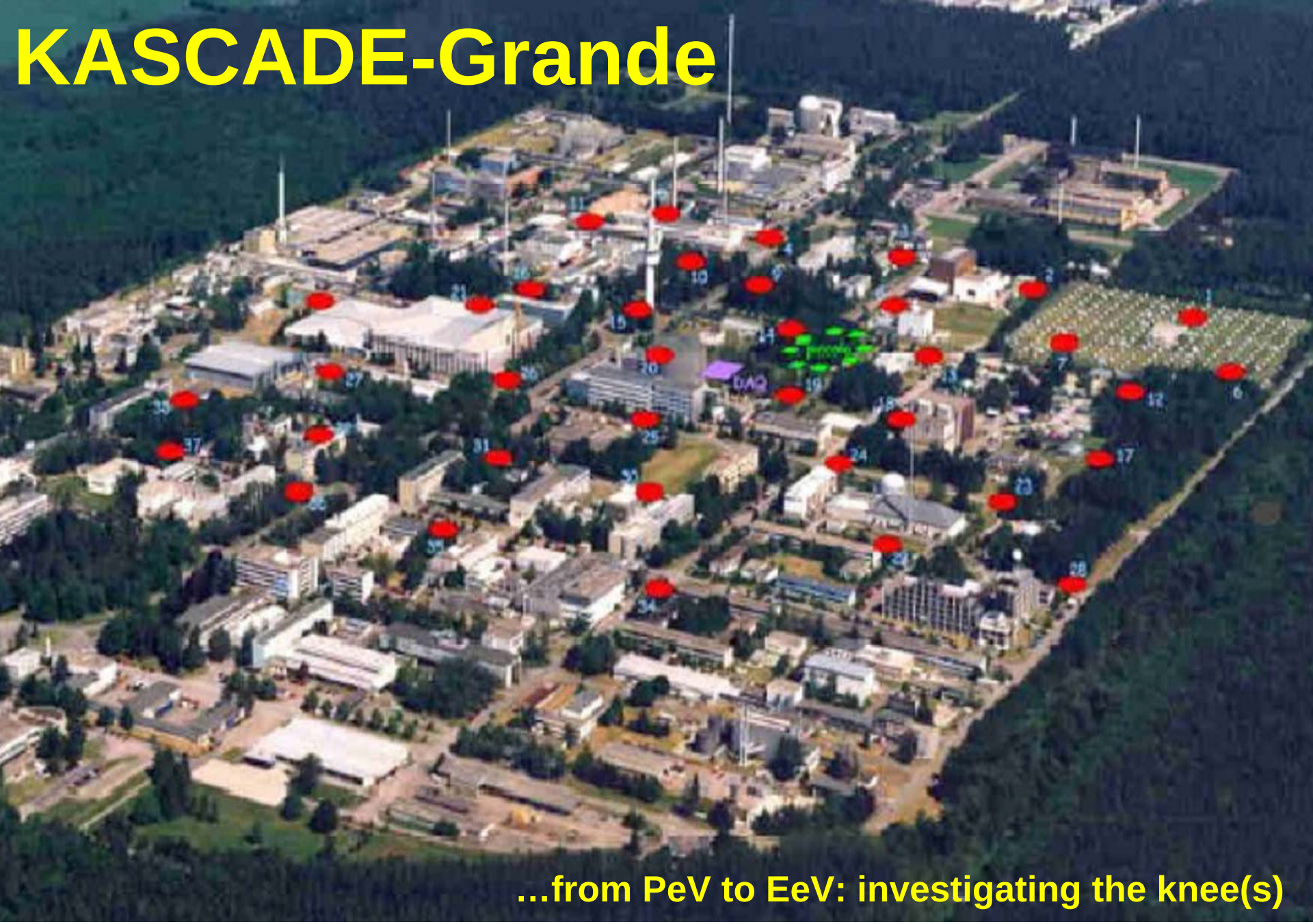
KASCADE-Grande

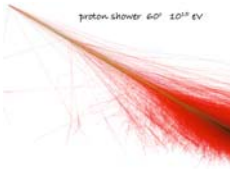


…from PeV to EeV: investigating the knee(s)

25 years KASCADE - Grande

- **49 collaborative papers in reviewed journals** (8 still in queue, short author list papers not included)
- **55 PhD thesis**
- **86 diploma/master thesis**

1992 Proposal
CORSIKA



1996 KASCADE

2000 model tests
light knee
KASCADE-Grande

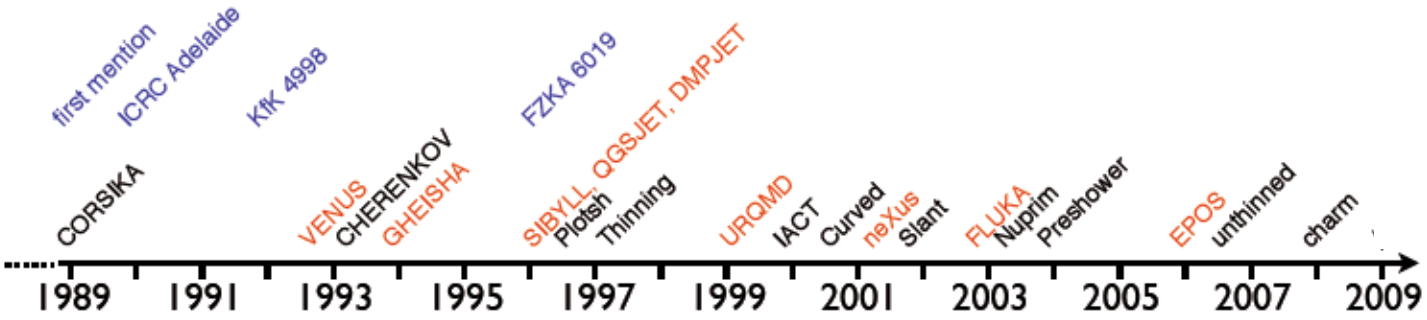
2004 γ limit
(an)isotropy
proof-of-principle radio detection
LOPES

2008 muon production height
iron knee
Karlsruhe Air Shower Test Facility
Cosmic Revelation

2012 EAS GHz emission
CROME

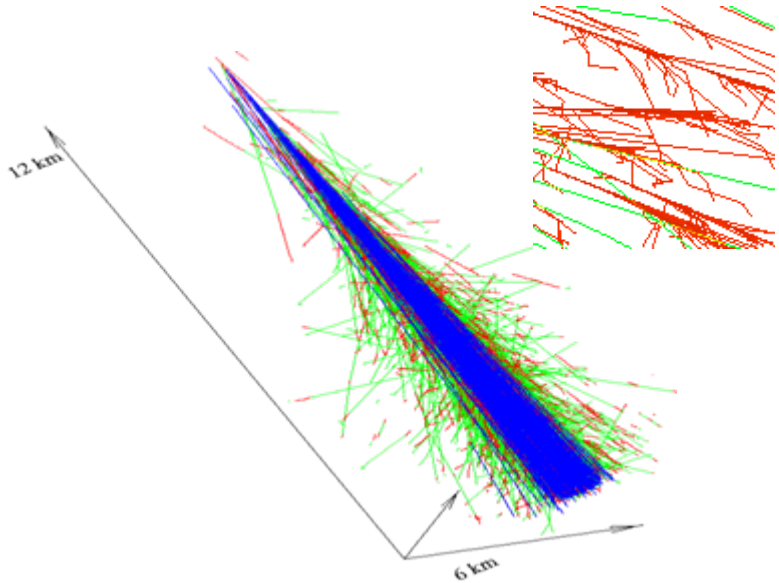
2016 light ankle
Xmax by radio
KCDC

CORSIKA (COsmic Ray SImulations for KAscade)



Today:
>900 users in
>50 countries and
>50 experiments

> 1 day per
> 10^{15} eV shower



©Johannes Knapp

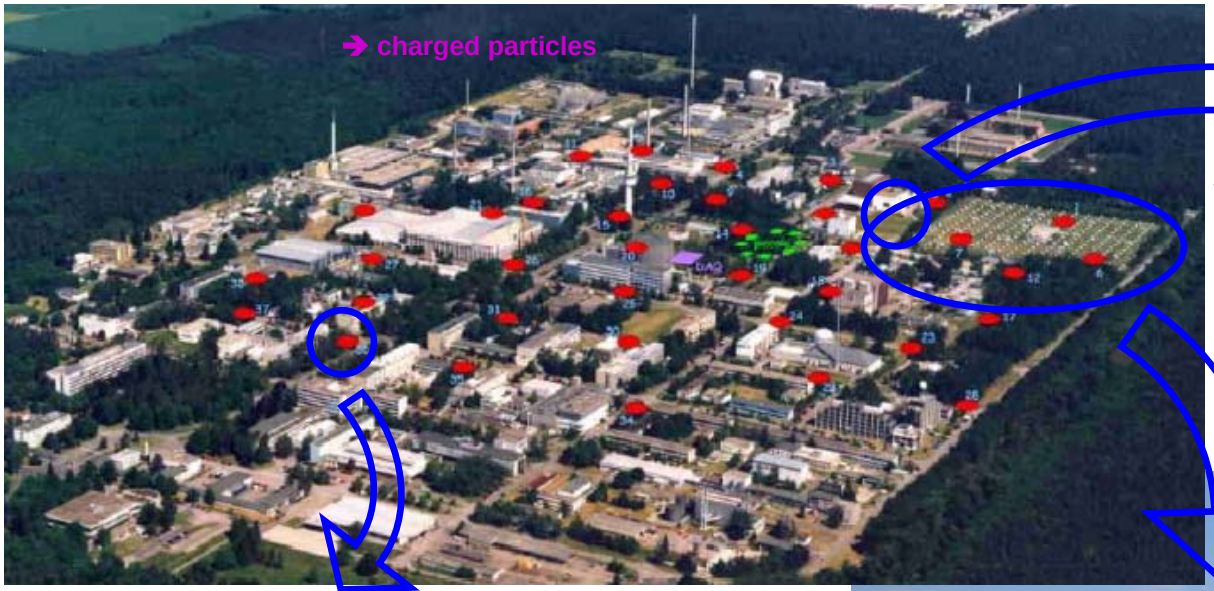
< 20 min per
10^{15} eV shower

~1000 citations

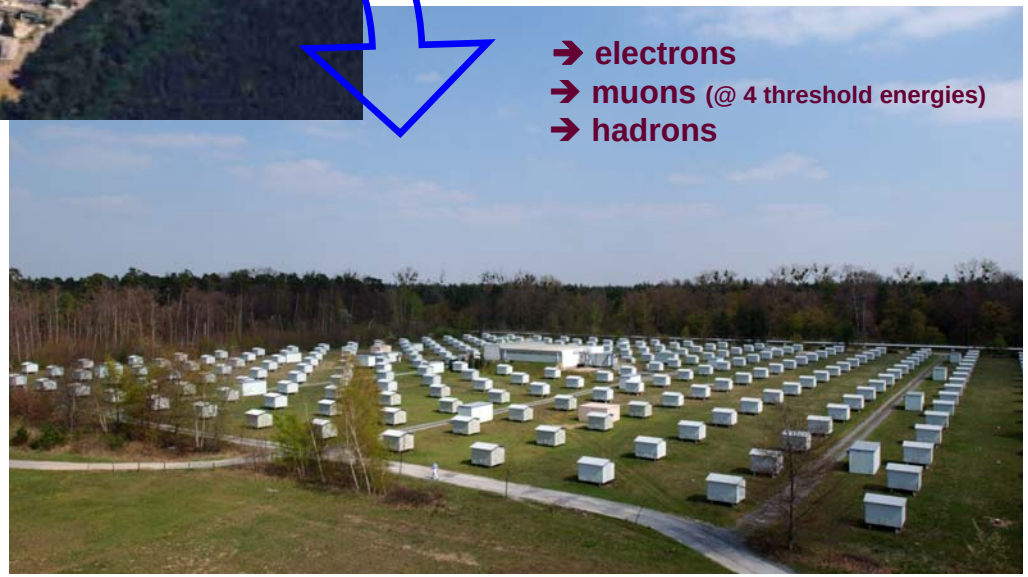
KASCADE-Grande

= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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



➔ electrons
➔ muons (@ 4 threshold energies)
➔ hadrons



KASCADE

KArlsruhe Shower Core and Array DEtector

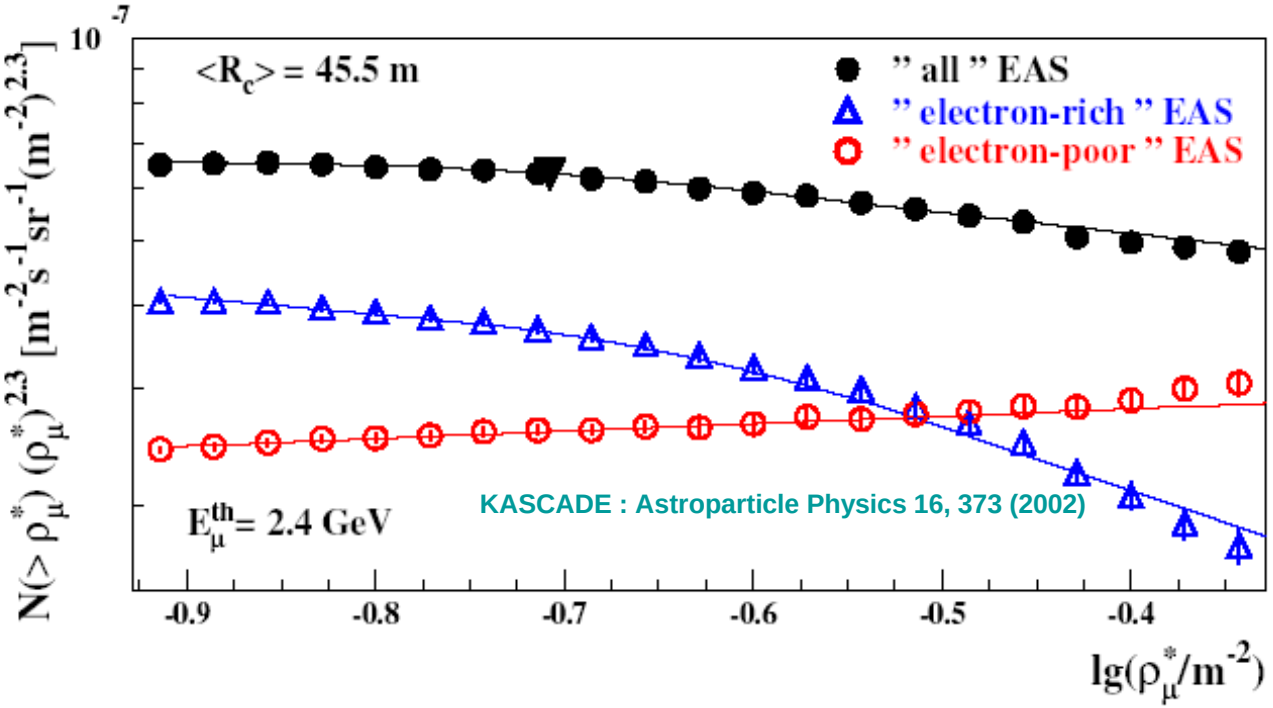
- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables: electrons, muons@4 thresholds, hadrons

T.Antoni et al. NIM A513 (2003) 490

Model independent multi-parameter analysis

Use of three observables:

- **high-energy local muon density ➔ energy estimator**
- **Total muon number and electron number ➔ mass estimator**

