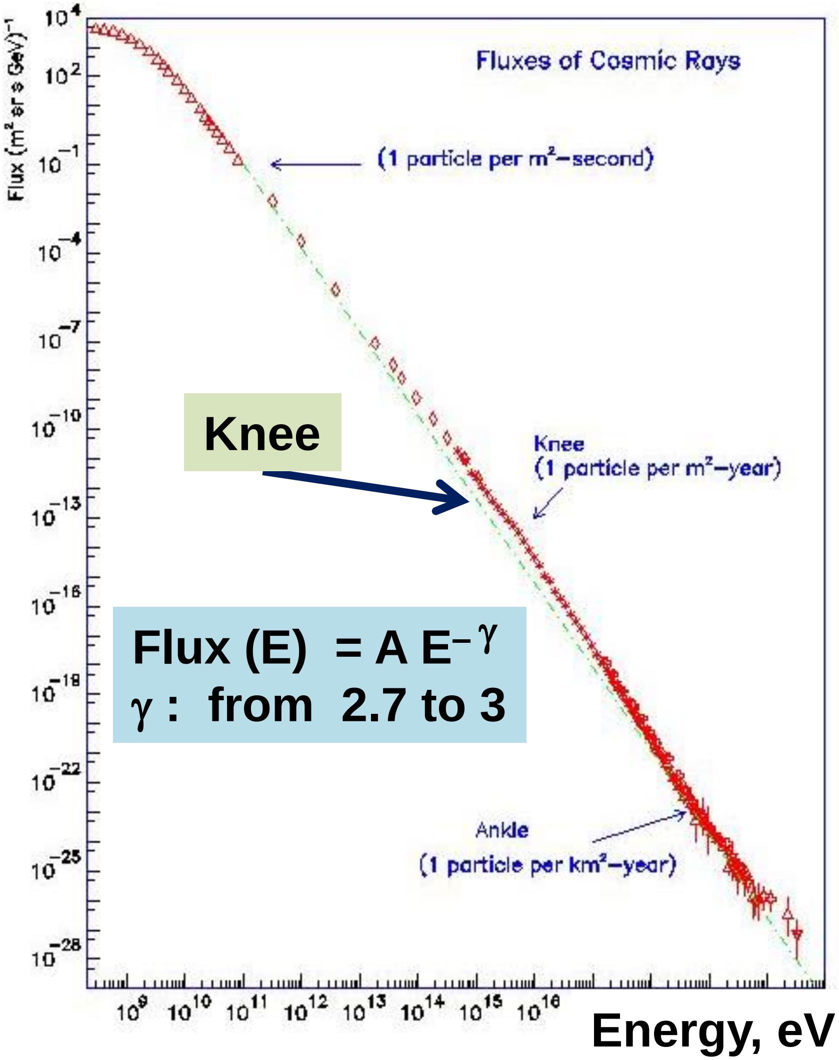
The TAIGA - a hybrid array for high energy gamma astronomy and cosmic ray physics.

N. Budnev, Irkutsk State University

For the TAIGA collaboration

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

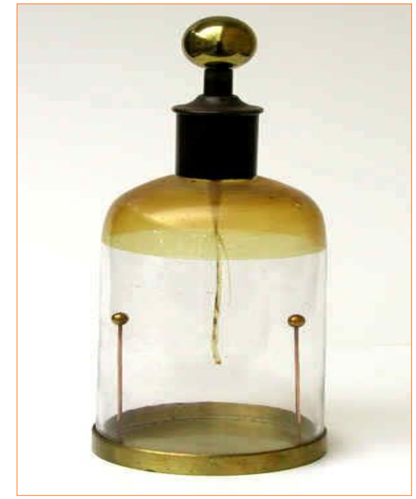
Flux **Energy spectrum**

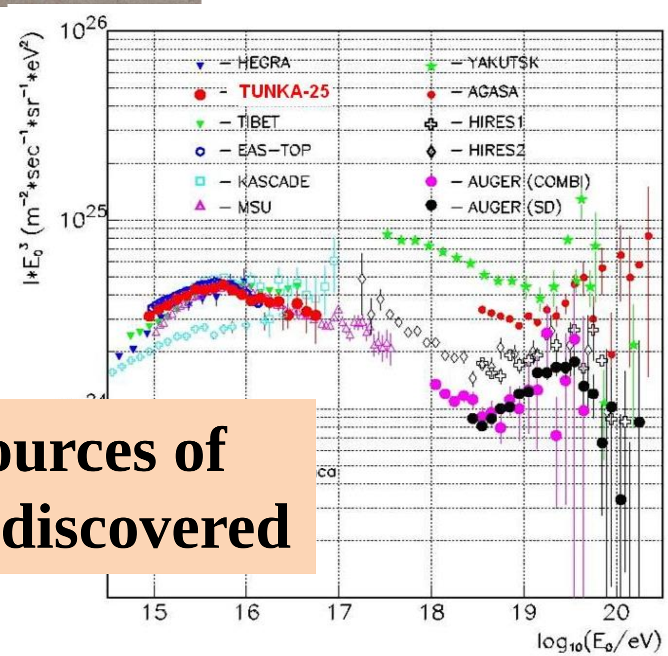


Knee

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

Energy, eV

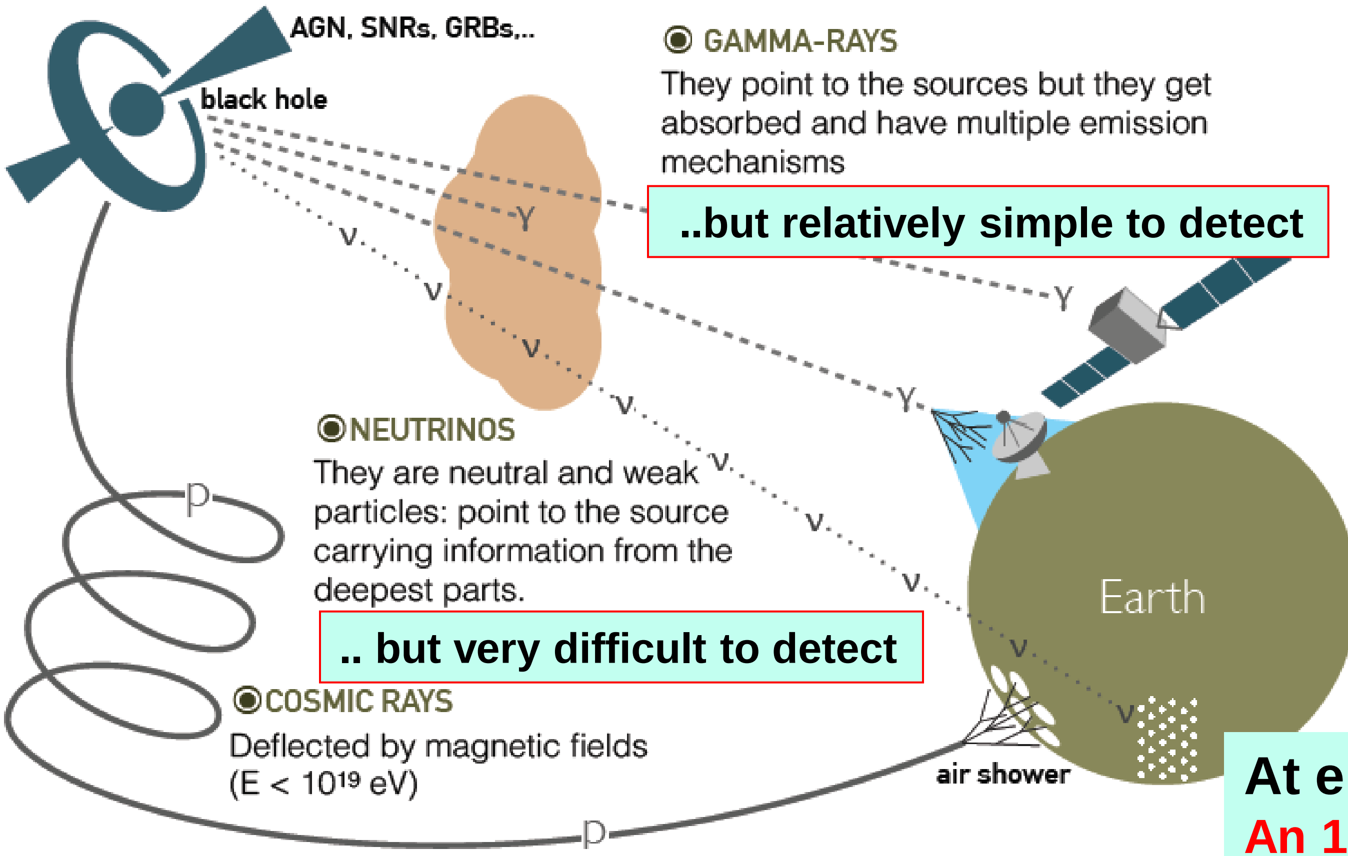




No any sources of CR were discovered

Gamma-astronomy & neutrino astronomy

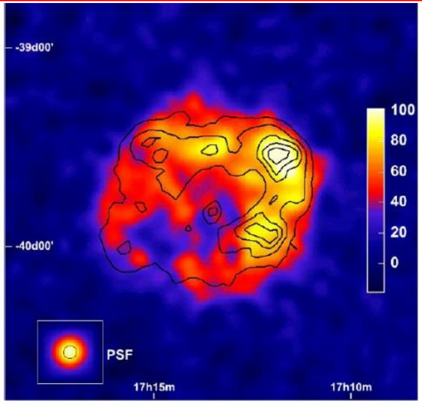
To understand a nature of an cosmic high energy accelerator one can detect gamma-rays or neutrinos.



..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

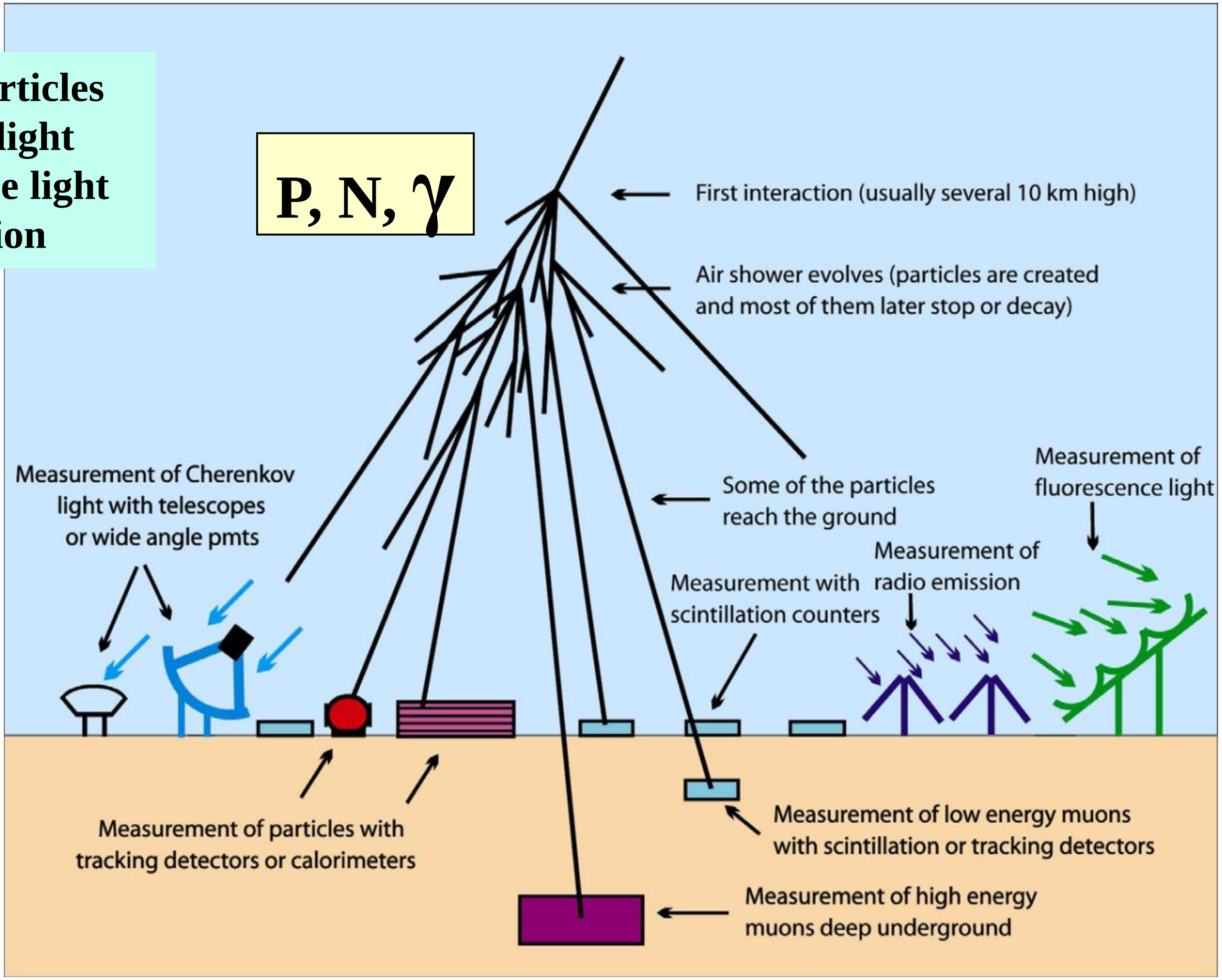
- 1 event / 10 year

An 1км^2 gamma detector

- 1 event / 3 hours!

Detection of EAS components - is a way to study high energy charged particles and gamma – rays.

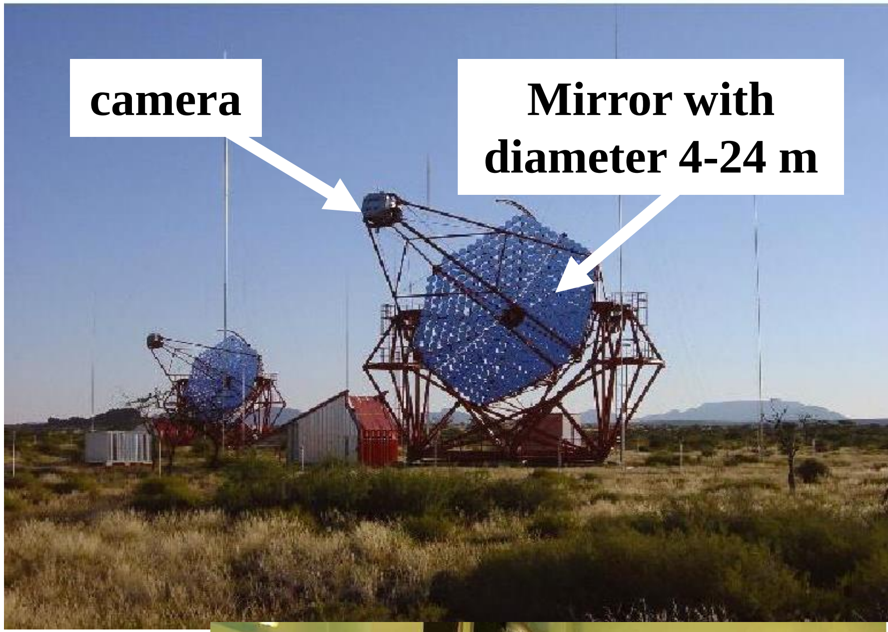
- Charged particles
- Cherenkov light
- Fluorescence light
-Radio emission

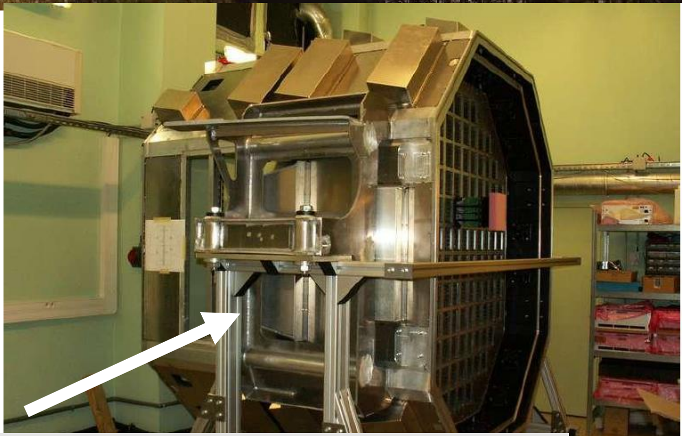


Main parameters: 1. Direction. 2. Energy. 3. Kind of a particle.

