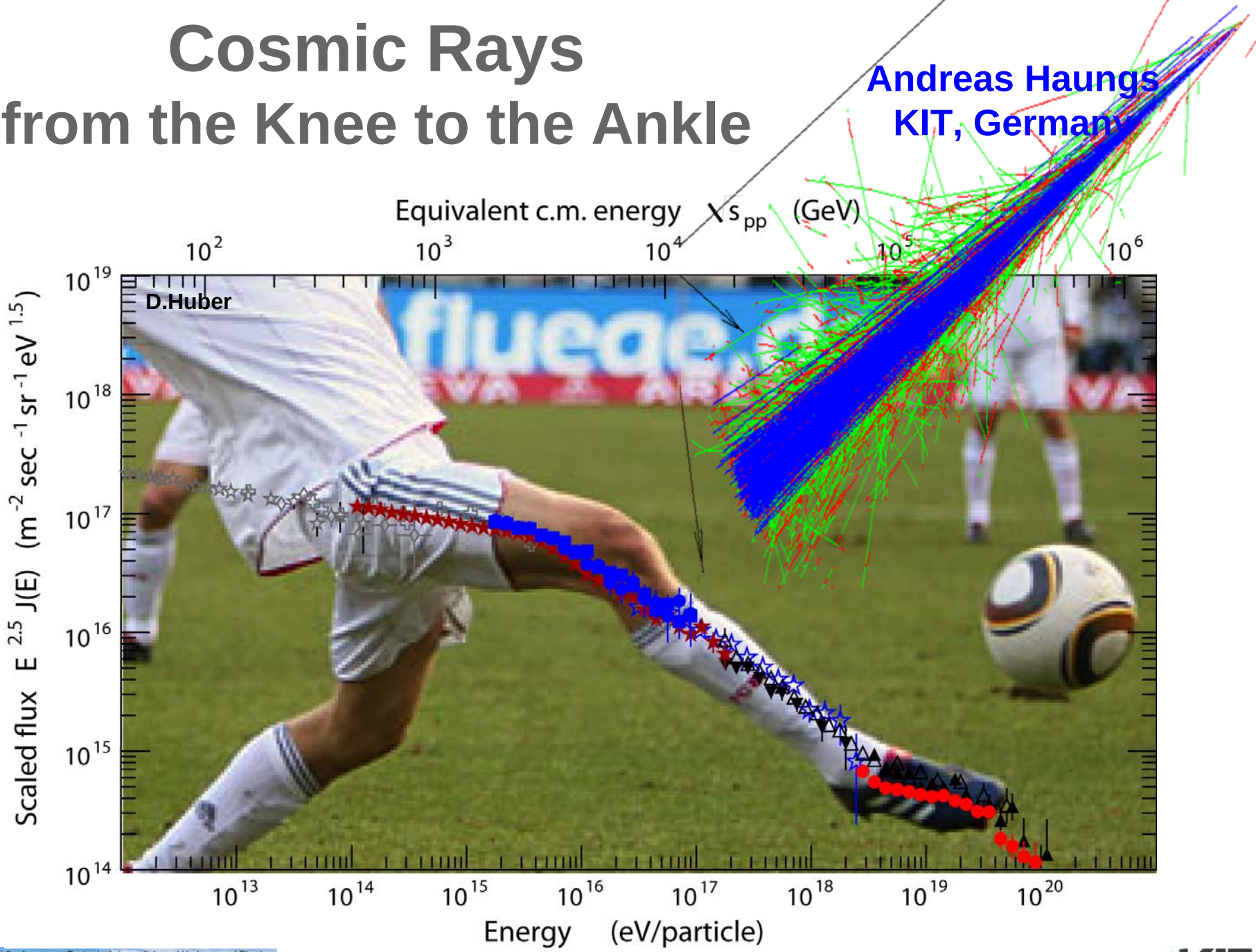
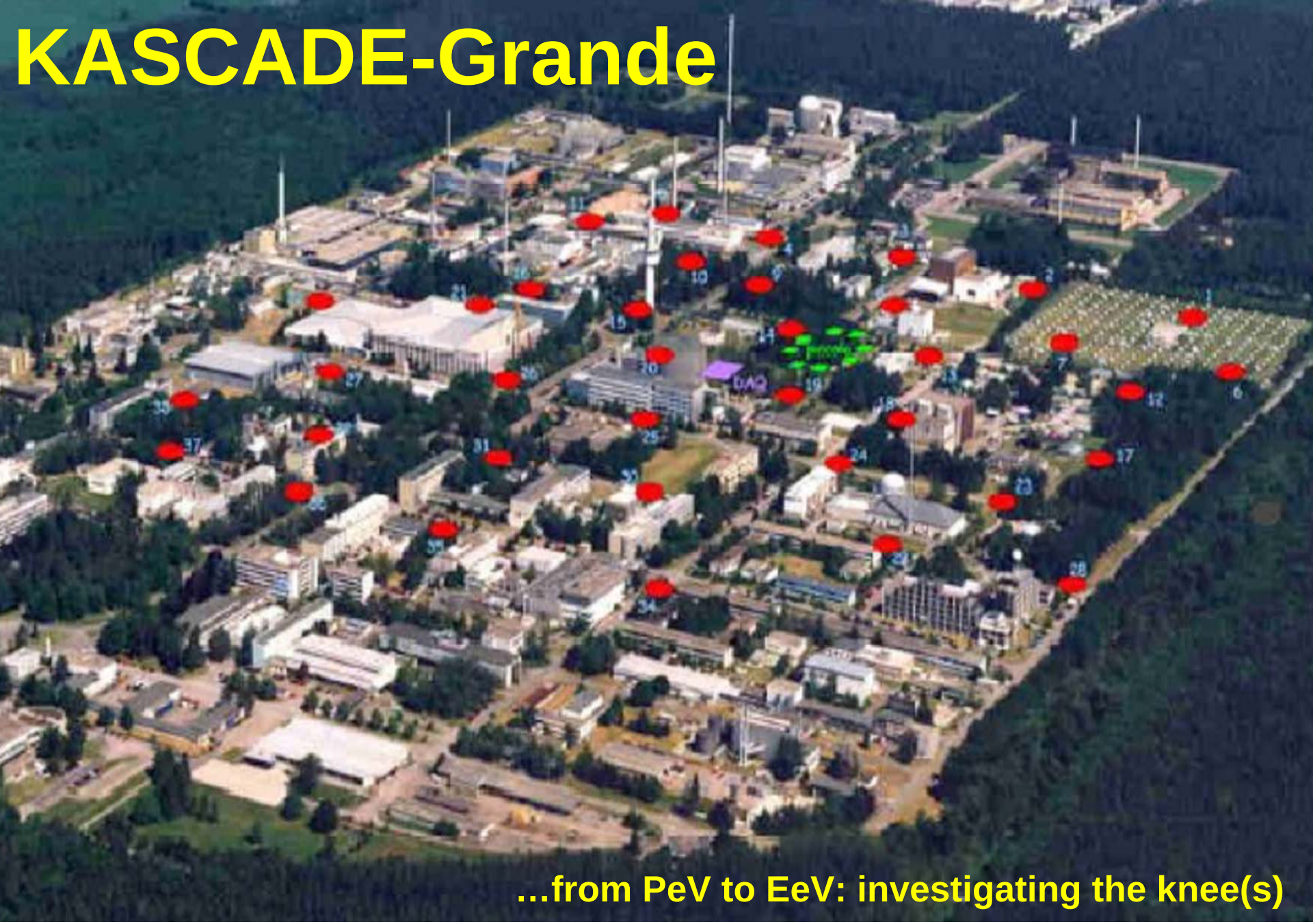
Cosmic Rays
from the Knee to the Ankle

Andreas Haungs
KIT, Germany



KASCADE-Grande

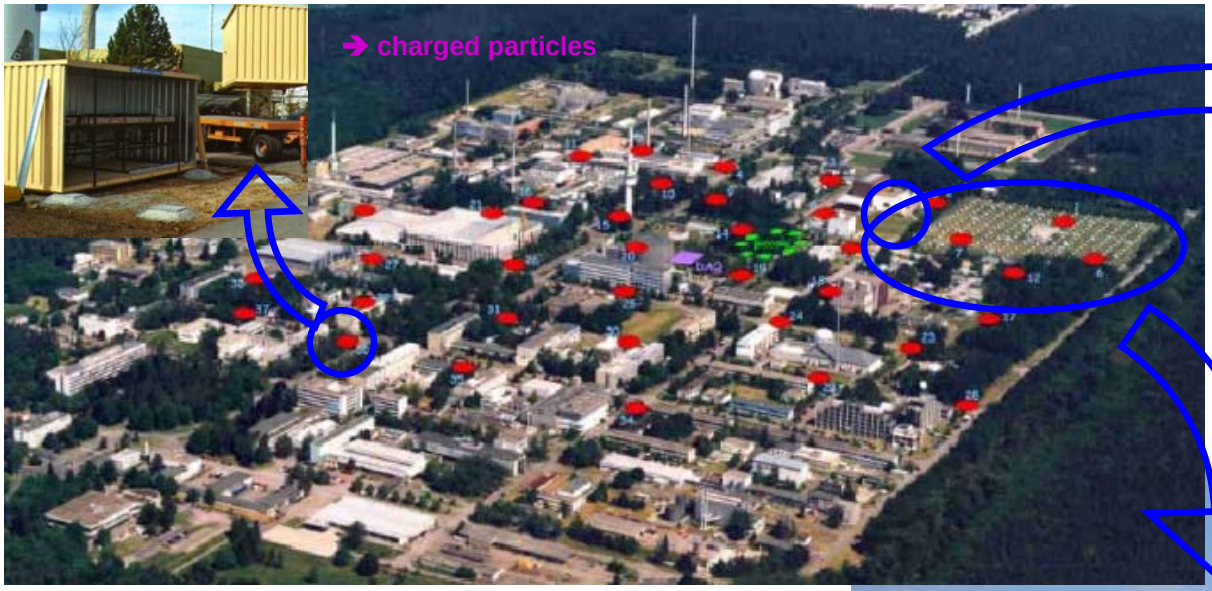


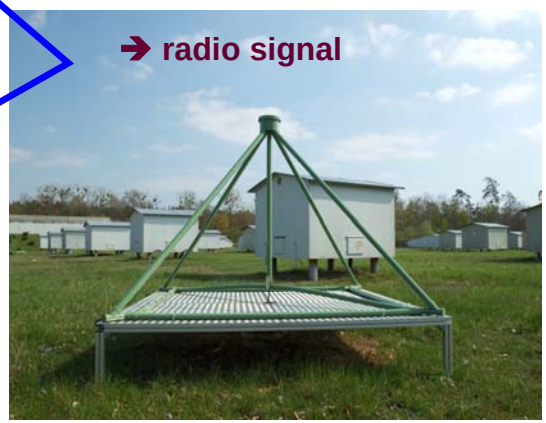
…from PeV to EeV: investigating the knee(s)

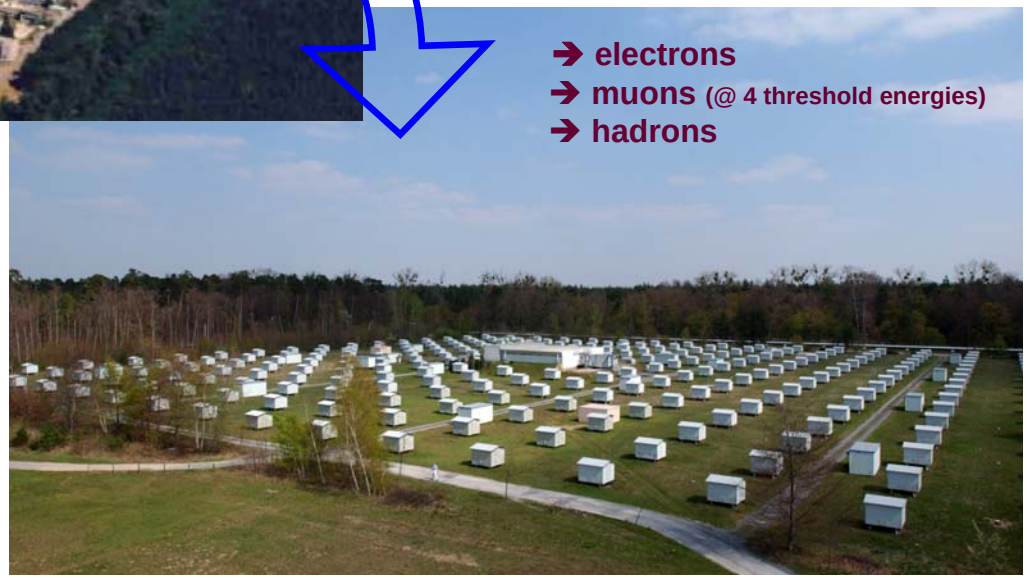
KASCADE-Grande

= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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

