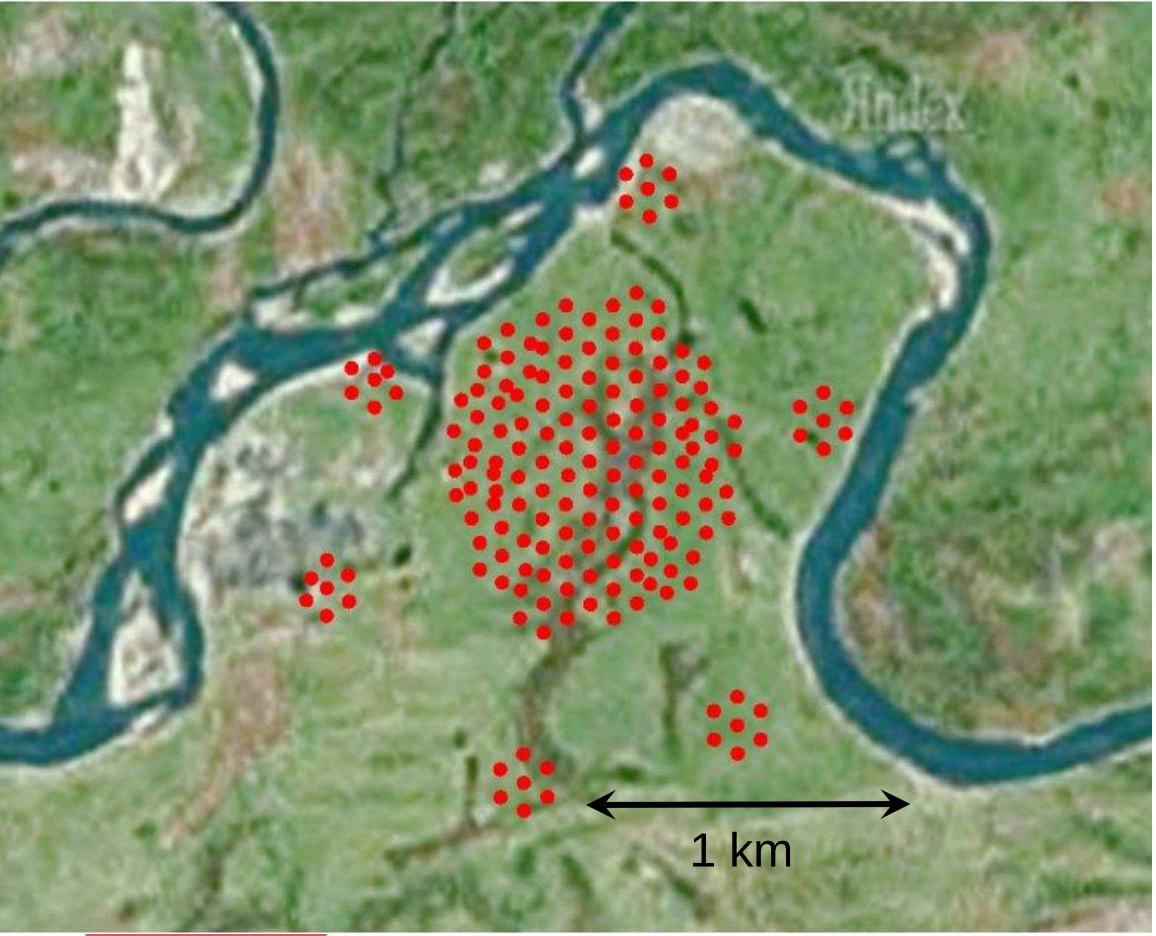
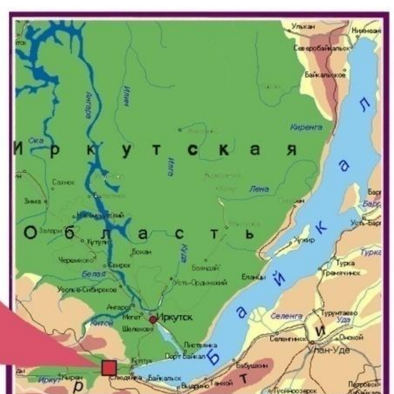
Results and Perspectives of the Tunka Experiments for Cosmic Ray Study.

Vasily Prosin (Skobeltsyn Institute of Nuclear Physics MSU, MOSCOW)

For the Tunka and TAIGA Collaborations

CRIS-2015, 14 – 16 of September 2015





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

Tunka Valley

Republic Buryatia

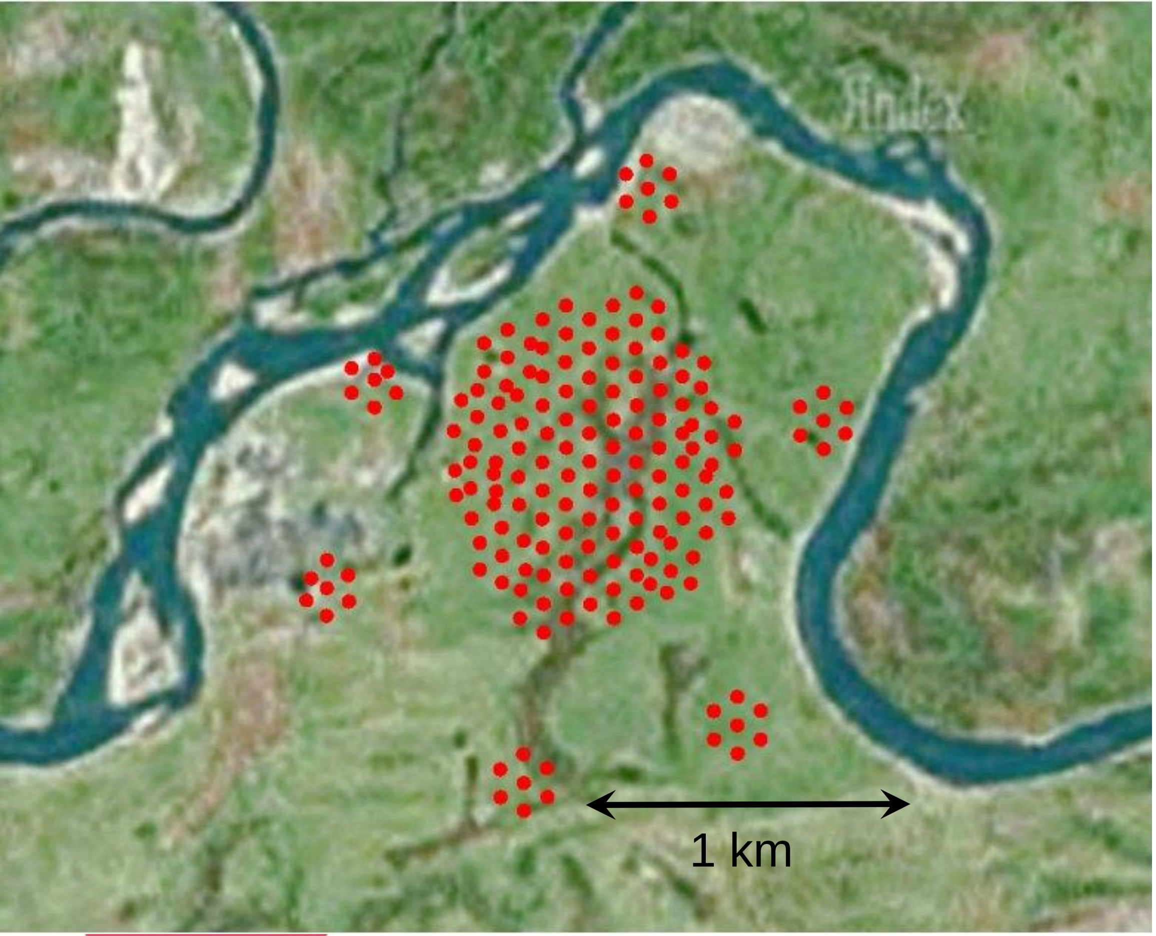
150 km from Irkutsk

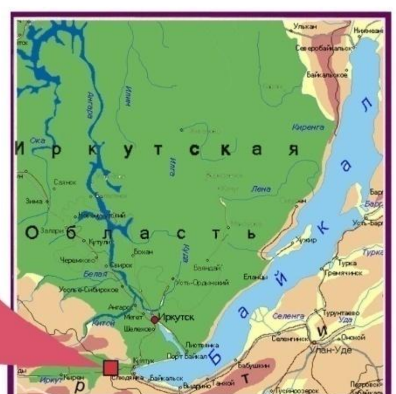
50 km from the shore of lake Baikal


ТУНКИНСКИЙ РАЙОН
НАЦИОНАЛЬНЫЙ ПАРК

EXPERIMENTS
in Tunka Valley

Tunka-133

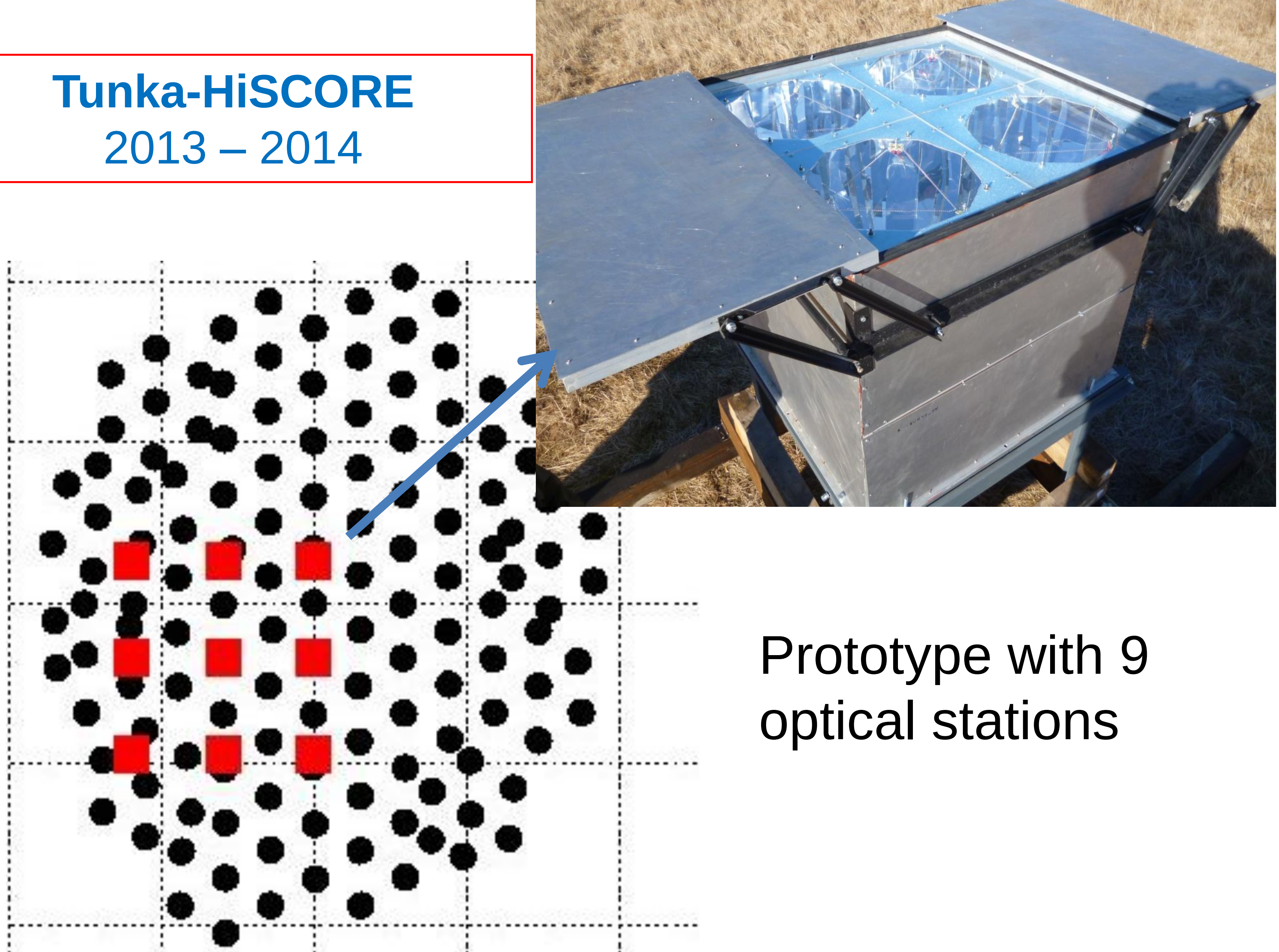




51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

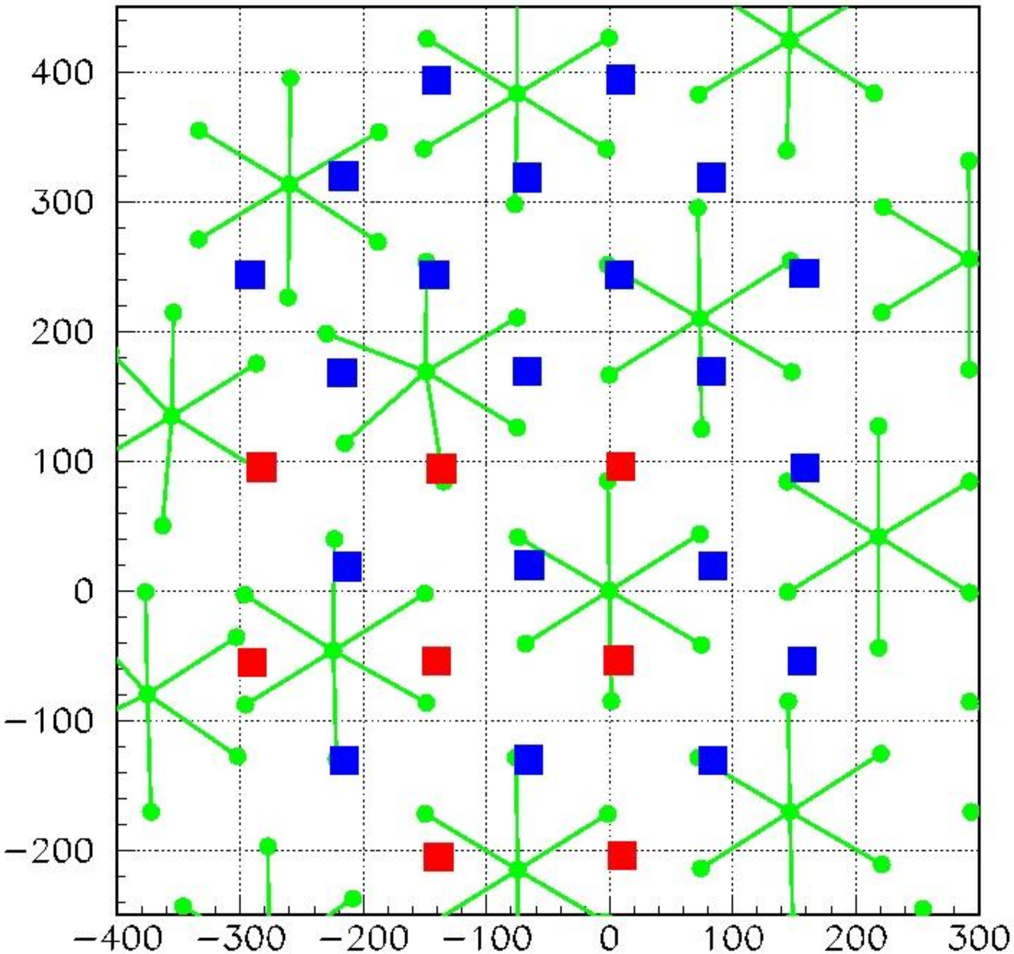
175 optical detectors
EMI 9350 and HAMAMATSU Ø 20 cm

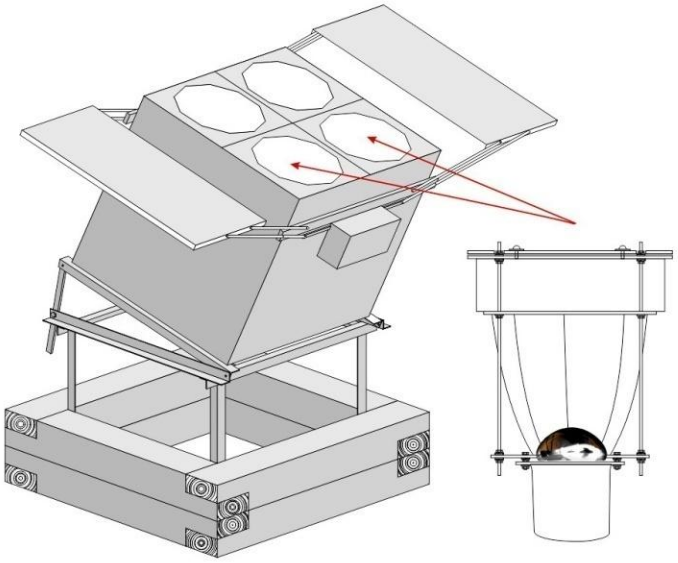
Tunka-HiSCORE
2013 – 2014



Prototype with 9 optical stations

Tunka-HiSCORE (2015-2016) – 28 stations





All the stations will be tilted for 25° to the South for observation of Crab Nebulae

