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

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Talk Outline

1) The Experiments and the techniques to evaluate the primary energy and mass
2) All Particle Spectrum results
3) Primary Composition results → i.e. mass groups spectra
4) Conclusions

Indirect Measurement

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

Cherenkov Detectors

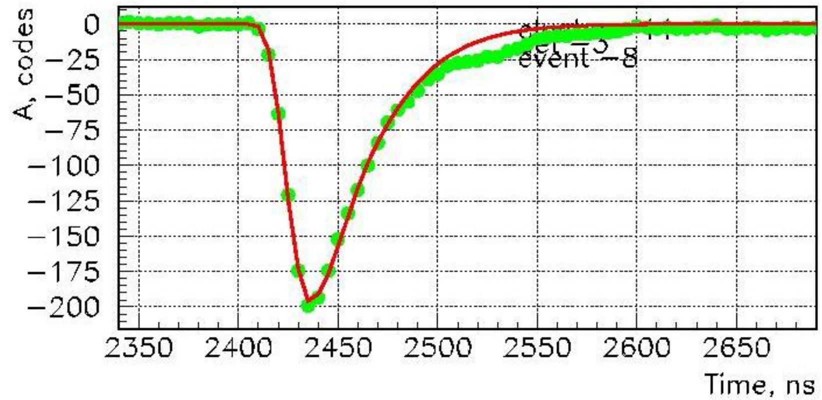
I. Calorimetric Measurement
II. Low Duty Cycle
III. Energy Calibration → EAS simulation
IV. Primary Mass → X_{max} → EAS simulation
V. Absolute Flux Calibration comparing with surface arrays spectra

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

TUNKA $(X_0 = 938\ \mathrm{g\ cm^{-2}})$

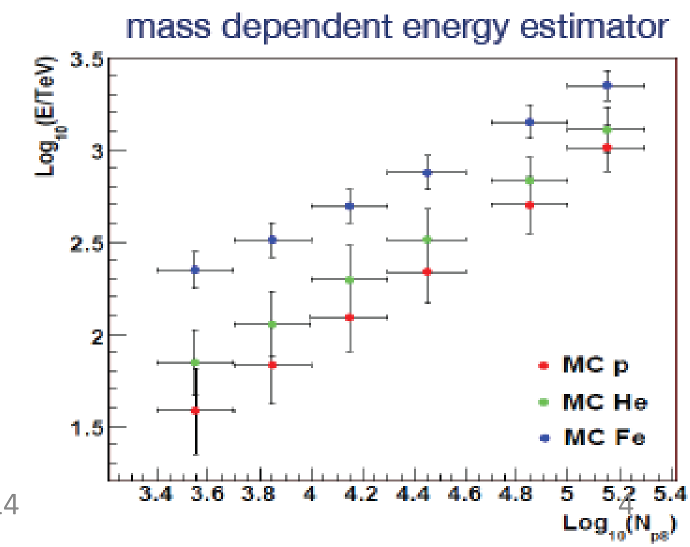
- $E = C\, Q_{200}^{\,g} \rightarrow g = 0.94 \pm 0.01$ (Corsika)
- Primary mass:
  - Amplitude LDF steepness
  - $\tau_{eff}(400)$



A → pulse amplitude, t → front delay,
Q → pulse area, $\tau_{eff} = (Q/1.24\ A)$

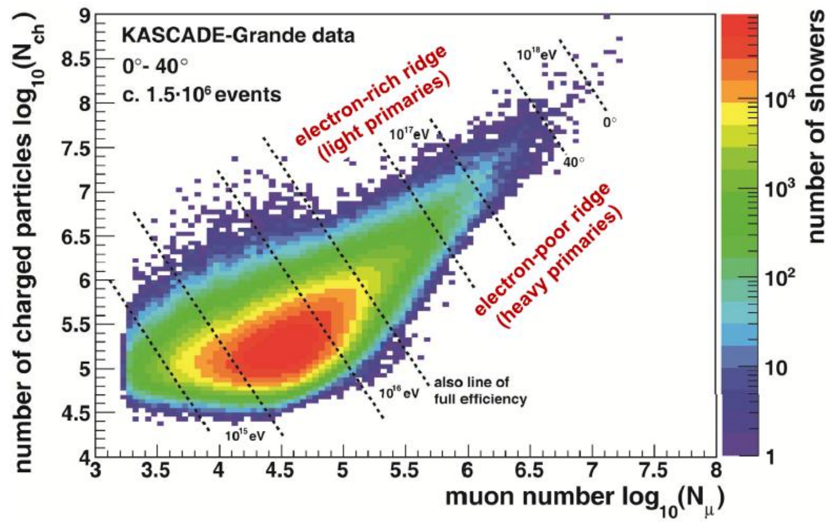
ARGO-YBJ $(X_0 = 600\ \mathrm{g\ cm^{-2}})$

- Energy → Np_8 → EAS simulation uses a chemical composition from the H4a model
- Mass → Np_8 vs s' correlation → (+ WFCTA) N_{max} vs L/W combination



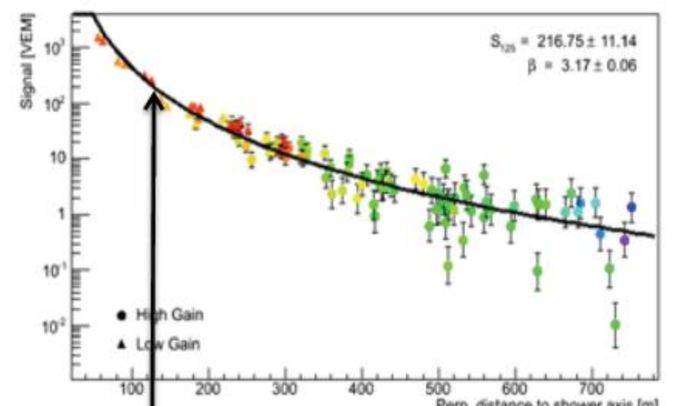
KASCADE-Grande ($X_0 = 1020$ g cm^{-2})

- Primary energy and mass estimator → N_{ch}, N_{μ} combination



IceTop ($X_0 = 680$ g cm^{-2})

- S_{125} → VEM at 125 m from shower core →Primary energy calibrated by EAS simulations→ primary composition derived from the H4a model

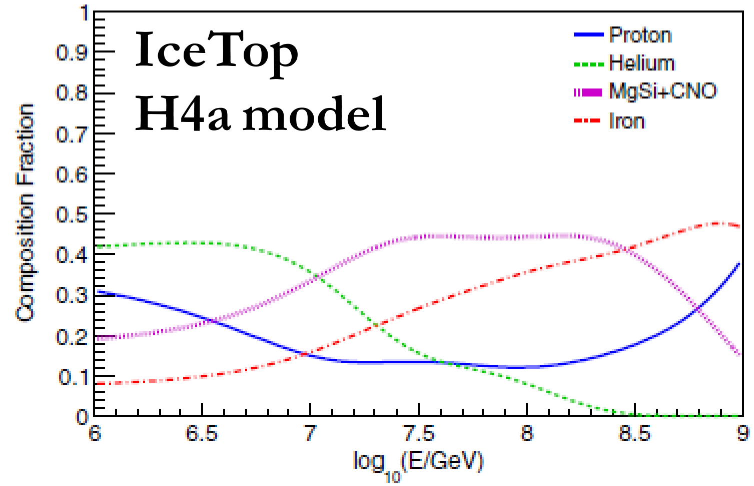


$$S(r) = S_{125}\, e^{-\frac{d \sec\theta}{\lambda}} \left(\frac{r}{125\,m}\right)^{-\beta - k \log\left(\frac{r}{125\,m}\right)}$$

- $E = f(X, A)$

- Possible choices:

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 primary chemical composition gets smaller near to EAS maximum

