The Tunka Experiment: Cosmic Ray and Multi-TeV Gamma-Ray Astronomy Arrays in the Tunka Valley

Bayarto Lubsandorzhiev
Institute for Nuclear Research of RAS, Moscow Russia
for
TUNKA and TAIGA Collaborations

Outline

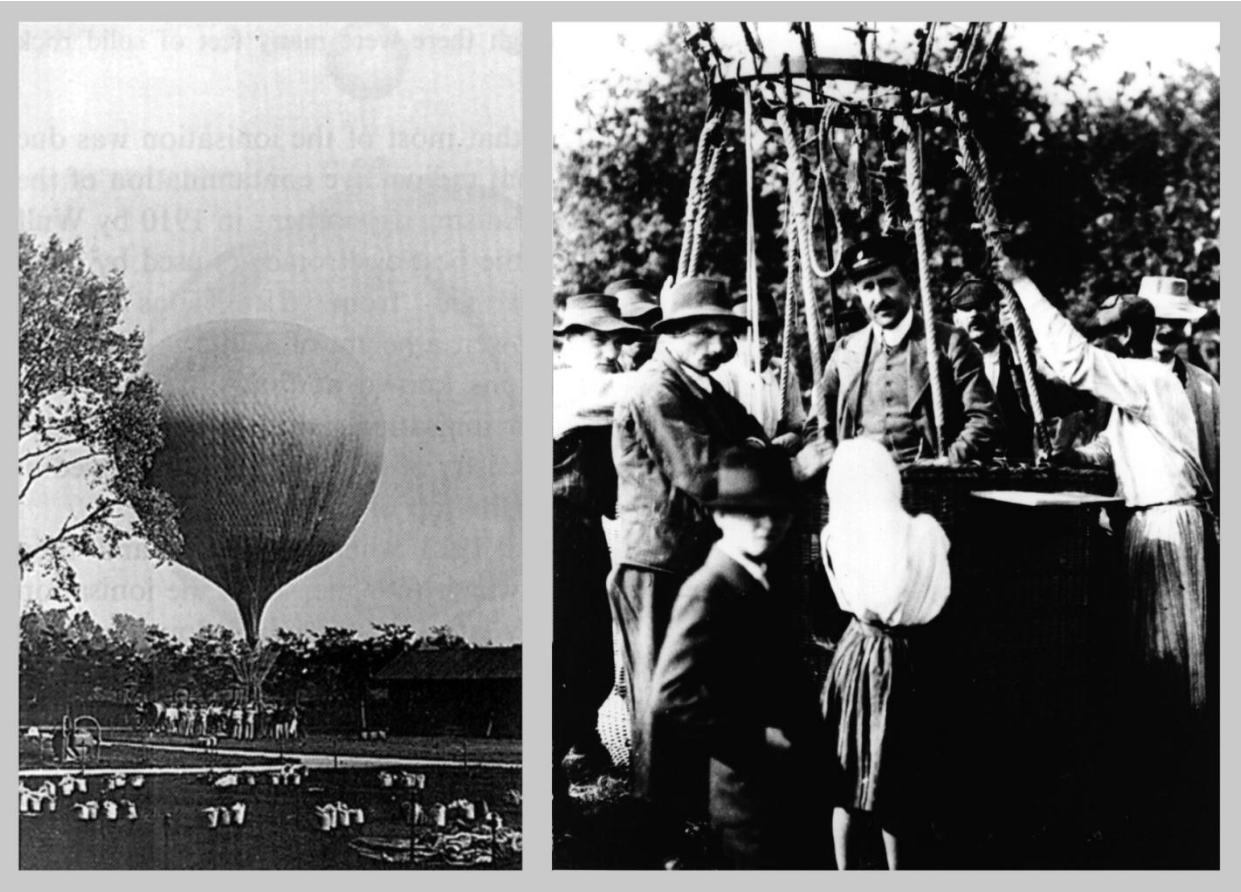
Introduction

Tunka-25

Tunka-133

TAIGA
(Tunka Advanced Internatinal Gamma and cosmic ray Array)

Victor Hess 1912 г. – the discovery of cosmic rays



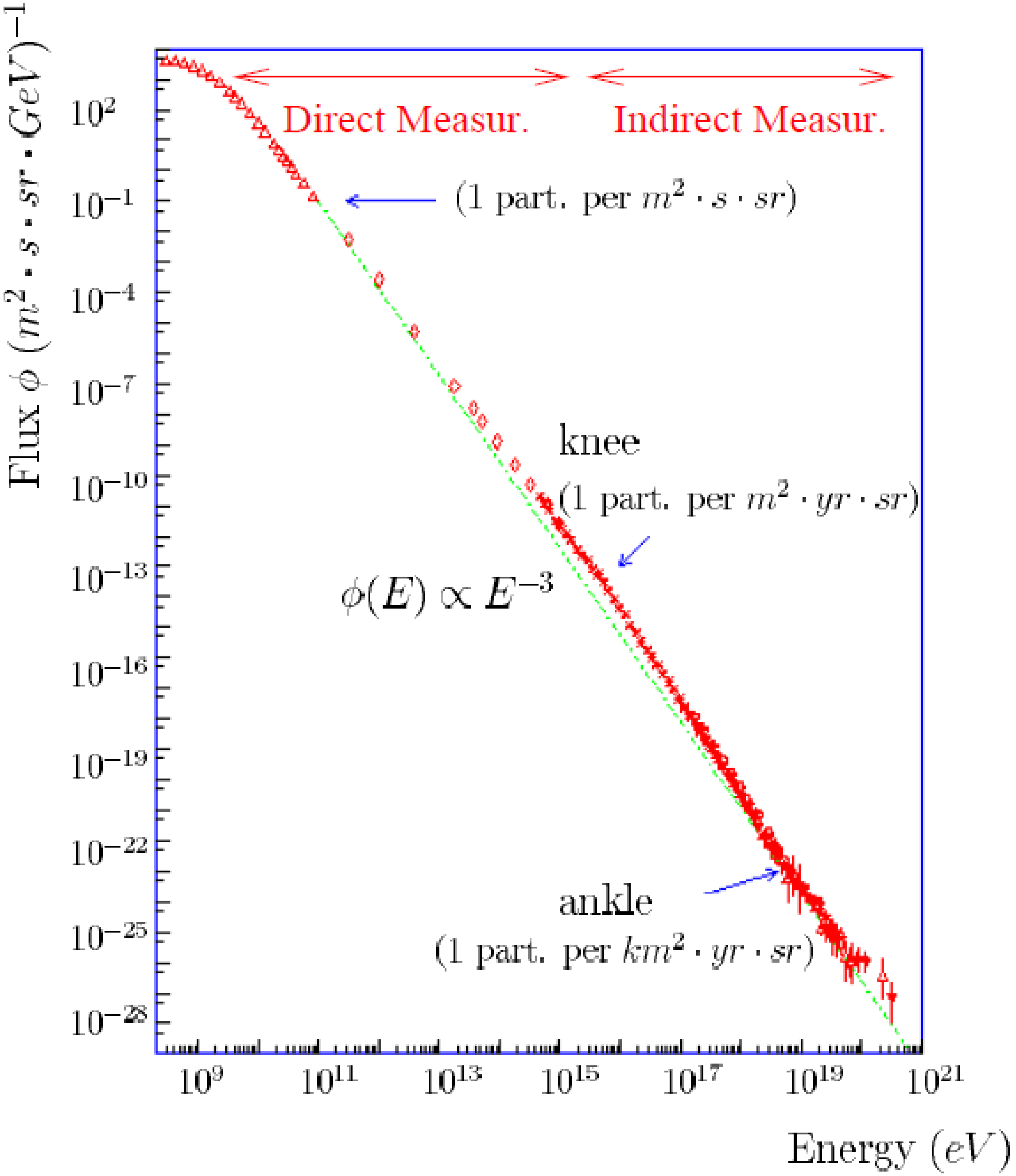
On a balloon at an altitude of 5000 meters Victor Hess discovered “penetrating radiation” coming from space.
Nobel prize 1936

The origin of cosmic rays? – XX-XXI century mystery!

Where from? - Energy?

Where? - Sources?

How? - Acceleration mechanisms?

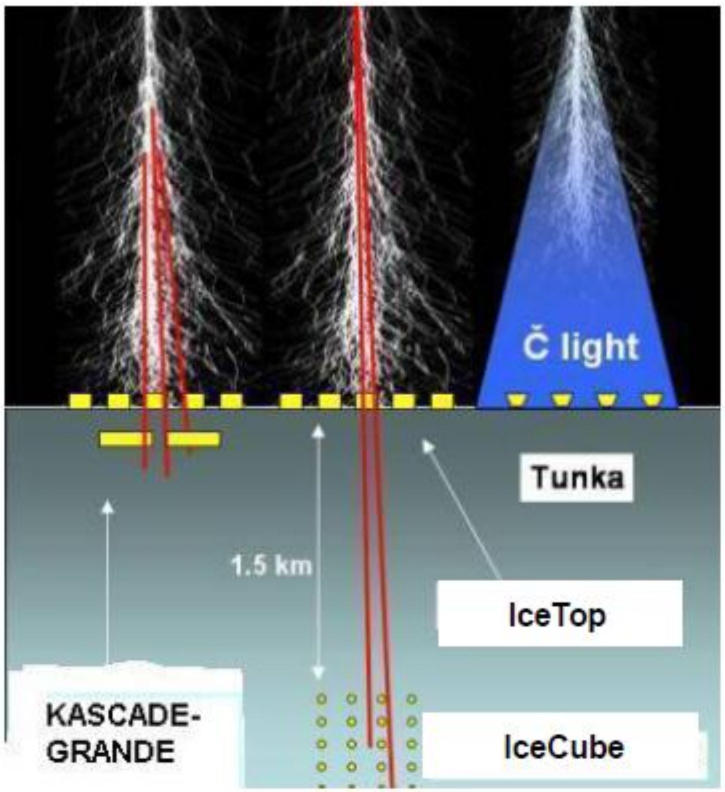


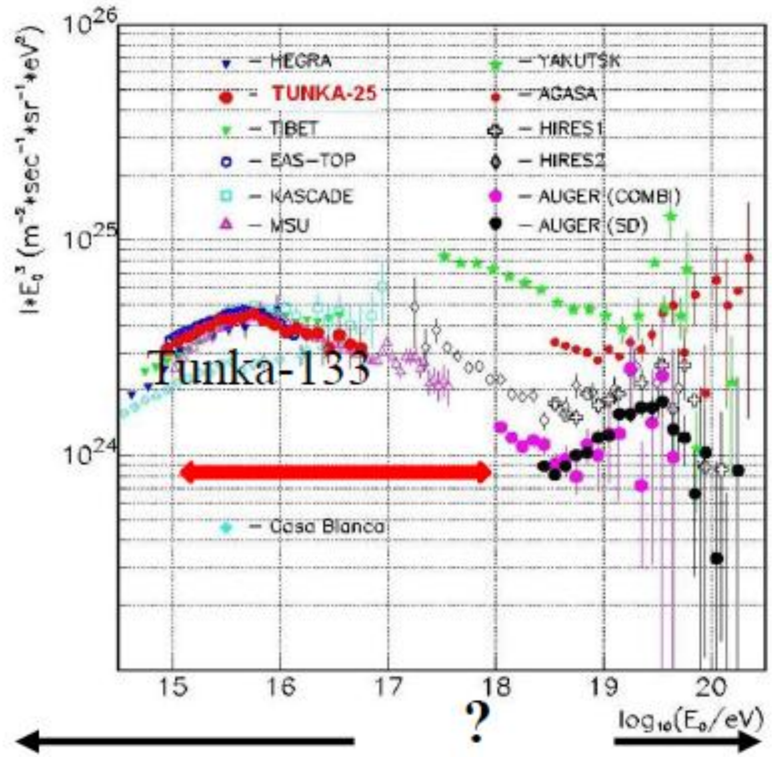
Flux ϕ $(m^2 \cdot s \cdot sr \cdot GeV)^{-1}$
Direct Measur.
Indirect Measur.
(1 part. per $m^2 \cdot s \cdot sr$)
knee
(1 part. per $m^2 \cdot yr \cdot sr$)
$\phi(E) \propto E^{-3}$
ankle
(1 part. per $km^2 \cdot yr \cdot sr$)
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
Energy (eV)

Search for the Acceleration Limit of Galactic Sources

- Energy range 10^{16}-10^{18} eV demands:
- 1 km² with spacing smaller than that at Auger
- complementary techniques

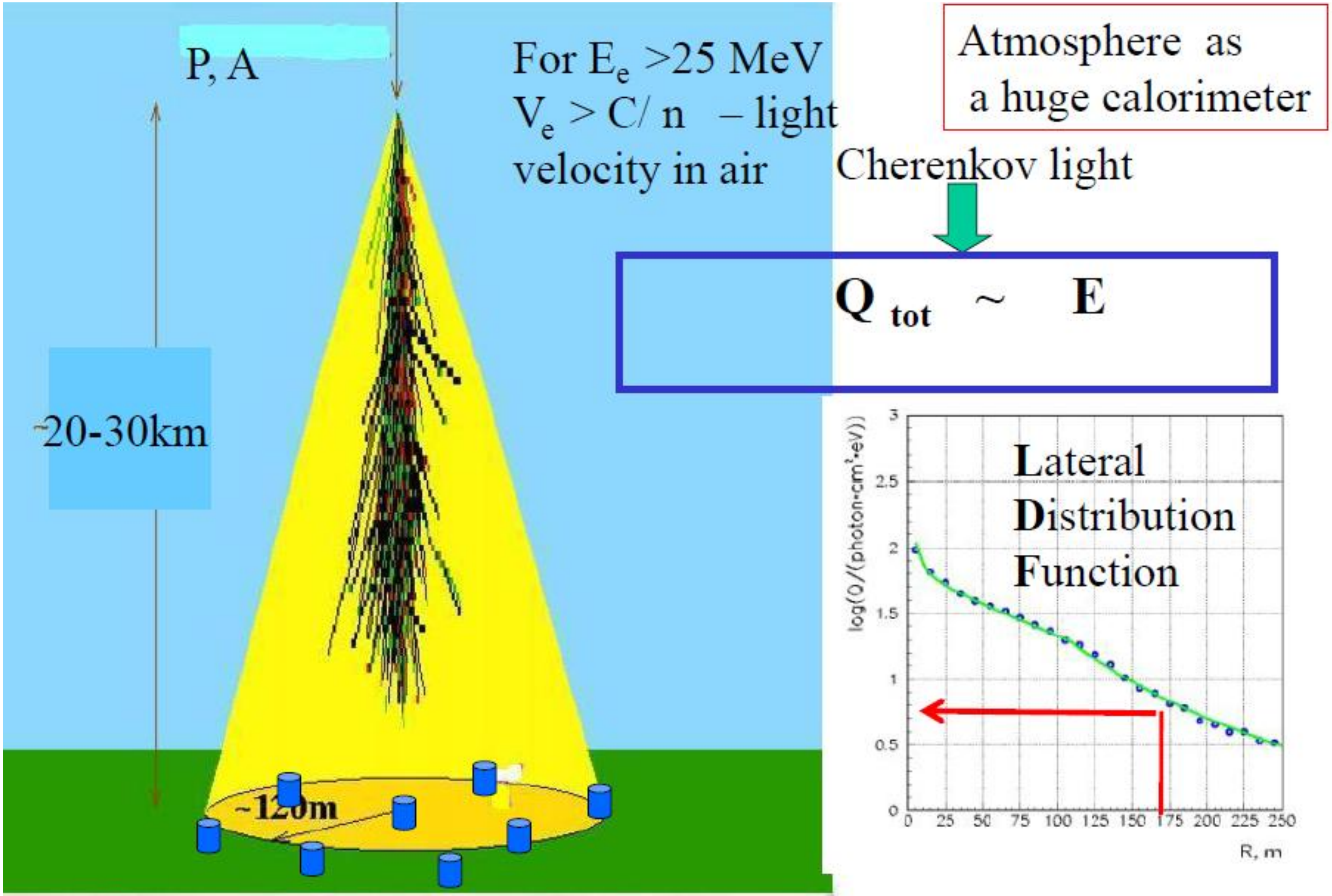
- KASCADE-Grande	*terminated*
- IceTop/IceCube	***in operation***
- **Tunka-133 (calorimetric)**	***in operation***
- NEVOD-DÉCOR	***in operation***
- Auger low energy extension	***in operation***
- ***HiSCORE***	*planned*
- *LHAASO*	*planned*





CR from SNR CR from AGN

Detection of Cherenkov light from EAS



Photons detectors

E (PeV) = 0.4 Q(175) ph· ev^{-1} cm^{-2}

Advantage of Cherenkov Technique:

1. Good energy resolution - up to 15%
2. Good accuracy of X_{max} - 20 -25 g/cm^2
3. Good angular resolution - 0.1 – 0.3 deg
4. Low cost – Tunka-133 – 1 km^2 array:

   $0.5\ 10^6$ Eur (construction and deployment)

+

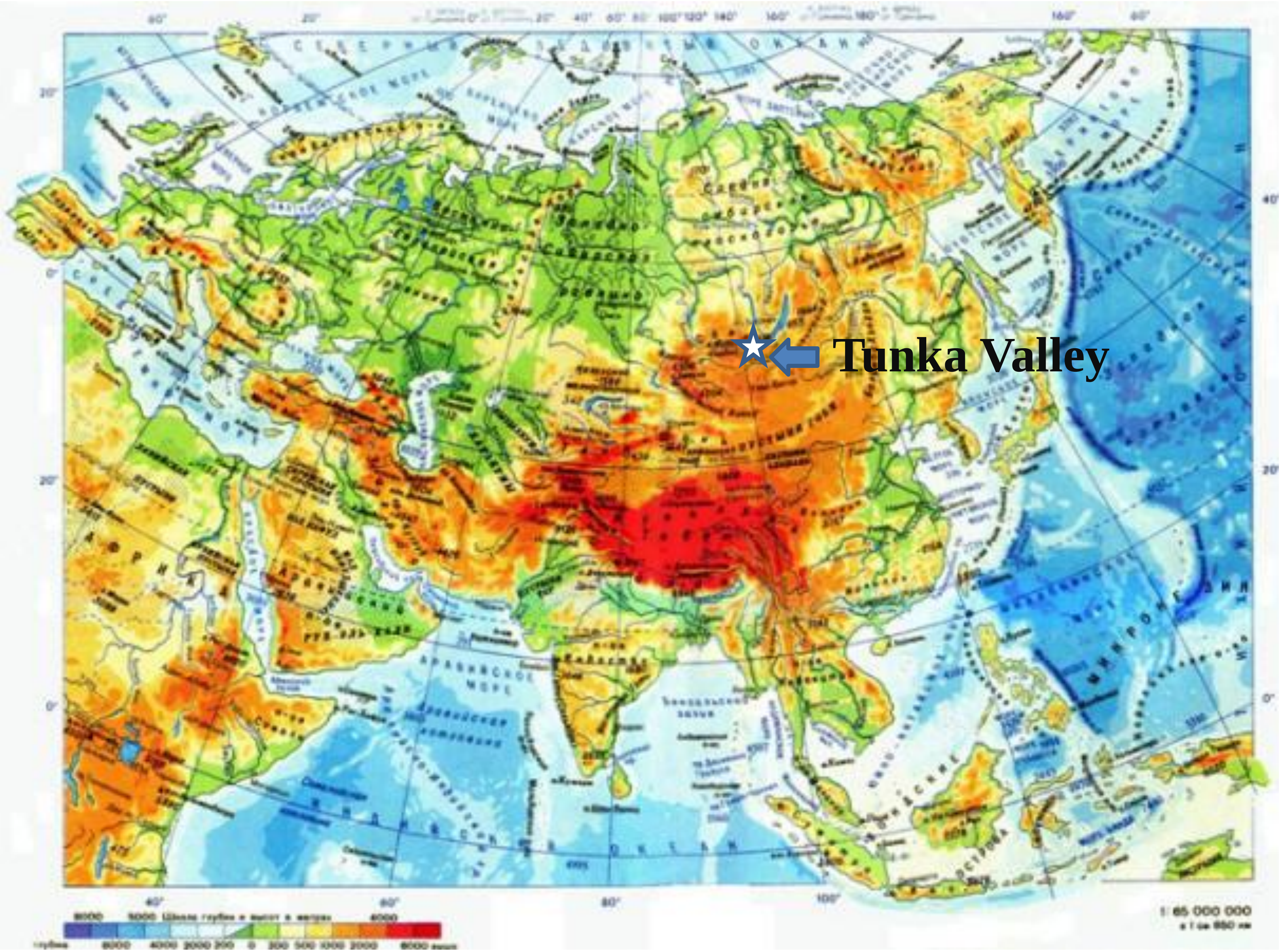
   $0.2\ 10^6$ Eur(PMTs)

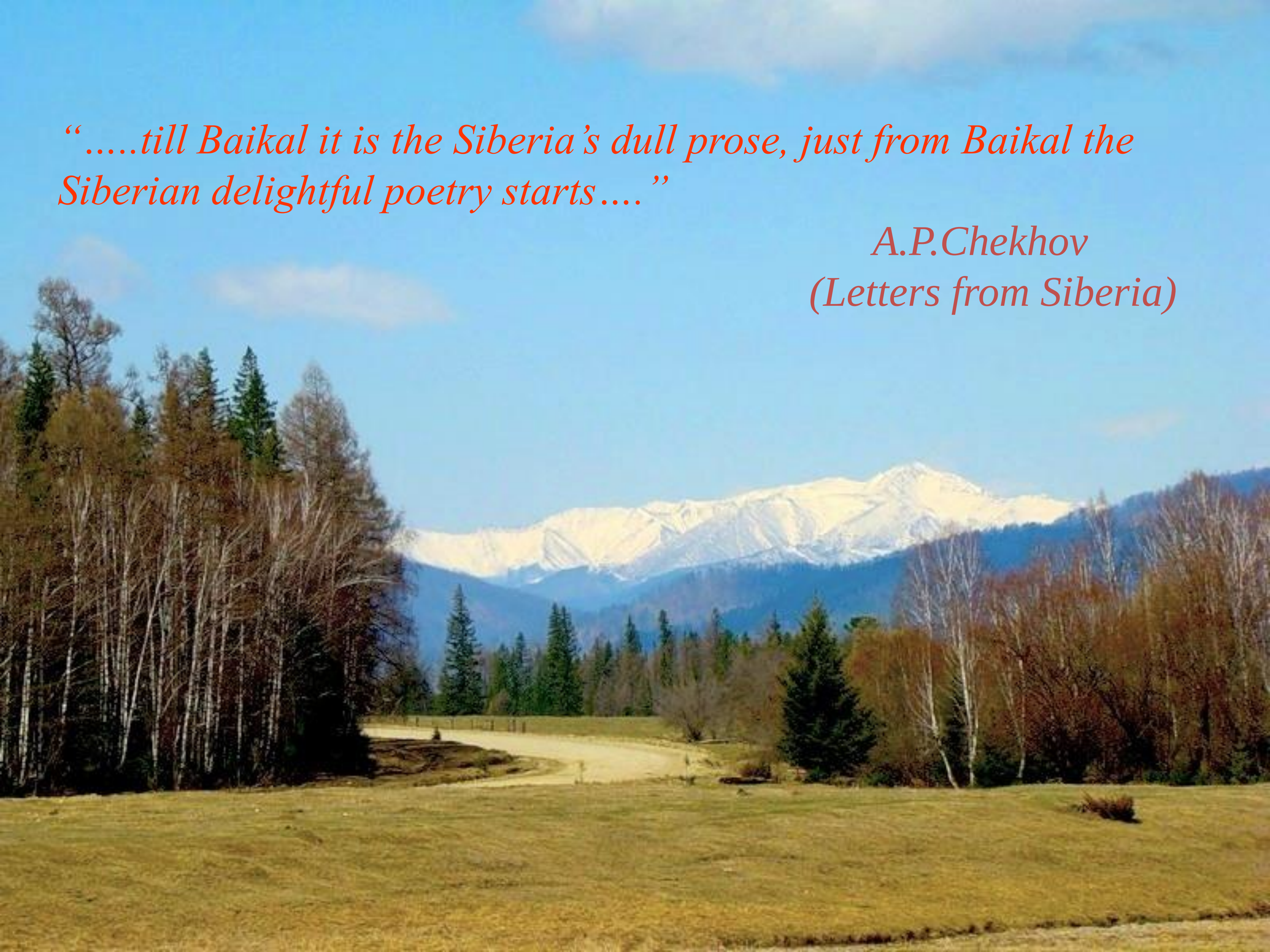
100 km^2 array - 10^7 Eur

Disadvantage:

1. Small time of operation (moonless, cloudless nights) – 5-10%

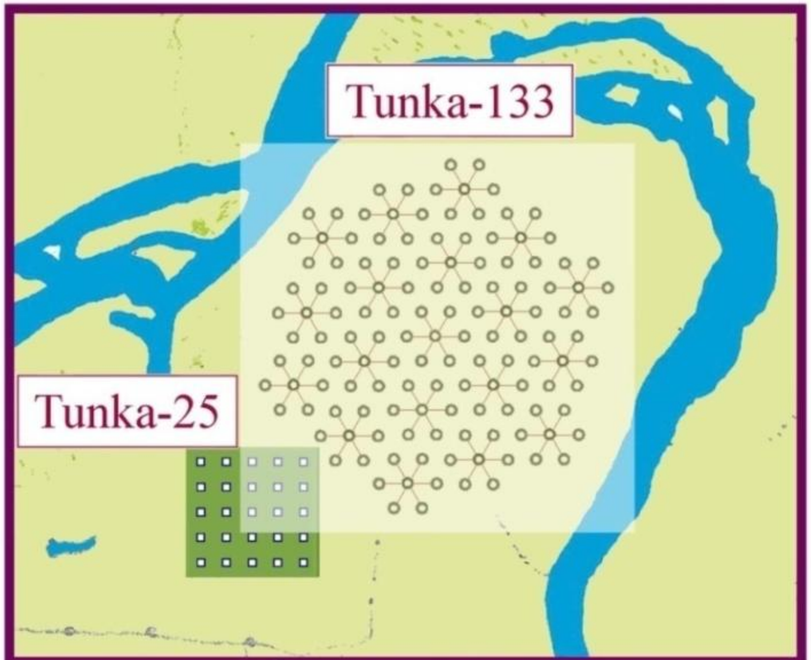
Cherenkov experiments in the Tunka Valley

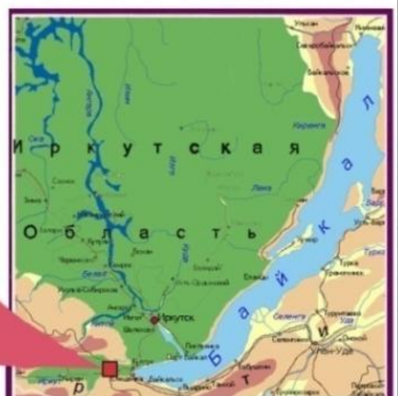

Tunka Valley


"…..till Baikal it is the Siberia's dull prose, just from Baikal the Siberian delightful poetry starts…."
A.P.Chekhov
(Letters from Siberia)

Cherenkov experiments in the Tunka Valley

1993 - ……….

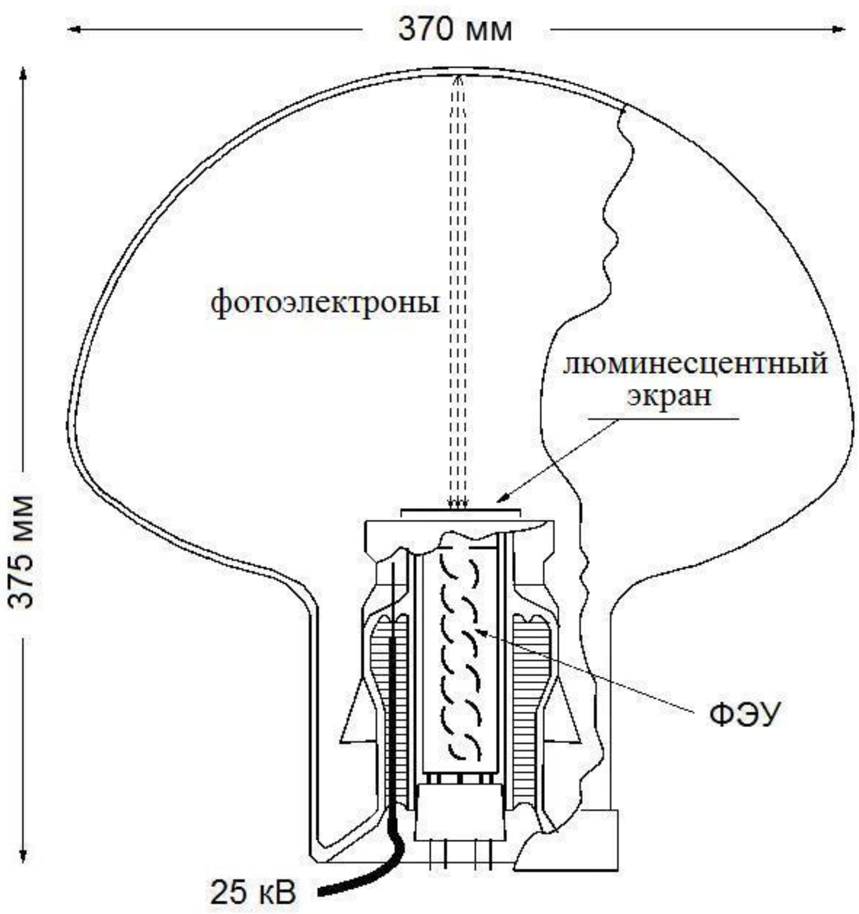


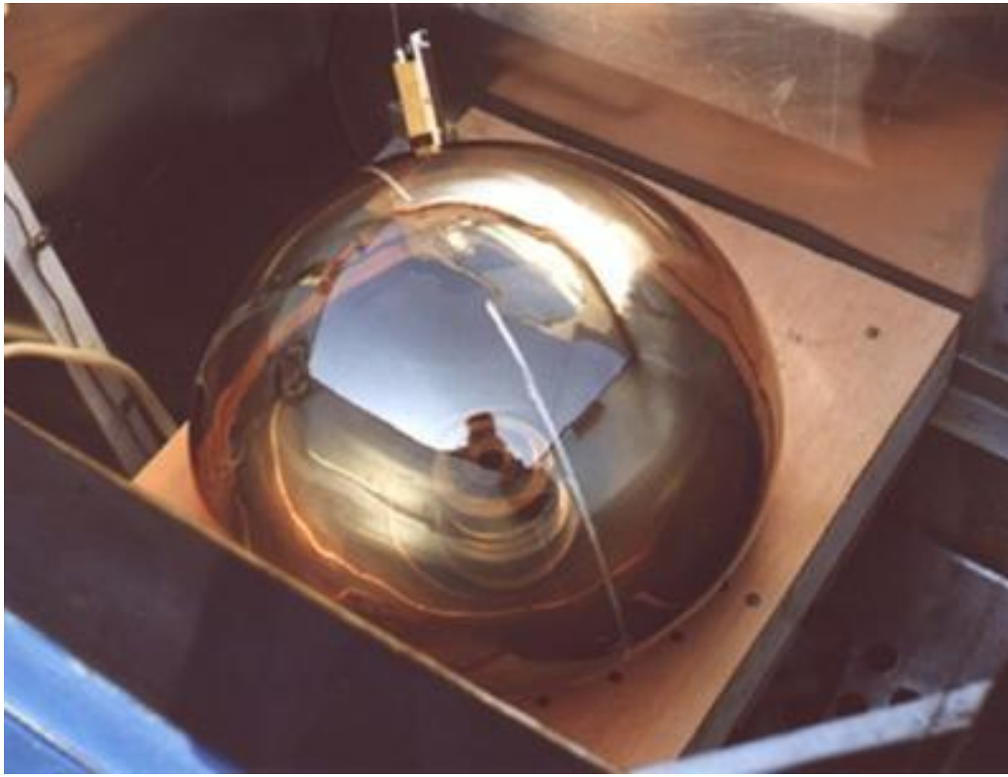


51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

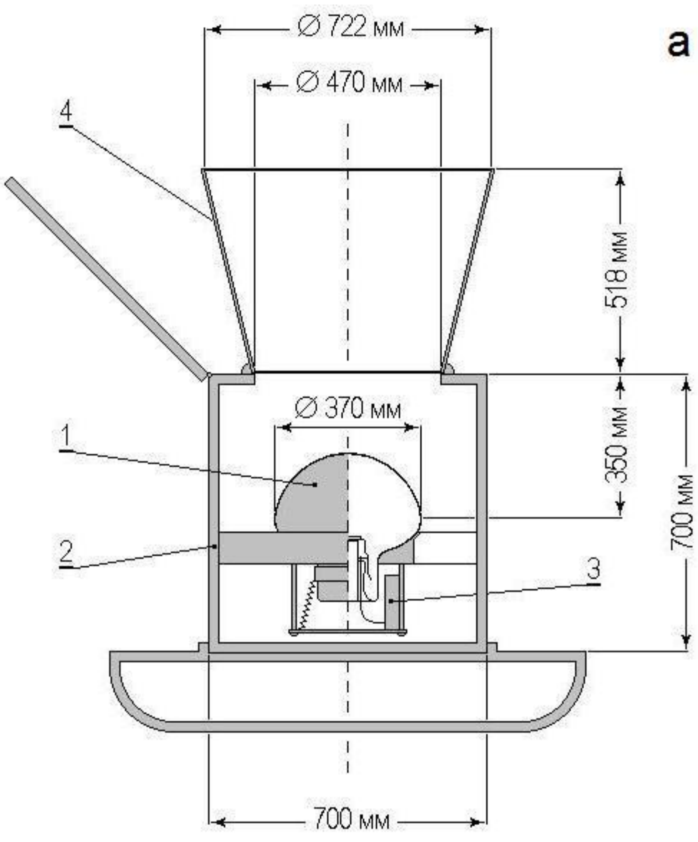
1991-1992: first experiments at the Lake Baikal ice with QUASAR-370 photodetectors (*Bezrukov, Kuzmichev, Lubsandorzhiev et al.)*

