TAIGA experiment: present status and perspectives.

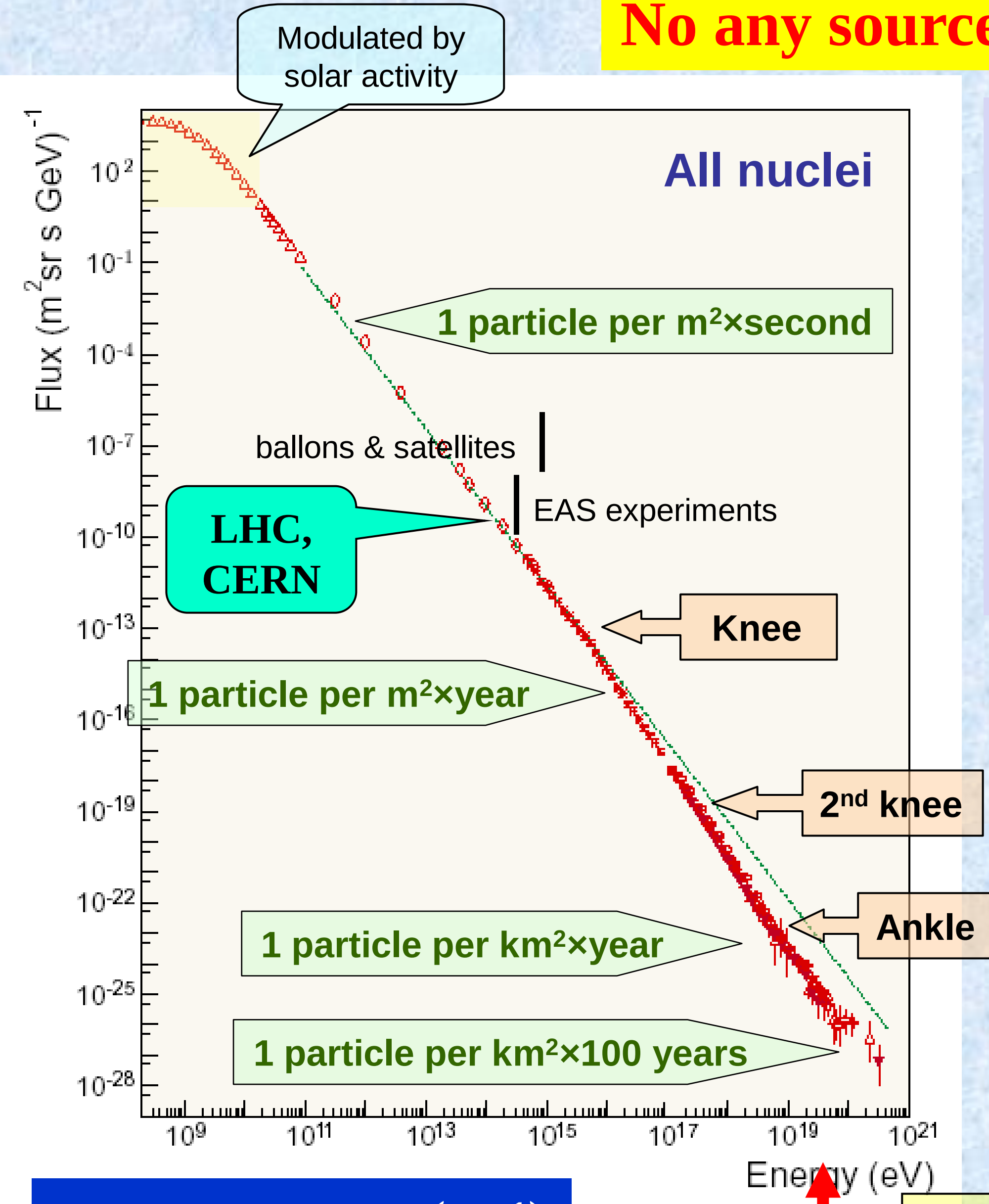
N.Budnev, Irkutsk State University
For TAIGA collaboration

April 17, 1912: In a balloon at an altitude of 5000 meters, Victor Hess discovered "penetrating radiation" coming from space

Even very well isolated gold-leaf electroscopes are discharged at a slow rate.

A bird's eye view of the ALL-PARTICLE CR SPECTRUM

No any sources are discovered up to now!

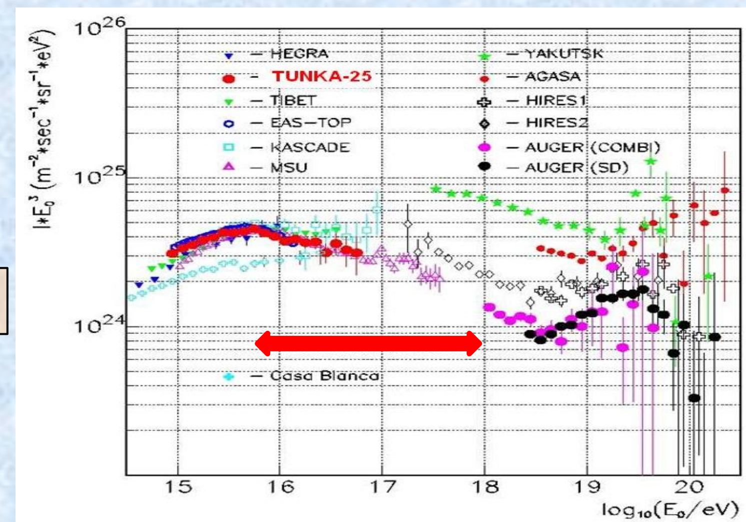


$$F(E) = A E^{-(\gamma+1)}$$

Expected GZK cutoff

Probably, they are:

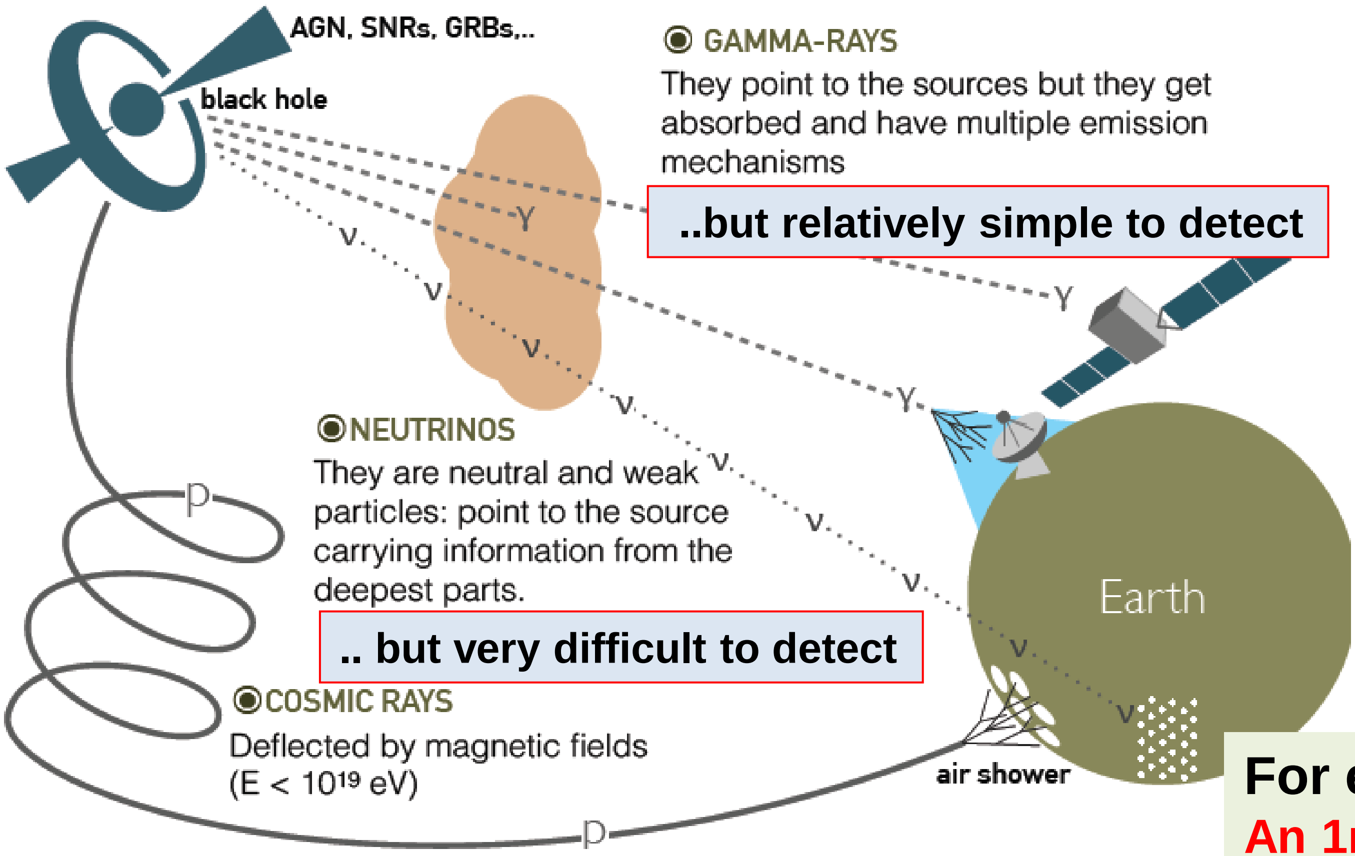
1. Galactic sources: Supernova remnants, Environment of black holes, Pulsar wind nebulae, Gamma-ray binaries, Globule clusters, Microquasars, … and a lot of Unidentified sources.
2. Extragalactic sources : Active Galactic Nuclear, Gamma-ray bursts….?????????
3. Decays of super heavy particles???????



$$P + \gamma \rightarrow \Delta \rightarrow n + \pi$$

Gamma-astronomy & neutrino astronomy

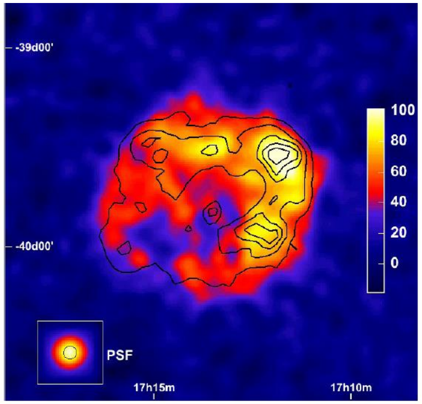
The best way to understand a nature of a cosmic high energy accelerator is to detect gamma-rays or neutrinos.



..but relatively simple to detect

.. but very difficult to detect

RX J1713.7 – remnant of a super-nova



For energy > 30 TeV

An 1км^3 neutrino detector

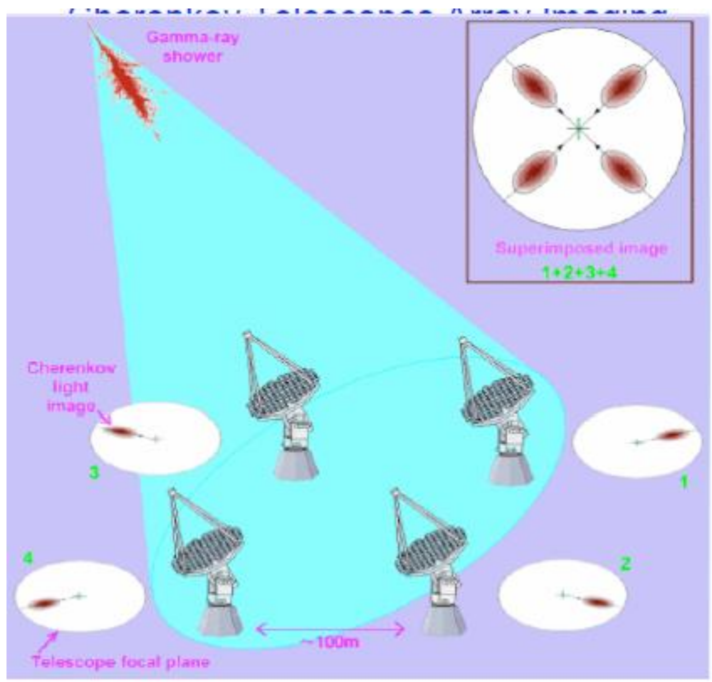
- 1 event / 10 years

An 1км^2 gamma detector

- 1 event / 1 hour!

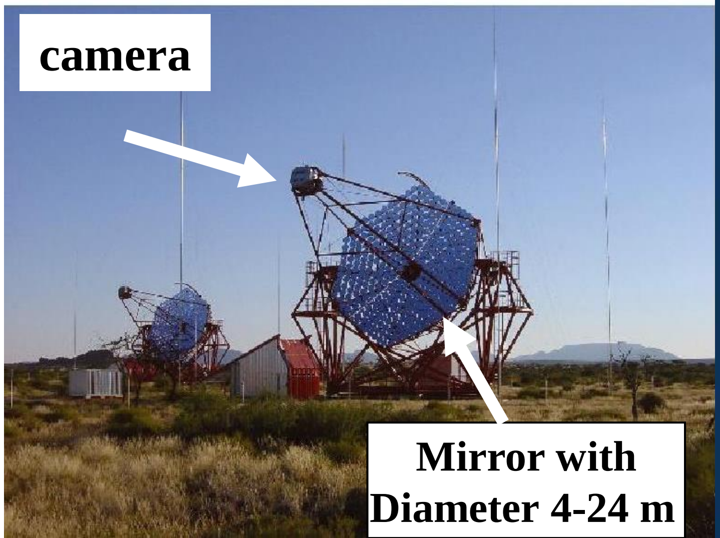
IACT - *Imaging Atmospheric Cherenkov Telescopes*

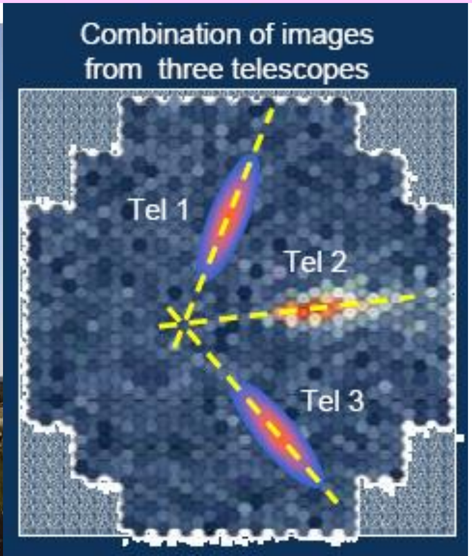
HEGRA
HESS
MAGIC
VERITAS
S ~ 0.01 km^2
Future Project
CTA



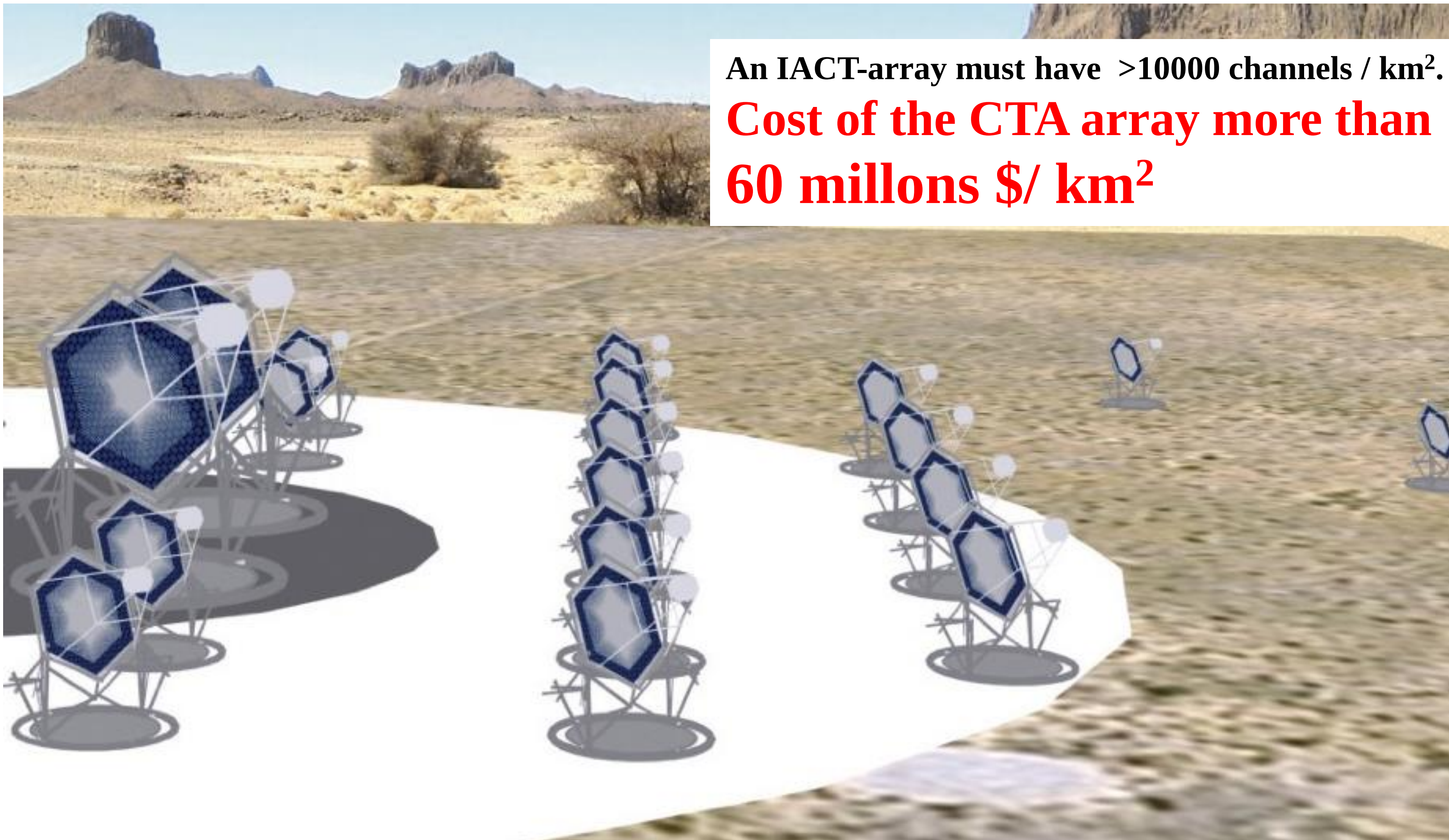
About 200 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays.
But no gamma- quantum with energy more then 80 TeV were detected up to now.
An area of an array should be 1 km^2 at least!

An IAST is narrow-angle Telescope (3-5° FOV) consisting of a mirror of 4 -28 m diameter which reflects EAS Cherenkov light into a camera where EAS image is formed





CTA project: 100 IACT on aria 7 кm^2

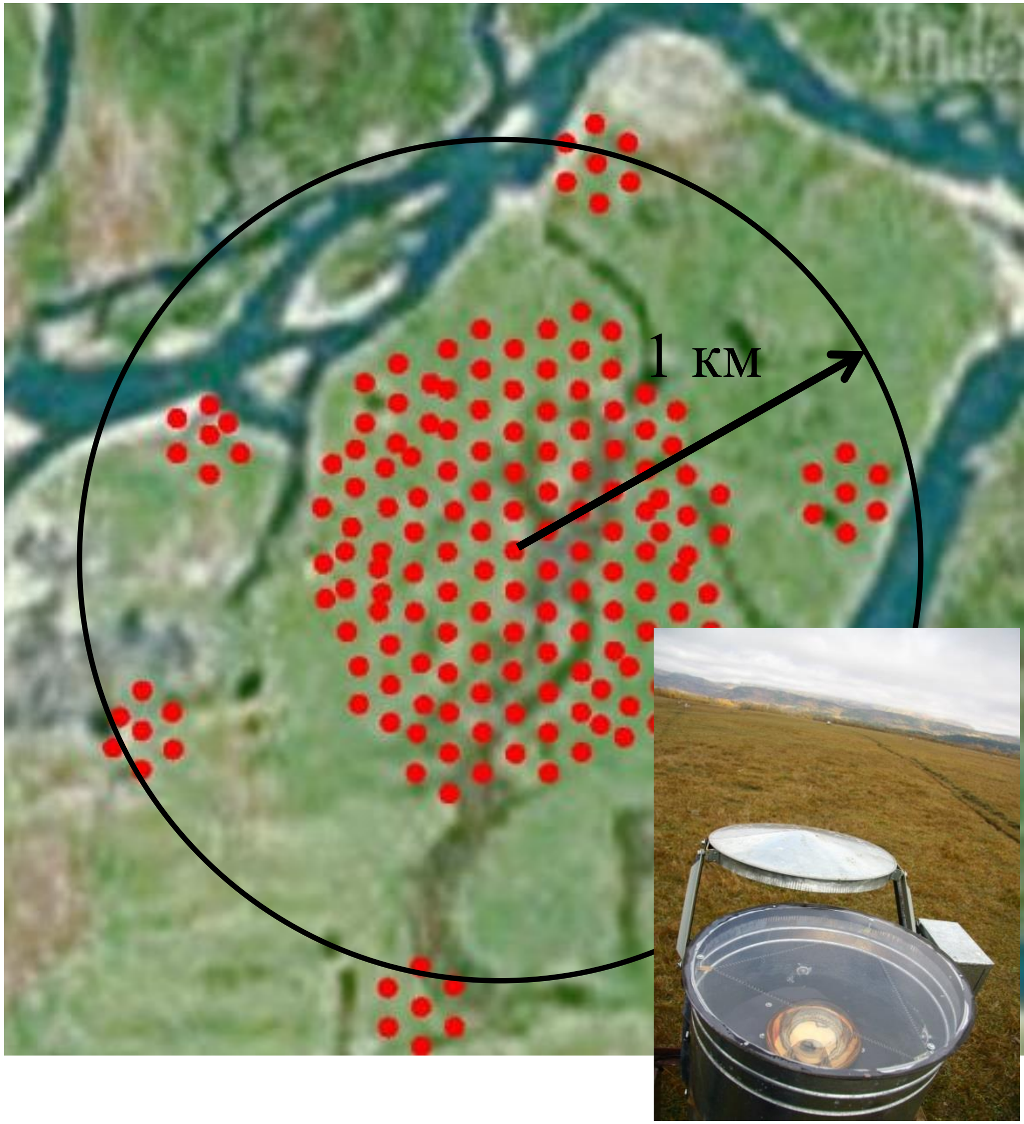


An IACT-array must have >10000 channels / km^2.

