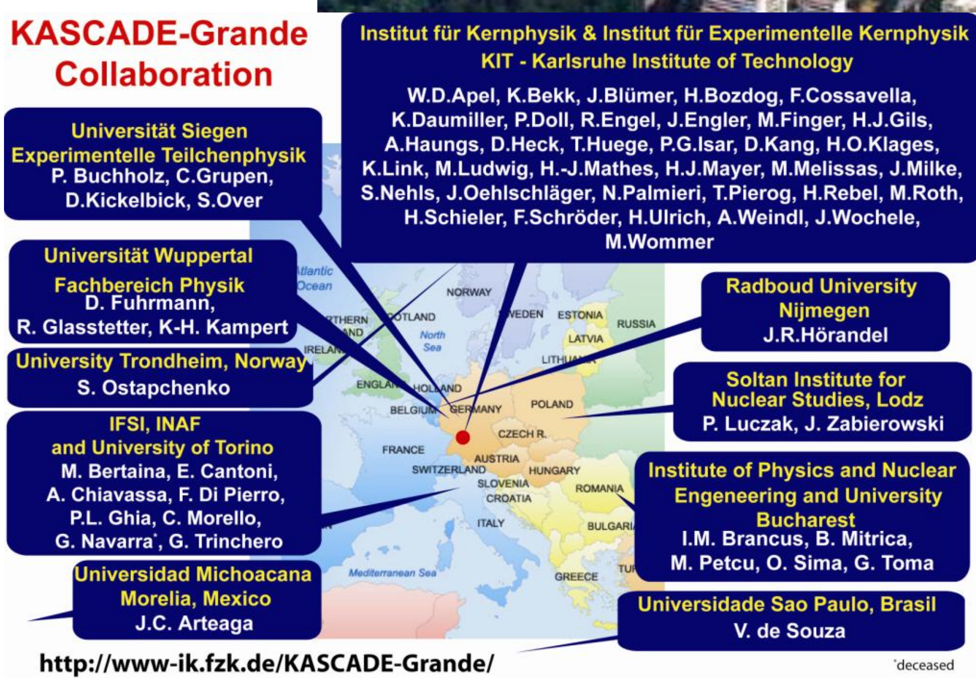
Measurement of the cosmic ray spectrum and large scale anisotropies with the KASCADE-Grande experiment

Andrea Chiavassa

Universita` degli Studi di Torino

KASCADE-Grande experiment



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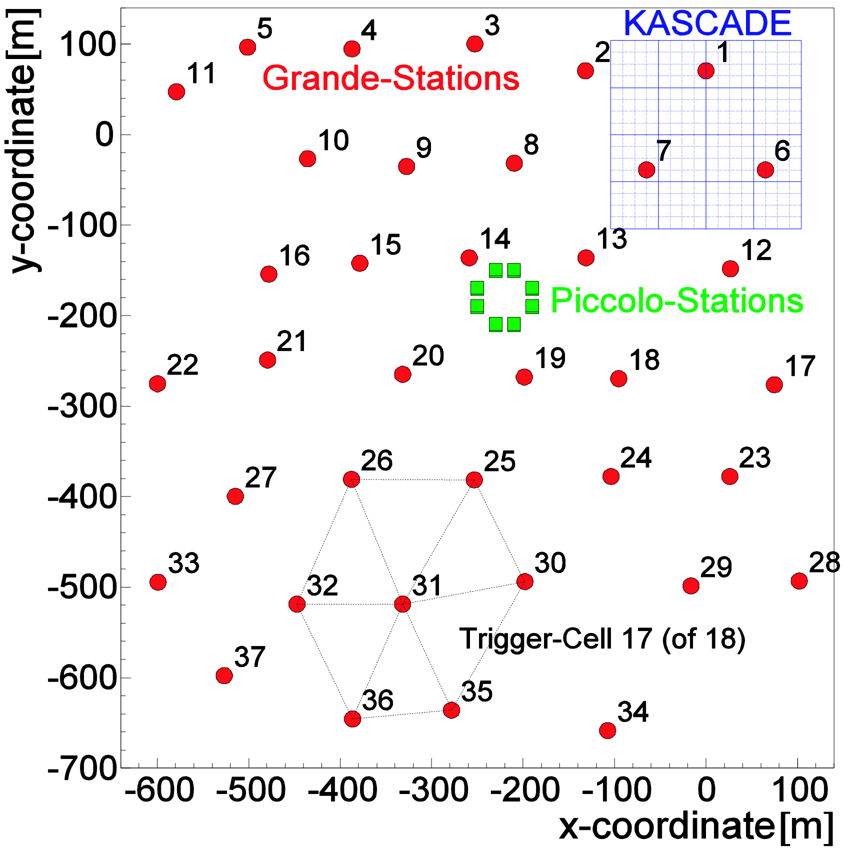
KASCADE-Grande detectors & observables



Grande array → cover an area of 0.5 km^2, detecting EAS with high resolution

Detector	Detected EAS component	Detection Technique	Detector area (m^2)
Grande	Charged particles	Plastic Scintillators	37x10
KASCADE array e/γ	Electrons, γ	Liquid Scintillators	490
KASCADE array μ	Muons (E_μ^{th}=230 MeV)	Plastic Scintillators	622
MTD	Muons (Tracking) (E_μ^{th}=800 MeV)	Streamer Tubes	4x128

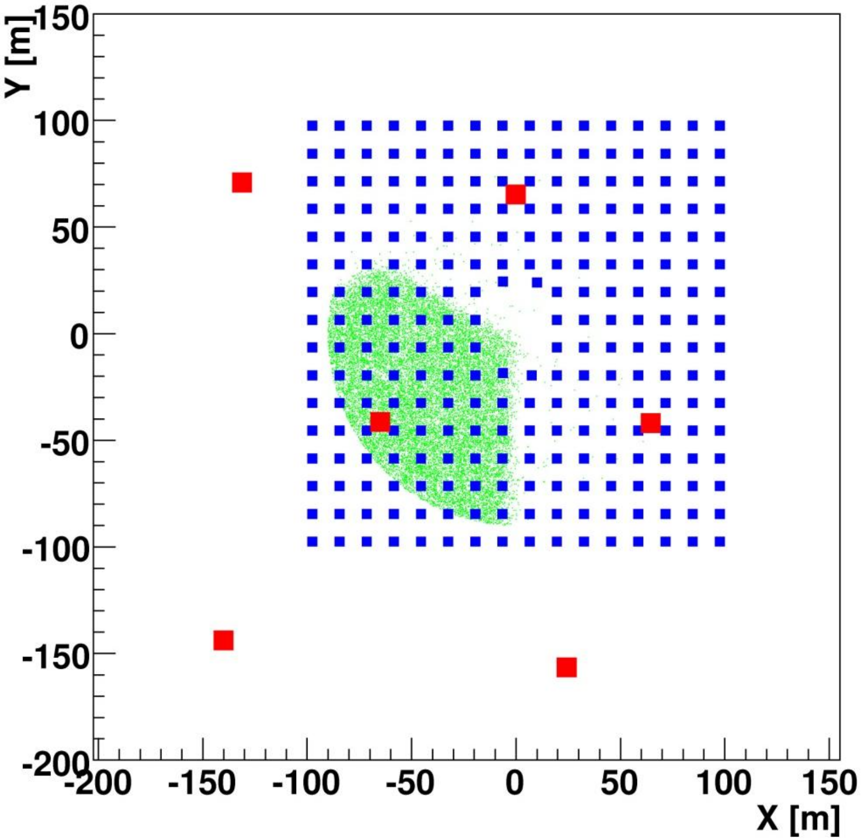
- Shower core and arrival direction
- Shower Size (N_{ch} number of charged particles)
  - Grande array

- μ Size (E_μ>230 MeV)
  - KASCADE array μ detectors
- μ density & direction (E_μ>800 MeV)
  - Streamer Tubes

KASCADE-Grande Data taking concluded in Fall 2012.