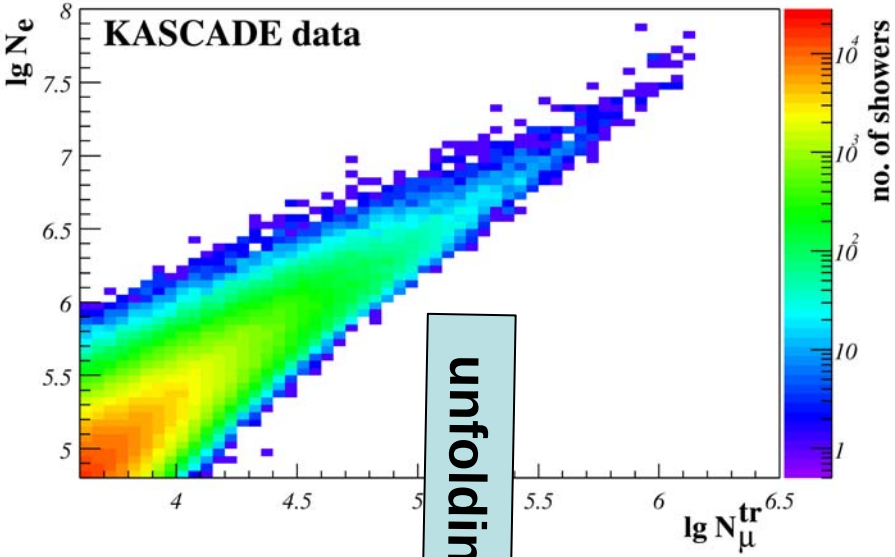


- **KNEE CAUSED BY DECREASING FLUX OF LIGHT ELEMENTS**
- **Do we need hadronic interaction models?**

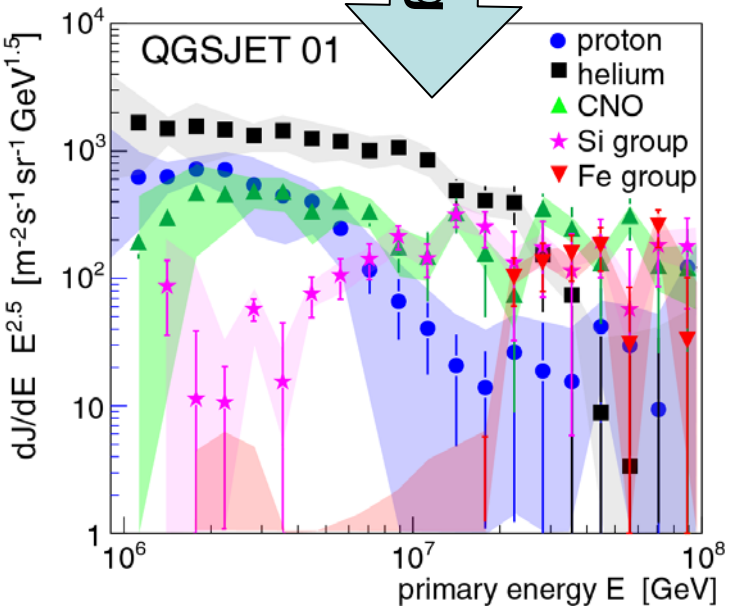
  ➔ yes, for normalization of absolute energy and mass scale!!

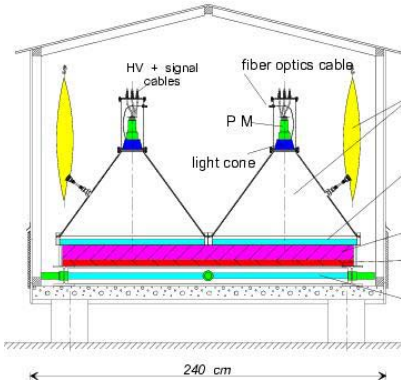
T.Antoni et al. Astroparticle Physics 16 (2002) 373

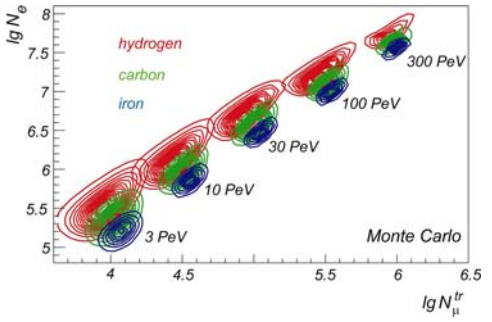
KASCADE : energy spectra of single mass groups



unfolding







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

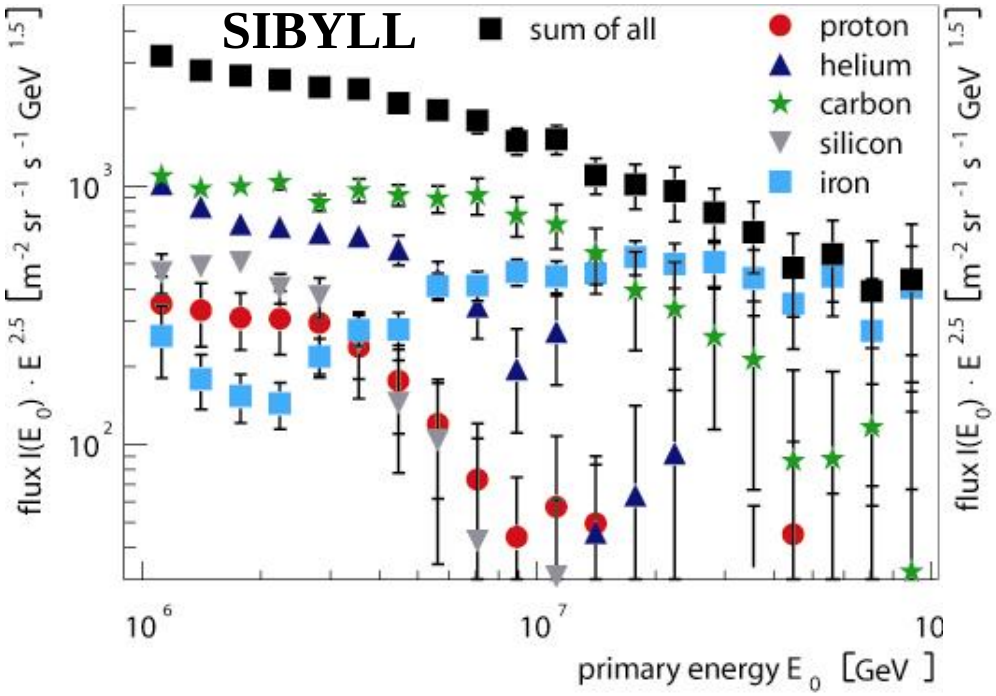
$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

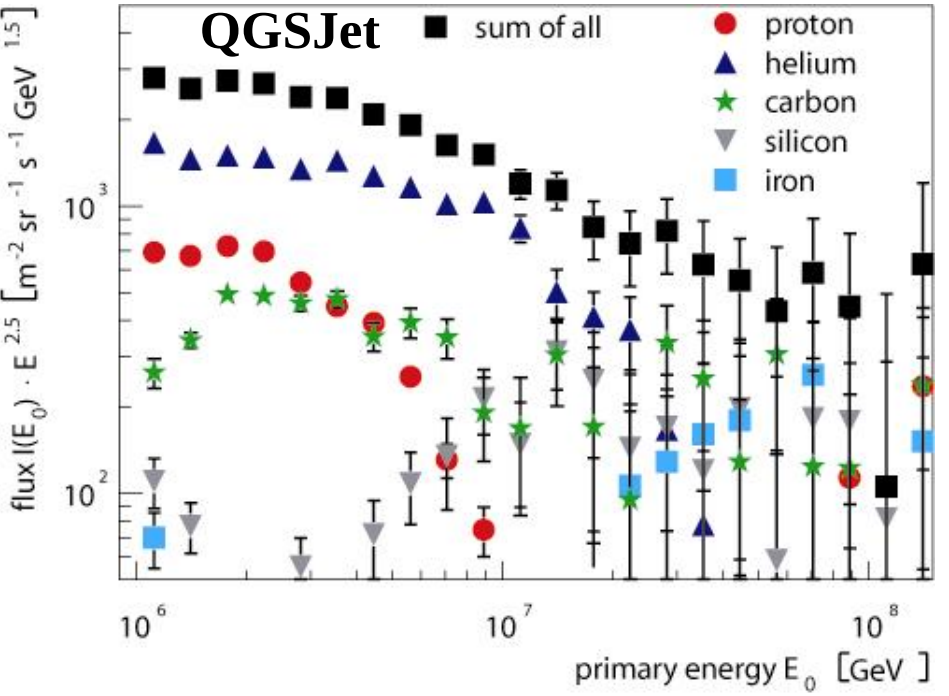
- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25

KASCADE results

- same unfolding but based on different hadronic interaction models embedded in CORSIKA





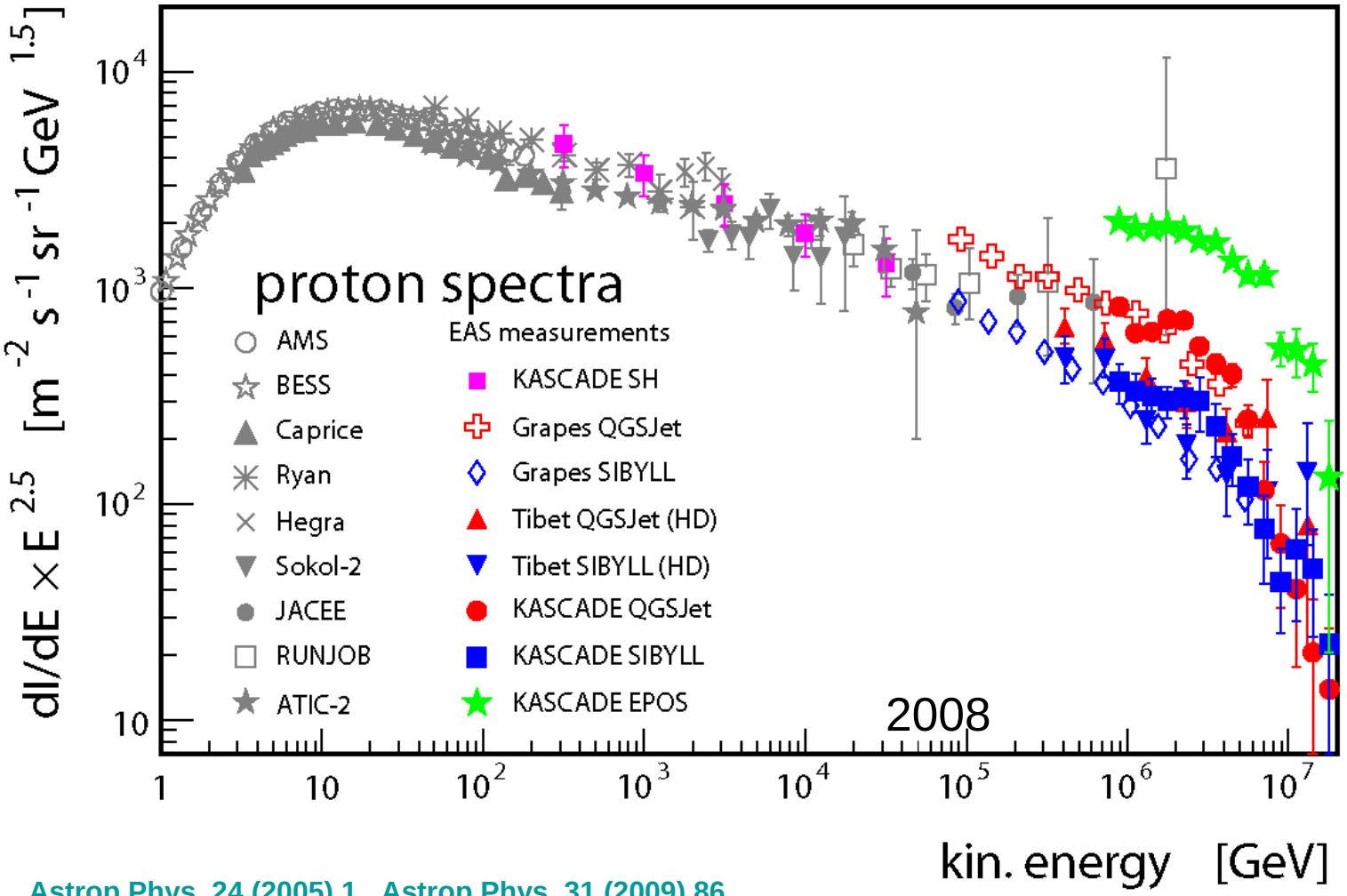
- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different for different high-energy hadronic interaction models

KASCADE collaboration,
Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

observation of a „light“ knee at 2-4·10^{15} eV

The proton spectrum

- a bit outdated….needs update (new experiments, new hadronic models)

