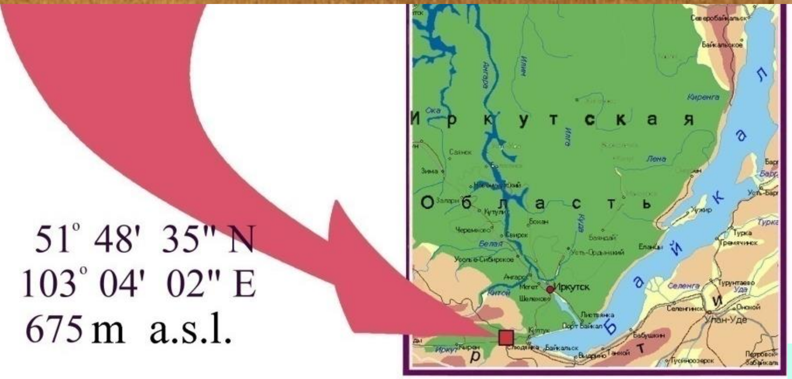
The TAIGA experiment - current status, recent results and development prospects.



N. Budnev,

L. Kuzmichev

For TAIGA collaboration

Grant RSCF 23-72-00016

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
- Fisica Generale Universita di Torino and INFN, Torino, Italy

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

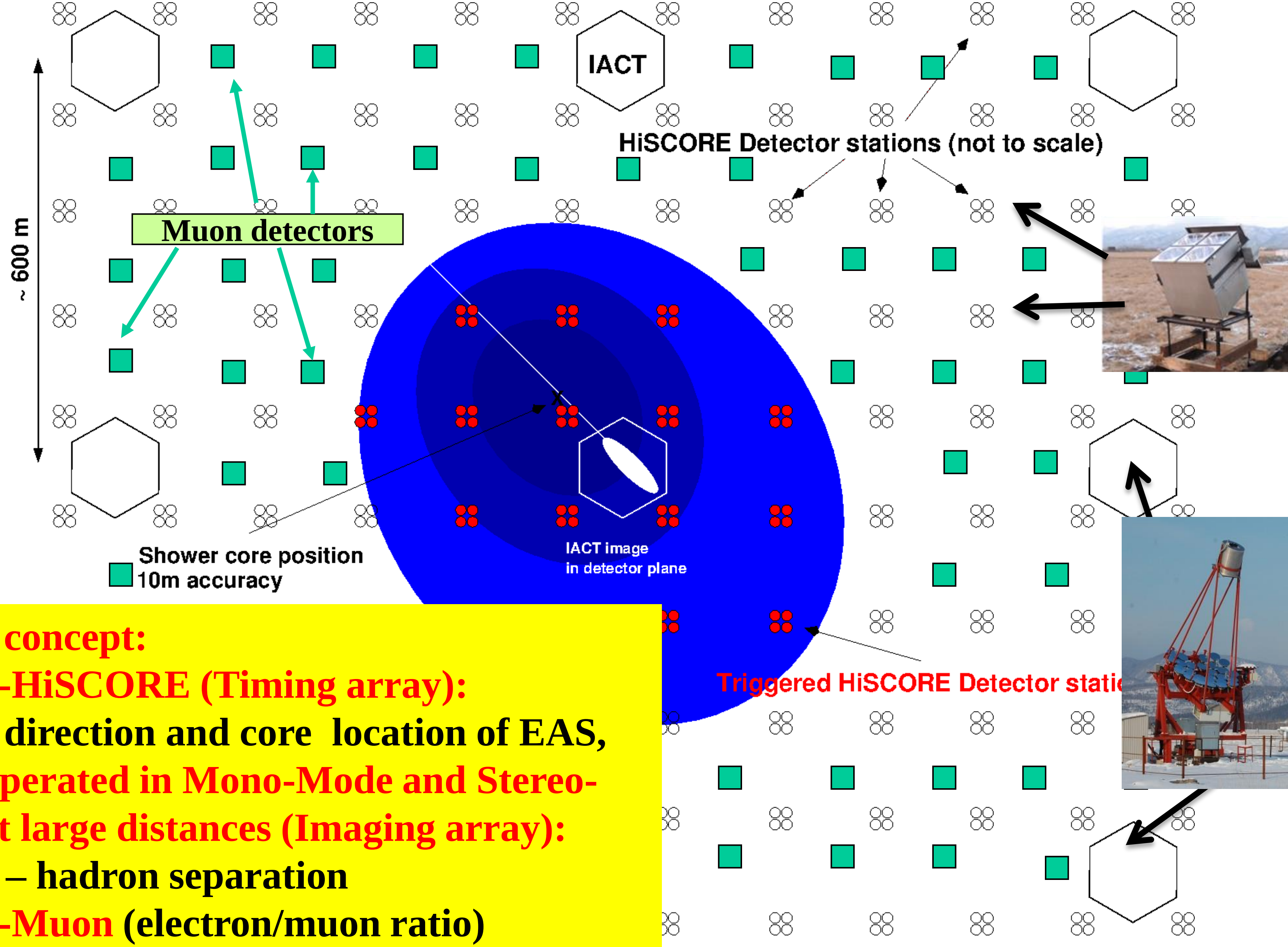
The main initial goal: to find a cost-effective way to create a large-scale installation for high-energy gamma-ray astronomy by combining wide-angle Cherenkov timing TAIGA-HiSCORE array with several small-sized Imaging Atmospheric Cherenkov Telescopes of TAIGA- IACT array.

Hybrid concept

TAIGA- IACT at large distances: gamma – hadron separation

TAIGA-HiSCORE Wide Angle Timing Array: energy, direction, core location

TAIGA: Imaging + non-imaging techniques



Hybrid concept:

TAIGA-HiSCORE (Timing array):

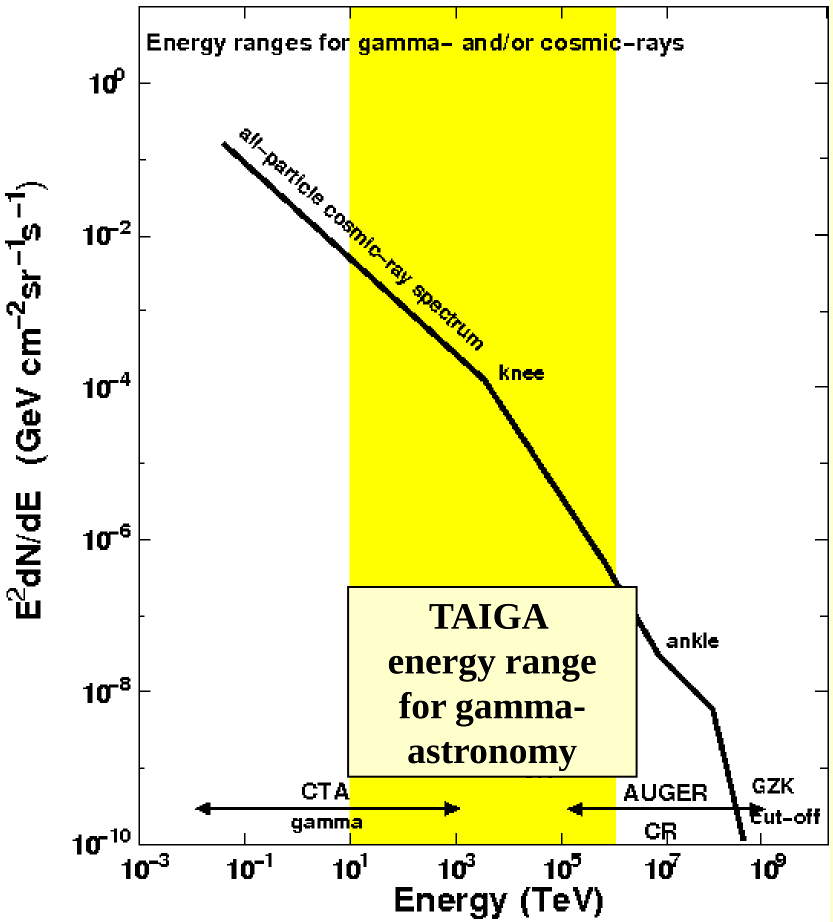
Energy direction and core location of EAS,

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

gamma – hadron separation

TAIGA-Muon (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), J0341+5258, 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.

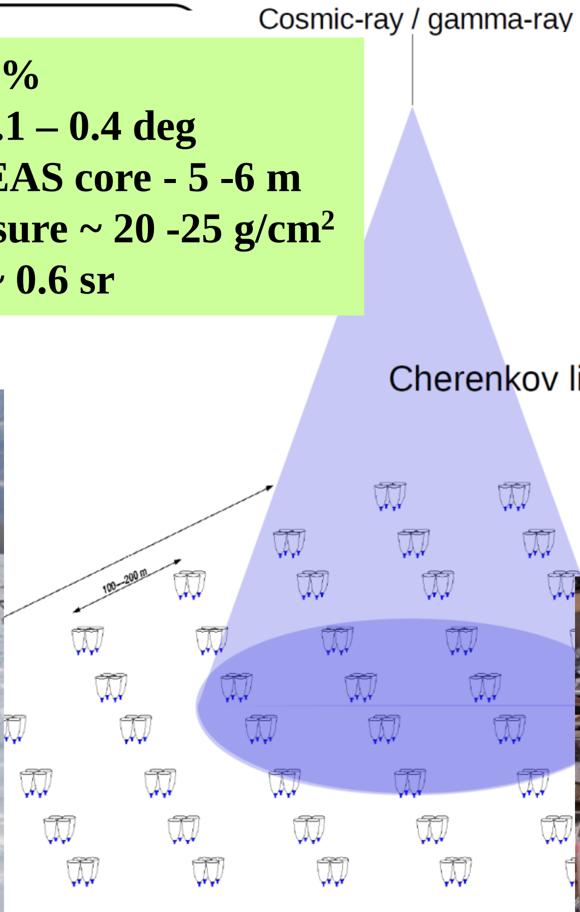
6. Study of the CR energy spectrum and mass composition in energy range 100 TeV- 1000 PeV.

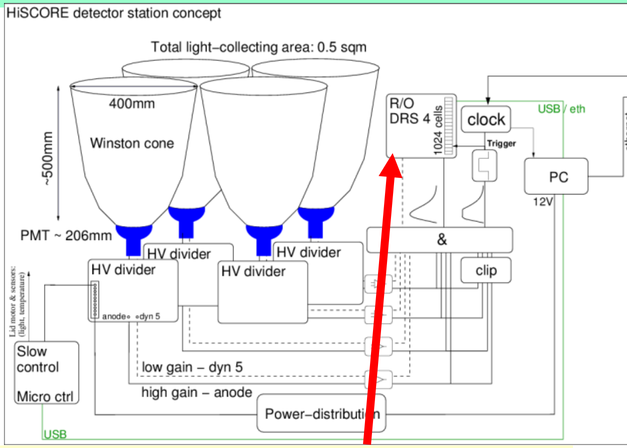
7. Fundamental physics (University transparency and photon-axion oscillation, indications of Lorentz invariance violation, evidence of Dark matter, etc).

TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

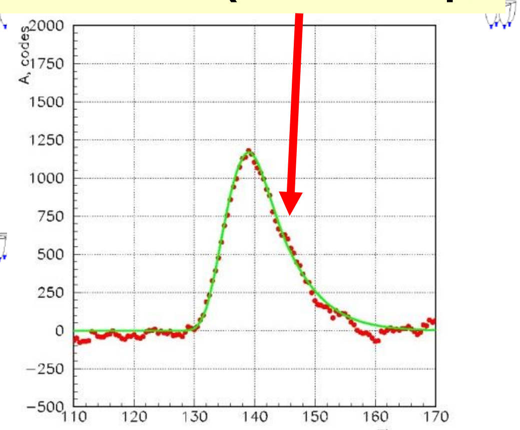
Consist of 120 Cherenkov stations distributed on 1,1 km² area with spacing 106 m. Each station includes four 8 inch PMTs equipped with a segmented Winston cone. The resulting total light collection area of a station is 0.5 m². Threshold for CR- 100TeV, for γ- 50TeV

1. Energy resolution ~ 15%
2. Angular resolution ~ 0.1 – 0.4 deg
3. Accuracy positioning EAS core - 5 -6 m
4. Accuracy of X_{max} measure ~ 20 -25 g/cm²
5. Large Field of View: ~ 0.6 sr

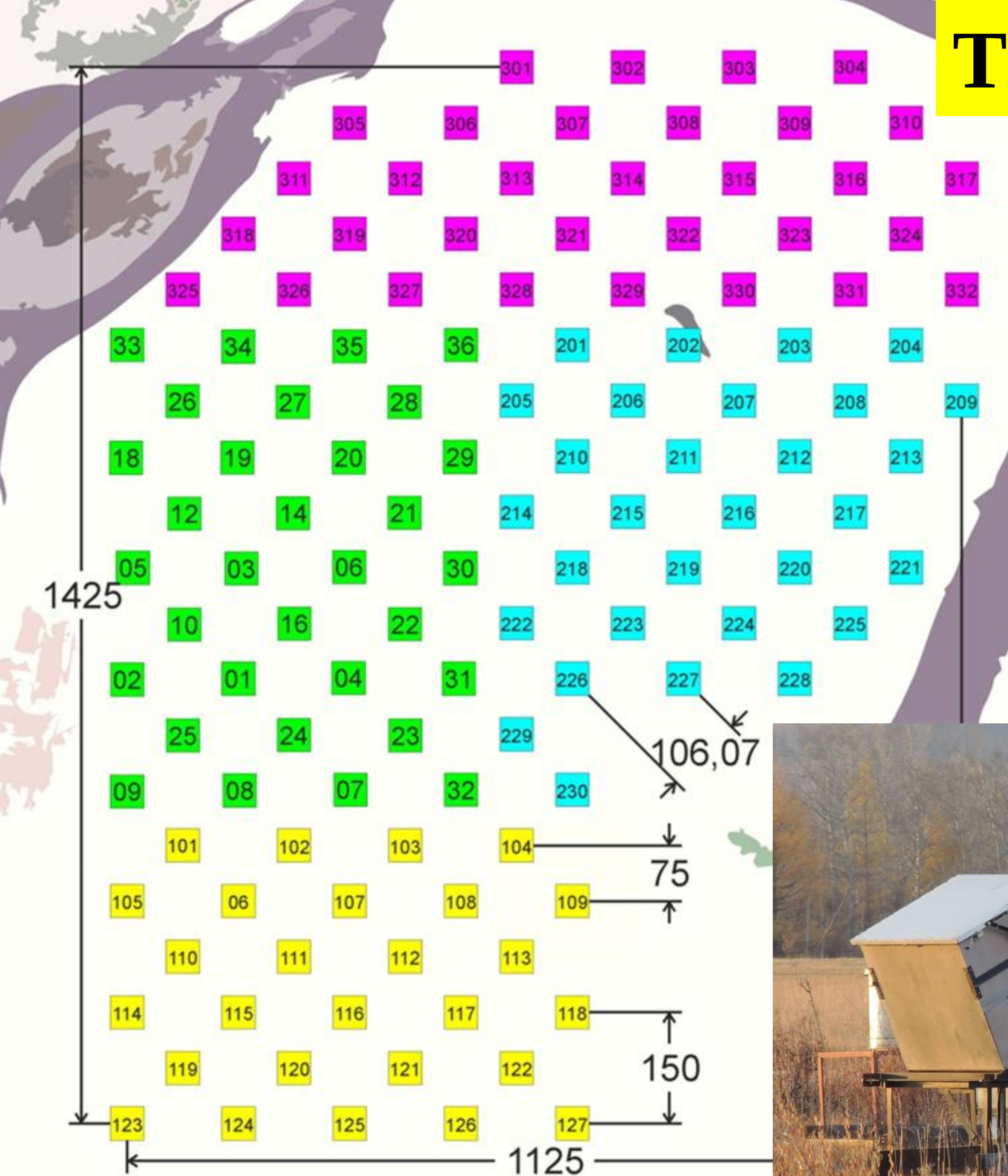




DRS-4 board (0.5 ns step)

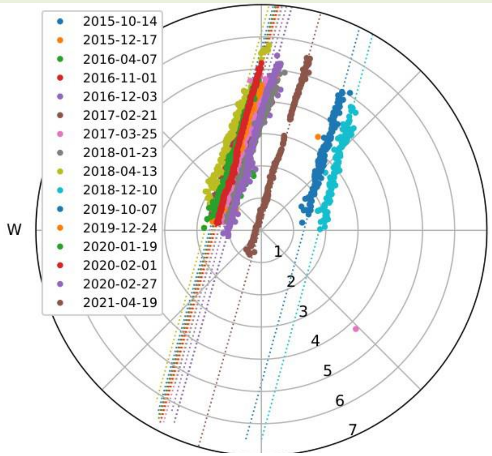


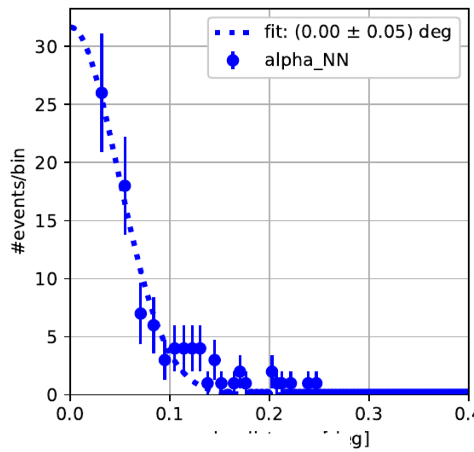
TAIGA-HiSCORE

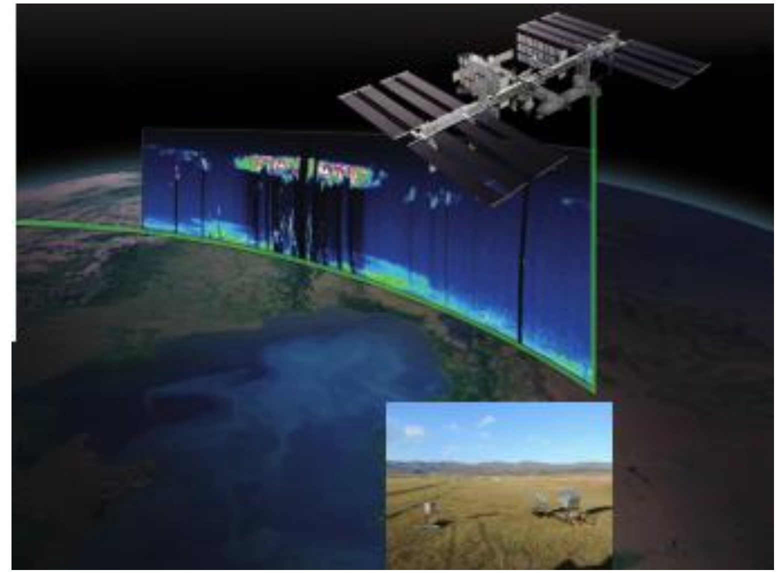


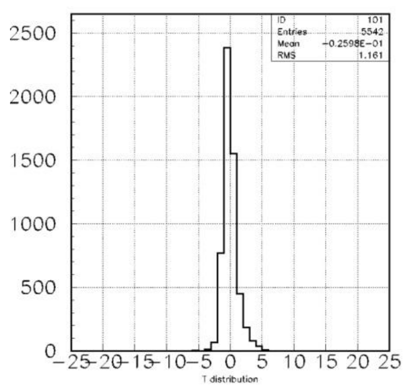
An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE

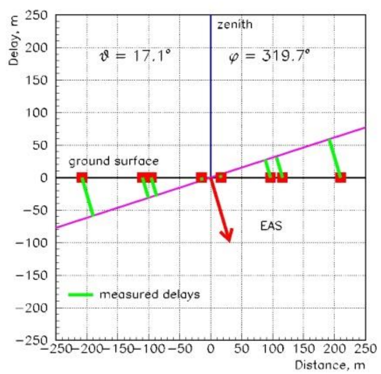
16 CALIPSO passages detected by TAIGA-HiSCORE





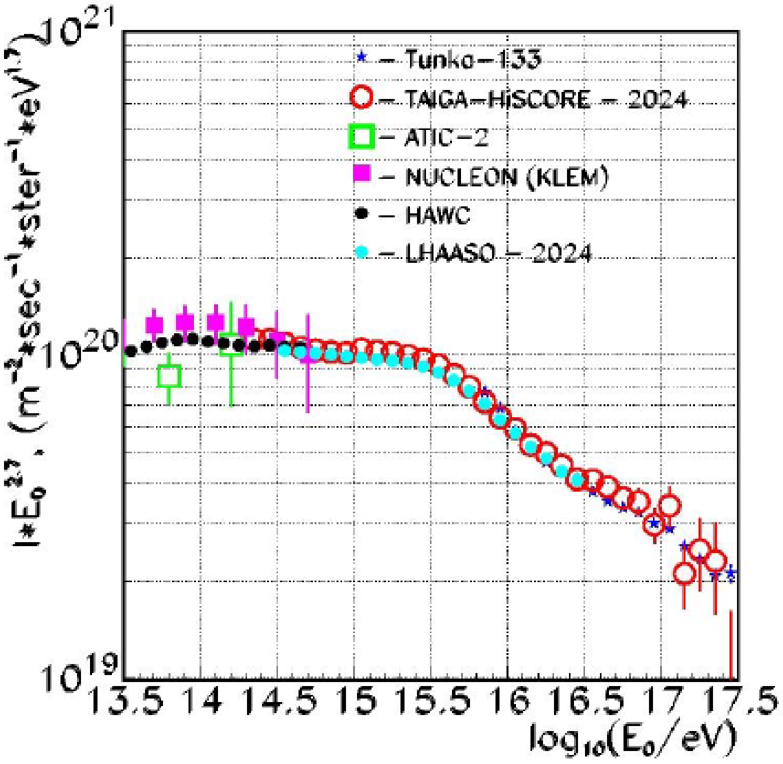


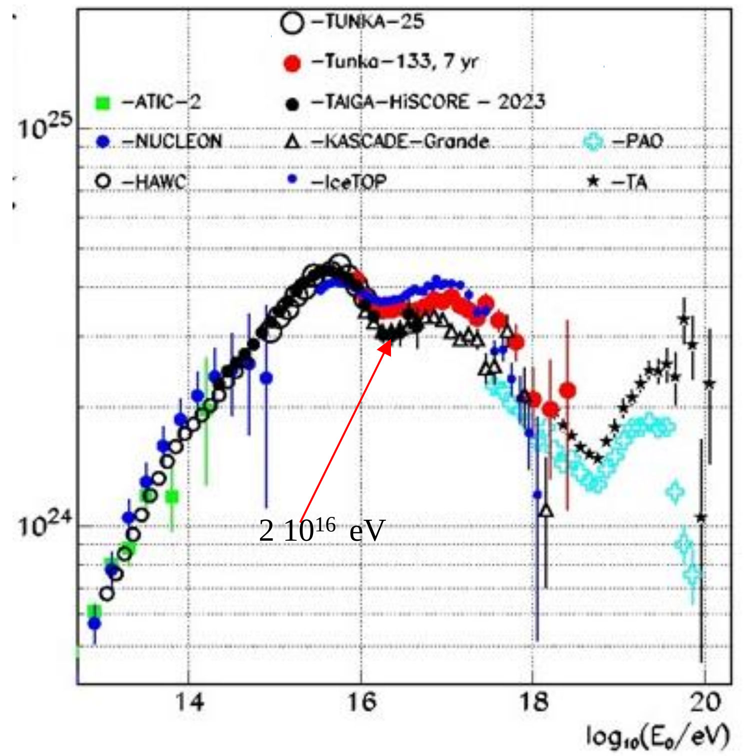




Lidar on-board ISS, Calipso and other satellites - excellent instrument for TAIGA- HiSCORE time calibration
– flat timing profile
- precision pointing

