Tunka-133: Results of 5 Years Observation and Future Experiments – HiSCORE, Grande, IACT

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

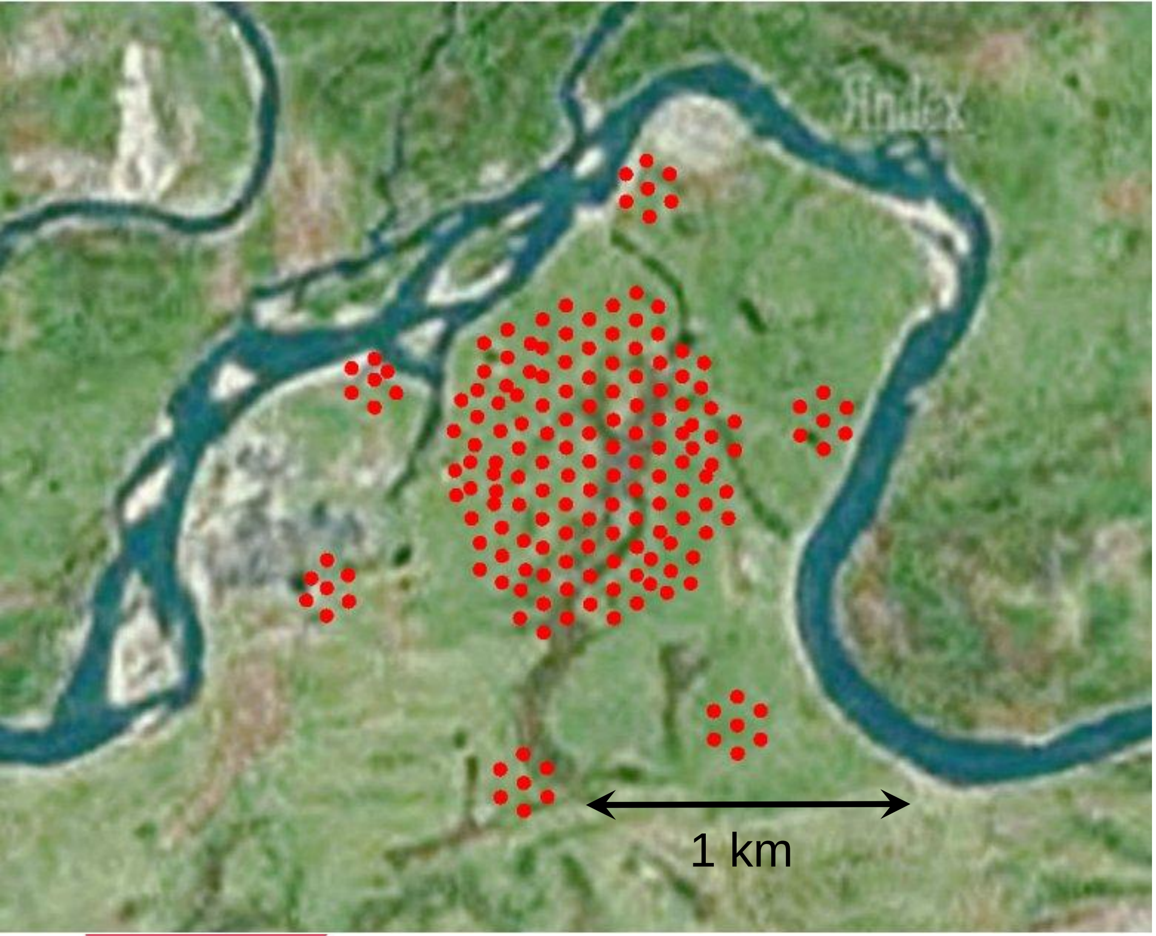
From Tunka and TAIGA Collaborations

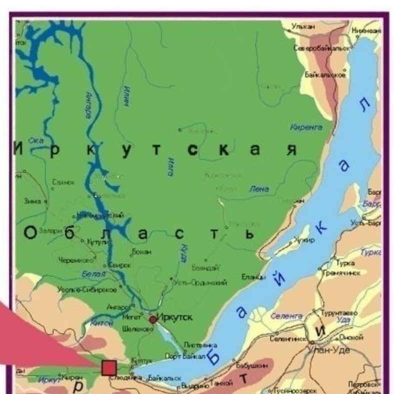
The EAS Cherenkov light array Tunka-133 with ~3 km^2 geometric area operates since 2009.
Five winter seasons of data acquisition (~10^7 triggers) permitted us to reconstruct primary energy spectrum and mass composition in the energy range $6 \cdot 10^{15}$ to 10^{18} eV.

The further experiments in Tunka Valley will be: scintillation stations (Tunka-Grande), Tunka radio extension (Tunka-REX), Tunka-HiSCORE, Tunka-IACT.

To start gamma-astronomy experiments in Tunka Valley researchers from a number of Russian and European Institutes arranged a Collaboration TAIGA (Tunka Advanced Instrument for cosmic ray and Gamma-Astronomy).

The complex installation will consists of the net of wide-angle (1 sr. field of view) Cherenkov light optical stations (Tunka-HiSCORE), several (~ 5) IACT telescopes based on spherical mirrors of 10 m^2 area (Tunka-IACT) and muon scintillation detectors of the total area ~2000 m^2.





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

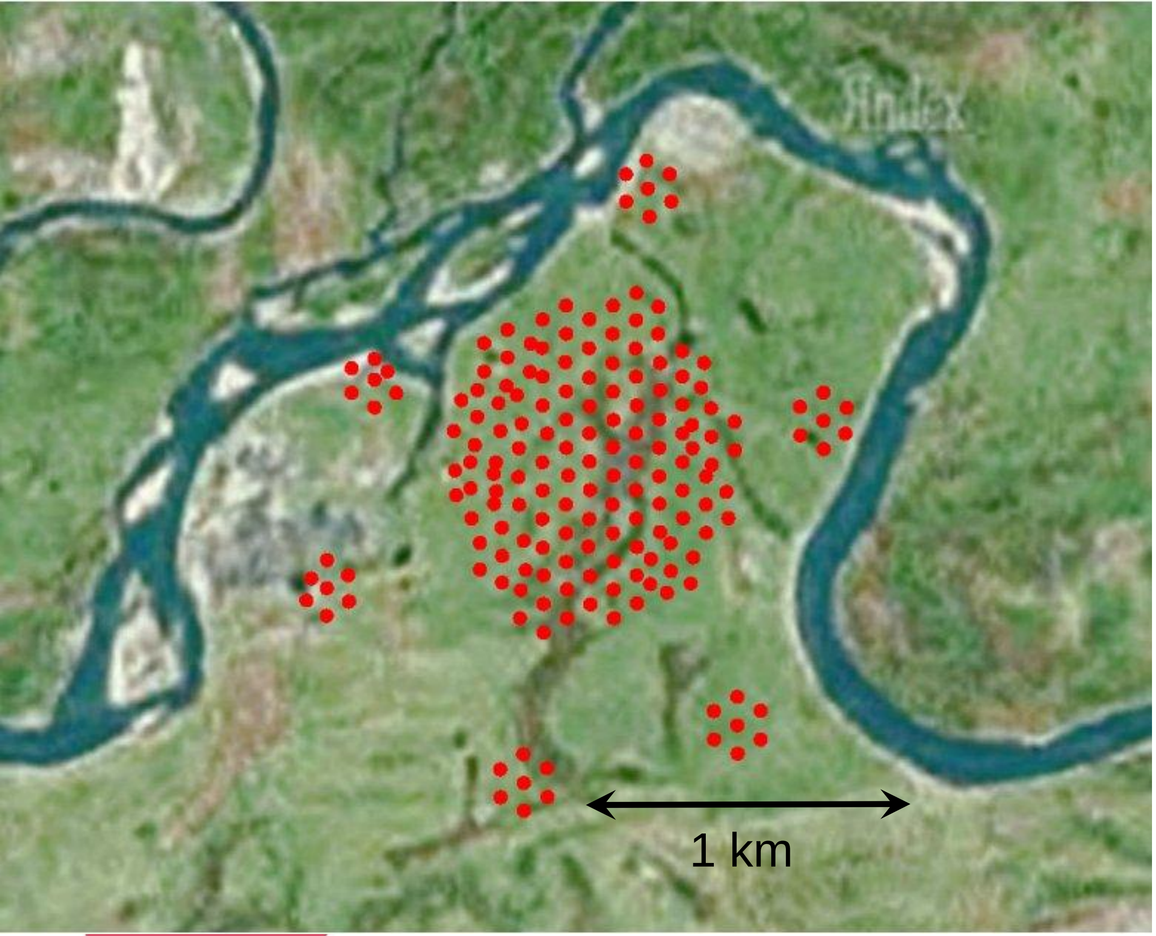
EXPERIMENTS
in Tunka Valley

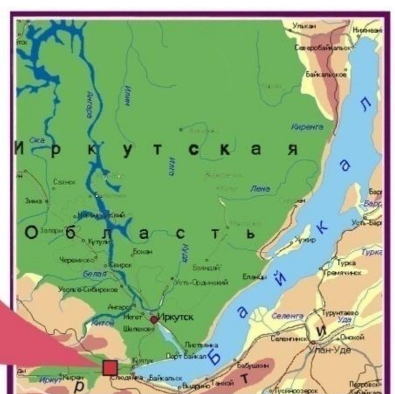
NOW (2013-2014):

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.

