Recent results from the Pierre Auger Observatory

Carola Dobrigkeit for the Pierre Auger Collaboration

EXPLORING
the terascale and beyond

Exploring the terascale with cosmic rays……

- *This talk is about ultra-high-energy cosmic rays...*
- *... arriving at Earth with energies ~ 10^{18} - 10^{20} eV...*
- *... this means ~ 1 EeV – 100 EeV .*

A bit of history....

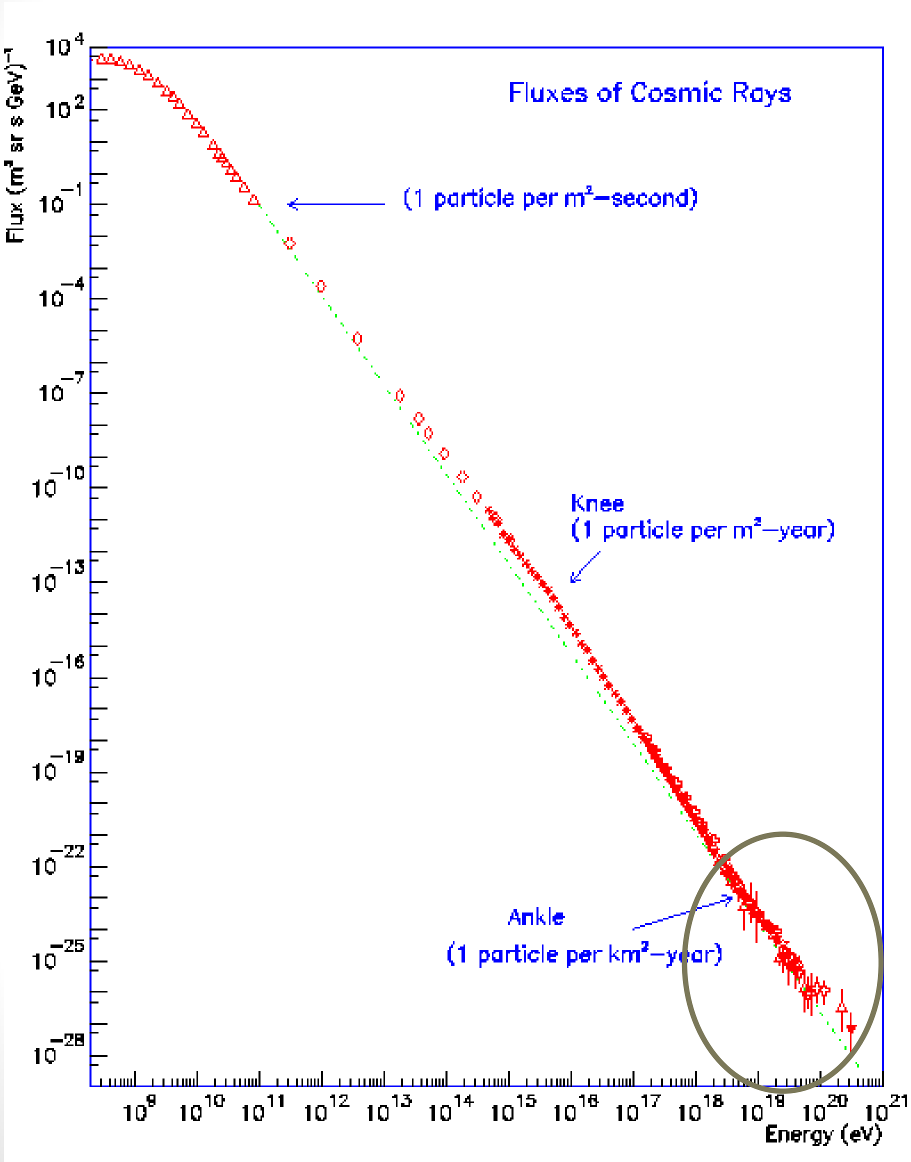
- Cosmic rays have been discovered in 1912 by Victor Hess.

- The first cosmic ray with a macroscopic energy of 10^{20} eV was observed in 1962 by John Linsley and Livio Scarsi in the Volcano Ranch array in New Mexico.

- In 1991 the Fly's Eye cosmic ray research group in the USA observed a cosmic ray event with energy estimated as 3×10^{20} eV (50 joule). Other events with energies around 10^{20} eV had been reported in the previous 30 years, but this was clearly the most energetic! It was known as the ***Oh-My-God particle*.**

- In 1994 The AGASA group in Japan and the Yakutsk group in Russia each reported an event with an energy of 2×10^{20} eV.

The cosmic ray flux



- Almost 12 orders of magnitude in energy
- Almost 33 orders of magnitude in flux

~ 3 – 5 10^{15} eV: knee

limiting energy galactic CR accelerators; onset of diffusion losses from the galaxy

~ 10^{17} eV : second knee

fading of heavy galactic CR component

~ 3 10^{18} eV: ankle

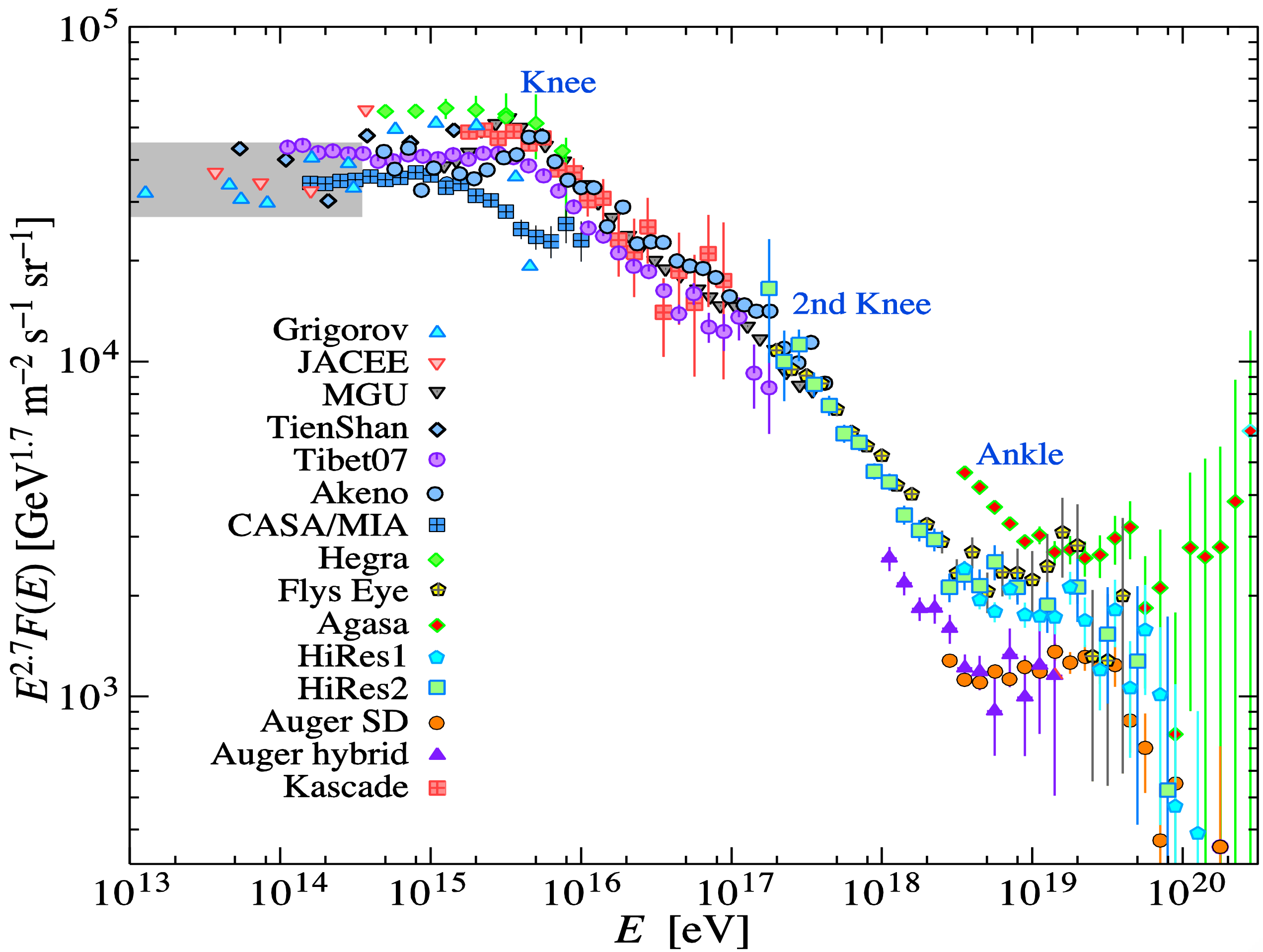
onset of the extragalactic CR component; energy losses of extragalactic protons by pair production

~ GZK cuttof around 6 x 10^{19} eV

interaction with the CMB

J. Cronin, T.K. Gaisser, and S.P. Swordy, Sci. Amer. 276, 44 (1997)

The all-particle spectrum from air shower measurements…



PDG: K. Nakamura et al., JPG 37, 075021 (2010) (http://pdg.lbl.gov)

The shaded area shows the range of the direct cosmic ray spectrum measurements.

The UHE cosmic-ray puzzle: open questions...

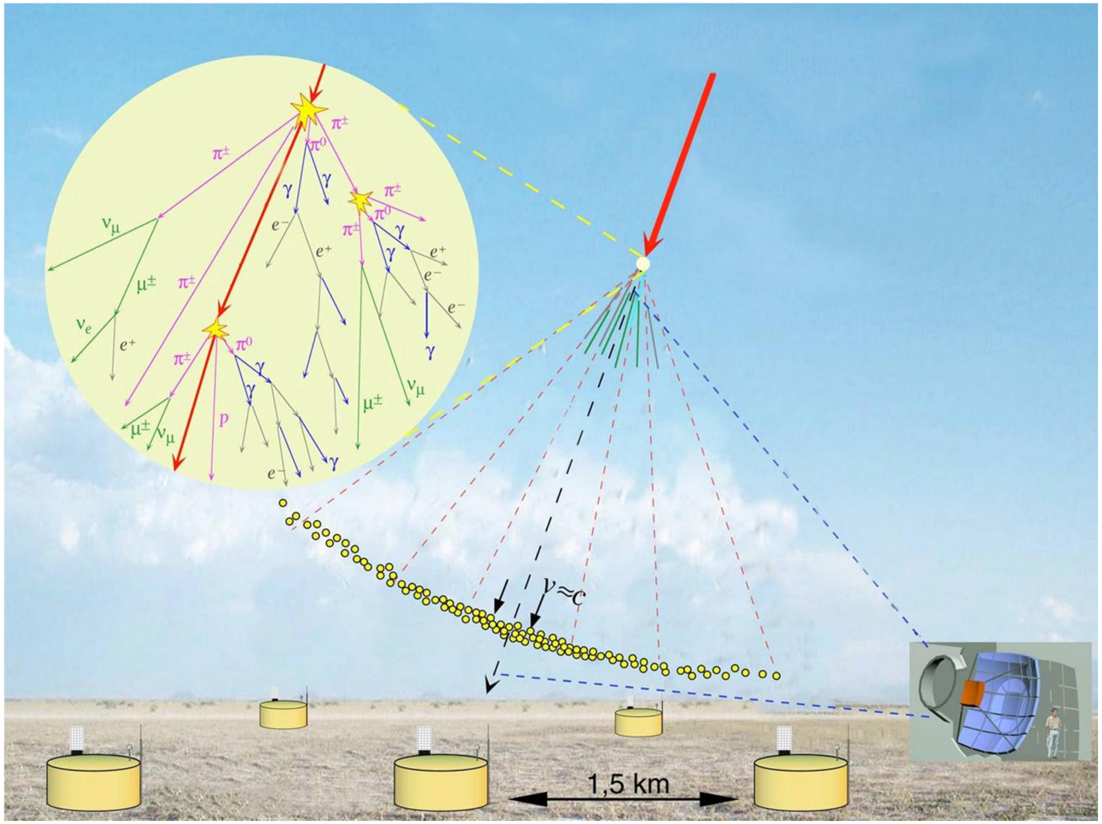
- How cosmic rays are **accelerated** at $E > 10^{19}$ eV ?
- What are the **sources**?
- How can they **propagate** along astronomical distances at such high energies?
- What can we learn about **cosmic objects**, **large-scale structure** of the universe and **magnetic fields**?
- Can we do **particle astronomy**?
- What can we learn about **particle interactions** at these otherwise inaccessible energies, which reach 450 TeV in the center-of-mass system?
- What is the **mass composition** of cosmic rays?

The Pierre Auger Observatory

- **It is the largest cosmic ray array ever built.**
- **Its main scientific goal is studying cosmic rays in the highest energy region(10^{18} eV $\leq E \leq 10^{20}$ eV) in order to get clues about their origin, acceleration mechanisms and propagation, composition, energy spectrum, angular distribution and their interactions.**
- **It combines two complementary detection techniques (hybrid detection).**
- **Is taking data since 2004 and construction finished in 2008.**

What do we measure?

At these high energies, cosmic rays are observed through the air showers they produce in the atmosphere....



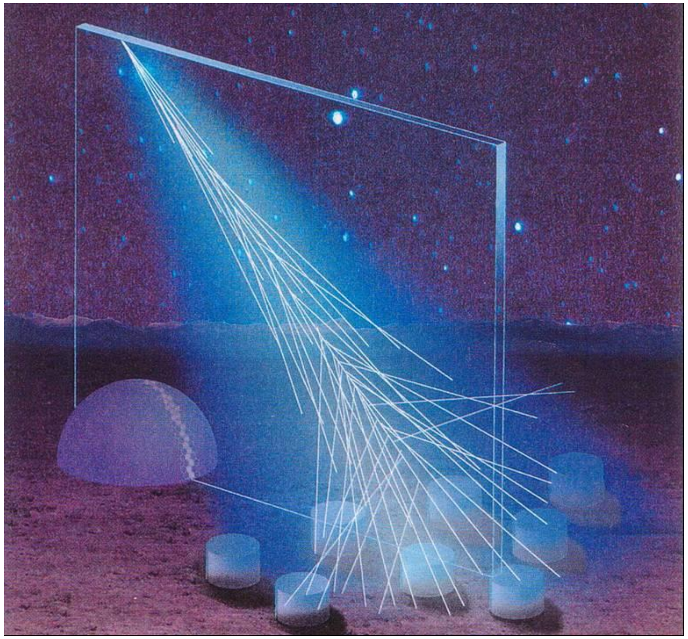
Hybrid detection:

Fluorescence Detector:

- **Almost calorimetric energy measurement**
- **Longitudinal development**
- **10-15% duty cycle**
- **Complex acceptance calculation**

Surface Detector Array:

- **100% duty cycle**
- **Simple geometrical acceptance**
- **Extracting primary energy and mass is model dependent**

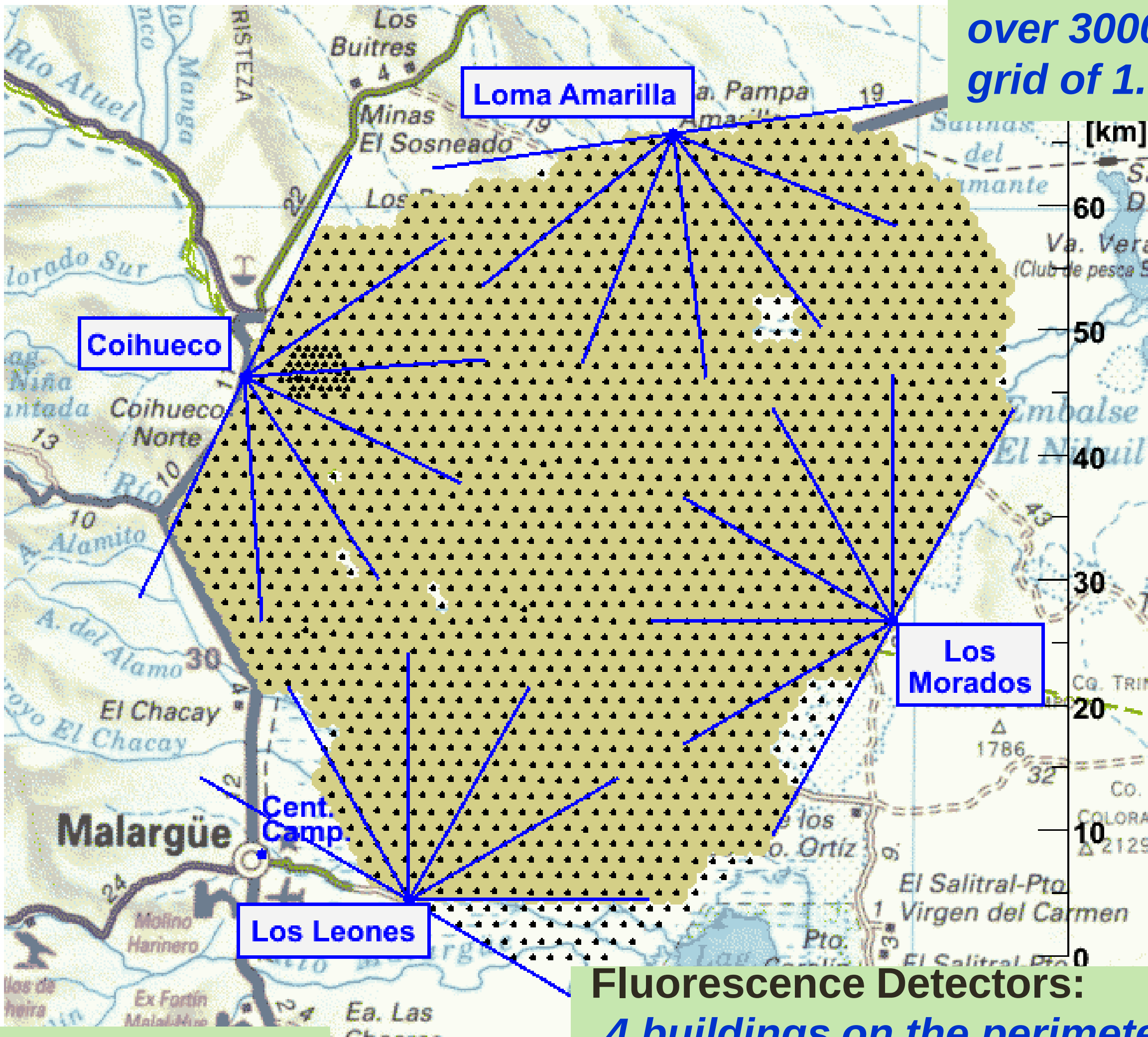


Combining both techniques allows:

- **cross calibration in energy**
- **better angular resolution**

The Pierre Auger Observatory

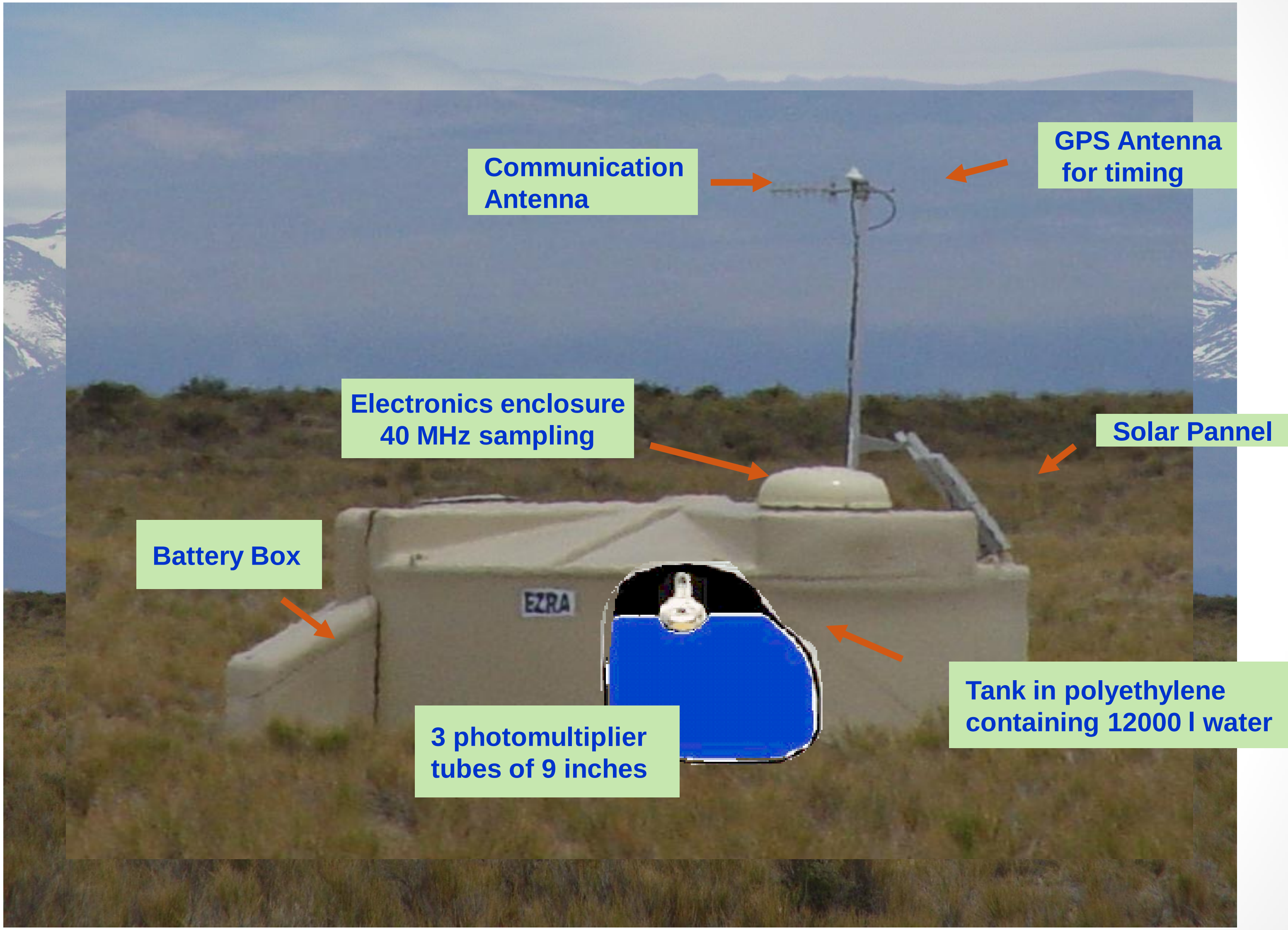
Surface array:
1660 stations displayed over 3000 km² on a grid of 1.5 km side.



Total area ~ 3000 km²
Aperture ~ 7000 km² sr

Fluorescence Detectors:
4 buildings on the perimeter of the array housing 24 telescopes, angle 2°-32° elevation

A surface station (SD)



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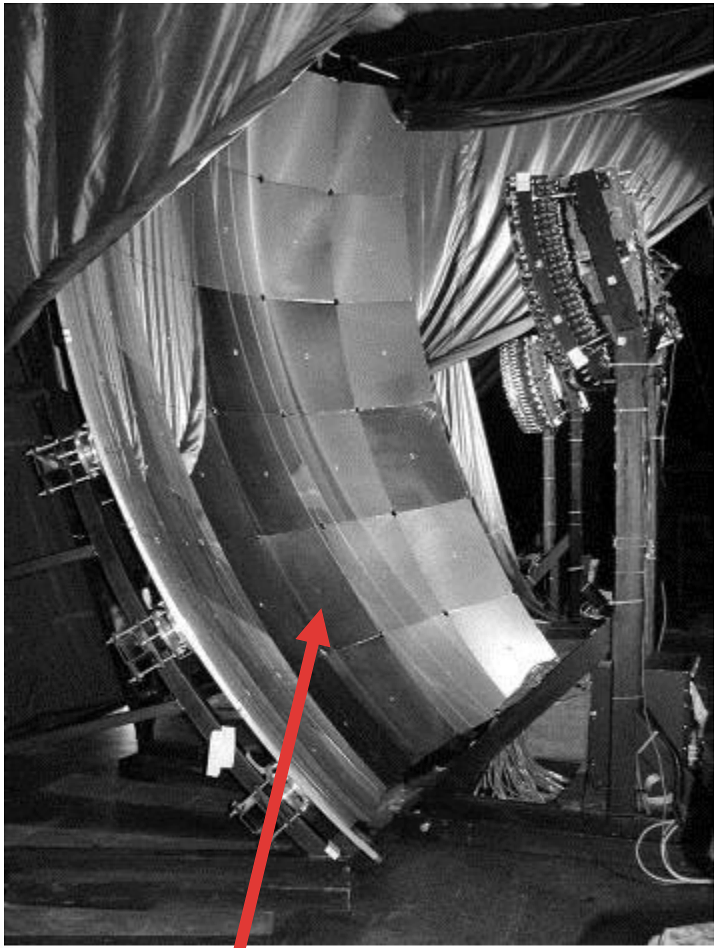
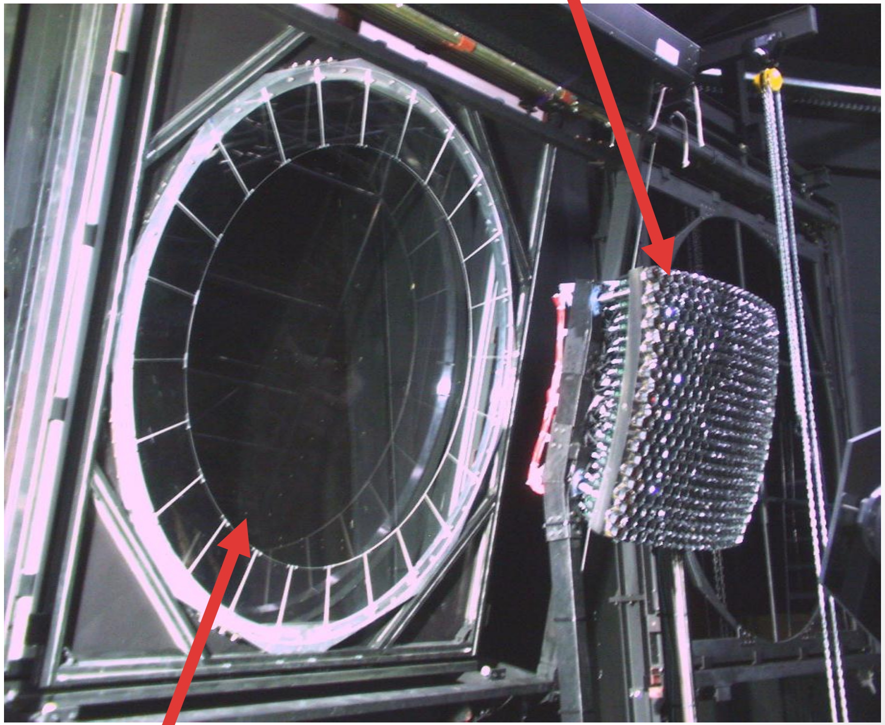
A fluorescence telescope (FD)



mirror 3 m^2

440 pixel camera
10 MHz sampling



aperture, corrector ring and filter

Atmospheric Monitoring and Calibration

Atmospheric Monitoring

Central Laser Facility

LIDAR in each fluorescence detector building

Absolute Calibration

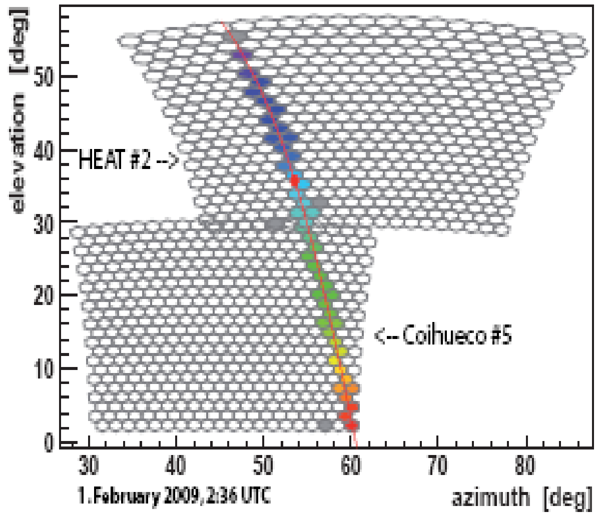
Drum for uniform illumination of the camera used for calibration.

