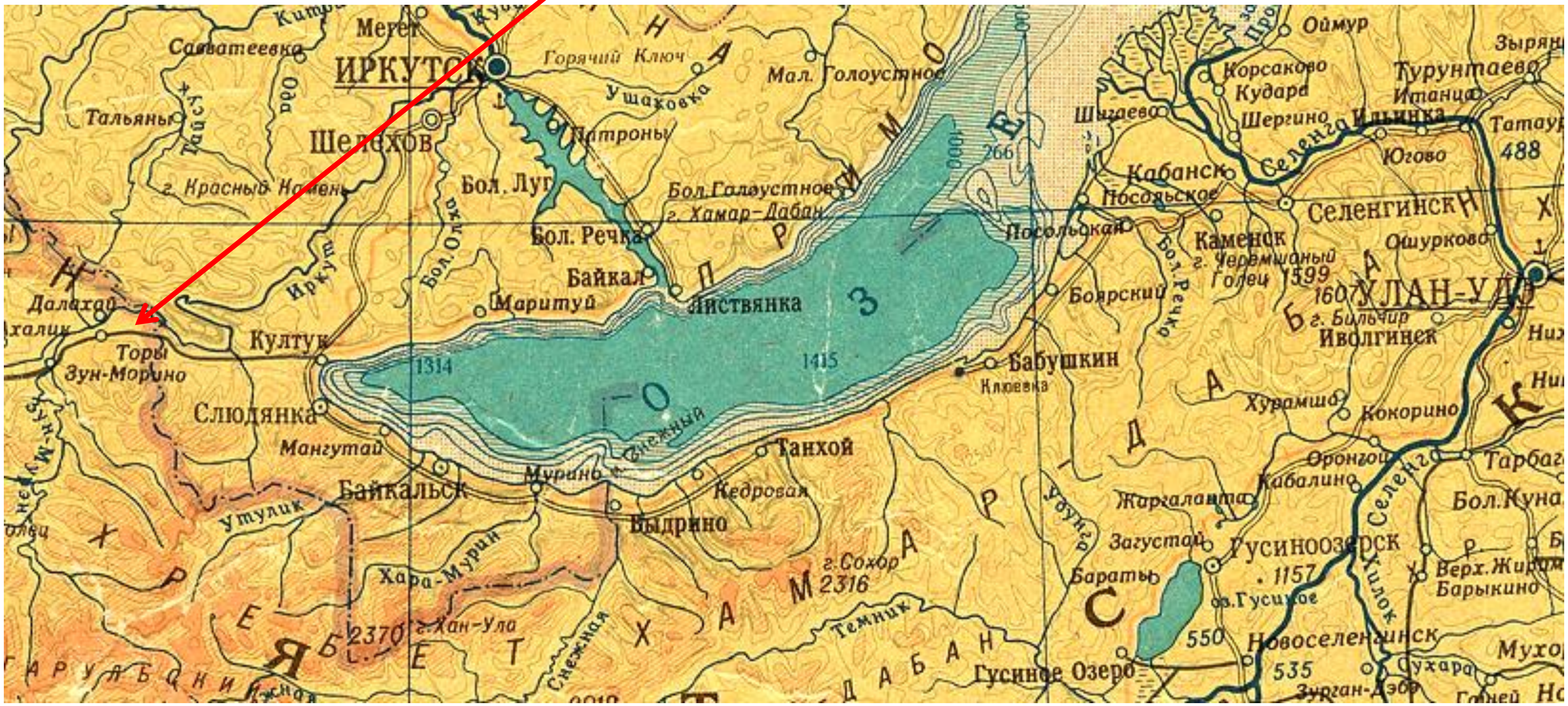
30 years of cosmic ray research in the Tunka Valley.



N. Budnev, L. Kuzmichev For TAIGA-collaboration

Astrophysical complex in the Tunka Valley - stages of development

1992 – 4 photodetectors with Quasar-370 on ice of the lake Baikal.

1993 – shift to the Tunka Valley (50 km from the lake Baikal)

1993 – 1995 - **TUNKA-4 wide-angle Cherenkov array** – the first CR spectrum in the knee region using only Cherenkov light data.

1996 – 1999 - TUNKA-13 array – improved CR spectrum and mass composition

1998 – 2000 - QUEST (Quasars-370 on EAS-TOP) calibration experiment.

2000 – 2005 - Tunka-25 array - precise CR spectrum in energy range 0,8 – 100 PeV using new data analysis methods.

2006 - …….. Tunka -133 3 km^2 array – the feature in the CR spectrum at an energy of 20 PeV and the "second knee" at energy 100 PeV…..

2012 – 2019 – Tunka-Rex – CR energy spectrum and mass composition using radio data and original methods

2014 - ……. - TAIGA - HiSCORE – precise CR energy spectrum at an energy of 0,2 – 1000 PeV

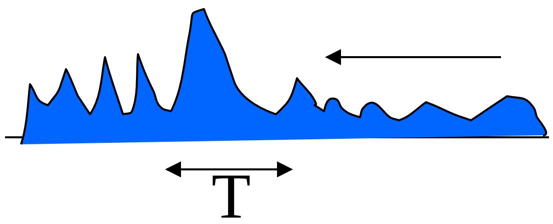
2015 - …….. - Tunka –Grande - CR energy spectrum at an energy of 0,2 – 1000 PeV

2017 - ……. .- TAIGA-IACTs - a net of Imaging Atmospheric Cherenkov Telescope

The main specificity of the Tunka experiment are using wide-angle installations to detected Cherenkov light of EAS

The energy threshold of the Cherenkov array linearly depends on the area of the photomultiplier

Cherenkov's pulse and night sky background



$$\frac{\text{Signal}}{\text{Background}} = \frac{S_D \bullet P_{ph} \bullet \eta}{\sqrt{\Delta\Omega \bullet S_D \bullet I_b \bullet T}} \approx 5$$

$P_{ph} \sim E$ - energy

$$E_{th} \sim \frac{\sqrt{I_b \bullet \Delta\Omega \bullet T}}{\sqrt{S_D \bullet \eta}}$$

S_D – PMT square

η- quantum sensitivities.

P_{ph} – Cherenkov photon flux

T - pules duration (20 –40 ns)

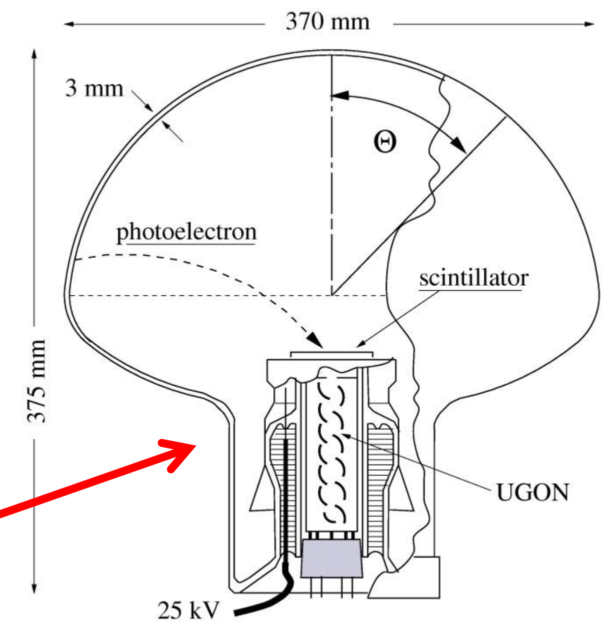
$\Delta\Omega$ - aperture

I_b – background of night sky

$\approx 2.10^{12}$ photons/m^2 s

For $S_D \sim 0.1\ m^2$ and $\eta \approx 0.1$: $E_{th} \approx 100$ TeV

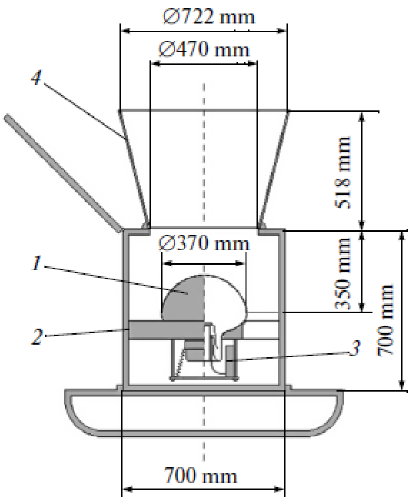
PMT Quasar-370

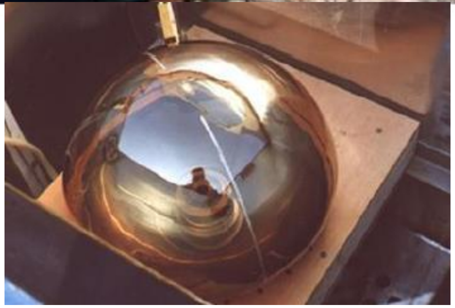


The beginning of cosmic ray research in the Tunka Valley is associated with the Baikal Neutrino Project.

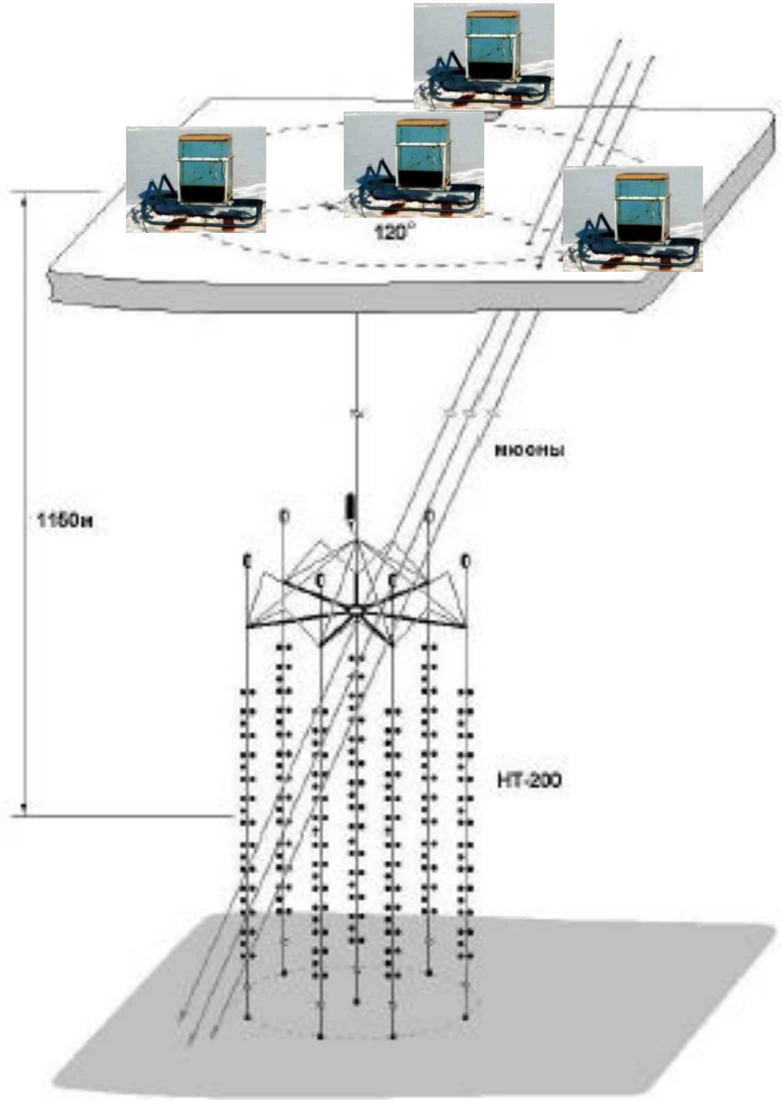
1991-1993 – experiment SMEGA (Surface Mobile EAS Cherenkov Array)

The purpose of the experiment was to experimentally check the accuracy of restoring the direction of atmospheric muons using the underwater NT-36 setup on lake Baikal.

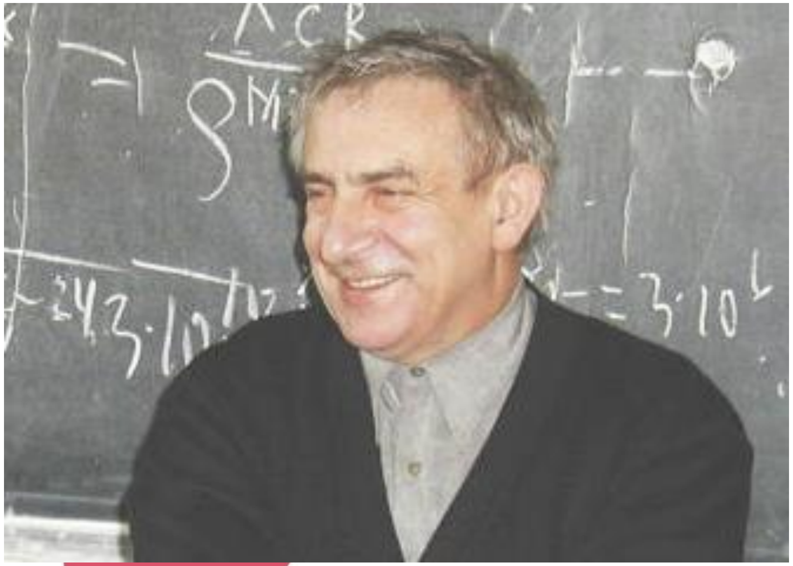


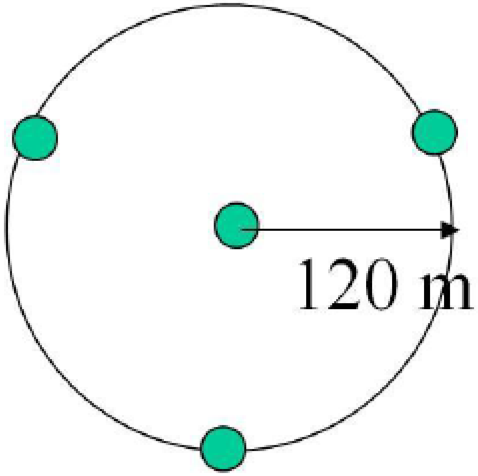


PMT Quasar-370G

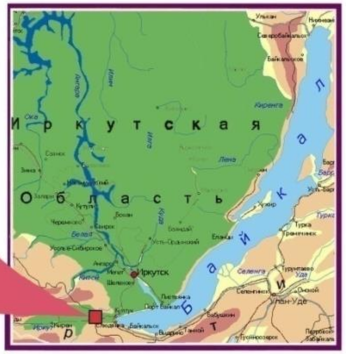


Tunka-4 array (1993-1996)

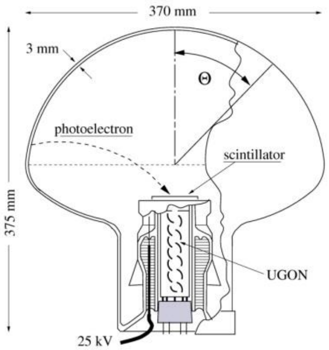




51°48’ 35” N
103° 04’02” E
675 m a.s.l.



The high sensitivity of the array was achieved due to the use of “Quasar-370” photodetectors.



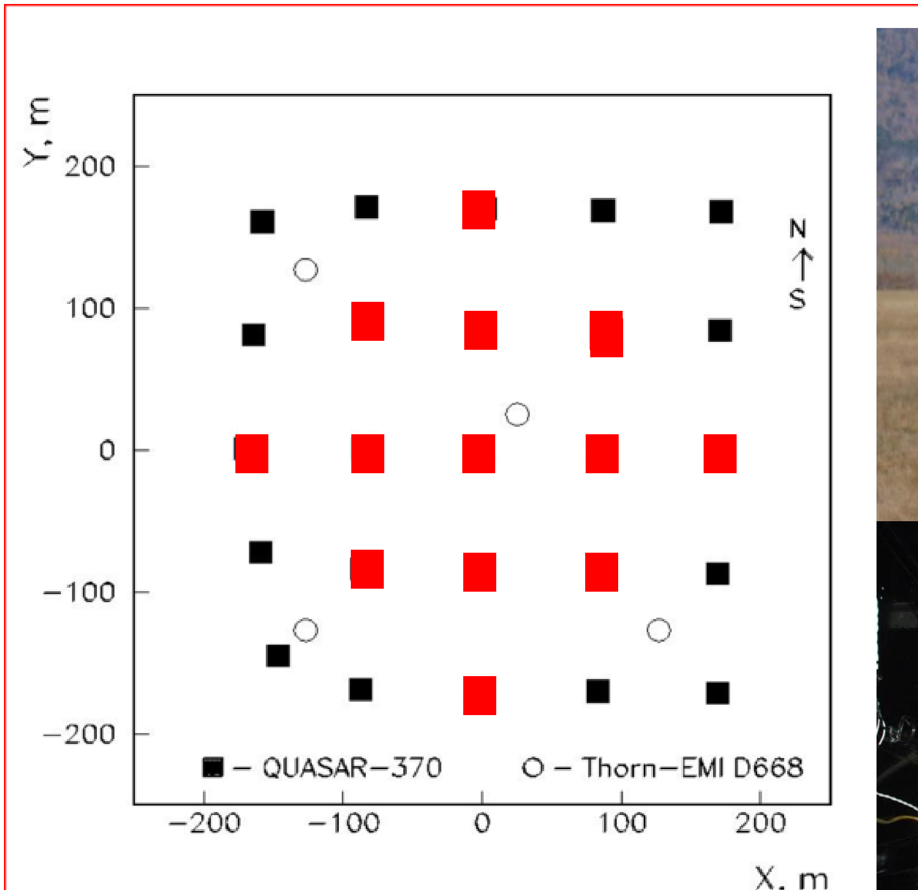
Director of API ISU Yu. Parfenov suggested to use infrastructure of the ISU radiophysical test site in Tunka Valley for cosmic ray study.

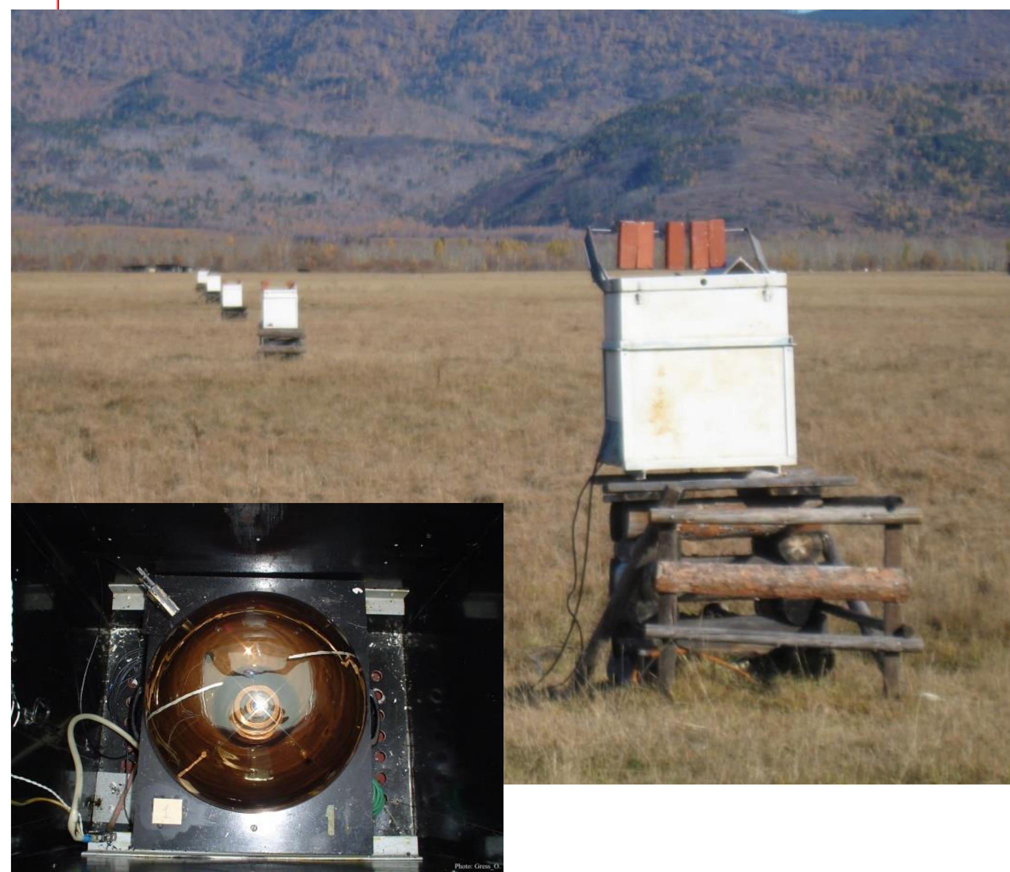
For the first time, the CR spectrum was measured in the knee area with using only Cherenkov light

Tunka EAS Cerenkov light installation with QUASAR-370 PMT

1996 – 1999 – Tunka-13 – 13 QUASAR-370 PMT (red square)
1998 – 2000 – QUEST (5 PMTs QUASAR-370 at EAS-TOP in LNGS).
2000 – 2005 – Tunka-25, S = 0.1 km^2 in the Tunka Valley –

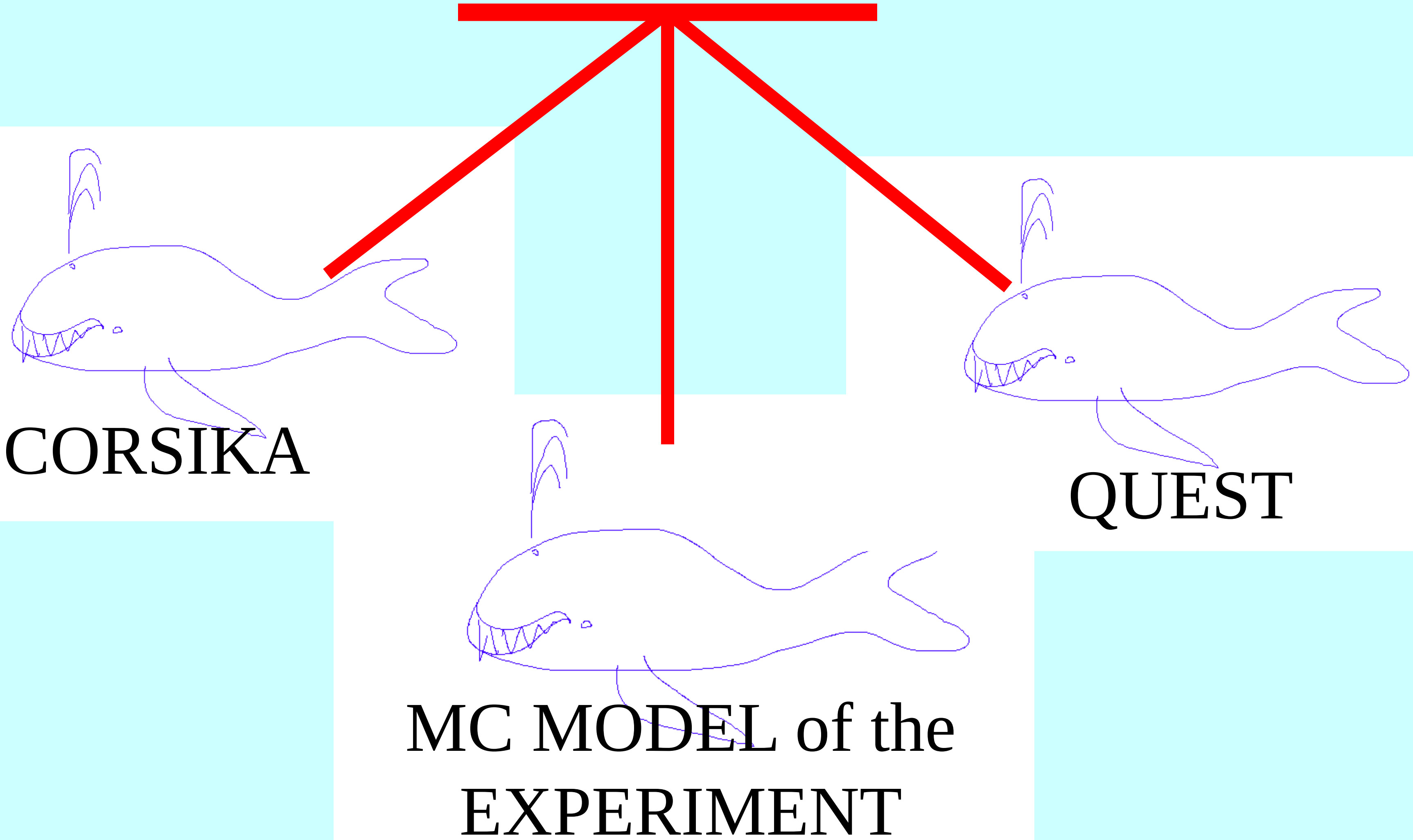
Energy range 0.8· – 100 PeV .





