Review of indirect cosmic ray measurements

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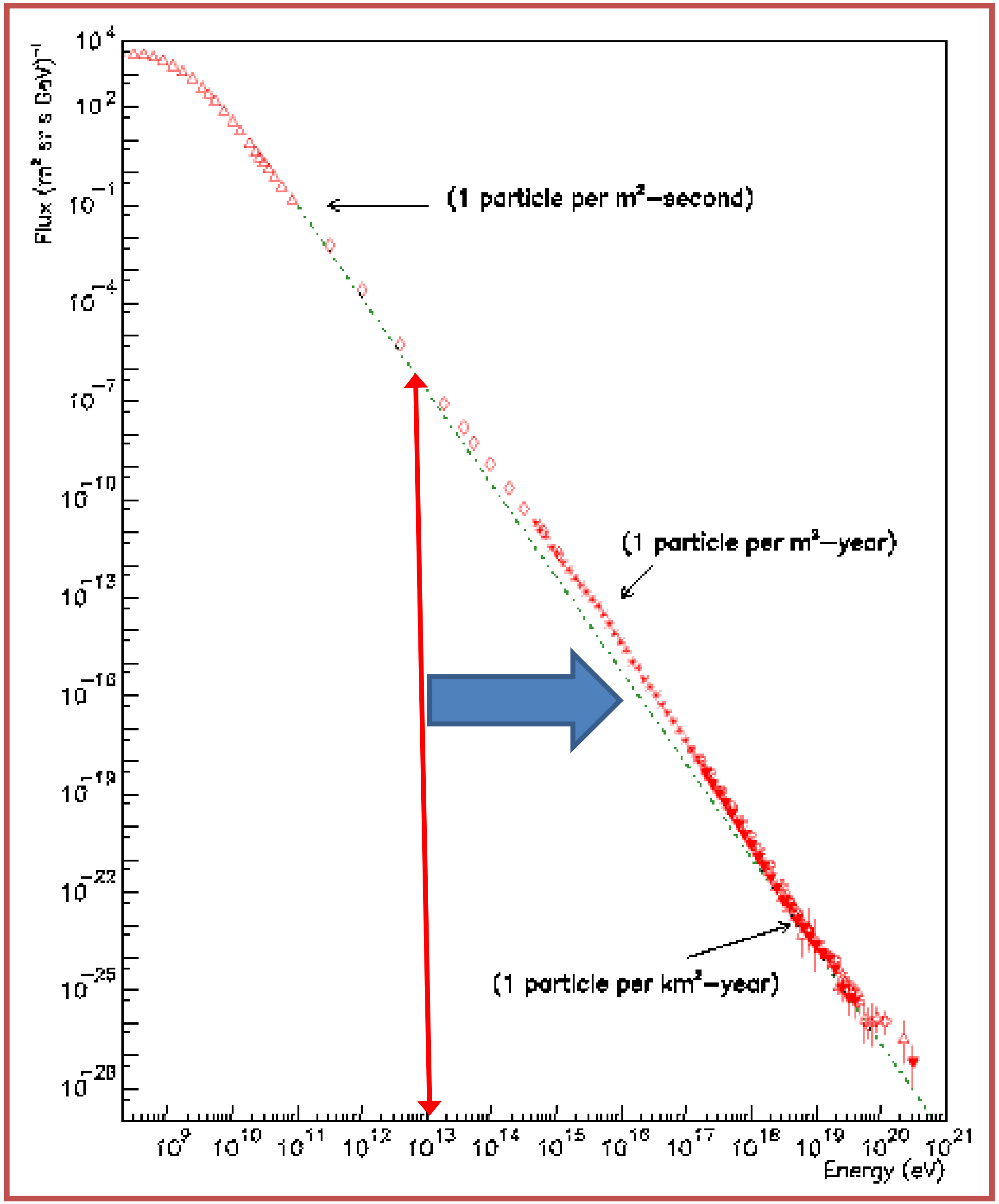
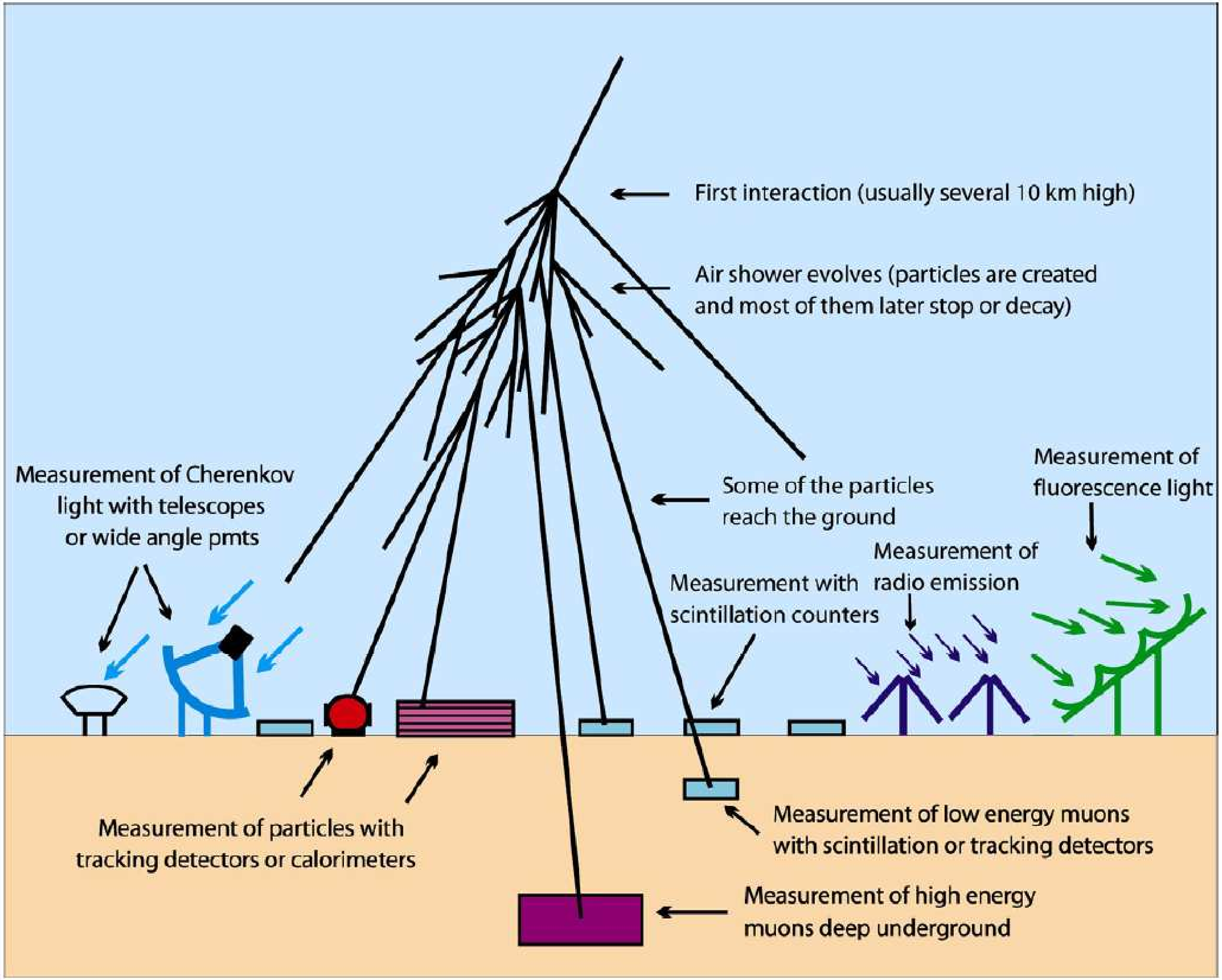
SciNeGHE 2012, Lecce 20-22 June 2012

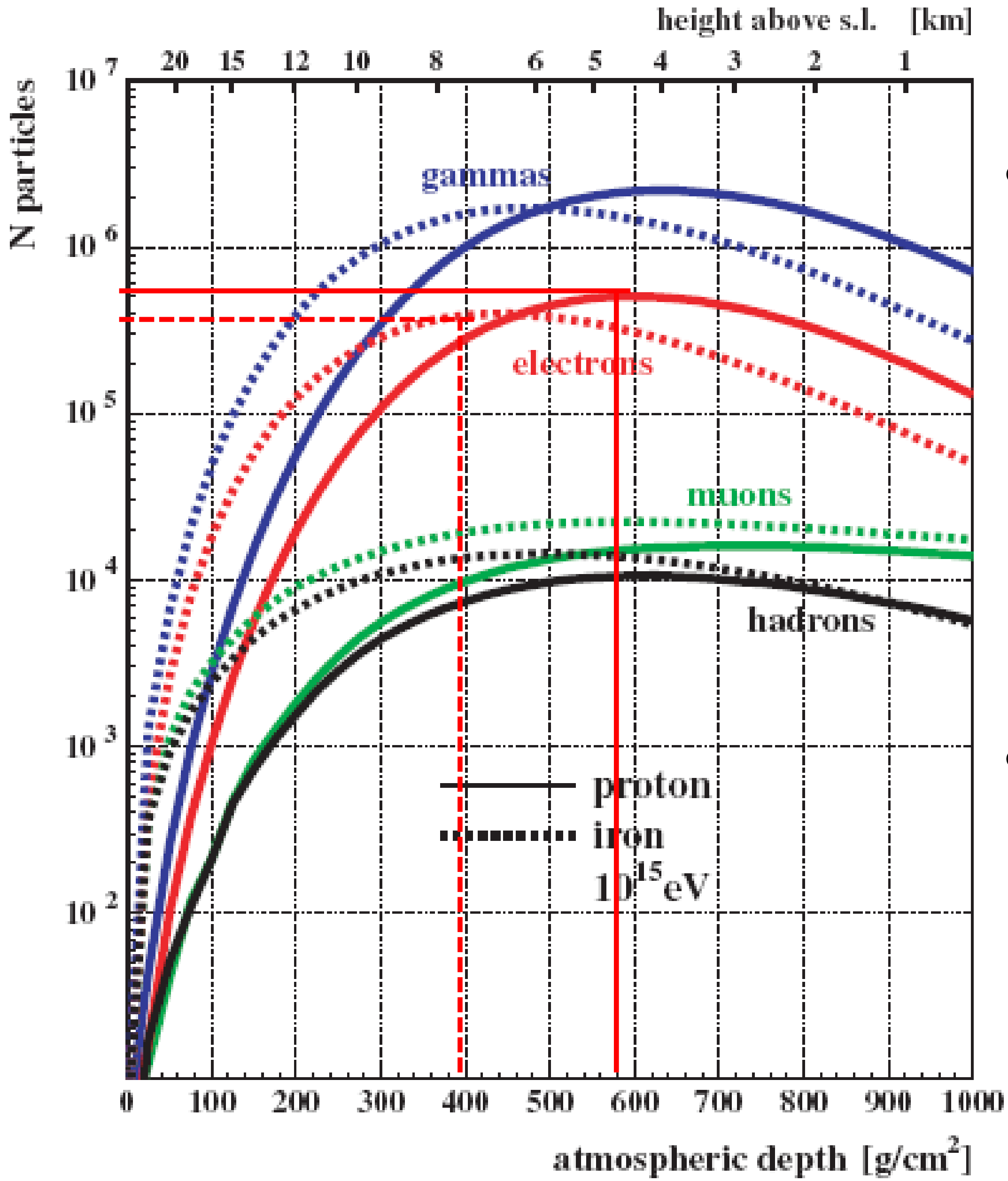


- 10^{13}-10^{15} eV
  - Overlap with direct measurements
  - Galactic radiation
- 10^{14}-10^{18} eV
  - knee
  - Galactic-Extragalactic transition
- $>10^{18}$ eV
  - Extragalactic radiation

- Information required are:
  - ***Arrival Direction***
  - ***Energy***
  - ***Mass***

EAS development in atmosphere





- Near maximum of the EAS $e^{\pm}$ and μ numbers are nearly similar for H or Fe primaries

  → ok for E

  → bad for A

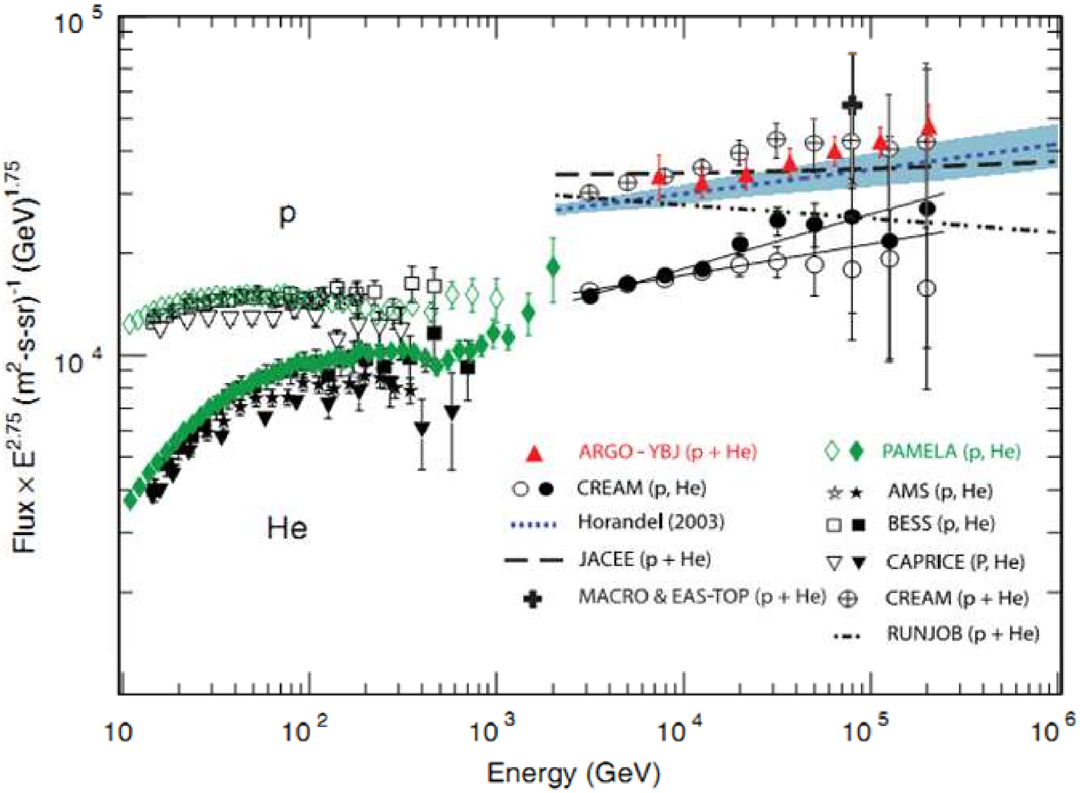
- Height of maximum depends on E

  → array location

- **Calorimetric measurements**
  - Faint signals (only high energies)
  - Fluorescence Light → 10% duty cycle
  - Radio → very promising
- **Sampling**
  - Stable and reliable techniques
  - Hadronic interaction models dependence

$10^{13} - 10^{15}$ eV

- MILAGRO
  - Water cherenkov detector
  - 2630 m
- TIBET AS-γ
  - Scintillation counters
  - 4300 m
- ARGO-YBJ
  - RPC carpet
  - 4300 m
- Ice-Cube
  - High energy μ detector
  - Cherenkov light emitted in Ice
  - 1450 m ice deep