Cost of the CTA array more than 60 millons \$/ km^2

Tunka-133 array: 175 wide angle Cherenkov detectors distributed on 3 km² area (2006-2012y)

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



50 km from Lake Baikal

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
Institute of Applied Phys. of Irkutsk State University, Irkutsk, Russia;

S.F.Beregnev, S.N.Epimakhov, N.N. Kalmykov, N.I.KarpovE.E. Korosteleva, V.A. Kozhin, L.A. Kuzmichev, M.I. Panasyuk, E.G.Popova, V.V. Prosin, A.A. Silaev, A.A. Silaev(ju), A.V. Skurikhin, L.G.Sveshnikova I.V. Yashin,
Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow, Russia;

B.K. Lubsandorzhiev, B.A. Shaibonov(ju) , N.B. Lubsandorzhiev
Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;

V.S. Ptuskin
IZMIRAN, Troitsk, Moscow Region, Russia;

Ch. Spiering, R. Wischnewski
DESY-Zeuthen, Zeuthen, Germany;

A.Chiavassa
Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.

Advantage of the Tunka-133 array:

1. Good accuracy positioning of EAS core (5 -10 m)
2. Good energy resolution (~15%, in principal up to - 5%)
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**

Disadvantage:

1. The accuracy of measurement is not sufficient for gamma / hadron separation
2. The energy threshold is rather high (~ 50 PeV).

From Tunka Collaboration to 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 Russian Academy of Science (INR RAN), Moscow, Russia
Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS (IZMIRAN), Troitsk, Russia
Joint Institute of Nuclear Physics (JIRN), Dubna, Russia
National Research Nuclear University (METHI), Moscow, Russia
Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk, Russia
Novosibirsk State University (NSU), Novosibirsk, Russia
Deutsches Elektronen Synchrotron (DESY), Zeuthen, Germany
Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
Institut fur Experimentalphysik, University of Hamburg (UHH), Germany
Max-Planck-Institut für Physik (MPI), Munich, Germany
Fisica Generale Universita di Torino and INFN, Torino, Italy
ISS , Buharest, Rumania

Towards Very High Energy Gamma-Ray Astronomy array at Tunka Valley

TAIGA – Tunka Advanced Instrument for cosmic rays and Gamma Astronomy – 5 arrays

=

Tunka-133

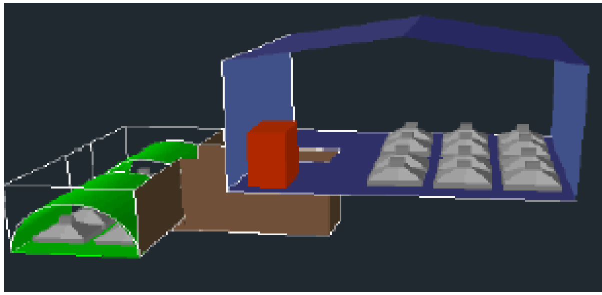
+

Tunka-Rex

+

+

+

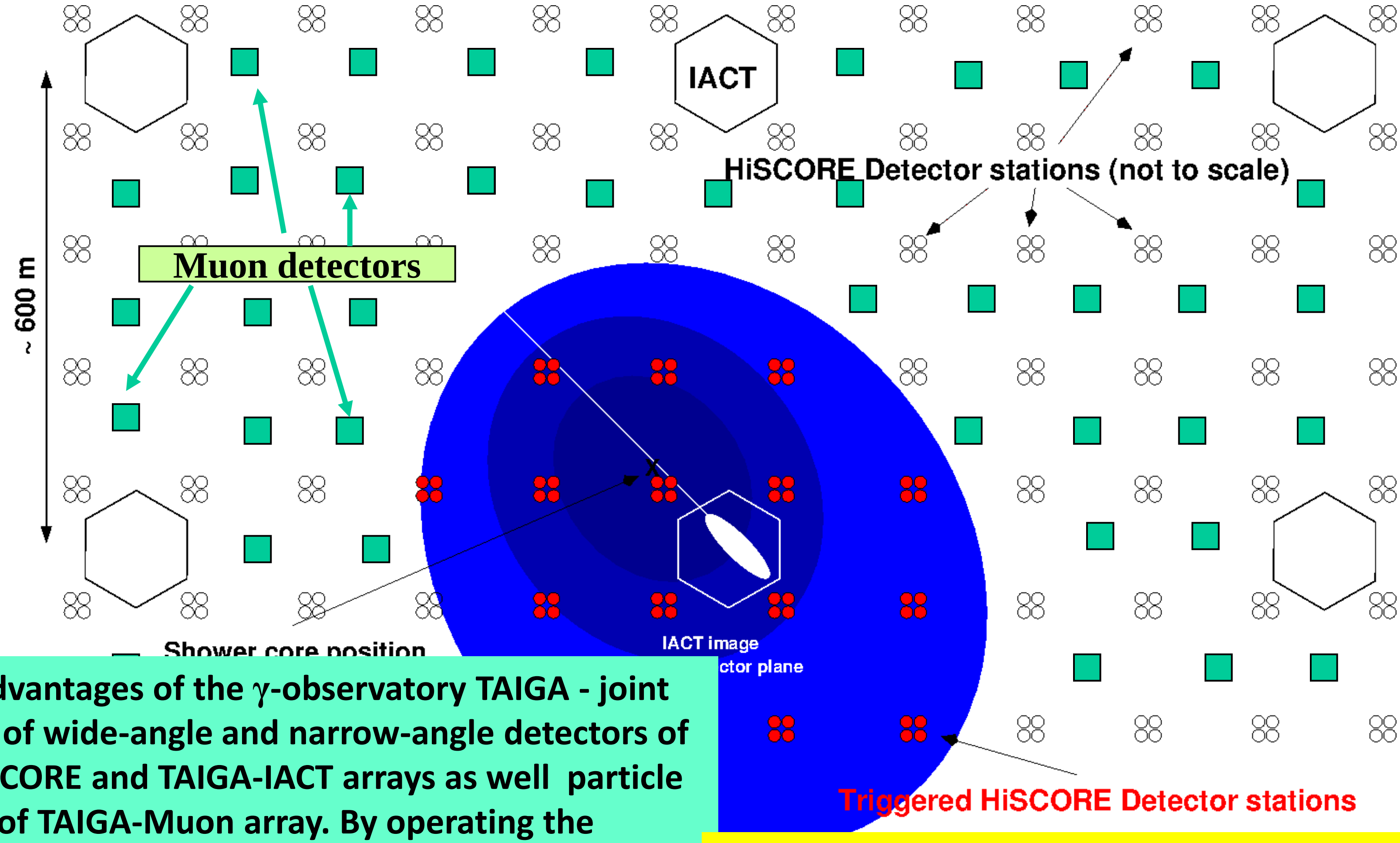


TAIGA-HiSCORE array -net of 500-700 non imaging wide-angle stations distributed on area 5 km^2
Angular resolution – 0.1 deg,
Core position - 5-10 m
Energy resolution 10 – 15%
Pulse form - hadron rejection.

TAIGA-IACT array -net of 10- 16 Imaging Atmospheric Cherenkov Telescopes with mirrors – 4.2 m diameter.
Charged particle background rejection using imaging technique.

TAIGA-Muon (including Tunka – Grande) array net of scintillation detectors, including underground muon detectors with area - $10^2 \longrightarrow 2\ 10^3$ m^2 area
Charged particle background rejection.

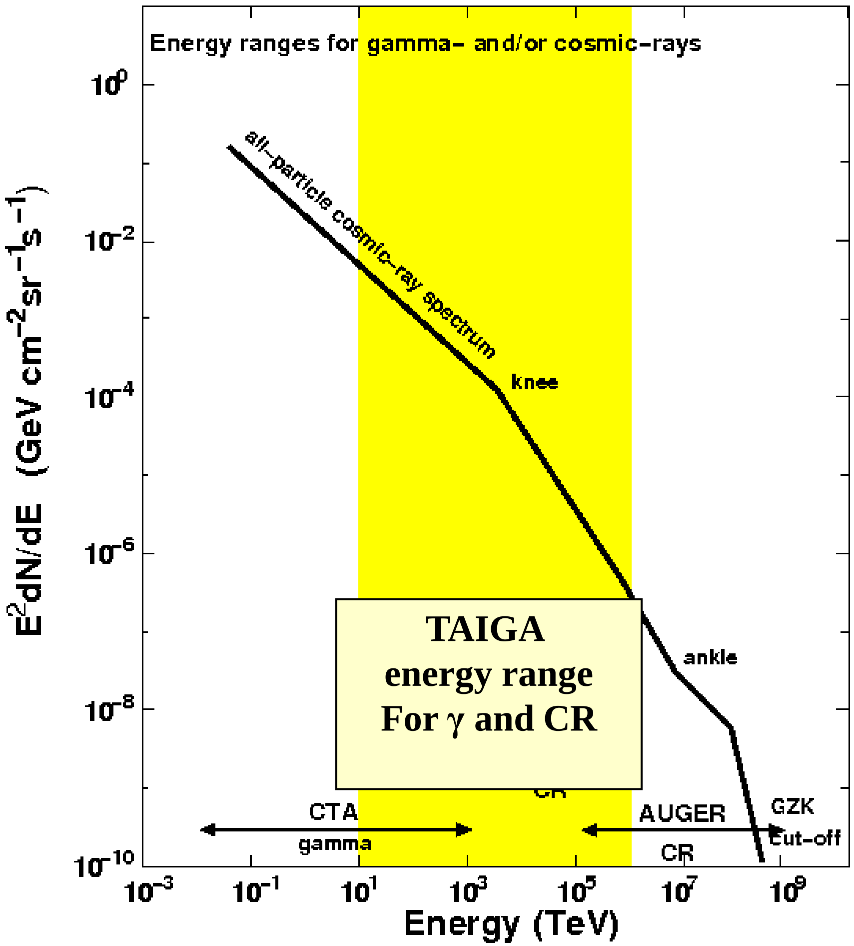
TAIGA: Imaging + non-imaging techniques



The key advantages of the γ-observatory TAIGA - joint operation of wide-angle and narrow-angle detectors of TAIGA-HiSCORE and TAIGA-IACT arrays as well particle detectors of TAIGA-Muon array. By operating the telescopes in mono-scopic mode with distances of the order of 600 m between the telescopes, the total area covered per telescope is larger than the area that could be covered using the same number of telescopes as a stereoscopic system (requiring distances of roughly 300 m in the 10–100 TeV energy range).

Timing array TAIGA - HiSCORE: core position, direction and energy reconstruction.
Gamma/ hadron separation
Imaging array TAIGA-IACT - (image form, monoscopic operation) &
TAIGA-Muon (electron/muon ratio)

Main Topics for the TAIGA observatory



Gamma-ray Astronomy

Search for the PeVatrons.
VHE spectra of known sources: where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition anisotropies from 10^{14} to 10^{18} eV.
10^8 events (in 1 km^2 array) with energy > 10^{14} eV

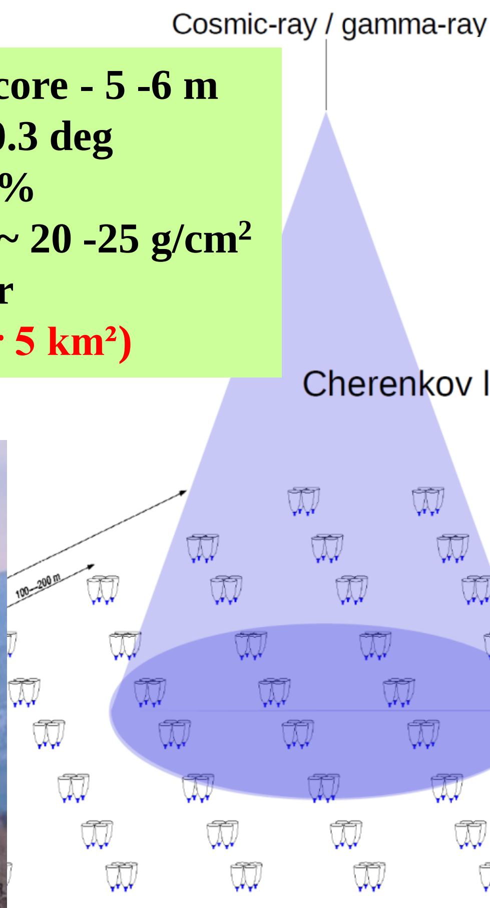
Particle physics

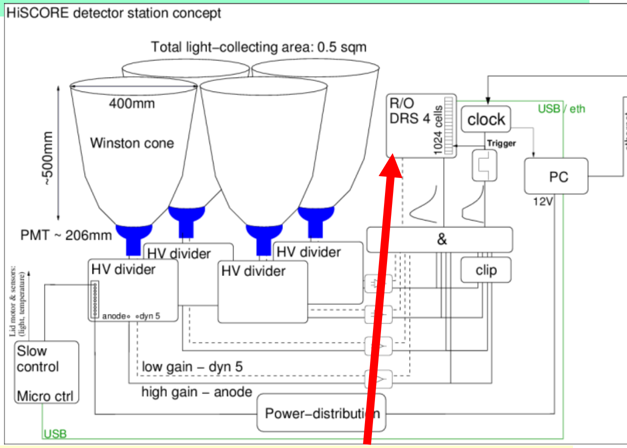
Axion/photon conversion.
Hidden photon/photon oscillations.
Lorentz invariance violation.
pp cross-section measurement.
Quark-gluon plasma.

TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

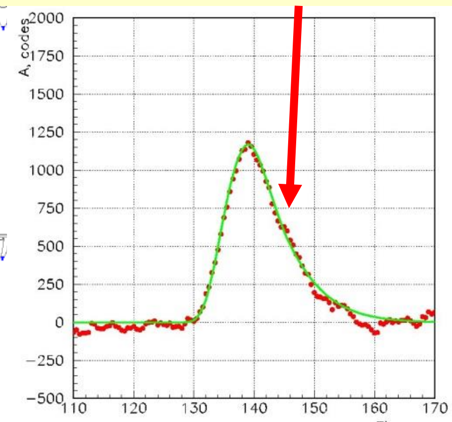
- **Wide-angle time- amplitude sampling non-imaging air Cherenkov array.**
- **700 detectors on area 5 km^2**
- **Spacing between Cherenkov stations 80-100 m ~ 100 -150 channels / km^2.**

1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.3 deg
3. Energy resolution ~ 10 - 15%
4. Accuracy of X_{max} measure ~ 20 -25 g/cm^2
5. Large Field of view: ~ 0.6 sr
Total cost ~ 10 ·millions $ (for 5 km²)

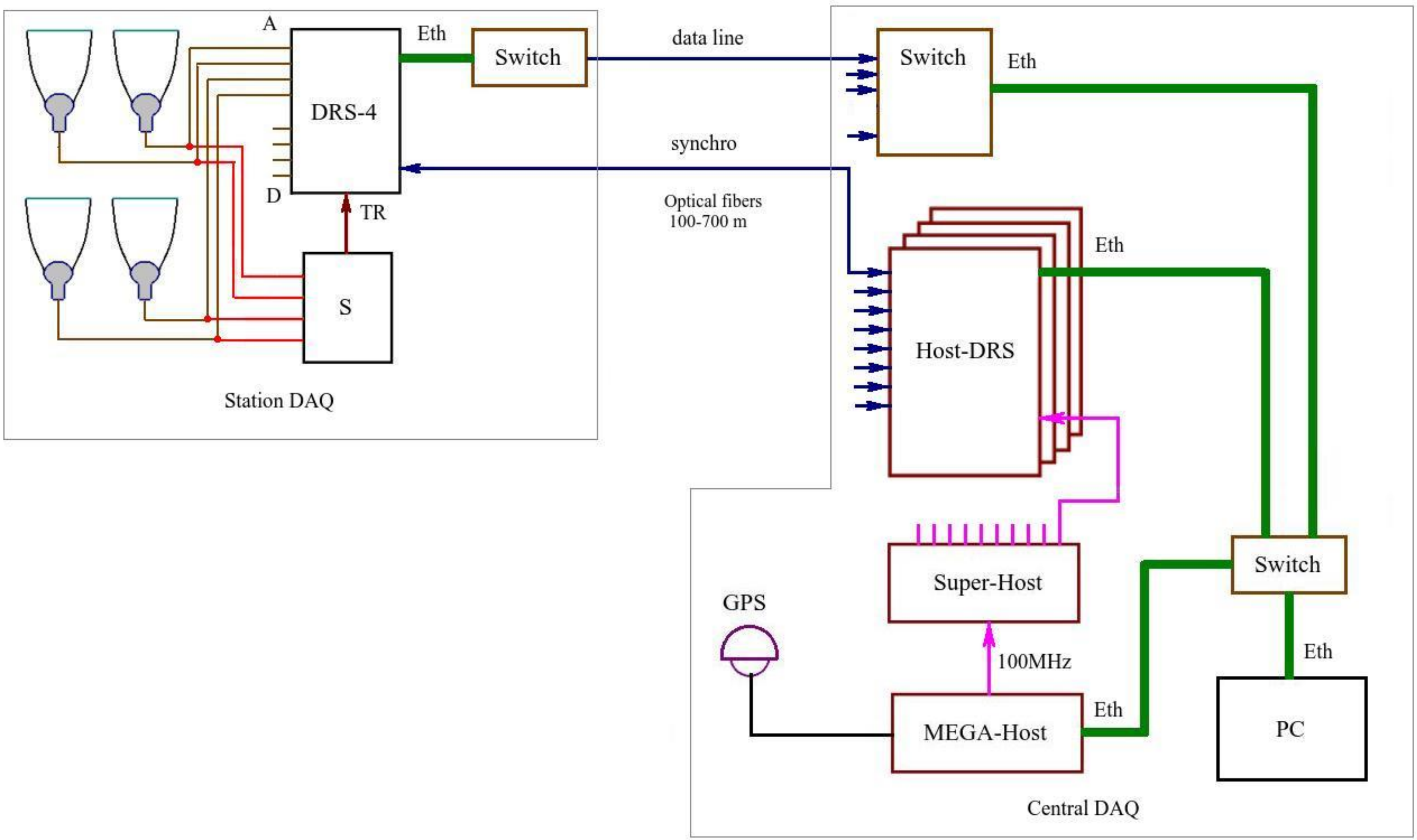




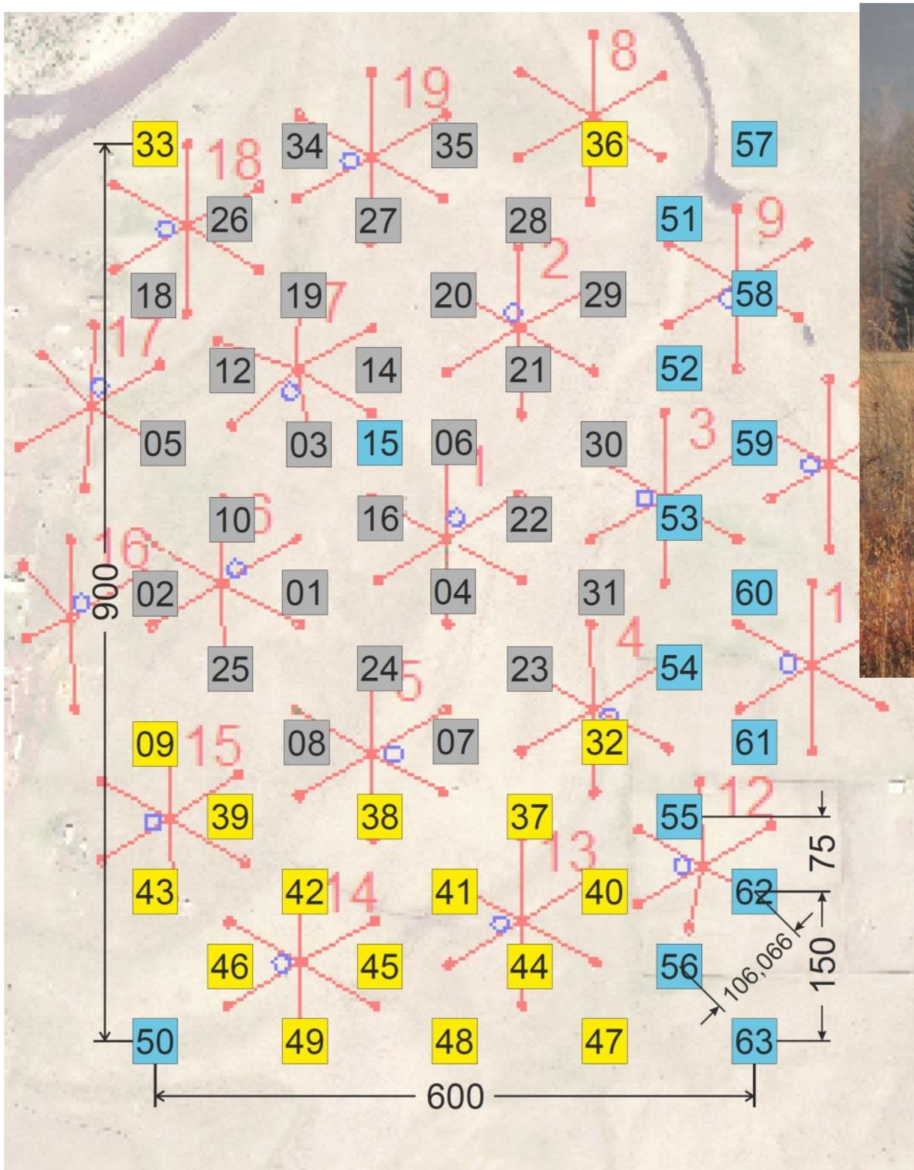
DRS-4 board (0.5 ns step)