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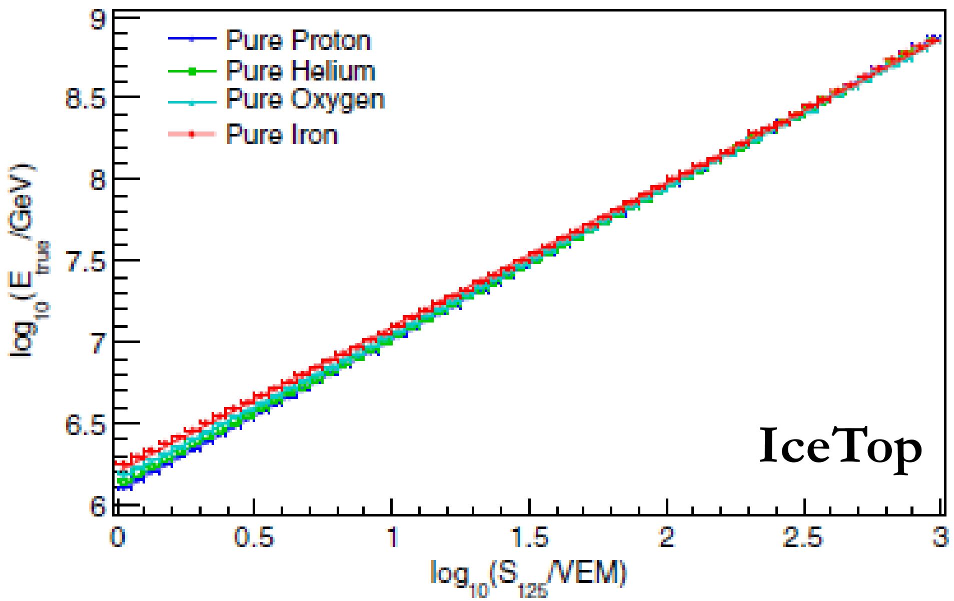
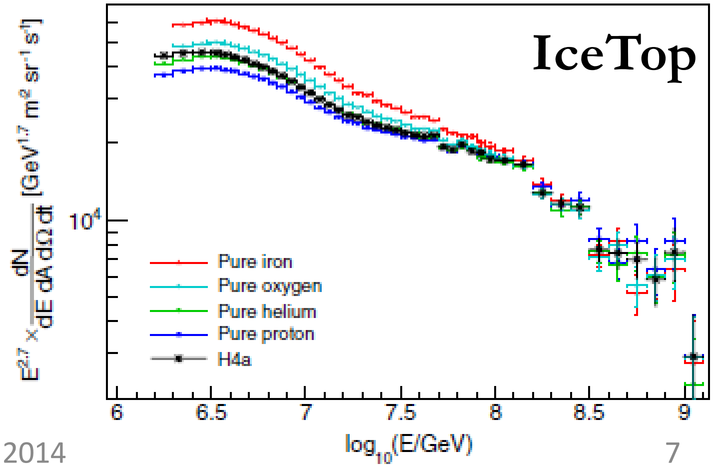
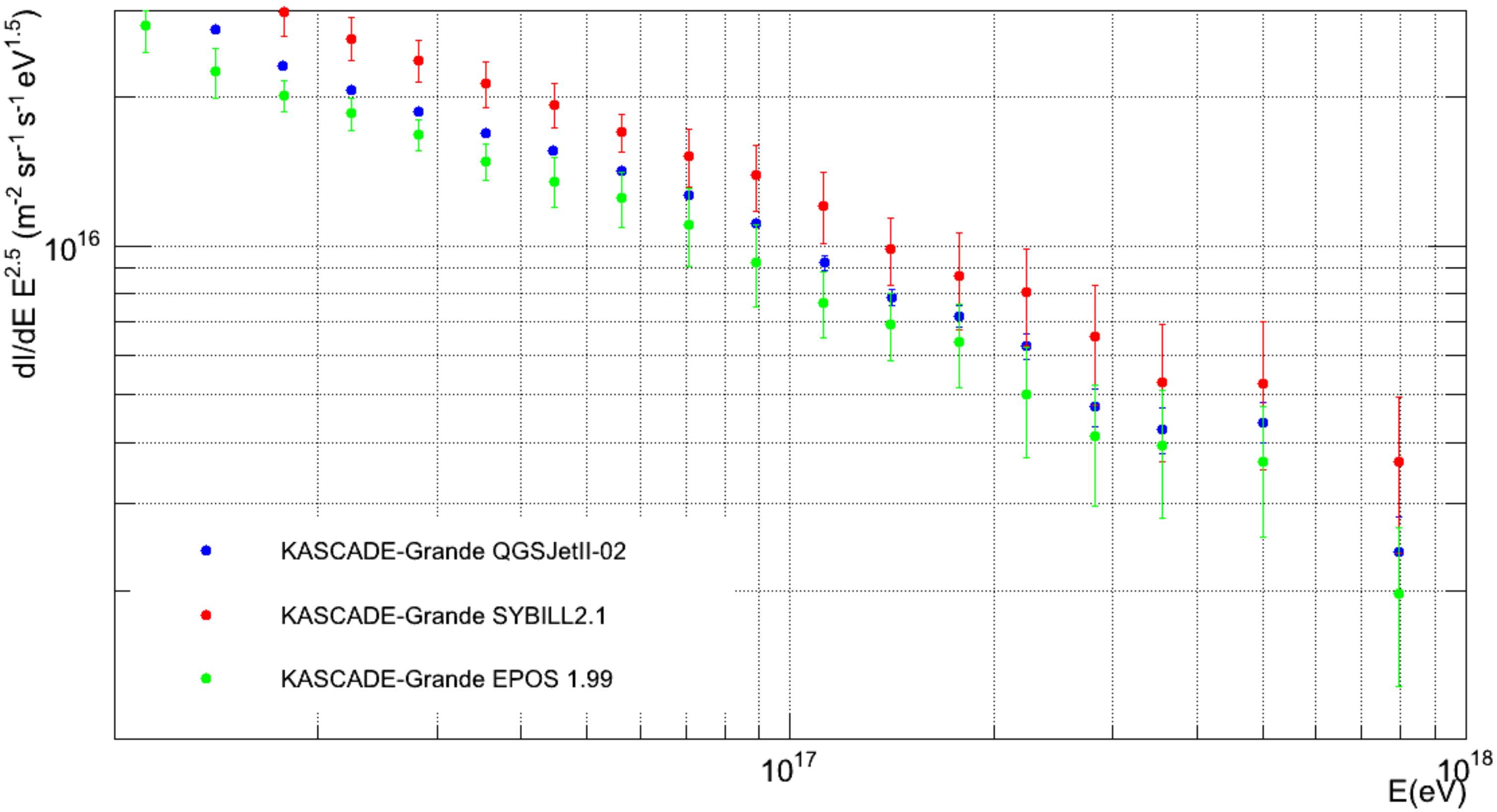
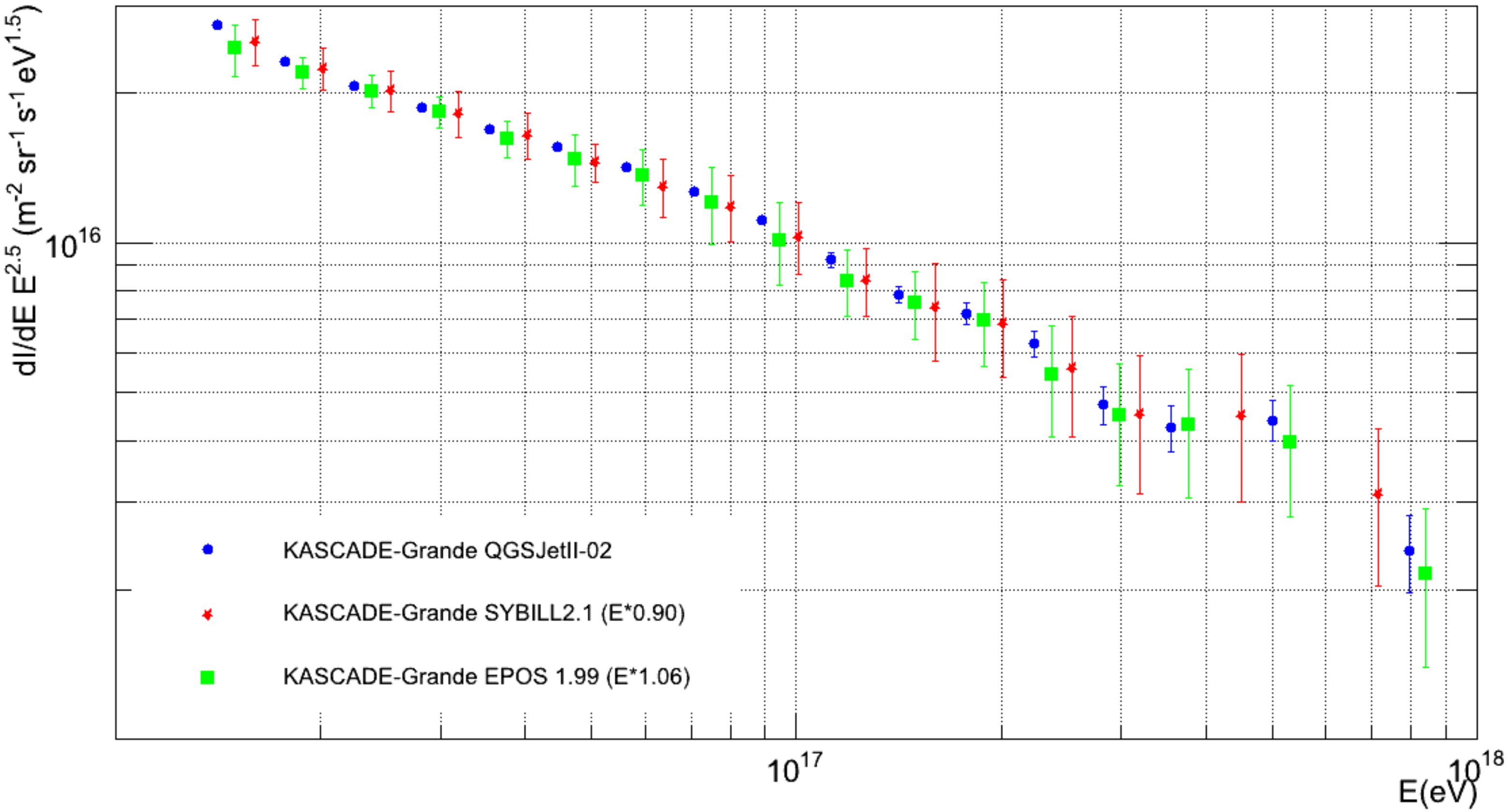