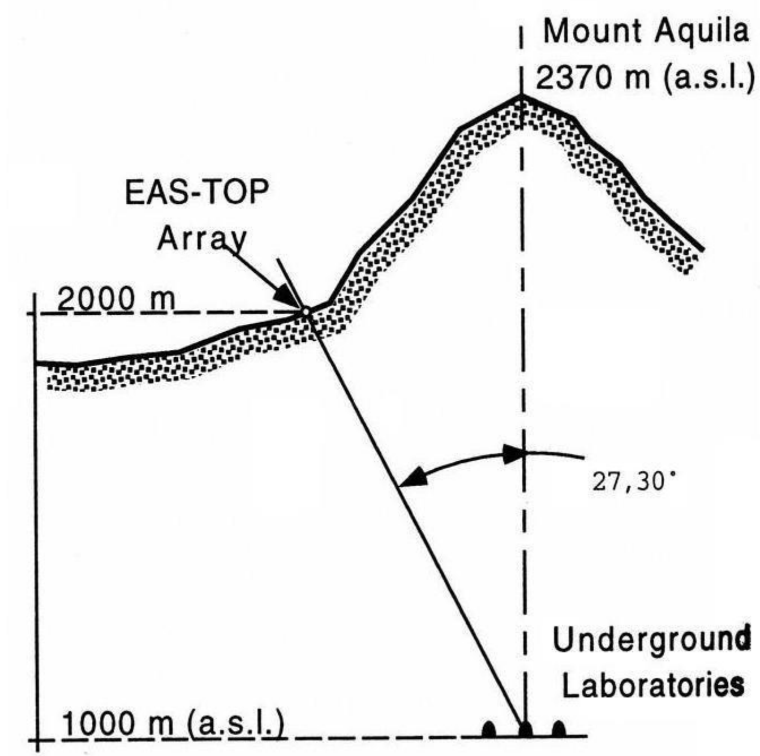
The authors of the installation Tunka-25 array

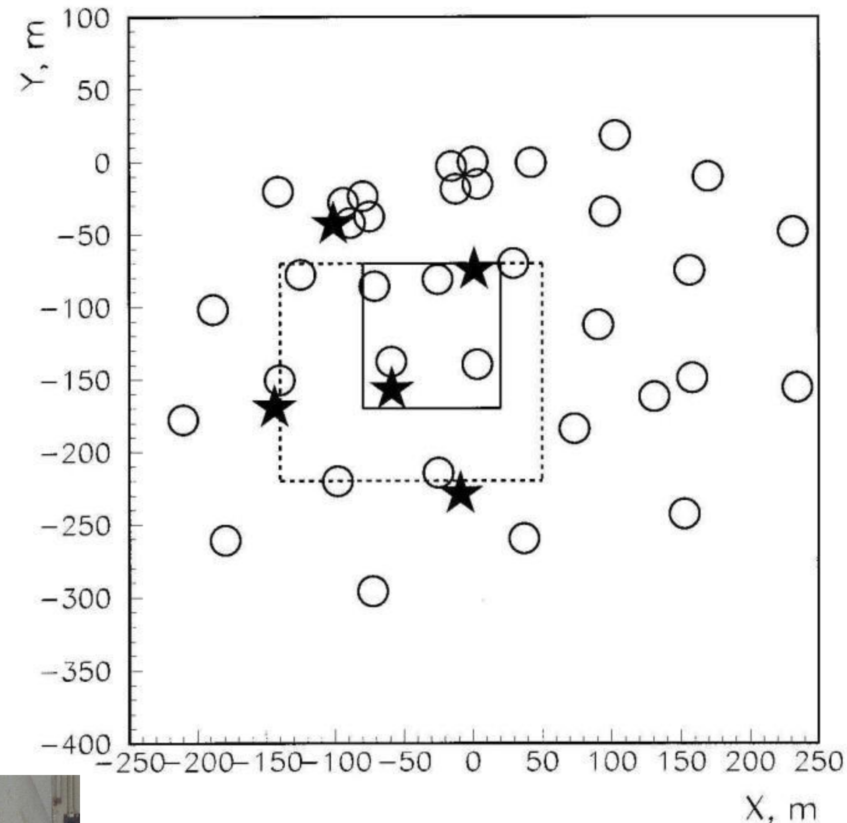
TUNKA data analysis is based on three whales

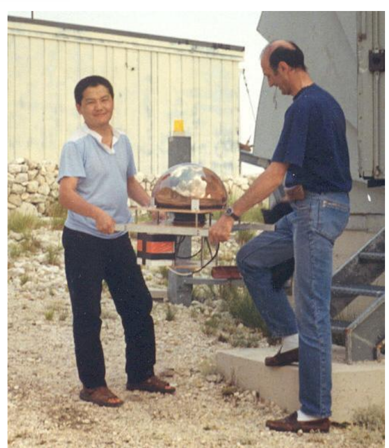


Experiment QUEST (QUasars at EaS-Top)

for absolute energy calibration of Tunka Cherenenkov detectors.







★- Wide-angle Cherenkov detectors with Quasar-370G

○ - Scintillation detectors

EAS Energy

$$E = A \cdot [N_{ph}(200m)]^{g}$$

$g = 0.94 \pm 0.01$ (For $10^{16} - 10^{18}$ eV)

Data processing methods

Q (200) -Cherenkov light flux density at a core distance of 200m

Average CR mass A

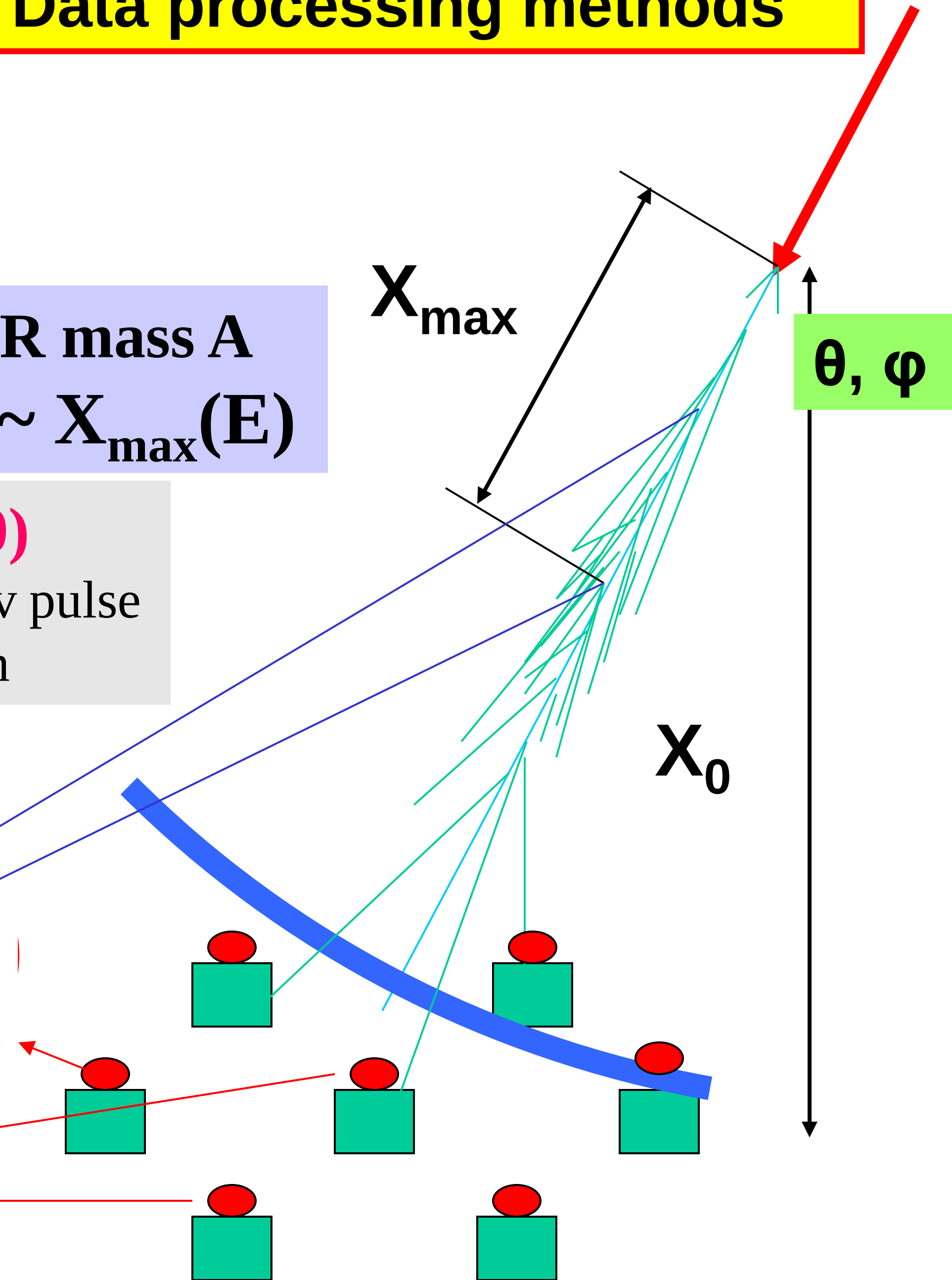
$$LnA(E) \sim X_{max}(E)$$

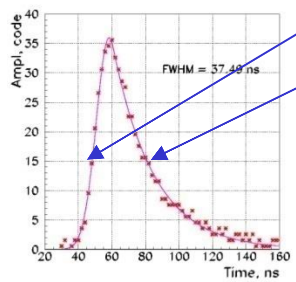
$$X_{max}(E) = C - D \cdot \lg \tau(400)$$

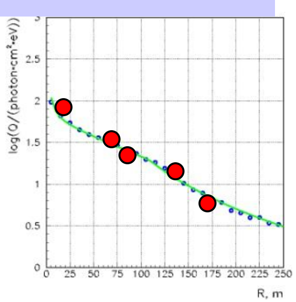
τ(400) - duration of a Cherenkov pulse at distance 400 m EAS core from

$$X_{max}(E) = F(P)$$

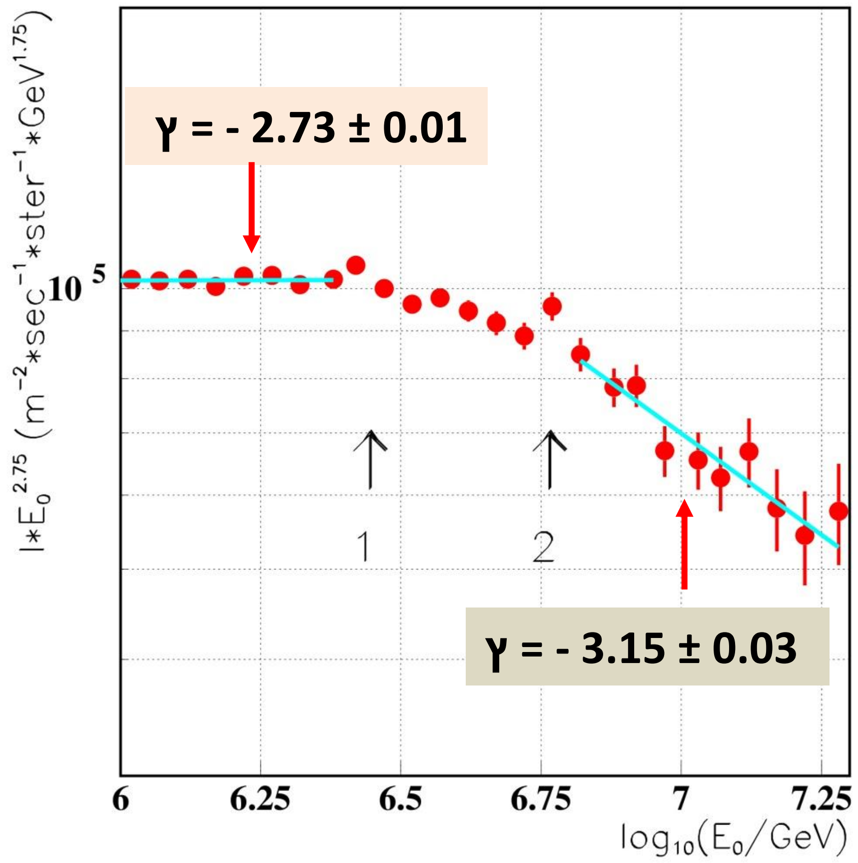
P -Steepness of a Lateral Distribution Function (LDF)

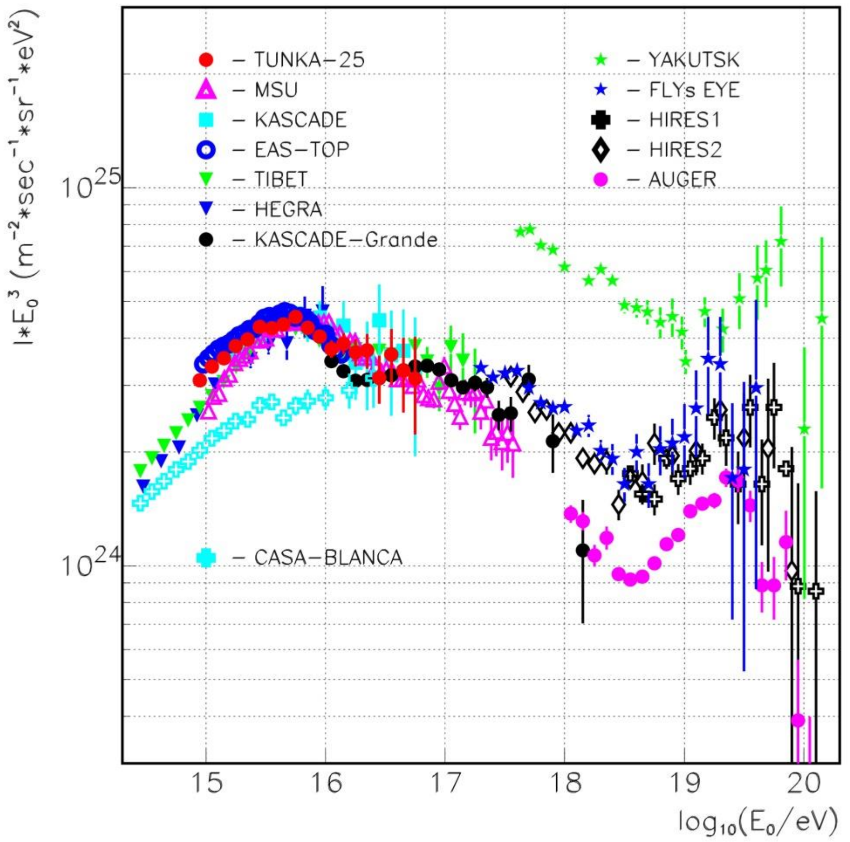






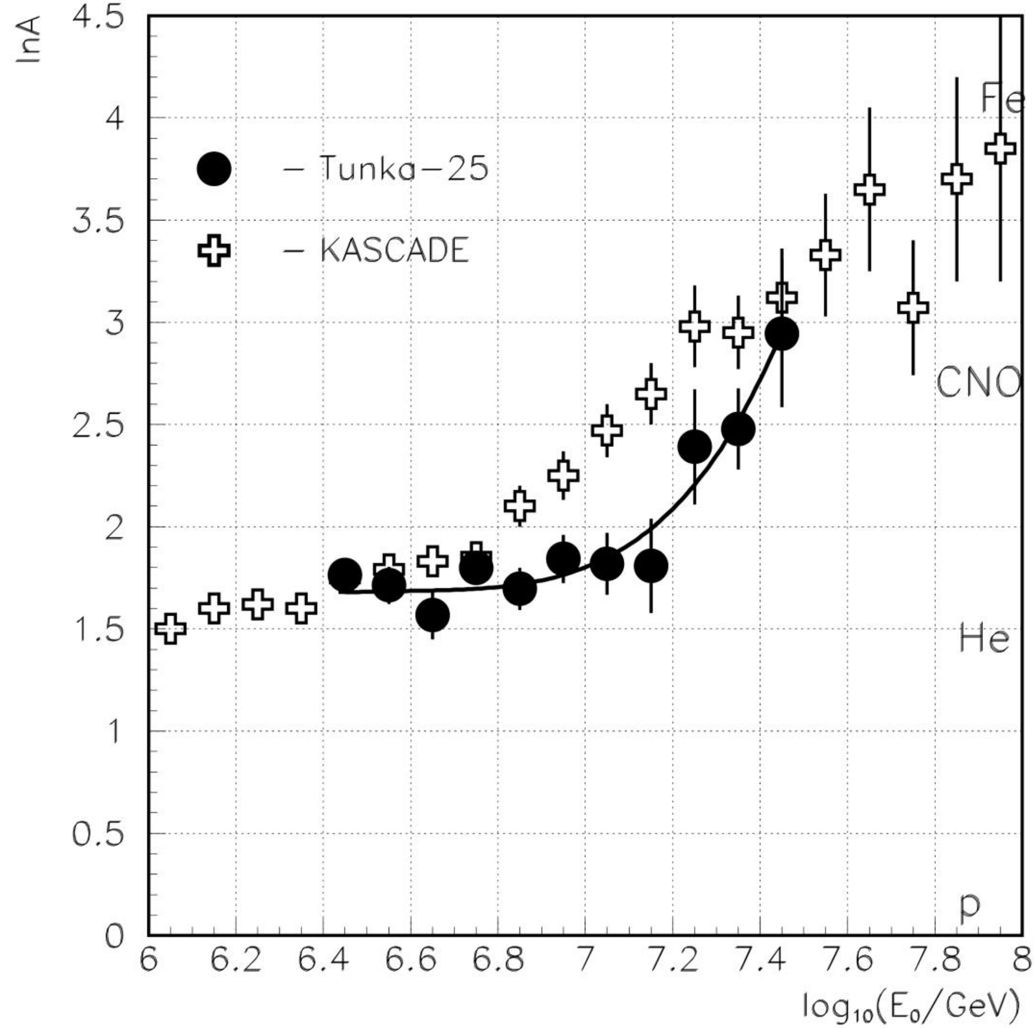
Tunka-25 energy spectrum





Astroparticle Physics. 2013. -V.50–52,. - P. 18–25
doi.org/10.1016/j.astropartphys.2013.09.006

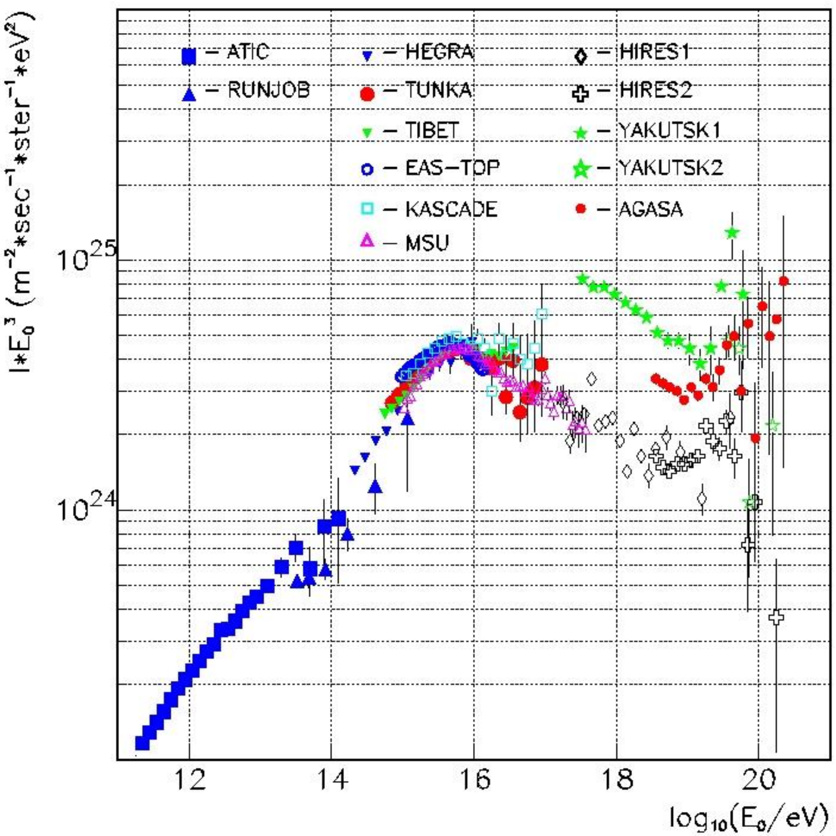
The Tunka-25 cosmic ray mass composition

