



The Pierre Auger Observatory

Recent results

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

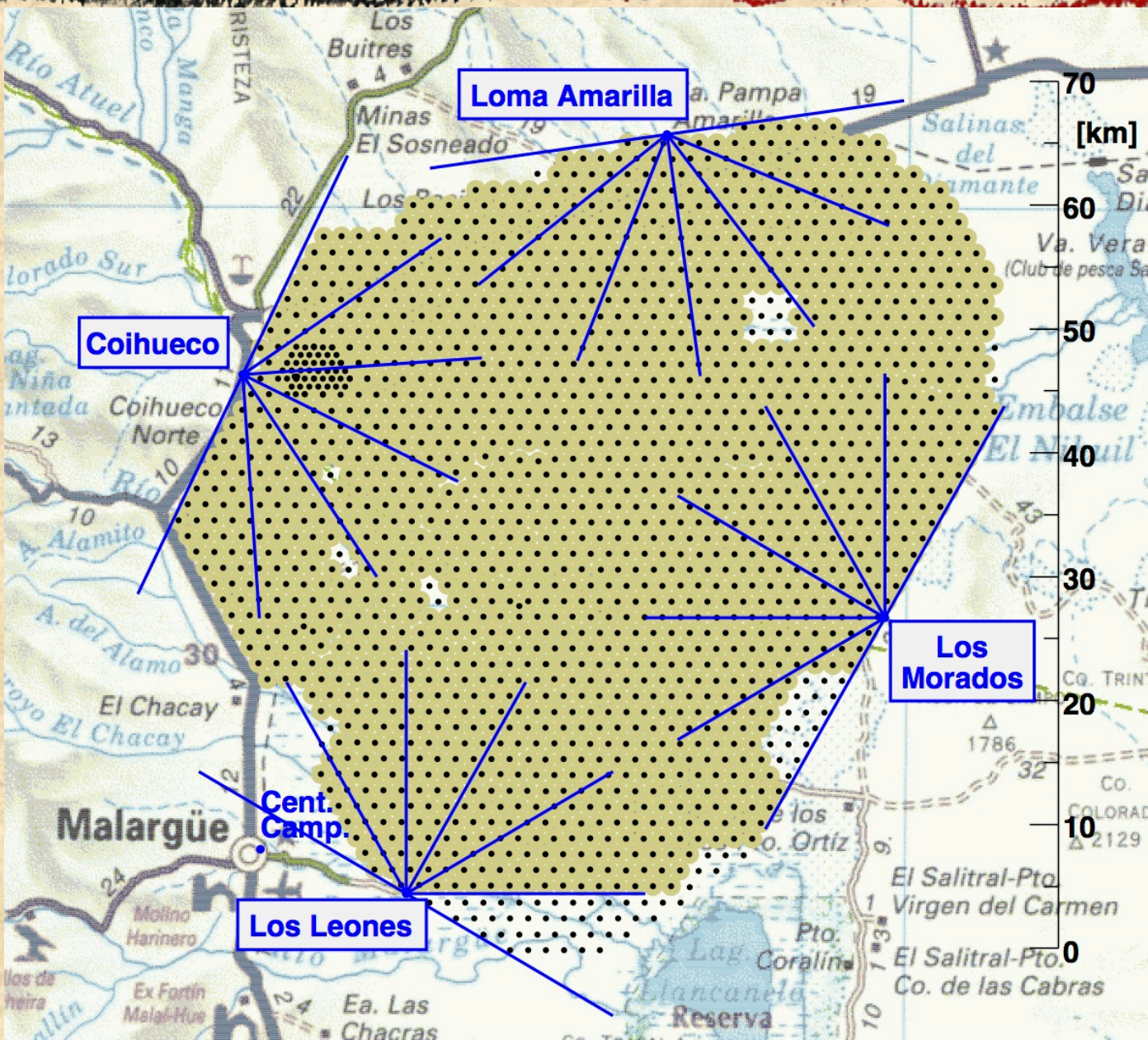
Outline

- 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

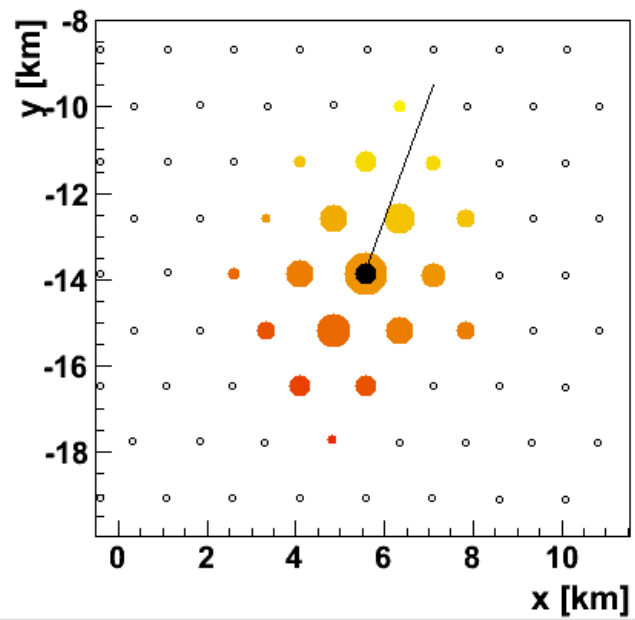
SD event

29/07/2012 SD 15894780

Event Info | MC info

Event 15894780 :-)
Time 1027623241 s 230515000 ns
3TOT & 4C1; 6T5
Candidates: 19 (Acc: 2, Bad: 1)

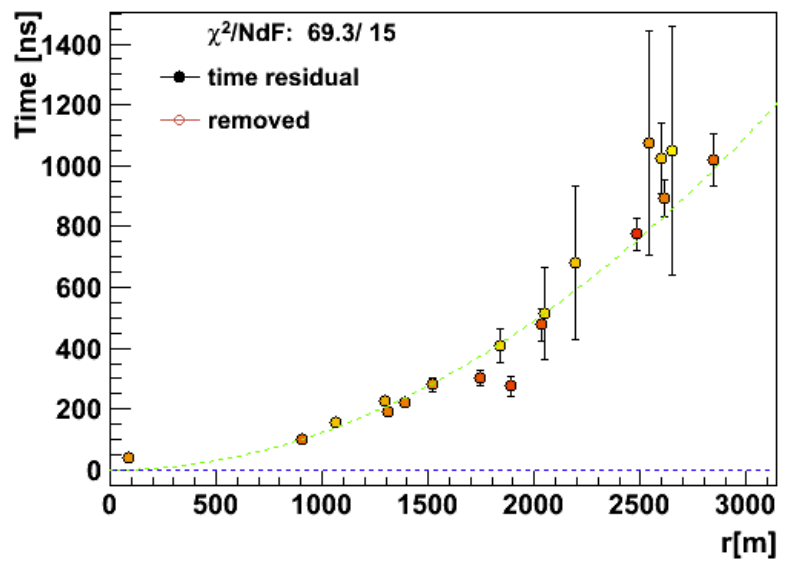
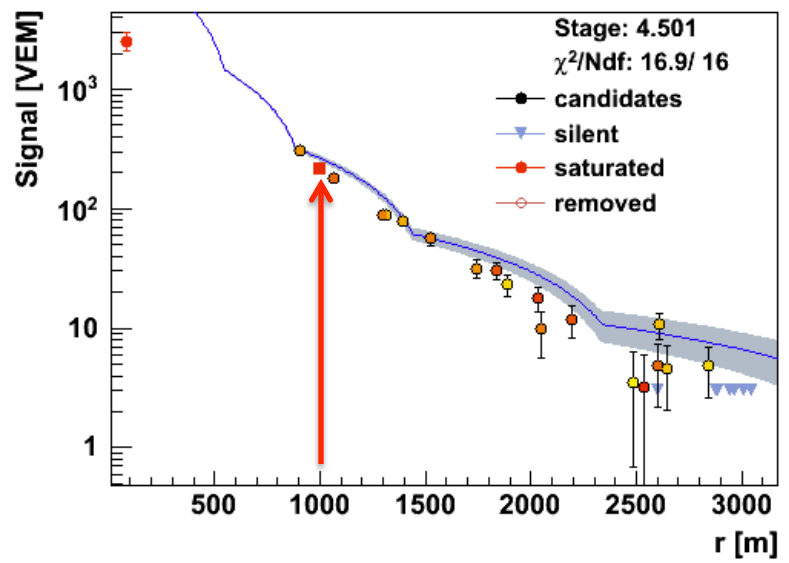
$(\theta, \phi) = (50.1 \pm 0.1, 70.6 \pm 0.2)$ deg
S1000 = 213.1 ± 6.9 (± 16.3) VEM
 $(x,y) = (5.51 \pm 0.02, -13.97 \pm 0.02)$ km
 β (fixed) = -2.13 (± 0.17)
 γ (fixed) = 0.09
R = 13.56 ± 0.38 km
 $r_{opt} = 1330.86$ m



Stations | Options

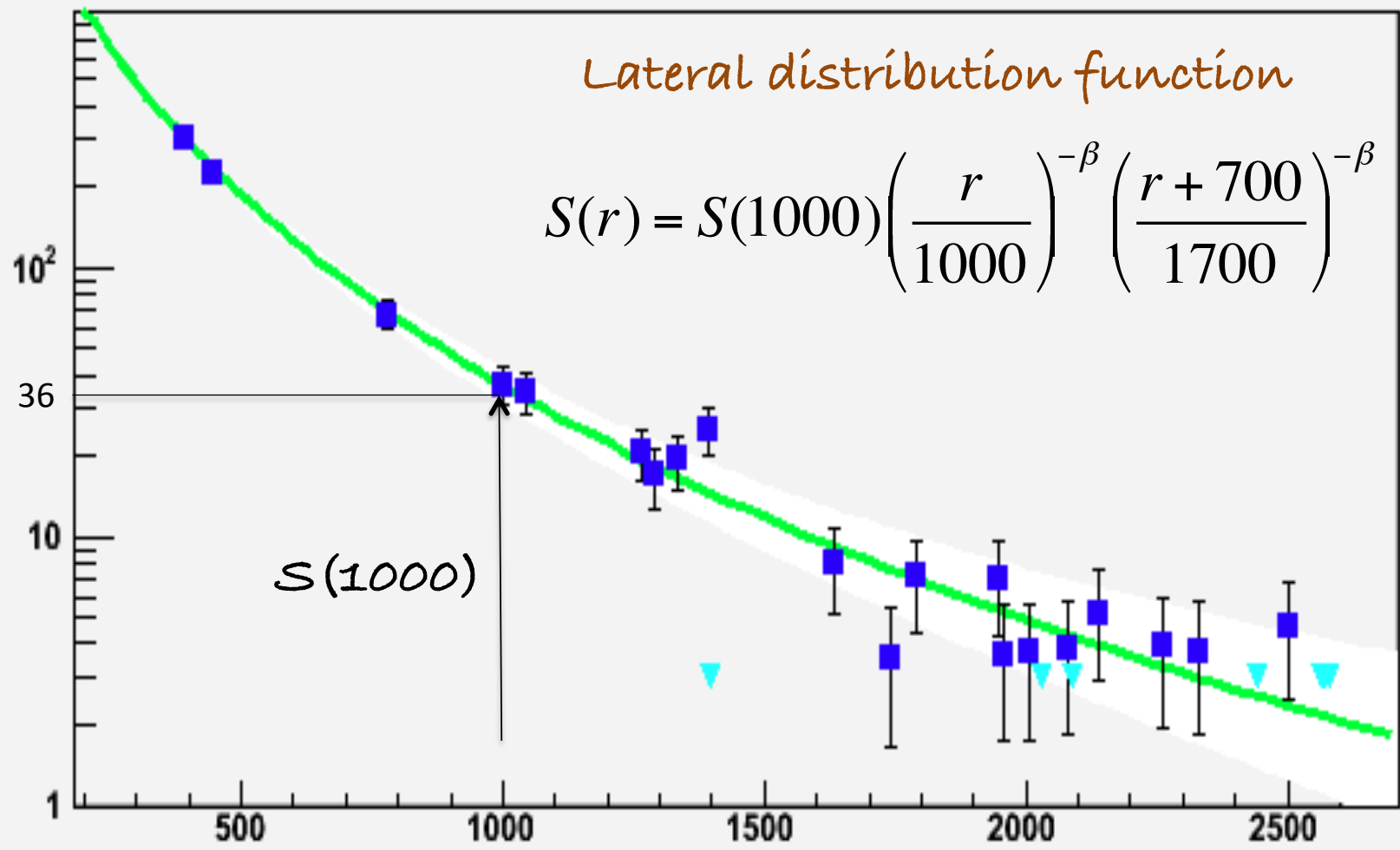
Station	TOT	VEM
501	TOT	2528.0 VEM
250	TOT	302.9 VEM
538	TOT	181.6 VEM
497	TOT	89.5 VEM
498	TOT	89.3 VEM
262	TOT	77.6 VEM
499	TOT	56.2 VEM
264	TOT	31.4 VEM
540	TOT	30.2 VEM
265	TOT	23.3 VEM
255	TOT	17.7 VEM
539	TOT	11.9 VEM
490	TOT	10.7 VEM
534	TOT	9.7 VEM
256	TOT	4.8 VEM
455	TOT	4.8 VEM
532	TOT	4.6 VEM
271	Thr1	3.5 VEM
263	Thr1	3.2 VEM
286	Thr1	2.1 VEM out of time
348	Thr1	2.2 VEM out of time

LDF and Time | VEM Traces | Dynode (HG) | Anode (LG)



The Surface Detector

Lateral distribution function fit



SD inclined event

20/4/2011 SD 11549518

Event Info | MC info

Event 11549518 :-)

Time 987344978 s 924917000 ns

4C1; 6T5

Candidates: 72 (Acc: 10, Bad: 68)

$$E = (3.53 \pm 0.21) \times 10^{19} \text{ eV}$$

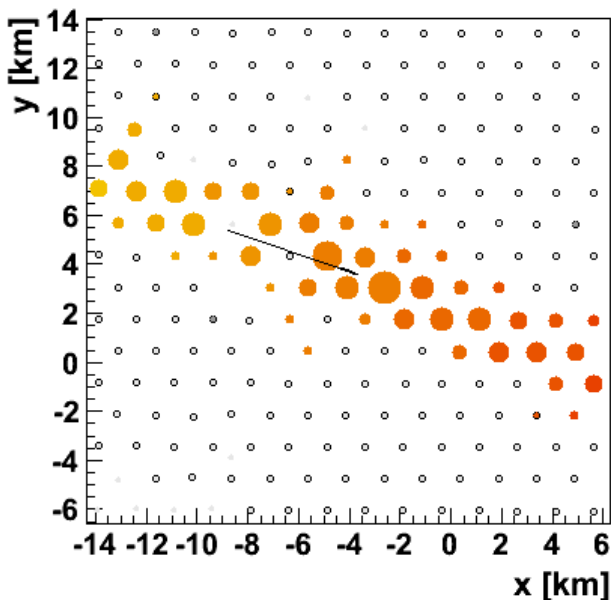
$$(\theta, \phi) = (81.2 \pm 0.0, 161.0 \pm 0.0) \text{ deg}$$

$$N19 = 7.1 \pm 0.4$$

$$(x, y) = (-4.03 \pm 0.23, 3.73 \pm 0.09) \text{ km}$$

$$\beta \text{ (fixed)} = 0.00 (\pm 0.00)$$

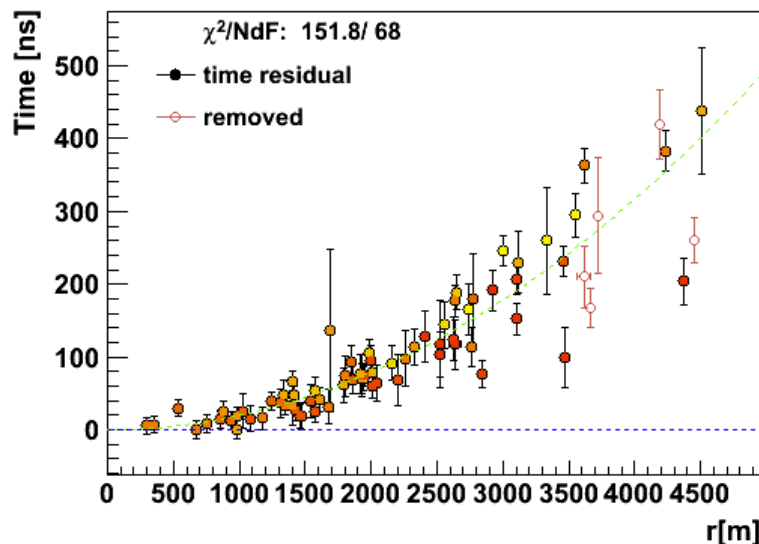
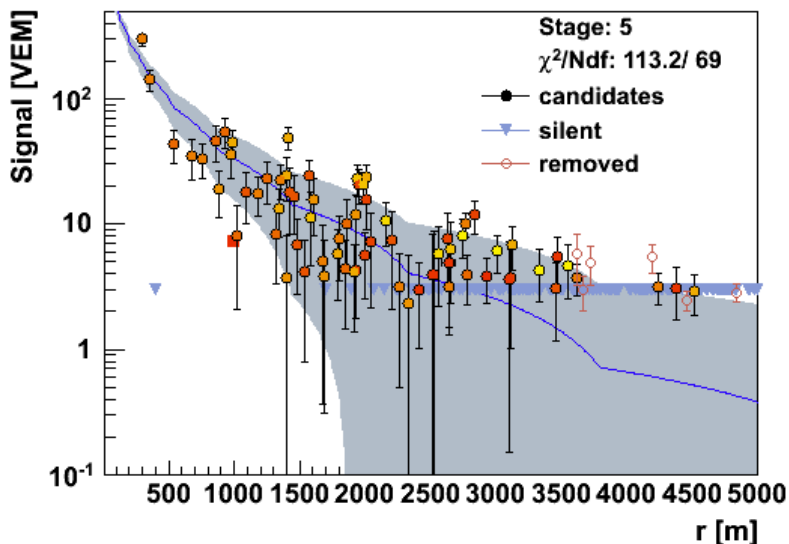
$$R = 84.39 \pm 0.24 \text{ km}$$



Stations | Options

811	TOT	298.6	VEM
1235	TOT	141.4	VEM
503	TOT	54.5	VEM
1695	TOT	48.5	VEM
505	TOT	45.7	VEM
1795	TOT	45.1	VEM
814	TOT	43.1	VEM
1232	TOT	35.9	VEM
825	Thr2	34.9	VEM
1233	TOT	33.2	VEM
1752	TOT	24.3	VEM
1016	TOT	24.1	VEM
1819	TOT	23.4	VEM
1746	TOT	22.9	VEM
511	TOT	22.8	VEM
829	TOT	22.6	VEM
683	TOT	20.8	VEM
1735	TOT	20.5	VEM
1828	TOT	18.9	VEM
1017	TOT	18.1	VEM
1019	TOT	17.9	VEM
813	Thr2	17.6	VEM
1715	Thr2	16.5	VEM
1718	TOT	15.7	VEM

LDF and Time | VEM Traces | Dynode (HG) | Anode (LG)



