The Tunka multi – component EAS detector for high energy cosmic ray studies

N.Budnev, Irkutsk State University

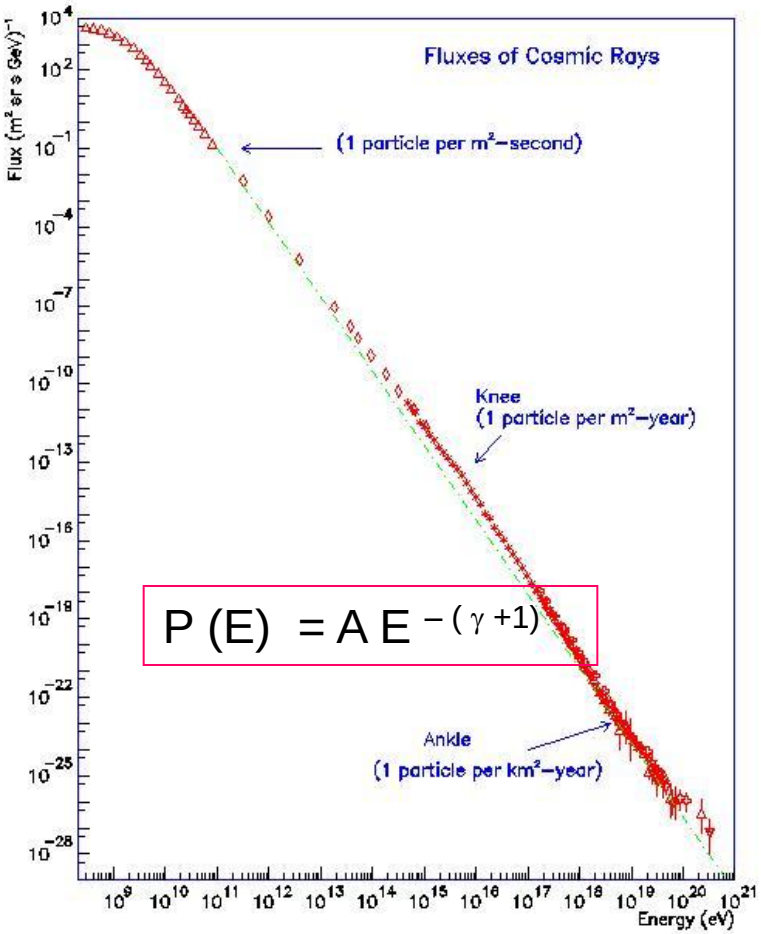
For Tunka - collaboration

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

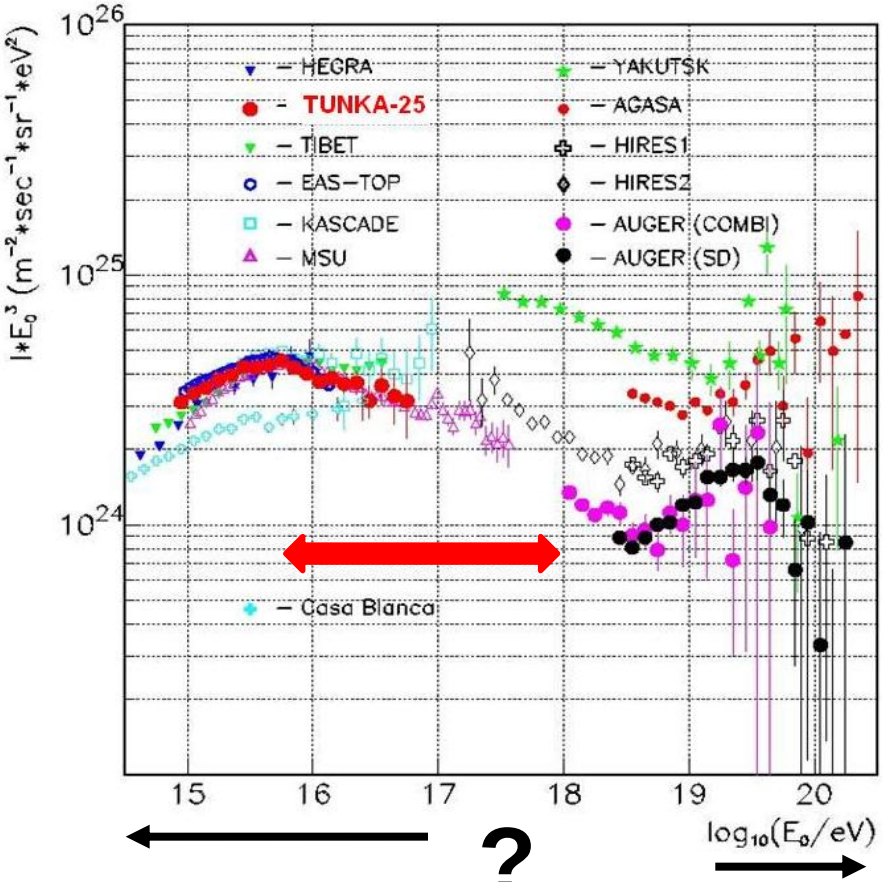
Even very well isolated gold-leaf electroscopes are discharged at a slow rate.

The bird's eye view on a CR energy spectrum

CR Flux (E) x E^3



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



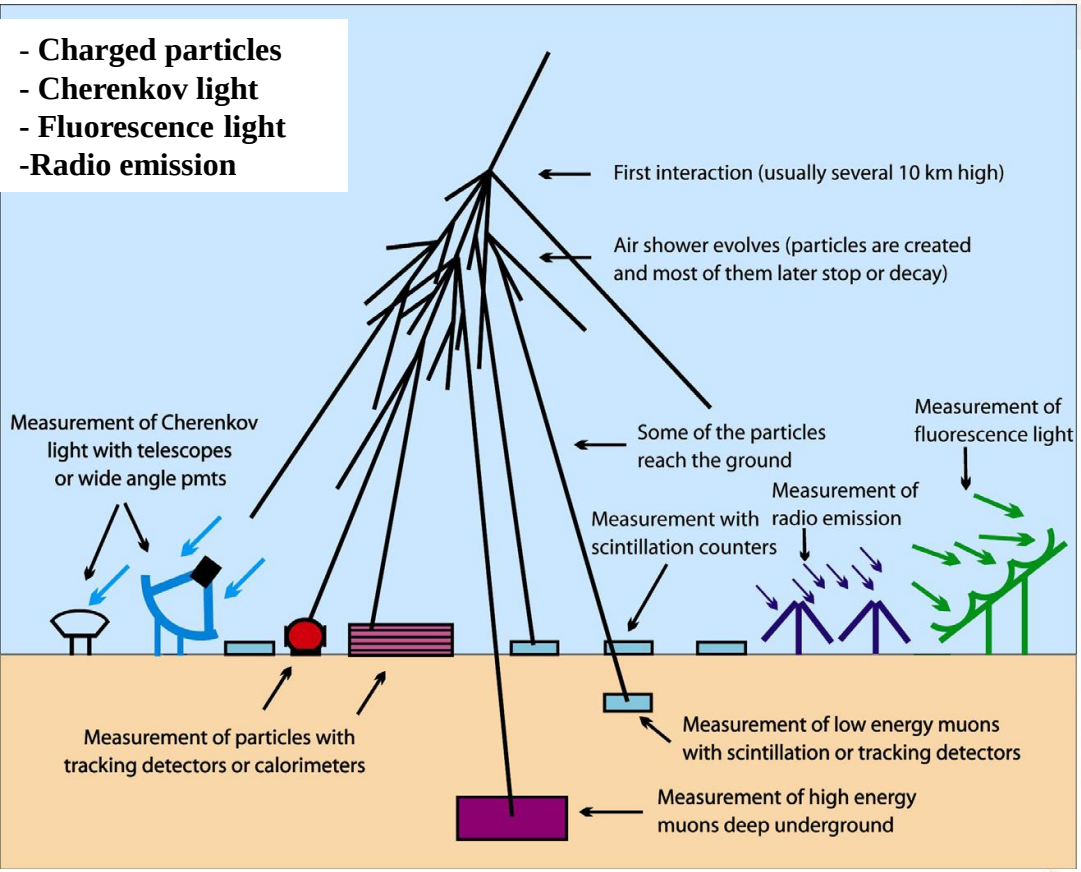
?

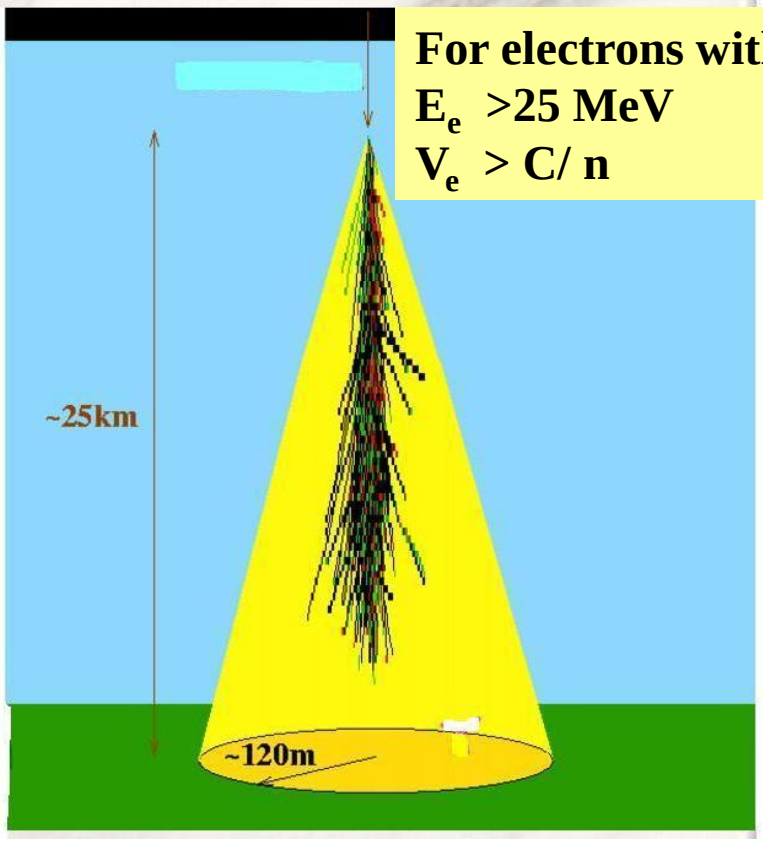
SNR, Pulsars….
- Galactic Cosmic rays ??

AGN, GRB…
- Extragalactic Cosmic rays ??

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

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





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

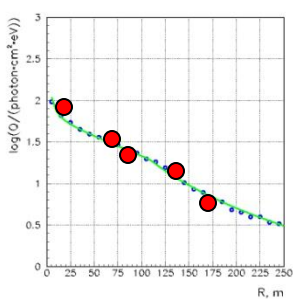
$$LnA(E) \sim X_{max}(E)$$

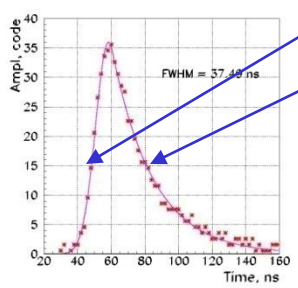
$$X_{max}(E) = C - D \cdot \lg \tau(400)$$

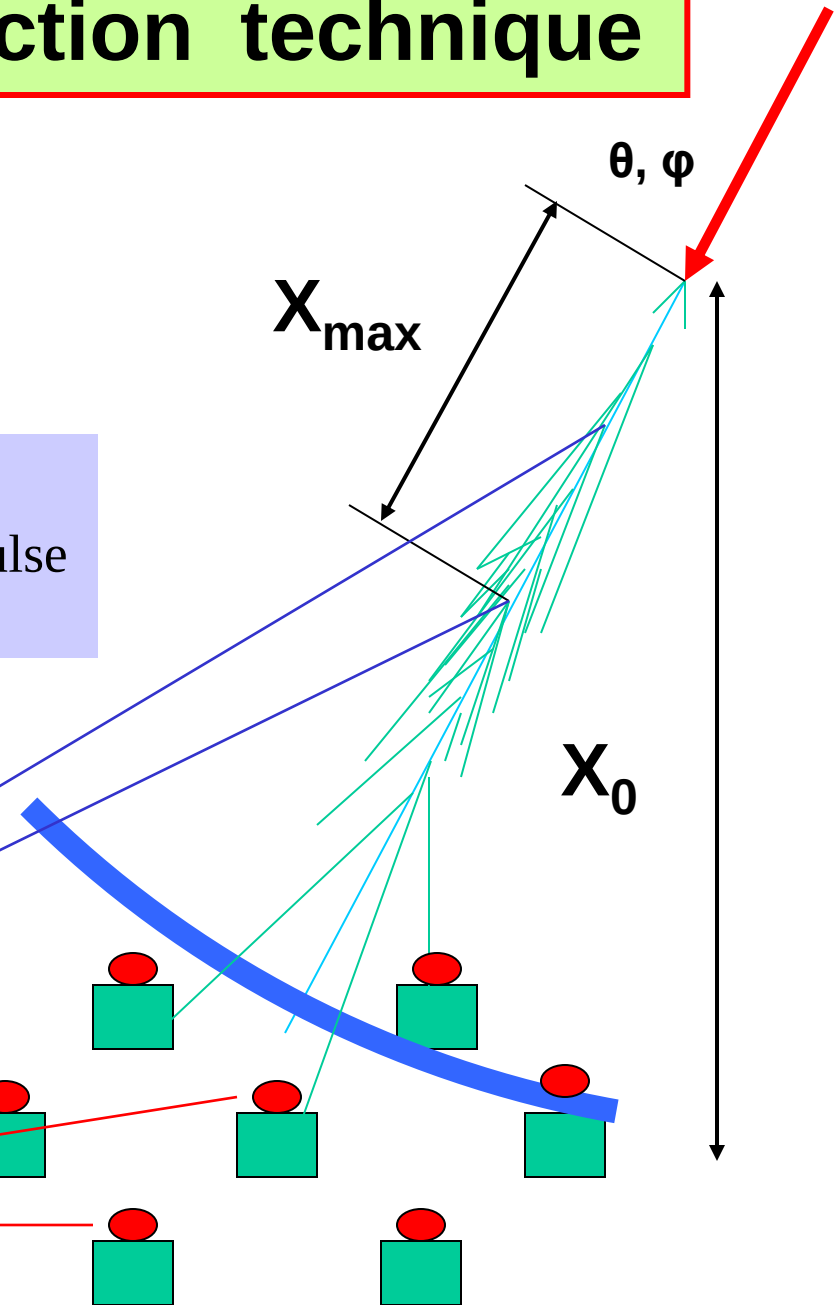
$\tau(400)$ - duration of a Cherenkov pulse at distance 400 m EAS core from

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

P -Steepness of a Lateral Distribution Function (LDF)







Advantage of Cherenkov Technique:

1. Good energy resolution - up to 10% (probably 5% ?)
2. Good accuracy of X_{max} measurement - 20 -25 g/cm^2
3. Good angular resolution - 0.1 – 0.3 deg
4. Low cost of an array:

The cost of Tunka-133 – 1 km^2 array is:

0.5 10^6 Euro (construction and deployment)

+ 0.2 10^6 Euro (PMTs).