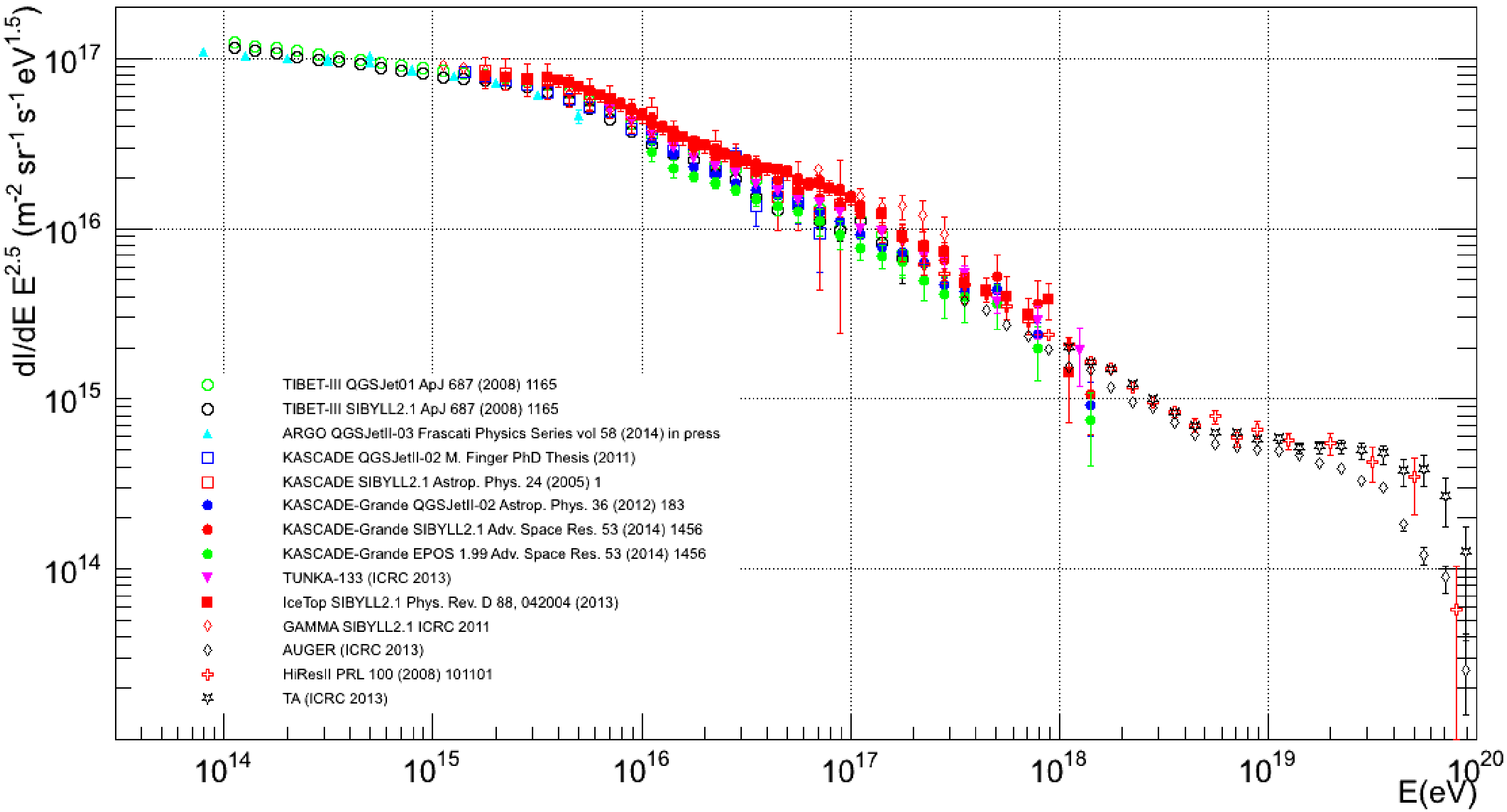
- Major differences in Energy Calibration are due to the high energy hadronic interaction model used in EAS simulation
- KASCADE-Grande all particle energy spectrum calibrated using different hadronic interaction models.



- KASCADE-Grande all particle energy spectrum → Energy shifted according to the mean differences found by the simulation

