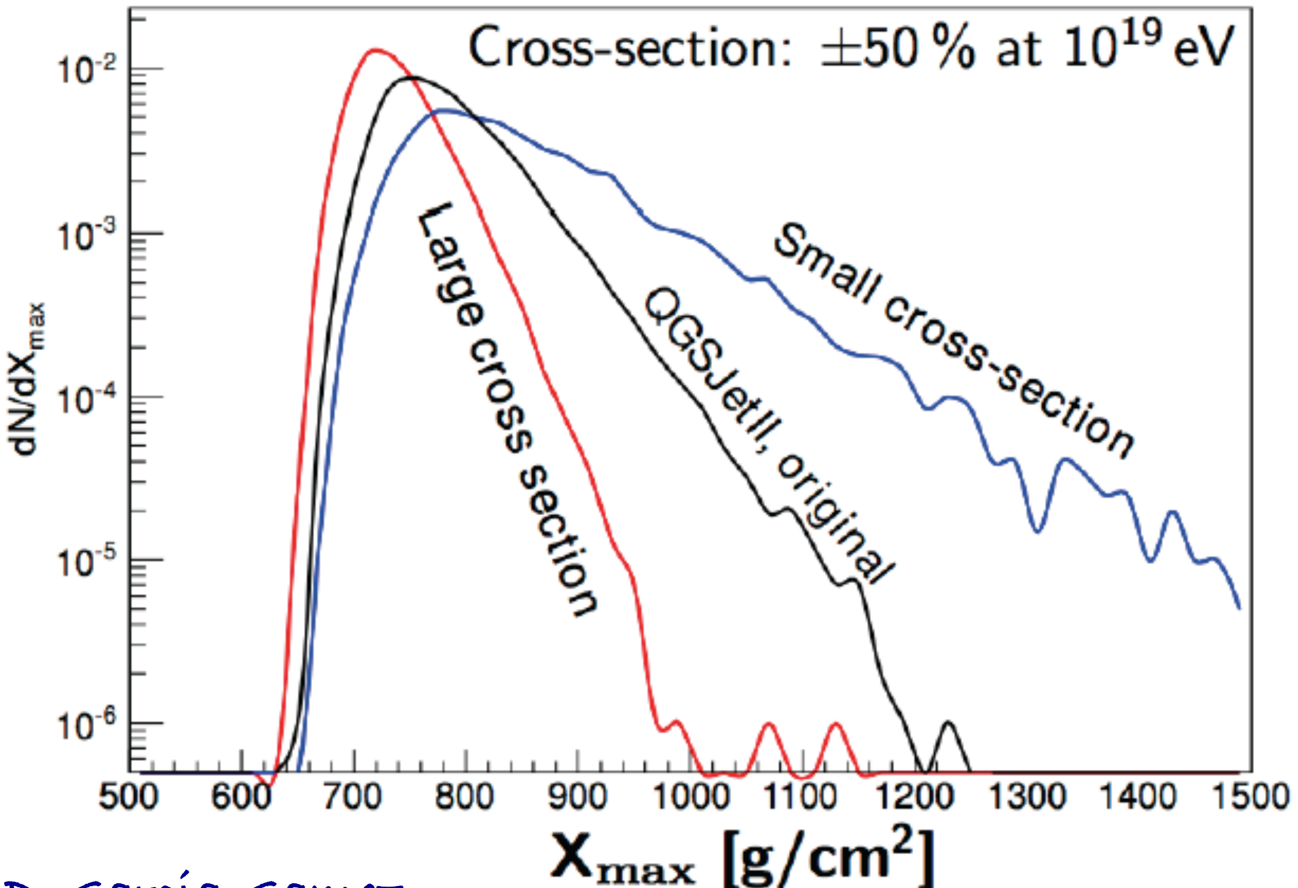
- First analysis of p-air cross section
- Restrict energy to region 10^{18} to $10^{18.5}$ eV
- Average cms. energy 57 TeV
- This region substantial fraction of the osmic rays behave as protons

- Define observable Λ_η (exponential shape of the tail of the X_{max} distribution:

$$dN / dX_{\max} \propto \exp\left(-X_{\max} / \Lambda_{\eta}\right)$$

pp Cross section (Phys. Rev. Lett. 109, 062002 (2012))

X_{max}-tail method:

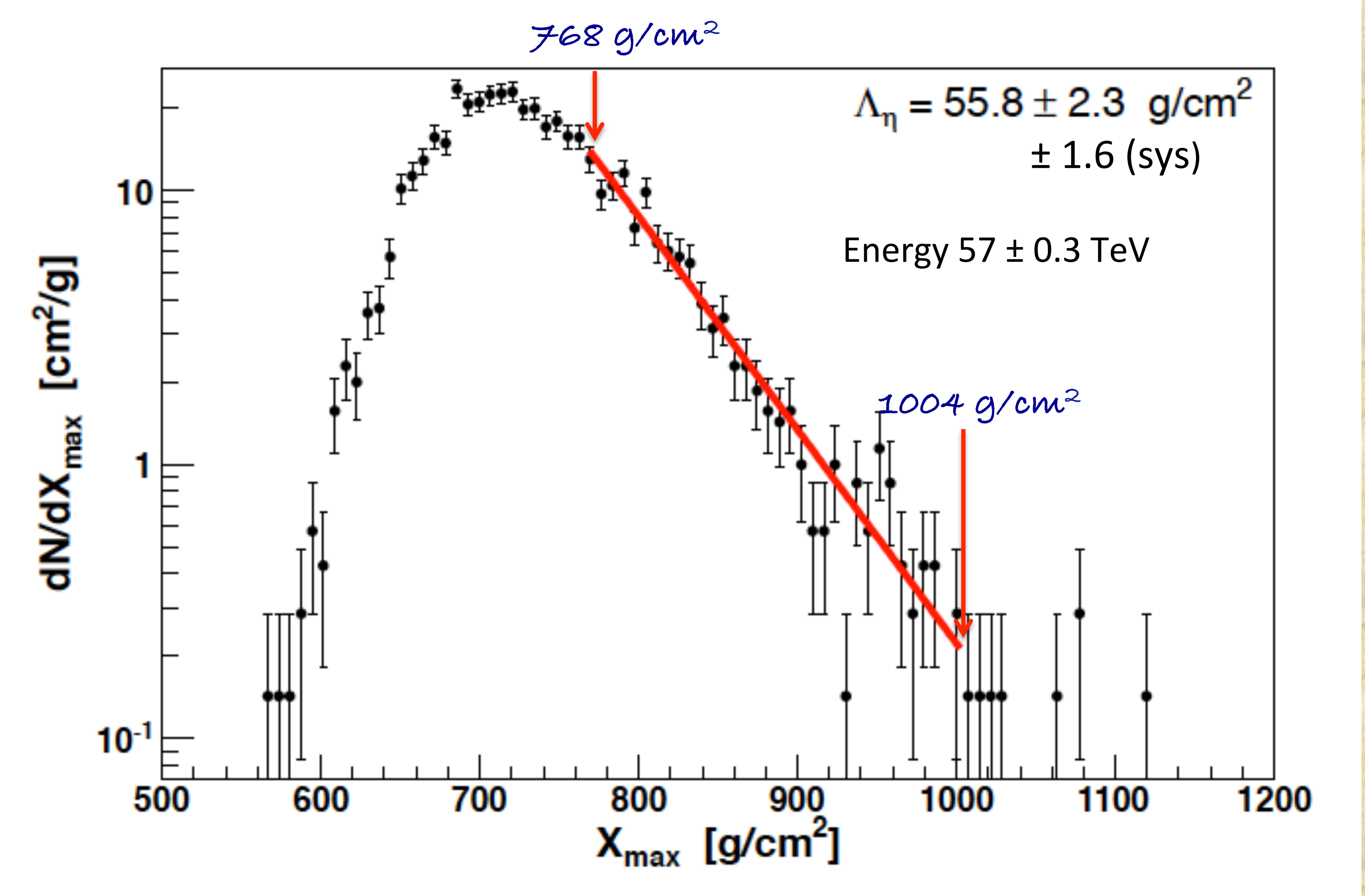


D. Garcia-Gamez

$$\frac{dN}{dX_{max}} \propto \exp\left(\frac{X_{max}}{\Lambda_\eta}\right)$$

the tail of the X_{max} distribution is sensitive to the proton-air cross section

Unbiased X_{max} distribution



pp Cross section

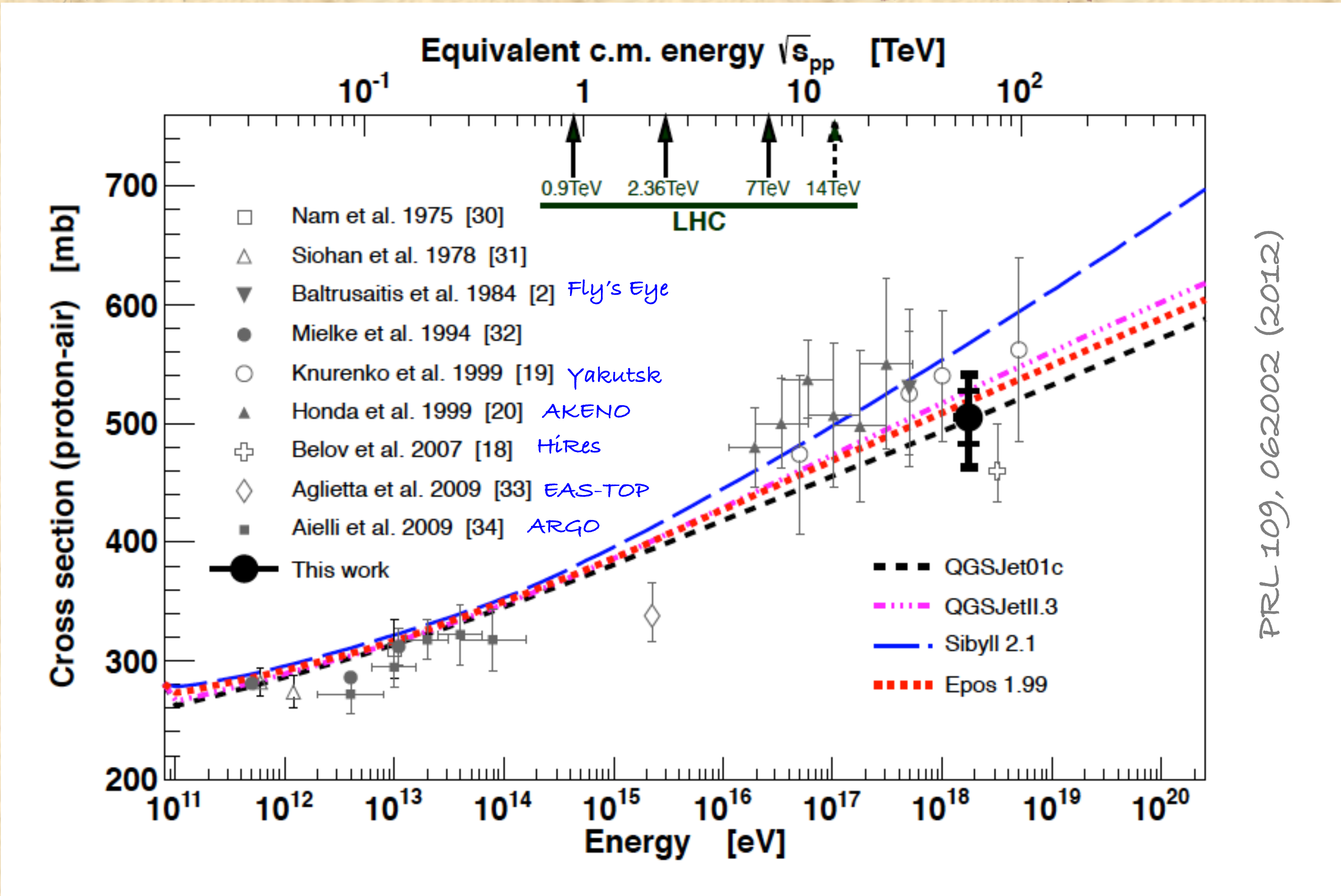
- To convert Λ_η into a cross section have to rely on simulation
- Correct cross sections by an energy dependent factor:

$$f\left(E, f_{19}\right) = 1 + \left(f_{19} - 1\right) \frac{\lg\left(E / 10^{15} eV\right)}{\lg\left(10^{19} eV / 10^{15} eV\right)}$$