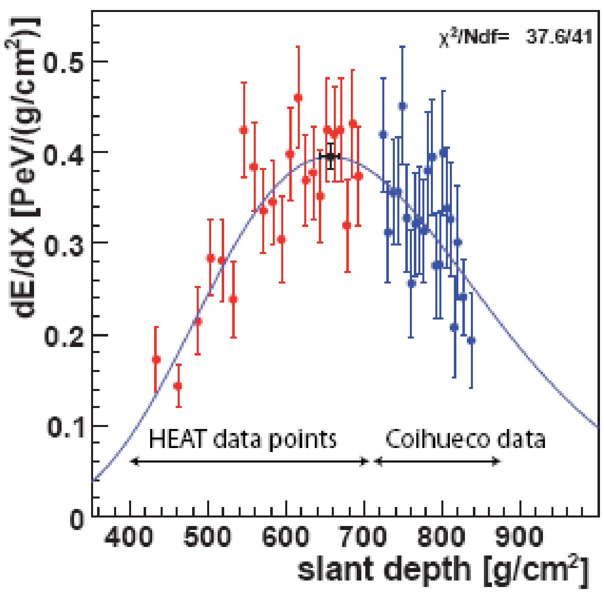
Enhancements...

Goals:

- Enable observation of CRs of lower energies, extending measurements of the energy spectrum down to region of 2nd knee (10^{17} eV).
- Measure additional properties of showers to get more information about the nature of the primary particles.
- Test new detection techniques (MHz & GHz).

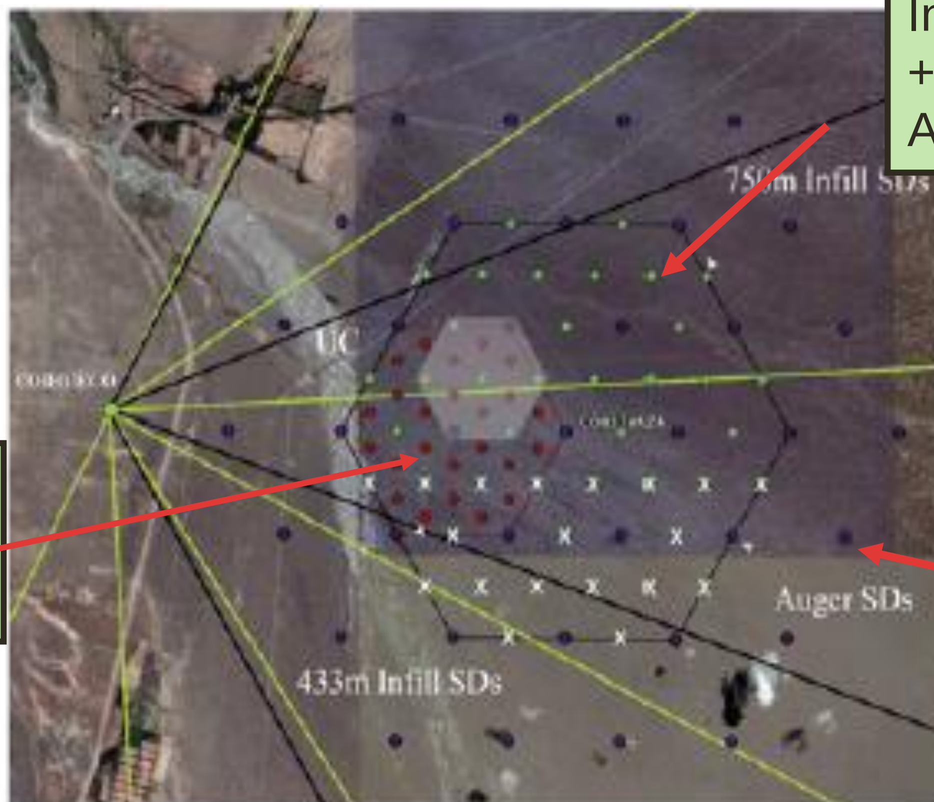
HEAT High Elevation Auger Telescopes





AMIGA (Auger Muon and Infill for the Ground Array)

Infill array 750m
+ 42 detectors
Area ~23.5 km^2

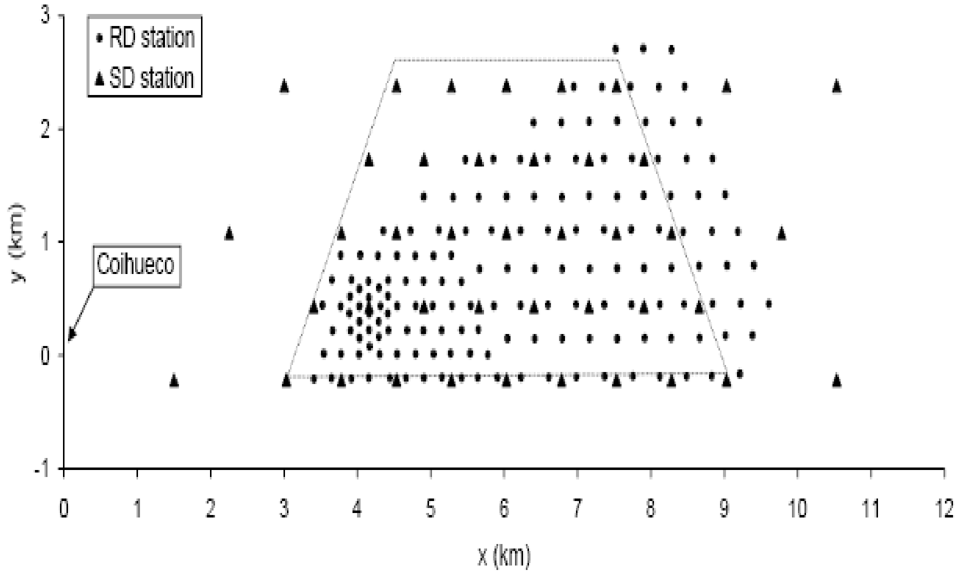


Infill array 433m
+ 24 detectors
Area ~5.9 km^2

Original tanks

Muon counters below each of the 85 tanks

AERA (Auger Engineering Radio Array)



Layout of AERA: Radio detector stations are put on triangular grids with grid constants of 175 m, 250 m and 375 m.

Further projects/ advances:

Air-shower detection through molecular Bremsstrahlung emission in the microwave band

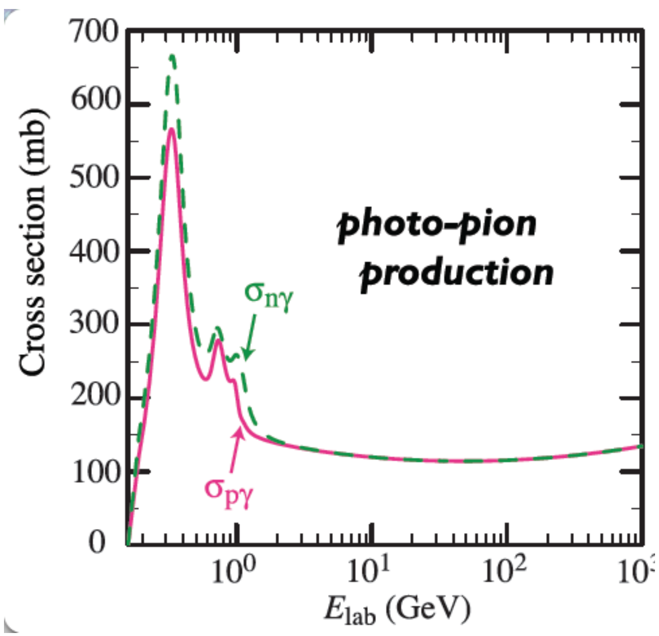
Energy Spectrum

Why cosmic rays of 10^{20} eV must come from "nearby" ?

- $p + \gamma_{CMB} \rightarrow p + e^- + e^+$

or

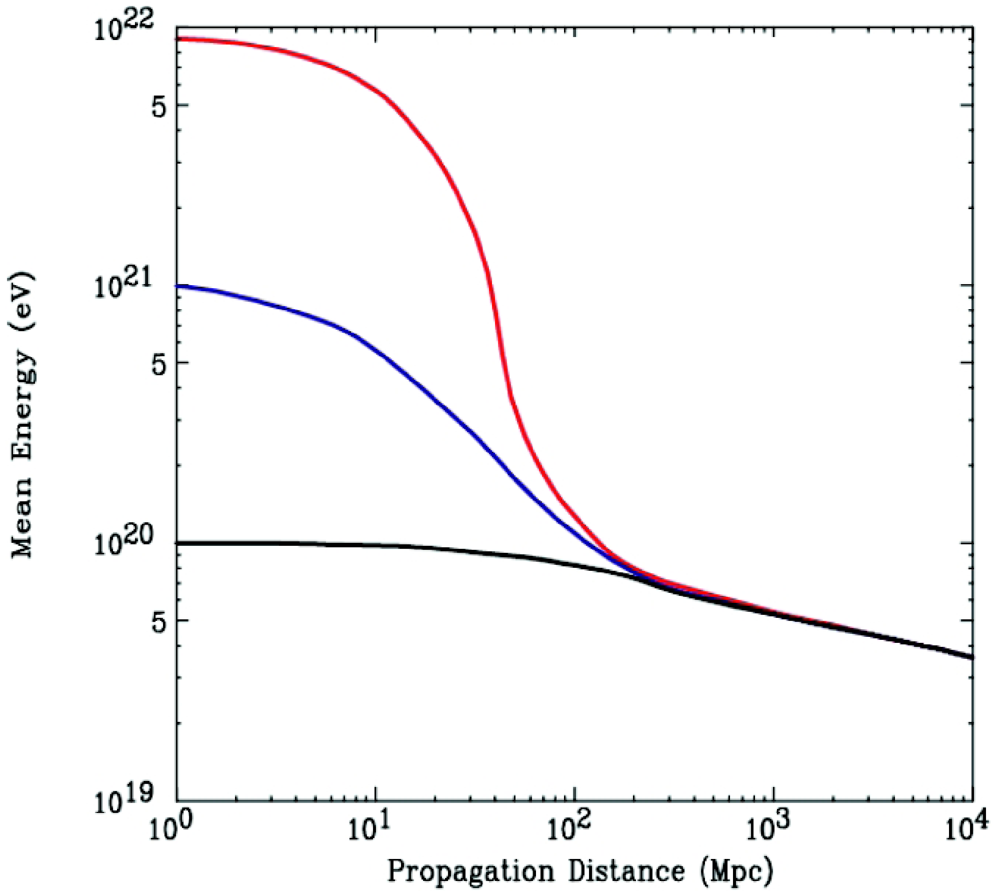
- $p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$
- $\rightarrow \Delta^+ \rightarrow n + \pi^+$
- $\rightarrow \Delta^+ \rightarrow p + \pi^0 + \pi^0$



etc..

Universe is opaque for $E > E_{GZK}$!
Direct test of Lorentz transformations at extreme energies!

The GZK horizon*:



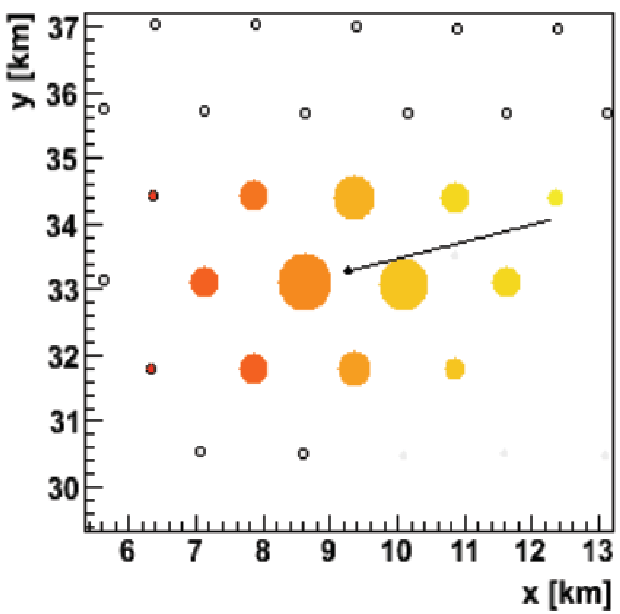
Cosmic rays of 10^{20} eV must come from “nearby”(≤200Mpc)

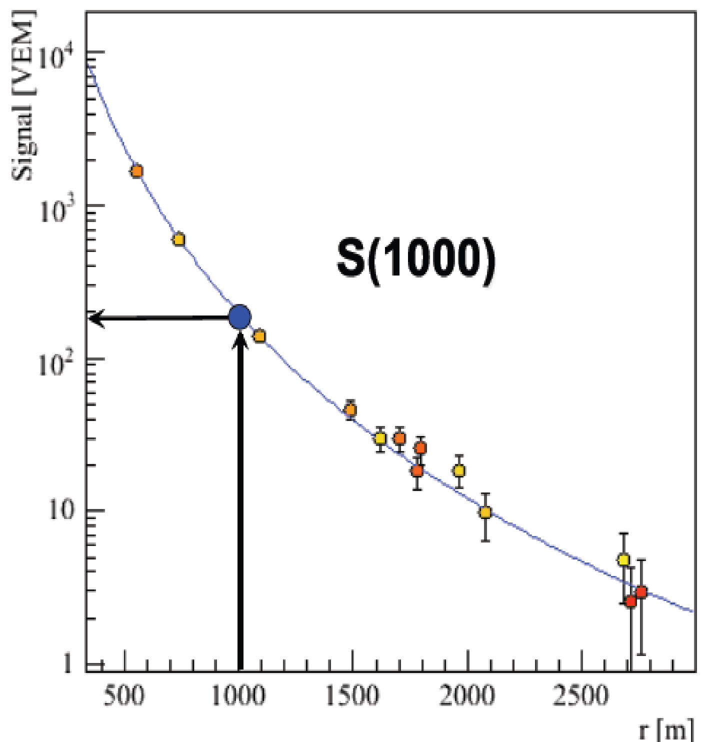
* Prediction: Greisen and Zatsepin & Kuzmin in 1966.

Energy spectrum....

- What do we need to know in order to measure the cosmic ray spectrum and the flux??
- How many particles above a certain energy and area, time, solid angle spanned by the detector...

An example of an SD observation

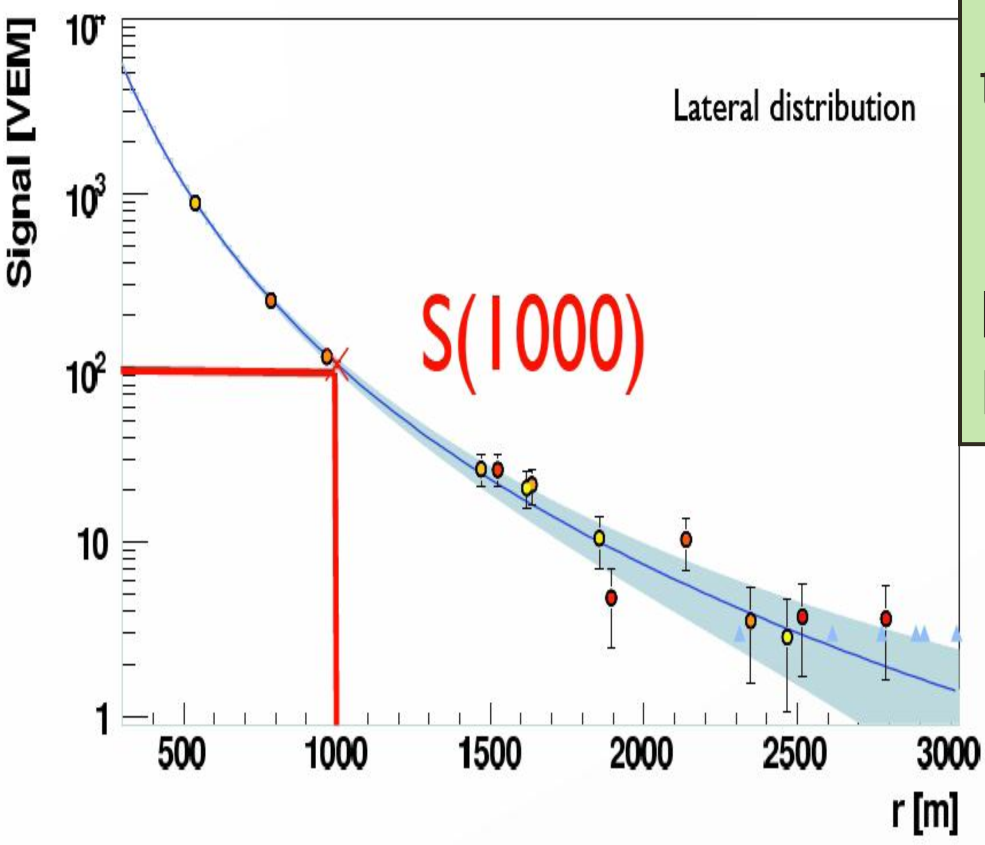




- Fit with Lateral Distribution Function (NKG type)
- Parameters determinated from fit: core position, S(1000)

S(1000) good energy estimator

Energy estimator: signal @ 1000 m from the core

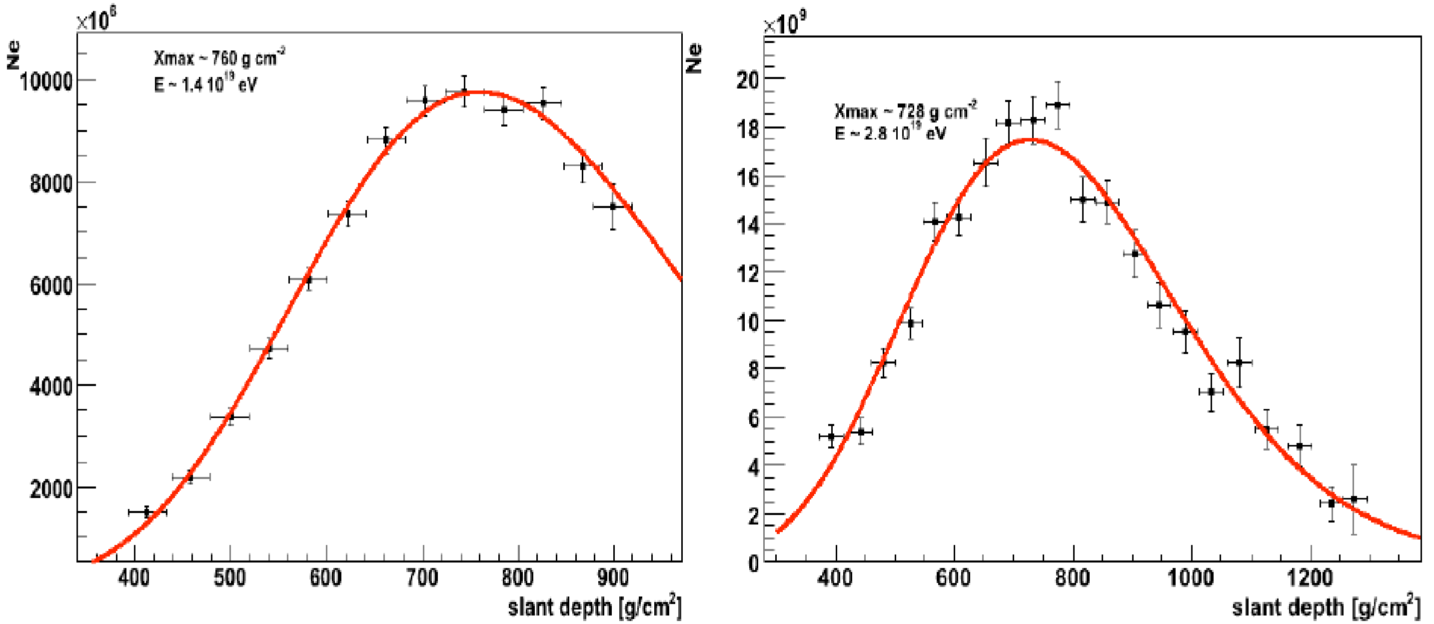


Energy estimator: **S(1000)**

- Relate **S(1000) to S_{38}** to correct for attenuation
- Relate S_{38} to E_{FD} using hybrid events with SD & FD data

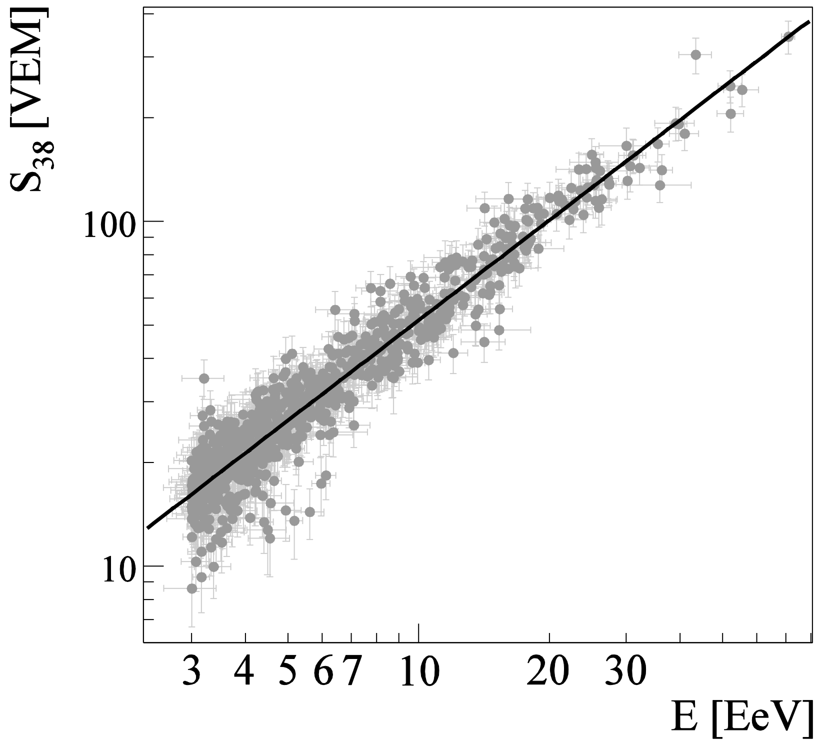
An example of an FD observation

Calorimetric measurement of the energy.



Longitudinal profile: energy deposit in the atmosphere as a function of slant depth

Combining SD x FD...