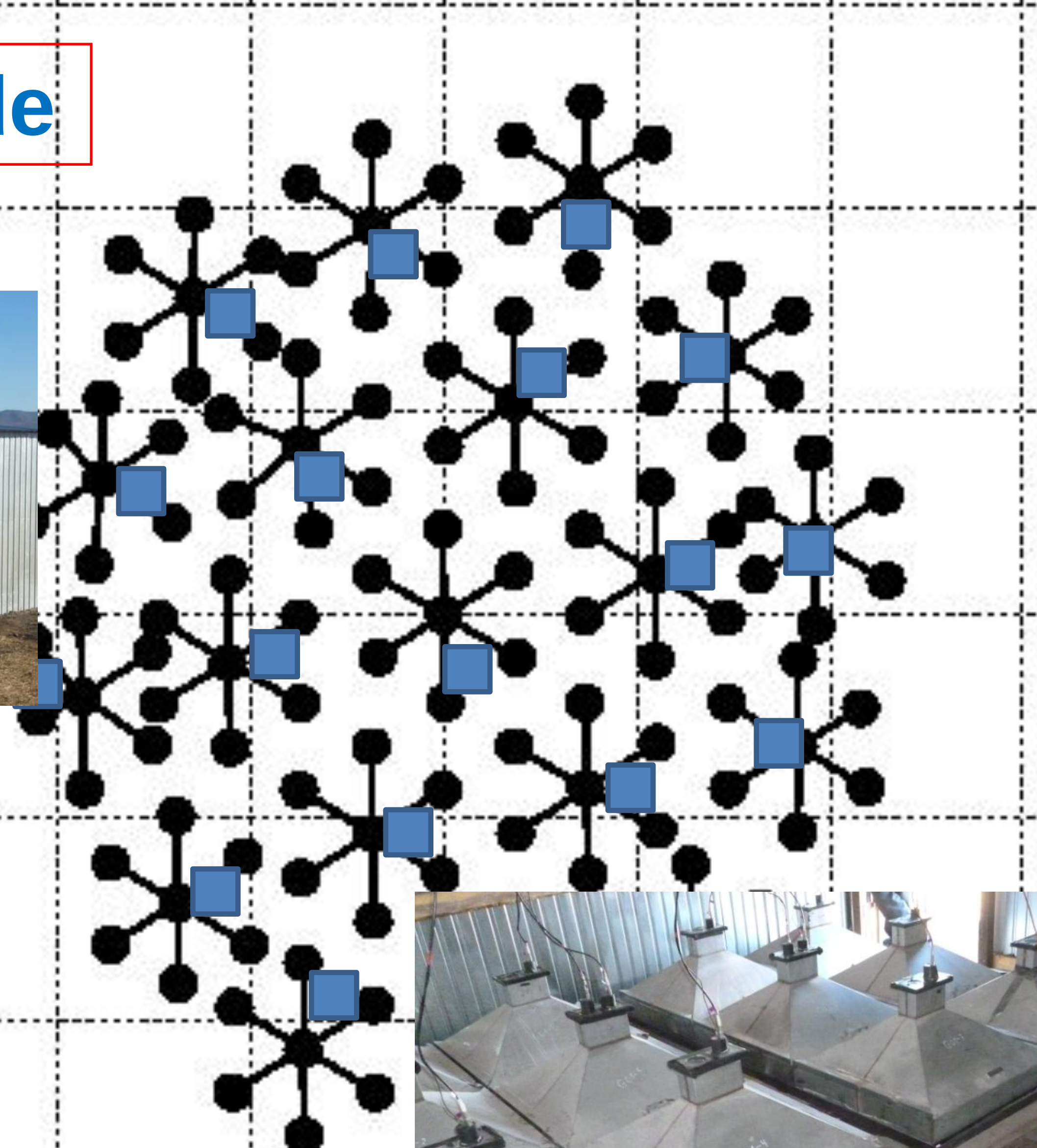
About 20-60 γ-events from Crab are expected during 100 h of observation.

Tunka-REX

Connection of 2 antennas to
2 free channels of FADC

38 antennas are situated at the area of 1 km^2 now.

Tunka-Grande



19 stations

228 detectors (0.64 m^2) on the surface

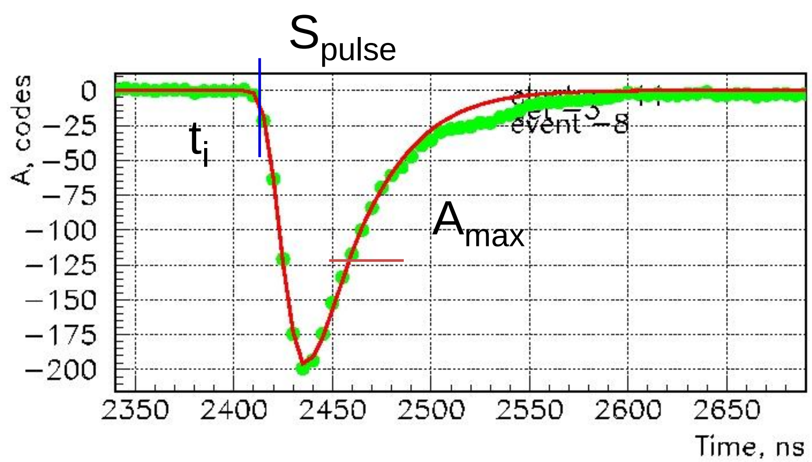
152 detectors undeground (muons detectors), total area = 100 m^2

Tunka-133 data processing

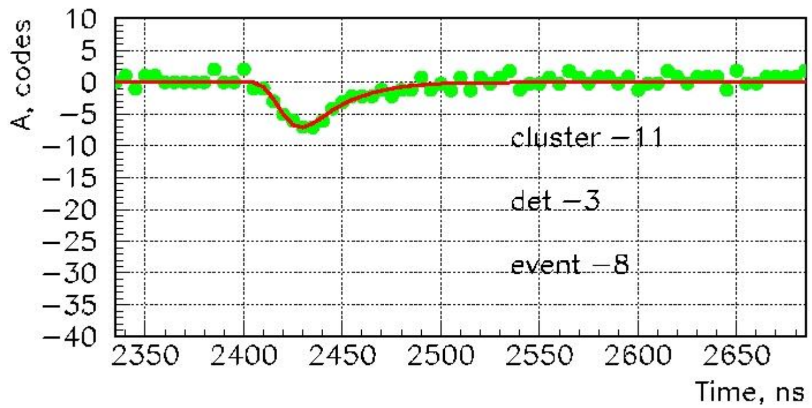
Tunka-133 Single detector readout:
Fitting of the pulse and measuring of the parameters: $Q=c \cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

Time step = 5 ns

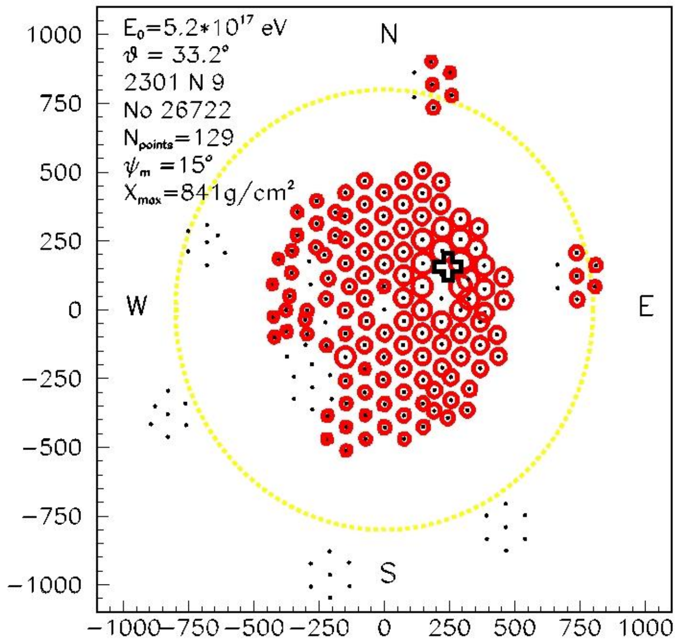
anode:



dynode:

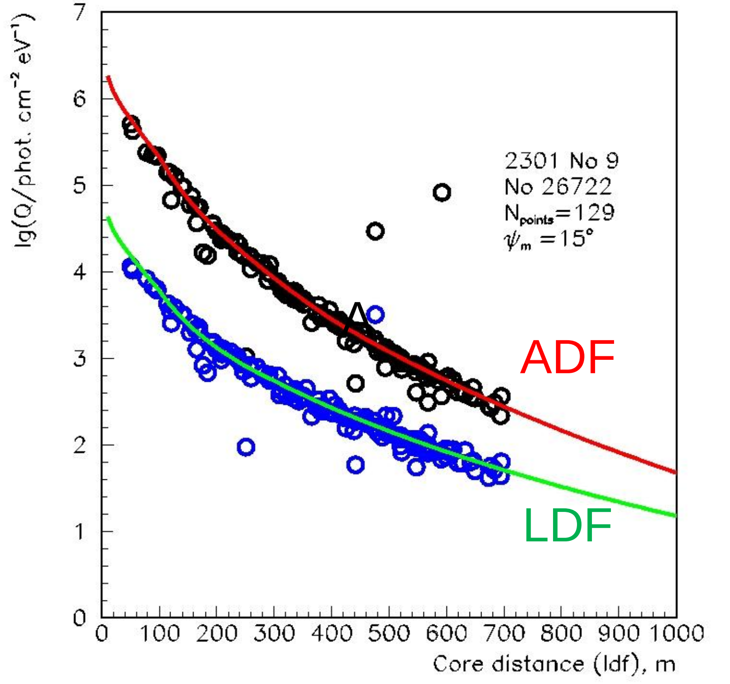


Single event example

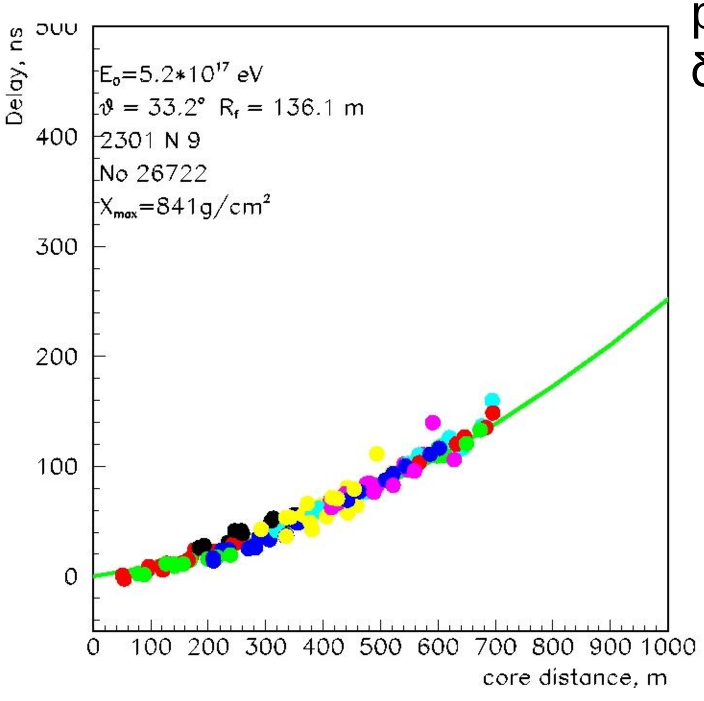


Plan

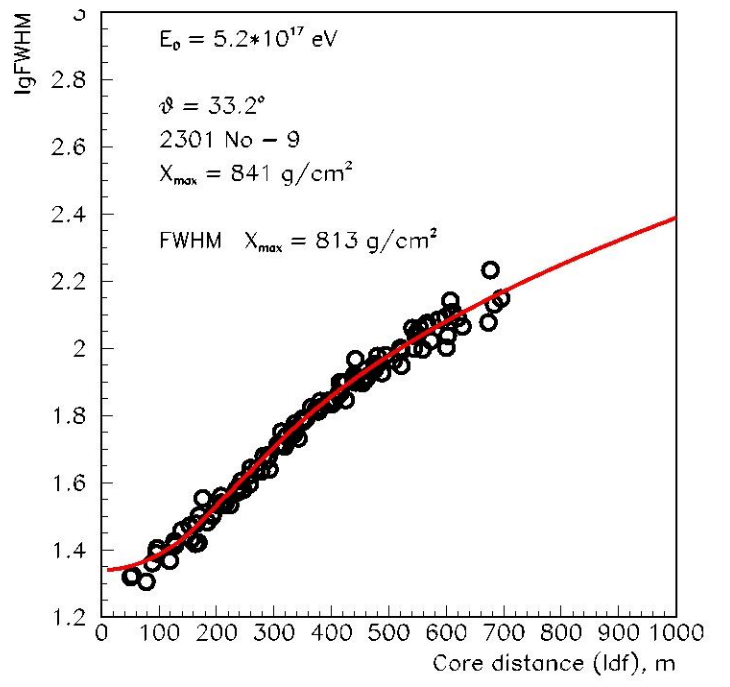
ADF and LDF



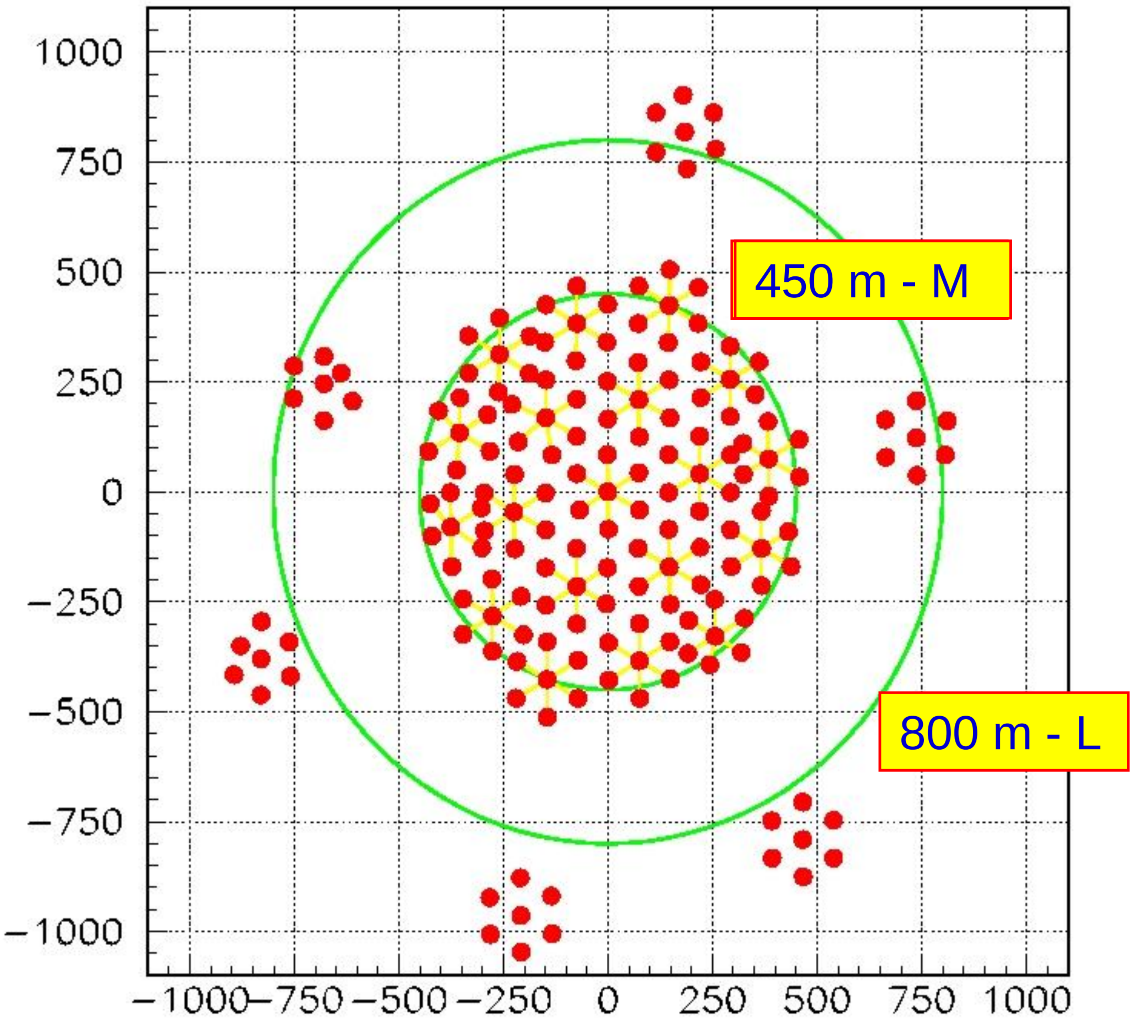
Curve
EAS time front
provides
$\delta\theta<0.5°$



τ_{eff} vs. core distance



Effective areas



Tunka-133 Experimental Data

5 winter seasons: 2009-2010 , 2010-2011, 2011-2012, 2012-2013, 2013-2014
262 clear moonless nights
~ 1540 h of observation with a trigger frequency ~ 2 Hz
~ 10 000 000 triggers
The cuts for the energy spectrum used:
$\theta \leq 45°$

M: $R_{center} < 450$ m:

~ 270 000 events with $E_0 > 6 \cdot 10^{15}$ eV – 100% efficiency
~ 99 000 events $E_0 > 10^{16}$ eV
~ 4000 events $E_0 > 5 \cdot 10^{16}$ eV
~ 983 events $E_0 > 10^{17}$ eV

L: $R_{center} < 800$ m:

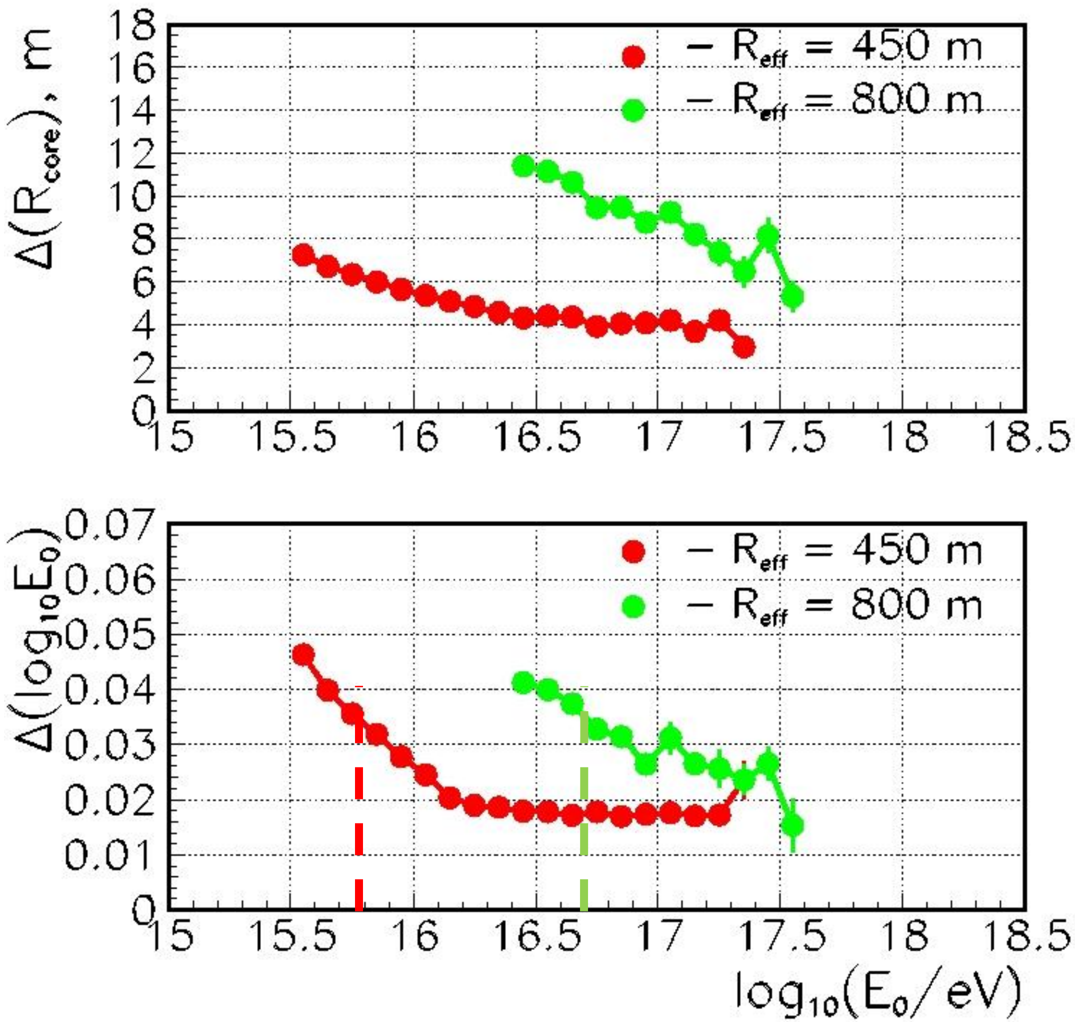
~ 12400 events $E_0 > 5 \cdot 10^{16}$ eV
~ 3000 events $E_0 > 10^{17}$ eV

EAS parameters accuracy: experimental estimations by chessboard method

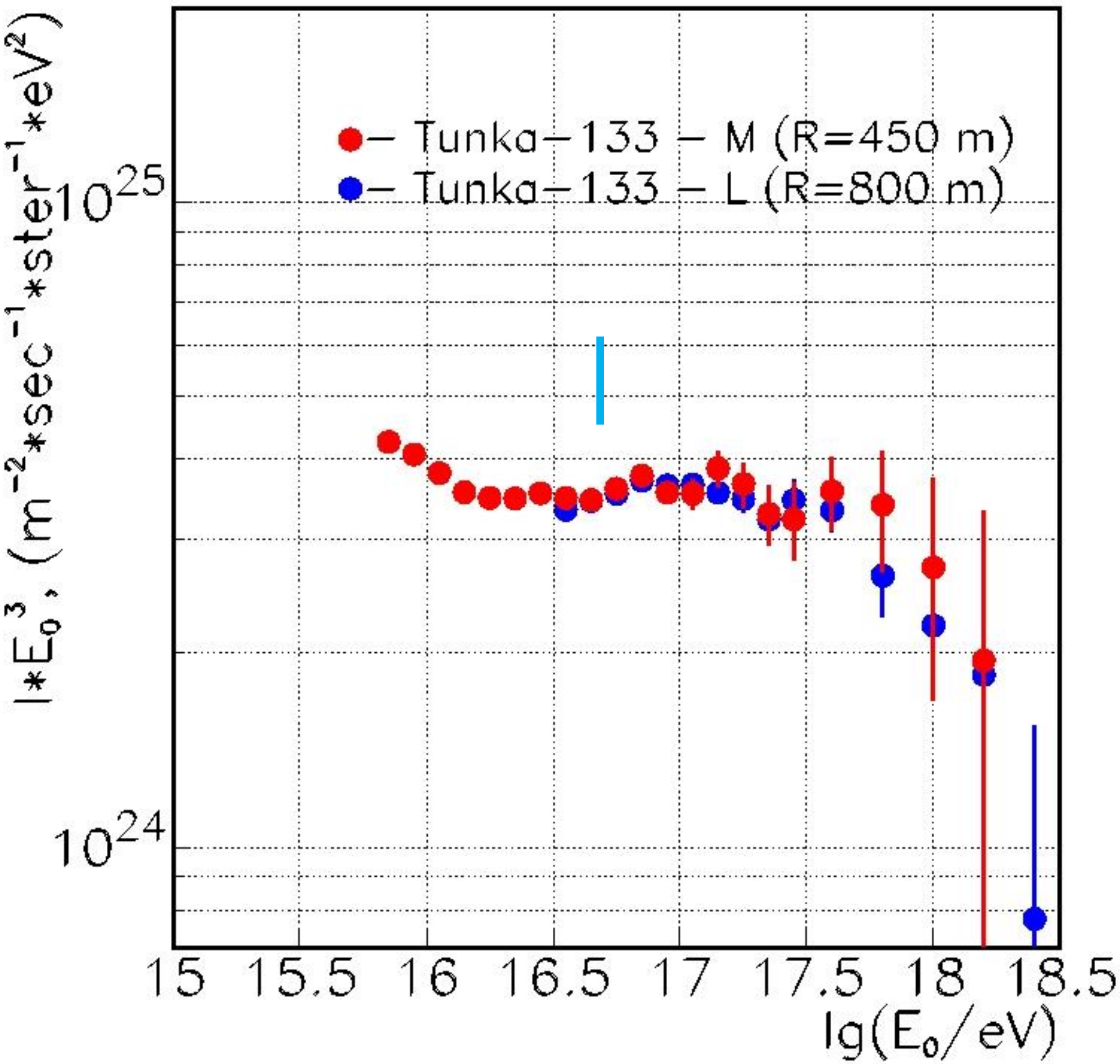
Separation to two sub-arrays:
a) odd detectors
b) even detectors - comparison of EAS parameters:

Error=Difference/√2

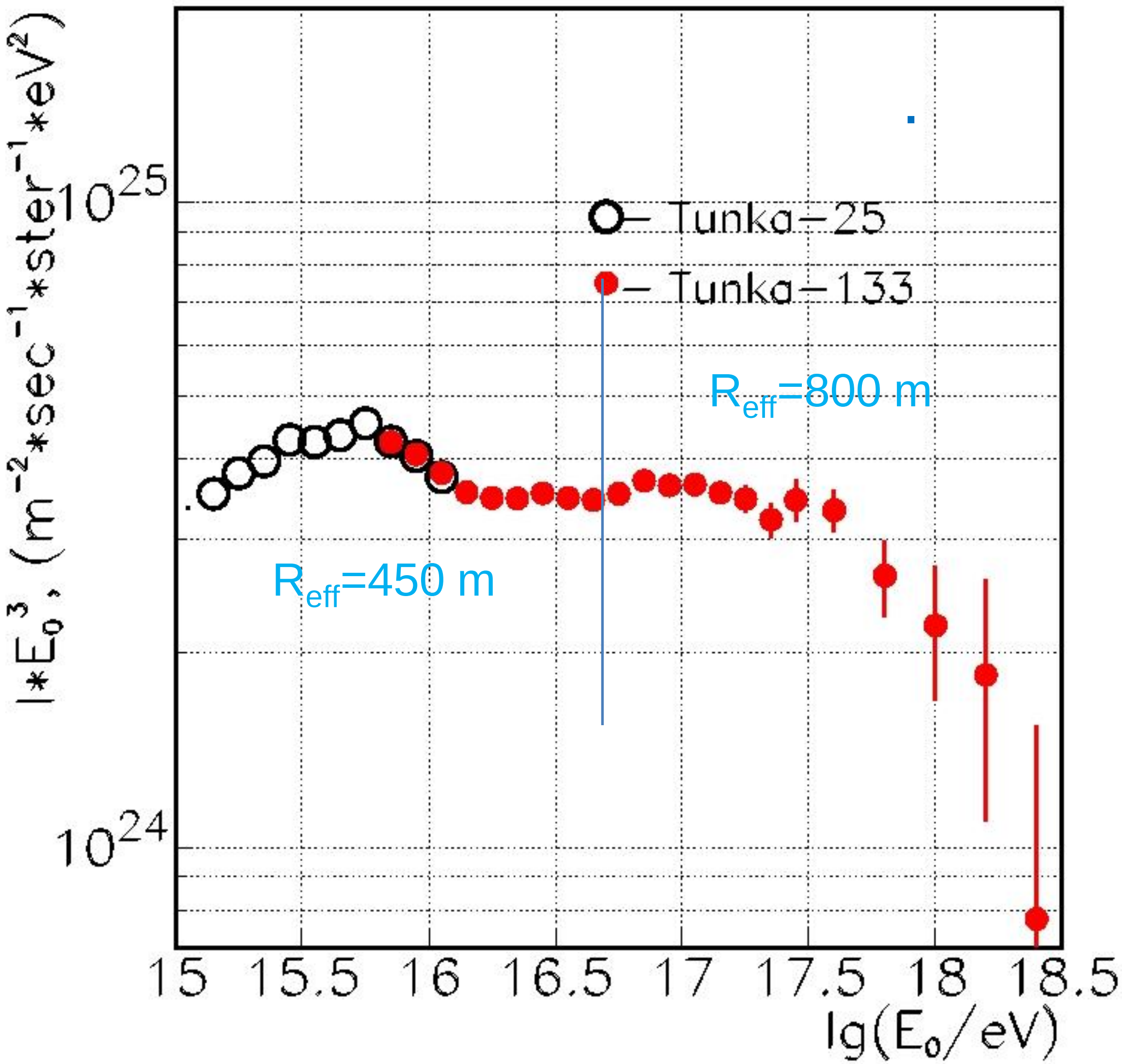
Lines – threshold for spectrum



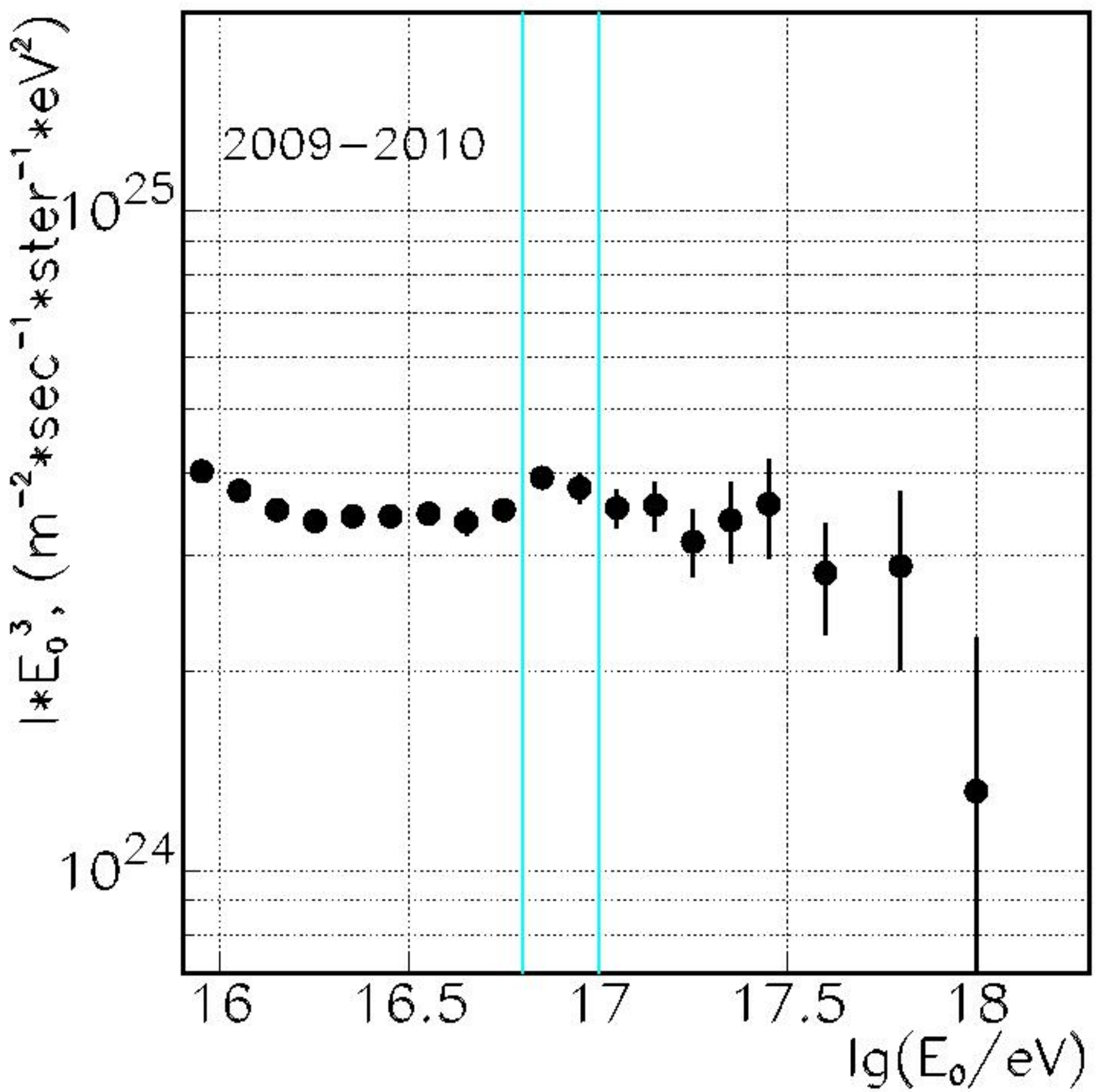
Combined energy spectrum construction



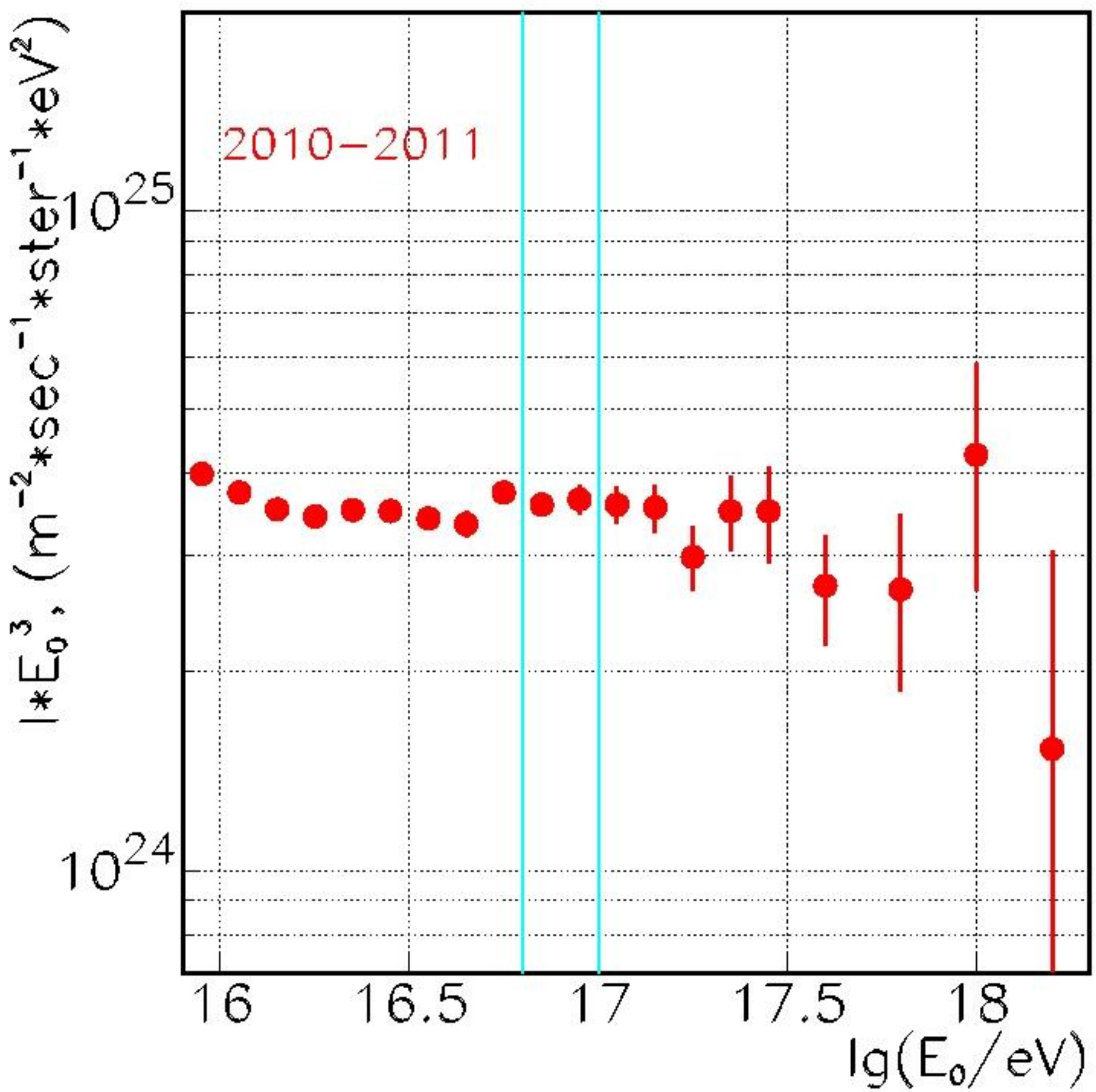
Combined differential primary energy spectrum



