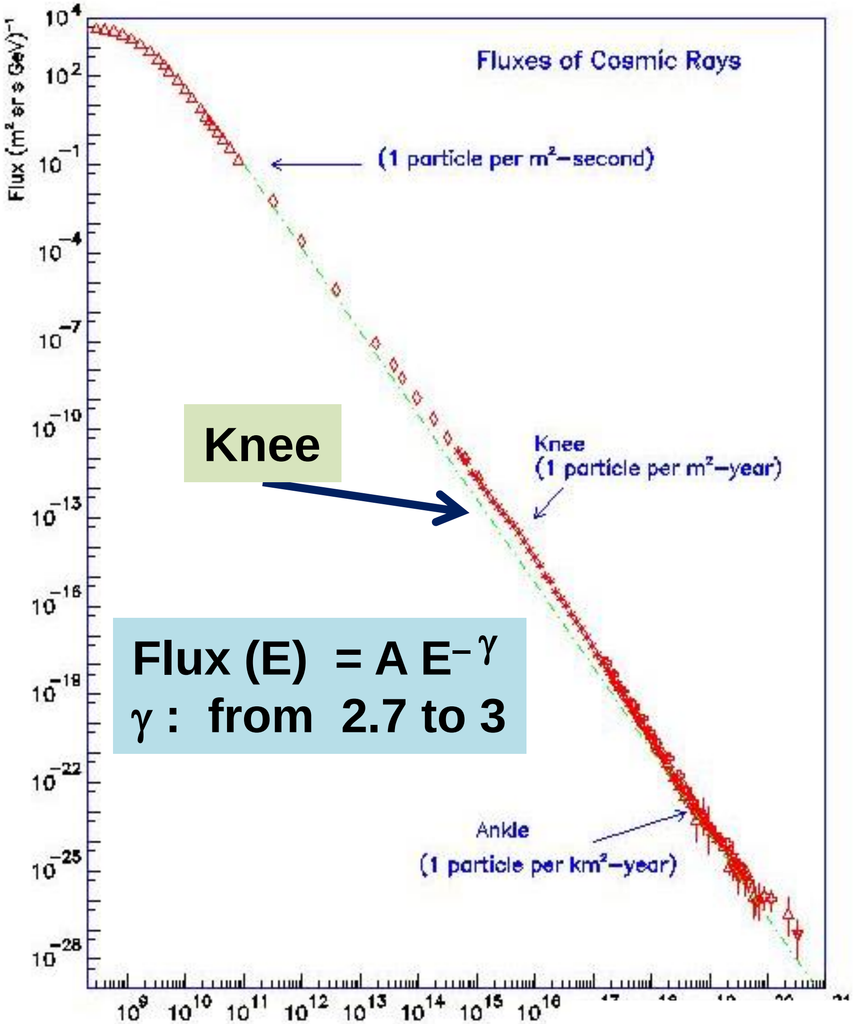
The present status and future of the TAIGA complex for cosmic ray physics, gamma-ray astronomy and astroparticle physics

N. Budnev, L. Kuzmichev **For TAIGA collaboration**

RSF Grant 23-72-00016

More than 100 years have passed since Victor Hess discovered "penetrating radiation" coming from space.

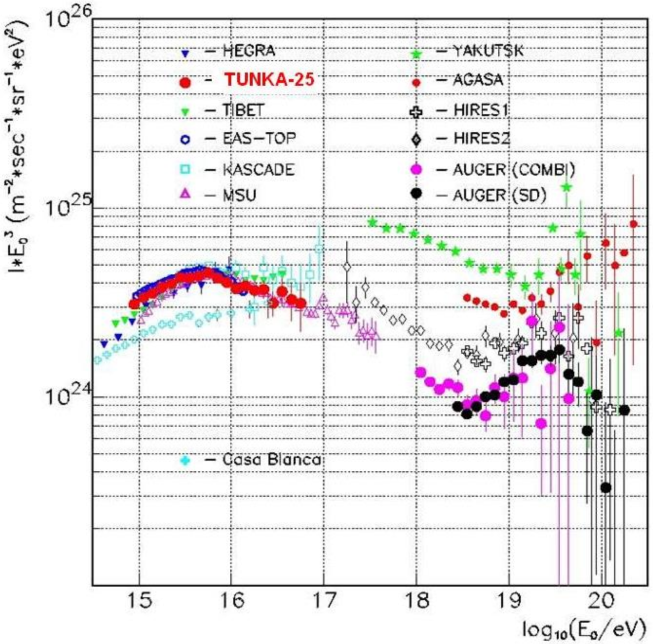
Flux **Energy spectrum**



Knee

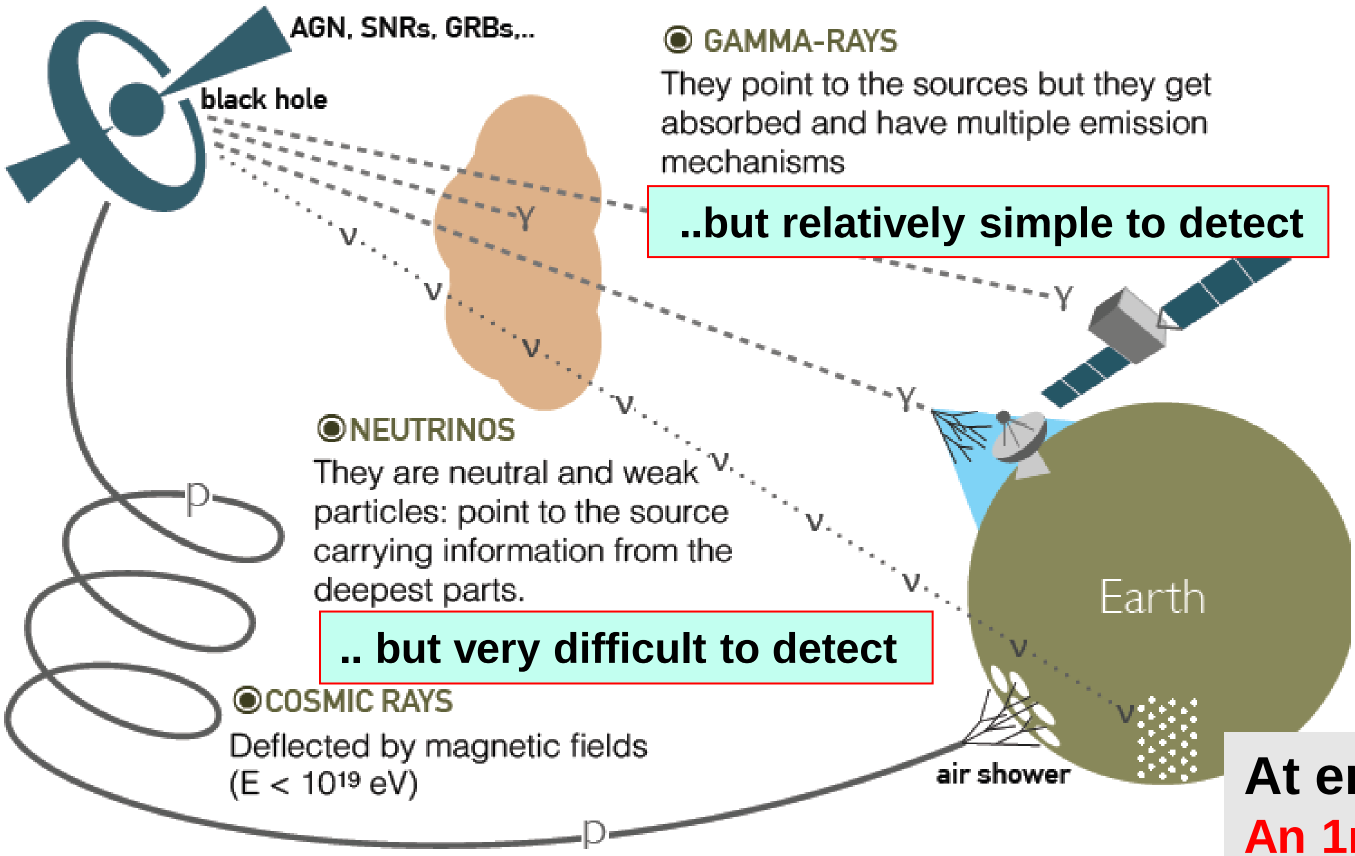
Flux (E) = A $E^{-\gamma}$
γ : from 2.7 to 3

Energy, eV



Gamma-astronomy & neutrino astronomy

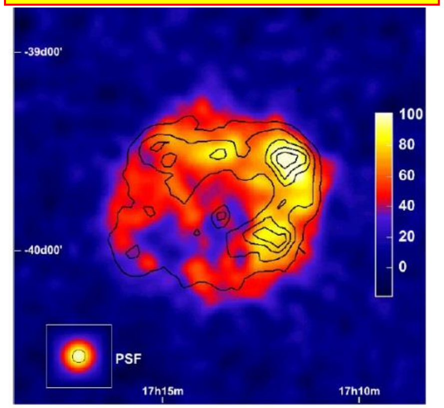
To understand a nature of cosmic high energy accelerators should be detected gamma-rays and neutrinos.



..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

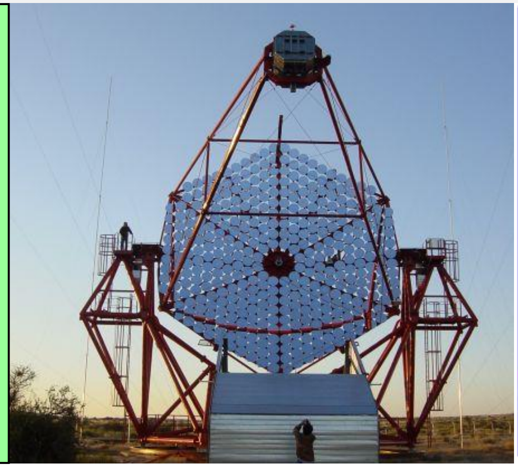
- 1 event / 1 year

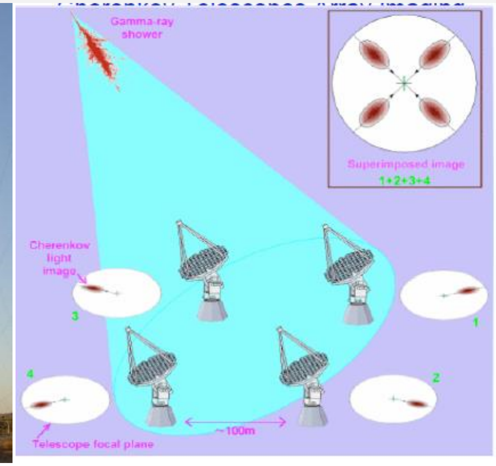
An 1км^2 gamma detector

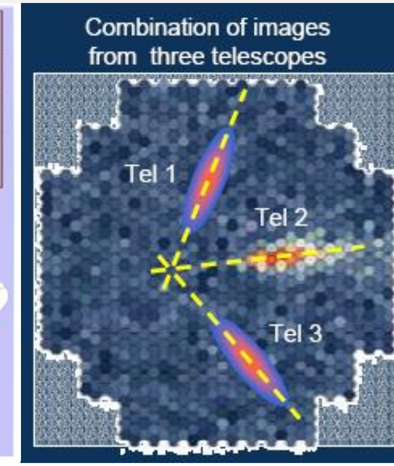
- 1 event / 20 minut!

Imaging Atmospheric Cherenkov Telescopes (IACT) - as instruments for the ground based gamma astronomy