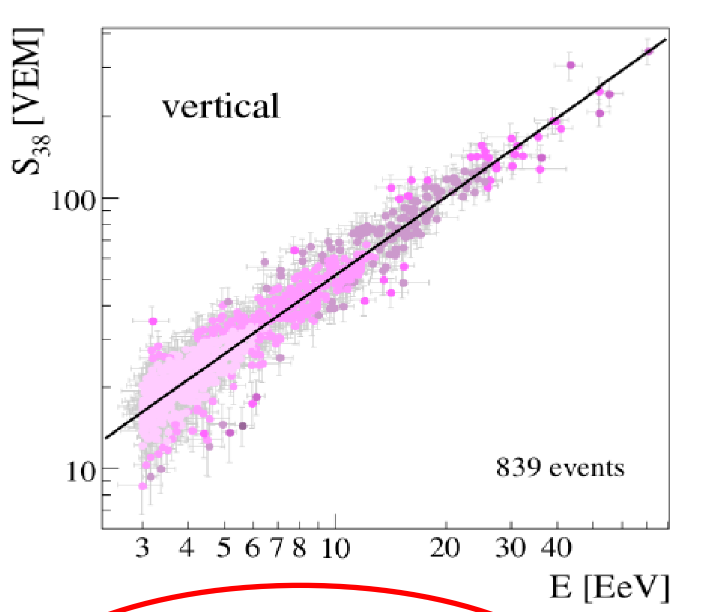


Correlation between S38 and E for the 839 selected hybrid events used in the fit. The most energetic event has an energy of about 75 EeV.

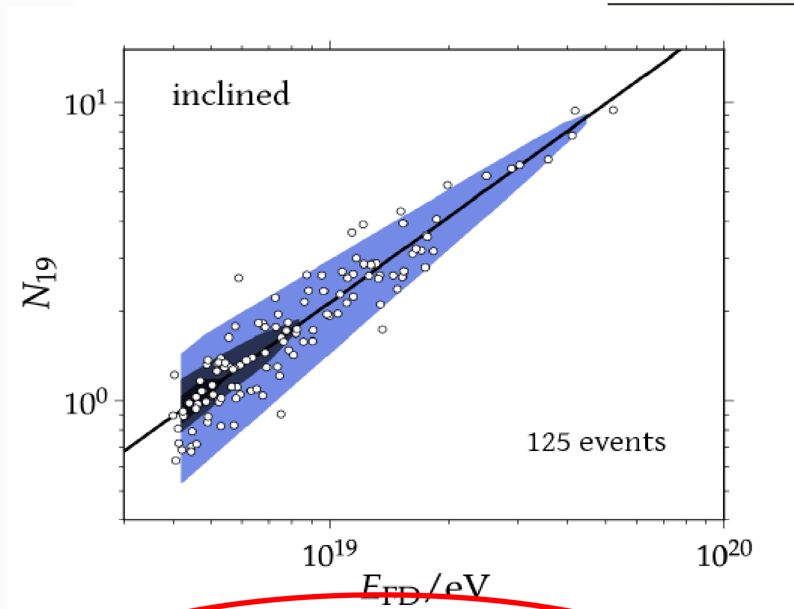
Pesce for the Auger Collab. Proc.32nd ICRC2011

SD energy calibration

- Energy calibration with events recorded by both FD and SD
- High quality events (+ fiducial field of view for vertical events)



- $E_{SD}^{\text{vertical}} = A \cdot S_{38}^{B}$
  $A = (1.68 \pm 0.05) \times 10^{17}\,\text{eV}$
  $B = 1.035 \pm 0.009$
- systematic uncertainties:
  7% (15%) at 10 EeV (100 EeV)

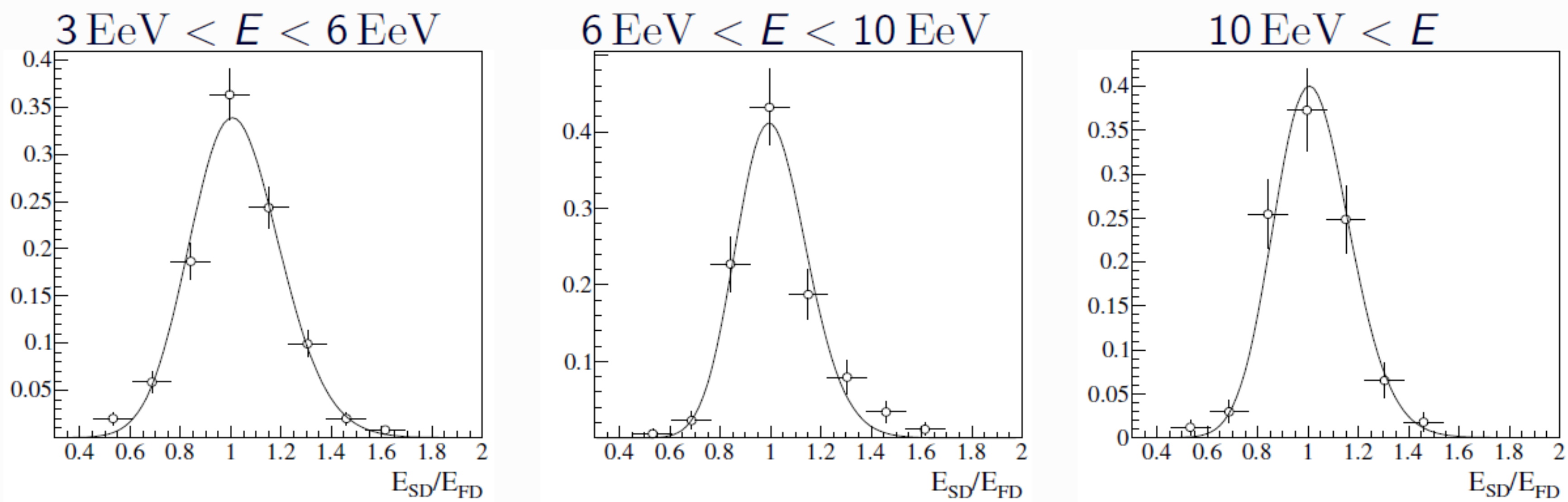


- $E_{SD}^{\text{inclined}} = A \cdot N_{19}^{B}$
  $A = (4.69 \pm 0.09) \times 10^{18}\,\text{eV}$
  $B = 1.05 \pm 0.02$
- systematic uncertainties:
  13% (50%) at 10 EeV (80 EeV)
- muon deficit in simulations

I. Maris for Pierre Auger Collab, UHECR Symposium 2012, CERN

SD energy resolution

obtained from the golden hybrid events

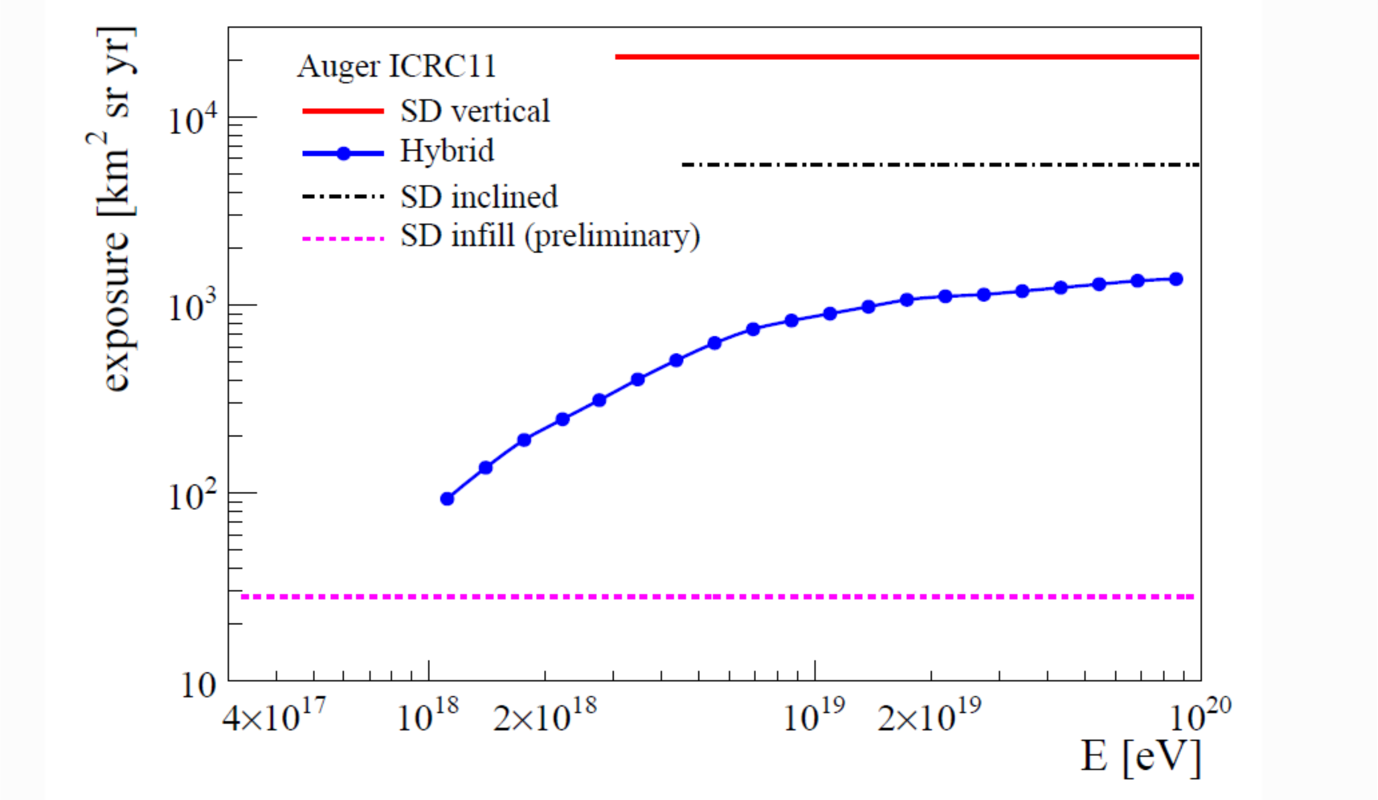


$\sigma_{SD}/E_{SD} = (16 \pm 1)\%$ $\sigma_{SD}/E_{SD} = (13 \pm 1)\%$ $\sigma_{SD}/E_{SD} = (12 \pm 1)\%$

Contributions:

- shower-to-shower fluctuations $\approx 10\%$
- reconstruction uncertainties 12% at 3 EeV and 6% above 10 EeV

The different exposures...



Exposures @ 10 EeV : SD vertical 20905 km^2 sr year
Hybrid 885 km^2 sr year
SD inclined 5600 km^2 sr year
SD infill 26 km^2 sr year

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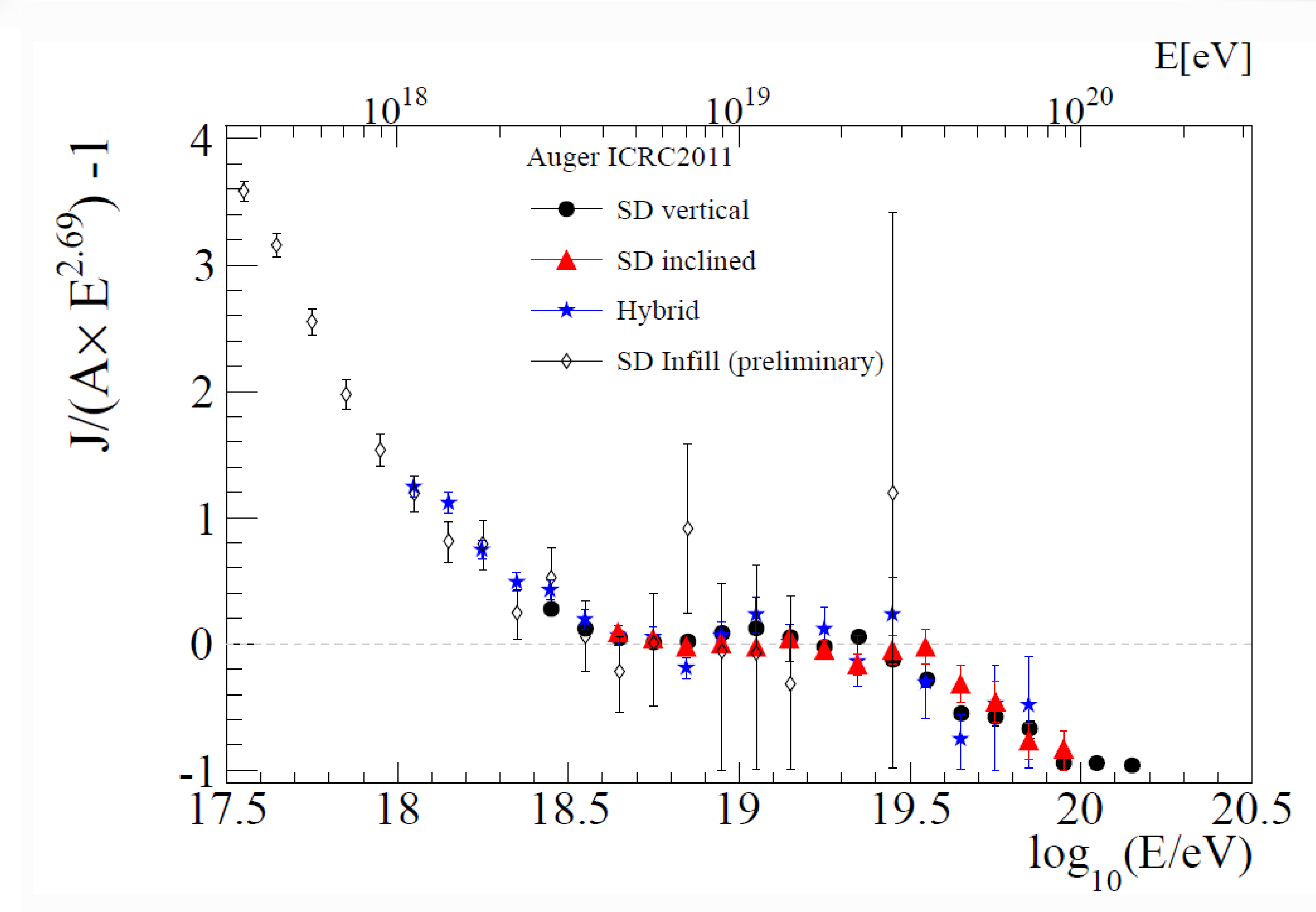
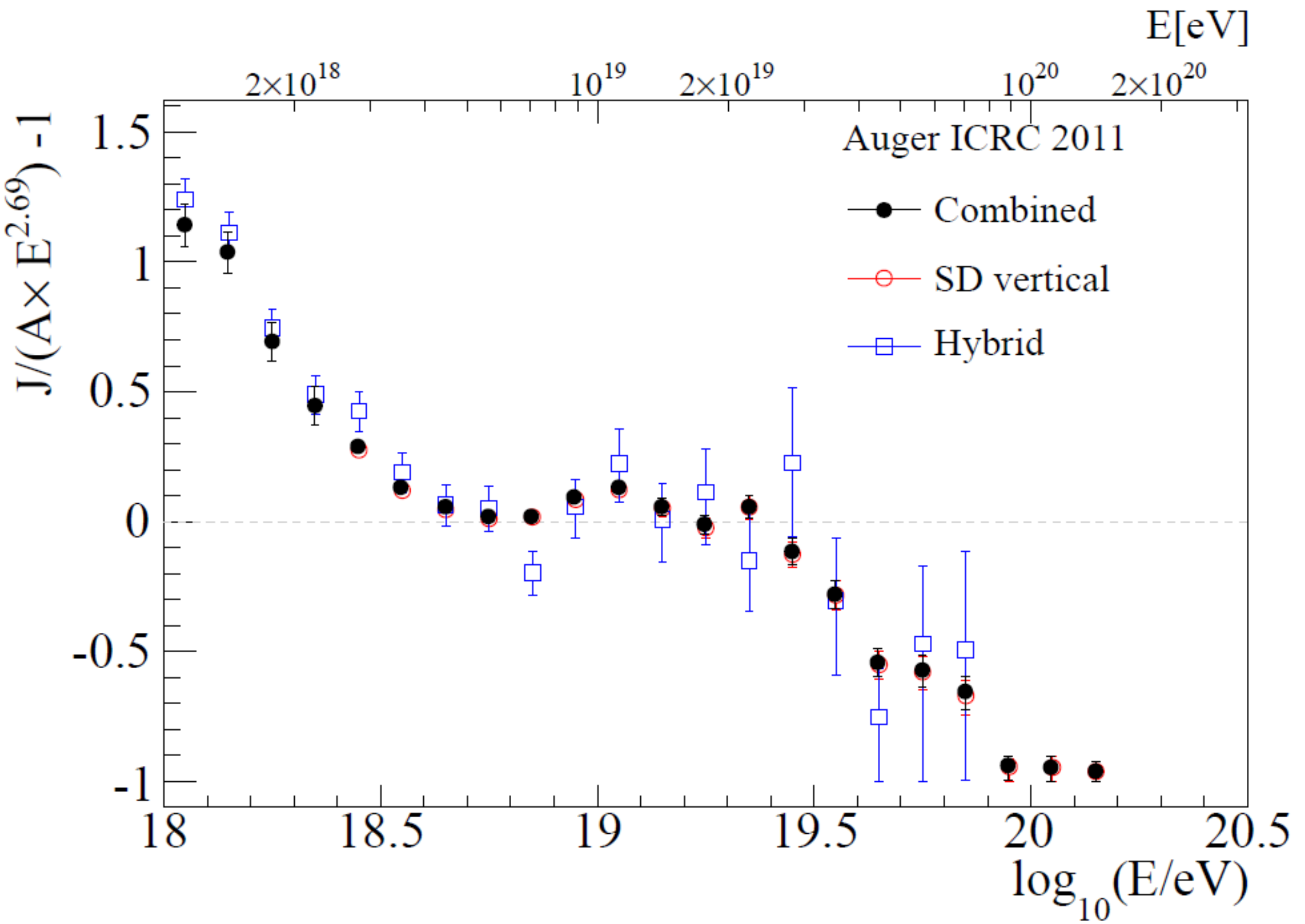
The energy spectrum

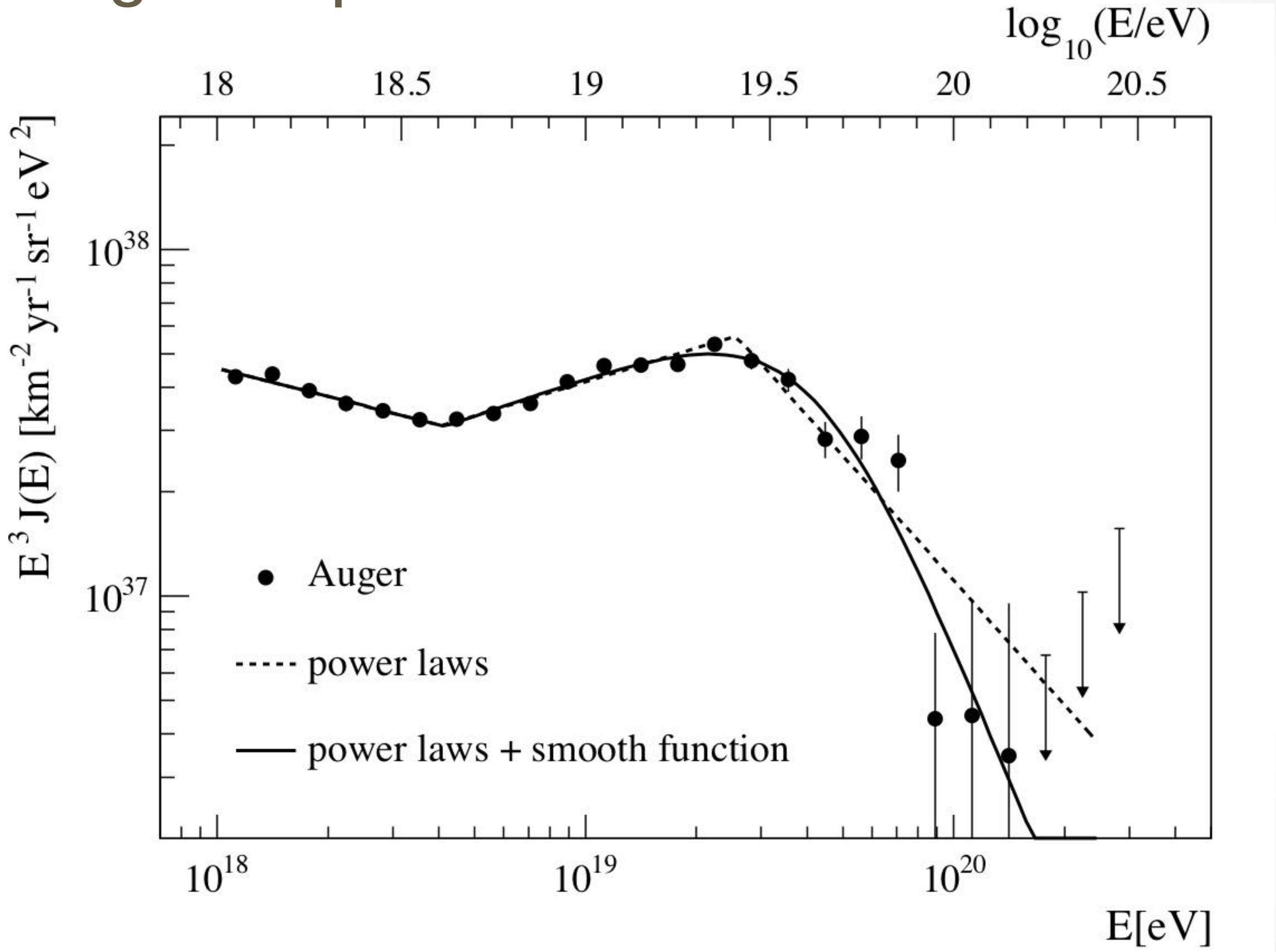


The combined energy spectrum

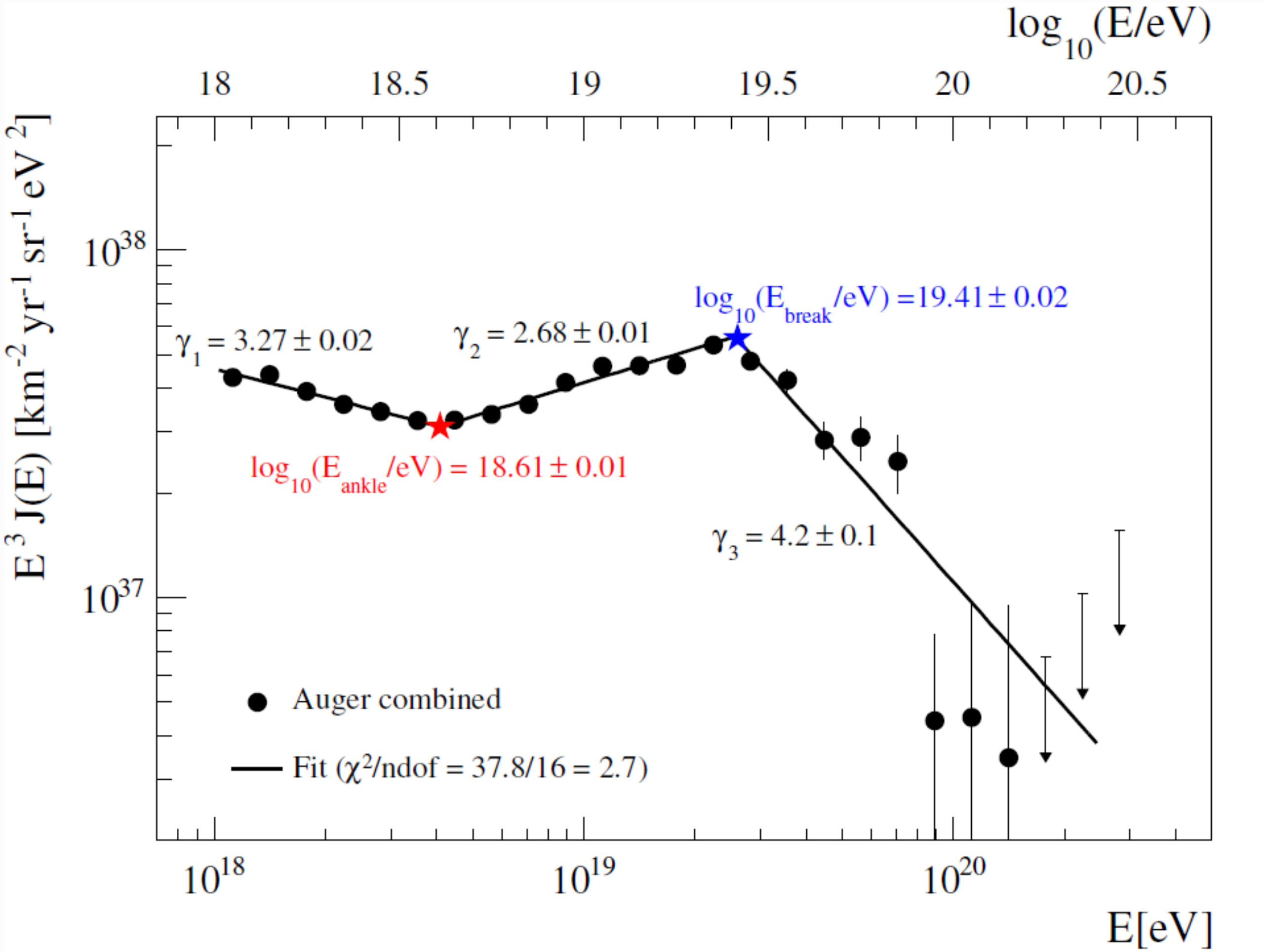


Spectra in very good agreement : better than 1.5%

Fitting the spectrum...