Data acquisition system of the TAIGA-HiSCORE array

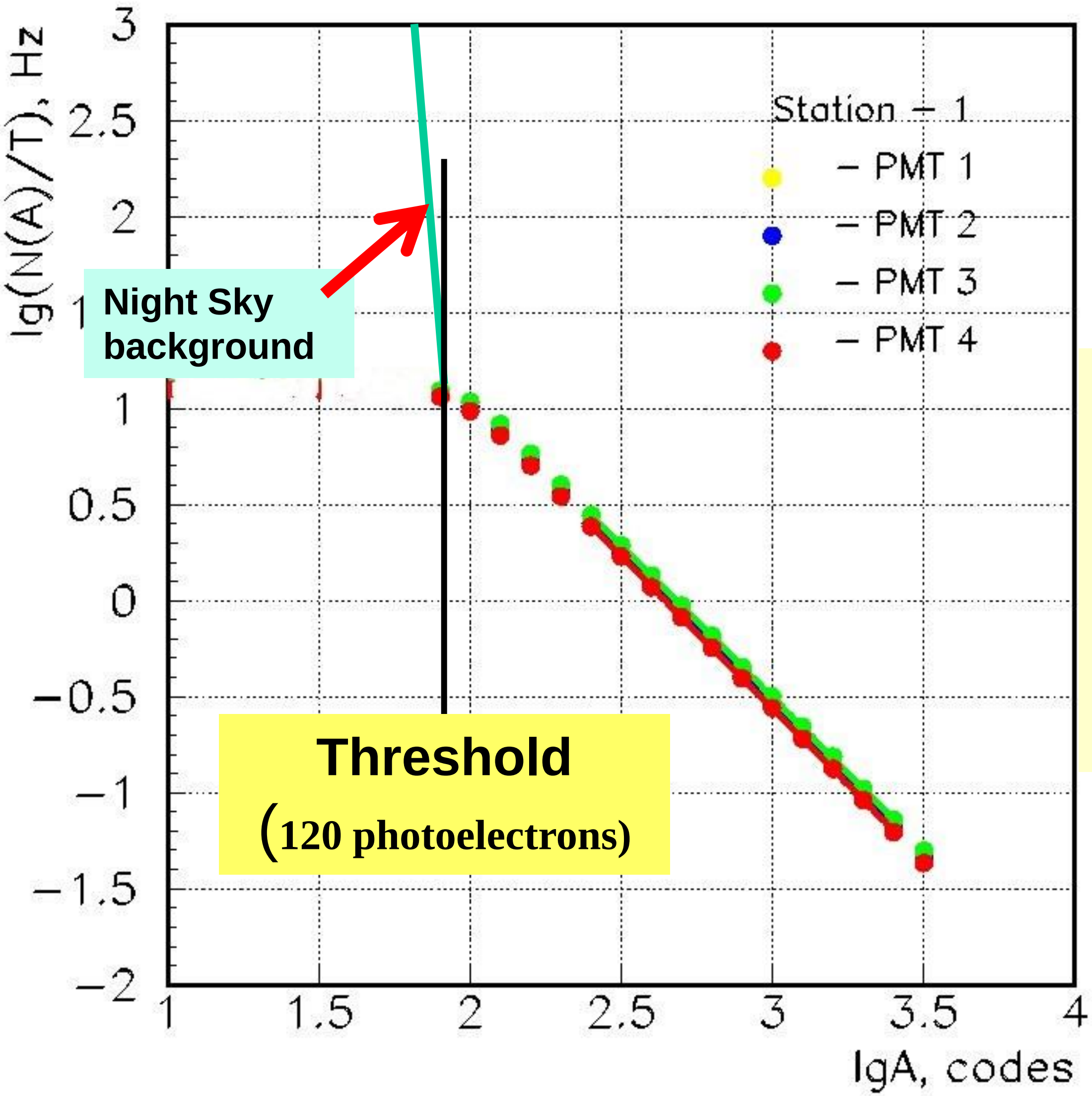


TAIGA-HiSCORE 2016 year setup



60 detectors on area
(S=0.6 km^2)
Spacing - 106 m.

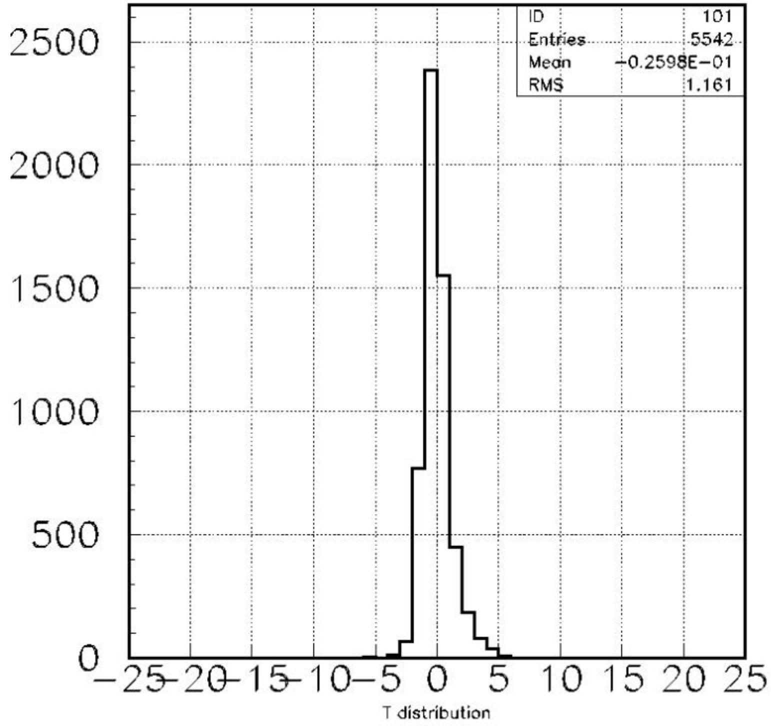
An amplitude spectrum of PMTs pulses of a TAIGA-HiSCORE optical station

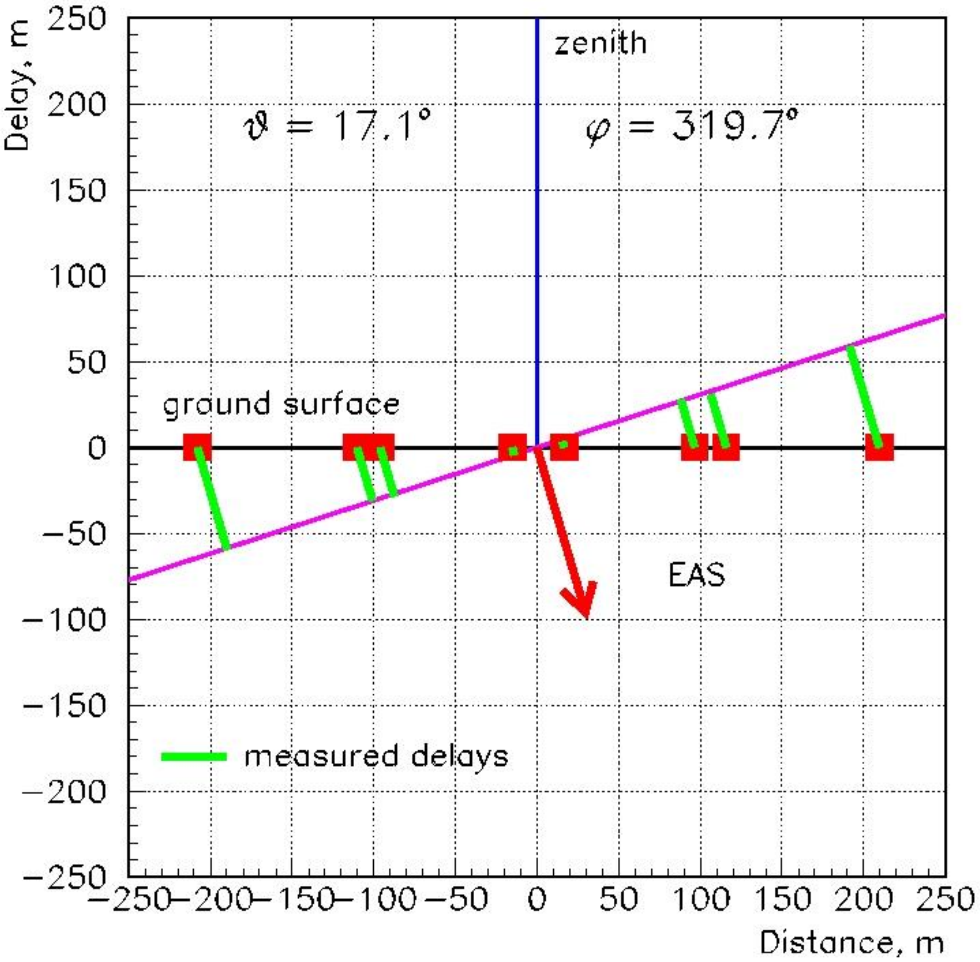


Threshold Cherenkov photons flux:
0.25 – 0.3 ph / cm^2

Or ~ 30 TeV for gamma EAS
And ~60 TeV for hadron EAS
(for the array with area ~ 1 km^2)

The accuracy of EAS axis direction reconstruction





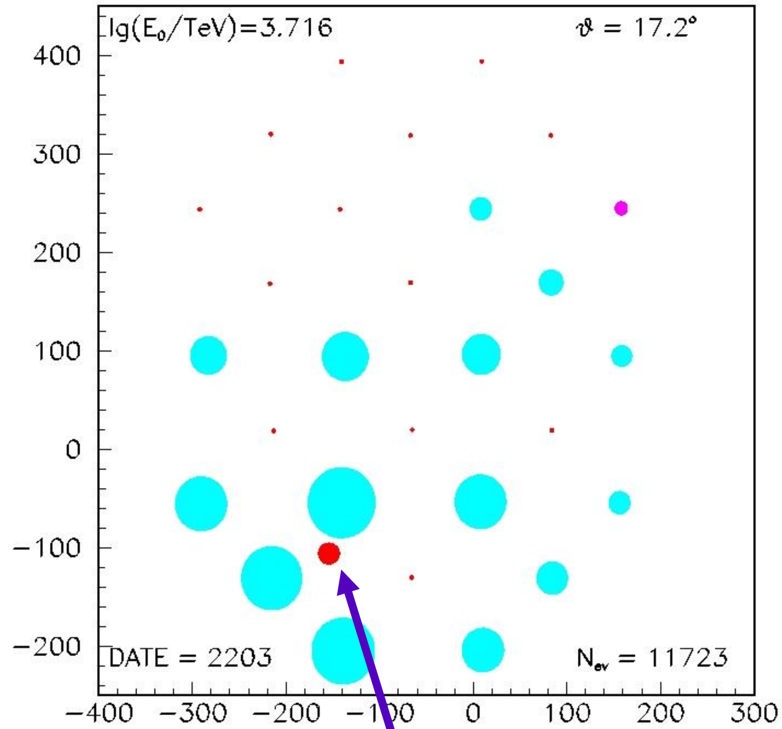
The RMS=1.1 ns for TAIGA-HiSCORE provides an accuracy of an γ and CR arrival direction about 0.1 degree

2014 – 2015 year data

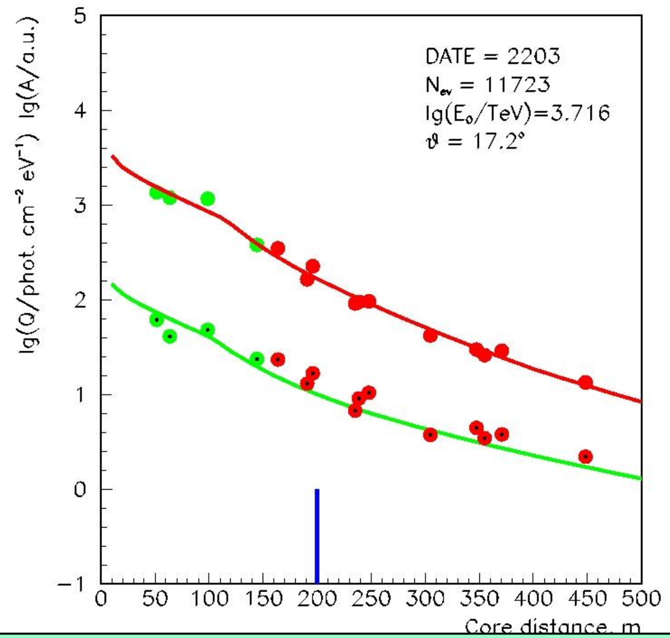
894525 single Cherenkov light pulses

>4 stations coincidence ~50,738 events

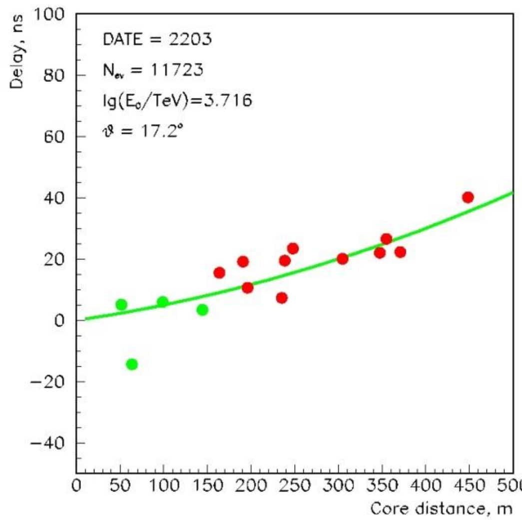
>9 stations coincidence – 2000 events



Reconstructed core position for an event, the area of the circles is proportional to *logA*, with *A* the station signal amplitude

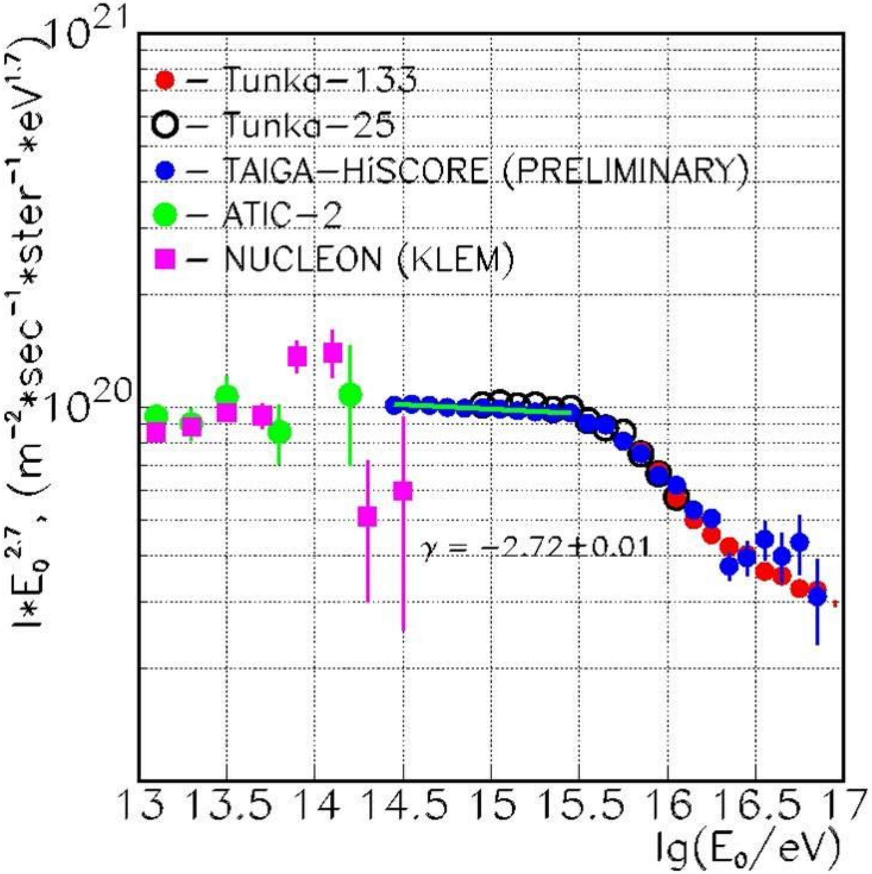


Amplitude – distance function



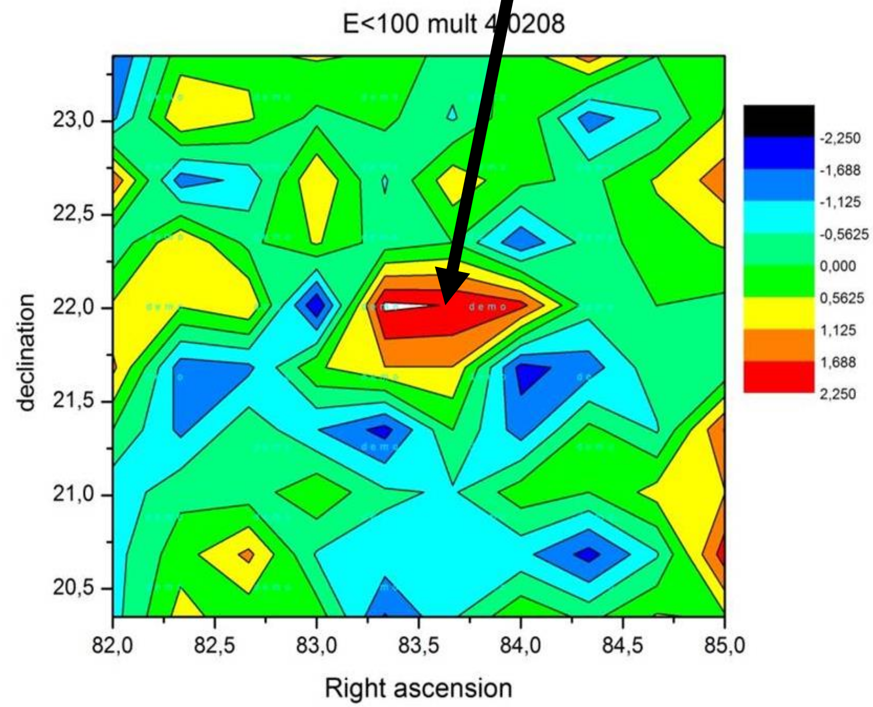
Arrival time delay vs distance R from EAS core

TAIGA-HiSCORE (0.25 км²) results (PRELIMINARY!)