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

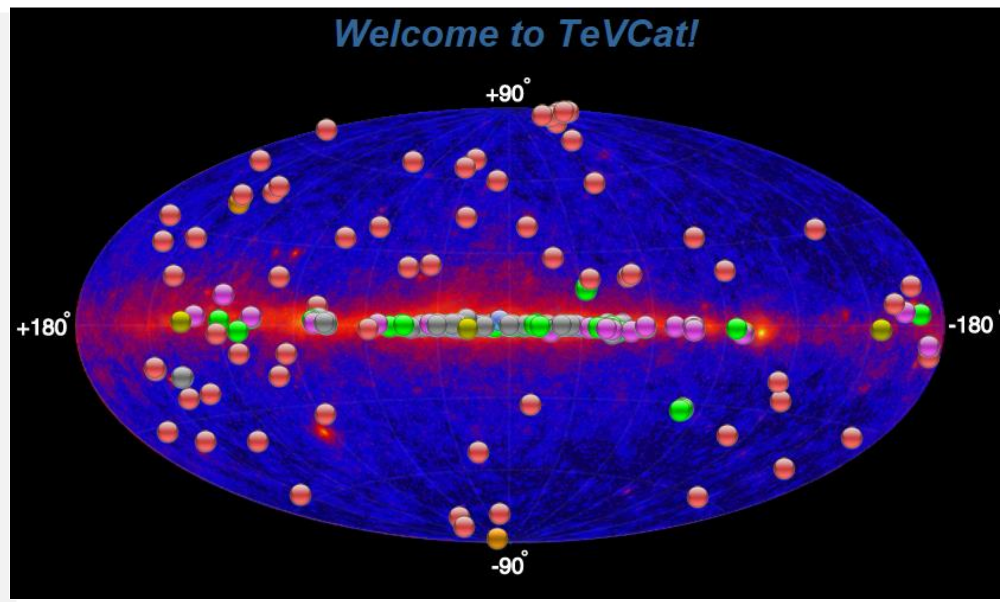






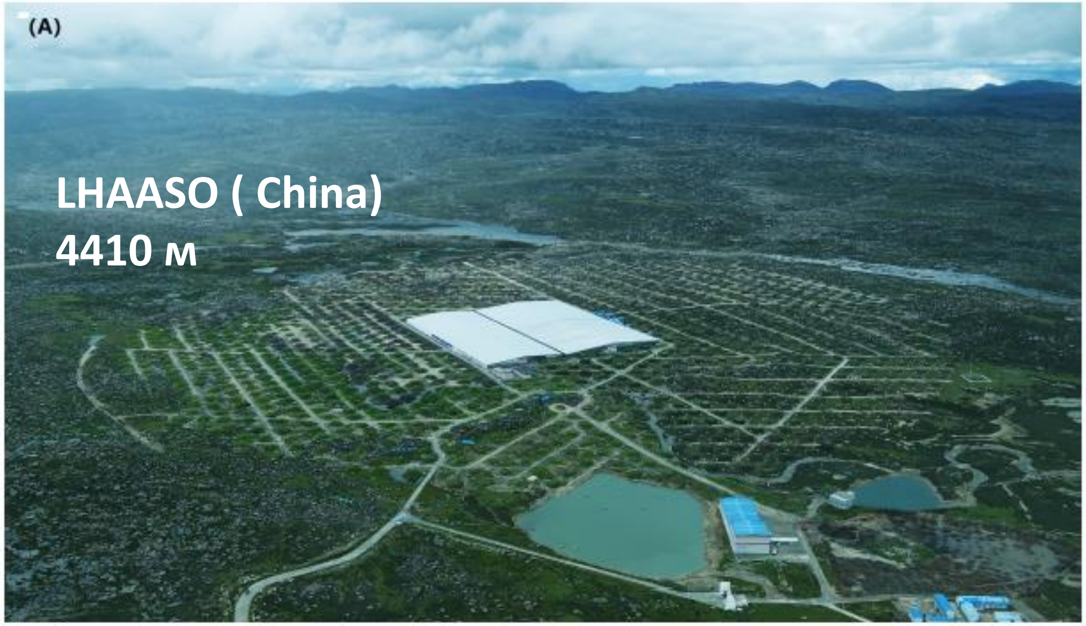
More than 200 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays. But only a few photons with energy more than 50 TeV were detected up to now with IACT.

An area of an array should be a few square kilometers as minimum for High Energy Gamma Astronomy .



It is too much expensive with IACT!

High-altitude installations



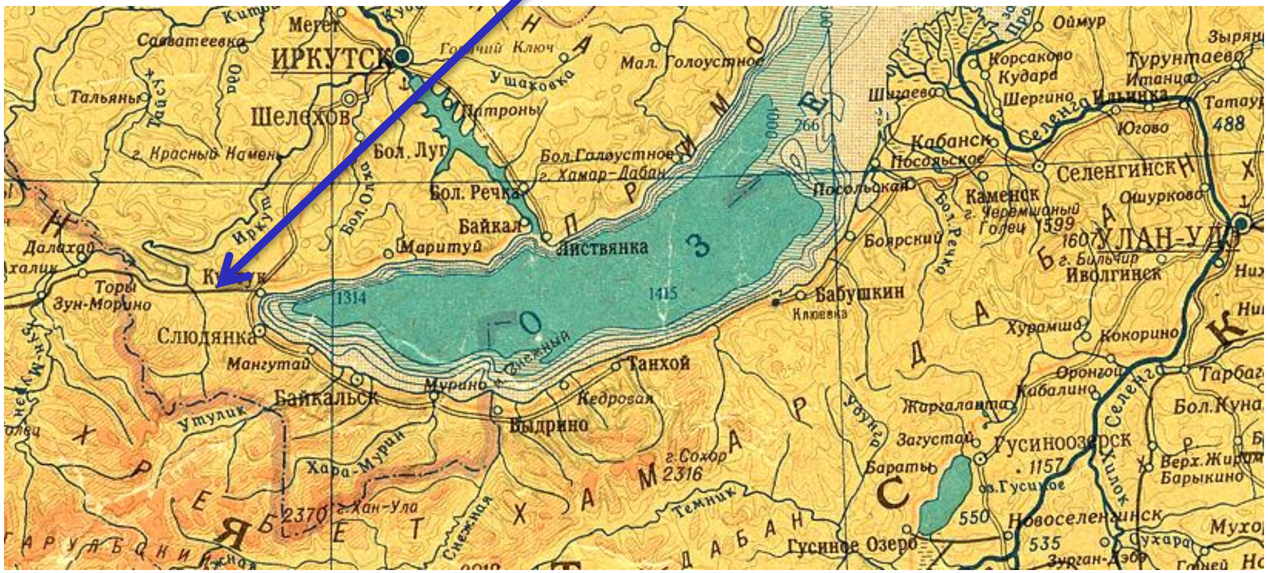
LHAASO: 1 km^2, 5200 scintillation detectors, 1200 water muon detectors.

HAWC: 0.02 km^2, 300 water tanks

Tibet: 0.06 km2, 64 water muon detectors (1/20 LHAASO)

LHAASO:
Discovery of “PeVatrons” - sources of photons with E > 100 TeV

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

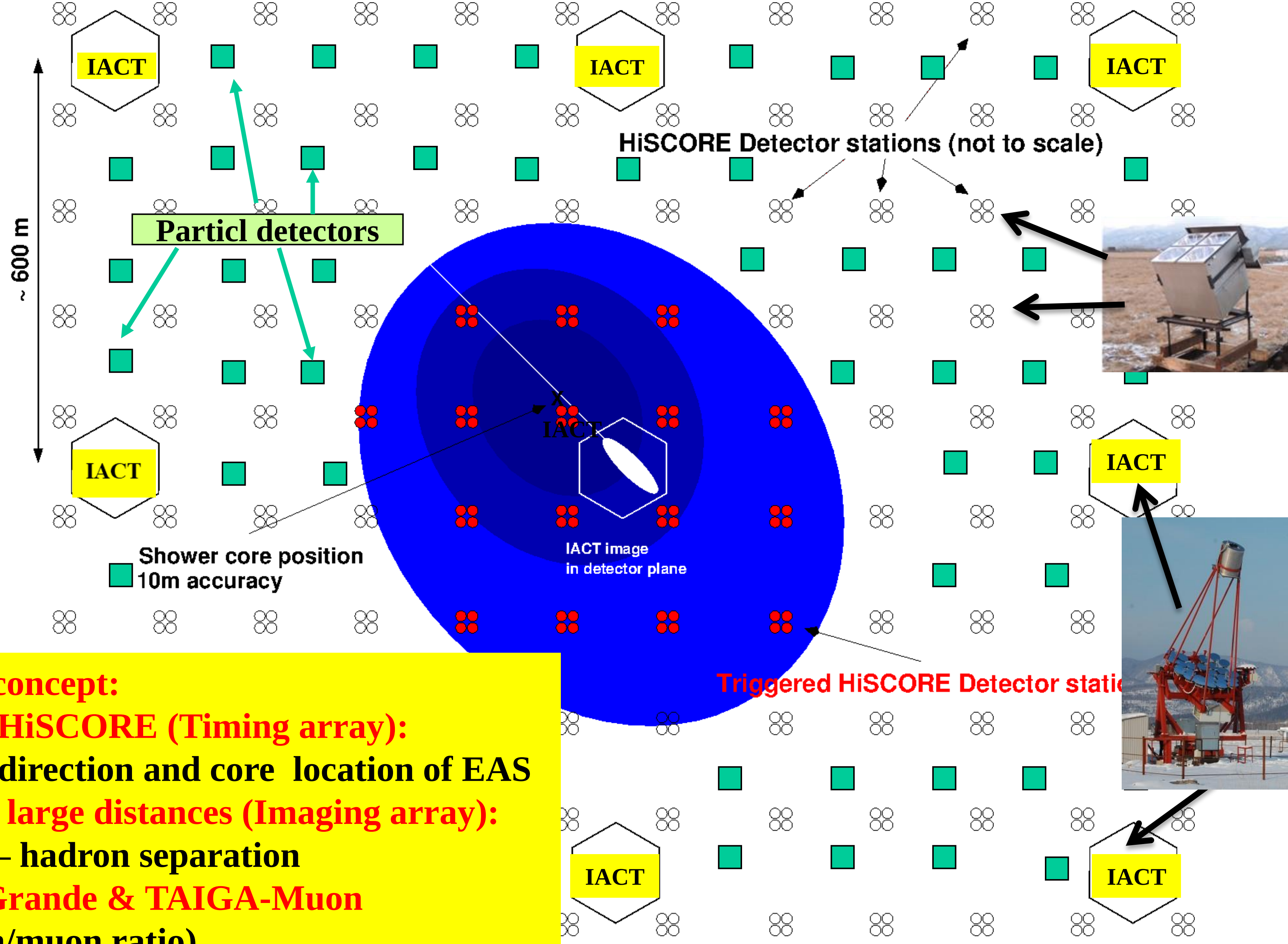
2006 - …….. Tunka -133 - 3 km^2 array – the feature in the CR spectrum at an energy of 20 PeV and the “second knee” at energy 100 PeV…..

2014 -… TAIGA - HiSCORE – precise CR energy spectrum in energy 0,2 – 100 PeV

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 and particle detectors.

TAIGA: Imaging + non-imaging techniques

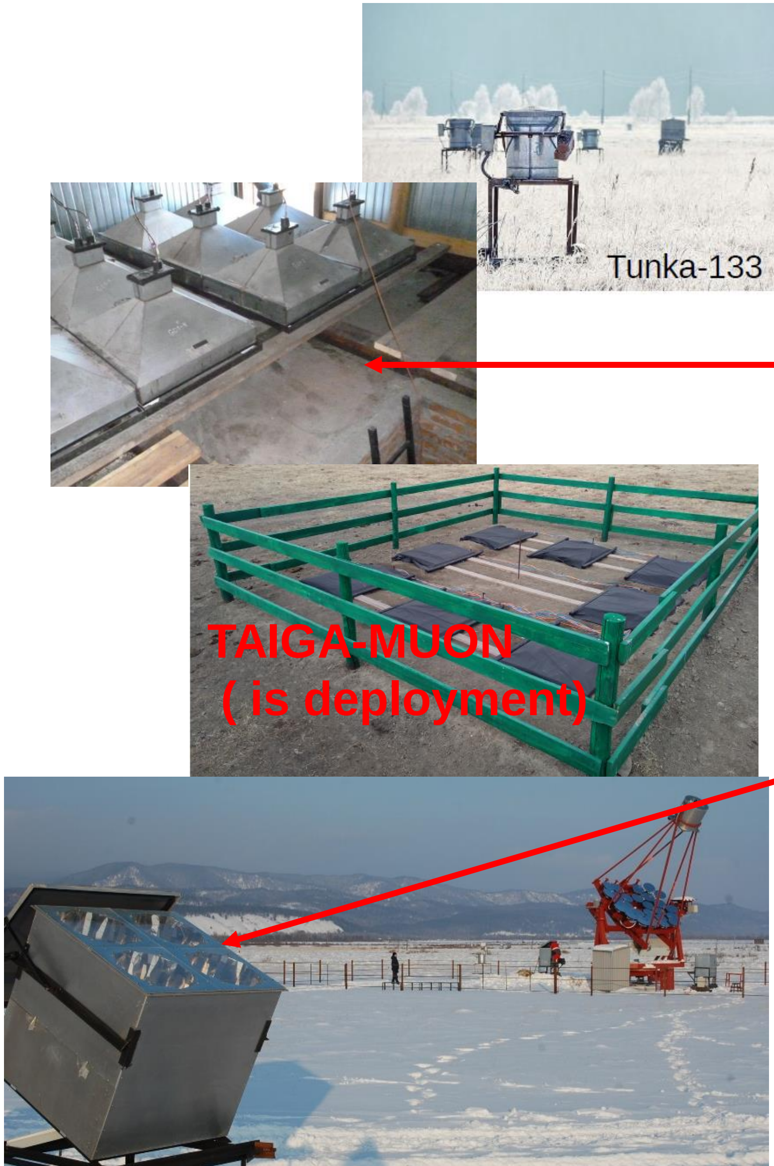


Hybrid concept:
TAIGA-HiSCORE (Timing array):
Energy, direction and core location of EAS
IACT at large distances (Imaging array):
gamma – hadron separation
Tunka-Grande & TAIGA-Muon
(electron/muon ratio)

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

TAIGA-1 Astrophysical Complex



Tunka-133 Cherenkov EAS array (2009)
Area – 3 km^2

Tunka-Grande (2015)
Detection of charged particles (electrons, muons)

TAIGA – HiSCORE
(finishing of deployment in 2021)

TAIGA -IACT
IACT – Imaging Atmospheric Cherenkov Telescope

10 ^{18} eV

Cosmic Rays (protons and nuclei)

