The knee and beyond: results from KASCADE-Grande, IceTop and TUNKA

Andrea Chiavassa
Universita` agli Studi di Torino

24th European Cosmic Rays Symposium
Kiel 1-5 September 2014

Talk Outline

1) Indirect measurements: primary energy and mass evaluation
2) All Particle Spectrum results
3) Primary Composition results → mass groups spectra obtained by single events classification
4) Conclusions

Indirect Measurement

Primary energy and mass evaluated by EAS measurements
→Limited by EAS development fluctuations
→ Minimum at EAS Maximum

Cherenkov Detectors

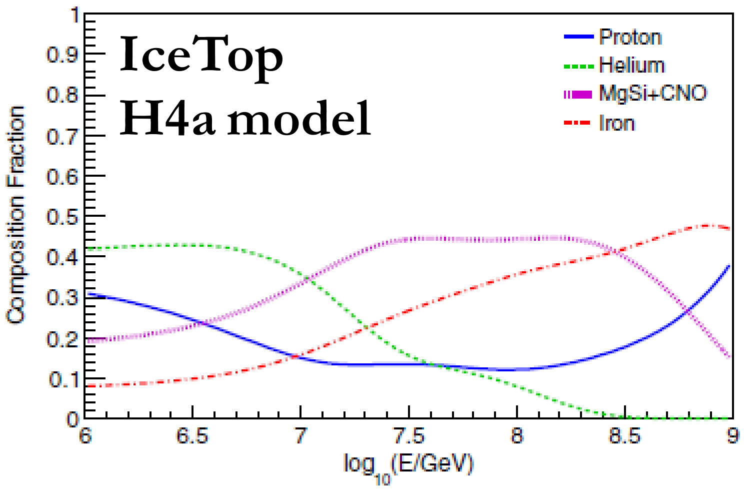
I. Calorimetric Measurement
II. Low Duty Cycle
III. Energy Calibration → EAS simulation
IV. Primary Mass → X_{max} → EAS simulation
V. Absolute Flux Calibration comparing with surface arrays spectra

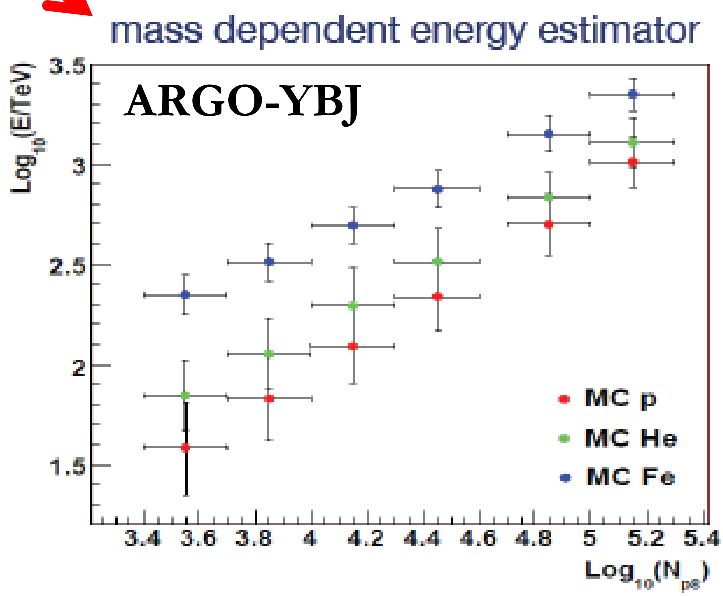
Surface Arrays

I. EAS detected at fixed atmospheric depth
II. High Duty Cycle
III. Energy Calibration → EAS Simulation (hadronic model and chemical composition assumption)
IV. Primary Mass → Correlation between EAS parameters → N_e vs N_μ

• E = *f*(X, A)

1) Pure chemical composition
2) <A> from a model

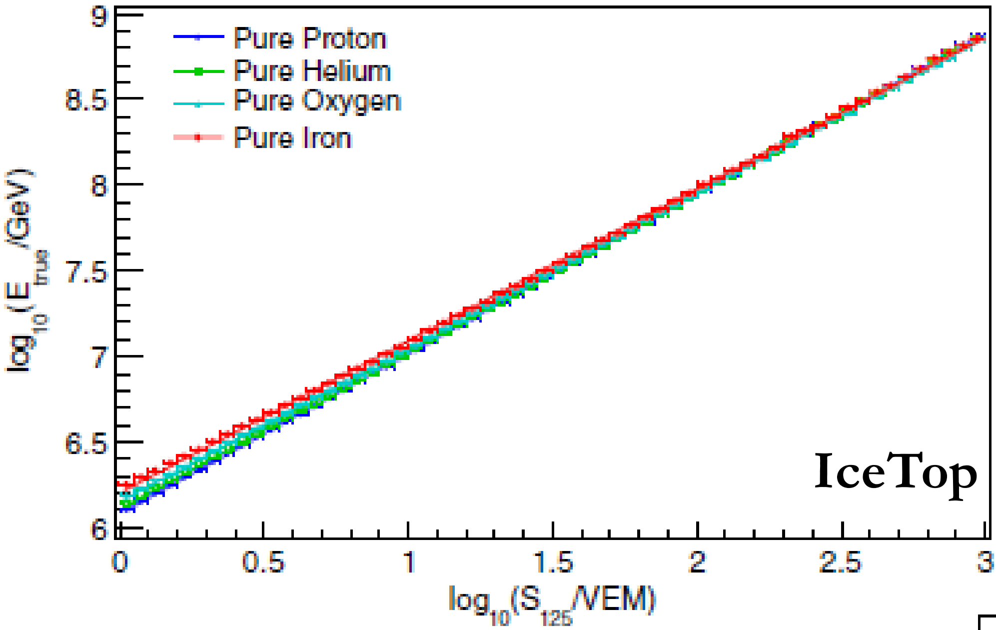




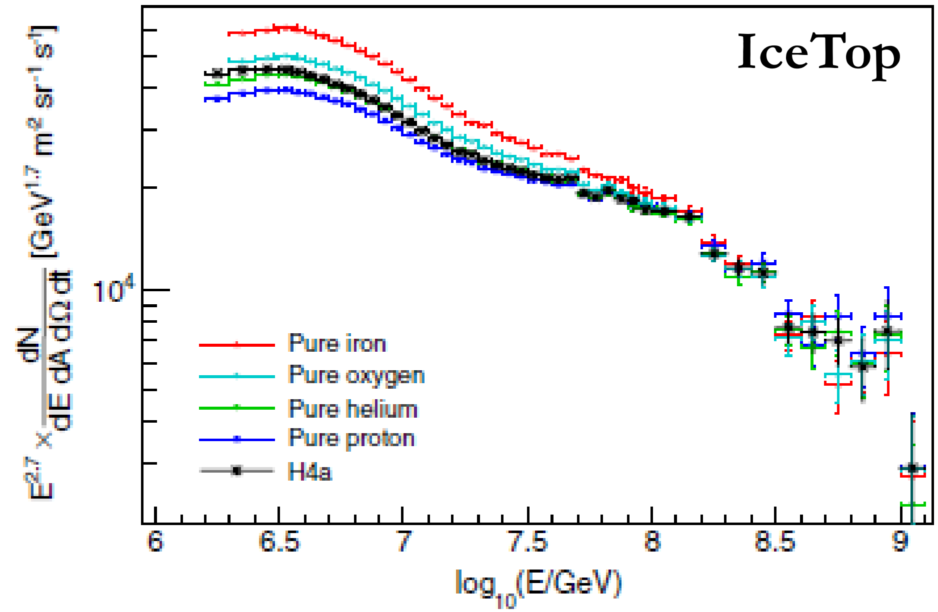
3) Estimate primary mass from N_{ch}/N_{μ}

