Cosmic Rays Measurements around the Knee

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RICAP-14
Noto – Septmber 30th – October 3rd

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

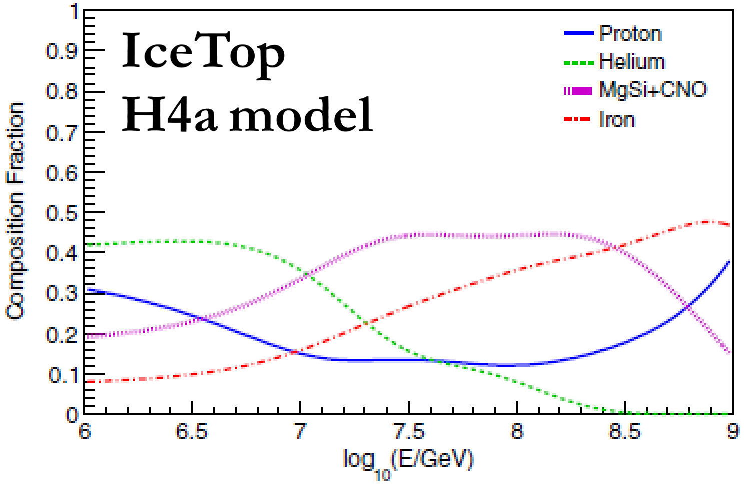
I. EAS detected at fixed atmospheric depth
II. High Duty Cycle
III. Energy Calibration → EAS Simulation (hadronic model and chemical composition assumption)
IV. Primary Mass → Correlation between EAS parameters → N_e vs N_μ

• E = *f*(X, A)

1) Pure chemical composition

– Two limiting cases (H and Fe) can be derived: the all particle spectrum is included in between these two values.

2) <A> from a model

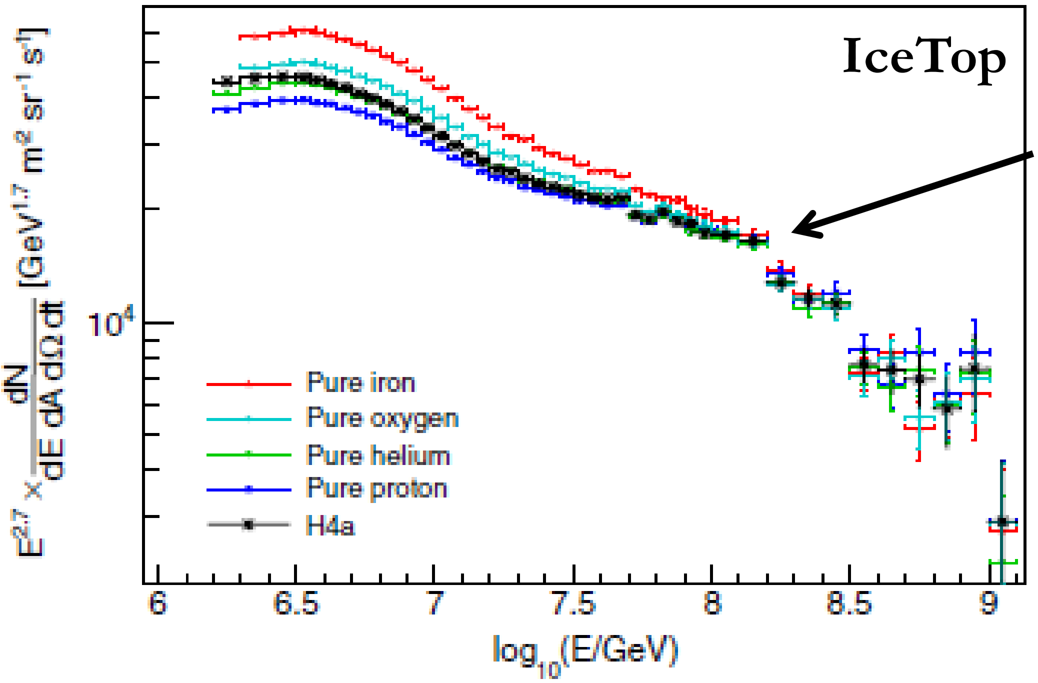


3) Estimate primary mass

from N_{ch}/N_{μ}

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

KASCADE-Grande



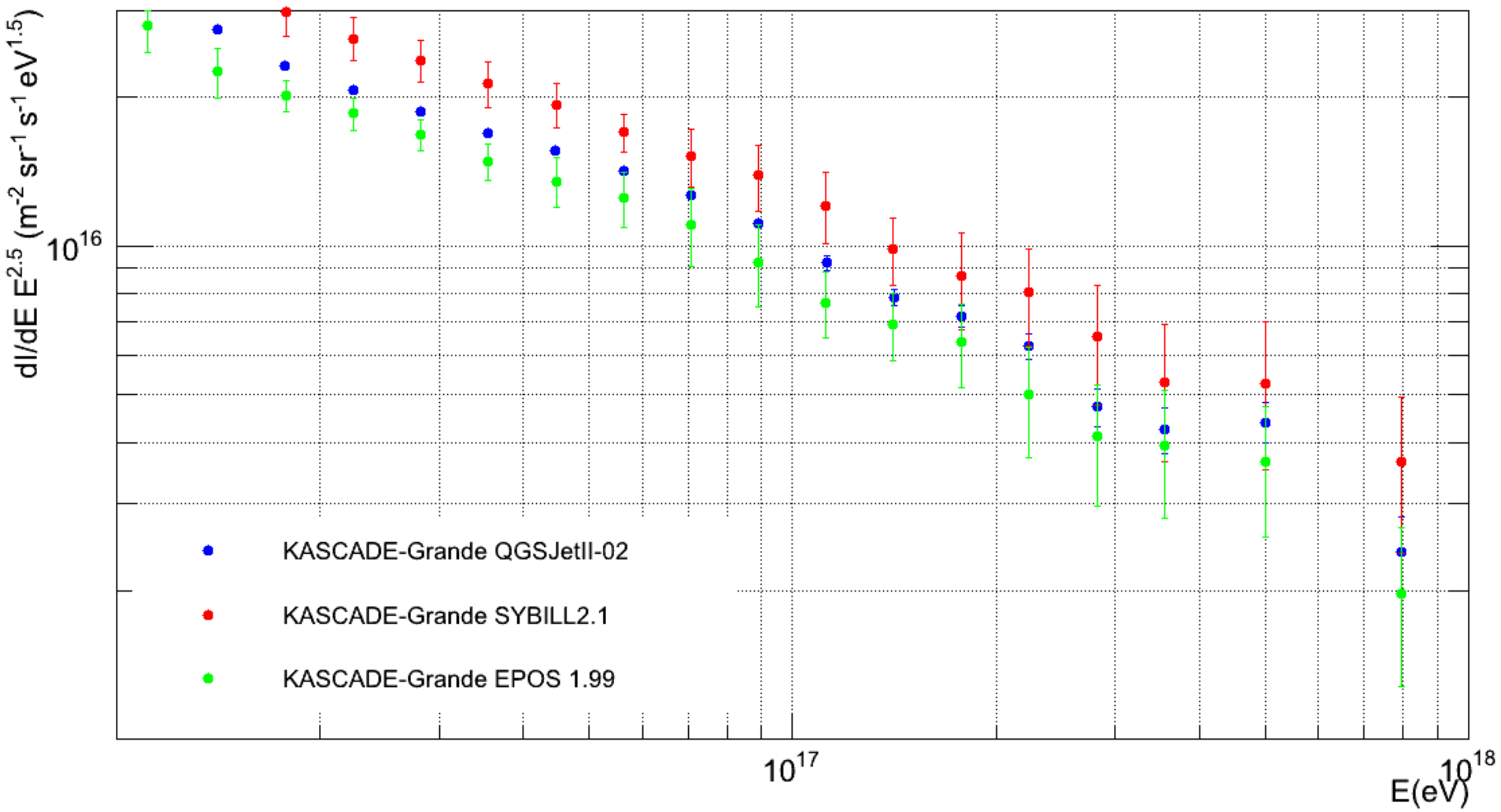
Dependence from A becomes smaller near to EAS maximum

