Mass composition studies around the knee with the Tunka-133 array

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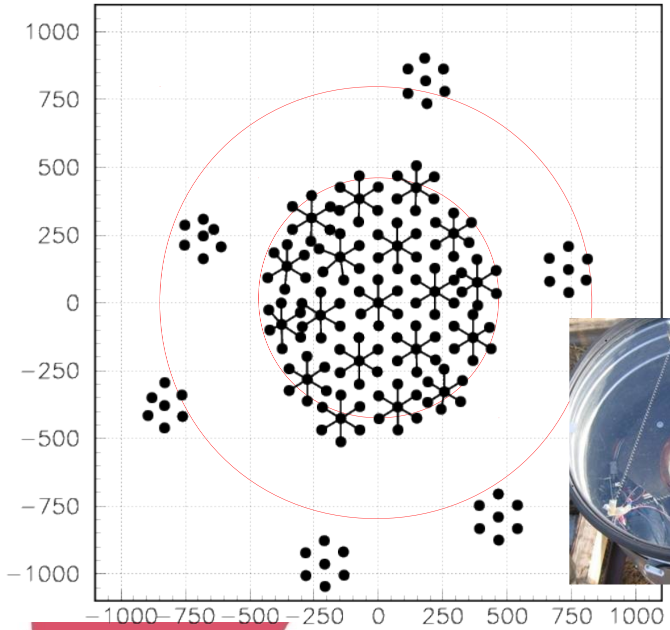
for the Tunka-133 collaboration

Tunka-133

The Tunka-133 array



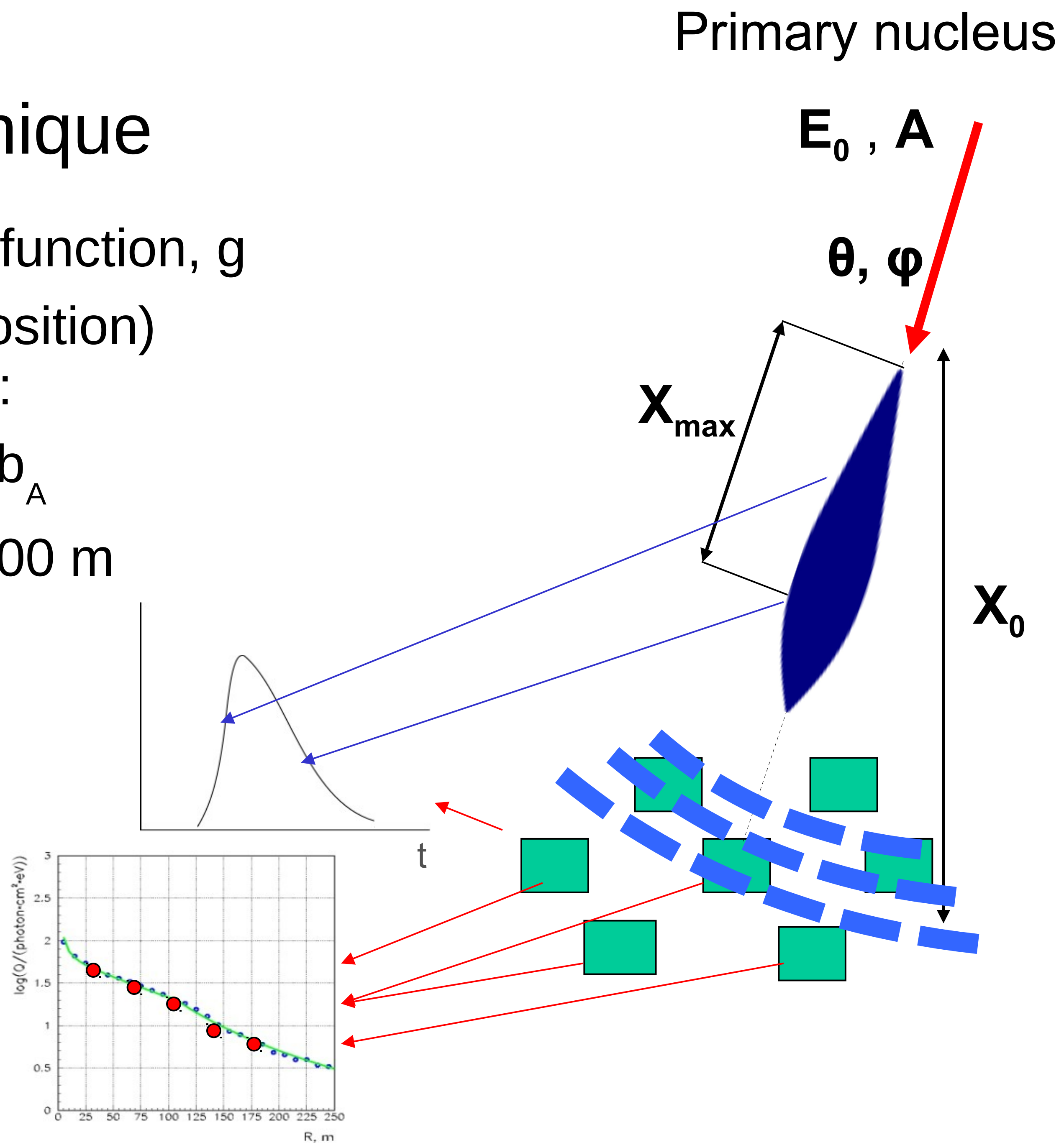
51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

- non-imaging wide-angle Cherenkov array
- the knee energy range
- Tunka Valley, Russia
- in operation since 2010
- Tunka-25 is predecessor
- consists of 175 OD (8” PMT)
- 19 + 6 clusters
- spacing 85 m
- inner part R ~ 450 m (0.6 km^2)

  outer part R ~ 800 m (2.0 km^2)

Detection technique

- $E_0 \sim Q(200)^g$ (LDF function, g depends on composition)
- X_{max} reconstruction:
  1. ADF steepness b_A
  2. Pulse width at 400 m



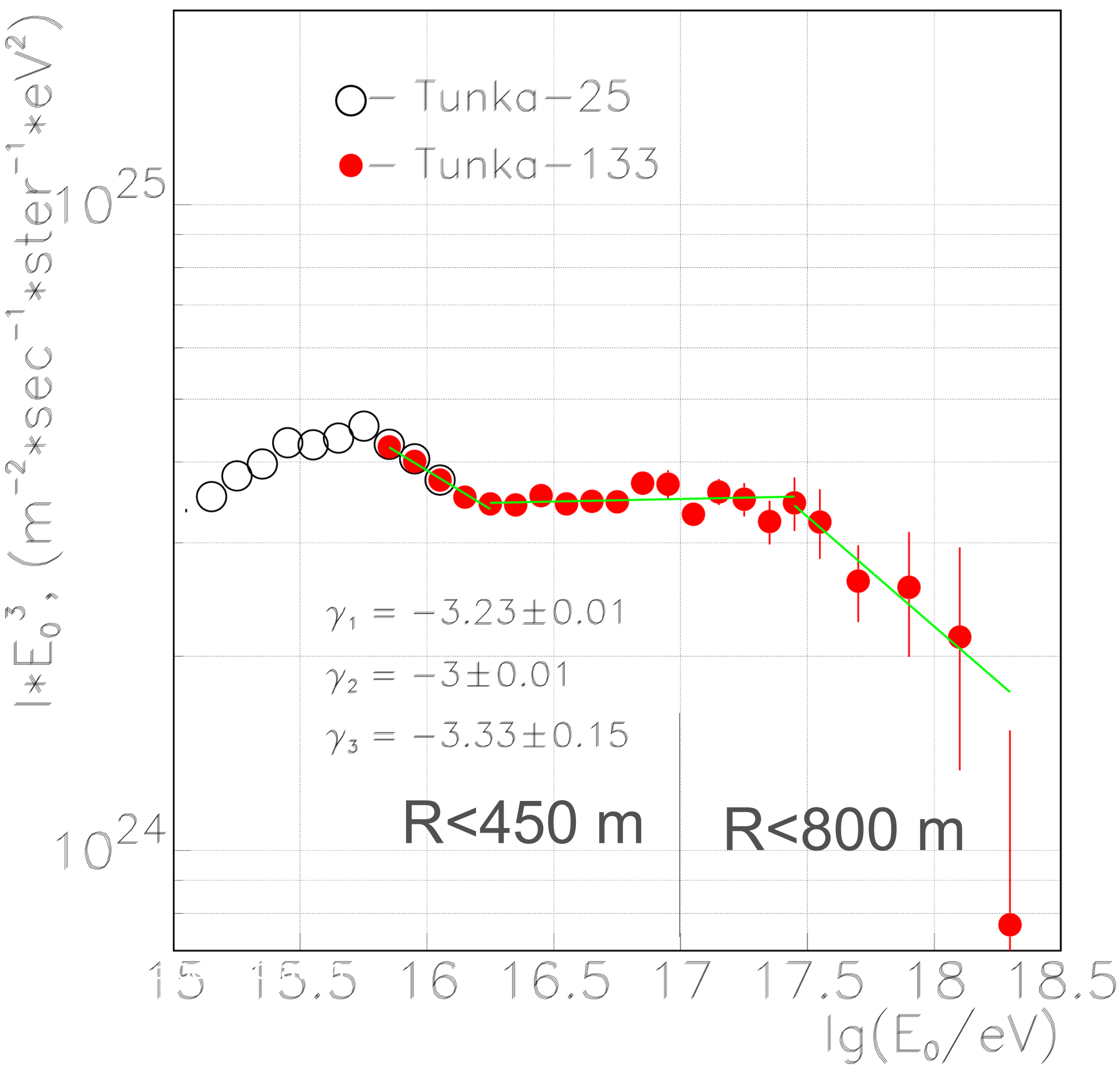
3-years data (status 2013)

3 winter seasons: 2009-2010 , 2010-2011, 2011-2012
165 clean moonless nights
~ 980 h of observation with a trigger frequency ~ 2 Hz
~ 6 000 000 triggers
The cuts for the energy spectrum used:
$\theta \leq 45°$

$R_{core} < 450$ m:
~ 170 000 events with $E_0 > 6 \cdot 10^{15}$ eV – 100% efficiency
~ 60 000 events $E_0 > 10^{16}$ eV
~ 600 events $E_0 > 10^{17}$ eV

