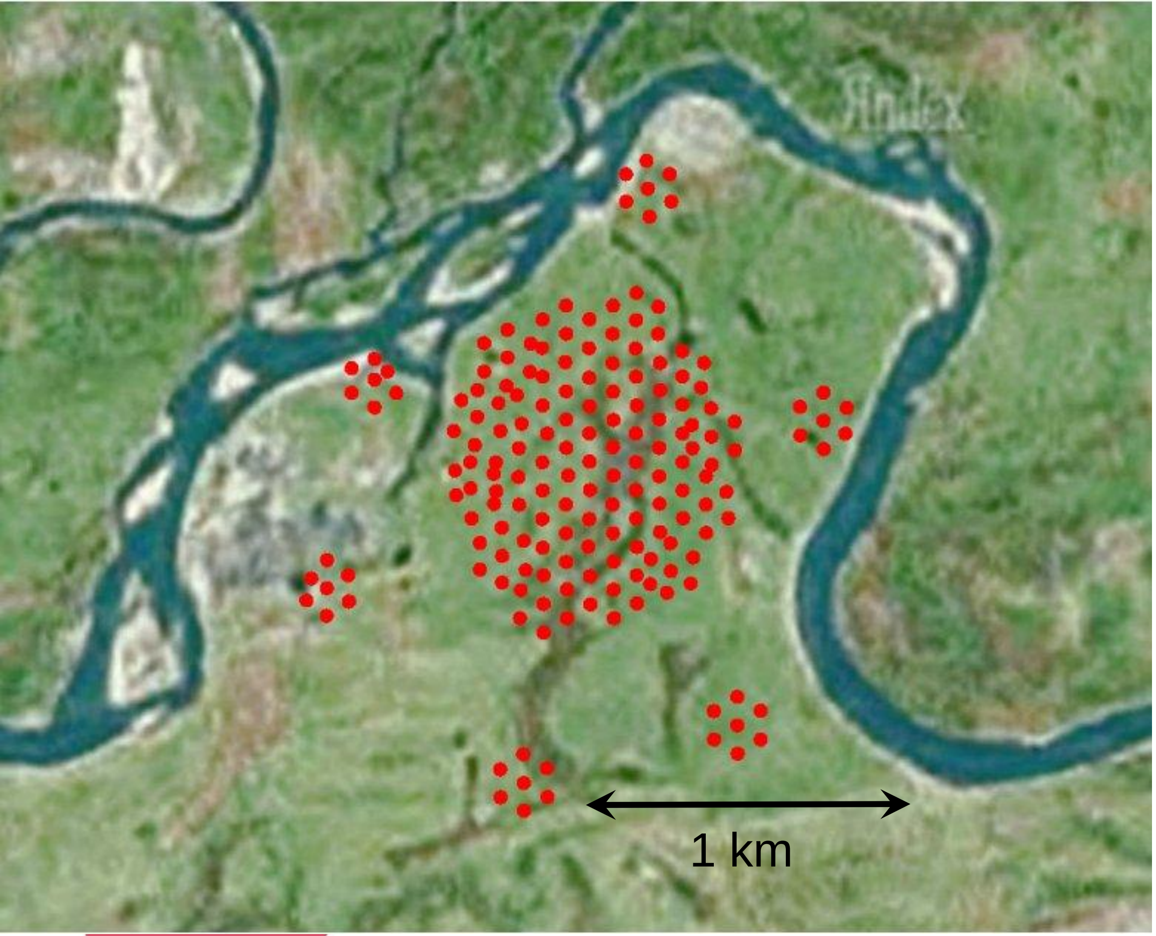
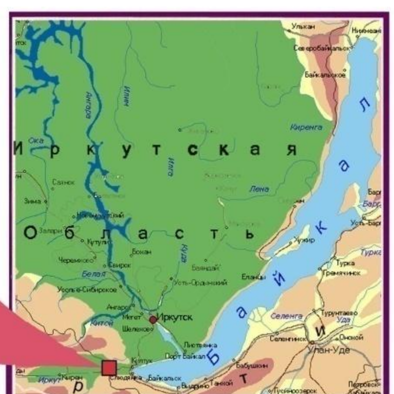
Primary CR Energy Spectrum and Mass Composition by the Data of Tunka-133 Array

Vasily Prosin (Skobeltsyn Institute of Nuclear Physics MSU, MOSCOW)

From Tunka and TAIGA Collaborations





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

Tunka Valley

Republic Buryatia

150 km from Irkutsk

50 km from the shore of lake Baikal


ТУНКИНСКИЙ РАЙОН
НАЦИОНАЛЬНЫЙ ПАРК

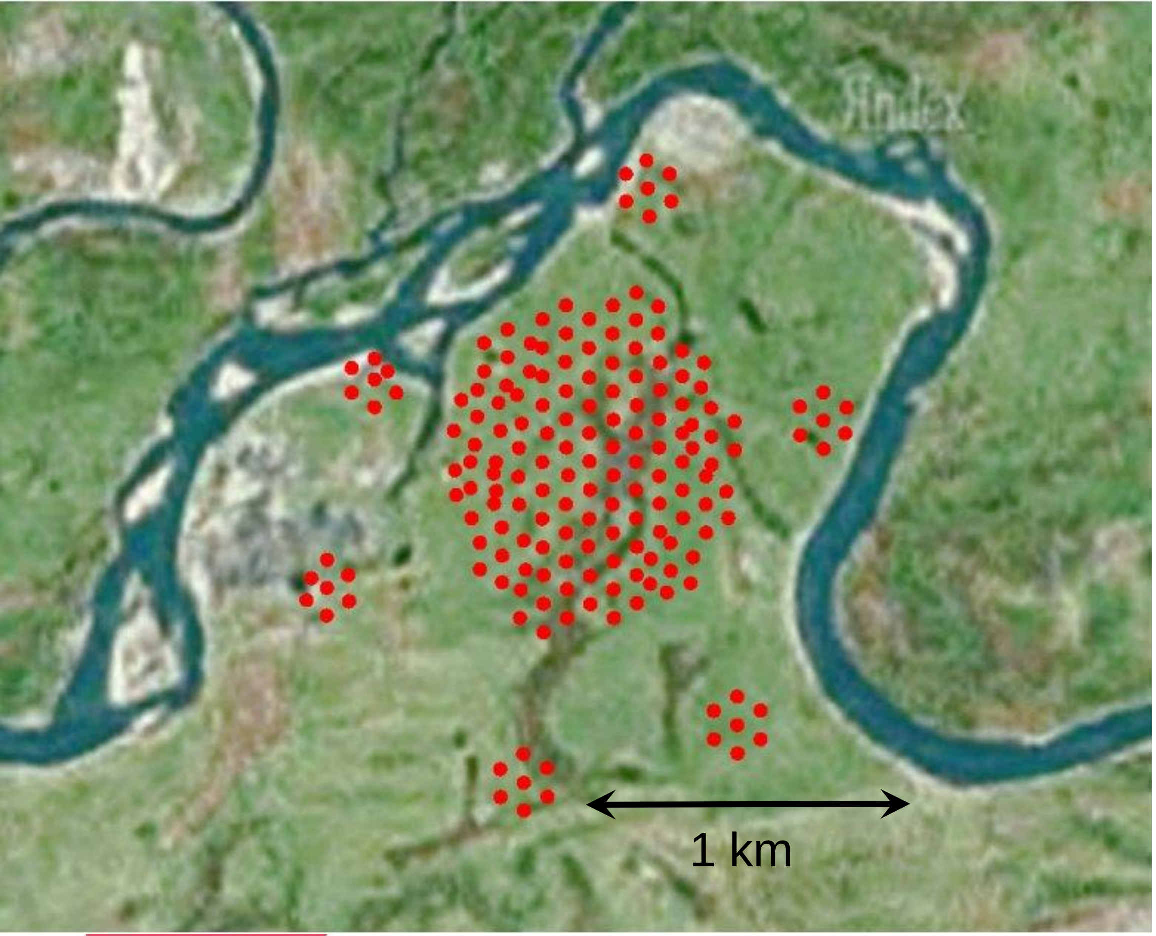
EXPERIMENTS
in Tunka Valley

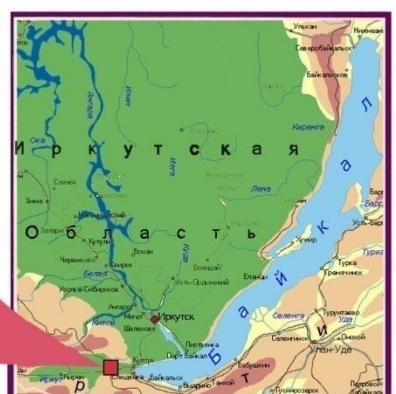
NOW (2013-2014):

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**

UNDER CONSTRUCTION AND DEPLOYMENT:

1. **Scintillation detectors of electrons and muons (former EAS-TOP and KASCADE-Grande detectors) 19 stations (total area for muons 100 m^2)**
2. **Tunka-HiSCORE 33 stations**
3. **Net of IACT with mirrors of 10 m^2 area (5 telescopes)**
4. **New Scintillation detectors of muons total area 2000 m^2**
5. **Tunka-Rex +20 radio antennas**

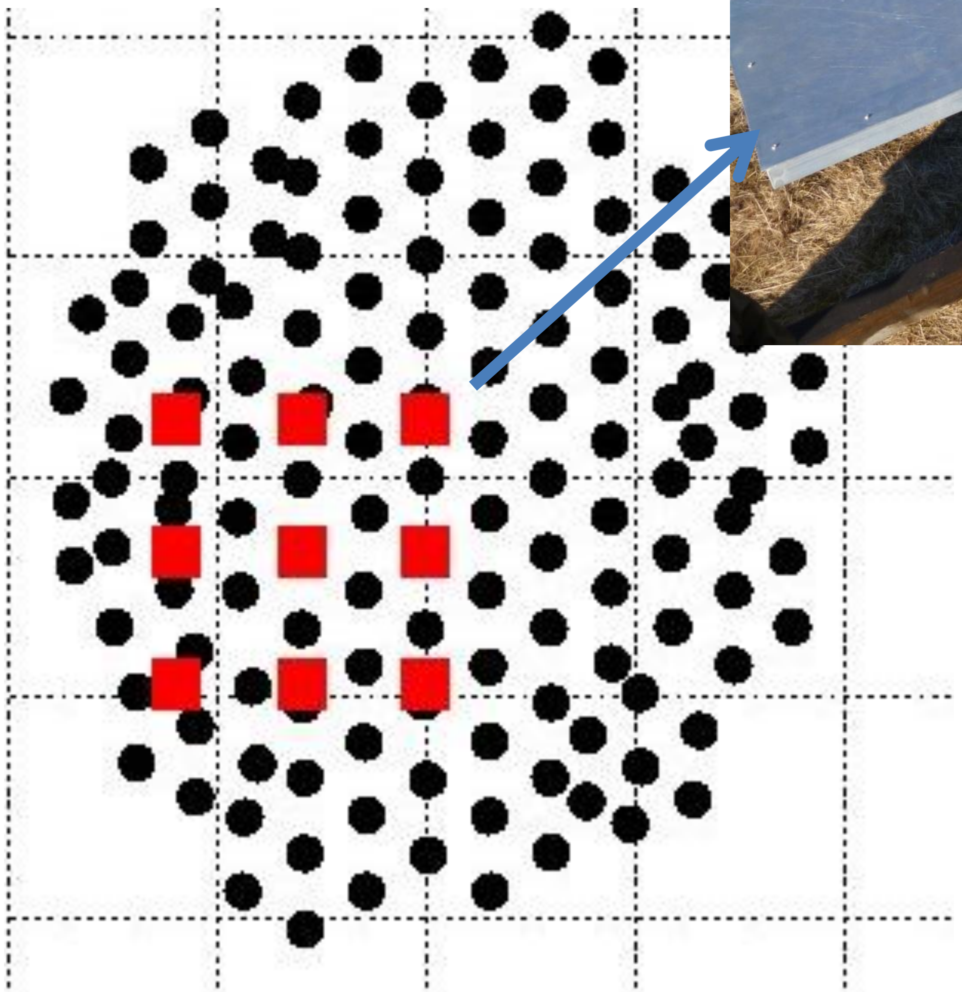




51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

175 optical detectors
EMI 9350 and HAMAMATSU Ø 20 cm

Tunka-HiSCORE prototype
9 optical stations

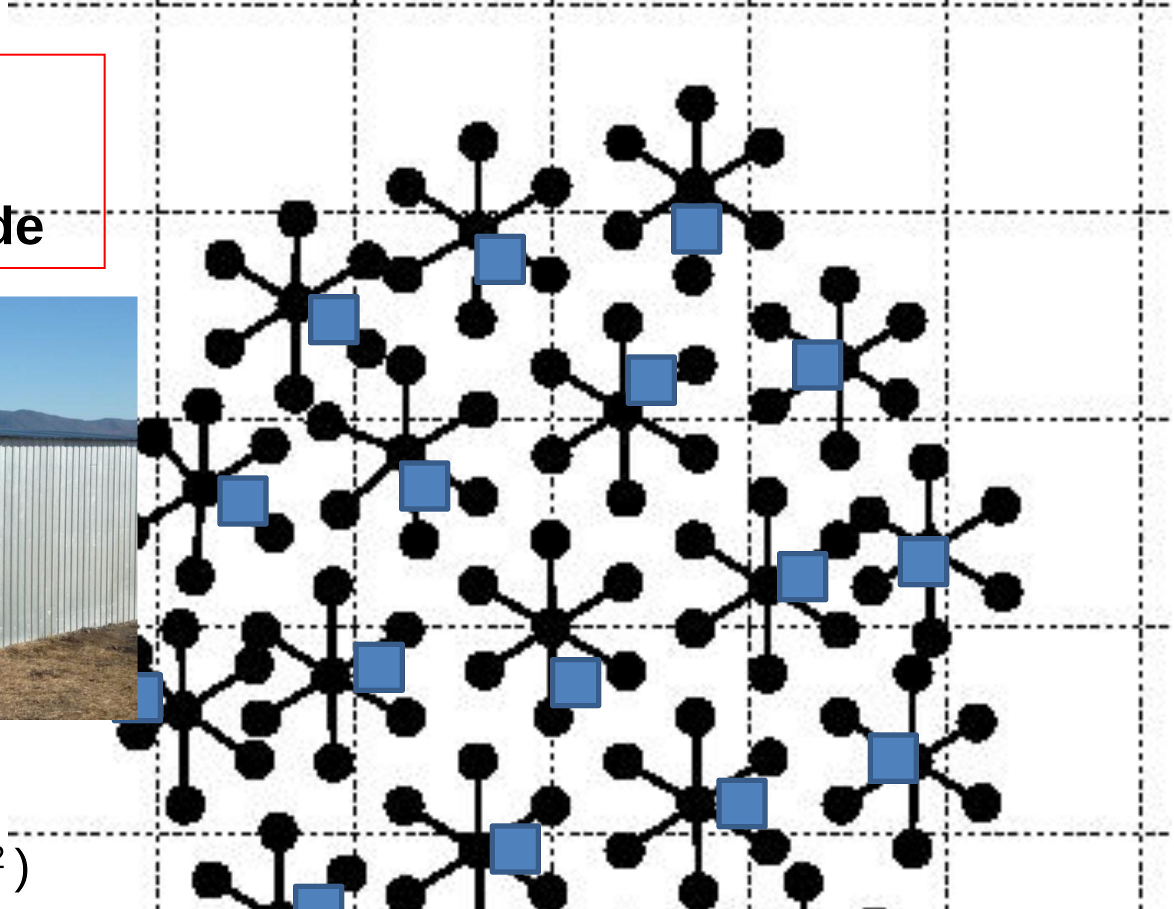


Tunka-REX

Connection of 2 antennas to 2 free channel of FADC

Scintillation station from Kascade-Grande

19 stations



228 detectors (0.64 m^2) on the surface

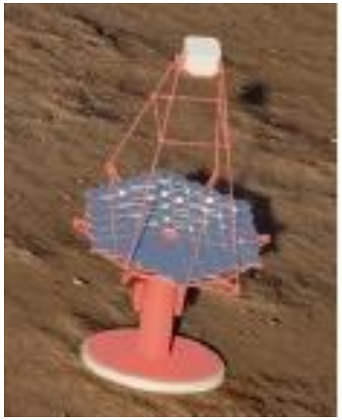
152 detectors undeground (muons detectors, total area 100 m^2