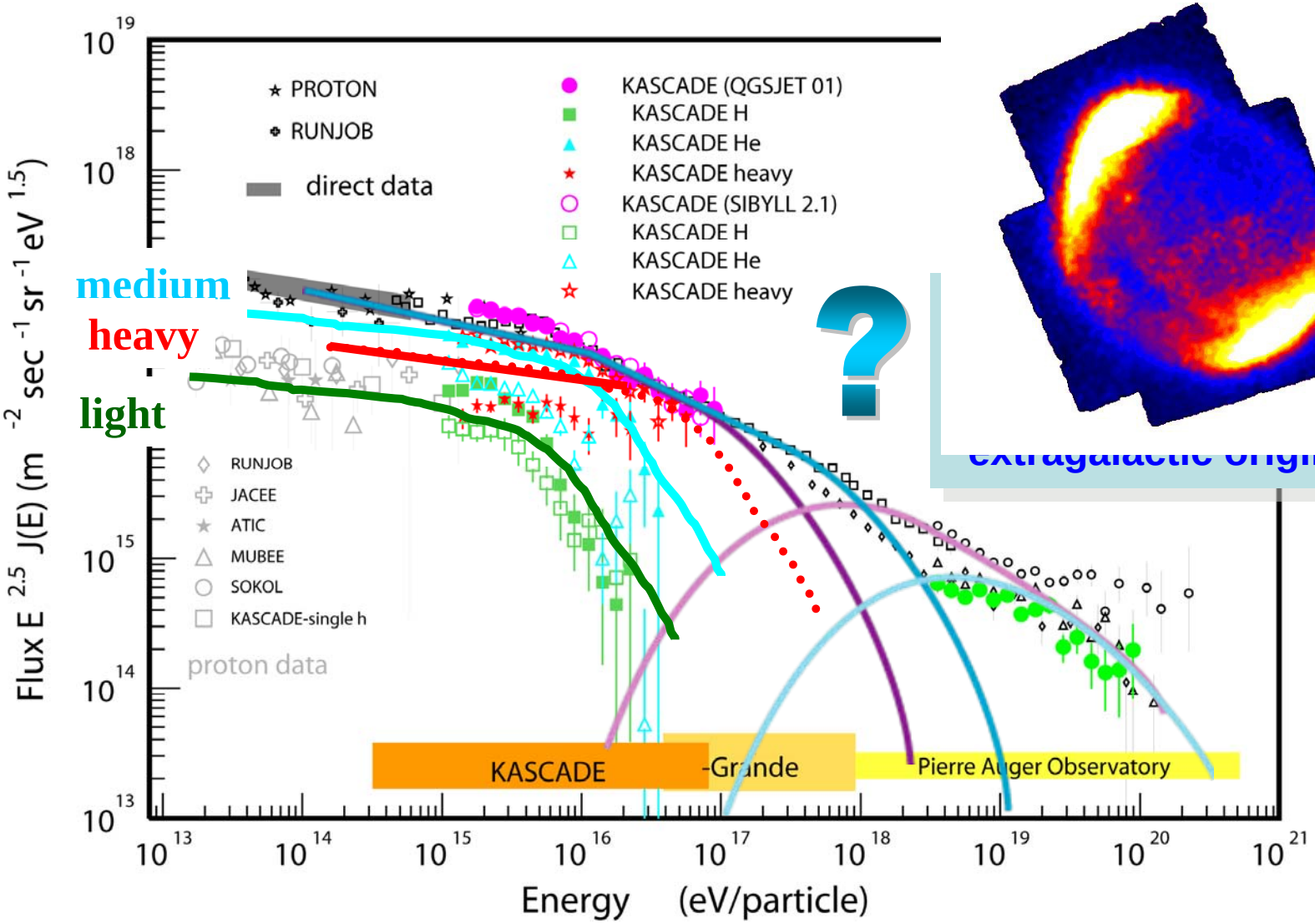


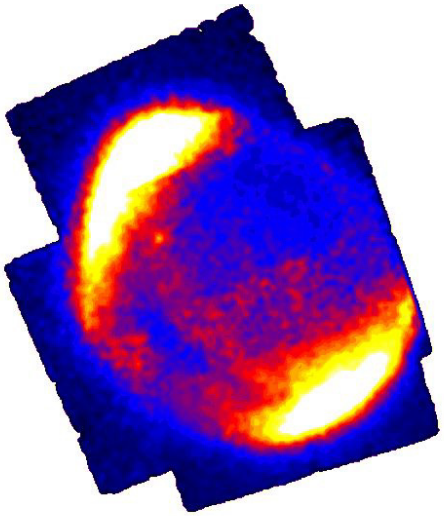




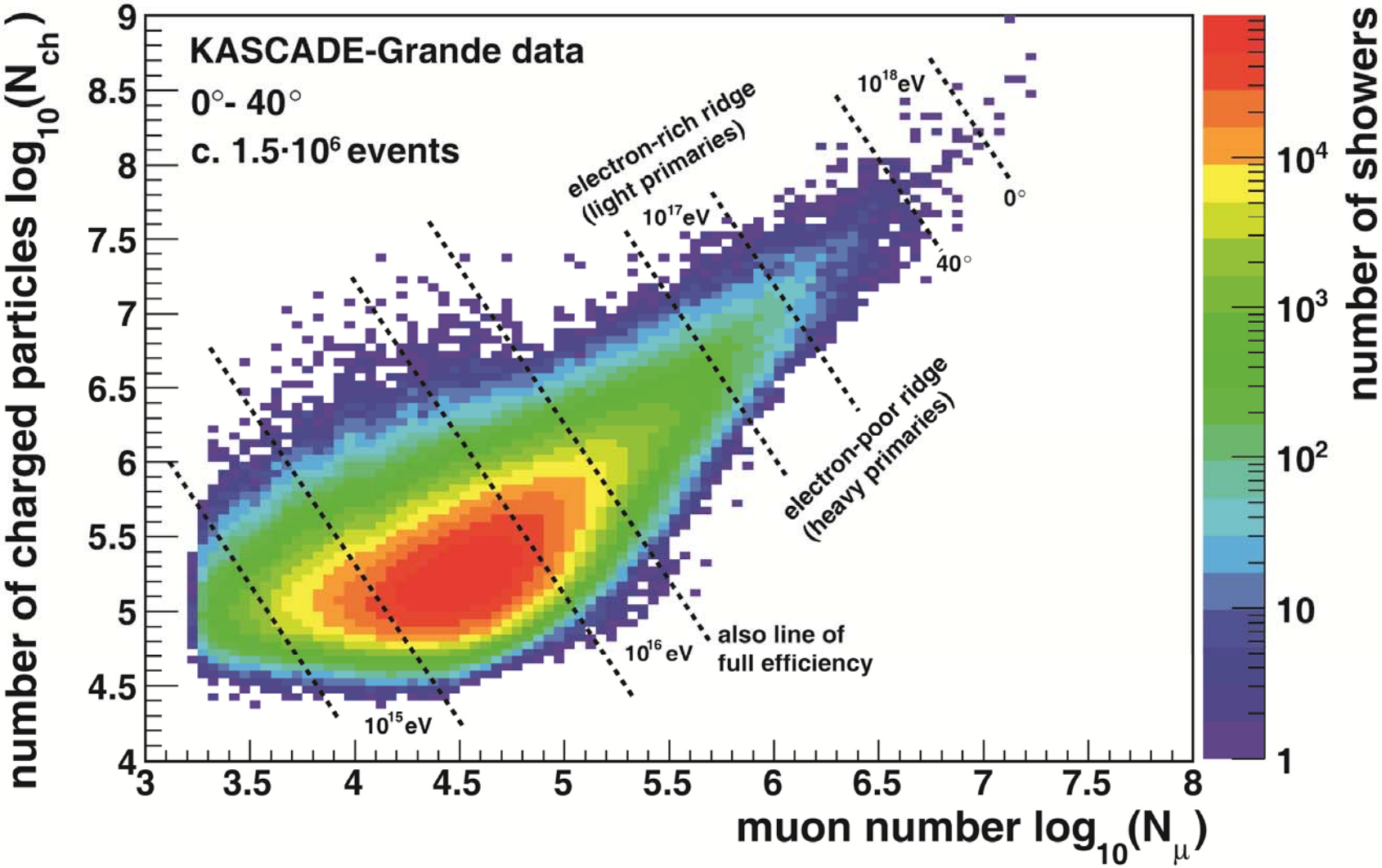
- **core and direction** (from Grande)
- **shower size** (charged particles)
- **muon number** (from KASCADE)
- **local muon density** (from KASCADE)
- **local charged particle density S(500)**
- **...**

Result KASCADE ➔ Motivation KASCADE-Grande





2-dimensional shower size spectrum



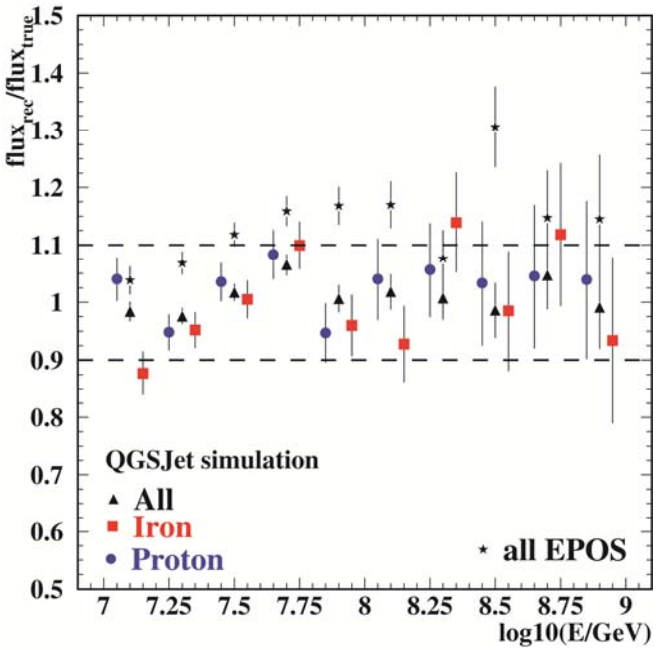
➔ **determination of primary energy**

➔ **separation in "electron-rich" and "electron-poor" event**

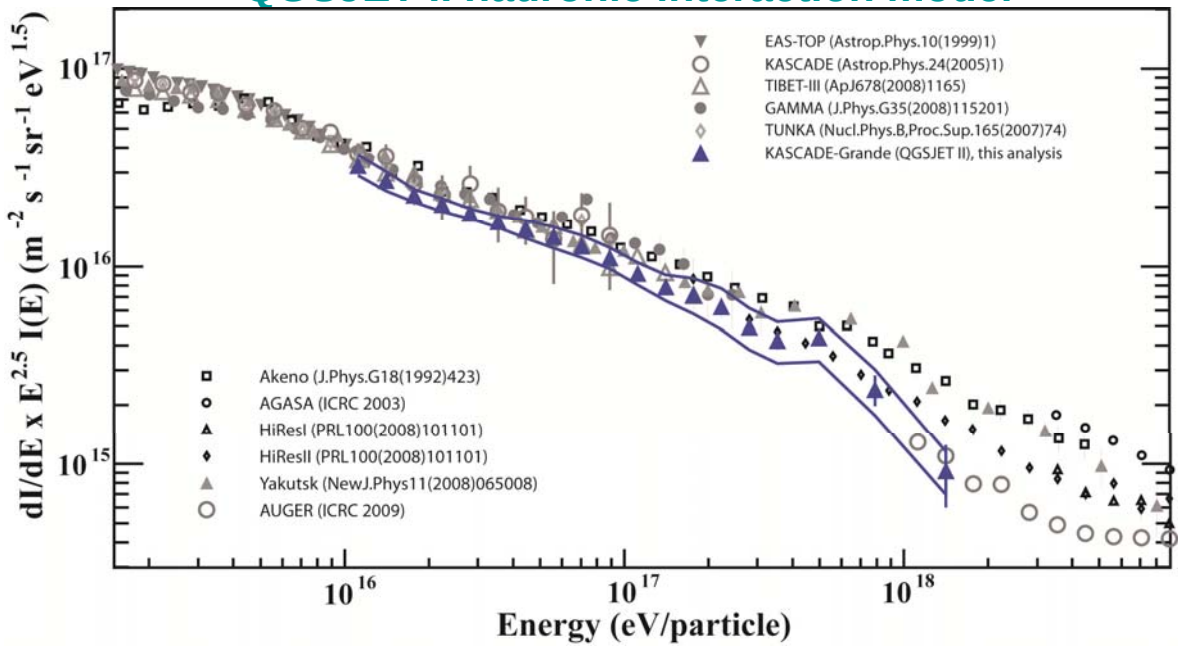
All-particle energy spectrum :