The cost of a Cherenkov EAS 100 km^2 array

- about 10^7 Euro

Disadvantage:

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

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;

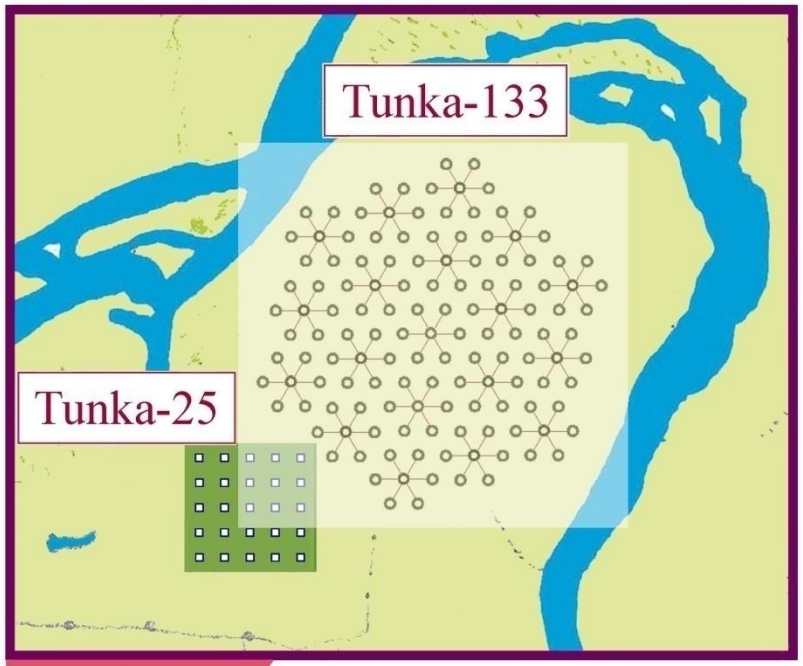
B.K. Lubsandorzhiev, B.A. Shaibonov(ju) , N.B. Lubsandorzhiev
Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;

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

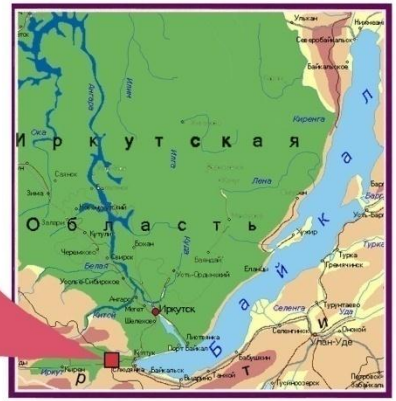
Ch. Spiering, R. Wischnewski
DESY-Zeuthen, Zeuthen, Germany;

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

2009 year



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

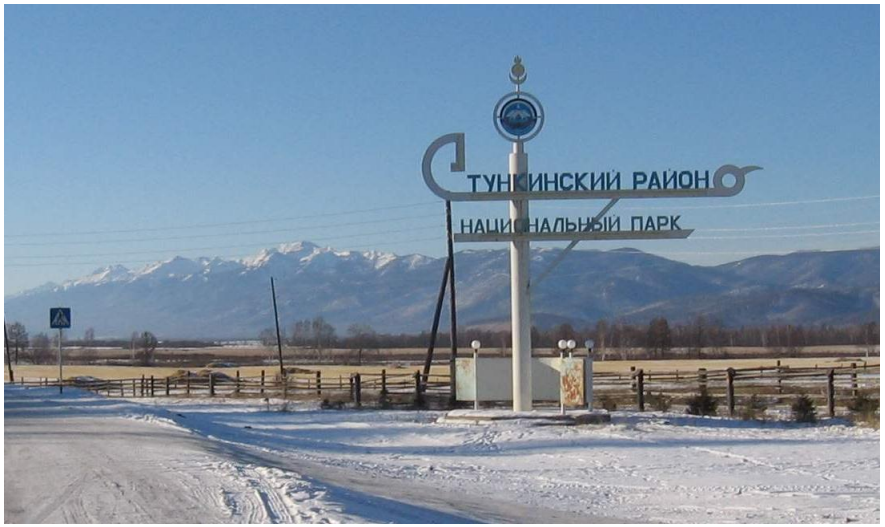


50 km from Lake Baikal

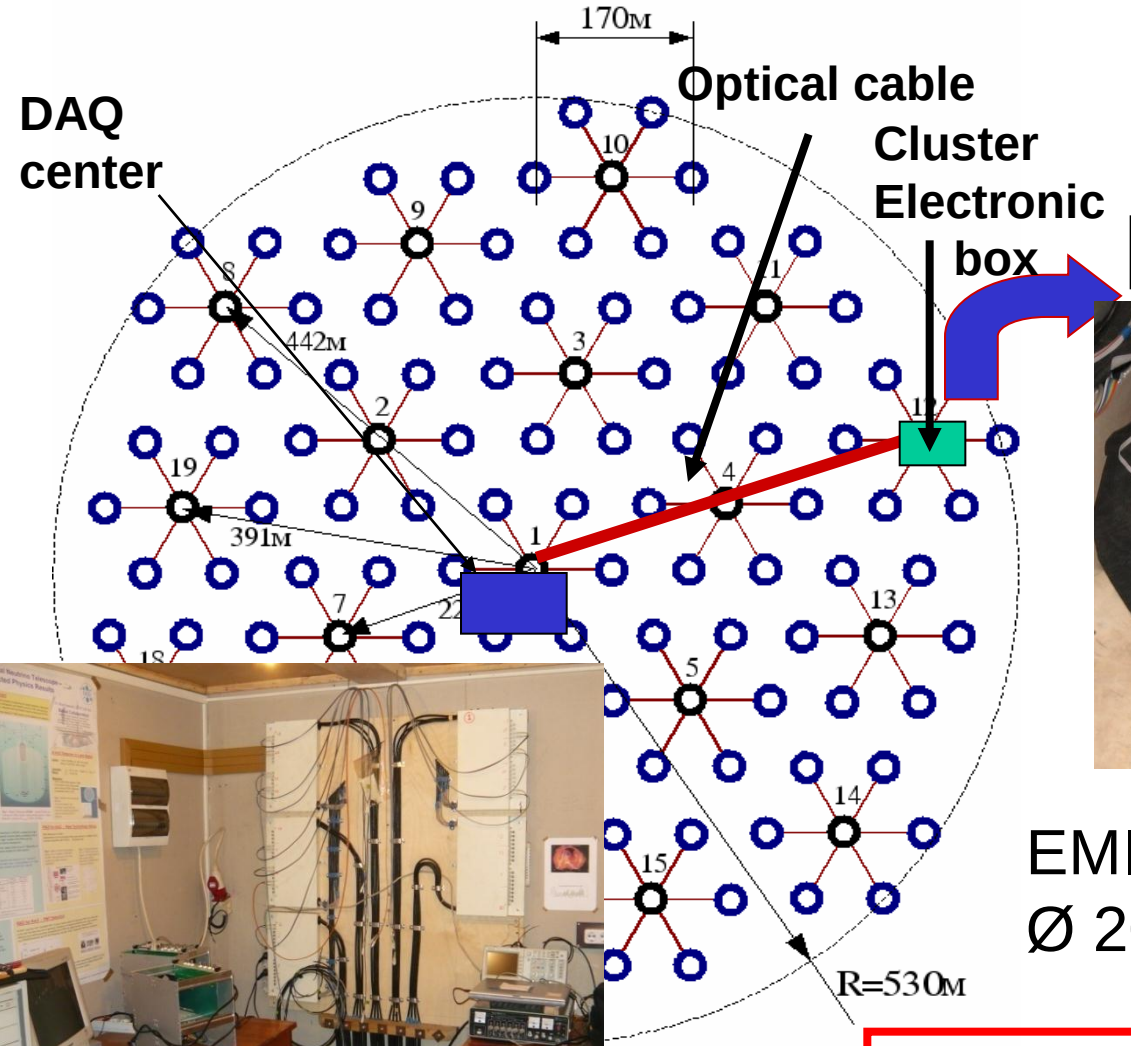
Tunka-133 – 1 km^2 "dense" EAS Cherenkov light array

Energy threshold 10^{15} eV

Accuracy: core position ~ 10 m
energy resolution ~ 15%
$\delta X_{max} < 25$ g·cm^{-2}