- For each hadronic interaction model, f19 is obtained that reproduces the measured value of Λ_η

- Use hadronic interactions models:
    - QGSJet01 (523.7 mb),
    - QGSJetII.3 (502.9 mb),
    - SIBYLL 2.1 (496.7 mb),
    - EPOS 1.99 (497.7 mb)

pp Cross section



PRL 109, 062002 (2012)

pp Cross section

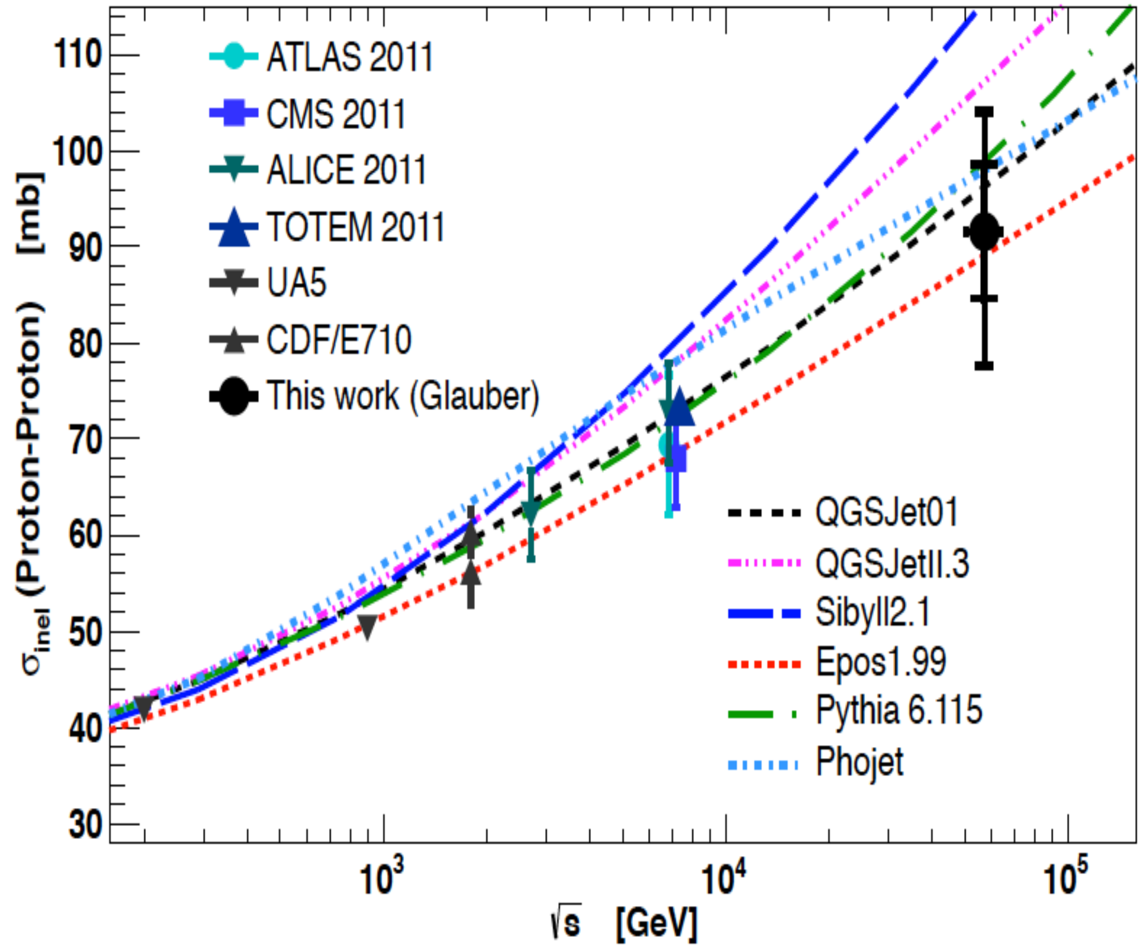
TABLE I: Summary of the systematic uncertainties.

Description	Impact on $\sigma_{p\text{-air}}^{\text{prod}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma_{p\text{-air}}^{\text{prod}}$	± 7 mb
Photons, $<0.5\,\%$	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb

$$\sigma_{p\text{-air}}^{\text{prod}} = \left[505 \pm 22(\text{stat})\ ^{+28}_{-36}(\text{sys})\right]\ \text{mb}$$

pp Cross section

PRL 109, 062002 (2012)



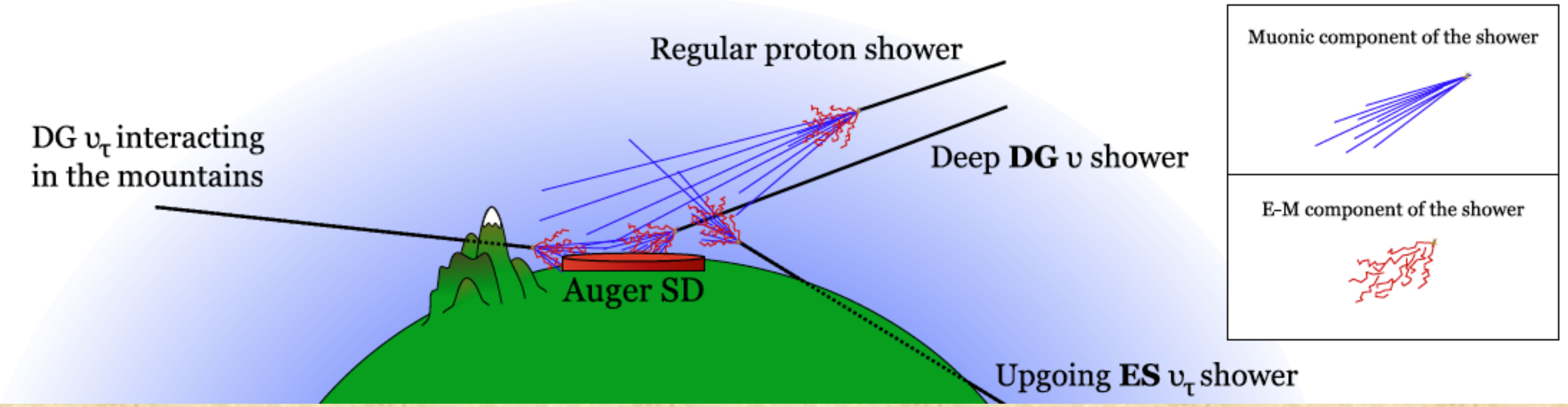
Use Glauber model to extract inelastic and total cross section

$$\sigma_{pp}^{\mathrm{inel}} = [92 \pm 7(\mathrm{stat})\ ^{+9}_{-11}(\mathrm{sys}) \pm 7(\mathrm{Glauber})]\ \mathrm{mb},$$

$$\sigma_{pp}^{\mathrm{tot}} = [133 \pm 13(\mathrm{stat})\ ^{+17}_{-20}(\mathrm{sys}) \pm 16(\mathrm{Glauber})]\ \mathrm{mb}.$$

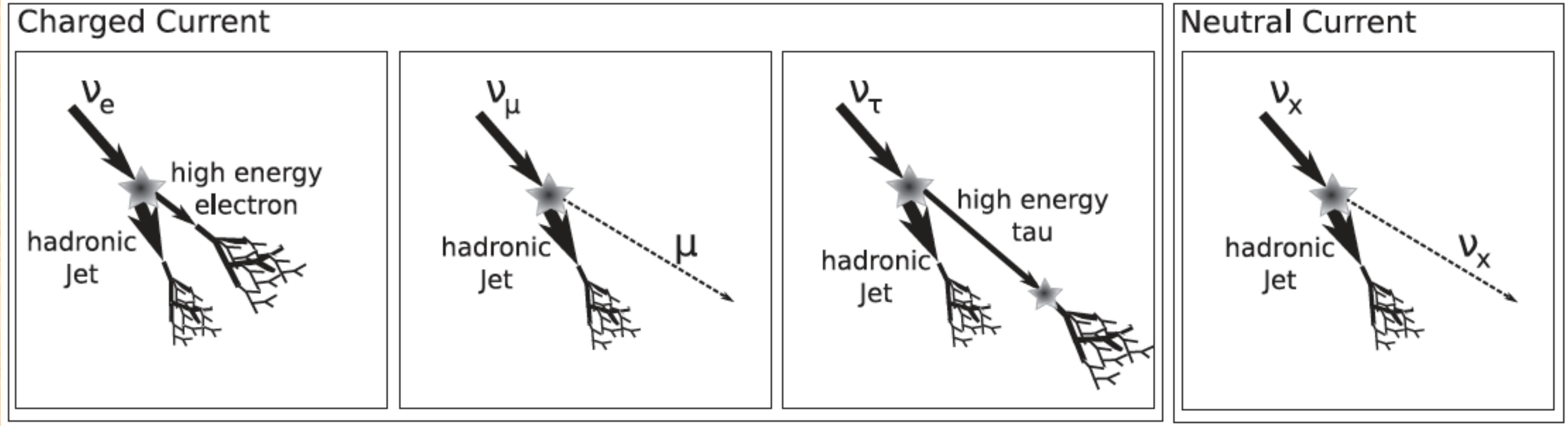
Neutrinos and Photons

Neutrinos



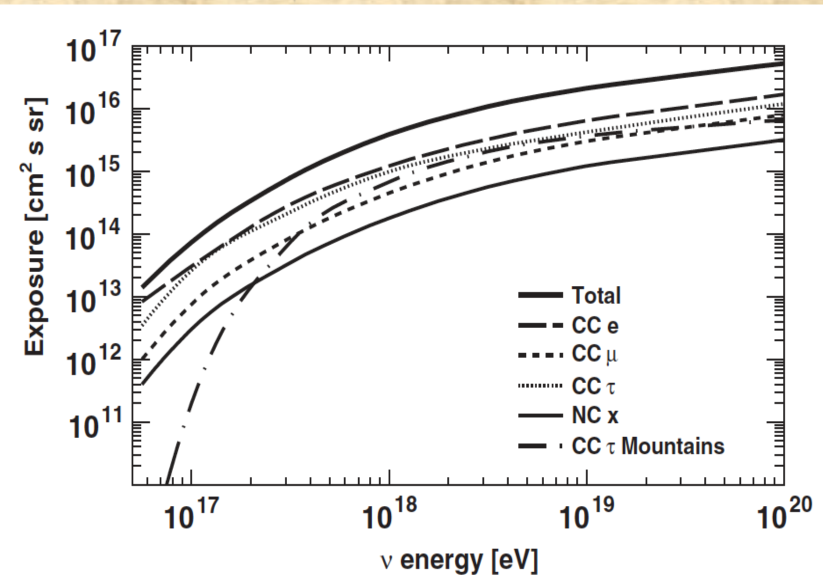
Types of atmospheric showers induced by neutrinos

