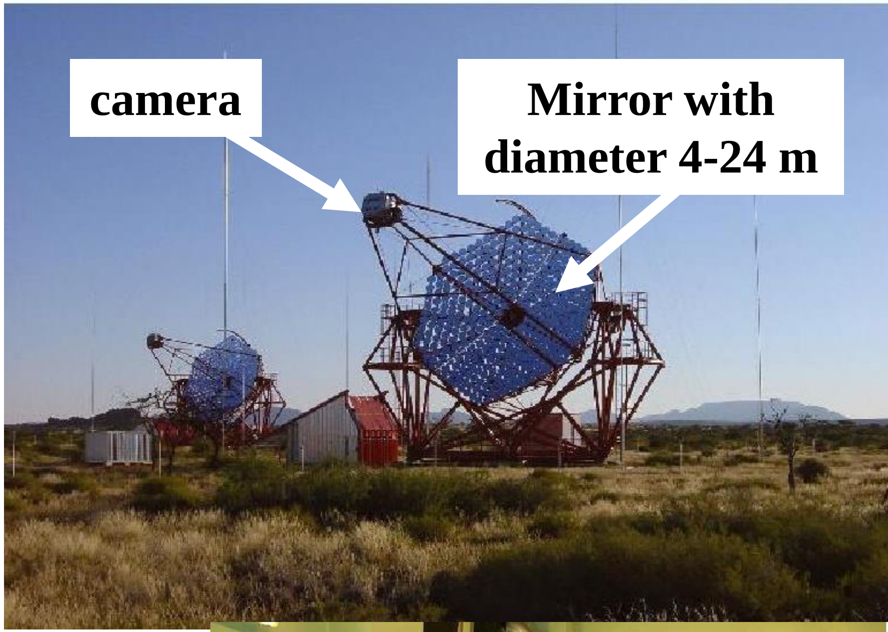
TAIGA - an advanced hybrid detector complex for astroparticle physics and high energy gamma-ray astronomy in the Tunka valley.

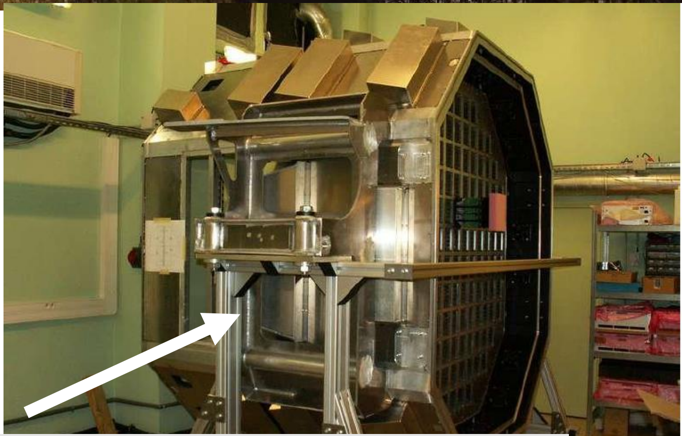
N.Budnev, Irkutsk State University

For TAIGA collaboration

At present an Imaging Atmospheric Cherenkov Telescopes (IACT) are the main instruments for the ground based high energy gamma astronomy

An Imaging Atmospheric Cherenkov Telescope (IACT) - narrow-angle telescope (3-5 FOV) with a mirror of 4 -24 m diameter which reflects EAS Cherenkov light into a camera with up to 1000 PMT where Cherenkov EAS image is formed.

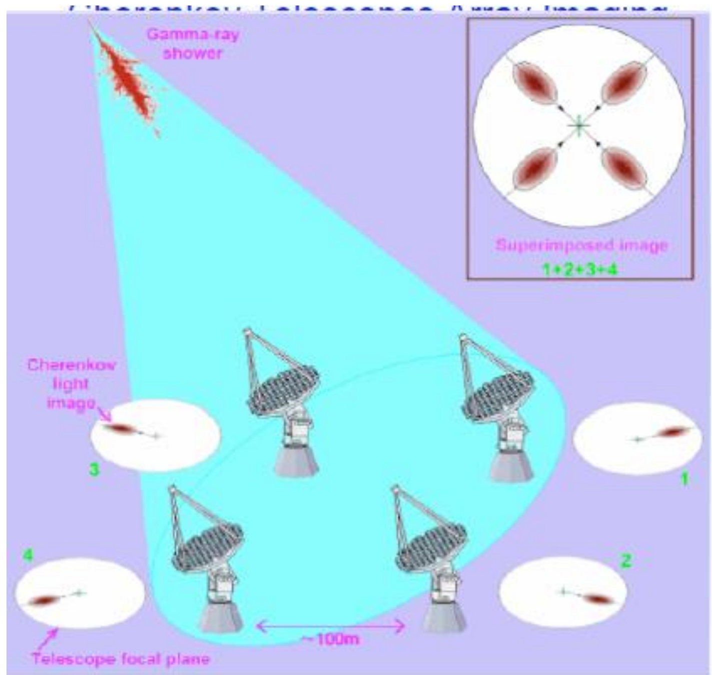


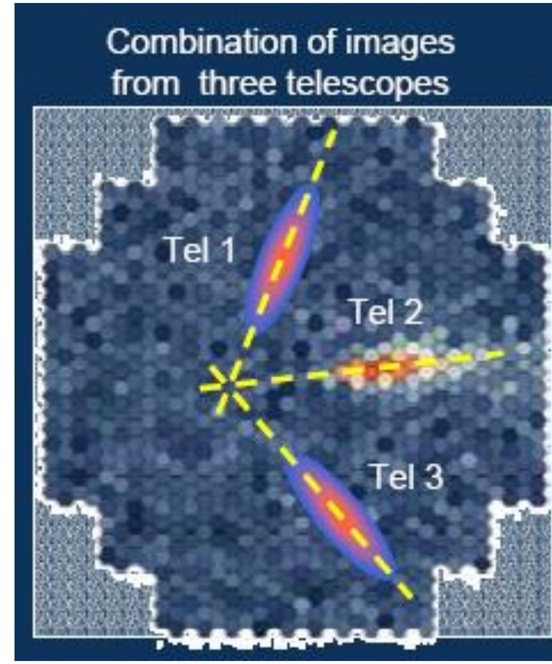


H.E.S.S. camera (D = 3 m!)

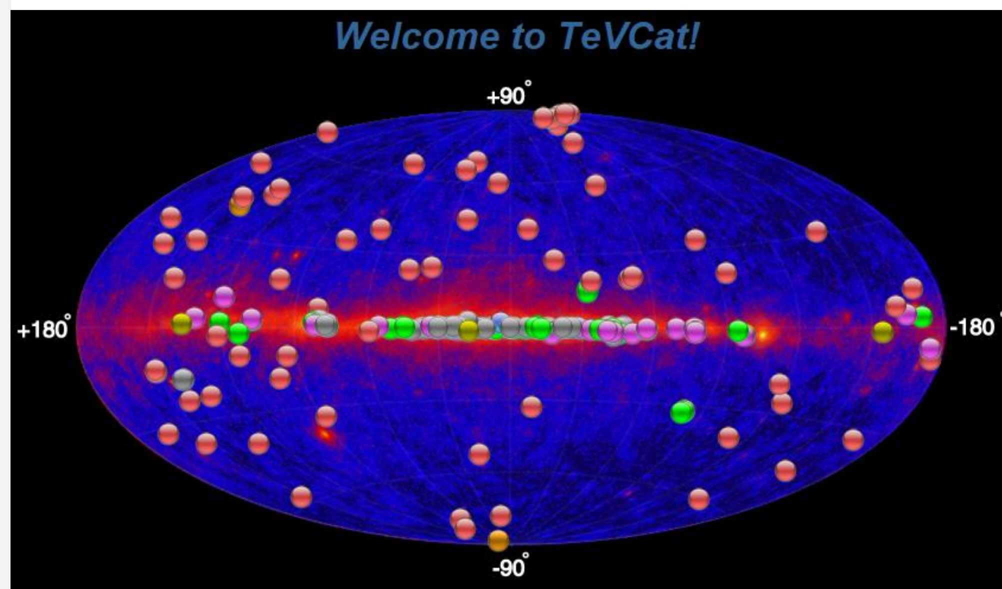
Imaging Atmospheric Cherenkov Arrays (2-5 IACT)

Whipple
HEGRA
H.E.S.S.
MAGIC
VERITAS
S ~ 0.1 km^2





About 200 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays.
But a few gamma quantum with energy more then 50 TeV were detected up to now.
An area of an array should be a few square kilometers as minimum to detect high energy gamma rays.



EAS Cherenkov light detection technique by wide angle arrays in the Tunka - Experiment

EAS Energy

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

$g = 0.94 \pm 0.01$

Average CR mass A

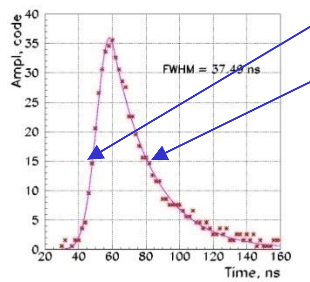
$LnA \sim X_{max}$

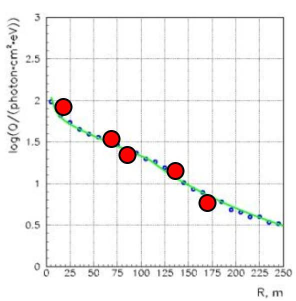
$X_{max} = C - D \cdot \lg \tau(400)$

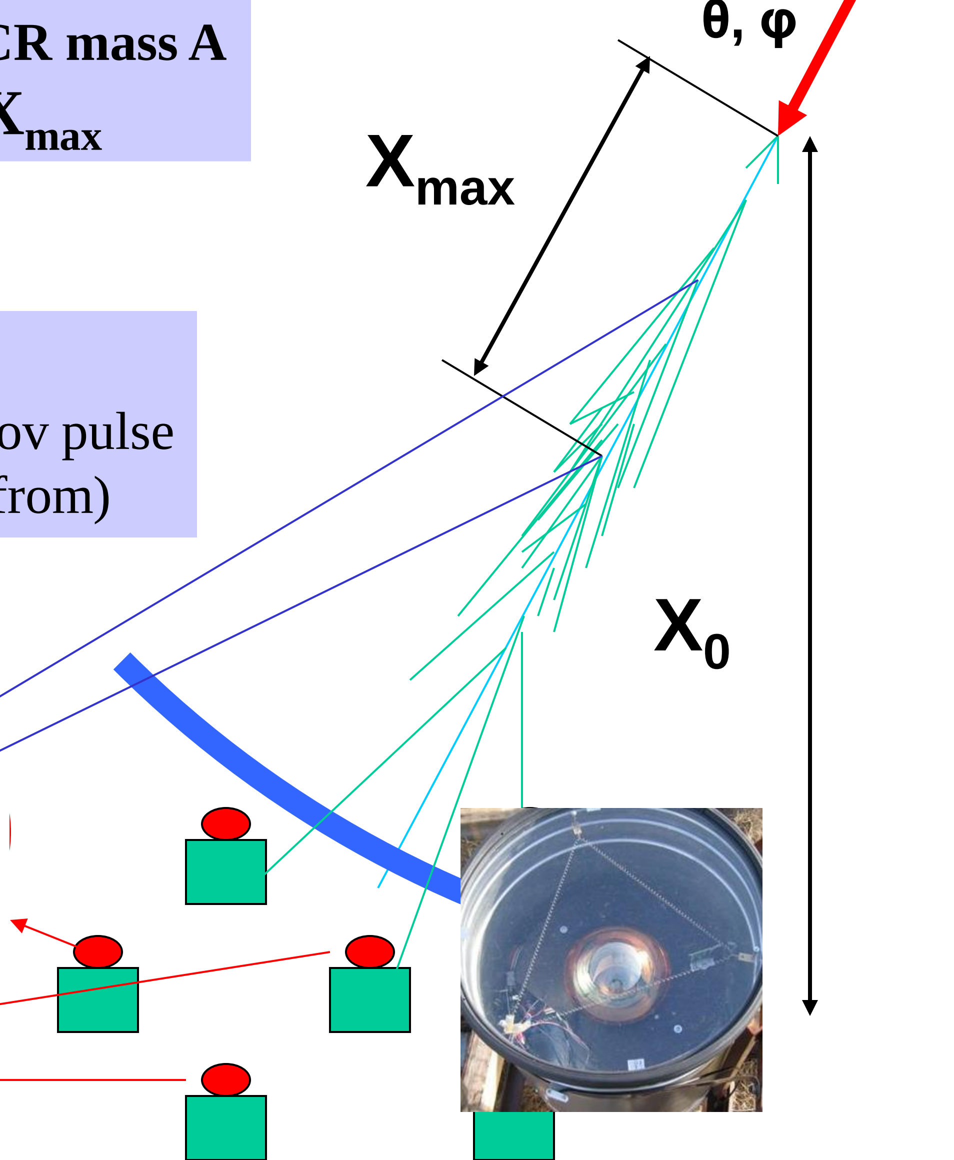
(τ(400) - width of a Cherenkov pulse at distance 400 m EAS core from)

$X_{max} = F(P)$

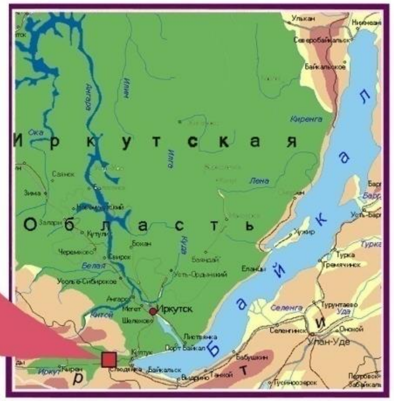
P -Steepness of a Lateral Distribution Function (LDF)





