The TAIGA - an advanced hybrid detector complex for astroparticle physics, cosmic ray physics and gamma-ray astronomy

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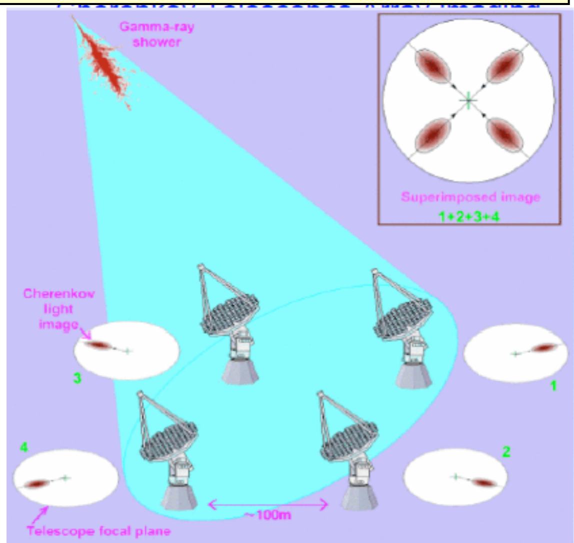
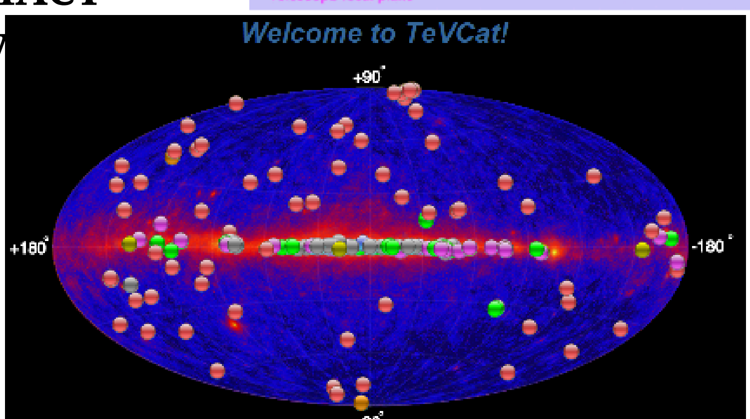
For TAIGA collaboration.

Two ways of EAS Cherenkov light detection in gamma-astronomy and cosmic ray physics

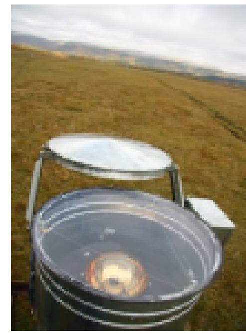
Imaging Cherenkov arrays - HEGRA, HESS, MAGIC, VERITAS…

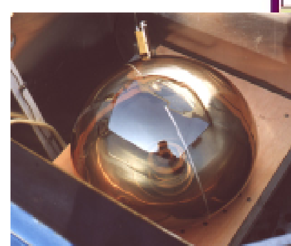
More then 200 sources (SNR, PWN, pulsars etc.) of gamma rays with energy more than 1 TeV were discovered with IACT arrays

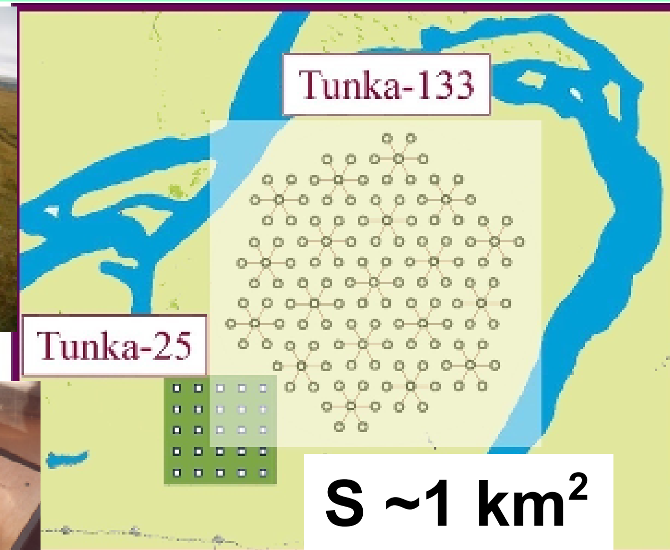


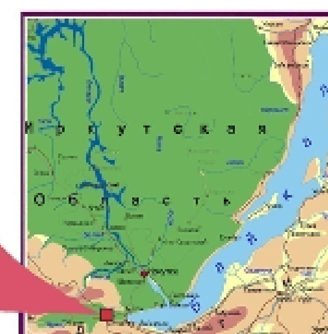


Non-imaging timing Cherenkov arrays in the Tunka valley.







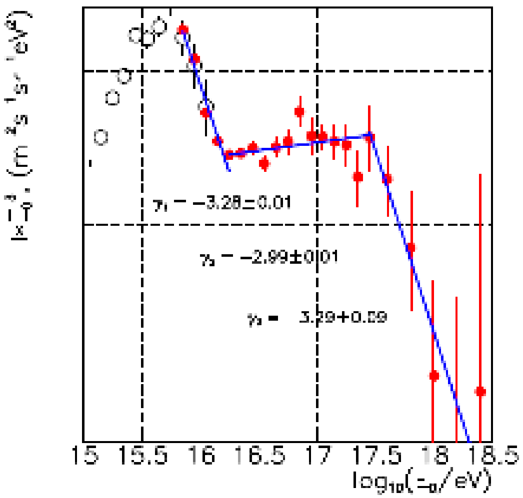


51° 48' 35'' N
103° 04' 02'' E
675 m a.s.l.

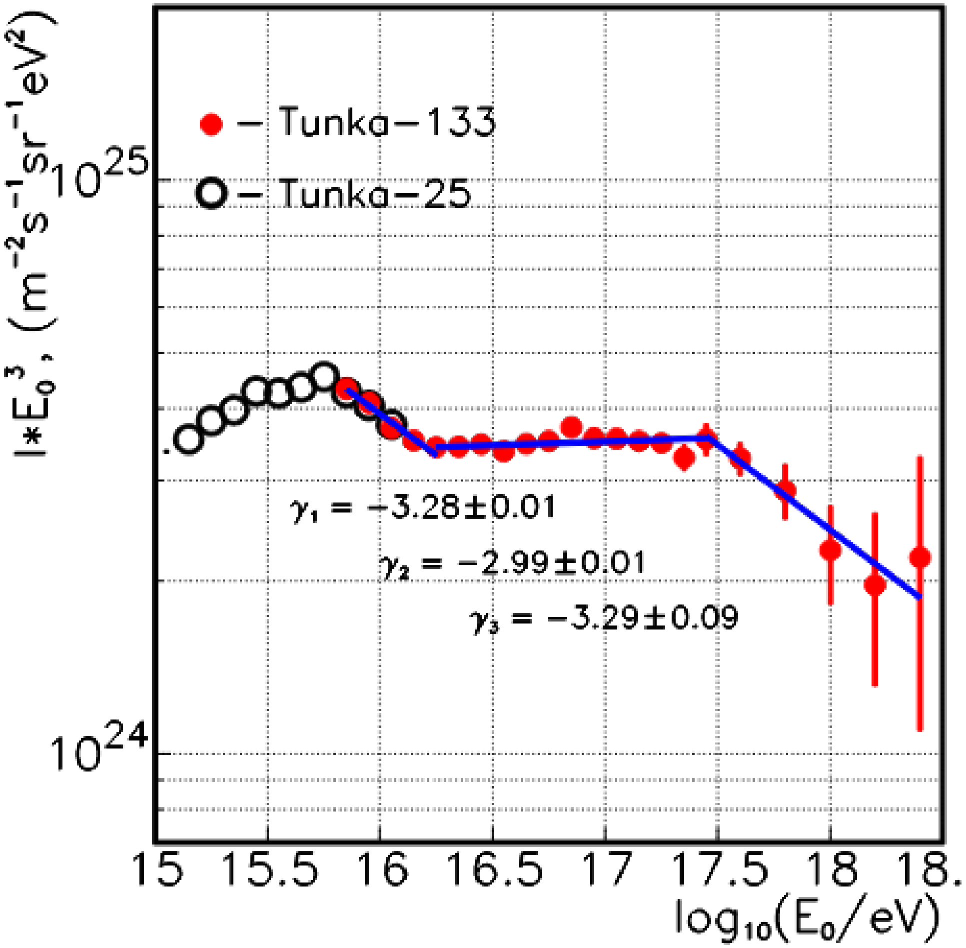
All particles energy spectrum $I(E)\cdot E^3$ (7 years)

Advantages of 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 (Xmax ~ 20 -25 g/cm²).
3. Good angular resolution (~ 0.5 degree).
4. Low cost.