FD event

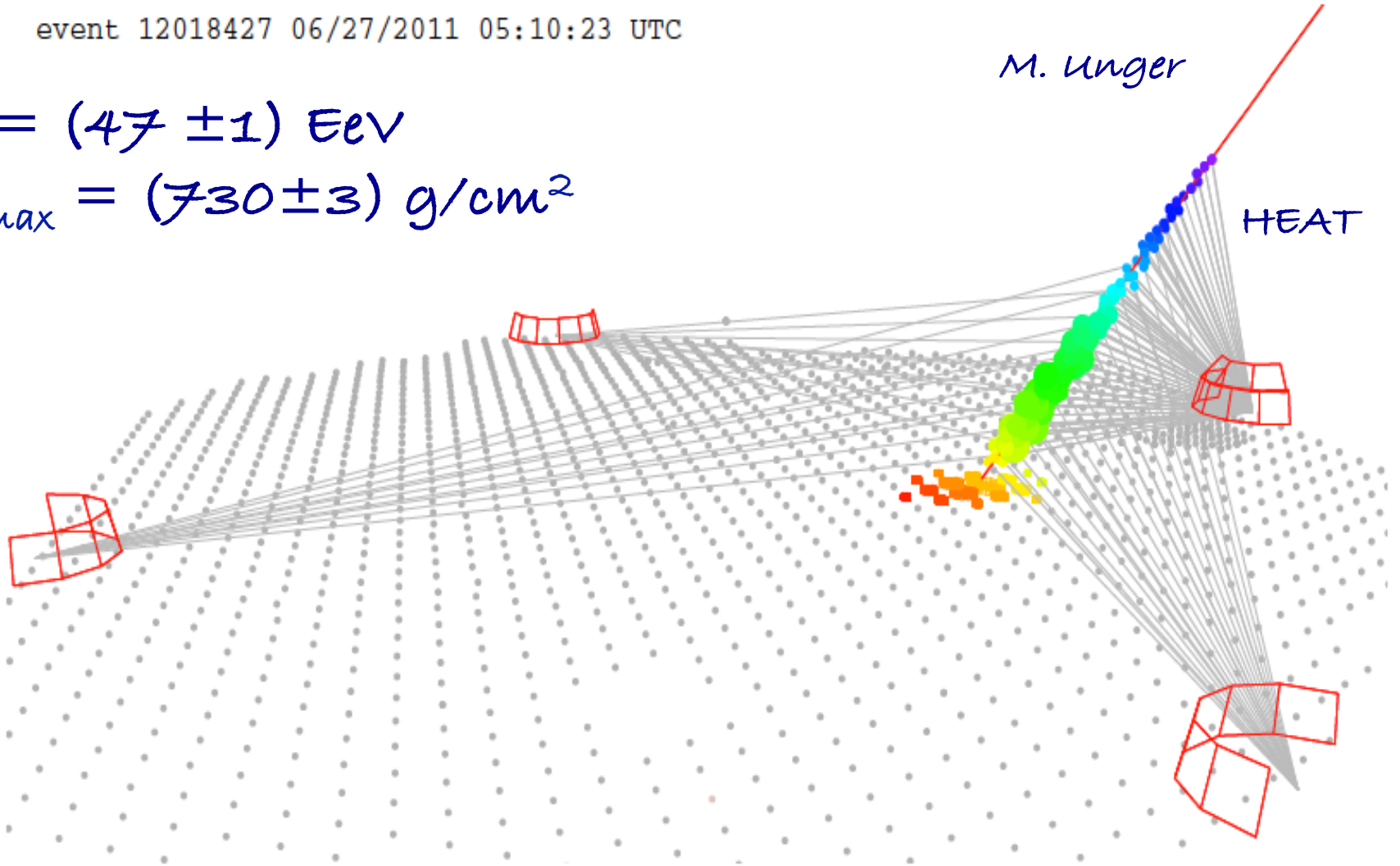
event 12018427 06/27/2011 05:10:23 UTC

$$E = (47 \pm 1) \text{ EeV}$$

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

M. Unger

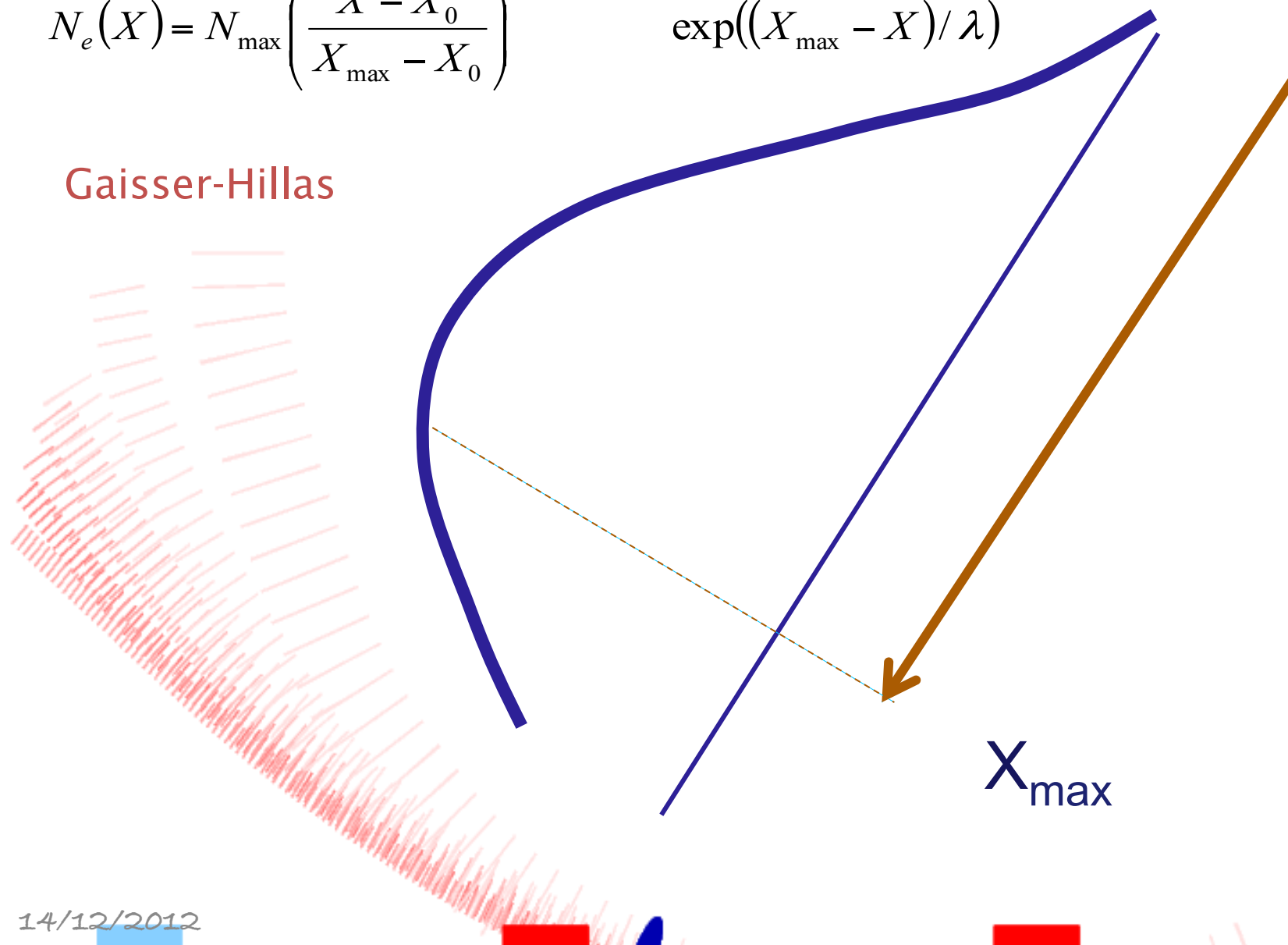
HEAT



x_{max}

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

Gaisser-Hillas



X_{max}

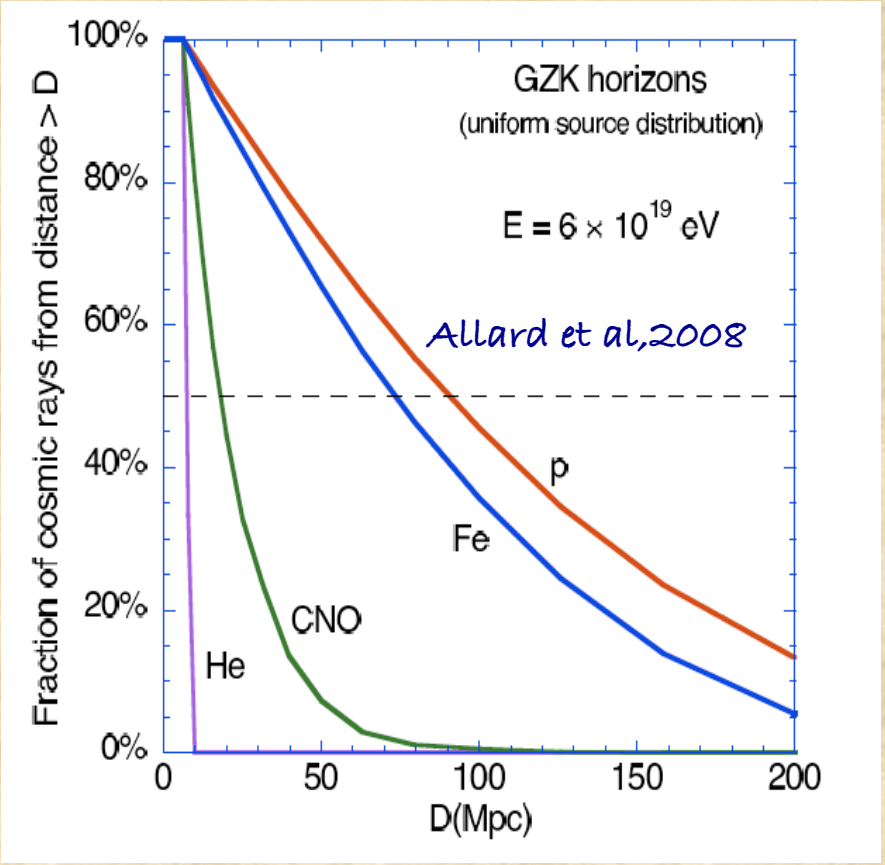
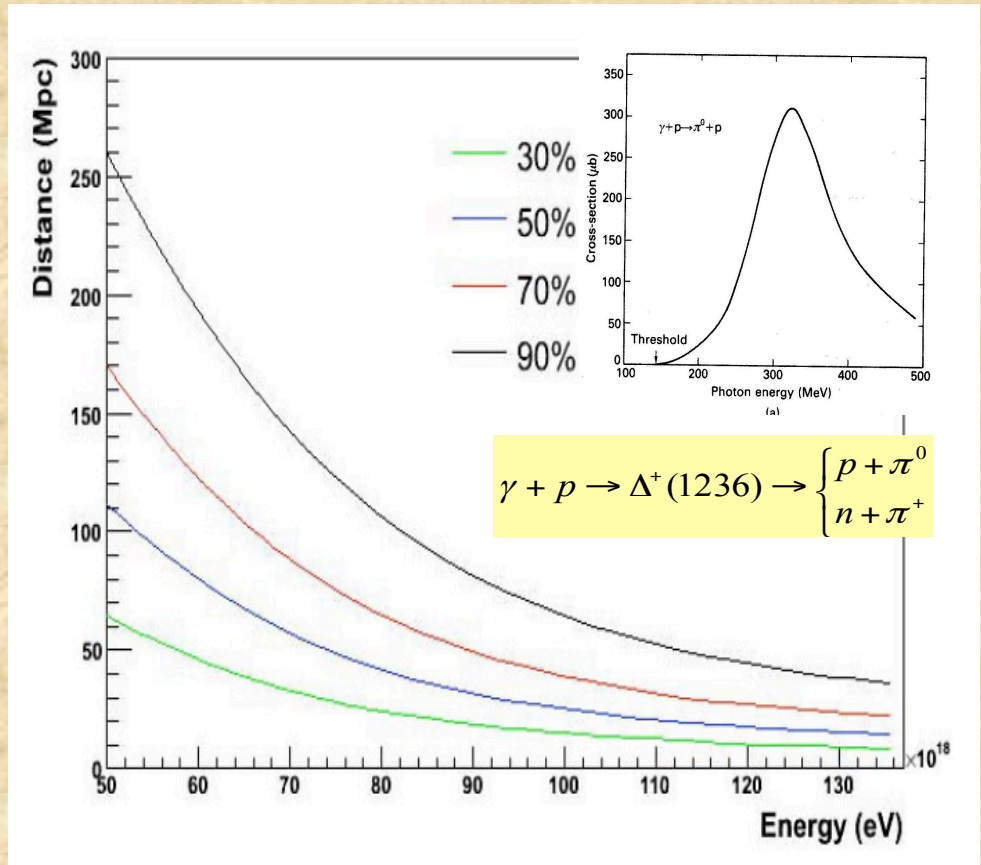


The cosmic rays spectrum

The cosmic ray spectrum

- Auger is sensitive to energies $> 1 \text{ EeV}$ (10^{18} eV)
- Greisen-Zatsepin-Kuzmin (GZK) prediction (suppression of Flux above $\sim 40 \text{ EeV}$ due to $\Delta(1236)$ resonance 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



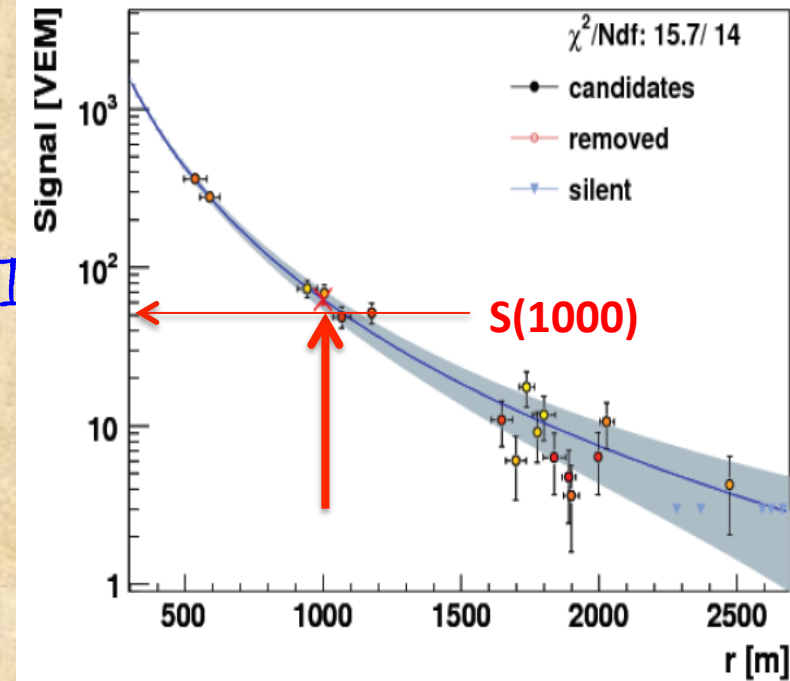
The spectrum (a note on Energy calibration)

□ SD Energy calibration

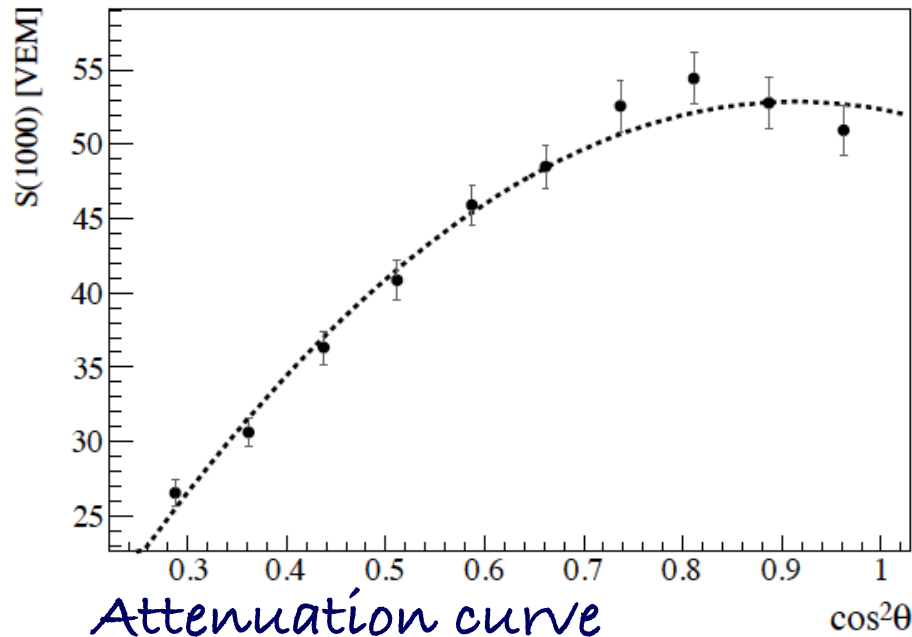
- Energy extracted from lateral distribution function [S(1000)]
- Global fitting

□ FD Energy calibration

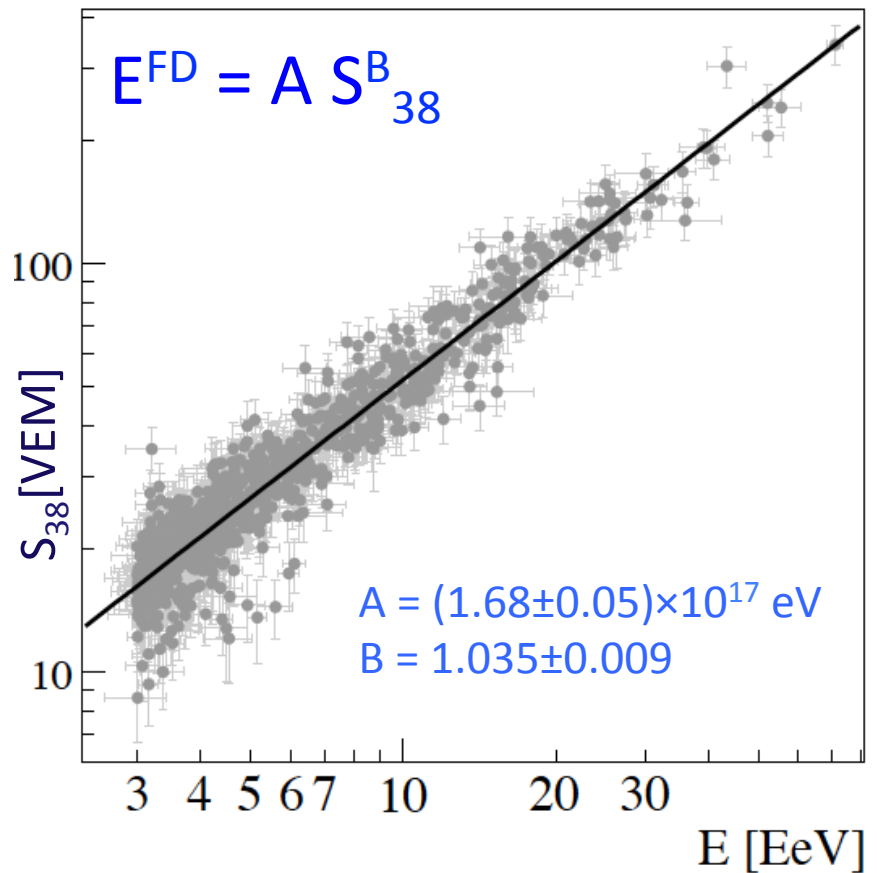
- Energy deposited proportional to fluorescence light emitted. Light converted into energy deposited using absolute fluorescence yield in 337nm band (5.05 ± 0.71) photons/MeV.
- Corrected for environmental factors



The spectrum (a note on Energy calibration)