Towards High Energy Gamma-Rays Astronomy in Tunka Valley

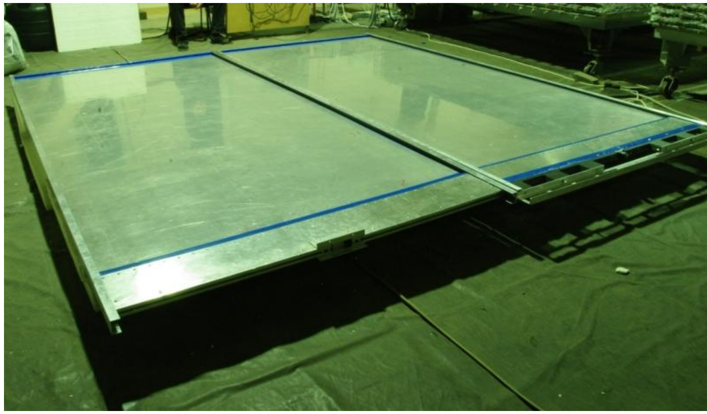
TAIGA – Tunka Advanced Instrument for cosmic rays and Gamma Astronomy

Array design concept

- **Non imaging wide-angle optical stations (HiSCORE type)**



- **Net of imaging telescopes with mirrors of 10 m^2 area.**



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

TAIGA Collaboratipn

Germany

Hamburg University(Hamburg)
DESY (Zeuthen)
MPI (Munich)
Humbolt University

ITALY

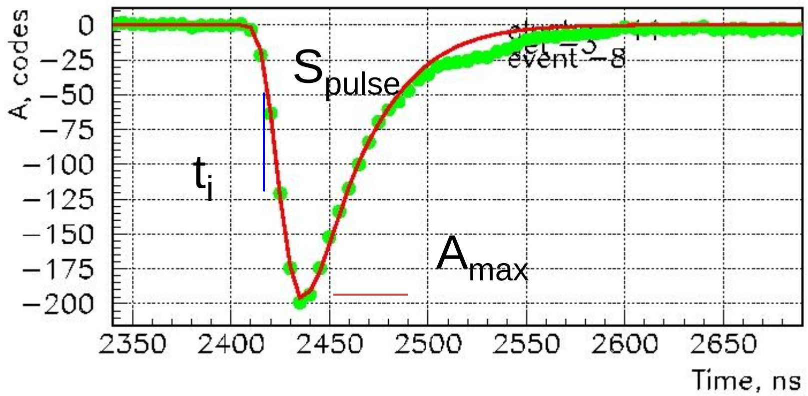
Torino University

Russia

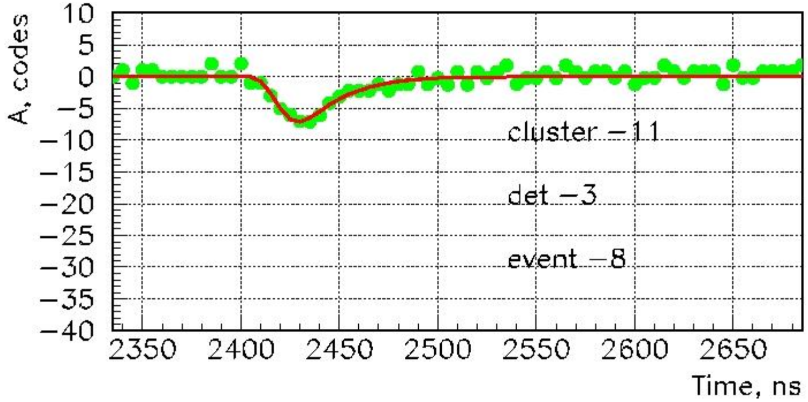
MSU(SINP)(Moscow)
ISU (API) (Irkutsk)
INR RAS(Moscow
JINR (Dubna)
MEPHI(Moscow)
IZMIRAN (Moscow)
Kurchatov Institute (Moscow)
IPSM(Ulan-Ude)

Single detector readout:
Fitting of a pulse and measuring of the parameters: $Q=c\cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

anode:

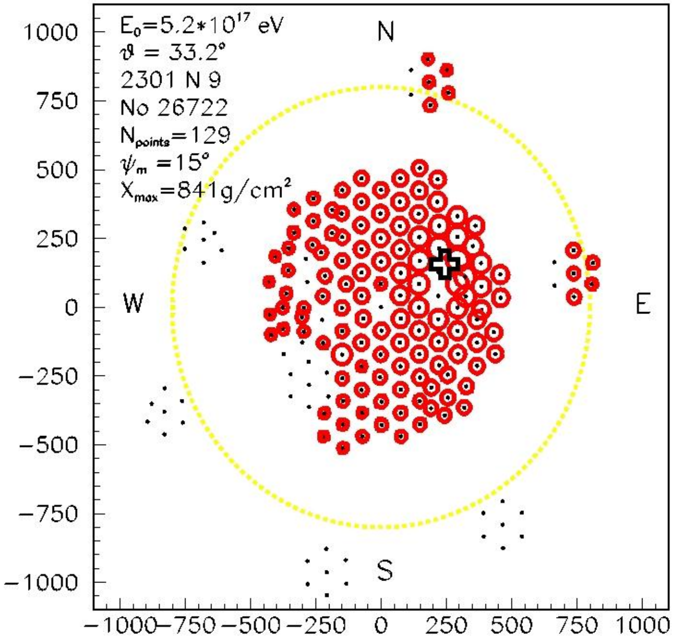


dinode:

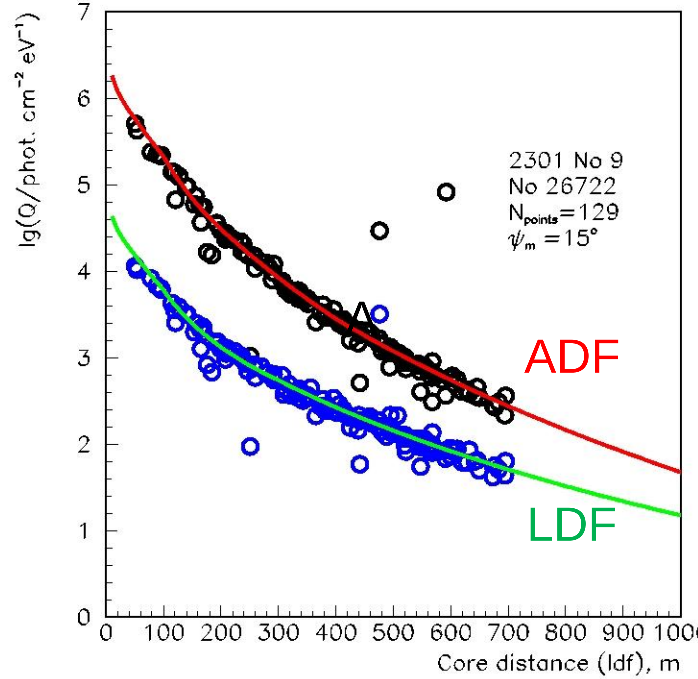


Single event example

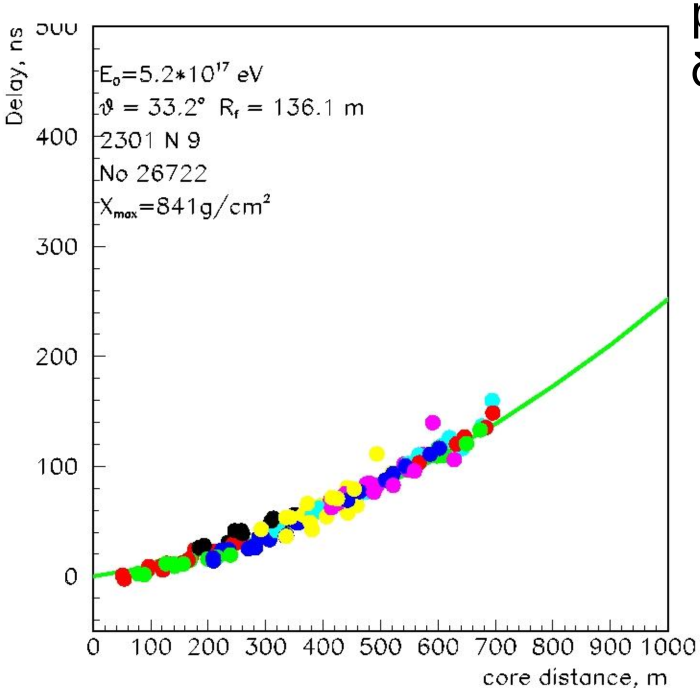
Plan



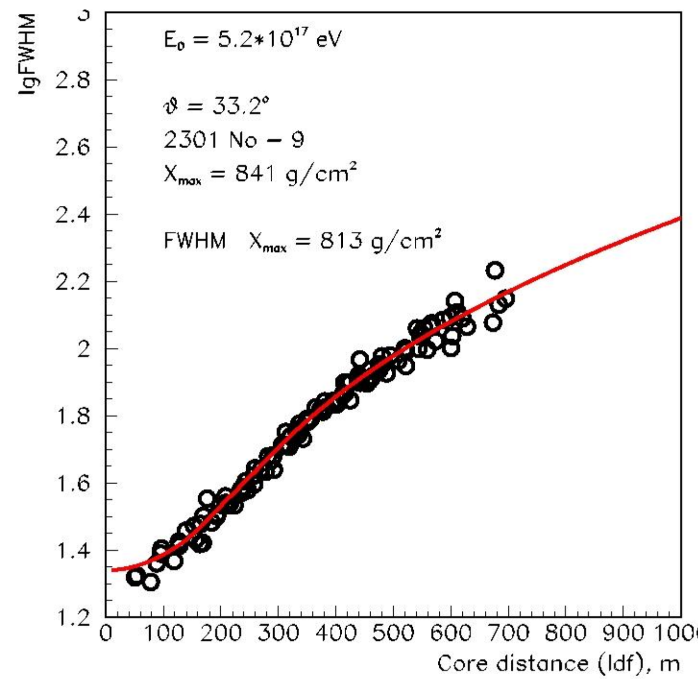
ADF and LDF



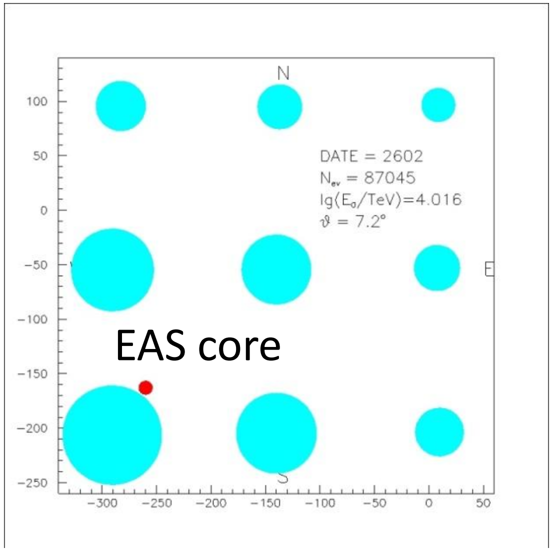
Curve EAS time front provides δθ<0.5°



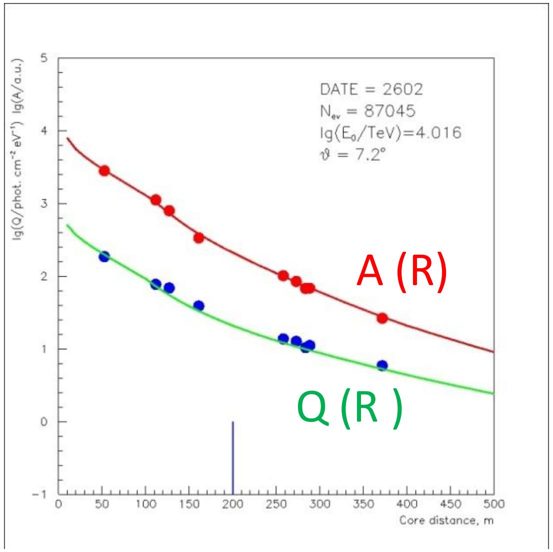
τ_{eff} vs. core distance

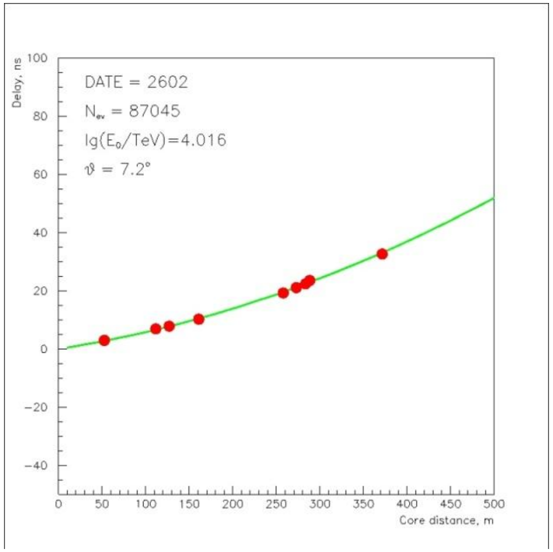


Tunka-HiSCORE event example
Zenith angle = 7.2°
Energy = 10^{16} eV

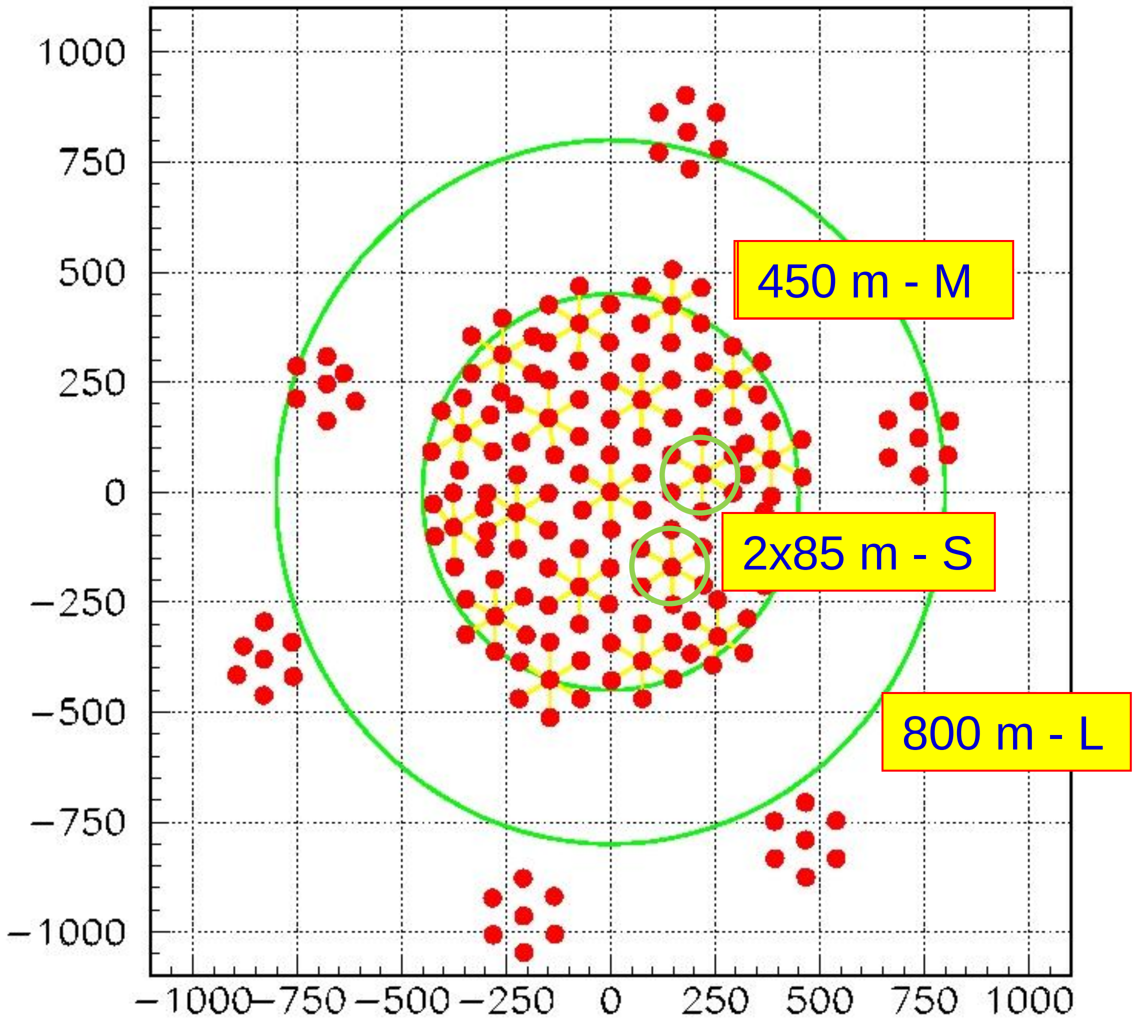


Shower front





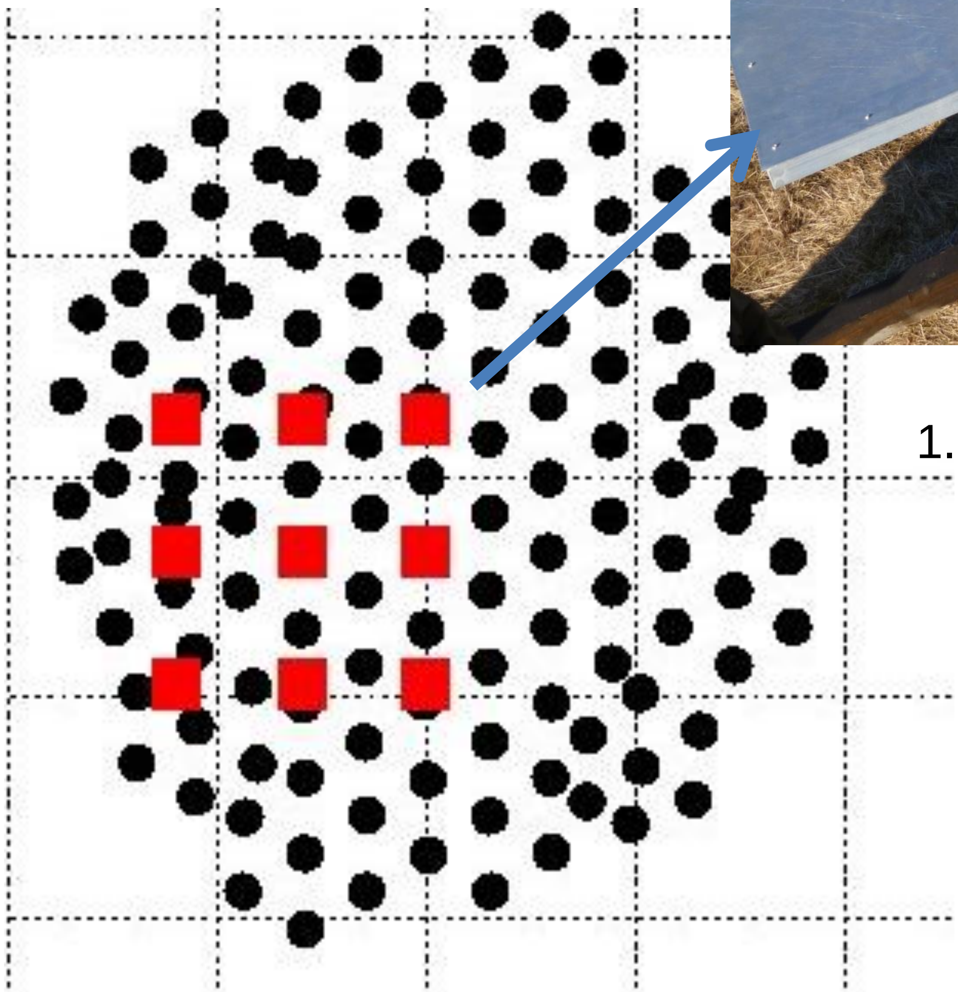
Effective areas



EAS parameters accuracy: experimental estimations

Comparison of one the same shower parameters, measured by different arrays.

Tunka-HiSCORE prototype
9 optical stations



1. **Comparison of Tunka-133 and HiSCORE results –**

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
LogE_0 difference –
$\Delta lgE_0 < 0.051$ (12%)

EAS parameters accuracy: experimental estimations

2. **Dividing of the Tunka-133 detectors to two sub-arrays:**
   a) odd detectors
   b) even detectors -
   comparison of EAS parameters reconstruction with different sub-arrays

M:	**$E_0 > 10^{16}$ эВ:**	**EAS core position difference –**	**$\Delta R < 8$ m**	
		$LogE_0$ difference –	**$\Delta lgE_0 < 0.033$**	**(8%)**
	$E_0 > 5\cdot10^{16}$ эВ:	**EAS core position difference –**	**$\Delta R < 6$ m**	
		$LogE_0$ difference –	**$\Delta lgE_0 < 0.017$**	**(4%)**
L:	**$E_0 > 5\cdot10^{16}$ эВ:**	**EAS core position difference –**	**$\Delta R < 13$ m**	
		$LogE_0$ difference –	**$\Delta lgE_0 < 0.051$**	**(12%)**

Experimental data

5 winter seasons: 2009-2010 , 2010-2011, 2011-2012, 2012-2013, 2013-2014

262 clear moonless nights

~ 1540 h of observation with a trigger frequency ~ 2 Hz

~ 10 000 000 triggers

The cuts for the energy spectrum used:

$\theta \leq 45°$

M: $R_{center} < 450$ m:

~ 270 000 events with $E_0 > 6 \cdot 10^{15}$ eV – 100% efficiency

~ 99 000 events $E_0 > 10^{16}$ eV

~ 4000 events $E_0 > 5 \cdot 10^{16}$ eV

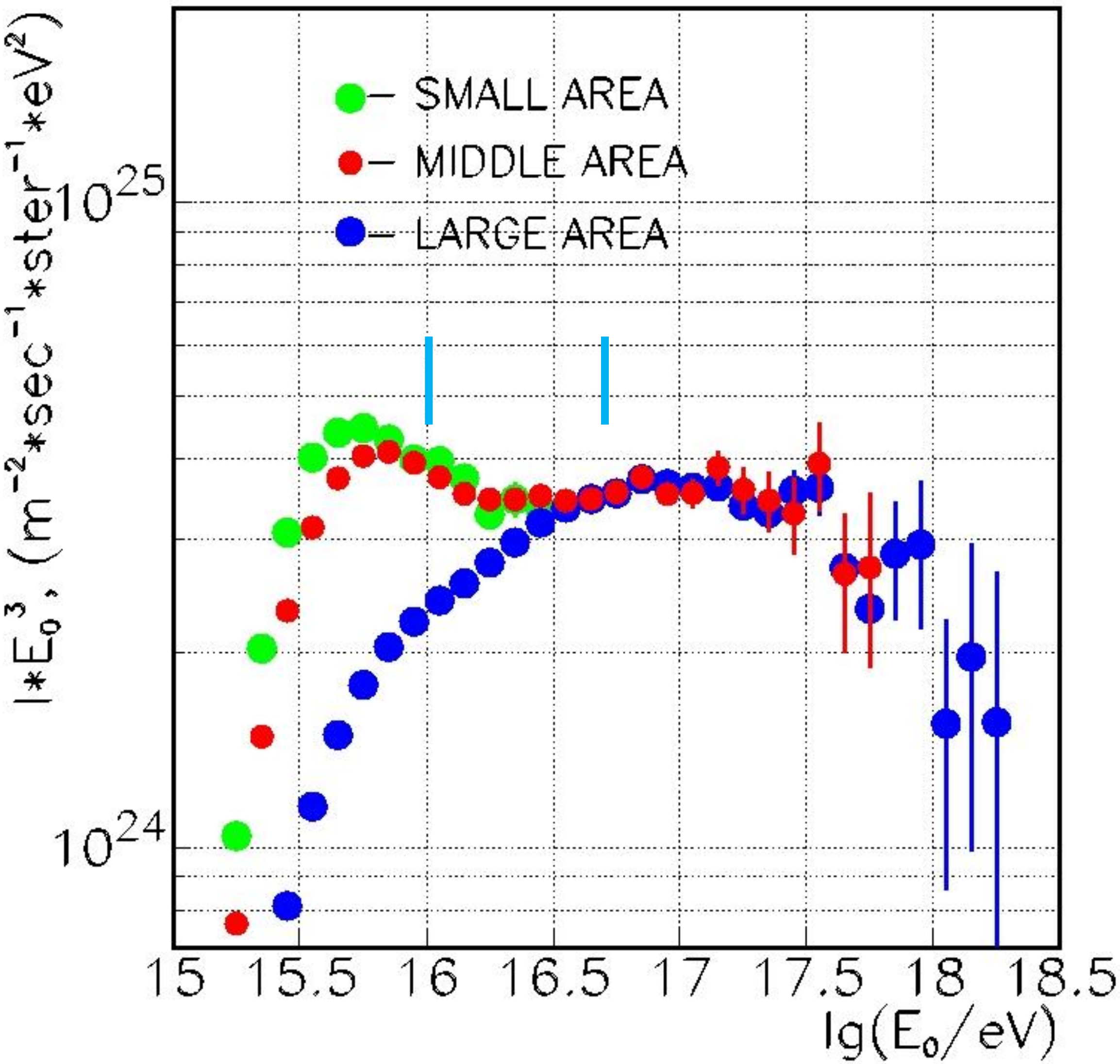
~ 983 events $E_0 > 10^{17}$ eV

L: $R_{center} < 800$ m:

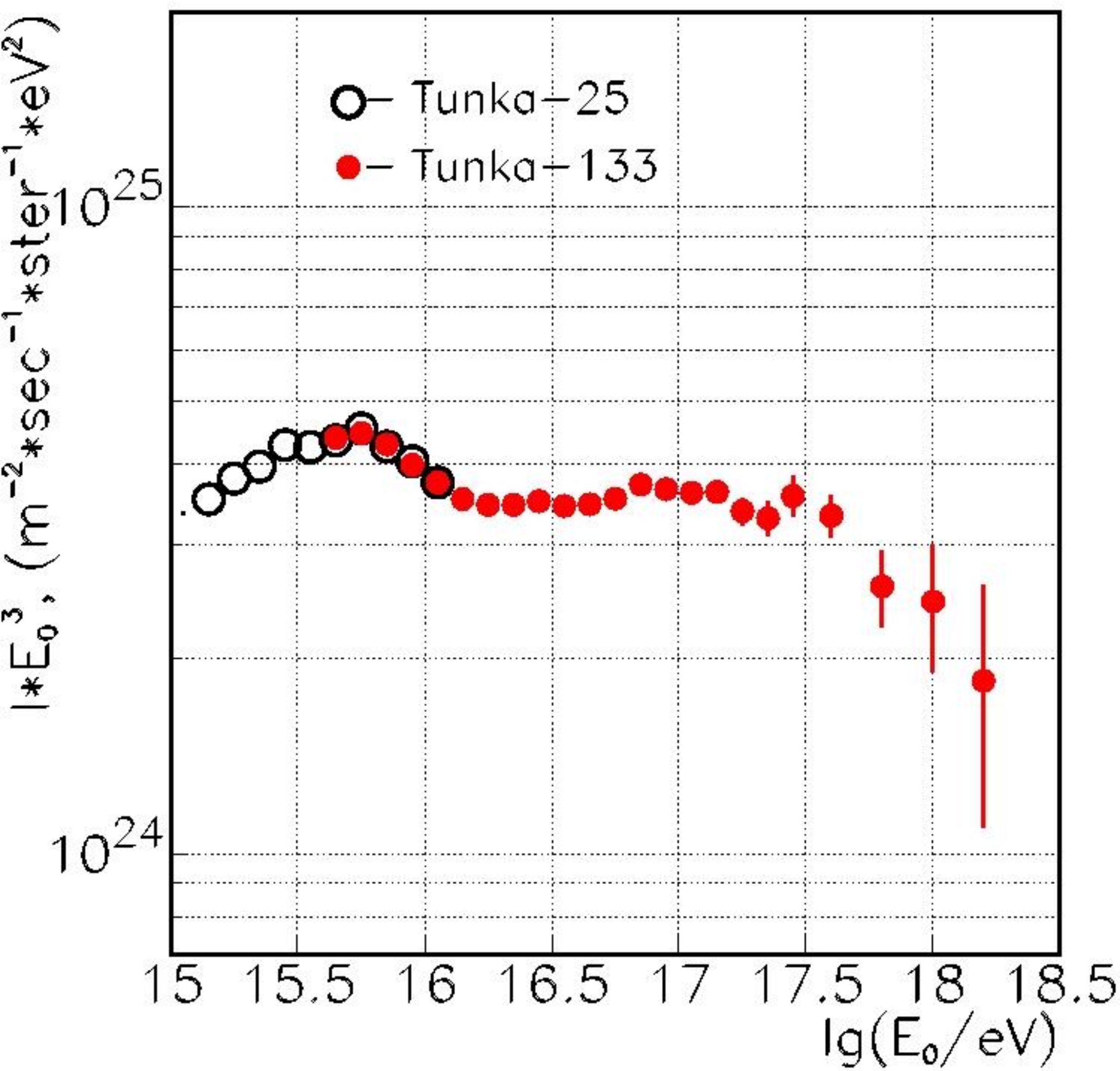
~ 12400 events $E_0 > 5 \cdot 10^{16}$ eV