An Imaging Atmospheric Cherenkov Telescope - a main instrument for high energy gamma astronomy at present

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



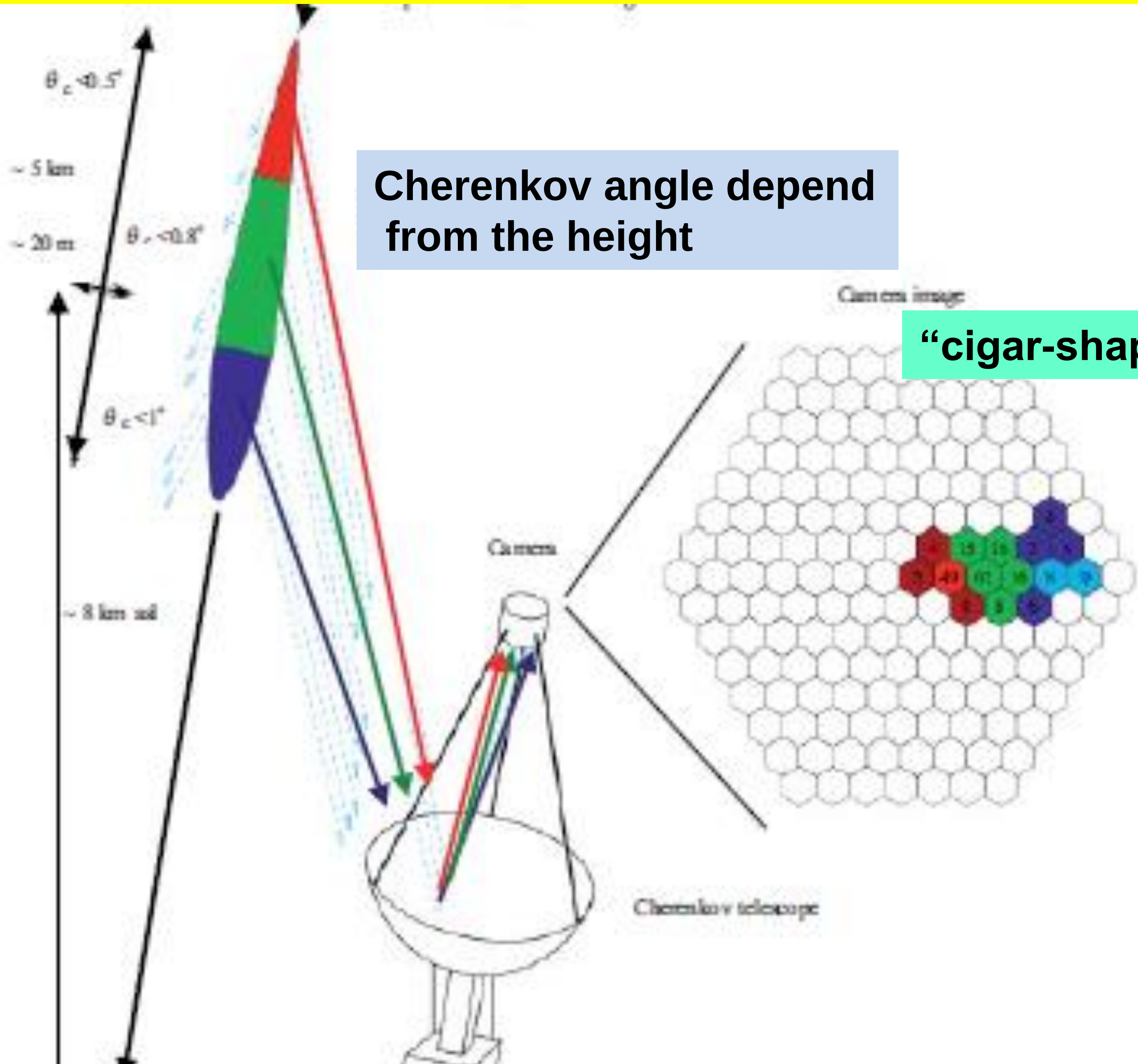


H.E.S.S. camera (D = 3 m!)

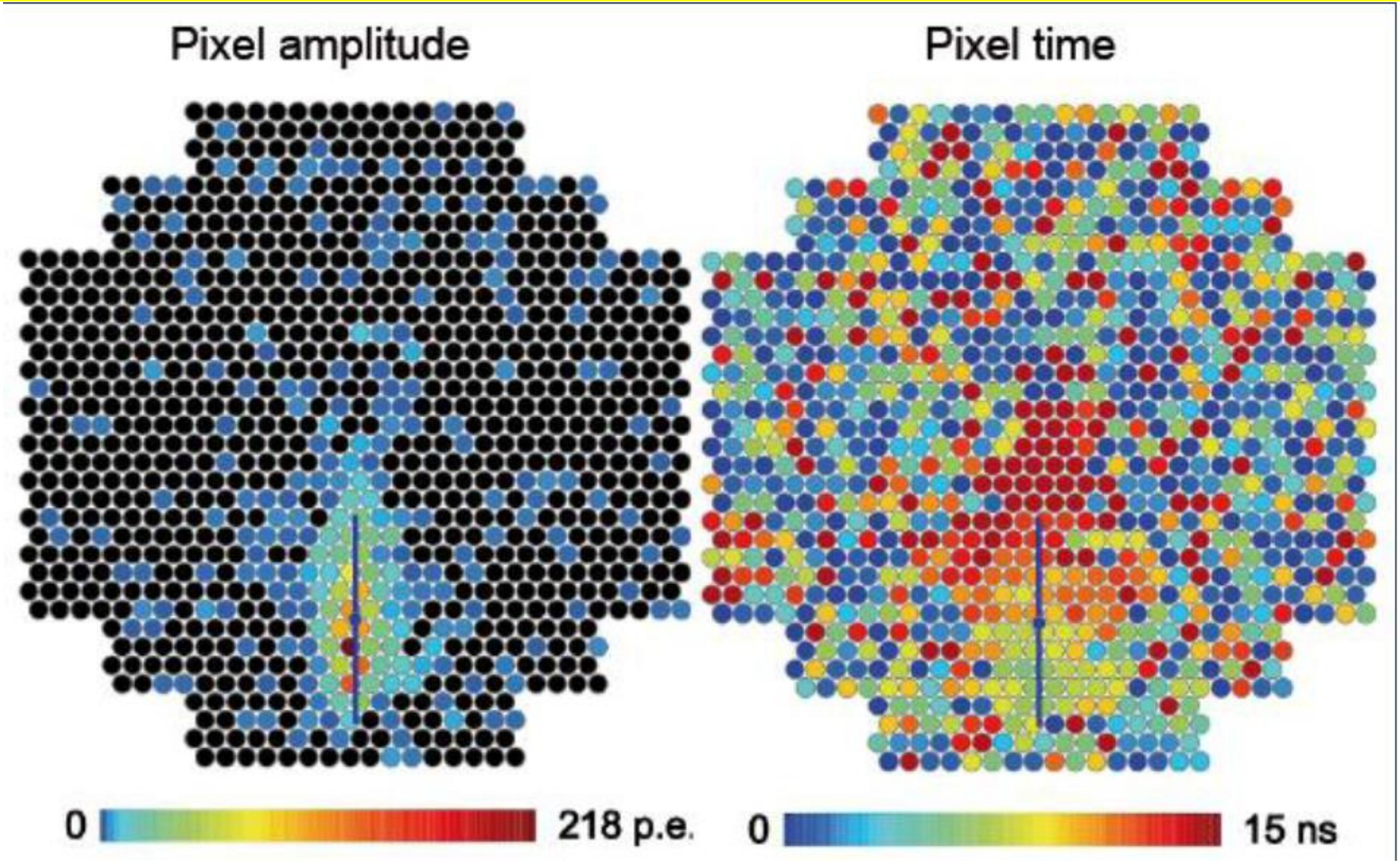
The formation of an image from EAS

Cherenkov angle depend from the height

“cigar-shaped“ form

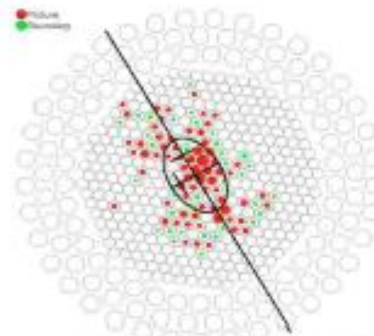


An EAS imaging in the H.E.S.S. camera

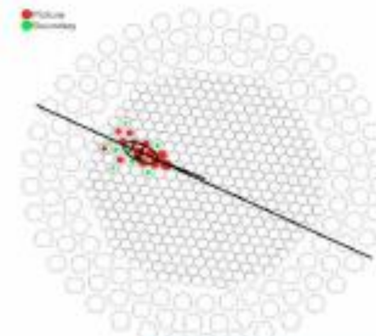


Whipple 10 m Reflector and Camera, 1984
Prototype Imaging System

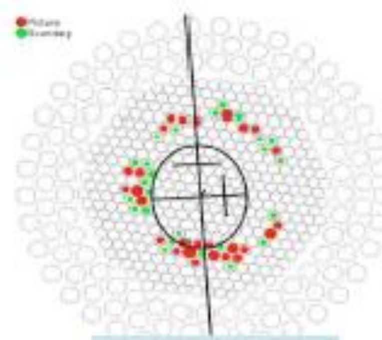
Types of images seen by atmospheric Cherenkov camera



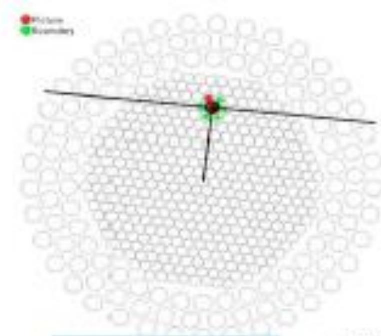
Hadron



Gamma ray

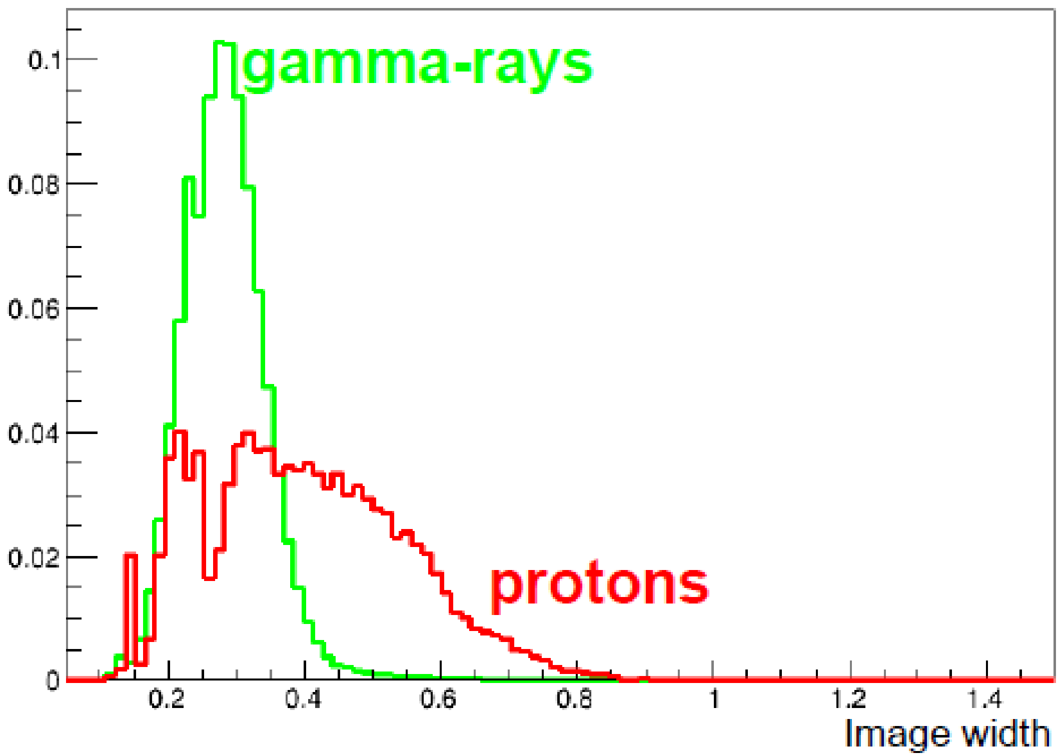


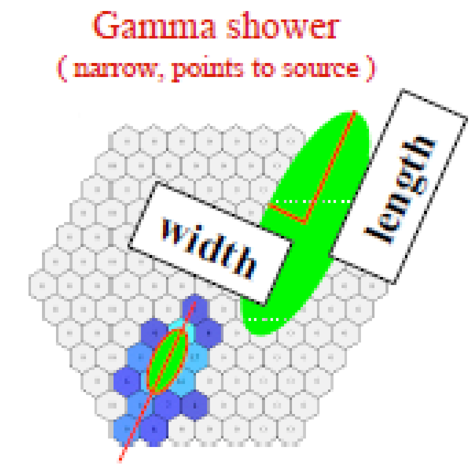
Muon Ring

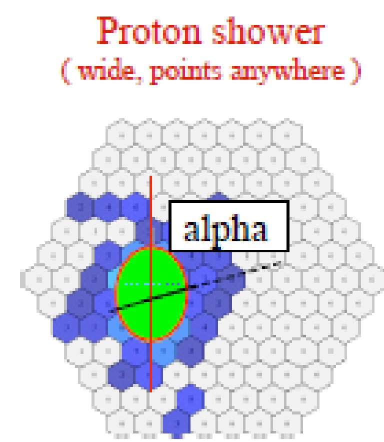


Sky Noise

Selection events from gamma-rays by Hillas parameters







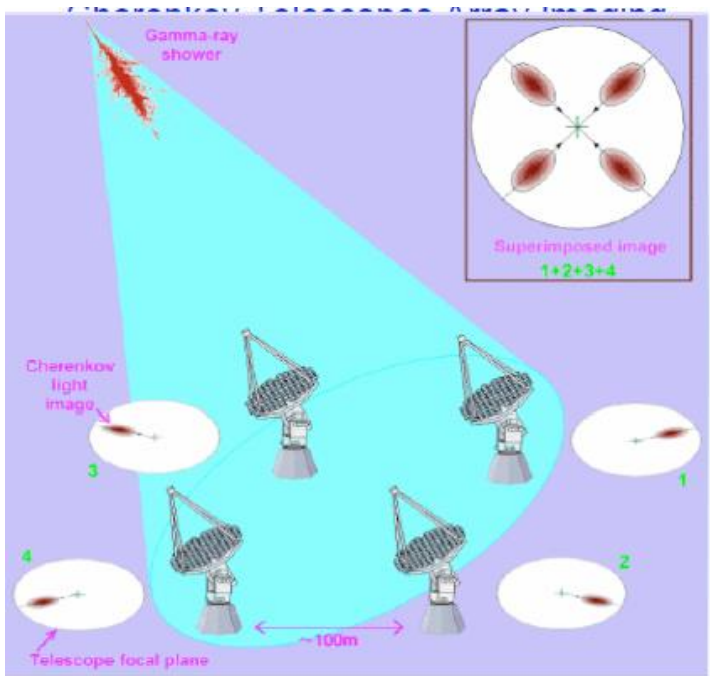
Q –factor = $k_1 / \sqrt{K_2}$

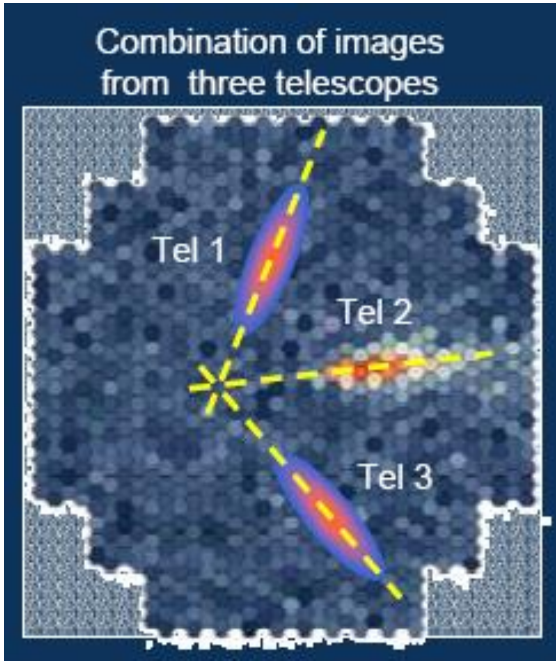
K_1 - fraction of gamma ray events

K_2 - background events after selection

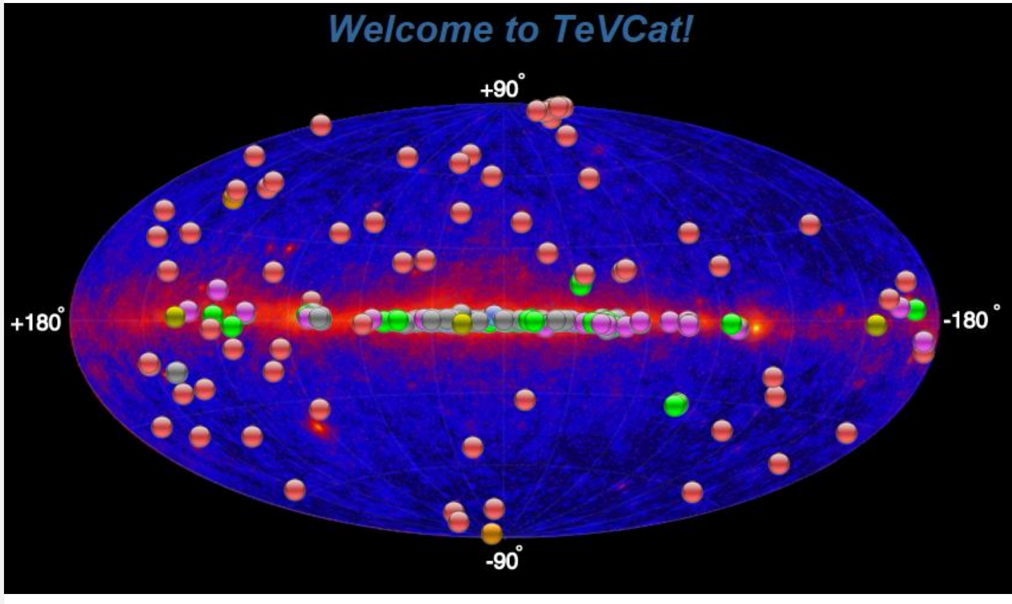
Imaging Atmospheric Cherenkov Arrays (2-5 IACT)

Whipple
HEGRA
HESS
MAGIC
VERITAS
S ~ 0.01 km^2





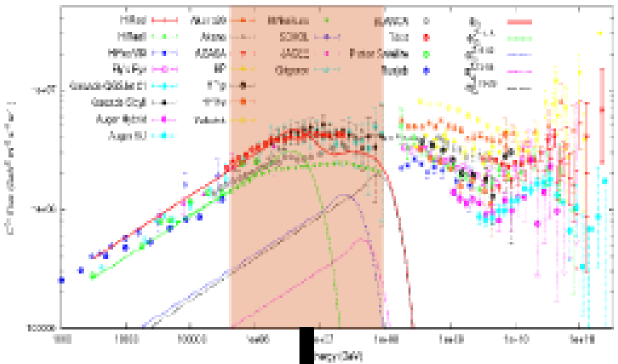
More then 160 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays.
But no gamma quantum with energy more then 80 TeV were detected up to now.
An area of an array should be a few square kilometers as minimum to detect high energy gamma.
Cost of an IACT array **30 M$** /km^2 at least!