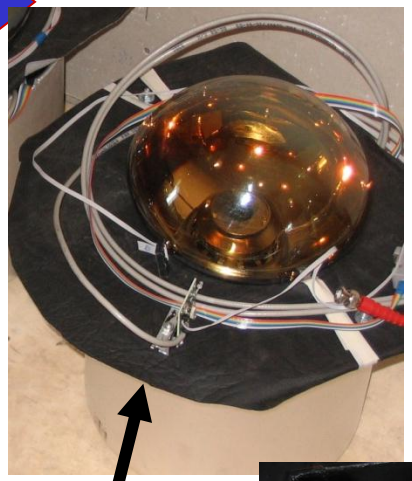


2009 y. Tunka-133: 19 clusters, 7 detectors in each cluster

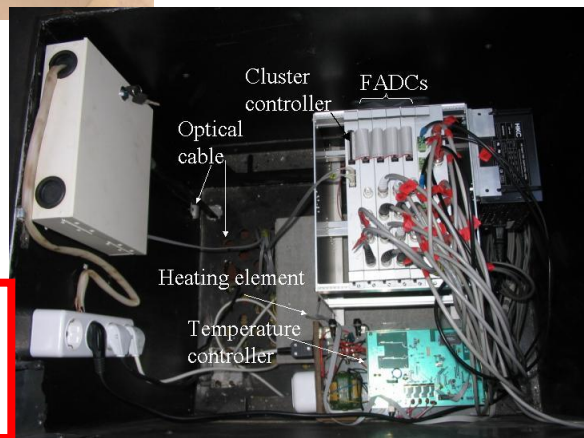


Optical detector

Cluster box

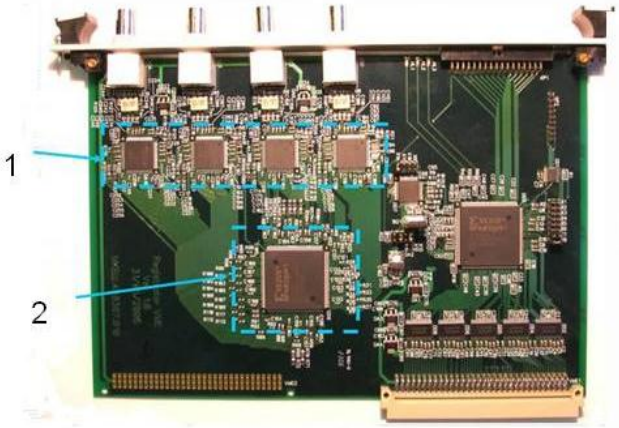


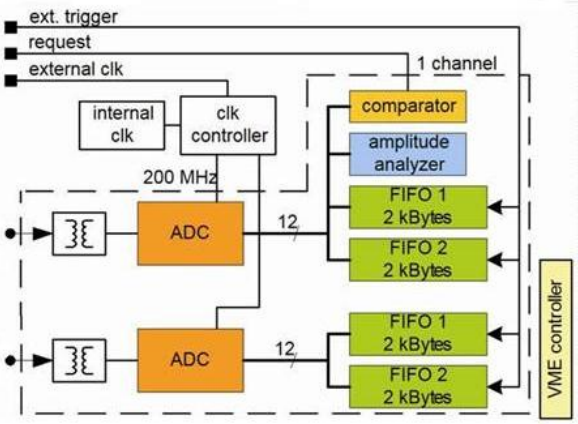
EMI 9350
Ø 20 cm



4 channel FADC
200 MHz, 12 bit

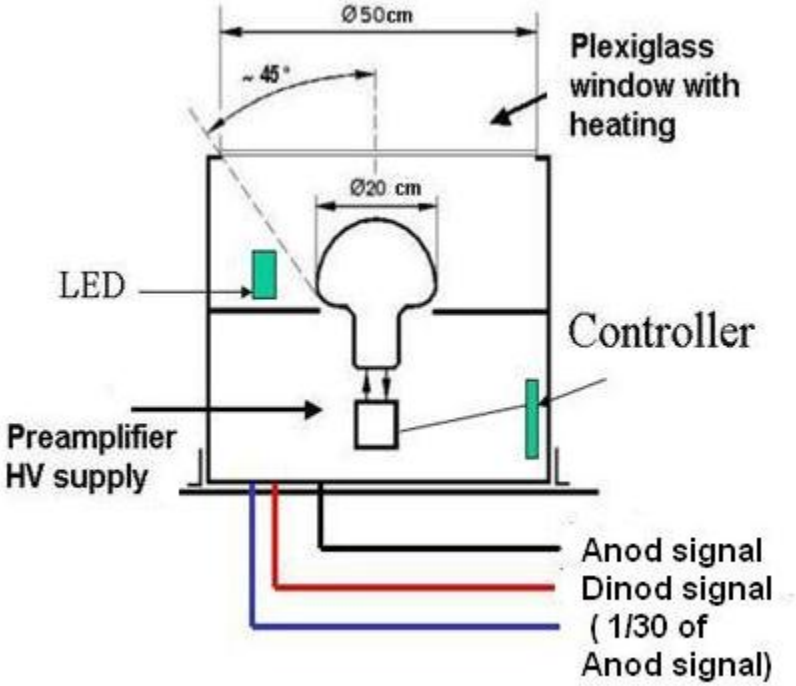
Cluster electronics

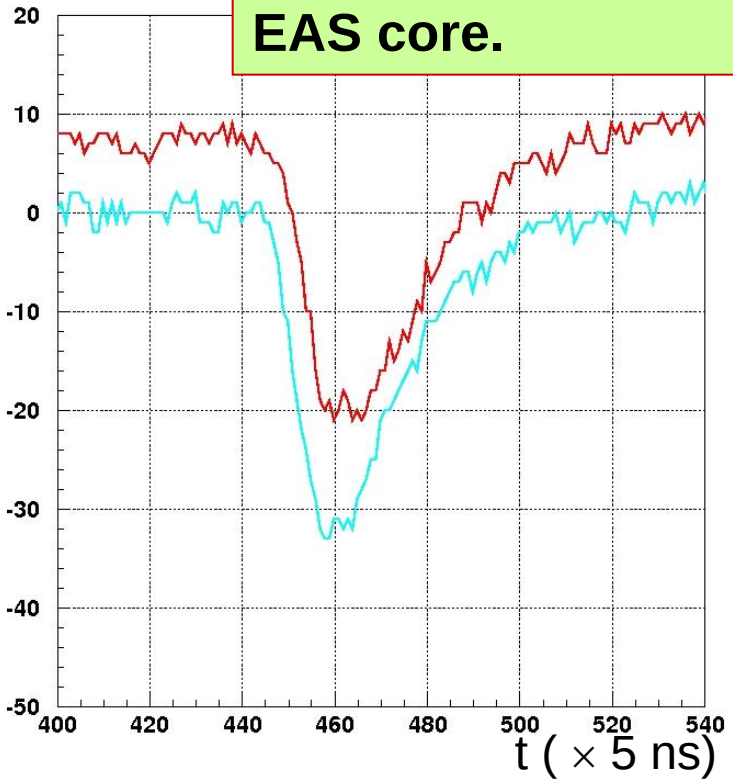




1. ADC AD9430, 12 bit, 200 MHz
2. FPGA XILINX Spartan-3

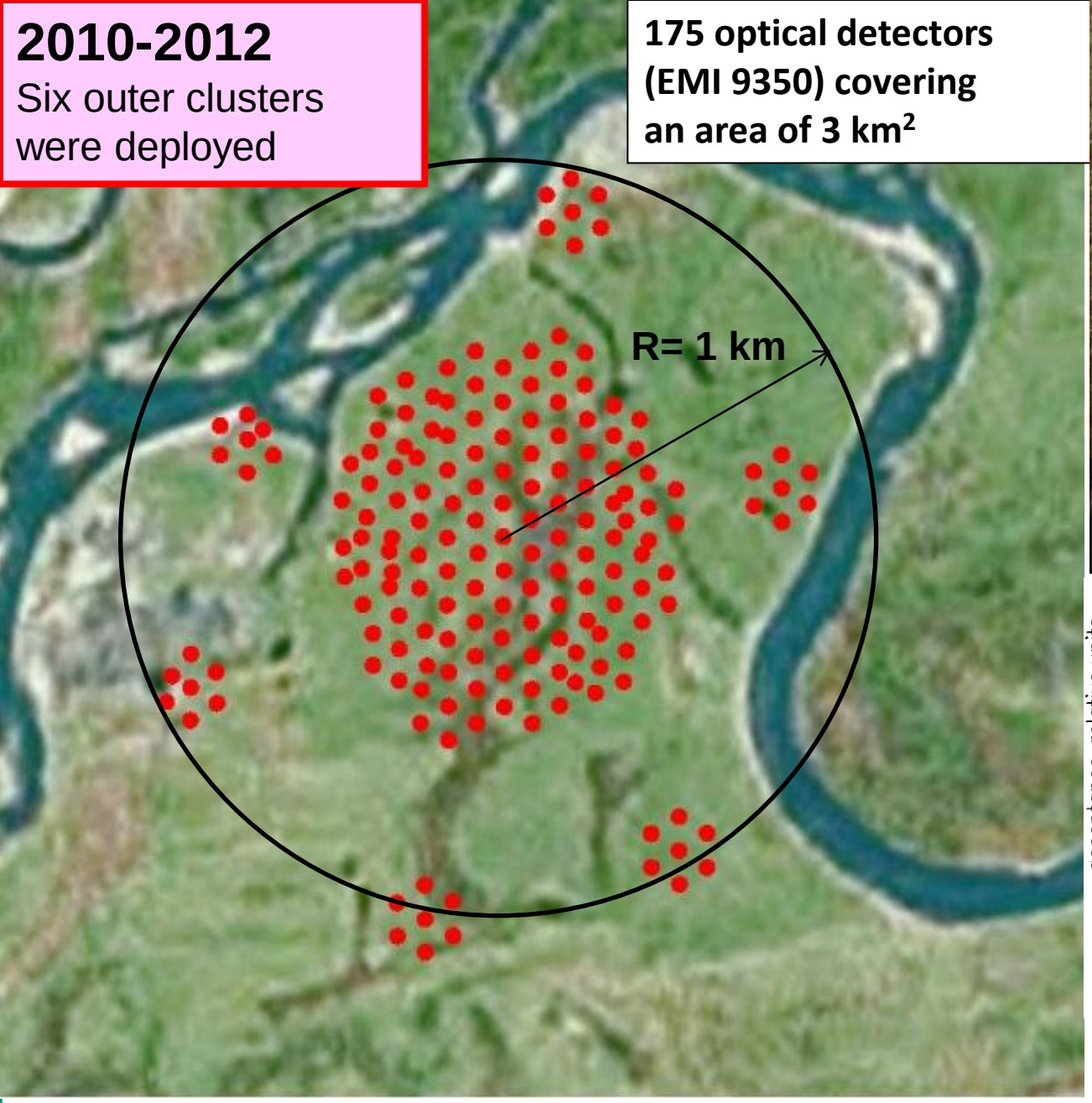
Cherenkov light pulses of two detectors of a cluster located at a distance 700 m from EAS core.

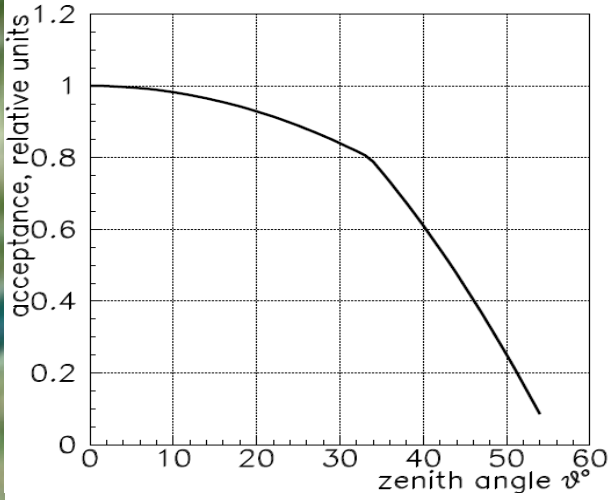




2010-2012
Six outer clusters were deployed

175 optical detectors (EMI 9350) covering an area of 3 km^2

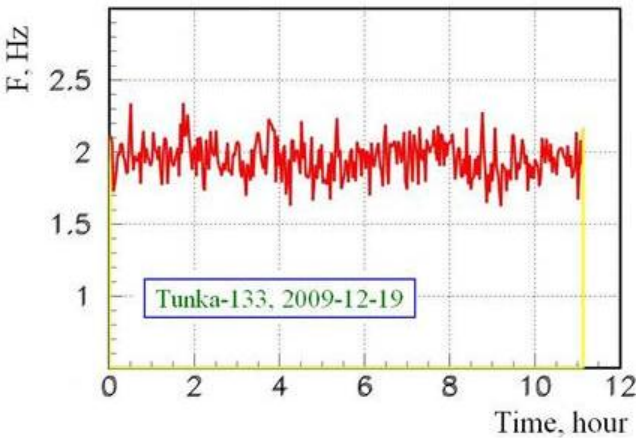




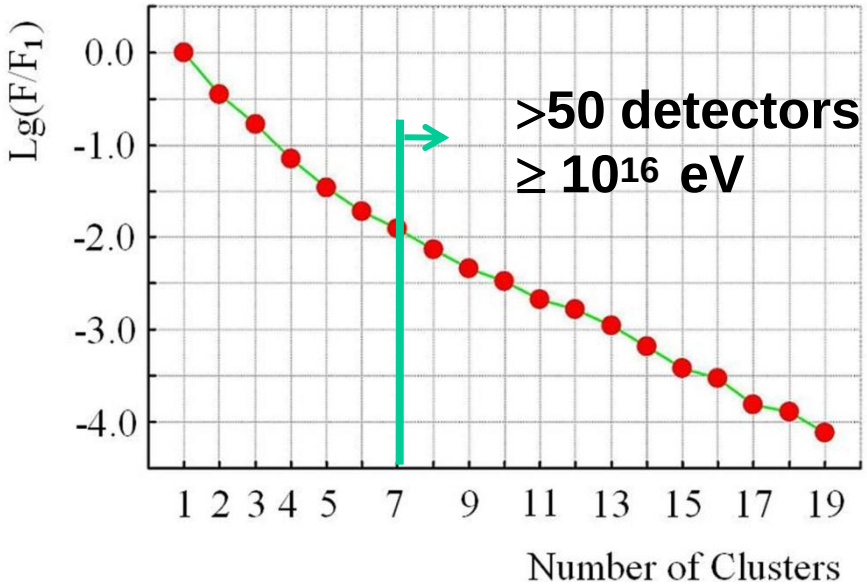
Angular sensitivity

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 energy $\geq 10^{15}$ эВ.



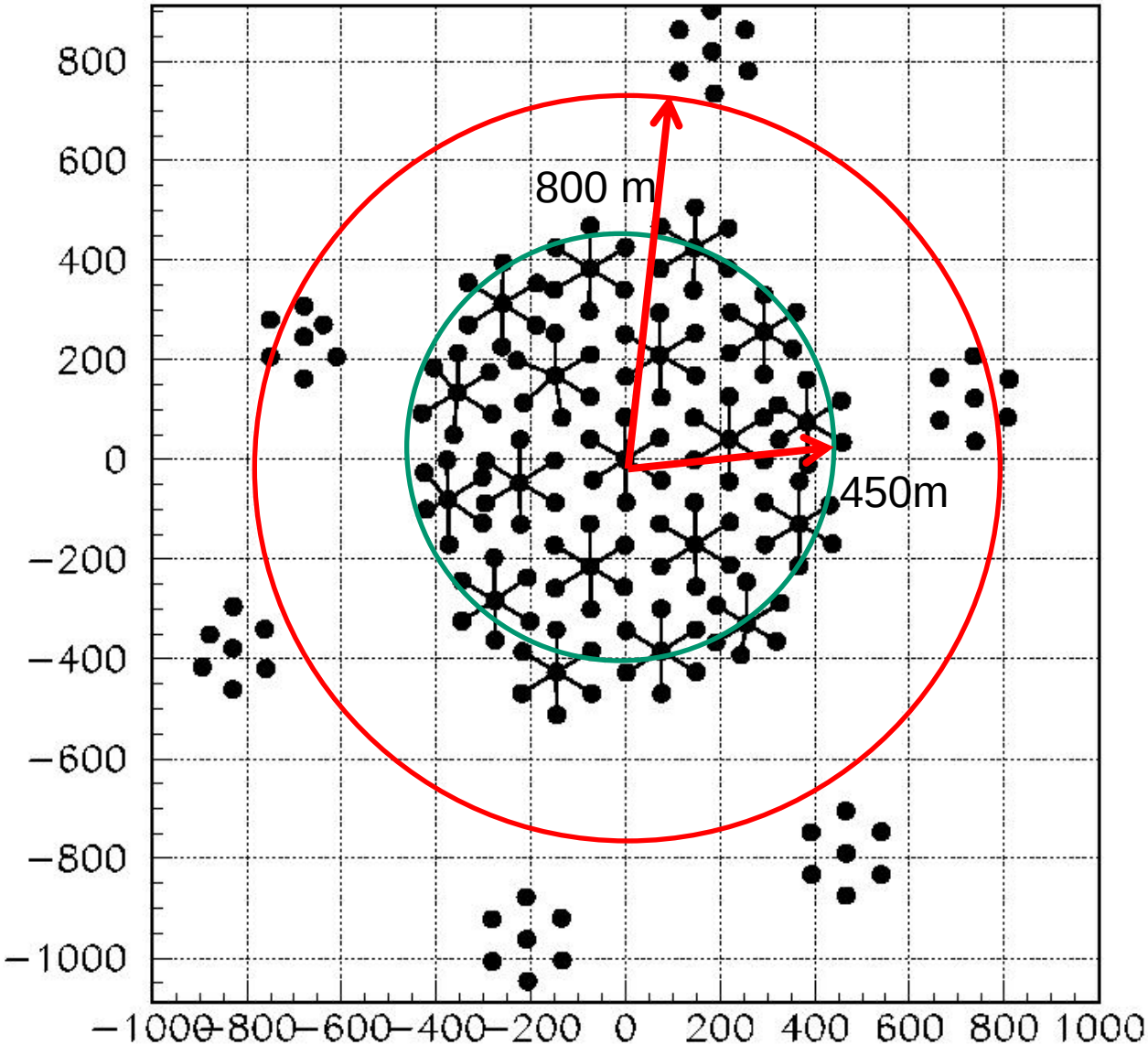
Trigger counting rate during one night .



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

Distribution of the number of hitted clusters in an event.

