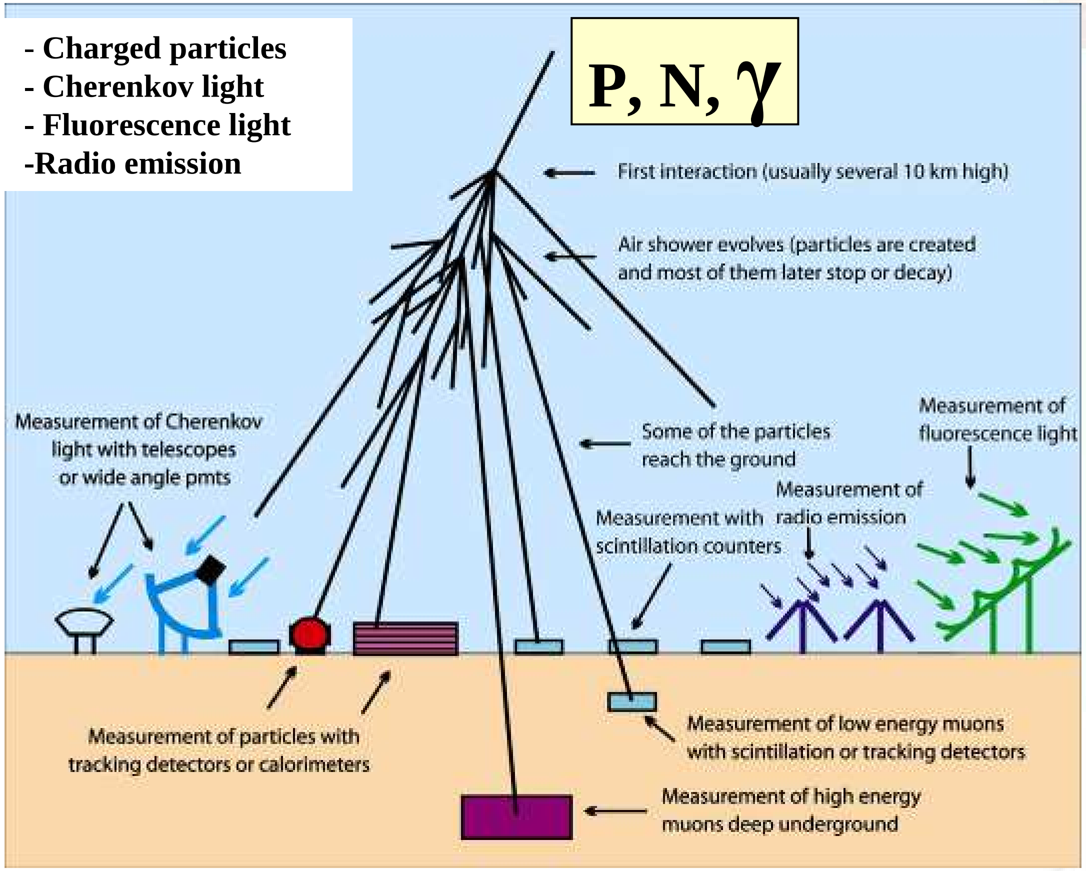
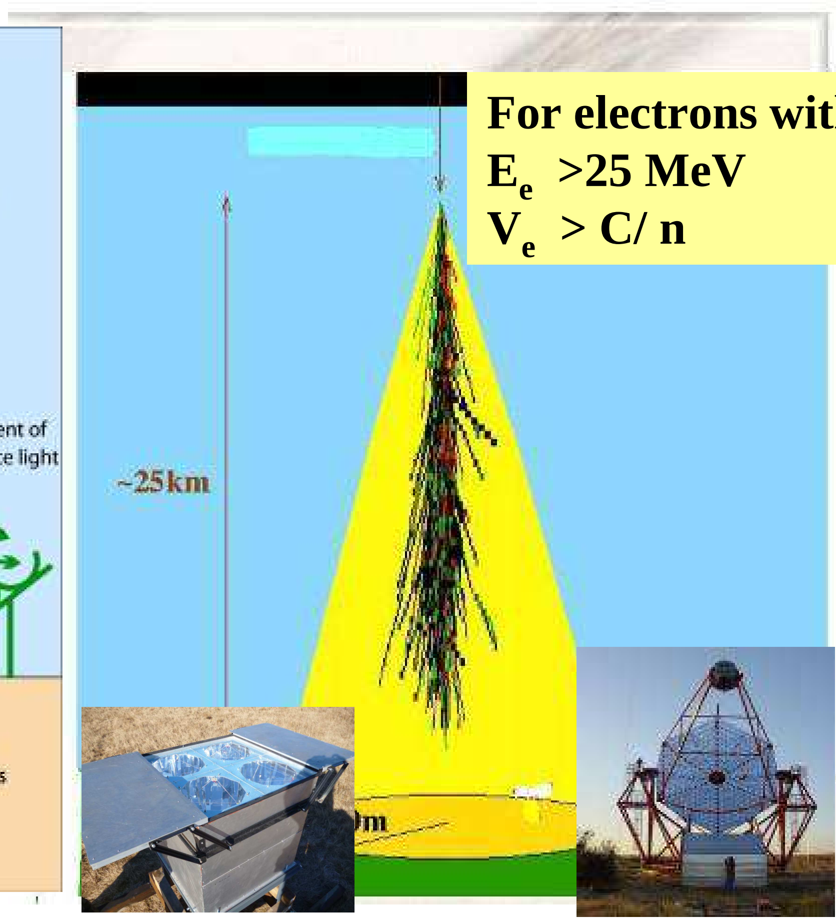
The Tunka experiment: from cosmic ray to gamma-ray astronomy.

N.Budnev, Irkutsk State University

For Tunka&TAIGA - collaboration

High energy charged particles and gamma – ray detections





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

Atmosphere as a huge calorimeter

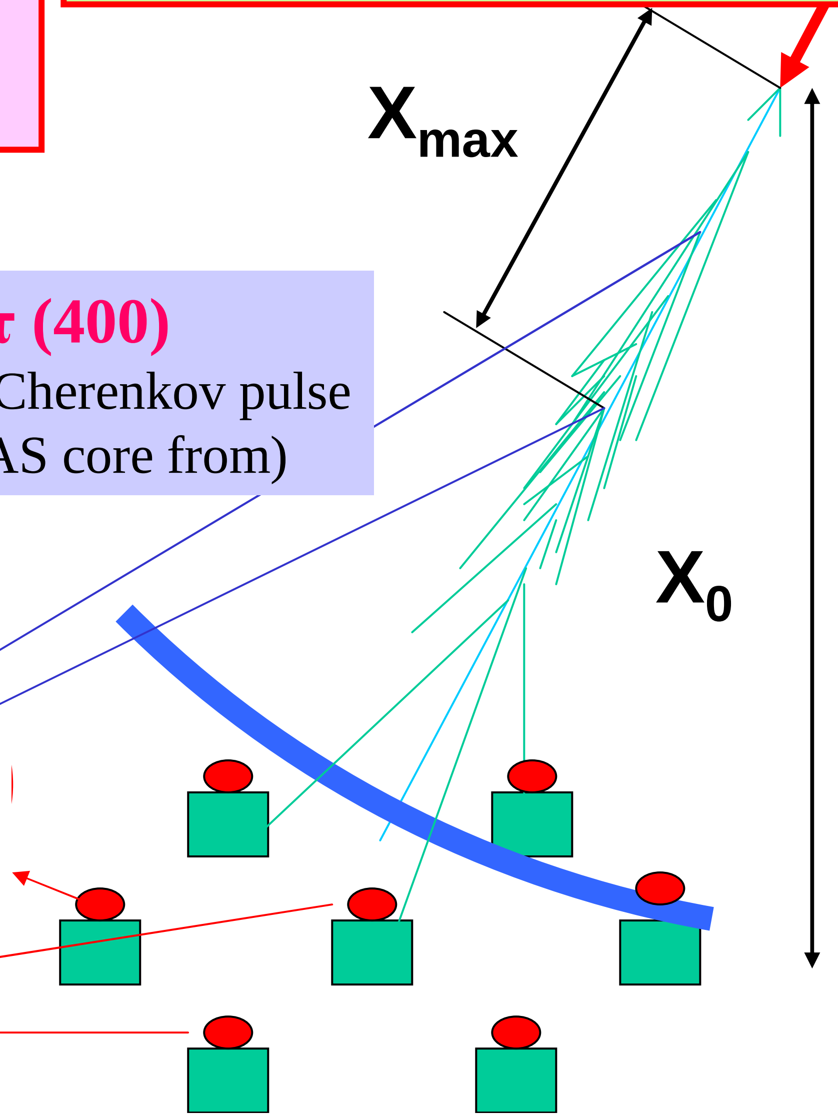
EAS Energy

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

Density of Cherenkov light at distance 200 m from core

$g = 0.94 \pm 0.01$ (for $10^{16} - 10^{18}$ eV)

EAS Cherenkov light wide-angle detection technique



Average CR mass A

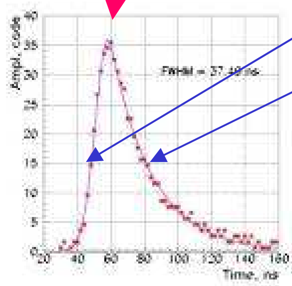
$LnA \sim X_{max}$

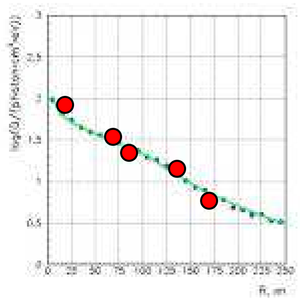
$X_{max} = C - D \cdot \lg \tau(400)$

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

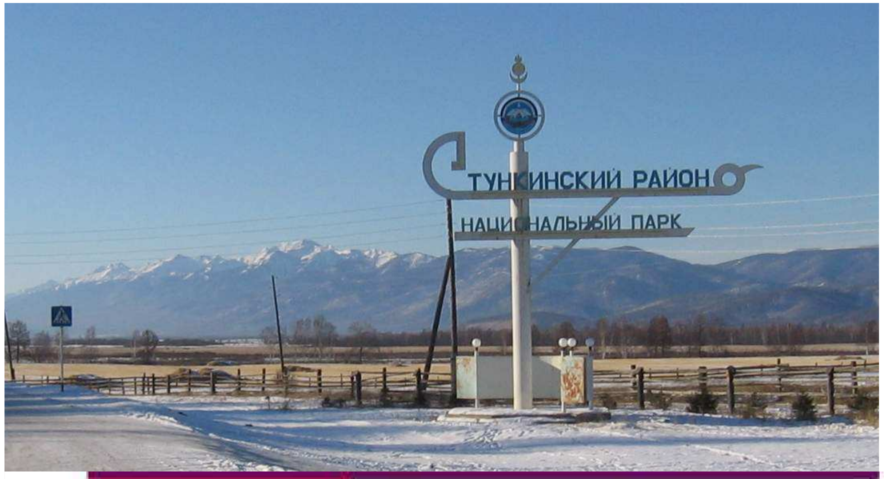
$X_{max} = F(P)$

P -Steepness of a Lateral Distribution Function (LDF)



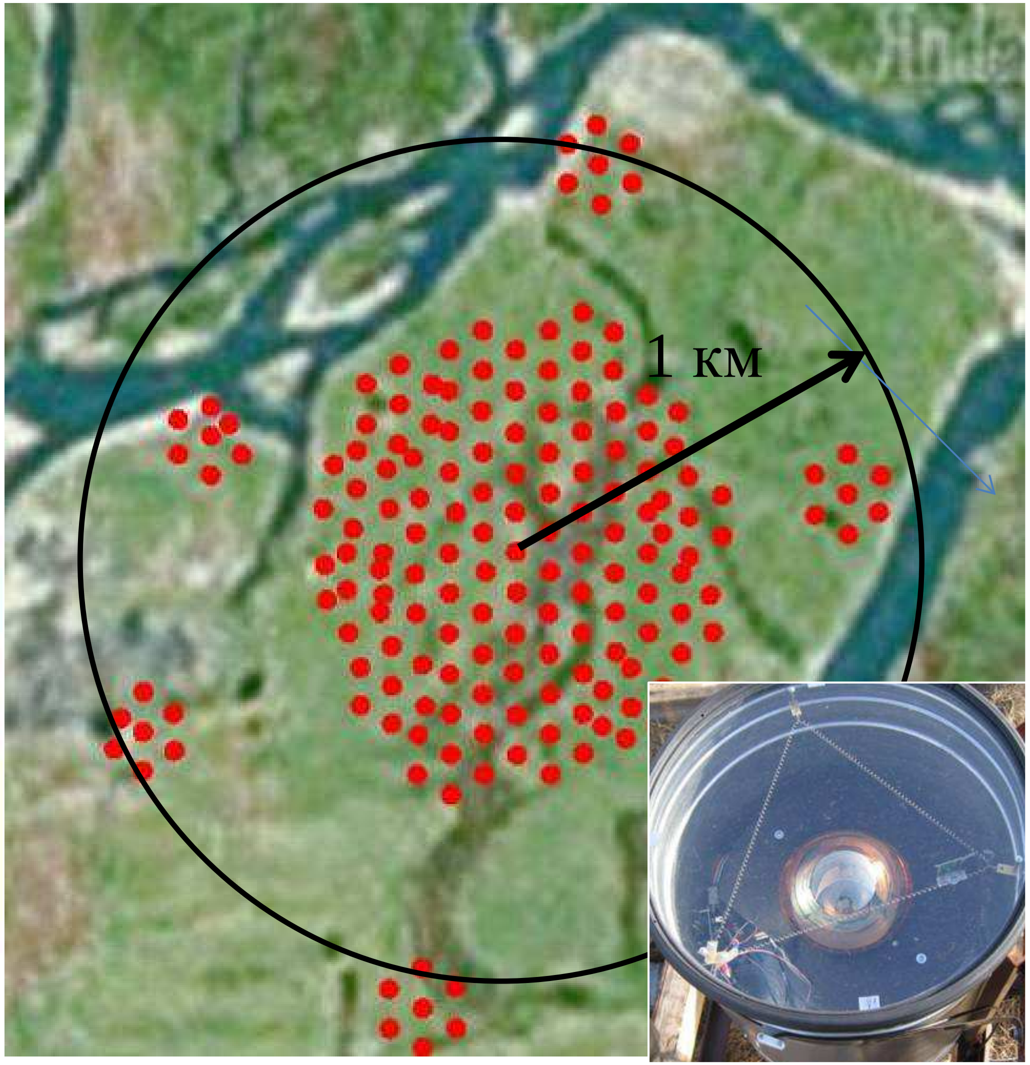


Tunka-133 array: 175 optical detectors distributed on 3 km^2 area



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

50 km from Lake Baikal



Tunka Collaboration

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Advantage of the Tunka-133 array:

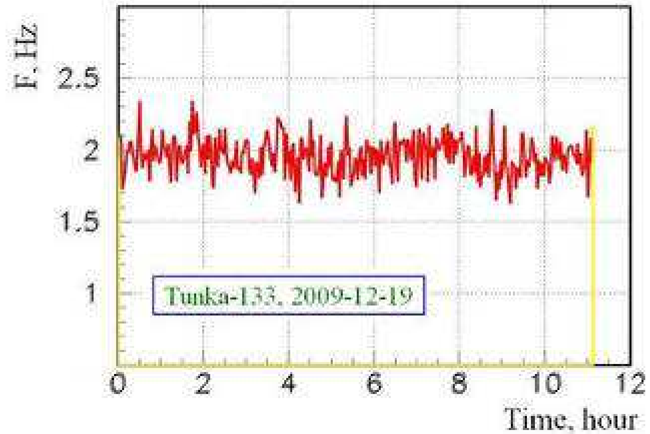
1. Good accuracy positioning EAS core (5 -10 m)
2. Good energy resolution (~15%, in principal up to - 5%)
2. Good accuracy of primary particle mass identification (accuracy of X_{max} measurement ~ 20 -25 g/cm^2
3. Good angular resolution ~0.1 – 0.3 deg
4. Low cost: **the Tunka-133 – 3 km^2 array ~ 10^6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

Disadvantage:

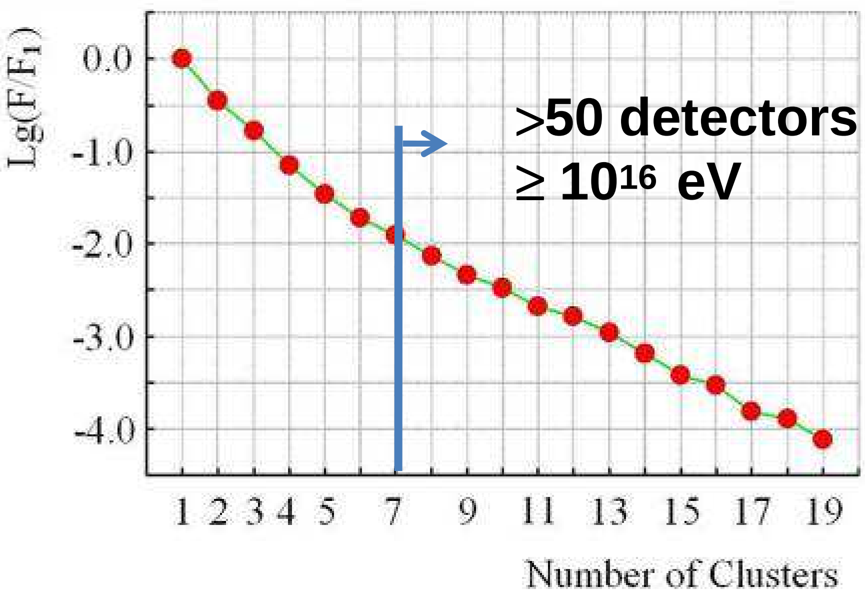
Short time of operation (moonless, cloudless nights) – 5-10%

Five seasons of Tunka-133 array operation

1540 h of good weather for observation with a trigger frequency ~ 2 Hz
10 000 000 events
> 12 000 events with an energy ≥ 50 PэB
> 3000 events with an energy ≥ 100 PэB.