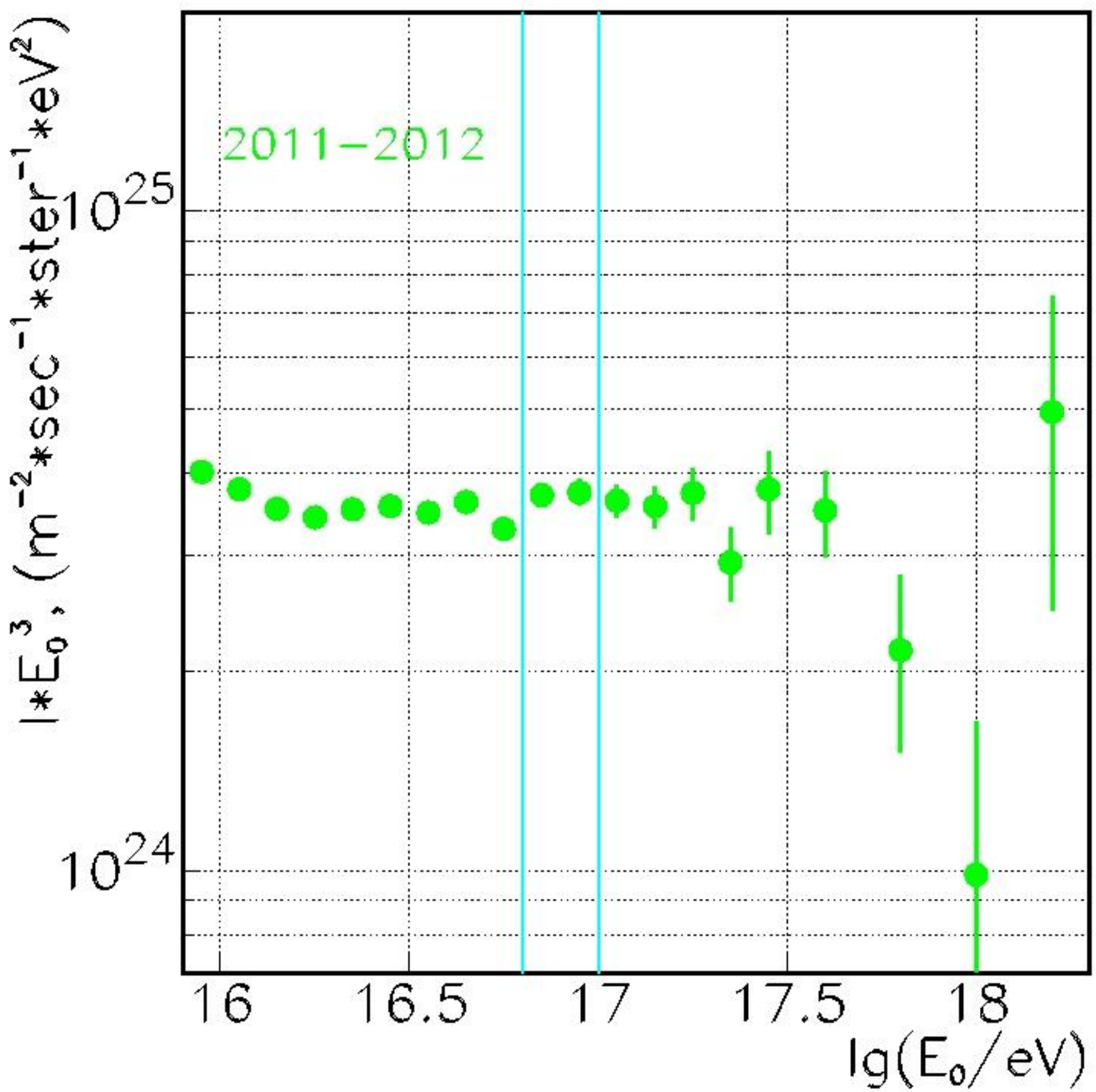
Single year spectrum



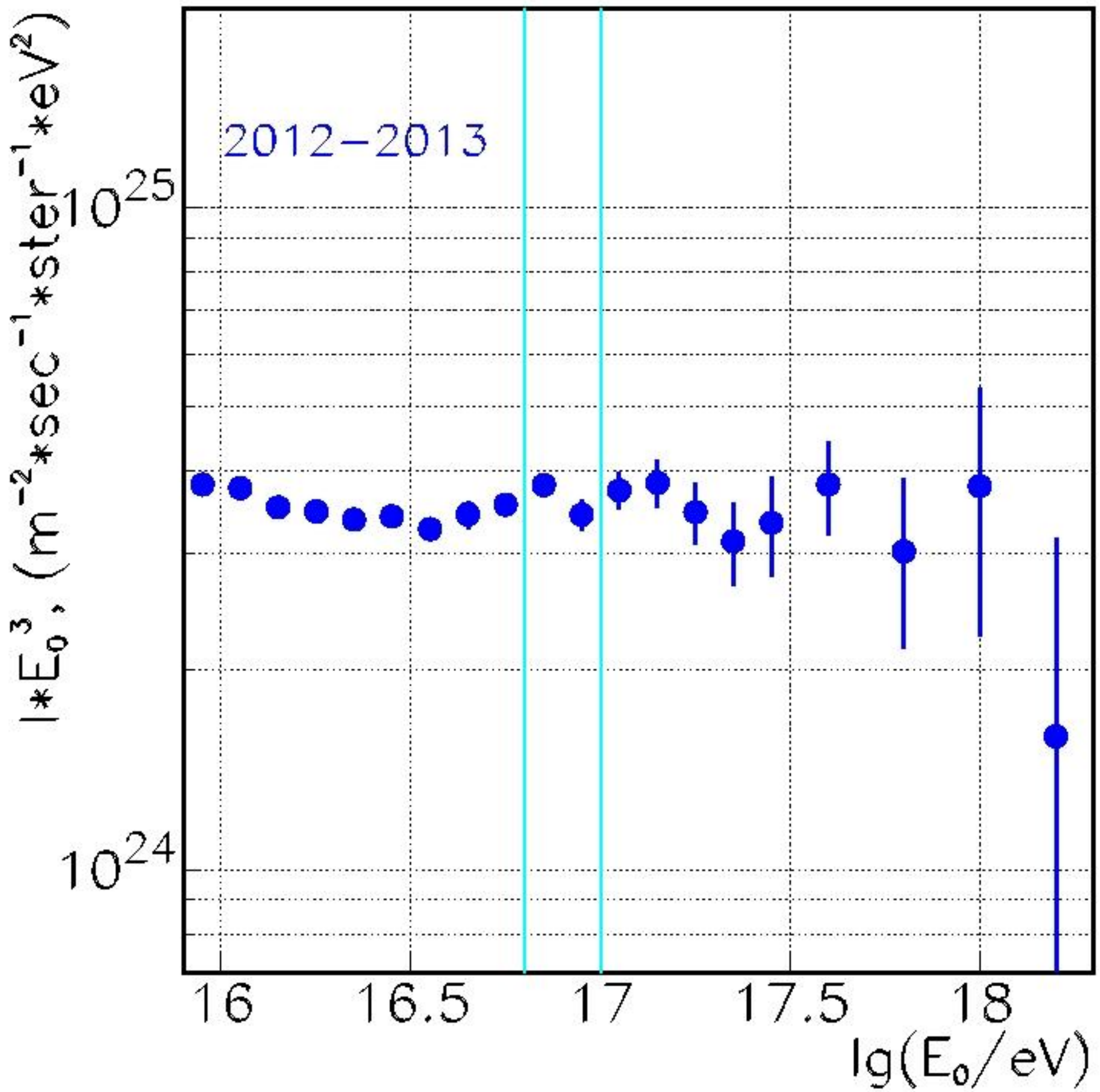
Single year spectrum



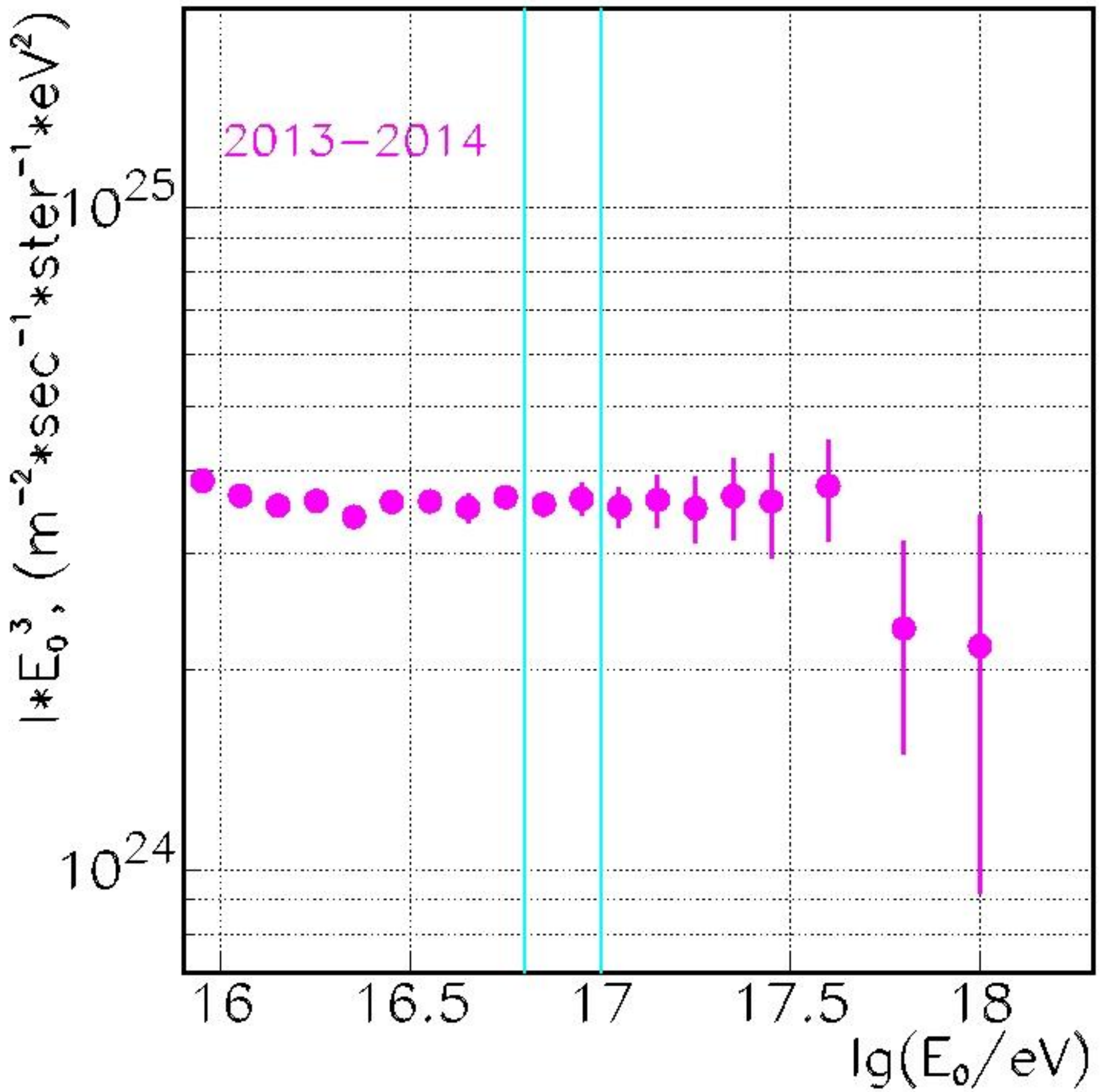
Single year spectrum



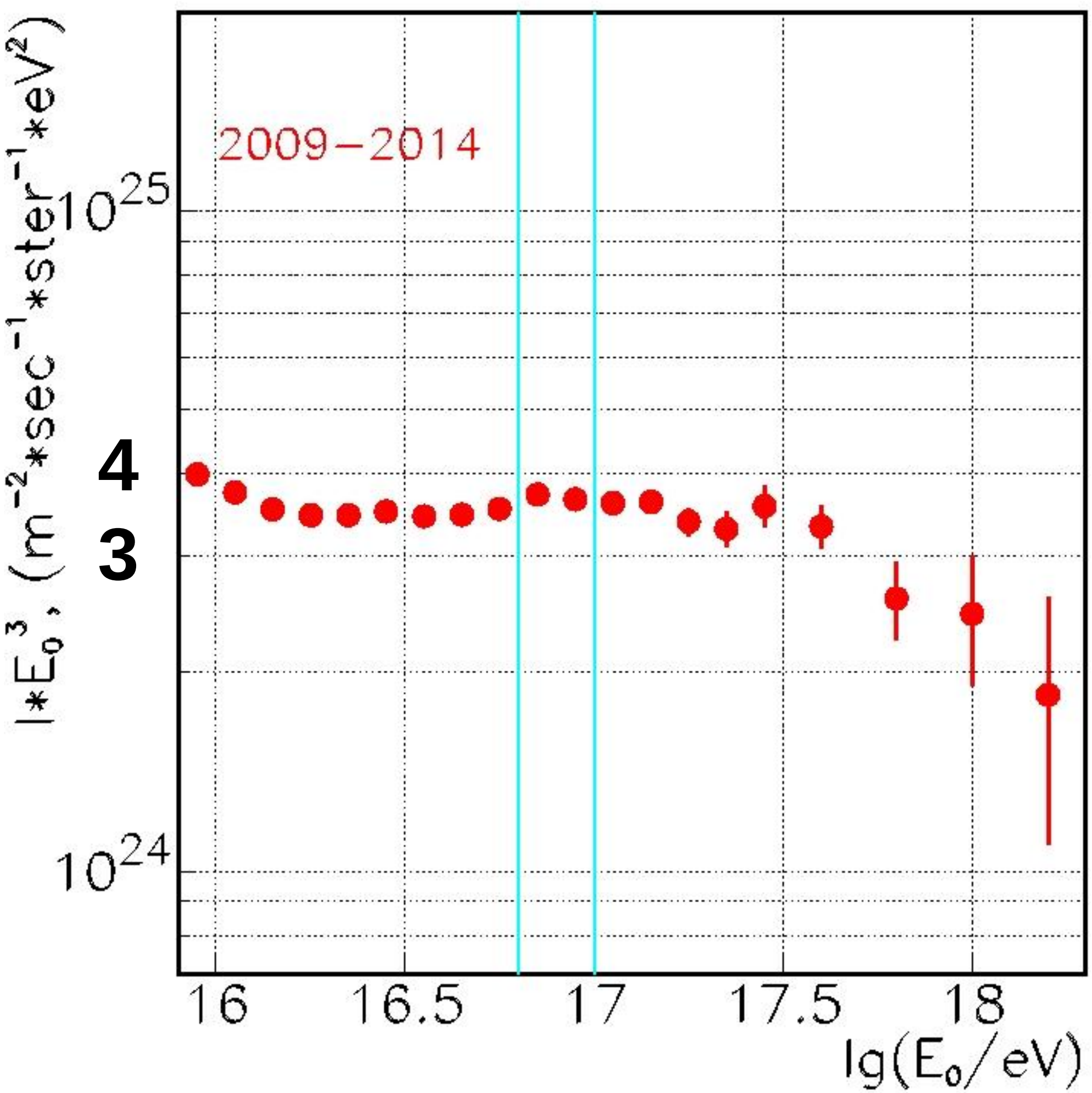
Single year spectrum



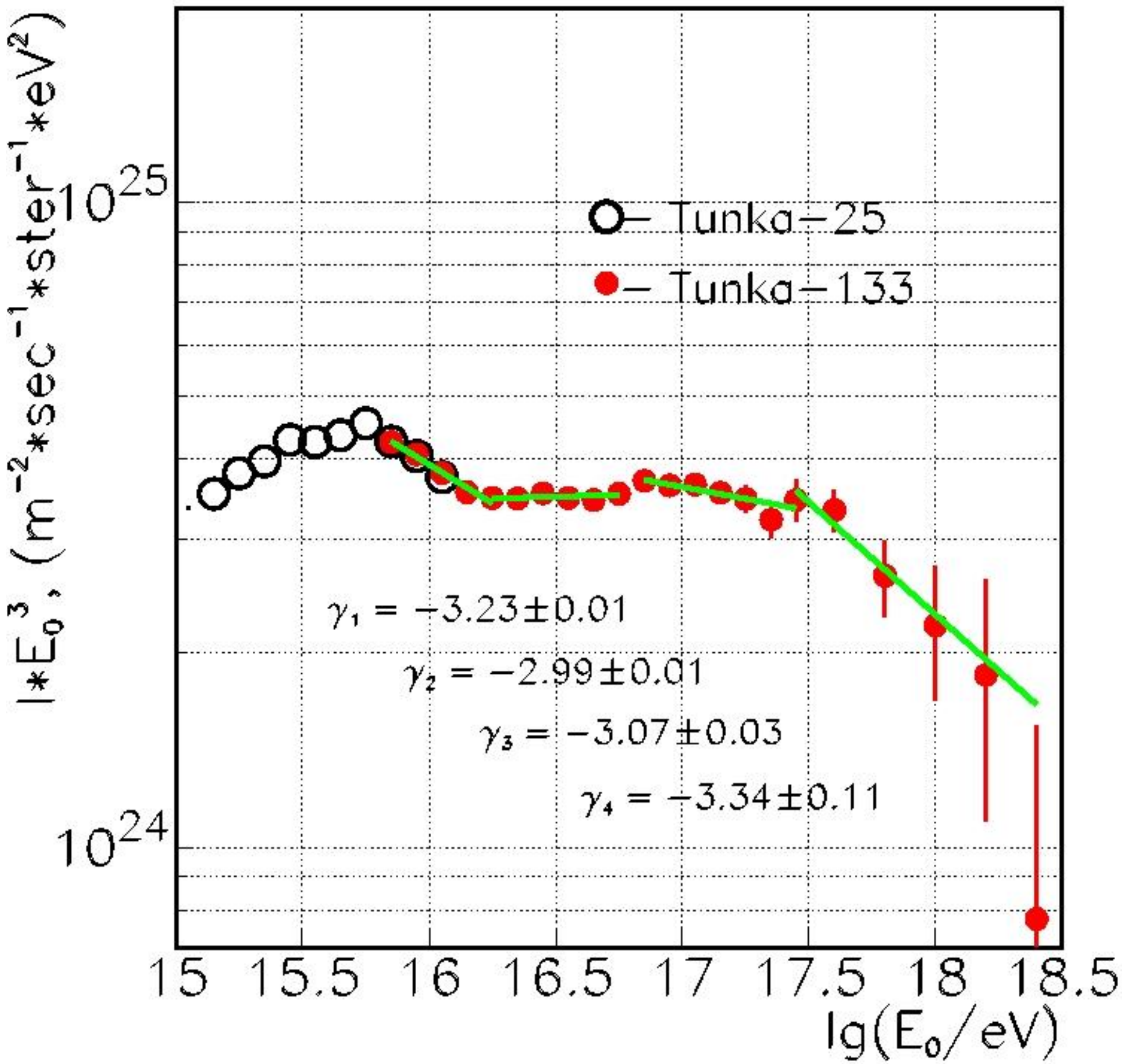
Single year spectrum



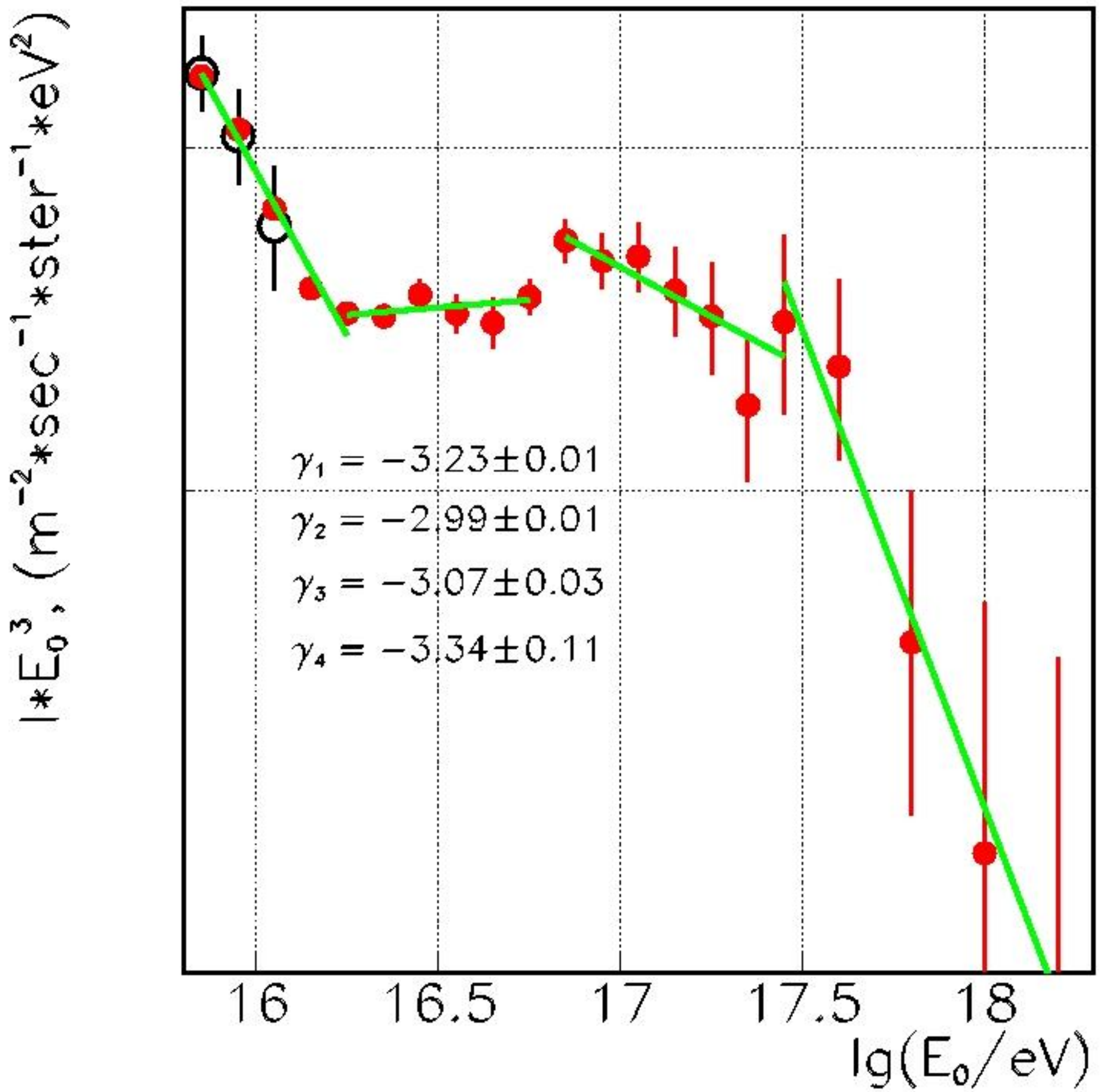
Five years summarized spectrum



Energy spectrum: power law fitting



Structure of the “second” knee



Tunka-HiSCORE data processing

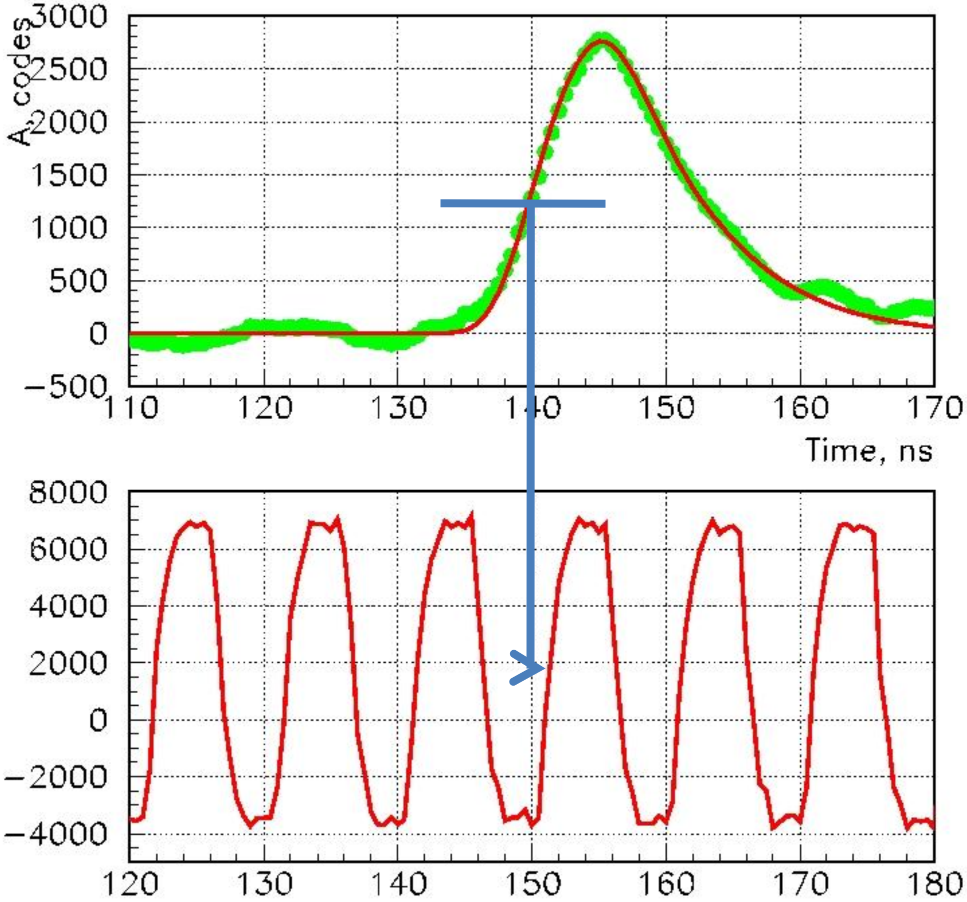