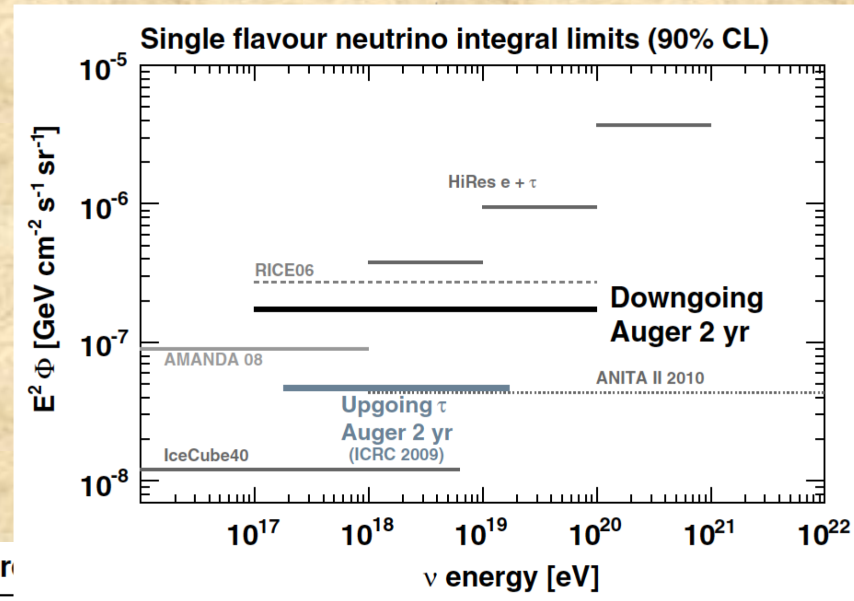
Auger, PRD84, 122005 (2011)

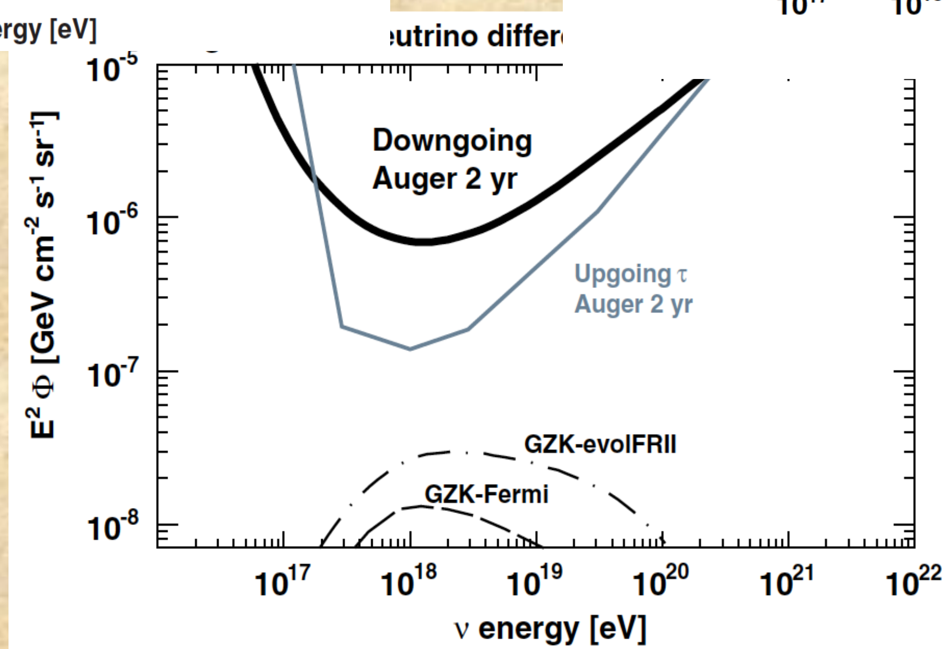


Neutrinos

Auger, PRD84, 122005 (2011)

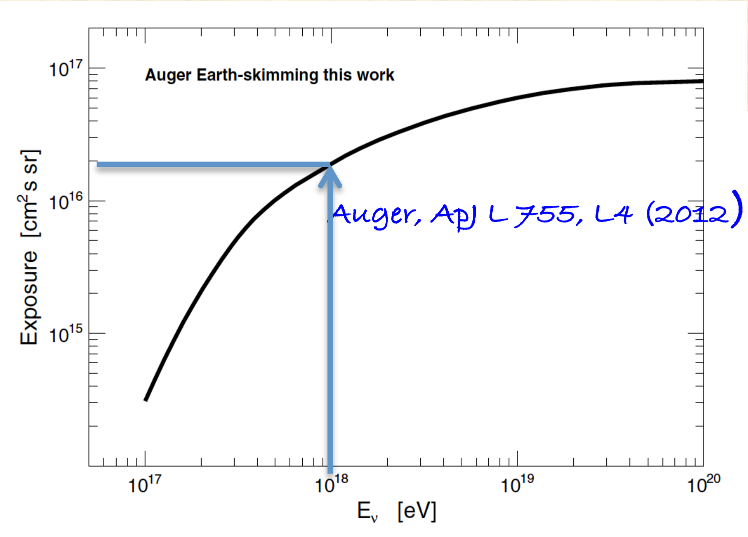


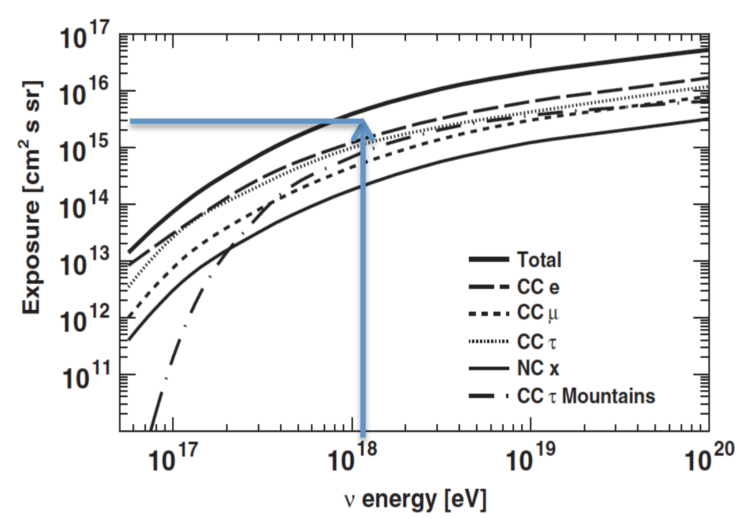


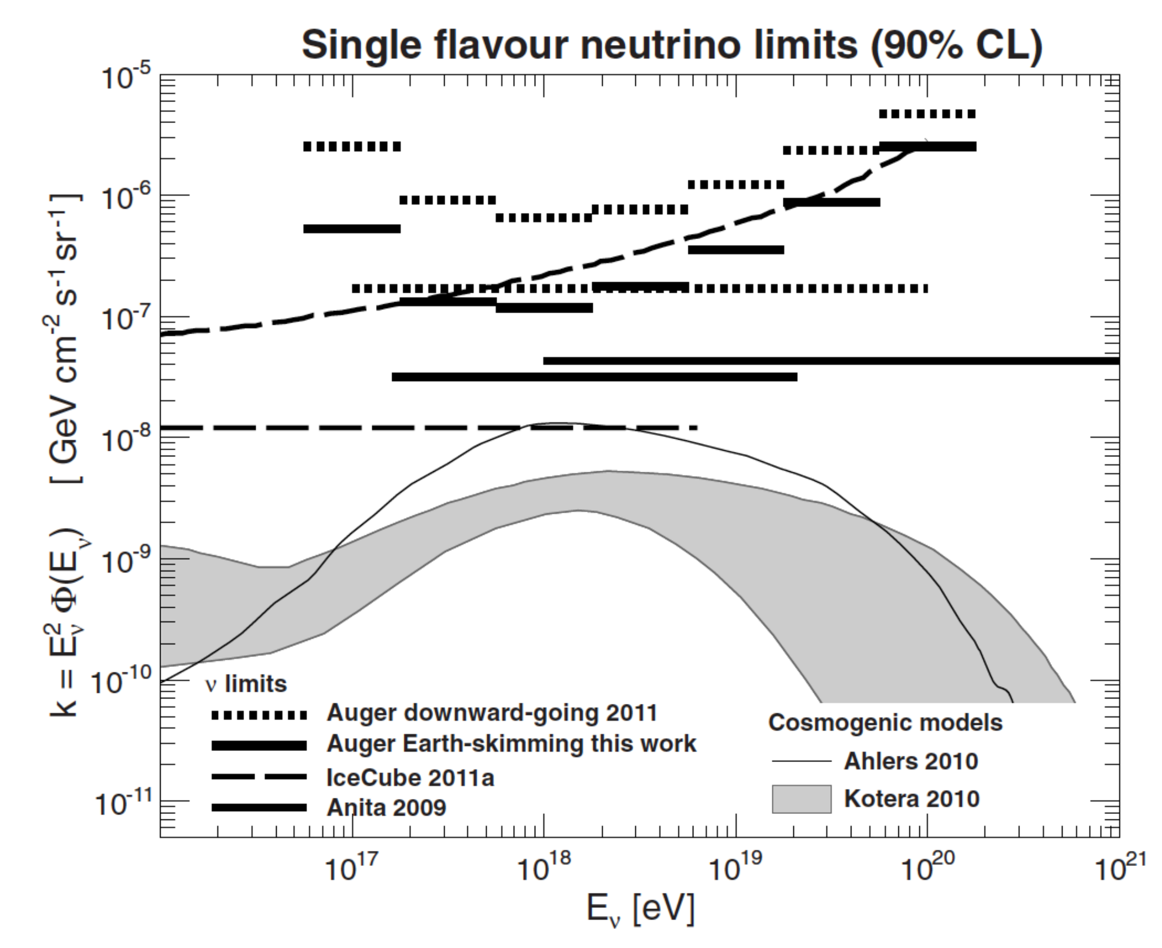


Neutrinos

Auger, ApJ L 755, L4 (2012)