KASCADE-Grande

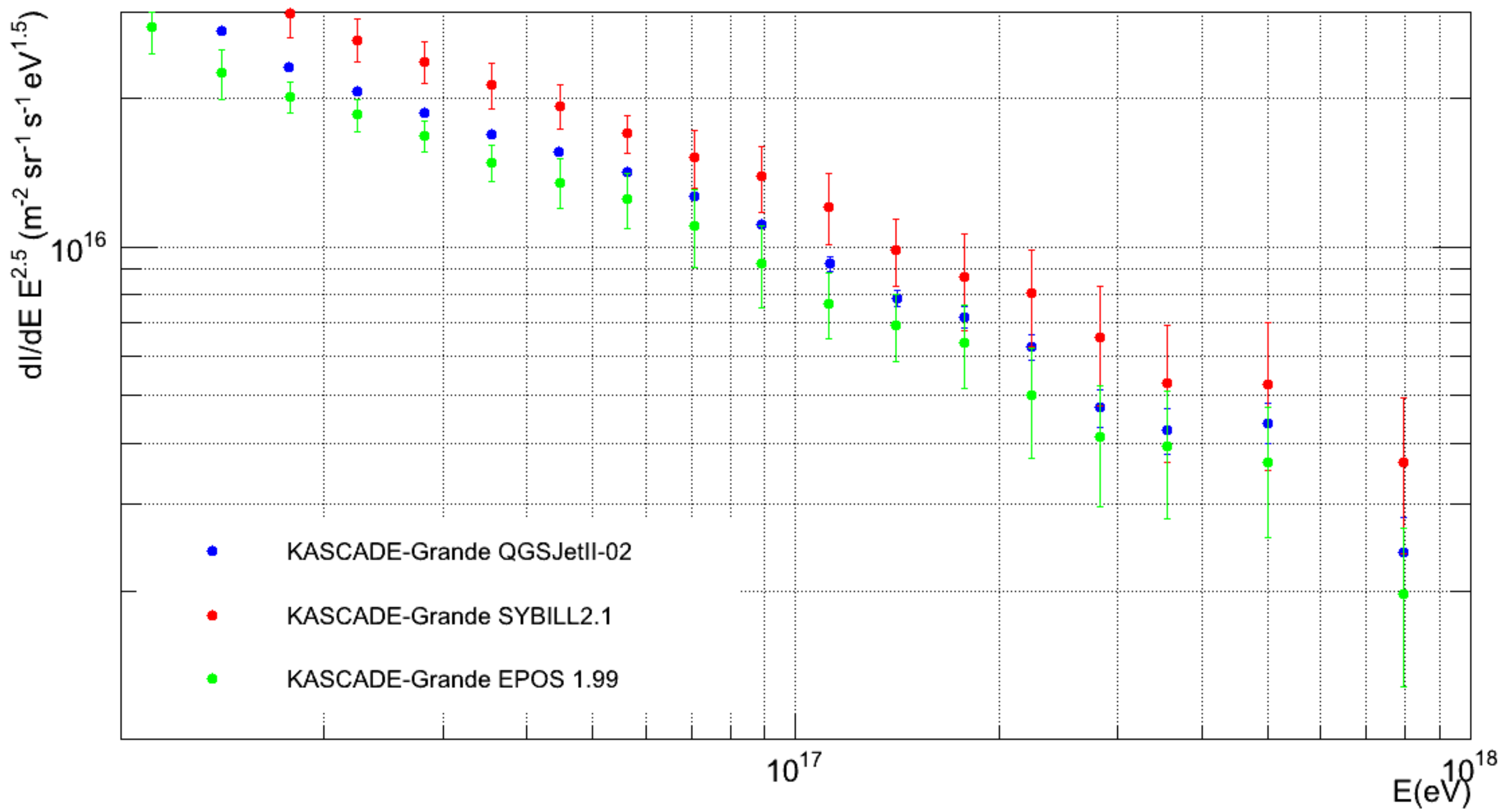
$$k = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_H}{\log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_H}$$



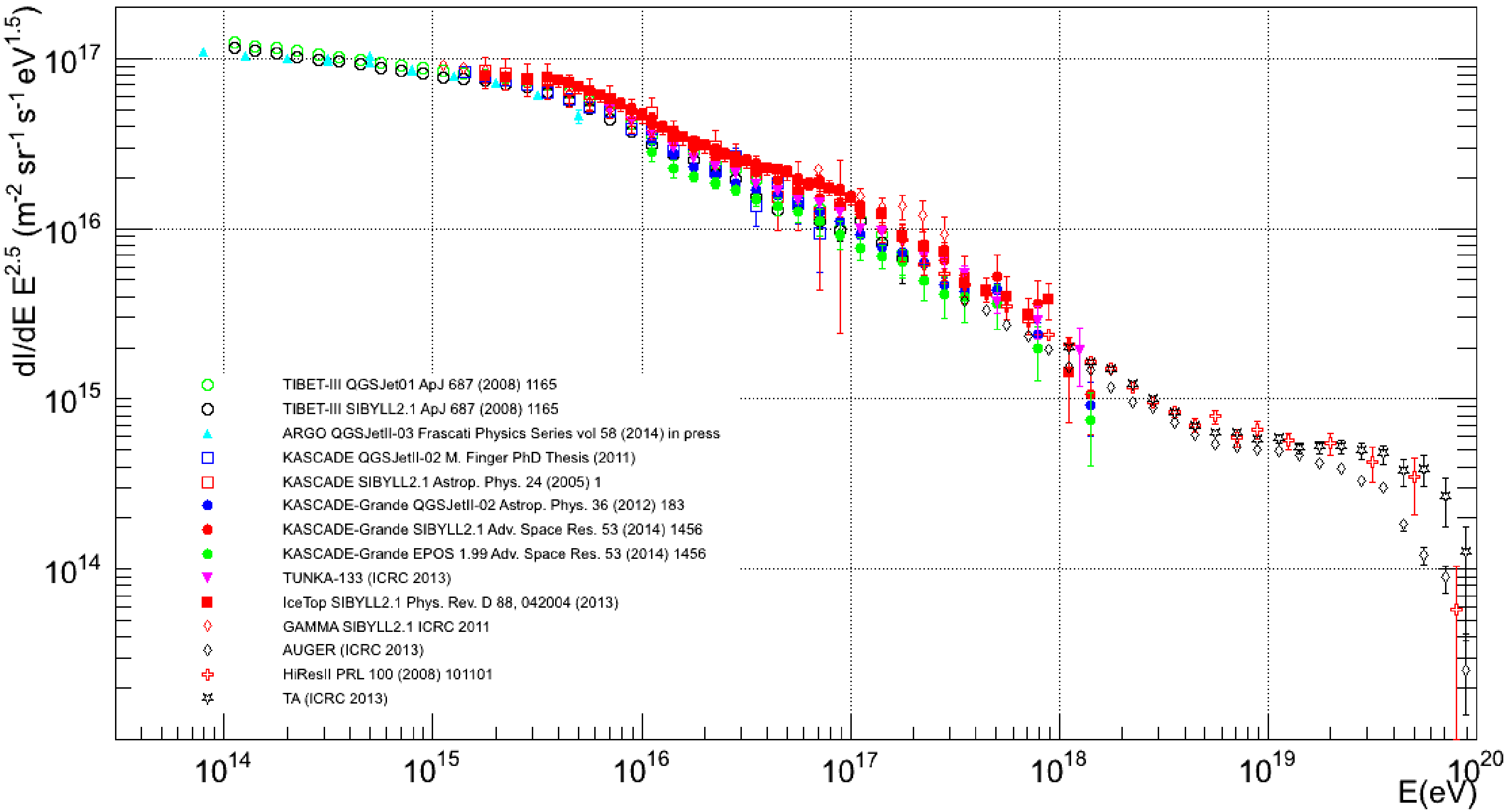
Dependence from A becomes smaller near to EAS maximum



- Energy Calibration considerably depends on the **high energy hadronic interaction model** used in EAS simulation
- KASCADE-Grande all particle energy spectrum obtained by different hadronic interaction models.

