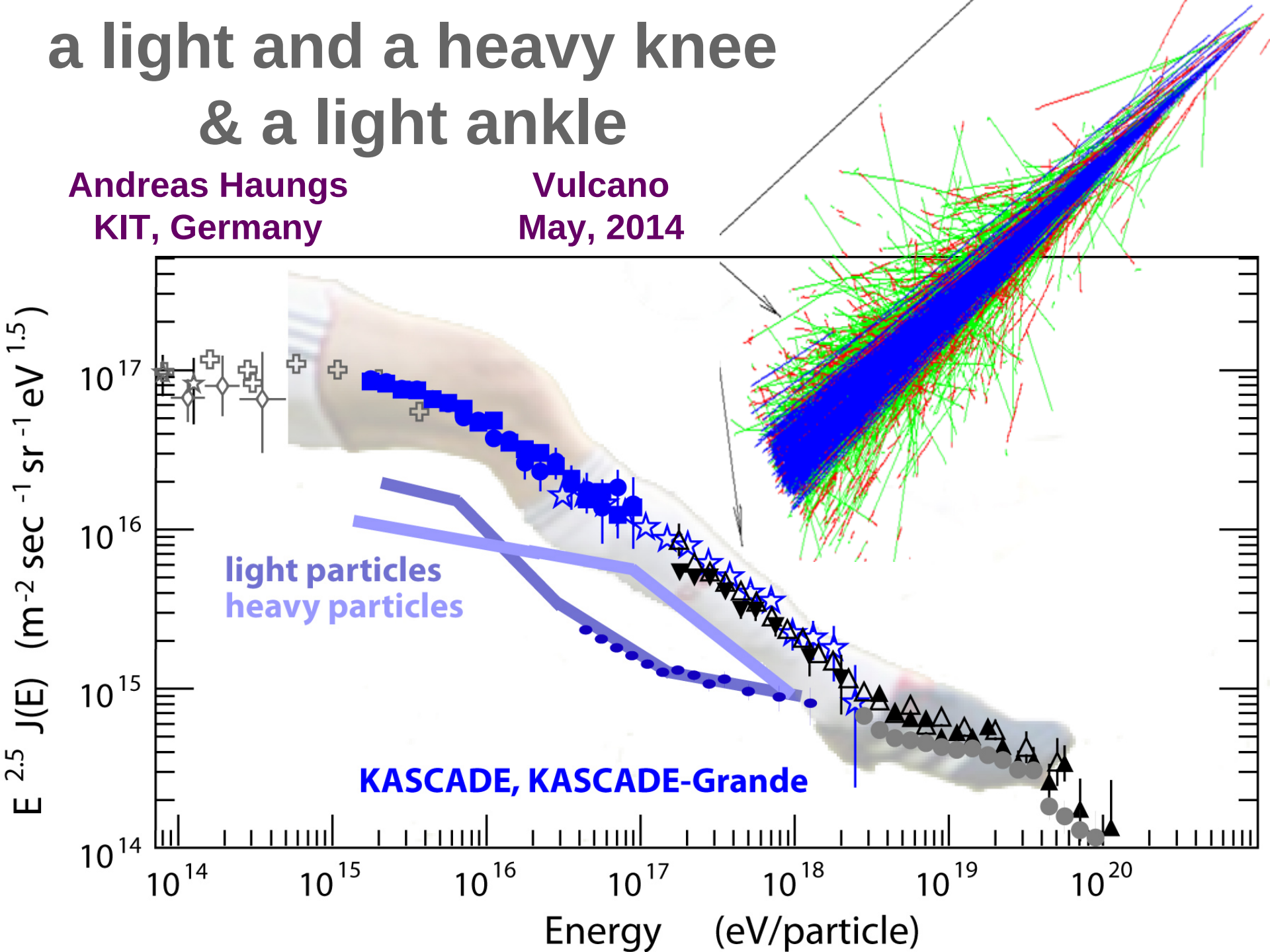
a light and a heavy knee & a light ankle

Andreas Haungs
KIT, Germany

Vulcano
May, 2014



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

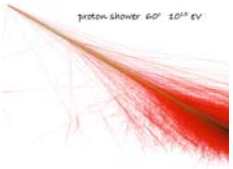
2000 model tests
light knee

2004 KASCADE-Grande
γ limit
(an)isotropy
proof-of-principle radio detection
muon production height
LOPES

2008 Karlsruhe Air Shower Test Facility
iron knee
CROME
Cosmic Revelation
EAS GHz emission

2012 KCDC
light ankle
Xmax by radio

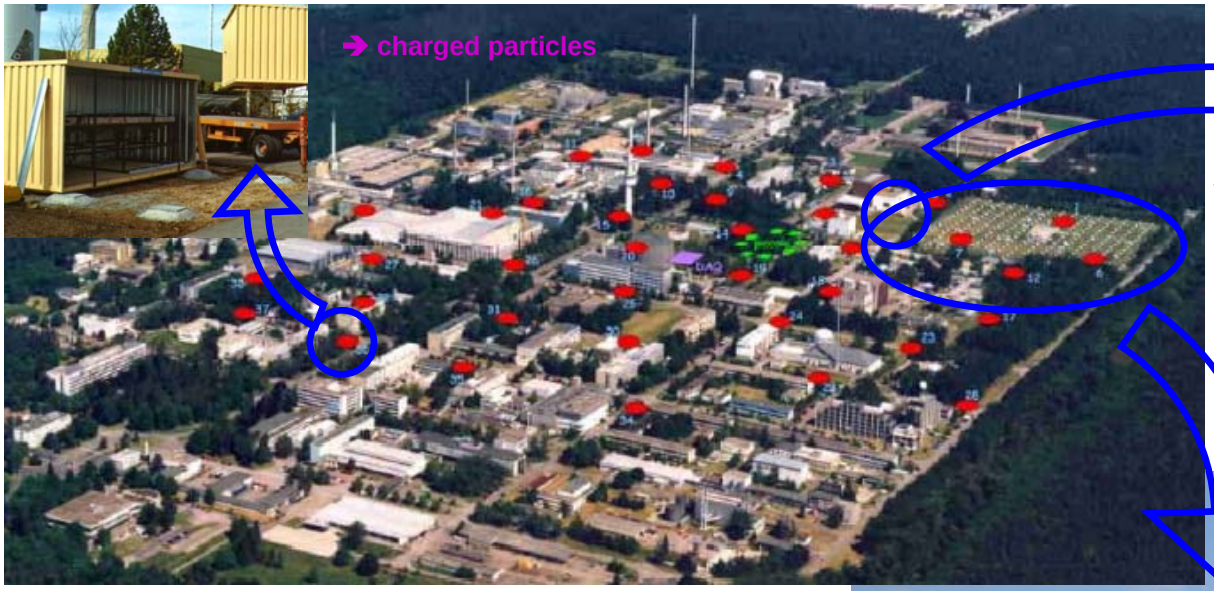
2016



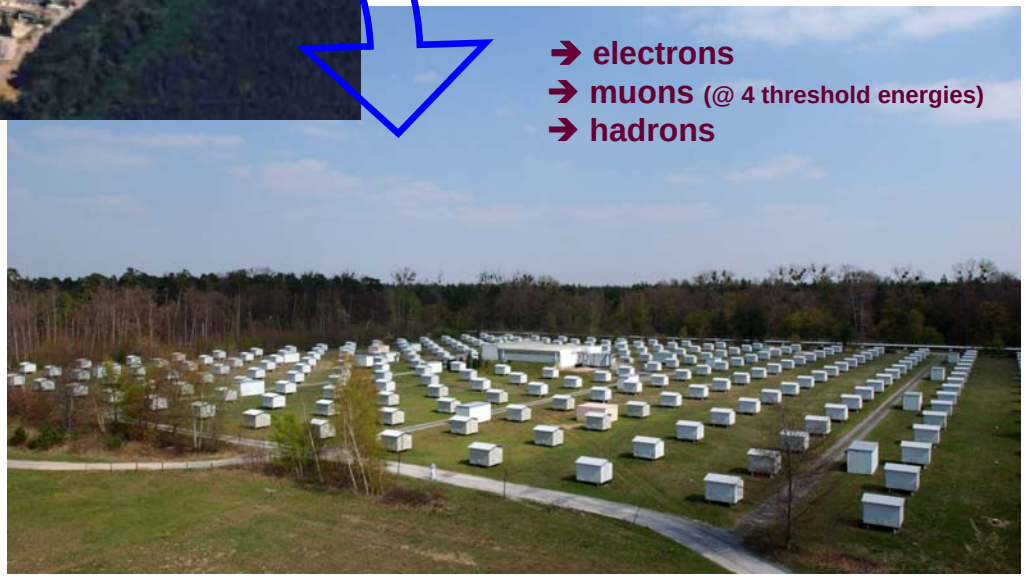
KASCADE-Grande

= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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

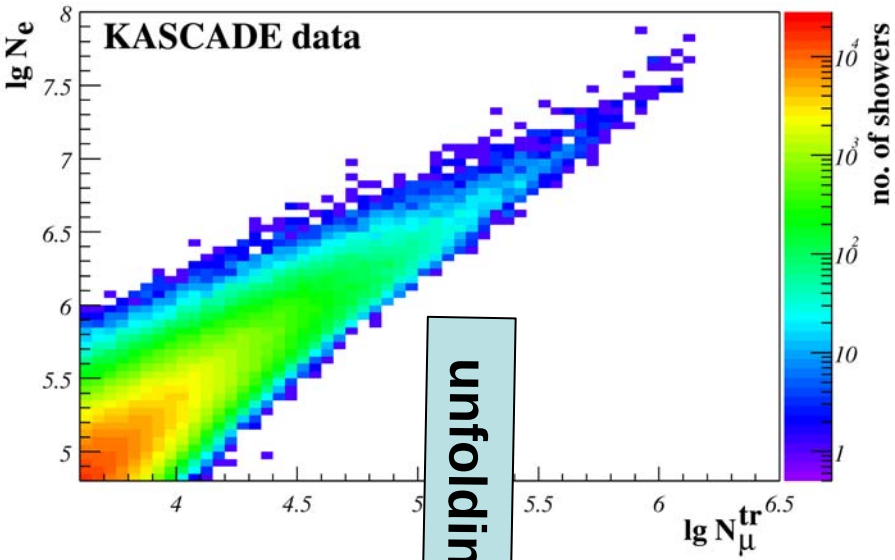


➔ electrons
➔ muons (@ 4 threshold energies)
➔ hadrons

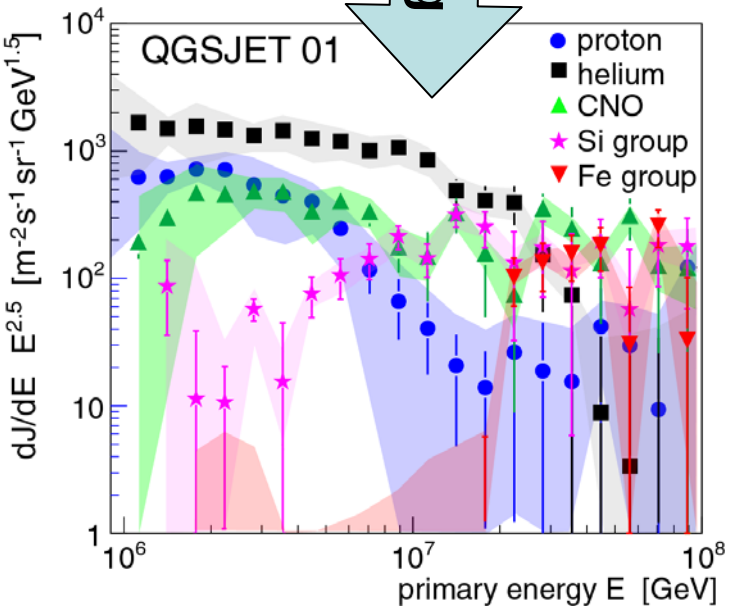


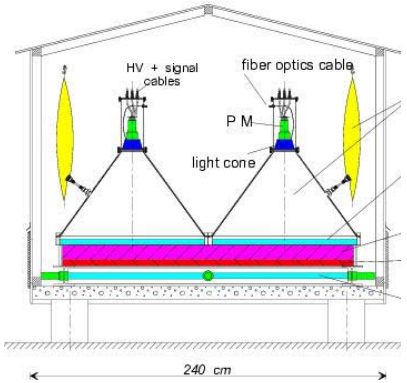
- **core and direction** (from Grande)
- **shower size** (charged particles)
- **muon number** (from KASCADE)
- **local muon density** (from KASCADE)
- **local charged particle density S(500)**
- **...**