Fitting the spectrum...



Three power laws fit

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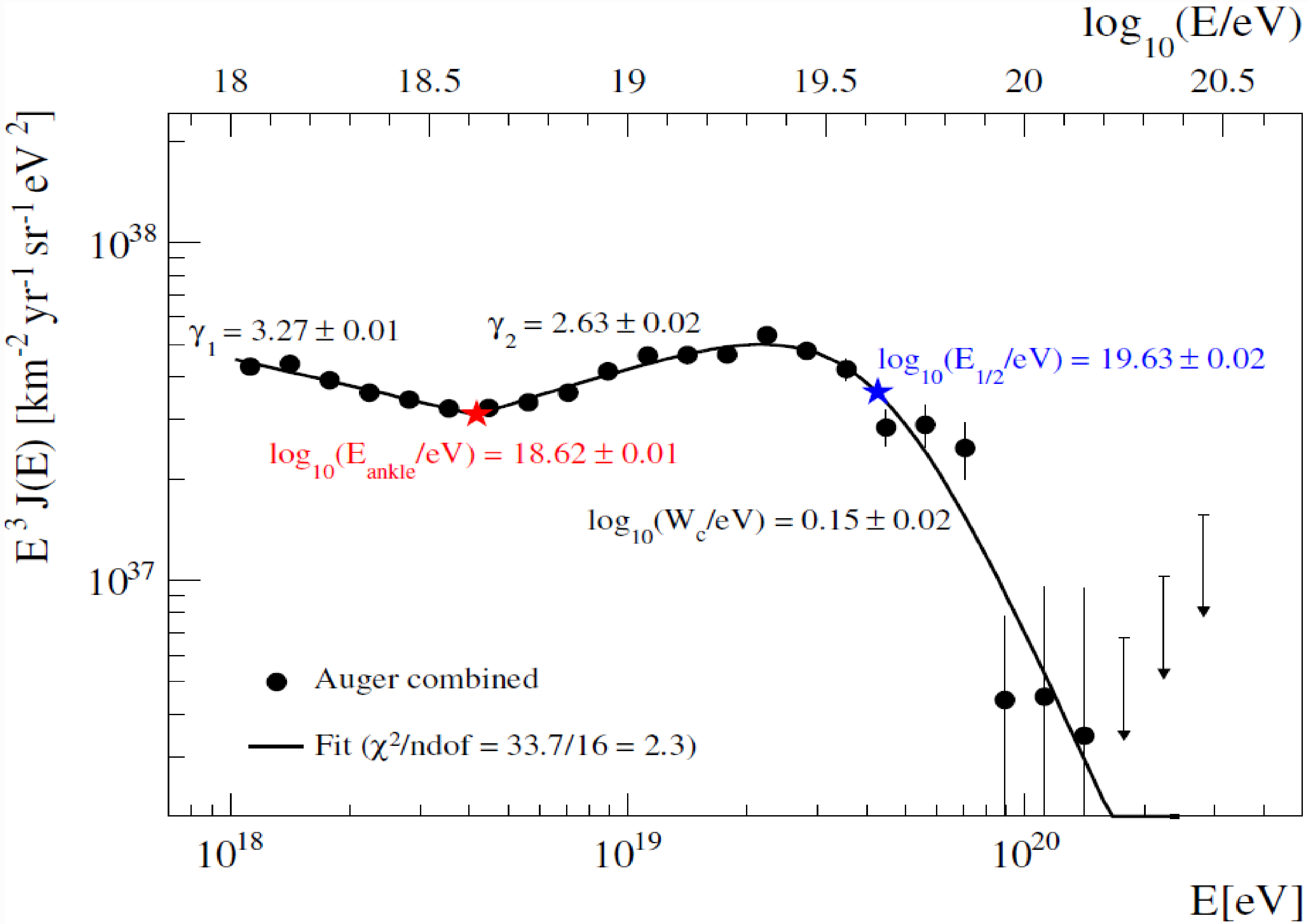
Fitting the spectrum...



Two power laws and a Fermi-like suppression

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Energy spectrum summary:

- Four measurements of the cosmic ray flux with the Pierre Auger Observatory having in common only the energy scale;
- Spectra in good agreement in the entire energy range above 1 EeV up to 100 EeV;
- The dominant systematic uncertainty stems from that of the overall energy scale, which is estimated to be 22%;
- Ankle observed @ 4.1 x 10^{18} eV ;
- Flux suppression observed @ 4.3 x 10^{19} eV;
- Significance of the suppression larger than **20σ;**
- Suppression similar to that expected for GZK, although it could also be due to a changing injection spectrum.

Energy spectrum outlook...

- Continue maintenance and data taking above 50 EeV (≈ 4 years of full array).

- Extend the energy rage down to 10^{17} eV with the data from the 750 m infill and with HEAT and possible extension with the 350 m infill;

- Reduce the systematic uncertainties on the energy improving reconstruction and reducing the uncertainty in the fluorescence yield.

Mass Composition

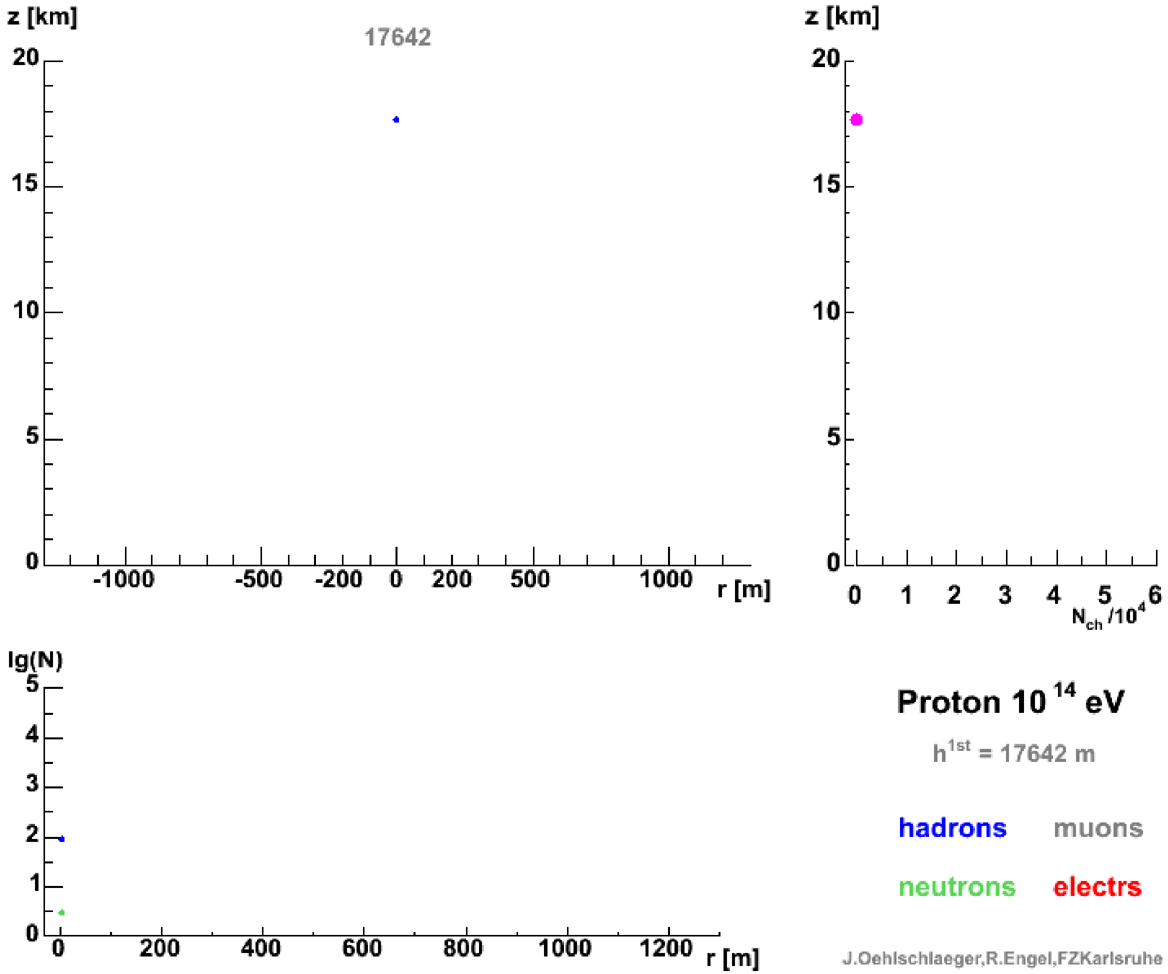
Measurement of the depth of maximum of air showers

- Mass composition cannot be measured directly and is inferred from observations of the longitudinal development of extensive air showers;

- The atmospheric depth at which the longitudinal development of na EAS reaches its maximum, X_{max}, is correlated with the incident cosmic ray which induced the shower;

- The change of $< X_{max} >$ per decade of energy (*elongation rate*) and the shower-to-shower fluctuations $RMS(X_{max})$ are sensitive to changes in composition with energy.

Let us ‘see’ a shower developing...



Measurement of the depth of maximum of EAS

- X_{max} is measured from the longitudinal development of air shower in the FD
- 6744 hybrid events above 10^{18} eV after the quality cuts recorded between Dec 2004 and Sep 2010;
- Full longitudinal development in field of view of the FD.

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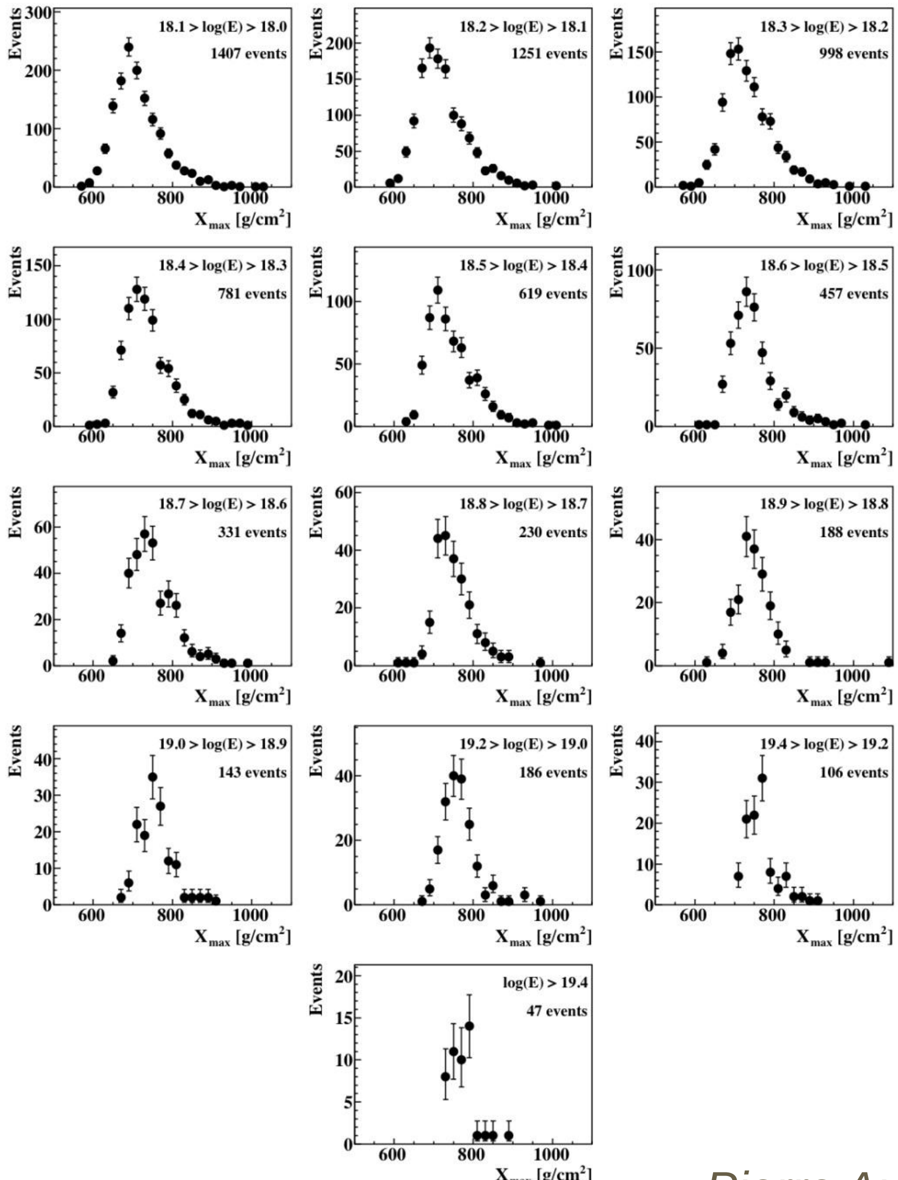
X_{max} distributions for different energy ranges...



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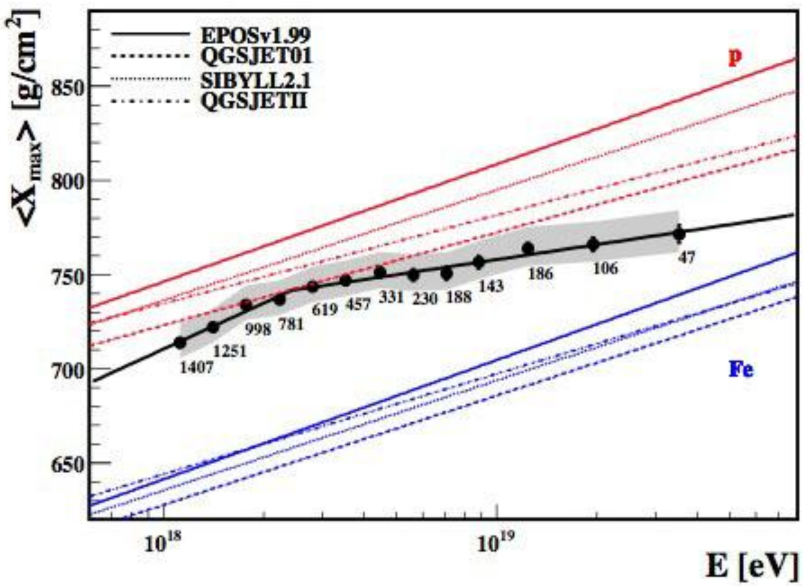
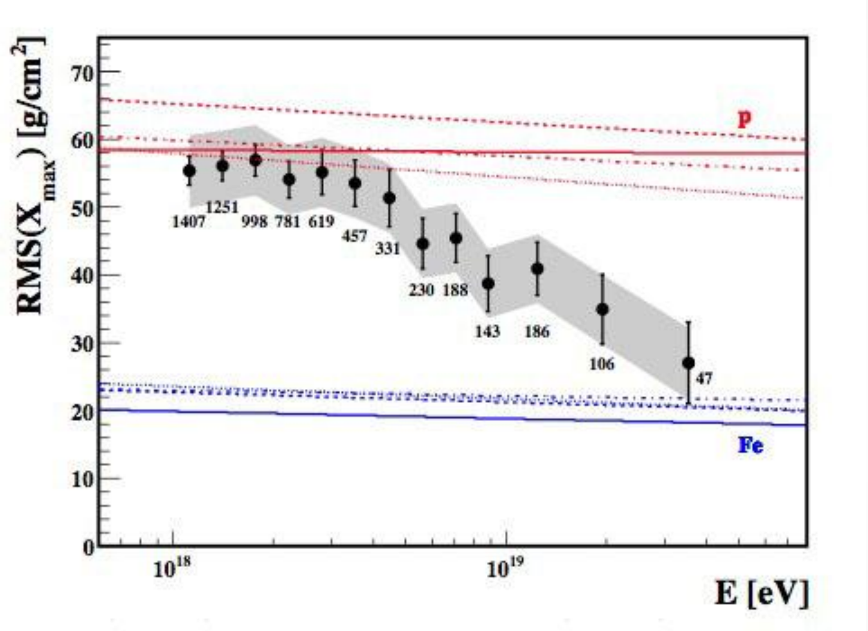
$<X_{max}>$ and $RMS\ (X_{max})$ as a function of energy:





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Results:

IF the properties of hadronic interactions do not change significantly within the observed energy range and **IF** the models provide a realistic description of these interactions at UHE, then:

- the change in the elongation rate would imply in the energy dependence of the composition around the ankle and support the hypothesis of transition from galactic to extragalactic origin;
- the comparison of data and simulations leads to a gradual increase of the average mass up to ~ 40 EeV;
- the decreasing fluctuations are an independent signature of an increasing average mass of the primary particles;

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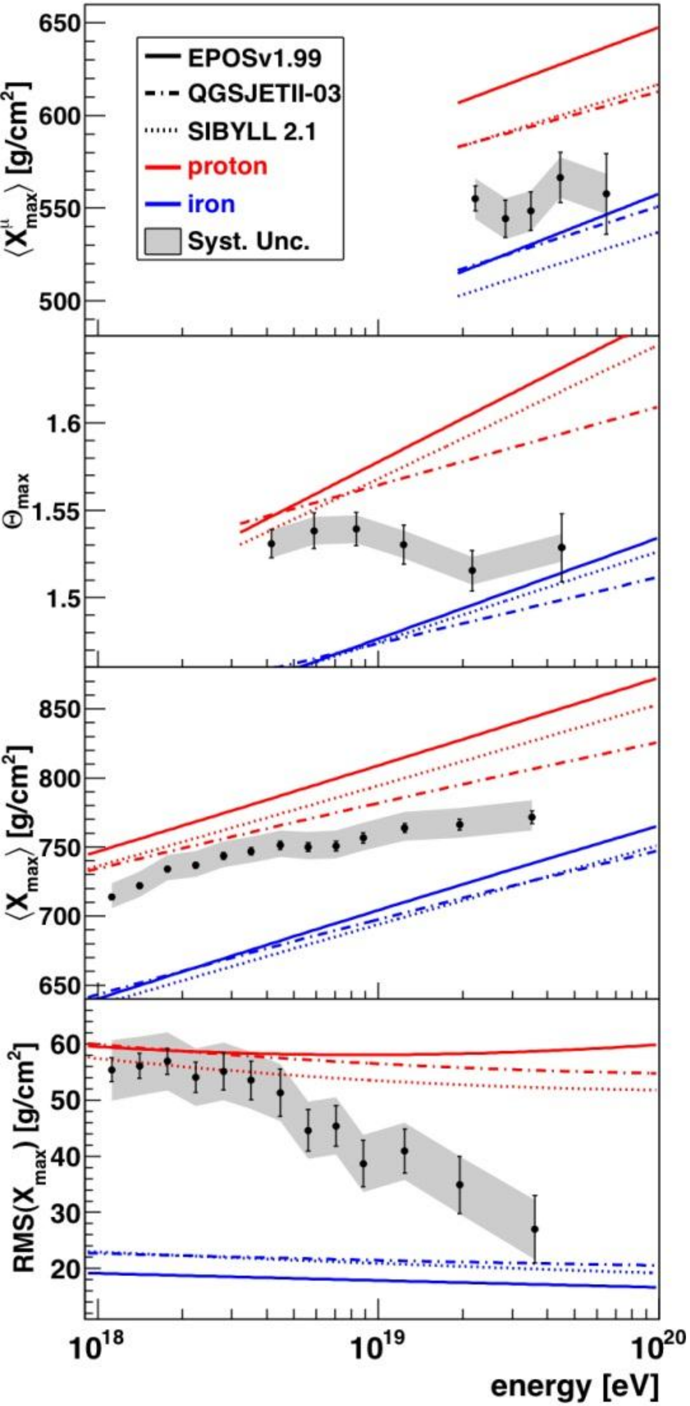

Other quantities used for composition measurements

Complementary information derived from asymmetry properties of the particle signal in the surface detector stations and the depth profile of muon production points, also derived from the surface detector data: same indications.

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The Pierre Auger Observatory and particle physics

If the cosmic ray is a proton and it collides with a nucleon at rest...

Energy of the primary	**Equivalent $\sqrt{s}$**
2.5 x 10^{16} eV	7 TeV *
10^{17} eV	14 TeV
2.5 x 10^{18} eV	70 TeV
10^{19} eV	140 TeV

The Auger Observatory and particle physics:

- A cosmic-ray particle with 10^{19} eV impinging on a nucleus of the atmosphere corresponds to a total energy in the cms of

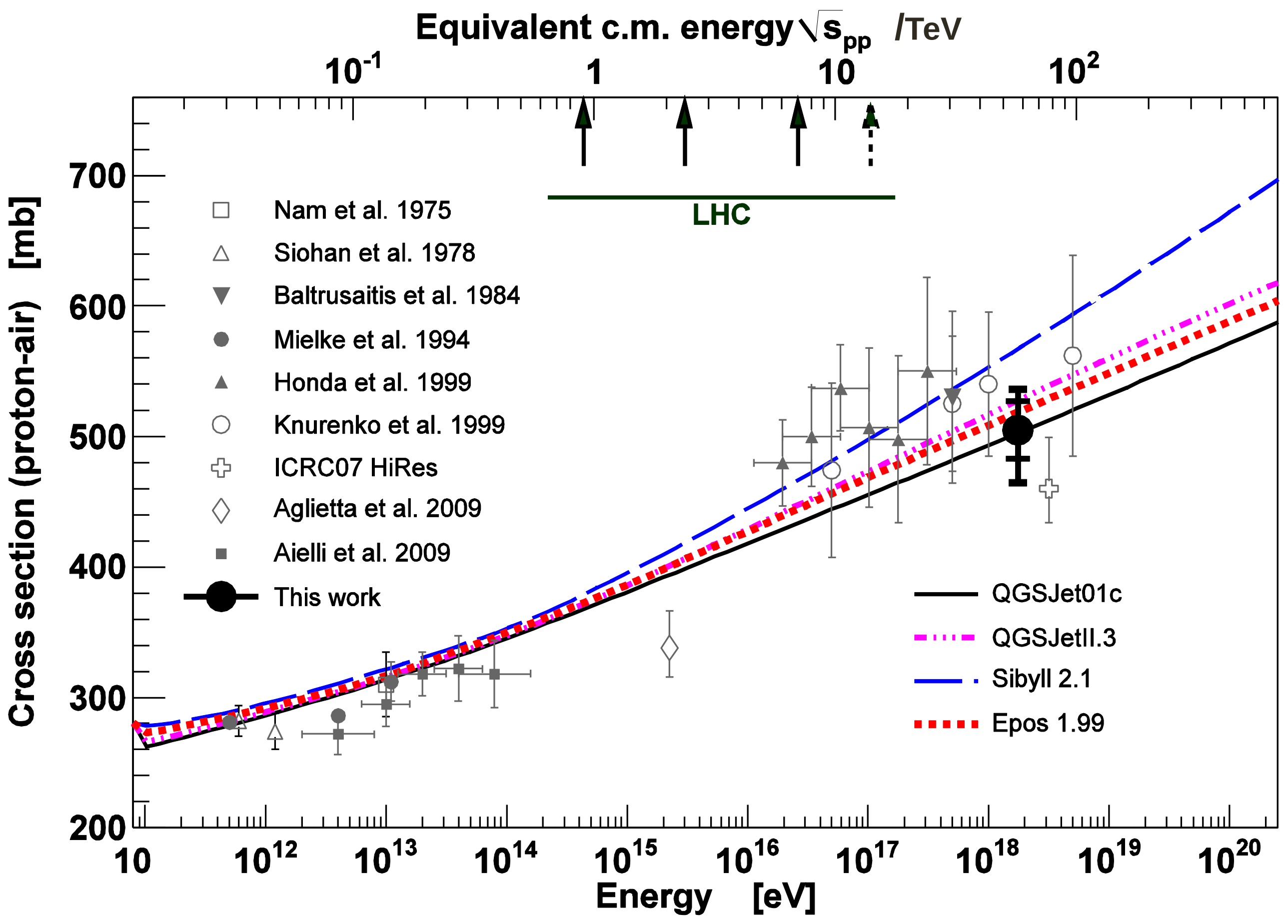
$$\sqrt{s} \approx 140 \text{ TeV}$$

- Therefore we are observing particles being produced in the very forward region in hadronic collisions at these energies!

- If we only knew the composition of the incident particle!

☹

Nevertheless: p-air cross section @ 57± 6 TeV



Inner error bars statistical only, outer include all systematic uncertainties for a helium fraction of 25% and 10 mb photon systematics.

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And still to come...

- *... and the next step will be the p-p cross section....* ☺

Anisotropy Studies

A direct conclusion:

If the suppression of the cosmic ray spectrum at 4×10^{19} eV is due to GZK effect, the cosmic rays with higher energies should be coming from sources nearby!

In this case....

