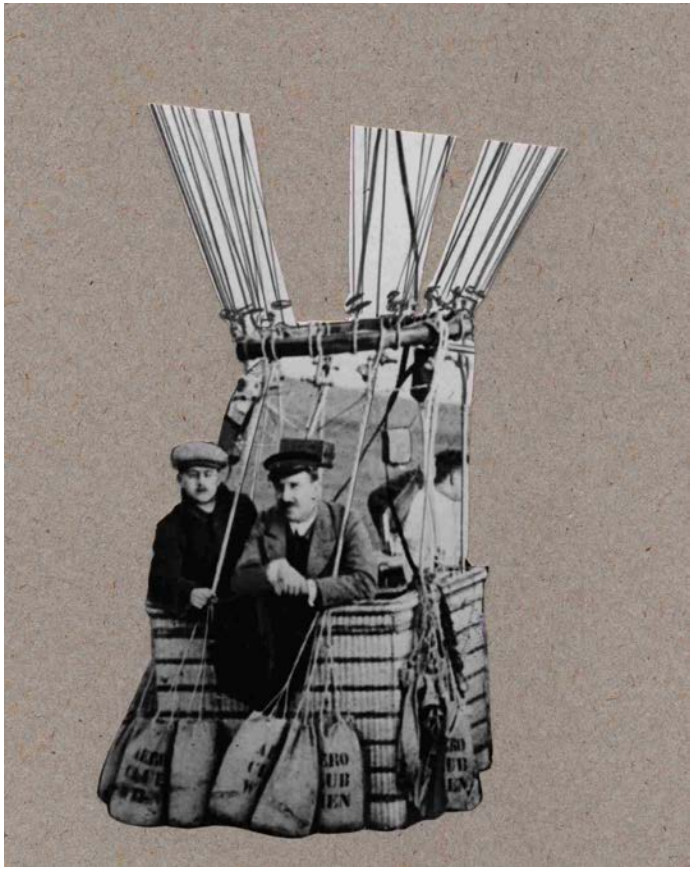
TAIGA - Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy – present status and perspectives.

N.Budnev, Irkutsk State University

For Tunka - collaboration

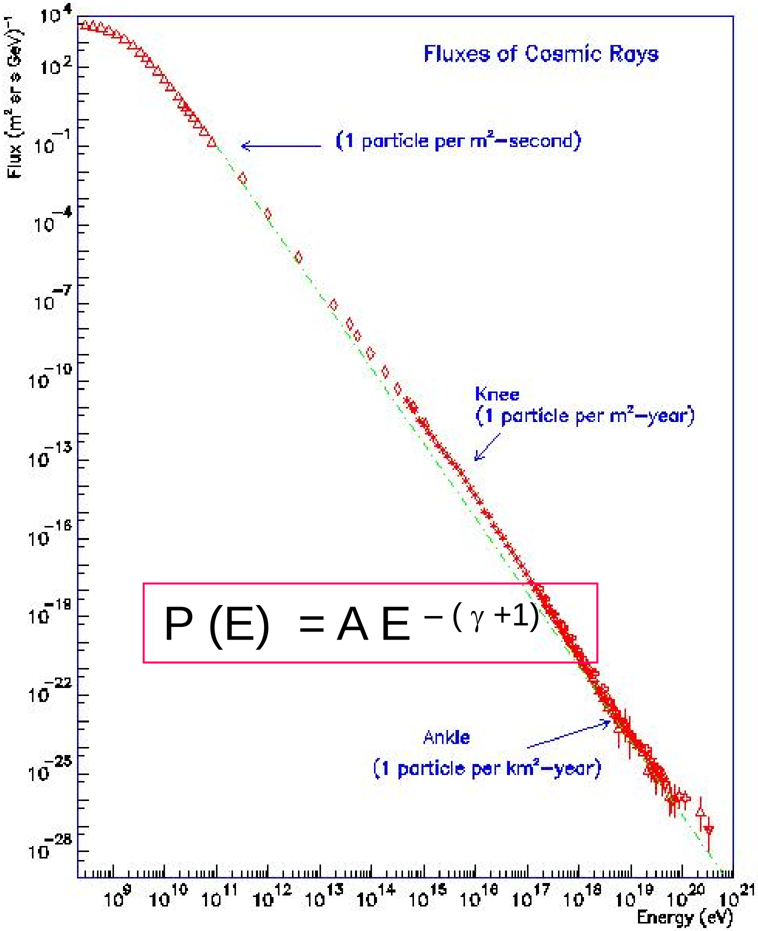
April 17, 1912: In a balloon at an altitude of 5000 meters, Victor Hess discovered "penetrating radiation" coming from space

Even very well isolated gold-leaf electroscopes are discharged at a slow rate.

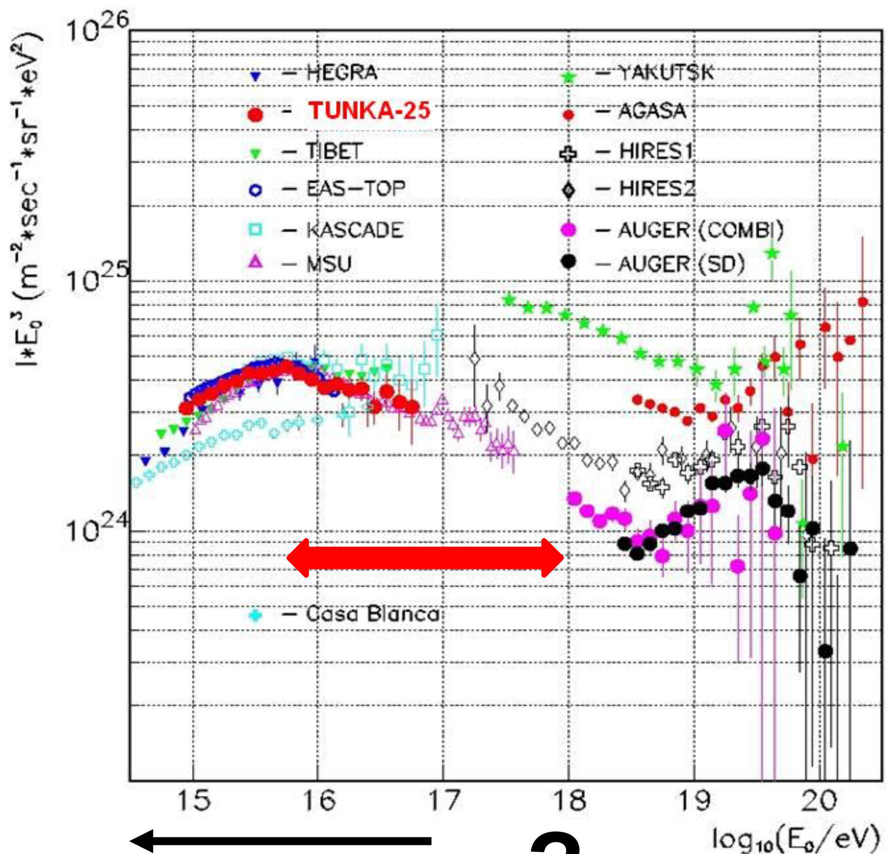


The bird's eye view on a CR energy spectrum

CR Flux (E) x E ^{3}



$$P(E) = A E^{-(\gamma + 1)}$$



?

Galactic Cosmic rays: SNR, Pulsars…

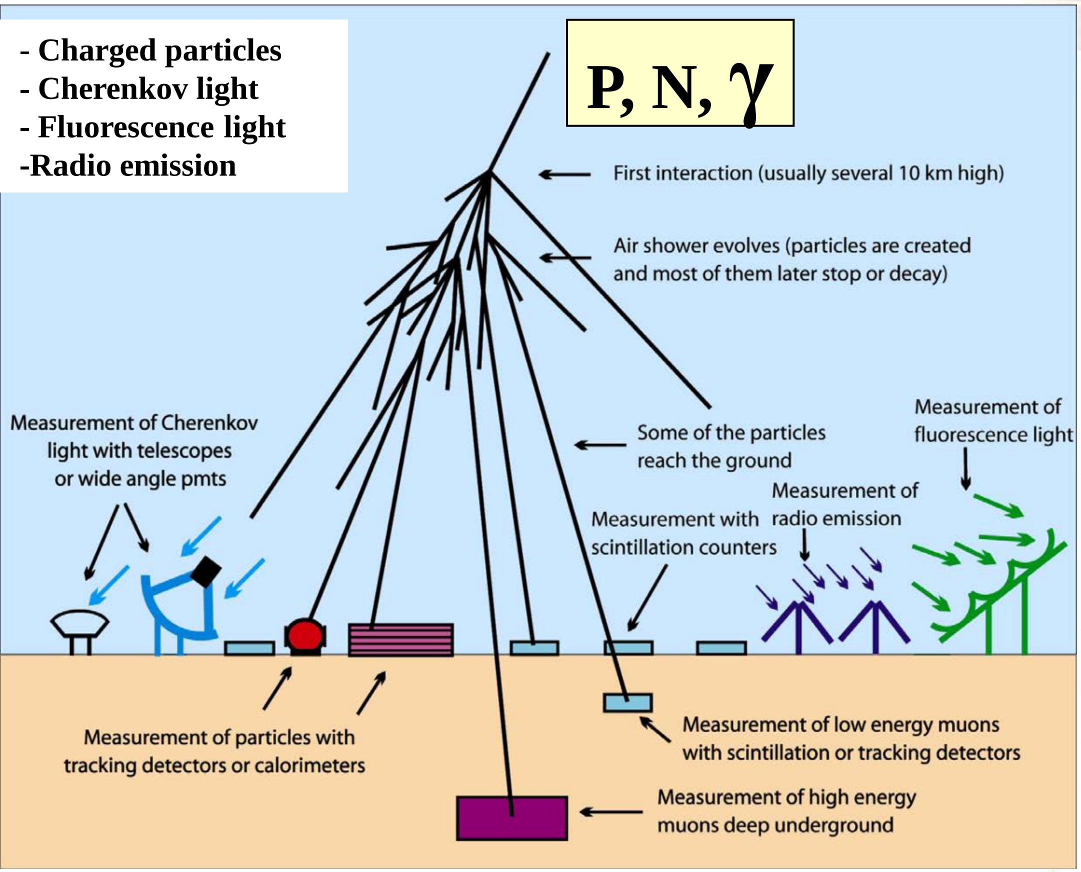
Extragalactic Cosmic rays: AGN, GRB…

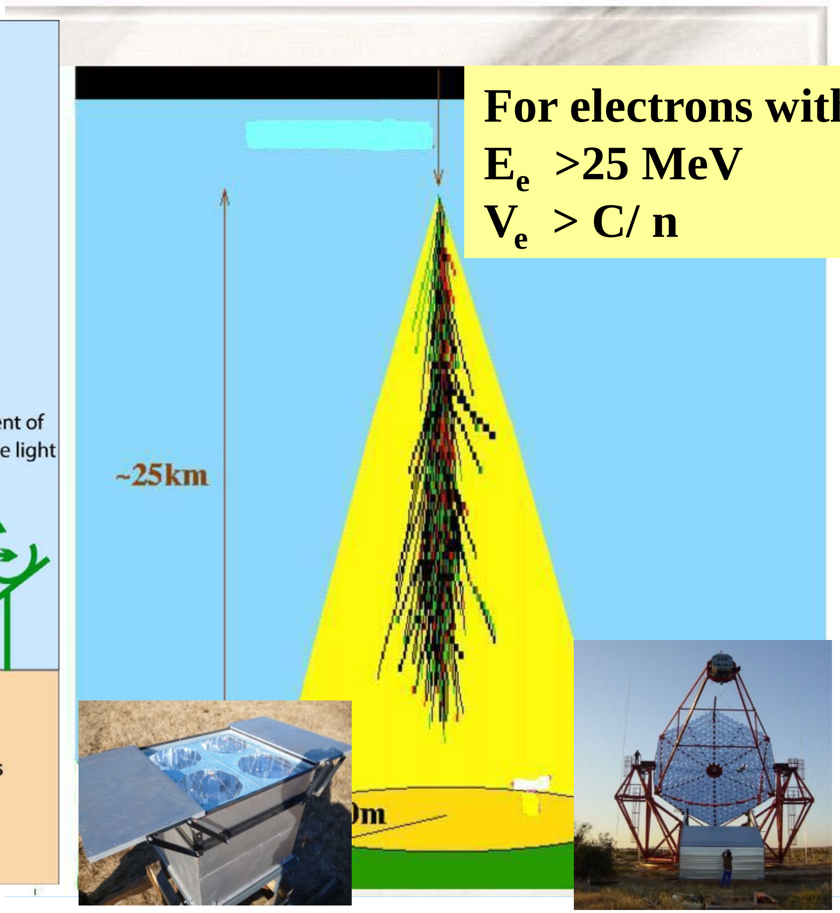
Decays of super massive particles or topological defects??????

An extensive air shower (EAS)
discovered by P. Auger (1938)

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

P, N, γ





For electrons with
E_e >25 MeV
V_e > C/ n

Atmosphere as a huge calorimeter

EAS Energy

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

$$g = 0.94 \pm 0.01$$

EAS Cherenkov light detection technique

Average CR mass A

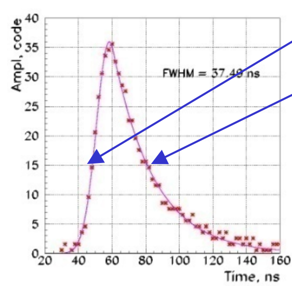
$$LnA \sim X_{max}$$

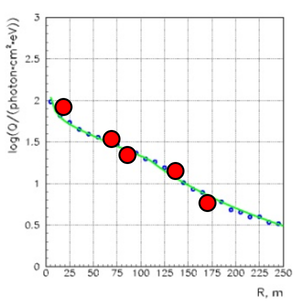
$$X_{max} = C - D \cdot \lg \tau(400)$$

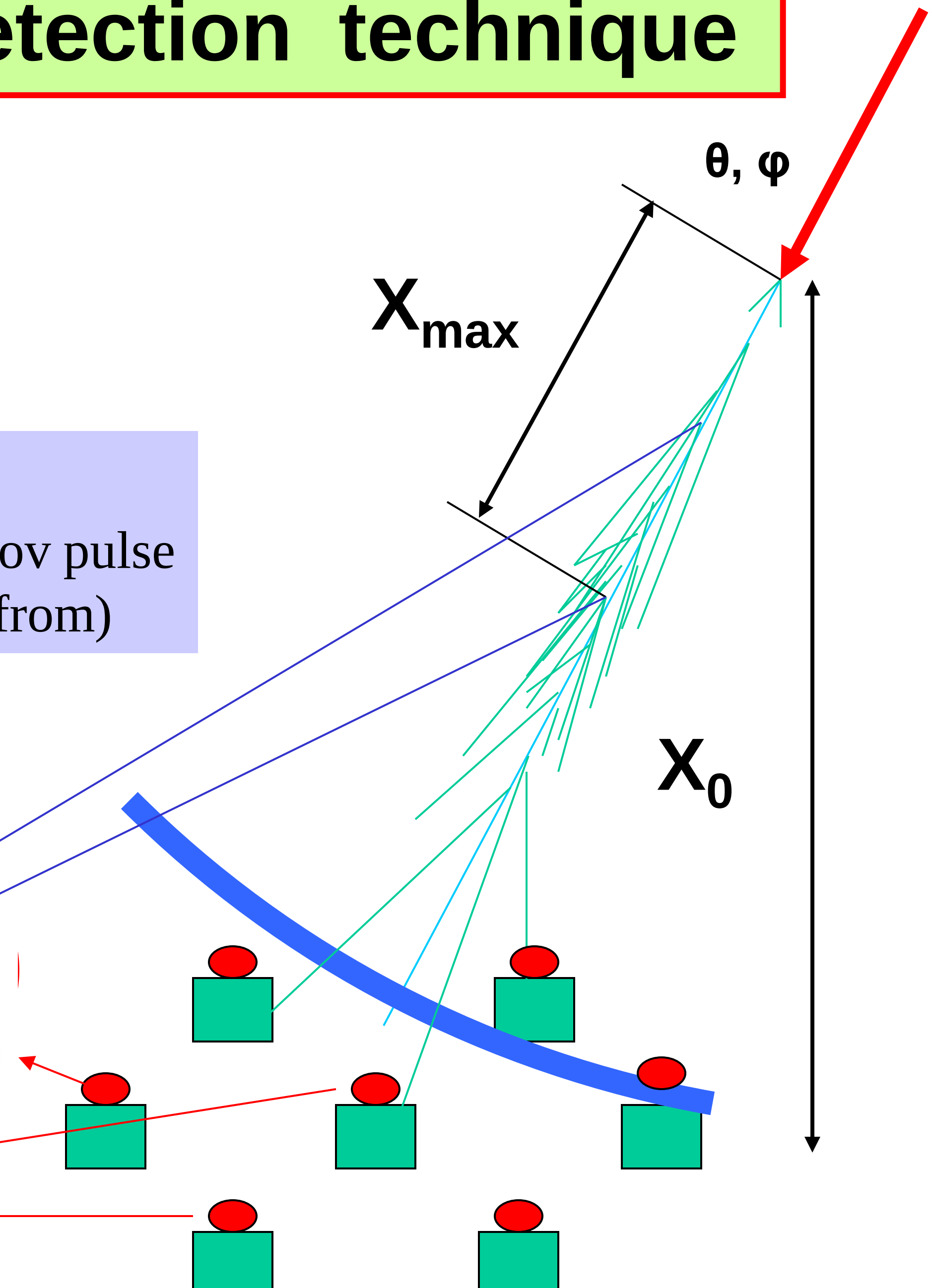
($\tau(400)$ - width of a Cherenkov pulse at distance 400 m EAS core from)

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

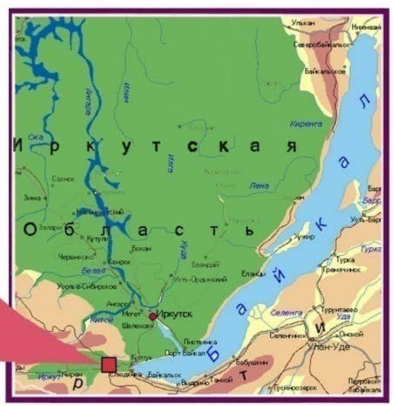
P -Steepness of a Lateral Distribution Function (LDF)







2006-2012 year Tunka-133 array:
175 optical detectors on 3 km^2 area



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

50 km from Lake Baikal

Tunka Collaboration

S.F.Beregnev, S.N.Epimakhov, N.N. Kalmykov, N.I.KarpovE.E. Korosteleva, V.A. Kozhin, L.A. Kuzmichev, M.I. Panasyuk, E.G.Popova, V.V. Prosin, A.A. Silaev, A.A. Silaev(ju), A.V. Skurikhin, L.G.Sveshnikova I.V. Yashin,
Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow, Russia;

N.M. Budnev, O.A. Chvalaev, O.A. Gress, A.V.Dyachok, E.N.Konstantinov, A.V.Korobchebko, R.R. Mirgazov, L.V. Pan'kov, A.L.Pahorukov, Yu.A. Semeney, A.V. Zagorodnikov
Institute of Applied Phys. of Irkutsk State University, Irkutsk, Russia;

B.K. Lubsandorzhiev, B.A. Shaibonov(ju) , N.B. Lubsandorzhiev
Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;

V.S. Ptuskin
IZMIRAN, Troitsk, Moscow Region, Russia;

Ch. Spiering, R. Wischnewski
DESY-Zeuthen, Zeuthen, Germany;

A.Chiavassa
Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.