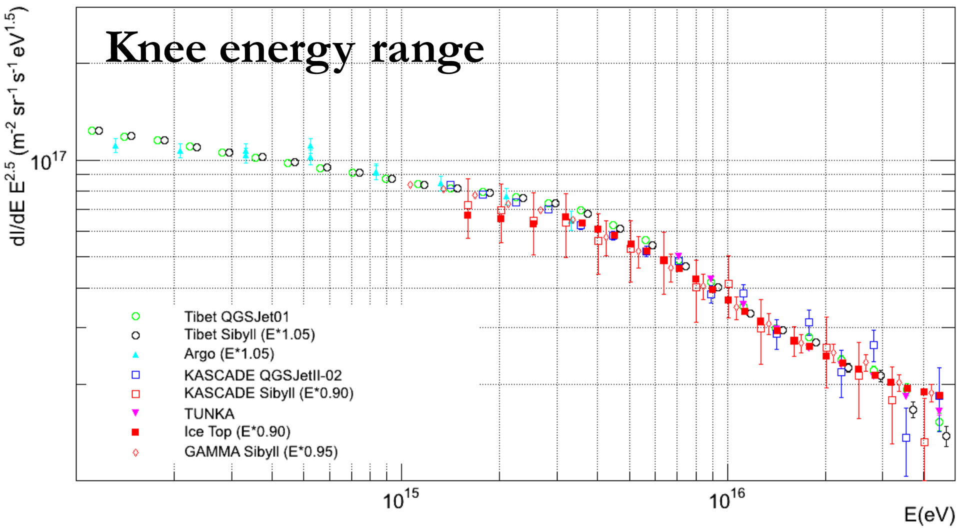


All Particle Spectrum



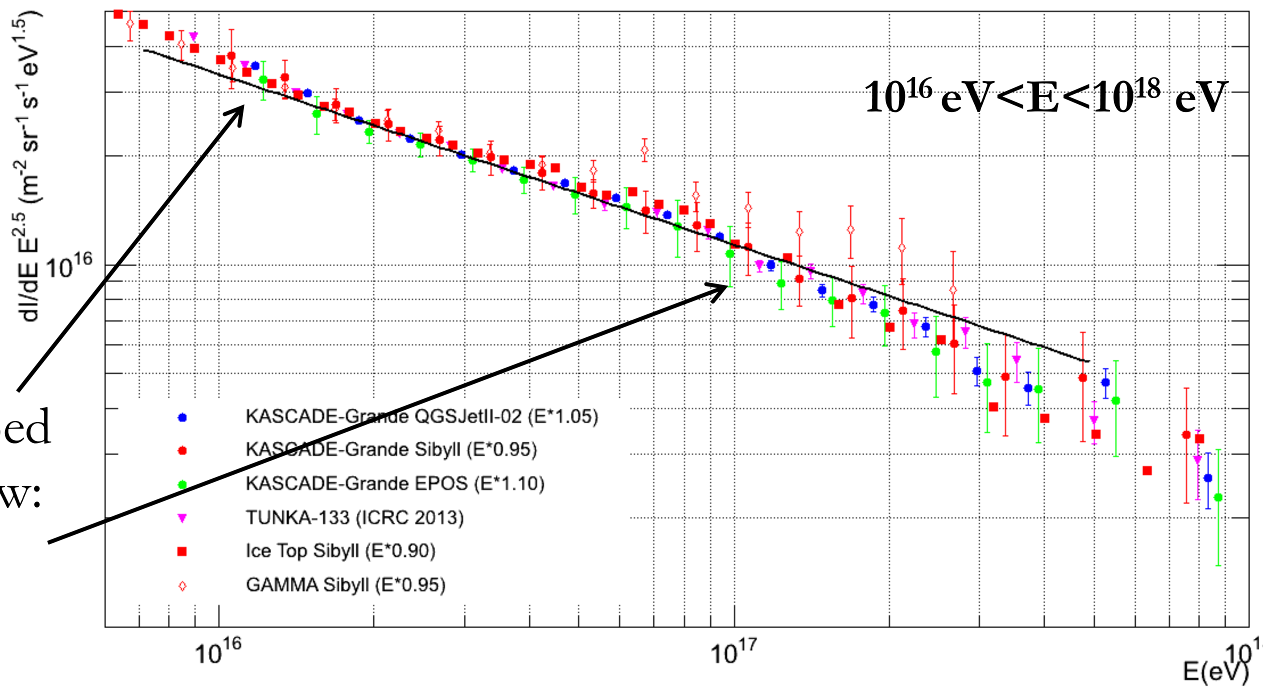
i. Differences between experiments

ii. Spectral features are very similar (at energies slightly different)



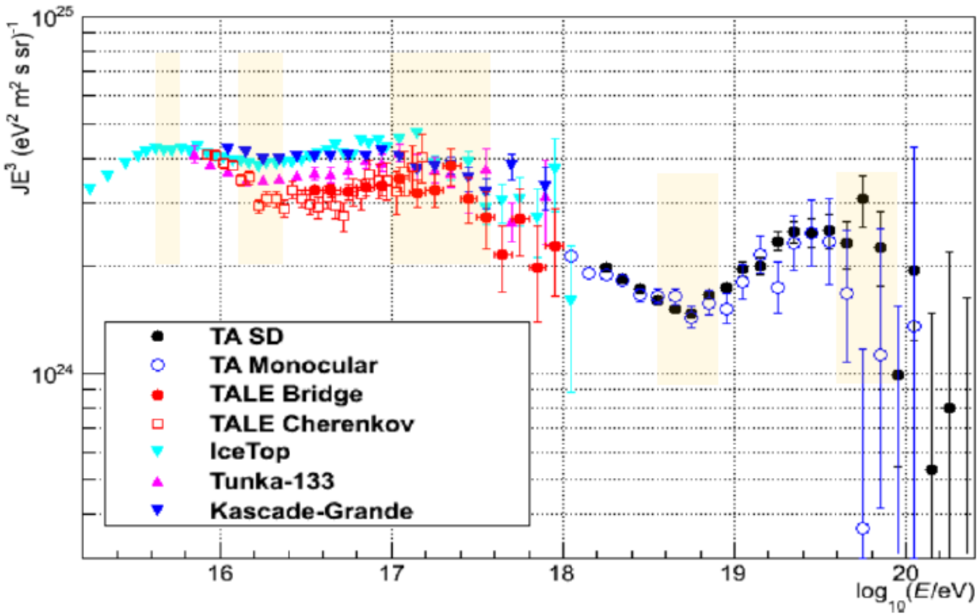
All particle spectra obtained shifting the energies by a factor smaller than what can be estimated as systematic error: i.e. 15-20%

Difference between measurements can be mainly attributed to systematic effects in the energy calibration



Spectra cannot be described by a single slope power law: hardening (~10^{16} eV) steepening (~10^{17} eV)

Recent updates from ISVHECRI (18-22 August 2014, CERN)



