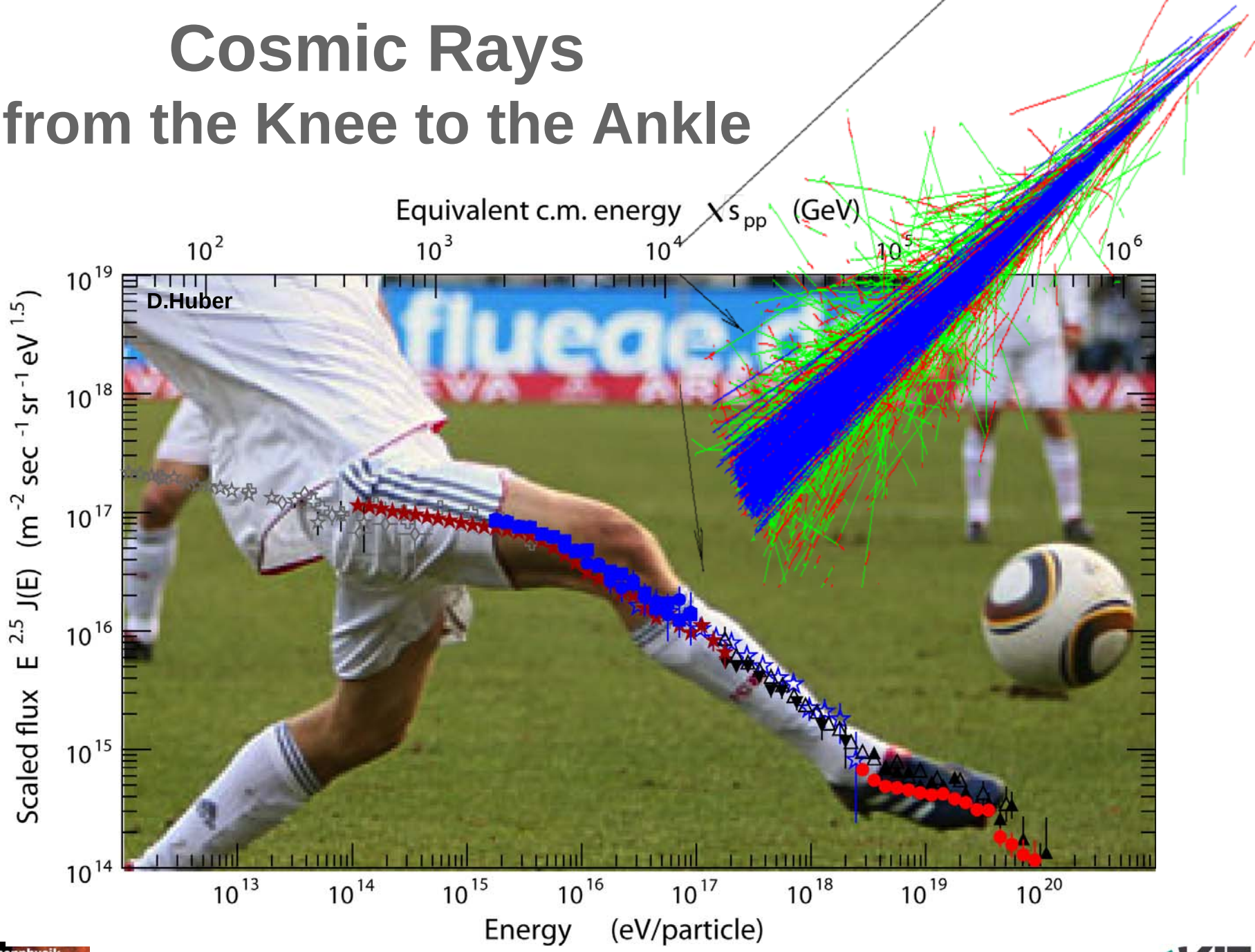
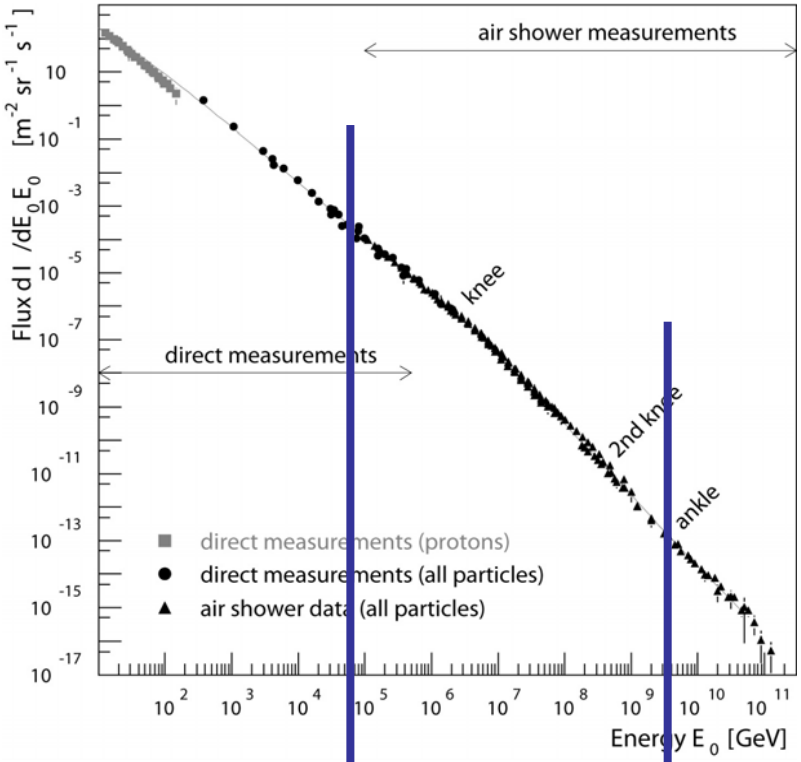
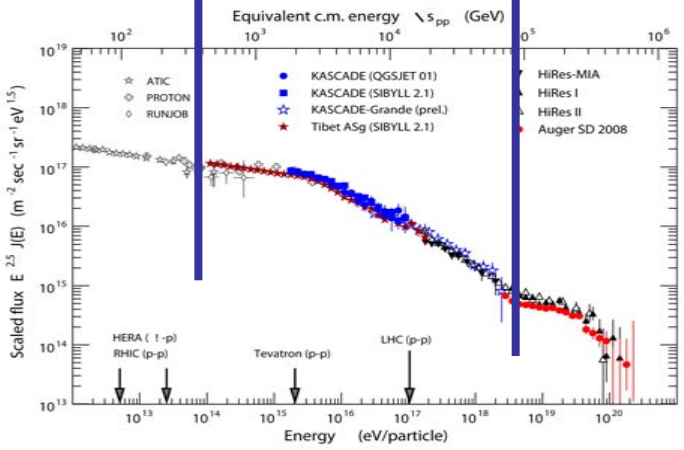
Cosmic Rays
from the Knee to the Ankle



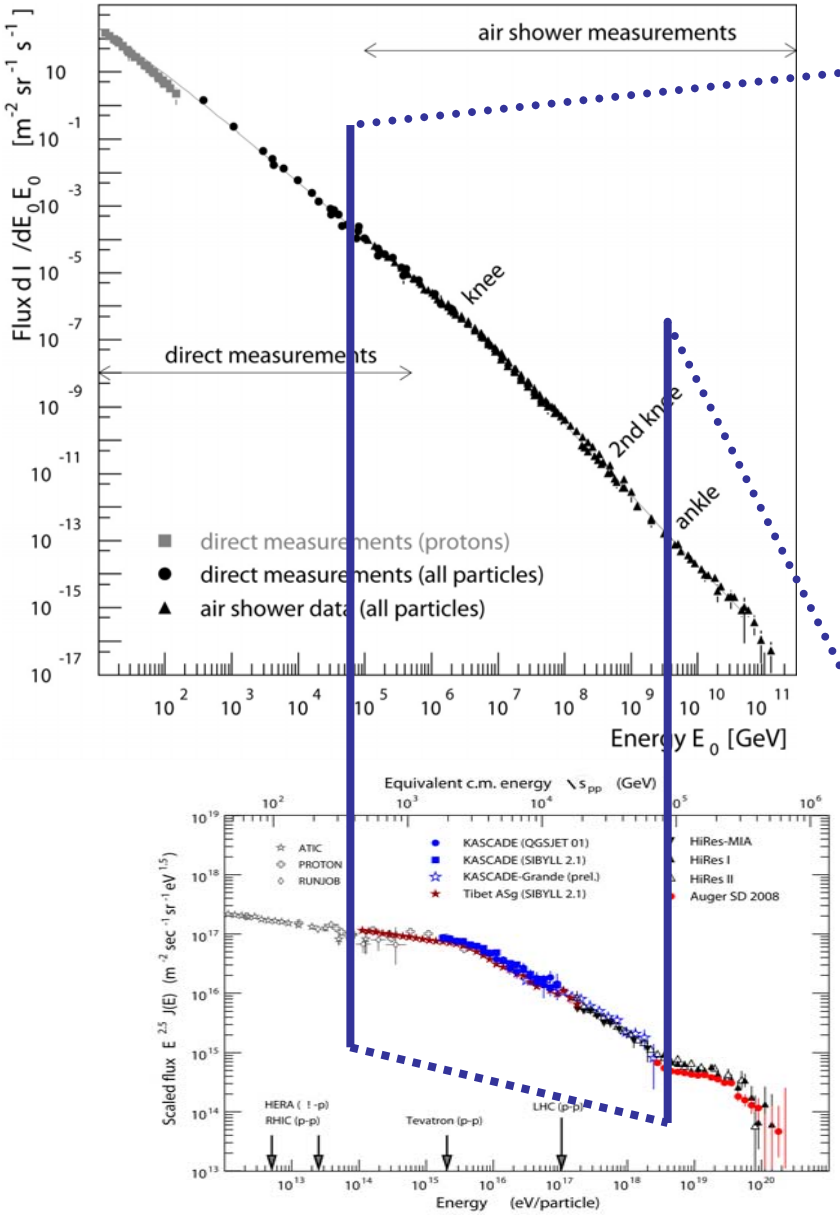
Questions to the knee-to-ankle energy range





Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293

Questions to the knee-to-ankle energy range



Overlap direct-indirect measurements?

Hadronic interaction models?

Rigidity dependent knee?

Sharpness of knee?

Composition at knee?

Fine-structures in spectrum?

Iron knee?

End of Galactic Spectrum?

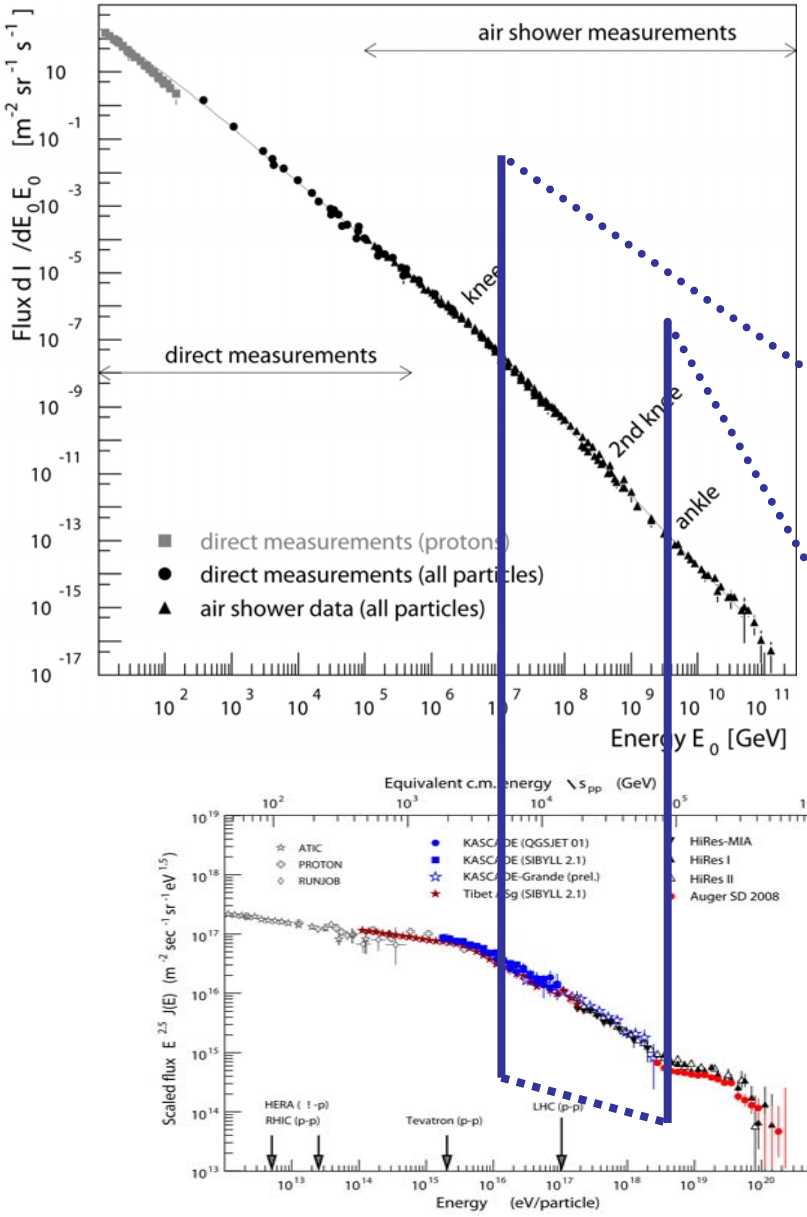
Second knee?

Transition galactic – xgalactic?

Anisotropy?

Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293

Questions to the knee-to-ankle energy range



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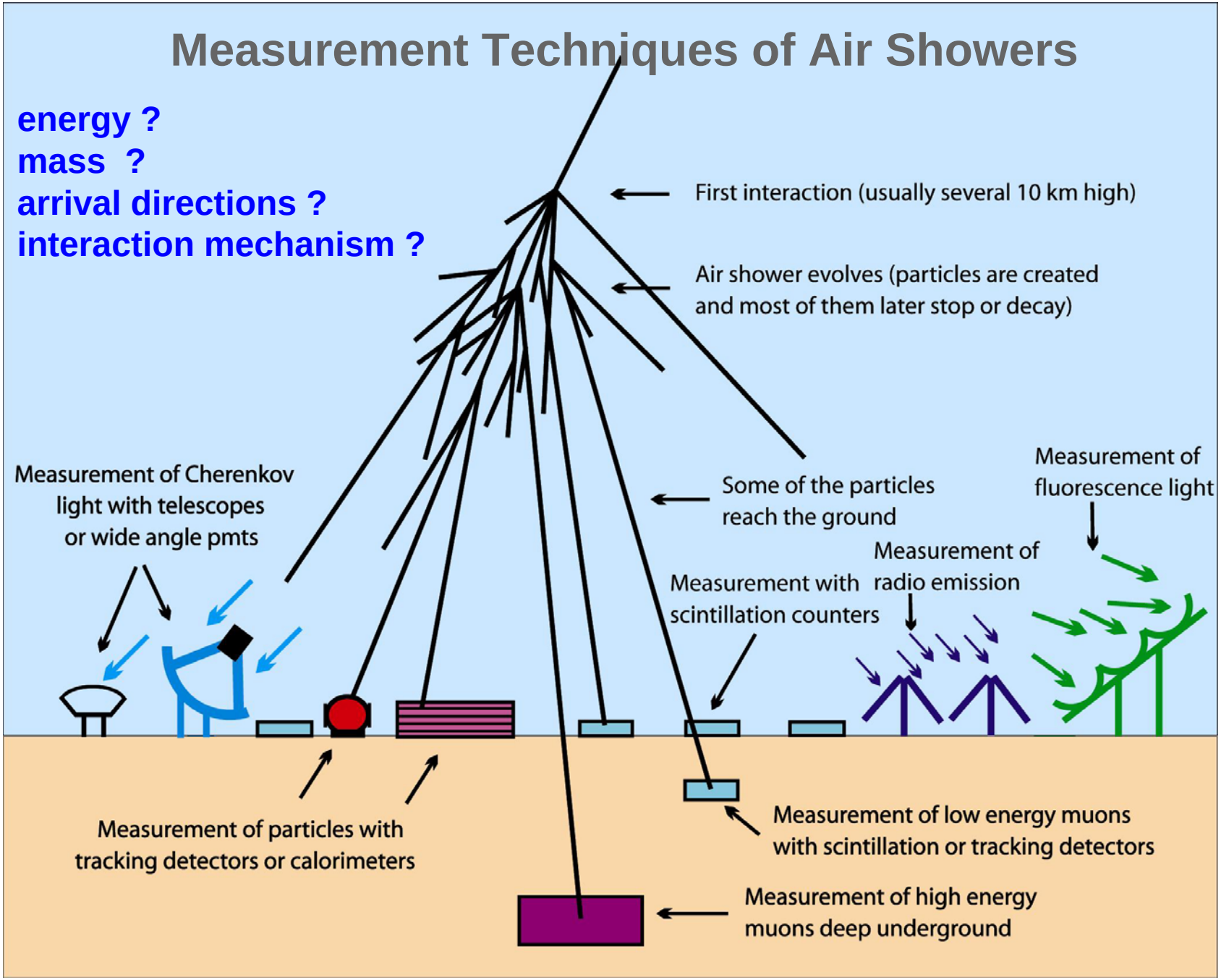
Engel, Blümer, Hörandel:
Progress in Particle and Nuclear Physics 63 (2009) 293

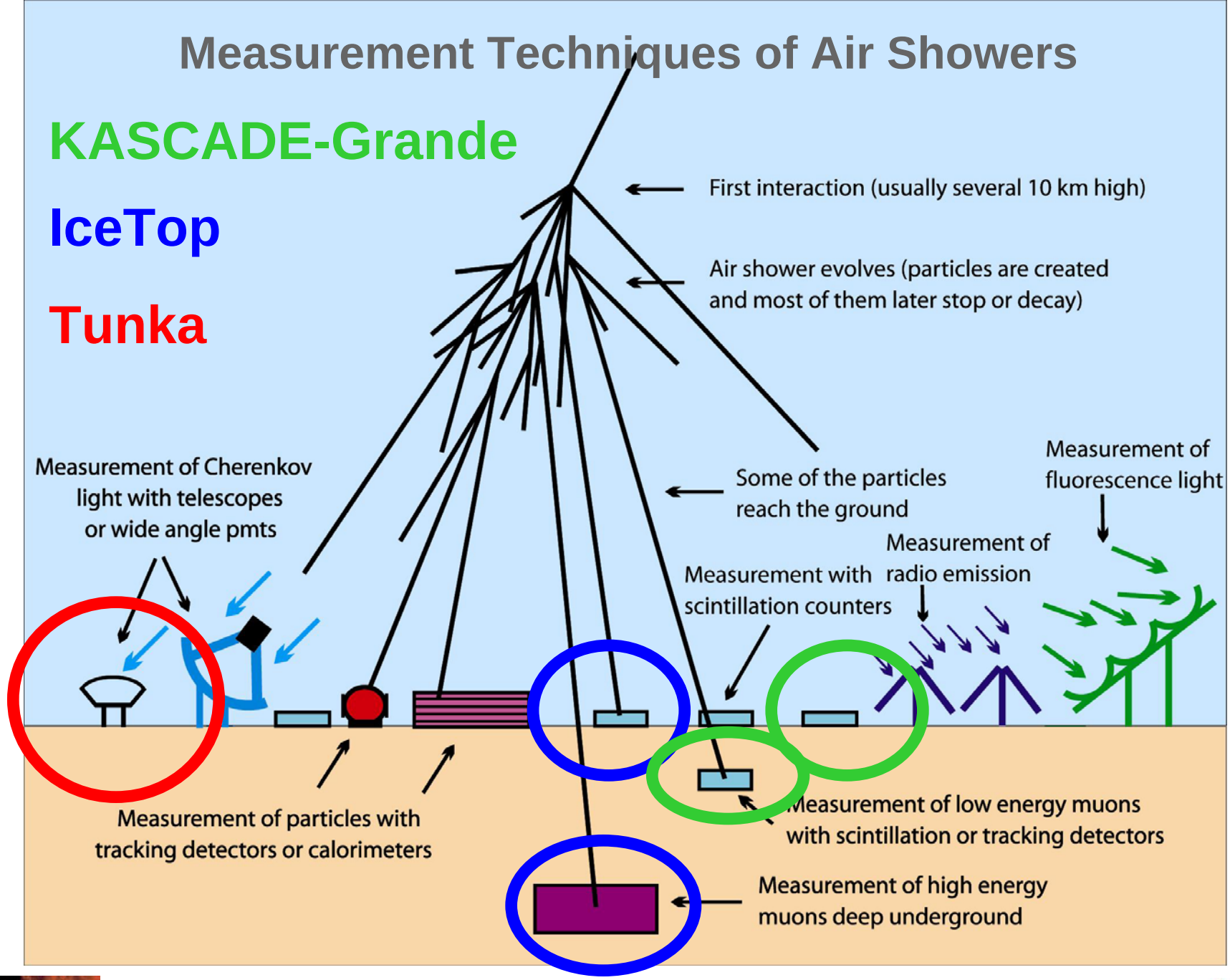
Measurement Techniques of Air Showers

energy ?
mass ?
arrival directions ?
interaction mechanism ?

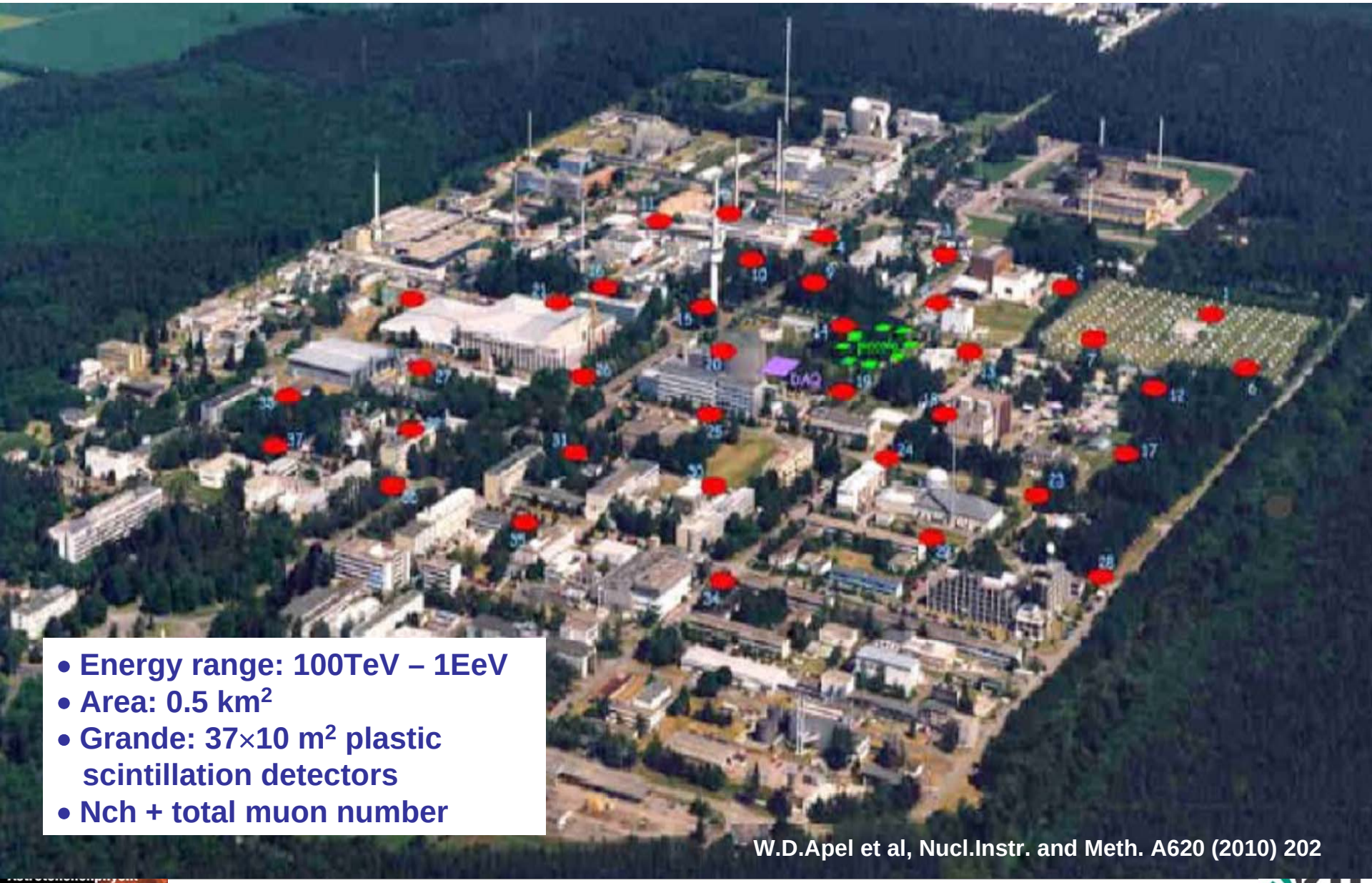


Present Main Experiments 10^{16}-10^{18}eV

Measurement Techniques of Air Showers



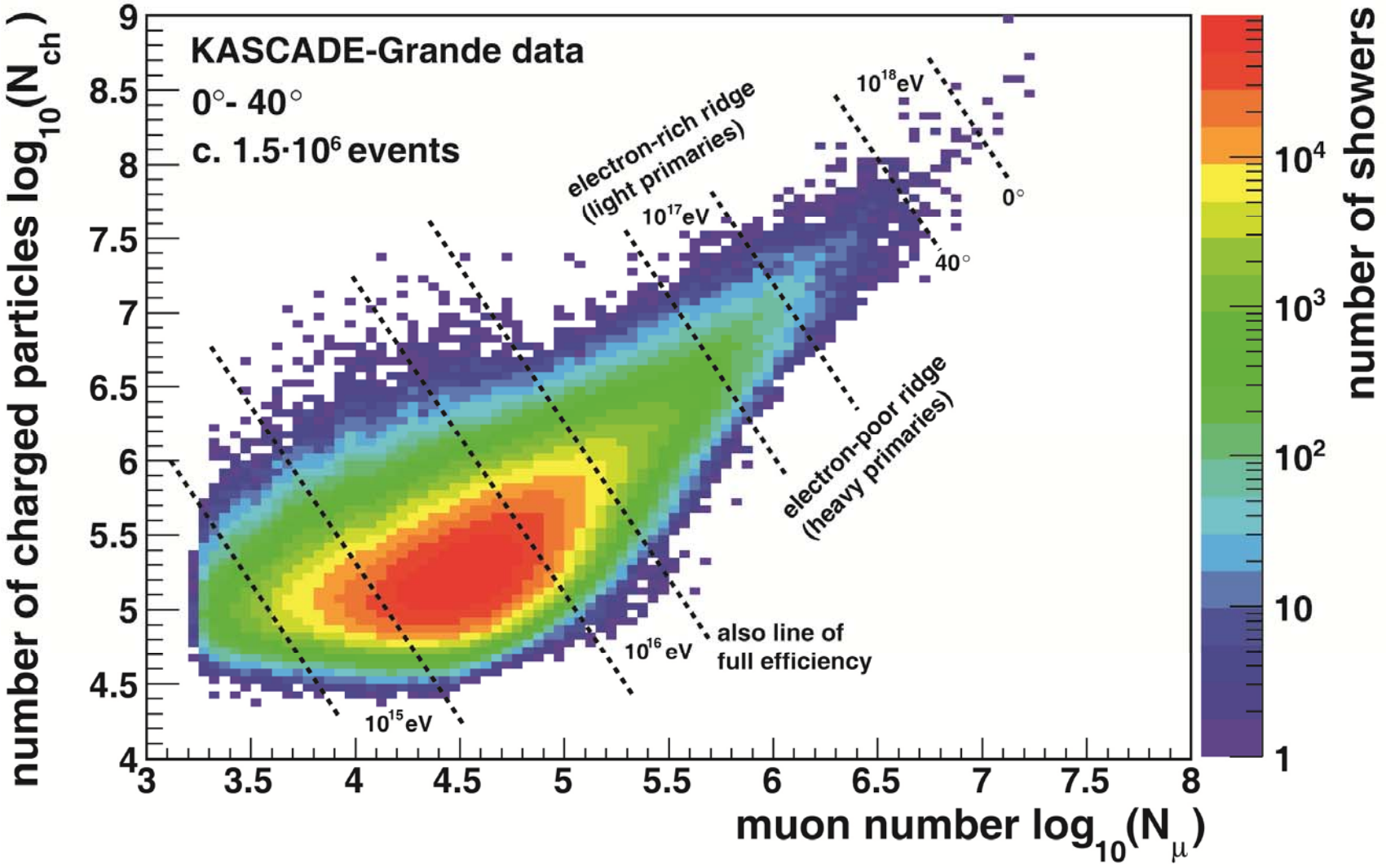
KASCADE-Grande



- Energy range: 100TeV – 1EeV
- Area: 0.5 km^2
- Grande: 37×10 m^2 plastic scintillation detectors
- Nch + total muon number