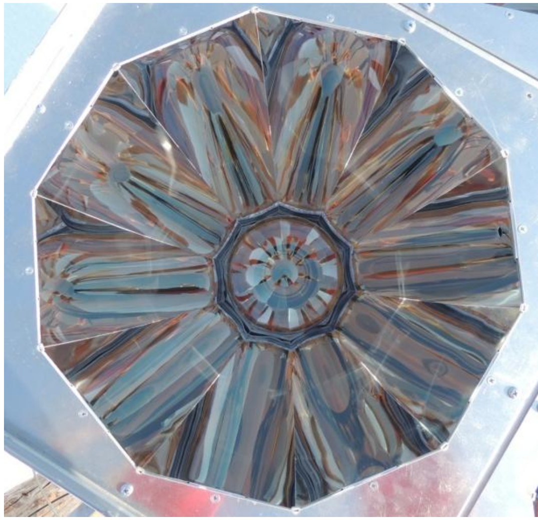
175 optical detectors
EMI 9350 and HAMAMATSU Ø 20 cm

Ways to threshold decreasing

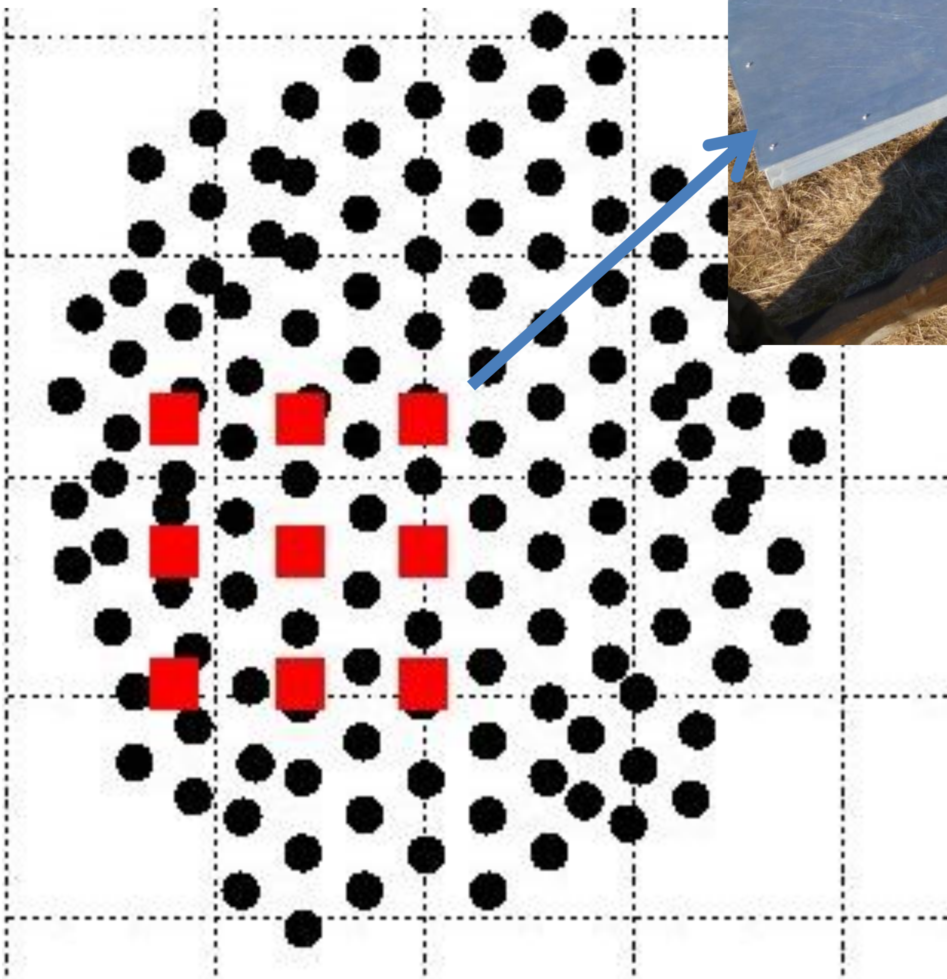
$$E_{th} \sim (S_D \cdot \eta)^{-1/2} \cdot (W_{CP})^{1/2}$$

1. Winston cone increases S_D to 4 times
2. Four detectors in one station.
3. Decreasing of $\mathbf{W_{CP}}$ to ~10 ns
   (2 times less than at Tunka-133).

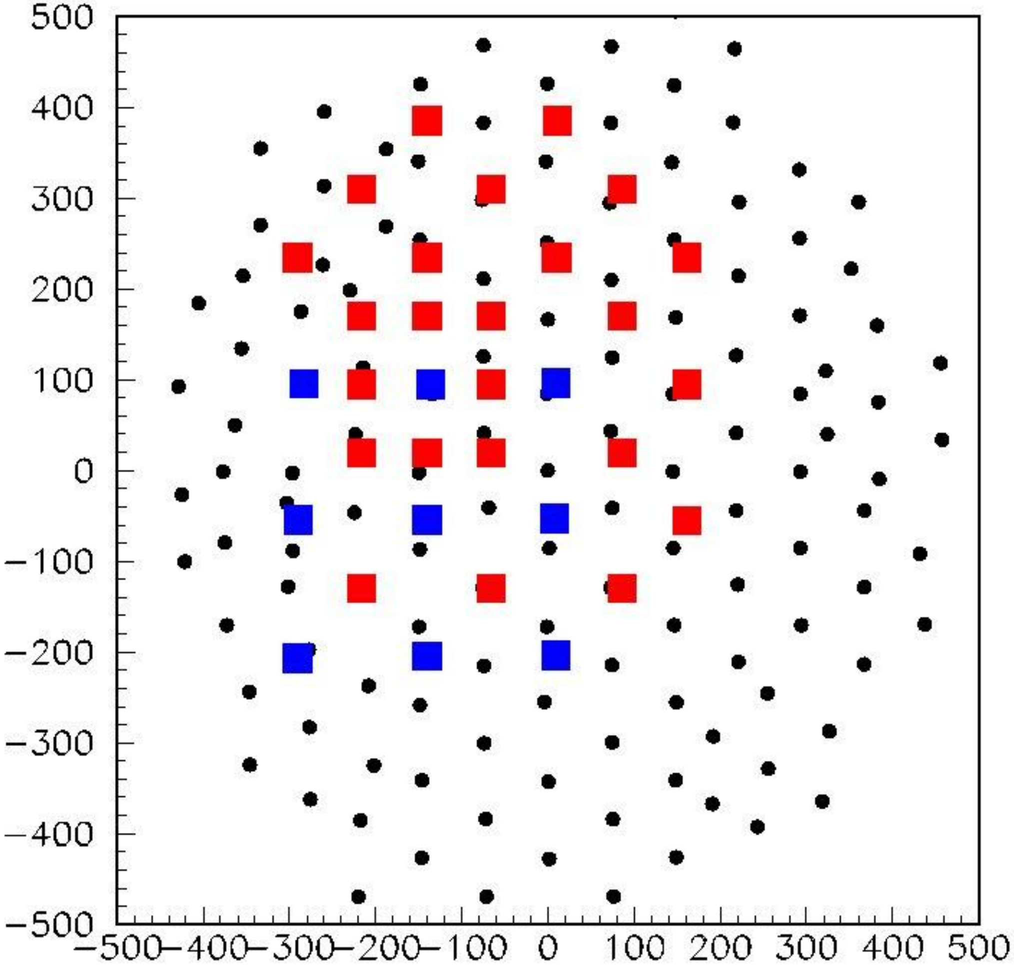
Winston cone
(Hamburg Univ. design)

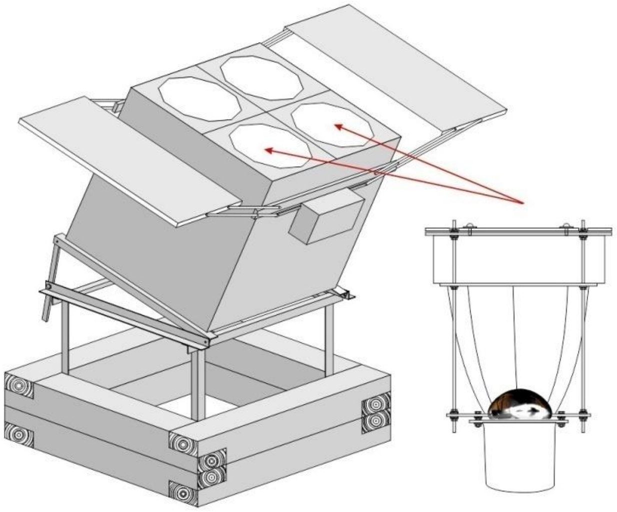



Tunka-HiSCORE prototype
9 optical stations



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





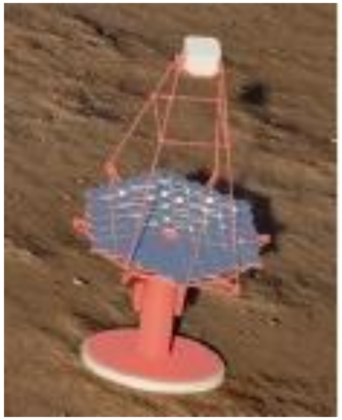
All the stations will be tilted for 30° to the South for observation of Crab Nebulae

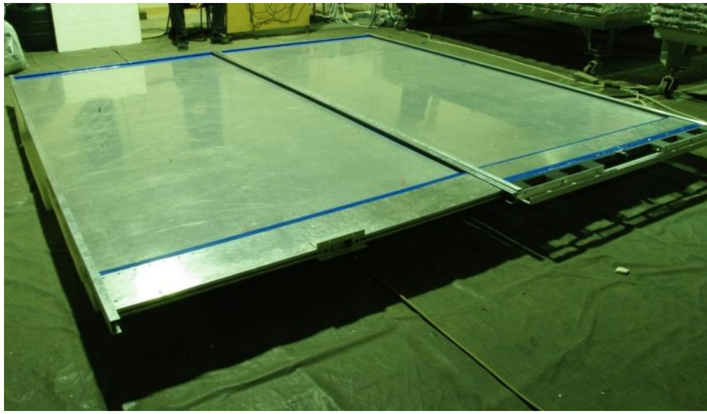
About 20-60 γ-events from Crab are expected during 100 h of observation.