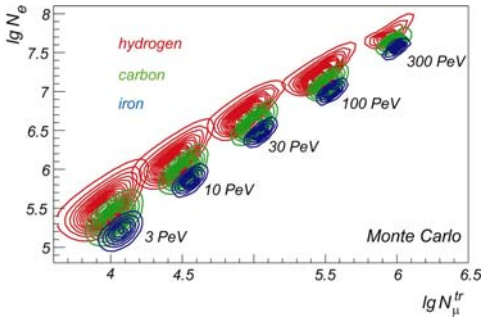
KASCADE : energy spectra of single mass groups



unfolding







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

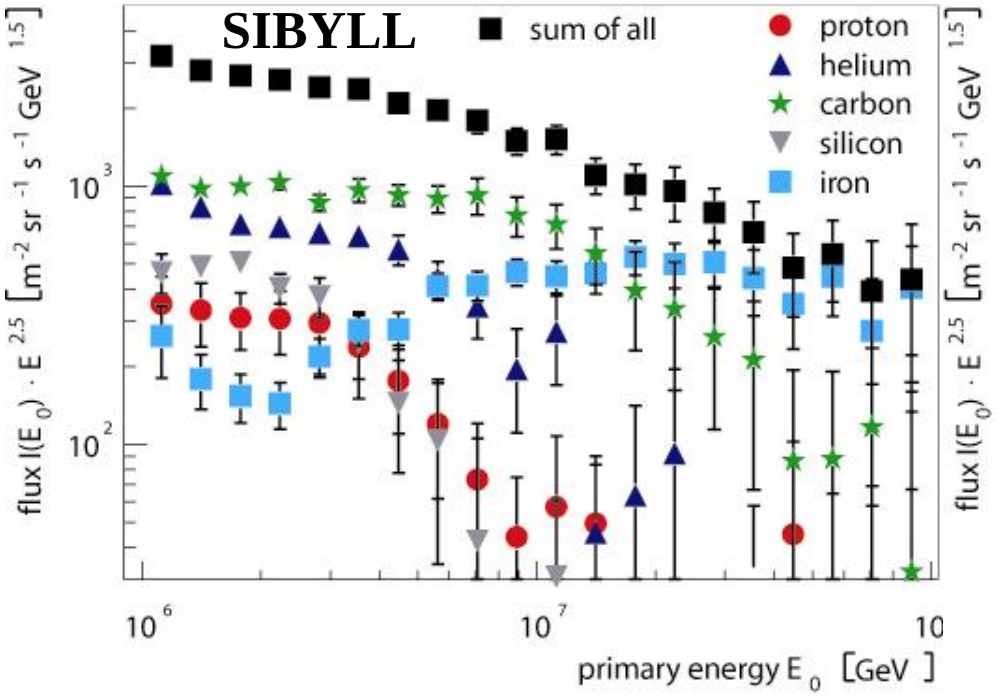
$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E)\, d\lg E$$

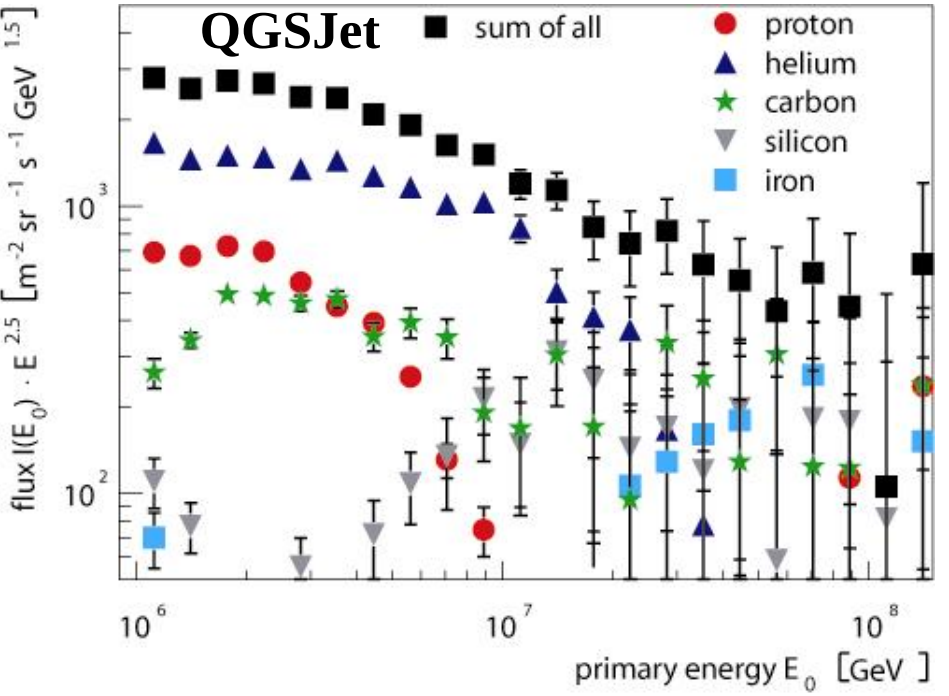
- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

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

KASCADE results

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



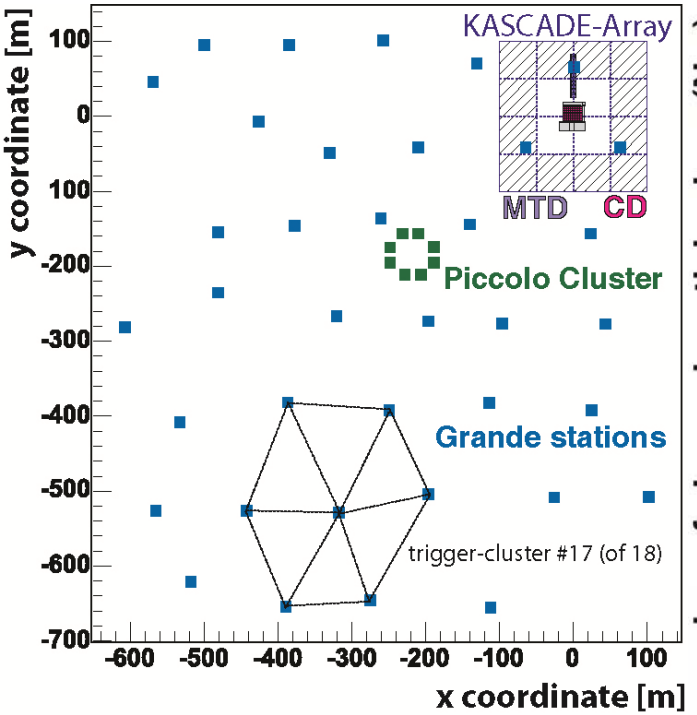


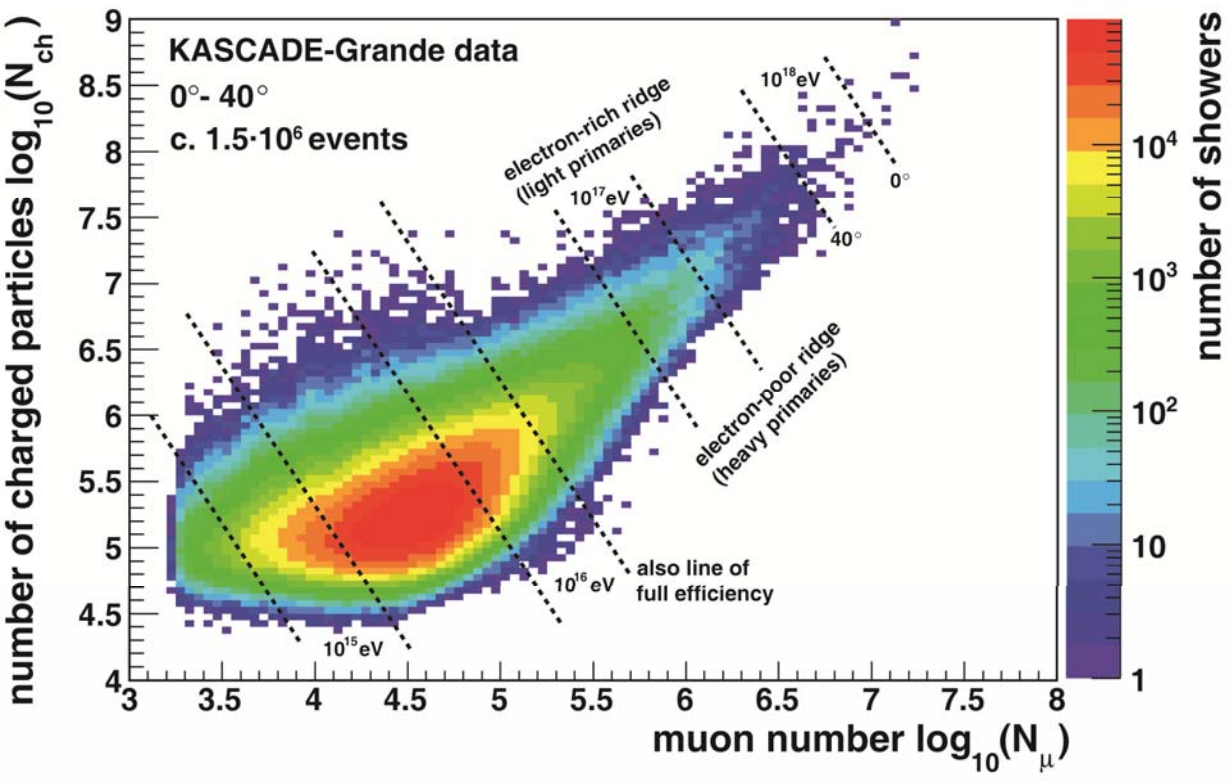
- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different for different high-energy hadronic interaction models