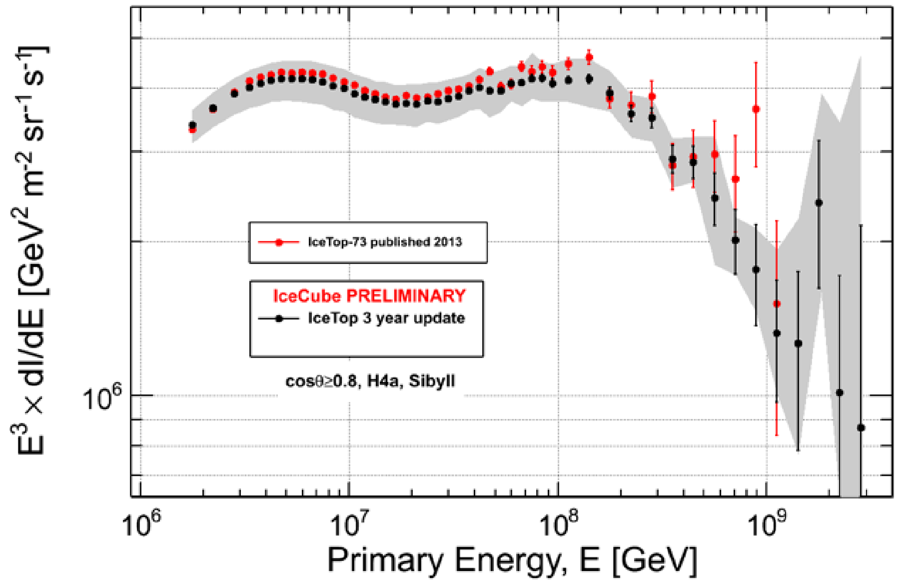
TALE → Confirms spectral features

Concavity ~10^{16} eV

Break ~10^{17} eV

IceTop → Spectral shape confirmed

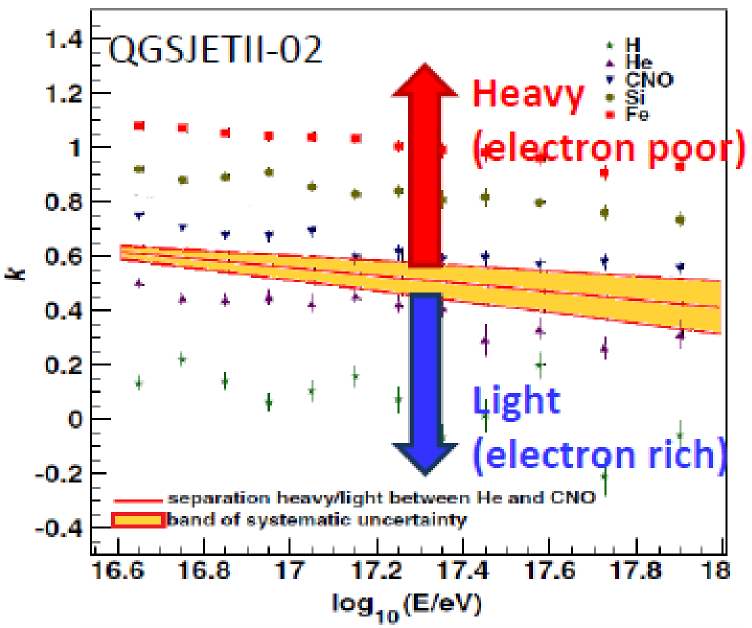
Normalization slightly lower



Mass Group Spectra

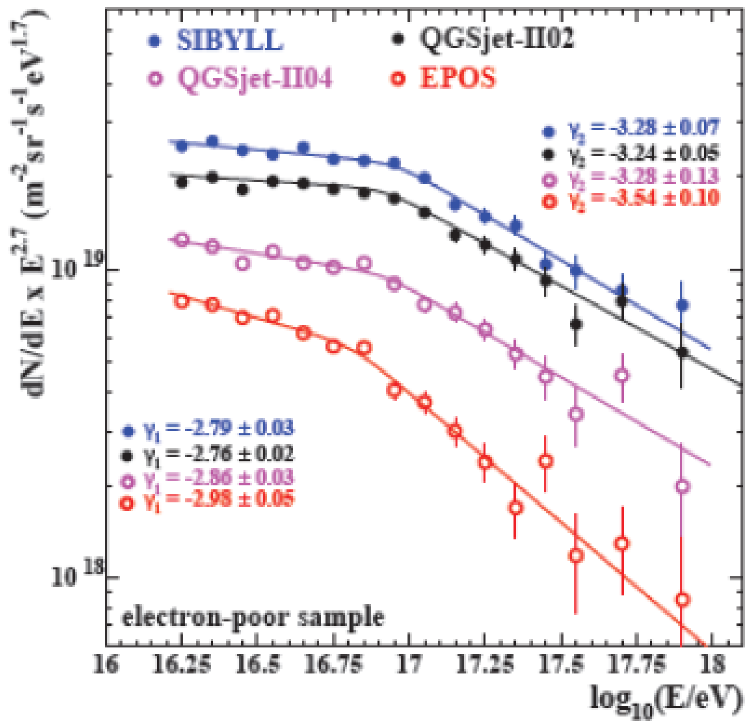
- **KASCADE-Grande**
  - Event Selection based on the measured N_{ch}/N_{μ} ratio

KASCADE-Grande Coll., PRD87 (2013)



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

Heavy mass group spectrum

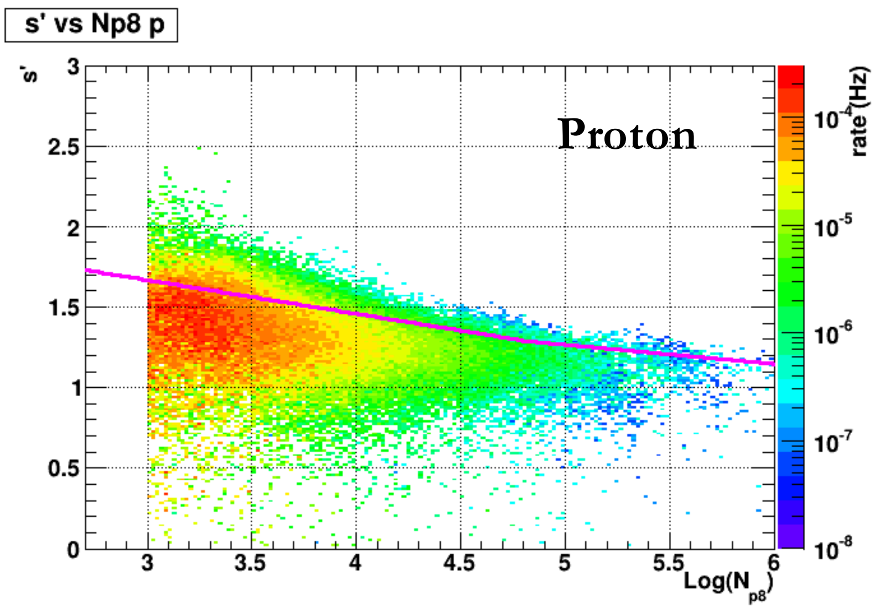


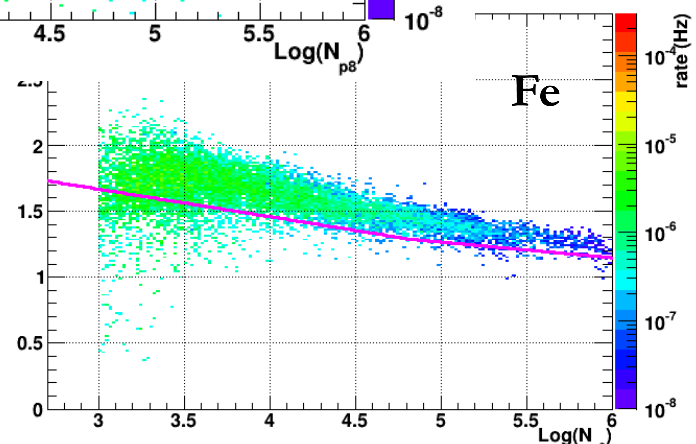
KASCADE Grande Coll., Adv. in Space R. (2013)

Fluxes depend on the interaction model, spectral features not

ARGO-YBJ

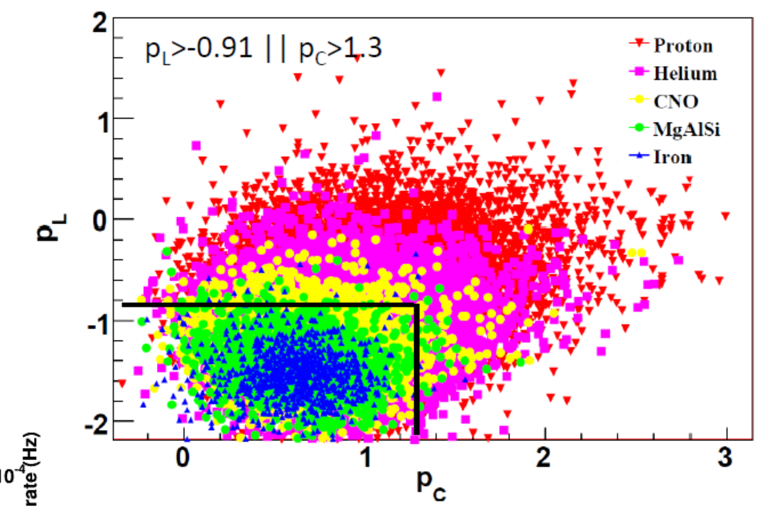
- Selection using RPC data alone.
- Np_8 vs s'





