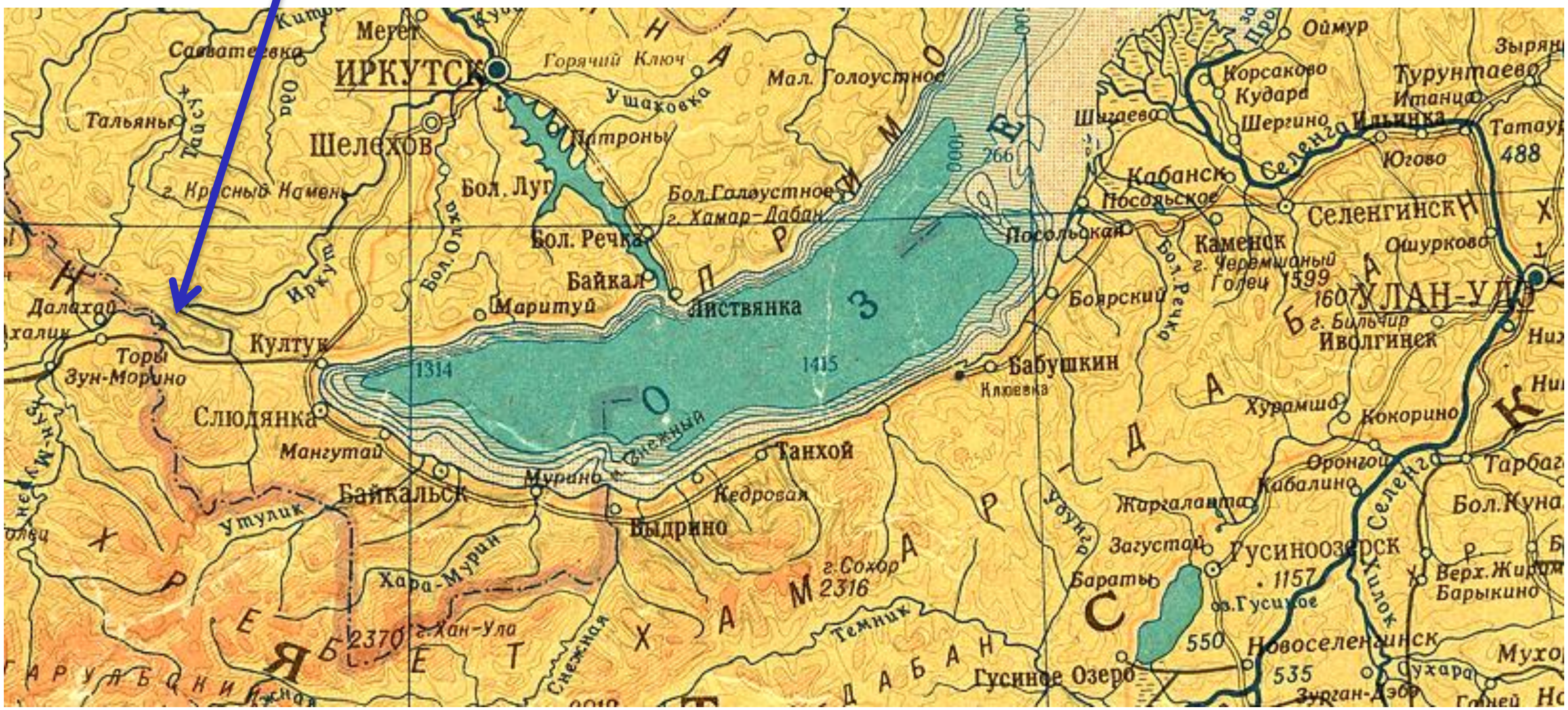
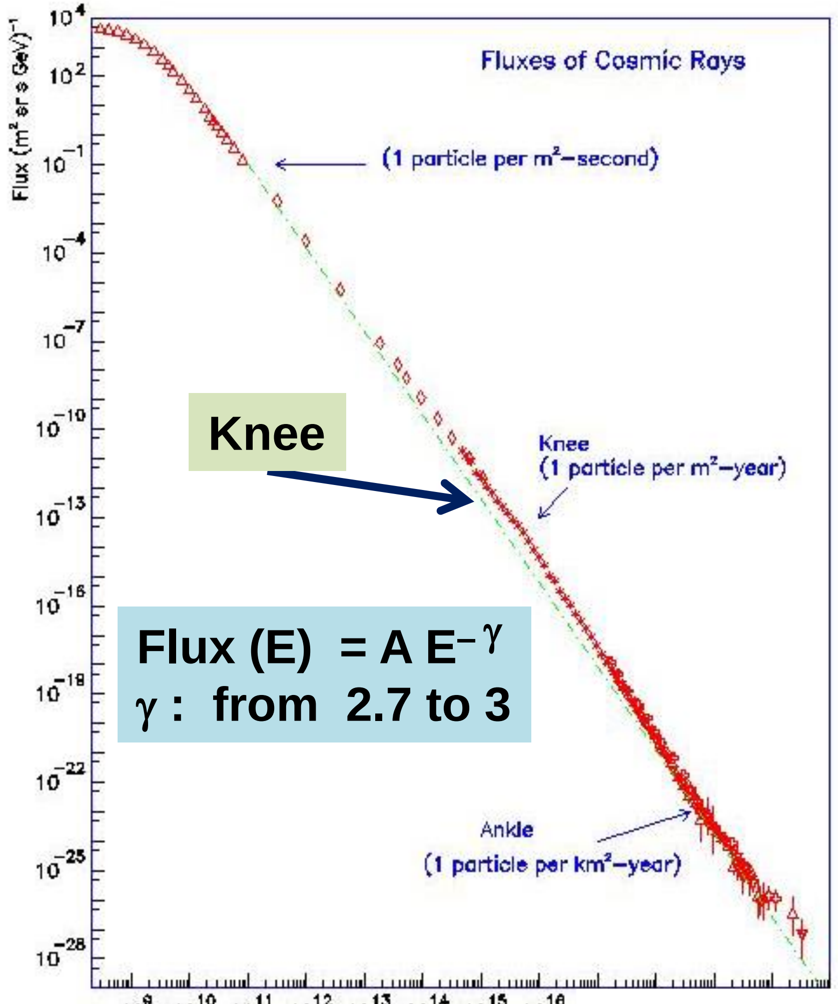
The TAIGA Gamma Observatory – a new window into the high-energy Universe.



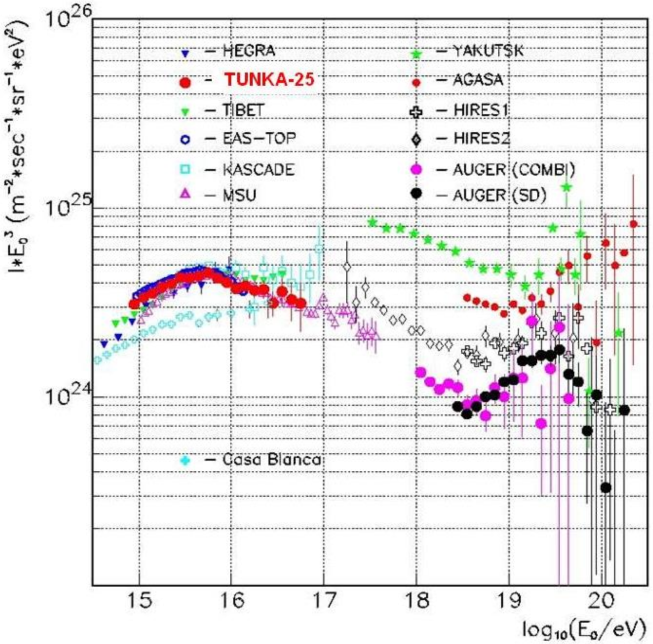
N. Budnev, L. Kuzmichev For TAIGA collaboration

112 years after discovery by Victor Hess "penetrating radiation" coming from space.

Flux **Energy spectrum**

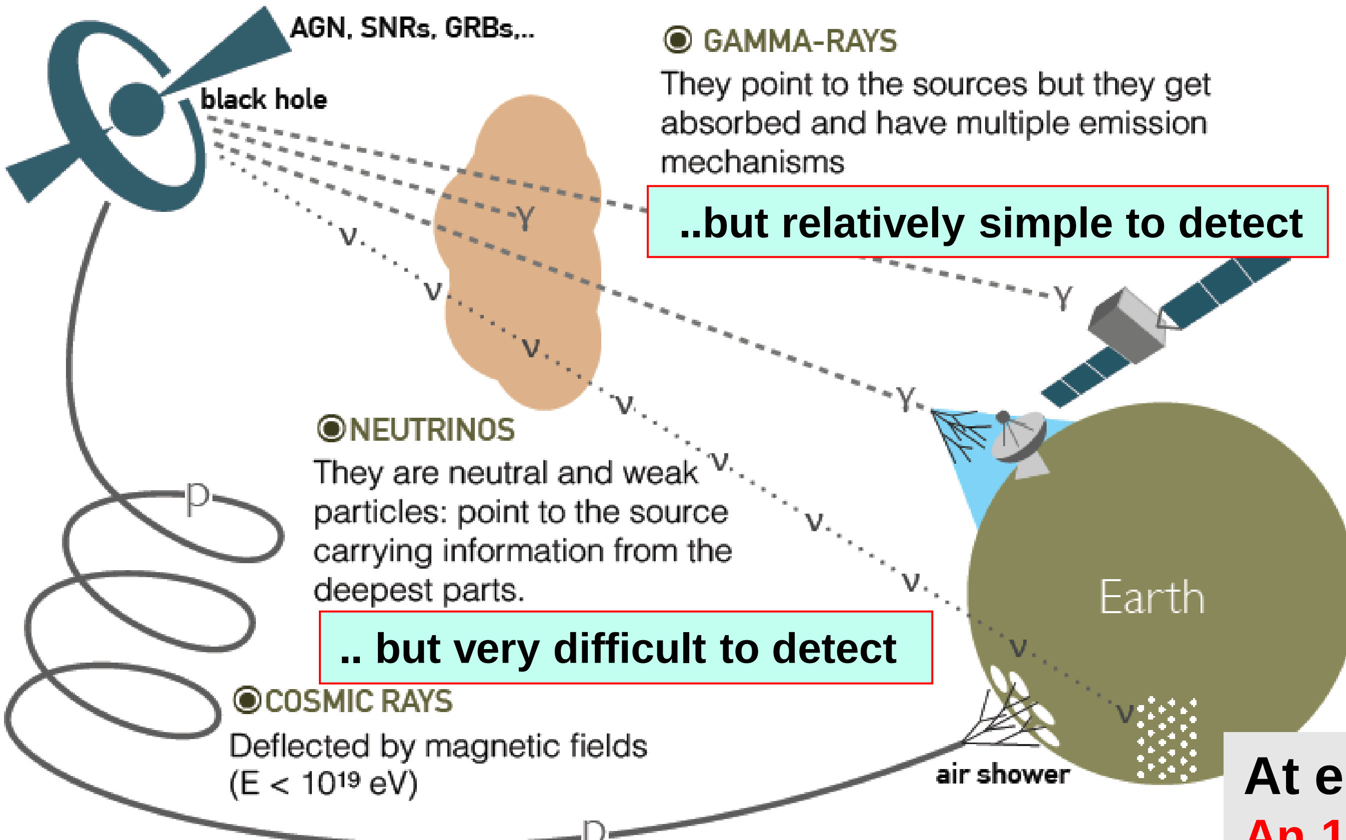


Energy, eV



Gamma-astronomy & neutrino astronomy

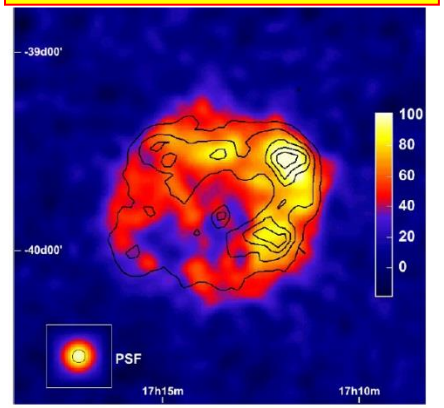
To understand a nature of an cosmic high energy accelerator one can detect gamma-rays or neutrinos.



..but relatively simple to detect

.. but very difficult to detect

RX J1713.7 – remnant of a super-nova

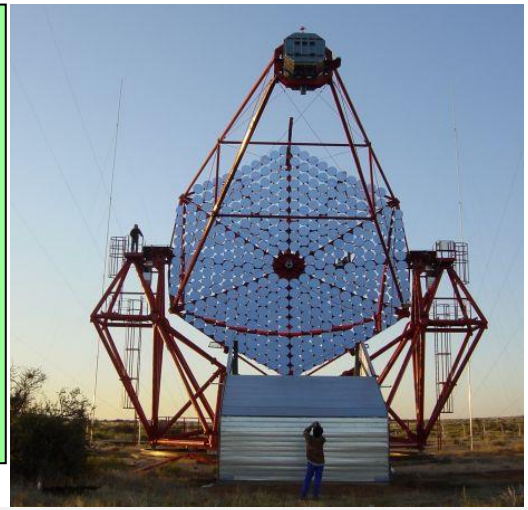


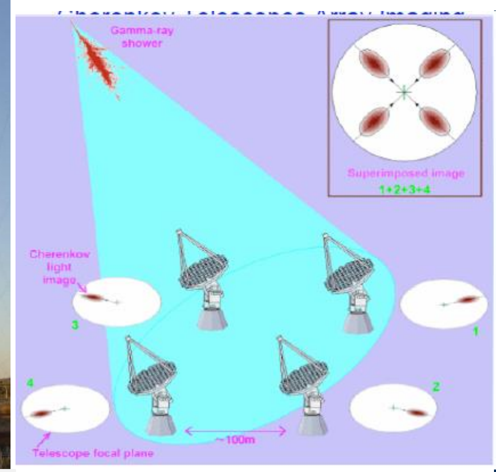
At energy > 30 TeV

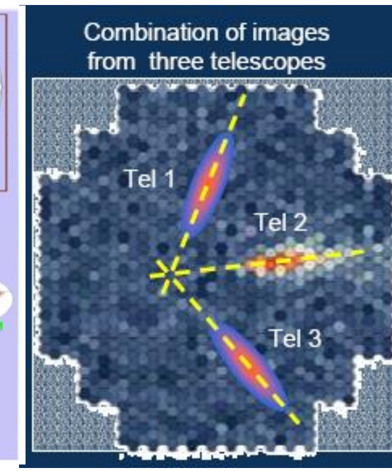
An 1км^3 neutrino detector
- 1 event / 1 year
An 1км^2 gamma detector
- 1 event / 20 minut!

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

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



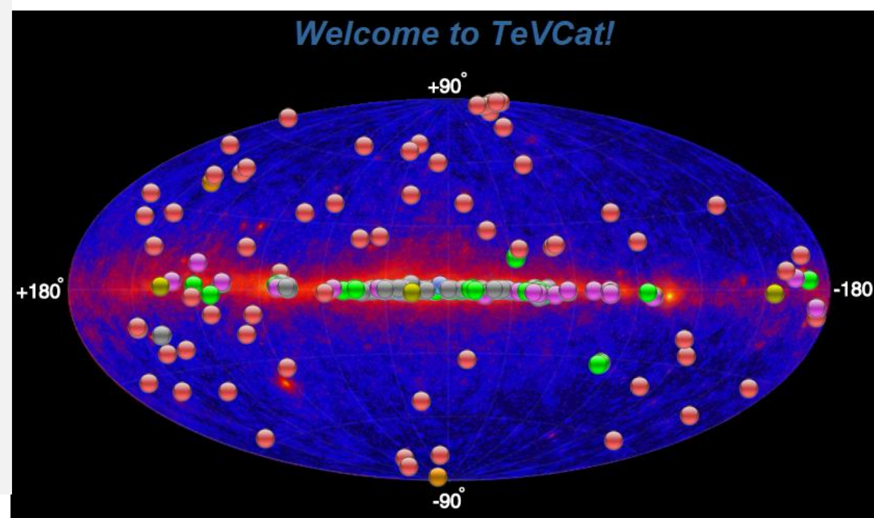




More than 200 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays. But only a few gamma quantum with energy more than 50 TeV were detected up to now with IACT.

For high-energy gamma-ray astronomy, the area of an array should be measured in square kilometers and even tens of square kilometers.

It is too much expensive with IACT!



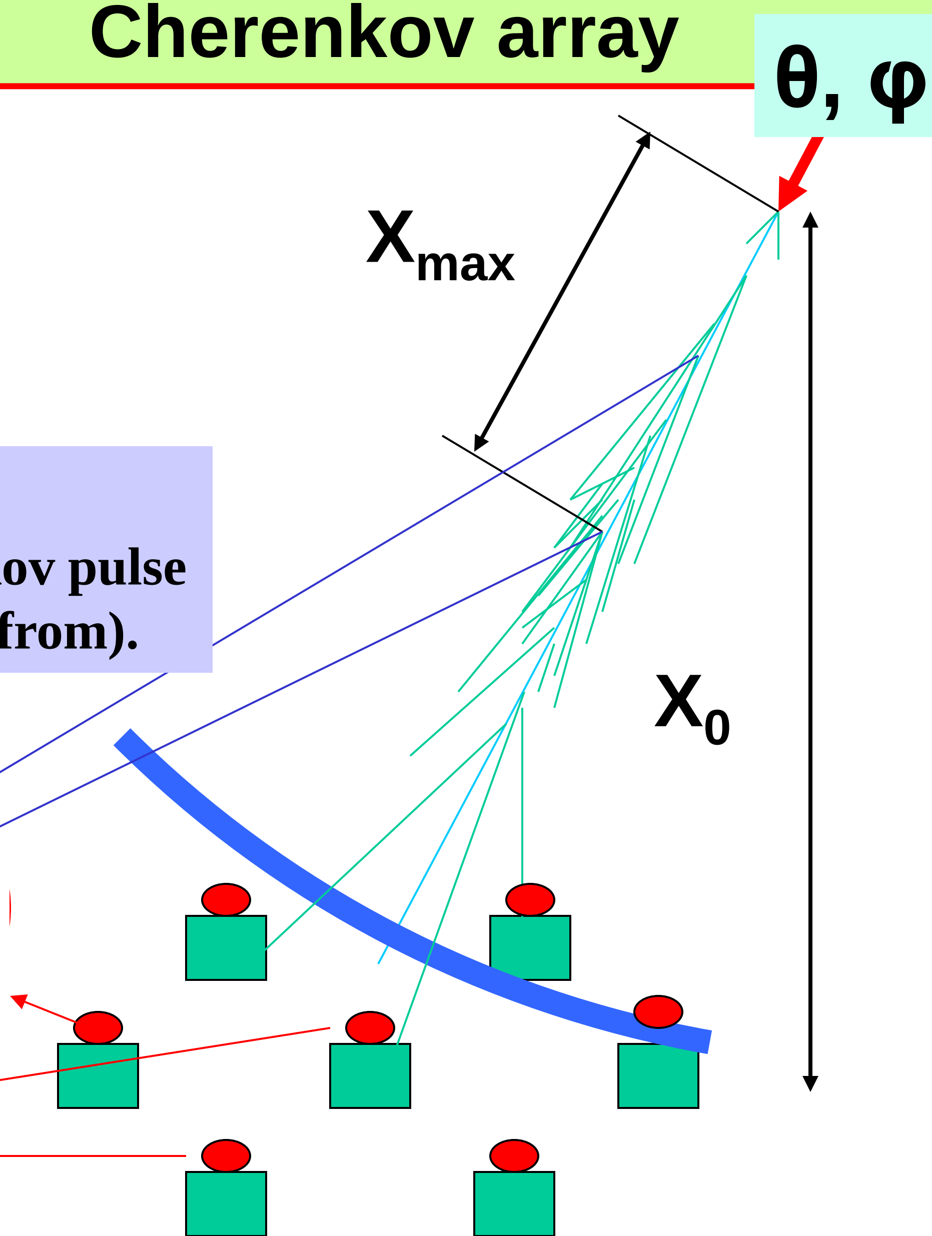
EAS Energy

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

$$g = 0.94 \pm 0.01$$

at energy E = 1 – 1000 PeV

EAS Cherenkov light detection with wide-field-of-view timing Cherenkov array

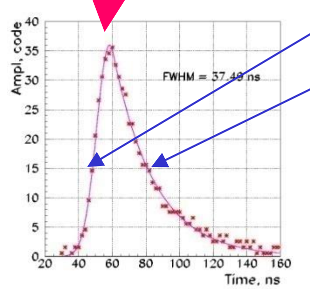


Average CR mass A

$$\ln A \sim X_{max}$$

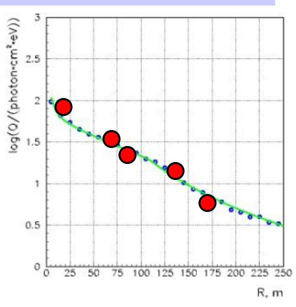
$$X_{max} = C - D \cdot \lg \tau(400)$$

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



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

P -Steepness of a Lateral Distribution Function (LDF)



Wide-field-of-view timing Cherenkov arrays in the Tunka valley

1992 – 4 photodetectors with Quasar-370 on ice of 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

2000 – 2005 - Tunka-25 array - precise CR spectrum in energy range 0,8 – 100 PeV

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…..