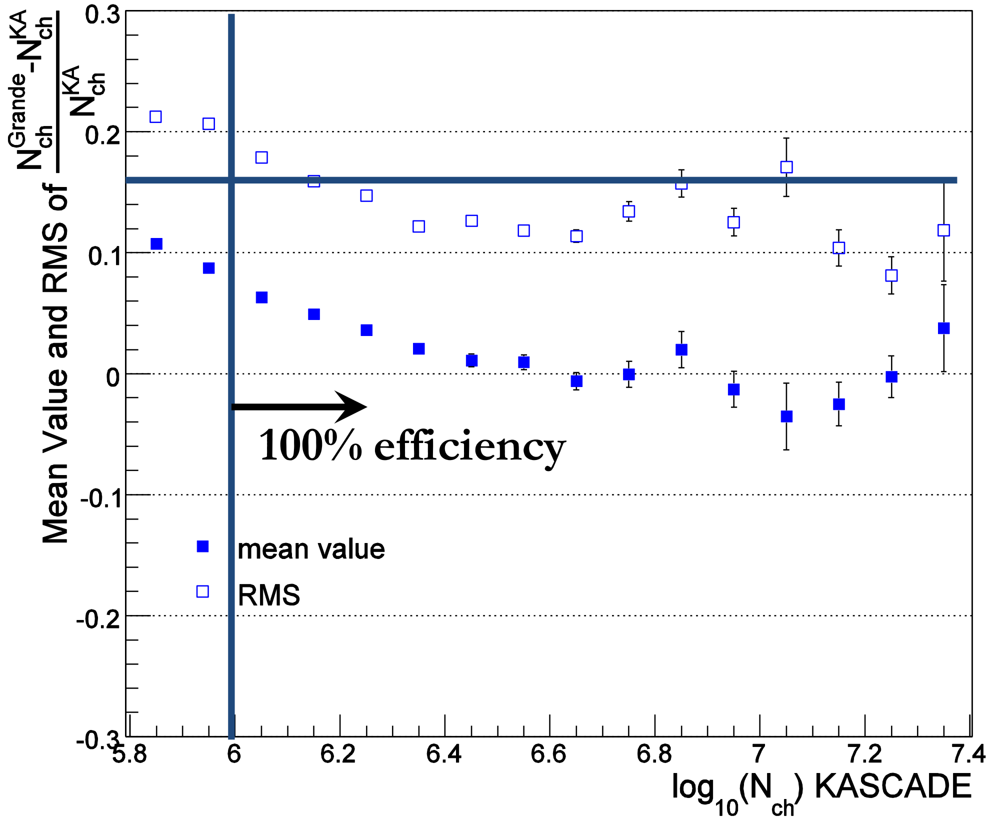
All the Grande scintillators and PMT have been transferred to the TUNKA-133 experiment

KASCADE-Grande accuracies with a subsample of common events KASCADE + Grande



■ KASCADE stations

■ Grande stations



Apel et al. NIMA 620 (2010) 202-216

All particle energy spectrum

- Combination of N_{ch} and N_{μ}
- Five different angular bins

$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_{H}}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_{H}}$$

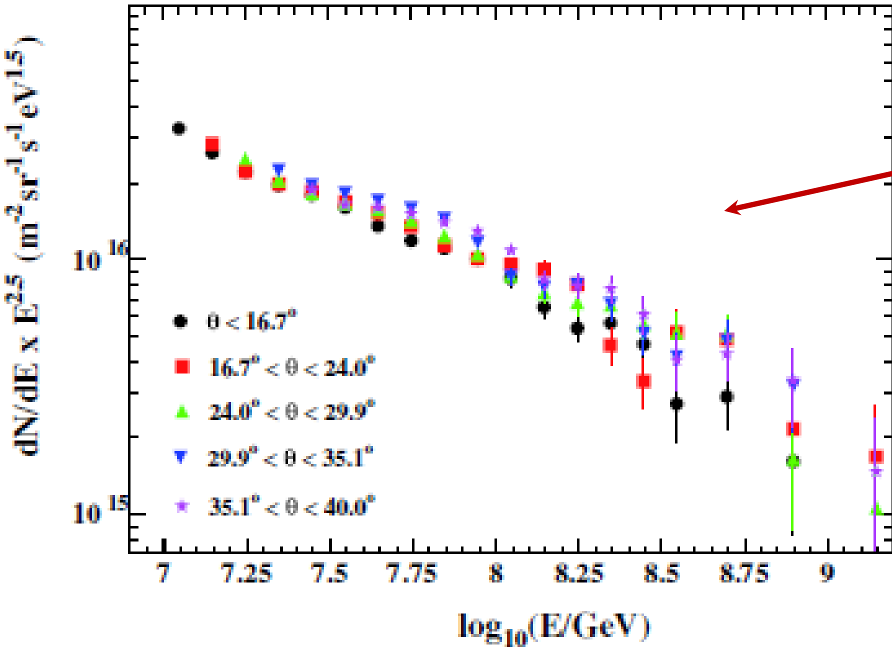
$$Log(N_{ch}/N_{\mu})_{H,Fe} = c_{H,Fe} \cdot Log(N_{ch}) + d_{H,Fe}$$

- k parameter evaluates chemical composition, used as a weight in the expression correlating N_{ch} and E

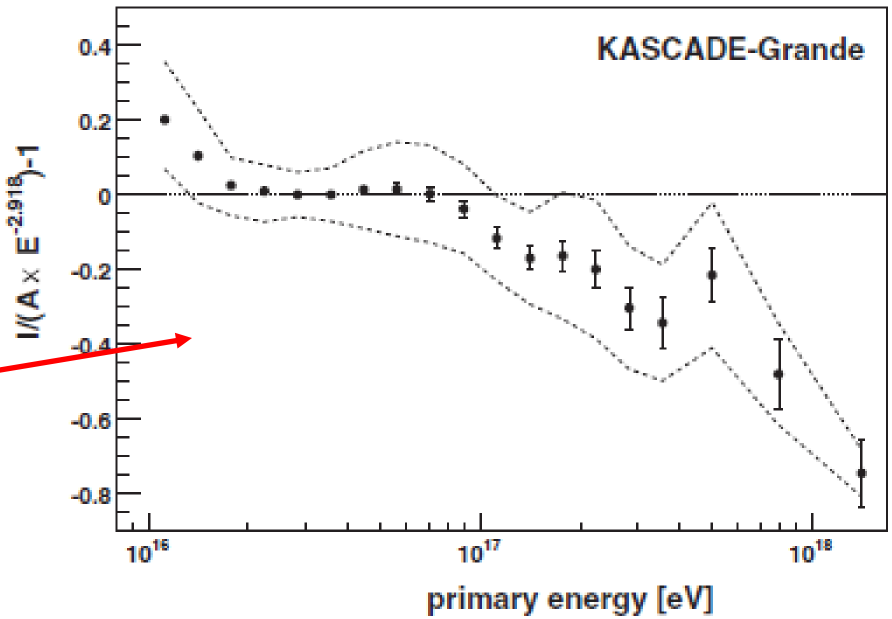
$$\log_{10} E = [a_H + (a_{Fe} - a_H) \cdot k] \cdot \log_{10} N_{ch} + b_H + (b_{Fe} - b_H) \cdot k$$