ARGO-YBJ mesurement of the light (i.e. H+He) spectrum

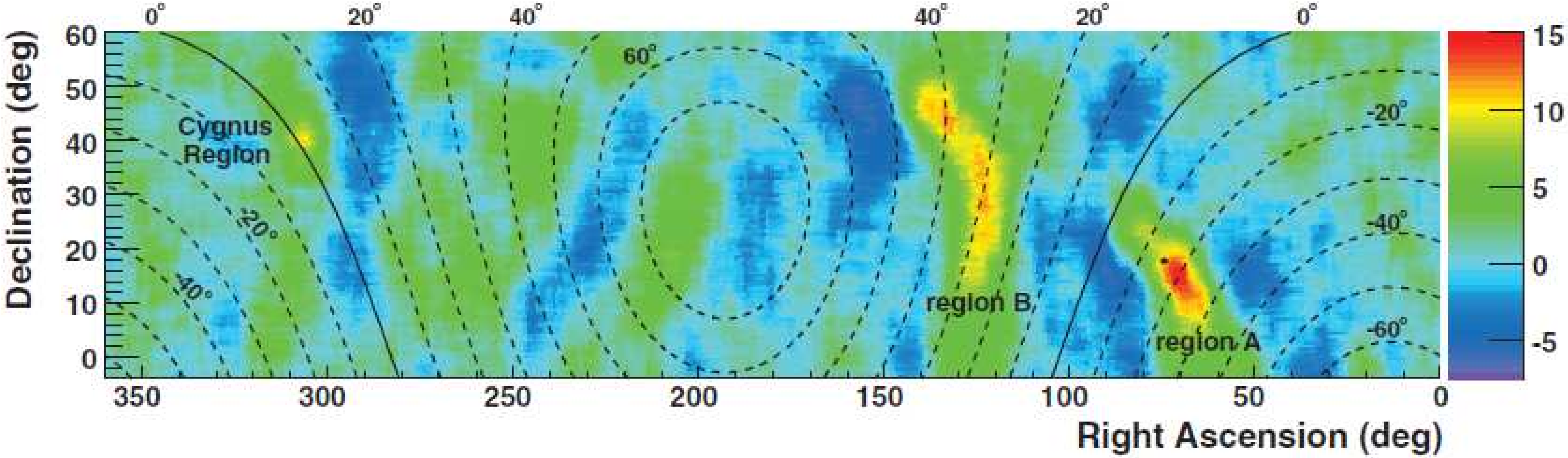
- $5 \times 10^{12} < E < 2 \times 10^{14}$ eV
- Multiplicity distribution N(M)

$$N(M) = \Omega \int_{E_1}^{E_2} \bar{A}_{\rm eff}(E', M) N(E') dE'.$$

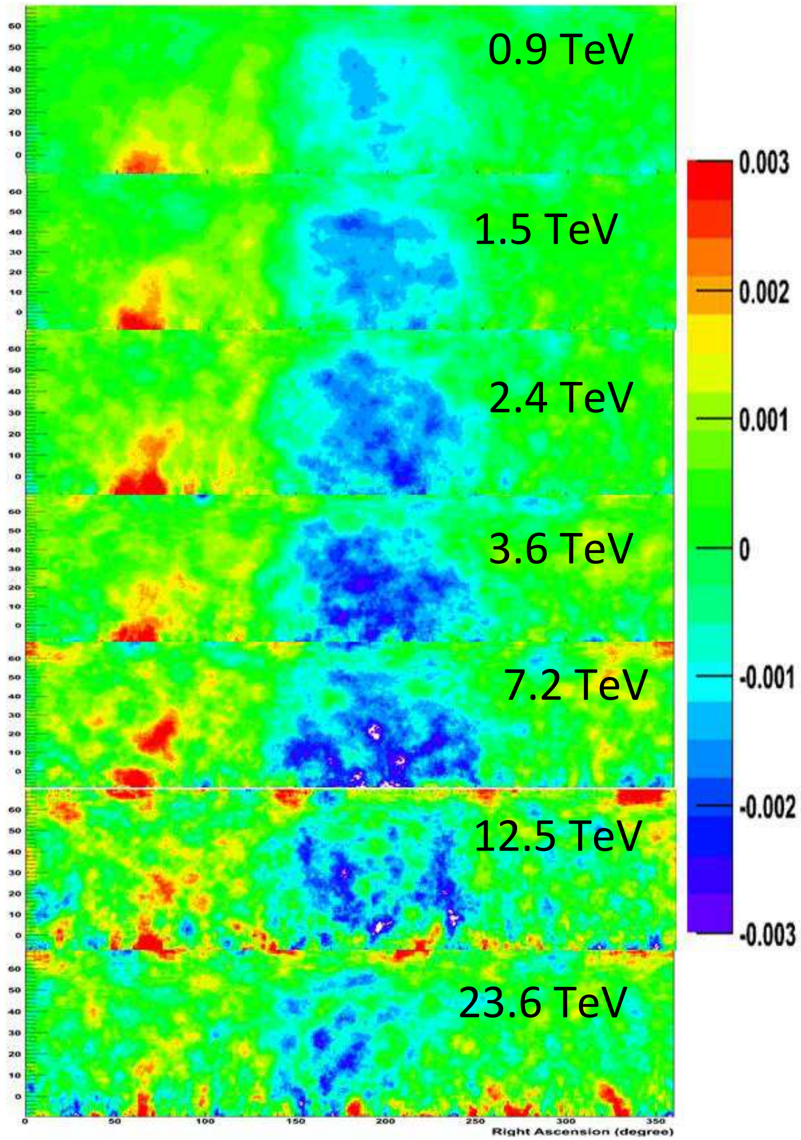
- Unfolding procedure → N(E)
- Total uncertainty lower tan 10%
- CNO contribution <2%

Anisotropy

- MILAGRO (PRL **101**, 221101 (2008))
  - Events with $\theta<45°$ and $N_{PMT}>20 \rightarrow E_{median}\sim10^{12}$ eV
  - Significance map made with 10° smoothing and no discrimination between γ and charged cosmic rays
  - Excesses called "Region A" and "Region B" have peak significance of 15.0σ and 12.7σ



- **ARGO-YBJ** detected the same structures with higher resolution and as a function of primary energy.



G. Di Sciascio presentation at Vulcano 2012

Medium Scale Anisotropy by ARGO-YBJ

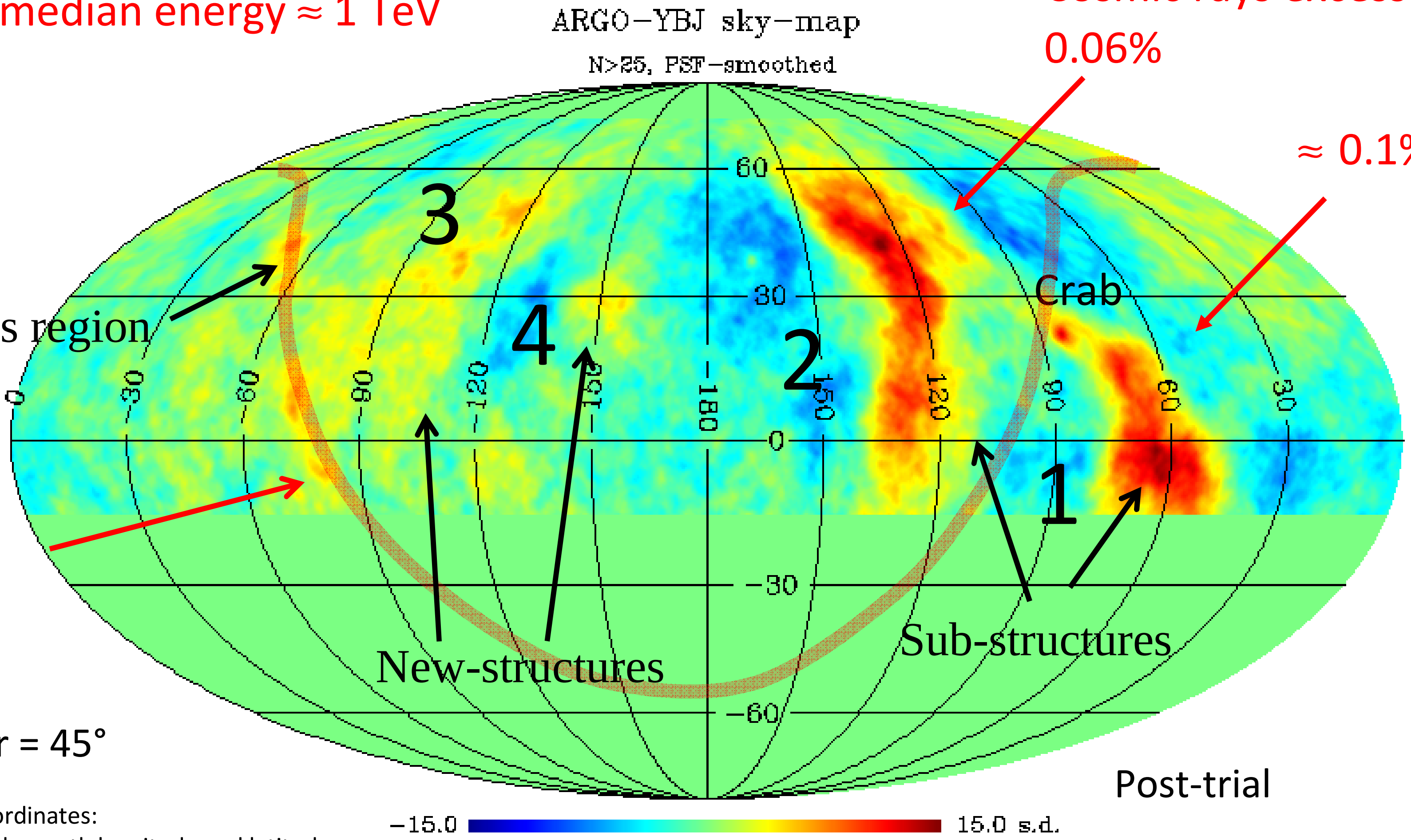
Map smoothed with the detector PSF for CRs

Proton median energy ≈ 1 TeV

Cosmic rays excess ≈ 0.06%

≈ 0.1%

Cygnus region



Galactic Plane

Δt = 3 hr = 45°

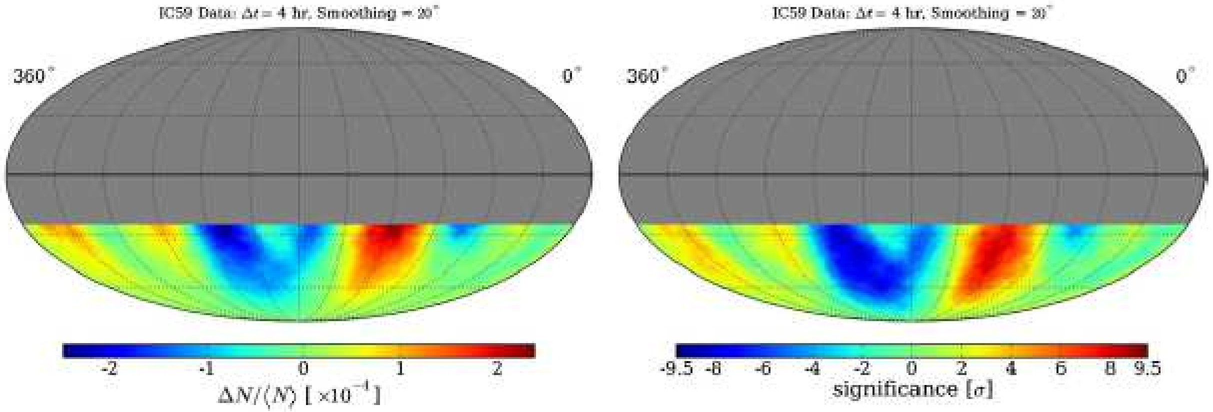
Post-trial

Equatorial coordinates:
projection of the earth longitude and latitude

Anisotropies in the Southern emisphere

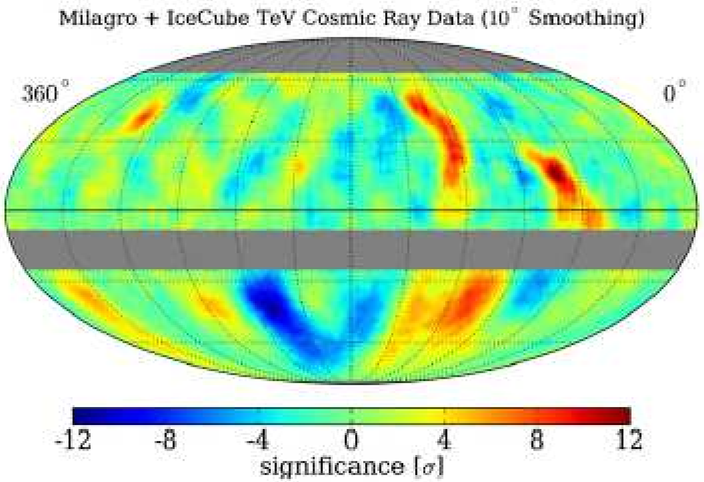
Ice Cube as μ detector, 1450 m below ice level

E_{median} ~ 20 TeV



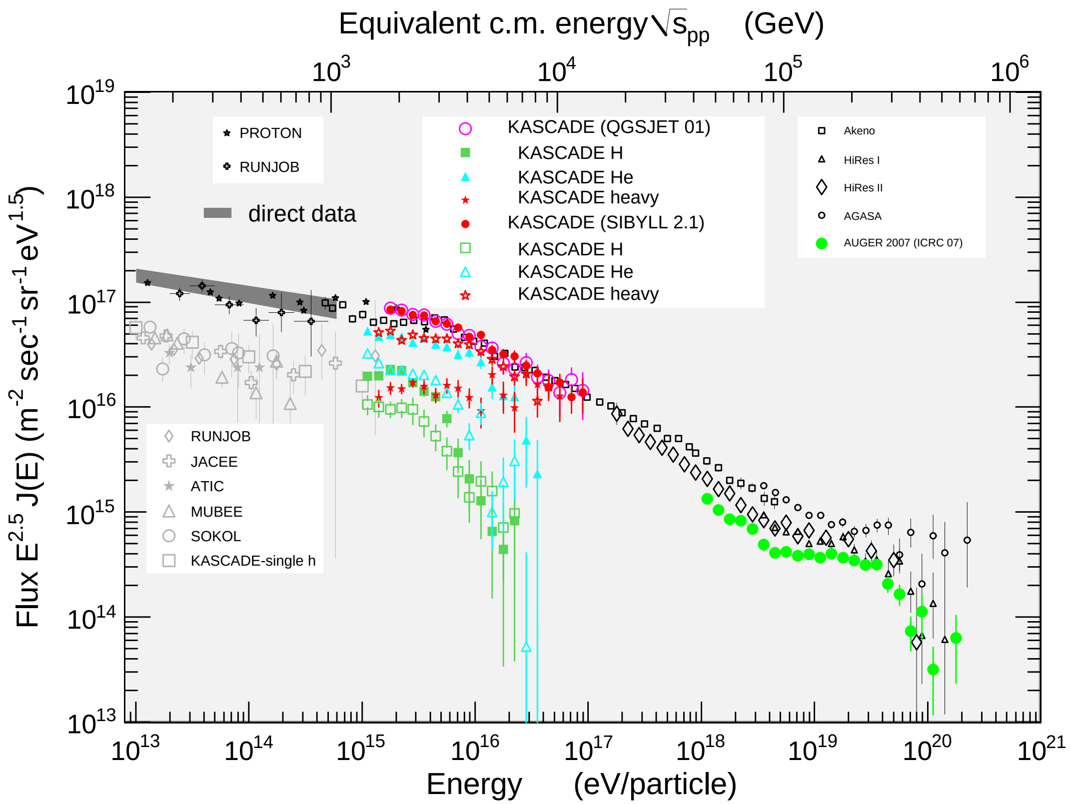
Most significant structure extends over 20° in r.a.
Post trial significance 5.3σ

ApJ **740**:16 (2011)