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

Tunka Collaboration

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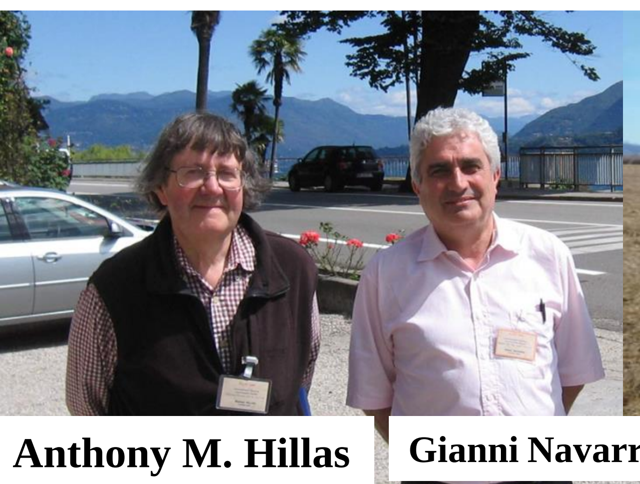


Anthony M. Hillas   Gianni Navarra

Inauguration of the Tunka-133 Array (September, 2009y)

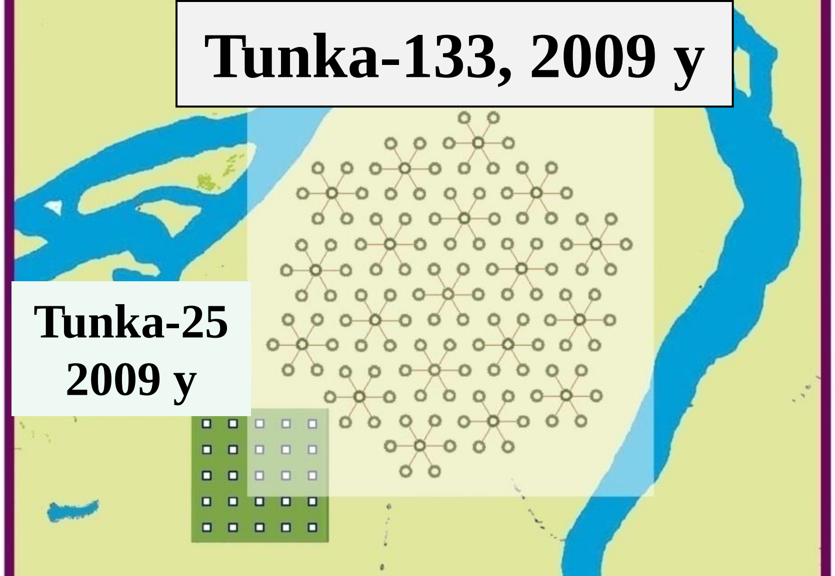
Tunka-133 – the largest wide-angle Cherenkov EAS array, 3 km^2 area

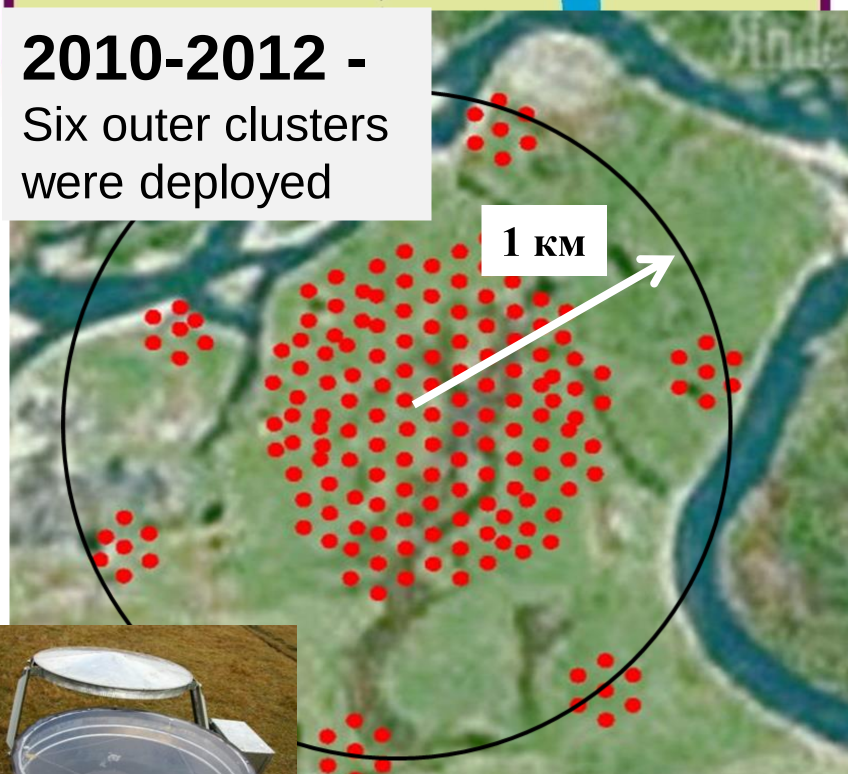
- Accuracy positioning of EAS core 5 -10 m
- Energy resolution ~ 10 - 15%
- Accuracy for Xmax ~ 20 -25 g/cm^2.
- 3. Good angular resolution (~ 0.5 degree)
- 4. Low cost: the Tunka-133 array ~ 10^6 Euro

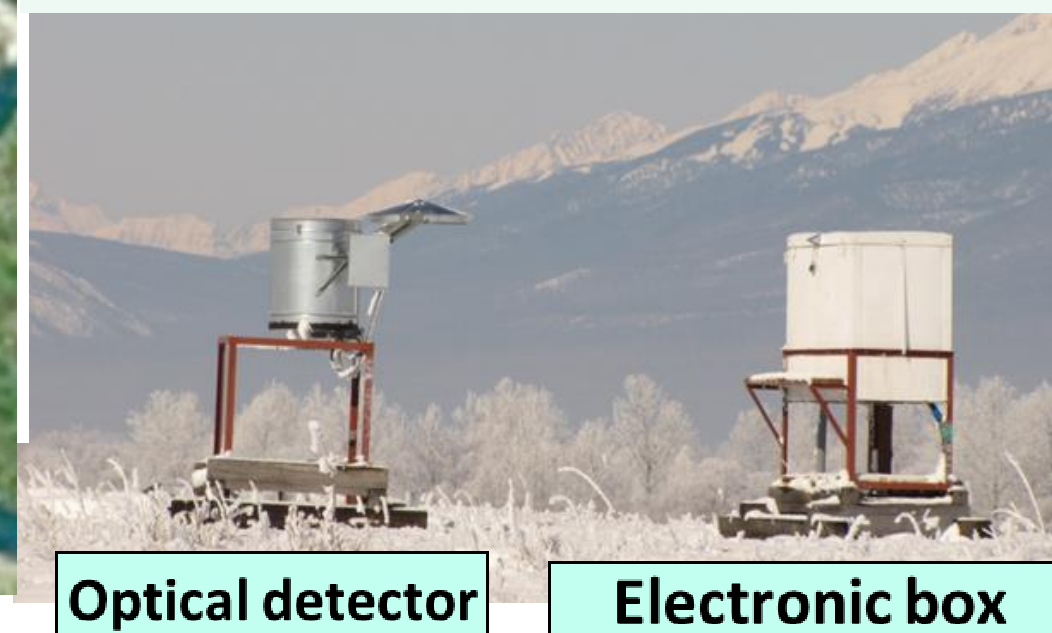
Statistics for one year of operation (400 hours):

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

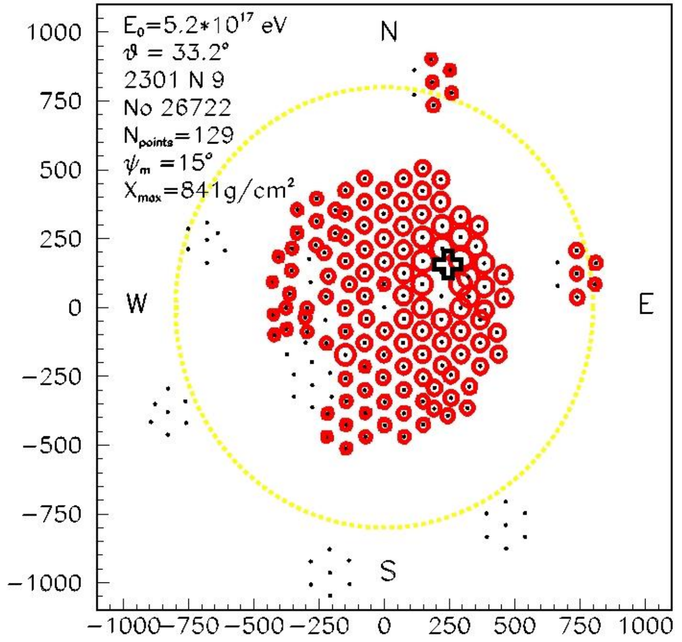
Energy threshold 10^{15} eV







An event example



Hitted detectors

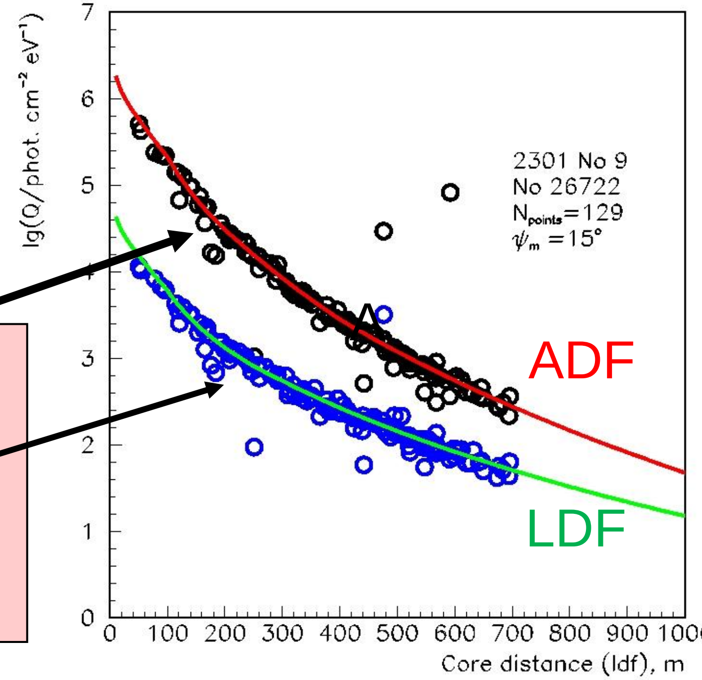
ADF

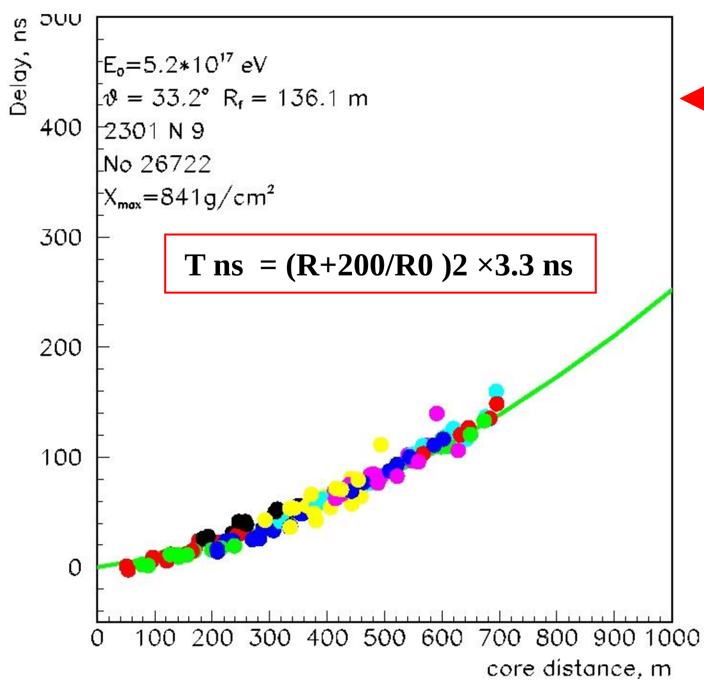
Amplitude distant function

&

LDF

Lateral Distribution function

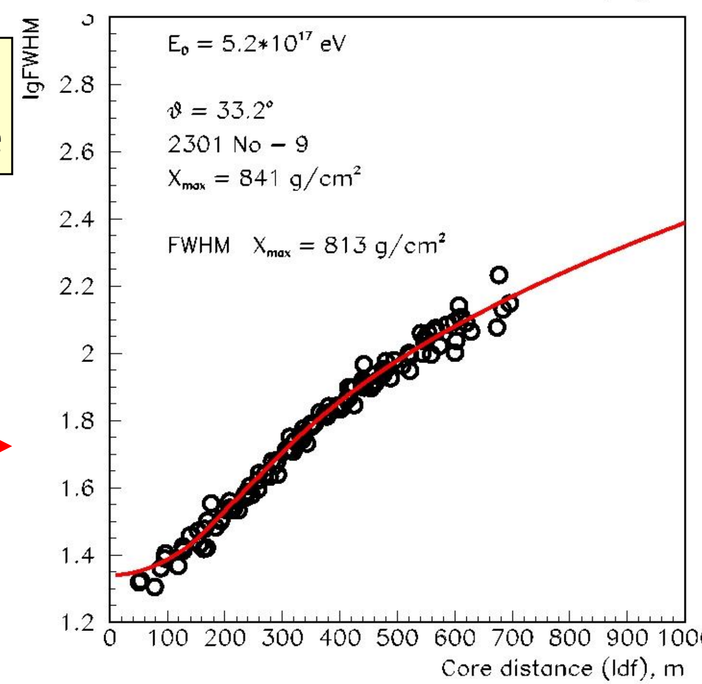




T ns = (R+200/R0)2 ×3.3 ns

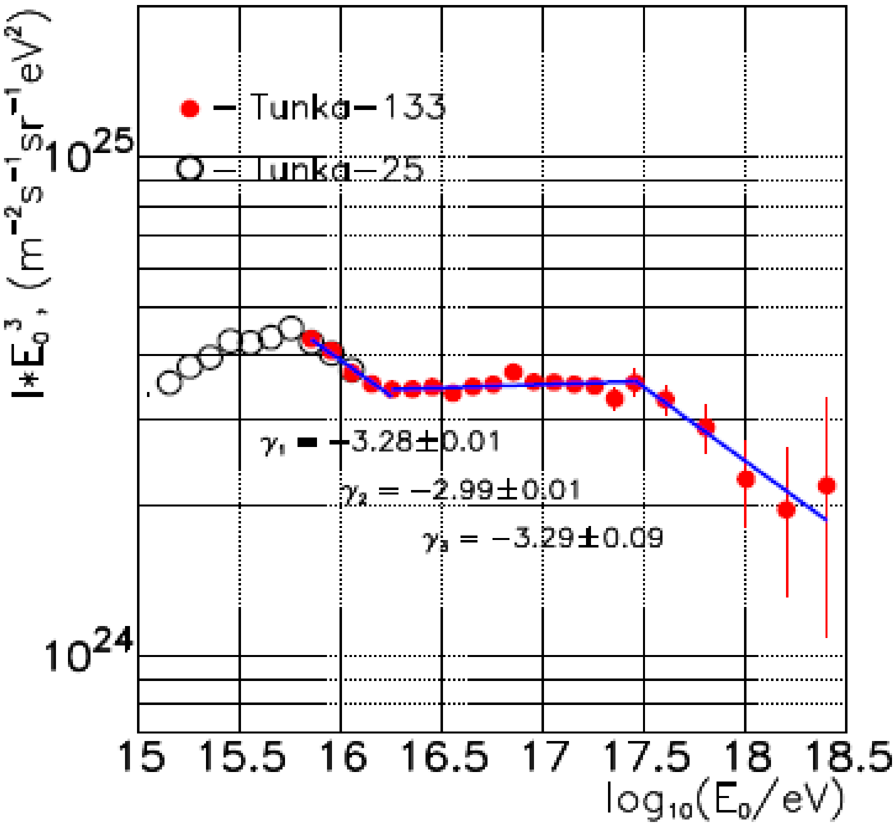
Delay time vs. Distance from core

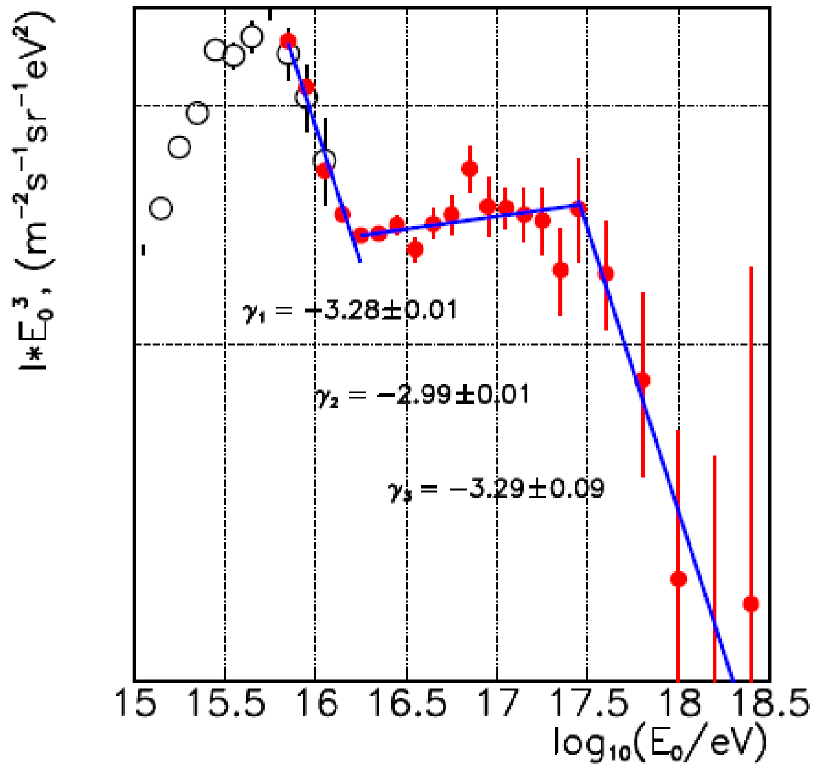
WDF – width distant function



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, ΔƔ ~ 0.2-0.3
Difference in intensity ~30% , due to difference in energy calibration ~10% ?
The second knee 100 -300 TeV, ΔƔ ~ 0.3

TAIGA – Collaboration

since 2013y

- 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

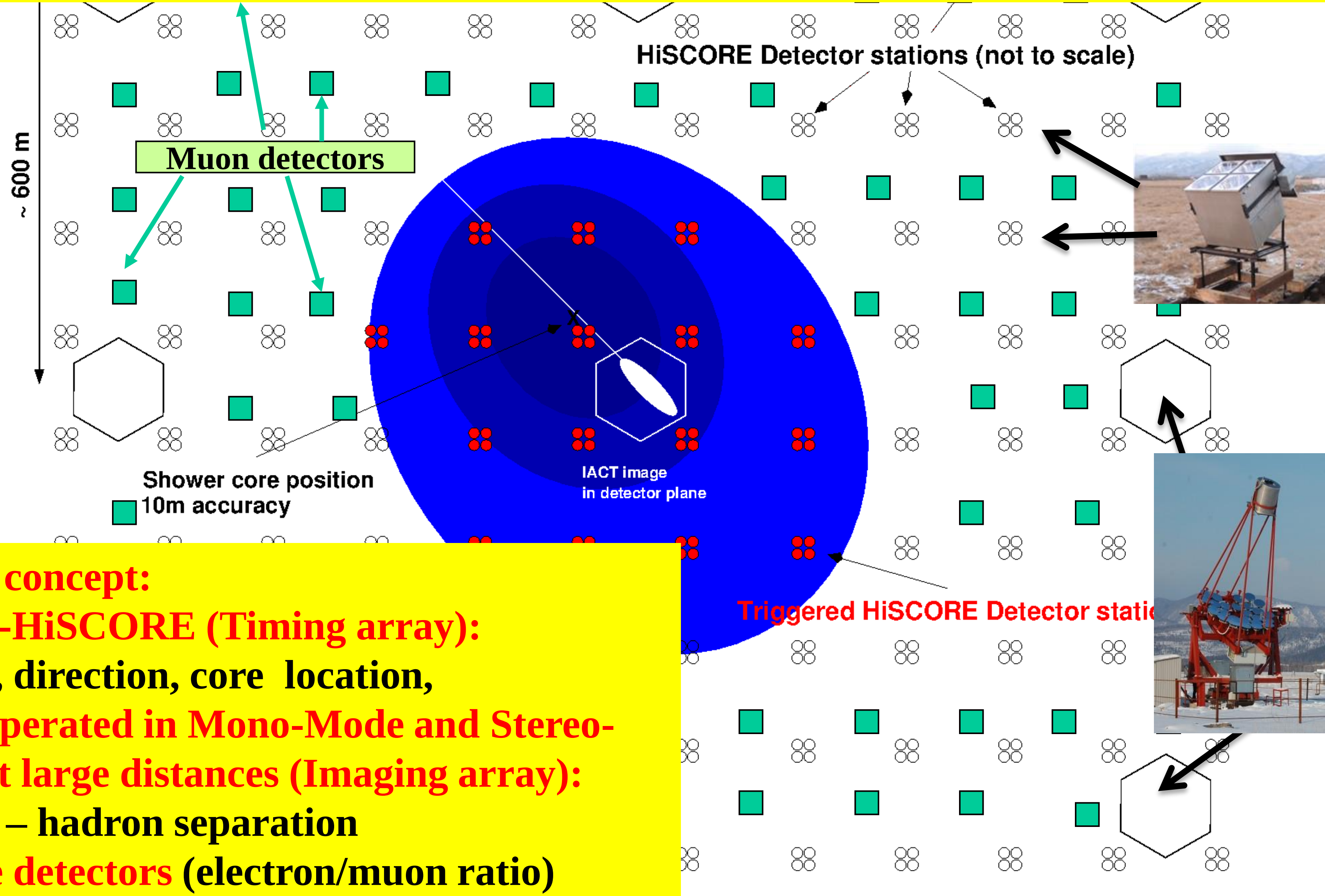
- Deutsches Elektronen Synchrotron (DESY), Zeuthen, Germany
- Institut fur Experimentalphysik, University of Hamburg (UH), Germany
- Max-Planck-Institut für Physik (MPI), Munich, Germany
- Fisica Generale Universita di Torino and INFN, Torino, Italy