~ 3000 events $E_0 > 10^{17}$ eV

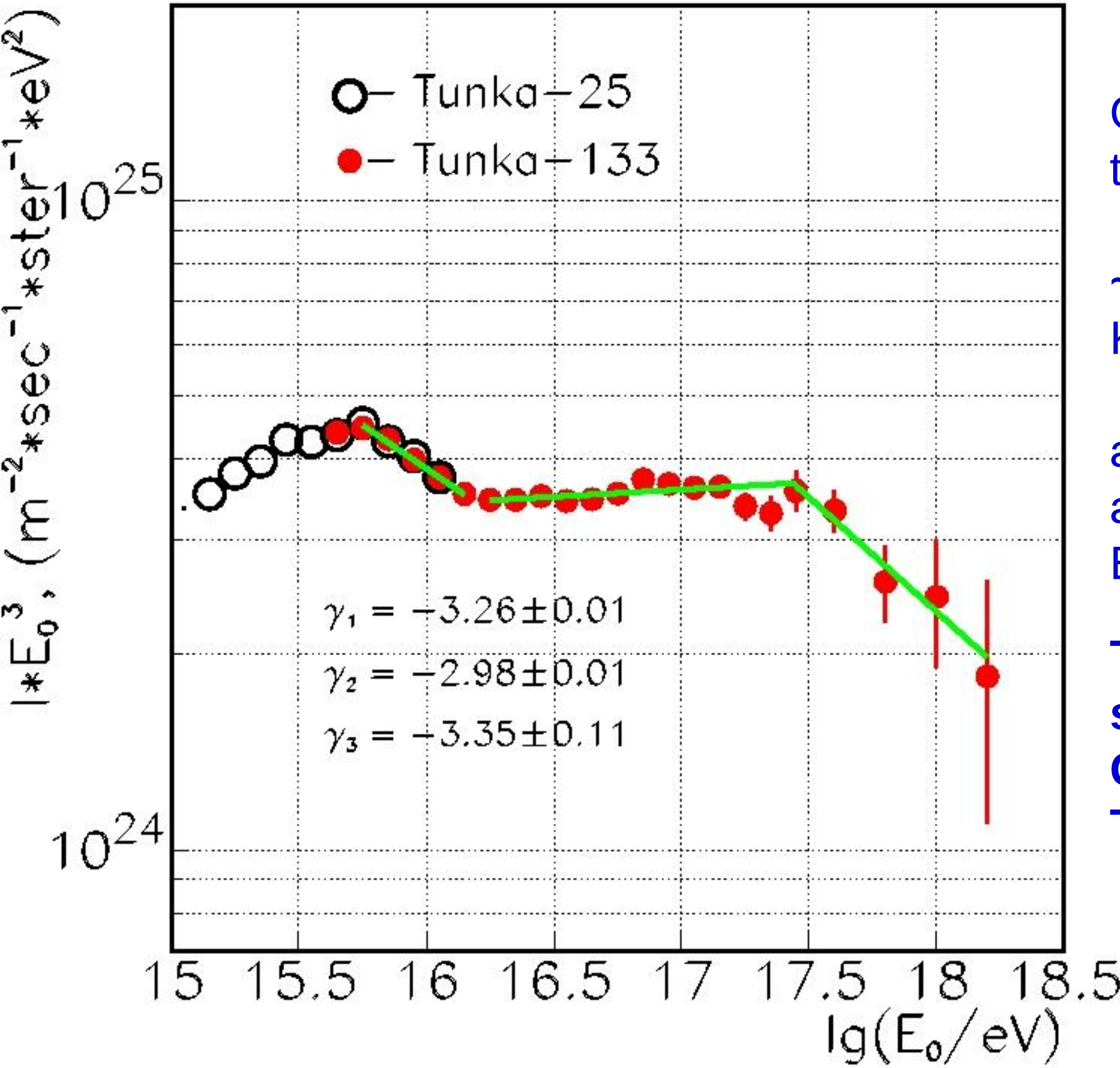
Combined energy spectrum construction



Combined differential primary energy spectrum



Energy spectrum: power law fitting

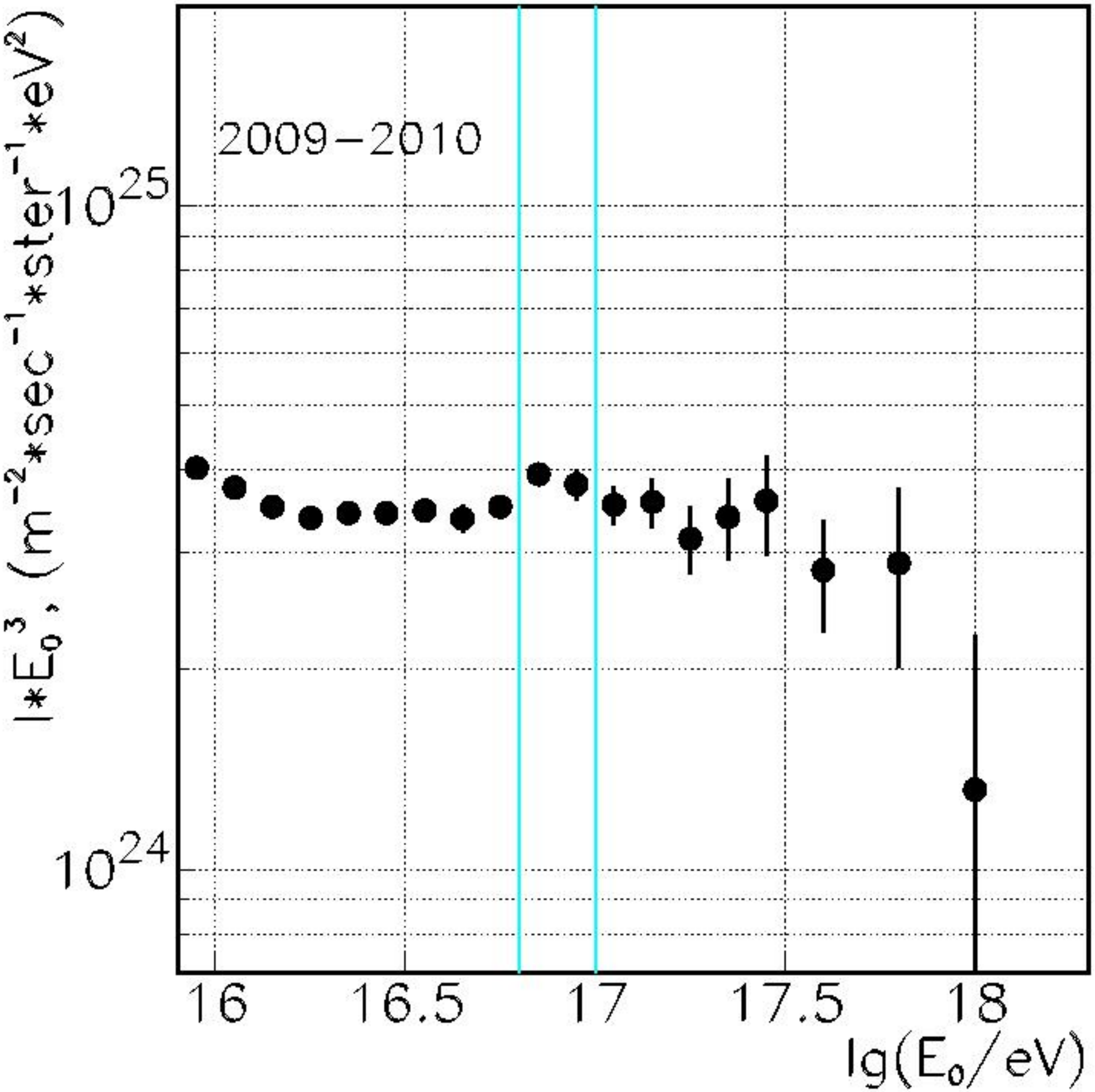


One can see two sharp features at the energies:

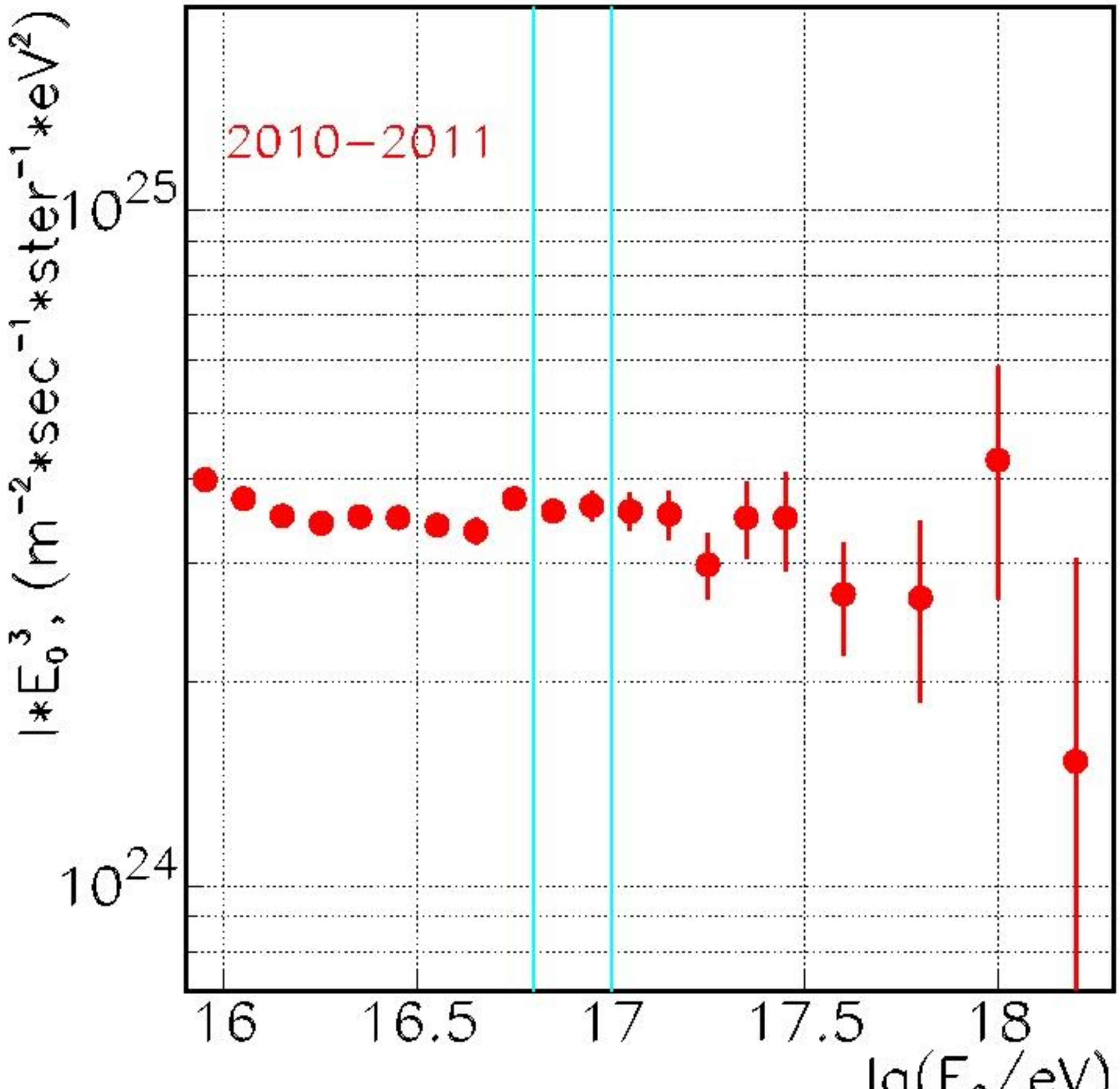
~$2\cdot10^{16}$ (first announced by KASCADE-Grande in 2010)

and ~$3\cdot10^{17}$ (similar to that, announced by Yakutsk and Fly's Eye in 90^{th})

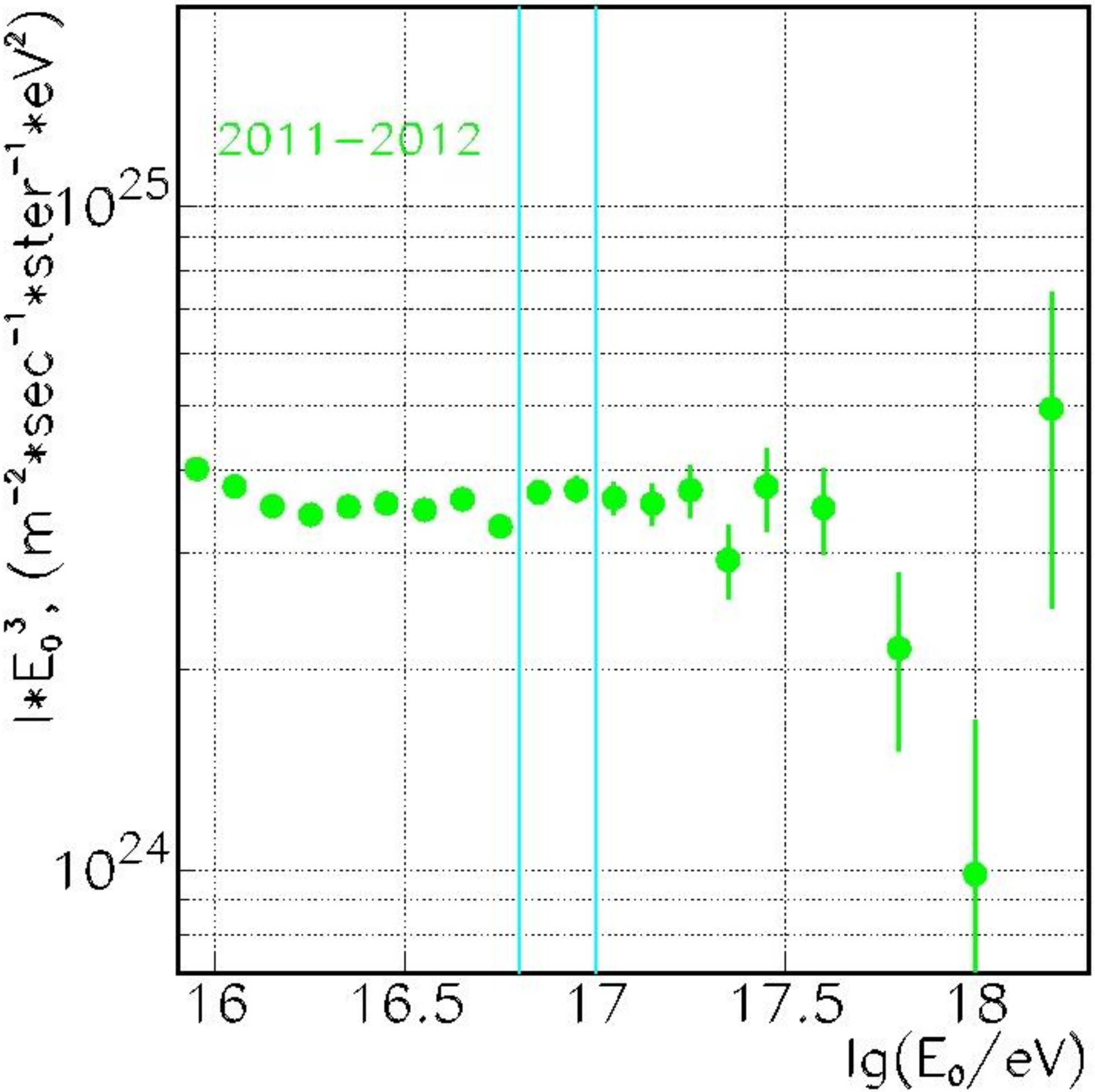
The power law index at $E_0>10^{17}$ is similar to that obtained by the Giant Experiments: TA, HiRes, Auger.



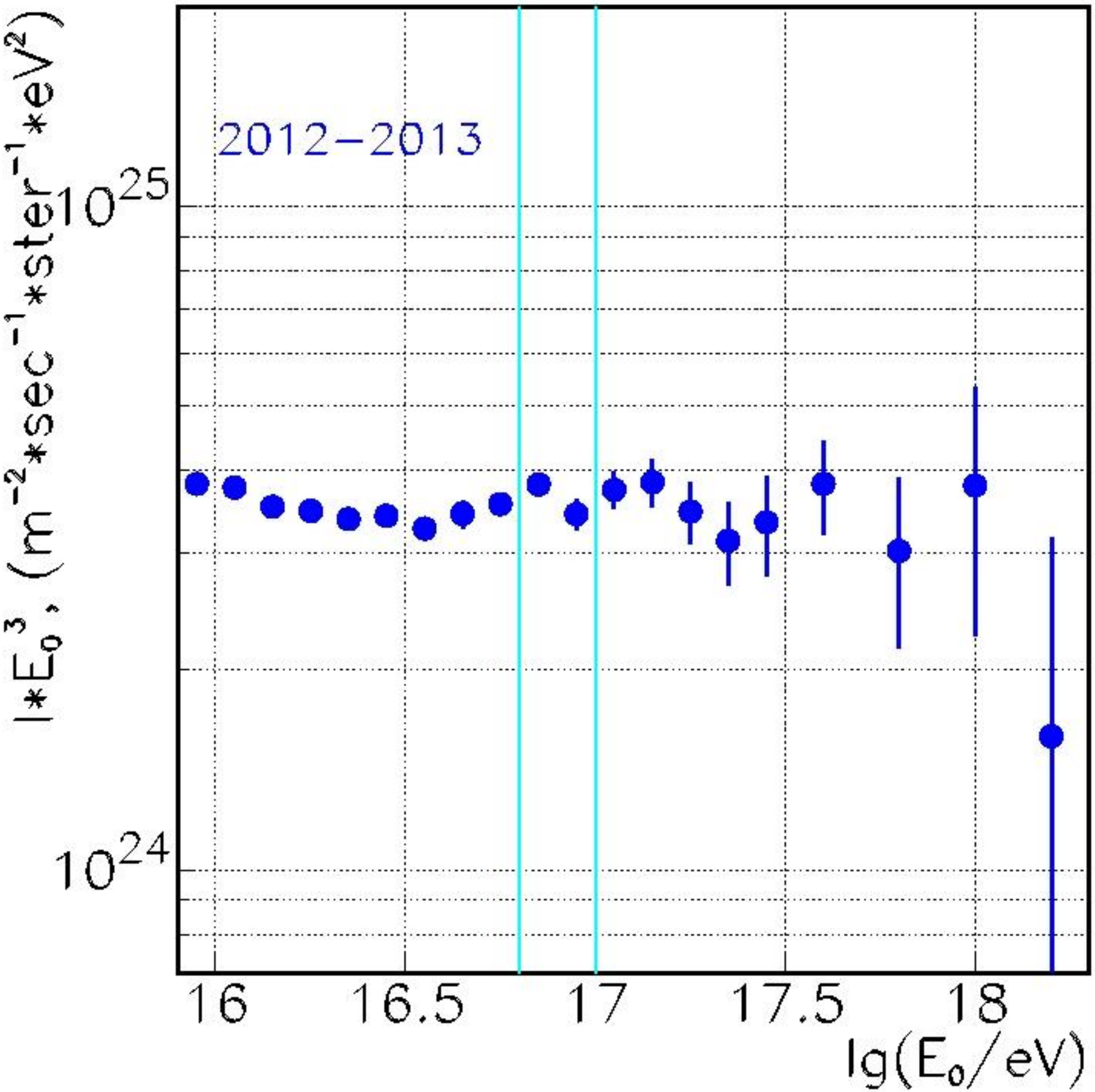
2009−2010
I*E0^3, (m^-2*sec^-1*ster^-1*eV^2)
10^25
10^24
16
16.5
17
17.5
18
lg(E0/eV)