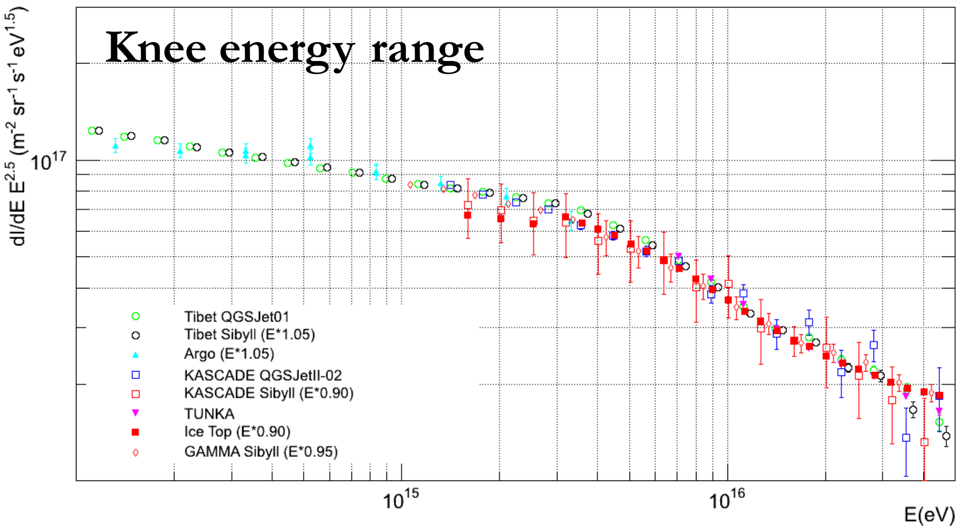


All Particle Spectrum



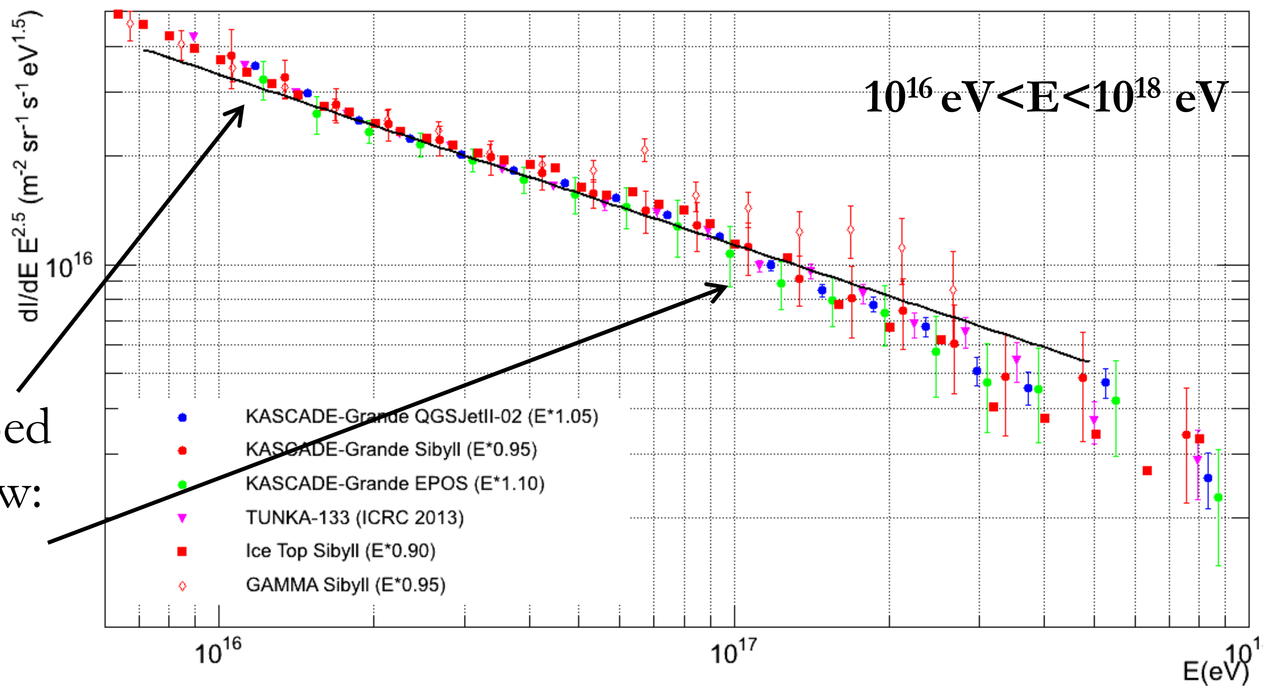
i. **Differences between experiments**

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



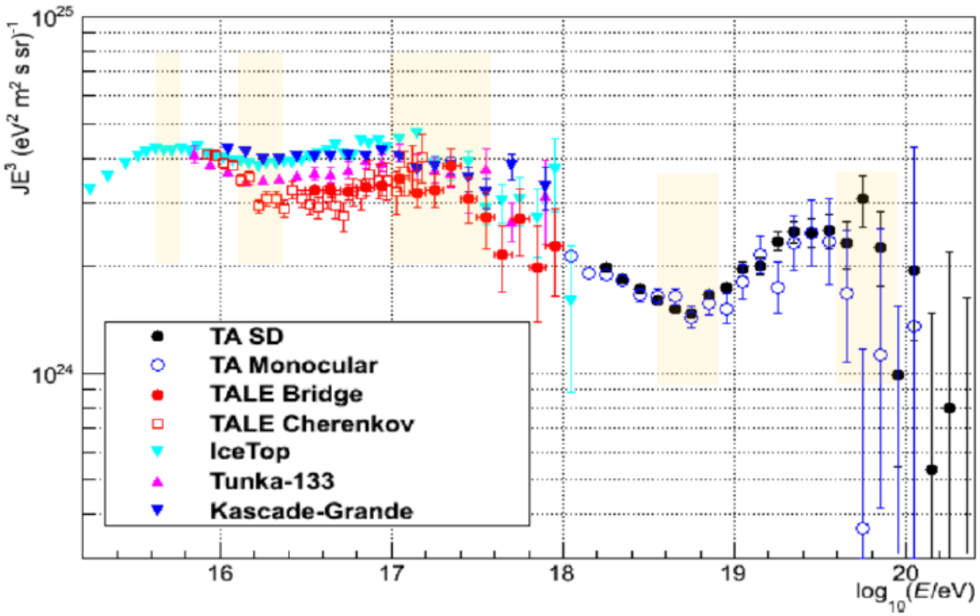
All particle spectra obtained shifting the energies by a factor smaller than what can be estimated as systematic error: i.e. 15-20%

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



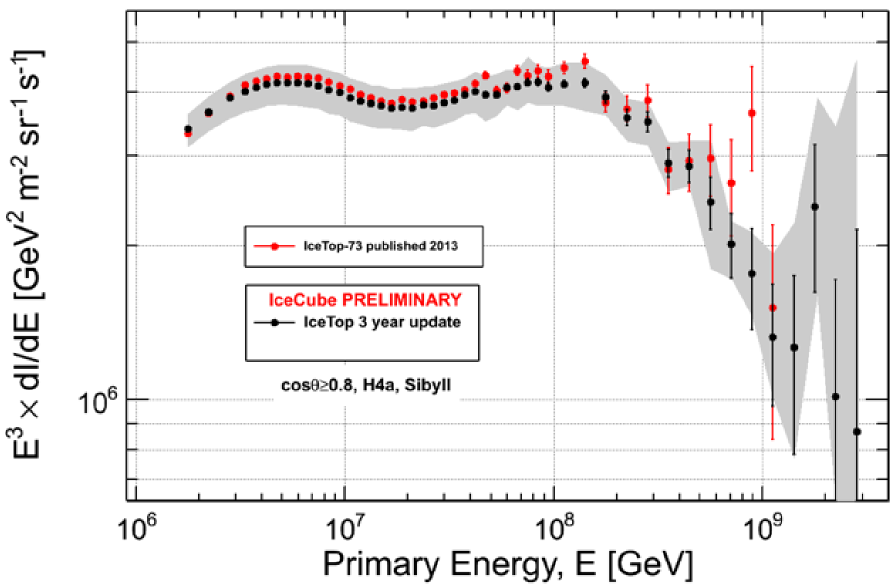
Spectra cannot be described by a single slope power law:
hardening (~10^{16} eV)
steepening (~10^{17} eV)

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



TALE → Confirms spectral features
Concavity ~10^{16} eV
Break ~10^{17} eV

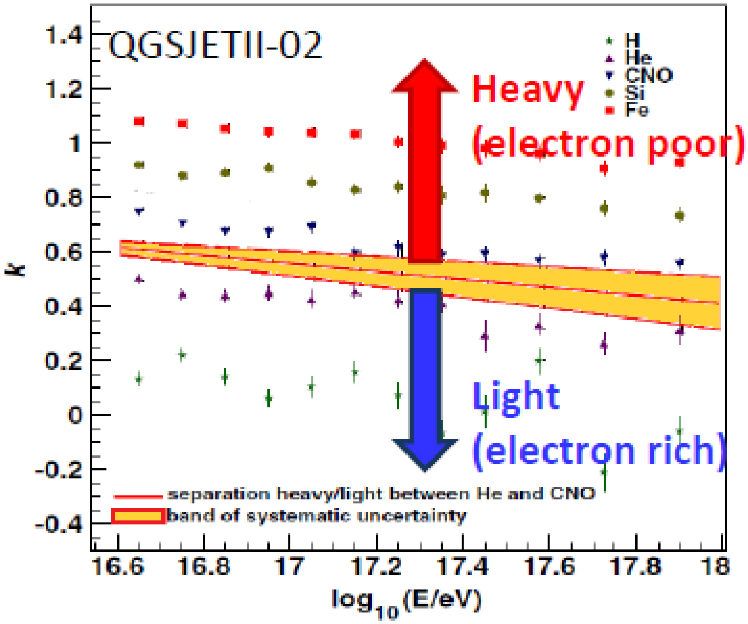
IceTop → Spectral shape confirmed
Normalization slightly lower



Mass Group Spectra

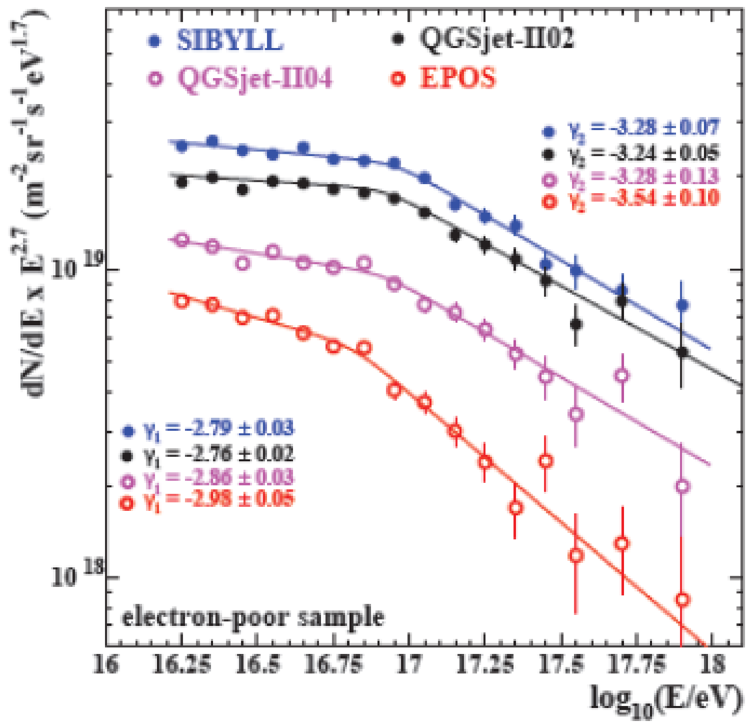
- KASCADE-Grande
  - Event Selection based on the measured N_{ch}/N_{μ} ratio

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

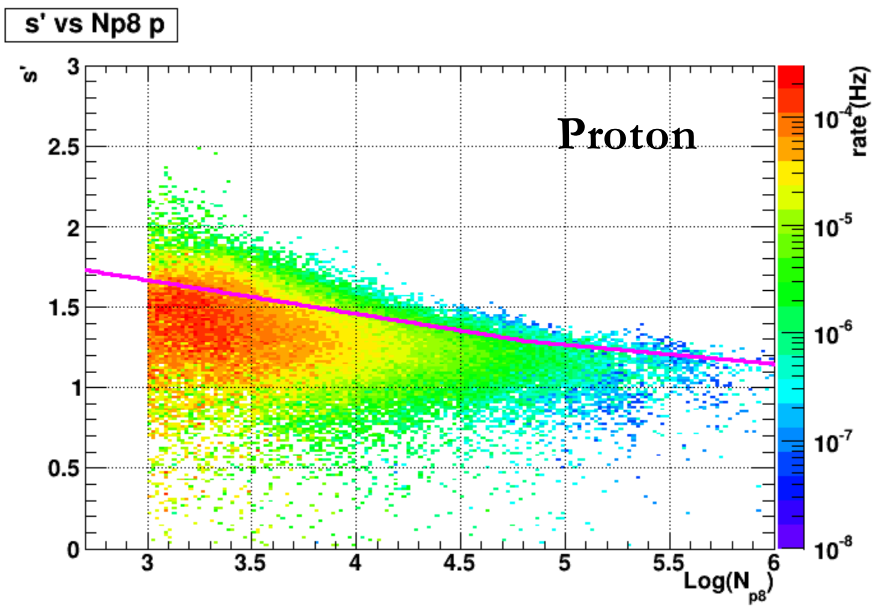


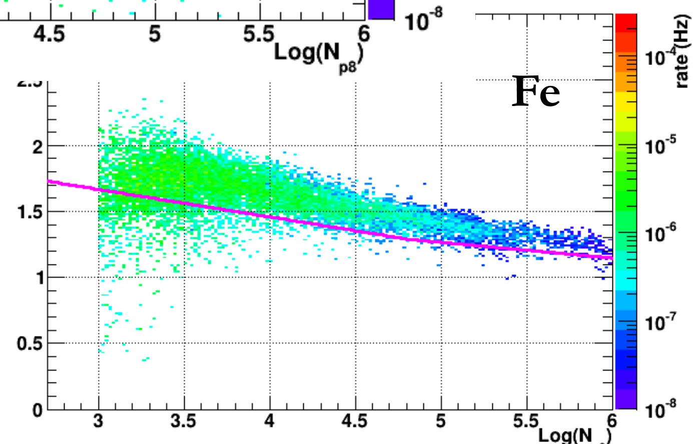
KASCADE Grande Coll., Adv. in Space R. (2013)