10 ^{14} eV

Gamma-ray astronomy

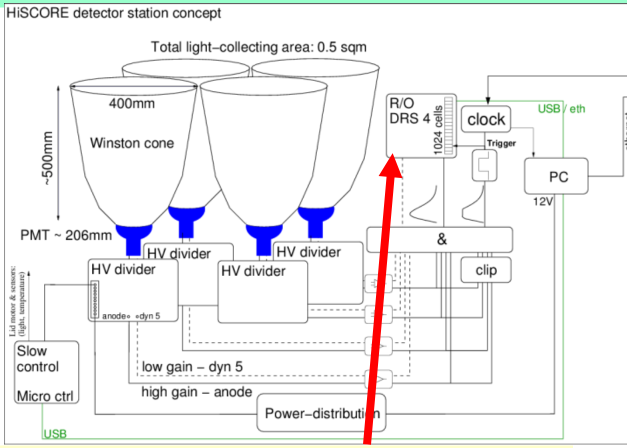
10 ^{12} eV

TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

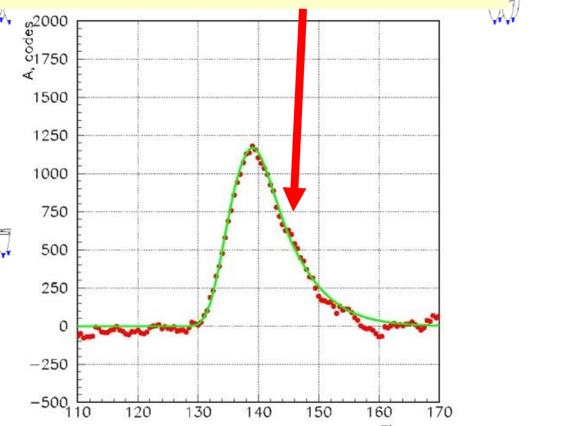
Consist of 120 Cherenkov stations distributed on 1,1 km^2 area with spacing 106 m. In each station there are four 8 inch PMTs equipped with a Winston cone. The total light collection area of a station is 0.5 m^2. Threshold for CR- 100TeV, for γ- 50TeV

1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.4 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)



The TAIGA – IACT

First IACT - 2017,

Second IACT - 2019,

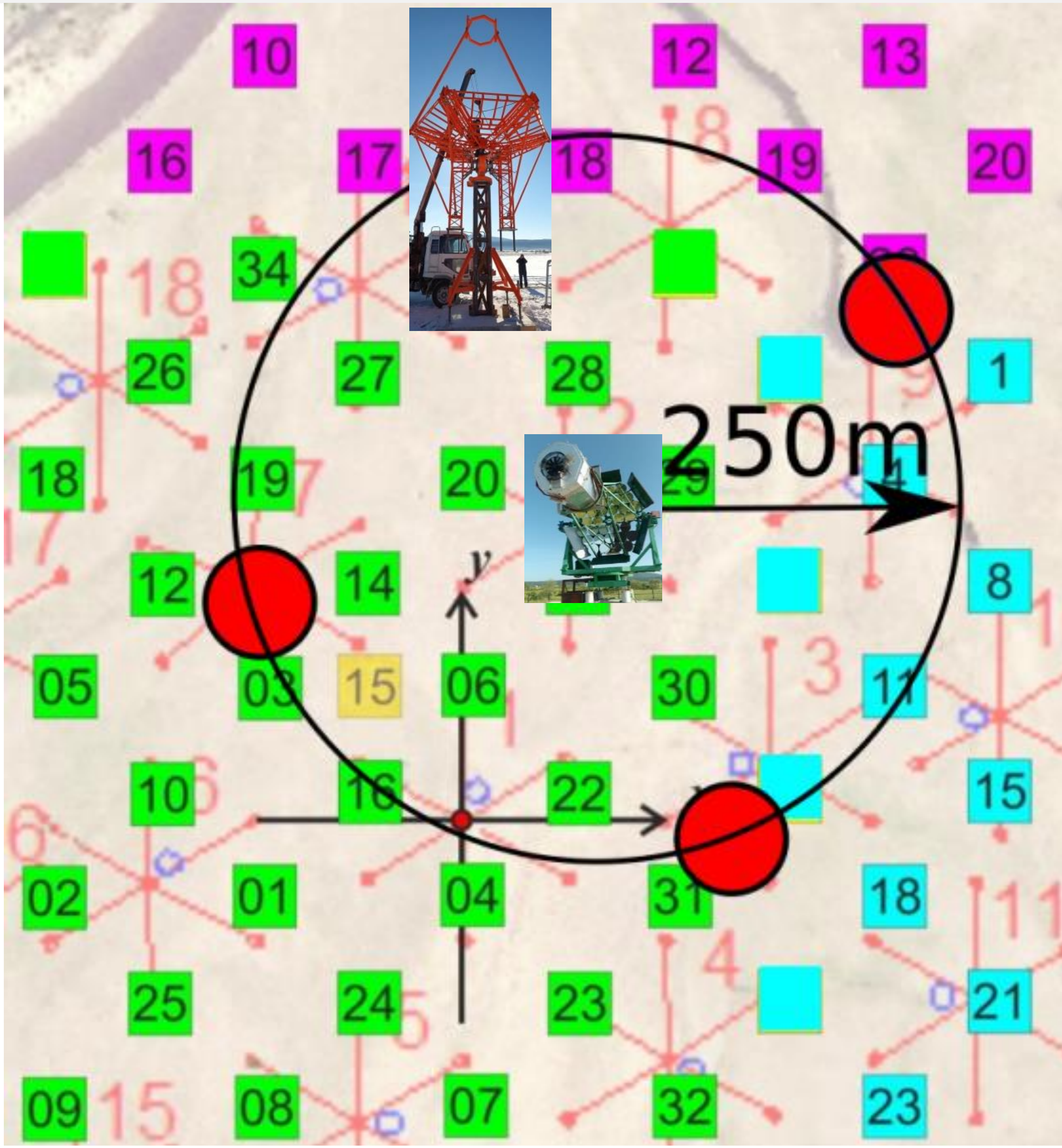
Third IACT - 2022,

Fourth IACT - 2025

- **34-segment reflectors (Davis-Cotton)**
- **Diameter 4.3 m, area ~10 m^2**
- **Focal length 4.75 m**
- **Camera - 600 PMT, 9.6^o FoW**
- **Threshold energy ~ 2 - 3 TeV**

.

IACT & wide-angle Cherenkov detectors of the TAIGA-1 facility.



The main tasks for the TAIGA-1 complex

- Studying cosmic rays in the energy range of 10^{14}-10^{18} eV, with an emphasis on the mass composition and energy spectrum in the region of the first and second knee

- Studies of galactic PeVatrons using TAIGA-IACTs and the TAIGA-HiSCORE facilities.

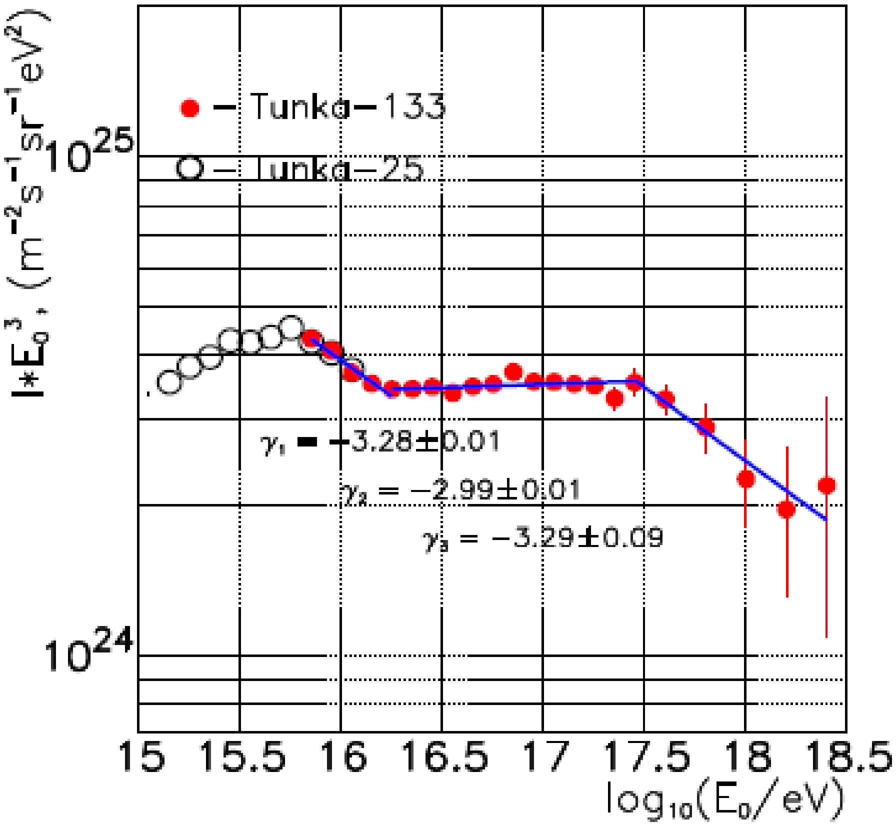
- Search for TeV-range gamma-rays from GRB, as well as gamma-rays associated with energetic neutrinos detected by the Ice-Cube and Baikal-GVD neutrino telescopes.

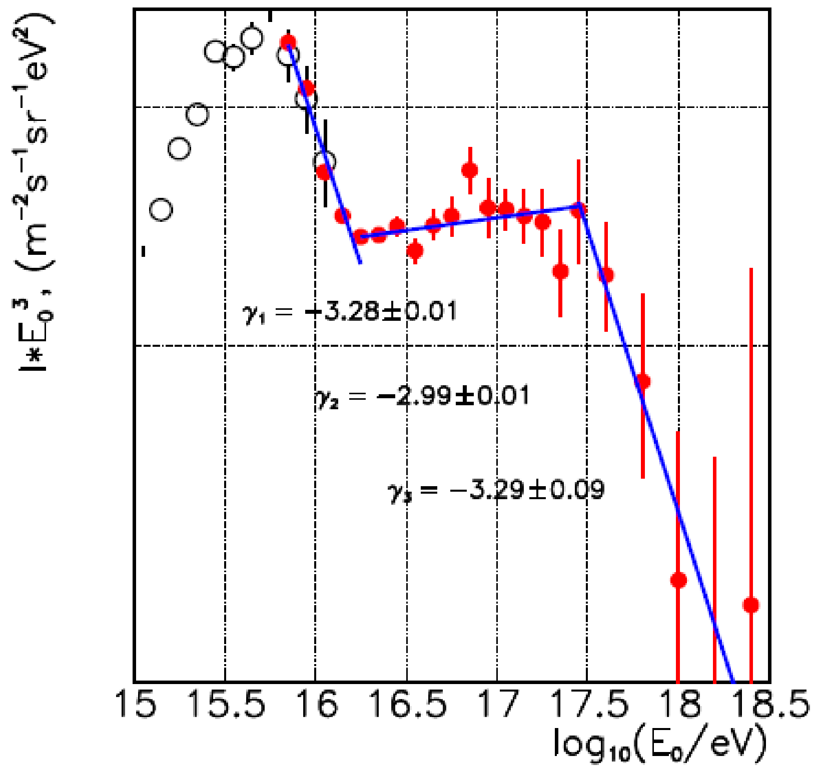
- Testing the detectors of the TAIGA-100 installation

High energy cosmic ray physics, some results.

The all particles energy spectrum $I(E) \cdot E^3$ (7y)

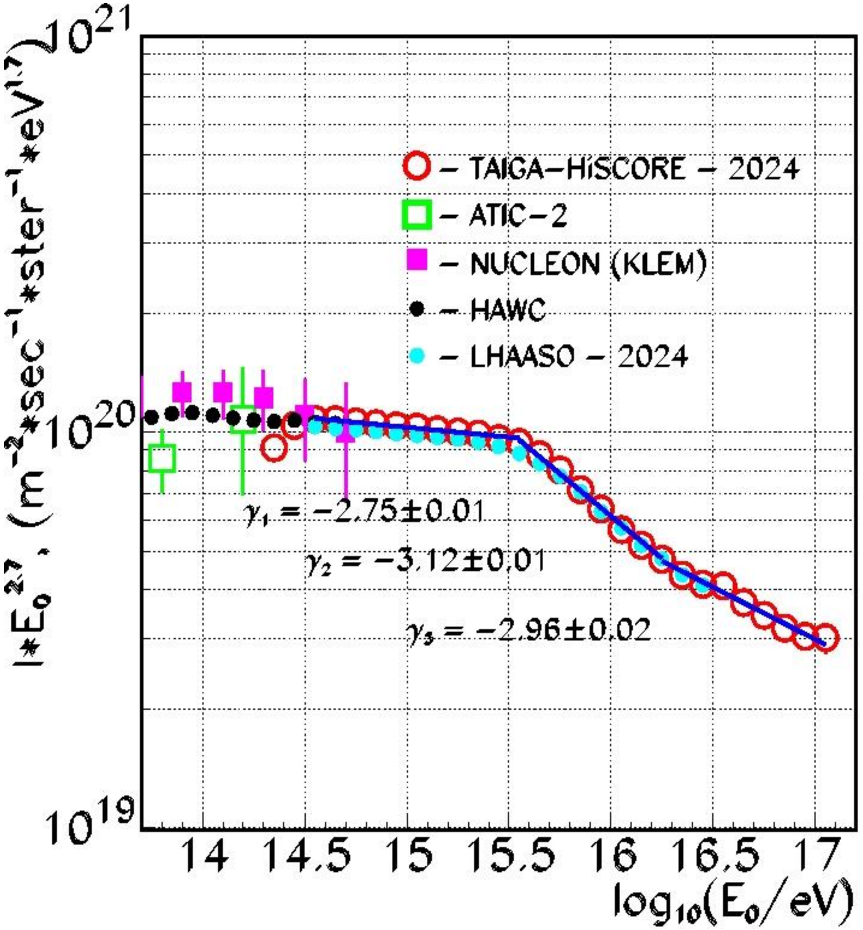
energy resolution ~ 15%, in principal up to - 10%