Tunka-HiSCORE record (DRS-4): parameters: $Q=c\cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

Time step = 0.5 ns

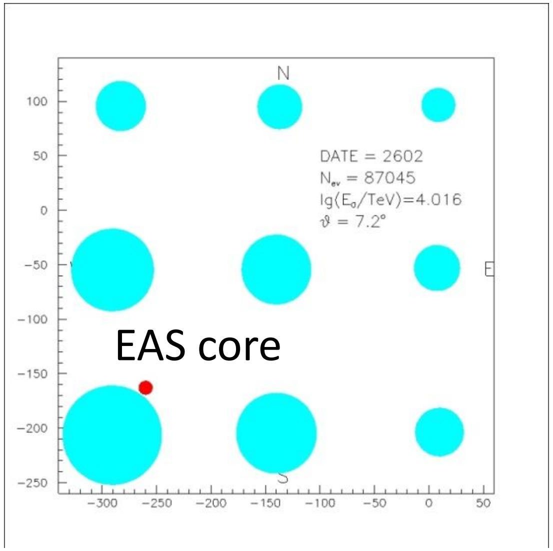
Cerenkov light pulse record

Delay measurement accuracy = 0.2 ns

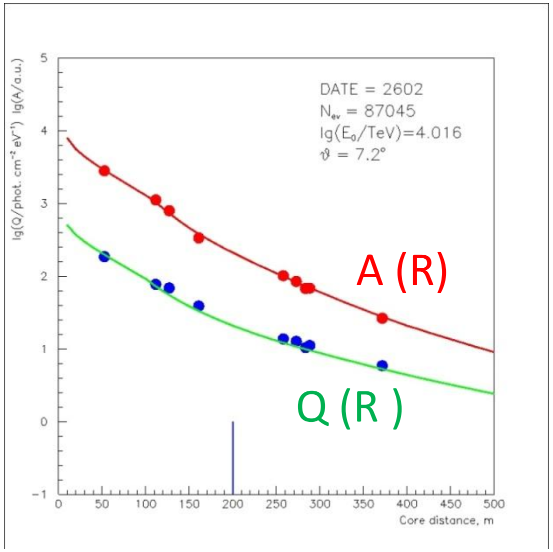
Clock signal 100 MHz

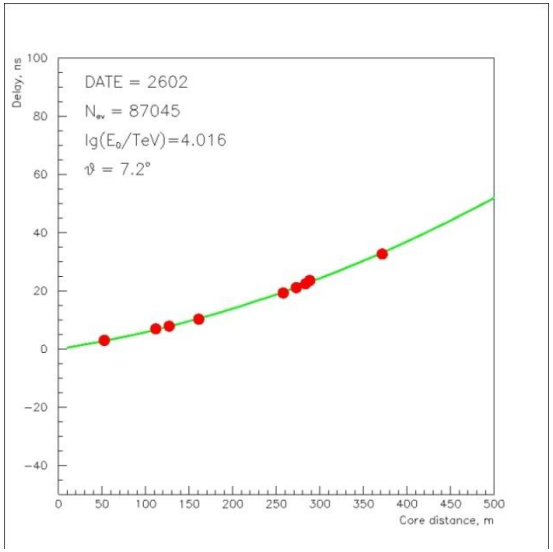


Tunka-HiSCORE event example
Zenith angle = 7.2°
Energy = 10^{16} eV



Shower front





Tunka-HiSCORE Experimental Data

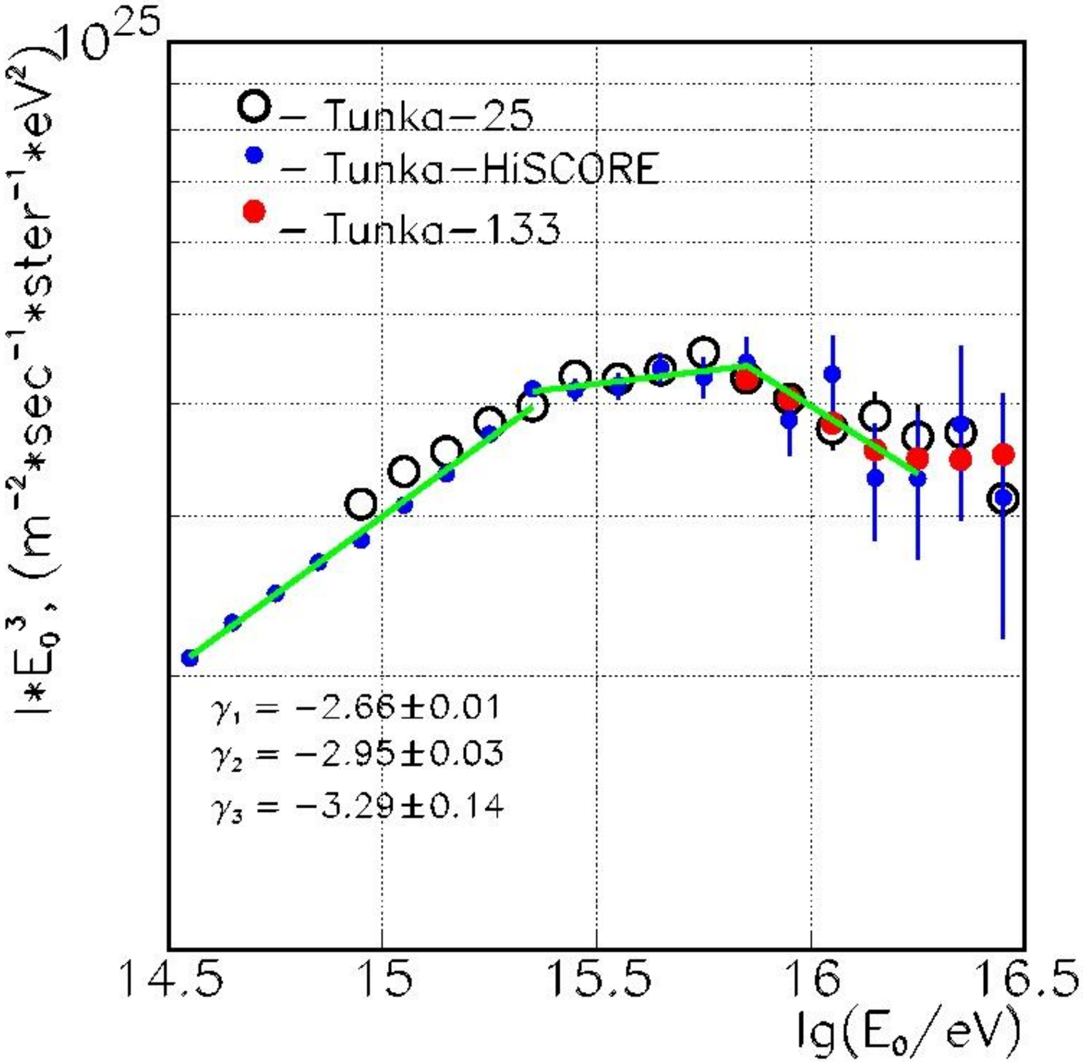
84 h during 13 clean moonless nights in February and March of 2014