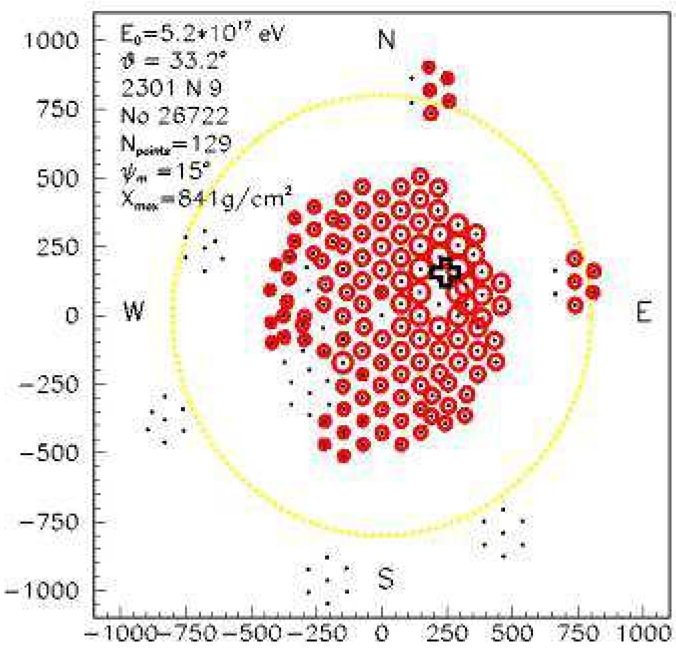
Trigger counting rate during one night .



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

Distribution of the number of hitted clusters in an event.

An event example



Hitted detectors

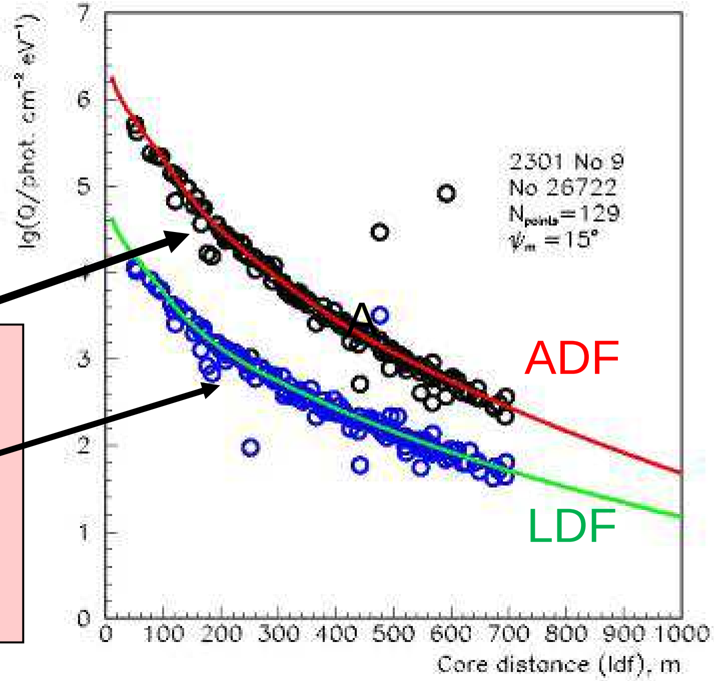
ADF

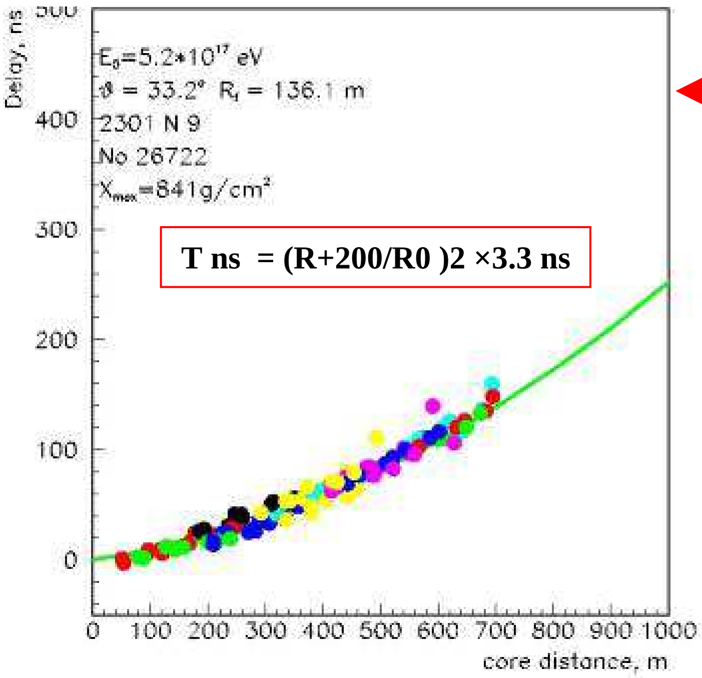
Amplitude distant function

&

LDF

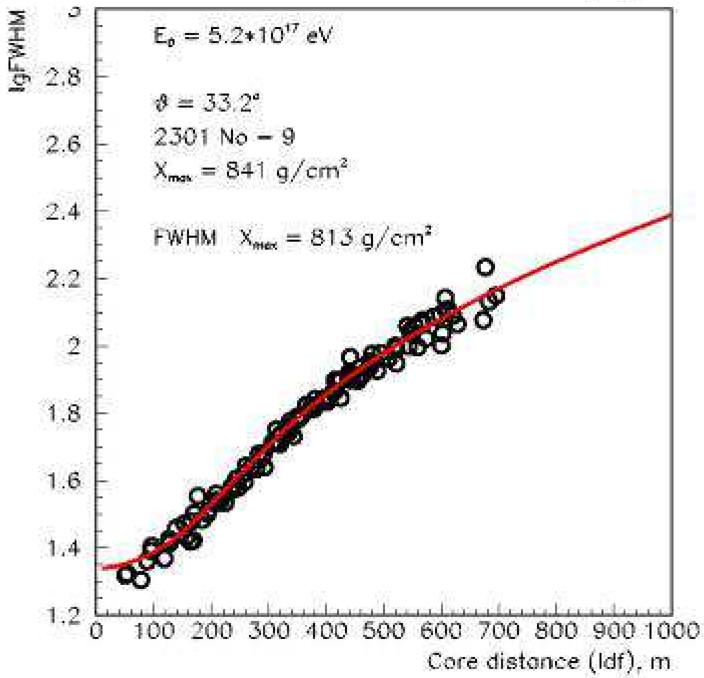
Lateral Distribution function



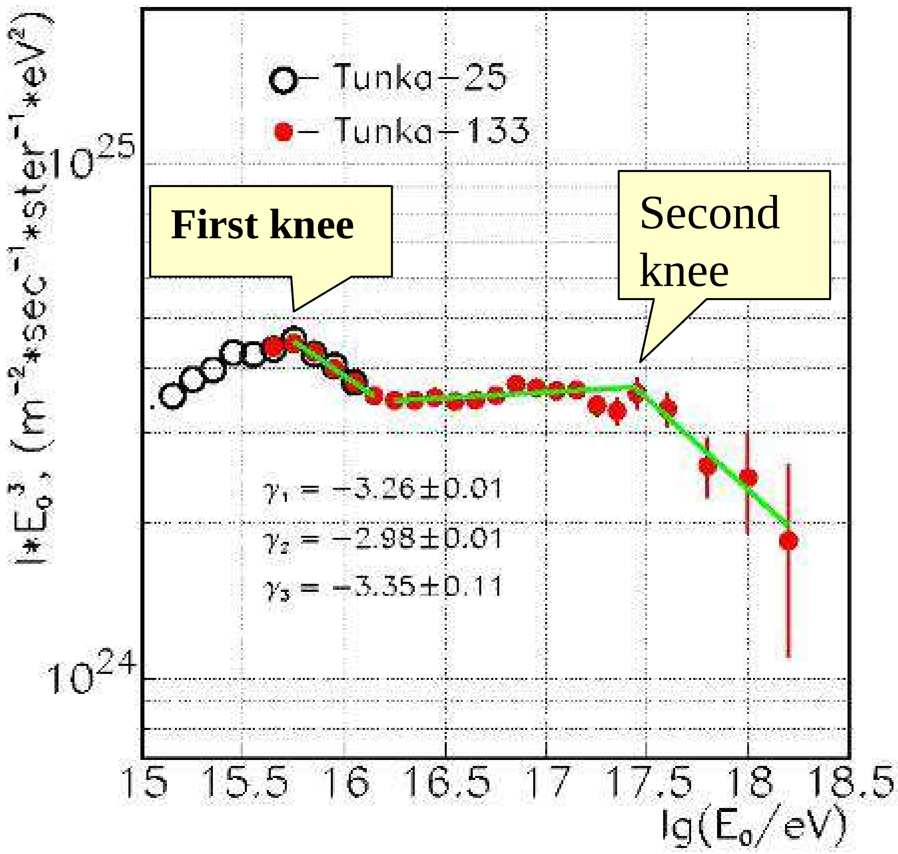


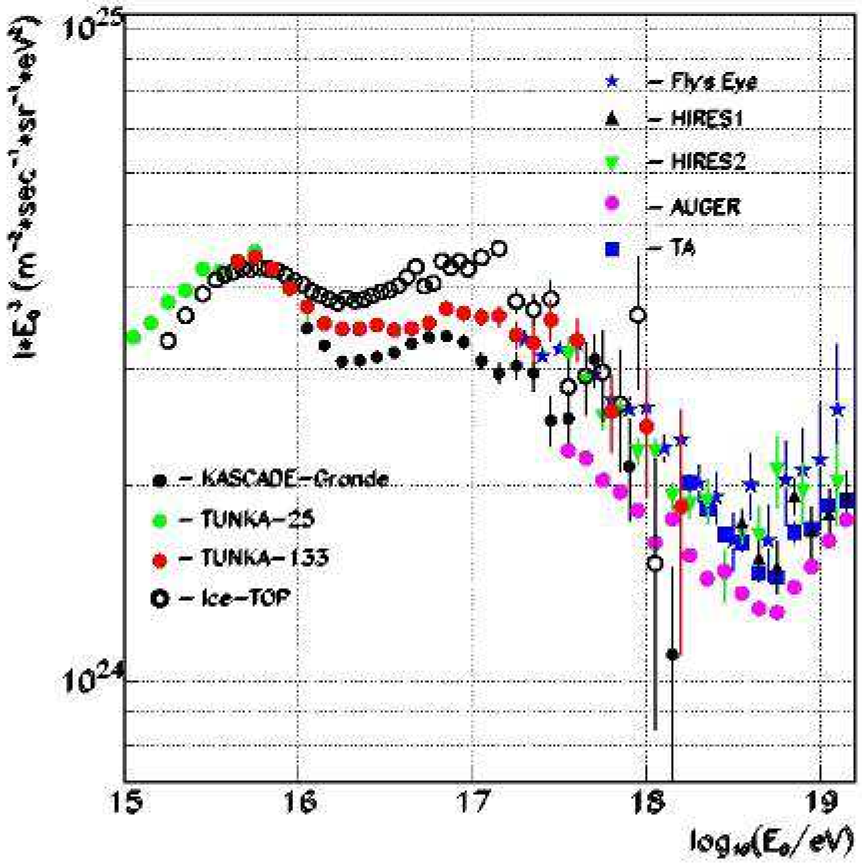
Delay time vs. Distance from core

WDF – width distant function

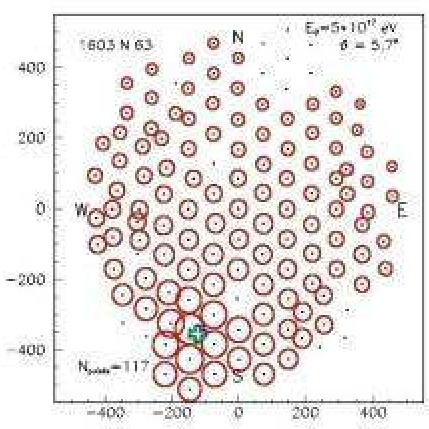


The all particles energy spectrum $I(E)\cdot E^3$





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..