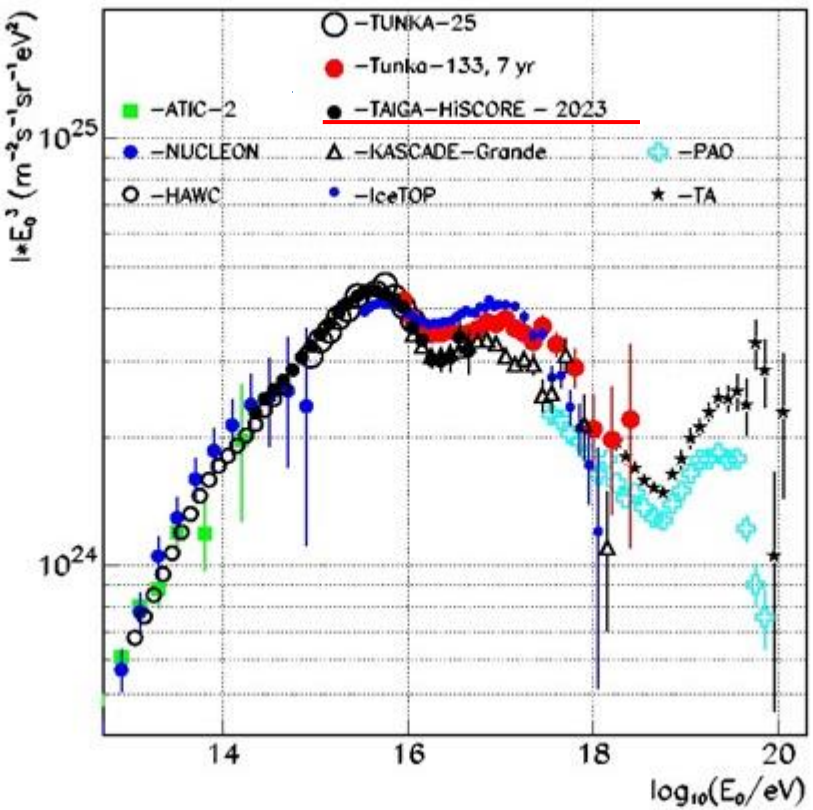




~4200 events with $E_0 > 10^{17}$ eV

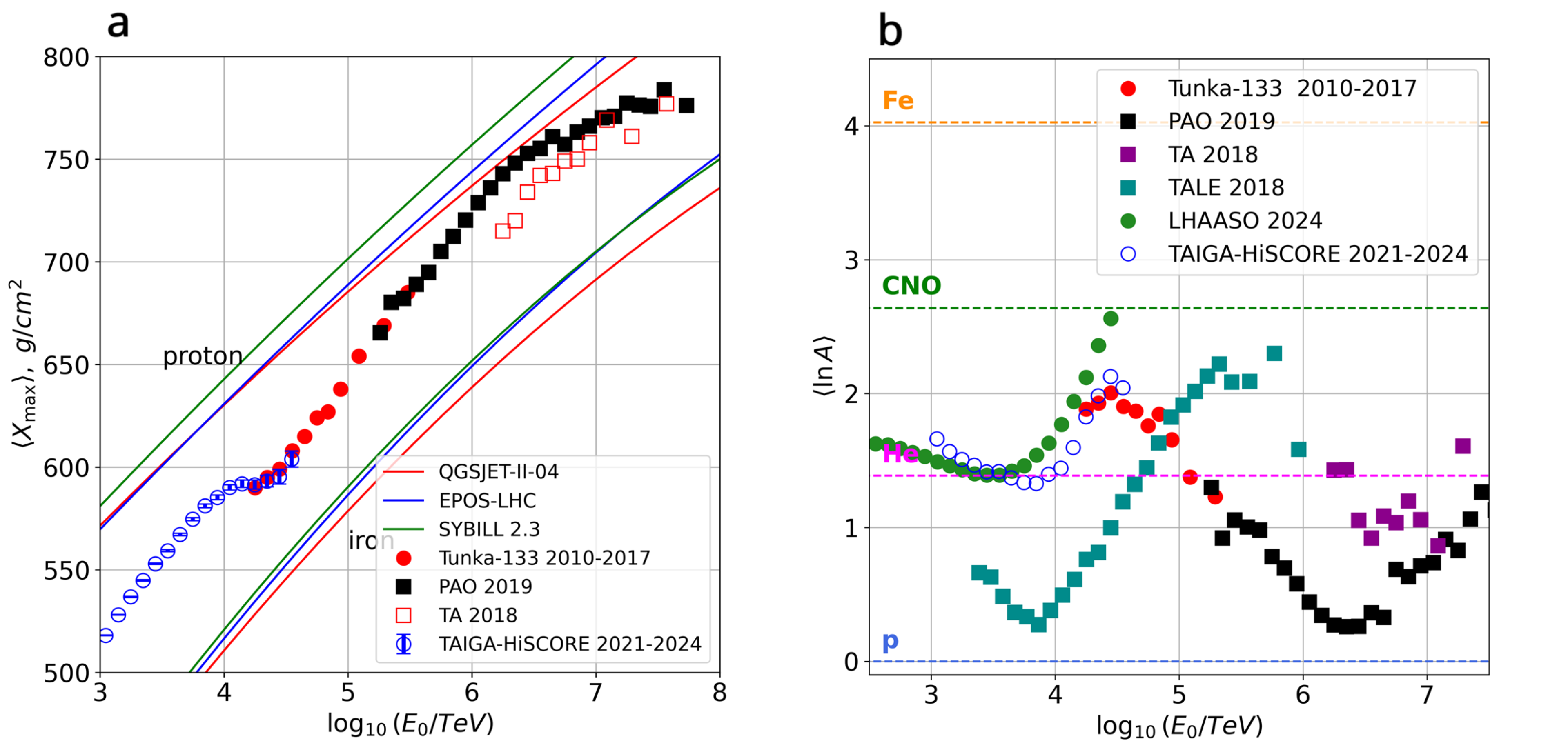
Spectrum Steepening at energy E = 15 – 20 TeV, ΔƔ ~ 0.2-0.3
Difference in intensity ~30% , due to difference in energy calibration ~10% ?
The second knee 100 -300 TeV, ΔƔ ~ 0.3





TAIGA-HiSCORE energy spectrum

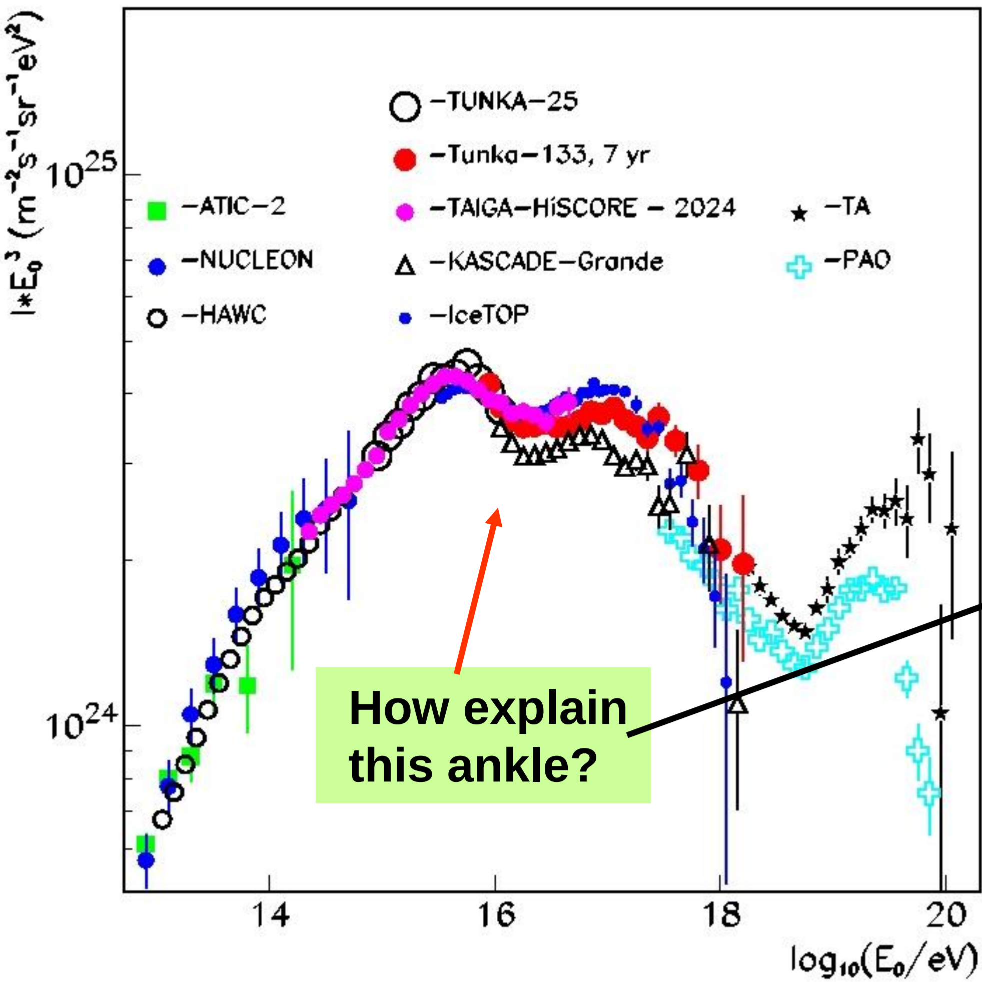
Comparison of the Tunka-25 &Tunka-133 & TAIGA-HiSCORE energy spectra with other experimental data

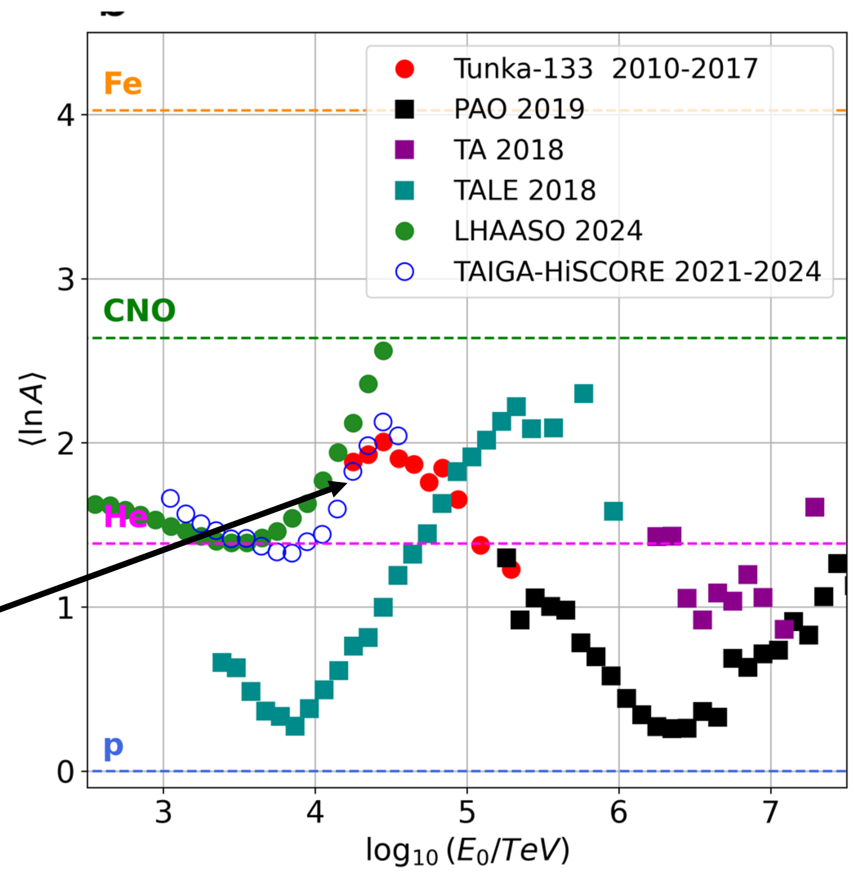


Mean Depth of EAS maximum X_{max} ($g \cdot cm^{-2}$)

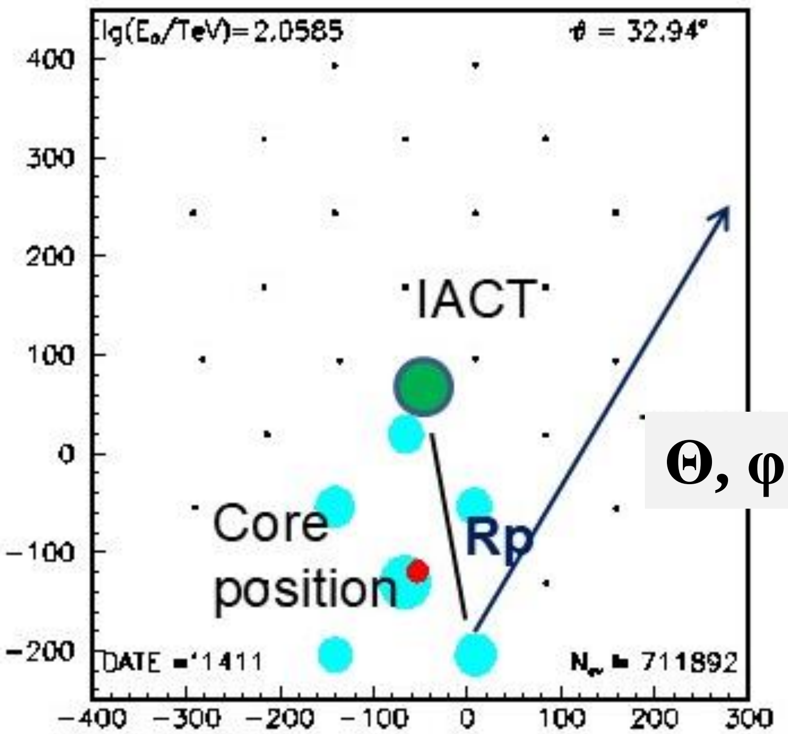
Mean logarithm of primary mass.