Stretched energy scale



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

APP, 117 (2020) 102406

TAIGA - Collaboration

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(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
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Institut fur Experimentalphysik, University of Hamburg (UH), Germany
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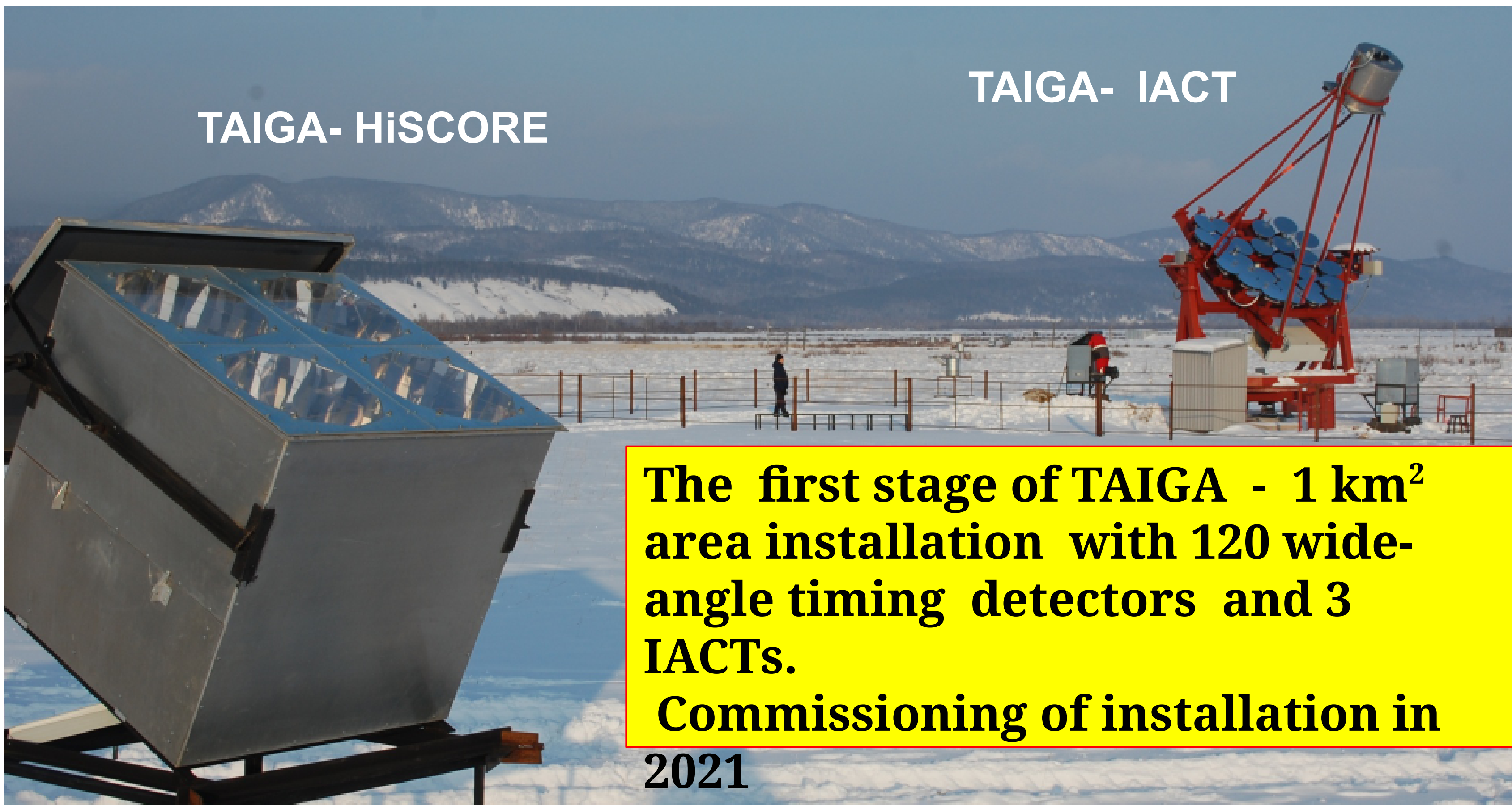
ISS , Bucharest, Rumania

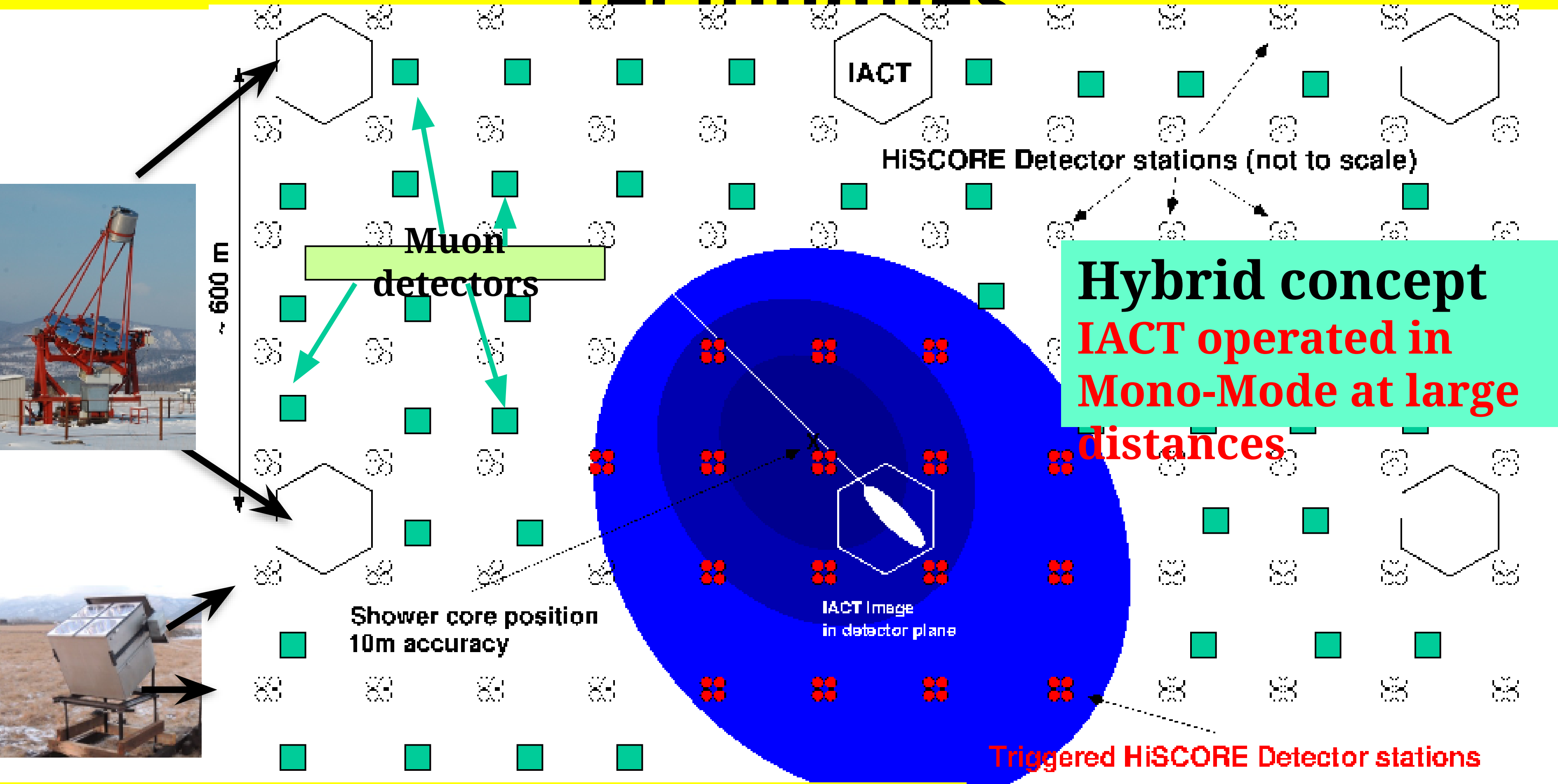
The TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) - a hybrid detector for very High energy gamma-ray astronomy and cosmic ray physics in the Tunka valley, Siberia, Russia

The main idea: A cost effective approach for construction of large area installation is a joint operation of wide-field-of-view timing Cherenkov detectors (the *non-imaging technique) with a few small-size Imaging Air Cherenkov Telescopes.*



The first stage of TAIGA - 1 km^2 area installation with 120 wide-angle timing detectors and 3 IACTs.
Commissioning of installation in 2021

TAIGA: imaging + non-imaging techniques

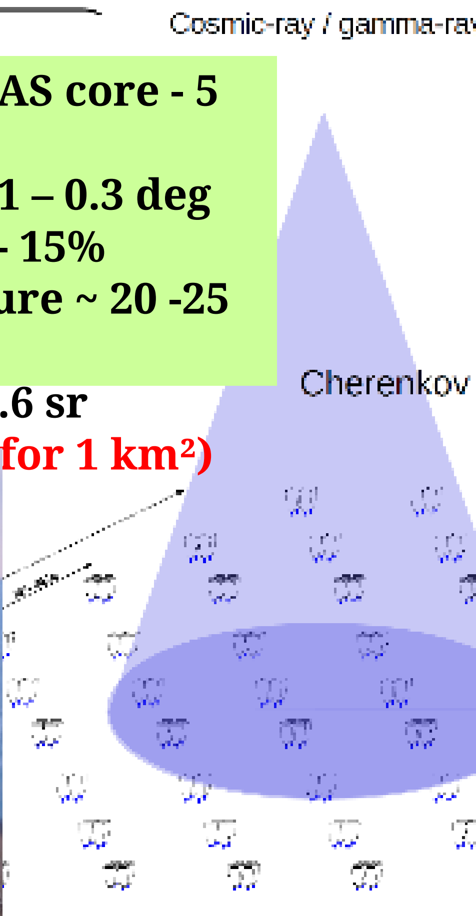


Hybrid concept
IACT operated in Mono-Mode at large distances

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

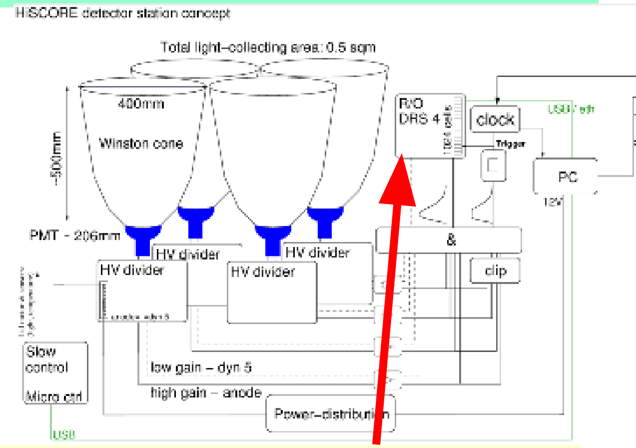
TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

- **Wide-angle time- amplitude sampling non-imaging air Cherenkov array.**
- **Spacing between Cherenkov stations 80-120 m (106 m at present) ~ 80 -150 channels / km^2.**