ARGO-YBJ

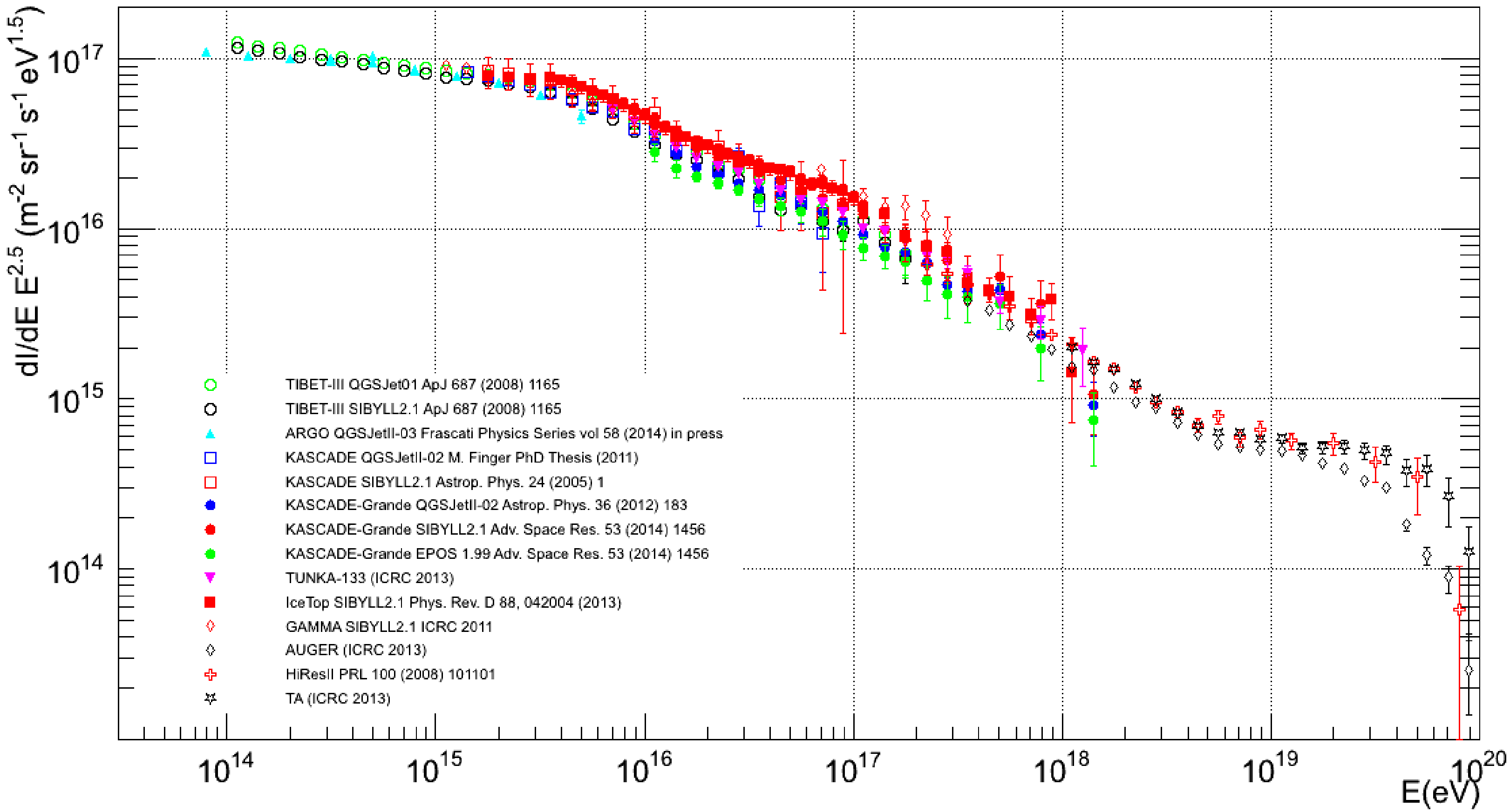
$N_{p8}(\theta)$ is converted to N_{p8max} →
i.e. the value of the experimental observable at EAS maximum.

The N_{p8max} calibration to primary energy is mass independent

- 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.

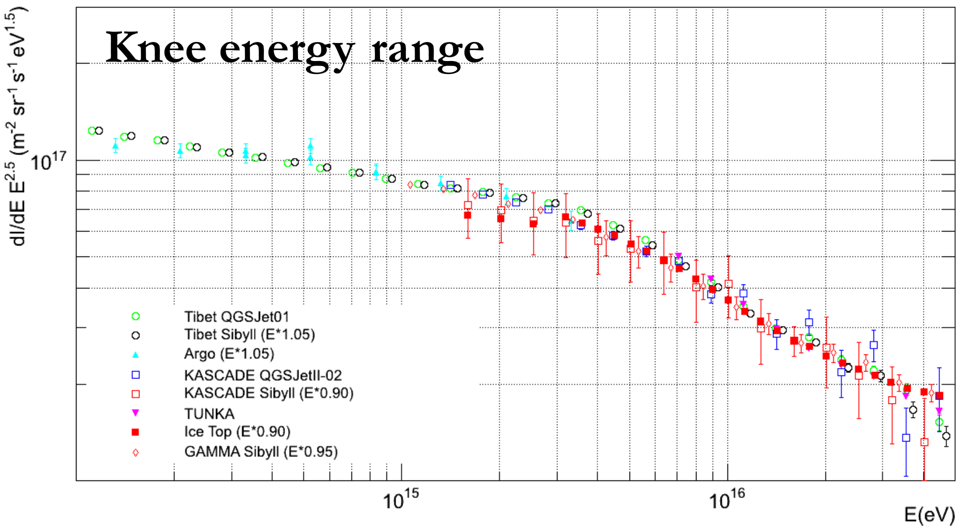


All Particle Spectrum



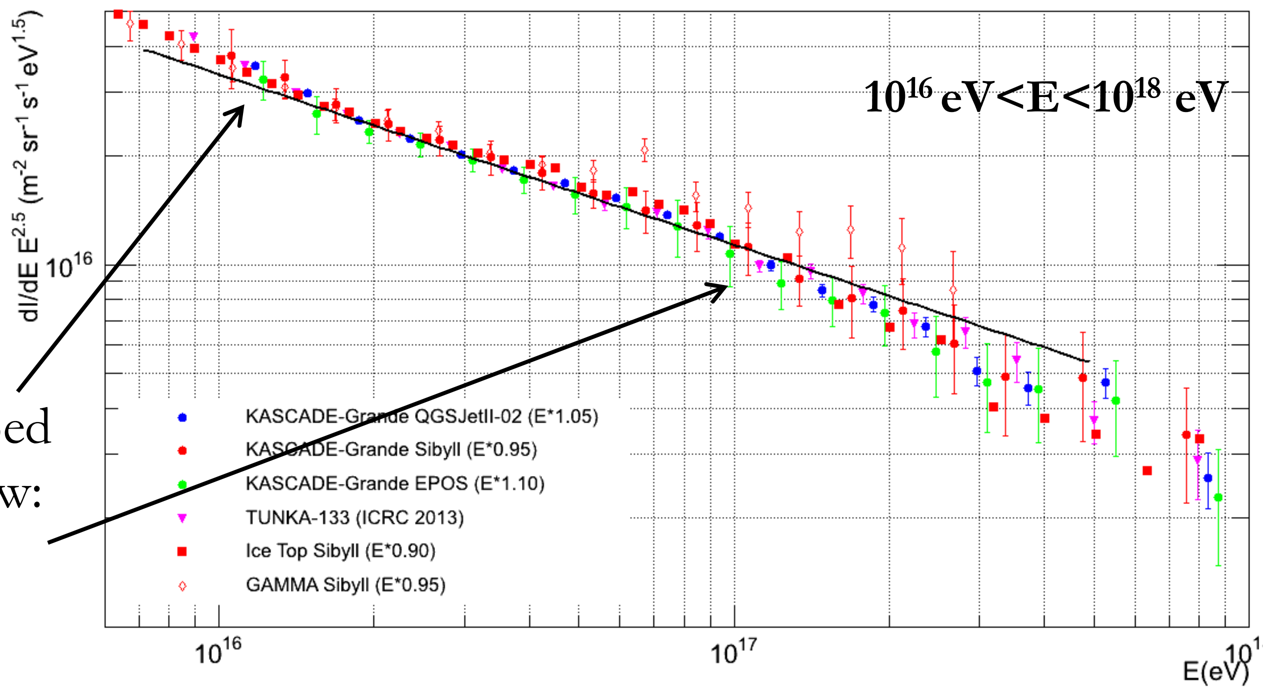
i. Differences between experiments

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



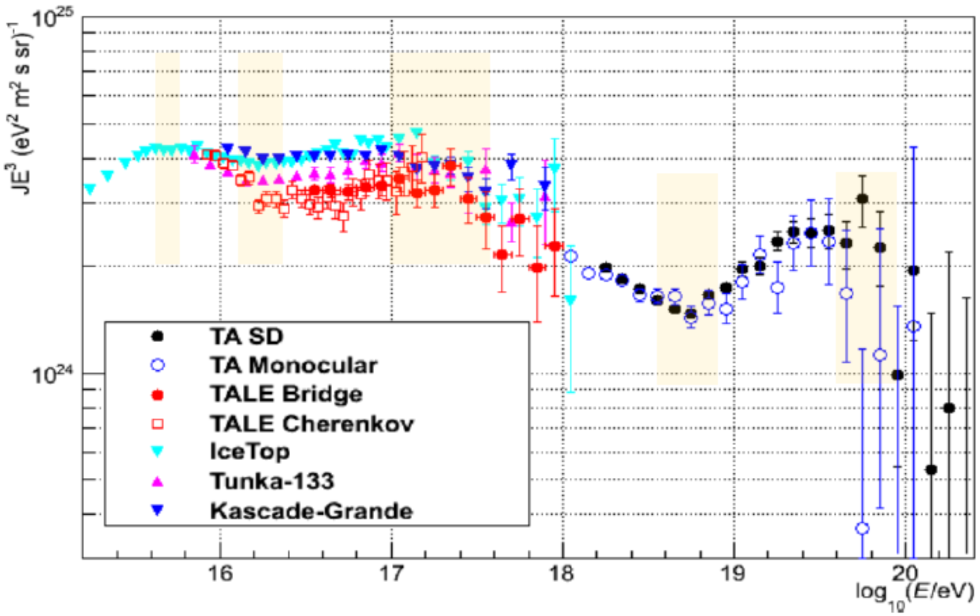
All particle spectra obtained shifting the energies by a factor smaller than what can be estimated as systematic error: i.e. 15-20%