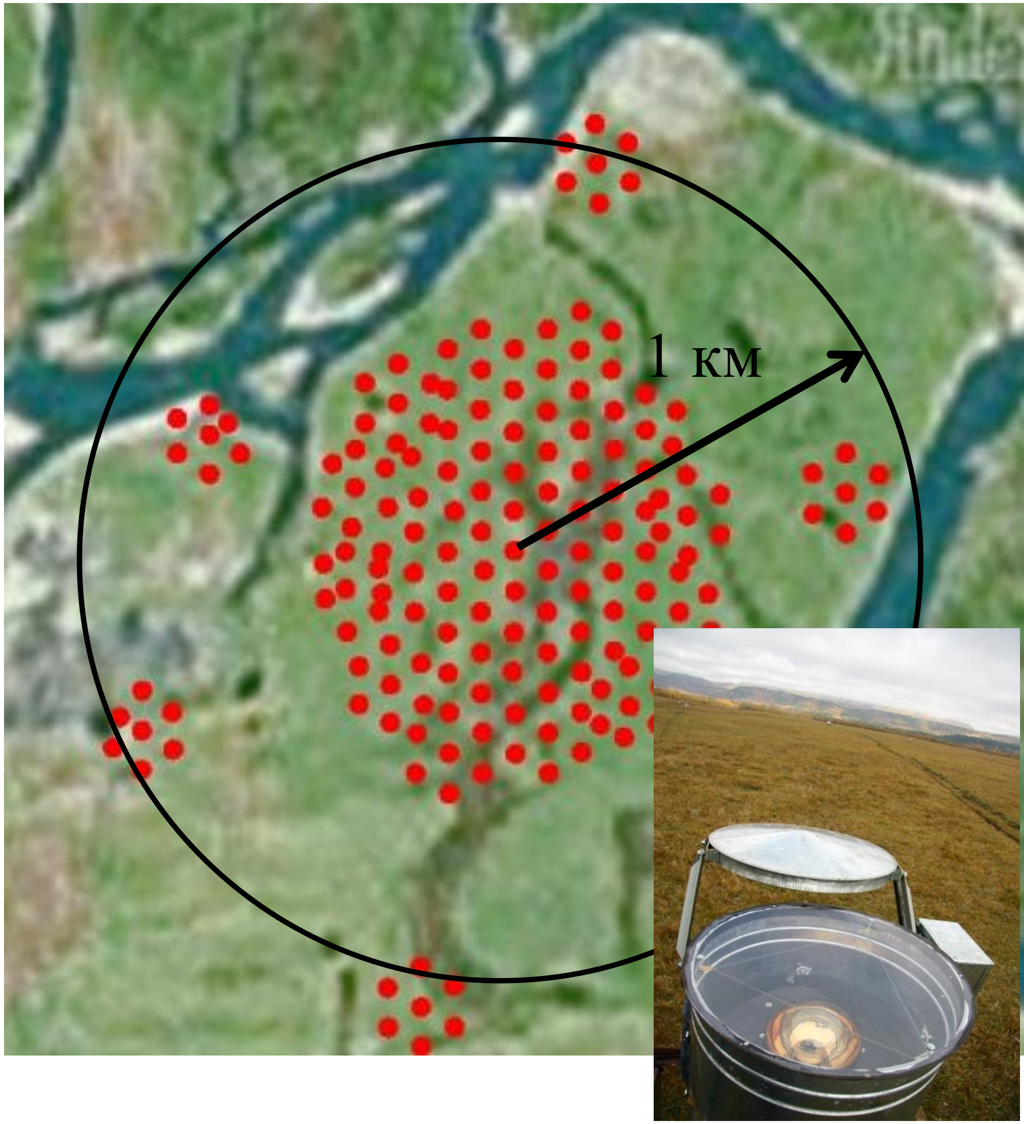


Tunka-133 array: 175 Cherenkov detectors distributed on 3 km^2 area, in operation since 2009y



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

50 km from Lake Baikal

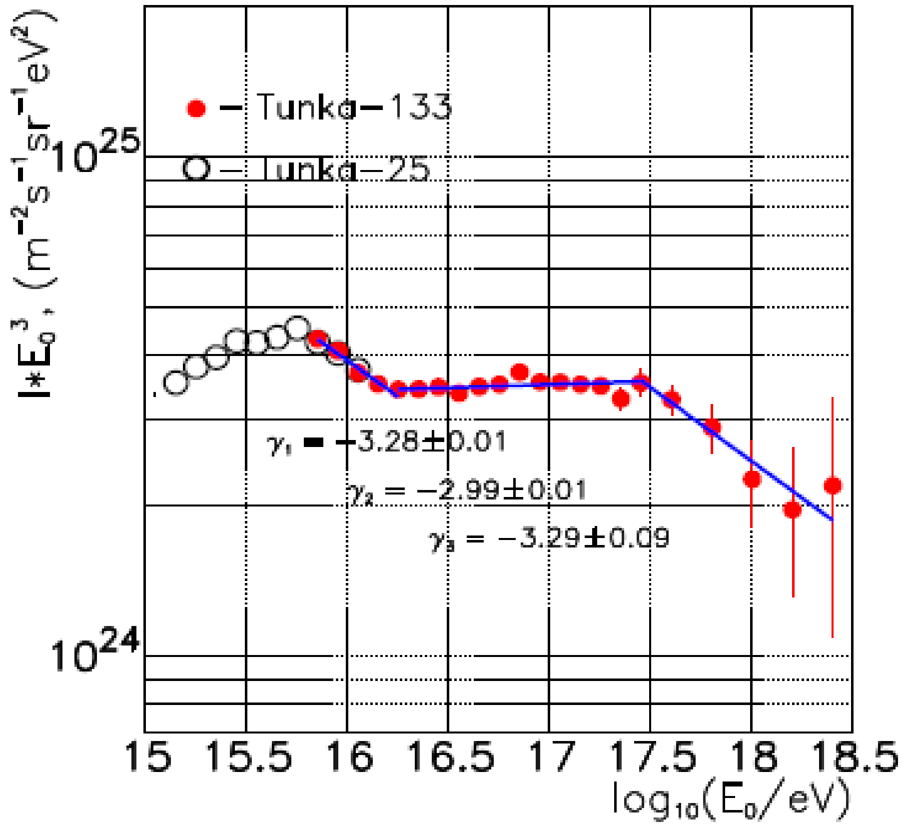


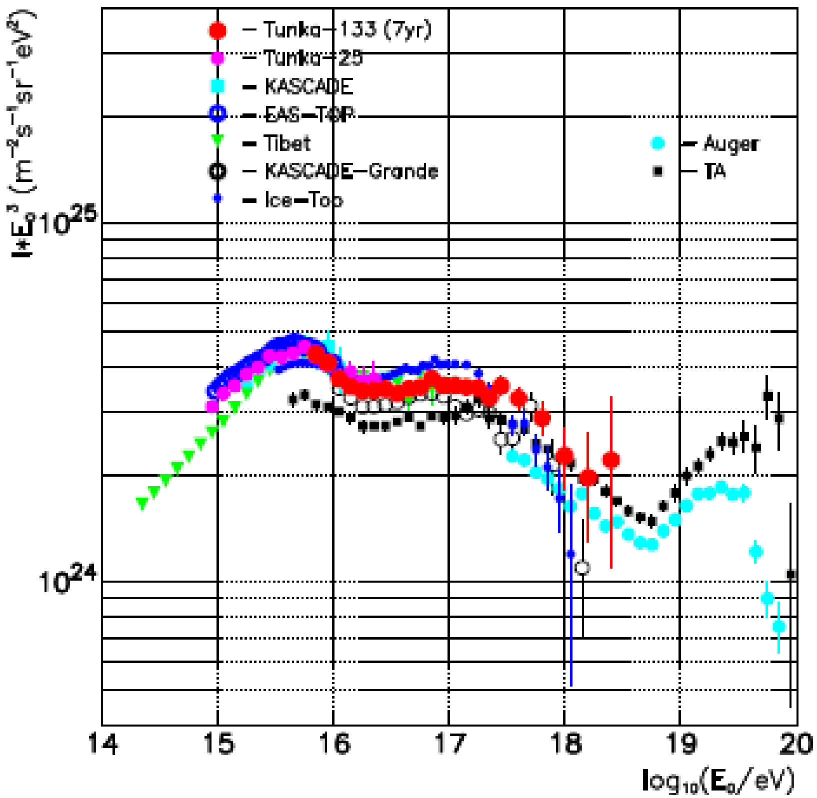
Advantage of the Tunka-133 array:

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**

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

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





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..

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

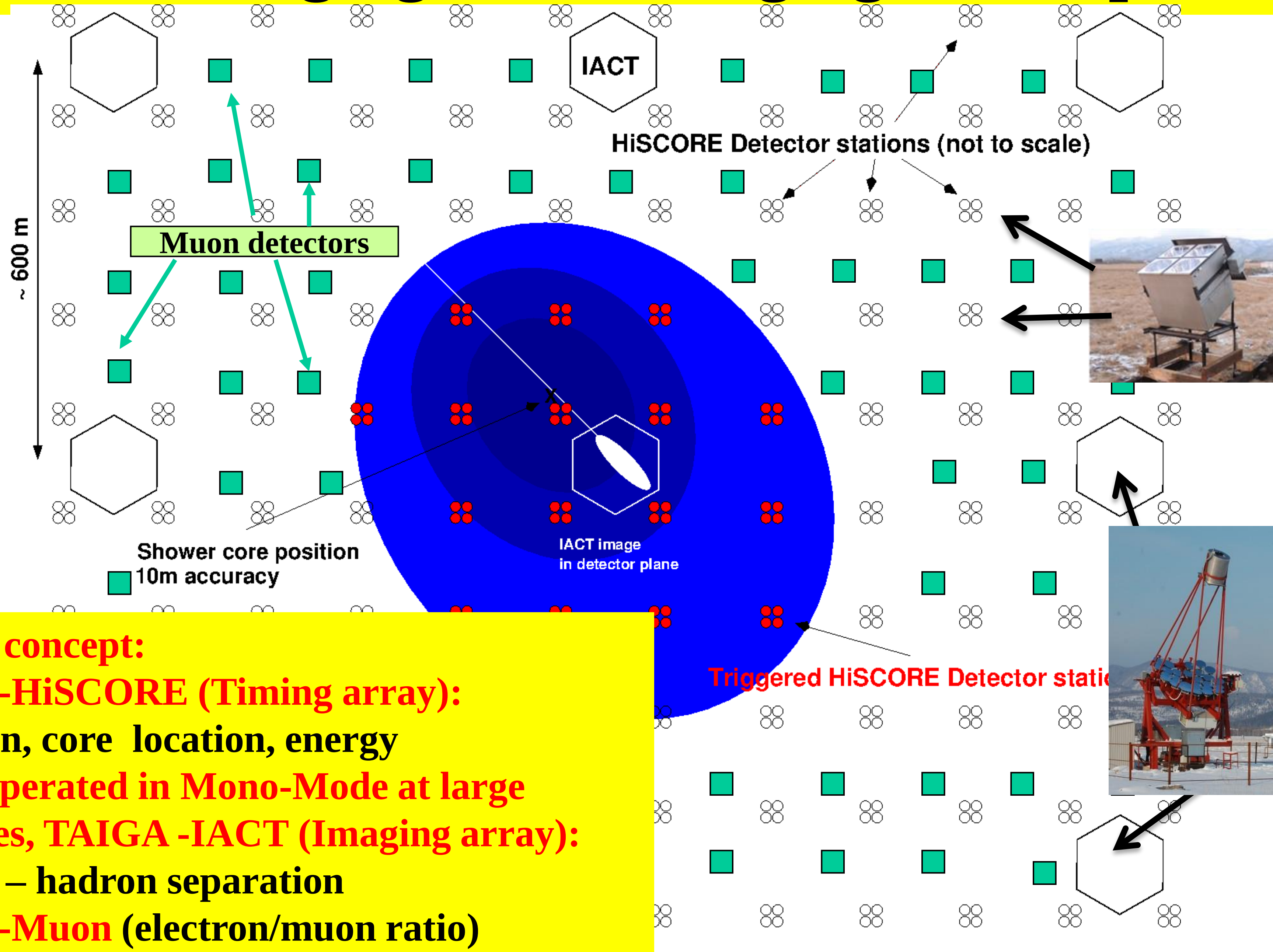
The TAIGA experiment - a hybrid array for very High energy gamma-ray astronomy and cosmic ray physics in the Tunka valley

The main idea: **A cost effective way to construct a large area installation is common operation of wide-field-of-view timing Cherenkov detectors (the *non-imaging technique) with a few relatively cheap, small-sized imaging Air Cherenkov Telescopes.***

The first stage of TAIGA - 1 km^2 area array with 120 wide-angle timing Cherenkov detectors and 3 IACTs.

Commissioning of array is expected in 2020y.