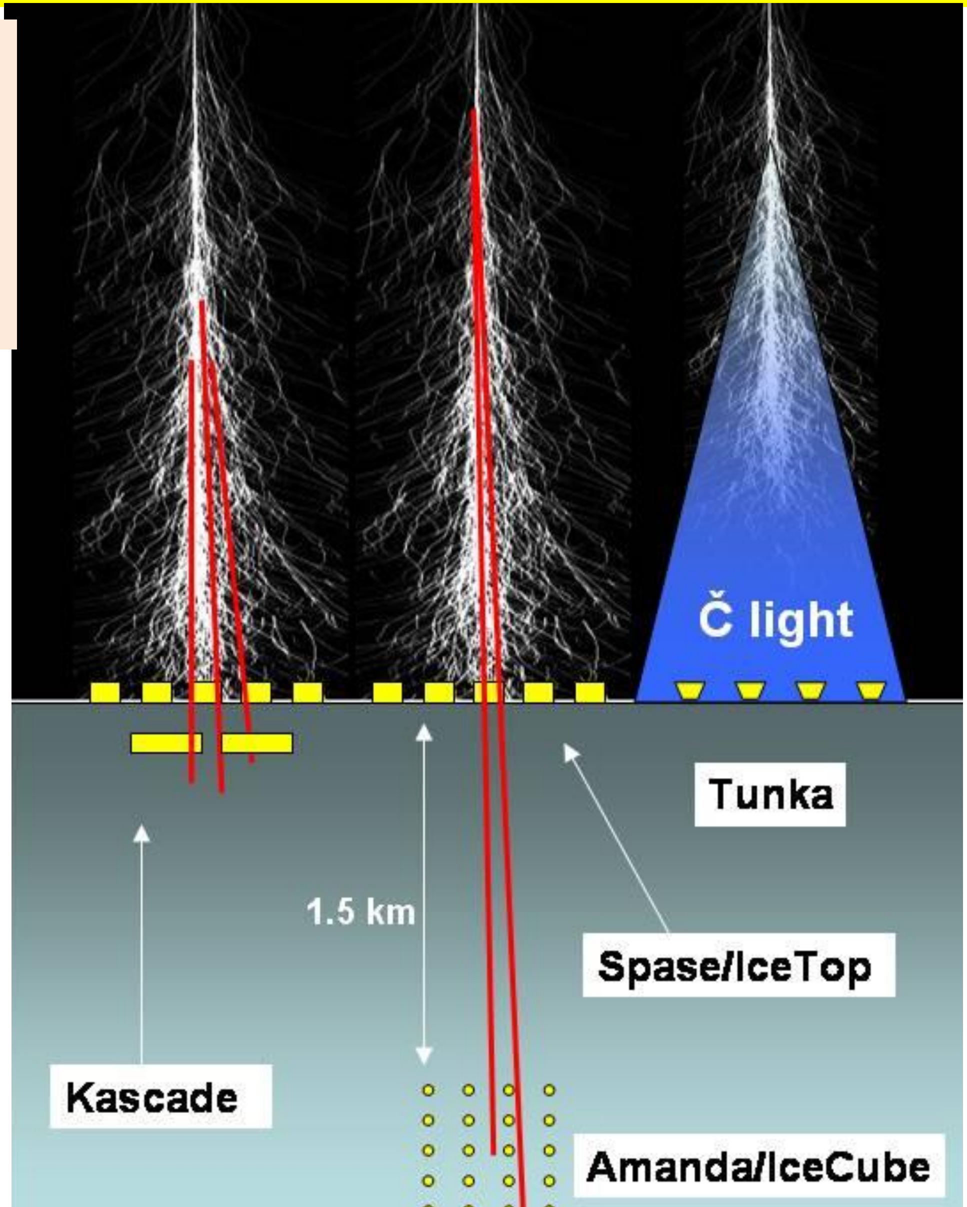


Astroparticle Physics. 2013. -V.50–52,. - P. 18–25
http://dx.doi.org/10.1016/j.astropartphys.2013.09.006

Towards 1 km^2 square Tunka Cherenkov array

Projects of dense installations with an area of about a 1 km^2 for the study of cosmic rays in the energy range of 10 - 1000 PeV.





Some important steps towards Tunka-133 – 1 (3) km^2 wide-angle Cherenkov array for energy range 3 – 1000 PeV

1. 2002: G.Navarra suggested to ask for PMTs from MACRO for the new Tunka array.

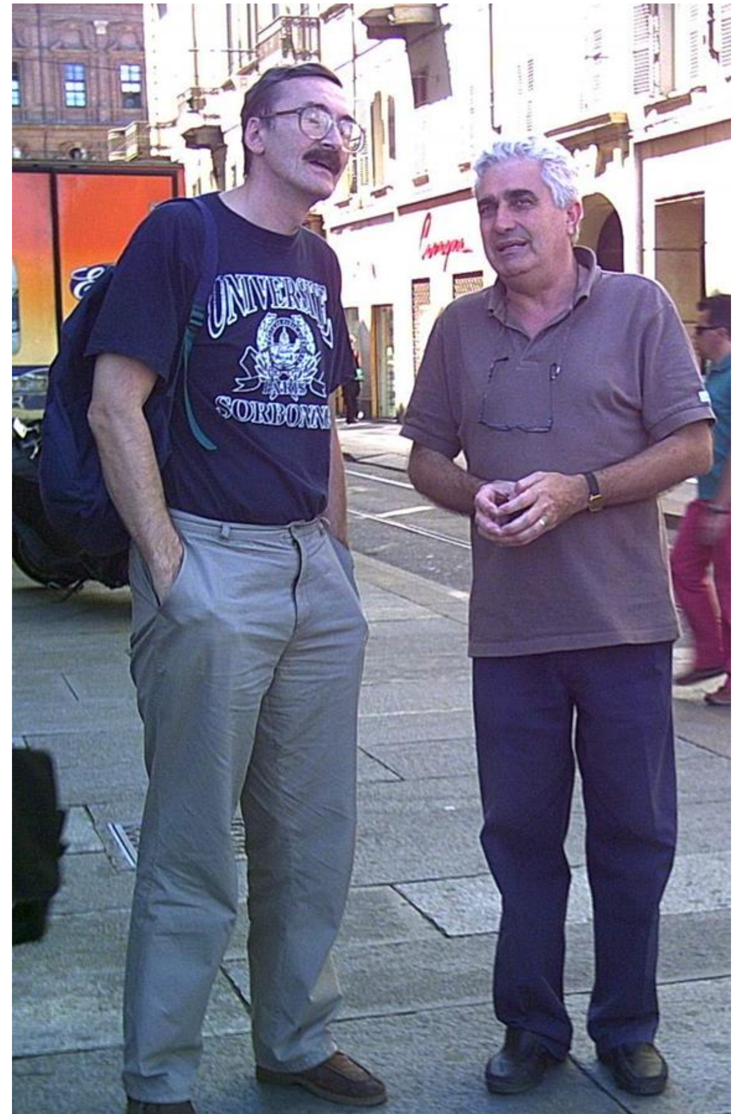
2. 30.12.2003: 200 PMT in Moscow.

3 2004 : Starting R&D with financial support from DFG- RFBR.

4. 2005: Optical cable (~ 10km) from the closed project EAS1000.

5. 2006 : Starting of financial support of the project from Ministry of Education and Science.

Project budget ~ 100 -150 KEuro per year



Leonid Kuzmichev& Gianni Navarra

Tunka Collaboration

N.M. Budnev, O.A. Chvalaev, O.A. Gress, A.V.Dyachok, E.N.Konstantinov, A.V.Korobchebko, R.R. Mirgazov, L.V. Pan'kov, A.L.Pahorukov, Yu.A. Semeney, A.V. Zagorodnikov
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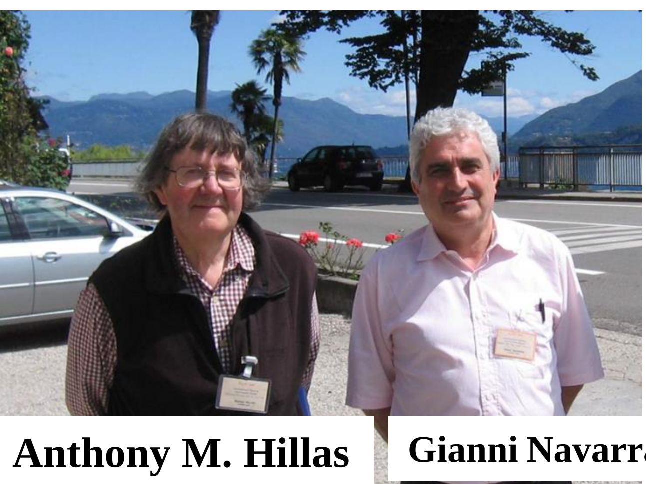
DESY-Zeuthen, Zeuthen, Germany;
A.Chiavassa, G. Navarra
Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.



Anthony M. Hillas **Gianni Navarra**

Start of deployment – 2006y

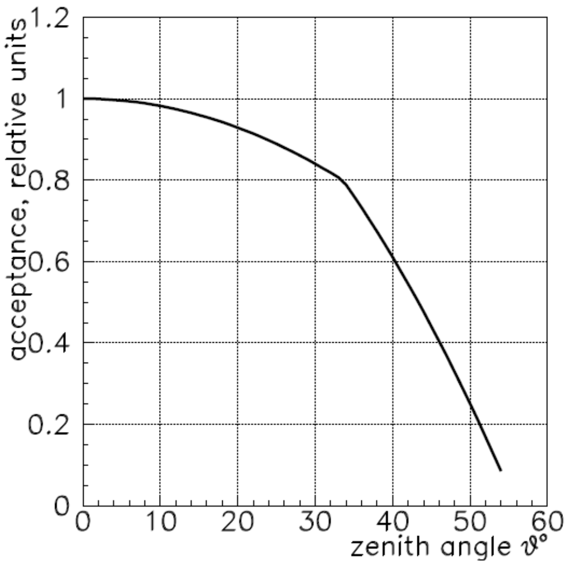
18 000 m of trenches for cable lines





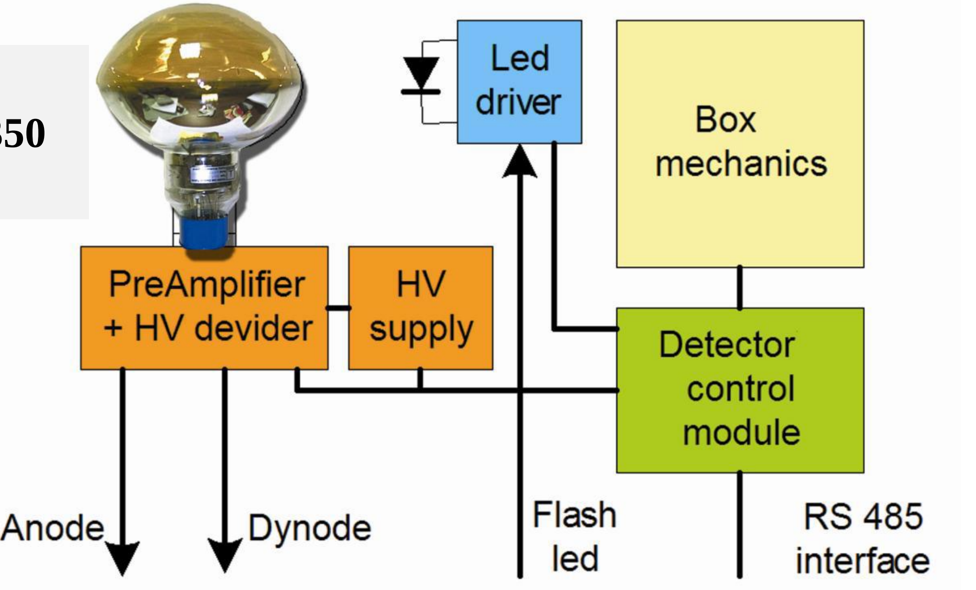

Optical detector of the Tunka-133

Angular sensitivity



In the first version, a mechanism with bicycle sprockets to open and close the lid was used.

PMT
EMI 9350
20 cm



Prof. Pietro Fré
SCIENTIFIC COUNSELLOR of THE ITALIAN EMBASSY in the RUSSIAN FEDERATION