Combined Ice Cube and Milagro sky maps.
Smoothing 10°

$10^{14} < E < 10^{18}$ eV



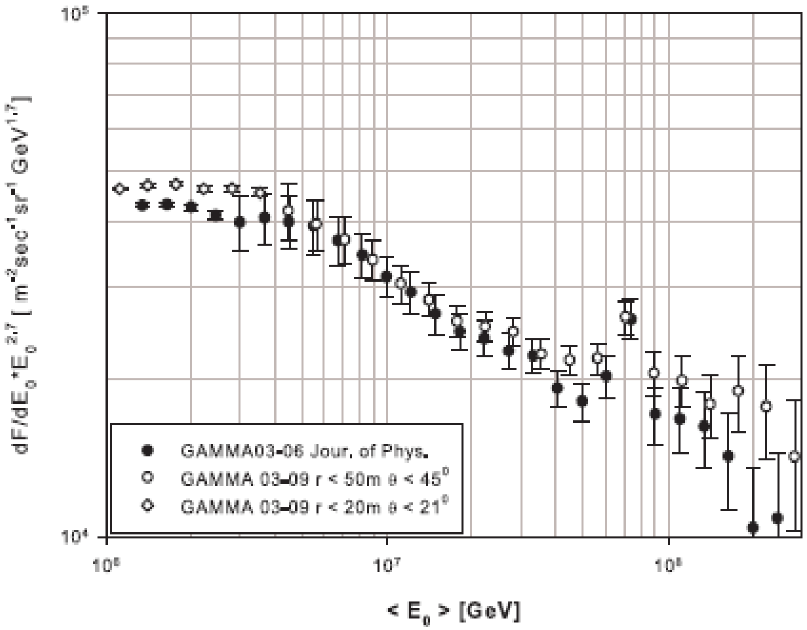
Experimental results

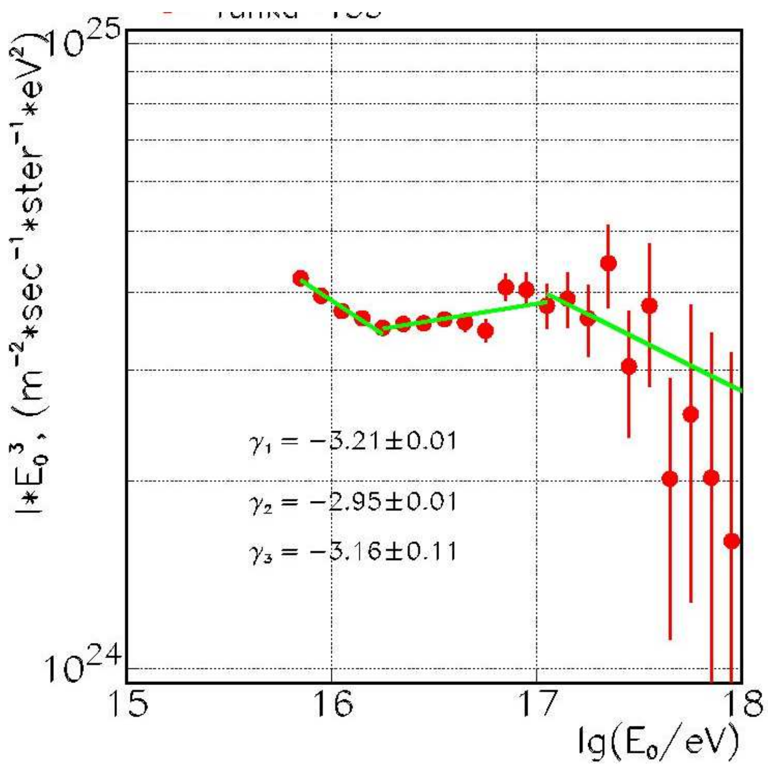
- Proton spectrum agrees with direct measurements
- Knee observed in the spectra of all EAS components
- Primary chemical composition gets heavier crossing knee energies
- Knee is attributed to light primaries
- Radiation is highly isotropic.

Experiments operating between 10^{16}-10^{18} eV

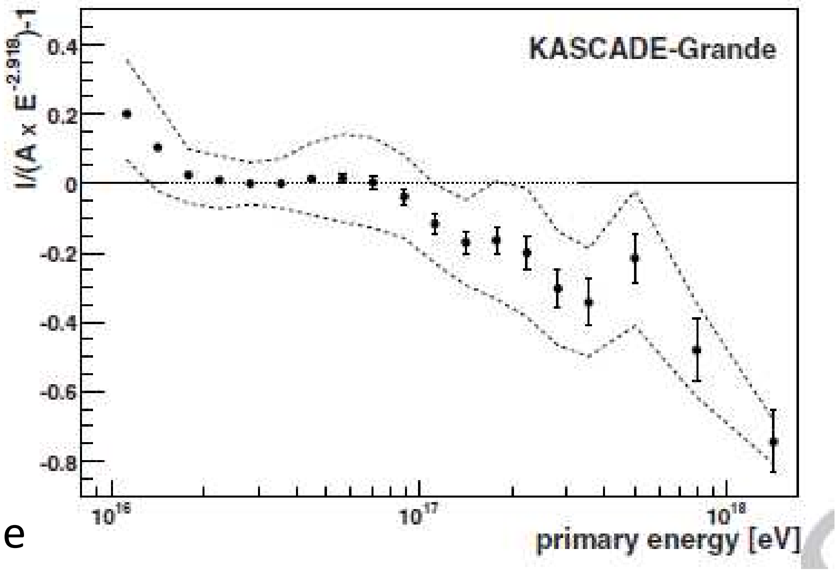
- **KASCADE-Grande (110 a.s.l.)**
  - N_{ch}, N_{μ} (Scintillators)
  - Shower Size →NKG like ldf
- **TUNKA-133 (675 m a.s.l.)**
  - Atmospheric Cherenkov light
  - Q125
- **GAMMA (3200 m a.s.l.)**
  - N_{ch}, N_{μ} (Scintillators)
  - Shower Size → NKG like ldf
- **IceTop (2835 m a.s.l.)**
  - Cherenkov light emitted in ice
  - S125
- **Auger Infill (1400 m a.s.l.)**
  - Cherenkov light emitted in water tanks
  - S450
  - Hybrid detector

GAMMA, ICRC 2011





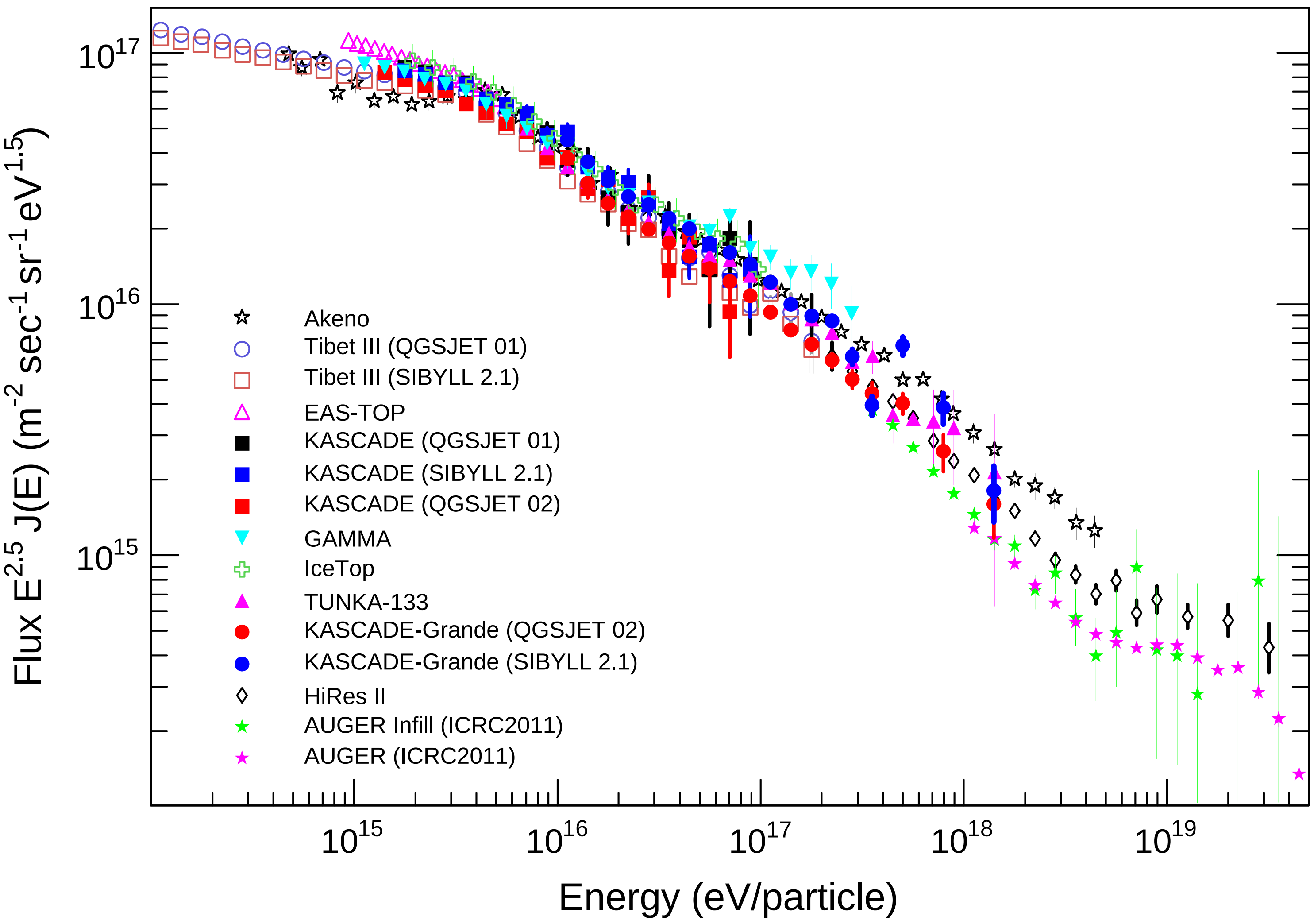
TUNKA-133, ICRC 2011

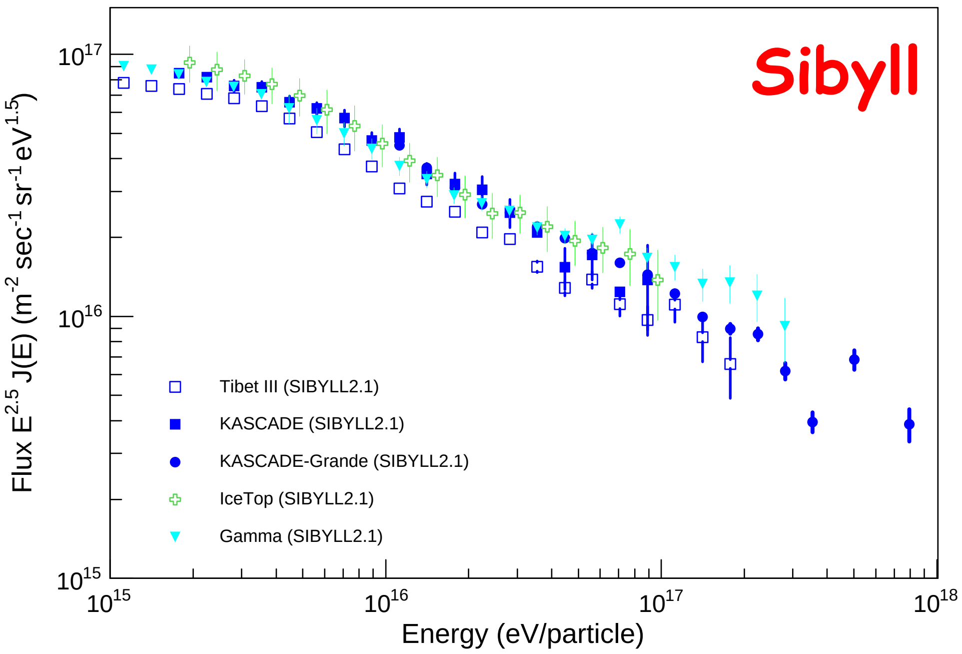


KASCADE-Grande

http://dx.doi.org/10.1016/j.astropartphys.2012.05.023

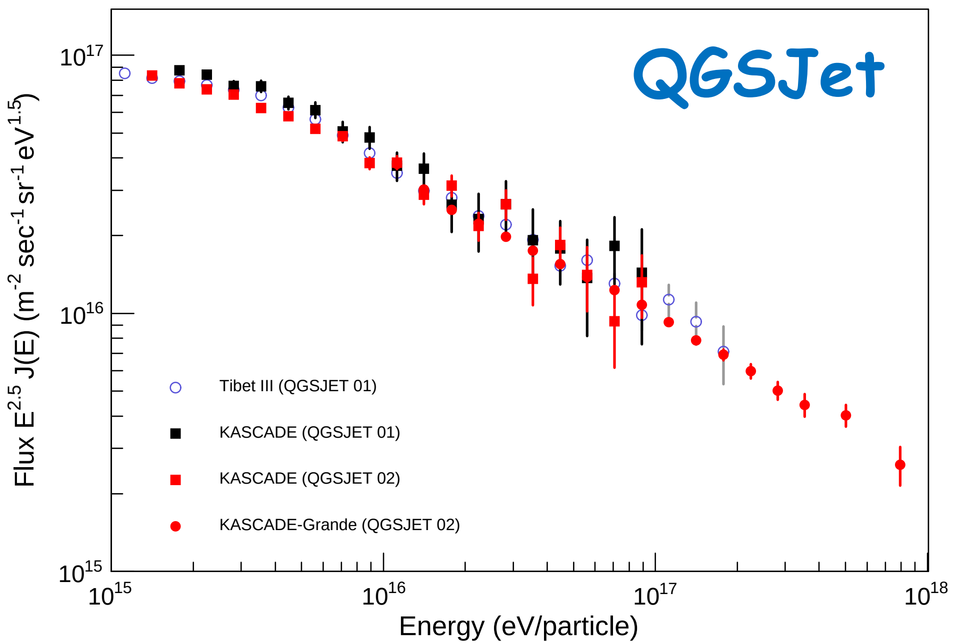
All particle Cosmic Rays Energy Spectrum





Same data as previous plot, results are grouped by the interaction model used to convert the experimental observable(s) to primary energy

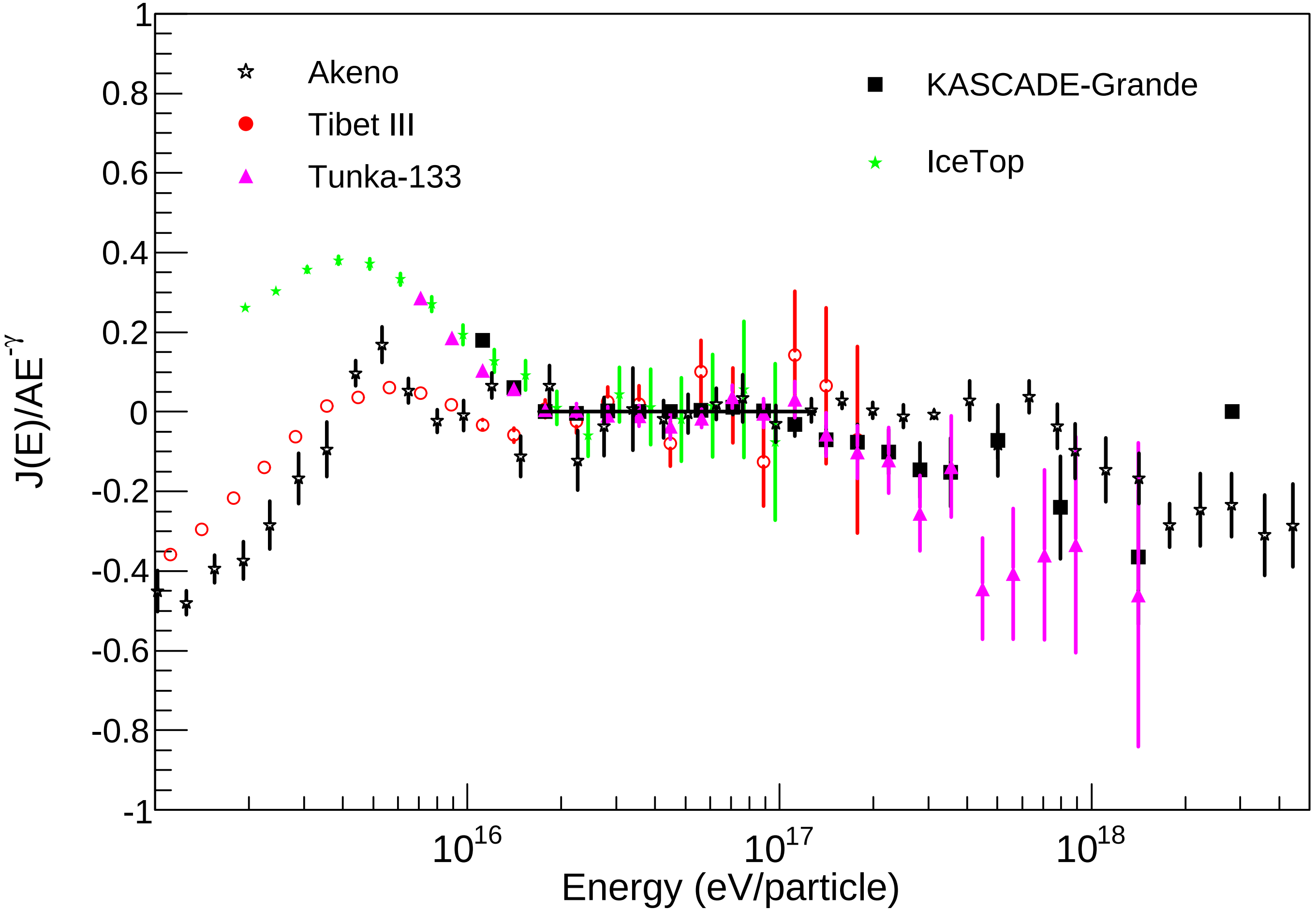
Flux differences can mainly be attributed to hadronic interaction used to convert to primary energy