Advantage of the Tunka-133 array:

1. Good accuracy positioning EAS core (5 -10 m)
2. Good energy resolution (~15%, in principal up to - 5%)
2. Good accuracy of primary particle mass identification (accuracy of X_{max} measurement ~ 20 -25 g/cm^2
3. Good angular resolution ~0.1 – 0.3 deg
4. Low cost: **the Tunka-133 – 3 km^2 array ~ 10^6 Euro**

Disadvantage:

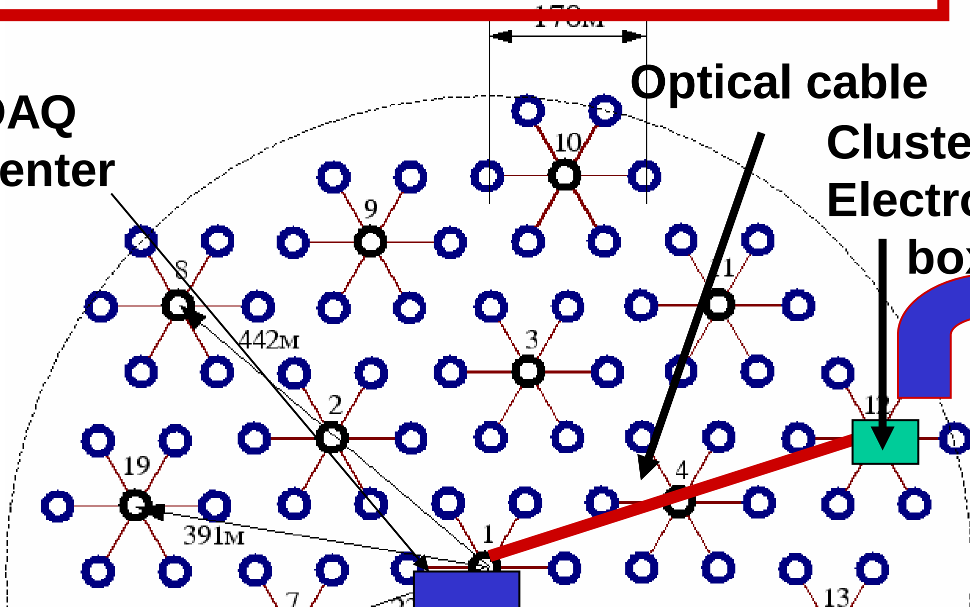
Short time of operation (moonless, cloudless nights) – 5-10%

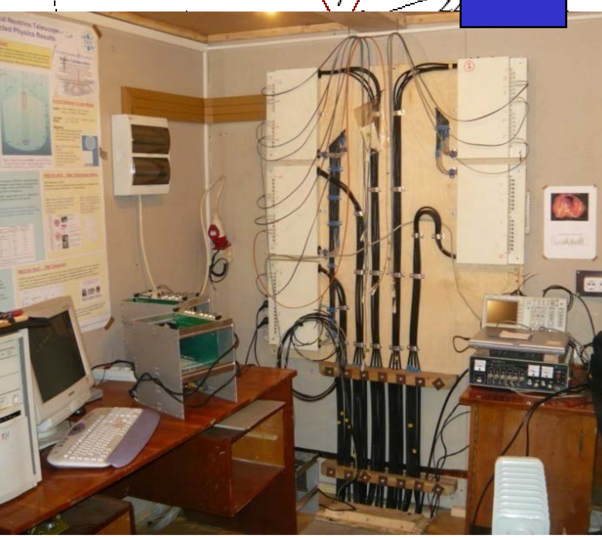
Tunka-133: 19 clusters,
7 detectors in each cluster

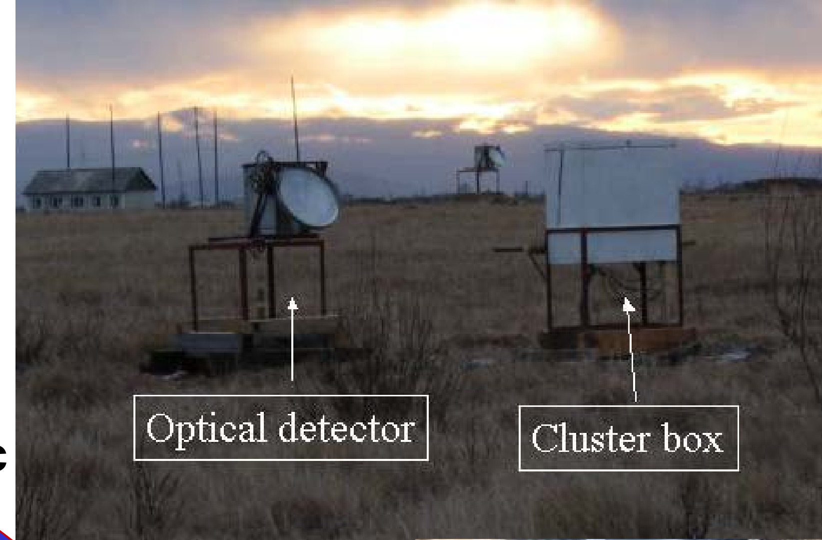
DAQ center

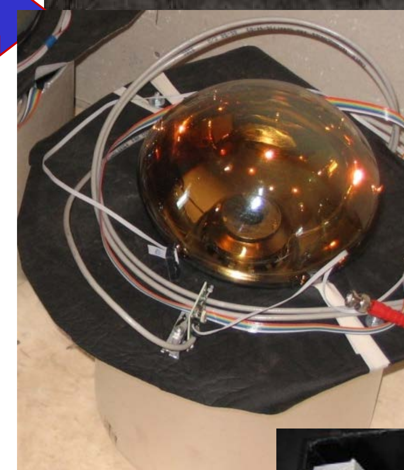
Optical cable

Cluster Electronic box

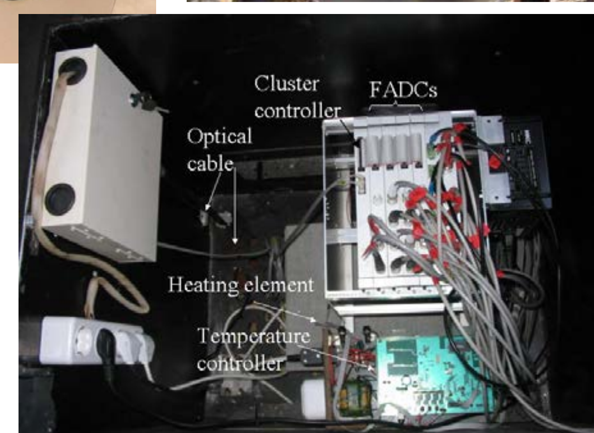








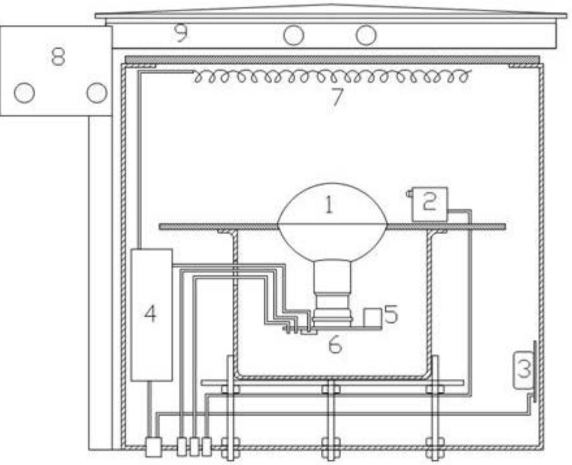
PMT
EMI 9350
Ø 20 cm



4 channel FADC boards
200 MHz, 12 bit

Optical detector of Tunka-133

Angular sensitivity



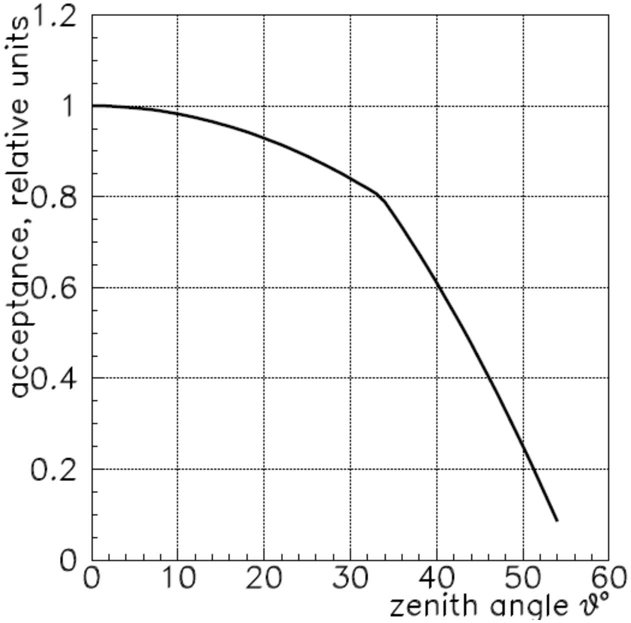
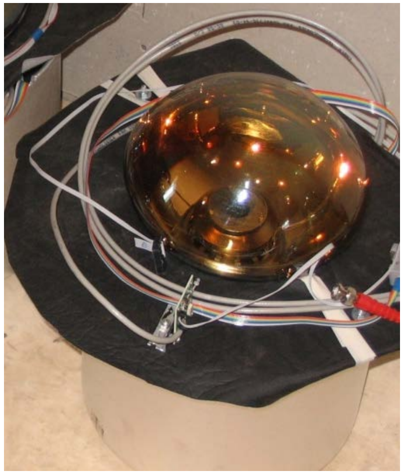
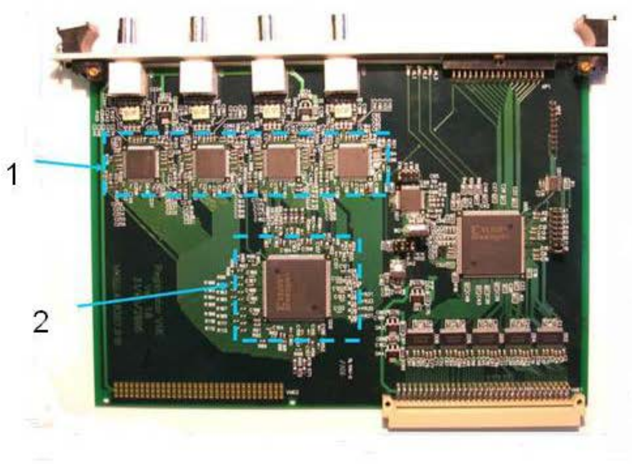


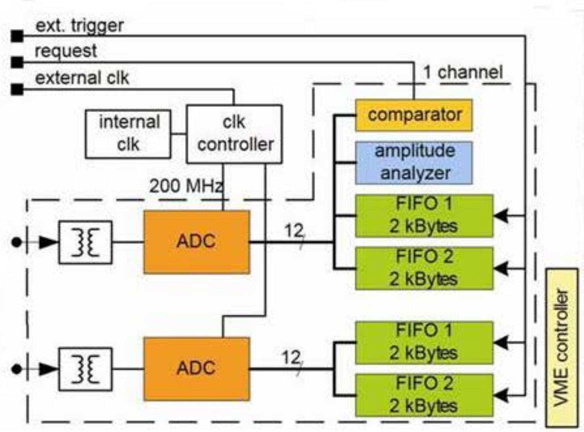
Fig. 4. The schematic drawing of the optical module: 1 – PMT Thorn EMI9350KB; 2- LED driver; 3 – temperature controller; 4 – DC-DC converter and heater driver; 5 - preamplifier; 6 – active voltage divider; 7 – heater of acrylic cover; 8 – lid driver; 9 – lid.

PMT
EMI 9350
Ø 20 cm



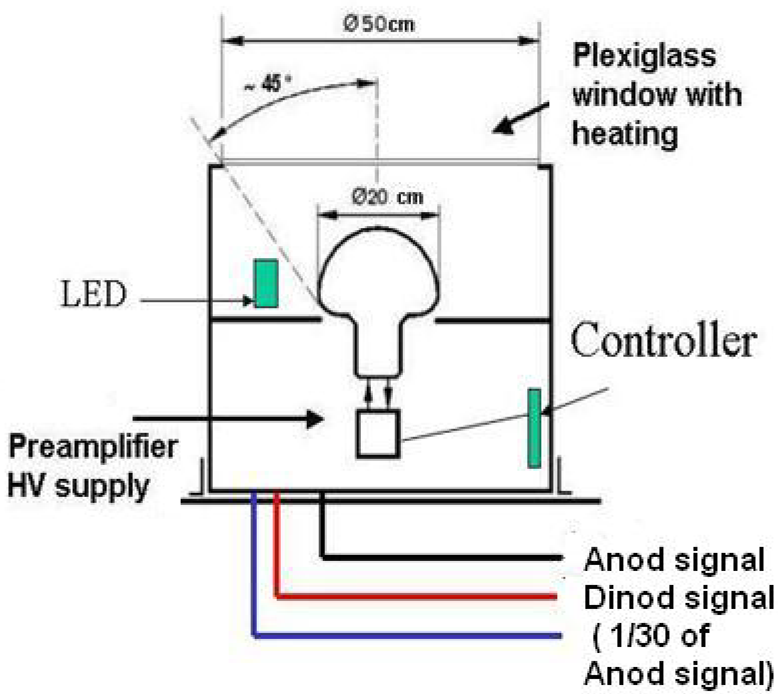
Cluster electronics

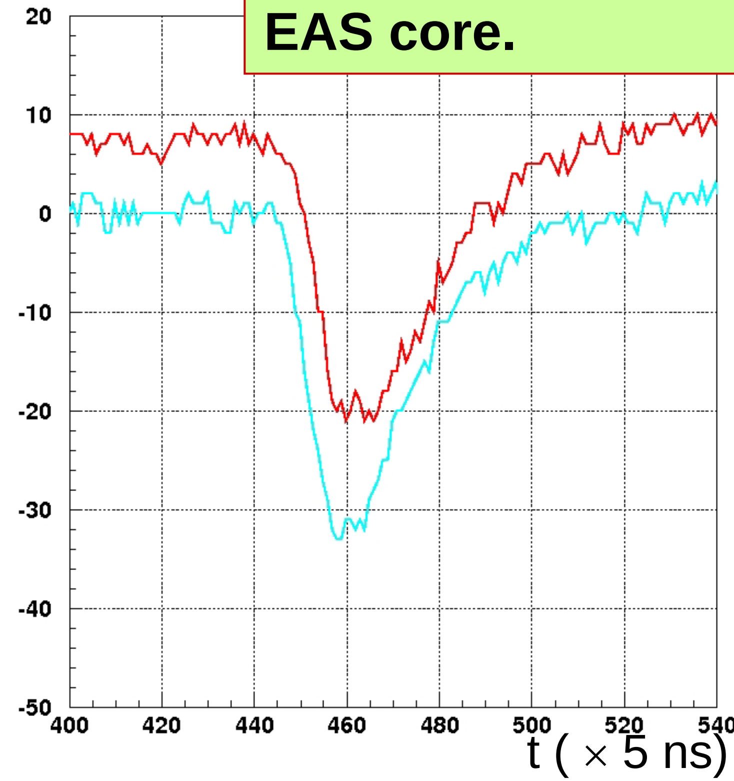




1. ADC AD9430, 12 bit, 200 MHz
2. FPGA XILINX Spartan-3

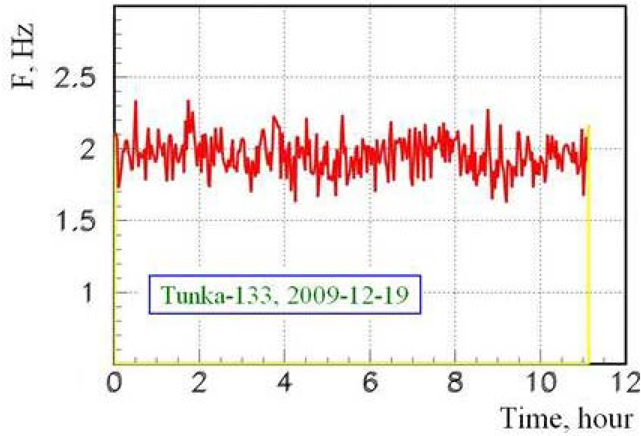
Cherenkov light pulses of two detectors of a cluster located at a distance 700 m from EAS core.