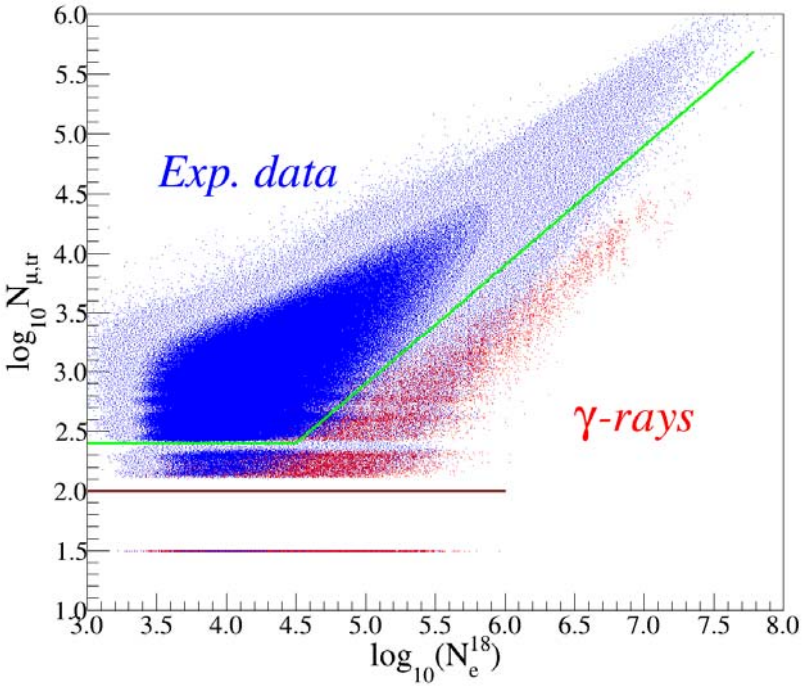


Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

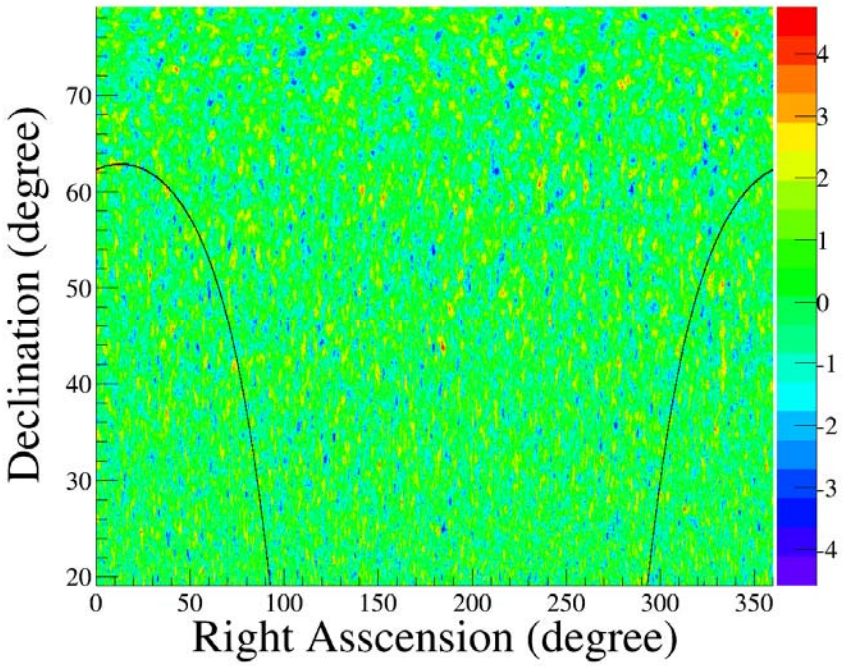
Gamma ray search at KASCADE

KASCADE collaboration,
Zhaoyang Feng, Donghwa Kang,
in preparation

- Data set from 1998.05.11 to 2010.05.14 ; $3 \cdot 10^8$ events



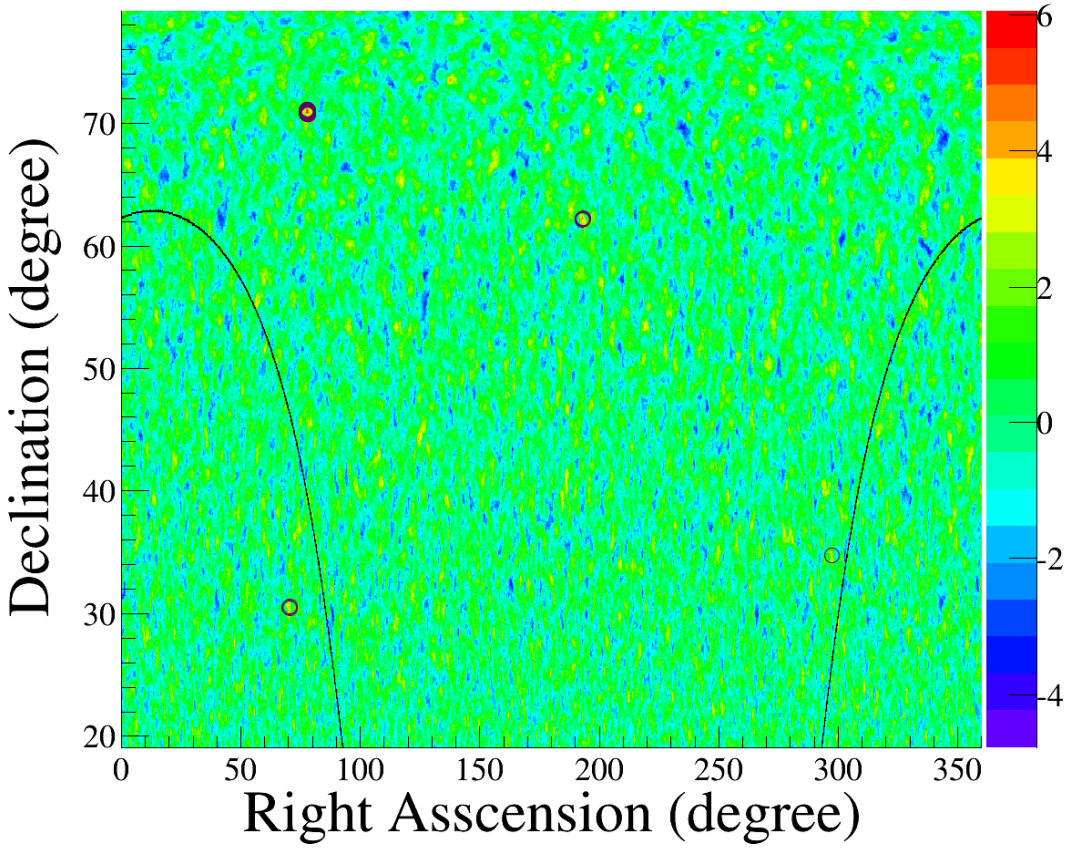
all events

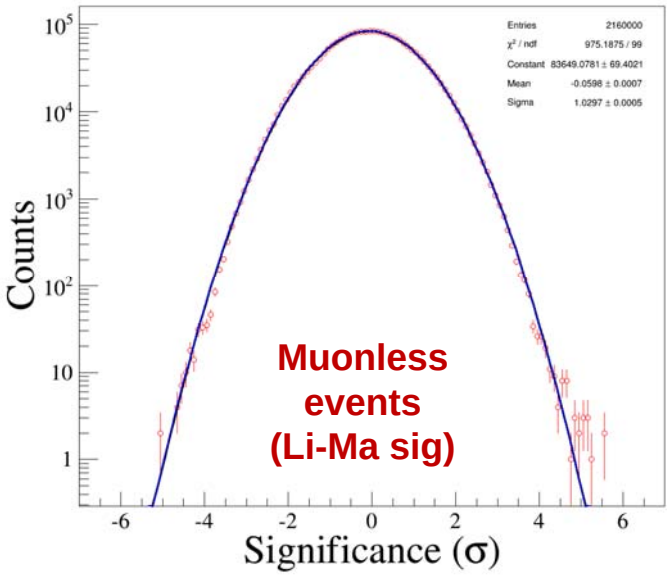


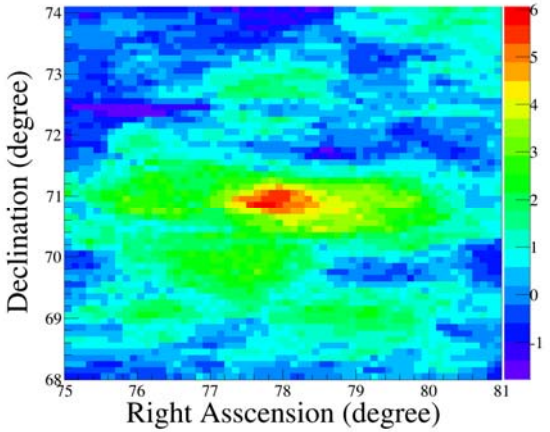
- selection of muon poor events (88170 events)
- Gamma energy: >168 TeV
- Background estimation (equi-distant zenith angles) Anemonori et al.
- Significance estimation (Li-Ma and Poisson signifcances)
- Diffuse flux limit calculated for different energies (Helene 1983)
- Upper point source limits calculated

Muonless events

muon rare events

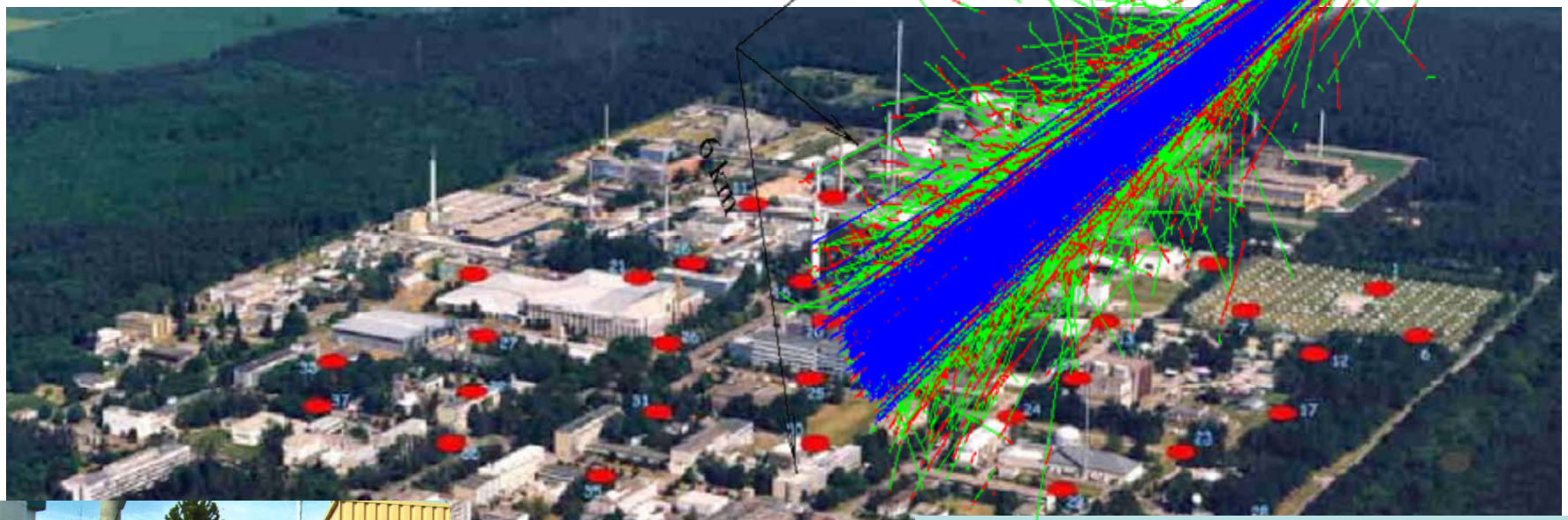






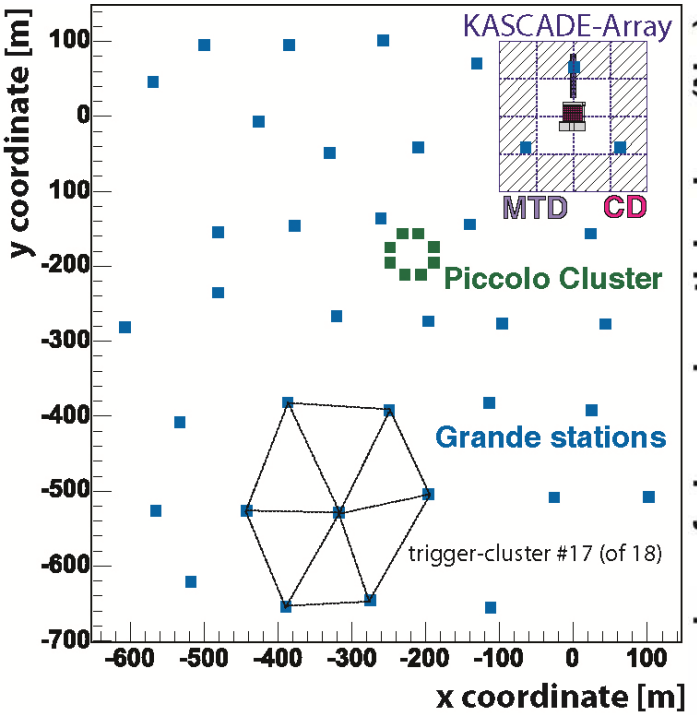
(ra,dec)=(77.75,70.85) Non=25, Noff=5.53
Li-Ma Sig=5.56
Poisson Prob=7.152e-10 Poisson Sig=6.052
27 cells

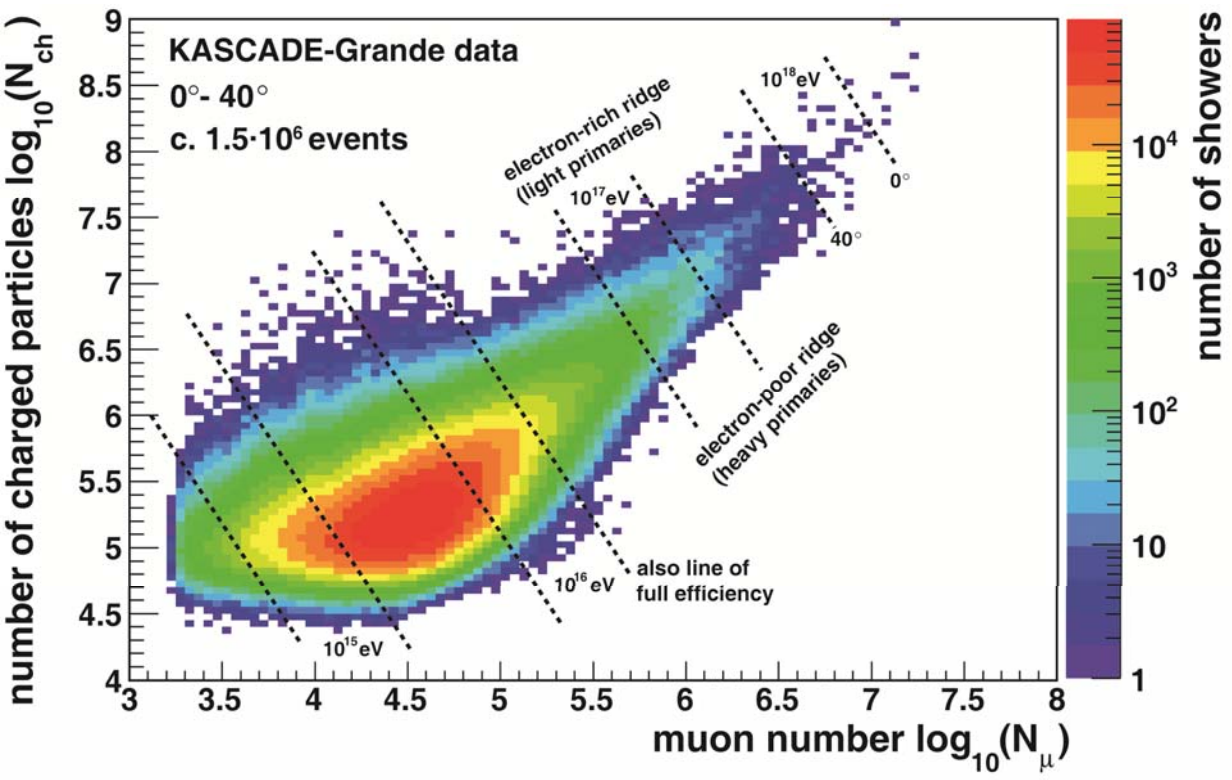
KASCADE-Grande : multi-parameter measurements



KASCADE + Grande
➔energy range:
100 TeV – 1 EeV
➔large area: 0.5 km²
➔Grande: 37x10 m² scintillators
➔Piccolo: trigger array

