Università degli studi di Torino
Corso di Laurea in Fisica

Comparison of KASCADE-Grande data and Astrophysical Models

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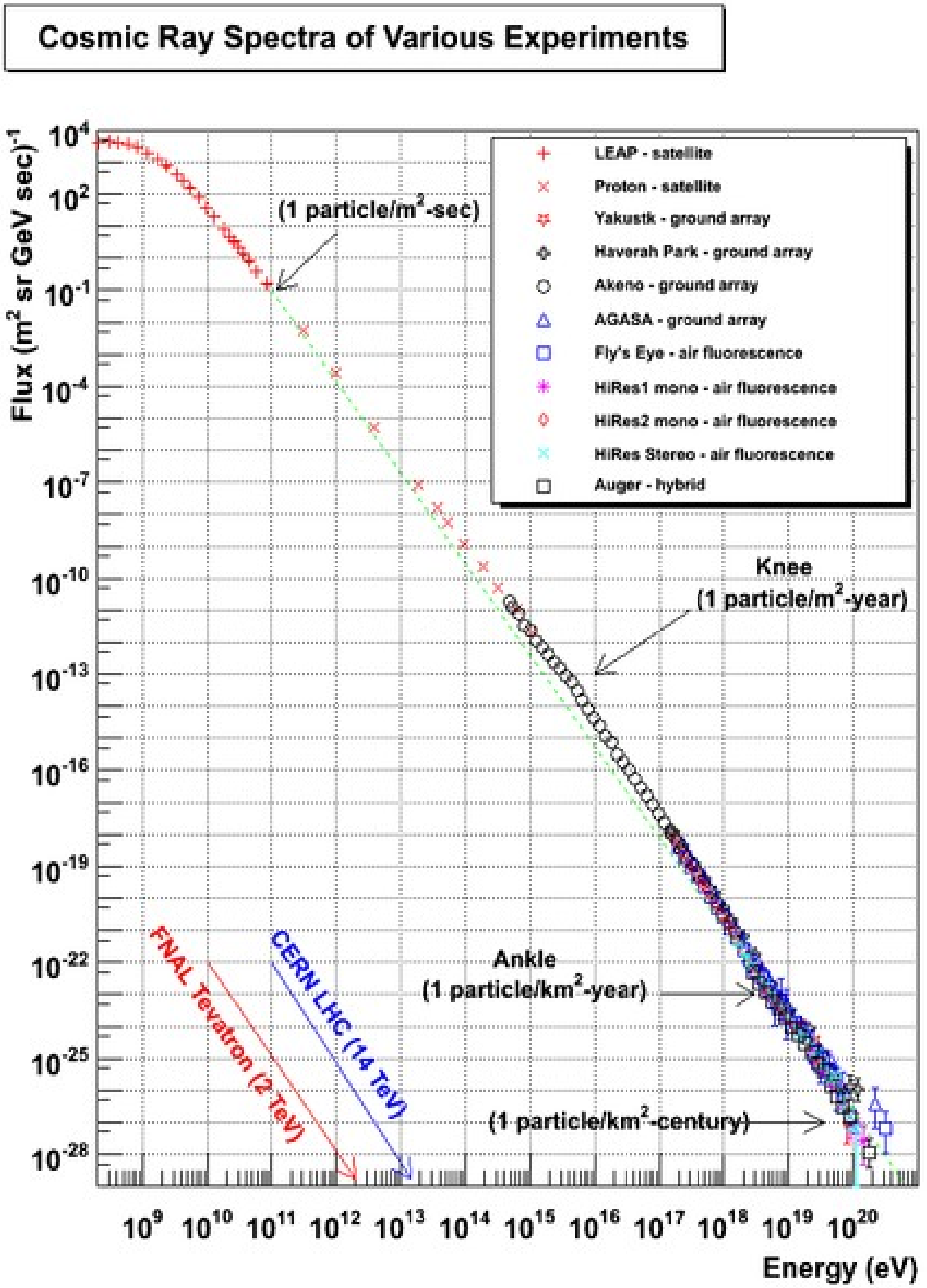
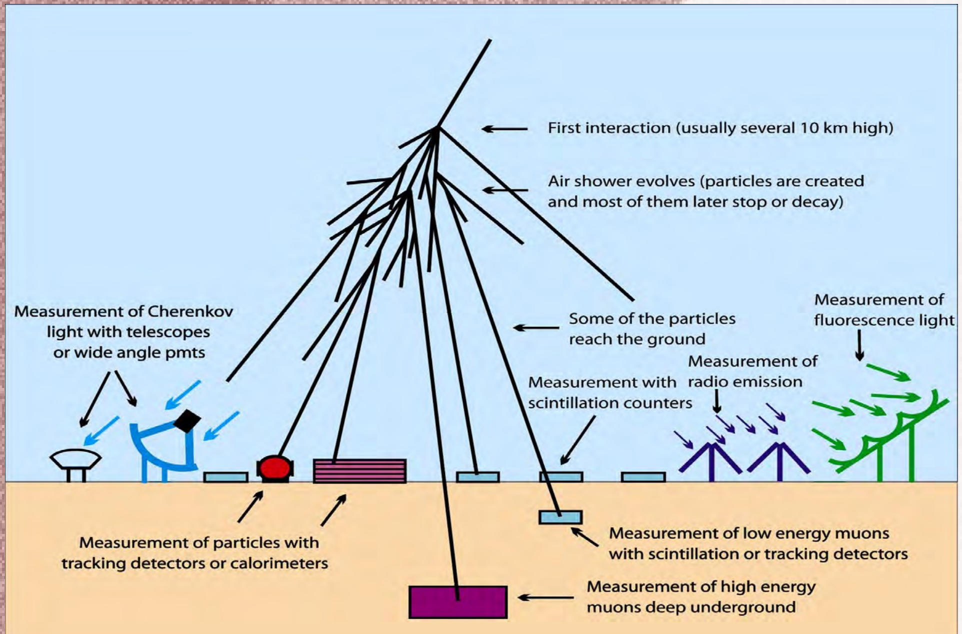
1.Introduction



- The cosmic ray flux can be described by a power law $$\frac{dN}{dE}\alpha E^{-\gamma}$$
- γ changes from 2.7 to 3.1 at $E\approx 3\times 10^{15}\,\text{eV}$ → *knee*
- The spectral index bends back to ~2.7 at $E\approx 3\times 10^{18}\,\text{eV}$ → *ankle*
- The Greisen-Zatsepin-Kuzmin cut-off at $$E\approx 5\times 10^{19}\,\text{eV}$$
- Most accredited astrophysical models for the interpretation of the knee:either acceleration or propagation mechanism of the cosmic rays in the Galaxy
- At energies above 10^{15} eV direct measurements are not feasible because of the very low flux



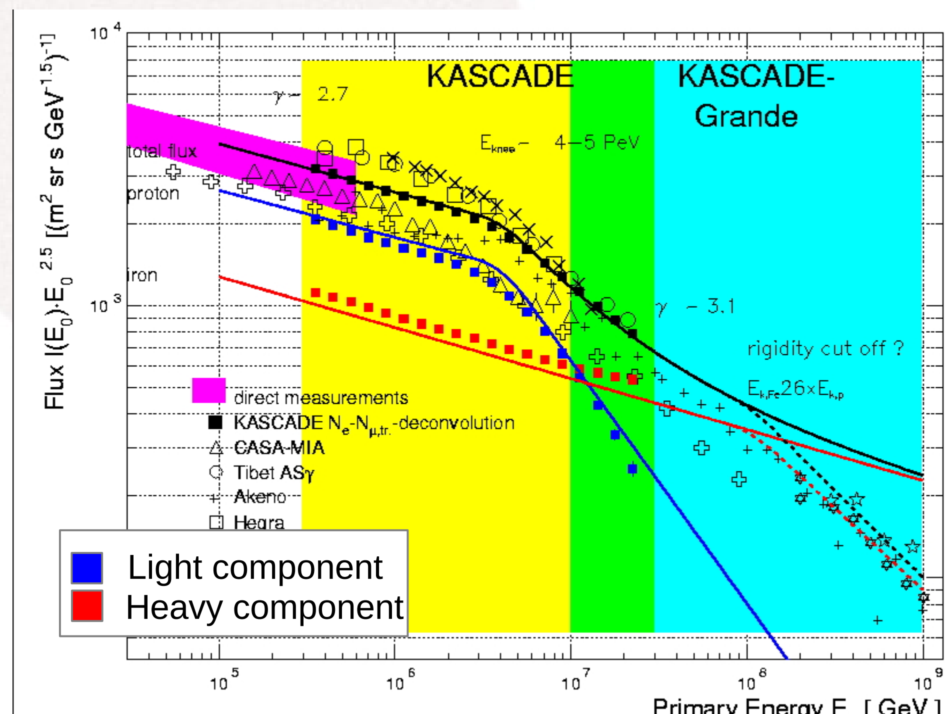
- Cosmic rays have to be studied by measuring the cascade of secondary particles induced by the interaction of primary particles with the atoms of the atmosphere → Extensive Air Showers(EAS)
- These showers are detected by extended detector arrays at ground level → KASCADE, EAS-TOP
- These experiments revealed that the knee is caused by a bending of the spectrum of the light component of cosmic rays

- According to the most promisig models, the individual knee of each primary element occurs at a constant rigidity of the particles