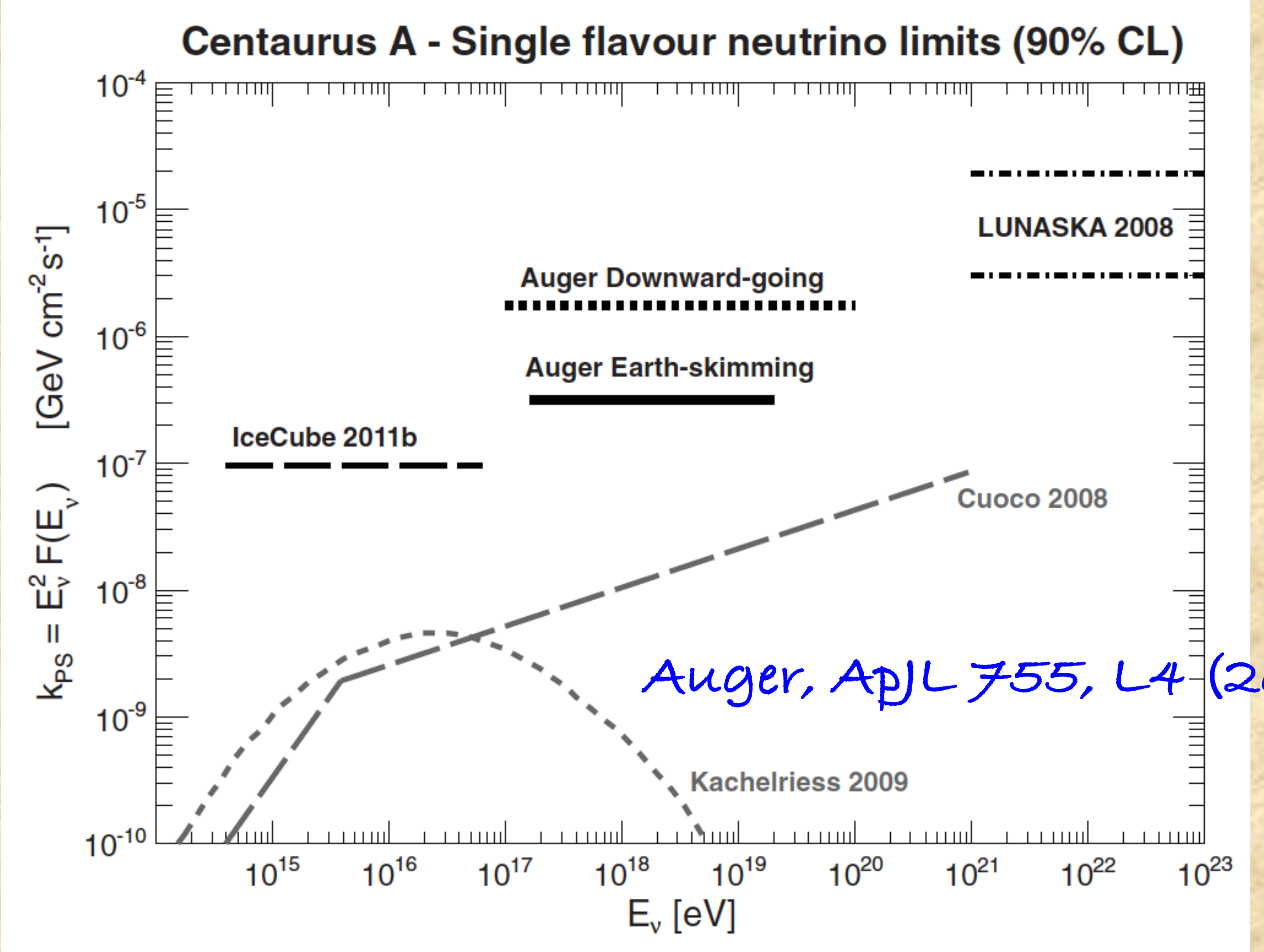






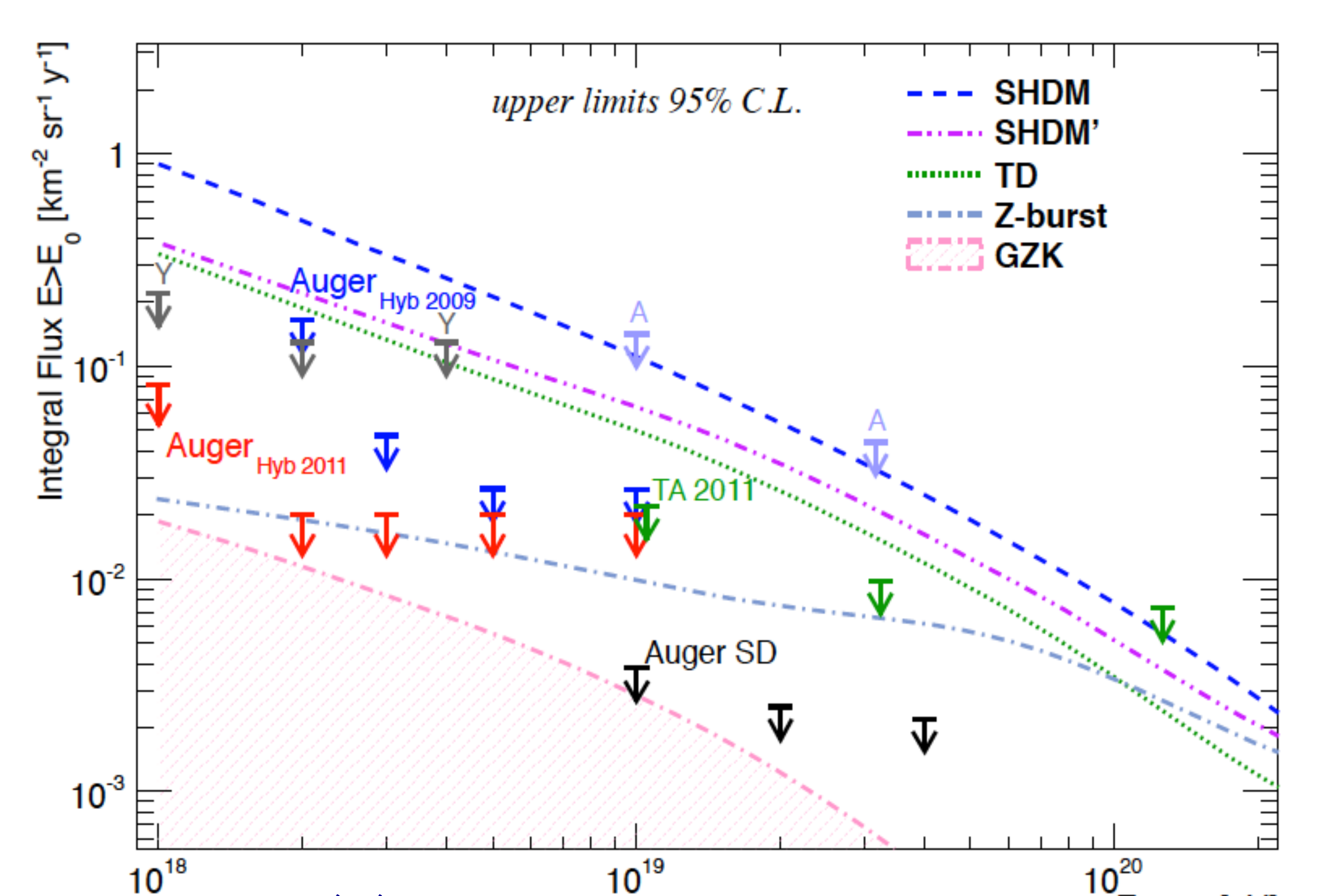
Neutrinos

Upper limit on single flavour $E^{-2}{}_{\nu}$ from AGN Centaurus A



Auger, ApJL 755, L4 (2012)