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

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



QGSJET II hadronic interaction model

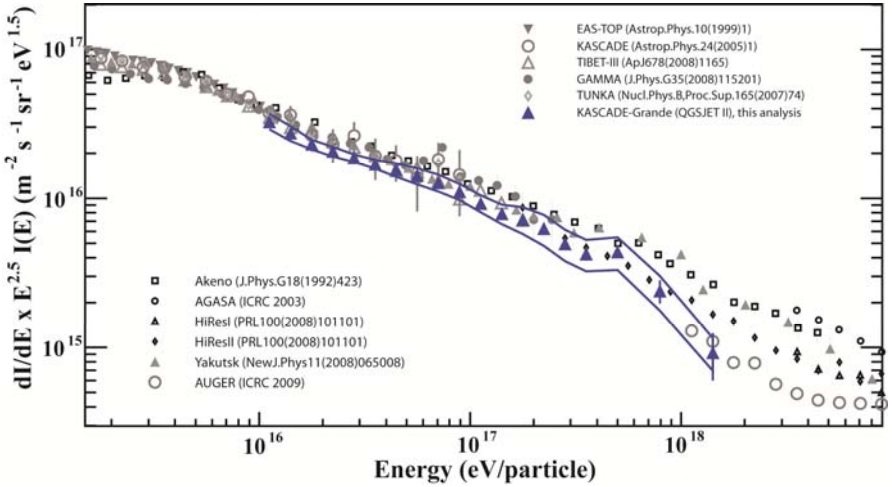


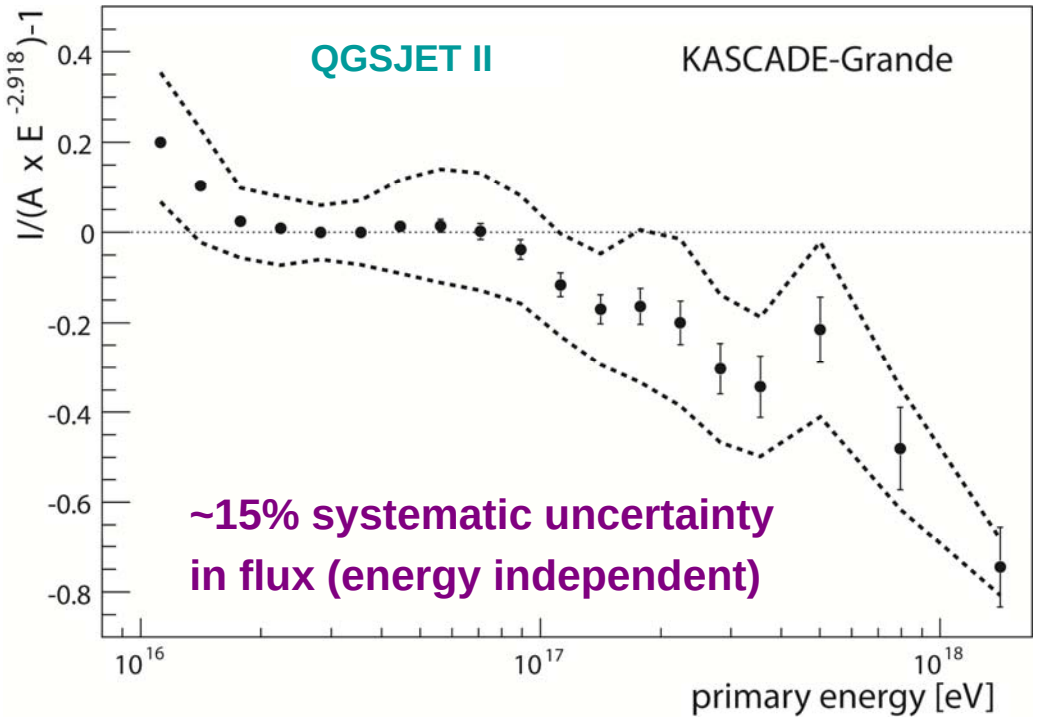
-different zenith angle bins
-no composition dependence

Astroparticle Physics 36 (2012) 183

KASCADE-Grande
all-particle energy spectrum

Astroparticle Physics 36 (2012) 183

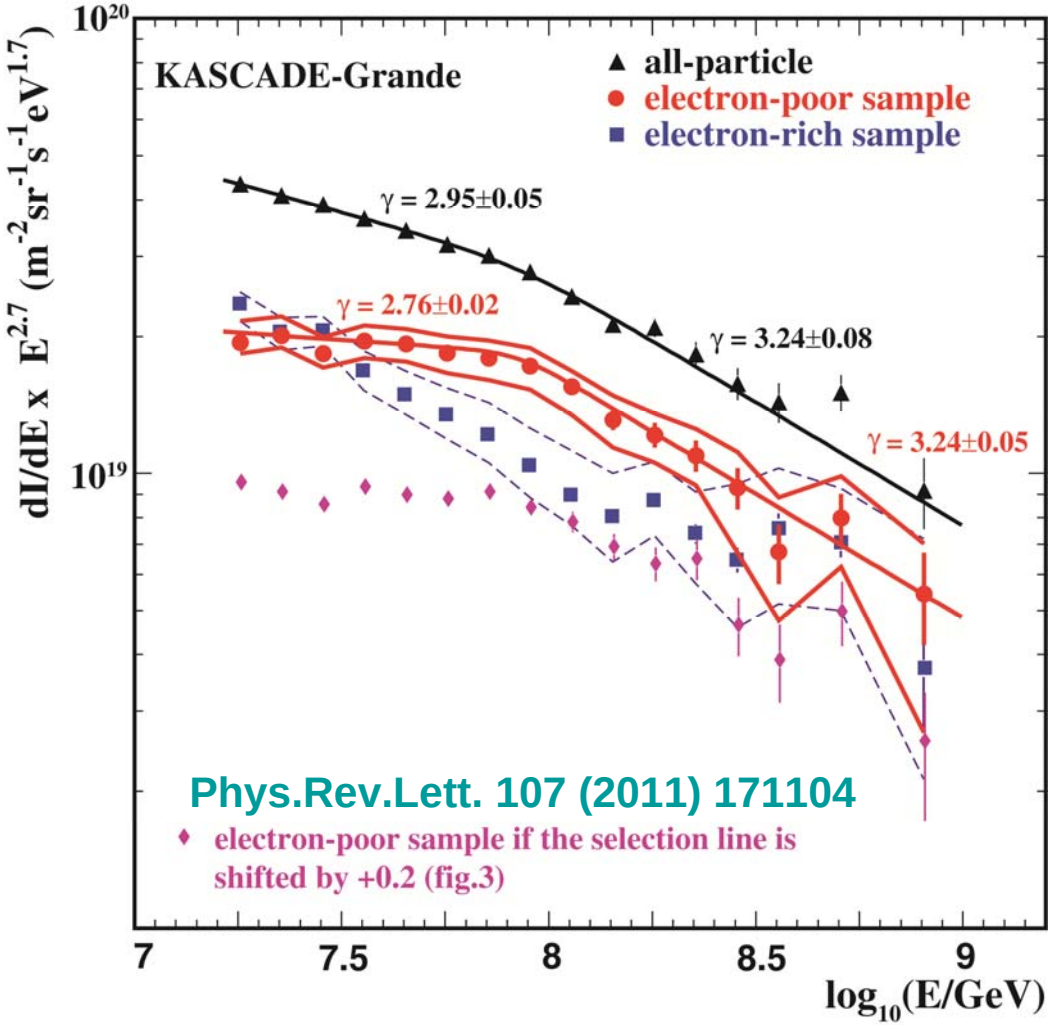




- **spectrum not a single power law**
- **hardening of the spectrum above 10^{16}eV**
- **steepening close to 10^{17}eV (2.1σ)**

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:

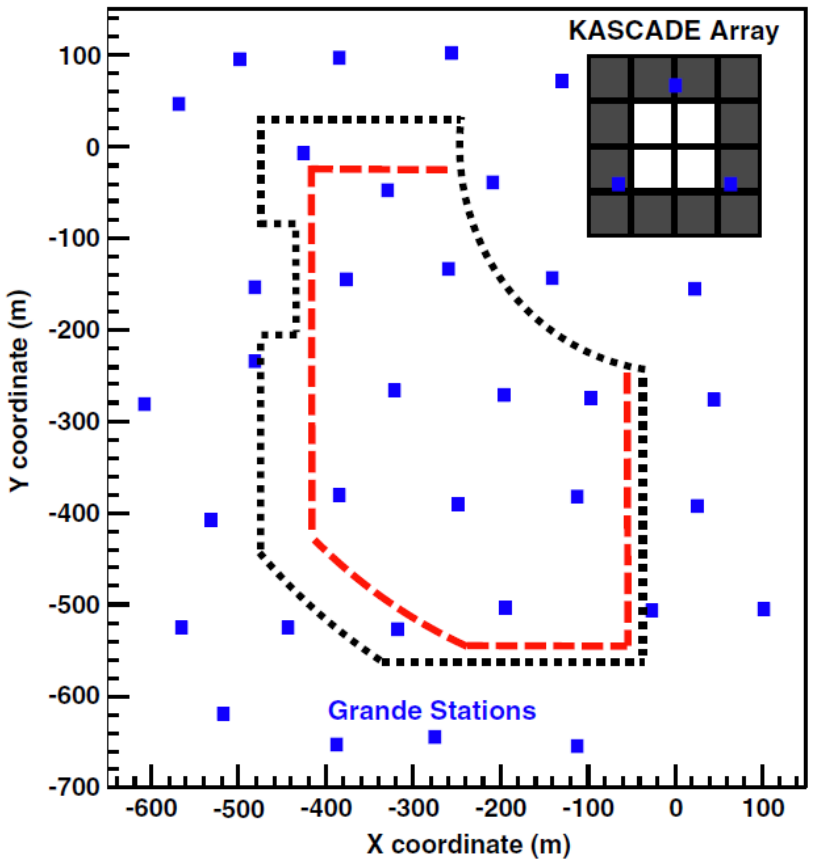
➔ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