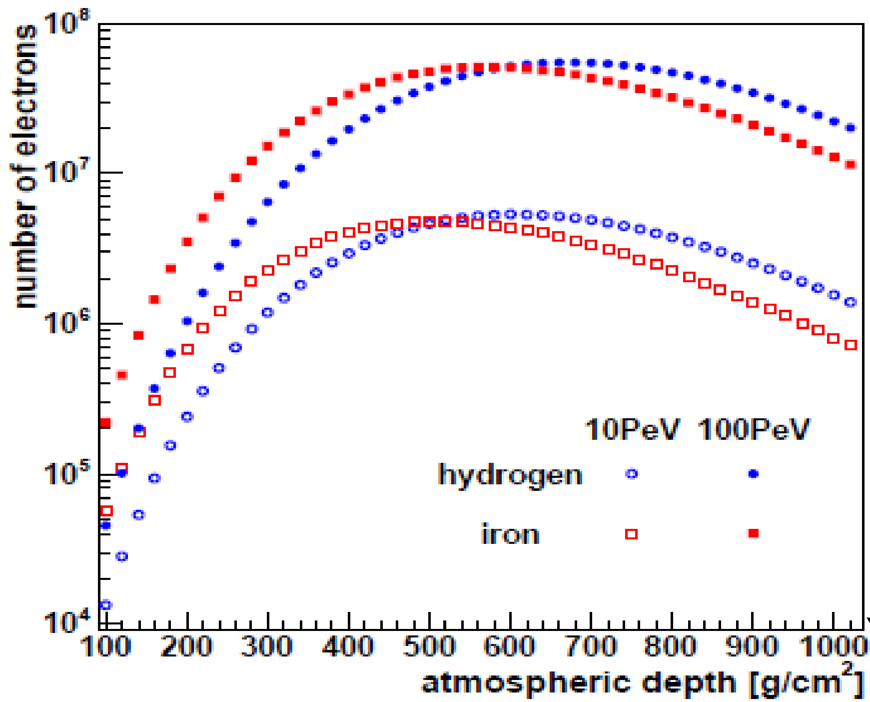
$$R=\frac{E}{Ze}$$

$$E^{H}_{knee}\approx 3-4x10^{15}\,eV$$

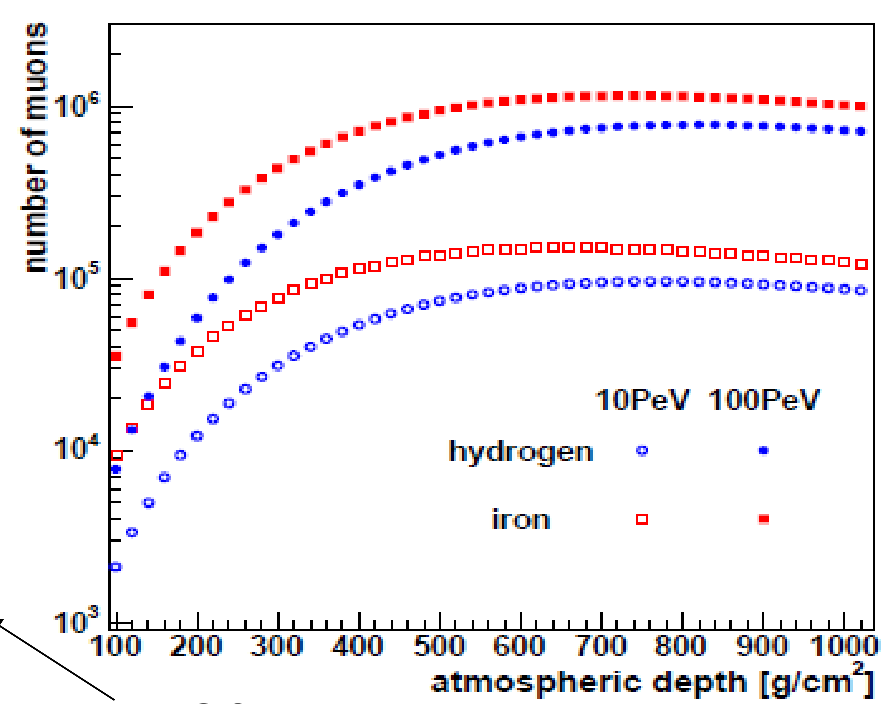
$$E^{Fe}_{knee}=26\times E^{H}_{knee}\approx 7-10\times 10^{16}\,eV$$

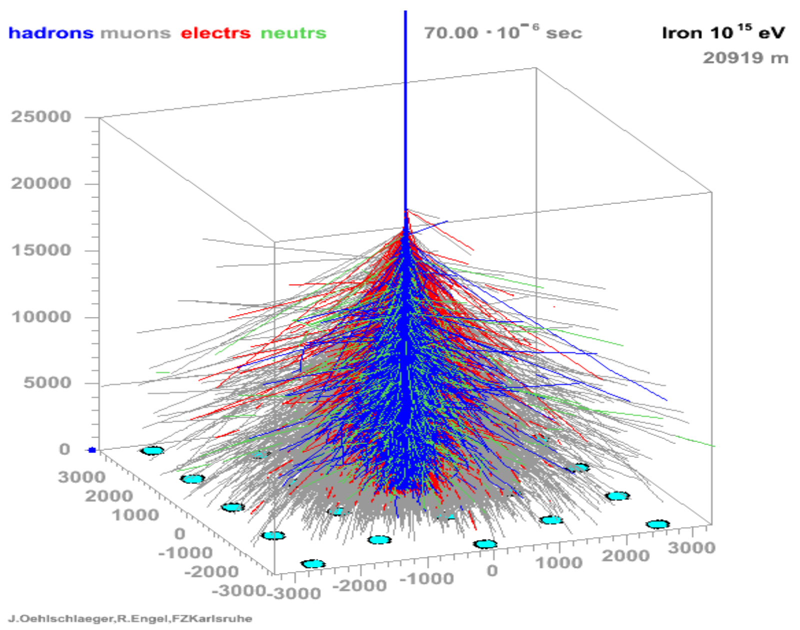


Electrons



Muons

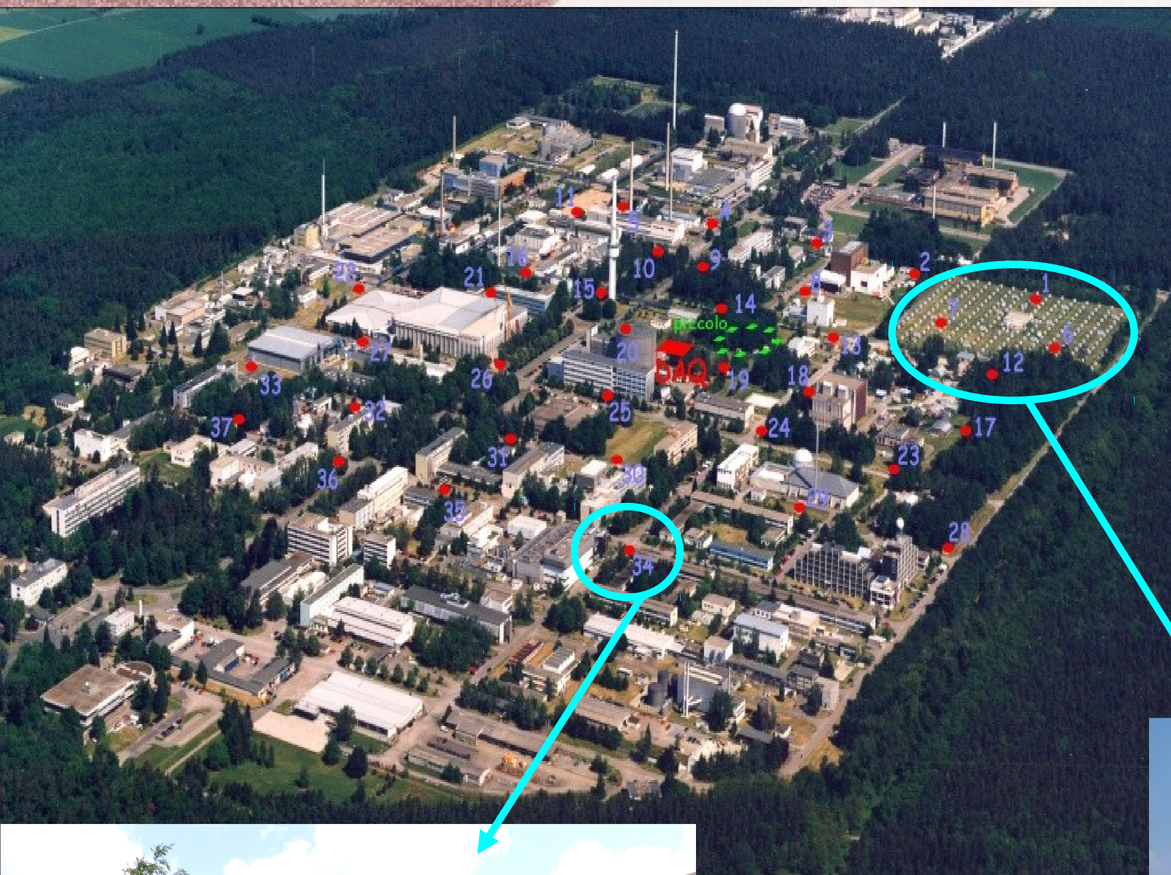




KASCADE

- The estimation of energy and mass of the primary charged particles is performed starting from the number of electrons and muons at observation level
- The number of muons is very low compared to that of electrons (10%) → $N_{ch} \sim N_e$
- To determine the fraction of proton and iron of the total flux, air showers are simulated
- This procedure allows also to determine the arrival direction of the primary particle and the impact point of the air shower