Photons update

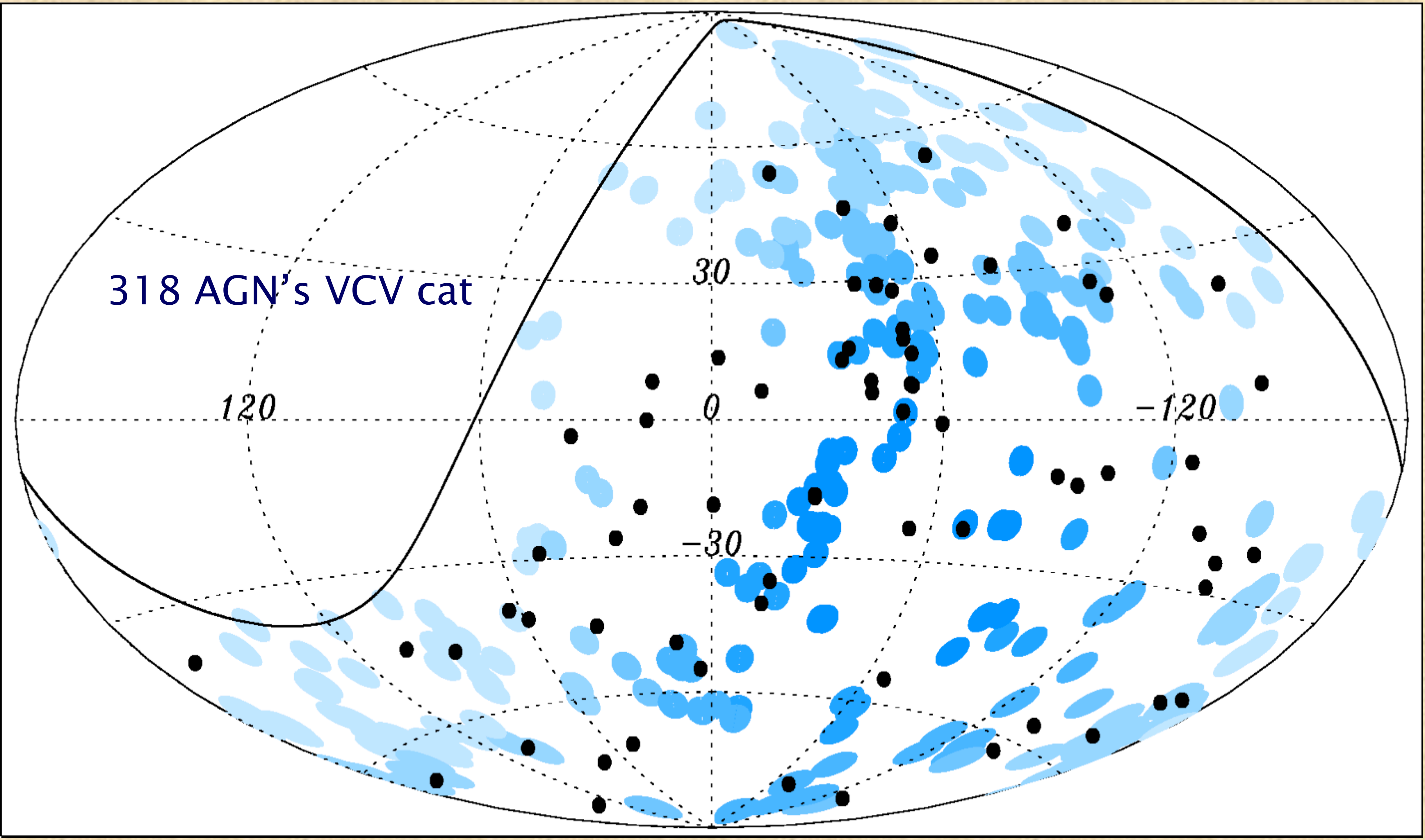


Scherini, uhecr 2012

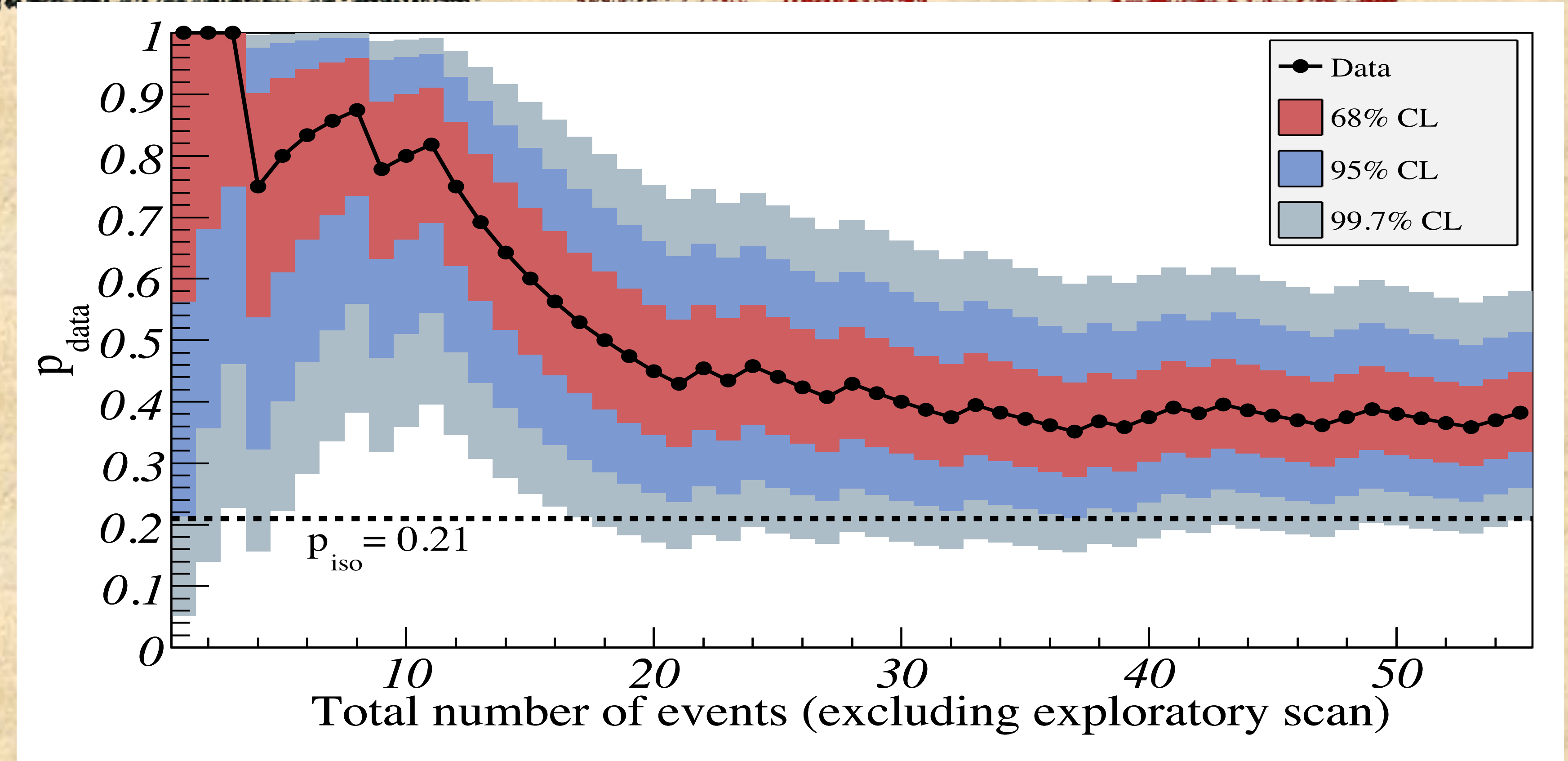
Anisotropy

Anysotropy (AstroPart. Physics 34, 314 (2010))

69 events with E ≥ 55 EeV (up to 31 Dec 2009)



Anysotropy: Astrop. Phys 34, 314 (2010)



$$P(p|N,k) = \frac{\Gamma(N+2)}{\Gamma(k+1)\Gamma(N-k+1)} p^k (1-p)^{N-k}$$

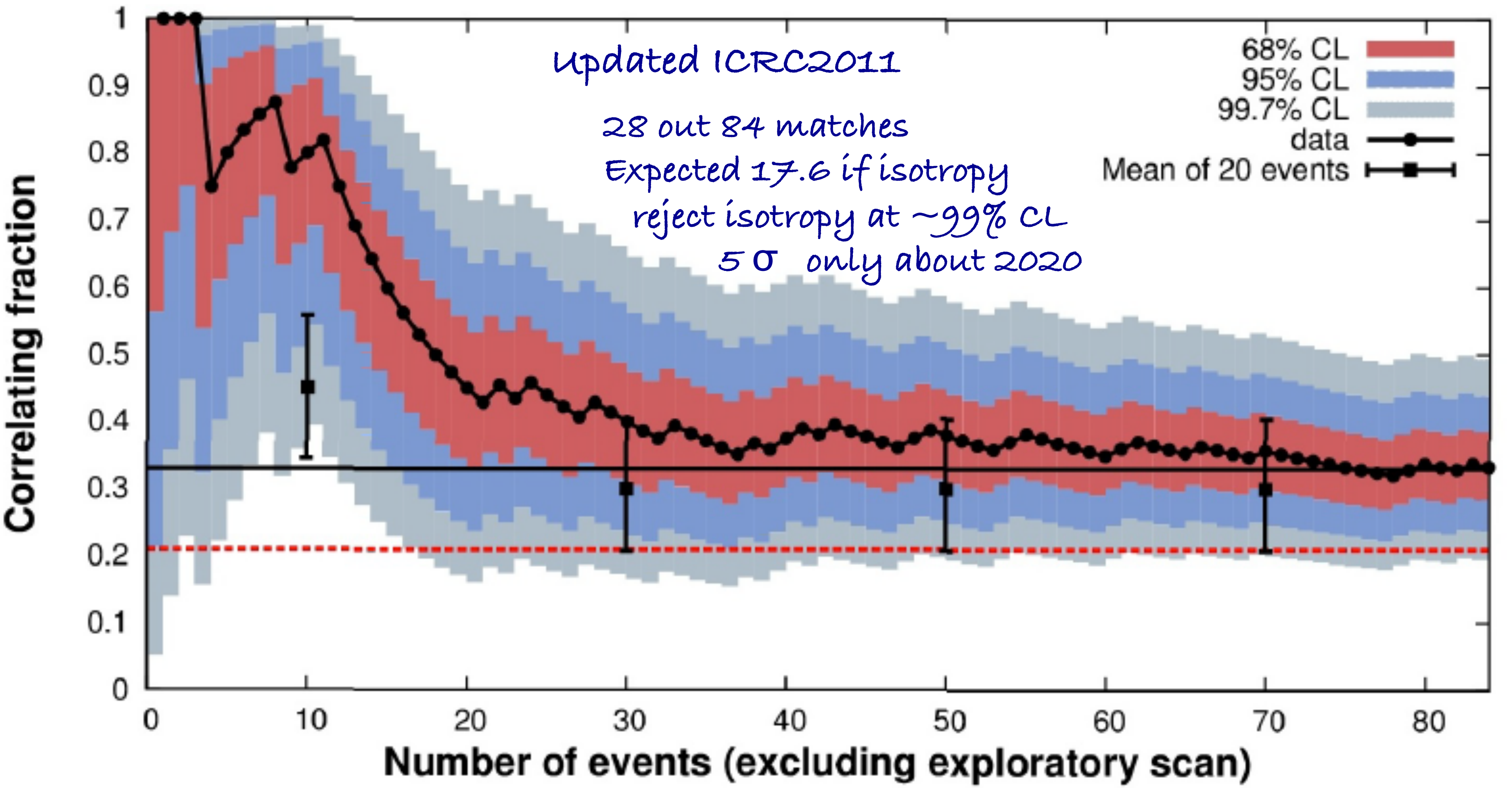
Isotropy of UHECR rejected at 99% CL

Correlation reduced from ~70% to ~40%

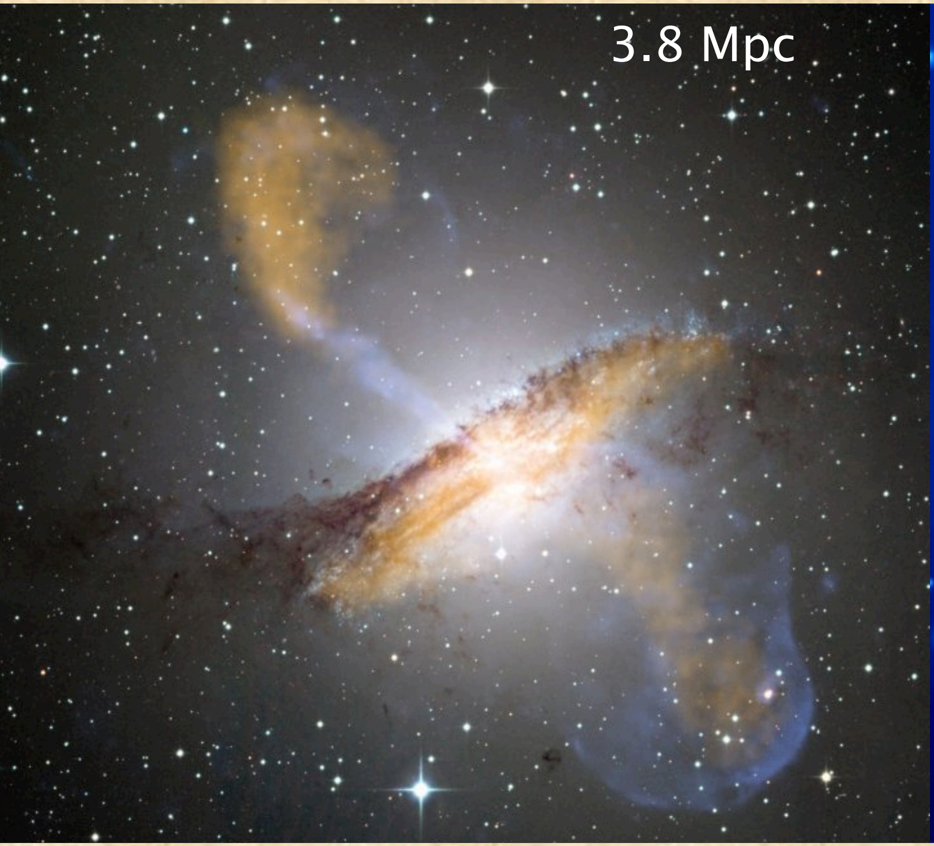
Stabilizing around ~40%

Posterior probability distribution for p (strength)

Anysotropy

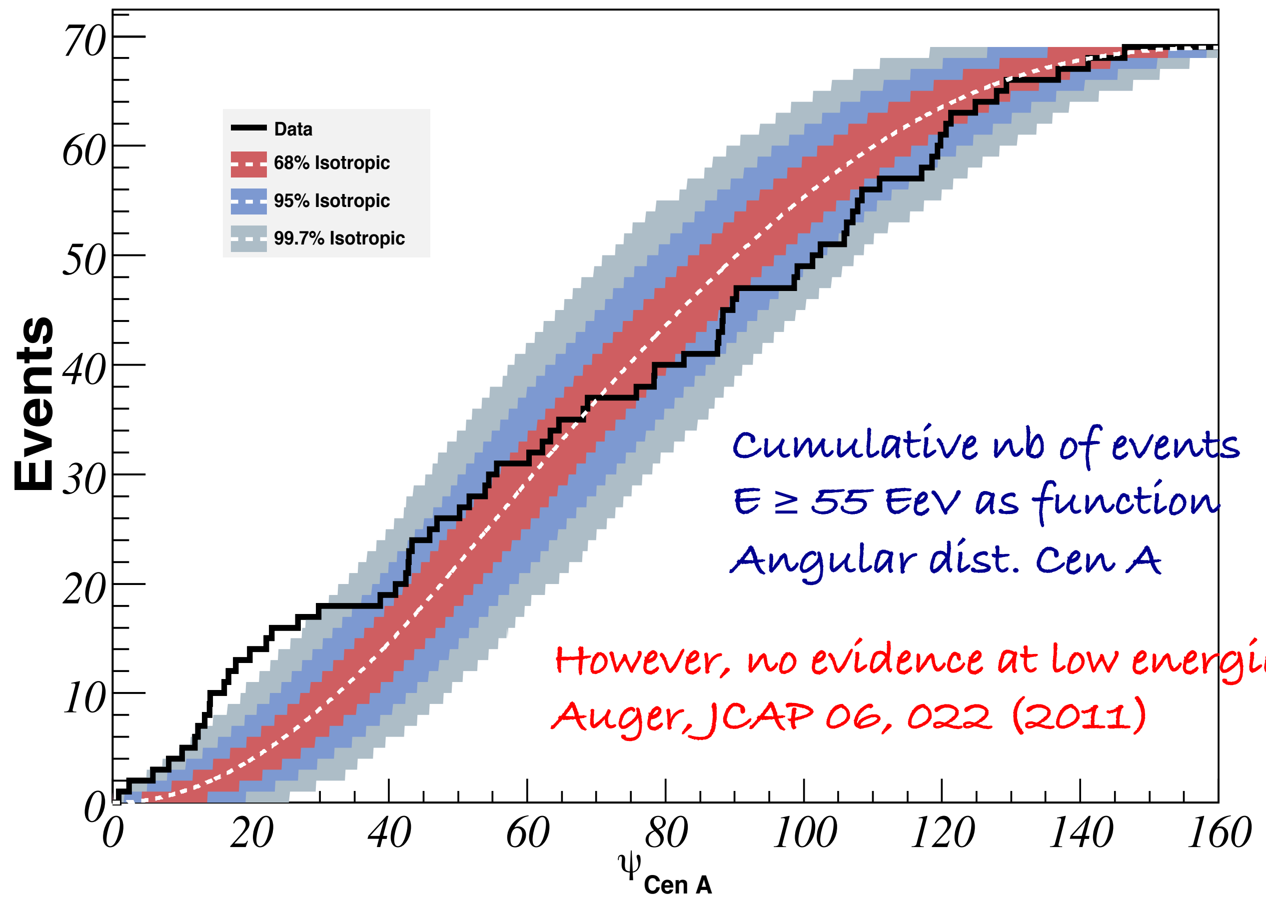

Updated ICRC2011
28 out 84 matches
Expected 17.6 if isotropy
reject isotropy at ~99% CL
5 σ only about 2020
68% CL
95% CL
99.7% CL
data
Mean of 20 events
Correlating fraction
Number of events (excluding exploratory scan)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80