Tunka-133 array with 6 distant external clusters



Statistics for 2009-2012 year

IN-events - core position inside circle: R < 450m

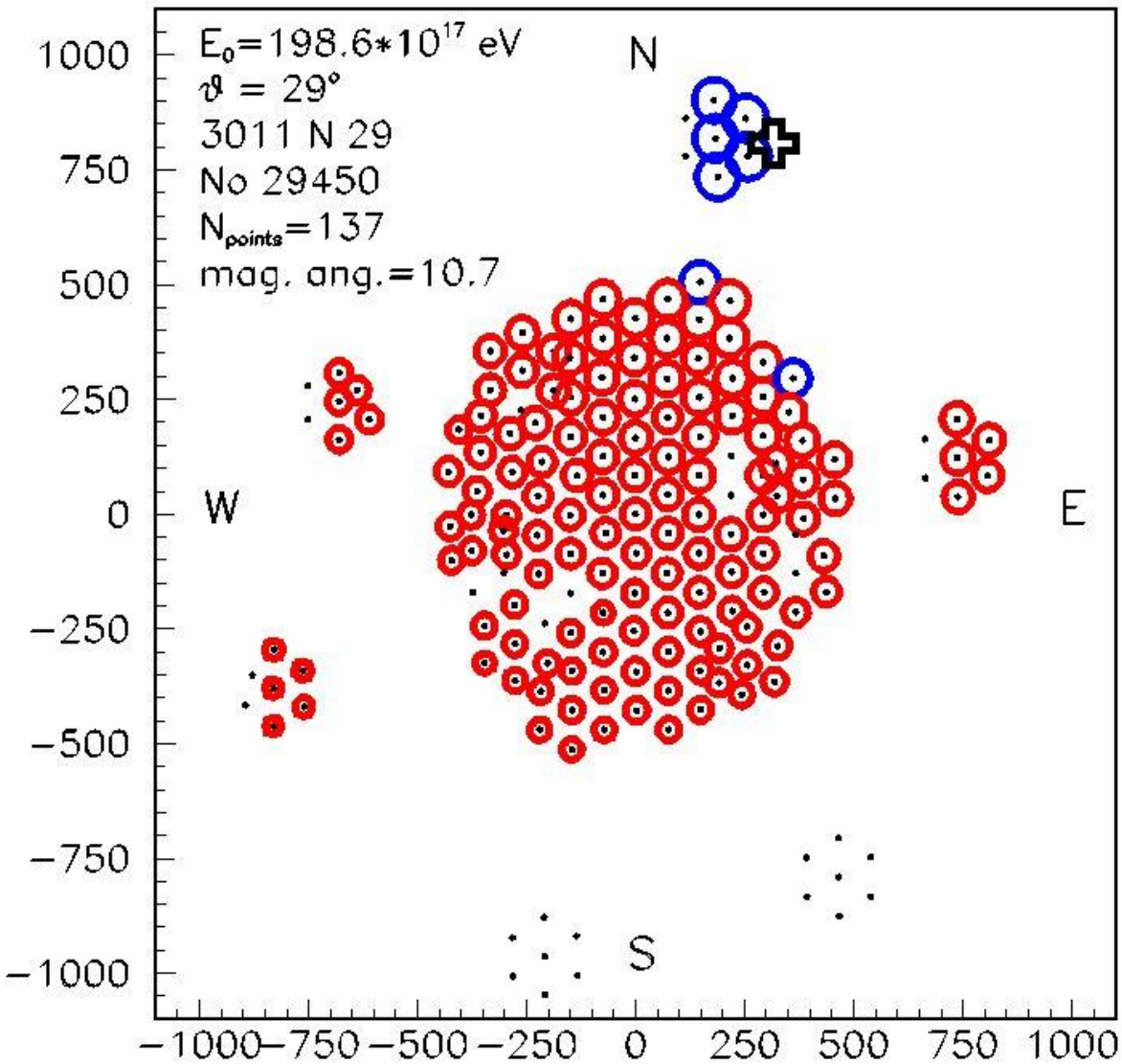
>10^{16} eV: 63490

>10^{17} eV: 605

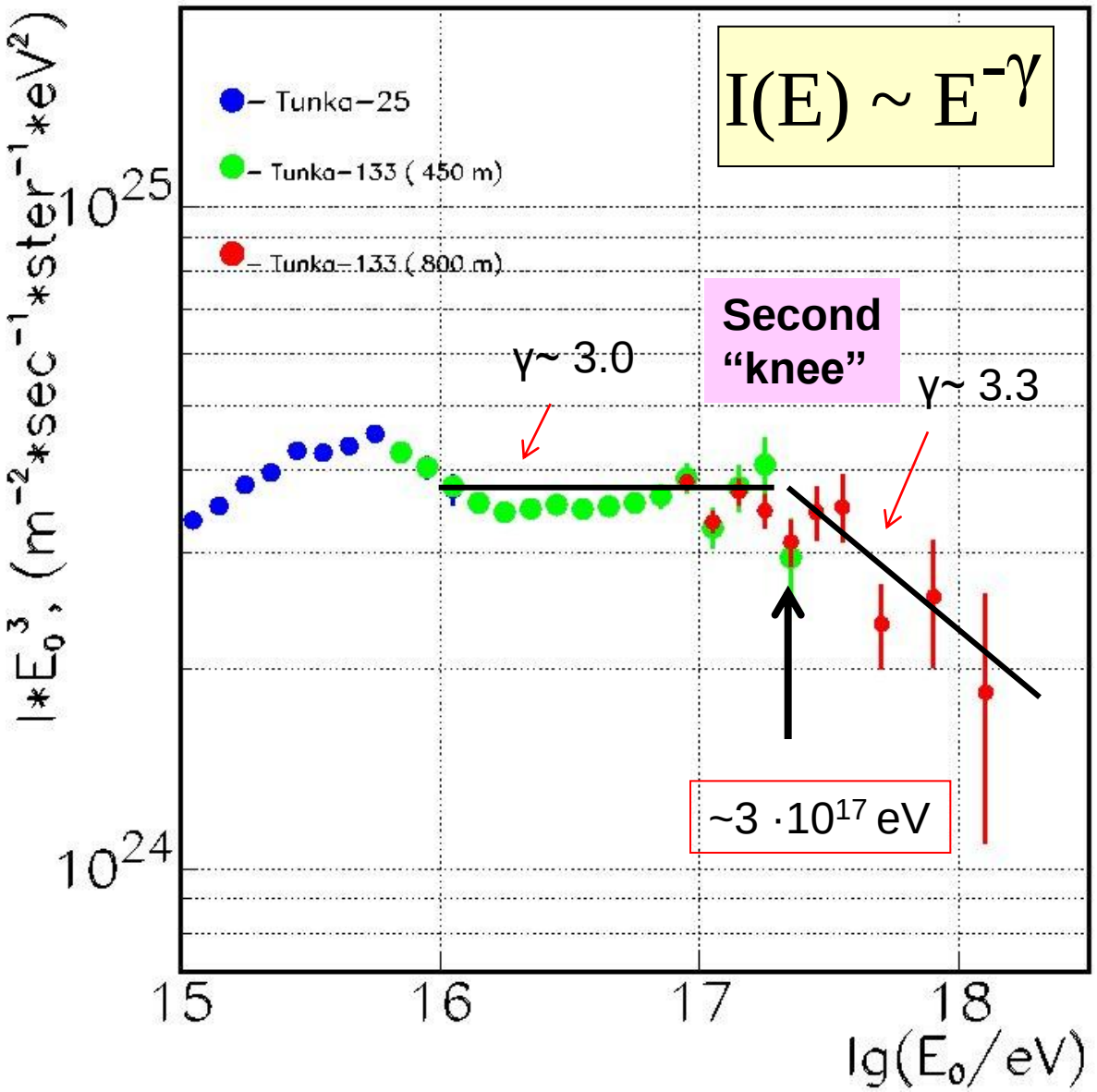
Out-events - core position inside ring: 450 m <R <800 m

> 10^{17} eV: 1900

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



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



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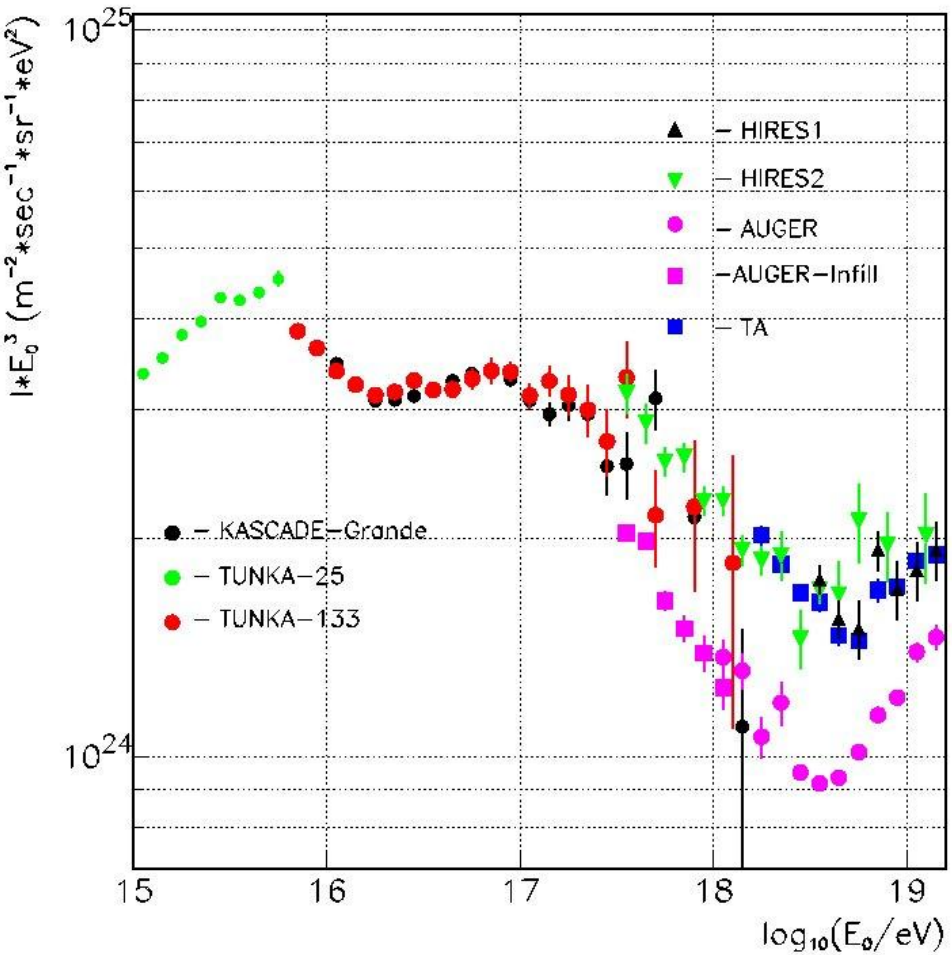


The energy spectrum in the range from 10^{16} to 10^{18} eV cannot be fitted with only one power law index

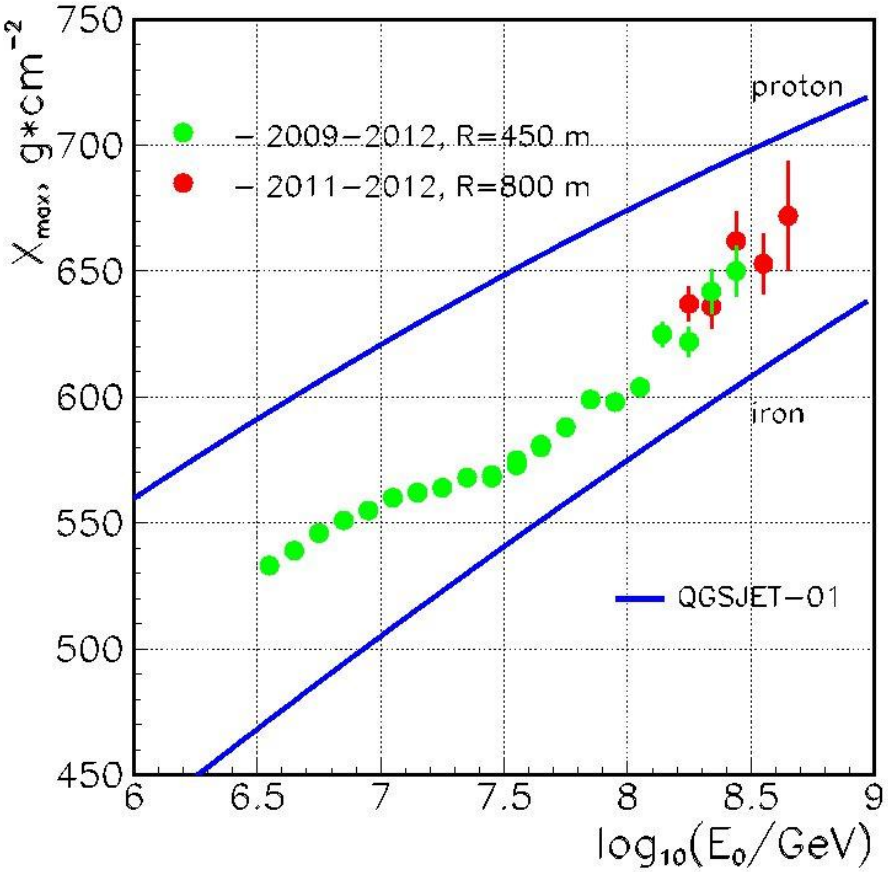
3.21 ± 0.01 ($6\cdot10^{15} – 2\cdot10^{16}$ eV)

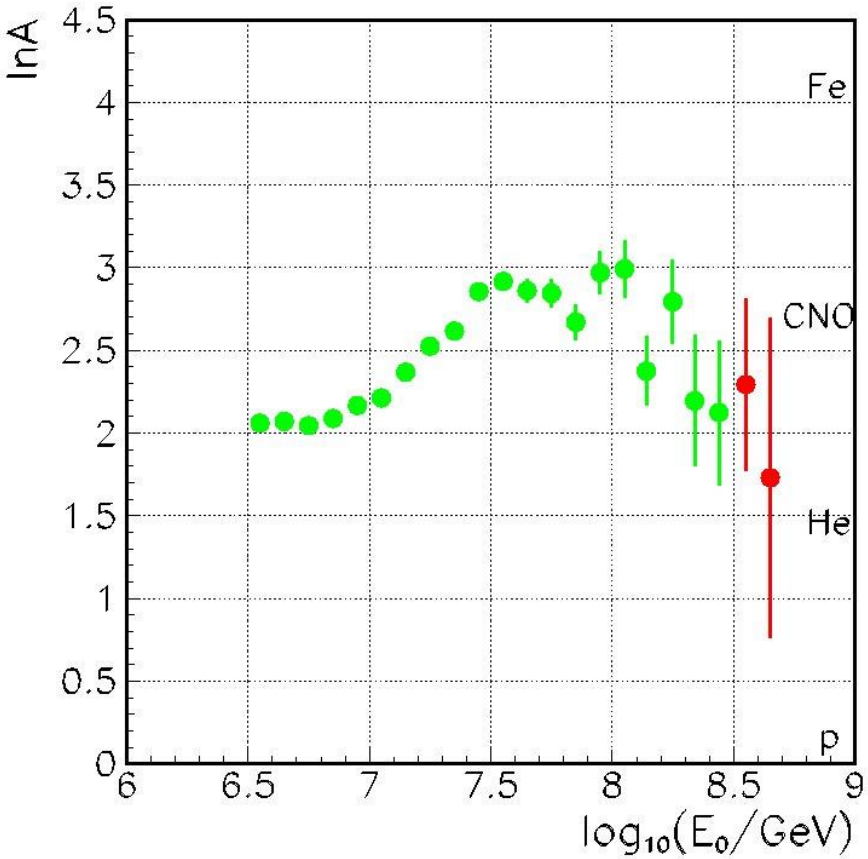
2.97 ± 0.01 ($2\cdot10^{16} – 10^{17}$ eV)

3.30 ± 0.1 ($3\cdot10^{17} – 10^{18}$ eV)

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 starting from an energy 100 PeV

Summary 1

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 EAS arrays.