TAIGA: Imaging + non-imaging techniques



Hybrid concept:

TAIGA-HiSCORE (Timing array):

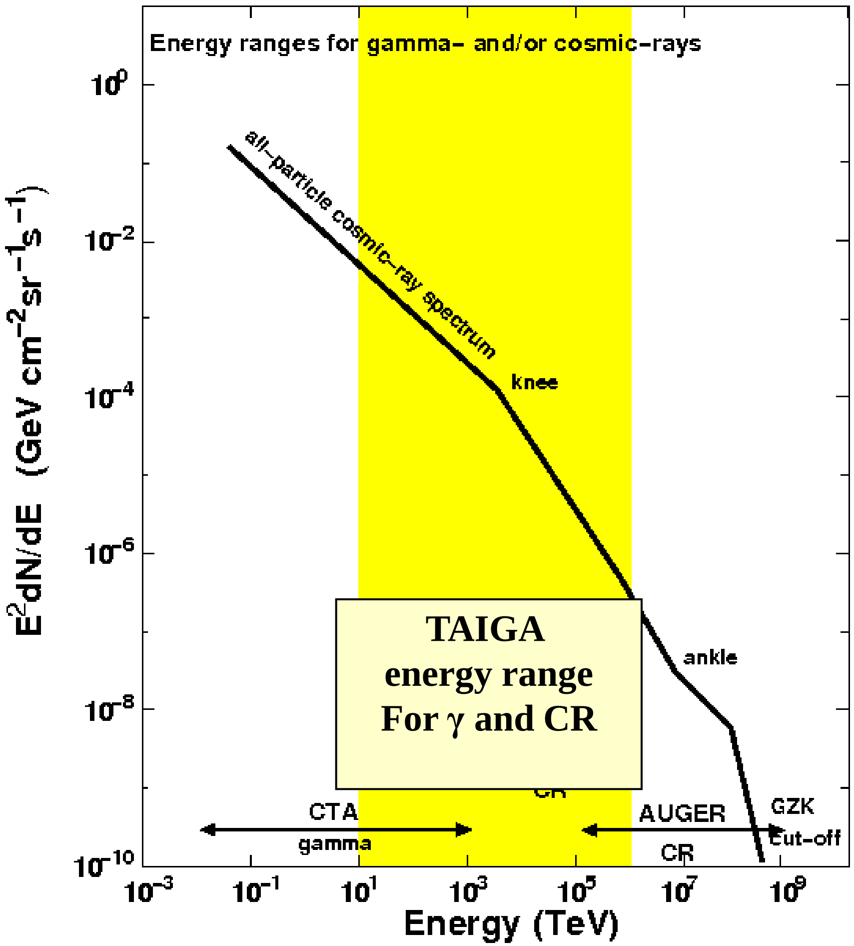
direction, core location, energy

IACT operated in Mono-Mode at large distances, TAIGA -IACT (Imaging array):

gamma – hadron separation

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} to10^{18} eV.

10^8 events (in 1 km^2 array)

with energy > 10^{14} eV

Particle physics

Axion/photon conversion.

Hidden photon/photon oscillations.

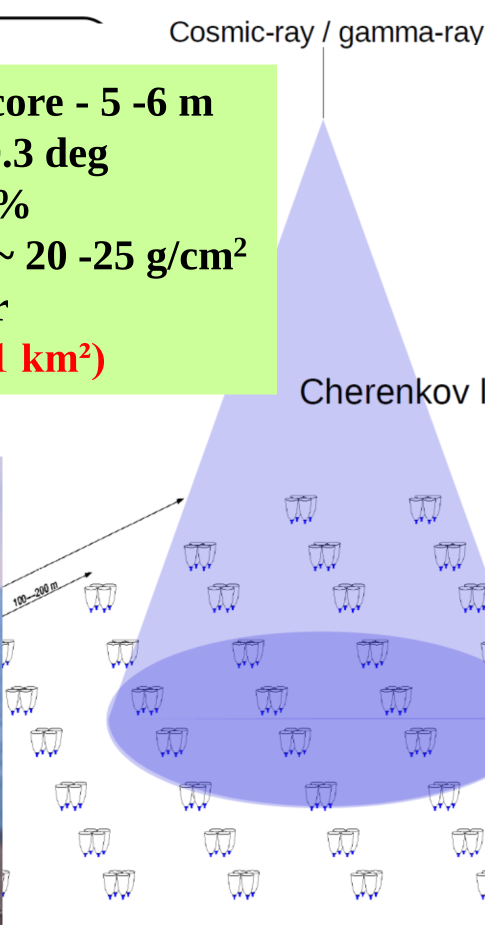
Lorentz invariance violation.

pp cross-section measurement.

Quark-gluon plasma.

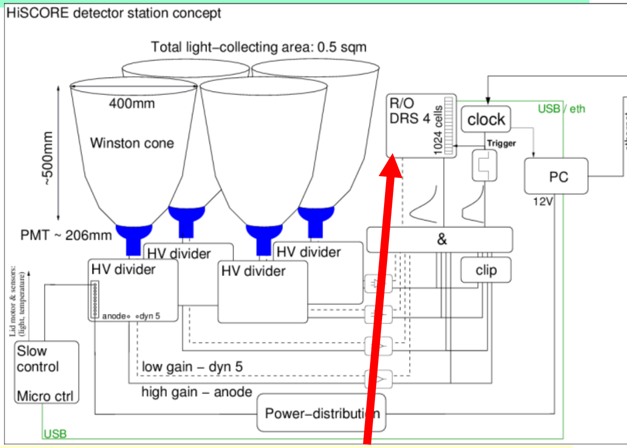
TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

- **Wide-angle time- amplitude sampling non-imaging air Cherenkov array.**
- **Spacing between Cherenkov stations 80-120 m ~ 80 -150 channels / km^2.**

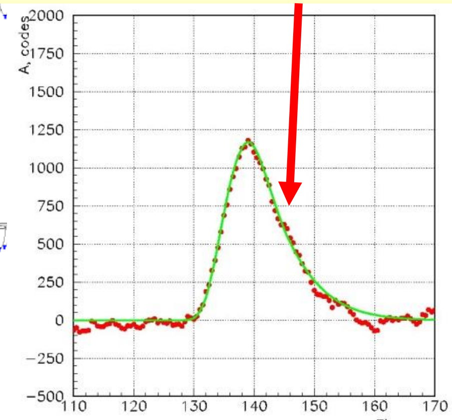


1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.3 deg
3. Energy resolution ~ 10 - 15%
4. Accuracy of X_{max} measure ~ 20 -25 g/cm^2
5. Large Field of view: ~ 0.6 sr

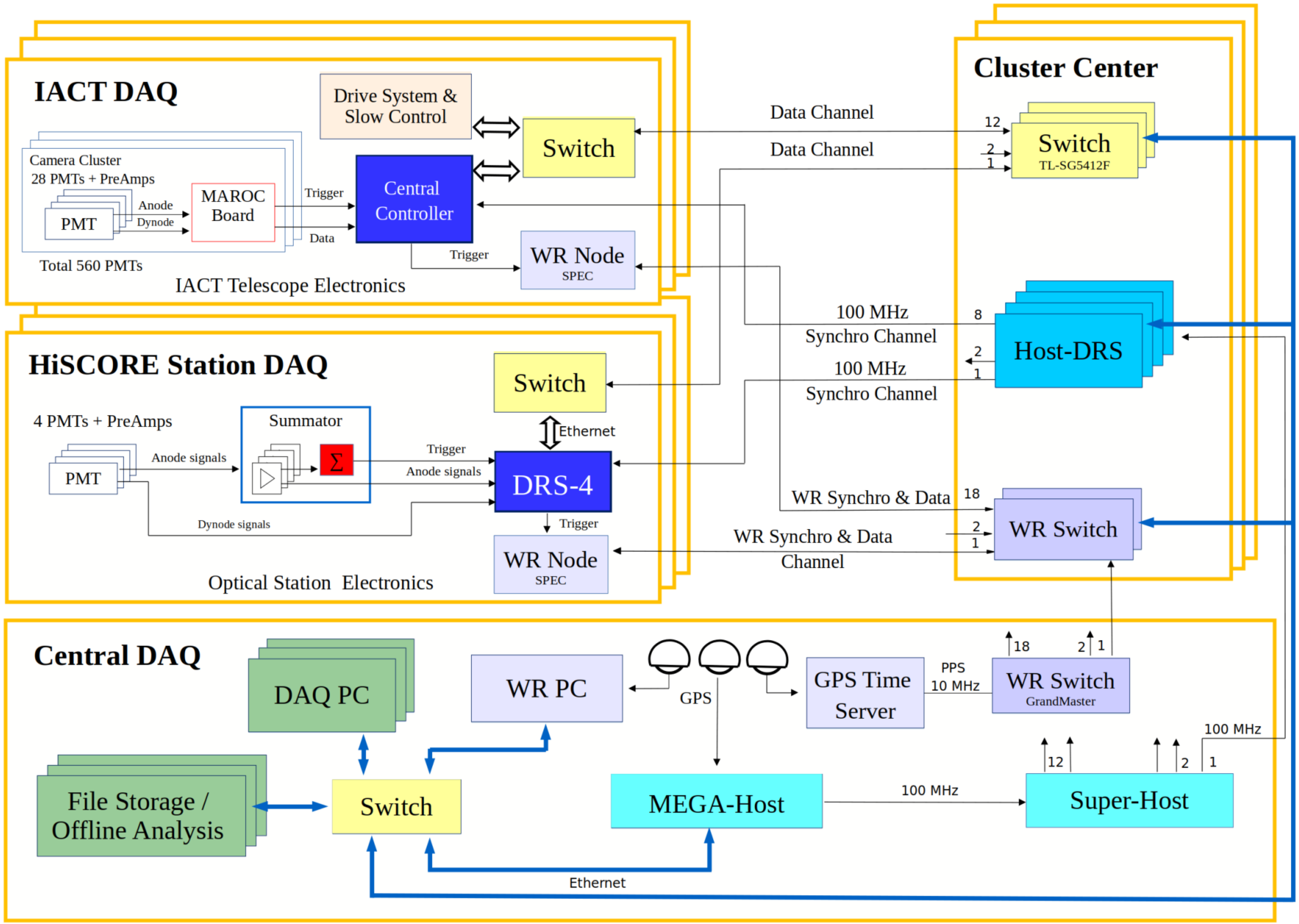
Total cost ~ 2 ·millions $ (for 1 km²)



DRS-4 board (0.5 ns step)