- Based on QGSJet II-02

Astroparticle Physics **36**, (2012) 183



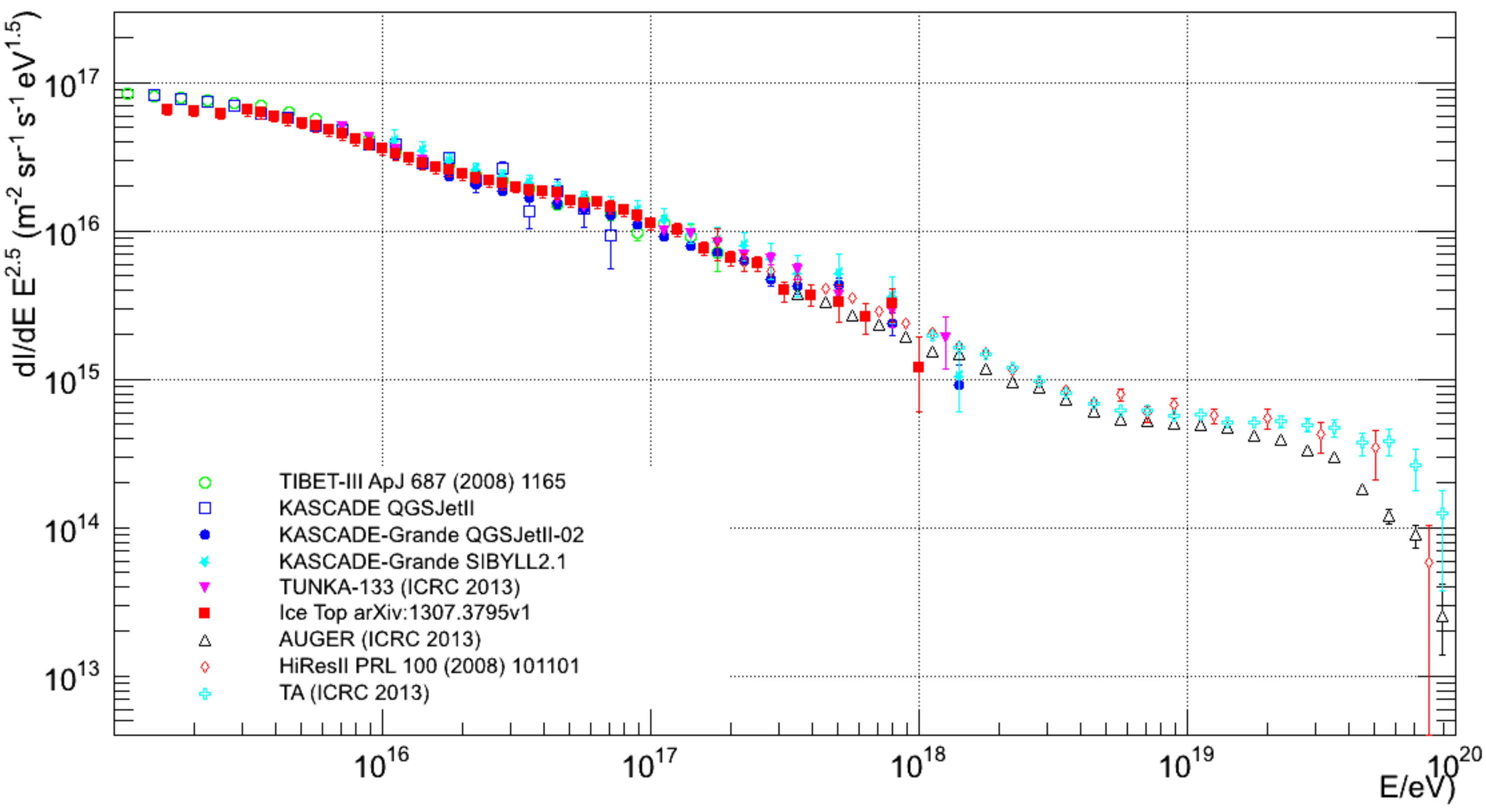
Energy spectra measured in the five angular bins
Spectra do not perfectly coincide: hint of problems in the simulation of the EAS development in atmosphere?



- Spectrum cannot be described by a single power law
- Hardening above 10^{16} eV
- Steepening close to 10^{17} eV significance 2.1σ

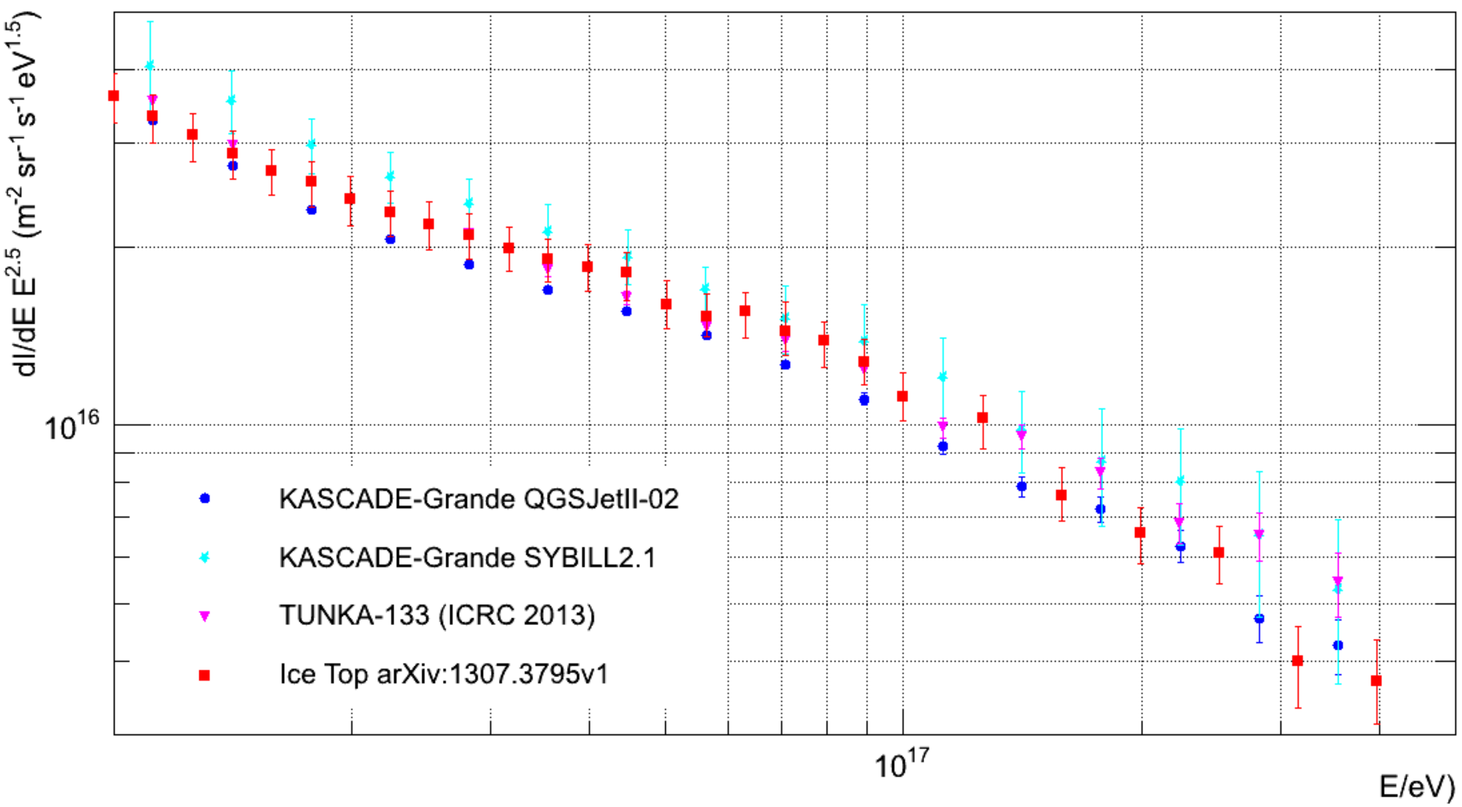
Astroparticle Physics **36**, (2012) 183

Comparison of different measurements of the cosmic ray spectrum.



