Primary Energy Spectrum by the Data of EAS Cherenkov Light Arrays Tunka-133 and TAIGA-HiSCORE and Some Other News from Tunka Valley.

Vasily Prosin for the Tunka and TAIGA Collaborations

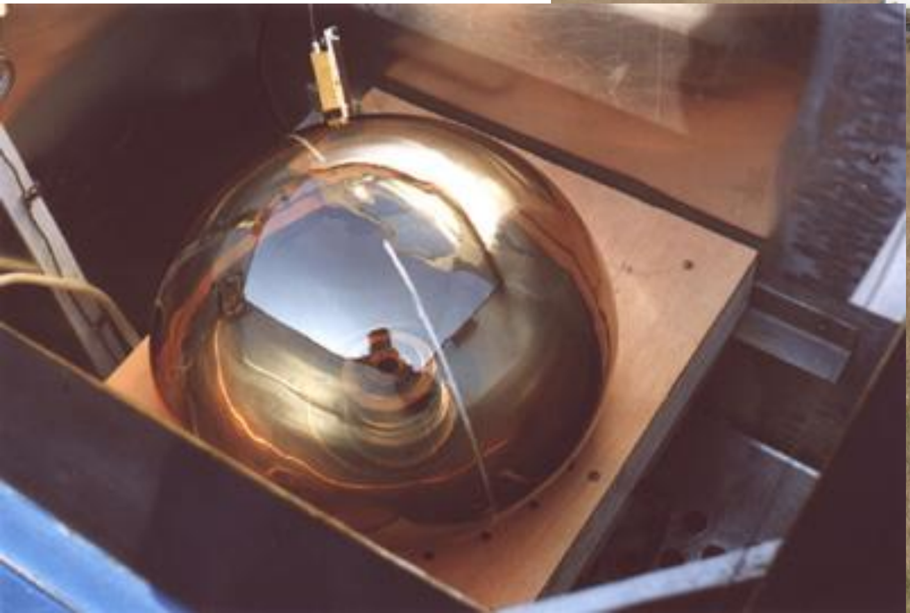
09.10.2018

History of the EAS Cerenkov light study in the Tunka Valley

Start of the first International Collaboration with leadership of Gianni Navarra and A.M. Hillas.

History of the EAS Cerenkov light study in the Tunka Valley

1998 – 2000 – QUEST (5 PMTs QUASAR-370 at EAS-TOP in LNGS).
2000 – 2003 – Tunka-25, S = 0.1 km^2 in the Tunka Valley –
Energy range $8 \cdot 10^{14} – 10^{16}$ eV .

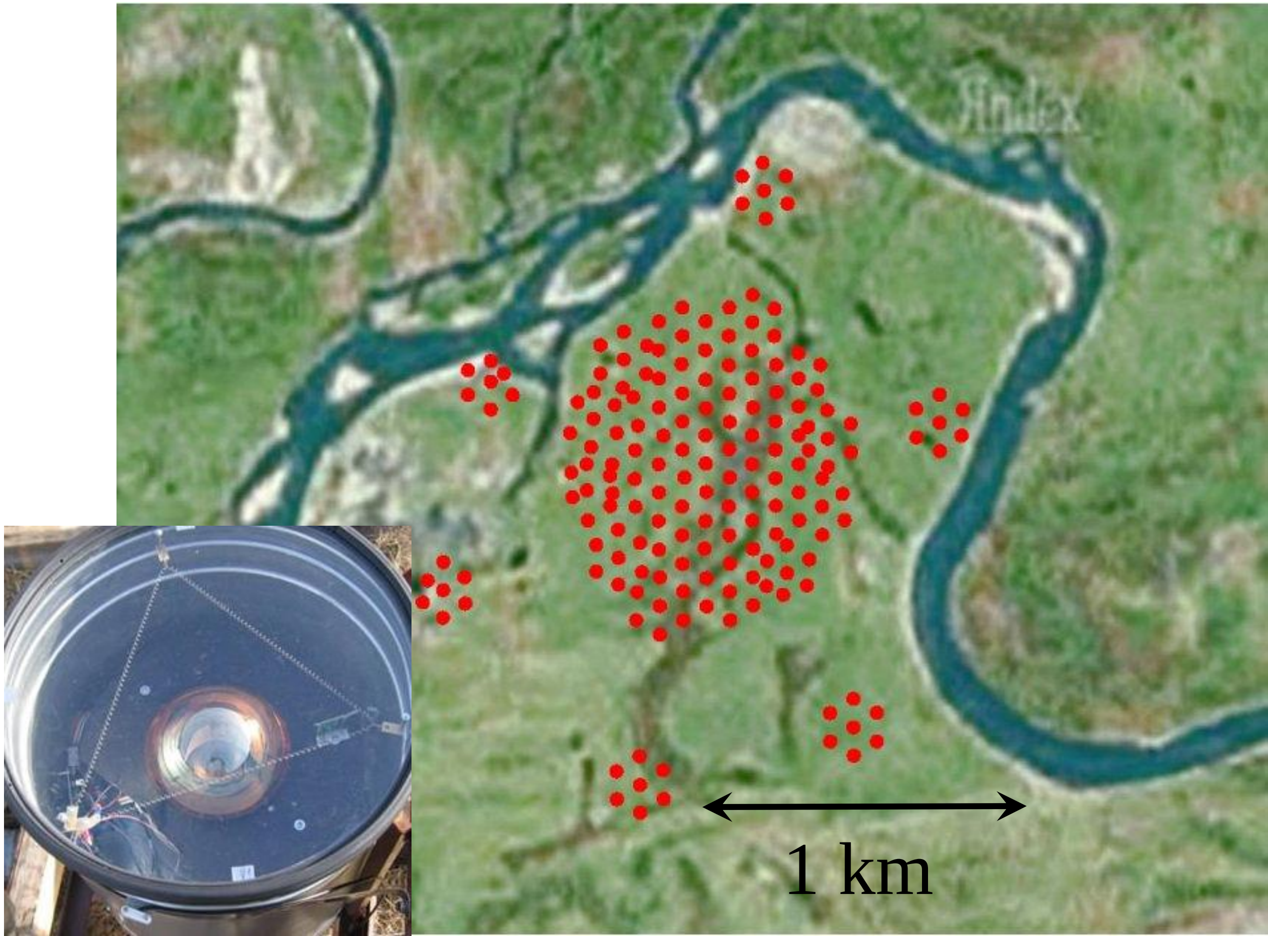


History of the EAS Cerenkov light study in the Tunka Valley

L. Kuzmichev and G. Navarra in Torino

2004 – 2009 – Tunka-133 – 133 PMTs, from former MACRO experiment in Gran Sasso (idea of Gianni Navarra)

Energy range: $6 \cdot 10^{15} - 10^{18}$ eV



TAIGA - collaboration

Germany

Hamburg University (Hamburg)
DESY (Zeuthen)
MPI (Munich)

Italy

Torino University (Torino)

Romania

ISS (Bucharest)

Russia

SINP MSU (Moscow)
API ISU (Irkutsk)
INR RAS (Moscow)
JINR (Dubna)
MEPHI (Moscow)
IZMIRAN (Moscow)
NSU (Novosibirsk)
BINR SB RAS (Novosibirsk)

The TAIGA experiment - a hybrid detector for very High energy gamma-ray astronomy and cosmic ray physics in the Tunka valley

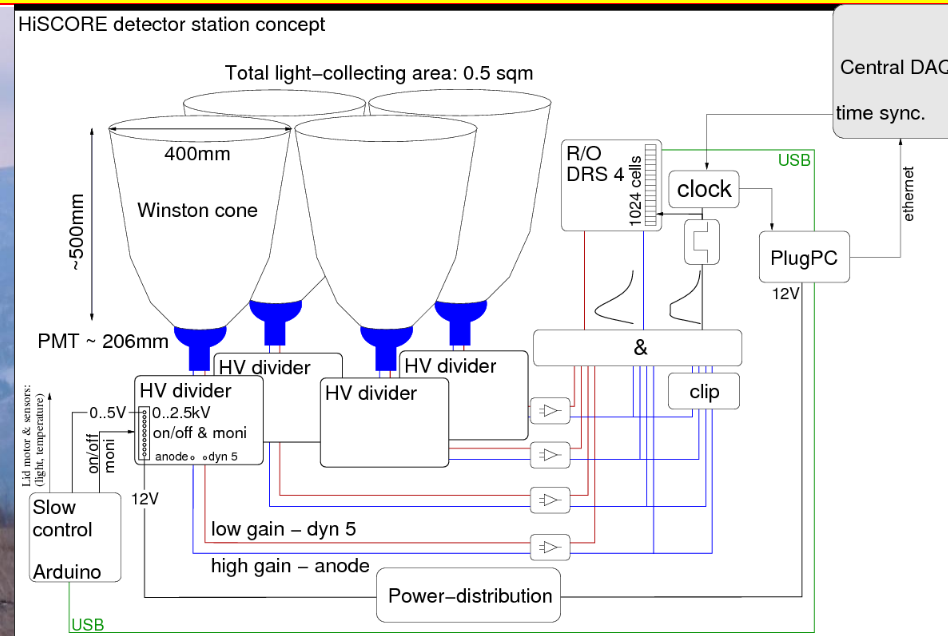
TAIGA = Tunka Advanced Instrument for cosmic rays and Gamma Astronomy

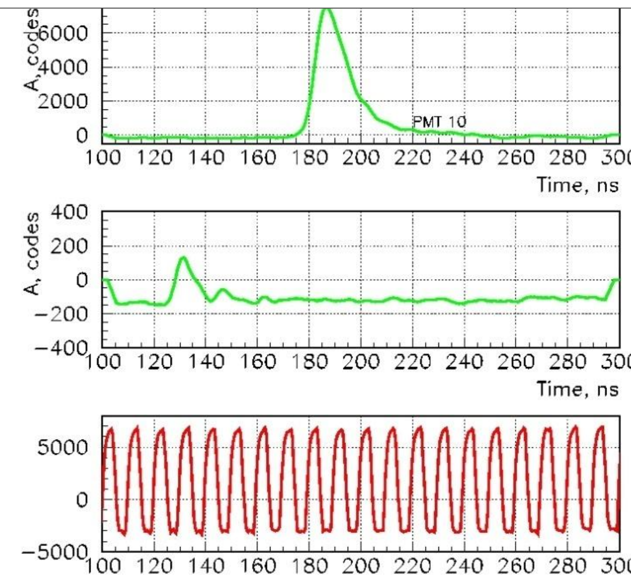
The main idea of large array of low threshold Air Cherenkov stations (the *non-imaging technique) with some Imaging Air Cherenkov Telescopes.*

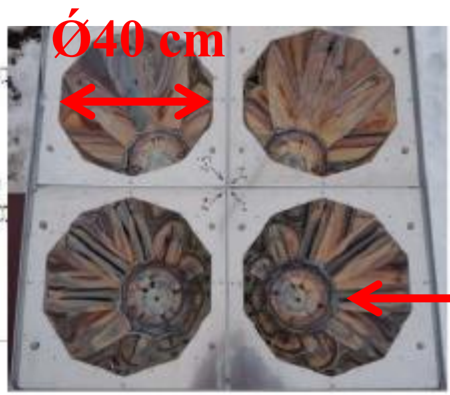
The first stage of TAIGA - 1 km^2 array of 120 wide-angle timing stations and 3 IACTs.