Ankle at energy $2 \cdot 10^{16}$ eV





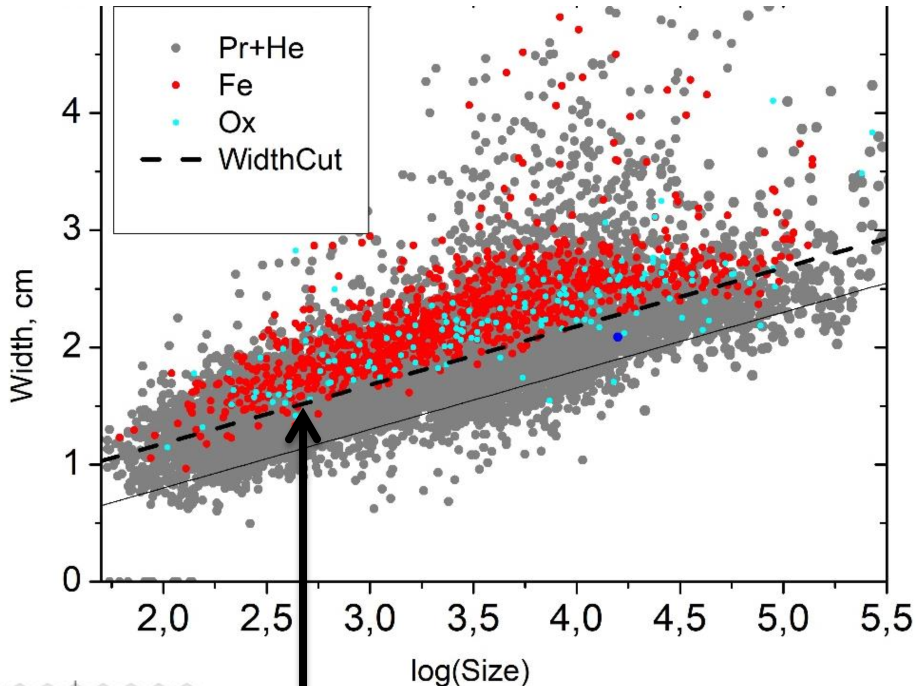
Detection of the CR light components (Proton + Helium) using TAIGA-HiSCORE and TAIGA–IACT installations



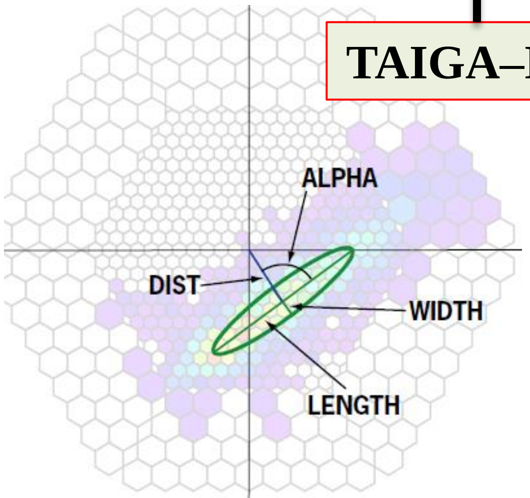
Θ, φ

TAIGA-HiSCORE: energy, direction and core position

Dependence of Width on Log (Size)

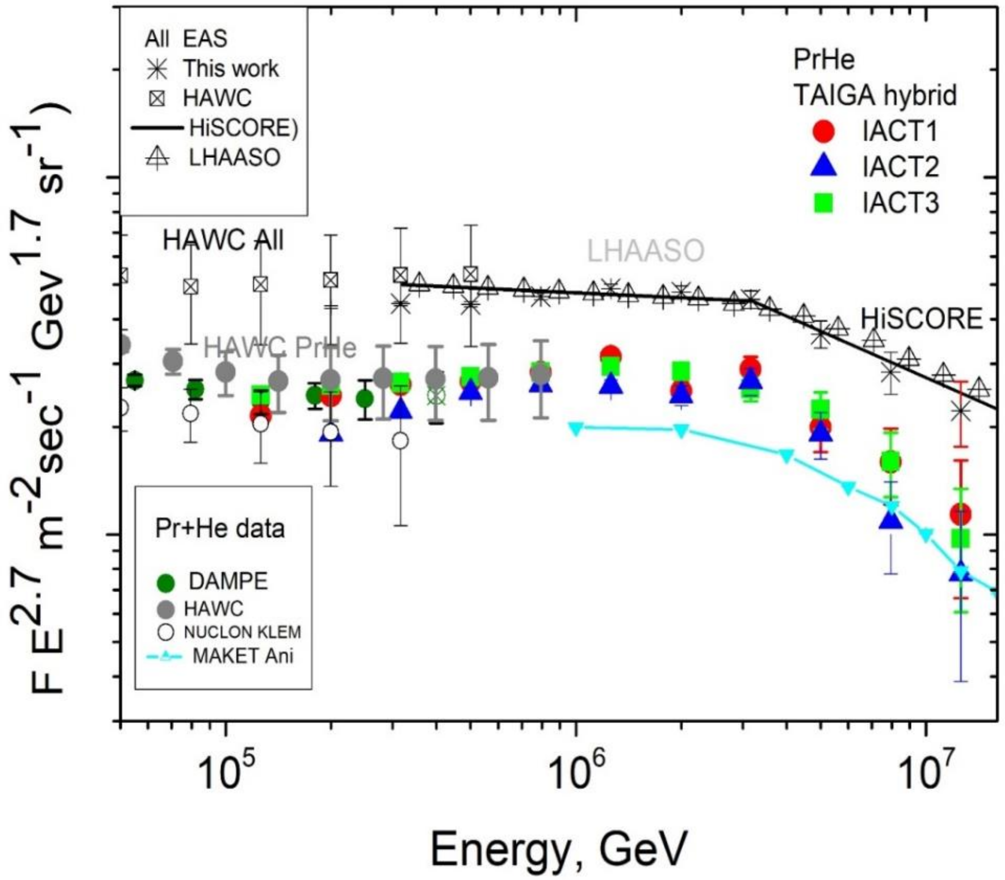


TAIGA–IACT: cut on image width



Size - total number of PE in EAS image

Light component of the CR (p, He) in the region of the " knee" based on the results of hybrid measurements.



Zenith angle<25 deg

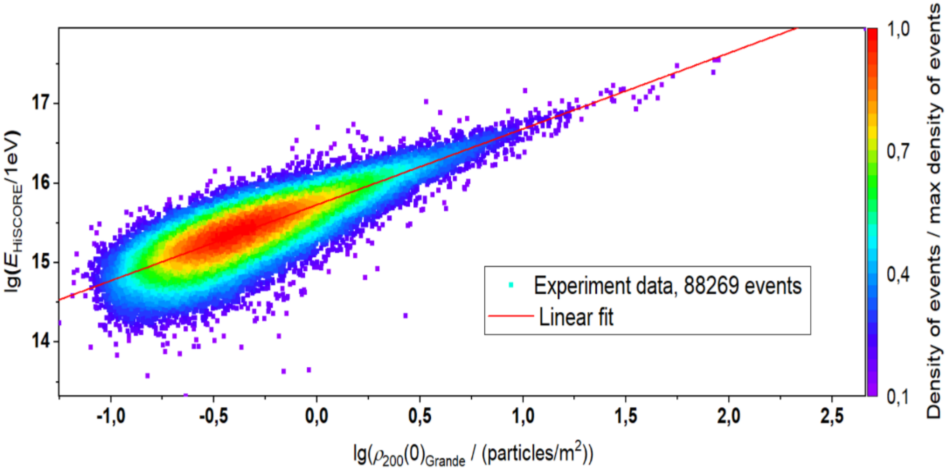
55 hours

70000 events

1. It is clearly seen a break at an energy of about 3 PeV in the spectra of the light component (P+He).
2. The intensity of P + He in the region of ~200 TeV is in good agreement with the data of the direct DAMPE and NUCLON experiments.
3. It is planned to develop a technique for selecting only protons.

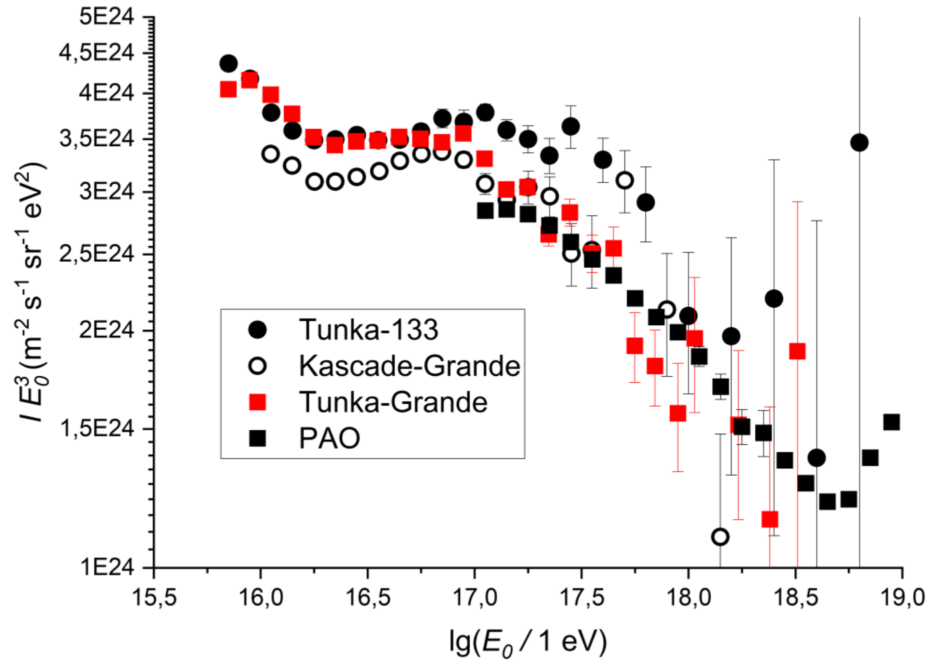
Tunka-Grande CR energy spectrum

To determine the energy of the EAS using data from the Tunka-Grande installation, the parameter ρ(200) is used - the density of charged particles at a distance of 200 m from the position of the EAS axis.



Correlation of the ρ200 parameter with the primary energy of EAS, reconstructed from the TAIGA-HiSCORE Cherenkov setup data.

Energy resolution - 26% for E ≥ 30 PeV.



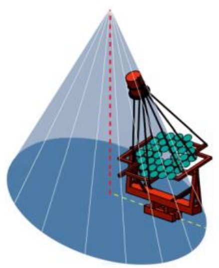
CR energy spectrum according to the Tunka-Grande installation data for 2017–2023

γ = −3,18 ± 0,005 for E<20 PeV
γ = −3,0 ± 0,01 for 20 PeV < E < 100 PeV
γ = −3,26 ± 0,03 for E > 100 PeV
(Second knee!)

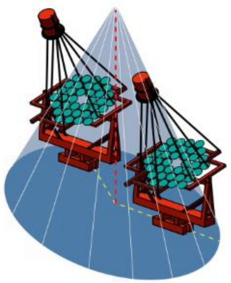
High energy gamma astronomy, some first results

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

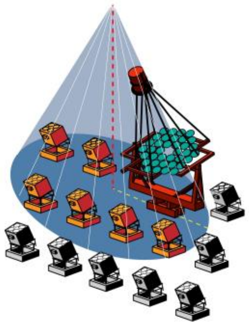
1. **Standalone mode of IACTs operation (E> 2-3 TeV).**
   Hadronic background rejection ~10 $^{-4}$