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

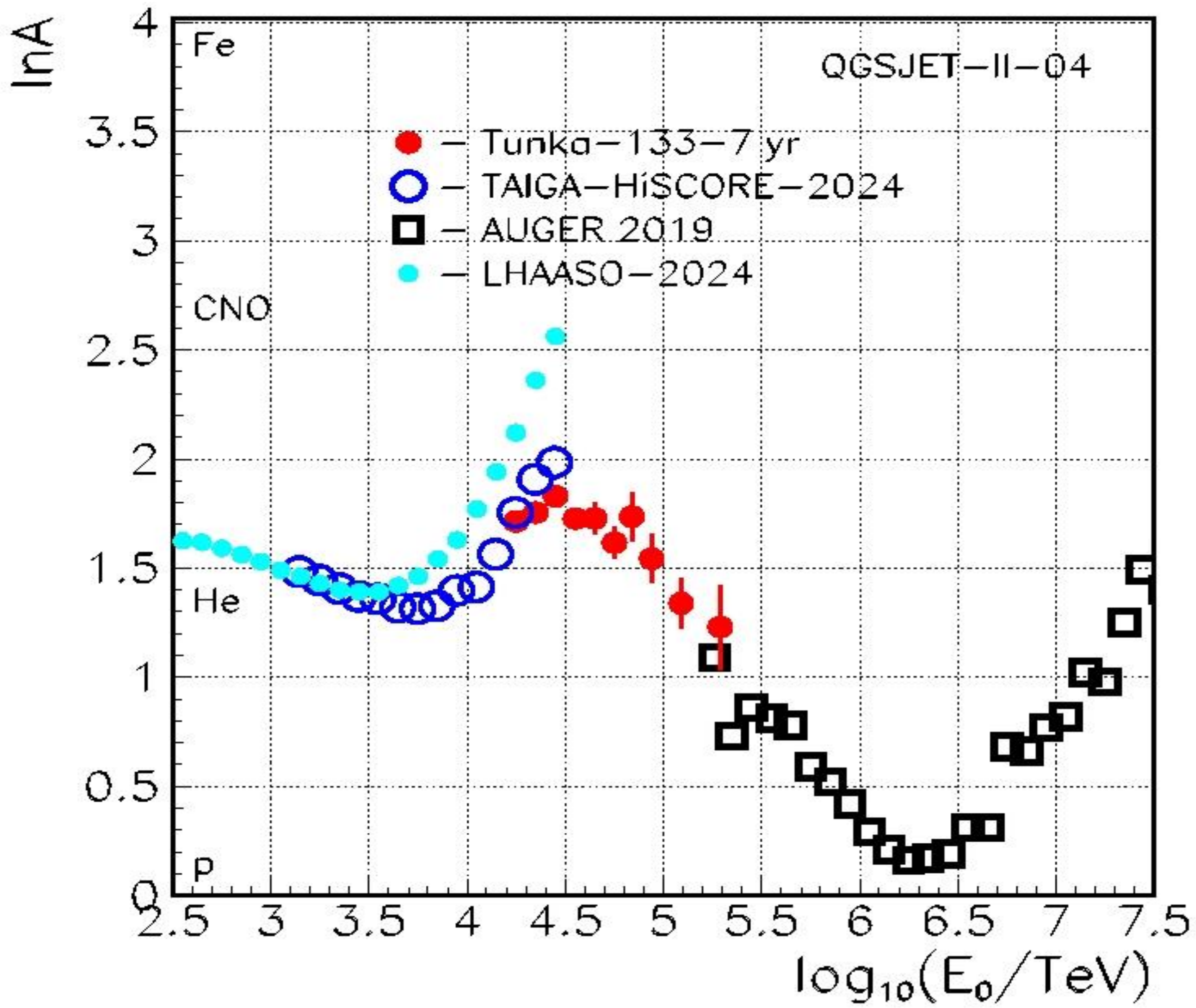




TAIGA-HiSCORE energy spectrum

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

Average mass composition of CR <lnA>, obtained from X max measurement data, depending on primary energy



Details in the report of M. Ternovoy.

Energy spectrum changes slope at 20 PeV.
<lnA> changes behavior at 30 PeV

The TAIGA – IACT

The TAIGA - IACT

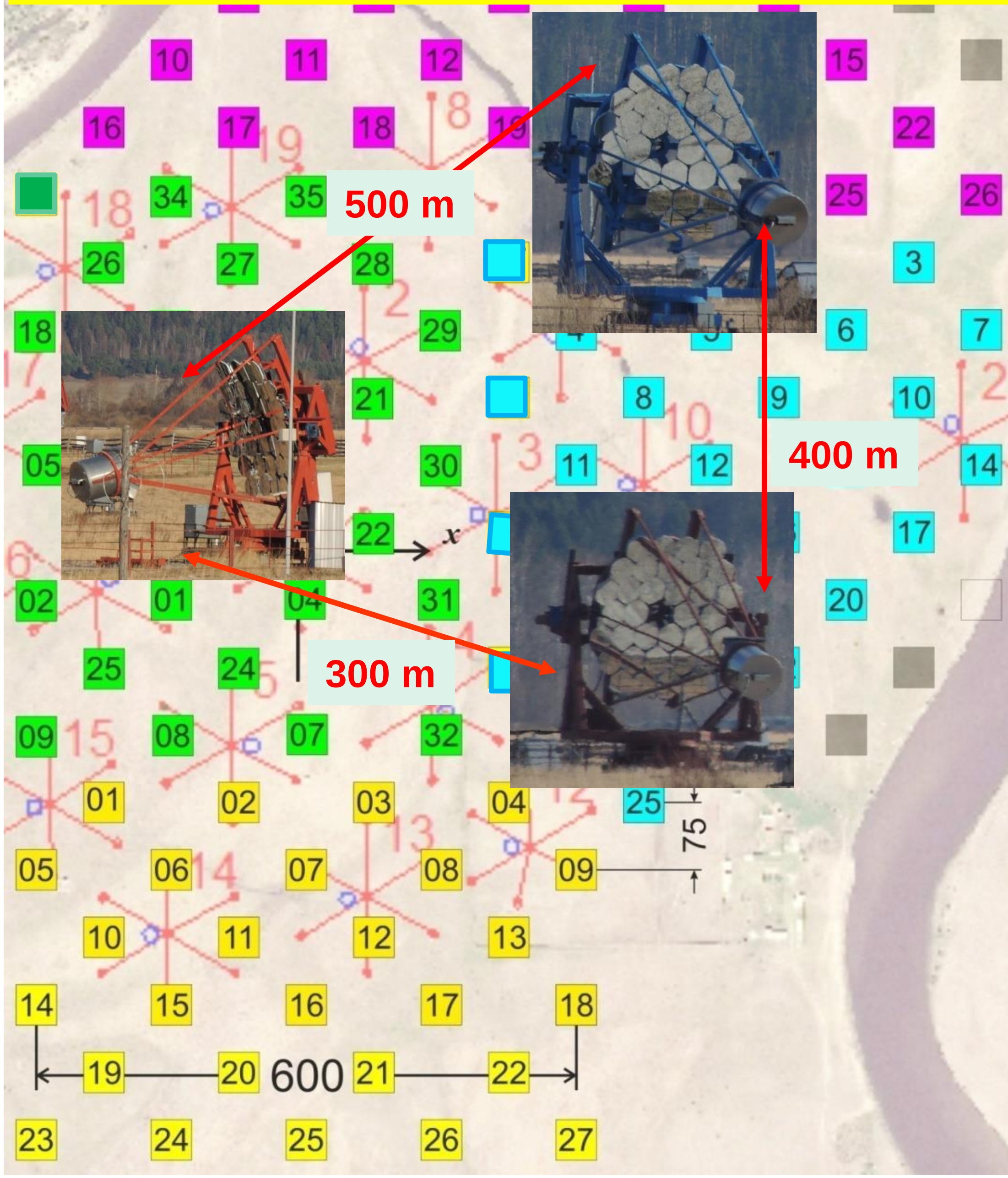
First 2017y, second 2019y, third 2022y

situated at the vertices of a triangle

with sides: 300 m, 400 m and 500 m about

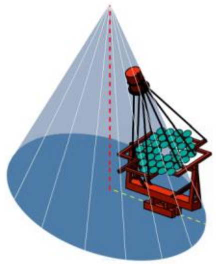
- 34-segment reflectors (Davis-Cotton)
  - Diameter 4.3 m, area ~10 m^2
  - Focal length 4.75 m
  - Threshold energy ~ 2 - 3 TeV
- Camera - 600 PMT XP1911 Ø 19 мм
- FoV - 9.6º (pixel FoV 0.36˚)
- PSF ~0.1˚
- CCD for checking telescope pointing direction.

TAIGA-1, in operation since 2022year

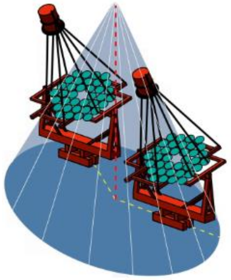


Four approaches for detecting of gamma rays in the TAIGA experiment by Cherenkov detectors

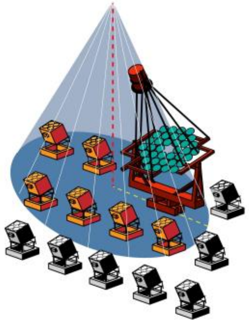
1. **Standalone mode of IACTs operation (E> 2-3 TeV).**
   Hadronic background rejection ~10^{-4}



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}**

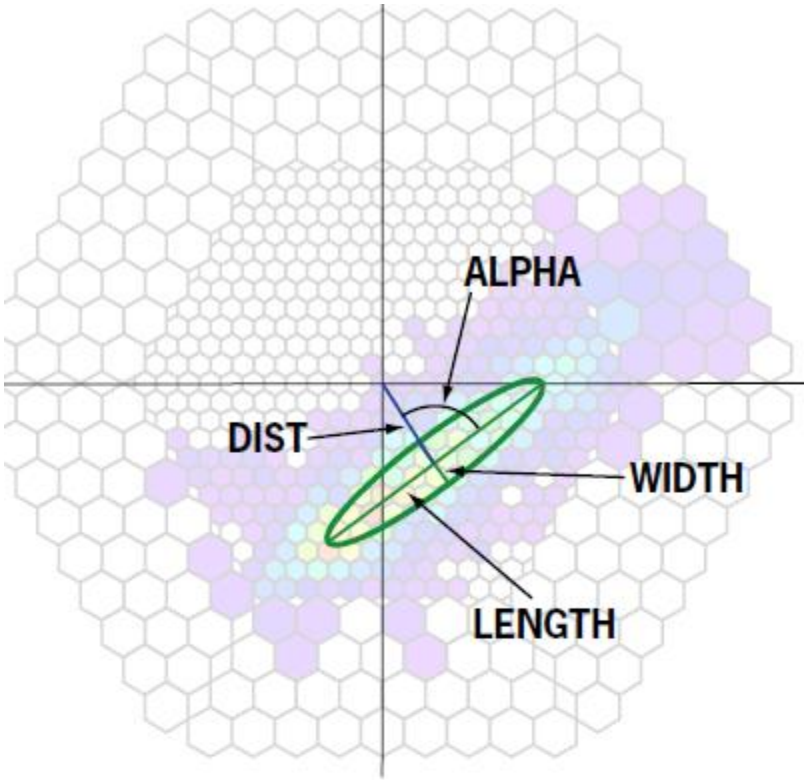


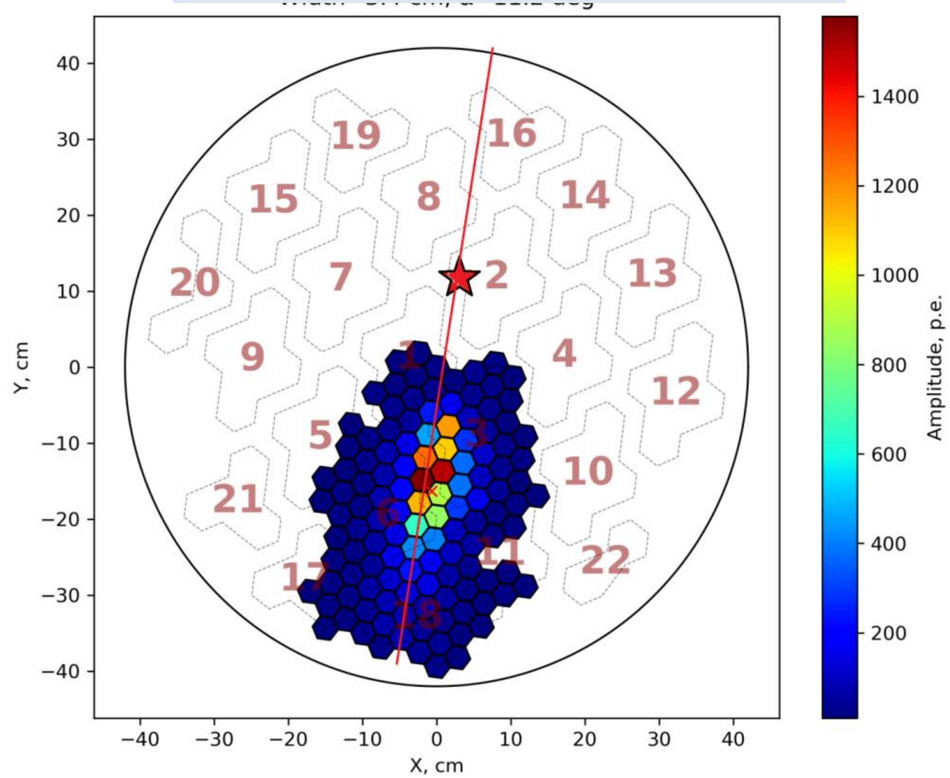
4. **TAIGA- HiSCORE > 300 TeV (additional hadron suppression is required using, for example, data of muon detectors)**