A/D=30, high linearity (>10^5 pe)
Fast LED driver with high dynamic range

Deployment of the array Tunka-133

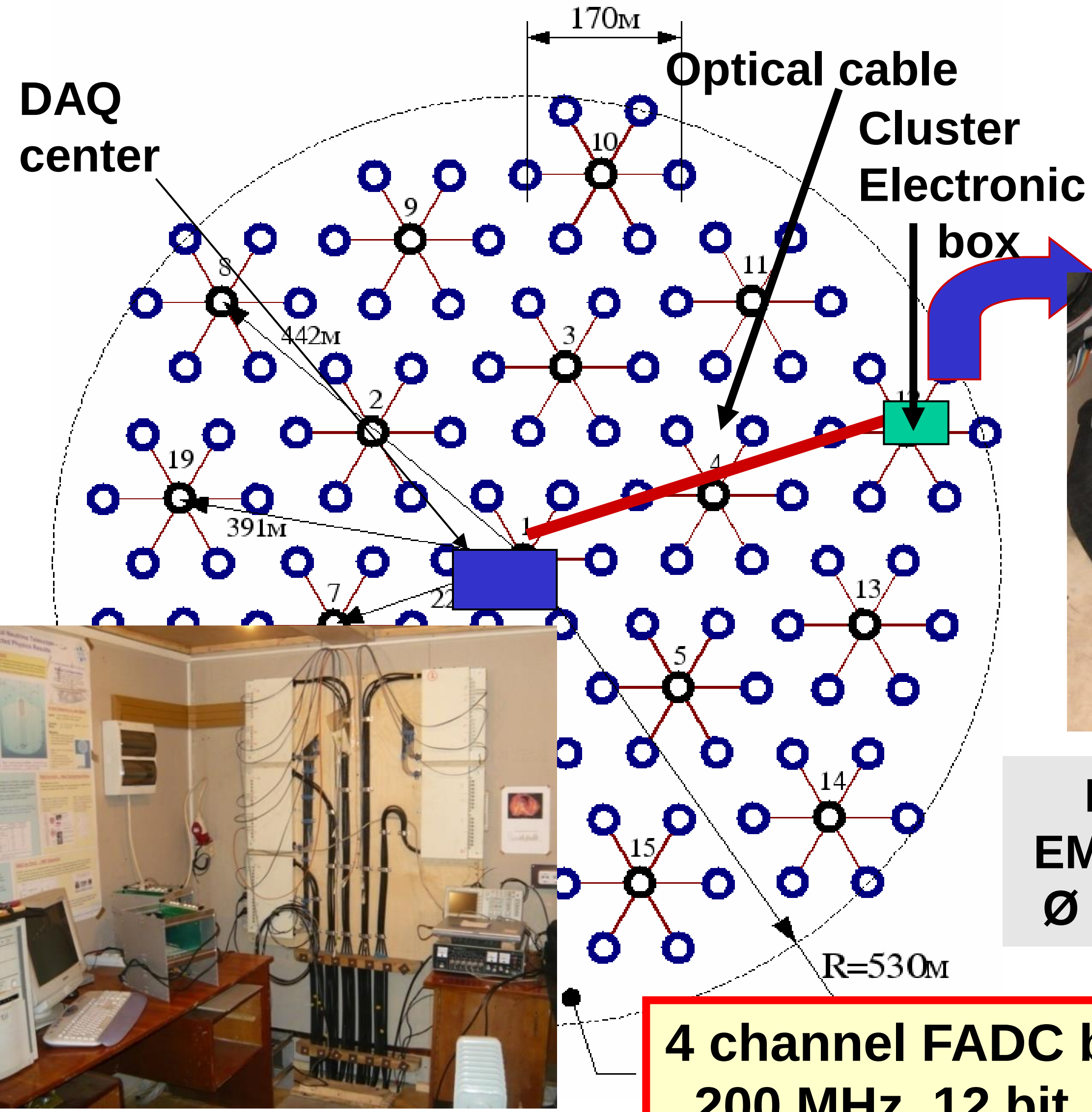
Detector preparing

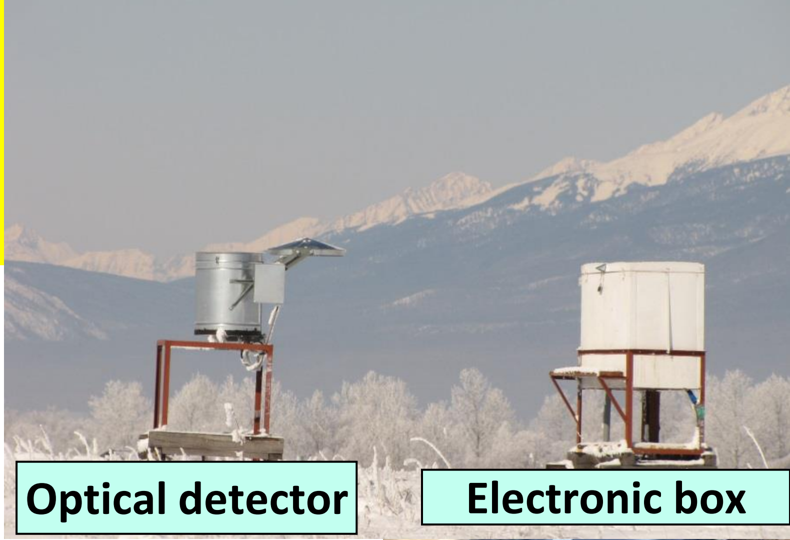
PMT preparing

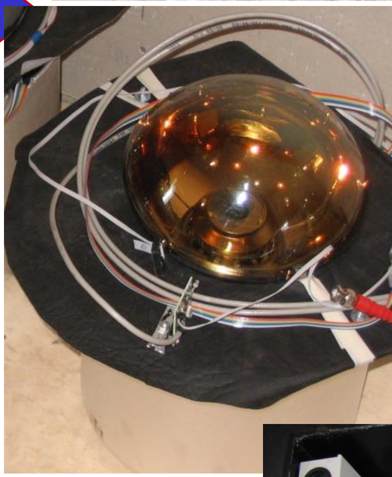
Detector installing

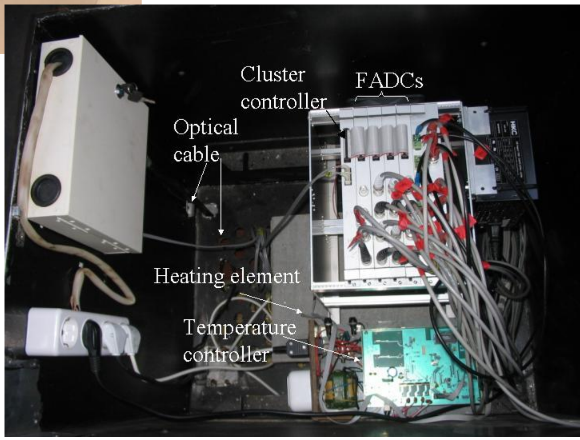
Installation of electronics

2009y. Central dense part of Tunka-133: 19 clusters, 7 detectors in each cluster





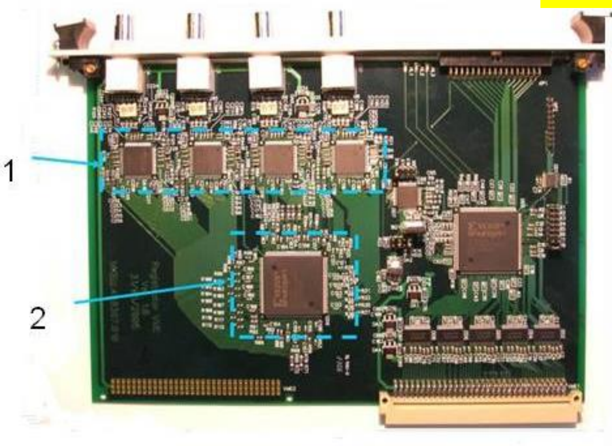


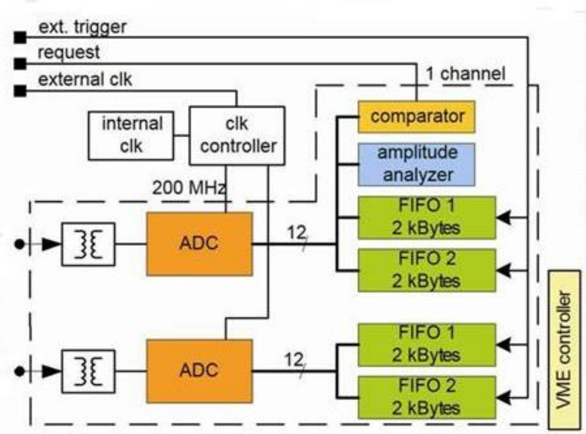


PMT
EMI 9350
Ø 20 cm

4 channel FADC boards
200 MHz, 12 bit

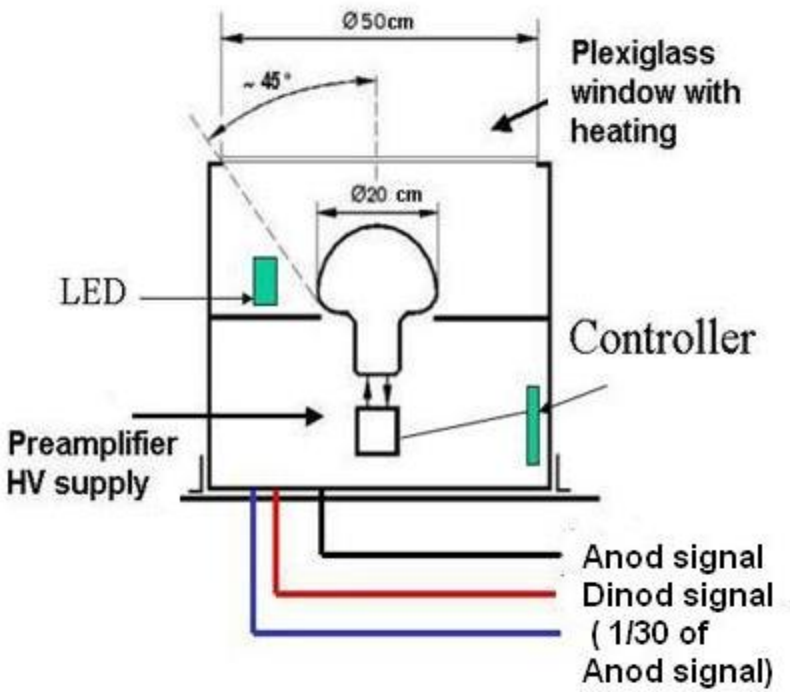
Cluster electronics

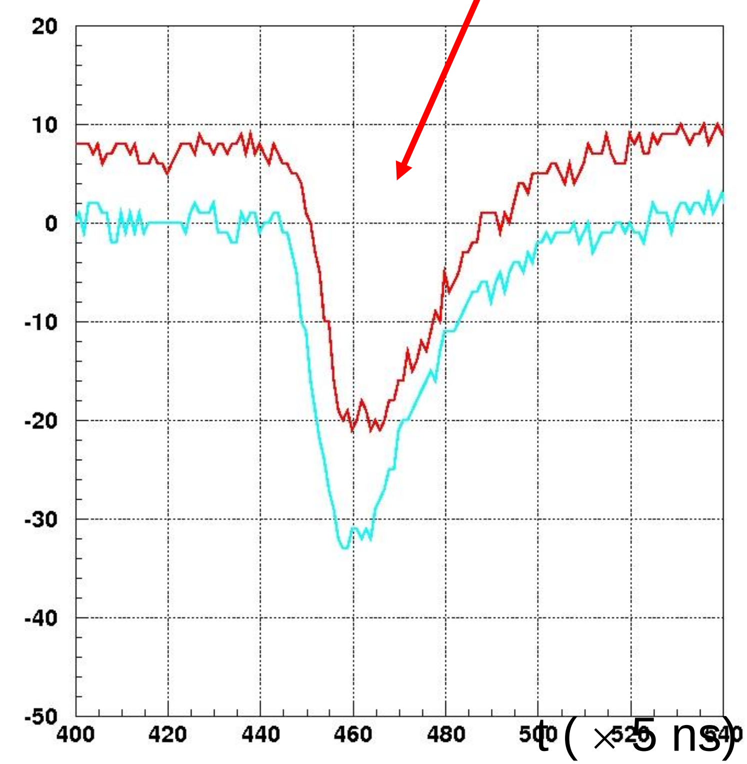




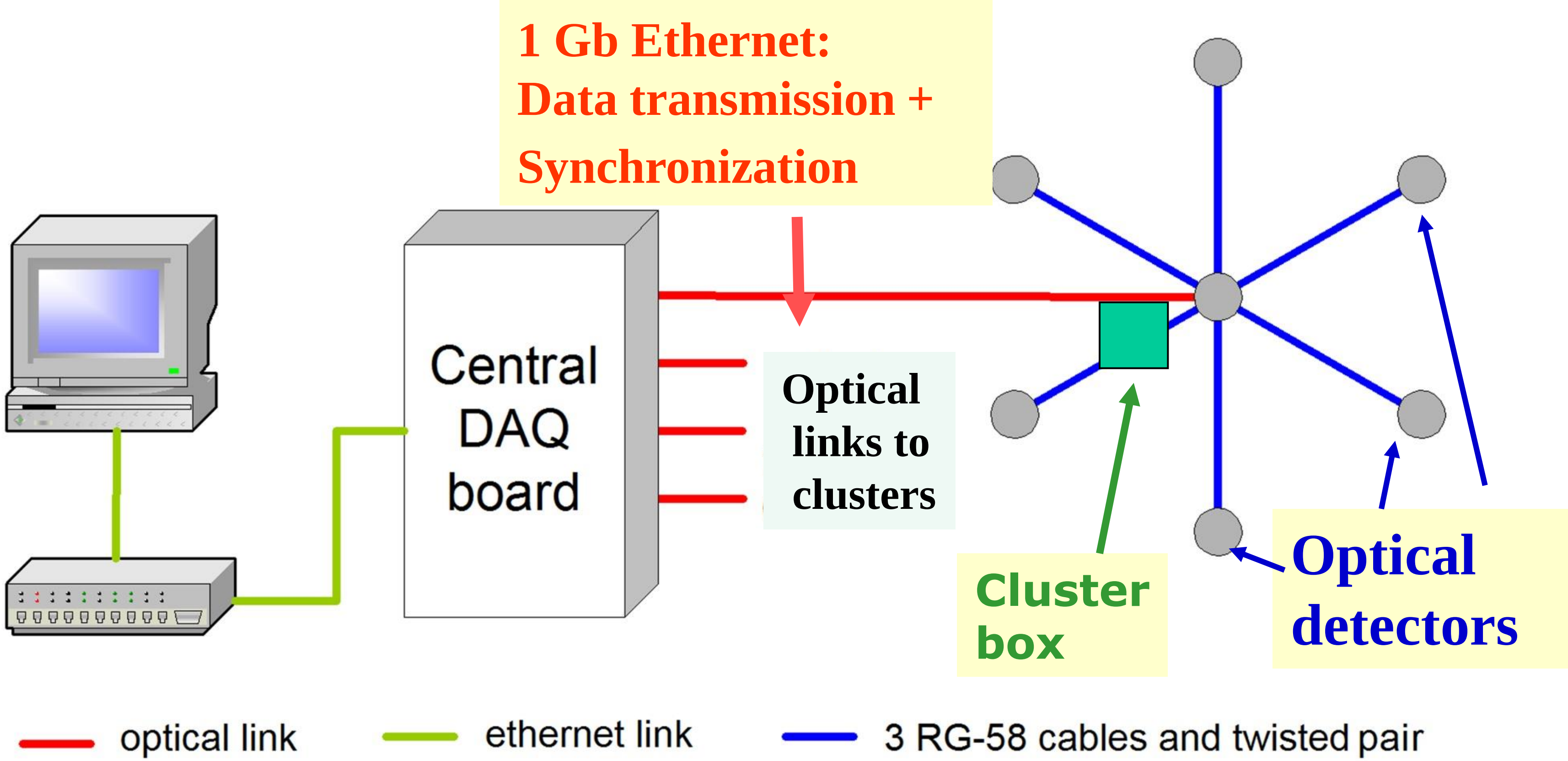
Cherenkov light pulses of two detectors of a cluster located at a distance 700 m from EAS core.

1. **ADC AD9430, 12 bit, 200 MHz**
2. **FPGA XILINX Spartan-3**

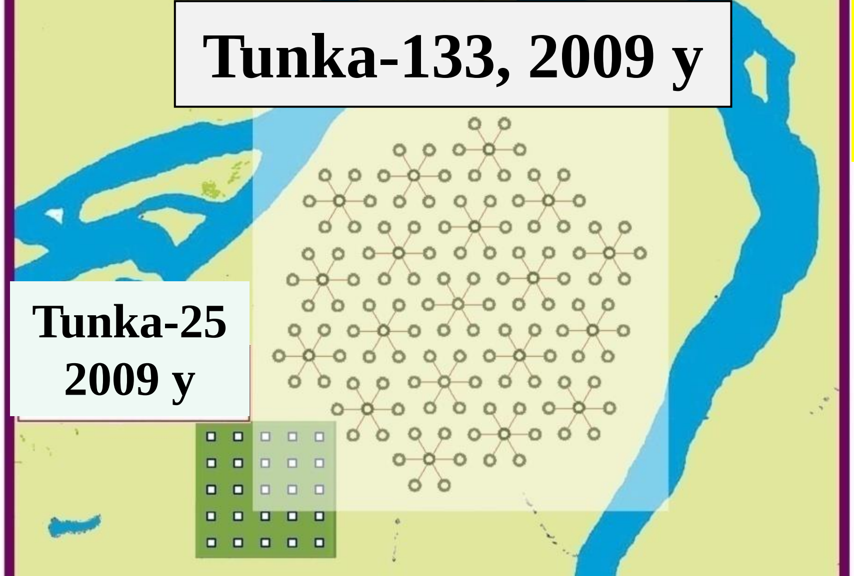




Concept of the Tunka-133 DAQ



Cluster Local trigger > 3 hitted detectors during 0.5 μs

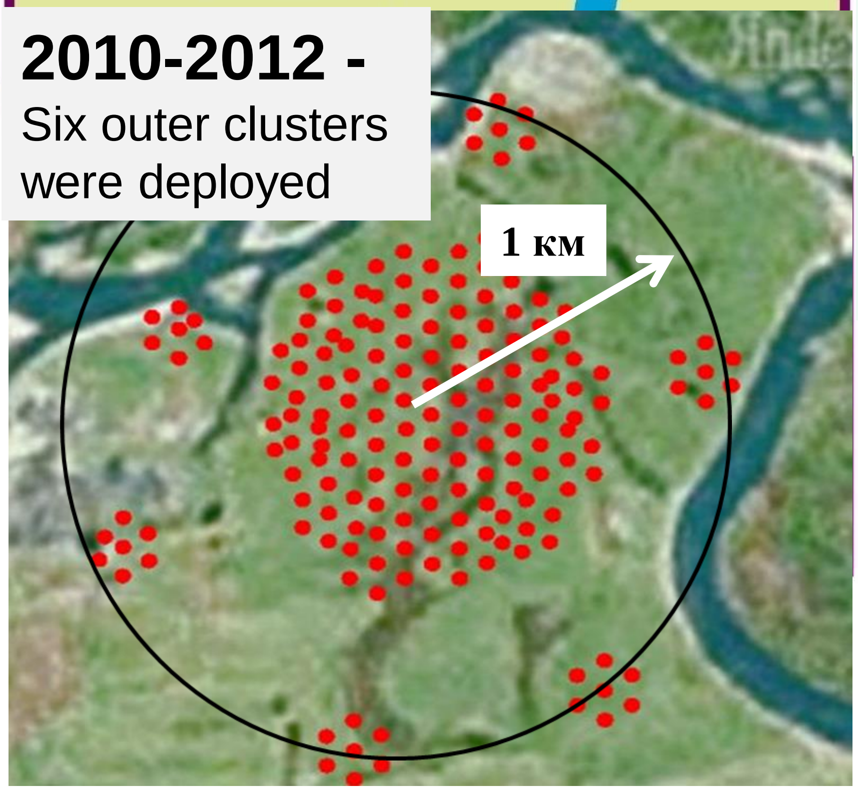


Tunka-133 with outer clusters –

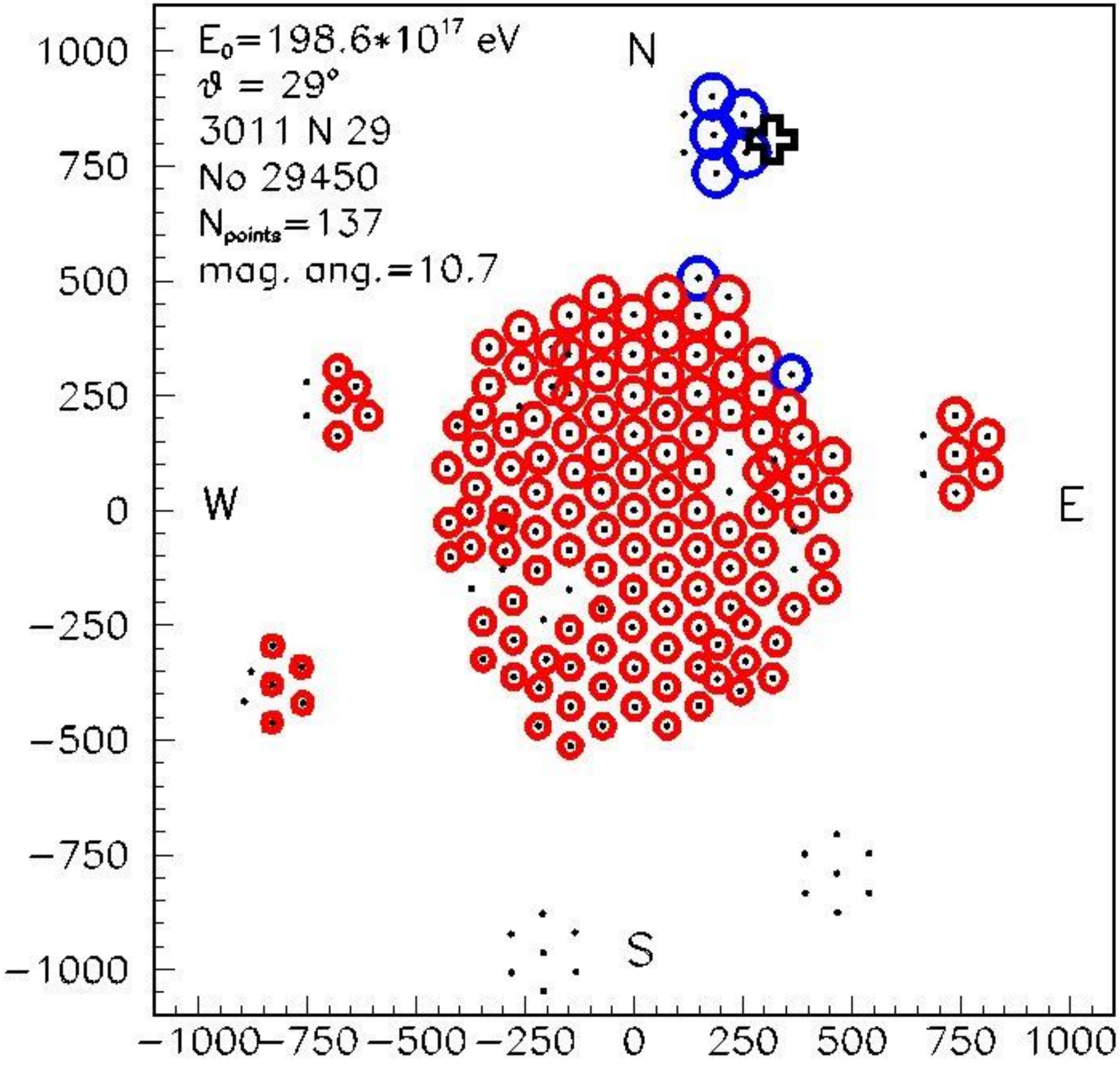
175 Cherenkov detectors, 3 km^2 area

Reconstruction of EAS with core position outside the “dense” array part .
For energy > 500 PeV an effective area of array increased in 10 times!
Statistics for one year of operation (400 hours):

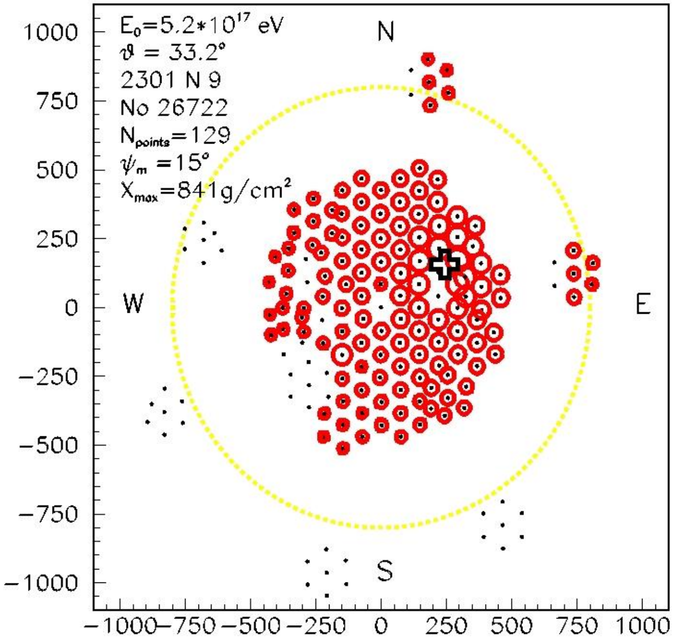
- > 3 PeV ~ 5.0•10^5 events
- > 100 PeV ~ 300 events
- > 1000 PeV ~ 2 – 3 events



Example of event: EAS energy $2\cdot10^{19}$ eV



An event example



Hitted detectors

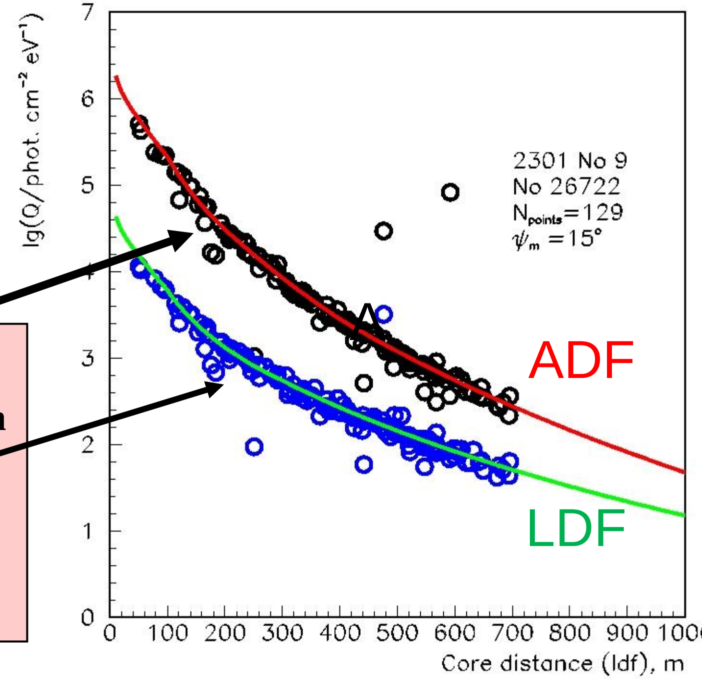
ADF

Amplitude distance function

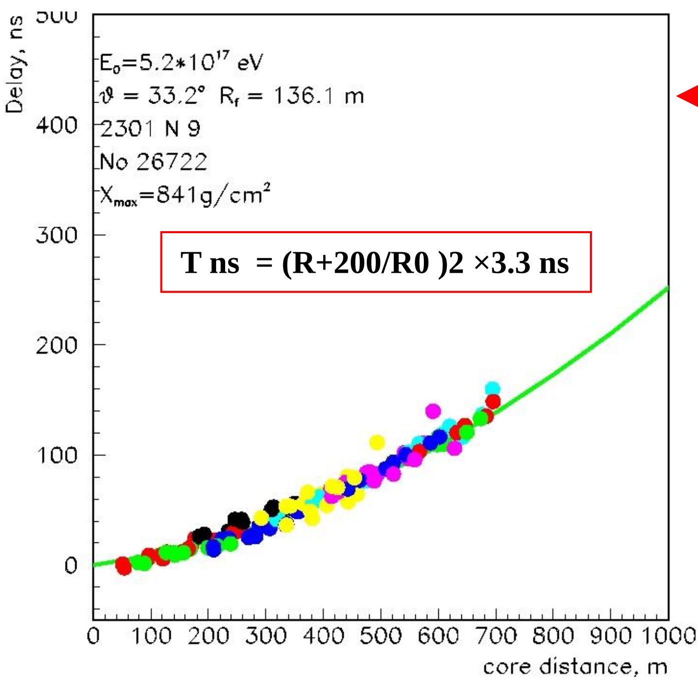
&

LDF

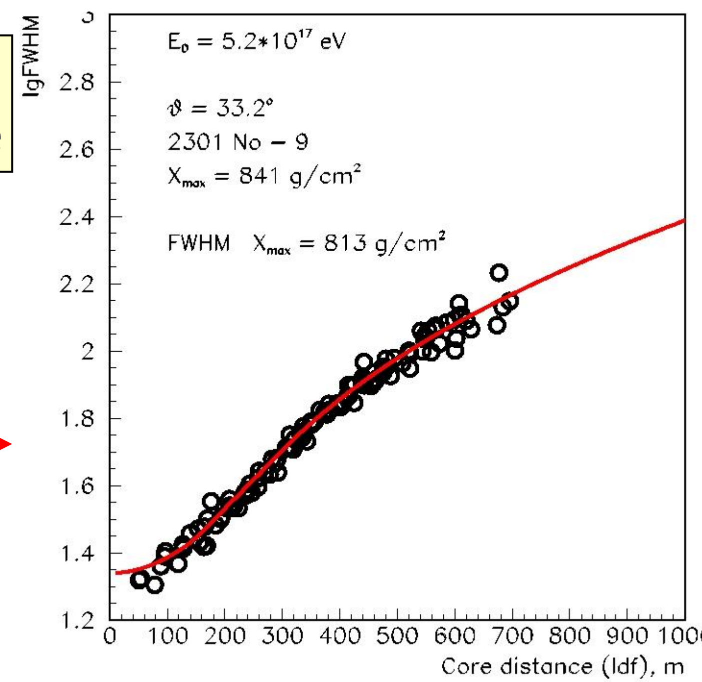
Lateral Distribution function



Delay time vs. Distance from core

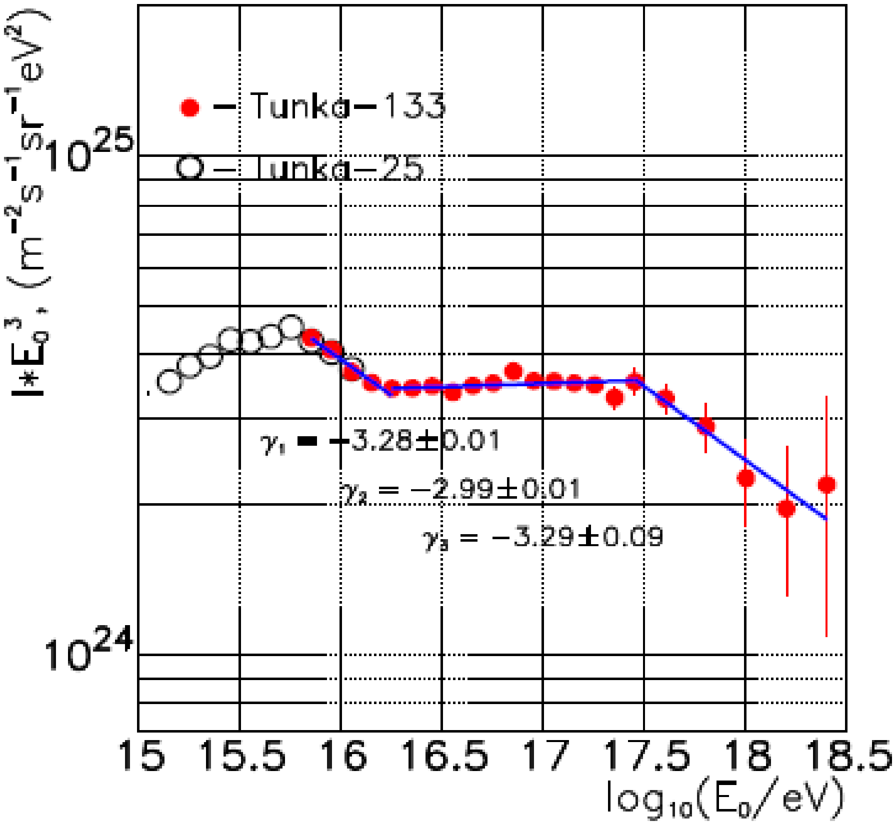


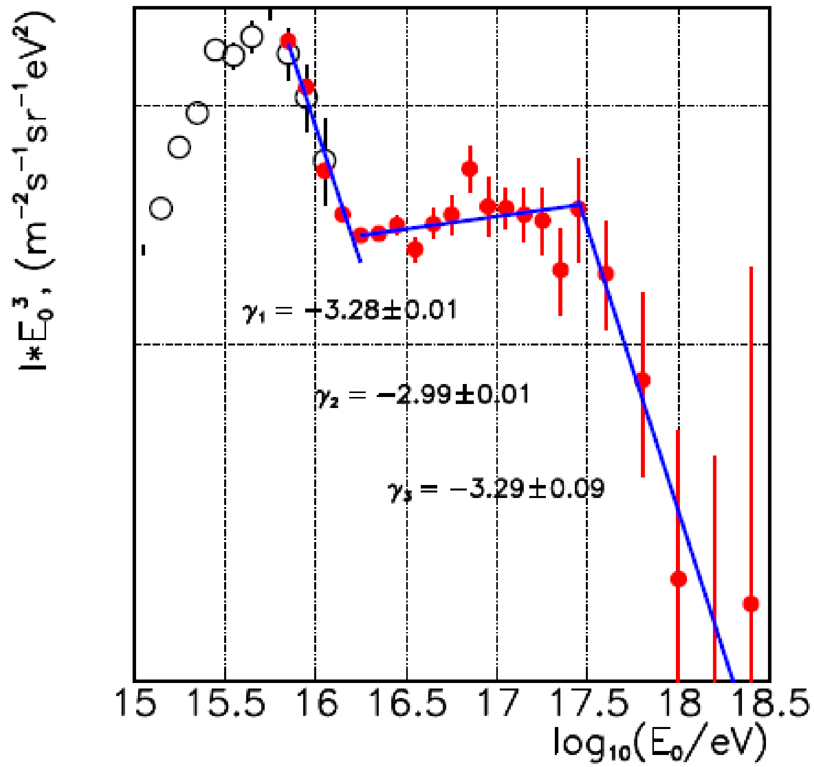
WDF – Width distance function



The all particles energy spectrum $I(E)\cdot E^3$ (7y)