KASCADE-Grande: the measurement





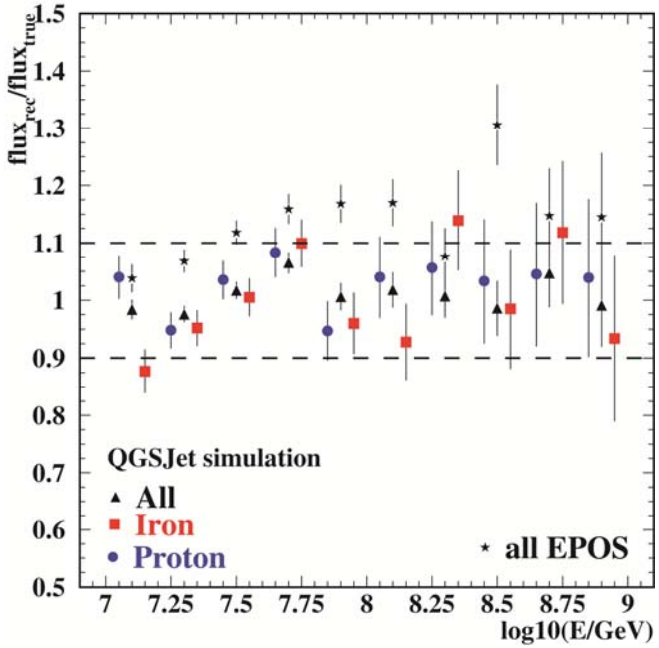
➔ **determination of primary energy**

➔ **separation in “electron-rich” and “electron-poor” event**

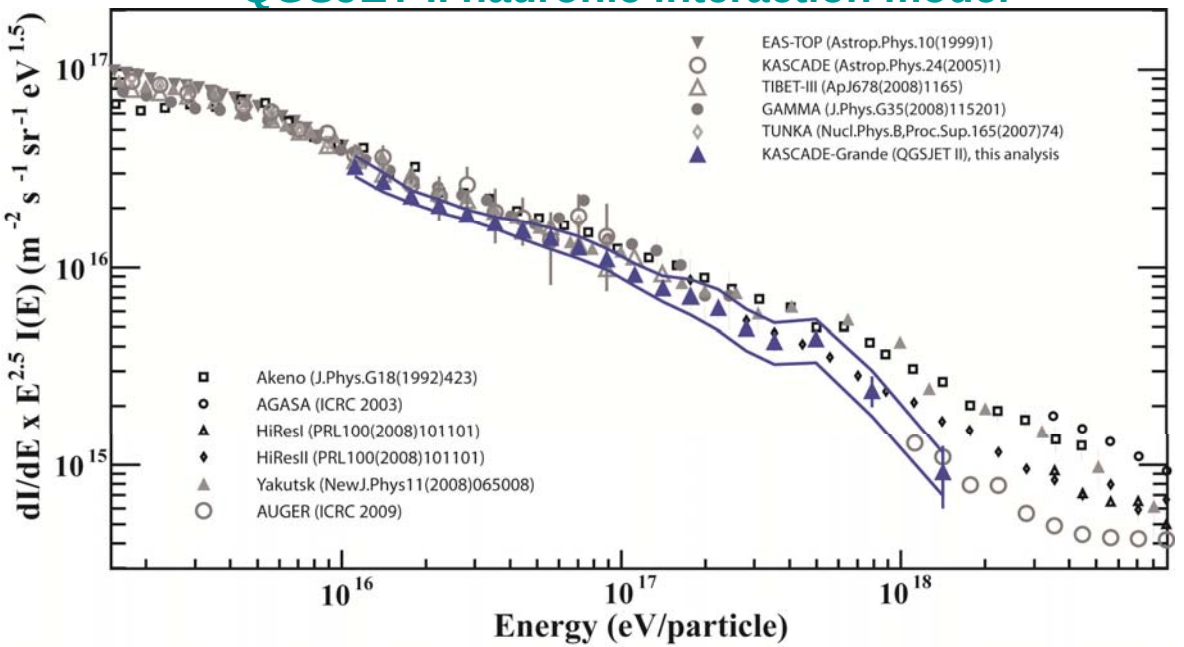
All-particle energy spectrum :

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

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$



QGSJET II hadronic interaction model

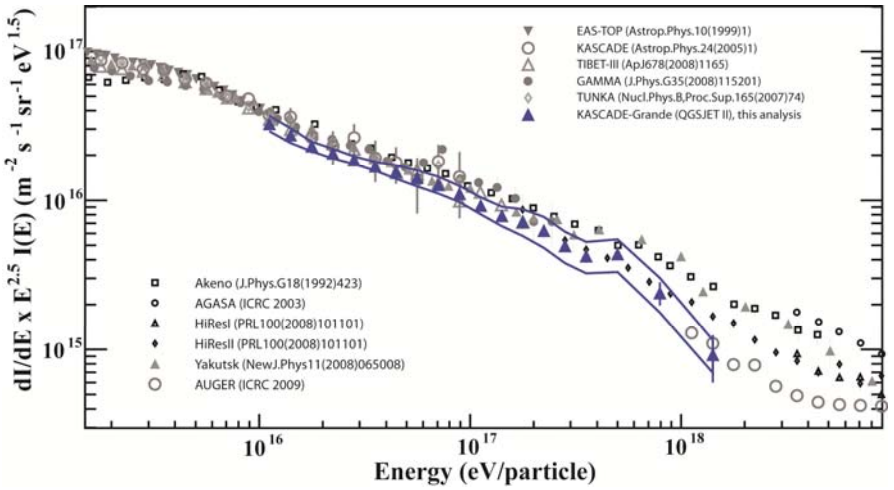


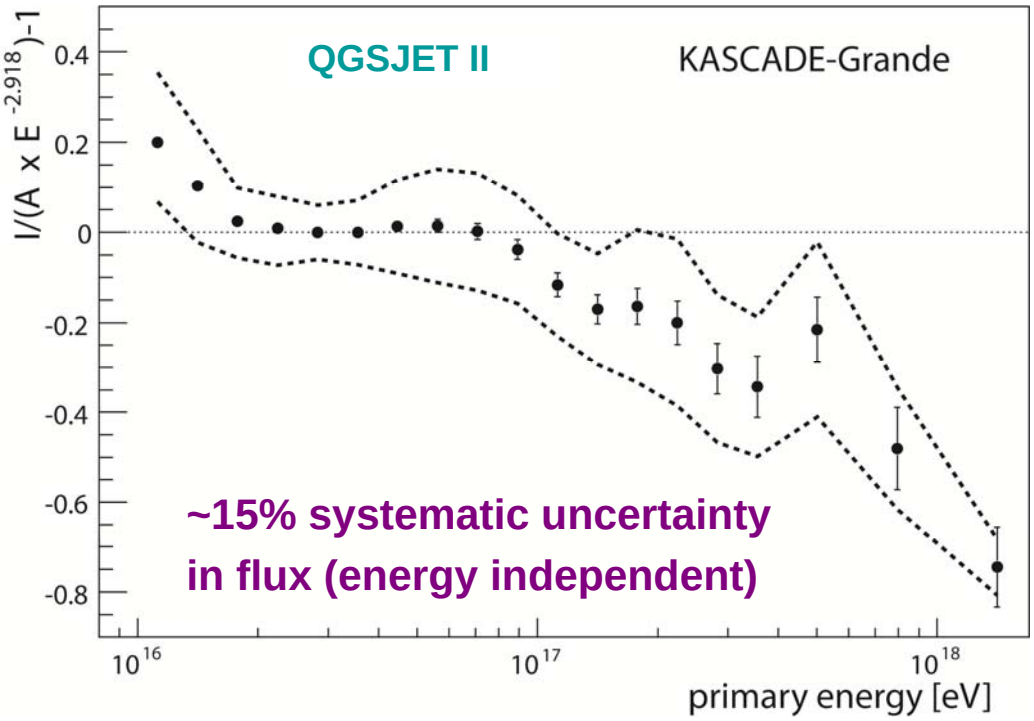
-different zenith angle bins
-no composition dependence

Astroparticle Physics 36 (2012) 183

KASCADE-Grande
all-particle energy spectrum

Astroparticle Physics 36 (2012) 183



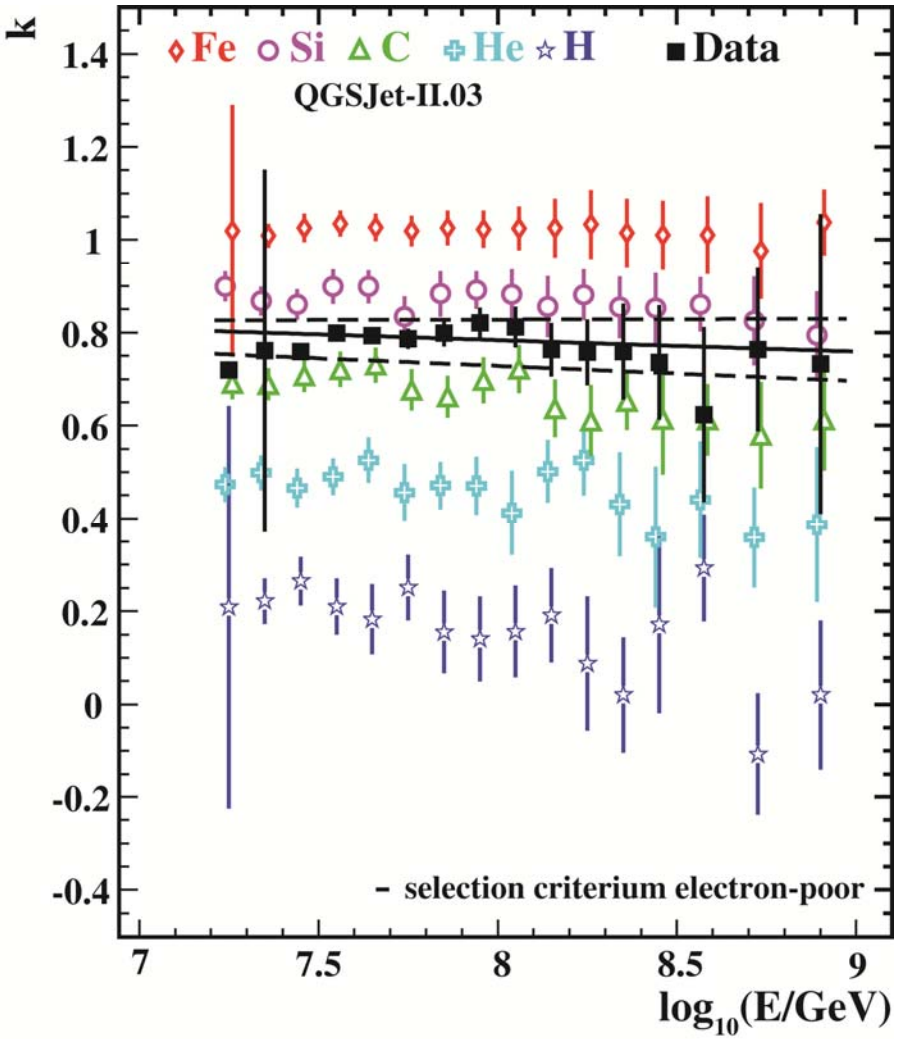


- **spectrum not a single power law**
- **hardening of the spectrum above 10^{16}eV**
- **steepening close to 10^{17}eV (2.1σ)**

Composition via shower size ratio :

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

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$



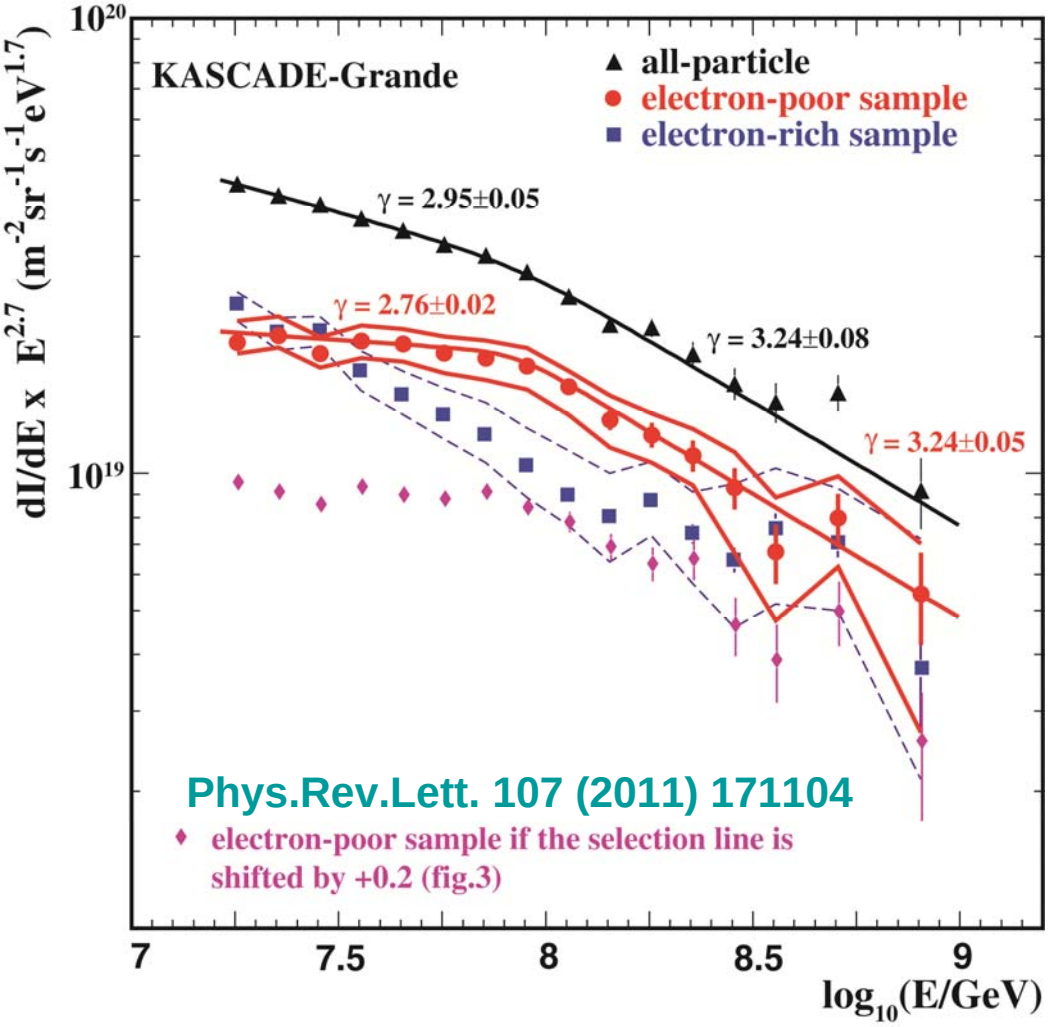
- k-parameter = normalized shower size ratio

➔ composition sensitive

➔ separation in
electron-rich (light)
electron-poor (heavy)
event samples!

KASCADE-Grande: Spectra of individual mass groups

$k = (\log_{10}(N_{ch}/N_{\mu}) - \log10(N_{ch}/N_{\mu})_p) / (\log10(N_{ch}/N_{\mu})_{Fe} - \log10(N_{ch}/N_{\mu})_p)$



observation of a „heavy“ knee at 8-9·10^{16} eV

- spectra of individual mass groups:

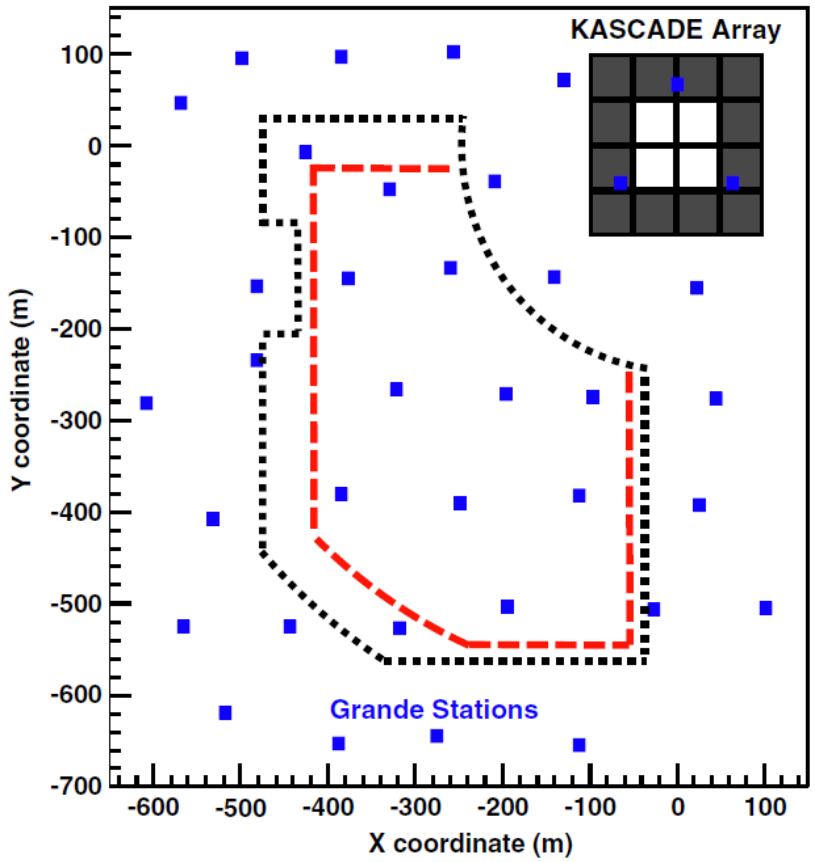
➔ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

➔ steepening due to heavy primaries (3.5σ)

➔ spectrum of more enhanced heavy sample has harder spectrum before break.