1993г. - Move to the Tunka Valley.
(*Bezrukov, Budnev, Kuzmichev, Lubsandorzhiev, Pokhil et al.*)



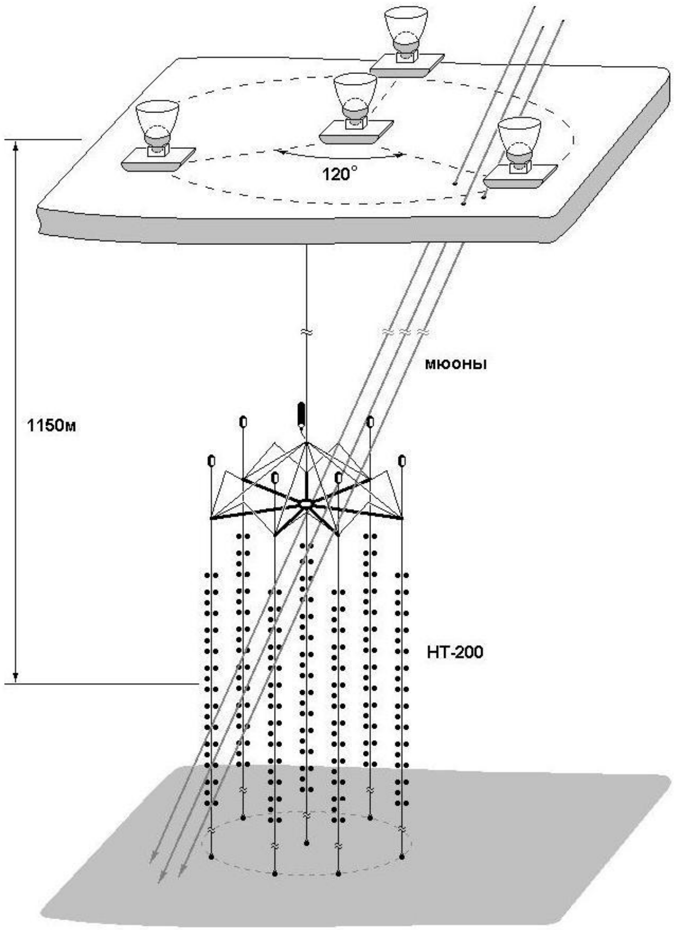


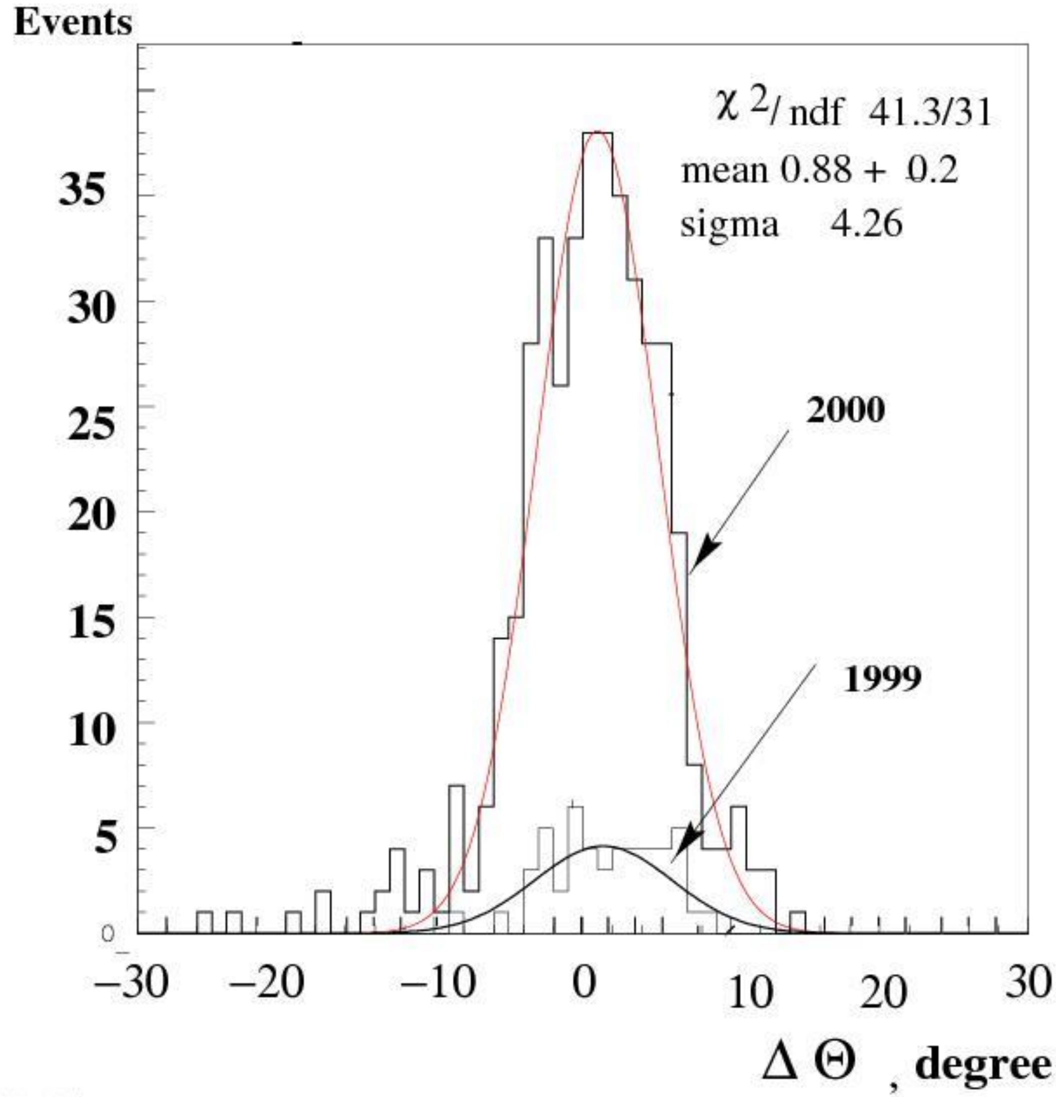
SMECA: Surface Mobile Eas Cherenkov Array



Kuzmichev, Lubsandorzhiev, Pokhil et al

Eth~400 TeV, <θ>~0.5°

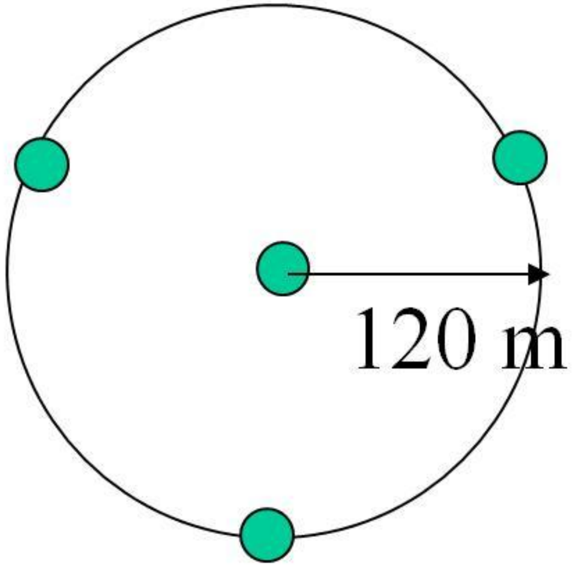

120°
мюоны
1150м
НТ-200


Events
χ 2/ ndf 41.3/31
mean 0.88 + 0.2
sigma 4.26
2000
1999
35
30
25
20
15
10
5
0
–30
–20
–10
0
10
20
30
Δ Θ , degree

Tunka Valley, Buryatia Republic

Tunka-4

4 QUASAR-370 phototubes



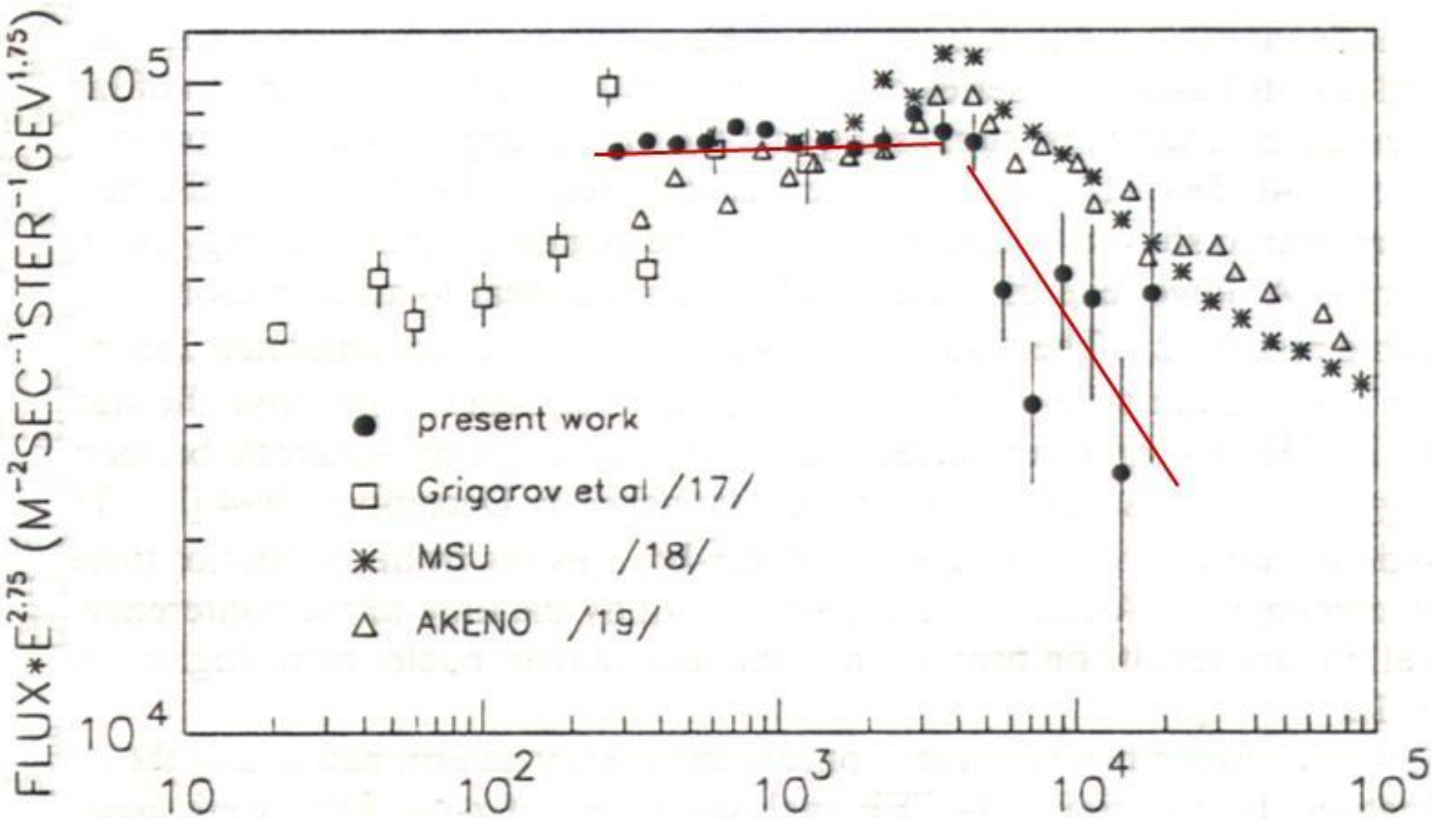


Fig.3 All particle spectrum

Bezrukov, Kuzmichev, Lubsandorzhiev, Pokhil et al. 24th ICRC 1995 Rome.

“Knee” in the energy spectrum at 3×10^{15} эВ.

TUNKA-25 COLLABORATION

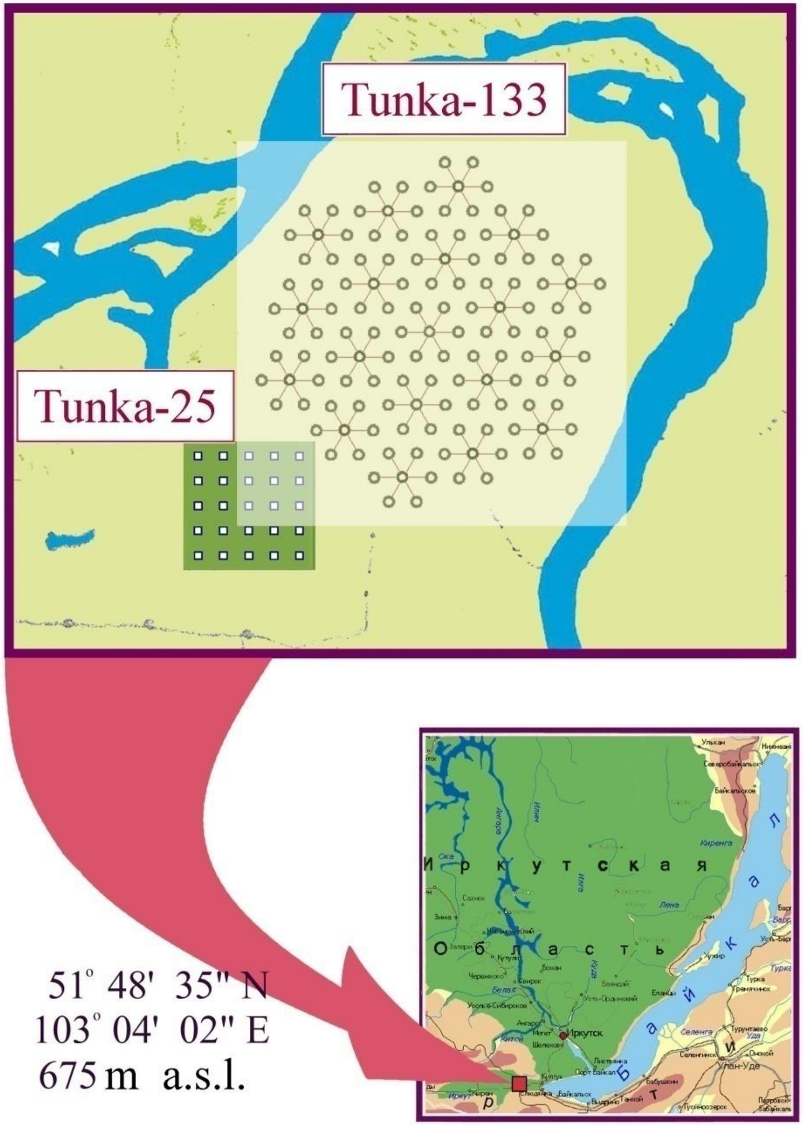
E.Korosteleva, L.Kuzmichev, V.Prosin, I.Yashin
Scobeltsyn Institute of Nuclear Physics of MSU (Moscow, Russia)

N.Budnev, O.Gress, L.Pankov, Yu.Semeney
Institute of Applied Physics of ISU (Irkutsk, Russia)

B.Lubsandorzhiev, B.A.Shaibonov (Jr)
Institute for Nuclear Research RAS (Moscow, Russia)

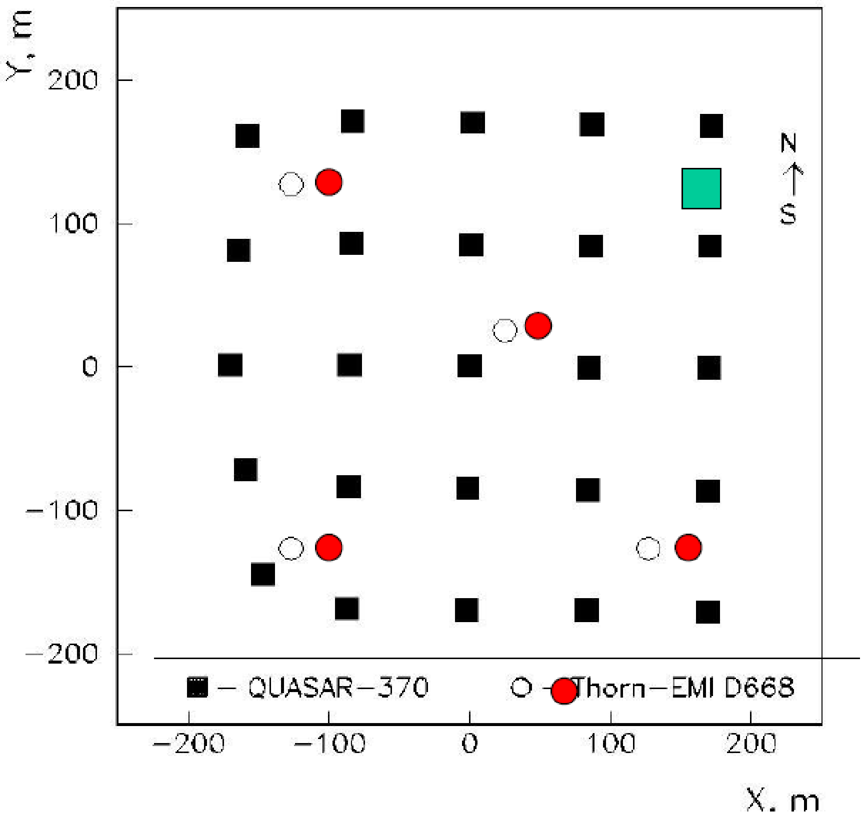
G.Navarra
University of Turin , Italy

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


Tunka-133
Tunka-25
И р к у т с к а я
О б л а с т ь
Б а й к а л
Иркутск
51° 48' 35'' N
103° 04' 02'' E
675 m a.s.l.


ТУНКИНСКИЙ РАЙОН
НАЦИОНАЛЬНЫЙ ПАРК

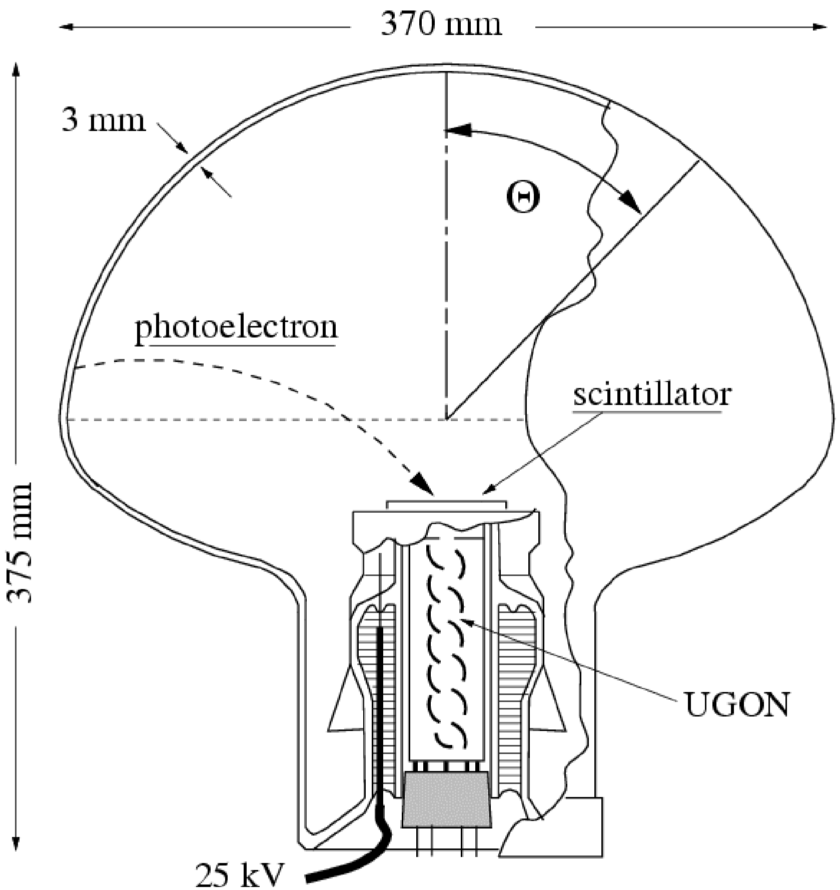
TUNKA-25

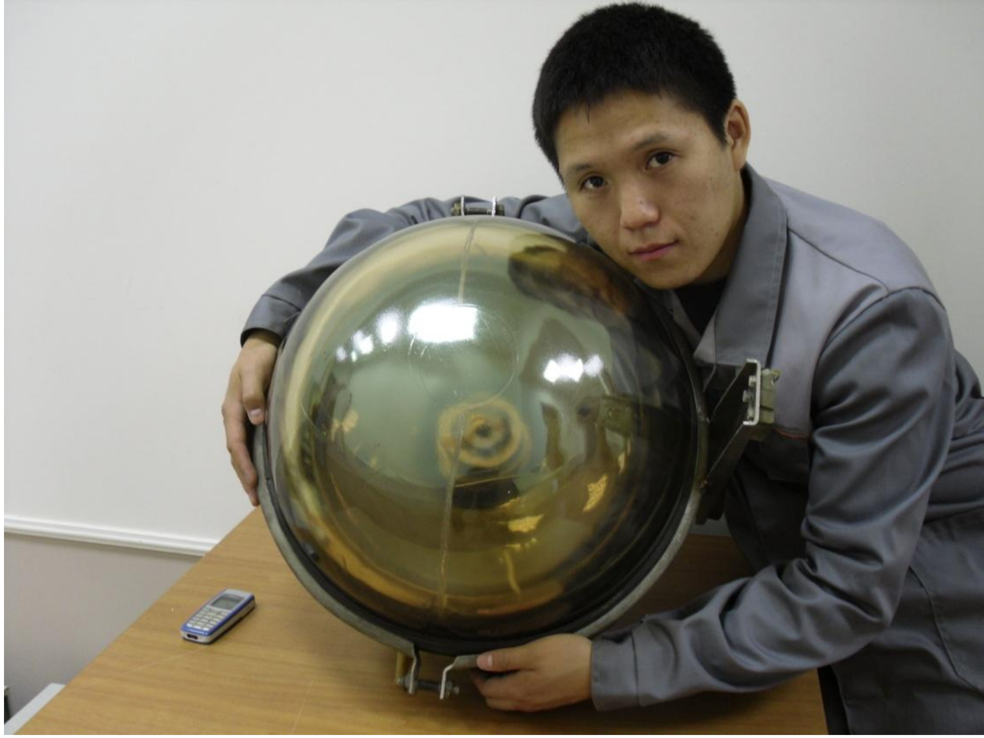


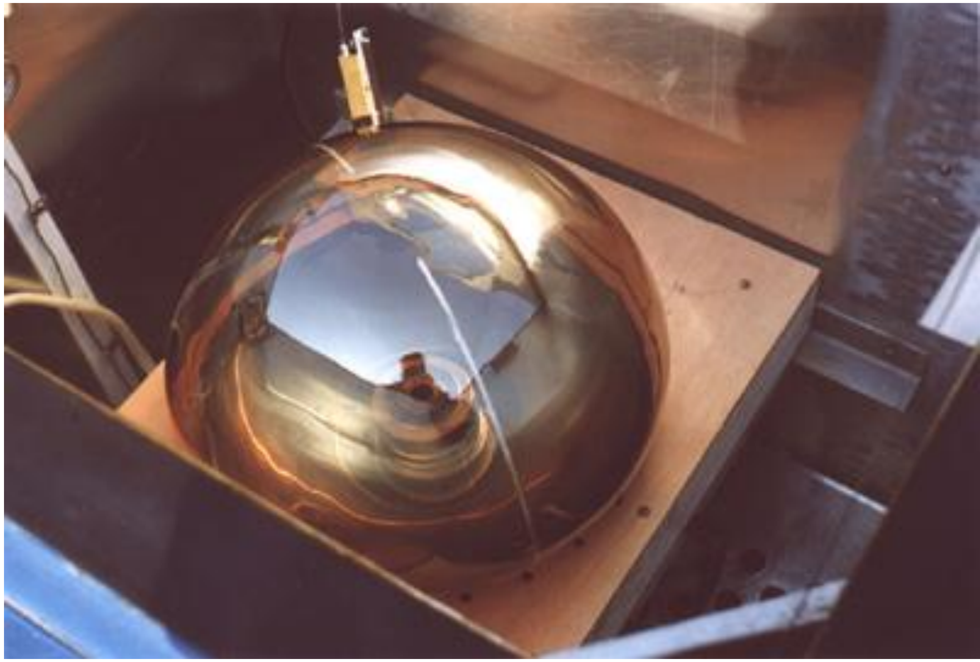
25 large sensitive area hybrid phototubes QUASAR-370G (37cm in diameter)
Area ~ $0.1 km^2$, E_{th} ~ $4x10^{14}$ eV, angular resolution ~0.5°

Studies of cosmic rays energy spectrum and mass composition in the energy range of 10^{15}-10^{17}eV

QUASAR-370G







TTS ~ 2 ns (FWHM)

SER ~ 70-80% (FWHM)

Δt < 1 ns

CE ~ 100%

QUASAR-370G

37 cm extended bialkali low resistance hemispherical photocathode

2π acceptance, CE ~ 100%

YSO+BaF_2 luminescent screen (phosphor or monocrystal)

Small 6 stages high anode current PMT (200μA max DC current)

Jitter - 2 ns (FWHM) (1ns for the best modification with LSO crystal)

SER – 70-80% (FWHM) (35-40% for tubes with LSO crystal)

NIMA 2000 V.A442 P.368.

NIMA 2008. V. 595. P.58-61.

IEEE TNS 2008 Vol.55 Issue 3 Part2 P.1333-1337.

NIMA 2009. V. 602. P.201-204

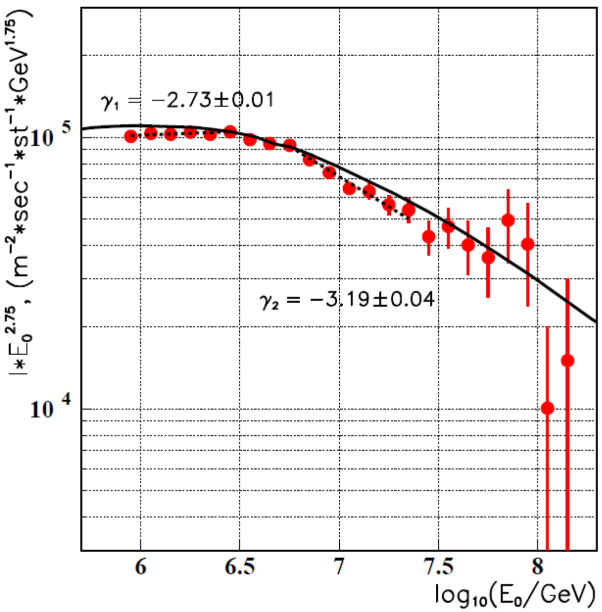
NIMA 2009. V. 610. P.68.