W.D.Apel et al, Nucl.Instr. and Meth. A620 (2010) 202

KASCADE-Grande: the data



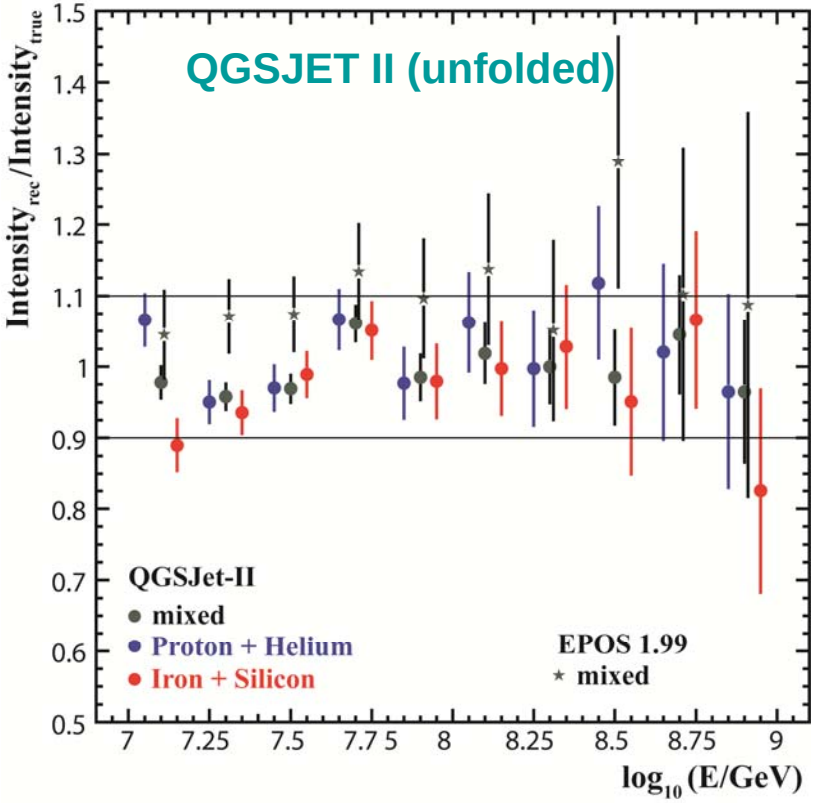
- **2-dimensional shower size distribution**

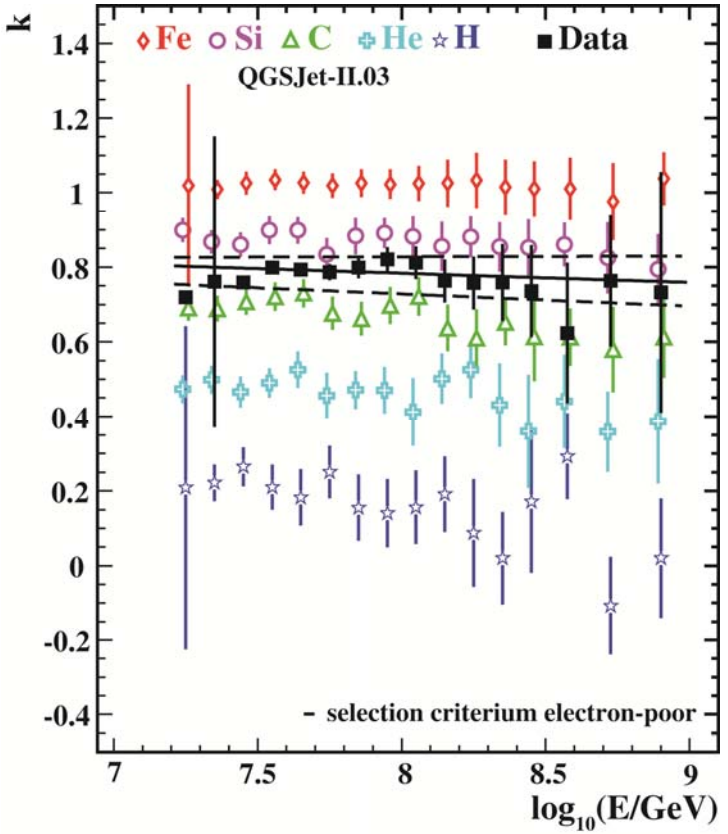
➔ **separation in "electron-rich" and "electron-poor" events**

KASCADE-Grande: reconstruction of energy spectrum and composition

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

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



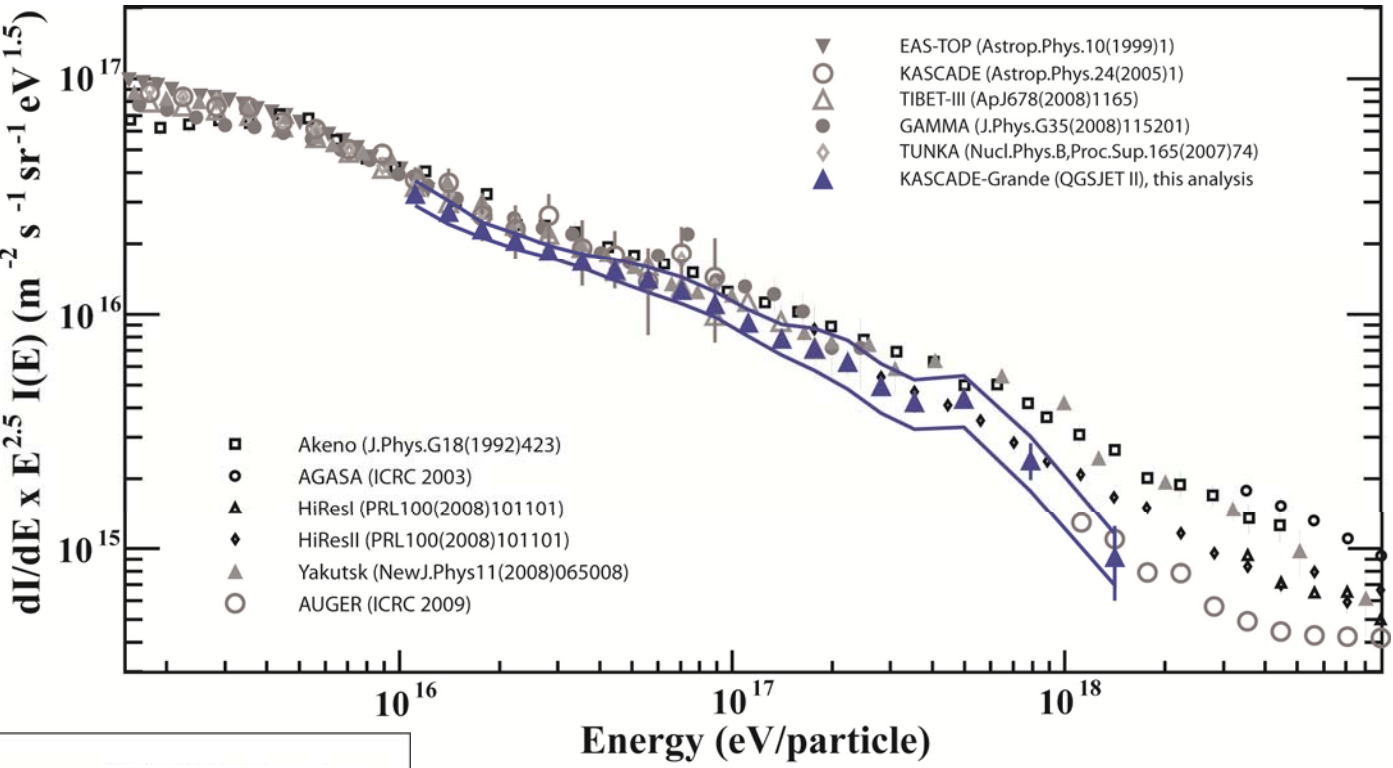


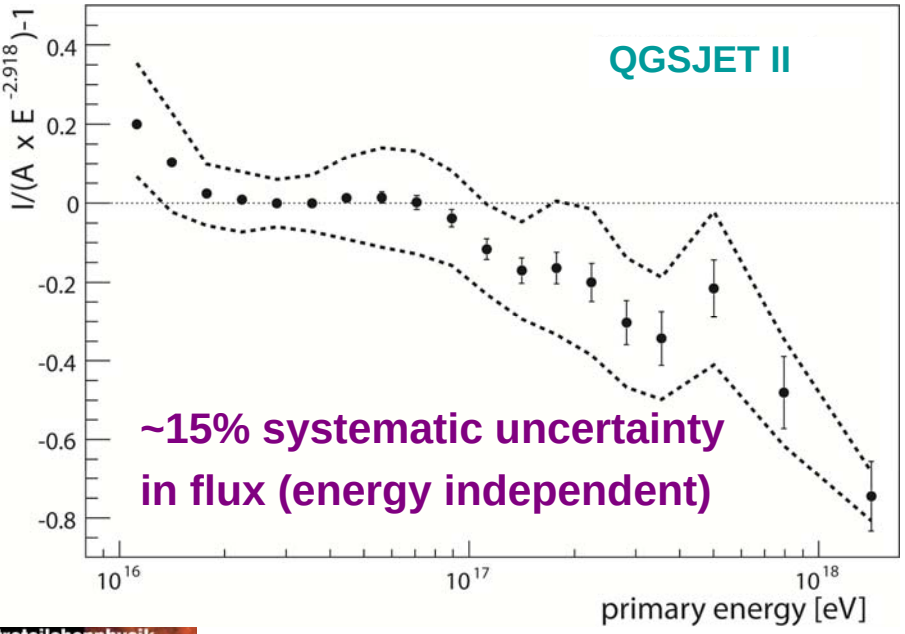
- no composition dependence
- ΔE/E ~ 20%

- composition sensitivity
- light/heavy separation

KASCADE-Grande
all-particle energy spectrum

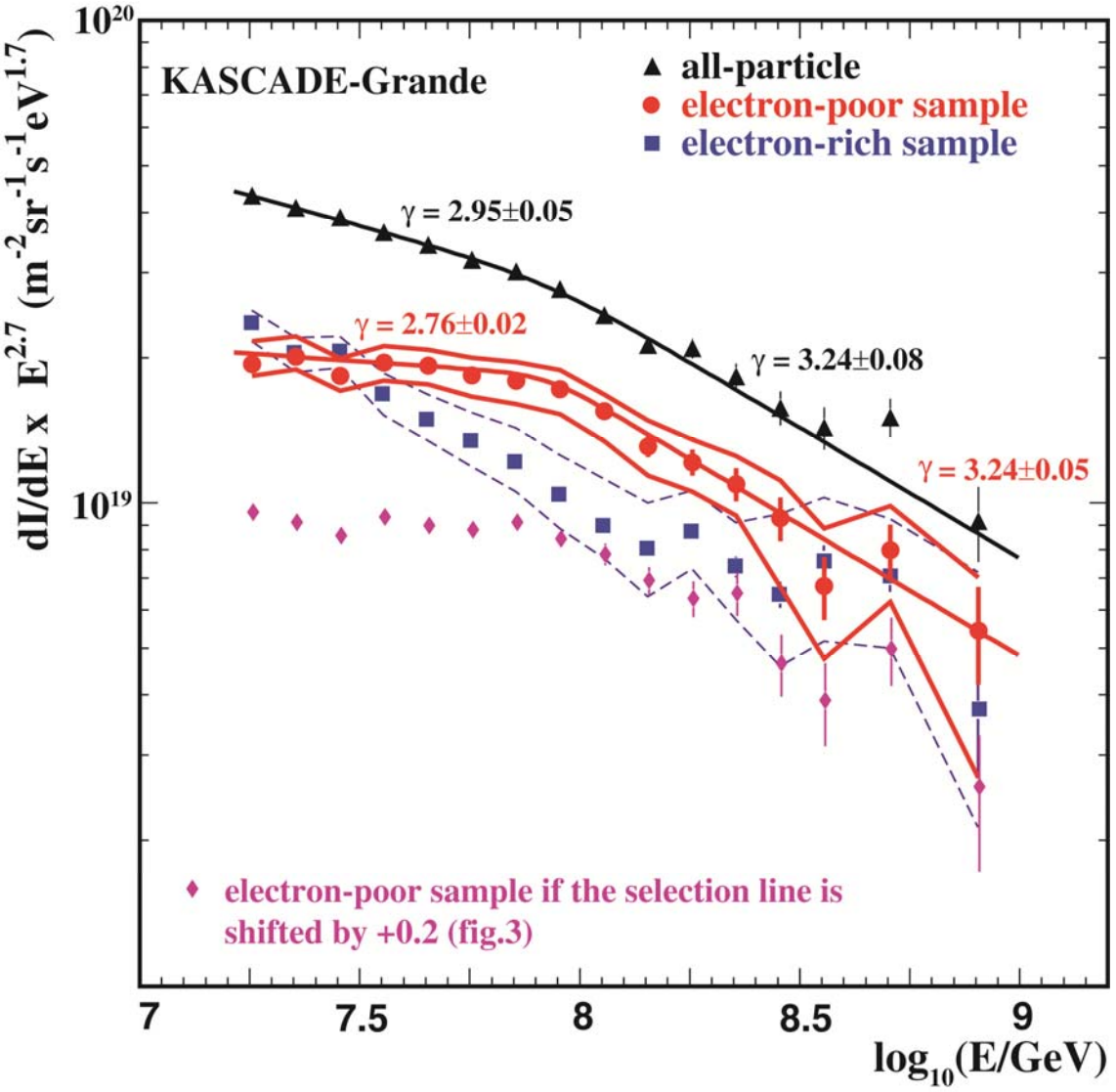
Astroparticle Physics 36 (2012) 183





- **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



- spectra of individual mass groups:

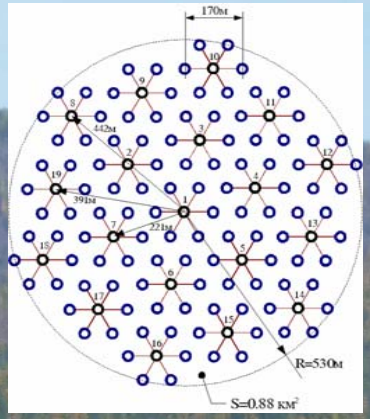
➔ steepening close to 10^{17}eV (2.1σ) in all-particle spectrum

➔ steepening due to heavy primaries (3.5σ)

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

Phys.Rev.Lett. 107 (2011) 171104

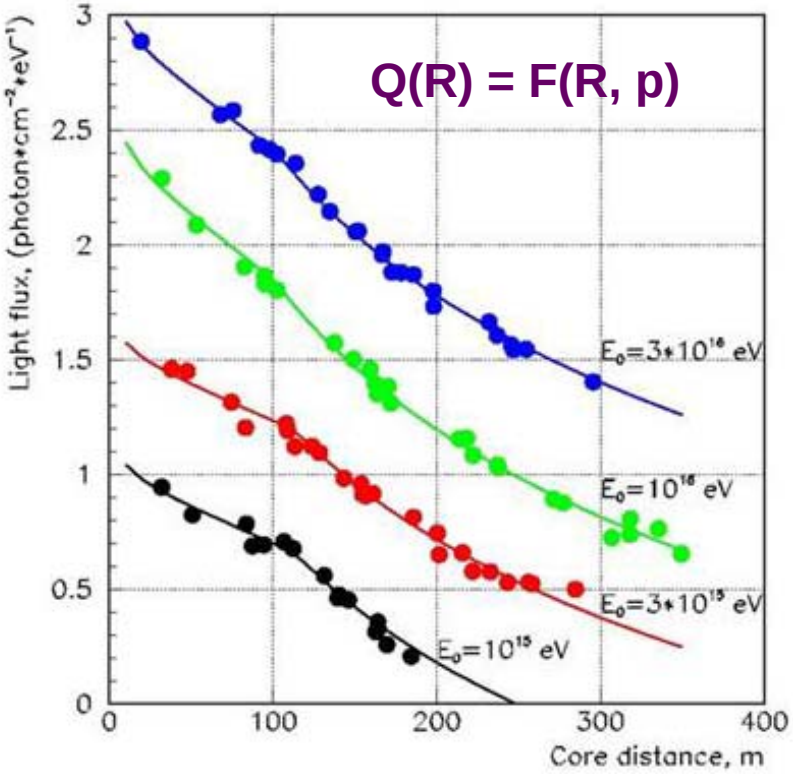
Tunka-133



- **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

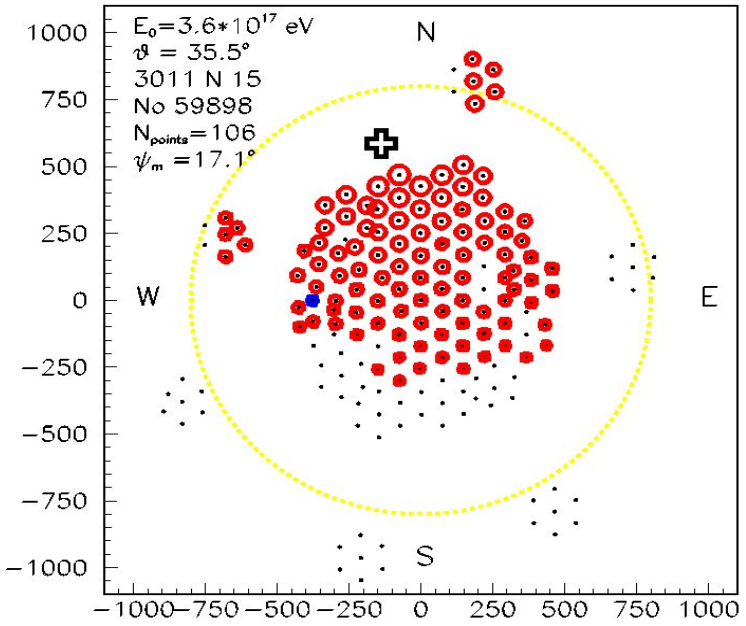


light flux at core distance 200 m

Q_{200} ~ Energy

steepness of LDF

P = Q(100)/Q(200) ➔ X_{max}

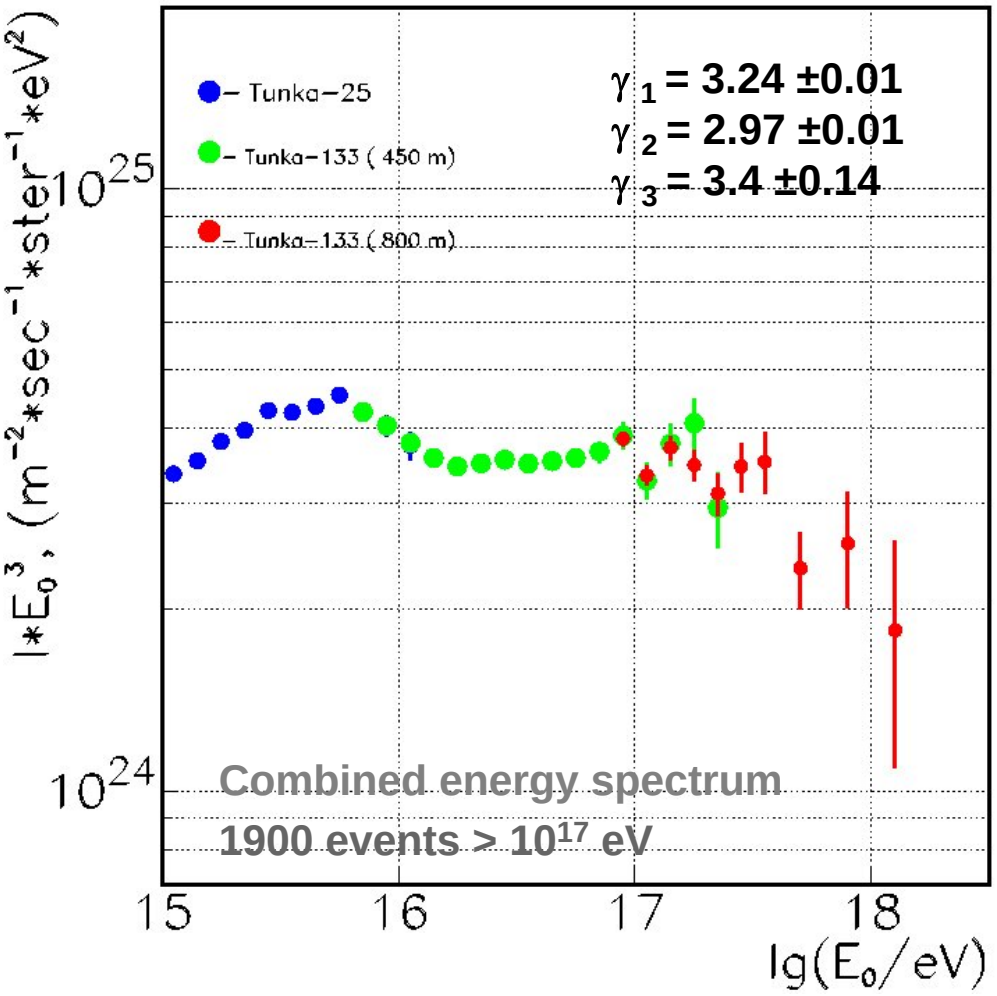


Accuracy: core location ~ 10 m
energy resolution ~ 15%
$\delta X_{max} < 25$ g·cm^{-2}

Energy threshold 10^{15} eV

Kuzmichev, ECRS 2012, Moscow

Tunka-133: all-particle energy spectrum



- all- particle spectrum:

➔ hardening clearly visible

➔ steepening visible (little above 10^{17}eV) with outer clusters

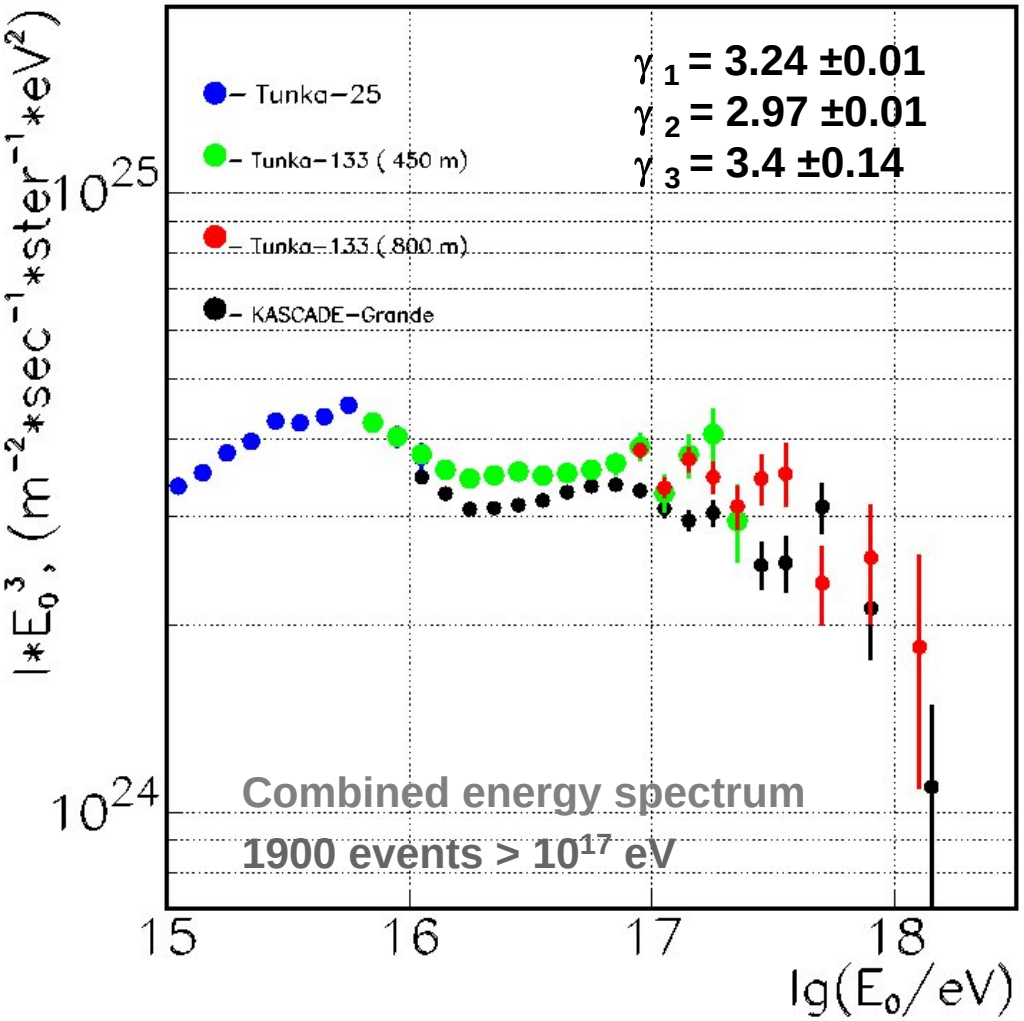
➔calibration by Monte Carlo; composition assumption

Kuzmichev, ECRS 2012, Moscow

$\sigma_{sys}(E)$ = 8% at E= 6 10^{15} eV from QUEST experiment

$\sigma_{sys}(E)$ = 15% at 10^{18} eV uncertainty in calibration factor

Tunka-133: all-particle energy spectrum



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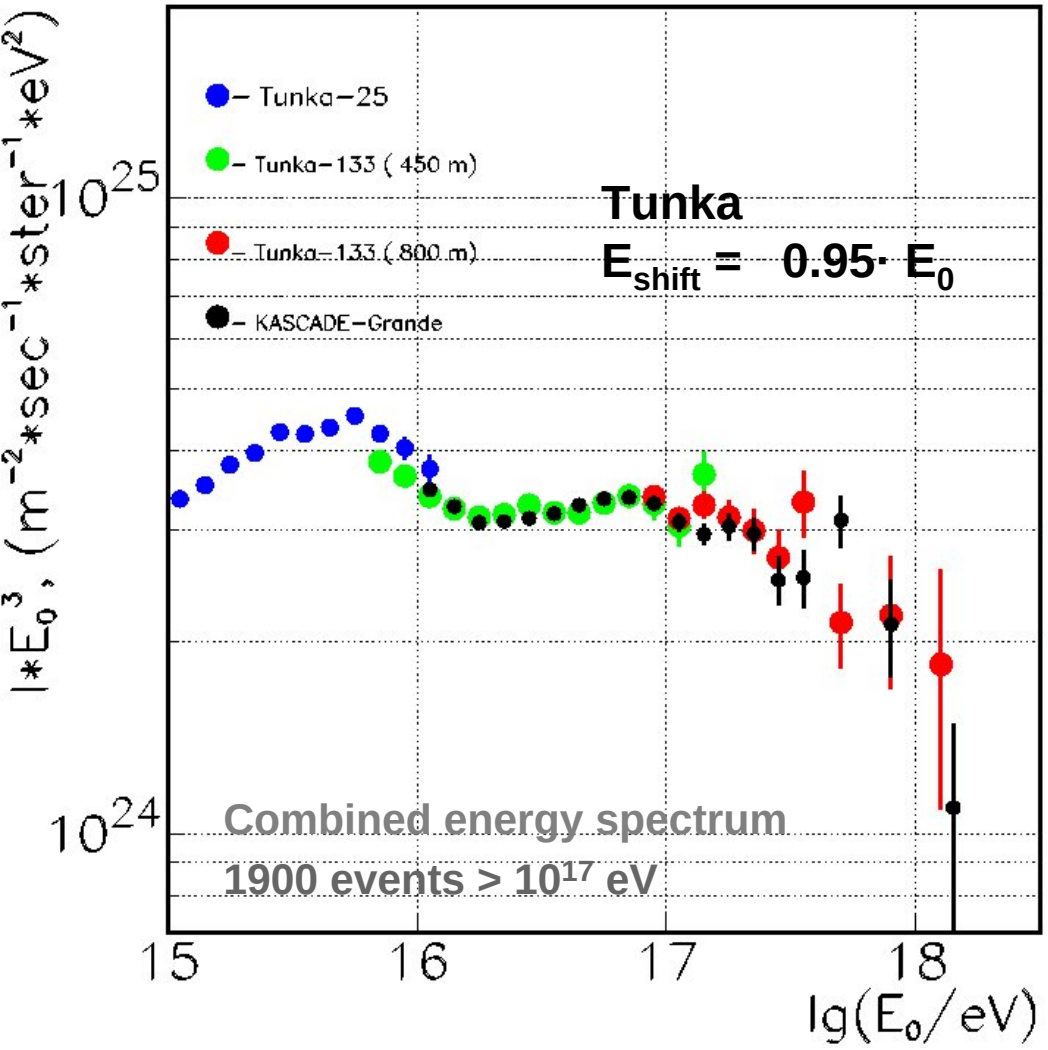