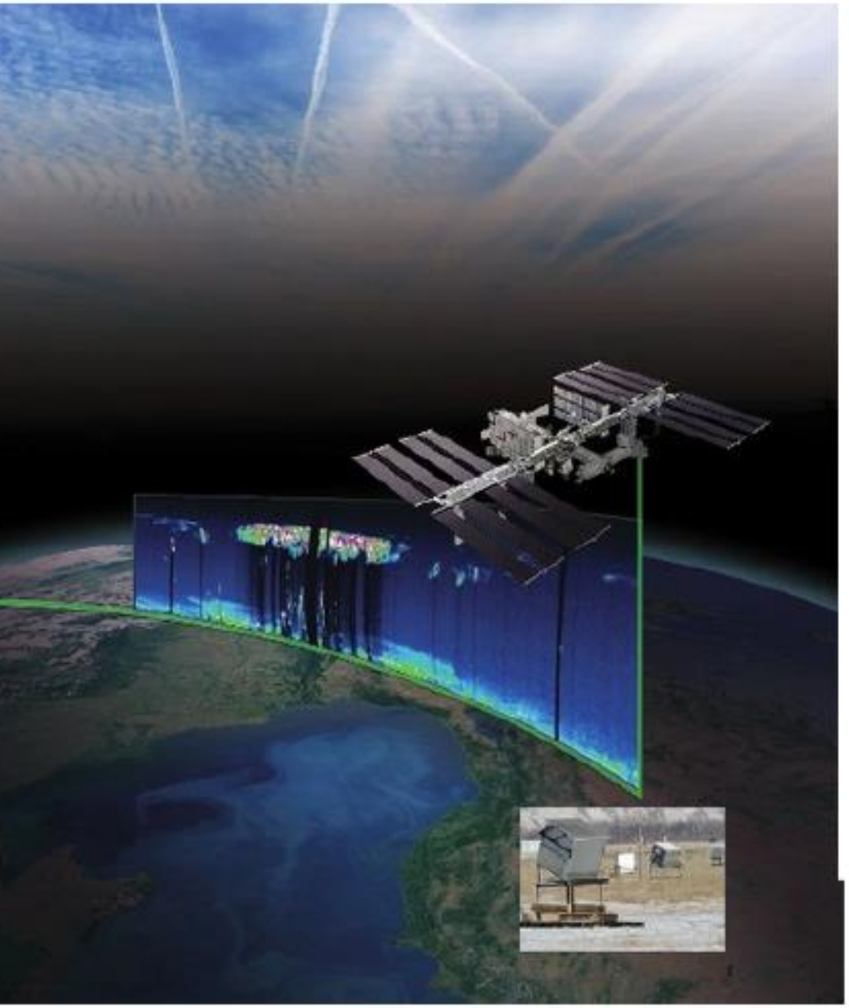
TAIGA-HiSCORE Energy spectrum

E< 100 TeV
Excess - 28 events (2.6 σ)



Search for the Crab with TAIGA-HiSCORE

A first TAIGA-HiSCORE “Point-source”



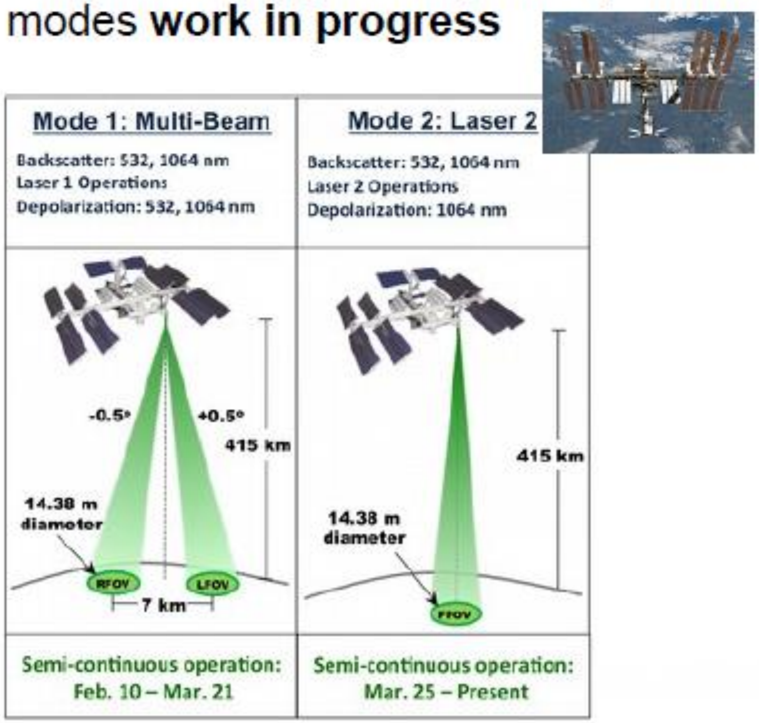
- 11/2015 & 02/2016 data:
  - High trigger-rate “flares”, 4 kHz pulsed emission
  - Point-like emission, moving source position
  - Coincidence with ISS (discovered by A. Porelli)
    - Onboard CATS LIDAR @ 1064nm, 532nm
    - LIDAR pointing offset to zenith axis: O(degrees)

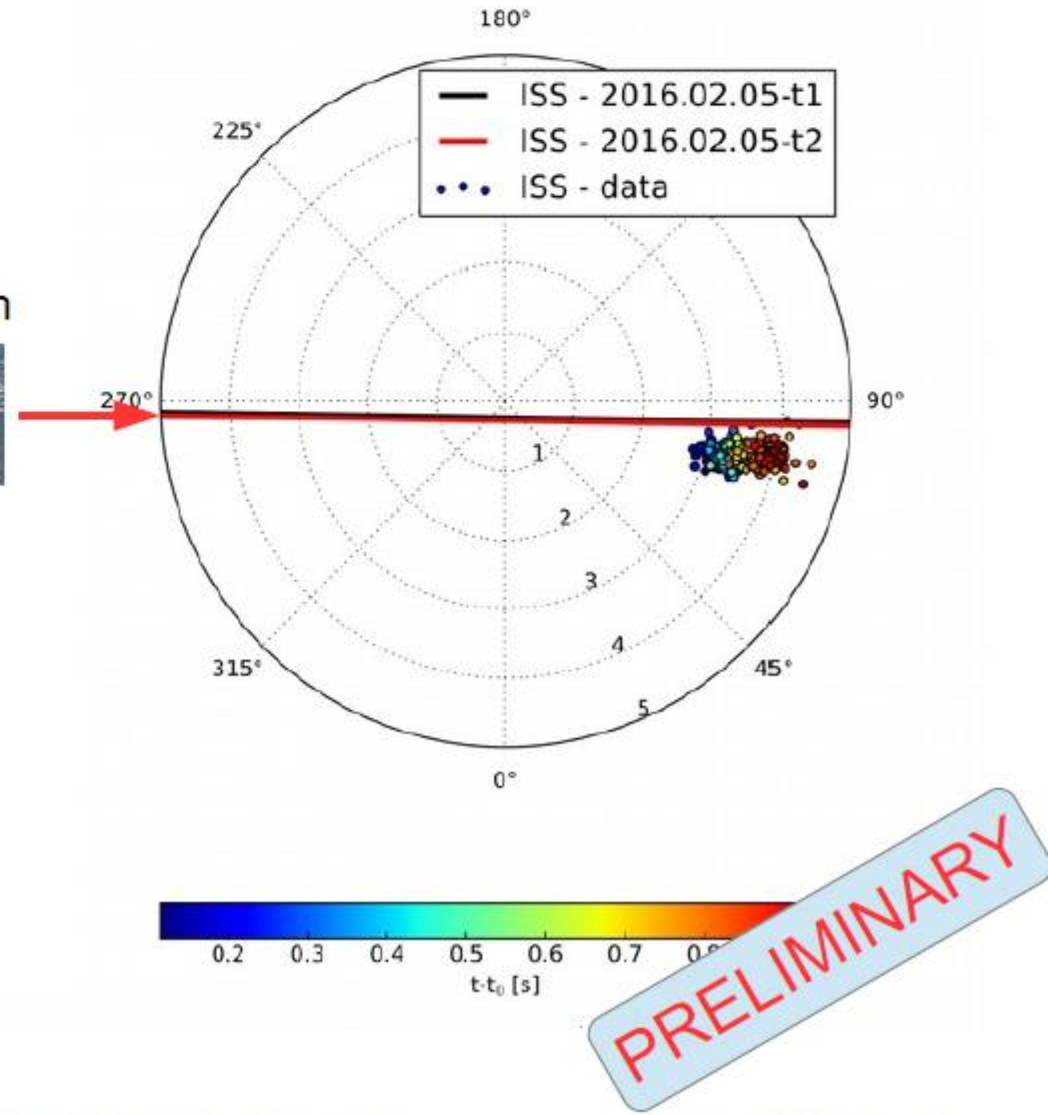
A first TAIGA-HiSCORE "Point-source"

Very recent results !

Height of orbit, Orientation angles of ISS and of Lidar have impact on actual observed event directions

Understanding geometry and operation modes **work in progress**





The TAIGA –IACT array

The TAIGA- IACT array will include
16 Imaging Atmospheric Cherenkov
Telescopes distributed with 600 – 1000 m
spacing over an area of 5 km^2.

The TAIGA- IACT will operate
Together with TAIGA-HiSCORE,
TAIGA-Muon, Tunka-133 and Tunka-Rex.

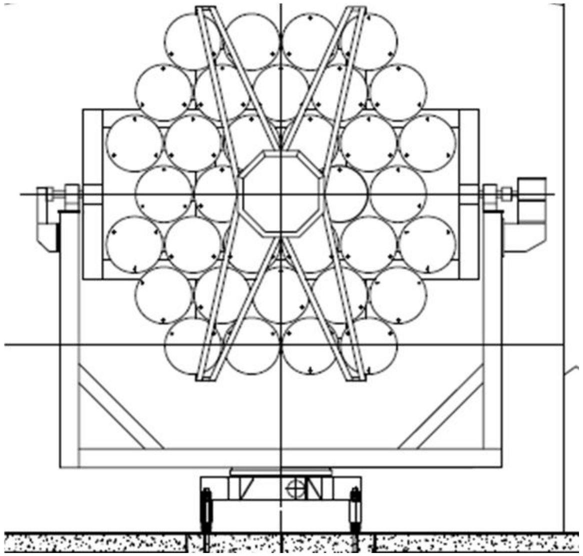
Threshold energy ~ 1 TeV
Angular resolution -0.03 degree
The sensitivity in the energy range 1-20 TeV
is 10^{-12} erg cm^{-2} s^{-1} (for 50 hours of observation)
The sensitivity in the energy range 30-200 TeV
is 10^{-13} erg cm^{-2} s^{-1} (for 10 events in 500 hours
of observation)

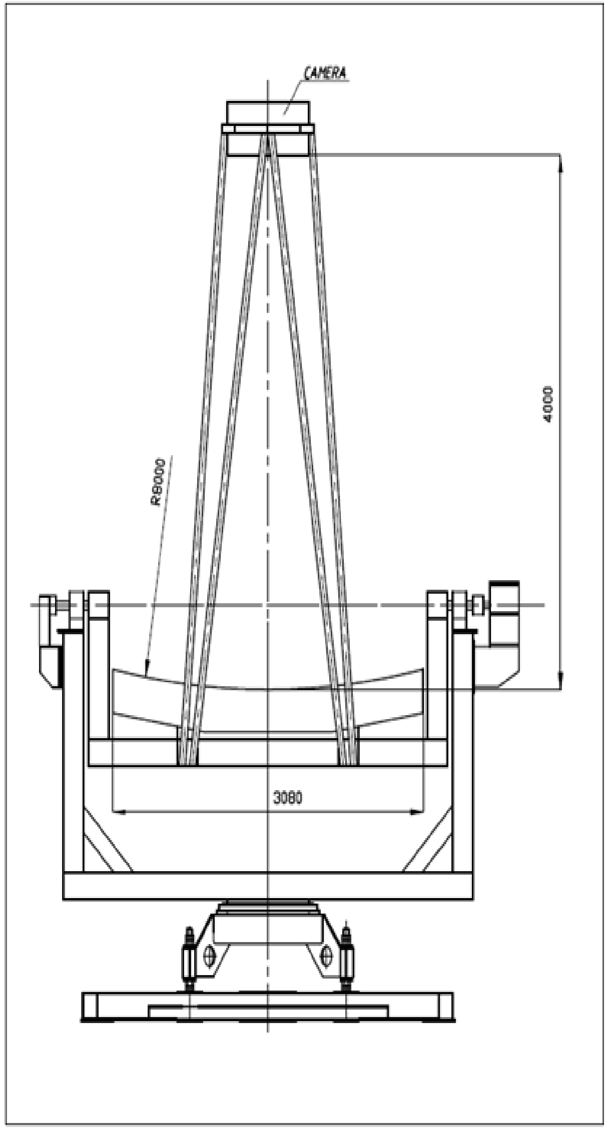
Low cost – 400 000$ / unit

Camera : 547 PMTs (XP 1911)
with 15 mm useful diameter of
photocathode.

Winston cone: 30 mm input size,
15 output size
1 single pixel = 0.36 deg
Full angular size 9.6x9.6 deg
DAQ - MAROC3

The mount of 1st TAIGA-IACT in JIRN



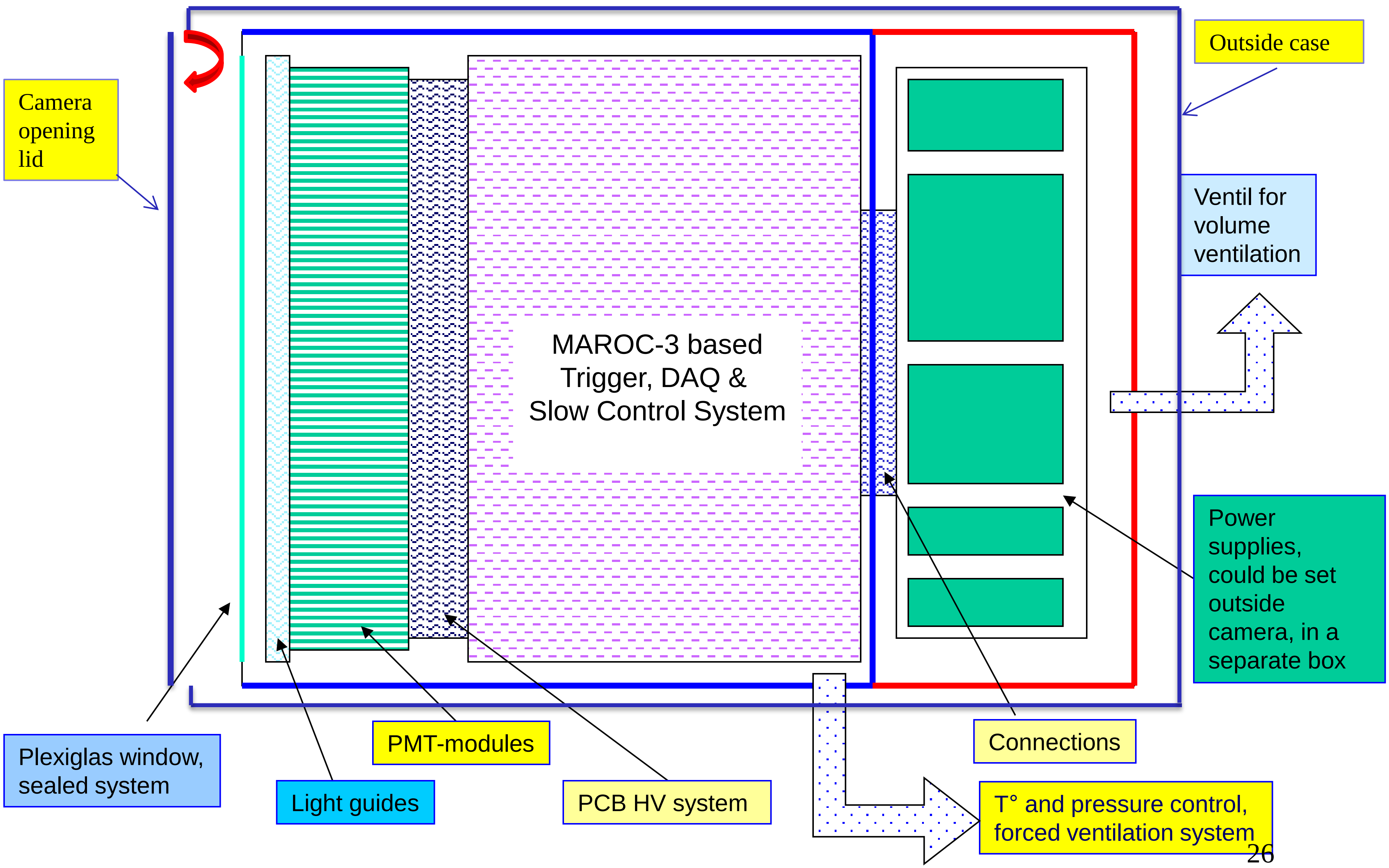


The HEGRA-like telescope mount :

- Davies-Cotton optic type
- Focal length: 4750 mm
- 34 spherical mirror segments
- Diameter of each segment: 60 cm
- Diameter of the mirror: 4.3 m
- The area: ~10 m^2,

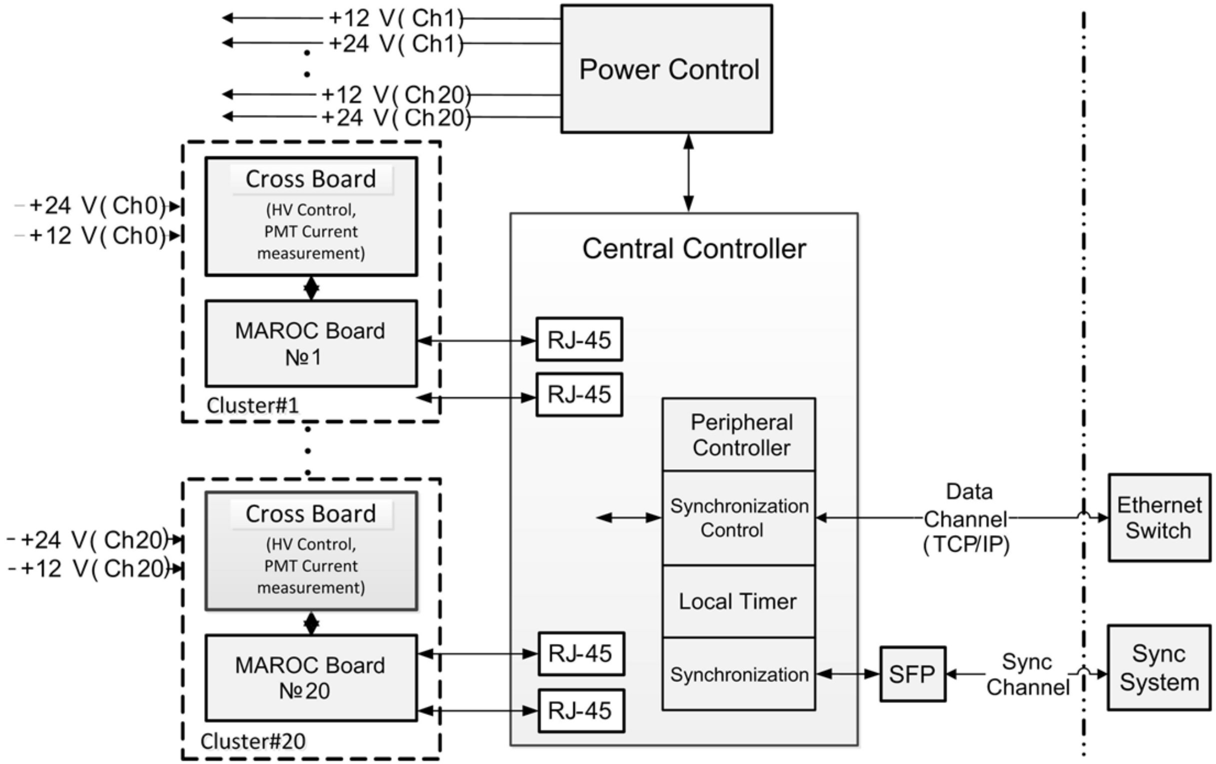
Assembling of the 1st mount, 2016y.

Conceptual design of the TAIGA-IACT camera mechanics



An electronic system of the camera includes:

- camera detection system;
- DAQ;
- triggering system;
- monitoring of noise current;
- PMT high-voltage supply



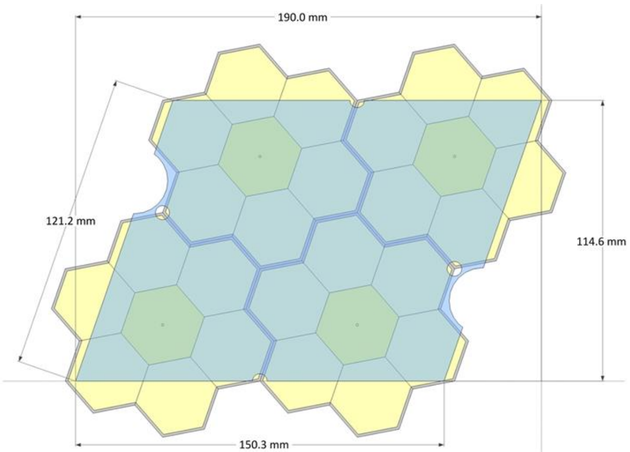
Detection system:
20 identical clusters serving 28 PMTs.

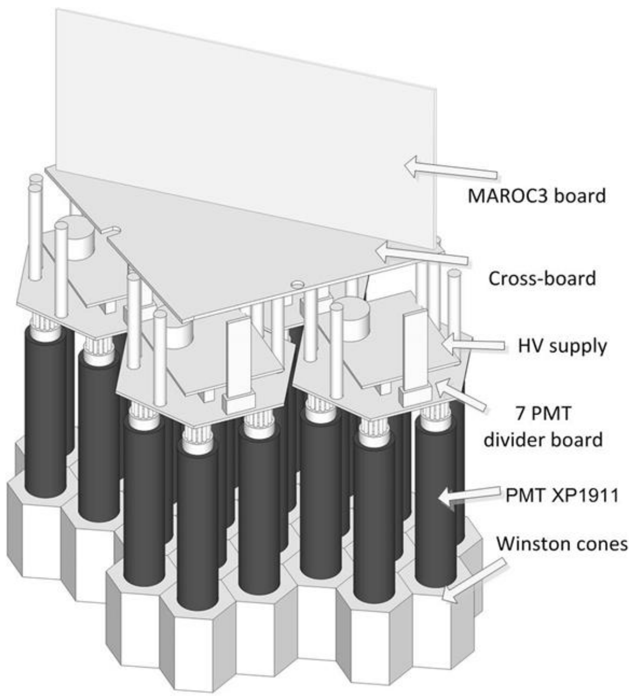
Central Controller:

controls of the PMT board operation (setting the high voltage and monitoring the PMT current), the common trigger formation, the PMT cluster data collection, synchronization, storage of data in the intermediate buffer, and the traffic of data between data collection centers and the Controller via Ethernet.

Communication between the boards and the PMT controller: standard LVDS.
Timing of trigger signals are not worse than 5 ns.
Data transfer rate is at least 20 Mbit/s.