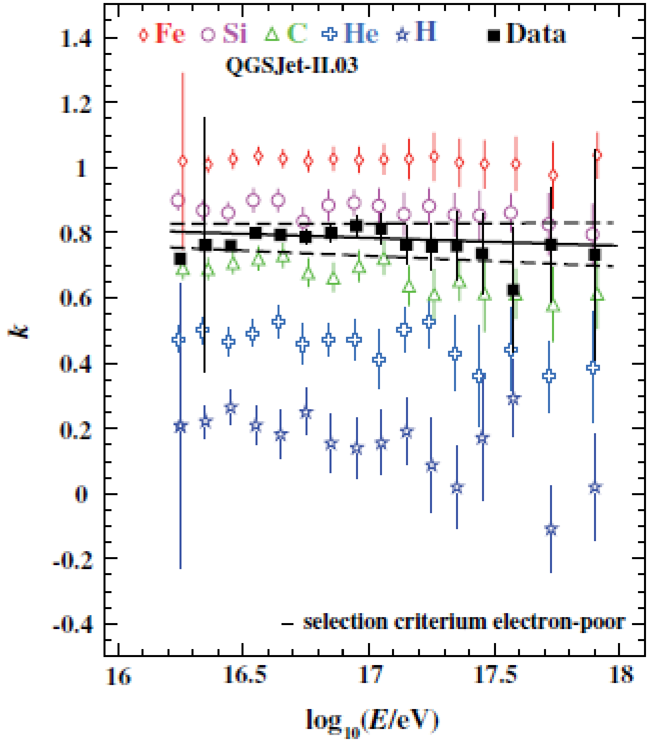
KASCADE-Grande all particle spectrum calibrated using SIBYLL2.1 →
Advances in Space Research, http://dx.doi.org/10.1016/j.asr.2013.05.008

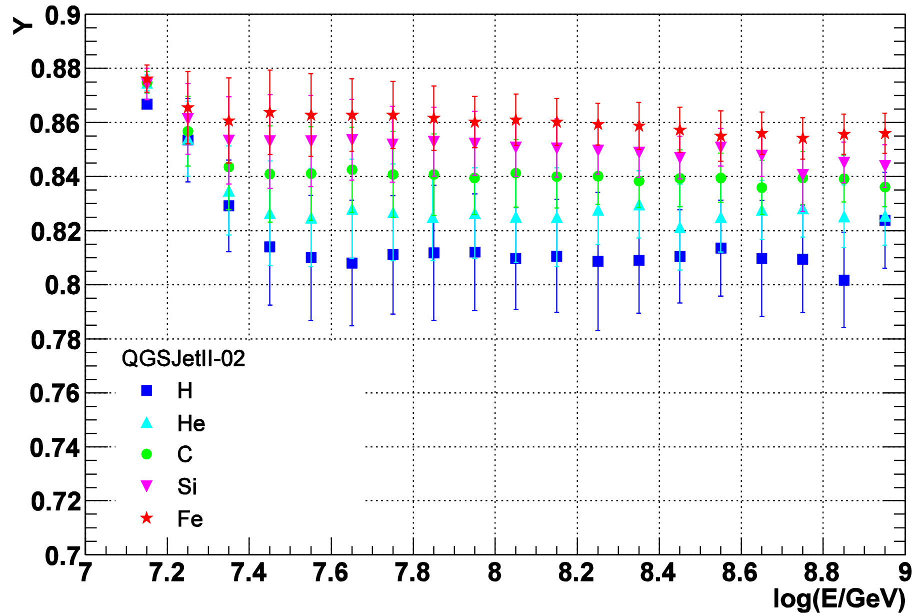
Zoom in the $10^{16} – 10^{18}$ eV energy range.
Differences in the absolute fluxes can be mainly attributed to the hadronic interaction models used to calibrate the experiments.
Spectral features are detected by different experiments operating at different altitudes



Event by event separation in two mass groups by the N_{ch}/N_{μ} ratio

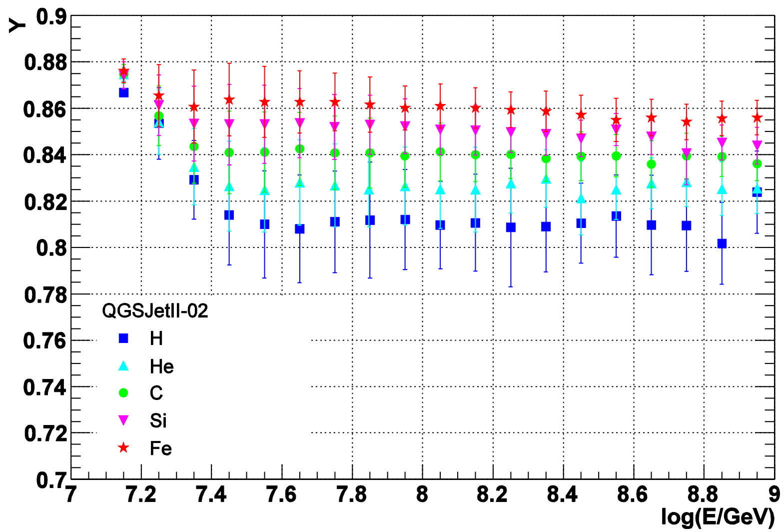
Two different ways of taking into account the EAS attenuation in atmosphere

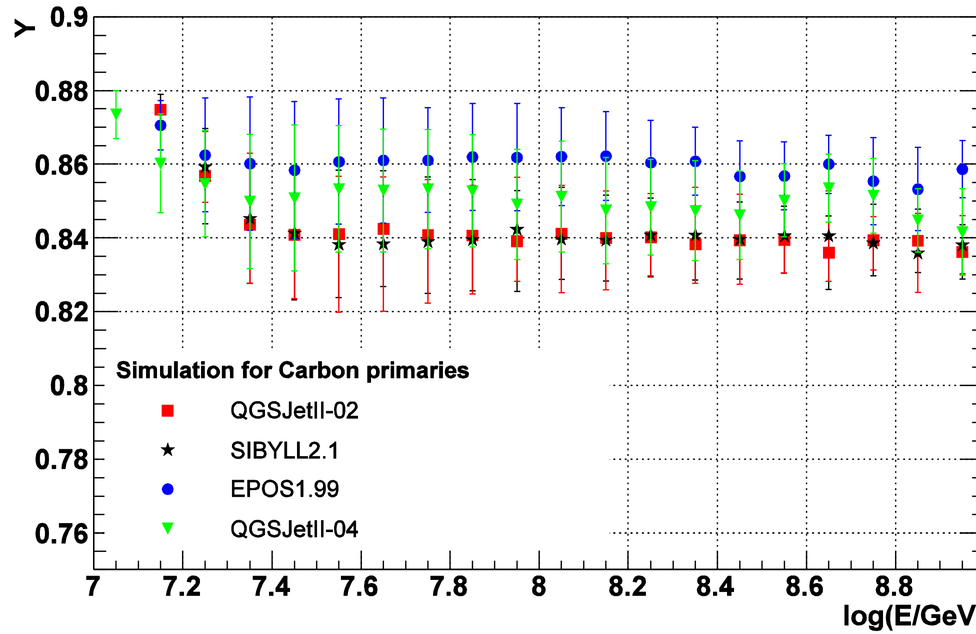




$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_H}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_H}$$