- Selection using RPC and WFCTA data
- N_{max}, Length, Width

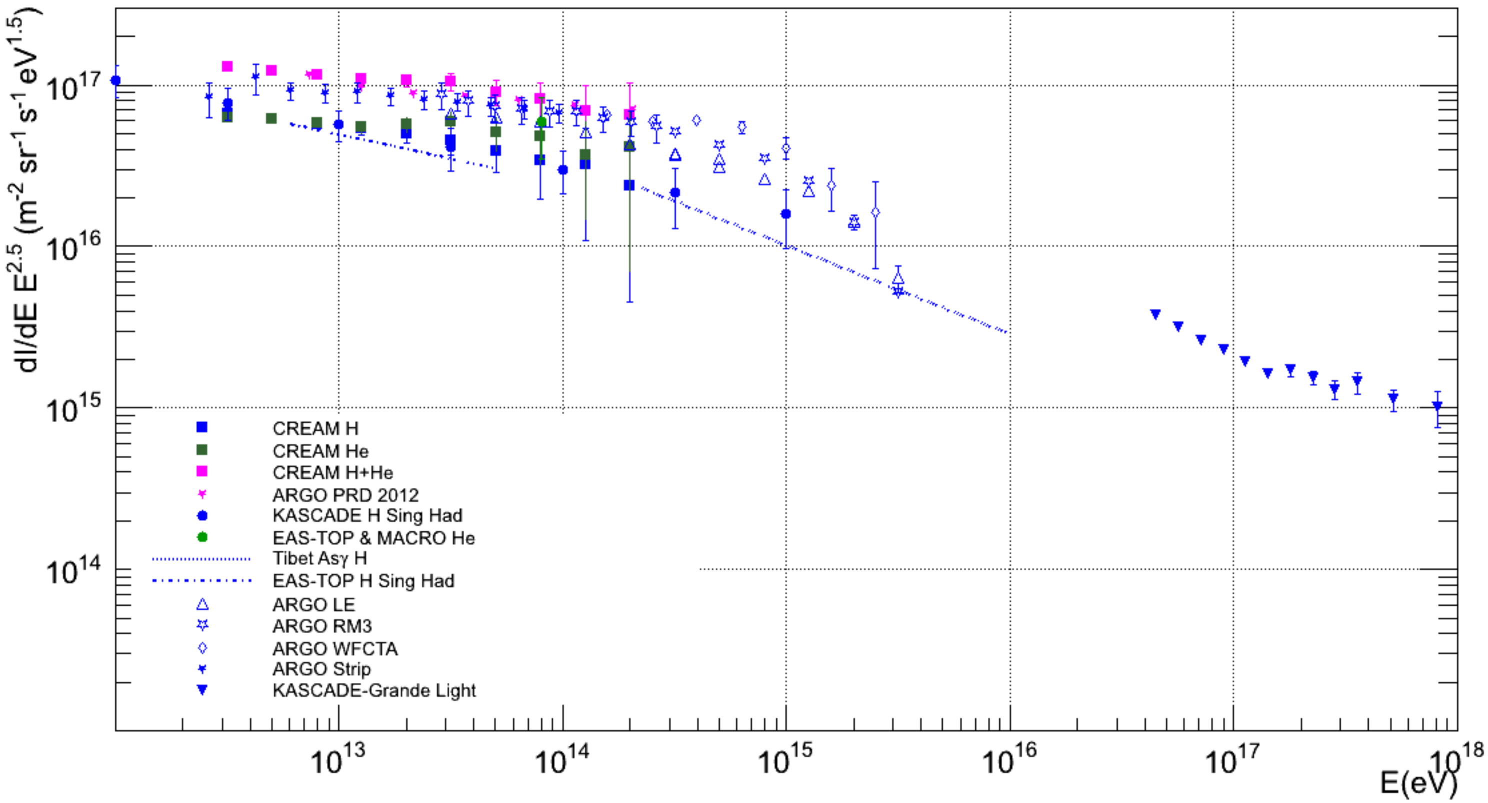
- $p_L = N_{max} - 1.44 log_{10}(E_{rec}/1TeV)$
- $p_C = L/W - 0.091 \times (R_p/10m) - 0.14 log_{10}(E_{rec}/1TeV)$



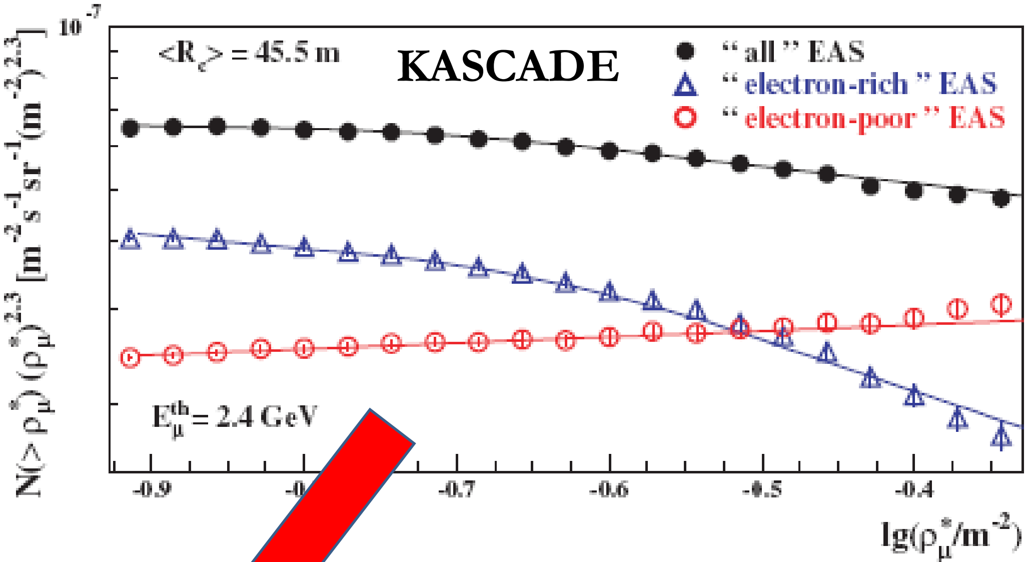
QGSJetII-03 + GHEISHA

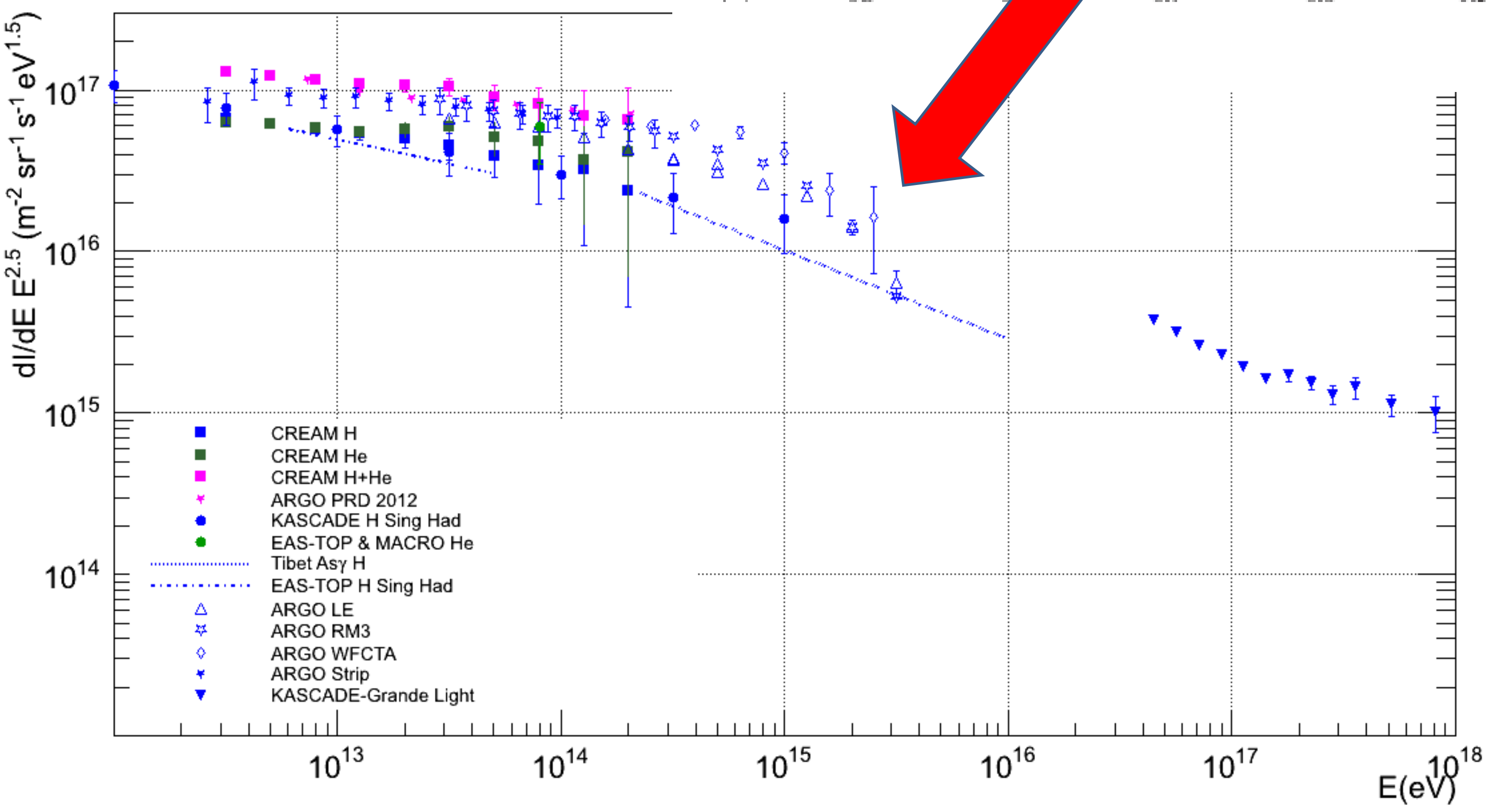
Light Mass Group Spectra

- Selection efficiency (i.e. fluxes) depends on the hadronic interaction model
- Spectral features:
  - ✓ ARGO → break at E~6-7x10^{14} eV
  - ✓ KASCADE-Grande → hardening at E = $10^{17.08\pm0.08}$ eV