2. The spectrum in the energy range of 10^{16} to 10^{18} eV cannot be fitted with single power law index. There is an indication on the second knee at ~$3\cdot10^{17}$ eV

   3.21 ±0.01 ($6\cdot10^{15}$ – $2\cdot10^{16}$ eV)

   2.97 ±0.01 ($2\cdot10^{16}$ – 10^{17} eV)

   3.30 ± 0.1 ($3\cdot10^{17}$ – 10^{18} eV)

3. Tunka spectrum is in a good agreement with KASCADE-Grande. The key problem – to increase an accuracy of absolute energy calibration. Is it possible to have 5% accuracy?

4. More statistics is necessary at the energy range of 10^{17} – 10^{18} eV. The Tunka-133 array will continue data taking for another 7-8 seasons.

5. Primary mass composition changes from the light (He) starting from "knee" energy to the heavy at $3\cdot10^{16}$ eV. The mass composition is still heavy at least up to 10^{17} eV. More statistics is necessary in the energy range 10^{17} – 10^{18} eV.

Tunka Collaboration -2012 year

1. Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow, Russia;
2. Institute of Applied Phys. of Irkutsk State University, Irkutsk, Russia;
3. Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;
4. IZMIRAN, Troitsk, Moscow Region, Russia;
5. DESY-Zeuthen, Zeuthen, Germany;
6. Dip. di Fisica Universita' di Torino and INFN, Torino, Italy.

7. A Haungs, F G Schroder, R Hiller, D.Kostunin
Institut f¨ur Kernphysik, Karlsruhe Institute of Technology (KIT), Germany

8. M Kleifges, 1, O Kromer, C Ruhle,
Institut f¨ur Prozessdatenverarbeitung und Elektronik, Karlsruhe Institute of Technology (KIT), Germany

8. D Besson, J Stockham, M Stockham
Department of Physics and Astronomy, University of Kansas, USA

9. D.Horns, M.Tlucziykont , R.Nachtigall, M.Kunnas, M.Bouker, S.. Epimakhov, U. Einhaus D. Hampf
Institut fur Experimentalphysik, Hamburg University, German

10. G.Rowell
School of Chemistry and Physics, University of Adelaide, Australia

In 2013 year we are waiting new members of Tunka-collaboration

11. MPI (Munich, Germany), JINR (Dubna), Mephi (Moscow), ASU (Barnaul), IKFIA (Yakutsk)……

Tunka Future

In near future we intend:

1. To supplement the Tunka-133 with a net of radio antennas [Tunka-REX (Radio Extension) array] in a first step for common operation with the Cherenkov array and then to explore of this novel detection technique for high energy CR studies.

2. To construct a net of large area detectors based on scintillation counters provided by the KASCADE-Grande Collaboration. To develop new and improve existing methods of CR studies and absolute calibration of the Tunka-133 array with joint measurements of Cherenkov and radio radiations as well as EAS charged component.

3. To deploy a fluorescent detector at 7-10 km distance from the Tunka-133 array for joint operation.

4. To create a non-imaging air shower array Tunka – HiSCORE (Hundred*i Square-km Cosmic ORigin Explorer) with at least 10 km² area to explore the γ-ray sky beyond 10 TeV and cosmic rays with energy 100 TeV - 1 EeV.

Tunka Rex – Tunka Radio Extension

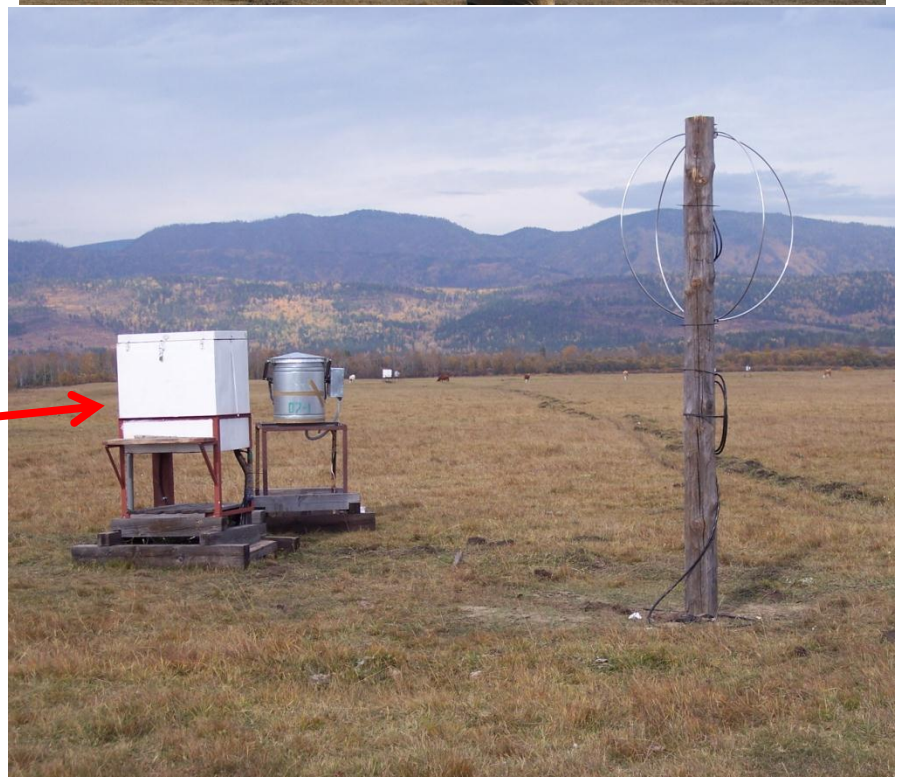
- At present time Tunka-Rex is an array of about 20 antennas, which covers an area of 1km^2. It measures the radio emission of cosmic-ray air showers above 10^{16} eV. It is triggered by the Tunka- 133 array. The radio-Cherenkov-hybrid measurements thus offer a unique opportunity for a cross calibration of both calorimetric detection methods.
- The main goal of Tunka-Rex is to determine the precision of the radio reconstruction for the energy and mass composition of CR , and thus to experimentally test theoretical predictions that the radio precision can be similar to the precision of air-Cherenkov and fluorescence measurements. At the same time, Tunka-Rex can demonstrate that radio measurements can be performed on a large area for a relatively cheap price. Finally, radio-antenna arrays have the perspective to increase the effective observation time compared to air-Cherenkov and fluorescence detectors by an order of magnitude.

Registration of radio signals from EAS

Short Aperiodic Loaded Loop Antenna (SALLA)
(A.Haungs et al. Institute fur Kernphysick, Forschungszentrum, Karslruhe, Germany

20 antennas SALLA were installed in autumn 2012

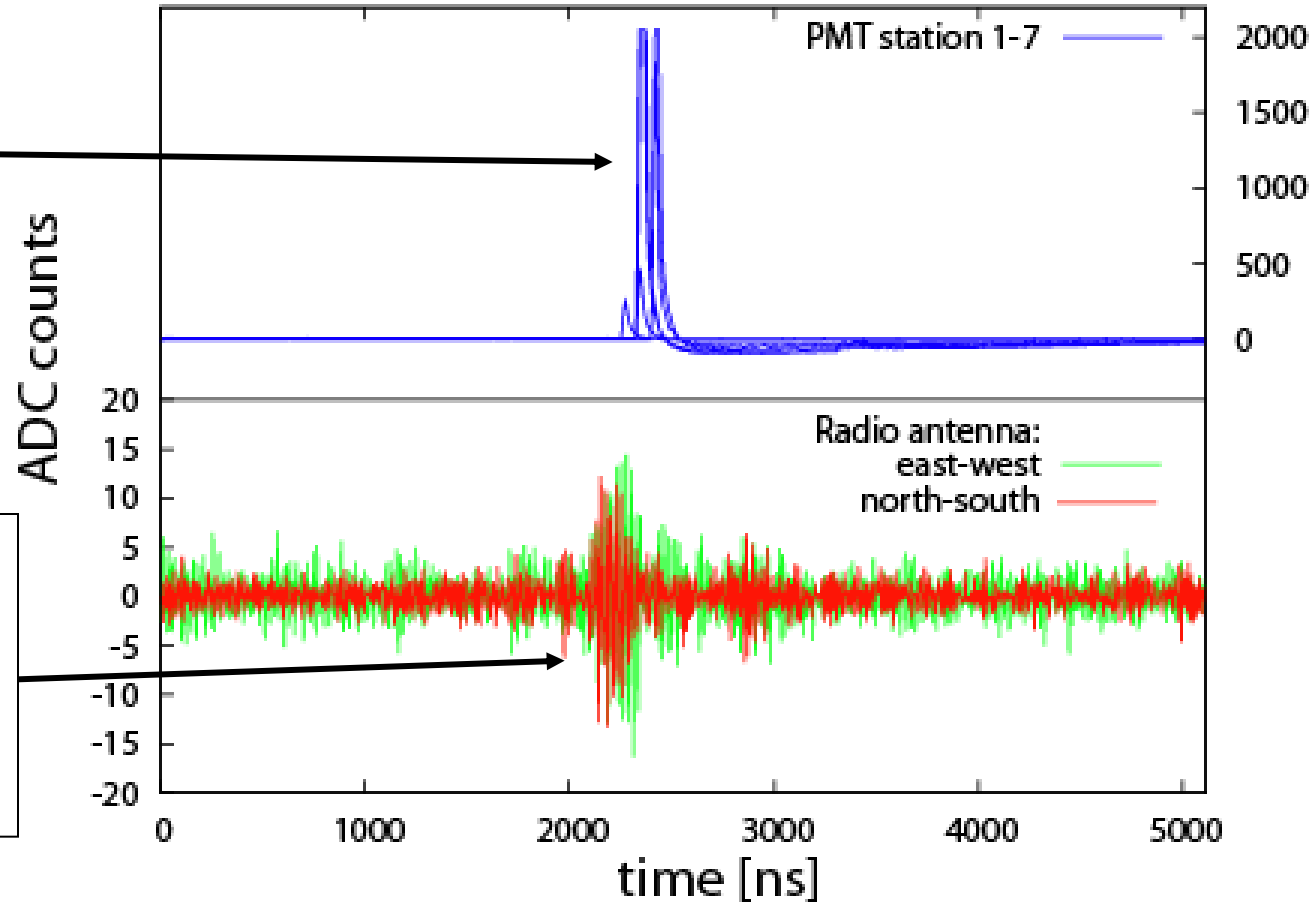
Antennas are connected to the free FADC channels of Tunka-133 cluster electronics



A lot of selected EAS radio candidates were found.

PMT signals

A radio pulse in both polarizations shortly before PMT signals



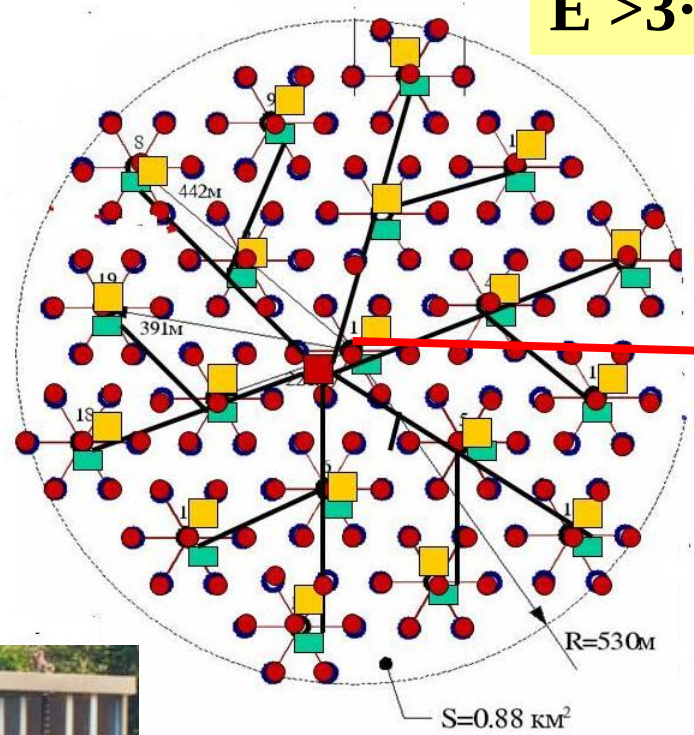
Detectors of charge EAS component

- **In 2012 the University of Torino transferred scintillation counters of KASKADE-Grande for joint operation with the Tunka-133 array. It is planned to start deployment of scintillation stations for detection of EAS charged particles in summer of 2013. All together 24 stations will be installed 10 m^2 area each.**

- **It will allow to develop new and improve existing methods of studies of CR in the energy region of Galactic cosmic rays acceleration limits and absolute calibration of the Tunka-133 array with joint measurements of Cherenkov and radio radiations as well as EAS charged component.**

2012 - 2013 years

More then 2000 events with E >3·10^{16} eV per season

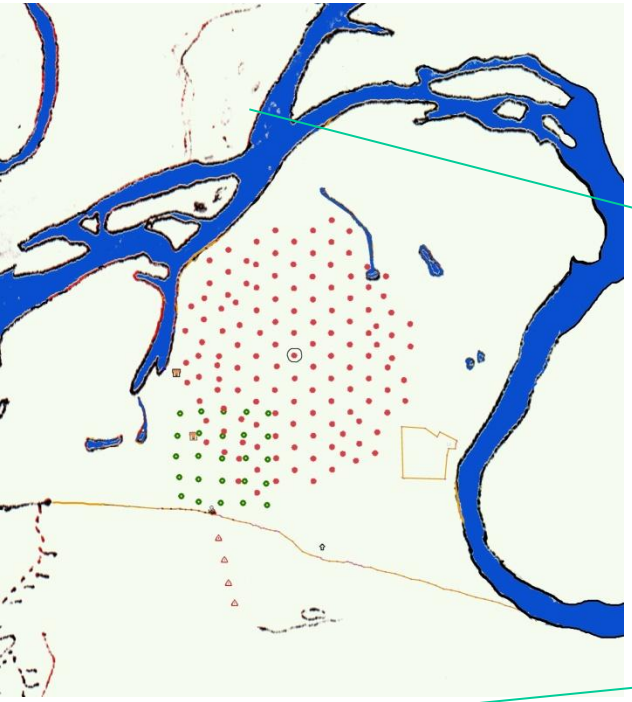


1 км

-20 scintillation counters, 10 m^2

-20 Radio -antennas SALLA

Cross calibration of Cherenkov light and fluorescent light methods.