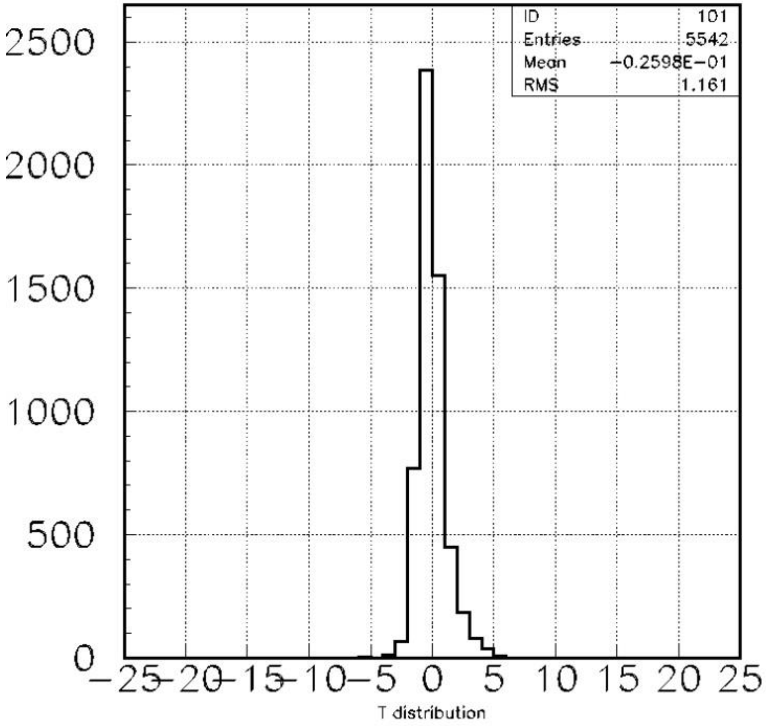


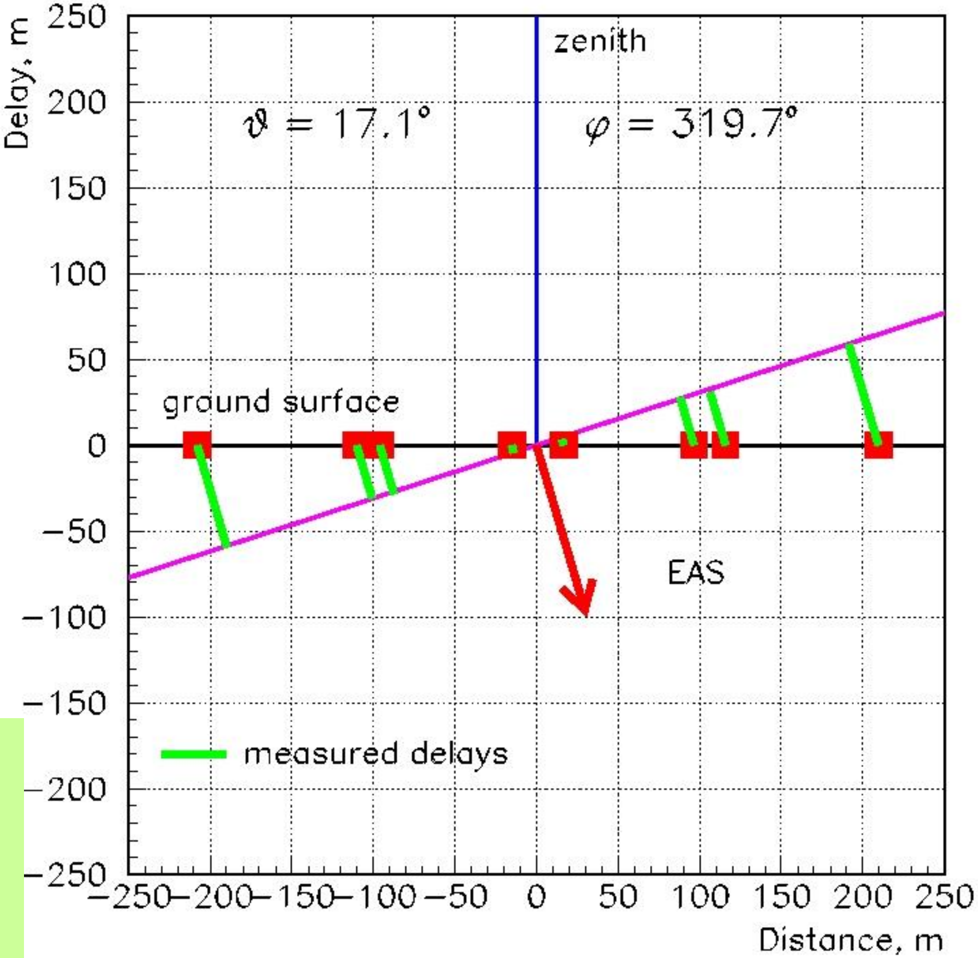
TAIGA DAQ



IACT DAQ
Drive System & Slow Control
Switch
Camera Cluster
28 PMTs + PreAmps
PMT
Anode
Dynode
MAROC Board
Trigger
Data
Central Controller
Trigger
WR Node
SPEC
Total 560 PMTs
IACT Telescope Electronics
HiSCORE Station DAQ
Switch
4 PMTs + PreAmps
Summator
Anode signals
PMT
Σ
Trigger
Anode signals
Ethernet
DRS-4
Dynode signals
Trigger
WR Node
SPEC
Optical Station Electronics
Cluster Center
Data Channel
Data Channel
12
2
1
Switch
TL-SG5412F
100 MHz
Synchro Channel
100 MHz
Synchro Channel
8
2
1
Host-DRS
WR Synchro & Data
18
WR Synchro & Data Channel
2
1
WR Switch
Central DAQ
DAQ PC
WR PC
GPS
GPS Time Server
PPS
10 MHz
WR Switch
GrandMaster
18
2
1
File Storage / Offline Analysis
Switch
MEGA-Host
100 MHz
Super-Host
12
2
1
100 MHz
Ethernet

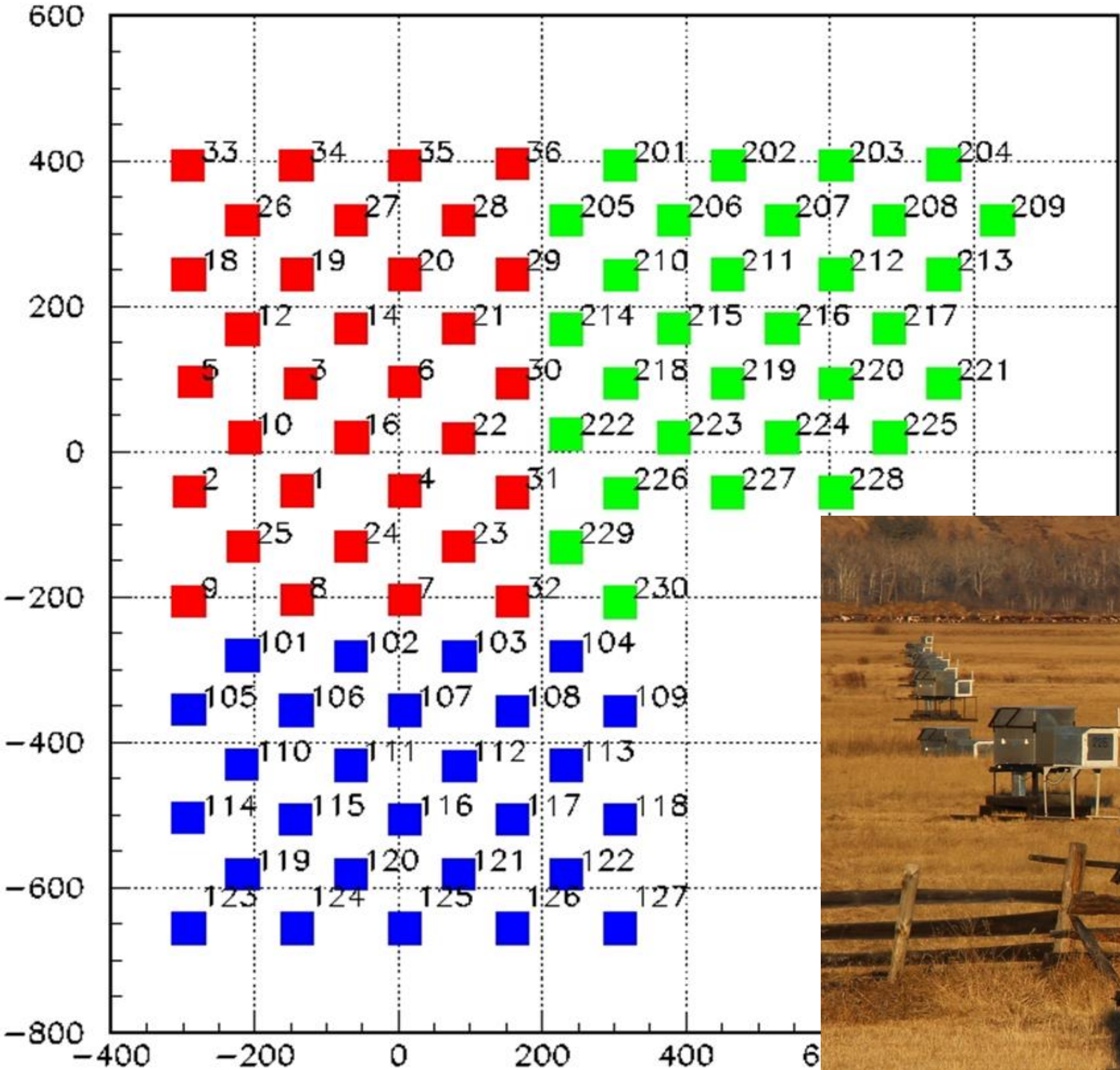
An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE





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

TAIGA-HiSCORE 2019 year setup



86 wide- angle Cherenkov detectors on area 0.75 km^2 about

The TAIGA – IACT

The TAIGA - IACT

First 2017y, second 2019y, third 2020y

situated at the vertices of a triangle

with sides:

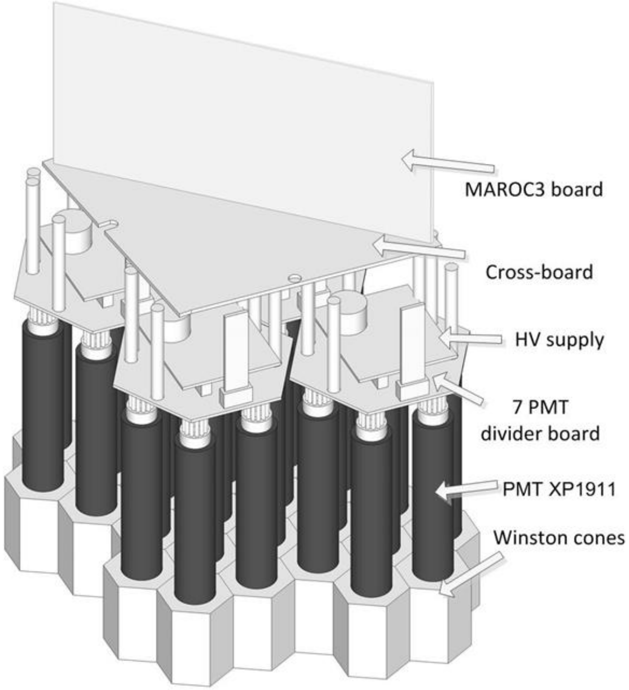
300 m, 400 m and 500 m about

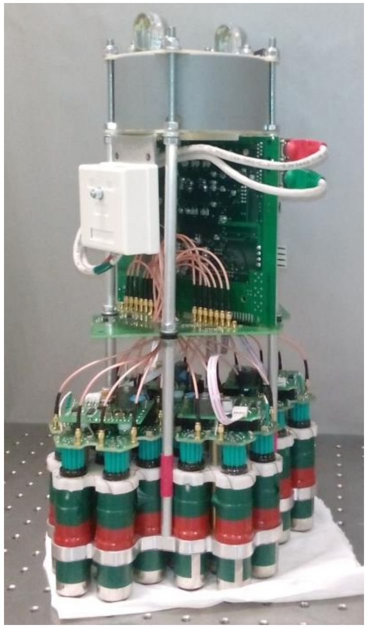
- **34-segment reflectors (Davis-Cotton)**
- **Diameter 4.3 m, area ~10 m^2**
- **Focal length 4.75 m**
- **Threshold energy ~ 1.5 TeV**

.

The Camera of the TAIGA-IACT

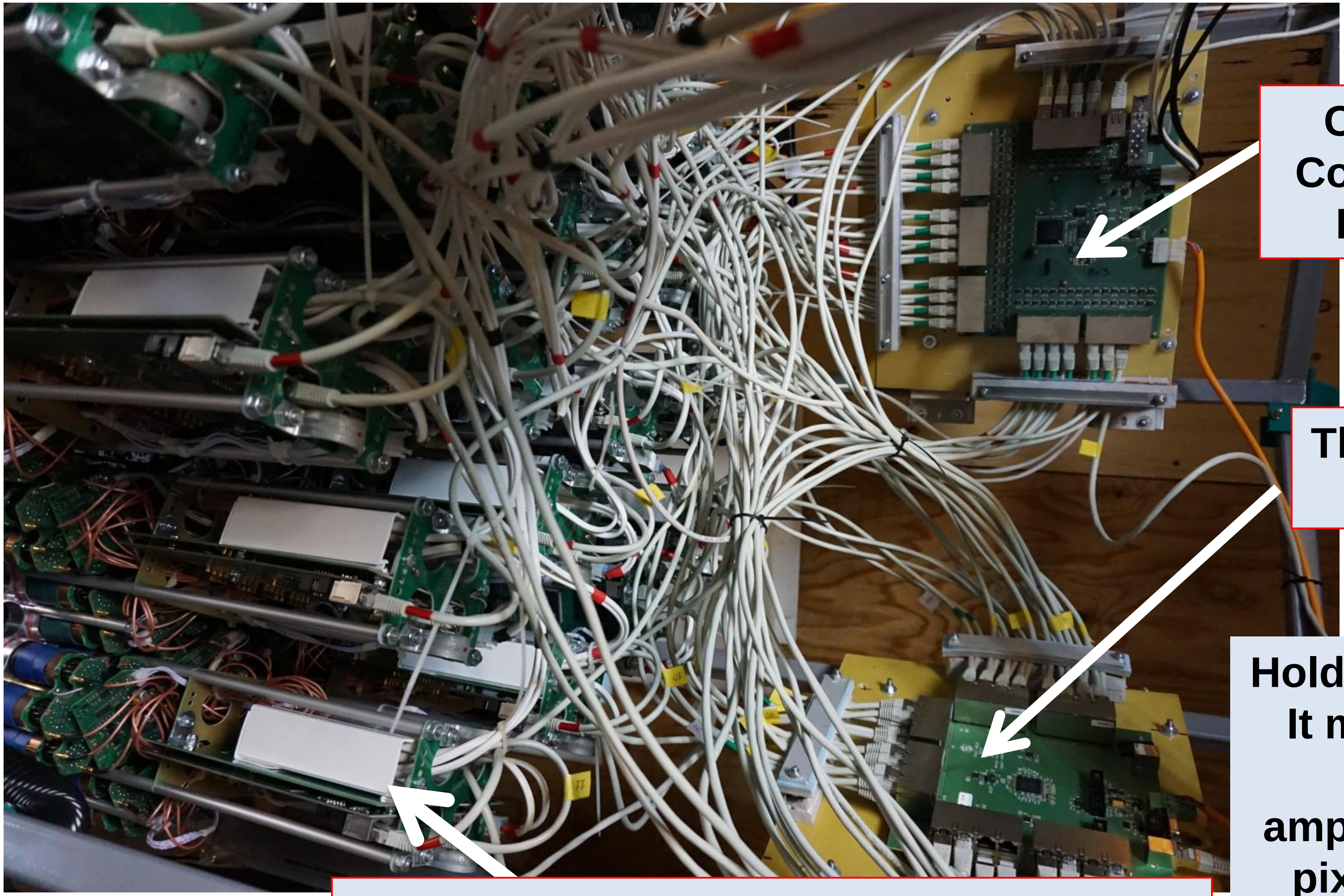
- 560 PMTs (XP 1911) with
- 15 mm useful diameter of photocathode
- Winston cone: 30mm input size
- each pixel = 0.36 deg
- FOV 10 x 10 deg





Basic cluster: 28 PMT-pixels. Signal processing: PMT DAQ board based on MAROC3 ASIC