- Above 6×10^{19} eV 50% of the protons should come from less than about 100 Mpc, while 20% should come from less than 200 Mpc.
- The arrival directions of the highest energy cosmic rays should correlate with the distribution of visible matter nearby, since it is very inhomogeneus.
- The angular resolution of the Auger Observatory above 1×10^{19} eV is less than 1°, while the deflection of protons or nuclei in the ~ μG magnetic field of our galaxy, at those energies is expected to be $\sim Z(10^{19} \mathrm{eV}/E)$

Anisotropy studies :

Large scale anisotropy (e.g. a dipolar distribution)

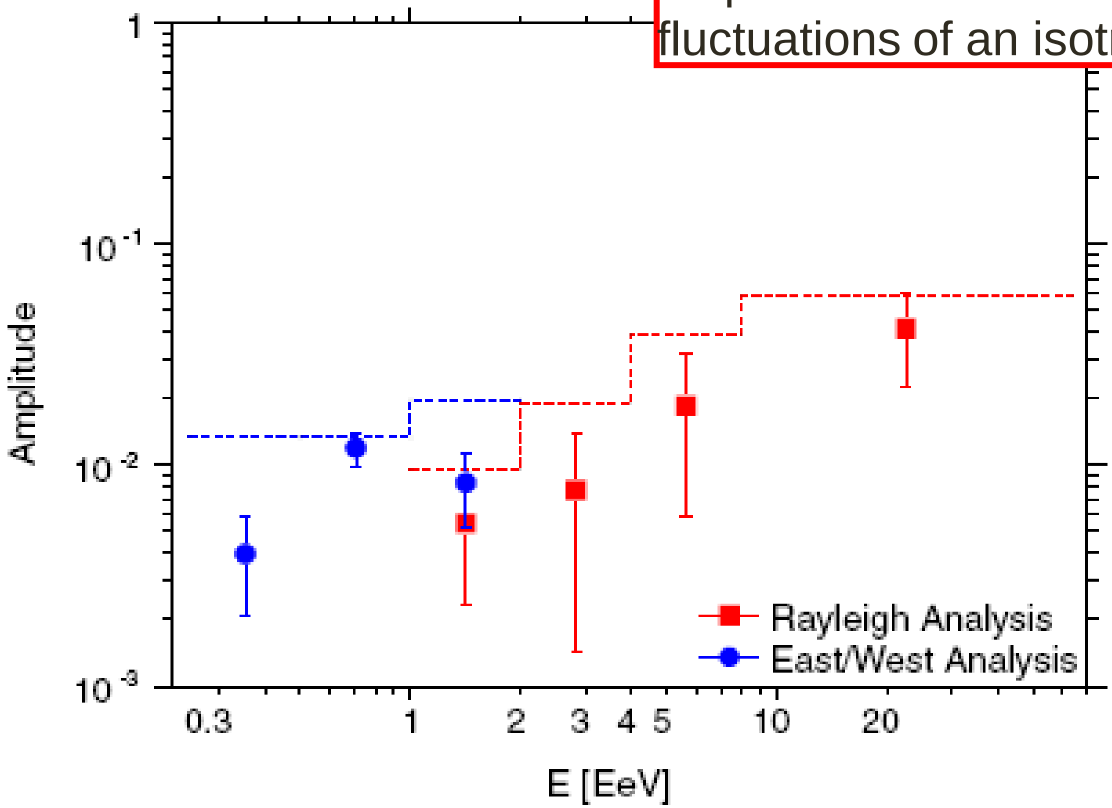
- certain classes of sources associated with large scale structures as the galactic center/plane/halo
- if detected, would help to establish the energy at which the extragalactic component takes over.

Small scale anisotropy(e.g. sources localized in small angular regions

- association of UHECRs with individual sources

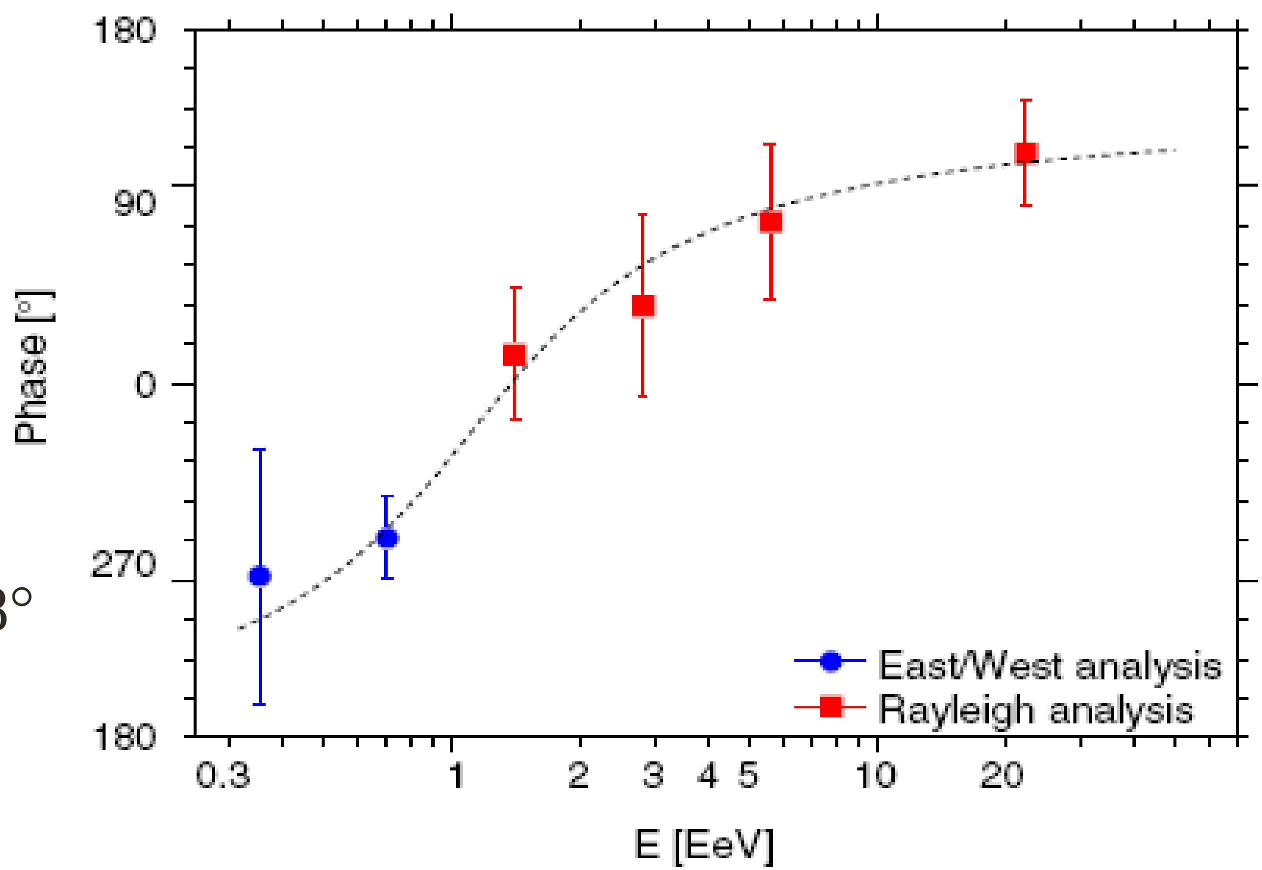
Search for 1st harmonic modulation in right ascension

Amplitude of the first harmonic as a function of energy. The dashed line indicates the 99% C.L. upper bound on the amplitudes that could result from fluctuations of an isotropic distribution.



Auger Collab., Astropart. Phys. 34 (2011) 627

Search for 1st harmonic modulation in right ascension

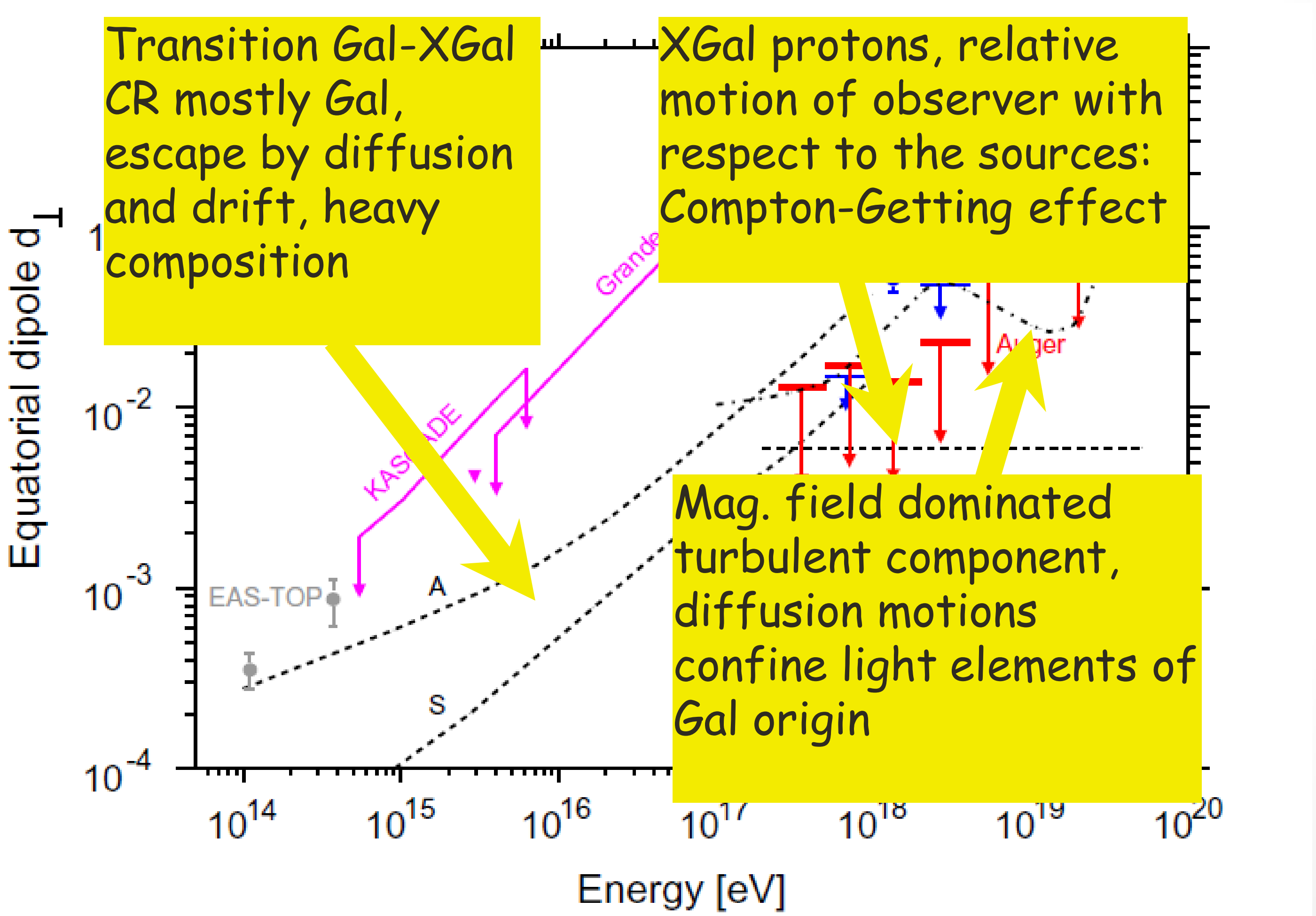


$\alpha_{GC} \cong 268°$

Expected to be randomly distributed in case of independent samples whose parent distribution is **isotropic**.

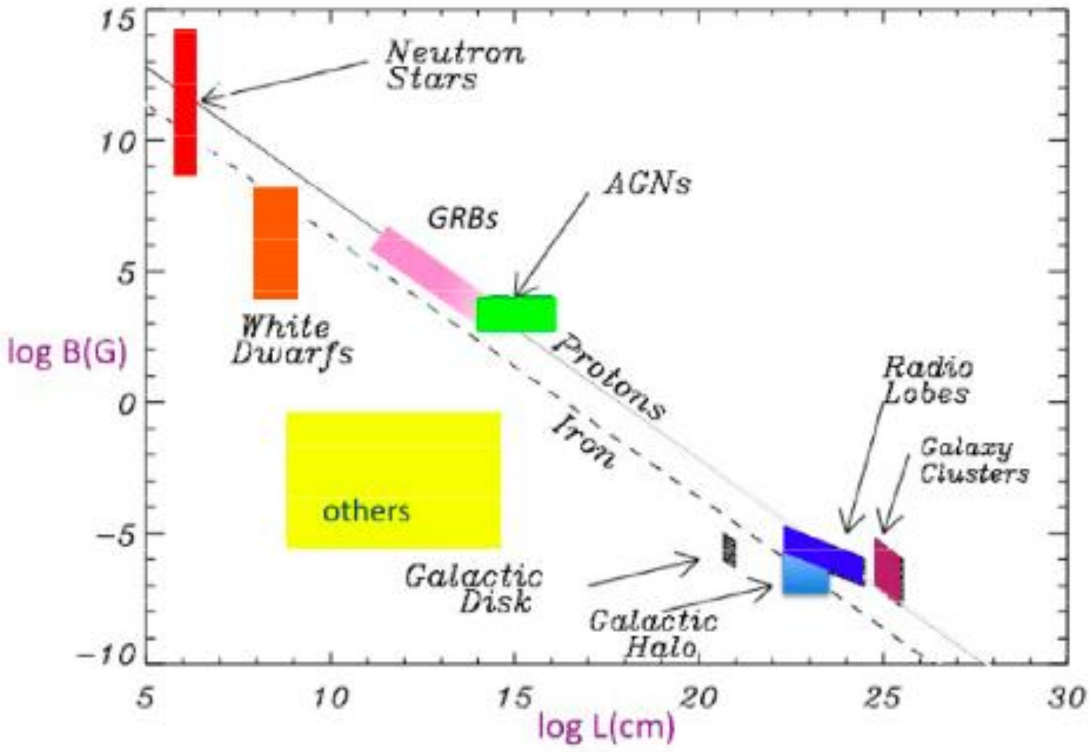
Auger Collab., Astropart. Phys. 34 (2011) 627

Upper limits on the anisotropy amplitude of the first harmonic modulation



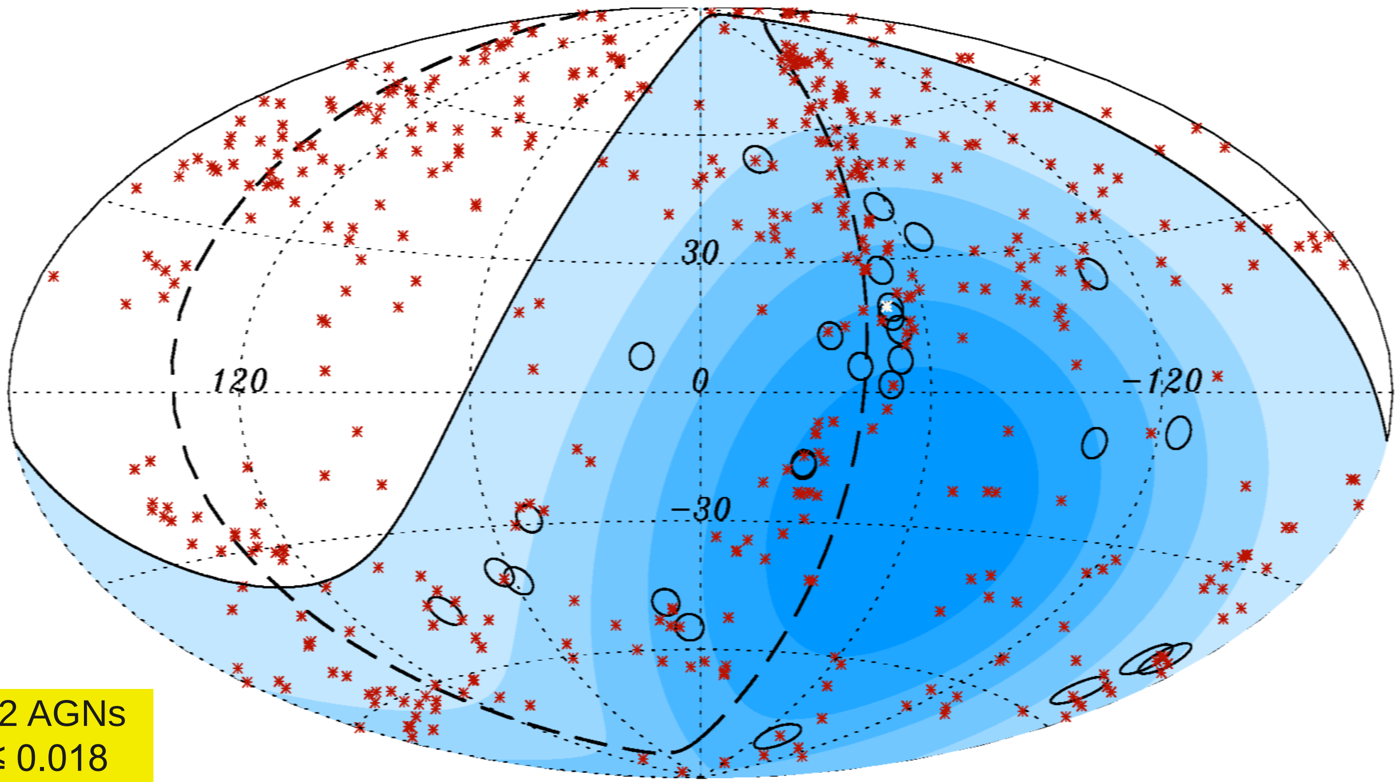
Auger Collaboration, Astroparticle Physics 34 (2011) 627

Hillas plot



Protons and iron nuclei @ 10^{20} eV

The Auger highest-energy sky map in galactic coordinates..



472 AGNs
z ≤ 0.018
318 in fov

Pierre Auger Collab. 2007, Science, 318, 939
Pierre Auger Collab.2008, Astropart.Phys, 29, 188

Does this map show evidence of anisotropy?

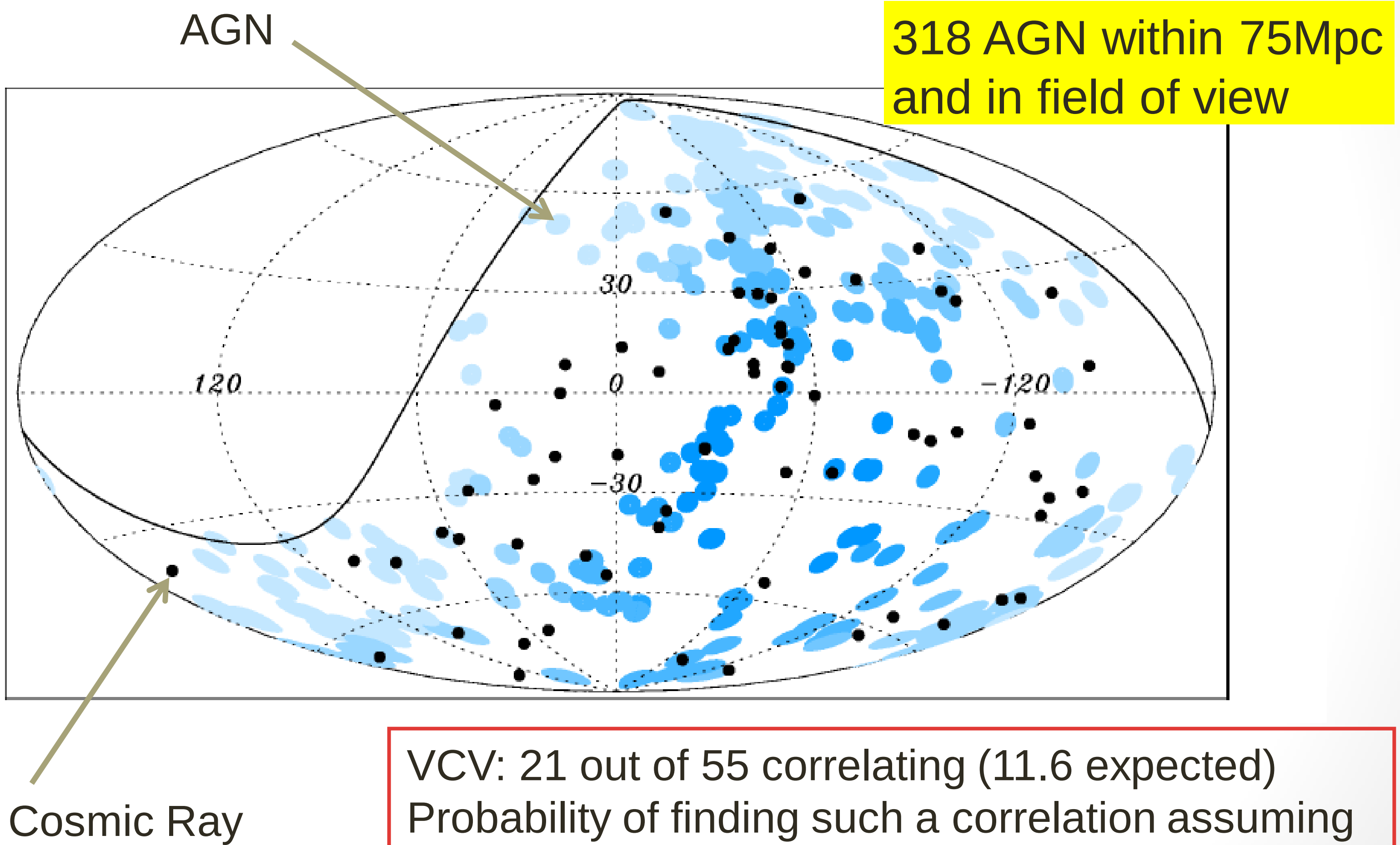
- No a priori hypothesis on the characteristics of correlation, thus exploratory scan on: angular distance (resolution and magnetic fields), AGN redshift (GZK cutoff), energy (magnetic field)
- The search: using data between 01Jan 2004 and 26 May 2006
- Correlation of $E>E_{min}$ events with Véron-Cetty catalog of $z<z_{max}$ within ψ degrees. Optimize **(E_{min}, z_{max}, ψ)** to maximize deviation from isotropy.
- The prescription: **FIX** test parameters: (period I: 8/14) E_{min} = 56 EeV, z_{max}= 0.018, ψ =3.1°
- accumulate *new* data. Terminate test when probability of isotropy to have yielded *new* data < 1%. (99% C.L.)

The confirmation.....

- Data collected between 27 May 2006 and 31 August 2007
- it only required 8 new events to fulfill prescription
- From 8 new events 6 correlate, probability to get from isotropy <1%
- Period II (8/13) **$P = 1.7\times10^{-3}$**

Null hypothesis (Isotropy of UHECR) rejected at 99% CL
Very large correlation (~70%) with extragalactic objects (traced by AGN).