energy resolution ~ 15%, in principal up to - 10%

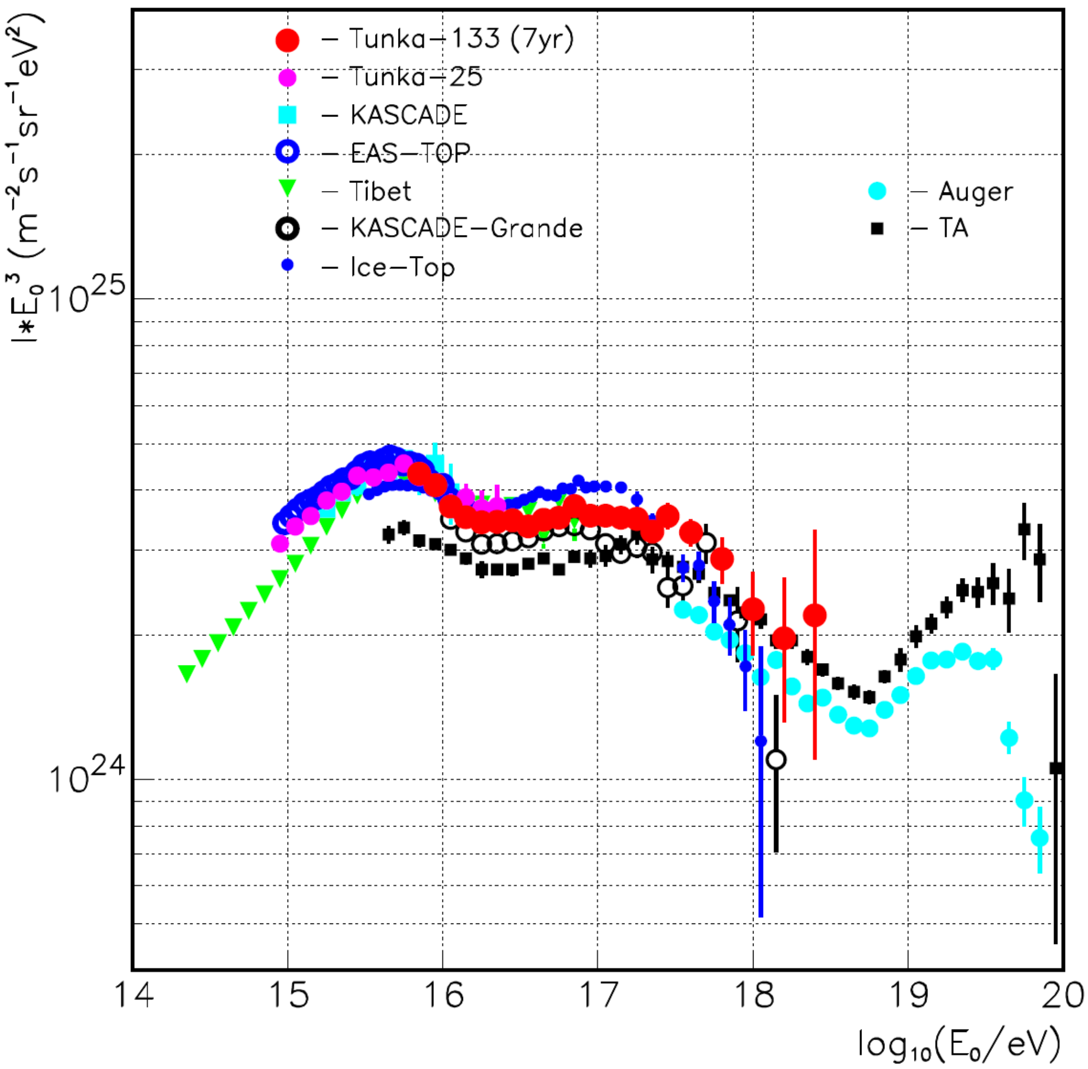




~4200 events with $E_0>10^{17}$ eV

Spectrum Steepening at energy E = 15 – 20 TeV, $\Delta\gamma$ ~ 0.2-0.3
Difference in intensity ~30% , due to difference in energy calibration ~10% ?
The second knee 100 -300 TeV, $\Delta\gamma$ ~ 0.3

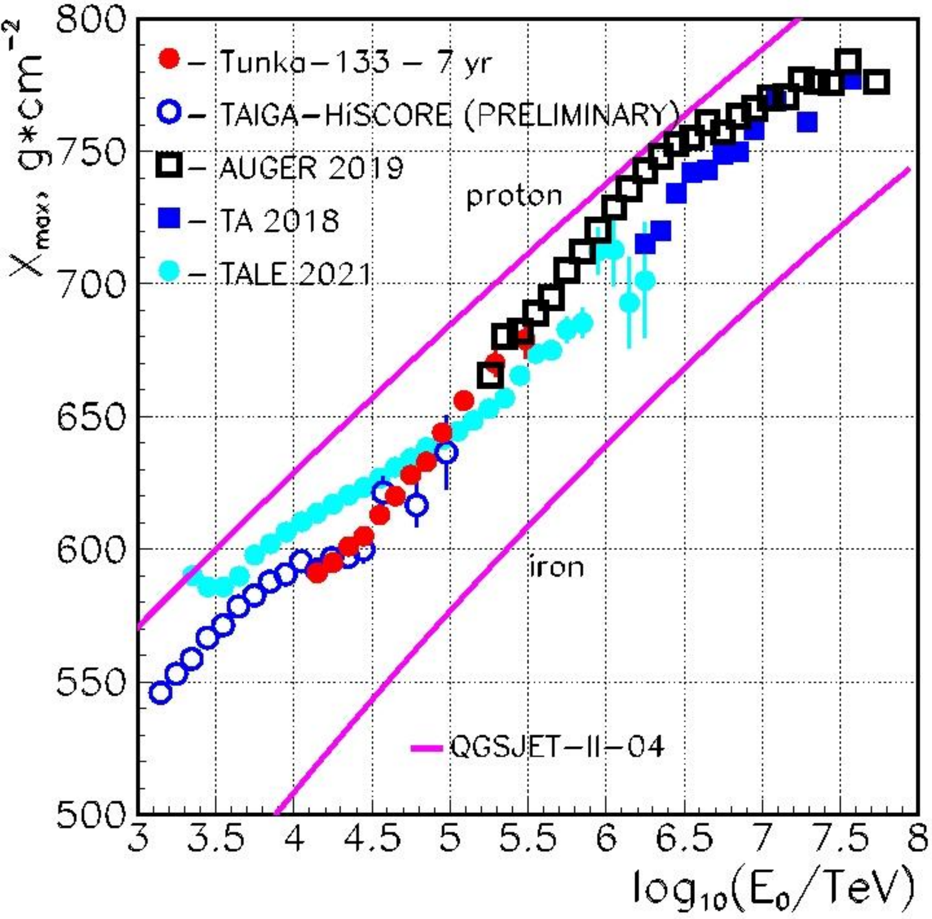
Comparison of the Tunka-25 &Tunka-133 energy spectrum with other experimental results



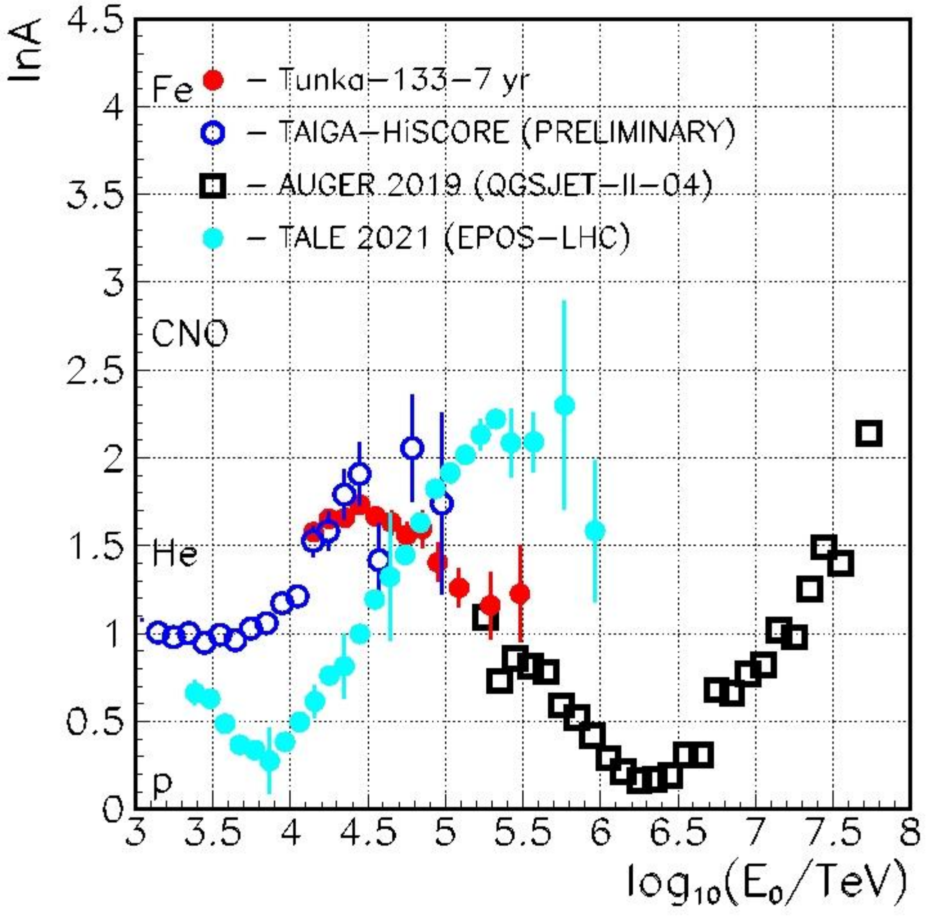
1. Agreement with KASCADE-Grande, Ice-TOP and TALE.

2. The high energy part do not contradict to the Fly's Eye, HiRes and TA spectra.

Mean Depth of EAS maximum X_{max} (g·cm^{-2})



Mean logarithm of primary mass.



Advantage of the Tunka-133 array:

1. Good accuracy positioning of EAS core (5 -10 m)
2. Good energy resolution (~15%)
2. Good accuracy of primary particle mass identification (accuracy of X_{max} measurement ~ 20 -25 g/cm^2).
3. Good angular resolution (~0.5 degree)
4. Low cost: **the Tunka-133 – 3 km^2 array ~ 10^6 Euro**

Energy threshold ~ 10^{15} eV
Statistics for one winter (400 hours):

> 3·10^{15} eV – 5·10^5 events
> 10^{17} eV – ~ 300 events

Disadvantage:
Rather high threshold ~ 3 PeV

Ways to decrease a detector threshold

$$E_{th} \sim (S_{det.}\,\eta)^{-1/2}\ (T_{signal})^{1/2}$$

1. Winston cones - PMT area increase in 4 times
   ($K = 1/\sin^2(\theta)$ $\theta = 30°$ - $K = 4$)

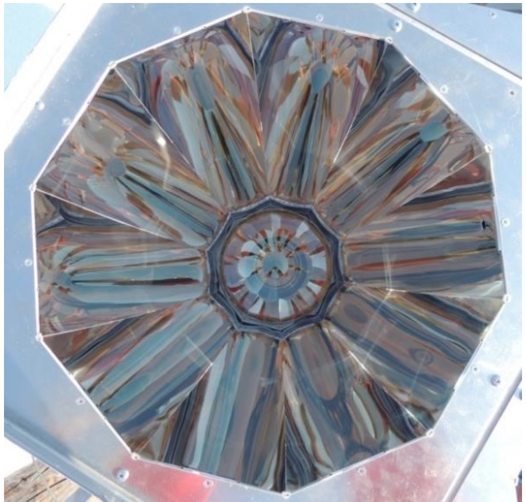
2. Analog summation of signals from some PMT in a detector

3. Decreasing of T_{signal} to 7-10 ns

4. QE max = 35-40% for PMT HAMAMATSU R7081-100

5. Using of wavelength shifter

Winston cone



2012y. Helmholtz-RFBR grant «Measurements of Gamma Rays and Charged Cosmic Rays in the Tunka-Valley in Siberia by Innovative New Technologies.

2013y. Grant of the Government of the Russian Federation «Multi-TeV gamma-ray astronomy and the origin of galactic cosmic rays»

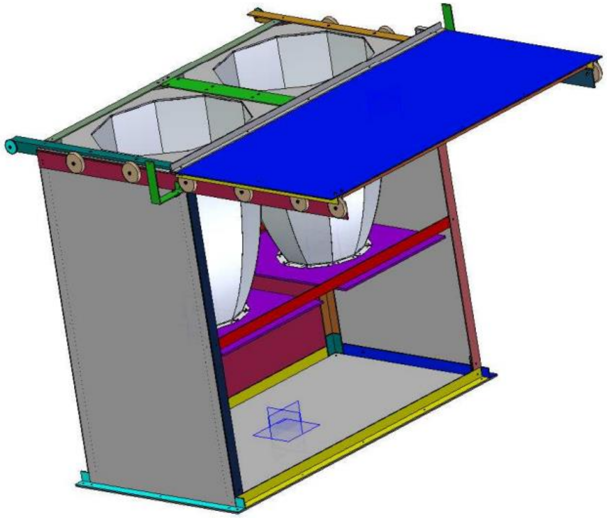
- **A low-threshold wide-angle Cherenkov array TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)**
- **A net of Imaging Atmospheric Cherenkov Telescope TAIGA-IACT**
- **A radio array Tunka-Rex**
- **A net of scintillation stations Tunka-Grande**

TAIGA - Collaboration

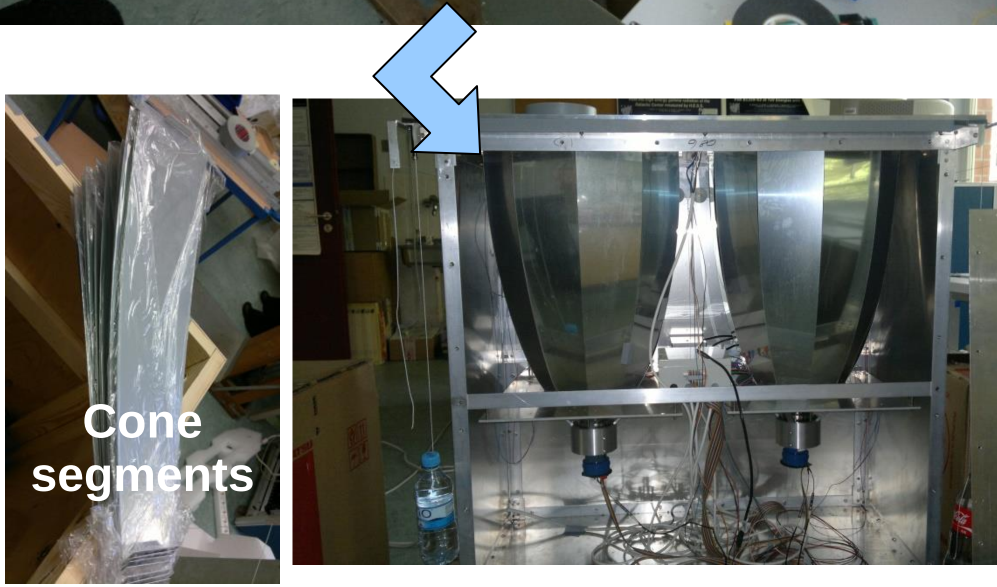
- Irkutsk State University (ISU), Irkutsk, Russia
- Scobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), Moscow, Russia
- Institute for Nuclear Research of RAS (INR), Moscow, Russia
- Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS (IZMIRAN), Troitsk, Russia
- Joint Institute for Nuclear Research (JINR), Dubna, Russia
- National Research Nuclear University (MEPhI), Moscow, Russia
- Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk, Russia
- Novosibirsk State University (NSU), Novosibirsk, Russia
- Altay State University (ASU), Barnaul, Russia

- Deutsches Elektronen Synchrotron (DESY), Zeuthen, Germany
- Institut fur Experimentalphysik, University of Hamburg (UH), Germany
- Max-Planck-Institut für Physik (MPI), Munich, Germany
- Fisica Generale Universita di Torino and INFN, Torino, Italy
- ISS , Bucharest, Rumania

First HiSCORE (High Sensitivity Cosmic Origin Explorer) detector station – Hamburg University design, spring 2012y



Prototype: with 2 PMT

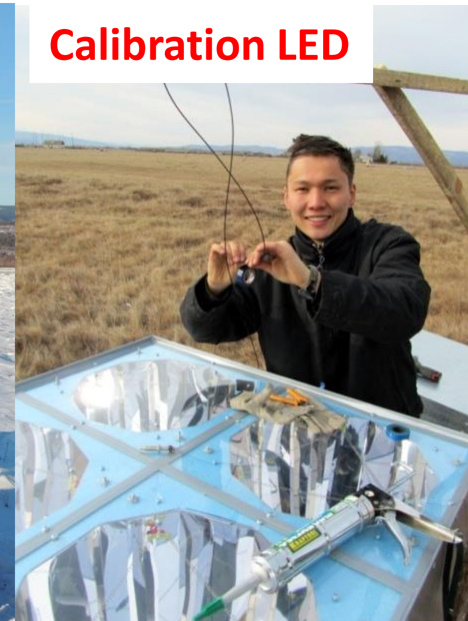


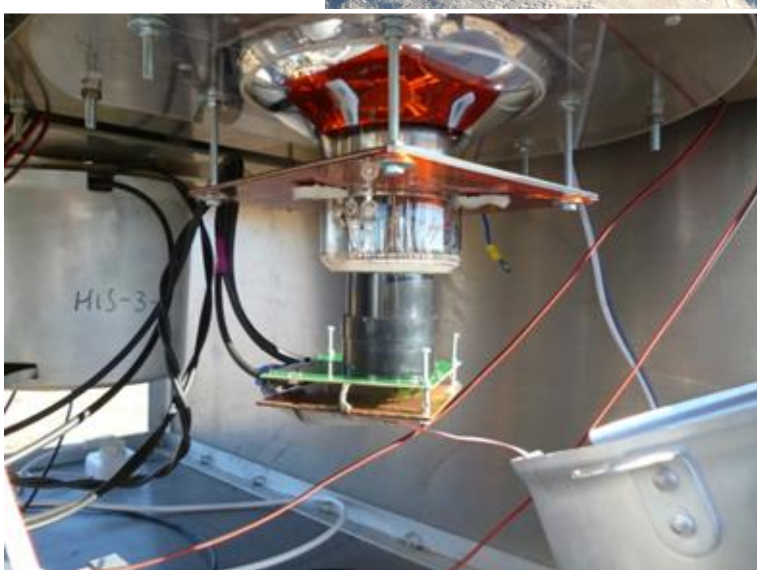
First design of a station with 4 PMTs, autumn 2012y.