$$Y_{CIC} = \frac{\ln N_{\mu}(\vartheta_{ref})}{\ln N_{ch}(\vartheta_{ref})}$$

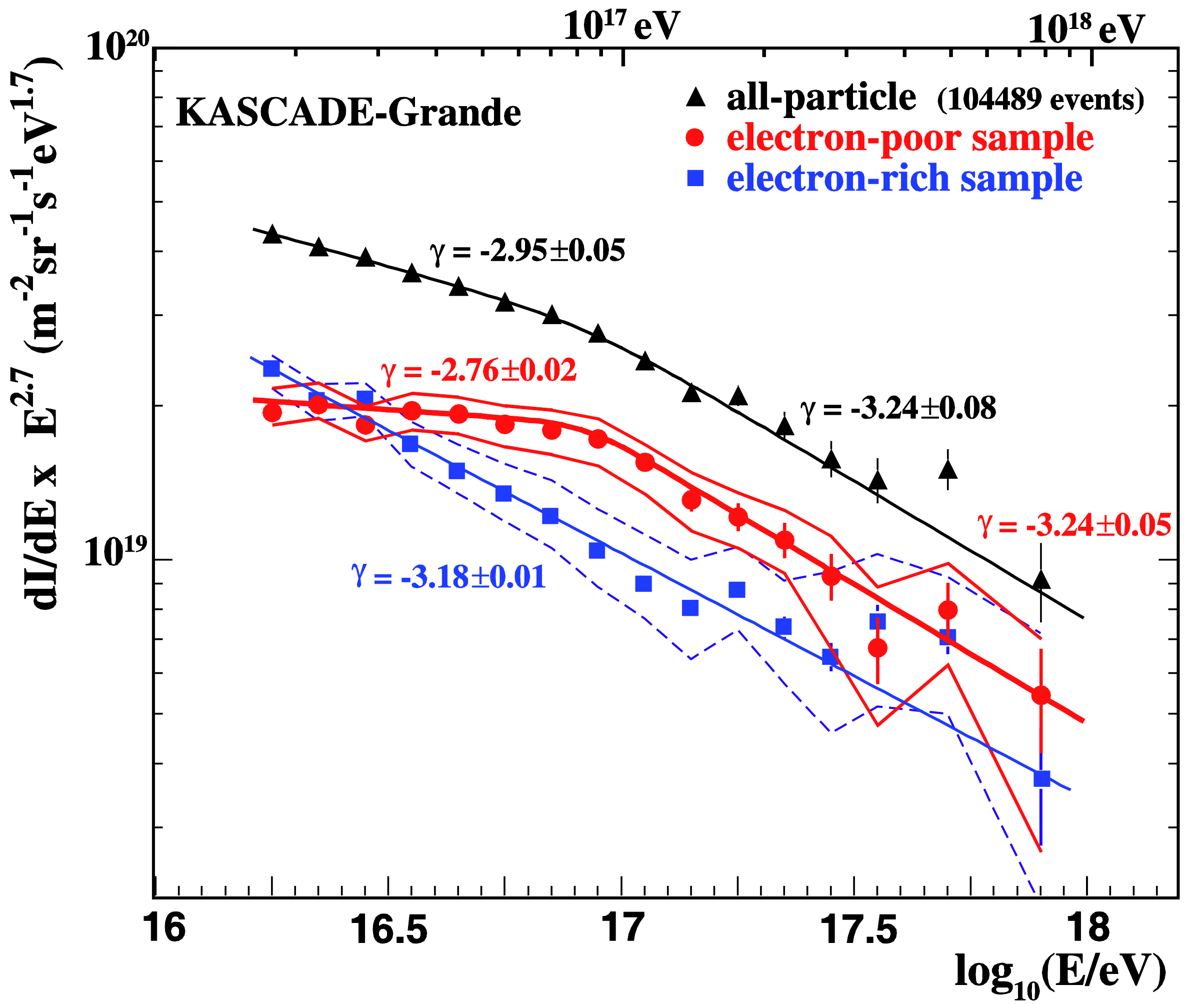




Y_{CIC} is constant with E
(E > full efficiency)

For a specific hadronic interaction model
Y_{CIC} increases with primary mass
choice of Y_{CIC} → choice of a primary mass

For a particular primary element
Y_{CIC} increases when calculated by a model generating EAS with higher N_{μ}
→ for the same primary mass the choice of Y_{CIC} is shifted



- Energy spectra of the samples obtained by an event selection based on the k parameter

- Spectrum of the electron poor sample → $k>(k_C+k_{Si})/2$ → steepening observed with increased significance → 3.5σ

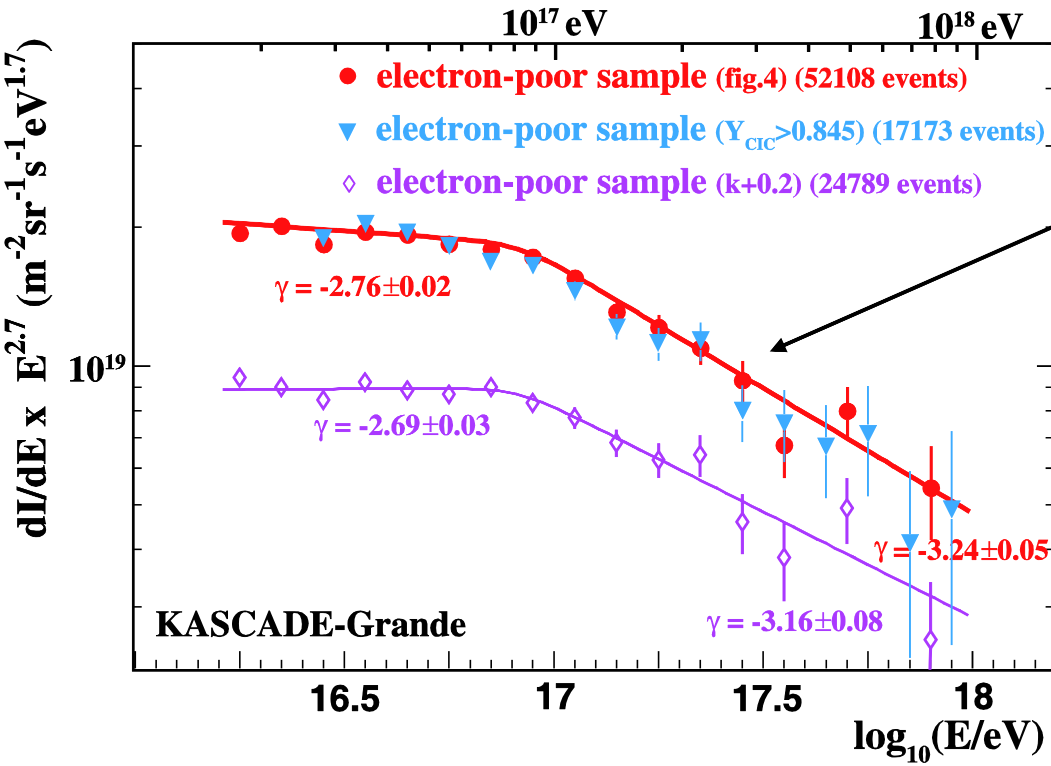
- Spectrum of electron rich events → can be described by a single power law → hints of a hardening above 10^{17} eV