Centaurus A (NGC 5128)



Centaurus A

- Centaurus A: closest AGN (3.8 Mpc)
- Central nuclous of this AGN is seen by HESS and FERMI-LAT
- Extensive radio galaxy ~ 5°×9°



Cumulative nb of events $E \geq 55$ EeV as function Angular dist. Cen A

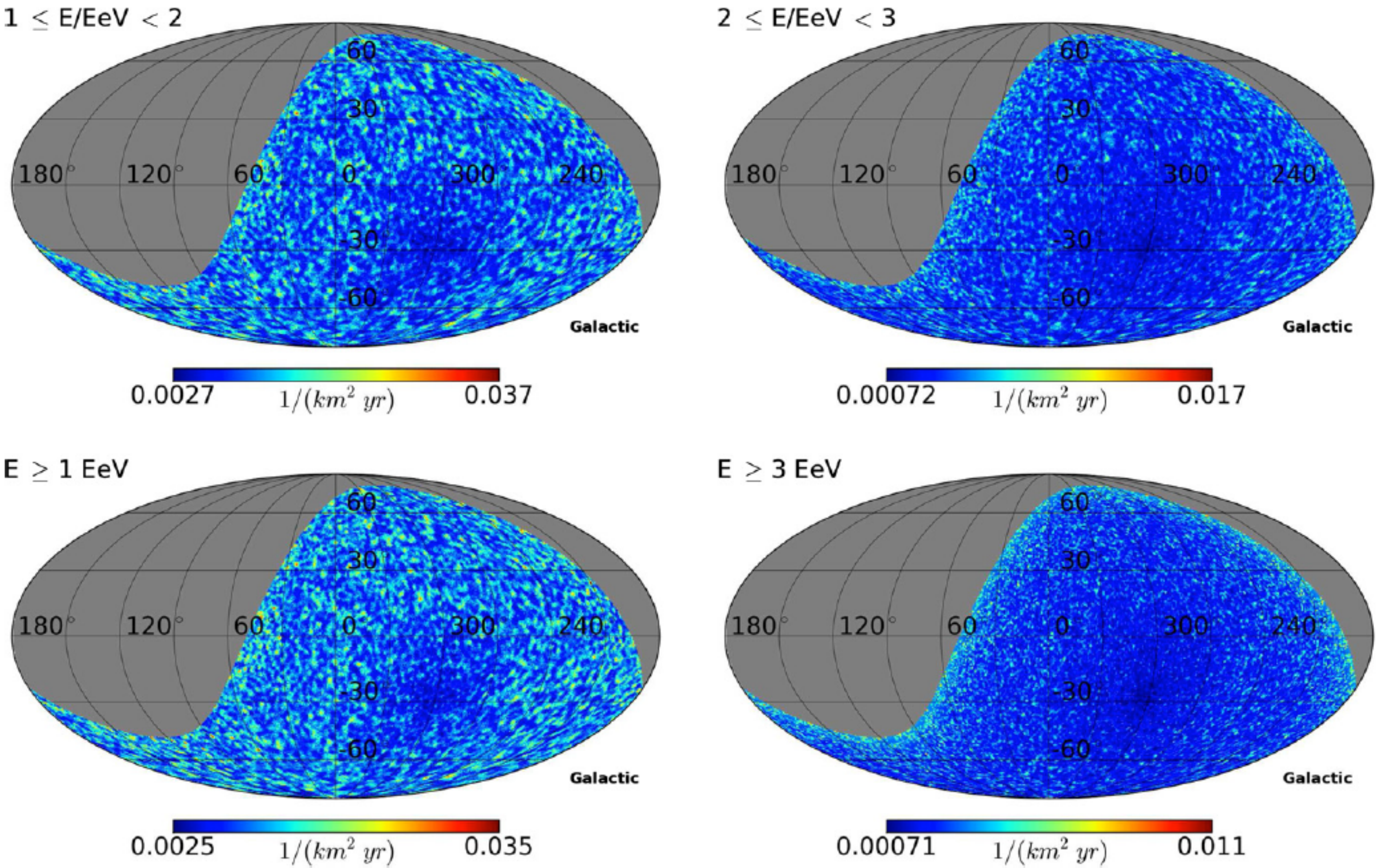
However, no evidence at low energies Auger, JCAP 06, 022 (2011)

Neutron Point Sources

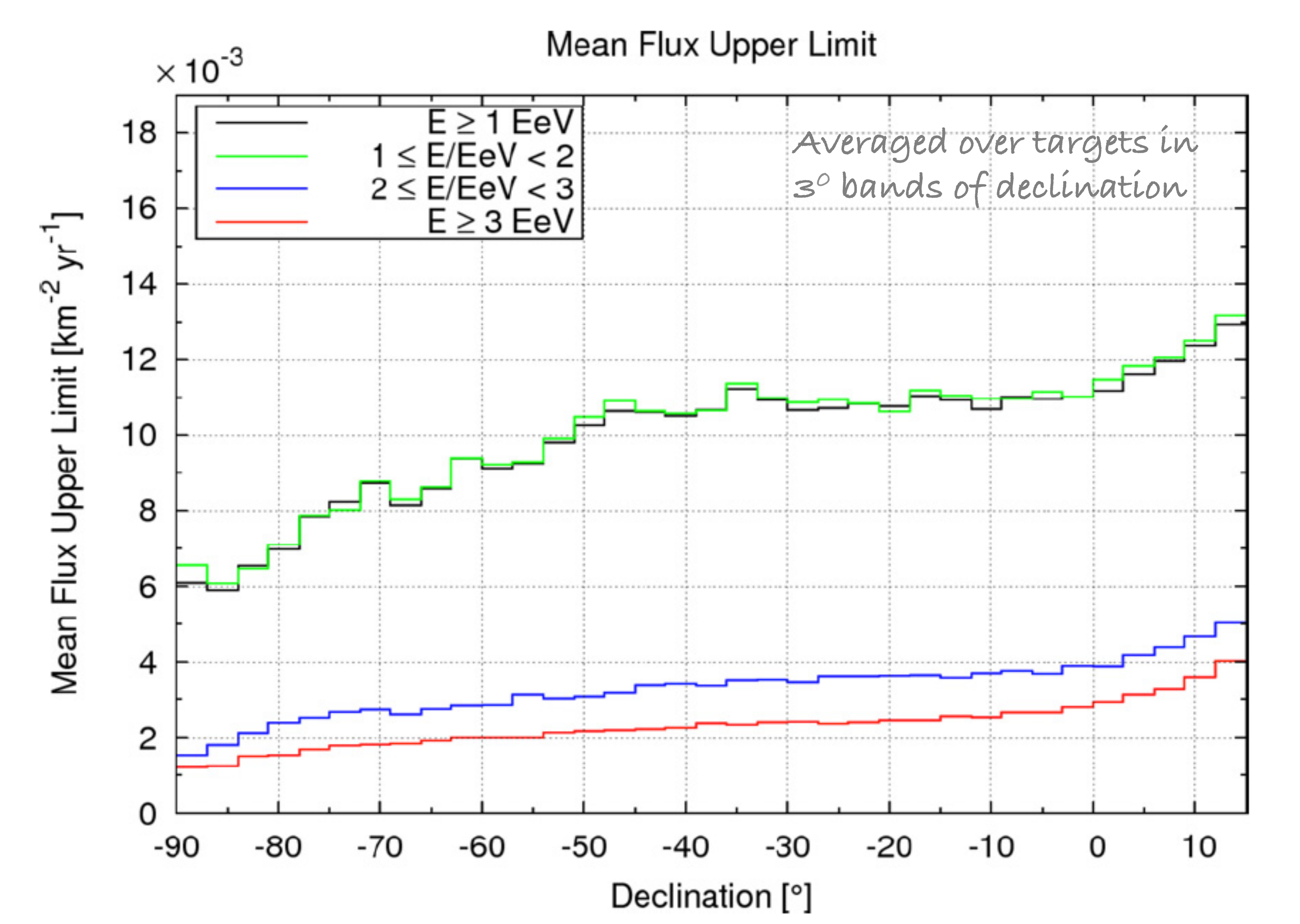
Neutrons point sources

- Neutrons are undeflected by galactic magnetic fields
- Flux of neutrons from discrete source would cause an excess of cr events in the direction of the source
- EeV neutron emitted by Galactic center could be seen
- 2 EeV neutrons from anywhere in the Galaxy can be seen
- Flux of gammas rays from some sources in the galaxy, could be associated to neutron fluxes detectable by Auger
- Select SD events with $\theta \leq 60^{0}$, good event reconstruction
- Exposure of 24,880 km^2 sr yr, with 429,138 events with energy ≥ 1 EeV
- Energy is the same as for the spectrum

Neutrons point sources



Neutrons point sources (upper limits)



Muon Shower content

Muon shower content

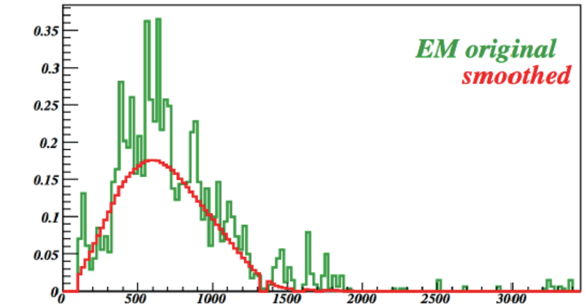
Measure Muon shower content by four methods

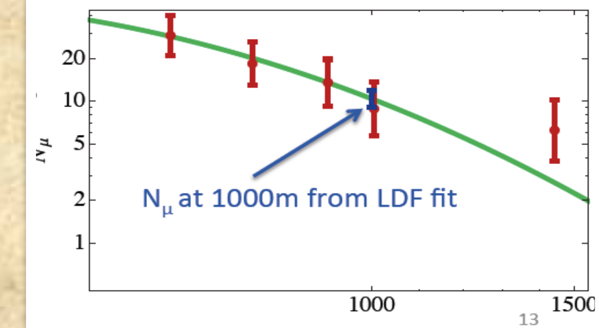
- Smoothing
  - Smoothing filter over traces
  - $S_\mu = S_{tot} - S_{em}$
- Multivariate muon counter
  - Neural Network prediction of N_μ at each tank
- Inclined showers
  - Shower size $N_{19} \propto N_\mu$