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 → 2 10^3 m^2 area.**

TAIGA Collaboratipn

Germany

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

ITALY

Torino University

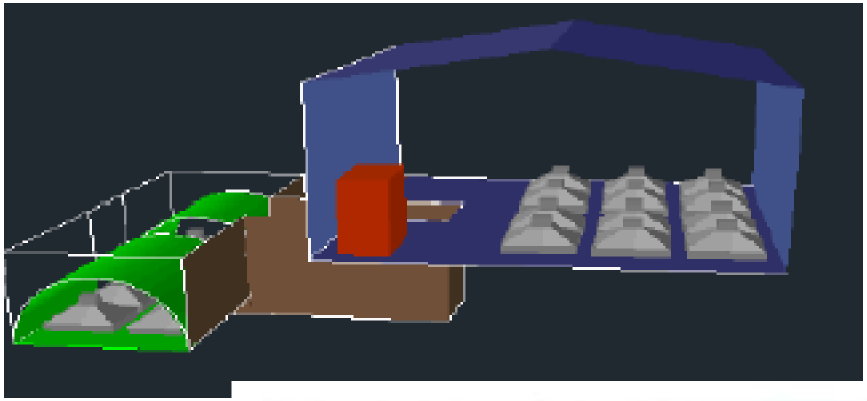
Russia

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

Tunka-REX

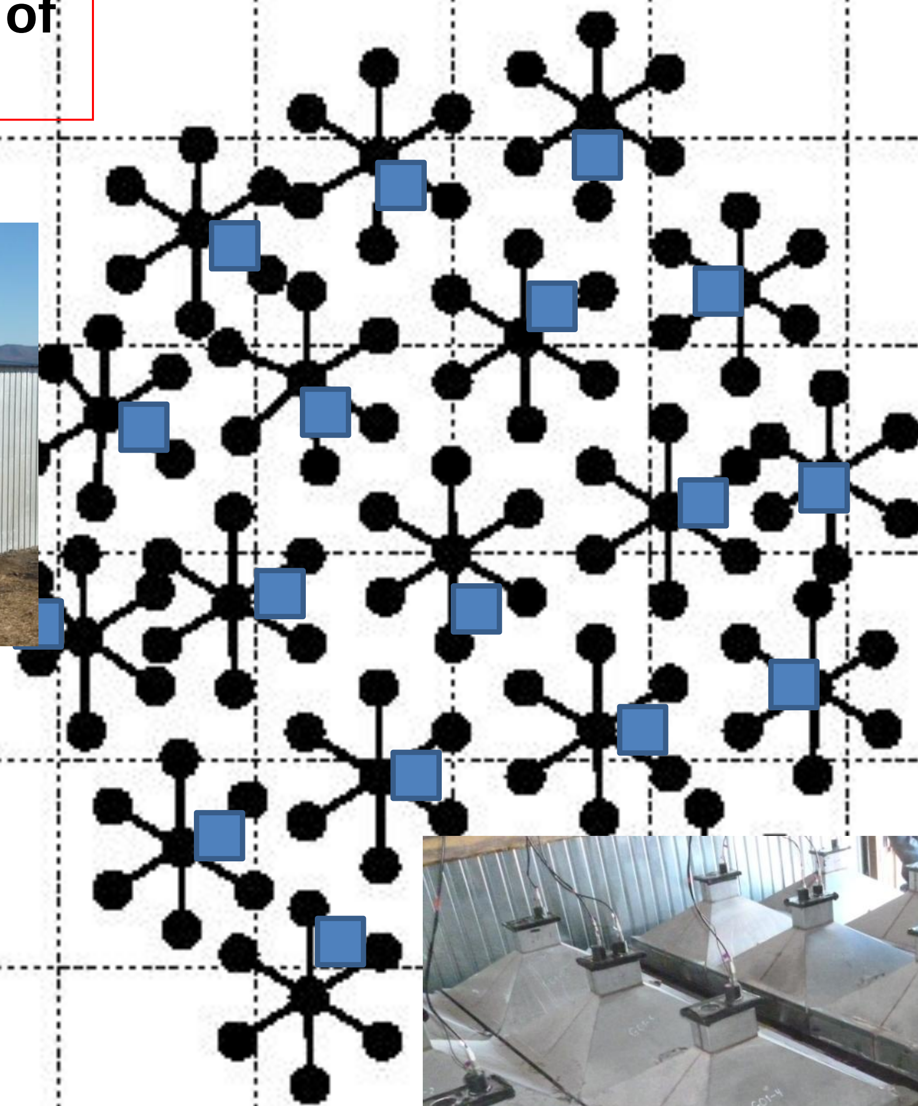
Connection of 2 antennas to 2 free channel of FADC

Tunka-Grande:
Transportation of SD to Tunka Valley



Tunka-Grande:
The first muon detector

Scintillation stations of Tunka-Grande



19 stations

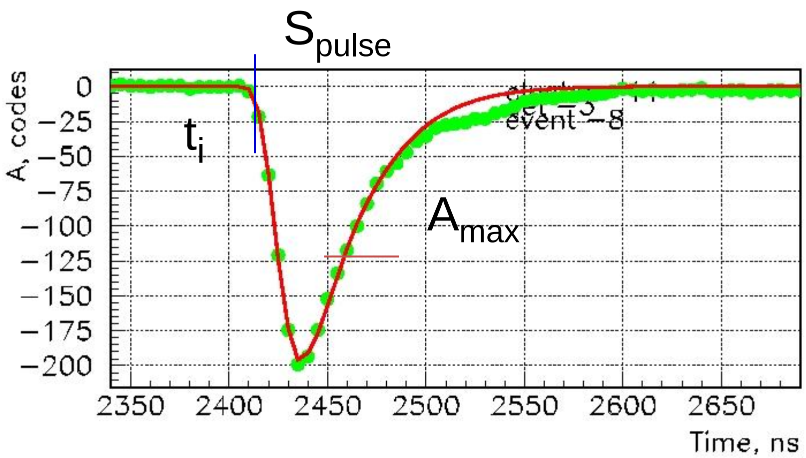
228 detectors (0.64 m^2) on the surface

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

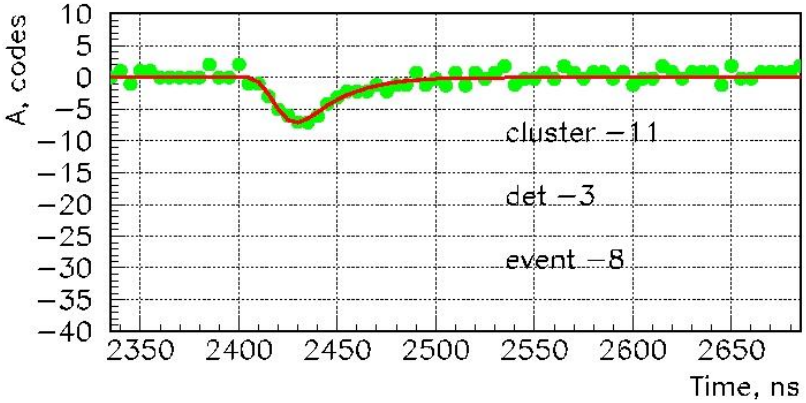
Single detector readout:
Fitting of a pulse and measuring of the parameters: $Q=c\cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

Time step = 5 ns

anode:

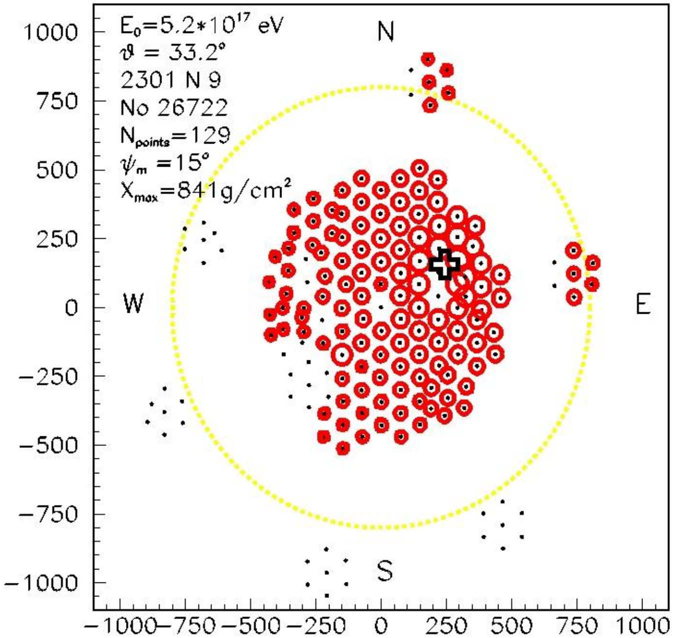


dinode:

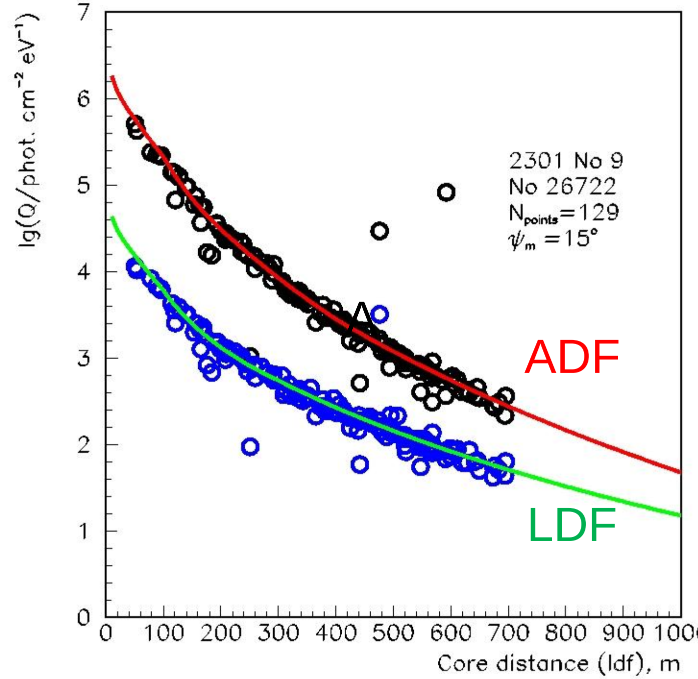


Single event example

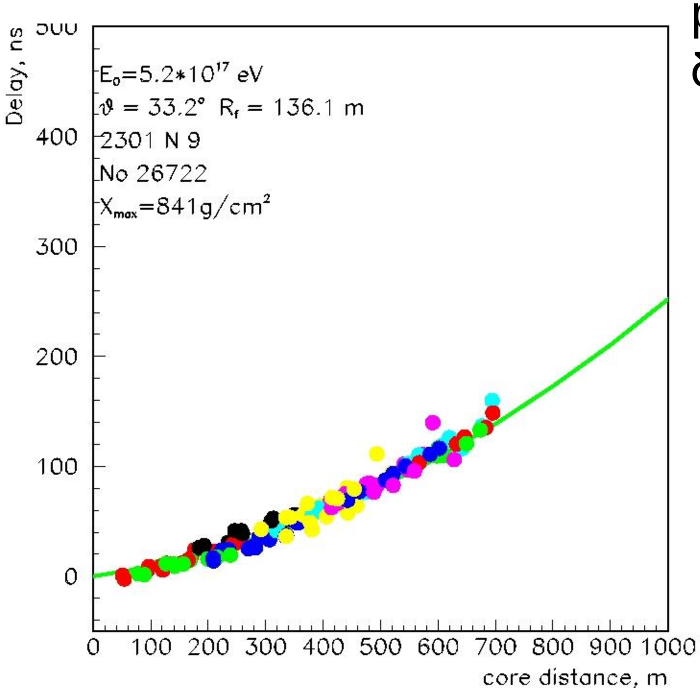
Plan



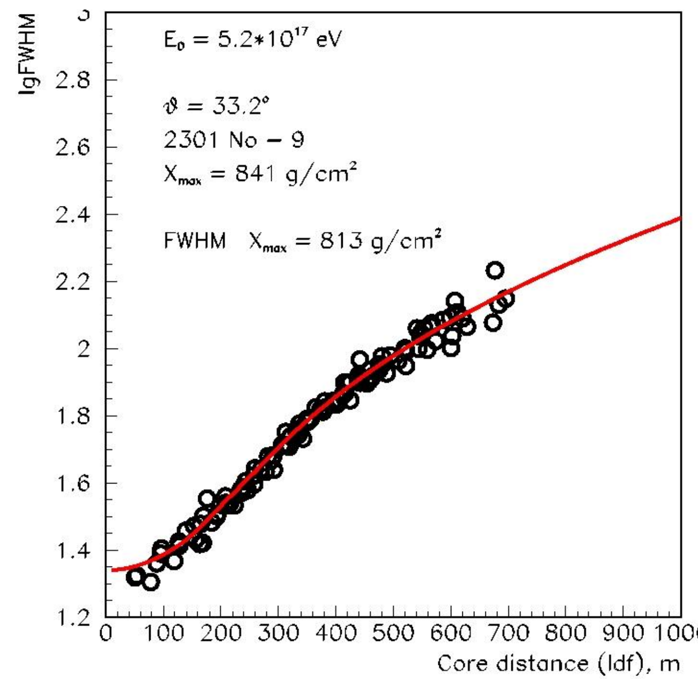
ADF
and
LDF



Curve
EAS time front
provides
$\delta\theta<0.5°$



τ_{eff} vs. core distance



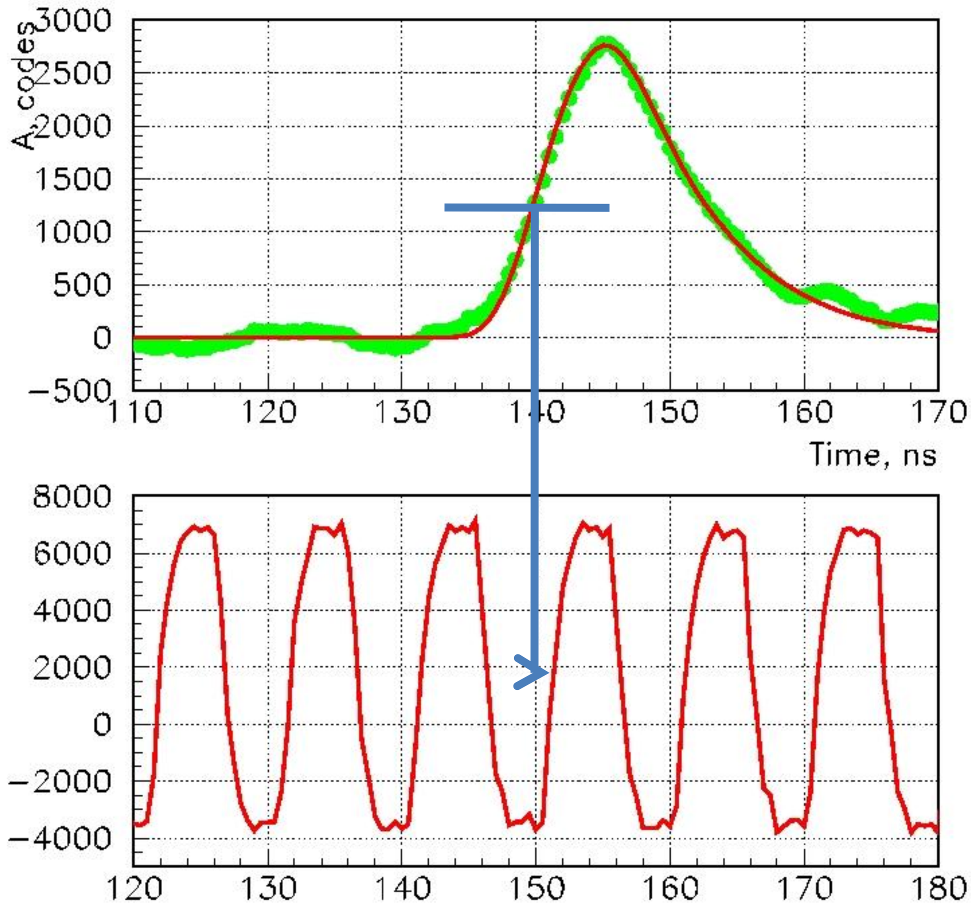
Tunka-HiSCORE record (DRS-4): parameters: $Q=c\cdot S_{pulse}$, A_{max}, t_i , $\tau_{eff}=S/A/1.24$