$\gamma_1 = -2.76 \quad 0.02$

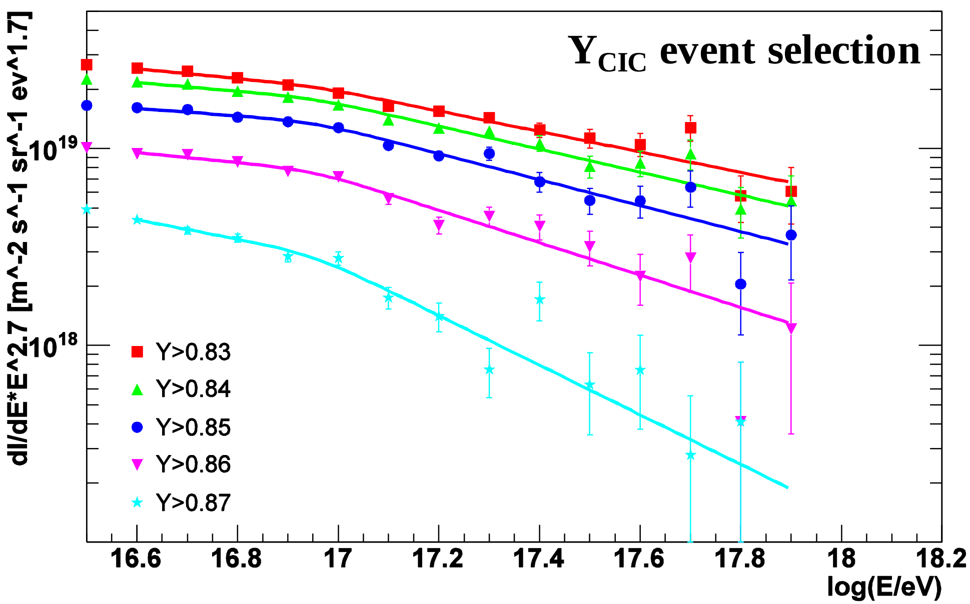
$\gamma_2 = -3.24 \quad 0.05$

$E_b = 10^{16.92 \quad 0.04}$ eV

Phys. Rev. Lett. **107** (2011) 171104



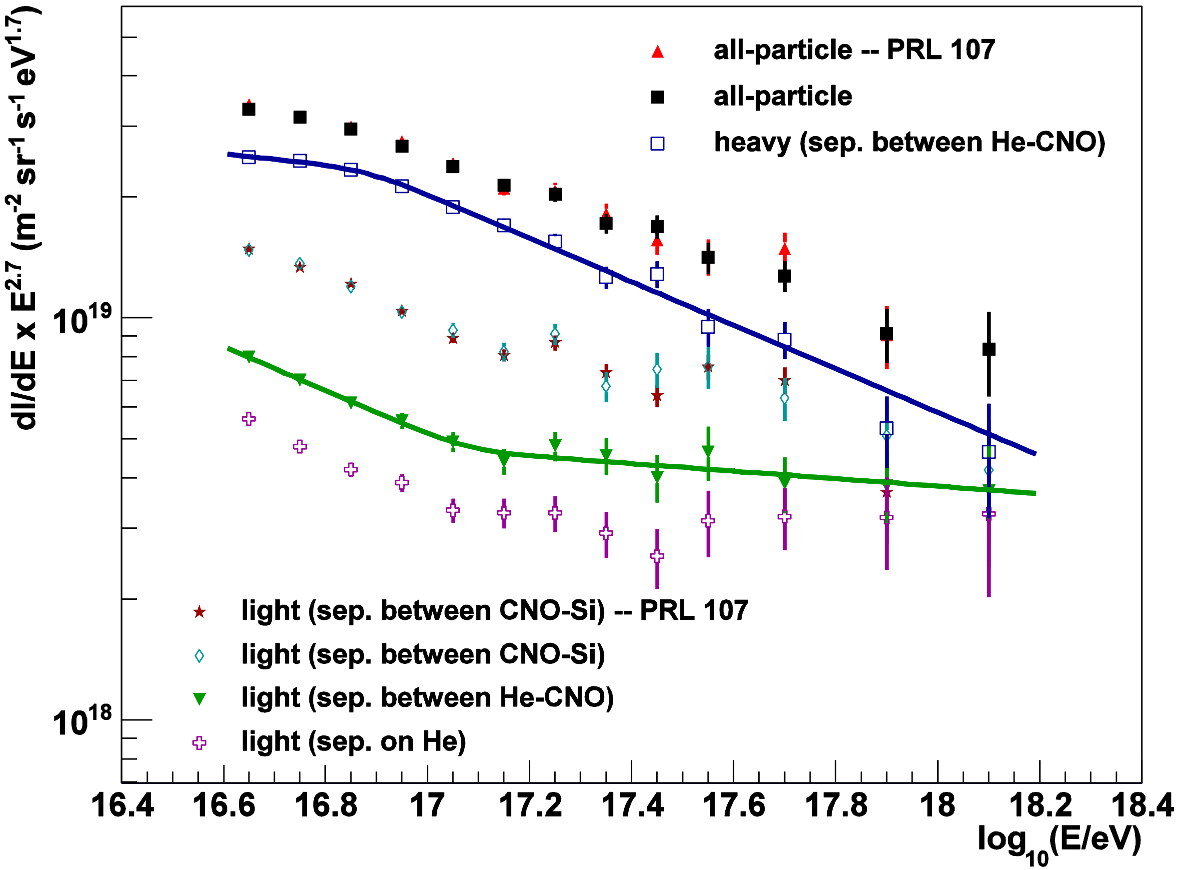
- ✓ Spectra obtained with the two different strategies agree
- ✓ Steepening observed at the same energy independently of the cut choice
- ✓ The steepening of the electron poor sample is enhanced cutting at higher Y_{CIC} values



Phys. Rev. Lett. **107** (2011) 171104

To enhance possible structures of the electron rich sample →

$k < (k_C + k_{He})/2$



$\gamma_1 = -3.25 \;\; 0.05$

$\gamma_2 = -2.79 \;\; 0.08$

$E_b = 10^{17.08 \;\; 0.08}$ eV

$N_{meas} = 579$

$N_{exp} = 467$

$P(N>N_{meas}) \approx 7.23 \times 10^{-09}$

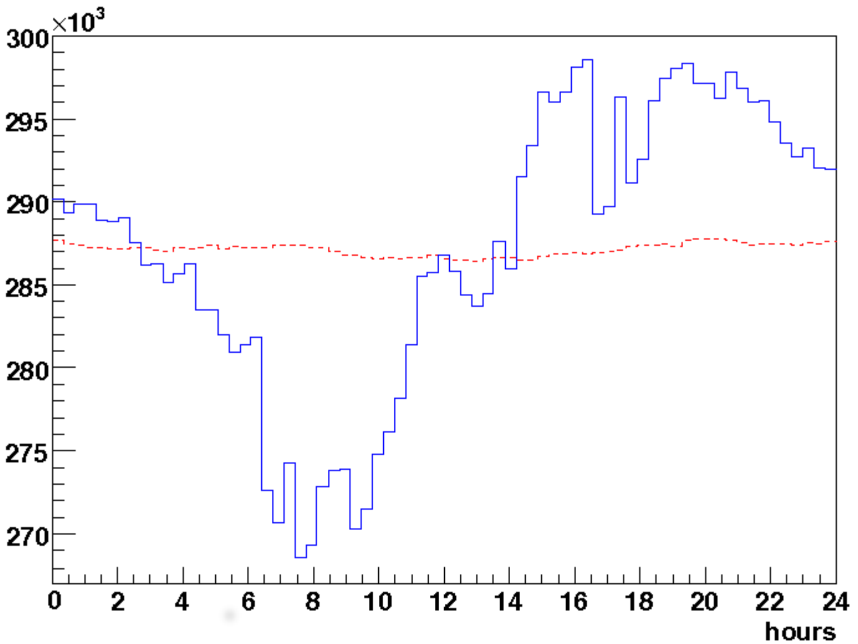
5.8σ significance

- **Spectra obtained enhancing the electron-rich event selection show a significant hardening above 10^{17} eV**