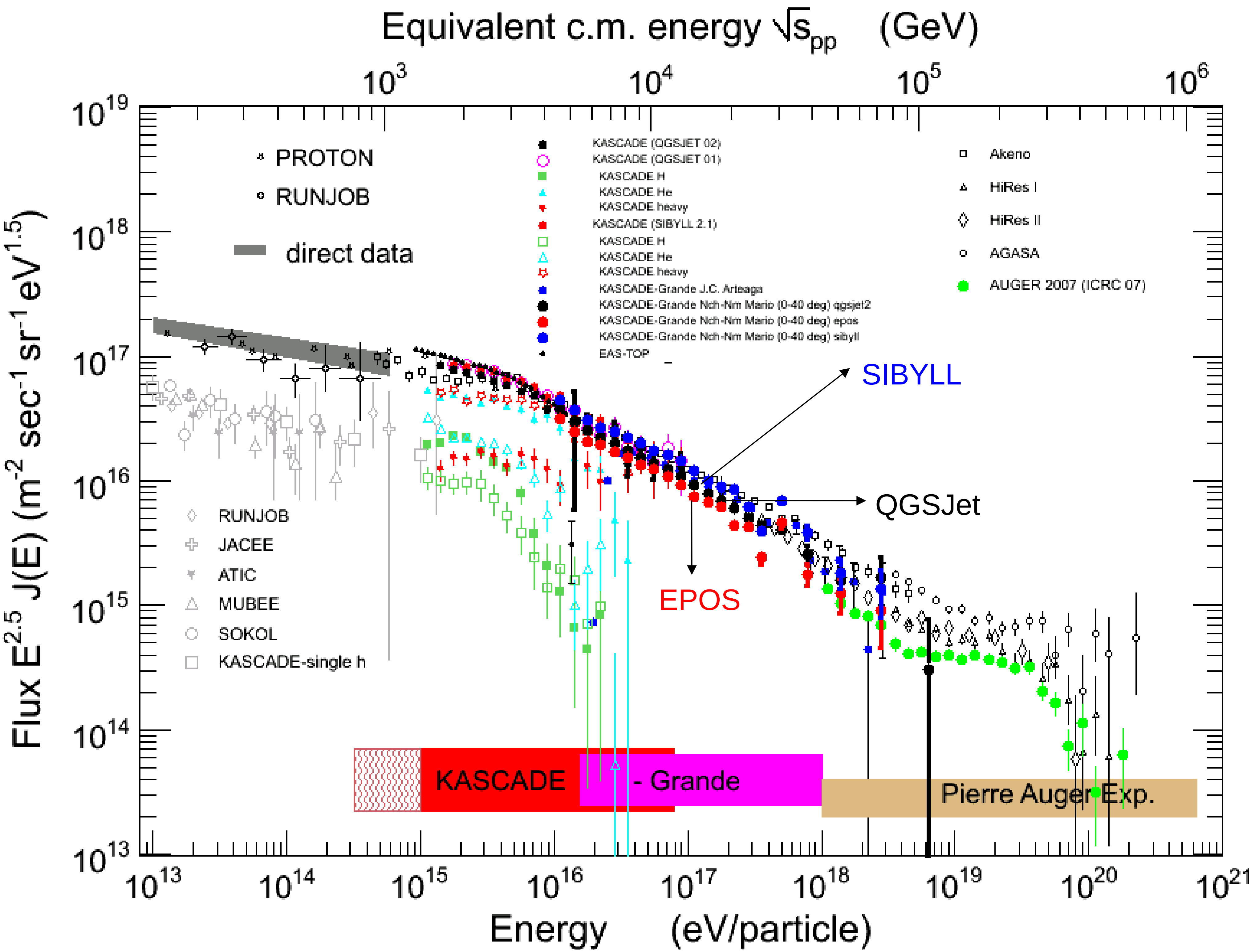
2.KASCADE-Grande



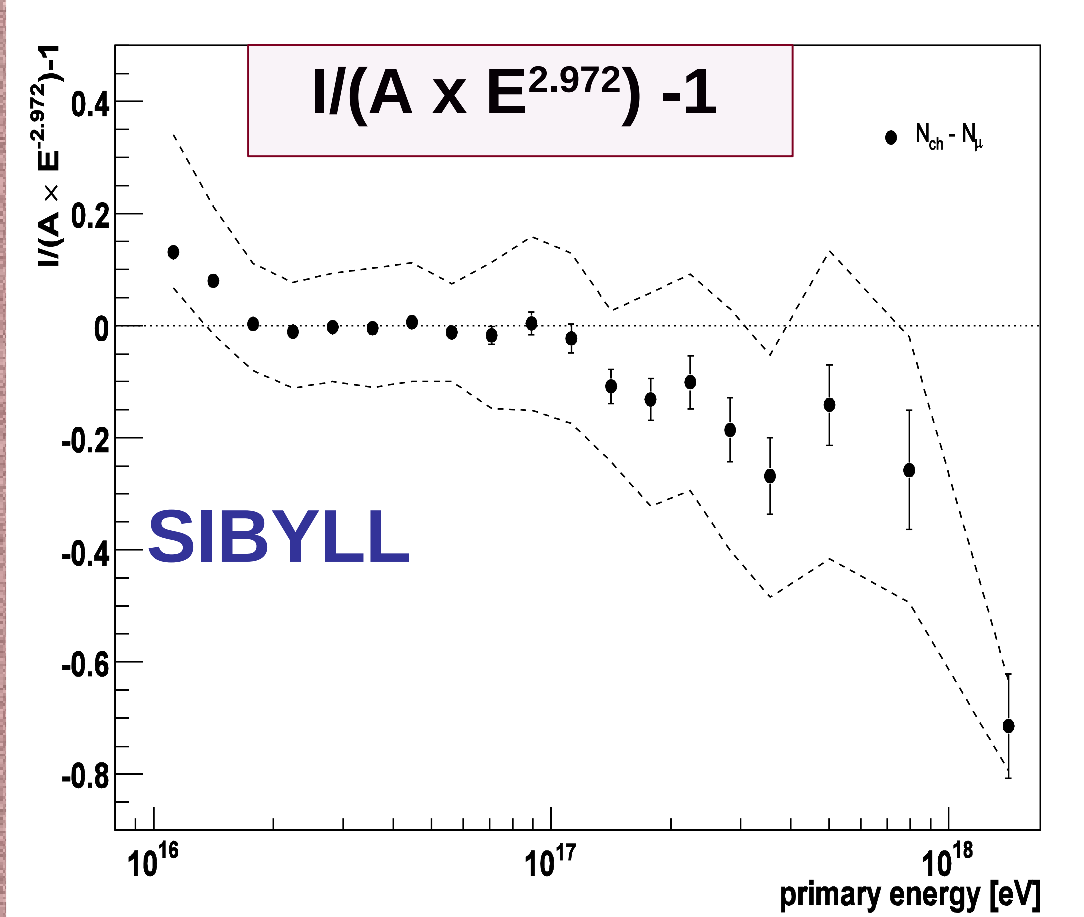
- Multi-detector experiment for the measurement of air showers induced by primary cosmic rays in the energy range 10^{16} – 10^{18} eV
- Located at Campus North of the Karlsruher Institut für Technologie (KIT) in Germany
- It is the extension of the original KASCADE experiment

Grande stations: charged particles detectors

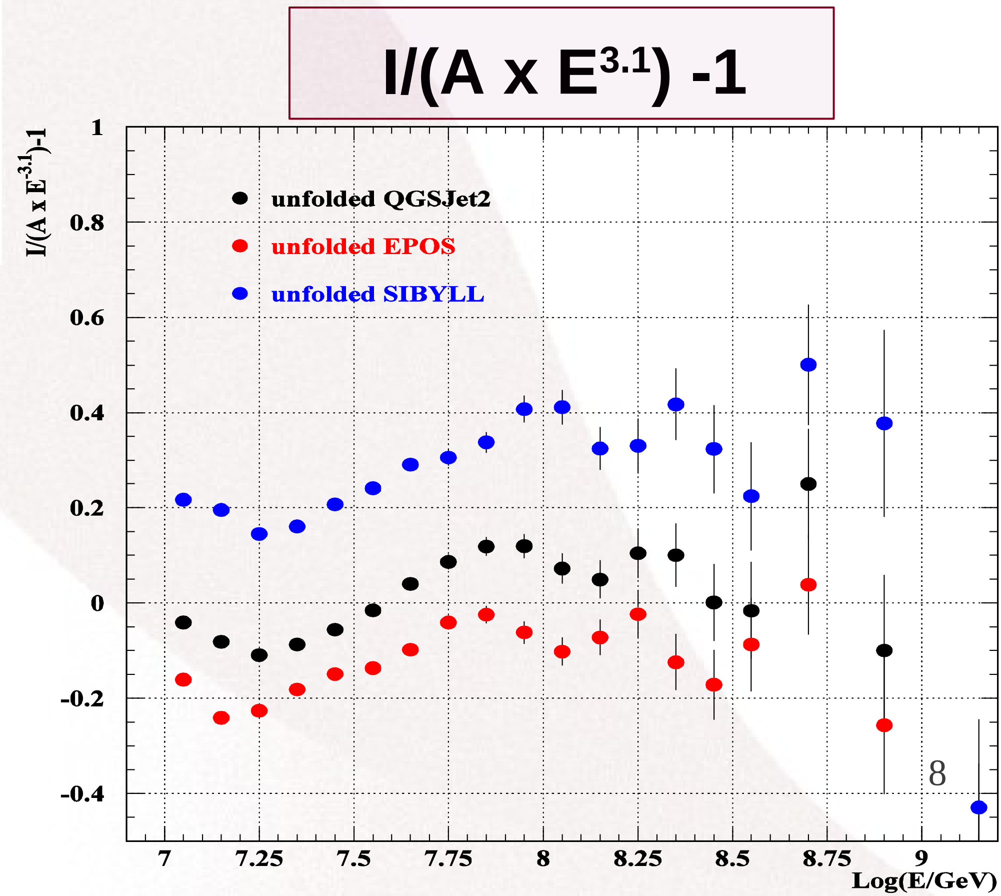
KASCADE stations: μ detectors



Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^3
10^4
10^5
10^6
PROTON
RUNJOB
direct data
KASCADE (QGSJET 02)
KASCADE (QGSJET 01)
KASCADE H
KASCADE He
KASCADE heavy
KASCADE (SIBYLL 2.1)
KASCADE H
KASCADE He
KASCADE heavy
KASCADE-Grande J.C. Arteaga
KASCADE-Grande Nch-Nm Mario (0-40 deg) qgsjet2
KASCADE-Grande Nch-Nm Mario (0-40 deg) epos
KASCADE-Grande Nch-Nm Mario (0-40 deg) sibyll
EAS-TOP
Akeno
HiRes I
HiRes II
AGASA
AUGER 2007 (ICRC 07)
SIBYLL
QGSJet
EPOS
RUNJOB
JACEE
ATIC
MUBEE
SOKOL
KASCADE-single h
KASCADE
- Grande
Pierre Auger Exp.
Flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)



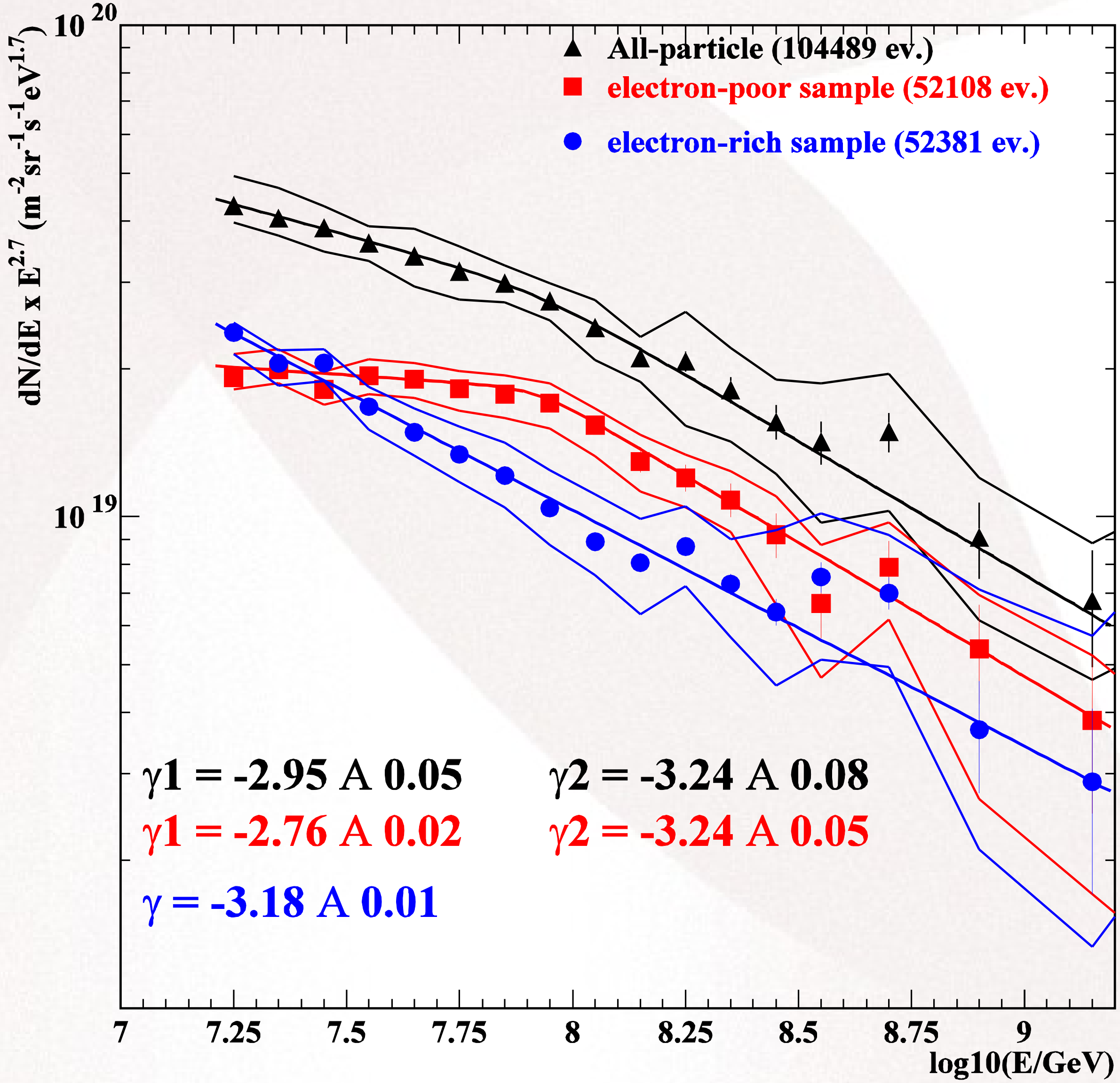
- The resulting all-particle spectrum obtained with KASCADE-Grande
- Some structures do not allow to describe the spectrum with a single slope index
- Just above 10^{16} : concave behaviour