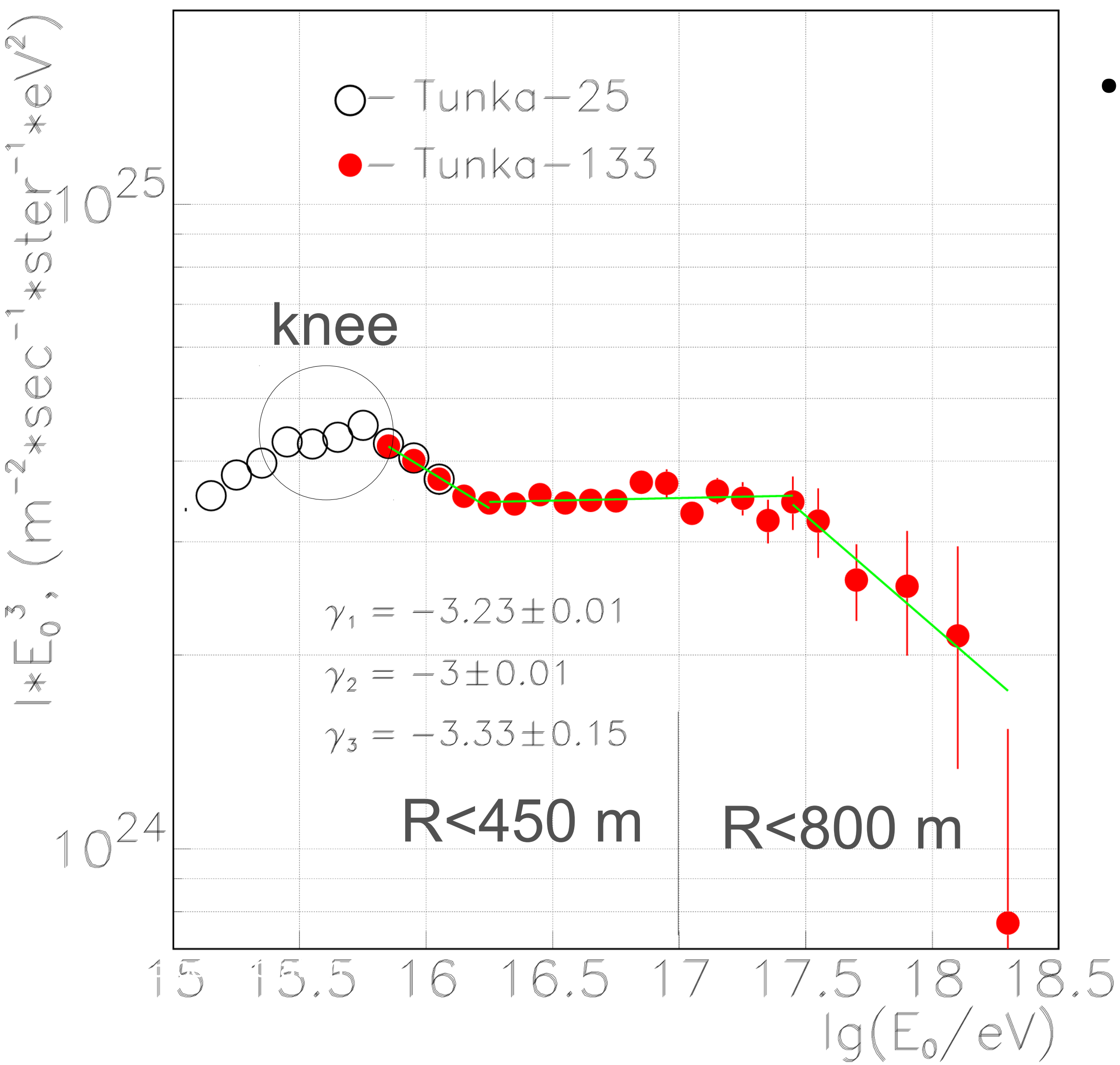
$R_{core} < 800$ m:
~ 1900 events $E_0 > 10^{17}$ eV

Energy spectrum: status 2013



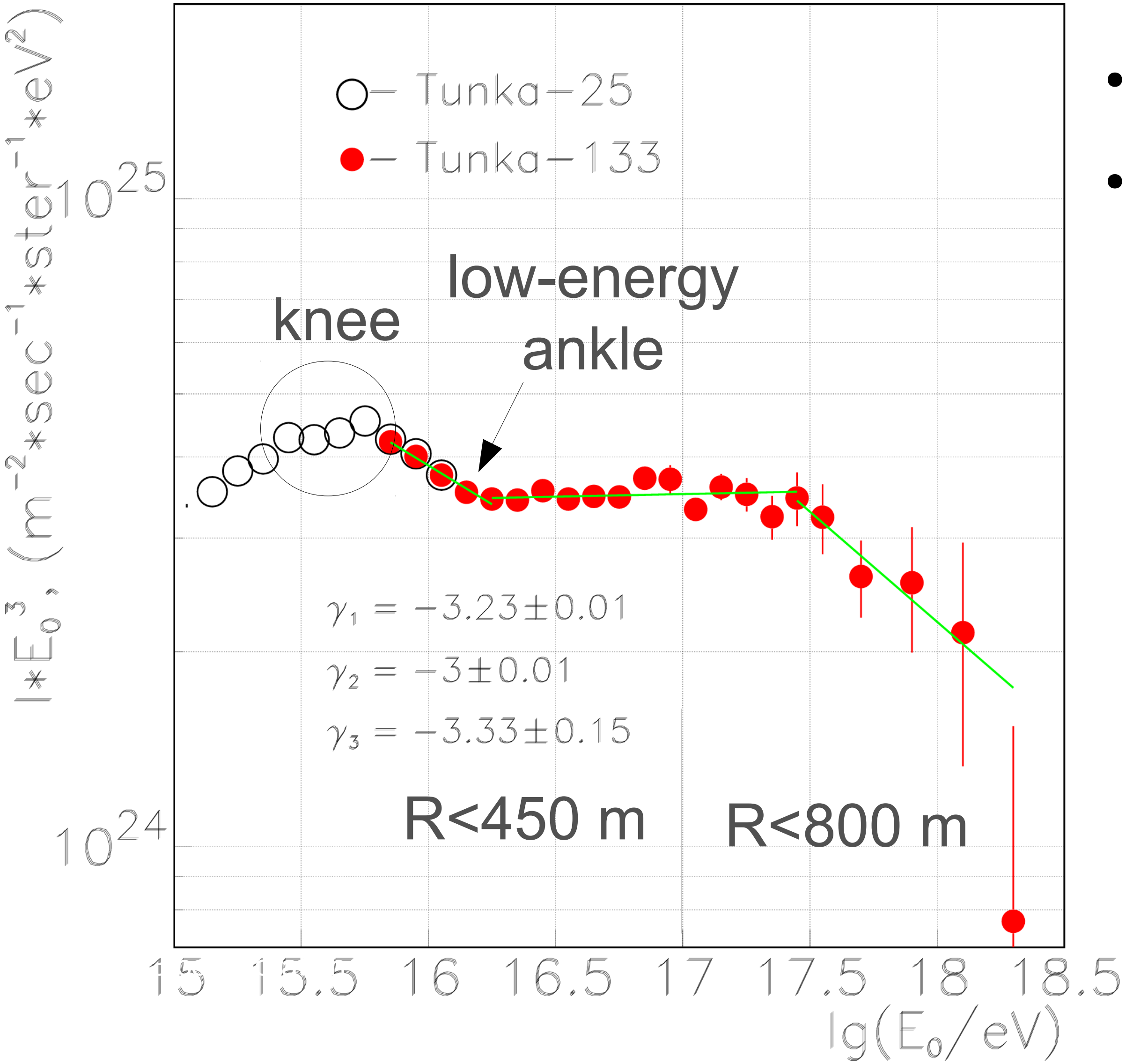
What do we see?