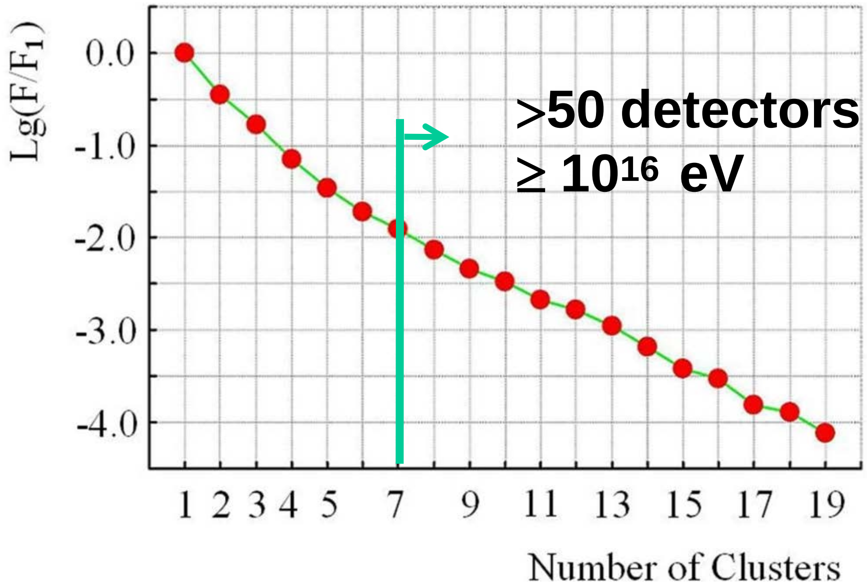


Three seasons of array operation

2009 - 2010 :286 hours of good weather .
2010 – 2011: 305 hours of good weather.
2011 – 2012: 380 hours of good weather
> $6 \cdot 10^{6}$ events with an energy $\geq 10^{15}$ эВ
> 1900 events with an energy $\geq 10^{17}$ эВ.



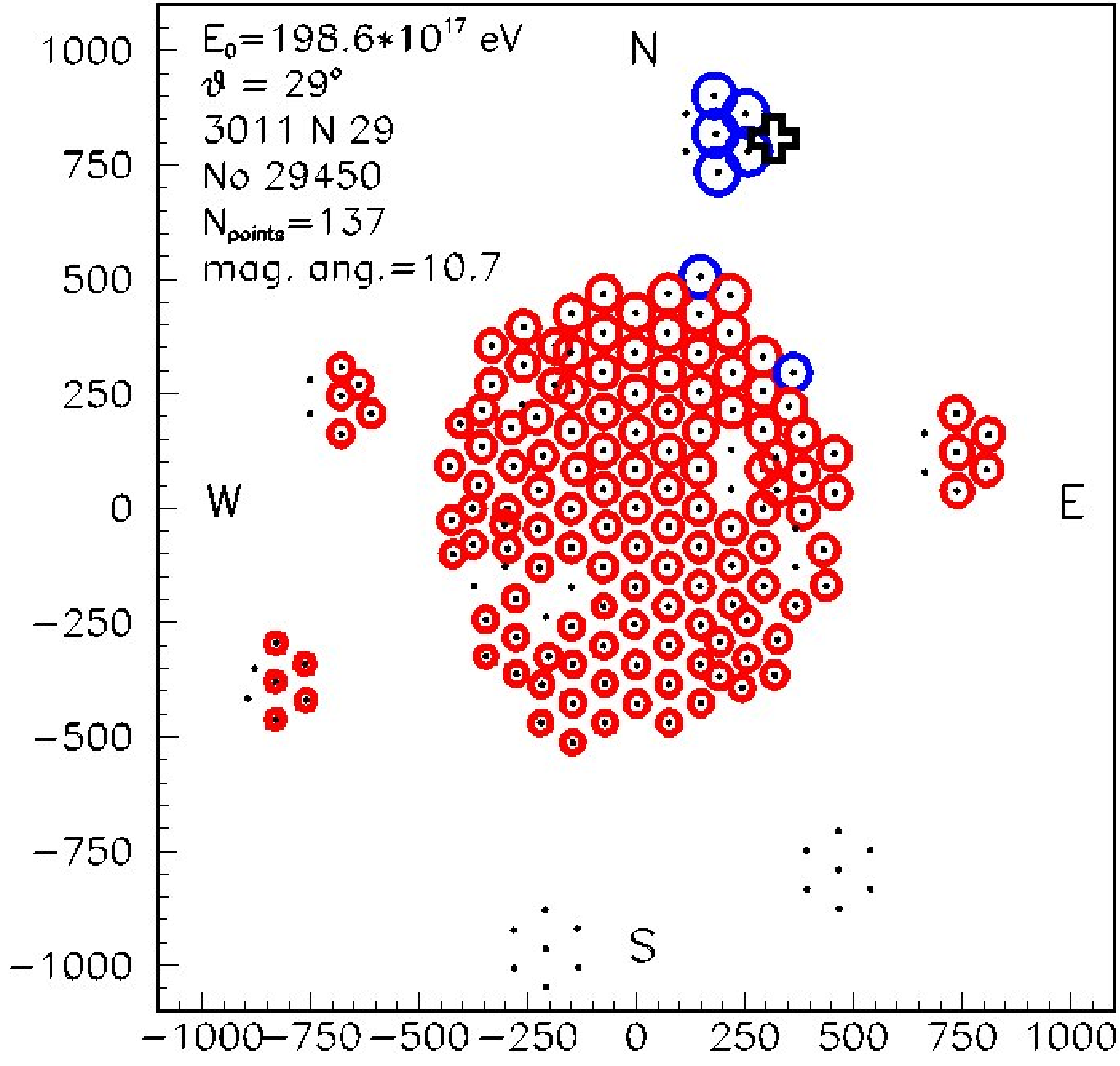
Trigger counting rate during one night .



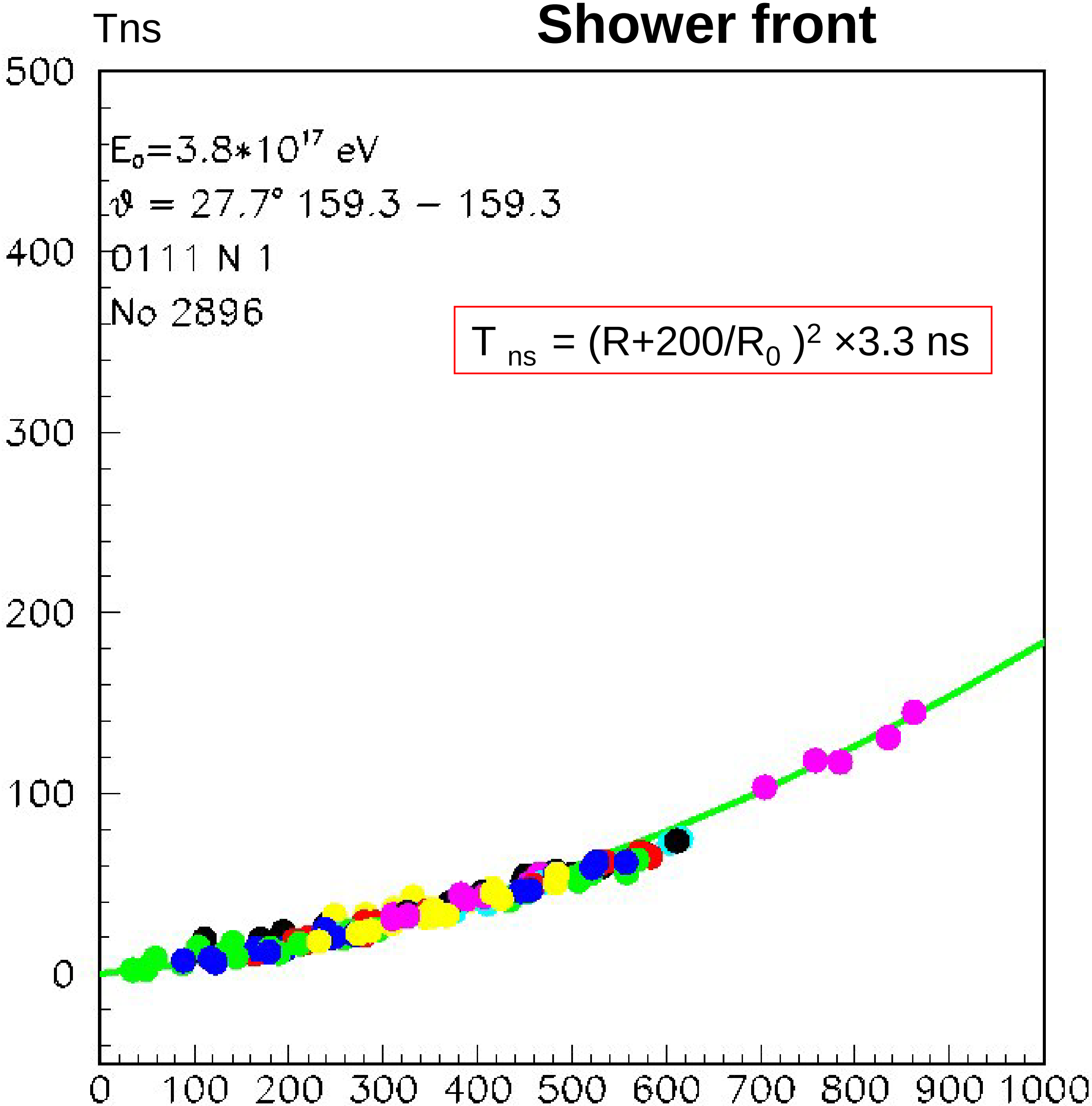
>10 events during every night with number of hit detectors more than 100.

Distribution of the number of hitted clusters in an event.

Example of event: EAS energy $2 \cdot 10^{19}$ eV

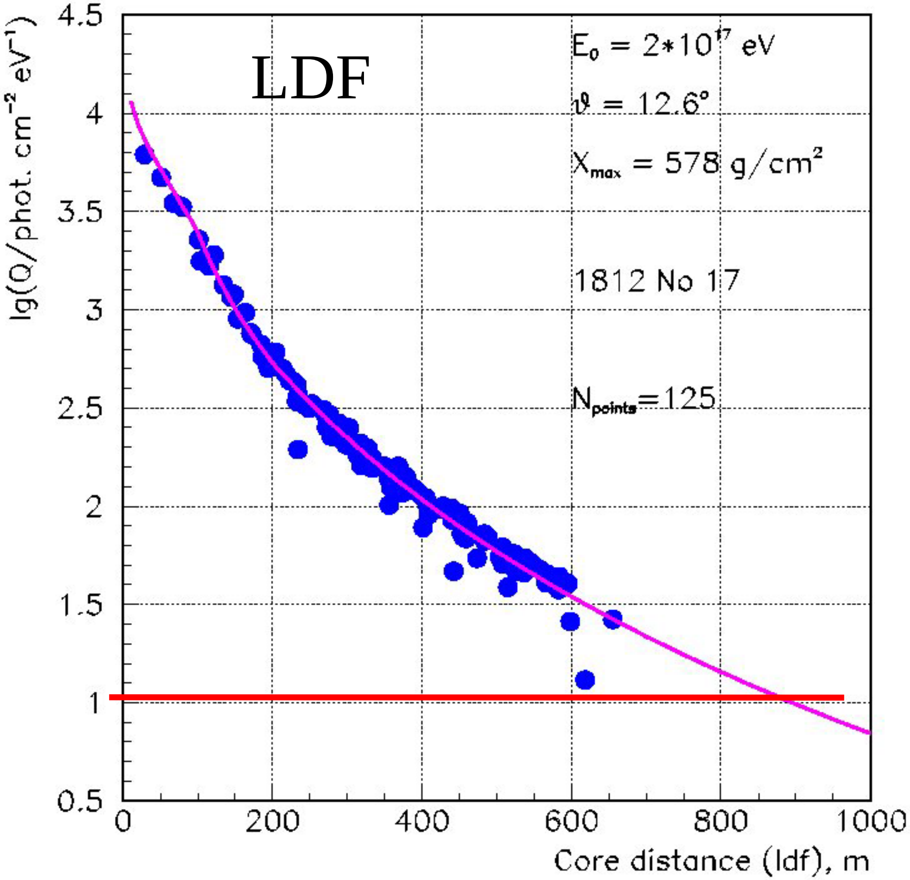


Shower front

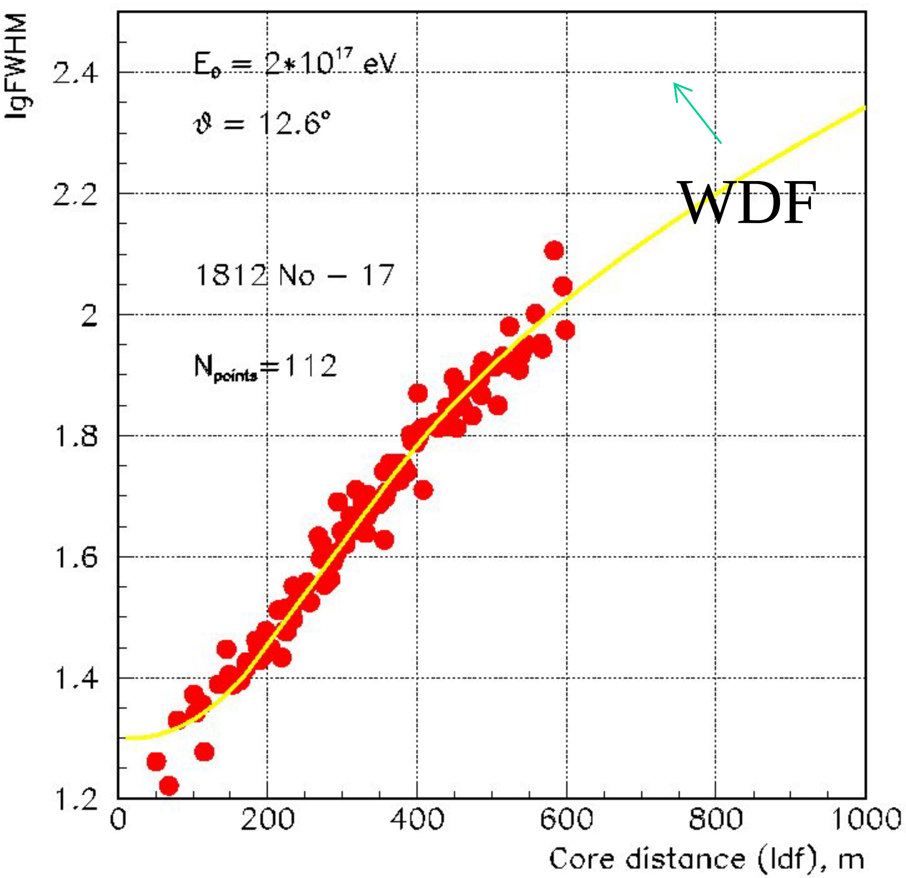


An event characteristics

Lg N_{ph}^{exp} (R)



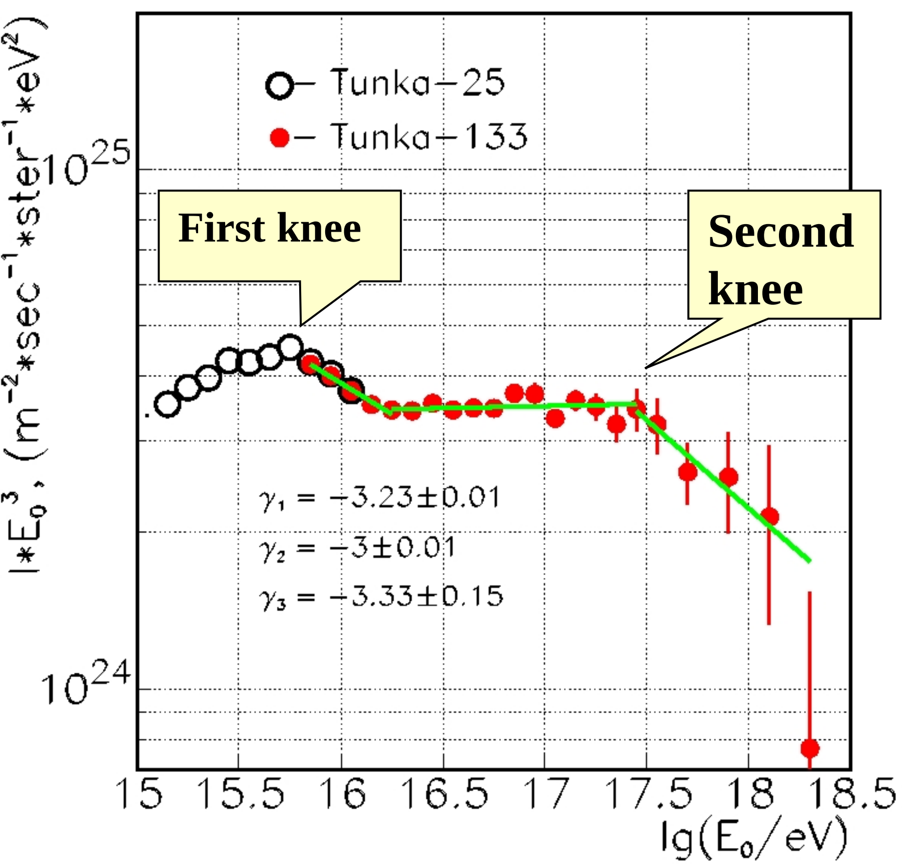
Lg τ(R)