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Kuzmichev, ECRS 2012, Moscow

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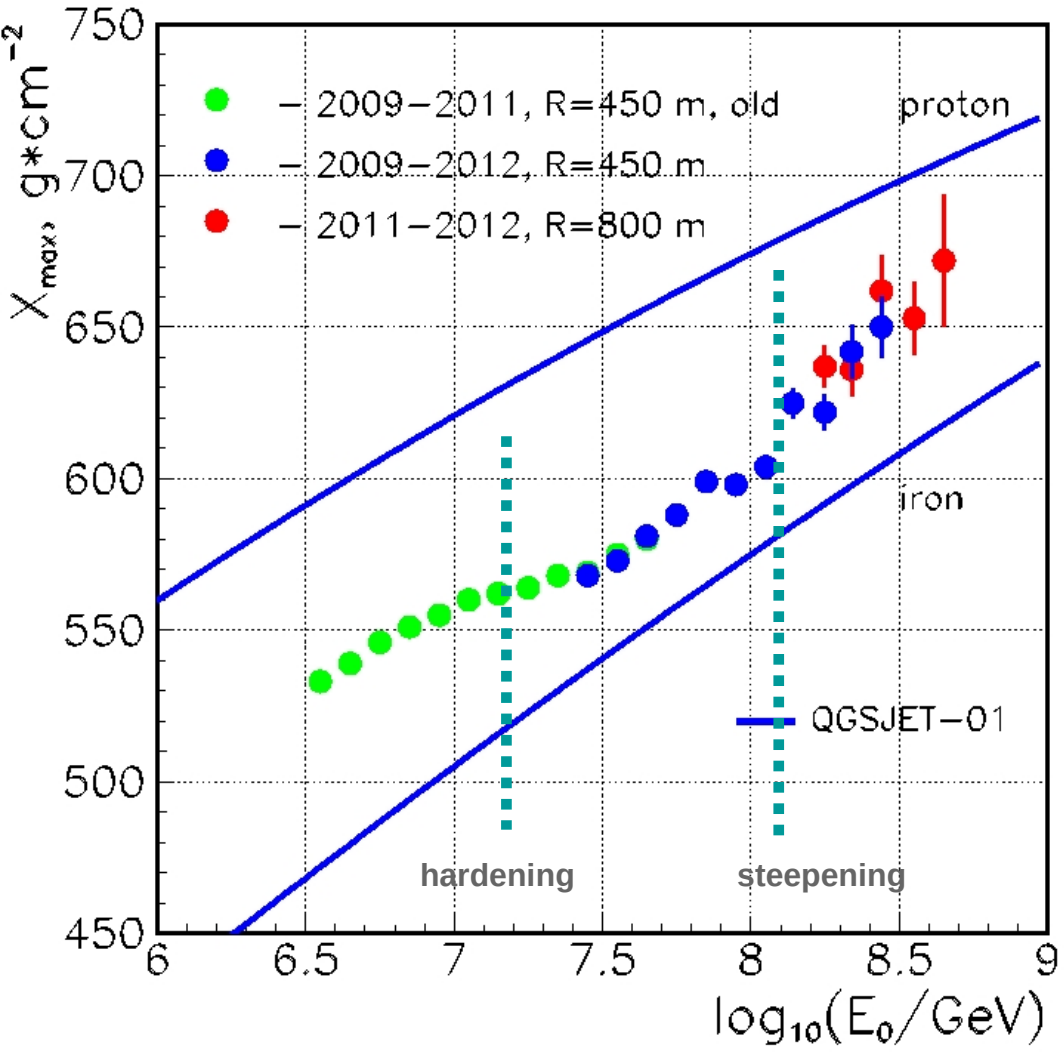
$\sigma_{sys}(E)$ = 15% at 10^{18} eV uncertainty in calibration factor

Tunka-133: composition

PRELIMINARY



- mean mass:

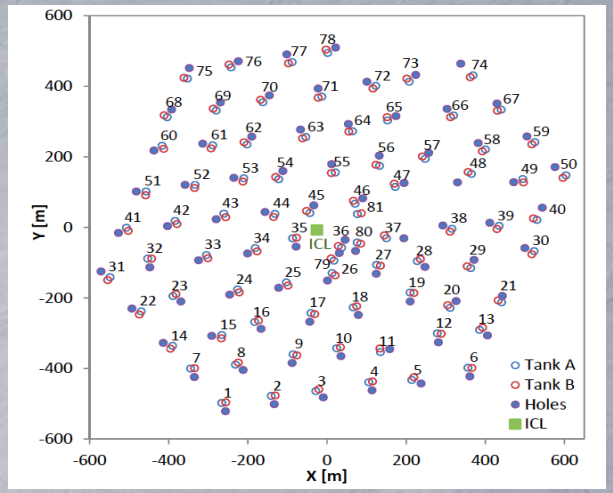
➔ tendency heavier at hardening

➔ tendency lighter at steepening

➔ absolute scaling model dependent

Kuzmichev, ECRS 2012, Moscow

IceTop



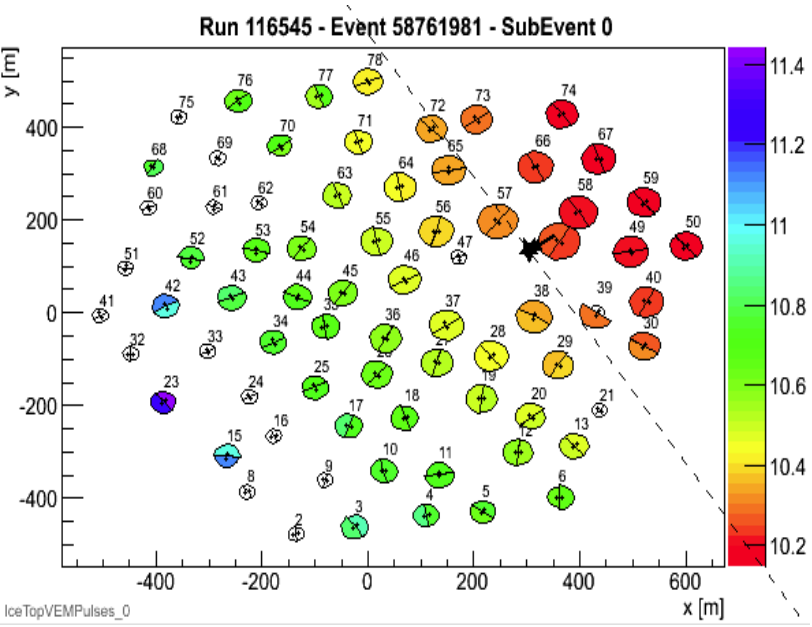
125m

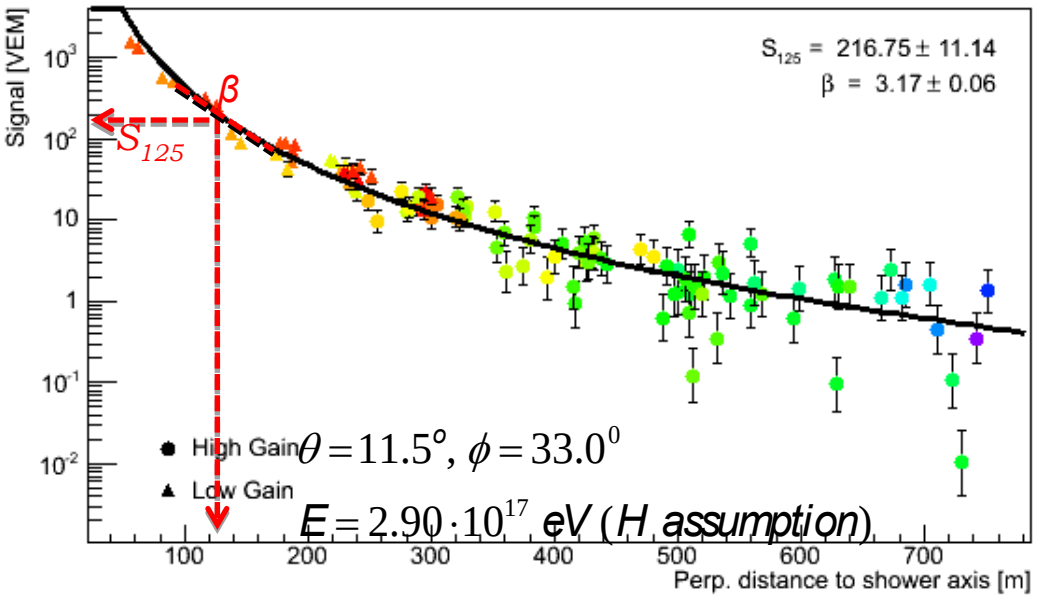
10m

Dense Core

- Energy range: PeV – 1EeV
- Area: 0.5 km^2
- 2835m altitude (680 g/cm^2)
- 79 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

IceTop: Shower Reconstruction



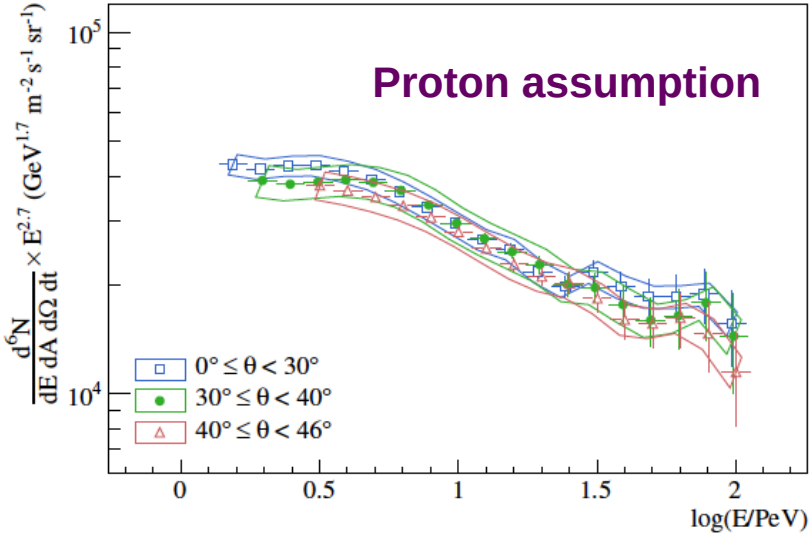


$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

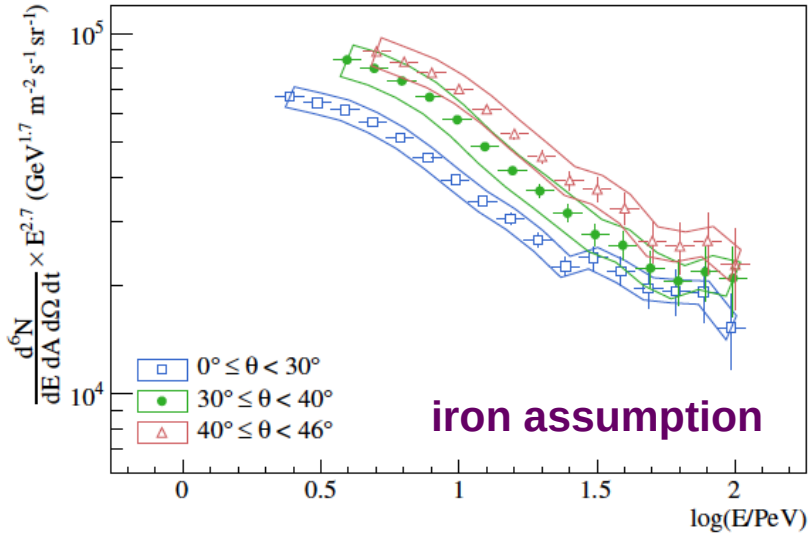
$$E / S_{125} \sim 1\ PeV / VEM$$

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

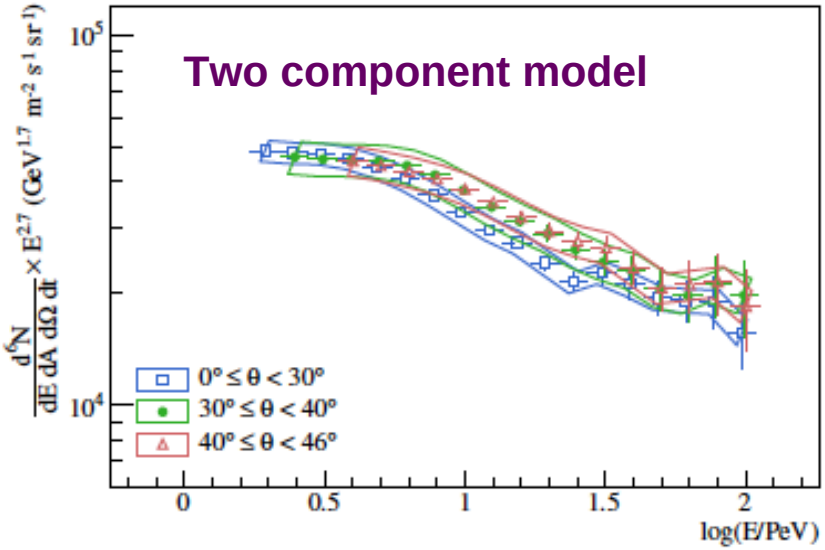
IceTop-26 All-Particle Spectrum 10^{15}-10^{17}eV