Fluxes depend on the interaction model, spectral features not

ARGO-YBJ

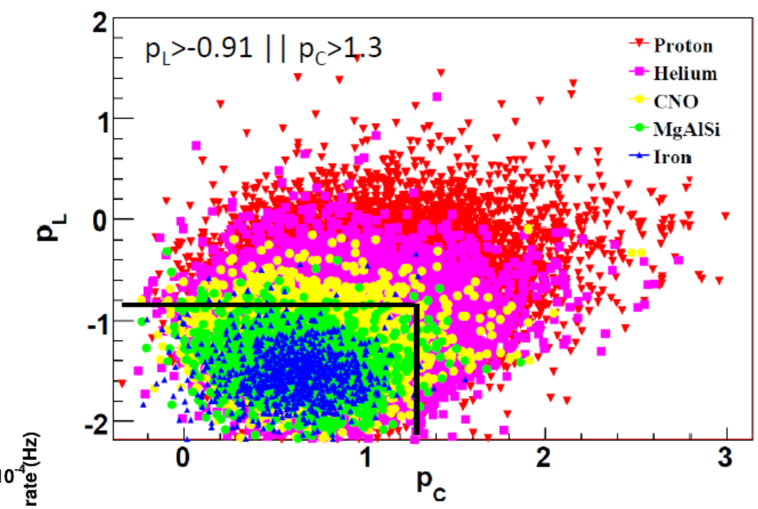
- Selection using RPC data alone.
- Np_8 vs s'





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

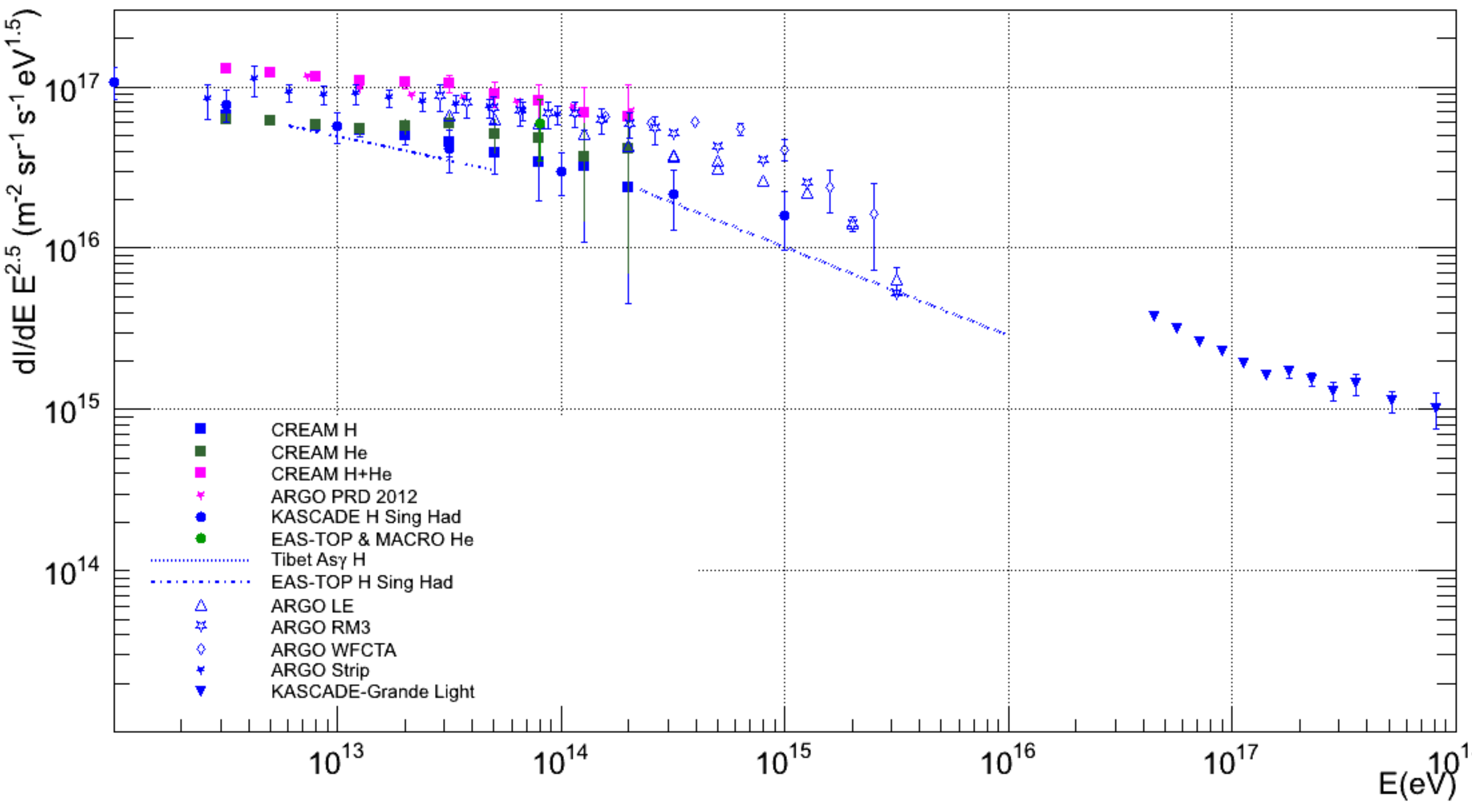
- $p_L = N_{max} - 1.44 log_{10}(E_{rec}/1TeV)$
- $p_C = L/W - 0.091 \times (R_p/10m) - 0.14 log_{10}(E_{rec}/1TeV)$