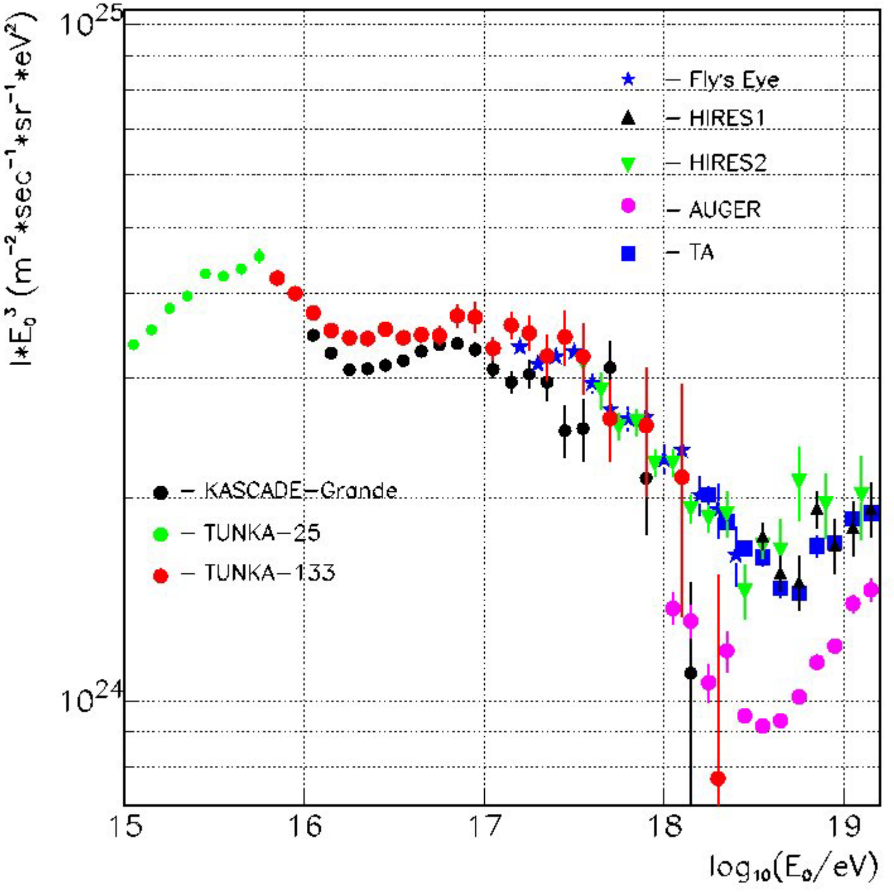


Fitting experimental points with Lateral Distribution function

Fitting of τ(R) with Width – Distance Function.

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

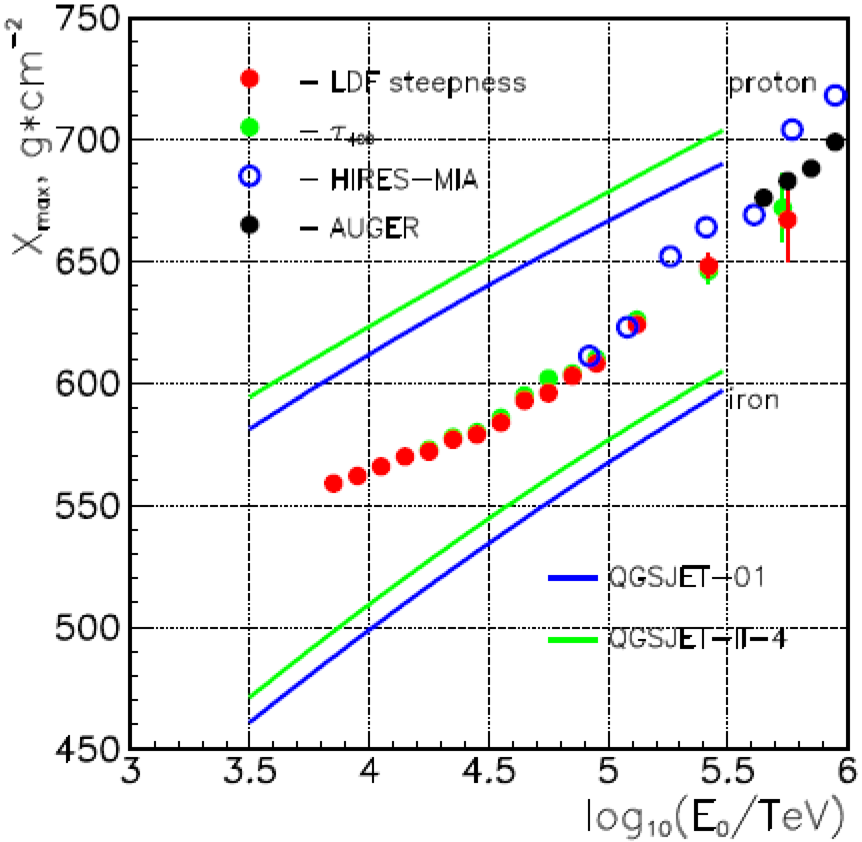


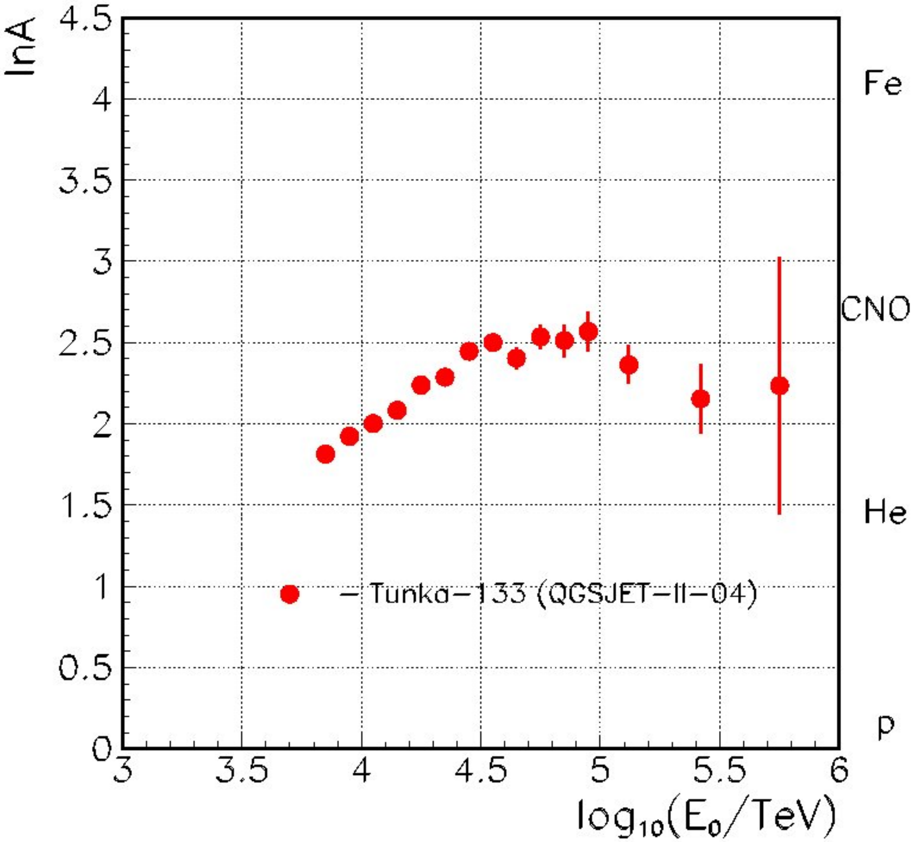


1. Agreement with KASCADE-Grande
2. Agreement with old Fly's Eye, HiRes and TA spectra.

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

Mean logarithm of primary mass.

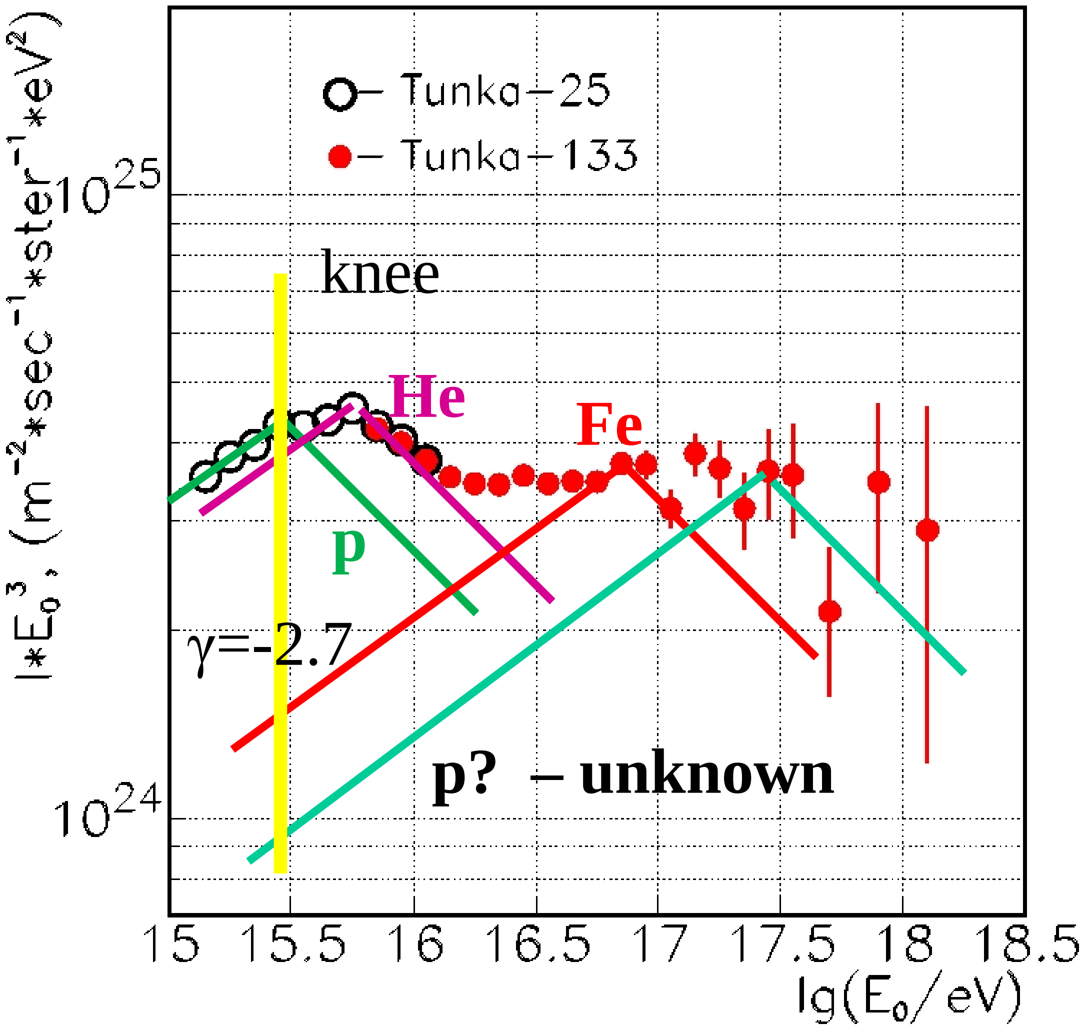




The primary CR mass composition changes from light (He) to heavy up to energy ~ 30 PeV

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

Tunka CR energy spectrum



Primitive composition analysis in the knee (following A.Erlykin & A.Wolfendale):

p – 14%

He – 41% …

Fe – 12%

Unknown – 21%

Conclusion:

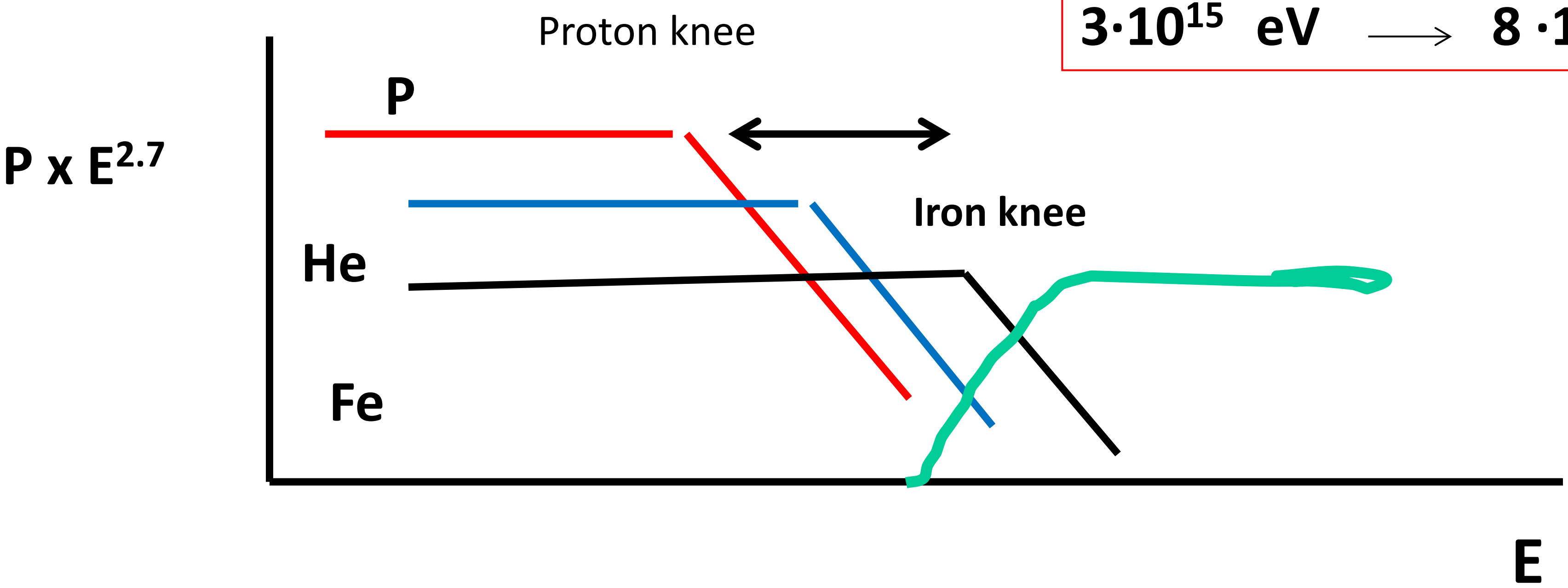
1. **He** dominates in the knee.
2. Unknown component can not be galactic or it's spectrum is different.
3. **Fe** domination is not close to 100% at $8 \cdot 10^{16}$ eV.