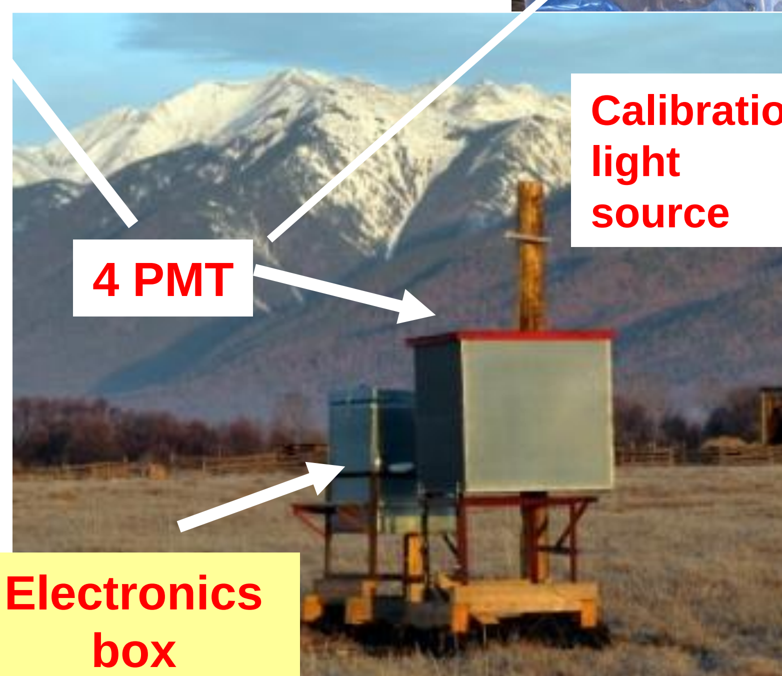
- 4 PMTs   EMI -9350

-Tunka-133 front –end electronic

- The lids opened by hands

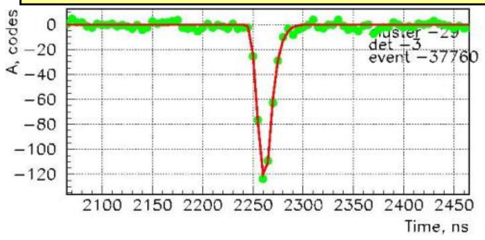




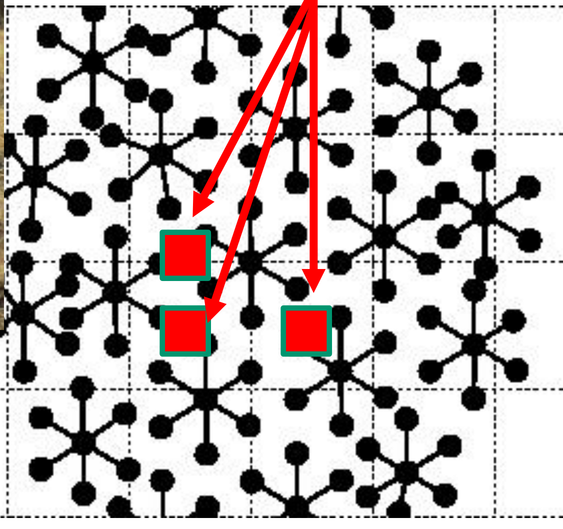


In October 2012y 3 TAIGA-HiSCORE optical stations with 4 PMT were put in operation together with Tunka-133

Signal from TAIGA -HiSCORE

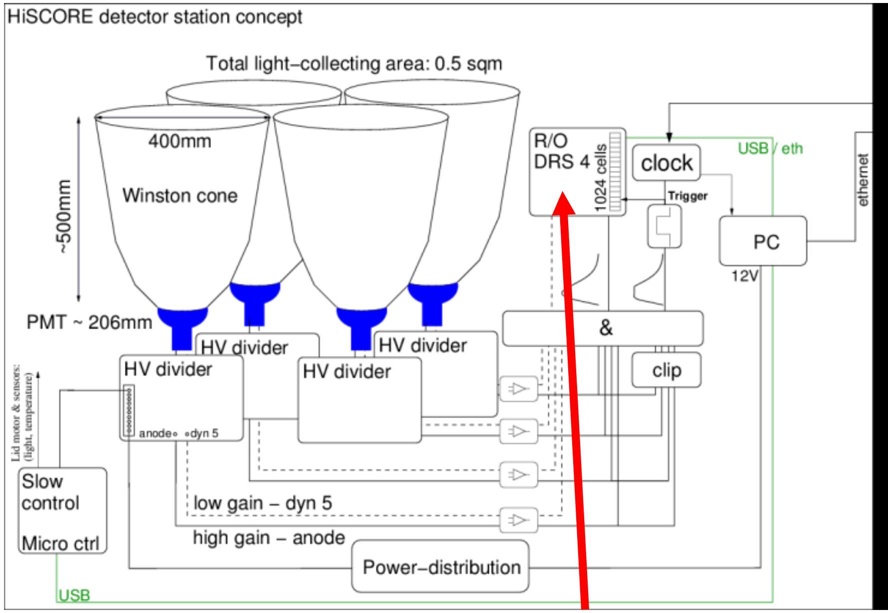


New TAIGA- -HiSCORE

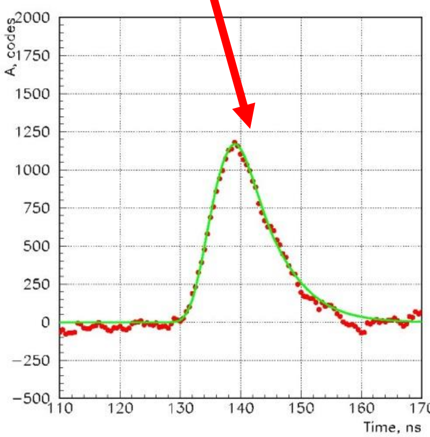


Cherenkov detectors of Tunka-133 array

Next design of the optical station of the TAIGA-HiSCORE installation



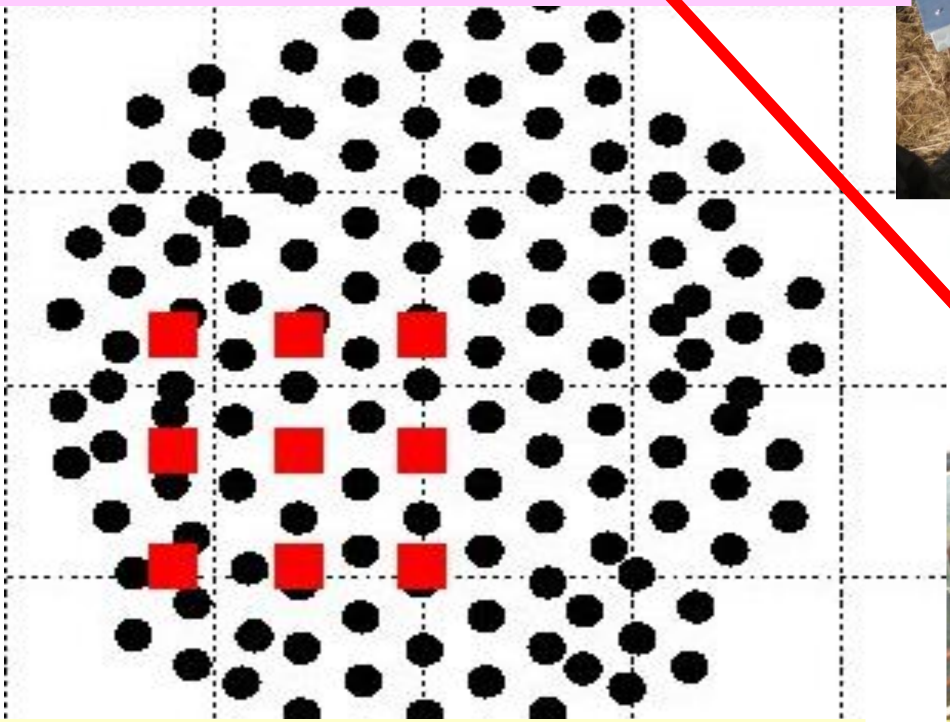
DRS-4 board (0.5 ns step)



PMT HAMANTSU R5912

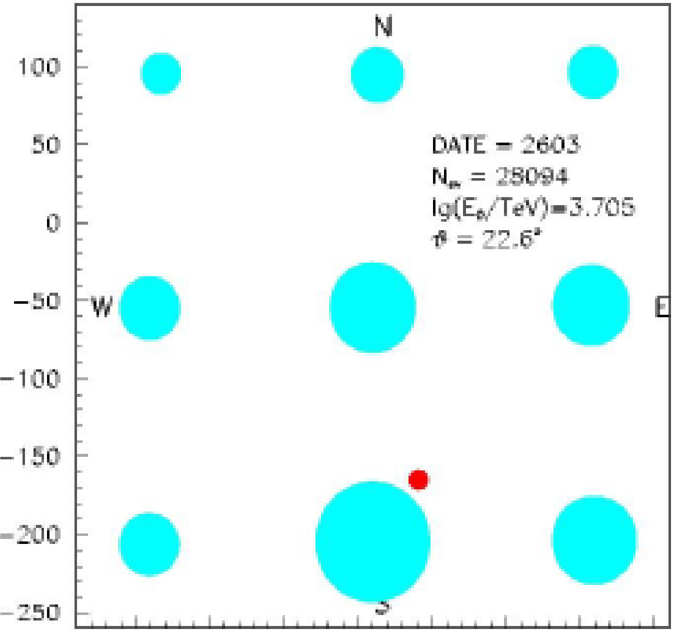
TIAGA-HiSCORE, 2013 year setup. 9 Cherenkov stations

Optical stations with PMT R5912 (8'')
New readout system.
New DAG based DRS-4 bord



For E > 3·PeV:
Arrival direction difference – $\Delta\psi \sim 0.1°$
EAS core coordinate difference – < 7 m, ΔY < 7 m
LogE difference – lgE < 0.051 (1 2%)

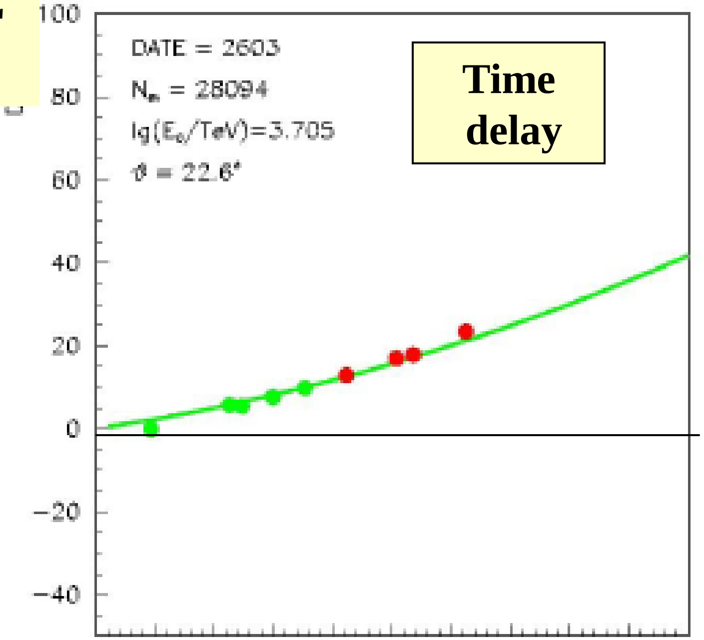
TAIGA-HiSCORE event example



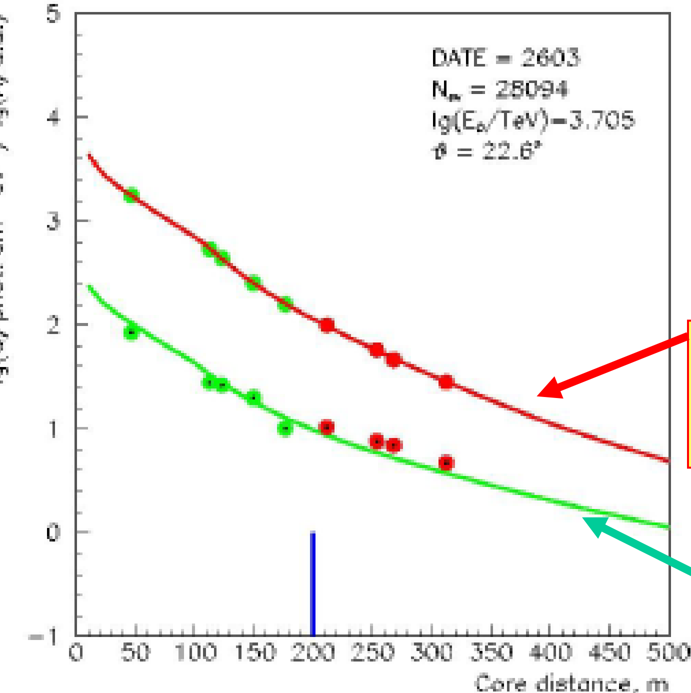
Red – anode

Green – dynode

$T_i=((Ri+250)/Rs)^2 - (250/Rs)^2)/c$



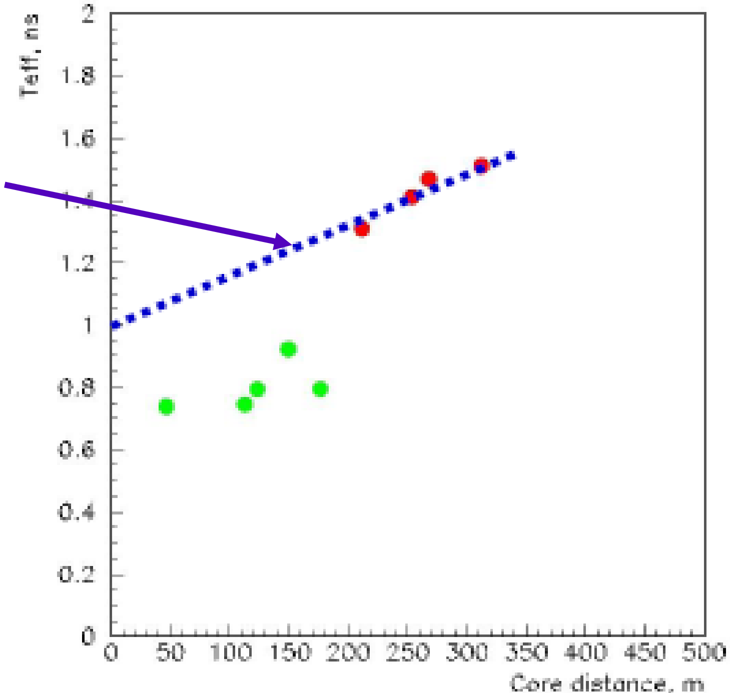
Core distance, m



Width –Distance Function (WDF)

Amplitude- Distance Function (ADF)

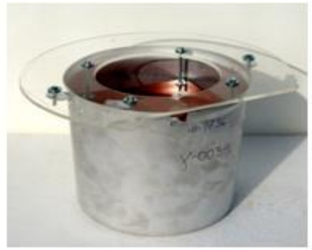
Lateral –Distribution Function (LDF)