- The air shower simulations rely on hadronic interaction models
- The analyses using different hadronic models result in similar structures, but the spectra are shifted in the energy scale

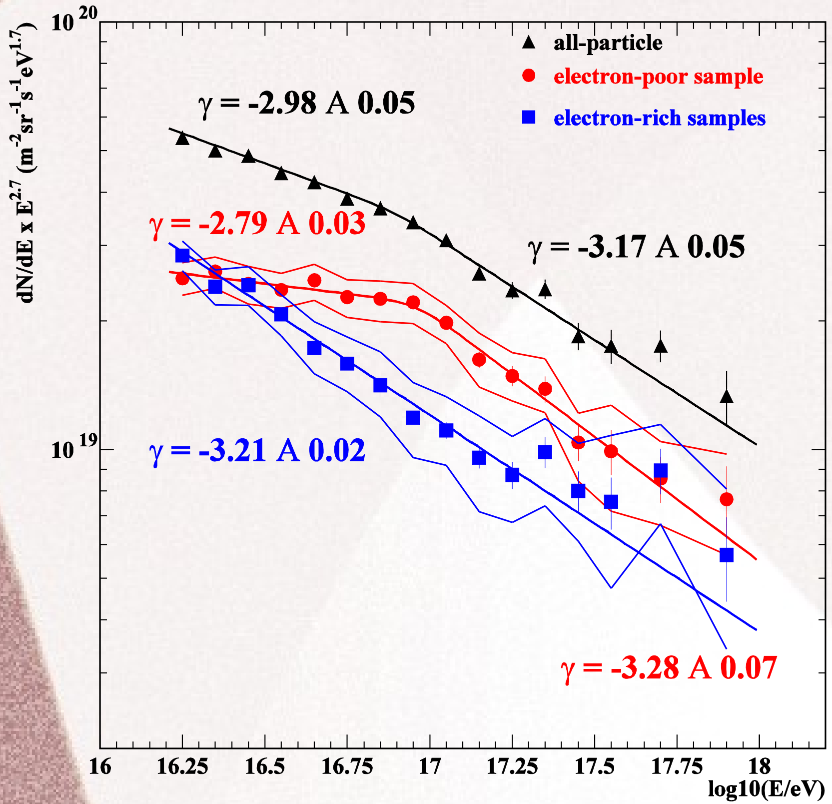
QGSJet

FLUX ALL PARTICLE, E.R. & E.P. SAMPLES

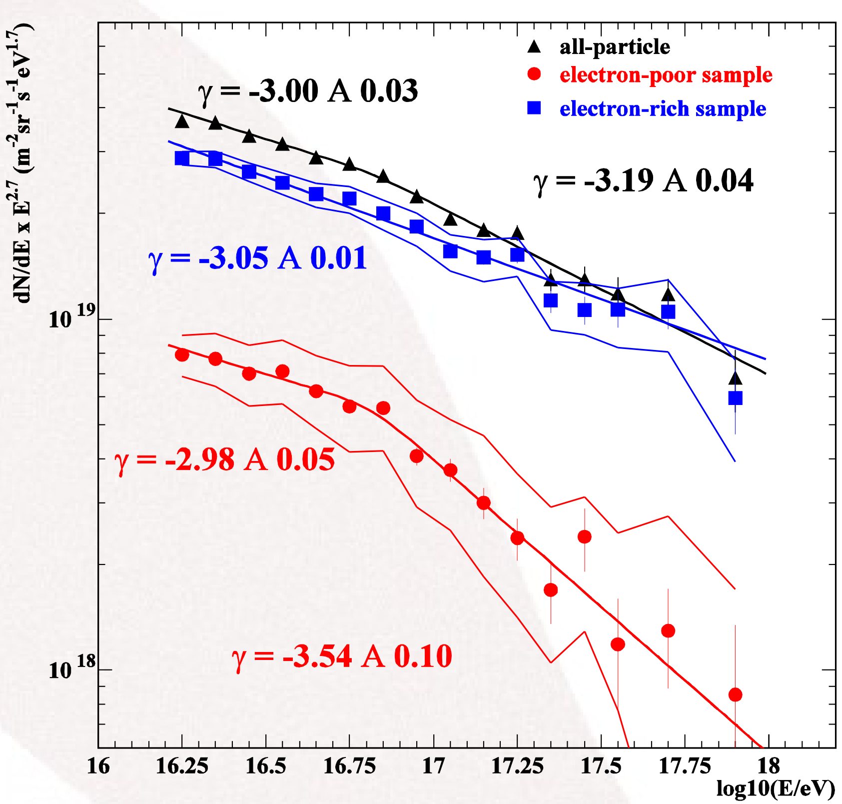


SIBYLL and EPOS

FLUX ALL PARTICLE, E.R. & E.P. SAMPLES



SIBYLL



EPOS

3.Comparing data & models

Two astrophysical models have been studied

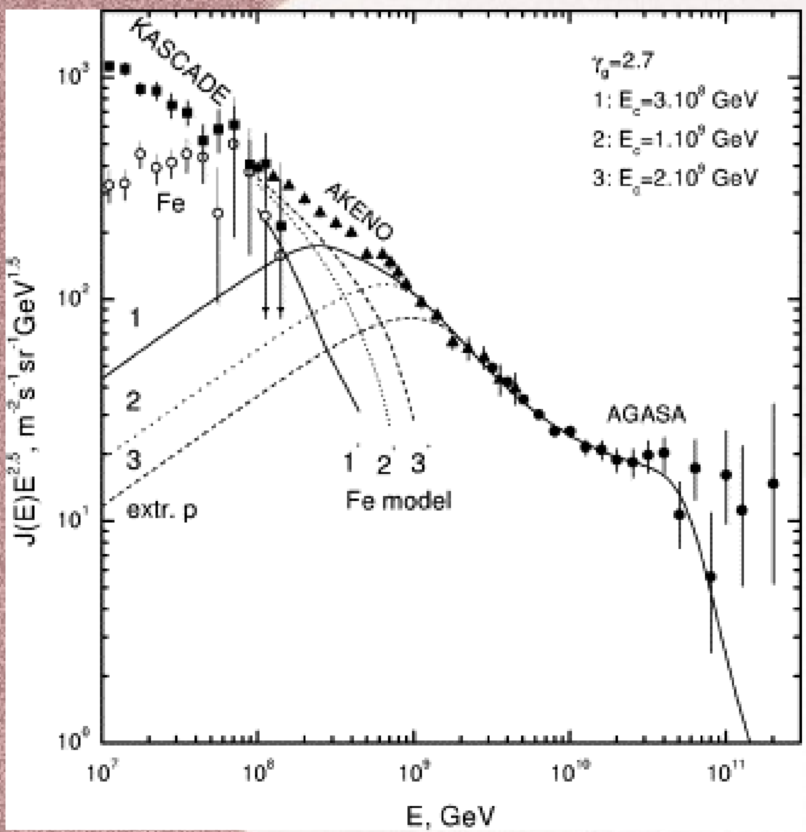
and then compared to KASCADE-Grande data,

in order to confirm or exclude

their interpretations of the cosmic rays spectrum

in the energy range 10^{16} – 10^{18} eV

Berezinsky's model



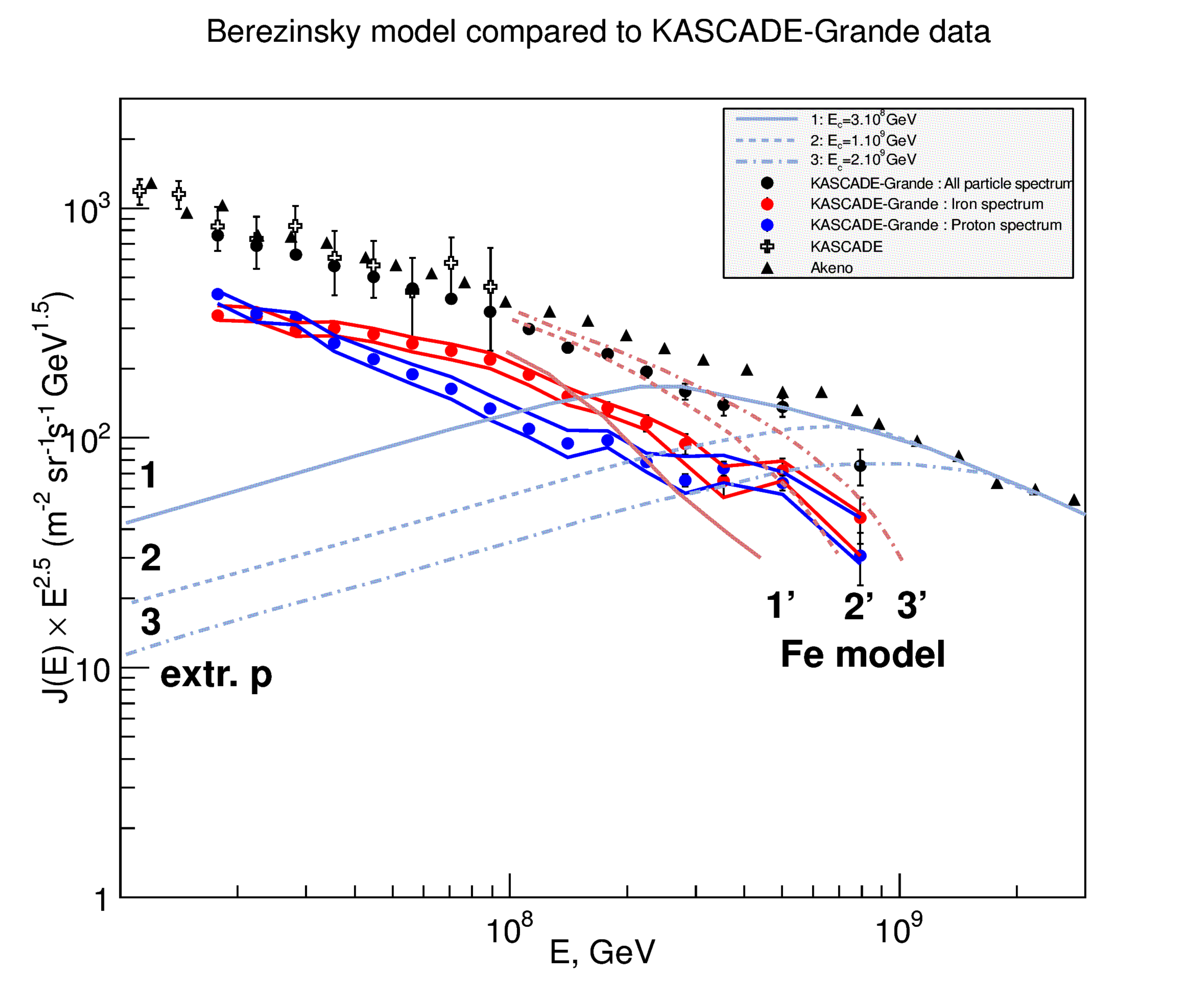
- Assumptions:

1- UHECRs in the energy range $1x10^{18}$-$8x10^{19}$ eV are extragalactic protons

2- at energies $E>1x10^{17}$ eV only iron nuclei as galactic component survive

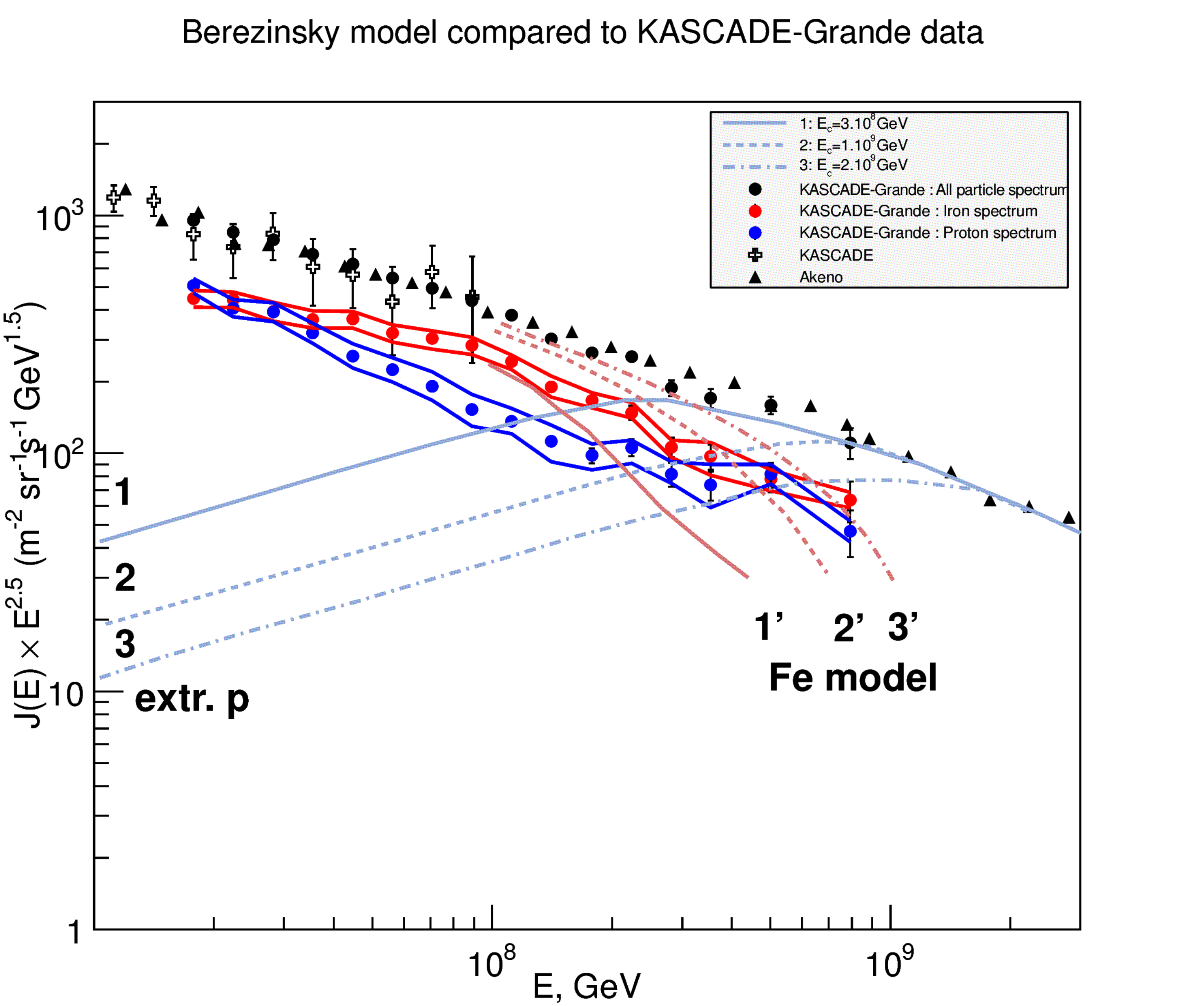
- The spectrum of extragalactic protons in the energy range $1x10^{17}$ -$8x10^{21}$ eV has been calculated
- The iron spectrum is obtained by subtracting the flux of extragalactic protons from the observed all particle (Akeno-AGASA)
- The transition from galactic to extragalactic cosmic rays occurs at crossing of extragalactic protons and galactic iron spectra; no pronounced feature in the all-particle spectrum
- The pairs of curves correspond to different values of the free parameter E_c - maximum of extragalactic protons curve

QGSJet



- Berezinsky model has been calibrated with Akeno-AGASA data → the expected total flux is higher than QGSJet all paticle spectrum
- Depending on the value of E_c, the heavy component could be compatible
- The light component has a totally different shape

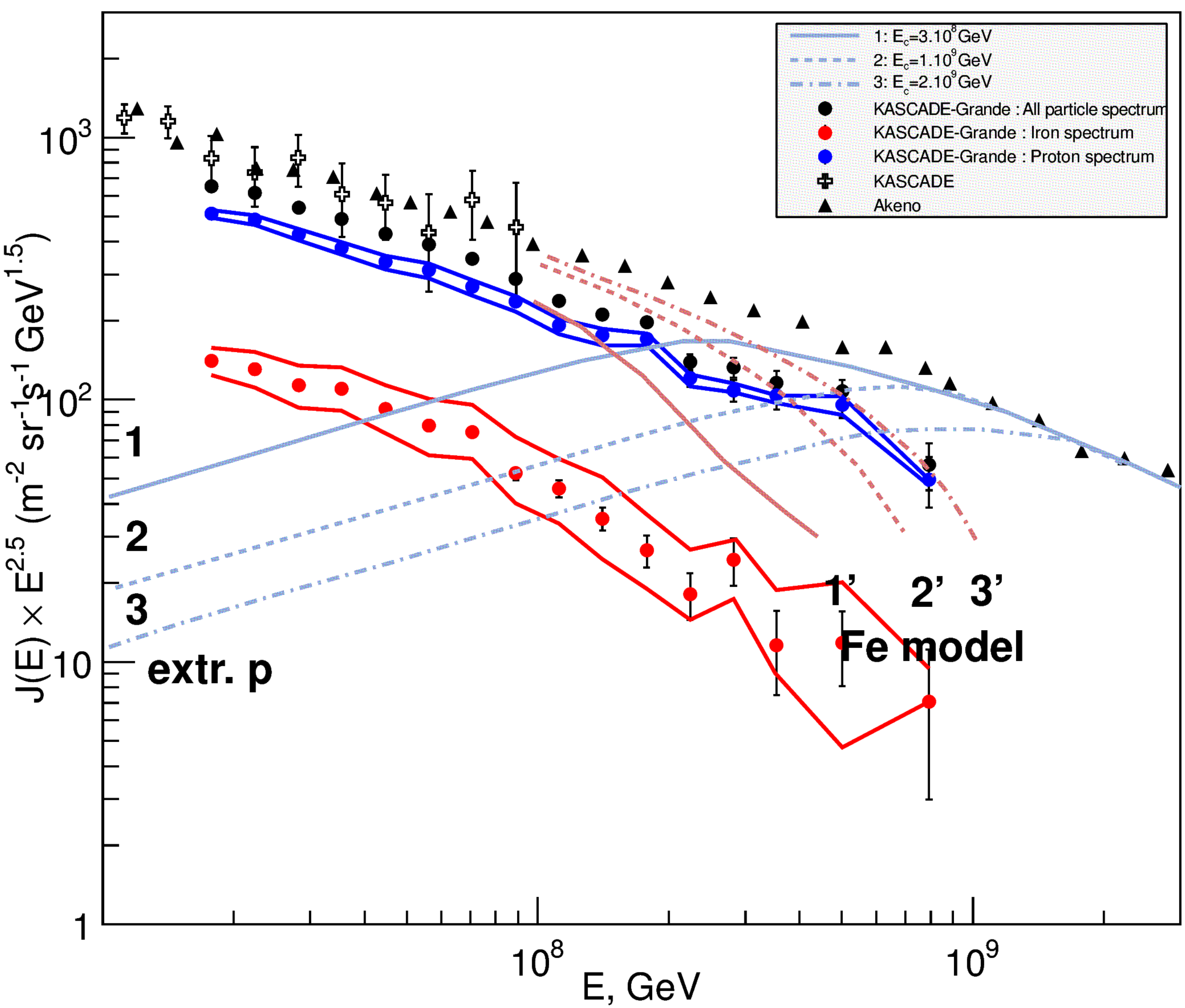
SIBYLL



- Sibyll total flux is in agreement with Akeno-AGASA total flux
- The heavy component is compatible
- The light component has a totally different shape and abundance

EPOS

Berezinsky model compared to KASCADE-Grande data



- All the spectra obtained with EPOS seem to be not compatible with those predicted by Berezinsky

Hillas' model

According to this model, there are three distinct parts of the cosmic ray flux:

(i)“A”: extending from low energies. Same rigidity spectrum for all nuclei

$$R^{-2.69}$$

multiplied by a turn-down factor

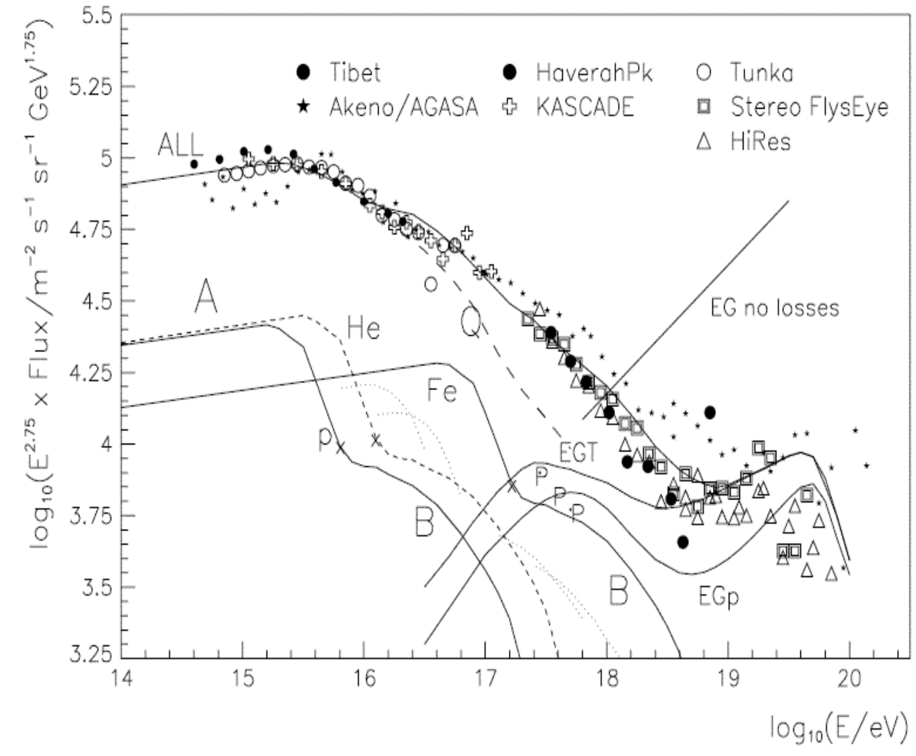
$$f(R)=\frac{1}{\left[1+\left(\frac{R}{R_0}\right)^{2.5}\right]^{0.5}}, R_0=3\times10^{15}V$$

(ii)”EG”: extragalactic component; H+He having a spectrum $\alpha E^{-2.3}$

before suffering losses by CMBR

(i)+(ii) = Q → This is not enough

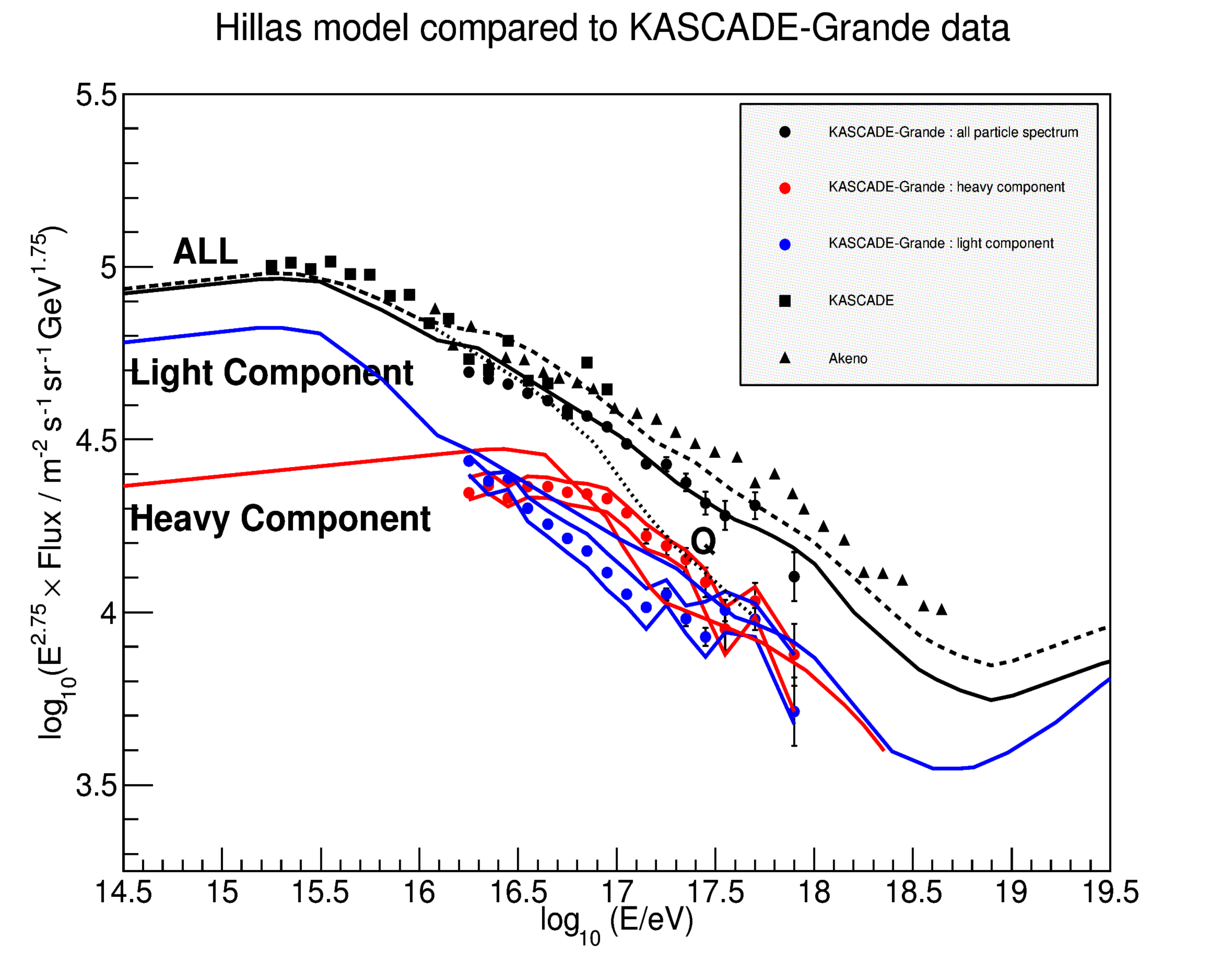
(iii)”B”: a third component is needed in order to make up the measured all particle spectrum



In order to compare the model with KASCADE-Grande data:

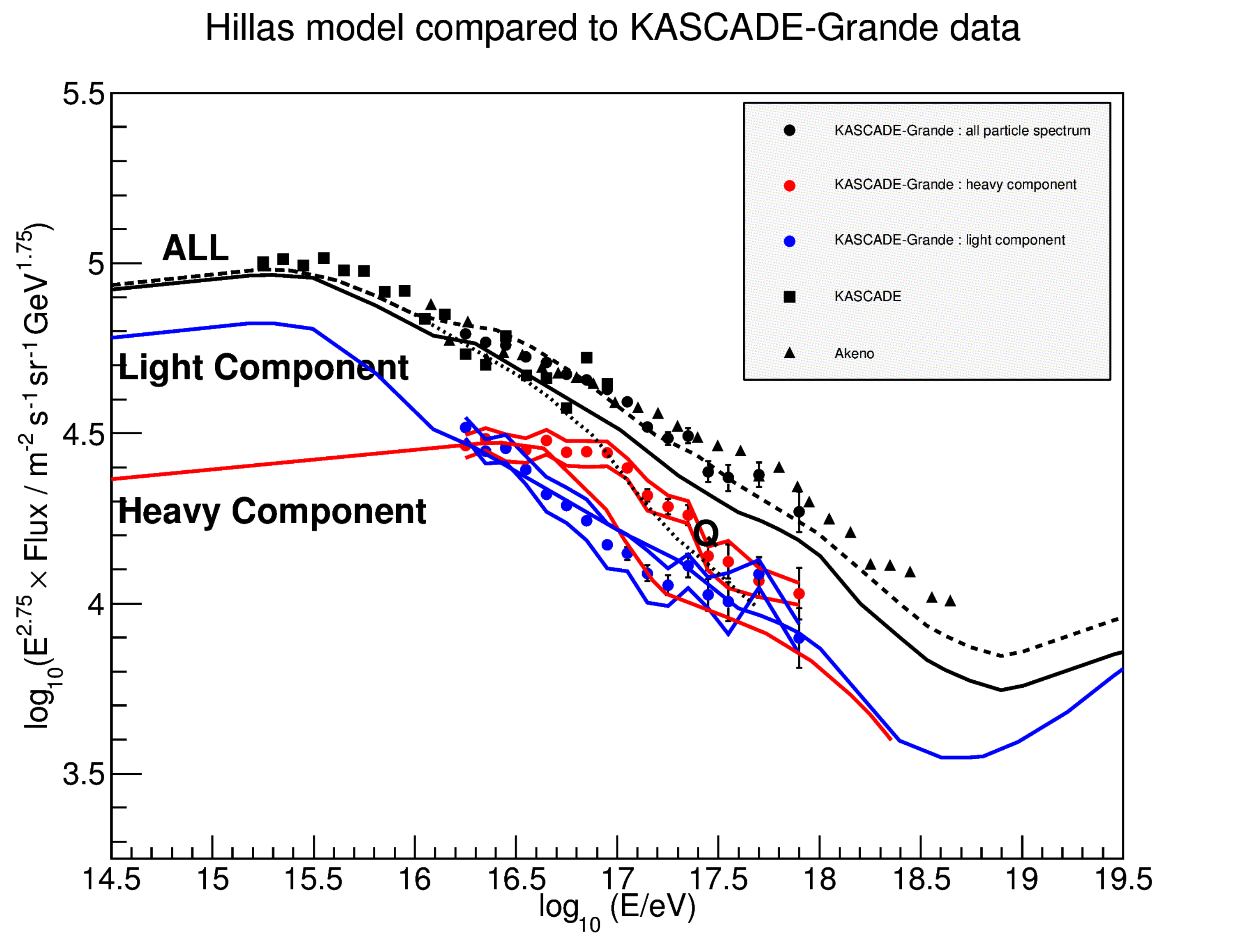
- Protons + Helium + CNO → Light component
- Ne-S + Iron → Heavy component

QGSJet



- The shape of both the light and the heavy component is compatible with the data
- For the light component, there is only a little discrepancy of abundance
- For the heavy component, the knee seems to be shifted compared to the data, in addition of the problem of the abundance