➔ light+medium primaries show steeper spectrum, but fit by power law okay
➔ possibility for hardening above 10^{17}eV

KASCADE-Grande: spectrum of light primaries

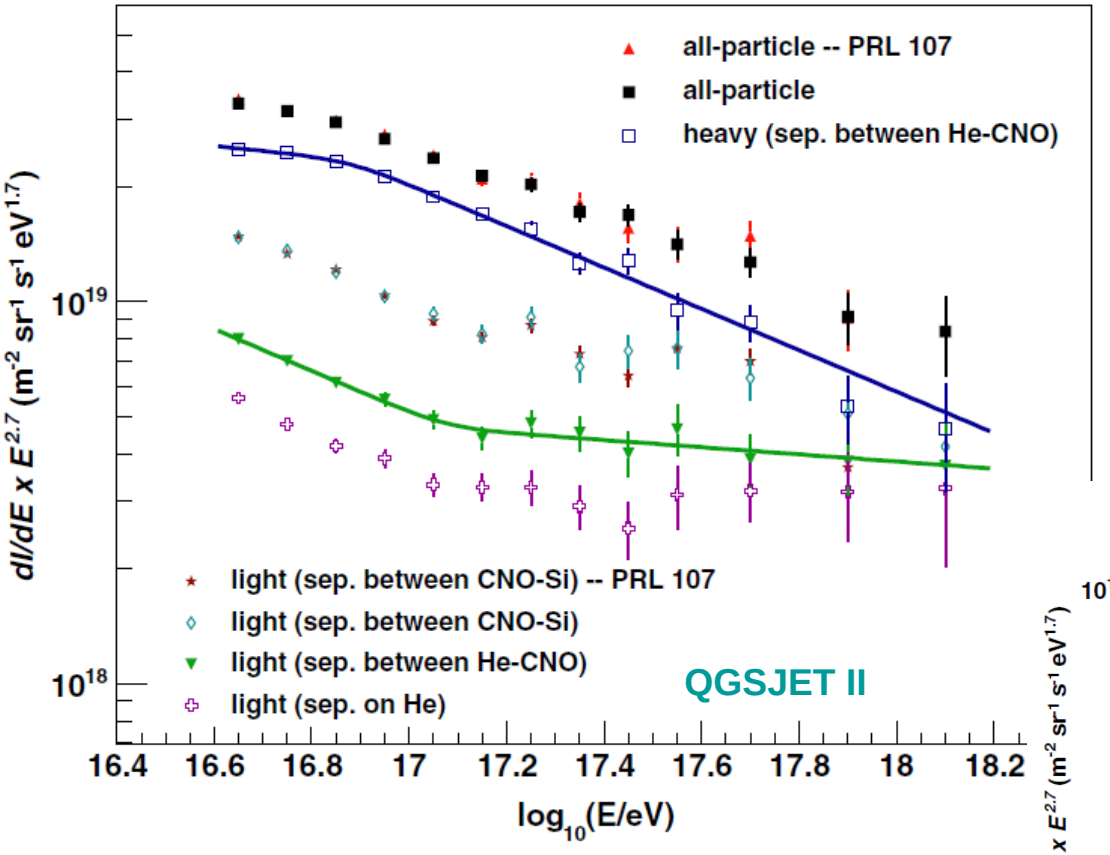


- **re-investigation of the spectrum of light primaries:**

➔ **increased area (higher threshold)**
➔ **1 year more data**
➔ **improved selection cut**

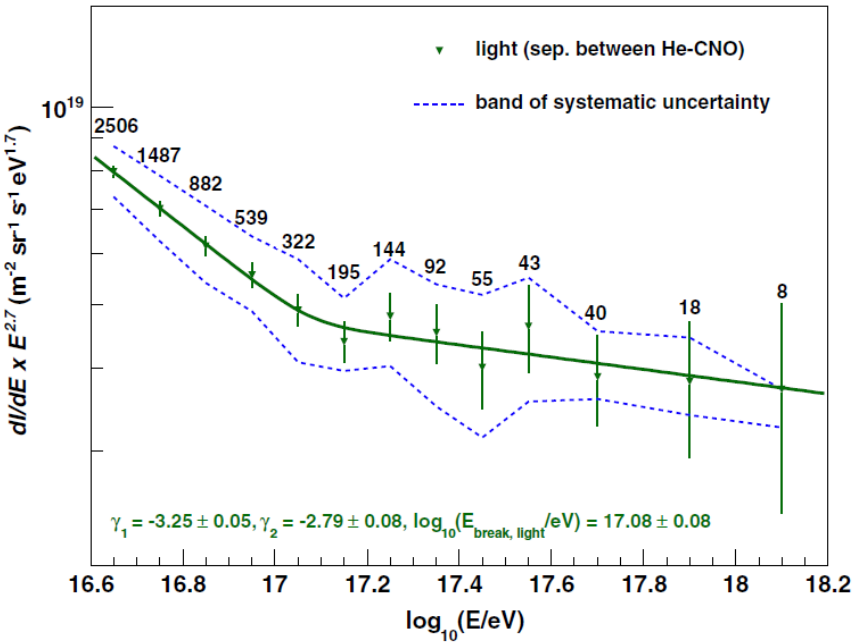
Phys.Rev.D (R) 87 (2013) 081101

KASCADE-Grande: spectrum of light primaries



➔ **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**

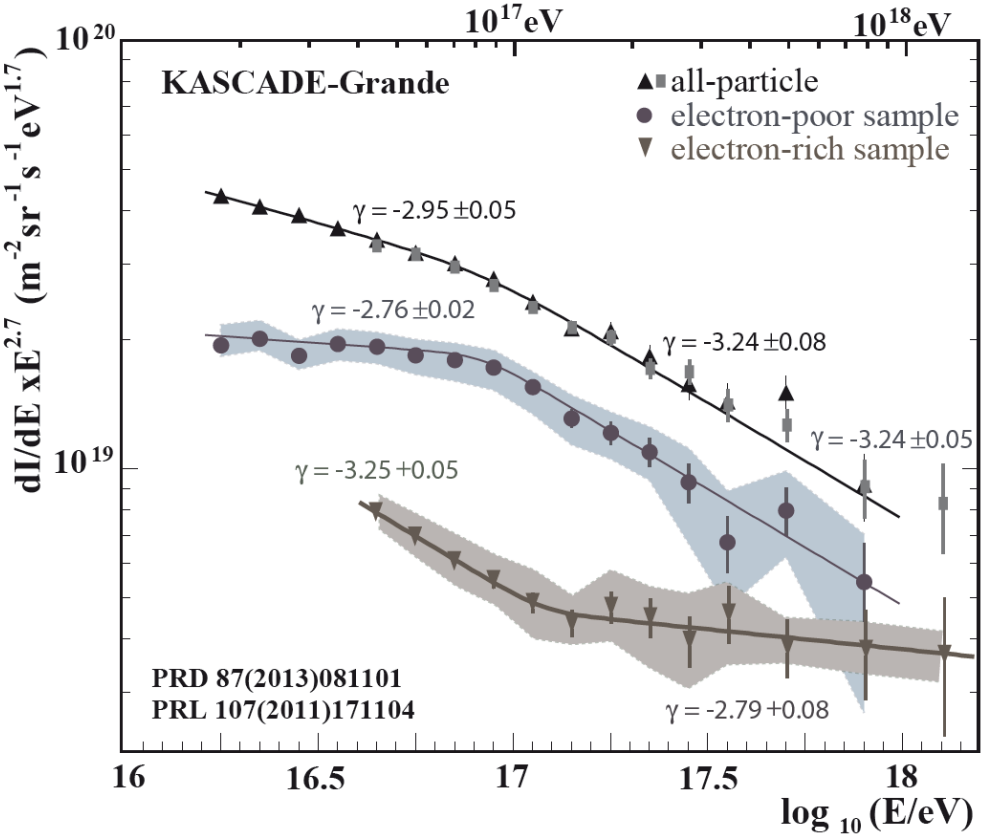
➔ **slope change from γ = -3.25 to γ = -2.79!**



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

observation of a „light“ ankle at 1-2·10^{17} eV

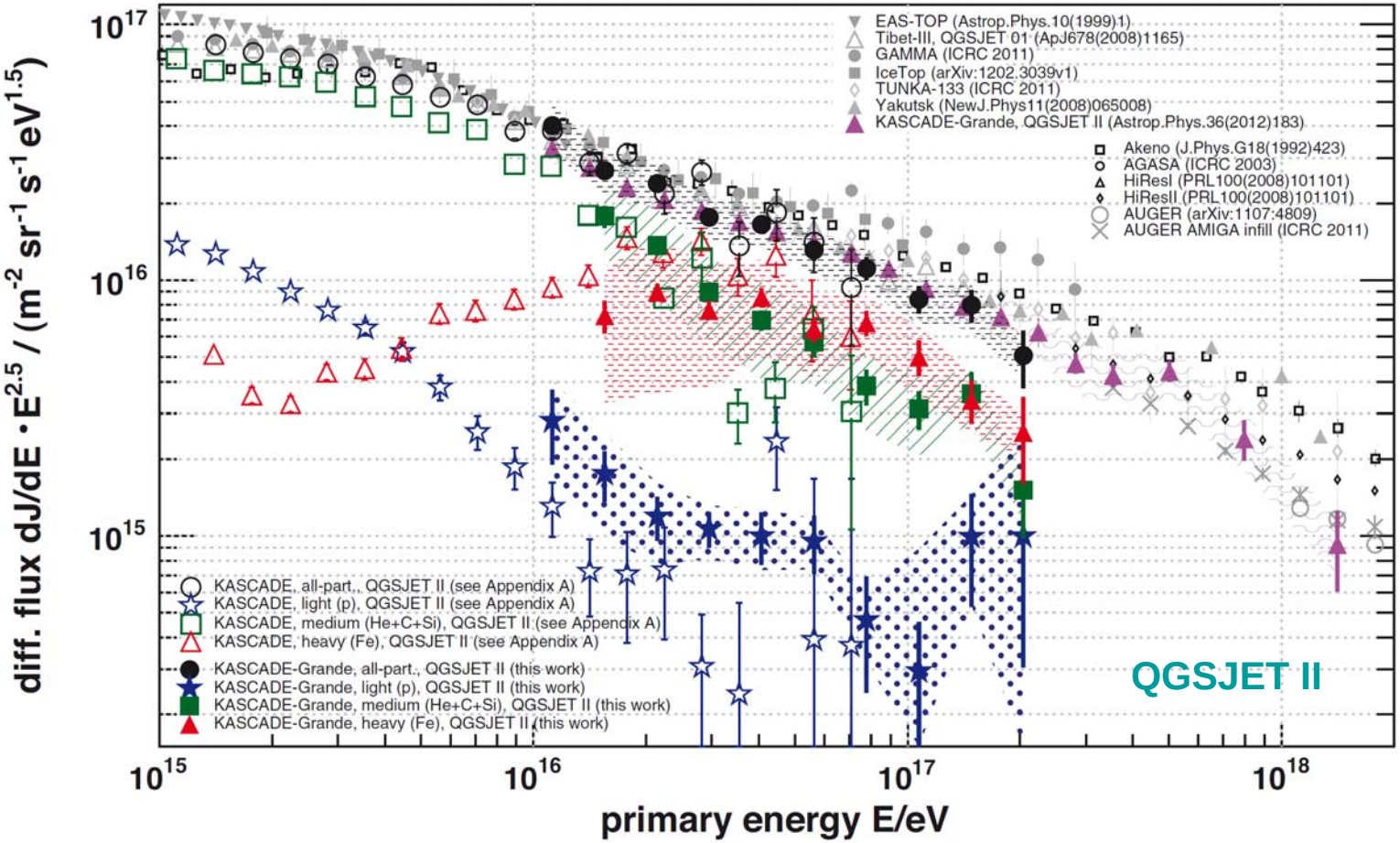
KASCADE-Grande
energy spectra of mass groups



- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**
- **slope change from γ = -3.25 to γ = -2.79!**

Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

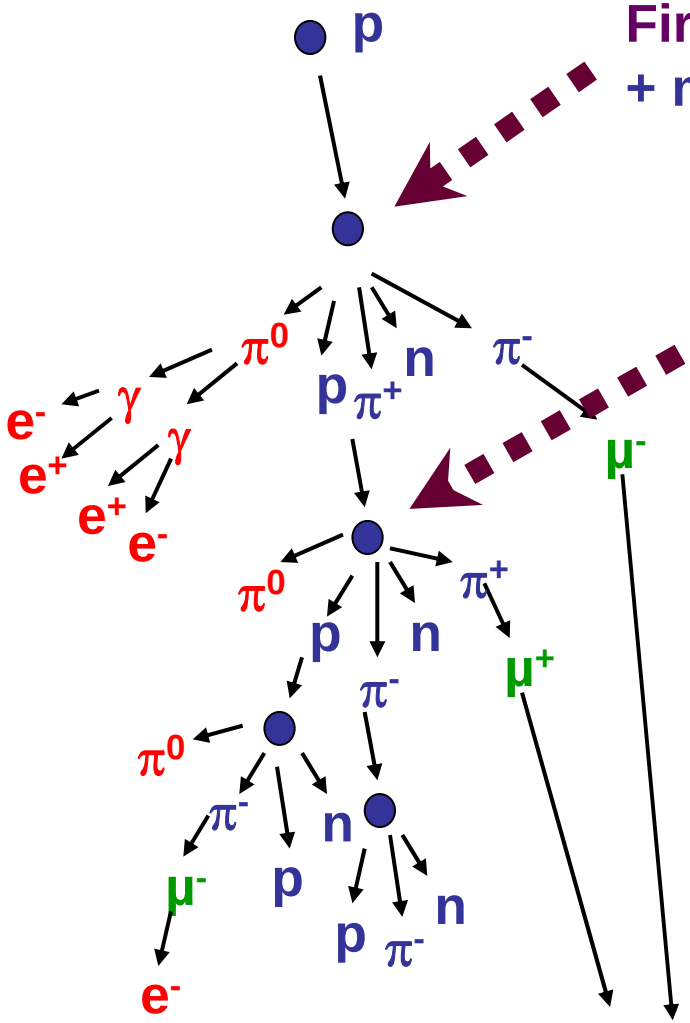
Unfolding results: KASCADE and KASCADE-Grande



spectra of individual mass groups:
proton medium (He+C+Si) iron
➔ all spectra overlap and agree well!
➔ all three show a knee-like feature!!