Phys. Rev. D **87**, 081101(R) (2013)

Search for Large Scale Anisotropies

- East-West method
  - Allows to remove counting rate variations due to atmospheric and instrumental effects
- Data set from December 2003 to October 2011 (10^7 events)
  - $\theta < 40°$
  - $\mathrm{Log}\ N_{ch} > 5.2$



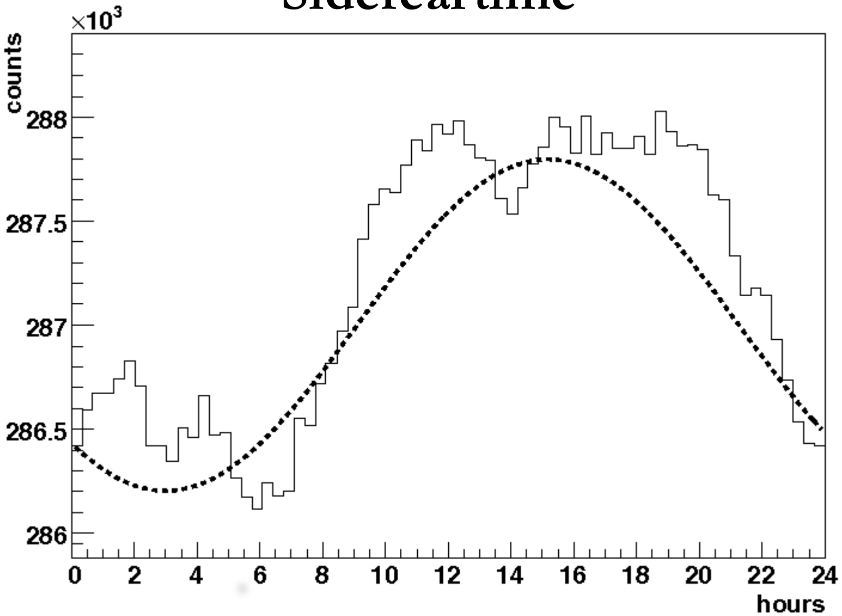
Counting rate distribution in Solar Time

- Blue line → no corrections

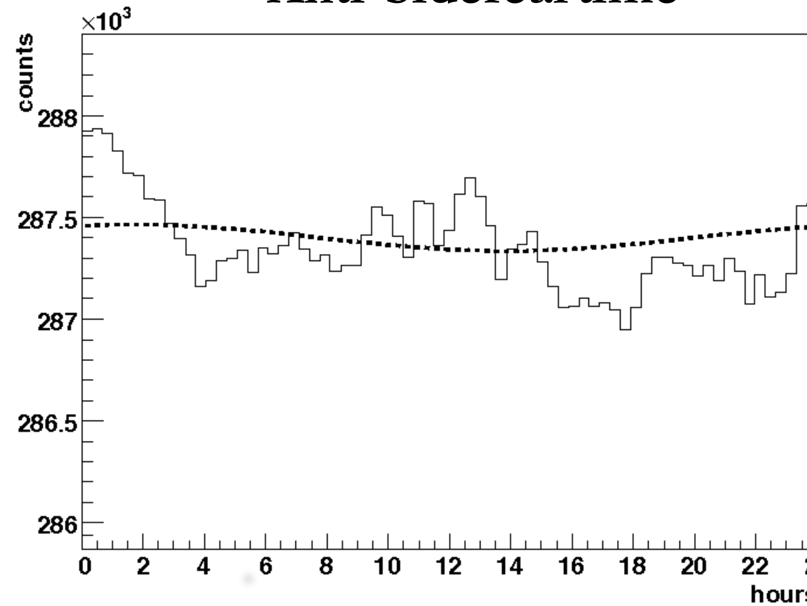
- Red line → E-W method

Counting rate distributions (20 minutes bins) in Sidereal and Anti-sidereal times, applying the East-West method.

Sidereal time



Anti-Sidereal time



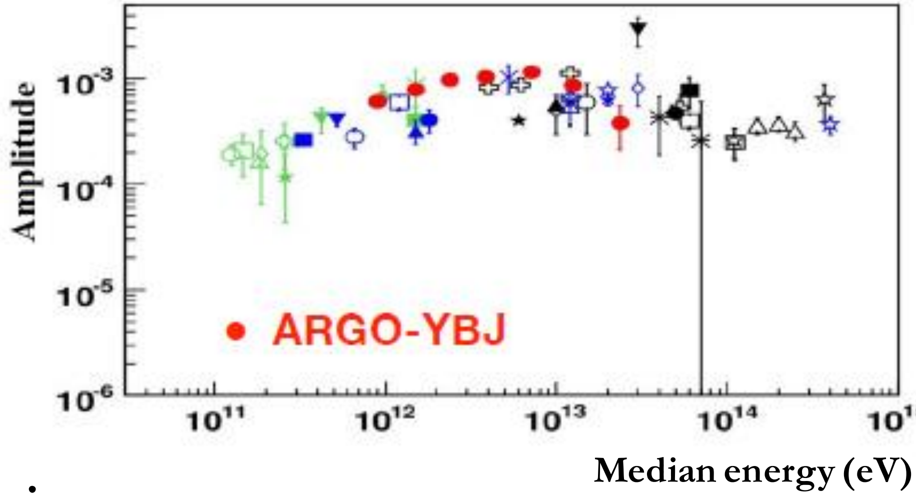
First harmonic analysis in Sidereal, Solar and Anti-sidereal times

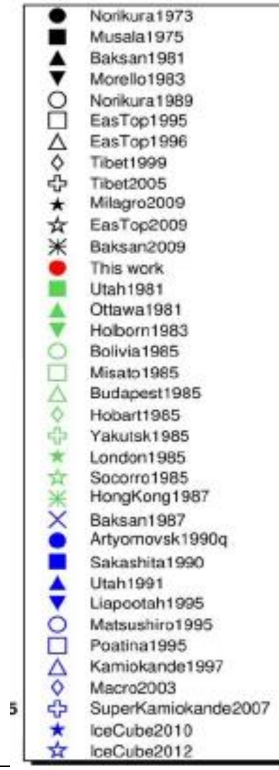
Time	Amplitude ($Ax10^{-2}$)	Phase (hours)	Rayleigh Probability
Sidereal	0.28±0.08	15.1±1.1	0.2%
Solar	0.15±0.08	23.9±2.1	17%
Anti-sidereal	0.02±0.08	1.8±14.4	96%

Log $N_{ch} > 5.2$ → median energy $E \sim 3.3x10^{15}$ eV

The probability that the amplitude of the sidereal time amplitude is due to a background fluctuation is ***0.2%*** (i.e. ***3.5 σ***).