Energy spectrum: status 2013



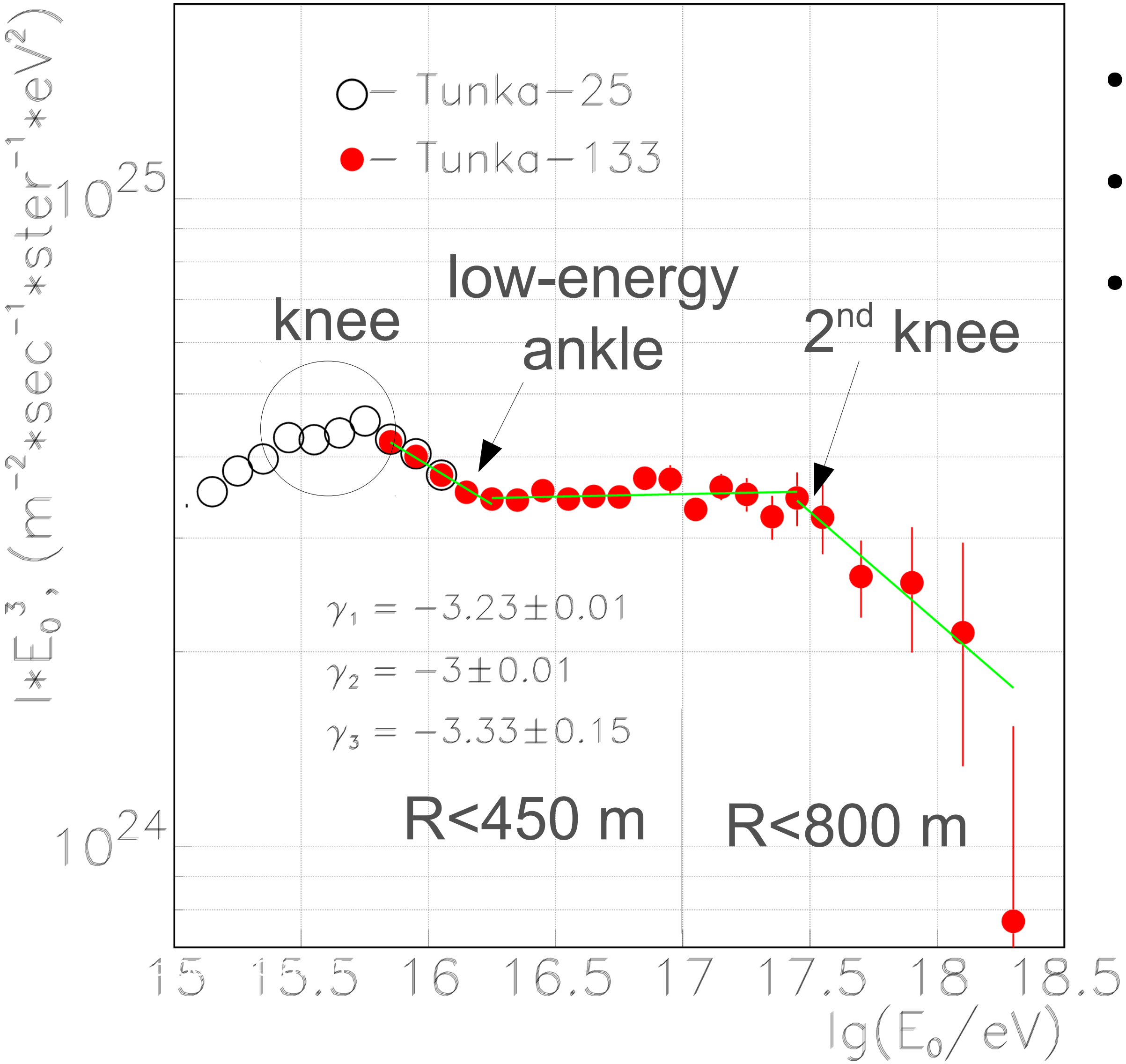
- composite knee

Energy spectrum: status 2013



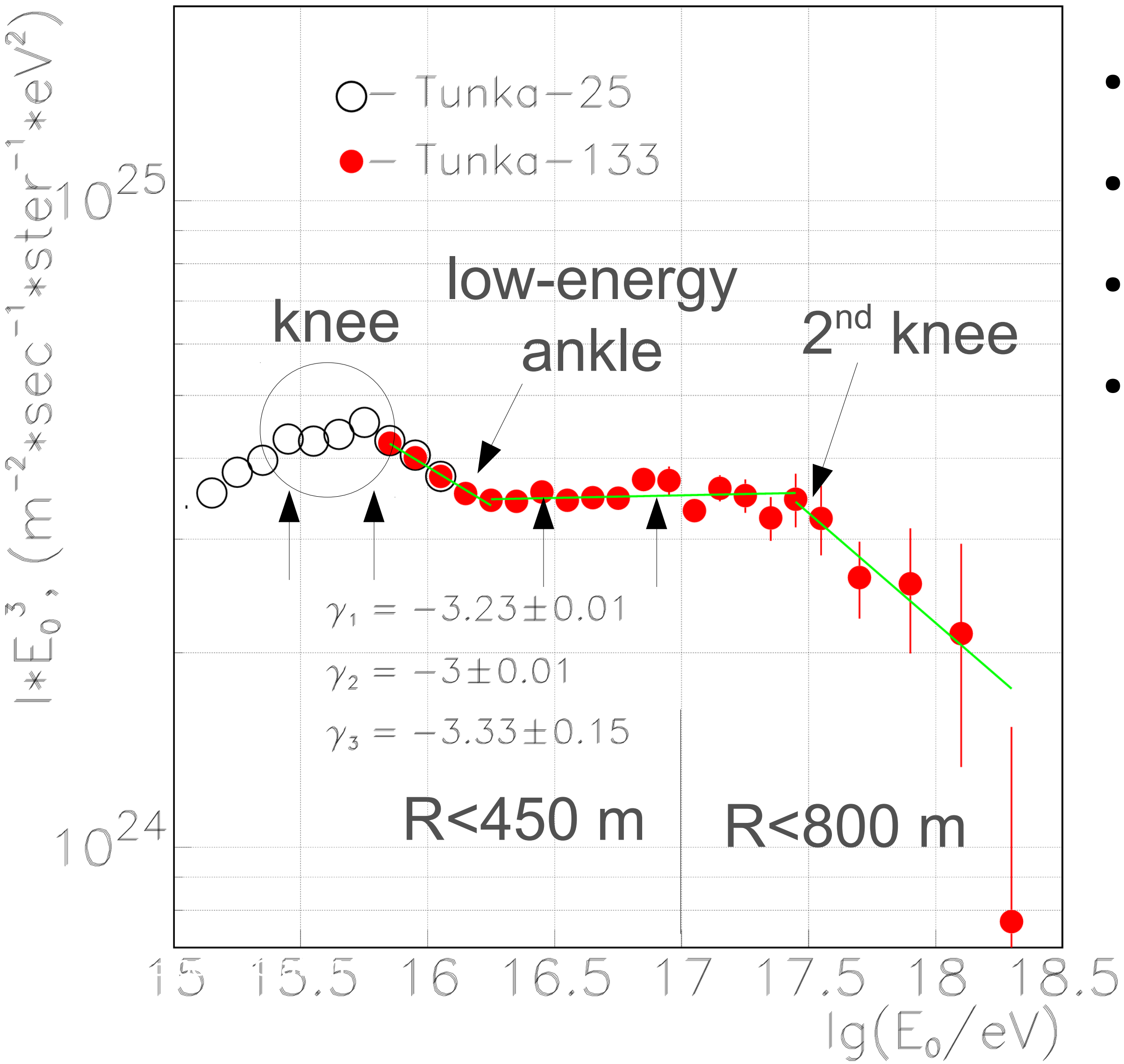
- composite knee
- low-energy ankle

Energy spectrum: status 2013



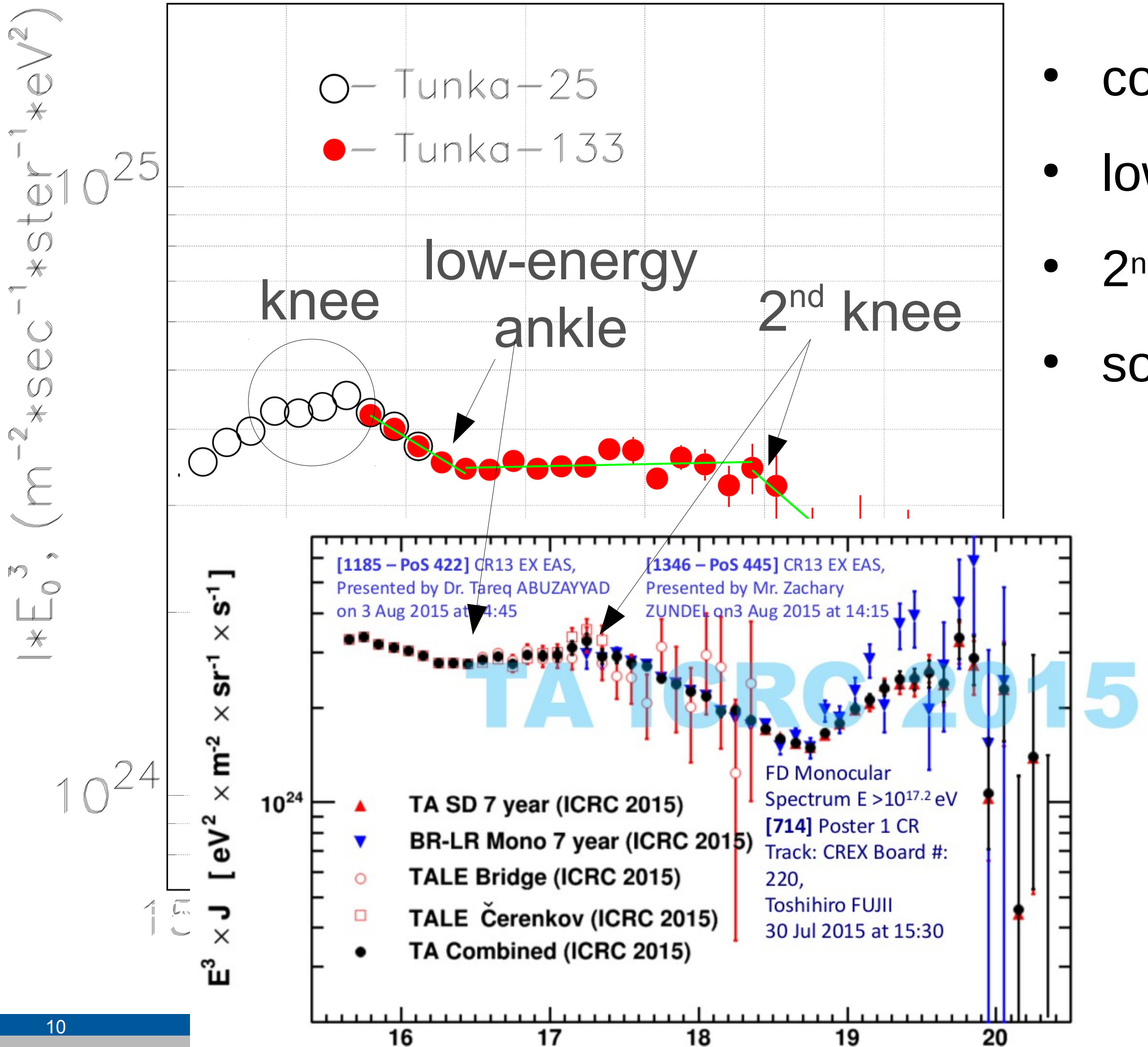
- composite knee
- low-energy ankle
- 2nd knee