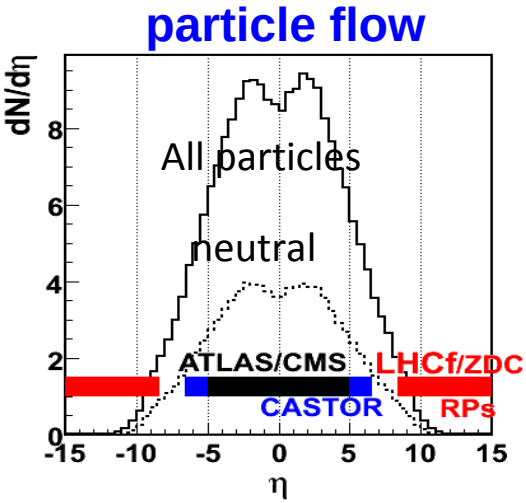
Astroparticle Physics 47 (2013) 54

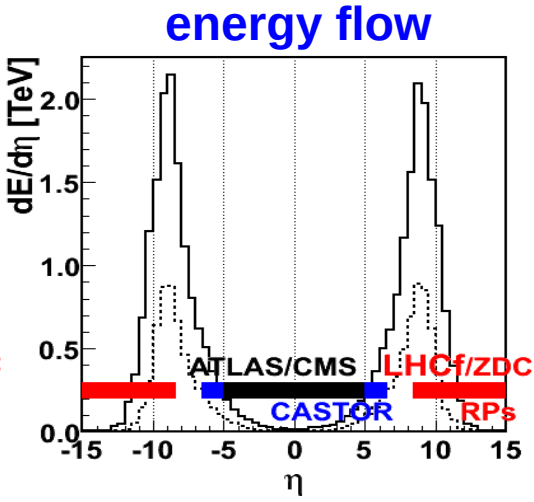
Validity of Hadronic Interaction Models



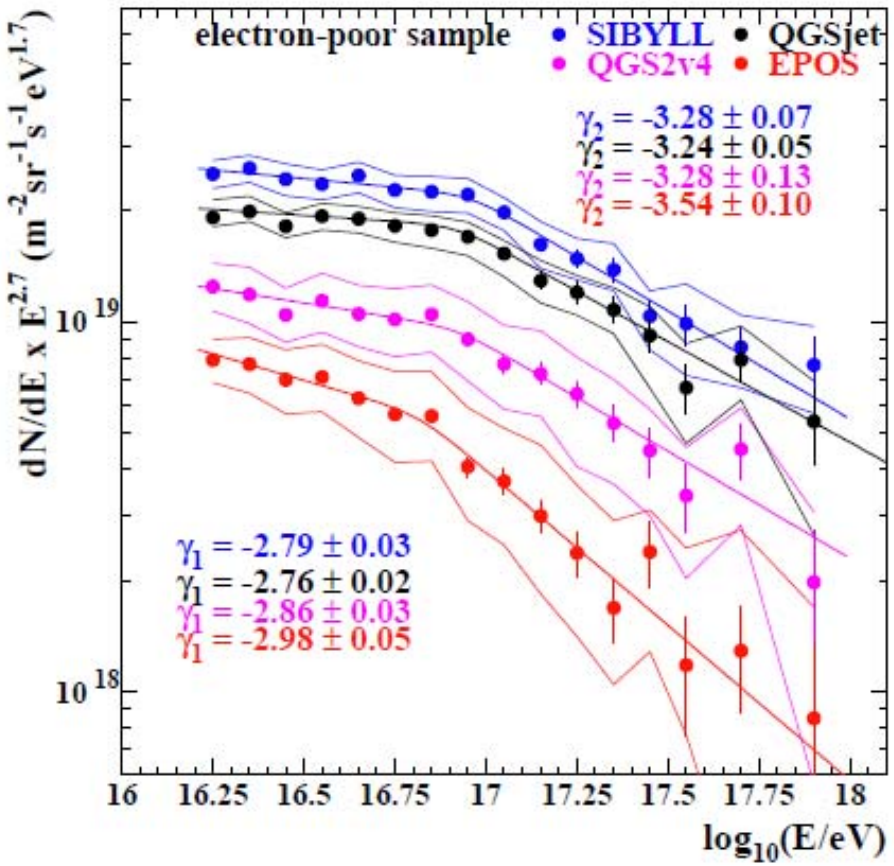
First, high energy interaction: LHC
+ multiparameter measurements EAS

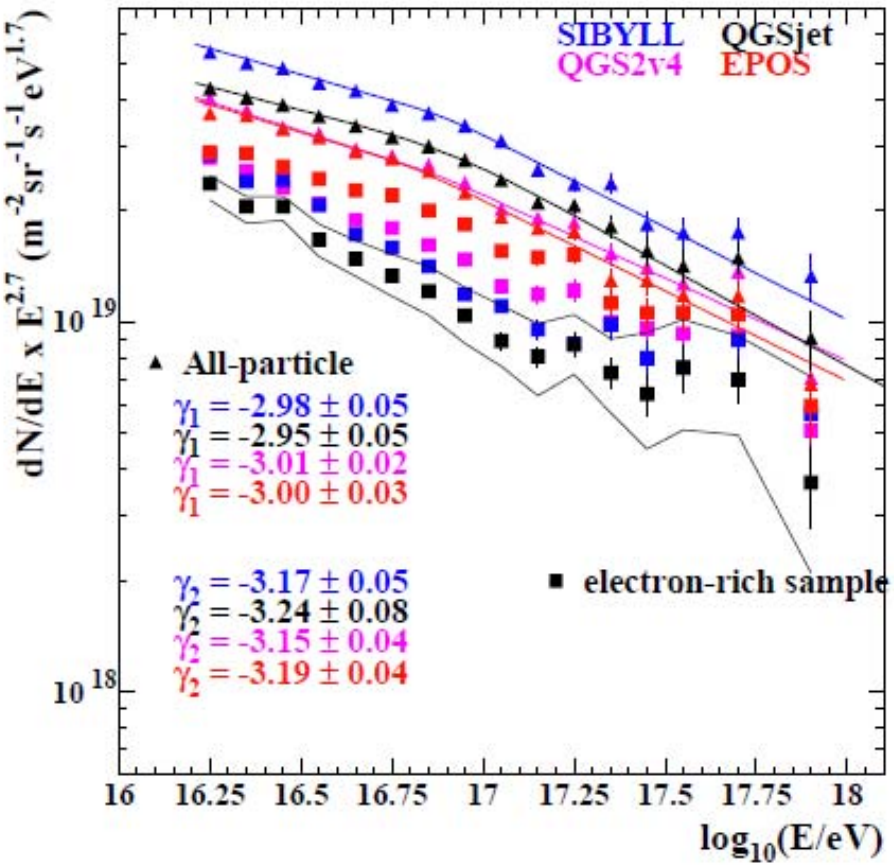
Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS





KASCADE-Grande: model dependence





- Structures of all-particle, heavy and light spectra similar

➔ knee by light component and heavy component; ankle by light component

- relative abundances different for different high-energy hadronic interaction models

Advances in Space Research 53 (2014) 1456

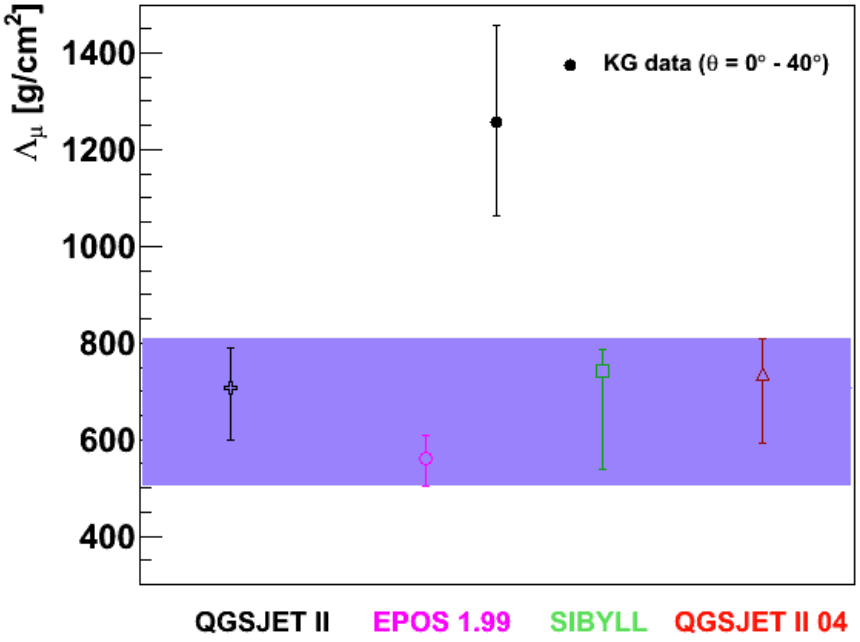
KASCADE-Grande: Muon Attenuation Length

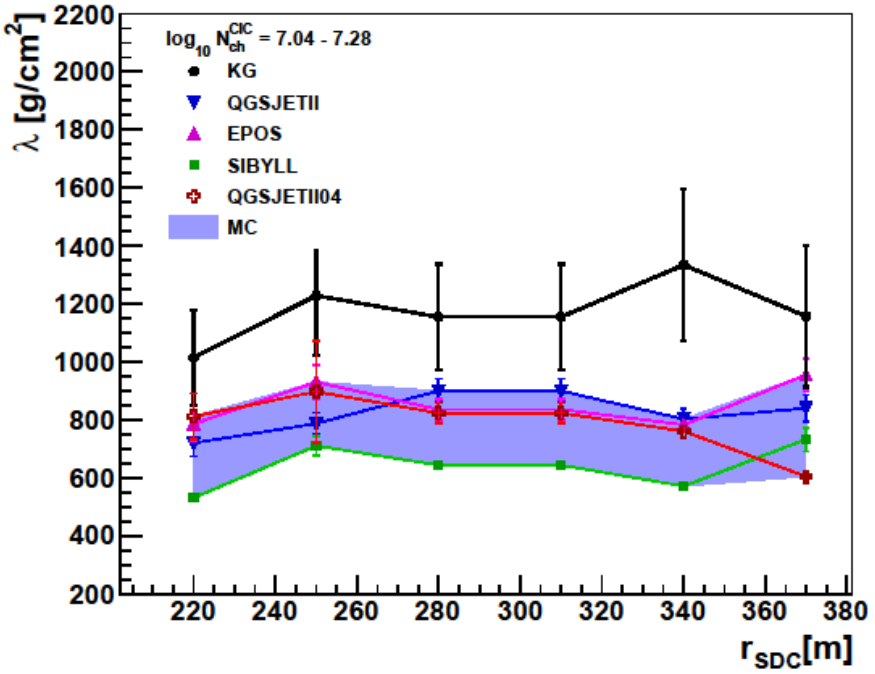
total muon number

$N_\mu = N_{\mu,0} \exp[- X_0 \sec(\theta) / \Lambda_\mu]$

local muon density

$\rho_\mu(r) = \rho_{\mu,0}(r) \exp[- X_0 \sec(\theta) / \lambda_\mu(r)]$



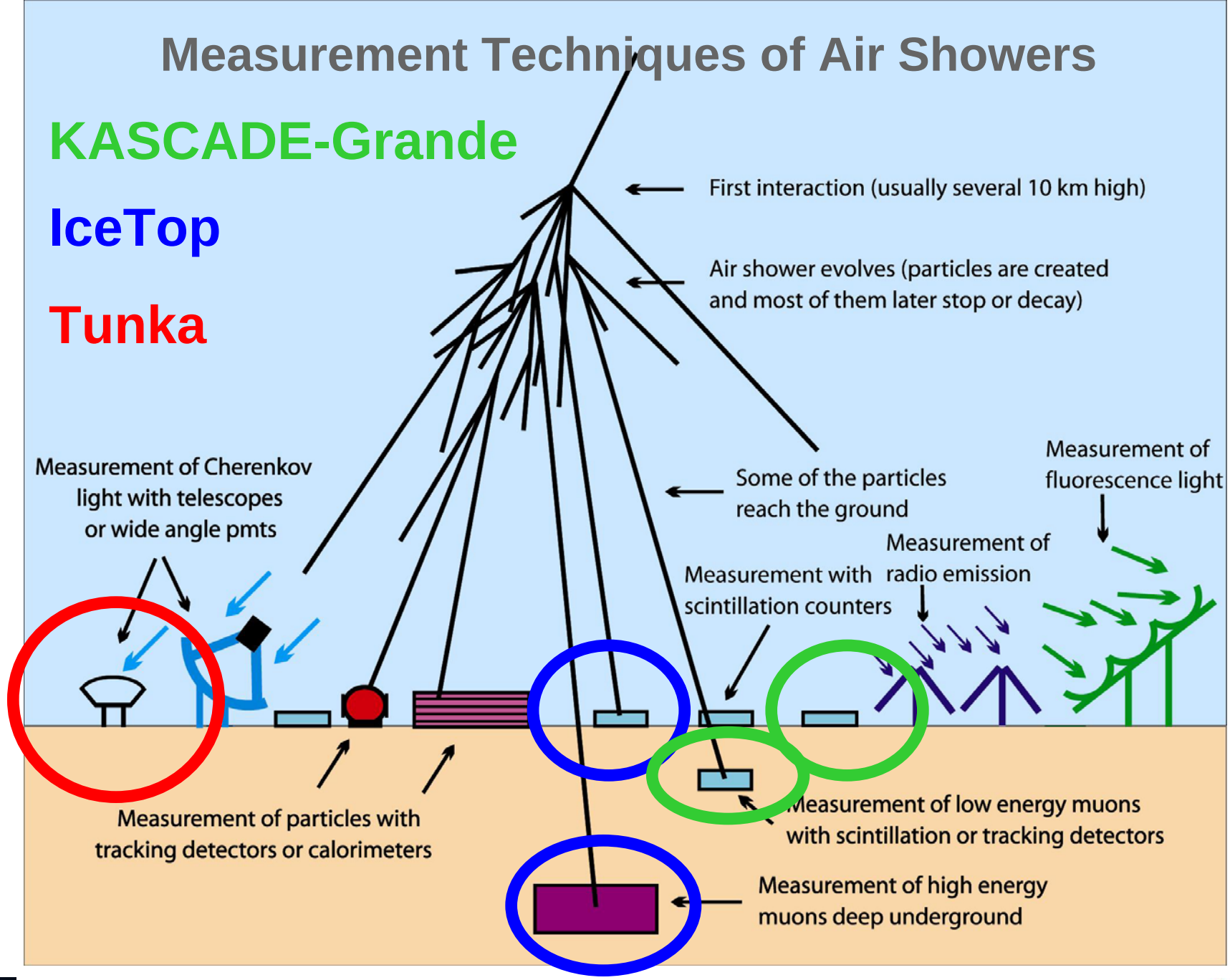


attenuation length measured is different from the predictions of Monte Carlo
➔ observed evolution of the muon content of EAS in the atmosphere is not described by the hadronic interaction models
➔ influences absolute energy and mass scale, but not spectral features