(a) Proton assumption



(b) Iron assumption



(c) Two-component model

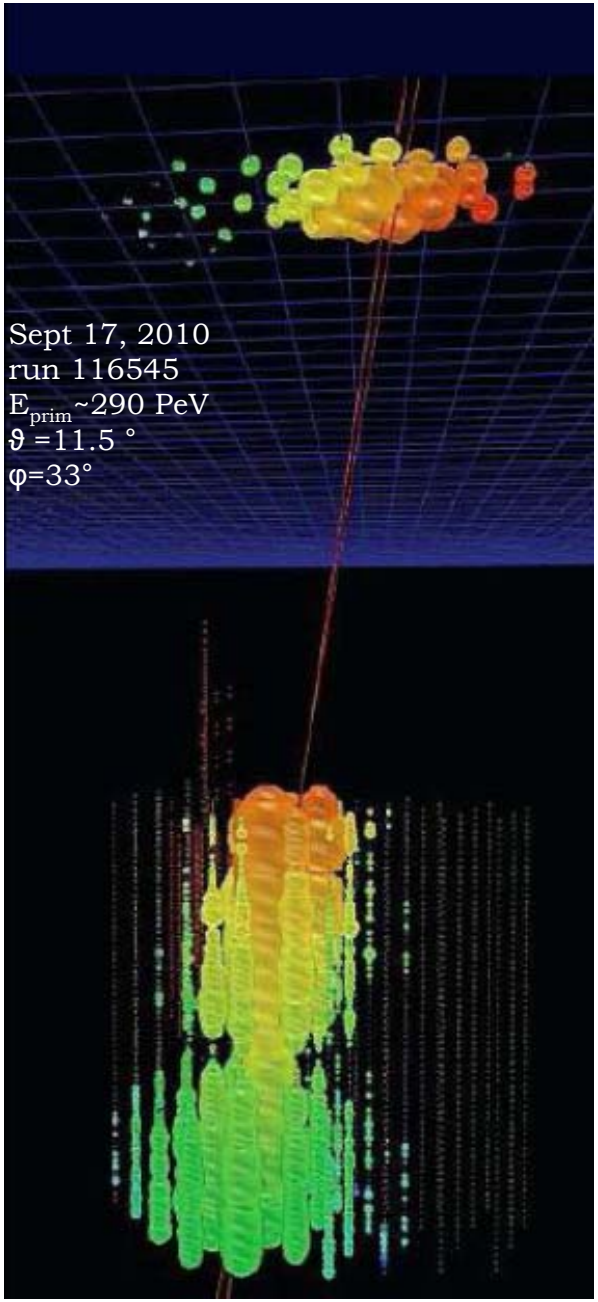
➔ **Energy spectrum with composition assumption**

➔ **Composition sensitivity of shower attenuation with zenith angle**

➔ **Knee and hardening visible**

➔ **Pure iron excluded**

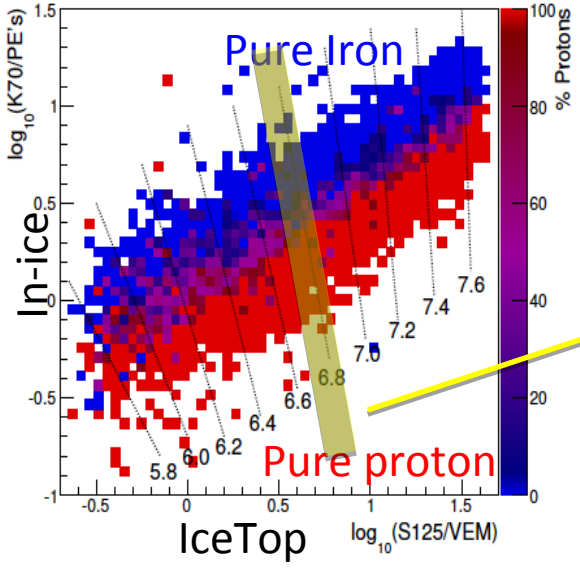
Submitted to Astrop. Phys., (arXiv:1202.3039)

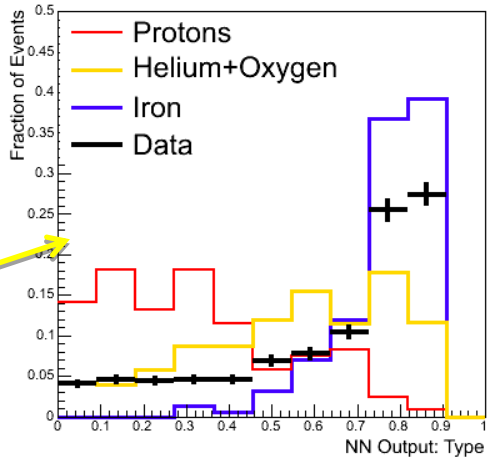


IceTop-40/IceCube-40 Composition Method

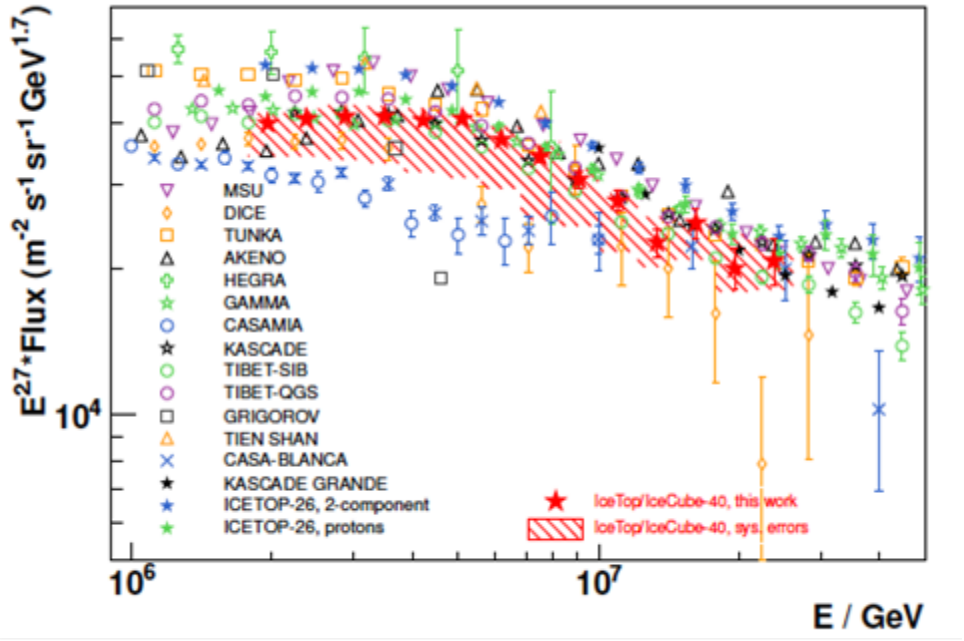
K70 is a measure of muon bundle size in IceCube (analogous to S125 on the surface).

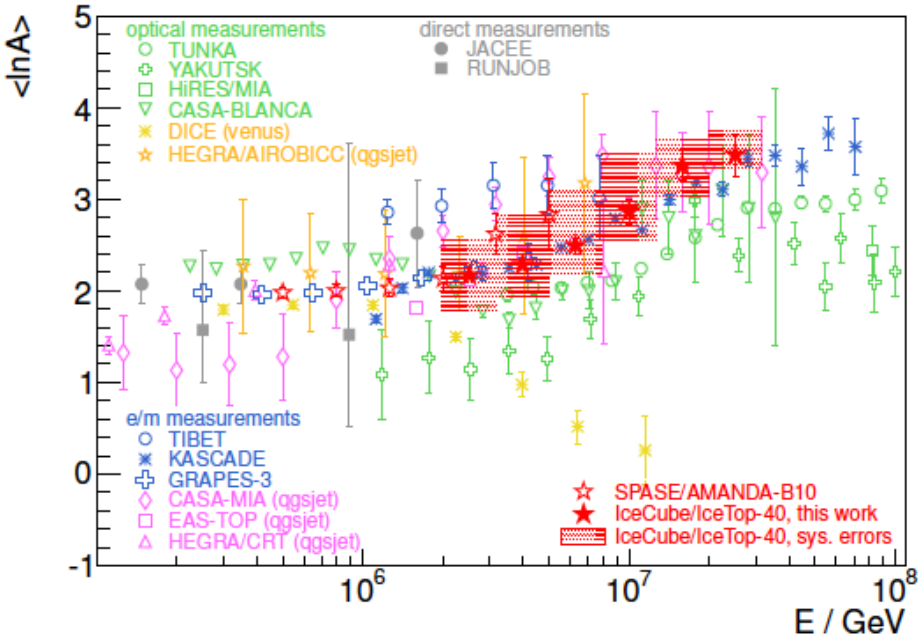
Neural Network Analysis:
Input: S125, K70 from 1 month of data
Output: Primary E & <lnA>





IceTop-40/IceCube-40 Spectrum & Composition 10^{15}-$10^{16.5}$eV





➔advanced method of combining energy and composition reconstruction (smaller energy range, less statistics)

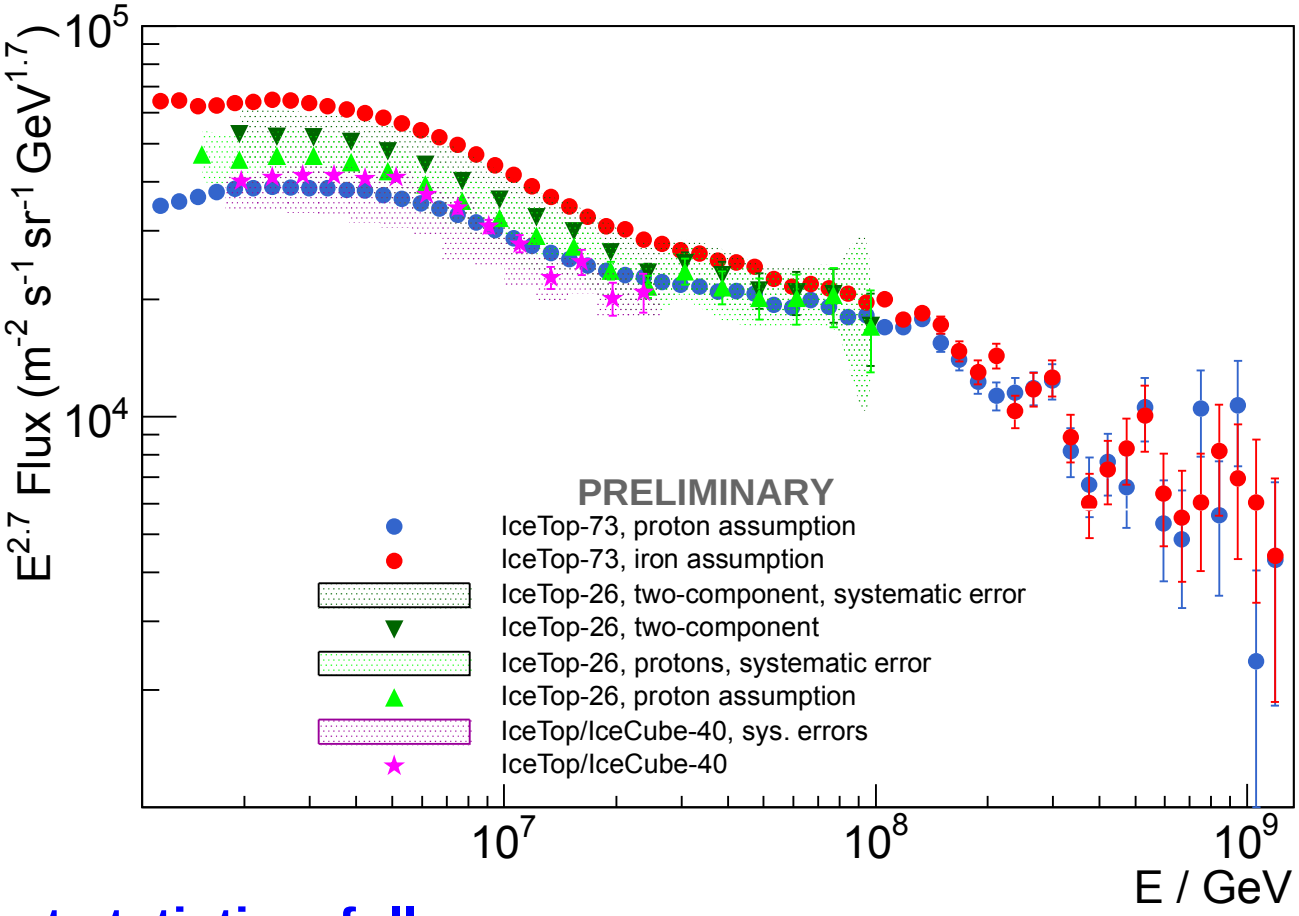
➔(first) knee clearly visible

➔composition gets heavier

➔hardening seems to be there

Submitted to Astrop. Phys., (arXiv:1207.6362)