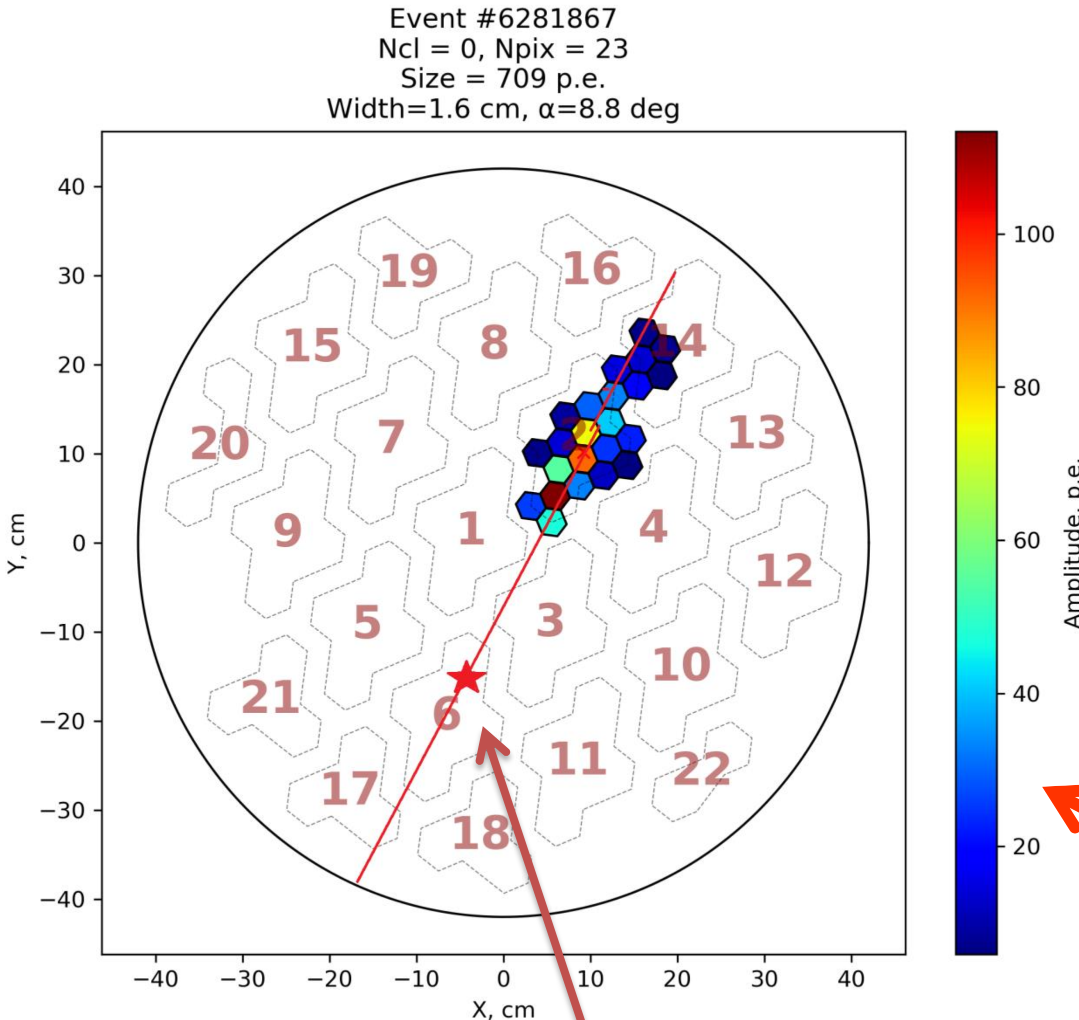
TAIGA-IACT and TAIGA-HiSCORE joint events.

Hillas parameters

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

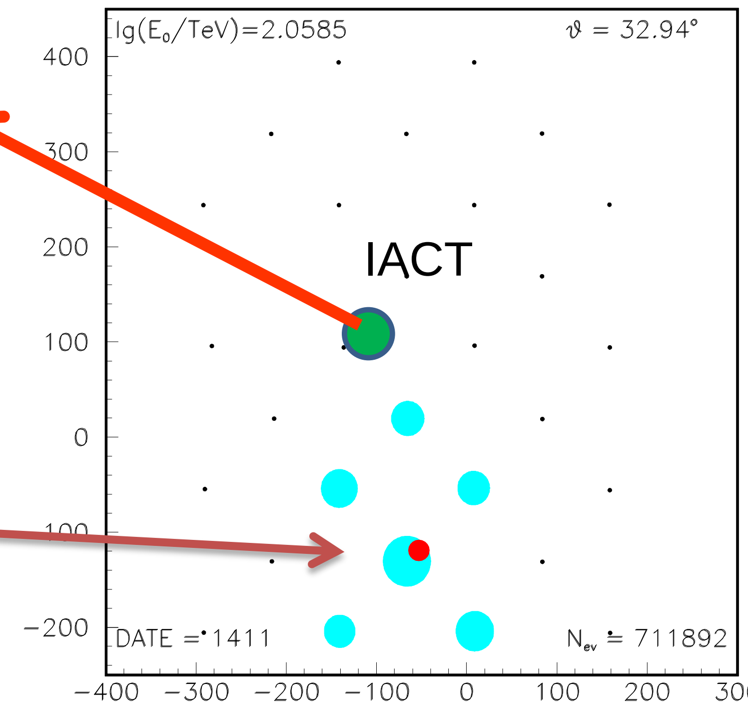






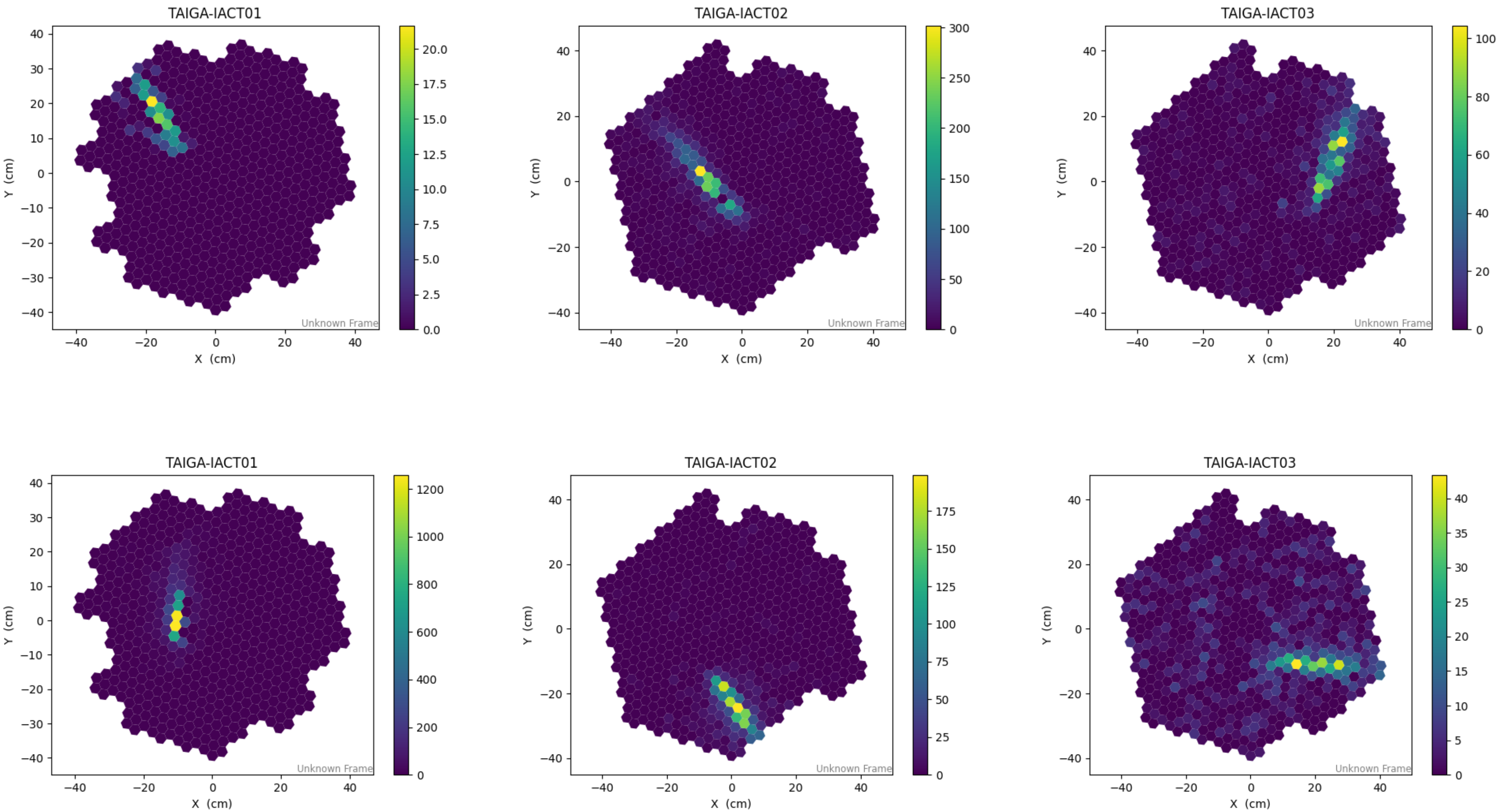
But some events looks as "Gamma-like"