The Camera basic units





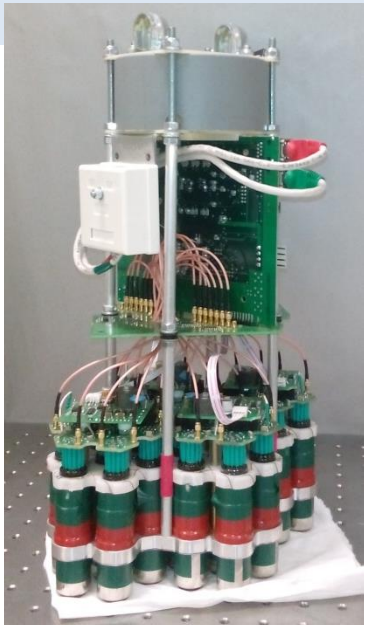
Detection system: 20 identical clusters are served by the Central Controller.

Central Controller:

- PMT board operation control (HV setting and PMT current monitoring);
- the common trigger formation; synchronization;
- cluster data collection, intermediate storage and the traffic to the data collection center (≥20 Mbit/s).

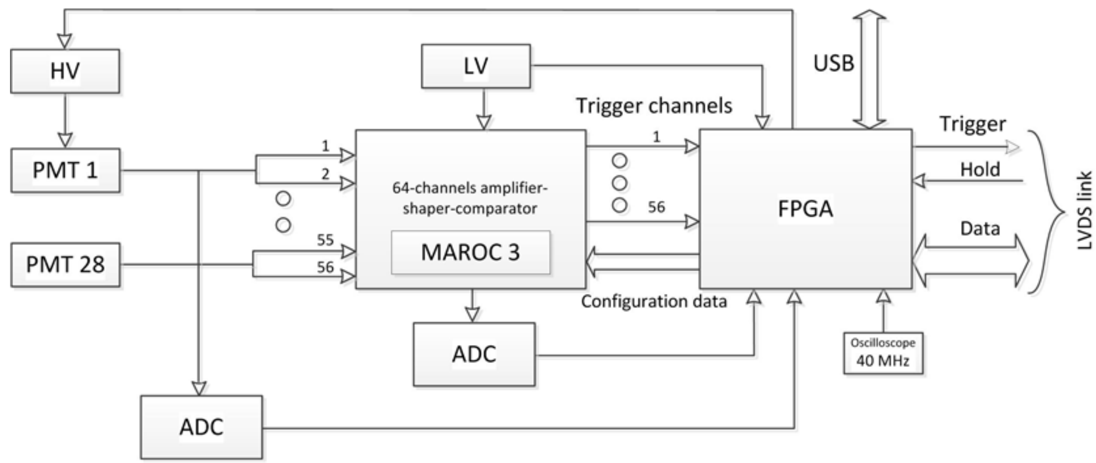
Communication between the boards and the controller: LVDS standard; timing of trigger signals ≤ 5 ns.

Basic cluster: 28 PMT-pixels arranged in four hexagonal cells 7HEX. The shaded area: the cross-board plate. Signal processing: PMT DAQ board based on the MAROC3 ASIC
.



The MAROC3 ASIC board

The basis of the camera readout electronics is the 64-channel ASIC MAROC3, which receives signals from the 28 PMTs.



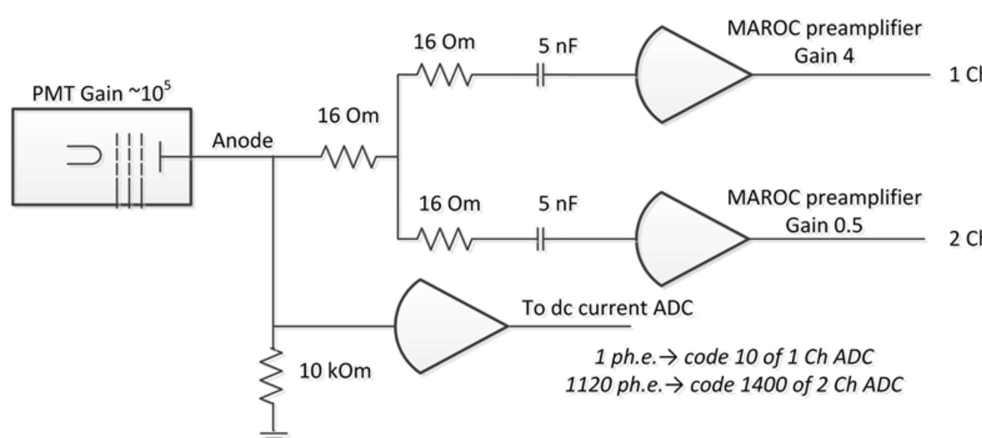
Each channel:

- preamplifier with 6 bit adjustable amplification;
- charge-sensitive amplifier and a comparator with an adjustable threshold.

Two channels of MAROC3 process the signals from one PMT spited to provide the necessary dynamic range.

The ASIC chip has:

- multiplexed analogue output to an external 12-bit Wilkinson ADC with a shaped signal proportional to the input charge;
- 64 output trigger signals.



The ASIC MAROC3 board

FPGA (FPGA EP1C6Q240C6):

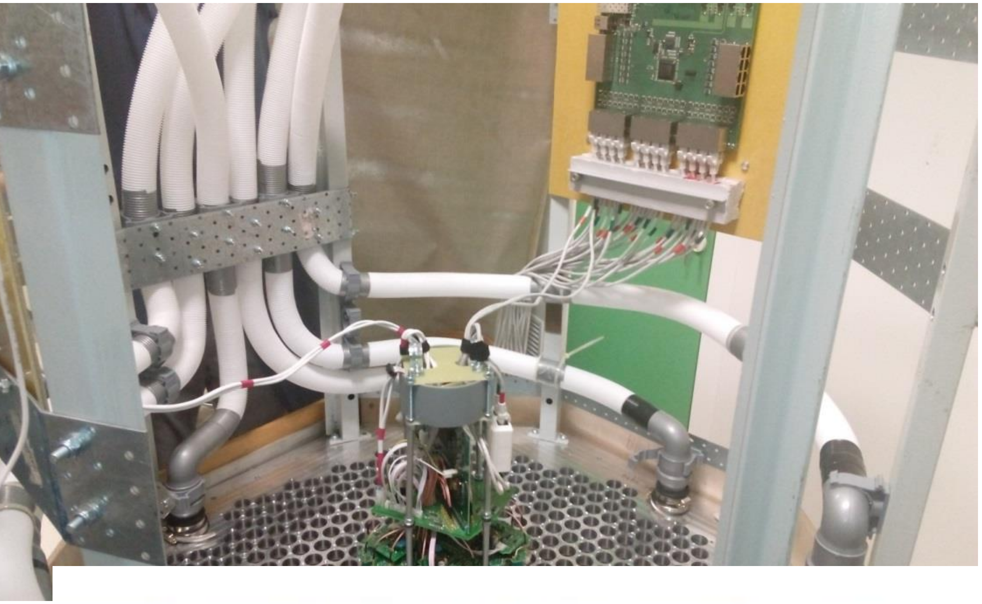
- formation of the first level trigger (*n*-majority coincidences from 28 PMTs);
- control of the settings of the 64-channel ASIC;
- the ADC operation.

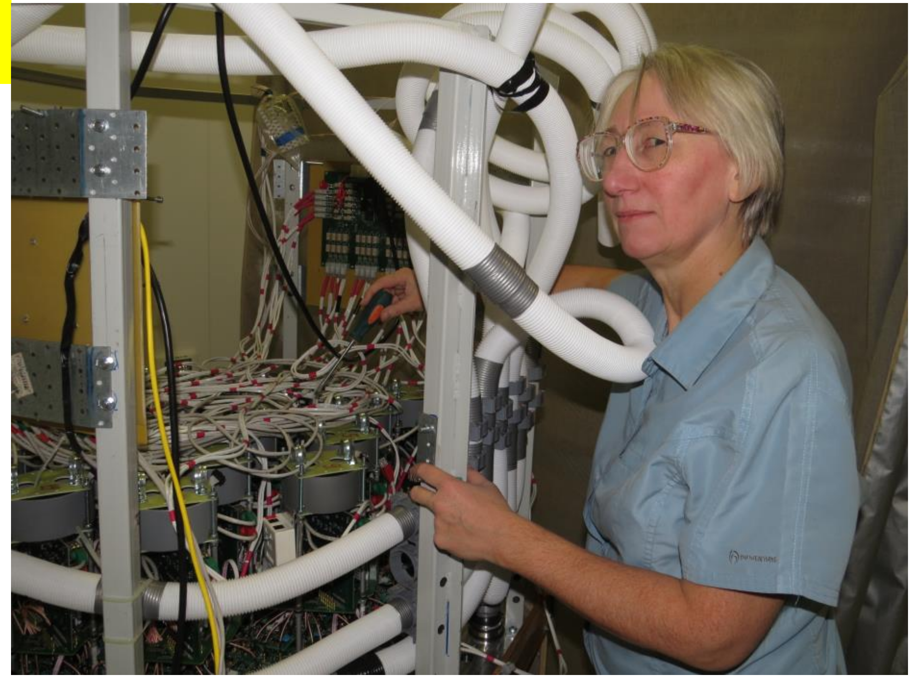
The system of the MAROC3 control:

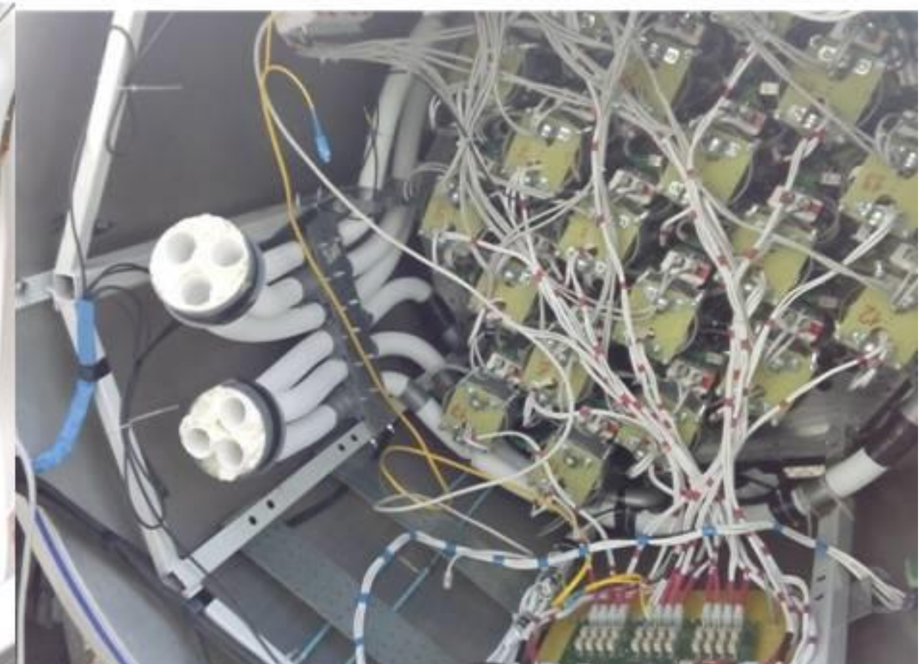
- generating of a local trigger;
- analog-to-digital converting;
- load of the MAROC3 configuration and the interface with the upper level system.

The "Dead" time is not more than 200 μs: it is about 1% of full-time detection at the expected rate of ~ 50 s^{-1}

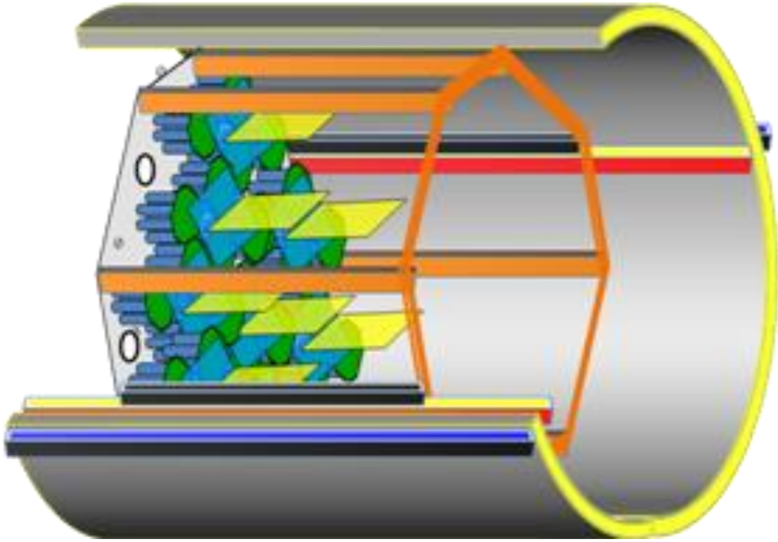
Inside the TAIGA-IACT camera



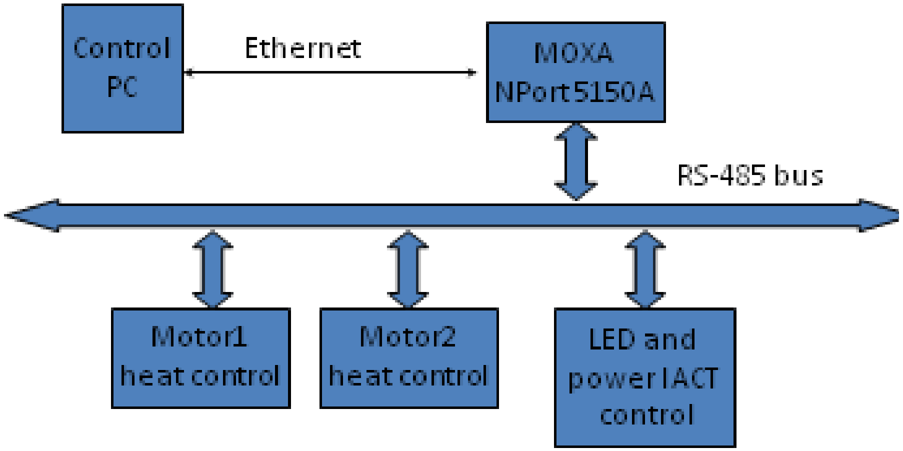


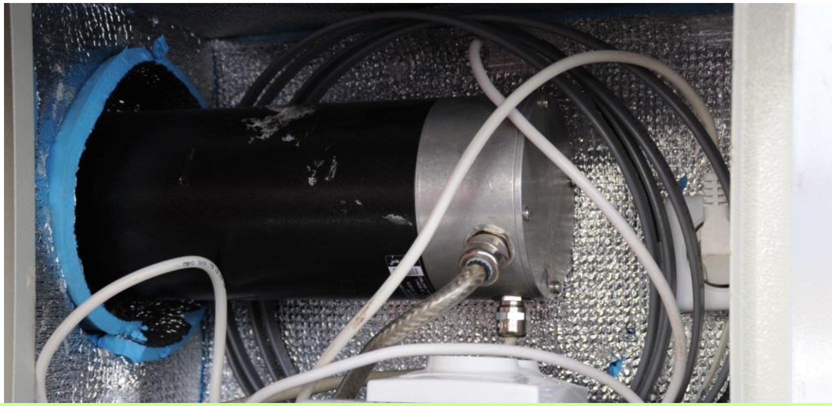


The TAIGA-IACT Camera Container



IACT heat, motor, power and LED control





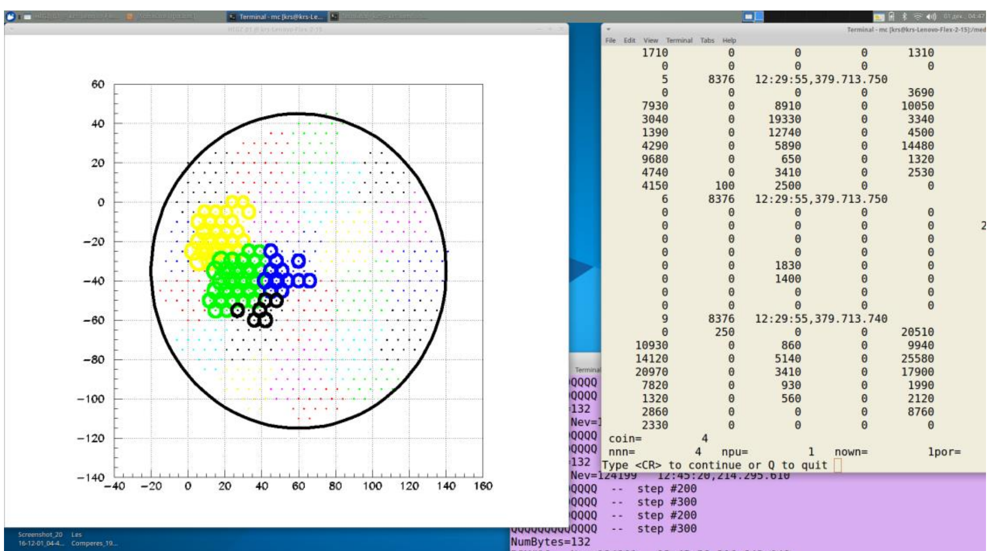
Main tasks:

Relay set control

- -Power 12, 24, 48V ON/OFF
- -Temperature monitoring (have 2 temperature sensors DS18b21)
- -Mirror heat and function ON/OFF

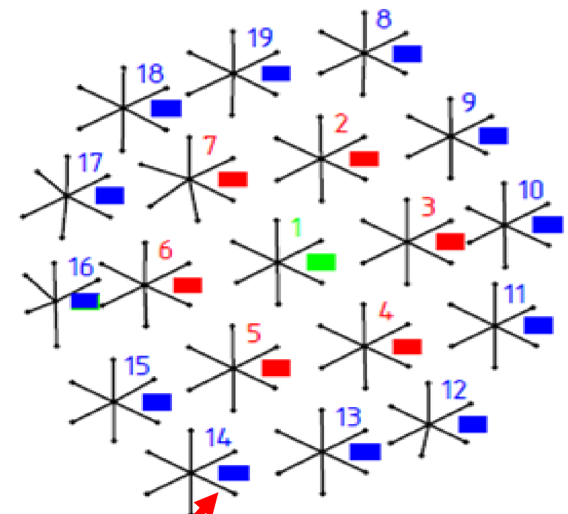
Calibration LED control

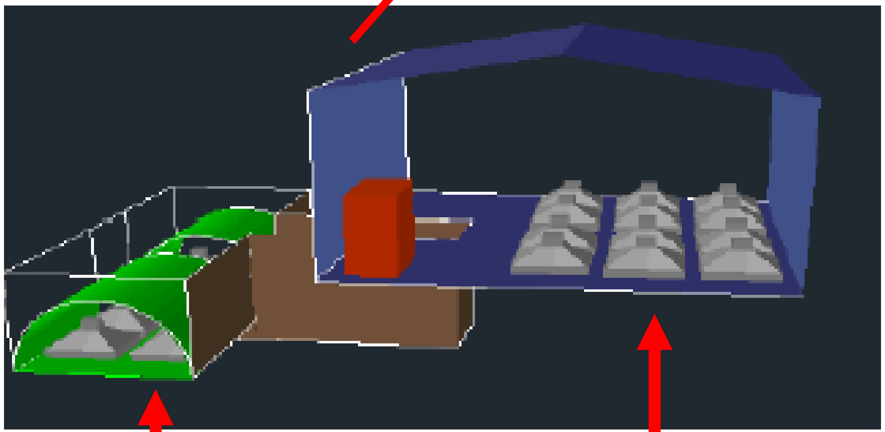
The first light



The Tunka –Grande scintillation array

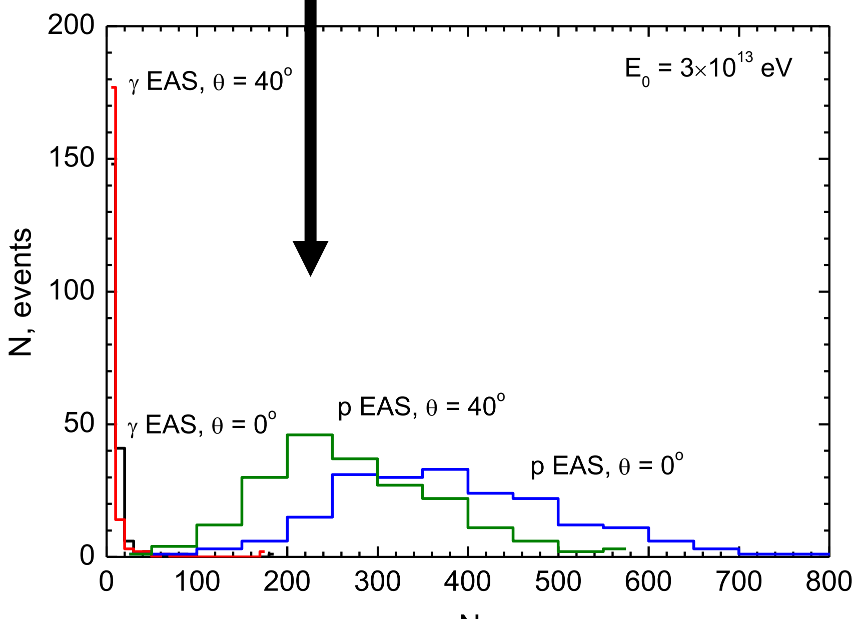
- **Permanent absolute energy calibration of Cherenkov arrays Tunka-133 and Tunka-HiSCORE.**
- **Round-the-clock duty cycle;**
- **Trigger for radio array Tunka-Rex**
- **Improvement of mass composition data**
- **Rejection of p-N background**