IceTop-73 Data: Preliminary Energy Spectrum



➔ **best statistics, full energy range**

➔ **calibration by Monte Carlo; composition assumption**

➔ **hardening clearly visible**

➔ **steepening visible (little above 10^{17}eV)**

➔ **all methods agree to each other**

S.Tilav ISVHECRI 2012

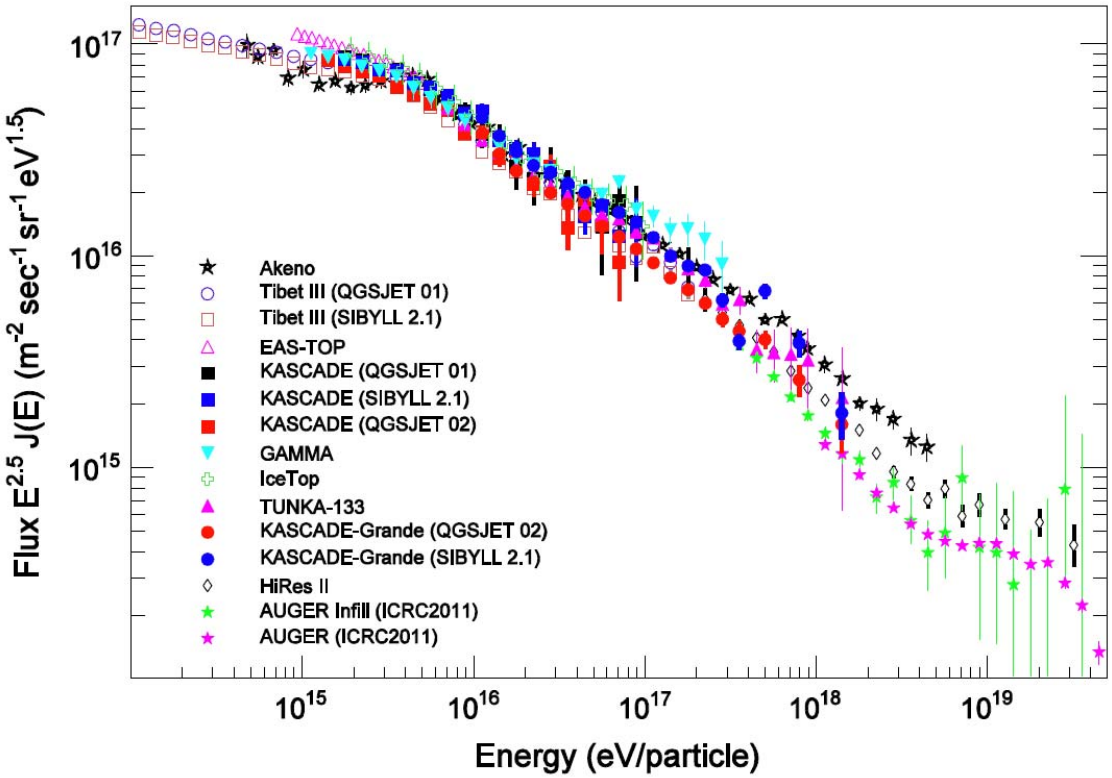
All-particle cosmic rays energy epectrum

KASCADE-Grande - Tunka - IceTop

- **Same structures observed**
- **Absolute scale difference: <20%**

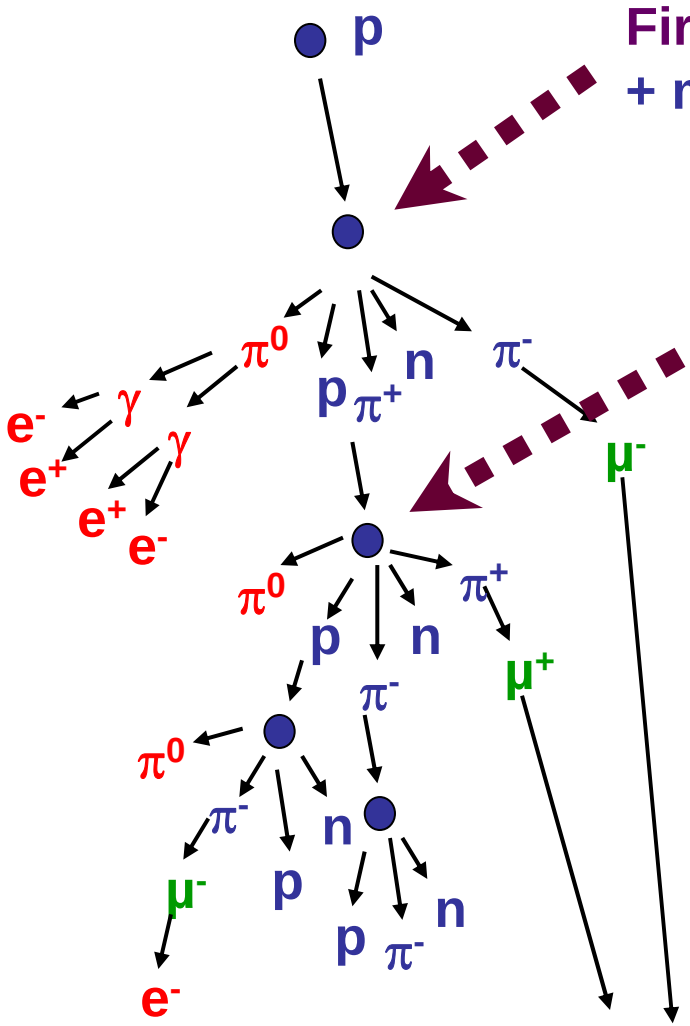
(despite different observables and observation levels)

🡐 within systematics (by method and composition sensitivity!)



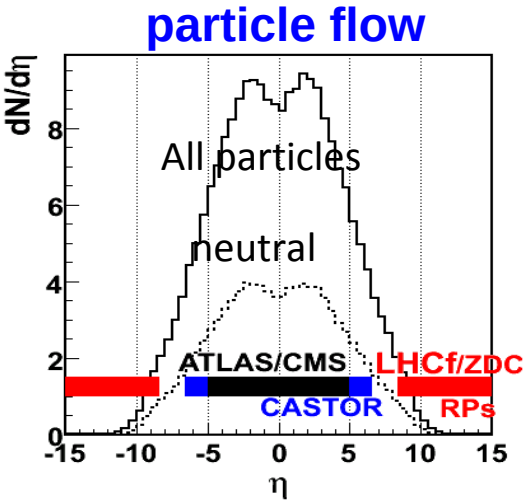
Differences between the experiments for same hadronic interaction model are in the same order than between results of different hadronic interaction models at one experiment.

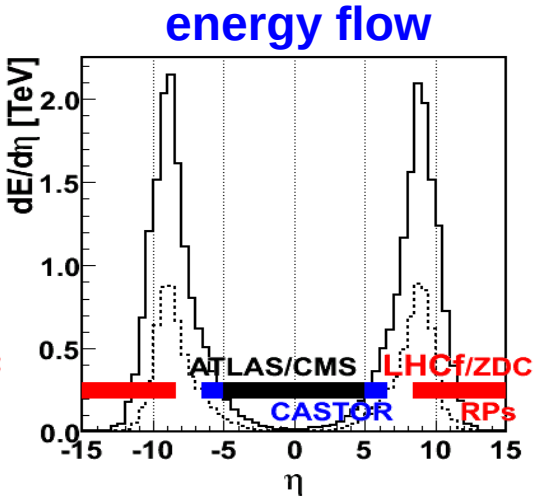
Validity of Hadronic Interaction Models



First, high energy interaction: LHC
+ multiparameter measurements EAS

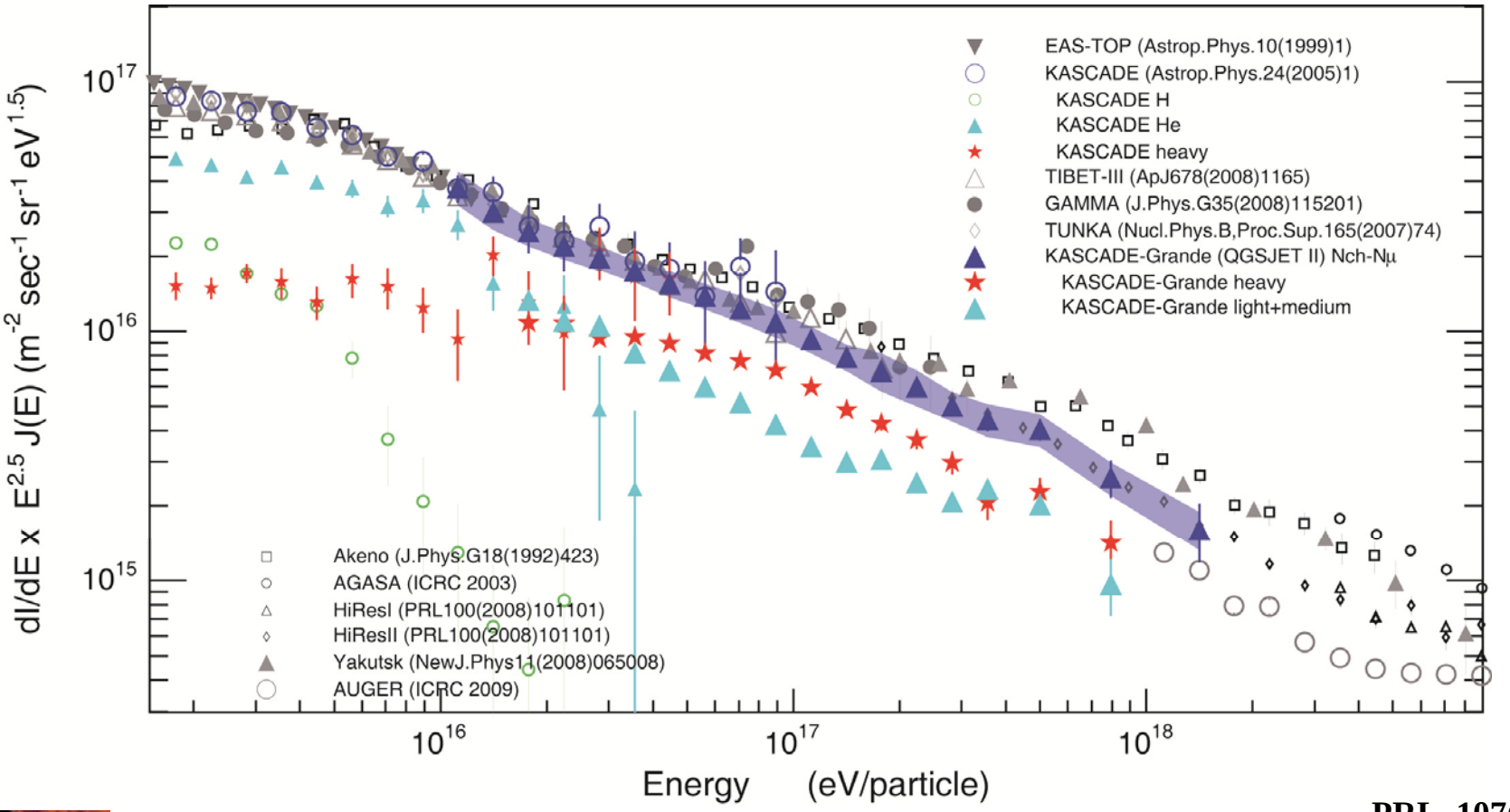
Secondary interactions:
Fix target experiments
+ multiparameter measurements EAS





Light and Heavy Knees

- ➔ **KASCADE: knee of light primaries at ~$3 \cdot 10^{15}$eV**
- ➔ **hardening at 10^{16}eV due to knee of medium component**
- ➔ **KASCADE-Grande: knee of heavy primaries at ~$9 \cdot 10^{16}$ eV**
- ➔ **heavy knee less distinct compared to light knee**



PRL, 107(2011)