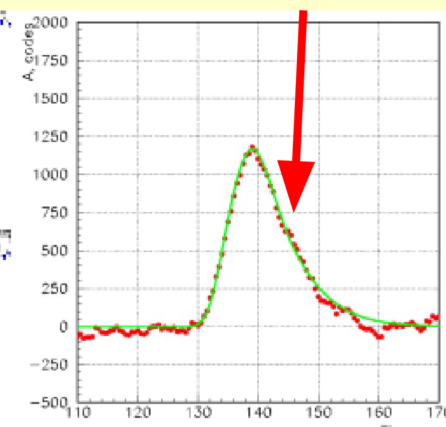


1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.3 deg
3. Energy resolution ~ 10 - 15%
4. Accuracy of X_{max} measure ~ 20 -25 g/cm^2
5. Large Field of view: ~ 0.6 sr

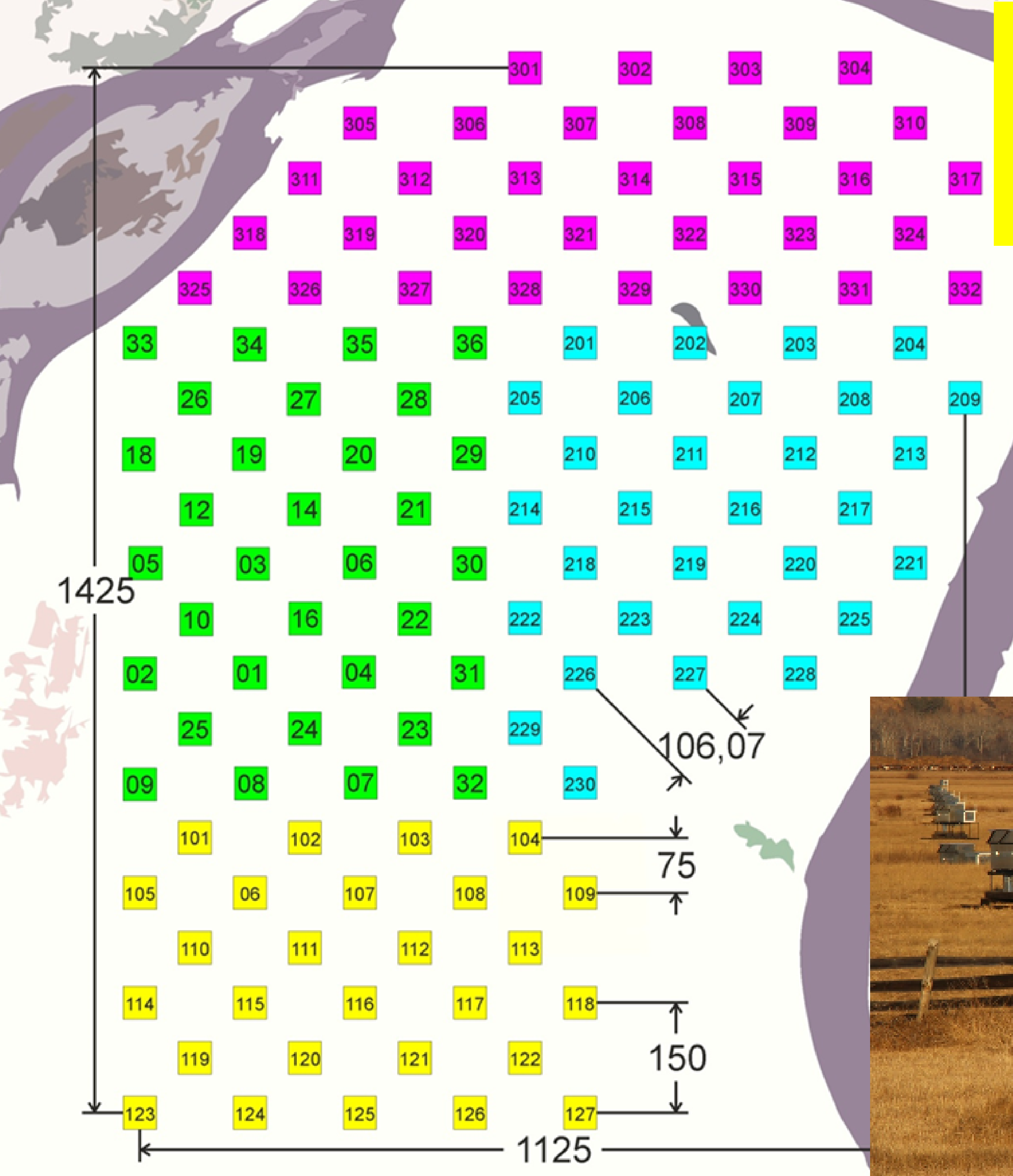
Total cost ~ 8 millions $ (for 1 km^2)



DRS-4 board (0.5 ns step)



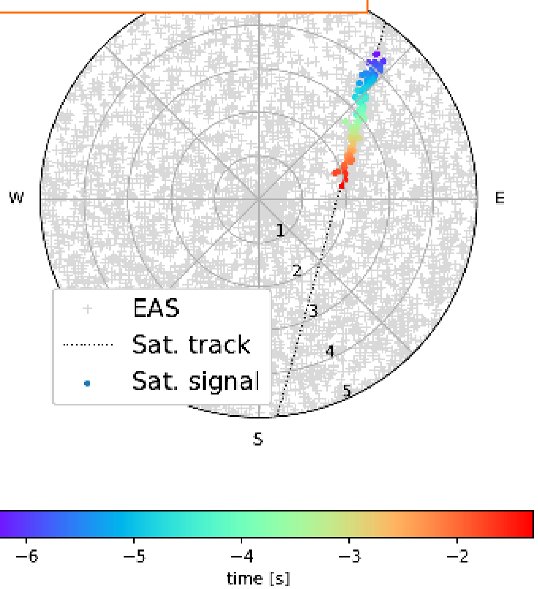
TAIGA-HiSCORE 2021y – 120 Cherenkov stations



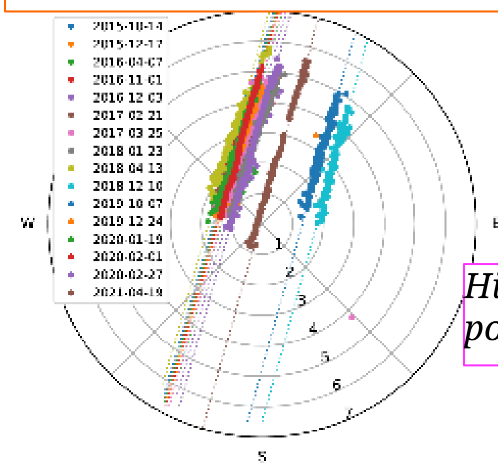
TAIGA:
Precision calibration using satellite-based Lasers

- Space based LIDARs are ideal tools to calibrate AirCherenkov Arrays and IACTs
  - absolute pointing (source independent), internal timing, cross-calibration …
- TAIGA pioneered usage of satellites LIDARs : Int.Space Station (CATS), Calipso-Satellite
  - 2015-2017: 12 observations of Int.SpaceStation Laser [PoS(ICRC2017)754]
  - 2015-2021: 16+ Calipso observations
- Calipso: started targeted observations with IACTs in April, 2021 (stereo mode)

Calipso on HiSCORE-Sky 10.12.2018



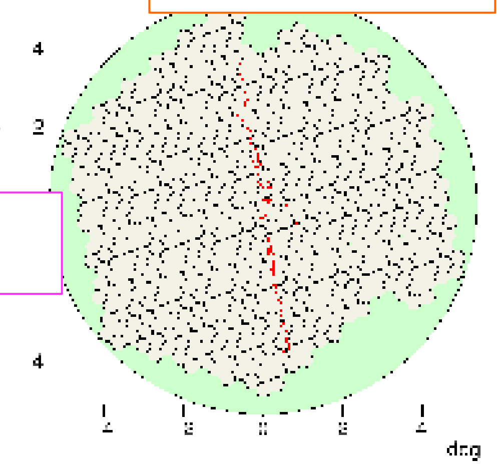
16 passages over HiSCORE-Sky in 2015-2021



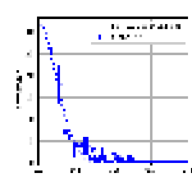
Camera - HiSCORE

HiSCORE absolute pointing: 0.1° (ISS)