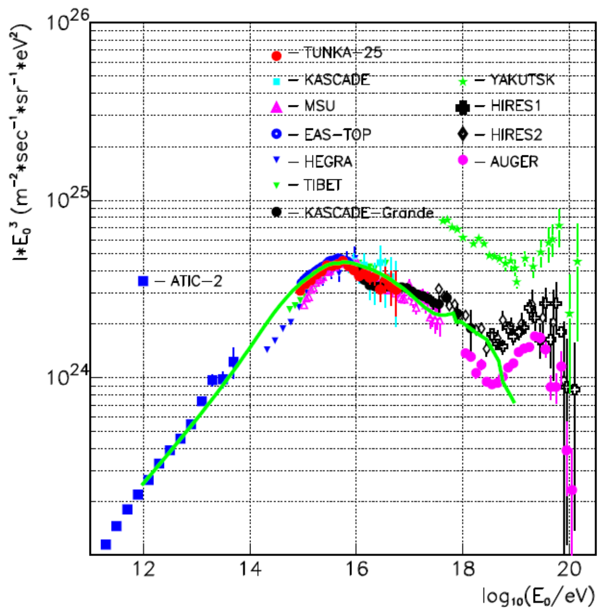
TUNKA-25: main results

Cosmic ray energy spectrum and mass composition in the energy range of 10^{15}-10^{17}eV

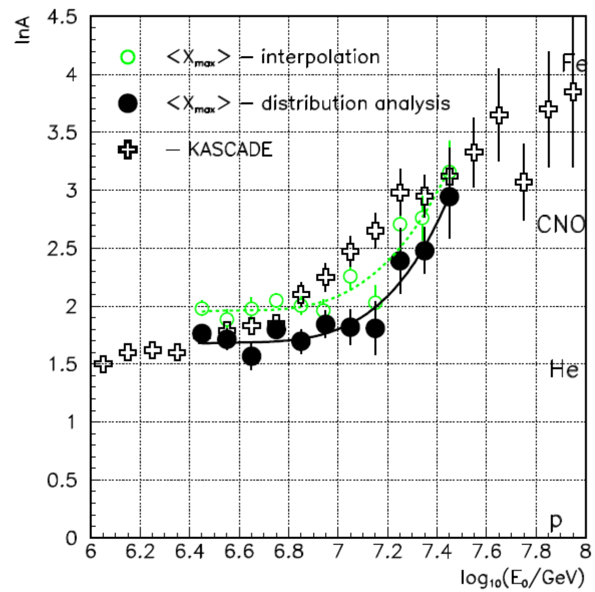
Astroparticle Physics 2013, V.50-52, P.18

Energy spectrum





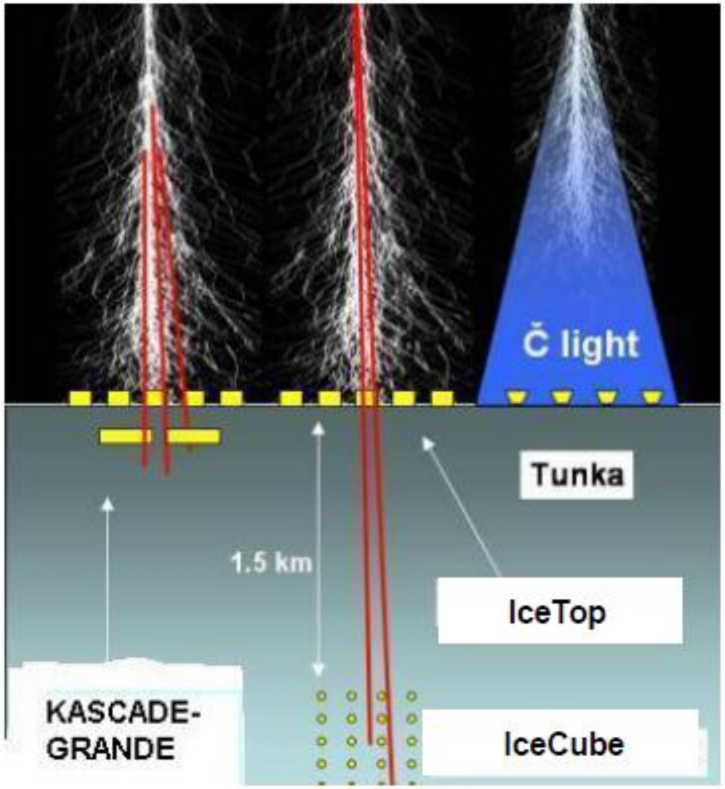
Mass composition

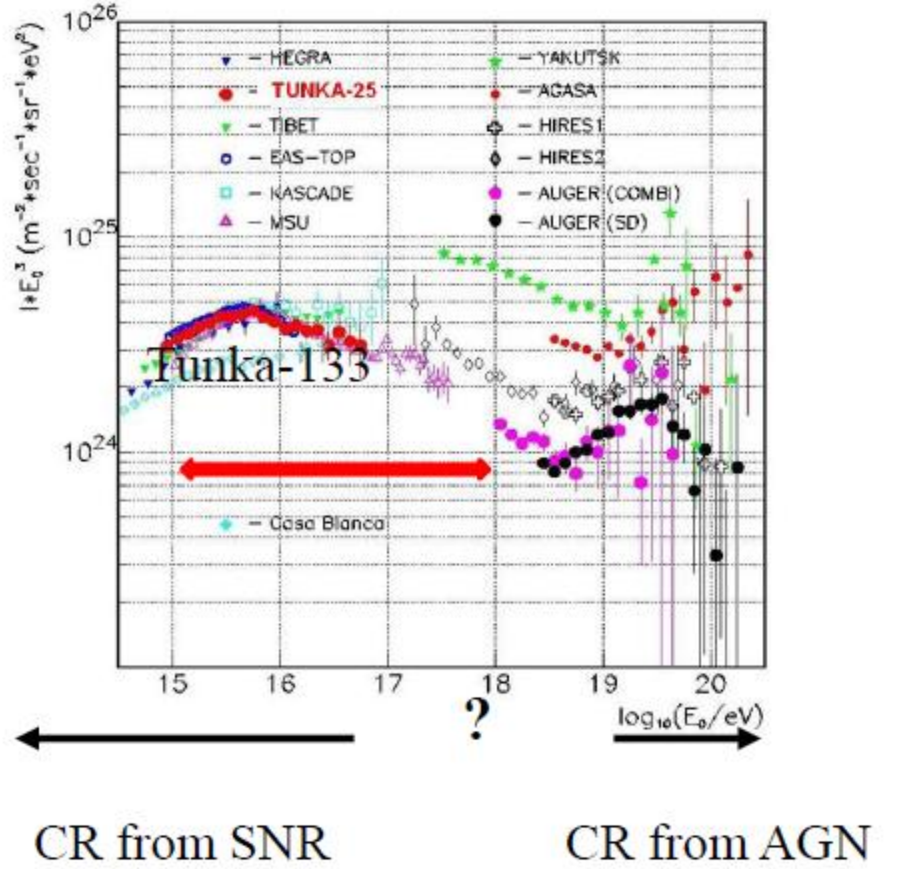


Search for the Acceleration Limit of Galactic Sources

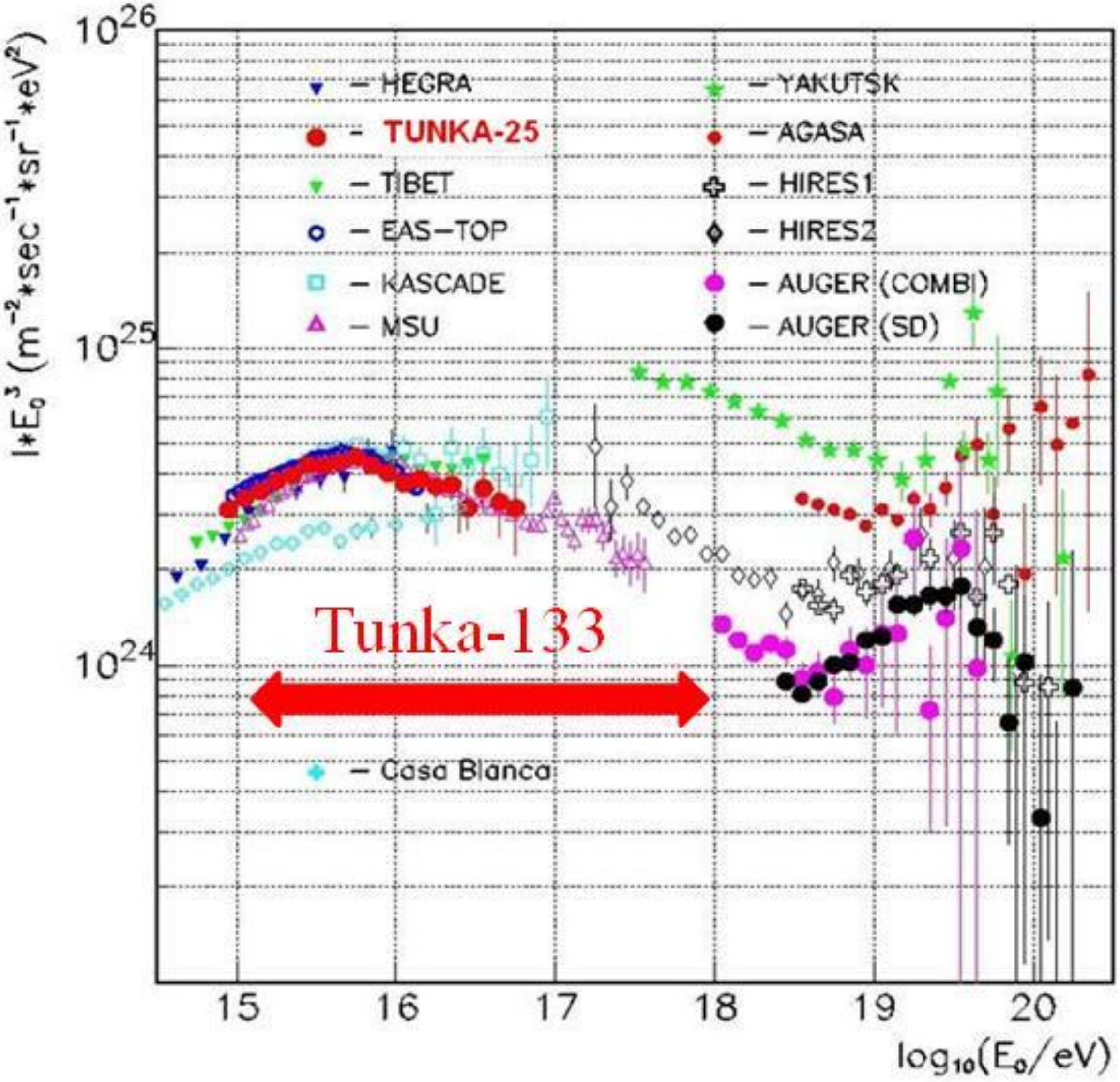
- Energy range 10^{16}-10^{18} eV demands:
- 1 km² with spacing smaller than that at Auger
- complementary techniques

- KASCADE-Grande	*terminated*
- IceTop/IceCube	***in operation***
- **Tunka-133 (calorimetric)**	***in operation***
- NEVOD-DÉCOR	***in operation***
- Auger low energy extension	***in operation***
- ***HiSCORE***	*planned*
- *LHAASO*	*planned*

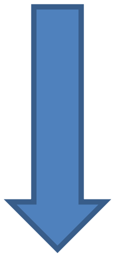




Primary cosmic rays in the energy range of $10^{15} – 10^{18}$ eV



S ~ 1км²;
r ~ 80-100 m;
s(∅) ≥20cm



Tunka-133

3 km^2 Cherenkov array Tunka-133

TUNKA-133 collaboration

S.F. Berezhnev, N.N. Kalmykov, E.E. Korosteleva, V.A. Kozhin, L.A. Kuzmichev, M.I. Panasyuk, V.V. Prosin, A.A. Silaev, A.A. Silaev(ju), A.V. Skurikhin, I.V. Yashin, A.V. Zablotsky – **Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow,**

N.M. Budnev, O.A. Chvalaev, O.A. Gress, A.V. Kochanov, A.V. Korobchebko, R.R. Mirgazov, L.V. Pan'kov, 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 the Russian Academy of Sciences, Moscow, Russia;**

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

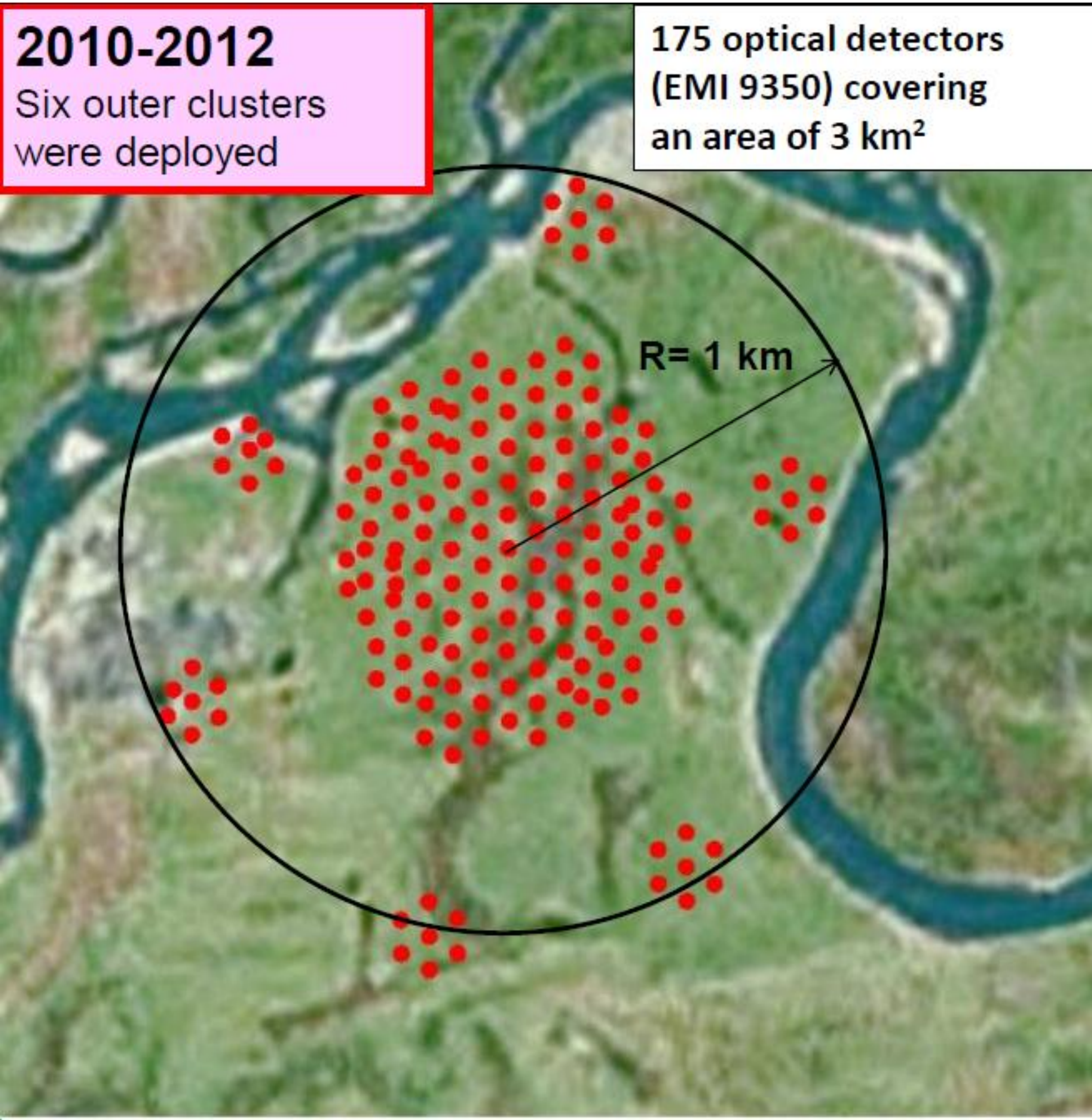
Ch. Spiering, R. Wischnewski
– **DESY-Zeuthen, Zeuthen, Germany;**

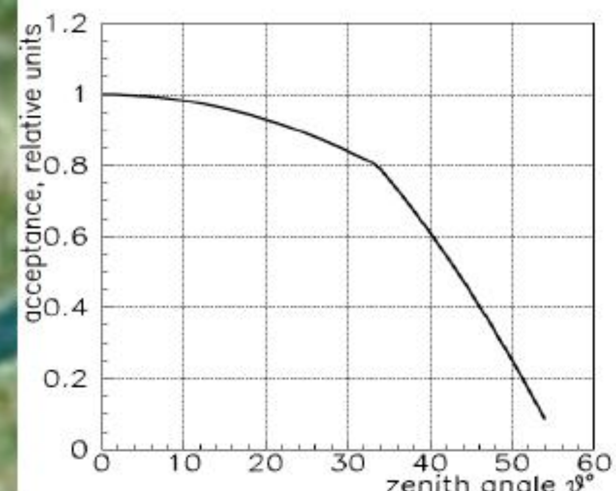
G. Navarra , A. Chiavassa
– **Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.**

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

2010-2012
Six outer clusters were deployed

175 optical detectors (EMI 9350) covering an area of 3 km²





Angular sensitivity

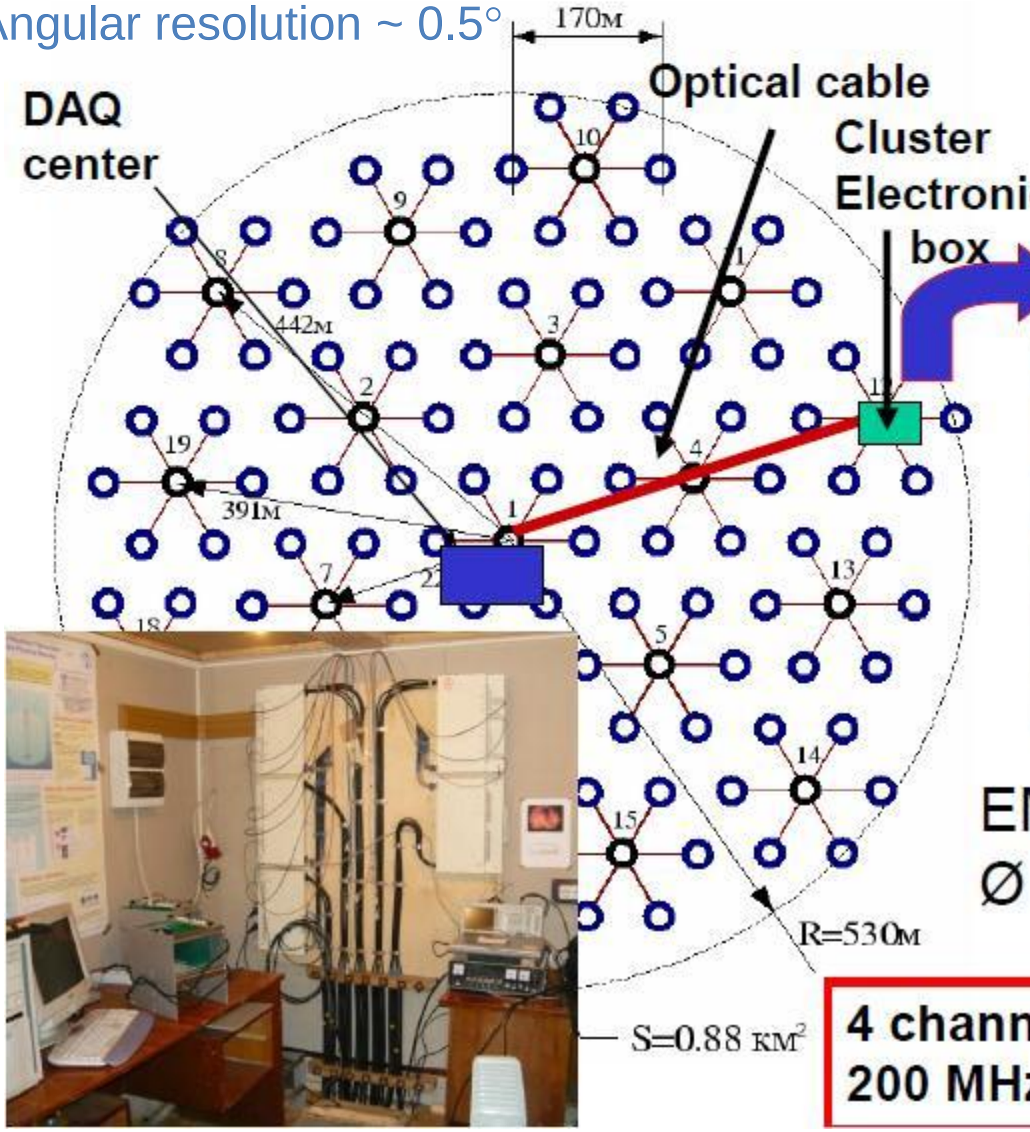
~3 km² dense Cherenkov array

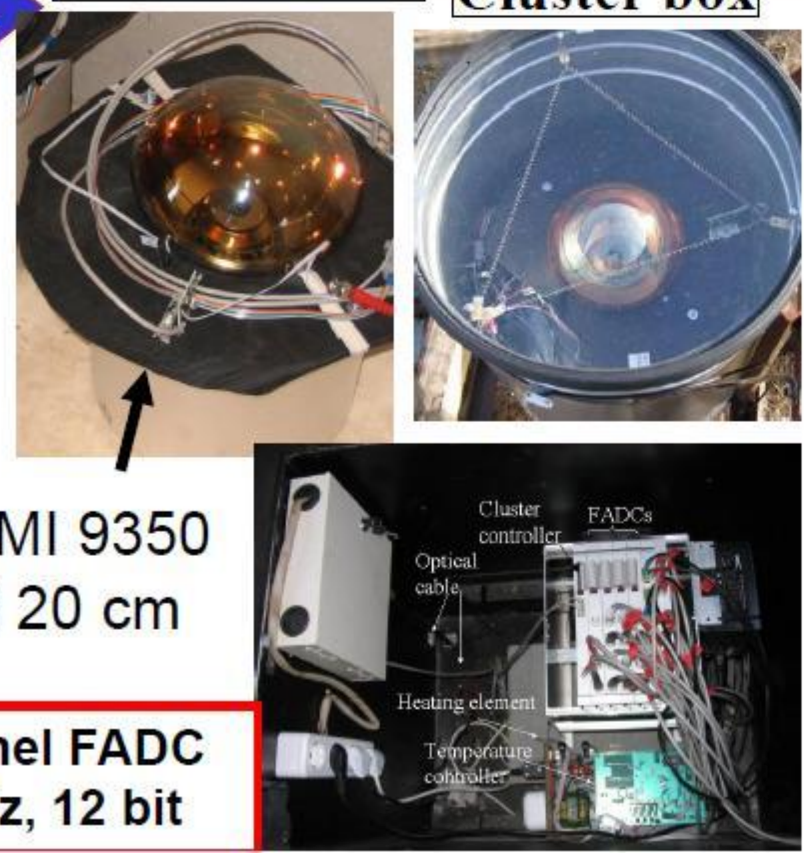
175 optical detectors (8” PMTs – EMI9350KB)

~3 km² area

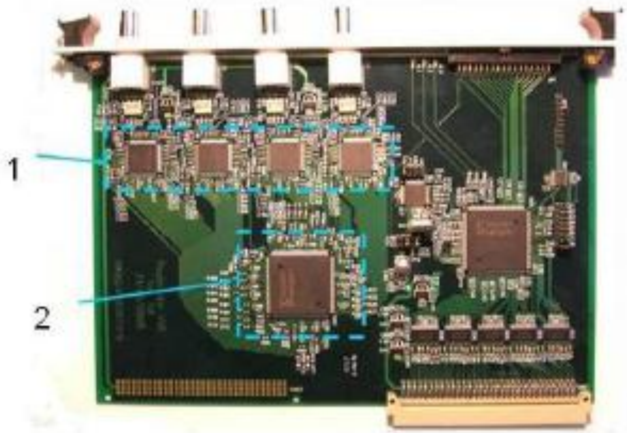
E_{th} ~ 10^{15} eV

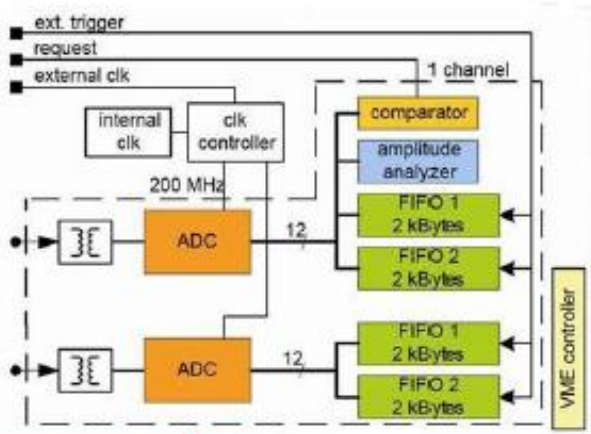
Angular resolution ~ 0.5°





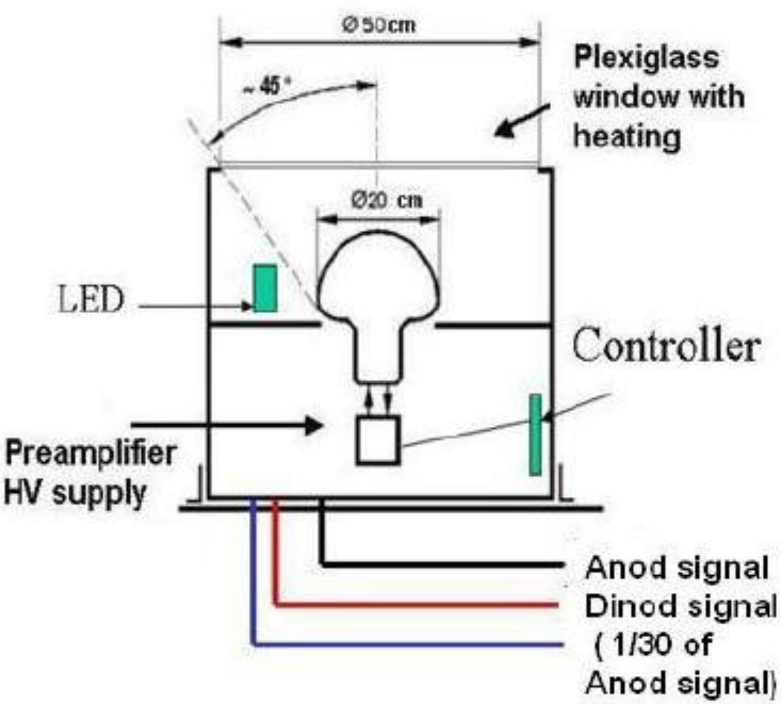
Cluster electronics

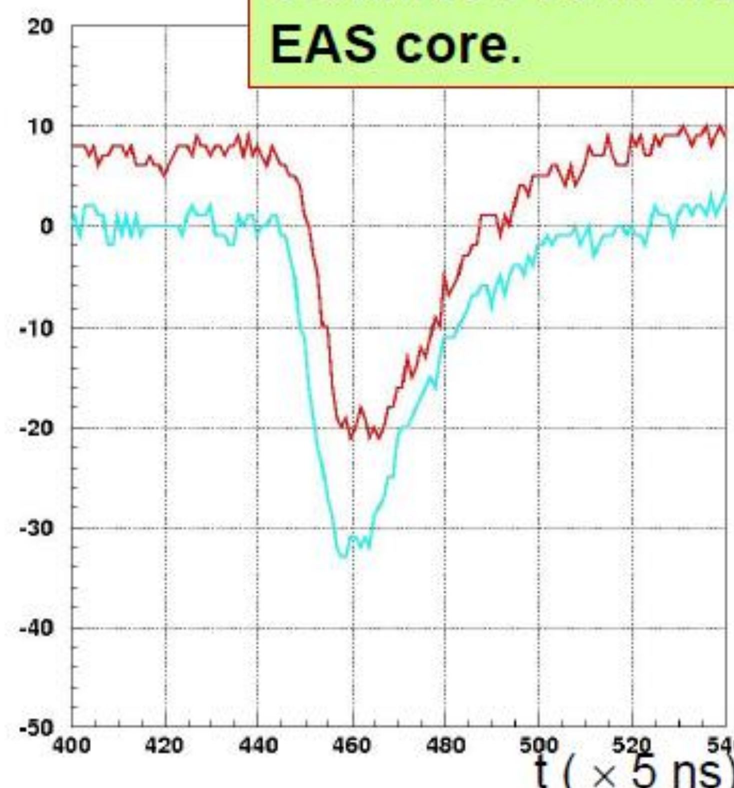




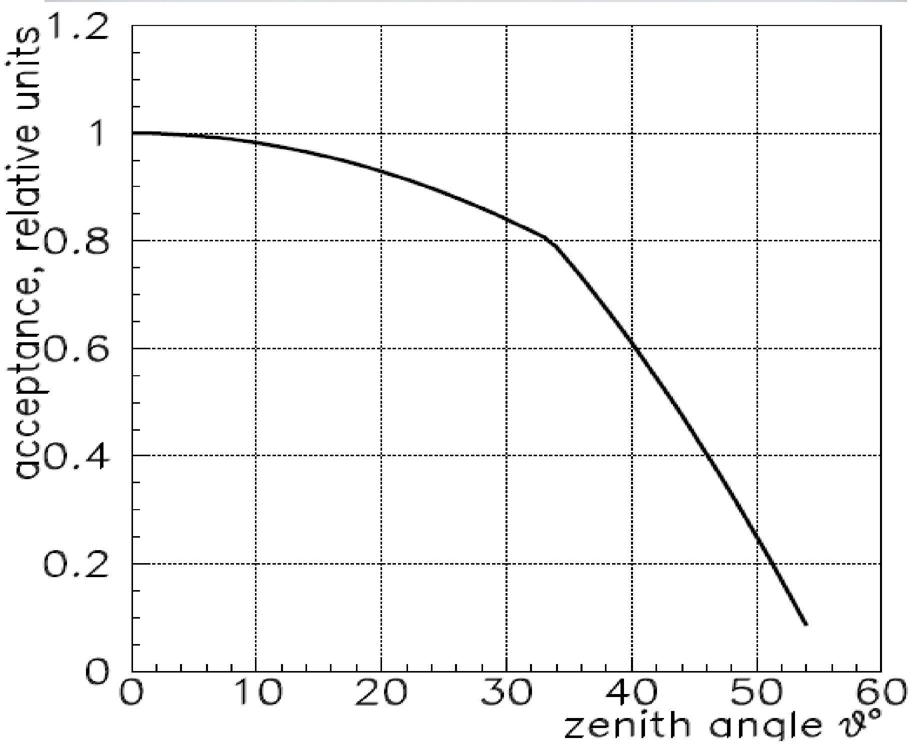
1. ADC AD9430, 12 bit, 200 MHz
2. FPGA XILINX Spartan-3