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

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

KASCADE-Grande: the measurement





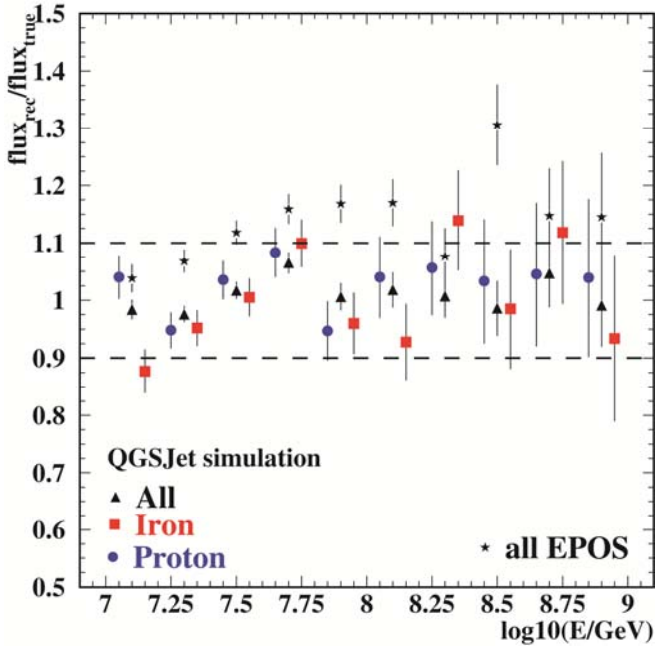
➔ **determination of primary energy**

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

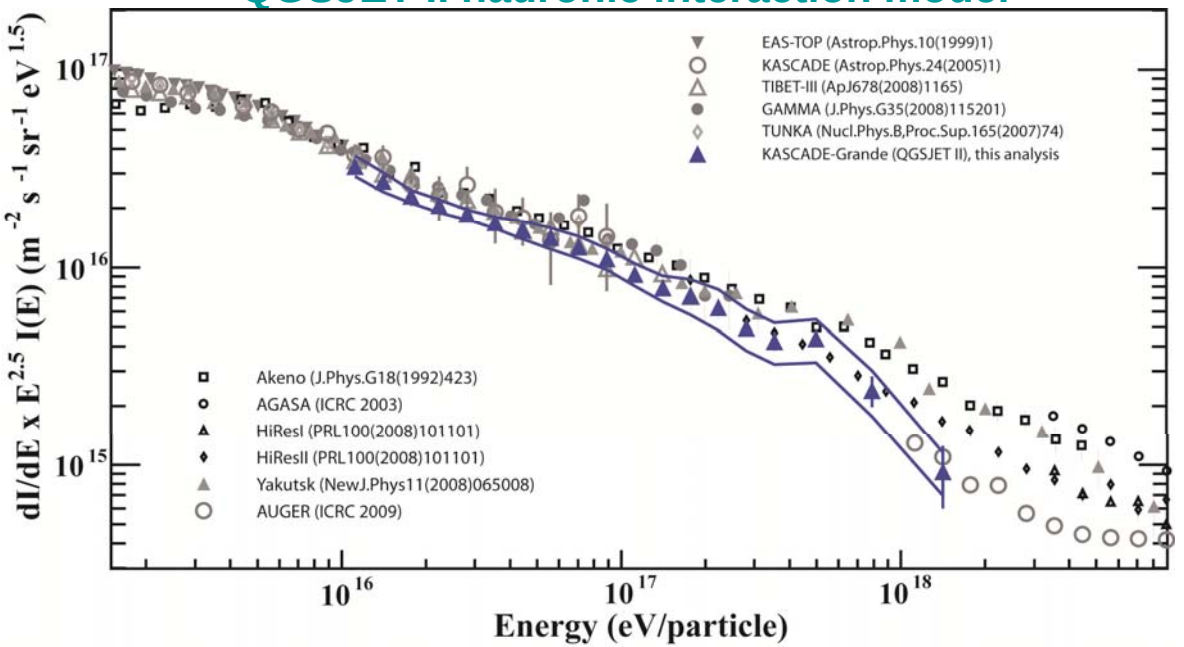
All-particle energy spectrum :

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

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



QGSJET II hadronic interaction model

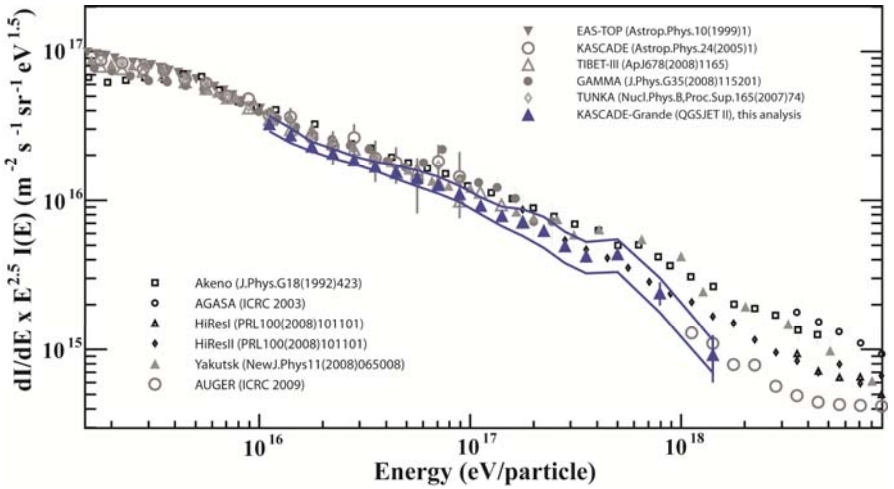


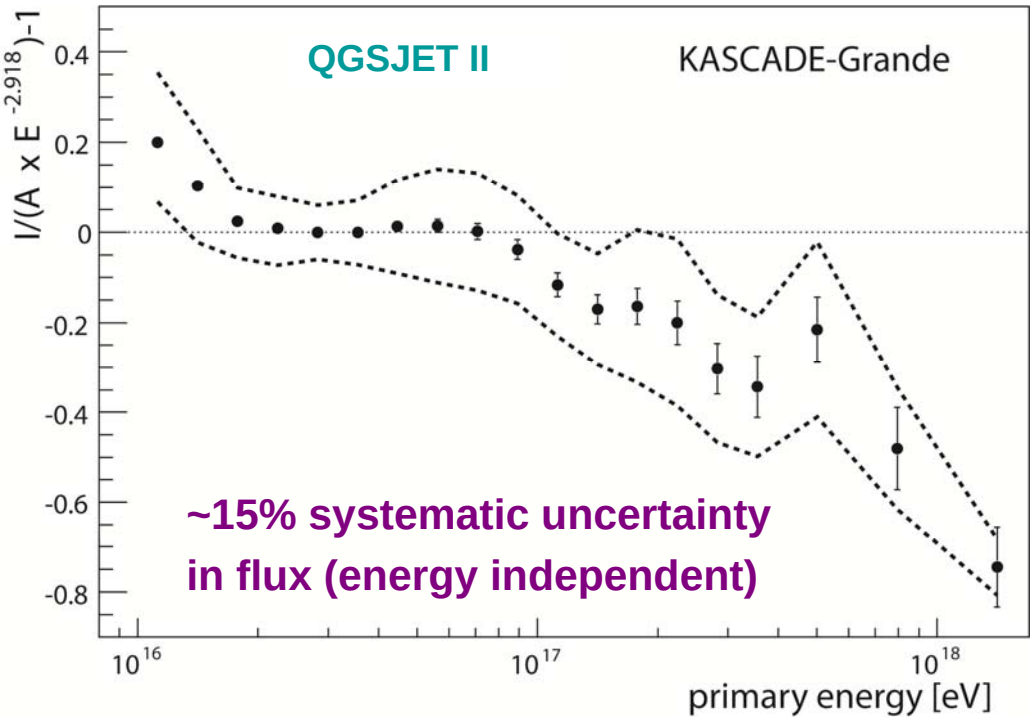
-different zenith angle bins
-no composition dependence

Astroparticle Physics 36 (2012) 183

KASCADE-Grande
all-particle energy spectrum

Astroparticle Physics 36 (2012) 183



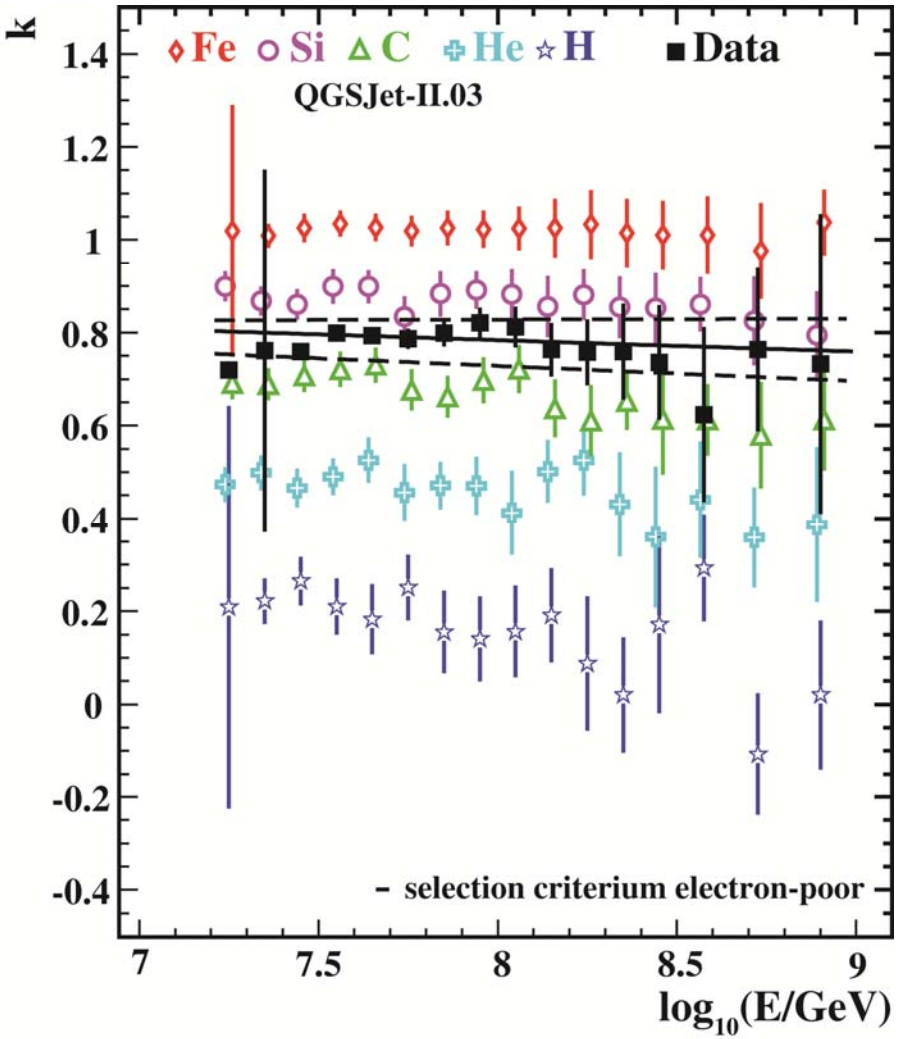


- **spectrum not a single power law**
- **hardening of the spectrum above 10^{16}eV**
- **steepening close to 10^{17}eV (2.1σ)**

Composition via shower size ratio :