The TAIGA (Tunka Advanced Instrument for Gamma Astronomy and cosmic ray physics)

The main goal: **to find a cost-effective way to create a large-scale installation for high-energy gamma-ray astronomy by combining wide-angle Cherenkov detectors with several relatively cheap small-sized Imaging Atmospheric Cherenkov Telescopes.**

TAIGA – from CR physics to gamma astronomy

Imaging + non-imaging techniques



Hybrid concept:

TAIGA-HiSCORE (Timing array):

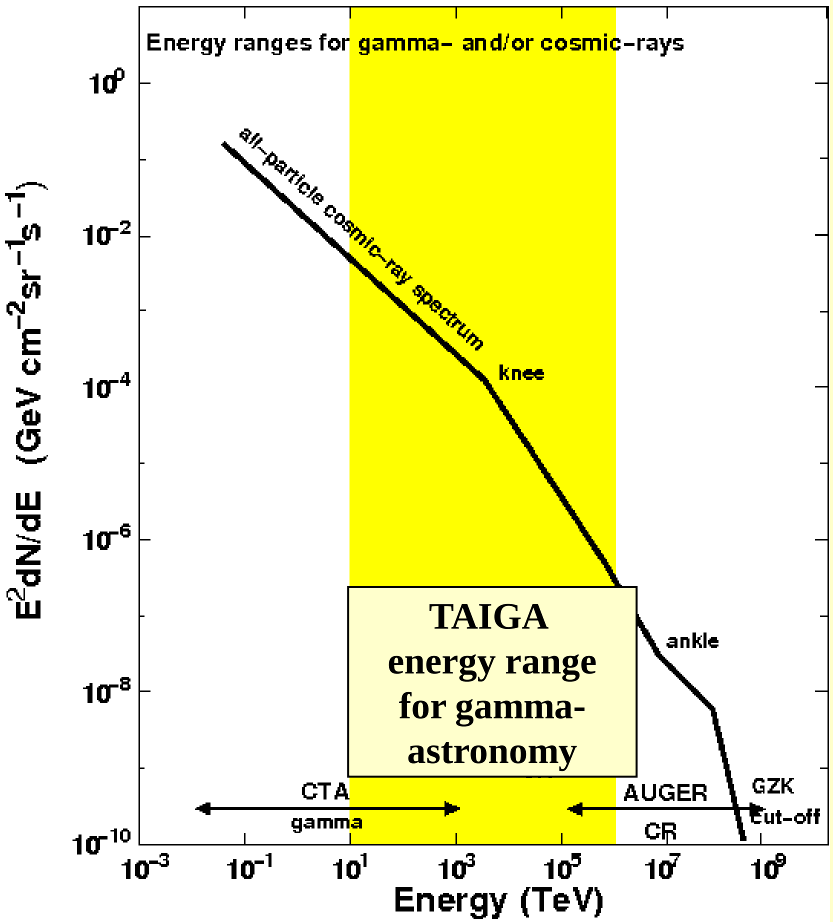
energy, direction, core location,

IACT operated in Mono-Mode and Stereo-Mode at large distances (Imaging array):

gamma – hadron separation

Particle detectors (electron/muon ratio)

Main Topics for the TAIGA observatory



1. Study of energy spectrum of gamma-rays from galactic sources: Crab Nebula. J2227+610 (G106.3+2.7), Dragonfly Nebula (J2019+367), J2031+4157 (Cygnus Cocoon), Tycho and search for new sources.

2. Long-term monitoring and study of the bright blazars energy spectrum: 1ES 0229+200, 1ES 1959+650, Mrk 501, Mrk 421, Arp 220, M82.

3. Search for an excess of diffuse gamma rays with energies above 100 TeV.

4. Search for gamma quanta from close GRBs and associated with IceCube and Baikal-GVD neutrinos.

5. Search for Astrophysical Nanosecond Optical Transients with TAIGA-HiSCORE Array.

6. Study of the CR energy spectrum and mass composition in energy range 100 TeV- 1000 PeV.

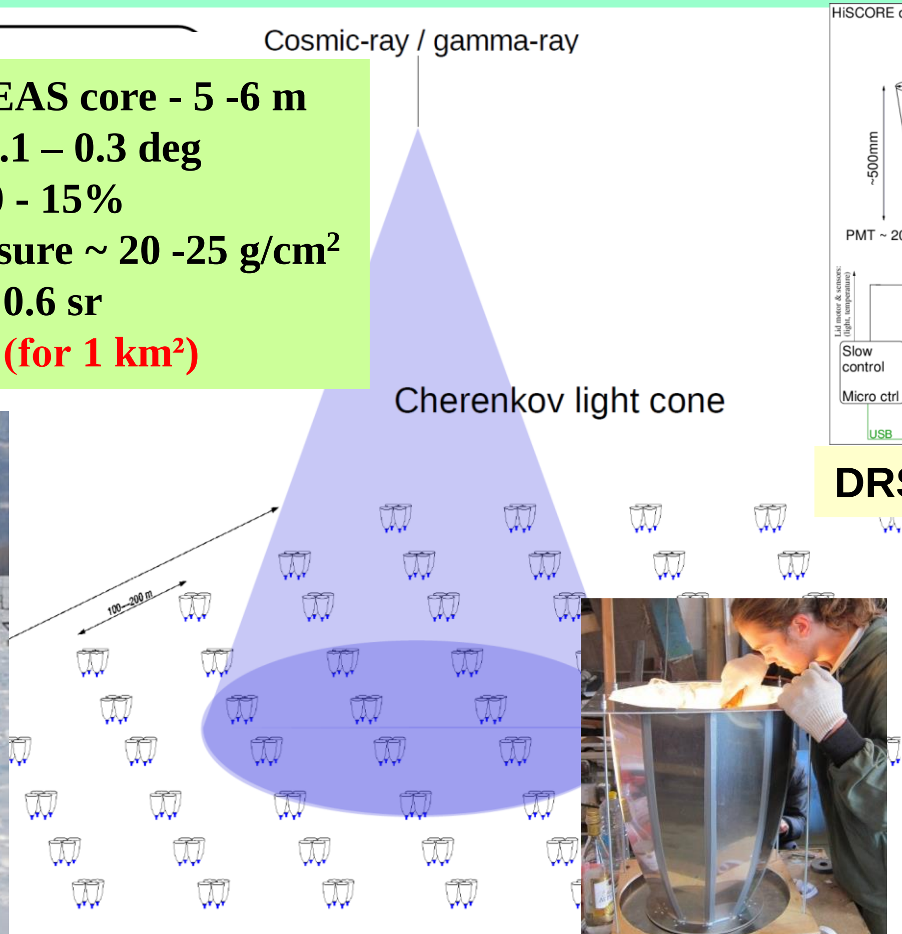
7. Fundamental physics (University transparency and photon-axion oscillation, indications of Lorentz invariance violation, evidence of Dark matter, etc).

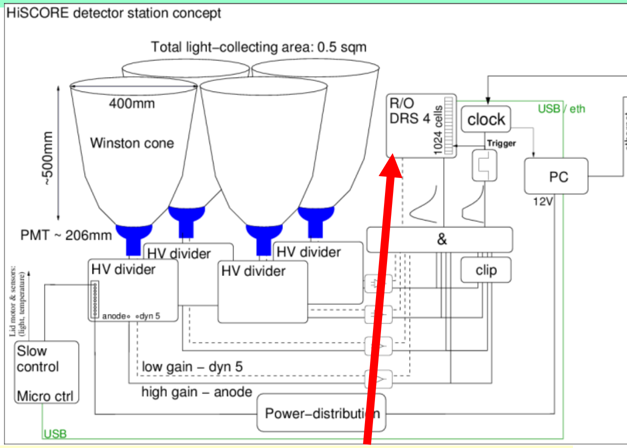
TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

Consist of 120 Cherenkov stations distributed on 1,1 km^2 area with spacing 106 m. Each station includes four 8 inch PMTs equipped with a segmented Winston cone. The resulting total light collection area of a station is 0.5 m^2. **Threshold for CR- 100TeV, for γ- 50TeV**

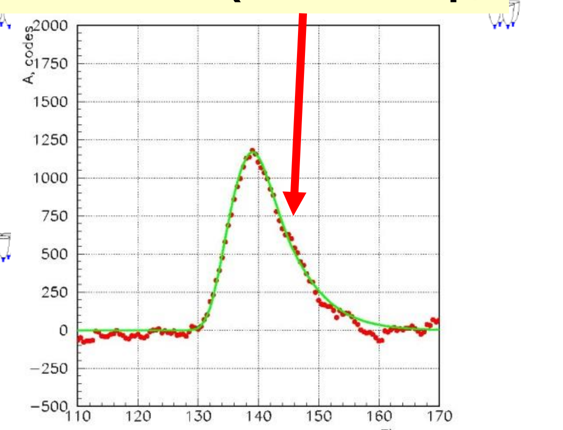
1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.3 deg
3. Energy resolution ~ 10 - 15%
4. Accuracy of X_{max} measure ~ 20 -25 g/cm^2
5. Large Field of view: ~ 0.6 sr

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

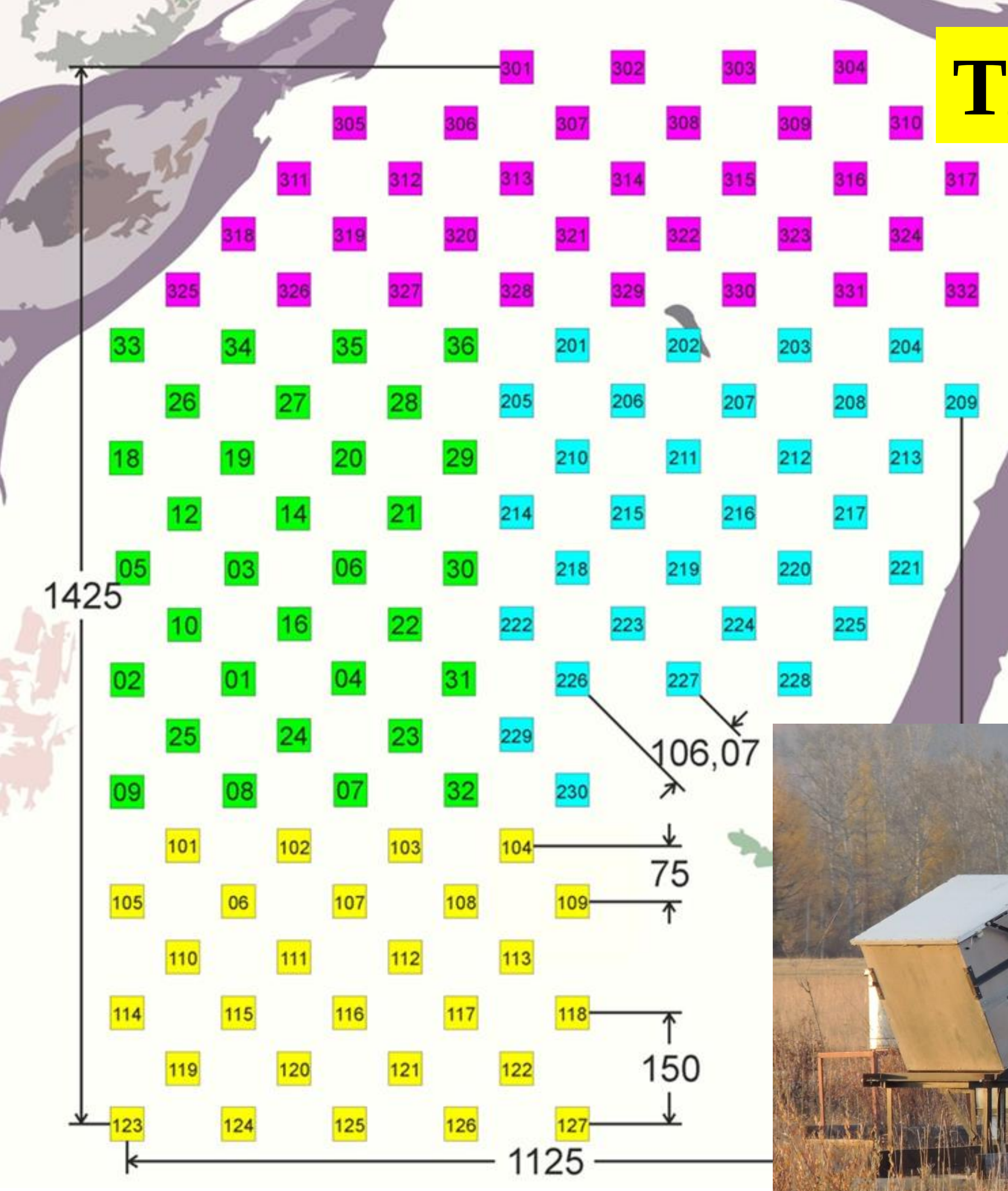




DRS-4 board (0.5 ns step)

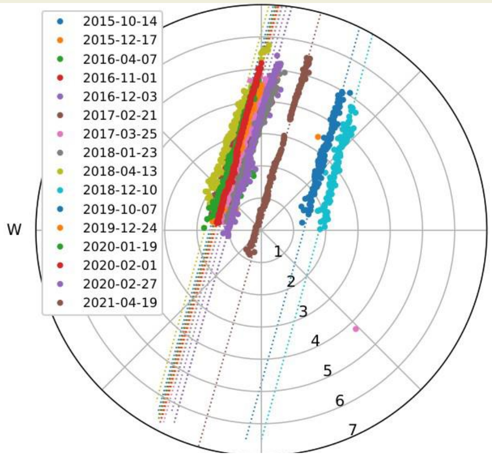


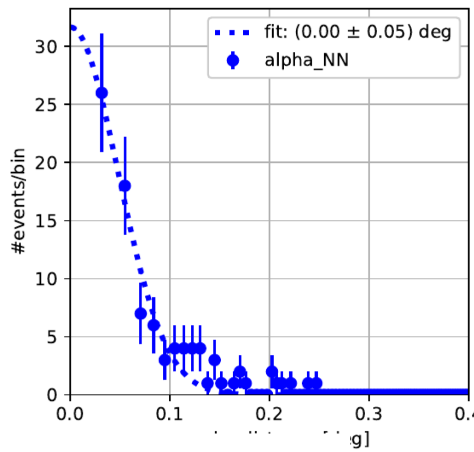
TAIGA-HiSCORE

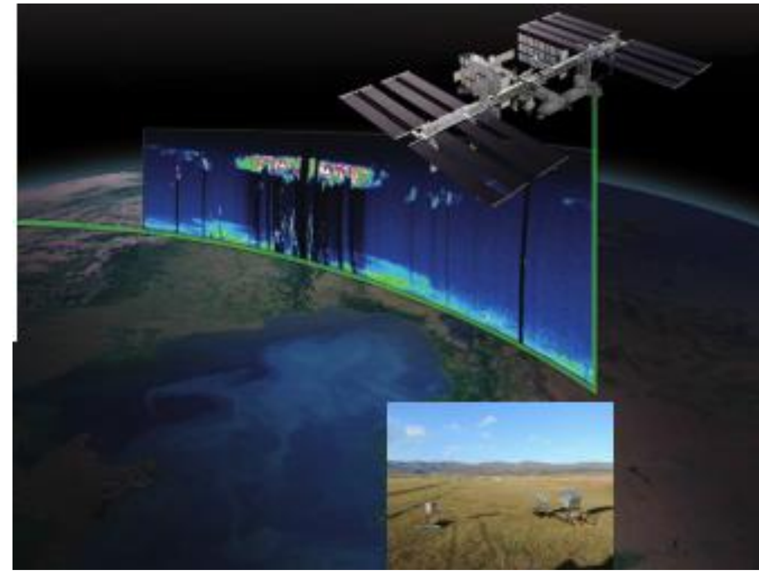


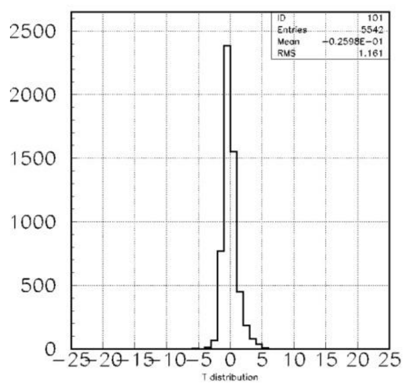
An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE

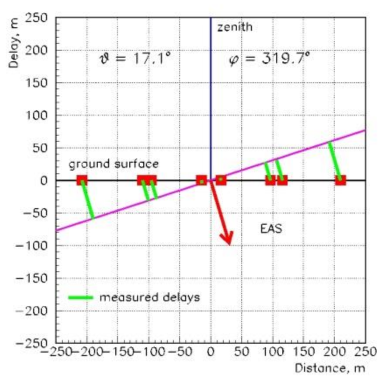
16 CALIPSO passages detected by TAIGA-HiSCORE









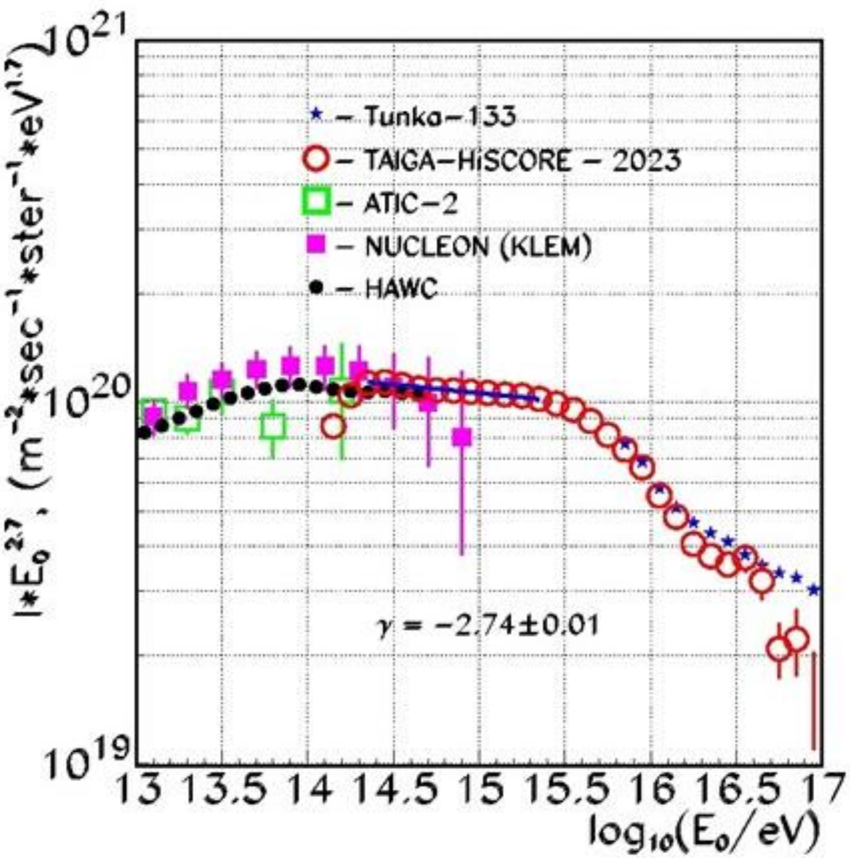


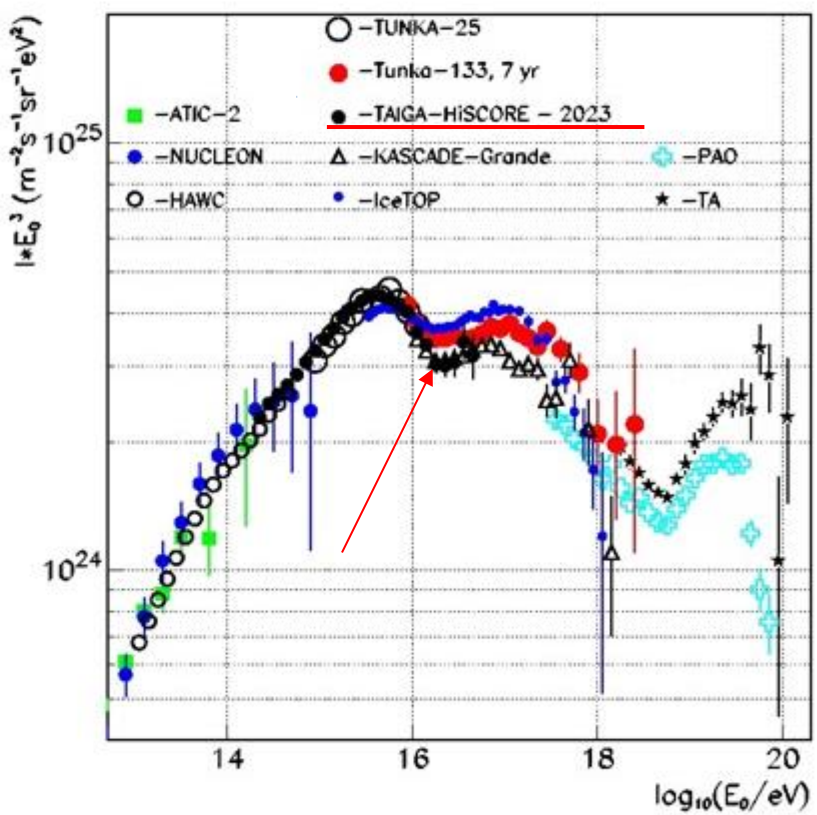
Lidar on-board ISS, Calipso and other satellites - excellent instrument for TAIGA- HiSCORE time calibration