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





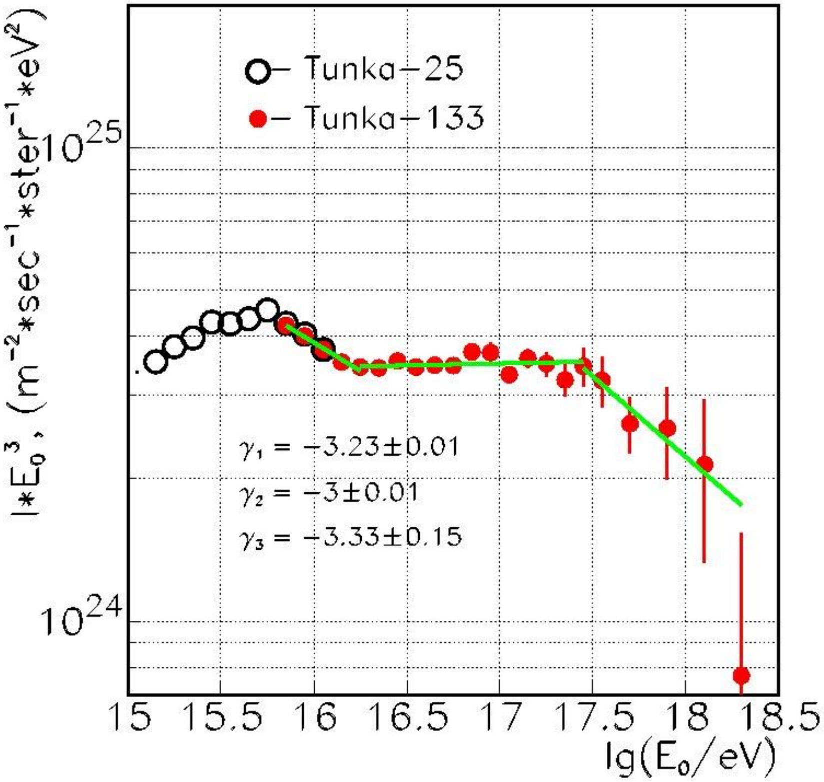
PMTs – 8” EMI9350KB

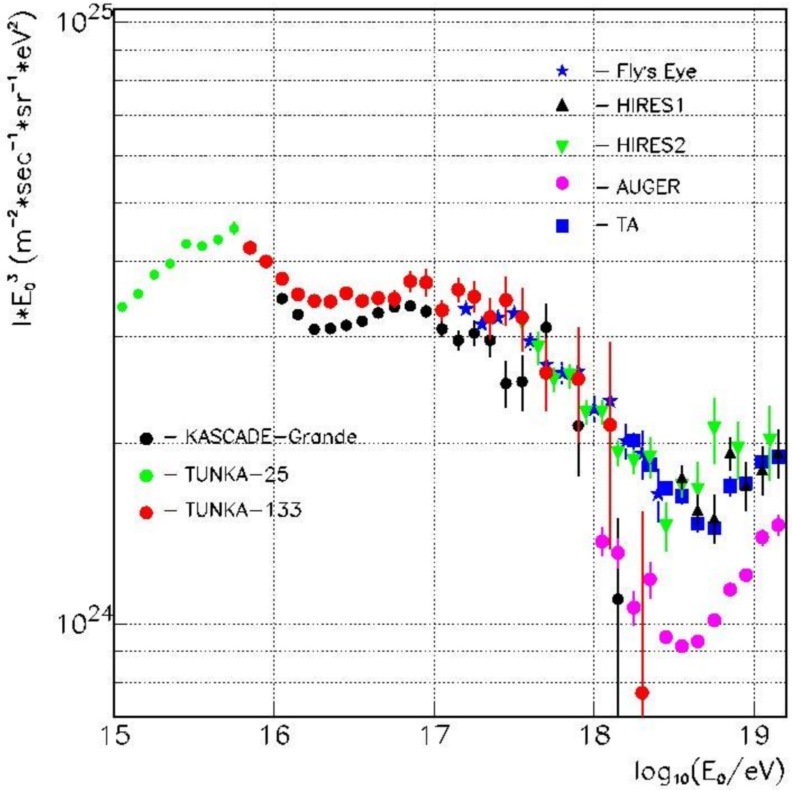



14-4

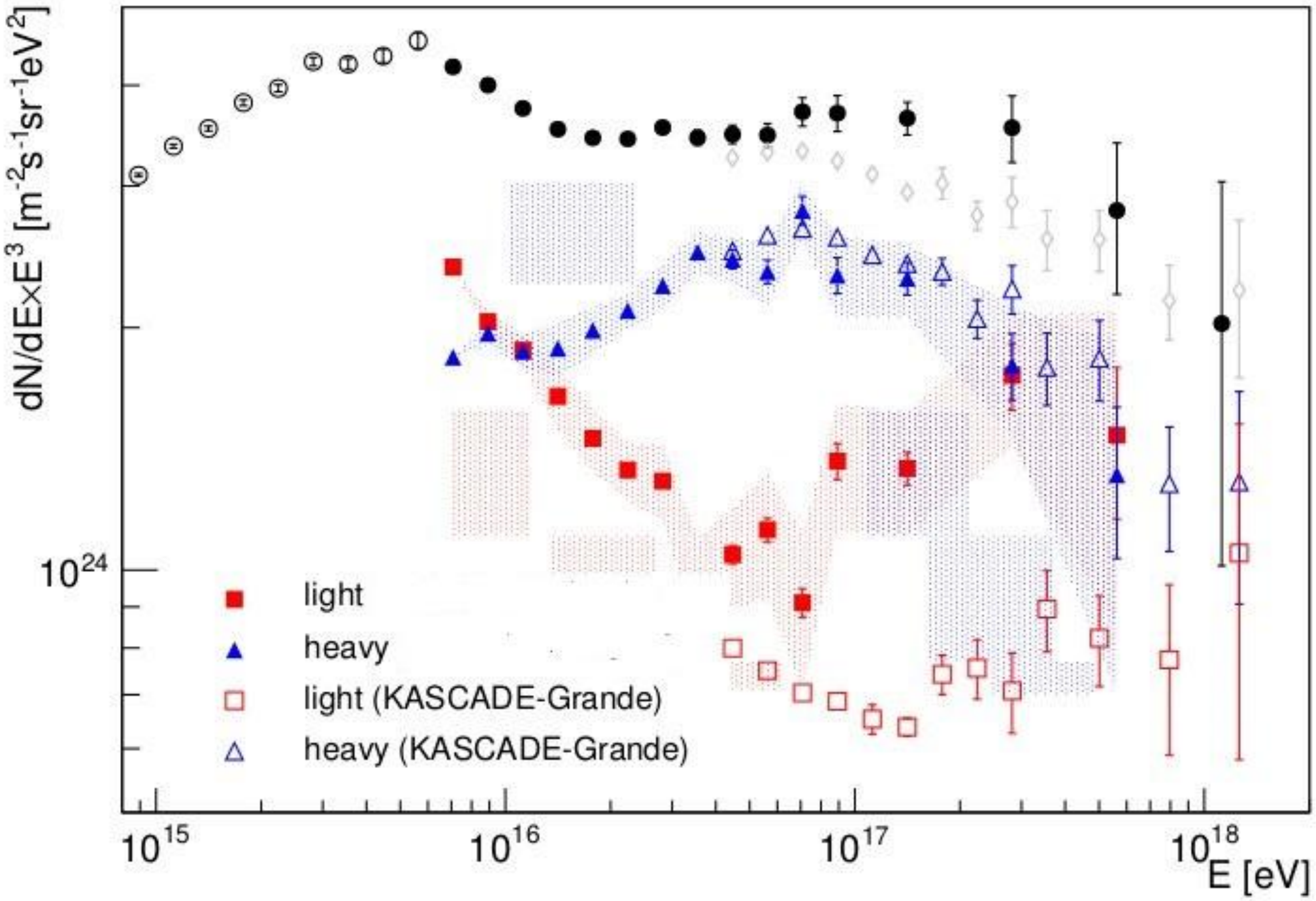
TUNKA-133: recent results

Energy spectrum

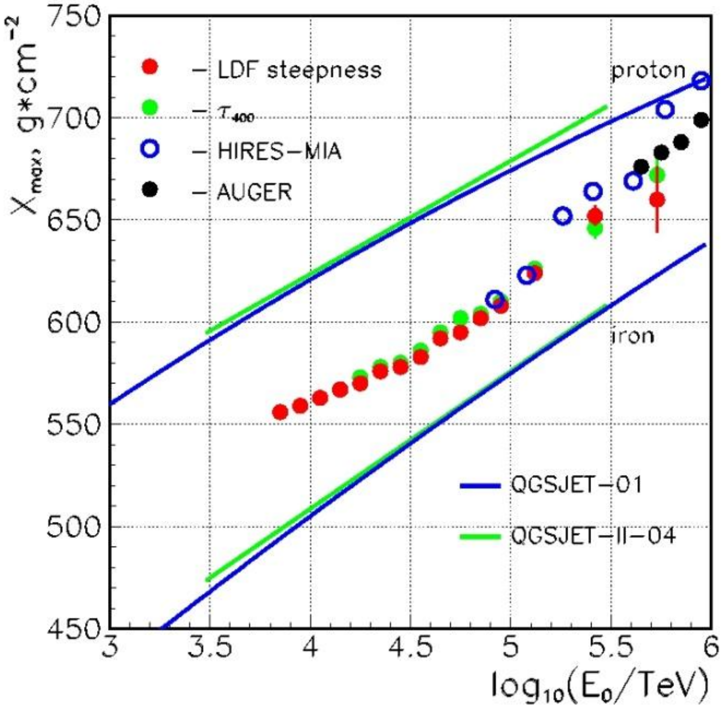


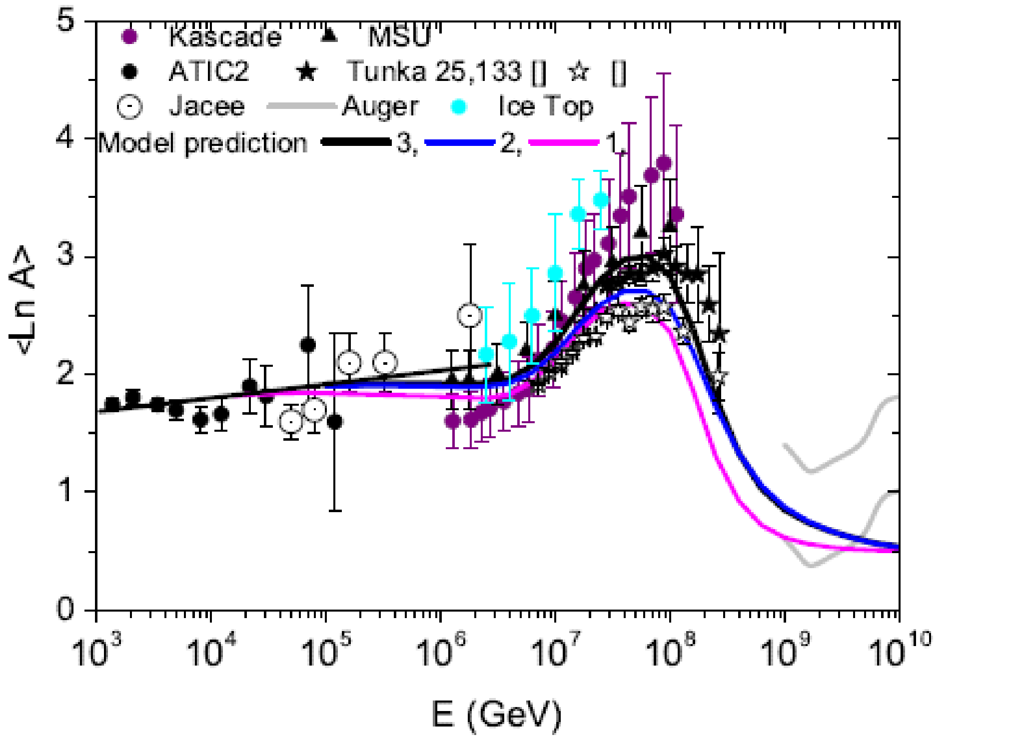


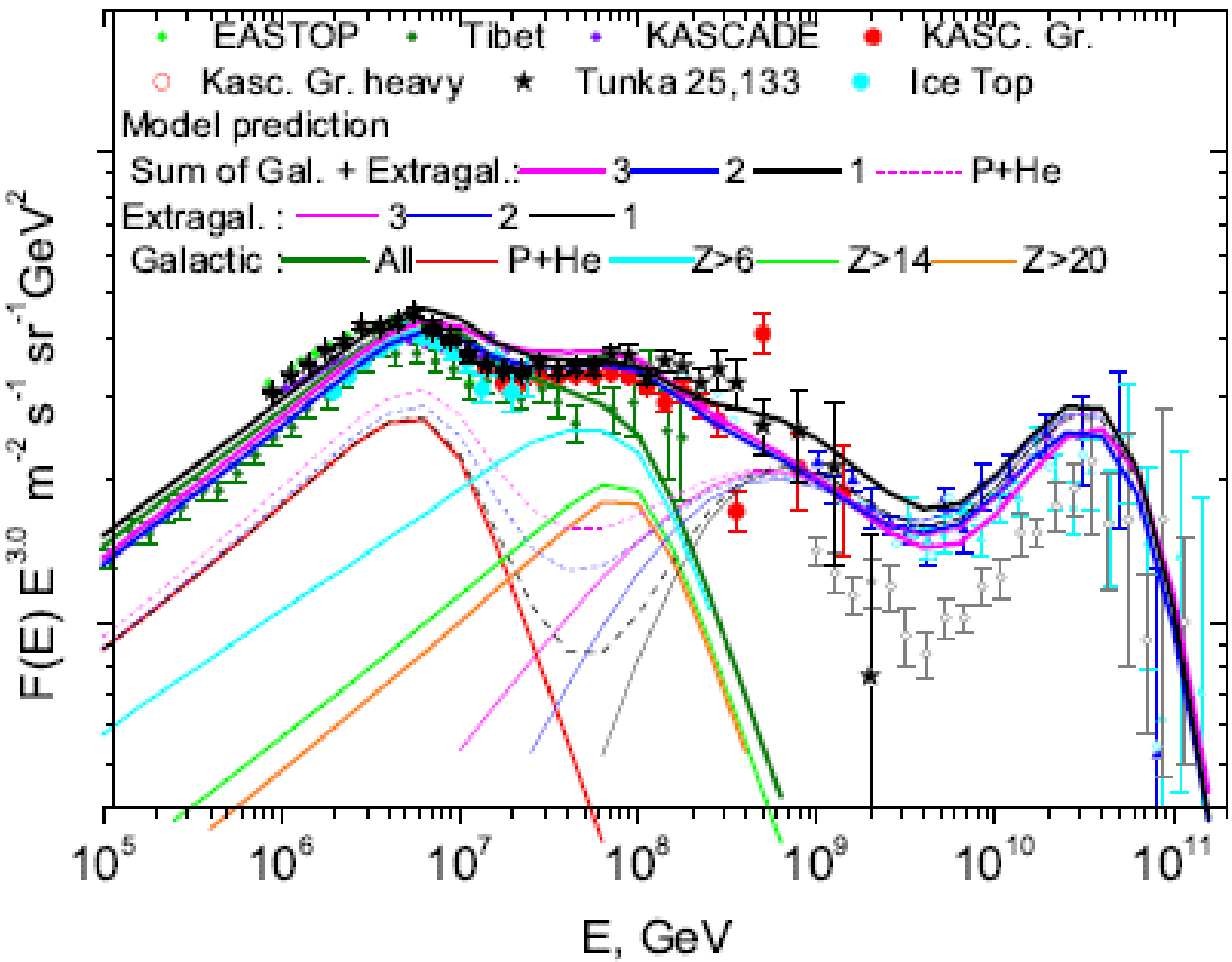
Energy spectrum of “light” and “heavy” components



Mass composition






EASTOP
Tibet
KASCADE
KASC. Gr.
Kasc. Gr. heavy
Tunka 25,133
Ice Top
Model prediction
Sum of Gal. + Extragal.: 3 2 1 P+He
Extragal. : 3 2 1
Galactic : All P+He Z>6 Z>14 Z>20
F(E) E^3.0 m^-2 s^-1 sr^-1 GeV^2
E, GeV
10^5
10^6
10^7
10^8
10^9
10^10
10^11

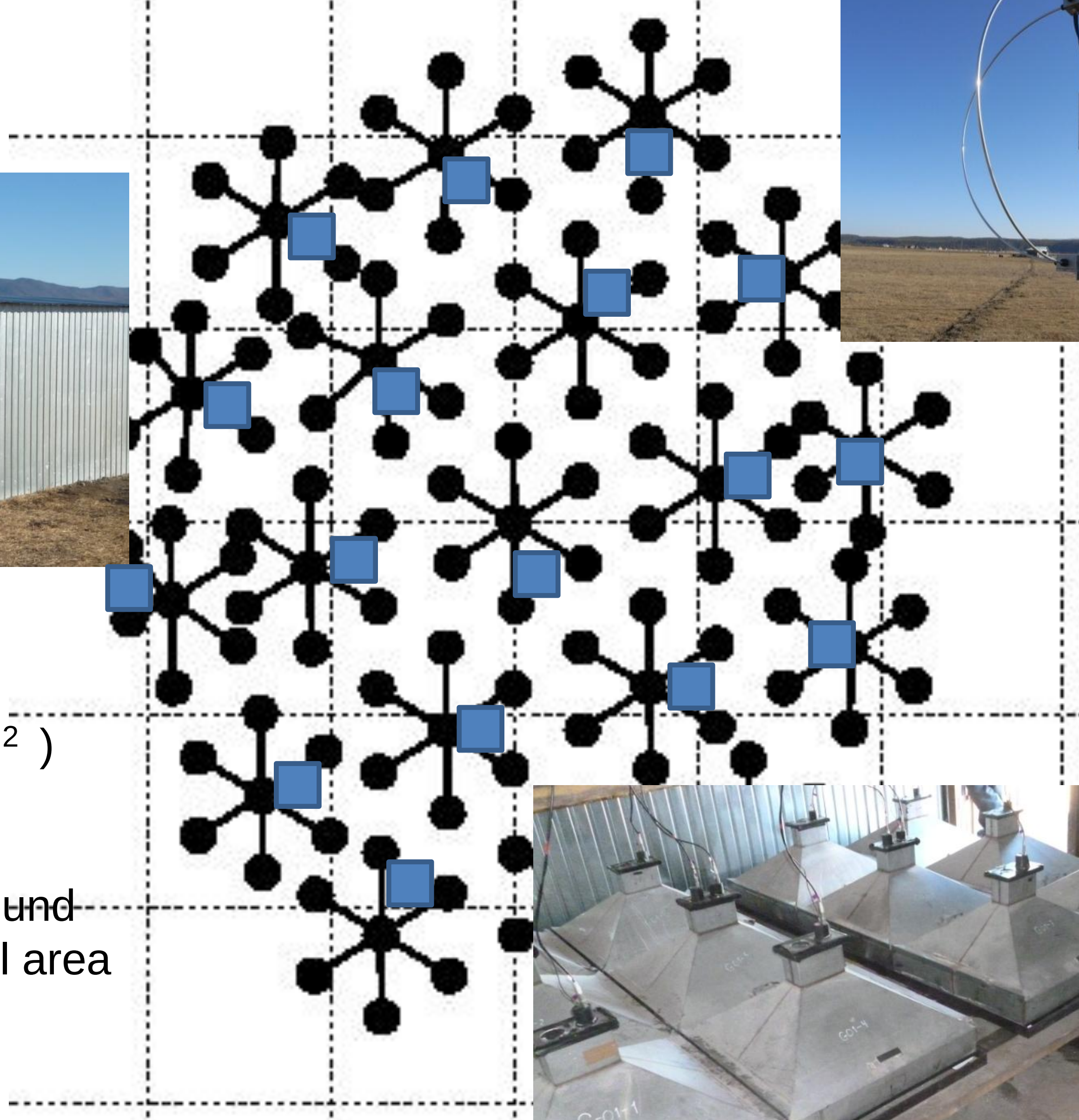
Scintillation detectors from Kascade-Grande

19 stations

228 detectors (0.64 m^2) on the surface

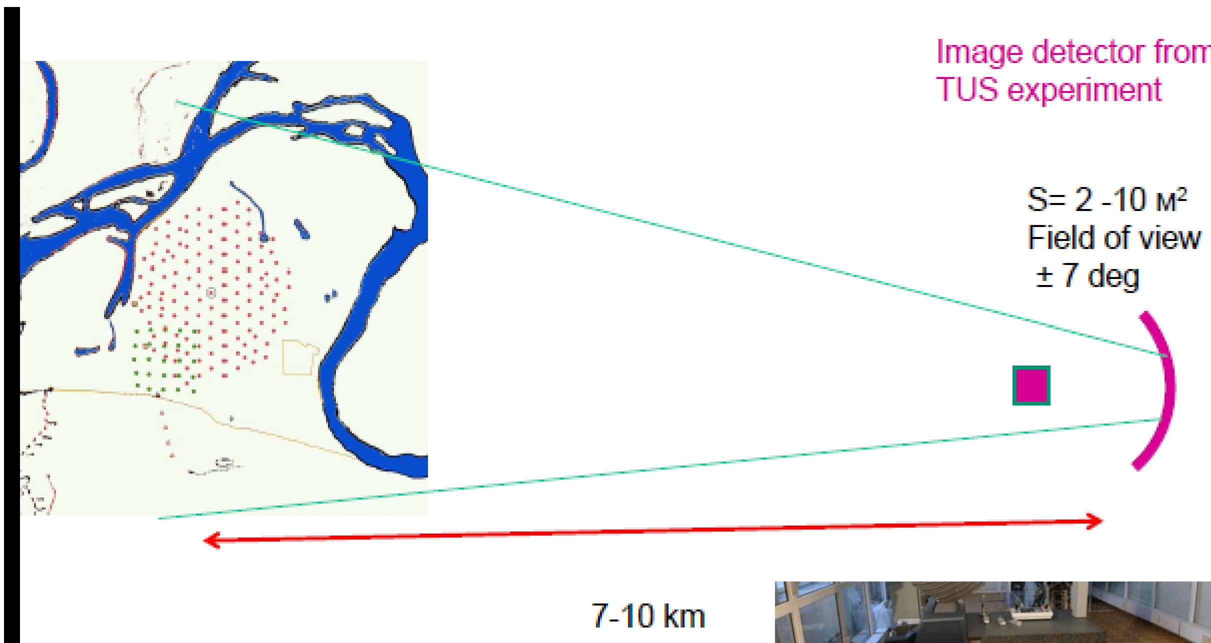
152 detectors undeground (muons detectors, total area 100 m^2

Net of 25 radioantenna



Further extension of Tunka-133 includes muon detectors, radio, fluorescent det.

Fluorescent detector



The movable support produced by JINR

Cross calibration of Cherenkov light and fluorescent light methods.

……………………………………………
Случайно на ноже карманном
Найди пылинку дальних стран -
И мир опять предстанет странным,
Закутанным в цветной туман

А.А.Блок

Light Emitting Diodes & Cherenkov experiments

LEDs are everywhere

XXI century – LEDs century

Oleg Vladimirovitch Losev
(1903-1942)

“Losev’s glow” or
“Losev’s effect” – 1922-1923.
Green glow in SiC crystals

Giant LED bright displays

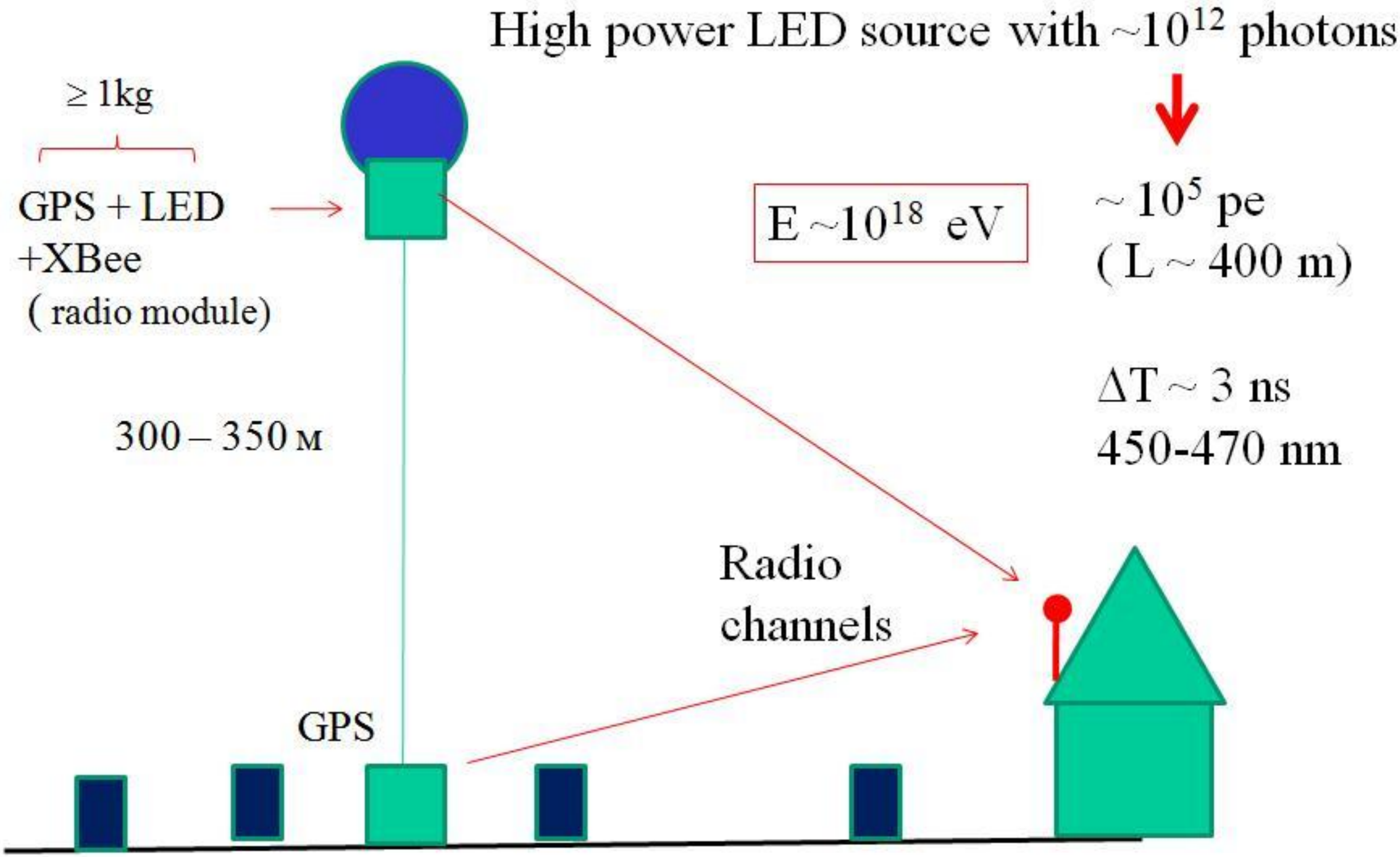
Street and Highway Lights

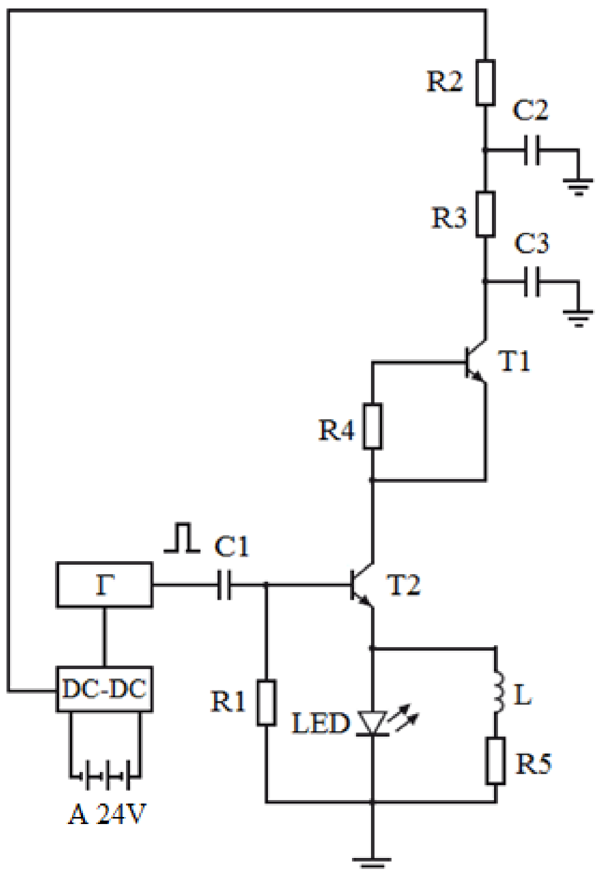
White LEDs car light

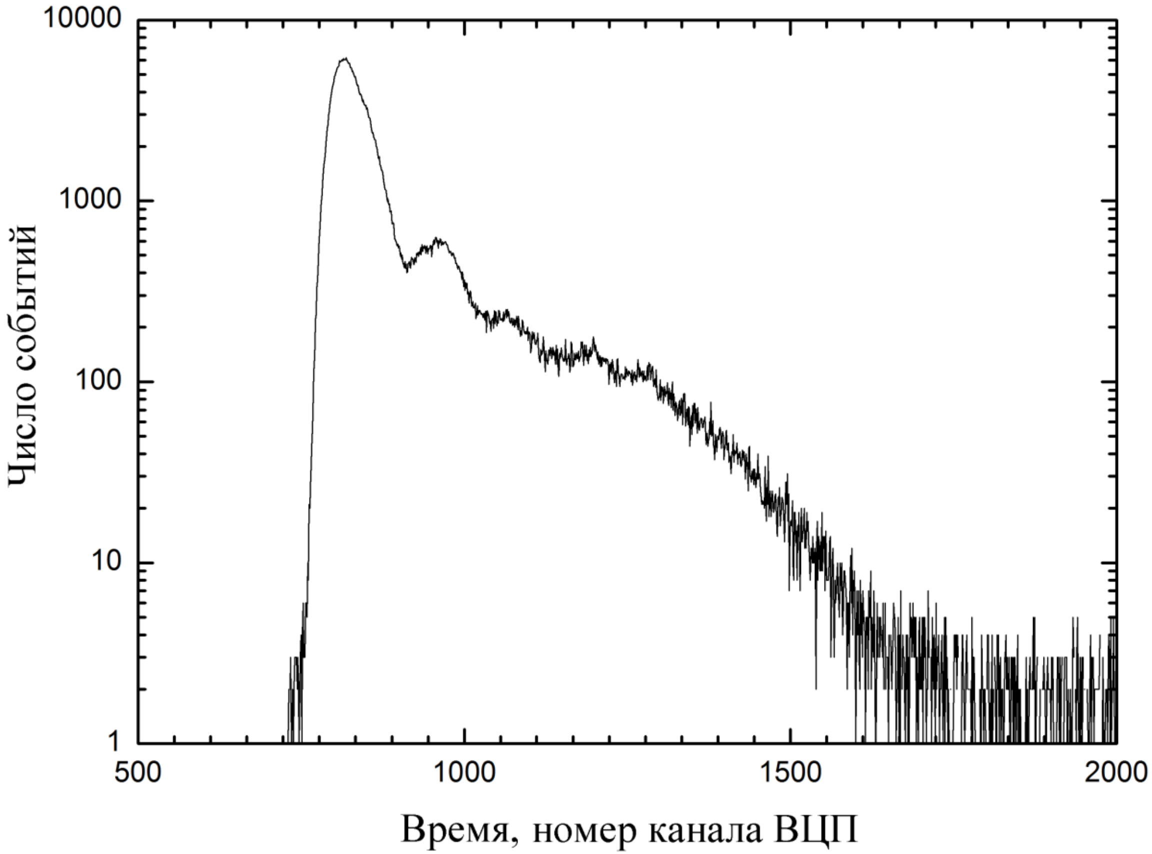
Gas station near Moscow

Bizzarre application

Tunka-133 LED calibration system

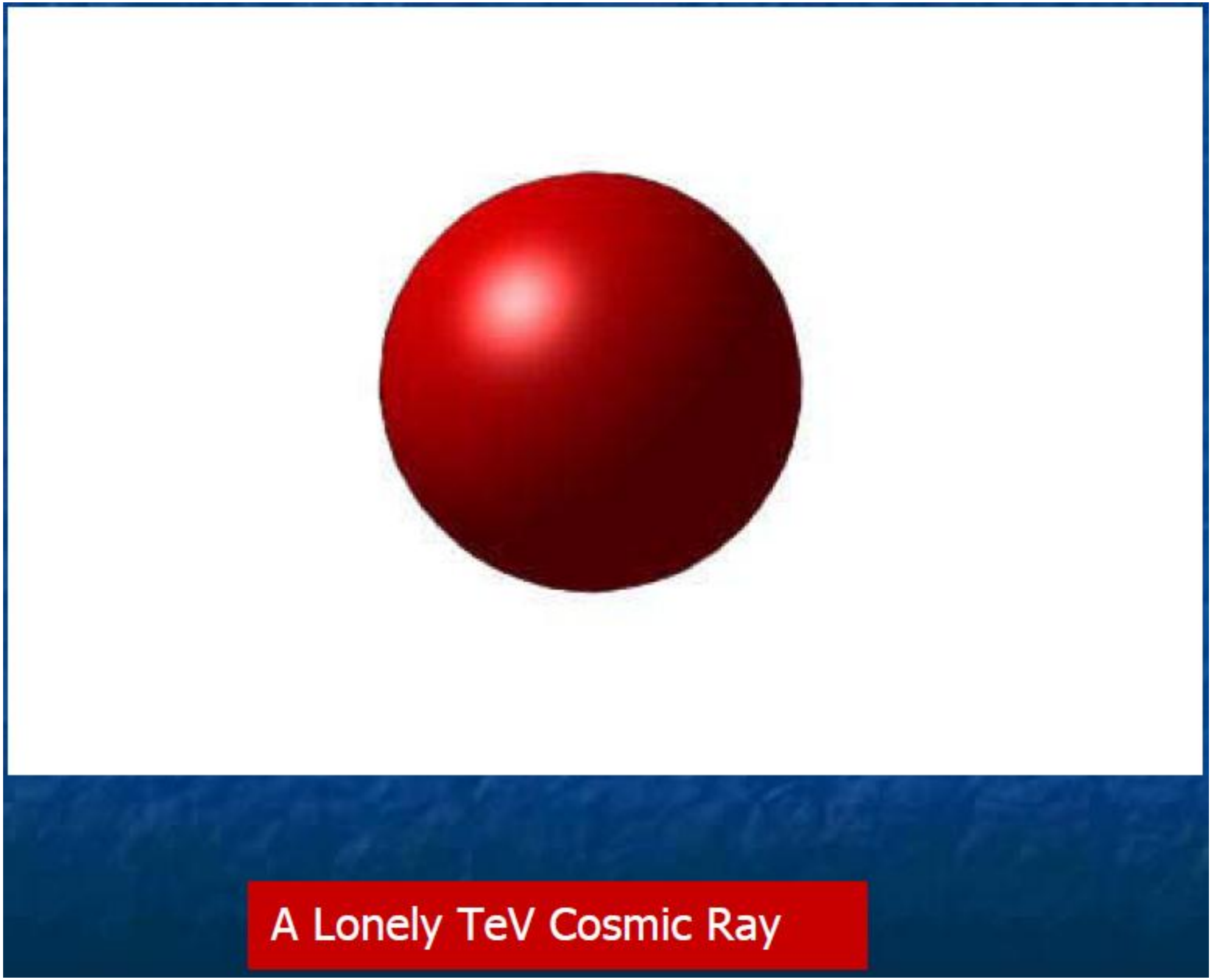






One high power LED (Royal Blue), ~ 10^{12} photons per pulse, 3 ns (FWHM)