Energy spectrum: status 2013



- composite knee
- low-energy ankle
- 2nd knee
- some minor bumps

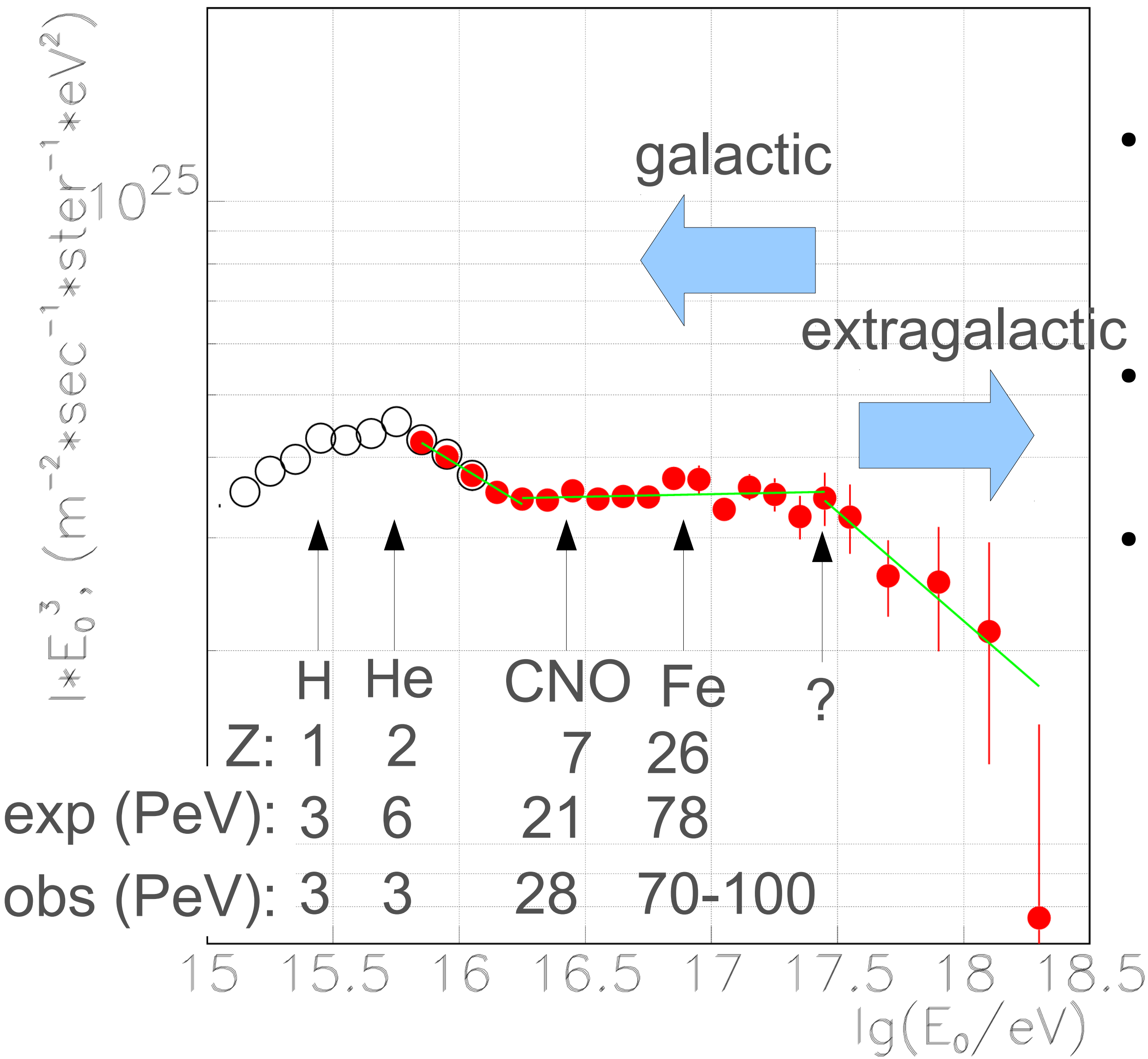
Energy spectrum: status 2013



- composite knee
- low-energy ankle
- 2nd knee
- some minor bumps

TA sees the same spectrum structure

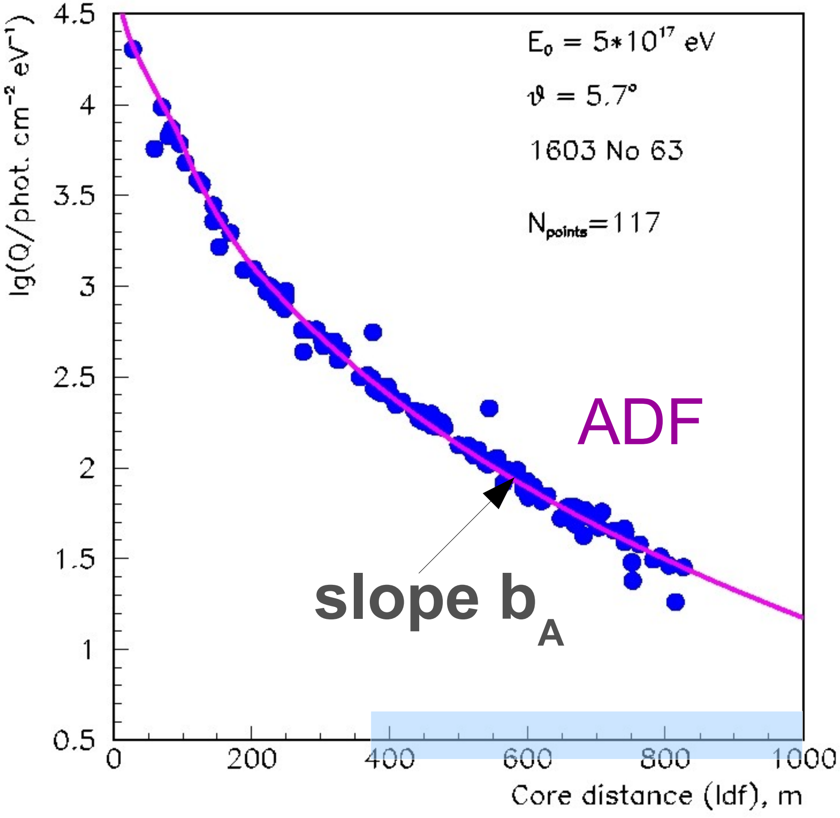
Energy spectrum: interpretation

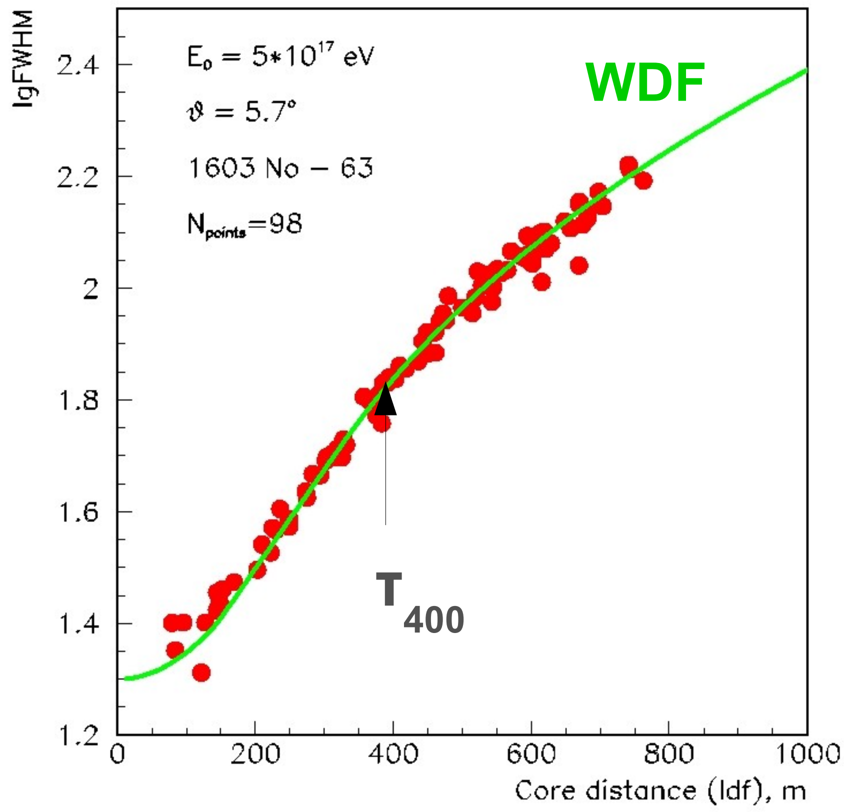


the classical view:

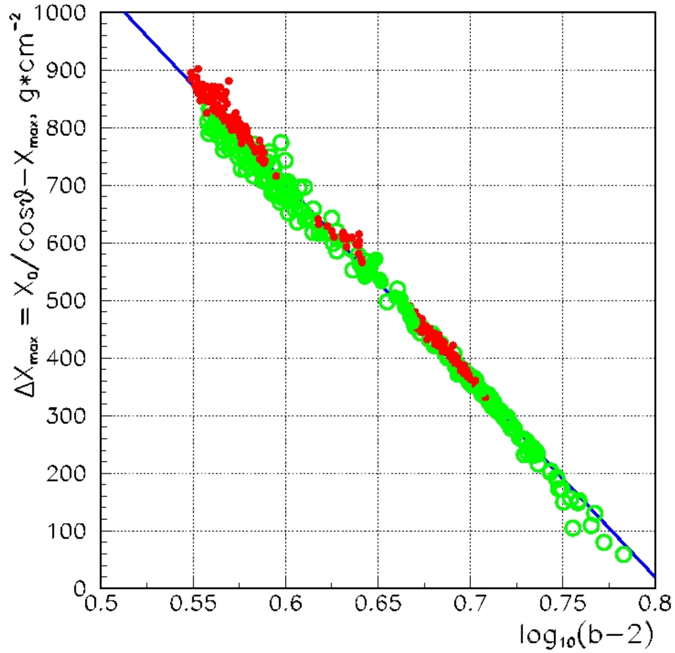
- rigidity dependent cut-offs of different nuclei groups (E_c~Z)
- the composite knee – hydrogen and helium
- the 2nd knee – acceleration limit of the Galaxy

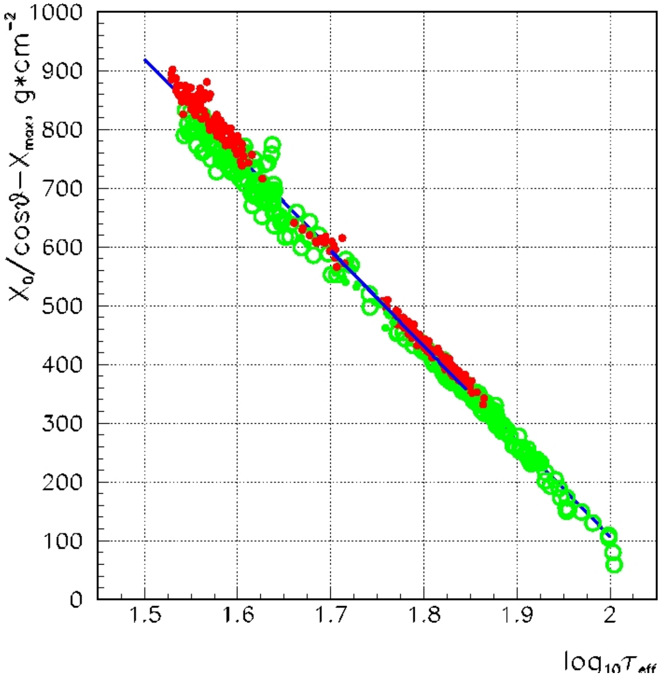
Two methods of X_{max} reconstruction: ADF and WDF





Correlation of parameters b_A and τ_{400} with X_{max}



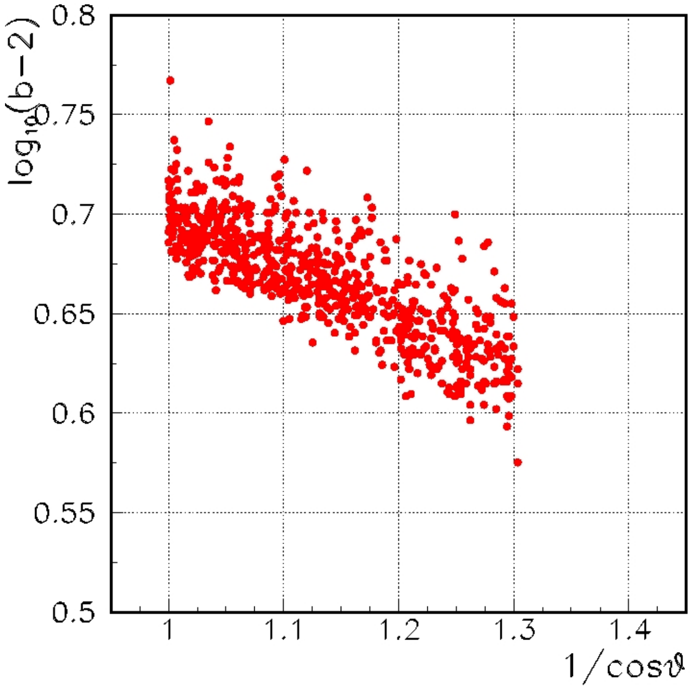


- linear correlation of parameters according to CORSIKA
- The regression coefficients can be estimated from either CORSIKA or using a *phenomenological approach*

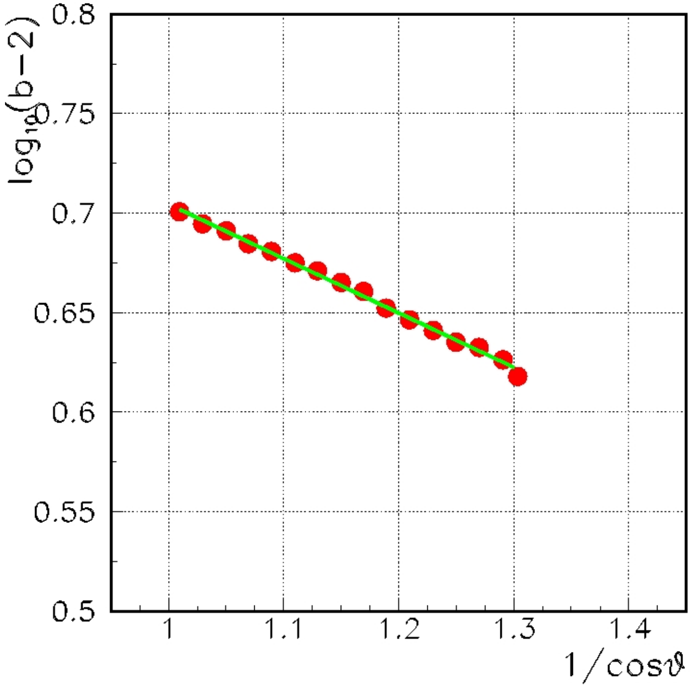
PHENOMENOLOGICAL APPROACH:
ADF steepness vs. zenith angle

$E_0 = 3 \cdot 10^{16}$ eV

~3500 events: $16.4 < \log_{10}(E_0/\mathrm{eV}) < 16.5$



→



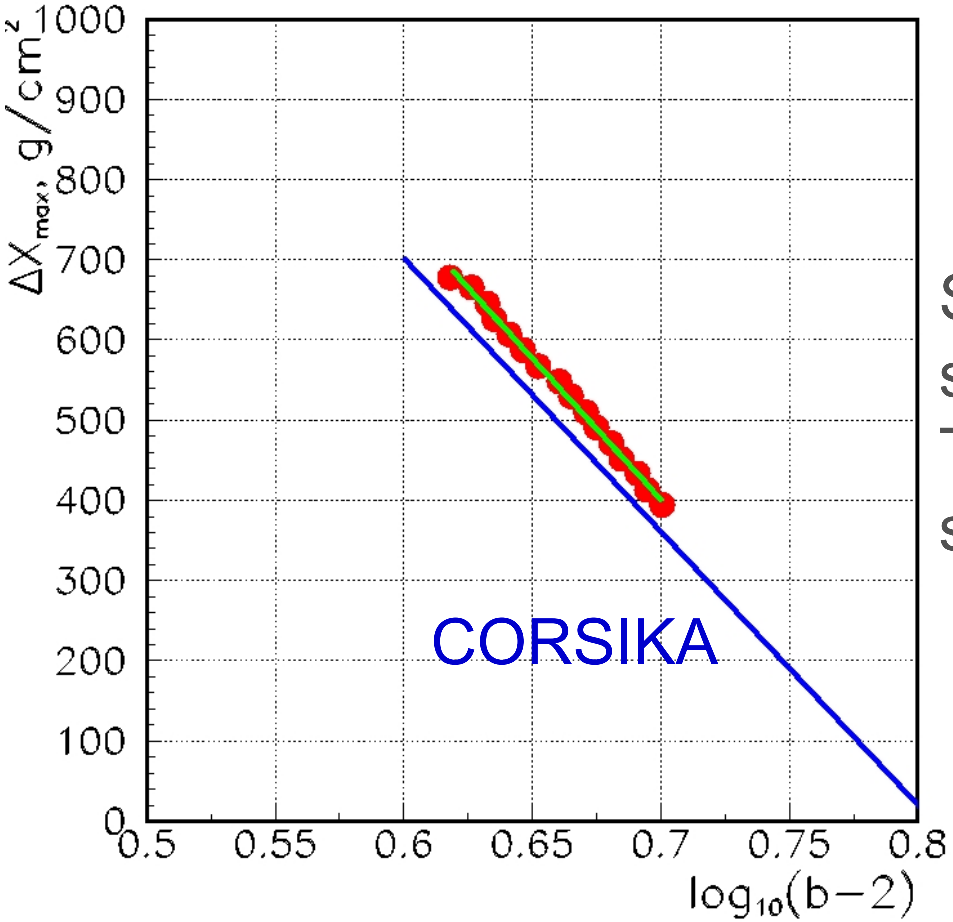
$\cos\theta \rightarrow \Delta X_{max} = X_0/\cos\theta - X_{max}$