Camera of IACT-2



Central Controller Board

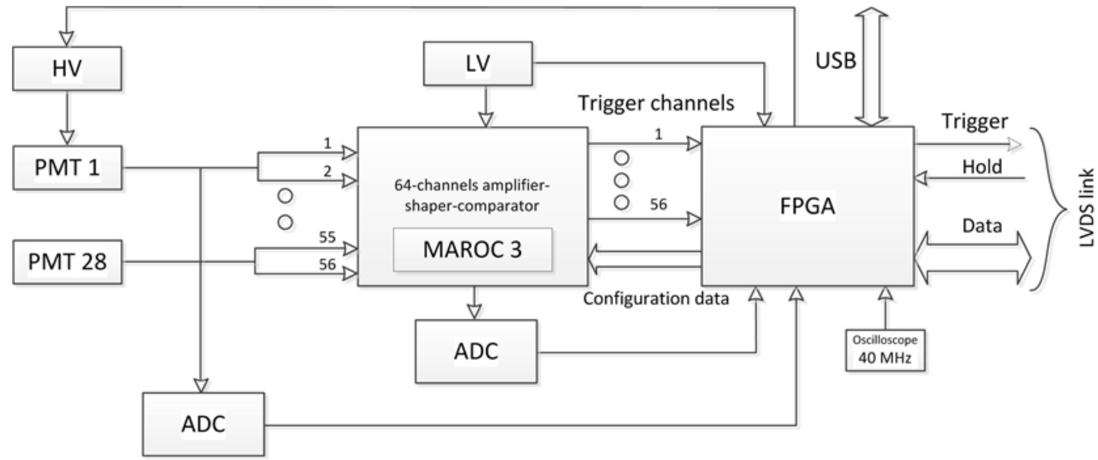
The Fast_Hold Boards

Hold on all clusters. It make possible to read out amplitudes from all pixels of camera

28 PMTs cluster on the base of MAROC-3

The MAROC3 ASIC board

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



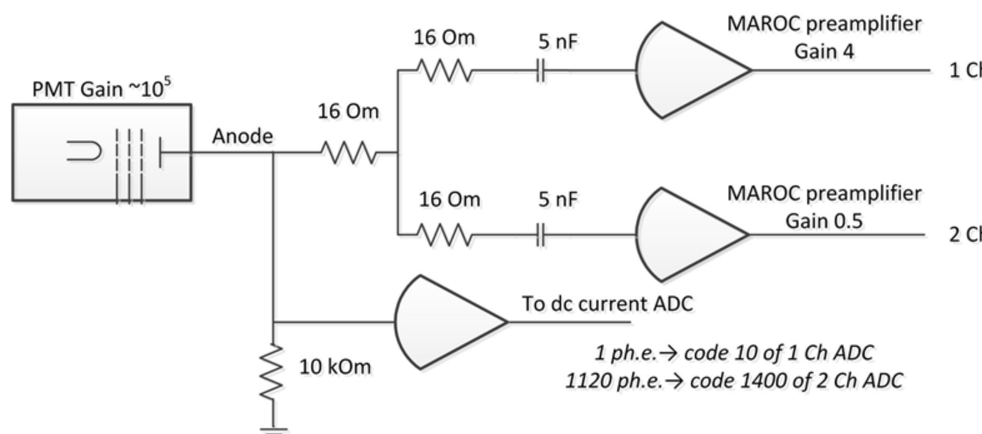
Each channel:

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

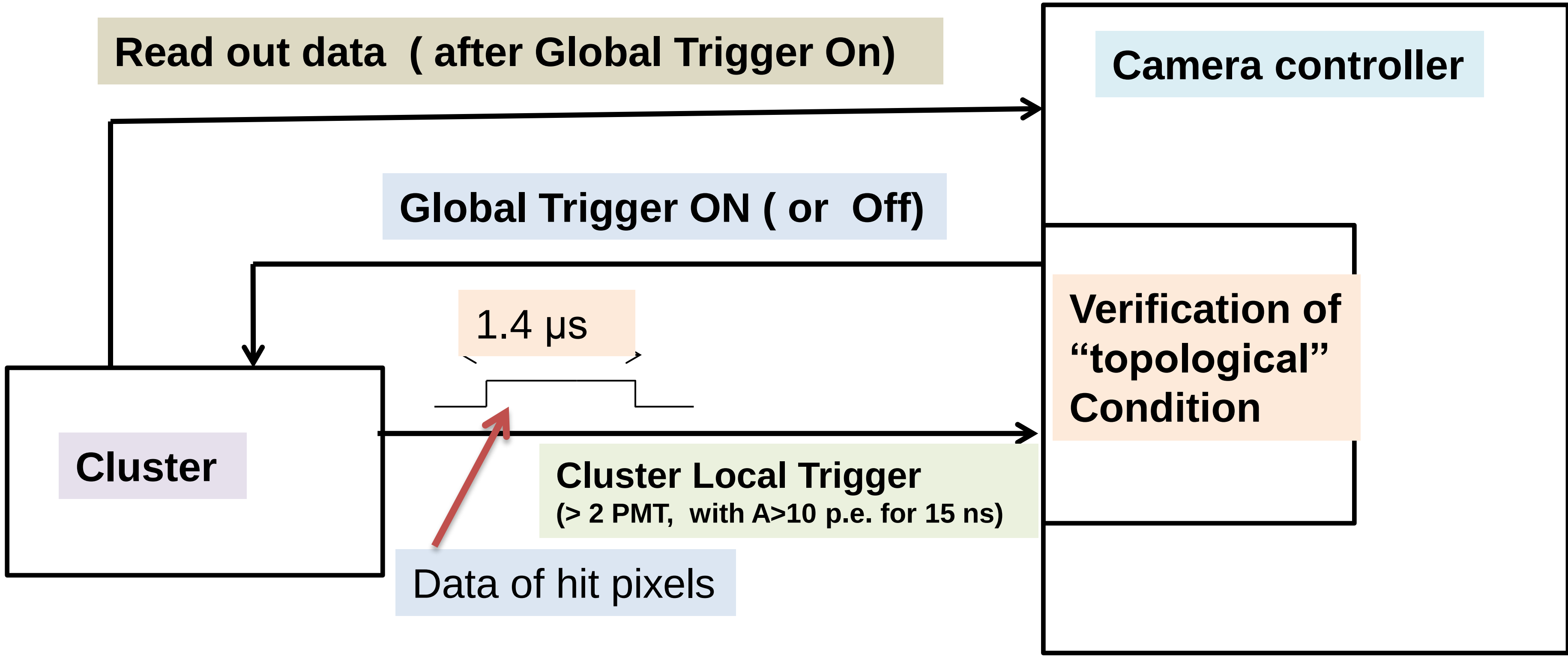
Two channels of MAROC3 process the signals from one PM splited to provide the necessary dynamic range.

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.



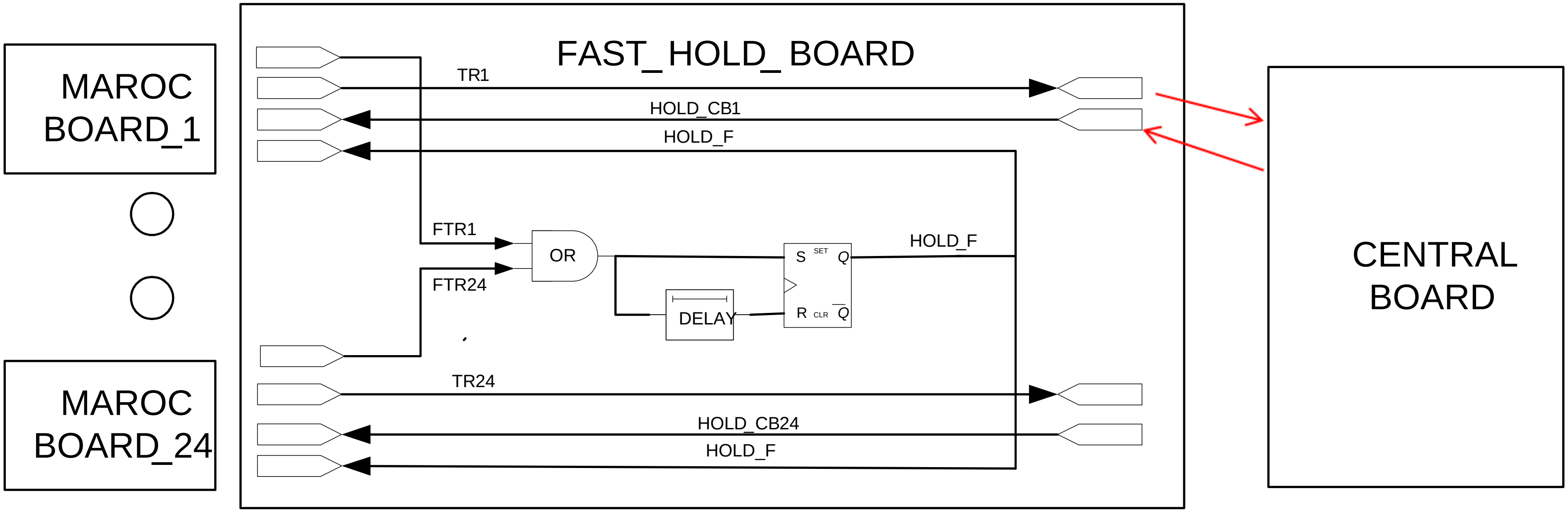
“Topological trigger”



Cluster Local trigger – at least two hit pixel (A> 10 p.e. for 15 ns)
“Topological” condition - these pixels must be adjacent

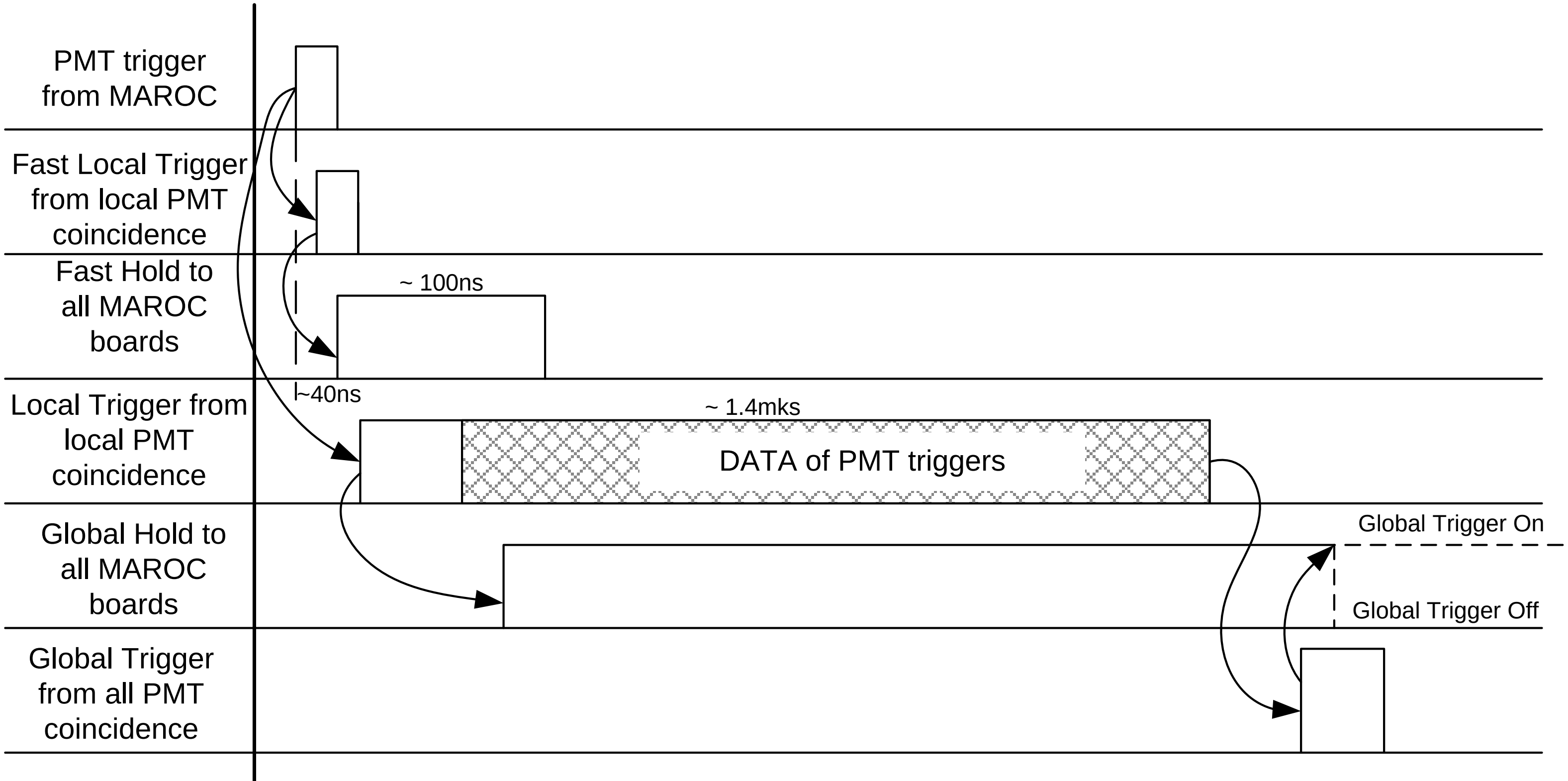
Topological condition decrease of camera counting rate in 10 times

FAST_HOLD_BOARD function diagram



Это Global Trigger
(через 2 мкс

Time diagram of the trigger system with FAST_HOLD



•The local trigger is generated on coincidence of local PMT triggers and transmits to the FAST_HOLD Board.

FAST_HOLD is formed by the FAST_HOLD Board on any local trigger and is transmitted to all MAROC boards where the level of their slow shapers is fixed. The duration of the signal is about 100 ns.