Toy pilotless quadrocopter for time calibration of Tunka-133



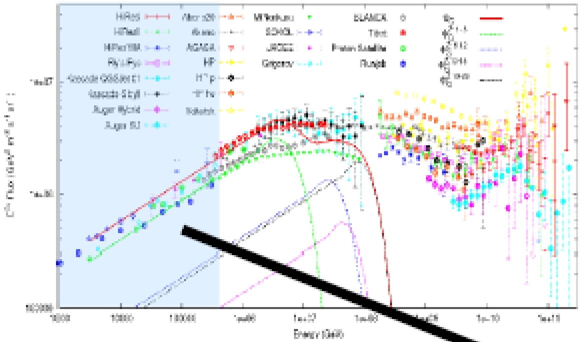
Trevor Weeks

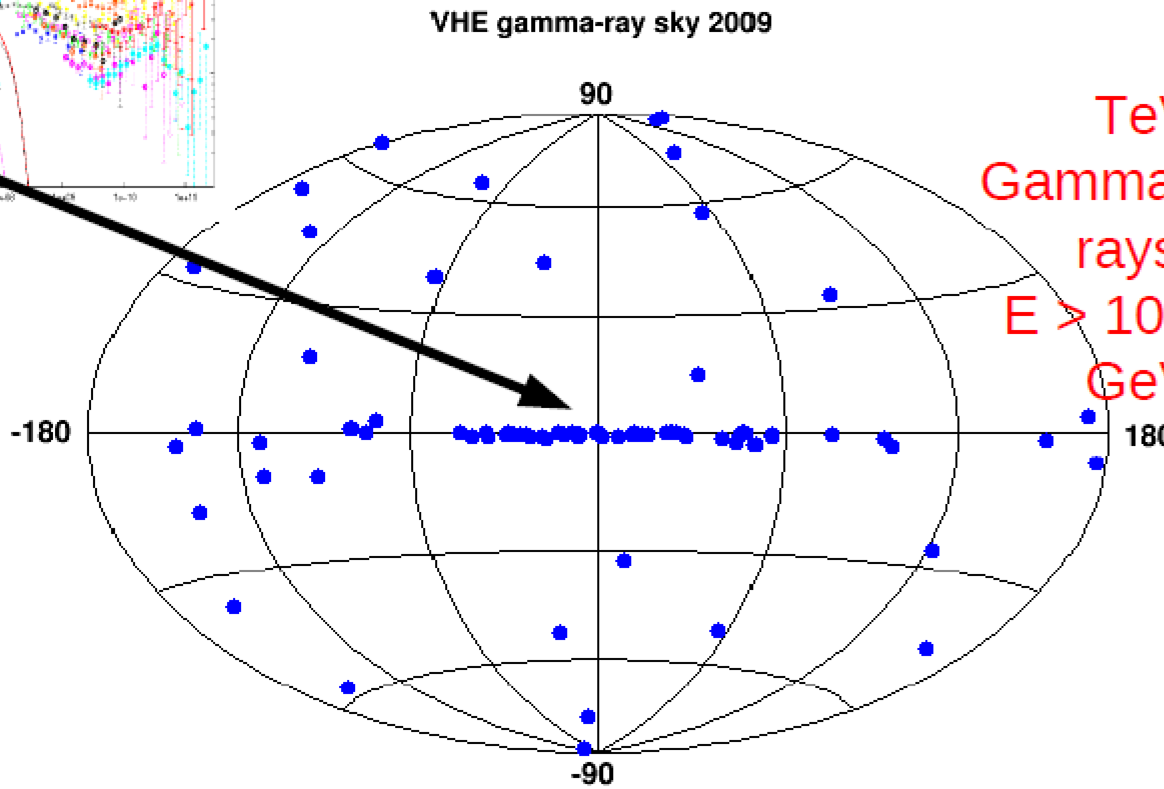
To multi-TeV gamma-ray astronomy

Crimea Experiment 1959-1965, Chudakov, et al., (SNR, radio galaxies)

Tevatron sky

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

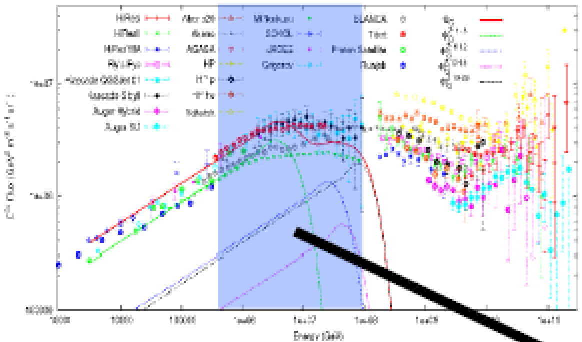


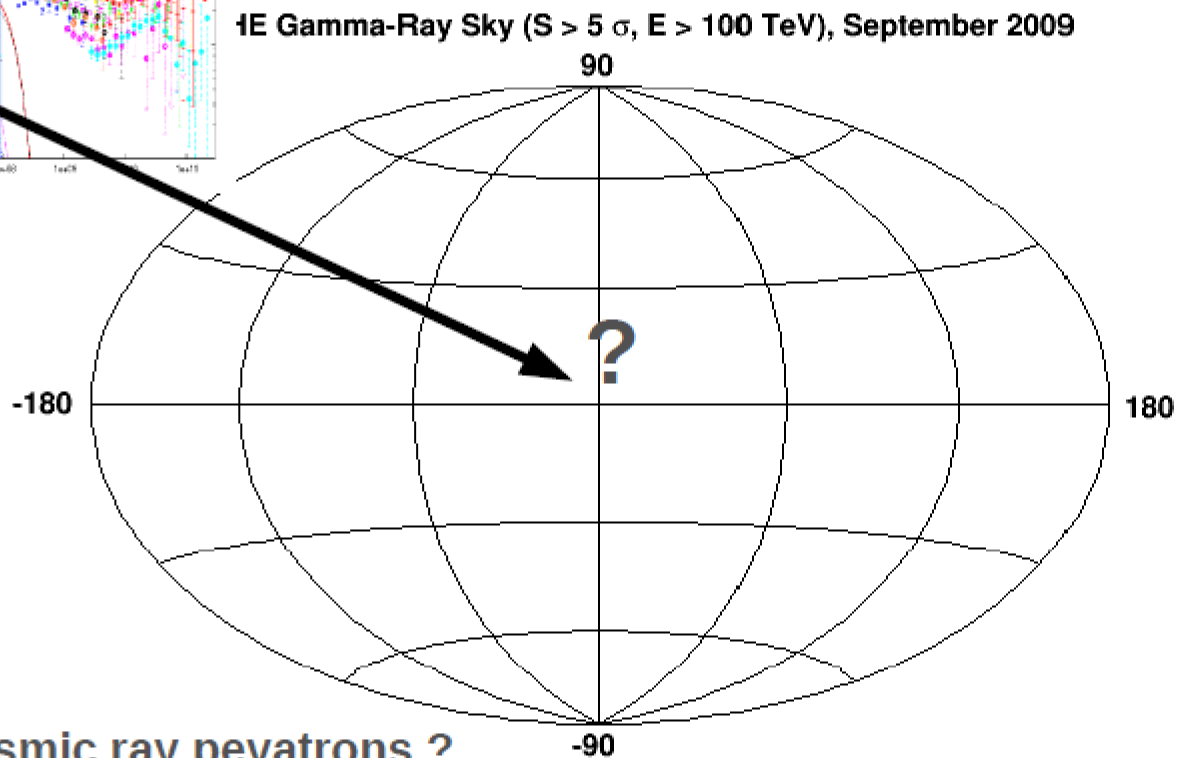


TeV Gamma-rays: E > 100 GeV

Pevatron sky

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



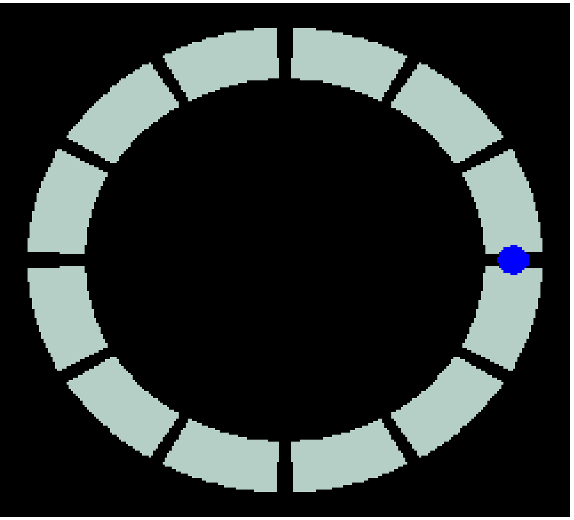


Where are the cosmic ray pevatrons ?

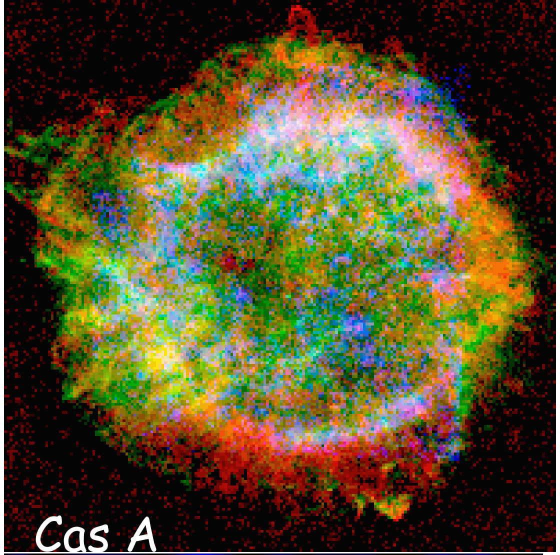
HELMHOLTZ
GEMEINSCHAFT

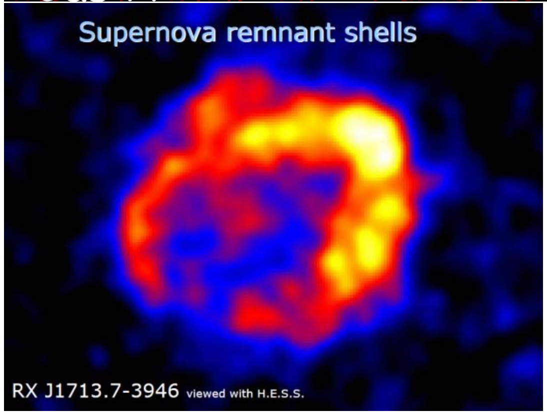
How could cosmic accelerators work?

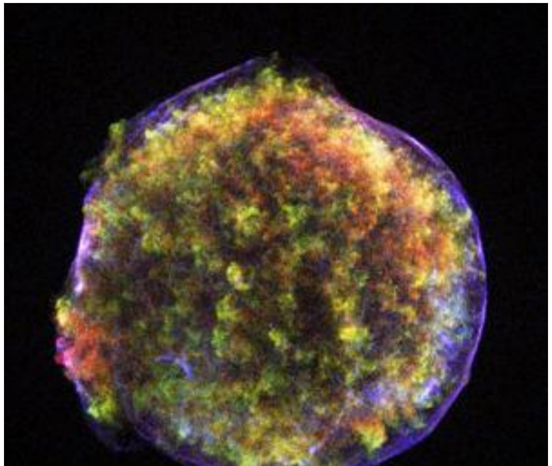
Man-made accelerators



SNR – the main source of Galactic cosmic rays







1933. Baade&Zwikky. SNe explosions - the source of CR

1949. Fermi. Theory of CR acceleration

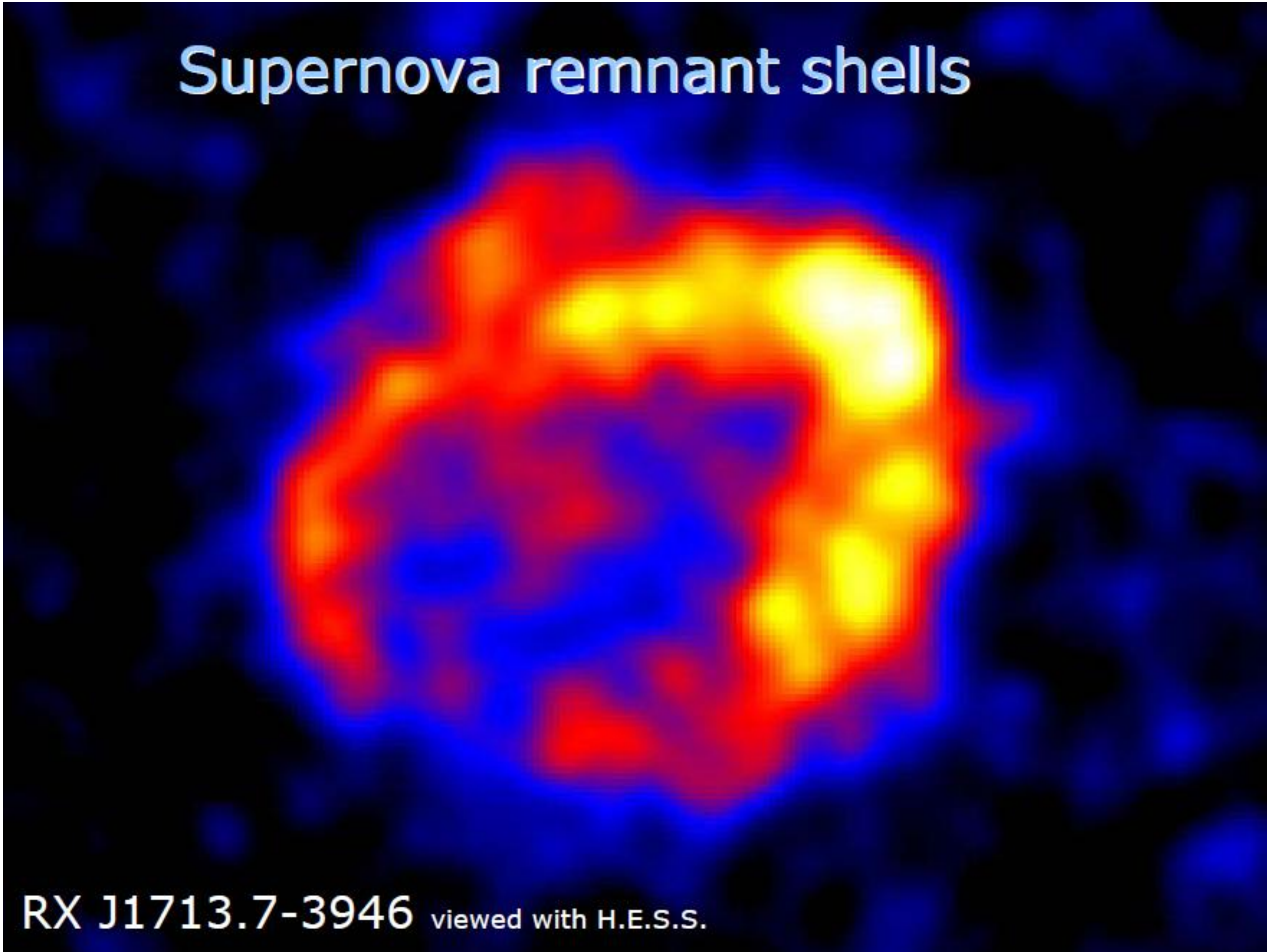
1963. Ginzburg&Syrovatsky. Transition of 10% of shell’s kinetic energy into CR is enough for Galactic CR origin

1977-1978. Krymsky, Bell et all. Theory of CR acceleration on shock wave

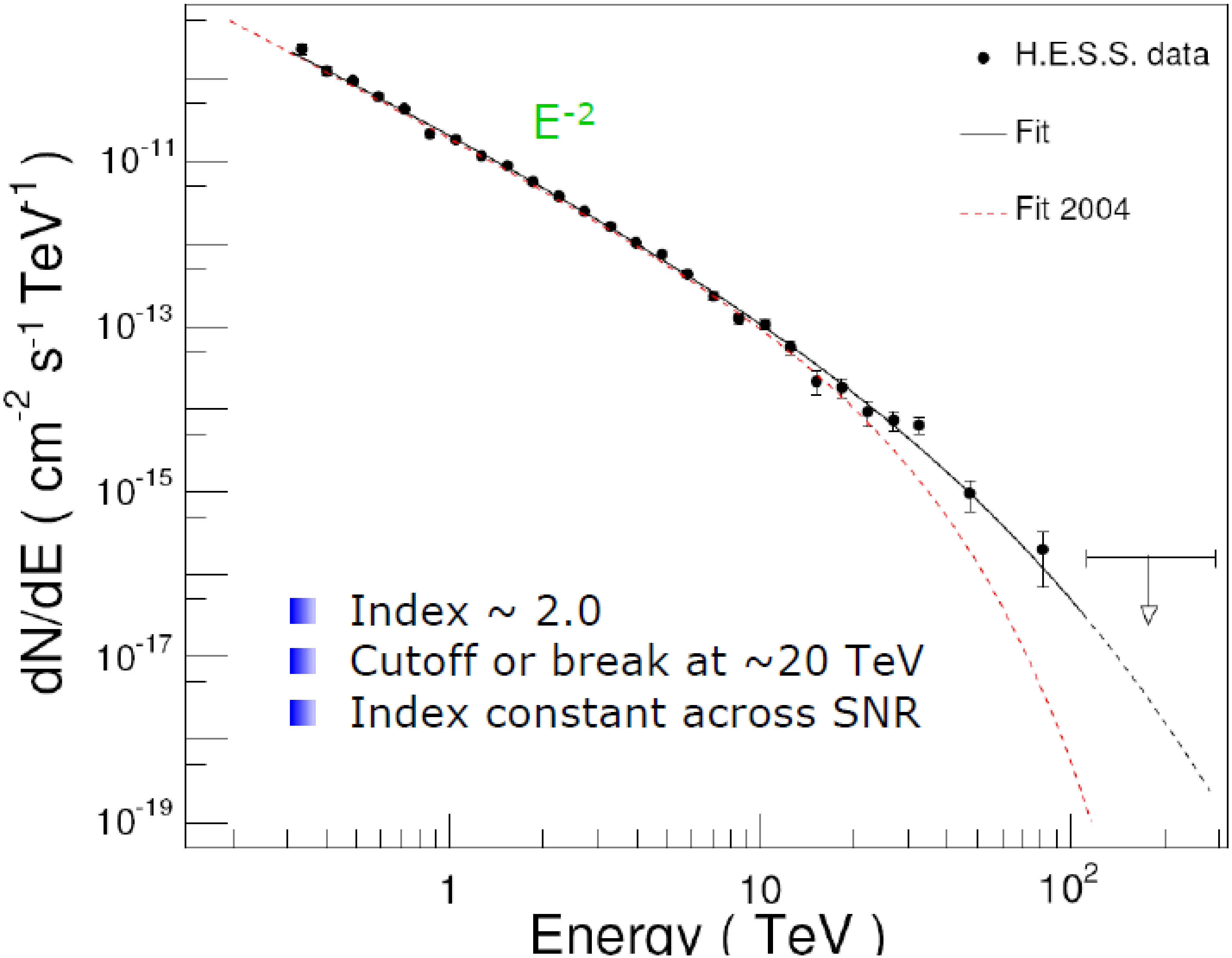
1993-1996. Berezhko et al. Nonlinear theory CR acceleration on shock waves.

2003-2005. Bell, Berezhko, Voelk, Ptuskin, Zirakashvili. Magnetic field enhancement on sock wave front - Emax ~ $Z \cdot 10^{15}$ eV

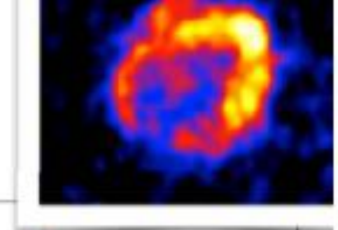
So far there are no any reliable proofs of hadronic acceleration mechanisms!!!

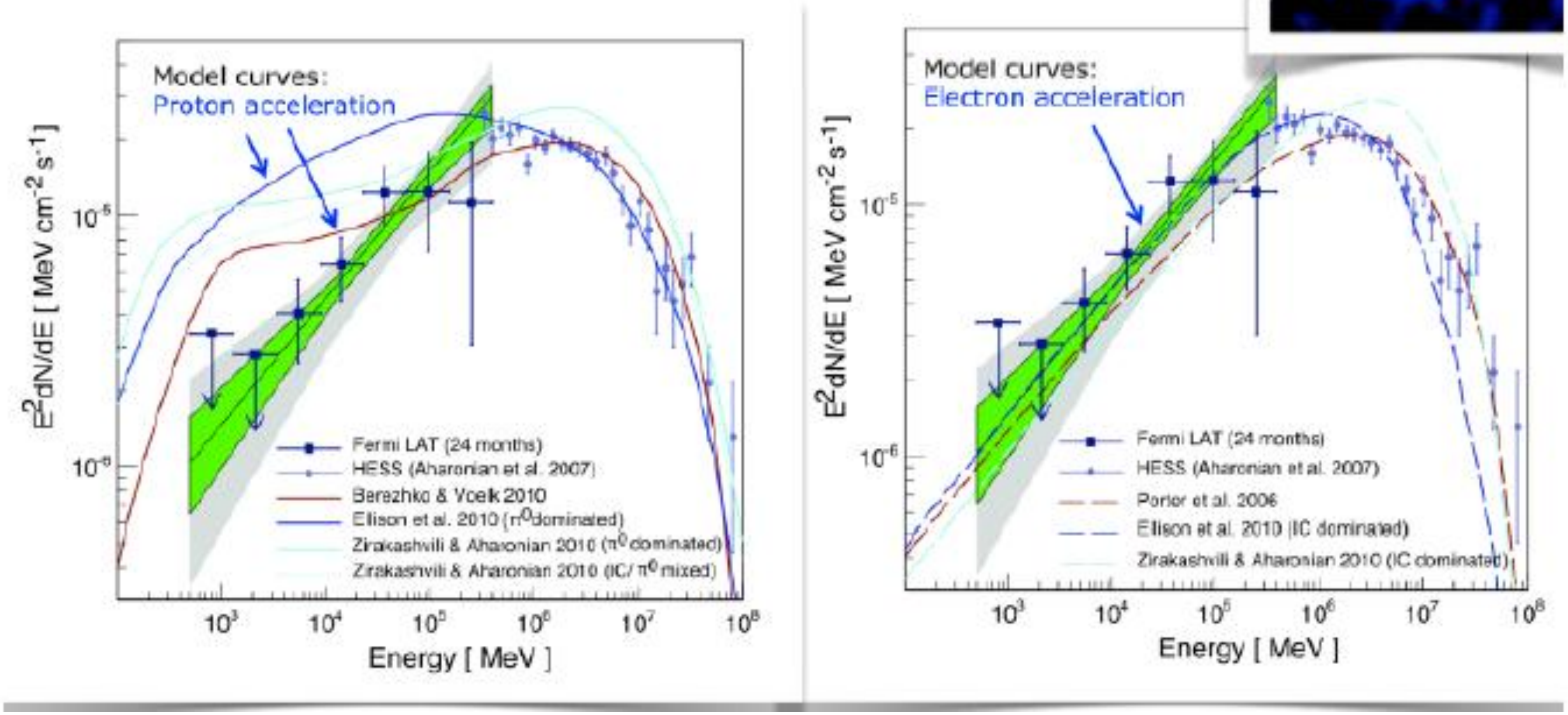

Supernova remnant shells
RX J1713.7-3946 viewed with H.E.S.S.

Particle acceleration to beyond 100 TeV



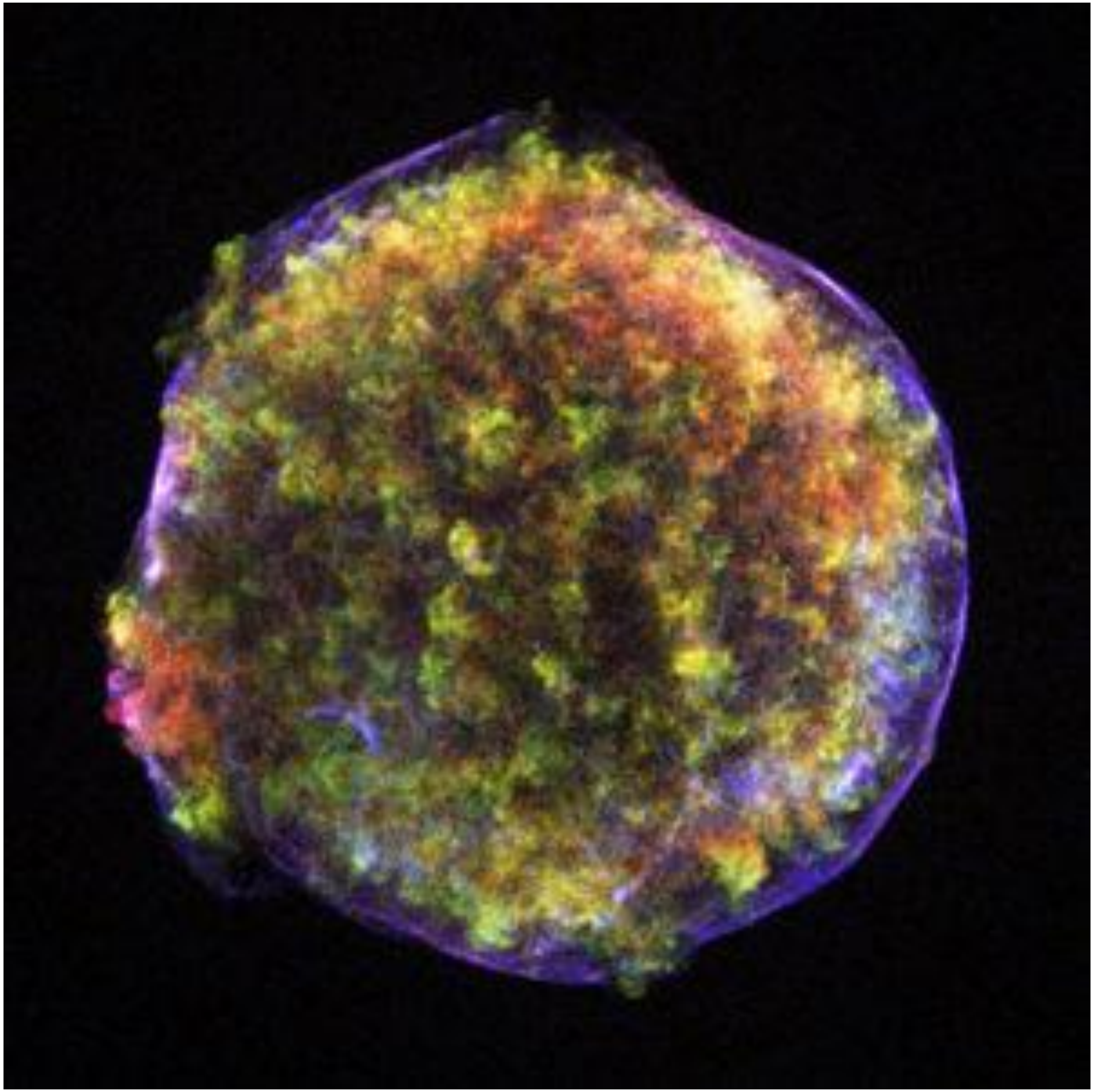
The best candidate? RX J1713.7-3946



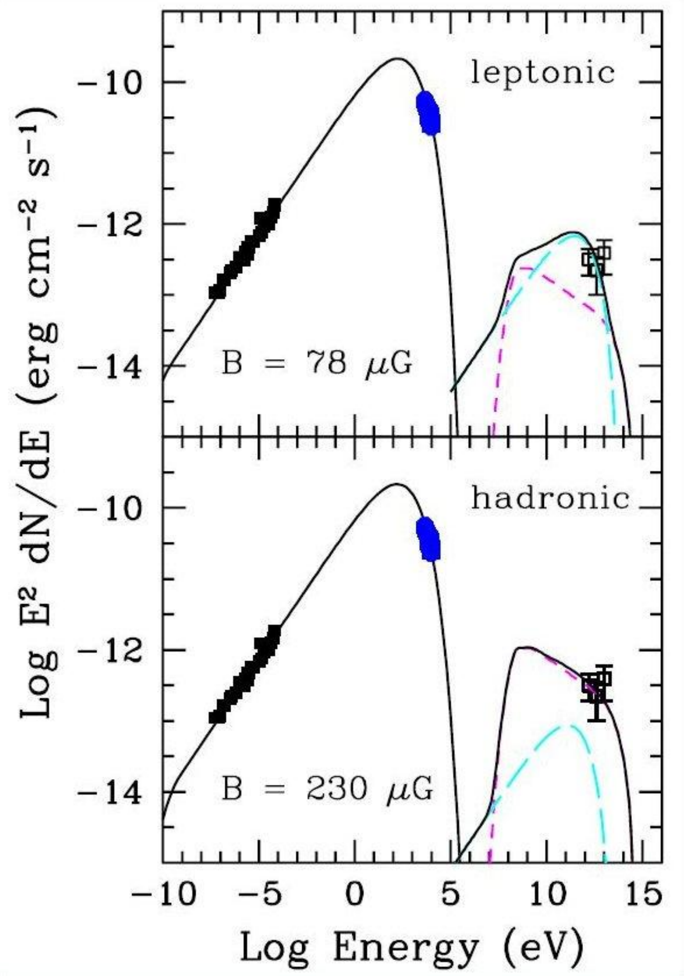


H.E.S.S.

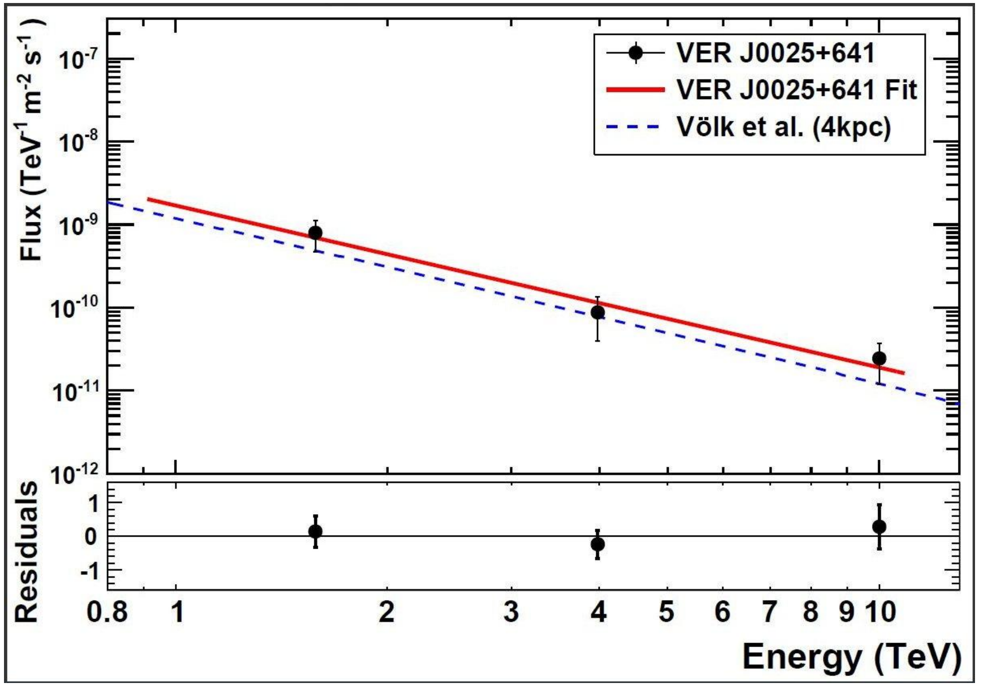
SN1572 Tycho Brahe



VERITAS



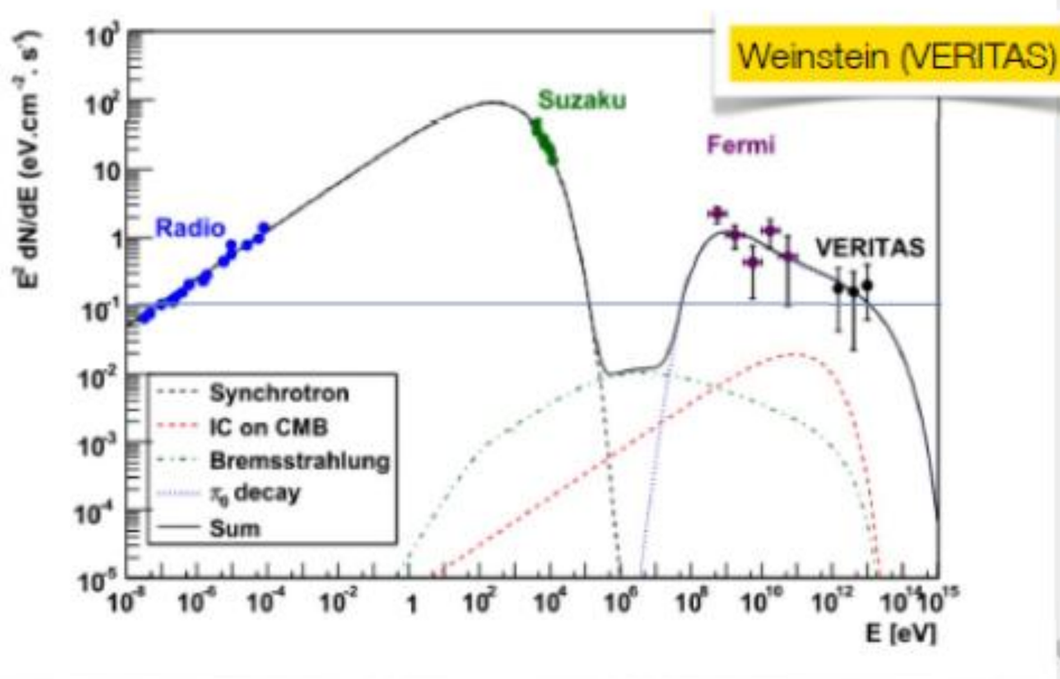
leptonic
B = 78 μG
hadronic
B = 230 μG
Log E² dN/dE (erg cm⁻² s⁻¹)
Log Energy (eV)



VER J0025+641
VER J0025+641 Fit
Völk et al. (4kpc)
Flux (TeV⁻¹ m⁻² s⁻¹)
Residuals
Energy (TeV)

Tycho SNR might now be the best case

- Tycho detected with both Fermi-LAT and VERITAS
- Leptonic model strongly disfavored
- No cutoff in VERITAS →acc time = SNR age → max proton energy > 300 TeV
- But beware drawing strong conclusion from spectral modeling. Also very weak source, both in Fermi-LAT and in VERITAS



Case	$E_{p,max}$ (TeV)	Distance (kpc)	E_{SNR} (erg)
"near"	340	2.78	10^{51}
"far"	540	3.58	$2x10^{51}$

Half a pevatron?