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



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

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

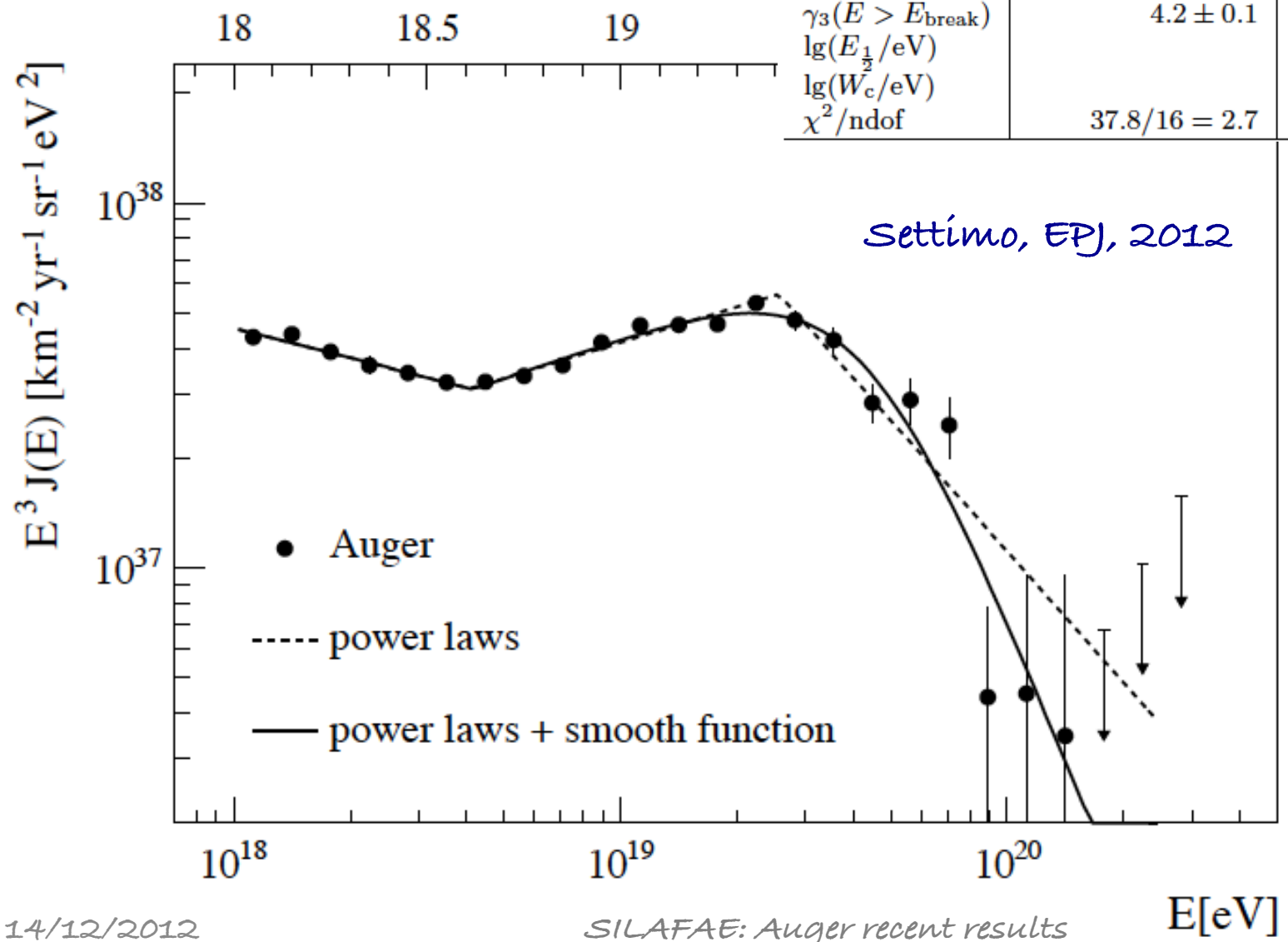
$$S_{38} \equiv S(1000) / CIC(\theta)$$

$$a = 0.87 \pm 0.04$$

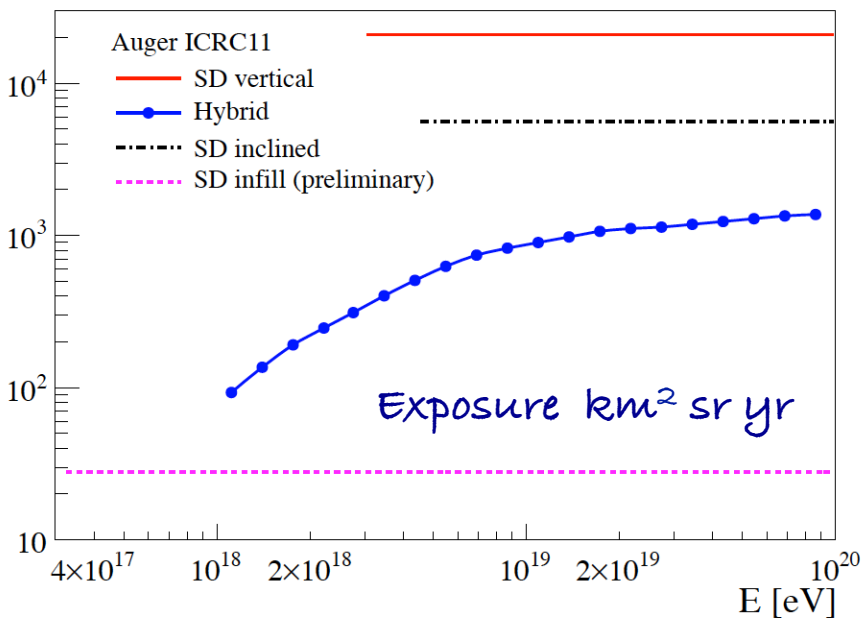
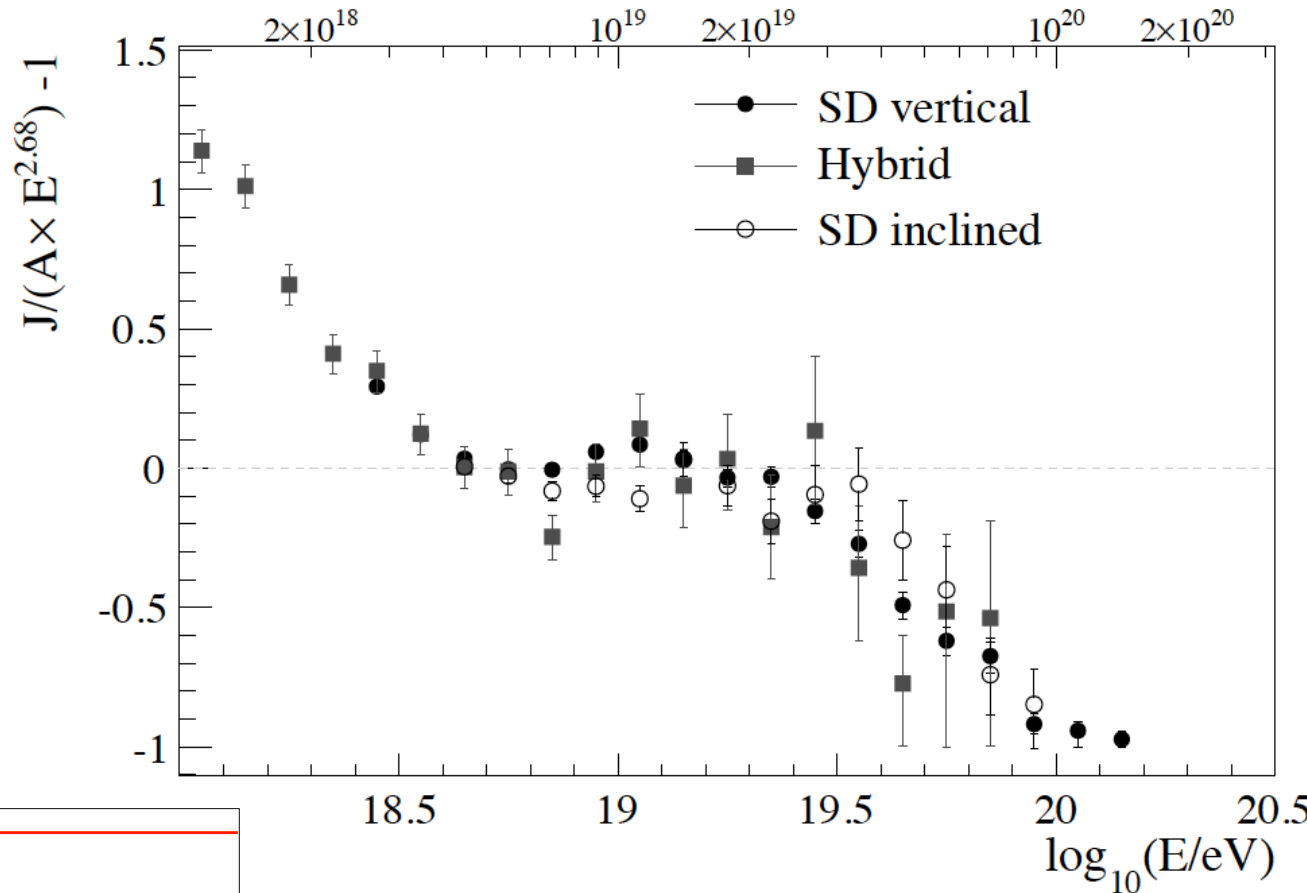
$$b = -1.49 \pm 0.20$$

The Spectrum

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

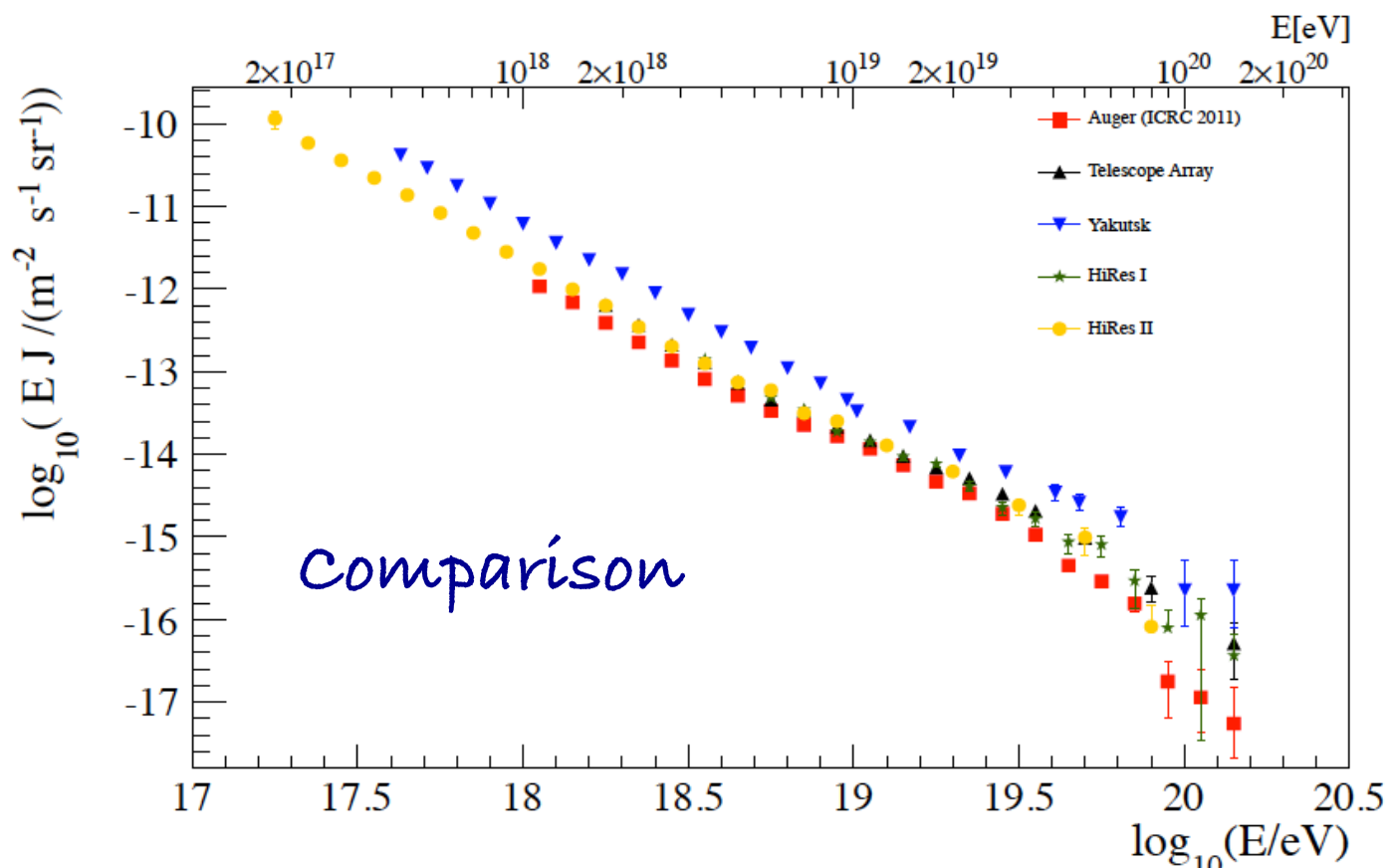


The Spectrum



\mathcal{E} : Auger recent results

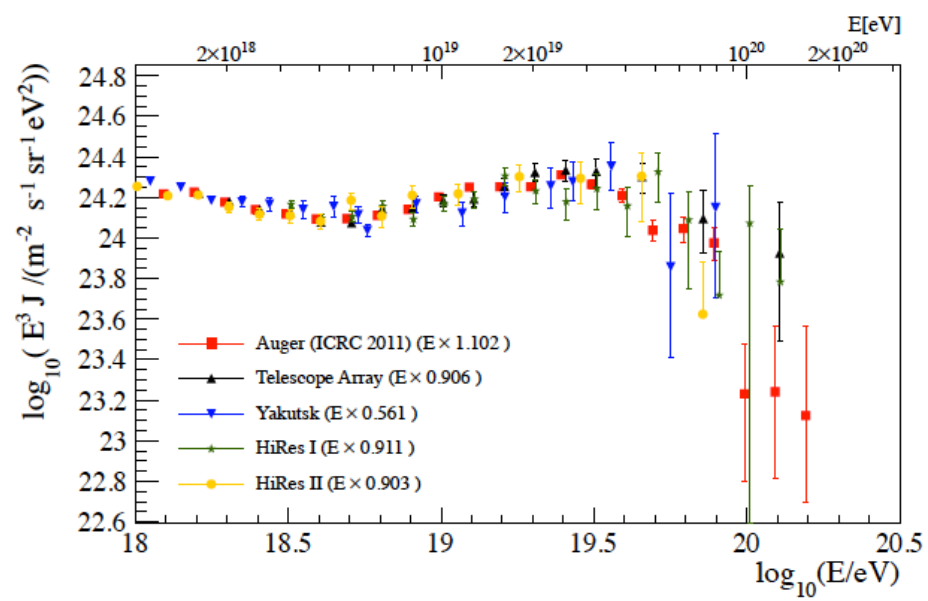
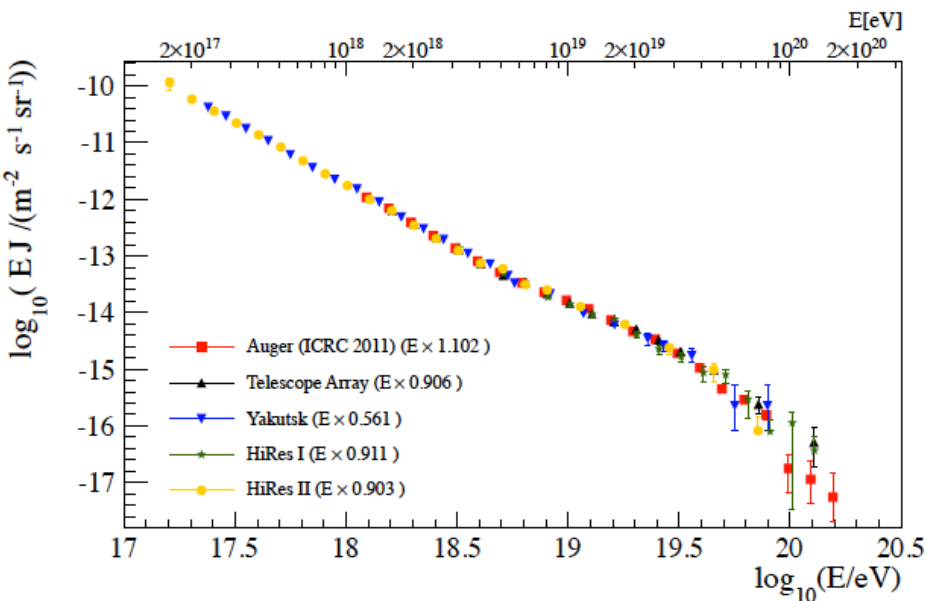
The cosmic rays spectrum



	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

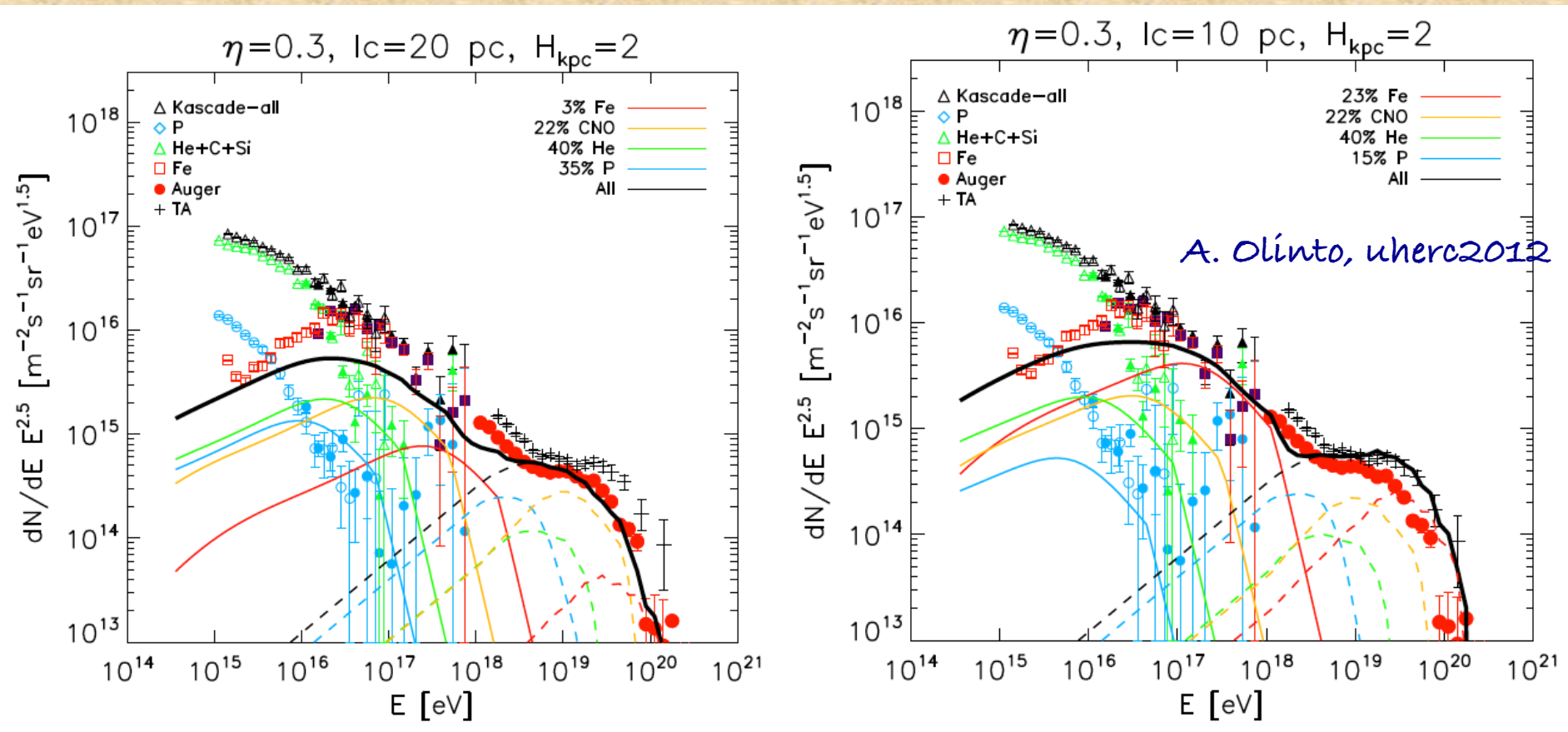
The cosmic rays spectrum: comparison

After Energy re-scaling



The cosmic rays spectrum

Exhaustion of sources?