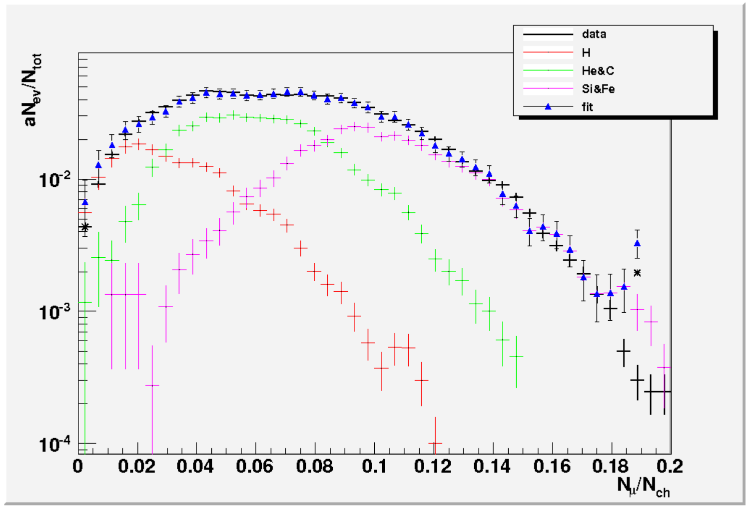
1. **This difference mainly concerns the absolute energy scale**

2. **Structures are visible in most of the spectra**

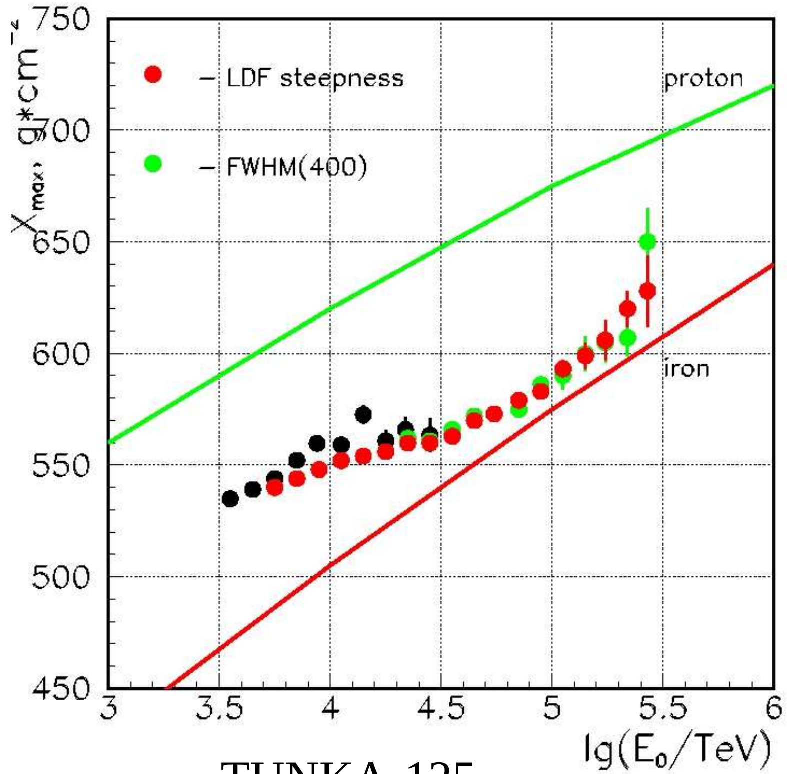
Residual plot obtained fitting each spectrum with a single slope power law above the structure claimed by KASCADE-Grande (1.7×10^{16}-$1,3 \times 10^{17}$ eV)



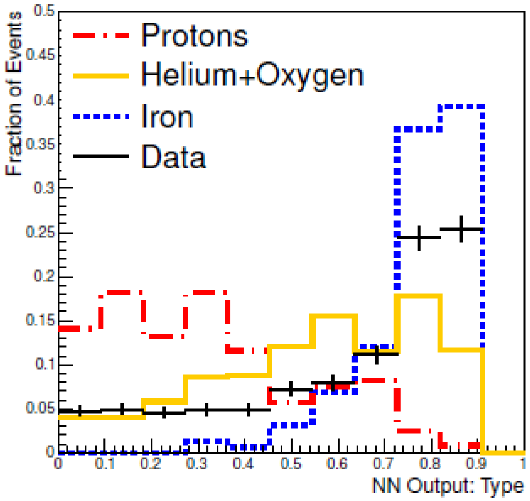
Chemical composition studies



KASCADE-Grande N_{μ}/N_{ch} distributions
ICRC 2011



TUNKA-125
ICRC 2011
Cherenkov light ldf steepness
Q(100)/Q(200)



Ice Top → S_{125}
Ice Cube → K_{70}
Neural Network analysis
ICRC 2011

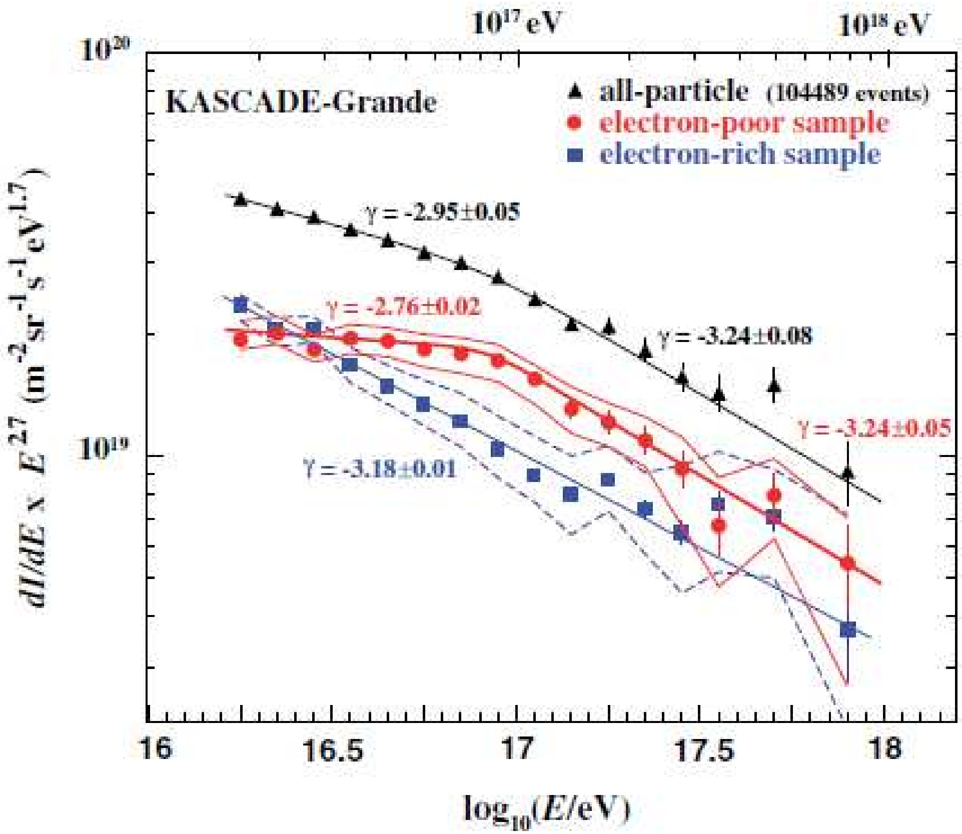
Spectra of different Mass Groups

- KASCADE-Grande

- Events selected in two samples → N_{μ}/N_{ch}

- Change of slope of the heavy component spectrum detected at ~8x10^{16} eV

PRL **107**, 171104 (2011)



$E > 10^{18}$ eV

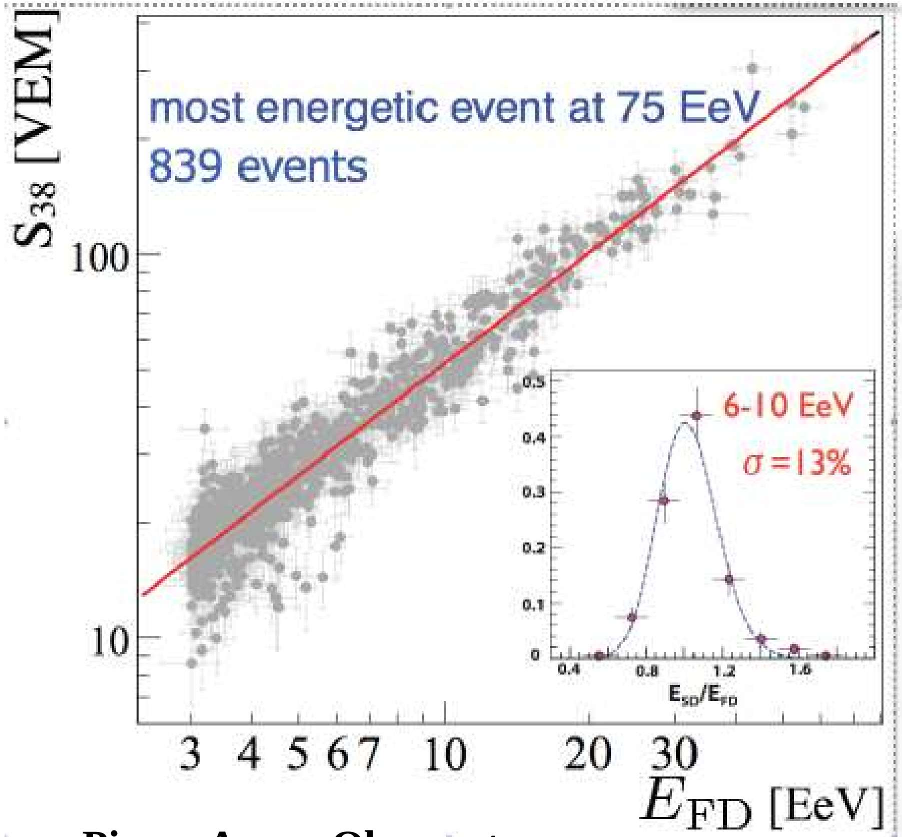
- Auger
  - 1600 water tank. 1500m spacing
  - 4 Fluorescence Light Telescopes
- Telescope Array
  - 507 scintillators. 3 m^2 each. 1200 m spacing
  - 3 Fluorescence Light Telescopes

Slides from the talks given at the:
International Symposium on Future Directions in UHECR Physics.
CERN 13-16 February 2012
http://indico.cern.ch/conferenceDisplay.py?confId=152124

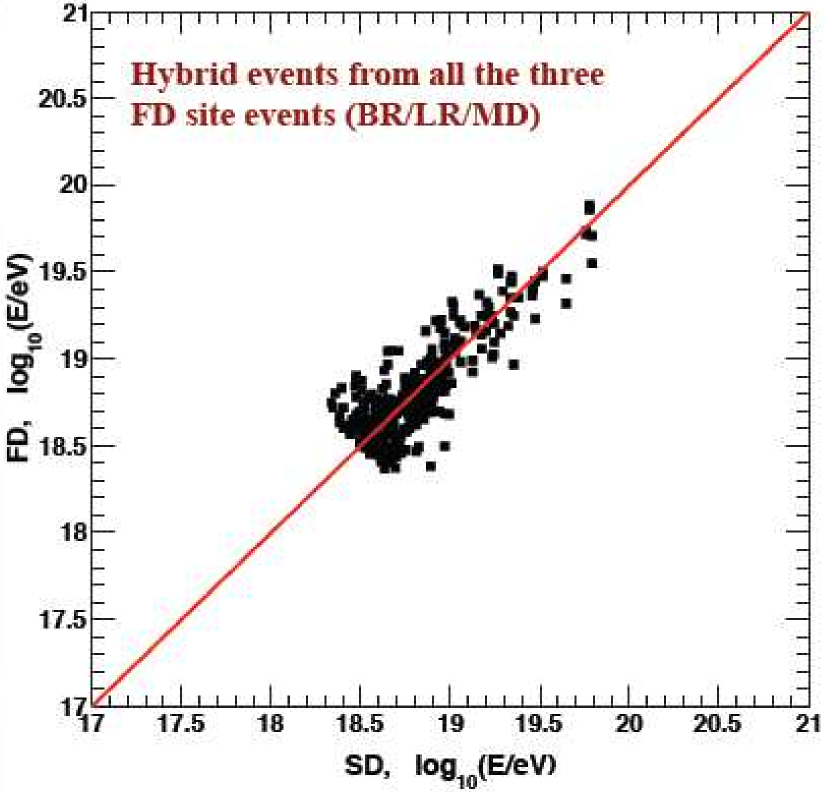
SD Energy: Scaled to FD energy, measured by means of calorimetry

$$E = E_{\mathrm{FD}}(S_{38}^{\mathrm{CIC}}) = a_{\mathrm{h}} S_{38}^{b_{\mathrm{h}}}$$

$$E = E_{\mathrm{FD}}(E_{\mathrm{MC}}(S_\theta)) = \frac{1}{\left\langle \frac{E_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{h}}} E_{\mathrm{MC}}(S_\theta)$$