E = 50 TeV
Width = 0.19°

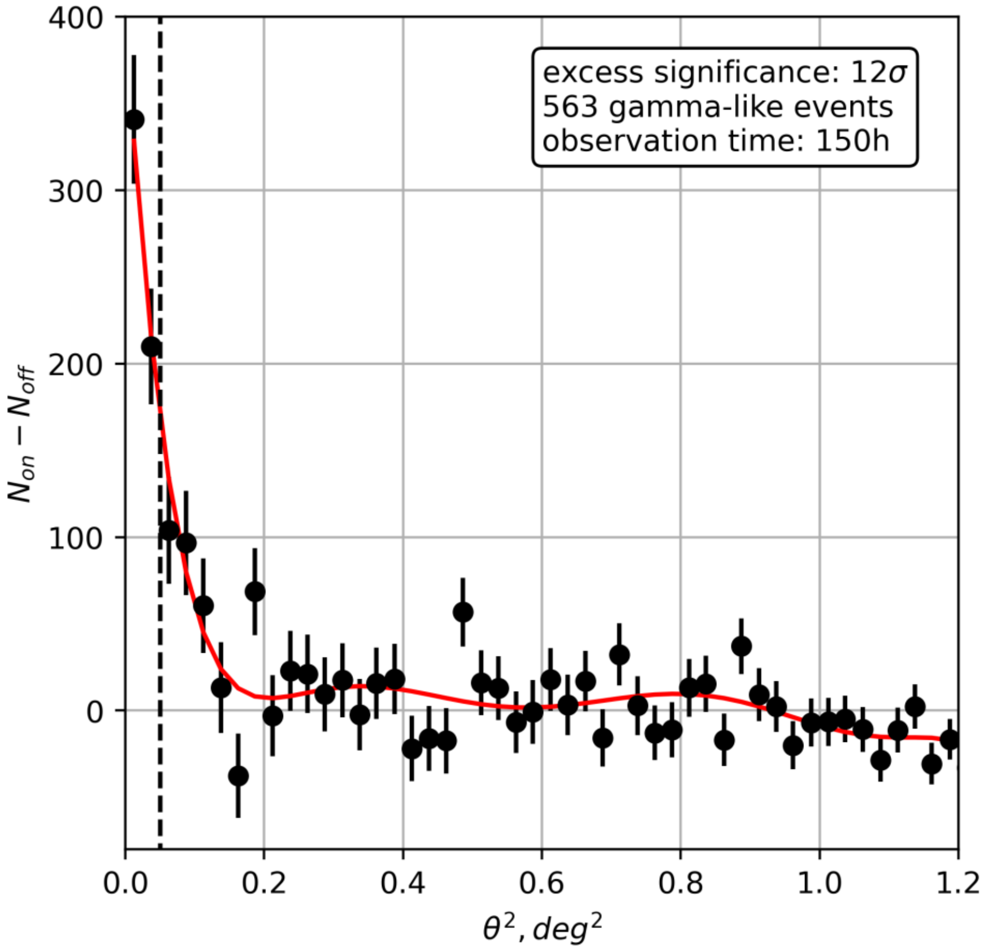


Core position

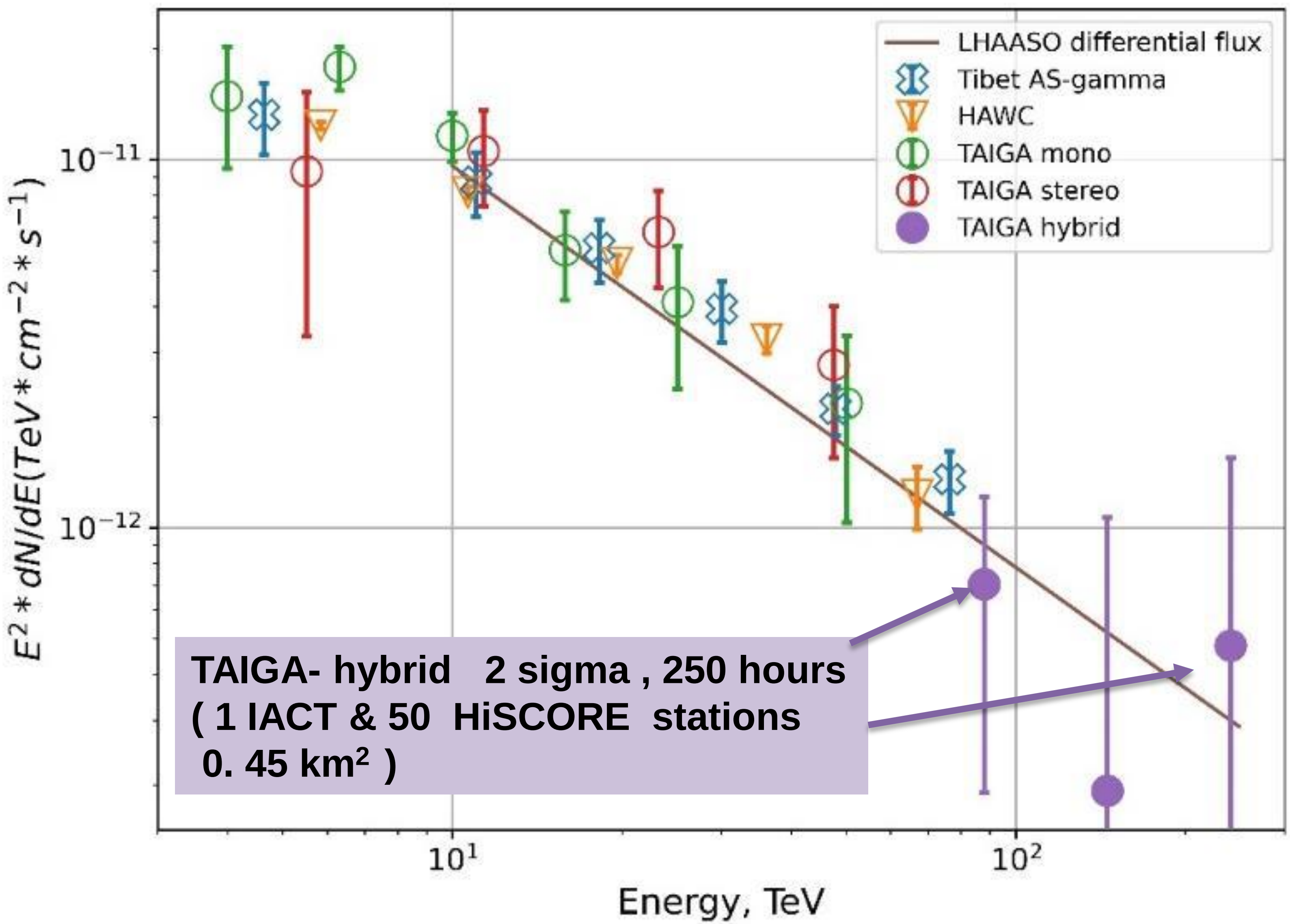
EAS detection by three IACT at a distance of 300 m – 400 m – 500 m in stereoscopic mode for high energies



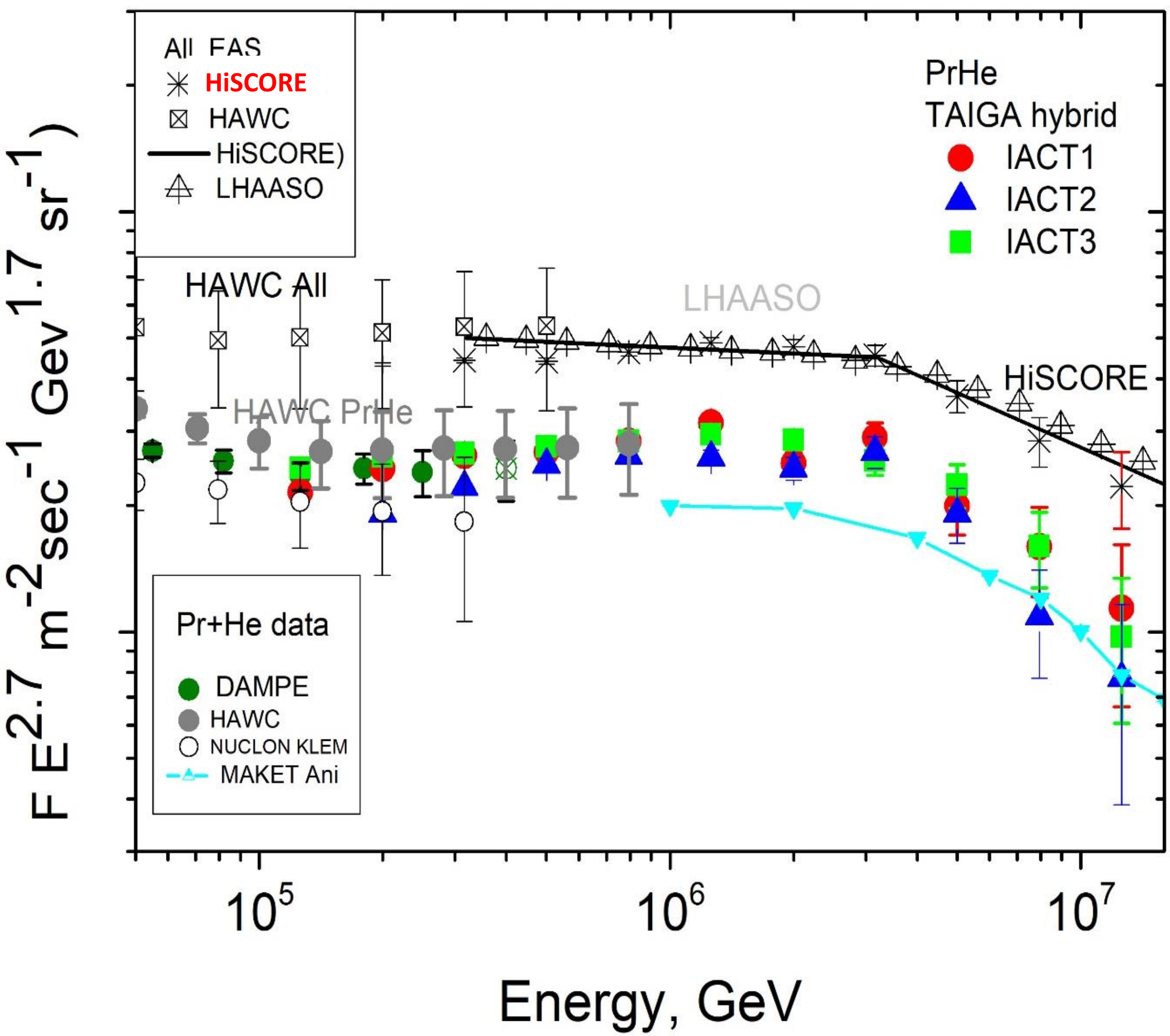
Background subtracted Θ^2-distributions for 150 hours of the Crab Nebula observation (mono mode)



The energy spectrum of gamma quanta from the Crab Nebula



Separation of the light component (p, He) of CR using TAIGA-HiSCORE & IACTs

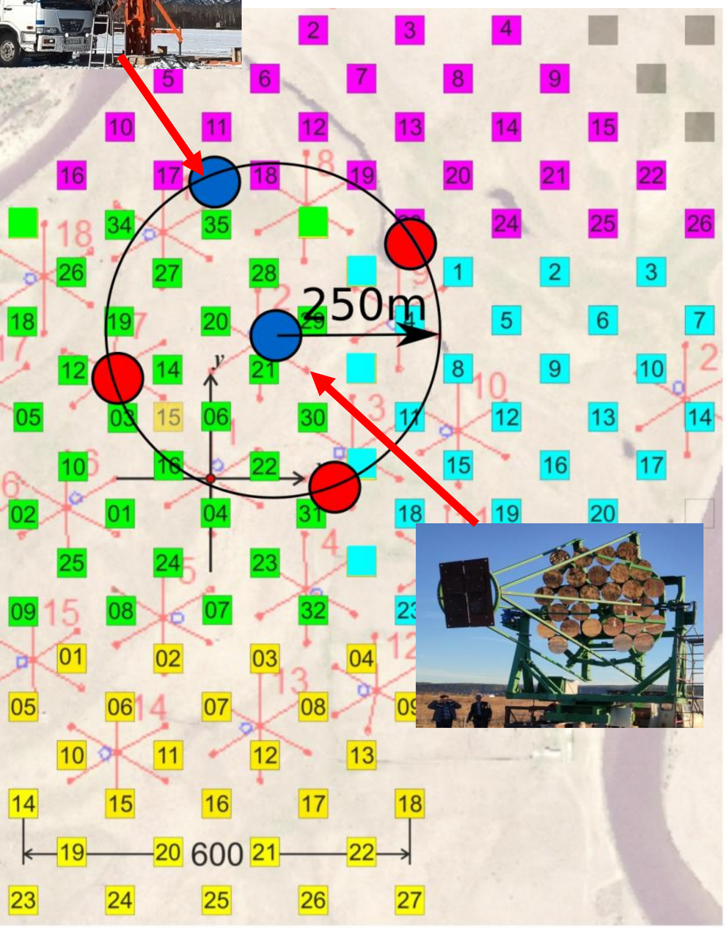


1. Knee for light component at 3 PeV

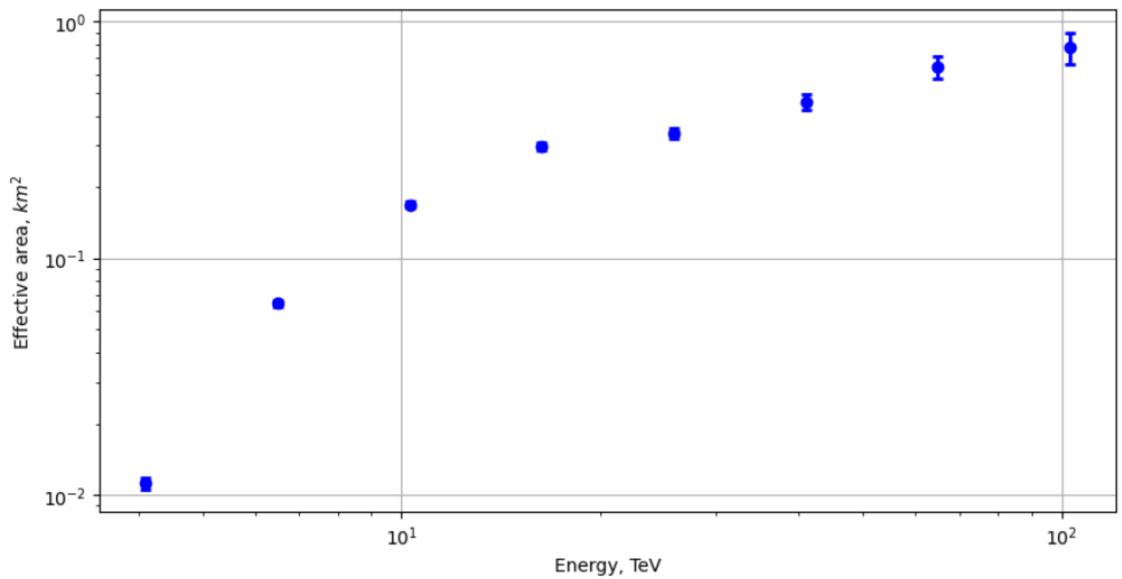
2. In the knee area light component proportion ~60-70%