Time step = 0.5 ns

Cerenkov light pulse record

Delay measurement accuracy = 0.2 ns

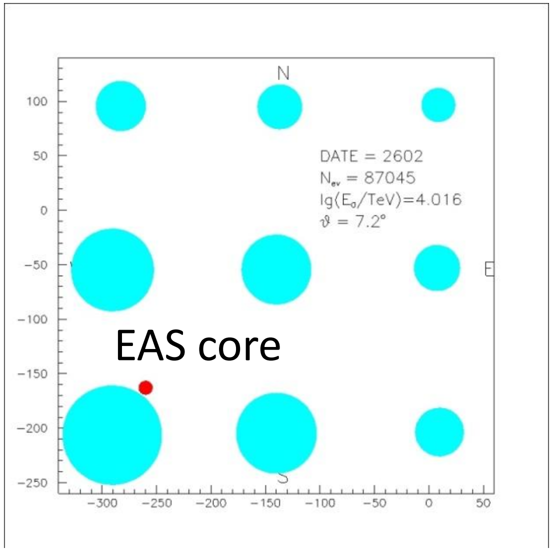
Clock signal 100 MHz

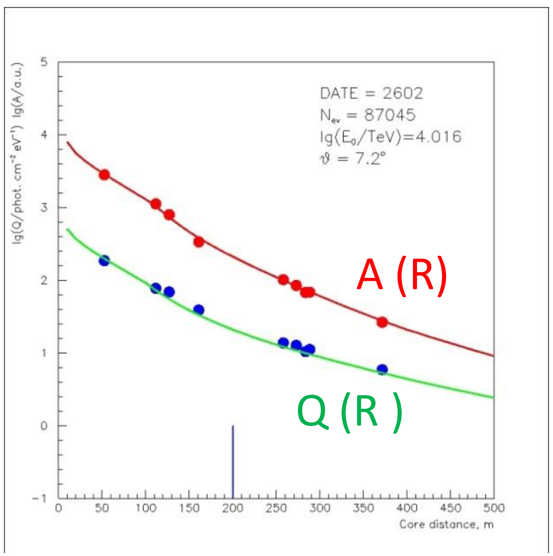


Tunka-HiSCORE event example

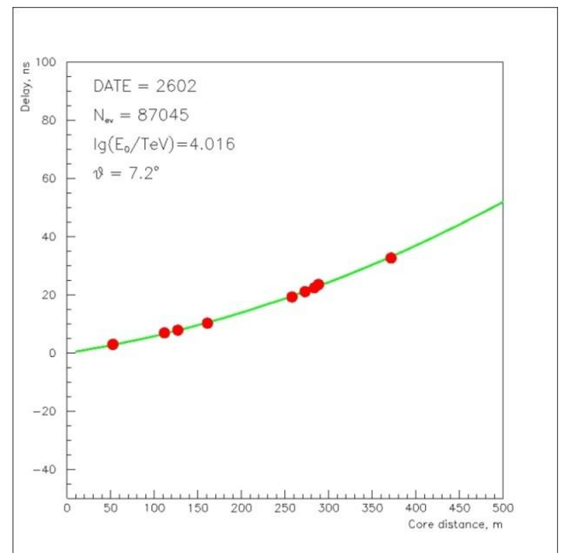
Zenith angle = 7.2°

Energy = 10^{16} eV





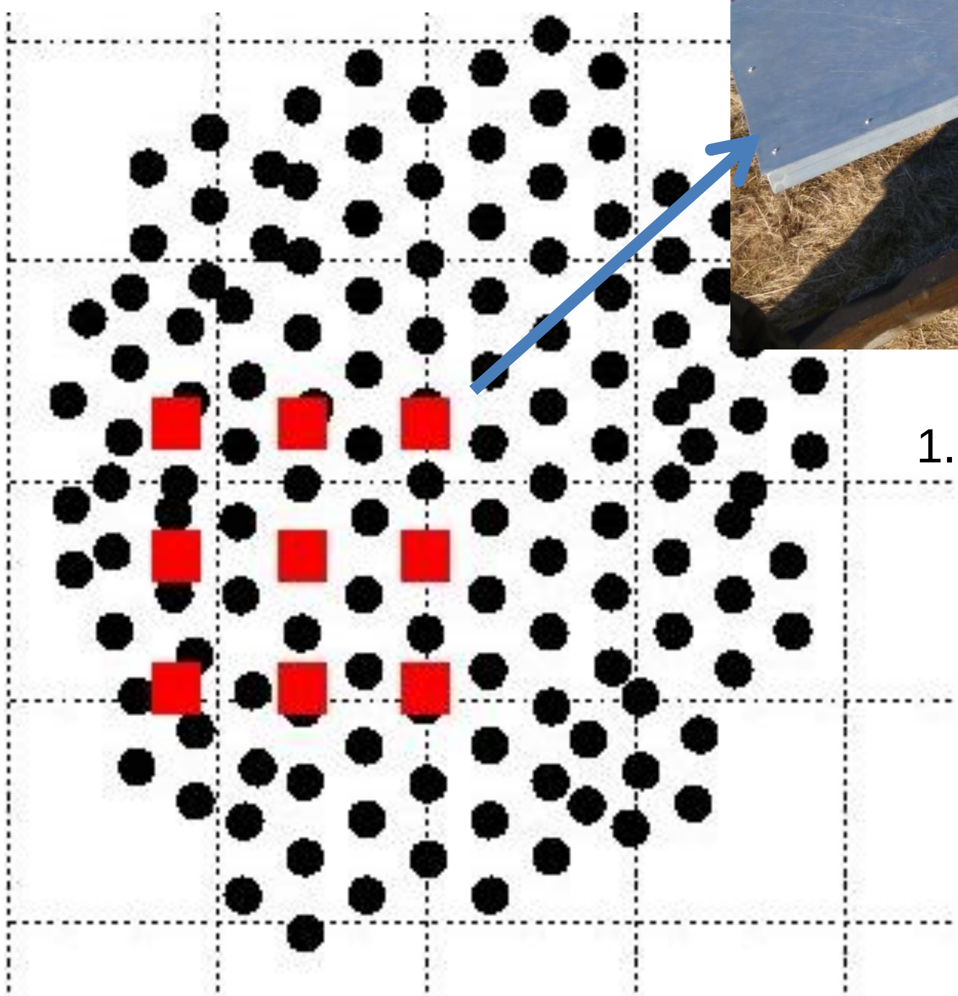
Shower front



EAS parameters accuracy: experimental estimations

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

Tunka-HiSCORE prototype
9 optical stations

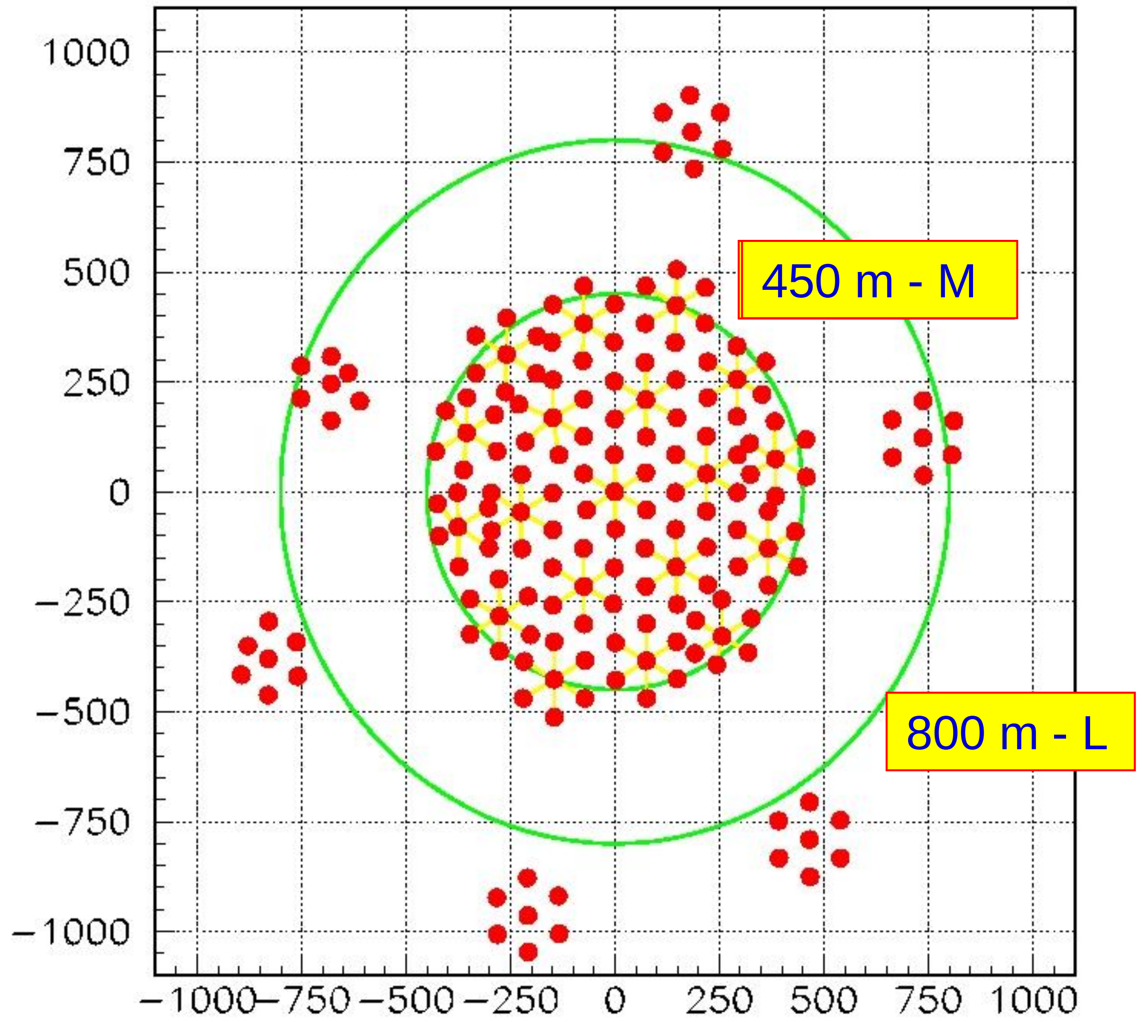


1. **Comparison of Tunka-133 and HiSCORE results –**

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
$\log E_0$ difference –
$\Delta \lg E_0 < 0.051$ (12%)

Effective areas



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 two 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:
$\theta \leq 45°$

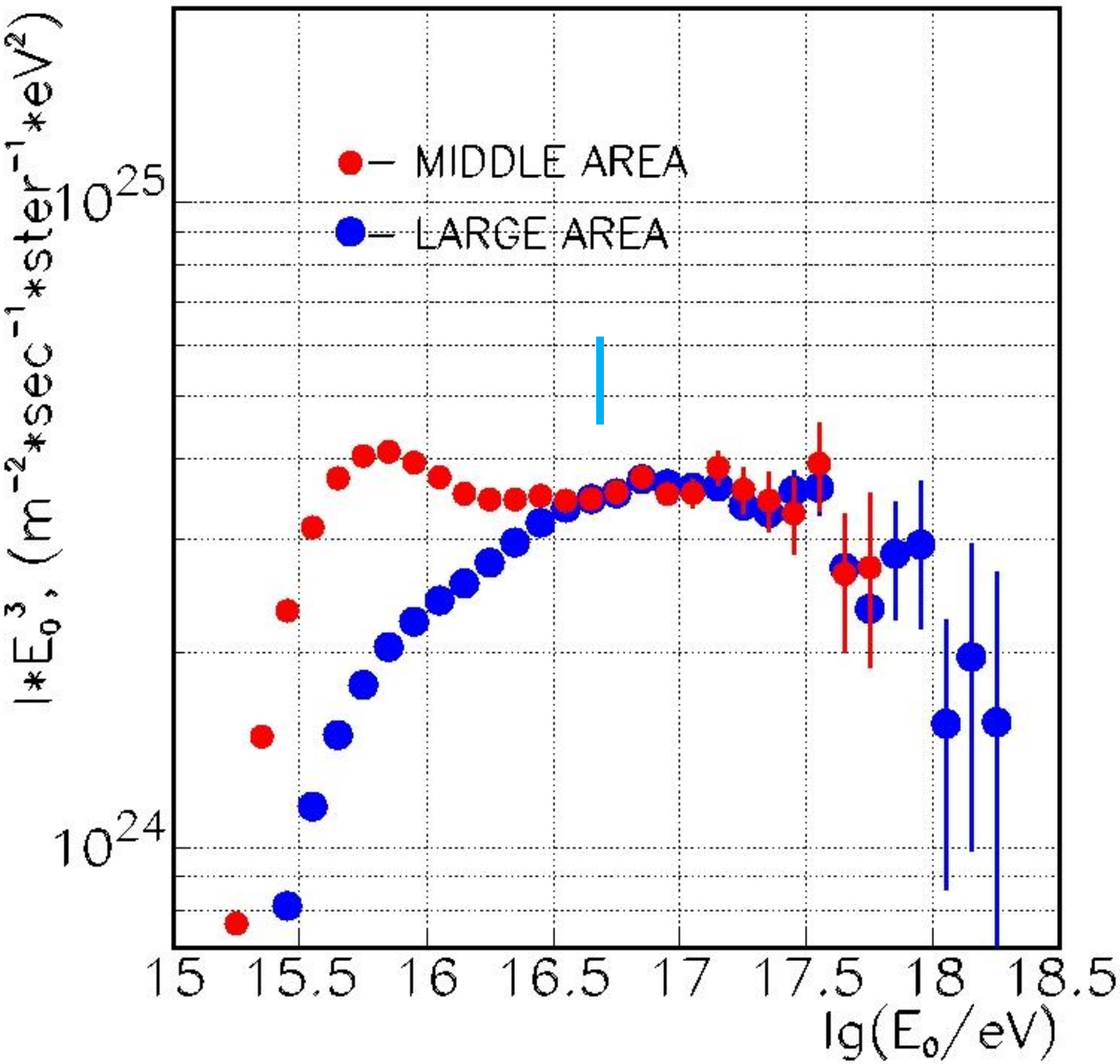
M: $R_{center} < 450$ m:

~ 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

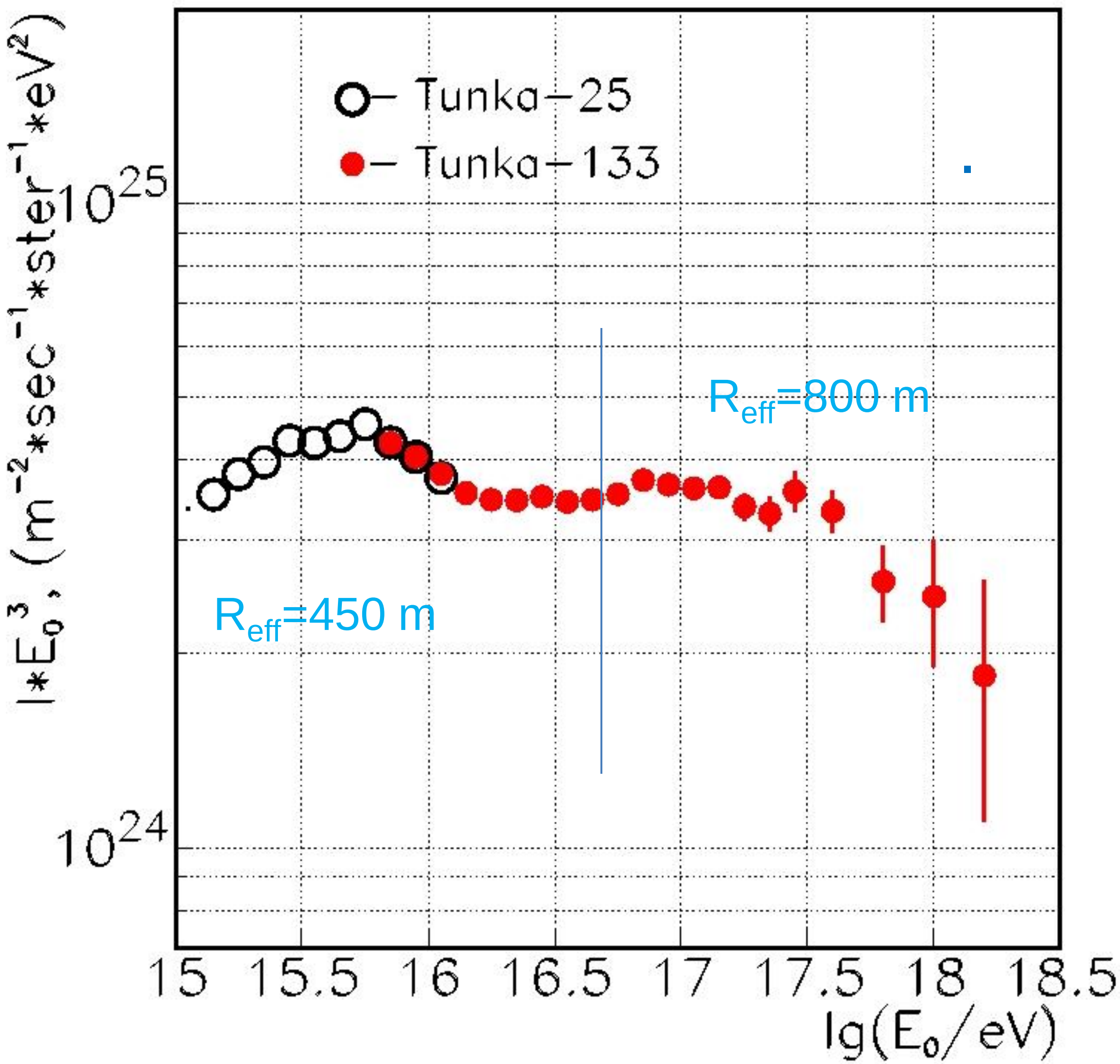
L: $R_{center} < 800$ m:

~ 12400 events $E_0 > 5 \cdot 10^{16}$ eV
~ 3000 events $E_0 > 10^{17}$ eV

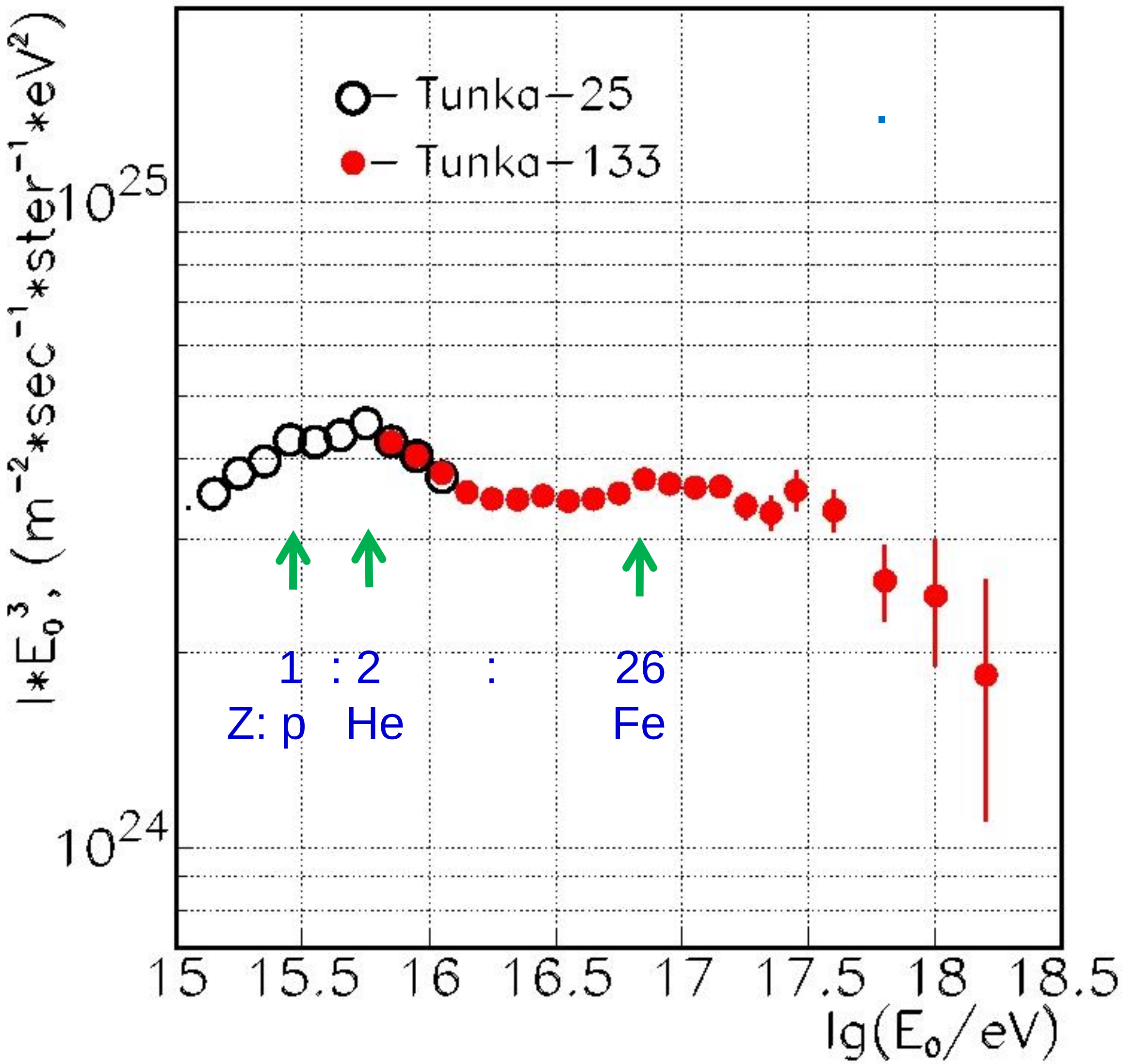
Combined energy spectrum construction



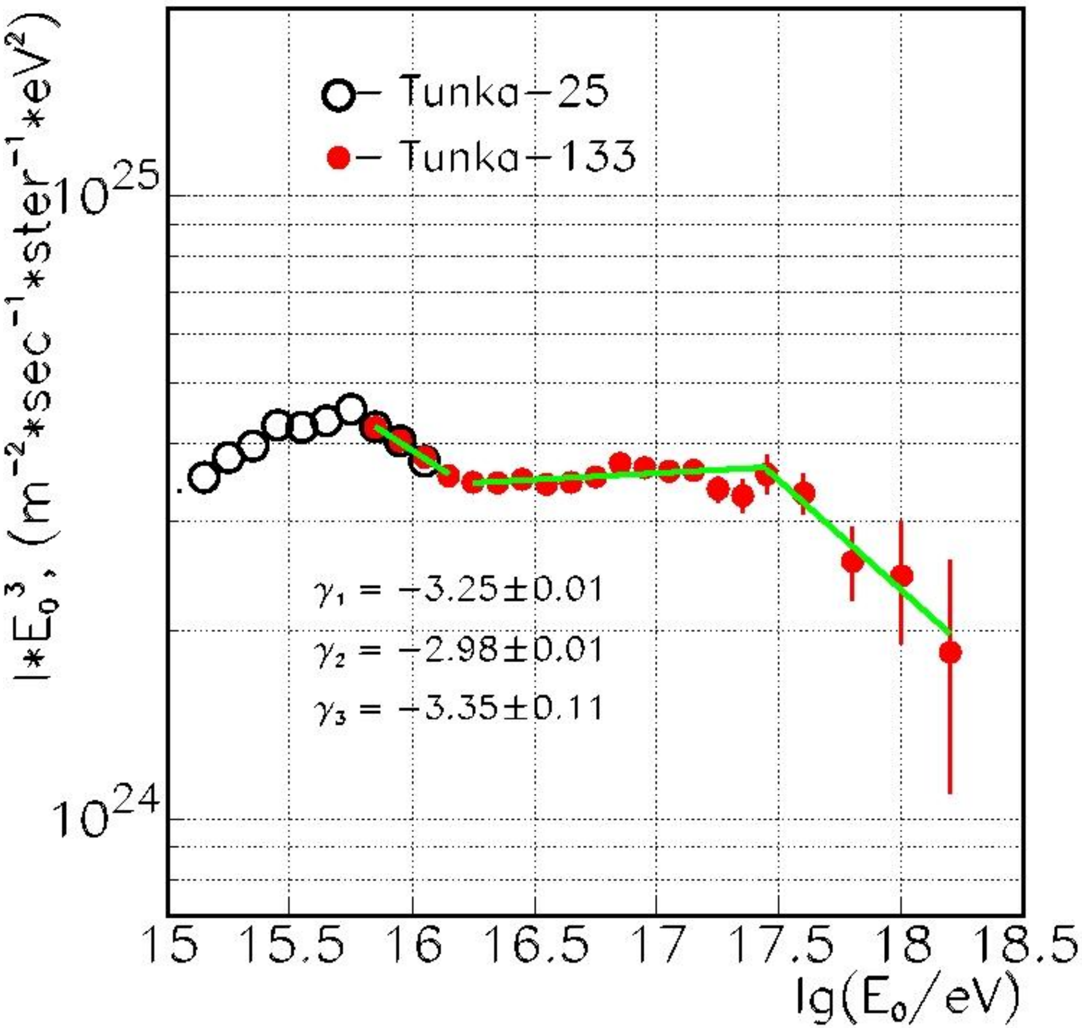
Combined differential primary energy spectrum