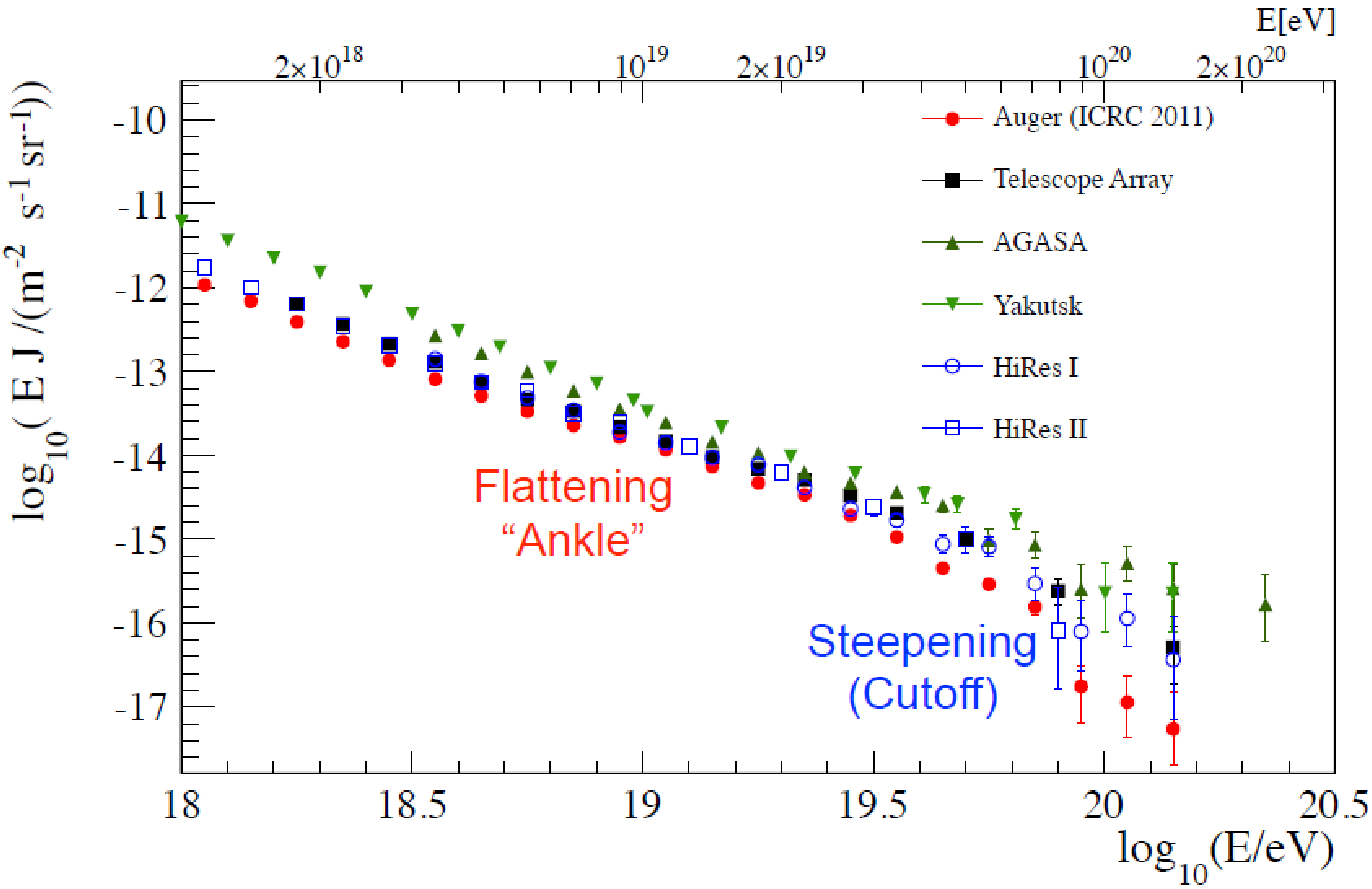


Pierre Auger Observatory

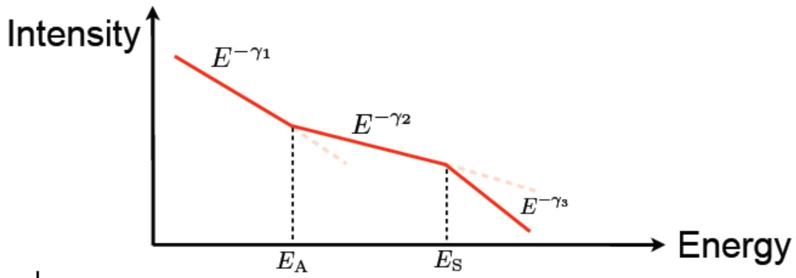


Telescope Array

UHECR Energy Spectrum



Three Power-law fit



	γ_1	γ_2	γ_3	$\log E_A$	$\log E_S$
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)

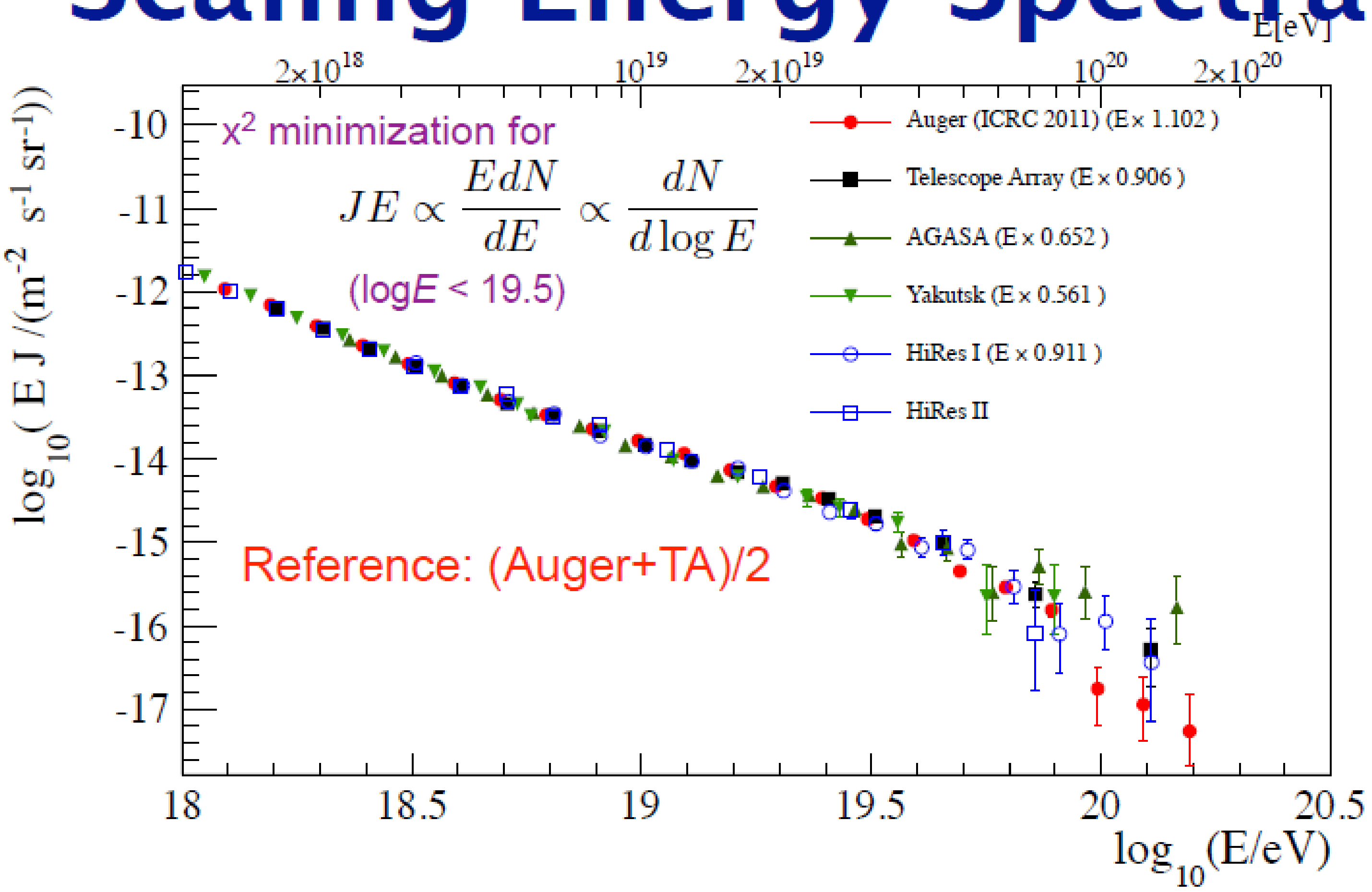
•AGASA: Takeda *et al.*, *PRL*, **81**, 1163 (1998)
•Yakutsk: Fit by the WG
•HiRes: Abbasi *et al.*, *PRL*, **100**, 101101 (2008)
•Auger: ICRC2011 (F.Salamida icrc893)
•TA: ICRC2011 (B.Stokes/D.Ivanov icrc12

Energy Uncertainty Budget

	HiRes	Auger	TA
Calibration	10%	9.5%	10%
Fluorescence yield	6%	14%	11%
Atmosphere	5%	8%	11%
Reconstruction	15%	10%	10%
Invisible energy	5%	4%	(included above)
Total	**17%**	**22%**	**21%**

•HiRes: Abbasi et al., PRL 100 101101 (2008)
•Auger: ICRC2011
•TA: ICRC2011

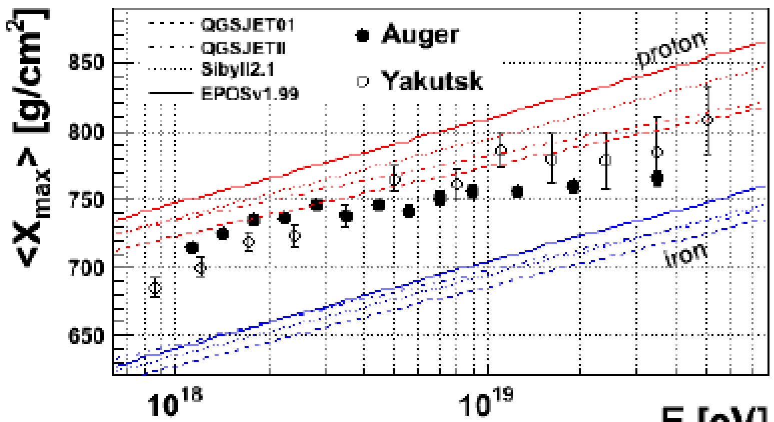
Scaling Energy Spectra



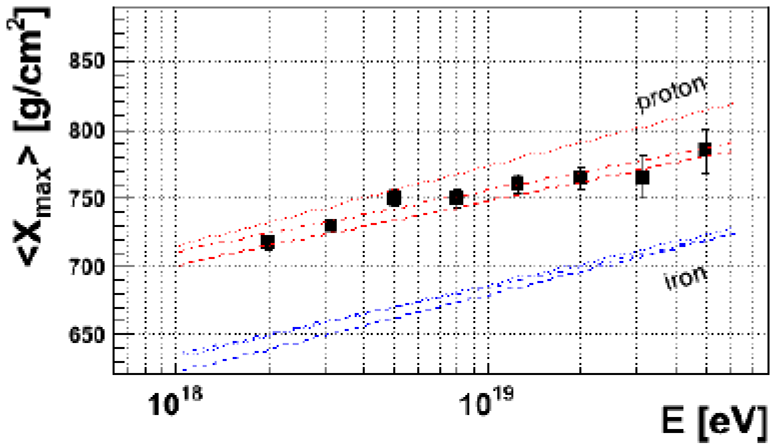
	Auger	TA	HiRes	AGASA	Yakutsk
$\log_{10} \alpha$ Relative to (Auger+TA)/2	-0.042 (0.003)	+0.042 (0.003)	+0.041 (0.005)	+0.19 ( )	+0.26 (0.004)

UHECR Composition

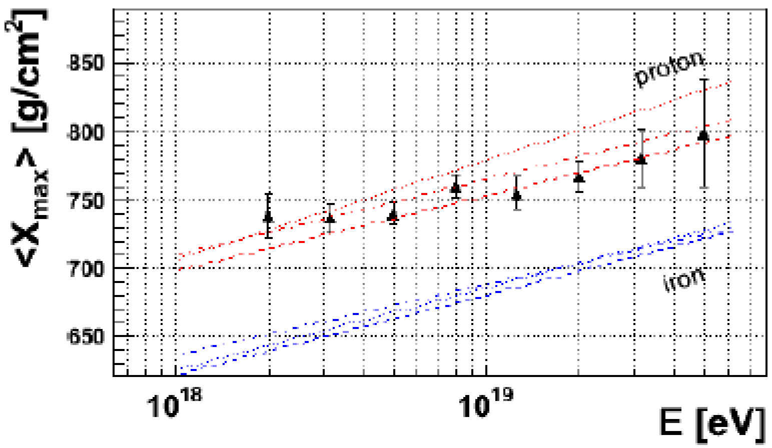
- **Measurements based on X_{max} → Fluorescence Light Telescopes**
- **Composition obtained comparing the $\langle X_{max} \rangle$ and/or $\sigma_{X_{max}}$ behaviour vs. energy with the expectations from a full simulation**