– flat timing profile

- precision pointing

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

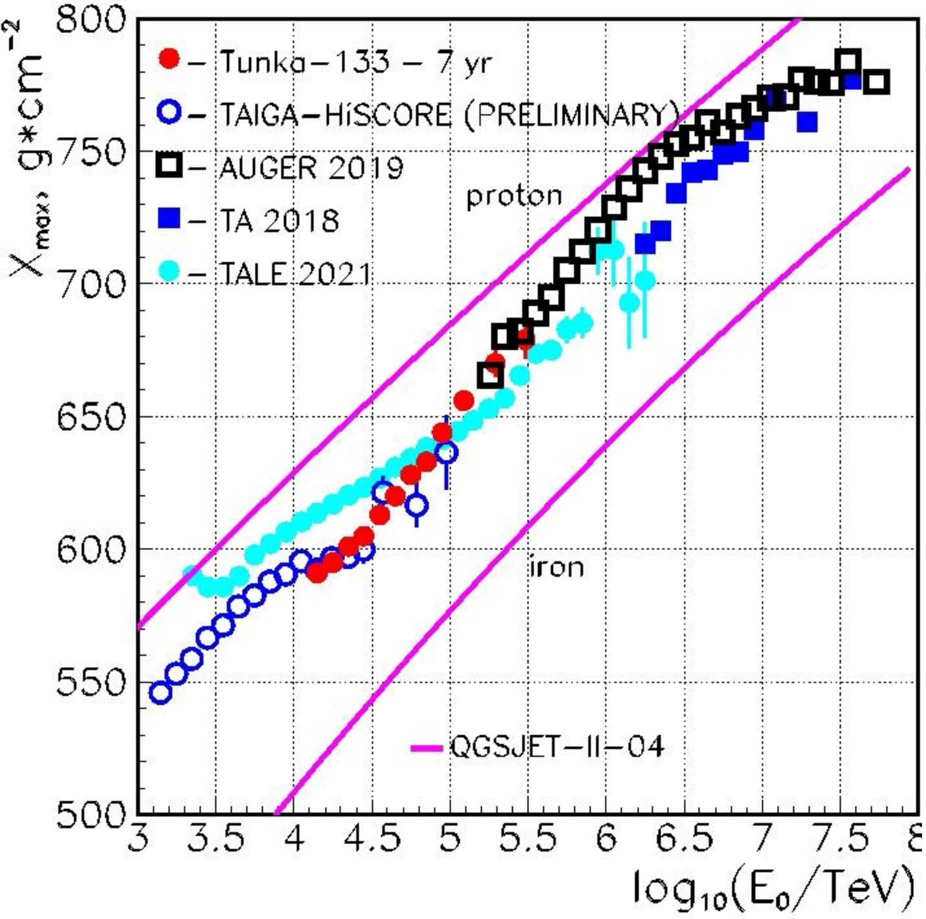




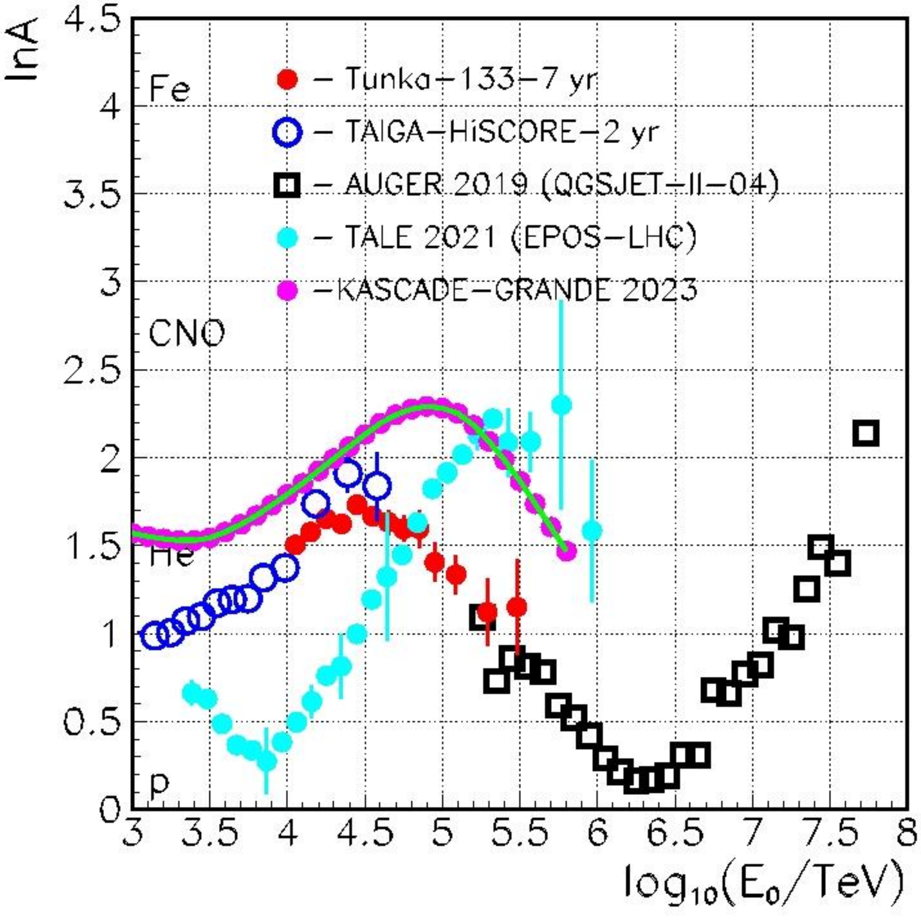
TAIGA-HiSCORE energy spectrum

Comparison of the Tunka-25 &Tunka-133 & TAIGA-HiSCORE energy spectra with other experimental data

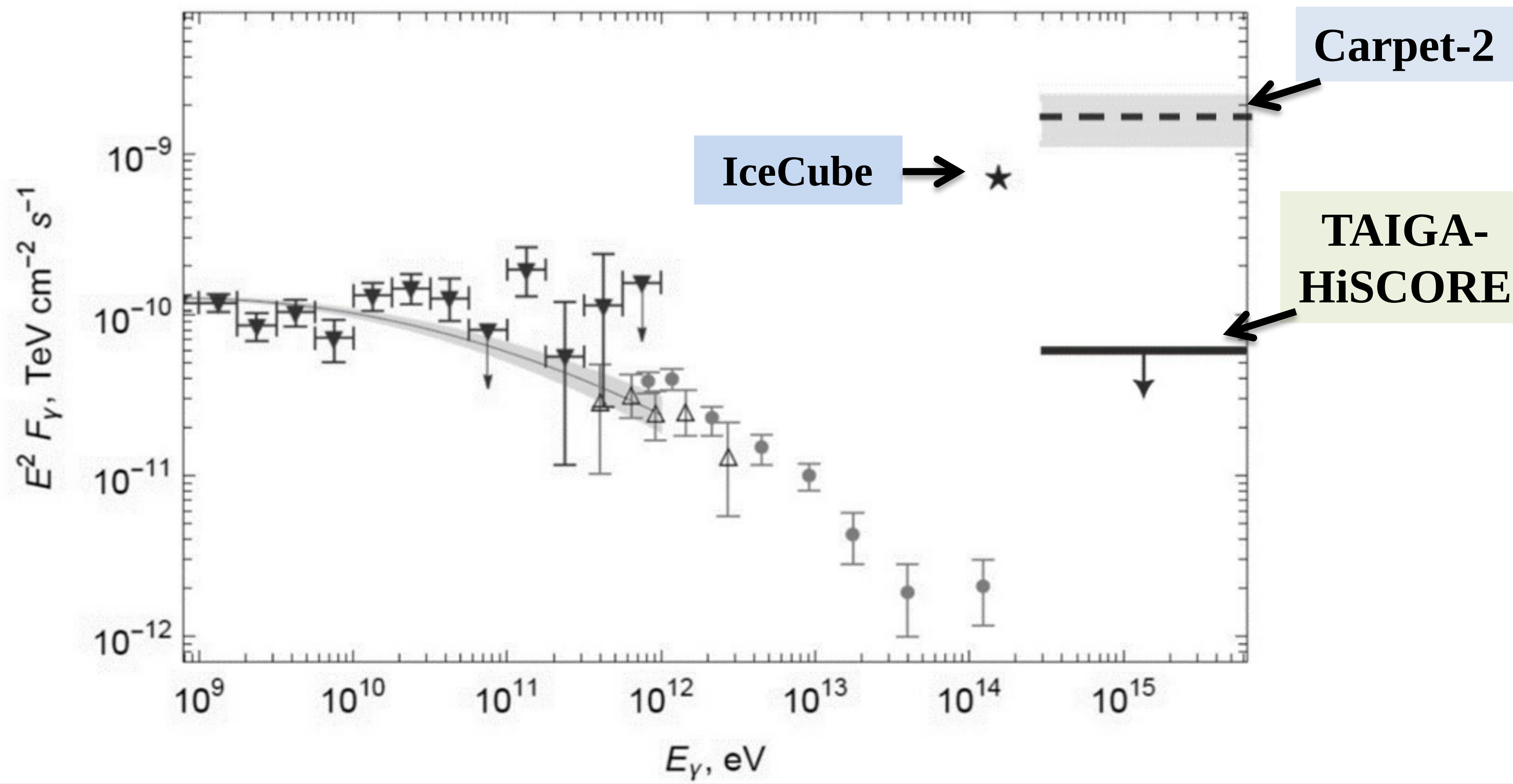
Mean Depth of EAS maximum X_{max} (g·cm^{-2})



Mean logarithm of primary mass.



Search for gamma rays with an energy of > 200 TeV (excess of the events number) in the direction of Cygnus Cocoon 13.10.2020 – 11.17.2020



The energy spectrum of Cygnus Cocoon gamma radiation. Gray line: time–averaged flow model 4 FGL; gray triangles-ARGO experiment data; gray circles – data obtained in the HAWC experiment; black triangles–flash detected by Fermi-LAT

Expected signatures of astrophysical optical transients:

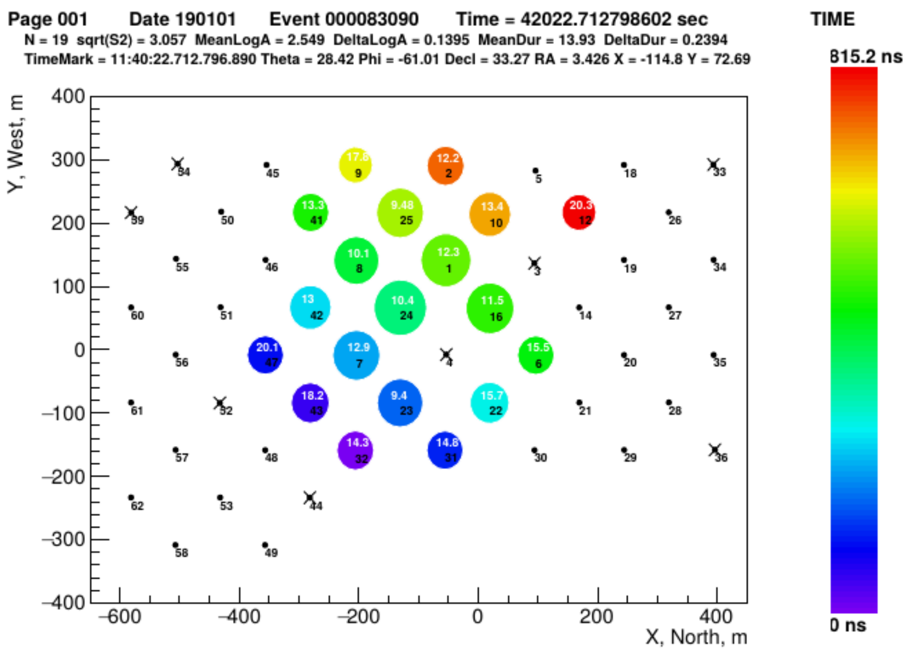
1. Small amplitude spreading among the triggered optical stations in an event

2. Good fit of optical stations response times by an exactly plane optical front

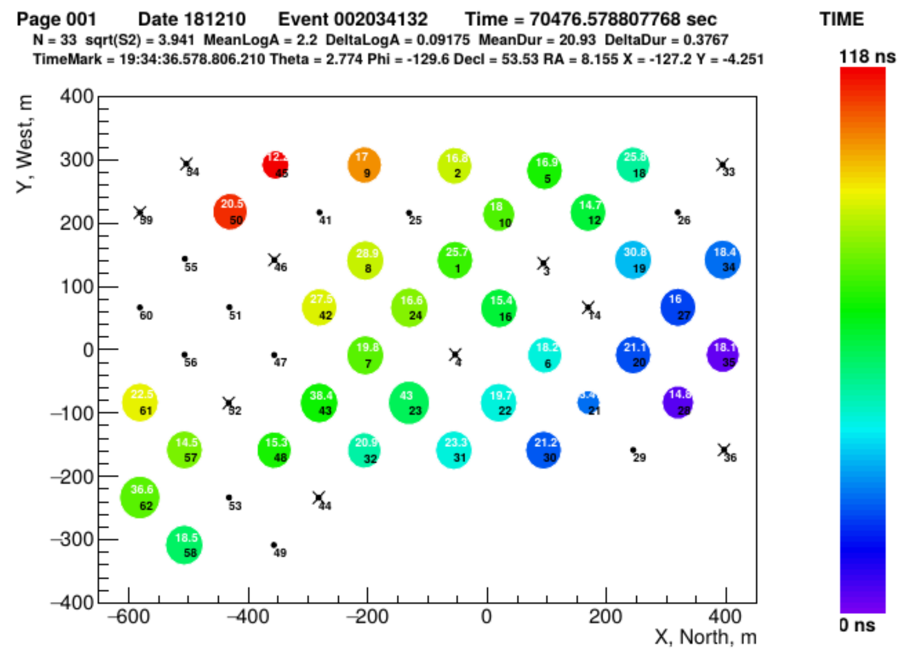
3. Uniform distribution of positions of flashed optical stations upon the surface of the TAIGA-HiSCORE array (no spot-like distribution like for EAS)

TAIGA-HiSCORE response to Cherenkov light from an EAS and to the flash of a remote point optical source

EAS



Distant point source (CALIPSO event)



The structure of satellite events compared to EAS events confirms the method to select events from distant optical point-like sources

The first results

No optical short transients were found.

**An approximate upper limit on the rate of events is:
for events with a flux density of photons greater than
10^{-4} erg/s/cm^2 and with a duration greater than ~5 ns,
the flux is less than ~2×10^{-3} events/sr/hour (preliminary)**

The TAIGA – IACT

The TAIGA - IACT

First 2017y, second 2019y, third 2022y,

situated at the vertices of a triangle

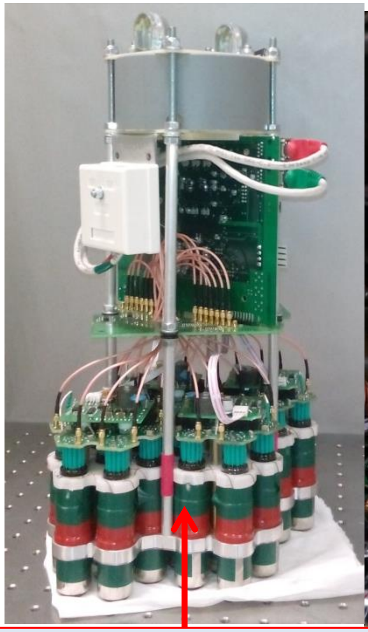
with sides:

300 m, 400 m and 500 m about.

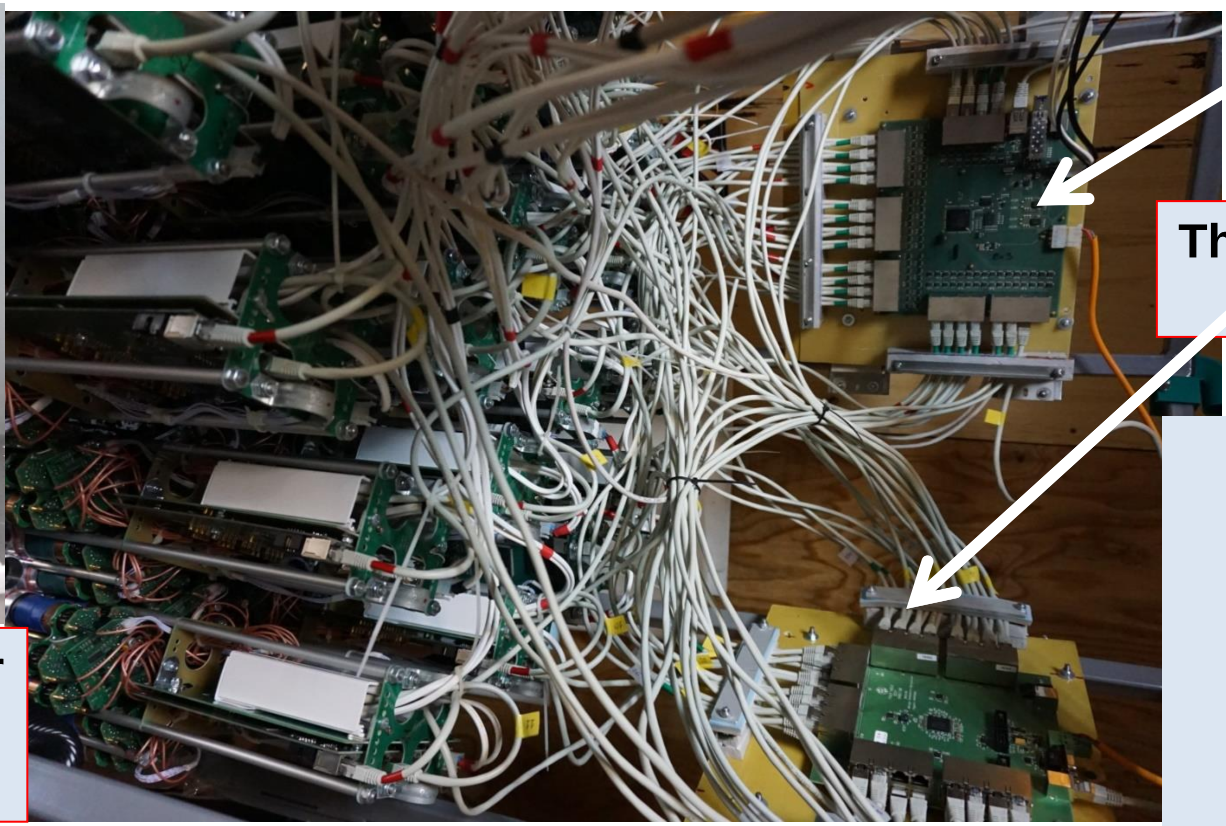
- **34-segment reflectors (Davis-Cotton)**
- **Diameter 4.3 m, area ~10 m^2**
- **Focal length 4.75 m**
- **Threshold energy ~ 2 - 3 TeV**
- **Camera - 595 PMT, 9.6^o FoW**

.