Current projects (high energy)

1. CTA (2017-18) - ~400 mln Euros (!)

2. HAWC (2014) - ~30 mln USD

3. LHAASO (2013-2018) ~150 mln USD

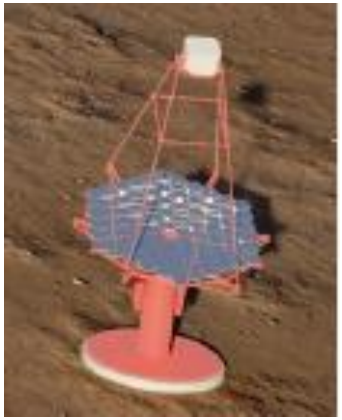
4. **TAIGA - ~10 mln Euros**

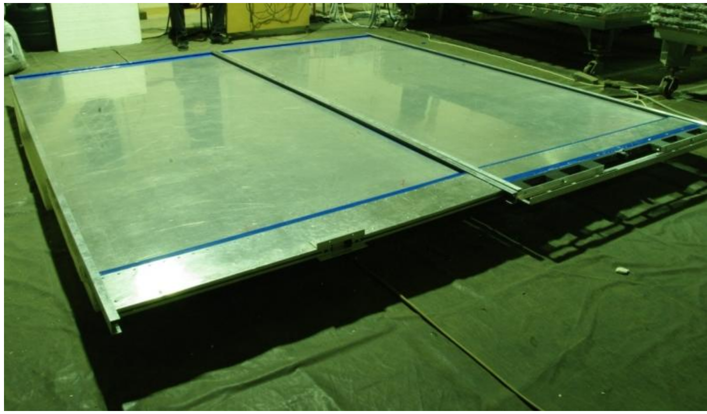
5. 5@5 (Bykov&Aharonyan)

Towards High Energy Gamma-Ray Astronomy array in the Tunka Valley

TAIGA

(Tunka Advanced International Gamma and cosmic ray Array)





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

- **Net of imaging telescopes $3\text{-}5\ m^2$ area**

- **Net of muon detectors $10^2 - 10^3\ m^2$ area.**

TAIGA Collaboration

MSU (SINP), Moscow
ISU (API), Irkutsk
Institute for Nuclear Research of RAS, Moscow
IZMIRAN, Moscow
JINR, Dubna
MEPhI, Moscow
IPSM SB RAS, Ulan-Ude
Altay State University, Barnaul
Kurchatov Institute, Moscow

University of Hamburg, Hamburg
DESY, Zeuthen
MPI, Munich
KIT, Karlsruhe
University of Tuebingen
University of Turin

Gamma-ray Astronomy

Search for PeVatrons.

VHE spectra of known sources: where do they stop?

Absorption on IR and CMB.

Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition from 10^{14} to10^{18} eV.

10^7 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.

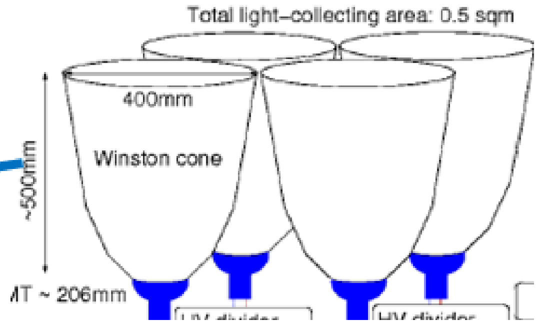
pp cross-section measurement ......

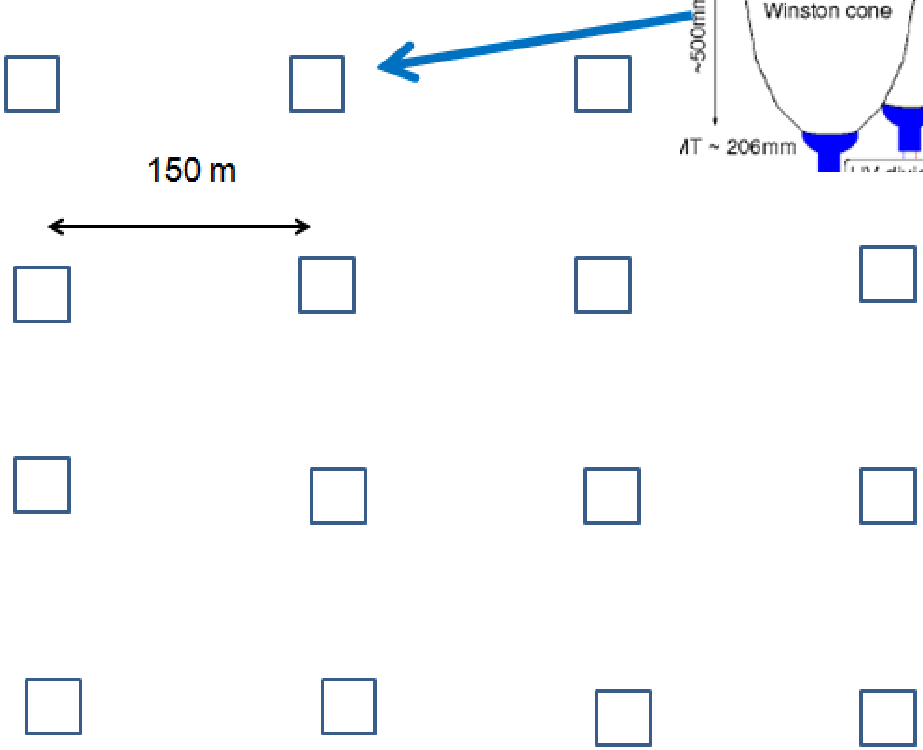
What we can see with 1 km^2 array (short list)

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**

HiSCORE concept

M.Tluczycont et al.





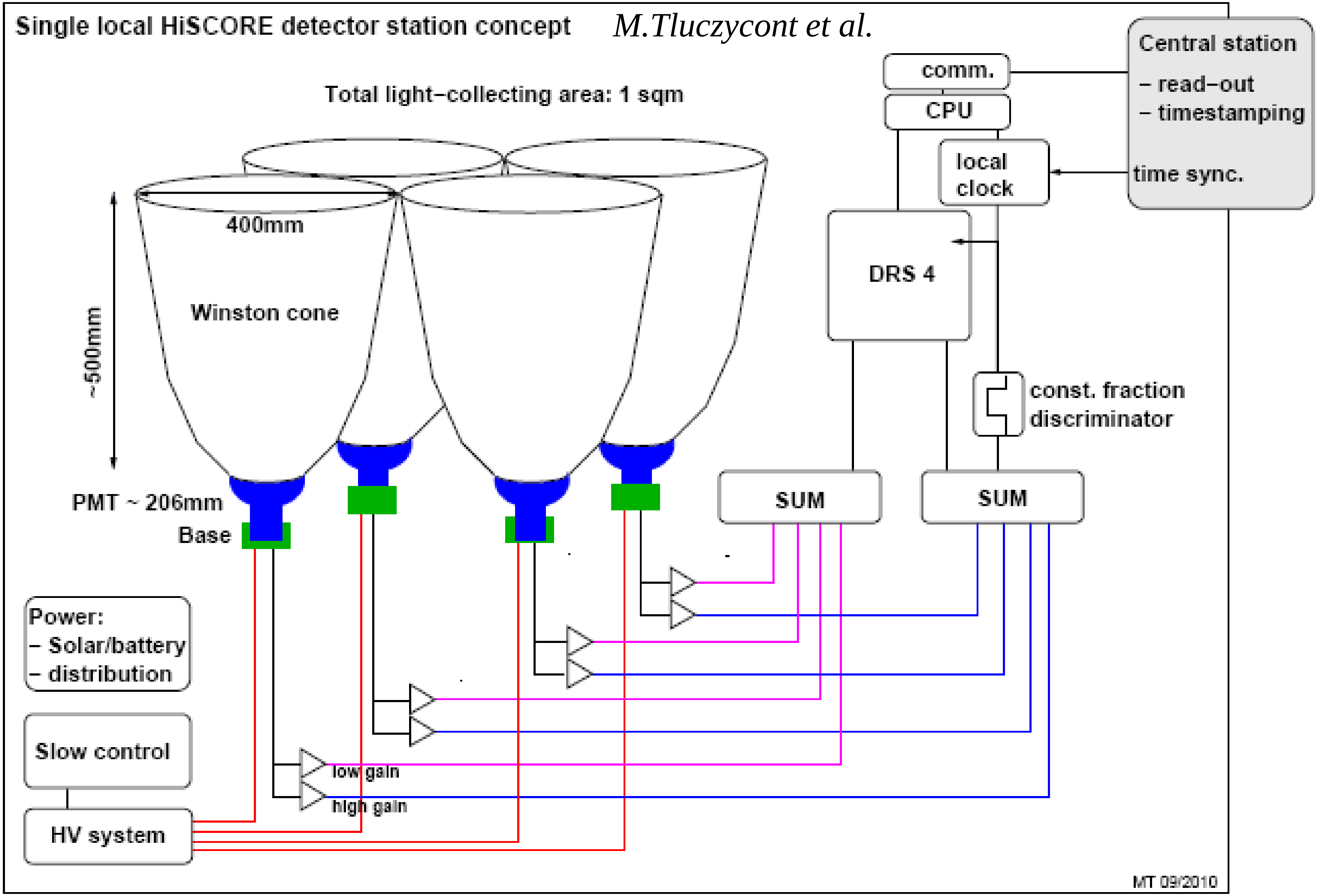
Area : from 1 to 100 km²

FOV ~ 0.6 ster (± 30°)

Energy threshold ~ 20 TeV

Ang. res ~ 0.1°

TAIGA optical station design



PMT candidates

EMI9350KB

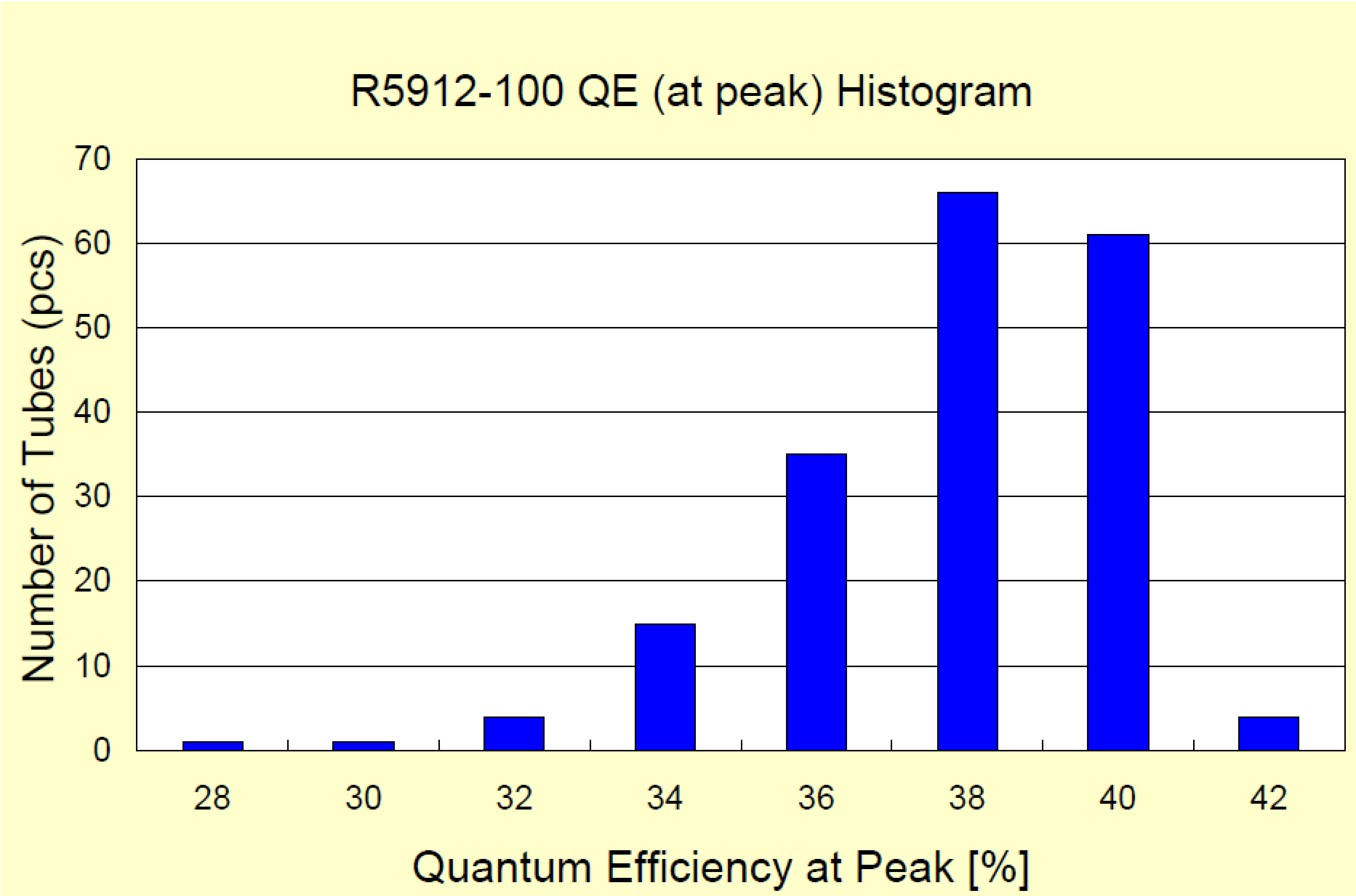
ET9352KB 6 sts

11” D784?

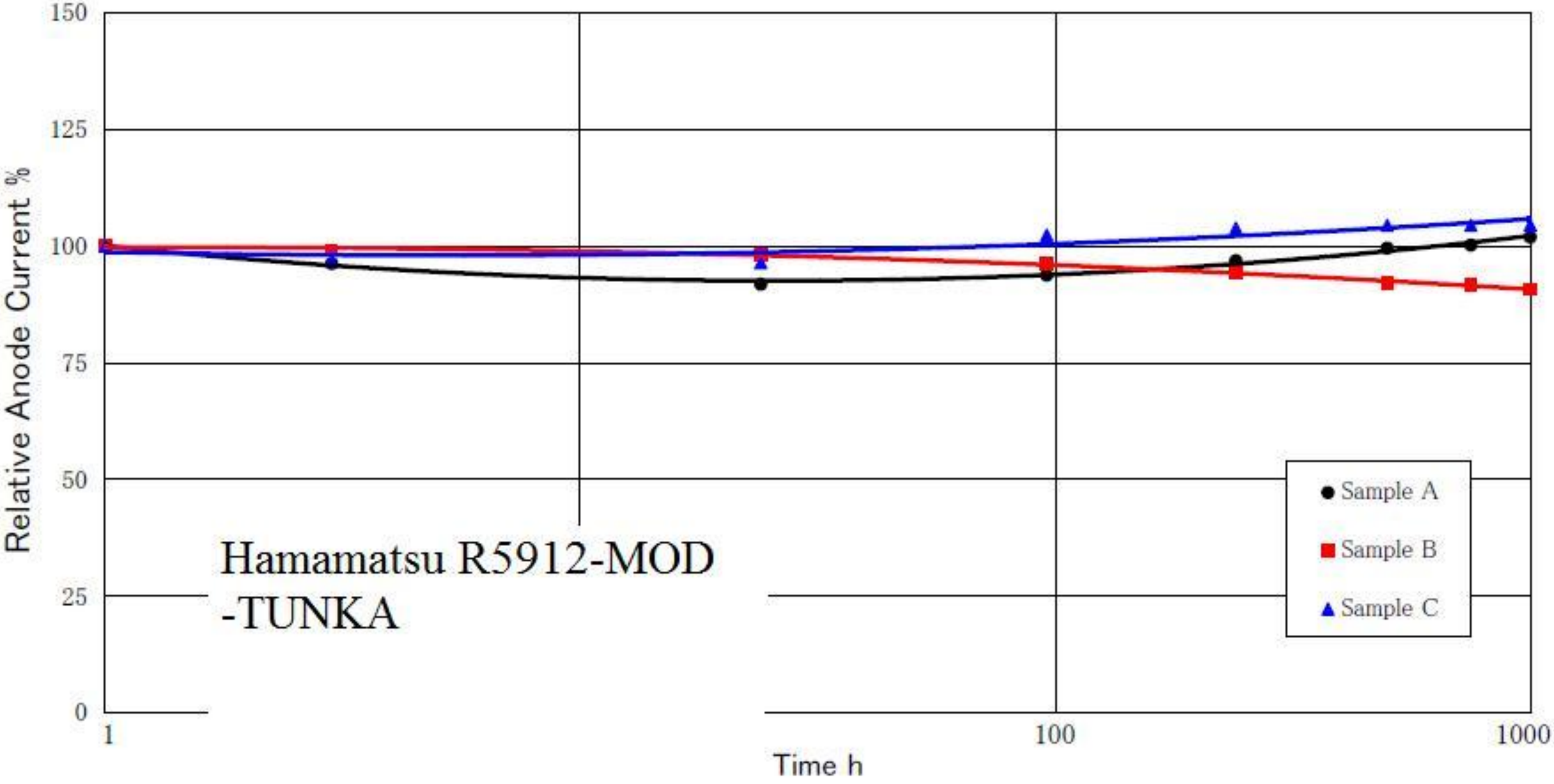
8” R5912

10” R7081

12” R1170


R5912-100 QE (at peak) Histogram
Number of Tubes (pcs)
0
10
20
30
40
50
60
70
28
30
32
34
36
38
40
42
Quantum Efficiency at Peak [%]

200 μA anode current



Ways of threshold decreasing

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

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

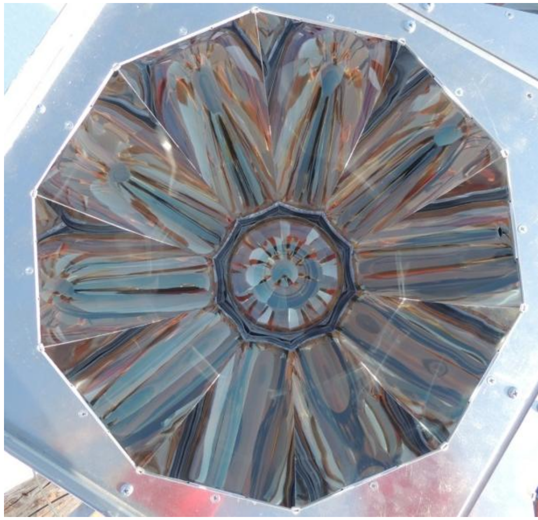
2. Analog summation of signals in one station

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

4. QE max = 35-40%

5. WLS foils

Winston cone



Energy threshold of Cherenkov array

$$\frac{\text{Signal}}{\text{noise}} = \frac{S \bullet Q_{ph}(200) \bullet \eta}{\sqrt{\Omega \bullet S \bullet I_{ph}\, \eta \bullet T}} \approx 5$$

$$Q_{ph}(175) = C \cdot E$$

$$E_{th} \sim \frac{\sqrt{I_{ph} \bullet \Omega \bullet T}}{\sqrt{S \bullet \eta}}$$

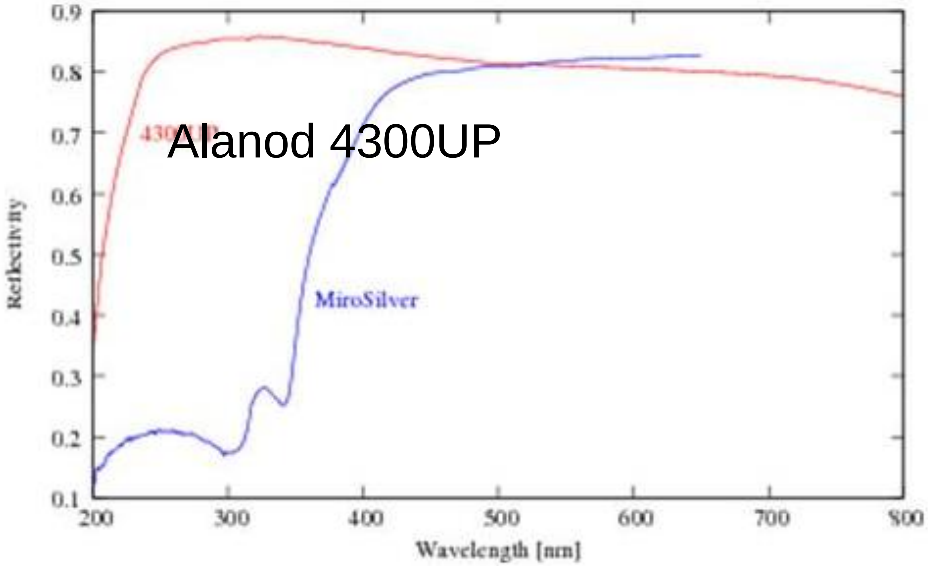
S– area of PMT photocathode
η- quantum efficiency (QE)
Q_{ph} (R) –Cherenkov light flux

T - duration of pulse
(20 –40 нс)
Ω - angle of view

I_{ph} – light night background
$\approx 3.10^8$ ph/cm^2 s

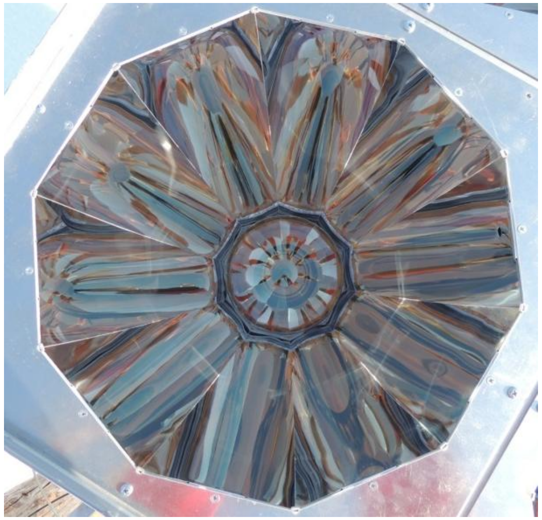
for S =0.1 m^2 и $\eta \approx 0.1$: $E_{th} \approx 100$ TeV

Refelectivity of Winston cone (Alanod4300UP)