KASCADE-Grande, ICRC 2013 #0772, paper in preparation

Present Main Experiments 10^{16}-10^{18}eV

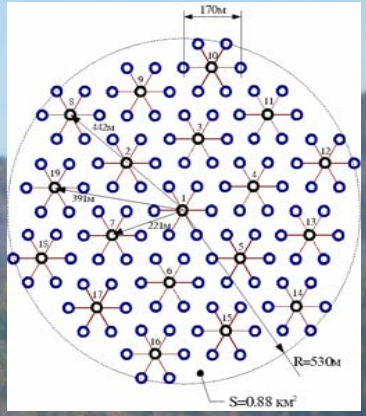
Measurement Techniques of Air Showers



Tunka-133

light flux at core distance 200 m Q_{200} ~ Energy

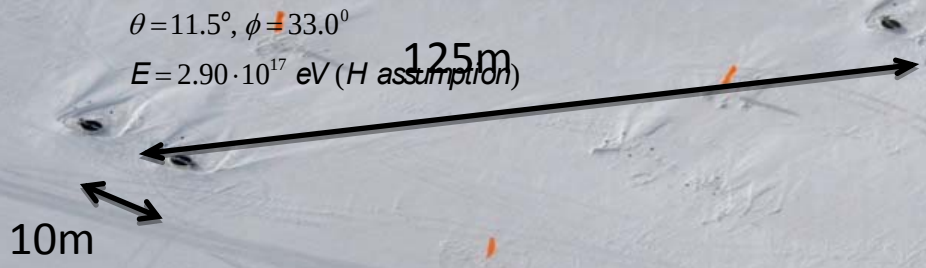
steepness of LDF P = Q(100)/Q(200) ➔ X_{max}

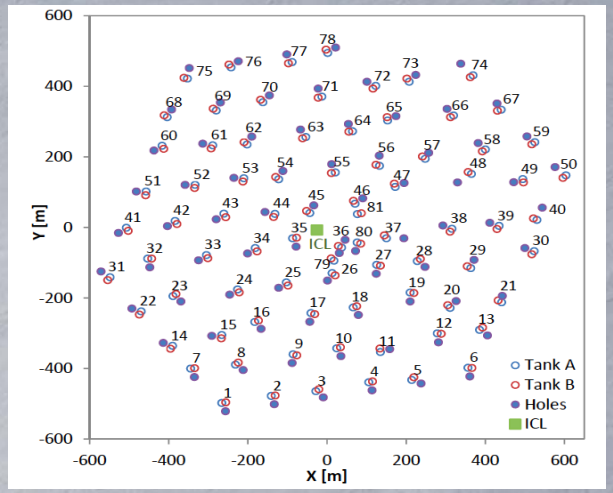


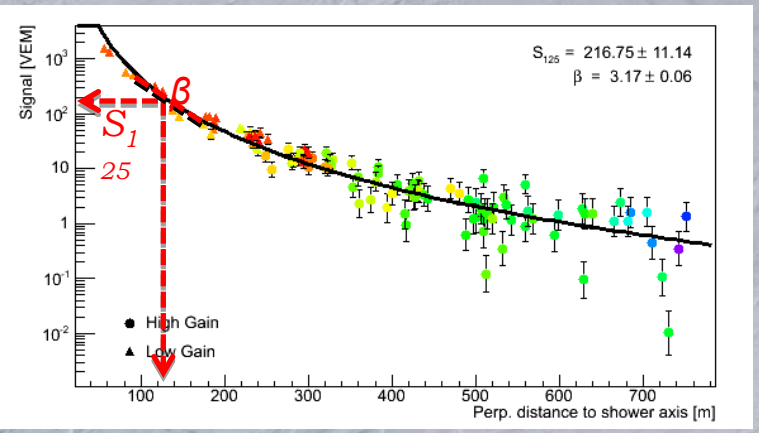
- Energy range: 100TeV – 1EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

NIM A (2013) accepted - http://dx.doi.org/10.1016/j.nima.2013.09.018

IceTop







- **Energy range: PeV – 1EeV**
- **Area: 1 km^2**
- **2835m altitude (680 g/cm^2)**
- **81 ice cherenkov stations**
- **LDF + particle density at 125m**
- **in-ice high-energy muons**

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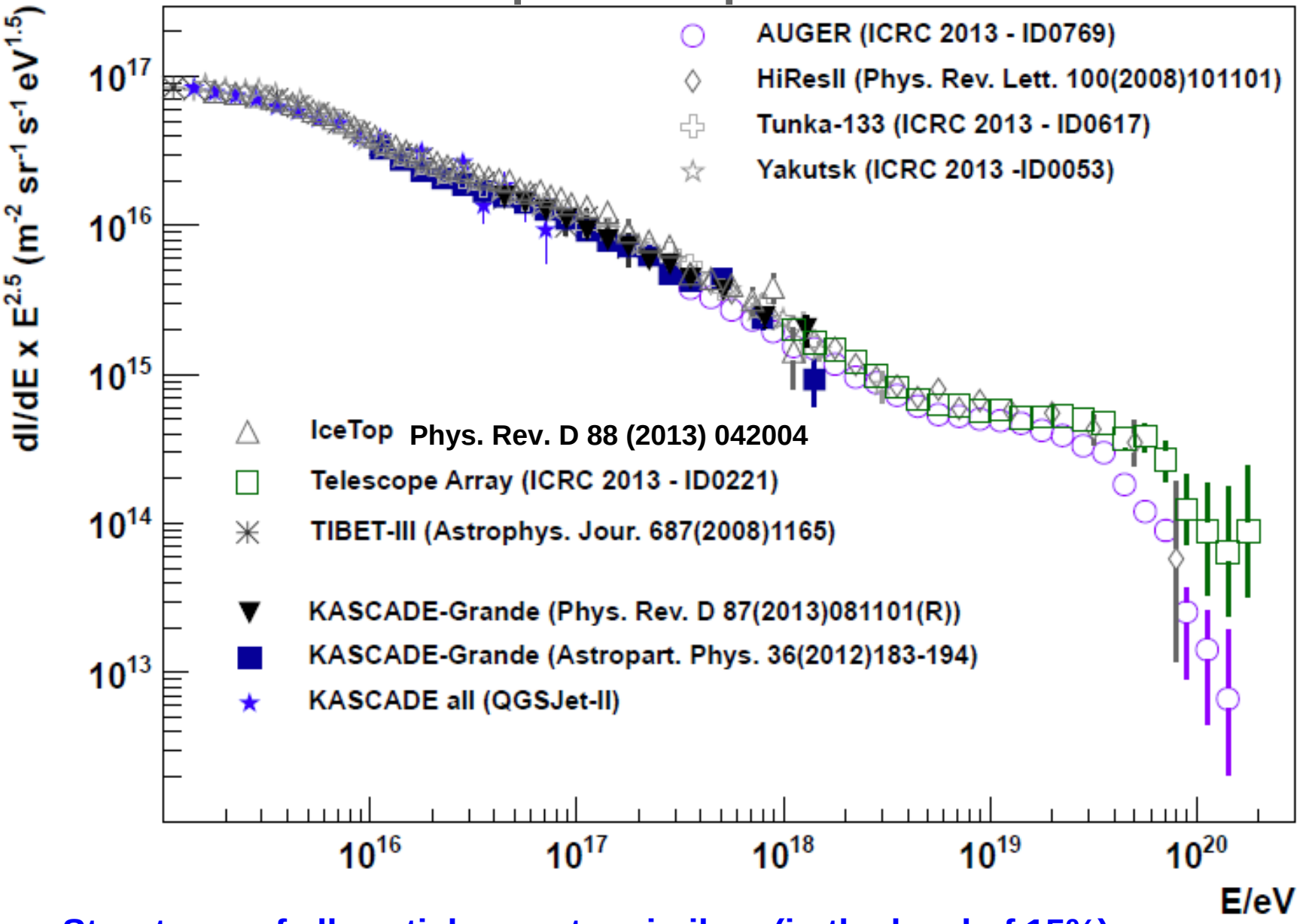
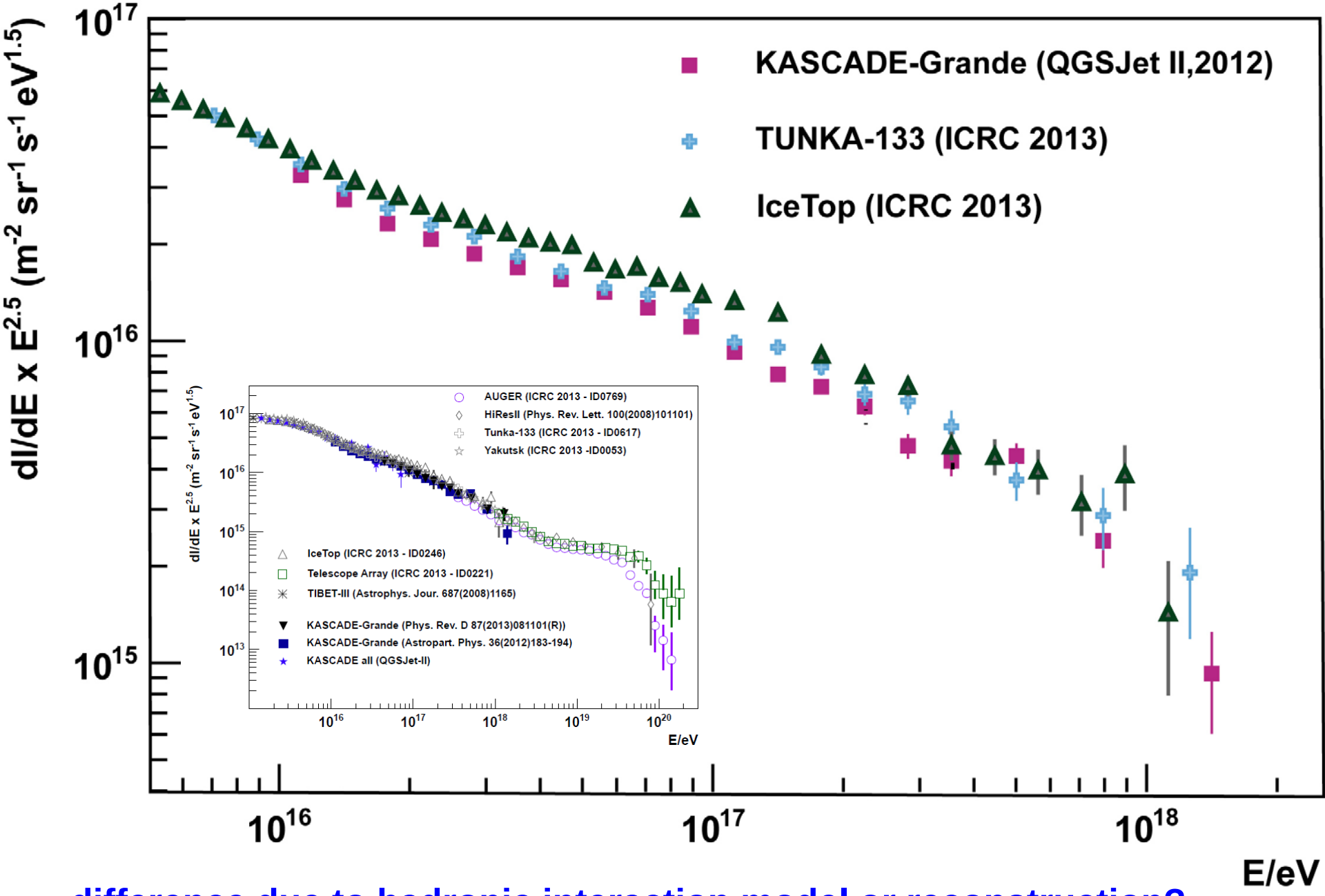
All-particle spectra

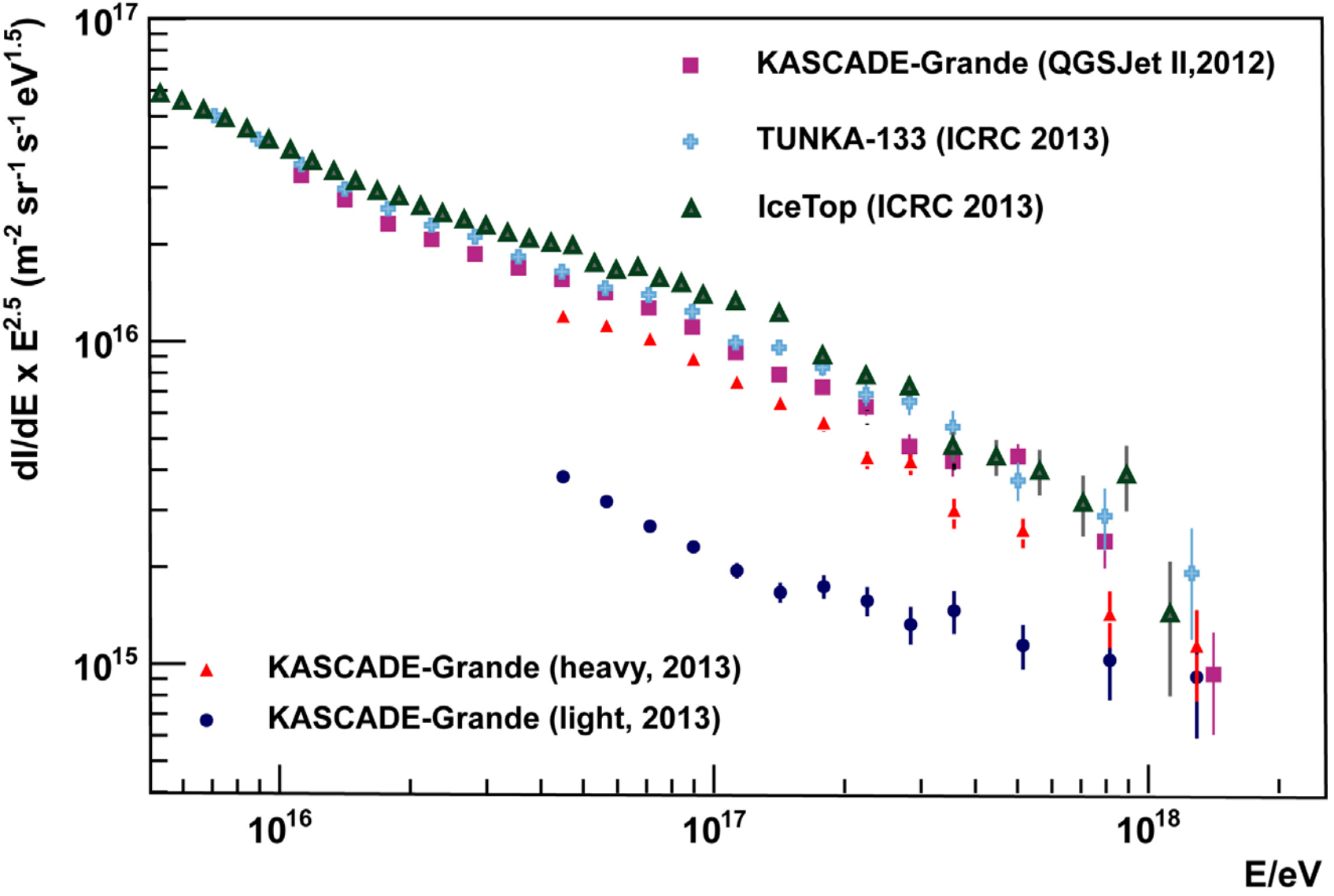


- Structures of all-particle spectra similar (in the level of 15%)