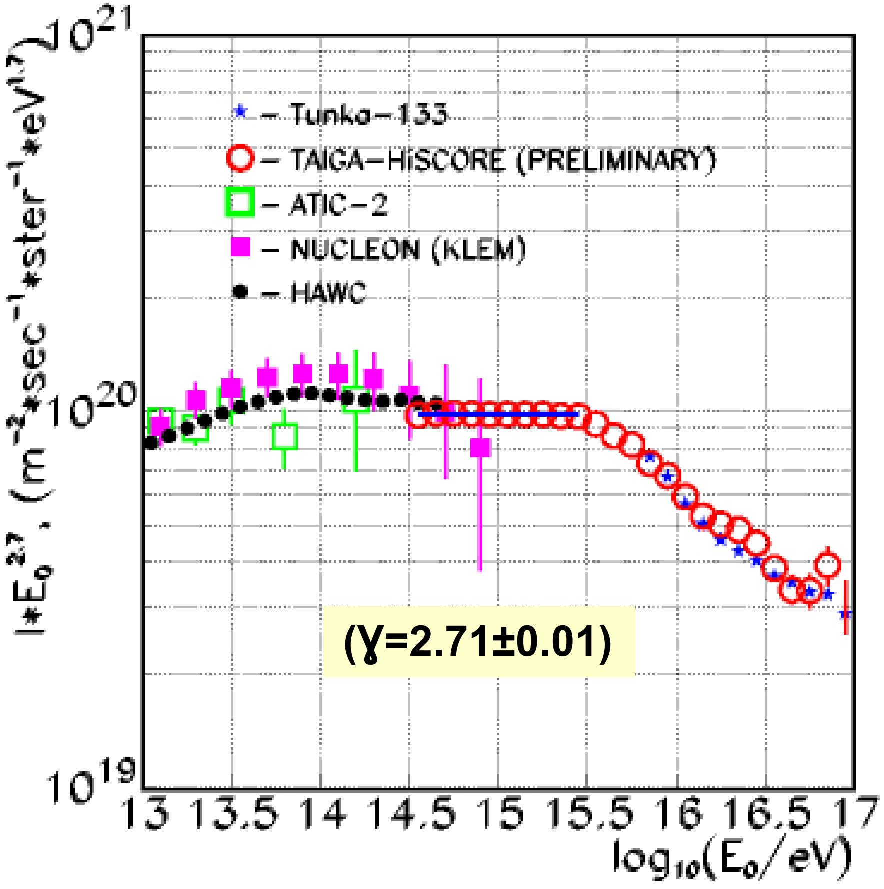
Calipso in IACT-1 19.4.2021

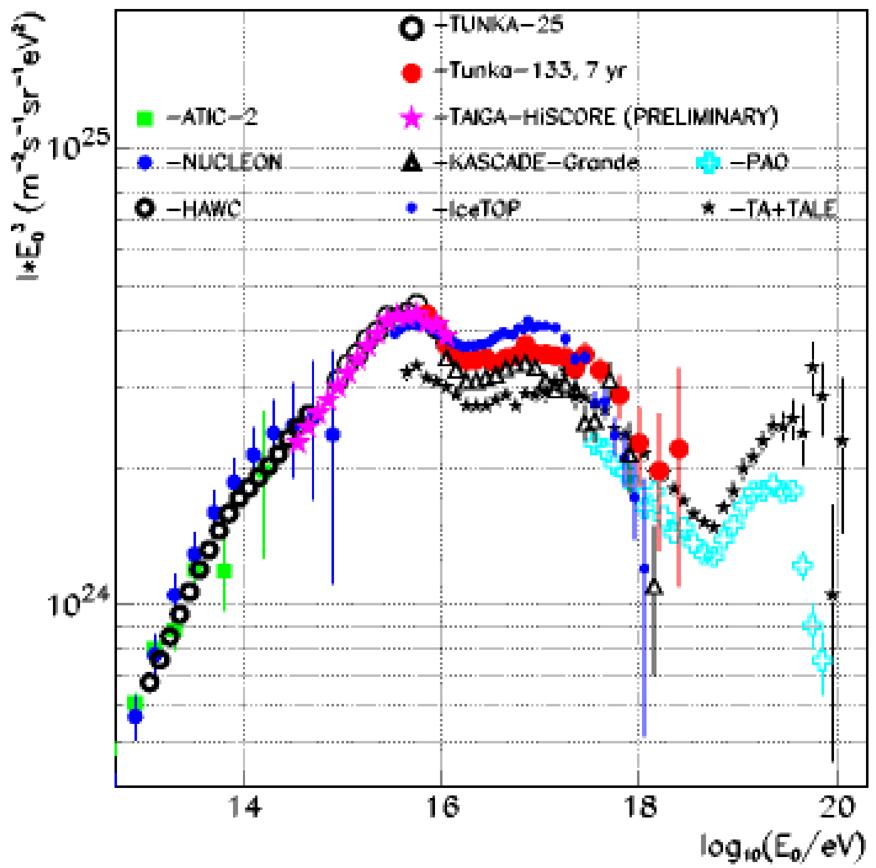


Estimation of PW pointing resolution: rms ~0.05°

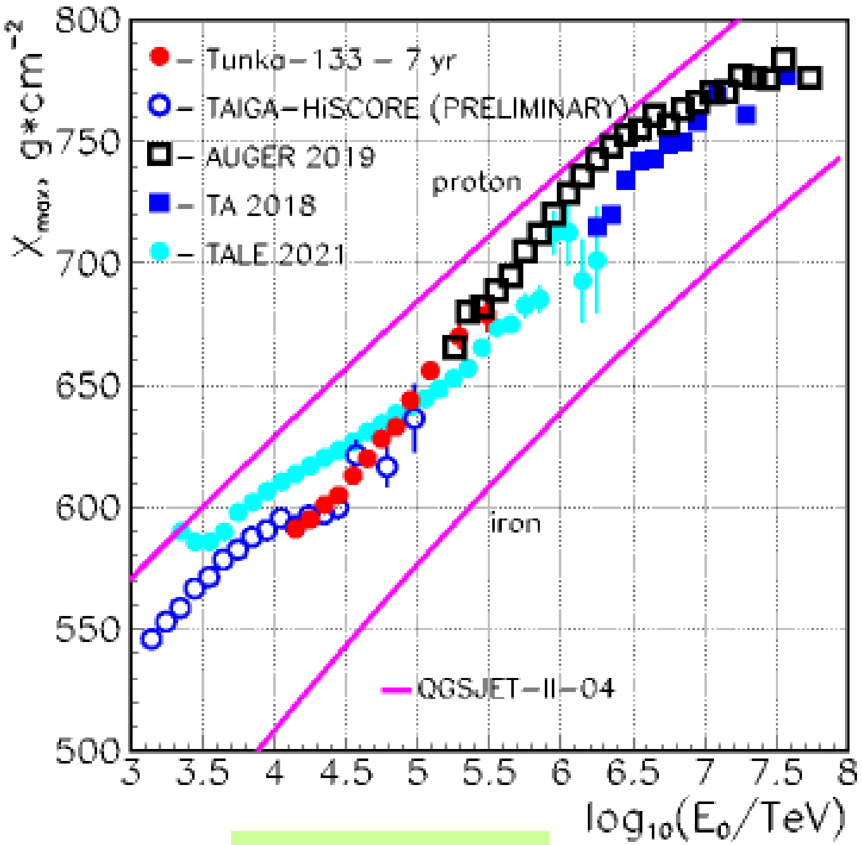


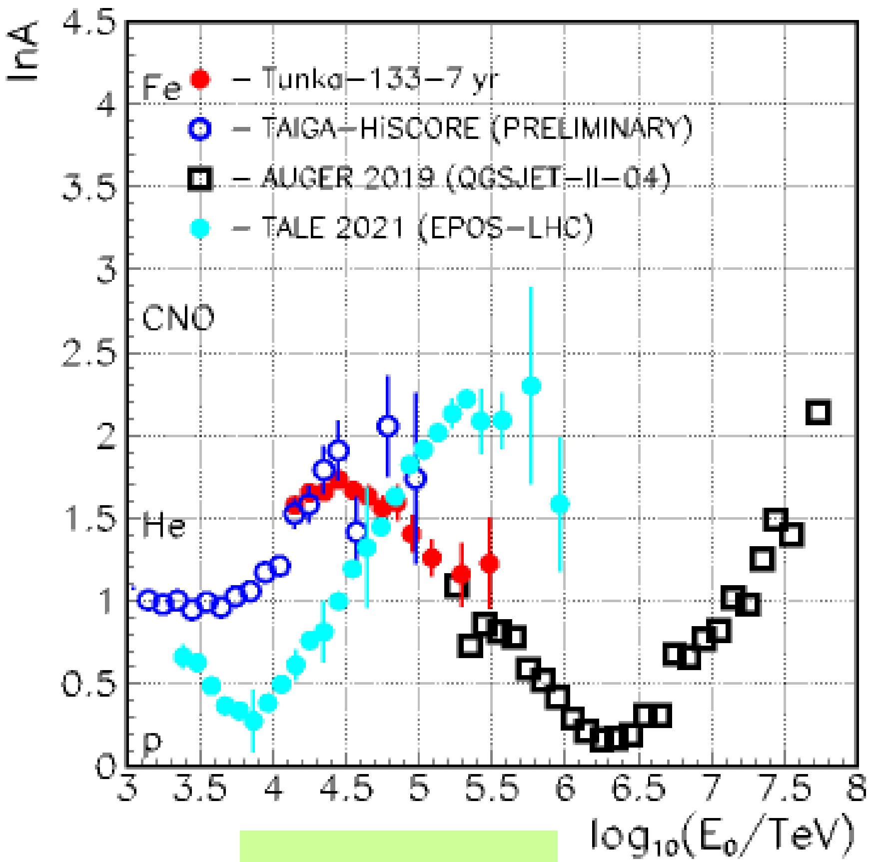
Cosmic ray energy spectrum ($I(E)\cdot E^3$)





Tunka-133 &TAIGA-HiSCORE mass composition





X_{max}

Ln A

The TAIGA – IACT

The TAIGA – IACT: First - 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 , FOV – 9.6° (!) 560 pixels

Threshold energy ~ 1.5 TeV

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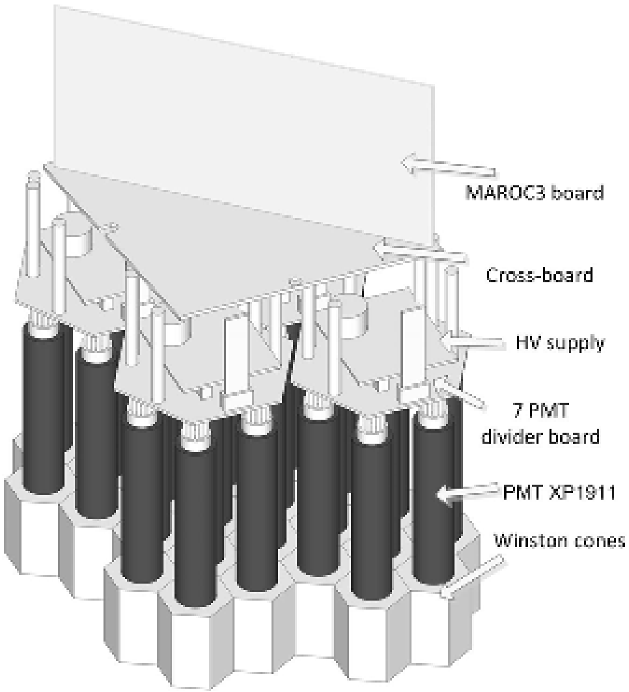
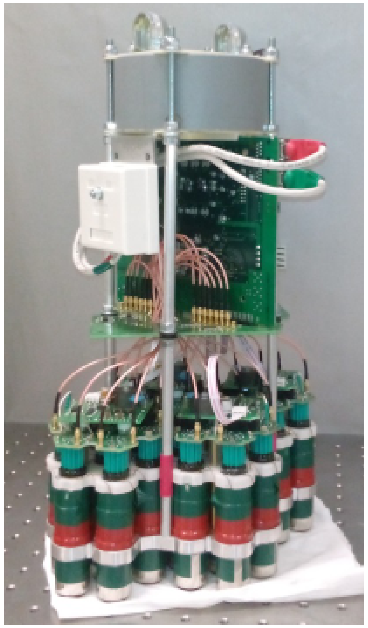
The Camera of the TAIGA-IACT