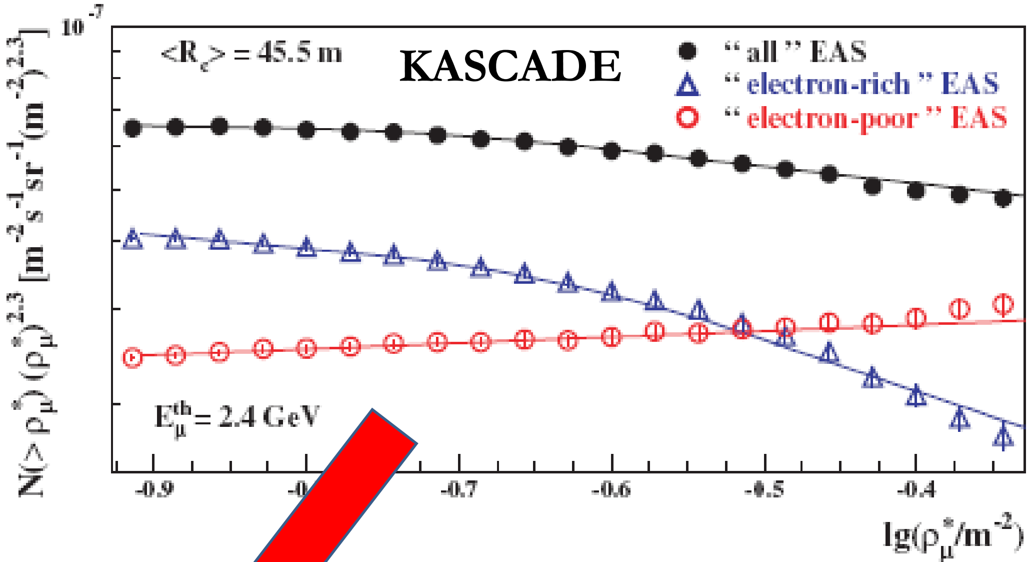
QGSJetII-03 + GHEISHA

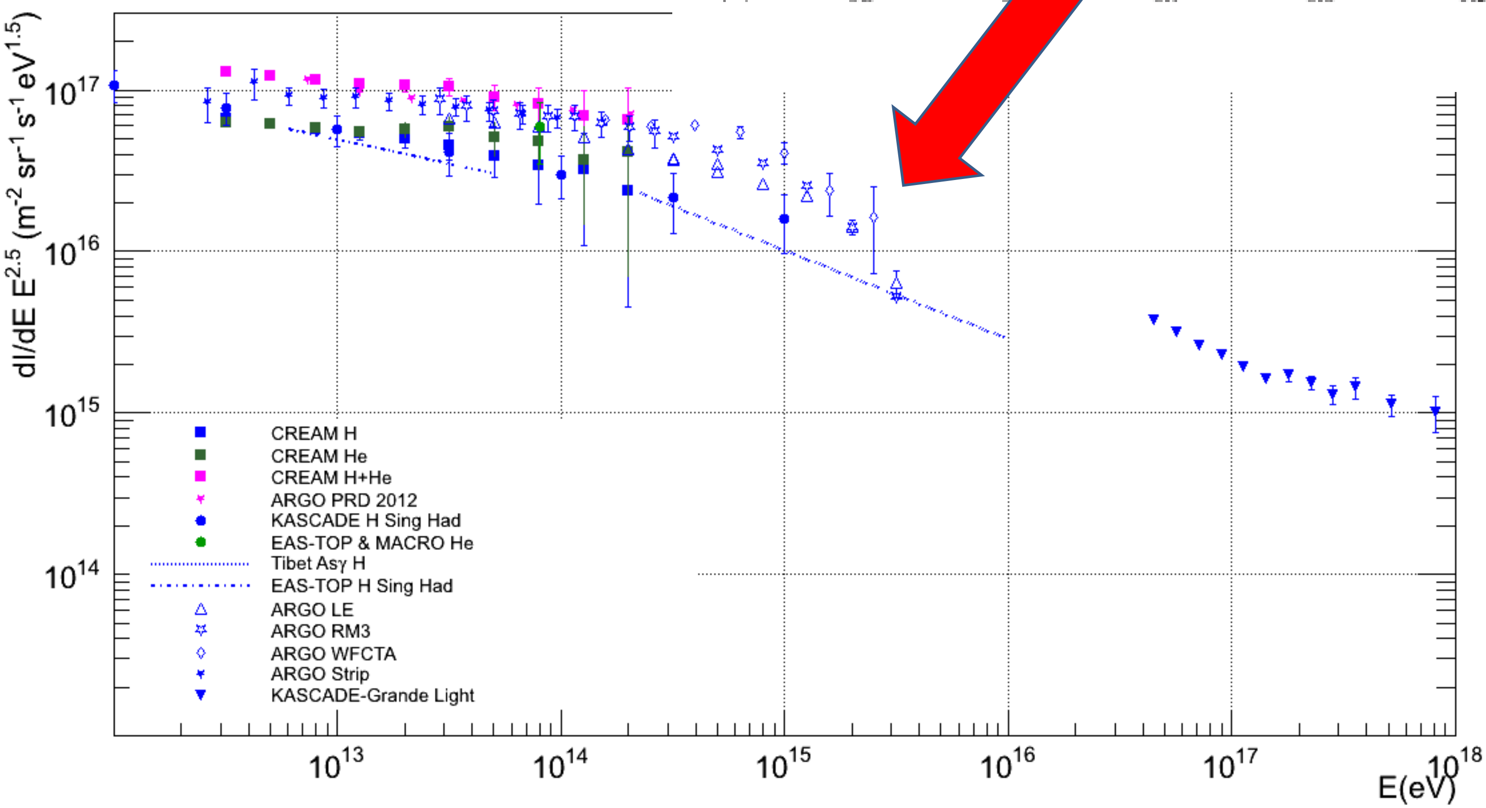
Light Mass Group Spectra

- ARGO-YBJ and KASCADE-Grande results
- Selection efficiency (i.e. fluxes) depends on the hadronic interaction model
- Spectral features are significant and model independent



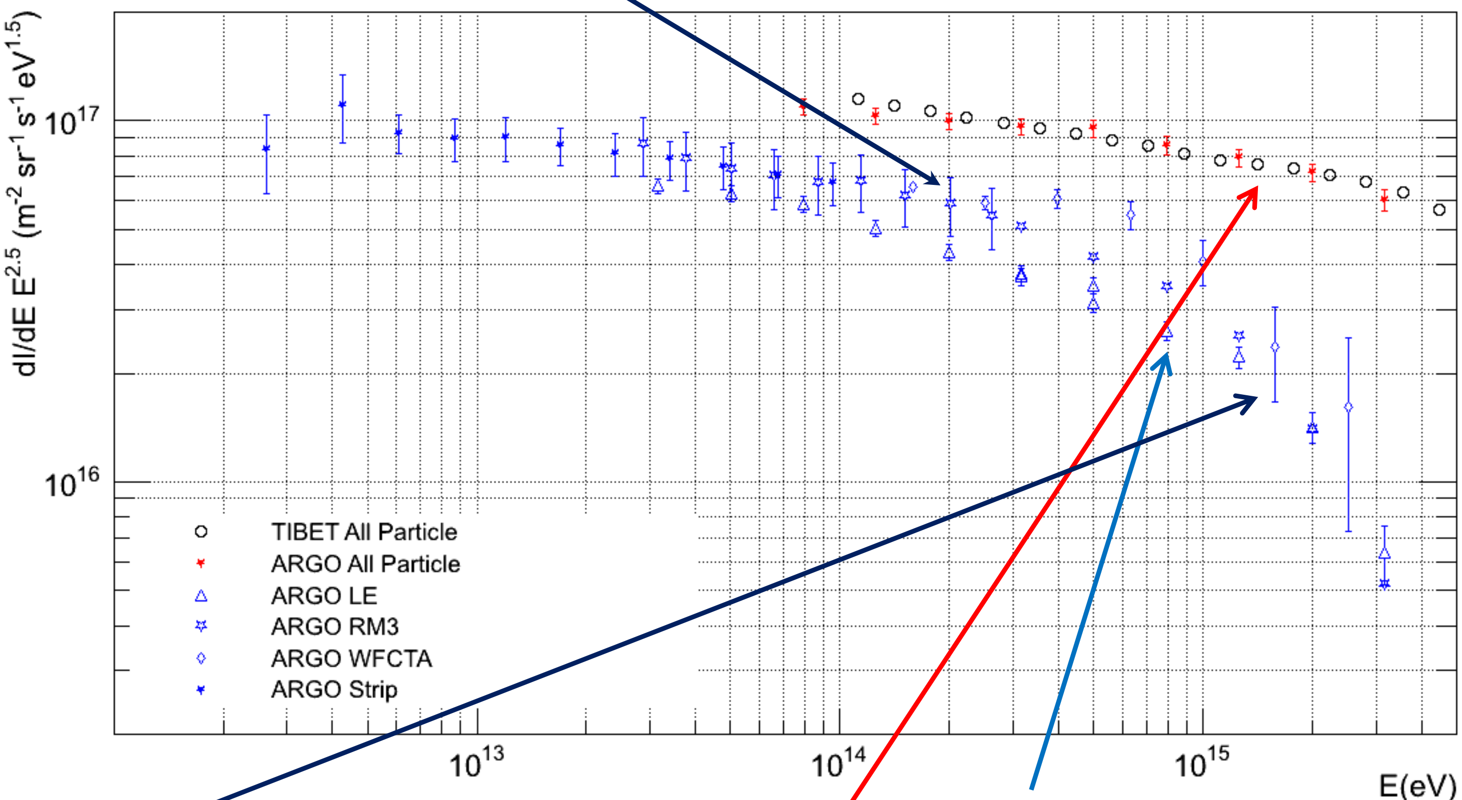
Integral flux above the change of slope → ~10^{-7} m^{-2} s^{-1} sr^{-1} → knee





ARGO-YBJ

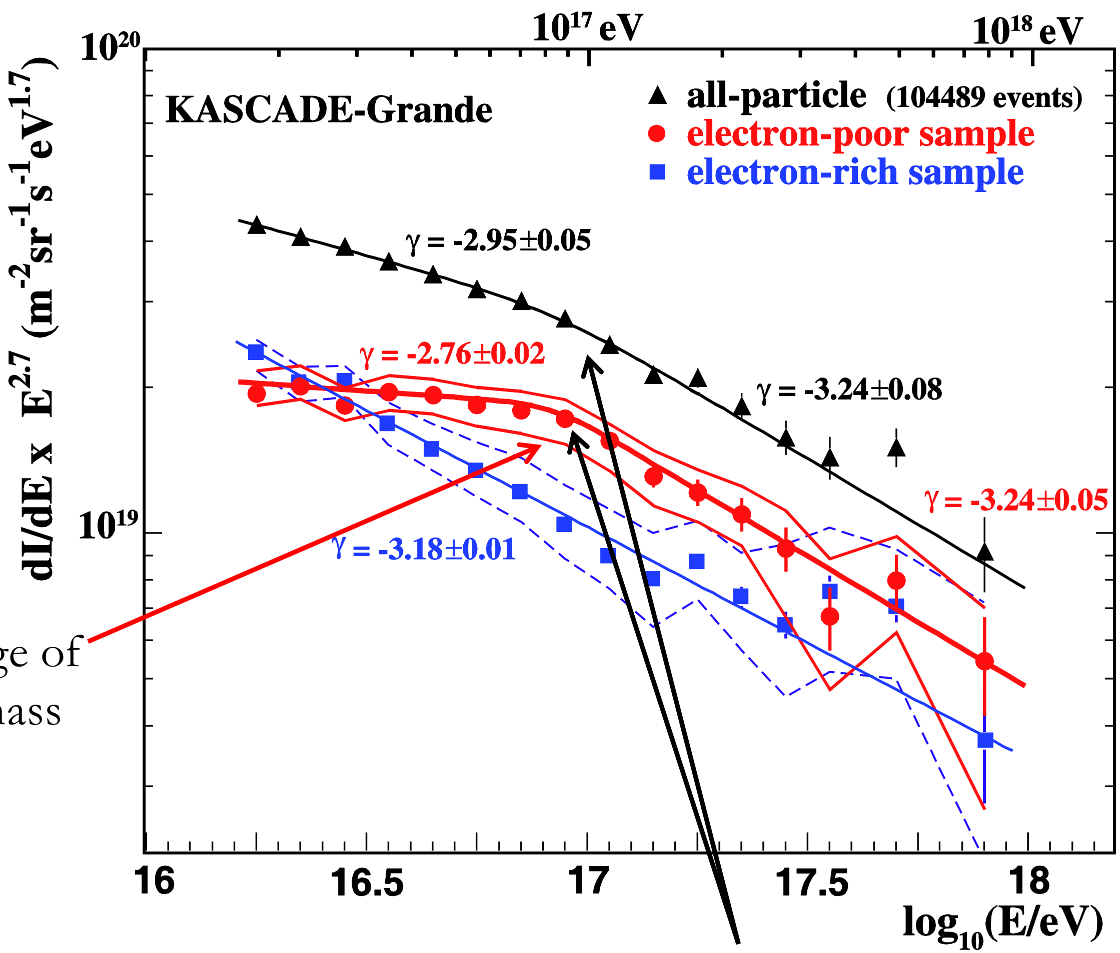
- Spectra depends on the specific analysis
- This plot does not include systematic errors
  → if considered spectra are marginally compatible