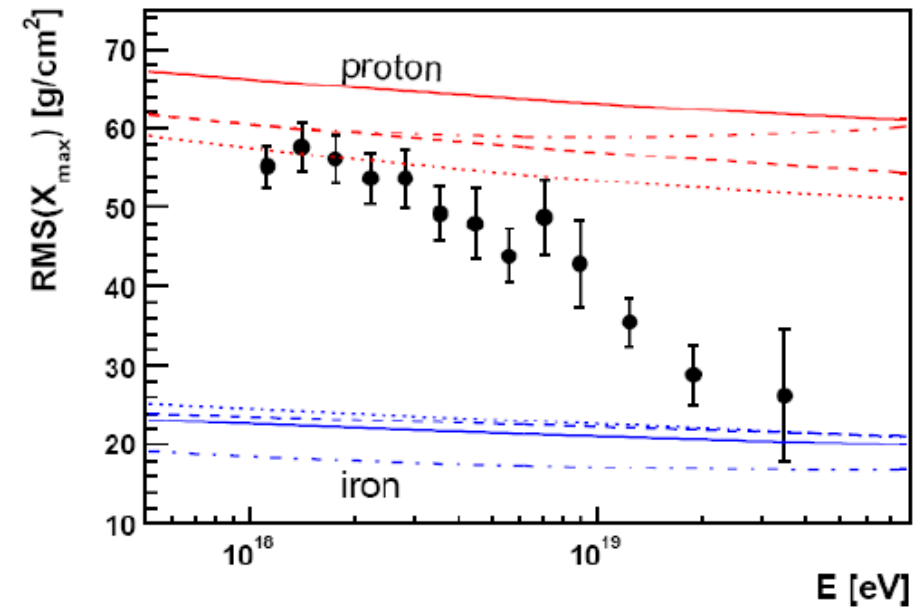
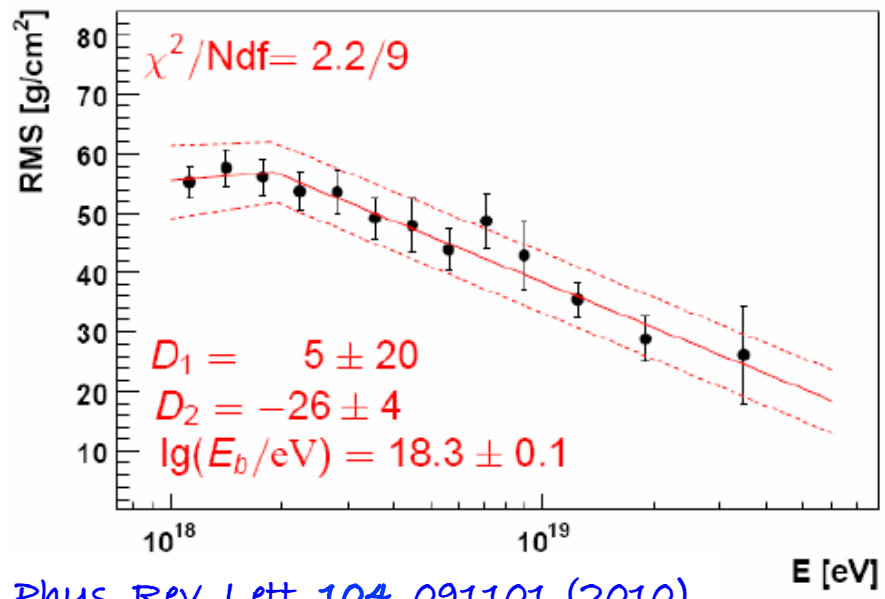
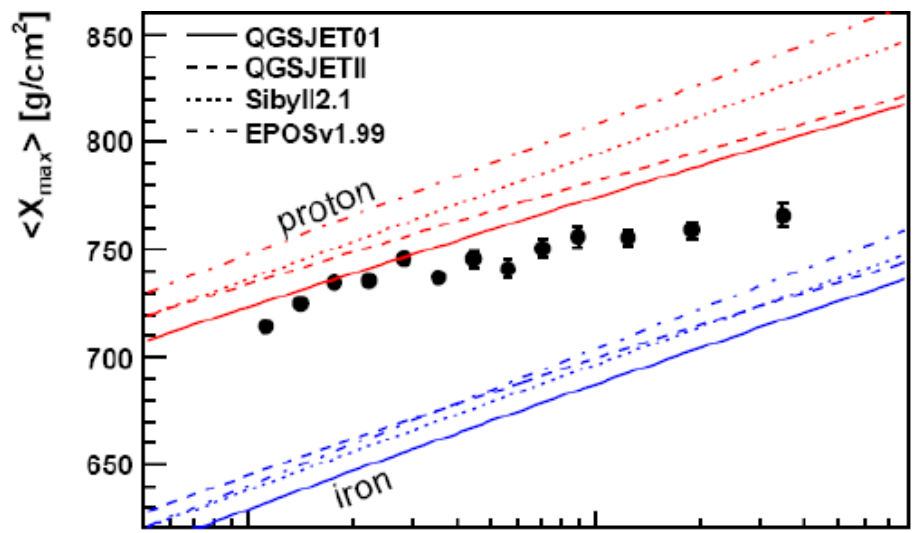
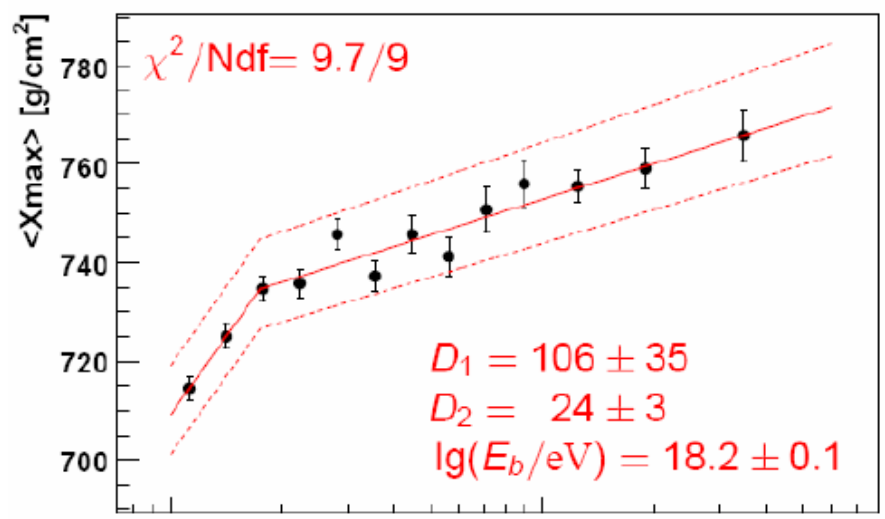


Mass composition

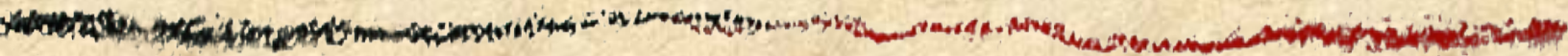
Mass Composition

- 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

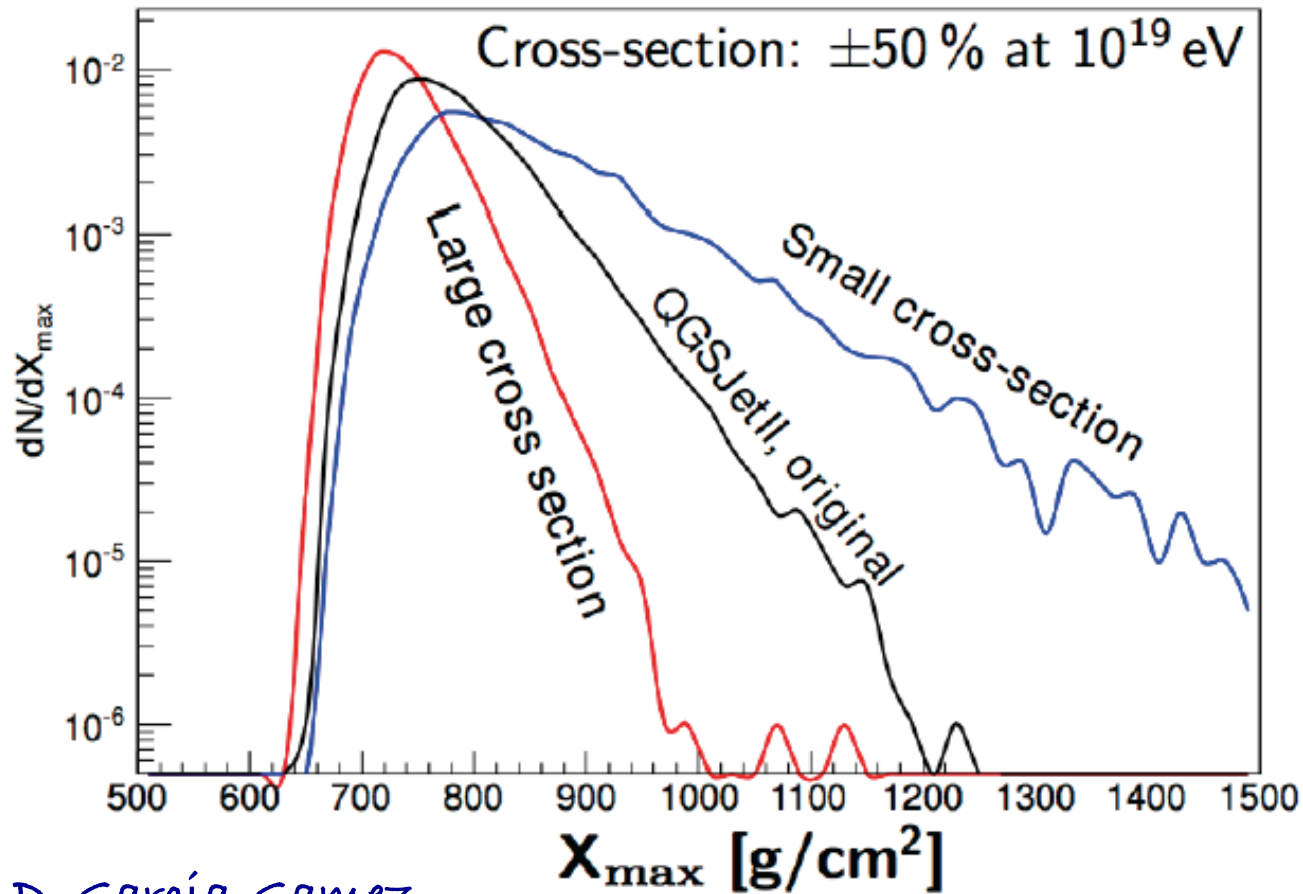
pp Cross section (Phys. Rev. Lett. 109, 062002 (2012))

- 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 cosmic 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:



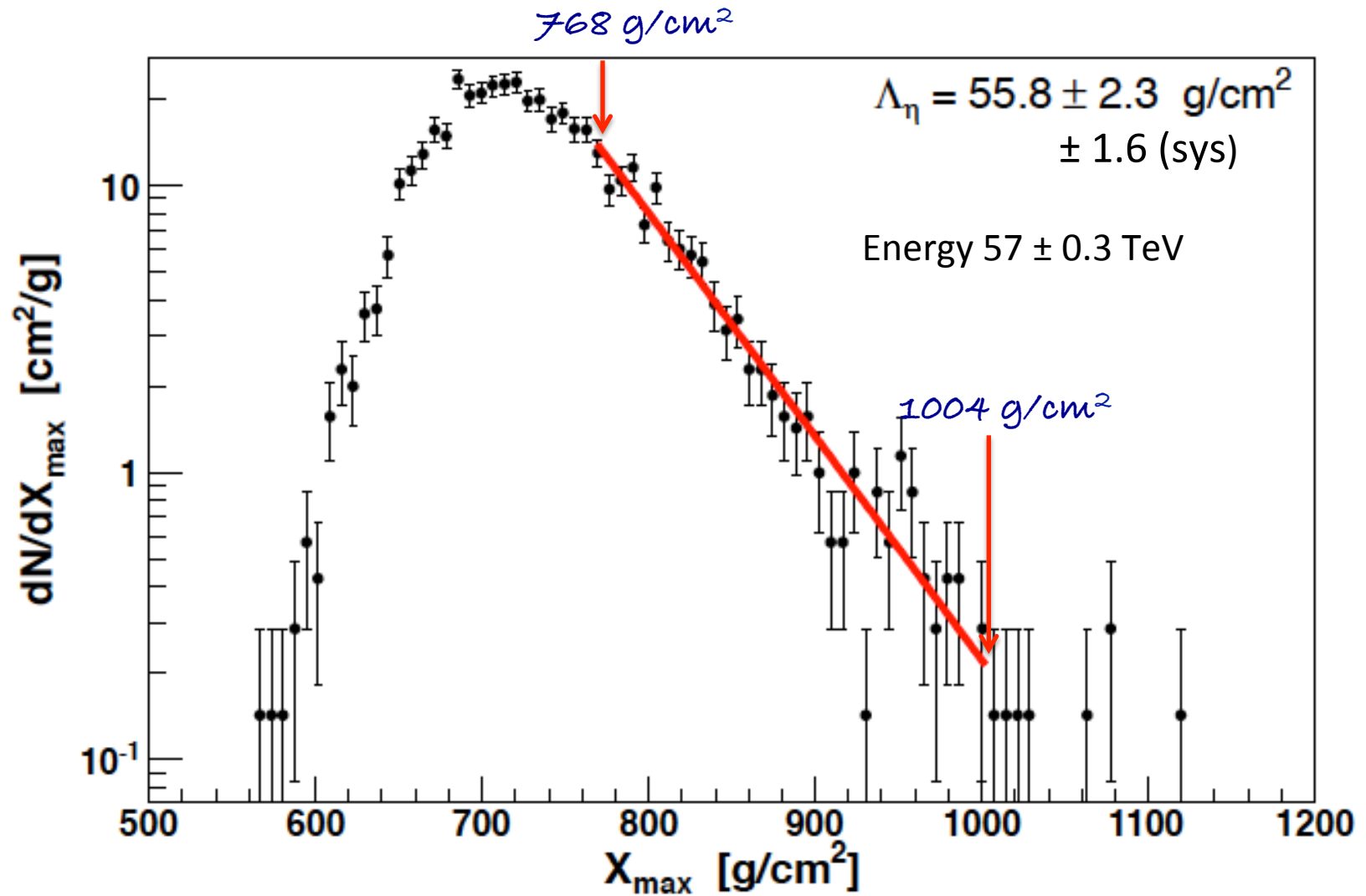
D. García-Gómez

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

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

pp Cross section

unbiased X_{\max} distribution



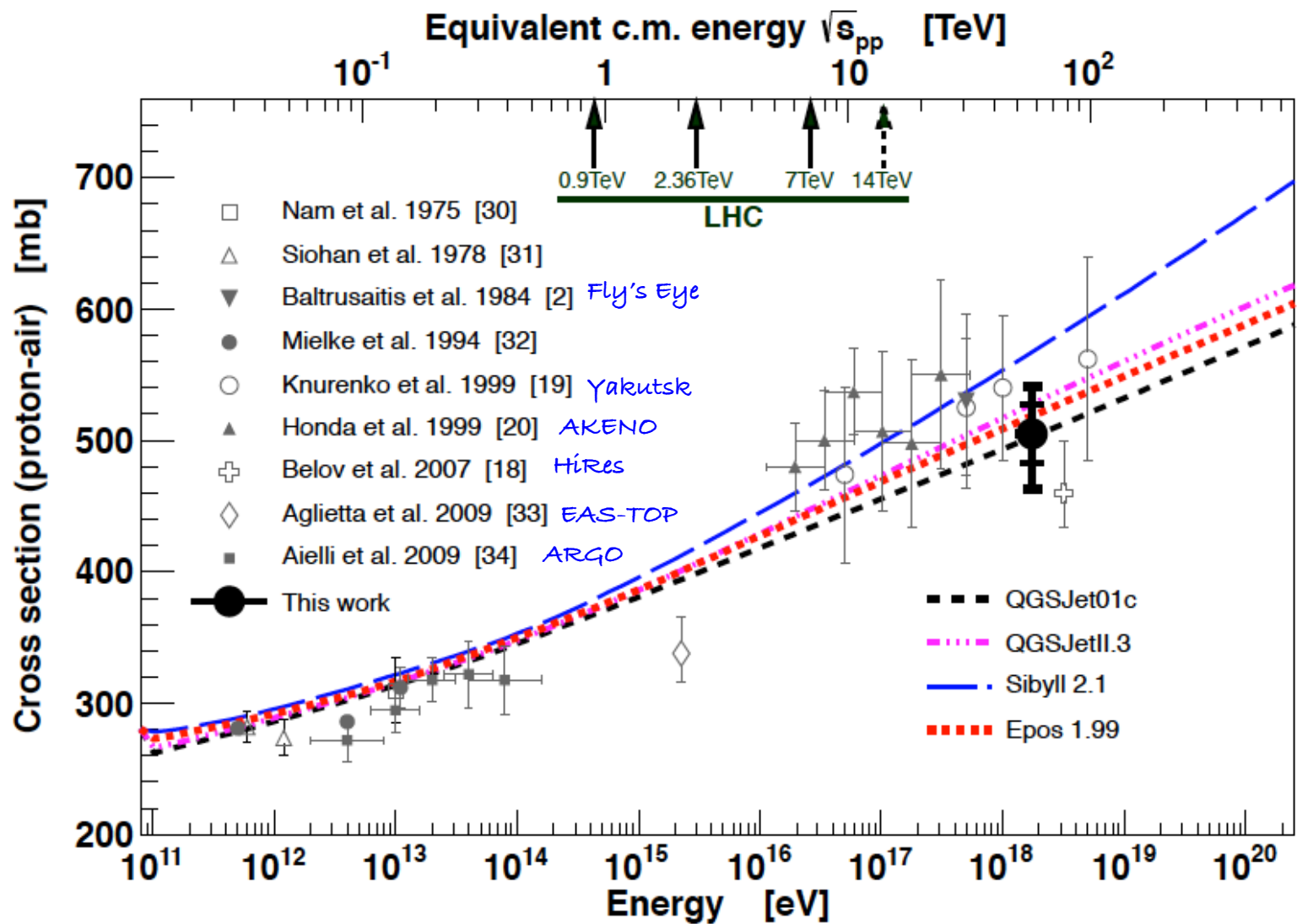
pp Cross section

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

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

- For each hadronic interaction model, f_{19} is obtained that reproduces the measured value of Λ_n
- Use hadronic interactions models:
 - QGSJet01 (523.7 mb),
 - QGSJet11.3 (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