Fife TAIGA IACT (2024-2026y)

3 +2 new IACT with of 4.3 m mirror diameter



Effective area for gamma detection for stereo mode after hadron suppression



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

IACT in operation

planned IACT

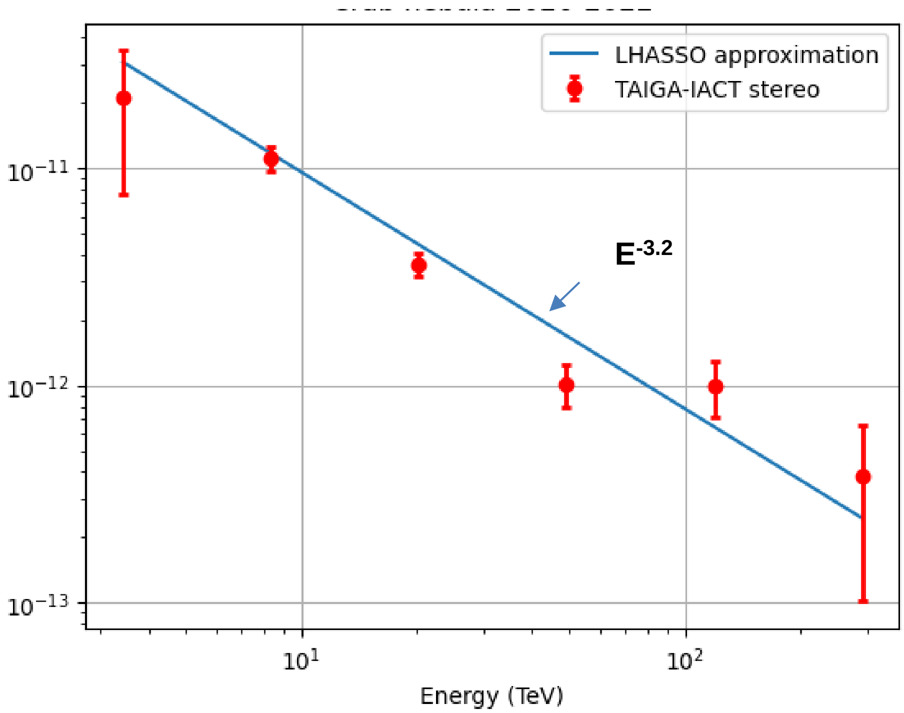
HiSCORE cluster#1

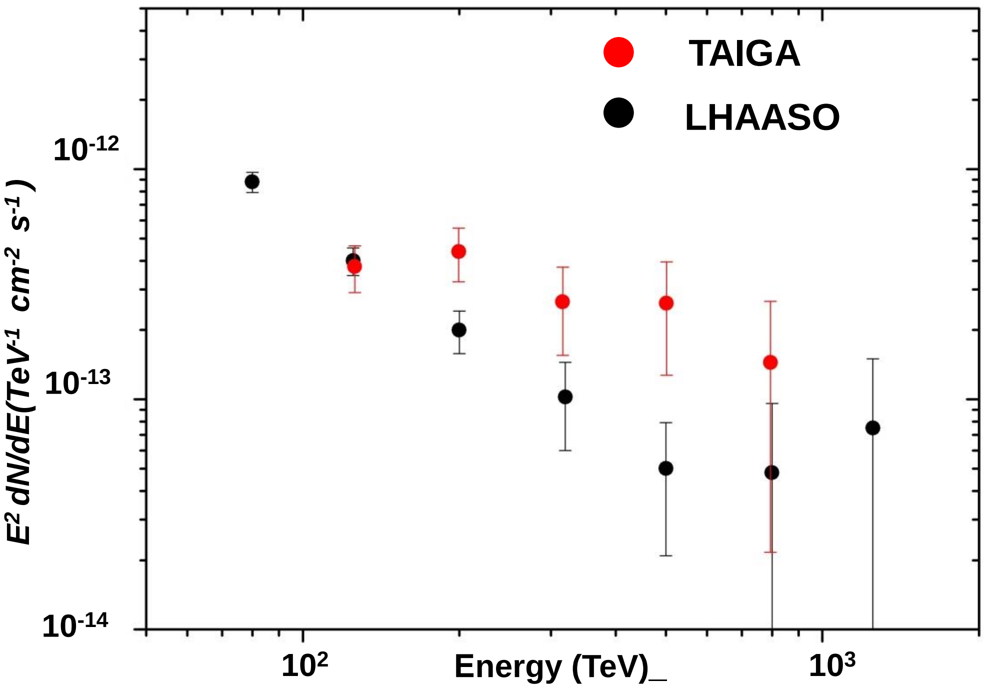
HiSCORE cluster#2

HiSCORE cluster#3

HiSCORE cluster#4

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





Two TAIGA-IACT stereo mode

158 hours of observation.
Significance 12 sigma,
12 events with energy > 100 TeV

Fife TAIGA-IACT stereo mode

Expected gamma-ray spectrum from the Crab Nebula provided that the spectrum at the source has a slope of -2.9
50 events with energies > 100 TeV are expected in 300 hours of observation.

Near future plan (2-3 y)

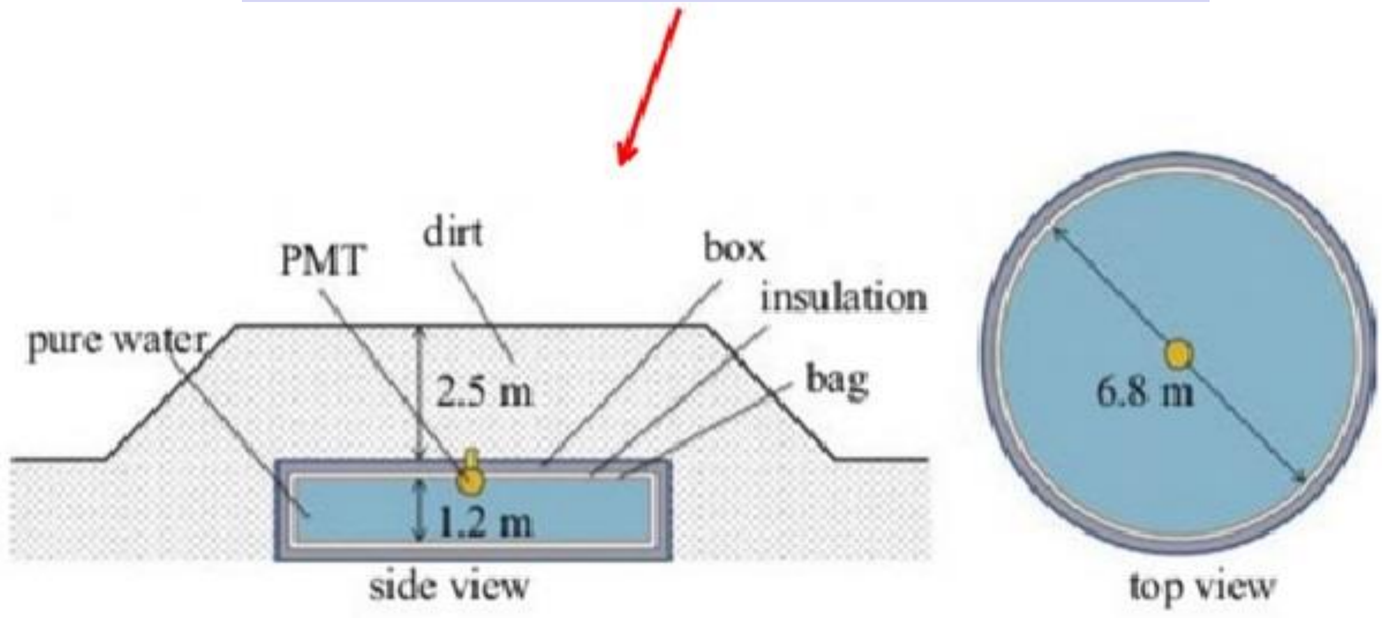
1. 12-15 external TAIGA-HiSCORE optical stations (increasing the effective area up to 1.5 -2 km^2)

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

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

Underground water Cherenkov detectors

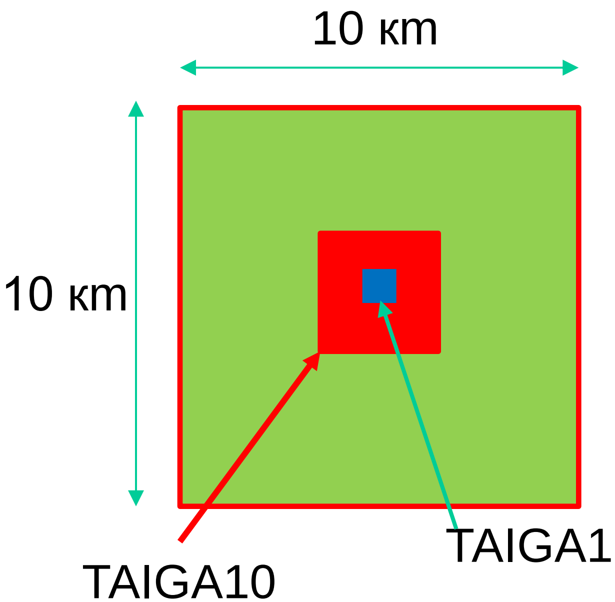
S ~ 40 m², height 1.2 m, depth 2 – 2,5 m.



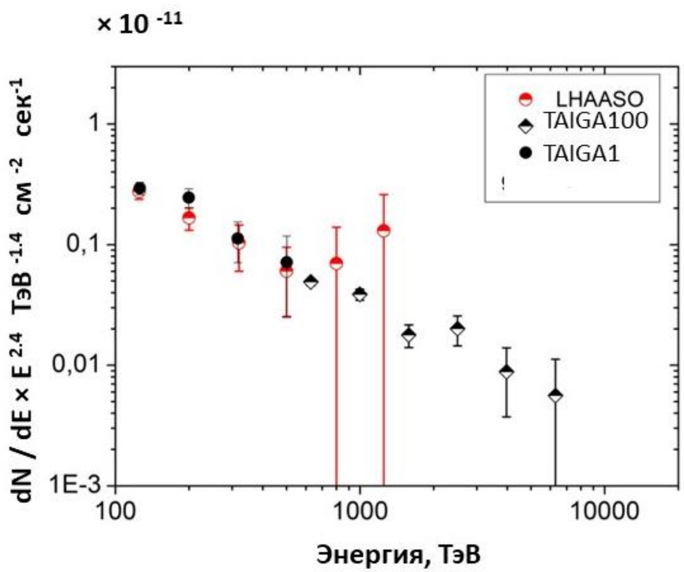
Deployment of the first water detectors: **at the site of the TAIGA-1, summer 2024.**

Deployment of the prototype of water Cherenkov detectors: at the site of the TAIGA-1, summer 2024

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)
~ 1000 scintillation detectors
~ 3000 underground water Cherenkov detectors, 40m² area
1-2 Fluorescent detectors

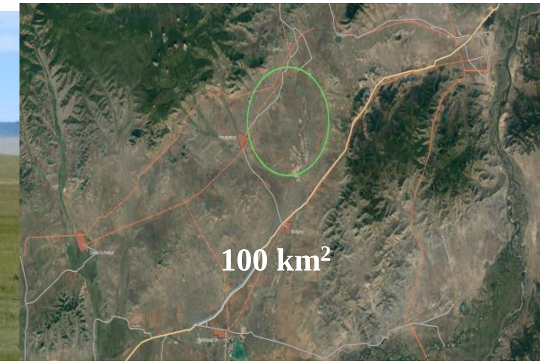


Energy range 100 TeV – 10 PeV.