Final design of the optical station of the TAIGA-HiSCORE installation

PMT
EMI ET9352KB
R5912 or R7081

+



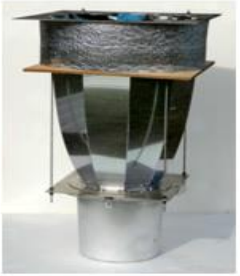
Bracket for PMT

+

Winston cone

=

Optical module



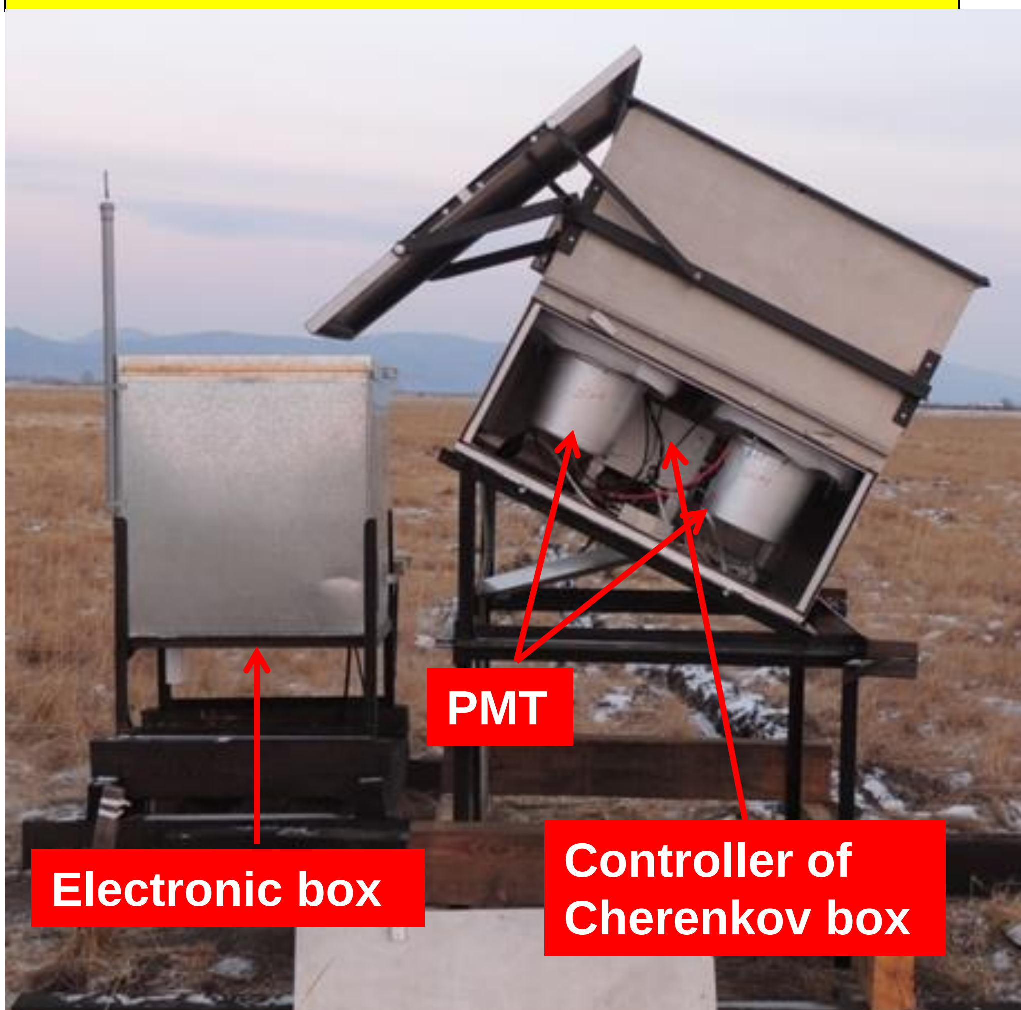
× 4 +

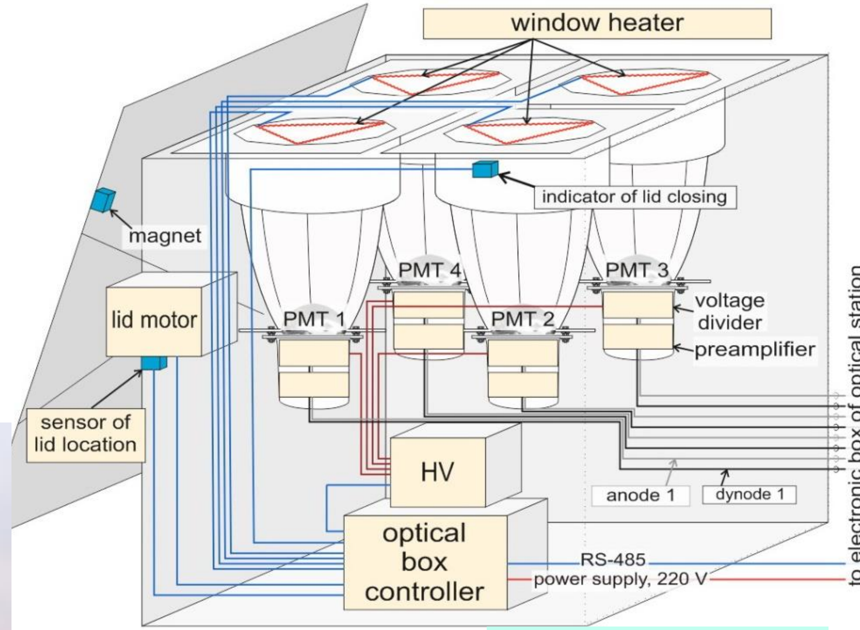
Optical station's box

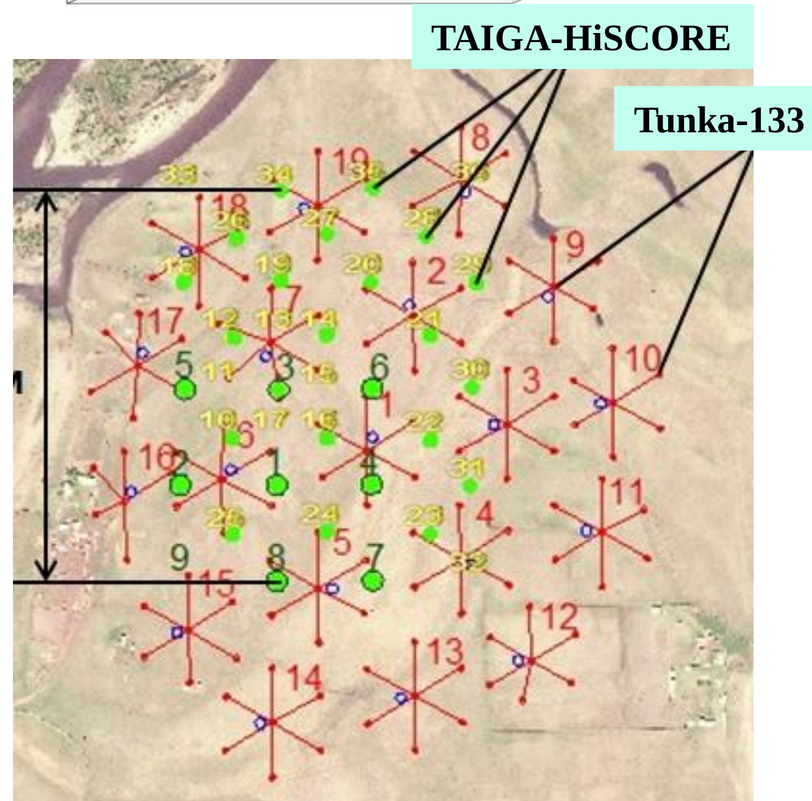
=

Optical station

TAIGA-HiSCORE, 2014 year setup. 29 Cherenkov stations

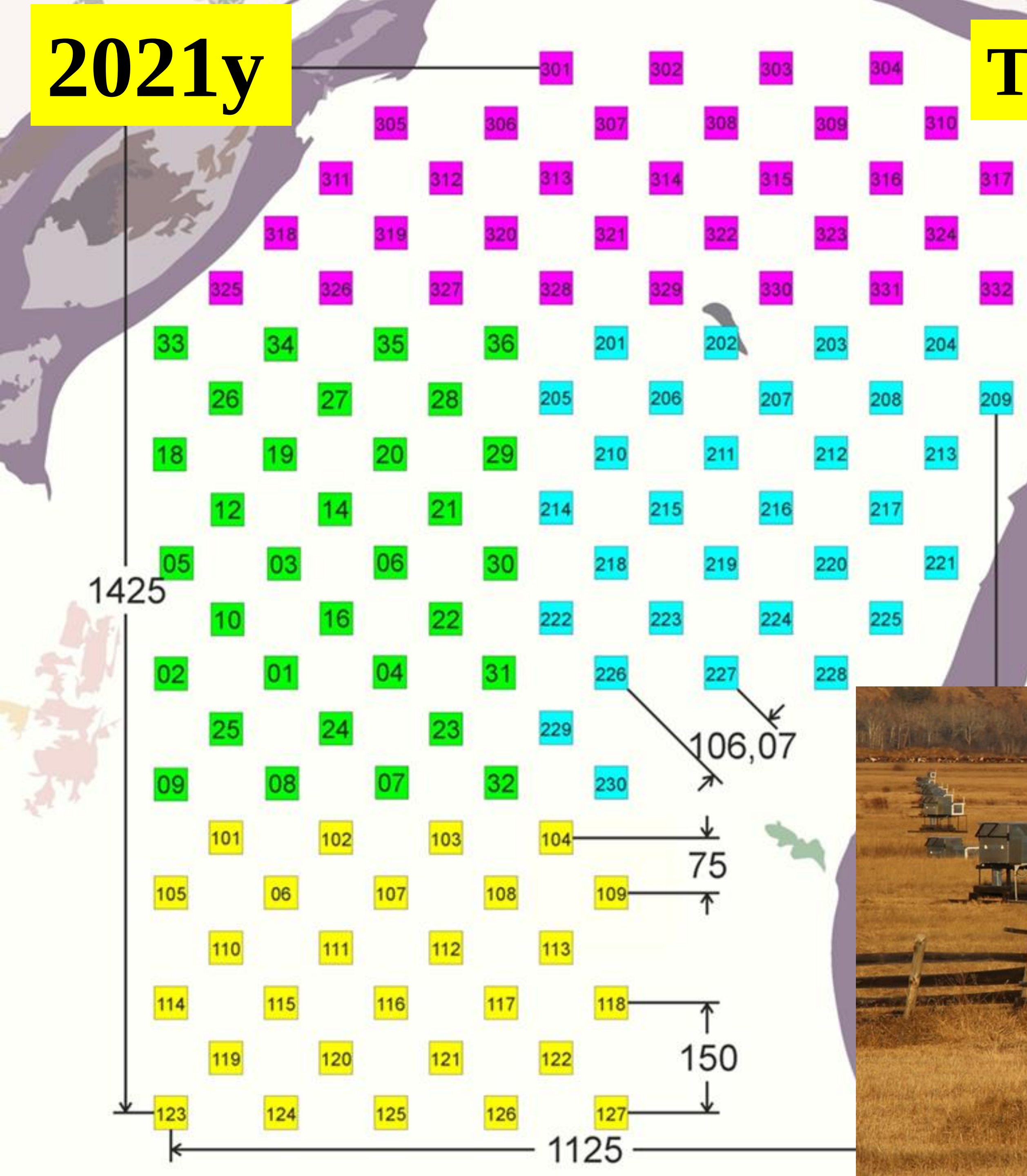






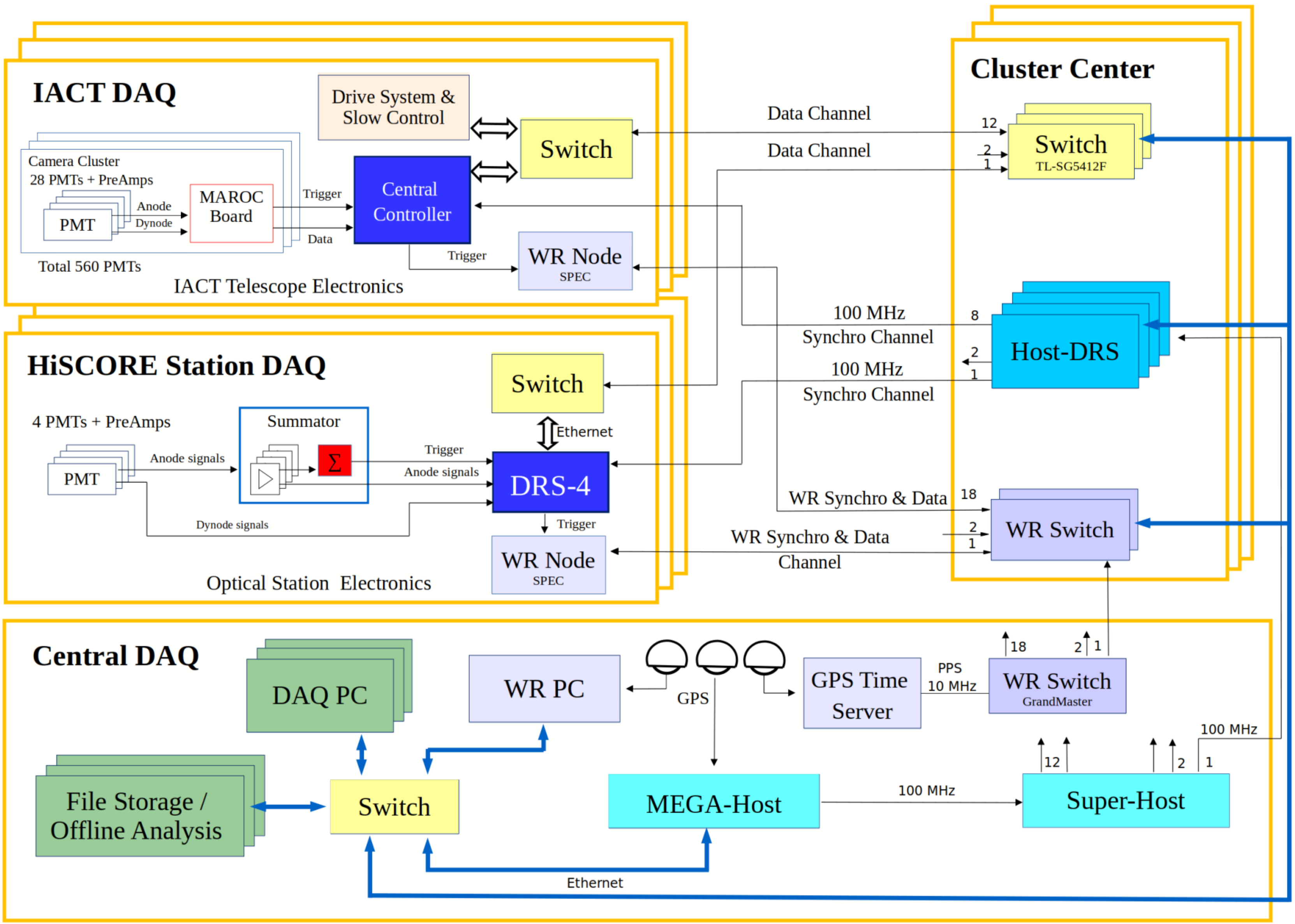
2021y

TAIGA-HiSCORE



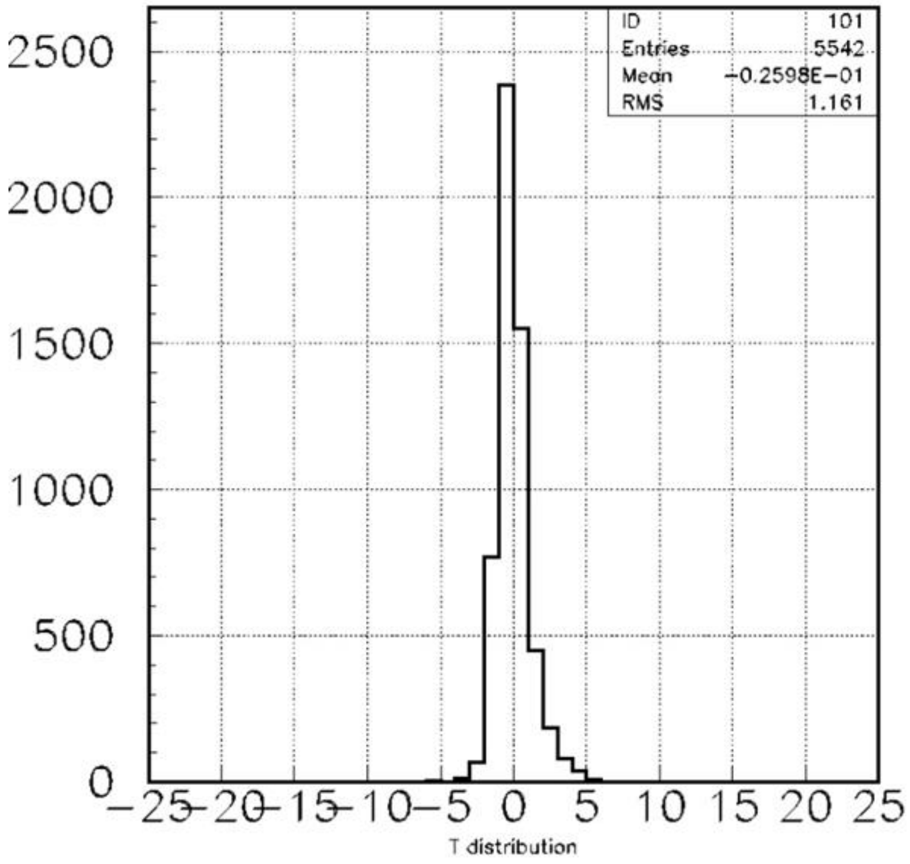
120 optical station on 1,1 km^2 aria

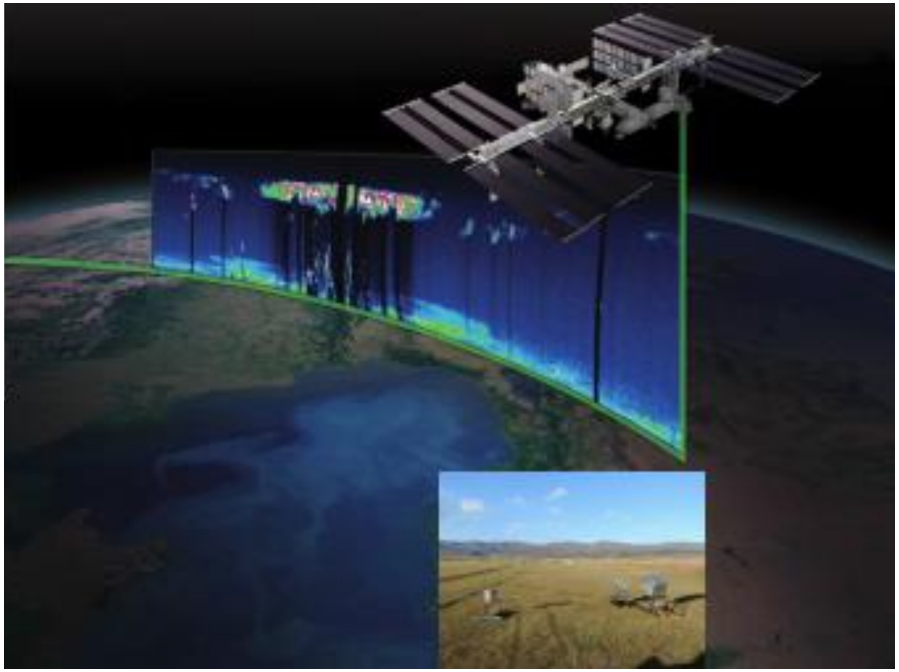
TAIGA DAQ



IACT DAQ
Drive System & Slow Control
Switch
Camera Cluster
28 PMTs + PreAmps
PMT
Anode
Dynode
MAROC Board
Trigger
Data
Central Controller
WR Node
SPEC
Total 560 PMTs
IACT Telescope Electronics
HiSCORE Station DAQ
Switch
4 PMTs + PreAmps
Summator
Anode signals
Trigger
Ethernet
DRS-4
Dynode signals
WR Node
SPEC
Optical Station Electronics
Cluster Center
Data Channel
Data Channel
Switch
TL-SG5412F
100 MHz
Synchro Channel
100 MHz
Synchro Channel
Host-DRS
WR Synchro & Data
WR Synchro & Data
Channel
WR Switch
Central DAQ
DAQ PC
WR PC
GPS
GPS Time Server
PPS
10 MHz
WR Switch
GrandMaster
100 MHz
File Storage / Offline Analysis
Switch
MEGA-Host
100 MHz
Super-Host
Ethernet

An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE





CATS Lidar,
532 nm, 4 khz, 10^13y/m²

The RMS=1.1 ns for TAIGA-HiSCORE detectors provides an accuracy of an γ and CR arrival direction about 0.1 degree

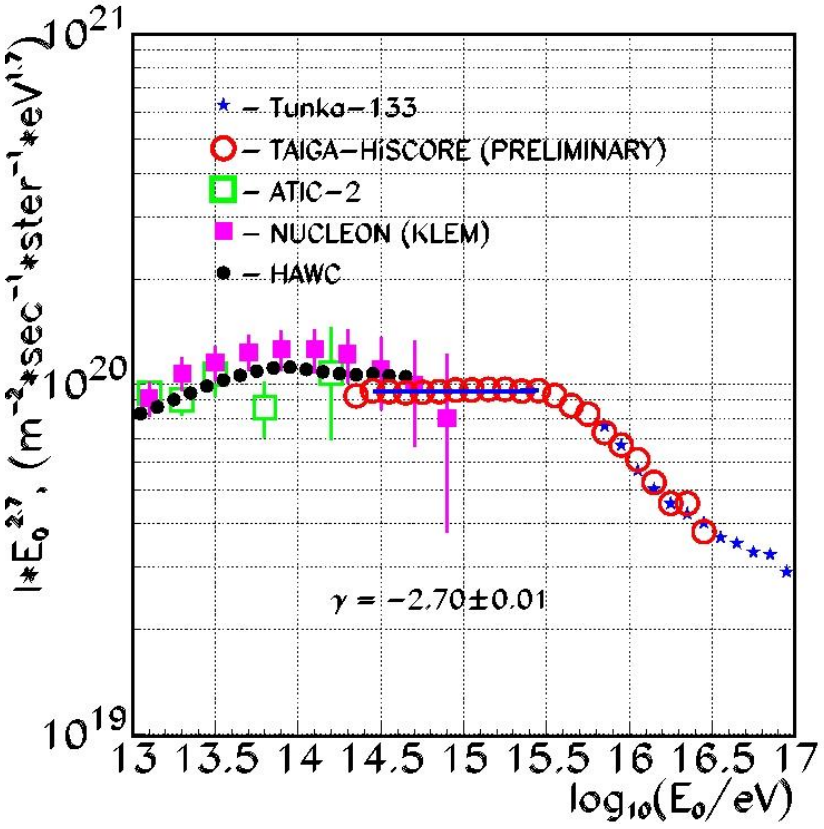
Precision verification with Laser on-board International Space Station (ISS) <0.1deg

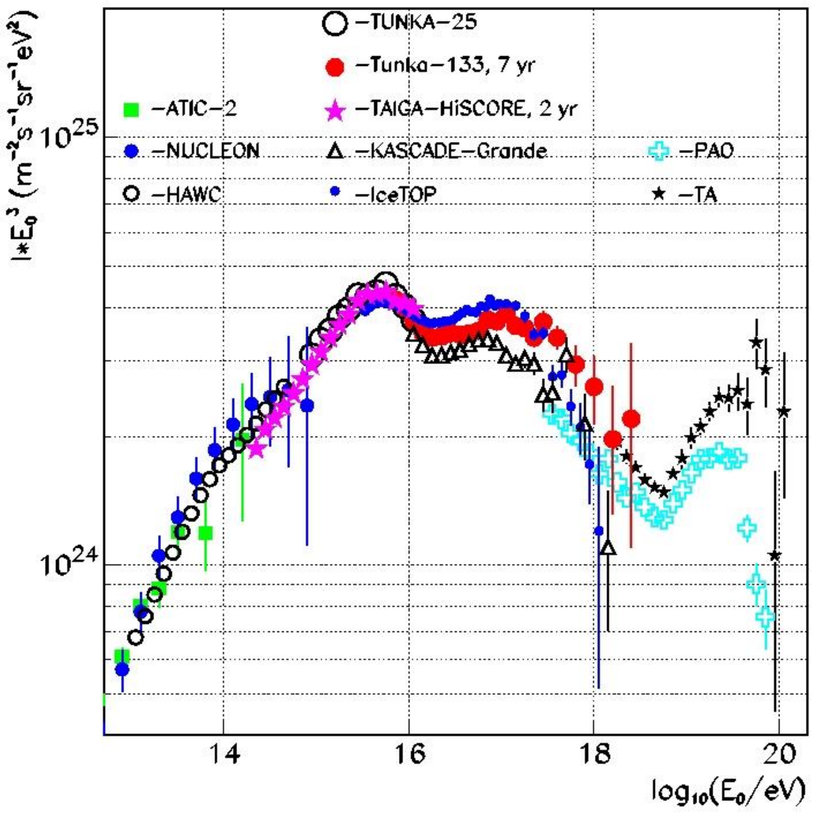
TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

TAIGA-1: 120 Cherenkov stations with spacing 106 m on 1,1 km^2 area. Each station consists of four 8 inch PMTs equipped with a segmented Winston cone (Alanod 4300UP foil). The resulting total light collection area of a station is 0.5 m^2. Threshold for CR- 0,1 PeV

Accuracy positioning EAS core - 5 -6 m
Angular resolution ~ 0.1 – 0.4 deg
Energy resolution ~ 10 - 15%
Accuracy of X_{max} measure ~ 20 -25 g/cm^2
Large Field of view: ~ 0.6 sr
Total cost ~ 2 ·millions $ (for 1 km²)

TAIGA-HiSCORE & Tunka-133 & Tunka-25 energy spectrum

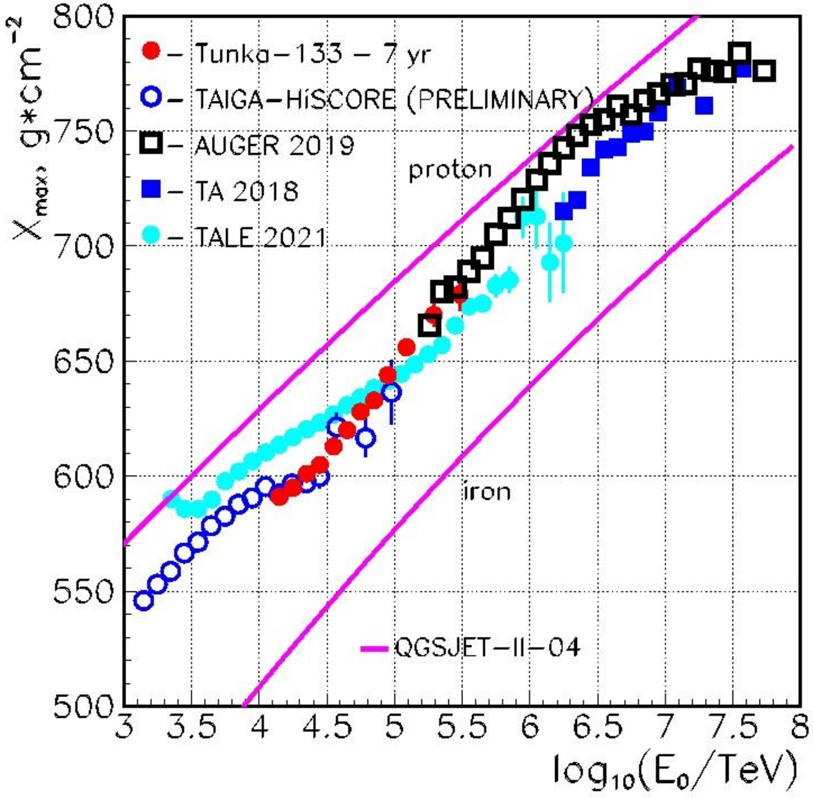


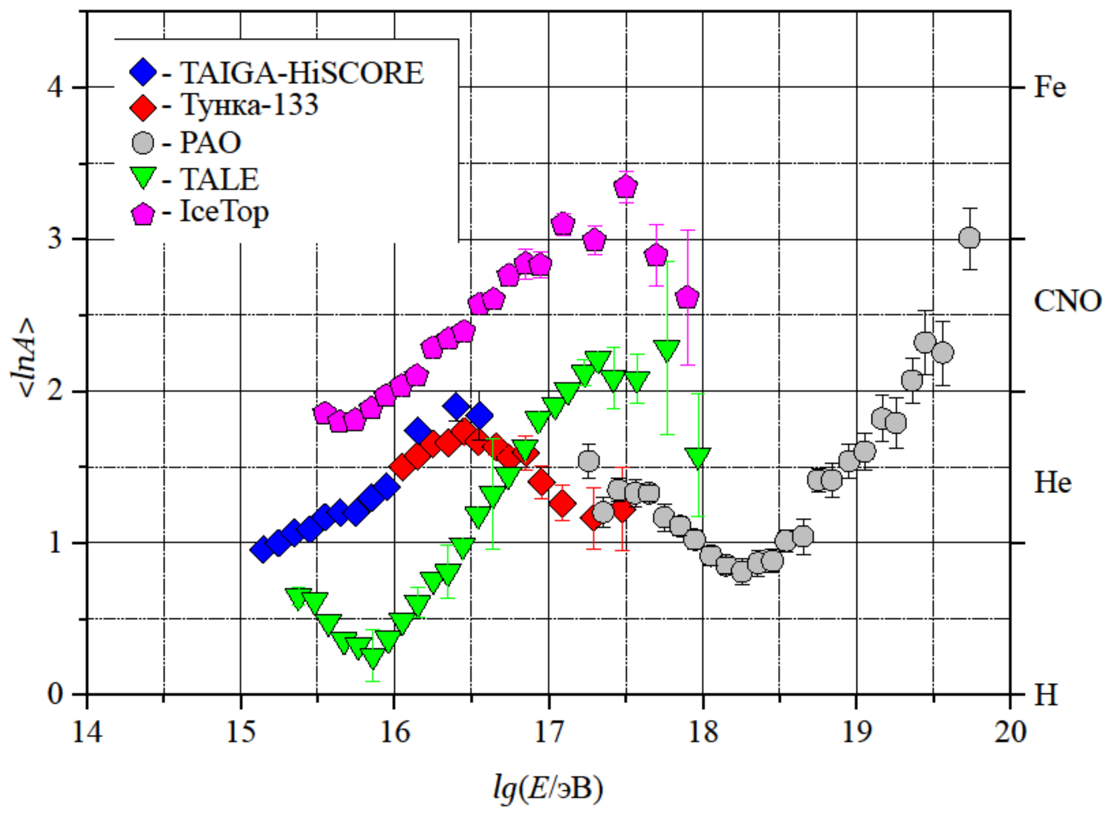


There is good agreement of Tunka energy spectrum both with direct balloons, satellite and high-altitude measurements at low energies, and with measurements on giant installations at extremely high energies (PAO , TA)

Mean Depth of EAS maximum X_{max} ($g \cdot cm^{-2}$)

Mean logarithm of primary mass.

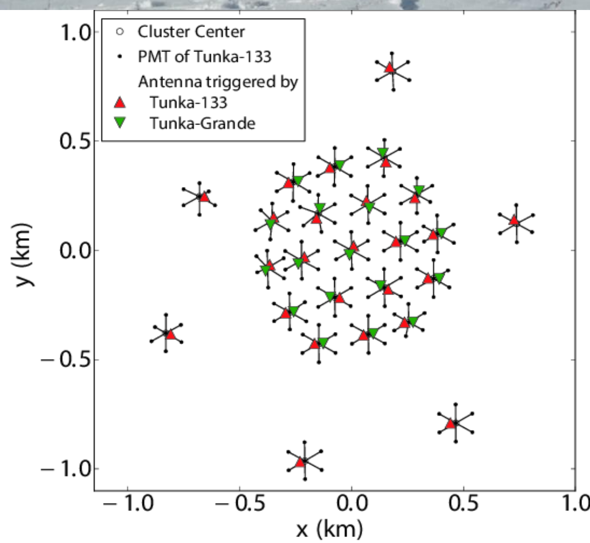




Our dependence on the energy of the average value of the logarithm of the atomic number is well extrapolated to the Auger results at energy 300 PeV and contradicts the results of the TALE experiment.