~ 145 000 events with $E_0 > 3 \cdot 10^{14}$ eV – 100% efficiency

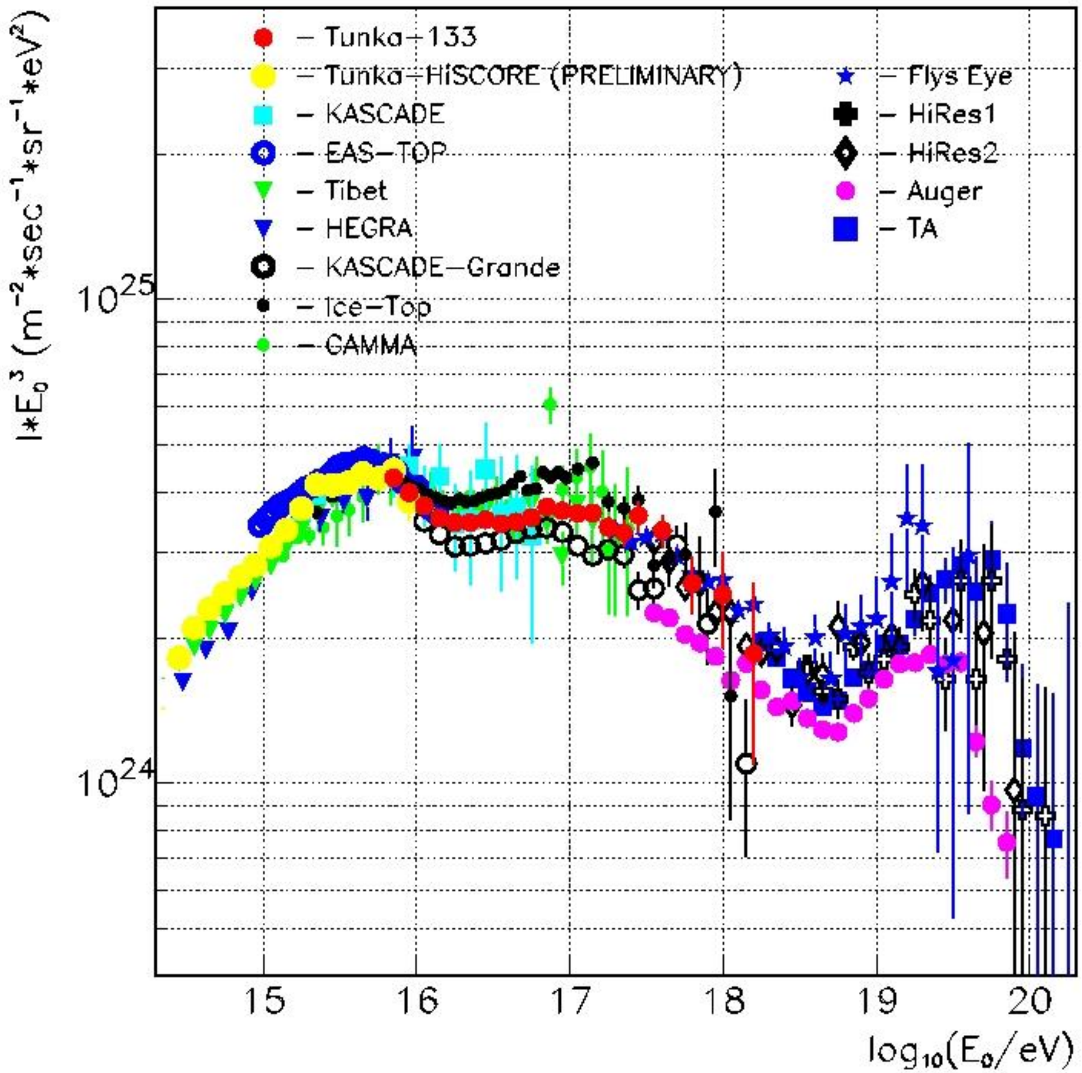
~ 21 000 events $E_0 > 10^{15}$ eV

~ 200 events $E_0 > 10^{16}$ eV

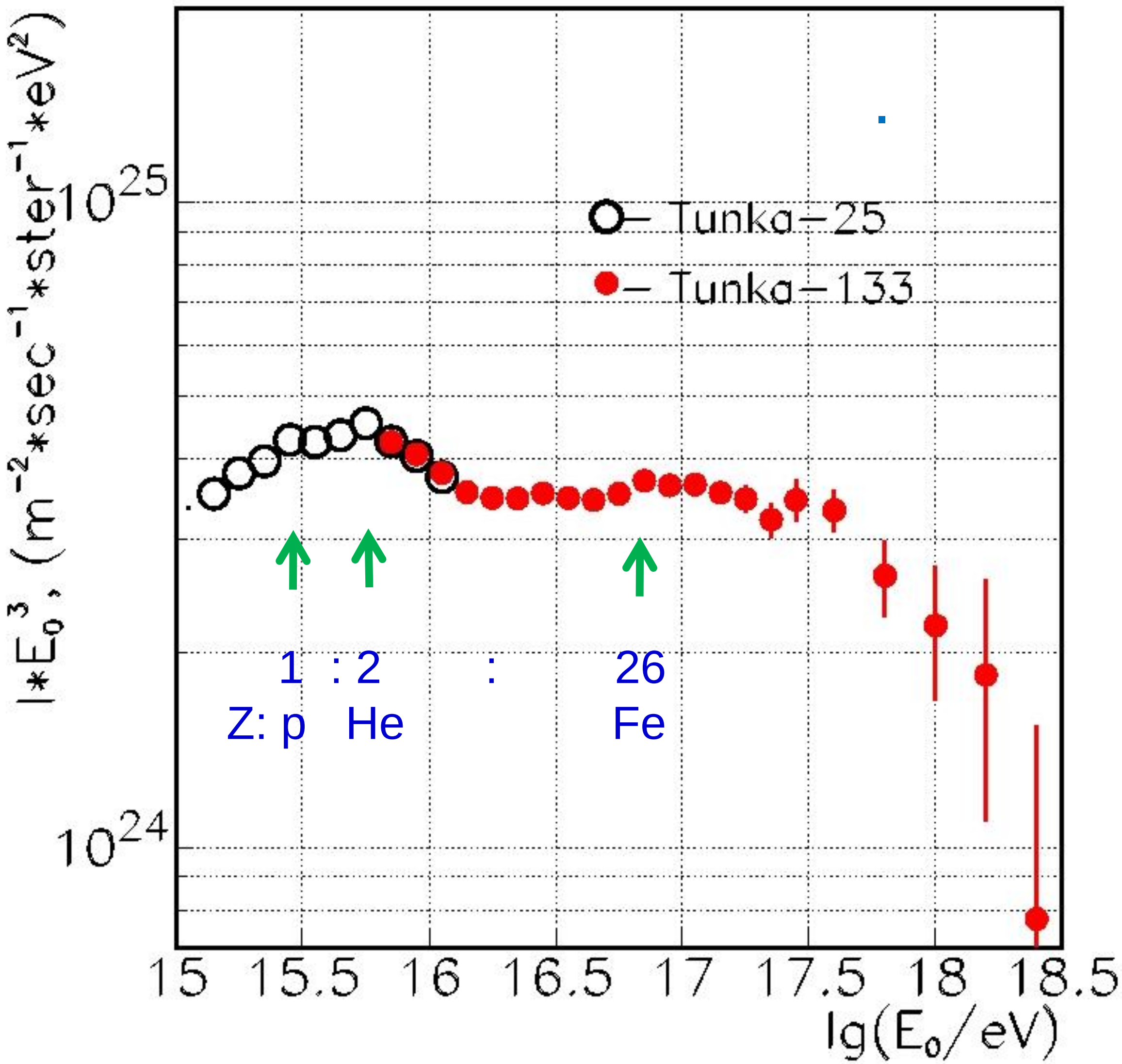
Spectrum Structure in the Knee



Energy Spectrum: Comparison of Experiments



Energy spectrum: Sharp features reflecting the termination energy for different elemental groups at one of the sources

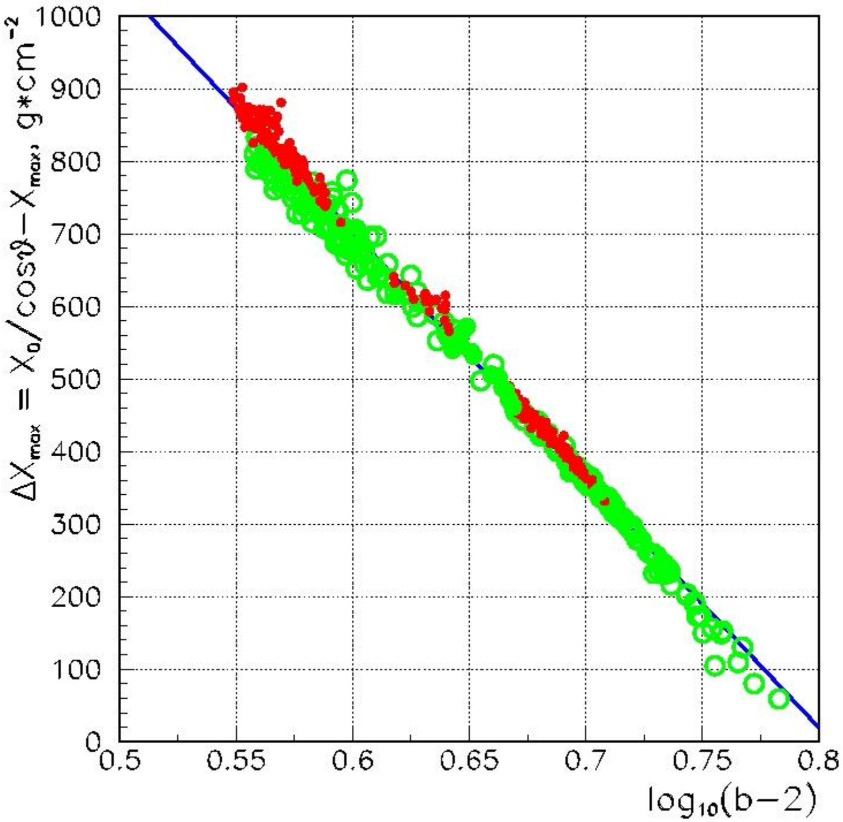


X_{max} method of mass analysis

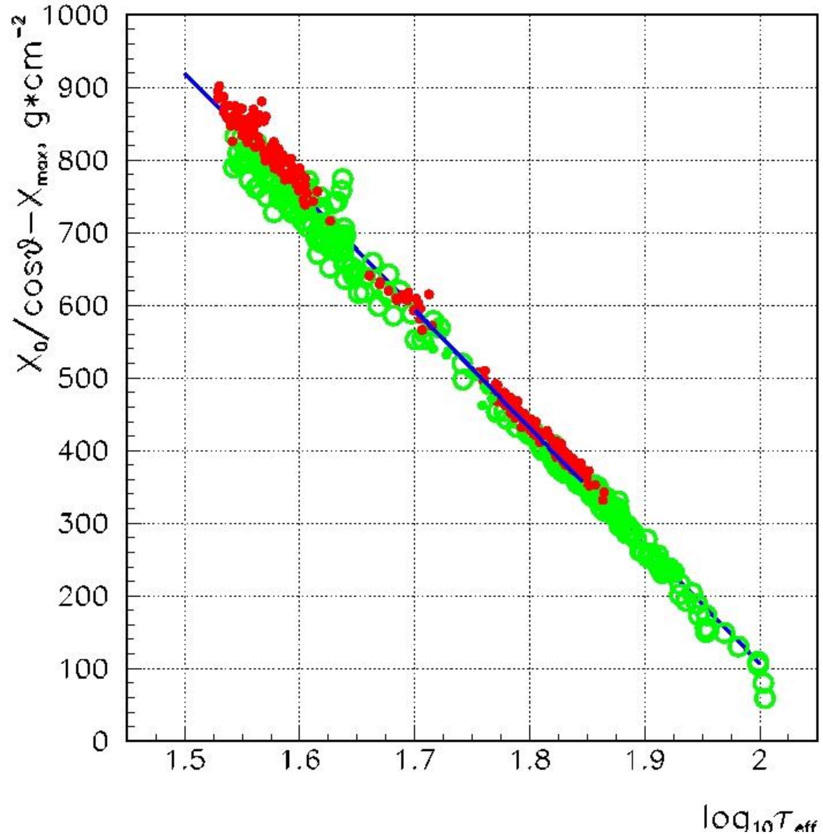
CORSIKA

(**Correlations are model, energy, zenith angle and composition independent**)

ΔX_{max} vs. b_A (ADF steepness)



ΔX_{max} vs. τ_{eff}(400)

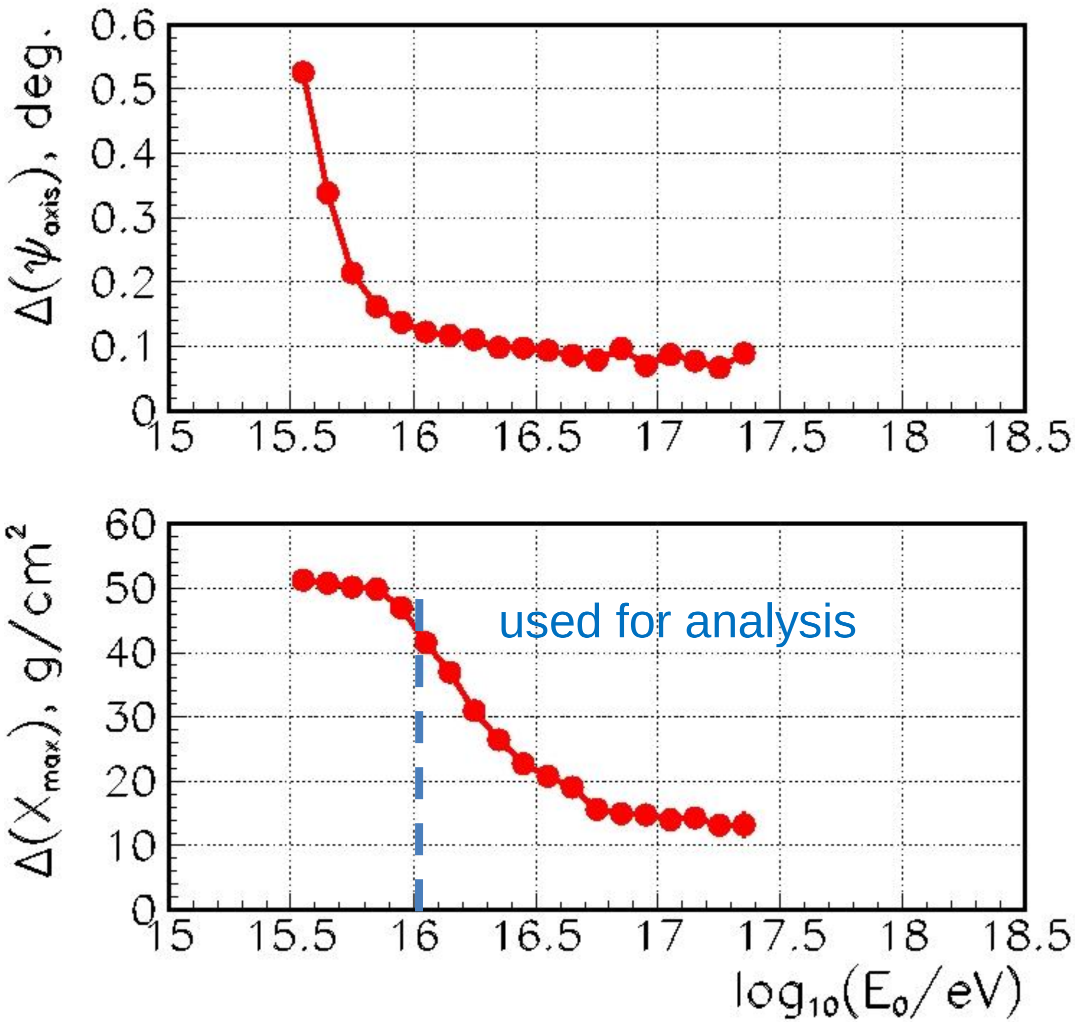


~ 500 events – 10^7 GeV < E_0 <10^8 GeV, θ = 0°, 30°, 45°
green – p, red – Fe

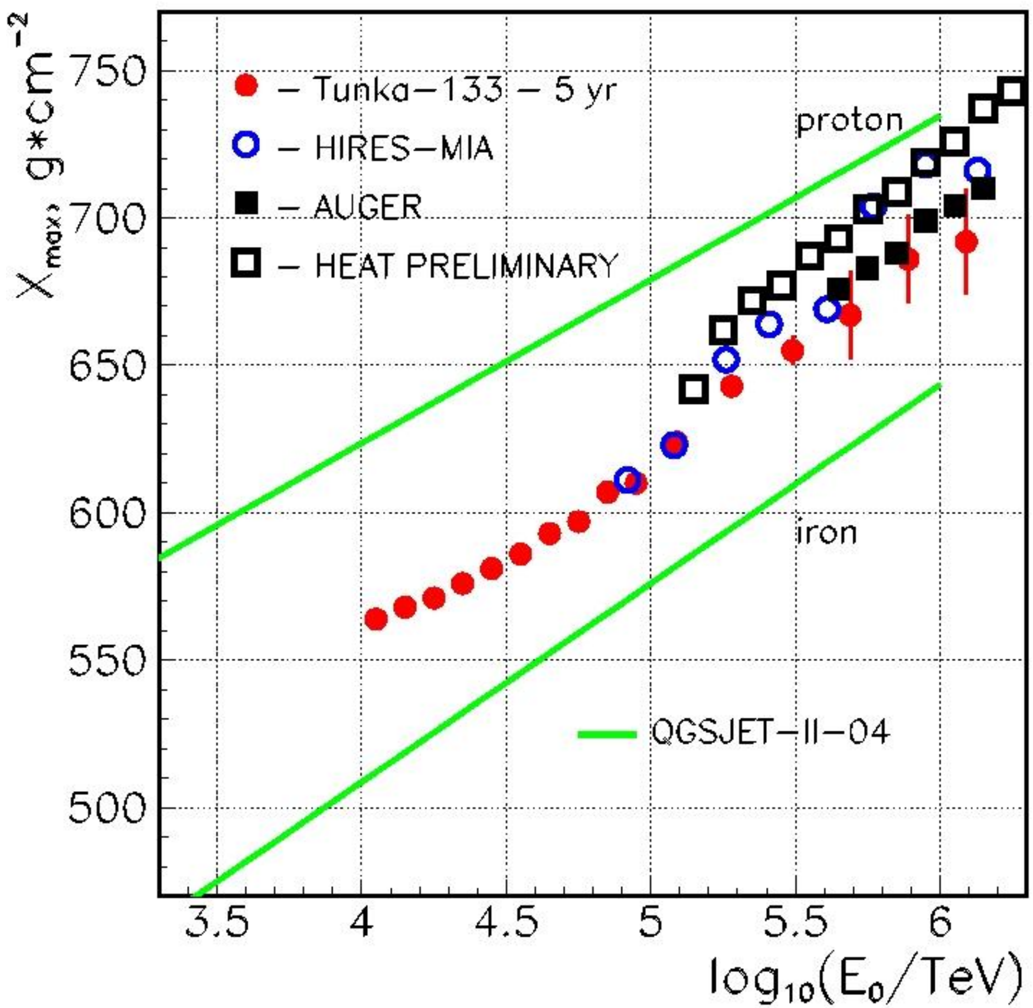
EAS arrival direction and X_{max} accuracy:

Chessboard method:

Error=Difference/√2

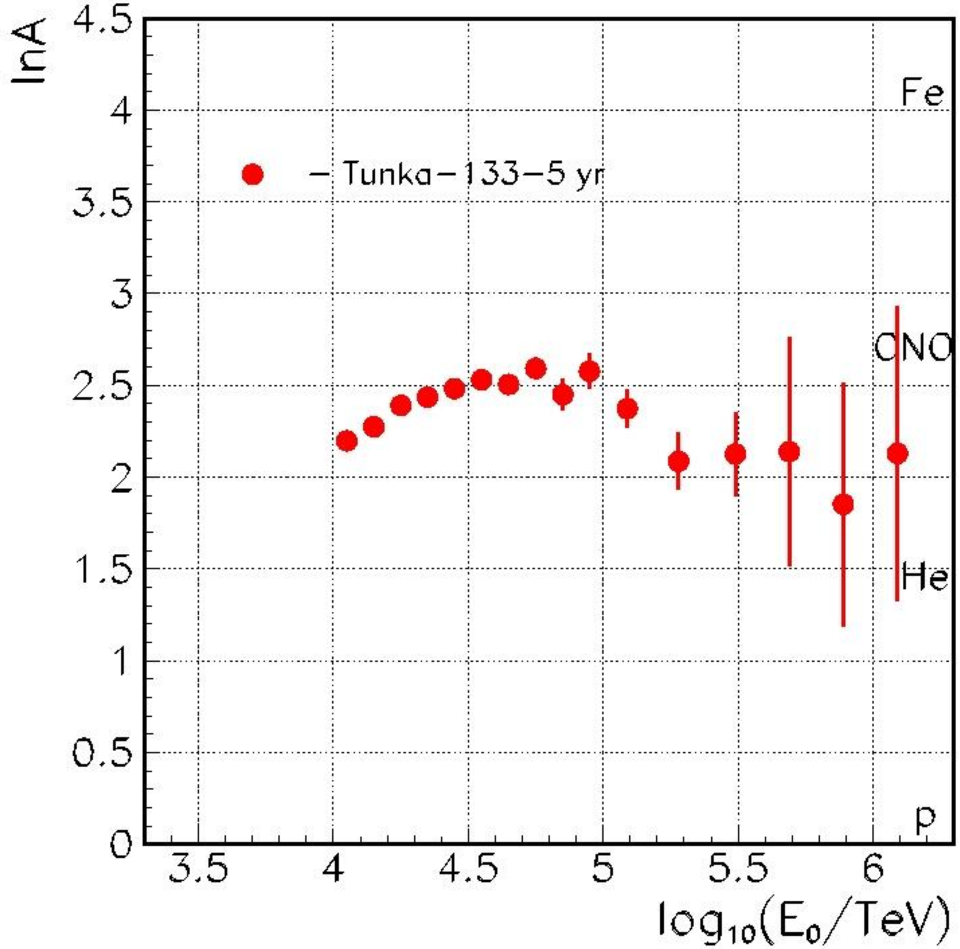


<X_{max}> vs. E_0

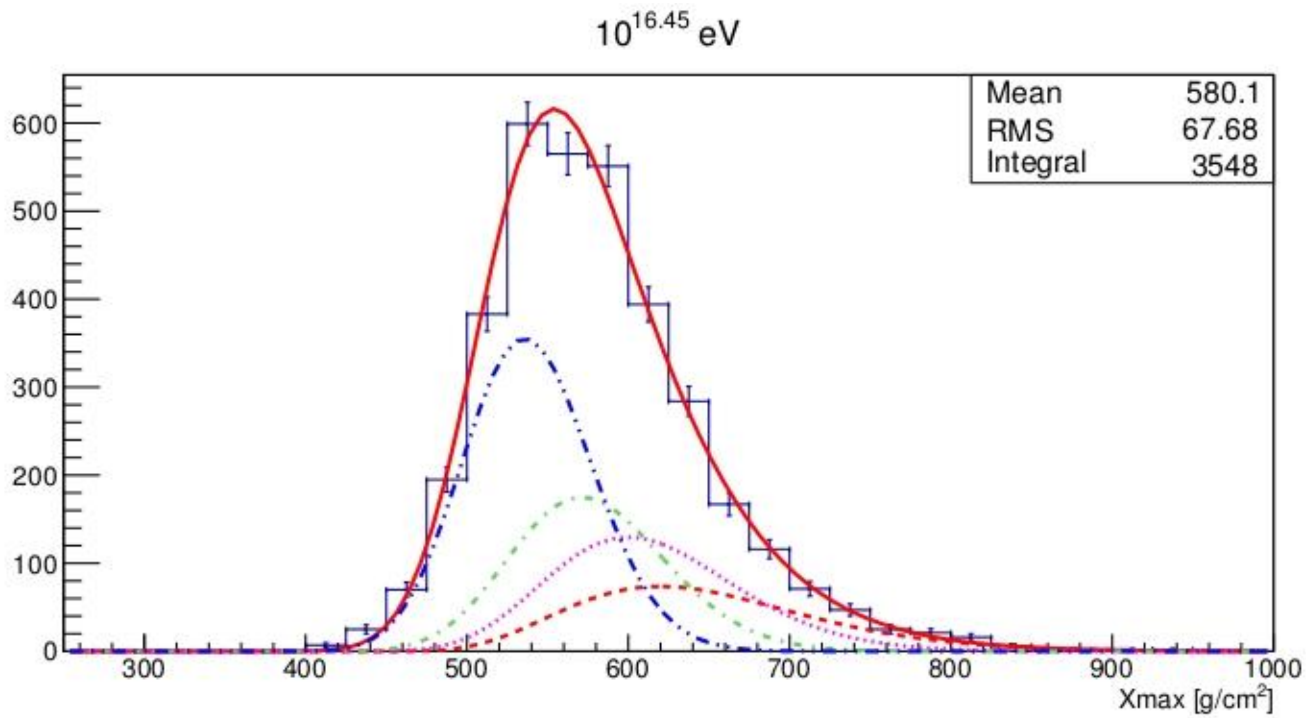


750
700
650
600
550
500
Xmax, g*cm-2
– Tunka-133 – 5 yr
– HIRES-MIA
– AUGER
– HEAT PRELIMINARY
proton
iron
QGSJET-II-04
3.5
4
4.5
5
5.5
6
log10(E0/TeV)

EXPERIMENT: MEAN <lnA> vs. E_0

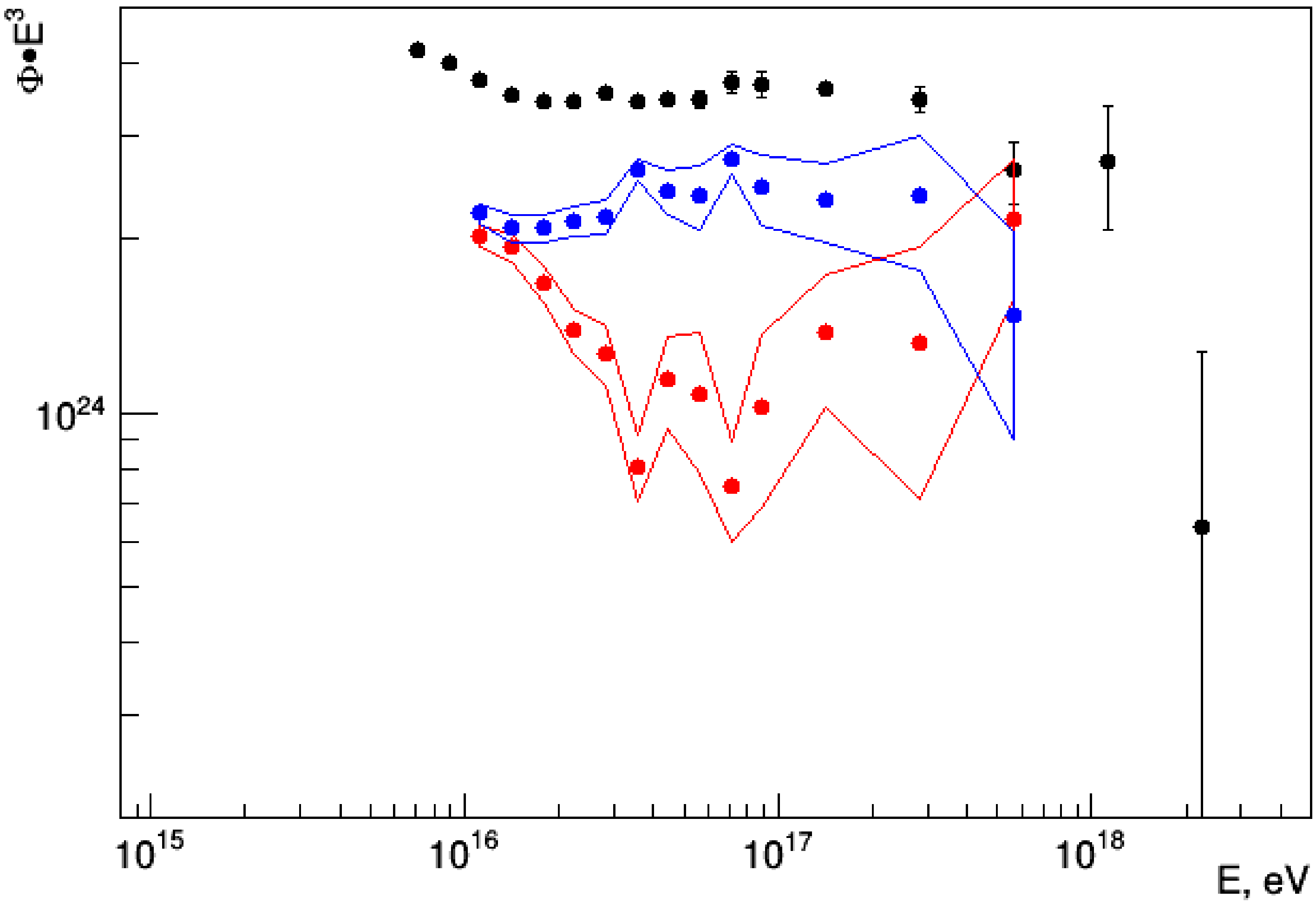


ANALYSIS of X_{max} DISTRIBUTIONS
PRELIMINARY



Fit with weighted sum of 4 group MC simulated distributions: Fe, CNO, He, p

Spectra of light (p+He) and heavy (all other) CR components (2015) PRELIMINARY



Further perspectives

To expand the energy range of mass analysis:

1. 10^{15} – 10^{16} – Tunka-HiSCORE-28 – adapting of Tunka-133 methods to the new array. Results will appear next (2016) year.

2. 10^{17} – 10^{18} – Total time duty measurements by Tunka-Rex and Tunka-Grande. Rate of data acquisition will be 20 times higher than for Cherenkov light experiment (4000 events/year). The first results are expected at the next (2016) year.

Tunka-REX

EAS energy measurement by the radio emission

Tunka-REX

Cerenkov light trigger (from Tunka-133). Independent EAS parameters reconstruction:

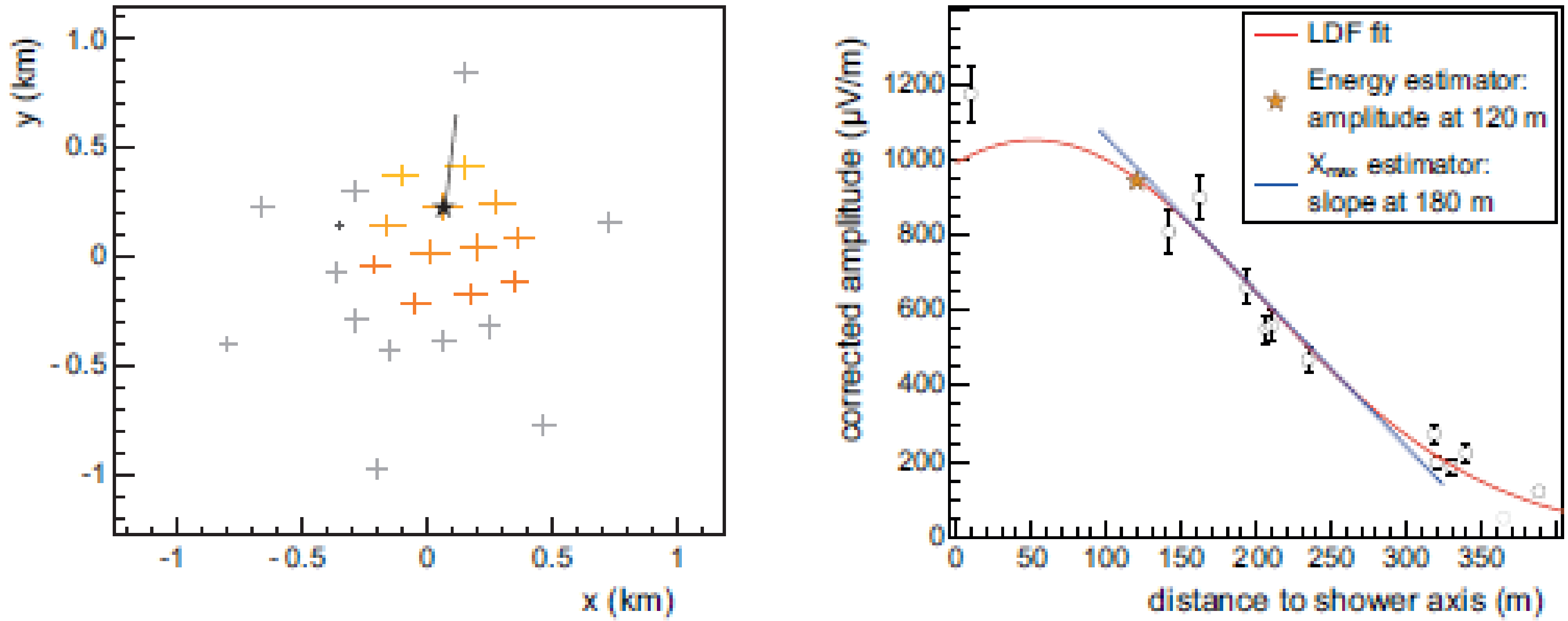
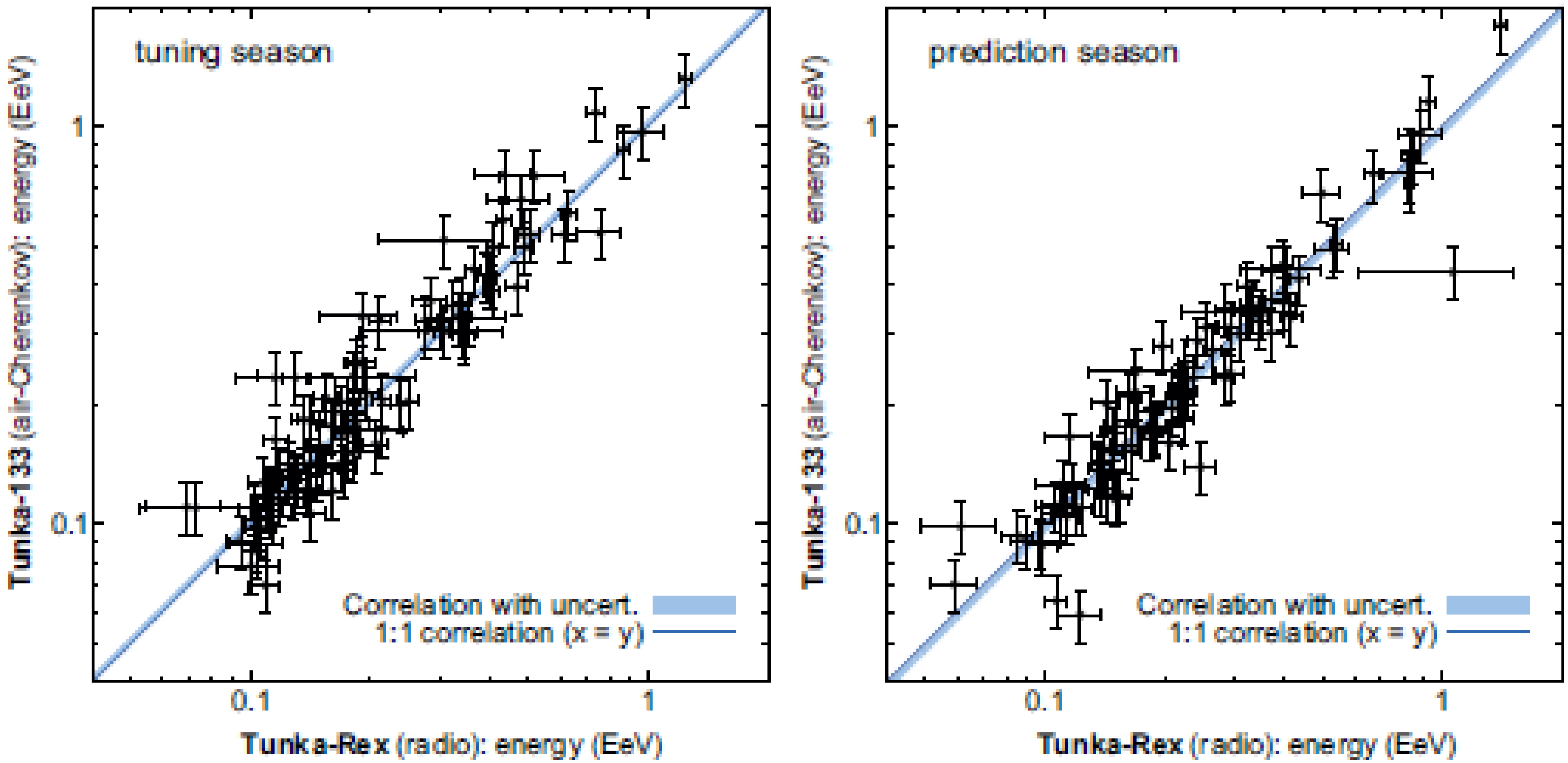


Figure 5. Example event. Left: footprint with arrival time in color code. Light gray crosses are stations below the signal-to-noise threshold. The small dark-gray cross is a station without measurement for this event. The star and the line indicate the reconstructed shower core and direction. Right: Lateral distribution after asymmetry correction and fitted LDF. The light gray point is a station below threshold.