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

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



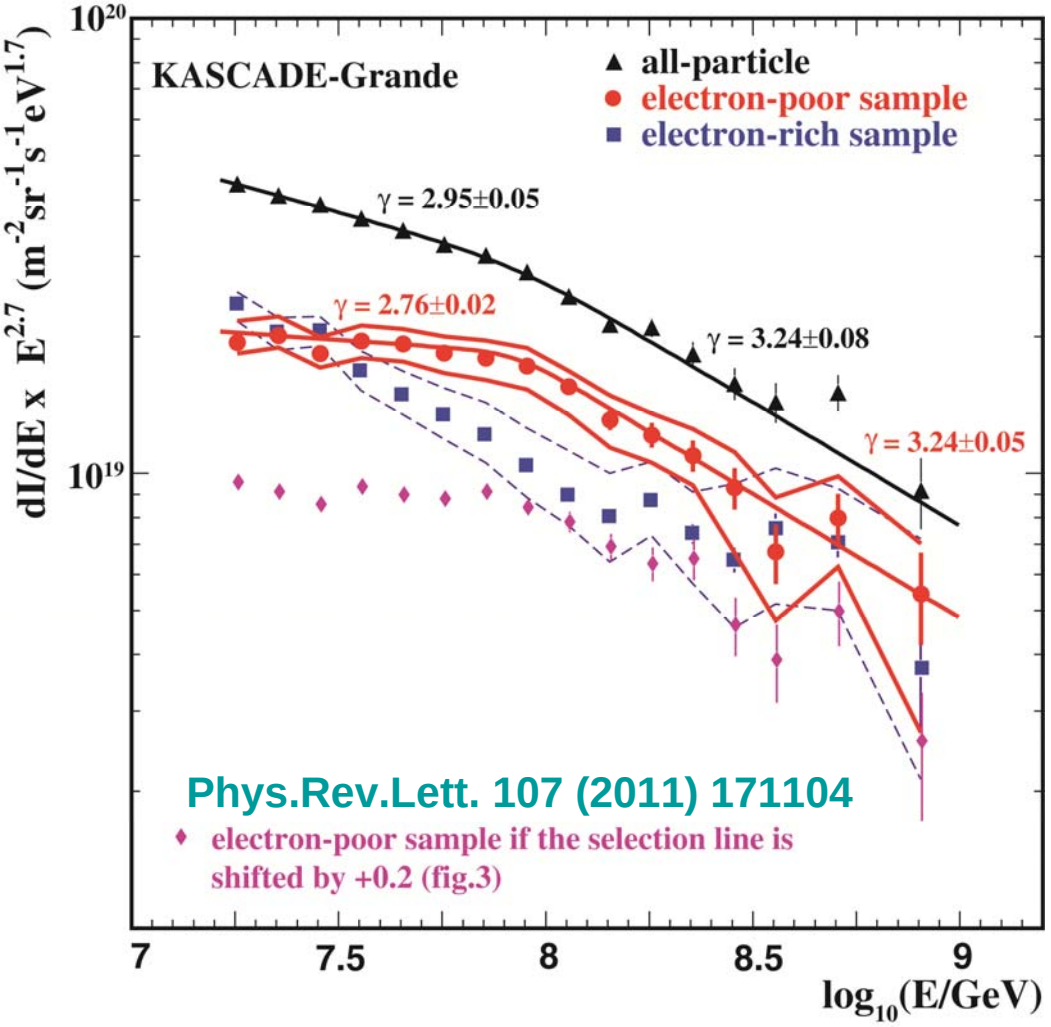
- k-parameter = normalized shower size ratio

➔ 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:

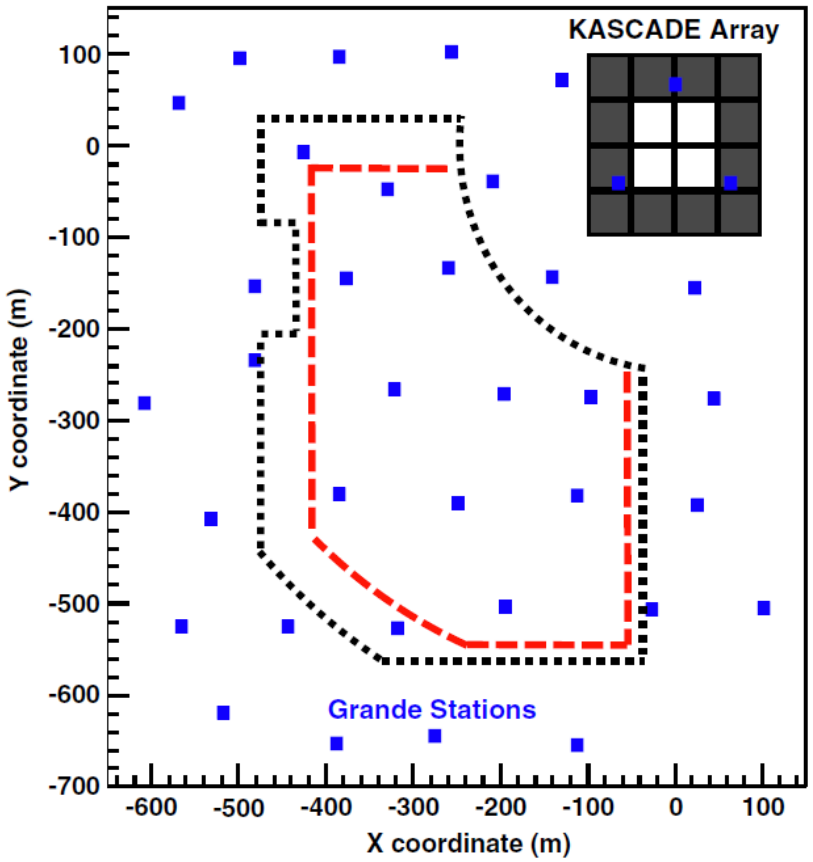
➔ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

➔ 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

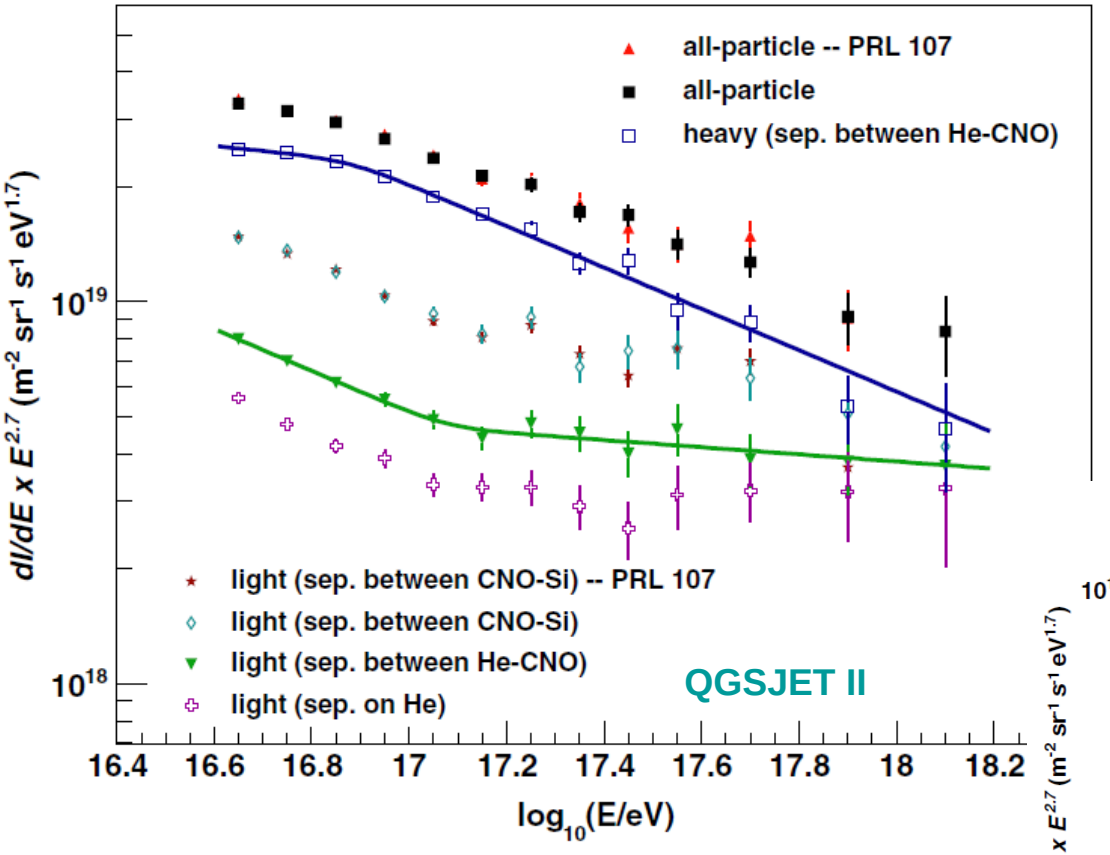


- **re-investigation of the spectrum of light primaries:**

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

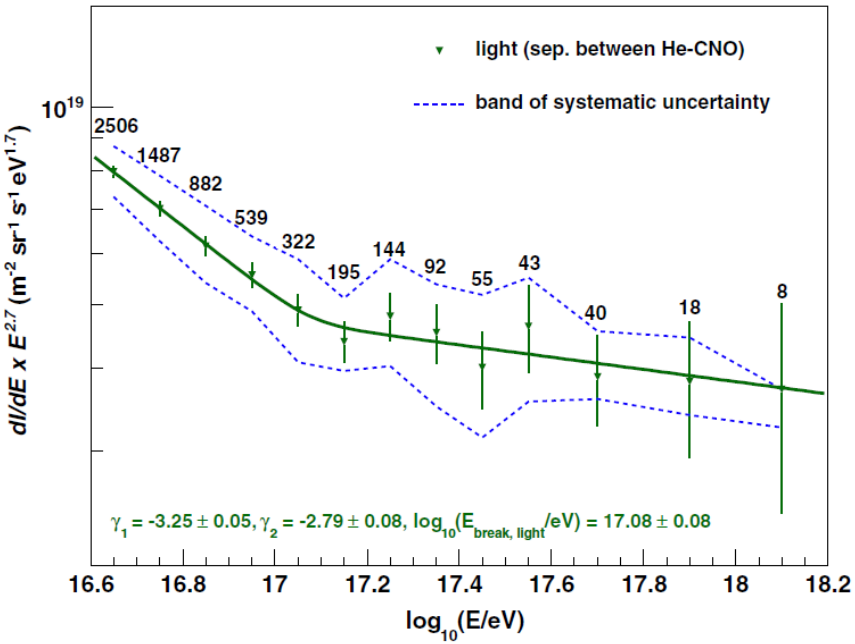
Phys.Rev.D (R) 87 (2013) 081101

KASCADE-Grande: spectrum of light primaries



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

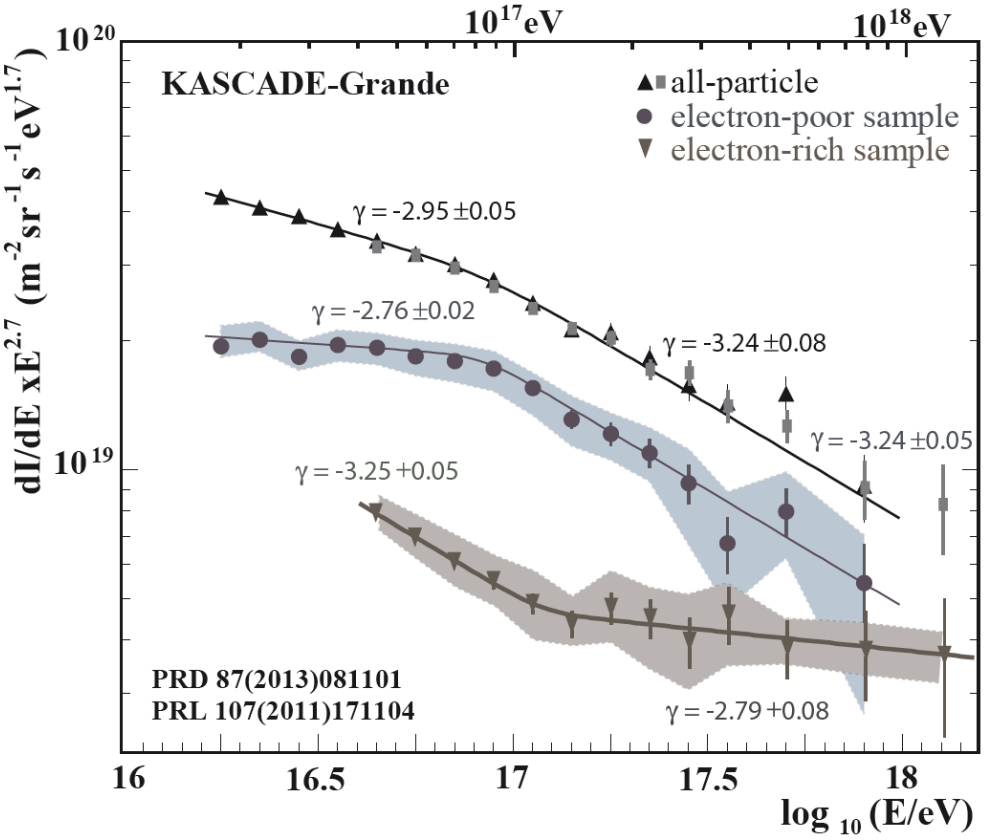
➔ **slope change from γ = -3.25 to γ = -2.79!**