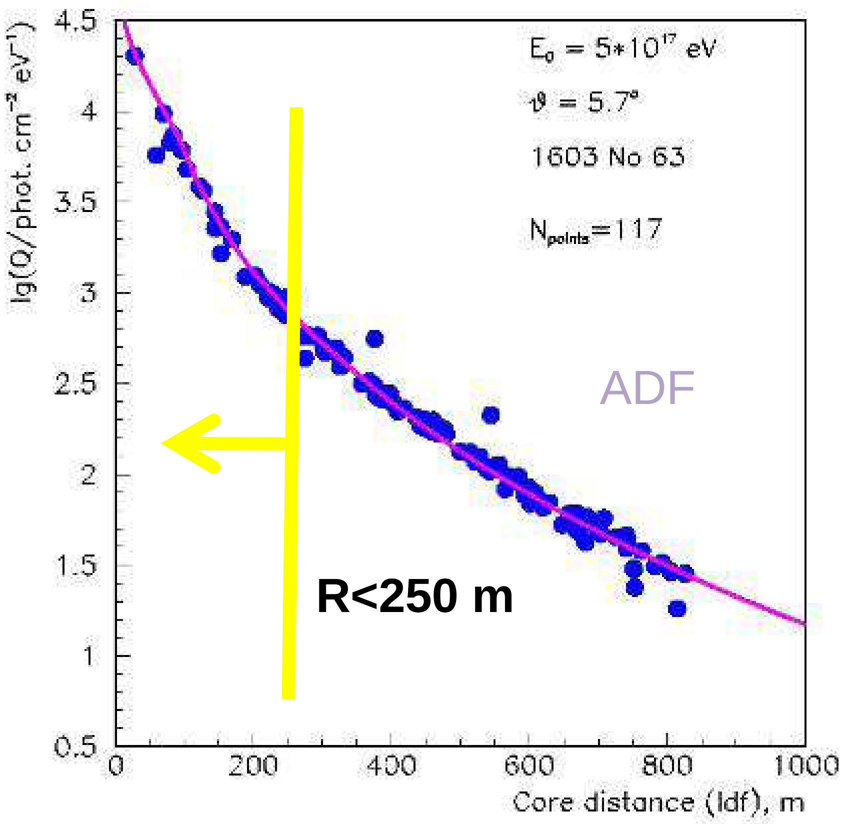


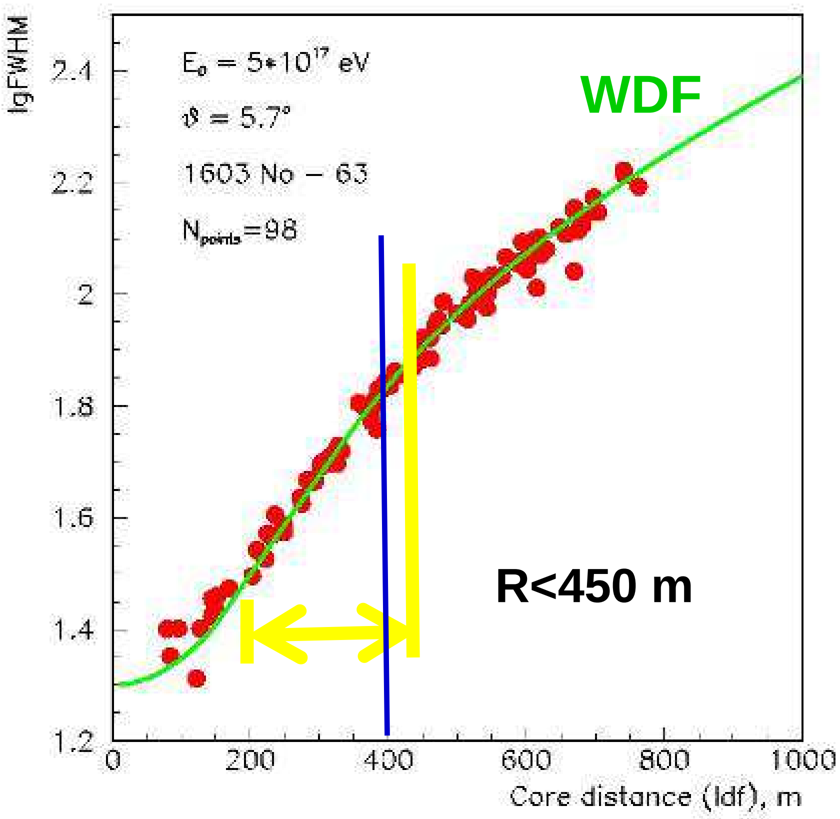
Mass composition: two methods of X_{max} measurement:

$\Delta X_{max} \leq 25$ g·cm^{-2}

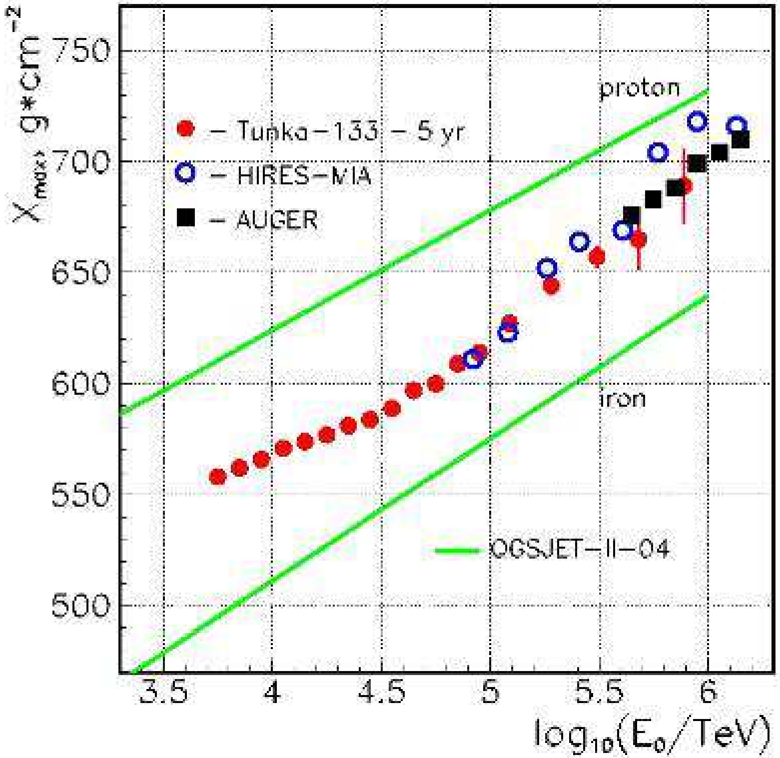
ADF steepness: $\mathbf{b_A}$

Pulse width at core distance 400 m: $\boldsymbol{\tau_{eff}(400)}$

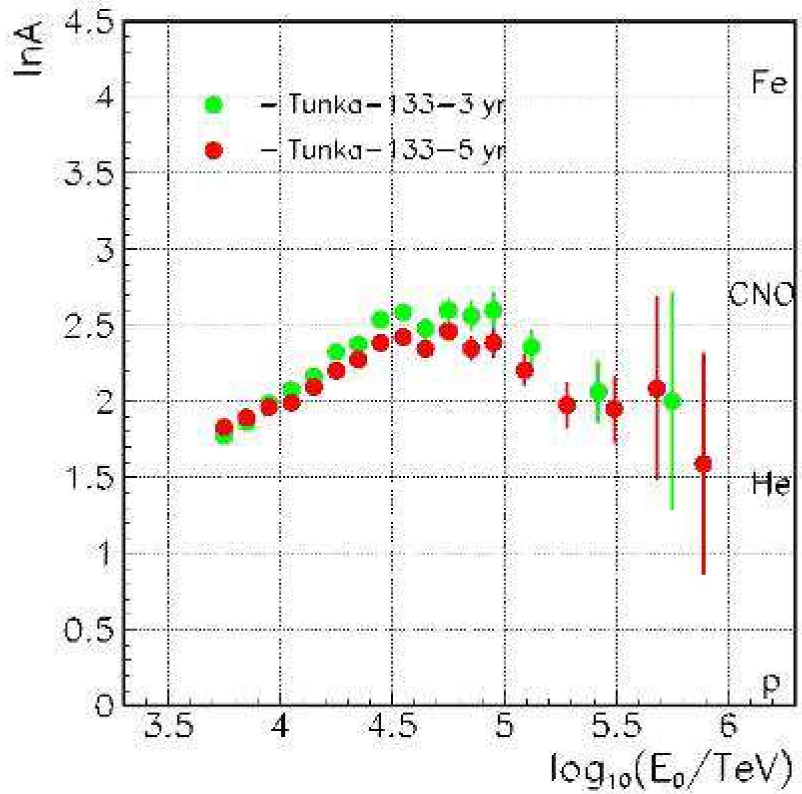




Mean Depth of EAS maximum X_{max} g·cm^{-2}

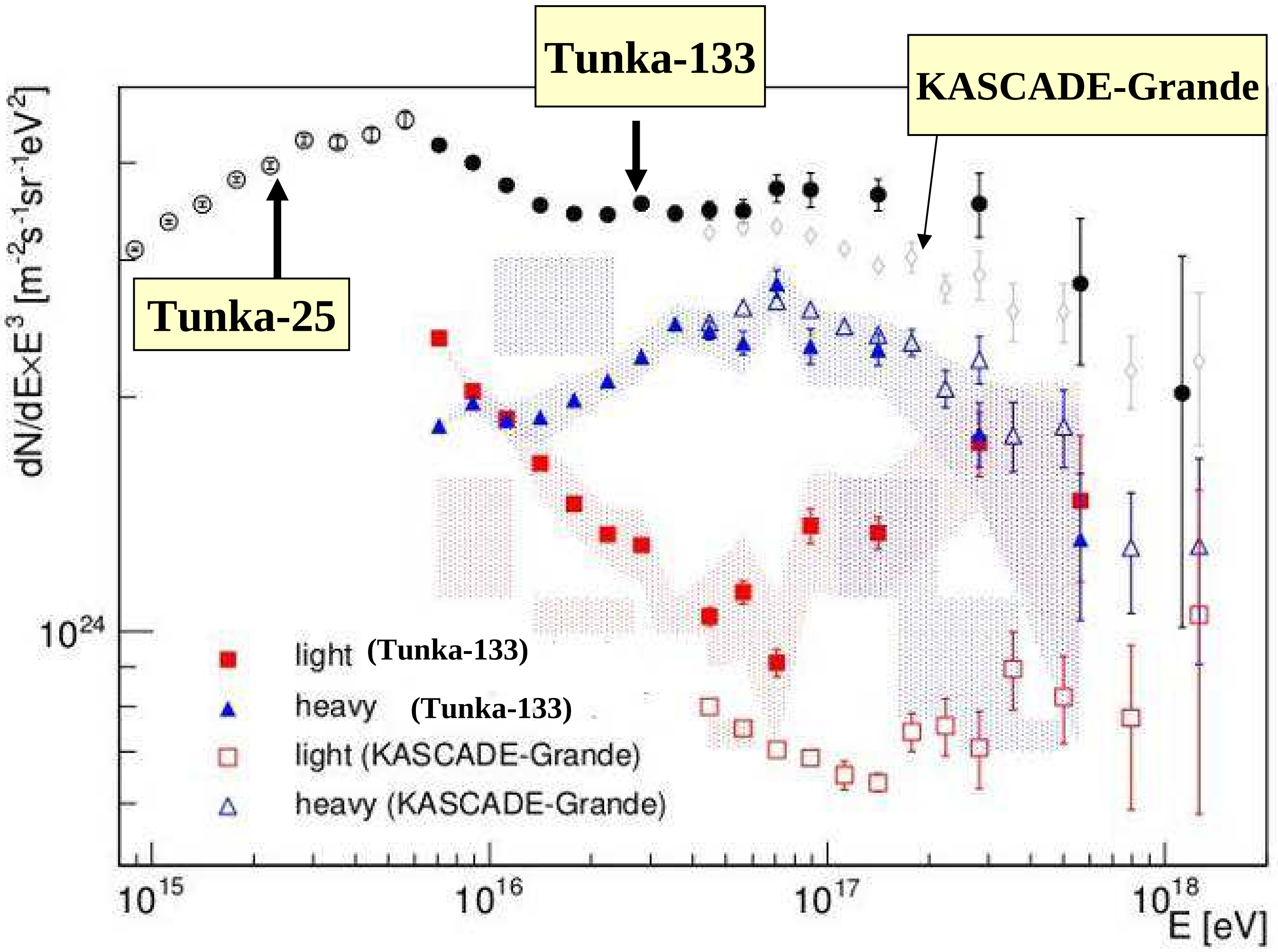


Mean logarithm of primary mass.



1. The Xmax do not contradict to that of HiRes-MIA and Auger data.
2. CR composition changes to heavy from 10 PeV to 30 PeV and changes back to light in the range 100 – 1000 PeV.

Spectra of light (p+He) and heavy (all other) CR components



Towards High Energy Gamma-Ray Astronomy array at Tunka Valley

TAIGA – Tunka Advanced Instrument for cosmic rays and Gamma Astronomy – 5 arrays

=

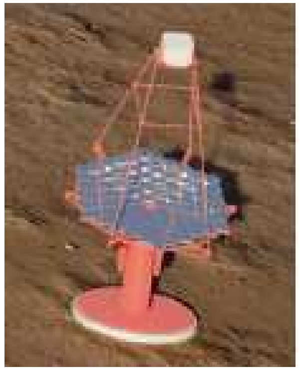
Tunka-133

+

Tunka-Rex

+

+



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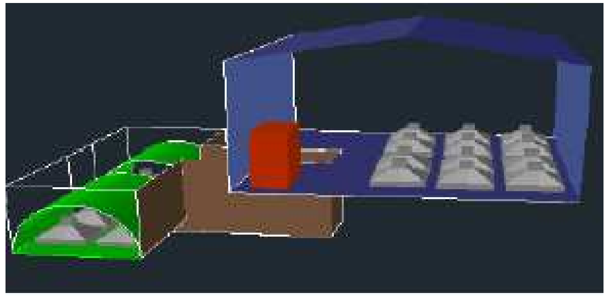


Tunka-HiSCORE array -net of non imaging wide-angle optical stations

Shower front and LDF sampling technique for core position and energy reconstruction.

Angular resolution – 0.1 deg,

Xmax measurement for hadron rejection.

Tunka-IACT array -net of Imaging Atmospheric Cherenkov Telescopes with mirrors - 4 m diameter about.

charged particle rejection using imaging technique.

Tunka – Grande array net of scintillation detectors, including underground muon Detectors with area - 10^2 → $2\ 10^3$ m^2 area

charged particle rejection.

From Tunka-Collaboration to TAIGA-Collaboration

Germany

Hamburg University(Hamburg)
DESY (Zeuthen)
MPI (Munich)
KIT (Karlsruhe)
Humbolt University (Berlin)

ITALY

Torino University (Torino)

Russia

MSU(SINP)(Moscow)
ISU (API) (Irkutsk)
JINR (Dubna)
IZMIRAN (Moscow)
INR RAS (Moscow)
MEPHI (Moscow)
Kurchatov Institute (Moscow)
IPSM(Ulan-Ude)

Main Topics for TAIGA

Gamma-ray Astronomy

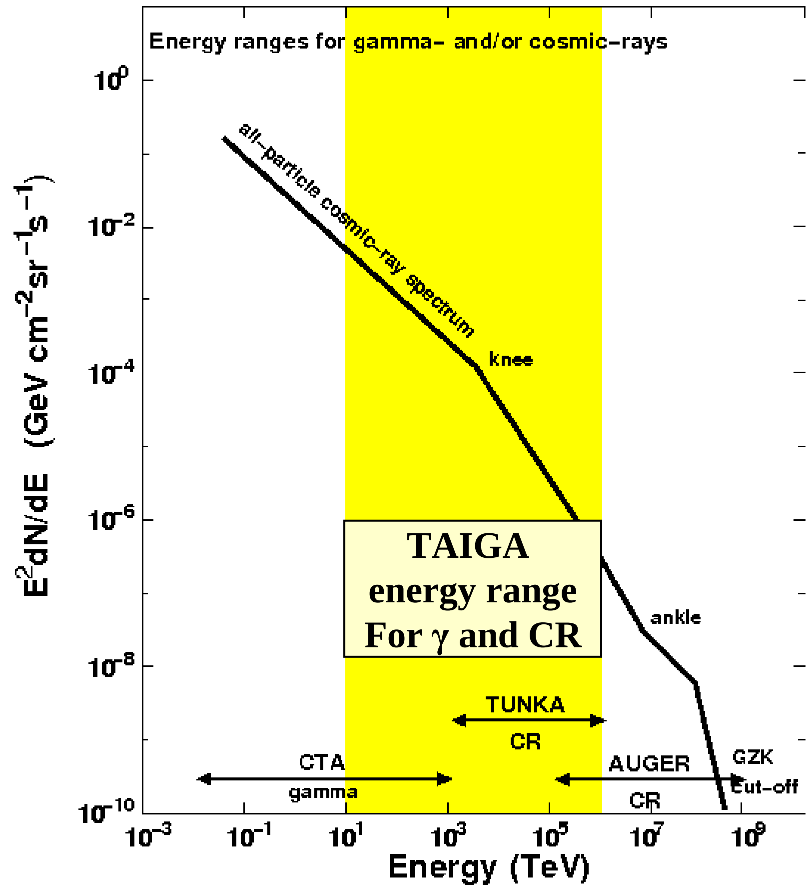
Search for the PeVatrons.
VHE spectra of known sources: where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition anisotropies from 10^{14} to10^{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.