➔ 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

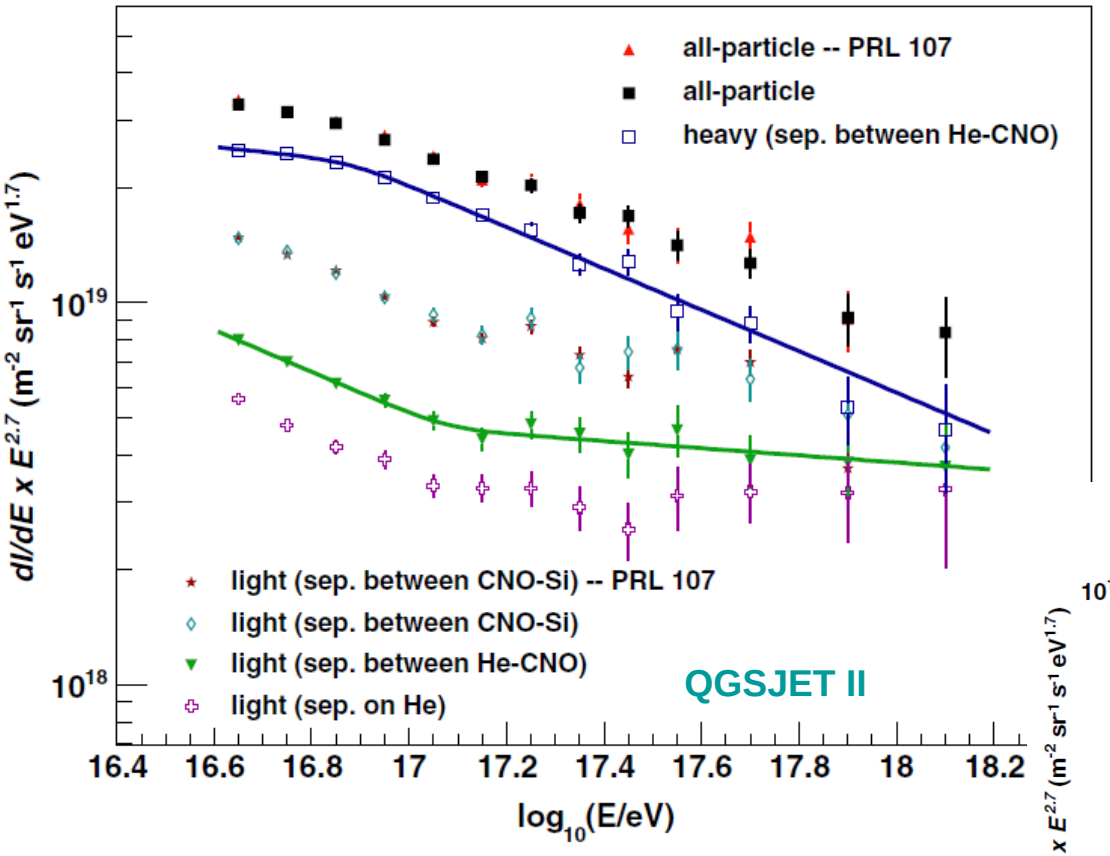


- **re-investigation of the spectrum of light primaries:**

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

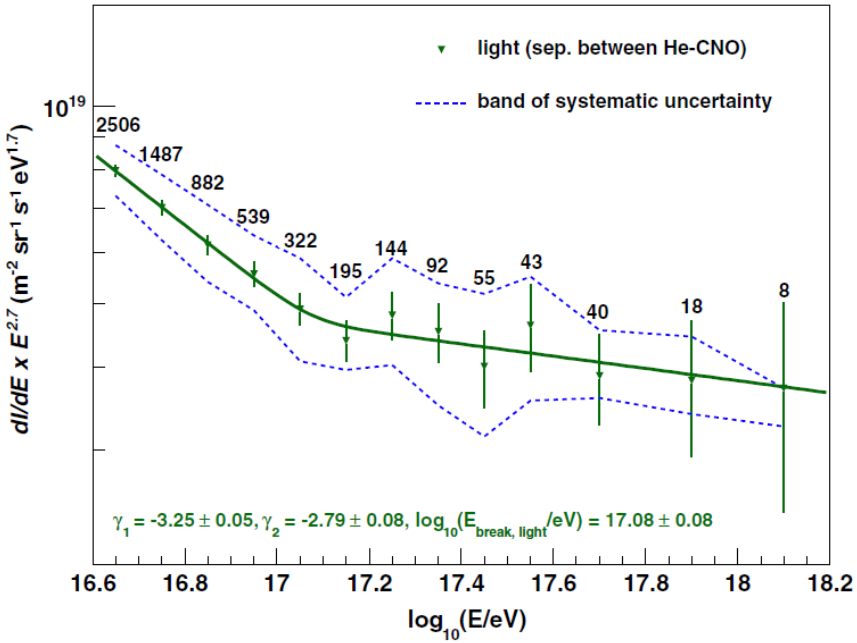
Phys.Rev.D (R) 87 (2013) 081101

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!**



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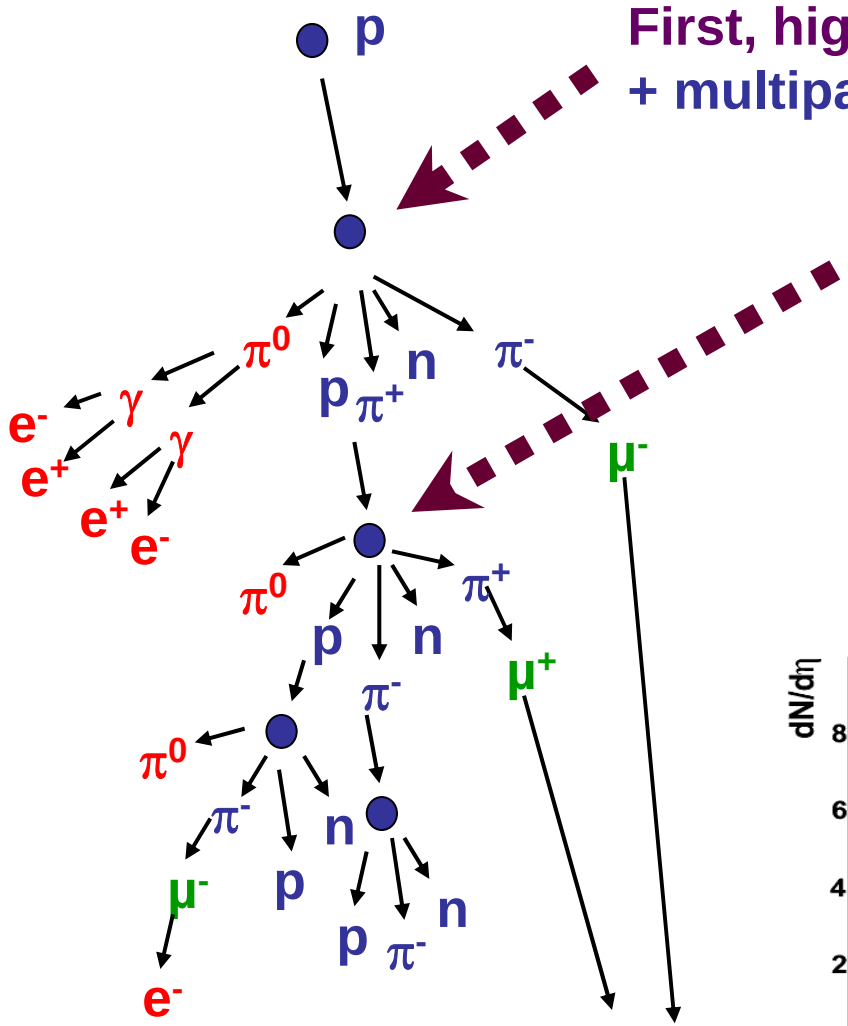
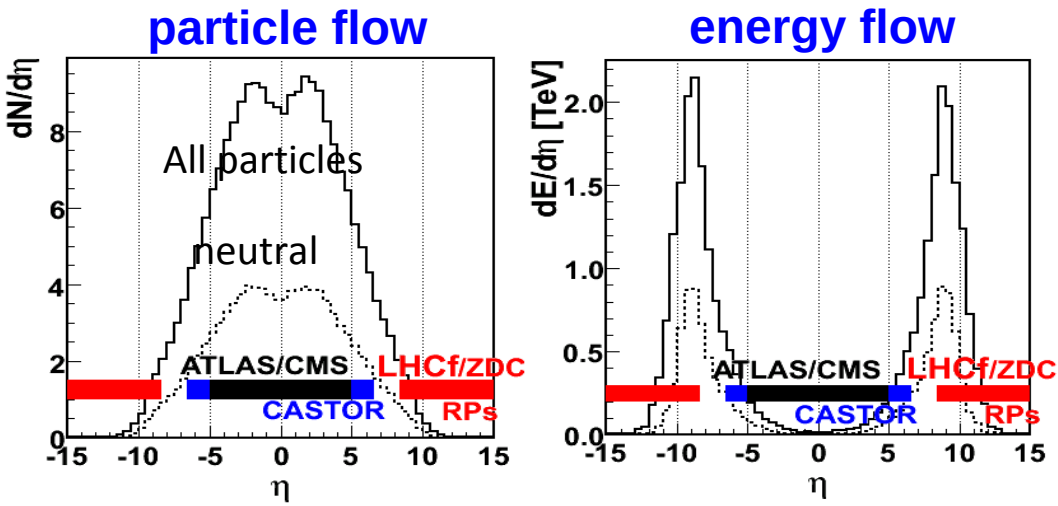
observation of a „light“ ankle at 1-2·10^{17} eV

Validity of Hadronic Interaction Models

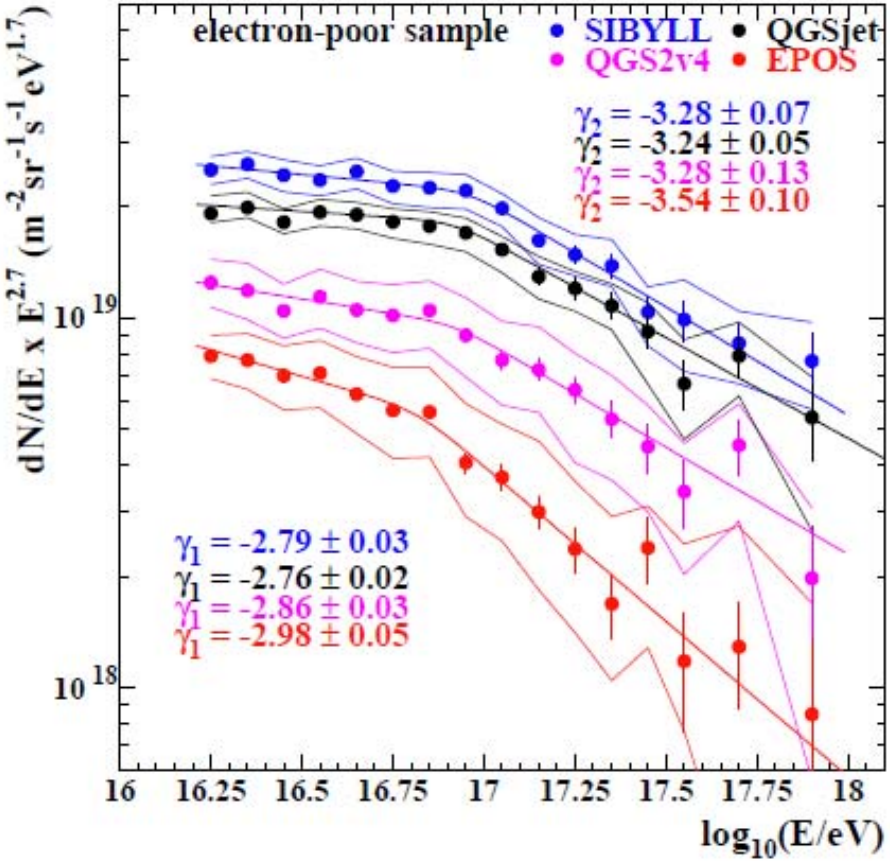


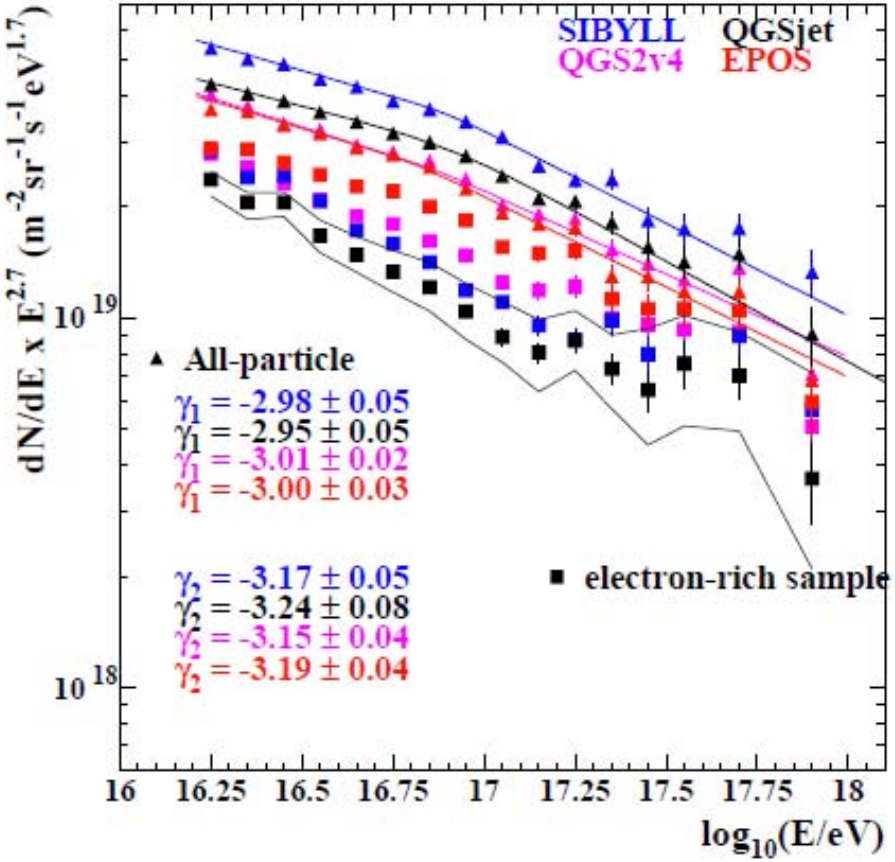
First, high energy interaction: LHC
+ multiparameter measurements EAS