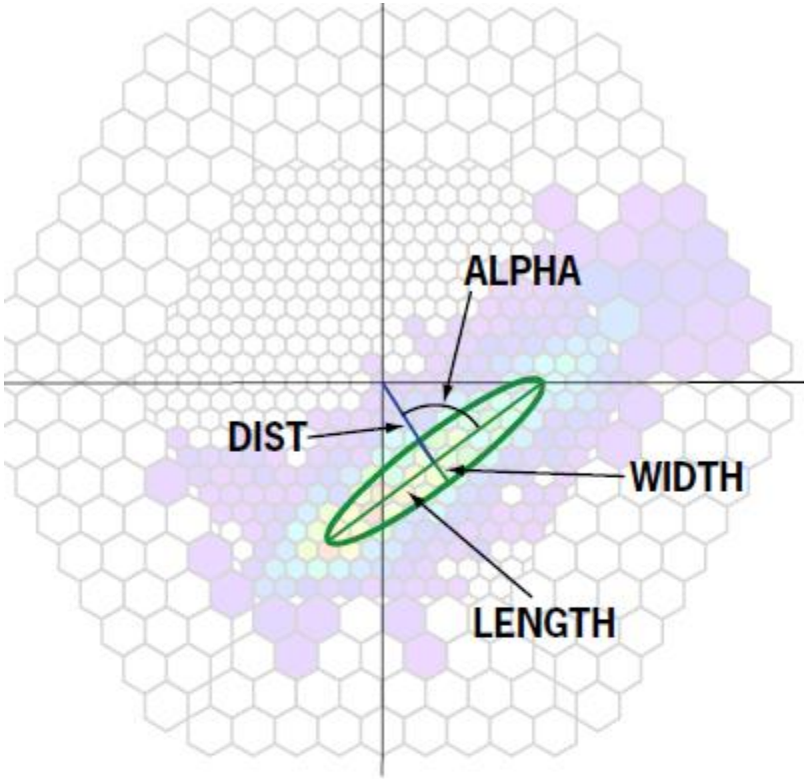
•The local trigger is generated on coincidence of local PMT triggers and transmits to the Central Board information about the PMT triggers.

•The global HOLD formed a Central Board on any local trigger and passed on all MAROC Boards.

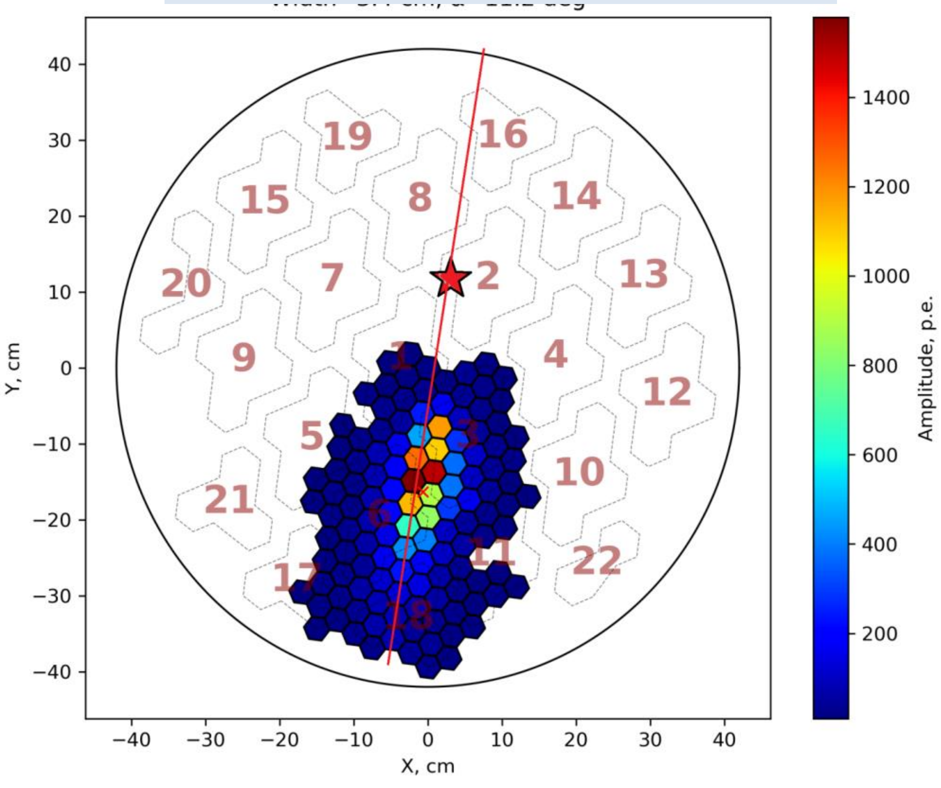
•The global trigger is generated on coincidence of all PMT triggers. If a global trigger is formed, all MAROC Boards starts the ADC. If a global trigger is not formed, the global HOLD reset.

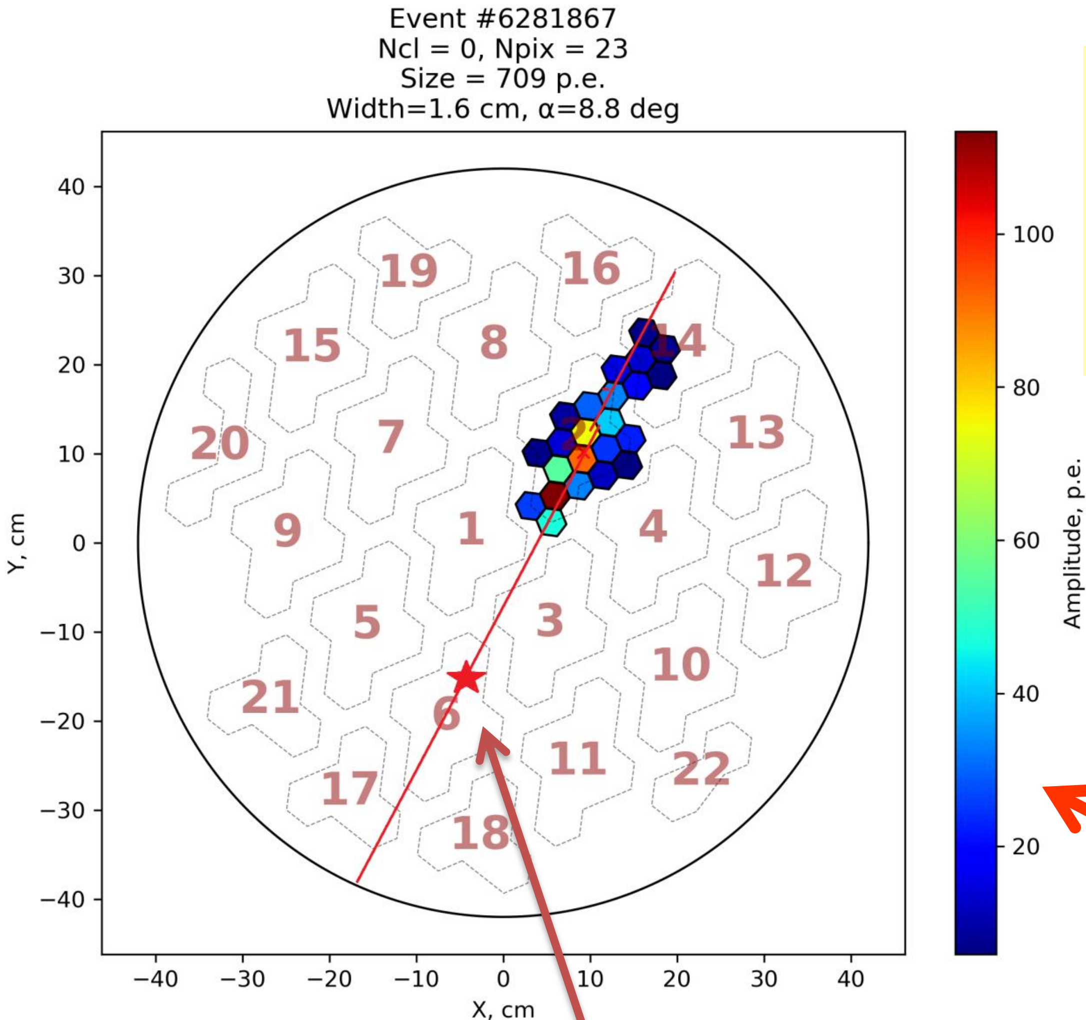
TAIGA-IACT and TAIGA-HiSCORE joint events.

Hillas parameters



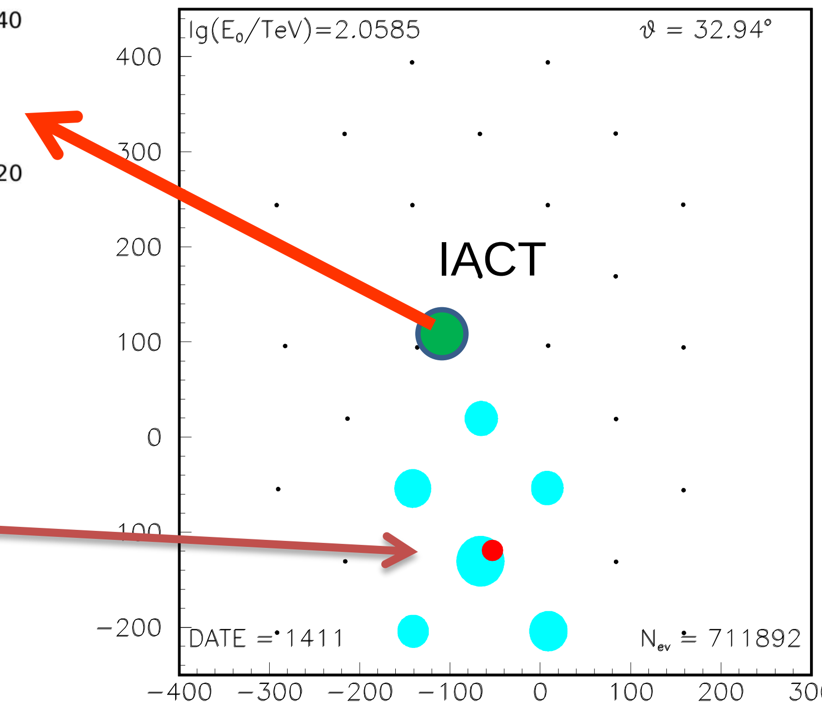
Most of events are “Hadron-like”
E = 880 TeV
width = 0.4°





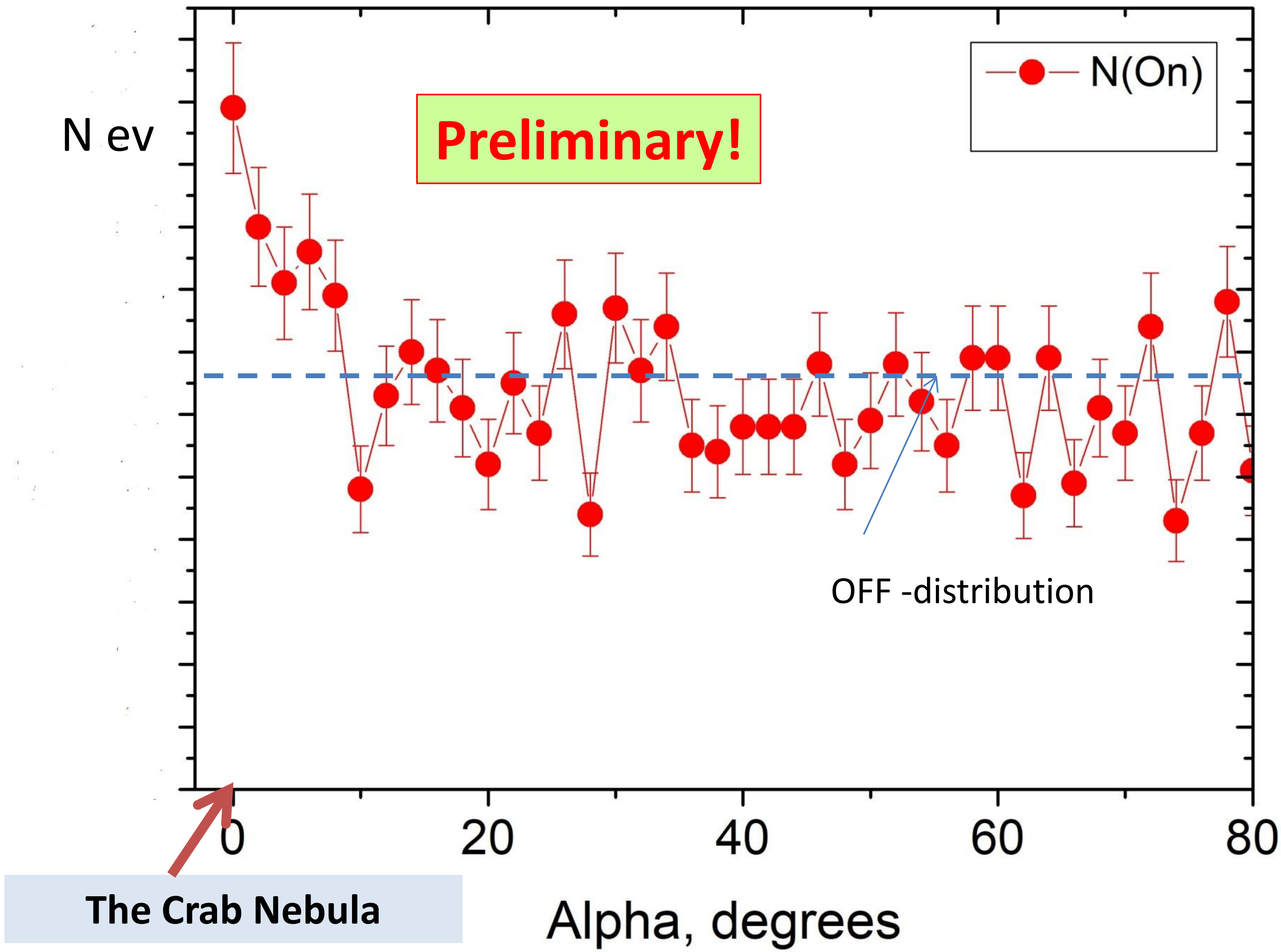
But some events looks as "Gamma-like"