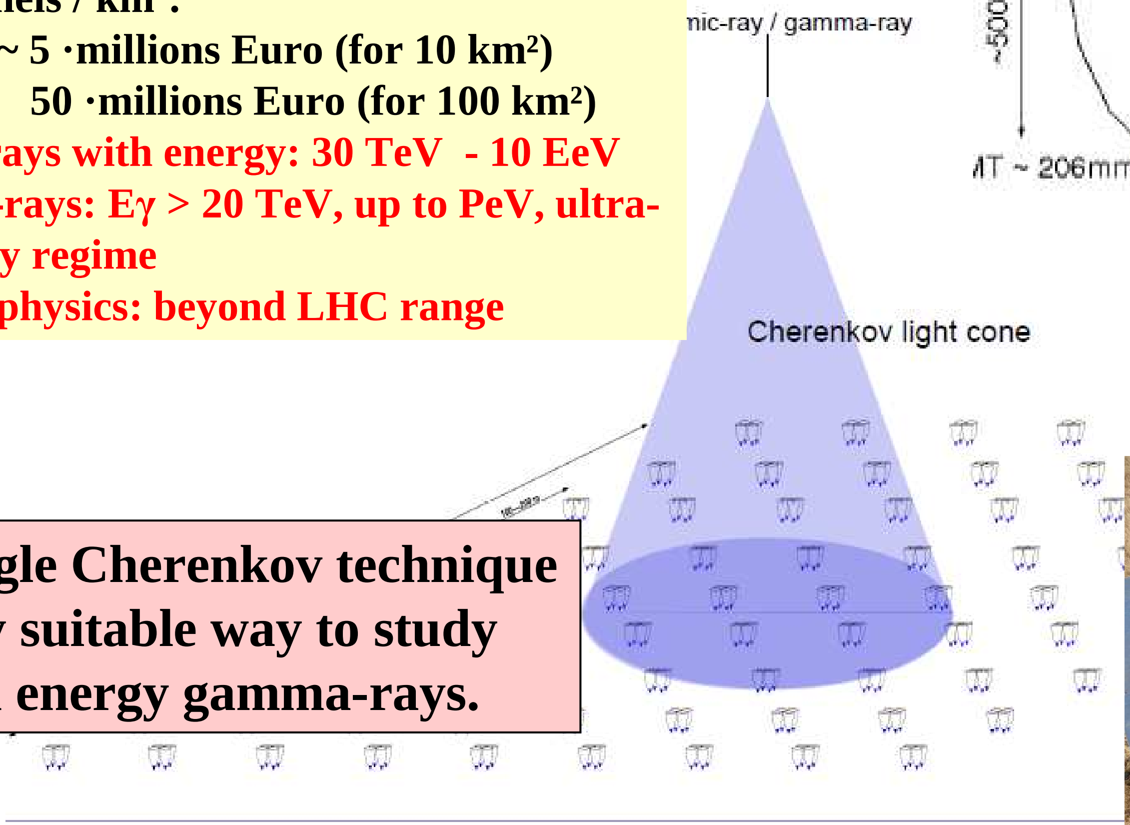
Observation time for some gamma sources per one year with TAIGA array (short list)

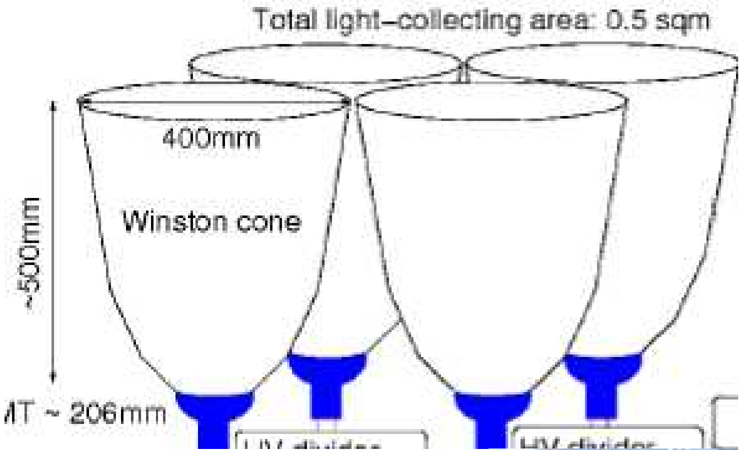
Name	RA degrees	Decl	Flux F at 1 TeV, $10^{-12}cm^{-2}\ s^{1}TeV^{-1}$ Γ	Flux F at 35 TeV, $10^{-17}cm^{-2}\ s^{-1}TeV^{-1}$ (from Milagro)	Time of observation per one year (x 0.5- weater factor)
Tycho SNR (J0025+641)	6.359	64.13	0.17 ±0.05 Γ=1.95 ±0.5		**236h**
Crab	83.6329	22.0145	32.6 ±.9.0 Γ=2.6 ±0.3	162.6 ±9.4	**110h**,
SNR IC443 (MAGIC J0616+225)	94.1792	22.5300	0.58 ±0.12 Γ=3.1 ±0.30	28.8 ±9.5	**112h**,
Geminga MGRO C3 PSR	98.50	17.76		37.7 ±10.7	**102h**,
M82 (Starburst Galaxy)	148.7	69.7	0.25 ±0.12 Γ=2.5 ±0.6±0.2		**325h,**
Mkn 421 (BL, z=0.031 Variable)	166.114	38.2088	50-200 Γ=2.0-2.6		**140h**
SNR 106.6+2.7 (J2229.0+6114)	337.26	61.34	1.42 ±0.33 ±0.41 Γ=2.29 ±0.33 ±0.30	70.9 ±10.8	**167h**
Cas A (SNR, G111.7-2.1)[6]	350.853	58.8154	1.26 ±0.18 Γ=2.61 ±0.24±0.2		**177h**
CTA_1(SNR,PWN)	1.5	72.8	1.3 Γ=2.3		**266 h**

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

Non-imaging air Cherenkov array
Angular resolution : ~ 0.1 degree
Large Field of view (FOV): ~ 0.6 sr
Area: from 1 km^2 ⟹ 100 km^2
Spacing between Cherenkov stations 100-200m
~200 channels / km^2.
Total cost ~ 5 ·millions Euro (for 10 km^2)
50 ·millions Euro (for 100 km^2)

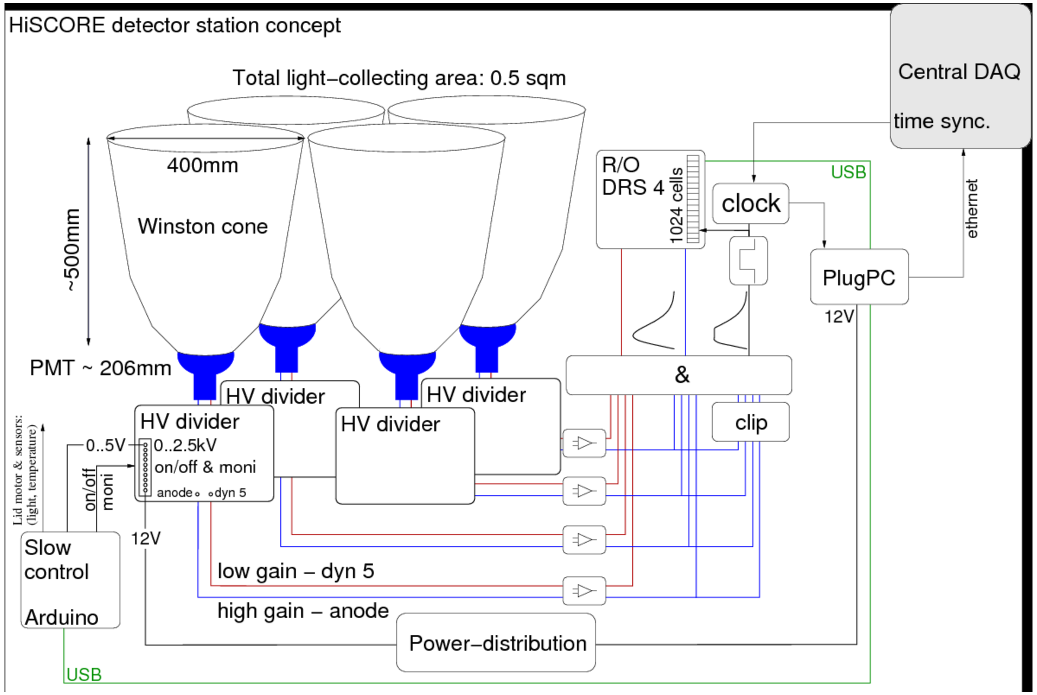
- **Cosmic-rays with energy: 30 TeV - 10 EeV**
- **Gamma-rays: Eγ > 20 TeV, up to PeV, ultra-high energy regime**
- **Particle physics: beyond LHC range**

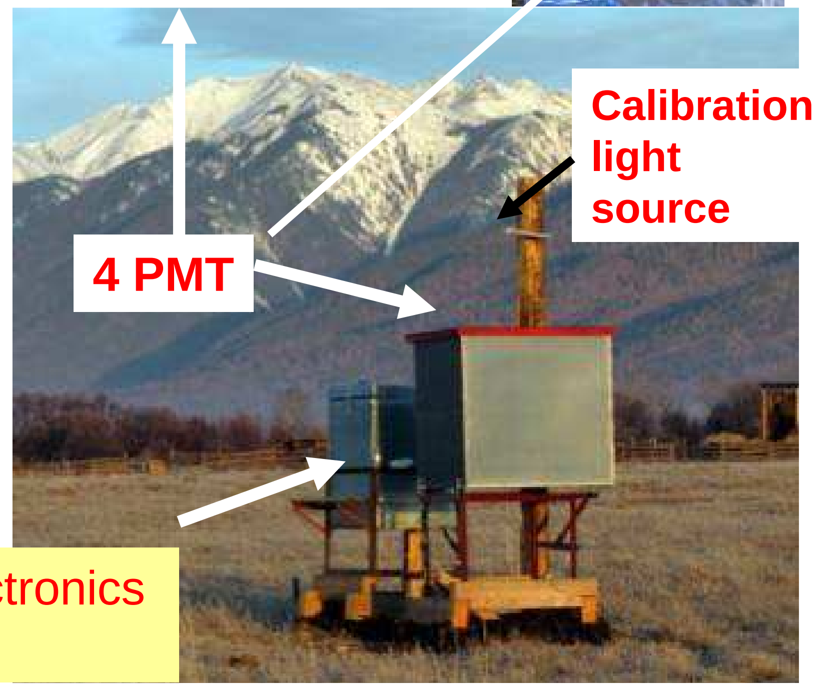




Wide-angle Cherenkov technique is very suitable way to study high energy gamma-rays.

Tunka-HiSCORE Cherenkov detector





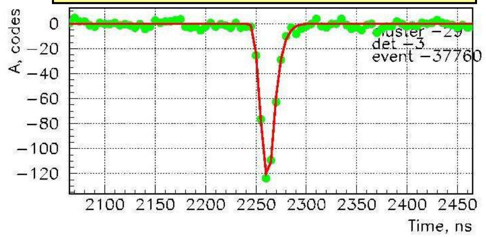
Calibration light source

4 PMT

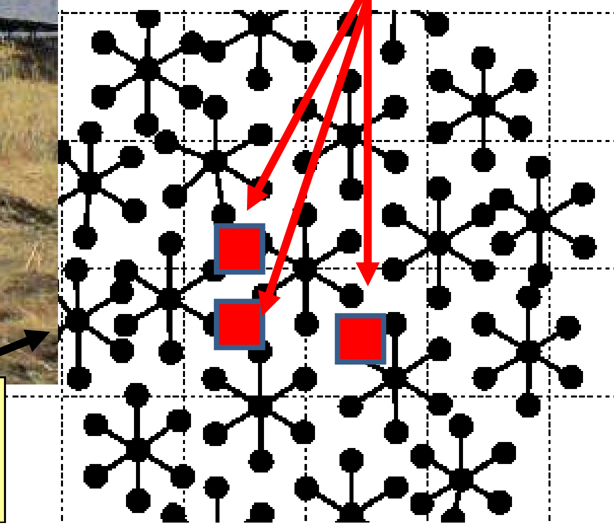
Electronics box

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

Signal from Tunka -HiSCORE



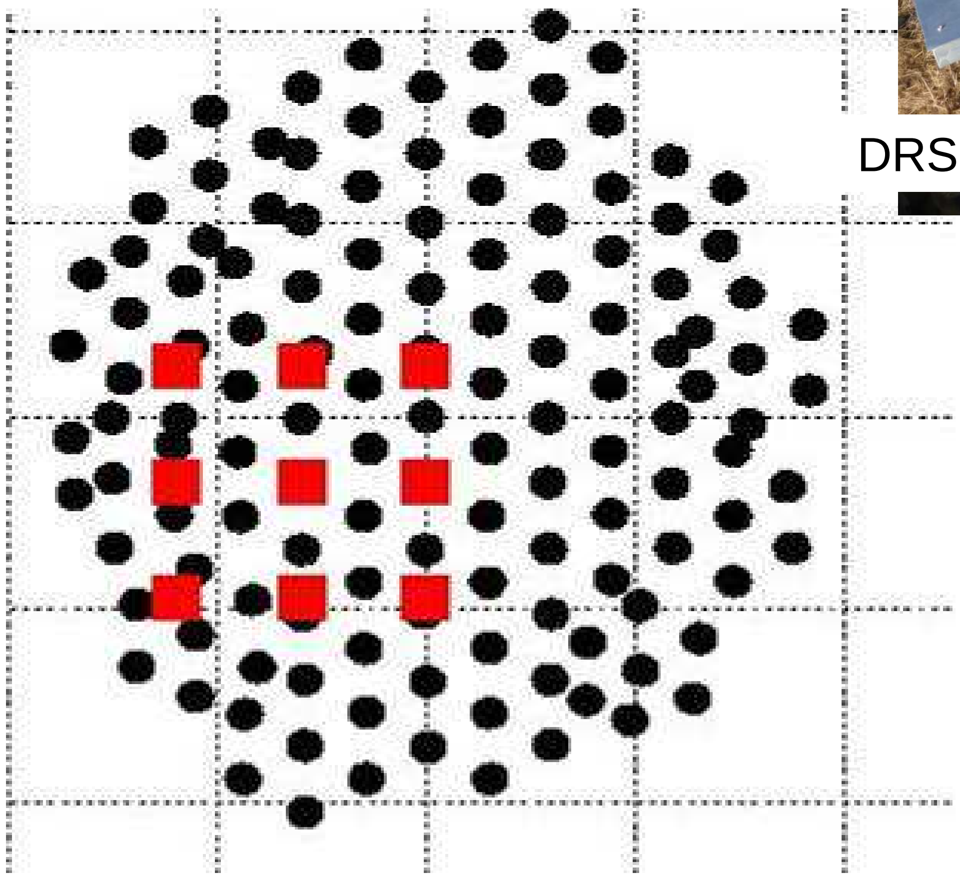
New Tunka -HiSCORE

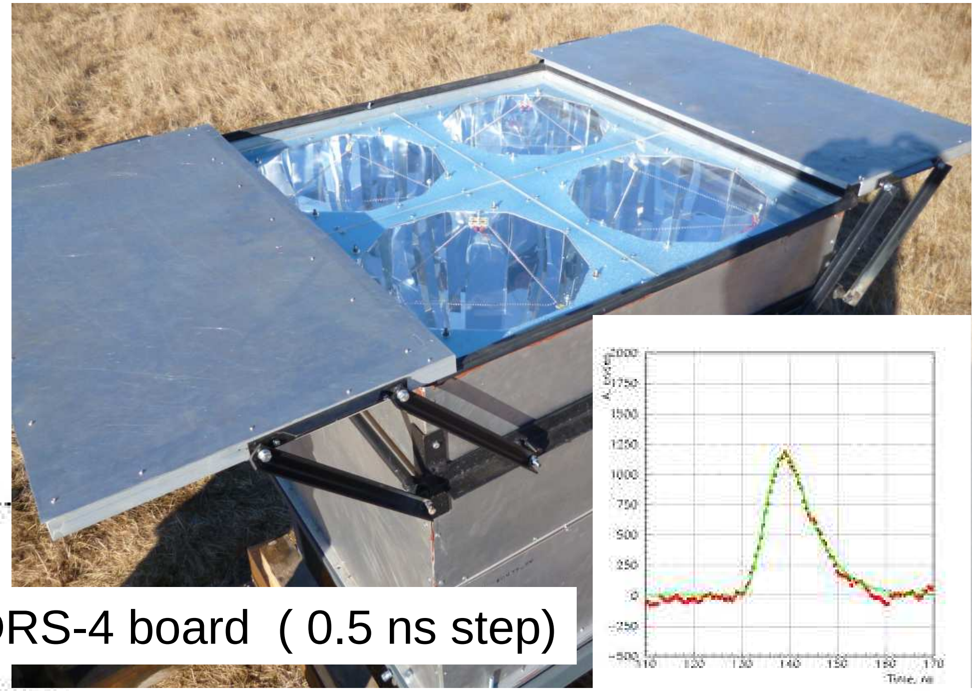


Cherenkov detectors of Tunka-133 array

October 2013
Prototype of Tunka-HiSCORE
9 Cherenkov stations

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





DRS-4 board (0.5 ns step)