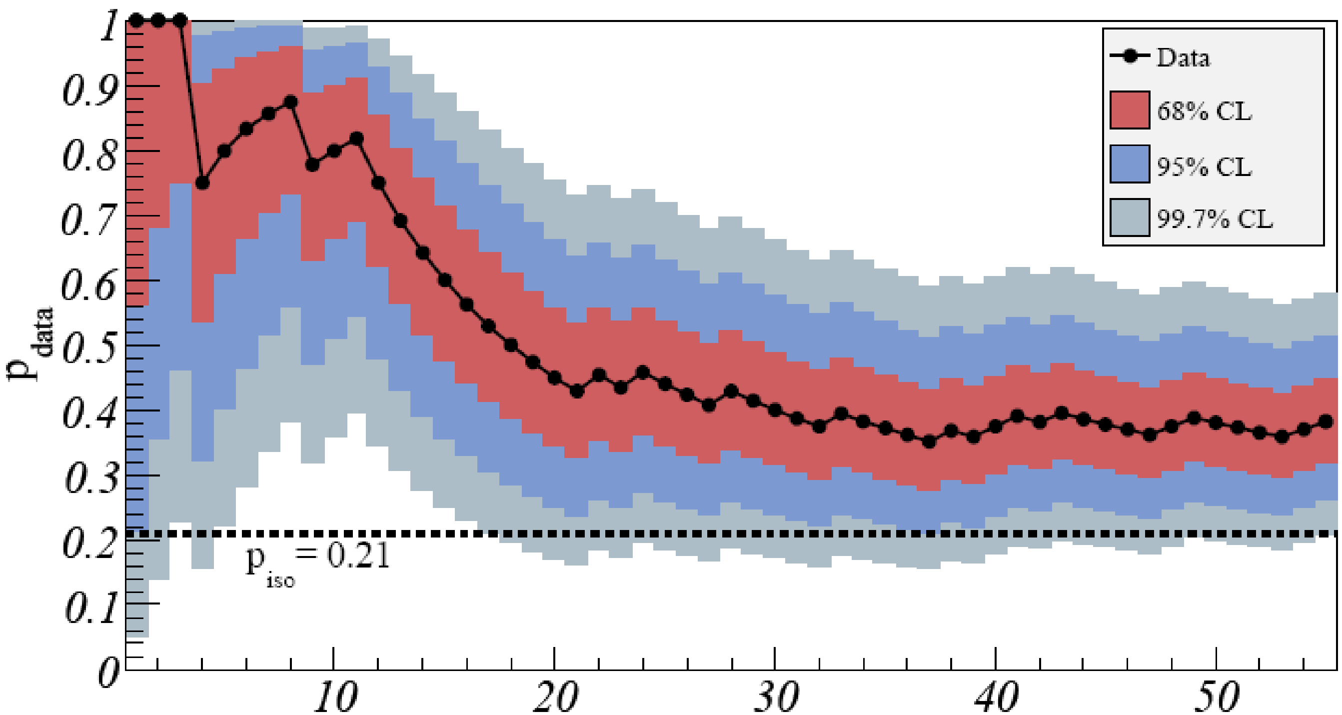
Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter



VCV: 21 out of 55 correlating (11.6 expected)
Probability of finding such a correlation assuming Isotropy:=0.003

Auger Collab. Astropart. Phys. 34 (2010) 314

Degree of correlation time-ordered



expected from isotropy

21%

Isotropy of UHECR rejected at 99% CL
Correlation reduced from ~70% to ~40%
Stabilizing around ~40%

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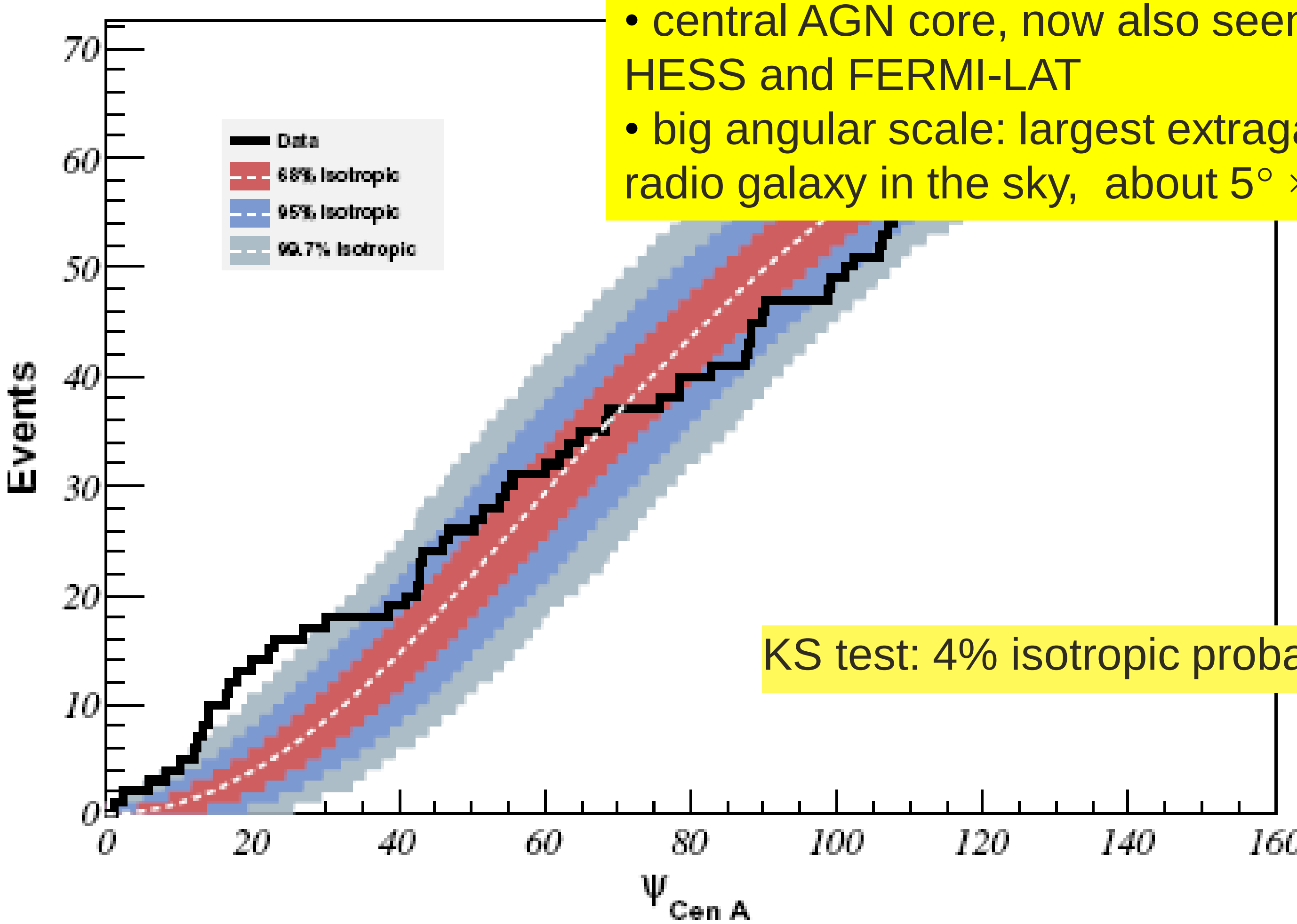
Cen A region: overdensity with largest significance

- Centauros A: nearest AGN (3.8 Mpc)
- central AGN core, now also seen by HESS and FERMI-LAT
- big angular scale: largest extragalactic radio galaxy in the sky, about 5° × 9°.



KS test: 4% isotropic probability

Overdensity is given by 13 arrival directions within 18° (3.2 expected from isotropy)

Composition from anisotropy:

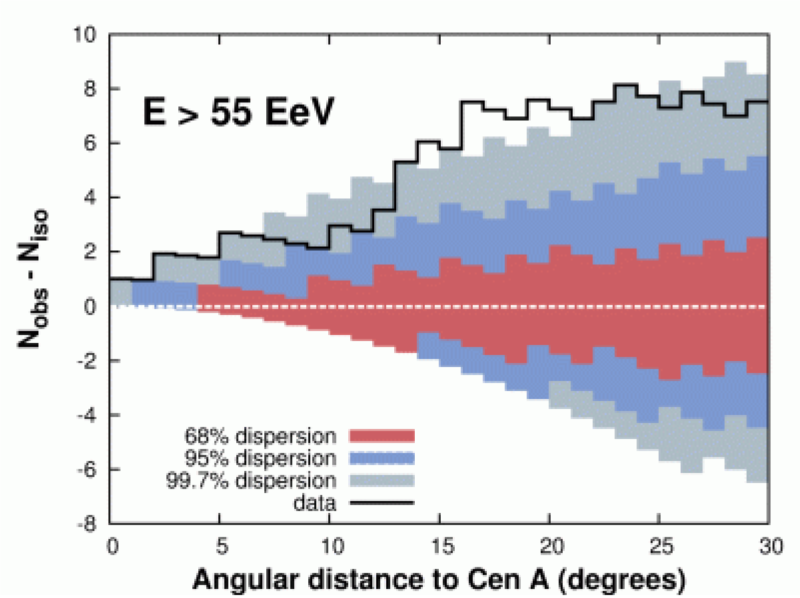
- **Primaries of atomic number Z and energy E follow the same tracks on a magnetic field as protons of energy E/Z (neglecting energy losses).**
- **Anisotropies due to heavy primaries for E>Eth should be present also for E>Eth/Z due to the protons accelerated in the same source.**

Therefore, we have searched for anisotropies above energy thresholds E_{th}/Z (E_{th} = 55 EeV) for representative values of $Z = 6$, 13 and 26 (i.e., energy thresholds of 9.2, 4.2 and 2.1 EeV). The results constrain the proton content at the sources in scenarios where the anisotropies at high energies are due to a heavy composition.

Pierre Auger Collab., JCAP06 (2011) 022

Composition from anisotropy

- **At high energies (above 55 EeV)**
  - **10/60** inside a 18 deg window around **CenA**, **2.44** expected by chance correlations.
  - **20/49** are less than 3.1 deg from a **VCV** AGN, **7.88** expected from random coincidence.



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Composition from anisotropy

- **At low energies**

Z	E_{min} [EeV]	N_{tot}	N_{obs}	N_{bkg}
6	9.2	4455	219	207 ± 14
13	4.2	16640	797	774 ± 28
26	2.1	63600	2887	2920 ± 54

CenA

Z	E_{min} [EeV]	N_{tot}	N_{obs}	N_{bkg}
6	9.2	3626	763	770 ± 28
13	4.2	13482	2852	2860 ± 54
26	2.1	51641	10881	10966 ± 105

VCV

No significant excess observed

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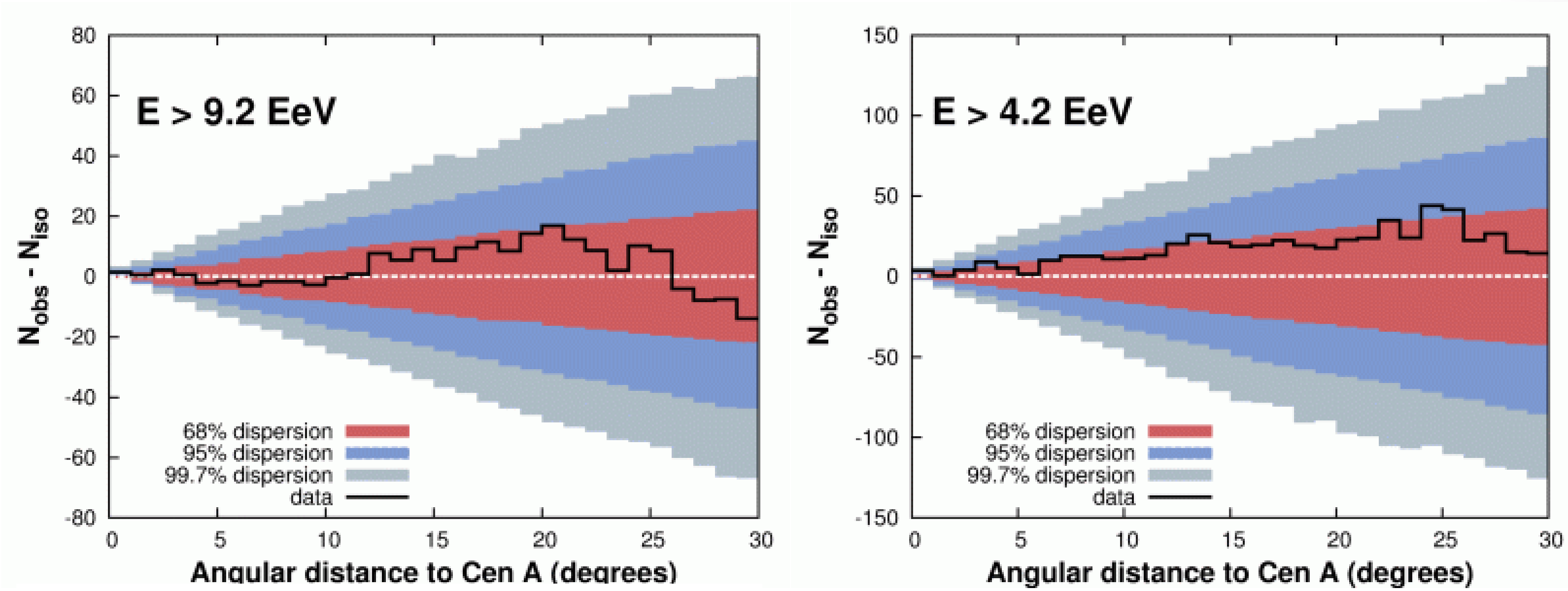
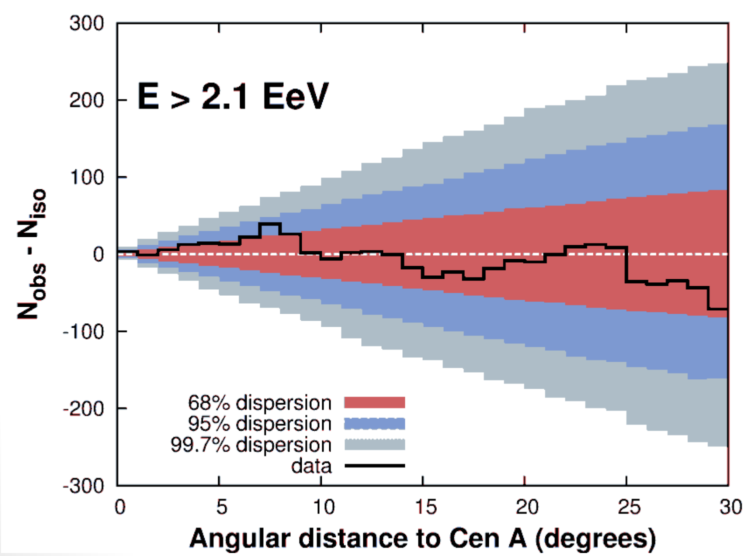
Composition from anisotropy





No indication of significant anisotropy at lower energies for different angular scales around CenA.

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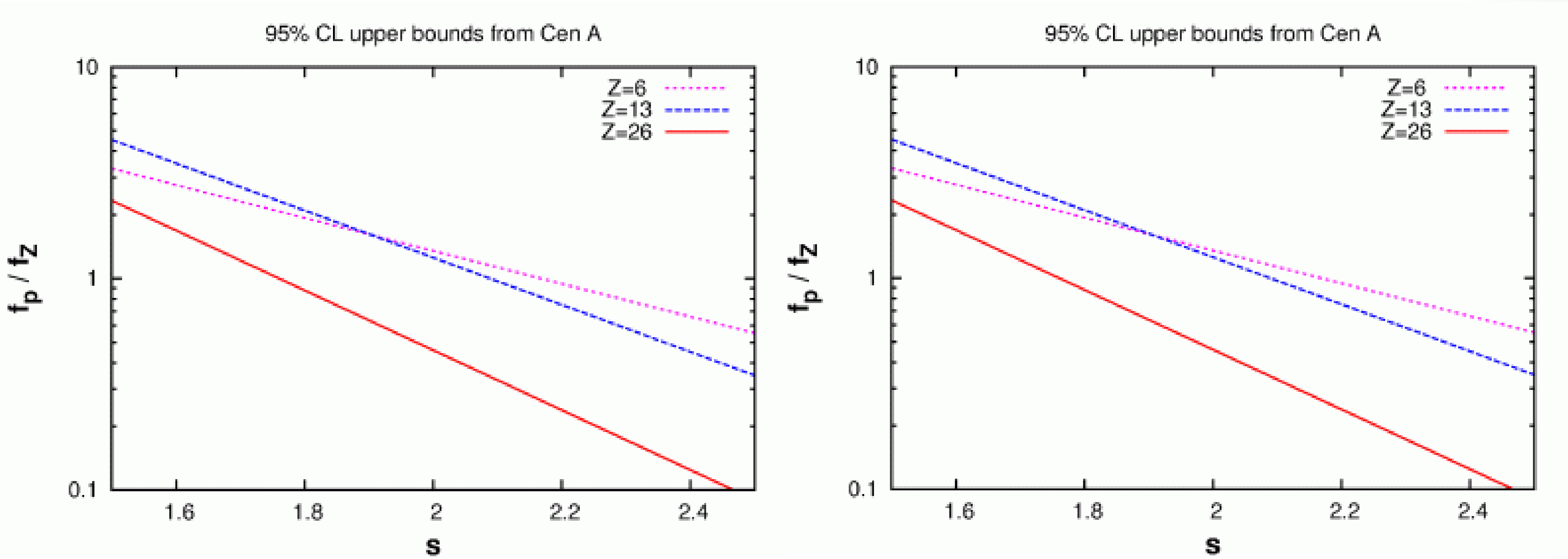
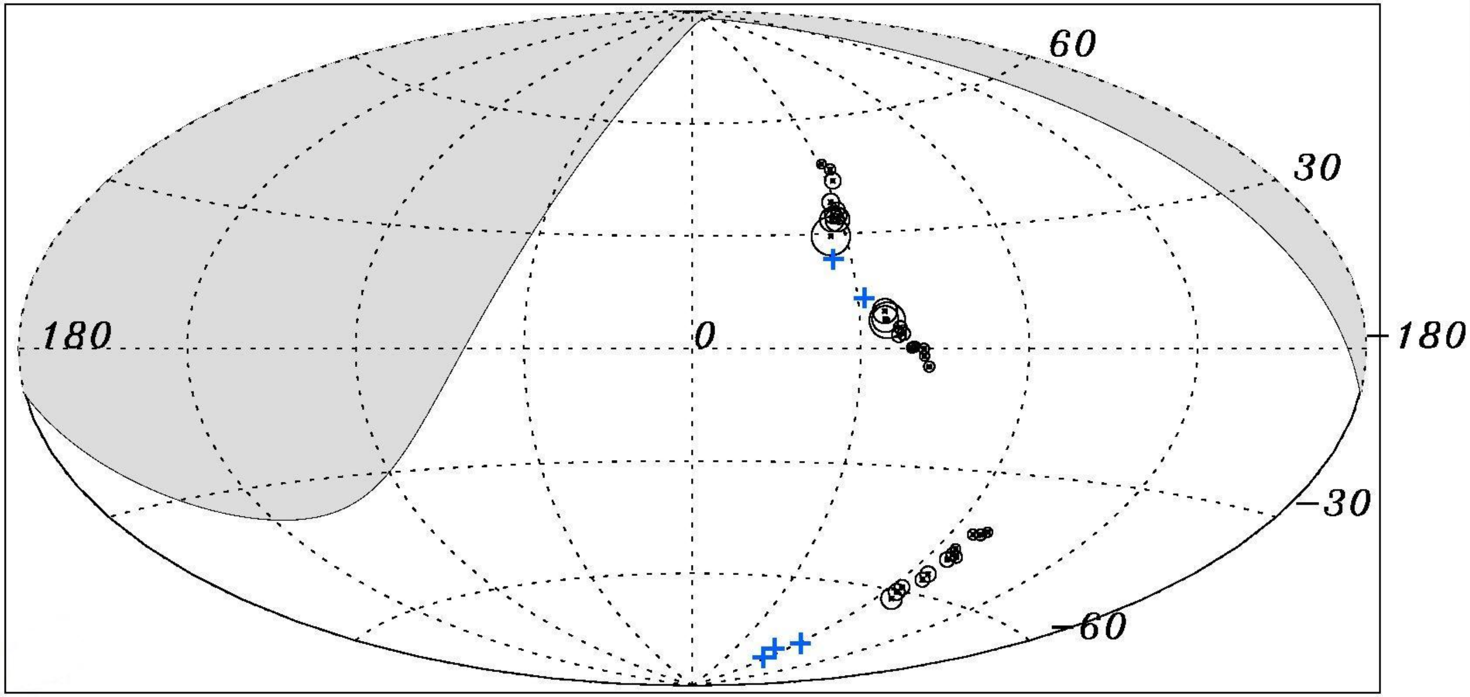
This result allows us to set limits...



Upper bounds at 95%CL on the allowed proton to heavy fractions in the source (assuming a two component mixture) as a function of the assumed low energy spectral index s (E^{-s}), obtained from the lack of excesses at low energies in 3.2 degree radius regions around CenA and nearby VCV AGNs.

Pierre Auger Collab., JCAP06 (2011) 022

The search for multiplets:



Observed multiplets with 10 or more events in galactic coordinates.

No statistically significant evidence for the presence of multiplets arising from magnetic deflections in the present data.

Pierre Auger Collab., Astrop. Phys. 35 (2012) 354

Limits on the diffuse flux of UHE Neutrinos

Searching for neutrinos with the Auger Observatory

- **Neutrinos can be produced by basically all cosmic hadron accelerators and travel undisturbed over long distances due to their extremely small cross-sections.**
- **Neutrinos are expected from the decay of charged pions, produced either in CR interactions within their sources or in the CR propagation through the background radiation;**
- **Top-down models proposed to explain the production of UHECR also predict neutrinos;**
- **Down-going neutrinos of all flavors may interact in the atmosphere through CC and NC-interactions and induce showers that can be detected using the Auger SD**
- **The Auger Observatory is sensitive to neutrinos of E > 1 EeV.**

*Auger Collab., PRL **100,** 211101 (2008);*
Auger Collab., Phys. Rev.D 79, 102001 (2009),
Auger Collab., Proc.31st ICRC2009

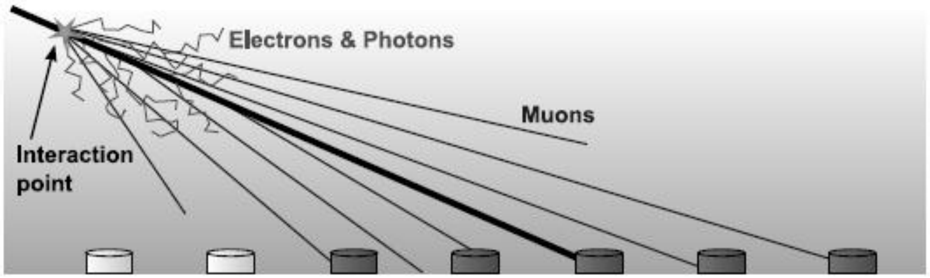
Detection of neutrinos

SD detectors may observe:

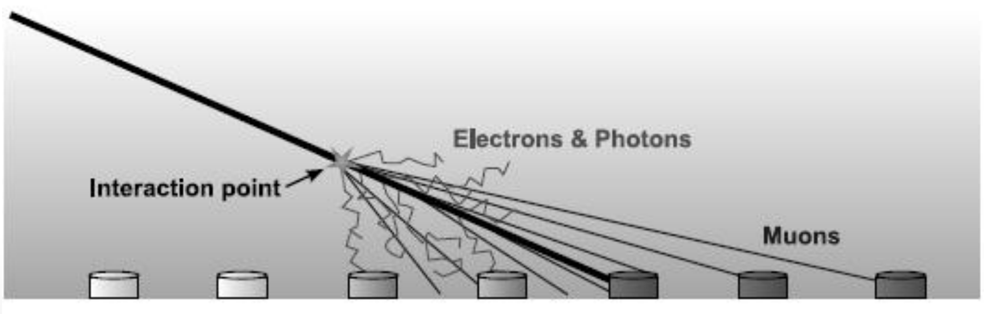
- Down-going neutrinos of all flavors may interact deep in the atmosphere through CC and NC-interactions and induce showers close to the ground that can be detected using the Auger SD .
- Tau neutrinos propagating through Earth may suffer CC interaction followed by decay in flight of the tau lepton. Such Earth-skimming tau neutrinos can be observed through the detection of up-going showers induced by the decay products of the emerging tau lepton.
- The Auger Observatory is sensitive to neutrinos of energy above 1 EeV;

Detection of neutrinos in Auger SD:

Down-going ν



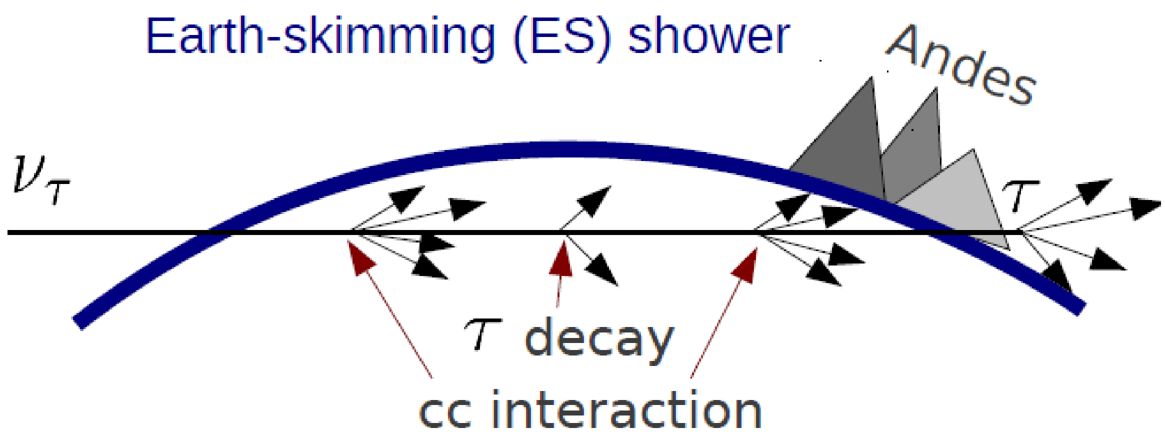
Inclined hadron-induced shower:
EM particles absorbed
only muons reach the detectors



Signature of quasi-horizontal neutrino-induced showers:

- **deep inclined young showers**, developing near the SD
- exhibiting shower fronts extended in time
- Elongated footprint
- Apparent velocity ~ c
- Early tanks, large ToT (EM)
- Late tanks, small ToT (μ)

Earth-skimming neutrino showers



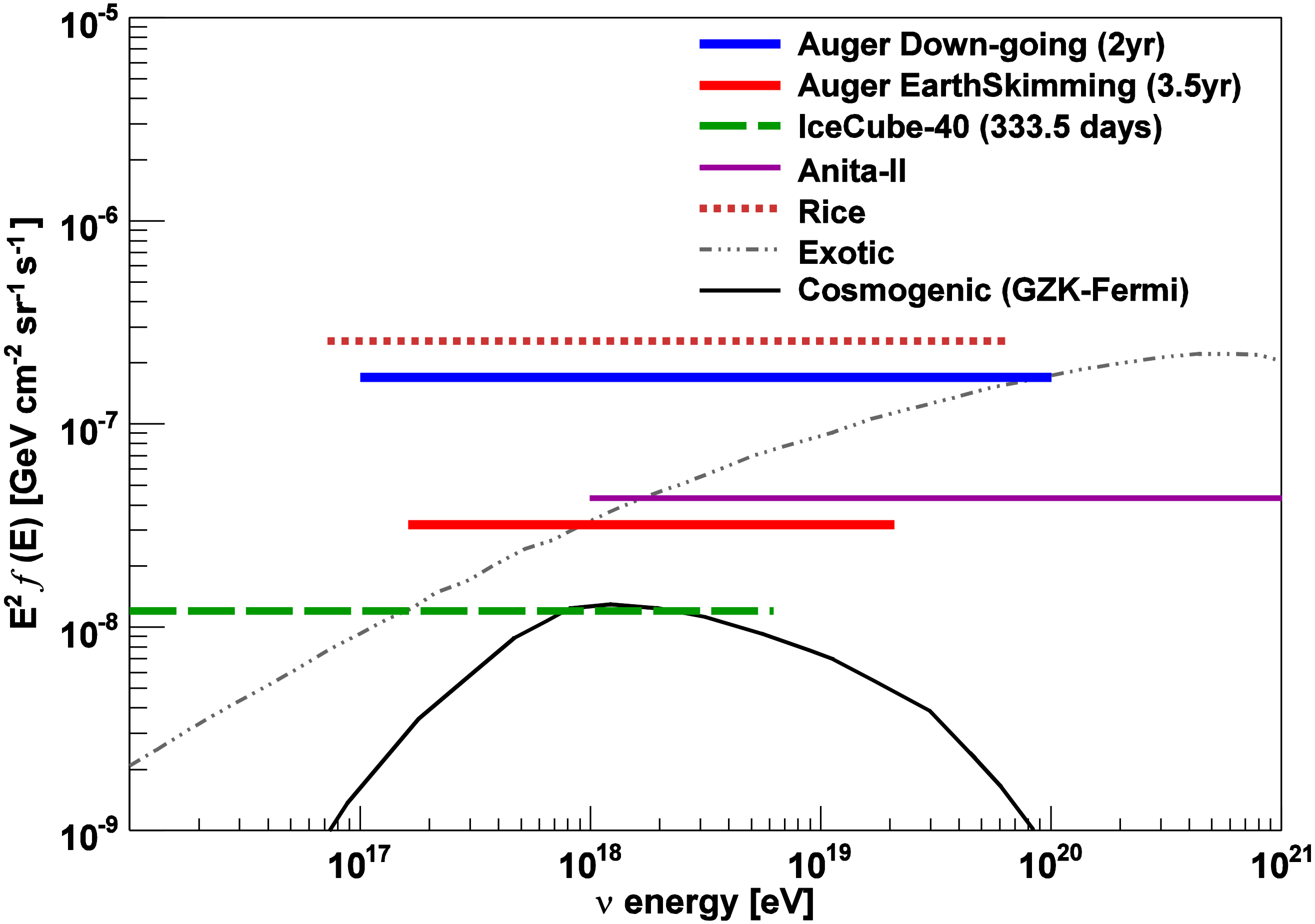
Results:

- **No neutrino candidates were found and an upper limit on the UHE diffuse flux of ultra-high energy neutrinos has been placed.**

- **Limits on diffuse neutrino flux from down-going neutrinos of all flavours with data in period 1 Nov 2007 to 28 Feb 2009;**

- **Limits from Earth-skimming (up-going) tau neutrinos with data in period 1 Jan 2004 to 28 Feb 2009.**

Limits on the neutrino flux:



Pierre Auger Collab. ICRC 2011
Pierre Auger Collab., Phys. Rev. D 84, 122005 (2011)

Limit on photon ratio

Limits on the photon ratio

- Direct observations of the longitudinal development of UHE showers resulted in limits at energies 2, 3, 5 and 10 EeV:

2 EeV	3 EeV	5 EeV	10 EeV
3.8 %	2.4 %	3.5 %	11.7 %

Auger Collaboration, Astropart. Phys. 31 (2009) 399
Auger Collaboration, Astropart. Phys. 29 (2008) 243
Auger Collaboration, Astropart. Phys. 27 (2007) 155

Recent limits on the photon ratio

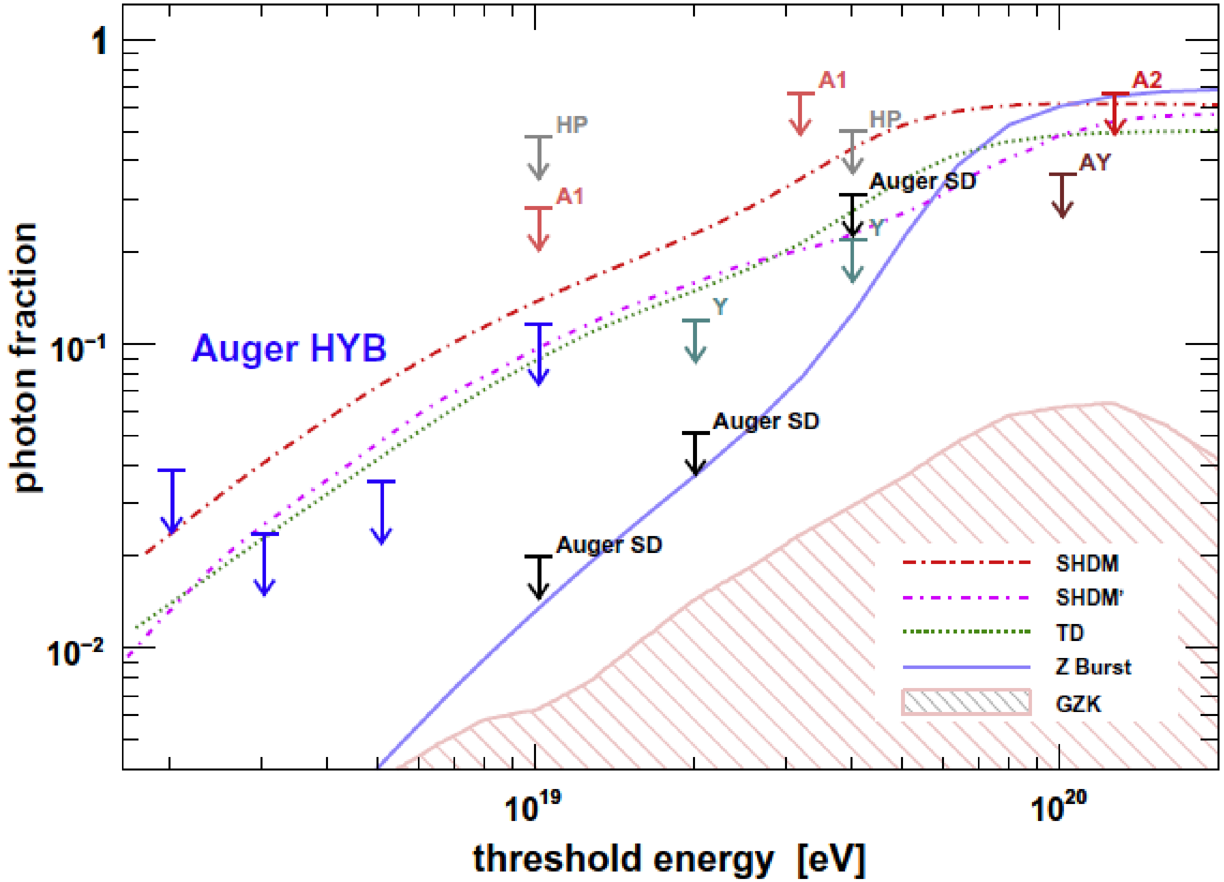
The recent limits derived on the photon fraction are

1 EeV	2 EeV	3 EeV	5 EeV	10 EeV
0.4 %	0.5 %	1.0 %	2.6 %	8.9 %

significantly improving previous results at the lower energies.

Auger Collaboration, ICRC 2011

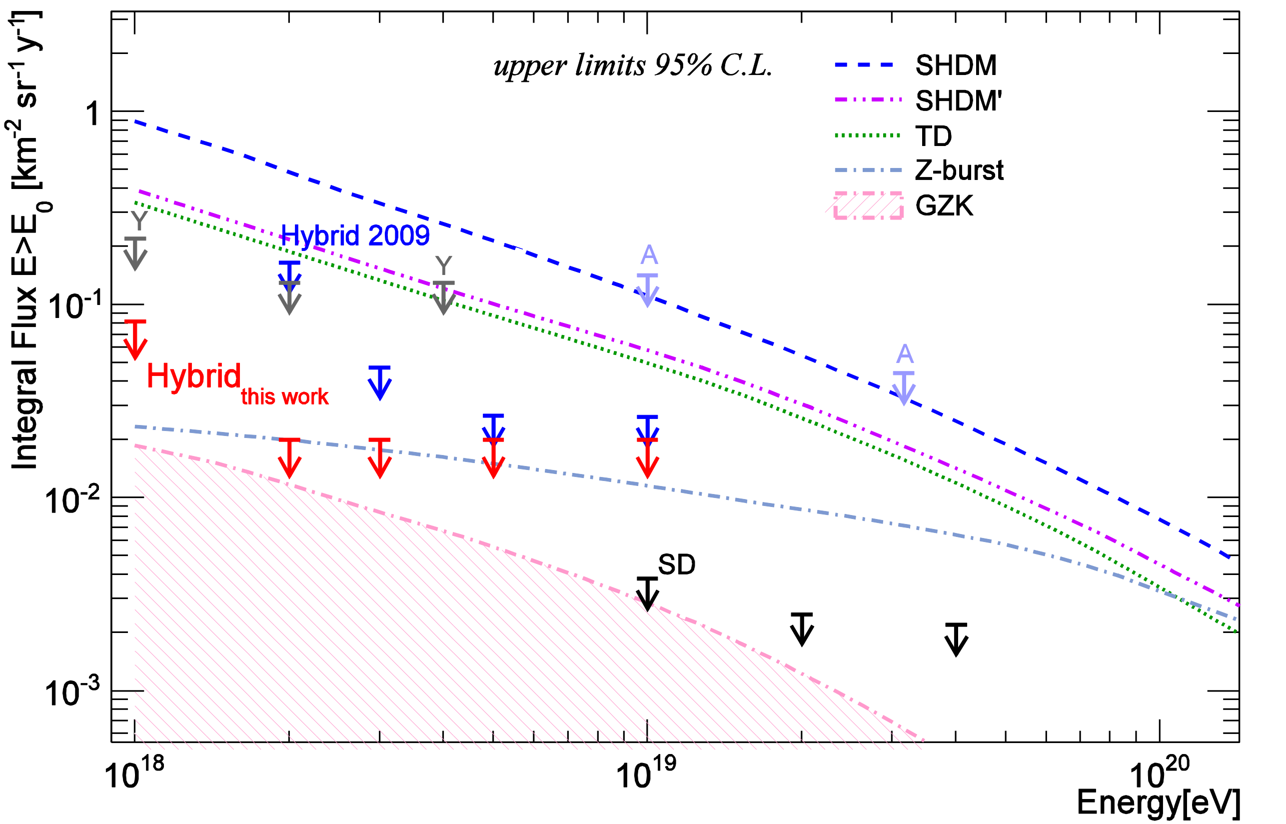
Limit on the photon fraction



Upper limits on the photon fraction in the integral cosmic-ray flux.

Auger Collaboration, Astropart. Phys. 31 (2009) 399
Auger Collaboration, Astropart. Phys. 29 (2008) 243

Recently: limit on the photon flux...



Upper limits on the photon flux above 1, 2, 3, 5 and 10 EeV derived in this work (red arrows) compared to previous limits from Auger (SD and Hybrid 2009, from AGASA (A) and Yakutsk (Y)

Pierre Auger Collab. ICRC 2011

Conclusions:

● The Pierre Auger Observatory is operating

● Features in the energy spectrum: position of the ‘ankle’ @ 4×10^{18} eV and suppression above 4×10^{19} eV confirming GZK;

● Correlation of UHE cosmic rays with distribution of nearby extragalactic matter and limits of the dipole at the 1% C.L.;

● Anisotropy onset at 75 Mpc consistent with GZK effect;

● **If** the models correctly describe hadronic interactions at 10^{18} eV and above, a tendency to heavier composition with energy;

● Limits on the photon ratio and on diffuse neutrino flux set; exotic models are disfavoured so far;

● Prospects: more statistics coming over Auger lifetime.

So,....

Stay tuned!

Thank you for your attention!

Backup Slides

Cosmic Ray Flux

- Exposure estimate:

$$\mathcal{E}(E) = \int_{T} \int_{\Omega} \int_{S_{\text{gen}}} \varepsilon(E, t, \theta, \phi, x, y) \cos\theta \, \mathrm{d}S \, \mathrm{d}\Omega \, \mathrm{d}t,$$

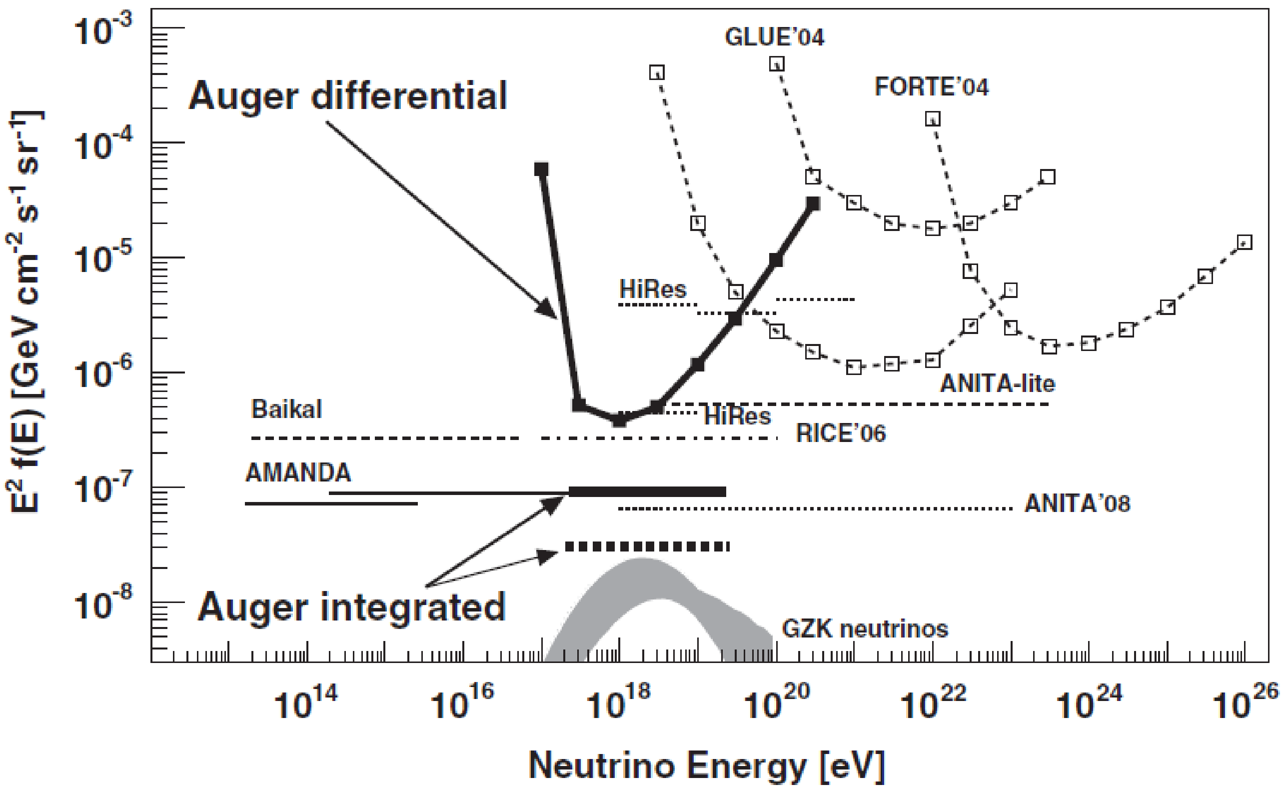
- Flux estimate:

$$J(E) = \frac{\mathrm{d}^4 N_{\text{inc}}}{\mathrm{d}E \, \mathrm{d}A \, \mathrm{d}\Omega \, \mathrm{d}t} \cong \frac{\Delta N_{\text{sel}}(E)}{\Delta E} \frac{1}{\mathcal{E}(E)},$$

Spectrum: Event selection criteria

- Showers must have a reconstructed zenith angle smaller than 60◦.
- In the plane perpendicular to the shower axis, the reconstructed shower core must be within 1500 m of the station used for the geometrical reconstruction.
- The contribution of Cherenkov light to the overall signal of the FD must be less than 50%.
- The Gaisser–Hillas fit [19,20] of the reconstructed longitudinal profile must be successful with $\chi 2$/ndof < 2.5.
- The maximum of the shower development, *X*max, must be observed in the field of view of the telescopes.
- The uncertainty in the reconstructed energy, which includes light flux and geometrical uncertainties, must be *σ(E)/E* < 20%.
- Only periods during which no clouds were detected above the Observatory are used.

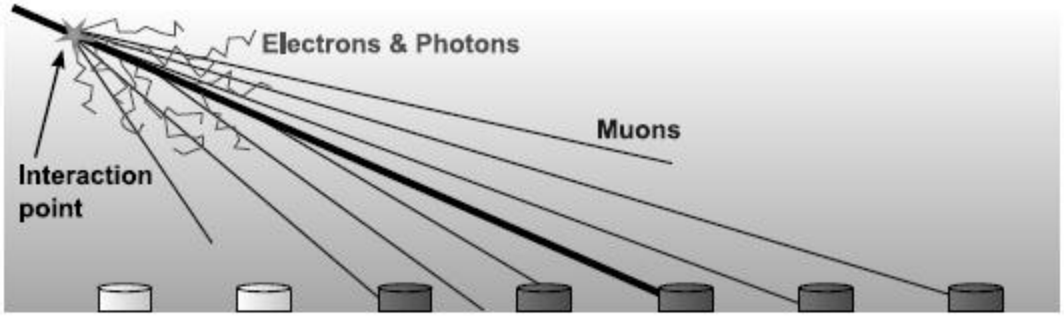
First limits on the neutrino fluxes



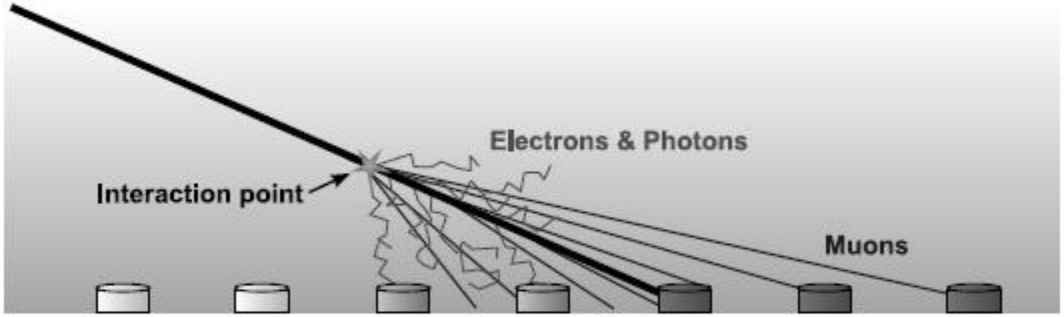
Limits at 90% CL for each flavor of diffuse UHE neutrino fluxes assuming a proportion of flavors of 1:1:1 due to neutrino oscillations.

Auger Collaboration, Phys. Rev. D 79, 102001 (2009)

How it is possible to distinguish neutrino showers?



Inclined shower induced by a hadron interacting high in the atmosphere: EM particles absorbed and only muons reach the detector



Deep inclined shower induced by a neutrino interacting deep in the atmosphere: early region has a significant EM component, late region only muons

Auger Collab., Proc.31st ICRC2009

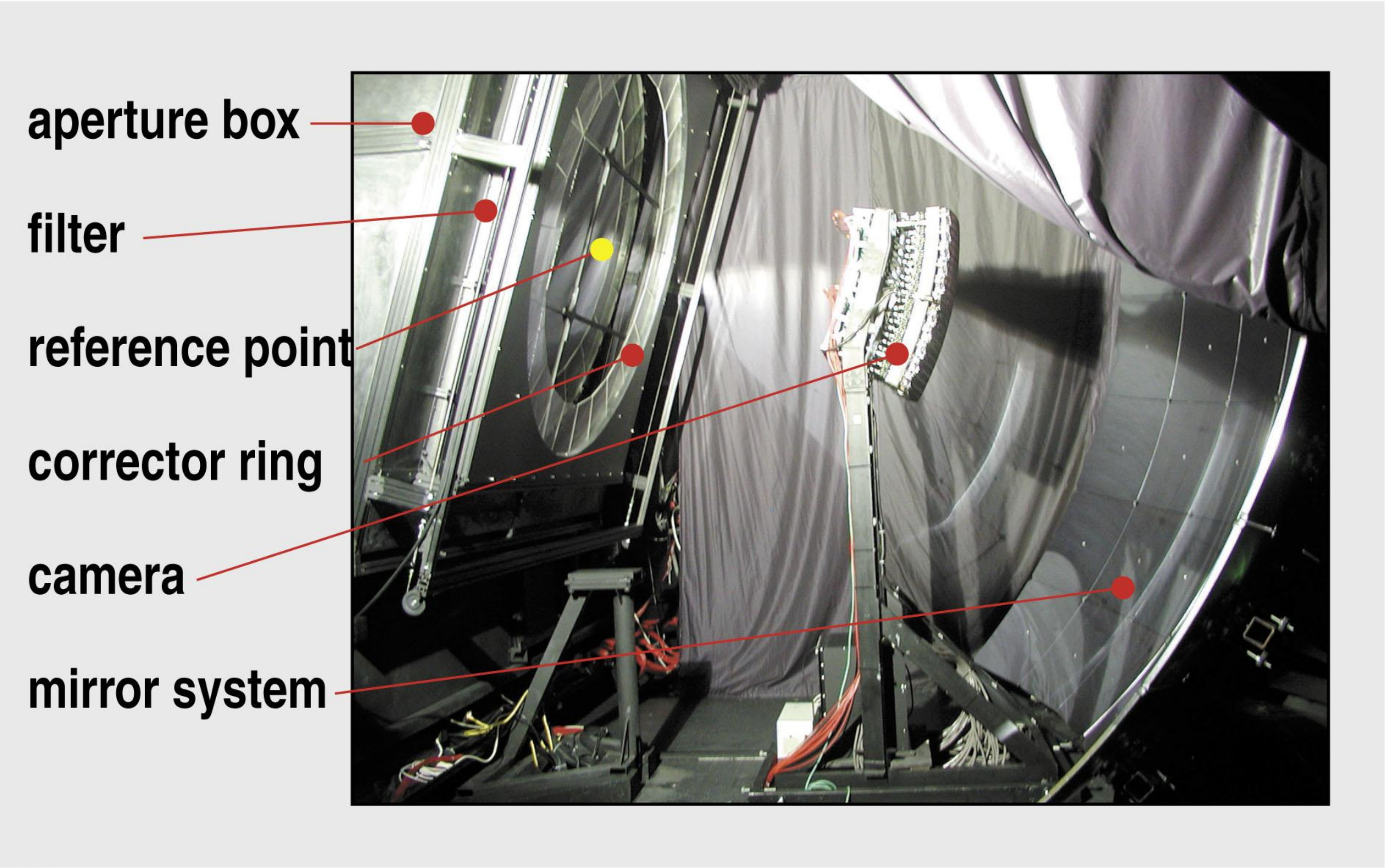
Limit on the photon ratio

Previous results:

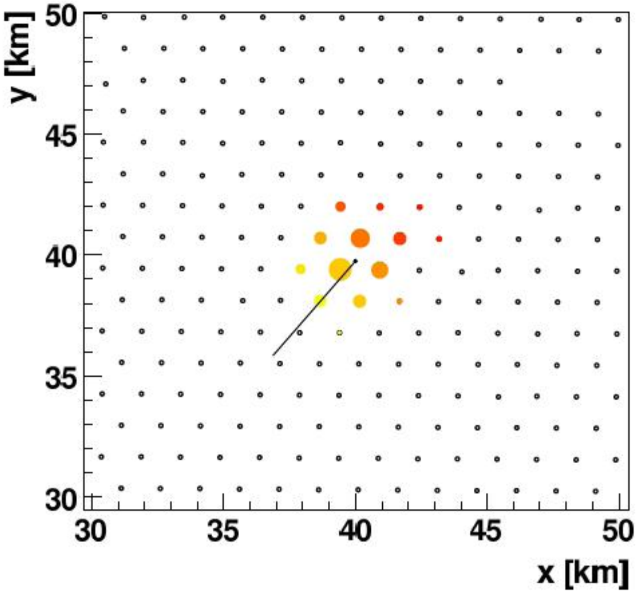
- Upper limit on the photon fraction of 16% above 10 EeV from X_{max} observed by the FD in hybrid mode (2007);
- Limit of 2% with events from the SD of energy above 10 EeV (2008);
- Direct observations of the longitudinal development of UHE showers resulted in limits at energies 2, 3, 5 and 10 EeV.