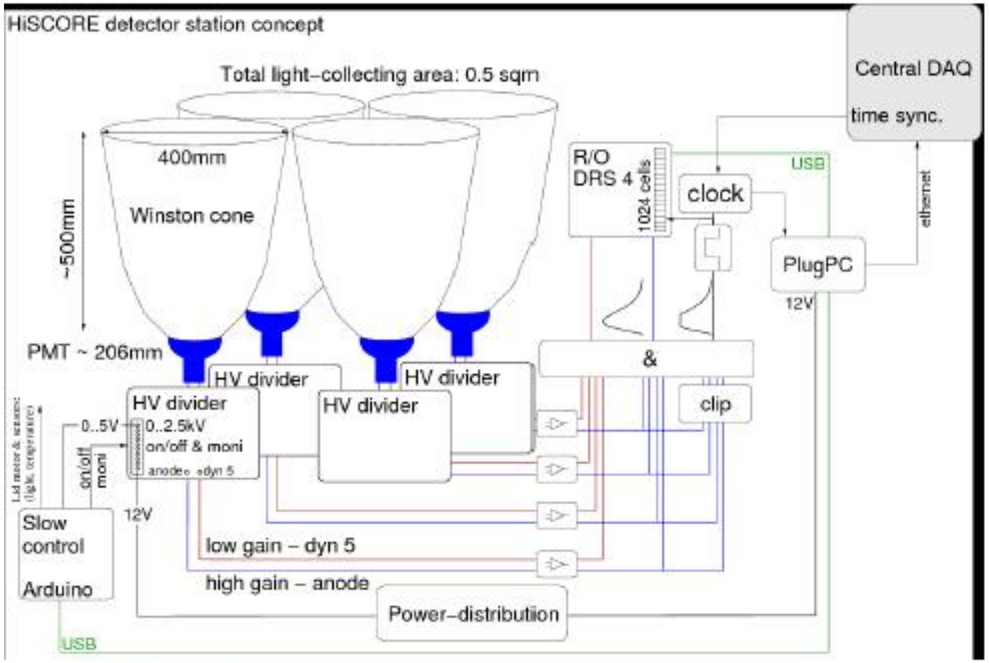
Optical station

Winston cone
Side view

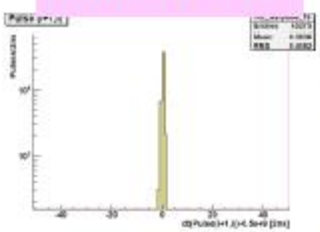


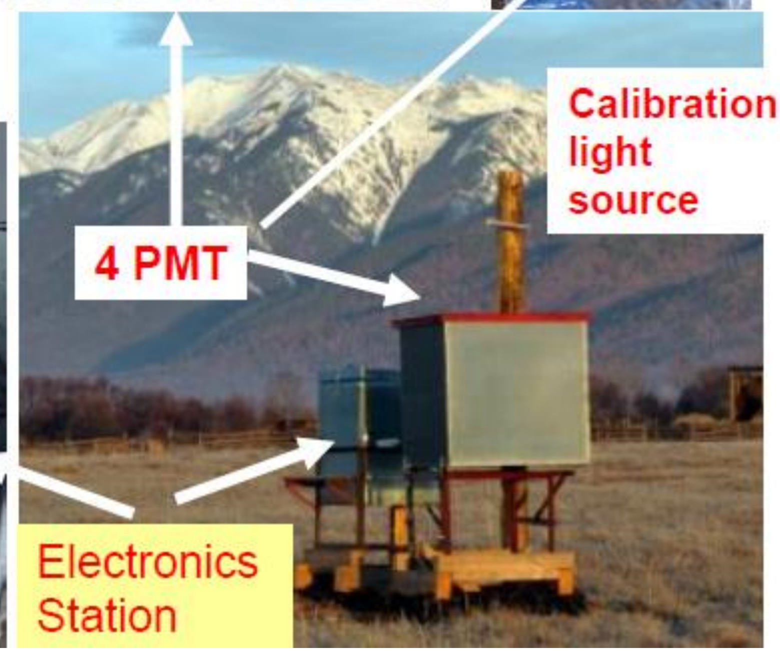
Winston cone
View from above

First optical station of TAIGA

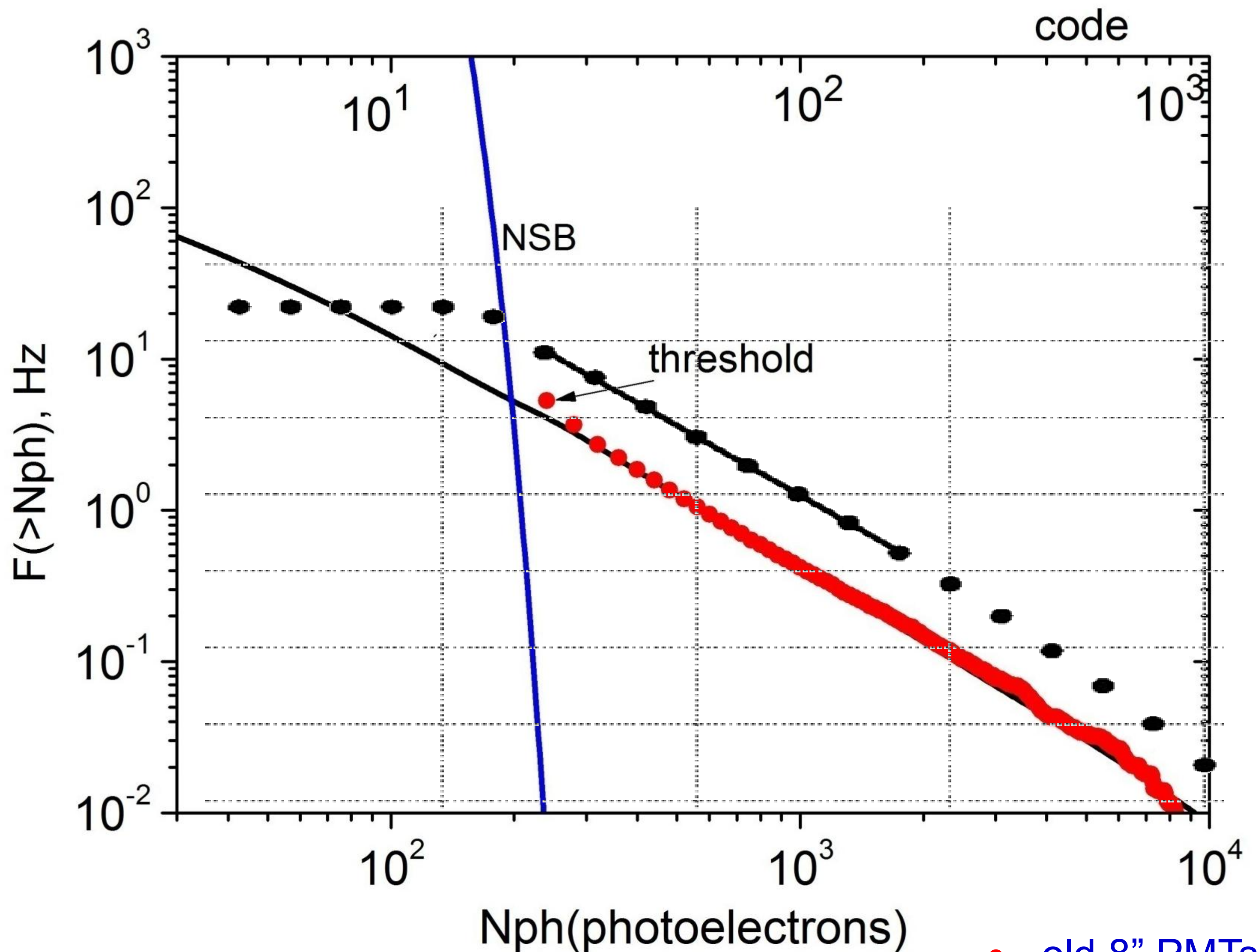


rms <0.2 ns

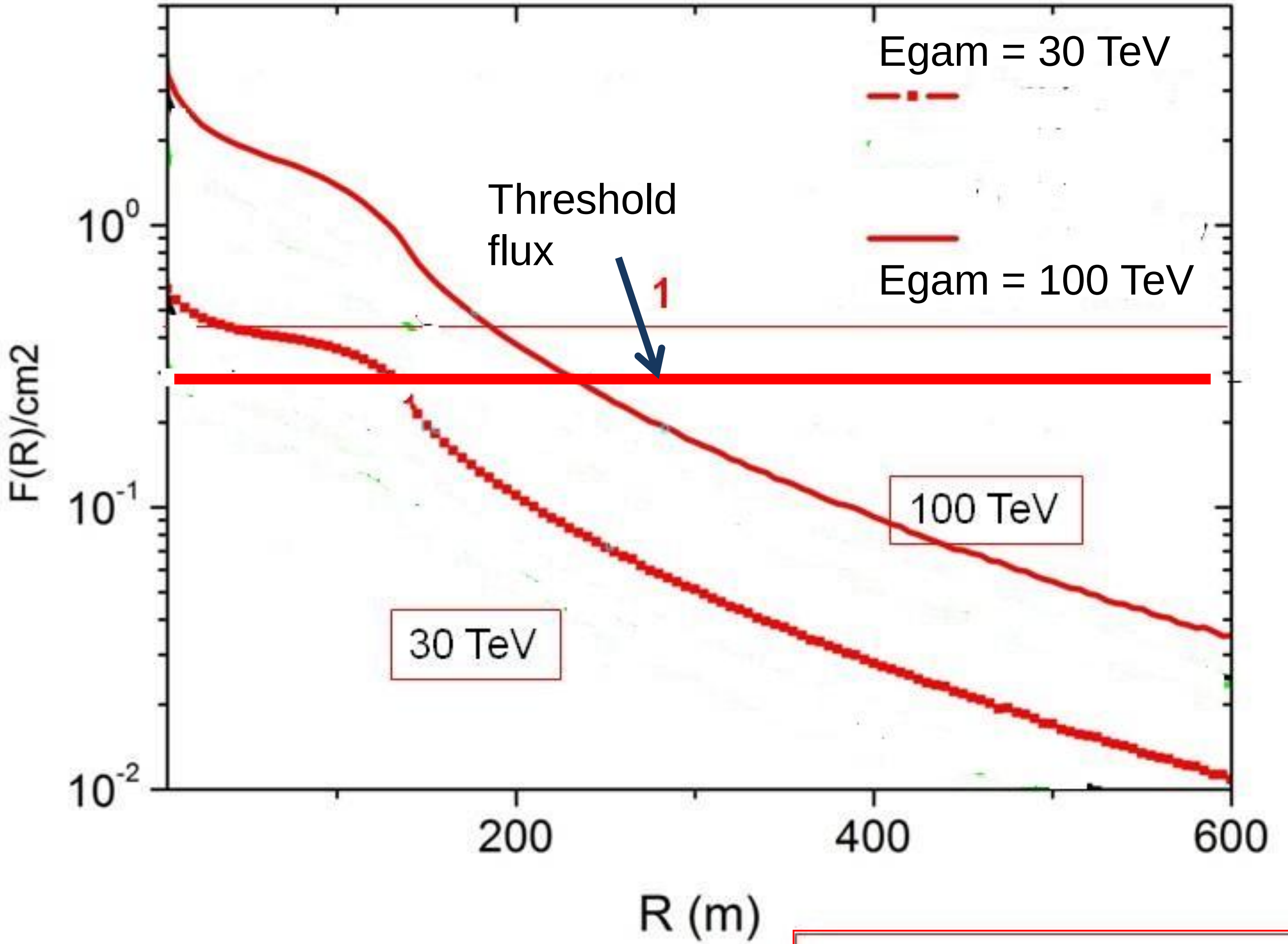




10 Hz rate - 30 TeV threshold!!!



● - old 8” PMTs from MACRO
● - new 8” PMTs

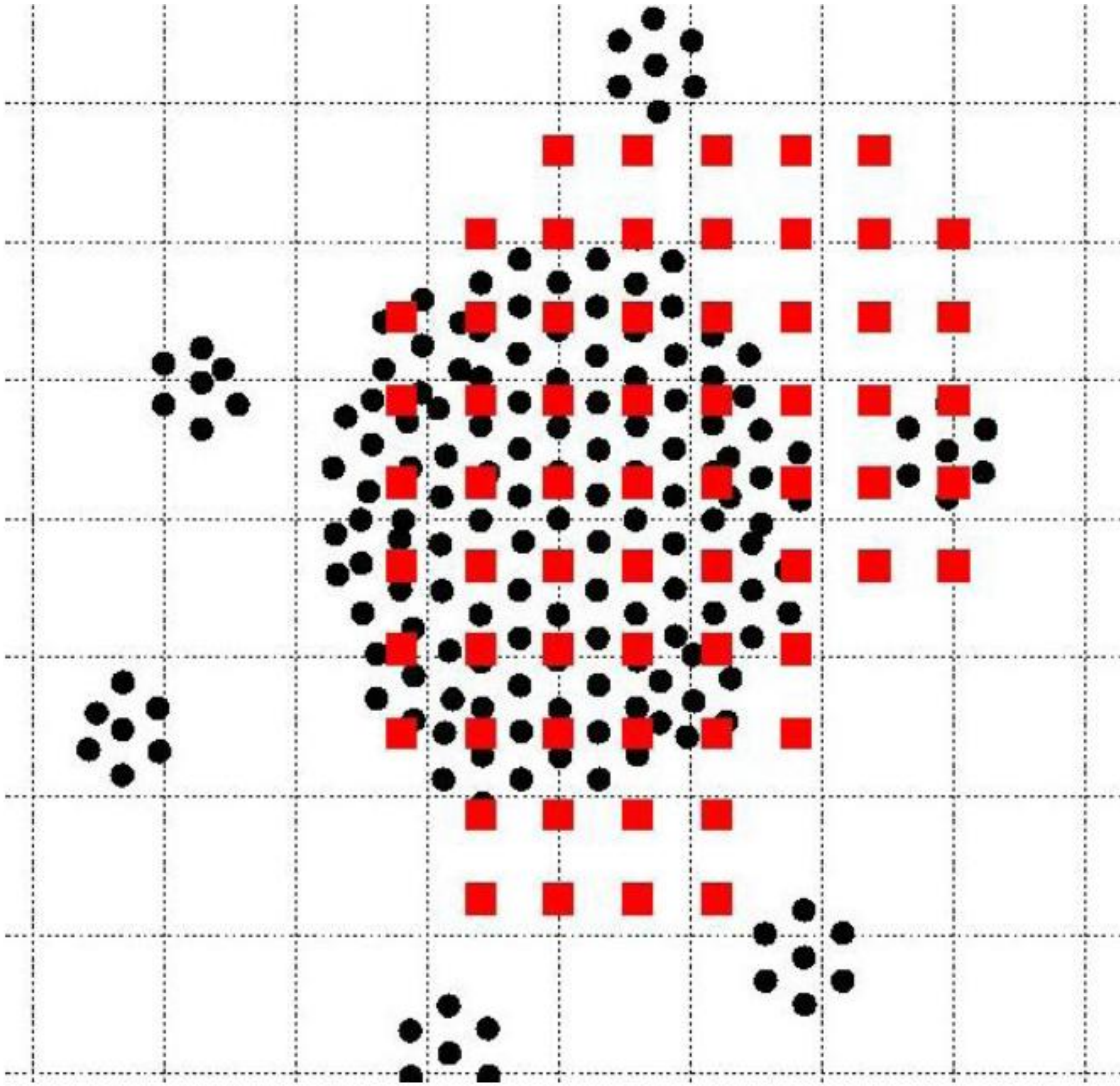


Q eff =0.10 T =10 ns

30 TeV threshold is already reached!!!

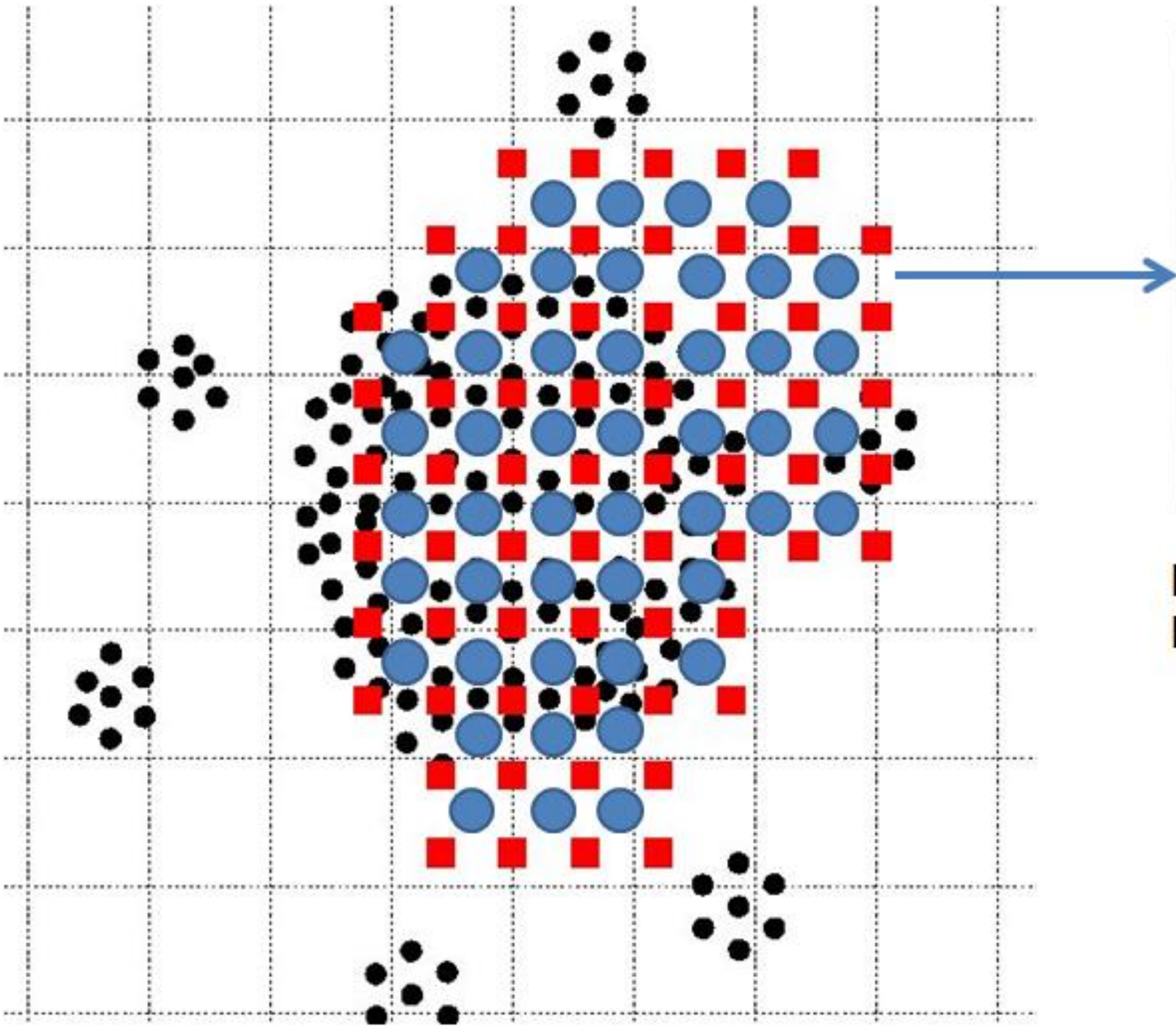
1 stage

64 stations (2014-15) – 1 sq.km array

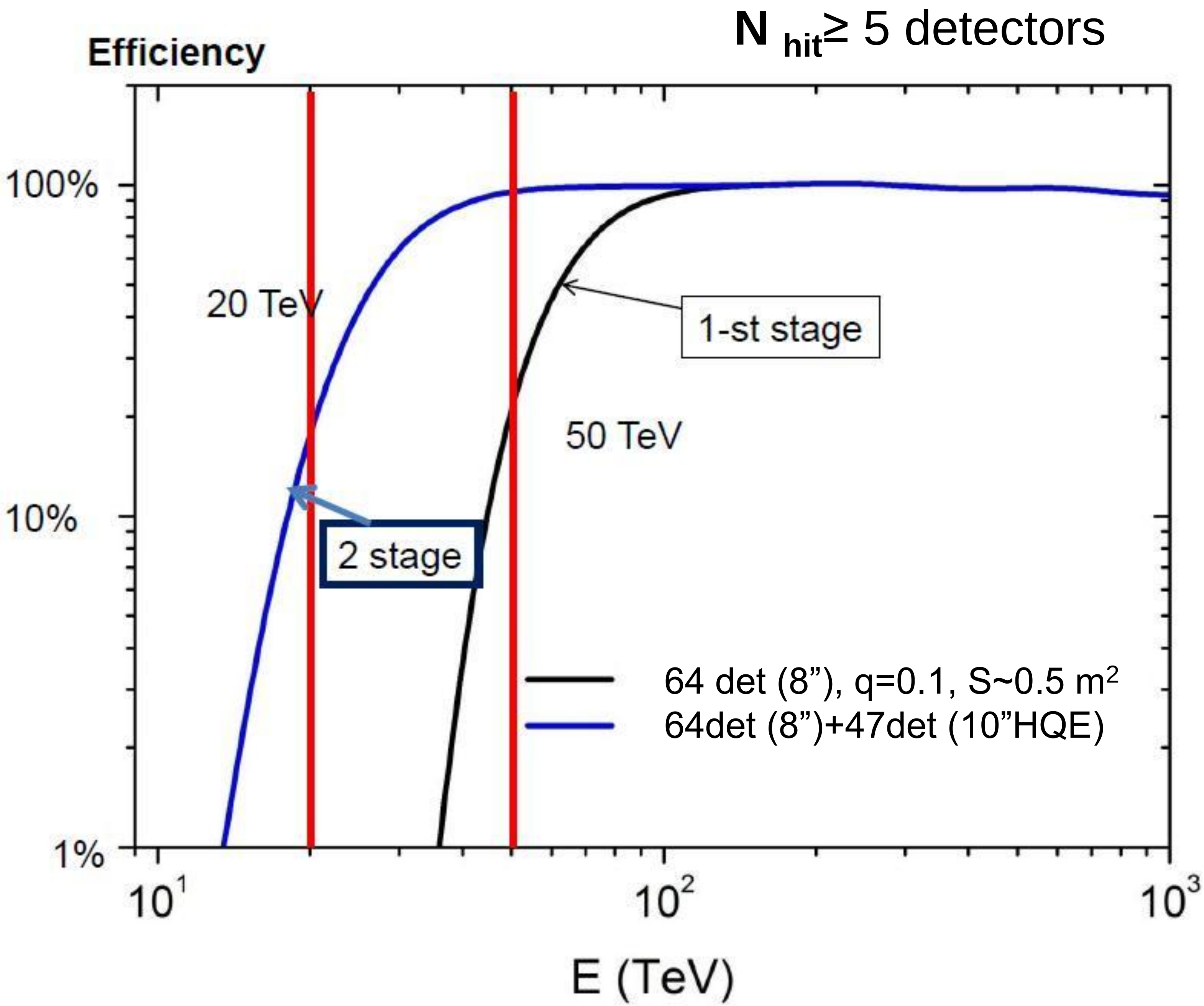


Stage 2

64 stations (8" PMTs) + 47 stations (10" PMTs) – 1 sq.km array



R7081 10" Hamamatsu



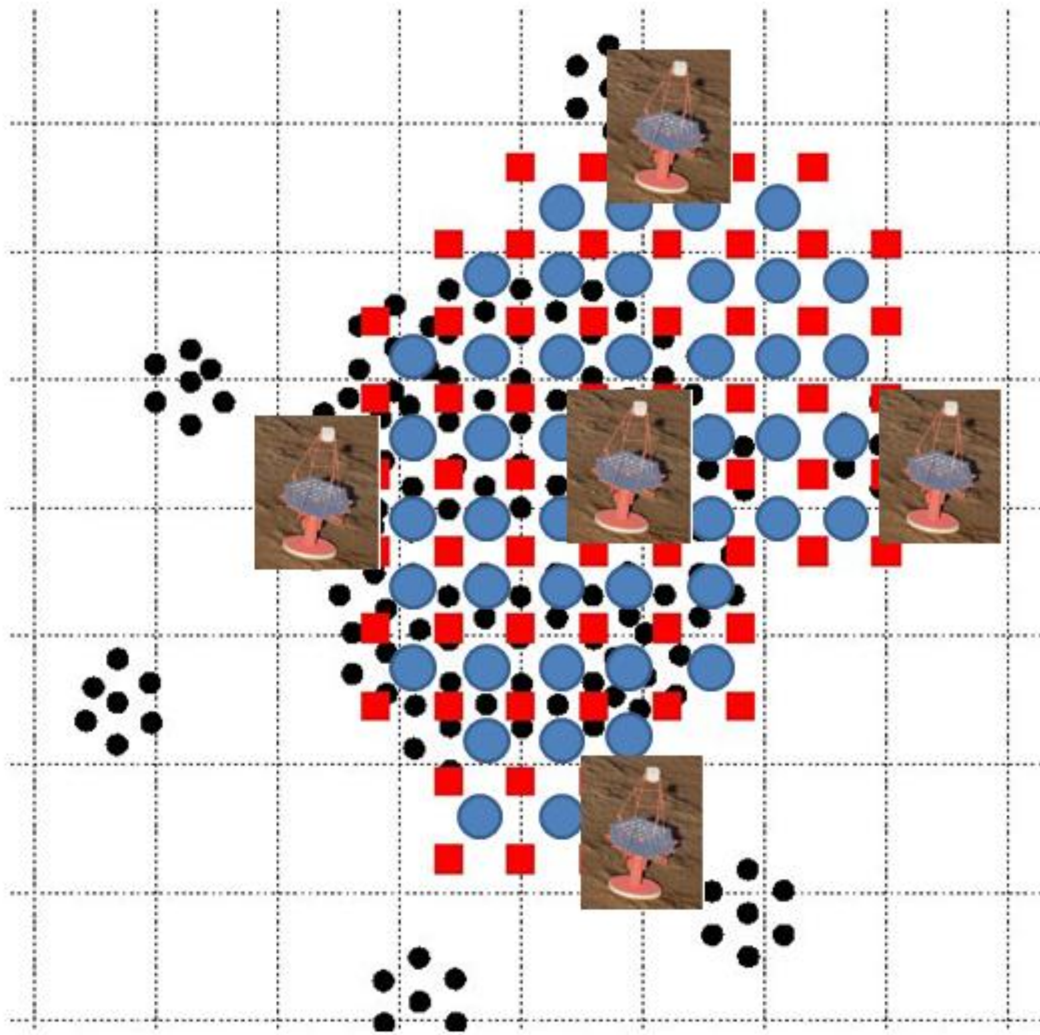
N $_{hit}$≥ 5 detectors
Efficiency
100%
10%
1%
20 TeV
50 TeV
1-st stage
2 stage
64 det (8”), q=0.1, S~0.5 m^2
64det (8”)+47det (10”HQE)
10^1
10^2
10^3
E (TeV)

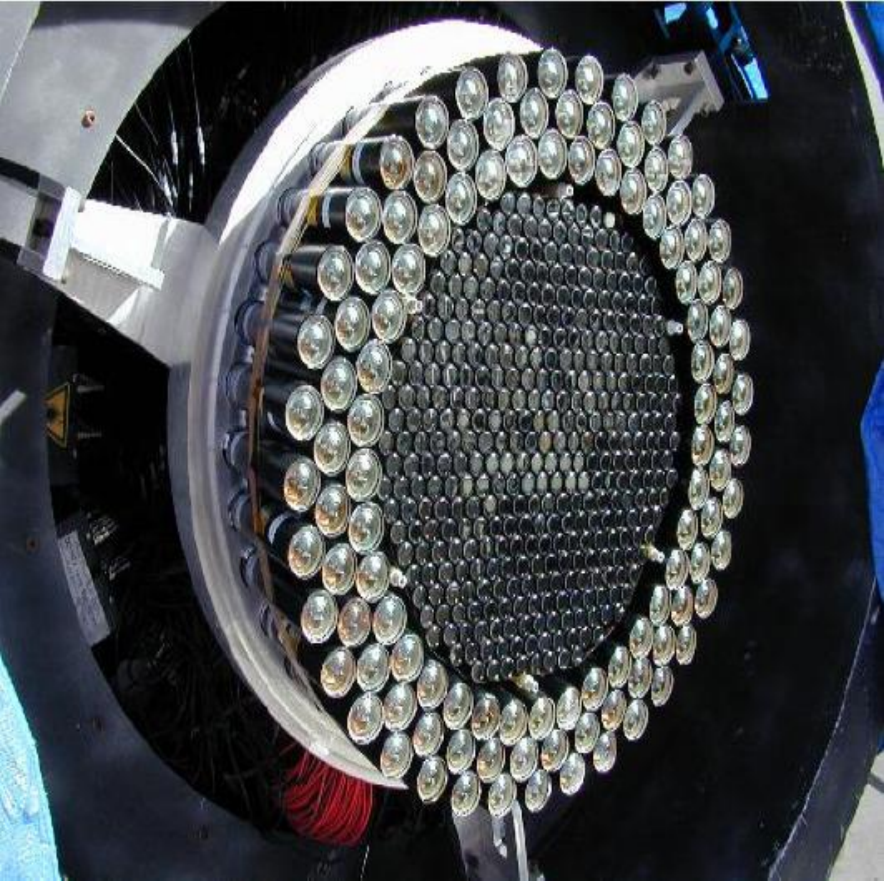
2+ stage

64 stations (8’’ PMTs) + 47 stations (10’’ PMTs) (1 sq.km array)

+

net of imaging telescopes



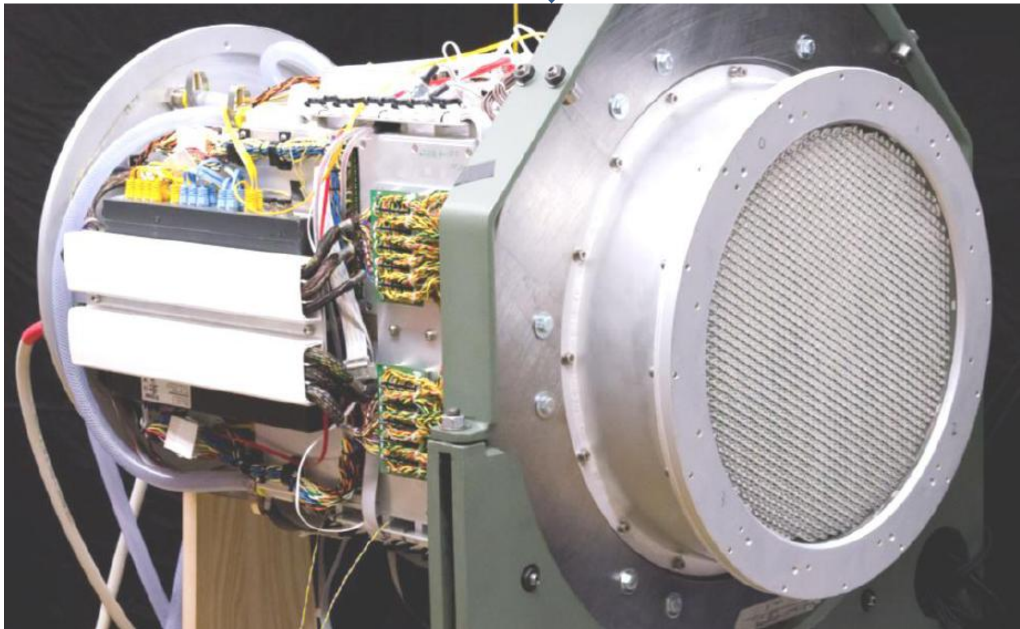


IACT camera prototypes (in 2014) based on:

PMTs

and/or

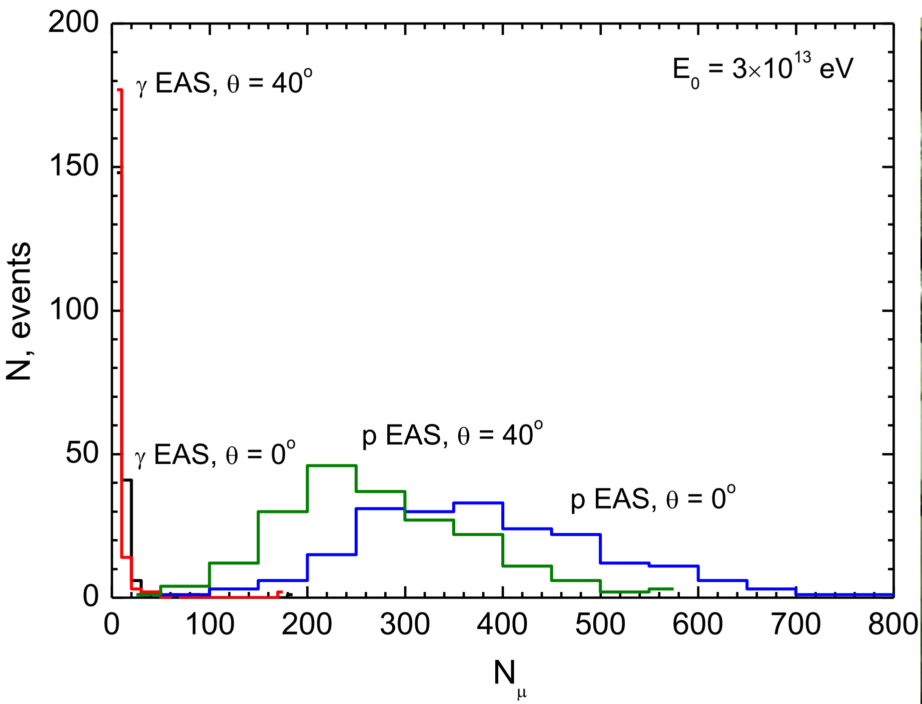
SiPMs (high PDE and low noise)



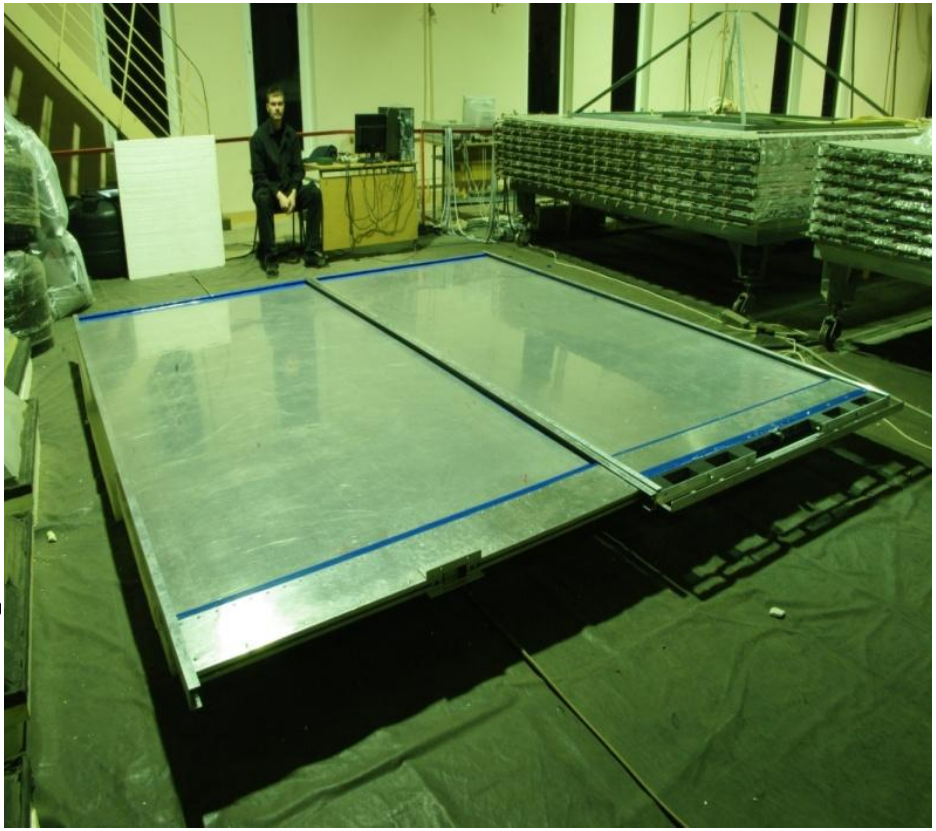
3-5 m^2 mirrors

3 stage

1000 m^2 muon detectors (0.1% of array area)

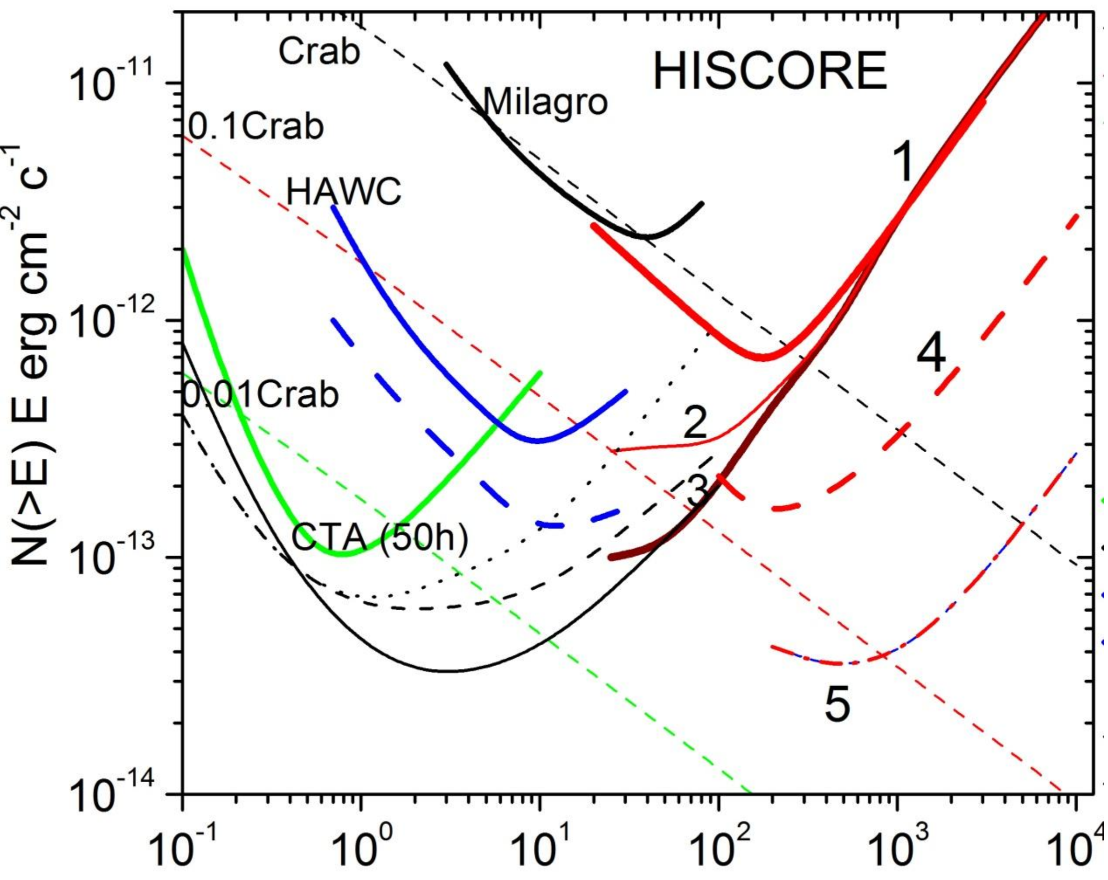


Rejection of hadron background by 10 times at 300 TeV



Scintillation detectors developed at IHEP

Gamma-ray point-source survey sensitivity for TAIGA
(50 events or 5σ for T = 500 hours)



1 – stage 1

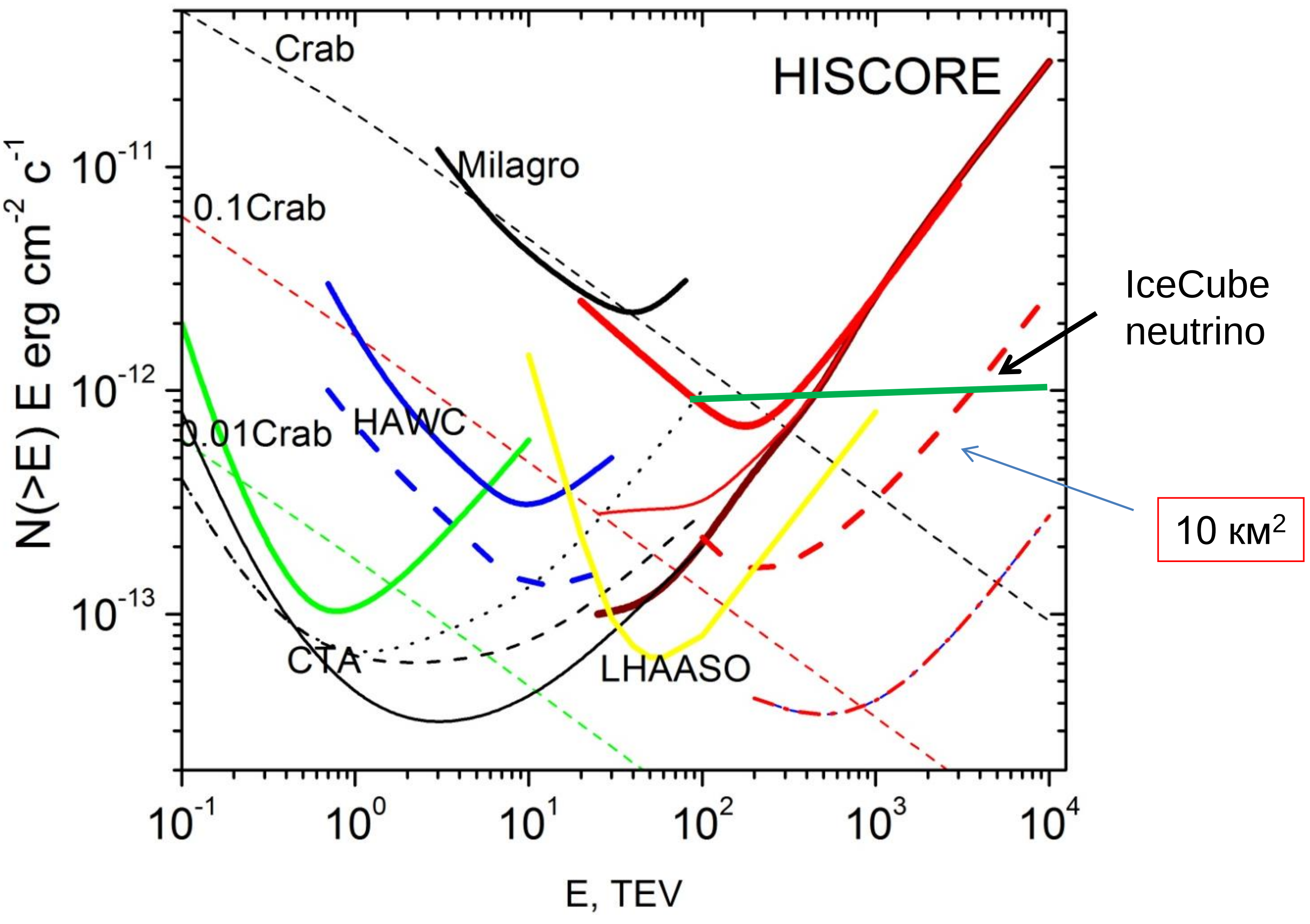
2 – stage 2

3 – stage 2+

4 – 10 km^2 (4 x 8" PMTs/station)

5 – 100 km^2 (1x 8" PMT/station)

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



Transbaikal region almost ideally suits to ~100 km^2 Cherenkov array

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 + 47 station with
188 PMT (10”) + 3-5 (?) mirrors
(S = 3 -5 m^2)
Cost: 2 M Euro.