Transition from Galactic to extragalactic CR

$E_{max} \sim Z \cdot B \cdot R$

$E_{max}(Fe) = 26 \times E_p$

$3 \cdot 10^{15}$ eV $\longrightarrow$ $8 \cdot 10^{16}$ eV

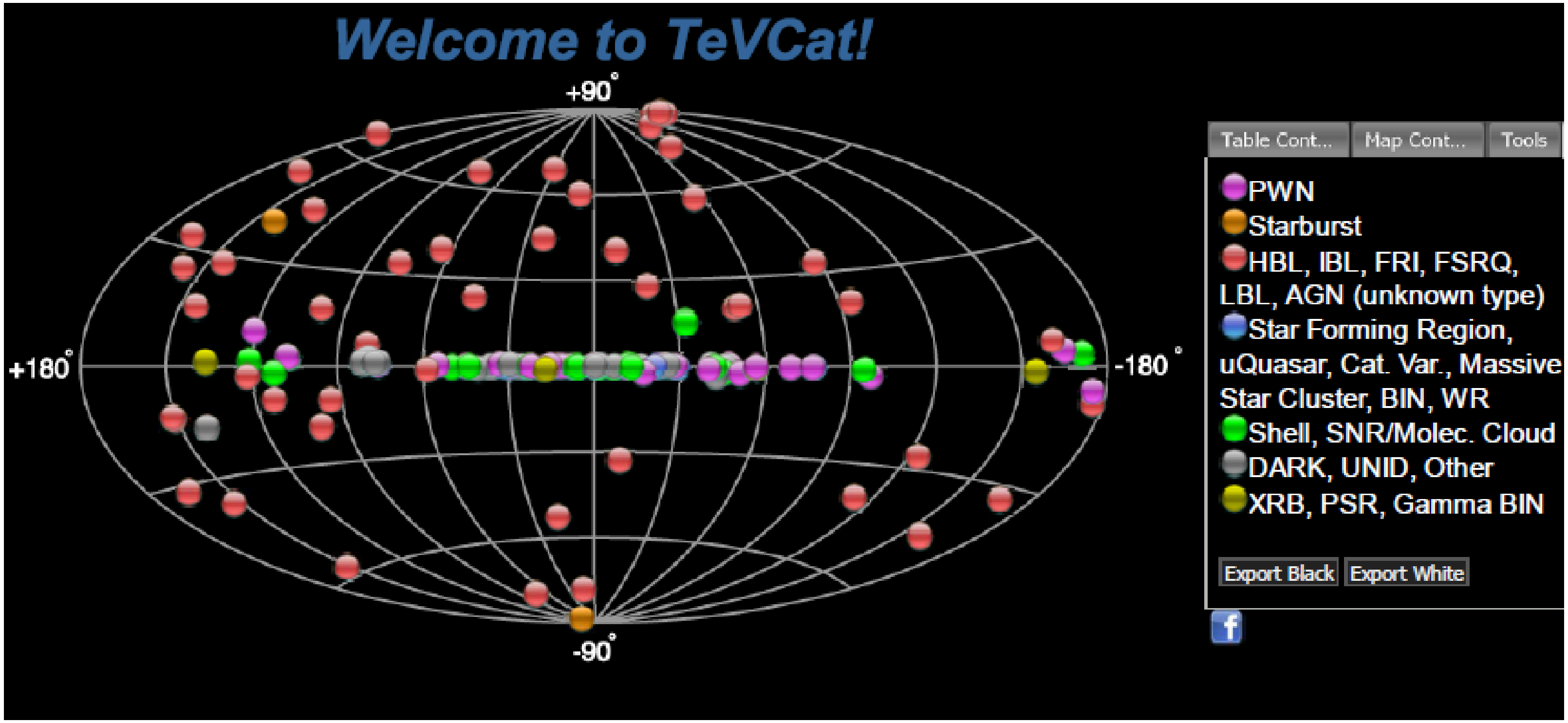


Galactic

Extragalactic

Towards High Energy Gamma-Ray Astronomy array at Tunka Valley

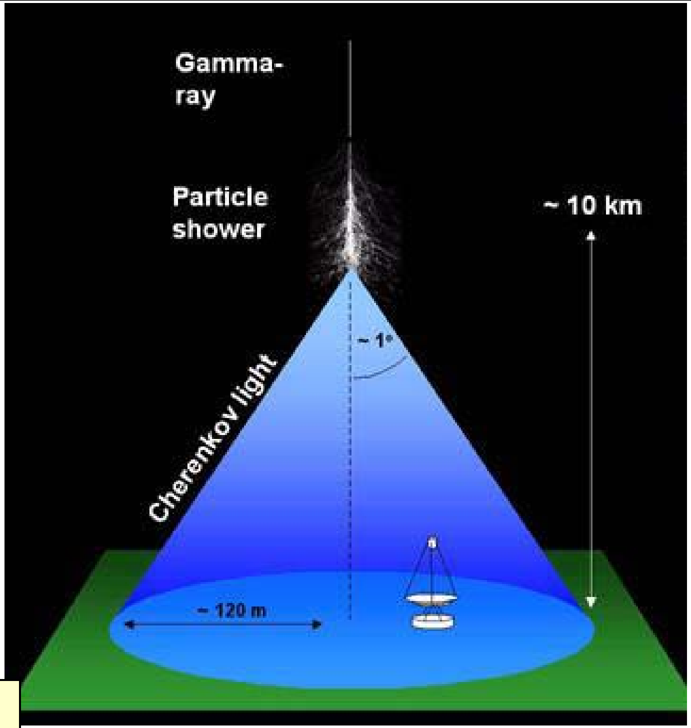
For recent years gamma-astronomy became the most dynamically developing direction of high energy astro- physics.



Advantages of gamma-astronomy - gamma-quanta preserve the direction to the source and in comparison with neutrino – relative simplicity of their detection.

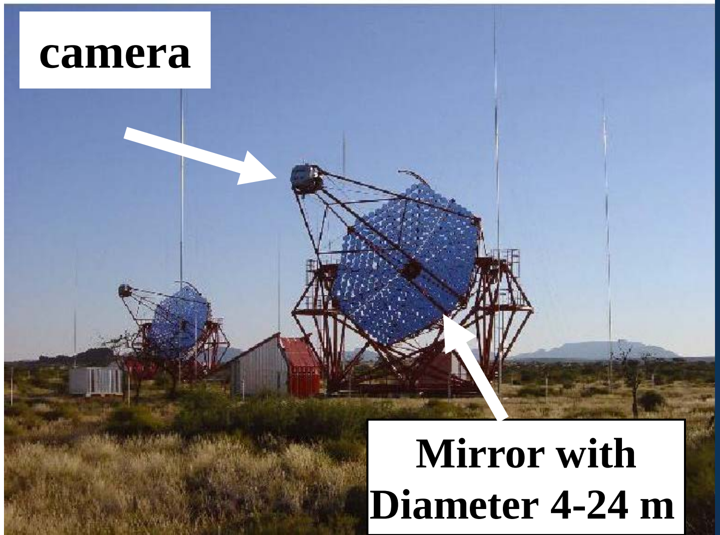
IACT - *Imaging Atmospheric Cherenkov Telescopes*

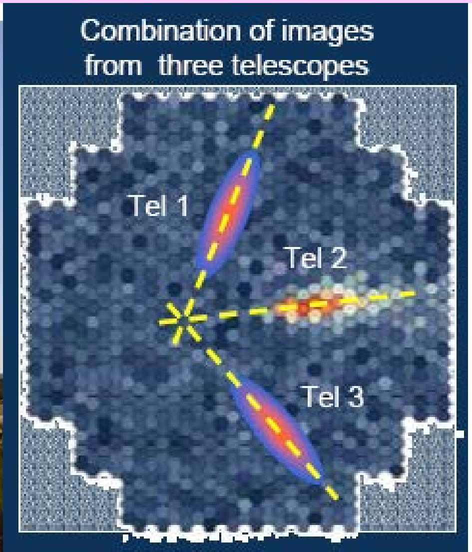
HESS
MAGIC
VERITAS
AIROBIC
Fermi
Argo-YbJ
Tibet-III
Future Projects
CTA – 2017-18
HAWC -2014
LHAASO – 2017-18



To detect Ultra-High energy gamma-rays effective area of array must be 10 km^2 at least.
An Imaging ACT must have >10000 channels / km^2.
Cost of the IACT more than 100 millons \$/ km^2

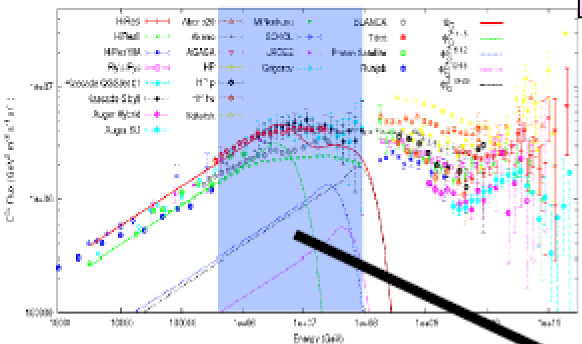
An IAST is narrow-angle Telescope (3-5° FOV) consisting of a mirror of 4 -24 m diameter which reflects EAS Cherenkov light into a camera where EAS image is formed

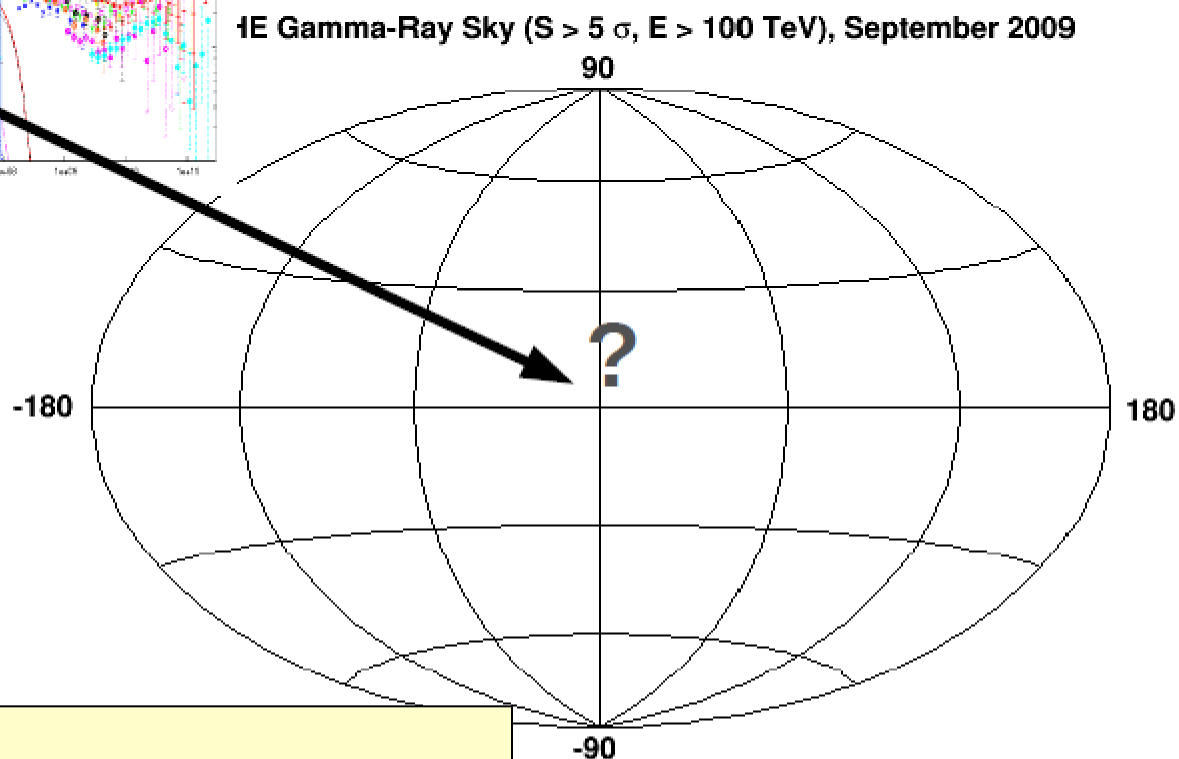




Pevatron sky

Gamma-radiation with energy 1 - 50 TeV from approximately 100 local sources has been detected, but no one with higher energy





Where are the cosmic pevatrons?

From Tunka-Collaboration to TAIGA-Collaboration

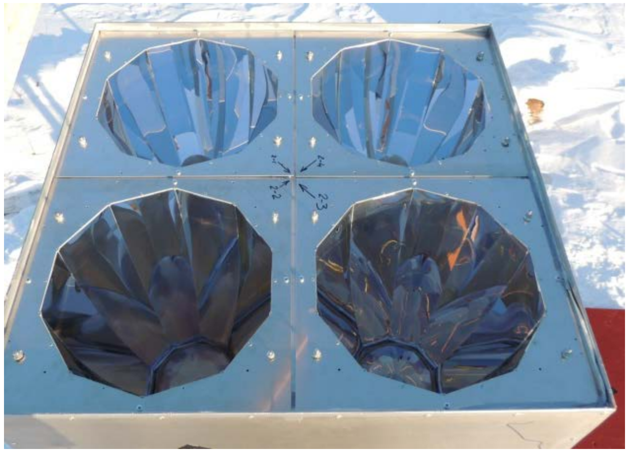
Irkutsk State University (ISU), Irkutsk, Russia
Scobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of Russian Academy of Science (INR RAN), Moscow, Russia
Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS (IZMIRAN), Troitsk, Russia
Joint Institute of Nuclear Physics (JIRN), Dubna, Russia
National Research Nuclear University (METHI), Moscow, Russia

Deutsches Elektronen Synchrotron (DESY), Zeuthen, Germany
Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
Institut fur Experimentalphysik, University of Hamburg (UH), Germany
Max-Planck-Institut für Physik (MPI), Munich, Germany
Tubingen University, (TU) Tubingen, Germany
Institute for Computer Science, Humboldt-University Berlin,

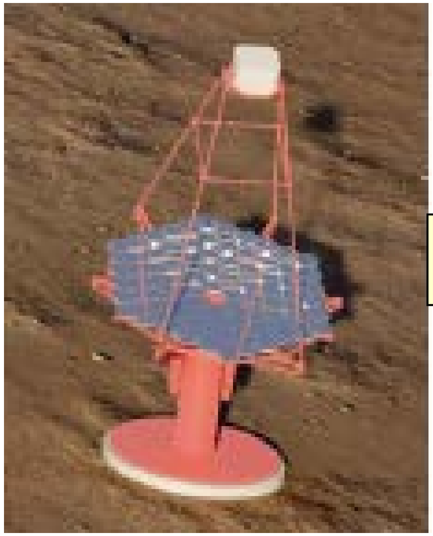
Fisica Generale Universita di Torino and INFN, Torino, Italy
School of Chemistry and Physics, University of Adelaide, Australia
ISS , Buharest, Romaia

TAIGA – Tunka Advanced Instrument for cosmic rays and Gamma Astronomy

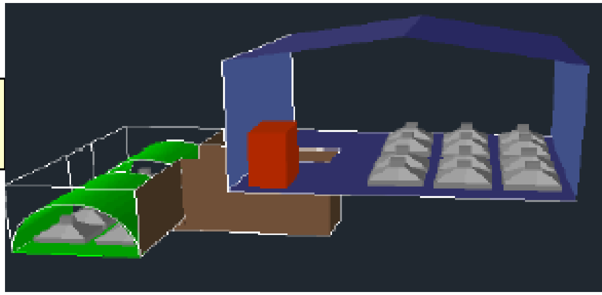
Array design concept



+



+



•Net of non imaging wide-angle optical stations
(HiSCORE type, M.Tluzikont et al)

Net of 3-4 m class imaging telescopes

Net of scintillation detectors (including underground muon detectors)
10^2 → $2\ 10^3$ m^2 area.

Main Topics for TAIGA

Gamma-ray Astronomy

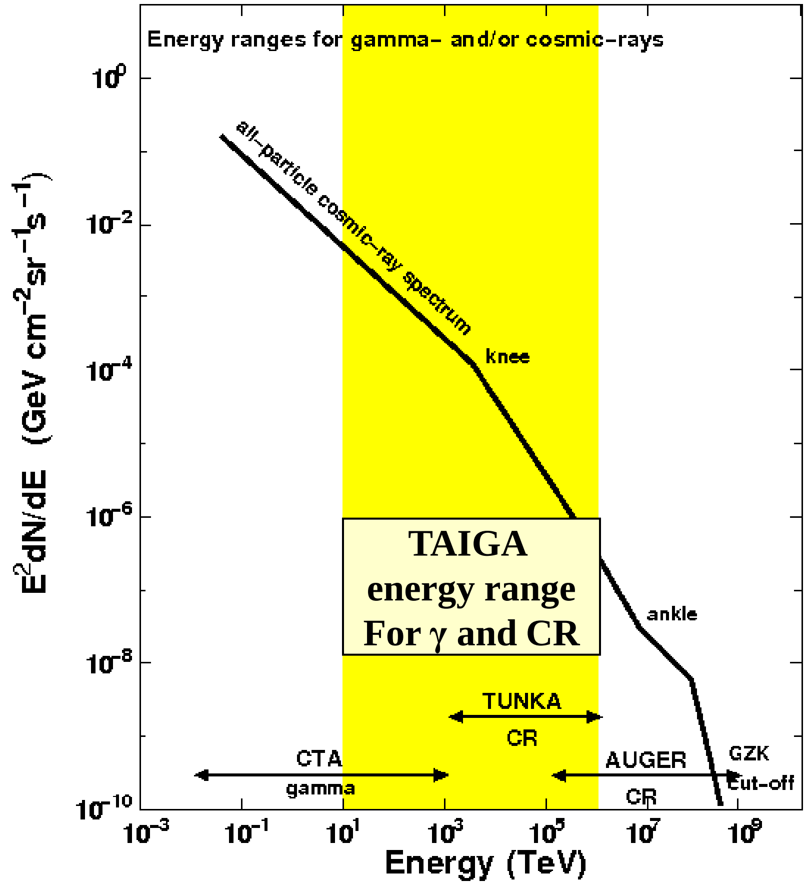
Search for the PeVatrons.
VHE spectra of known sources:
where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition
anisotropies
from 10^{14} to 10^{18} eV.
10^{8} events (in 1 km^{2} array)
with energy > 10^{14} eV

Particle physics

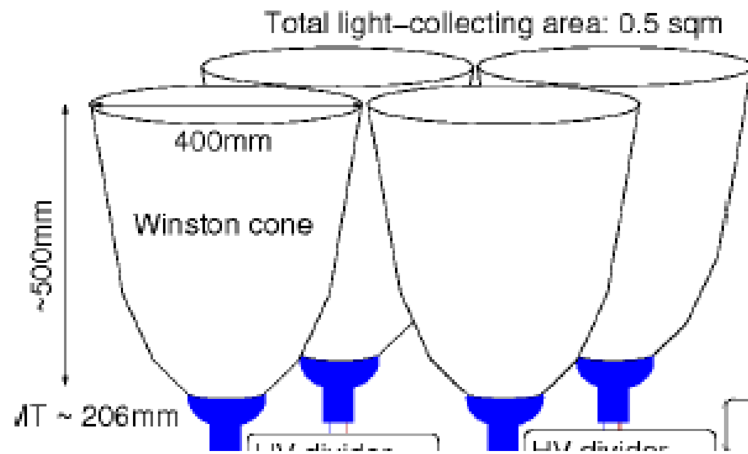
Axion/photon conversion.
Hidden photon/photon oscillations.
Lorentz invariance violation.
pp cross-section measurement.
Quark-gluon plasma.