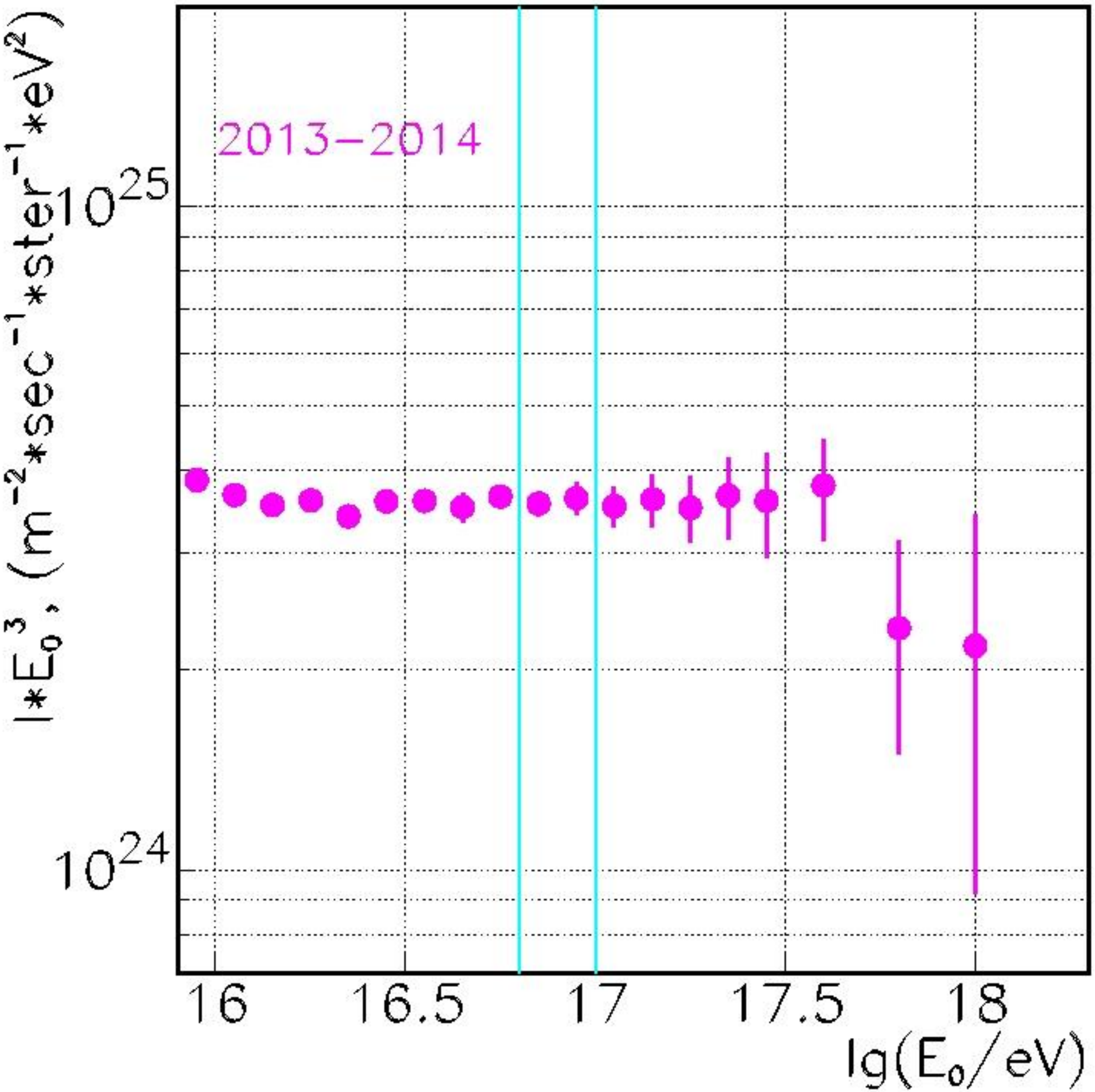
2010–2011
I*E0^3, (m^-2*sec^-1*ster^-1*eV^2)
10^25
10^24
16
16.5
17
17.5
18
lg(E0/eV)



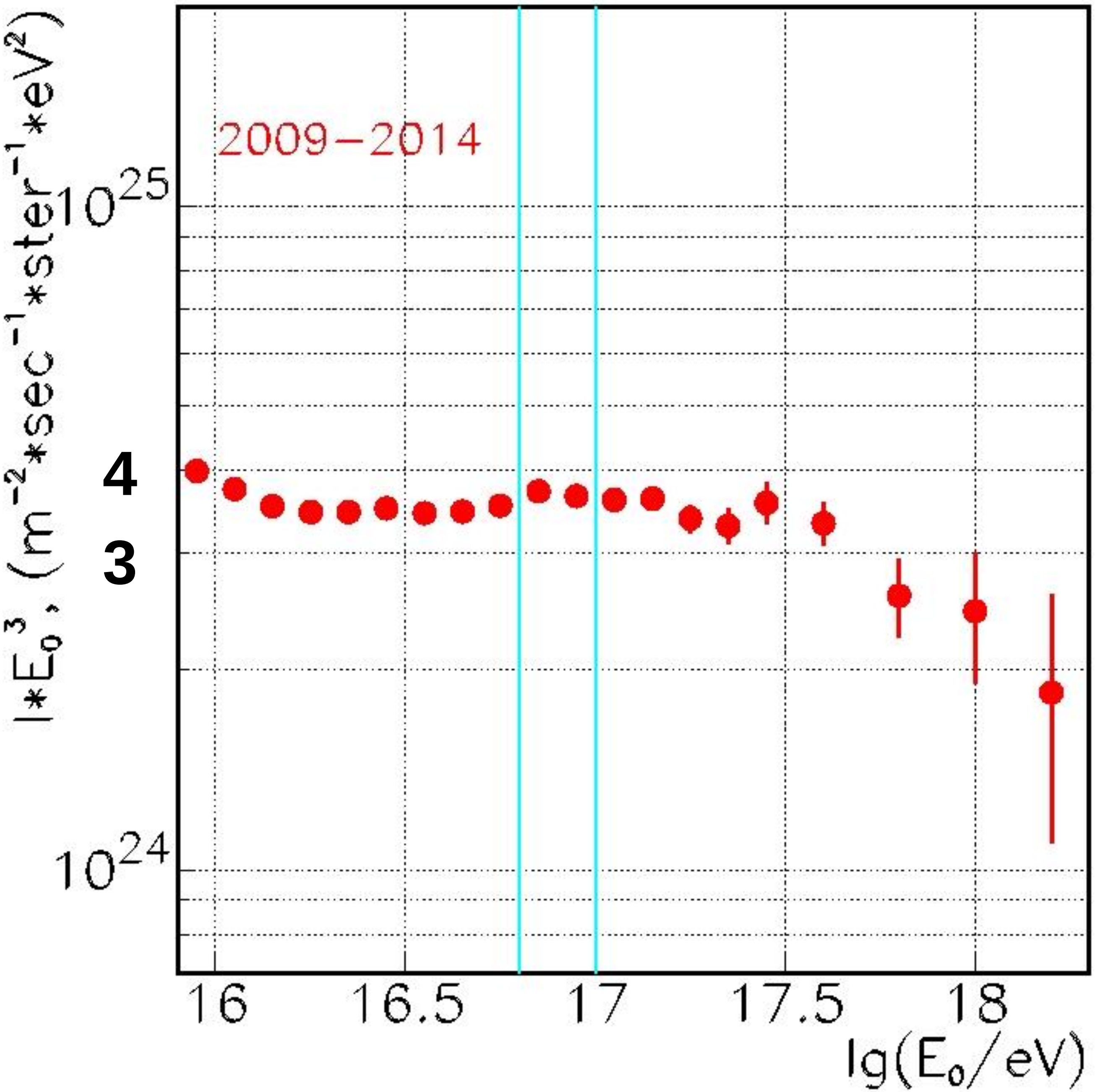
2011–2012
$I*E_0^3$, $(m^{-2}*sec^{-1}*ster^{-1}*eV^2)$
10^{25}
10^{24}
16
16.5
17
17.5
18
$lg(E_0/eV)$



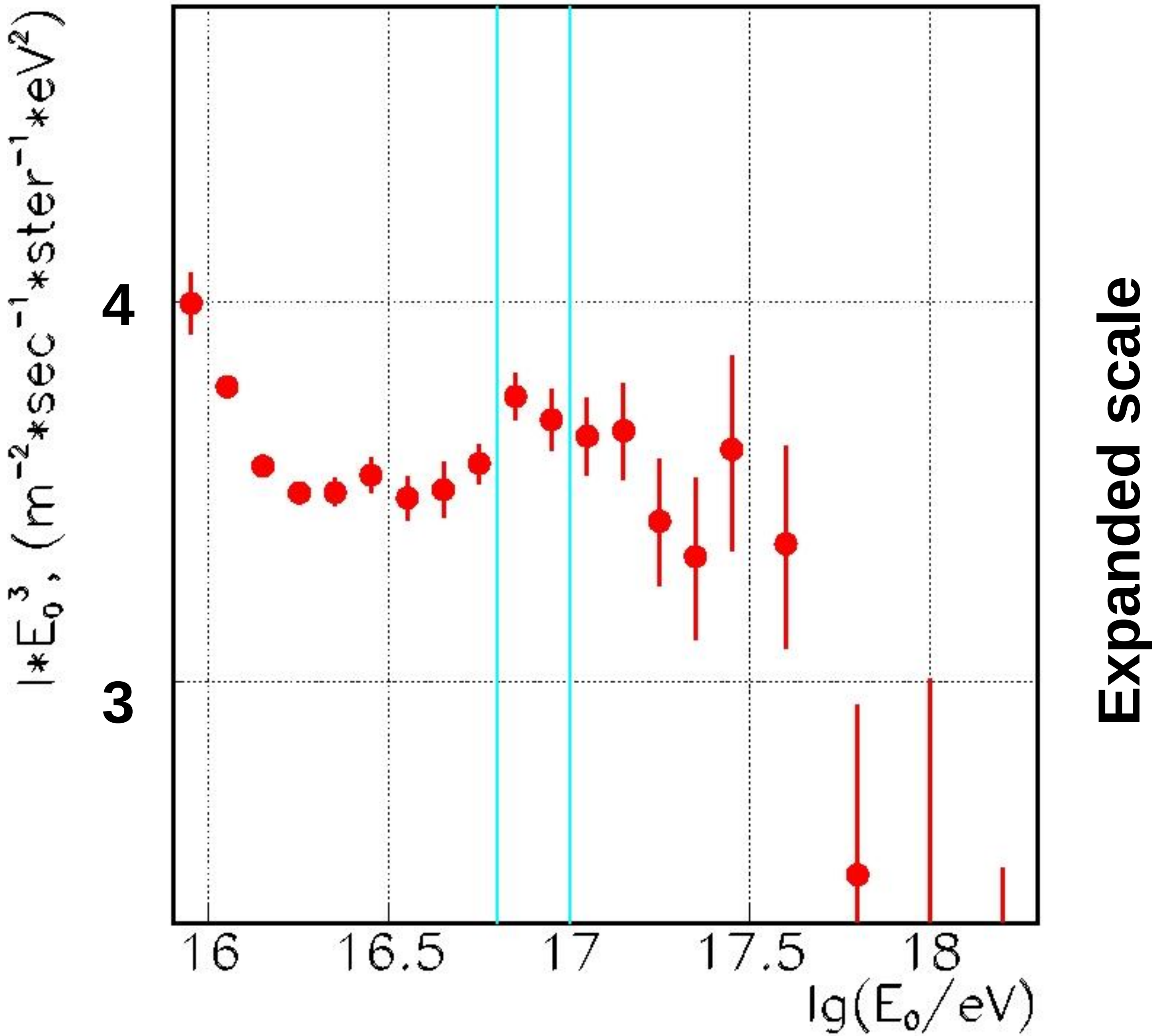
2012–2013
$I*E_0^3$, ($m^{-2}*sec^{-1}*ster^{-1}*eV^2$)
10^{25}
10^{24}
16
16.5
17
17.5
18
$lg(E_0/eV)$



2013–2014
10^{25}
10^{24}
16
16.5
17
17.5
18
$lg(E_0/eV)$
$I*E_0^3$, $(m^{-2}*sec^{-1}*ster^{-1}*eV^2)$

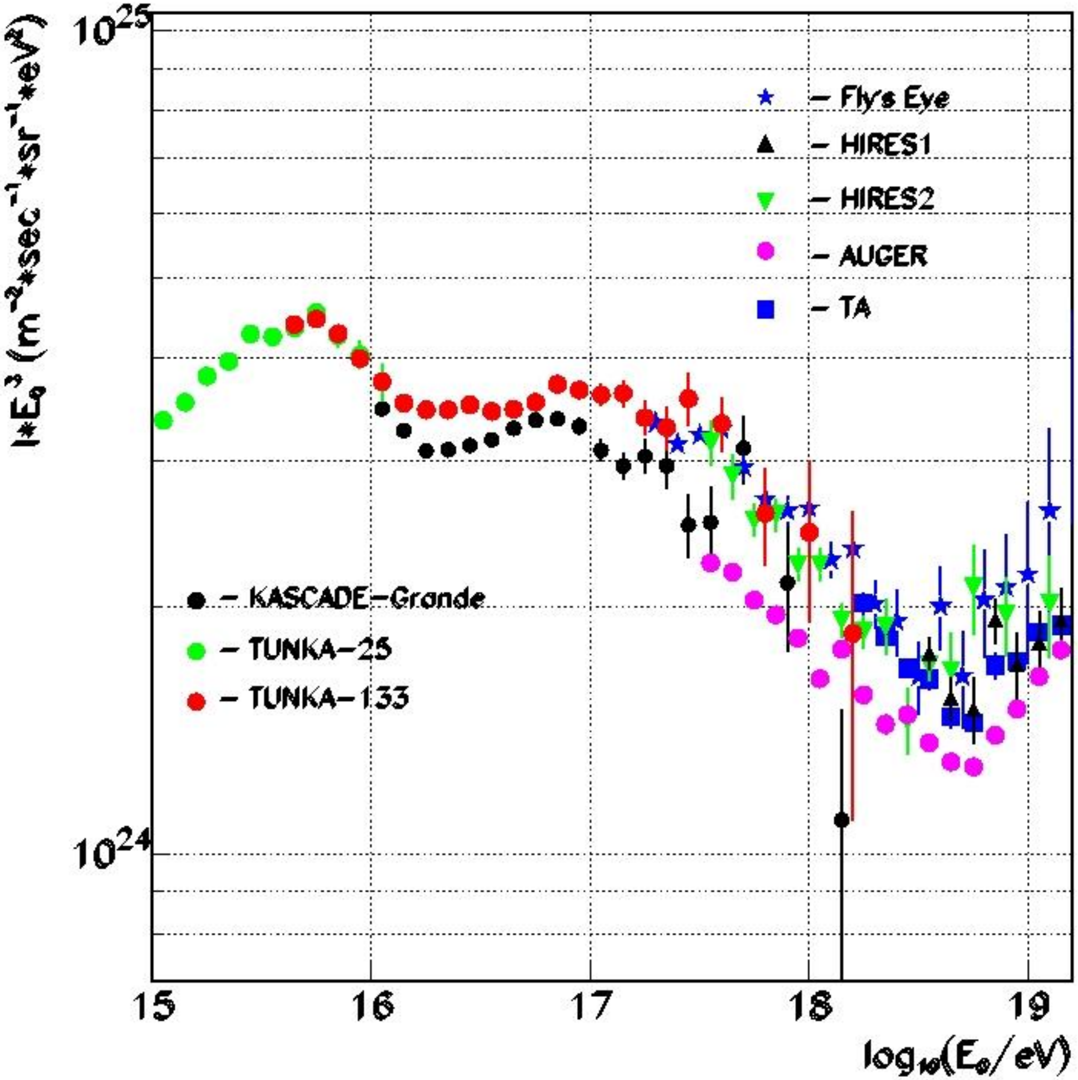


2009−2014
$I*E_0^3$, ($m^{-2}*sec^{-1}*ster^{-1}*eV^2$)
10^{25}
4
3
10^{24}
16
16.5
17
17.5
18
lg(E_0/eV)