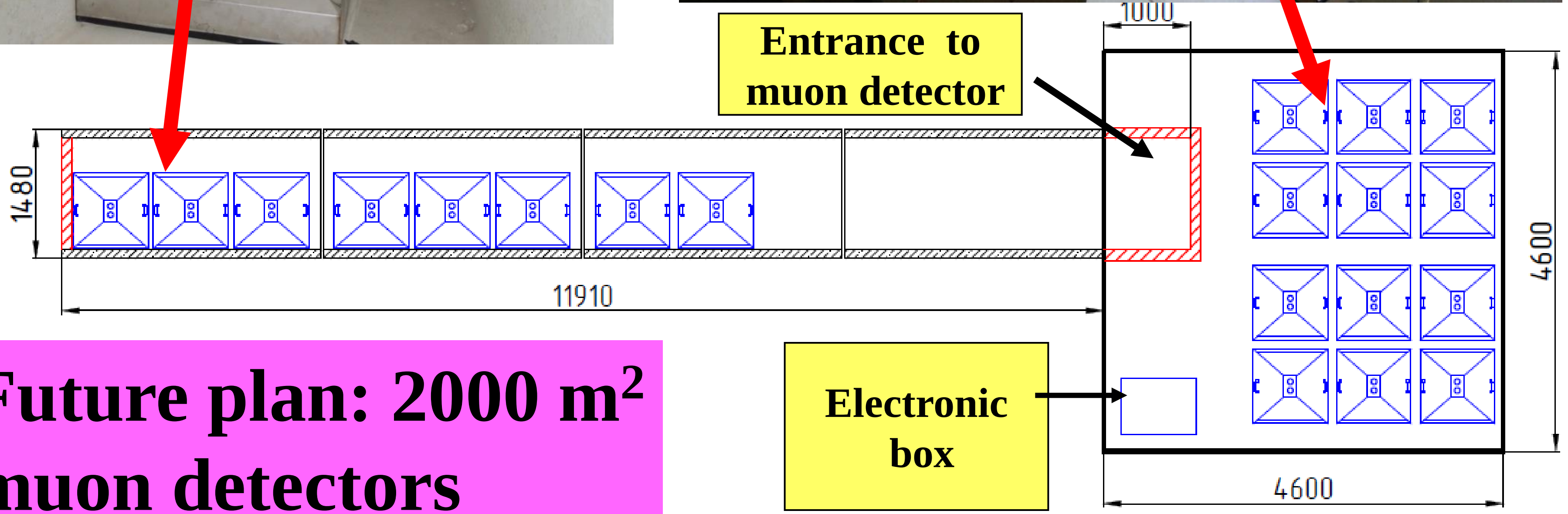
Underground Muon detector

Surface Electron detector



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

152 KASCADE-Grande scintillation counters in underground containers

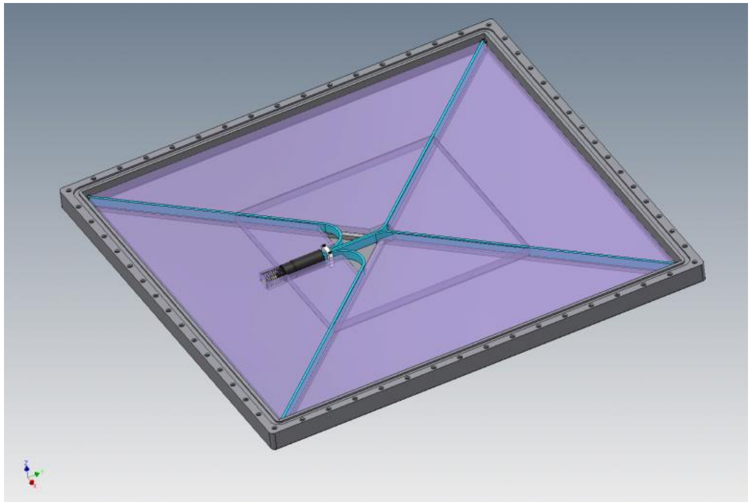


Future plan: 2000 m^2 muon detectors

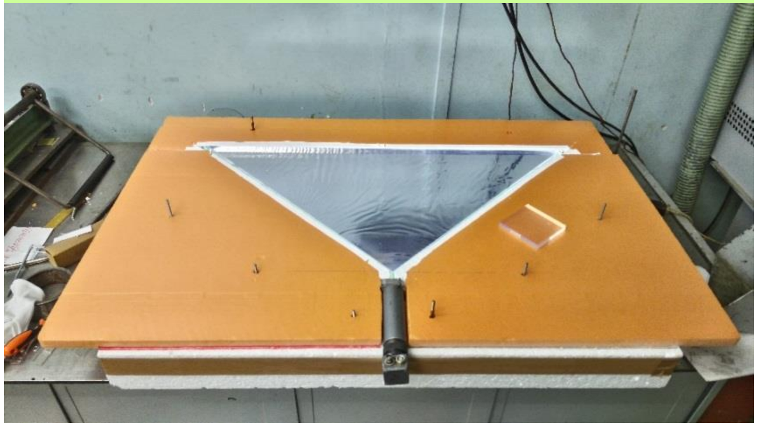
Muon detector development

Idea:

- **Counter dimension 1x1 m^{2}.**
- **Wavelength shifting bars are used for collection of the scintillation light on the PMT (PMMA doped with BBQ dye, bars length 860 and 716 mm, cross section 5x20 mm)**
- **Inexpensive, industrially produced plastic scintillator based on polystyrene, thickness 10-20 mm. is used (“Uniplast”, Vladimir)**
- **PMT with 25-46 mm photocathode could be is used for photon detection (FEU-84, FEU-85, FEU-176 were tested).**



Prototype (¼ of full scale detector)

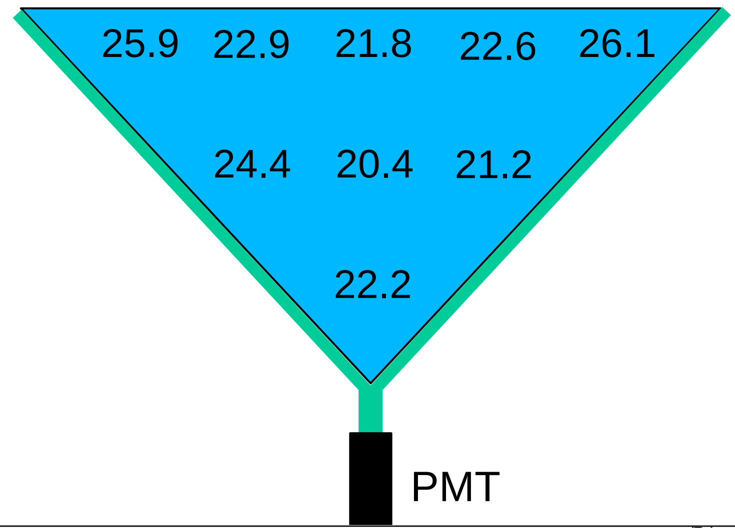


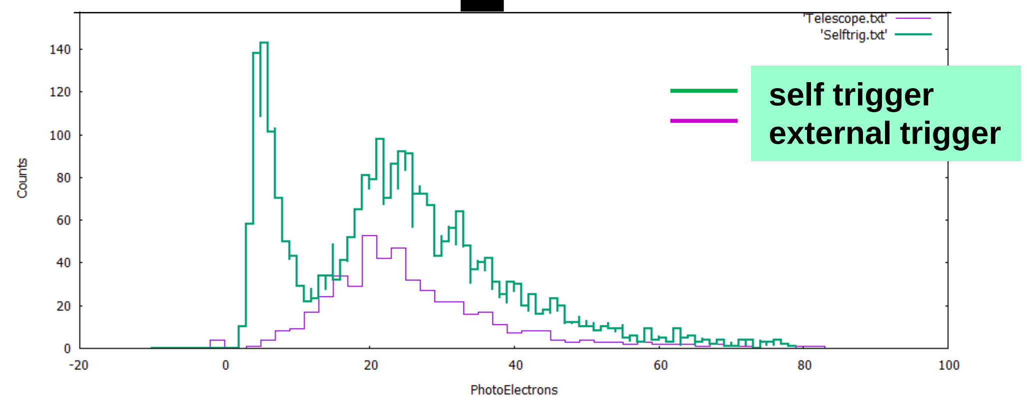
Prototype results

➢Prototype was tested with cosmic muons in 9 points. Two scintillation counters with 100x100 mm area positioned up and down are used in coincidence for external trigger.

➢Mean amplitude from cosmic muon is 23.1 photoelectrons with ±15% variation (minimum to maximum).

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





Plans:

- **October 2016y -- production of 2 full scale counters**
- **November 2016y – start of the tests at Tunka valley**

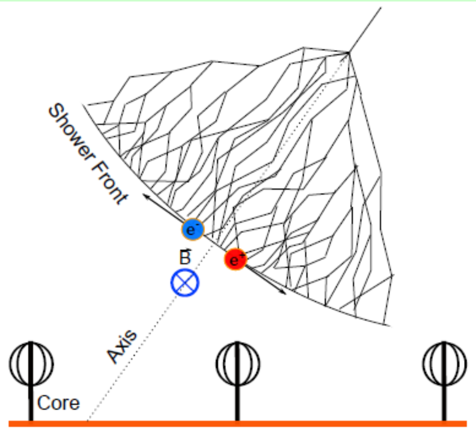
EAS radio signal detection in the TAIGA observatory

Promising novel technique to detect Cosmic Rays:

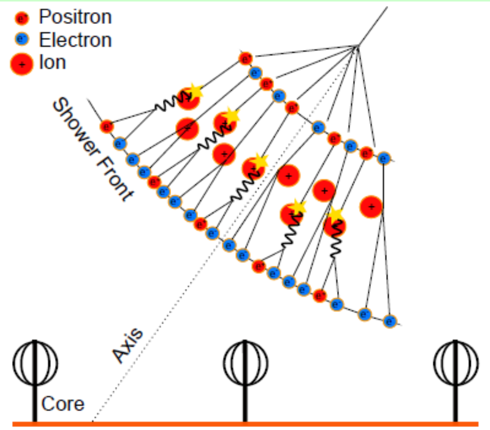
- Energy, direction, particle type
- low-cost, high duty-cycle

At present time achieved precision of the EAS energy measurement with Tunka radio array Tunka-Rex - 15% about and a precision of depth of the EAS maximum (Xmax) measurement better then 40 g/cm^2.

Tunka-Rex - a radio detector for cosmic-ray and gamma air showers, triggered by Tunka-133, TAIGA-HiSCORE and Tunka-Grande.

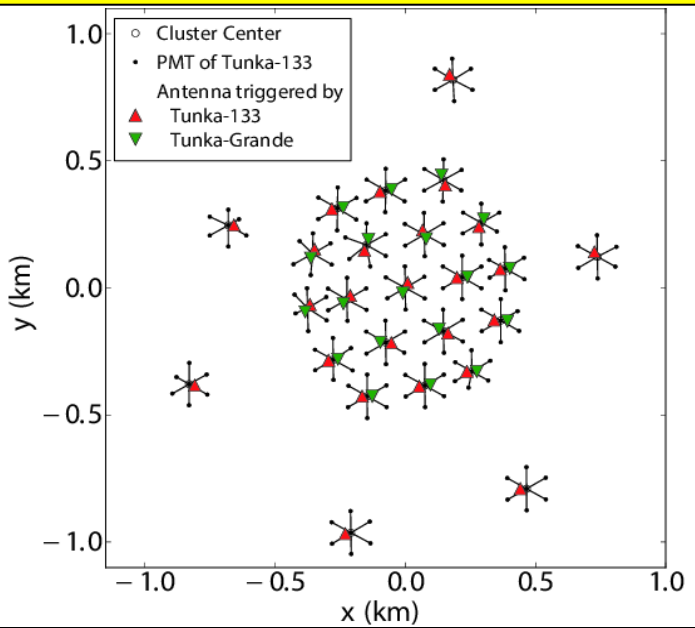


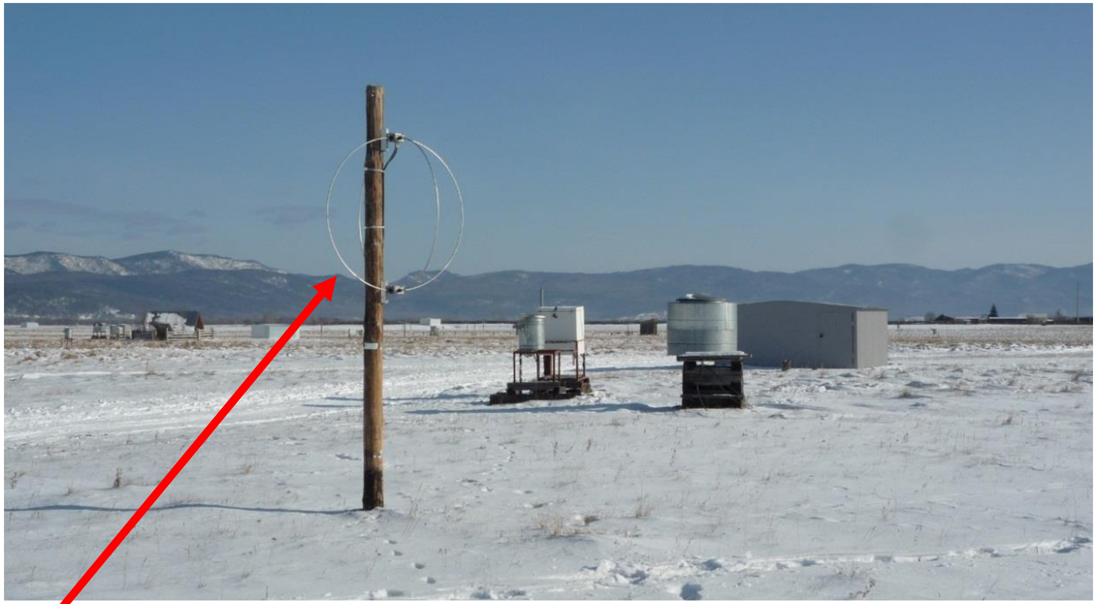
Geomagnetic effect: deflection of e^+ e^-, time-varying transverse current



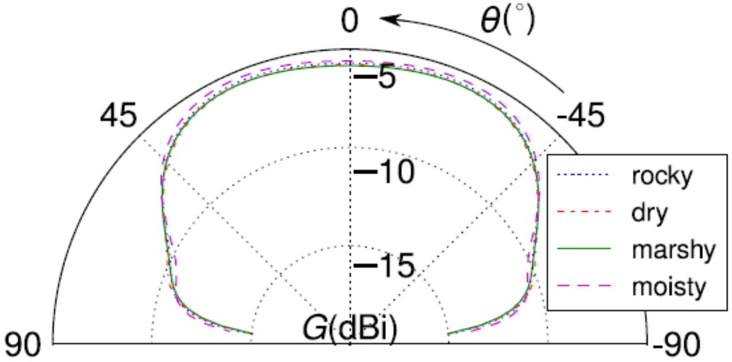
Askaryan effect, time-varying net charge (10% contribution)

Tunka-Rex (Tunka –Radio Extention) array





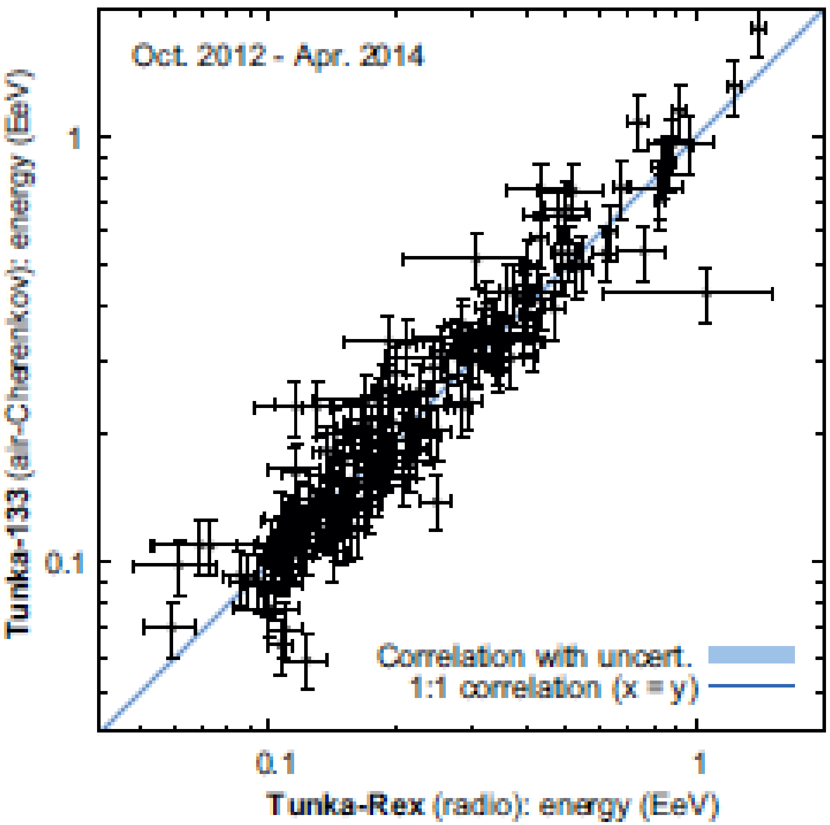
63 antenna stations triggered by Tunka-133, Tunka-Grande and TAIGA-HiSCORE arrays

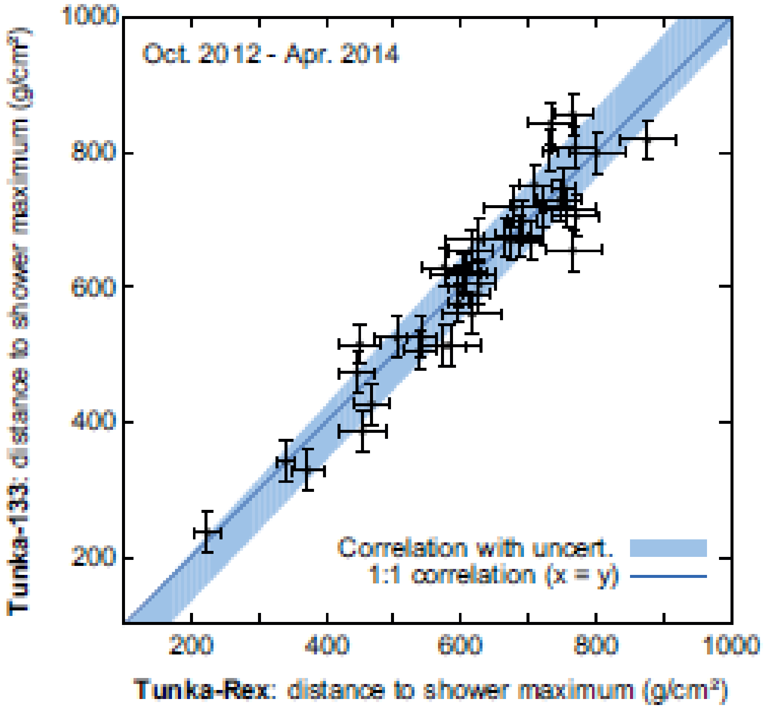


The gain G over zenith angle at 50MHz of the SALLA for dierent ground conditions.

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

The correlation of reconstructed radio and Cherenkov EAS energy and distance to shower maximum





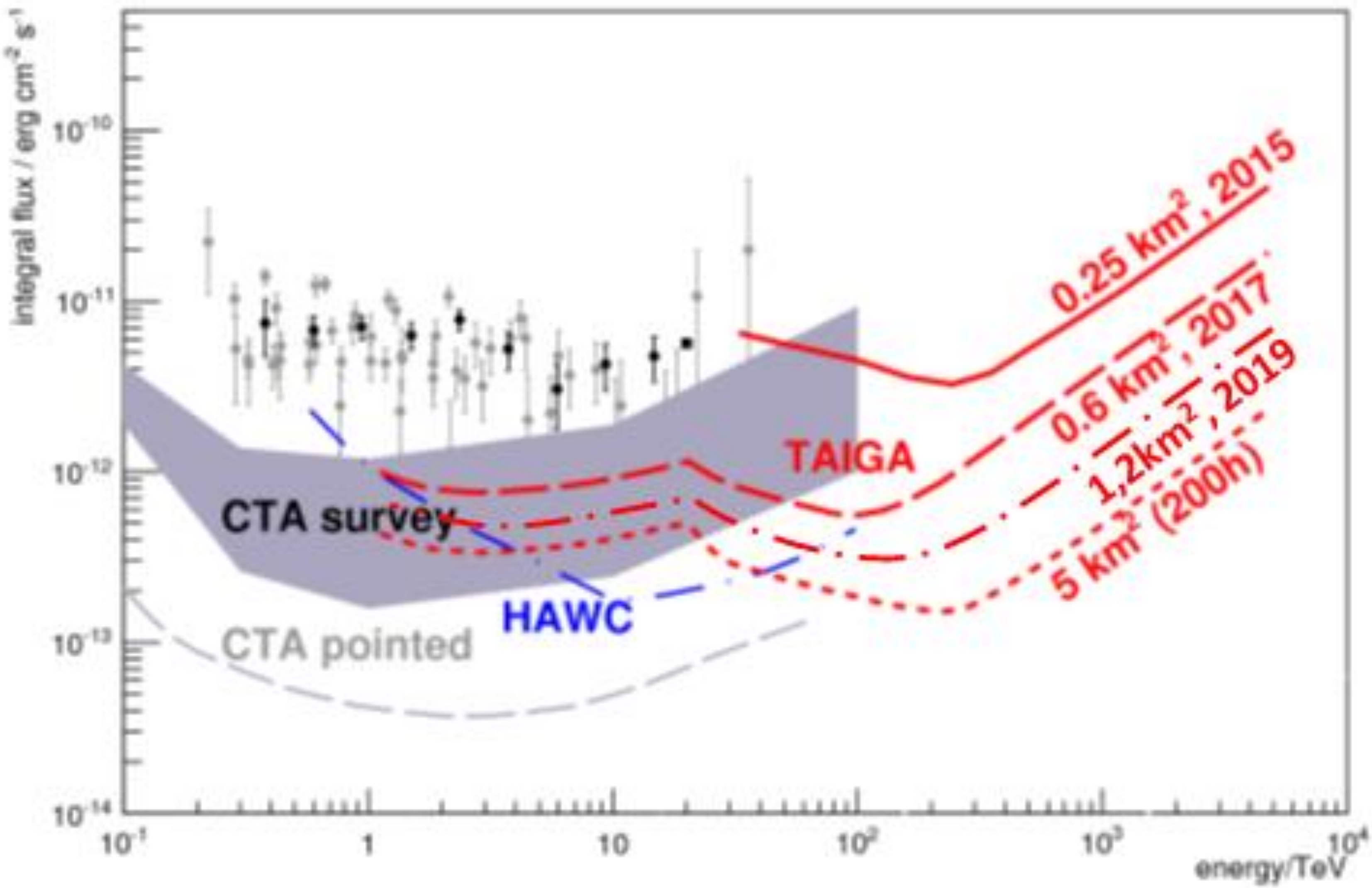
The correlation of reconstructed radio and Cherenkov energy

The Tunka-Rex energy resolution of 15%.