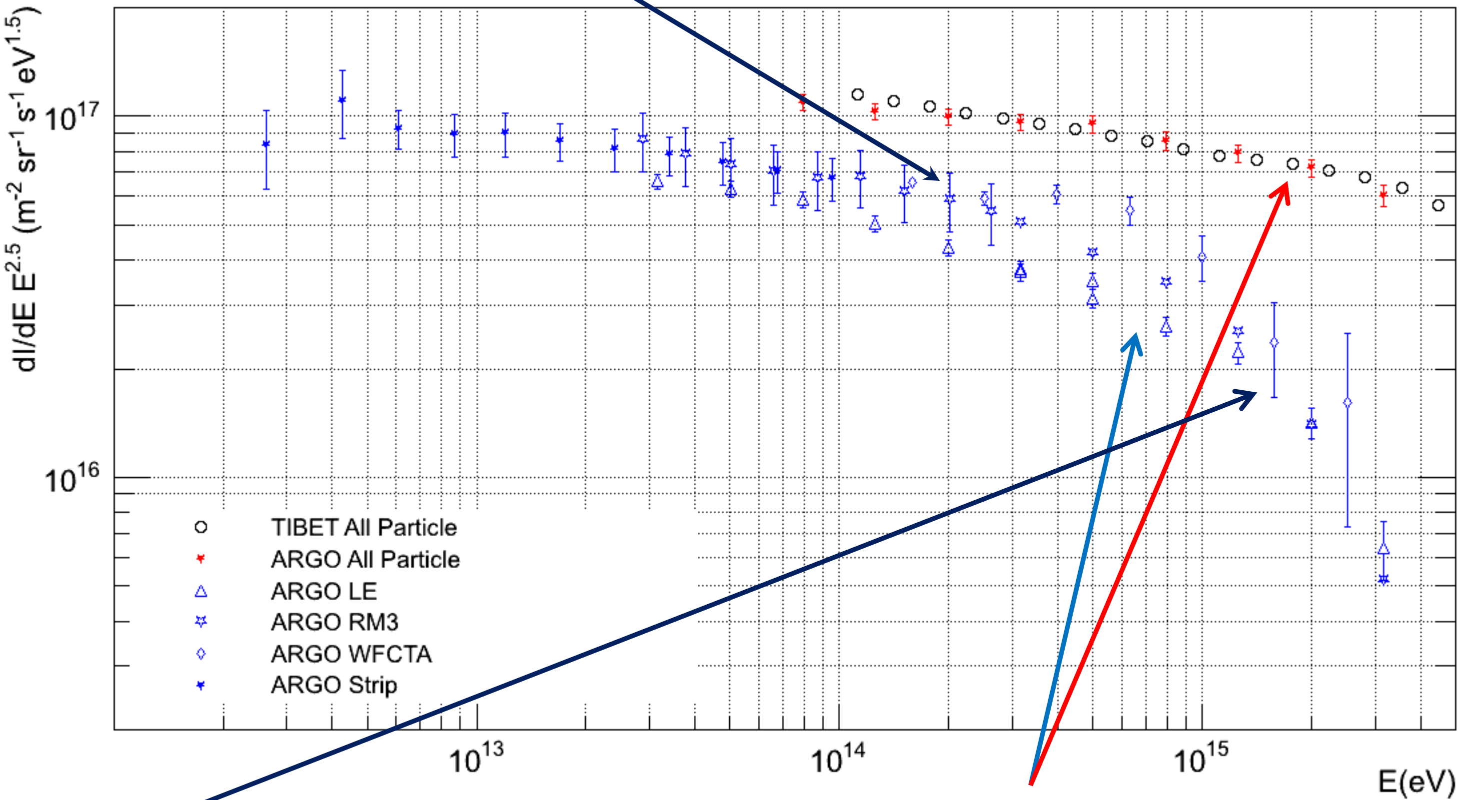
Integral flux above the change of slope → ~10^{-7} m^{-2} s^{-1} sr^{-1}
→ ~$2\text{-}4 \times 10^{15}$ eV





ARGO-YBJ

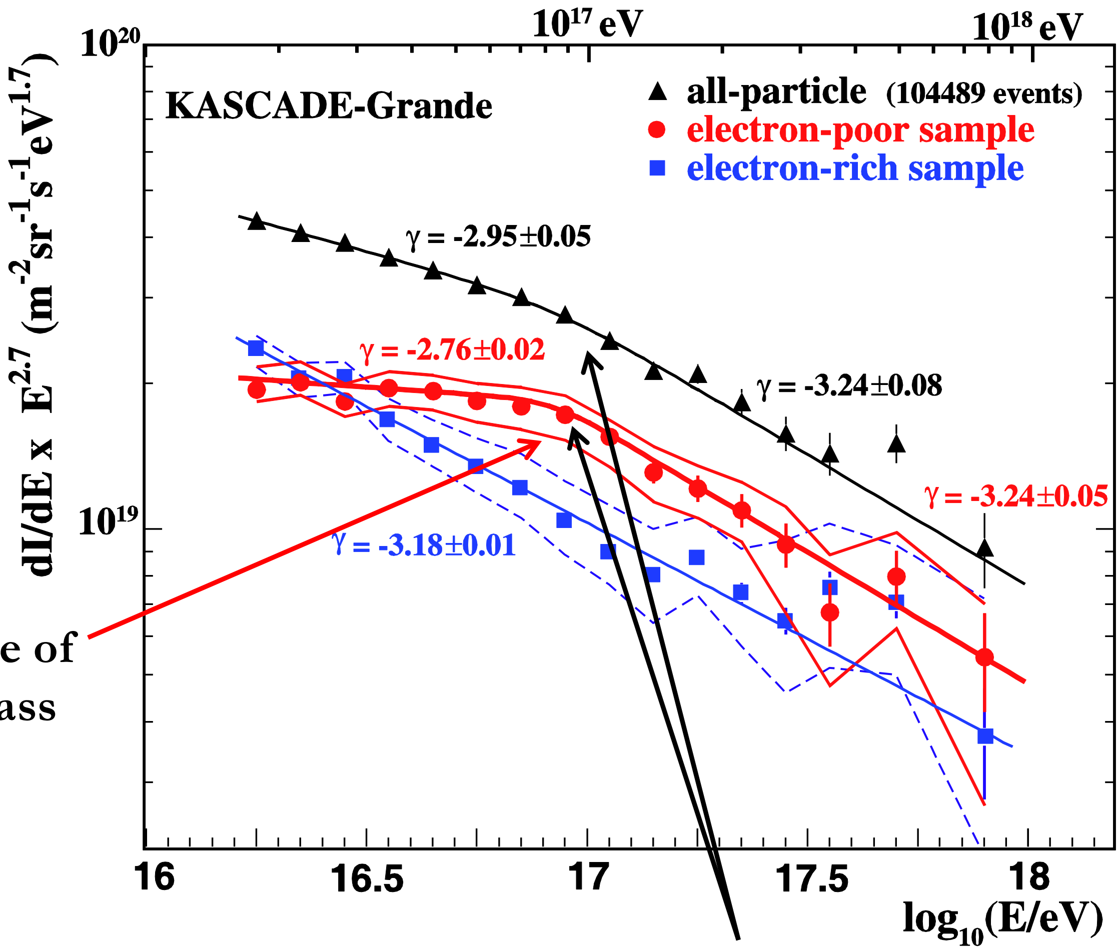
- Spectra depends on the specific analysis
- This plot does not include systematic errors
  → if considered spectra are marginally compatible



Spectral slopes above the "knee" are quite steep

All particle and light spectra show the change of slope at different energies

Heavy Mass Group Spectra

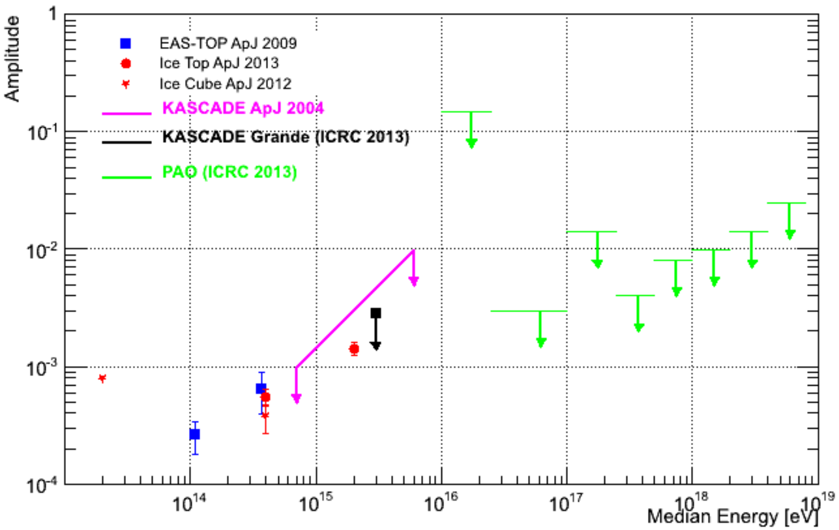


Evidence of a change of slope in the heavy mass group spectrum.
$E_{knee} = 8 \times 10^{16}$ eV