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 (2013) accepted - dx.doi.org/10.1016/j.asr.2013.05.008

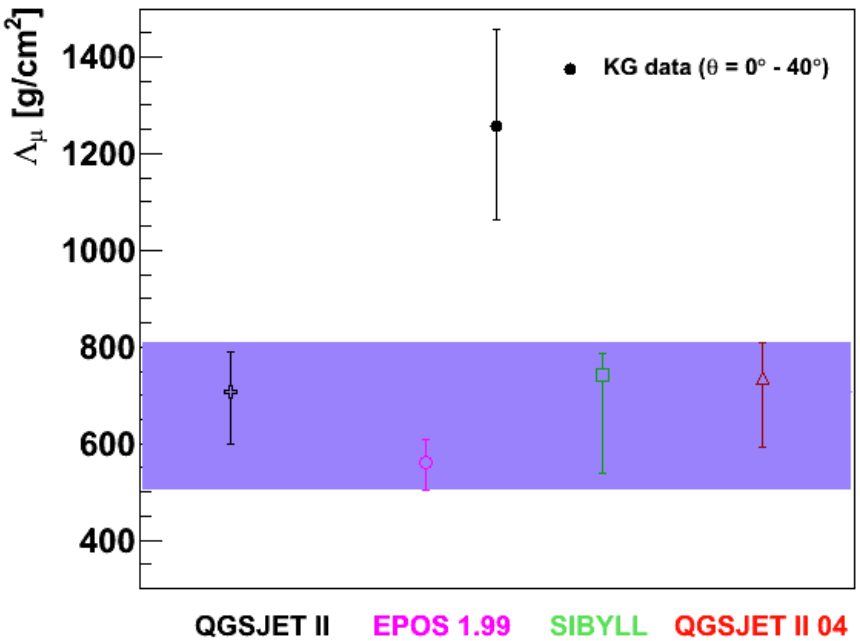
KASCADE-Grande: Muon Attenuation Length

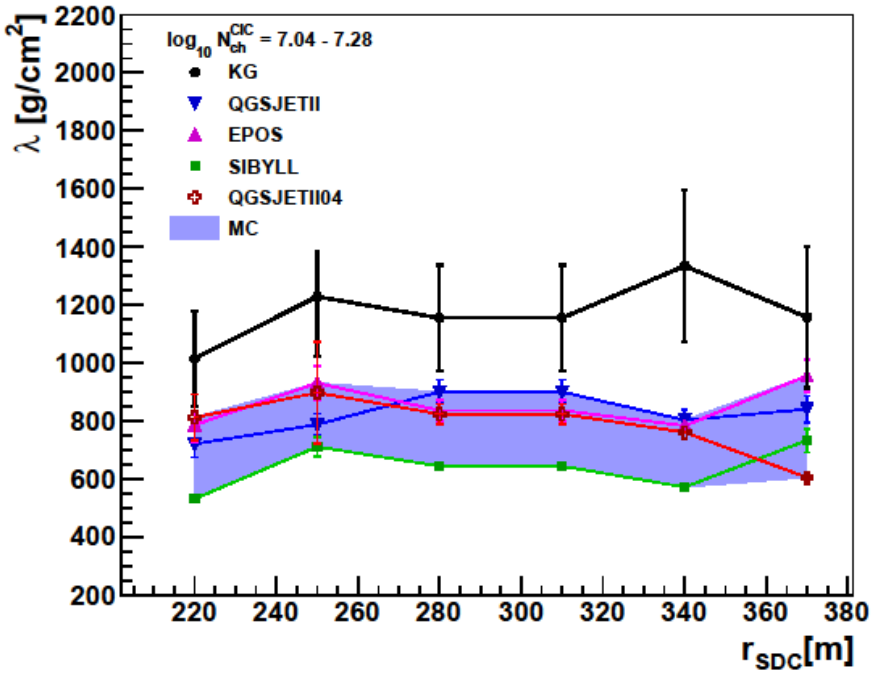
total muon number

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

local muon density

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



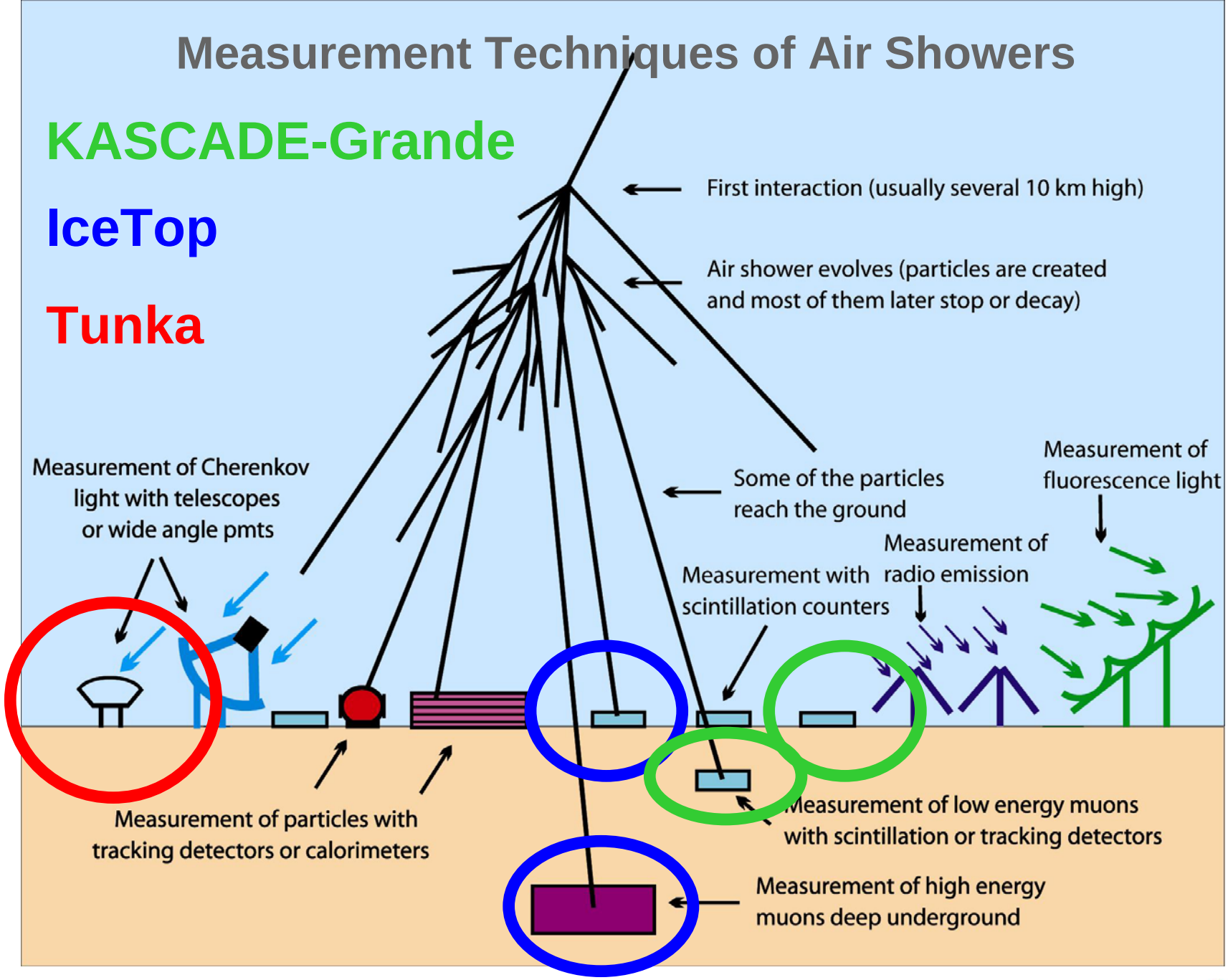


attenuation length measured is different from the predictions of Monte Carlo
➔ observed evolution of the muon content of EAS in the atmosphere is not described by the hadronic interaction models
➔ influences absolute energy and mass scale, but not spectral features

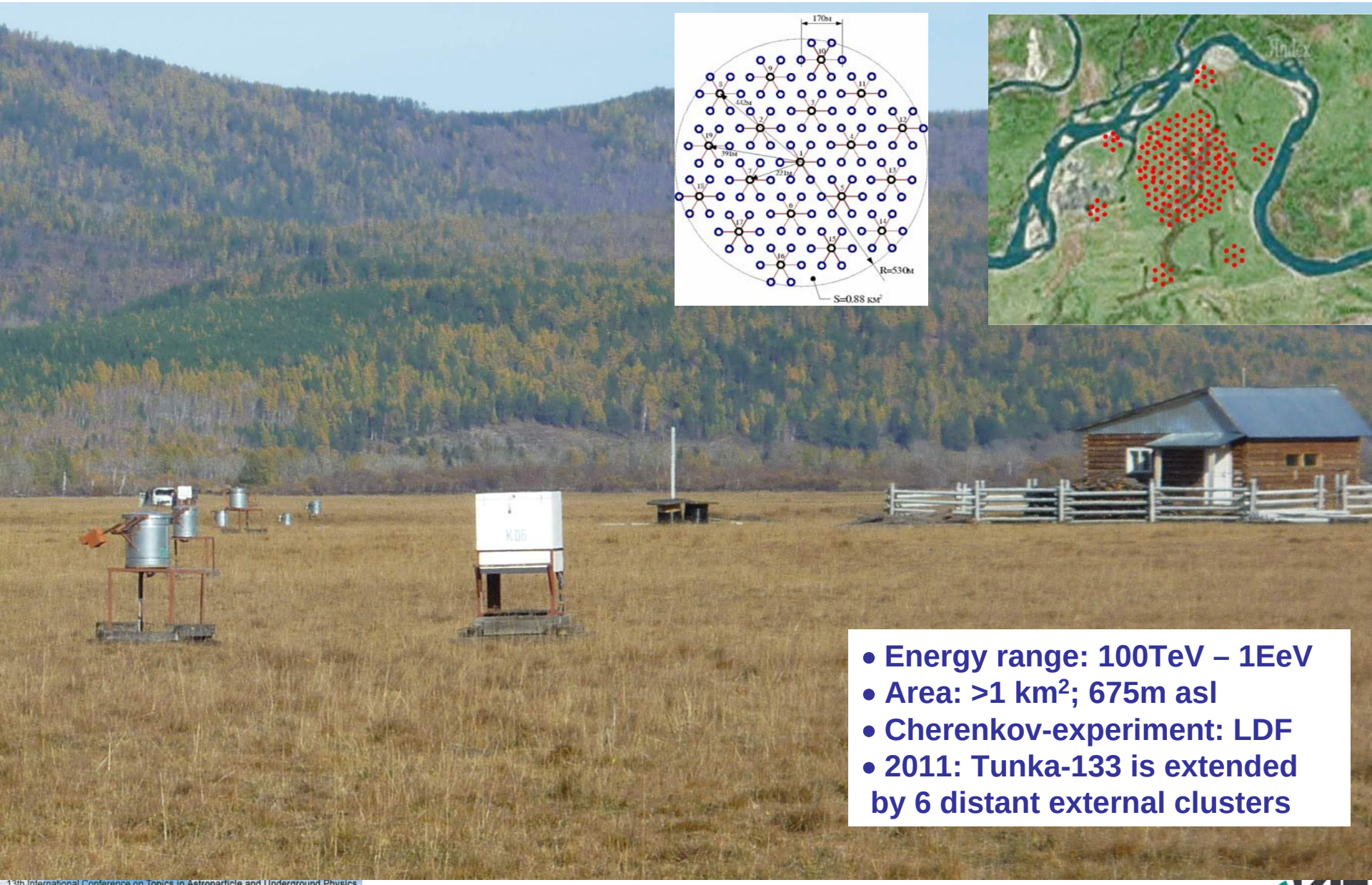
KASCADE-Grande, ICRC 2013 #0772, paper in preparation