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

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

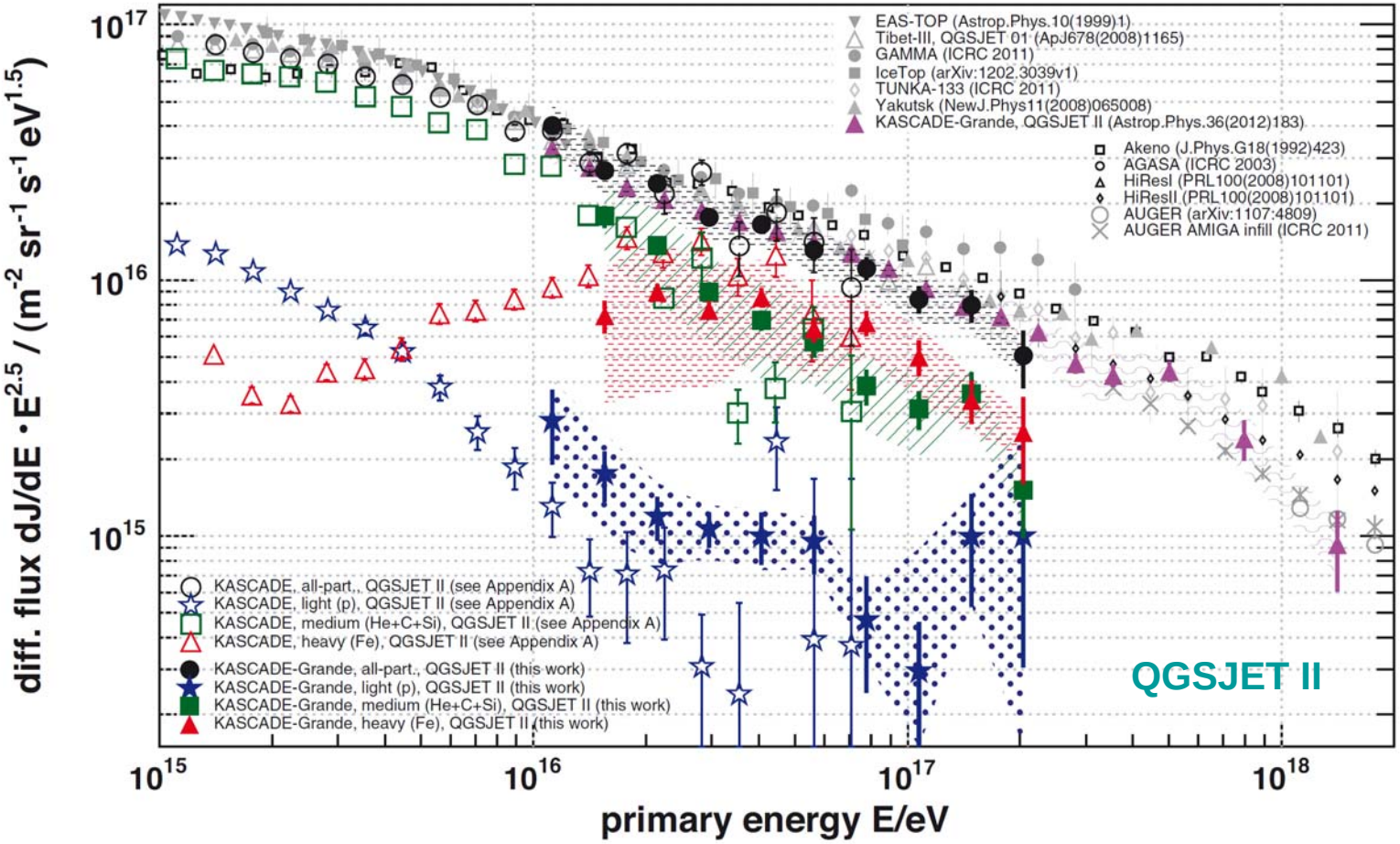
KASCADE-Grande
energy spectra of mass groups



- **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

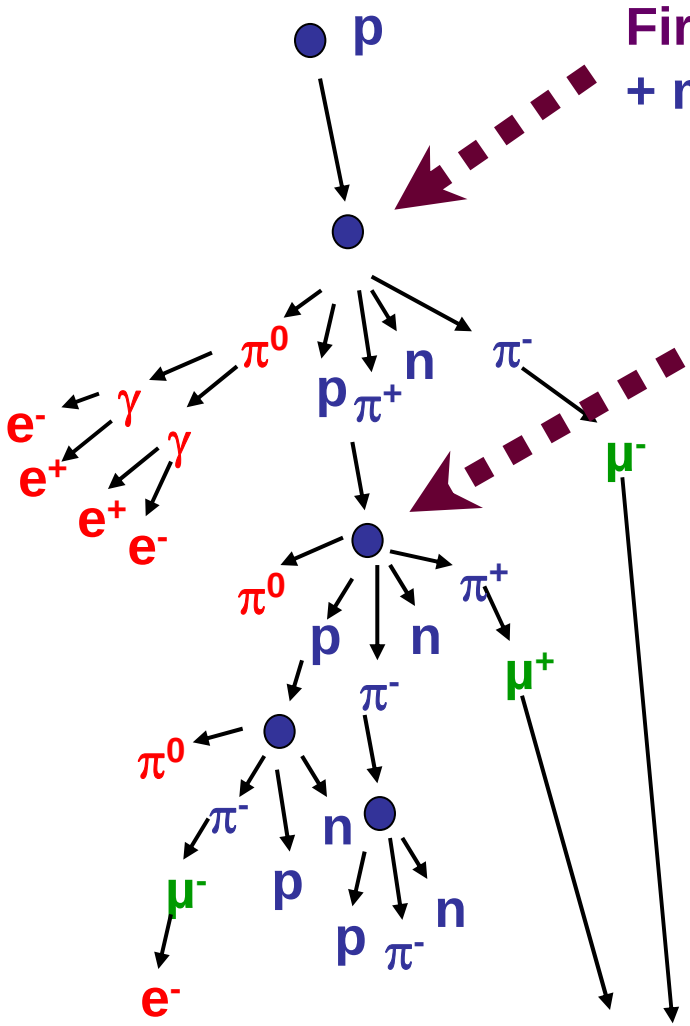
Unfolding results: KASCADE and KASCADE-Grande



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

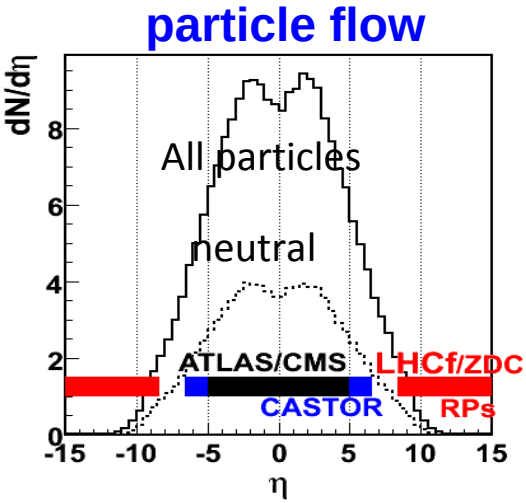
Astroparticle Physics 47 (2013) 54

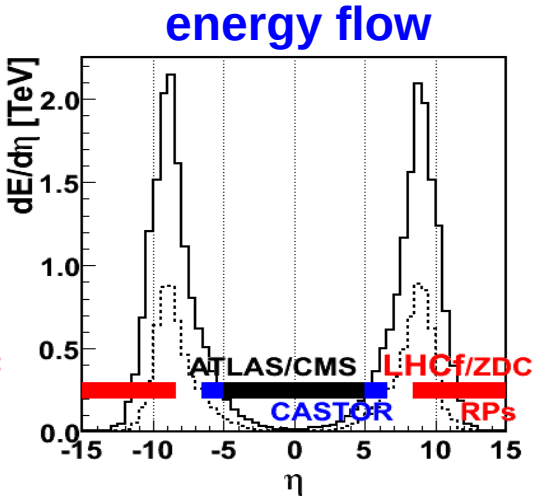
Validity of Hadronic Interaction Models



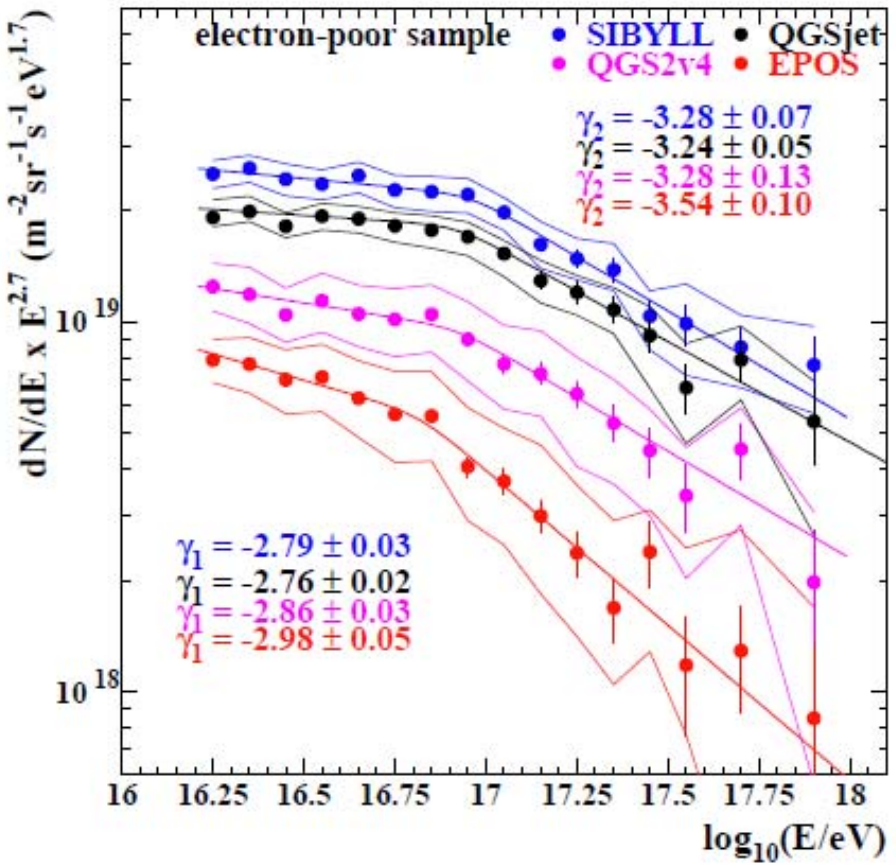
First, high energy interaction: LHC
+ multiparameter measurements EAS