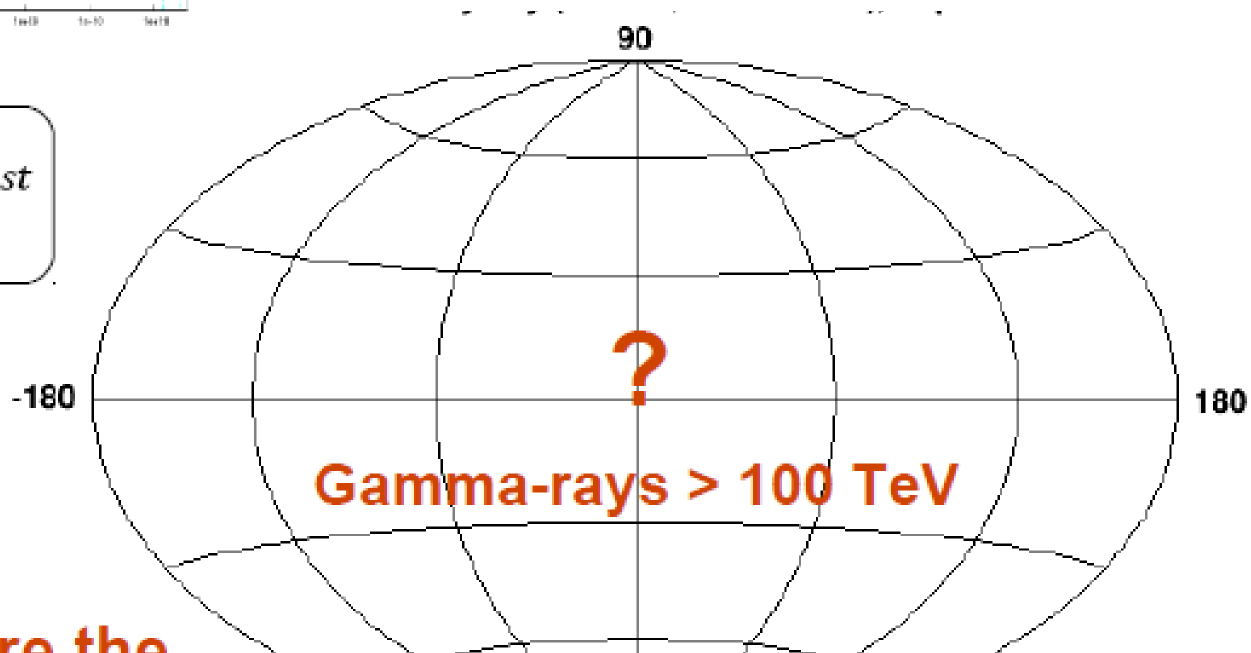
Gamma from Galactic Cosmic rays:

$E_\gamma \sim E_{CR} / 10$

Pevatron sky



$$p\ (p,\ \gamma) \longrightarrow \pi^0 + rest$$
$$\hookrightarrow \gamma\gamma$$



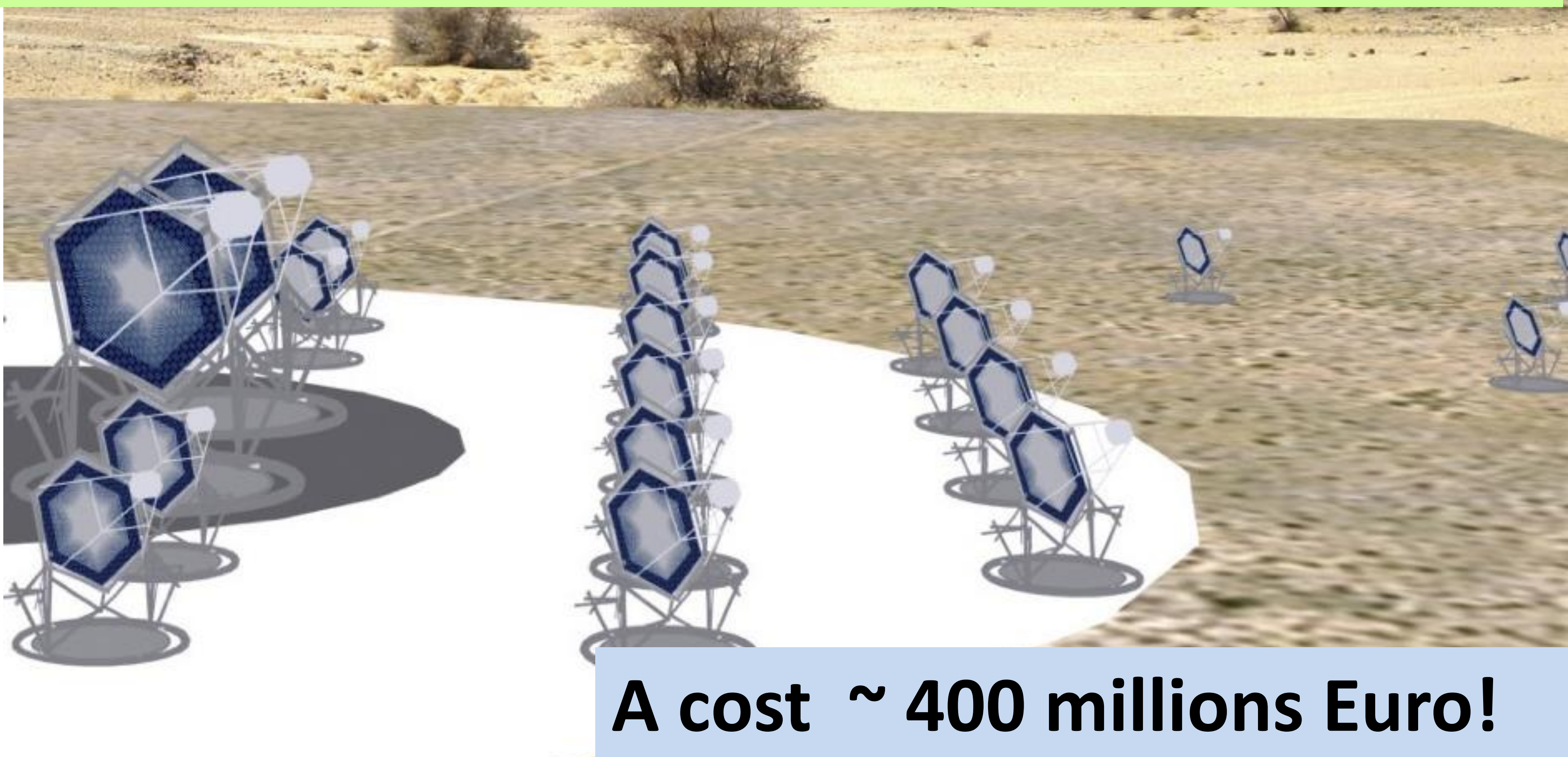
Where are the cosmic ray pevatrons ?

To search gamma with energy > 30 TeV)
Arrays with an area (1-10)km^2 are needed

CTA project - an observatory for ground based gamma-ray astronomy: South and North parts.

3 kinds of IACT:

Diameter of a mirror 23 - 24 м; FOV - 4-5^{o}; energy 10 – 100 GeV; (4 – 6 IACT)
Diameter of a mirror 10-12 м; FOV 6-8^{o} ; energy 100 GeV – 10 TeV (20 IACT)
Diameter of a mirror 4 -6 м; FOV 10^{o}; energy 10 - 300 TeV; (50 IACT on area 7 km^2)



A cost ~ 400 millions Euro!

EAS Energy

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

$g = 0.94 \pm 0.01$

EAS Cherenkov light detection with non-imaging timing wide-angle detectors

θ, φ

Average CR mass A

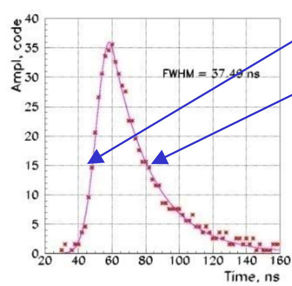
$LnA \sim X_{max}$

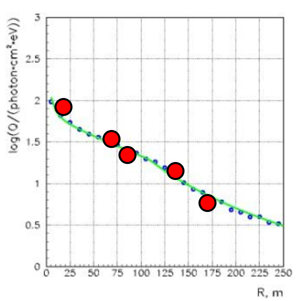
$X_{max} = C - D \cdot lg\, \tau(400)$

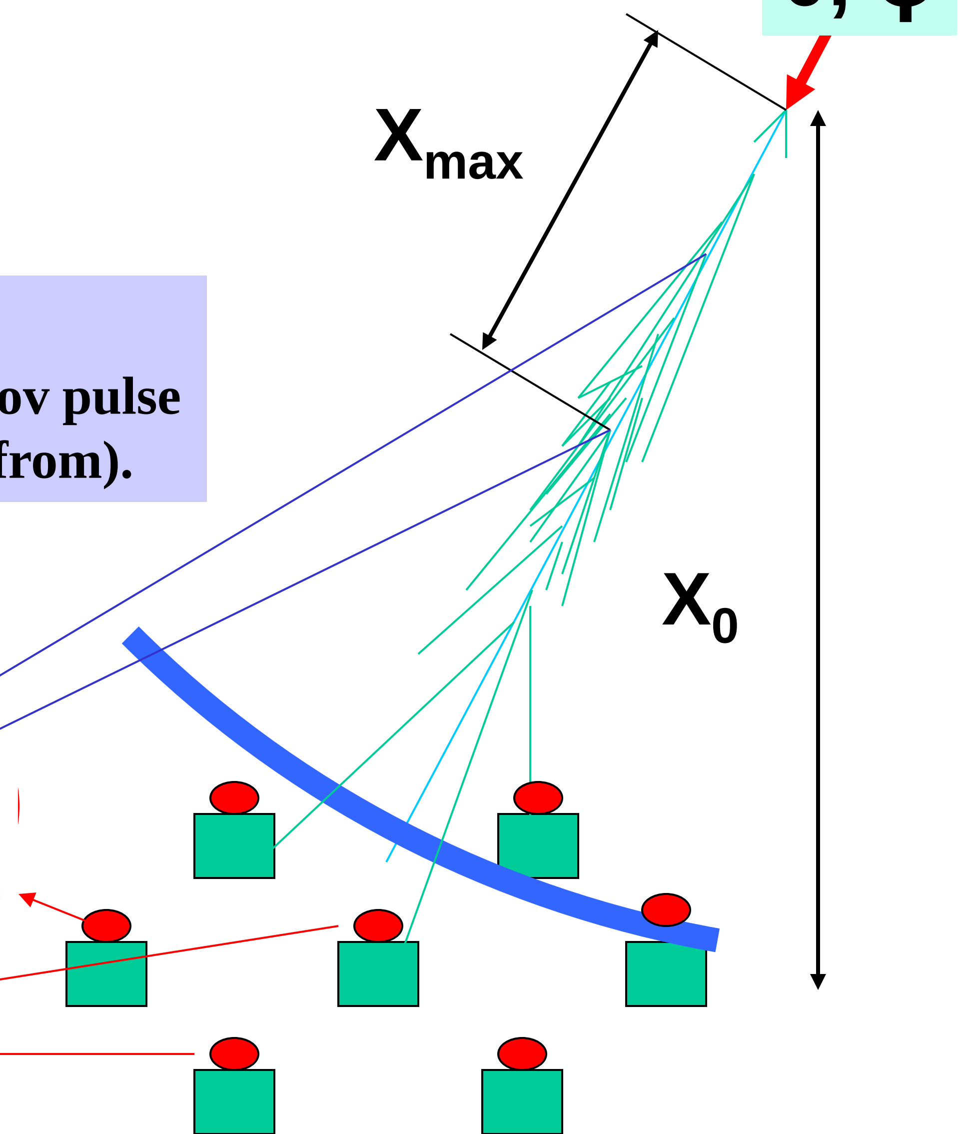
($\tau(400)$ - width of a Cherenkov pulse at distance 400 m EAS core from).

$X_{max} = F(P)$

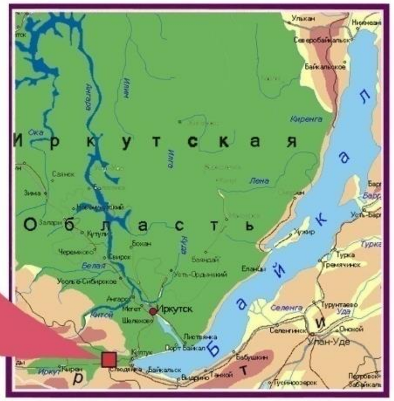
P -Steepness of a Lateral Distribution Function (LDF)





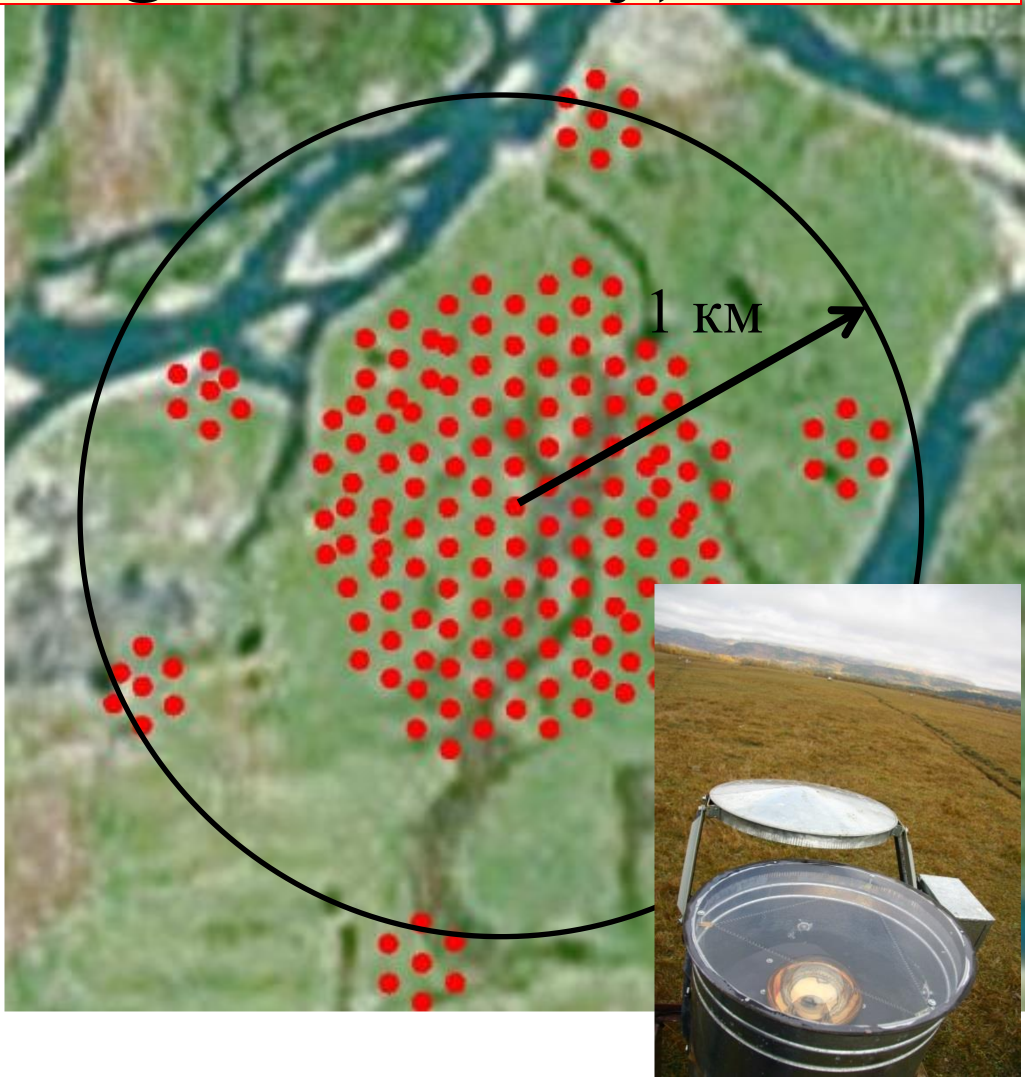


Tunka-133 timing array:175 wide-angle Cherenkov detectors distributed on area 3 km^2 (constructed during 2006-2012y)



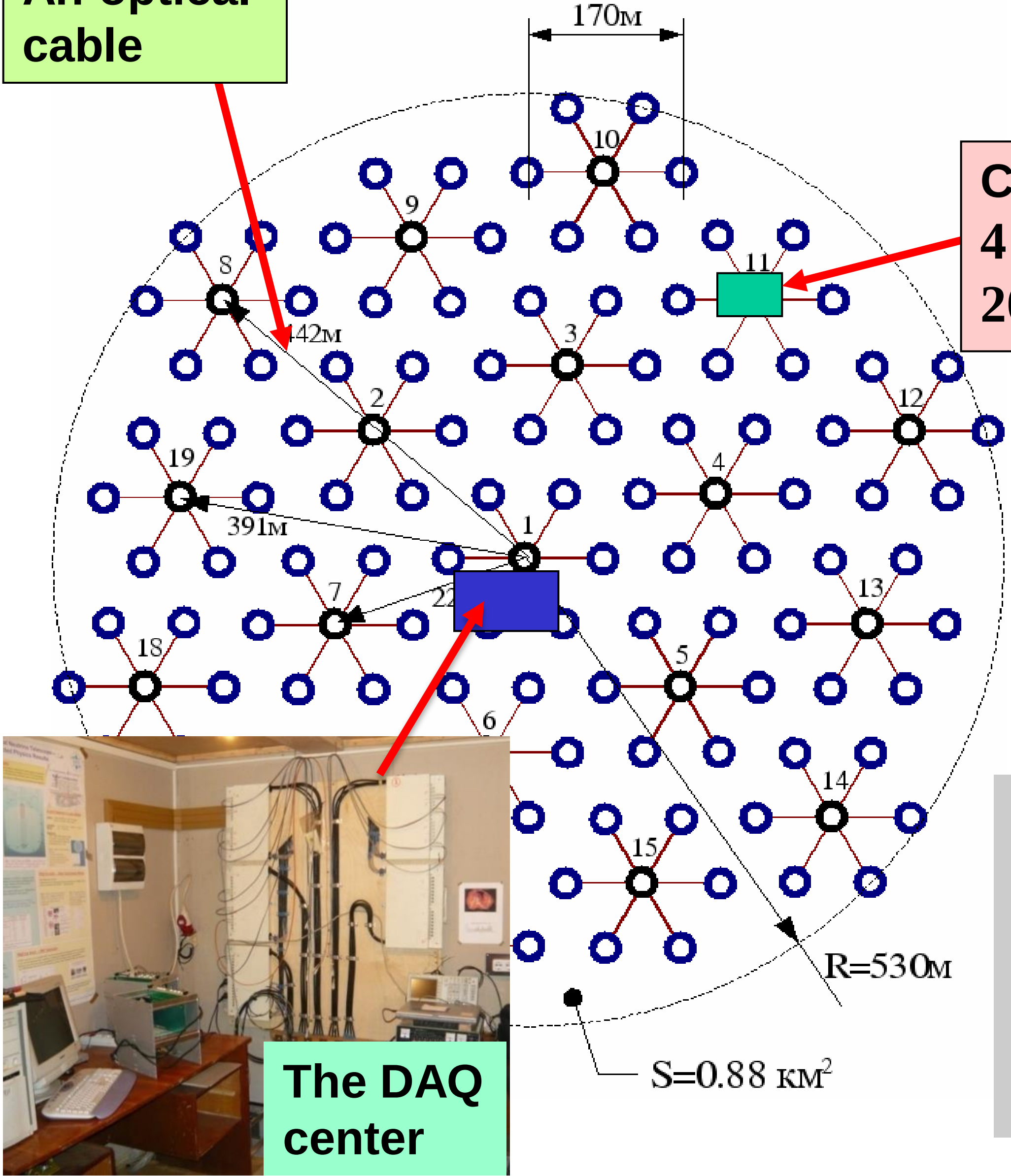
51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