Commissioning will be at the end of 2019

Low threshold wide angle station







Digitized with DRS-4.
Step = 0.5 ns
Synchronization and data taking via optical cable

Winston cone and PMT with 20 cm photocathode diameter

S tot = 0.5 m^2

TAIGA-IACT

D = 4.32m   F = 4.75m

29 glass mirrors of 60 cm diameter

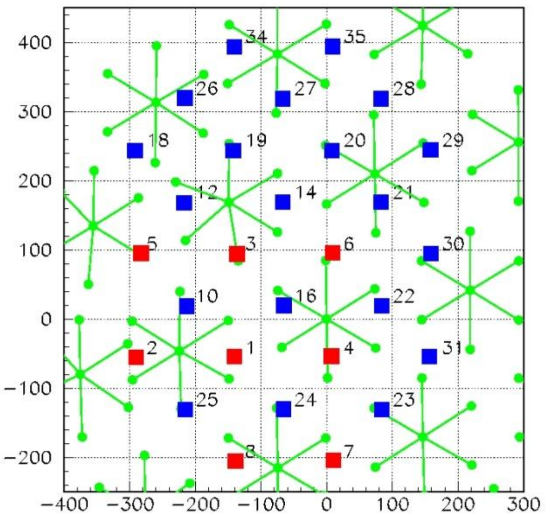
Camera : 560 PMTs (XP 1911) with 15 mm useful diameter of photocathode
Winston cone: 30 mm input size, 15 mm output size
aperture single pixel = 0.36°
FOV diameter ~ 9.6°

Energy threshold   ~1.5 TeV

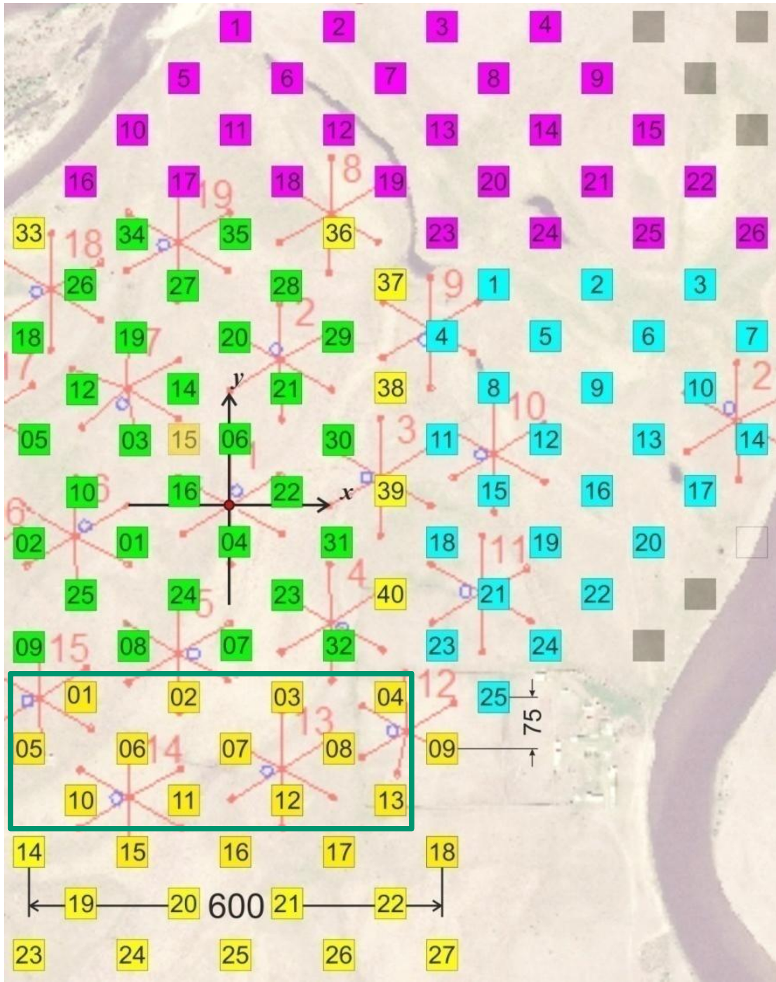
History of the EAS Cerenkov light study in the Tunka Valley

2014 – TAIGA-HiSCORE (High Sensitivity Cosmic Ray Explorer) – 9 stations

2016 – 2017
28 stations



2018
45 stations



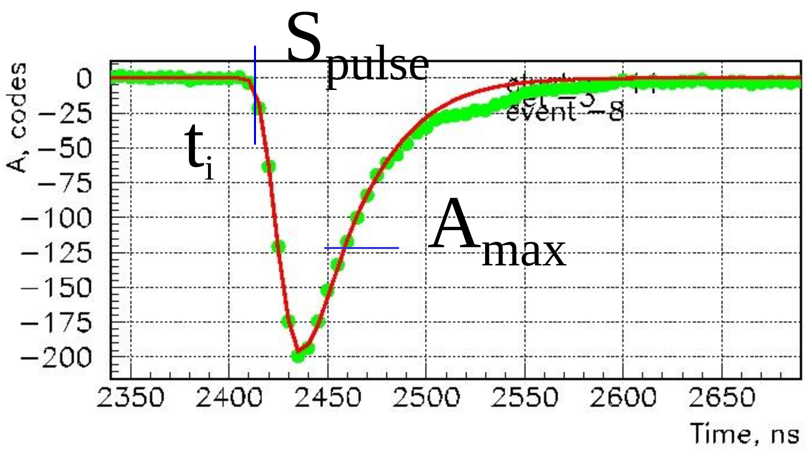
EAS Cherenkov Arrays Data Processing and Results

Tunka-133 single detector readout:

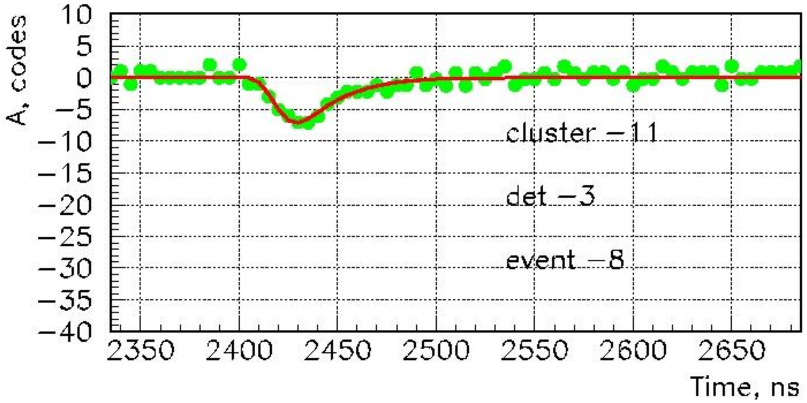
Fitting of the pulse and measuring of the parameters: $Q=c\cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

Time step = 5 ns

anode:

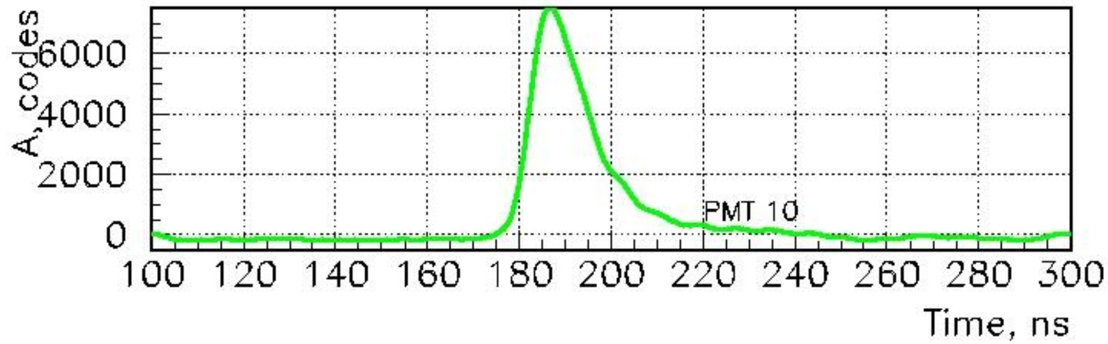


dynode:

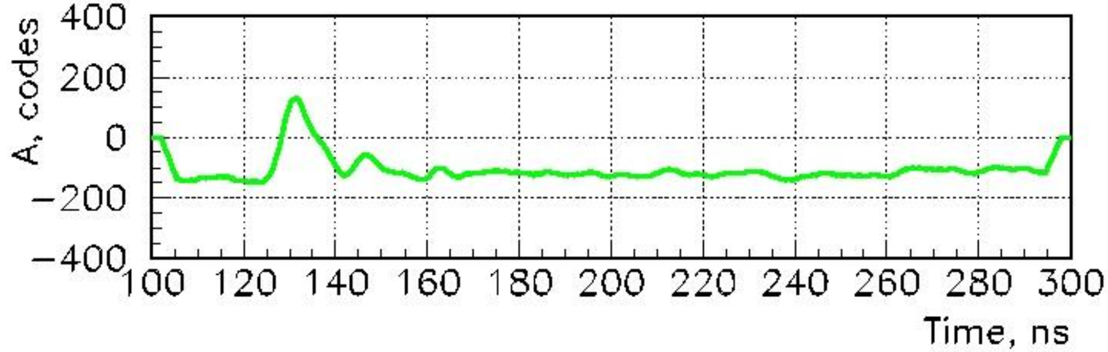


HiSCORE station sum record 2017-2018

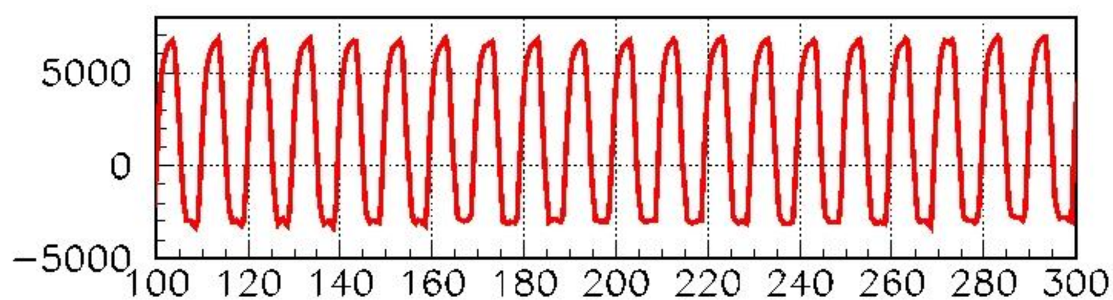
anode:



dynode:

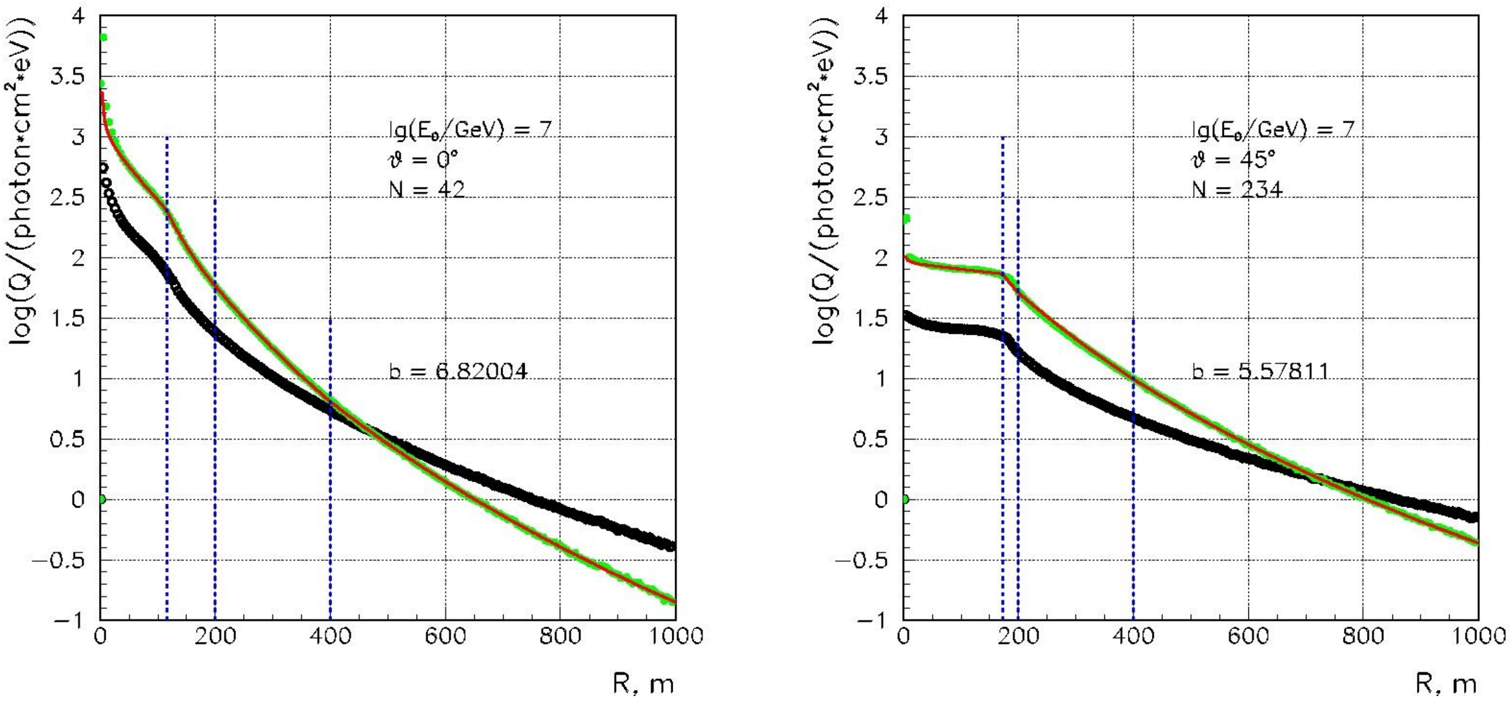


synchronisation:



EAS parameters reconstruction

CORSIKA: Fitting functions – LDF and ADF

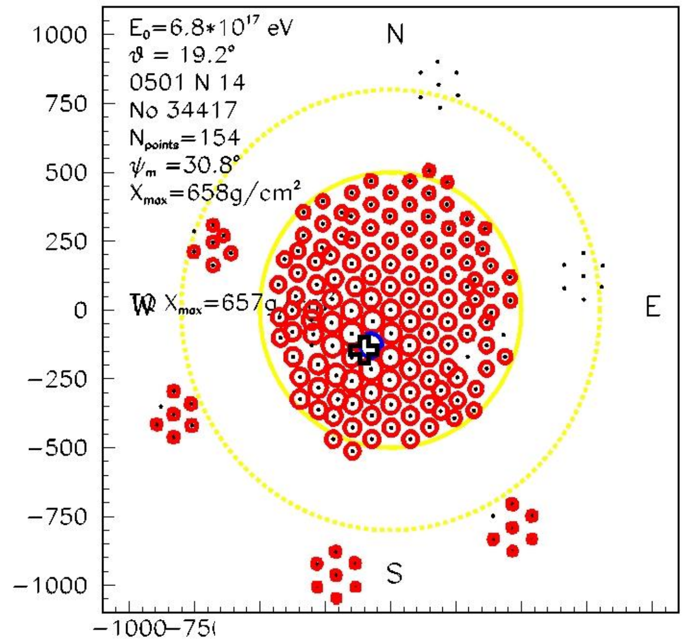


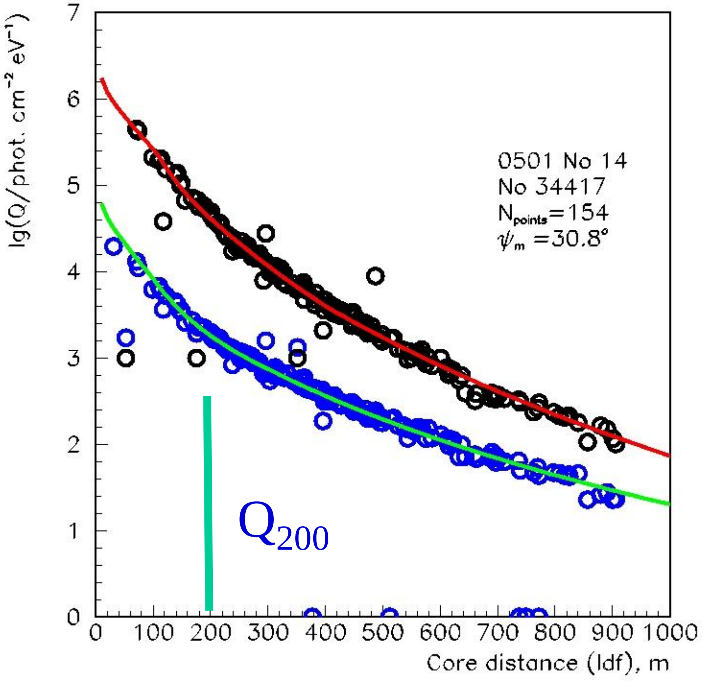
ADF: **$A(R) = A(400)\cdot((R/400+1)/2)^{-bA}$ steepness**: $\mathbf{b_A}$

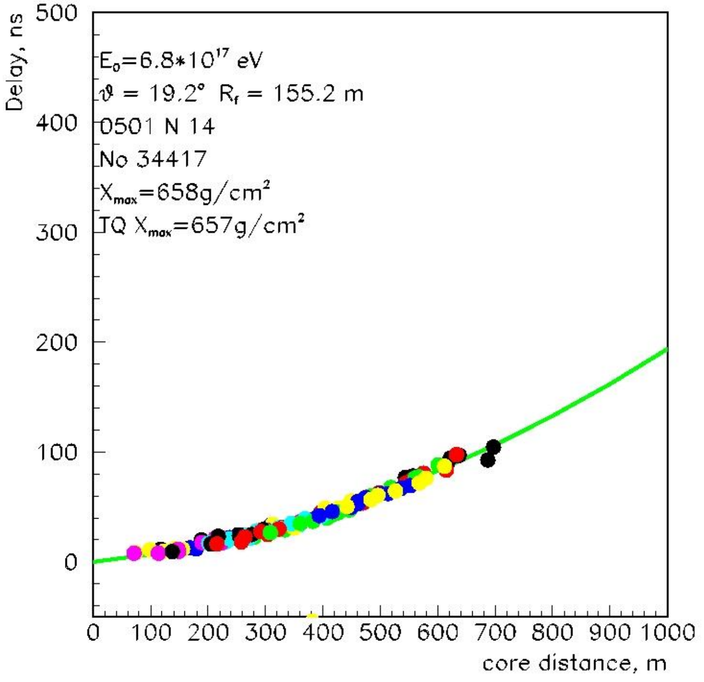
LDF: **$Q(R) = Q(300)\cdot((R/300+1)/2)^{-bQ}$** steepness: $\mathbf{b_Q}$

$$\mathbf{b_A > b_Q}$$

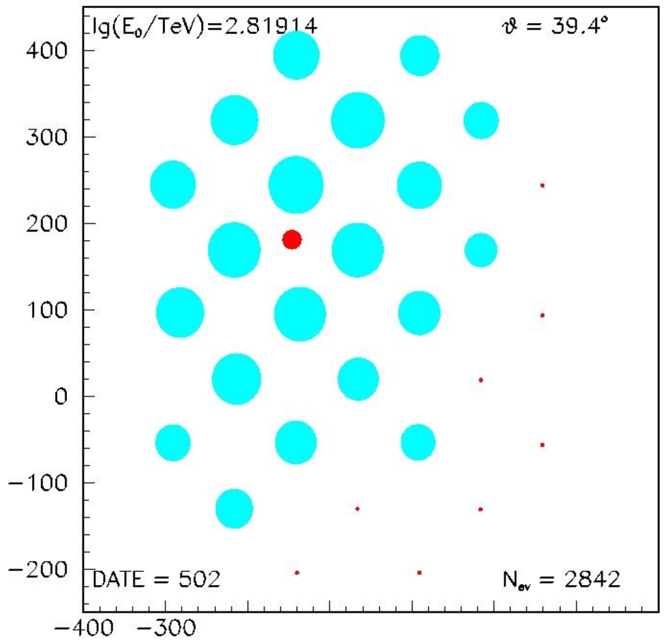
An Example of Tunka-133 event reconstruction

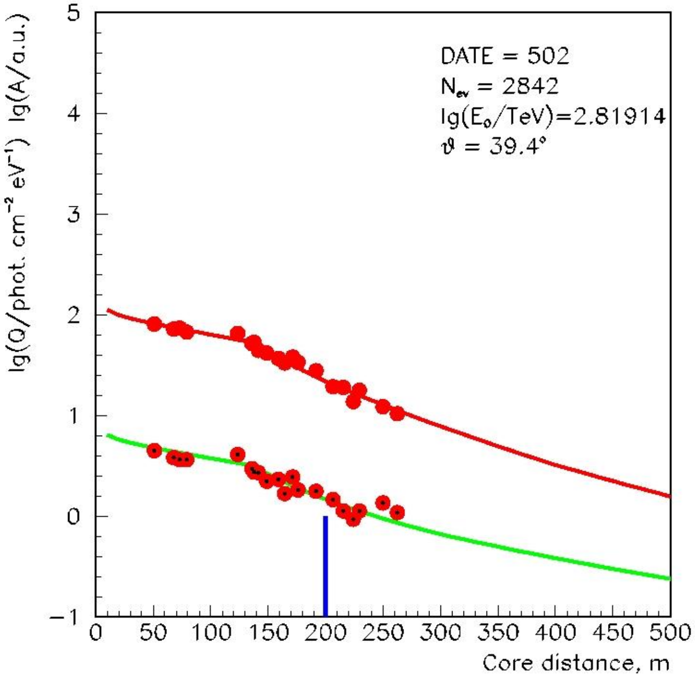


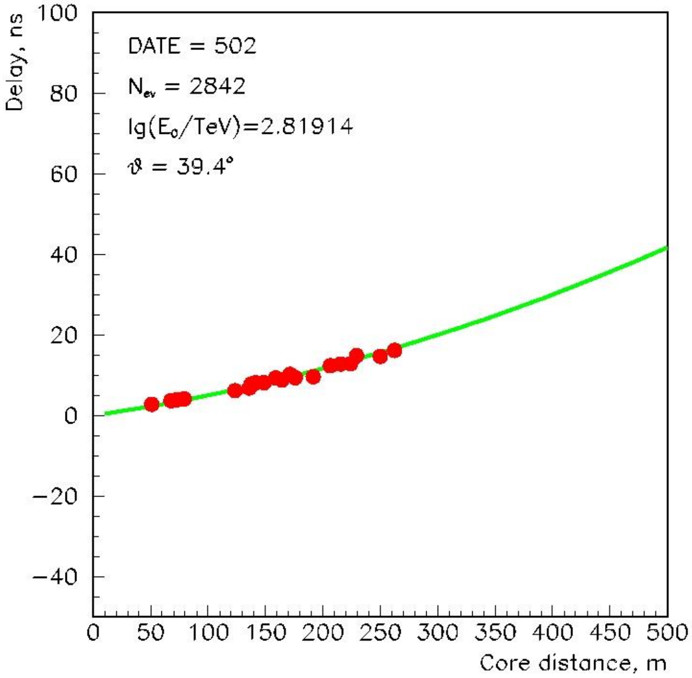




An Example of TAIGA-HiSCORE event reconstruction



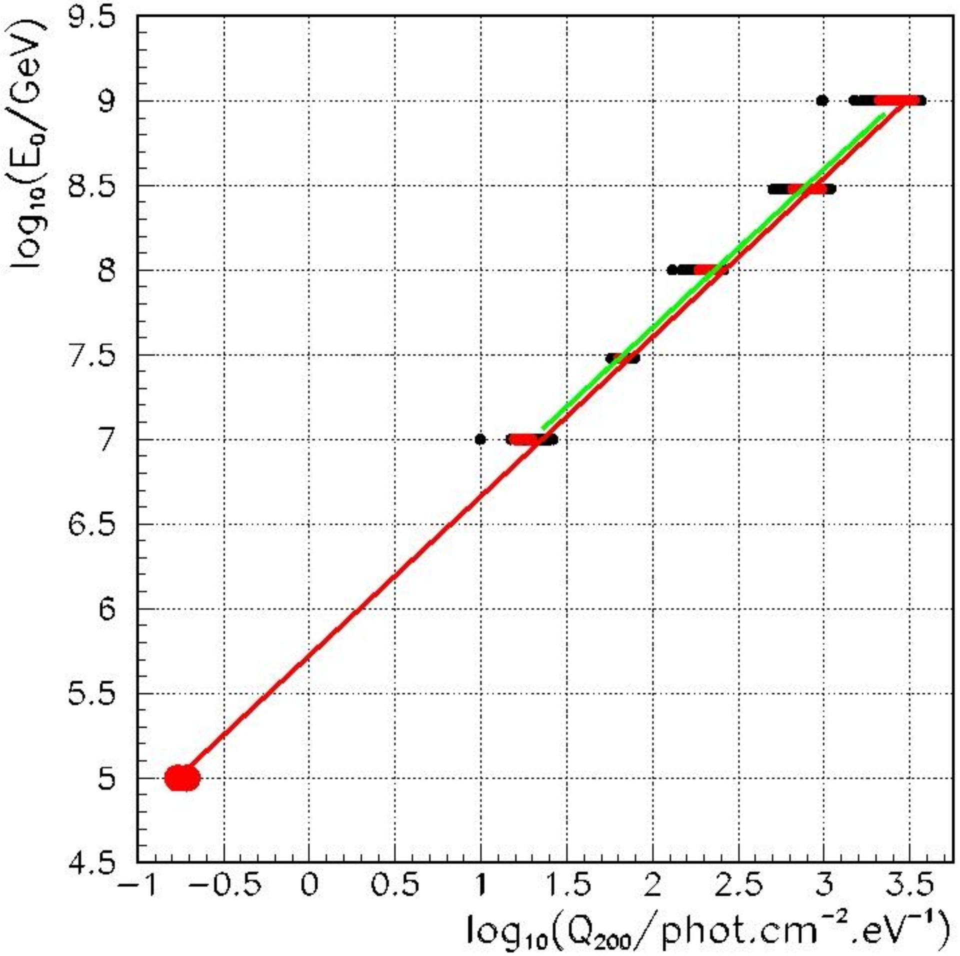




EAS paramerters reconstruction by Cherenkov light flux density Q_{200}

Fitting of pulse amplitudes (A_i) with ADF.
Getting of X_0, Y_0 and ADF steepness (b_A).
Getting Q_{200} with LDF

$$E_0 = C \cdot Q_{200}^{0.94}$$



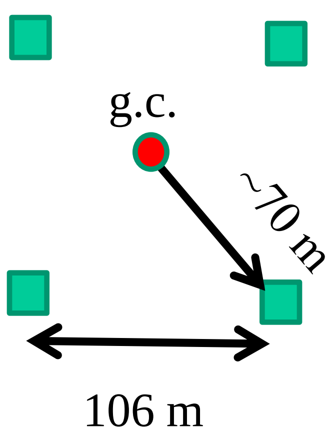
EAS parameters reconstruction by Q_{70}

For energy $E_0 < 10^{15}$ eV:

X_0, Y_0 is the gravity center of A_i for 4 stations, closest to the core.