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

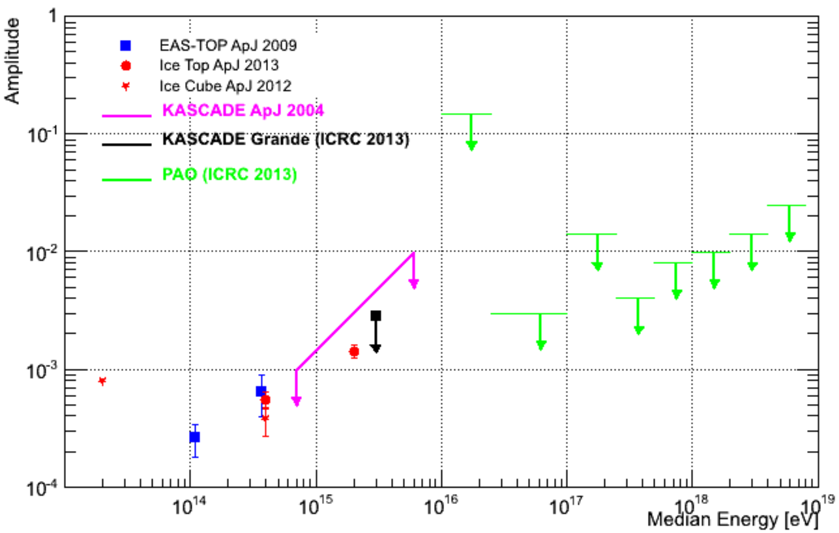


Evidence of a change of slope in the heavy mass group spectrum.
$E_{knee} = 8 \times 10^{16}$ eV

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

Large Scale Anisotropy searches

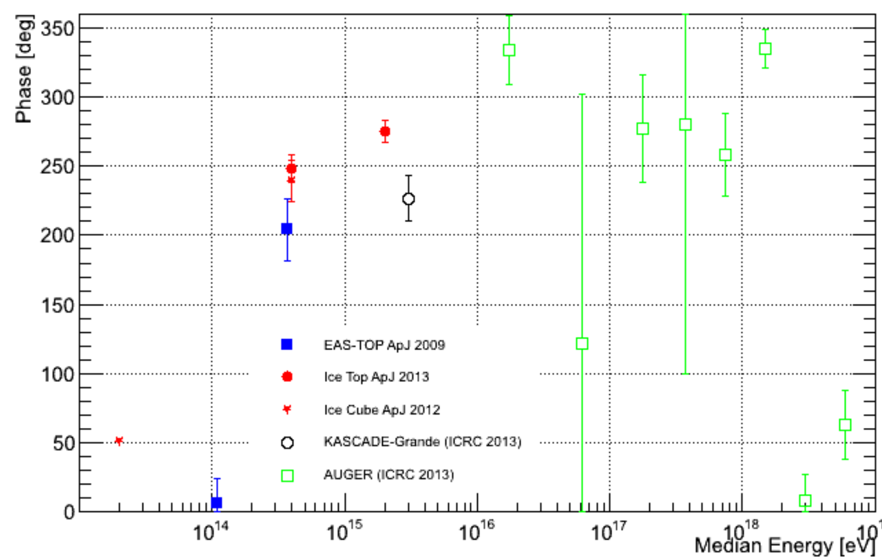
- The highest energy measured large scale anisotropy is at $2x10^{15}$ eV by the IceTop experiment.



Hints of an increasing amplitude crossing knee energy

Hint of a change of the phase for $E>10^{14}$ eV

Indication that the phases measured above $5x10^{14}$ eV are consistent



Results summary

- All particle spectrum
  - Main Features: knee ($4x10^{15}$ eV) & ankle ($4x10^{18}$ 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 $\sim 8x10^{16}$ eV

Exercise(*) to check the experimental data

- Calculate the element spectra:

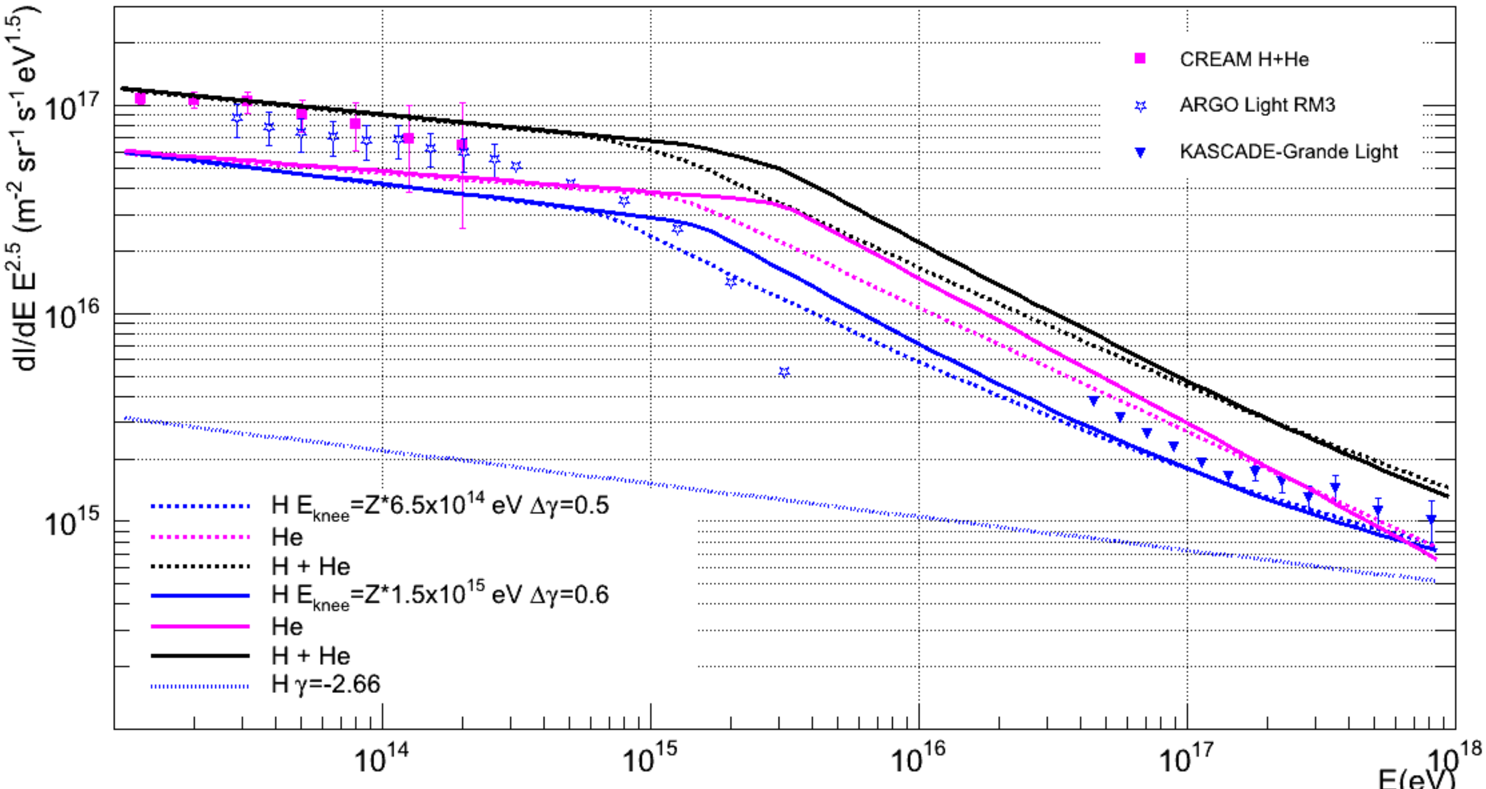
$$\Phi(E) = KE^{\gamma_1}[1+(\frac{E}{E_{knee}})^{\varepsilon}]^{\frac{\gamma_2-\gamma_1}{\varepsilon}}$$