4
3
I*E0³, (m⁻²*sec⁻¹*ster⁻¹*eV²)
16
16.5
17
17.5
18
lg(E0/eV)
Expanded scale

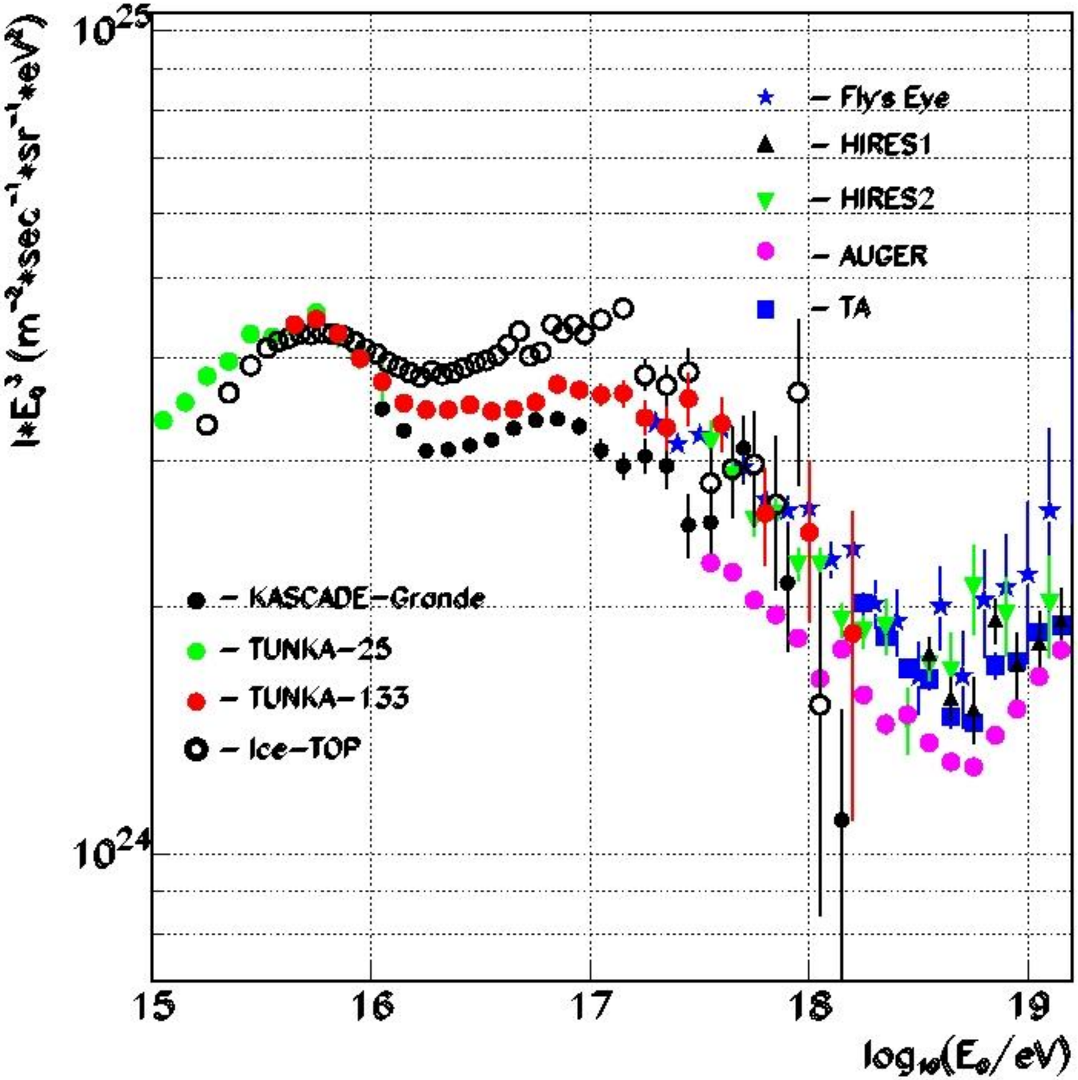
Combined spectrum: comparison with some other works



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

Another works in this range:
GAMMA
Ice-TOP
TA by Cerenkov light

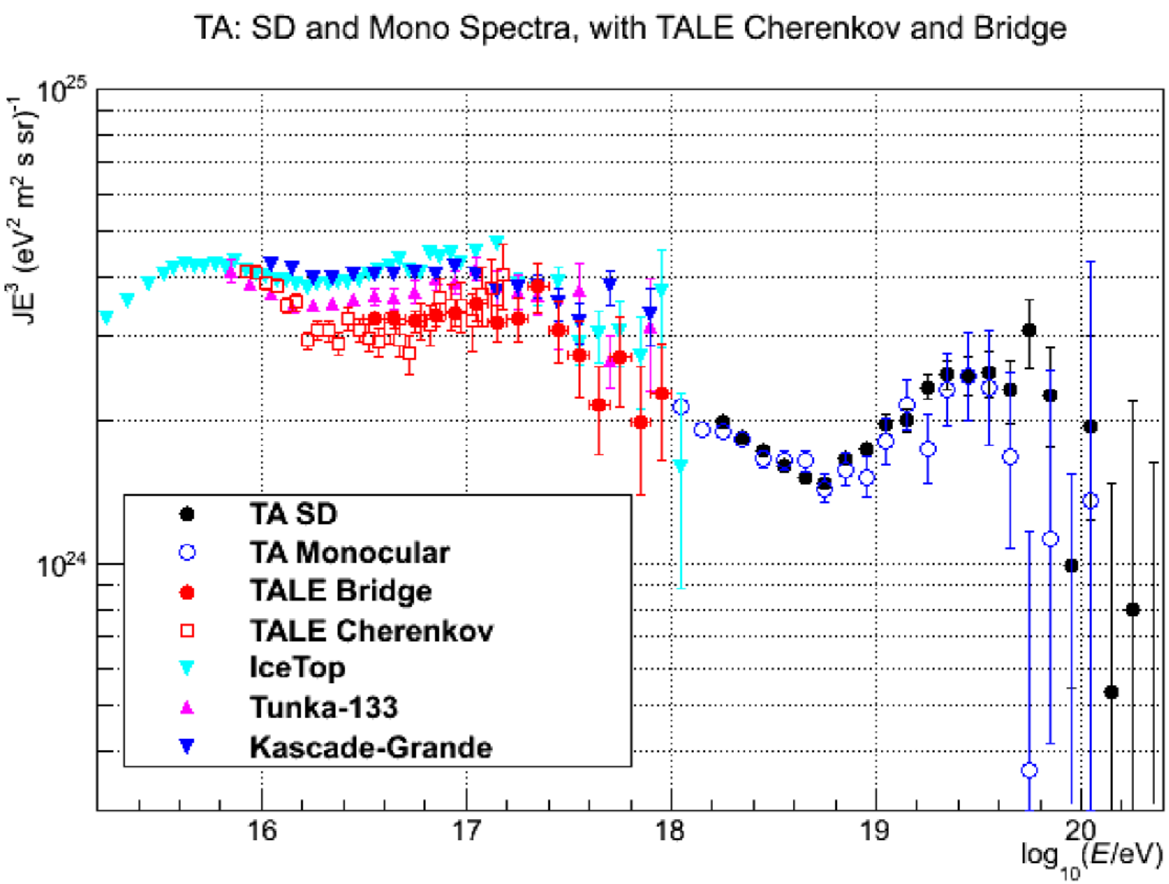
Combined spectrum: comparison with some other works



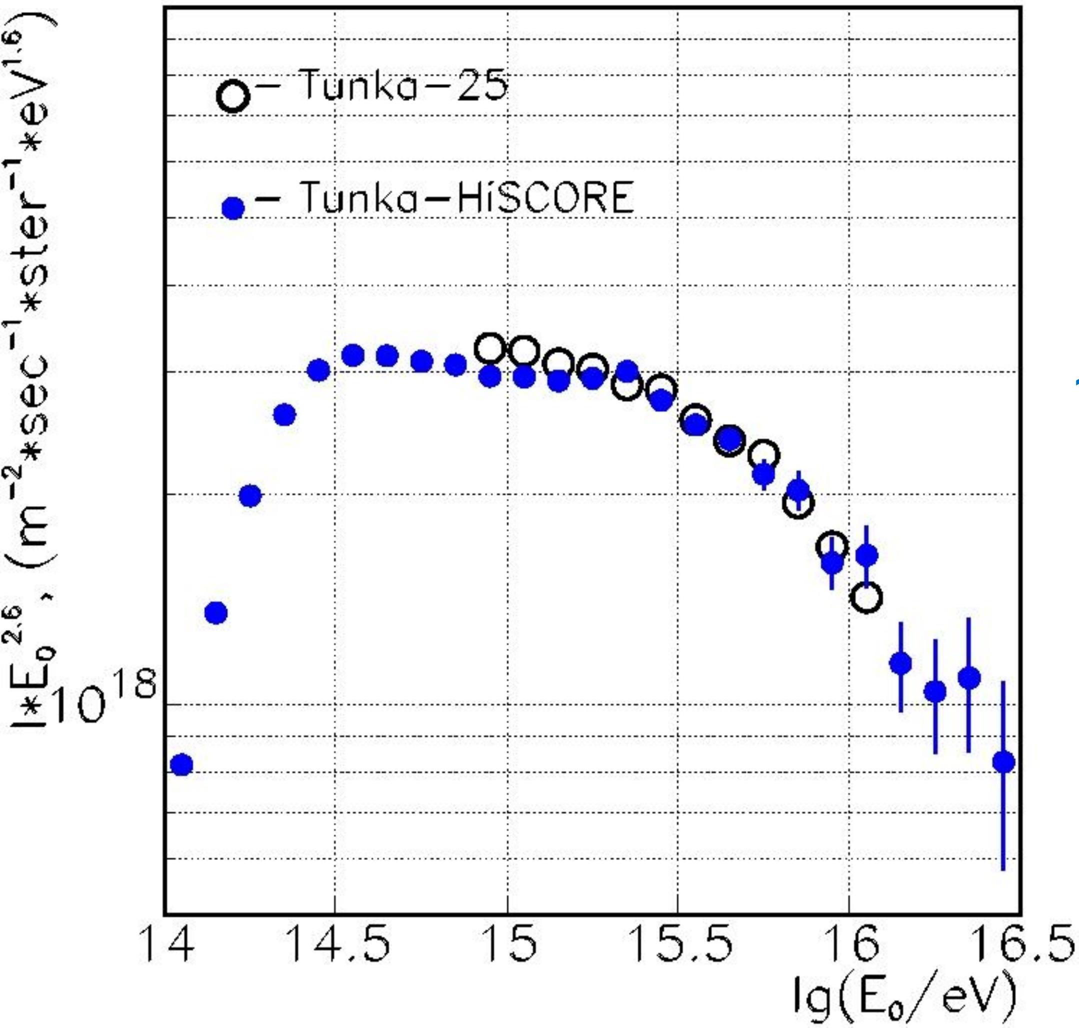
Agreement with KASCADE-Grande
Agreement with old Fly's Eye, HiRes and TA spectra.

Another works in this range:
GAMMA
Ice-TOP
TA by Cerenkov light

TA: TALE Cherenkov and Bridge PRELIMINARY



Tunka-HiSCORE:
All particle energy spectrum.
PRELIMINARY



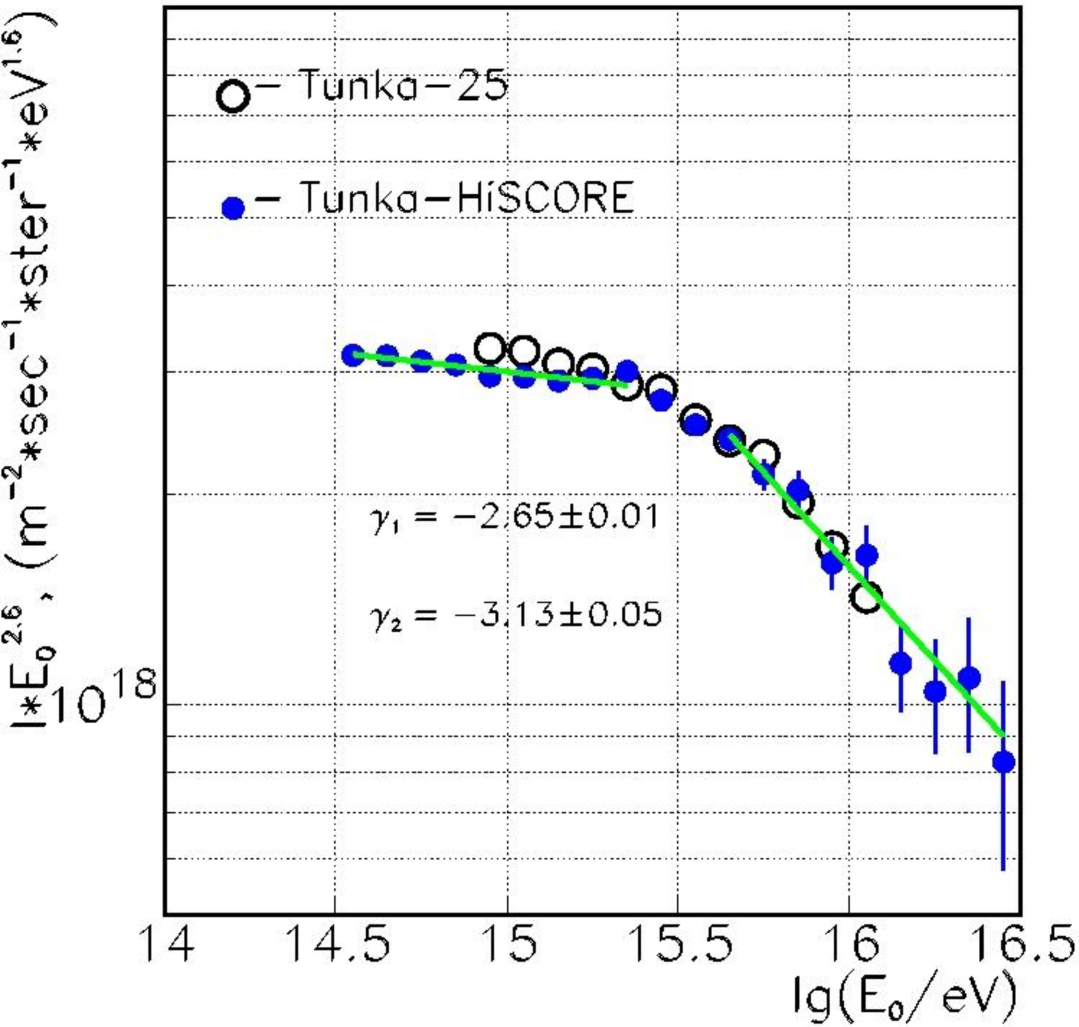
84 h during 13 clean moonless nights in February and March of 2014