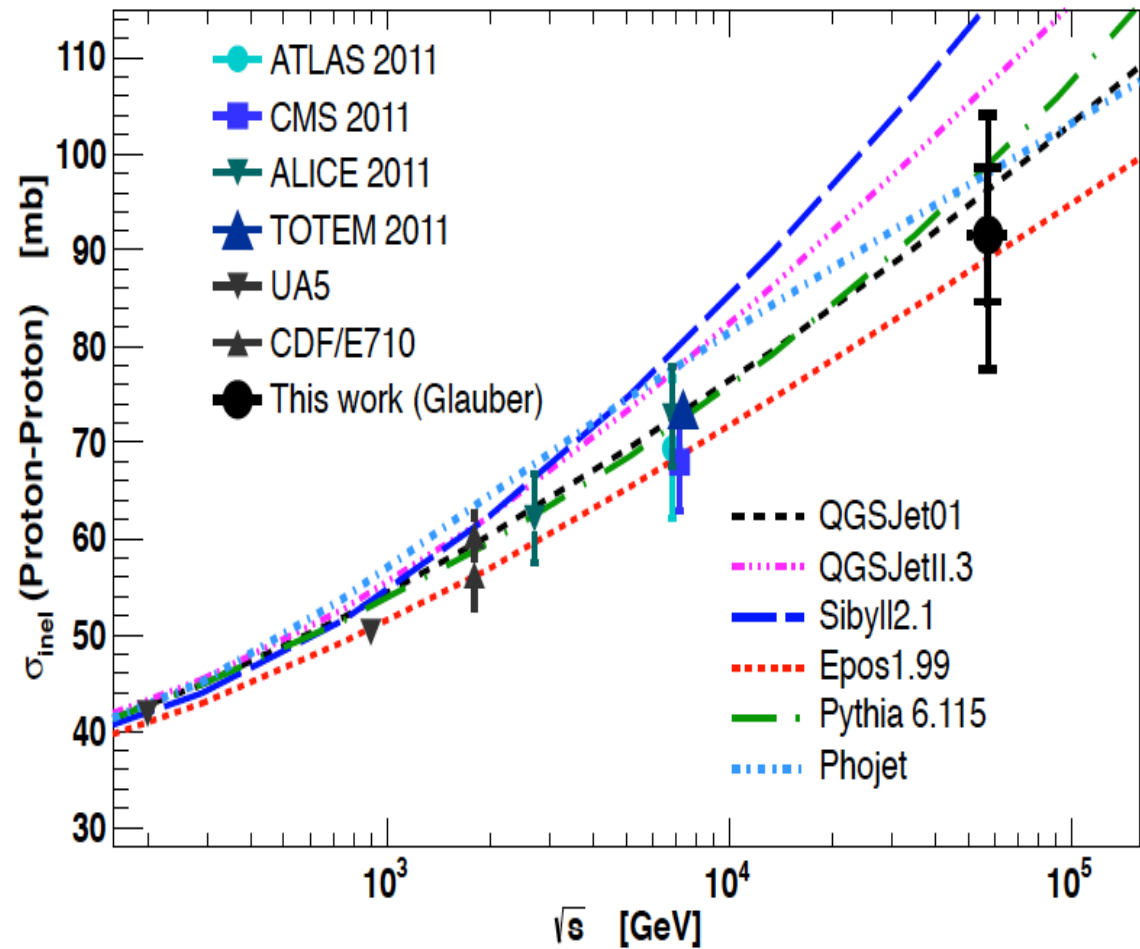
TABLE I: Summary of the systematic uncertainties.

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

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

pp Cross section

use Glauber model
to extract inelastic
and total cross
section



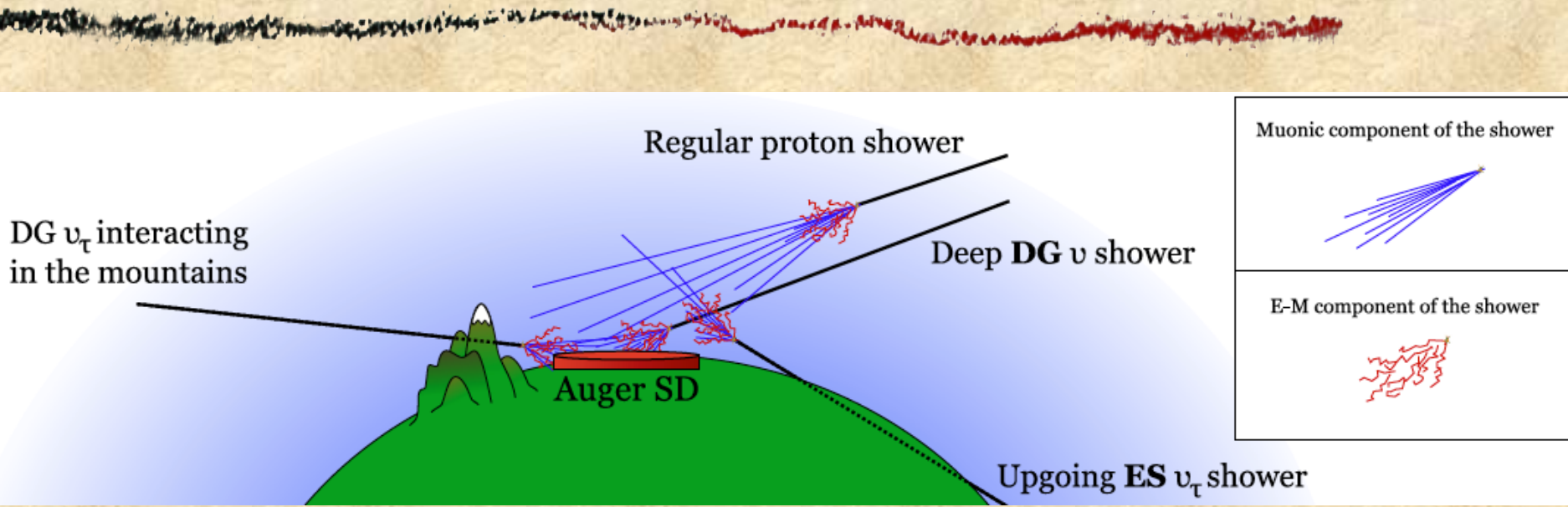
$$\sigma_{pp}^{\text{inel}} = [92 \pm 7(\text{stat}) \pm_{-11}^{+9}(\text{sys}) \pm 7(\text{Glauber})] \text{ mb},$$

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



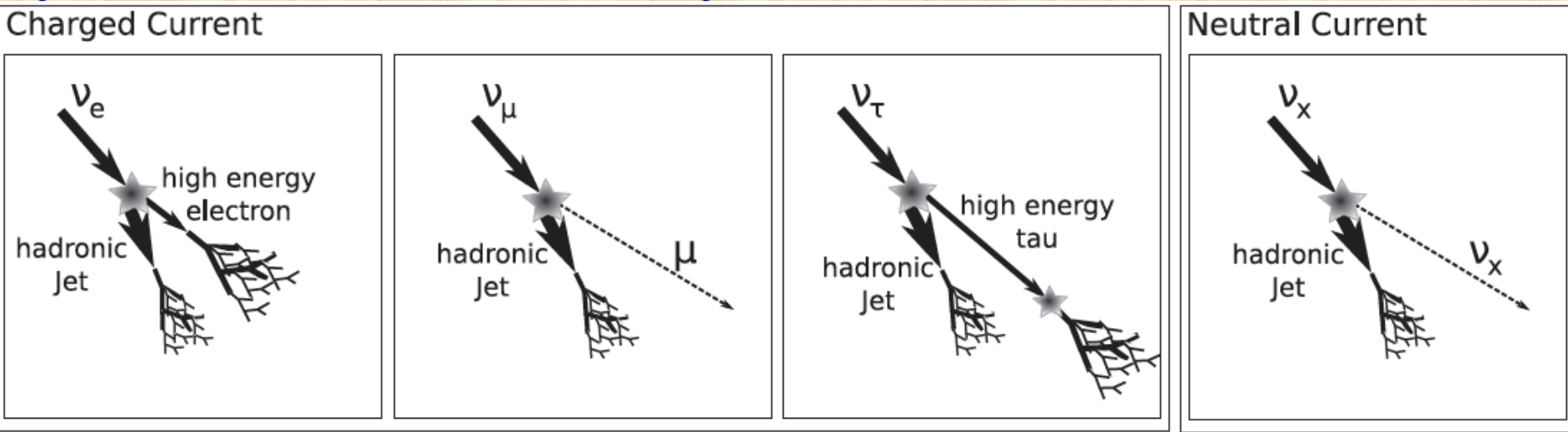
Neutrinos and Photons

Neutrinos

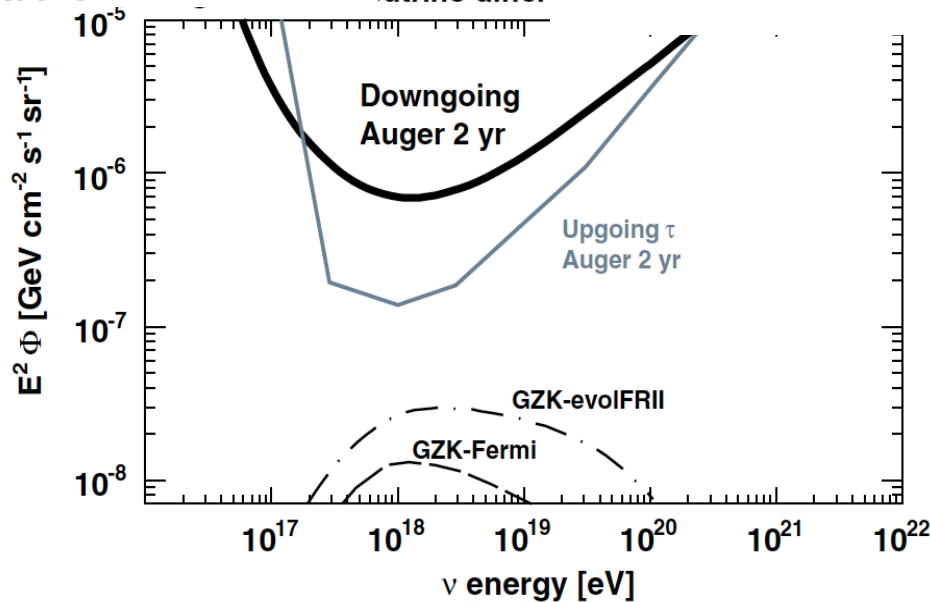
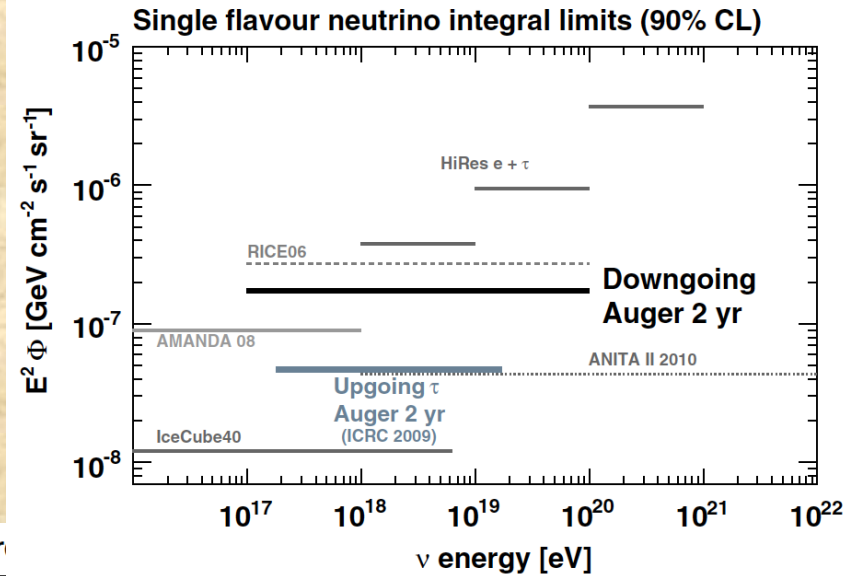
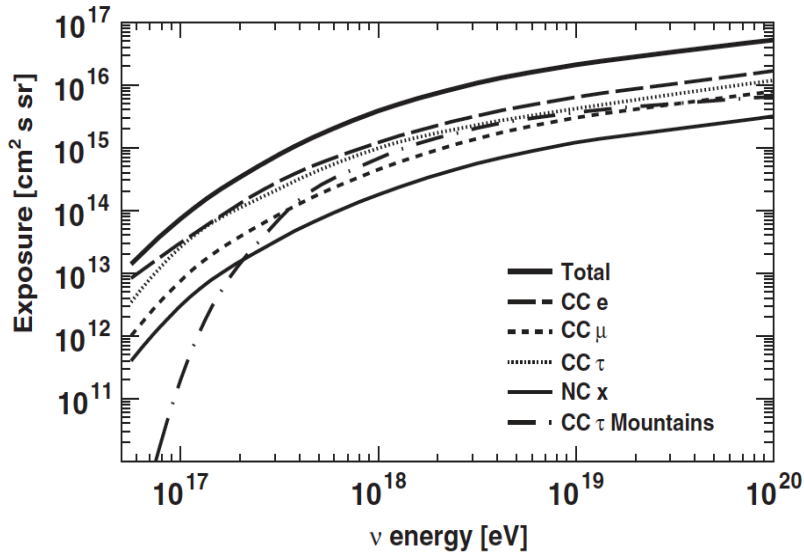


Types of atmospheric showers induced by neutrinos

Auger, PRD84, 122005 (2011)

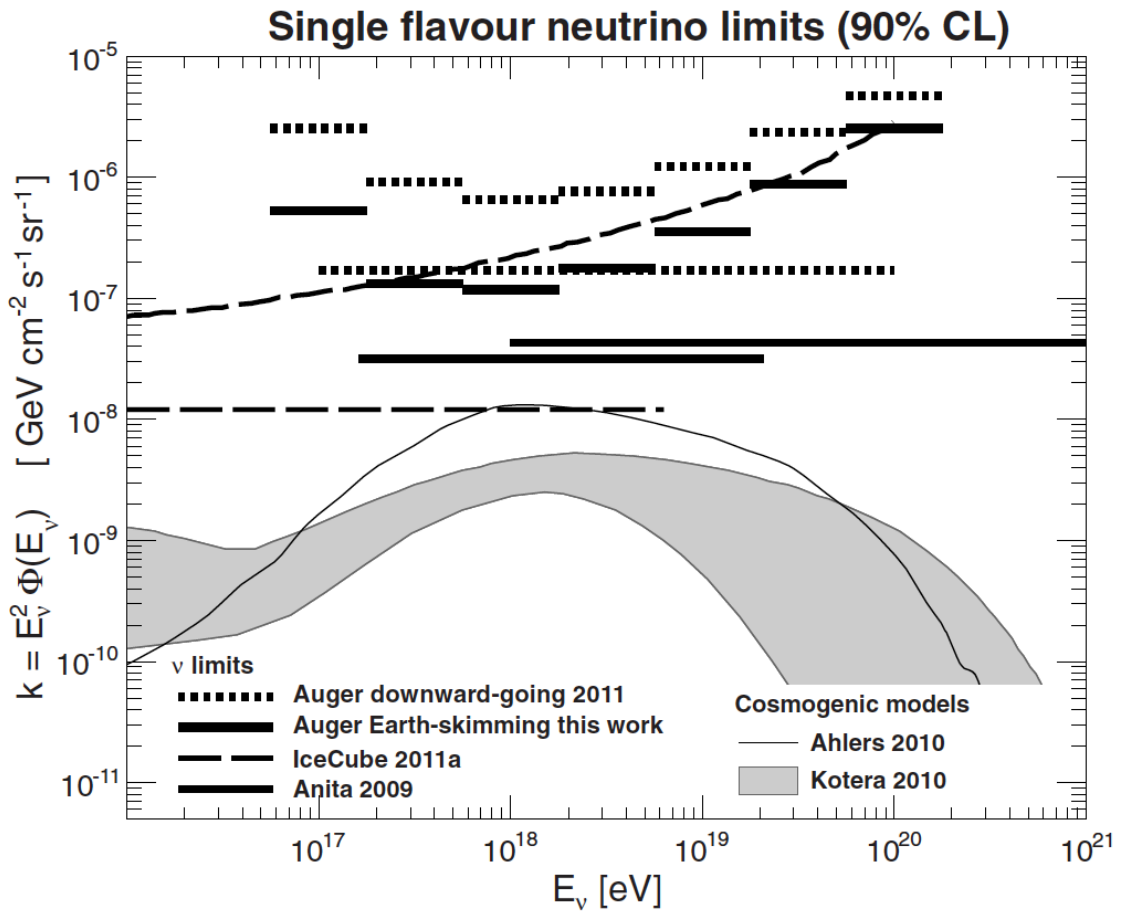
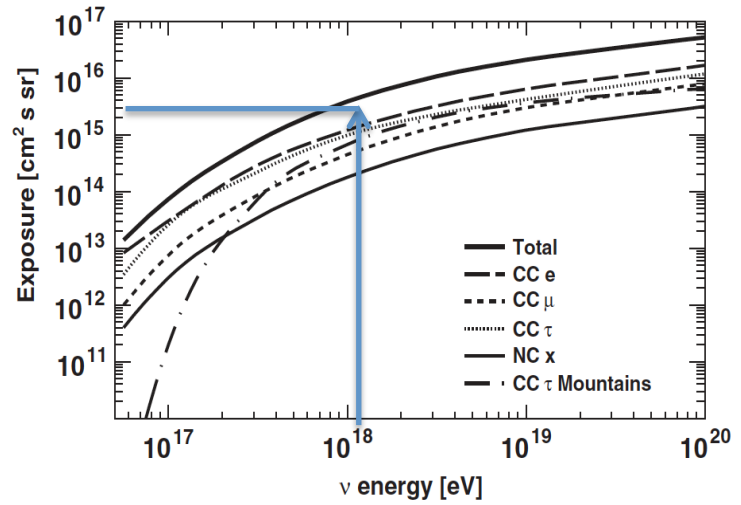
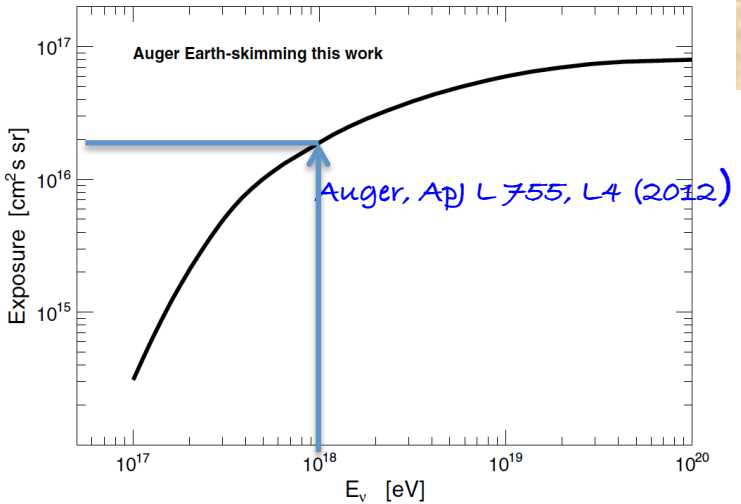