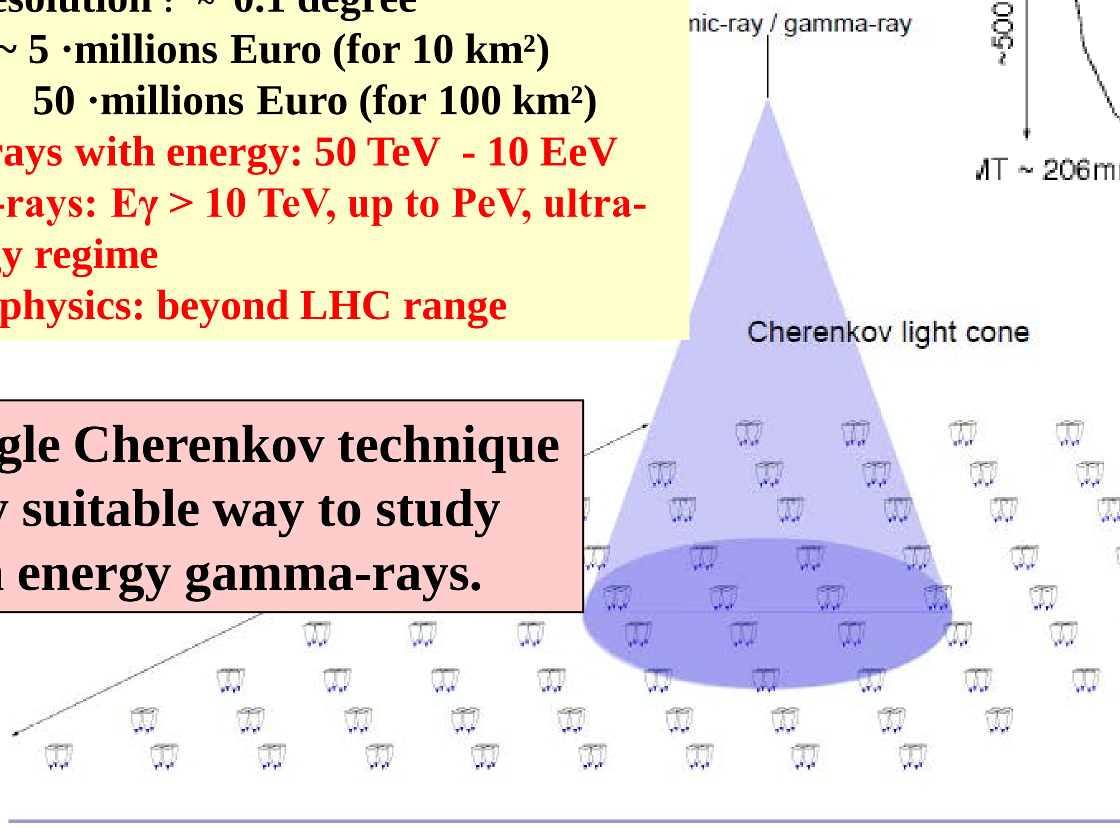


Tunka - HiSCORE (Hundred*i Square-km Cosmic Origin Explorer).

Non-imaging air Cherenkov array
Area: from 1 km² ⟹ 100 km²
Spacing between Cherenkov stations 100-200m
~200 channels / km².
Large Field of view: ~ 0.6 sr
Angular resolution : ~ 0.1 degree
Total cost ~ 5 ·millions Euro (for 10 km²)
50 ·millions Euro (for 100 km²)

- Cosmic-rays with energy: 50 TeV - 10 EeV
- Gamma-rays: Eγ > 10 TeV, up to PeV, ultra-high energy regime
- Particle physics: beyond LHC range





Wide-angle Cherenkov technique is very suitable way to study high energy gamma-rays.

Ways to decrease a detector threshold

$$E_{th} \sim (S_{det.}\,\eta)^{-1/2}\ (T_{signal})^{1/2}$$

1. Winston cones - PMT area increase in 4 times
   ($K = 1/\sin^2$ (tet) tet=30° - K =4)

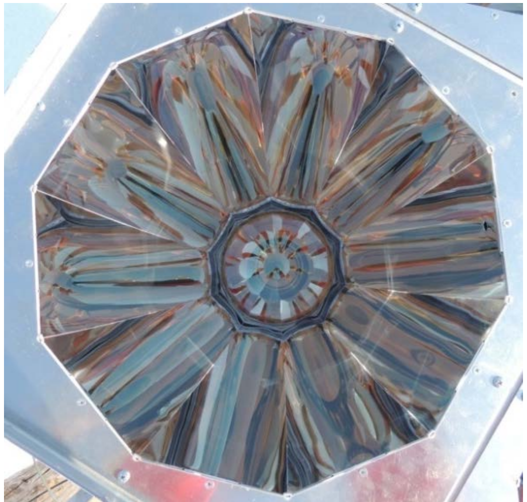
2. Analog summation of signals in one station

3. Decreasing of T_{signal} to 7-10 ns

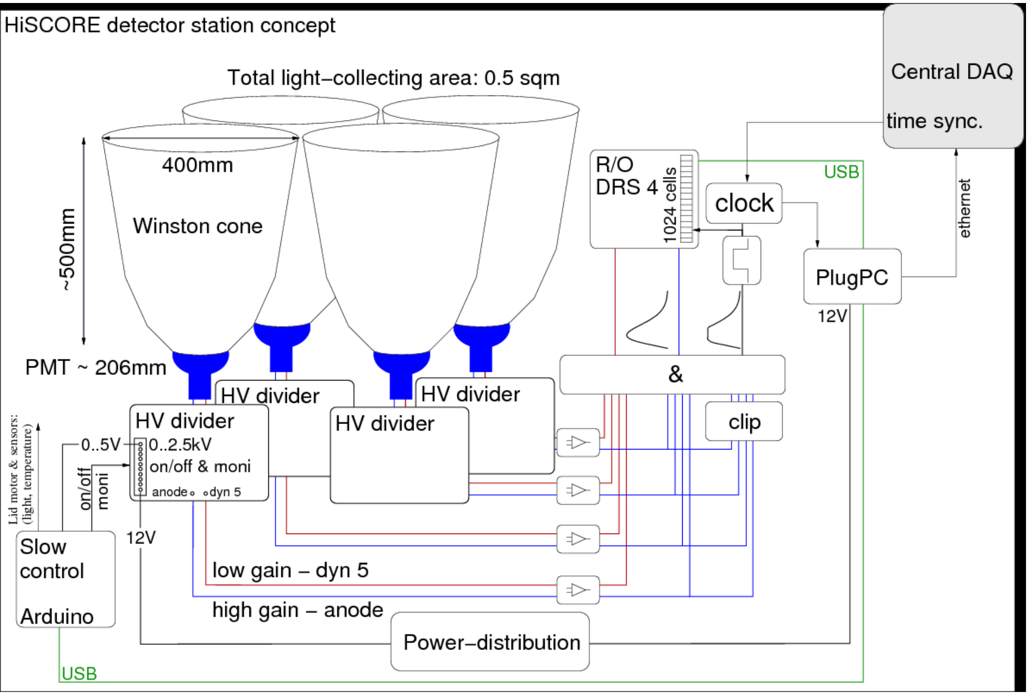
4. QE max = 35-40% for
PMT HAMAMATSU R7081-100

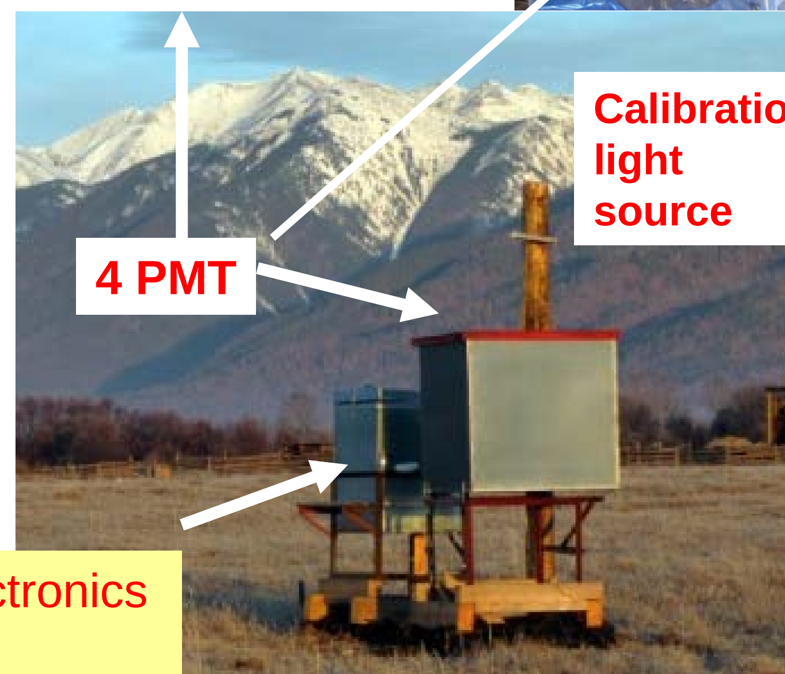
5. Using of wavelength shifter

Winston cone



Tunka-HiSCORE Cherenkov detector





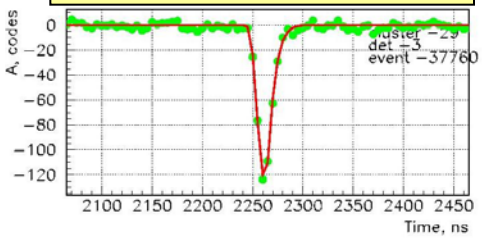
Calibration light source

4 PMT

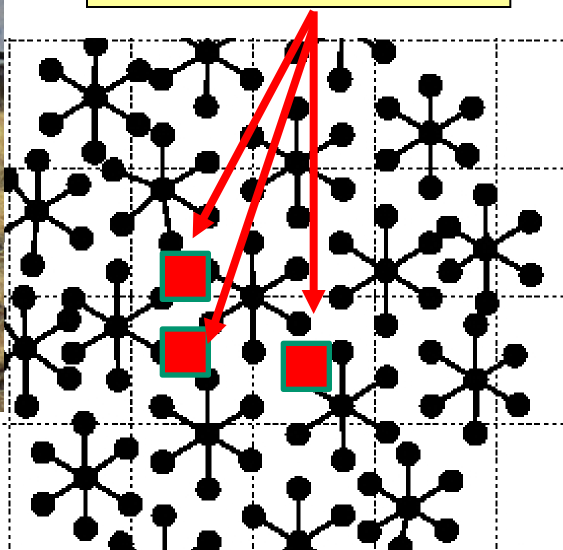
Electronics box

In October 2012 first setup of 3 Tunka-HiSCORE Cherenkov detectors were put in operation with Tunka-133

Signal from Tunka -HiSCORE



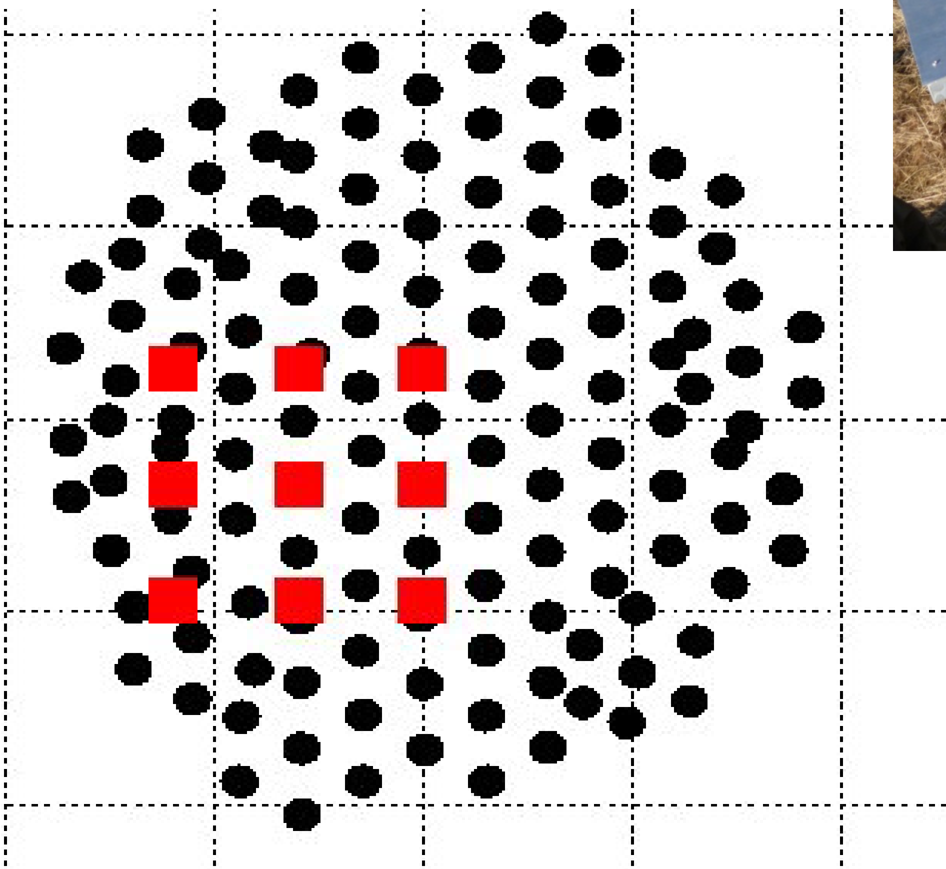
New Tunka -HiSCORE

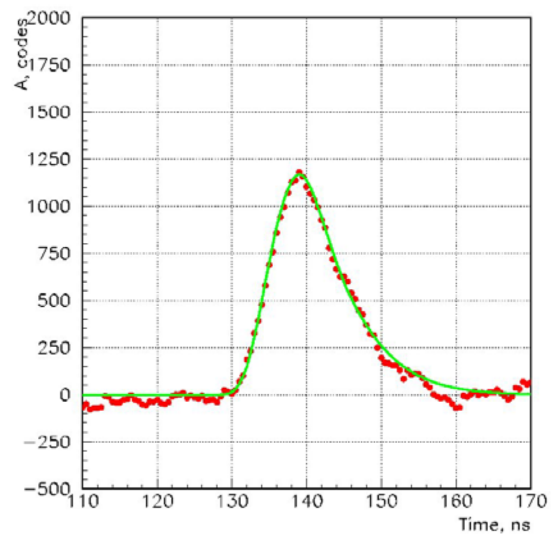


Cherenkov detectors of Tunka-133 array

October 2013
Prototype of Tunka-HiSCORE
9 Cherenkov stations

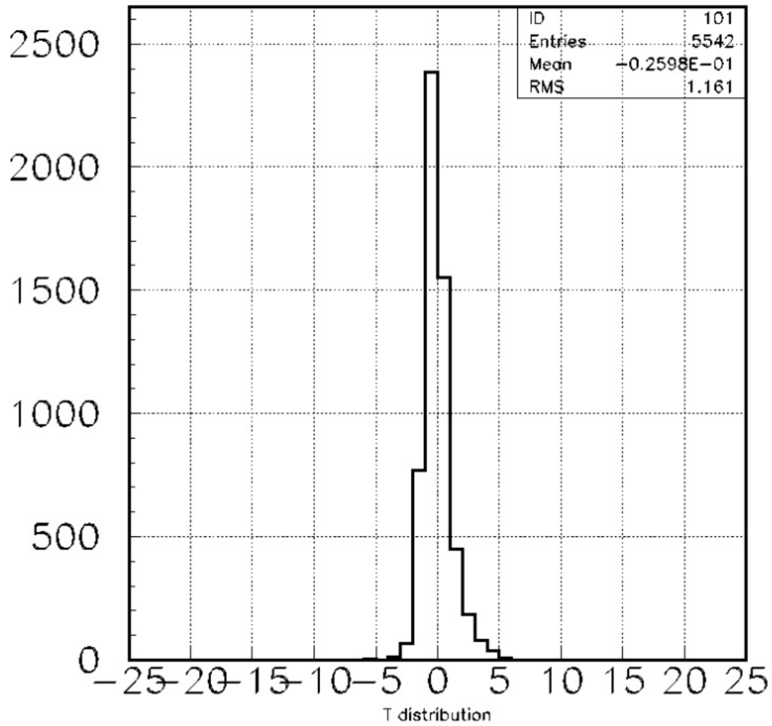
36 PMT R5912 (8")
New readout system.
New DAG based DRS-4 bord