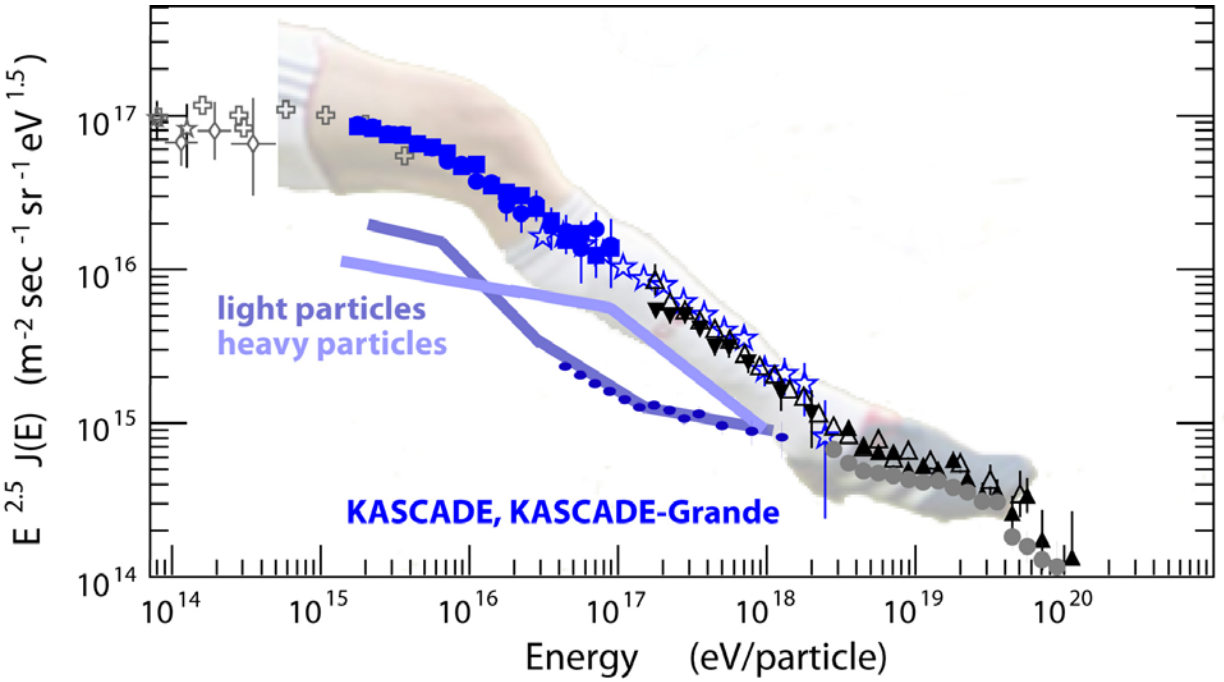
difference due to hadronic interaction model or reconstruction?

All-particle spectra



- spectra of individual masses (mass groups) are important!!

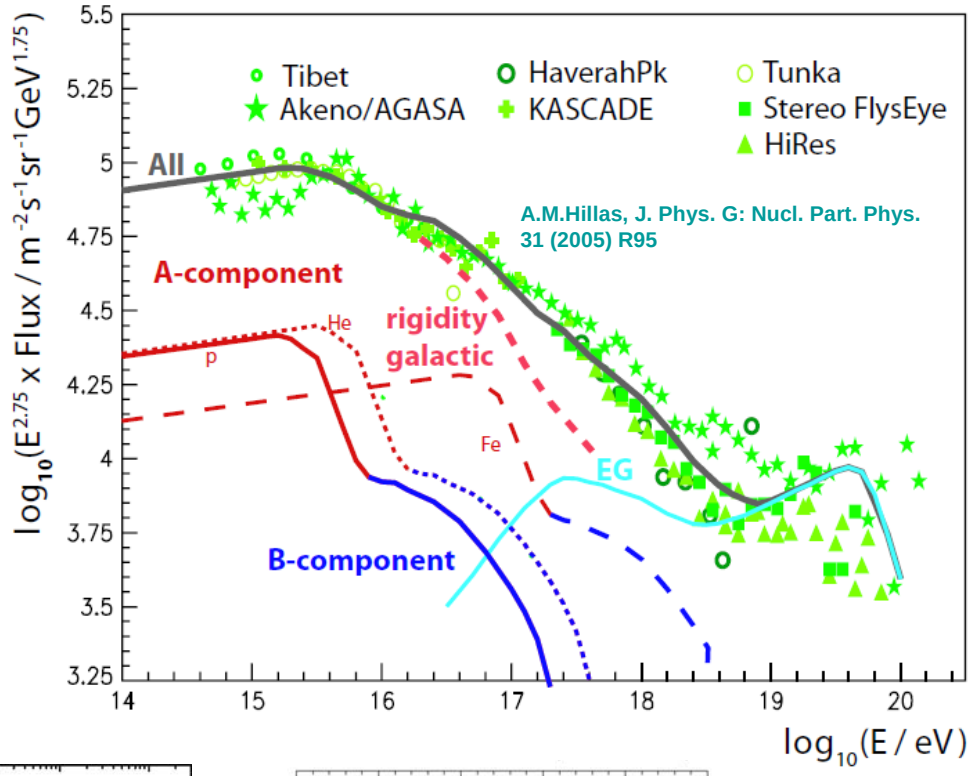
Light and Heavy Knees, Ankles, and Transition

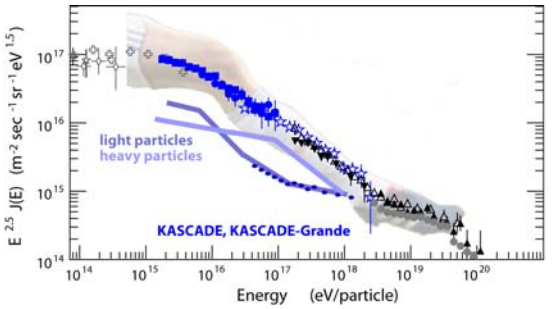


- ➔ **KASCADE: knee of light primaries at ~3·10^{15}eV**
- ➔ **Hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~9·10^{16} eV**
- ➔ **heavy knee less distinct compared to light knee**
- ➔ **mixed composition for 10^{15} to ~ 8·10^{17} eV**
- ➔ **light ankle at 1-2·10^{17} eV**

knee position $\propto Z$

Light and Heavy Knees, Ankles, and Transition



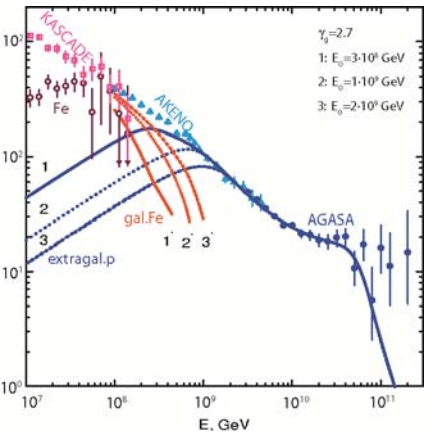


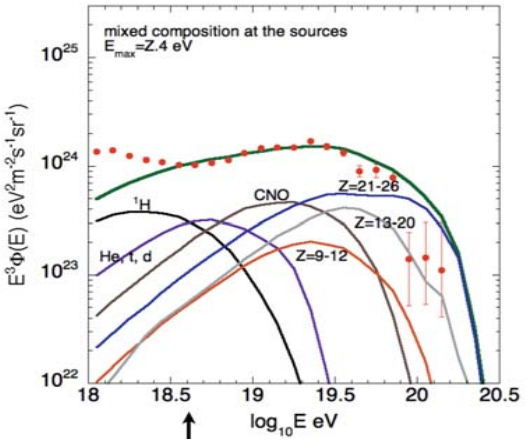
Questions:

- which astrophysical scenario (model) describes the data?

- exact energy and mass scale?

- spectral shape of individual masses?





V.Berezinsky, astro-ph/0403477

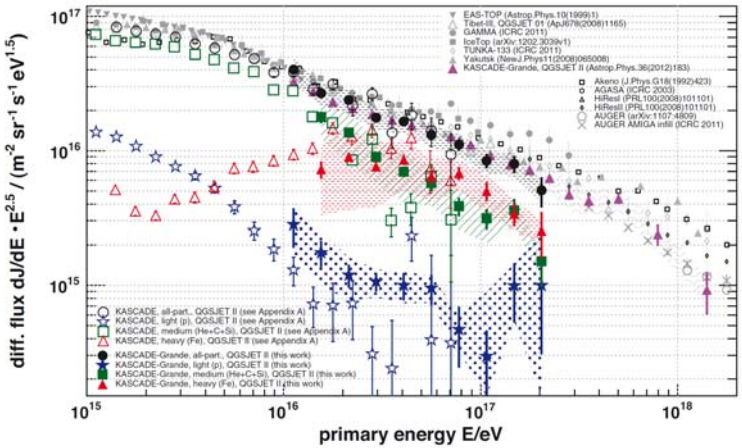
D.Allard, astro-ph/1111.3290

KASCADE-Grande: Next



- **KASCADE + KASCADE-Grande**
  - **finally closed end 2012**
  - **now dismantled**

- **combined analysis**
  - **for coherent spectrum and composition 10^{14}-10^{18} eV**

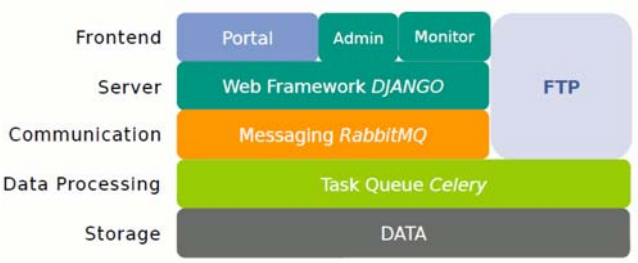


- **detailed data analysis (20y high-quality data)**
  - **testing hadronic interaction models**
  - **anisotropy studies**
  - **radio (LOPES and CROME)**

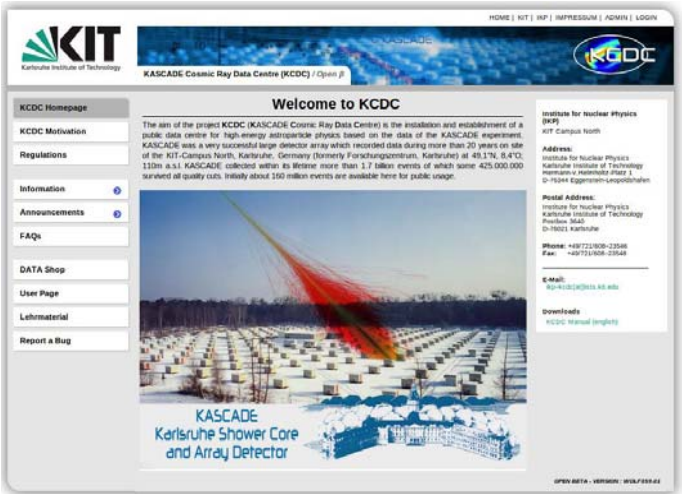
- **KCDC**
  - **KASCADE Cosmic ray Data Centre**

https://kcdc.ikp.kit.edu/

- **KCDC = publishing research data**
  from the KASCADE experiment
- **Motivation and Idea of Open Data:**
  general public has to be able to access and use the data
  the data has to be preserved for future generations



- **Web portal:**
  providing a modern software solution for publishing KASCADE data for a general audience
  In a second step: release the software as Open Source for free use by other experiments

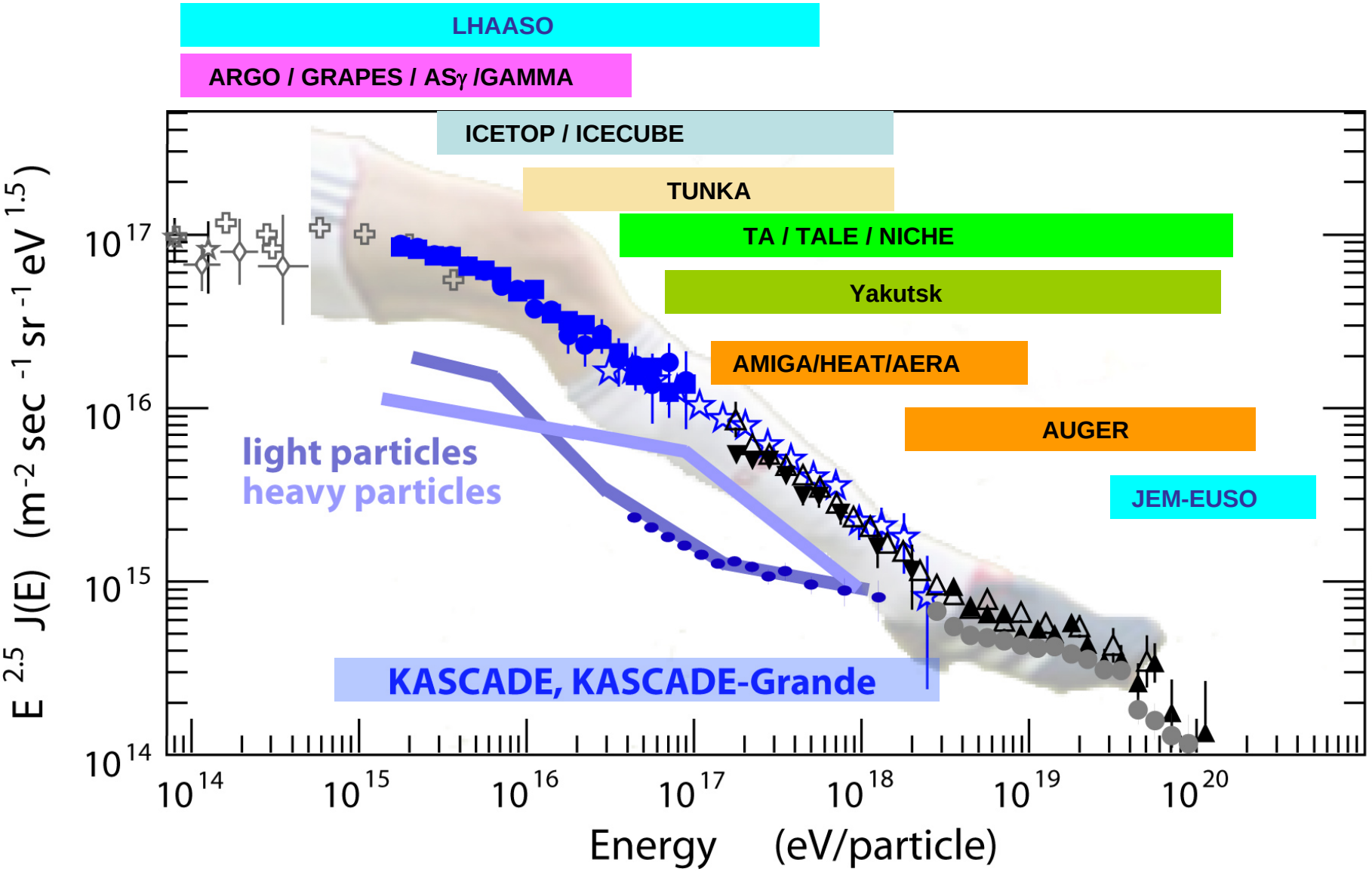


- **Data access:**
  $1.6 \cdot 10^8$ EAS events of first data release is now available

KASCADE-Grande: Mission Accomplished !!

open access to research data
https://kcdc.ikp.kit.edu

Summary



answers only by combining all information: stay tuned!