E = 50 TeV
Width = 0.19°



Core position

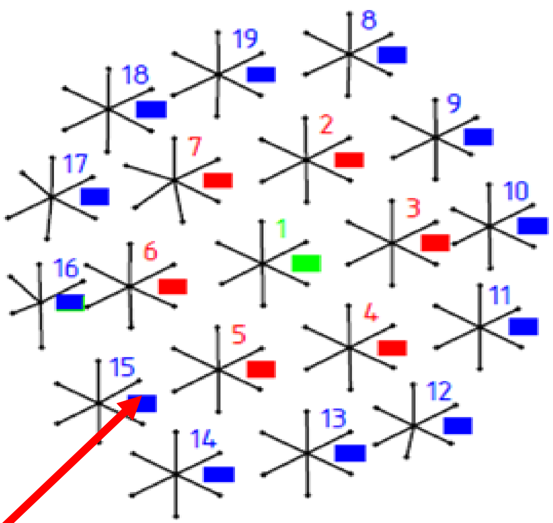
A histogram of the events distribution around direction on the Crab Nebula

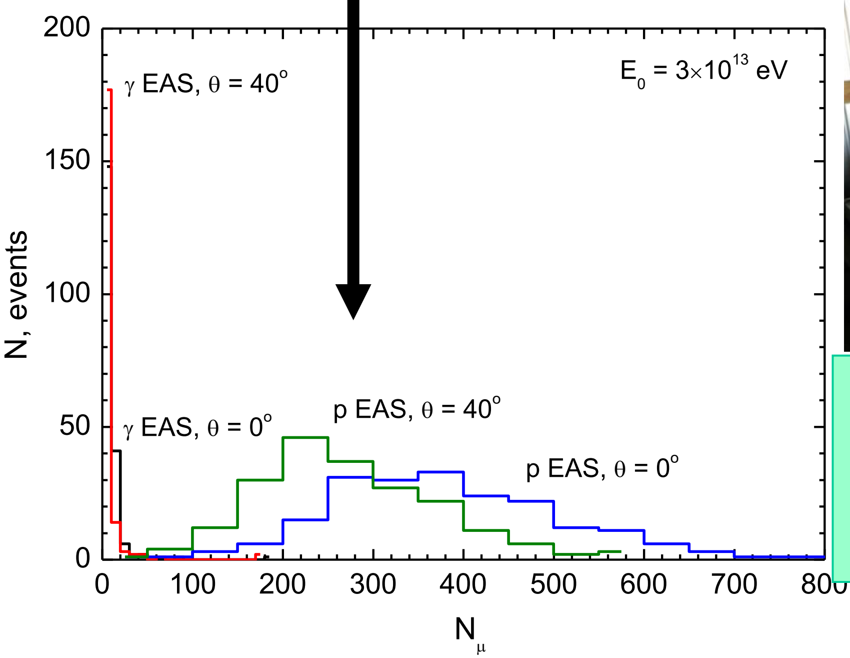


The TAIGA particle detectors.

The Tunka – Grande scintillation array

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





228 former KASCADE-Grande scintillation counters with S=0.64 m²

152 the same underground muon counters in 19 stations.

The TAIGA-Muon scintillation array

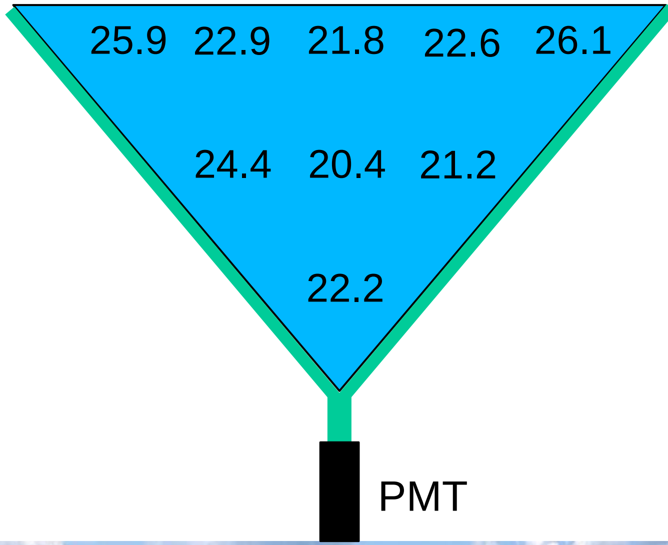
(Poster A.Ivanova et al)

Counter dimension 1x1 m^{2}.

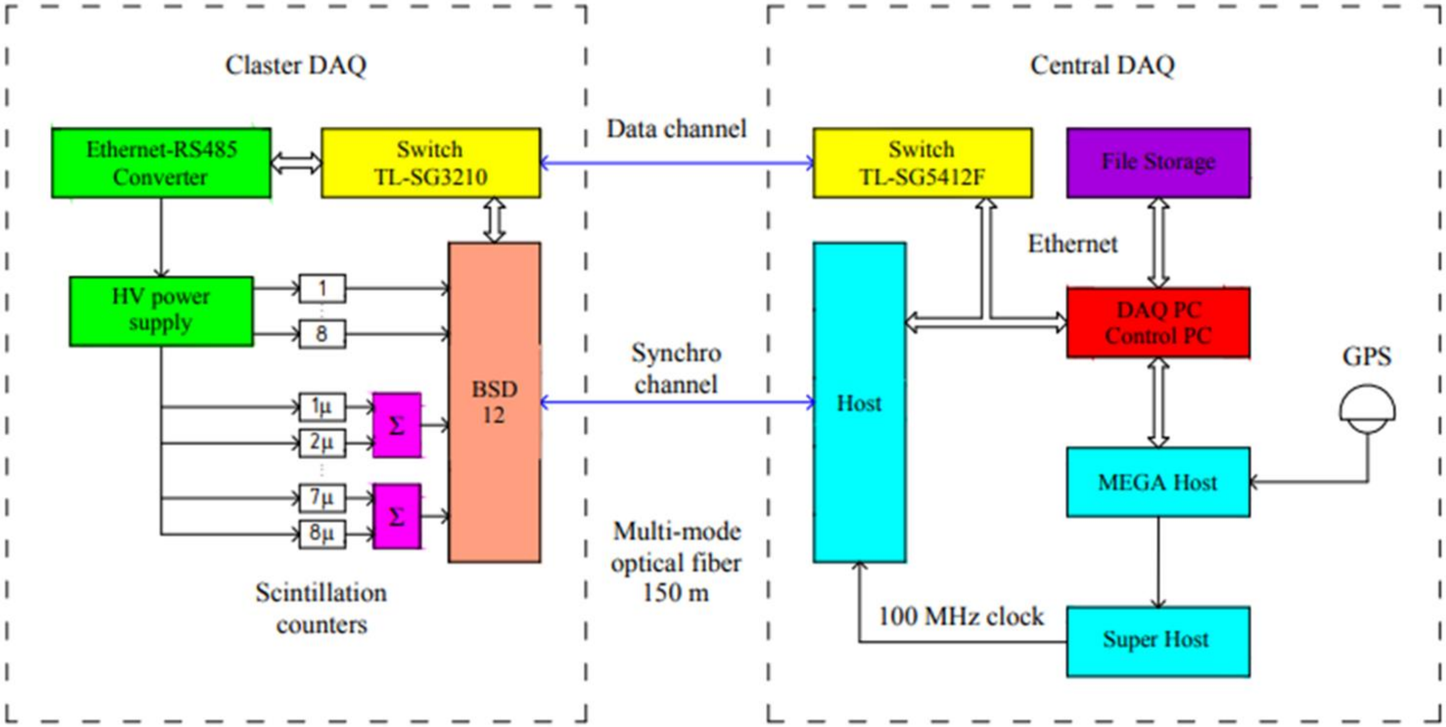
Wavelength shifting bars are used for collection of the scintillation light.

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



Data Acquisition System



Cluster DAQ consists of a 12-channel data acquisition module (BSD-12) , 2 ten-channel high-voltage power sources (HV power supply), a device for control of the high-voltage sources (Ethernet RS485 Converter), 4 two-channel analog signal summators (∑), and a Switch required for receiving and transmitting information.

Central DAQ includes data collection and storage devices (File Storage, DAQ PC), synchronization devices (MEGA Host, Host, and Super Host) , and elements responsible for data collection and transmitting of control information (Switches and Control PC). MEGA Host is connected to the GPS station and sends a clock signal with a frequency of 100 MHz to the cluster via Super Host and Host (synchronization accuracy is 10 ns).

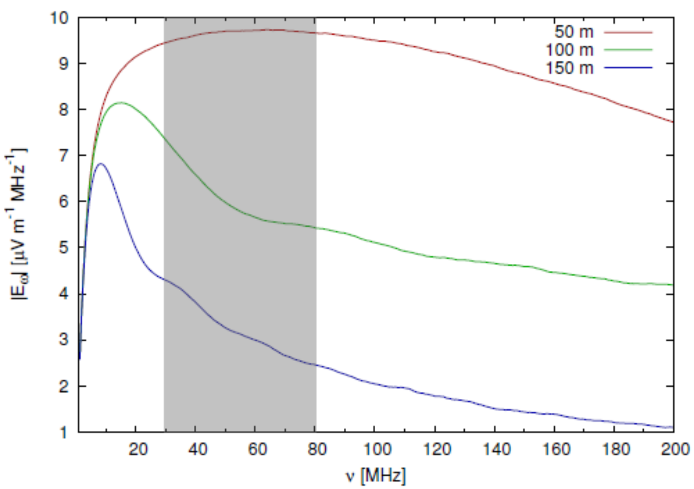
Air-shower radio emission

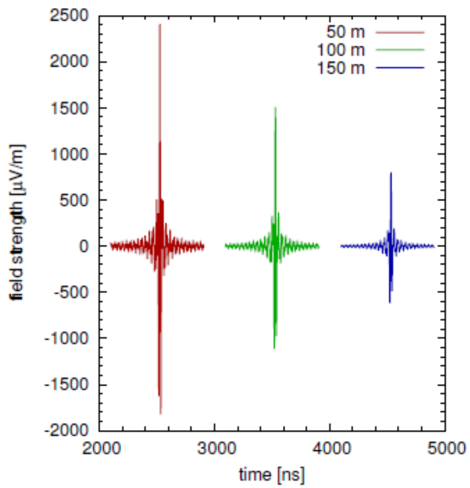
Mechanisms:

* Geomagnetic effect

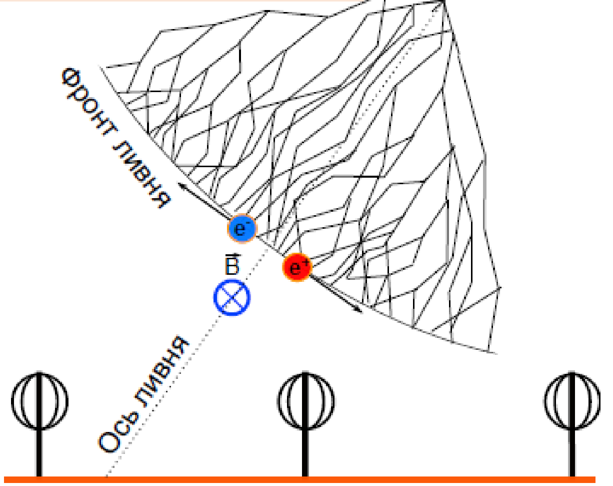
* Asatryan effect

Coherent Broadband Pulses

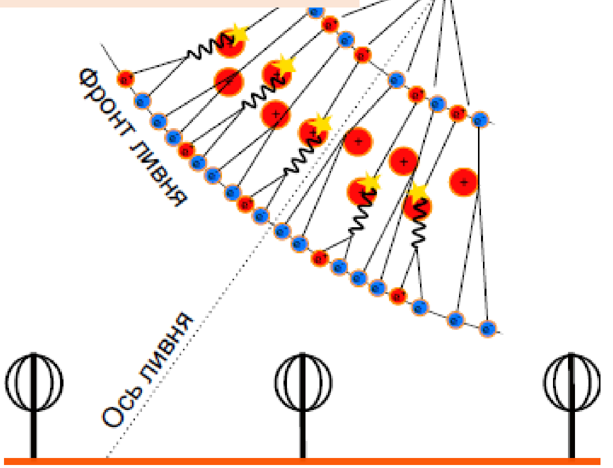




Geomagnetic effect



Askaryan effect



Advantages:

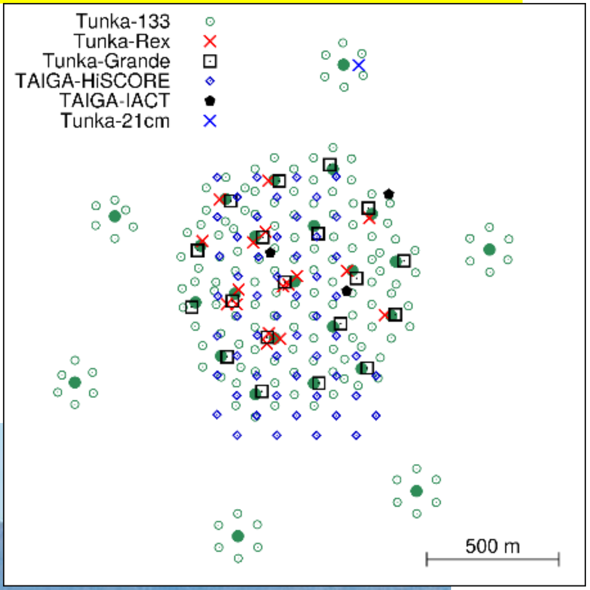
* Sensitive to the energy and shower maximum
* Almost full duty cycle
* Simple and cost-effective