About 350 gamma from Crab Nebula With energy > 500 TeV for 300 hours duaration of observation (3 years)
The significance level is 10 sigma.
Hadronic background rejection ~10 times by muon detectors

Borgoy steppe – a site for the TAIGA-100

Dzhidinsky District, Republic of Buryatia, 50.84° s. w., 105.81° v. d.



Astroclimatic features*

- high proportion of cloudless nights – 68–71%
- low precipitation and low water vapor content in the atmosphere (3.1–3.3 kg/m^2)
- low level of aerosols pollution in the atmosphere (AOT ≈ 0.11)
- low level of light pollution
- snow cover thickness – 2–3 cm

Topographic features*

- altitude of ~ 800 m a.s.l.
- area > 100 km^2
- site surface slope angles≤ 5°
- soils suitable for digging to a depth of more than 3 m
- water for water Cherenkov detectors is available
- absence of permafrost on the site

Infrastructure features

- 200 km from the regional center (Ulan-Ude)
- automobile, rail and air communications
- power supply - 3 power lines 35 kV and 110 kV
- availability of radio engineering and optical telecommunication systems

* according to the MODIS, VIIRS (NOAA) satellite systems, the MAIAC algorithm (Aqua, Terra) from 2019 to 2023 and the CALIPSO lidar from 2016 to 2021

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 many tens of square kilometers for UH gamma-astronomy and cosmic rays

A point source sensitivity of the TAIGA-1 (for 5 б) :

1 ·10^{-12} TeV /cm^2 s (300 hours, 30–100 TeV)

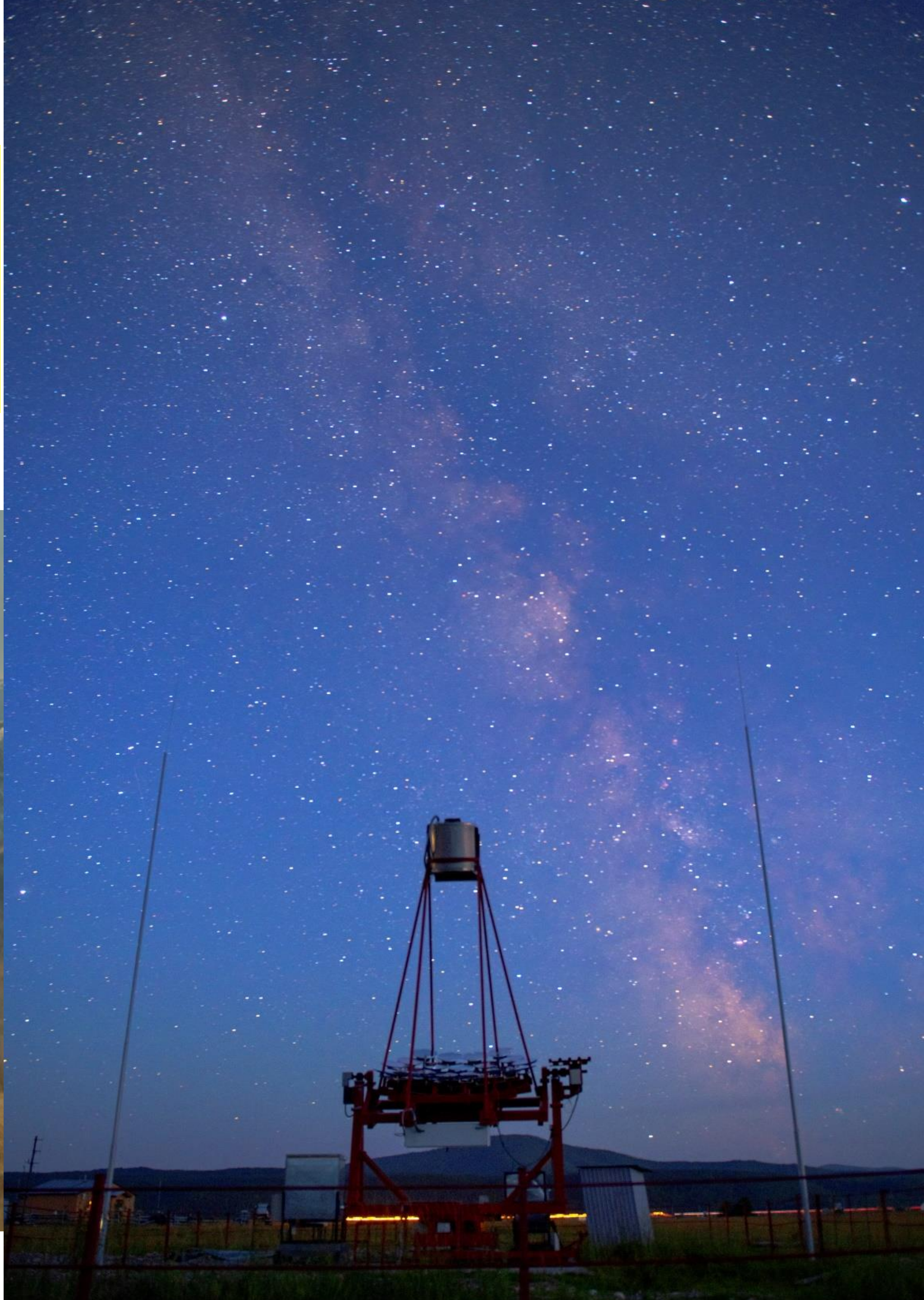
First data about Grab Nebula gamma ray energy spectra for E > 100 TeV by Cherenkov way in stereo and hybrid modes were got.

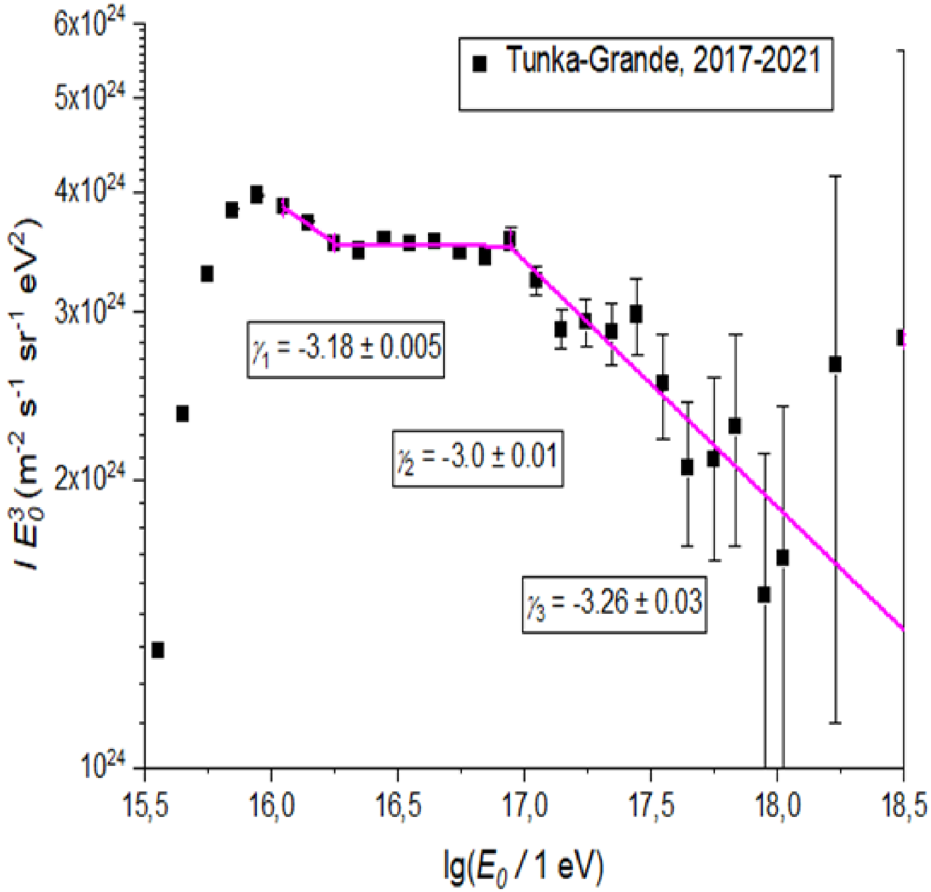
Near Future plan: two new 4 m class and one 6 m class IACT, new particle detectors (scintillation and Underground Cherenkov water)

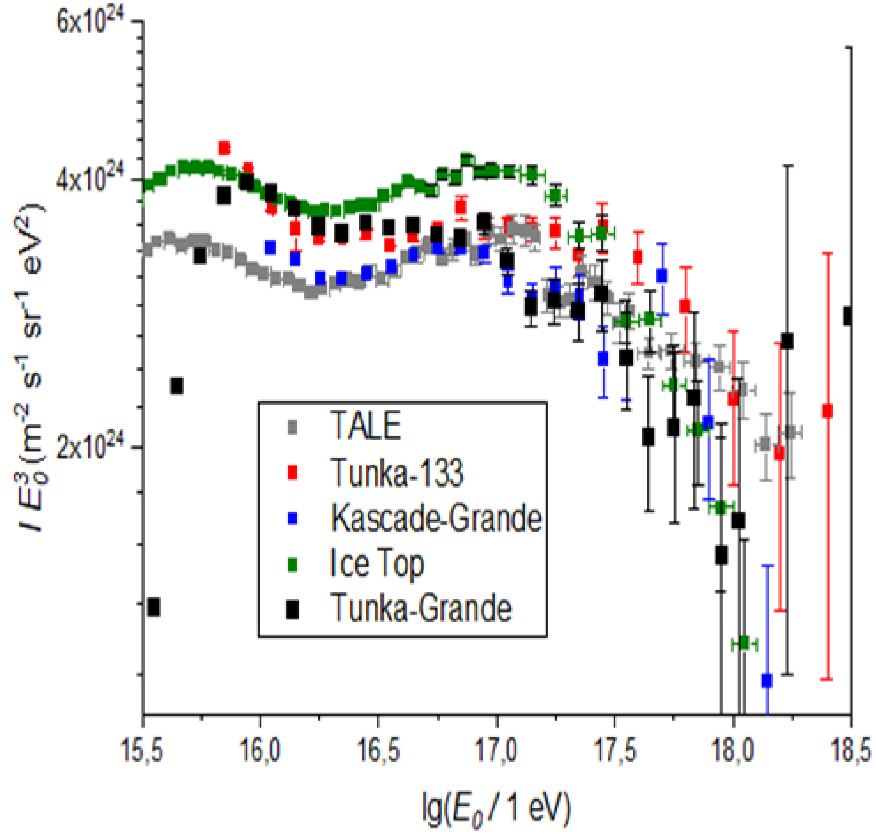
Next plan: 20 -100 square kilometers TAIGA + new technologies

- **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 underground water Cherenkov detectors, 40m^2 area**

Thank you for attention!