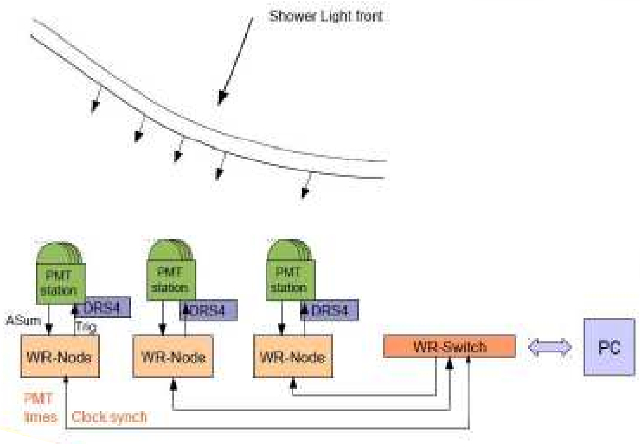
For $E_0 > 3 \cdot 10^{15}$ eV:

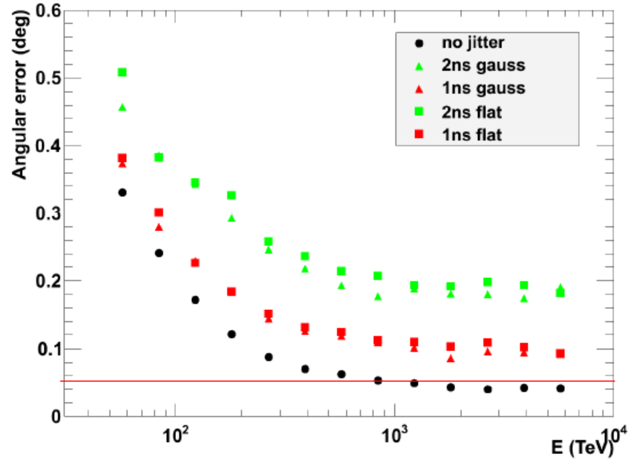
Arrival direction difference –
$\Delta\psi < 0.5°$

EAS core coordinate difference –
$\Delta X < 7$ m, $\Delta Y < 7$ m

LogE0 difference –
$\Delta lgE0 < 0.051$ (1 2%)

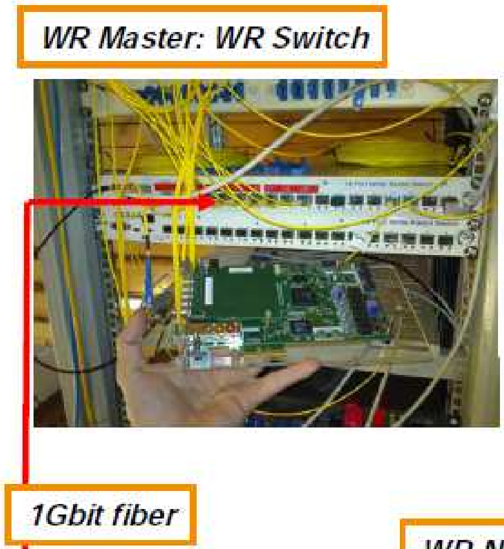
- Tunka-HiSCORE:
- "see N.Budnev (previous talk), and M.Tluczykont (plenary)
  - Ground array detector
  - Stations spacing ~150m over 1-100 km^2
  - nsec-time resolution between stations needed for optimal EAS-pointing
- MC simulations:
  - angular resolution degrades for >1nsec time resolution

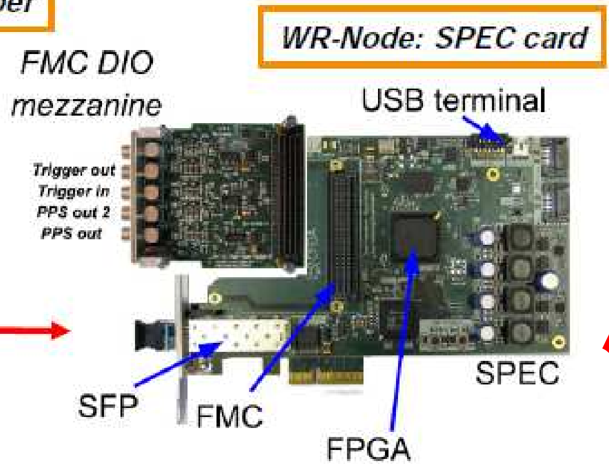


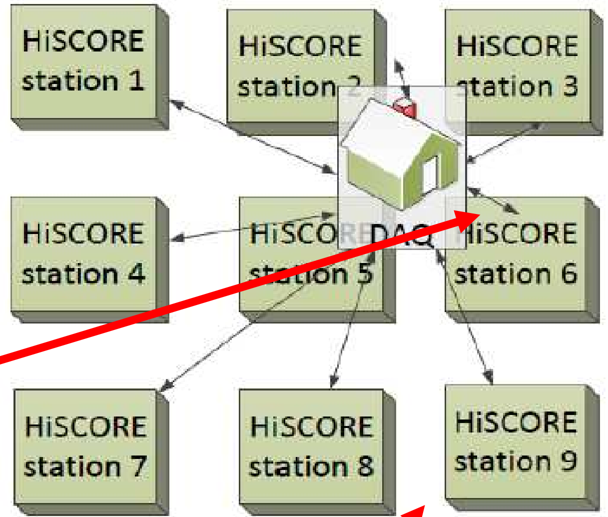


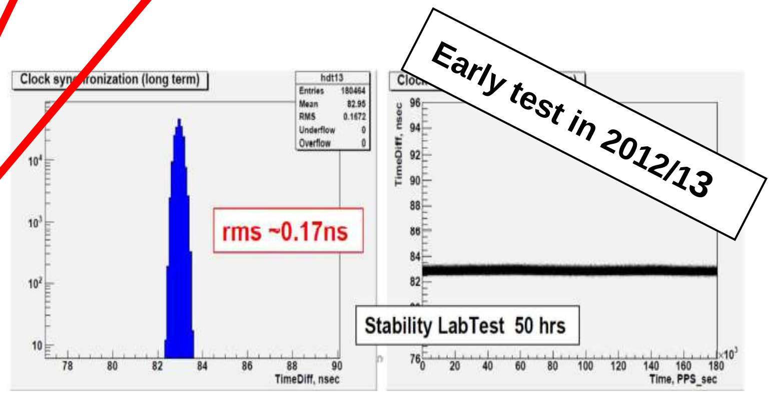
- **A distributed DAQ system for the HiSCORE detector based on the WhiteRabbit (WR) timing system has been developed in order to achive a sub-ns time resolution**

- **WR main components**

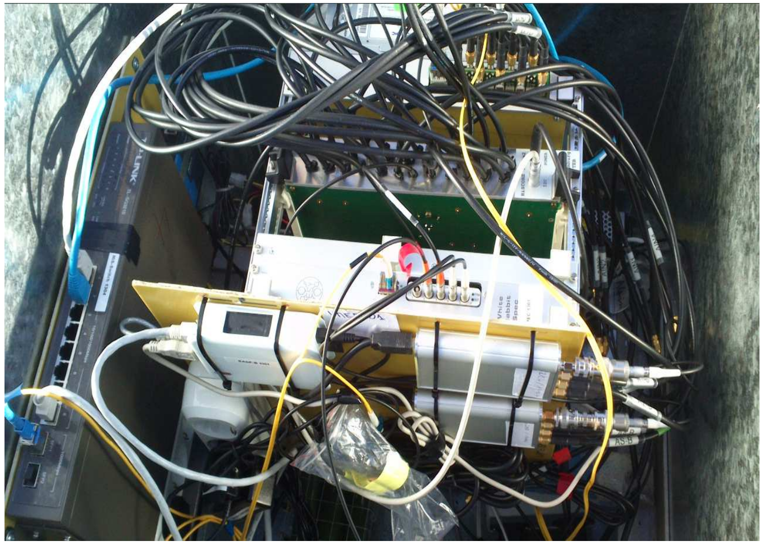


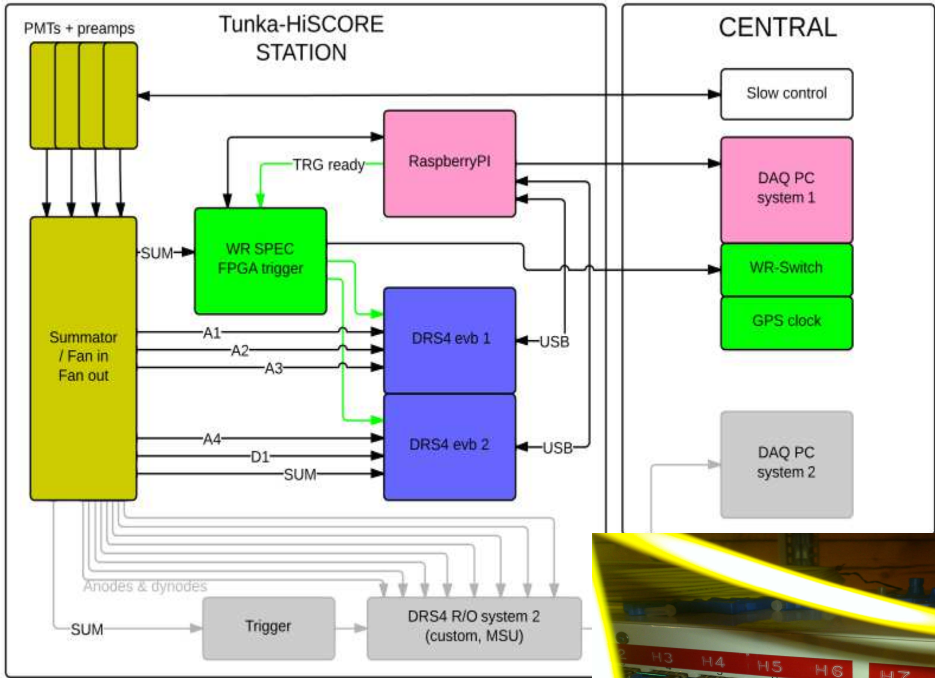


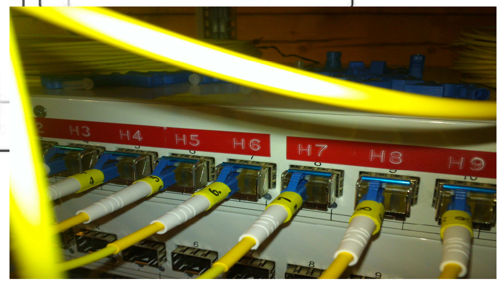




Phase stability < 0.2ns
Absolute time precision ~ 1ns



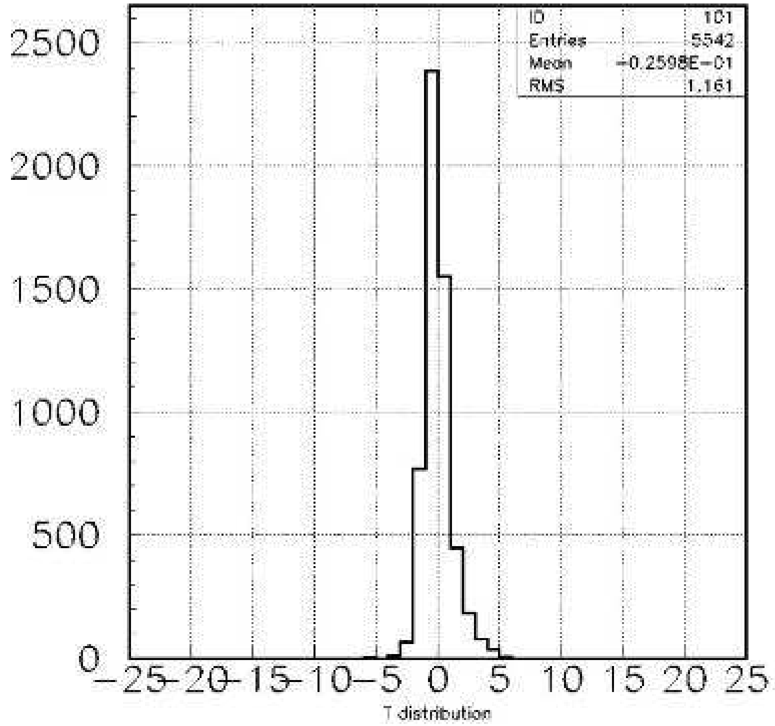


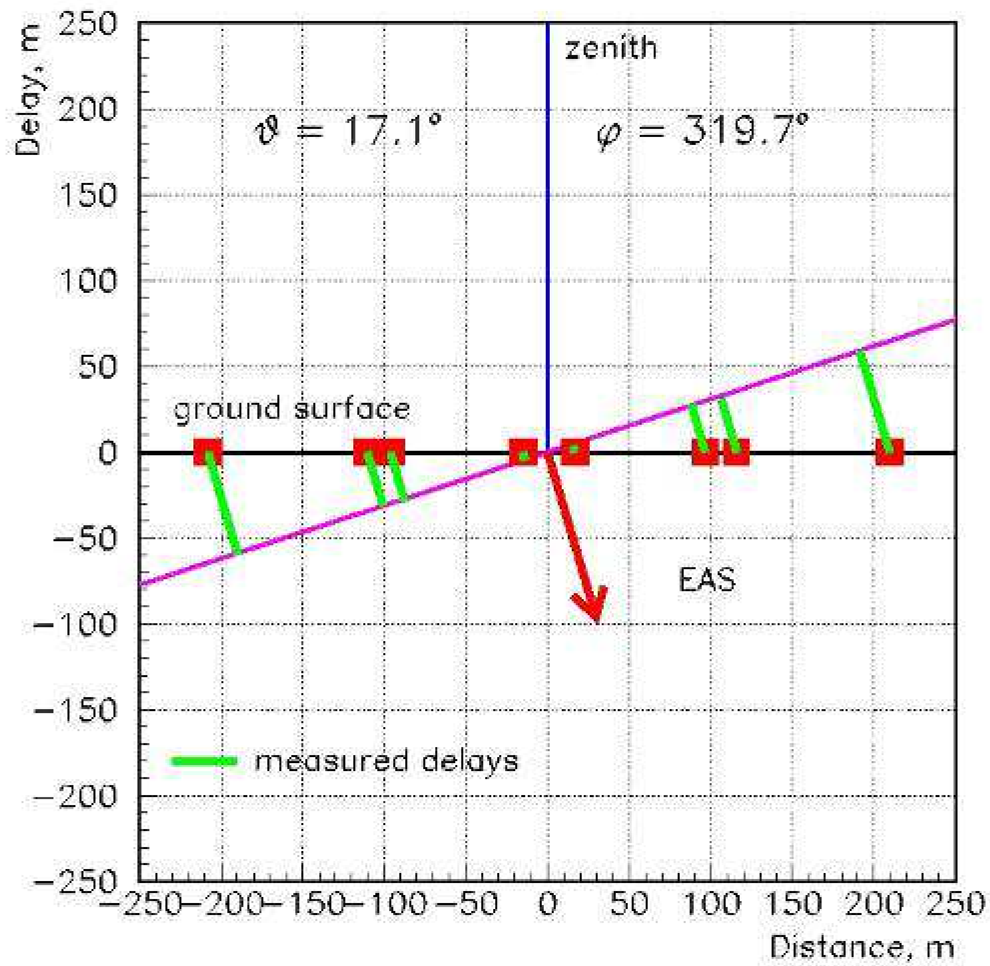


- **PMTs + Summator: signal**
  - 4 Anodes Sum (AS)
- **WR SPEC FPGA:**
  - trigger on the AS (9ns above the threshold)
- **RaspberryPI**: Connected to SPEC and DRS boards
  - When SPEC triggers: DRS start recording
  - When DRS recording is finished: ready flag sent to SPEC to trigger next event
  - Send data to the DAQ center
- **WR Switch:** synchronize all the array stations trigger time