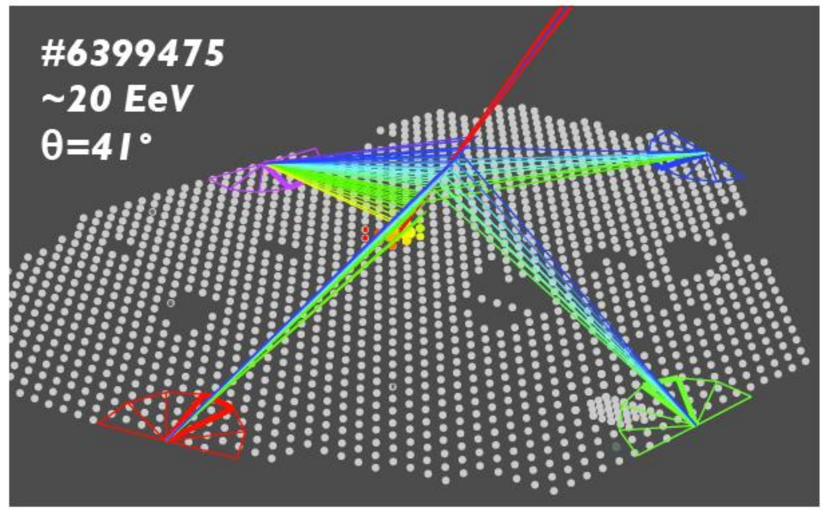
Auger Collaboration, Astropart. Phys. 31 (2009) 399
Auger Collaboration, Astropart. Phys. 29 (2008) 243
Auger Collaboration, Astropart. Phys. 27 (2007) 155

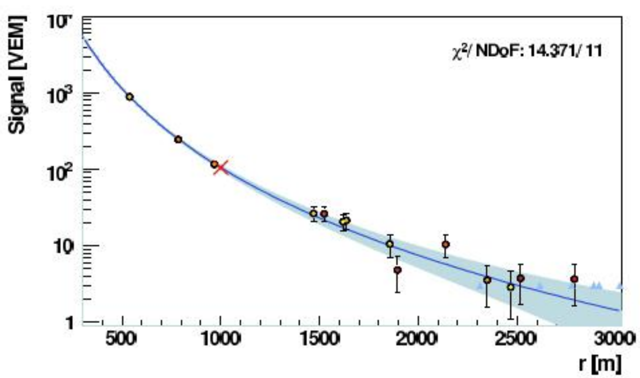
A fluorescence telescope (FD)

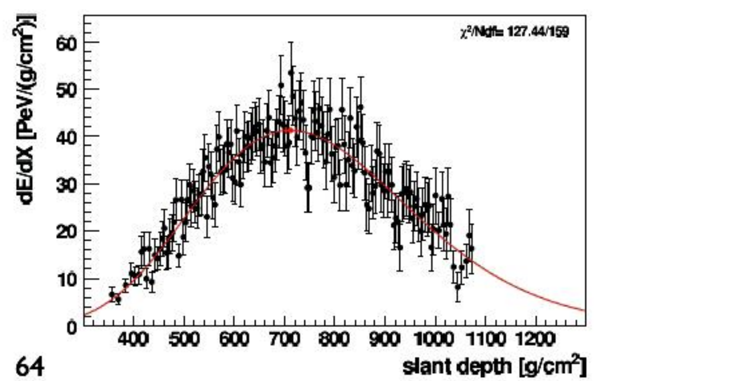


“Quadrocular” event









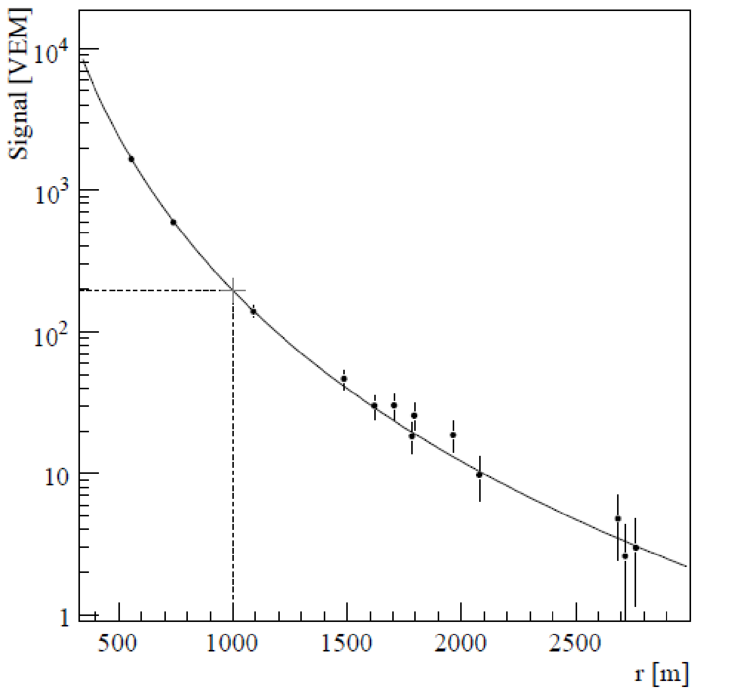
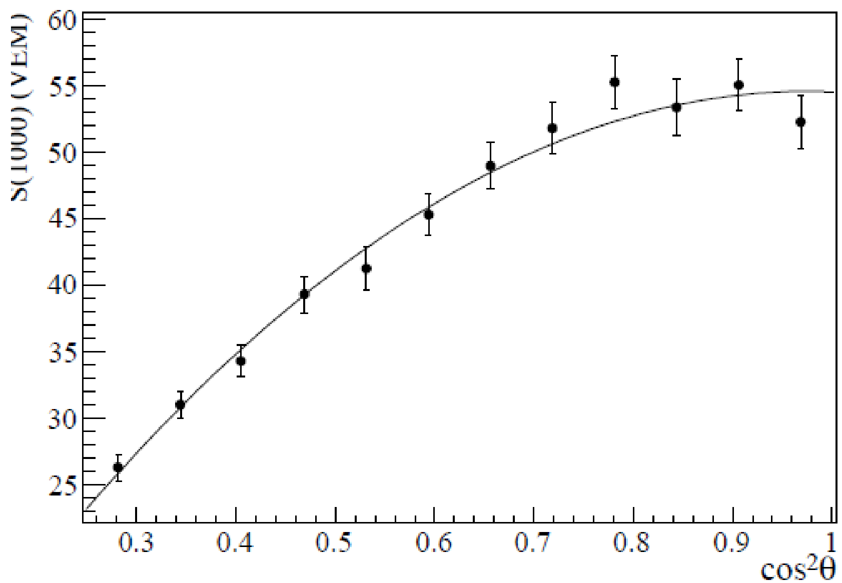


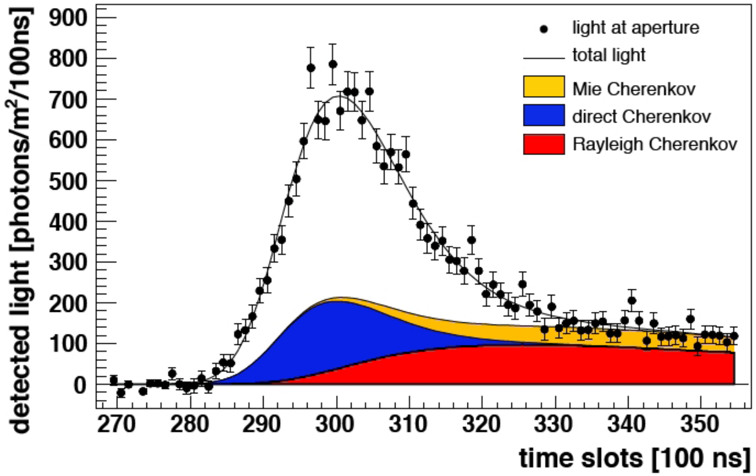
Fig. 1. Lateral distribution: filled circles represent recorded signals. The fitted value S(1000) is marked with a cross.

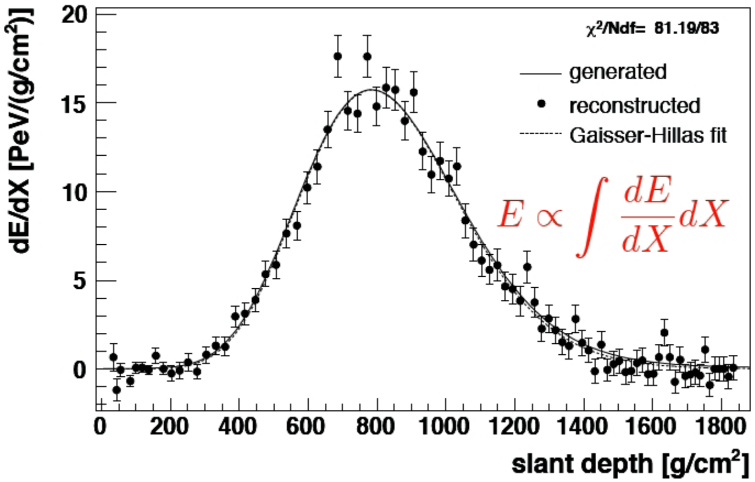


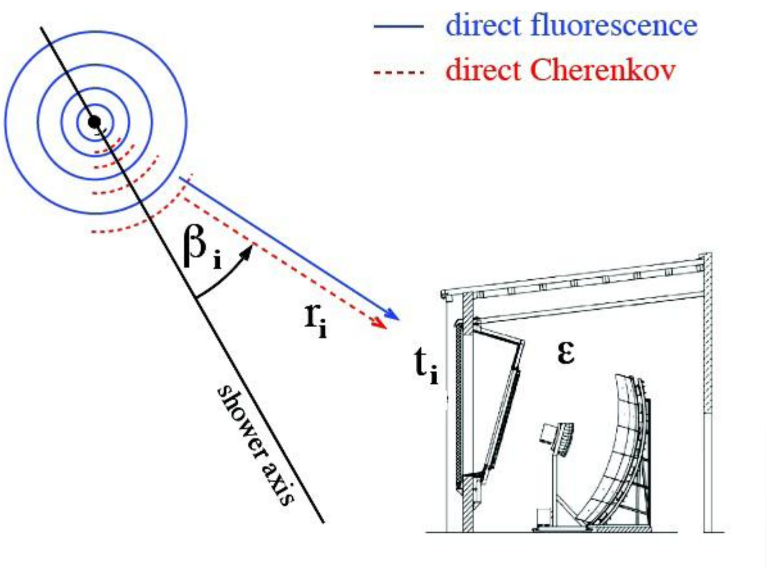
ig. 3. Derived attenuation curve, $CIC(\theta)$, fitted with a quadratic unction.

Auger Collab. Proc.31st ICRC2009

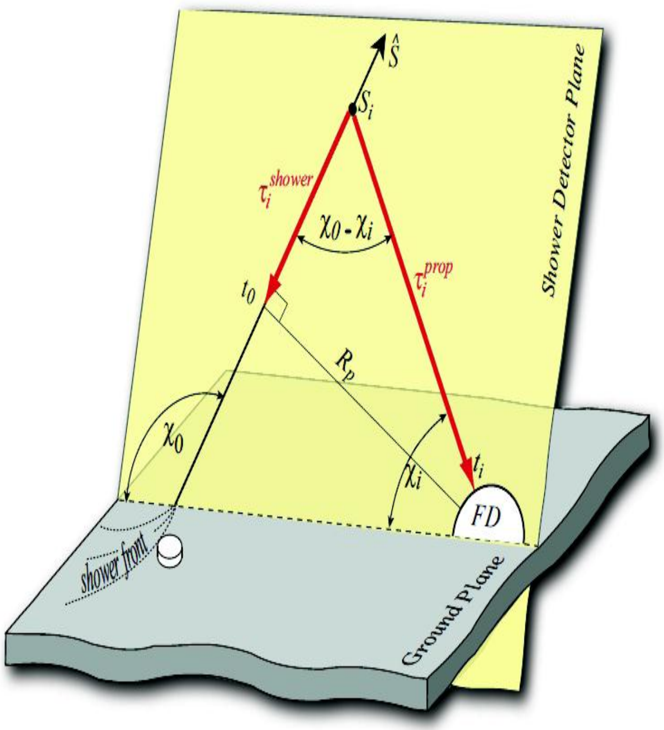
Energy from the FD

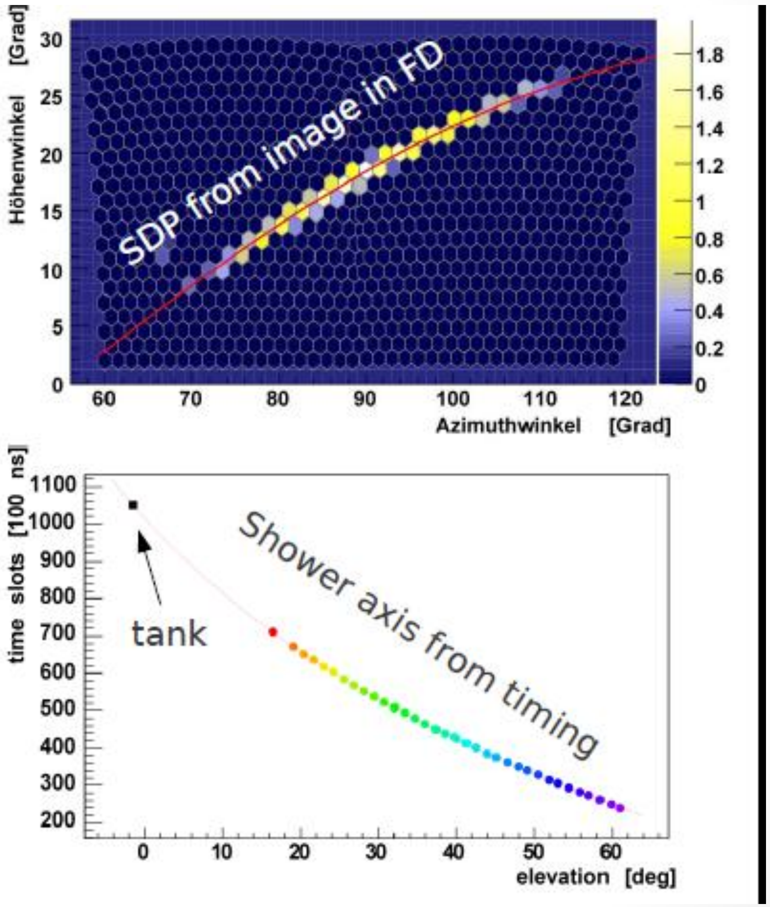






Hybrid geometrical reconstruction





First steps to excellent measurement of energy and composition

The detection of a large scale anisotropy in the energy range [0.1-10] EeV would be hailed as an important milestone, as it would constitute an important step forward to provide further understanding on the end of Galactic cosmic rays, and would help to establish at which energy the flux of extragalactic cosmic rays starts to dominate the cosmic ray energy spectrum.

Correlation of the highest energy cosmic rays with nearby extragalactic matter

- Previously data collected between 1Jan 2004 and 31 Aug 2007 showed evidence for anisotropy in the arrival directions of cosmic rays above the Greisen–Zatsepin–Kuz'min energy threshold, 6 x10^{19} eV.
- The anisotropy was measured by the fraction of arrival directions that are less than 3.1° from the position of an AGN within 75 Mpc (using the Véron-Cetty and Véron 12th catalog).
- Updata: same parameters, data through 31 Dec 2009 (15980 km^2 sr y).
- The number of arrival directions has increased from 27 to 69, allowing a more precise measurement.
- The correlating fraction is 38+7/-6%, (21% expected for isotropic cosmic rays).
- Previously: 99% confidence that the flux of cosmic rays is not isotropic. The P-value of 0.003 reported here does not increase confidence in anisotropy beyond what was reported.

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Comparisons with other catalogs

Other populations of nearby extragalactic objects:

- galaxies in the Two Micron All-Sky Survey (2MASS Redshift Survey 2MRS) and
- AGNs detected in hard X-rays by the Swift Burst Alert Telescope.
- Composition from anisotropy: anisotropies due to heavy primaries for $E > E_{th}$ should be also present at energies $E > E_{th}/Z$ for protons accelerated in the same source.

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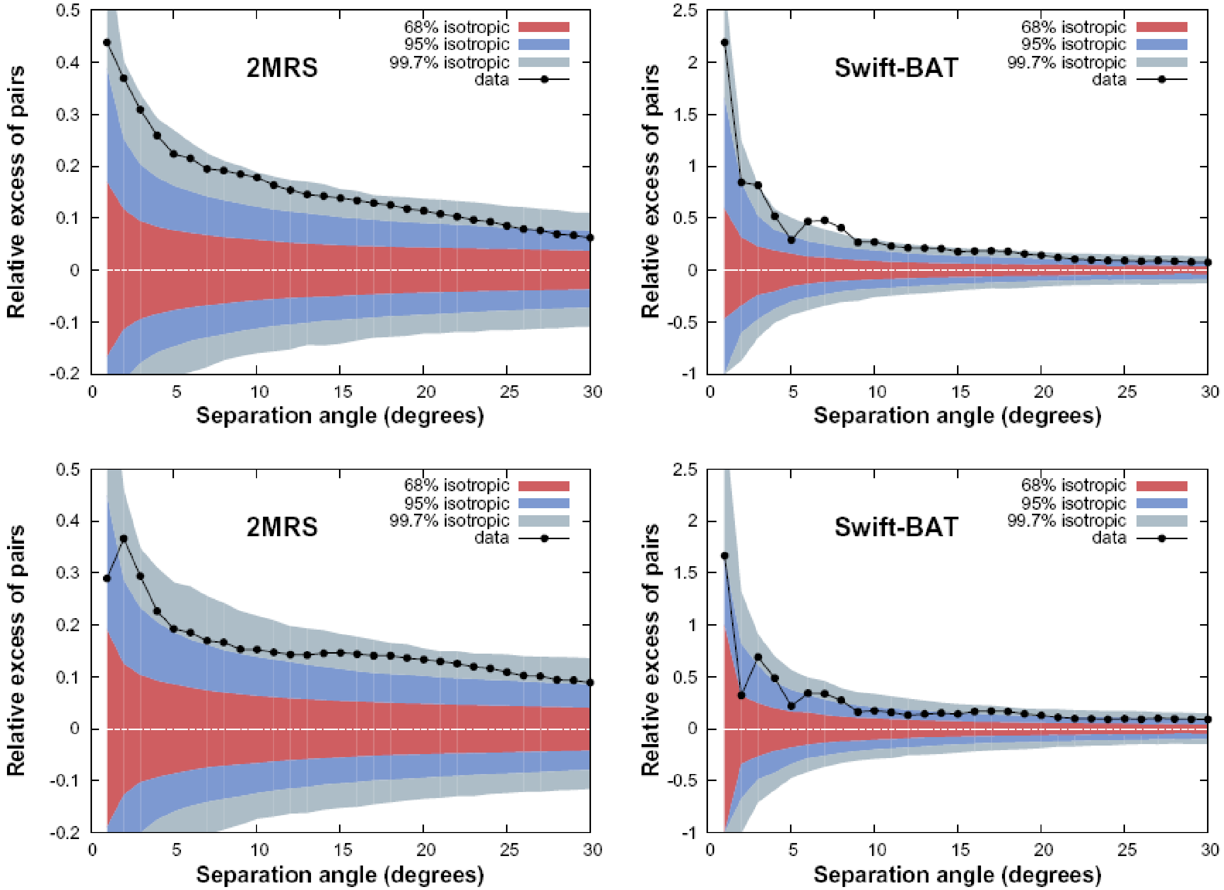
Cross-correlations CR and 2MRS/Swift BAT objects



Bottom line: period I excluded

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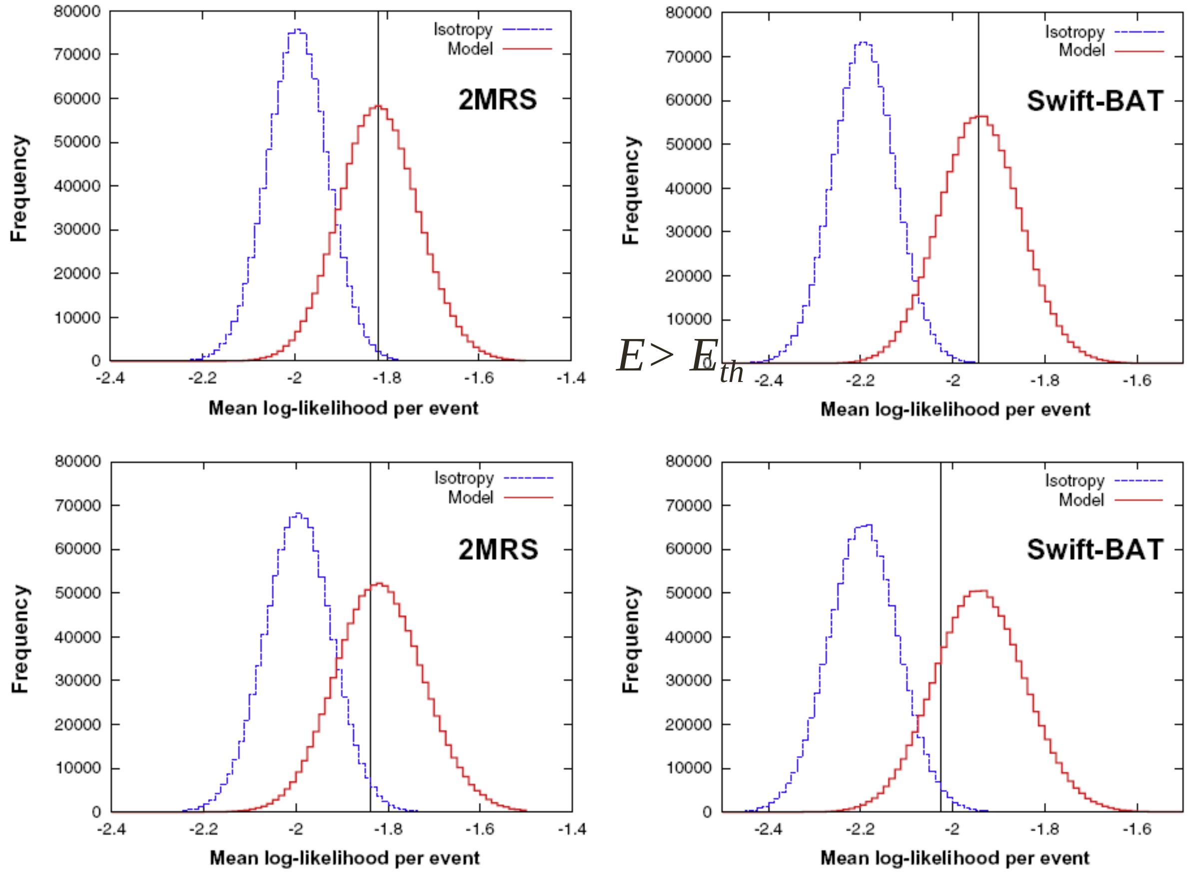
Comparison with objects from other catalogs



$E > E_{th}$

Bottom line: period I excluded

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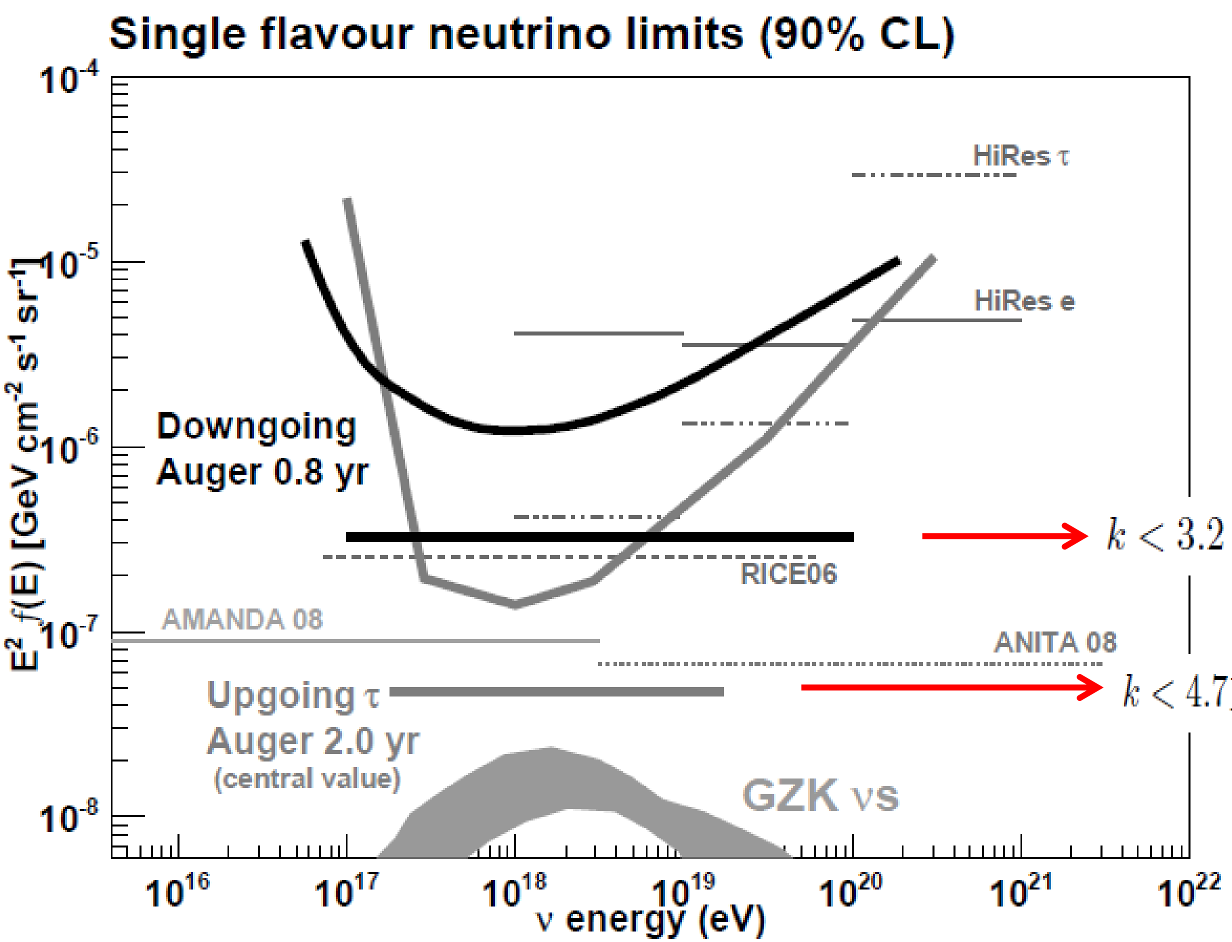
Limits on the neutrino fluxes



$k < 3.2 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

$k < 4.7^{-2.5}_{+2.2} \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

(*systematic uncertainties*)

Limits assuming a ν flux $dN(E)/dE = k \cdot E^{-2}$

Auger Collab. Proc.31st ICRC2009