Neutrinos



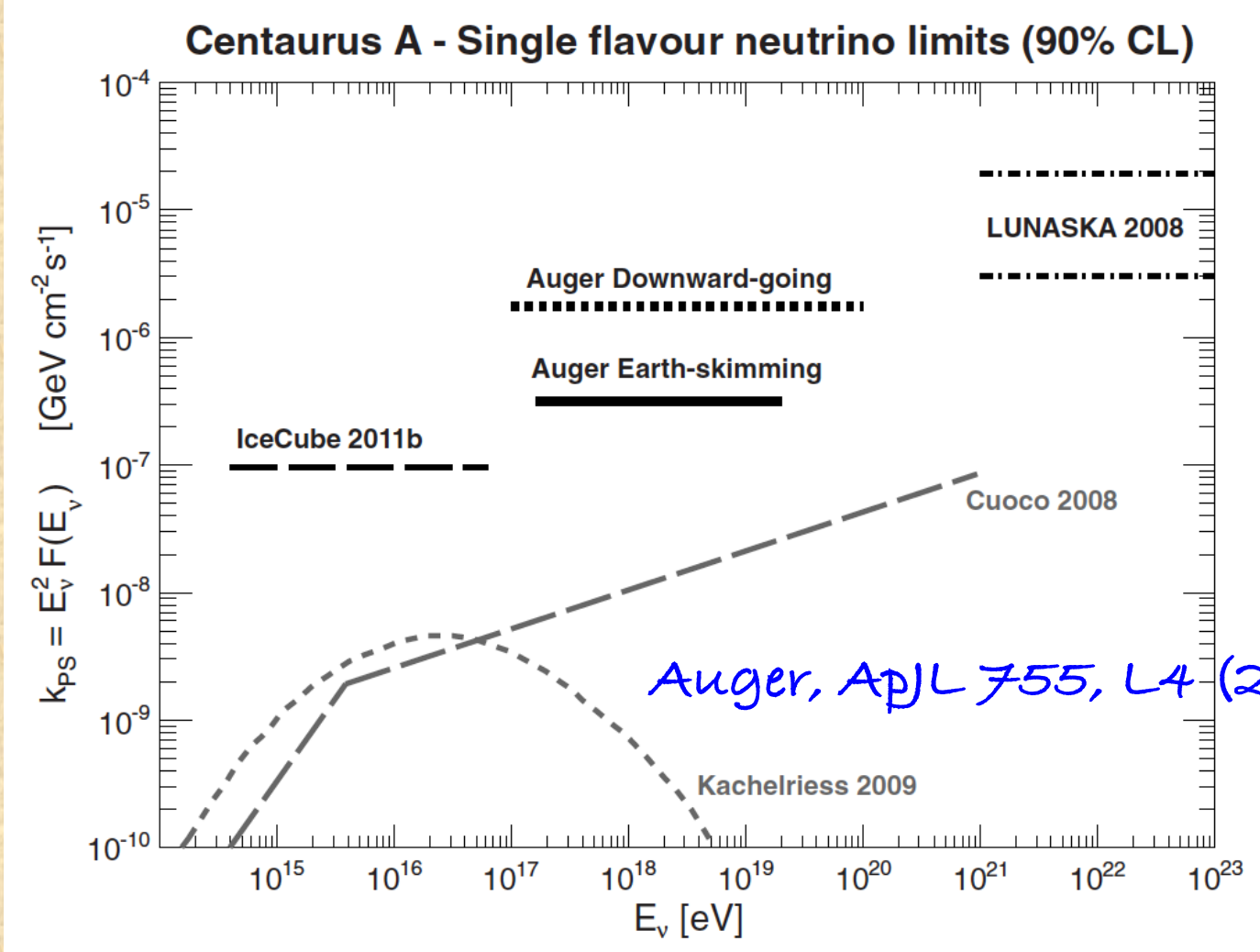
Neutrinos

Auger, ApJ L 755, L4 (2012)

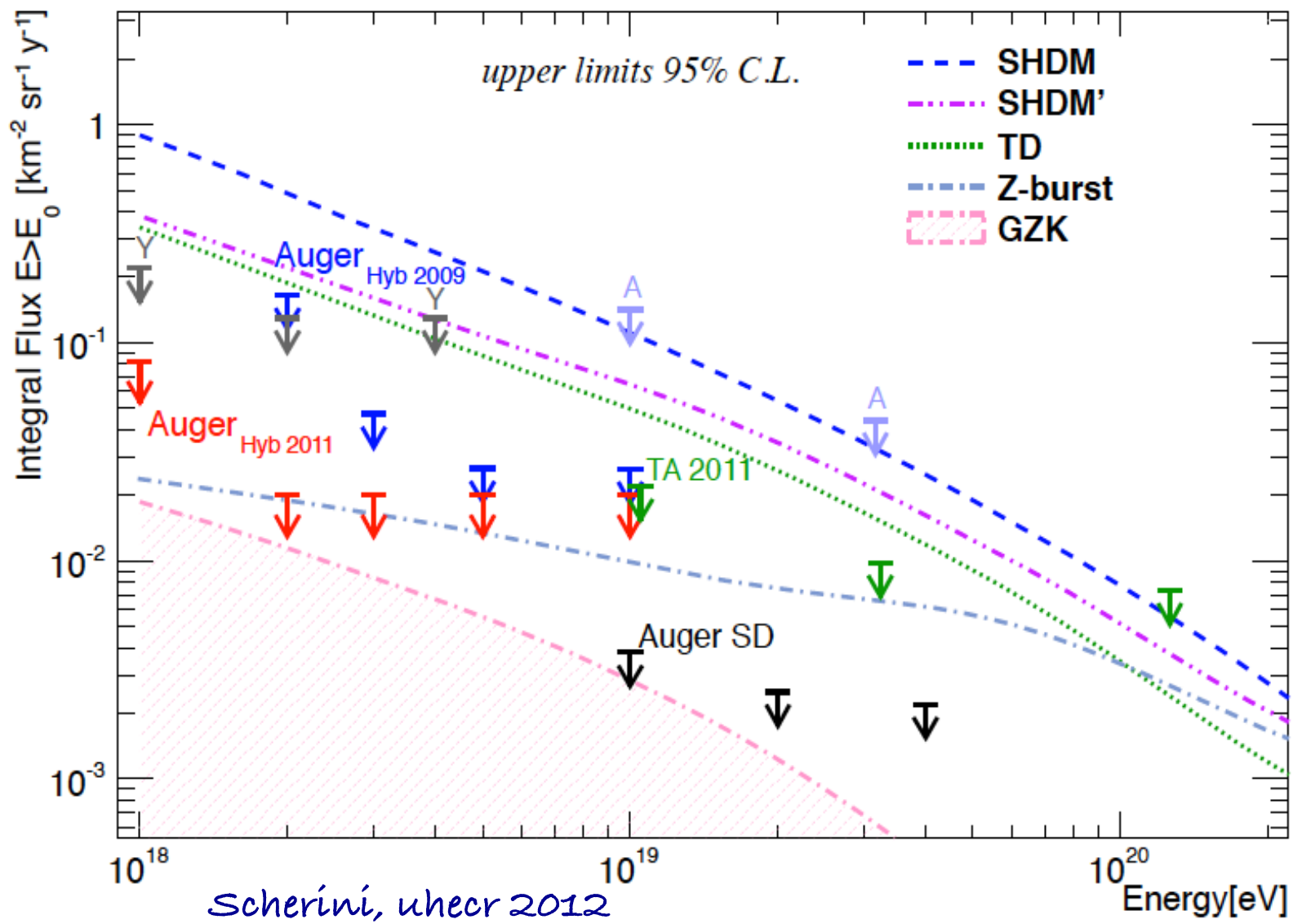


Neutrinos

Upper limit on single flavour E_ν^{-2} from AGN Centaurus A



Photons update

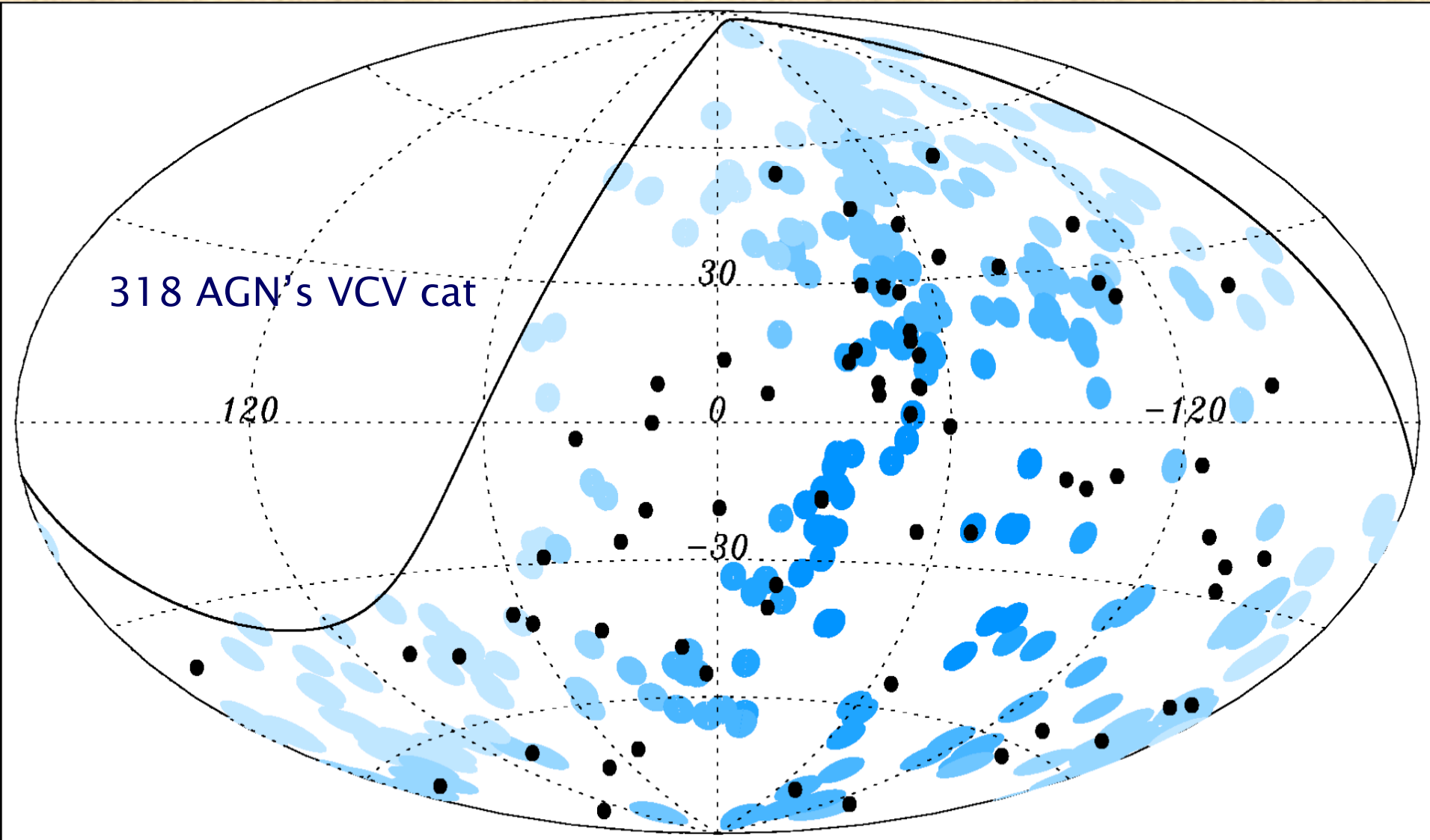




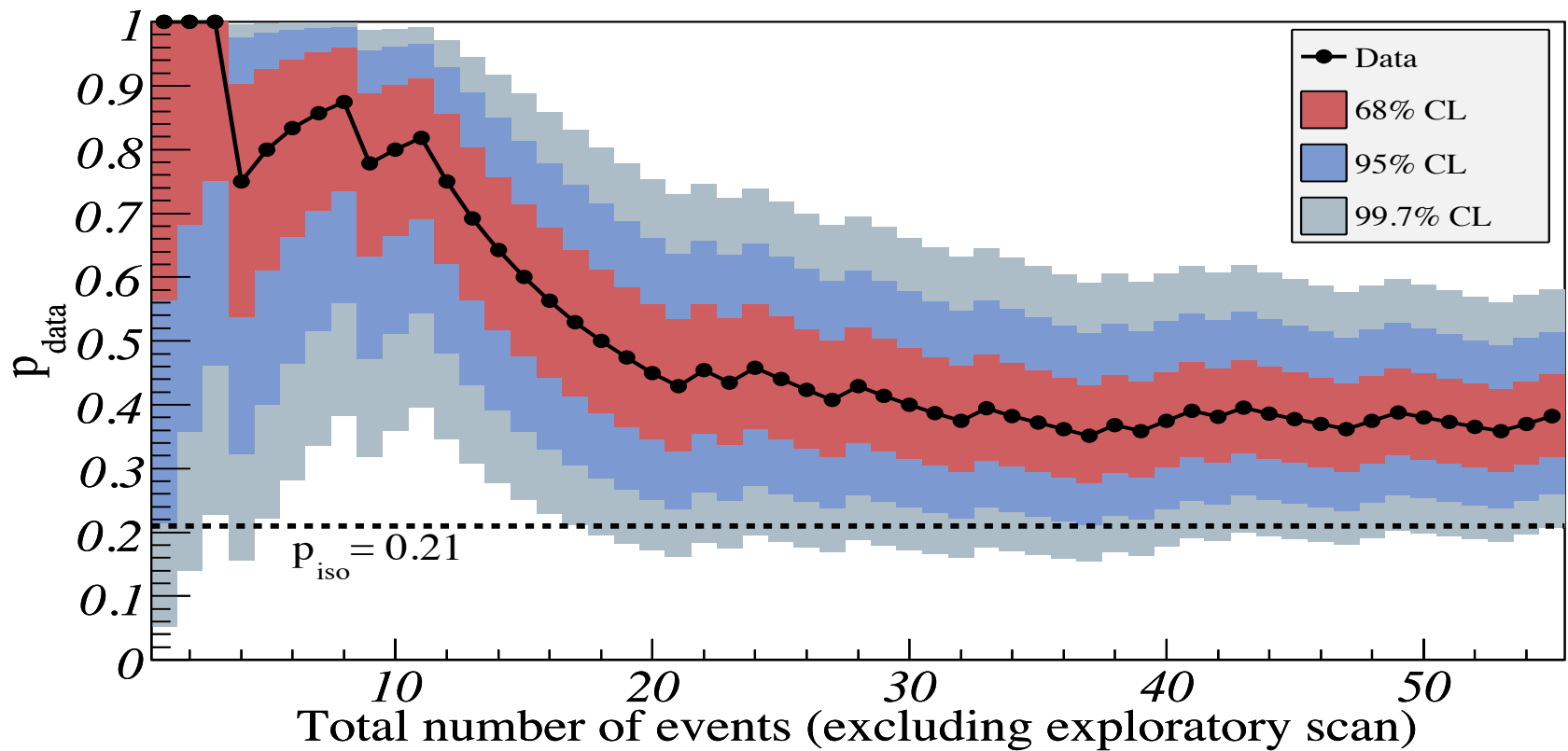
Anisotropy

Anisotropy (Astropart. Physics 34, 314 (2010))

69 events with $E \geq 55 \text{ EeV}$ (up to 31 Dec 2009)



Anisotropy: Astrop. Phys 34, 314 (2010)

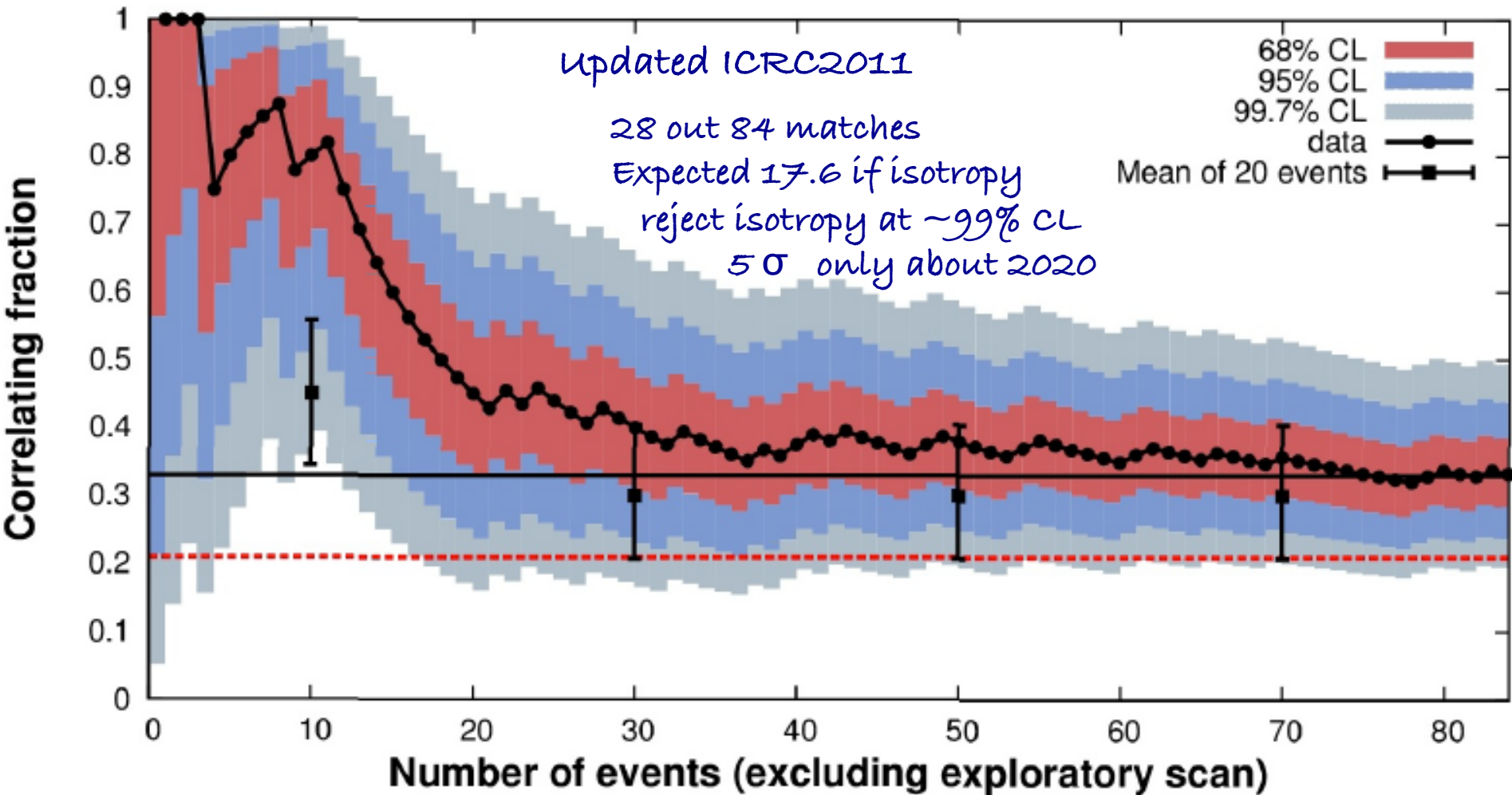


$$P(p|N, k) = \frac{\Gamma(N + 2)}{\Gamma(k + 1)\Gamma(N - k + 1)} p^k (1 - p)^{N-k}$$