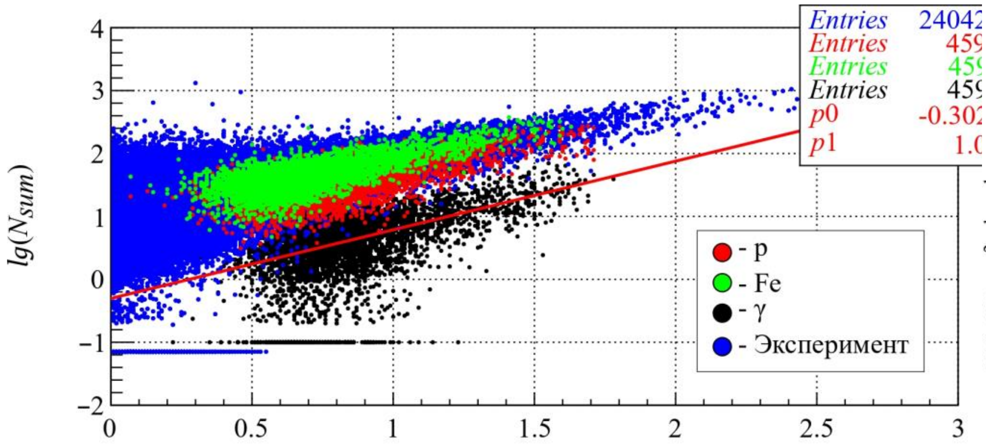


Tunka-Grande CR energy spectrum

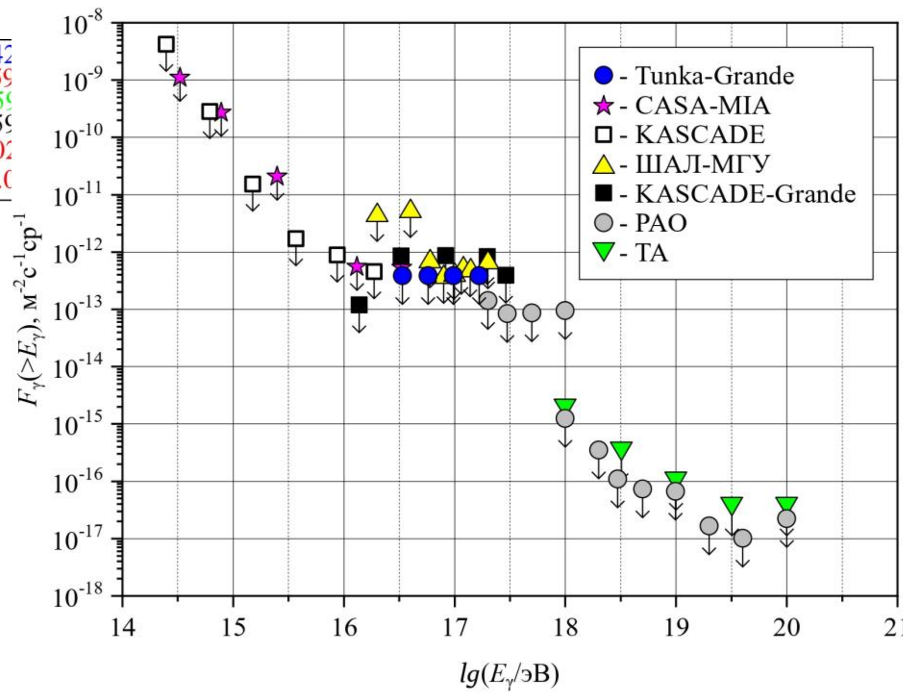
Comparison of the Tunka-Grande & Tunka-133 CR energy spectra with other experimental results

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

Search for diffuse ultra-high energy gamma quanta



lg ρ_{200} (particle/m^2)

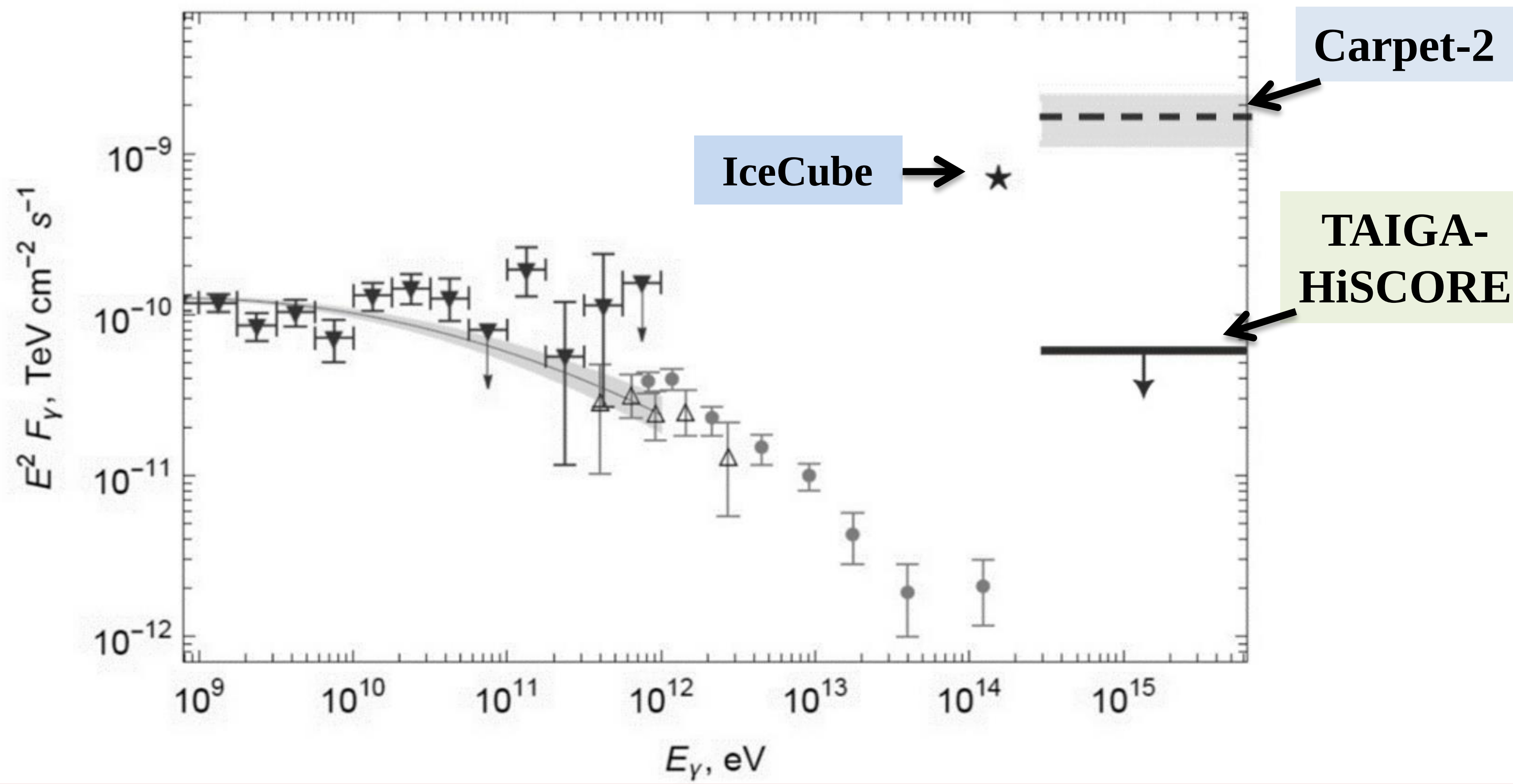


The criterion for selecting candidates for gamma induced EAS : N_{sum} - the number of the all detected muons in all underground scintillation counters located at distance more than 70 m from EAS axis.

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

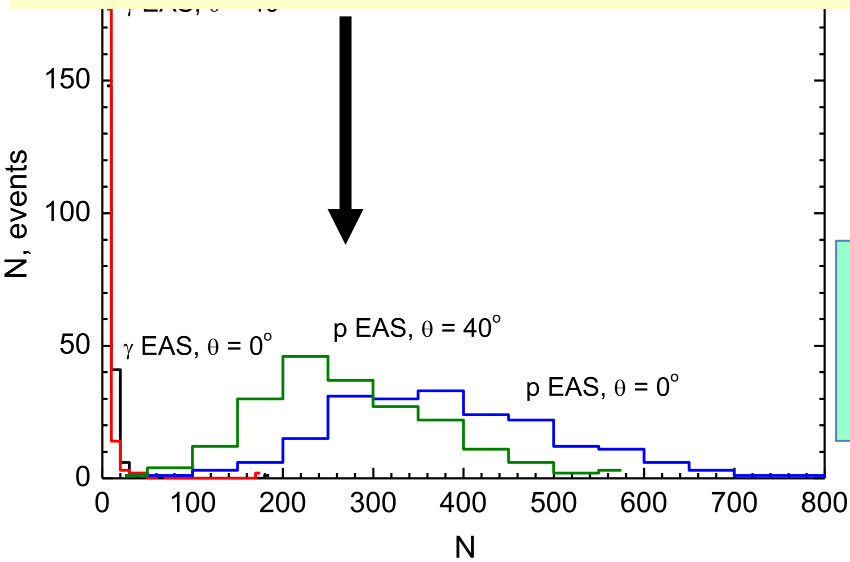
Search for gamma rays with an energy of > 200 TeV (excess of the events number) in the direction of Cygnus Cocoon 13.10.2020 – 11.17.2020



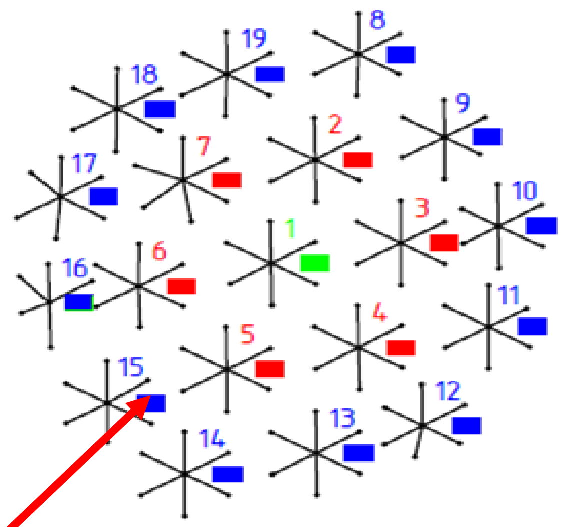
The energy spectrum of Cygnus Cocoon gamma radiation. Gray line: time–averaged flow model 4 FGL; gray triangles-ARGO experiment data; gray circles – data obtained in the HAWC experiment; black triangles–flash detected by Fermi-LAT

The TAIGA particle detectors.

- Permanent absolute energy calibration of Cherenkov arrays Tunka-133 and TAIGA-HiSCORE.
- Round-the-clock duty cycle;
- Study of the energy spectrum and mass composition of CR
- Search for diffuse gamma quanta in the energy range of 10 – 1000 PeV
- Study of thunderstorm phenomena, including TGE
- **Rejection of p-N background**



The Tunka – Grande scintillation array



228 former KASCADE-Grande scintillation counters with $S=0.64\ m^2$

152 the same underground muon counters in 19 stations.

More details in A.Ivanova talk

The TAIGA-Muon scintillation array

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

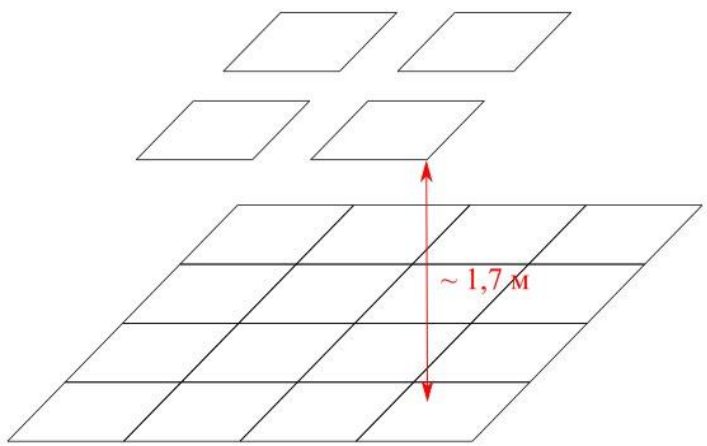
Wavelength shifting bars are used for collection of the scintillation light.

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 counters

Surface counters of a TAIGA-Muon cluster



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

Surface counters of a TAIGA-Muon cluster

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