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

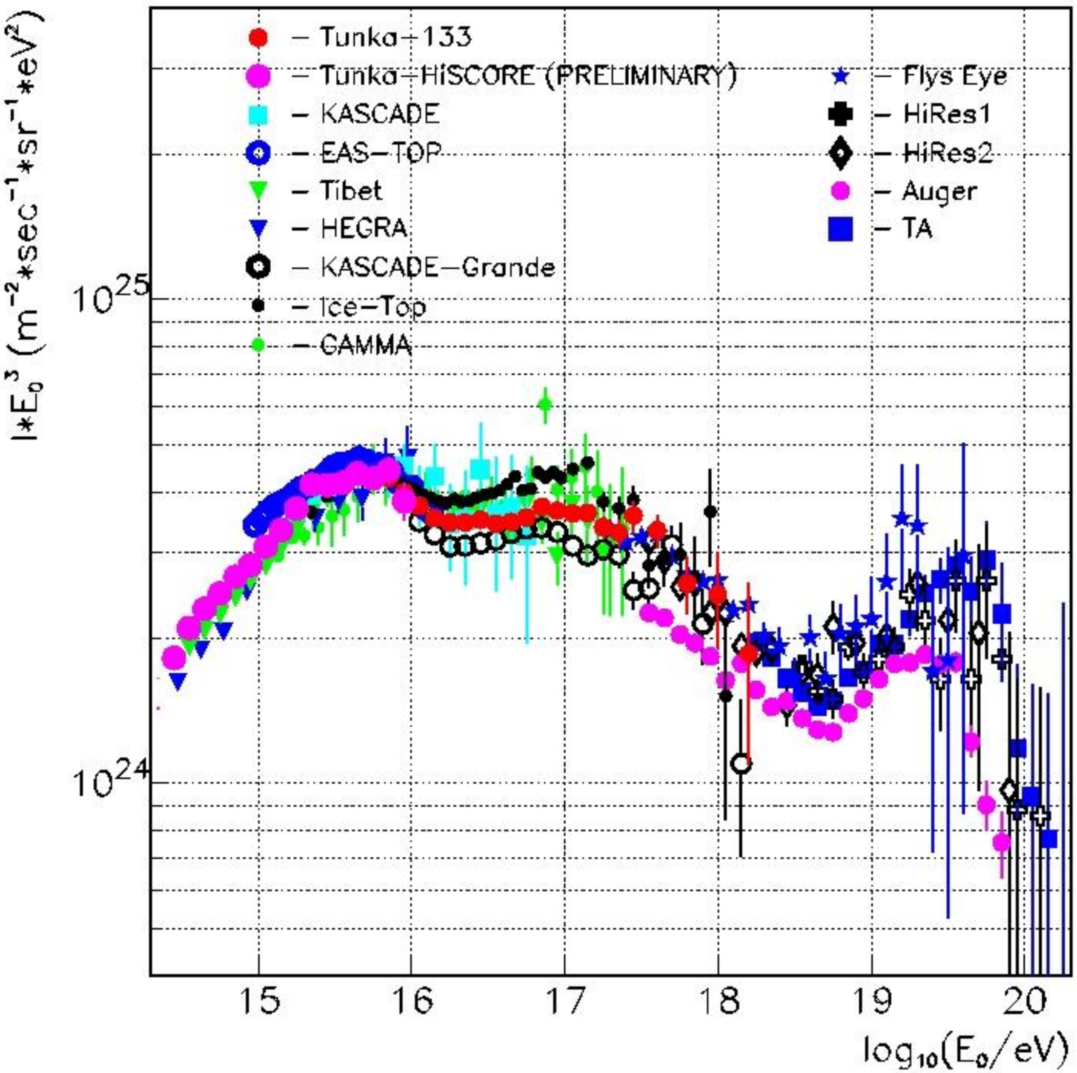
~ 21 000 events $E_0 > 10^{15}$ eV

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

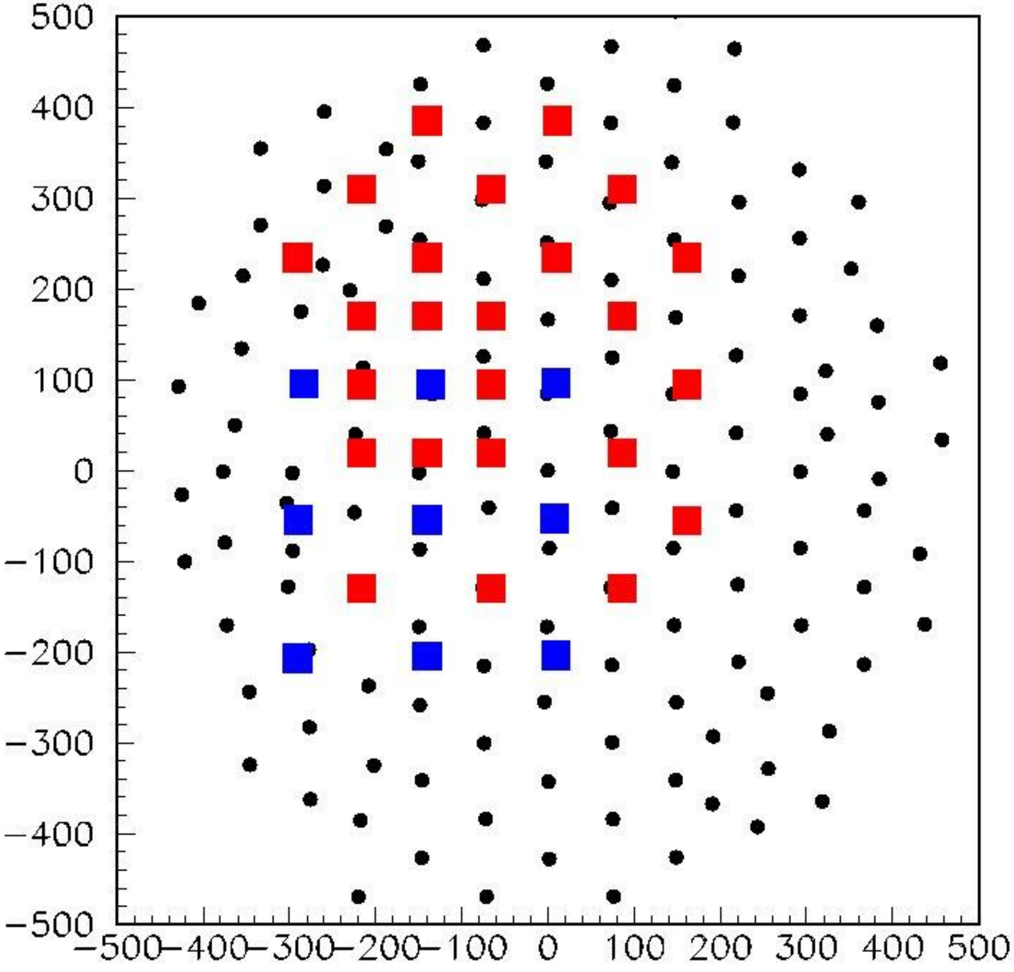
Tunka-HiSCORE:
All particle energy spectrum.
PRELIMINARY

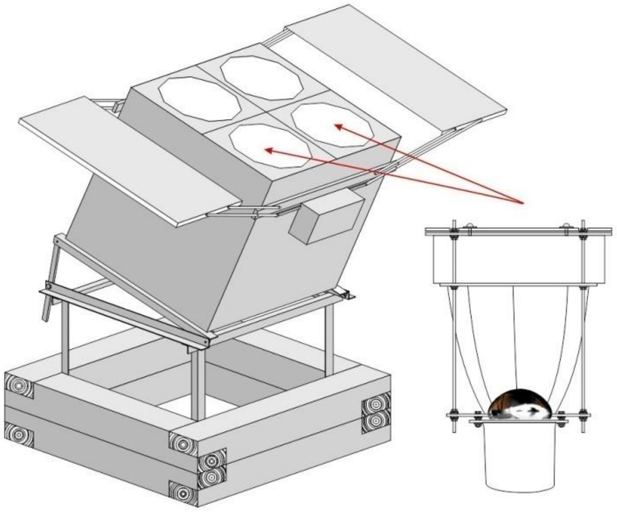


All particle spectra



Tunka-HiSCORE next winter (2014-2015) – 33 stations Decreasing of a threshold for γ to ~30 TeV

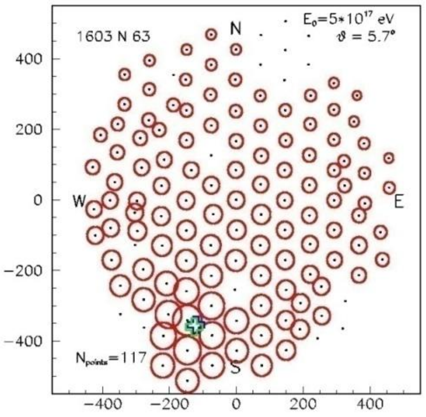




All the stations will be tilted for 30° to the South for observation of Crab Nebulae

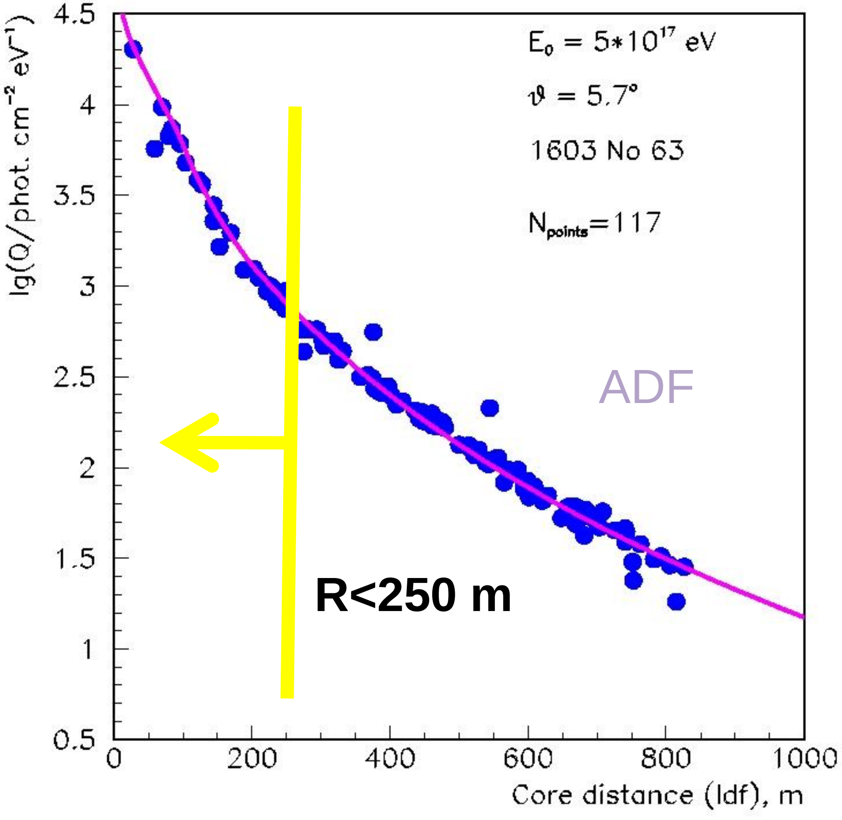
About 20-60 γ-events from Crab are expected during 100 h of observation.

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

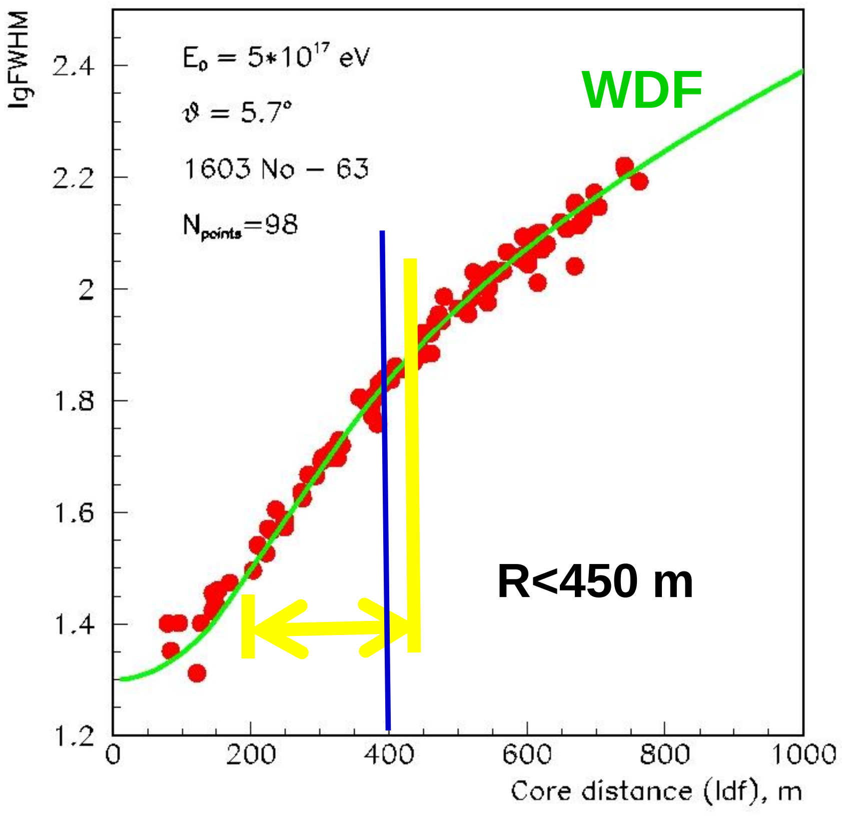


$\Delta X_{max} \leq 25$ g·cm^{-2}

ADF steepness: $\mathbf{b_A}$



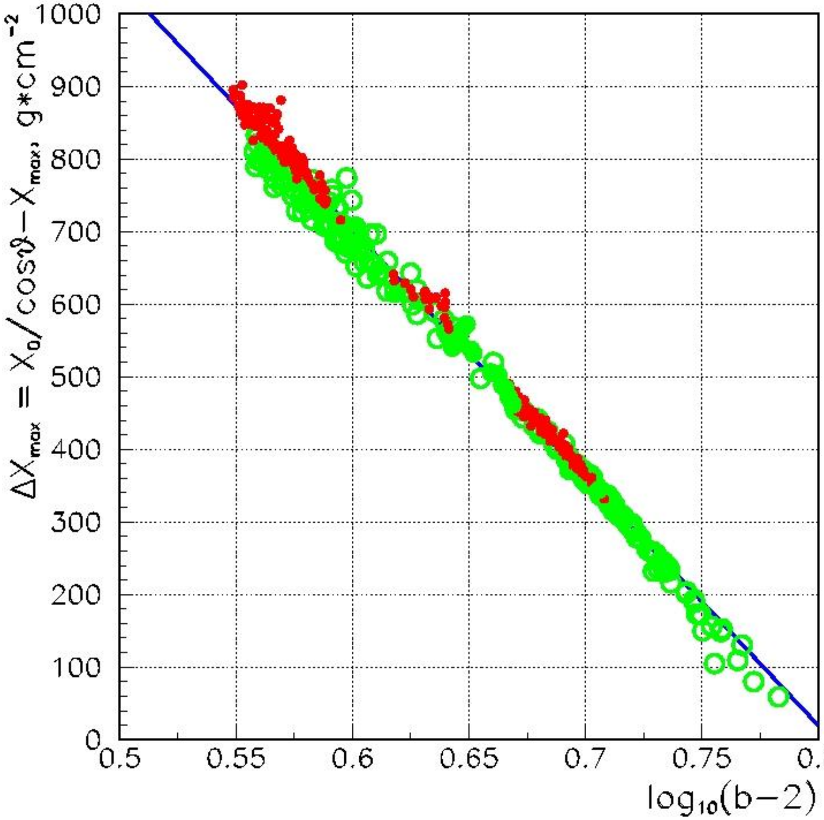
Pulse width at core distance 400 m: $\boldsymbol{\tau_{eff}}$**(400)**