- 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





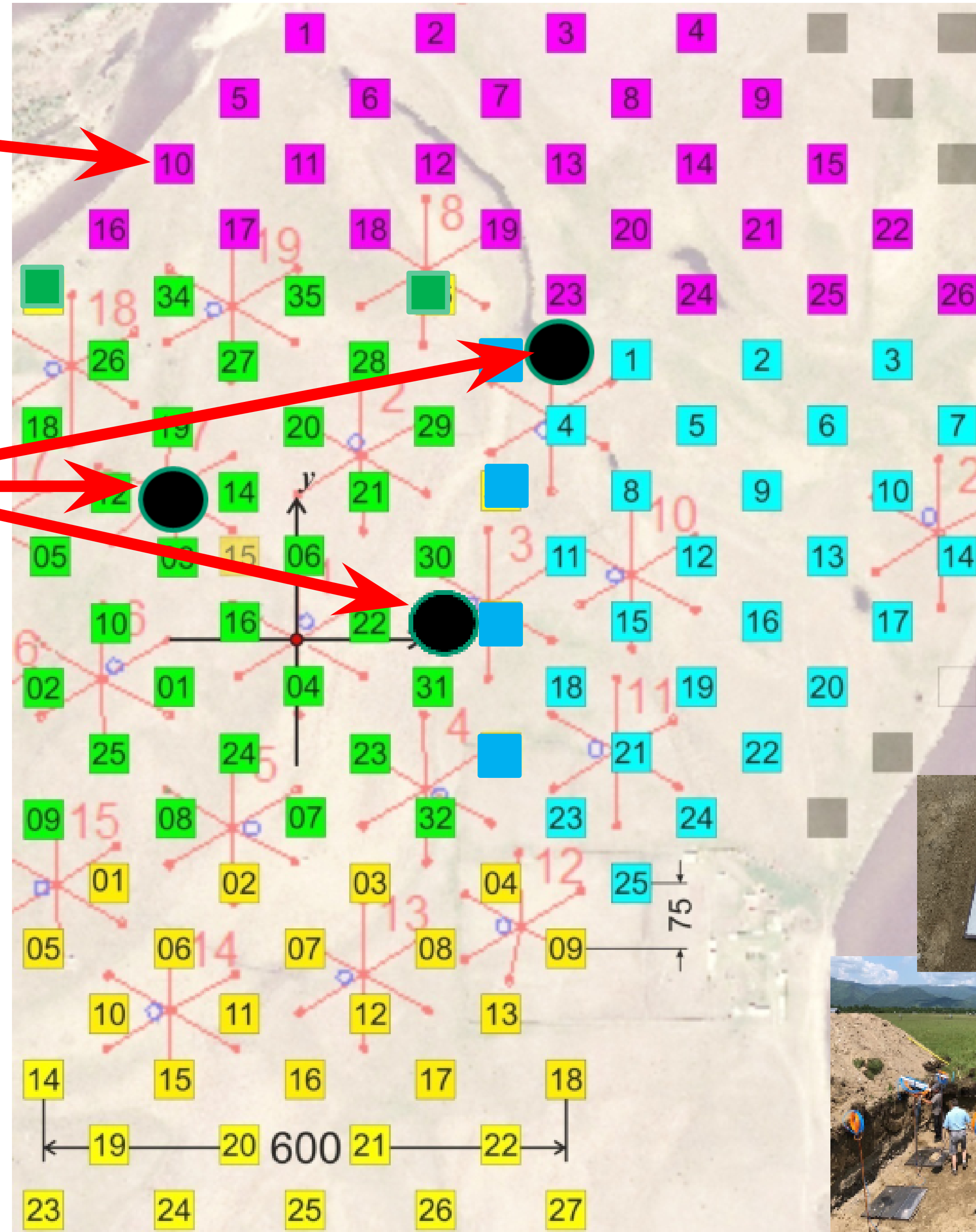
Basic cluster: 28 PMT-pixels. Signal processing: PMT DAQ board based on MAROC3 ASIC

TAIGA, 2021

1км²

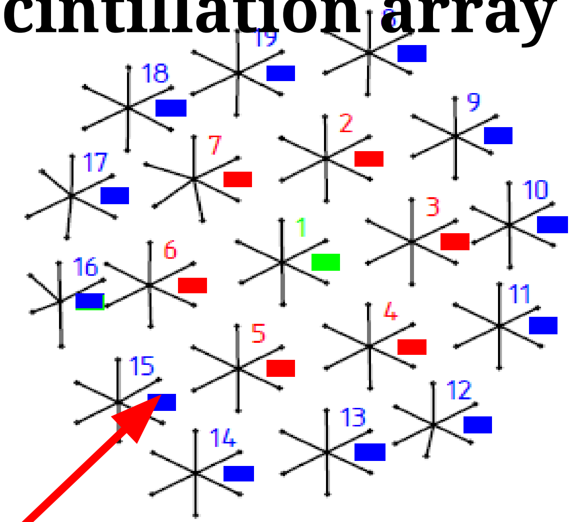
TAIGA-HiSCORE,
Optical stations

TAIGA-IACT

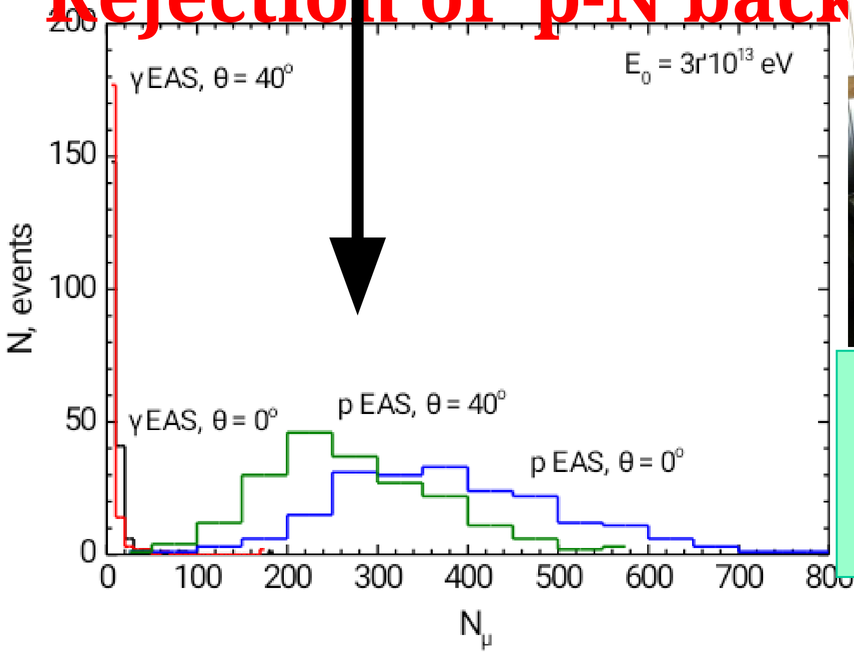


The TAIGA particle

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 m^2

152 the same underground muon counters in 19 stations.

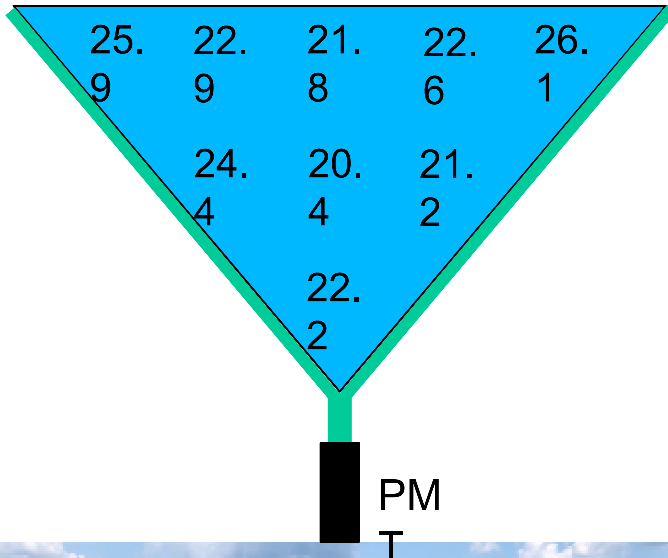
The TAIGA-Muon scintillation array

Counter dimension 1x1 m^{2}.

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

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

A clear peak in amplitude



Scientific program

- Search for the acceleration limit of particle in known supernova remnants and PWN: Crab Nebula и Boomerang (PWN), Tycho и Cas A (SNR), Dragonfly Nebula (2HWC J2019+367) ARGO J2031+4157 (Cygnus Cocoon)

- Long-term monitoring and study of the edge of the energy spectrum
of bright blazars as a method for searching for anomalies of gamma ray propagation in the Universe and searching for axion-like particles (1ES 0229+200, 1ES 1959+650, Mrk501, Mrk421, Arp 220, M82).

- Search for excessive diffuse gamma – rays with energies above 100 TeV, including gamma radiation accompanying neutrinos (10^{-4} from CR) which are recorded by the IceCube neutrino telescope.