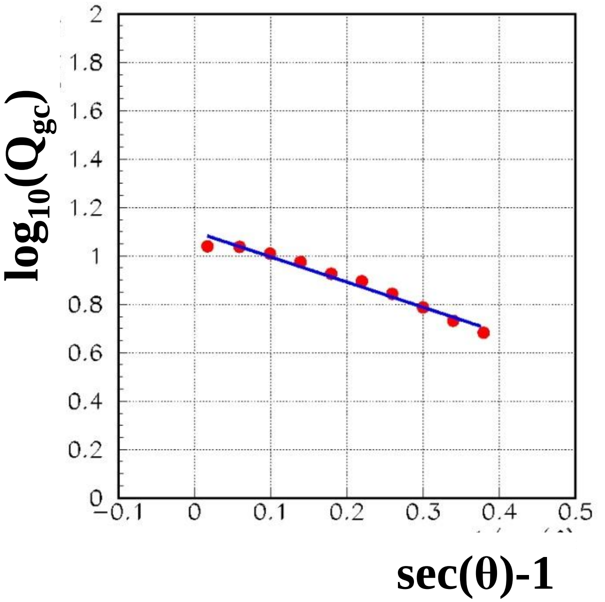
Q_{gc} is mean value by these 4 stations

Minimal event configuration:

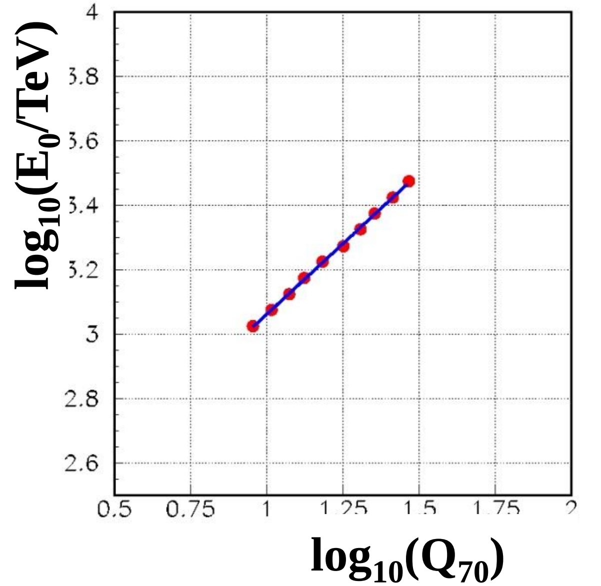


Experimental correlations are obtained for the energy range $10^{15} – 3\cdot10^{15}$ eV :

$$Q_{70} = Q_{gc}\cdot 1.06(\sec(\theta)-1) :$$

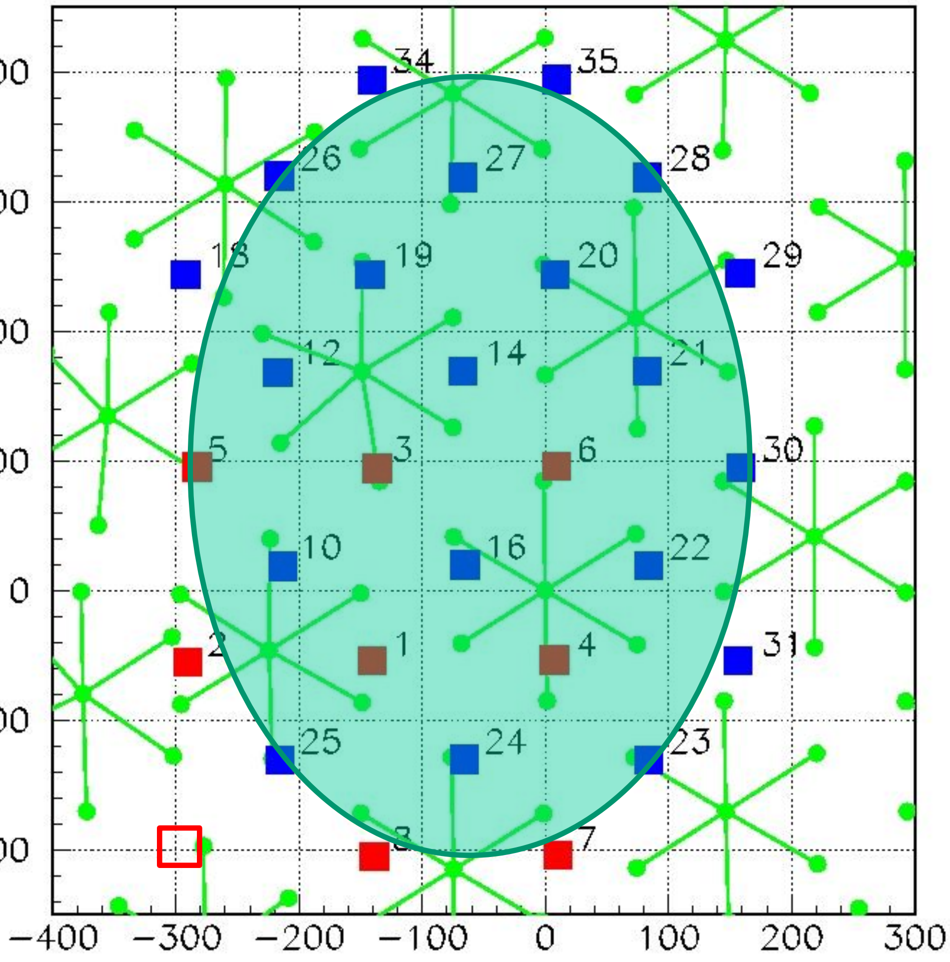


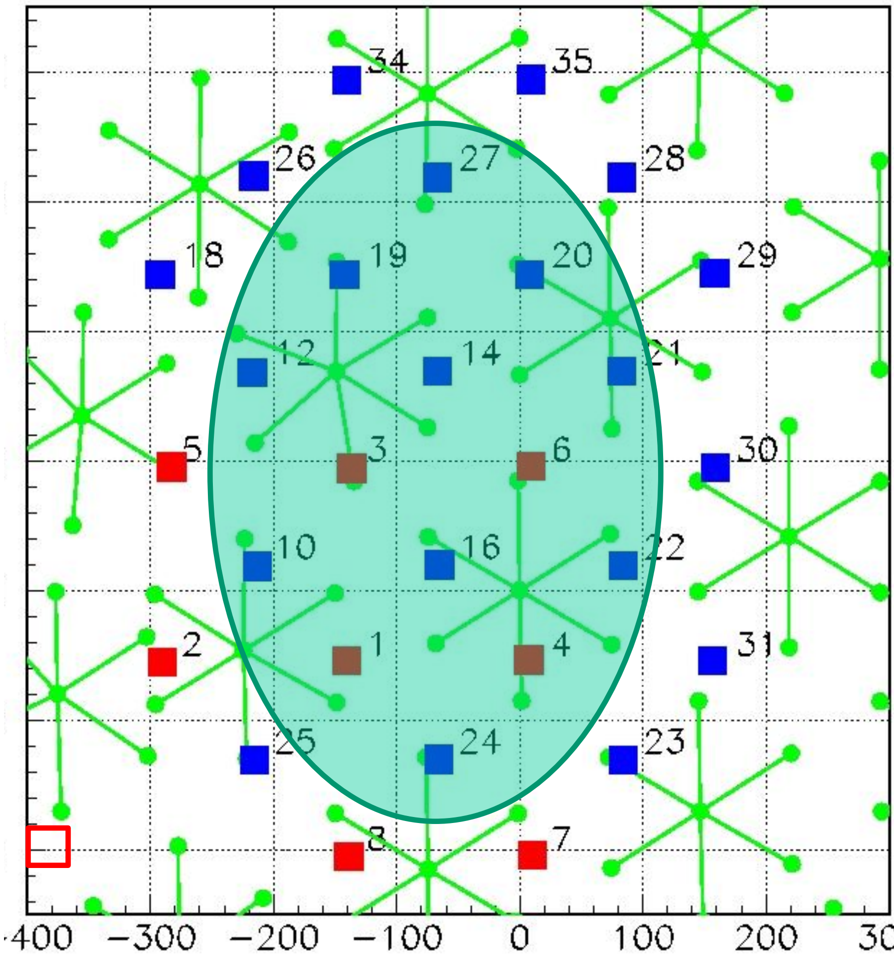
$$E_0 = C\cdot Q_{70}^{0.88} :$$



HiSCORE Effective Area

fitted events $E_0 > 10^{15}$ eV **gravity center events $E_0 < 10^{15}$ eV**





EXPERIMENTAL DATA

Tunka-133:
7 seasons, 350 nights, 2175 h, ~$1.5\cdot10^7$ single cluster events
100% effective registration:
~375,000 events with $E_0 > 6\cdot10^{15}$ eV,
~4,200 events with $E_0 > 10^{17}$ eV

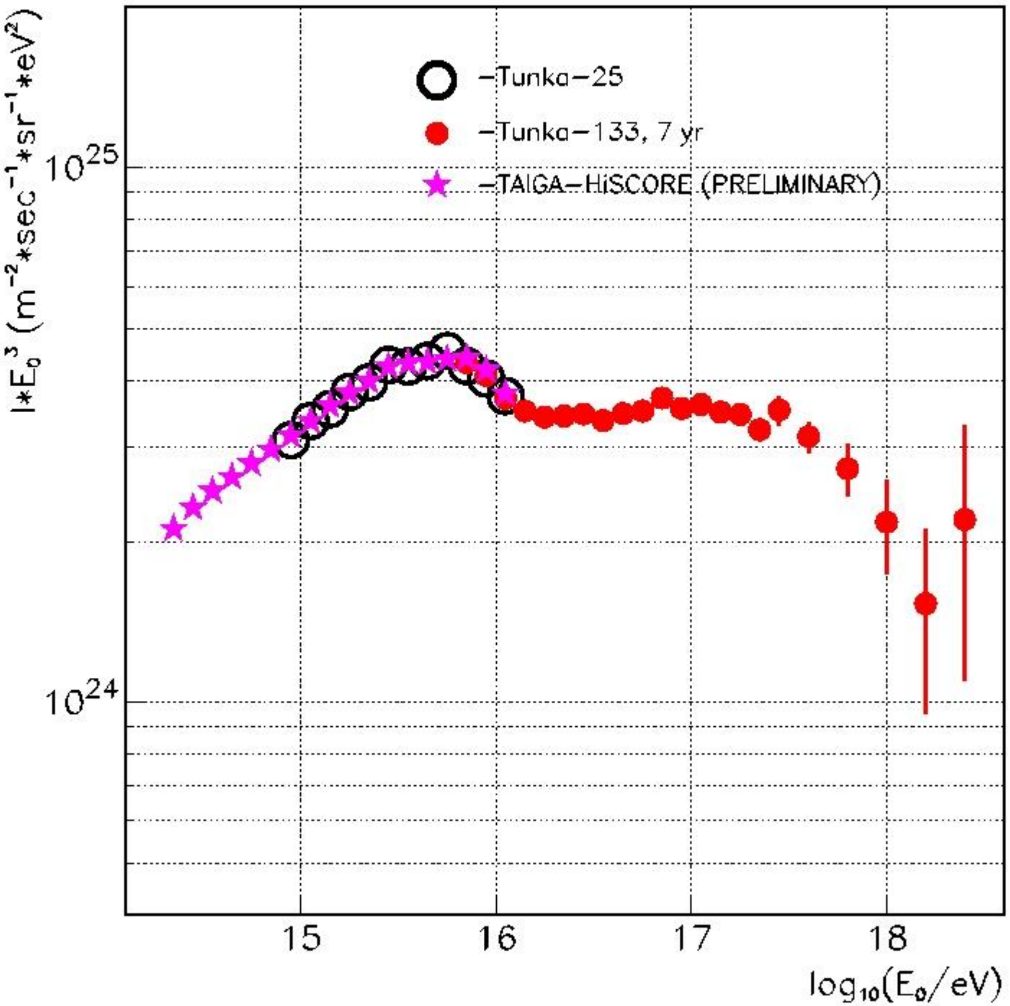
TAIGA-HiSCORE:
season 2017-2018, 35 nights, 180 h, ~$3\cdot10^8$ single station events
100% effective registration:

$2\cdot10^{14} – 3\cdot10^{14}$	~29,000 (one night 28.10.2018, Q_{70})
$3\cdot10^{14} – 10^{15}$	~700,000 (35 nights, Q_{70})
$10^{15} – 10^{17}$	~170,000 (35 nights, Q_{200})

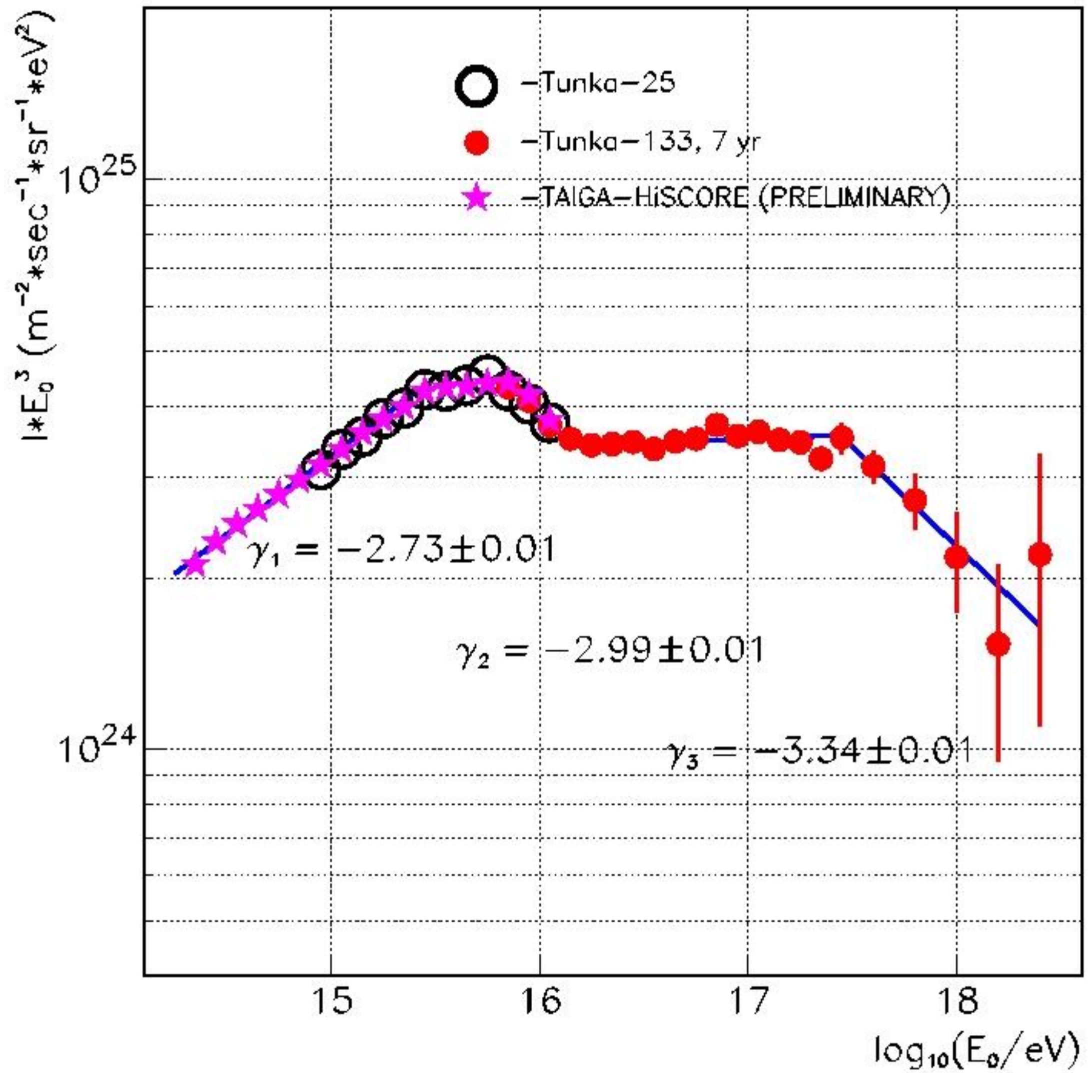
Tunka Primary Energy Spectra with EAS Cerenkov Light

Tunka-133:
350 clean moonless nights
2175 h
~375,000 events
With ~100% efficiency
~4200 events with $E_0 > 10^{17}$ eV

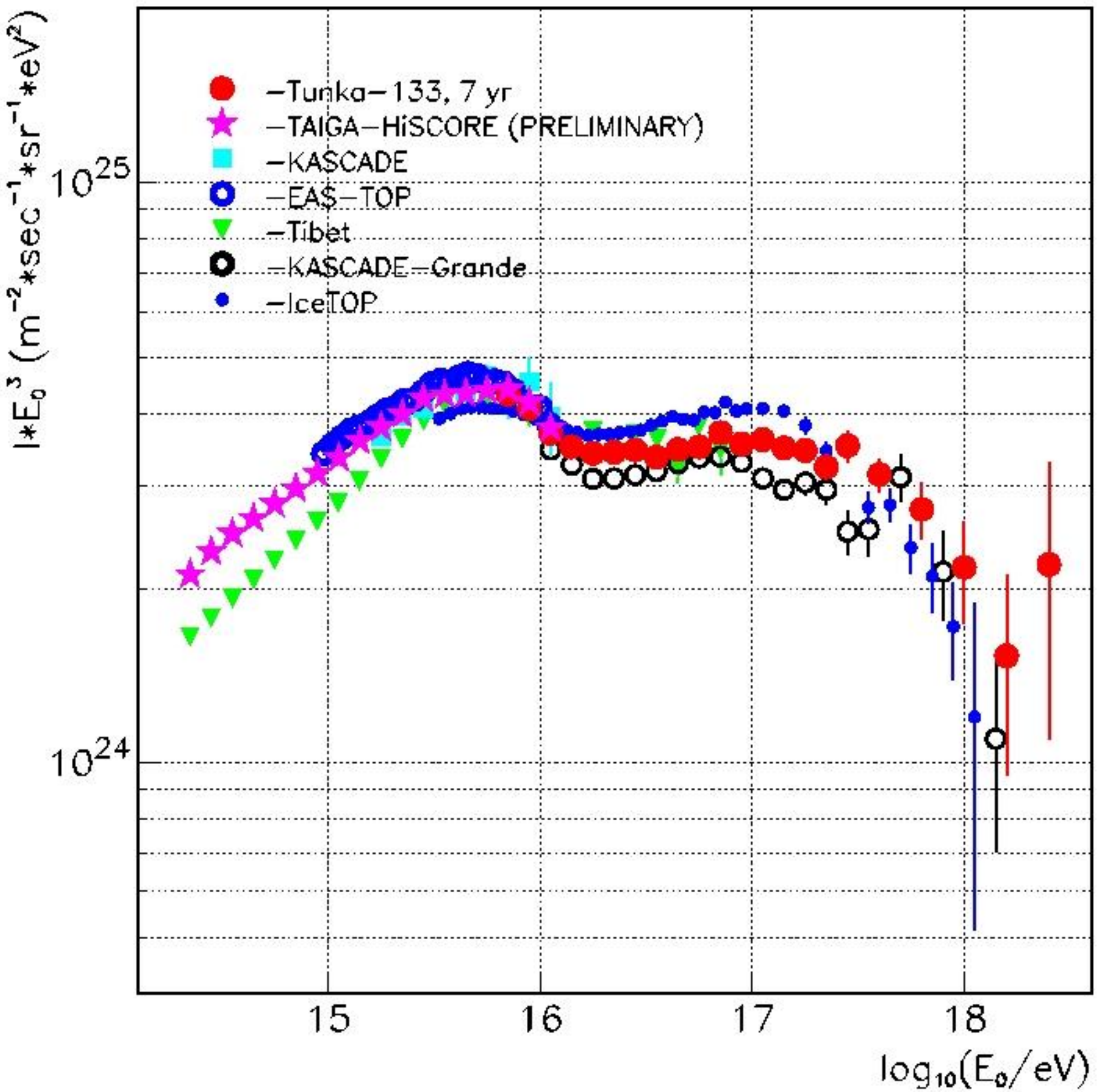
TAIGA-HiSCORE:
35 clean moonless nights
180 h
~900,000 events
with ~100% efficiency