- Assuming:
  - $E_{knee} = Z\ E_{knee}(p)$
    1. $E_{knee}(p) = 6.5\text{x}10^{14}$ eV (ARGO result)
    2. $E_{knee}(p) = 1.5\text{x}10^{15}$ 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
    1. $\Delta\gamma = 0.5$
    2. $\Delta\gamma = 0.6$
- 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

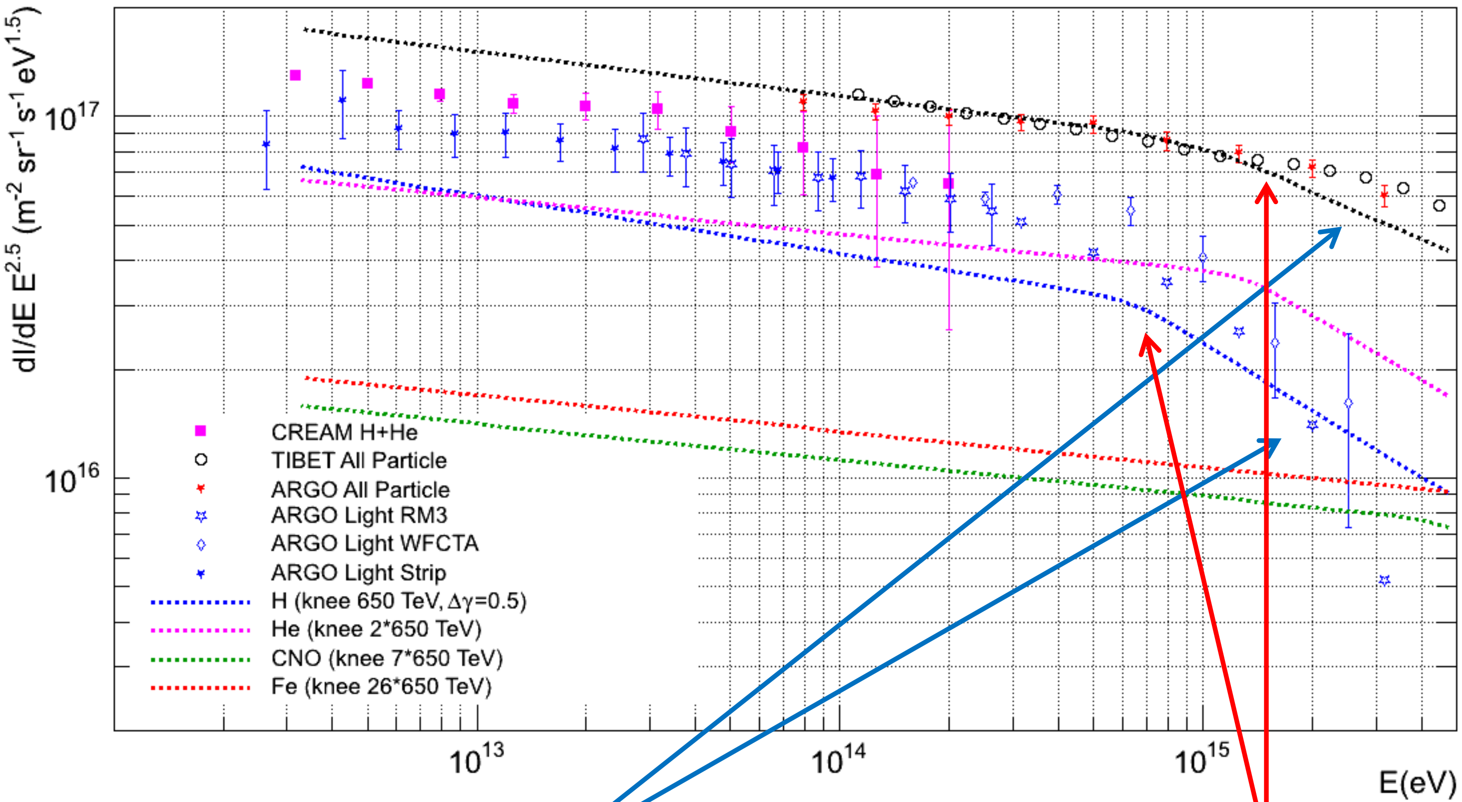
The points are not intended as an exact measure of H+He fluxes.



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

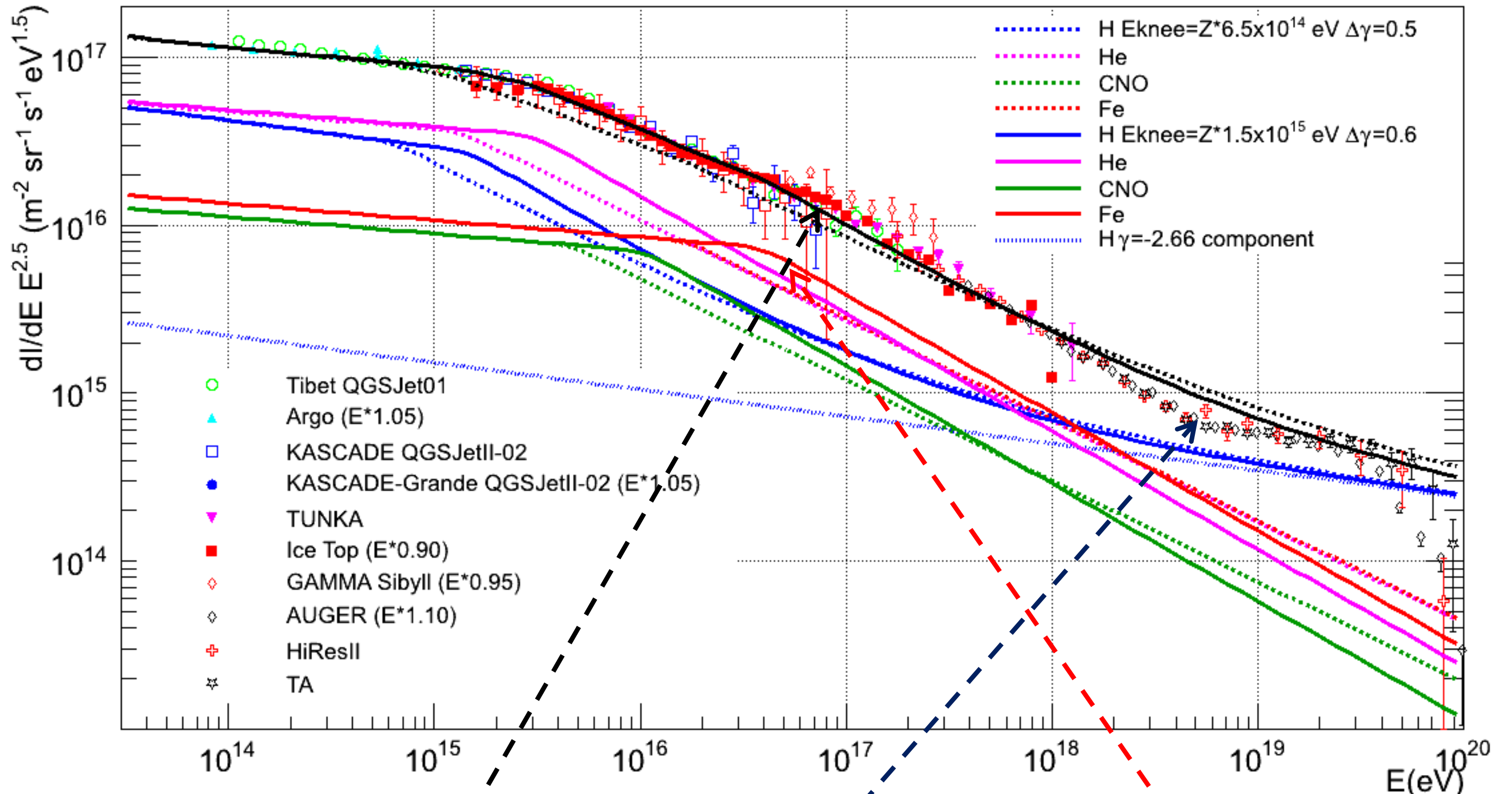


$\Delta\gamma = 0.5 \rightarrow$ not enough for light spectrum

$\rightarrow$ 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 ~10^{16} and ~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

- General agreement on the spectral features detected.
- Main differences in the measured fluxed can be attributed to the energy calibration (i.e. hadronic interaction models).
- A qualitative interpretation of the data can be obtained by elemental spectra with knees at the same rigidity and adding a smooth light component becoming dominant above $\sim 10^{17}$ eV.
- Future improvements require:
  - measurements of the single elements spectra (at least separate H and He).
  - anisotropy studies possibly for at least two mass groups.
    - EAS experiments maybe limited by EAS development fluctuations → can be limited measuring near to shower maximum
    - Will direct measurement (CREAM-ISS) reach the knee?