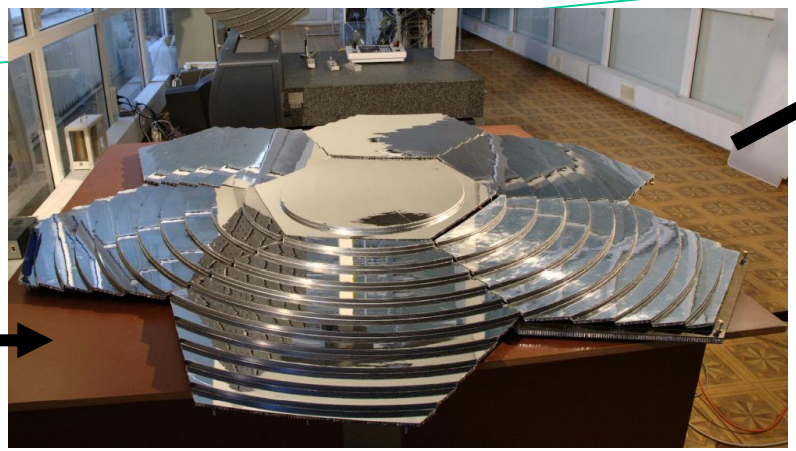


Image detector from TUS experiment

Mirror area is S = 10 м^2

Field of view ± 7 deg

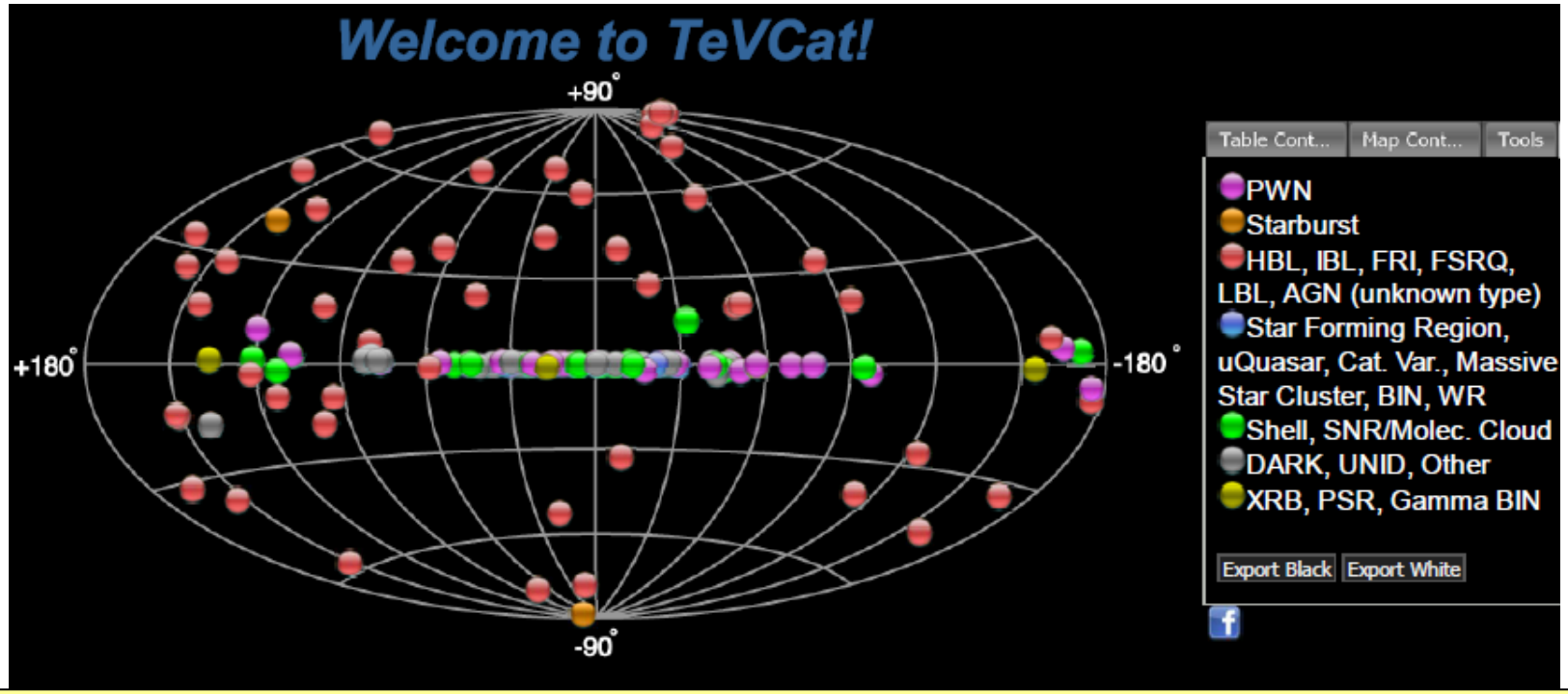
Gamma observatory

Tunka – HiSCORE

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

(More details: O.Gres', Poster No.72)

For recent years gamma-astronomy became the most dynamically developing direction of high energy astro- physics. Gamma-radiation with energy higher than 1 TeV from more then 100 local sources has been detected.



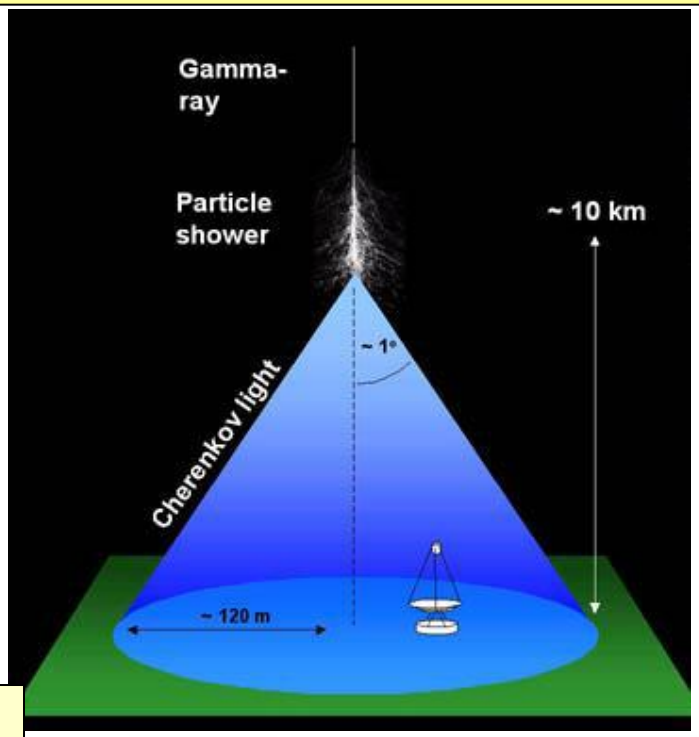
Advantages of gamma-astronomy:

- gamma-quanta preserve the direction to the source;

-relative simplicity of γ-ray detection in comparison with neutrino.

IACT - *Imaging Atmospheric Cherenkov Telescopes*

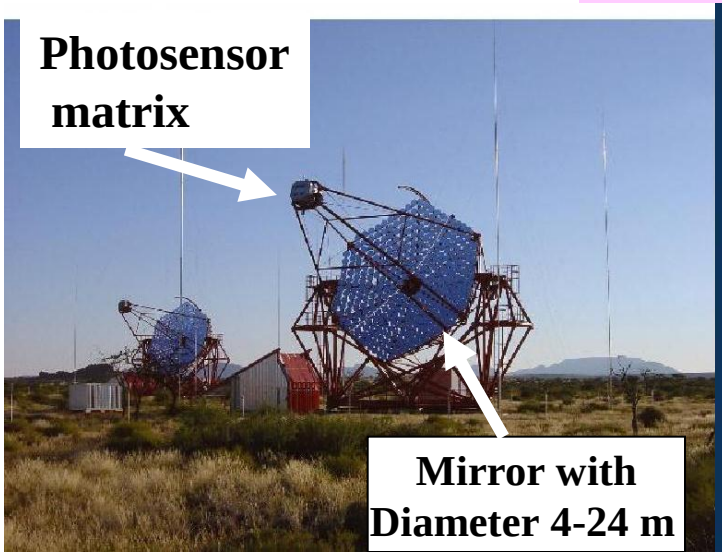
HESS
MAGIC
VERITAS
AIROBIC
Fermi
Argo-YbJ
Tibet-III
Future Projects
CTA – 2017-18
HAWC -2014
LHAASO – 2017-18

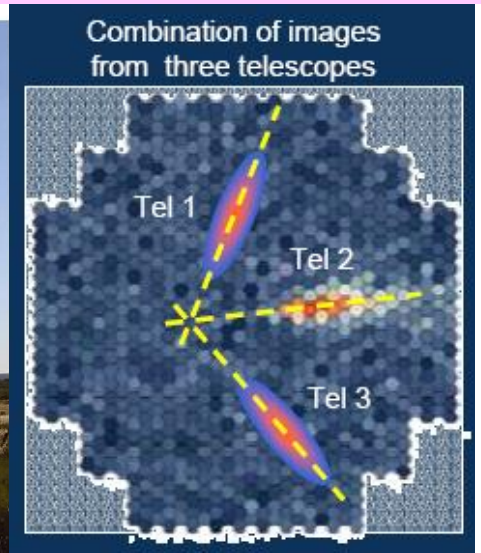


To detect Ultra-High energy gamma-rays effective area of array must be 10 km^2 at least.
An Imaging ACT must have >10000 channels / km^2.

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 matrix of photosensors, in which EAS image is formed





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

Non-imaging air Cherenkov array

Area: from 1 to 100 km^2

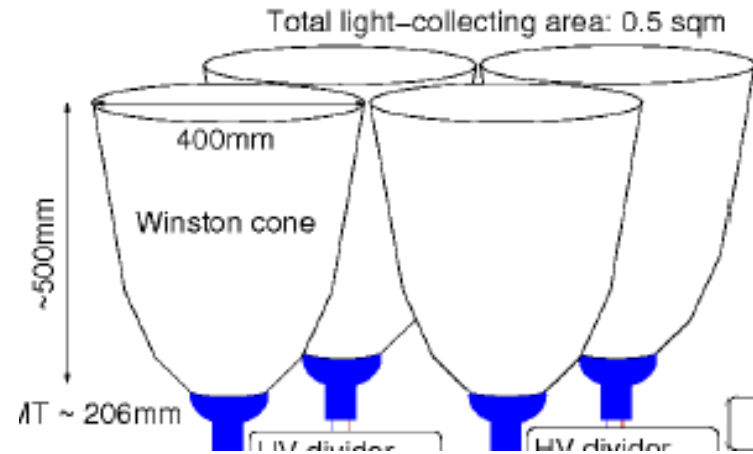
Spacing between detector stations 100-200 m

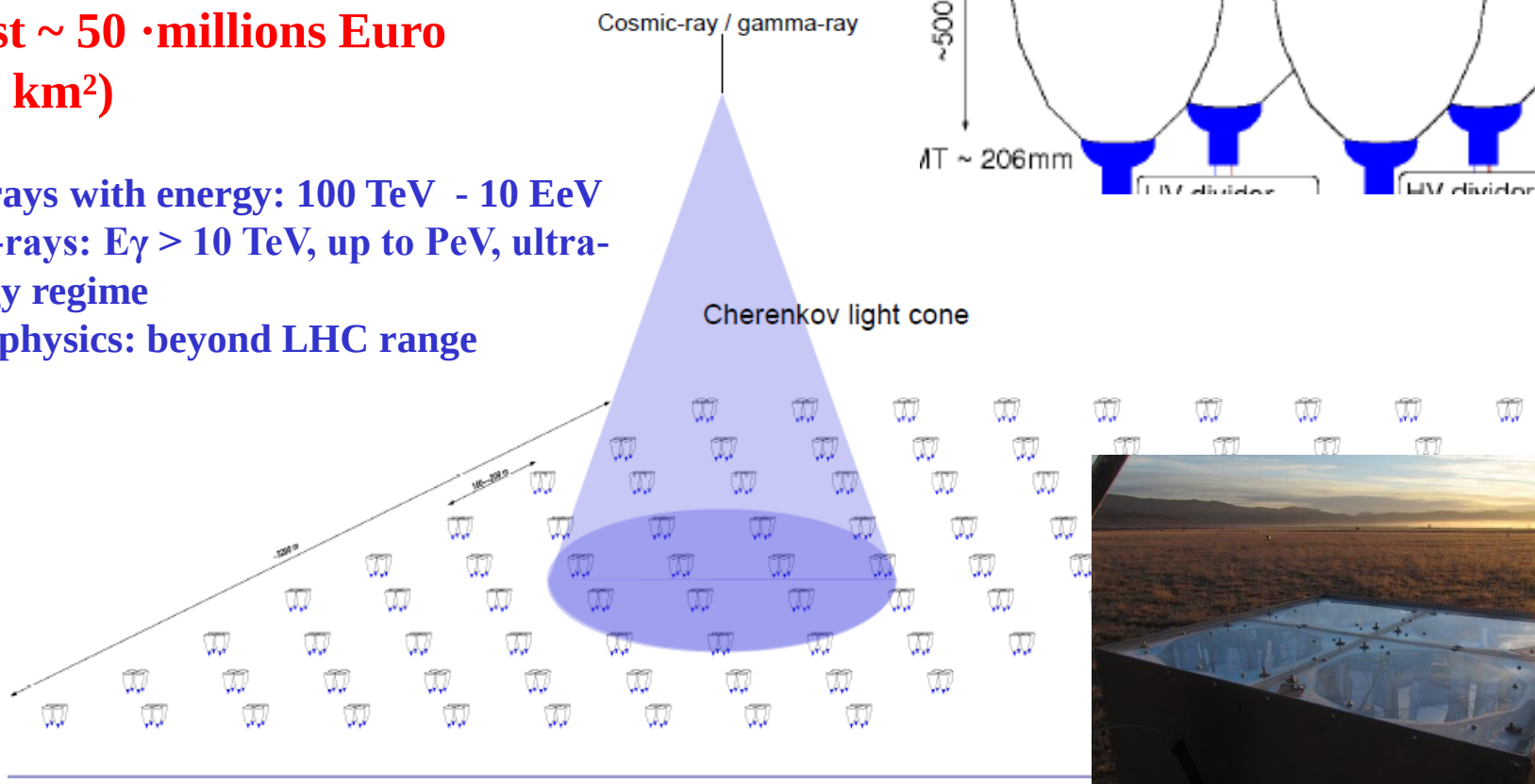
Large Field of view: ~ 0.6 sr

~200 channels / km.