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



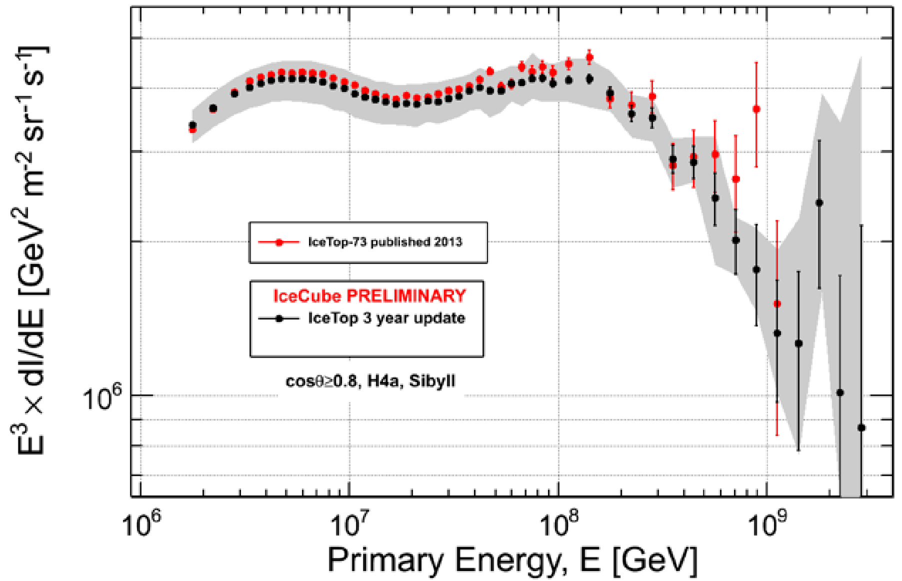
Spectra cannot be described by a single slope power law:
hardening (~10^{16} eV)
steepening (~10^{17} eV)

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



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

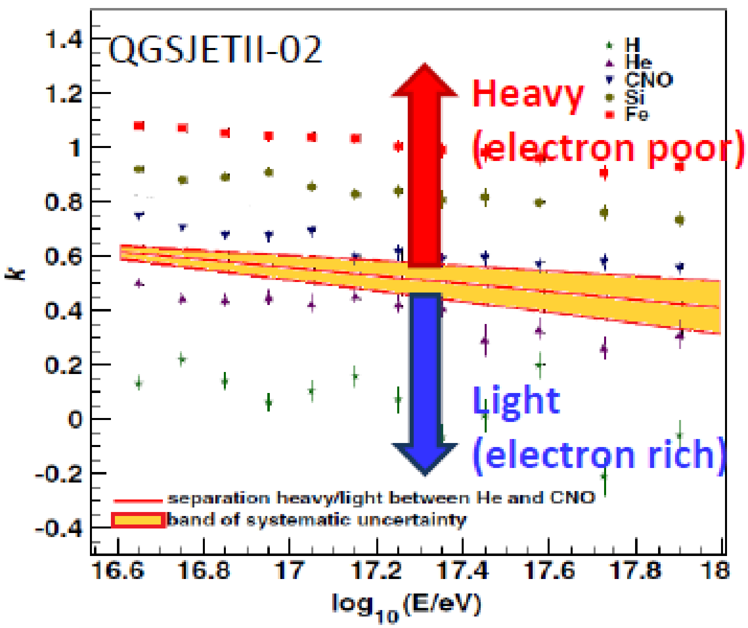
IceTop → Spectral shape confirmed
Normalization slightly lower



Mass Group Spectra: event by event classification

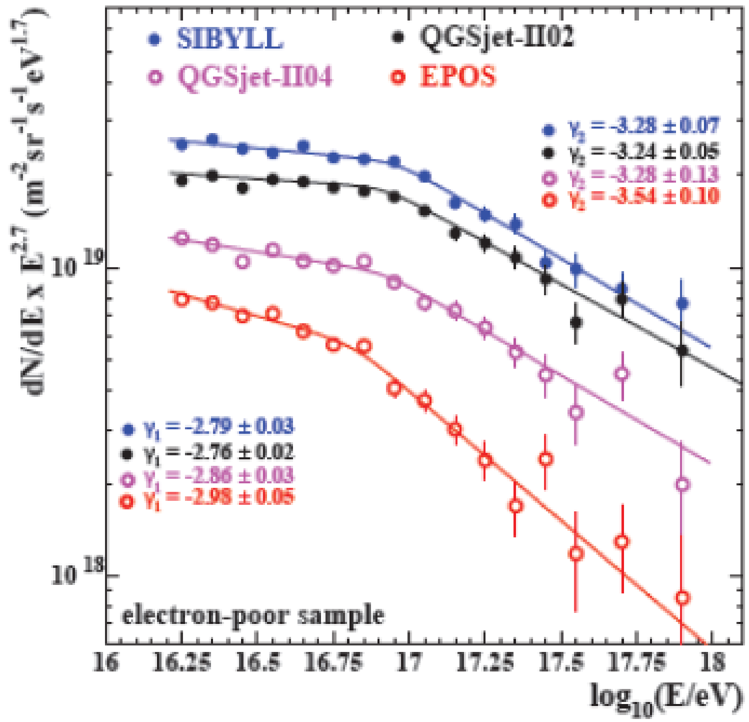
- KASCADE-Grande
  - Event Selection based on the measured N_{ch}/N_μ ratio

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



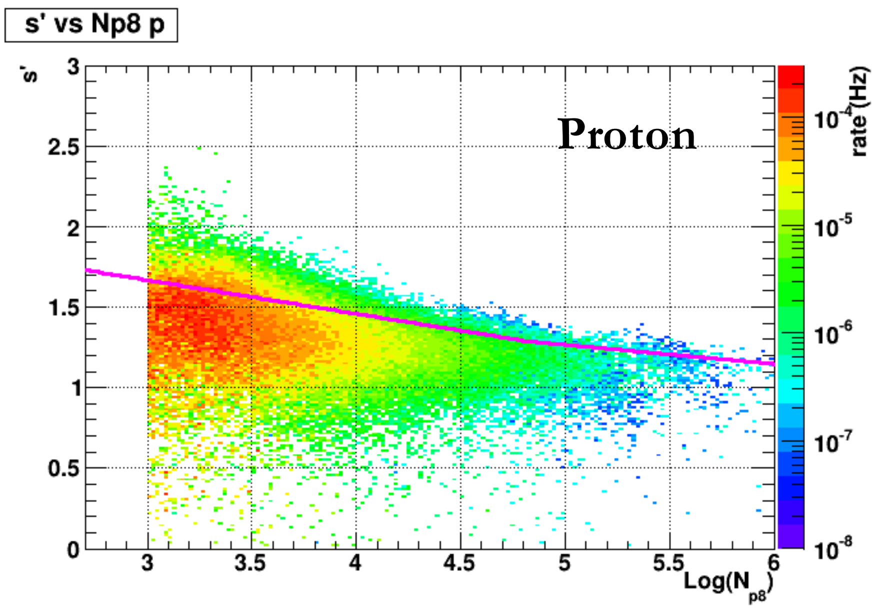
KASCADE Grande Coll., Adv. in Space R. (2013)