The correlation of reconstructed radio and Cherenkov distance to shower maximum/

The Xmax precision of Tunka-Rex is roughly 40 g/cm^2

Point source sensitivity of TAIGA to gamma rays

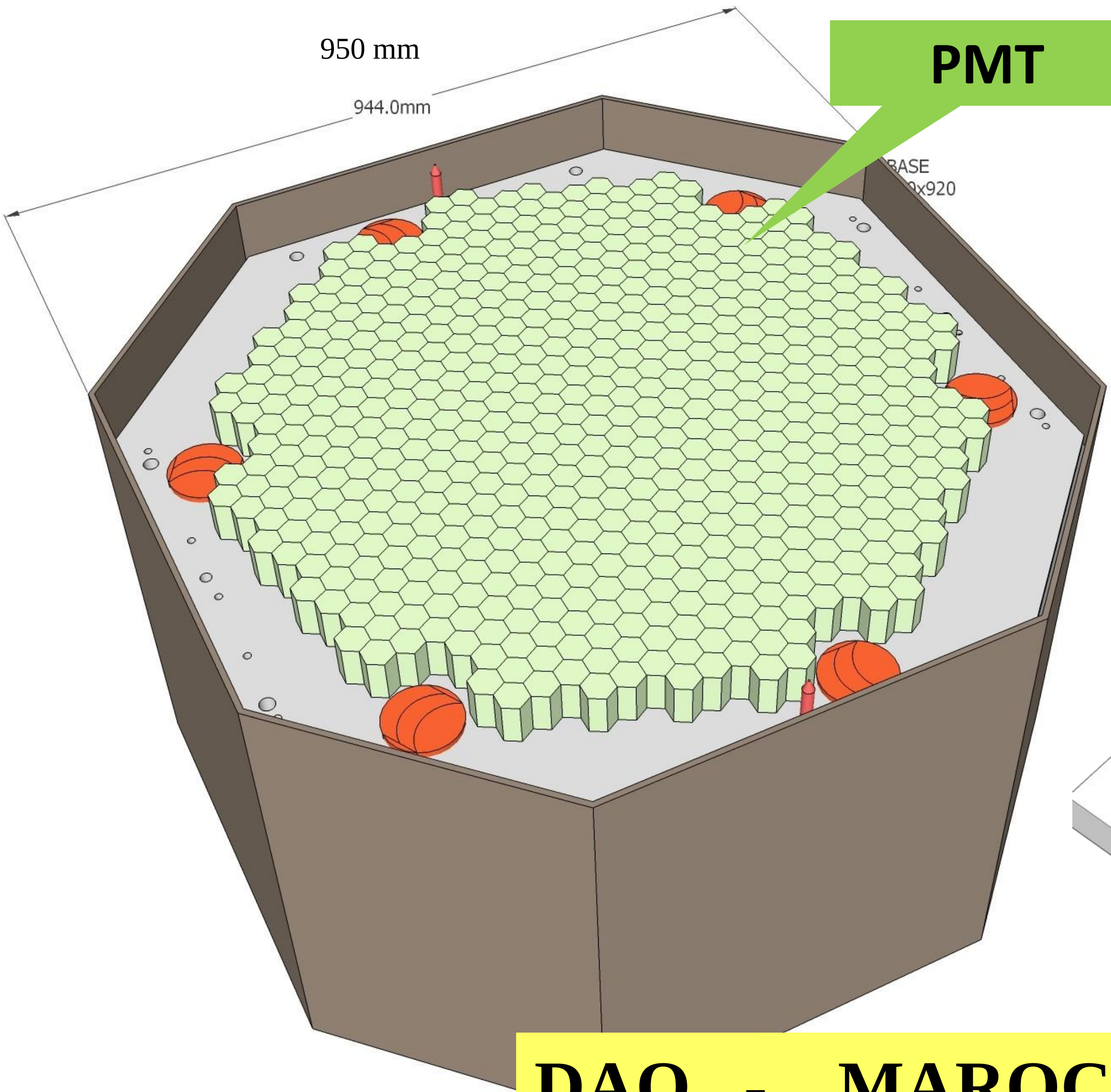


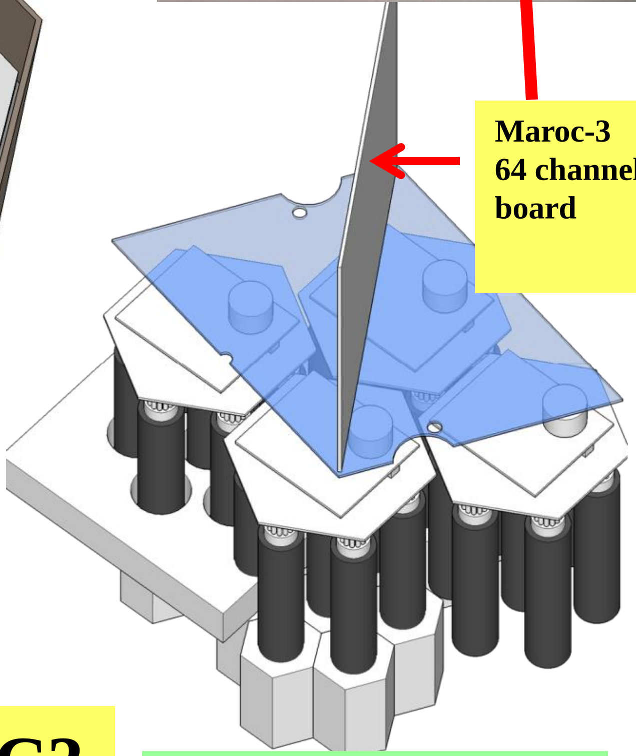
Summary and outlook

1. The key advantages of the γ-observatory TAIGA - joint operation of wide-angle and narrow-angle detectors of TAIGA-HiSCORE and TAIGA-IACT arrays, as well particle detectors of TAIGA-Muon array allow to increase spacing between expensive IACT up to 600 -1000 m and to operate in mono-scopic mode.
2. As a result, it is possible to have the array for high gamma-ray astronomy with cost about 6 millons \$/ km^2. Ten times less than CTA!
3. The new gamma – observatory TAIGA will allow:
   - To perform search for local Galactic sources of gamma-quanta with energies more than 20-30 TeV (search for PeV-trons) and study gamma-radiation fluxes in the energy region higher than 20-30 TeV at a record level of sensitivity.
   - To study energy spectrum and mass composition of cosmic rays in the energy range of $5 \cdot 10^{13}$ - 10^{18} eV at an unprecedented level of statistics.
   - To study the high energy part of the gamma-ray energy spectrum from the most bright blazars (absorption of gamma-quanta by intergalactic background, search for axion-photon transition).
4. We intend to have in 2019y 1 km^2 gamma-observatory TAIGA setup with 100 -120 Cherenkov station of the TAIGA-HiSCORE, 3 telescopes of the TAIGA-IACT and 500m^2 of muon detectors of the TAIGA-Muon array.

Thank you for attention!

The Camera of the TAIGA-IACT

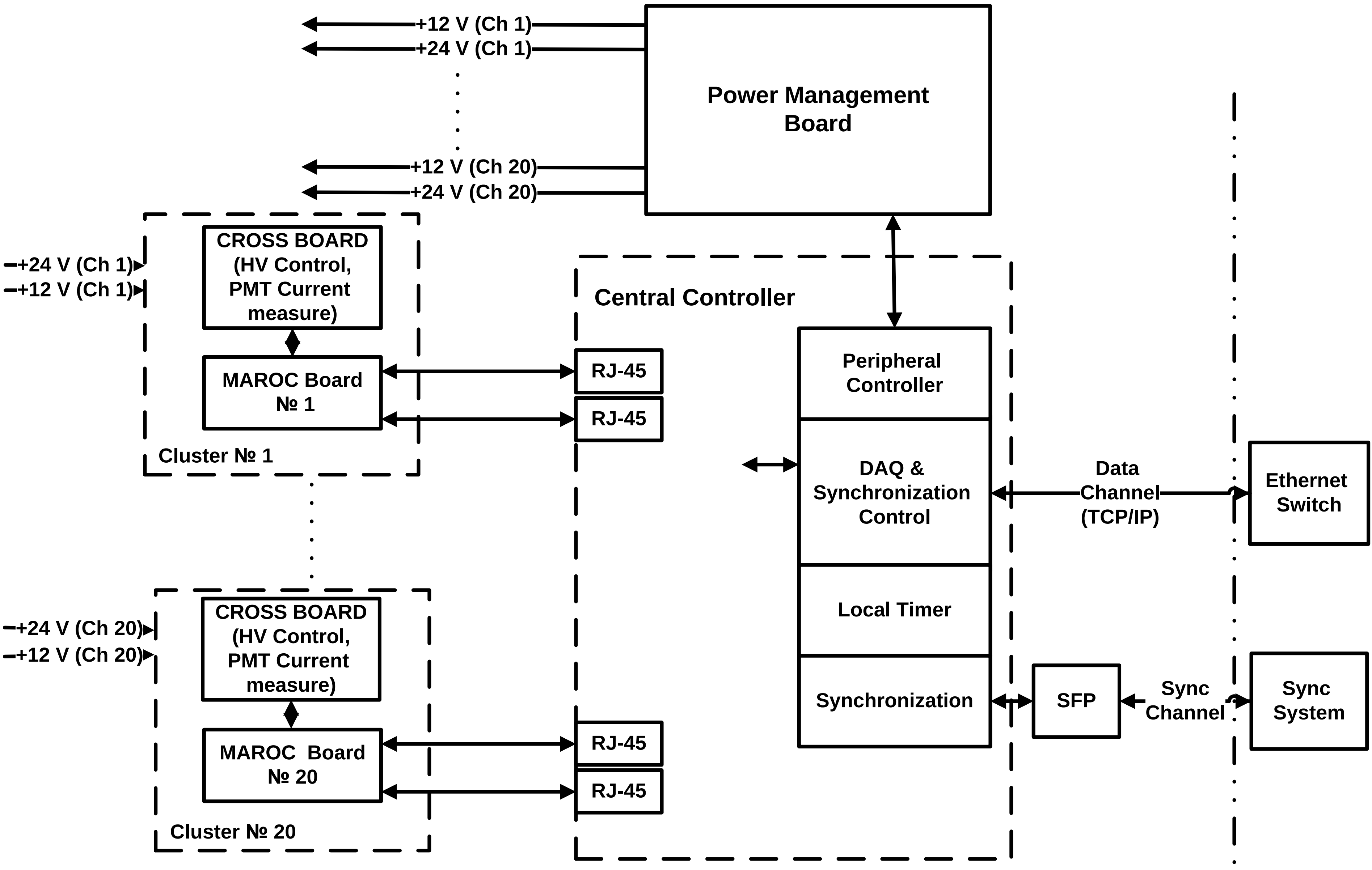




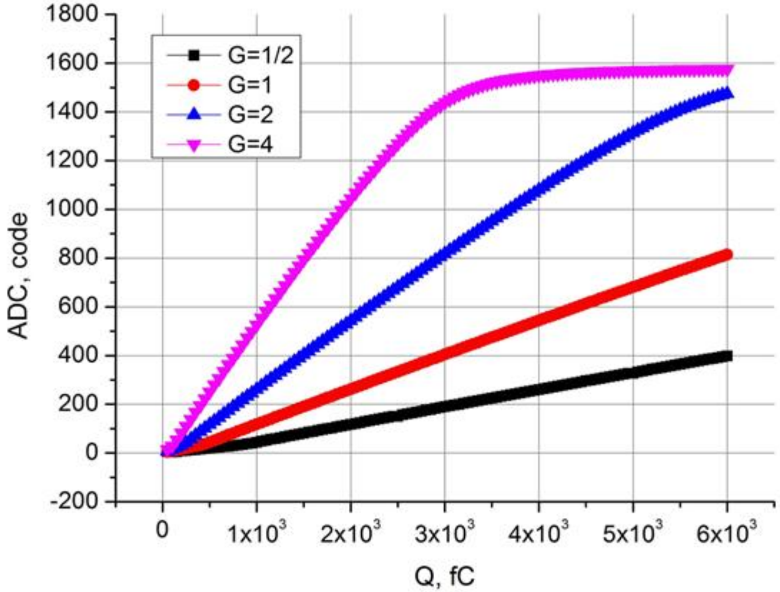
DAQ - MAROC3

Cluster – 28 PMTs

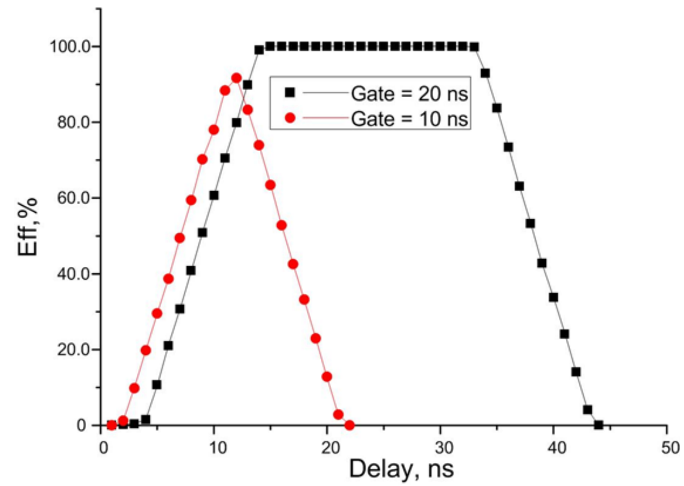
The TAIGA-IACT Camera Central Controller



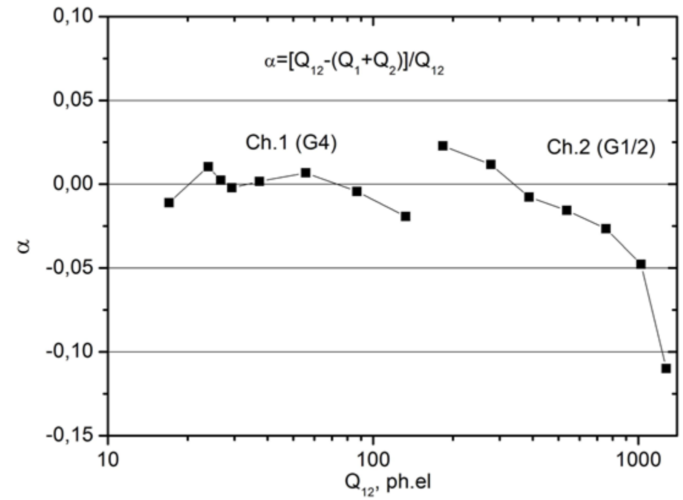
ASIC MAROC3 board test



Calibration characteristics of a spectrometric channel of the ASIC MAROC3 for different preamplifier transmission coefficients.



Dependence of the first level trigger formation efficiency on the delay.



The linearity of the single spectrometric channel

EAS Cherenkov light detection technique

EAS Energy

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

$$g = 0.94 \pm 0.01$$

Average CR mass A

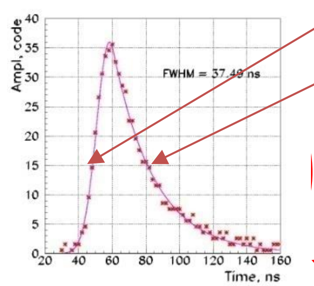
$$\mathrm{LnA} \sim X_{max}$$

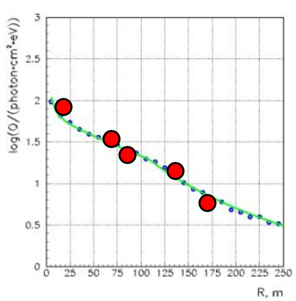
$$X_{max} = C - D \cdot \lg \tau(400)$$

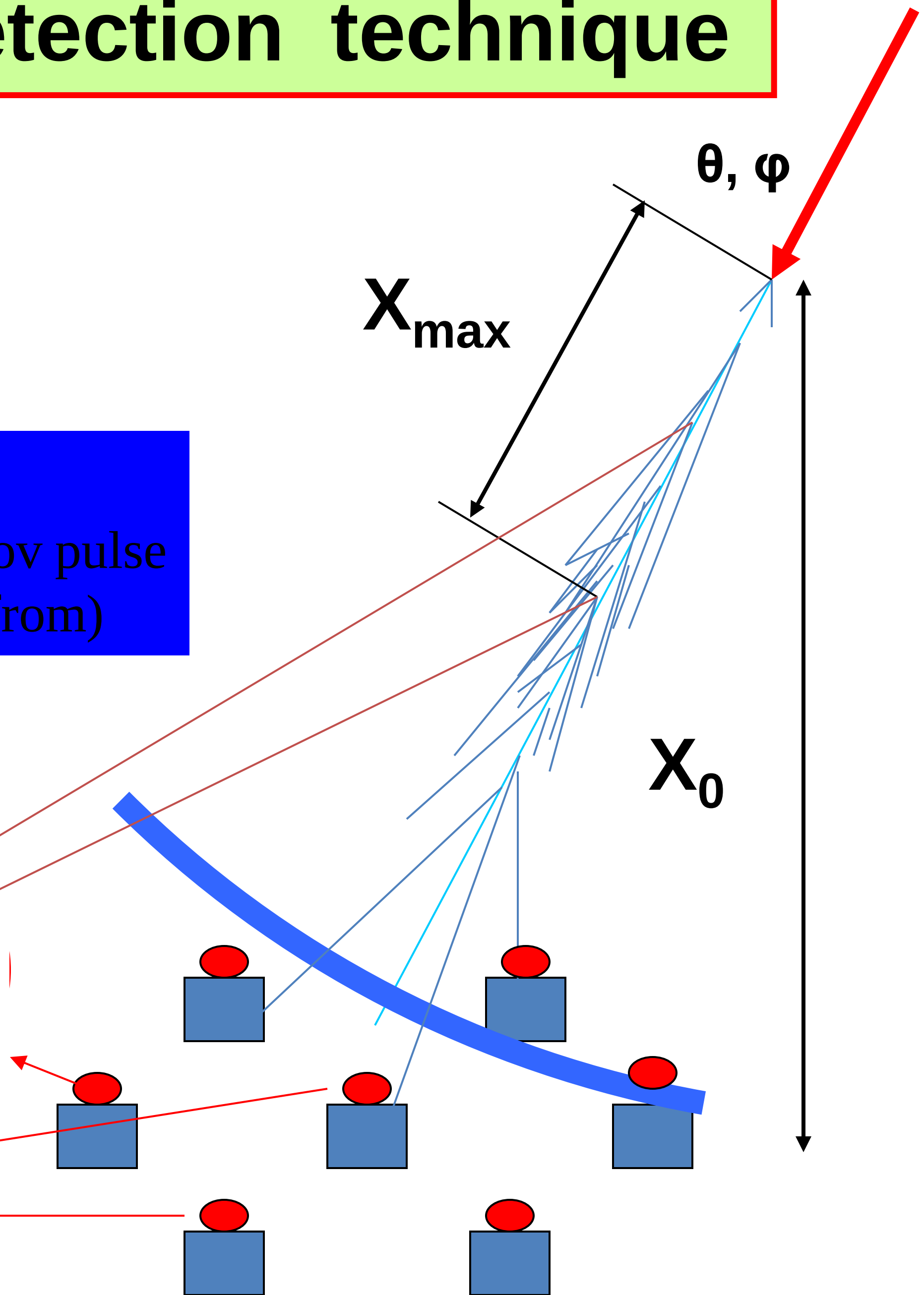
($\tau(400)$ - width of a Cherenkov pulse at distance 400 m EAS core from)