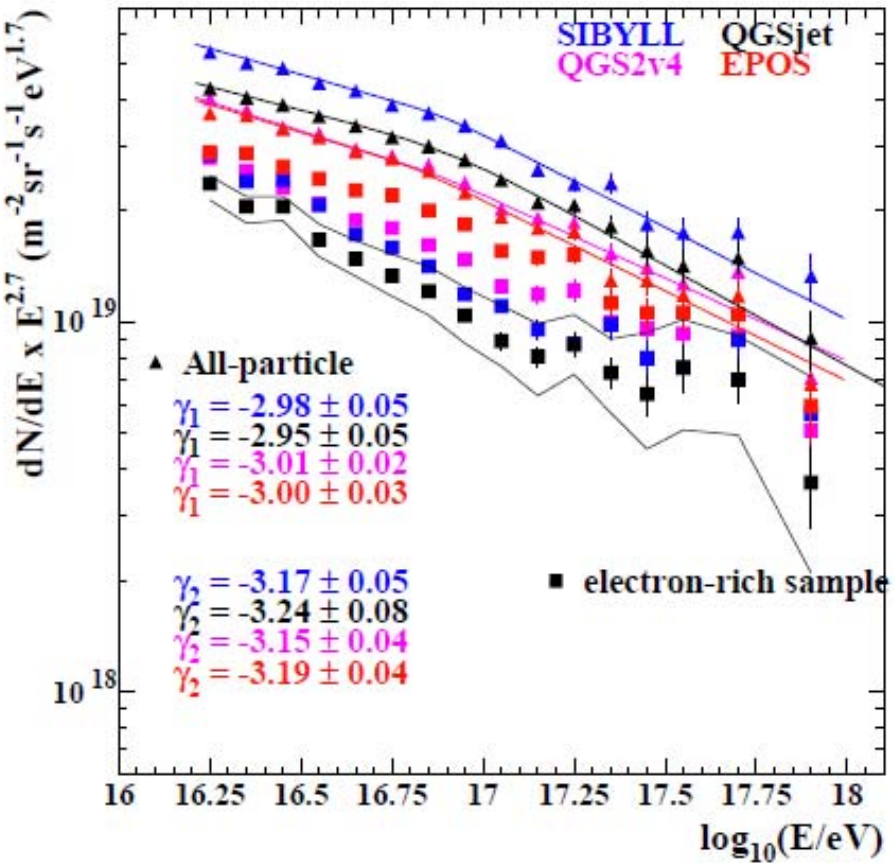
Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS





KASCADE-Grande: model dependence





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

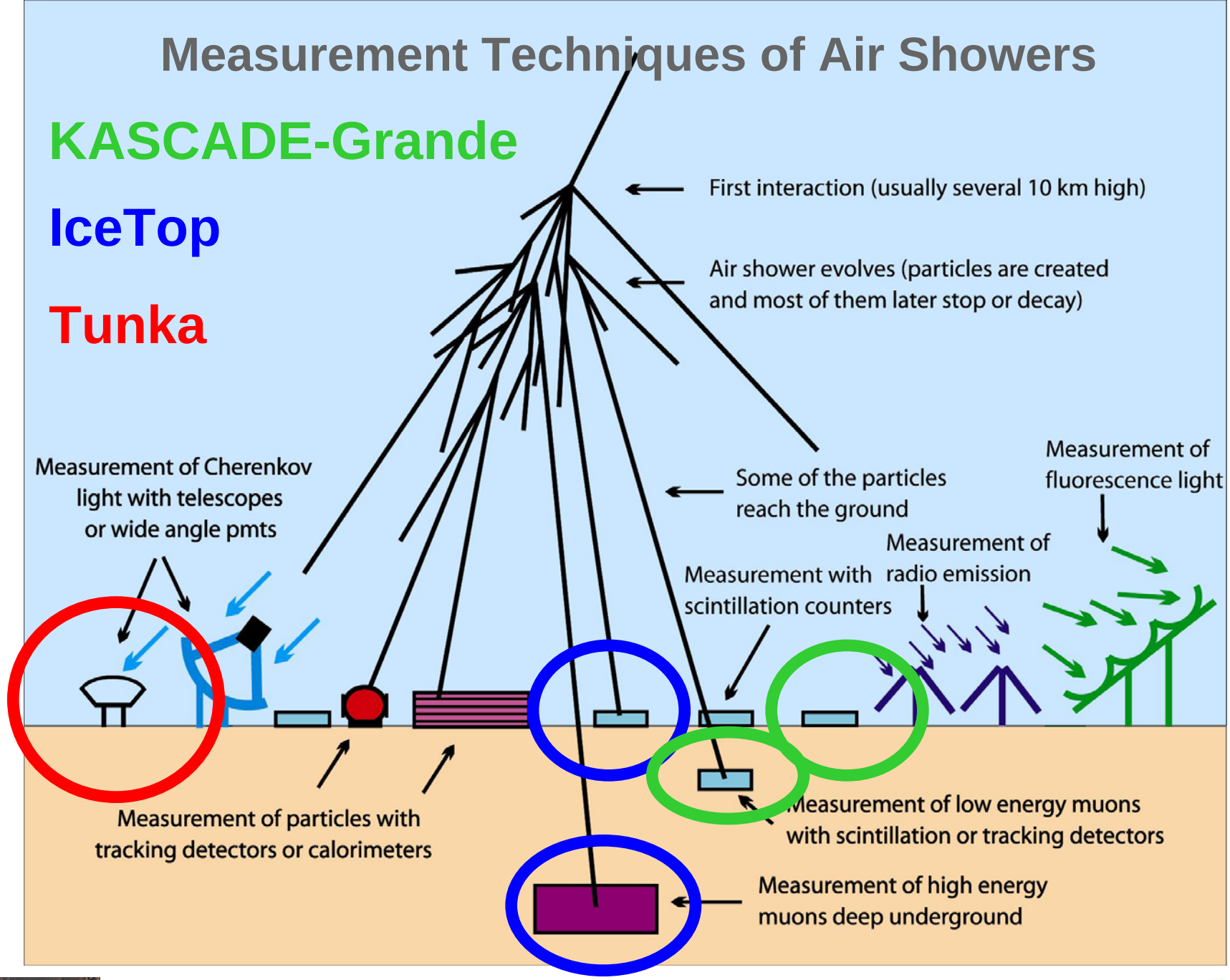
➔ knee by light component and heavy component; ankle by light component

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

Advances in Space Research 53 (2014) 1456

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

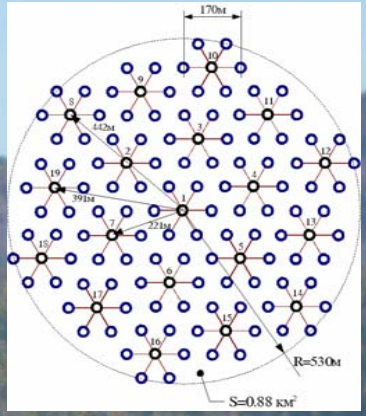
Measurement Techniques of Air Showers



Tunka-133

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

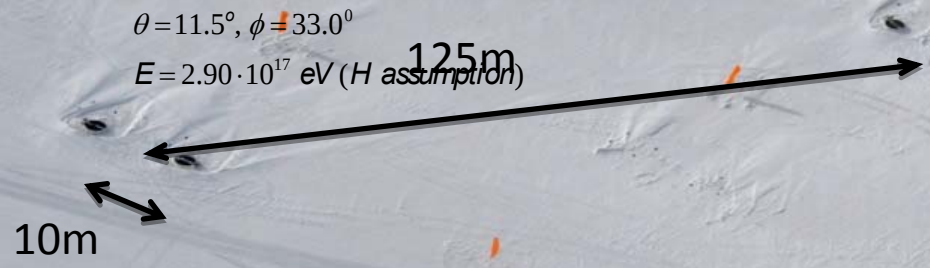
steepness of LDF P = Q(100)/Q(200) ➔ X_{max}

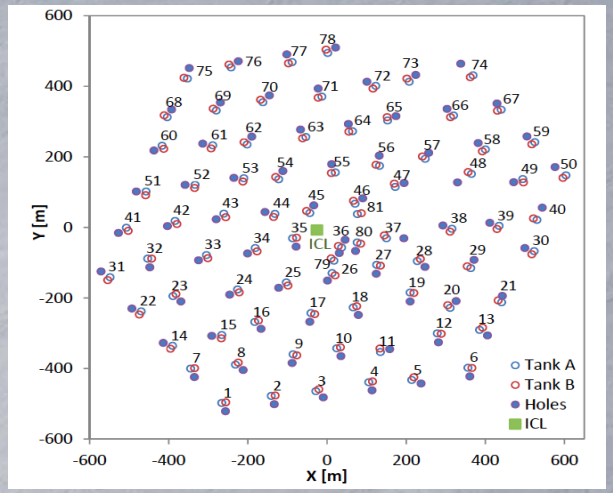


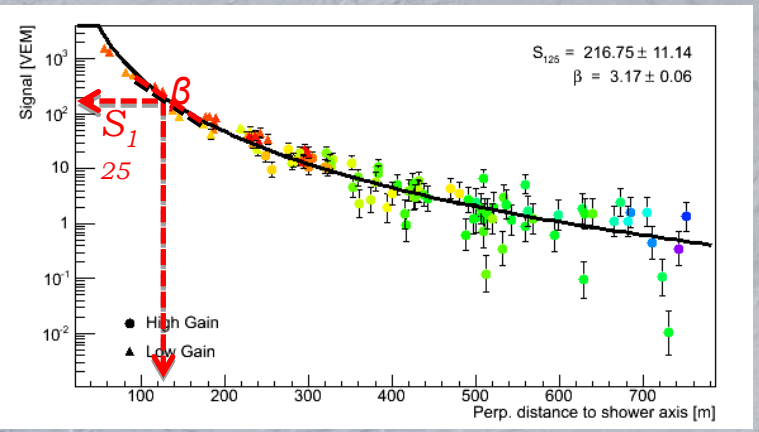
- Energy range: 100TeV – 1EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