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

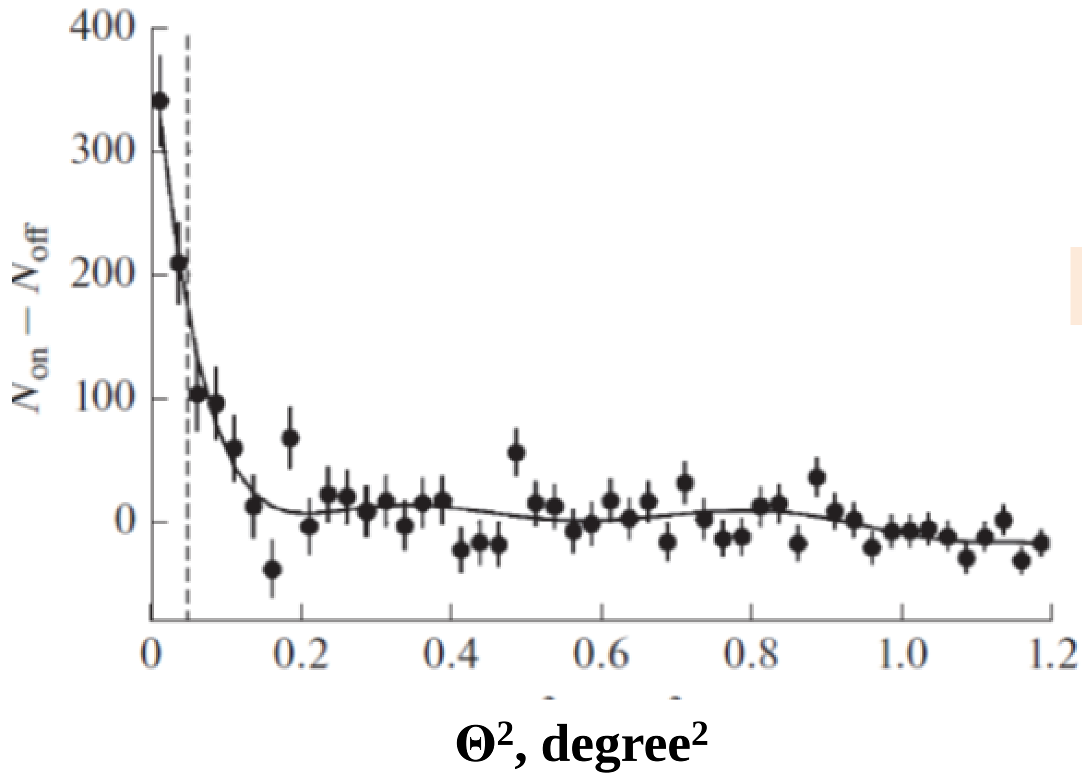


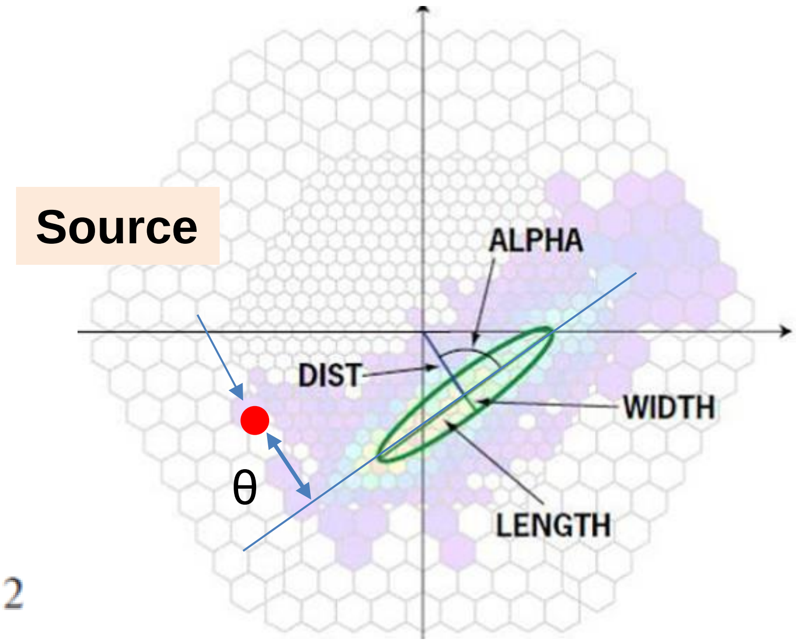
3. **Hybrid mode - joint operation of the TAIGA-HiSCORE and some IACTs (E > 40 TeV). Hadronic background rejection ~10^{-4}**



4. **TAIGA – HiSCORE, E > 300 TeV (additional hadron suppression is required)**

Observing the Crab Nebula in mono mode

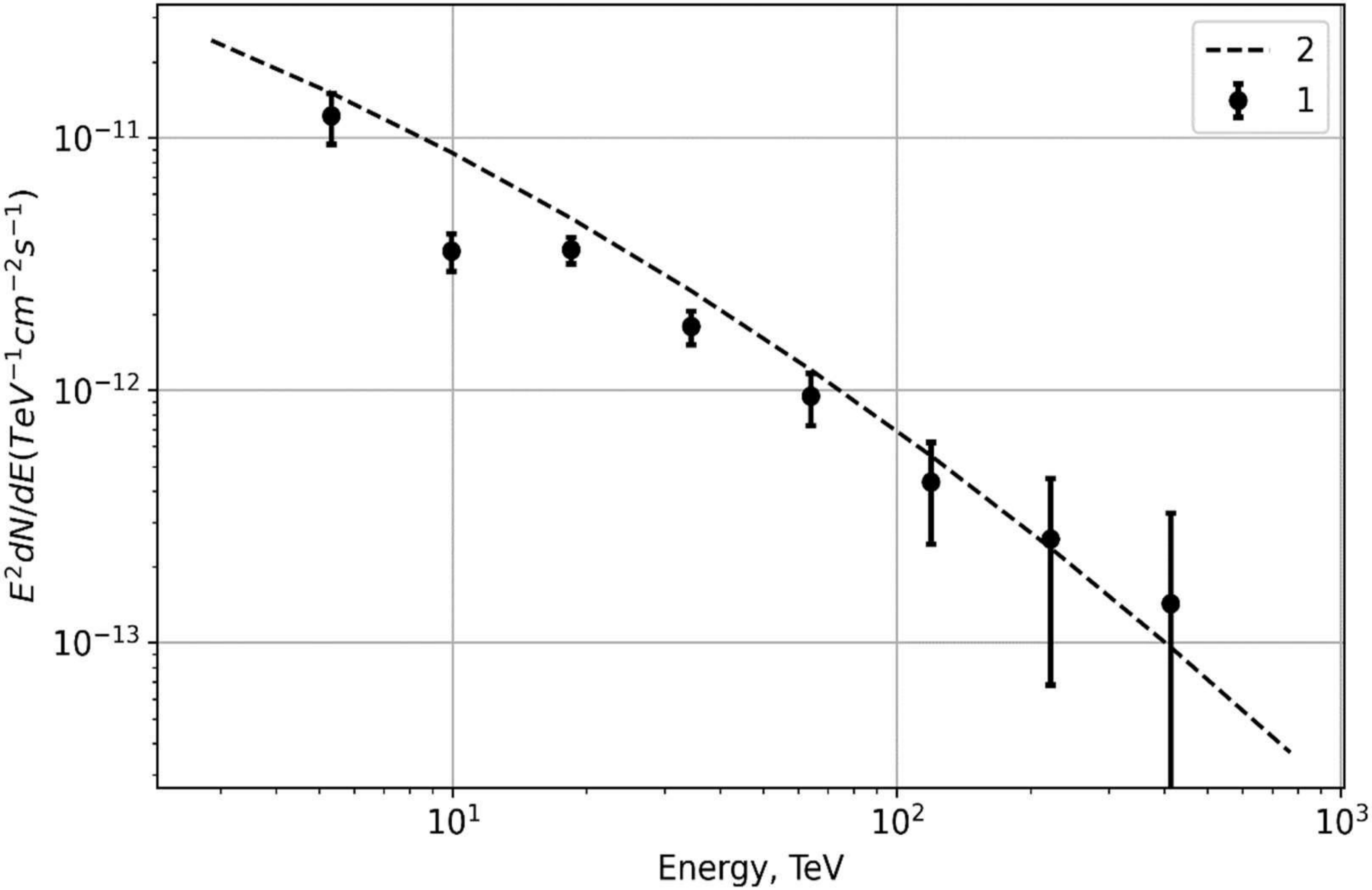




Background subtracted Θ^2-distributions for 150 hours Crab Nebula observation in mono mode

Excess is 560 events for 150 hours, significance level 12σ

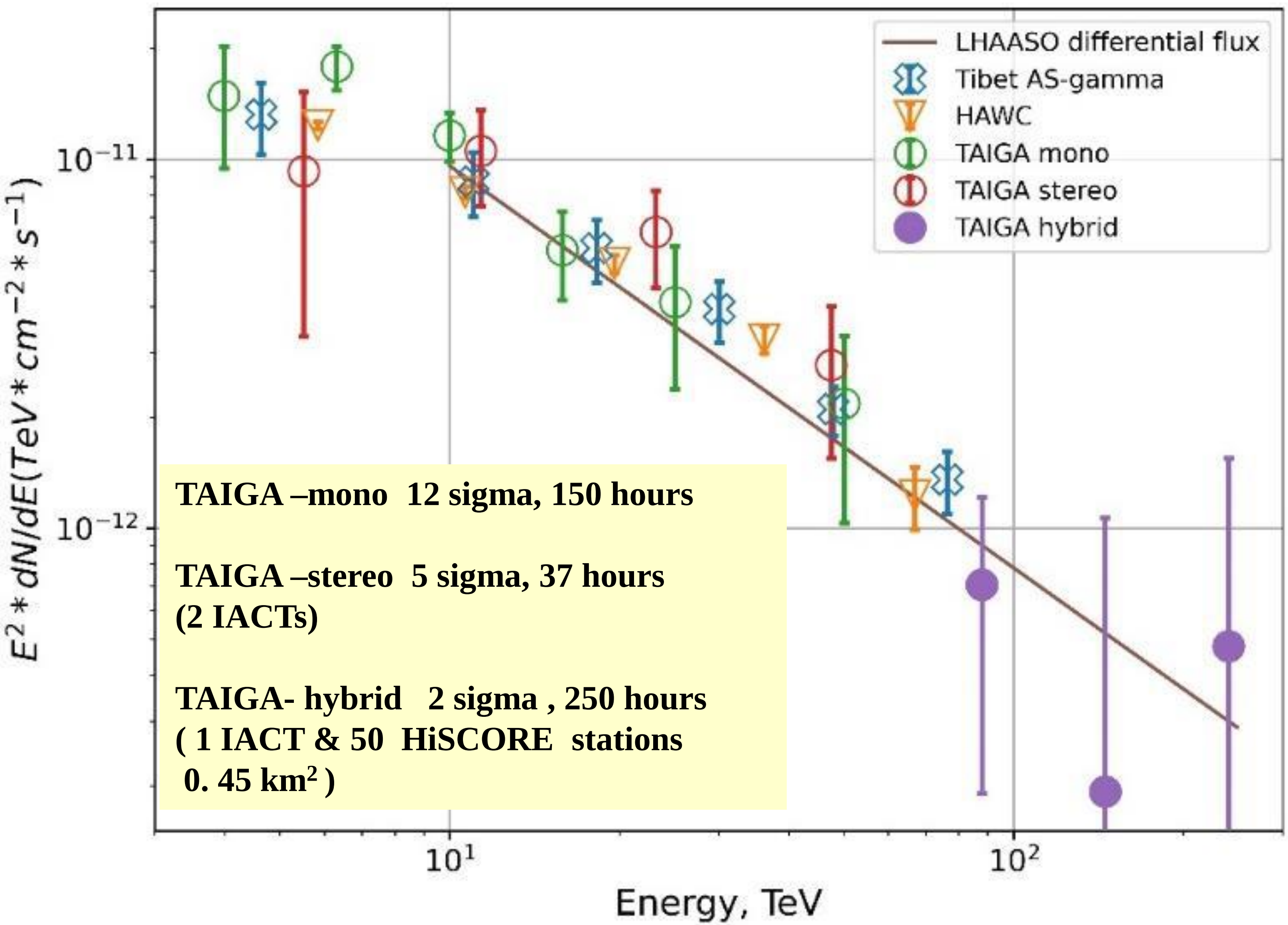
Energy spectrum of the Crab Nebula (stereo mode)



Data were got during 166 hours with 2 IACT $ 68 hours 3 IACT in 2020-2023

5 gamma-like events with energy above 100 TeV

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)

Search for TeV energy photons from gamma-ray bursts and alerts from the Baikal-GVD, IceCube and HAWC facilities

A system for automatic observation of GRB using TAIGA-IACT telescopes based on signals received from the General Coordinates Network (GCN) has been developed and implemented.

A total of 19 observations based on alerts were performed.
The default observation time for an alert is about 1 hour.

GRB 250327A (SWIFT BAT)
GRB 250320A (Fermi)
GRB 250129A (SWIFT BAT)
GRB 250128B (SWIFT&Fermi)
GRB 250101A (SWIFT BAT)
GRB 241229B (SWIFT&Fermi)
GRB 241228B (Fermi)

GRB 241209A (Fermi&SWIFT)
GRB 241201A (Fermi)
GRB 241025A (Fermi&SWIFT)
GRB 240930B (Fermi)
GRB 240905B (Fermi)
IC-240229A

NuEm-240118A (IC+HAWC)
GRB 231215A (Fermi&SWIFT)
GRB 231115A (Fermi&INTEGRAL)
GRB 230321B (FERMI)
GRB 230116E (Fermi)
GRB 221226A (FERMI)

Flash from binary pulsar Be/X-ray LS V +44 17 (Swift-BAT)
Coincidence targeting IceCube and HAWC NuEm-240118A.

In the case of early pointing at a source with a flux similar to GRB221009A, the TAIGA-IACT would have detected ~ 600 photons (14 sigma).

For a 10 times fainter source, 60 events would have been detected (5 sigma).