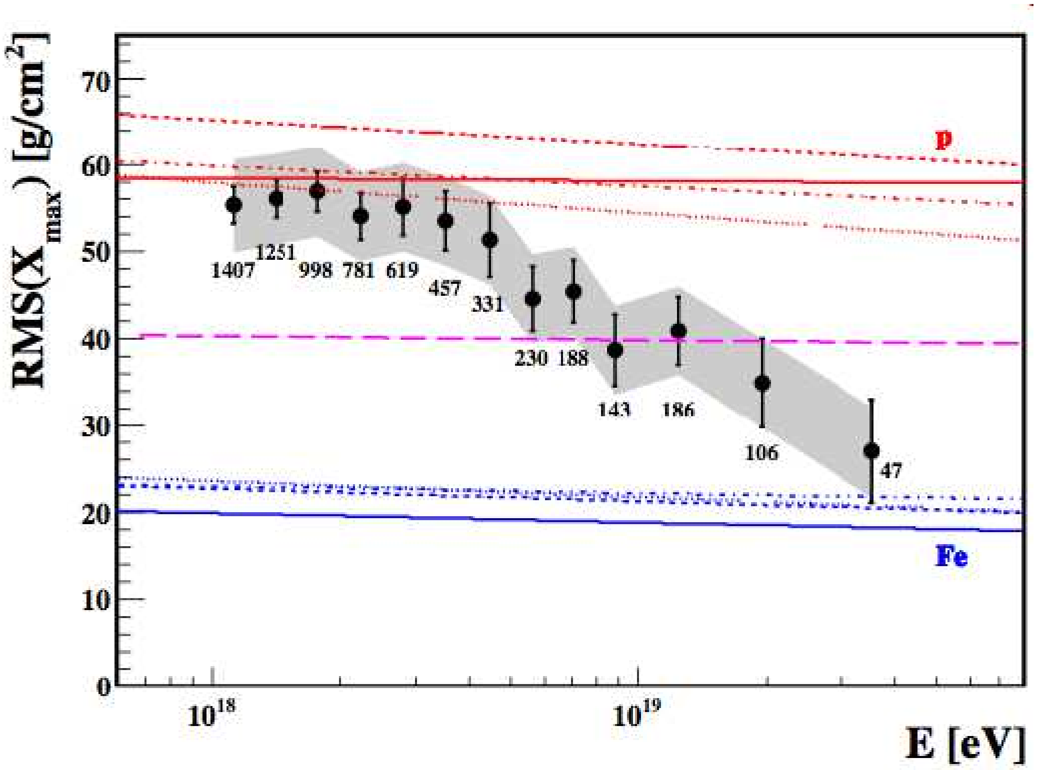


HiRes



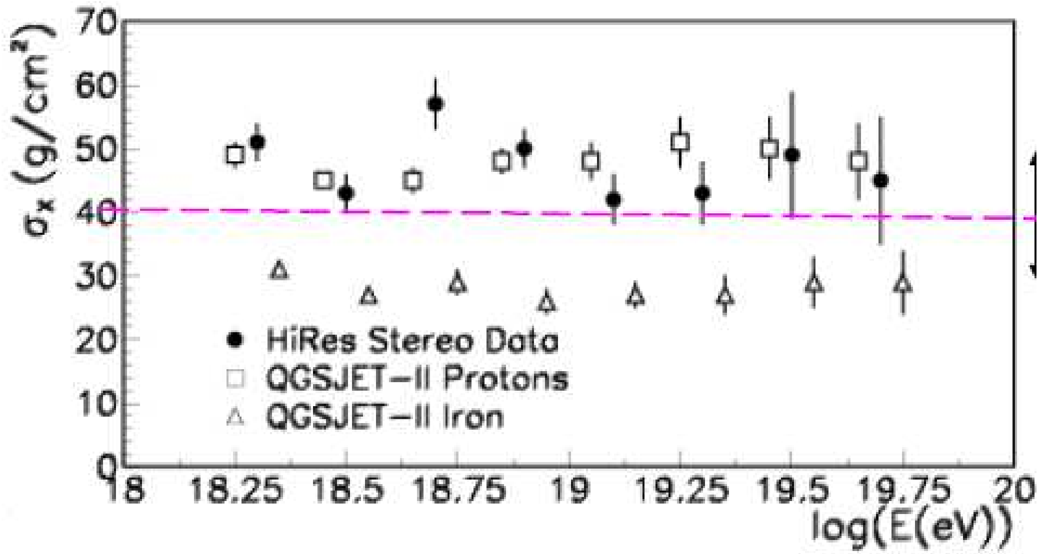
TA





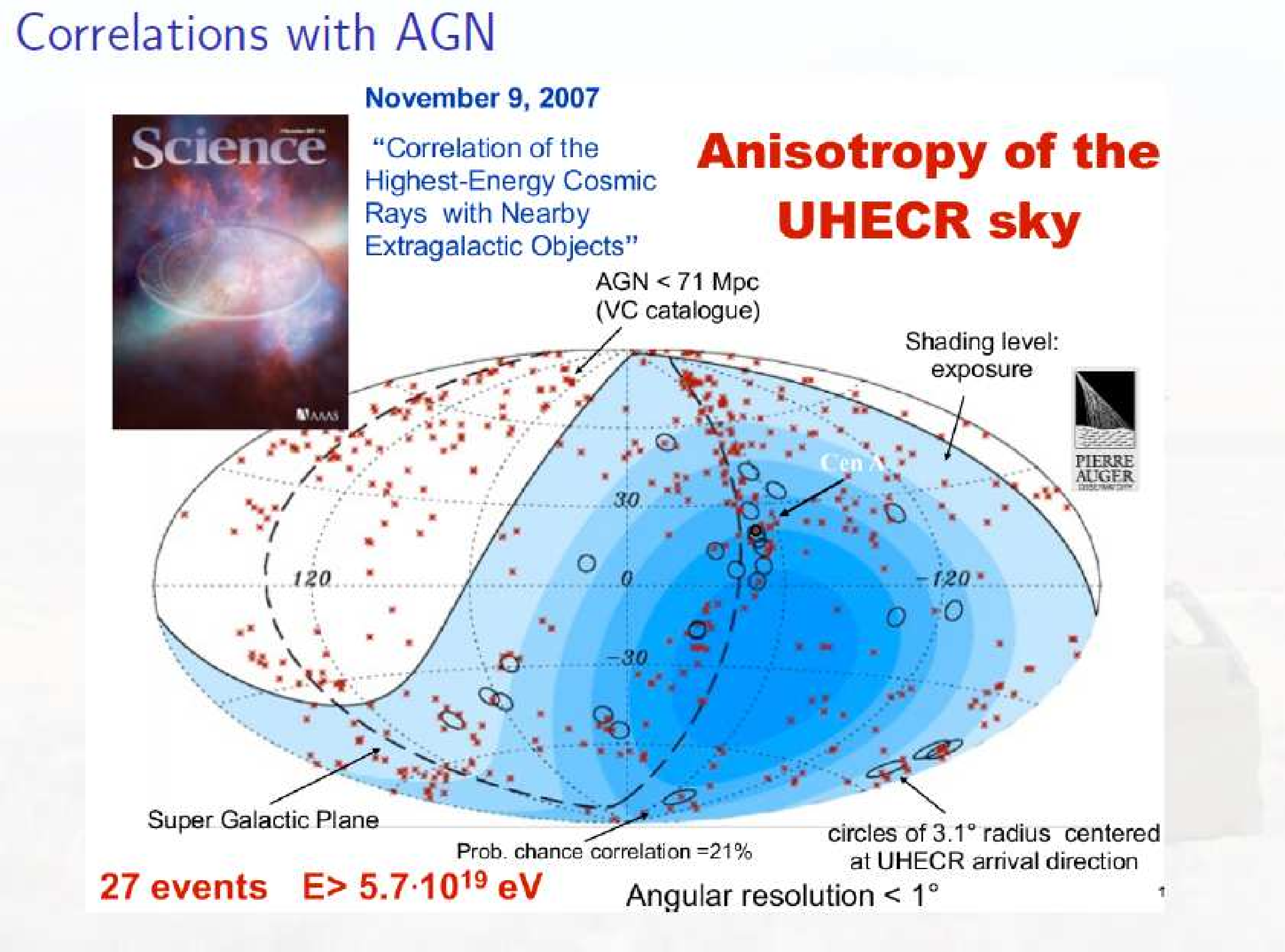
- **P.A.O. data indicate a change of chemical composition towards heavy elements**

- **HiRes data are compatible with a constant chemical composition**



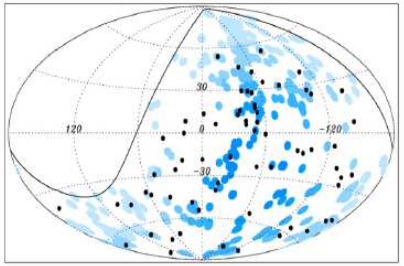
Due to limited statistics no strong incompatibility between the results

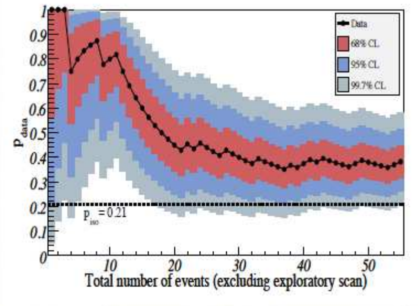
Anisotropies and correlations with extragalactic objects



Updated Auger analysis

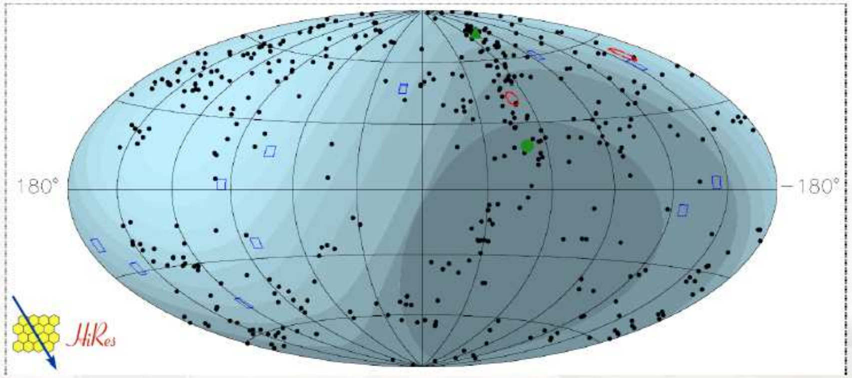
Auger collaboration, Astroparticle Phys. 34 (2010) 314





The updated analysis: 21 events correlate out of 55 total. The updated fraction of correlating events is $P = 0.38$

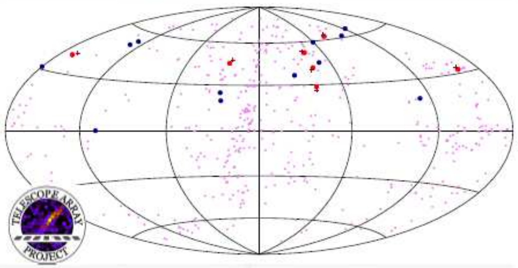
Search for AGN correlation in HiRes



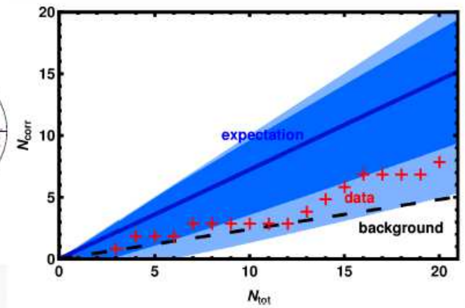
2 events out of 13 correlate, 3.2 expected from random coincidences

HiRes collaboration, Astropart.Phys. 30 (2008) 175-179

Search for AGN signal in Telescope Array



Equatorial coordinates



- Original estimate of the correlating fraction is not supported
- Consistent with the updated estimate
- Consistent with no correlation
- ~ 3 times the present statistics is needed for a conclusive test

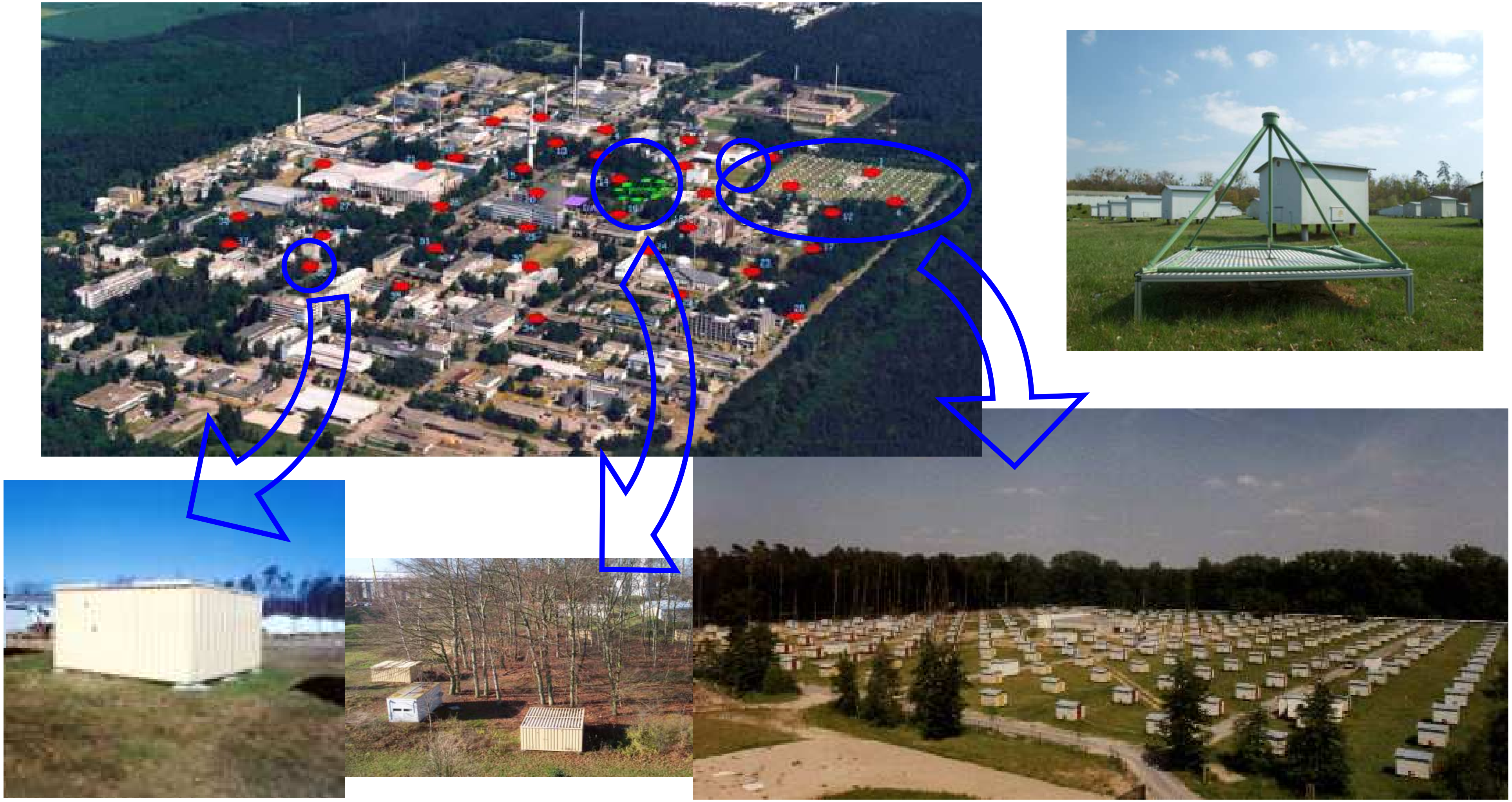
TA collaboration, 2011

Conclusions

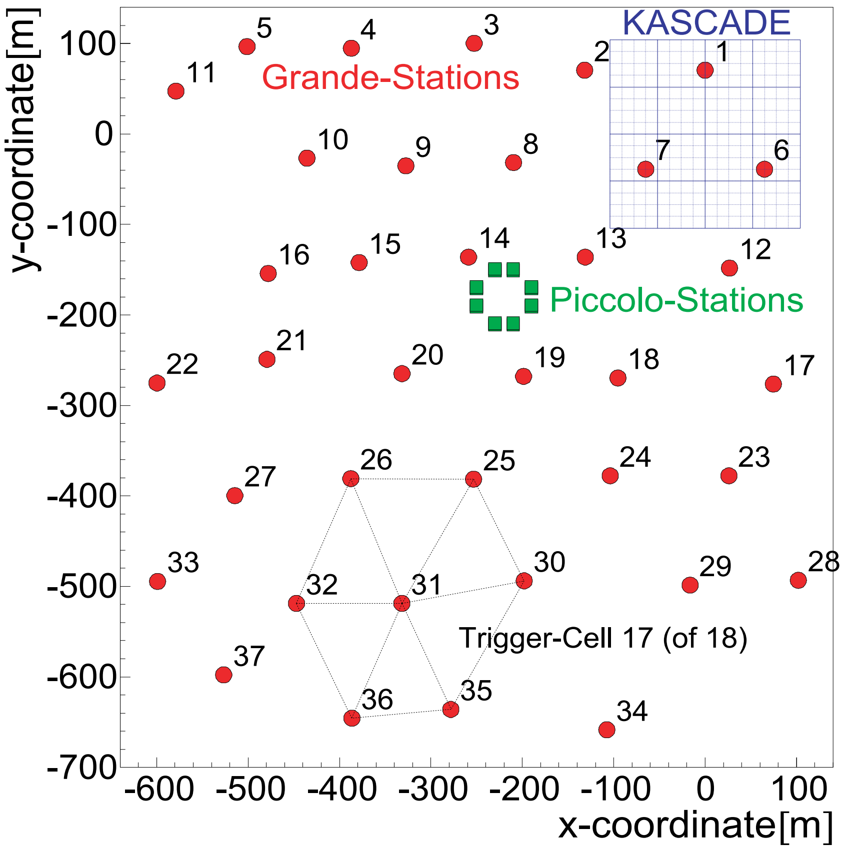
- **Below the knee**
  - Unexpected CR anisotropy
- **Around the knee**
  - Knee either due to limit of the acceleration in galactic sources (i.e. SNR) or of the containment inside galactic magnetic fields
  - Not yet identified the transition to extragalactic radiation
- **UHECR**
  - Well established spectral features: ankle & GZK suppression
  - Anisotropy E>60 EeV
  - Controversial measurement of the chemical composition.

KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV



KASCADE-Grande detectors & observables



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

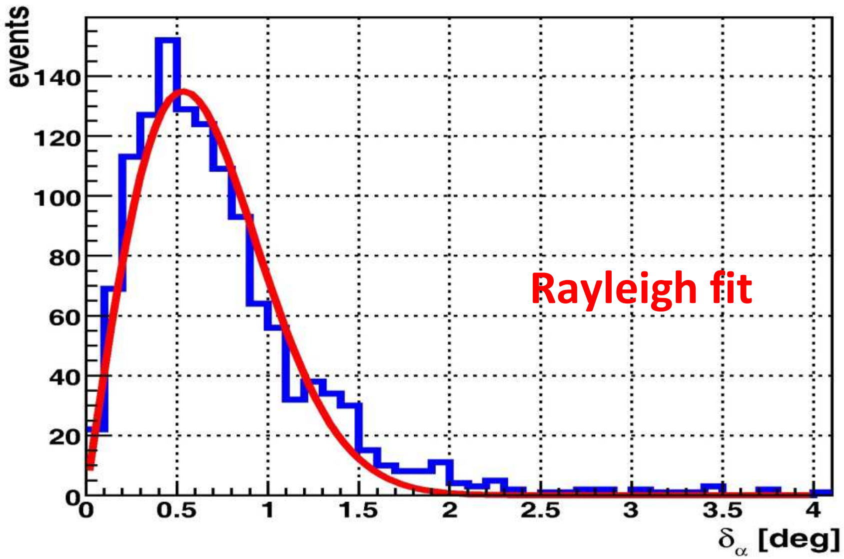
- Shower core and arrival direction
  - Grande array
- Shower Size (N_{ch} number of charged particles)
  - Grande array
    - Fit NKG like ldf

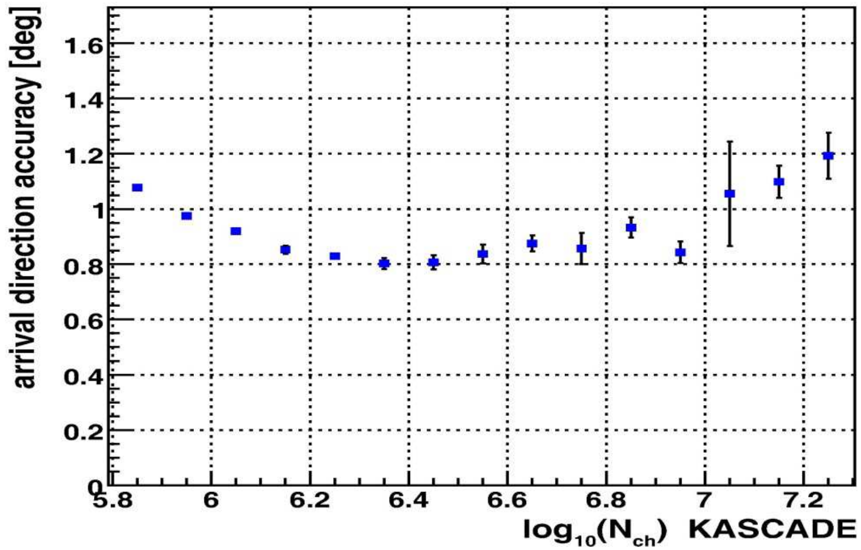
- μ Size (E_μ>230 MeV)
  - •KASCADE array μ detectors
    - •Fit Lagutin Function
- μ density & direction (E_μ>800 MeV)
  - •Streamer Tubes

Grande resolution measured with real events comparing the reconstruction with the KASCADE array.

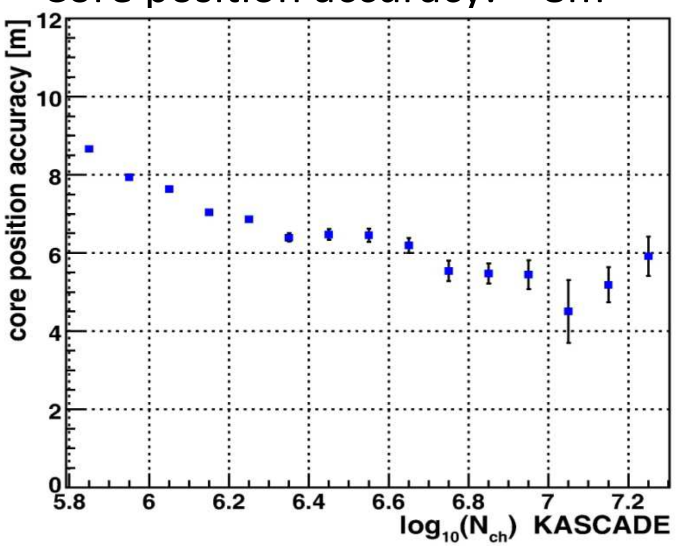
Arrival direction accuracy <1°

DATA

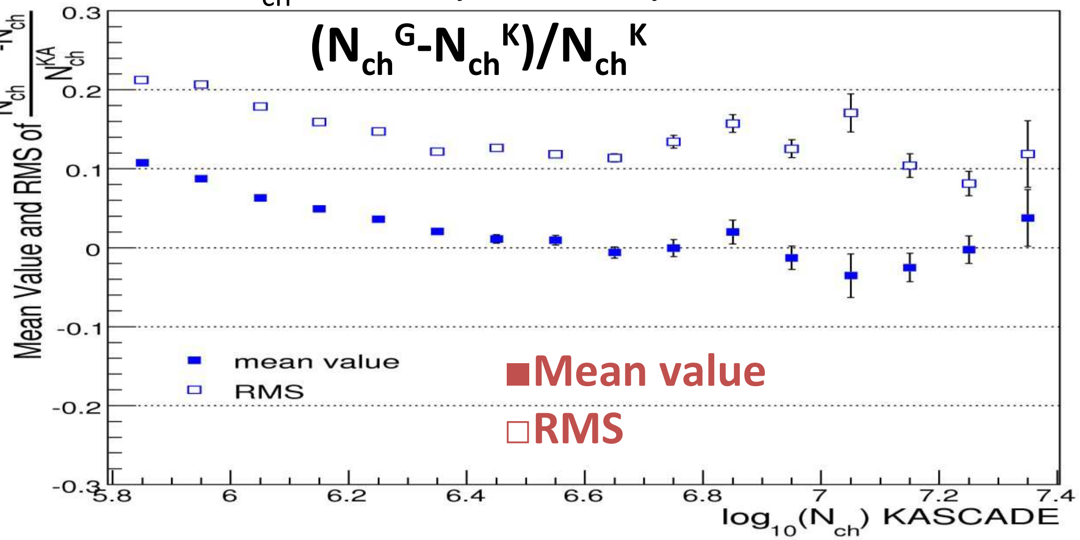




Core position accuracy: < 8m



N_{ch} accuracy: accuracy < 15%

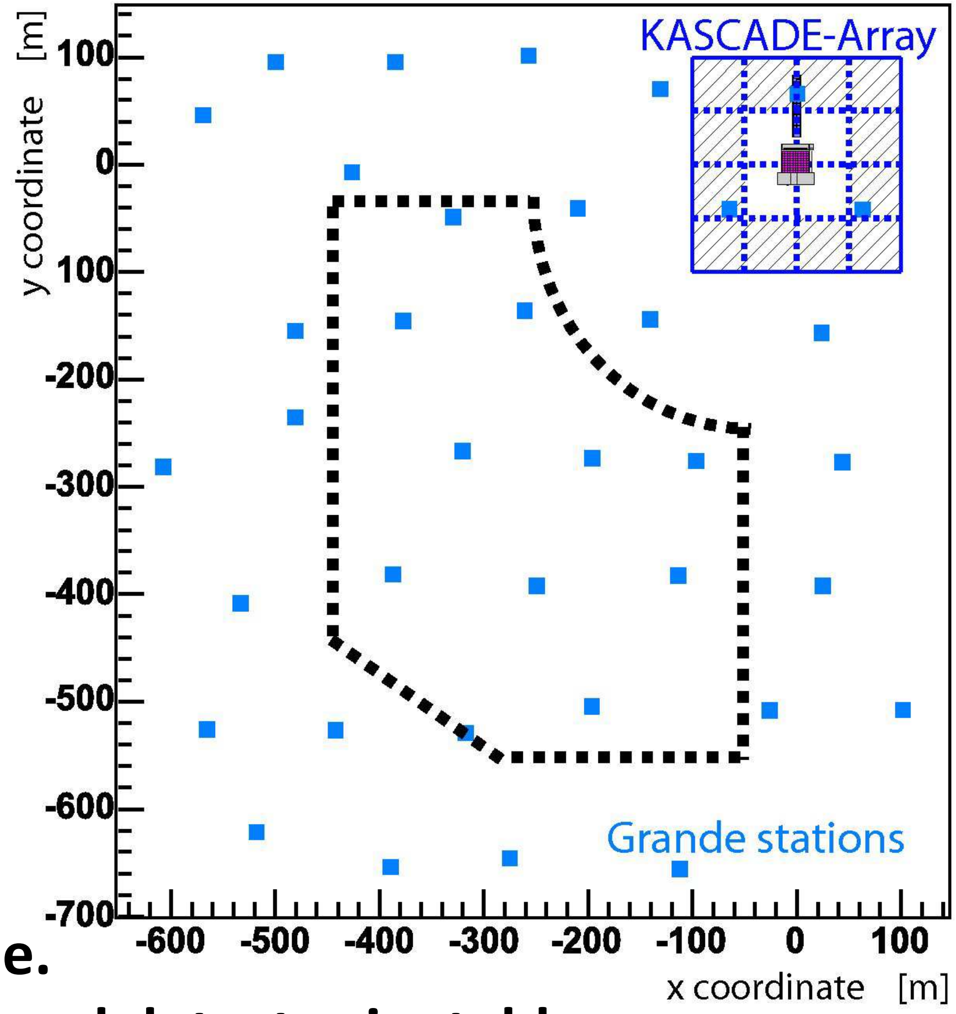


Apel et al. NIMA 620 (2010) 202-216

Reconstruction of the energy spectrum

We use three different methods:

- N_{ch} as observable
- N_{μ} as observable
- Combination of N_{ch} and N_{μ} as observables

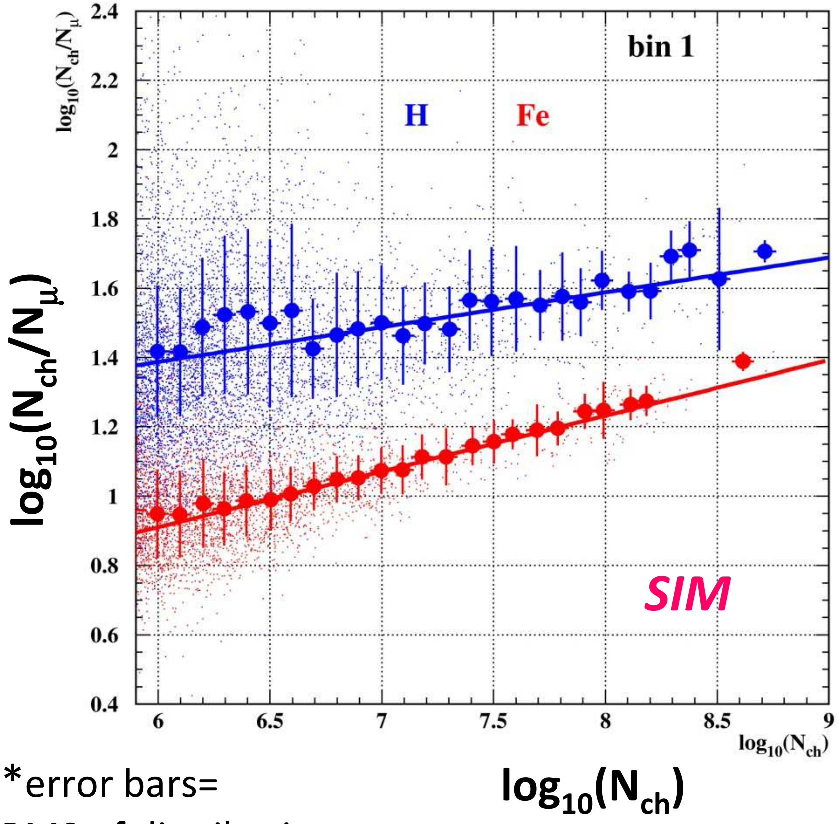


- 1173 days of effective DAQ time.
- Performance of reconstruction and detector is stable.
- $\theta < 40°$
- $250\ m < r_{KAS} < 600\ m$

$N_{ch} - N_{\mu}$ technique

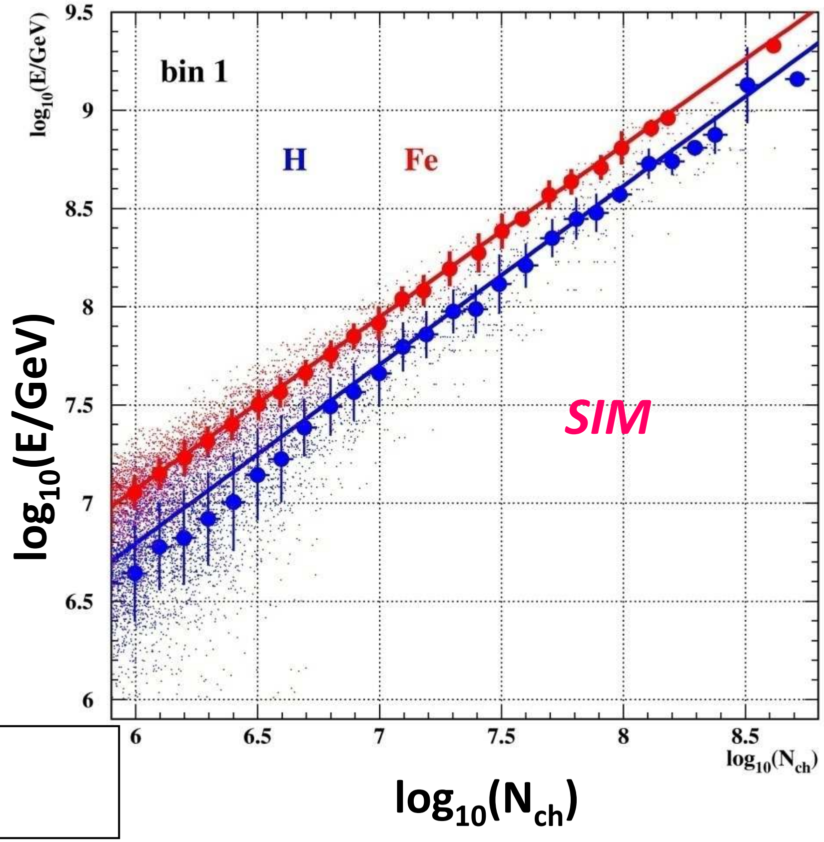
5 angular bins treated independently

$$\log_{10}(N_{ch}/N_{\mu})_{p,Fe} = c_{p,Fe}\log_{10}N_{ch} + d_{p,Fe}$$



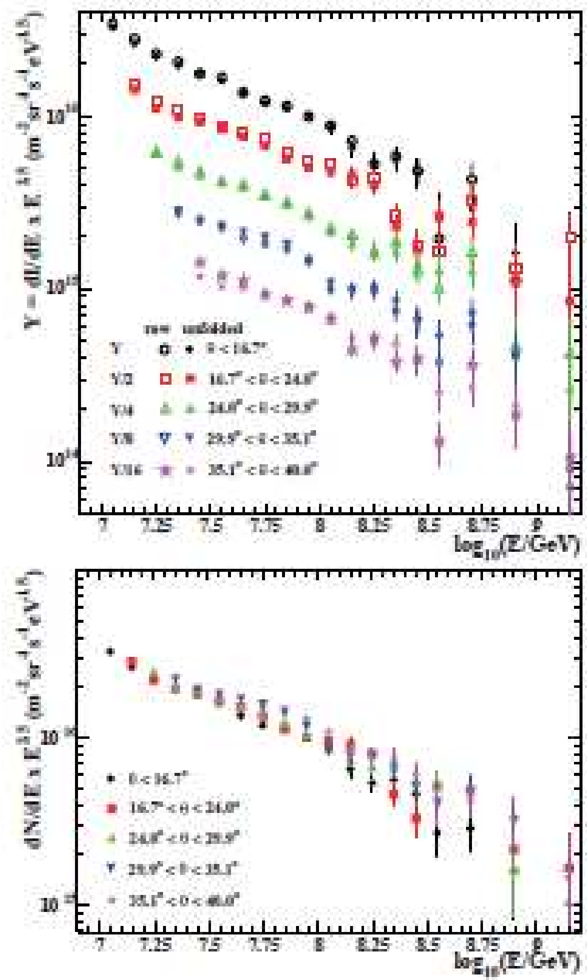
*error bars=
RMS of distributions

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

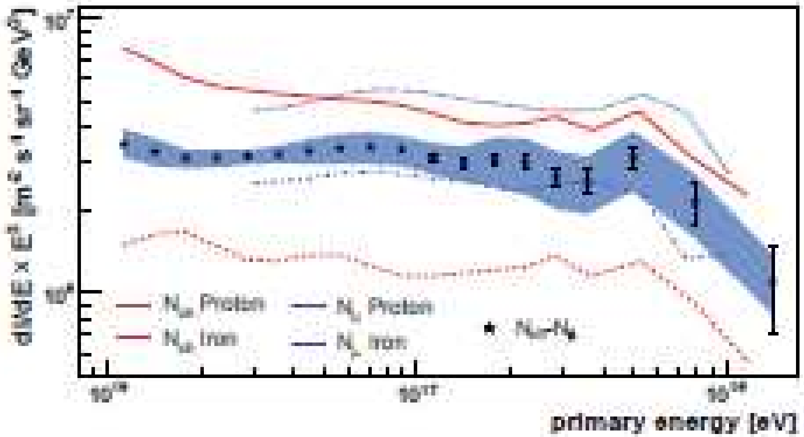


$$\log_{10}E_{p,Fe} = a_{p,Fe}\log_{10}N_{ch} + b_{p,Fe}$$

$$\log_{10}E = [a_p + (a_{Fe} - a_{,p})] \cdot k \cdot \log_{10}(N_{ch}) + [b_p + (b_{Fe} - b_p) \cdot k]$$