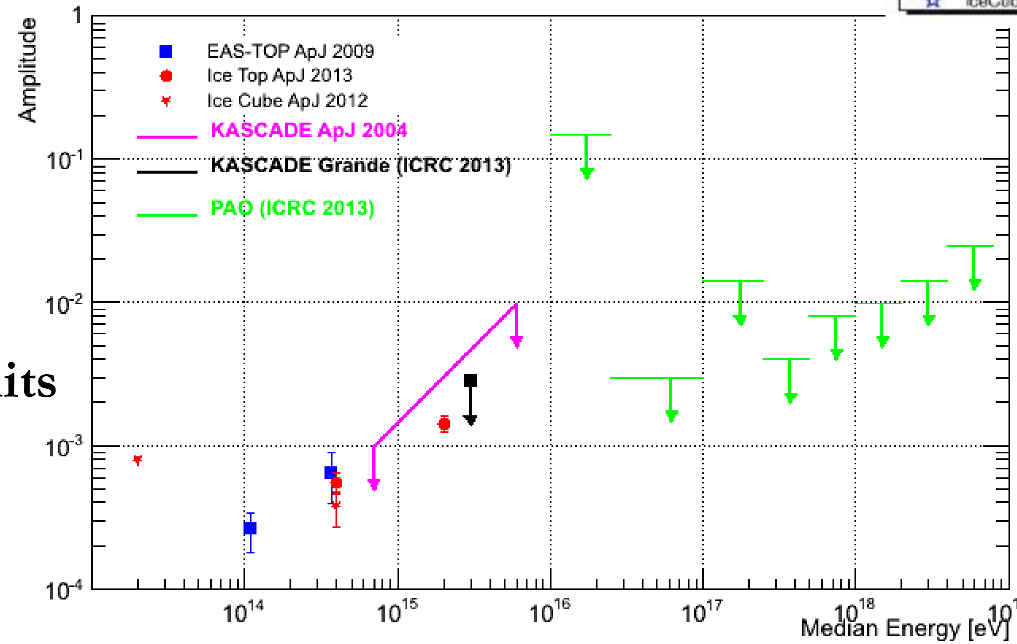
We calculate the ***99% C.L.*** upper limit → ***A < 0.47x10⁻²***





1^{st} Harmonic Amplitudes
Measured at different energies

$E < 10^{15}$ eV (thanks to G. DiSciascio)

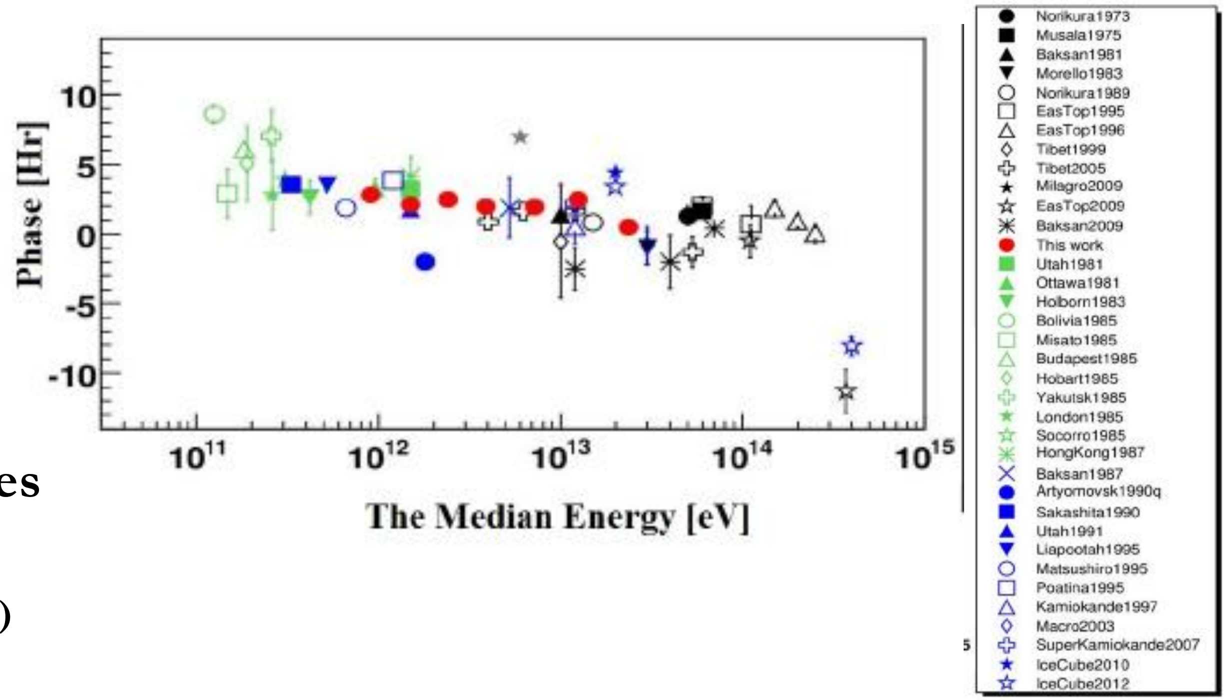


Hint of an increasing amplitude crossing knee energies

$E > 5x10^{15}$ eV → only upper limits

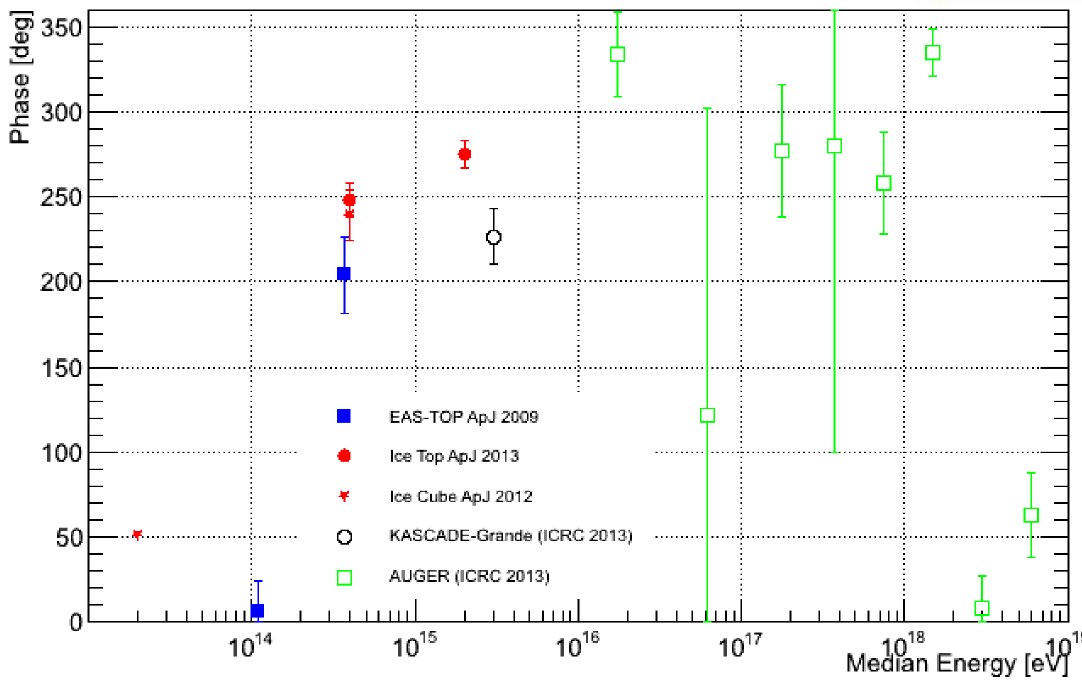
1^{st} Harmonic Phases Measured at different energies

$E < 10^{15}$ eV (thanks to G. DiSciascio)



Hint of a change of the phase for $E>10^{14}$ eV

Indication that the phases measured above 5×10^{14} eV are consistent



Conclusions

- Primary spectrum
  - 10^{16}<E<10^{18} eV → cannot be described by a singe slope power law.
    - Hardening ~10^{16} eV
    - Steepening ~8-9x10^{16} eV
- Heavy elements spectrum
  - Kneelike feature ~8x10^{16} eV
- Light elements spectrum
  - Hardening ~1.2x10^{17} eV
- Large Scale Anisotropy
  - A < 4.7x10^{-3} (median energy 3.3x10^{15} eV)
  - Phase is consistent with other measurements