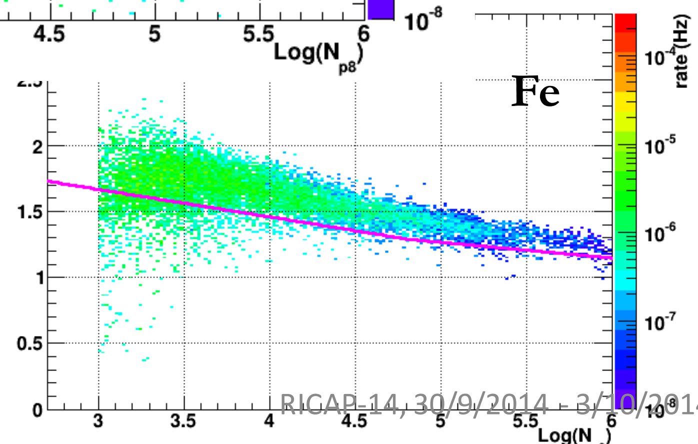
Fluxes depend on the interaction model, spectral features not

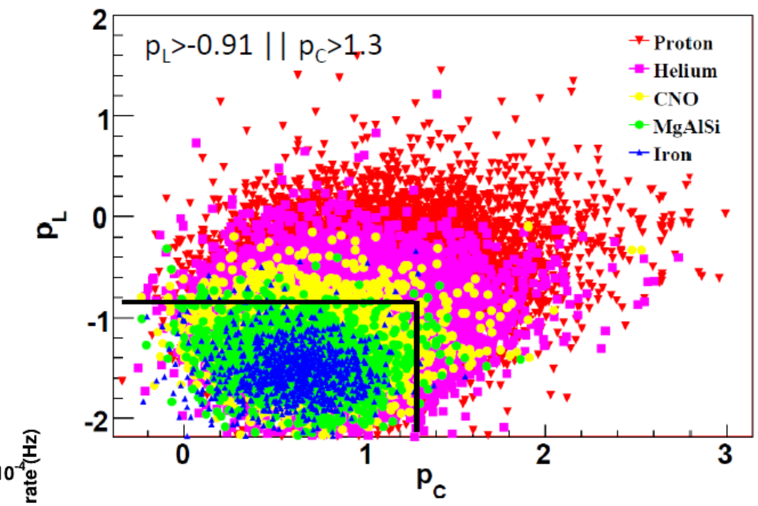
ARGO-YBJ

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

- Selection using RPC and WFCTA data
- N_{max}, Length, Width
  - $p_L = N_{max} - 1.44 log_{10}(E_{rec}/1TeV)$
  - $p_C = L/W - 0.091 \times (R_p/10m) - 0.14 log_{10}(E_{rec}/1TeV)$