(WR Swithc)

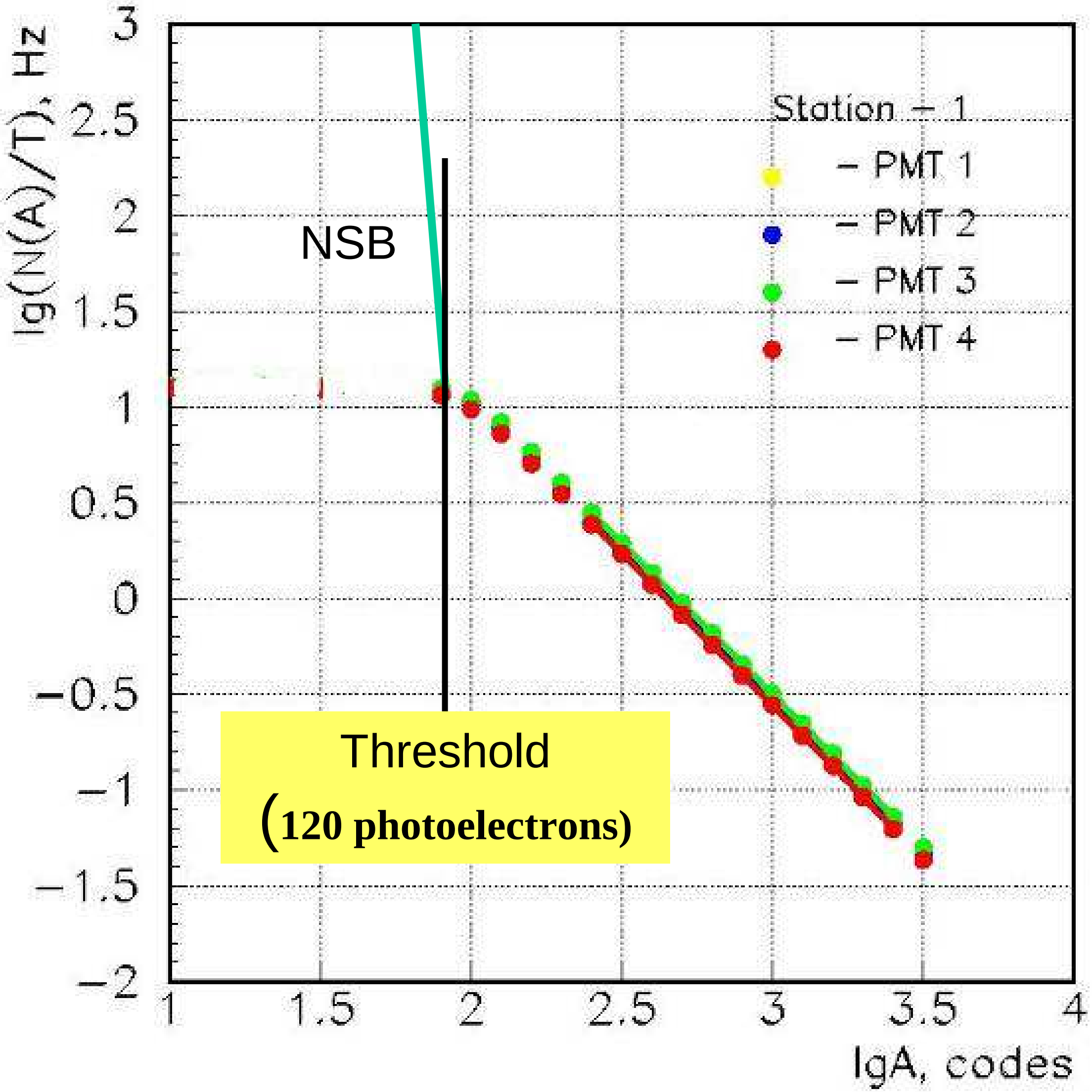
An accuracy of EAS axis direction reconstruction





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

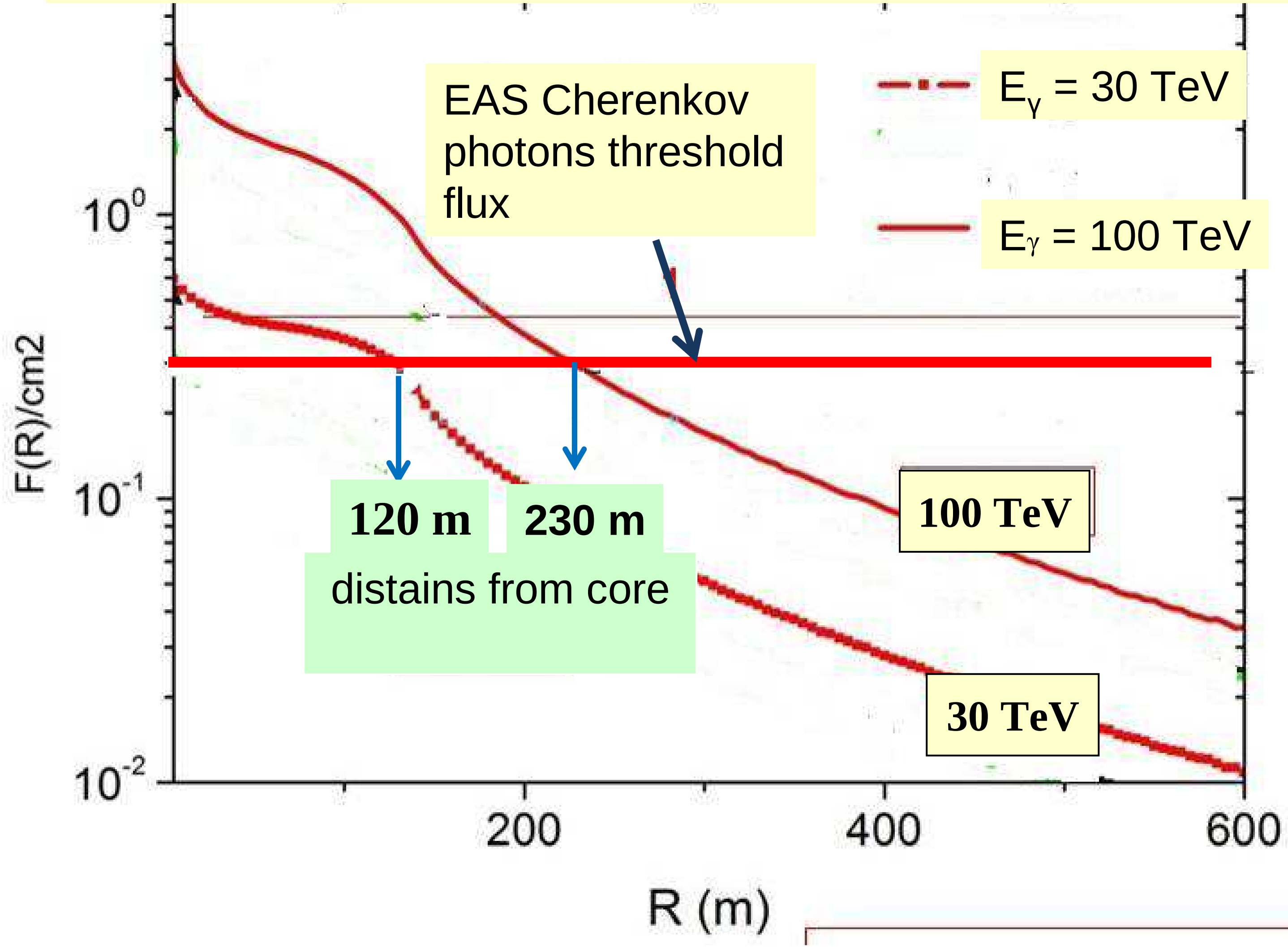
An amplitude spectrum of PMTs pulses of a Tunka-HiSCORE optical station



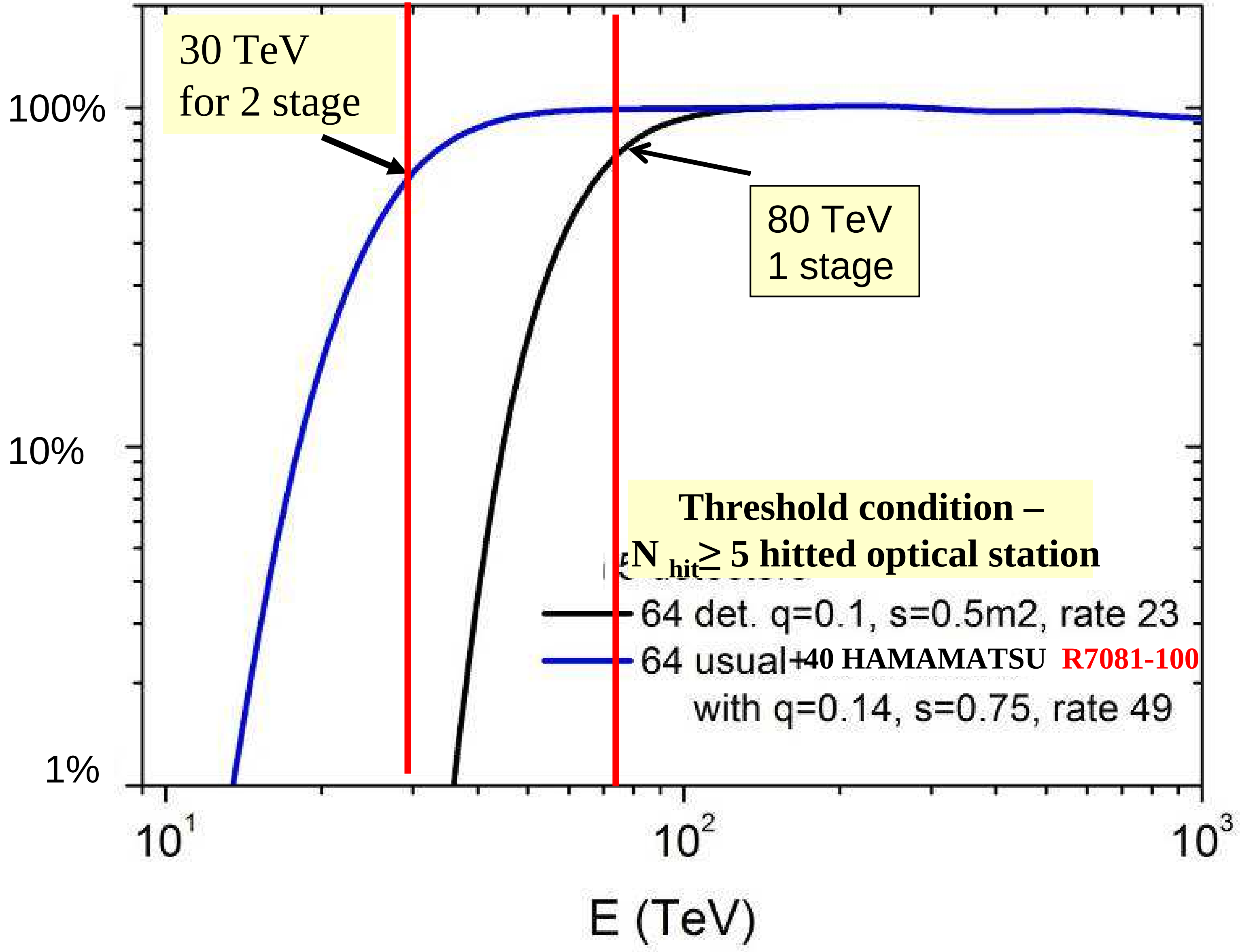
Counting rate = 12 -16 Hz

Threshold Cherenkov photons flux: 0.25 – 0.3 ph / cm^2

LDF of Cherenkov light from gamma-rays induced EAS And Threshold distains from core Threshold distains from core



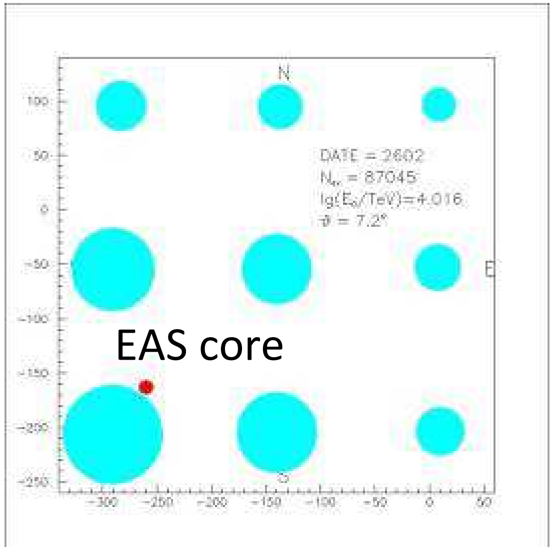
Efficiency of gamma ray detection with Tunka-HiSCORE