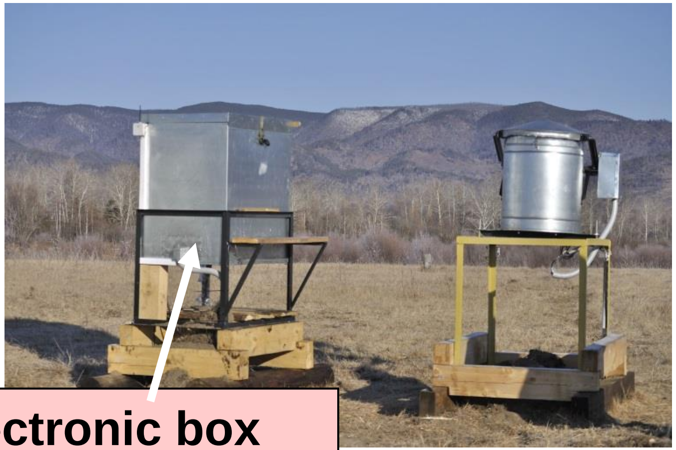
50 km from Lake Baikal



The Tunka-133 array

An optical cable

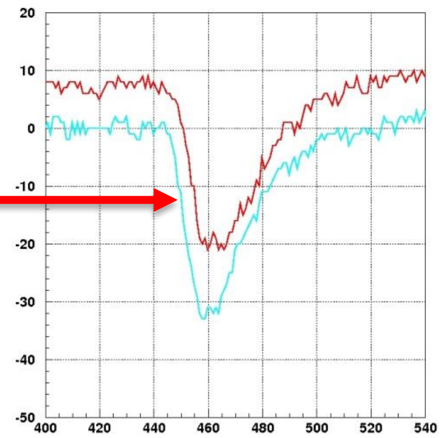




Cluster Electronic box
4 channel FADC boards
200 MHz, 12 bit

PMT
EMI 9350
Ø 20 cm

Cherenkov light pulses of two detectors located at a distance 700 m from EAS core.



The DAQ center

Tunka Collaboration

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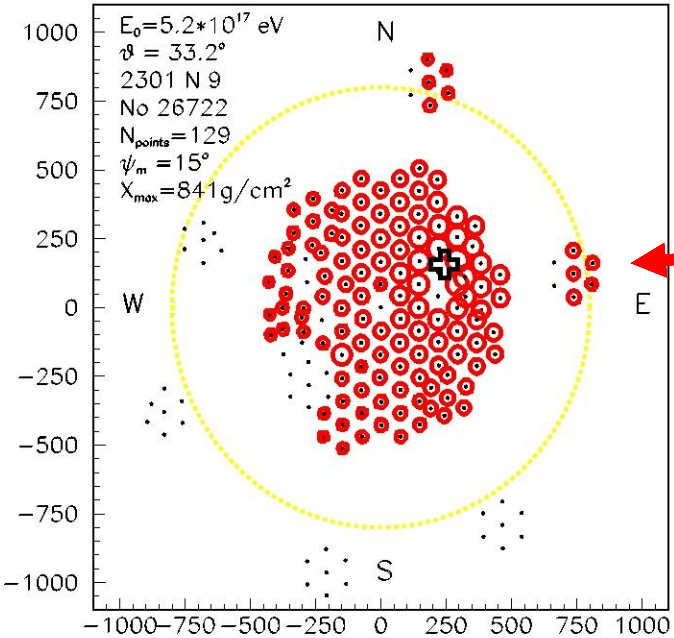
An EAS parameters reconstruction



Hit detectors

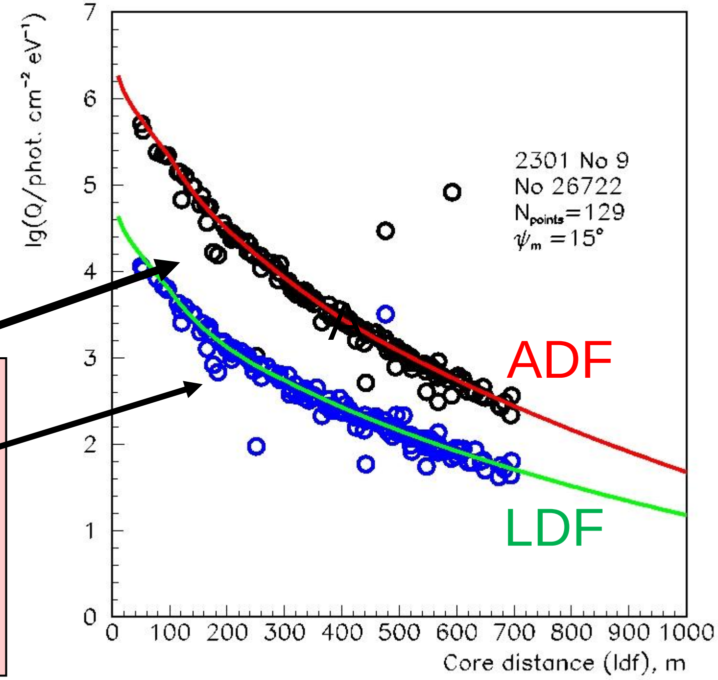
ADF

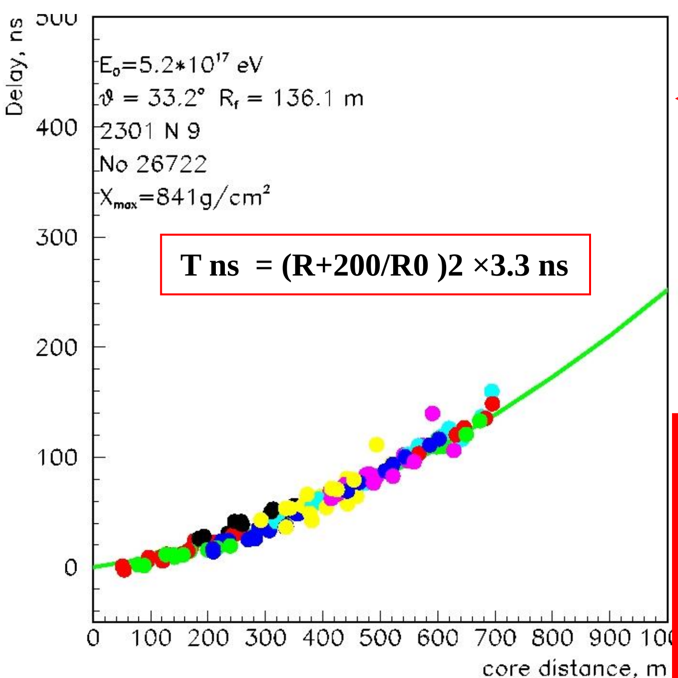
Amplitude distant function

&

LDF

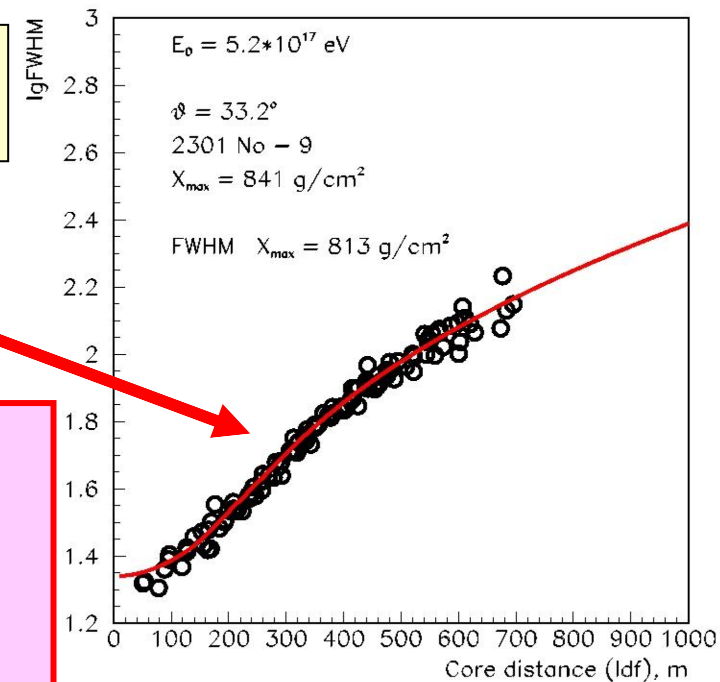
Lateral Distribution function





Delay time vs. Distance from core

WDF – width distant function



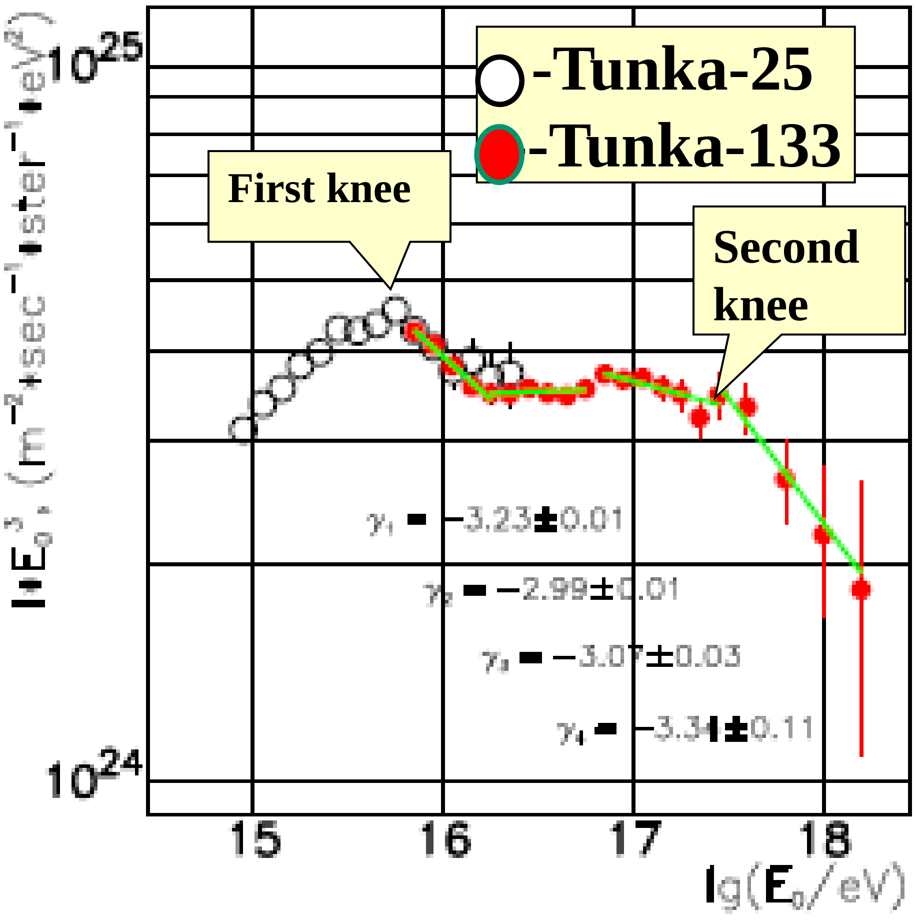
EAS Energy

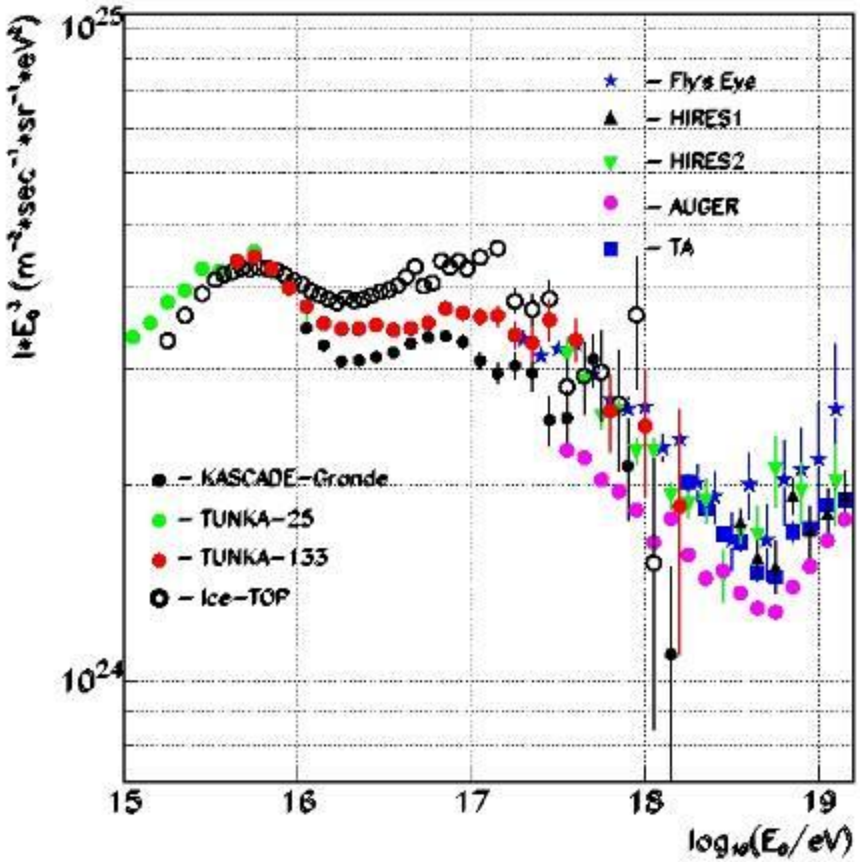
$$E = A \cdot [N_{ph}(200m)]^g$$

$$g = 0.94 \pm 0.01$$

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

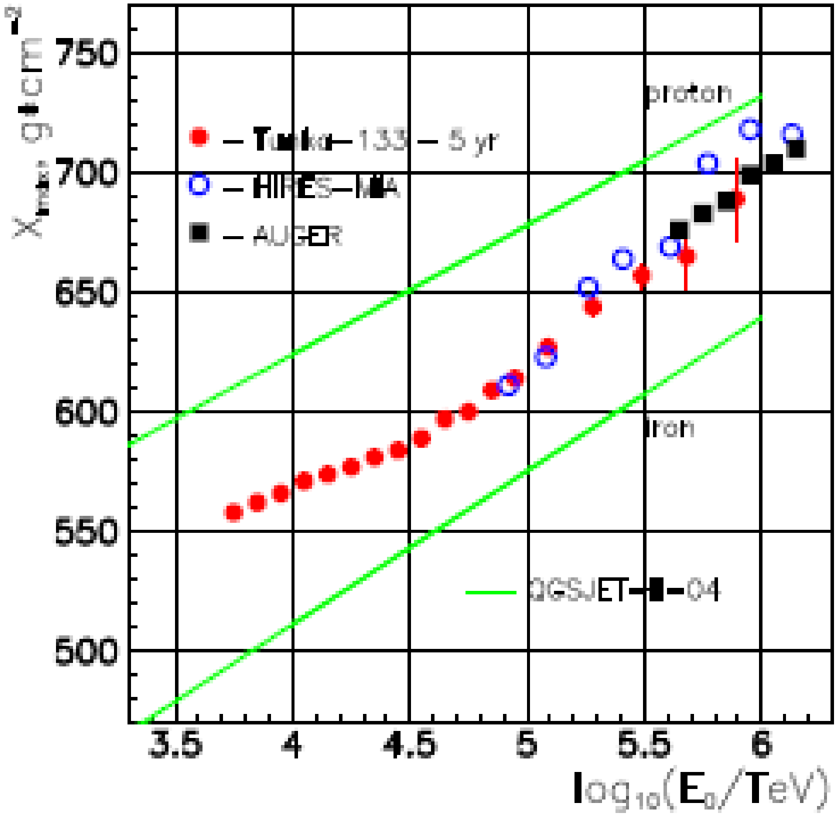
energy resolution ~ 15%, in principal up to - 5%



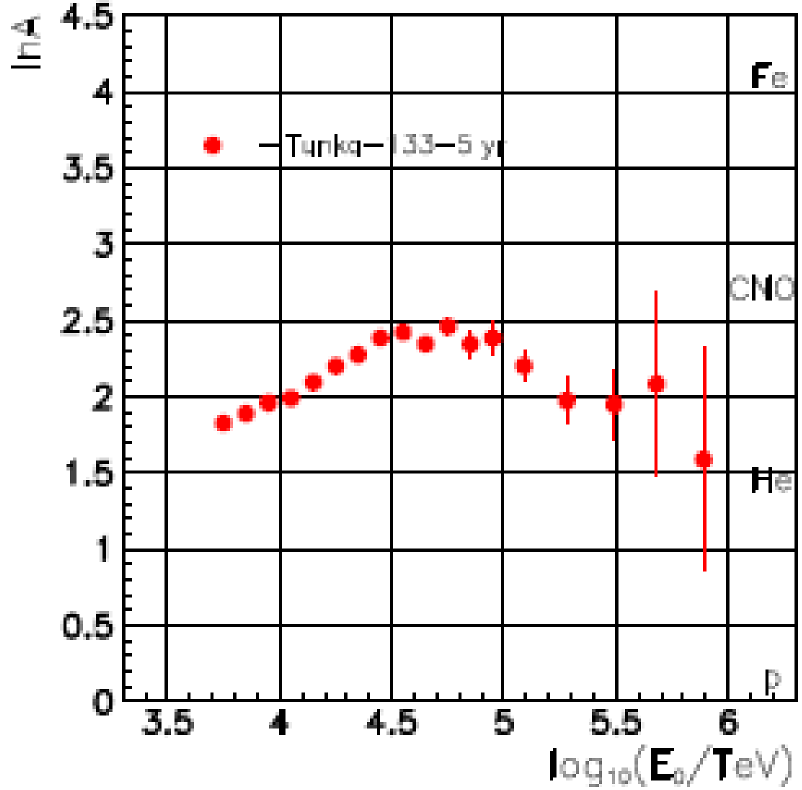


1. Agreement with KASCADE-Grande, Ice-TOP and TALE (TA Cherenkov).
2. The high energy tail do not contradict to the Fly's Eye, HiRes and TA spectra..