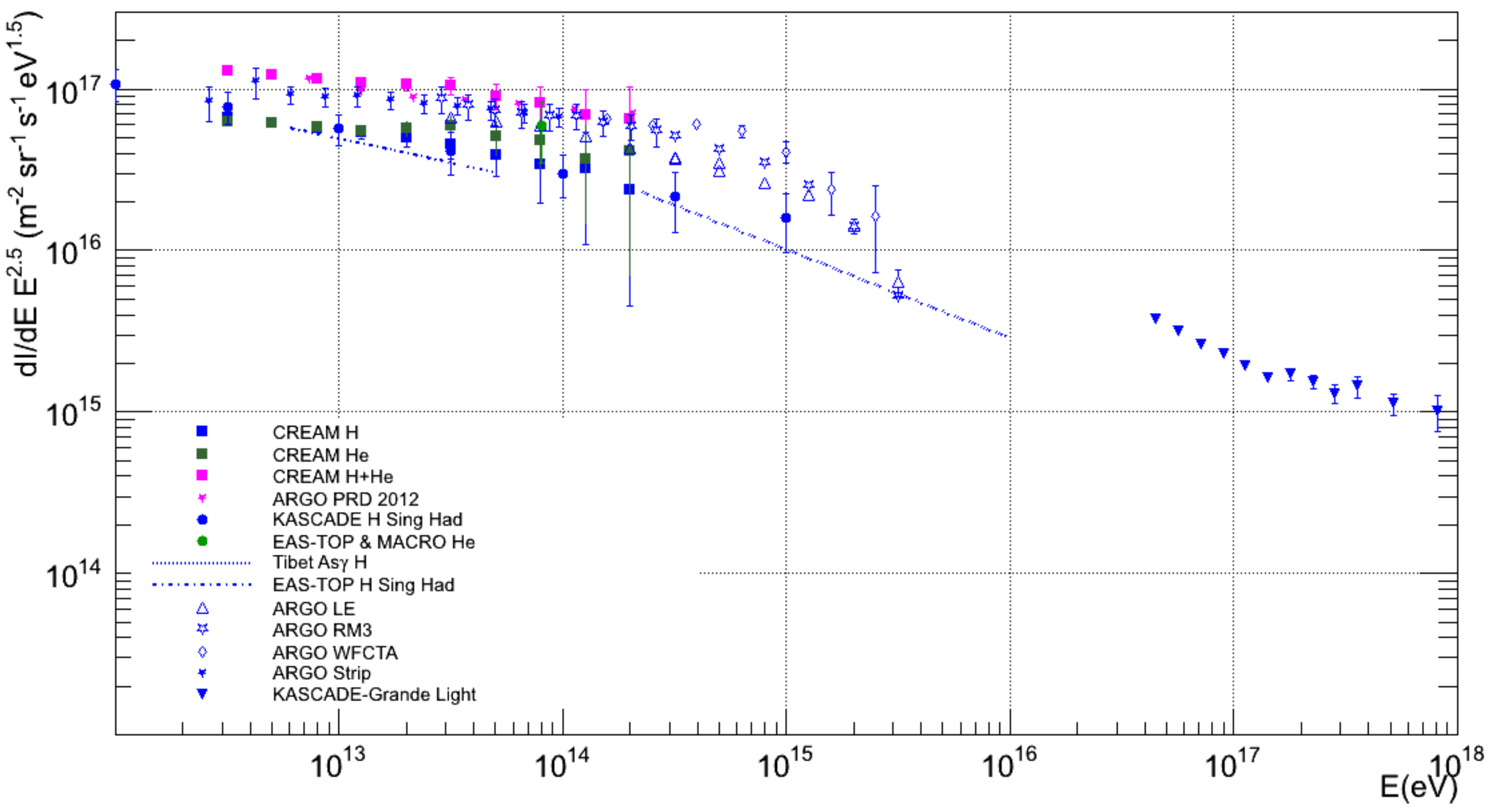




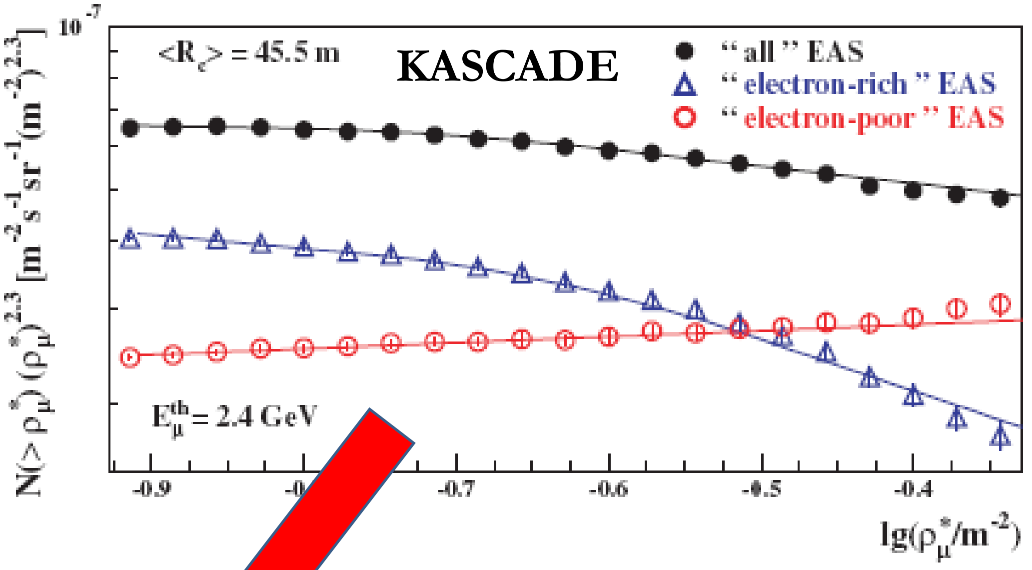
QGSJetII-03 + GHEISHA

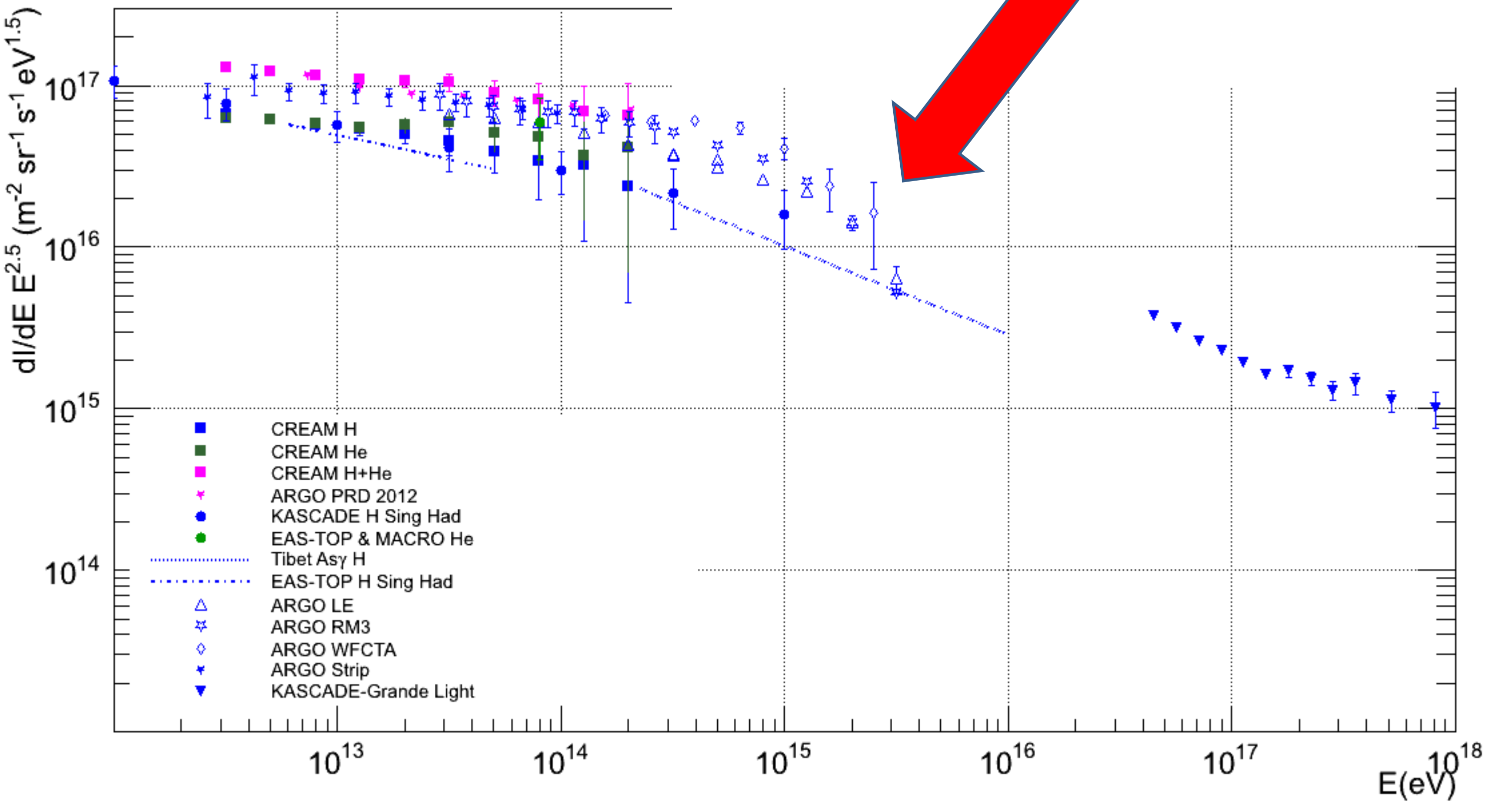
Light Mass Group Spectra

- 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



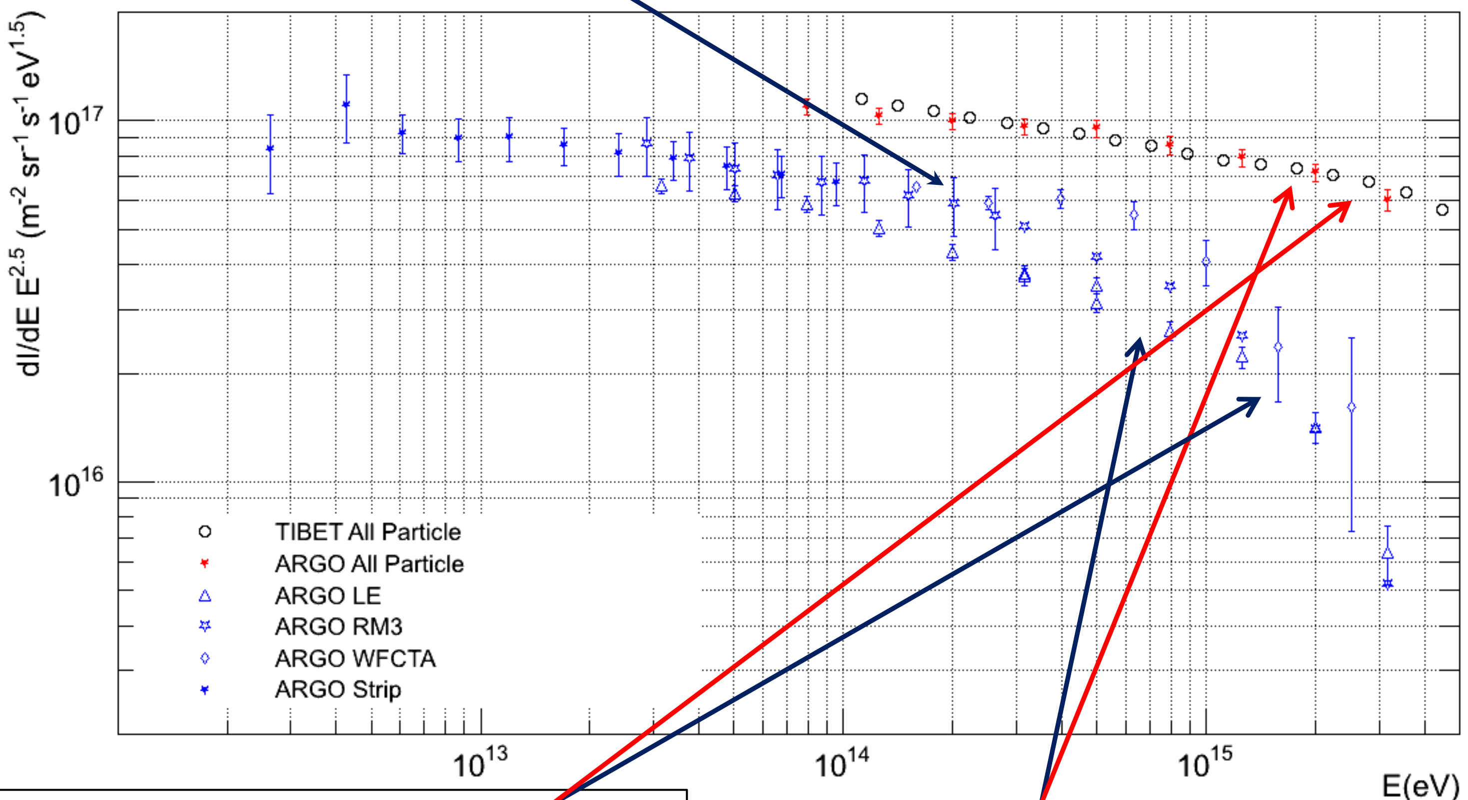
Integral flux above the change of slope → ~10^{-7} m^{-2} s^{-1} sr^{-1}
→ ~2-4x10^{15} eV





ARGO-YBJ

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



Spectral slopes of the "ligth" and "all particle" spectra above the "knee" are different