Search for astrophysical sub-microsecond optical transients with TAIGA-HiSCORE array

Expected signatures:

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

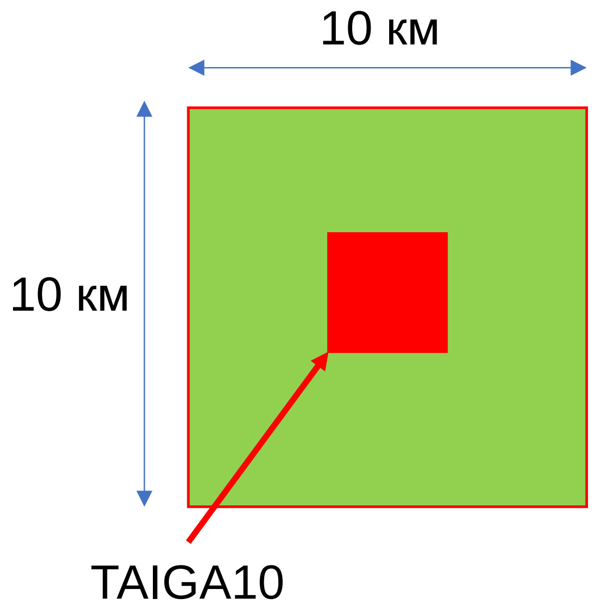
3. Uniform distribution of positions of flashed optical stations upon the surface of the TAIGA-HiSCORE array (no spot-like distribution like in EAS)

No optical 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 ~2x10^{-3} events/sr/hour (preliminary)

TAIGA-100 –

Installation with a hybrid detector system over an area of 100 km^2

TAIGA100 – for studying gamma rays fluxes with E > 1 PeV



~ 3500 wide-angle Cherenkov detectors:

1 PMT, FoV ~ 2 sr.

~ 3500 water muon detectors

6-7 IACTs, mirror diameter 4 m (from the TAIGA-1 installation)

1-2 IACTs, mirror diameter 10 m (mini ALEGRO)

1-2 small fluorescent telescopes

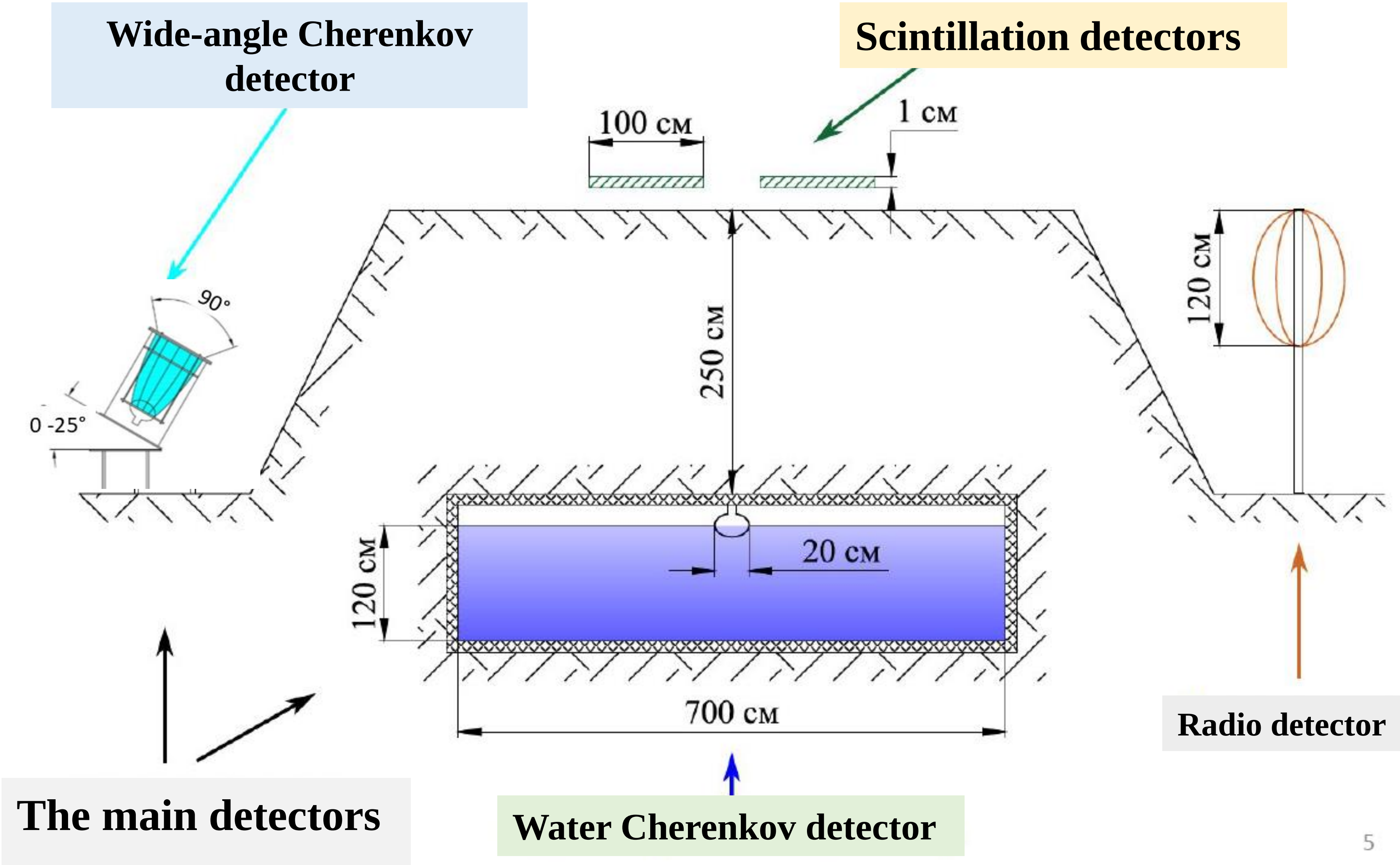
Super station (SS):

- wide-angle Cherenkov detector
- Cherenkov water muon detectors, area 40 m^2.
- Scintillation detector (1-2m^2)
- Radio detector

For TAIGA10 – distance between SS- 100m
Threshold E ~200 TeV. 500 stations

For TAIGA100 – distance between SS- 150 m
Threshold E ~ 400 TeV. 3000 stations

TAIGA-100 super station



TAIGA-100 scientific program

1. Gamma astronomy of ultra-high energies.

(Diffuse gamma radiation in the range of 1 – 10 PeV^2).

2. Cosmic rays in the range 10^{14} - 10^{19} eV.

(10^6 events per year with E > 10^{17}, protons separation).

3. Search for photons in the range of 10^{17} -10^{18} eV

4. Transient phenomena and gamma bursts.

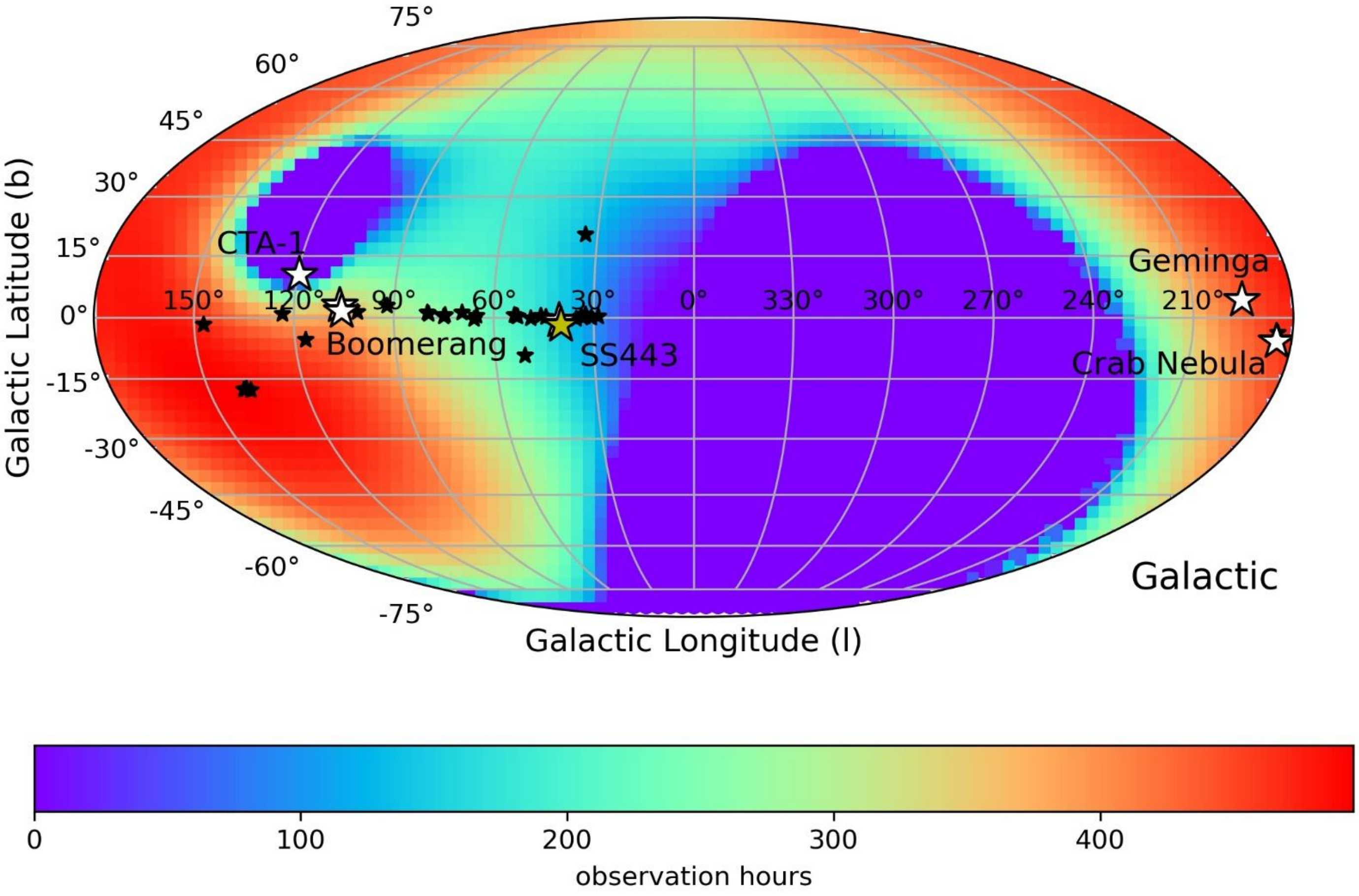
5. Horizontal showers and showers from neutrinos

(the mass of air above the installation is 10^9 tons, search for EAS with an angle greater than 60 degrees with a large number of electrons).