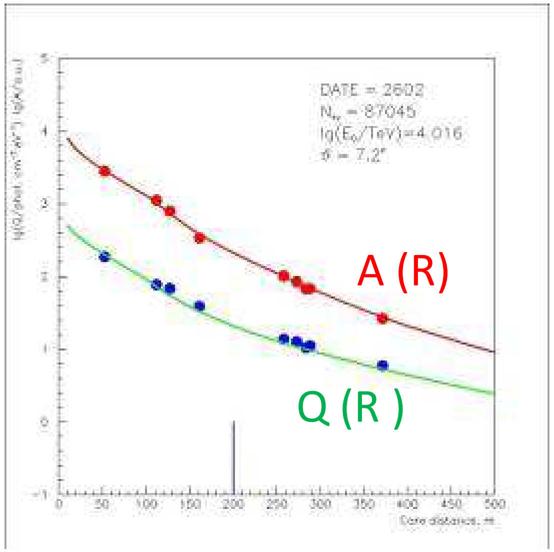


Tunka-HiSCORE event example

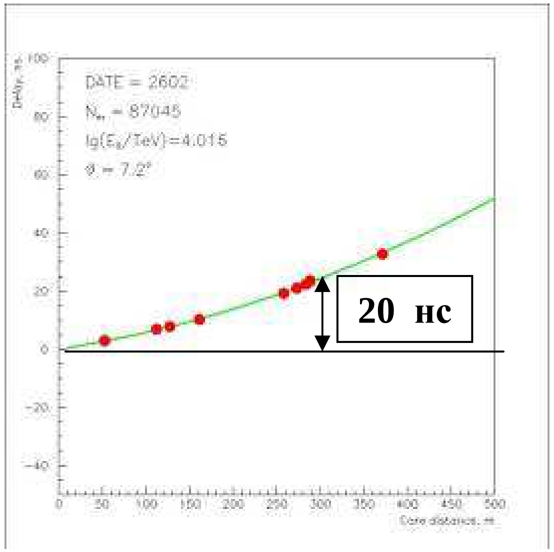
Zenith angle = 7.2°

Energy = 10^{16} eV

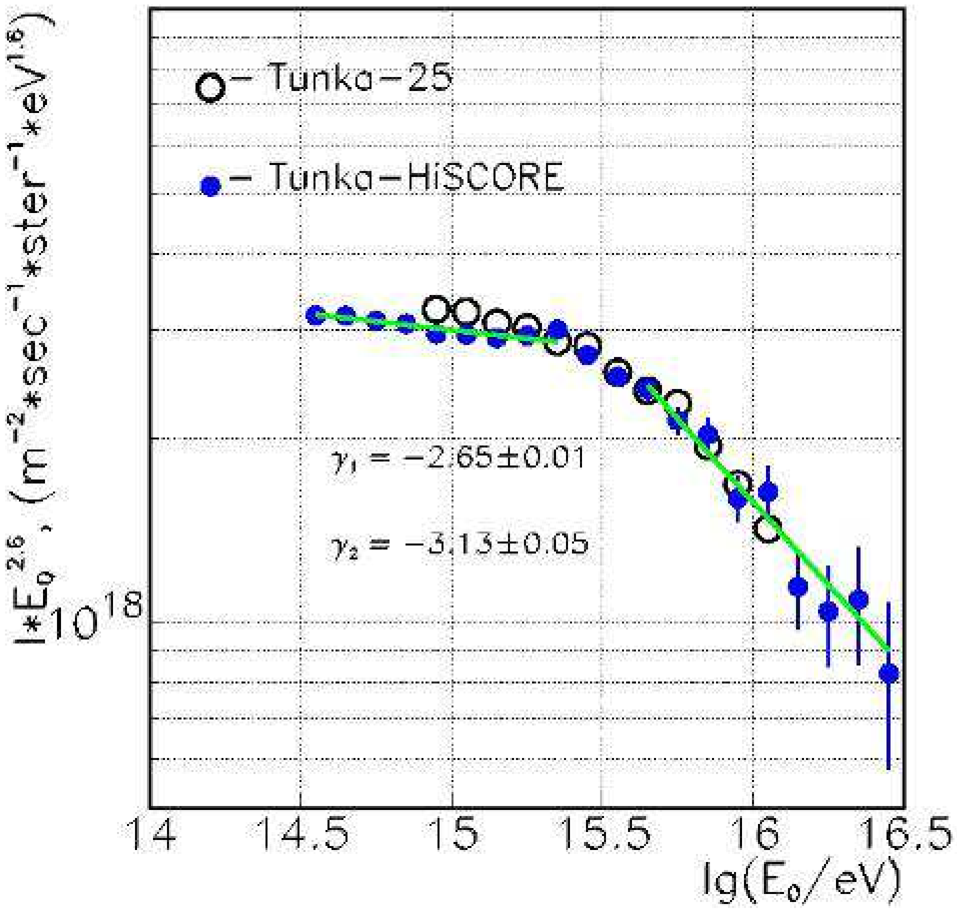




Shower front



Tunka-HiSCORE:
All particle energy spectrum.
PRELIMINARY



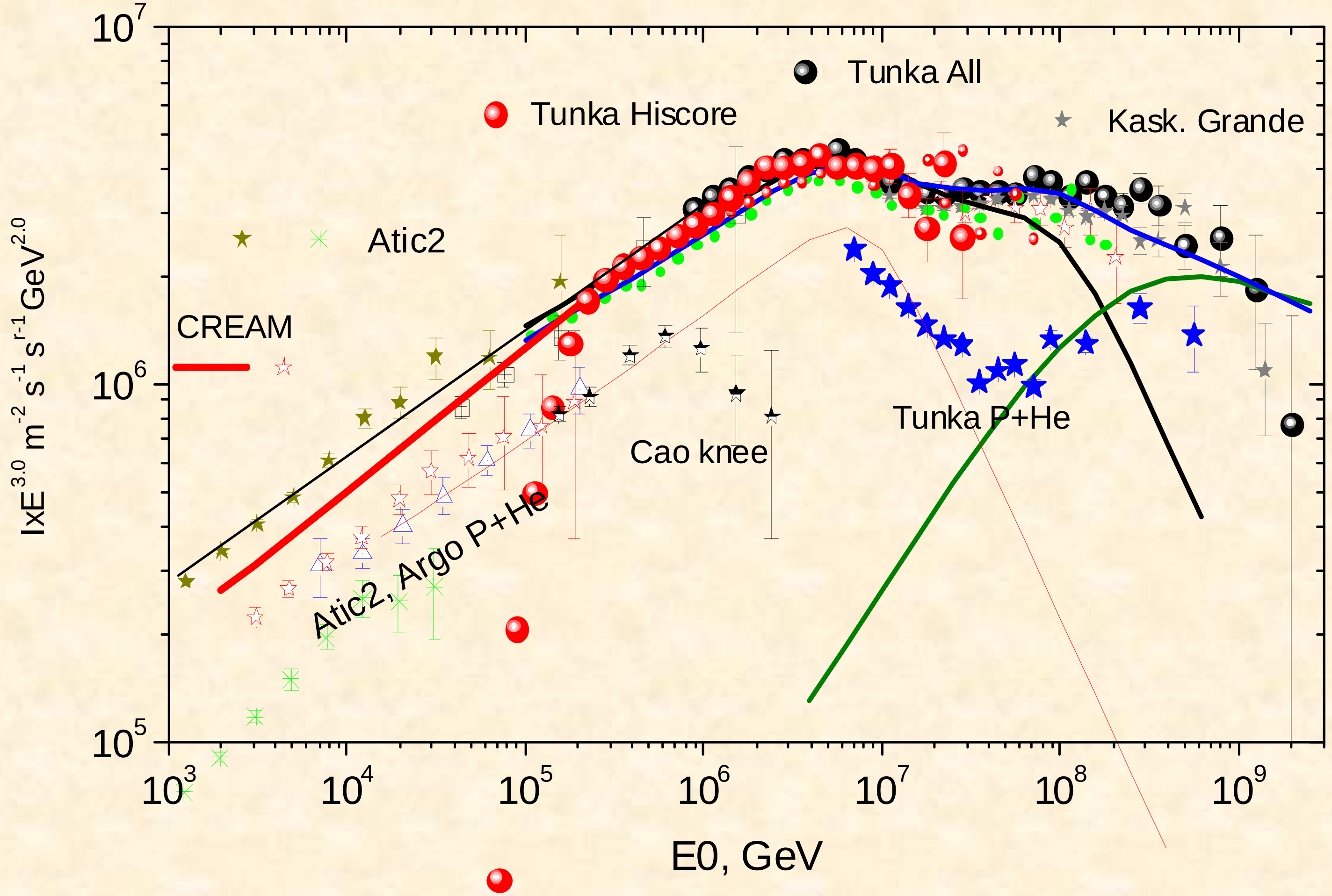
84 h during 13 clean moonless nights in February and March of 2014

~ 145 000 events with $E_0 > 3 \cdot 10^{14}$ eV – 100% efficiency

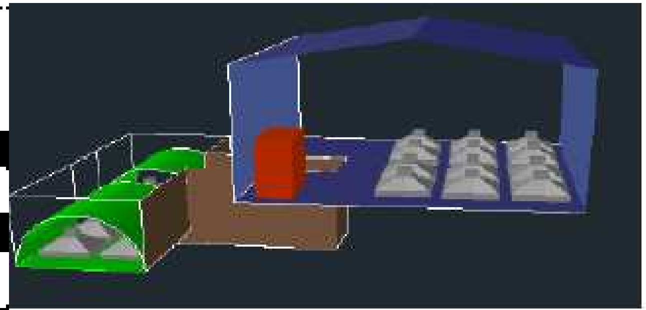
~ 21 000 events $E_0 > 10^{15}$ eV

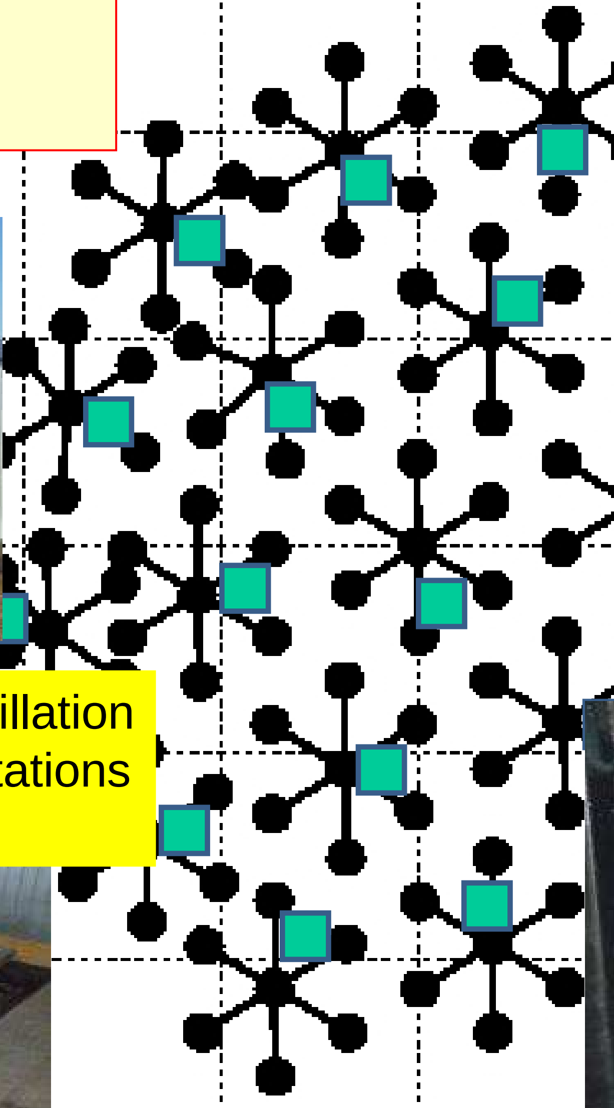
~ 200 events $E_0 > 10^{16}$ eV

All particle spectrum



Tunka –Grande array consisting of TAIGA



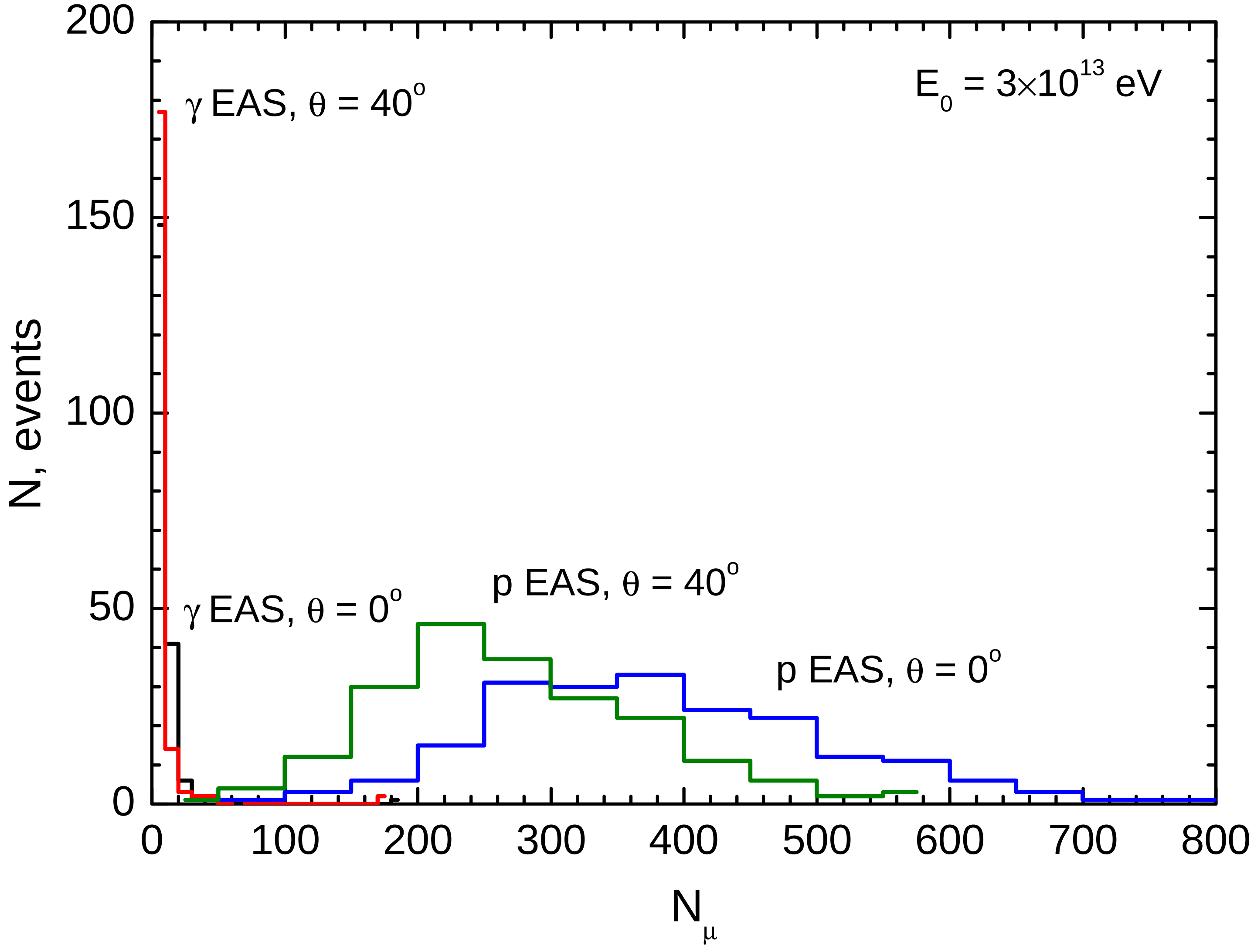


152 KASCADE-Grande scintillation counters in underground containers (muons detectors, total area 100 m^2 about)

228 KASCADE-Grande scintillation counters (0.64 m^2) in 19 stations on the surface

Future plan: 2000 m^2 muon detectors (0.2% of array area)

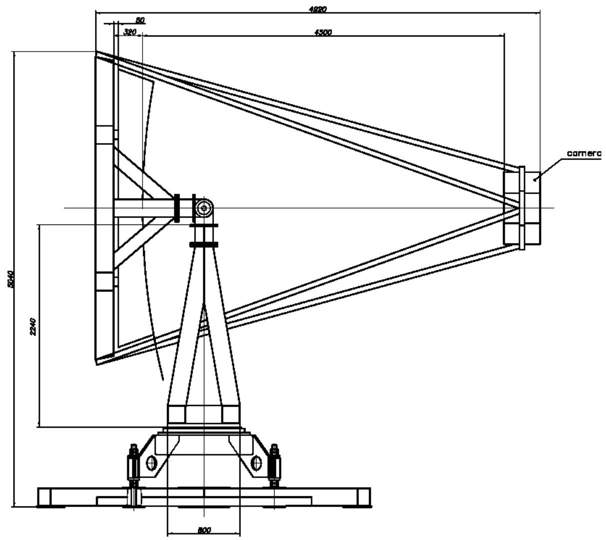
Rejection of p-N background with Tunka-Grande



Tunka –IACT array consisting of TAIGA

A system of 16 IACT (Imaging Atmospheric Cherenkov Telescopes) which will operate together with TUNKA-133 Tunka-HiSCORE and Tunka-Grande.