The Camera of the TAIGA-IACT



28 PMTs cluster on the base of MAROC-3



Central Controller Board

The Fast_Hold Boards

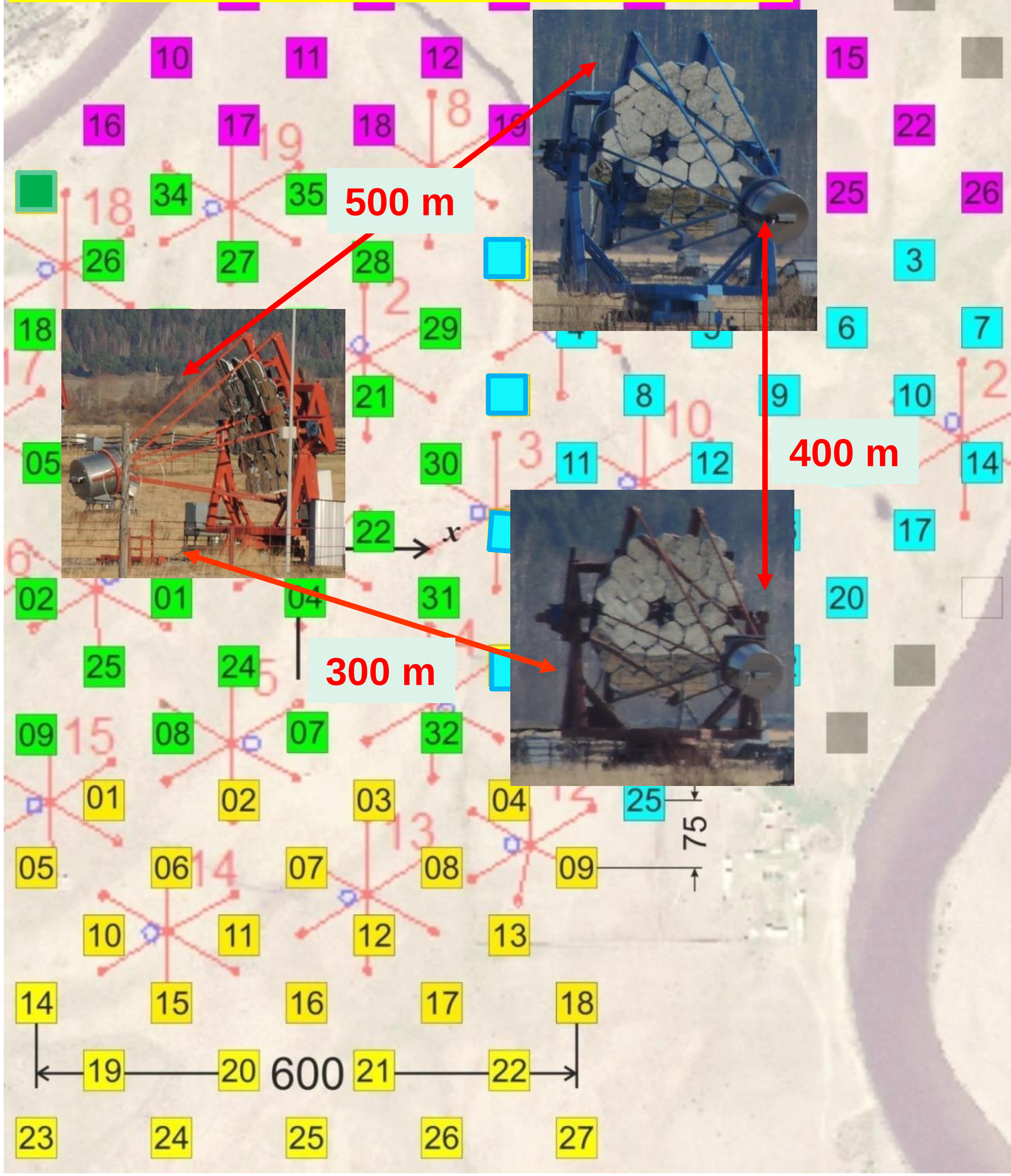
Hold on all clusters. It make possible to read out amplitudes from all pixels of camera

595 PMTs (XP 1911) with

- 15 mm useful diameter of photocathode
- Winston cone: 30mm input size
- each pixel = 0.36 deg
- FOV 9,6 x 9,6 deg

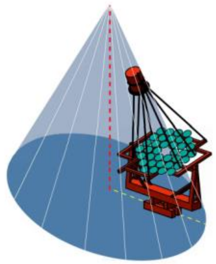

TAIGA-IACT-1
TAIGA-IACT-2
TAIGA-IACT-3
TAIGA-IACT-4
TAIGA-IACT-5

TAIGA-1, 2024year

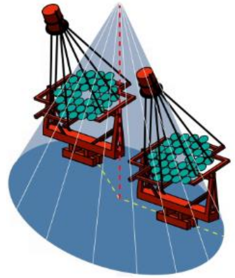


Four approaches for detecting of gamma rays in the TAIGA experiment by Cherenkov detectors

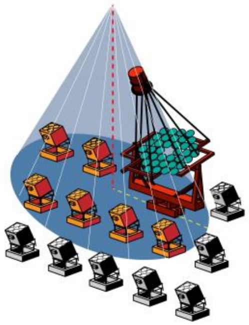
1. **Standalone mode of IACTs operation (E> 2-3 TeV).**
   Hadronic background rejection ~10 $^{-4}$



2. **Stereoscopic mode for large distances between the IACTs (E > 8 TeV). Hadronic background rejection ~5 10^{-5}**



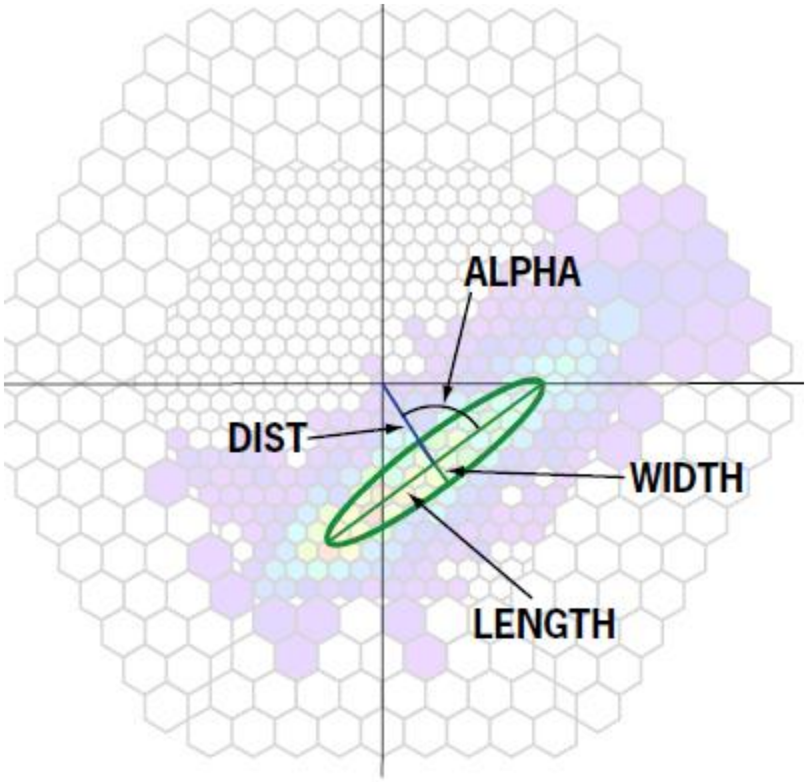
3. **Hybrid mode - joint operation of the TAIGA-HiSCORE and some IACTs (E > 40 TeV). Hadronic background rejection ~10^{-4}**



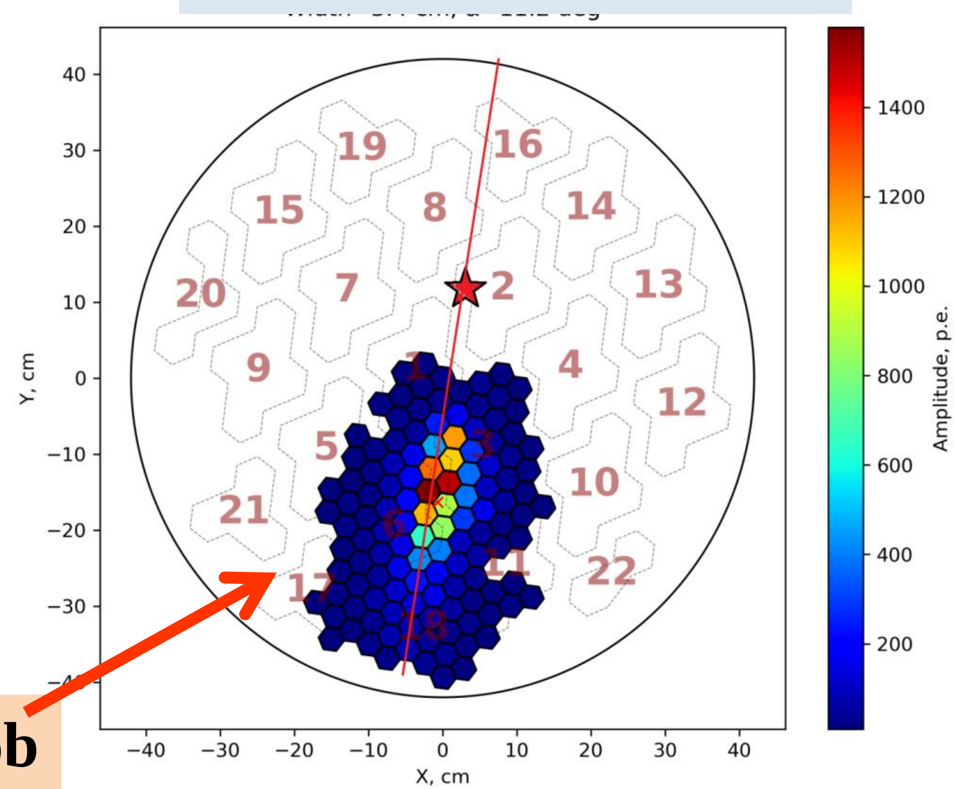
4. **TAIGA- HiSCORE > 300 TeV (probably an additional hadron suppression is required)**

TAIGA-IACT and TAIGA-HiSCORE joint events.

Hillas parameters

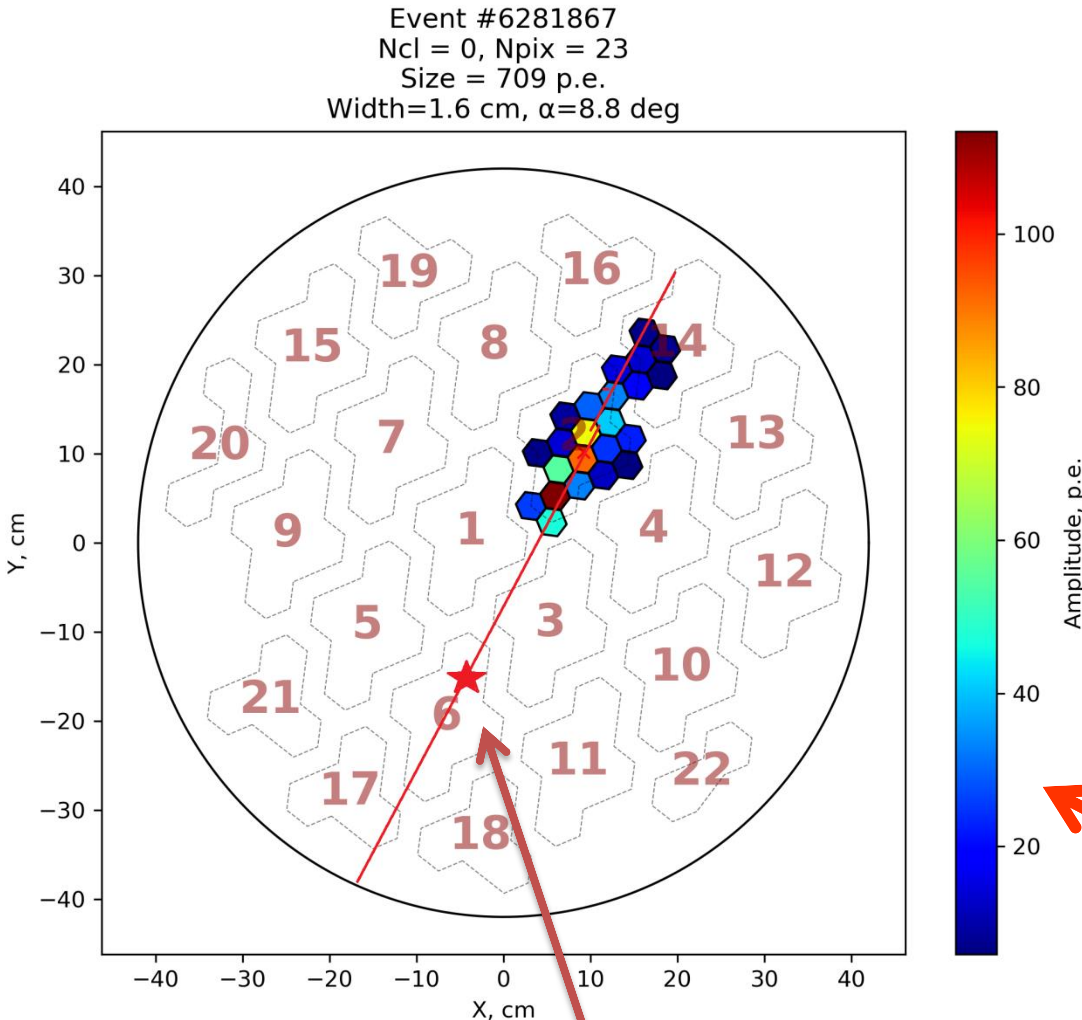


Most of events are "Hadron-like"
E = 880 TeV
width = 0.4°

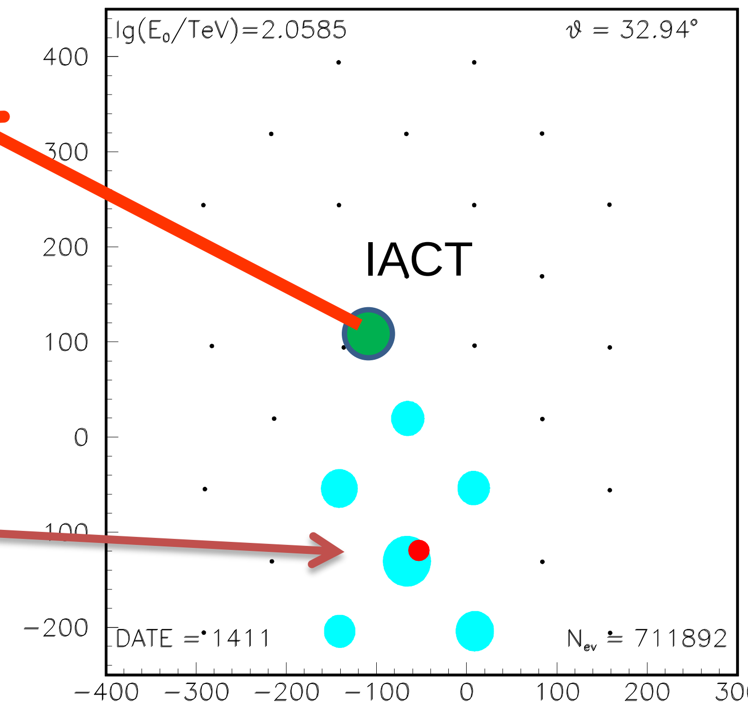


A wide blob

But some events looks as "Gamma-like"

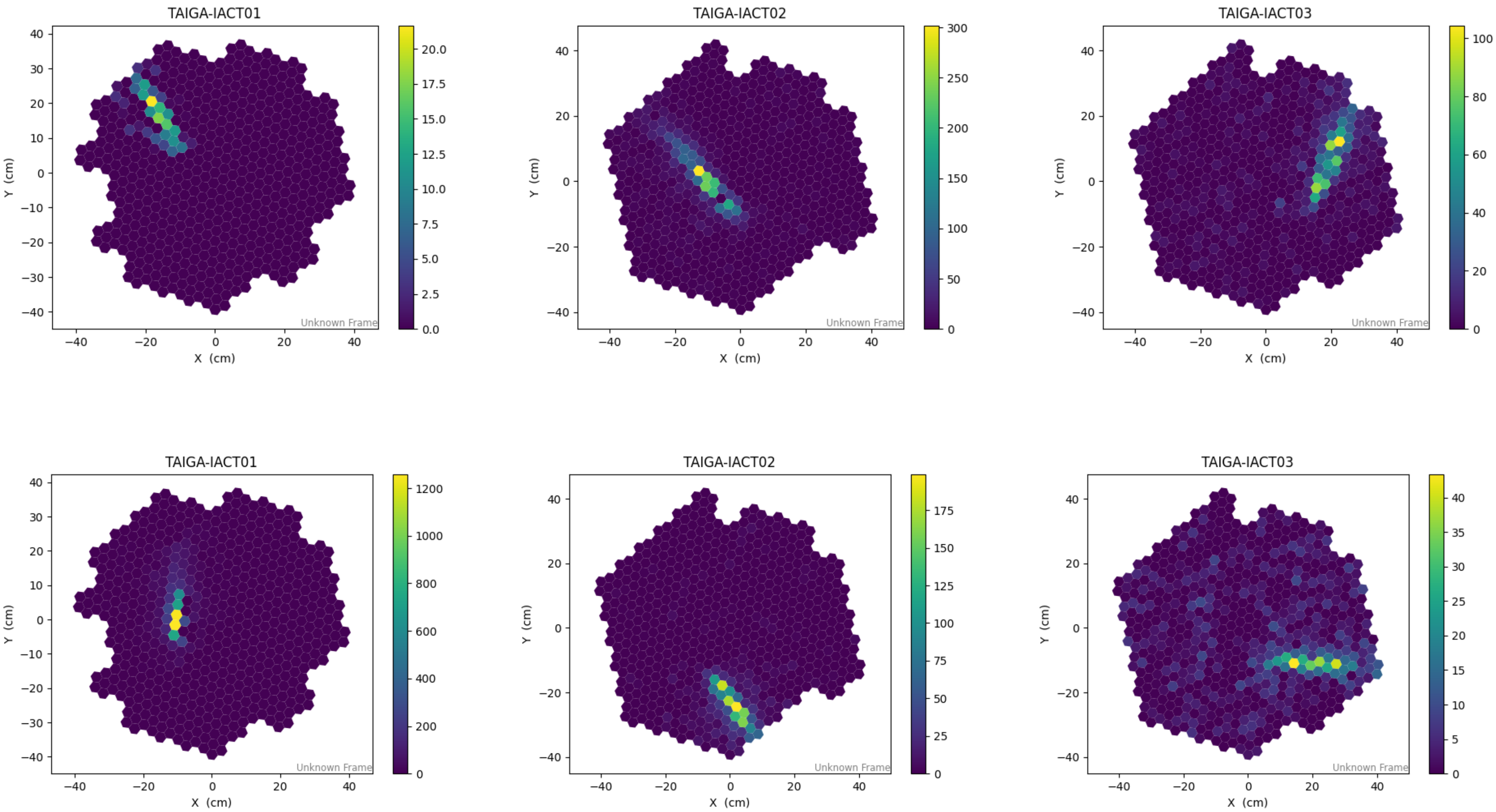


E = 50 TeV
Width = 0.19°

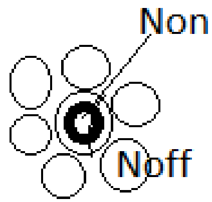


Core position

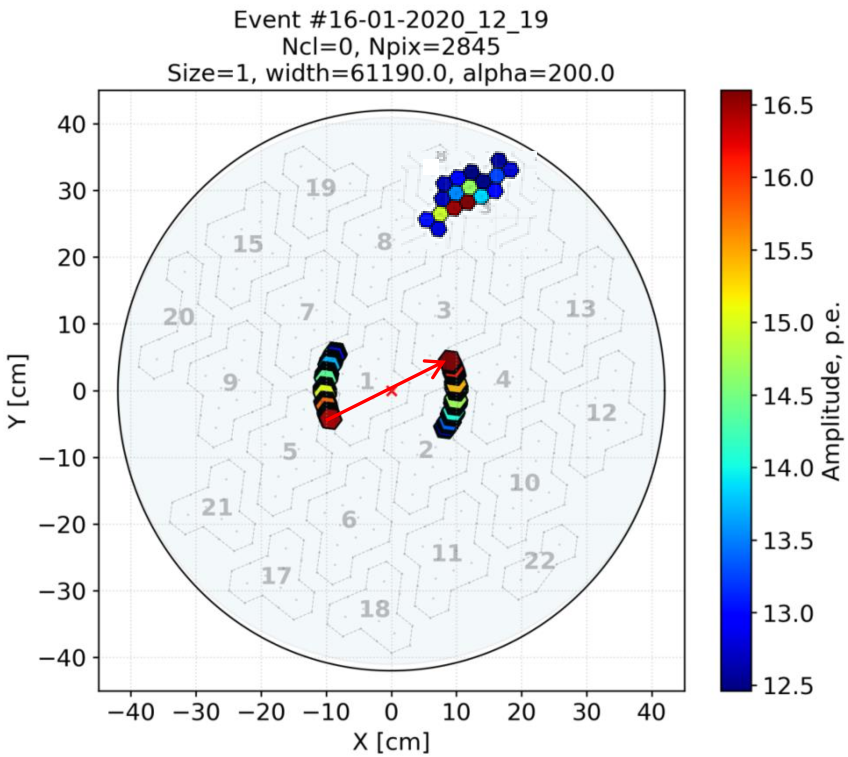
EAS detection by three IACT at a distance of 300 m – 400 m – 500 m in stereoscopic mode for high energies