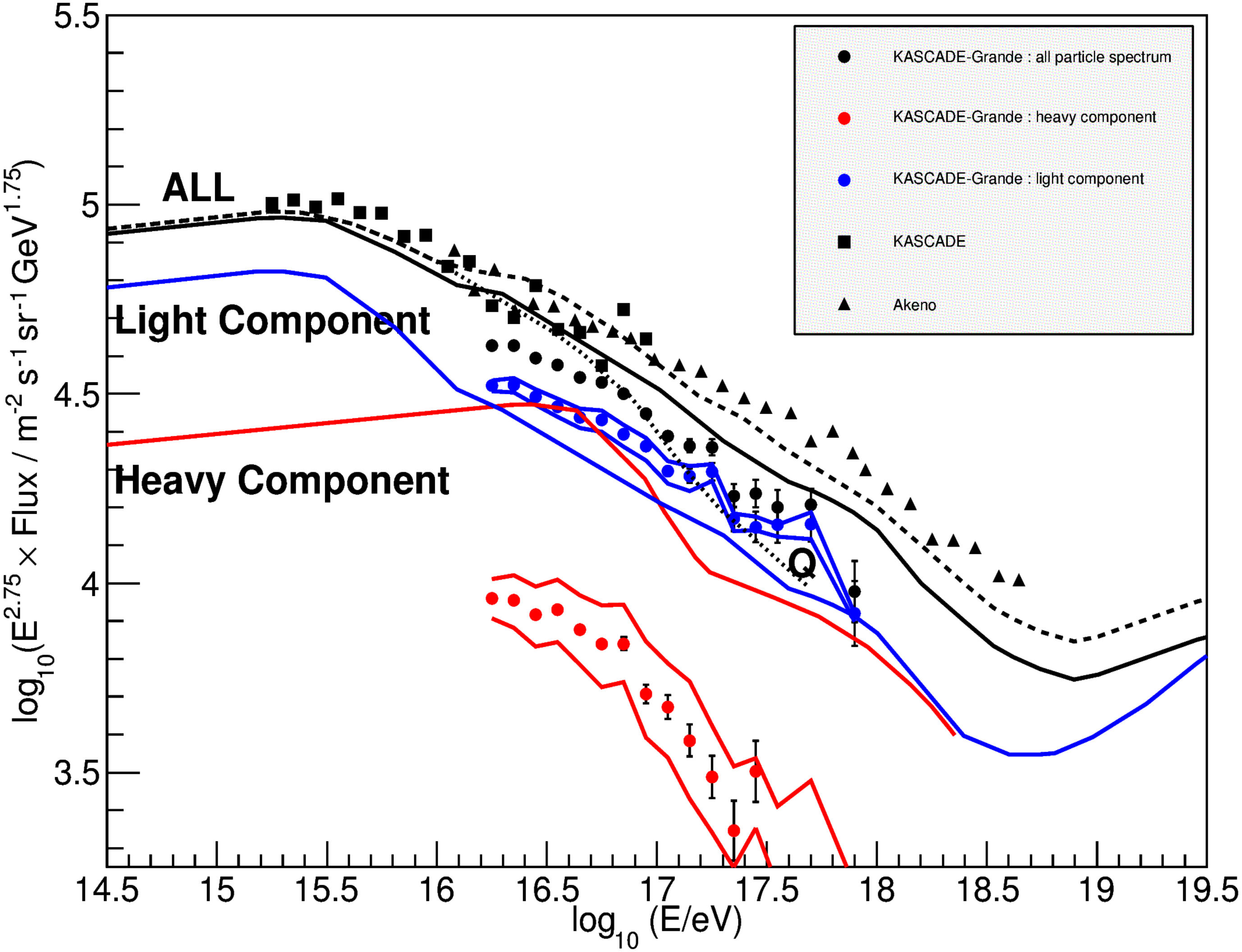
SIBYLL



- The abundance of SIBYLL is in perfect agreement with the model for all the components
- The light component is compatible
- The knee of the heavy component is shifted

EPOS

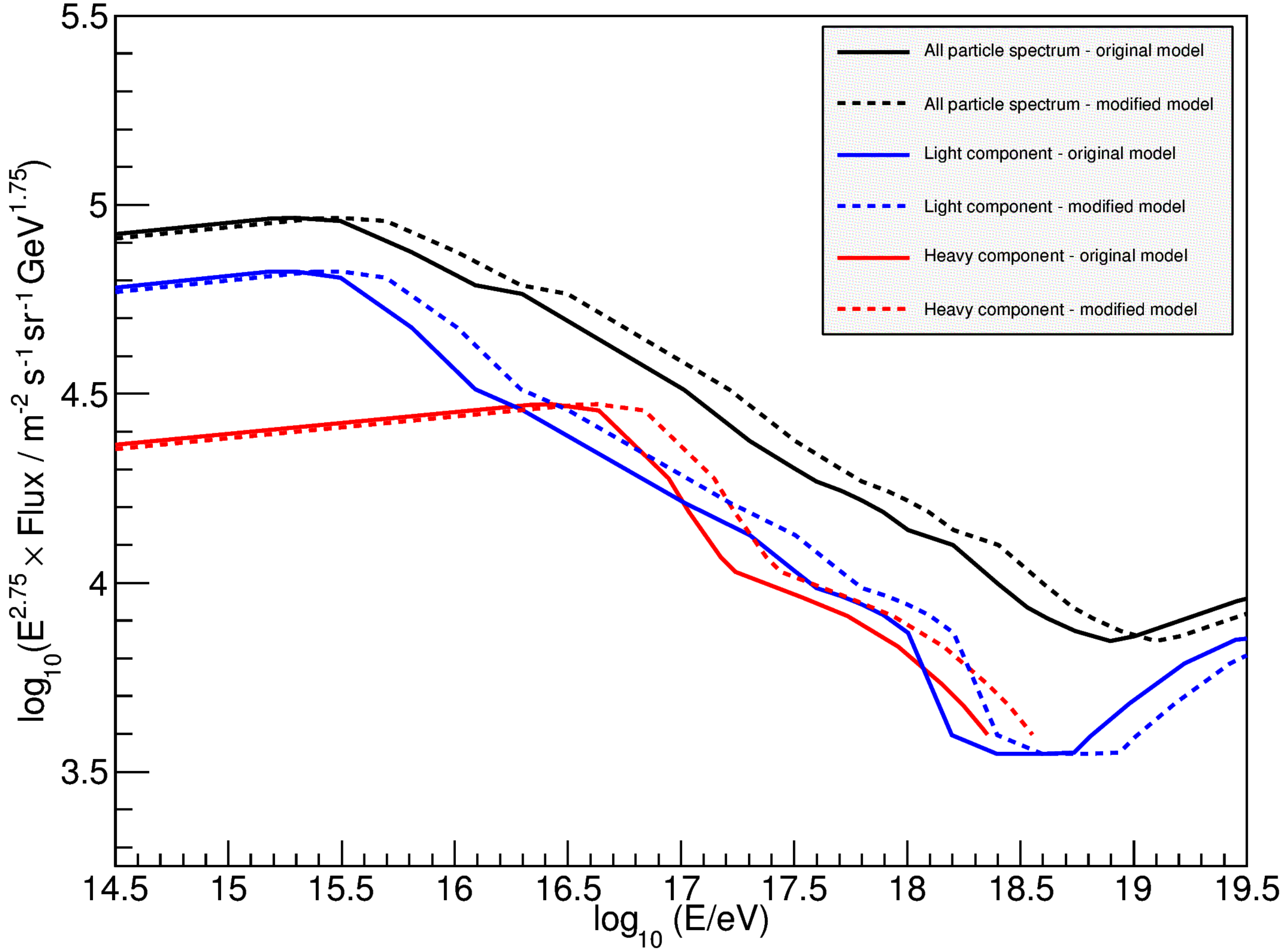
Hillas model compared to KASCADE-Grande data



- In this case, the predicted abundance is in agreement with none of the three components
- The shape is compatible

Modification

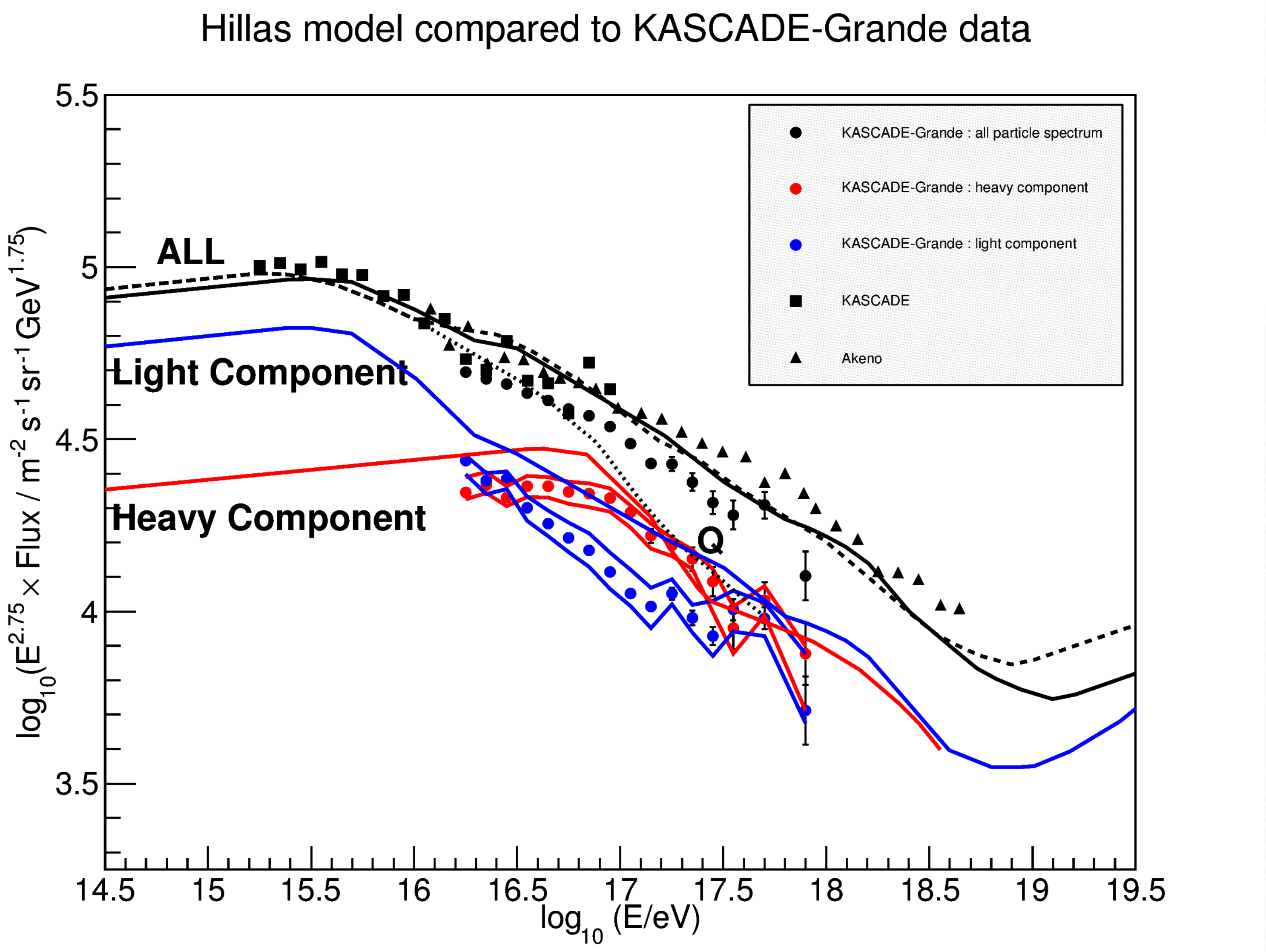
Hillas : shift of the light, heavy and total spectrum