Studies of cosmic rays by detecting EAS radio emission in the Tunka experiment.

Tunka-Rex- Tunka Radio extation



- 12 bit / 200 MHz signal digitalization
- 30-80 MHz radio band
- 10-40 m distance between antennas
- 63 antennas / 1km^2
- 10^{17}-10^{18} eV effective energy range
- Joint operation of radio, scintillator and air-Cherenkov detectors

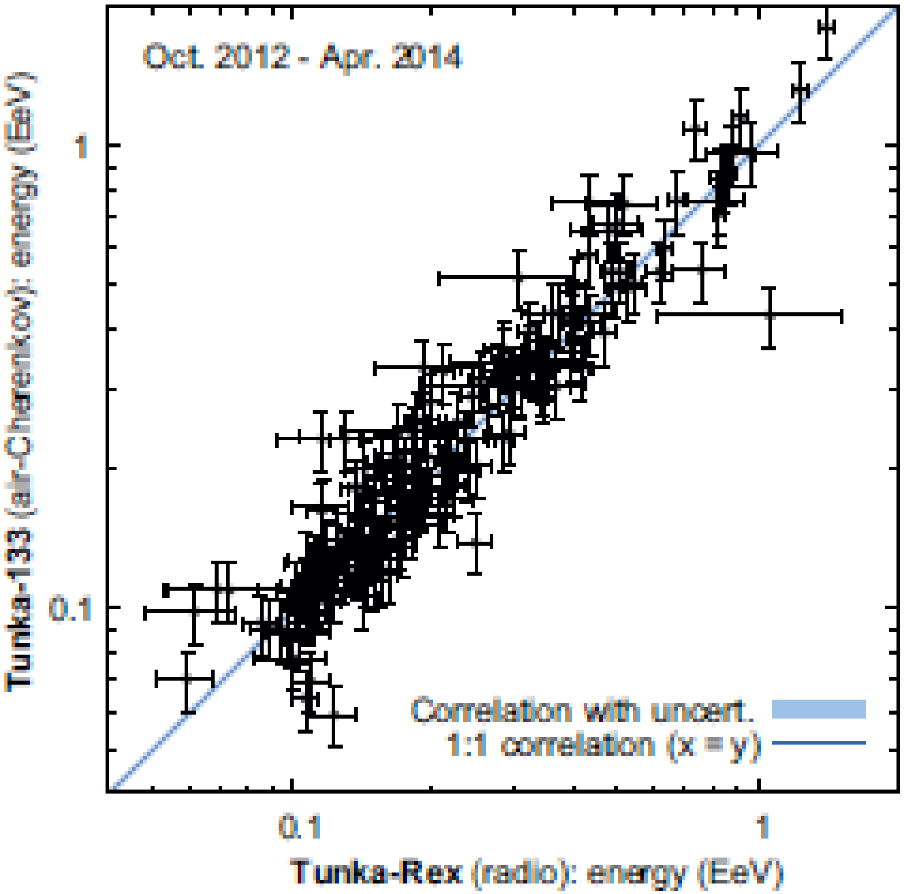
~100 events per season triggered by Tunka-133

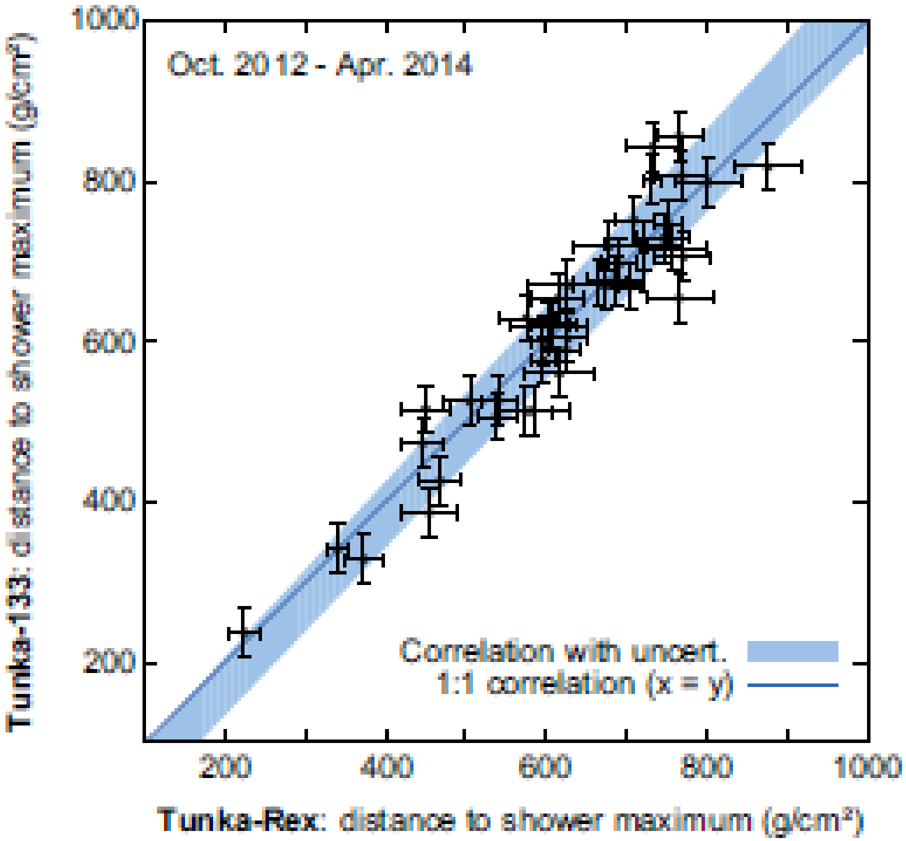
commission of Tunka-Grande with

~1000 events per season triggered by Tunka-133 and Tunka-Grande

2012	2013	2014	2015	2016	2017	2018+
18 antennas	25 antennas	44 antennas		63 antennas		open data

The correlation of reconstructed radio and Cherenkov EAS energy and depth of shower maximum

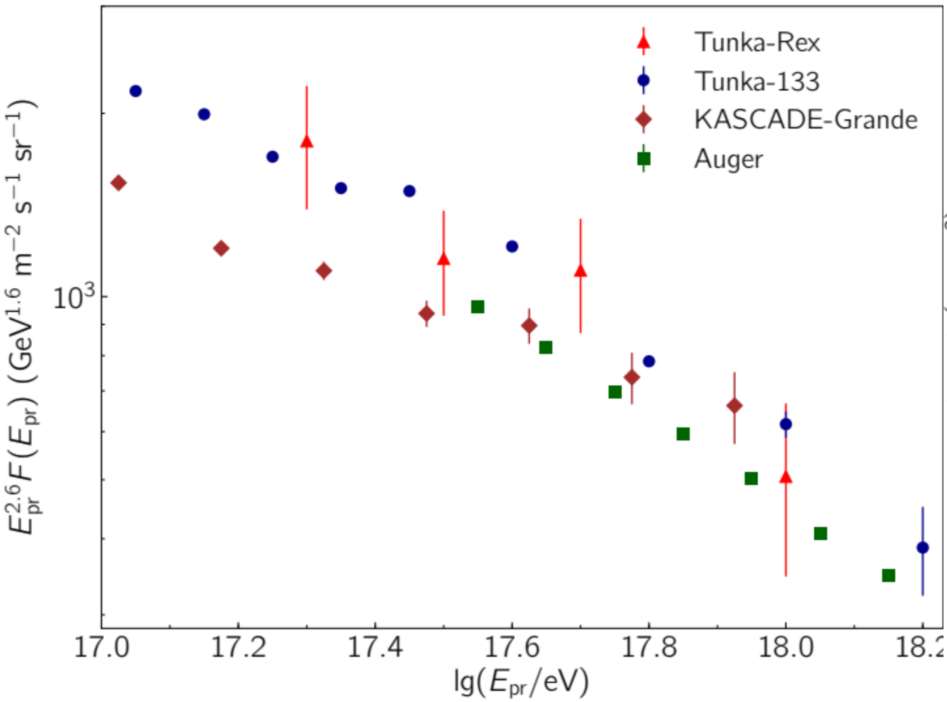


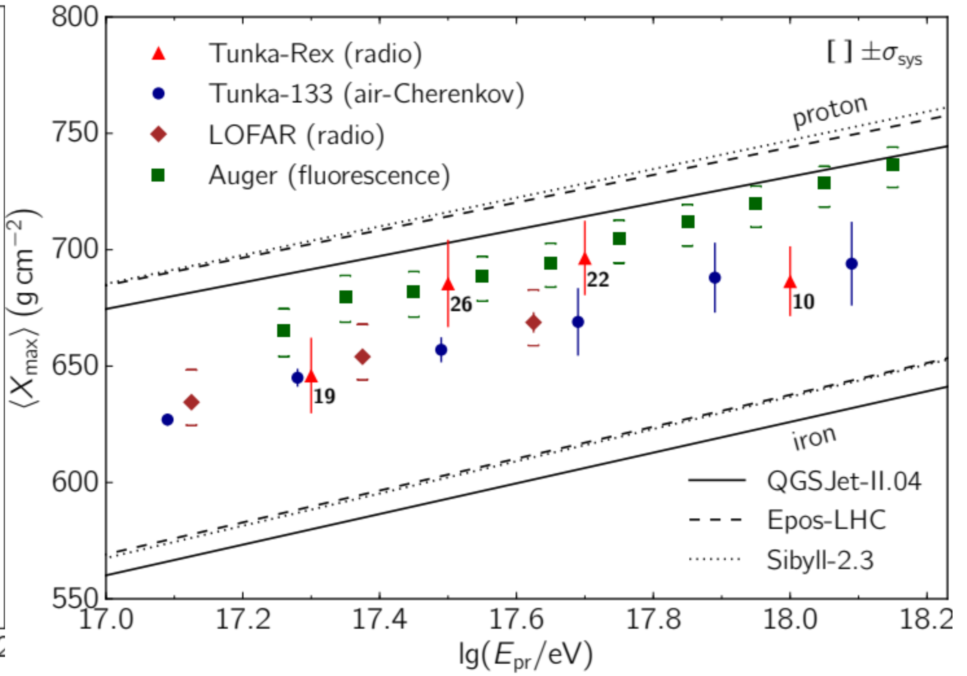


The correlation of reconstructed radio and Cherenkov energy
The Tunka-Rex energy resolution of 10%.

The correlation of reconstructed radio and Cherenkov Xmax
The Tunka-Rex Xmax resolution is 25 – 35 g/cm^2

Tunka-Rex energy spectrum and X_{max}





Energy resolution is 10%, X_{max} resolution is 25-35%

Reconstruction is based on template fitting of EAS pulses.

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Particle detectors in TAIGA-experiment

12.06.2014, KASCADE-GRANDE counters arrived to the TAIGA site

Disassembly, repair and assembly of detectors

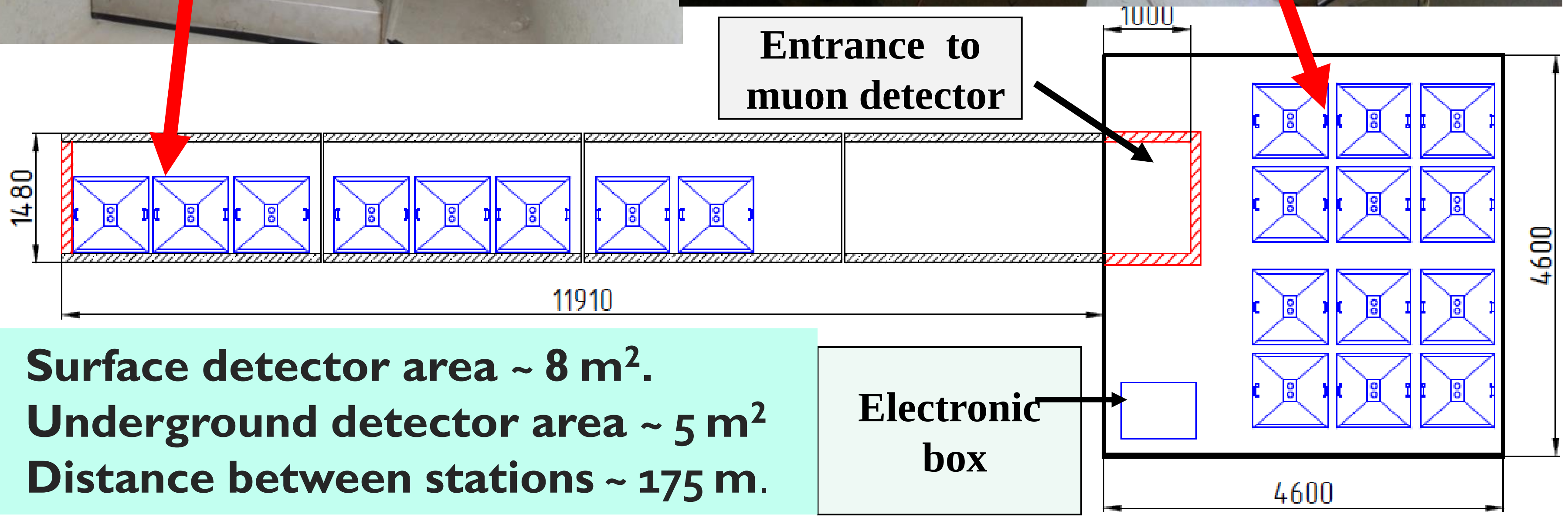



Construction of underground tunnel for muon detectors

Tunka - Grande scintillation array

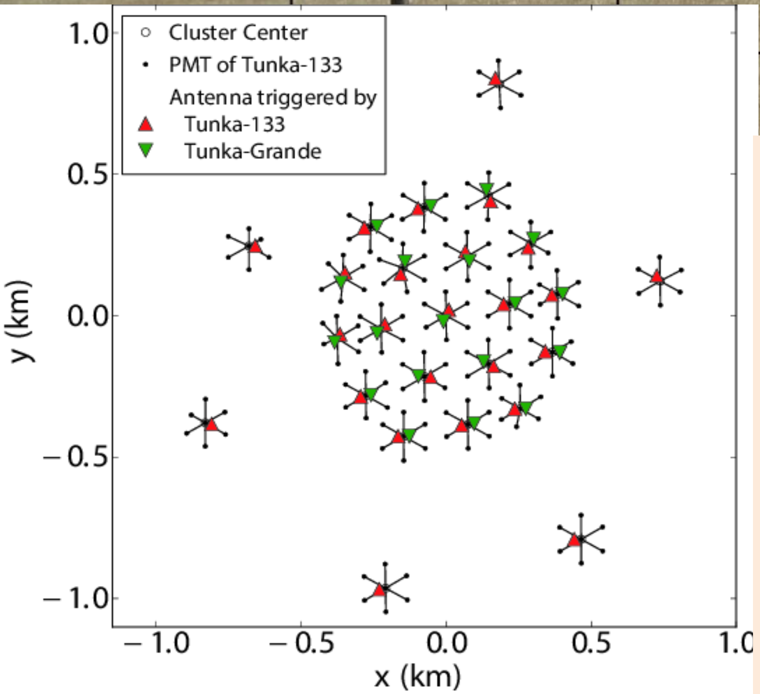
228 KASCADE-Grande scintillation counters (0.64 m^2) in 19 stations of the surface detector

152 KASCADE-Grande scintillation counters in underground containers

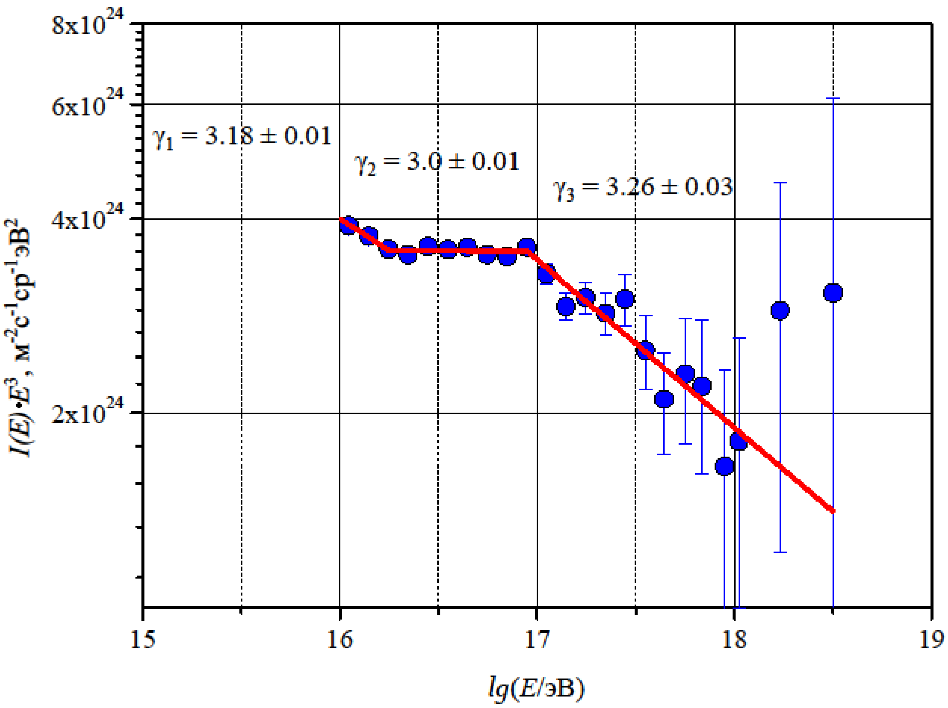


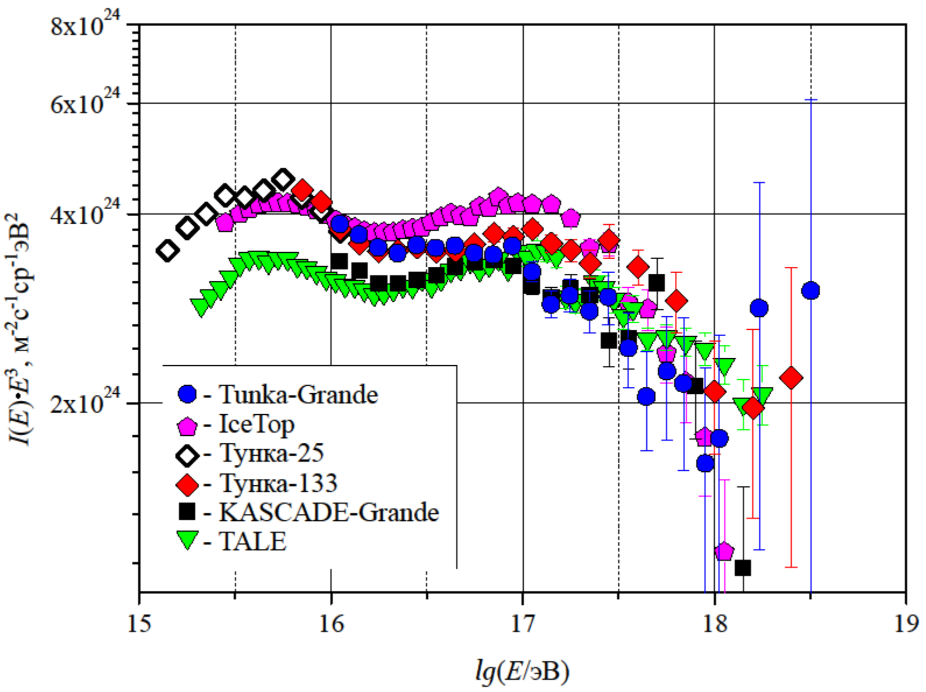
- Surface detector area ~ 8 m^2.
- Underground detector area ~ 5 m^2
- Distance between stations ~ 175 m.

Tunka-Grande scintillation array



- Common operation Tunka-133 & TAIGA-HiSCORE & Tunka-Rex & and Tunka-Grande scintillation array
- Cross calibration of Radio, Cherenkov and "particle" methods
- Check of reconstruction precision
- Crucial input to next generation cosmic-ray observatories





Tunka-Grande CR energy spectrum

Comparison of the Tunka-Grande & Tunka-133 CR energy spectra with other experimental results

~ 260000 events with energy E ≥ 10 PeV, zenith angle < 35°.

~ 2100 events with energy E ≥100 PeV, zenith angle θ <35°

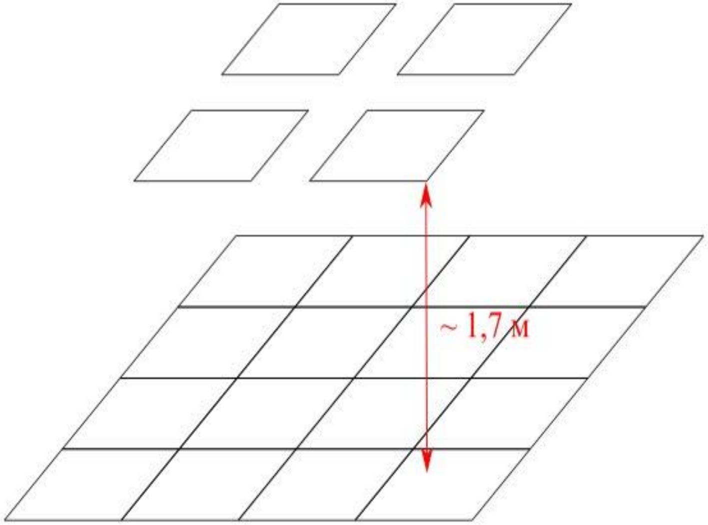
The TAIGA-Muon scintillation array

Counter dimension $1x1\ m^2$.

Wavelength shifting bars are used for collection of the scintillation light.

Mean amplitude from cosmic muon is 23.1 p,e, with ±15% variation.

A clear peak in amplitude spectrum is seen from cosmic muons in a self trigger mode



Summary

- **Tunka Valley has become one of the main centers of world-class cosmic ray research.**
- **For 30 years, a number of high-class installations for the study of high-energy cosmic rays have been built in the Tunka Valley.**
- **High-precision methods of restoring the energy spectrum and mass composition of primary cosmic rays have been developed based on data on Cherenkov and radio radiation of EAS as well on particle data.**
- **The energy spectrum of cosmic rays in the range of 4 orders of magnitude in energy is restored by the Cherenkov method. A number of features are observed in the energy spectrum that do not yet have a clear astrophysical interpretation.**
- **In the coming years, we plan to conduct detailed studies of the mass composition of cosmic rays, based on joint data from Tunka-133, TAIGA-HiSCORE, TAIGA-IACT, Tunka-Grande and TAIGA-Muon installations, what can be the key to understanding the nature of the features of the energy spectrum**