Disadvantages:

* Low signal-to-noise ratios (SNR) and many transient background (RFI)

Tunka-Rex (Tunka – Radio extension

* Detected energies - $10^{16.5}$ - $10^{18.5}$ eV
* Detector area - 3 km^2
* 63 antenna stations
* Frequency band 30 - 80 MHz
* Two trigger modes (Tunka-133 and Tunka-Grande)



~100 events per season triggered by Tunka-133

commission of Tunka-Grande w i th

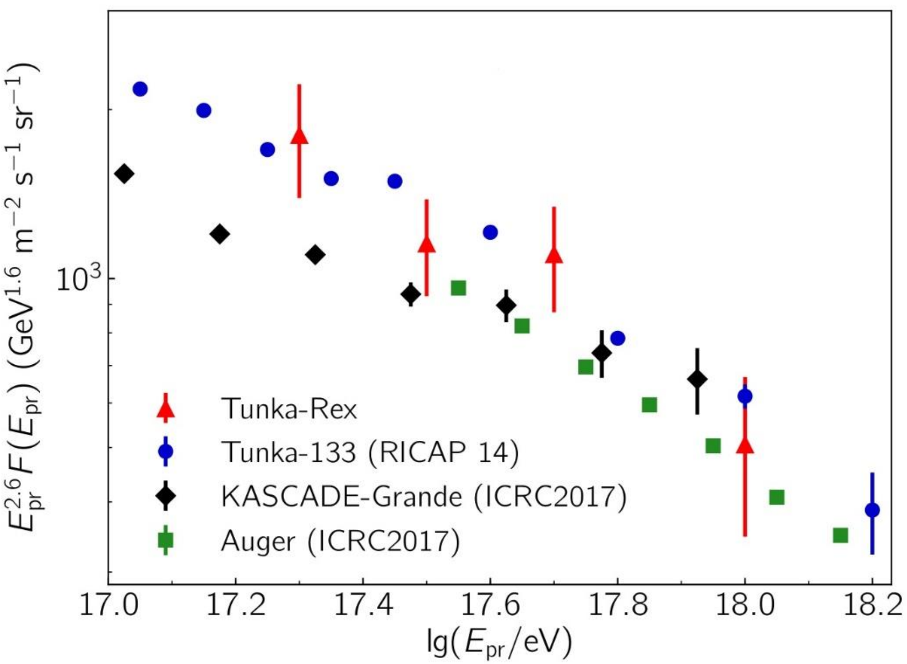
~1000 events per season triggered by Tunka-133 and Tunka-Grande

2012	2013	2014	2015	2016	2017	2018	2019
18 antennas	25 antennas	44 antennas		63 antennas			TRVO and decommission

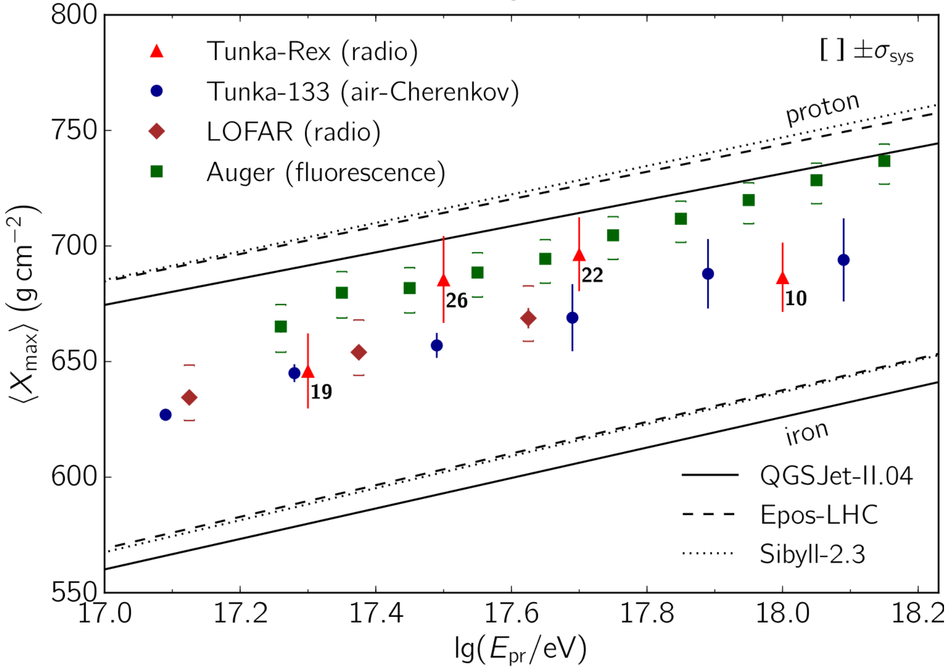
Tunka-Rex results

* Tunka-Rex successfully operated since 2012
* Energy resolution of 10-15%, shower maximum resolution of 25–35 g/cm²
* Ideal tool for energy scale calibration between CR experiments (KG + Tunka-133)
* SALLA will be used in the radio upgrade of the Pierre Auger Observatory
* Study of inclined air-showers
* Small engineering arrays
* Development of self-trigger for radio

Energy spectrum



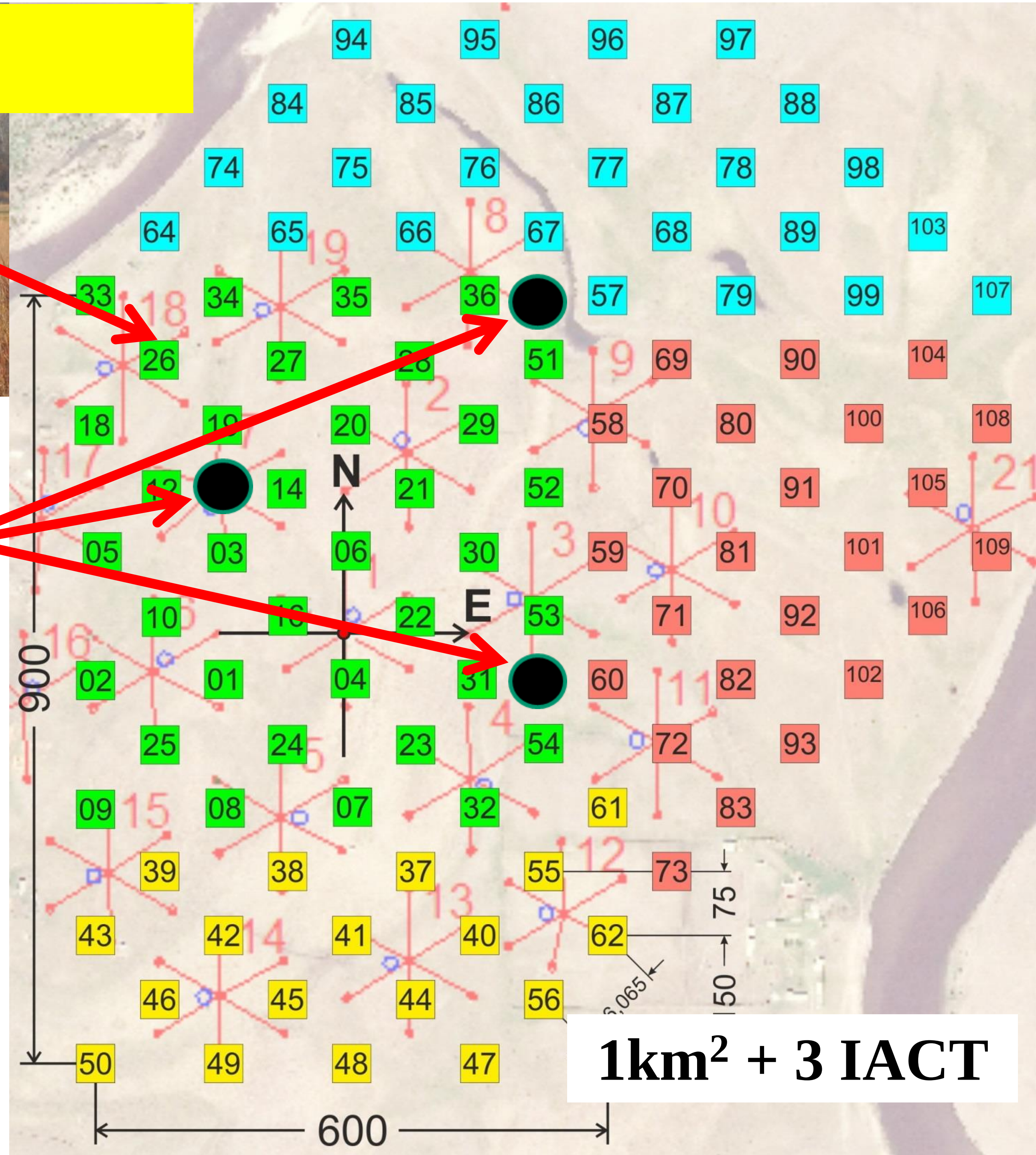
Mass composition



TAIGA, 2020


TAIGA-HiSCORE
120 detectors


3 TAIGA-IACT

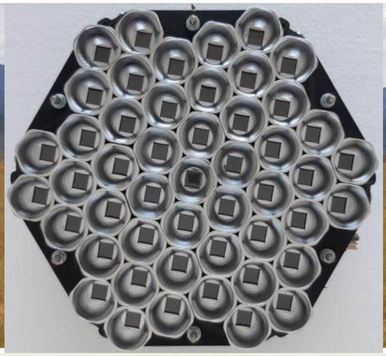

N
E
900
600
75
150
1km^2 + 3 IACT

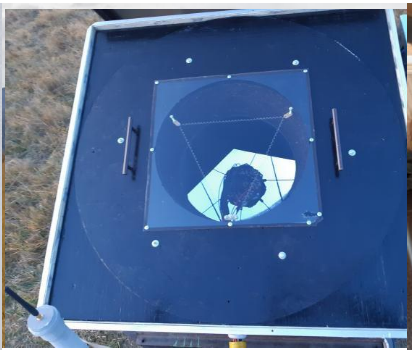
A compact-size wide Field of View IACT with a SiPM-based camera for energies above 10 TeV.

FoV of TAIGA-HiSCORE detectors is 60° but TAIGA-IACT – 10° as a result we have only 1% of joint events.

To study the gamma-ray with energy above 30 TeV we started off a development of a Small Image Telescopes (SAT) with a SiPM-based camera with a FoV up to 60° and an effective recording area of $1 m^2$. We intend to test 3 variants of the SAT optical system: spherical mirror, a system of Fresnel lenses, combination of the two mentioned technologies.

Prototype SIT (FOV ~ 20°, S ~ 0.1 m^2, 49 SIPM SensL MicroFC-60035-SMT, 6 ×6 mm^2) was installed in the Tunka Valley for operation together with the TAIGA-HiSCORE array in September 2019.





Examples of detected events by the SIT prototype

A future 10 square kilometer scale hybrid array for astroparticle physics, gamma-astronomy and cosmic ray physics

A site requirement:
- altitude – 2000 m about,
- no artificial light background,
- good astroclimat,
- enough vacant rather flat space,
- acceptable logistic condition,
- availability of electrical power

Tunka, Altay…..??????????

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TAIGA-HiSCORE - array.
A net of 1000 non imaging wide-angle detectors distributed on area 10 km^2 with spacing 100 m about
An EAS core position, direction and energy reconstruction.

TAIGA-IACT - array
of 12 - 16 IACT with mirrors – 4.3 m diameter.
Charged particles rejection using imaging technique.

TAIGA-Muon array
of scintillation detectors, including underground muon detectors with area - 2000 – 3000 m^2
Charged particles rejection

Summary and outlook

TAIGA aims at establishing a new, hybrid gamma-ray detection technology for >30 TeV

2020 year 1 km^2 TAIGA setup:

- **120 wide – angle Cherenkov detectors of TAIGA - HiSCORE "non-imaging" timing array**
- **3 Imaging Atmospheric Cherenkov Telescopes of TAIGA-IACT "imaging" array**
- **200 m^2 muon detectors of TAIGA-Muon and Tunka-Grande arrays.**

A point source sensitivity: **$2.5\ 10^{-13}$ TeV/cm^2 s (300 hours, 30–200 TeV)**

Commissioning seasons were successful

- **Stable operation, precision calibration in progress, E_{th}~30TeV**
- **CR energy spectrum 100 TeV – 1 EeV**
- **A signal from Crab in agreement with expectation.**
- **Joint operation of TAIGA-HiSCORE and IACT: data analyses is in progress**

Future plan. 10 square kilometers scale TAIGA

- **10 km^2 array with about 1000 Cherenkov detectors of TAIGA - HiSCORE "non-imaging" timing array**
- **12 – 16 Imaging Atmospheric Cherenkov Telescopes of TAIGA-IACT "imaging" array**
- **3000 m^2 muon detectors of TAIGA-Muon array.**

A point source sensitivity: **$2.5\ 10^{-14}$ TeV/cm^2 s (300 hours, 30–200 TeV)**

Thank you for attention!