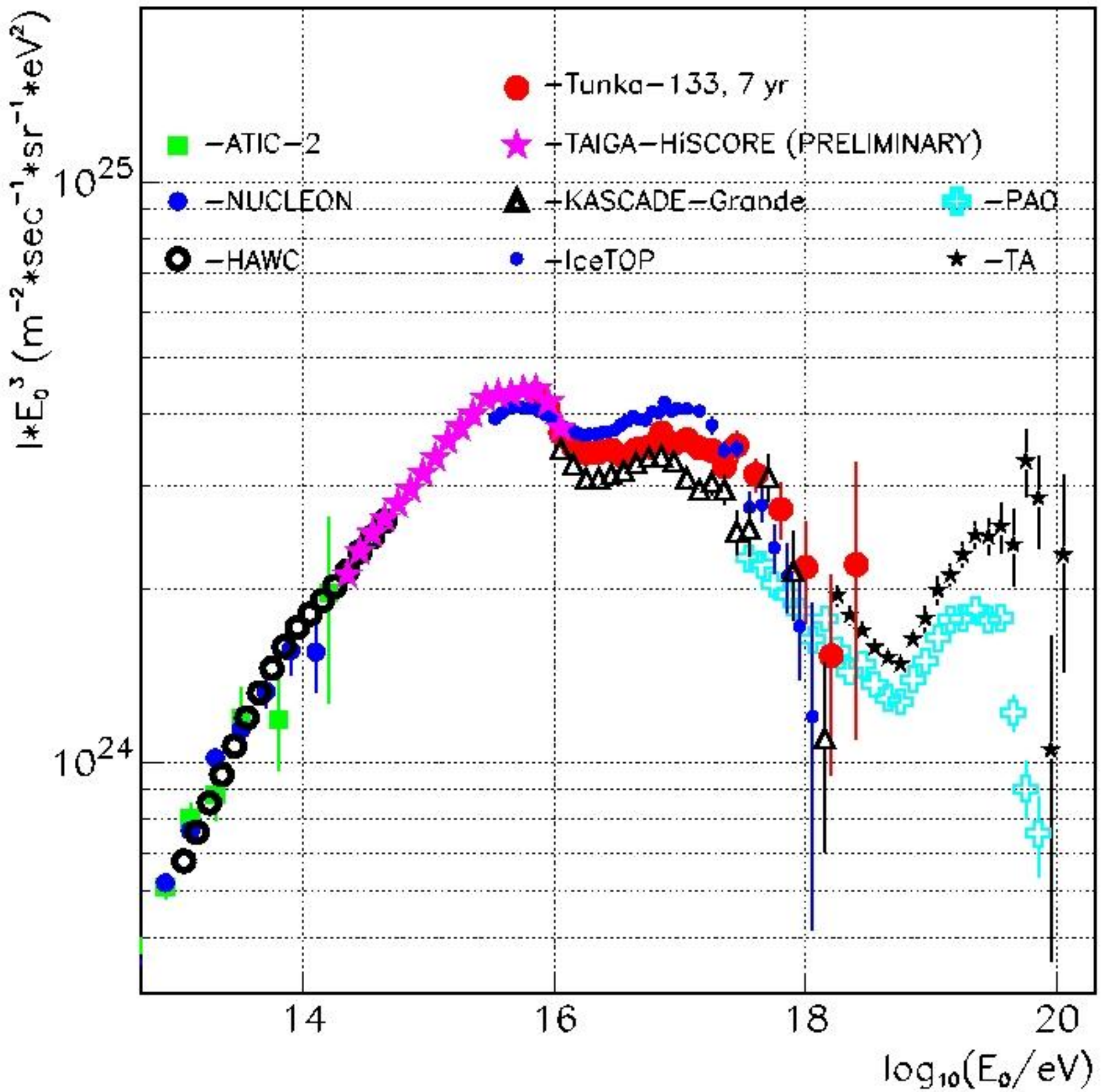
Energy spectrum: power law fitting



Energy spectrum comparison with intermediate enery experiments



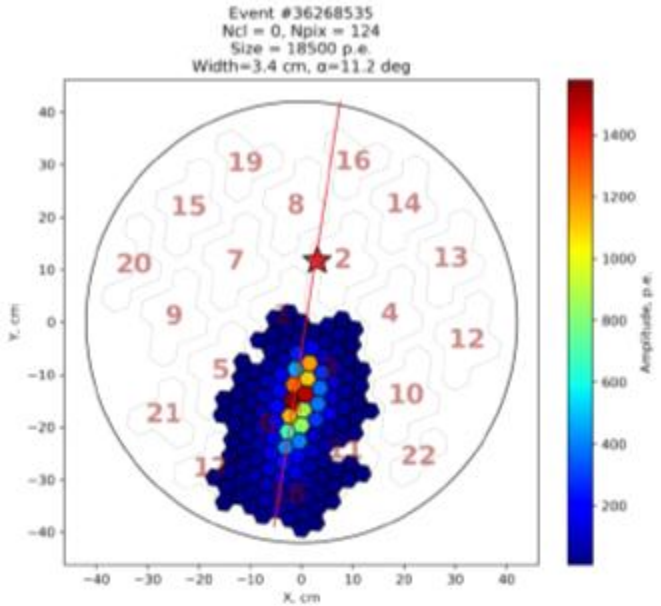
United Primary Energy Spectrum
$10^{13} - 10^{20}$ eV

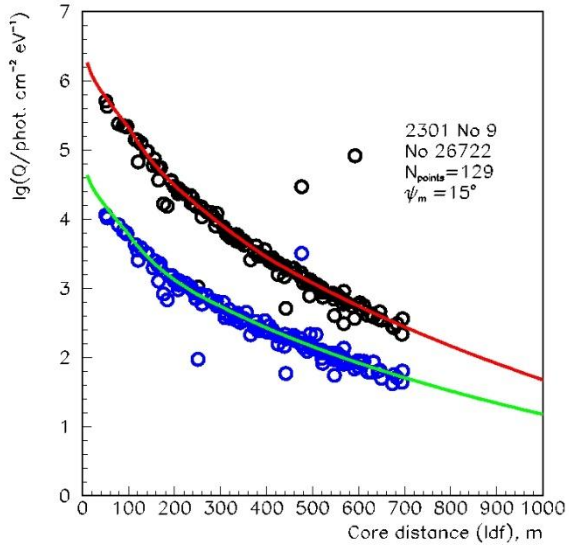


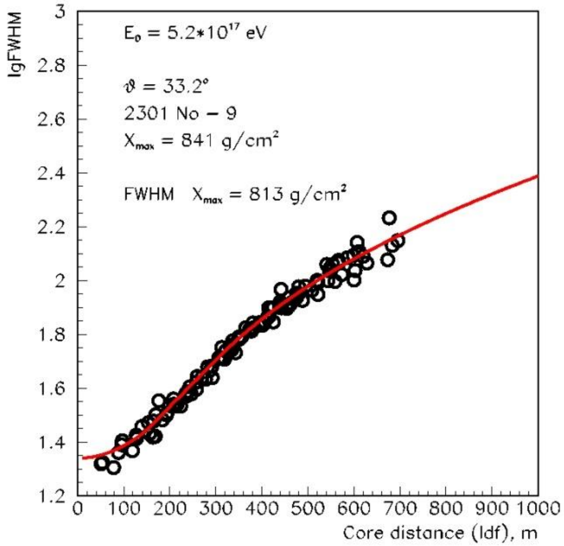
Perspectives of Mass Composition Study

$10^{14} – 10^{15}$ eV
IACT image analysis

$10^{15} – 10^{18}$ eV
Cerenkov light ADF steepness b_A
Cerenkov light pulse width at R_{core}= 300 – 400 m

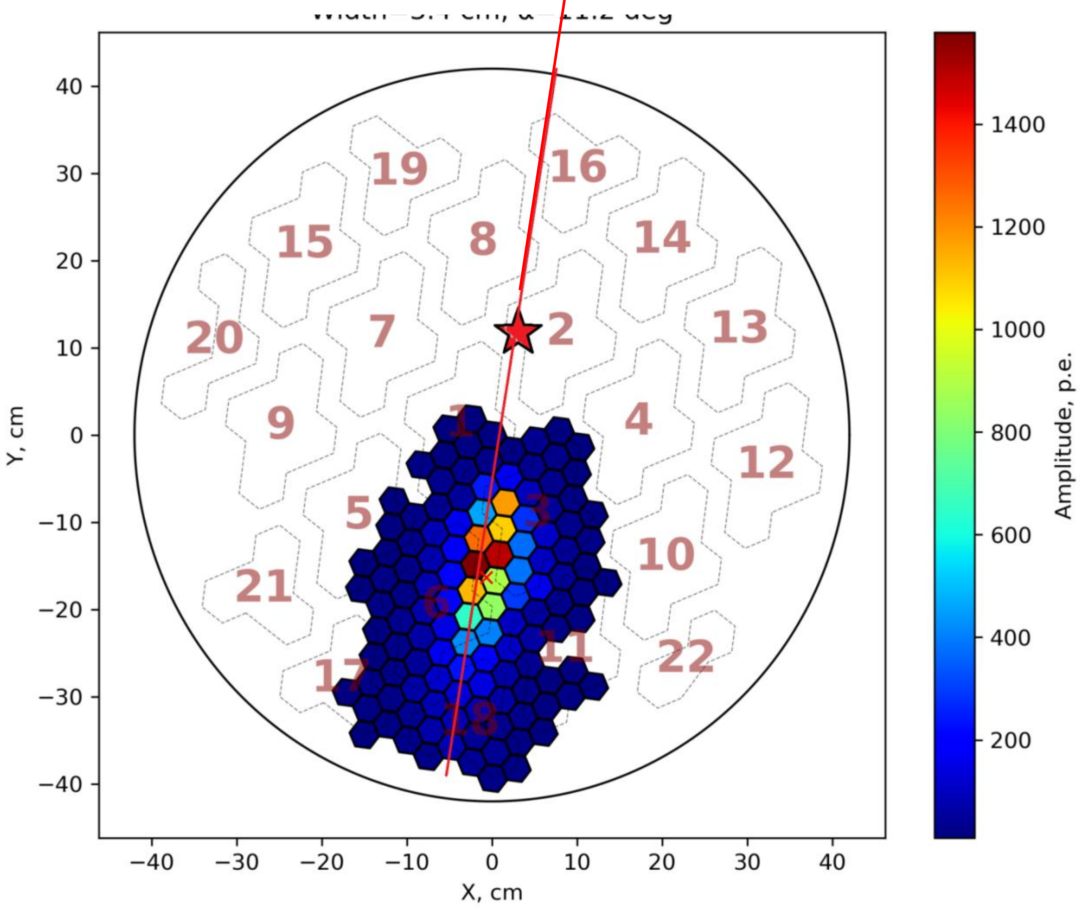






IACT and HiSCORE joint events

EAS core position
from HiSCORE



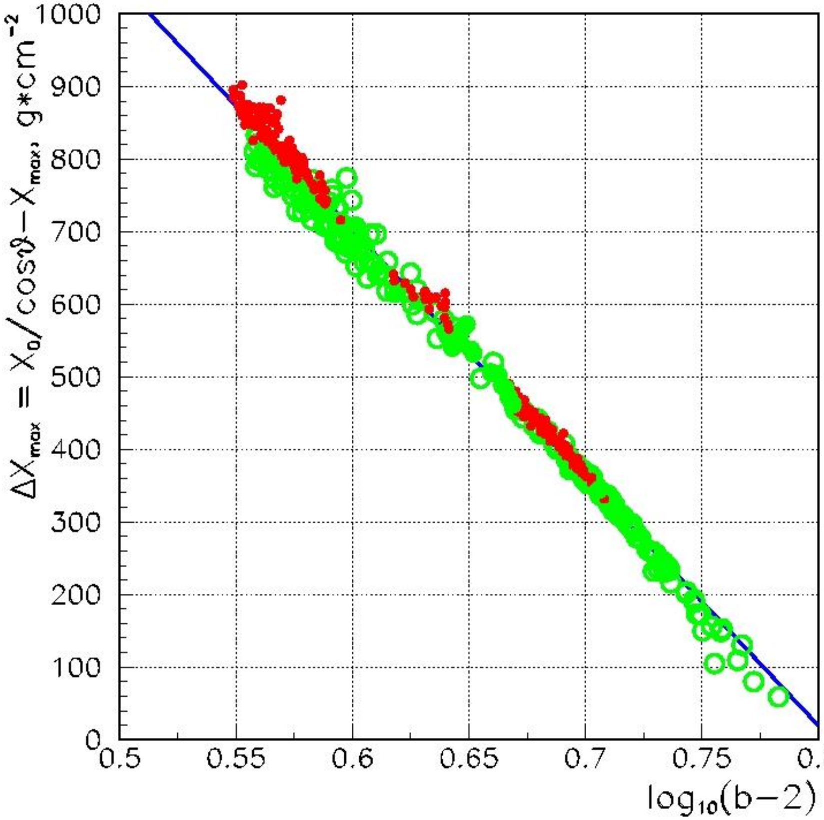
“Hadron –like” event

Energy from HiSCORE:
840 TeV

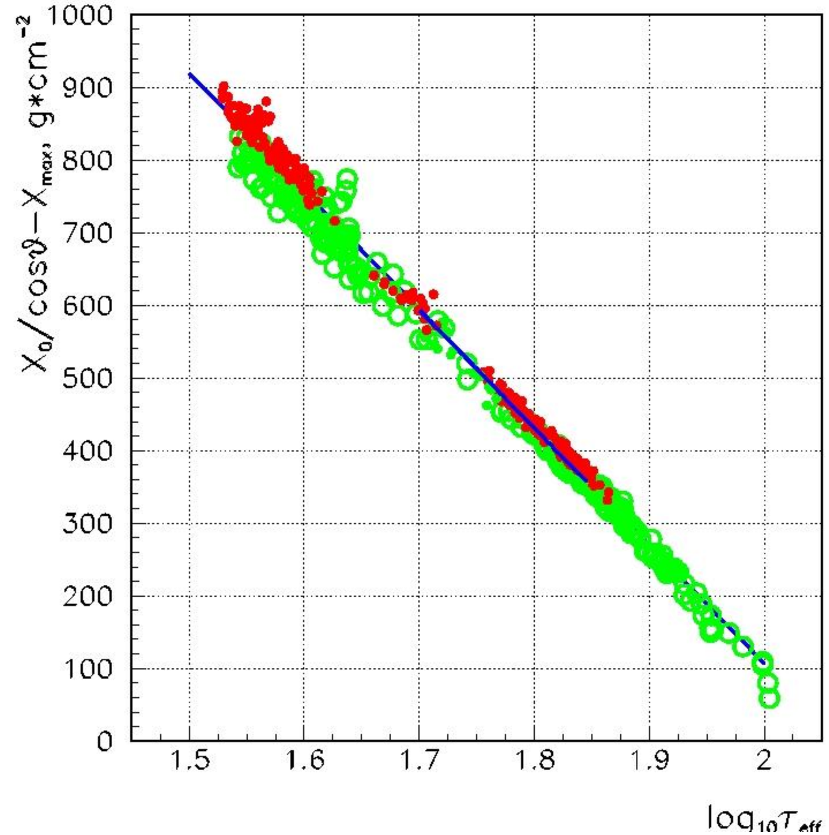
CORSIKA

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

ΔX_{max} vs. b_A (ADF steepness)