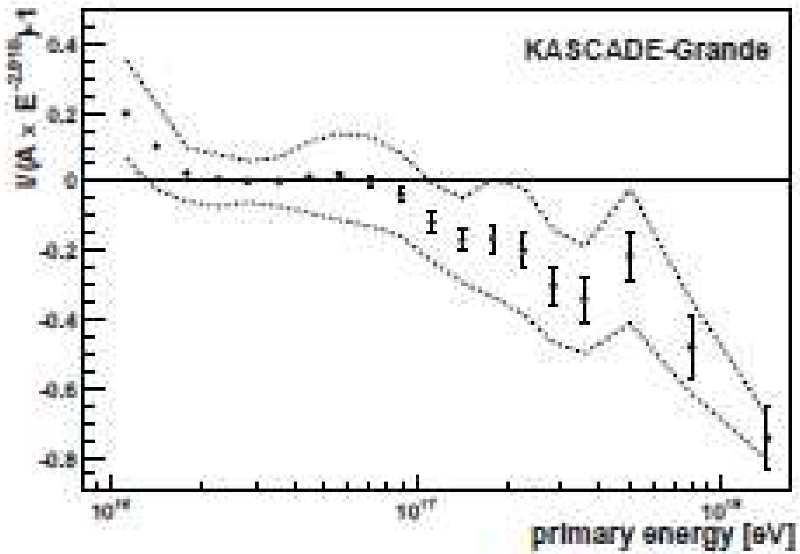


Spectra measured in the five different angular bins.



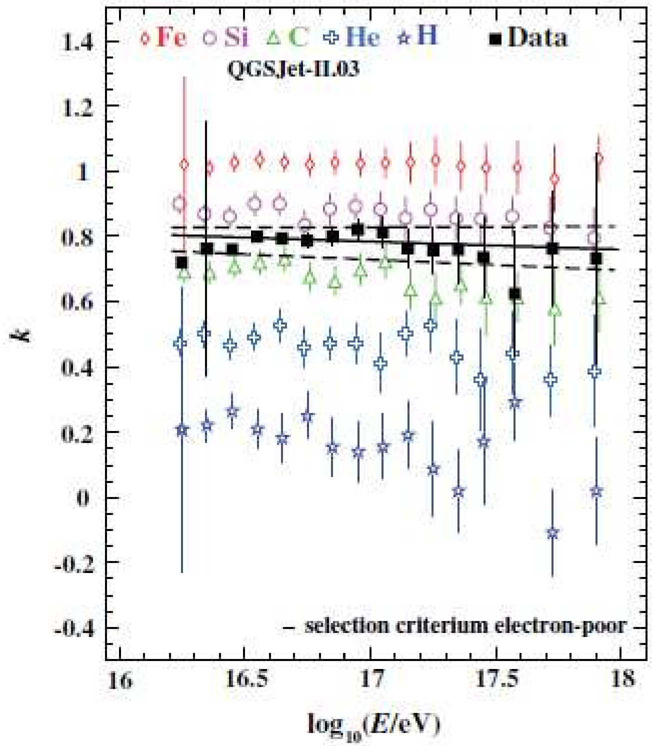
Spectra measured with different analysis are compatible.

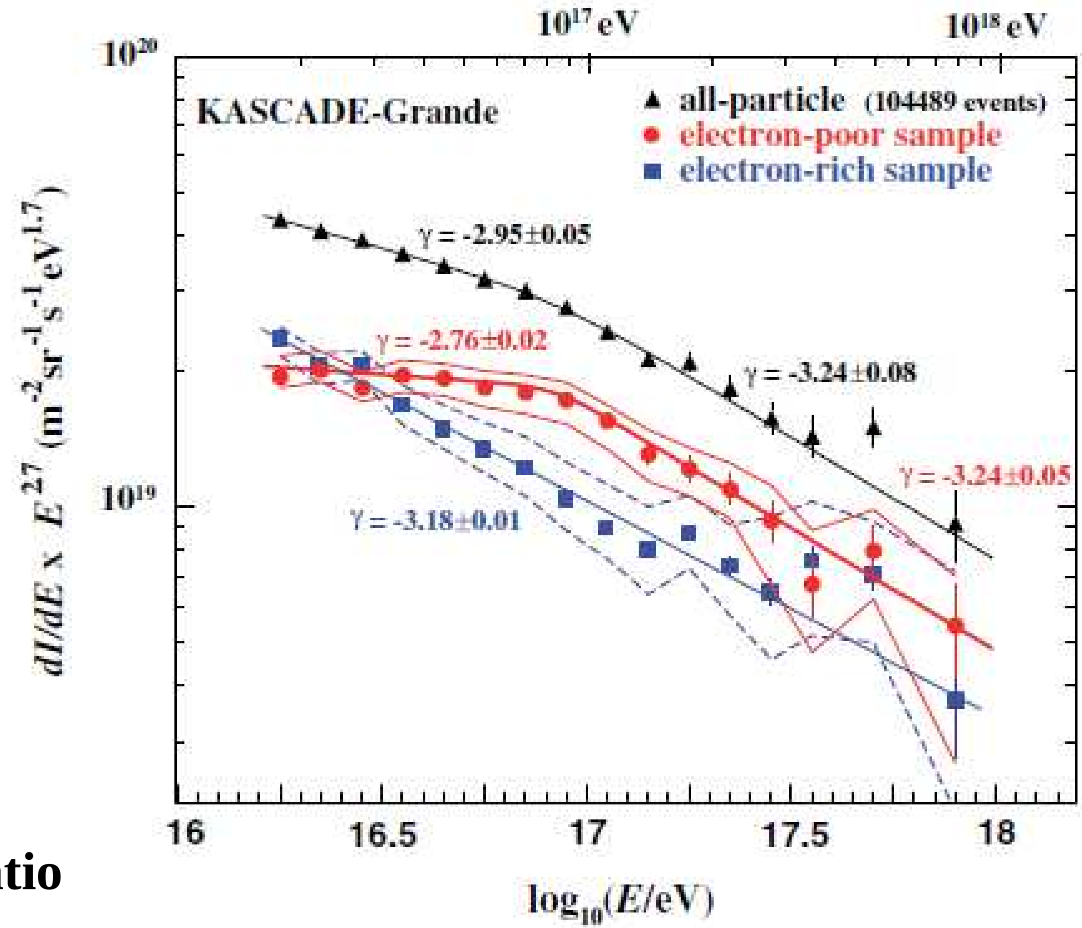
Spectrum cannot be described by a single power law



http://dx.doi.org/10.1016/j.astropartphys.2012.05.023

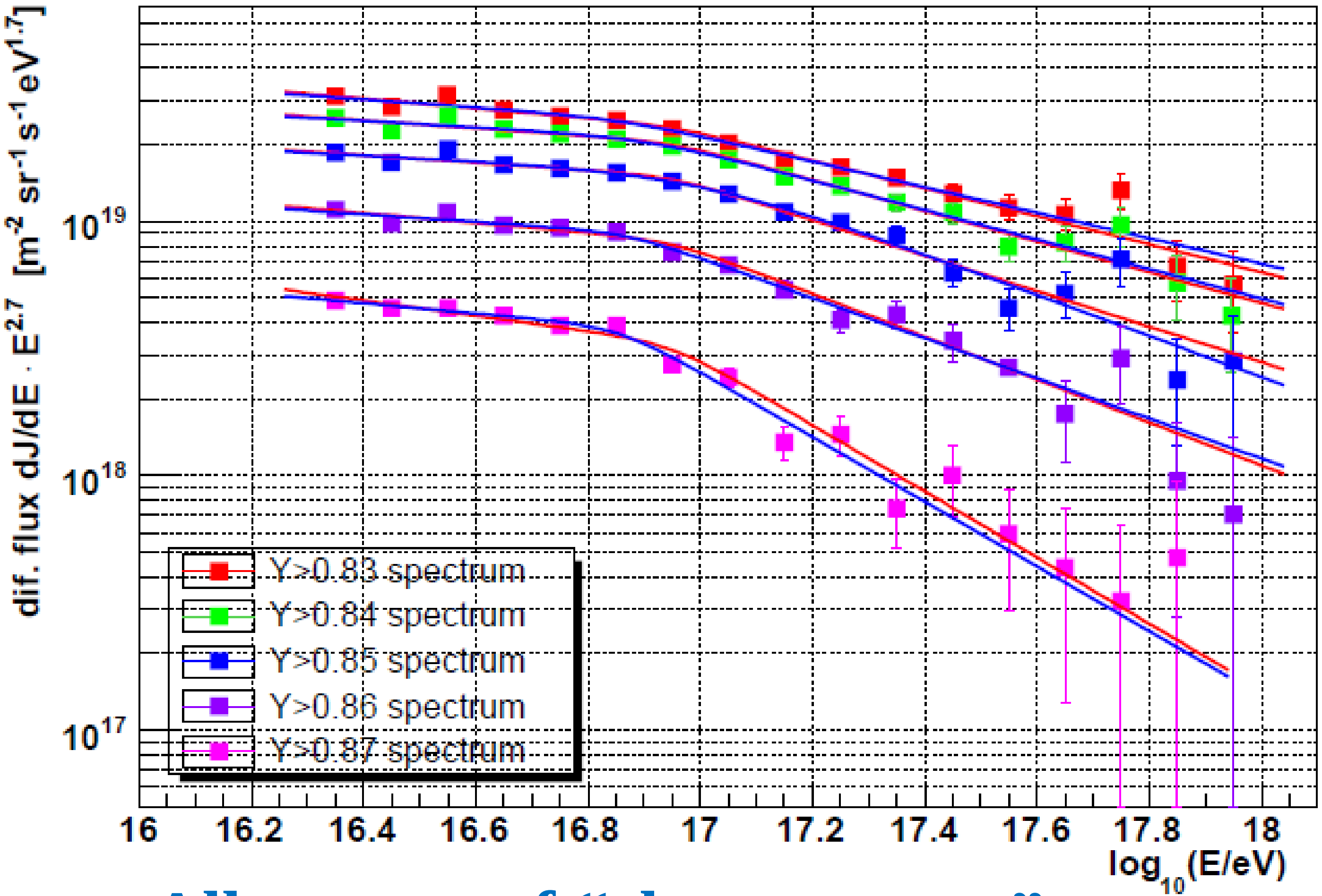
Structure ~10^{17} eV studied by mass group spectra





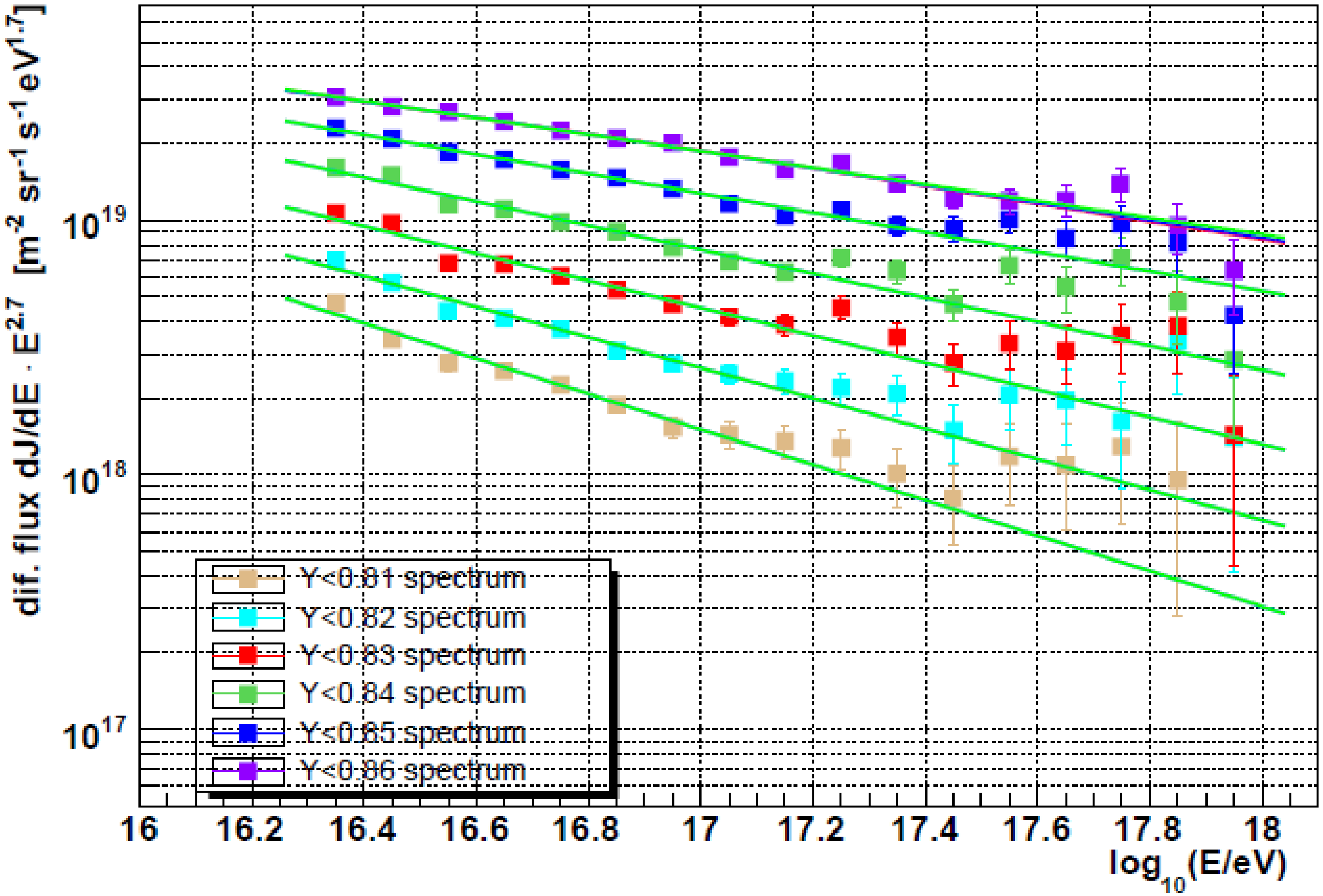
Event selection based on the ratio between N_μ and N_{ch}

Spectra obtained cutting at different values of $Y = \ln N_\mu / \ln N_{ch}$



All spectra of "electron poor" events show a change of slope

Spectra obtained cutting at different values of $Y = \ln N_\mu / \ln N_{ch}$



No spectra of "electron rich" events show a change of slope

KASCADE-Grande

- **All particle spectrum in the 10^{16}-10^{18} eV energy range cannot be described by a single power law**
- **Steeping of the spectrum around $8x10^{16}$ eV due to heavy component of primaries → first detection of the change of slope**