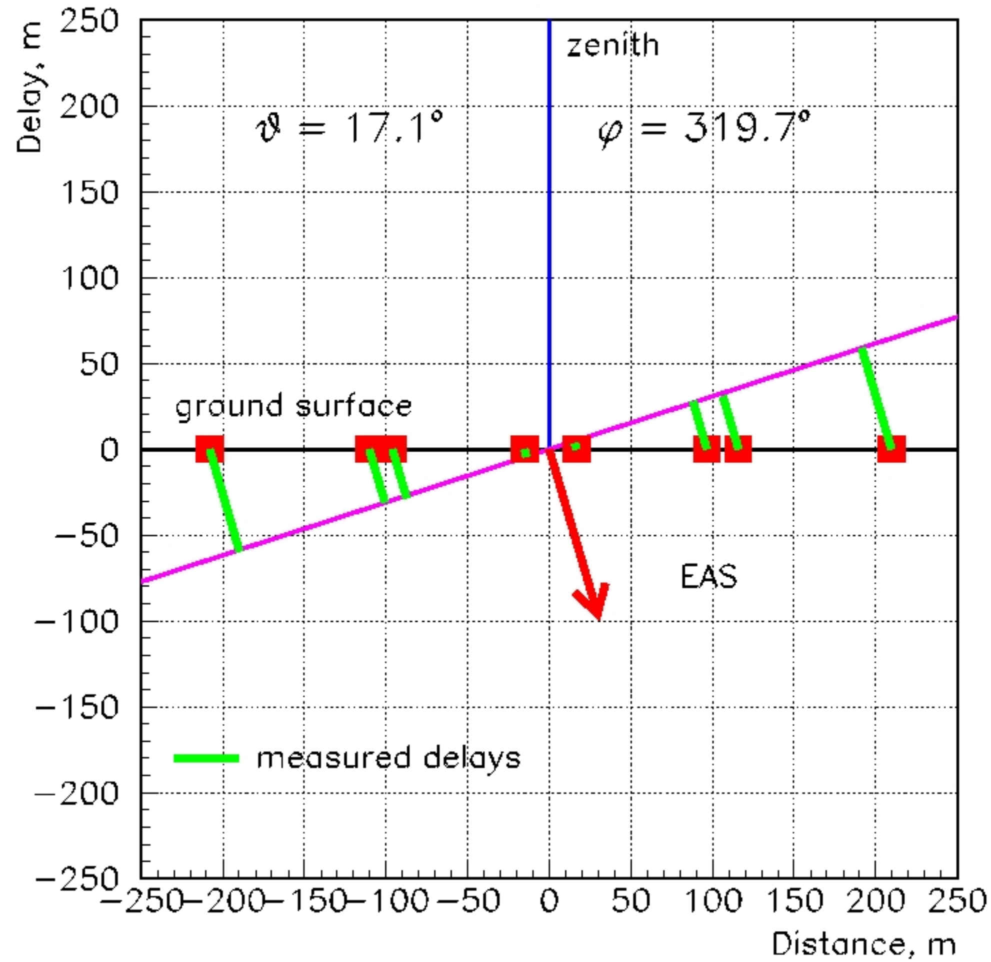




DRS-4 board (0.5 ns step)

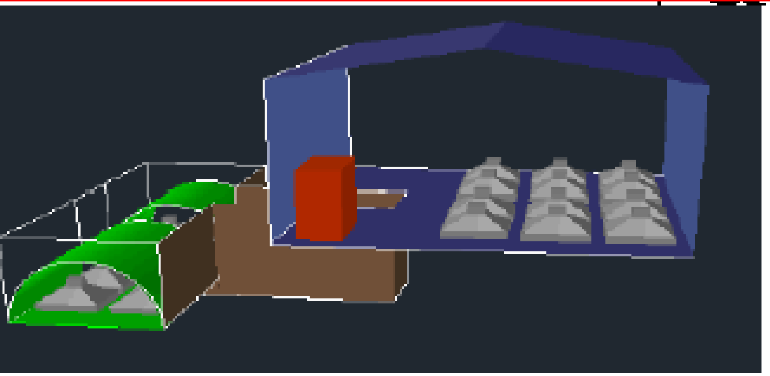
Accuracy of EAS axis direction reconstruction

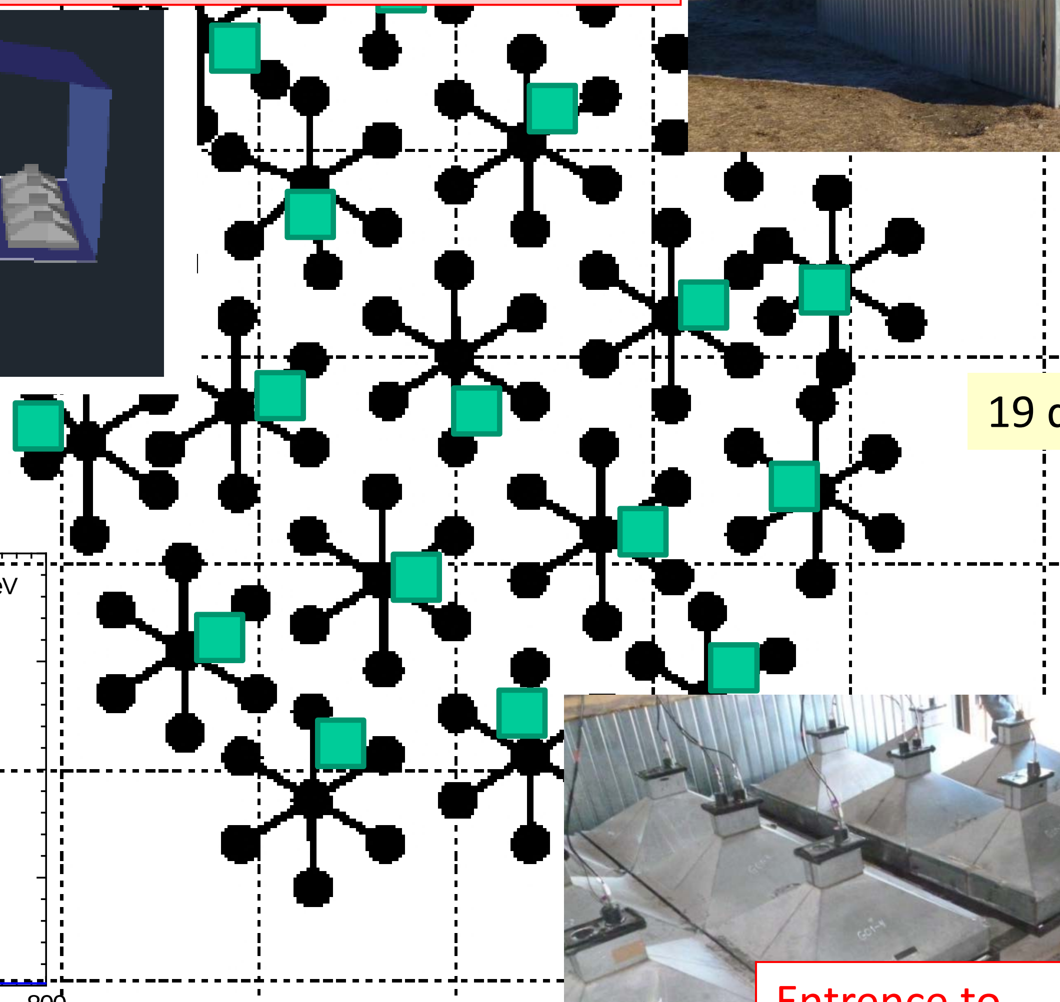


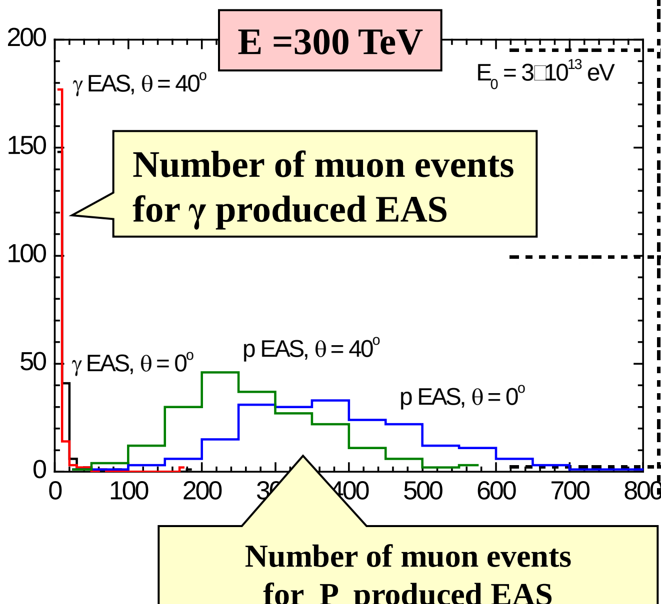


The RMS=1.1 ns for Tunka-HiSCORE provides an accuracy of an γ and CR arrival direction about 0.1 degree

A net of scintillation detectors- to reject p-N background



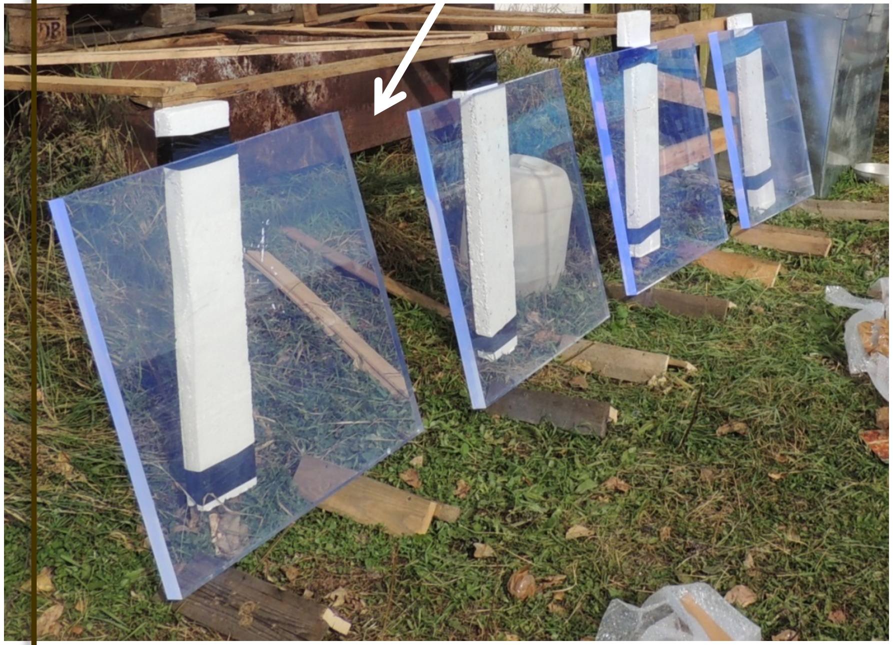




KASCADE-Grande scintillation counters

scintillator plate (800x800x40)

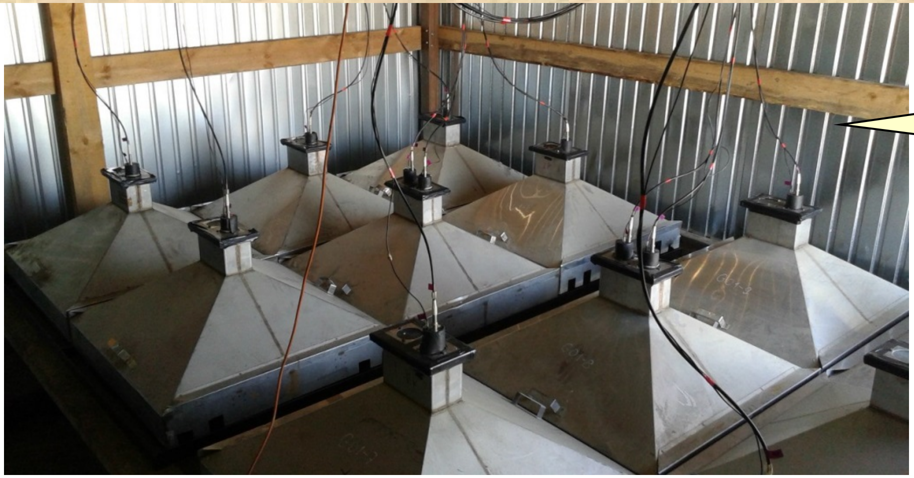
pyramid



PMT XP-3462

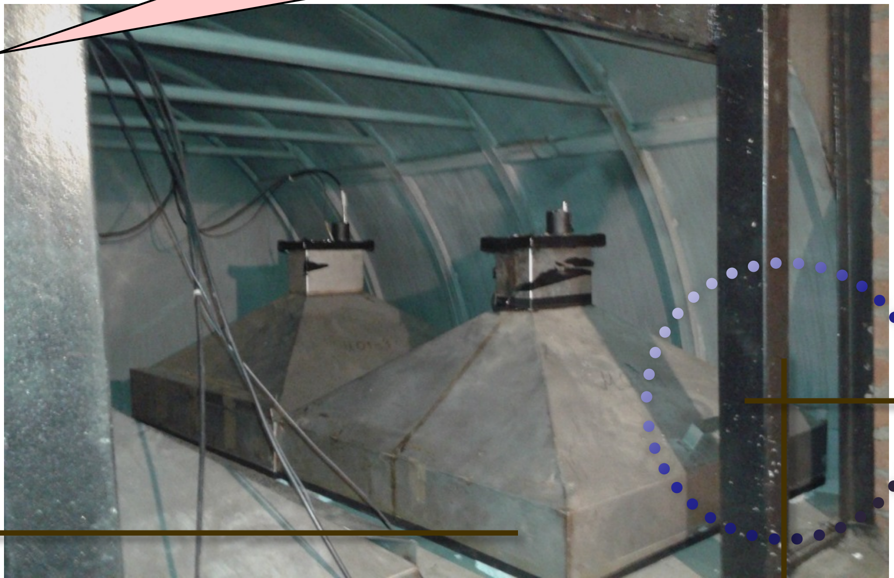
380 KASCADE-Grande scintillation counters arrived at the Tunka site

KASCADE-Grande scintillation counters in TAIGA

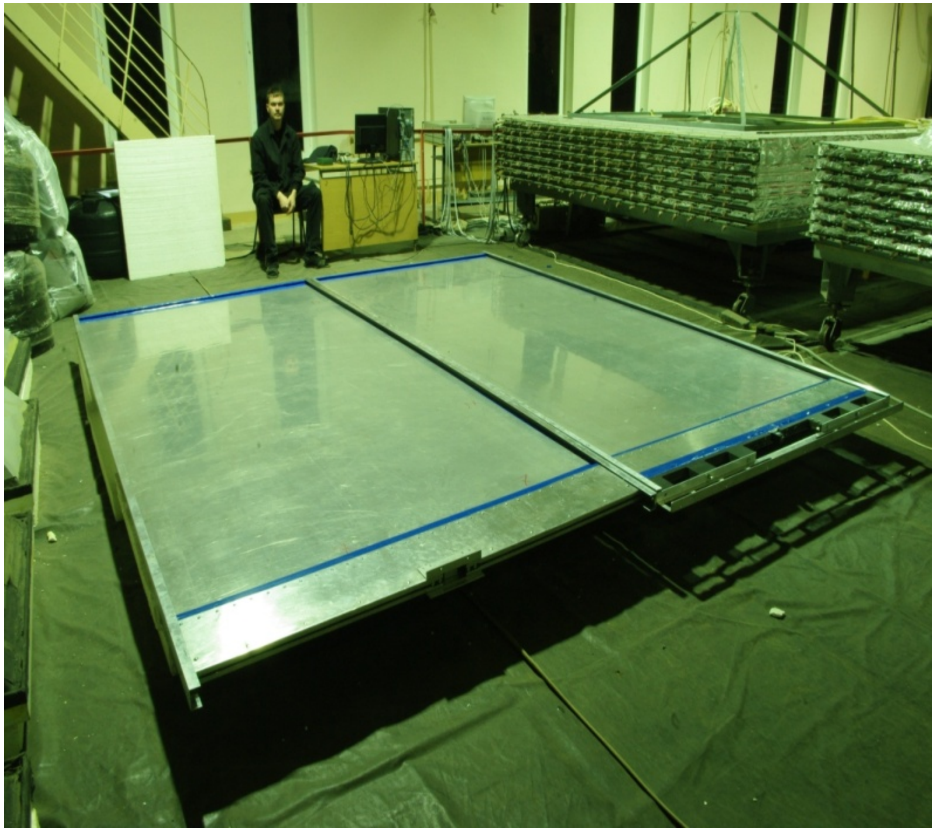


We intend to deploy 228 counters inside the surface detectors

We intend to deploy 152 counters inside underground muons detectors (total area 100 m^2)



Scintillation counters for 2000 m^2 underground muon detectors (~ 0.1% of array area)



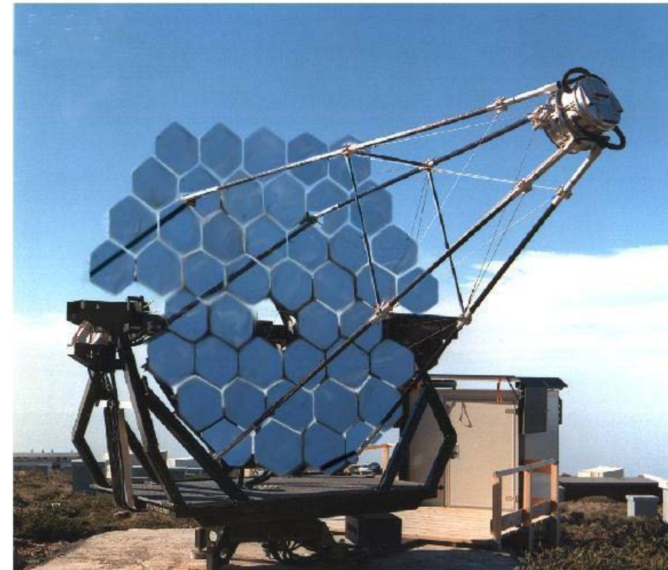
??????????
??????????