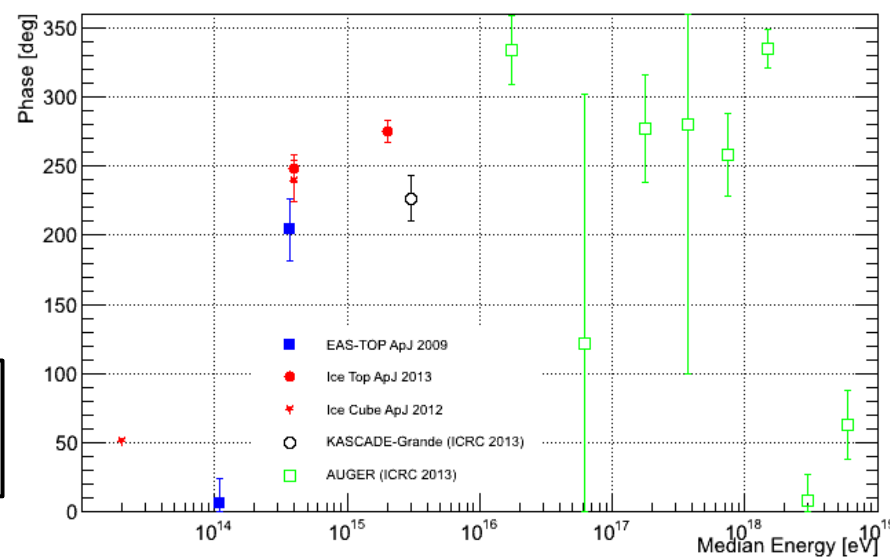
All particle and heavy mass group spectra show a steepening at similar energy

Large Scale Anisotropy searches

- The highest energy measured large scale anisotropy: 2×10^{15} eV (IceTop)



Hints of an increasing amplitude crossing knee energy



Possible change of the phase for E>10^{14} eV

Results summary

- All particle spectrum
  - Main Features: knee ($4 x 10^{15}$ eV) & ankle ($4 x 10^{18}$ eV)
  - Hardening slightly above 10^{16} eV
  - Steepening around 10^{17} eV
- Light Spectrum
  - Steepening
    - 6.5×10^{14} eV (ARGO)
    - $3\text{-}4 \times 10^{15}$ eV (KASCADE)

    Difficult to conciliate
  - Hardening $10^{17.08 \pm 0.08}$ eV
- Heavy Spectrum
  - Steepening at $\log(E/eV) = 16.92 \pm 0.04$

Exercise(*) to check the experimental data

- Calculate the element spectra:

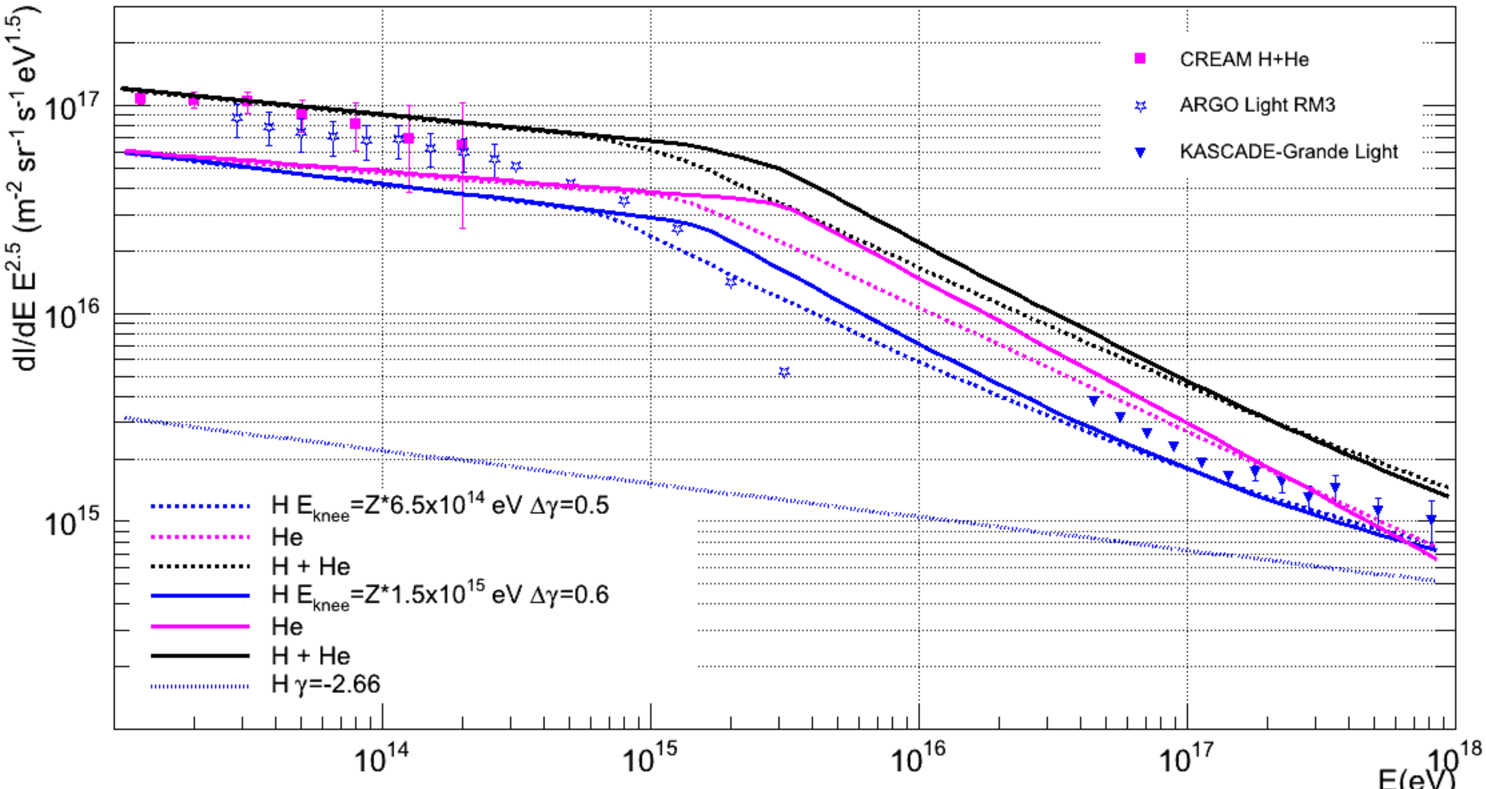
$$\Phi(E) = KE^{\gamma_1}[1+(\frac{E}{E_{knee}})^{\varepsilon}]^{\frac{\gamma_2-\gamma_1}{\varepsilon}}$$

- Assuming:
  - $E_{knee}(Z) = Z\, E_{knee}(p)$
    i. $E_{knee}(p) = 6.5\text{x}10^{14}$ eV (ARGO result)
    ii. $E_{knee}(p) = 1.5\text{x}10^{15}$ eV (KASCADE result)
  - γ_H & γ_{He} from CREAM measurements ($\gamma_{CNO}=\gamma_{Fe}=\gamma_{He}$)
  - Fluxes normalized to CREAM measurements at 10^{13} eV
  - Same $\Delta\gamma$ for all elements
    i. $\Delta\gamma = 0.5$
    ii. $\Delta\gamma = 0.6$
- Add an harder H component (γ=-2.66) dominating the H flux above 10^{17} eV