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

Measurement Techniques of Air Showers



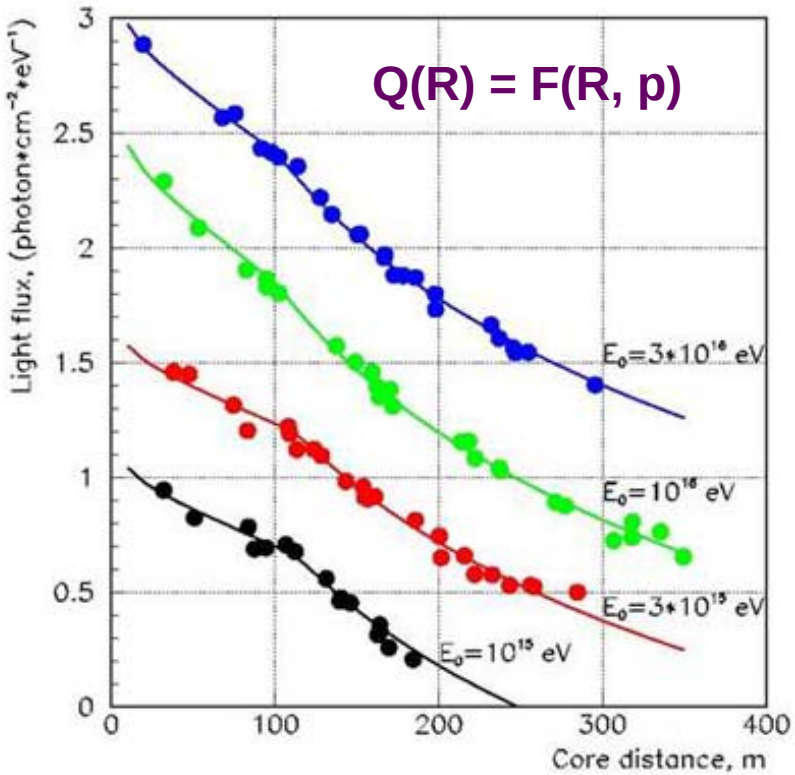
Tunka-133



- Energy range: 100TeV – 1EeV
- Area: >1 km^2; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

Tunka-133: reconstruction of energy spectrum and composition

Experimental data fitted with LDF

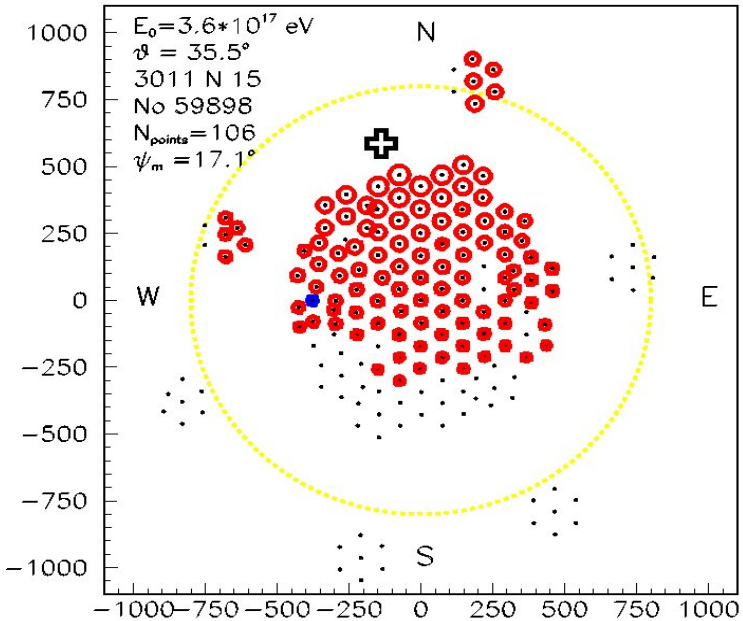


light flux at core distance 200 m

Q_{200} ~ Energy

steepness of LDF

P = Q(100)/Q(200) ➔ X_{max}

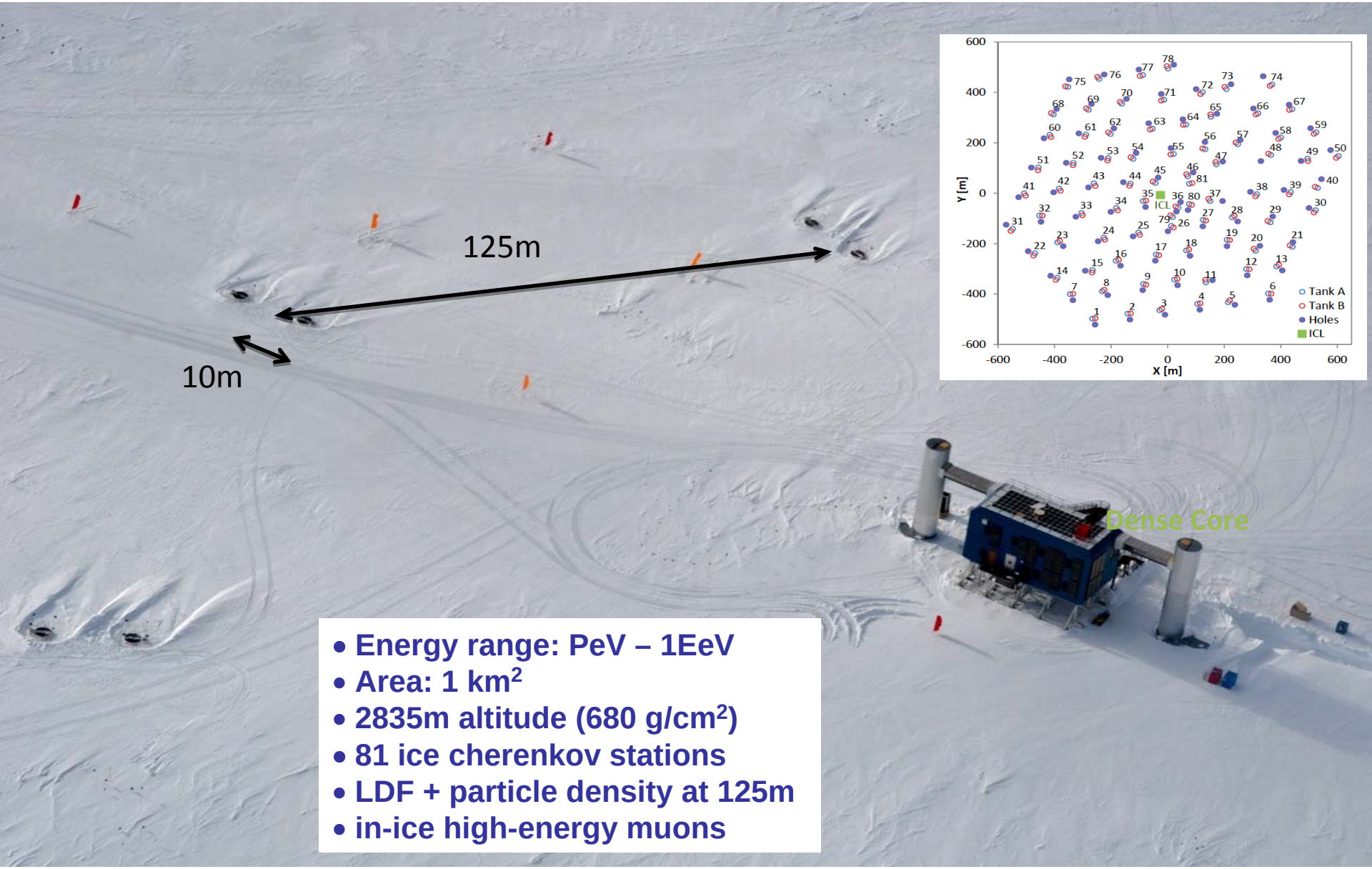


Accuracy: core location ~ 10 m
energy resolution ~ 15%
$\delta X_{max} < 25$ g·cm^{-2}