Mirror diameter – 4 m about
(34 mirrors with 60 cm diameters),
4.8 m focal distance
Spacing 300 – 600 (?) m
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°,
Low cost



Camera : 400 PMTs (XP 1911) with
15 mm useful diameter of photocathode
Winston cone: 30 mm input size, 15 output size
1 single pixel = 0.36 deg
full angular size 8.3 deg

DAQ - MAROC3

Very near future of Tunka experiment

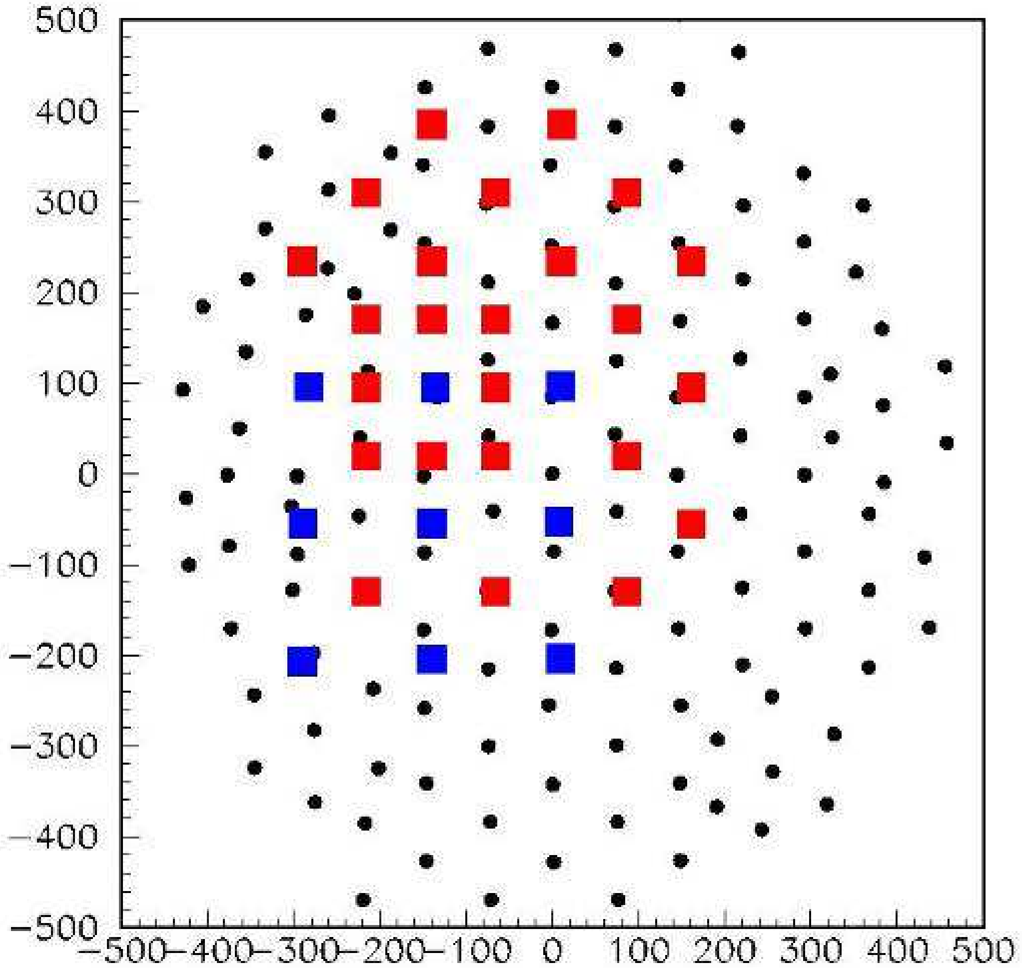
Spring 2014 y:

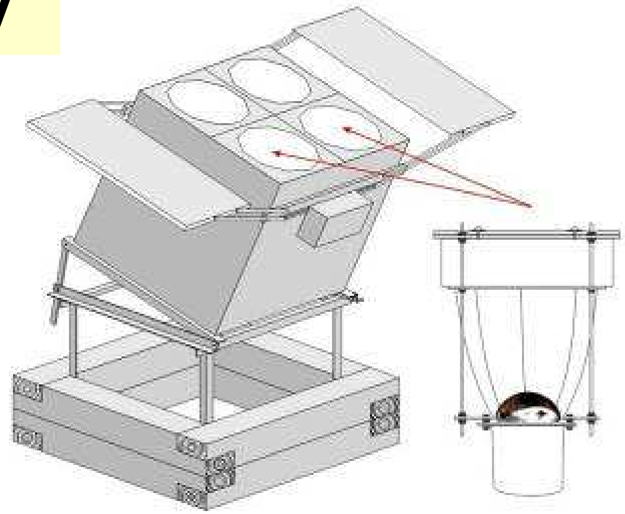
1. **Tunka-133 175 detectors single PMT of Ø 20 cm**
2. **Tunka-HiSCORE 9 stations 4 PMT with Winston cones**
3. **Tunka-Rex 25 radio antennas**
4. **Optical telescope of “Master” net**

November 2014 y :

1. **Scintillation station for electrons and muons detection (based on former KASCADE-Grande detectors) - 19 stations (total area for muons 100 m^2)**
2. **Tunka-HiSCORE - 33 stations**
3. **Prototype of IACT with mirrors of 15 m^2 area**
4. **Tunka-Rex + 25 radio antennas**

Tunka-HiSCORE October 2014y
– 33 stations
Decreasing of a threshold for γ to ~30 TeV

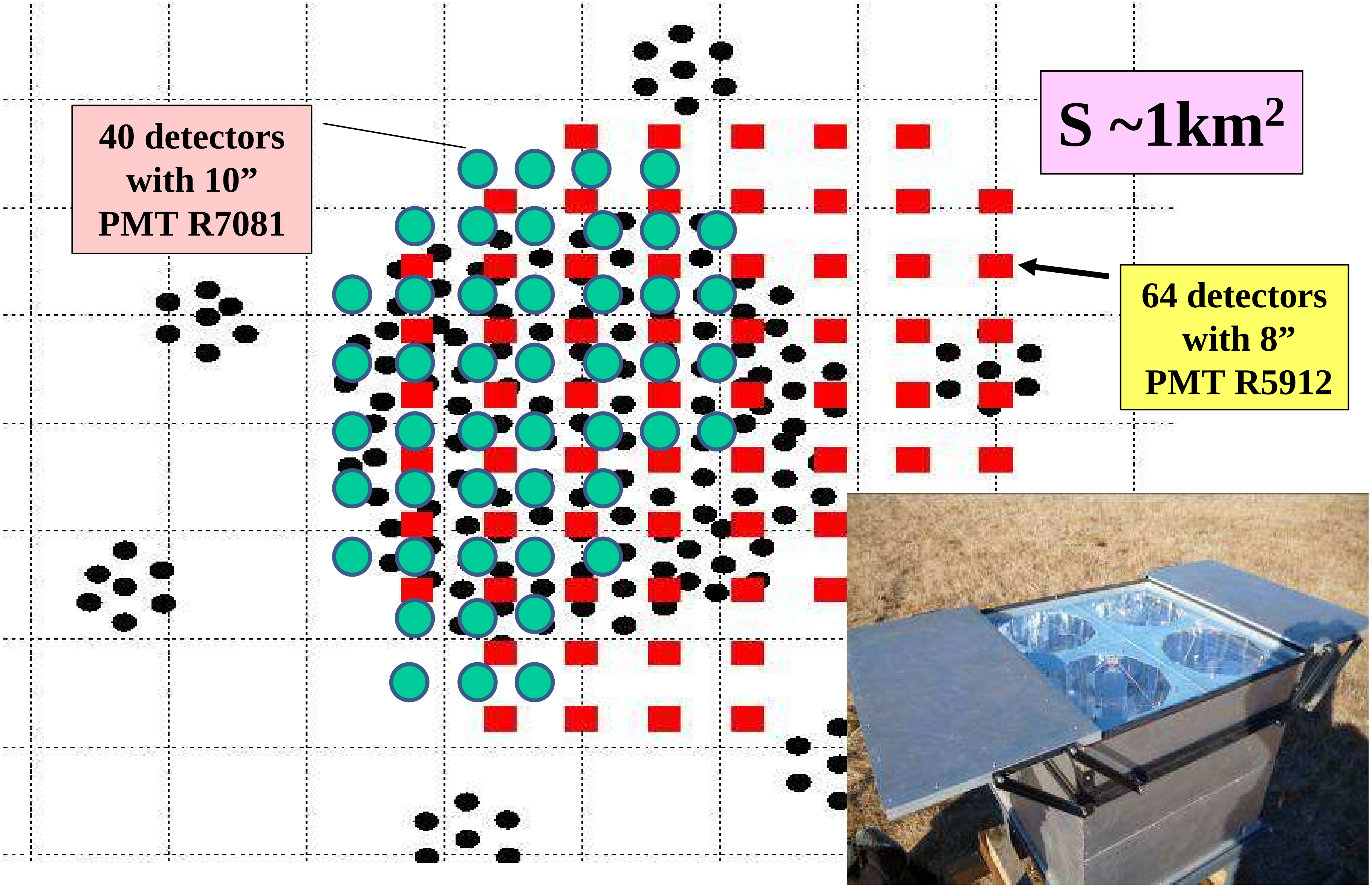




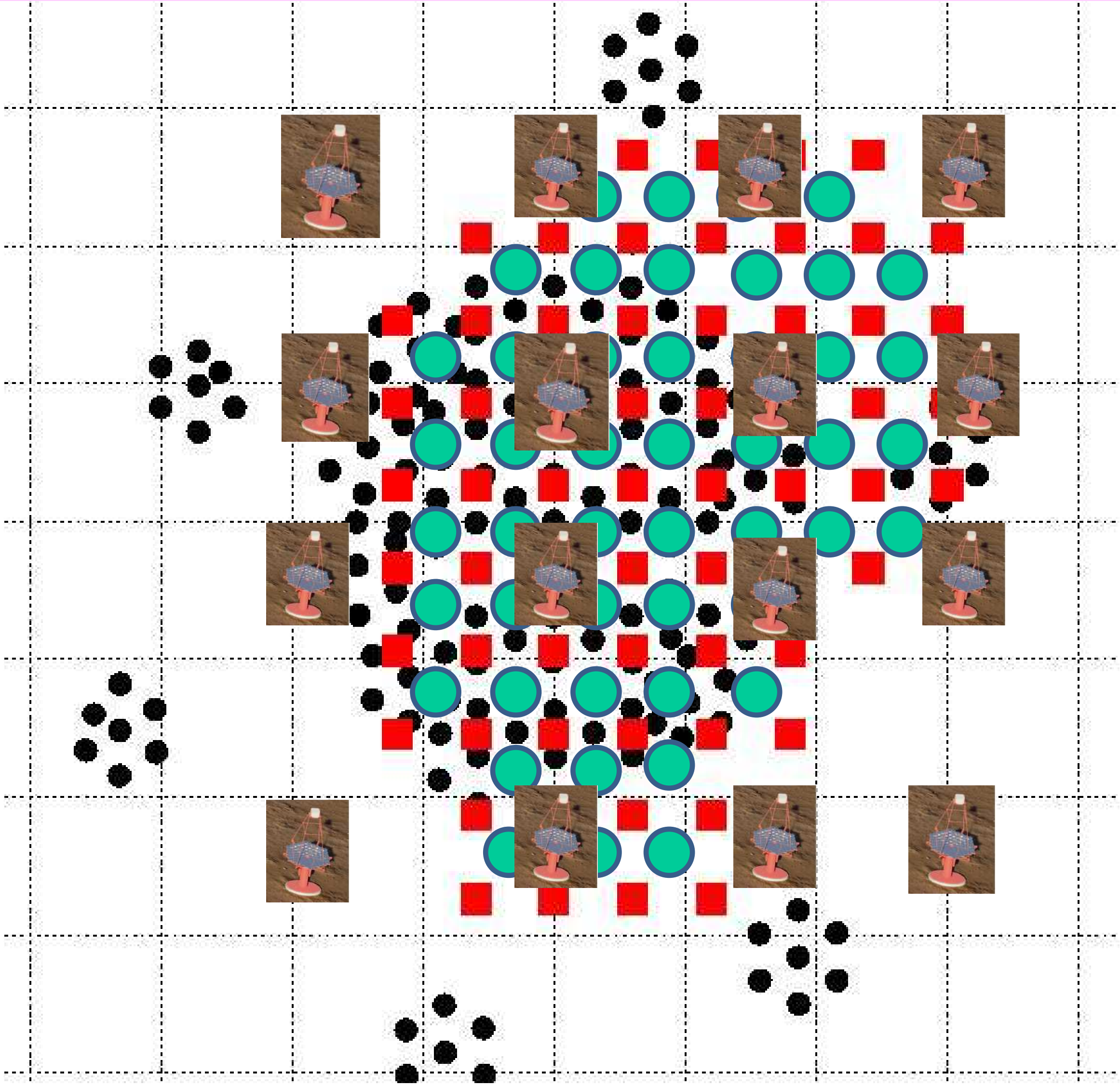
All the stations will be tilted for 30° to the South for observation of Crab Nebulae

About 10-20 γ-events from Crab are expected during 100 h of observation.

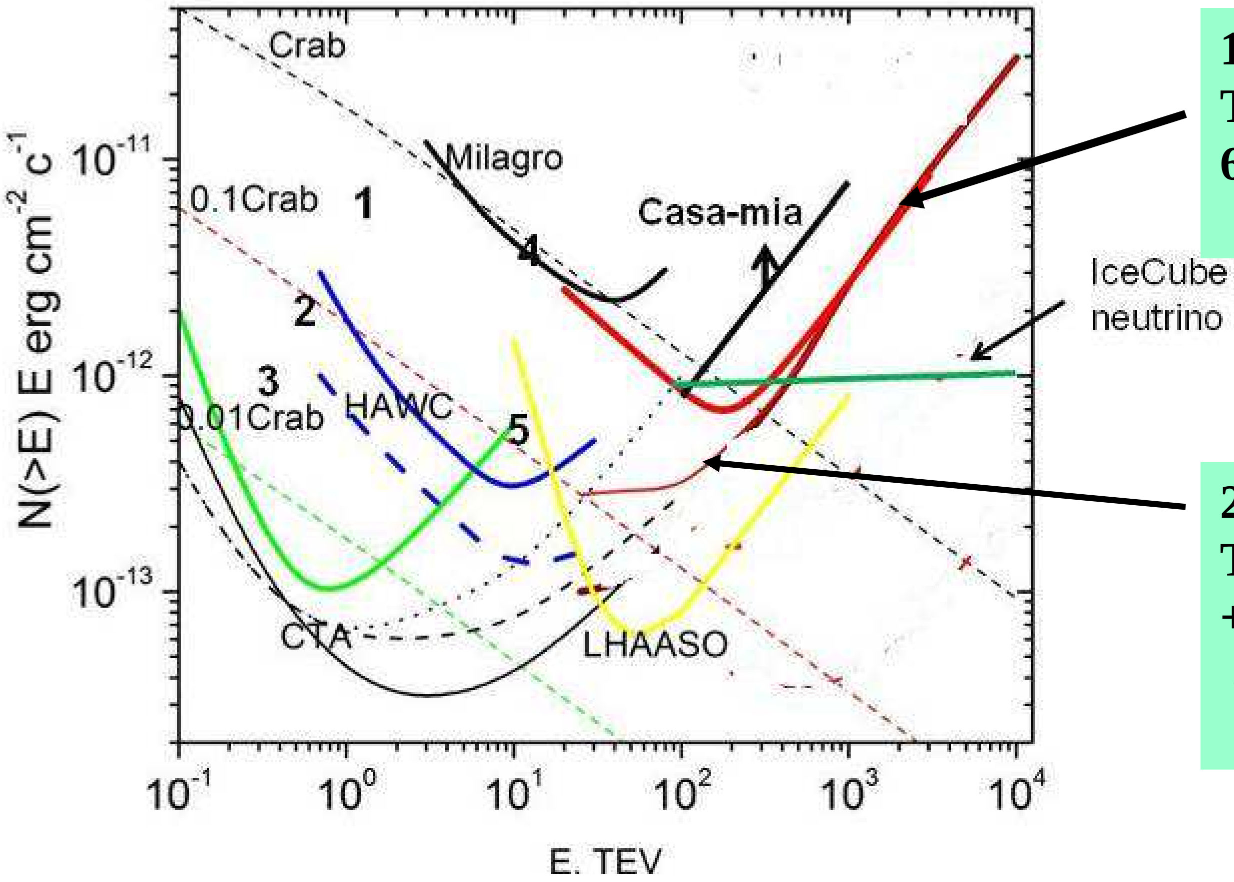
Stage 2 (2014-2016 years): 104 wide angle Tunka-HiSCORE Cherenkov detectors



Stage 3 (2015-2018 years): net of wide angle Cherenkov detectors + 16 imaging telescopes (IACT) + 2000m^2 muon detectors



Sensitivity for gamma rays



1st stage (2015y)
Tunka –HiSCORE
64 stations with 150 m spacing
(50 events 500 hours)

2d stage (2016 y)
Tunka –HiSCORE
+
5 IACT-telescopes
(very preliminary)

10 км² TAIGA (2013 – 2018) ~10 -12 Millions Euro

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

33 Tunka-HiSCORE optical stations in October 2014

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 HAMAMATSU R7081-100 (10”)
+ 5 Tunka- IACT
with mirrors (D = 4,2 m)
Cost: 2 M Euro.

2014-2016

2016 -2020

2014-2018

Extension of the array up to 10 км^2

2000 m^2 scintillation detectors Tunka-Grande
(0.1% of the whole area)
– 2-5 muons from 250 TeV protons
Cost: 2.5-3 M Euro.

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^{14} to 10^{18} eV were measured with high resolution. The second "knee" at energy $\sim 3 \cdot 10^{17}$ 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 $5 \cdot 10^{13}$ - 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!