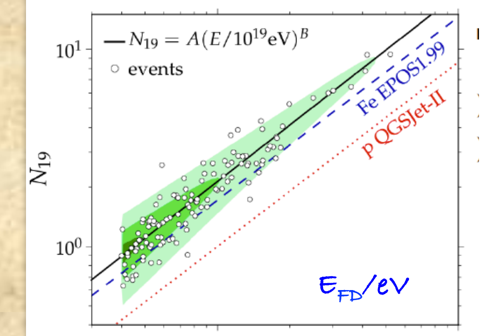
$$\frac{N_\mu^{data}}{N_\mu^{MC}} = \frac{N_{19}^{data}}{N_{19}^{MC}} = \frac{A(E_{FD}/10\,EeV)^B}{A_{MC}(E_{FD}/10\,EeV)^{B_{MC}}}$$

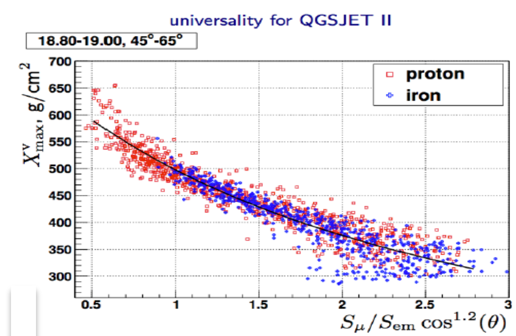
- Shower Universality

$$S_\mu^{fit} = S_{tot} / \left[1 + \cos^\alpha\theta / \left((X^v_{\max}/A)^{1/b} - a\right)\right]$$

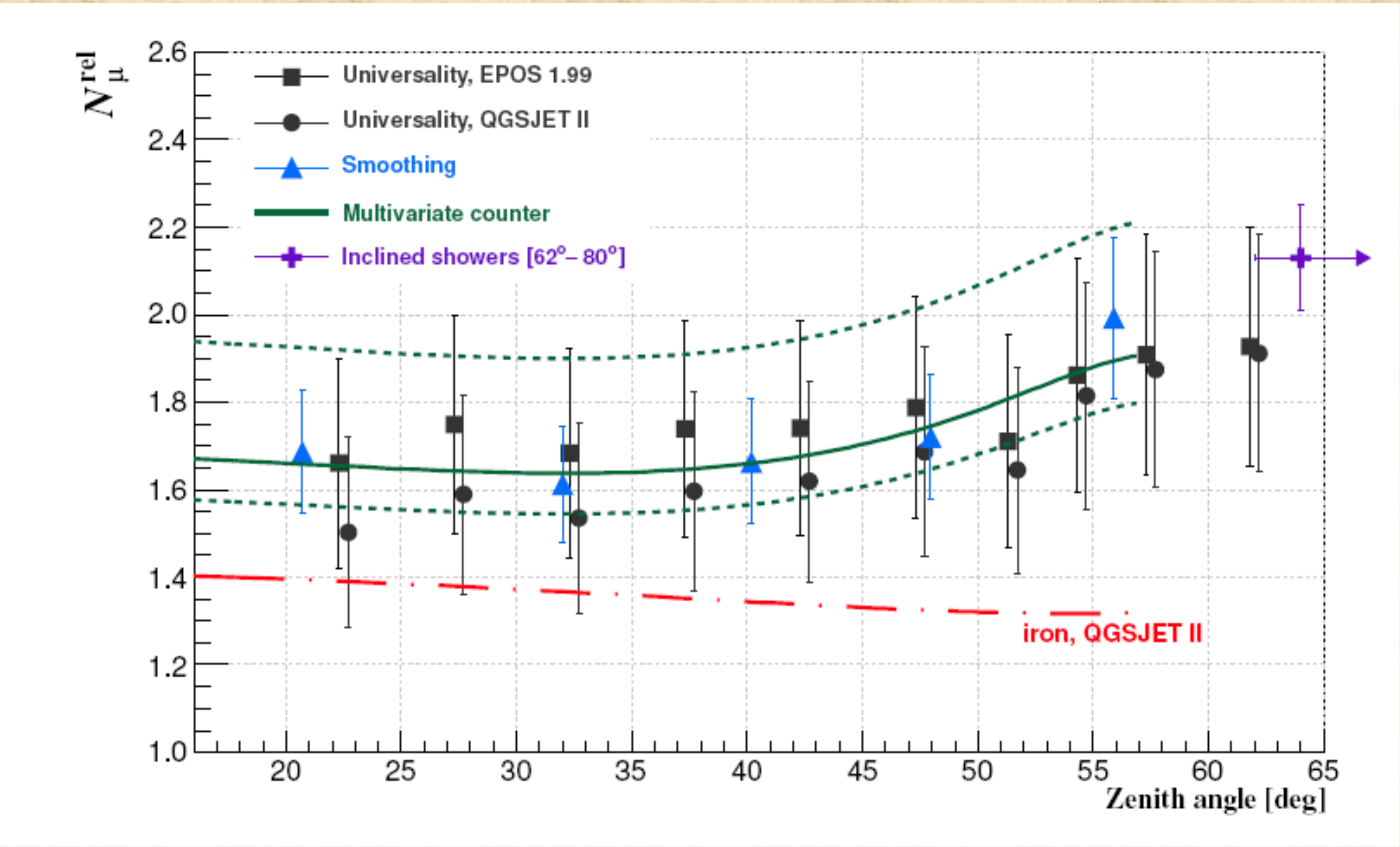








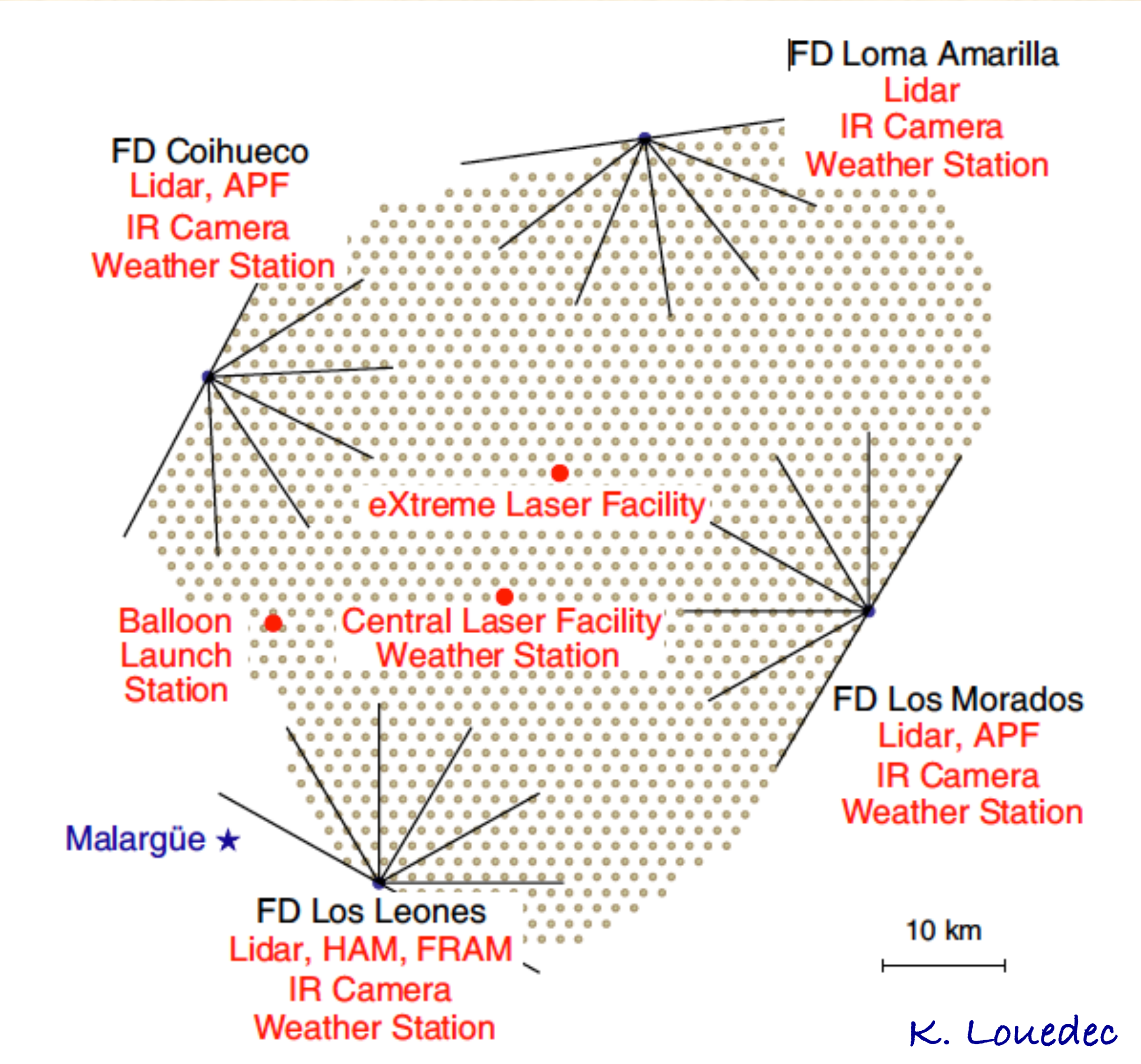
Muons



Auger Upgrades focused on better resulution of muon contents of the showers

Weather station

Atmospheric monitoring and calibration



K. Louedec

Weather station

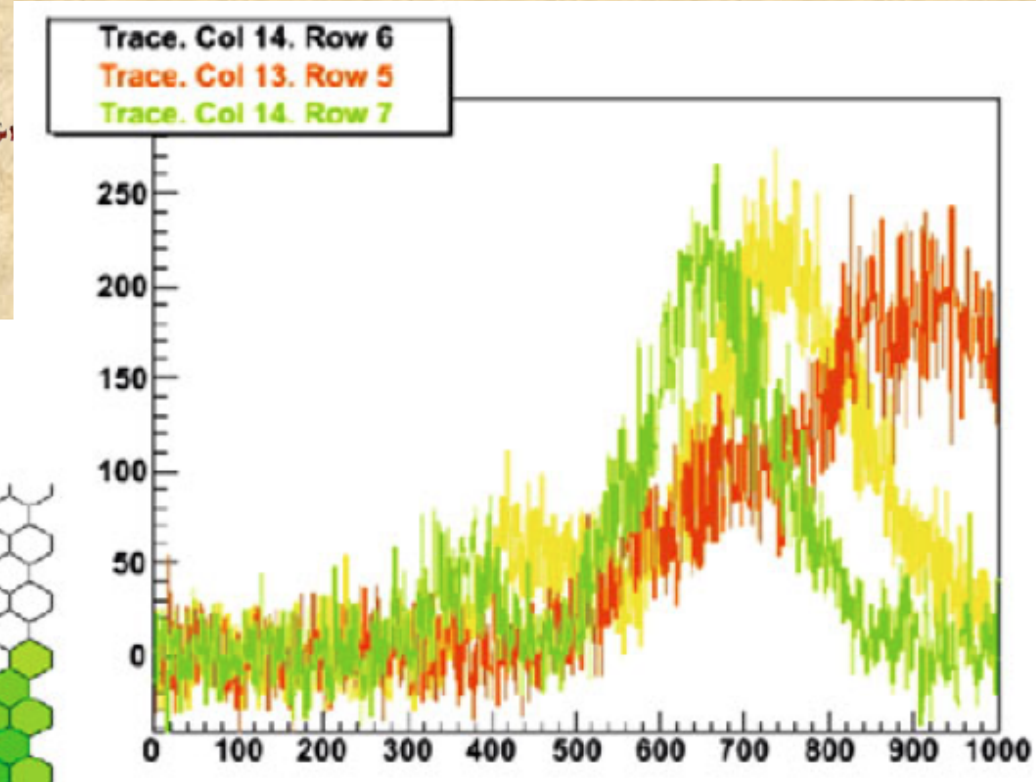
Except for brightest stars and the Milky Way the larges source of UV light is an afterglow which originates at about 80 km height.