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

Exercise(*) to check the experimental data

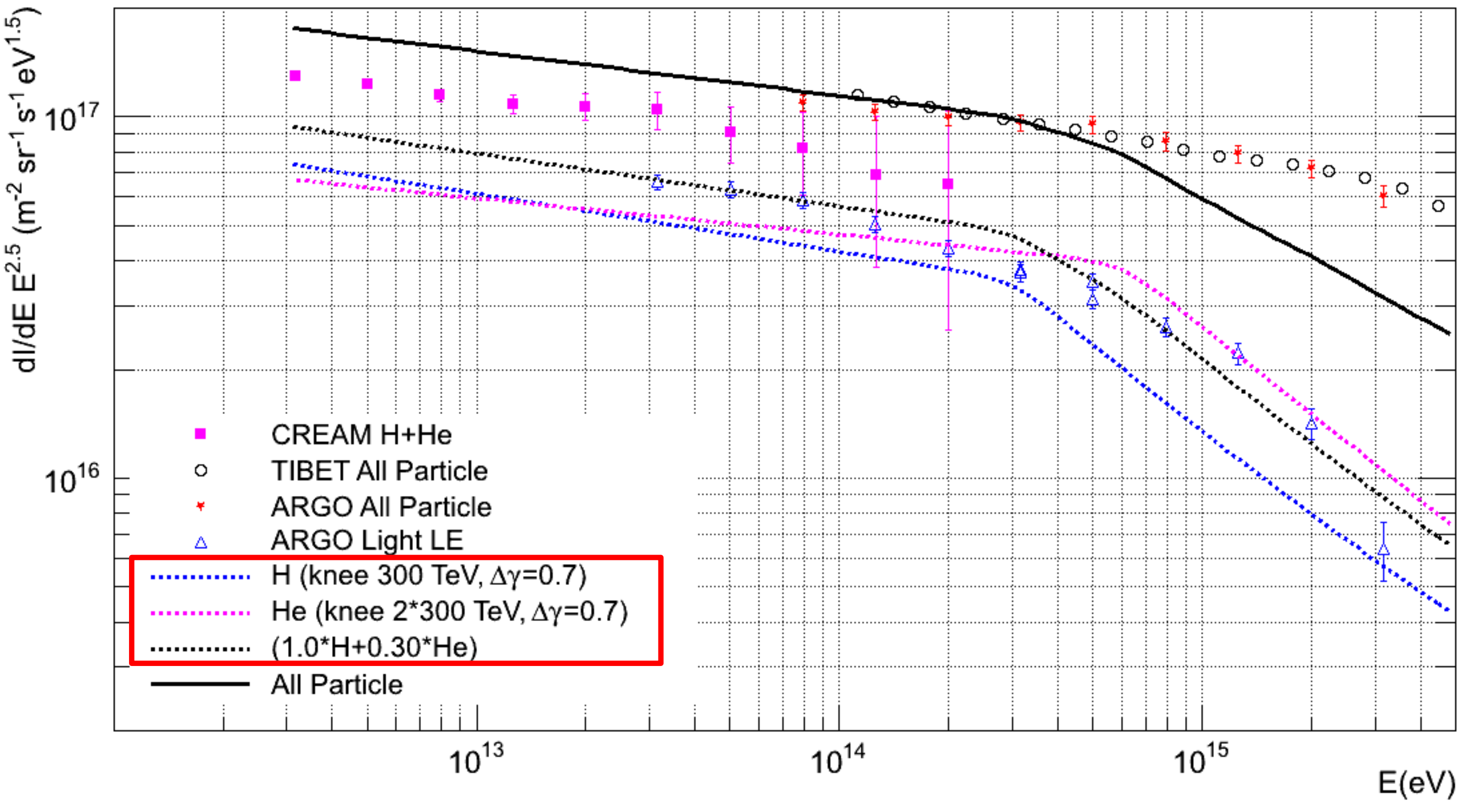
- Calculate the element spectra:

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

- Assuming:
  - Fluxes normalized to CREAM measurements at 10^{13} eV
  - γ_H & γ_{He} from CREAM measurements ($\gamma_{CNO}=\gamma_{Fe}=\gamma_{He}$)
  - $E_{knee}(Z) = Z\ E_{knee}(p)$
  - Same $\Delta\gamma$ for all elements
  - All particle = H+He+CNO+Fe
- 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

ARGO-YBJ 1st analysis



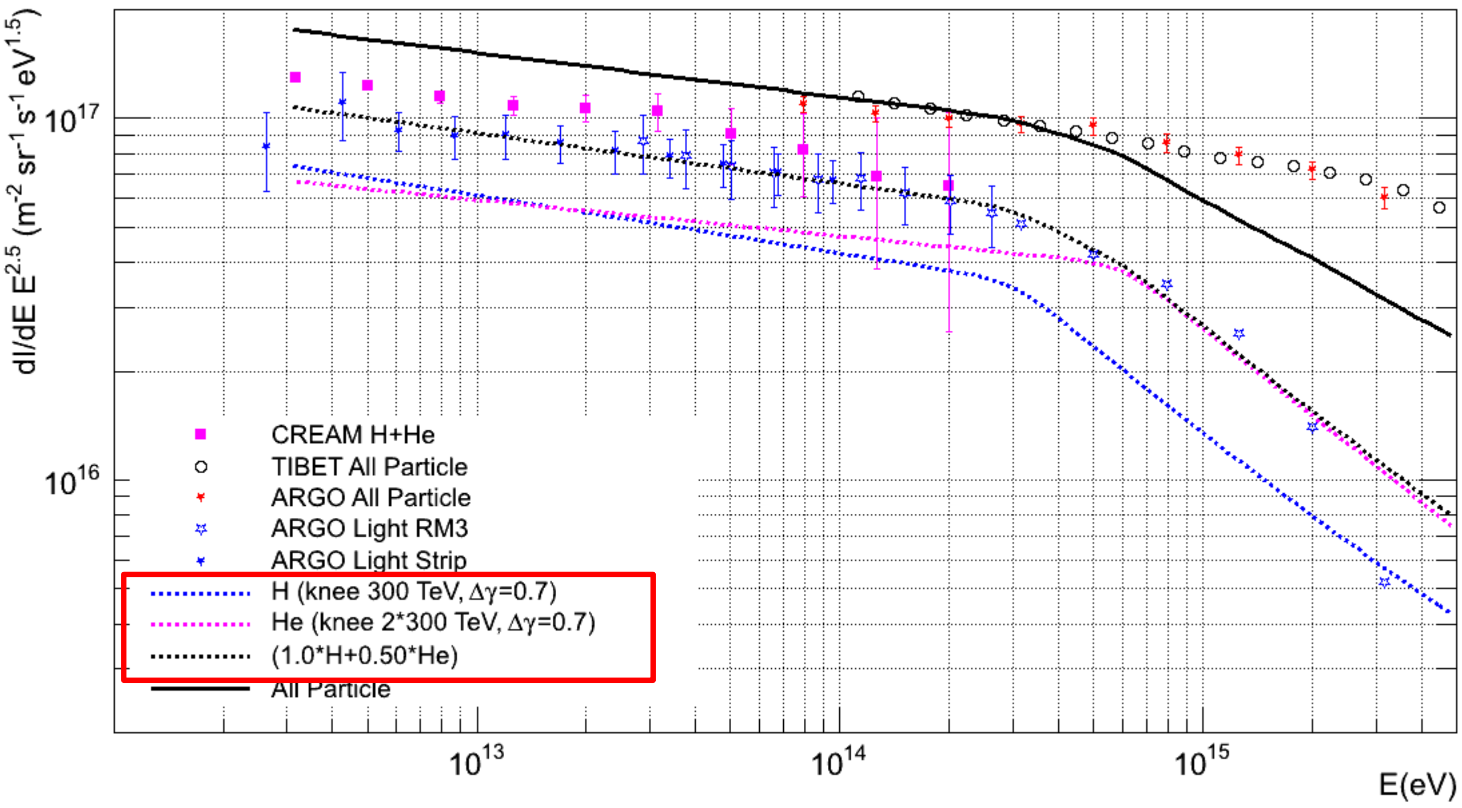
It is difficult to conciliate the light and all particle spectra (even assuming a knee energy scaling with A and a different $\Delta\gamma$ for He) without introducing a different (heavy) component.