- Study of CR mass composition in energy range 100-3000 TeV by hybrid approach

- Search for astrophysical optical transients, including signals from extraterrestrial civilizations (SETI) within the framework of the international Breakthrough Initiative program,

in the nanosecond range using the TAIGA-HiSCORE installation and the TAIGA-IACT.

- Investigation of the shape and surface of astrophysical objects with an angular resolution of the order of few tenths of a microsecond by a new method for measuring the parameters of stars-optical Interferometry (Intensity Interferometry) on a large base of 300-500 m using TAIGA-IACT array.

Four ways for detection of gamma ray in the TAIGA experiment

1. Autonomous operation of a single IACT for $E < 10\text{-}15$ TeV

2. Stereoscopic approach for large distances between the IACTs for $E \geq 10$ TeV

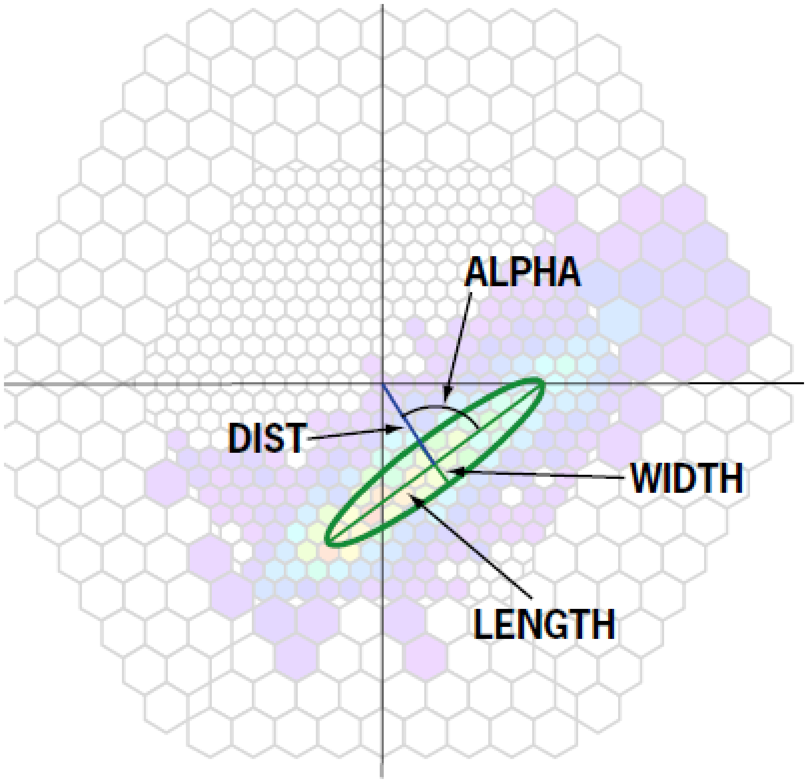
3. Hybrid approach - joint operation of the TAIGA-HiSCORE and the IACTs for $E \geq 40$ TeV.

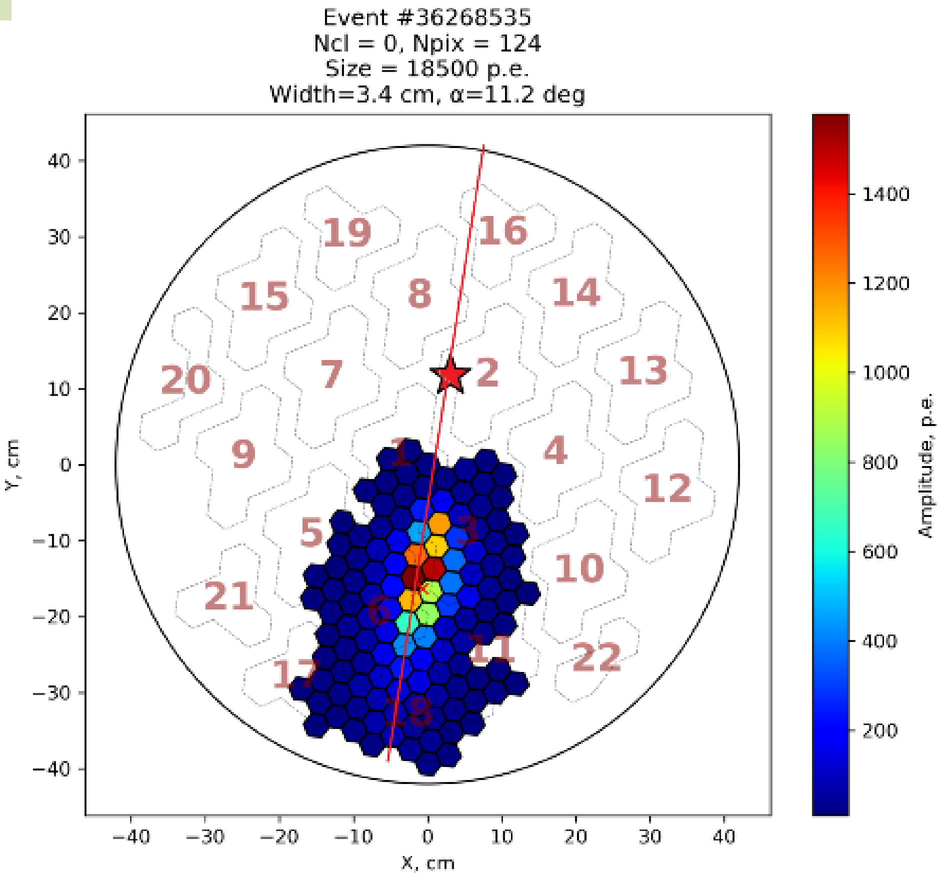
4. Hybrid approach - joint operation of TAIGA-HiSCORE and muon detectors for $E \geq 300\text{-}500$ TeV

TAIGA-IACT and TAIGA-HiSCORE joint events.

Hillas parameters

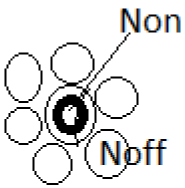
Most of events are "Hadron-like"
E = 840 TeV; width = 0.4°