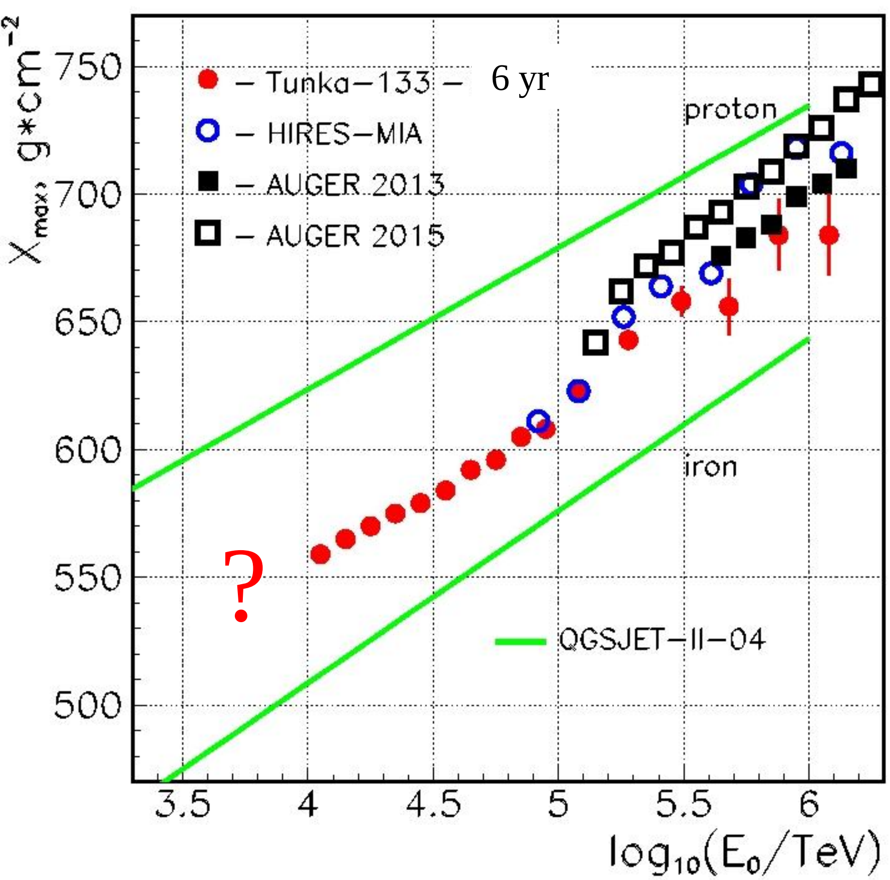


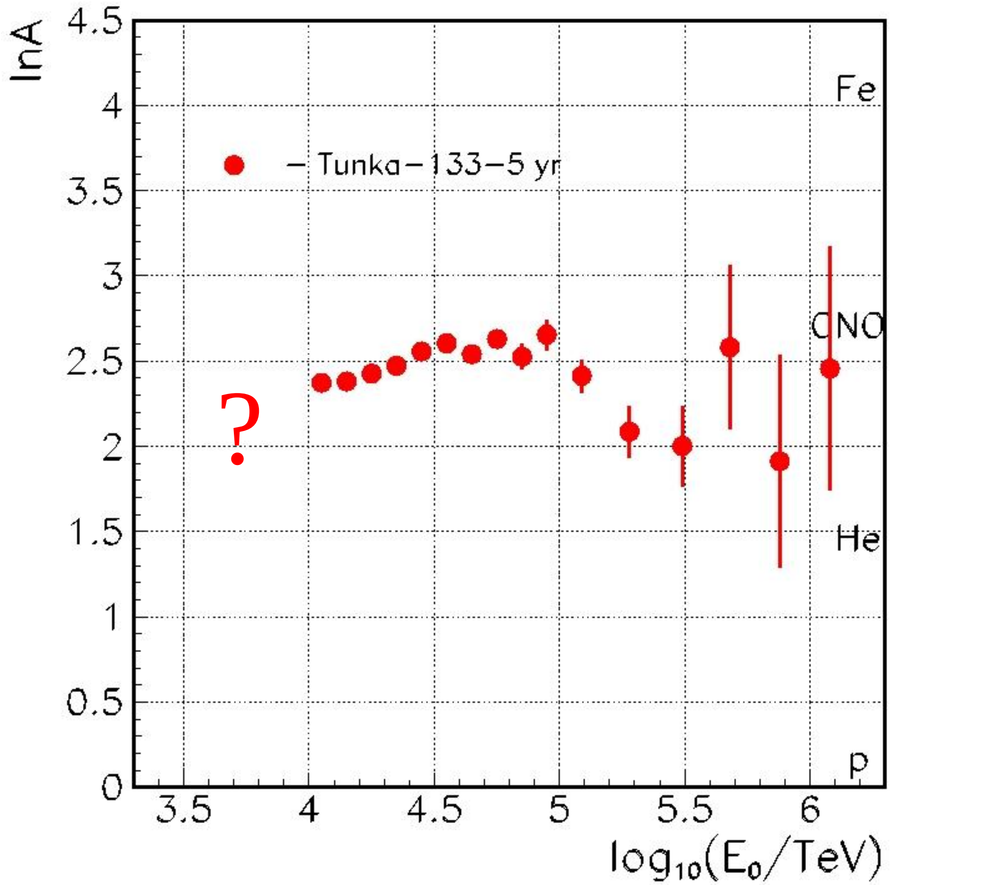
ΔX_{max} vs. $\tau_{eff}(400)$



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

$\langle X_{max} \rangle$ vs. E_0
Tunka-133 results of 2017

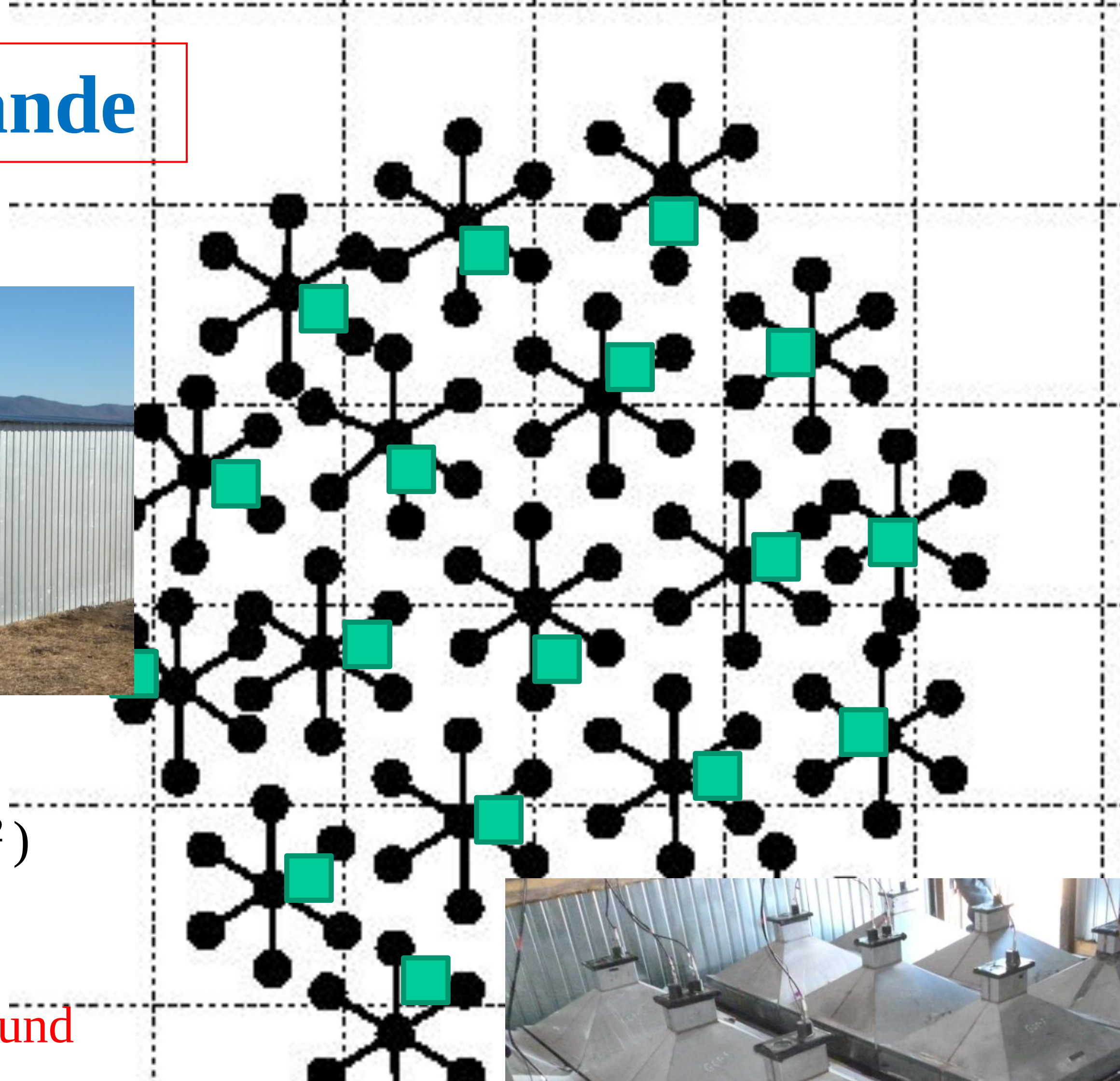




? – because of the works: ATIC-2, ARGO, HAWC

The new analysis of the TAIGA-HiSCORE data is needed.

Tunka-Grande



19 stations

228 detectors (0.64 m^2)
on the surface

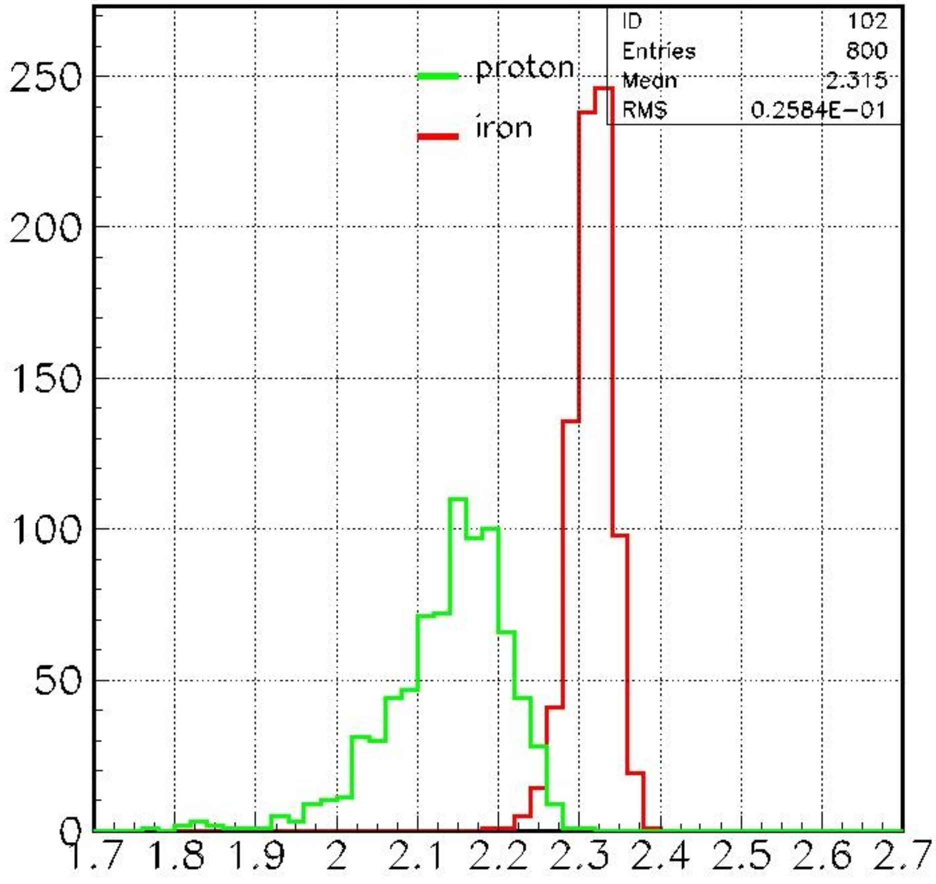
152 detectors undeground
(muons detectors),
total area = 100 m^2