$X_0 = 965\ \mathrm{g \cdot cm^{-2}}$

Supposed: $\langle X_{max} \rangle = 580\ \mathrm{g \cdot cm^{-2}}$ for $E_0 = 3 \cdot 10^{16}$ eV

(calibration to existing fluorescence data: HiRES/MIA and Auger(2007)

PHENOMENOLOGY: X_{max} by the ADF steepness



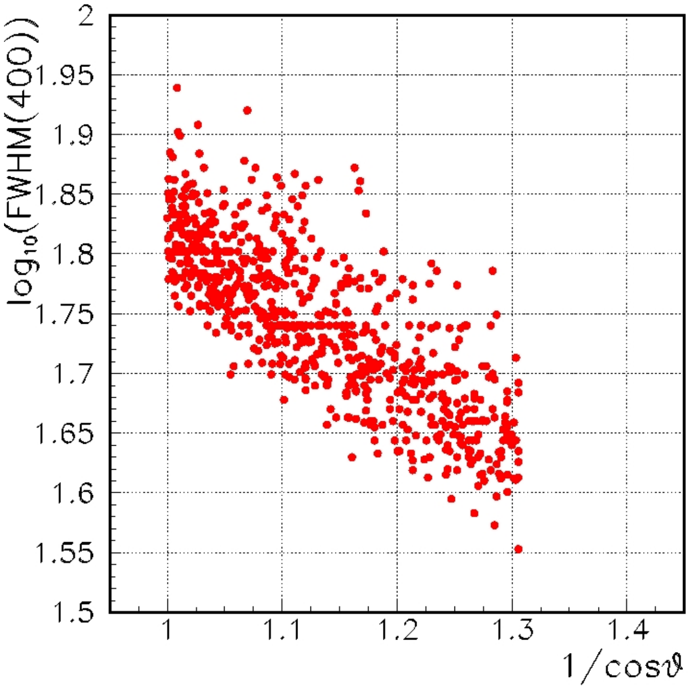
Slopes are the same.
The constant slightly differs.

$$\Delta X_{max} = 2865 - 3519 \cdot \log_{10}(b_A - 2), \;\; g \cdot cm^{-2}$$

PHENOMENOLOGICAL APPROACH: $\tau_{eff}(400)$ vs. zenith angle

$E_0 = 3 \cdot 10^{16}$ eV

~3500 events: $16.4 < \log_{10}(E_0/\mathrm{eV}) < 16.5$



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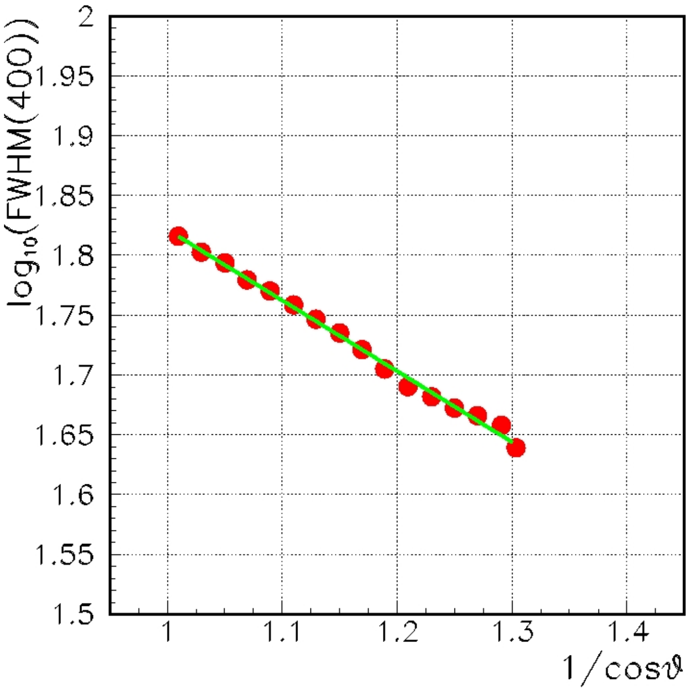

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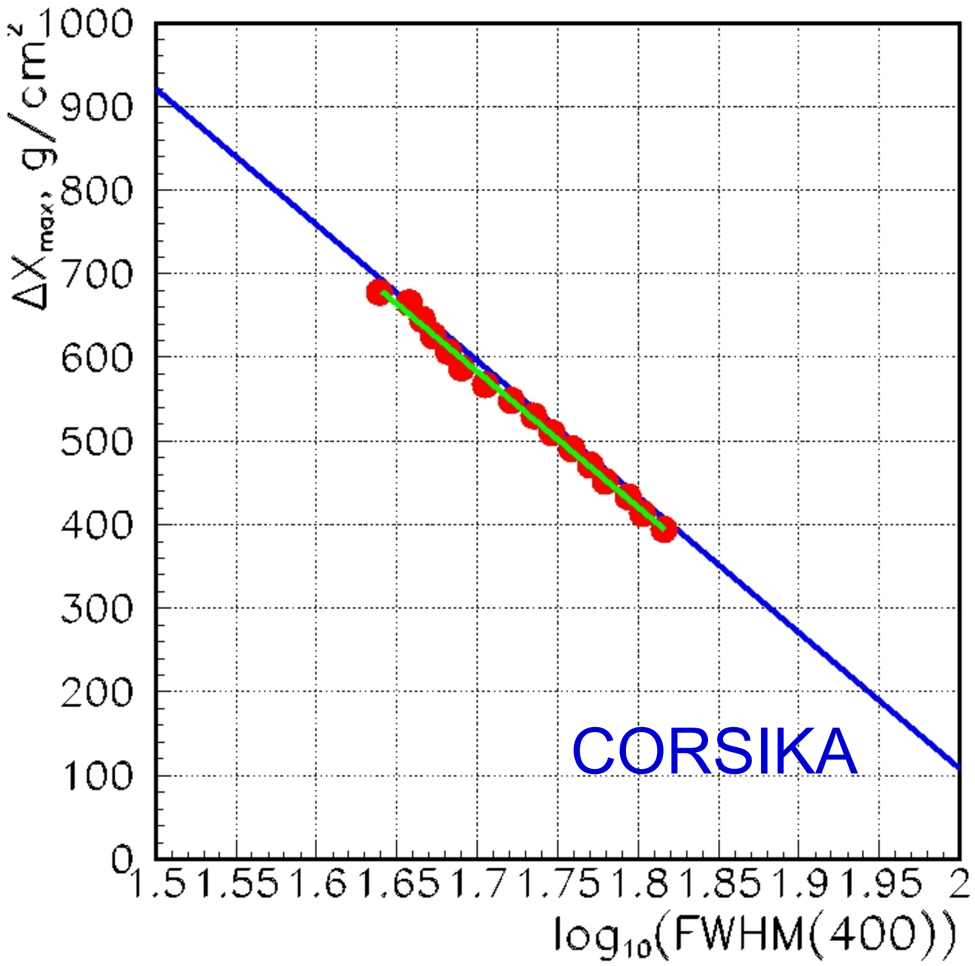
(calibration to existing fluorescence data: HiRES/MIA and Auger(2007)

PHENOMENOLOGY: X_{max} by τ(400)



Full agreement !

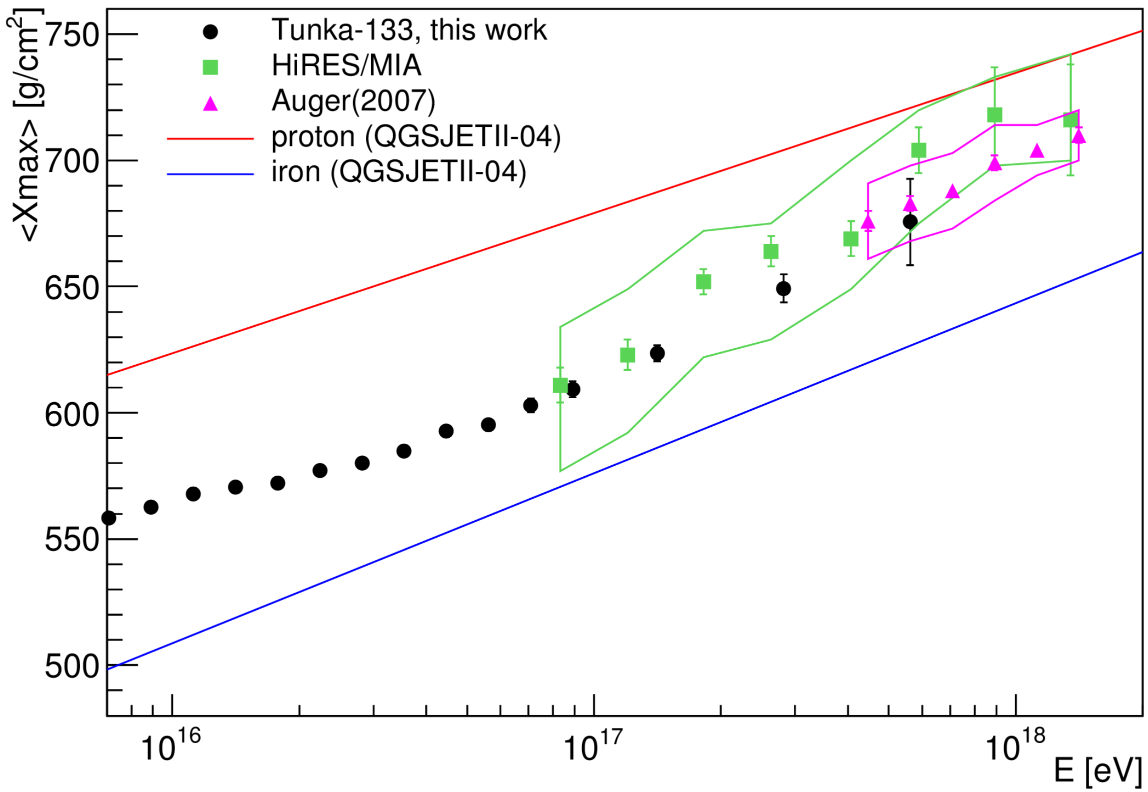
$$\Delta X_{max} = 3344 - 1624 \cdot \log_{10}(\tau_{400}),\ \ g \cdot cm^{-2}$$

$<X_{max}>$ results: status 2013

- R<450 m
- Θ<45 deg
- 99510 events:

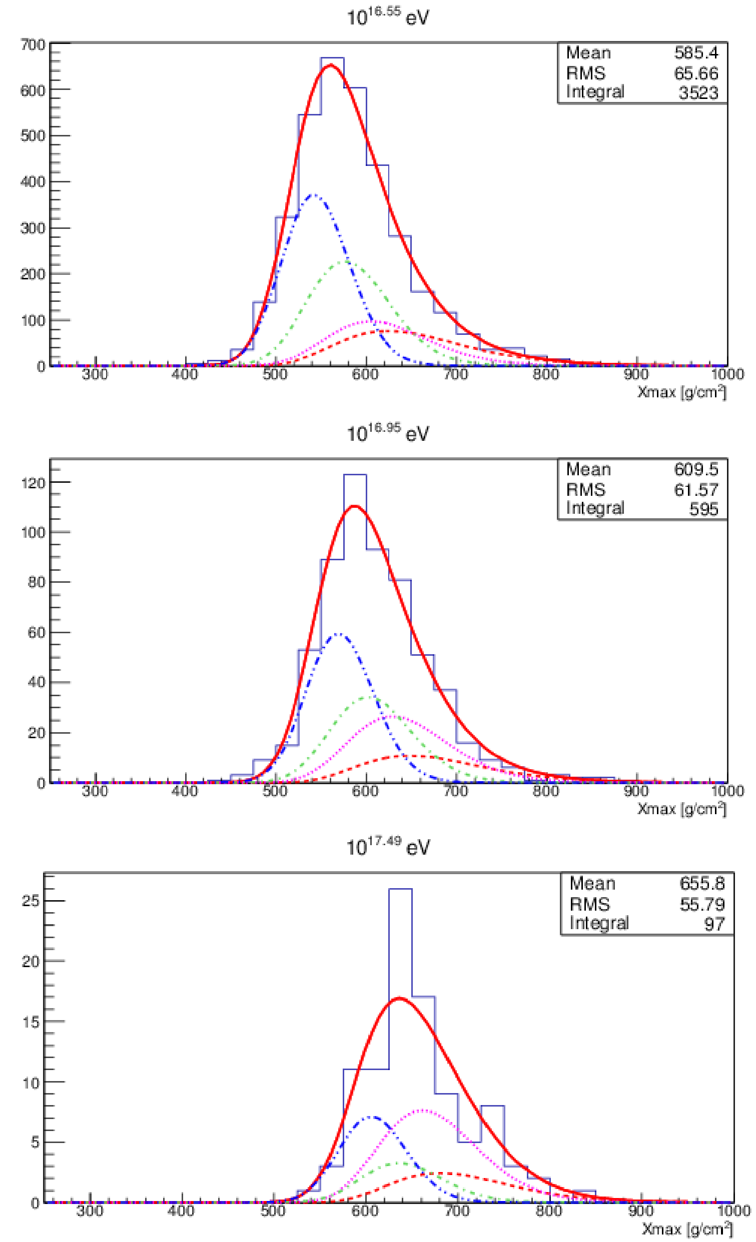
  53399 (>10 PeV)

  617 (>100 PeV)



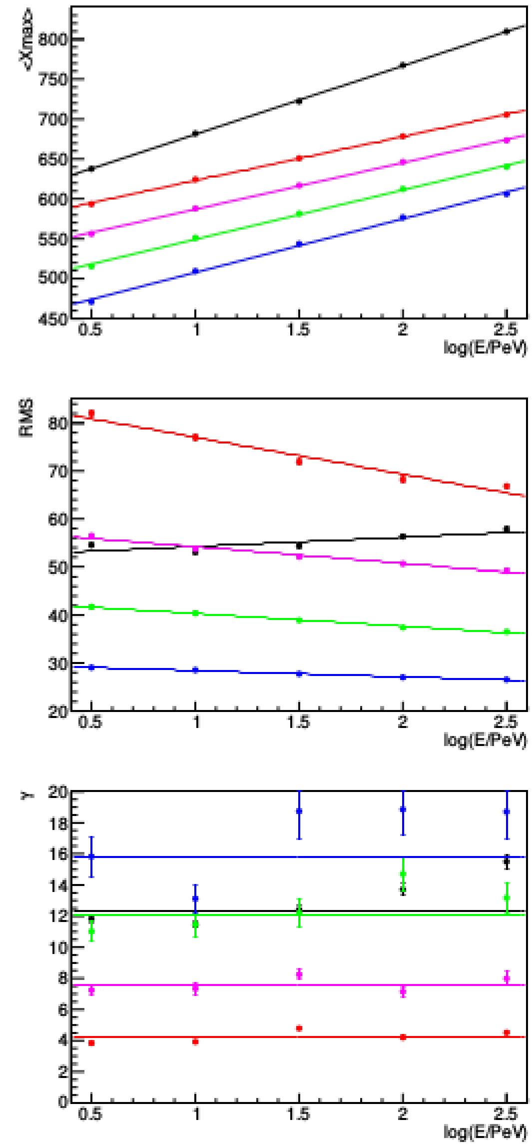
Elemental composition

- Each of the experimental X_{max} histograms is approximated with four groups of nuclei (H, He, N, Fe) to determine the elemental composition.
- **The method:** generated in CORSIKA distributions of different groups of nuclei are included in a composite model. The weight of each group in the superposition can be found by fitting the real X_{max} data.
- The X_{max} resolution should be taken into account (!).



X_{max} parametrization (QGSJETII04)

- Parametrization by Gamma-function and linear interpolation (H, He, N, Fe)



$$P_\gamma(x) = \frac{(x - x_0)^{\gamma-1}}{\Gamma(\gamma)\beta^\gamma} \exp\left(-\frac{x - x_0}{\beta}\right)$$

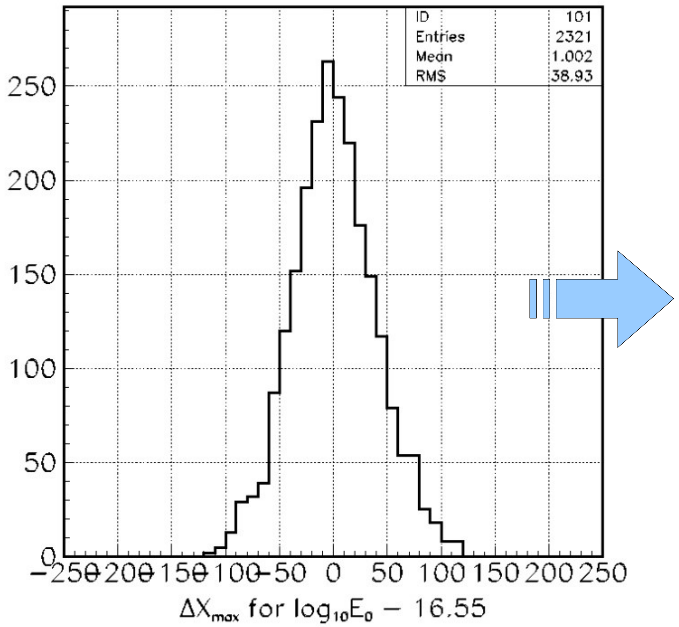
$$\overline{x} = \beta\gamma + x_0;$$

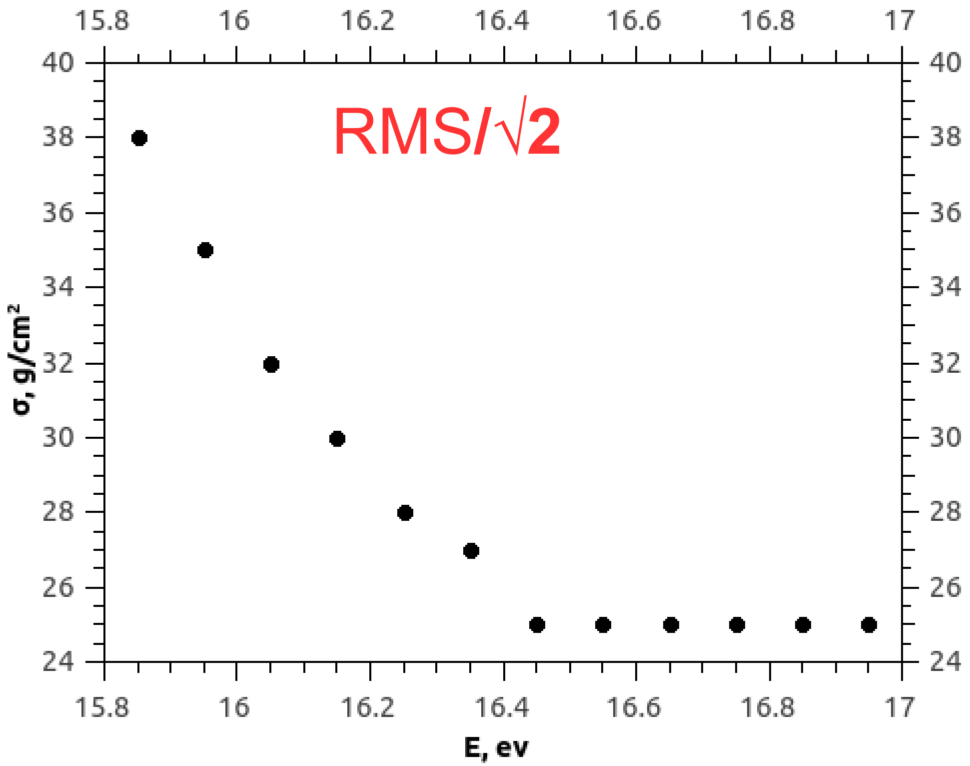
$$\sigma = \beta\sqrt{\gamma}.$$

- Then convolution with Gaussian with known standard deviation

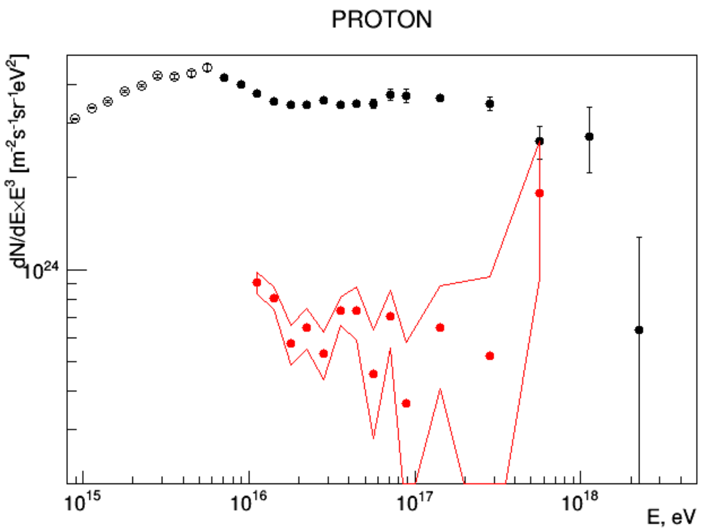
X_{max} resolution

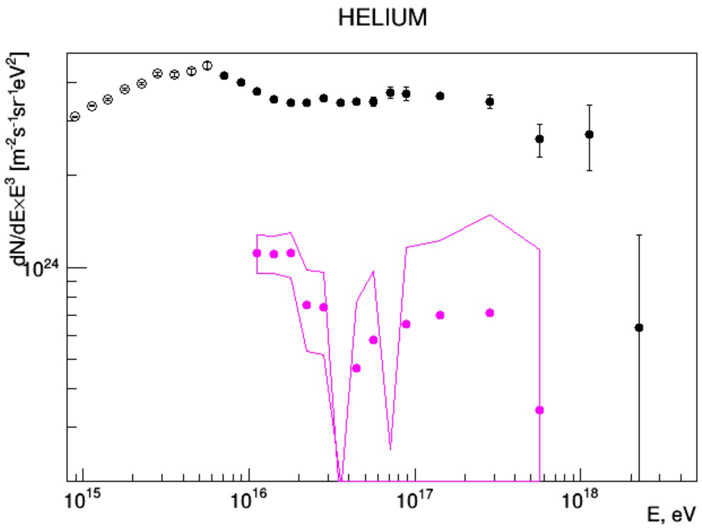
- Comparison both b- and τ- methods provided us a first estimation of the X_{max} resolution