ARGO-YBJ 2nd analysis

Better agreement at low energies → Light knee quite well reproduced

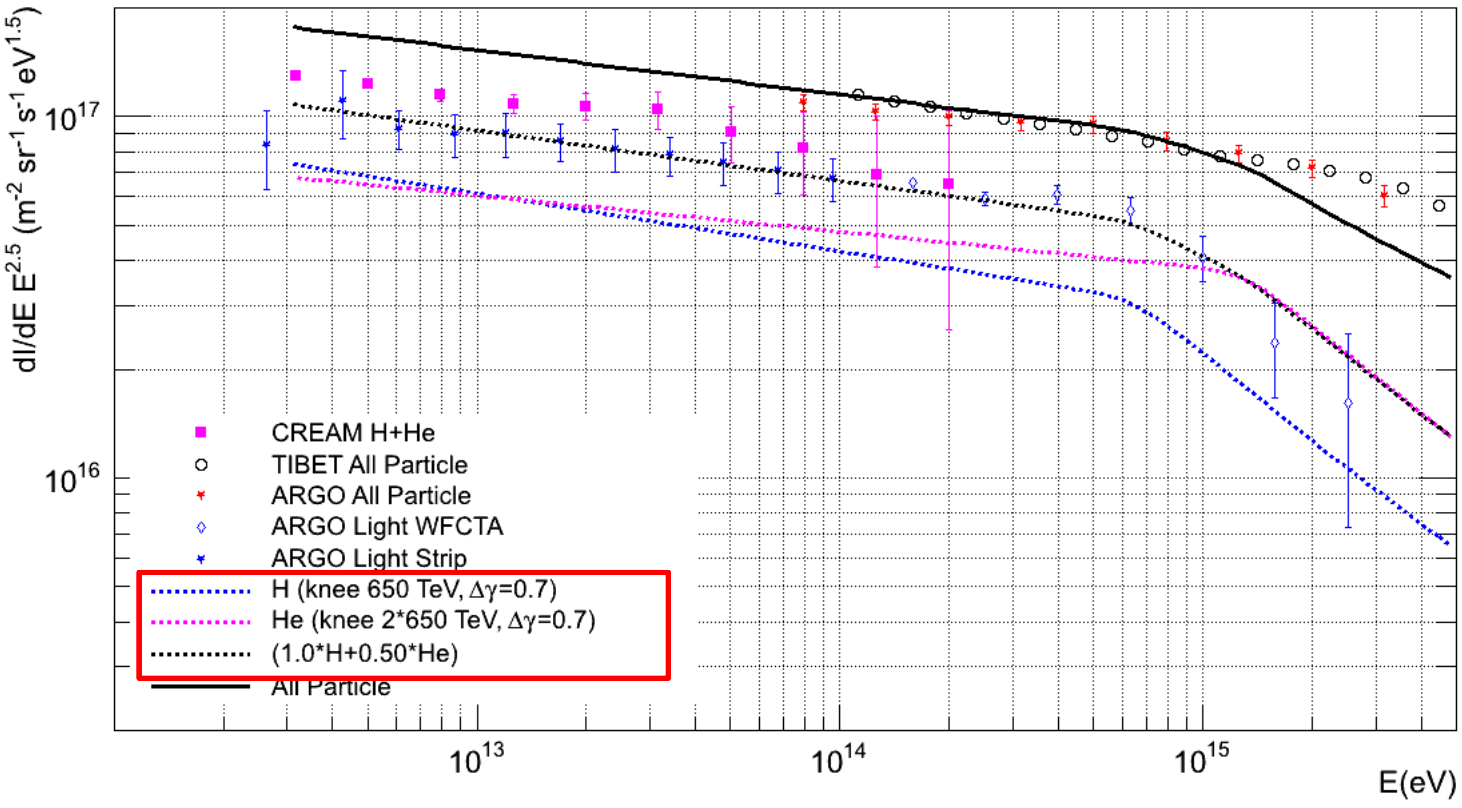
Not the All Particle spectrum

Hints of a selection efficiency changing with energy????

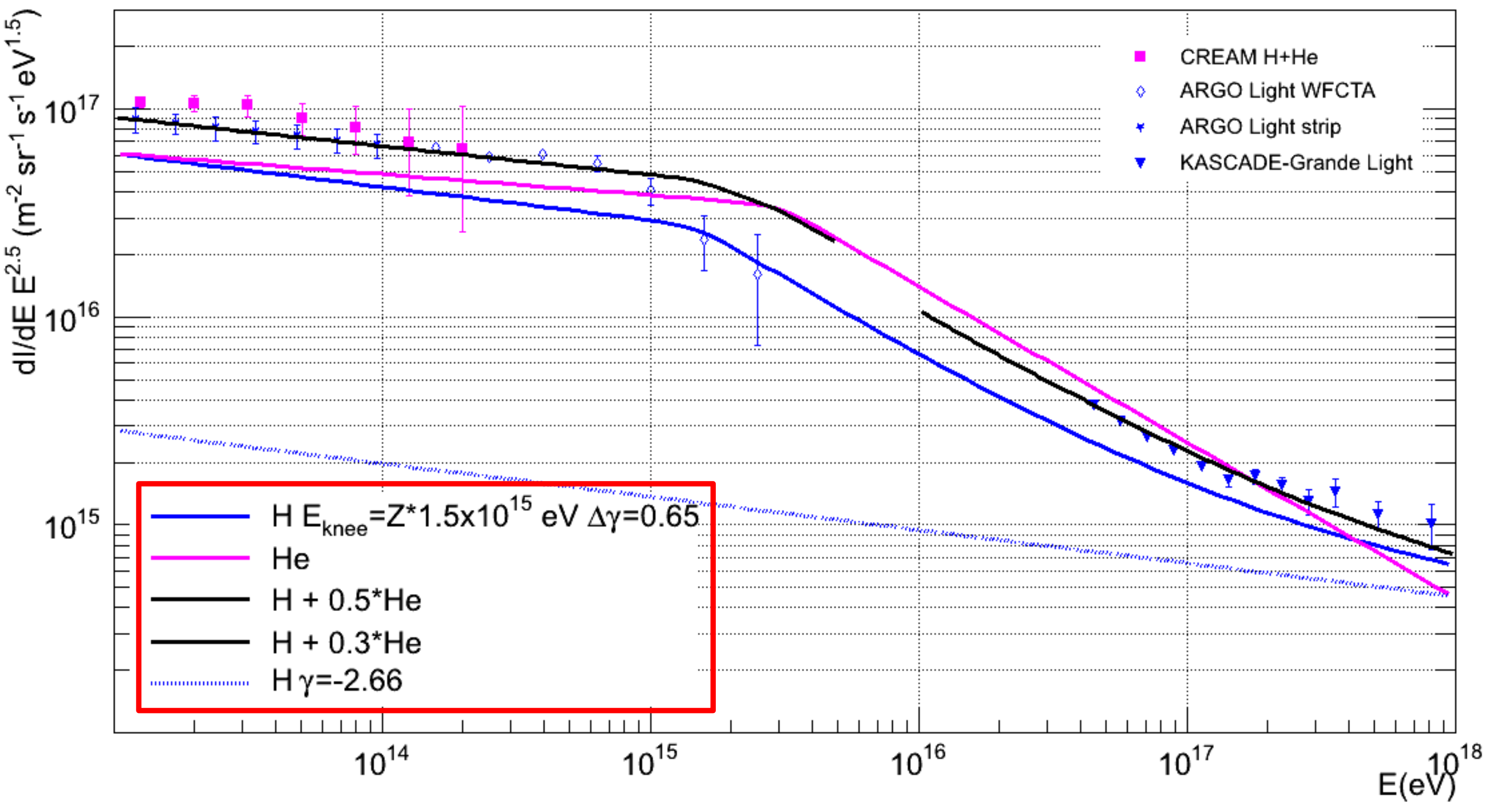


ARGO-YBJ + WFCTA analysis

The knee seems to be at a greater primary energy
All particle spectrum better (but not well) reproduced by the simple hypothesis of knees scaling with Z



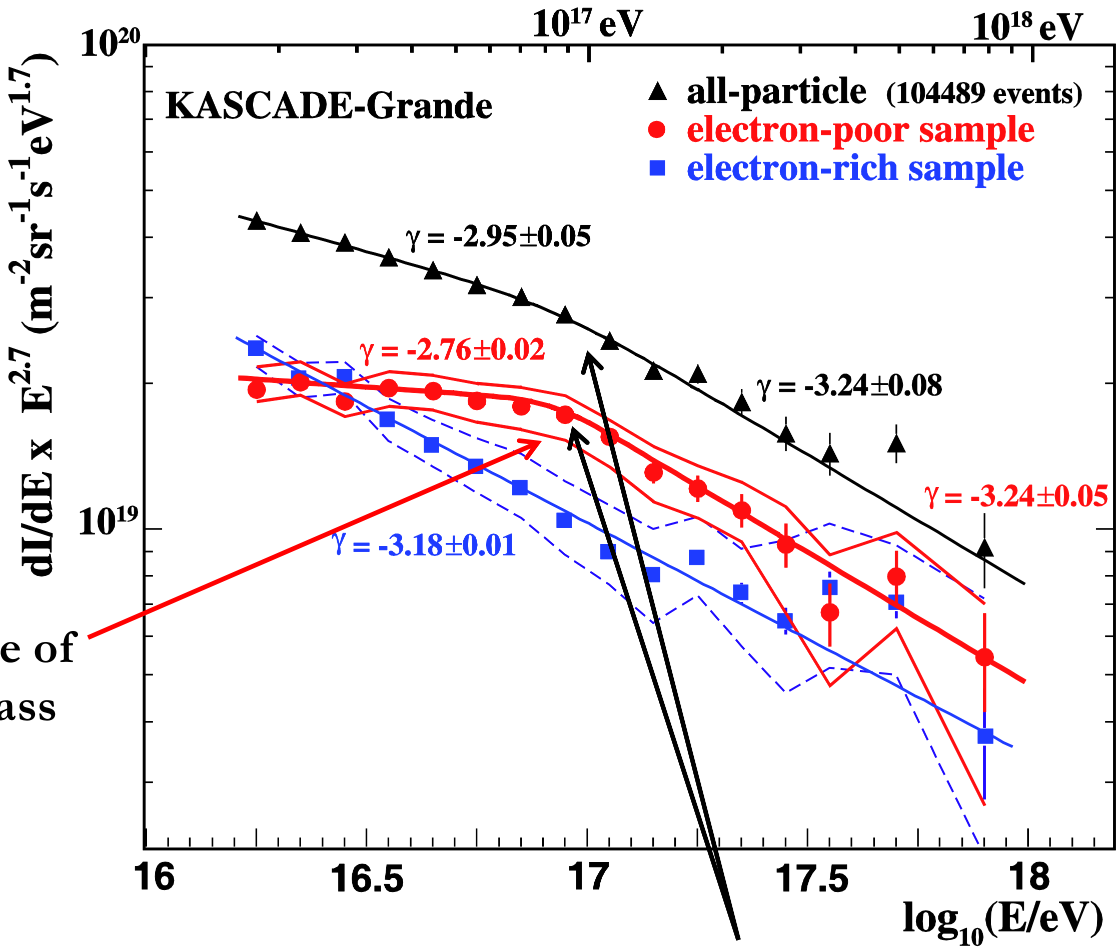
Light mass group spectra



Spectra calculated adding:

1) **"galactic" component calibrated using the CREAM measurements at 10^{13} eV and with knees at $Z*1.5x10^{15}$ eV**
2) **"additional component" becoming dominant at 10^{17} eV**

Heavy Mass Group Spectra

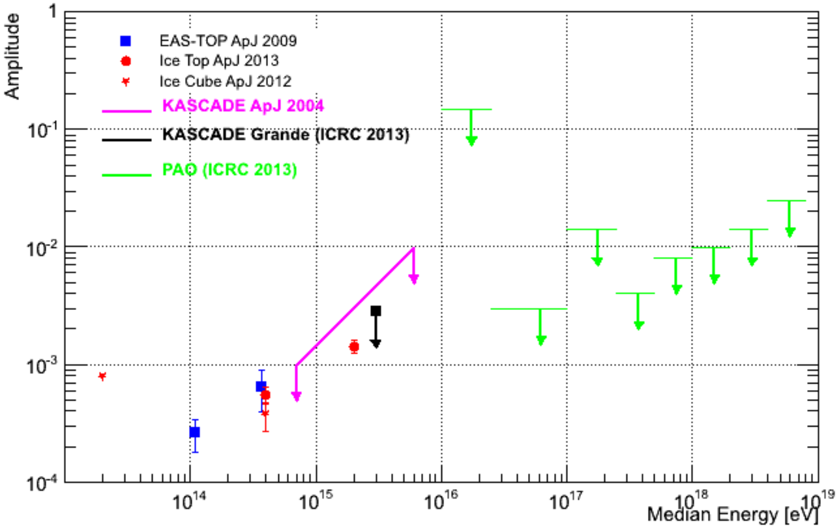


Evidence of a change of slope in the heavy mass group spectrum.
$E_{knee} = 8x10^{16}$ eV

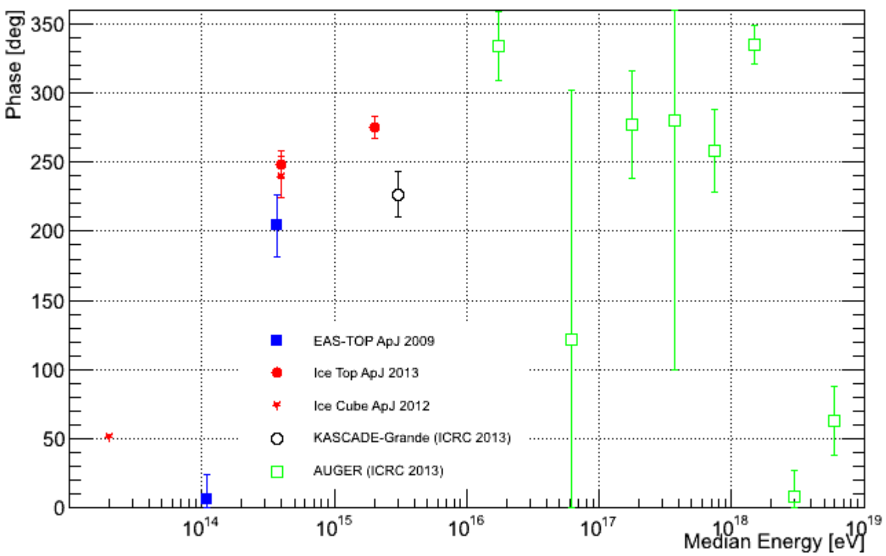
All particle and heavy mass group spectra show a steepening at similar energy

Large Scale Anisotropy searches

- The highest energy measured large scale anisotropy: $2x10^{15}$ eV (IceTop)

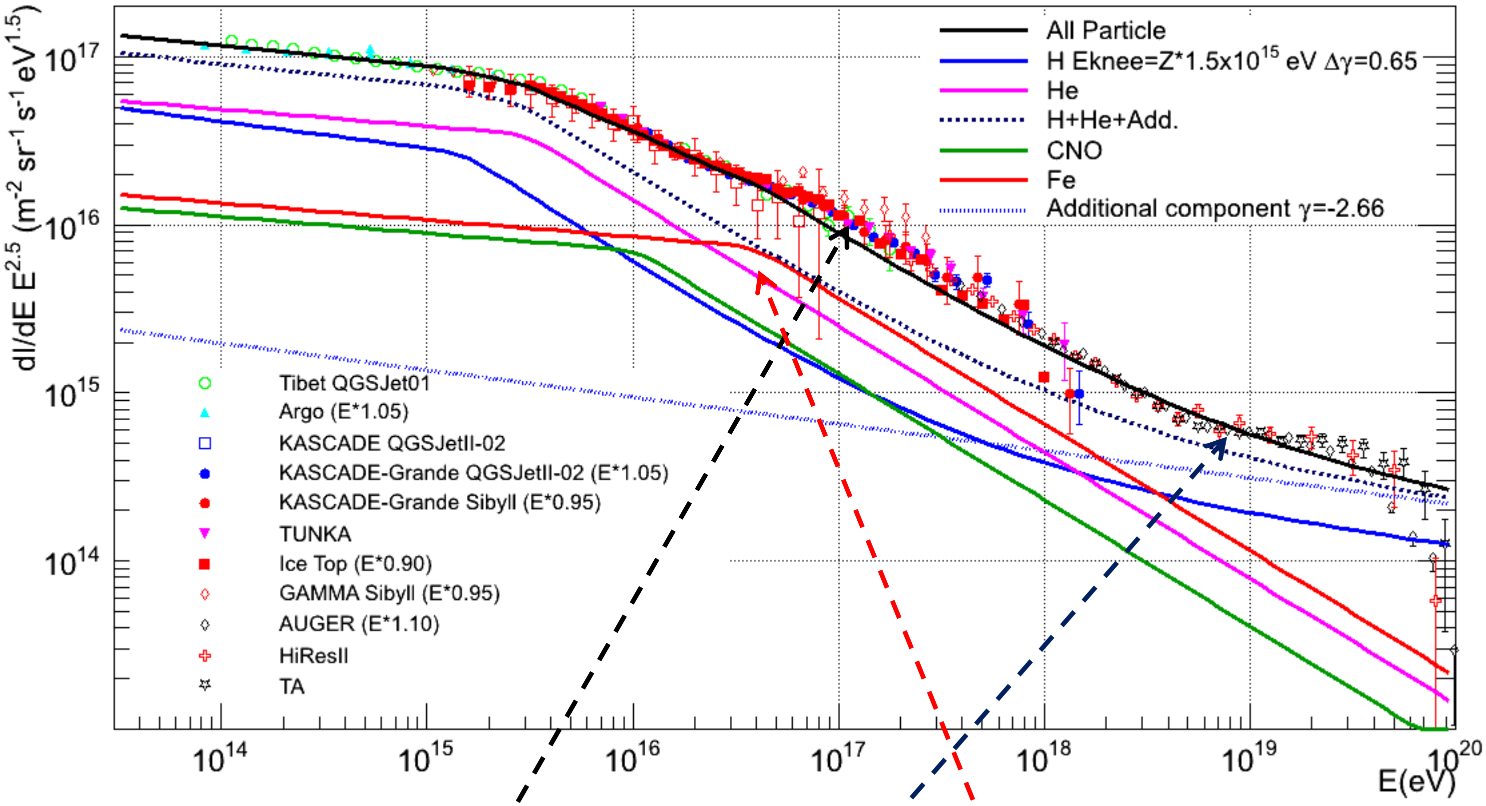


Hints of an increasing amplitude crossing knee energy



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

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 (heavy??)
(see T. Gaisser et al.)

Heavy E_{knee} is at too low energy?

E >10^{18} eV the chemical composition maybe too light

Summary and conclusions (I)

1. General agreement on the structure of the all particle spectrum.
   - Main Features: knee (4×10^{15} eV) & ankle (4×10^{18} eV)
   - Hardening slightly above 10^{16} eV
   - Steepening around 10^{17} eV
2. Features detected also in the light and heavy mass groups spectra
   - Light Spectrum
     - Steepening
       - $\leq 6.5 \times 10^{14}$ eV (ARGO)
       - $3\text{-}4 \times 10^{15}$ eV (KASCADE)

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

Conclusions (II)

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.

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