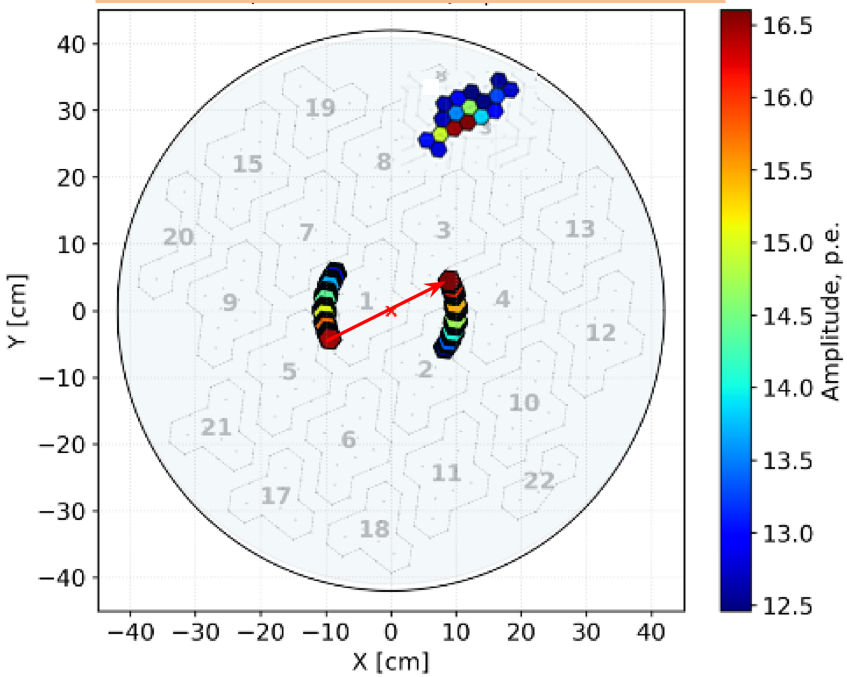


On (from the source) and Off (the background) events during the observation

Source Ra=83.633 Dec=22.014,



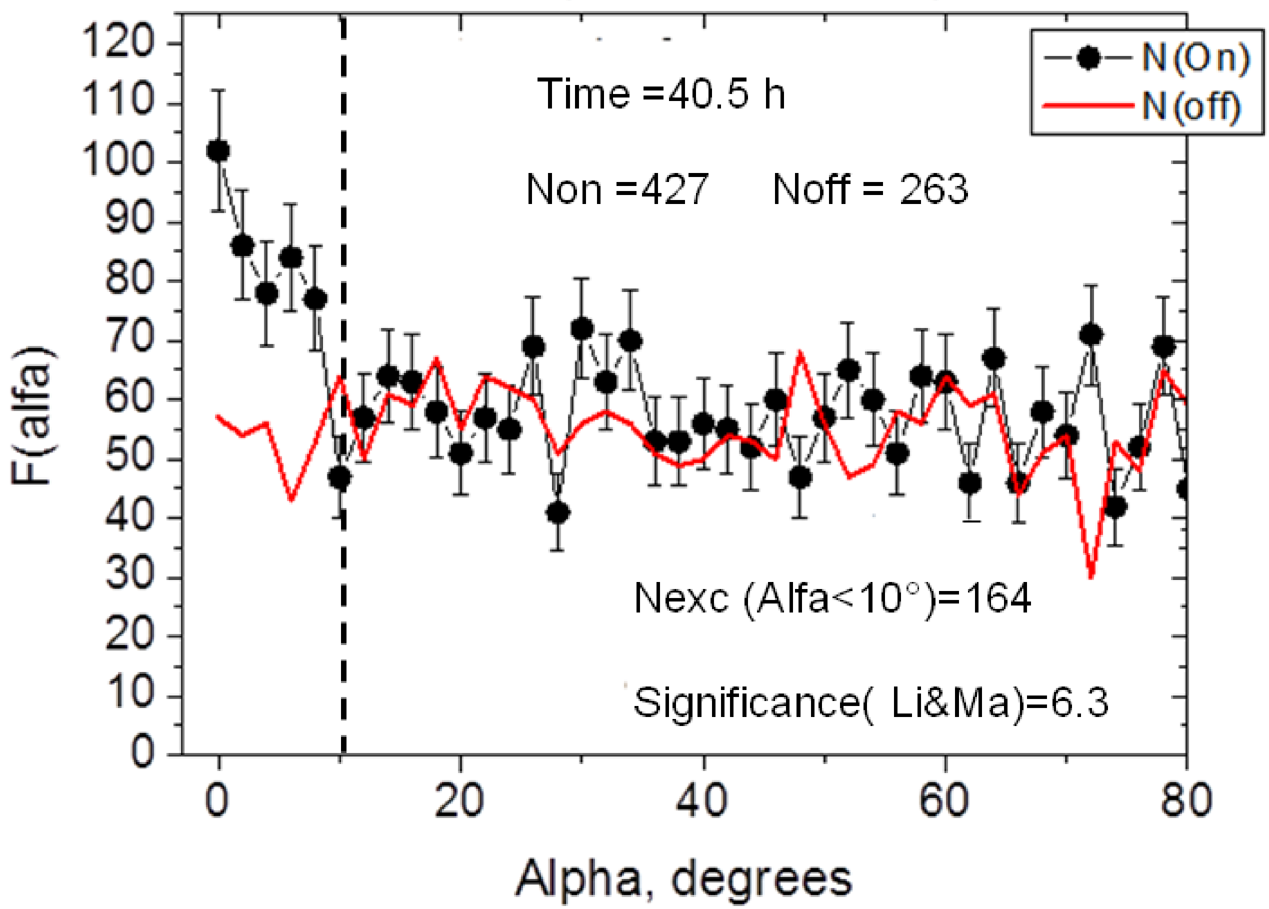
The position of the source on the camera in time



In 2019-2020 season the telescope observed the Crab Nebula in the wobble mode: The telescope is directed to a point shifted relative to the direction to the source (Ra_{Crab} + sec(Dec_{Crab})*1.2^{o} for 20 minutes, then Ra_{Crab} - sec(Dec_{Crab})*1.2^{o} for another 20 minutes.)

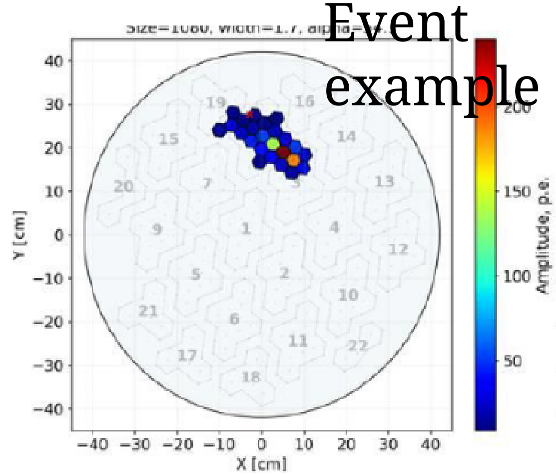
The background is estimated from the anti-source position. For each image, we can calculate parameters for the On and Off. The method allows not to divide the observation time between the measurement of the background and the measurements of the source.

Distribution over the alpha parameter for observations of the Crab Nebula (On) and background (Off) events from the source.

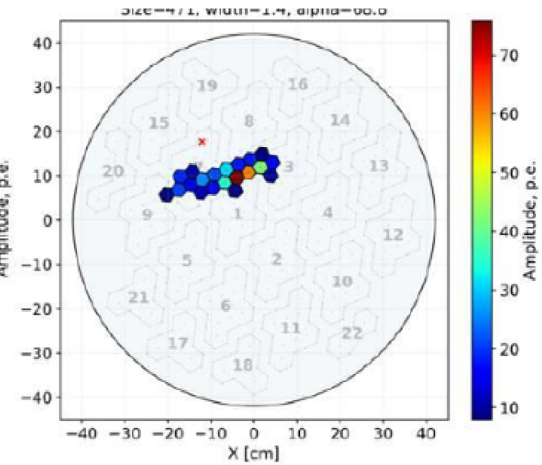


EASs detection by two telescopes located at a distance of 300 m - stereoscopic approach for high energies

Event example

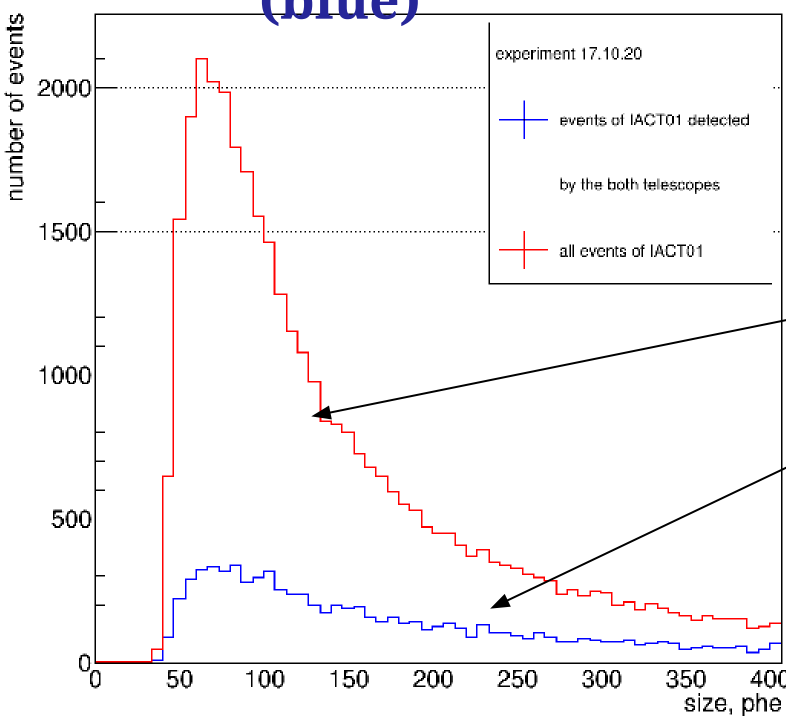


Size = 1080 pe, Width = 0.20 °



Size = 471 pe, Width = 0.17°

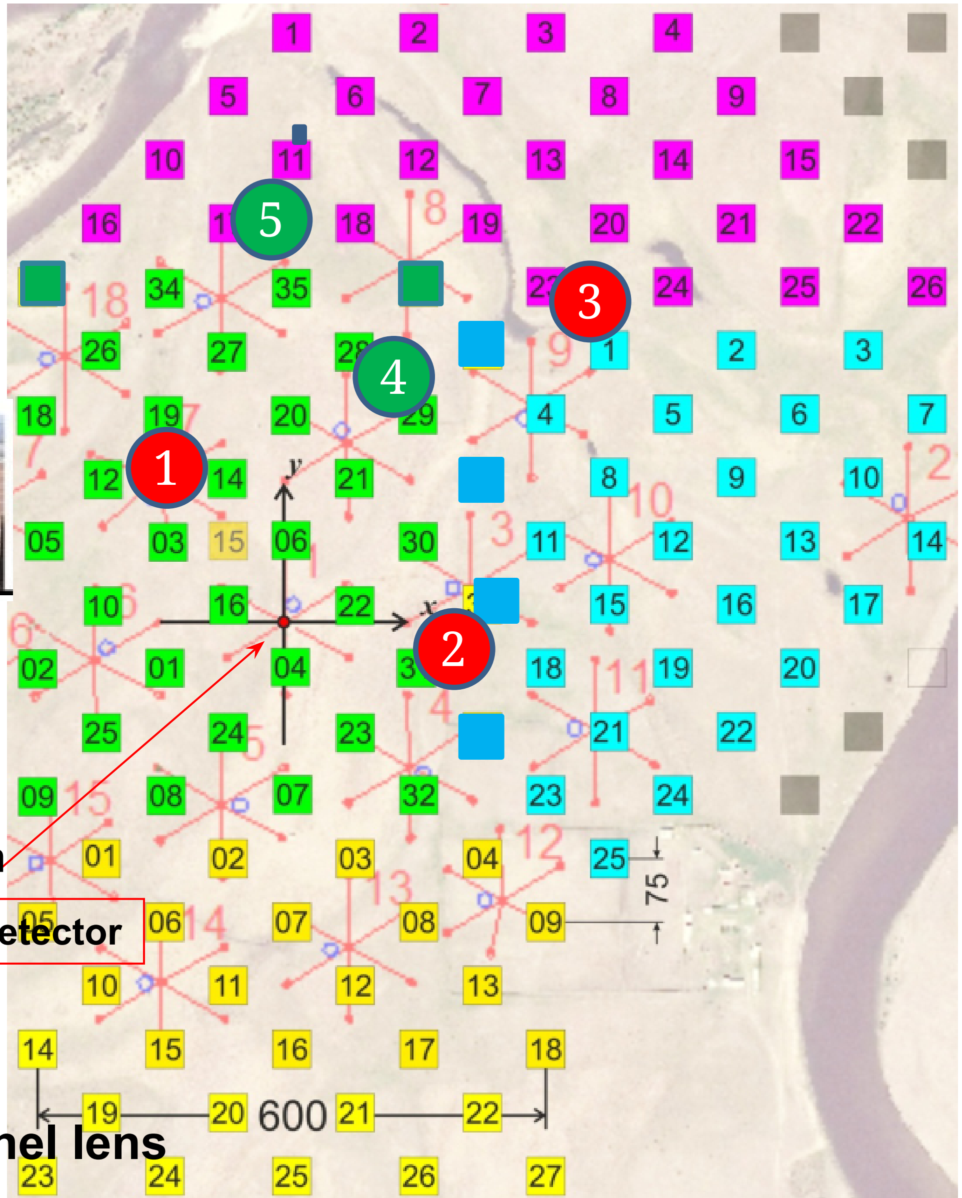
The size distribution for All events (red) and Stereo events (blue)