Perspectives of Mass Composition Study

Tunka-Grande data
for the energy range $10^{17} – 10^{18}$ eV
Composition sensitive parameter:

$S = \log_{10}(\rho_{\mu}(200) – C\cdot \log_{10}(\rho_{sc}(200)$
ρ_{μ} muon density
ρ_{sc} all particle density

C ~ 0.9



S – distribution

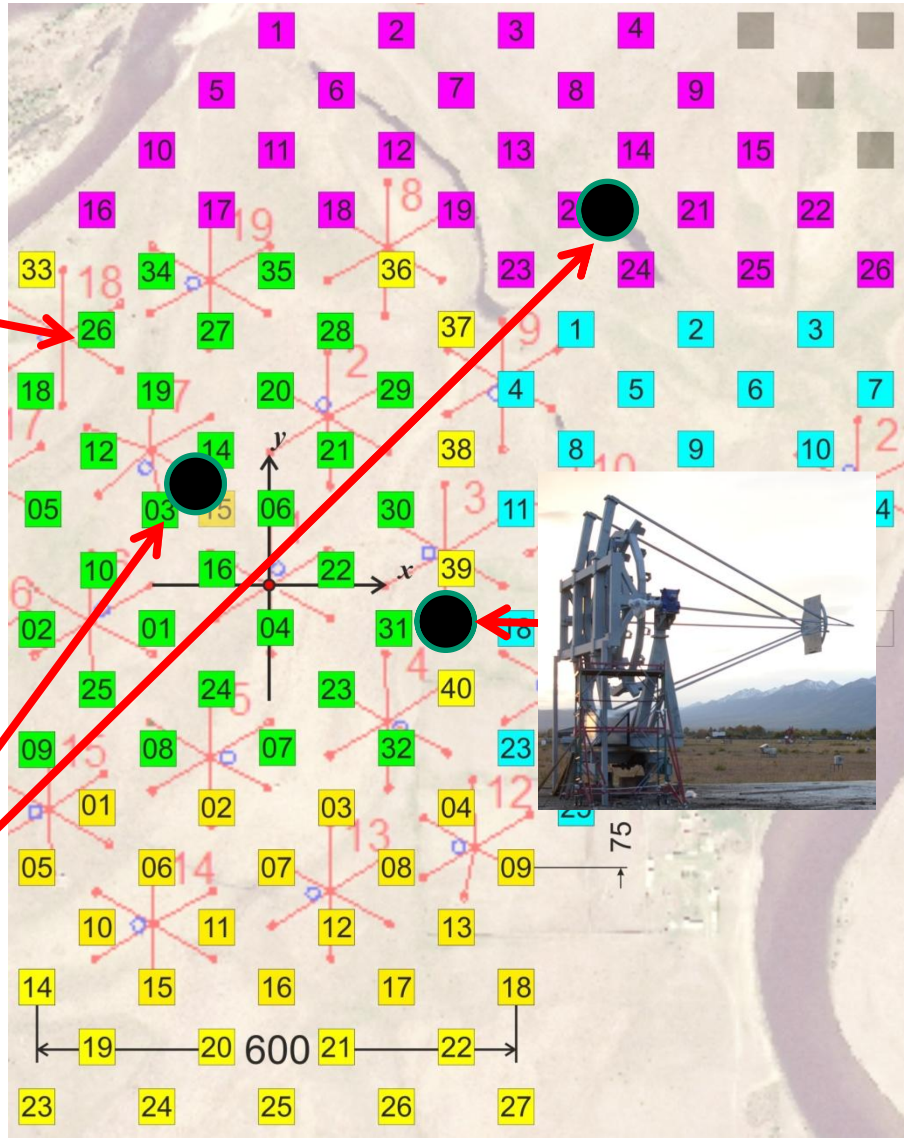
Tunka-REX

Connection of 2 antennas to
2 free channels of FADC

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

Plan for 2018-19

120 stations



For 100 hours

$3 \cdot 10^5$ hybrid events (CR mass composition)

50-100 hybrid events from Crab ($E \geq 40$ TeV)

Mirrors and camera
In April 2019

Long term plan for TAIGA

\+

\+

- **1000 wide angle optical station on the 10 km^2 area, energy threshold 30 TeV.**

- **15-20 IACTs (10 m^2 mirrors).**

- **Muon detectors with total area 3.0 10^3 m^2.**

Conclusions

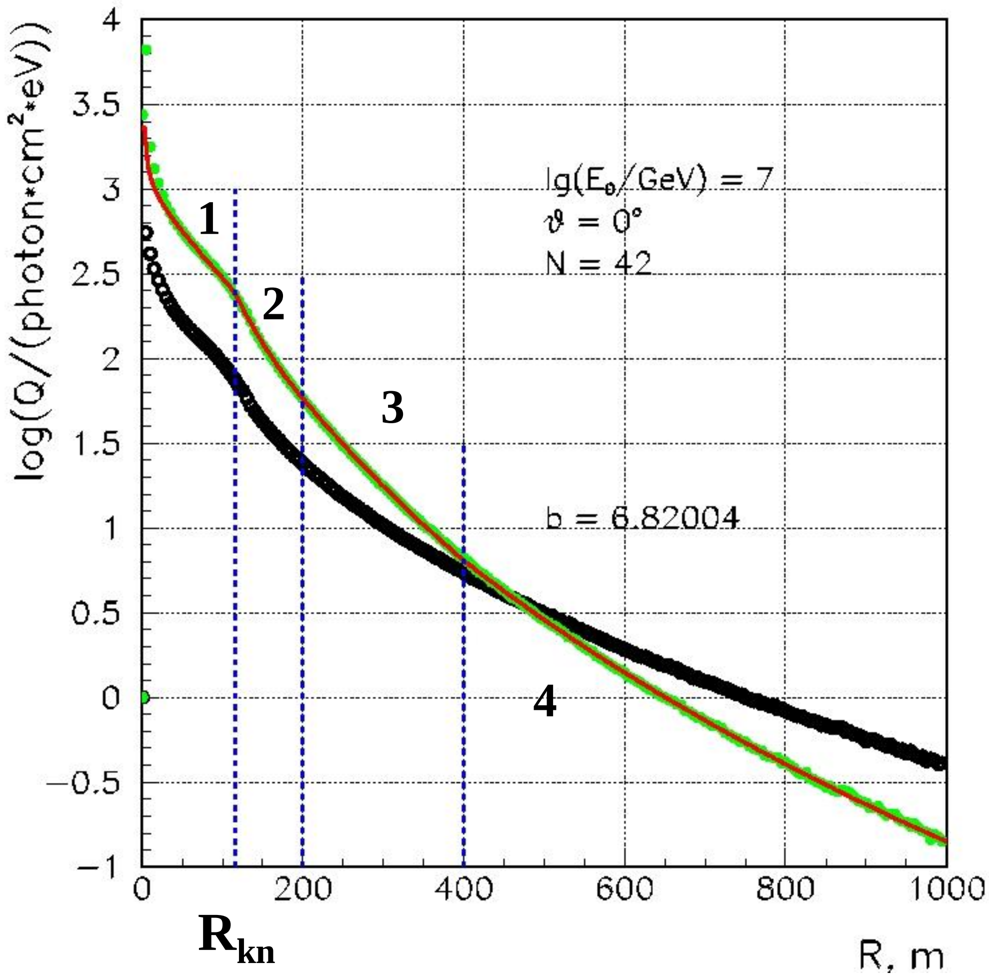
1. United primary energy spectrum, obtained by the same method of EAS Chernkov light flux measurement cover 4 orders of magnitude and let us confirm that the primary energy measurements are in good agreement from relatively low (10^{13} eV) to extremely high energy (10_{20} eV)
2. Deployment of the full scale TAIGA prototype – 120 wide-angle stations and three IACTs is planned for 2019.
3. The results from joint operation of HiSCORE and IACT we hope will let us estimate the primary mass composition for the energy around 10^{15} eV

Thank you!

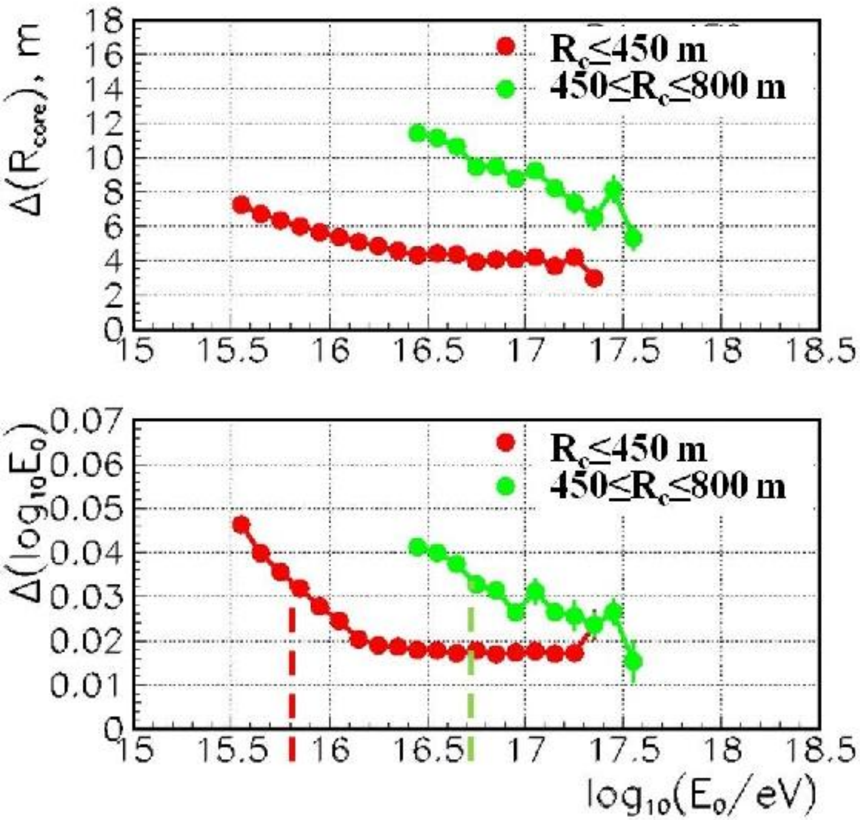
ADF:

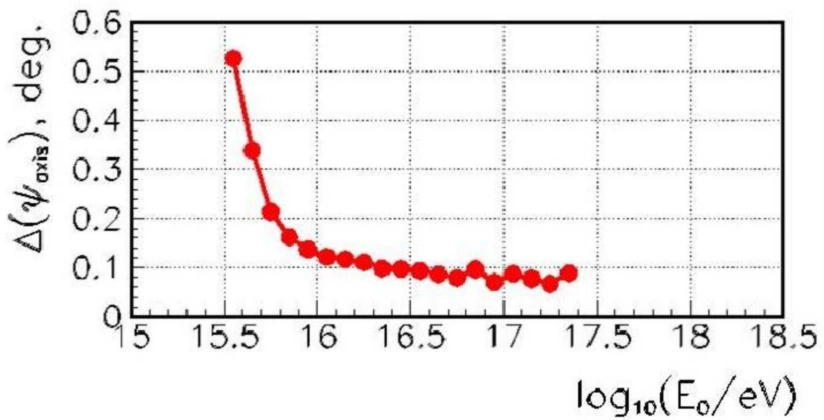
1. $A(R) = A_{kn} \cdot \exp((R_{kn}-R) \cdot (1+3/(R+2))/R_0)$
2. $A(R) = A_{kn} \cdot (R_{kn}/R)^c$
3. $A(R) = A(400) \cdot ((R/400+a)/(a+1))^{-b}$
4. $A(R) = A(400) \cdot ((R/400+1)/2)^{-b}$

All four variables ($\mathbf{R_0}$, $\mathbf{R_{kn}}$, **a** and **c**), describing the ADF shape in the different ranges of core Distance, are related to a single parameter of the ADF shape – the steepness **b.**



ICRC 2013


Δ(R_core), m
R_c≤450 m
450≤R_c≤800 m
Δ(log10E0)
log10(E0/eV)


Δ(ψ_axis), deg.
log10(E0/eV)