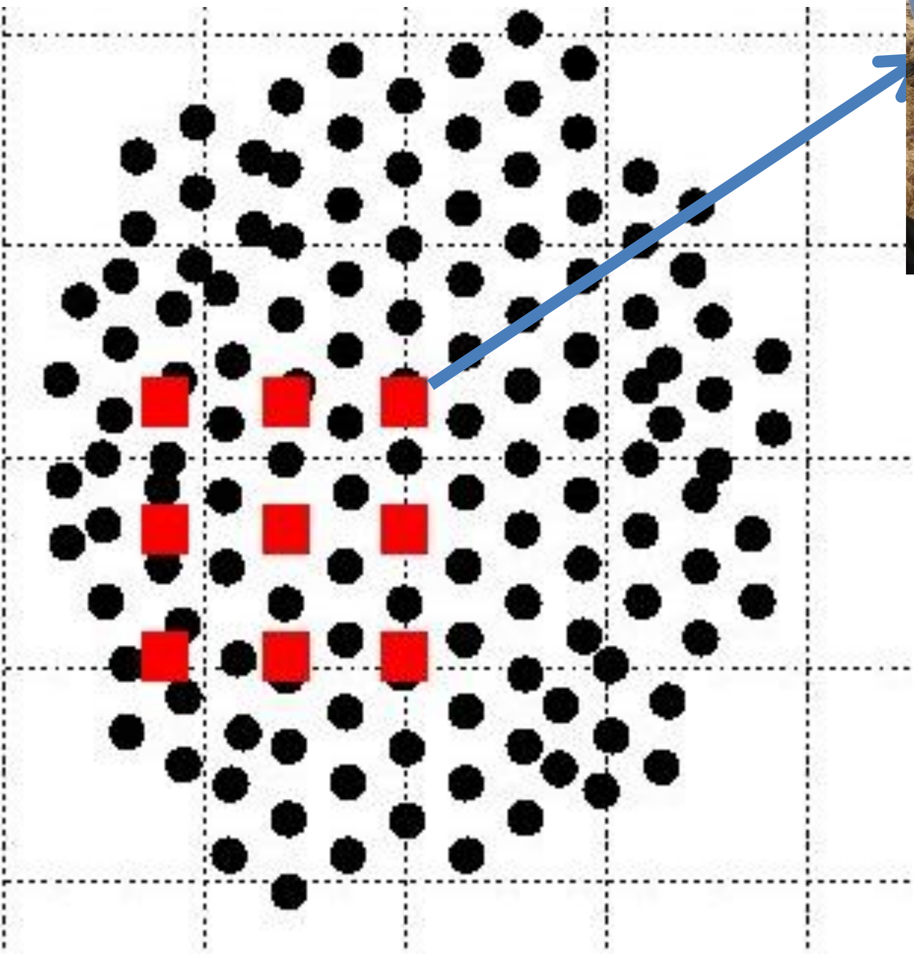
2014-2017

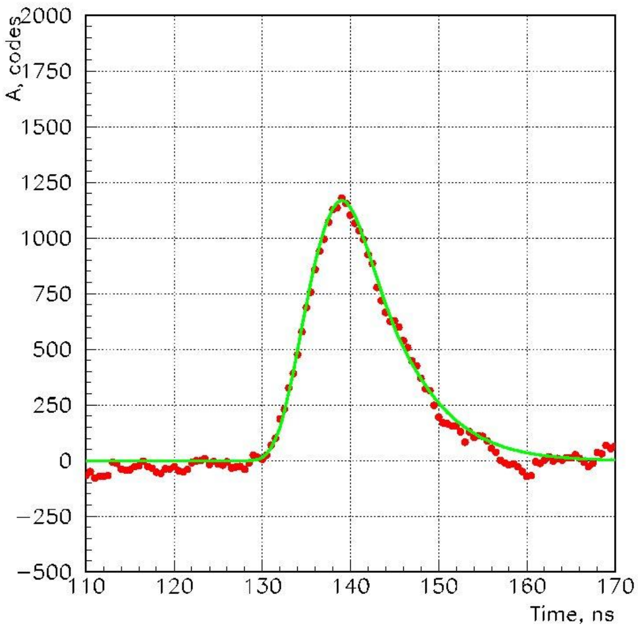
1000 m^2 scintillation detectors
(0.1% of the whole area)
– 2-5 muons from 250 TeV protons
Cost: 2.5-3 M Euro.

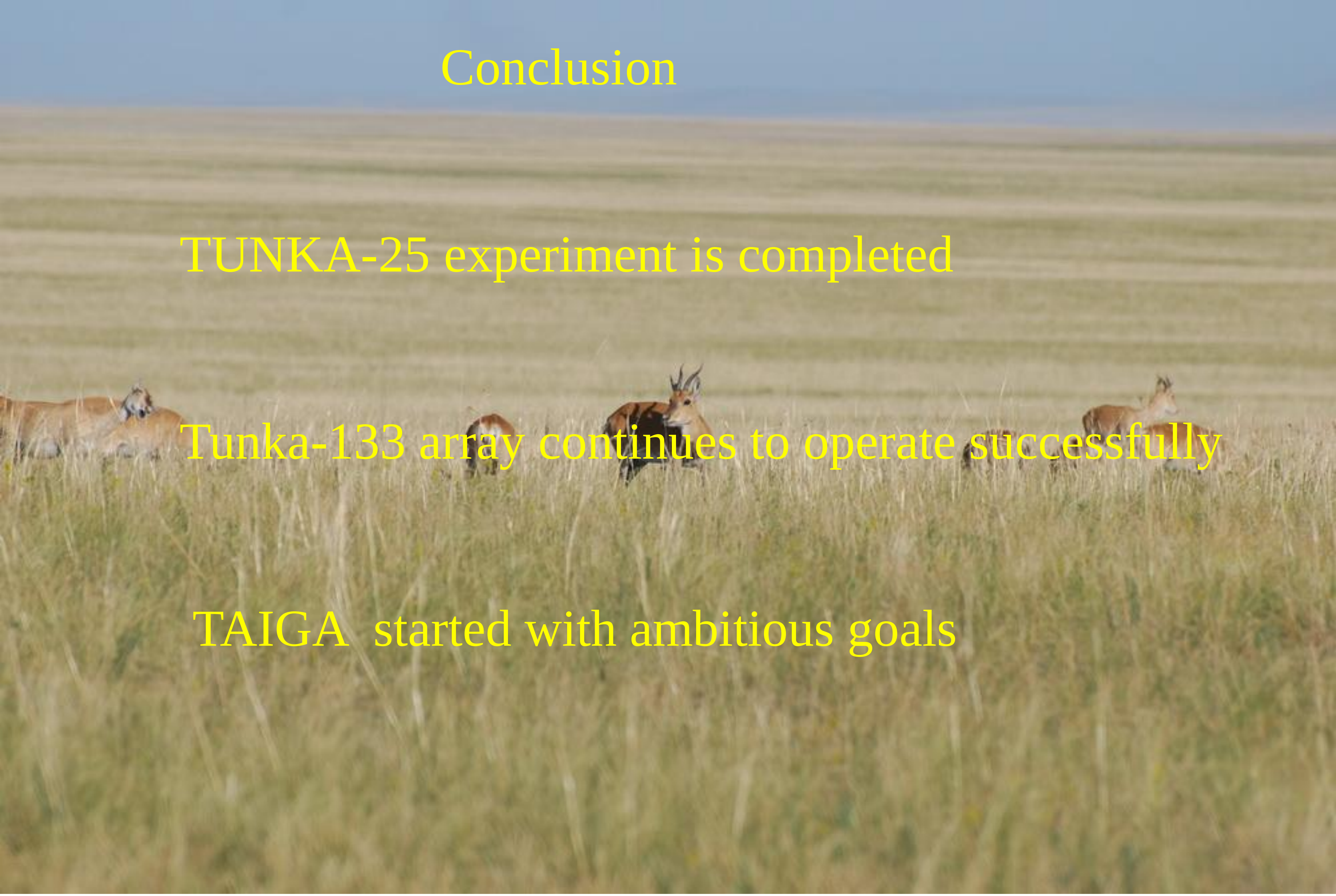
2014-2018

2013: 9 optical stations installed

36 PMTs R5912 (8’’ Hamamatsu)
New front-end electronics
Remotely controlled lids







Conclusion

TUNKA-25 experiment is completed

Tunka-133 array continues to operate successfully

TAIGA started with ambitious goals

The Tunka experiment: saccessfull development from Tunka-4 to Tunka-133 (3 km^2) and TAIGA (1-10 km^2)
(and m.b. to 100 км^2 array!?)

Ultimate solution of a century long problem of Cosmic Ray origin!?

Как будто не все пересчитаны звезды,
Как будто наш мир не открыт до конца
Н.С.Гумилев

There are more things in heaven and Earth, Horatio
Than are dreamt of in year philosophy
W.Shakespeare
Hamlet

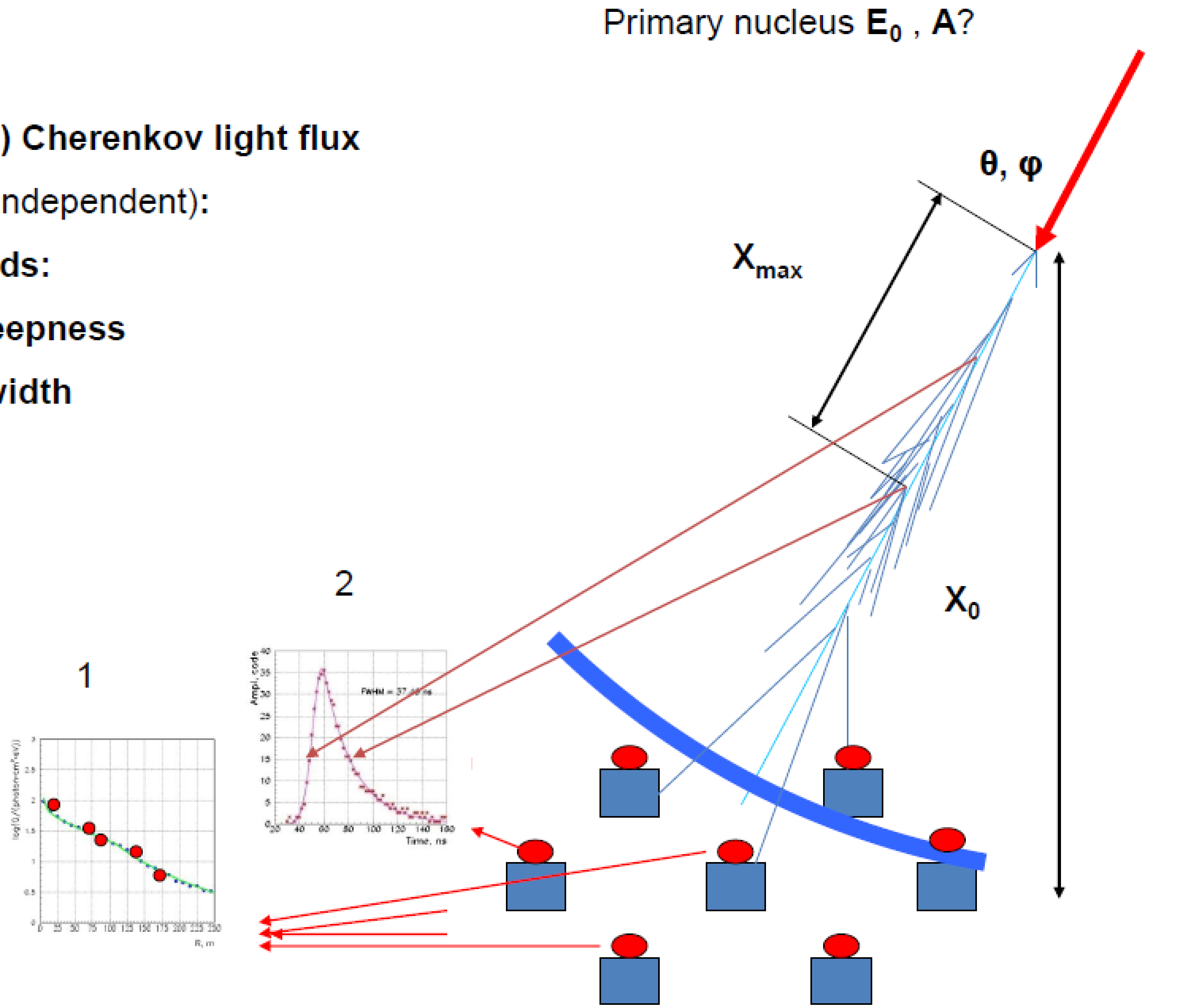

Thank you!

E_0 ~ Q(200) Cherenkov light flux

X_{max}(model independent)**:**

Two methods:

1. **LDF steepness**
2. **Pulse width**



Energy reconstruction

$$E = A\ (Q200)^{g}$$

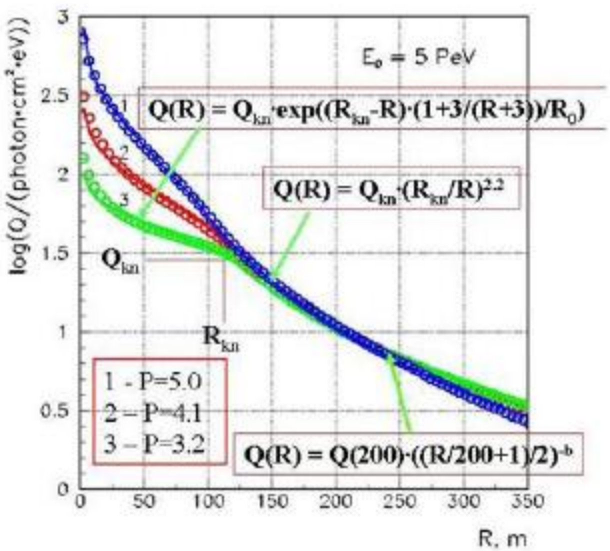
↑

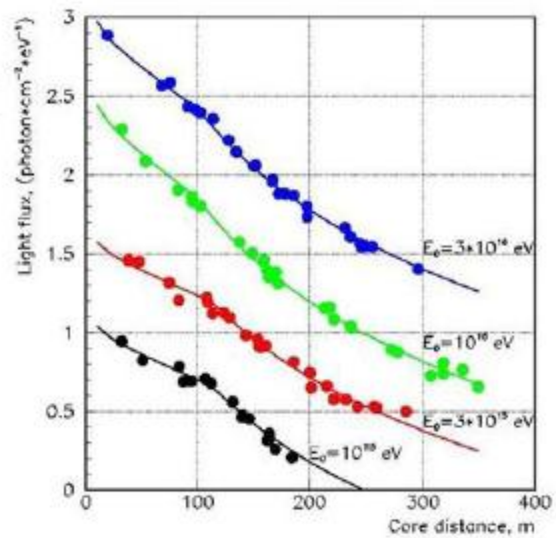
Density of Cherenkov light at core distance of 200 m

For $10^{16} – 10^{18}$ eV (CORSIKA):

$$g = 0.94 \pm 0.01$$

Usage of Cherenkov Light Lateral Distribution Function (LDF) for the Reconstruction of EAS Parameters





LDF from CORSIKA

Experimental data fitted with LDF

Q(R) = F(R, p) (only one parameter)

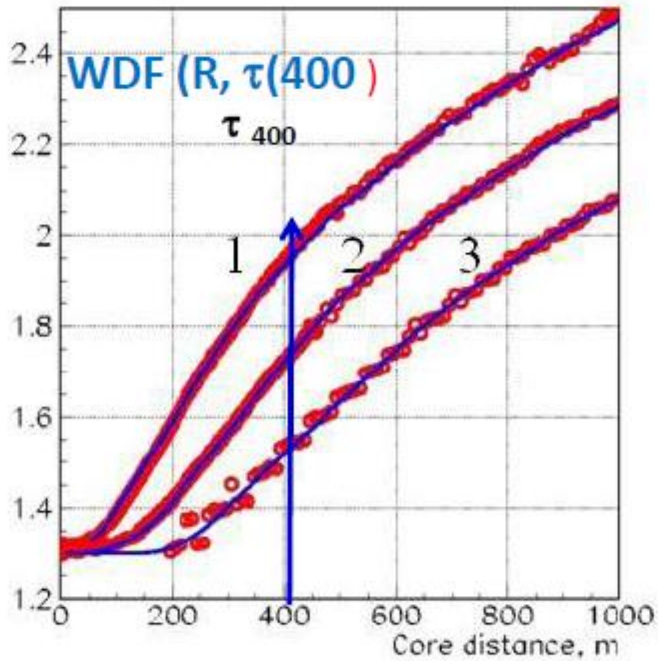
steepness of LDF →

light flux at core distance 175 m - $\mathbf{Q_{175}}$ ~ **Energy**

P = Q(100)/Q(200) → $\mathbf{X_{max}}$

X_{max} by using WIDTH DISTANCE FUNCTION (WDF)

$\lg\tau$ (R)

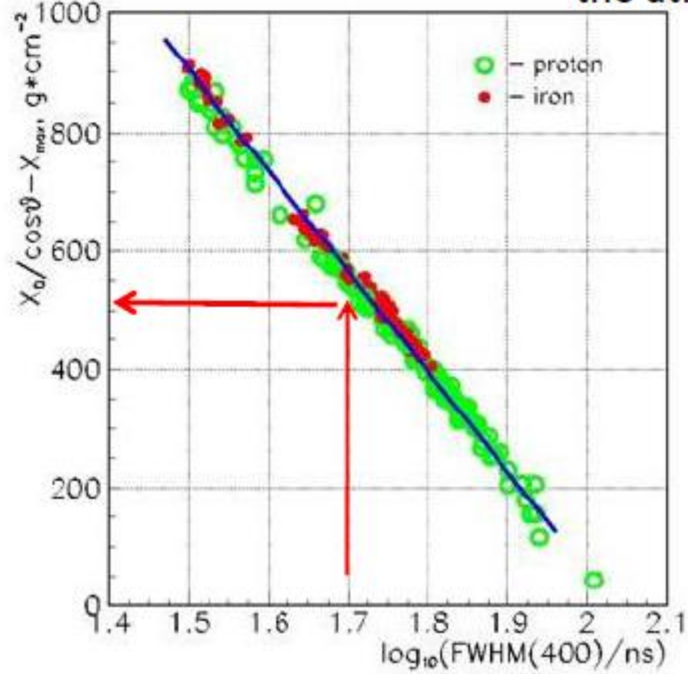


. Dependence of pulse duration from the distance from the core for EAS with different Xmax (CORSIKA + apparatus distortion)

(1 . ΔX= 154 г/см², 2 ΔX= 555 г/см²,

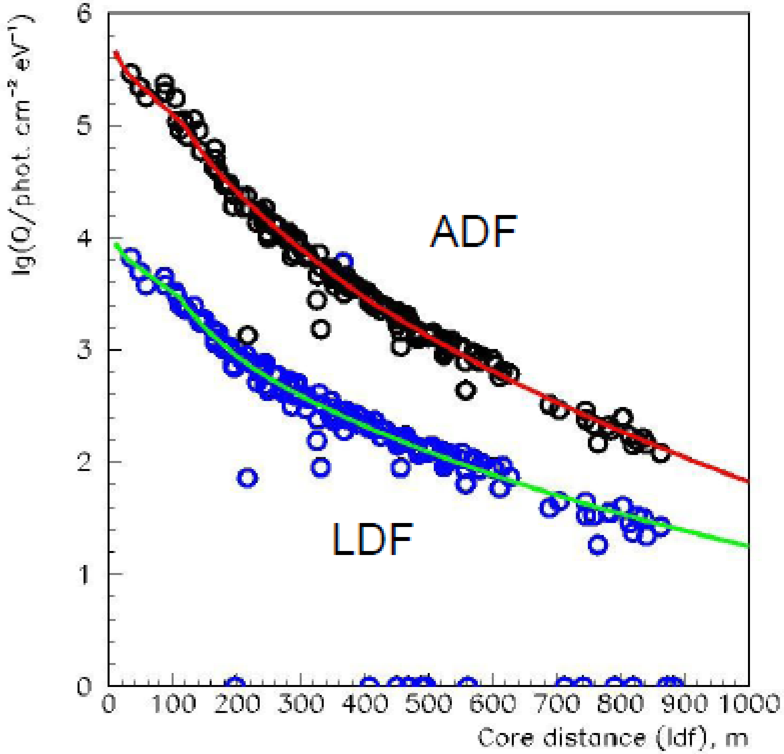
3. ΔX=877 г/см²)

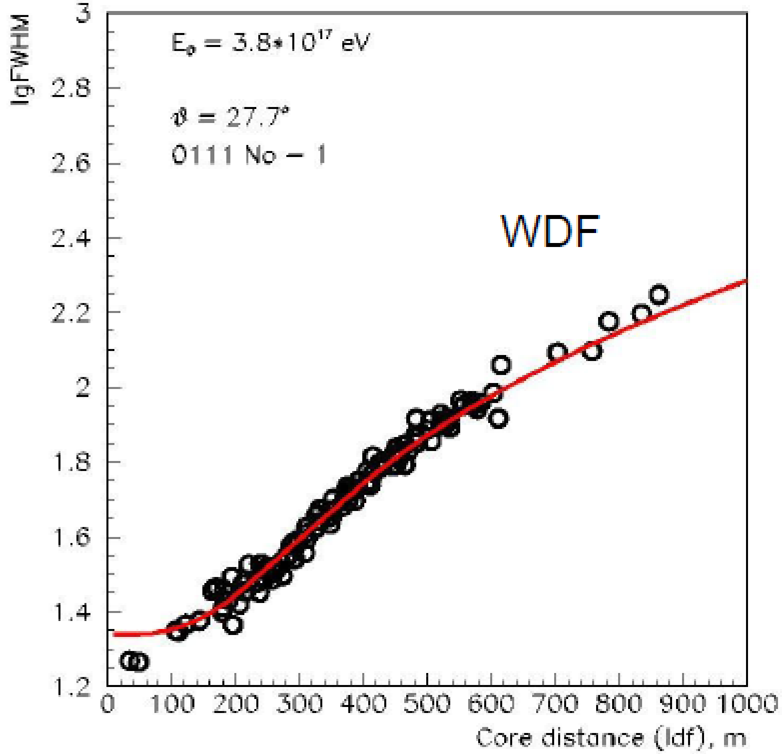
$\Delta X = X_0/\cos\theta - X_{max}$ (X_0 – depth of the atmosphere



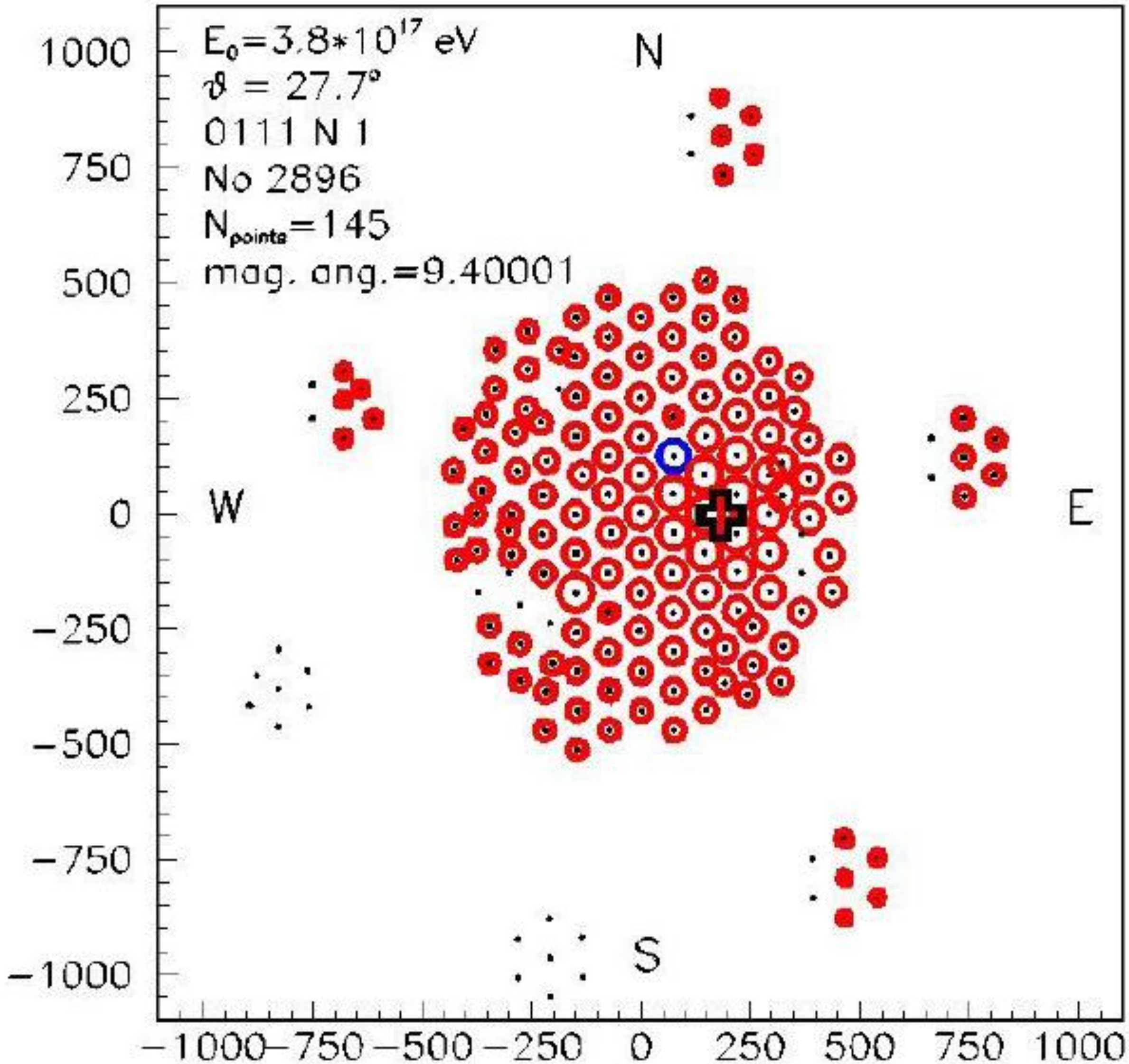
Dependence of ΔX ($X_0/\cos\theta - X_{max}$) from τ(400)

WDF – width distant function

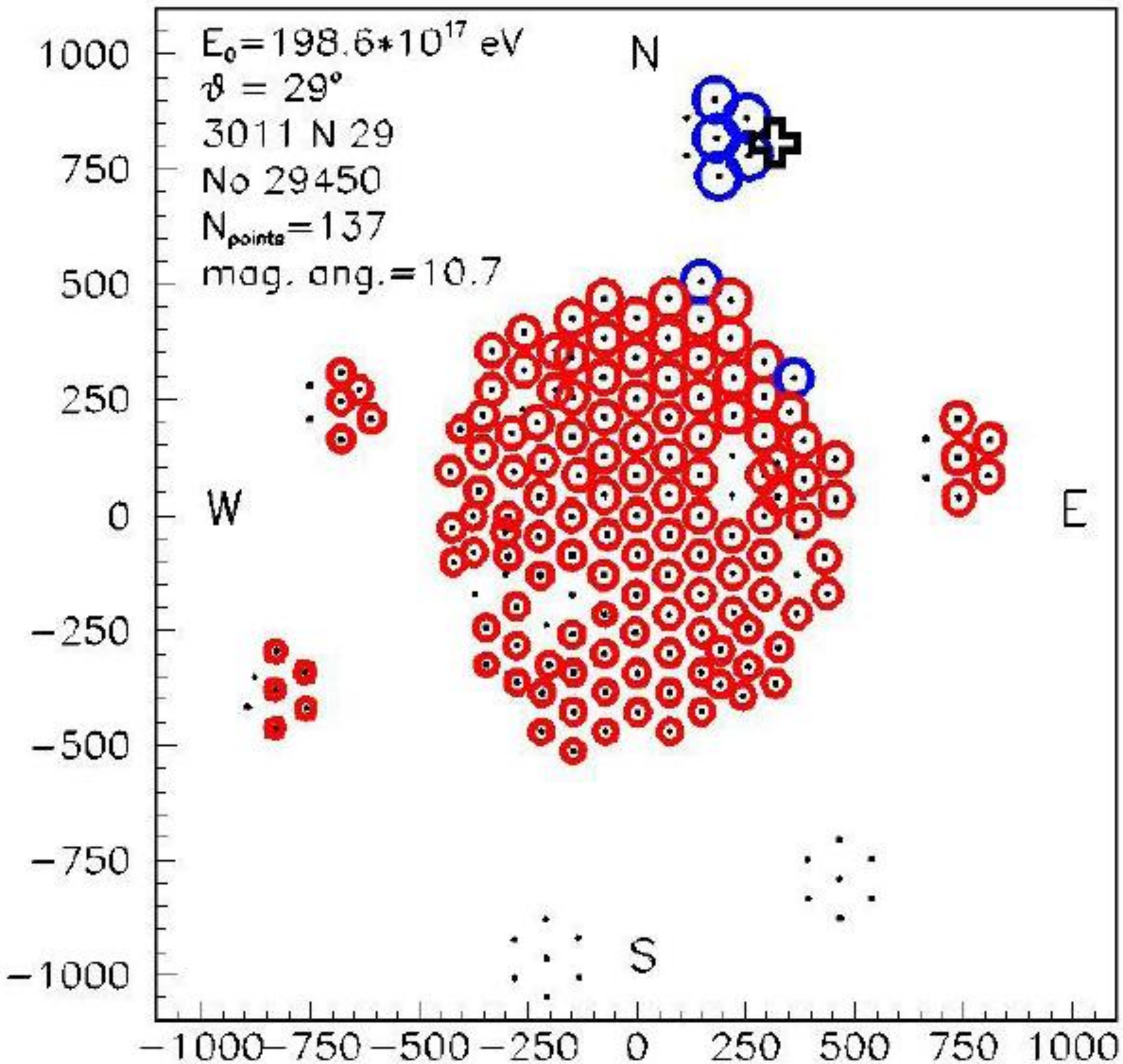




ADF – amplitude distant function is used for core location



$E_0=3.8*10^{17}$ eV
ϑ = 27.7°
0111 N 1
No 2896
N_{points}=145
mag. ang.=9.40001
N
W
E
S
1000
750
500
250
0
−250
−500
−750
−1000
−1000 −750 −500 −250 0 250 500 750 1000



E0=198.6*10^17 eV
ϑ = 29°
3011 N 29
No 29450
N_points=137
mag. ang.=10.7
N
W
E
S
1000
750
500
250
0
−250
−500
−750
−1000
−1000 −750 −500 −250 0 250 500 750 1000