Single telescope ~ 10-12 Hz

2 telescopes ~ 1 Hz

TAIGA - 2024



2-3 km

Fluorescent Detector

3 m^2 Fresnel lens

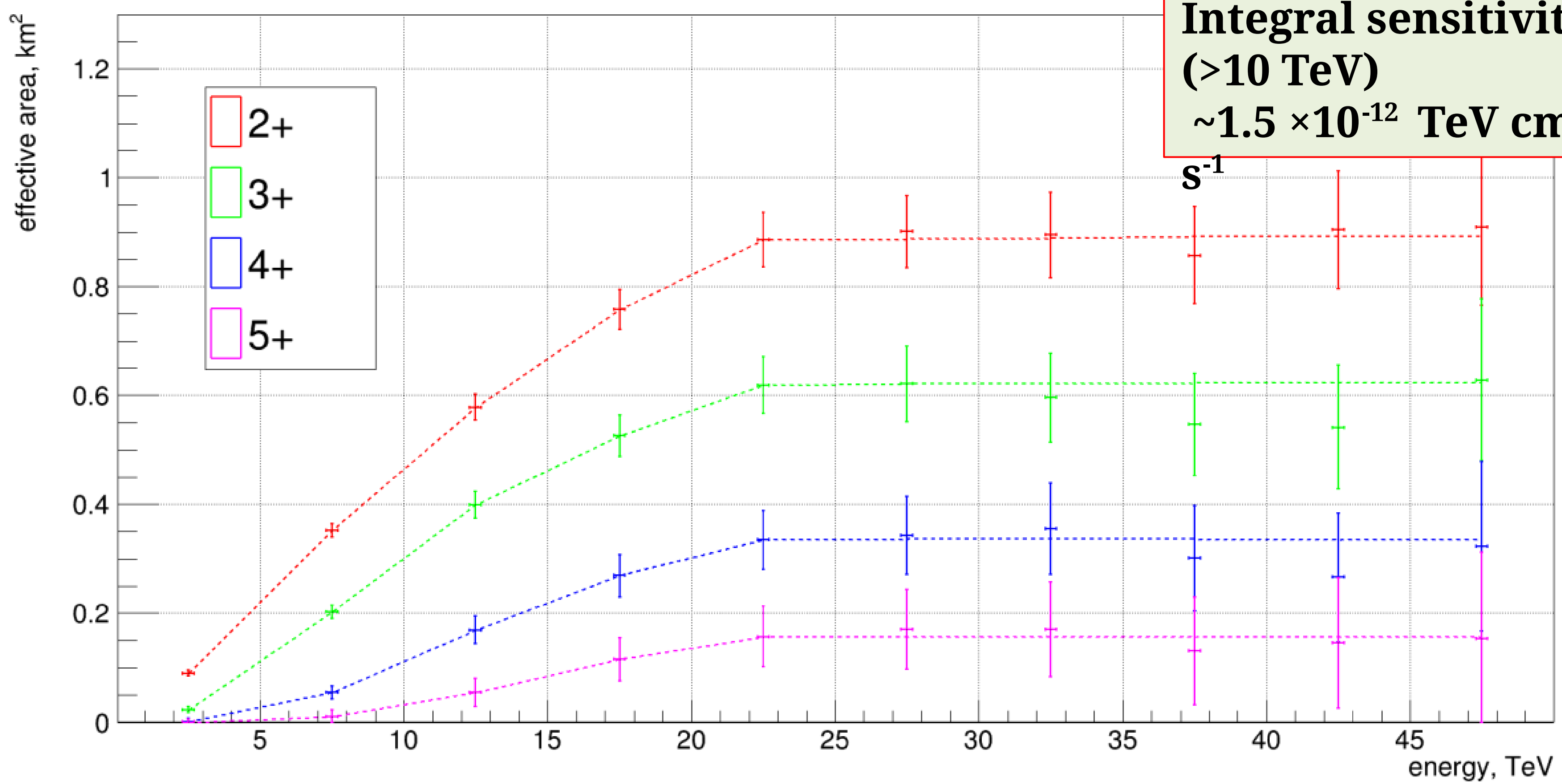
Three first IACT

Two new IACT

Fluorescent Detector

Area of muon detectors:
- from 150 m^2 to 400 m^2

The effective area for events detected by 2 or 3 or 4 or 5 telescopes of the TAIGA-IACT installation simultaneously.

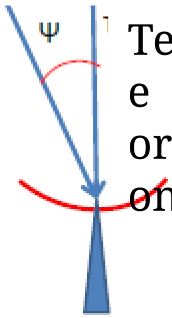


Integral sensitivity (>10 TeV) ~1.5 ×10^{-12} TeV cm^{-2} s^{-1}

The effective area for events detected by 5 telescopes simultaneously is 0.45 km^2 and reaches a maximum of 0.9 km^2 at an energy of 22 TeV.

Hybrid events with E>100 TeV (115 hours of Crab observation , 0.3 km^2 area of TAIGA-HiSCORE)

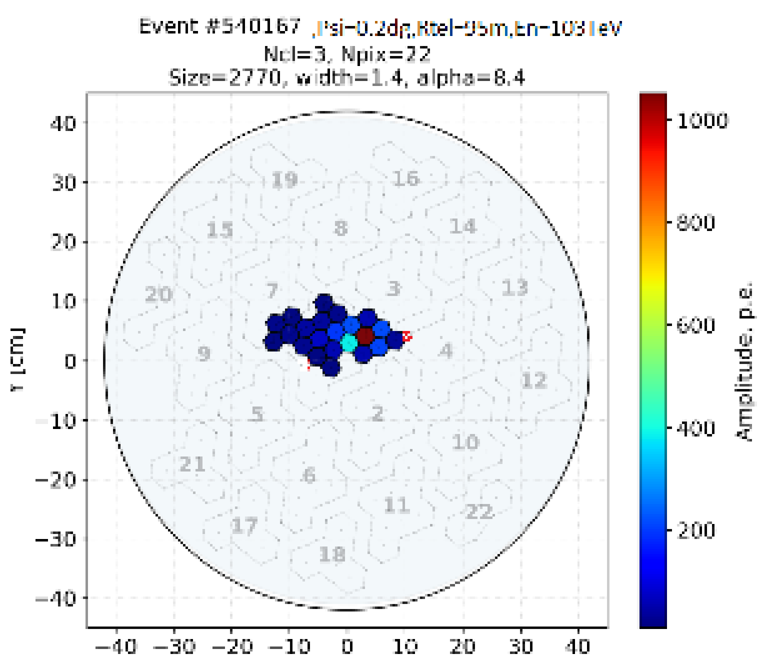
EAS direction

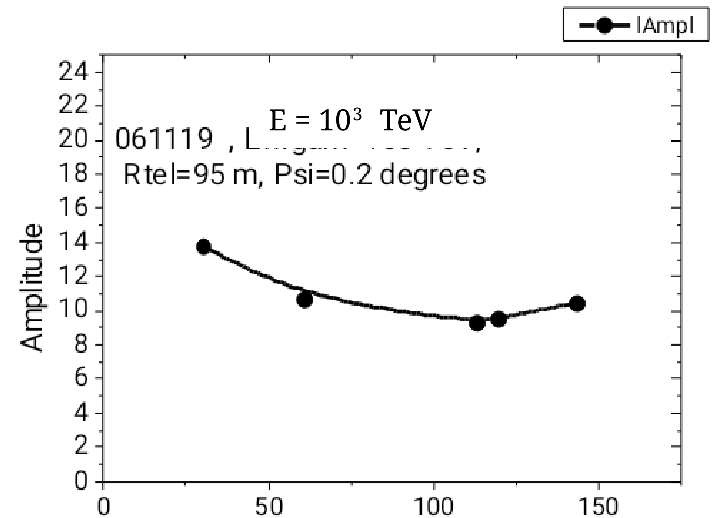


Telescope orientation

After cut on Ψ and Hillas parameters (50% of gamma rejection)
– 5 events with E> 100 TeV

Event example: E = 10^3 TeV, Ψ = 0.2°





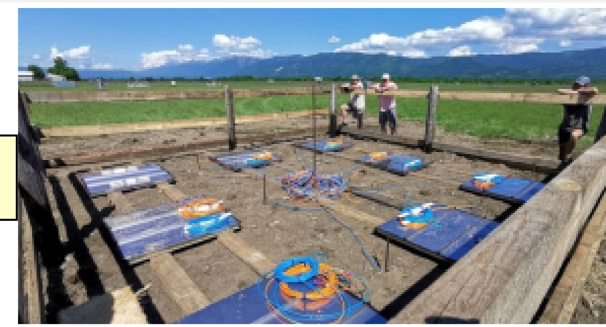
Distance from EAS core, m

Lateral distribution function , measured

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 astroclimate,
- enough vacant rather flat space,
- acceptable logistic condition,
- availability of electrical power

Tunka, Altay, Mongolia…??????



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 to develop a new hybrid technology for studying gamma rays with an energy of >30 TeV

2021 year 1 km^2 TAIGA setup:

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

Commissioning seasons were successful

- **Stable operation, precision calibration in progress,**
- **CR energy spectrum 100 TeV – 1 EeV**
- **Detection of gamma-rays from Crab and Mrk-421 in agreement with expectation.**
- **Joint operation of TAIGA-HiSCORE and IACT: data analyses is in progress**
- **Starting analysis of stereo events**

Future plan : 10 square kilometers scale TAIGA + new technologies

- **array with about 1000 Cherenkov detectors of TAIGA - HiSCORE "non-imaging" timing array**
- **10 – 15 Imaging Atmospheric Cherenkov Telescopes of TAIGA-IACT "imaging" array**
- **3000 m^2 muon detectors of TAIGA-Muon array.**
- **A point source sensitivity: 5 10^{-14} TeV/cm^2 s (500 hours, 50–200 TeV)**