(*) inspired by T. Gaisser et al. Front. Phys.2013

Light mass group spectra

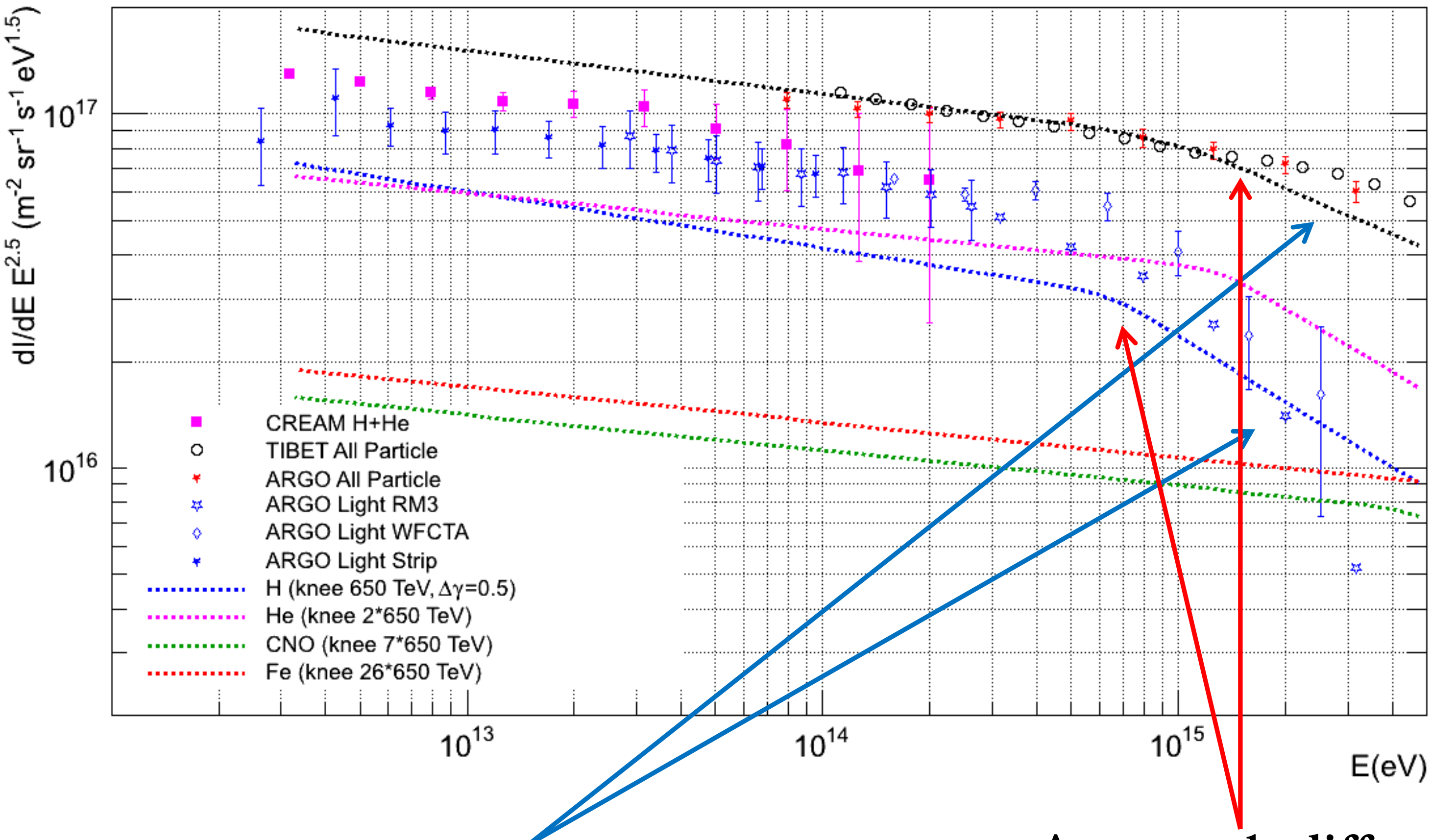
The points are not intended as an exact measure of H+He fluxes.



Spectra calculated assuming Peter's cycle and calibrated with the CREAM measurements can qualitatively describe the indirect experiments results.

ARGO light spectrum above the knee seems too steep

ARGO-YBJ

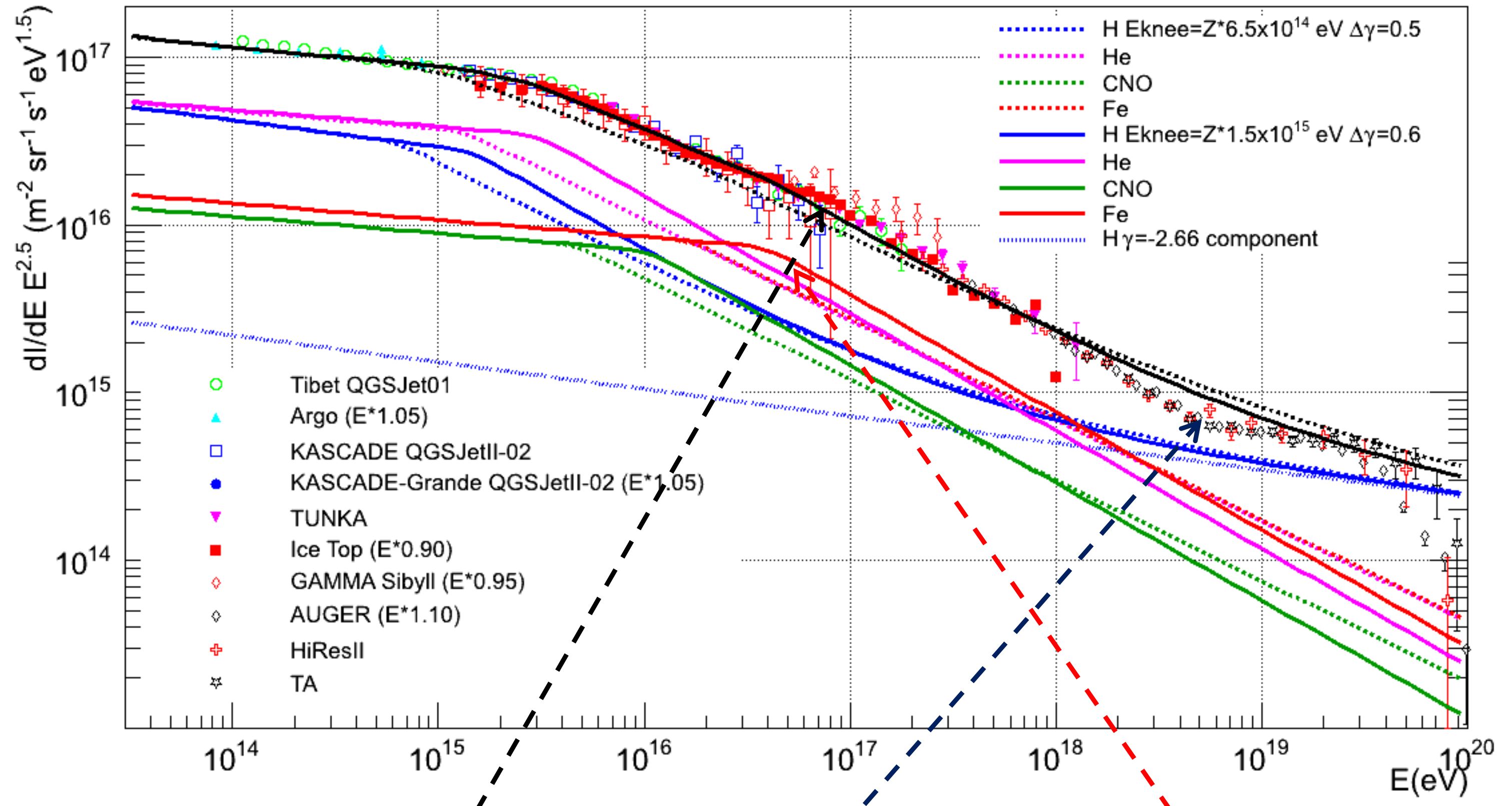


$\Delta\gamma = 0.5 \rightarrow$ not enough for light spectrum

$\rightarrow$ too much for all particle spectrum

Apparently different energies of the change of slopes are not incompatible with this simple description

Main qualitative features of the **all particle spectrum** can be described by this simple exercise……..



Faint structures at $\sim 10^{16}$ and $\sim 10^{17}$ eV cannot be reproduced → another component is necessary
(see T. Gaisser et al.)

Heavy E_{knee} is at too low energy?

10^{18} eV flux is too high and the chemical composition maybe too heavy

Conclusions

1) General agreement on the structure of the all particle spectrum.
2) Features detected also in the light and heavy mass groups spectra
3) Main differences can be attributed to the energy calibration (i.e. hadronic interaction models).

4) A qualitative interpretation of the data can be obtained by elemental spectra with knees at the same rigidity adding a smooth light component becoming dominant above $\sim 10^{17}$ eV.

- Future improvements from:
  - measurements of the single elements spectra in wide energy range (at least separate H and He).
    - EAS experiments are limited by EAS development fluctuations: even at shower maximum it is difficult to separate H and He.
    - Long duration space based measurement (CREAM-ISS): ok for statistics; limited by experiments mass?
  - anisotropy studies possibly for at least two mass groups.
  - connection with γ-rays detectors searching for "Pevatrons"