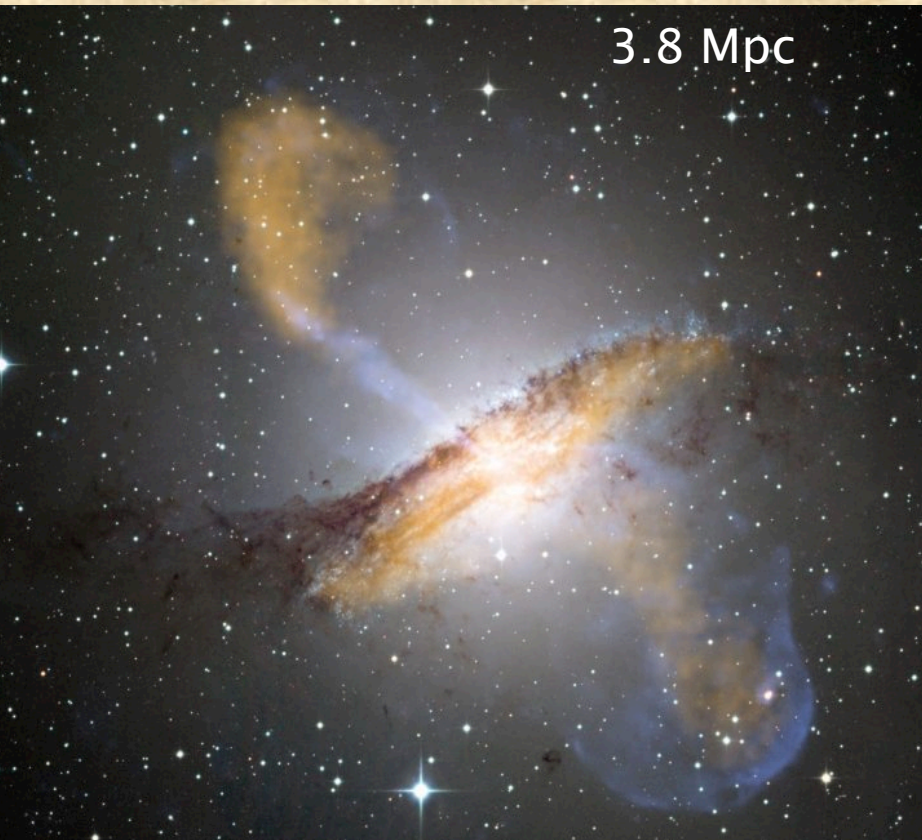
Isotropy of UHECR rejected at 99% CL
 correlation reduced from ~70% to ~40%
 stabilizing around ~40%

Posterior probability
 distribution for p (strength)

Anisotropy

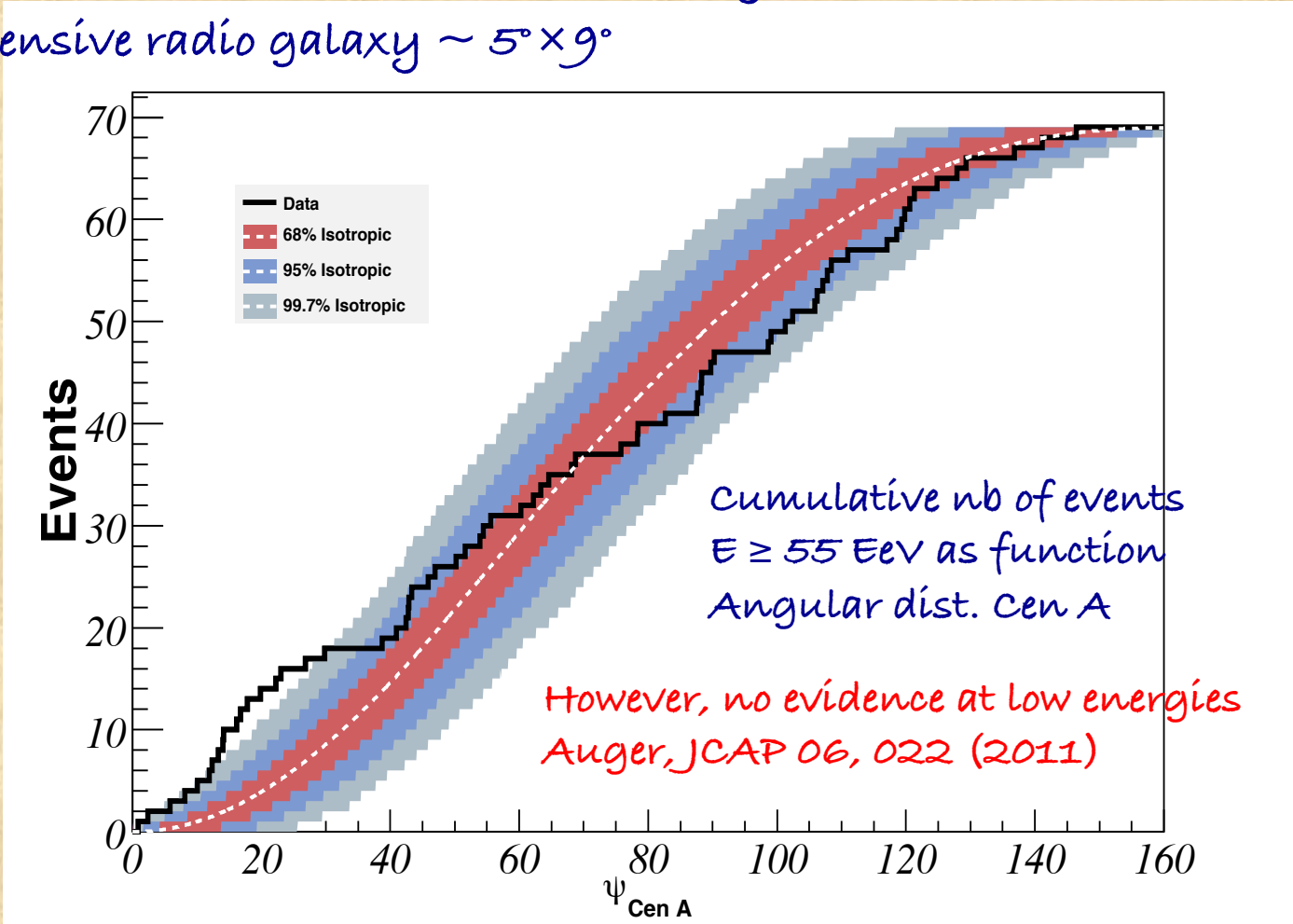


Centaurus A (NGC 5128)



Centaurus A

- Centaurus A: closest AGN (3.8 Mpc)
- Central nucleus of this AGN is seen by HESS and FERMI-LAT
- Extensive radio galaxy $\sim 5^\circ \times 9^\circ$





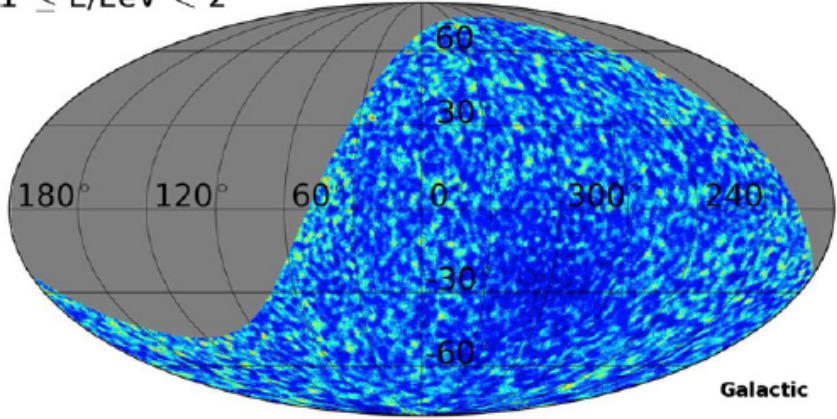
Neutron Point Sources

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 gamma rays from some sources in the galaxy, could be associated to neutron fluxes detectable by Auger
- Select SD events with $\theta \leq 60^\circ$, good event reconstruction
- Exposure of $24,880 \text{ km}^2 \text{ sr yr}$, with 429,138 events with energy $\geq 1 \text{ EeV}$
- Energy is the same as for the spectrum

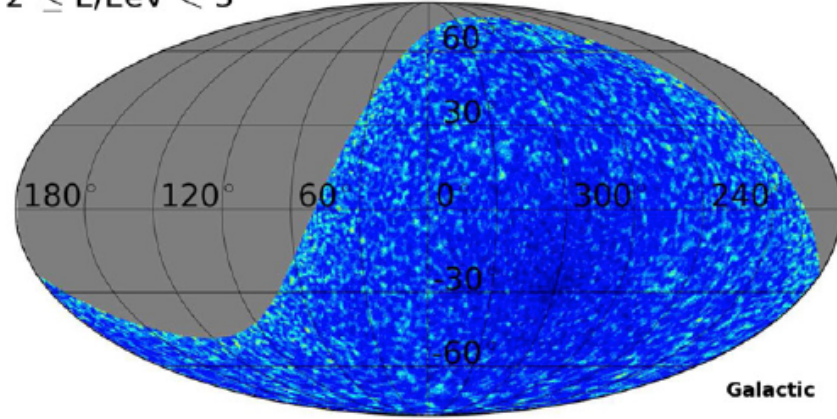
Neutrons point sources

$1 \leq E/E_{\text{eV}} < 2$



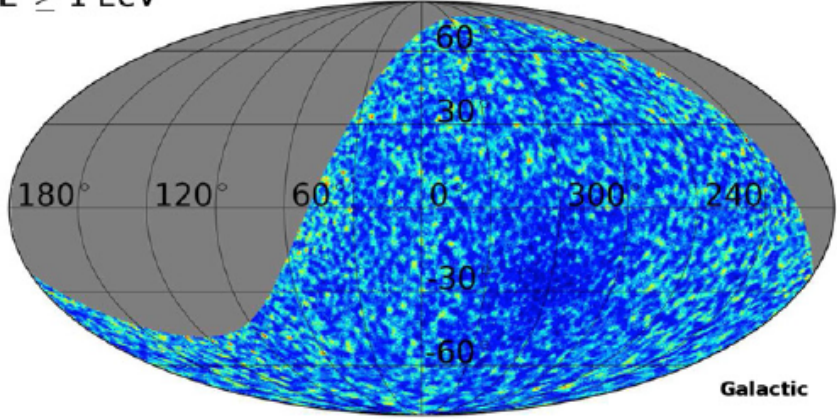
0.0027 $1/(km^2 yr)$ 0.037

$2 \leq E/E_{\text{eV}} < 3$



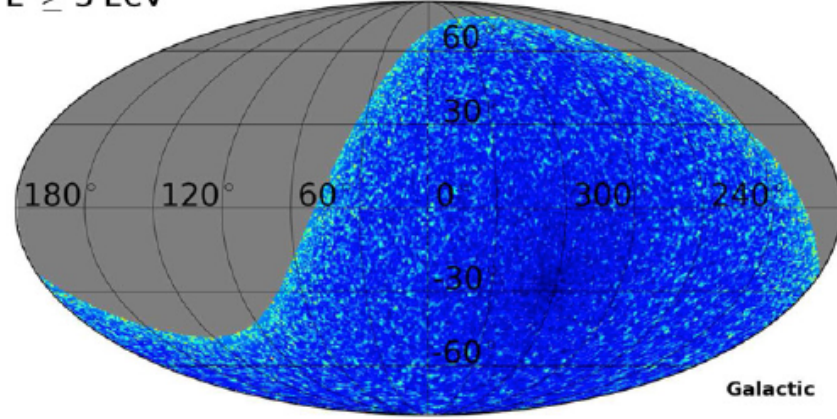
0.00072 $1/(km^2 yr)$ 0.017

$E \geq 1 \text{ EeV}$



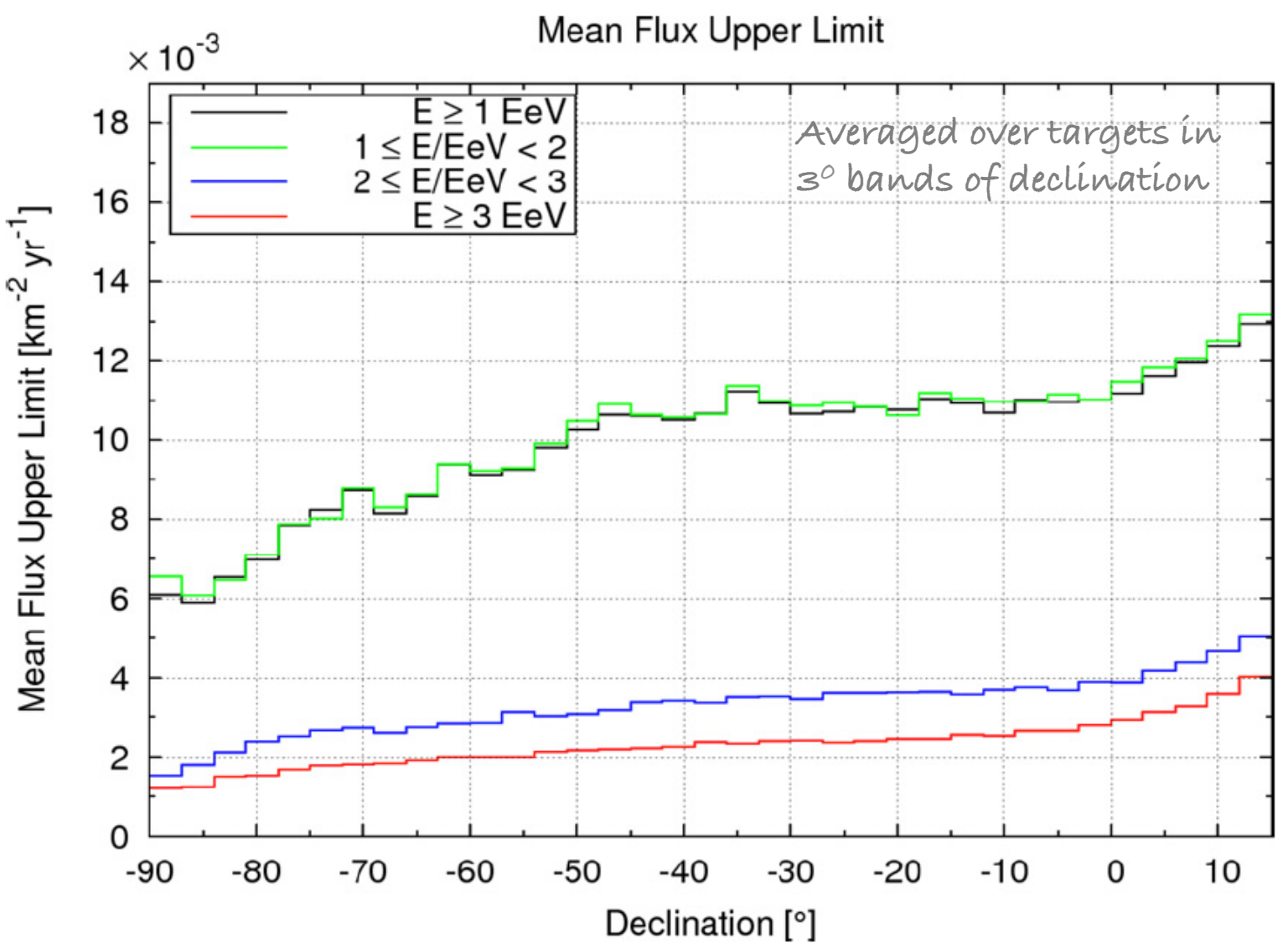
0.0025 $1/(km^2 yr)$ 0.035

$E \geq 3 \text{ EeV}$



0.00071 $1/(km^2 yr)$ 0.011

Neutrons point sources (Upper limits)



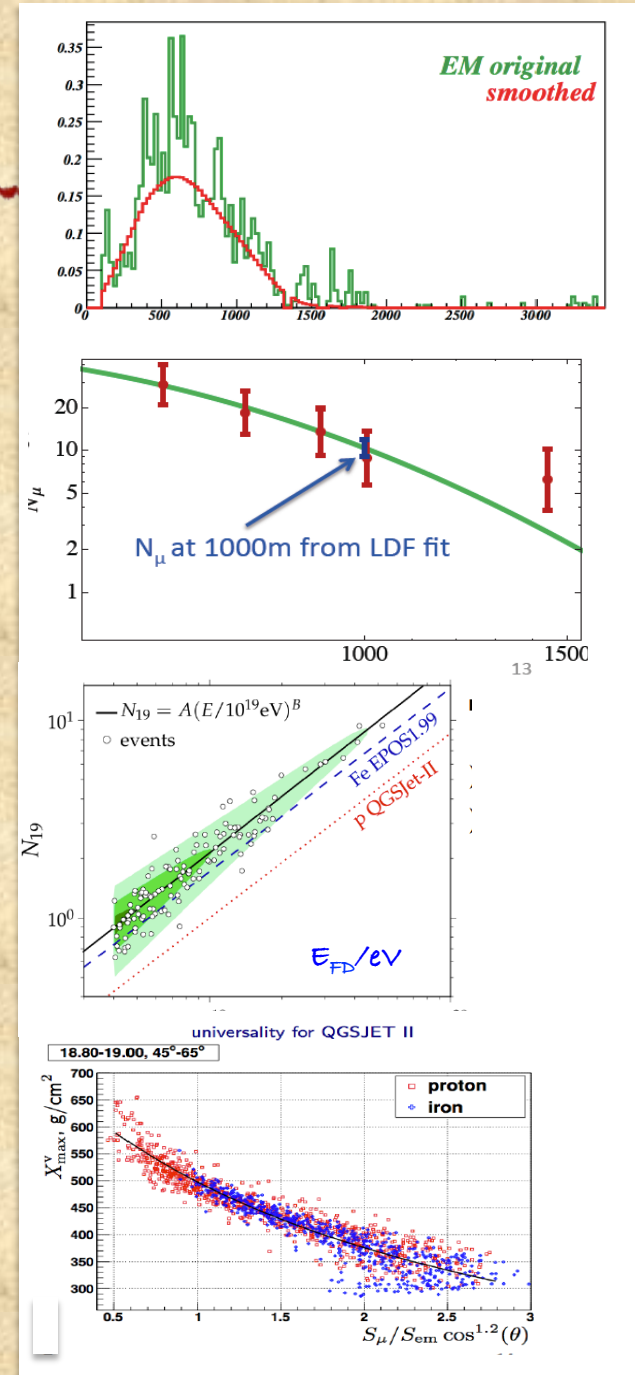


Muon Shower content

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 $N_{19} \propto N_{\mu}$

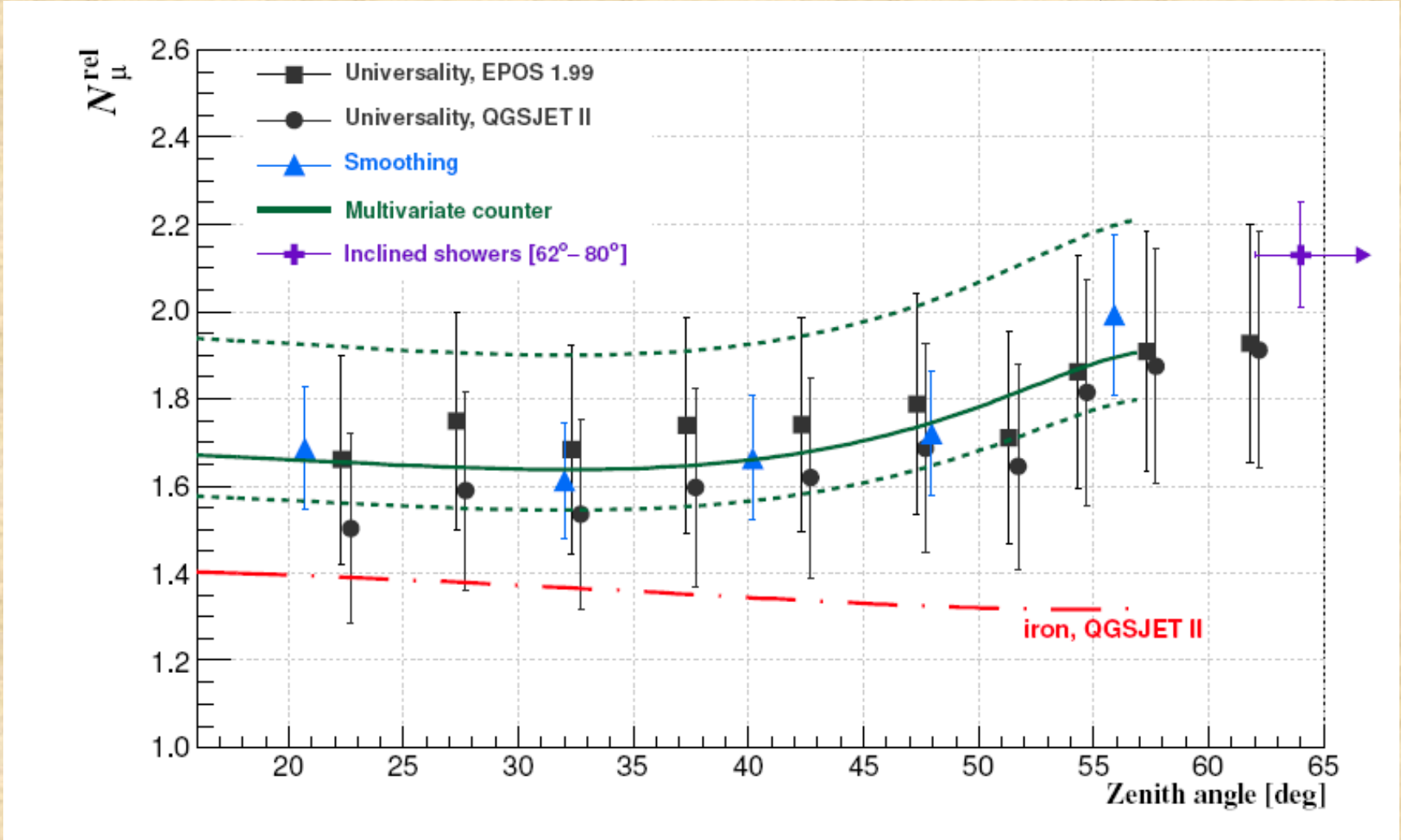


$$\frac{N_{\mu}^{data}}{N_{\mu}^{MC}} = \frac{N_{19}^{data}}{N_{19}^{MC}} = \frac{A(E_{FD}/10\text{EeV})^B}{A_{MC}(E_{FD}/10\text{EeV})^{B_{MC}}}$$