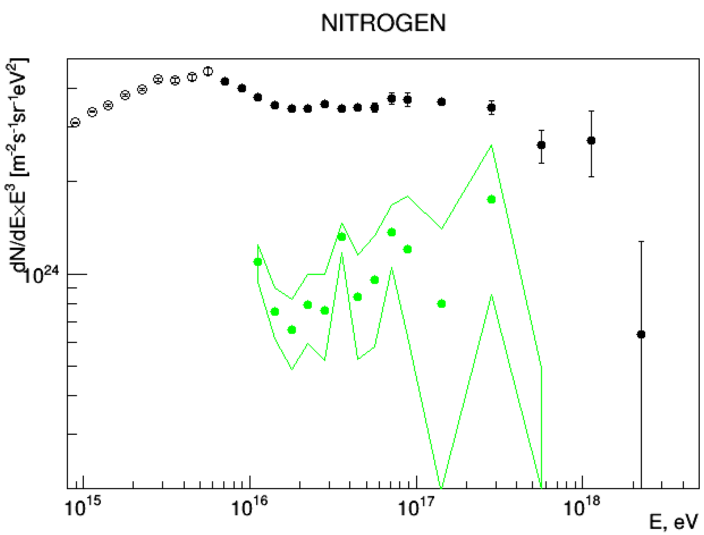


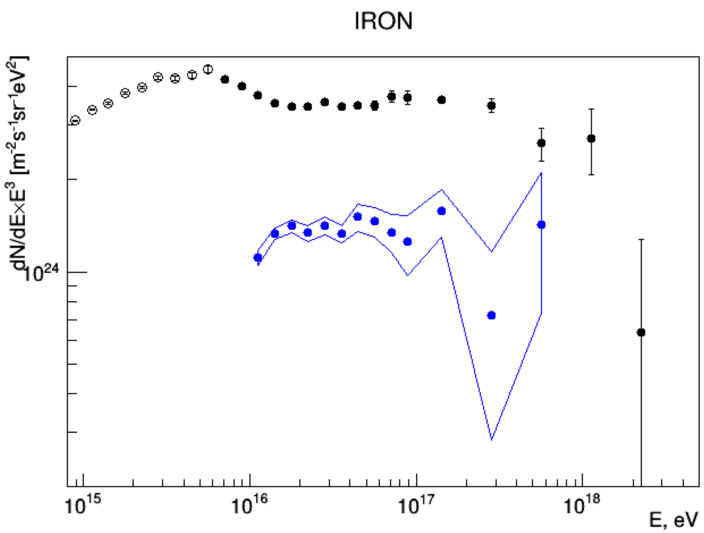


Elemental spectra: results



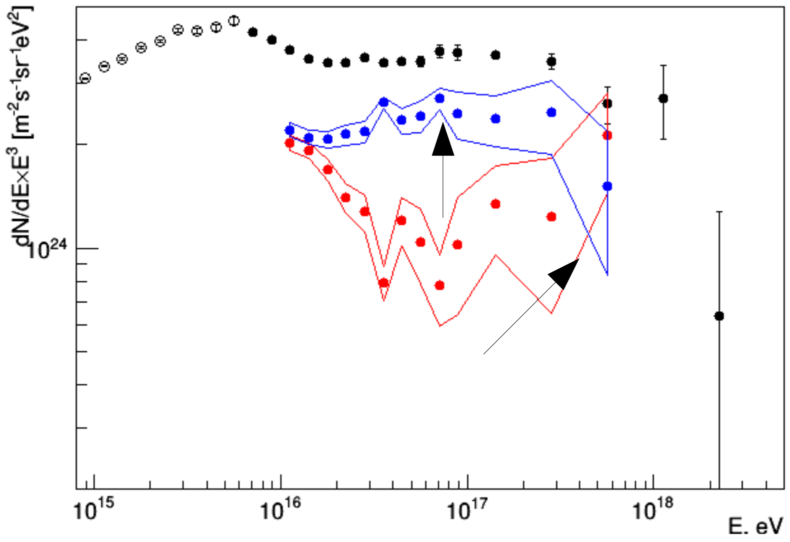


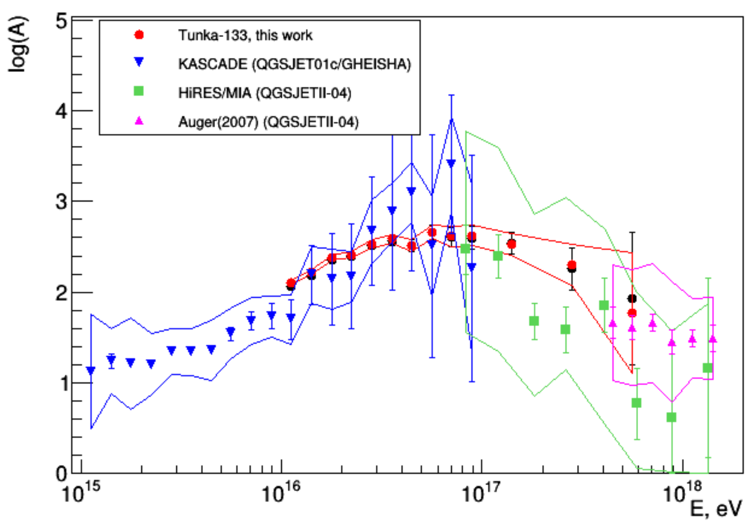


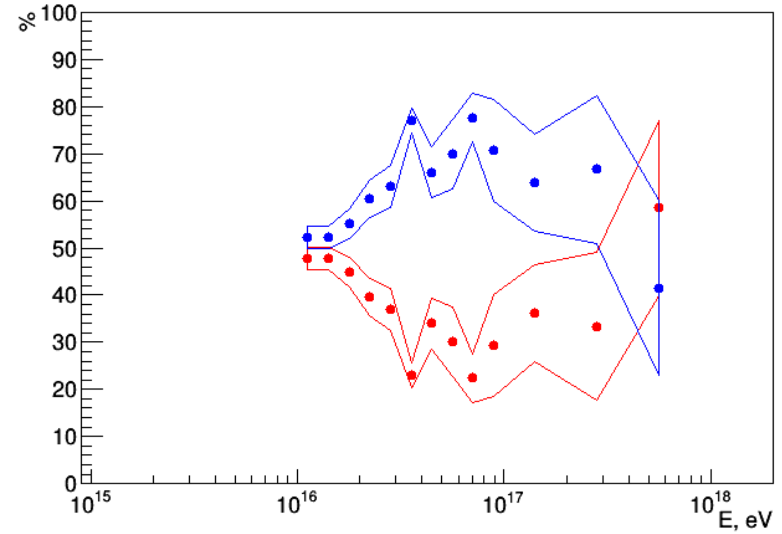


Light and heavy components

- The heavy component (N+Fe) has a break at 10^{17} eV, reaching a fraction value of 80%
- The light component starts to rise again above 10^{17} eV
- Up to now we cannot confirm the sharp decrease of <ln A> seen by KASCADE and the high <ln A> at 10^{17} eV







Main sources of systematic uncertainties

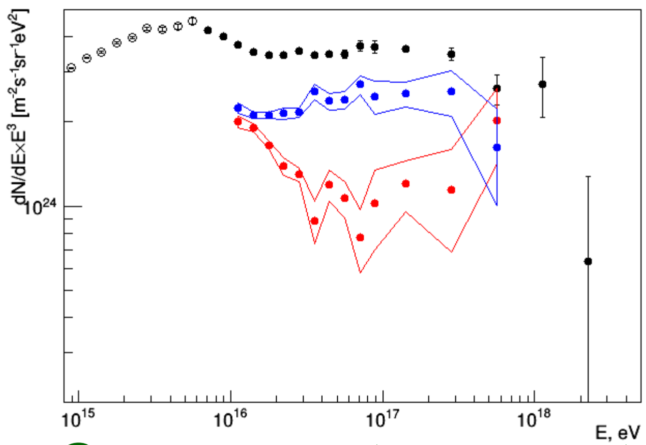
- X_{max} resolution

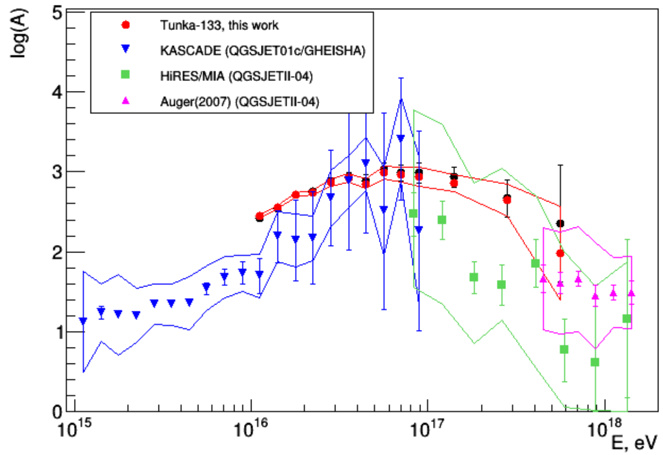
  Comparison both b- and τ- methods not fully correct because they have different behavior with energy → Solution: the chessboard method

- Absolute X_{max} calibration. Waiting for results of “low-energy” extensions TALE and HEAT (was presented at ICRC2015). Possible difficulties (!): the shift can be not a constant

Absolute X_{max} calibration

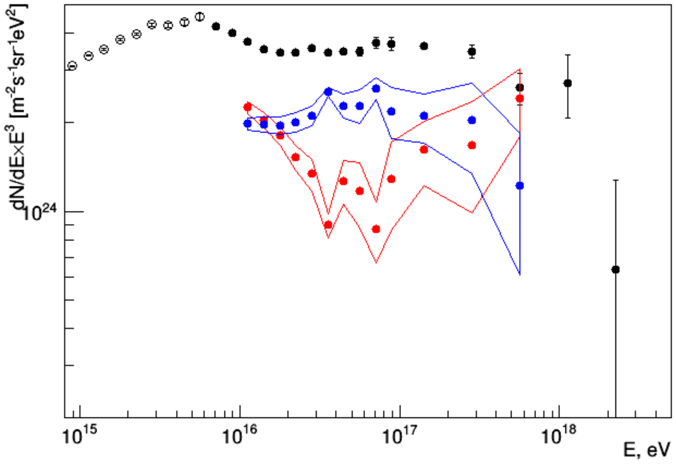
-10 g/cm²

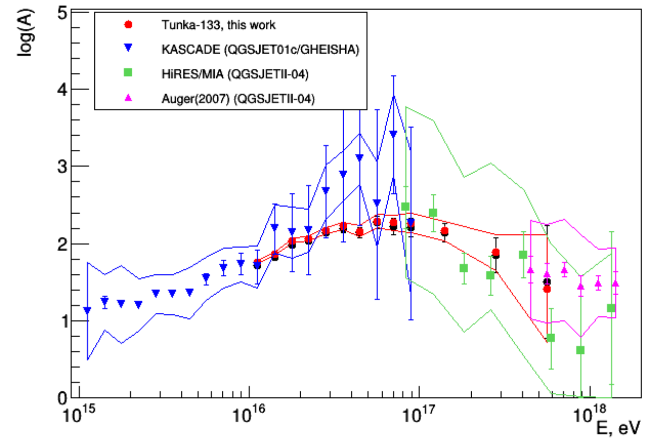




Components are not affected. Only the logarithm.