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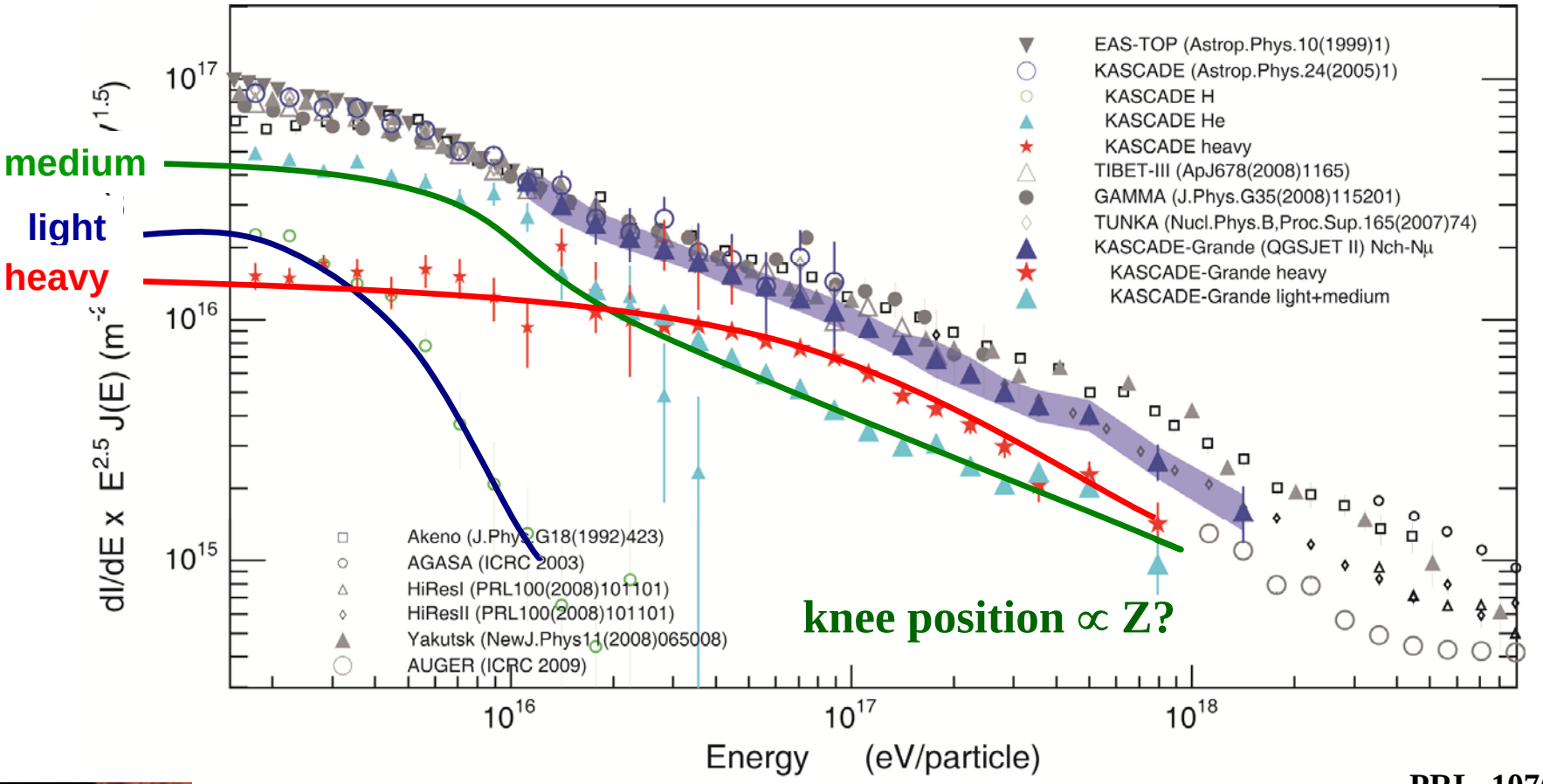
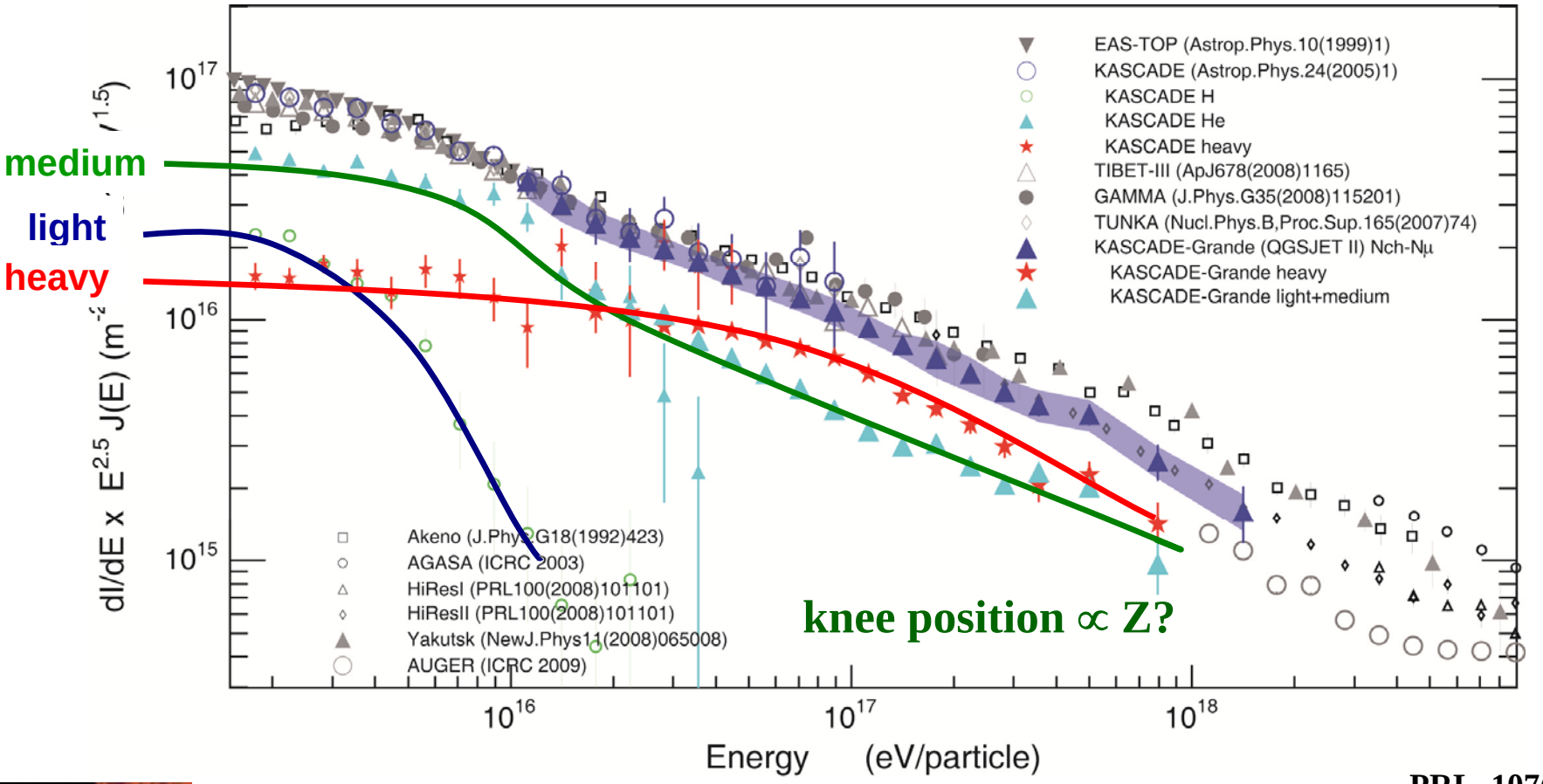


PRL, 107(2011)

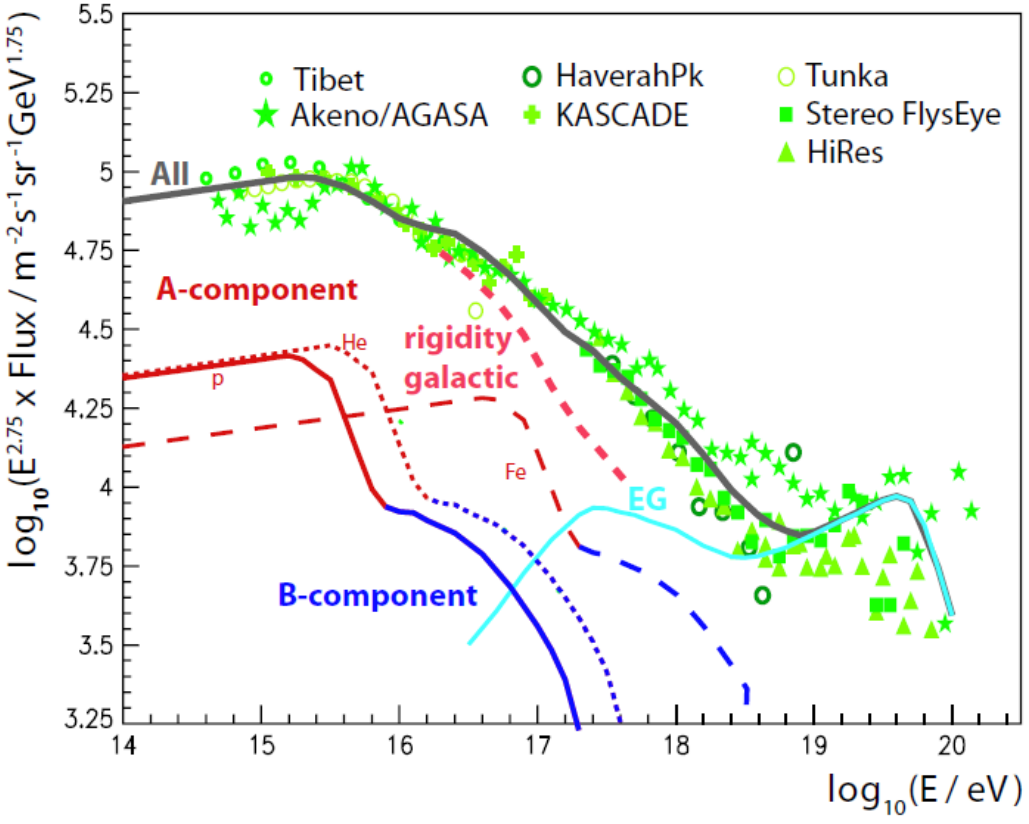
KASCADE-Grande - Tunka – IceTop: Composition

- similar tendencies
- absolute scale difference: still large
  (despite similar all-particle spectrum)
  ← hadronic interaction models??

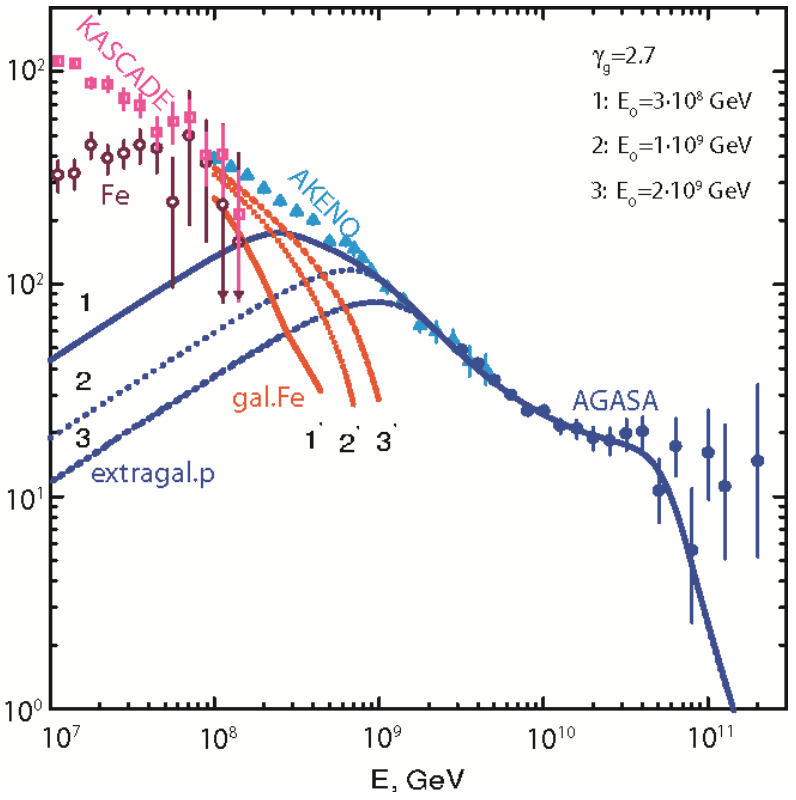


PRL, 107(2011)

Implications



A.M.Hillas, J. Phys. G: Nucl. Part. Phys. 31 (2005) R95

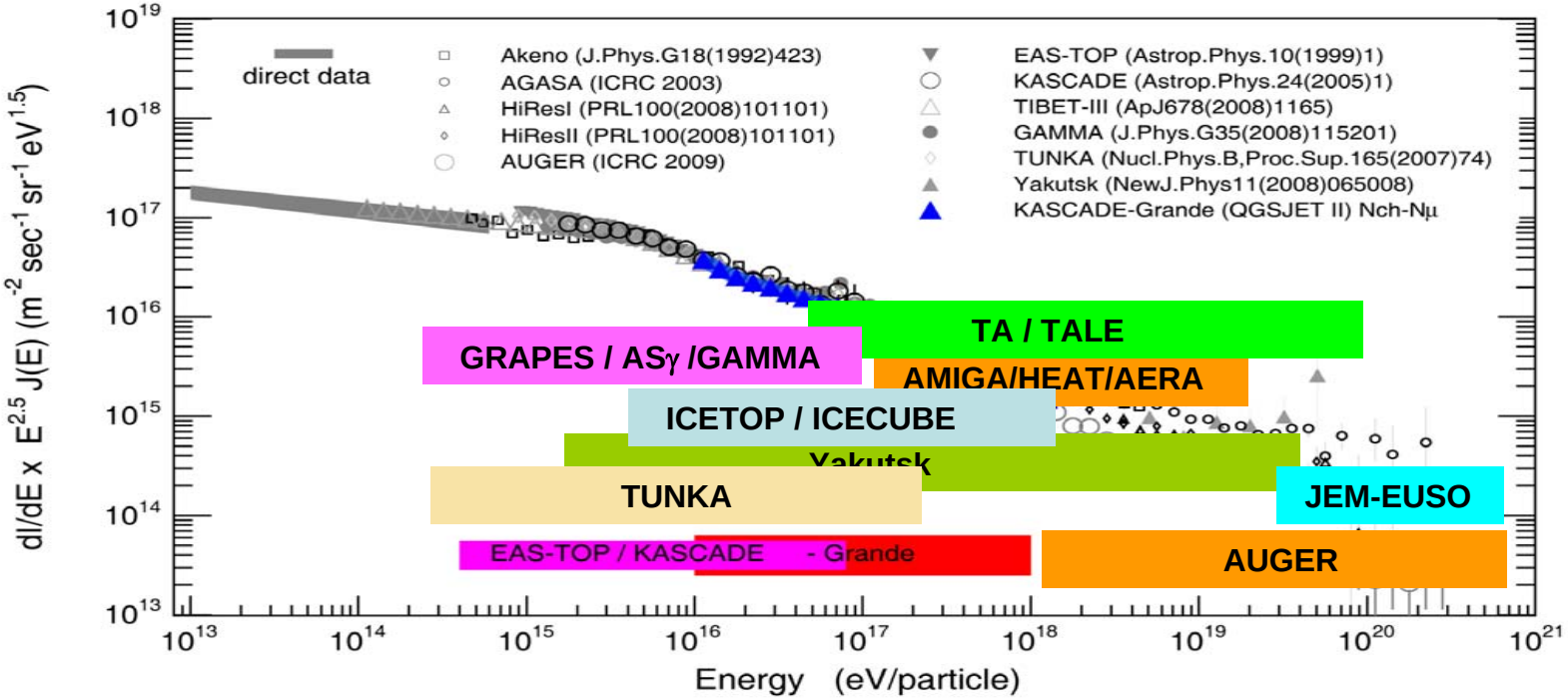


V.Berezinsky, astro-ph/0403477

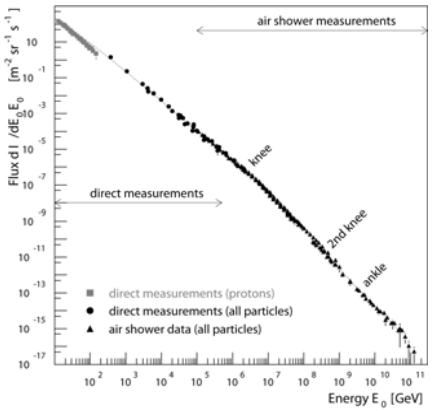
Experimental situation:

light knee above 10^{15}eV
spectrum concave at 10^{16}eV
heavy knee at 10^{17}eV
mixed composition around 10^{17}eV

Summary + Questions



- which astrophysical model describes the data?
- exact composition above heavy knee?
- why heavy knee less distinct than light knee?
- spectral forms of individual mass spectra?
- recurrence of protons?
- second knee?
- anisotropies?



answers only by combining all information: stay tuned!