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

IceTop



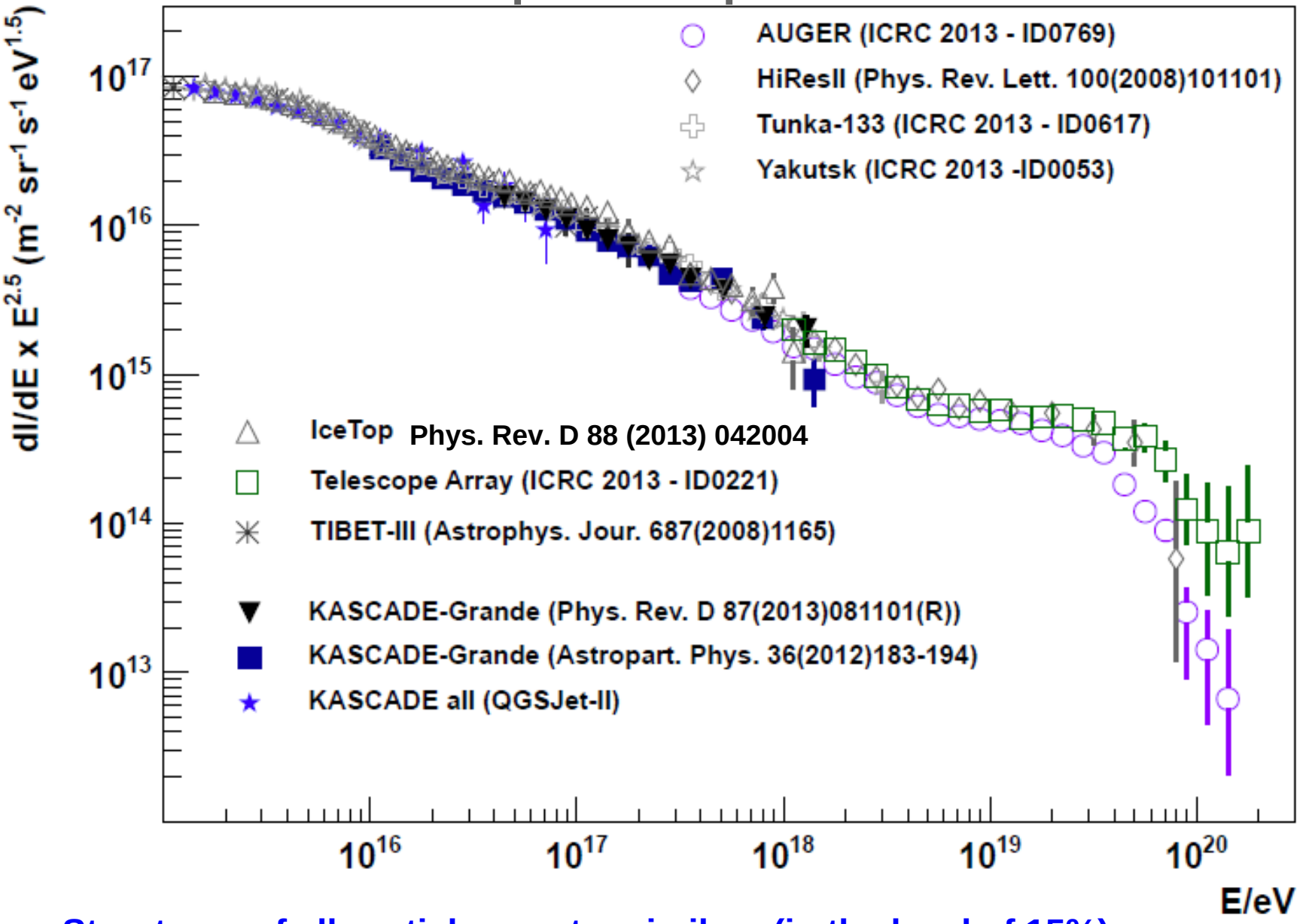




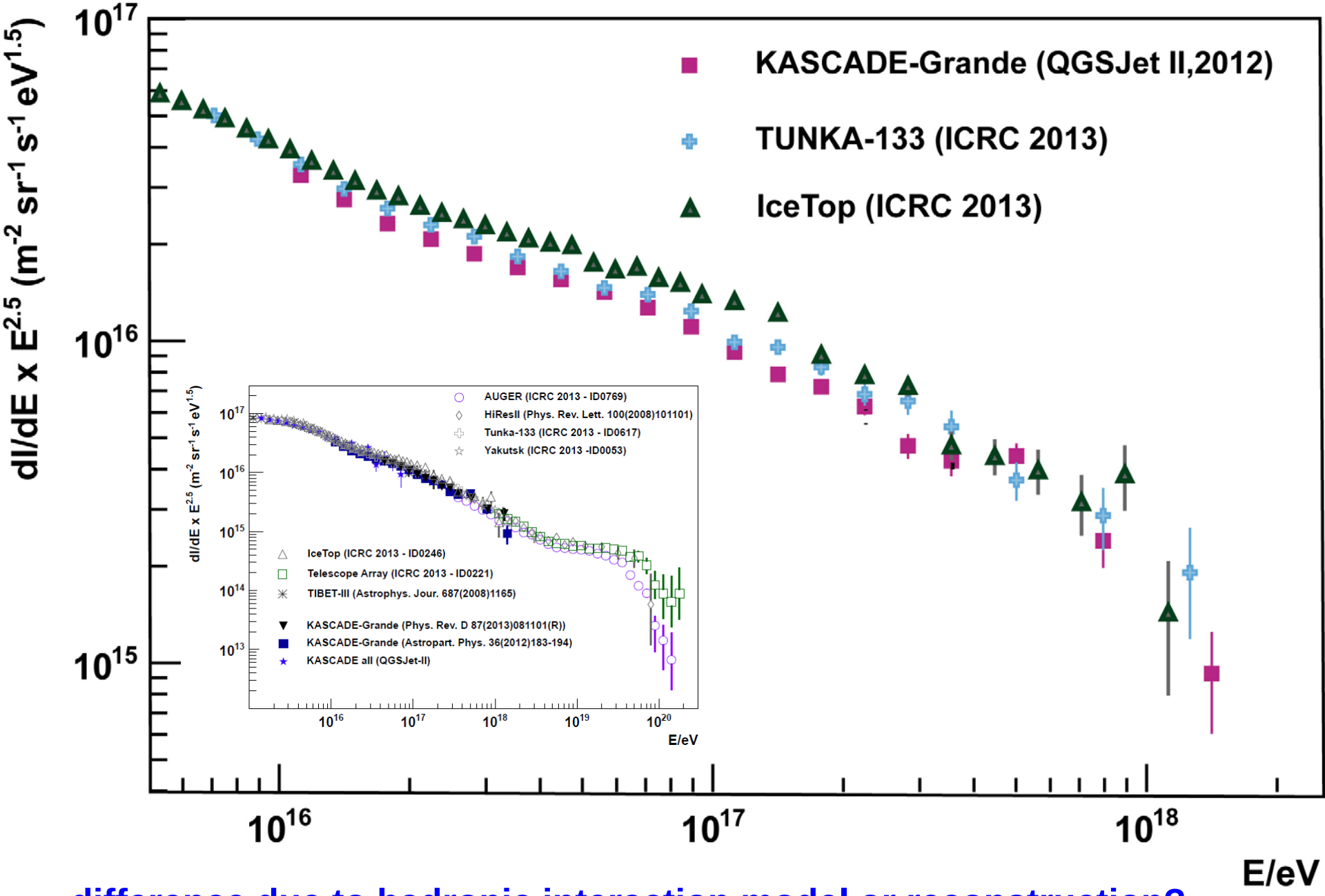
- **Energy range: PeV – 1EeV**
- **Area: 1 km^2**
- **2835m altitude (680 g/cm^2)**
- **81 ice cherenkov stations**
- **LDF + particle density at 125m**
- **in-ice high-energy muons**

Phys Rev D 88 (2013) 042004

All-particle spectra

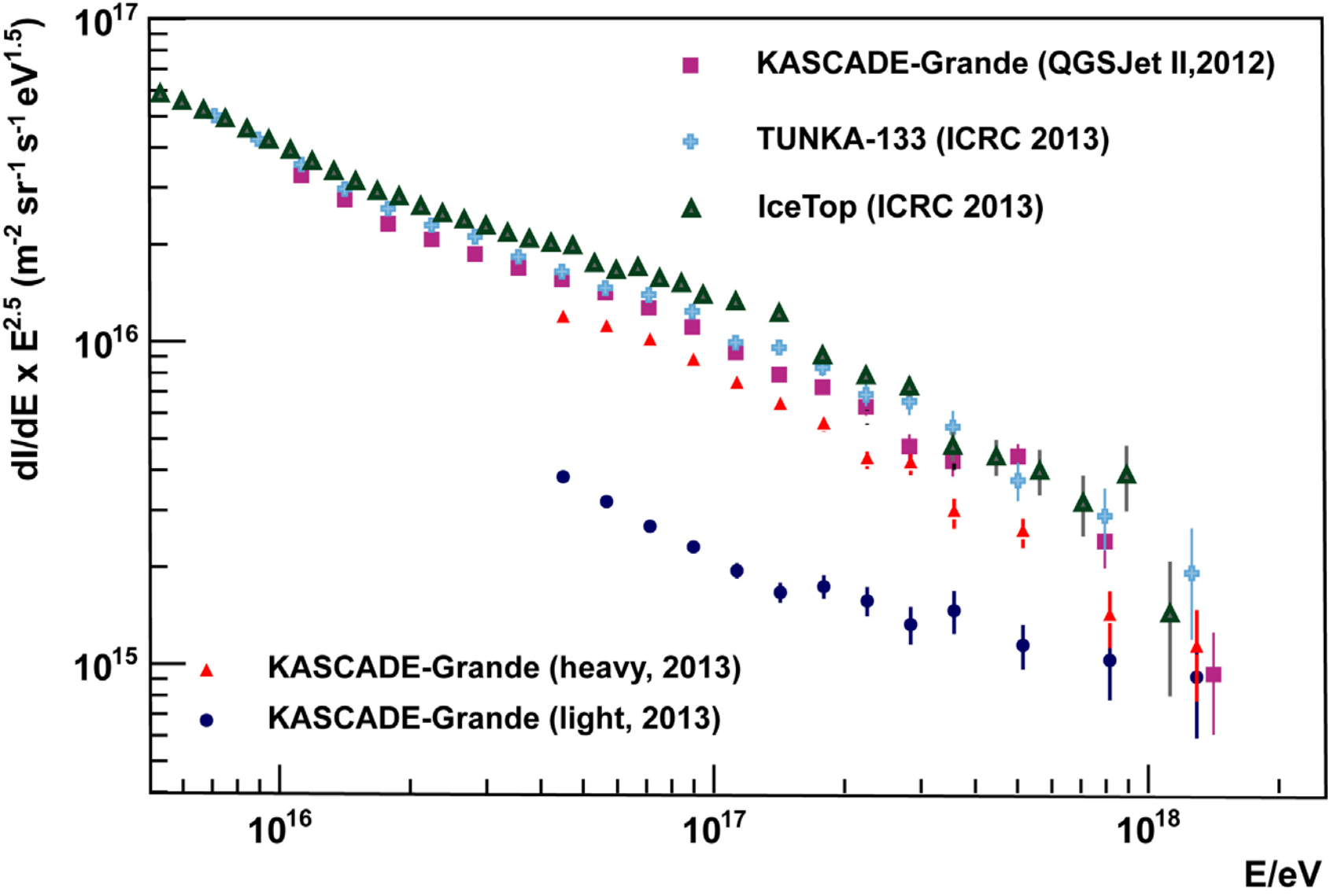


- Structures of all-particle spectra similar (in the level of 15%)



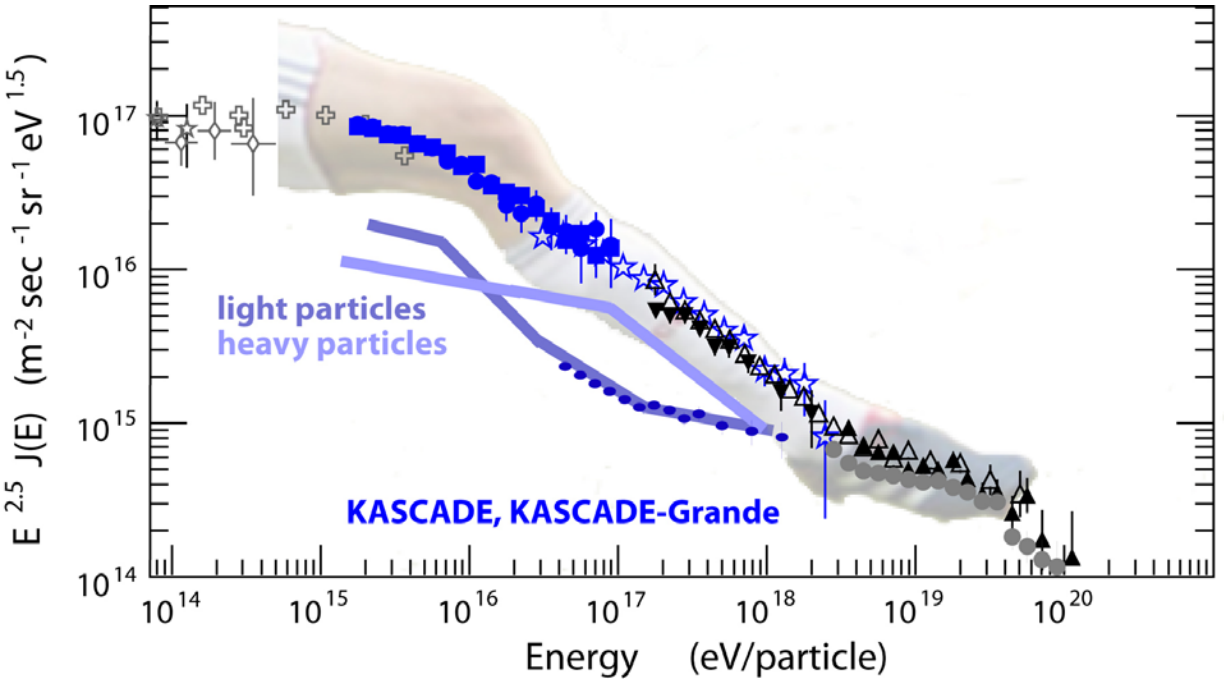
difference due to hadronic interaction model or reconstruction?