IHEP +Mephi

Imaging Atmospheric Cherenkov Telescopes (IACT) in TAIGA

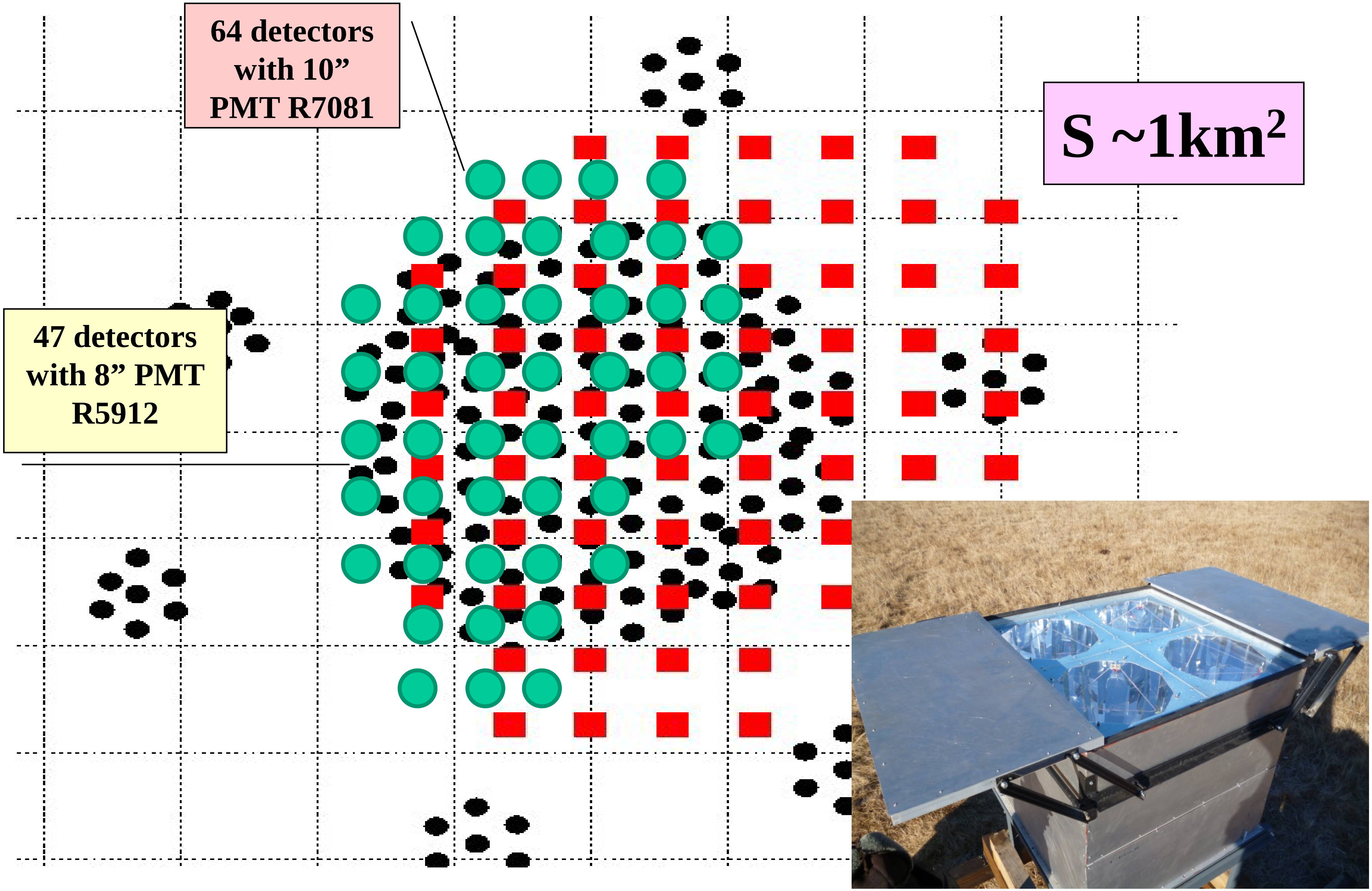
A system of ~ Ø 3-4m class IACT operating in conincidence with TUNKA-133 Tunka-HiSCORE and scintillation detectors.

Number of IACT – 16 (4 x 4)
Spacing ~330m
Covering an area of 1 km x 1 km
An energy range - TeV-EeV
Threshold energy ~ 2-3 TeV
Field of imaging cameras view of 8° x 8°
Pixel size -0.4°,
Number of cameras pixels – 400
Low cost



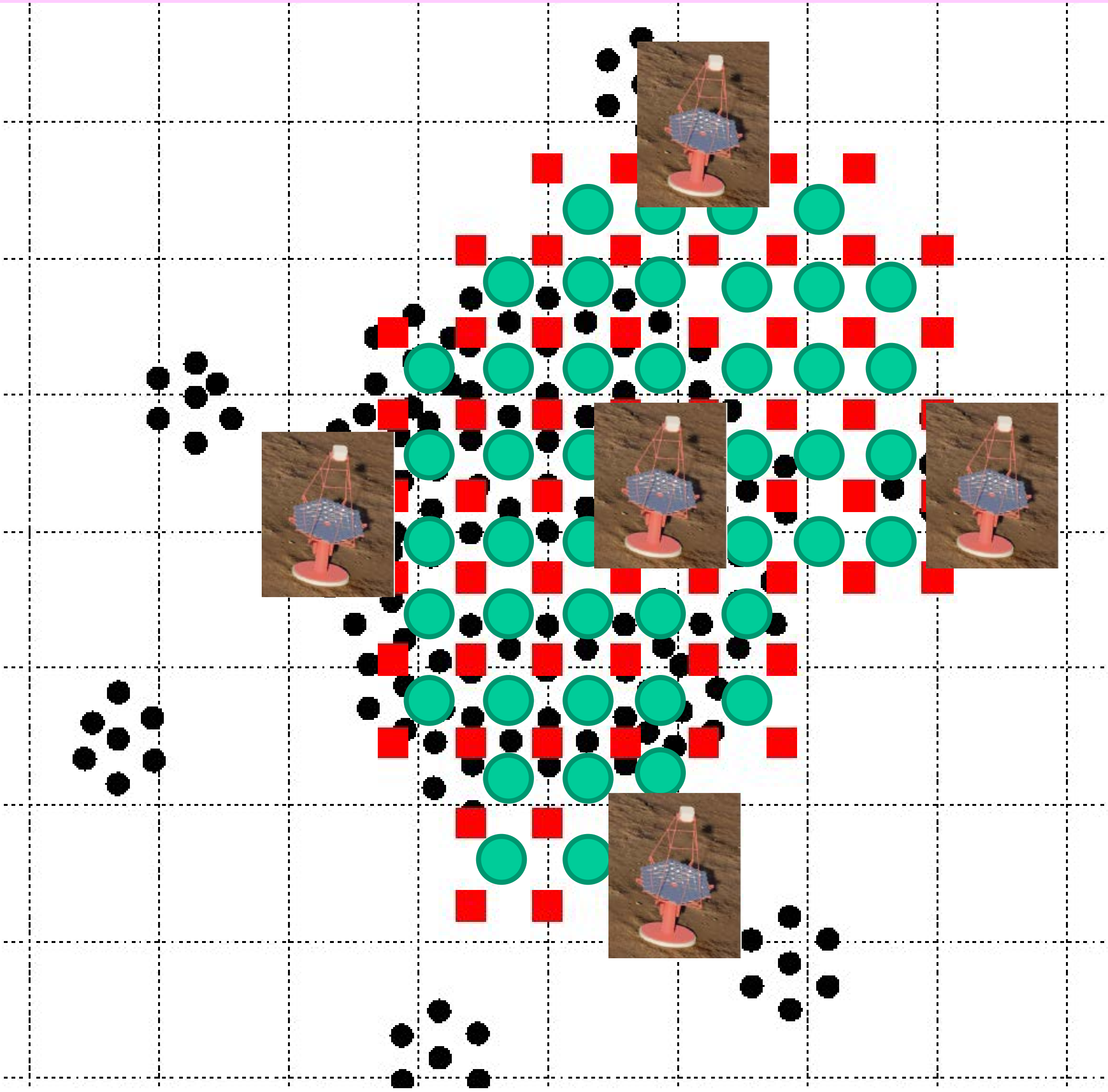
Howitzer D-30

Stage 2 (2014-2016 years): 111 wide angle Tunka-HiSCORE Cherenkov detectors

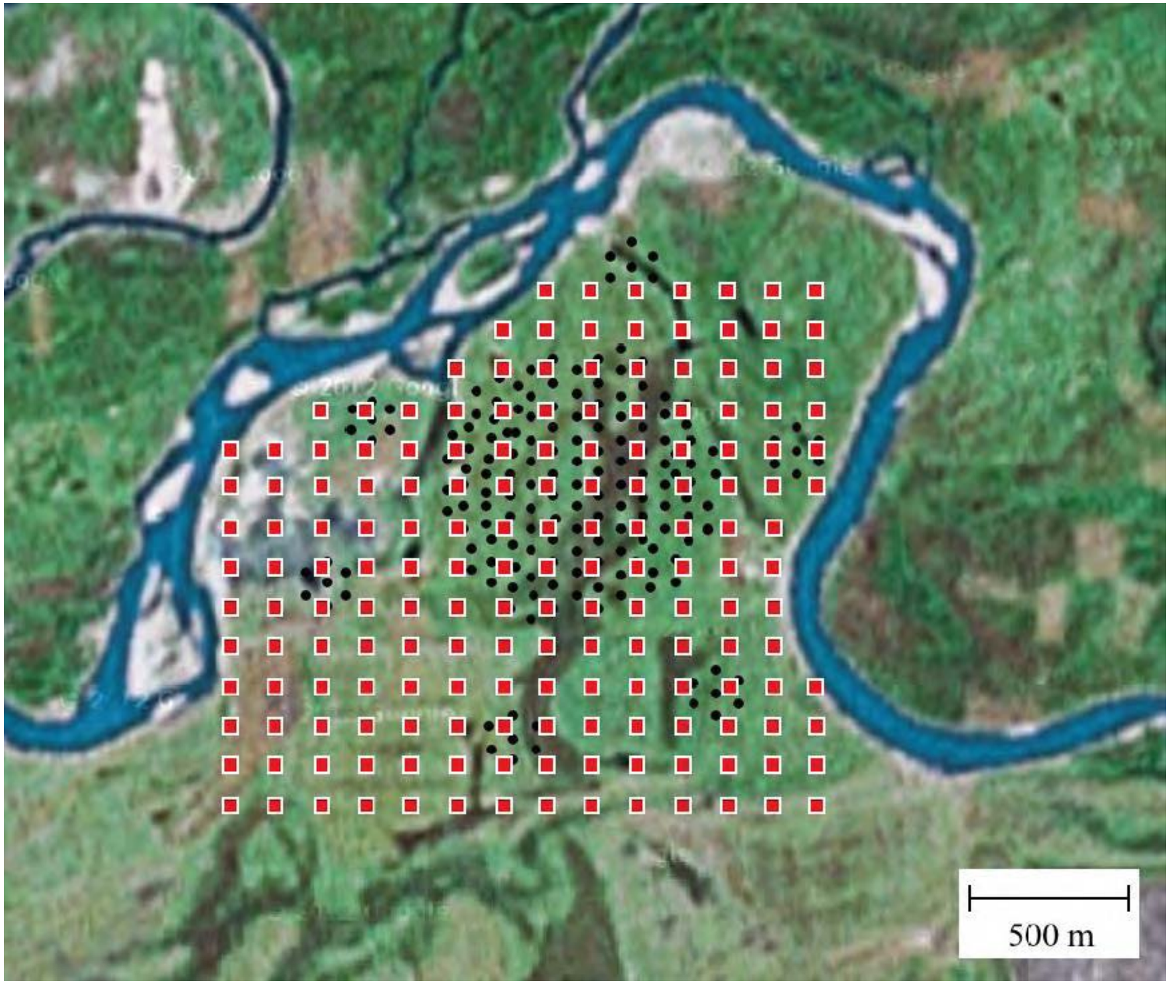


Stage 3 (2015-2018 years): net of wide angle Cherenkov detectors +

16 imaging telescopes (IACT) + 1000m^2 muon detectors



Stage 4 (2016-2020 years): toward to 10 km^2 gamma – observatory TAIGA



9 stations in October 2013

S=1 km^2, 64 stations, 150 m step, 240 PMTs (250 PMTs are available), 1 M Euro, 2013 – 2015

Decreasing of energy threshold

S = 1 km^2, +40 station with
160 PMT (10”) + 3-5 (?) mirrors
(S = 3 -5 m^2)
Cost: 2 M Euro.

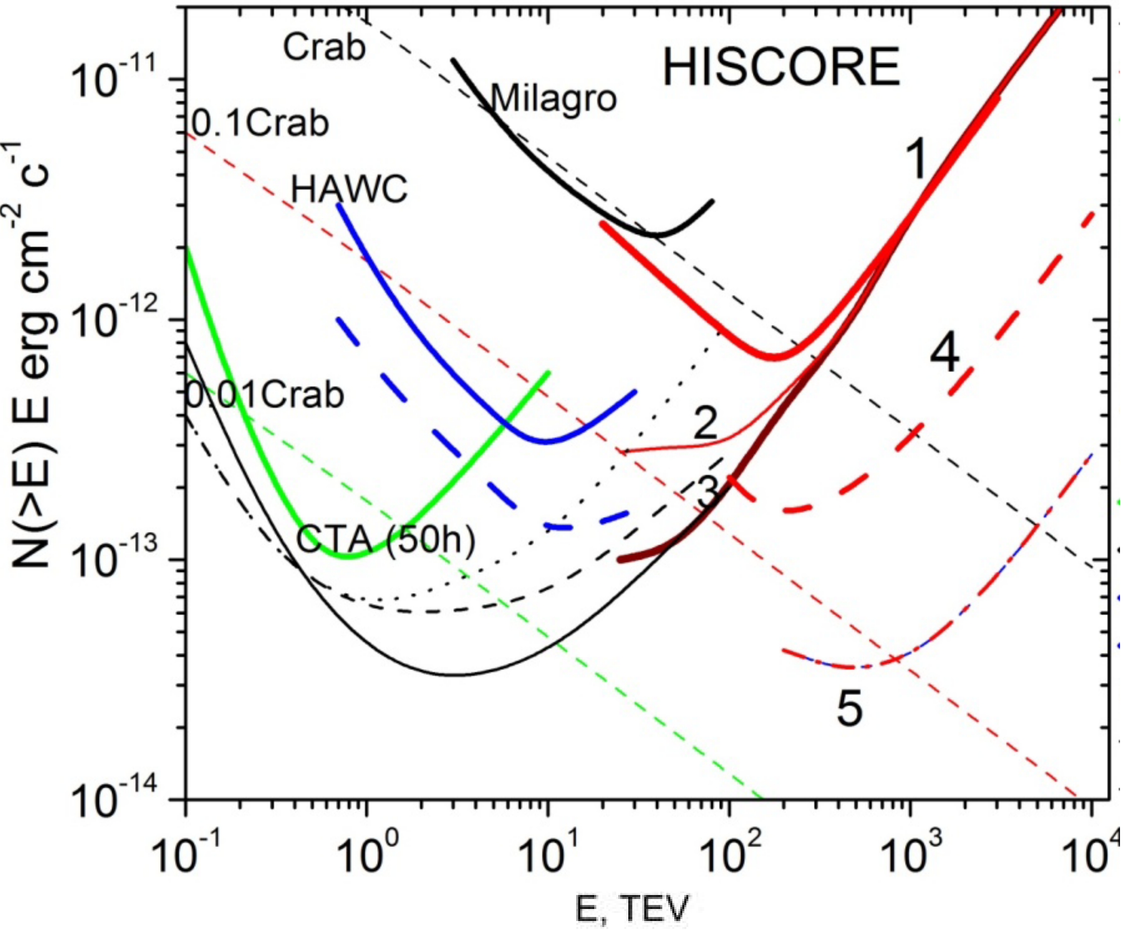
2014-2017

2016 -2020

2014-2018

Extension of the array up to 10 км^2

1000 m^2 scintillation detectors
(0.1% of the whole area)
– 2-5 muons from 250 TeV protons
Cost: 2.5-3 M Euro.



TAIGA:
50 events or 5 RMS,
T = 500 hours

LHAASO:
50 events or 5 RMS
1 year

CTA (2017-18) - ~400 Millions Euro (!)
LHAASO (2013-2018) ~150 Millions $

10 км^2 TAIGA (2013 – 2018) ~10 -12 Millions Euro

1 – 1 km^2, 4 PMTs per station (8” PMT)
2 – 1 km^2, + additional station (10” PMT)
3 – net of imaging telescopes
(very preliminary)

4 – 10 km^2 complex array
5 – 100 rm^2 complex array

Summary and outlook

1. **Cherenkov technique is very suitable way to study high energy cosmic rays as well gamma-rays, Tunka valley is one of the best place for construction of large Cherenkov arrays.**
2. **The structure of CR energy spectrum in the energy range of 10^{15} to 10^{18} eV were measured with high resolution. The second "knee" at energy ~$3\cdot10^{17}$ eV point out on transition from Galactic to extragalactic sources of CR.**
3. **The new gamma – observatory TAIGA will allow:**

- To perform search for local Galactic sources of gamma-quanta with energies more than 20-30 TeV (search for PeV-trons) and study gamma-radiation fluxes in the energy region higher than 20-30 TeV at the record level of sensitivity.

- To study energy spectrum and mass composition of cosmic rays in the energy range of $5\cdot10^{13}$ - 10^{18} eV at so far unprecedented level of statistics.

- To study high energy part of gamma-rays energy spectrum form the most bright balzars (absorption of gamma-quanta by intergalactic phone, search for axion-photon transition).

- Etc……………………..

Thank you!