- Since the knee of the heavy component was sistematically shifted compared to data, an attempt has been done
- The whole model – the three components – has been shifted by a factor

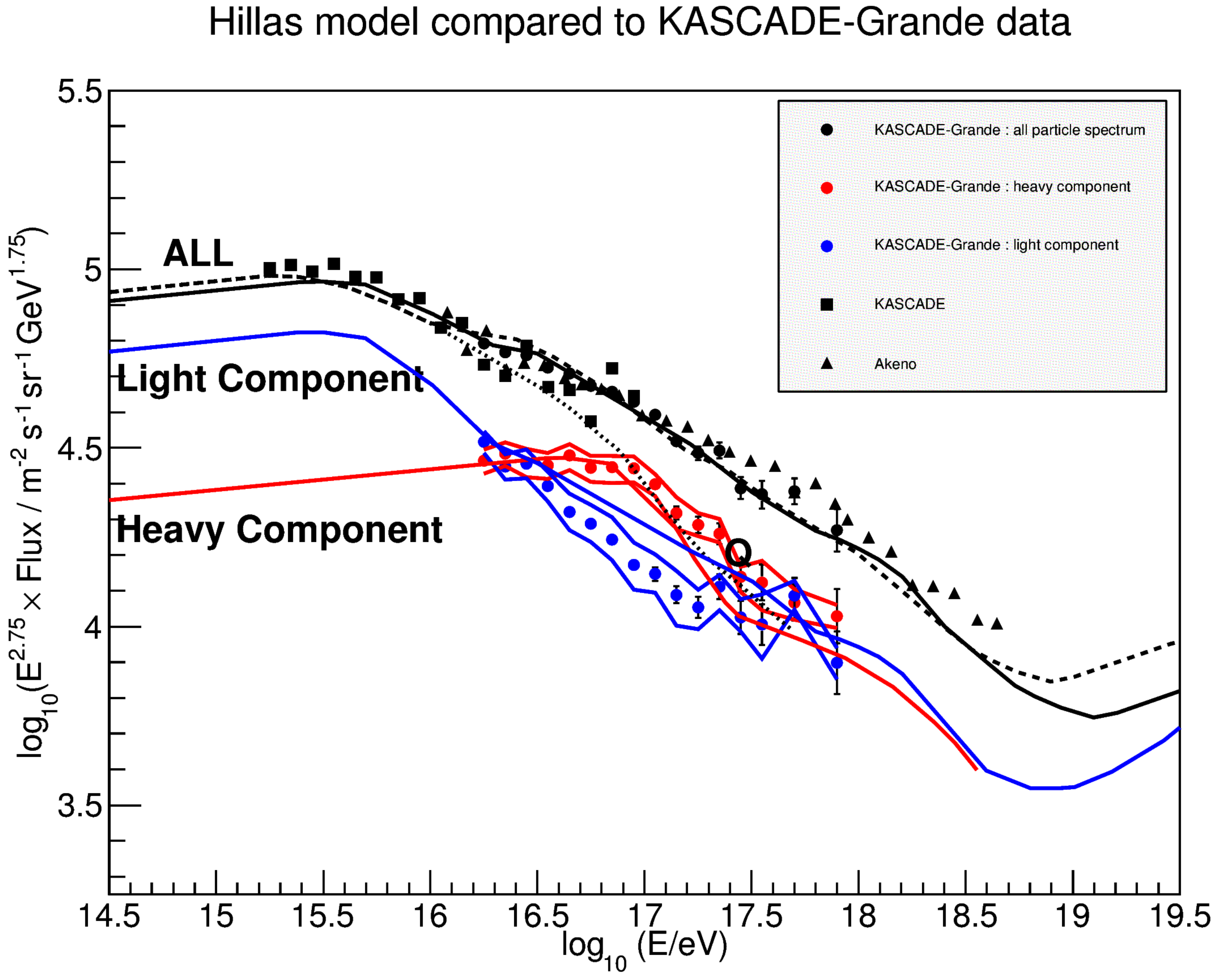
$\text{Log}_{10}E = 0.2 \rightarrow 1.6$ in energy

QGSJet - Shift



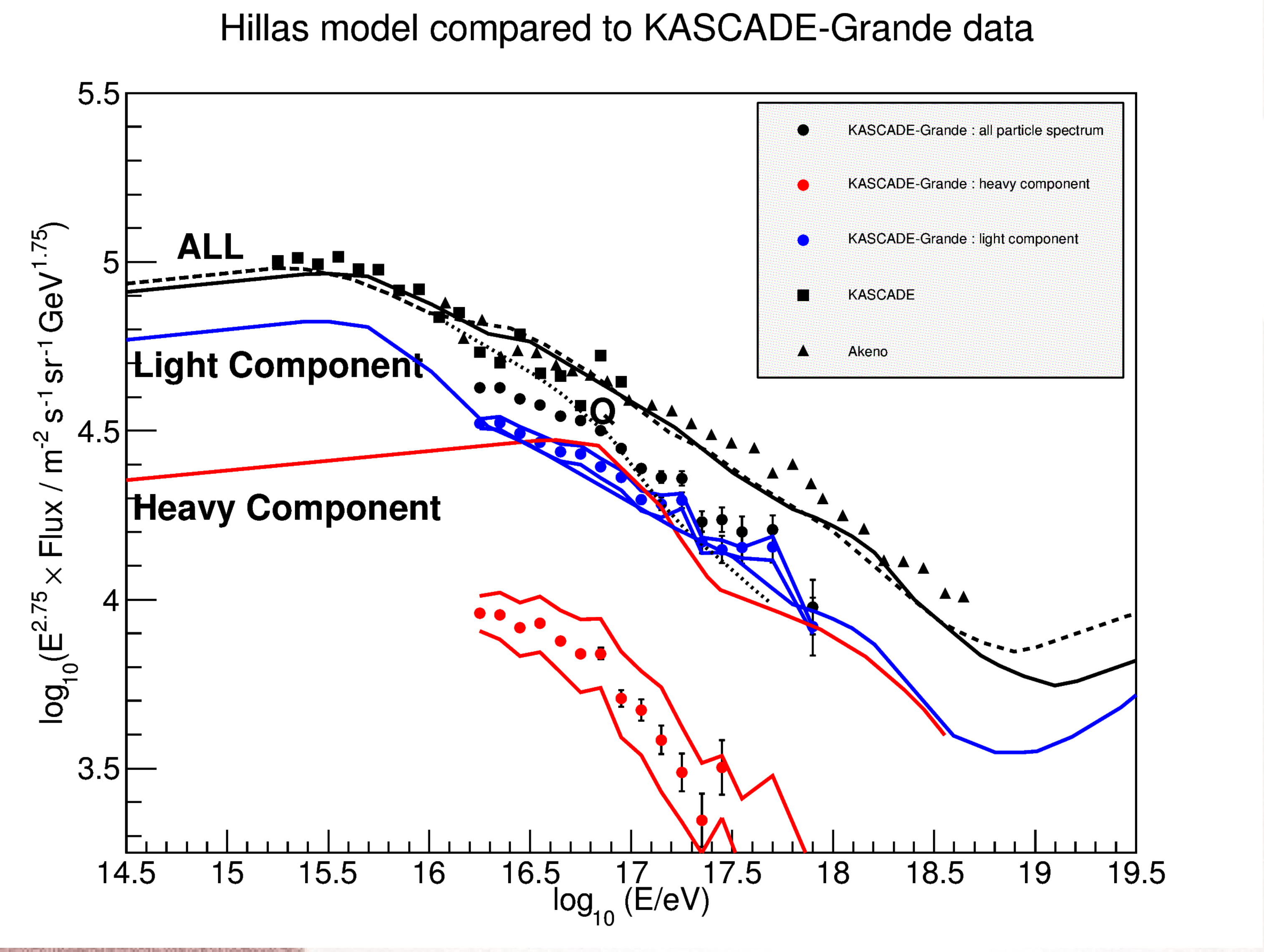
- The shape of the all particle spectrum is still compatible with the data
- The position of the knee of the heavy component matches now the one of QGSJet
- The abundance predicted by the model is still uncompatible

SIBYLL - Shift



- The shift improved the compatibility of the heavy component
- The light component is now slighty different because of the abundance

EPOS - Shift



- The light component is in perfect agreement
- Considering the shape, the heavy component seems to be compatible, while considering the abundace the discrepancy is big

χ^2 Test

	Light Component χ^2	Light Component $\chi^2_{red}(\sigma)$	Heavy Component χ^2	Heavy Component $\chi^2_{red}(\sigma)$
QGSJET	8,981	0,561	12,243	0,765
QGSJET shift	16,278	1,017	11,004	0,687
SYBILL	4,029	0,251	13,866	0,866
SYBILL shift	7,521	0,470	7,629	0,476
EPOS	16,371	1,023	50,302	3,143
EPOS shift	8,749	0,546	60,175	3,760

- In order to understand quantitatively the compatibility between the model and the data, a modified χ^2 has been calculated

$$\chi^2 = \sqrt{\sum \left(\frac{(y_i - f(x_i))}{\sigma_i} \right)^2}$$

$$\chi^2_{red} = \frac{\chi^2}{N} = \frac{1}{N} \sqrt{\sum \left(\frac{(\dot{y}_i - f(x_i))}{\sigma_i} \right)^2}$$

$N = degrees\ of\ freedom$

$y_i = KASCADE-Grande data$

$f(x_i) = Hillas\ model$

$$\sigma_i = \frac{(syst_{up} - sys_{down})}{2}$$

4.Conclusions

- Berezinsky model doesn't predict correctly the shape of the light component
- Hillas model can predict correctly the shape of both components, although the knee of the heavy component is a little bit shifted
- If the model (heavy, light and total component) is shifted by a factor of 1.6 in energy, it reproduces reasonably well KASCADE-Grande data interpreted by SIBYLL
- The abundance of heavy and light component is strongly dependent on the interaction model

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