On (from the source) and Off (the background) events during the observation



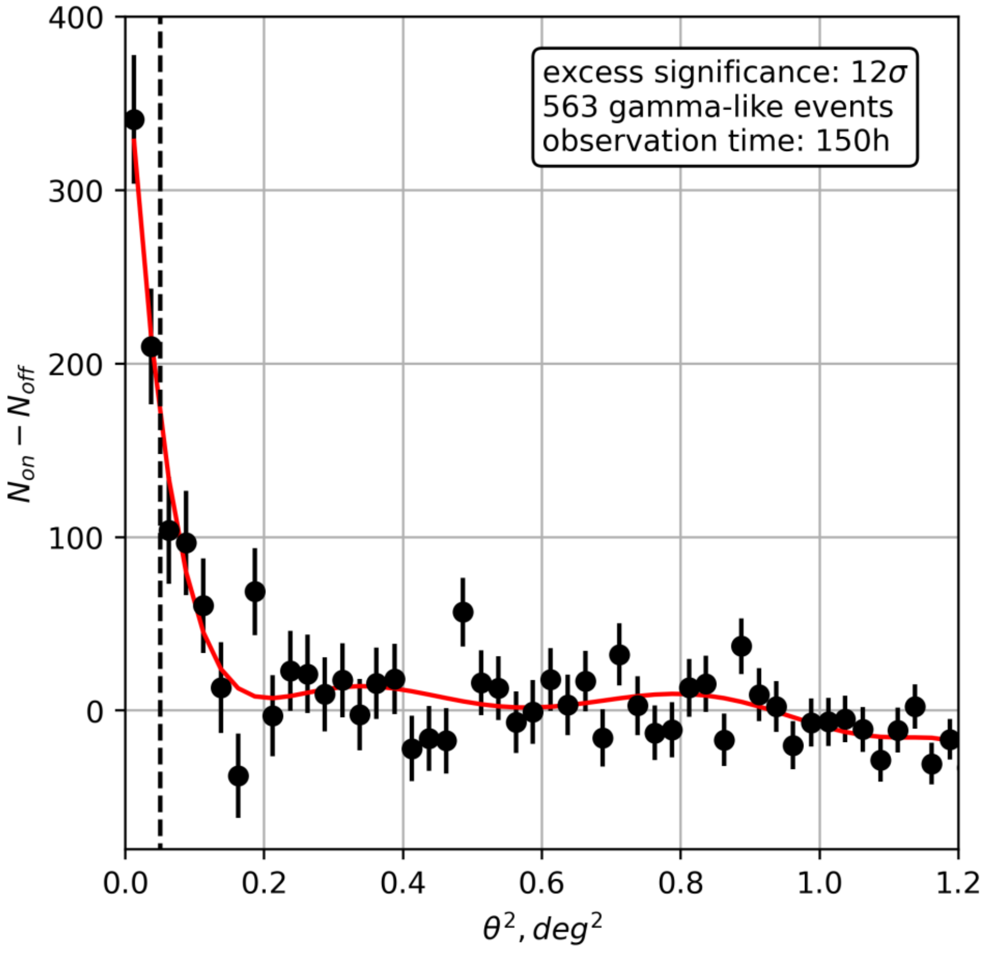
The position of the source on the camera in time



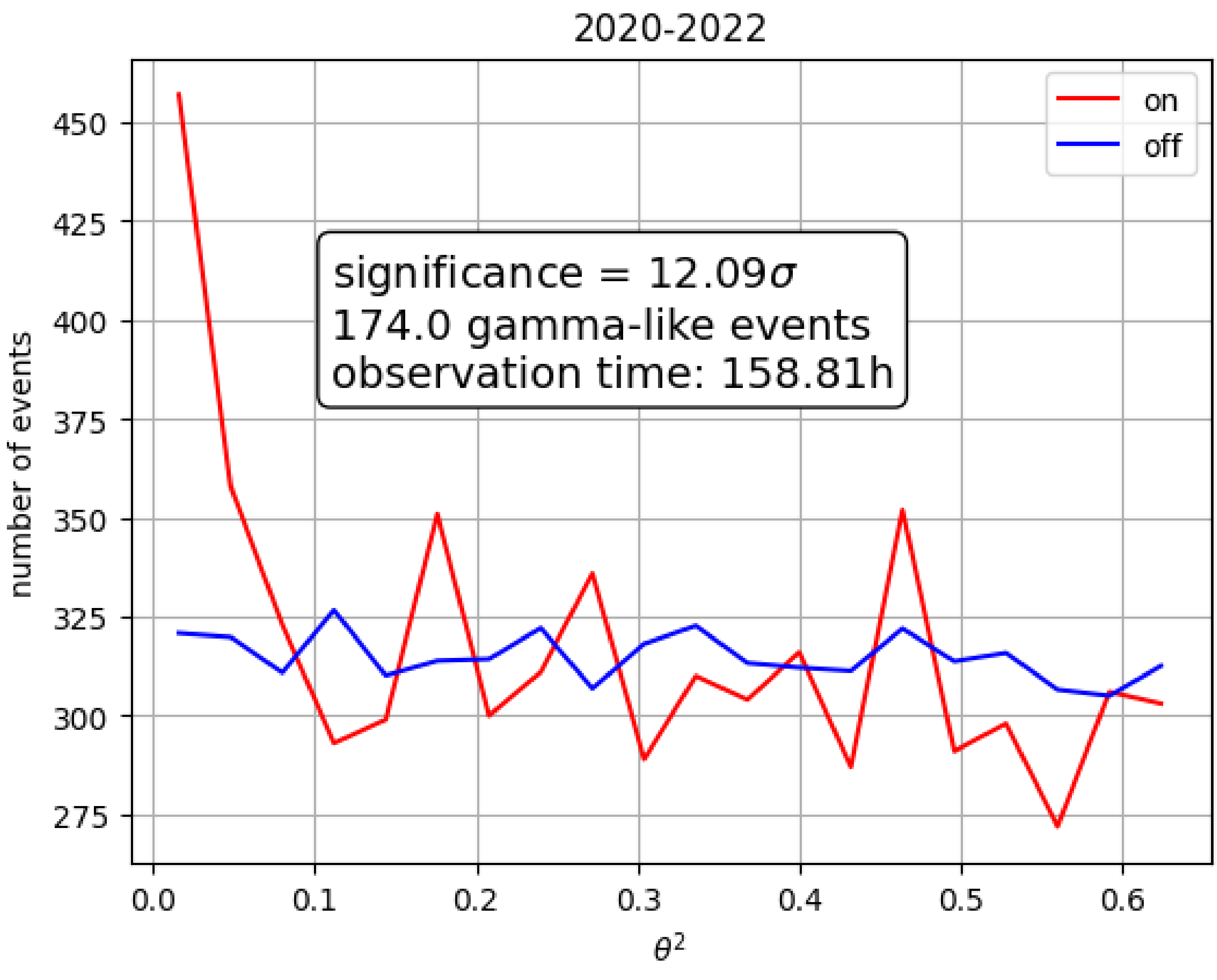
In TAIGA experiment a special the wobble mode is used to evaluate background events and study systematics when observing gamma radiation sources. In this mode the telescopes are directed to a point shifted relative to the direction to the source (Ra_{Crab} +1.2 degree (Dec_{Crab}) for 20 minutes, then Ra_{Crab} – 1.2 degree (Dec_{Crab}) for another 20 minutes.)

The background is estimated from the anti-source position. For each image, we can calculate parameters for the On and Off. The method allows not to divide the observation time between the measurement of the background and the measurements of the source.

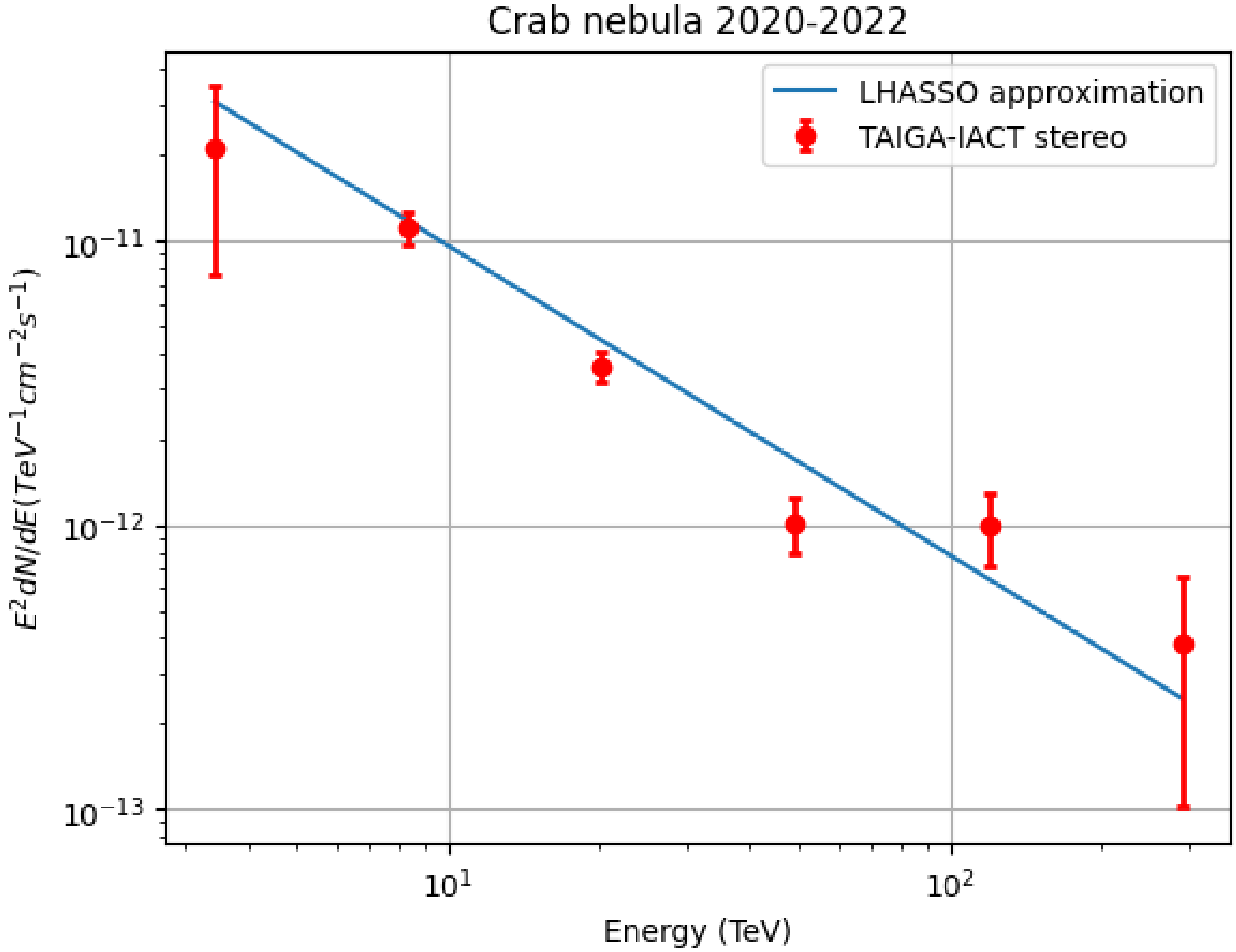
Background subtracted Θ^2-distributions for 150 hours Crab Nebula observation (mono mode)



Background subtracted Θ^2-distributions for 150 hours Crab Nebula observation (stereo mode)

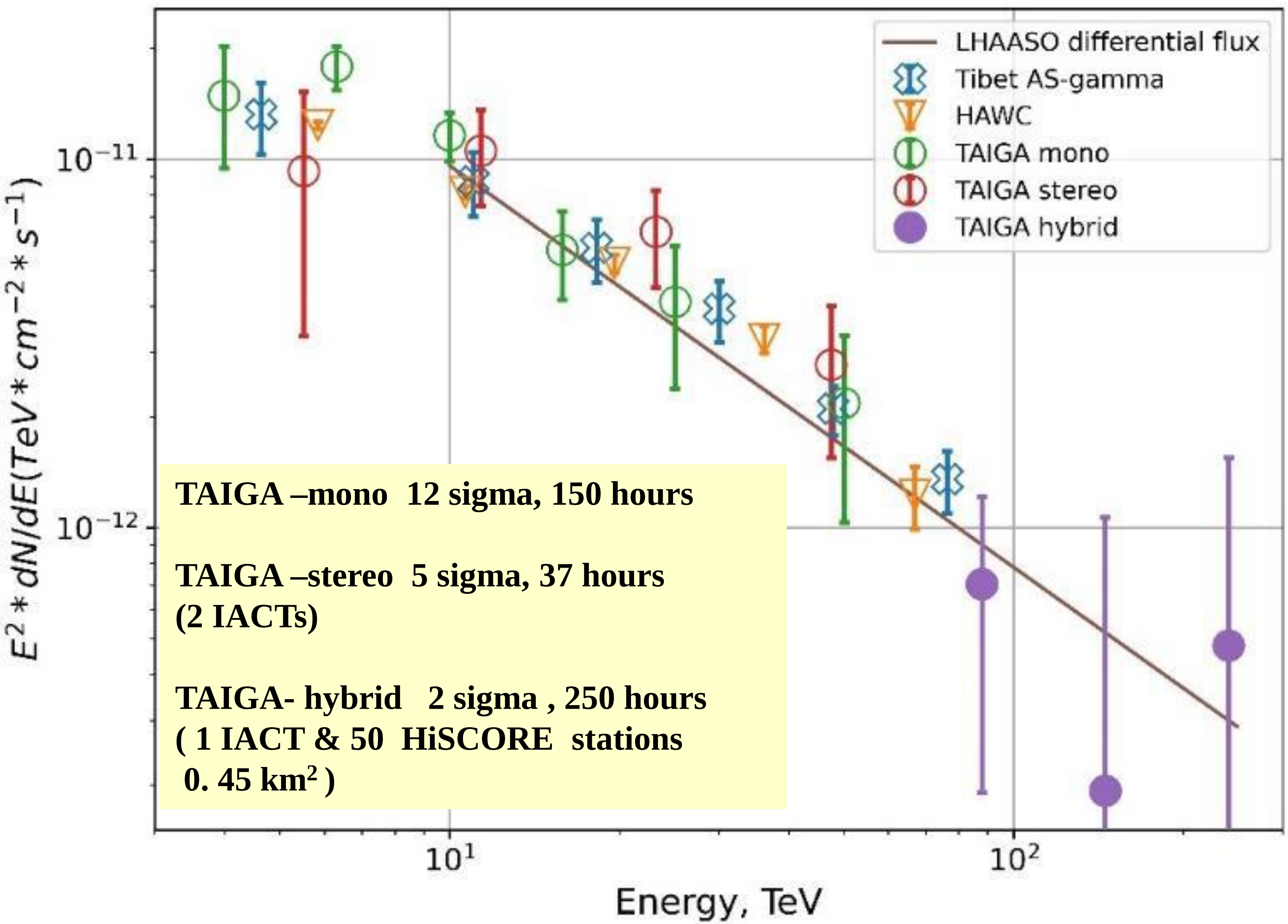


The energy spectrum of gamma quanta from the Crab Nebula (stereo mode)



TAIGA –stereo 5 sigma, 37 hours (2 IACTs)

The energy spectrum of gamma quanta from the Crab Nebula

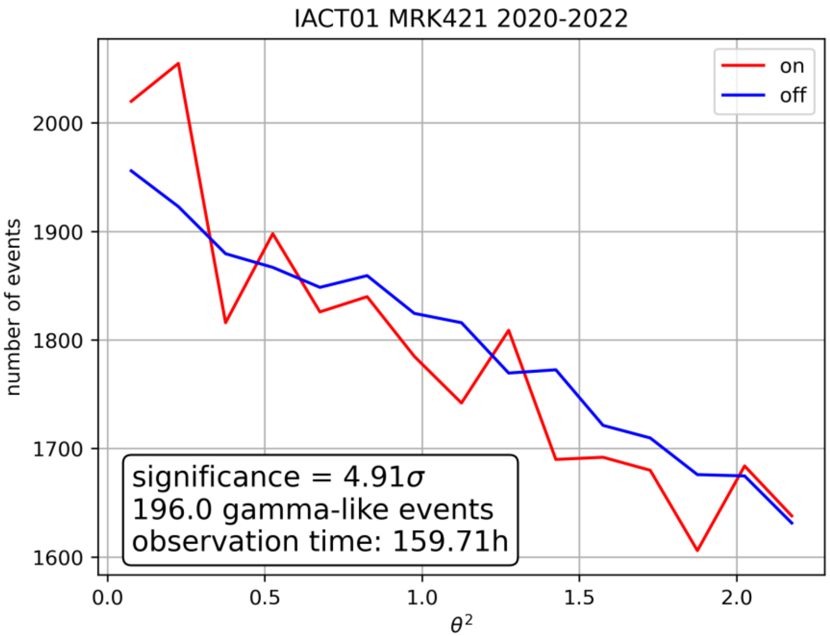


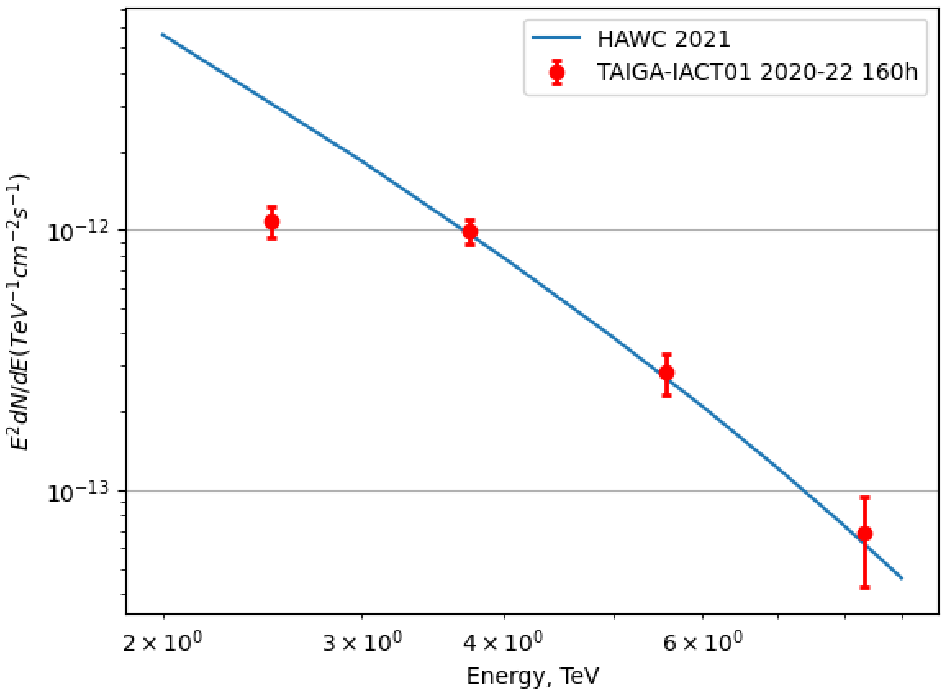
TAIGA –mono 12 sigma, 150 hours

TAIGA –stereo 5 sigma, 37 hours (2 IACTs)

TAIGA- hybrid 2 sigma , 250 hours (1 IACT & 50 HiSCORE stations 0. 45 km^2)

Gamma radiation of the blazar Markarian-421 according to the TAIGA-IACT01 data (mono mode)