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



Mean logarithm of primary mass.



The primary CR mass composition changes from light (He) to heavy up to energy ~ 30 PeV

A lightening of the mass composition take place for starting from an energy 100 PeV

Advantage of the Tunka-133 array:

1. Good accuracy positioning of EAS core (5 -10 m)
2. Good energy resolution (~15%)
2. Good accuracy of primary particle mass identification (accuracy of X_{max} measurement ~ 20 -25 g/cm^2).
3. Good angular resolution (~0.5 degree)
4. Low cost: **the Tunka-133 – 3 km^2 array ~ 10^6 Euro**

Disadvantage:

Short time of operation (moonless, cloudless nights) – 5-10%

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 of Nuclear Physics (JIRN), 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

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

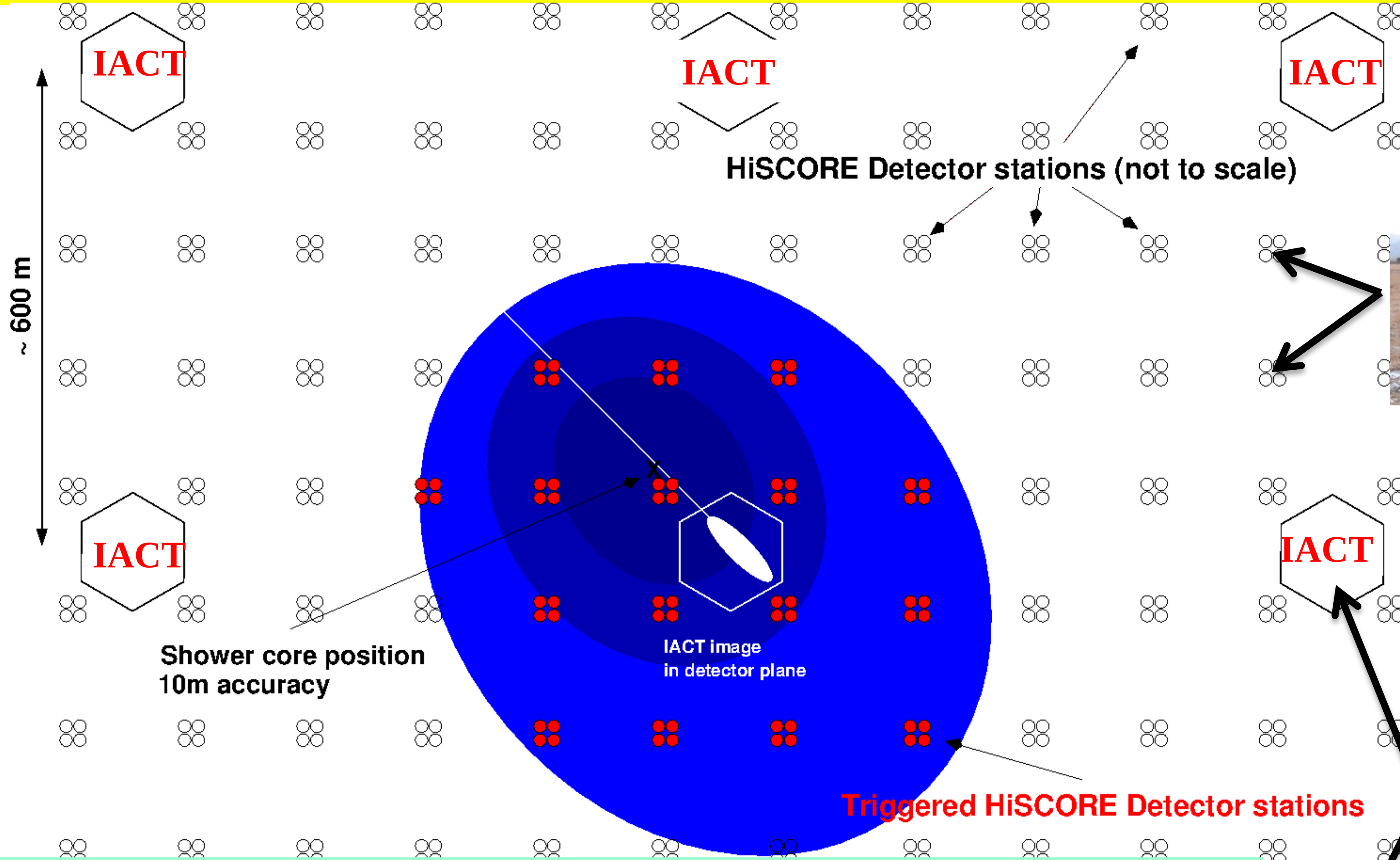
The TAIGA experiment - a hybrid array for very High energy gamma-ray astronomy and cosmic ray physics in the Tunka valley

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

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

Commissioning of array is expected in 2019y.

TAIGA: combine Imaging + Non-Imaging technique



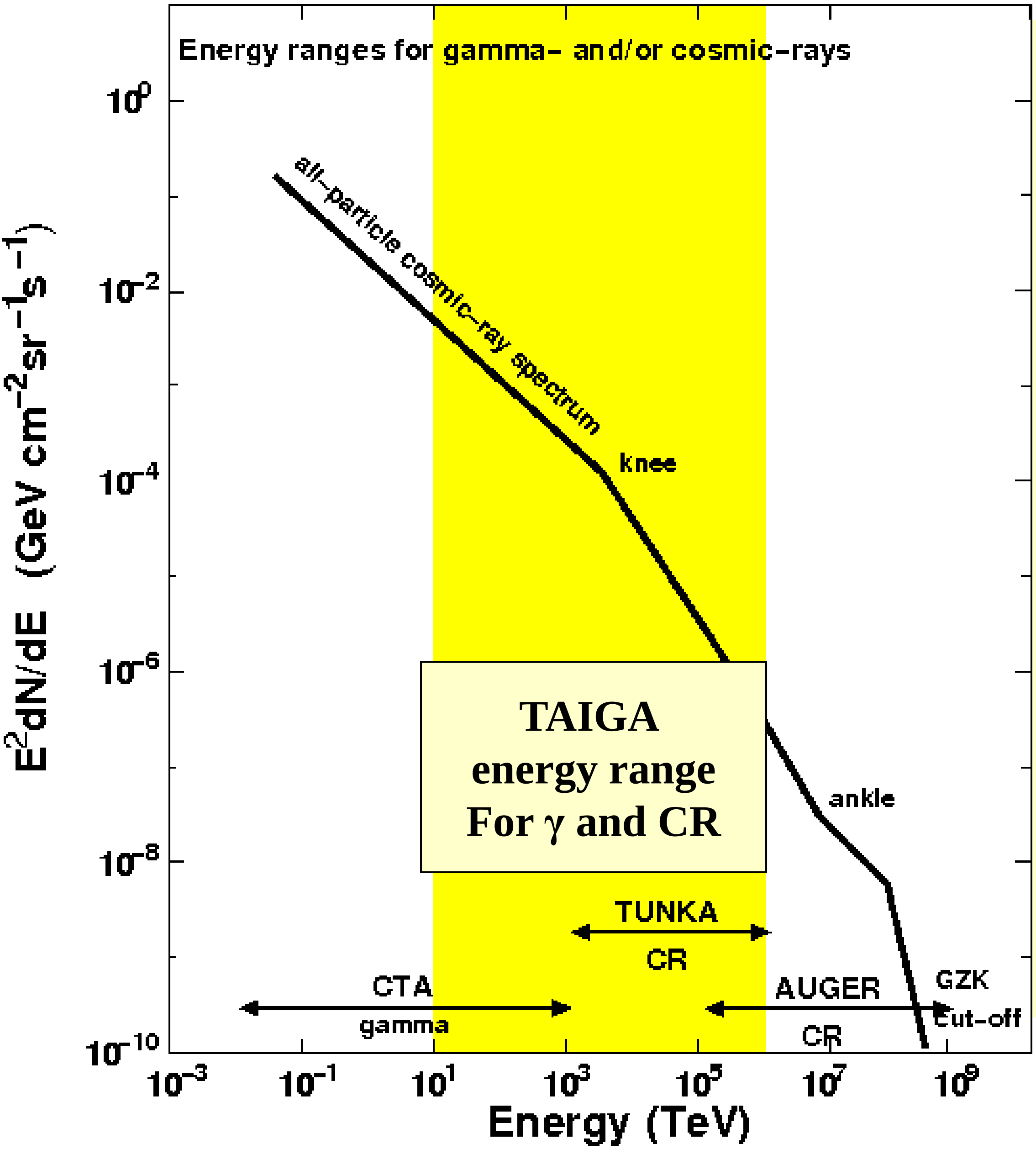
Hybrid concept

IACT operated in Mono-Mode at large distances

HiSCORE (Timing): direction, core location, energy

IACT (Imaging): gamma – hadron separation

Energy range and main topics for the TAIGA experiment



Gamma-ray Astronomy

Study of high-energy edge of spectrum of galactic gamma-ray sources. Search for the PeVatrons.

VHE spectra of known sources: what are the highest energy?

Absorption of high energy gamma.

Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition

Anisotropies from 10^{14} to 10^{18} eV.

Apply the new hybrid approach (common operation of IACTs and wide-angle timing array) for study of cosmic rays mass composition in the "knee" region (10^{14} - 10^{16} eV).

Particle physics

Axion/photon conversion.

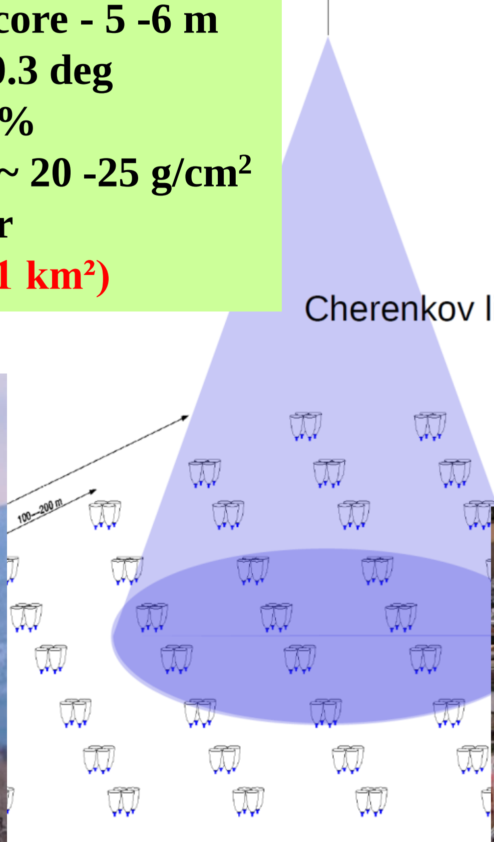
Lorentz invariance violation.

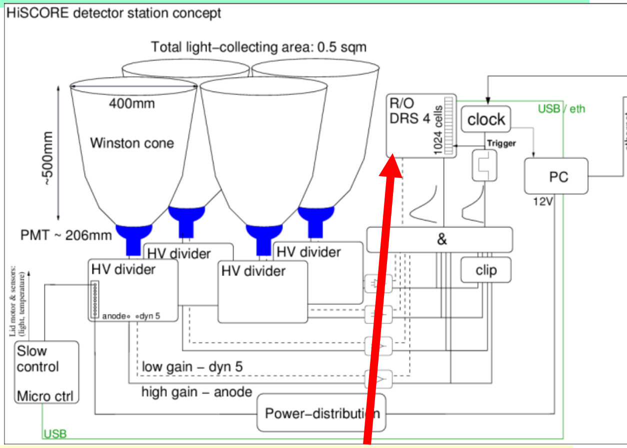
TAIGA-HiSCORE (High Sensitivity Cosmic Origin Explorer)

- **Wide-angle time- amplitude sampling non-imaging air Cherenkov array.**
- **Spacing between Cherenkov stations 80-100 m ~ 100 -150 channels / km².**

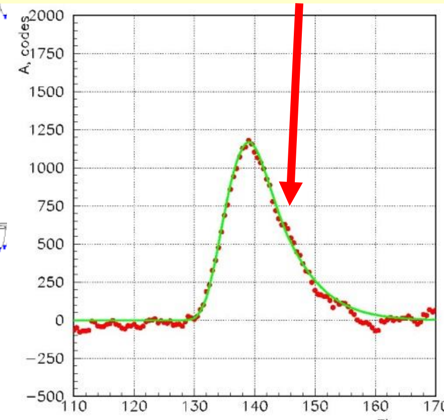
1. **Accuracy positioning EAS core - 5 -6 m**
2. **Angular resolution ~ 0.1 – 0.3 deg**
3. **Energy resolution ~ 10 - 15%**
4. **Accuracy of X_{max} measure ~ 20 -25 g/cm^2**
5. **Large Field of view: ~ 0.6 sr**