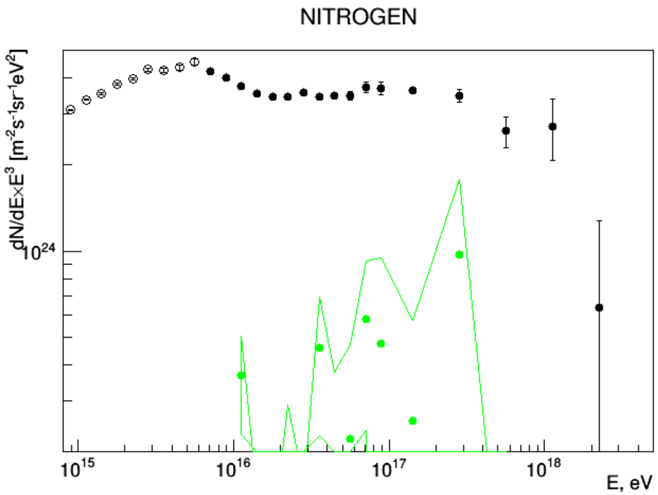
+10 g/cm²

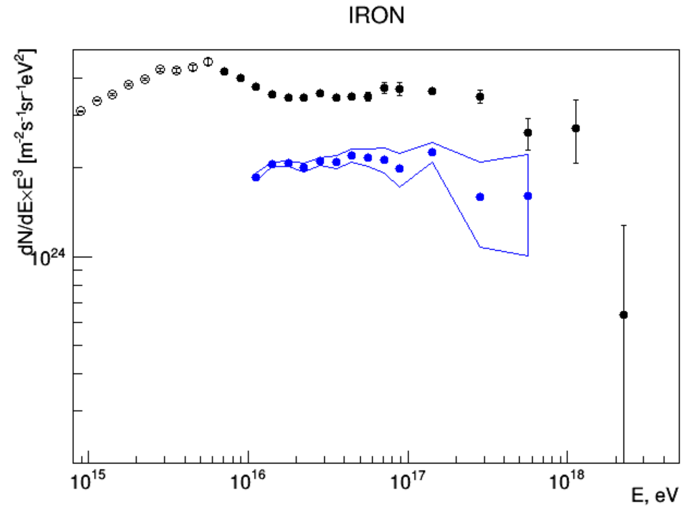




Absolute X_{max} calibration

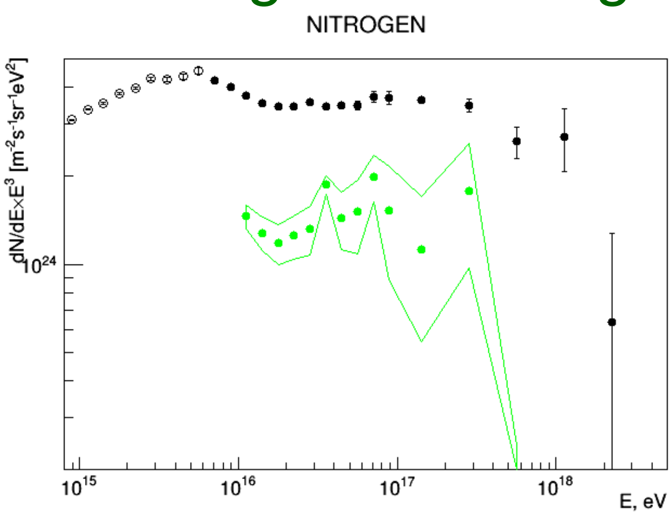
-10 g/cm^2

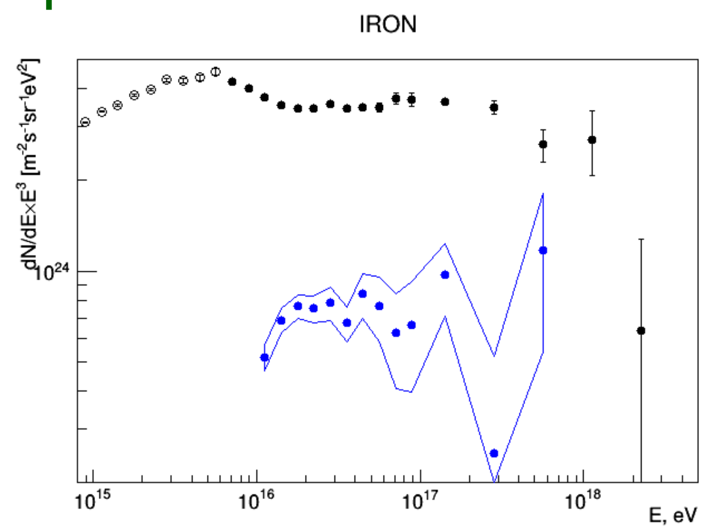




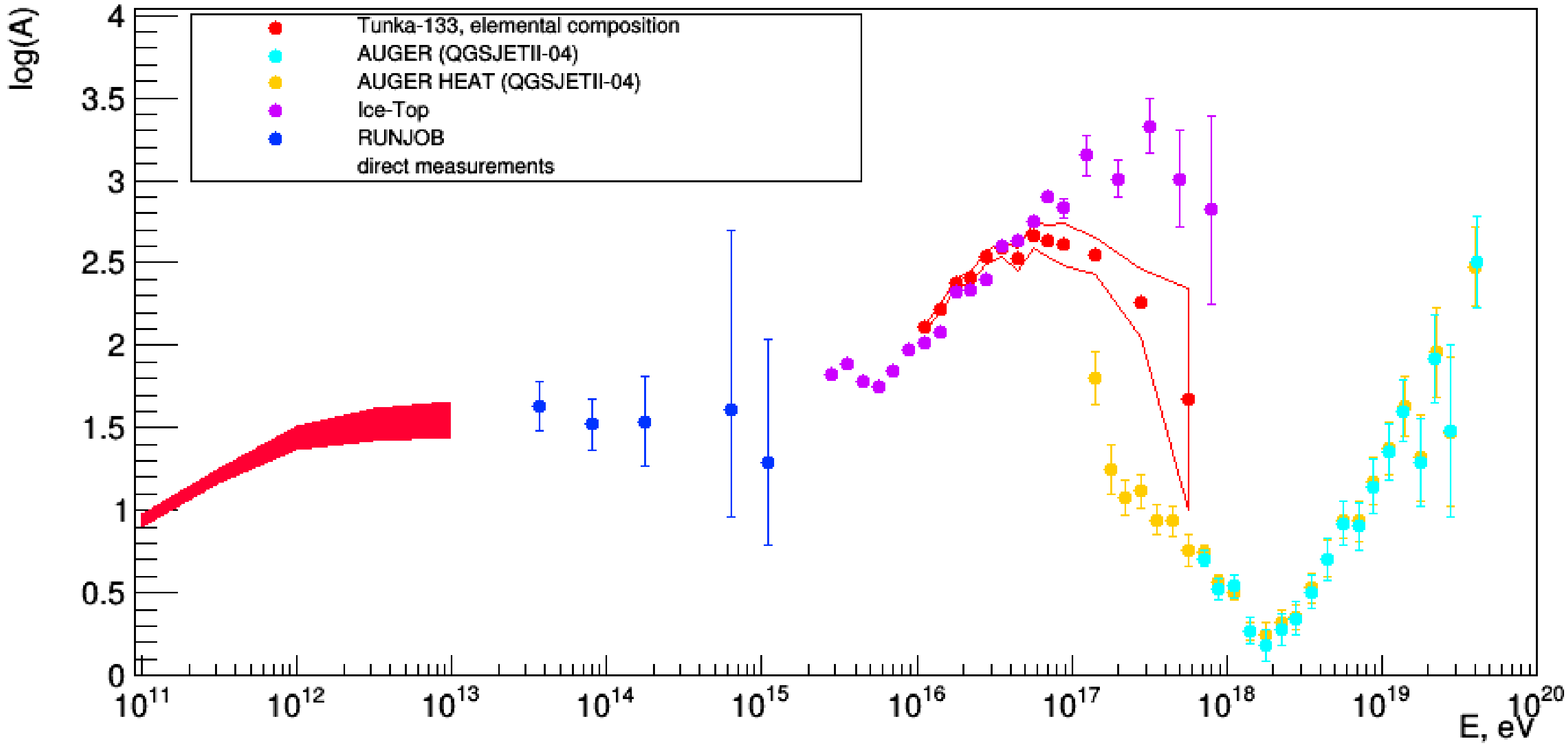
Exchange between groups N ↔ Fe and H ↔ He

+10 g/cm^2



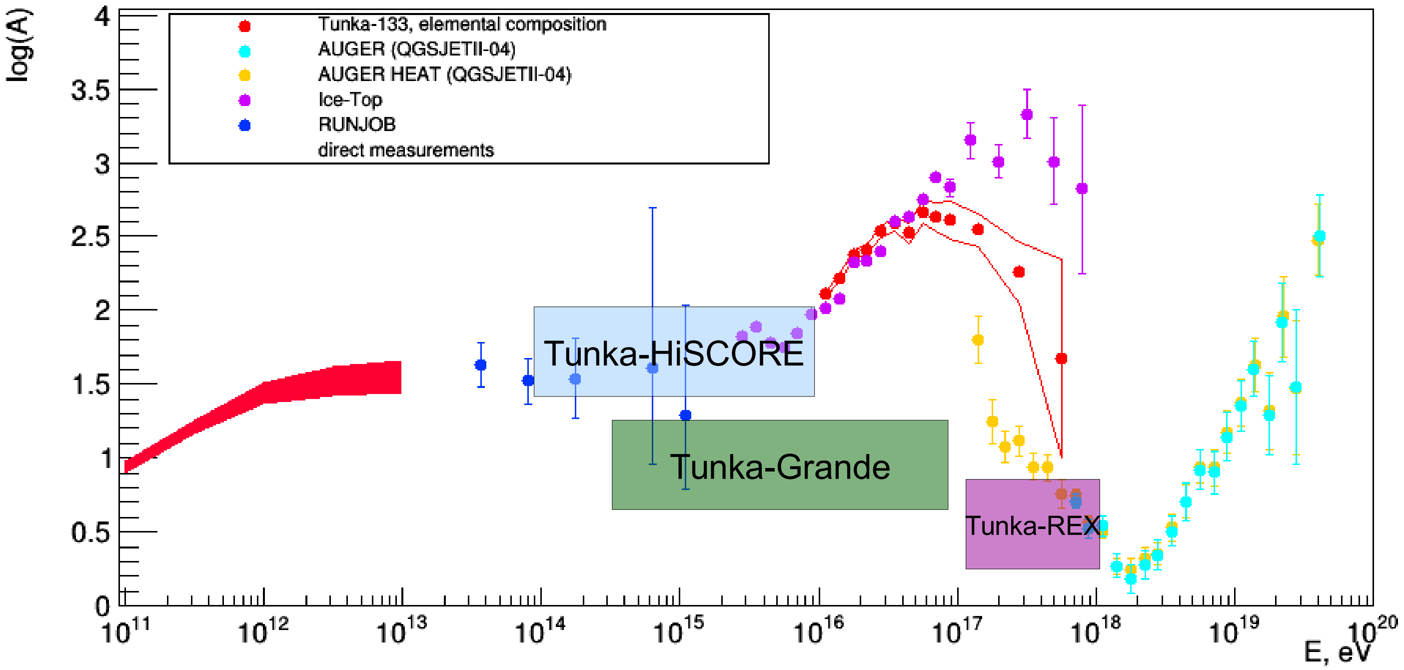


Most recent data. Where are we?



- T-133 and HEAT ?
- T-133 and Ice-Top ?

Tunka perspectives: Mass composition aspect



- Tunka Valley now is a host for a complex experiment **TAIGA** (**T**unka **A**dvanced **I**nternational **G**amma-ray and **C**osmic ray **A**strophysics): Tunka-Grande, Tunka-HiSCORE, Tunka-IACT. One more sensitive to X_{max} instrument Tunka-Rex. Elemental composition analysis can be automatically applied to new data.

Thank you!