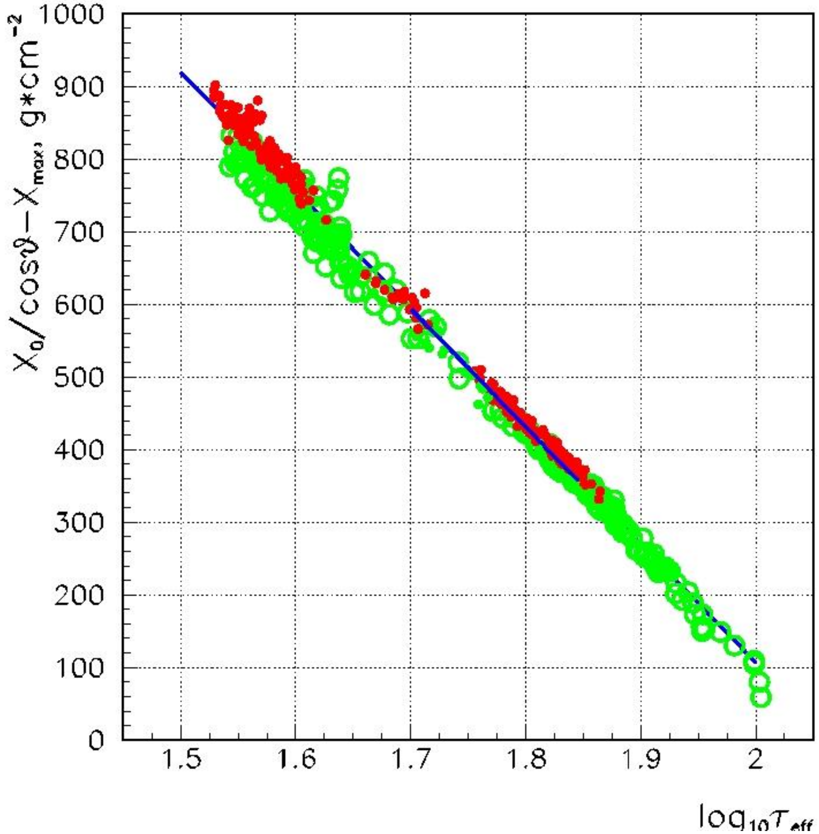
CORSIKA

(**Correlations are model, energy, zenith angle and composition independent**)

ΔX_{max} vs. **b_A**



ΔX_{max} vs. **$\tau_{eff}(400)$**

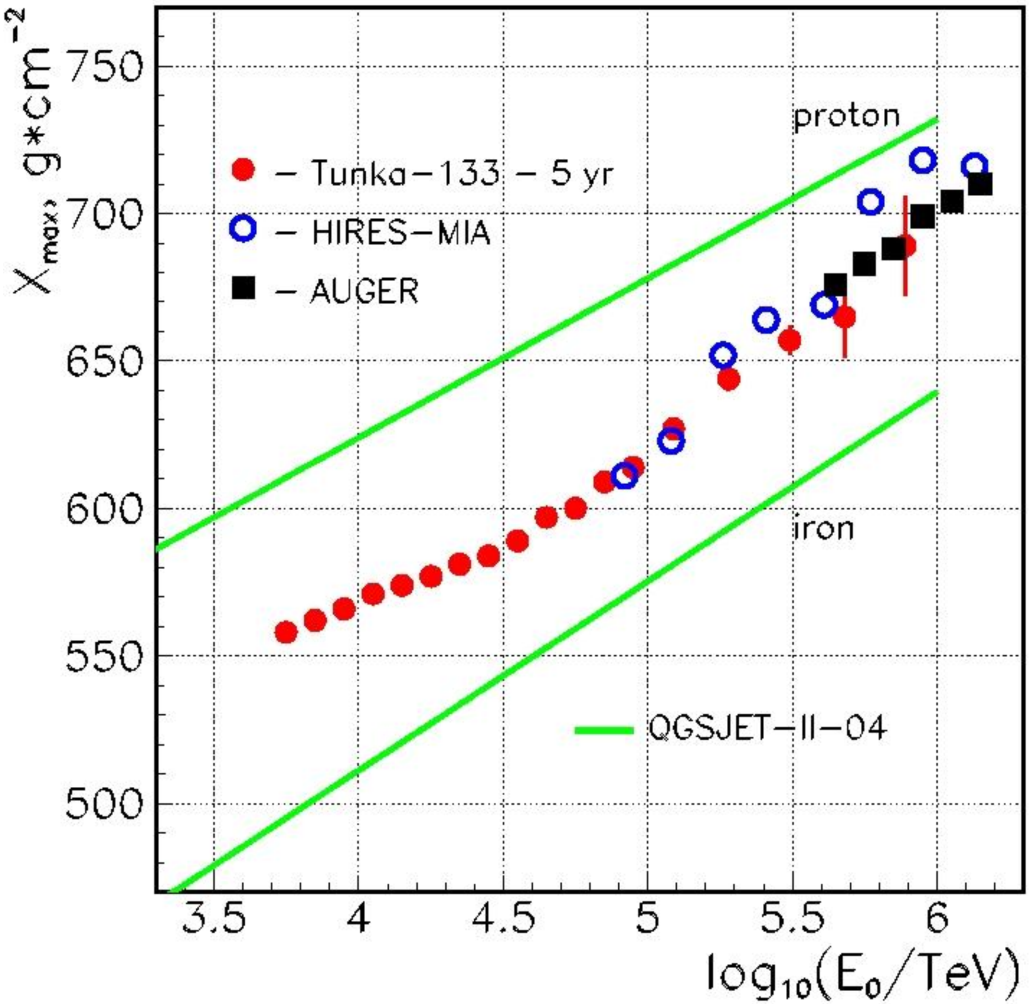


~ 500 events – 10^7 GeV < E_0 <10^8 GeV, θ = 0°, 30°, 45°

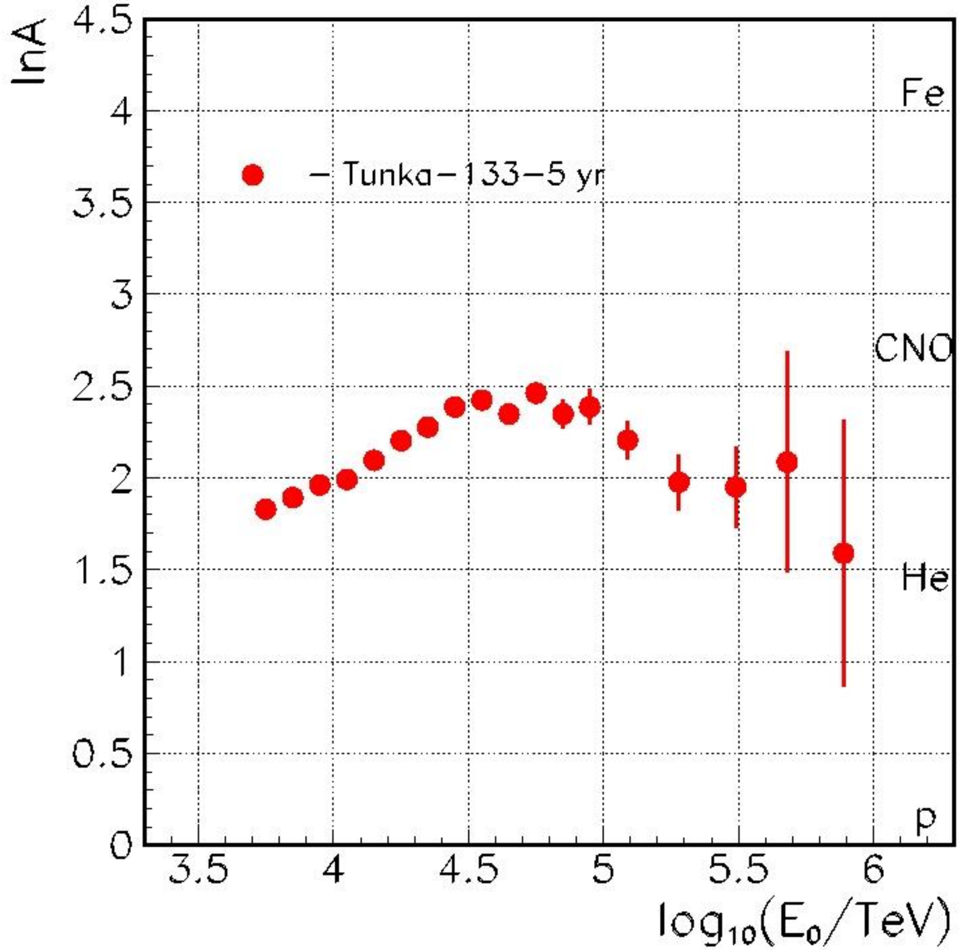
green – p, red – Fe

$\langle X_{max} \rangle$ vs. E_0

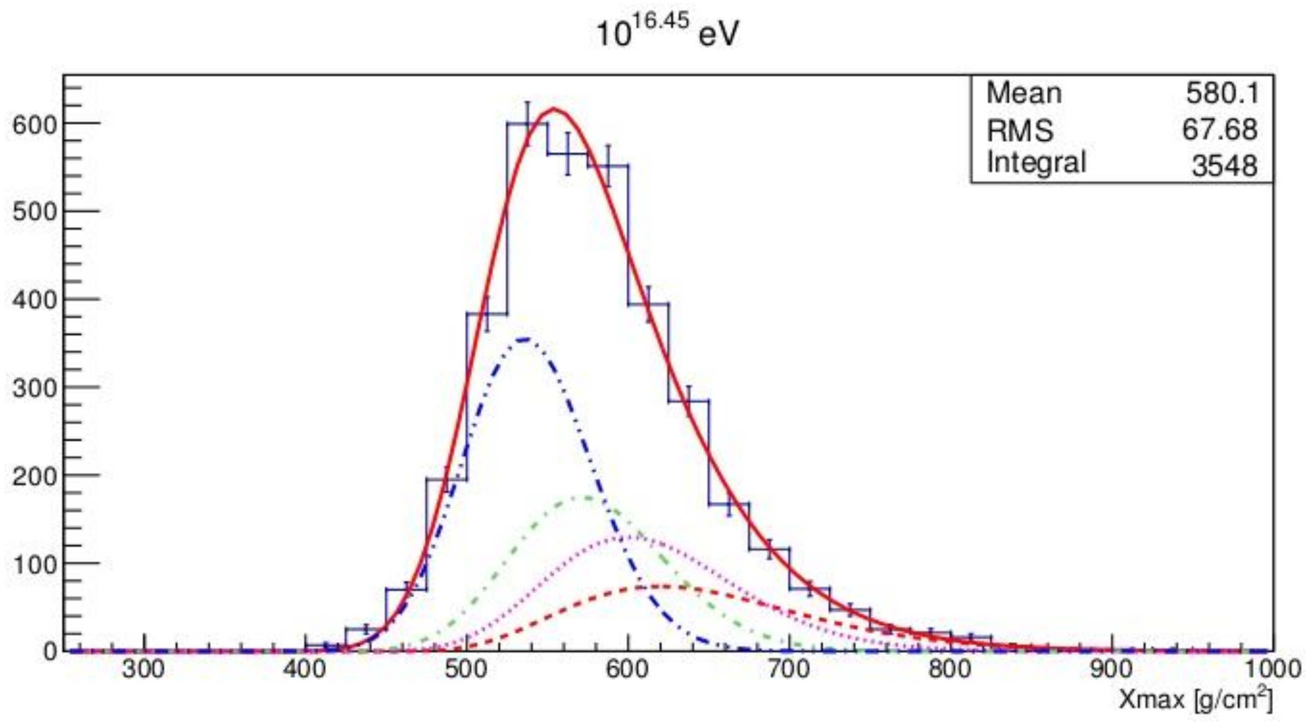
Agreement with HiRes-MIA and Auger results at $10^{17} - 10^{18}$ eV



EXPERIMENT: MEAN <lnA> vs. E_0

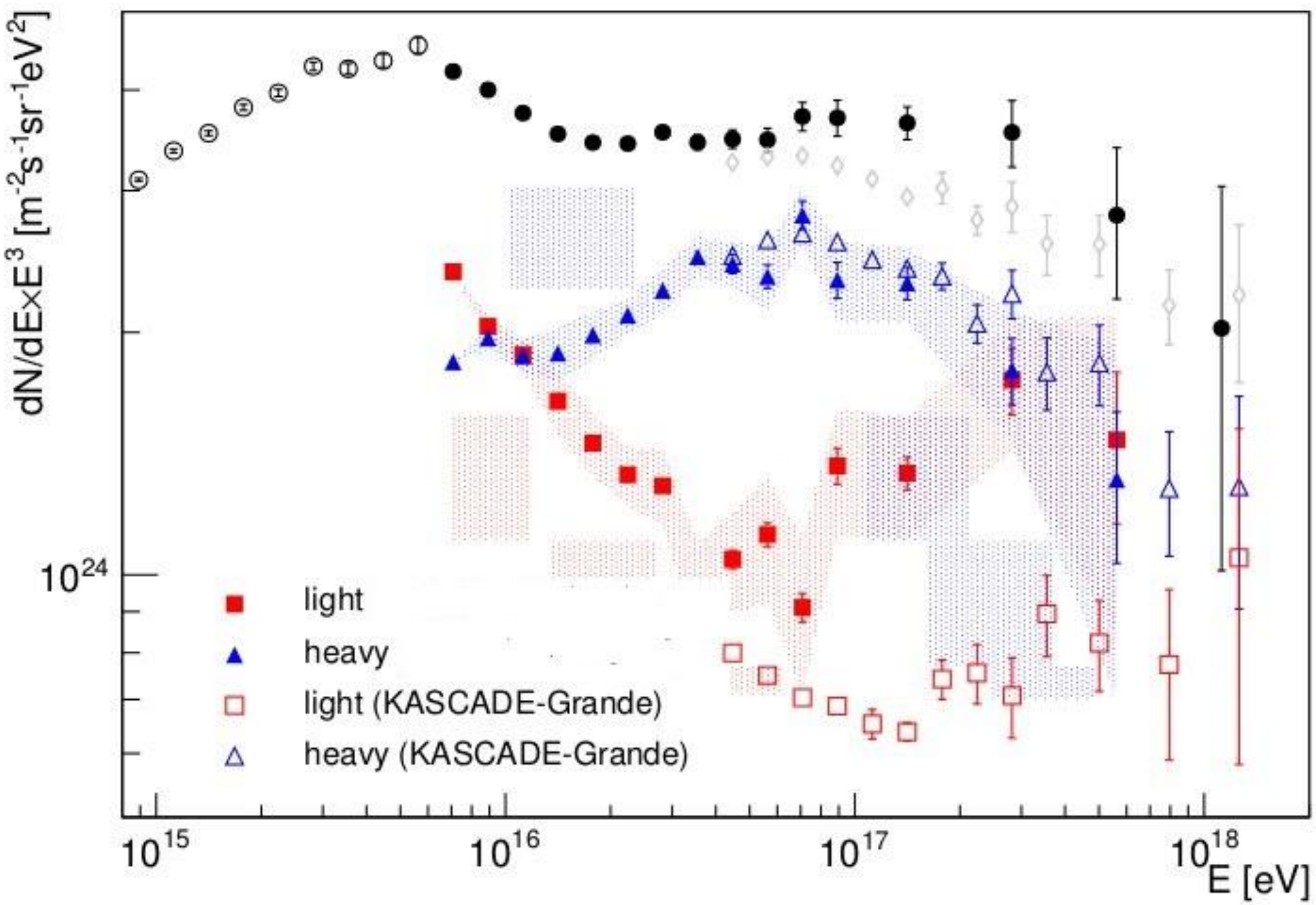


ANALYSIS of X_{max} DISTRIBUTIONS (2013)PRELIMINARY



Fit with weighted sum of 4 group MC simulated distributions: Fe, CNO, He, p

Spectra of light (p+He) and heavy (all other) CR components (2013)



CONCLUSIONS

1. The spectrum from 6.10^{15} to 10^{18} eV cannot be fitted with single power law index:

$\gamma = 3.26 \pm 0.01$ $5 \cdot 10^{15} < E_0 < 2 \cdot 10^{16}$ эВ.

$\gamma = 2.98 \pm 0.01$ $2 \cdot 10^{16} < E_0 < 3 \cdot 10^{17}$ эВ.

$\gamma = 3.35 \pm 0.11$ $E_0 > 3 \cdot 10^{17}$ эВ.

2. Agreement with KASCADE-Grande, Ice-TOP and TALE (TA Cherenkov).

3. The high energy tail do not contradict to the Fly's Eye, HiRes and TA spectra.

4. The X_{max} do not contradict to that of HiRes-MIA and Auger data.

5. Composition changes to heavy from 10^{16} to $3 \cdot 10^{16}$ and changes back to light in the range $10^{17} – 10^{18}$ eV.

Thank you!