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

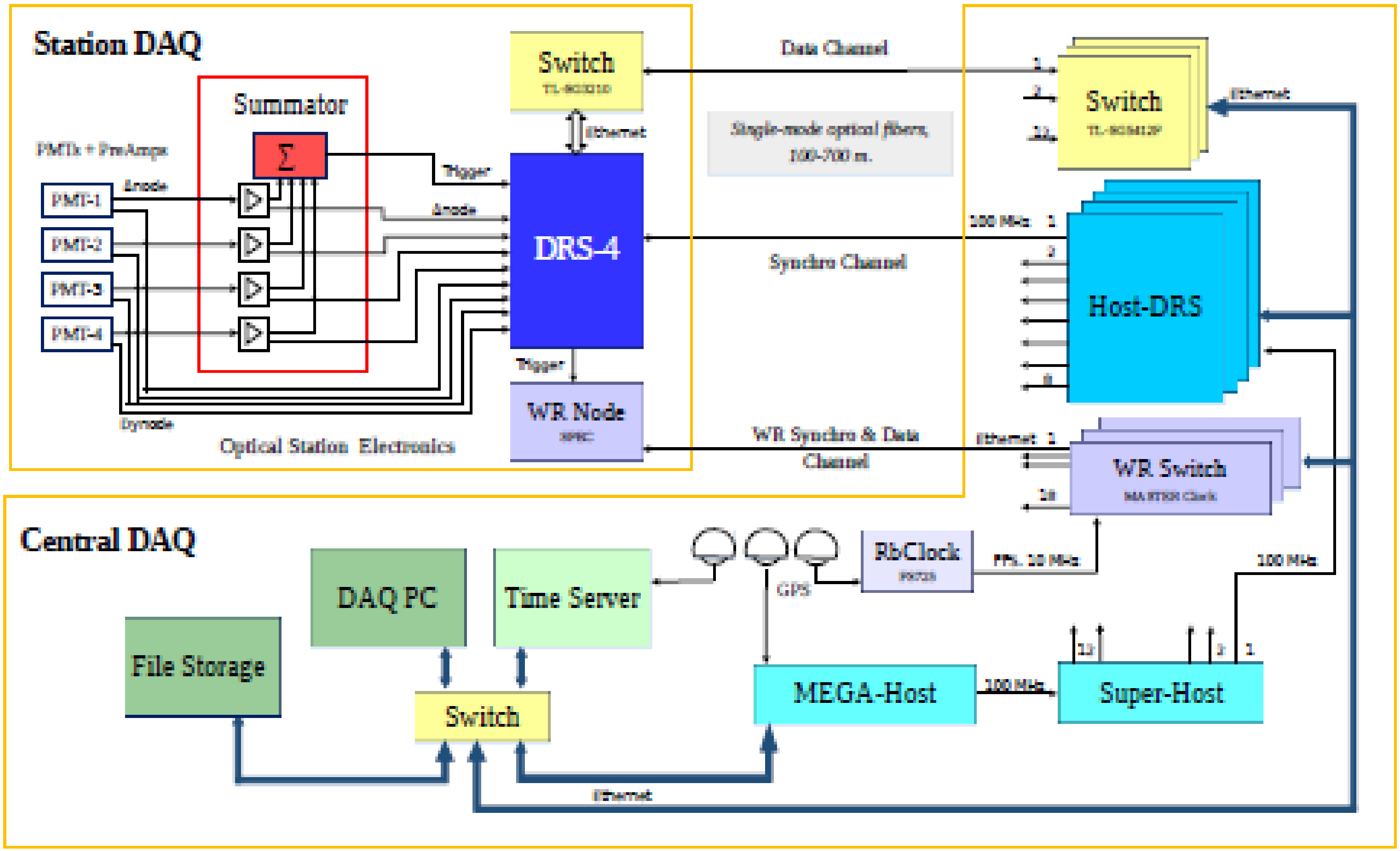




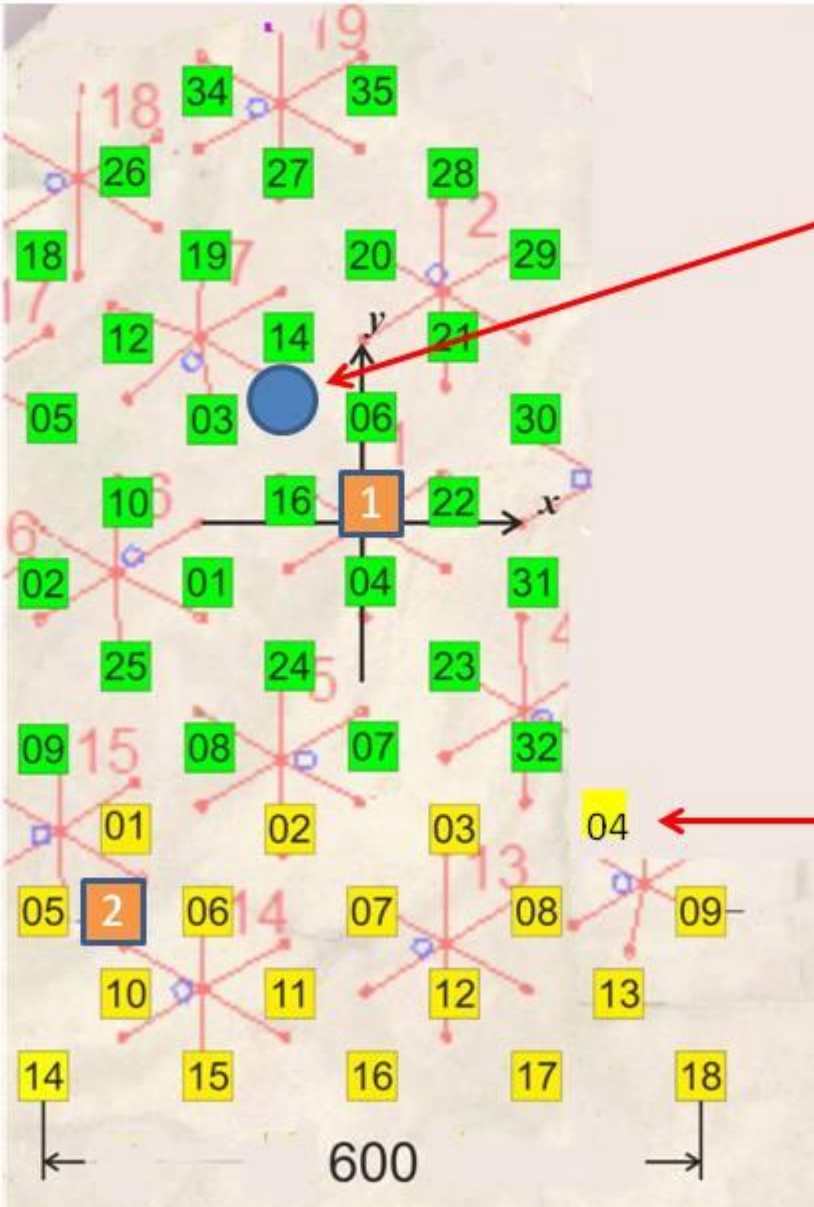
DRS-4 board (0.5 ns step)



TAIGA-HiSCORE DAQ system: stations and central part, including redundant GPS/RbClocks.



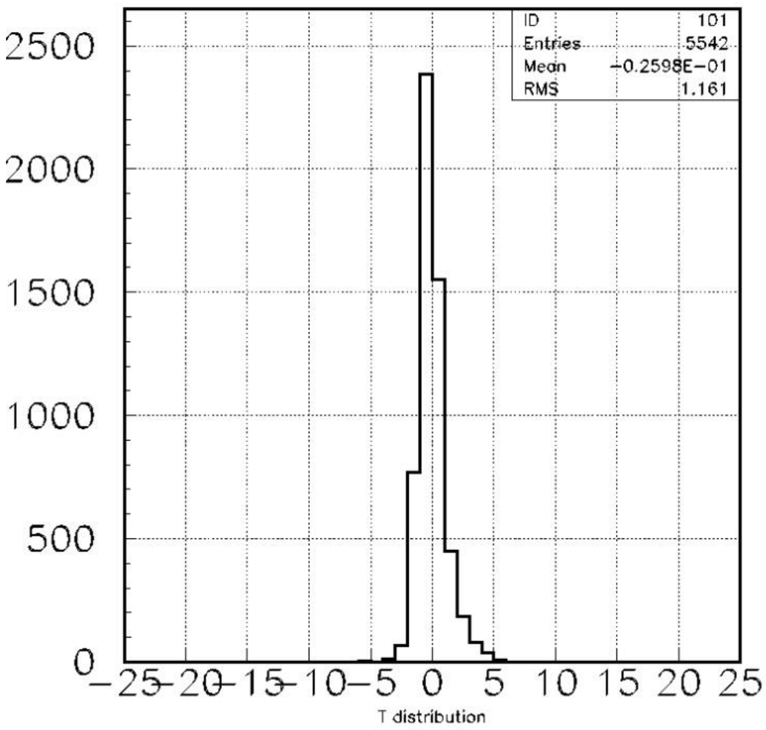
Pilot complex of the TAIGA: status 2017y

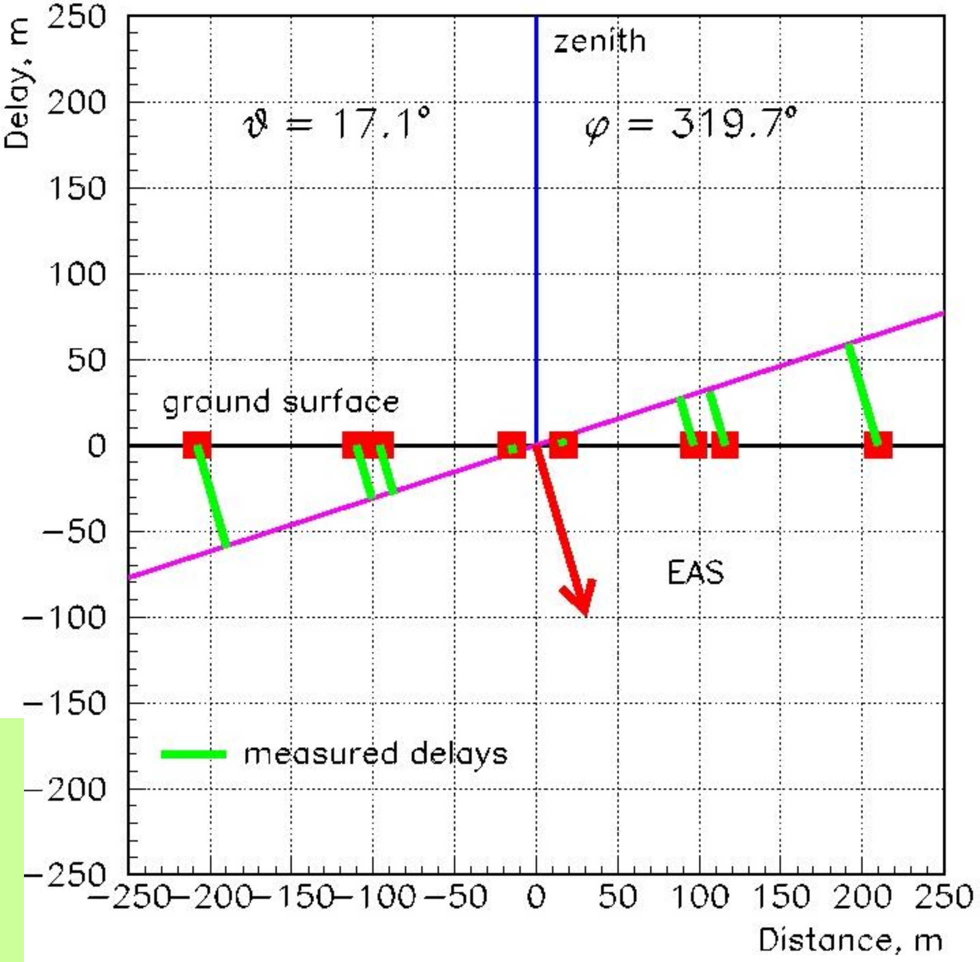


1 – IACT

53 TAIGA-HiSCORE optical stations with FOV: ~ 0.6 sr .
Spacing: 106 m

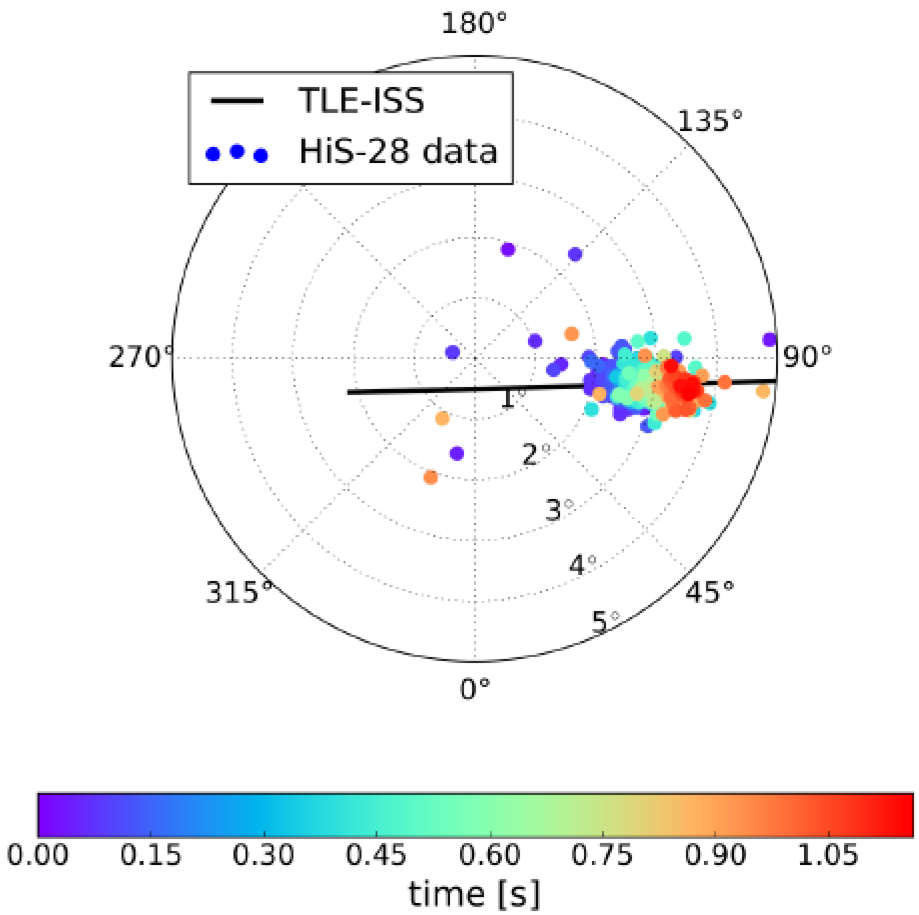
An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE

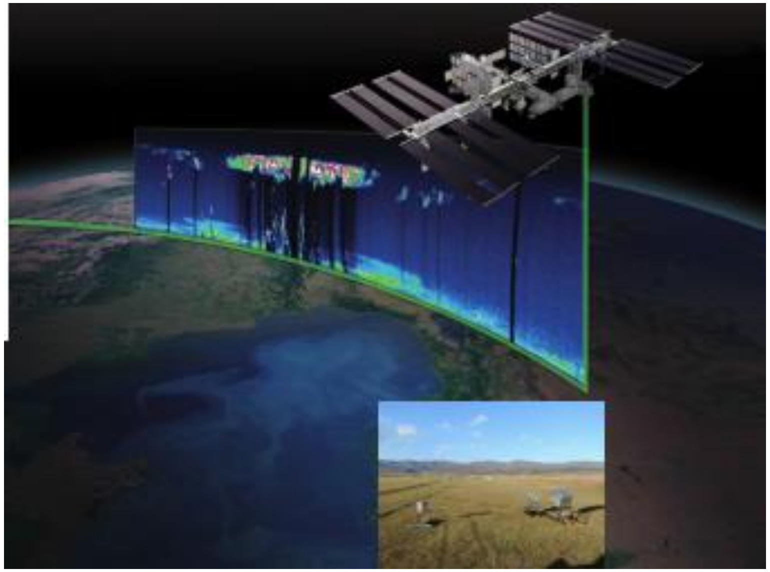




The RMS=1.1 ns for TAIGA-HiSCORE provides an accuracy of an γ and CR arrival direction about 0.1 degree

First TAIGA-HiSCORE results (0.25 км²)



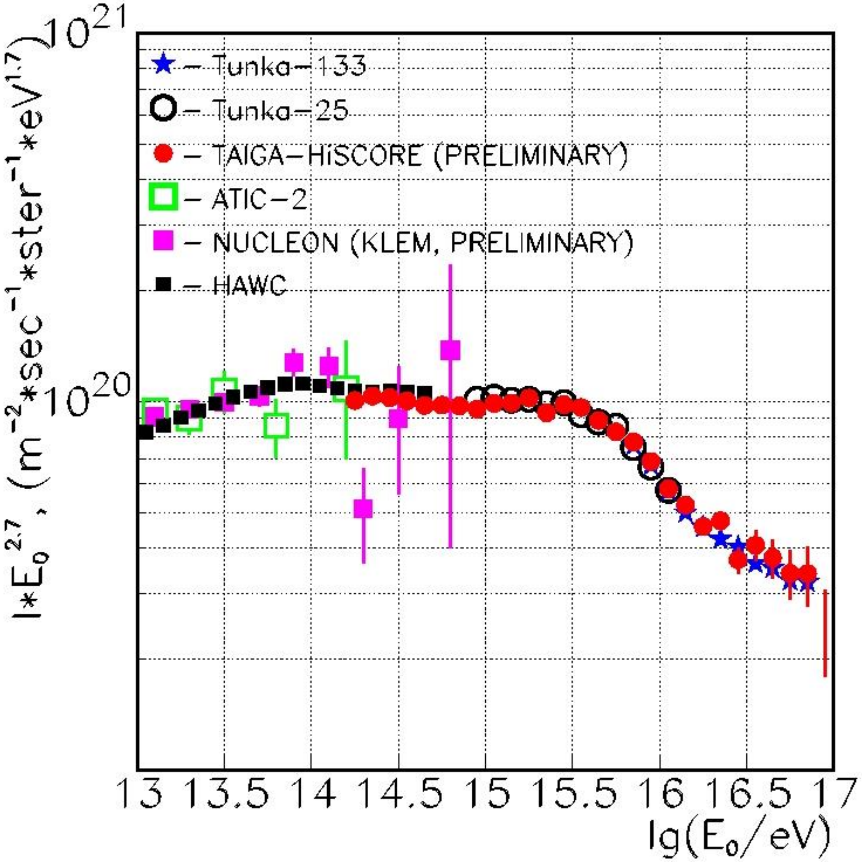


CATS Lidar,
532 nm, 4 khz, 10^13γ/m2

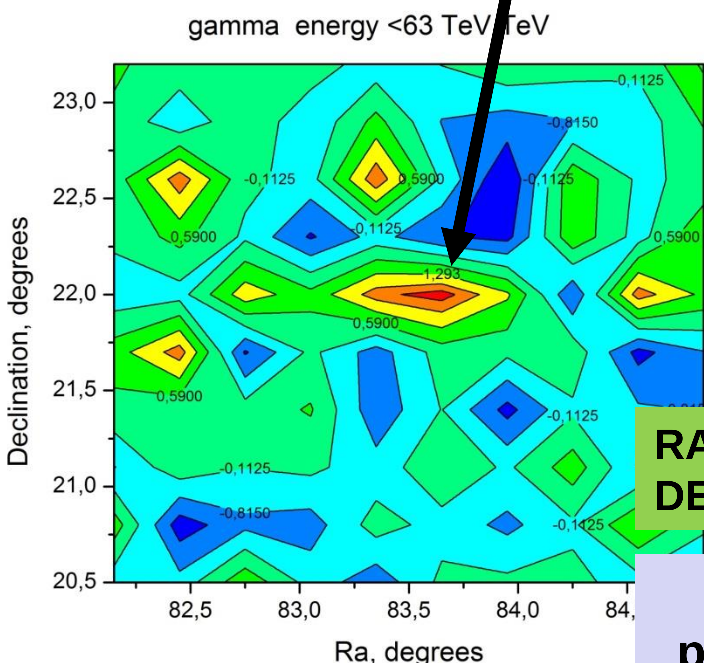
- **Excellent HiSCORE calibration source**
- **– flat timing profile**
- **- precision pointing**

Precision verification with Laser on-board International Space Station (ISS) <0.1deg

First TAIGA-HiSCORE results (0.25 км²)



A hint of signal compatible with expectation (~40 TeV < E< 100 TeV)



RA = 83.63°
DEC = 22°.00"

Very preliminary

Energy spectrum

Tentative Crab-search

The TAIGA – IACT

The first TAIGA - IACT
Is in commissioning since early 2017 :
- 34-segment reflectors (Davis-Cotton)
- Diameter 4.3 m, area ~10 m^2
- Focal length 4.75 m
- Threshold energy ~ 1.5 TeV