6. Exotics (dark matter, violation of Lorentz invariance, strangelets, etc.)

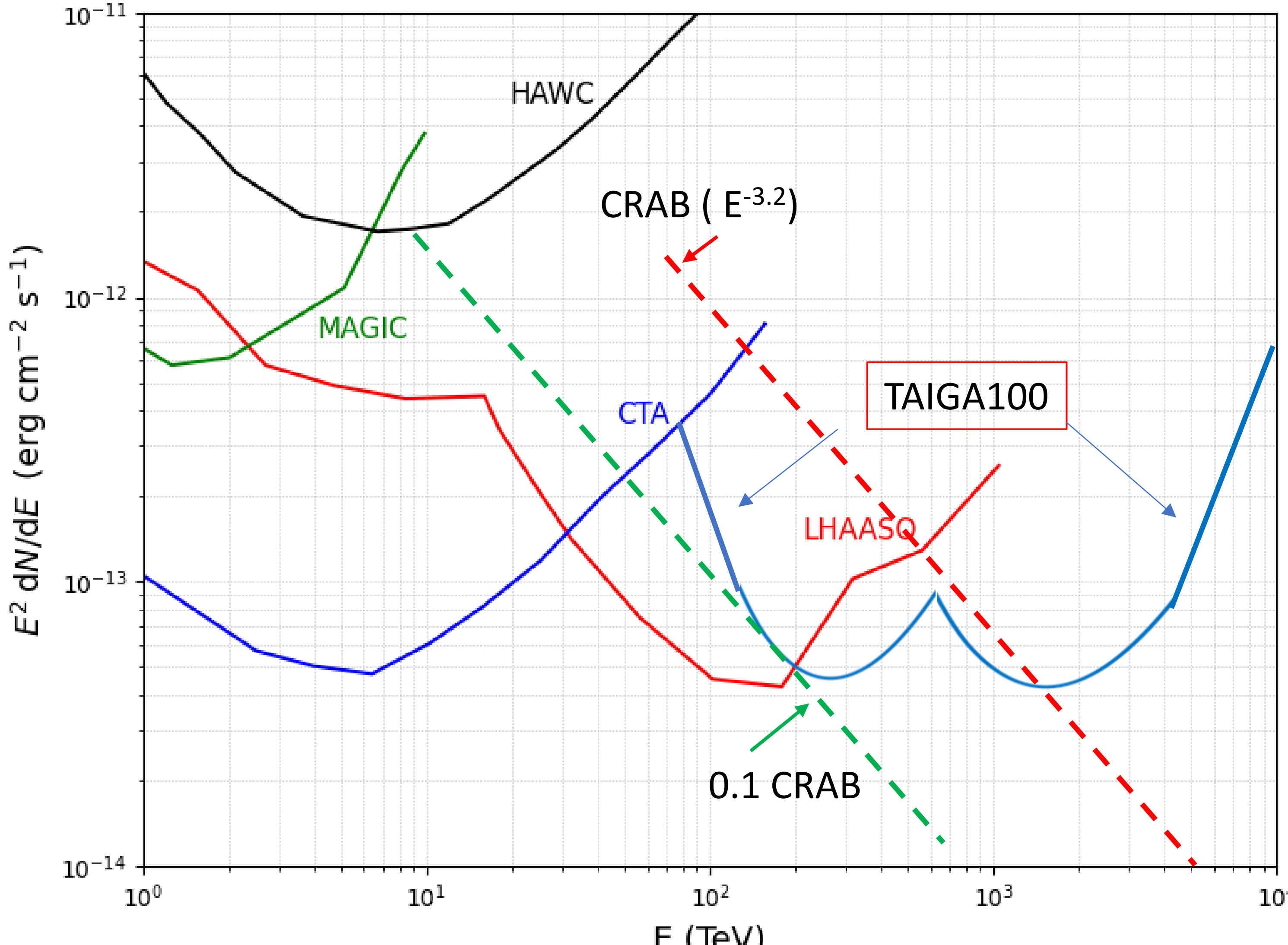
7. Geophysics - thunderstorms & EAS

Source observation time per year

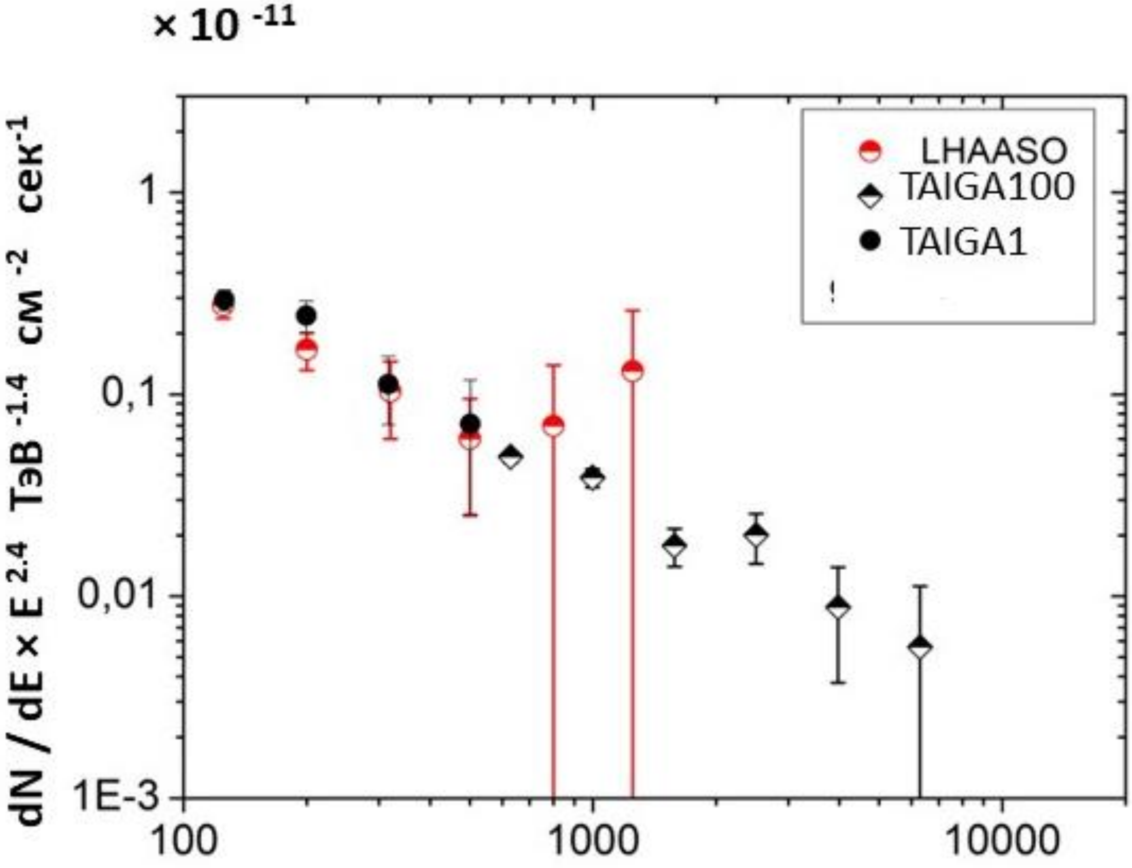


Winston cone of wide-angle Cherenkov detectors - 45º, tilt 25º

TAIGA -100 differential sensitivity
(4 bins per order) 5 sigma or 10 events



Expected gamma ray energy spectrum from the Crab Nebula

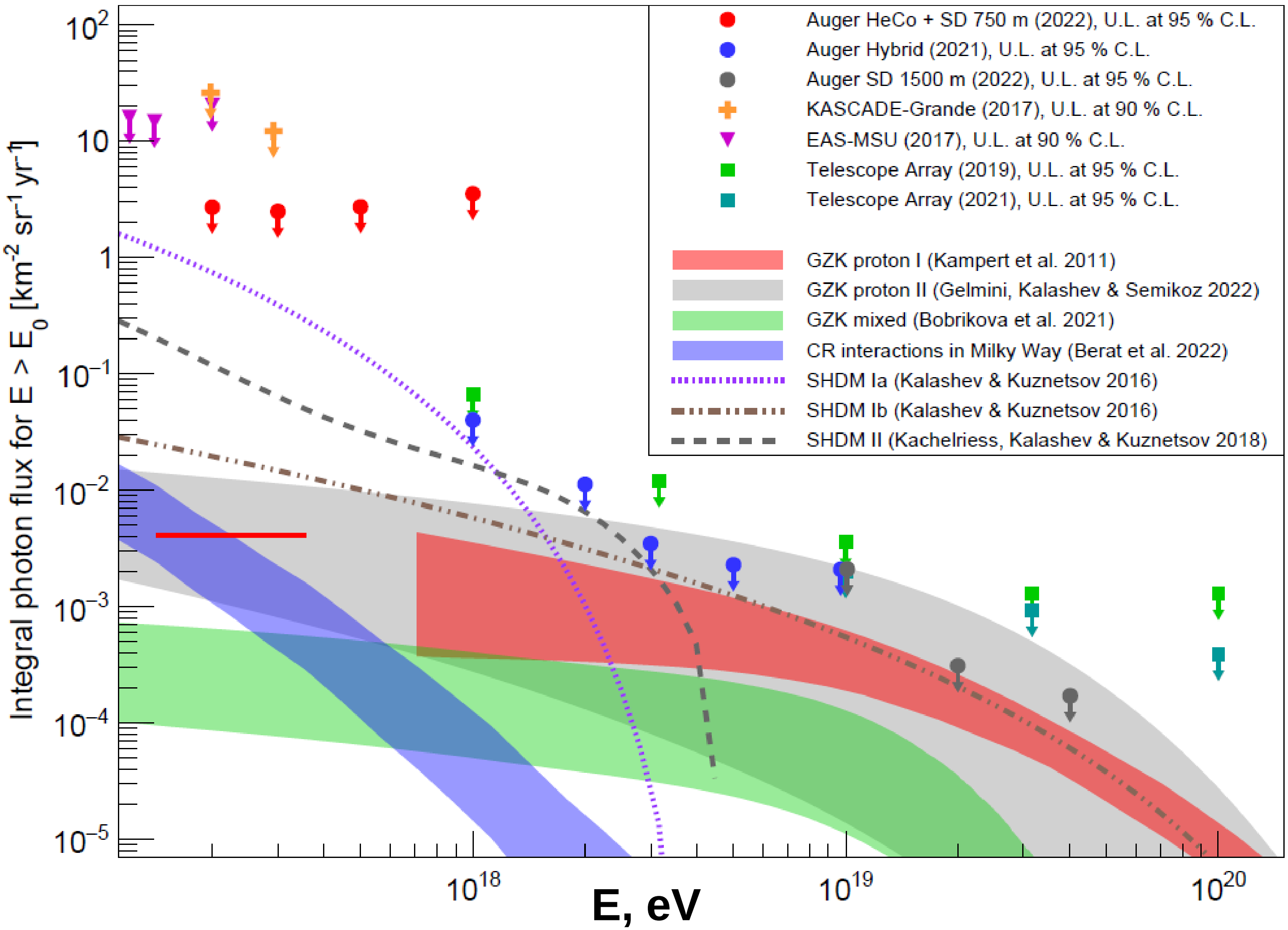


E, TeV

~ 350 gamma from Crab Nebula with E > 500 TeV for 500 hours of observation (3 years)

The significance level is 10 sigma

Search of GZK photons (E =10^{17}-10^{18} eV)



We expect 10 GZK ($P + \gamma_{rel} \rightarrow P + \pi^0 \rightarrow 2\gamma$) photons for 10 years

Charged cosmic rays

$E > 10^{17}$ eV - 10^{6} events per year
$E > 10^{19}$ eV - 10^{2} events per year

The main tasks:

- Mass composition by components.

- Checking models of transition from galaxy to metagalaxy cosmic rays.

- Are there galactic protons in this energy region?

Near future plan (2026 -2028): upgrade of TAIGA-1 & TAIGA-100 engineering array

1. **Design for the TAIGA-100 Astrophysical Complex with hybrid detectors system on area about 100 km, including full Monte-Carlo simulating and a site choice.**
2. **R&D of new detectors for TAIGA-100 facility (wide-angle optical stations, large-area water Cherenkov muon detectors, scintillation detectors, IACTs with SiPM cameras, fluorescence telescopes and radio detectors of EAS).**
3. **Deployment of the TAIGA-100 engineering array with an area of 0.5 km^2 for testing common operating with TAIGA-1.**
4. **Deployment of the fifth IACT with a mirror diameter of 4.3 m and one with a mirror diameter of 10 m.**

Requirements for TAIGA-100 site

1) Astro climate :

- minimum number of cloudless nights;
- high transparency of the atmosphere
- minimum humidity;
- the minimum level of background anthropogenic illumination.

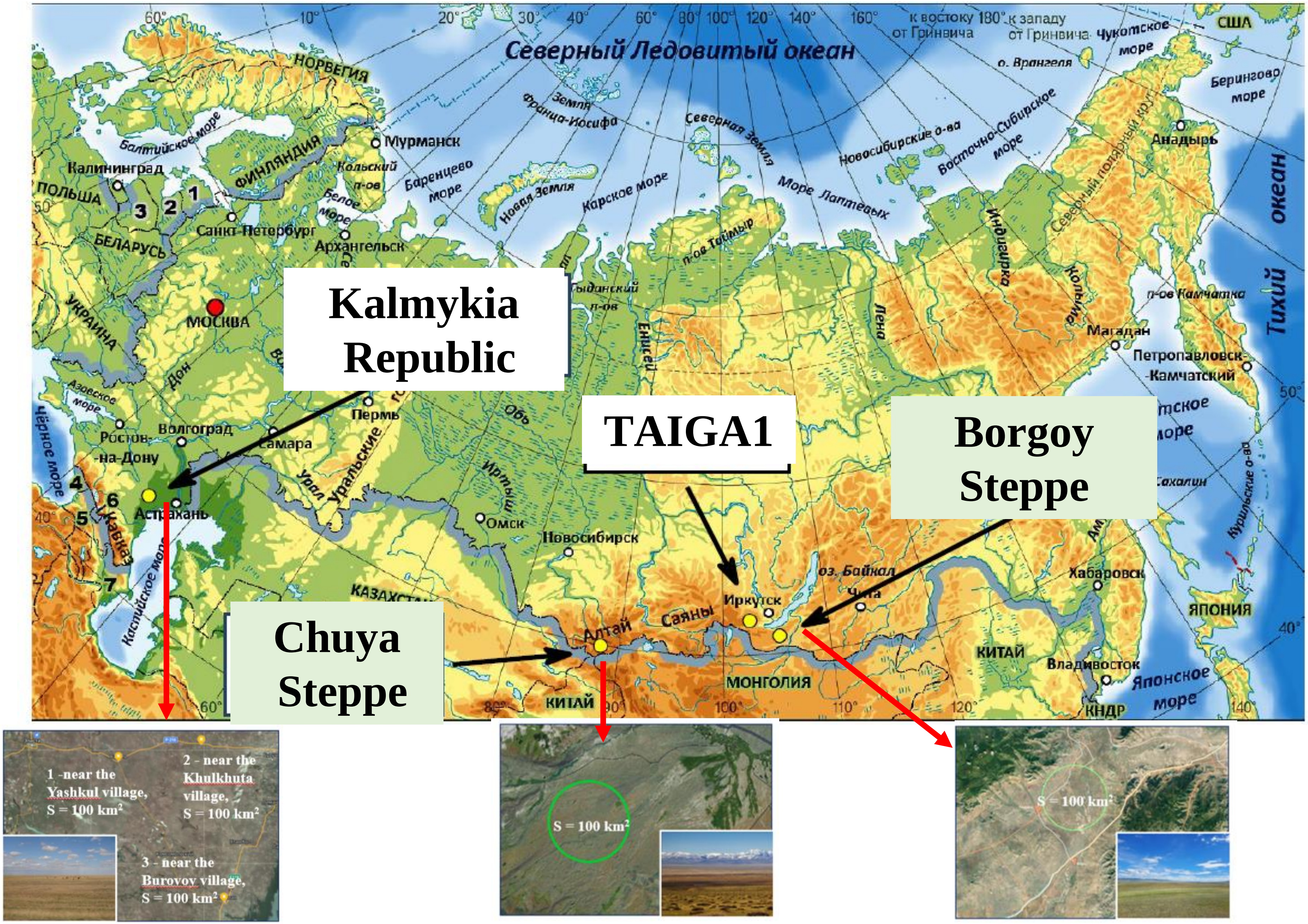
2) Terrain features :

- Altitude
- available for Astrophysical Complex area is ~ 100 km^2;
- the steepness of the slopes is up to 5^{o};
- the soils are suitable for digging at a depth of at least 3 m;
- availability of water for Water Muon Detectors.
- positive ground temperature at a depth of ~ 2 m.

3) Infrastructure :

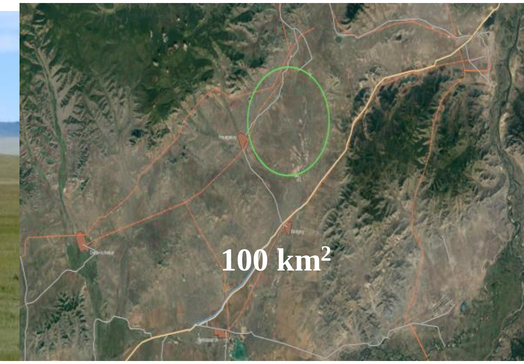
- distance to site;
- transport accessibility;
- land category, actual use;
- availability of affordable energy and telecommunication infrastructure.

Site for TAIGA-100



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 tens of square kilometers for UH gamma-astronomy.

TAIGA-100 opens up unique opportunities for solving problems of ultra-high-energy gamma-ray astronomy and ultra-high-energy cosmic rays and studying many other astrophysical objects and phenomena.

R&D work has begun on the TAIGA100 astrophysical complex project. It is planned to test the main TAIGA100 detectors (water Cherenkov muon detector and scintillation detectors, new Cherenkov detector, etc.) and the data collection system at the TAIGA-1 site before choosing a location for the new complex.

Thank you for attention!