Tunka-REX

Correlation of the shower energy reconstructed with Tunka-Rex radio and Tunka-133 air Cherenkov measurements:



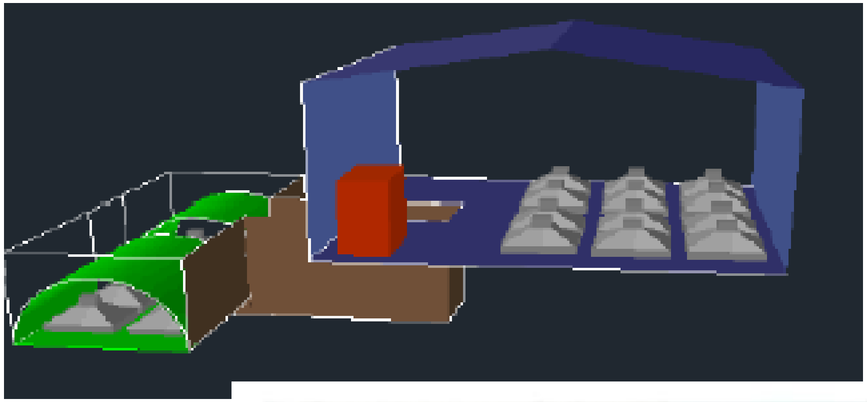
$$\frac{E_{CL} - E_{Radio}}{E_{CL}} = (17 \pm 2)\ \%$$

Tunka-Grande

Scintillation detectors for EAS
electron and muon measurements.

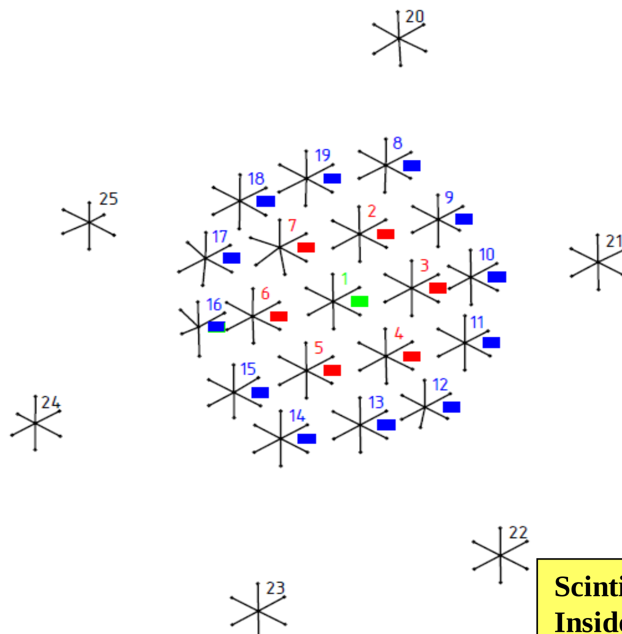
(Former EAS-TOP and KASCADE-Grande detectors)

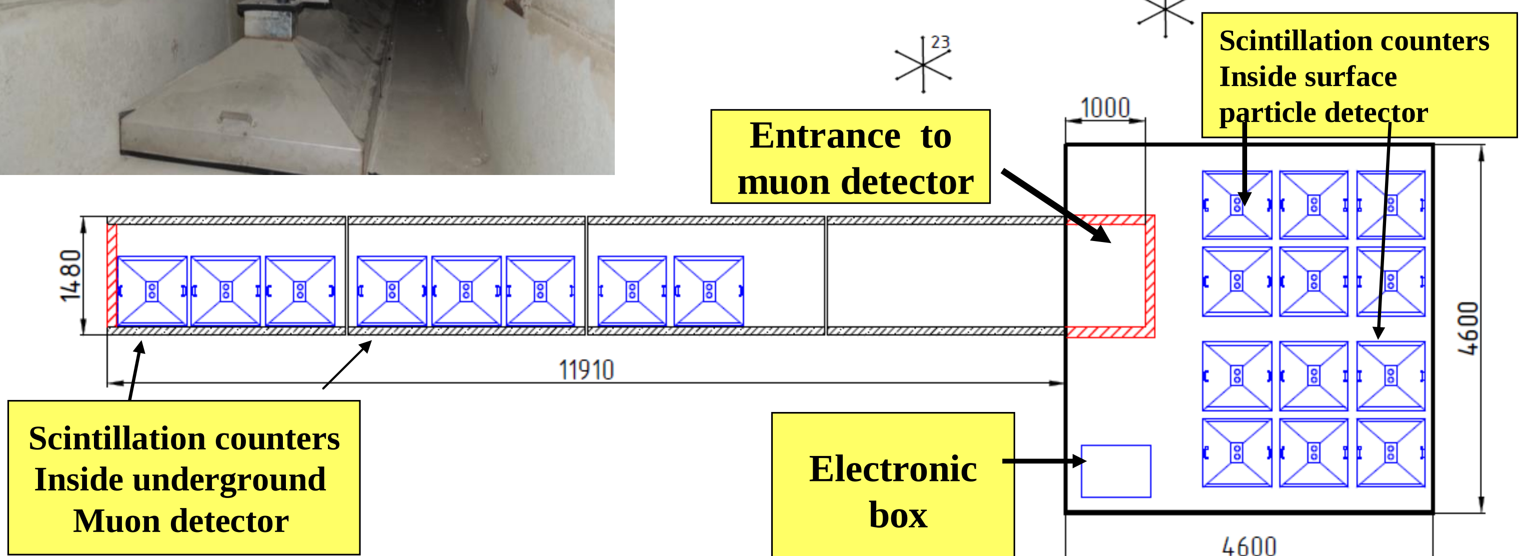
Tunka-Grande:
Transportation of SD to Tunka Valley



Tunka-Grande:
The first muon detector

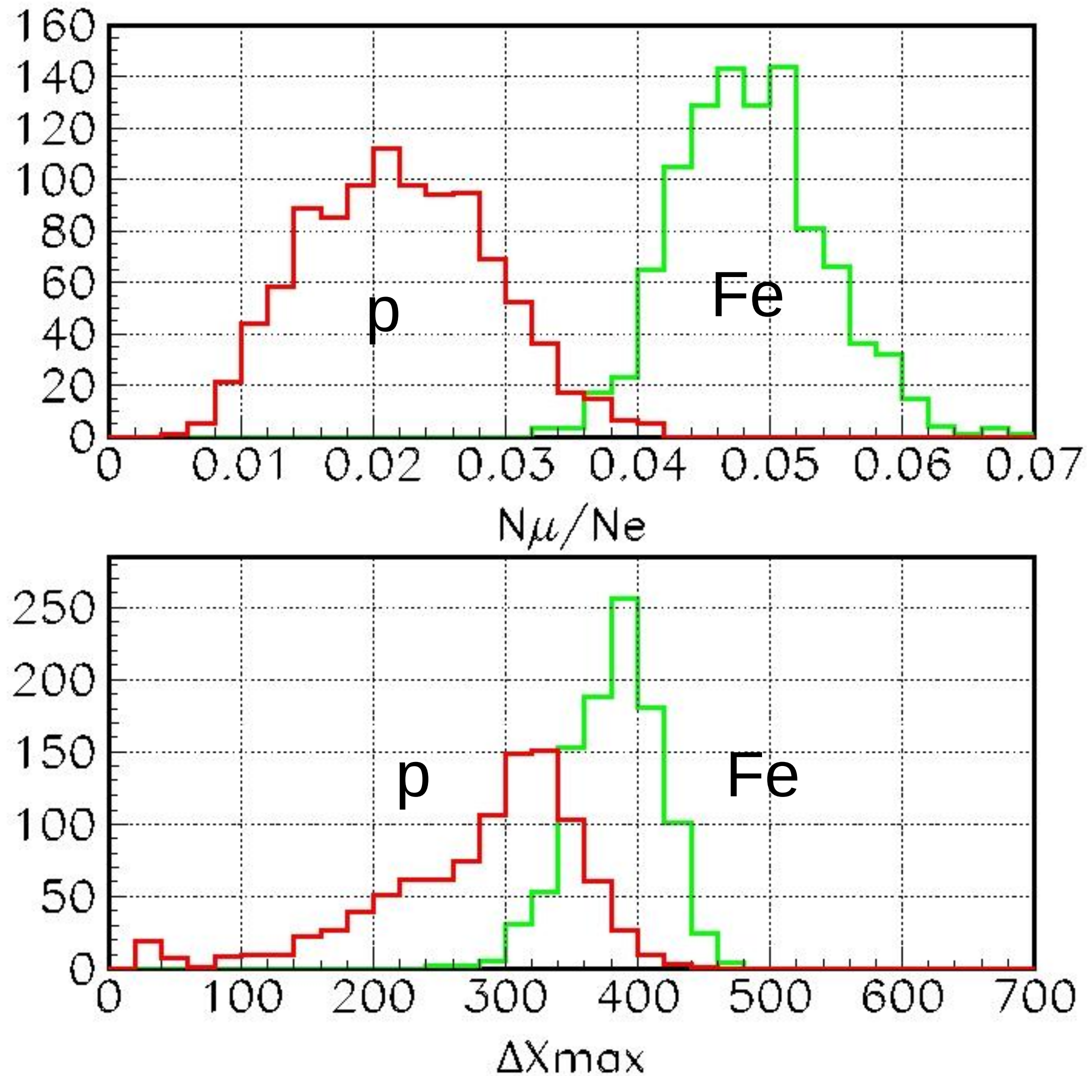
Tunka-Grande: Surface and underground detectors of EAS electrons and muons





AIRES simulation 10^{17} eV

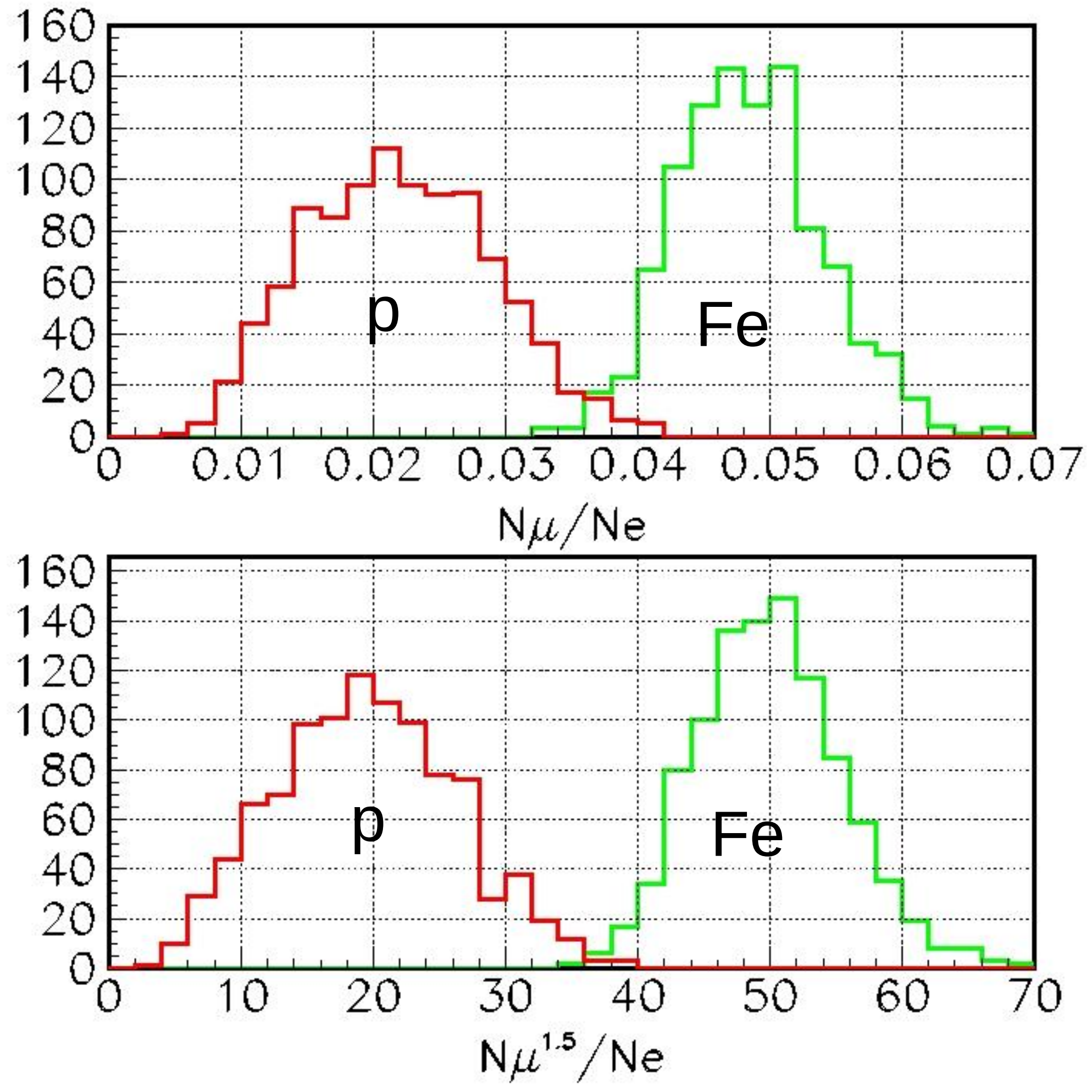
Mass resolution better than for X_{max} method:



AIRES simulation

$E_0 = 10^{17}$ eV, $\theta = 0°$

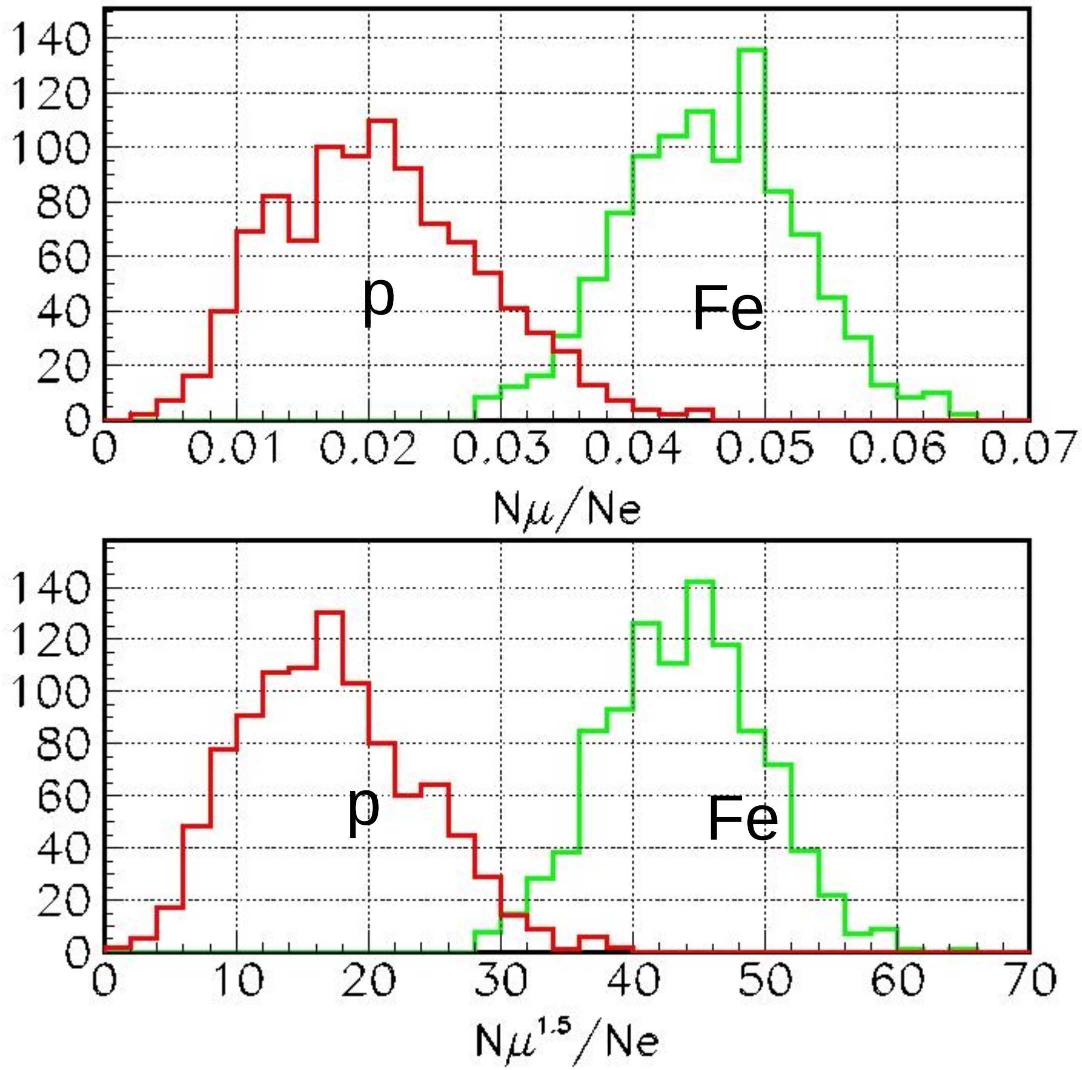
Improvement of mass resolution: Change of $\mathbf{N_\mu}$ to $\mathbf{N_\mu^{1.5}}$



AIRES simulation

$E_0 = 10^{17}$ eV, $\theta = 30°$

Improvement of mass resolution: Change of $\mathbf{N_\mu}$ to $\mathbf{N_\mu^{1.5}}$



CONCLUSIONS

1. The spectrum from 6.10^{15} to 10^{18} eV cannot be fitted with single power law index:

γ = 3.23 ±0.01	$5\cdot10^{15} < E_0 < 2\cdot10^{16}$ eV.
γ = 2.99 ±0.01	$2\cdot10^{16} < E_0 < 7\cdot10^{16}$ eV.
γ = 3.07 ±0.03	$7\cdot10^{16} < E_0 < 3\cdot10^{17}$ eV.
γ = 3.34±0.11	$E_0 > 3\cdot10^{17}$ eV.

2. Mass composition changes to heavy from 10^{16} to $3\cdot10^{16}$ and changes back to light in the range 10^{17} – 10^{18} eV, but the variations are less than it seemed about 5 years ago.

3. The X_{max} obtained at Tunka-133 do not contradict to that of HiRes-MIA and Auger data. But the new data from HEAT-AUGER shows more light composition (pure protons) before 10^{18} eV

4. Possible double structures in the first and the second knees as well as the possible variations of composition has to be investigated with new statistics from Tunka-HiSCORE-28 and Tunka-Grande arrays.

5. We hope to get the separate spectra of light and heavy nuclei at the energy range 10^{17} – 10^{18} eV. The results are expected next year (2016).

Thank you!