Energy threshold 10^{15} eV

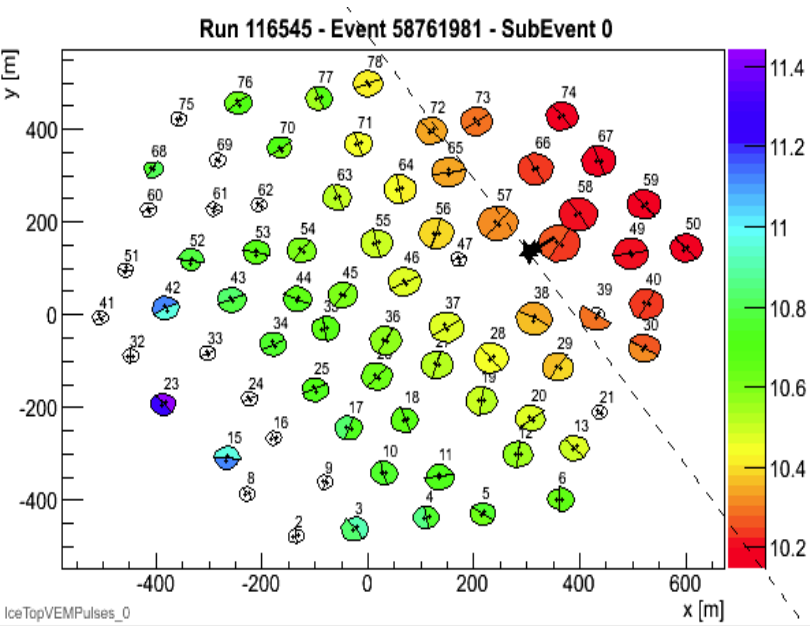
Kuzmichev, ECRS 2012, Moscow

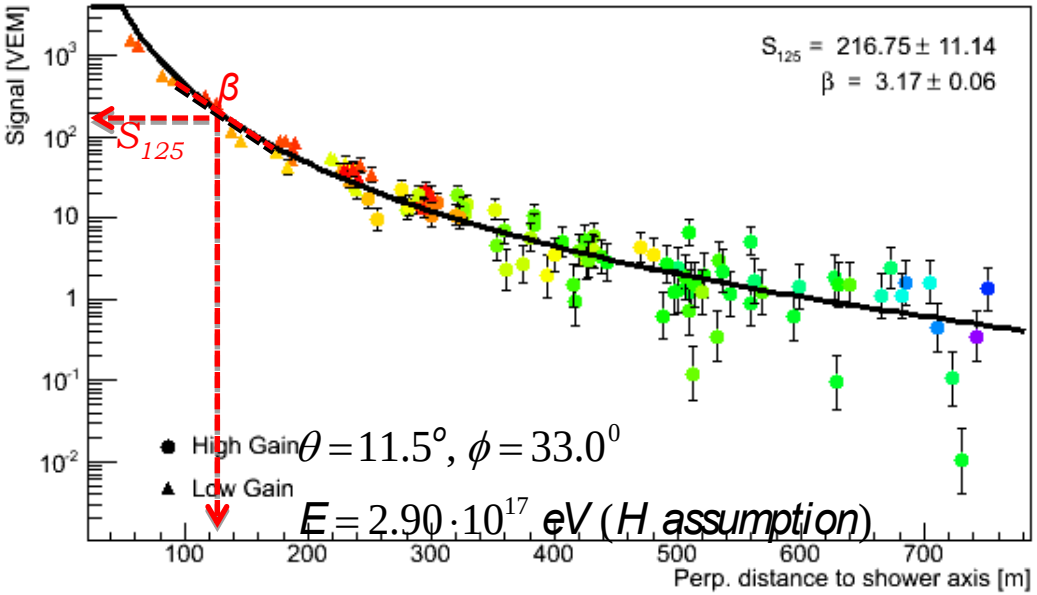
IceTop



- 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

IceTop: Shower Reconstruction



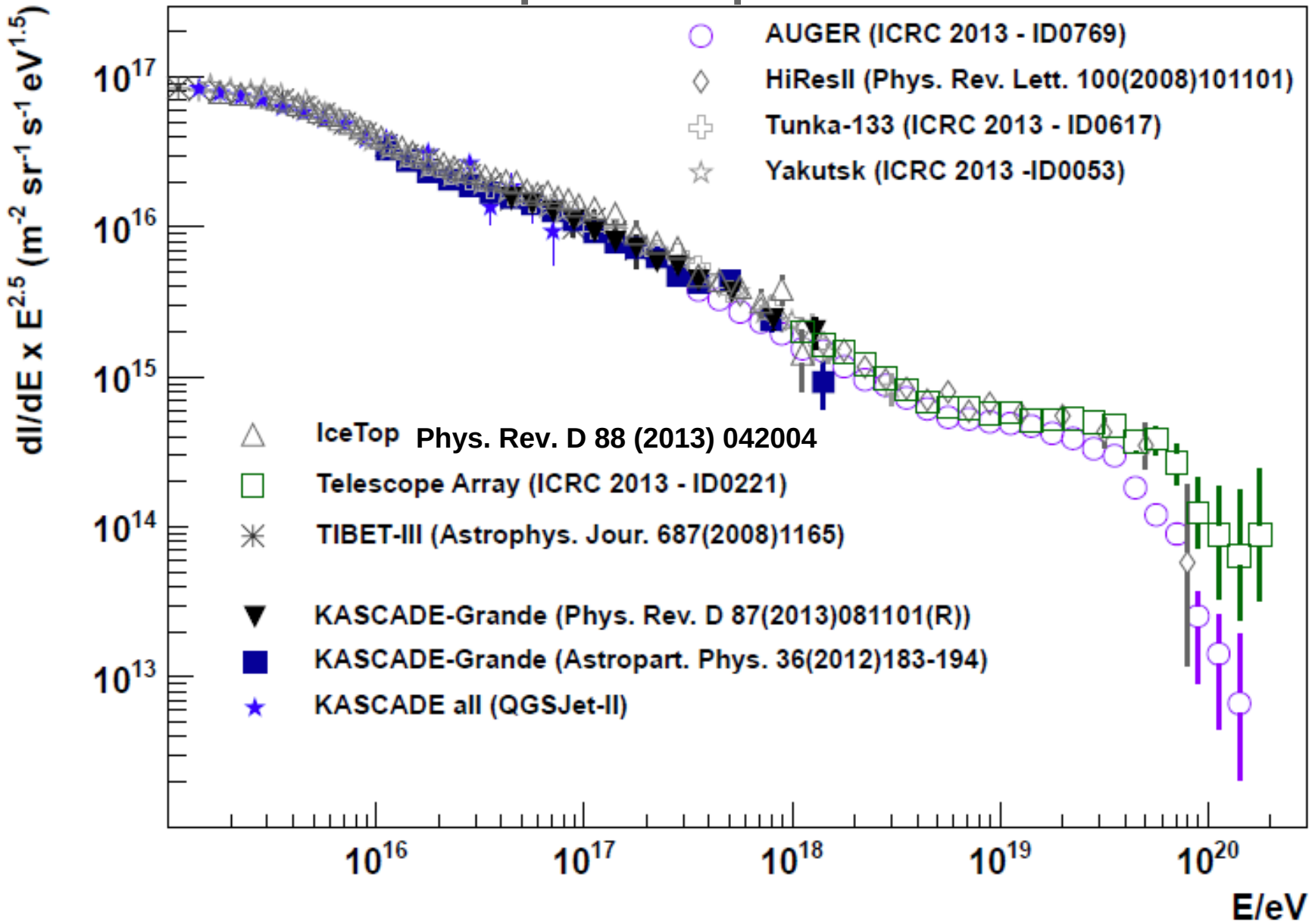


$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

$$E / S_{125} \sim 1\ PeV / VEM$$

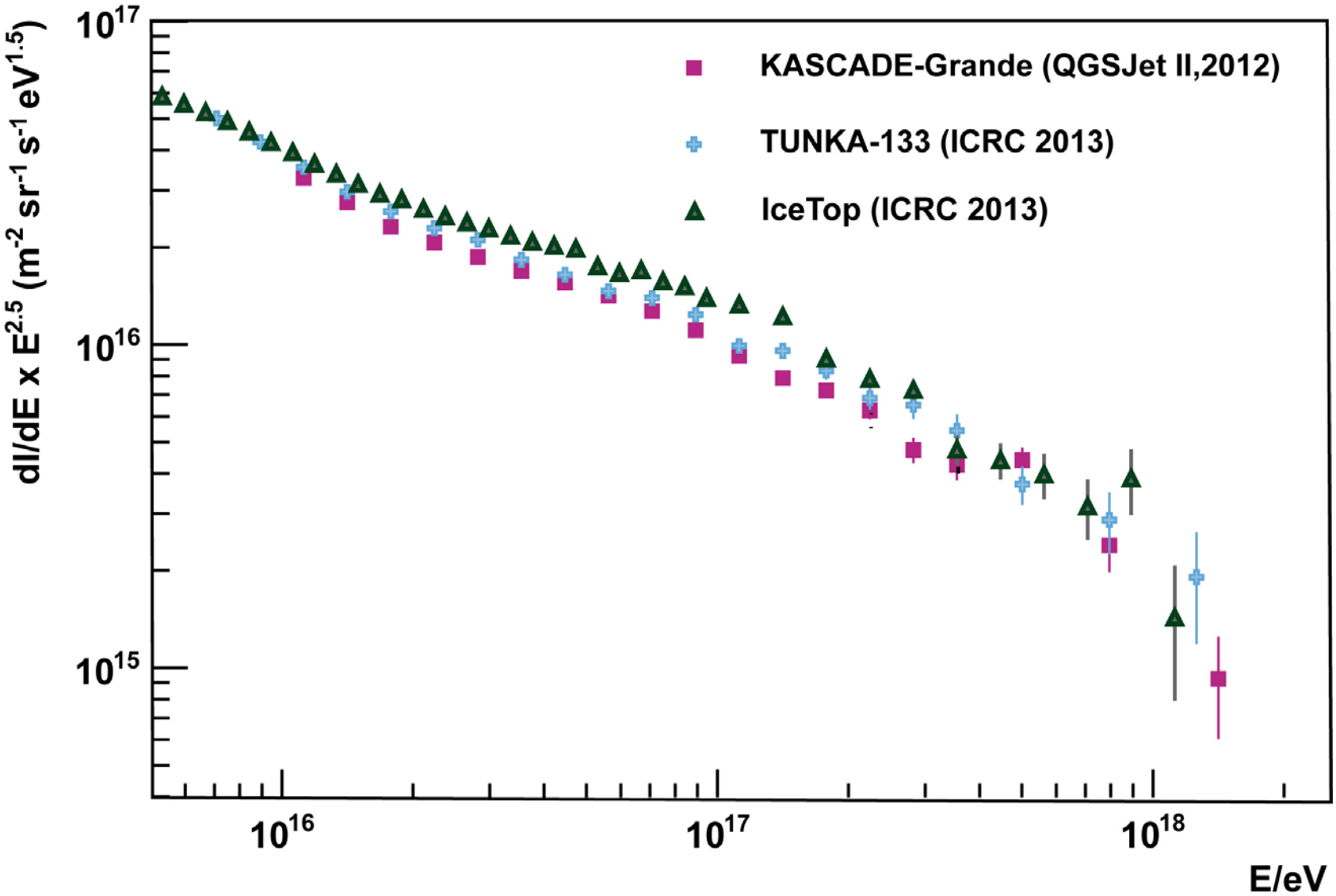
S_{125} : signal at r = 125m
β : slope at r = 125m
κ = 0.303 fixed

All-particle spectra



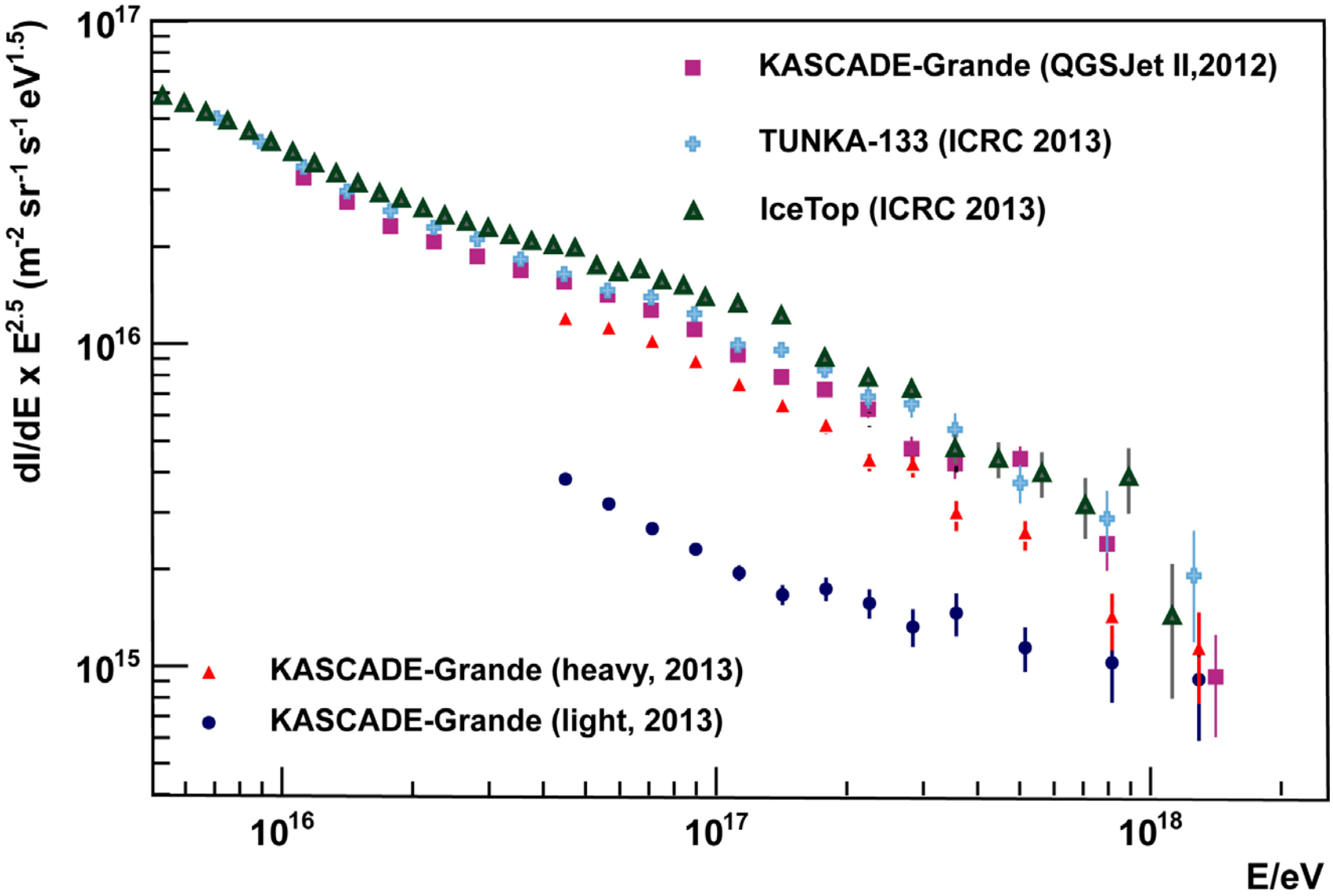
- Structures of all-particle spectra similar (in the level of 15%)