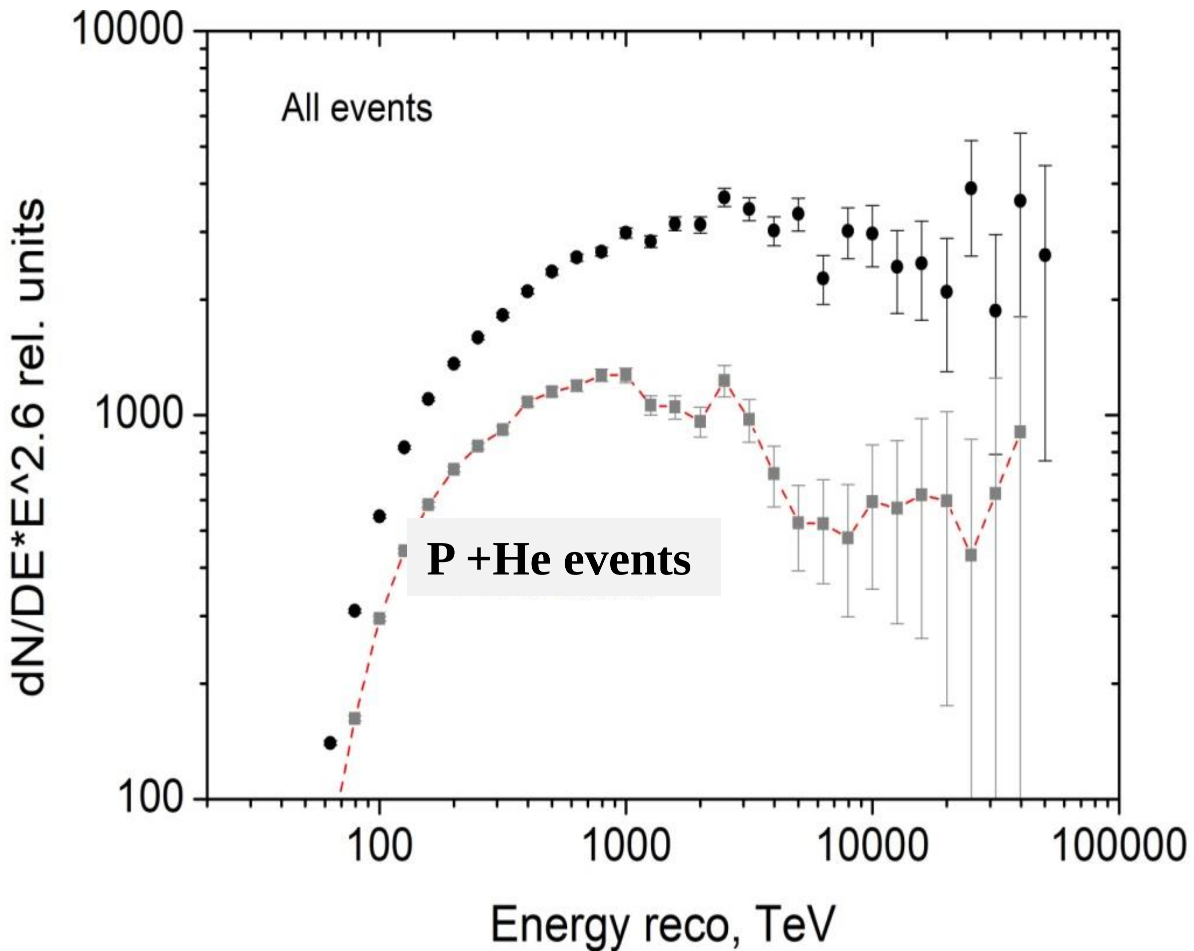




Θ²-distributions for of gamma quanta from the blazar Markarian-421

Energy spectrum of gamma quanta from the blazar Markarian-421

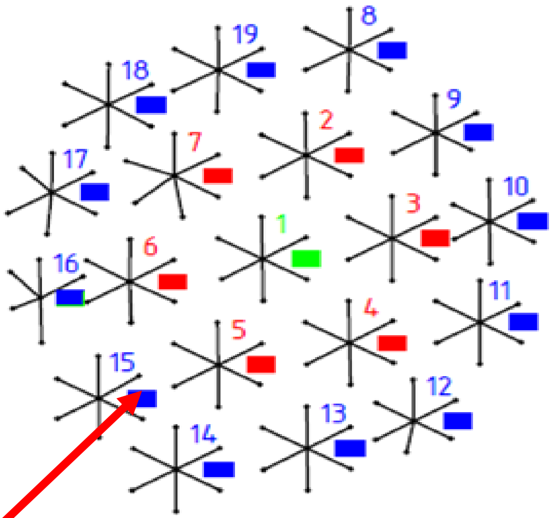
Energy spectra of all hybrid CR EAS (IACT1+TAIGA-HiSCORE) and a light component (protons+helium) for angles of 0-30 degrees

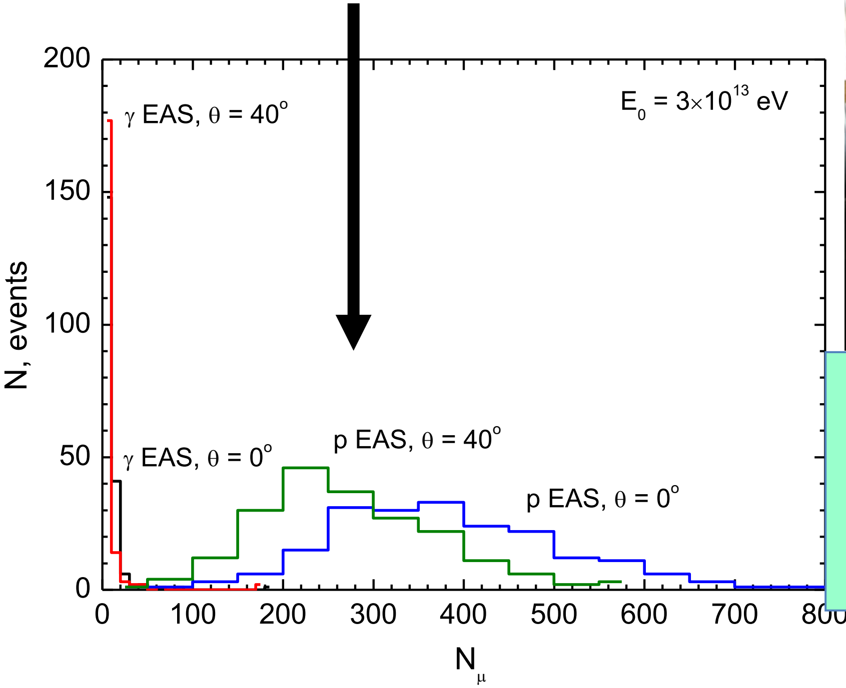


The TAIGA particle detectors.

The Tunka – Grande scintillation array

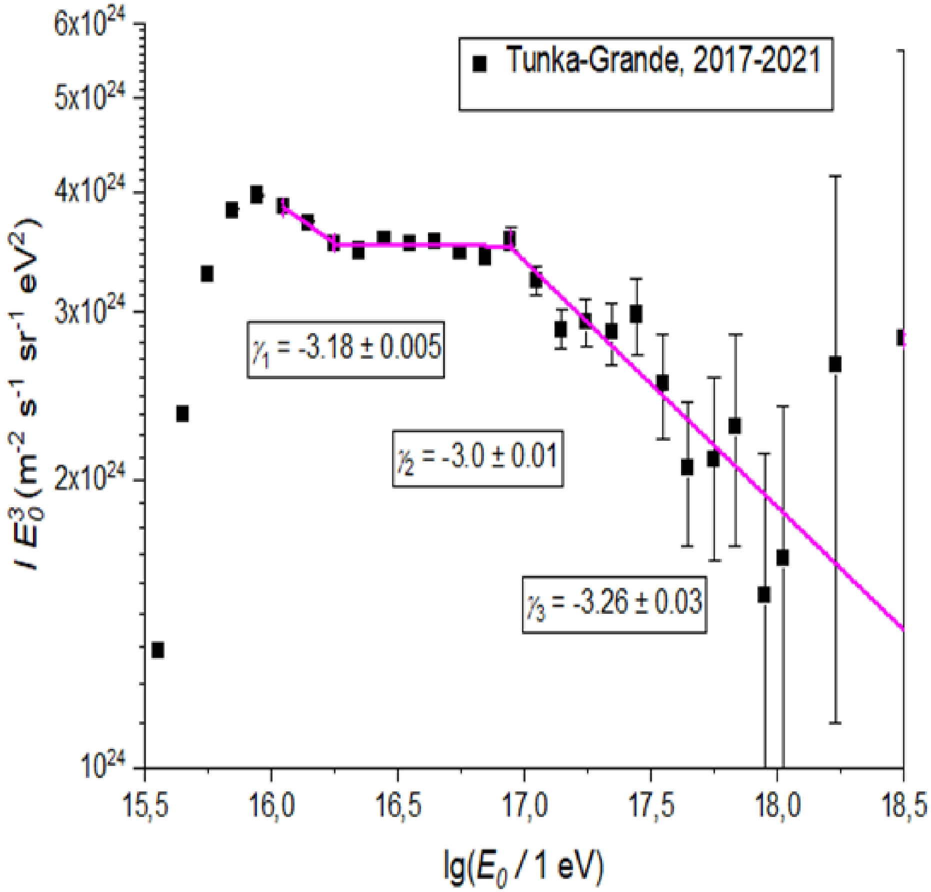
- Permanent absolute energy calibration of Cherenkov arrays Tunka-133 and TAIGA-HiSCORE.
- Round-the-clock duty cycle;
- Improvement of mass composition data
- **Rejection of p-N background**





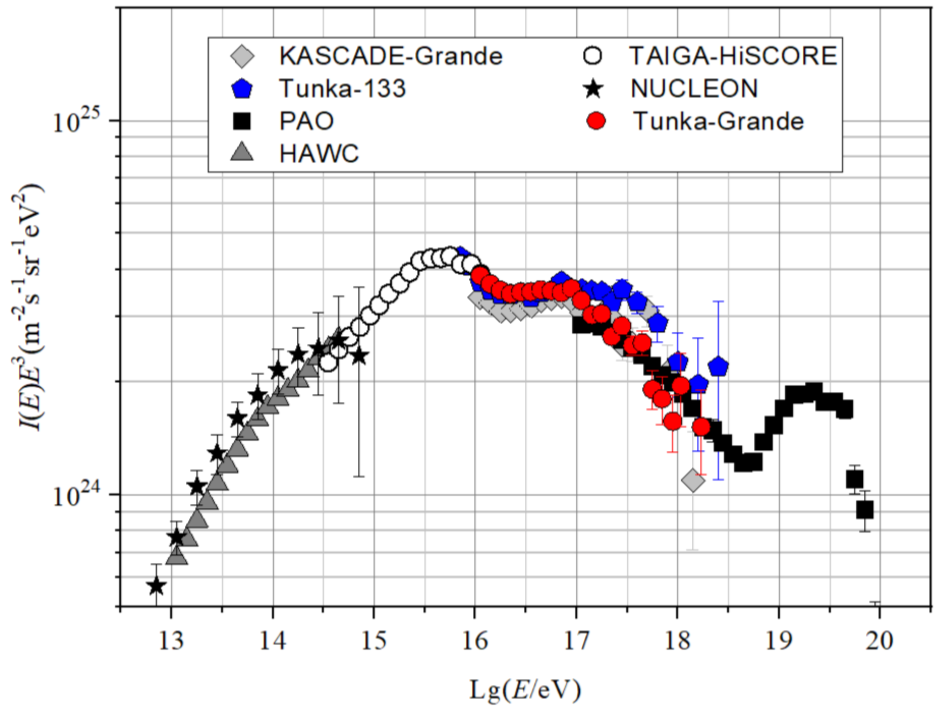
12 former KASCADE-Grande scintillation counters with S=0.64 m^2 in surface part of 19 station

8 the same underground muon counters in 19 stations.



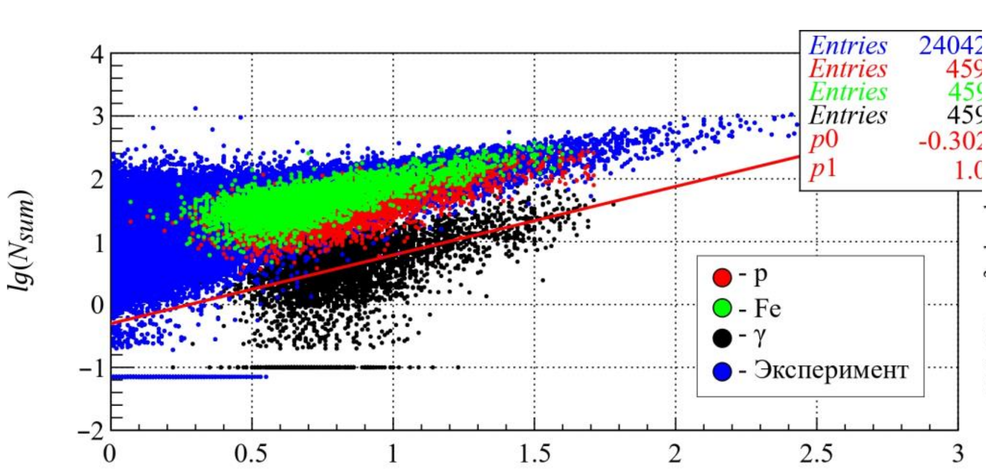
Tunka-Grande CR energy spectrum

~ 260000 events with energy E ≥ 10 PeV, zenith angle < 35°.
~ 2100 events with energy E ≥100 PeV, zenith angle θ <35°

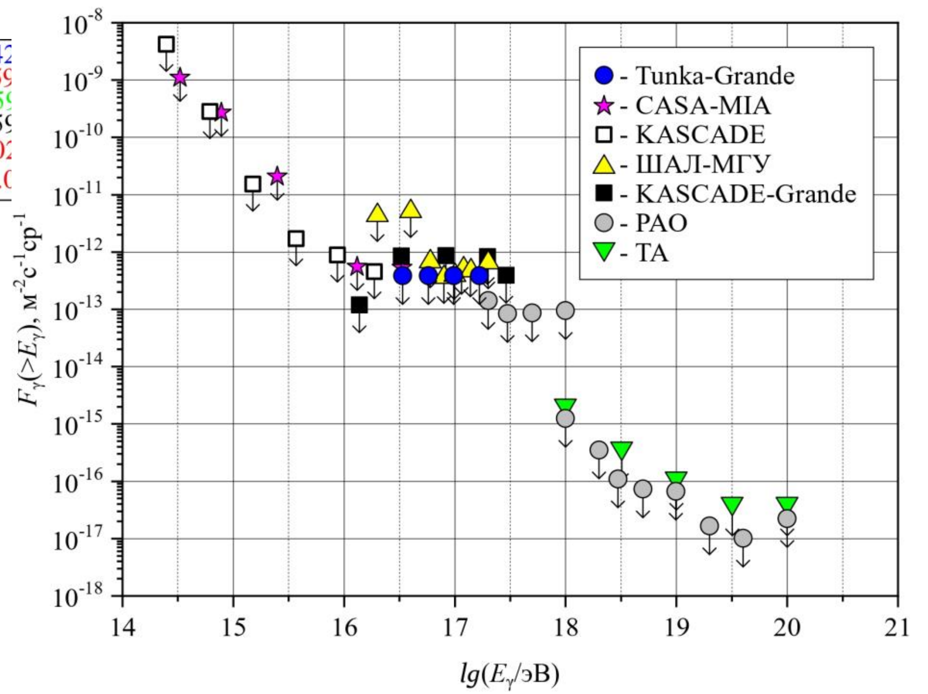


Comparison of the Tunka-Grande & Tunka-133 CR energy spectra with other experimental results

Search for diffuse ultra-high energy gamma quanta



lg ρ_{200} (particle/m^2)



The criterion for selecting candidates for gamma induced EAS : N_{sum} - the number of the all detected muons in all underground scintillation counters located at distance more than 70 m from EAS axis.

Limit on the integral flux of diffuse gamma quanta.

8900 hours (2017-2021y),
240,000 events with E ≥ 10 PeV
and 2,000 events with E ≥ 100 PeV

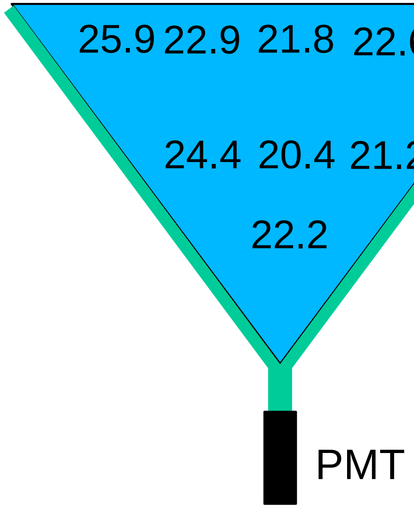
The TAIGA-Muon scintillation array

Counter dimension $1x1\ m^2$ designed NSU& BINP

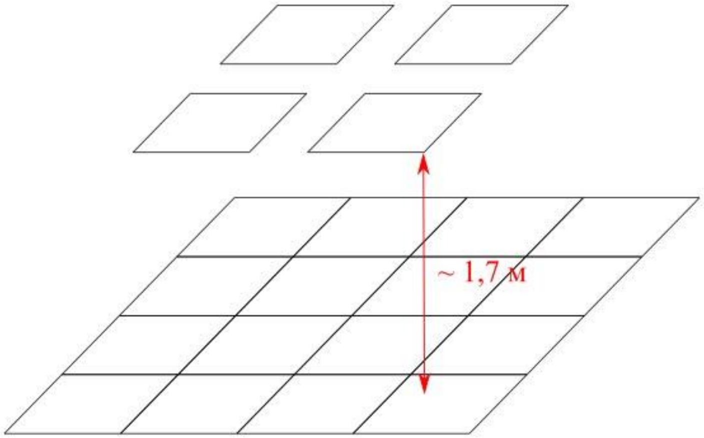
Wavelength shifting bars are used for collection of the scintillation light.

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

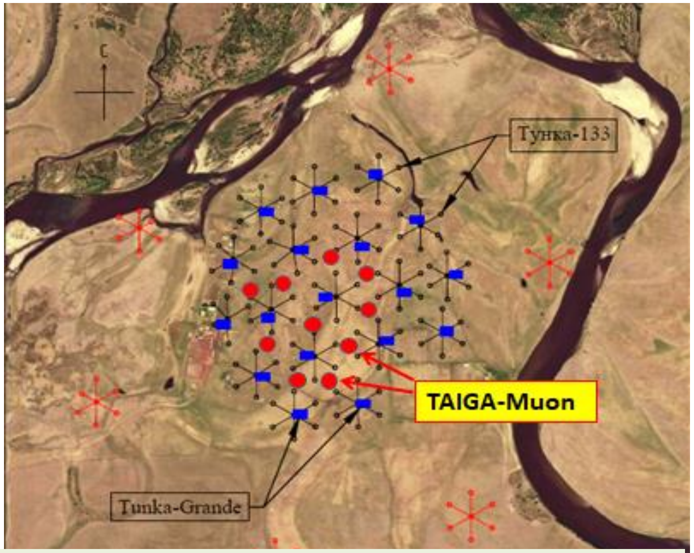


The TAIGA-Muon scintillation array



The position of the counters in a cluster of TAIGA-Muon

Surface counters of a TAIGA-Muon cluster

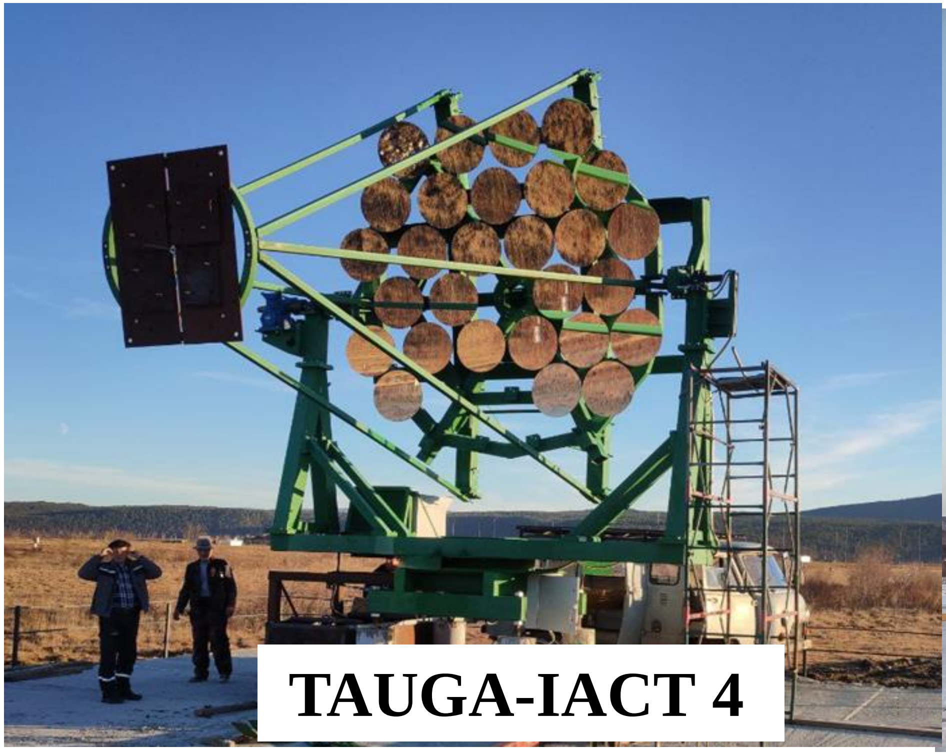


Location of clusters of the first stage of the TAIGA-Muon

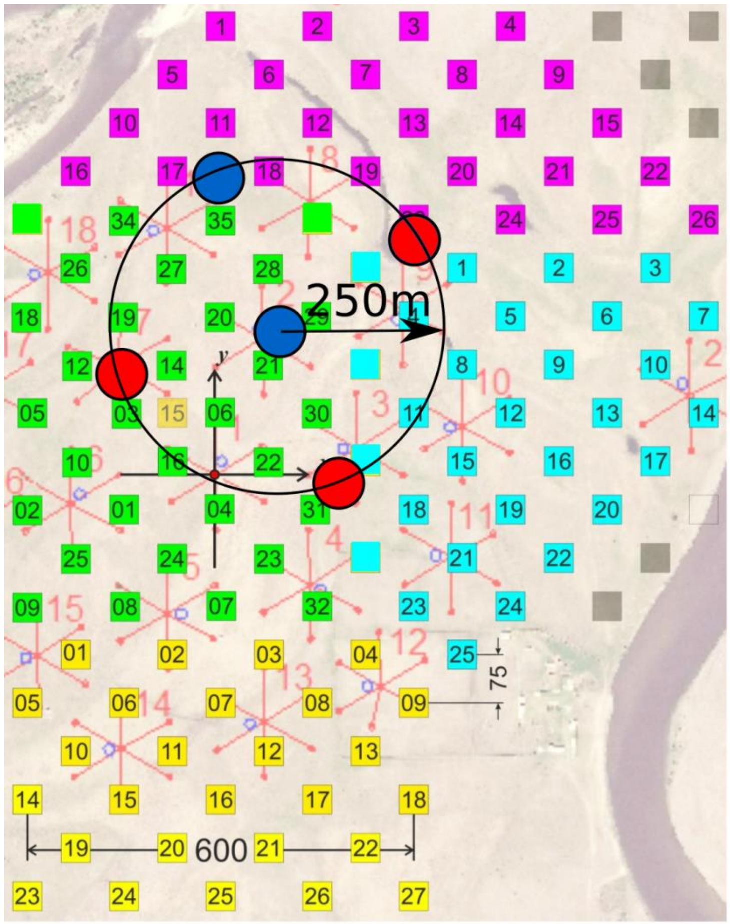
Underground counters of a TAIGA-Muon cluster