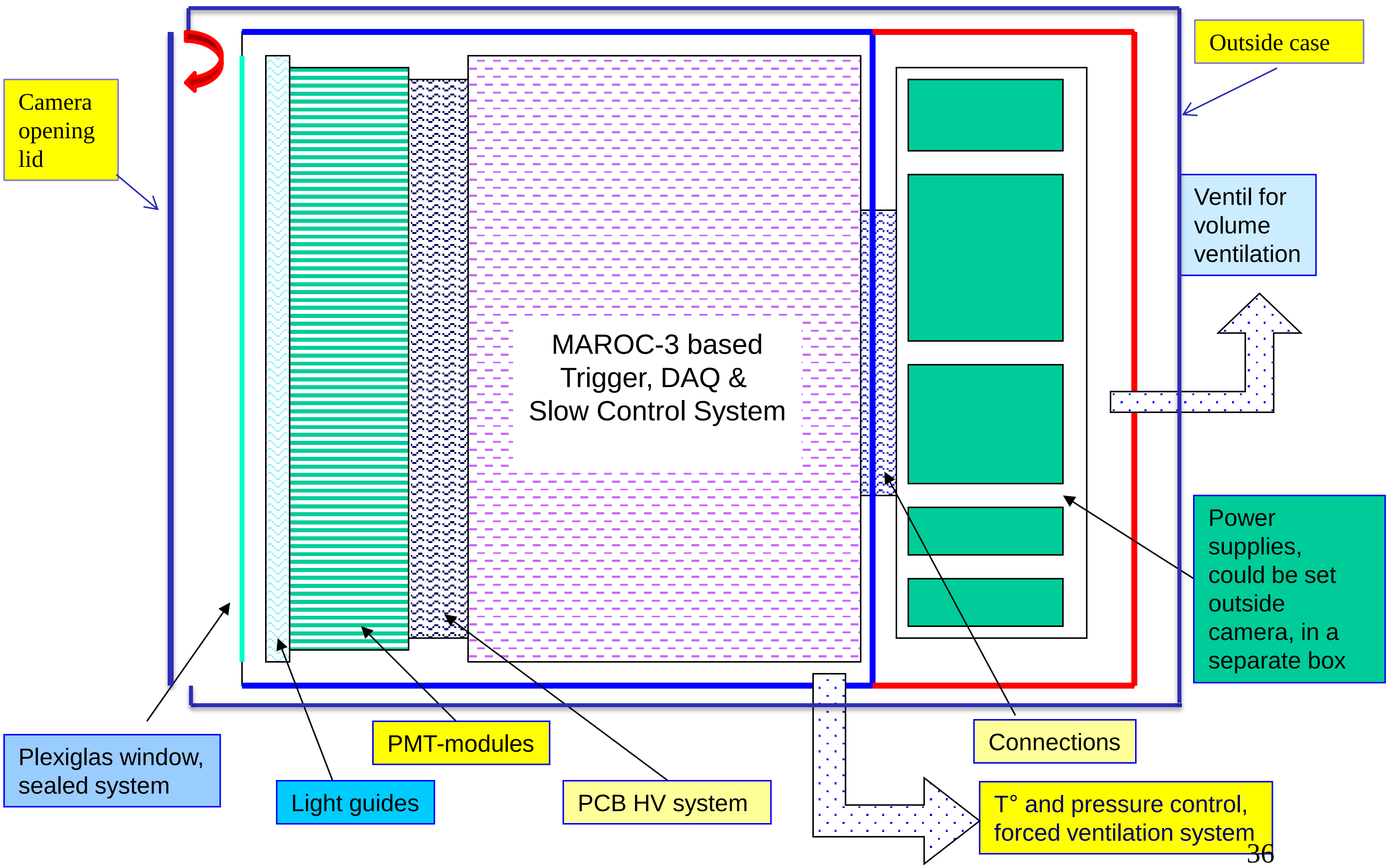
Next 2 IACTs in construction.

The final IACT array will include
16 IACTs over 10 km^2
with > 800 m spacing
(i.e. in “mono-mode”).

Will be operated in Hybrid-Mode,
with TAIGA-HiSCORE, TAIGA-Muon.

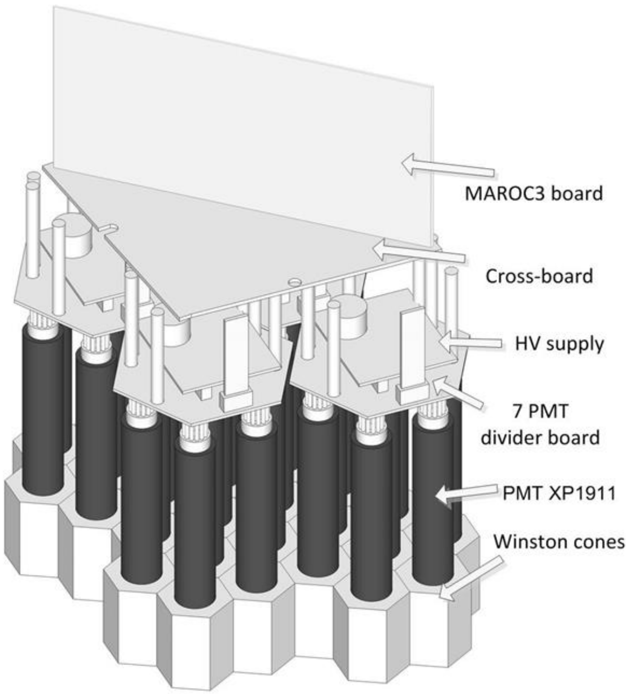
Assembling of the 1st mount.

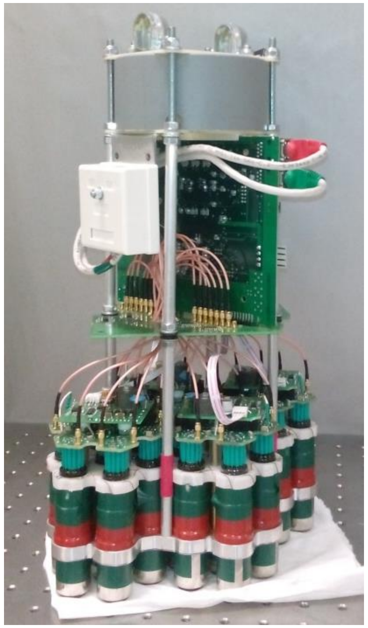
Conceptual design of the TAIGA IACT camera mechanics



The Camera of the TAIGA-IACT

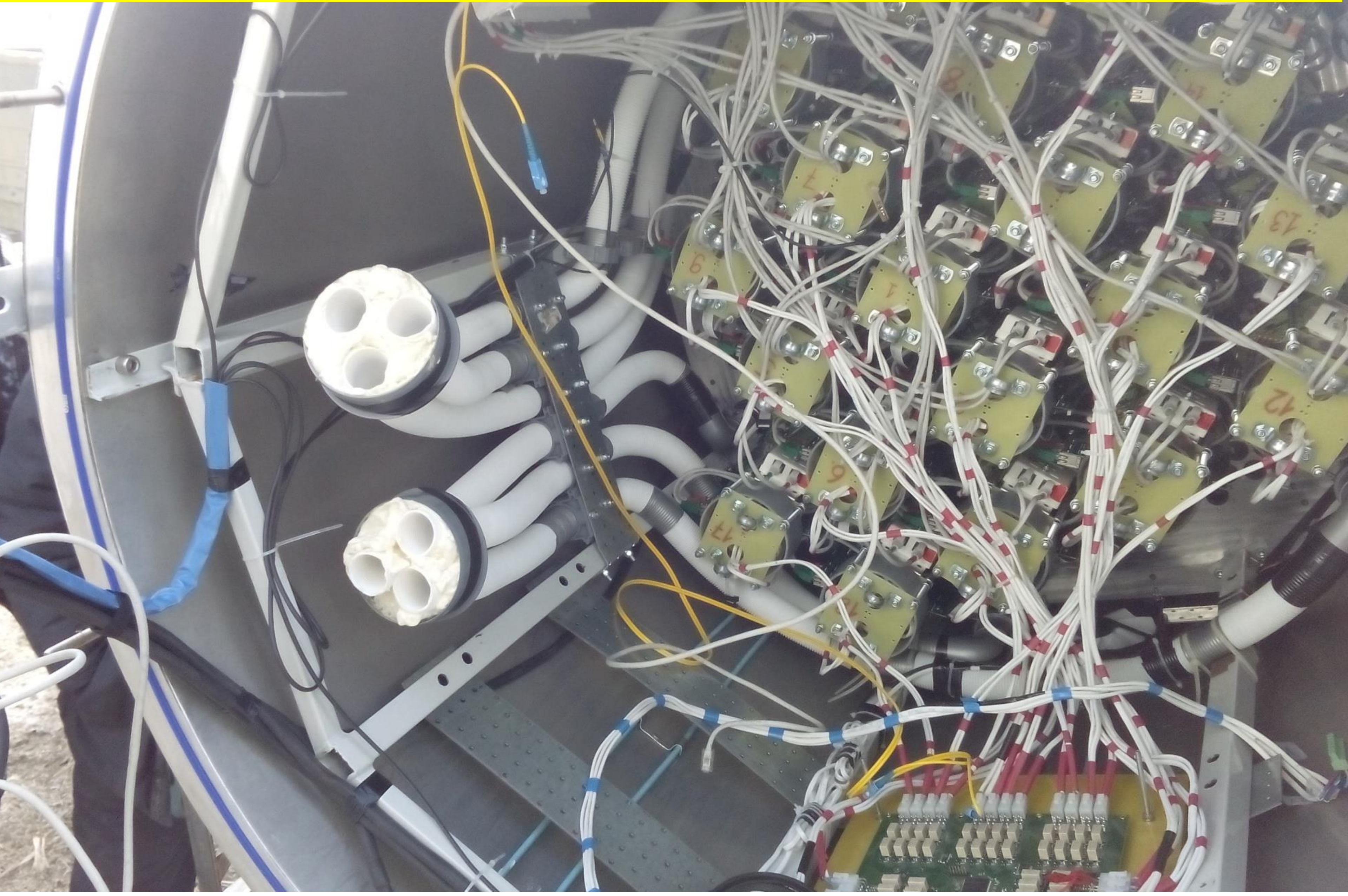
- 547 PMTs (XP 1911) with
- 15 mm useful diameter of photocathode
- Winston cone: 30mm input size
- each pixel = 0.36 deg
- FOV 10 x 10 deg





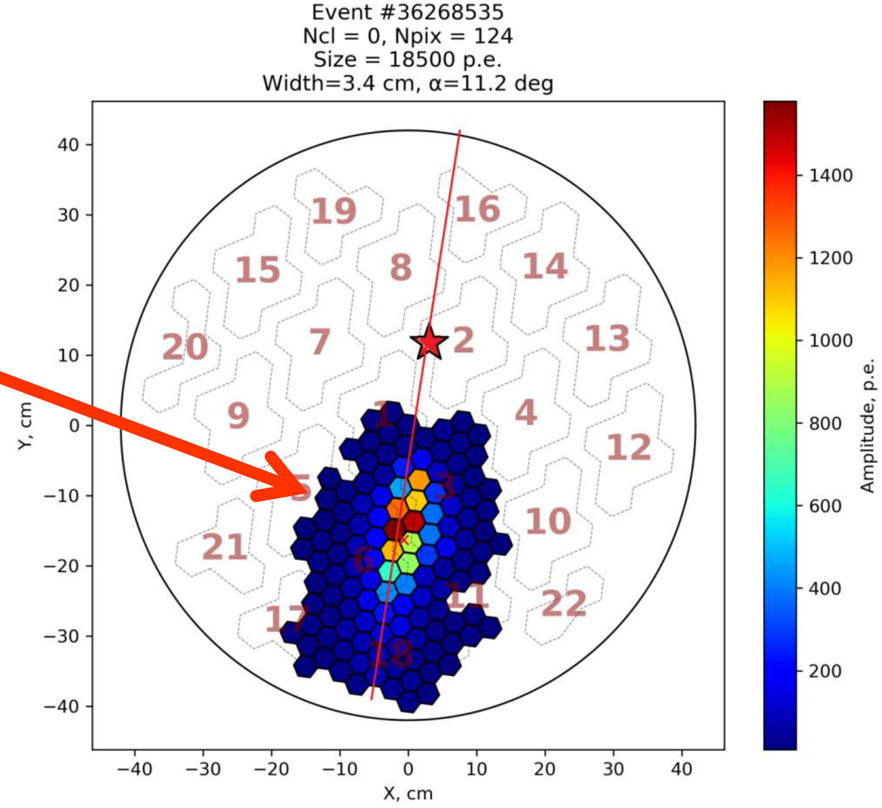
Basic cluster: 28 PMT-pixels. Signal processing: PMT DAQ board based on MAROC3 ASIC

Inside of the camera



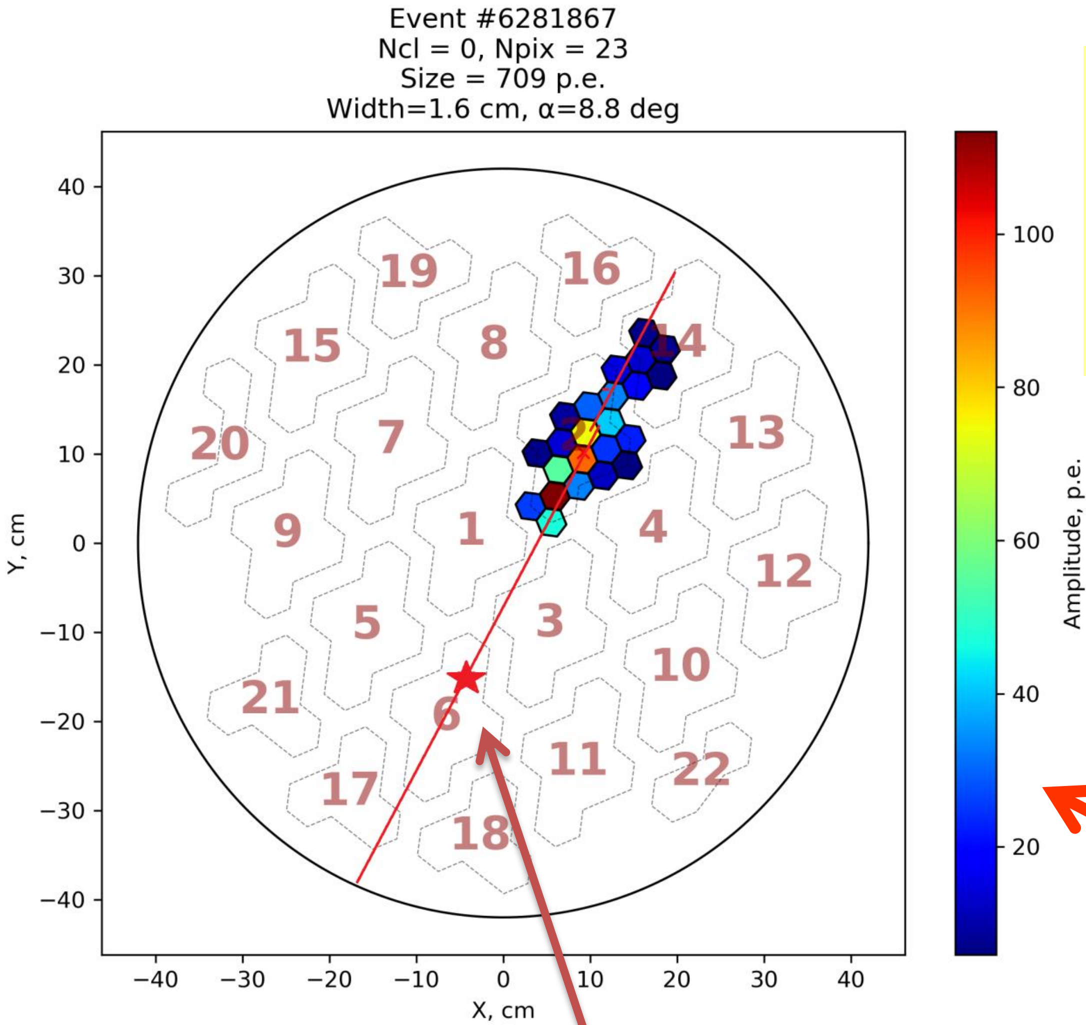
Season 2017 -2018: TAIGA-IACT and TAIGA-HiSCORE 10000 joint events.

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

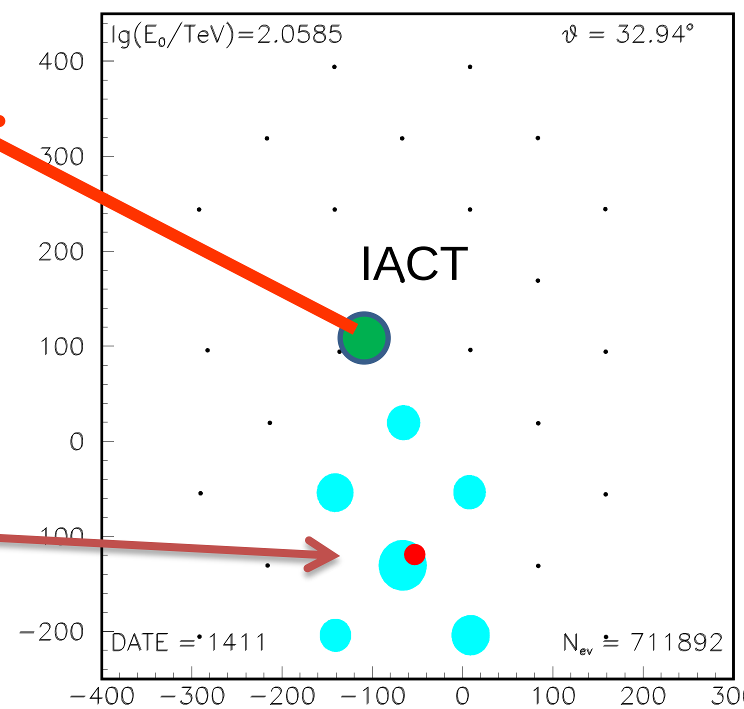


300 events in 0.7 ° around direction on Crab.
Expected number of gammas: 10-20 with E> 40 TeV

But some events looks as "Gamma-like".