All-particle spectra



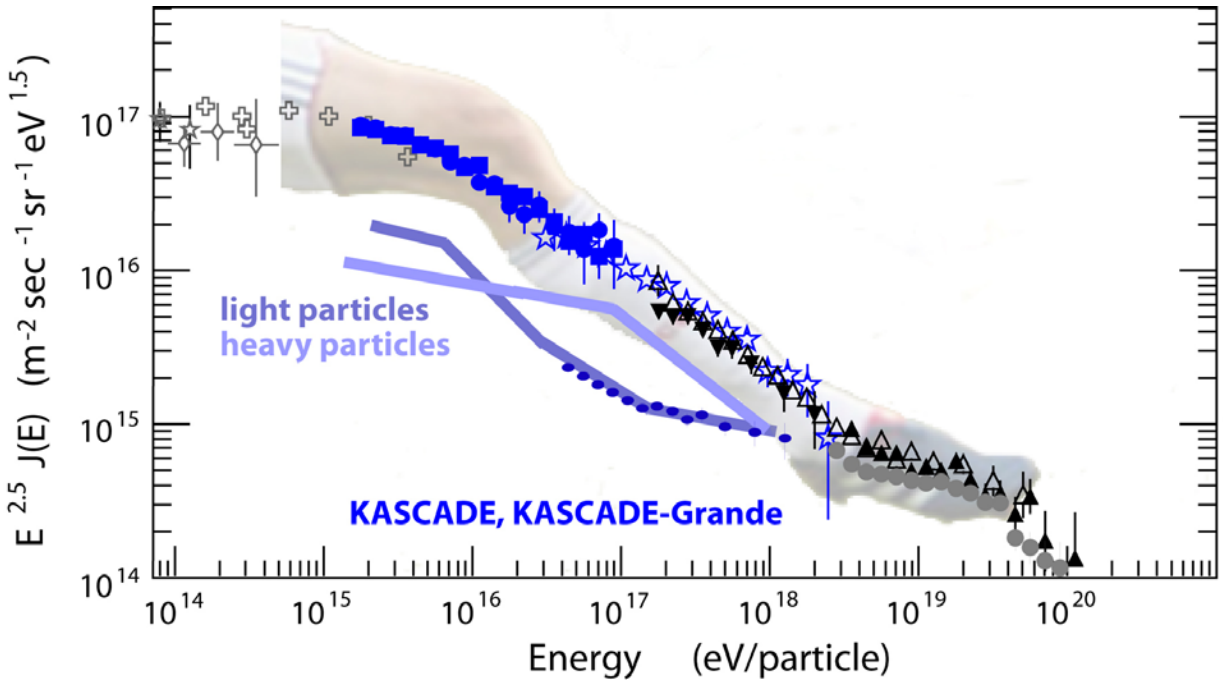
- Structures of all-particle spectra similar (in the level of 15%)

All-particle spectra



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

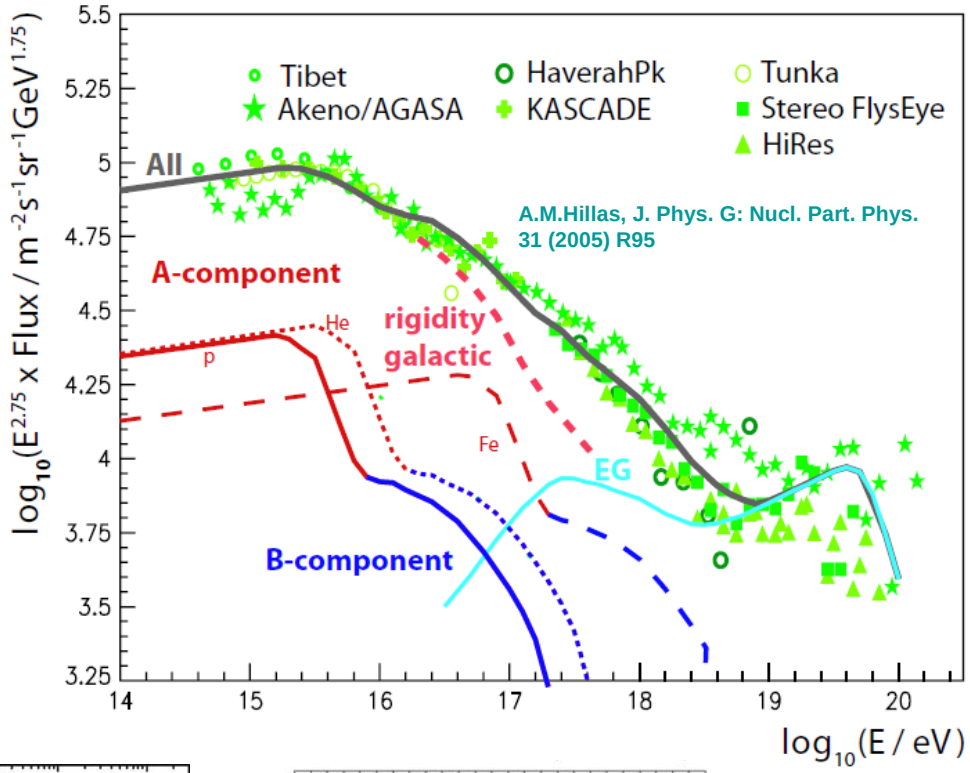
Light and Heavy Knees, Ankles, and Transition

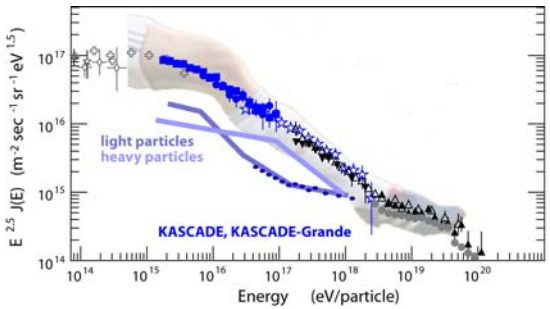


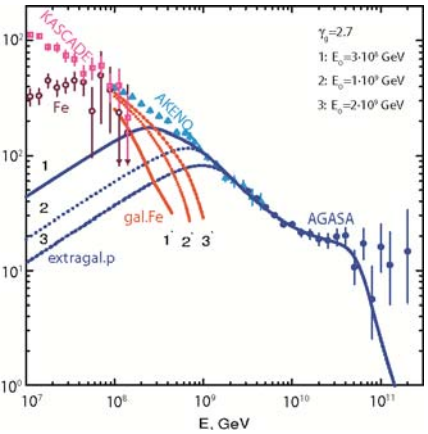
- ➔ **KASCADE: knee of light primaries at ~3·10^{15}eV**
- ➔ **Hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~9·10^{16} eV**
- ➔ **heavy knee less distinct compared to light knee**
- ➔ **mixed composition for 10^{15} to ~ 8·10^{17} eV**
- ➔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

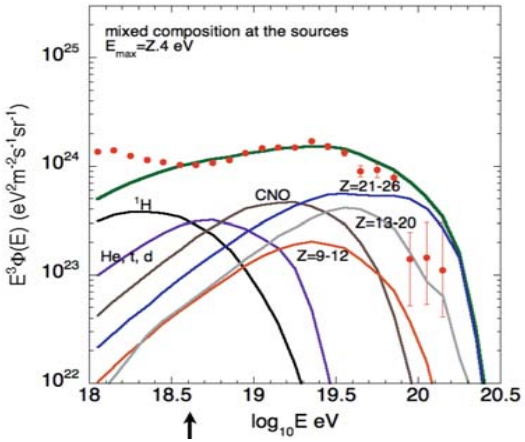
knee position $\propto Z$

Light and Heavy Knees, Ankles, and Transition









Questions:

- **which astrophysical scenario (model) describes the data?**
- **exact energy and mass scale?**
- **spectral forms?**

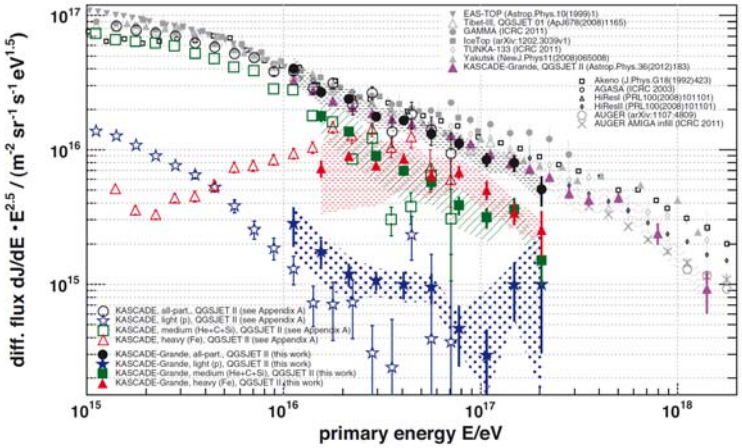
V.Berezinsky, astro-ph/0403477

D.Allard, astro-ph/1111.3290

KASCADE-Grande: Next

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

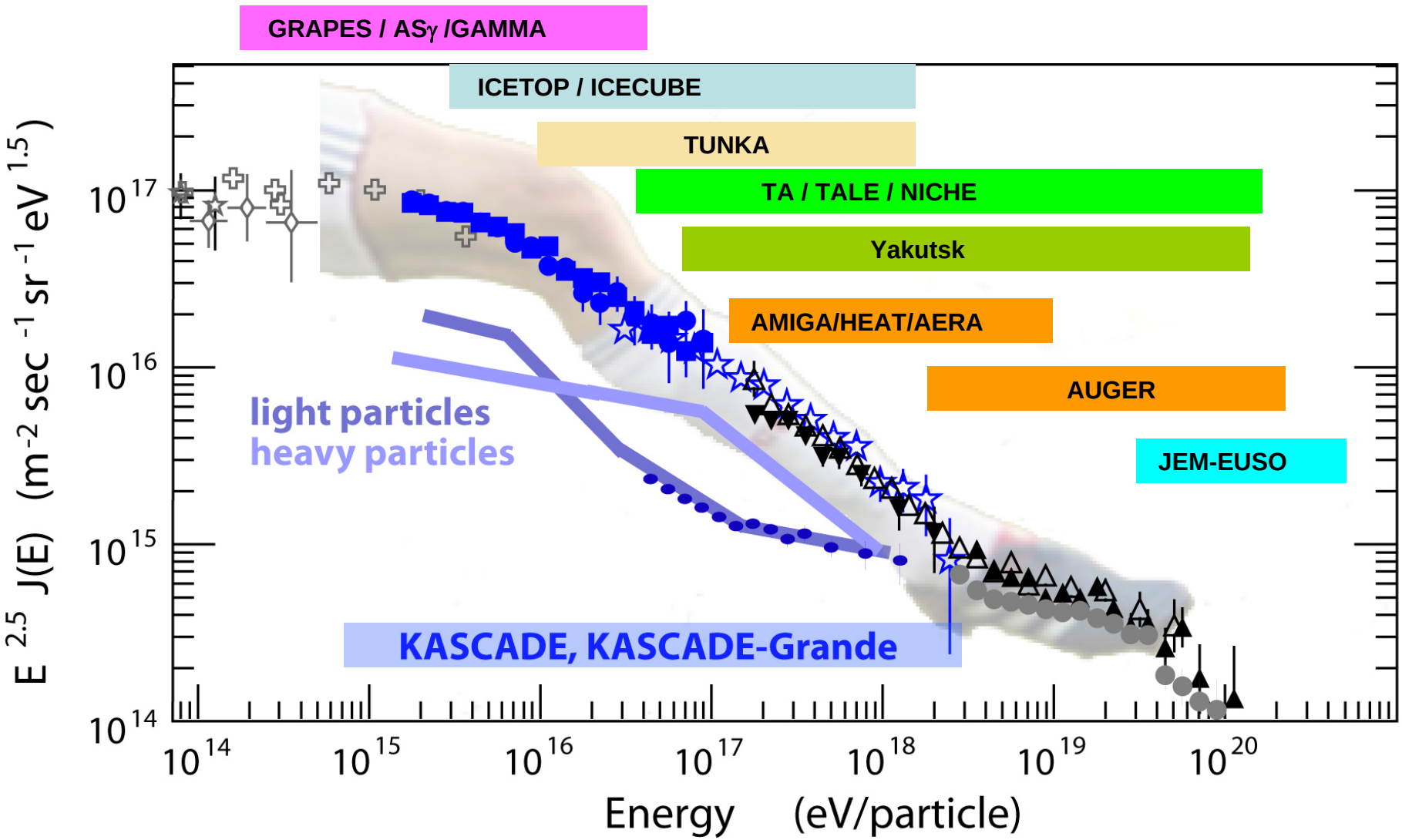
- **combined analysis**
  - for coherent spectrum and composition 10^{14}-10^{18} eV



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

- **KCDC**
  - KASCADE Cosmic ray Data Center

Summary



answers only by combining all information: stay tuned!