ELVES (Emission of Light and Very low frequency pertubations due to Eletromagnetic pulse Sources) are transient events that interest geophysicists. Confined to 80-95 km altitudes and extend up to 600 km, with flashes with last up to 1 ms.

Auger is sensitive to Elves, which occur very far away

Detecting Elves

R. Mussa



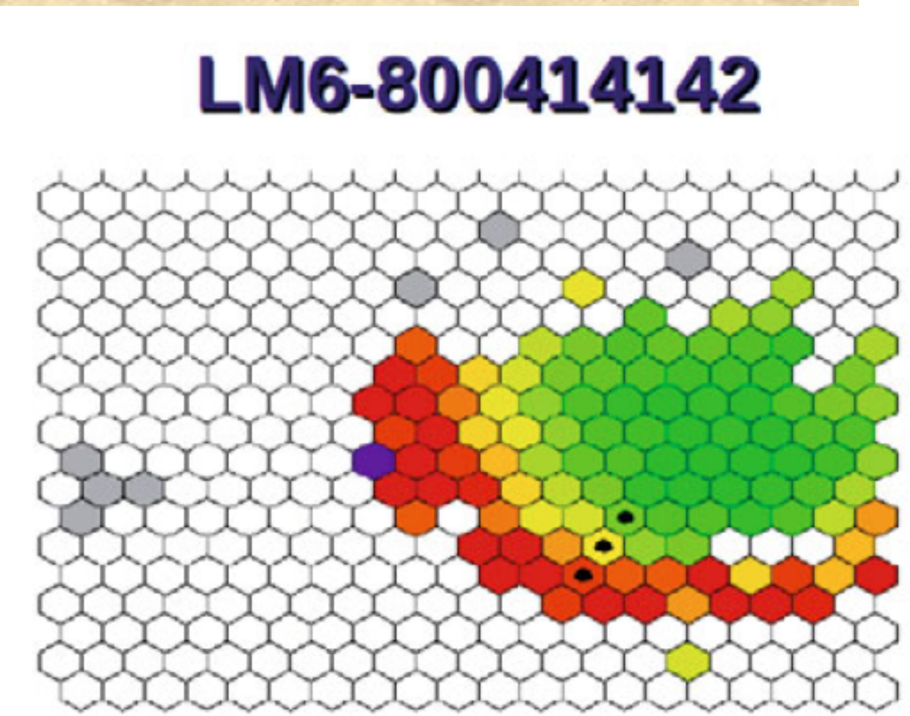
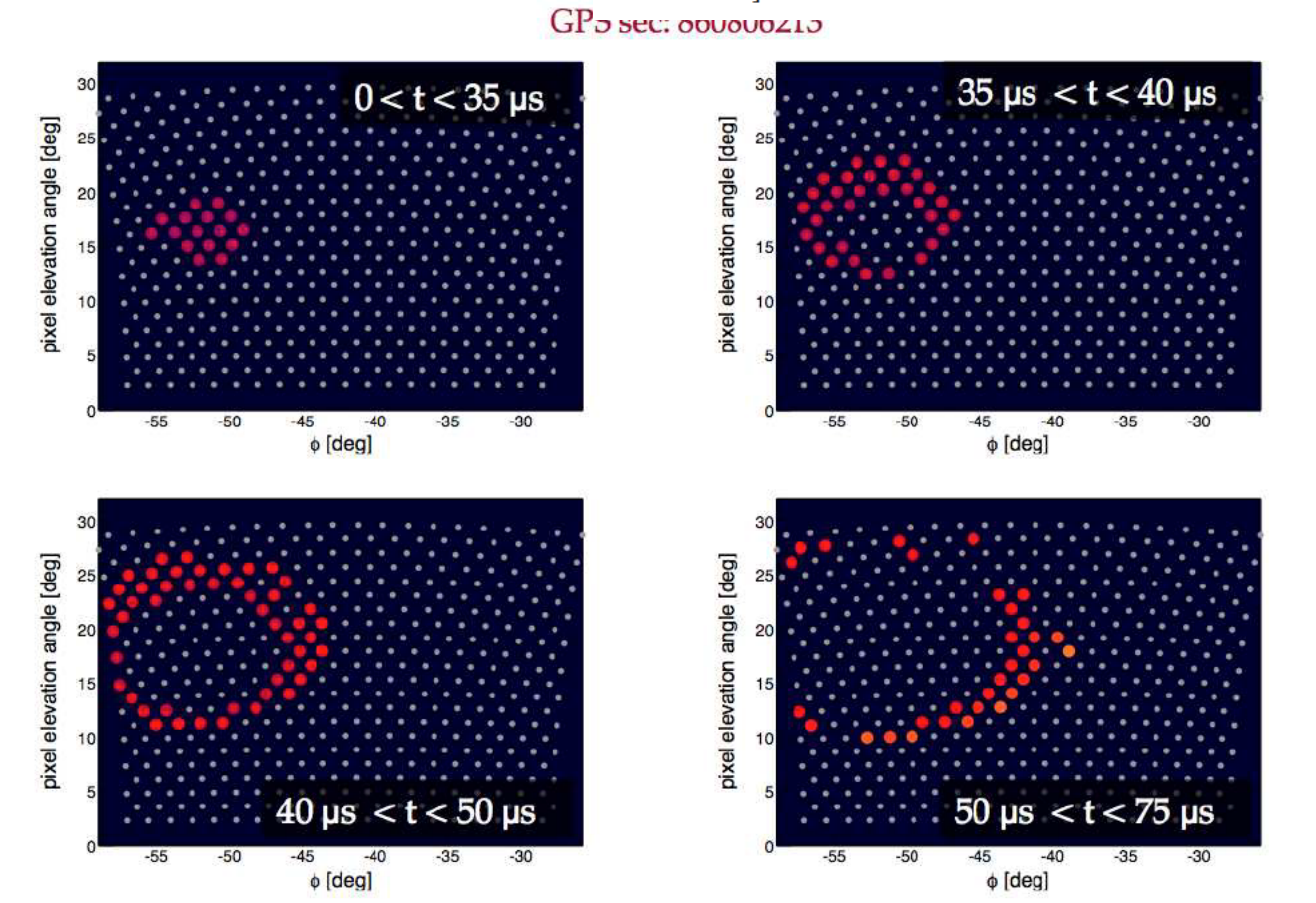


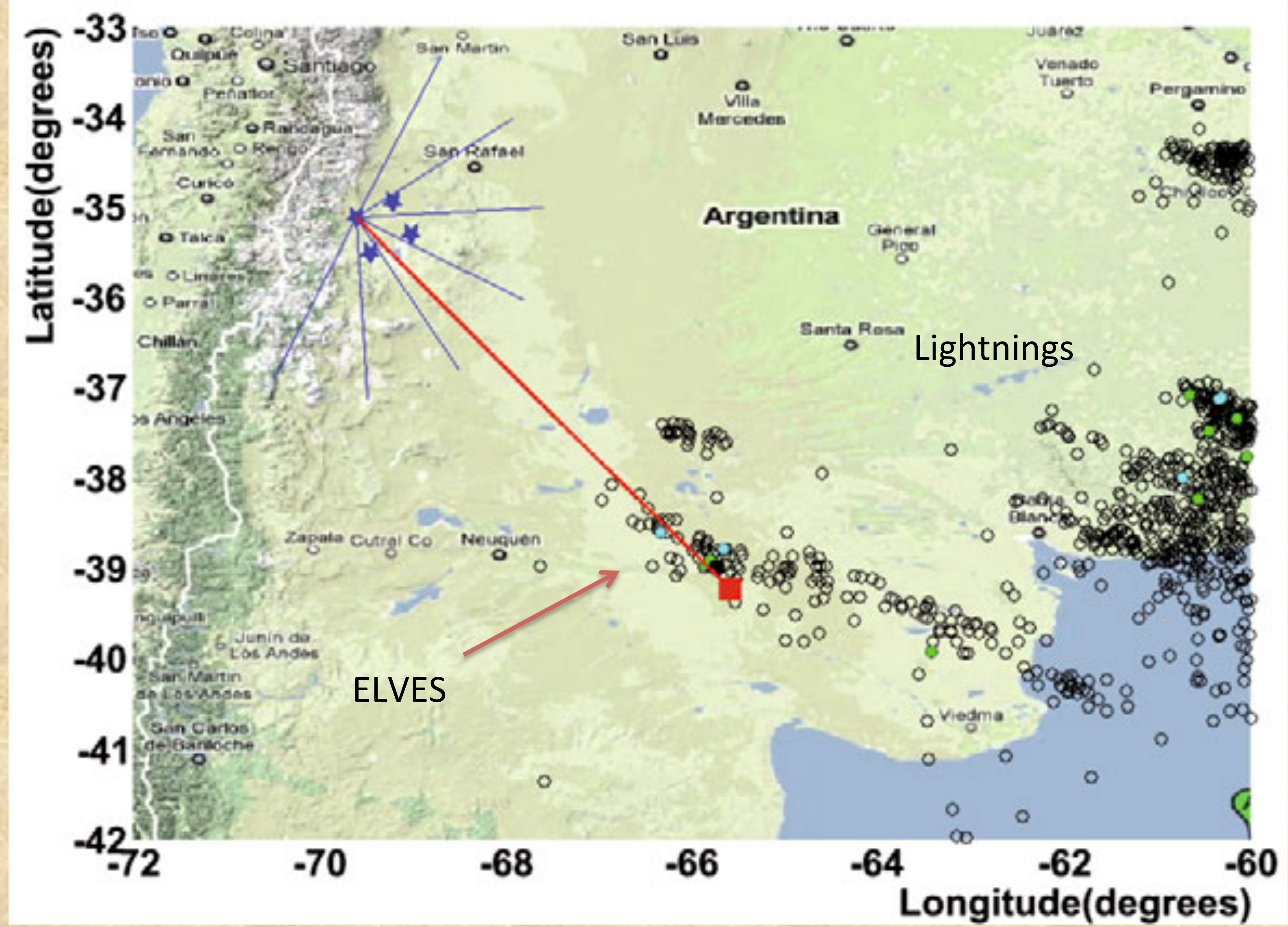
Fig. 1. The first event, observed at GPS time 800414142. Left: triggered pixels in LM-6 (pixel colors indicate the pulse timing: green pixels come earliest, red pixels are the last to fire; grey pixels are discarded in further analyses). Right: the FADC traces for the 3 pixels indicated by black dots in the left plot. Each trace is 1000 bins long, equivalent to 100 μs. Signals are in ADC counts.

Detecting Elves

Figure 13: FD camera image for 4 consecutive time windows as indicated. It shows the time evolution of an elve located at about 80 km altitude at a distance of 580 km from the observatory [29, A. Tonachini].



Detecting Elves



Conclusions

- Auger is a mature experiment at middle life
- Measurement of the spectrum with strong evidence of the GZK effect
- Anisotropy on arrival directions at highest energies
- Evidence for transition of mass composition at higher energies or signal of changing physics
- The muon problem: inconsistency with extrapolation from simulation models set at LHC energies

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