E = 50 TeV
Width = 0.19°



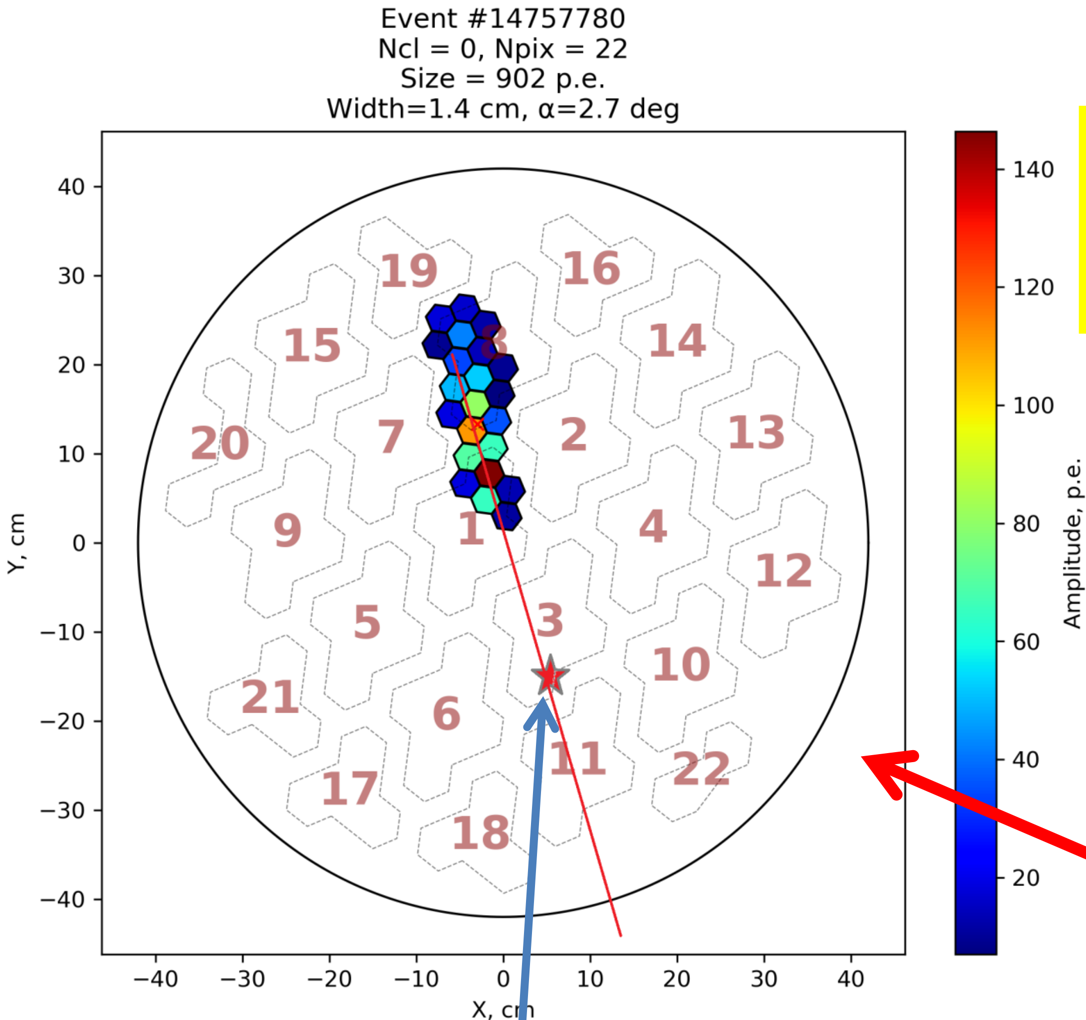
Core position

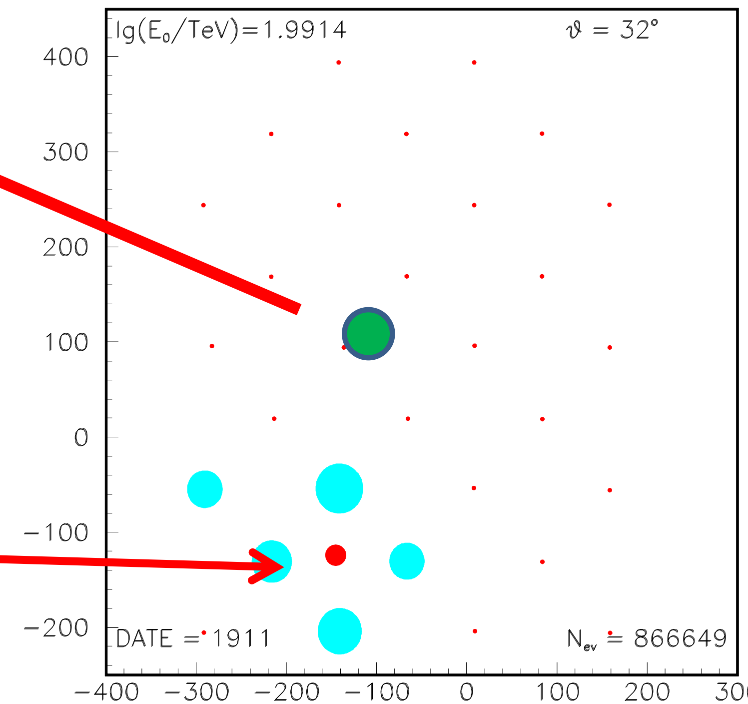
Another "Gamma-like" event.

E =50 TeV

θ = 37.0

φ = 331. 12

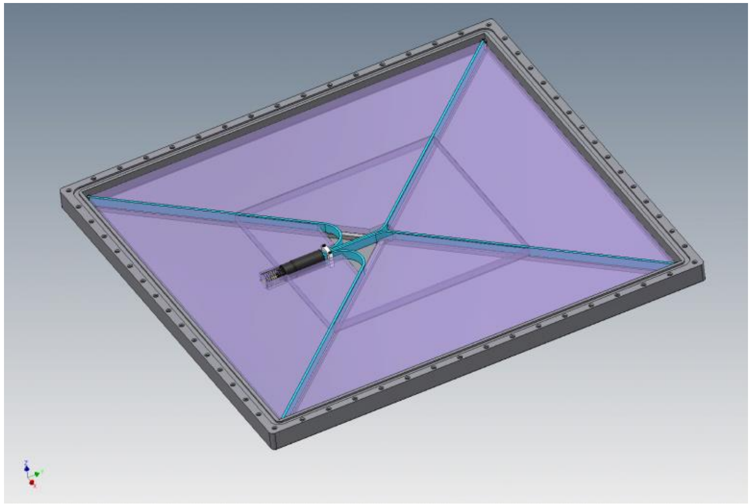




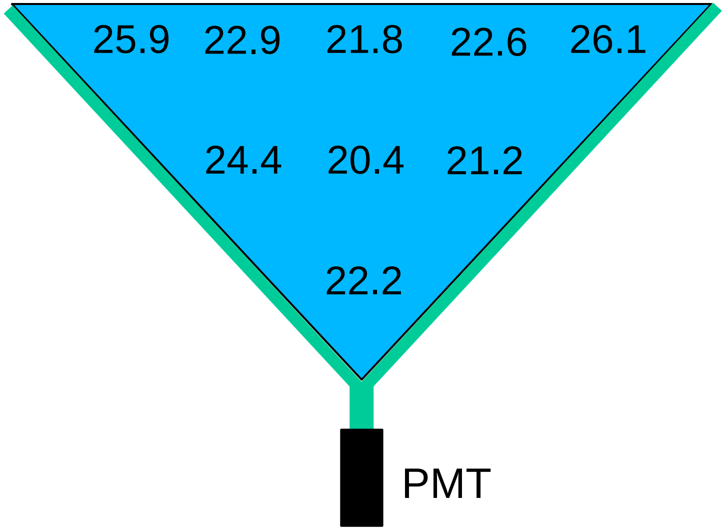
Core position

The TAIGA-Muon particle counter.

- **Counter dimension 1x1 m^2.**
- **Wavelength shifting bars are used for collection of the scintillation light on the PMT**
- **Mean amplitude from cosmic muon is 23.1 photoelectrons with ±15% variation (minimum to maximum).**
- **A clear peak in amplitude spectrum is seen from cosmic muons in a self trigger mode.**



¼ of full scale detector



Upgrades of the TAIGA experiment

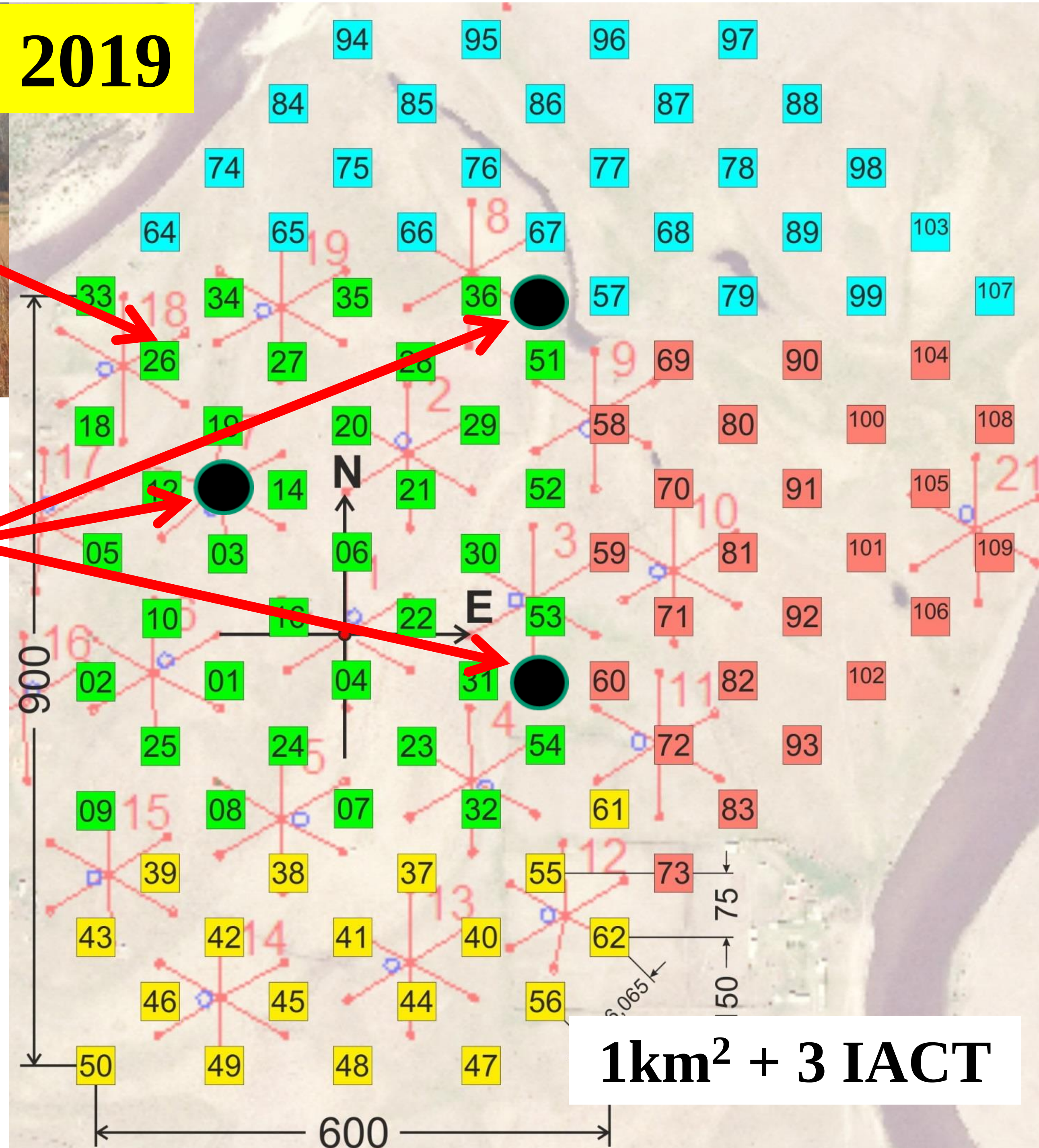
Funded TAIGA upgrade 2017-2019:
- **HiSCORE 0.25 km^2 (2016) → 1 km^2 (2019)**
- **two more IACTs**
- **Muon detectors (200m^2)**

Long term plan:
Upgrade up to 10 km^2 array with 1000 optical station of non-imaging TAIGA-HiSCORE and 16 IACTs + 3000m^2 of muon detectors.

TAIGA Status 2019

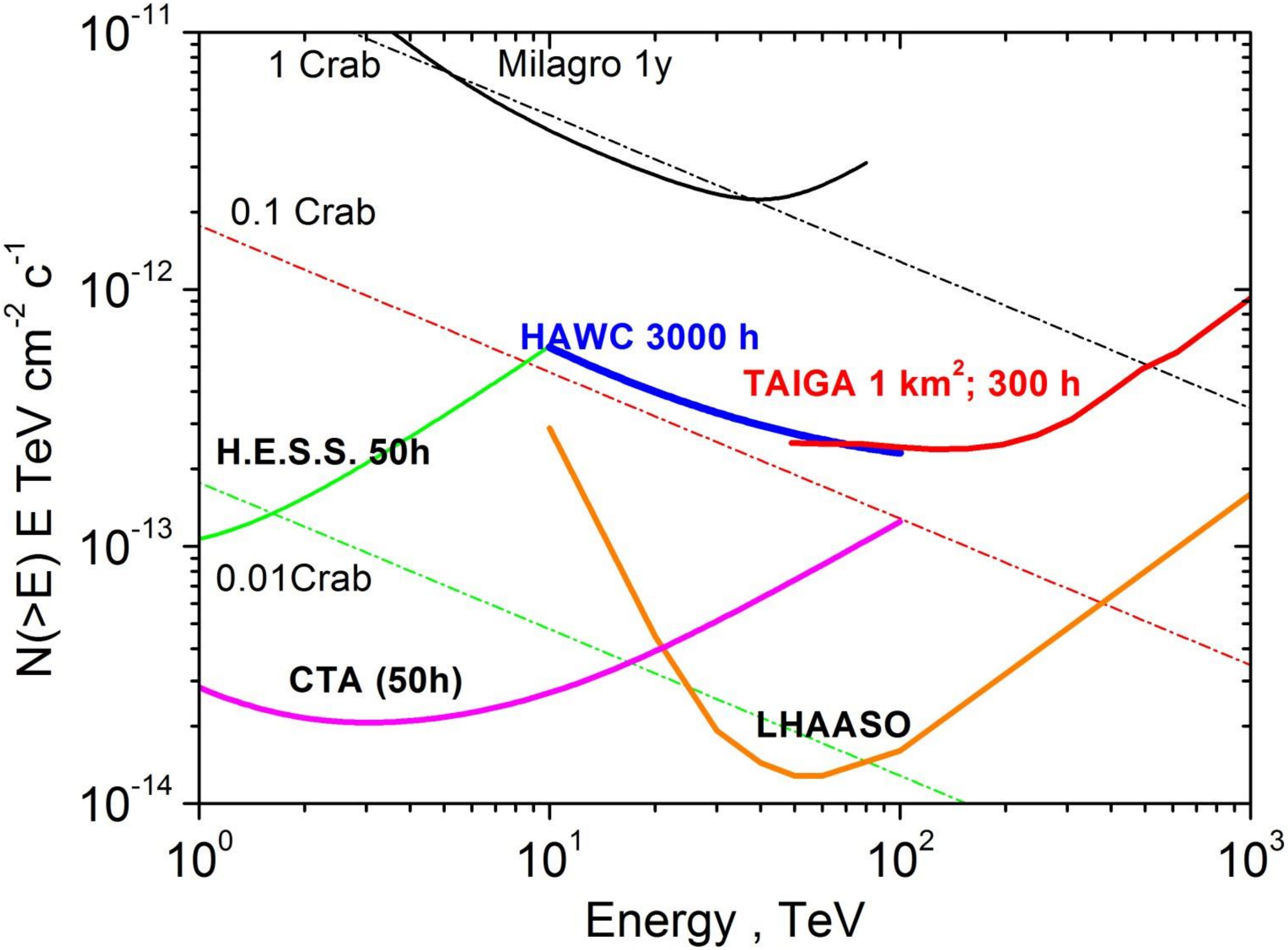
TAIGA-HiSCORE
120 detectors

3 TAIGA-IACT



1km^2 + 3 IACT

Integral point source sensitivity of TAIGA pilot complex (1 km^2)



TAIGA: A possible future 10 and more km² upgrade

TAIGA – Tunka Advanced Instrument for cosmic rays and Gamma Astronomy

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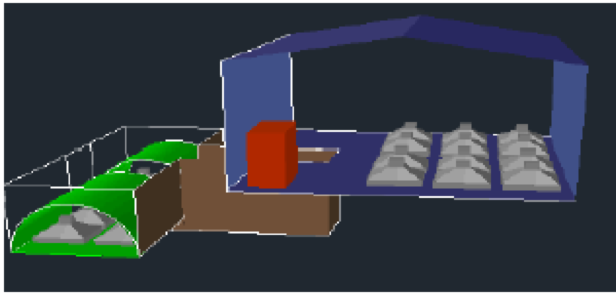

TAIGA-HiSCORE - array of 1000 non-imaging wide-angle detectors distributed on area 10 km² .
An EAS core position, direction and energy reconstruction.

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

TAIGA-Muon (including Tunka – Grande) - array of scintillation detectors, including underground muon detectors with area - 10^2 ⟶ $3\ 10^3$ m² area
Kind of primary particles separtion.

Conclusions

TAIGA aims at establishing a new, hybrid gamma-ray detection technology for >50 TeV

TAIGA in 2017/18: 0.4 km^2 array + first IACT

Commissioning seasons were successful

- **Stable operation, precision calibration in progress, E_{th}~50TeV**
- **CR energy spectrum below the knee**
- **Hint of a signal from Crab (in agreement with expectation)**
- **Precision absolute pointing: from Laser on-board ISS**
- **Joint operation of TAIGA-HiSCORE and IACT: data analyses is in progress.**

TAIGA pilot complex in 2019 (funding complete)

- **1 km^2 array: 120 wide-angle timing optical stations + 3 IACTs**
- **point source sensitivity: $2.5\ 10^{-13}$ TeV/cm^2/s (300 hr 30–200 TeV)**

Future option:

- **10 km^2 array: 1000 wide-angle timing optical stations + 10-16 IACTs**
- **point source sensitivity: ~$5\ 10^{-14}$ TeV/cm^2/s**


Thank you for attention!