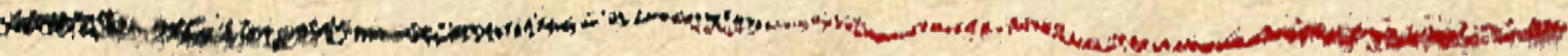
• Shower universality

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

MUONS

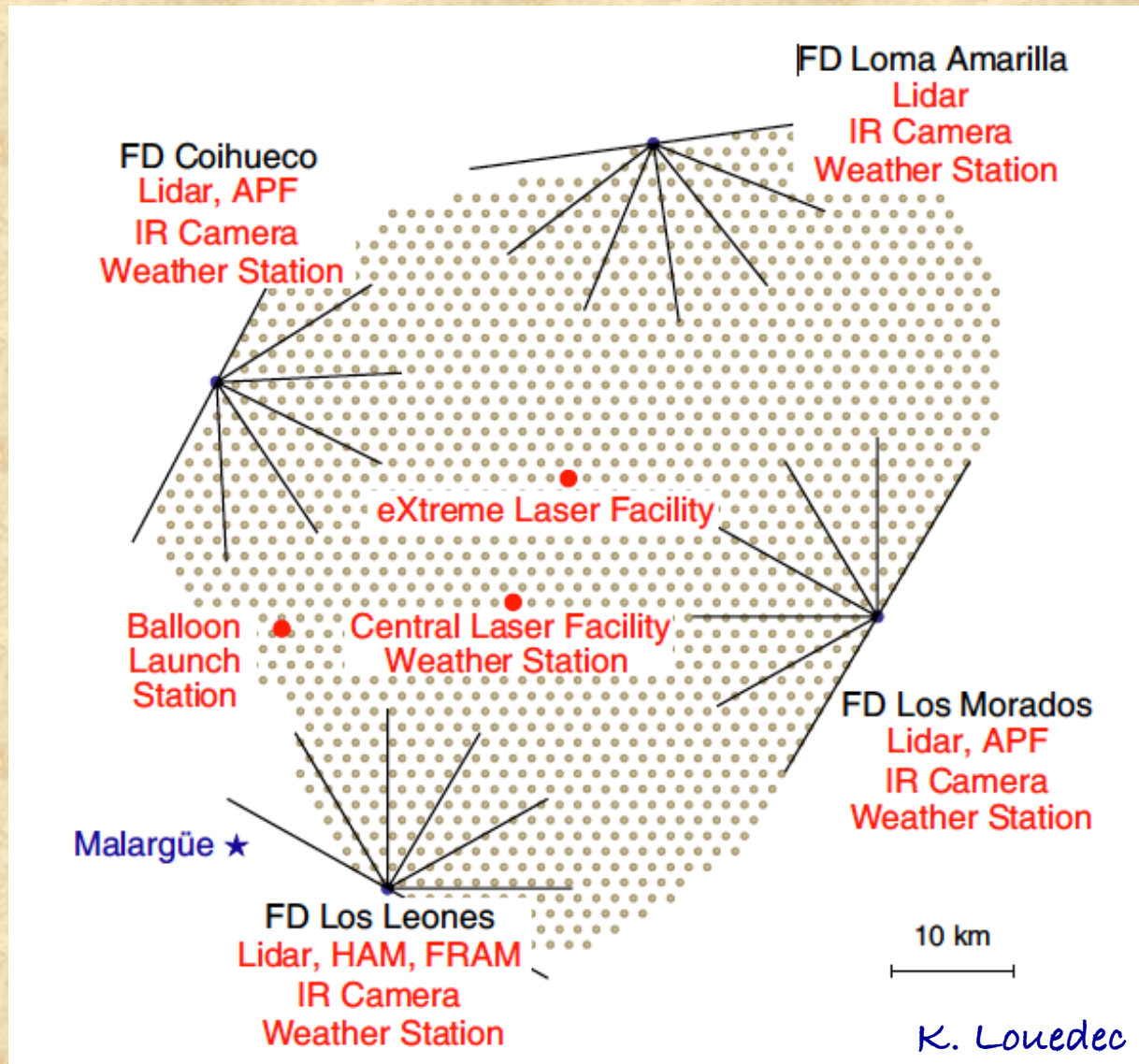


Auger upgrades focused on better resolution of muon contents of the showers



Weather station

Atmospheric monitoring and calibration



Weather station

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

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

Auger is sensitive to Elves, which occur very far away

Detecting Elves

R. MUSSA

LM6-800414142

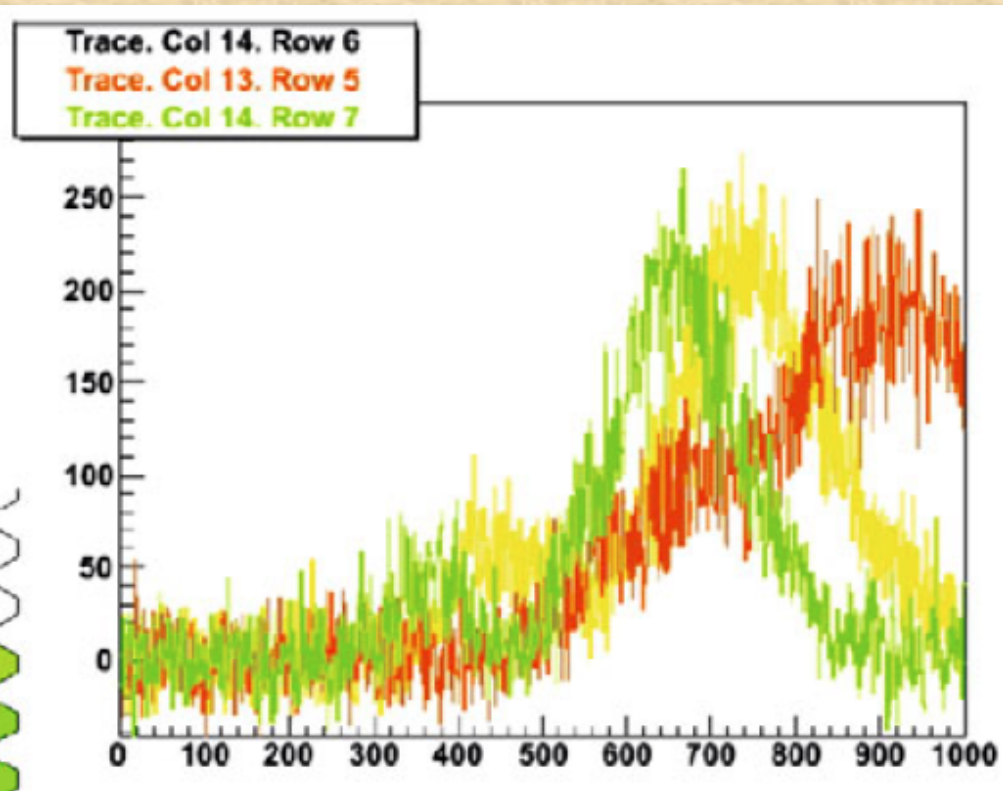
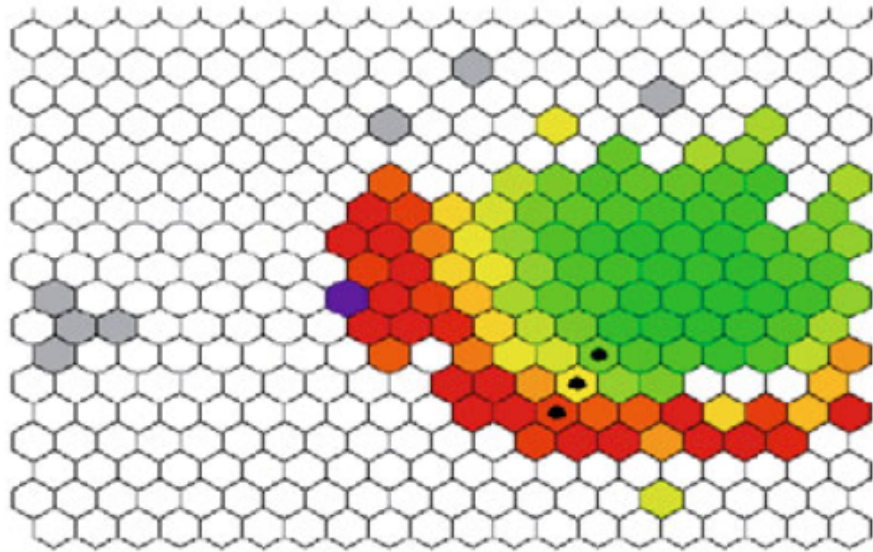
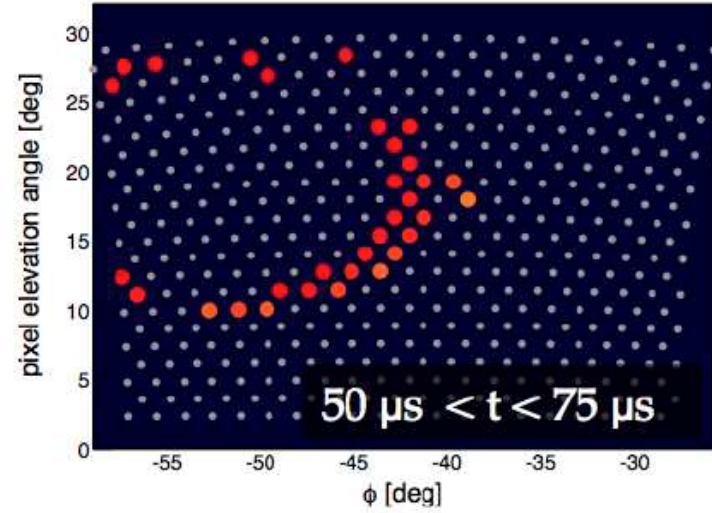
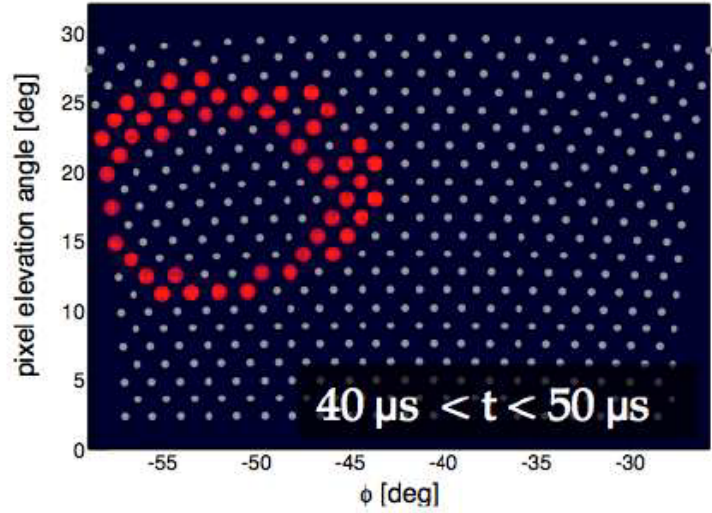
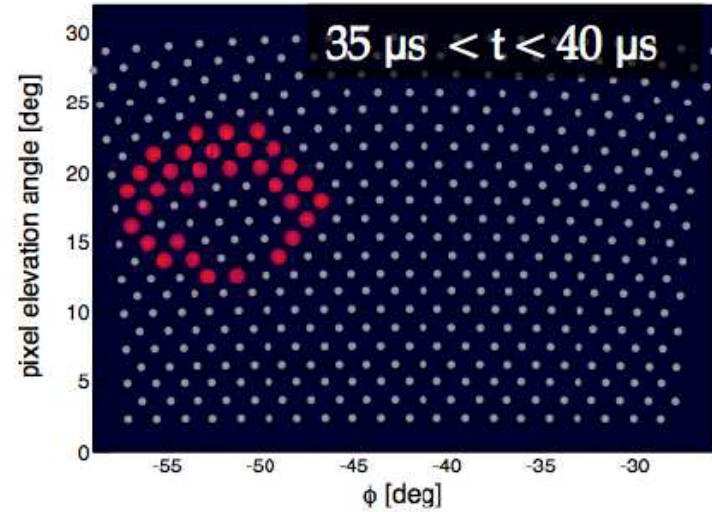
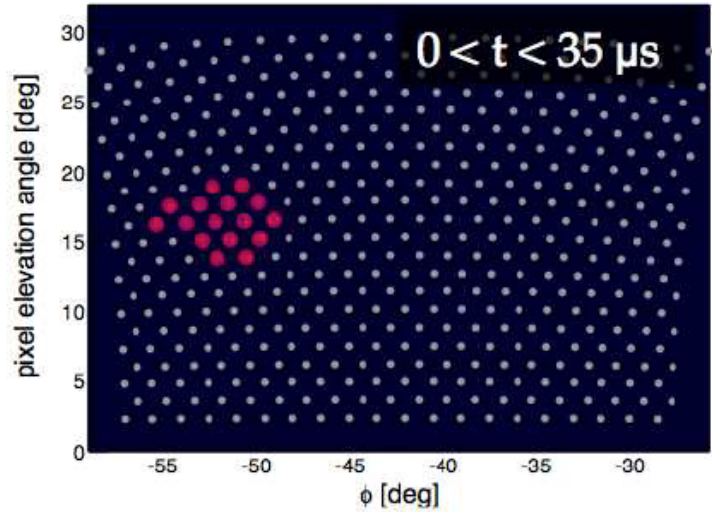


Fig. 1. The first event, observed at GPS time 800414142. Left: triggered pixels in LM-6 (pixel colors indicate the pulse timing: green pixels come earliest, red pixels are the last to fire; grey pixels are discarded in further analyses). Right: the FADC traces for the 3 pixels indicated by black dots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

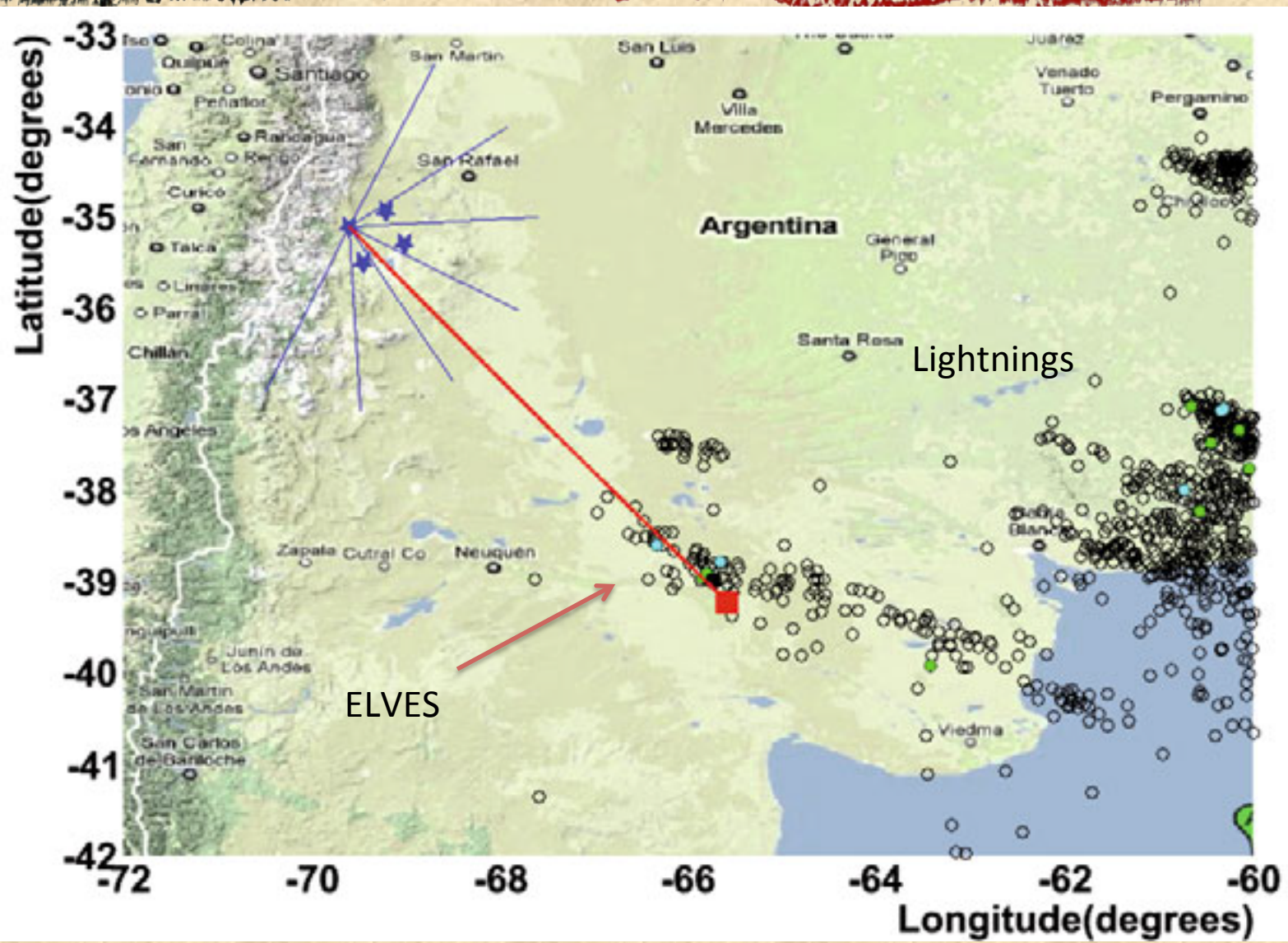
Detecting Elves

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].

GPS SEC: 000000210



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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