Near future plan (2-3 y)

1. Two telescopes with of 4.3 m mirror diameter and one with of 6 m mirror diameter

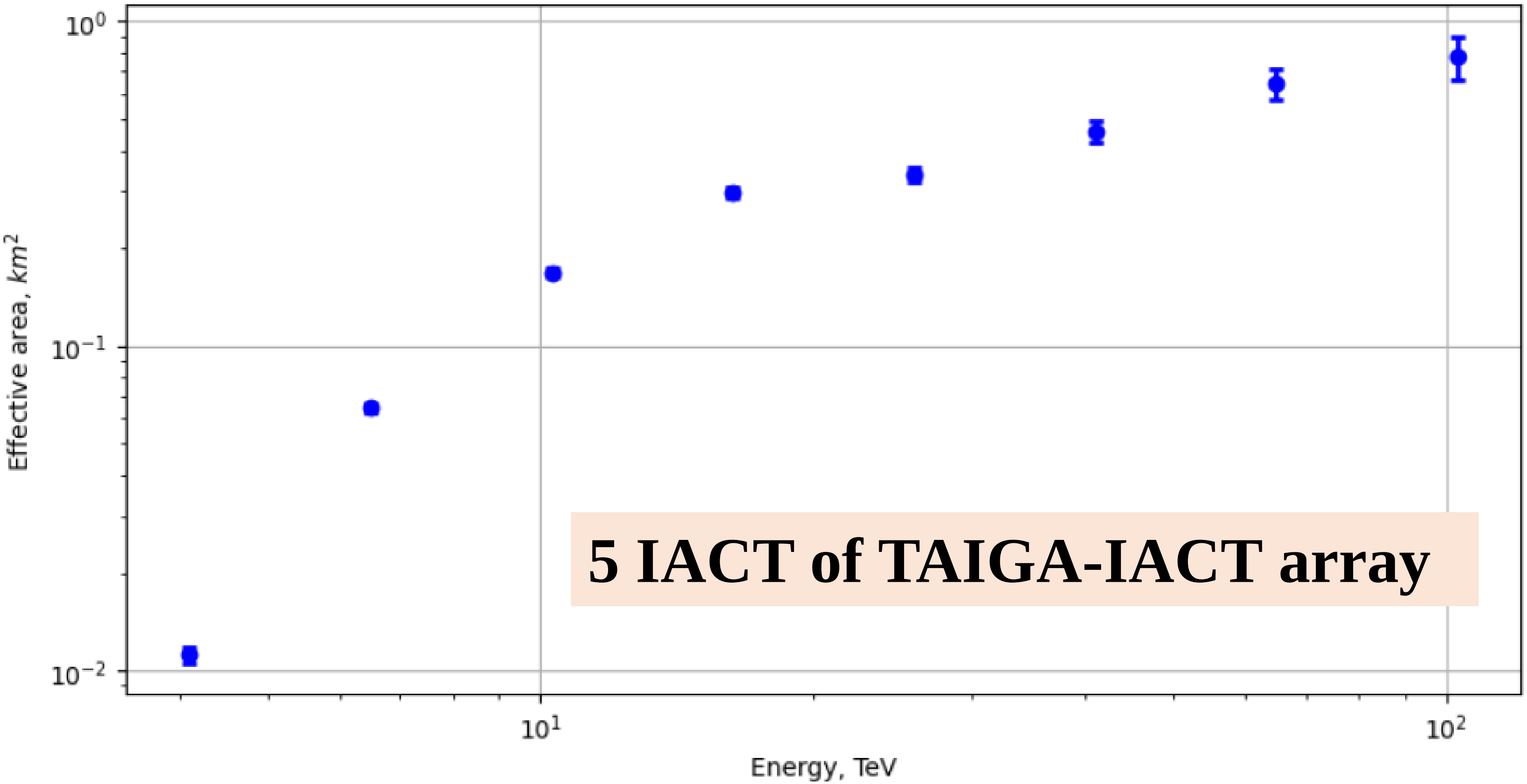


TAIGA-1, 2024 -2025



IACT in operation | planned IACT | HiSCORE cluster#1 | HiSCORE cluster#2 | HiSCORE cluster#3 | HiSCORE cluster#4

Effective area for gamma detection for stereo mode after hadron suppression



Relative suppression of proton background 10^{-4}

TAIGA -1 : 40-60 gamma E >100 TeV 300 h (2-3 seasons)

Near future plan (2-3 y)

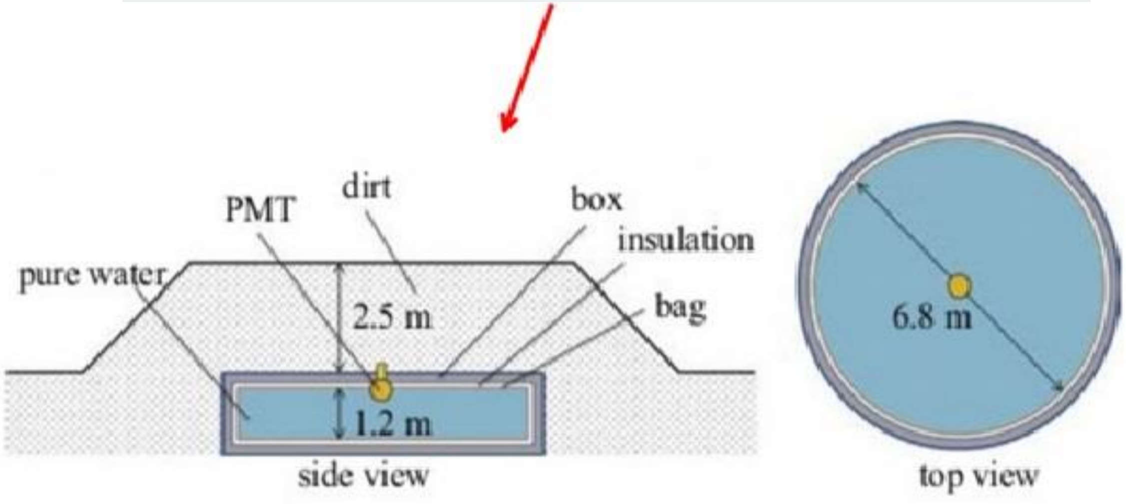
2. 12-15 external TAIGA-HiSCORE optical stations (increasing the effective area to 1.5 -2 km^2)

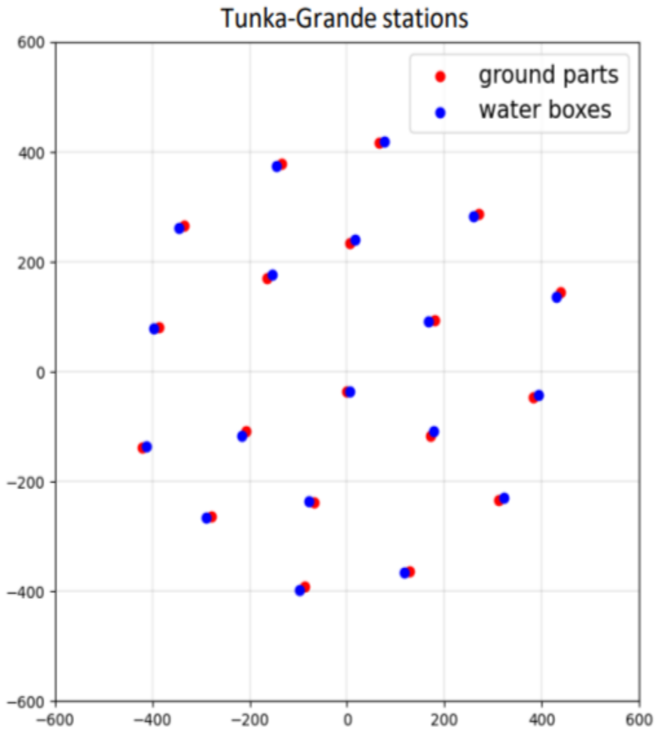
3. At least 400 m^2 of new scintillation muon detectors of the TAIGA-Muon installation

4. Experimental underground water Cherenkov detector with an area of 40 m^2

Underground water Cherenkov detectors

S ~ 40 m^2 , height 1.2 m, depth 2 – 2,5 m.





Deployment of the first water detectors: **on the territory of the TAIGA-1 experimental complex, summer 2024.**

Placement options:

1) Near Tunka-Grande array stations (in this case, Tunka-Grande ground detectors will act as the ground part of the detectors)
2) Near the TAIGA-Muon array stations (ground part - 4 scintillation counters similar to TAIGA-Muon counters located above the water tank)

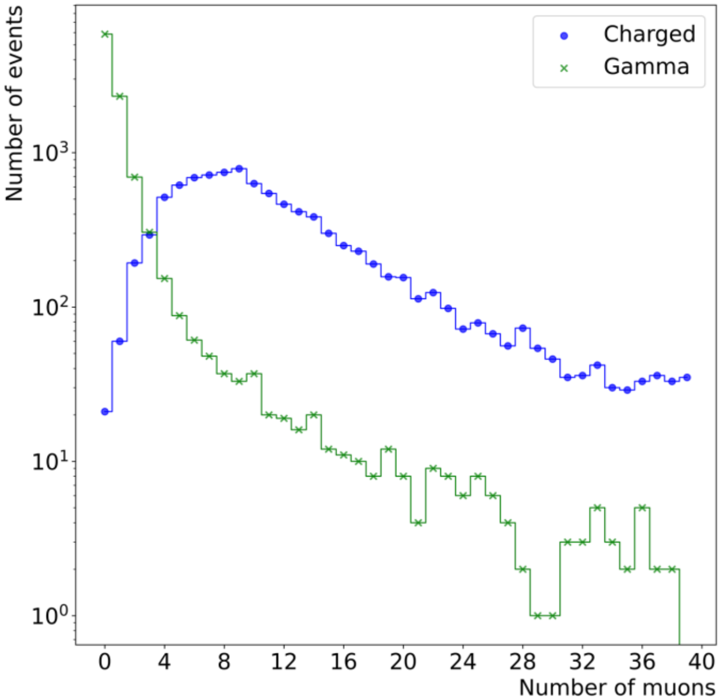
Simulation of underground water Cherenkov array of TAIGA-1

Main program: CORSIKA v.77401 (QGSJet-II-04)

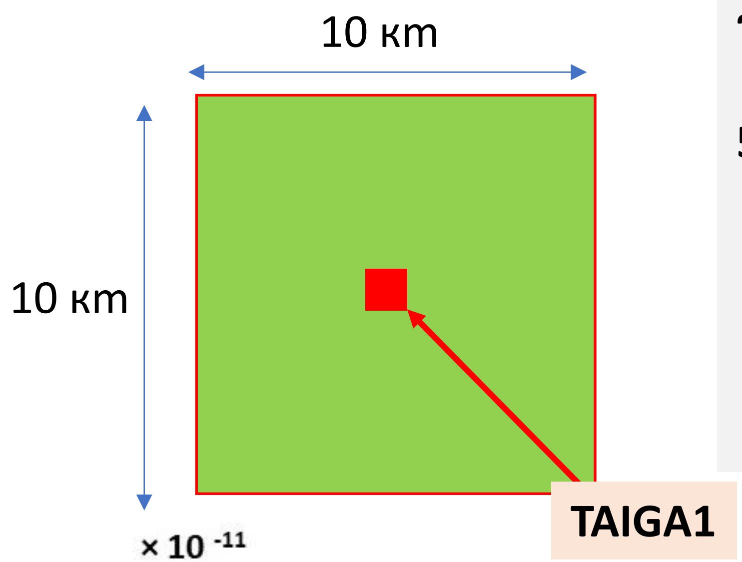
1) A total of about 40 thousand artificial EAS: 50% gamma composition, hadronic composition: 25% protons, 12.5% nitrogen (CNO), 12.5% iron nuclei;
2) Energy 1-10 PeV, $E^{-2.7}$, angles 0-45°;
3) Array is a simple geometric model of "cylinders", with 1 GeV energy threshold, 19 detectors are placed near Tunka-Grande array stations;
4) Axes of showers are within the circle of radius 400 m. the center coincides with the center of the array.

From the obtained distributions it follows that muon-free events are observed in ~0.5% of cases for hadron showers and in ~70% of cases for photon EASs.

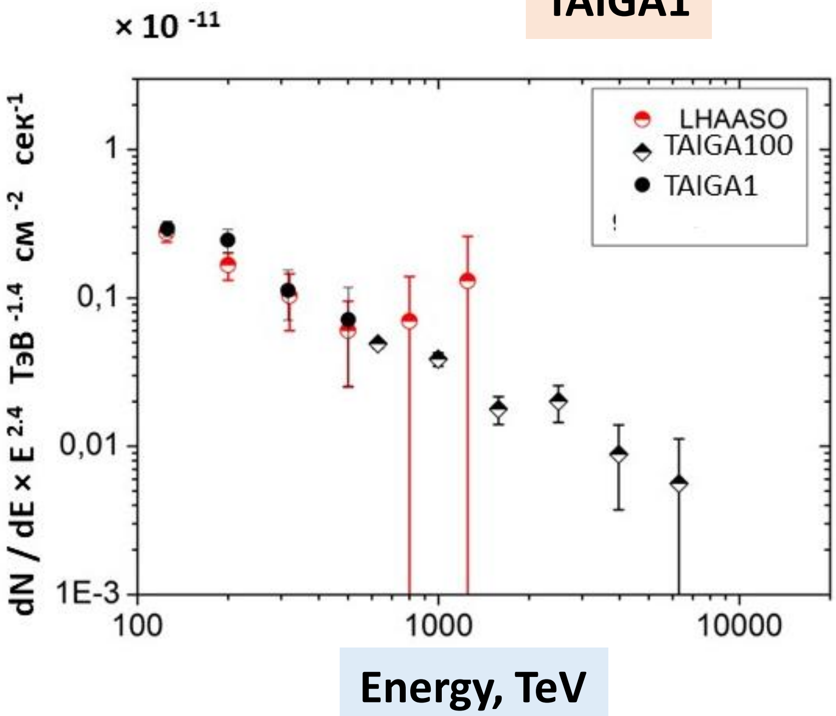
Hadronic background rejection > 100 times



Full scale TAIGA-100 array for PeV gamma astronomy



~ 3000 wide-angel Cherenkov stations with 1 PMT, FoV ~ 1 ster.
5 - 10 4 m class IACTs (like in Tunka-1)
1 -2 10 m class IACTs (mini ALEGRO)
~ 3000 scintillation detectors
~ 1000 underground water Cherenkov detectors, $40m^2$ area
1-2 Fluorescent detectors



Energy range 50 TeV – 10 PeV.

About 350 gamma from Crab Nebula With energy > 500 TeV for 300 hours duaration of observation (3 years)

The significance level is 10 sigma.

Summary and outlook

The experience of the first years of operation of the TAIGA-1 confirmed the effectiveness of the hybrid approach to create an installation with an area of tens of square kilometers for UH gamma-astronomy.

A point source sensitivity of the TAIGA-1 :

2.5 10^{-13} TeV/cm^2 s (300 hours, 30–200 TeV)

First data about Grab nebula gamma ray energy spectra for E > 100 TeV by Cherenkov way were got.

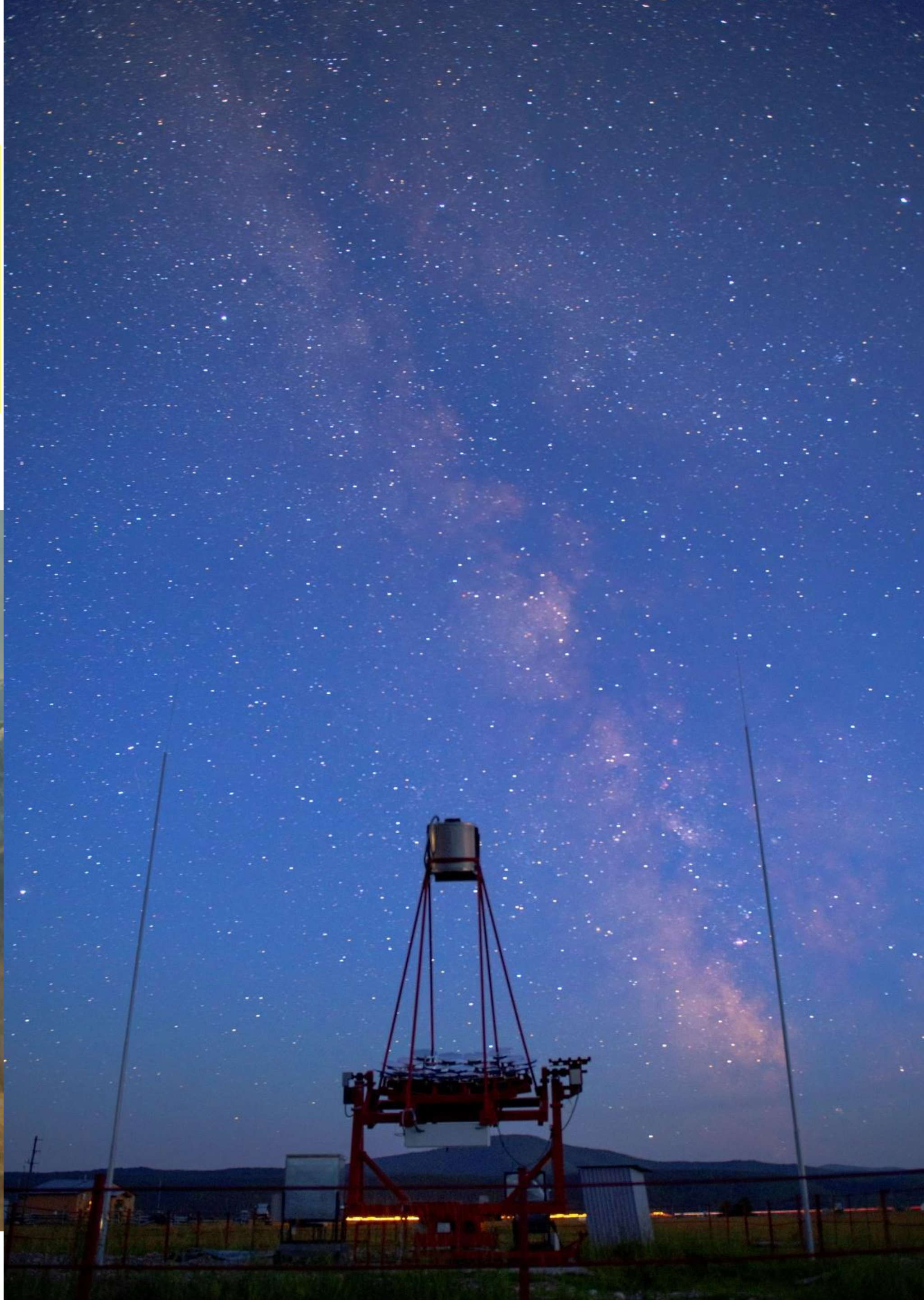
Near Future plan: two new 4 m class and one 6 m class IACT, new particle detectors (scintillation and Underground Cherenkov water)

Next plan: 20 -100 square kilometers TAIGA + new technologies

- **array with about 3 000 wide-angle Cherenkov detectors of TAIGA - HiSCORE "non-imaging" timing array**
- **5 -10 Imaging Atmospheric Cherenkov Telescopes of TAIGA-IACT array**
- **3000 m^2 muon detectors.**
- **1000 underground water Cherenkov detectors, 40m^2 area**

A point source sensitivity of TAIGA-100 ~ 10^{-15} TeV/cm^2 s (300 hours, E > 500 TeV)

Thank you for attention!



Welcome to Siberia!