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

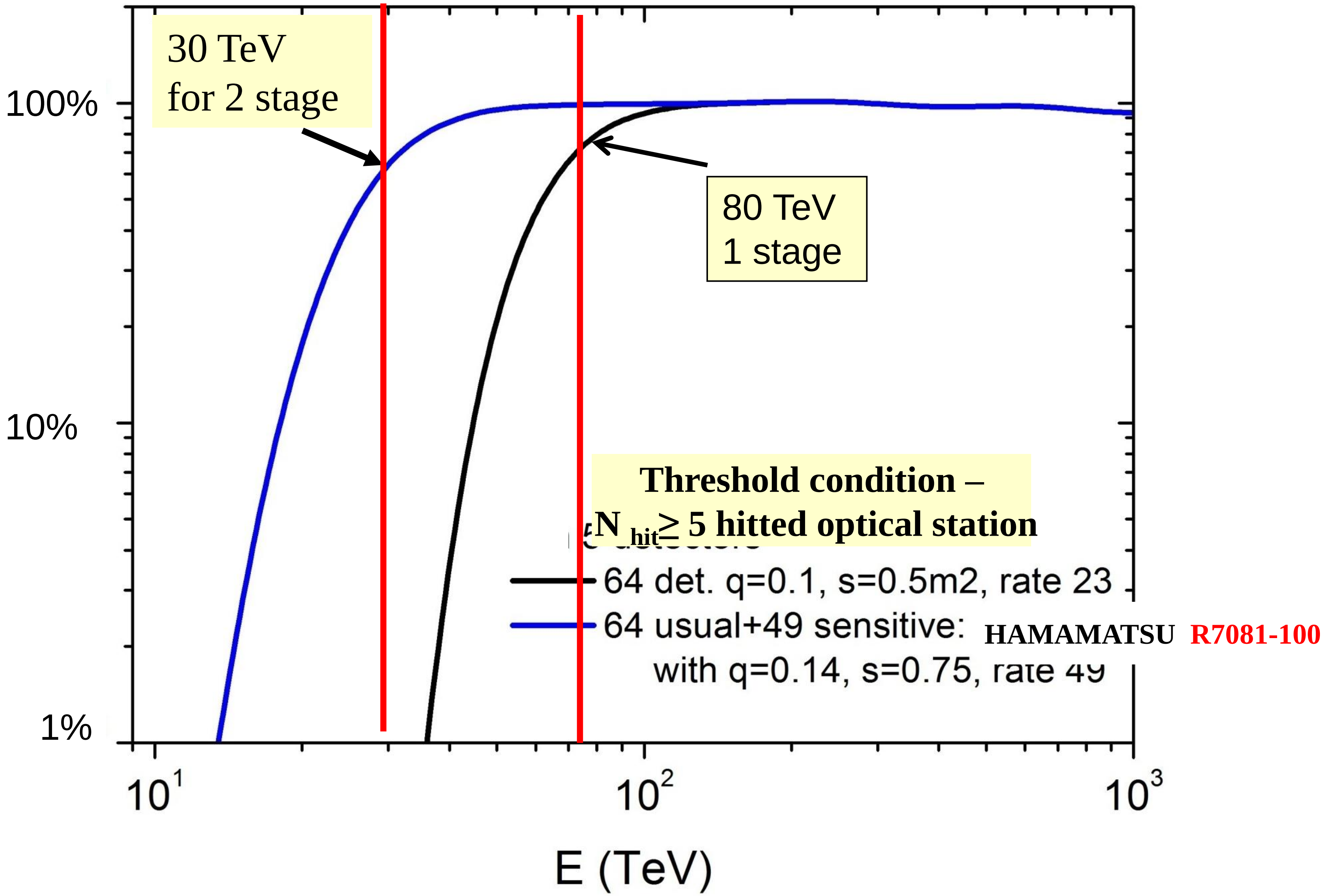
P -Steepness of a Lateral Distribution Function (LDF)



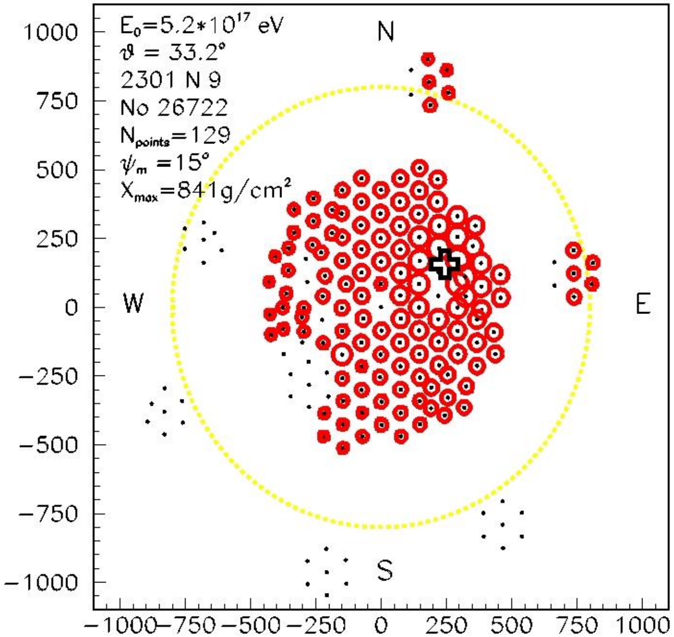




Efficiency of gamma ray detection with Tunka-HiSCORE



An event example



Hitted detectors

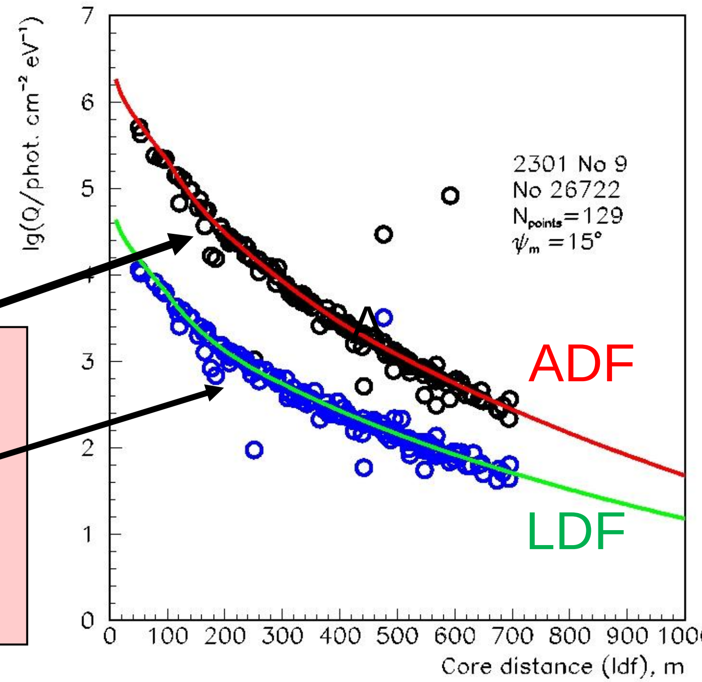
ADF

Amplitude distant function

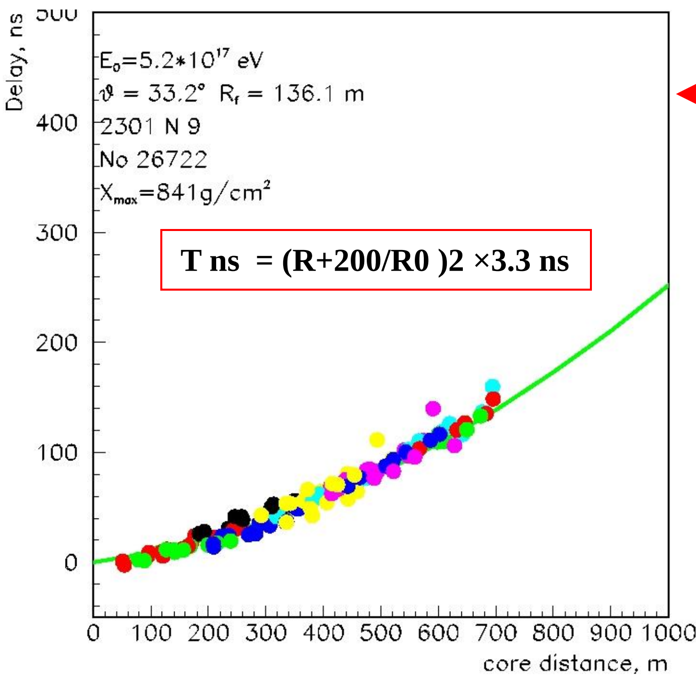
&

LDF

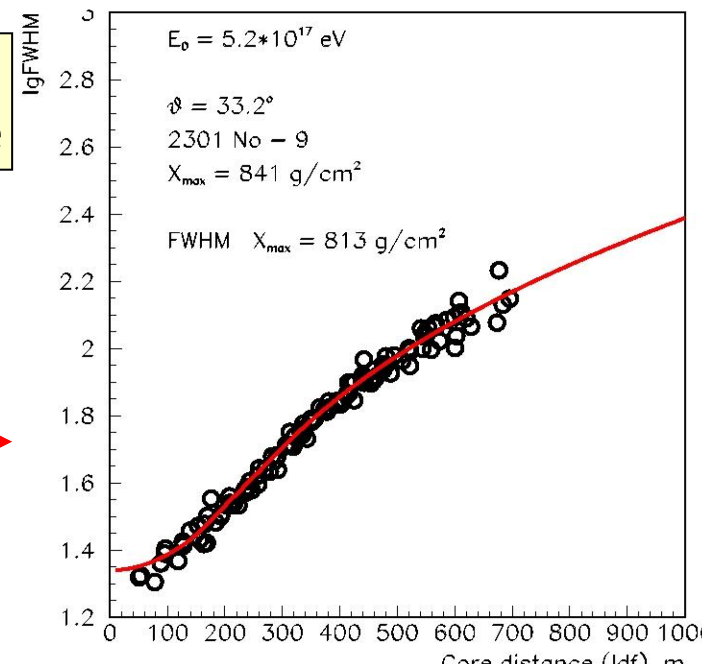
Lateral Distribution function



Delay time vs. Distance from core

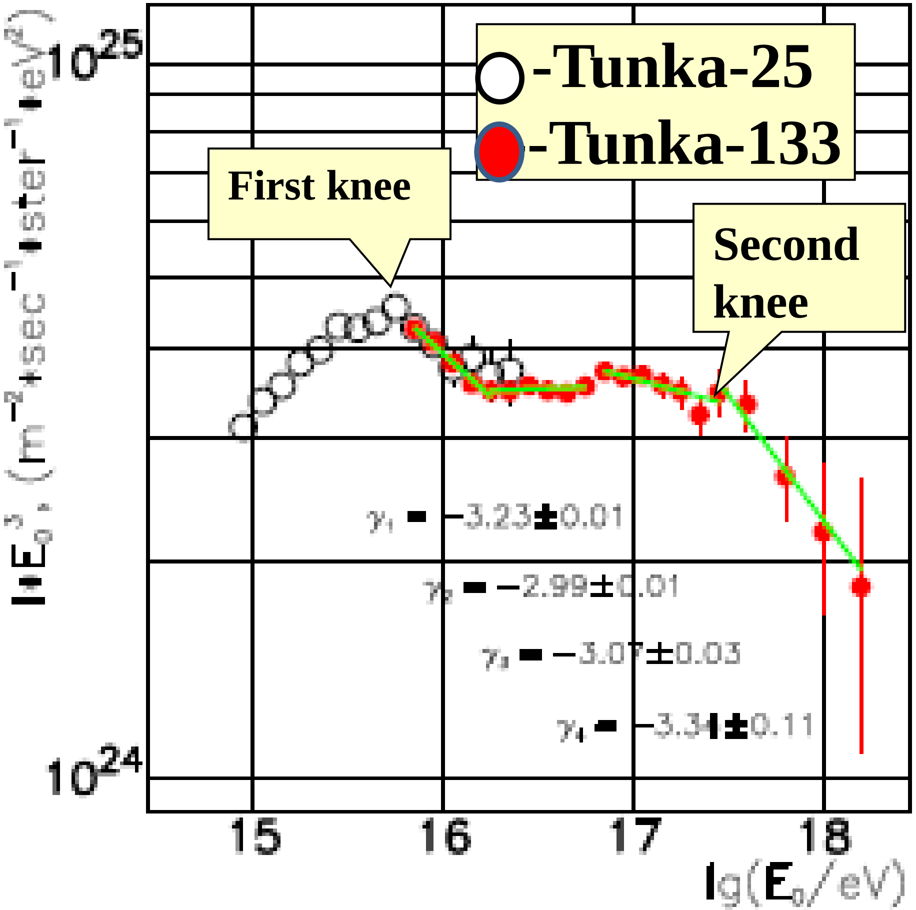


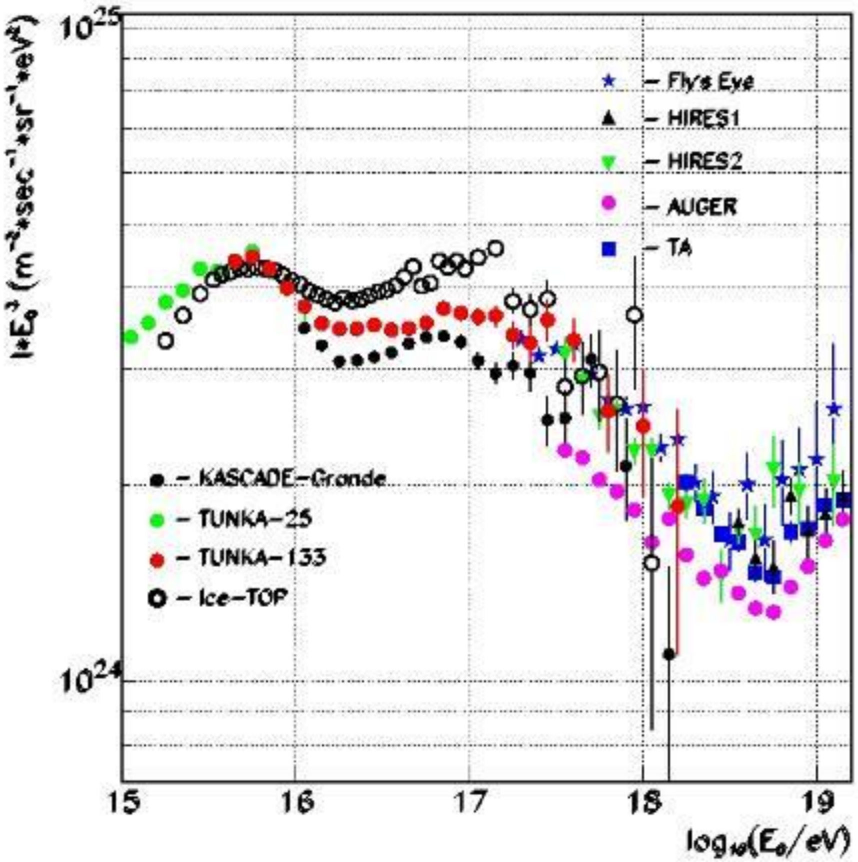
WDF – width distant function



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

energy resolution ~ 15%, in principal up to - 5%

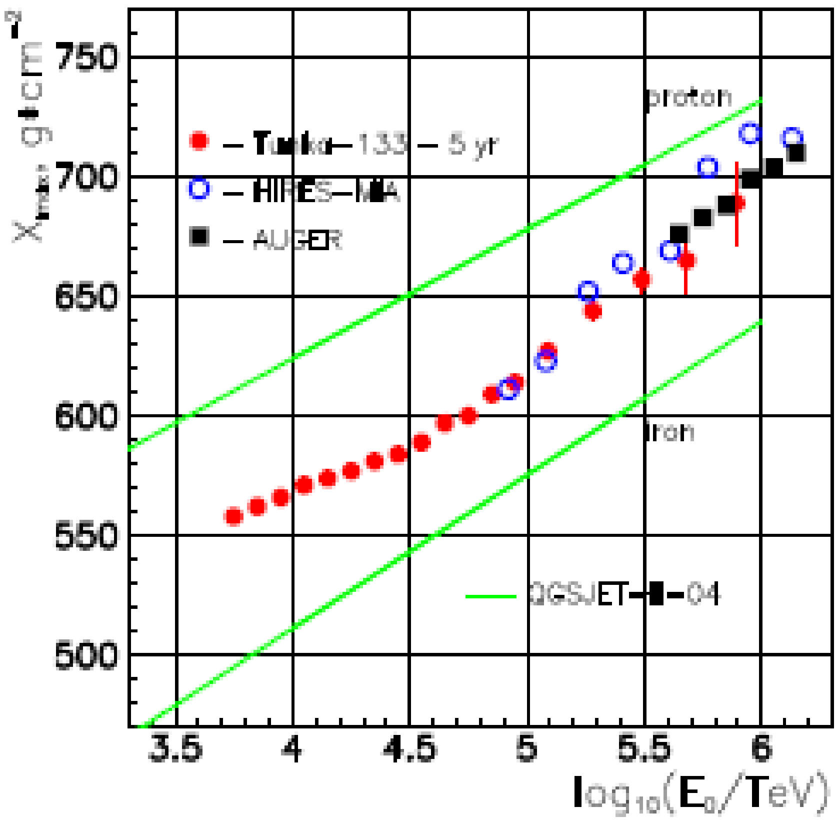


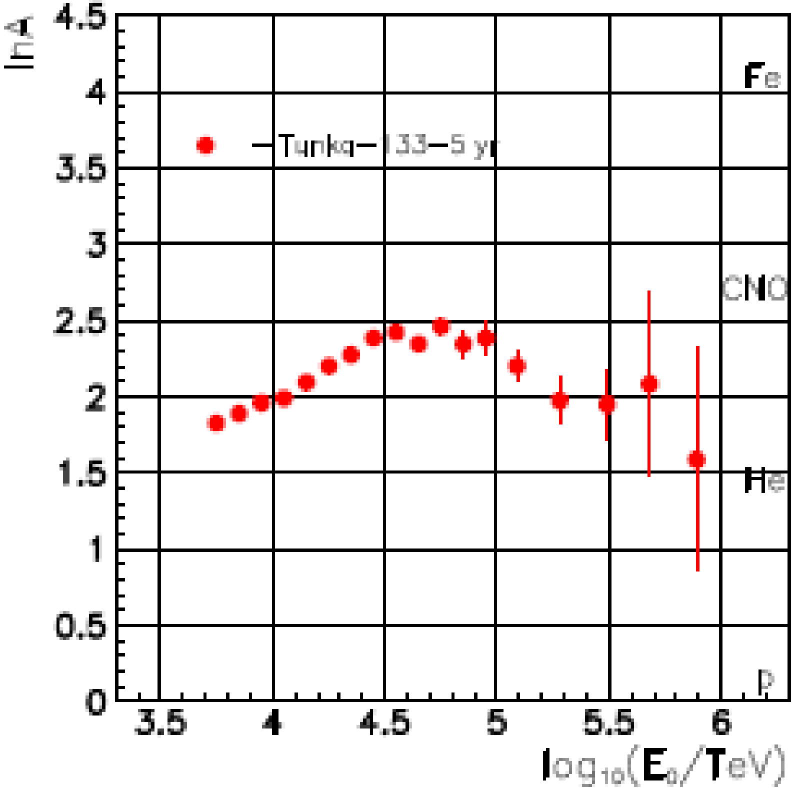


1. Agreement with KASCADE-Grande, Ice-TOP and TALE (TA Cherenkov).
2. The high energy tail do not contradict to the Fly's Eye, HiRes and TA spectra..

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

Mean logarithm of primary mass.

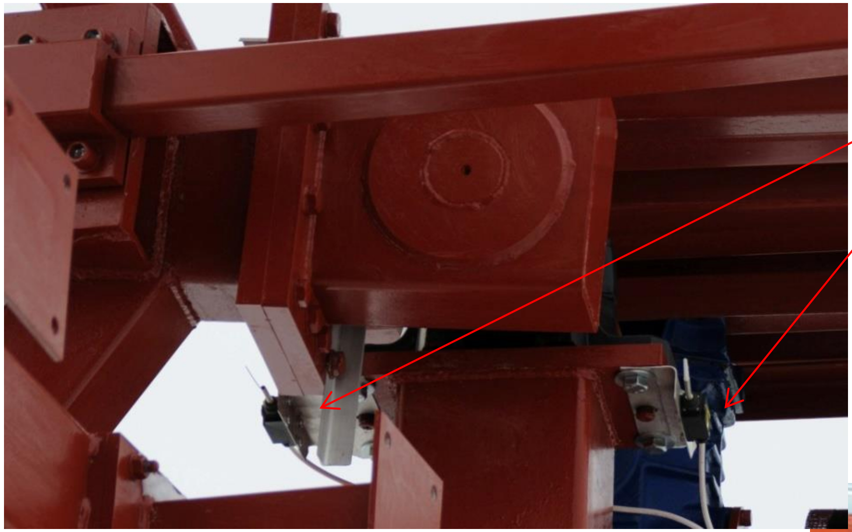




The primary CR mass composition changes from light (He) to heavy up to energy ~ 30 PeV

A lightening of the mass composition take place for starting from an energy 100 PeV

Movement Control – End Point Switchers & Rotation Limiter



EPS

Rotation Limiter (420^{o})