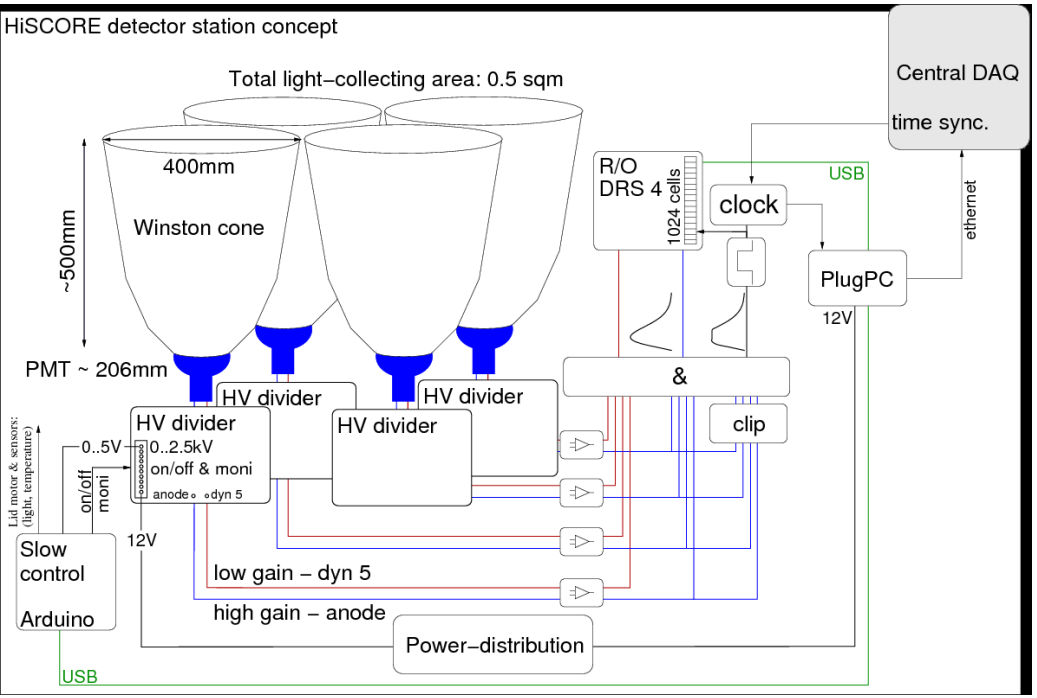
Total cost ~ 50 ·millions Euro (for 100 km^2)

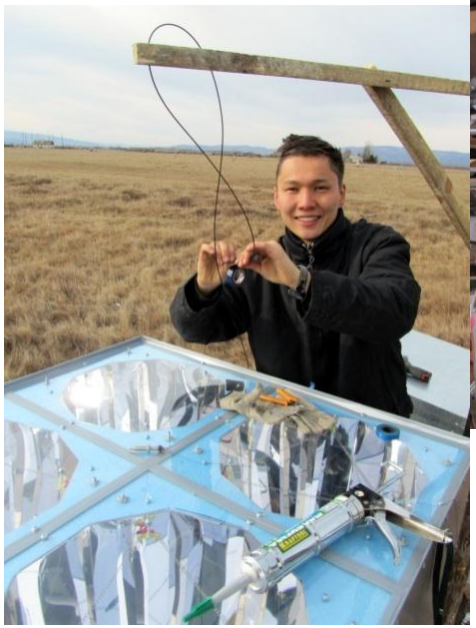
- **Cosmic-rays with energy: 100 TeV - 10 EeV**
- **Gamma-rays: Eγ > 10 TeV, up to PeV, ultra-high energy regime**
- **Particle physics: beyond LHC range**

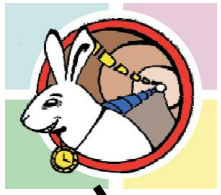




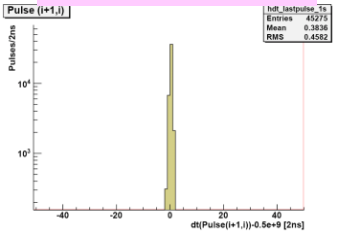
Tunka-HiSCORE optical station

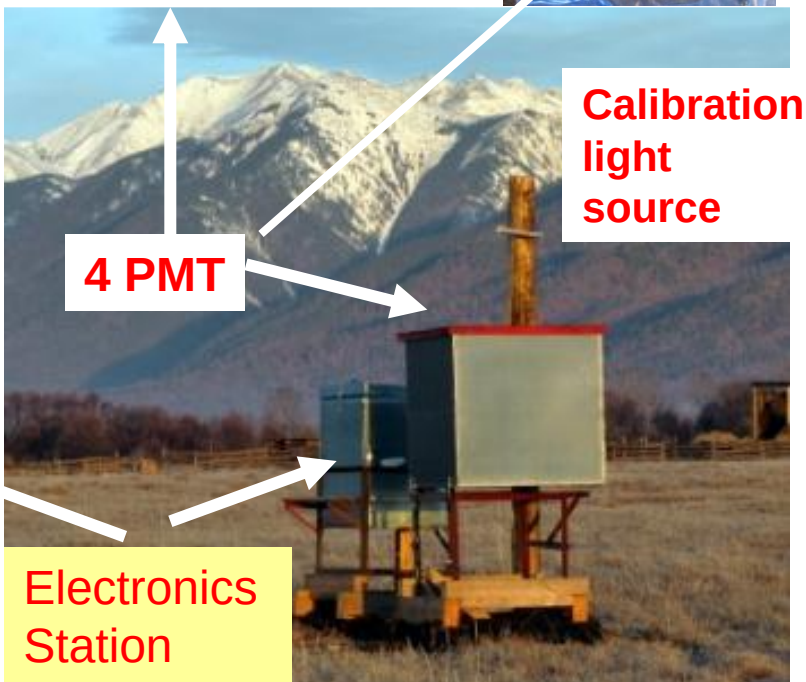






rms <0.2 ns





Main Topics for Tunka-HiSCORE

Gamma-ray Astronomy

Search for the PeVatrons.

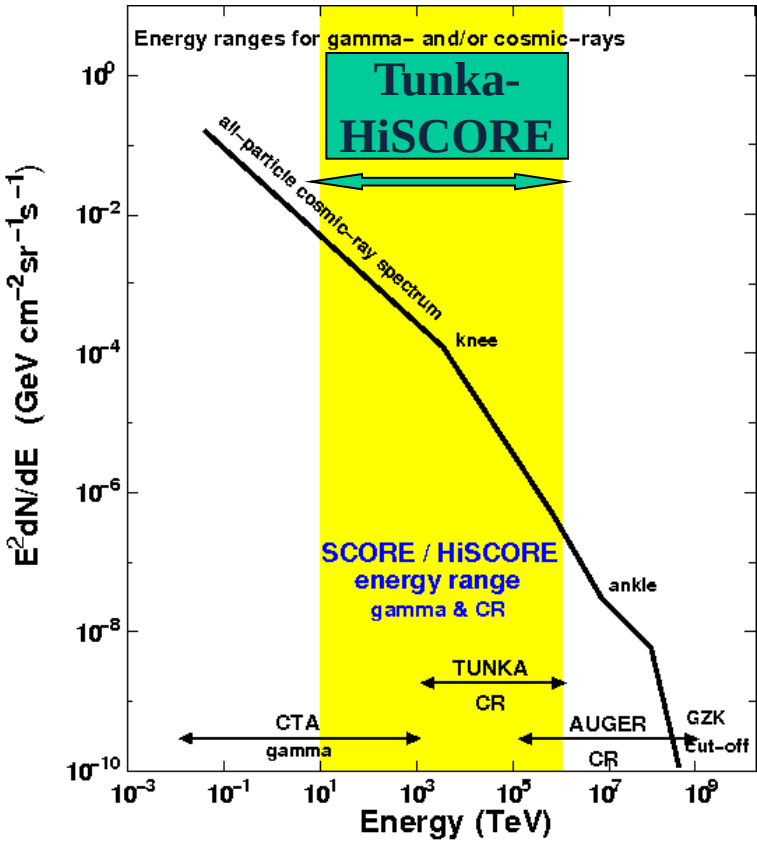
VHE spectra of known sources:
where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition
from 10^{14} to10^{18} eV.
10^8 events (in 1 km^2 array) with energy > 10^{14} eV
per one season (400 hours).

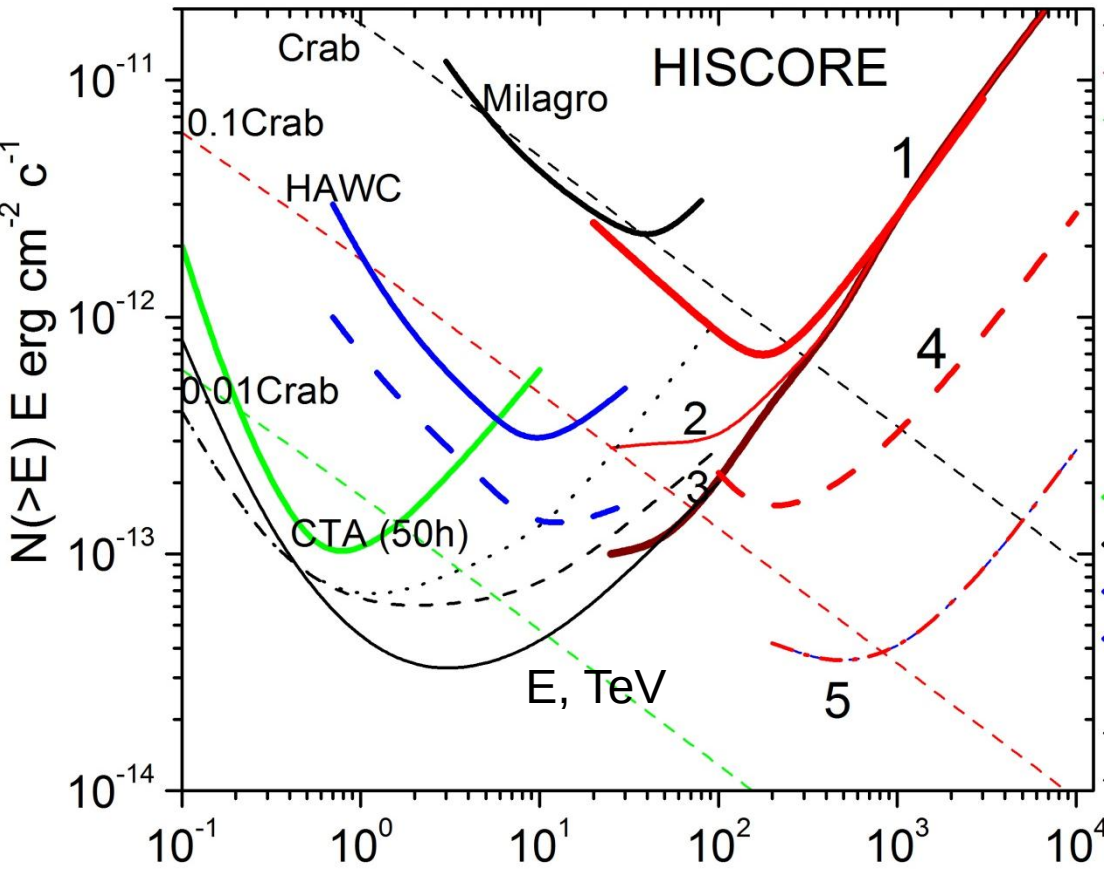
Particle physics

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



Gamma-ray point-source survey sensitivity for Tunka-HiSCORE

(for statistics: 50 events or 5 RMS during T = 500 hours)



1 – 1 km^2, 4 x 8'' PMTs per station

2 – 1 km^2, 4 x 12" PMTs per station + net of mirrors (S = 2 m^2, ±7-10° FOV, without imaging)

2' mounting of matrix in each mirror (not yet simulated)

3 = 2 plus 10^4 m^2 muon detectors

4 – 10 km^2 , 4 x 8" PMTs per station

4'- 10 km^2 for 12'' PMT (not yet simulated)

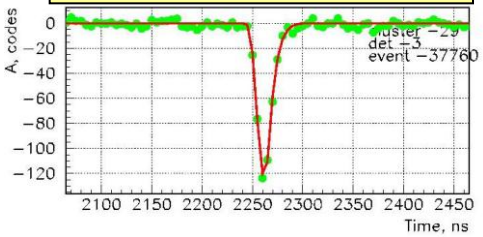
5 – 100 km^{2,4} x 8'' PMTs per station

What we can see with 1 km^2 array (short list)

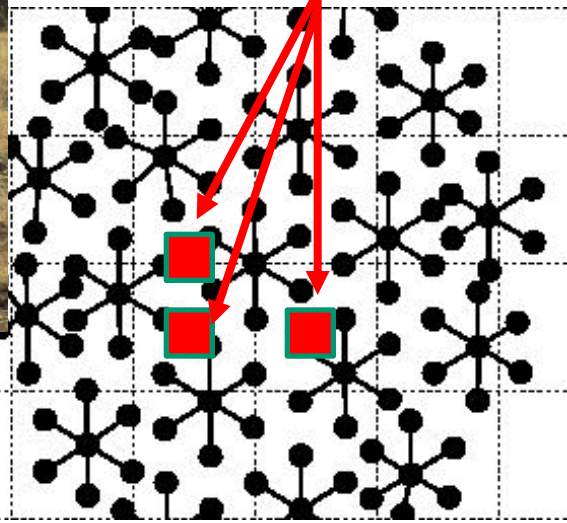
Name	RA degrees	Decl	Flux F at 1 TeV, 10^{-12}cm^{-2} s^{1}TeV^{-1} Γ	Flux F at 35 TeV, 10^{-17}cm^{-2} s^{-1}TeV^{-1} (from Milagro)	Time of observation per one year (x 0.5- weater factor)	Number of events per one season E> 20 TeV
Tycho SNR (J0025+641)	6.359	64.13	0.17 ±0.05 Γ=1.95 ±0.5		**236h**	**88**
Crab	83.6329	22.0145	32.6 ±.9.0 Γ=2.6 ±0.3	162.6 ±9.4	**110h**,	**680**
SNR IC443 (MAGIC J0616+225)	94.1792	22.5300	0.58 ±0.12 Γ=3.1 ±0.30	28.8 ±9.5	**112h**,	**2** –(from MAGIC) **50 (** from Milagro)
Geminga MGRO C3 PSR	98.50	17.76		37.7 ±10.7	**102h**,	**80**
M82 (Starburst Galaxy)	148.7	69.7	0.25 ±0.12 Γ=2.5 ±0.6±0.2		**325h,**	**22**
Mkn 421 (BL, z=0.031 Variable)	166.114	38.2088	50-200 Γ=2.0-2.6		**140h**	**20 - 1000**
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**	**140** (from VERITAS **235** (from Milagro)
Cas A (SNR, G111.7-2.1)[6]	350.853	58.8154	1.26 ±0.18 Γ=2.61 ±0.24±0.2		**177h**	**40**
CTA_1(SNR,PWN)	1.5	72.8	1.3 Γ=2.3		**266 h**	**200**

In October 2012 3 HiSCORE optical stations were put in operation together with Tunka-133

Signal from Tunka -HiSCORE



New Tunka -HiSCORE



Cherenkov detectors of Tunka-133 array

3 stations in October 2012

S=1 km^2, 60 stations, 150 m step, 240 PMTs (150 PMTs are available), 1 M Euro, 2012 – 2014

Decreasing of energy threshold

S = 1 km^2, 60 station with 240 PMT (12”) + 15 mirrors
(S = 2 m^2)
- Without matrix of PMTs
- With matrix of PMTs
Cost: 5 M Euro.