All-particle spectra



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

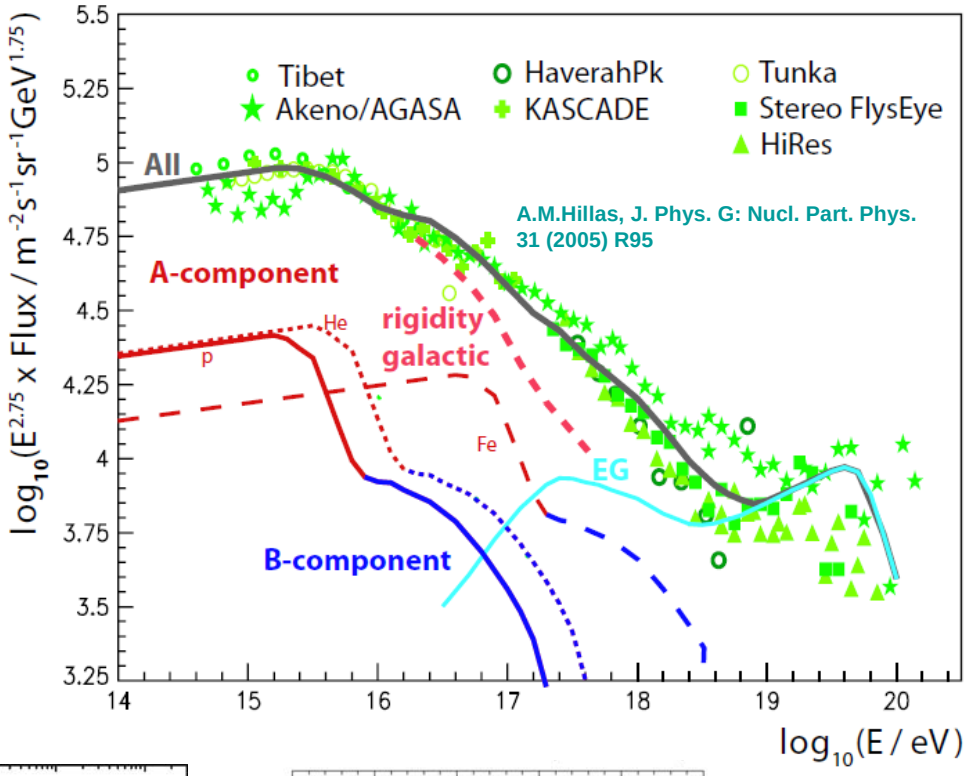
Light and Heavy Knees, Ankles, and Transition

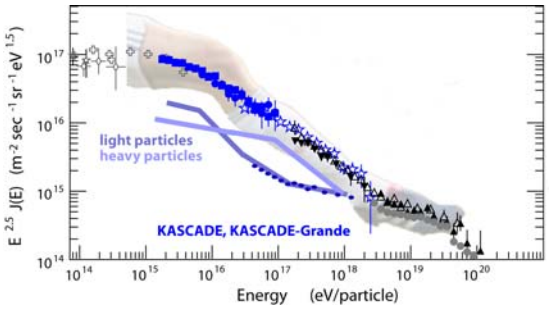


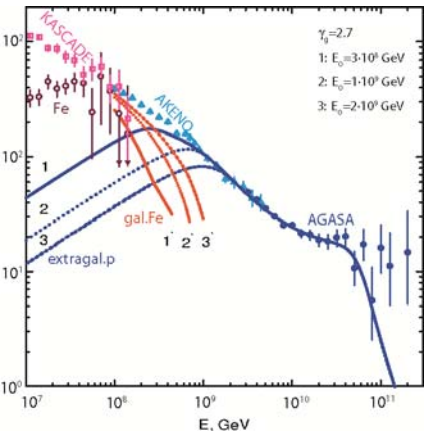
- ➔ **KASCADE: knee of light primaries at ~3·10^{15}eV**
- ➔ **Hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~9·10^{16} eV**
- ➔ **heavy knee less distinct compared to light knee**
- ➔ **mixed composition for 10^{15} to ~ 8·10^{17} eV**
- ➔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

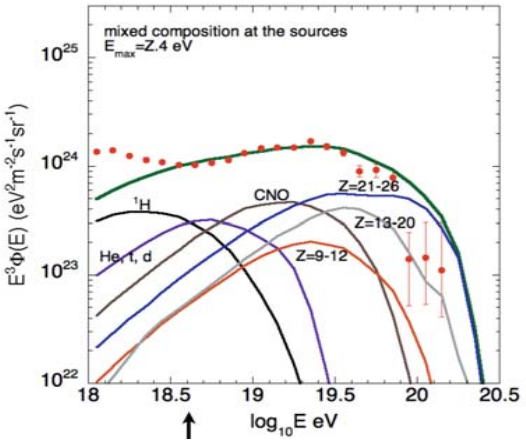
knee position $\propto Z$

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

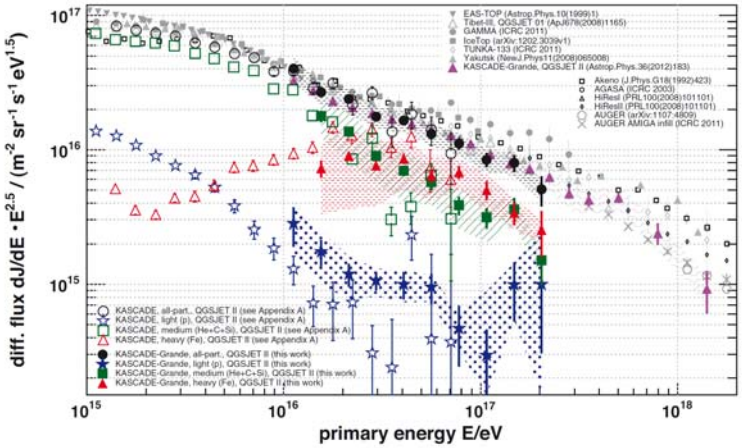
D.Allard, astro-ph/1111.3290

KASCADE-Grande: Next



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

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

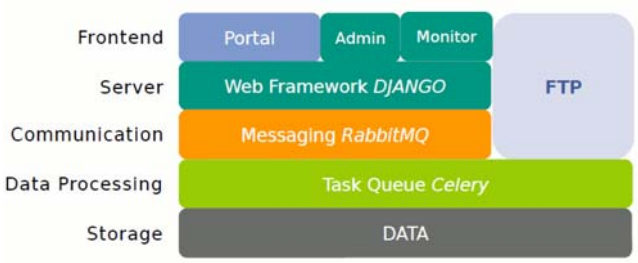


- **detailed data analysis (20y high-quality data)**
  - **testing hadronic interaction models**
  - **anisotropy studies**
  - **radio (LOPES and CROME)**

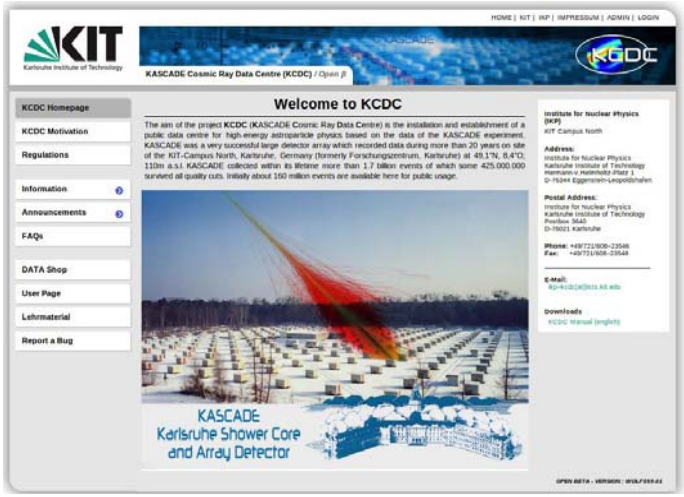
- **KCDC**
  - **KASCADE Cosmic ray Data Centre**

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

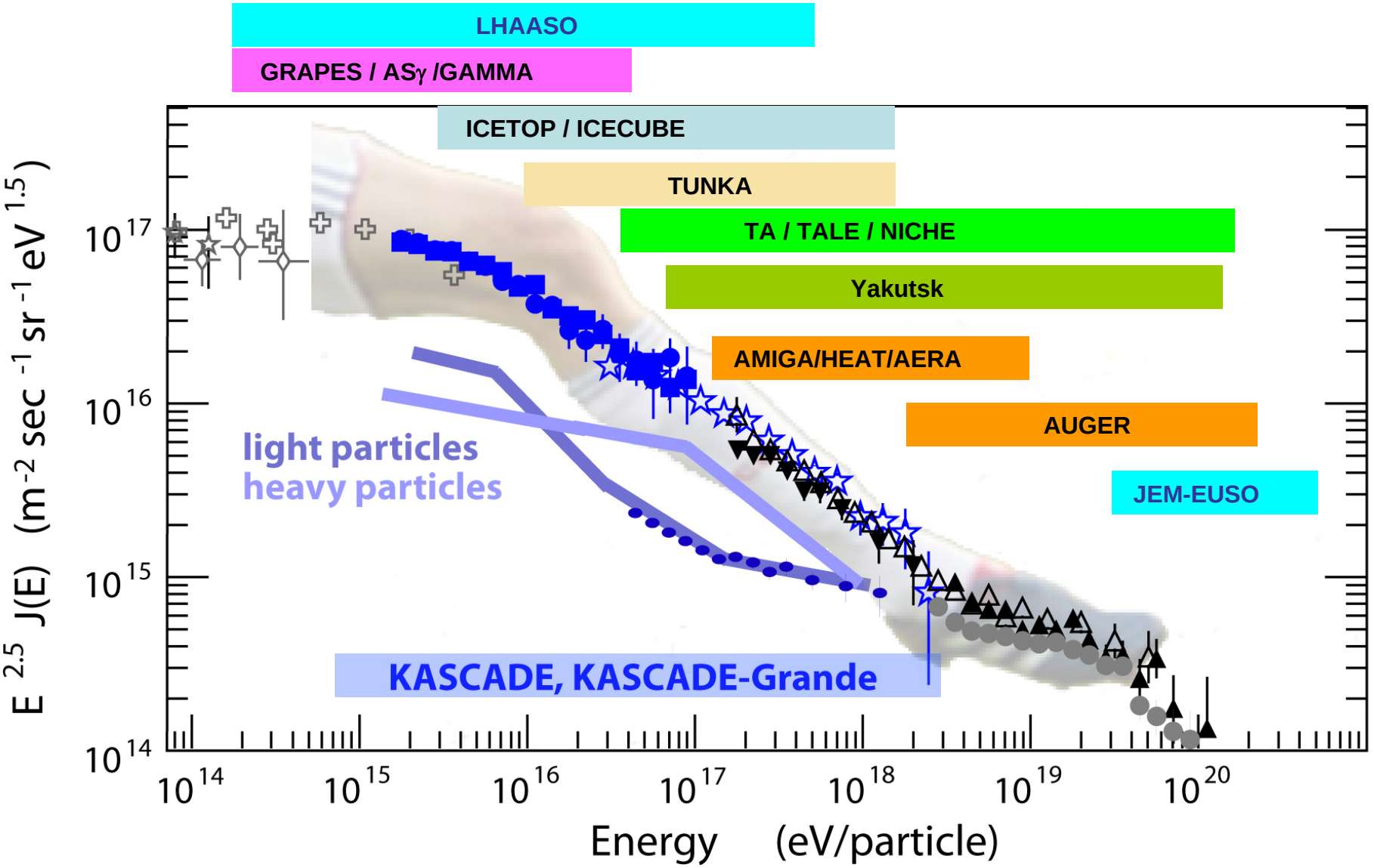


- **Data access:**
  $1.6 \cdot 10^8$ EAS events of first data release is now available

KASCADE-Grande: Mission Accomplished !!

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

Summary



answers only by combining all information: stay tuned!