10000 m^2 scintillation detectors (1% of the whole area)
– 2-5 muons from 25 TeV protons
Cost: 20-25 M Euro.

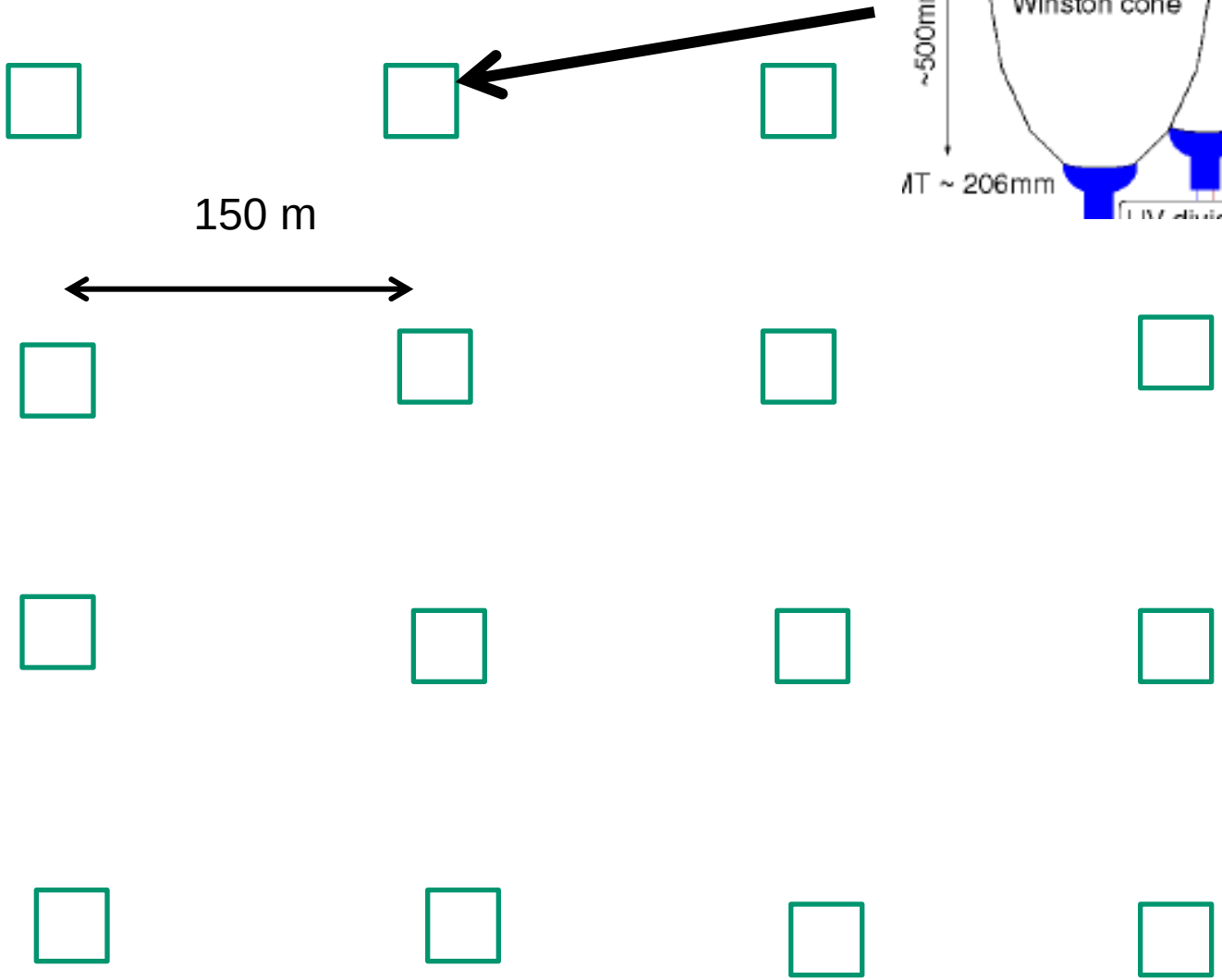
Increasing of area of array

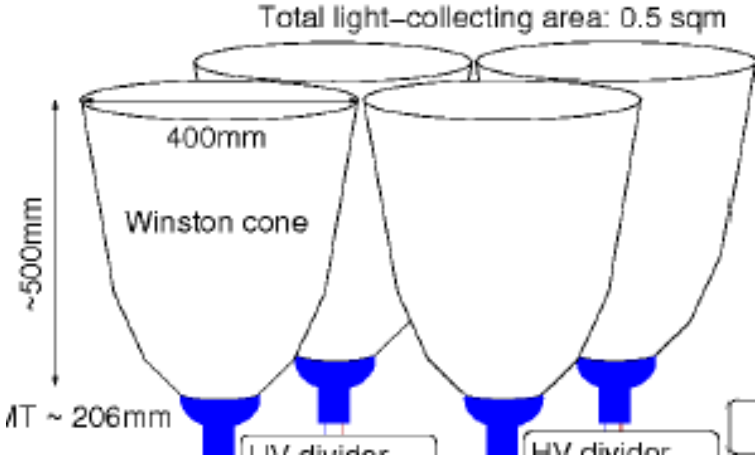
S = 10 km^2, 225 station , 200 m step, 1000 PMT, 5-6 M Euro.

Probably, choose new Place for deployment ?

S = 100 km^2, 2000 station,
1 PMT in station
10-12 M Euro

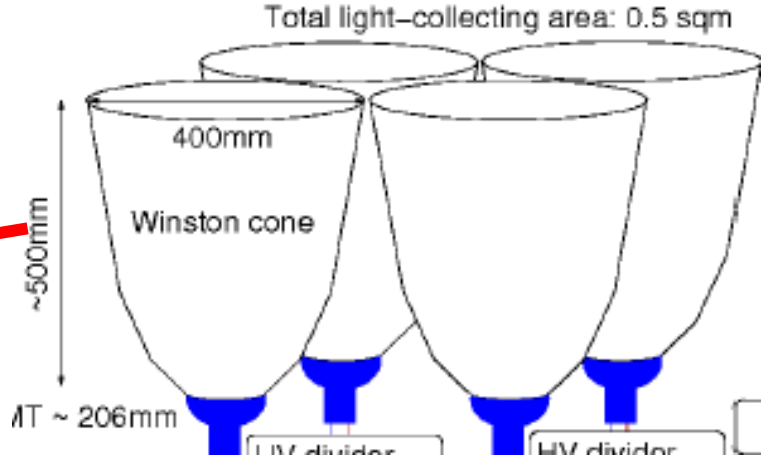
Tunka-HiSCORE – 1 km² stage 1





9352KB
8”, ET

Tunka-HiSCORE – 1km^2 stage 1A



150 m

300 m

Installing of PMTs matrix, Image techniques

2 m ^{2} mirror, ±7º FOV,

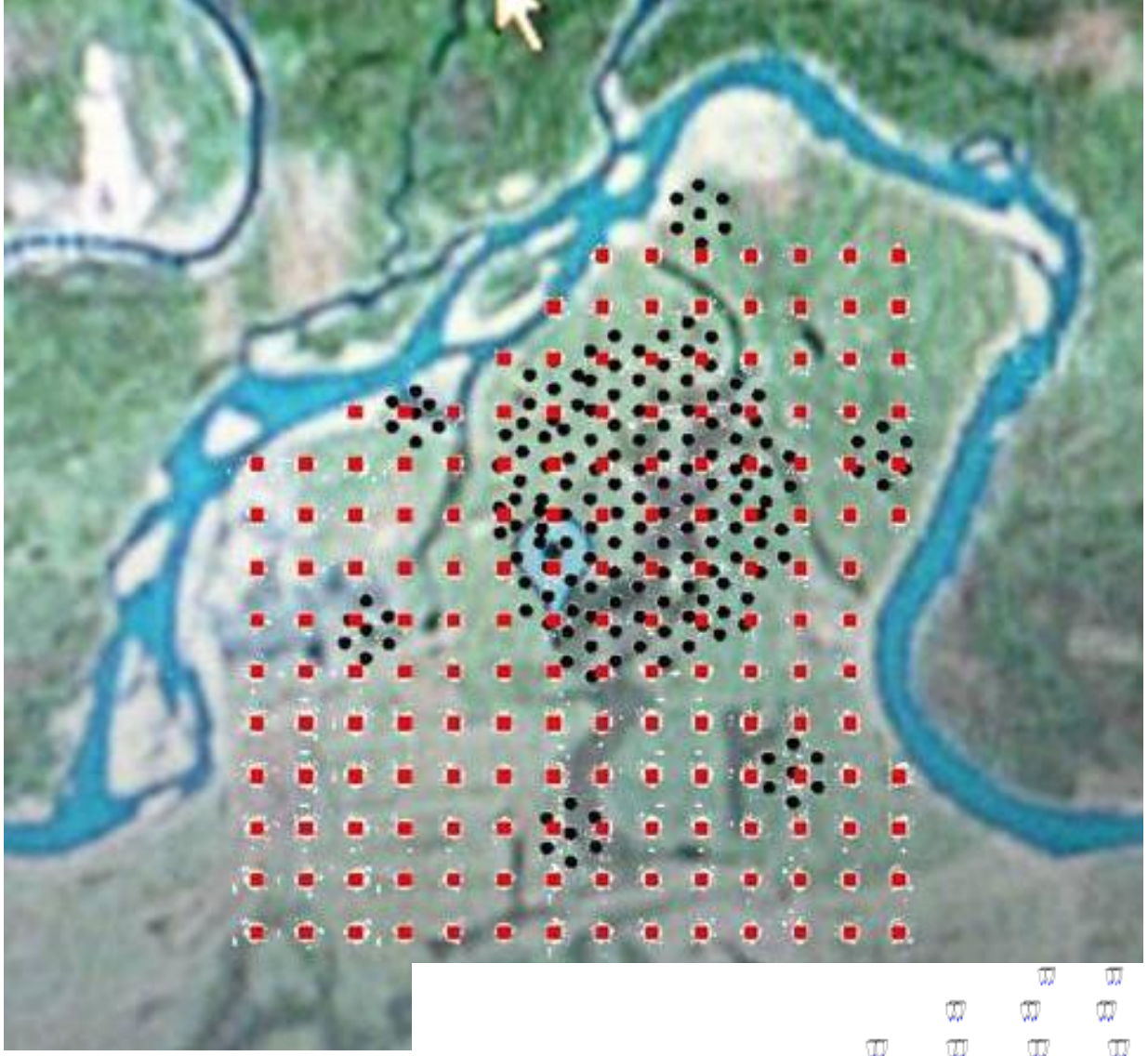
Tunka : 2013-2014

HiSCORE, stage 1

Scintillation detectors
S = 8-10 m^2

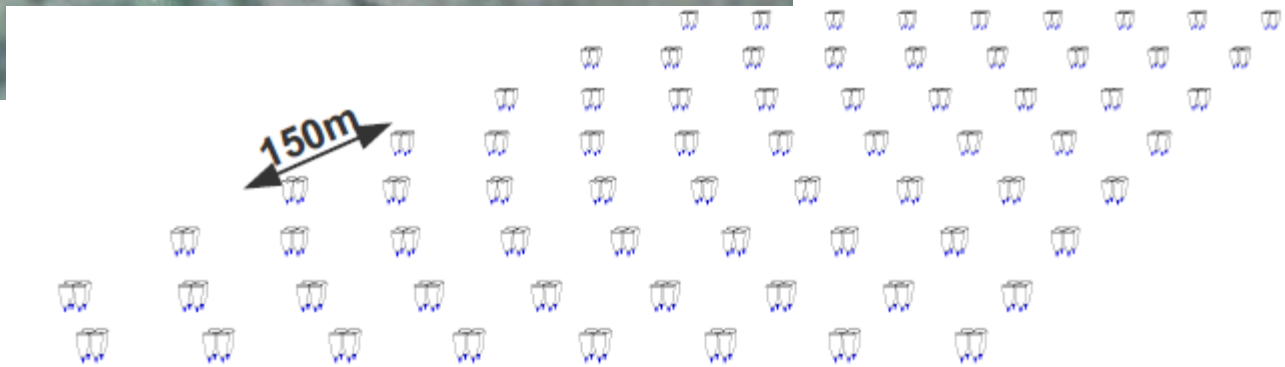
Tunka-133,
175 Cherenkov detectors

Radio antenna



2015-2016 year

Tunka-HiSCORE, stage 2, S = 10 km^2



Summary 2

1. In 2013 year Cherenkov Tunka-133 array will be supplemented with large scintillate detectors and a fluorescent light detector, so all components of EAS: Cherenkov, radio and fluorescent emission as well charge particles will be measurement in Tunka experiment.

2. In near future we intend to create the new Tunka-HiSCORE observatory with area at least 10 km^2 which 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 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).

- 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.

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Thank you!