Energy spectrum: Sharp features reflecting the termination energy for different elemental groups



Energy spectrum: power law fitting



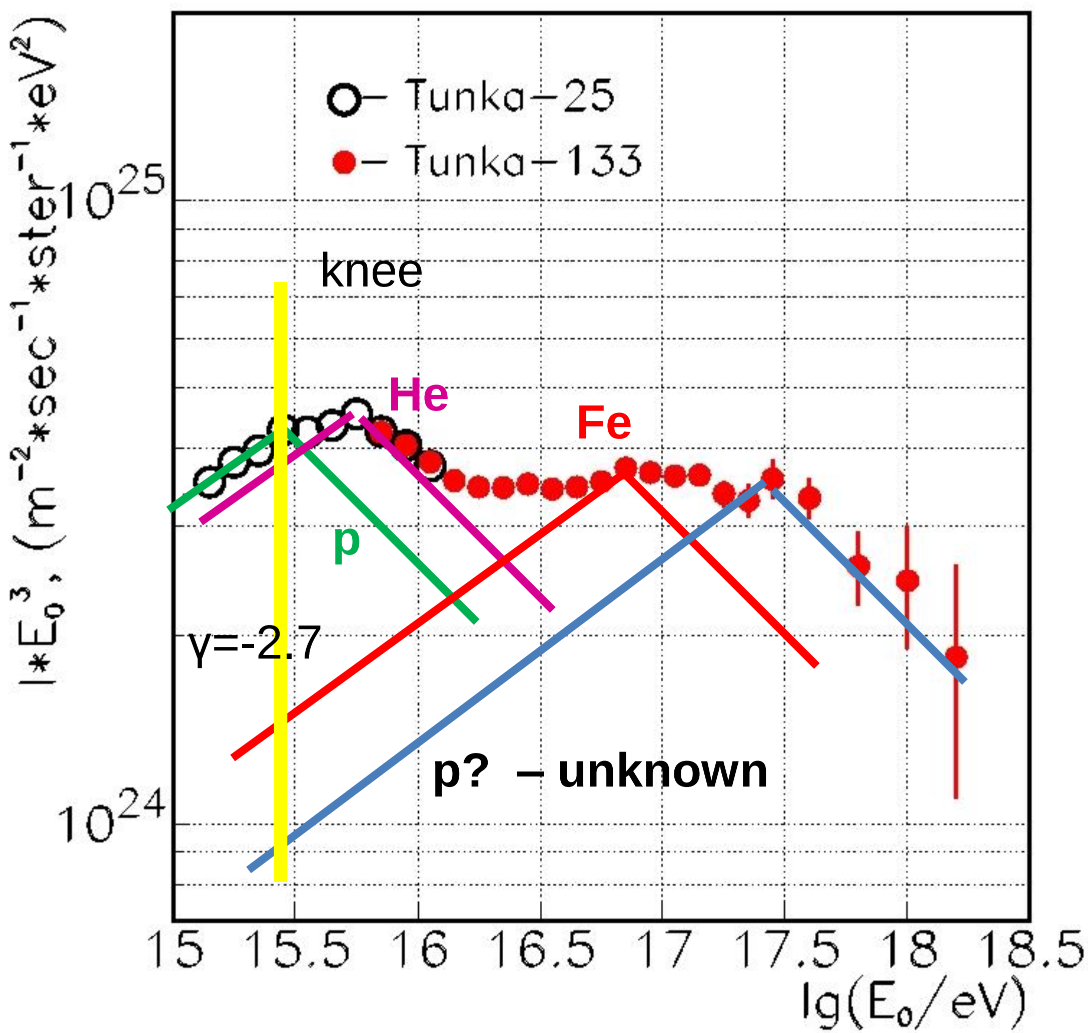
One can see two sharp features at the energies:

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

and ~$3\cdot10^{17}$ (similar to that, announced by 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.

Energy spectrum: Primitive composition analysis in the knee.



Assuming the similar spectra of all the components terminated at the energy $E_t = Z \cdot 3 \cdot 10^{15}$ eV one can estimate the composition at the knee energy:

p – 14%

He – 41% …

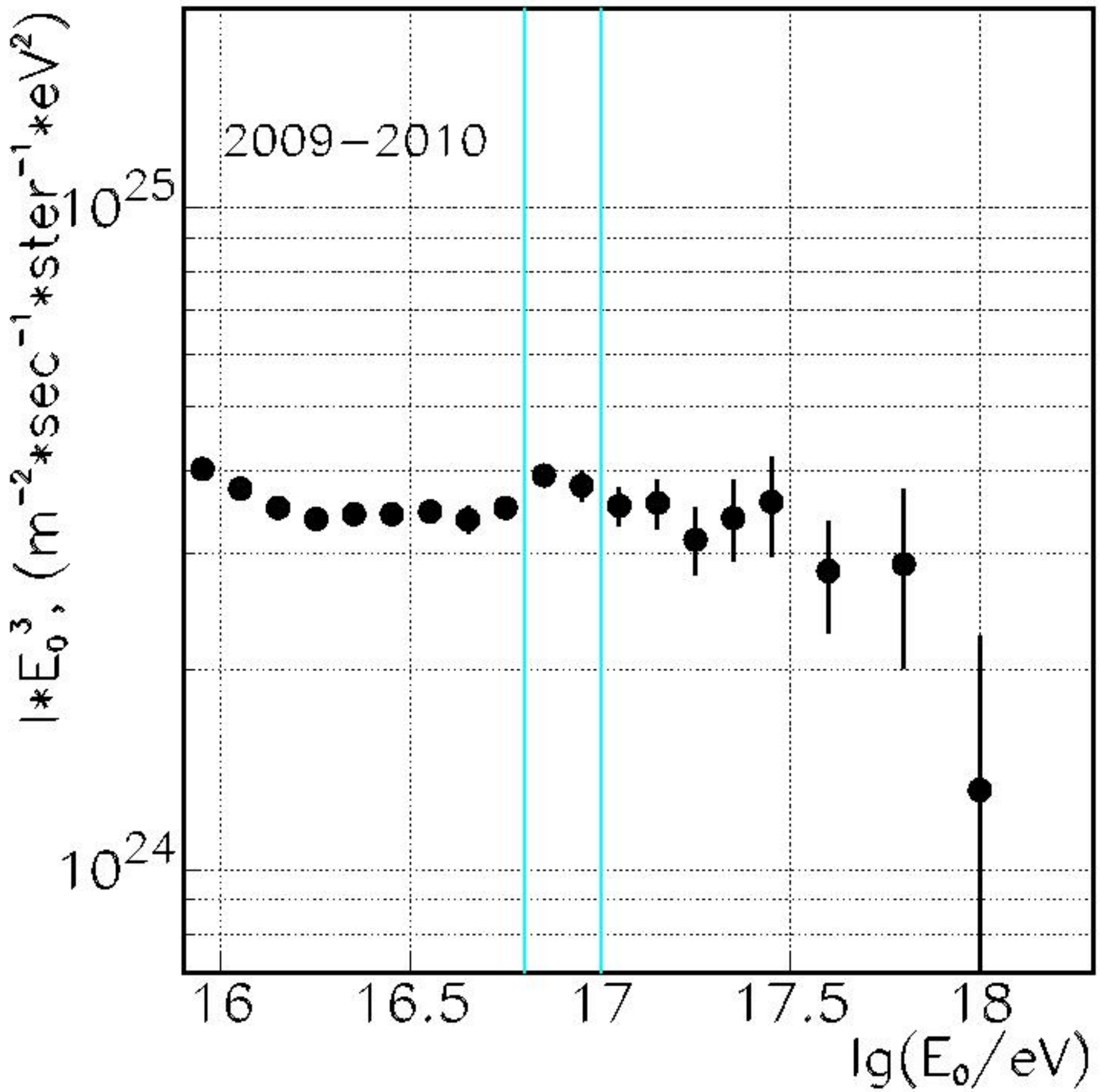
Fe – 12%

Unknown – 21%

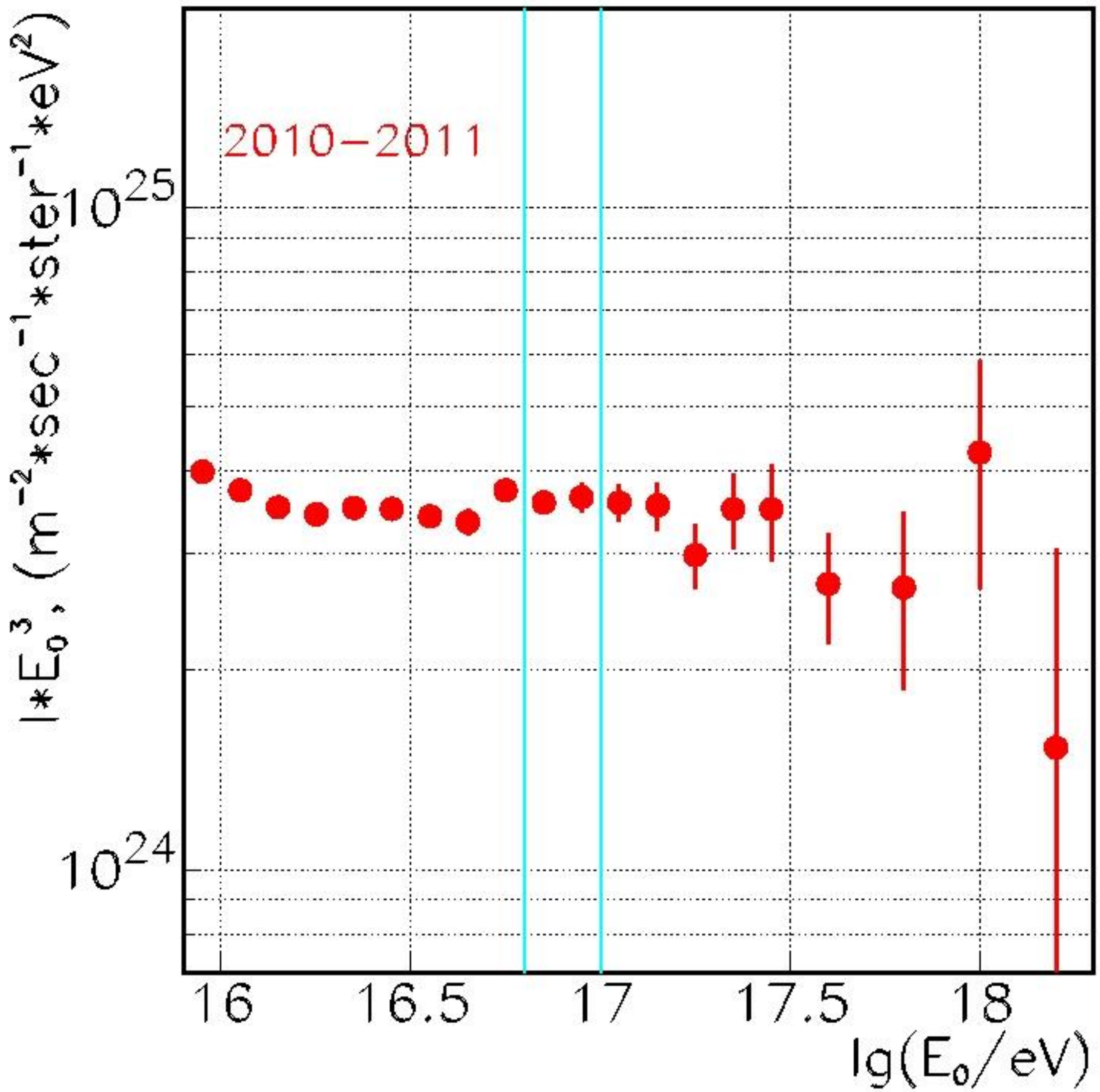
Conclusion:

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

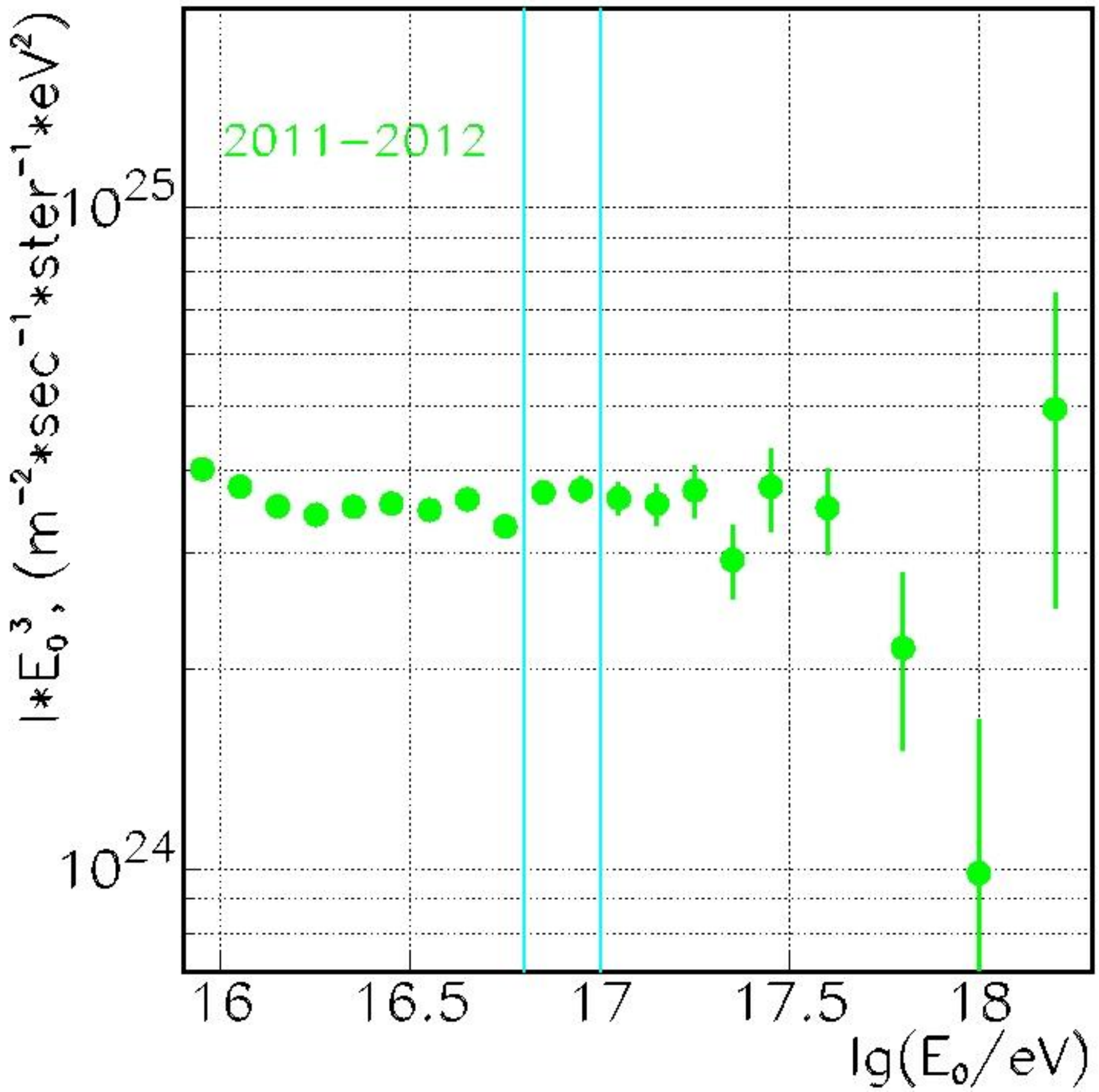
Single year spectrum



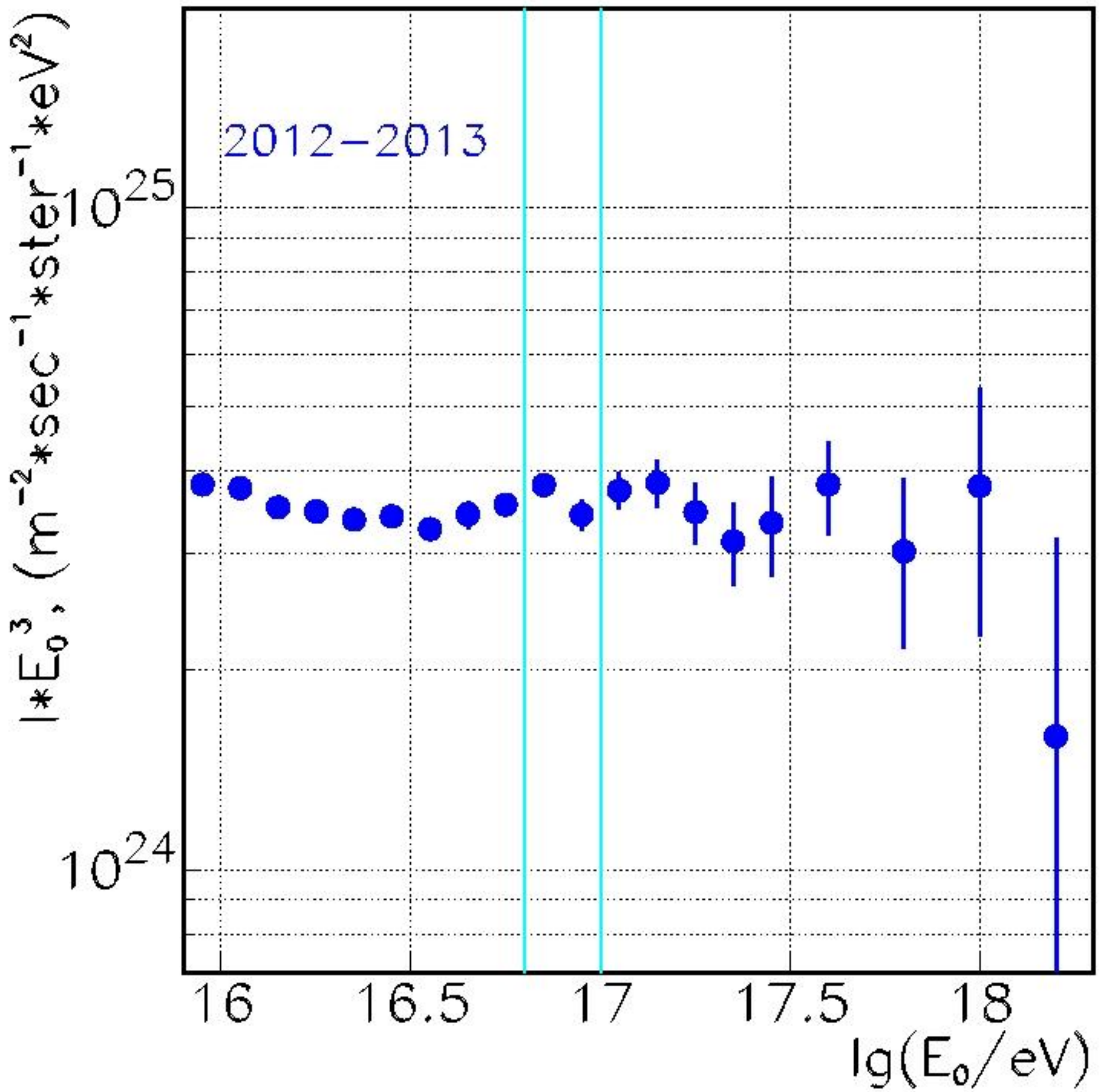
Single year spectrum



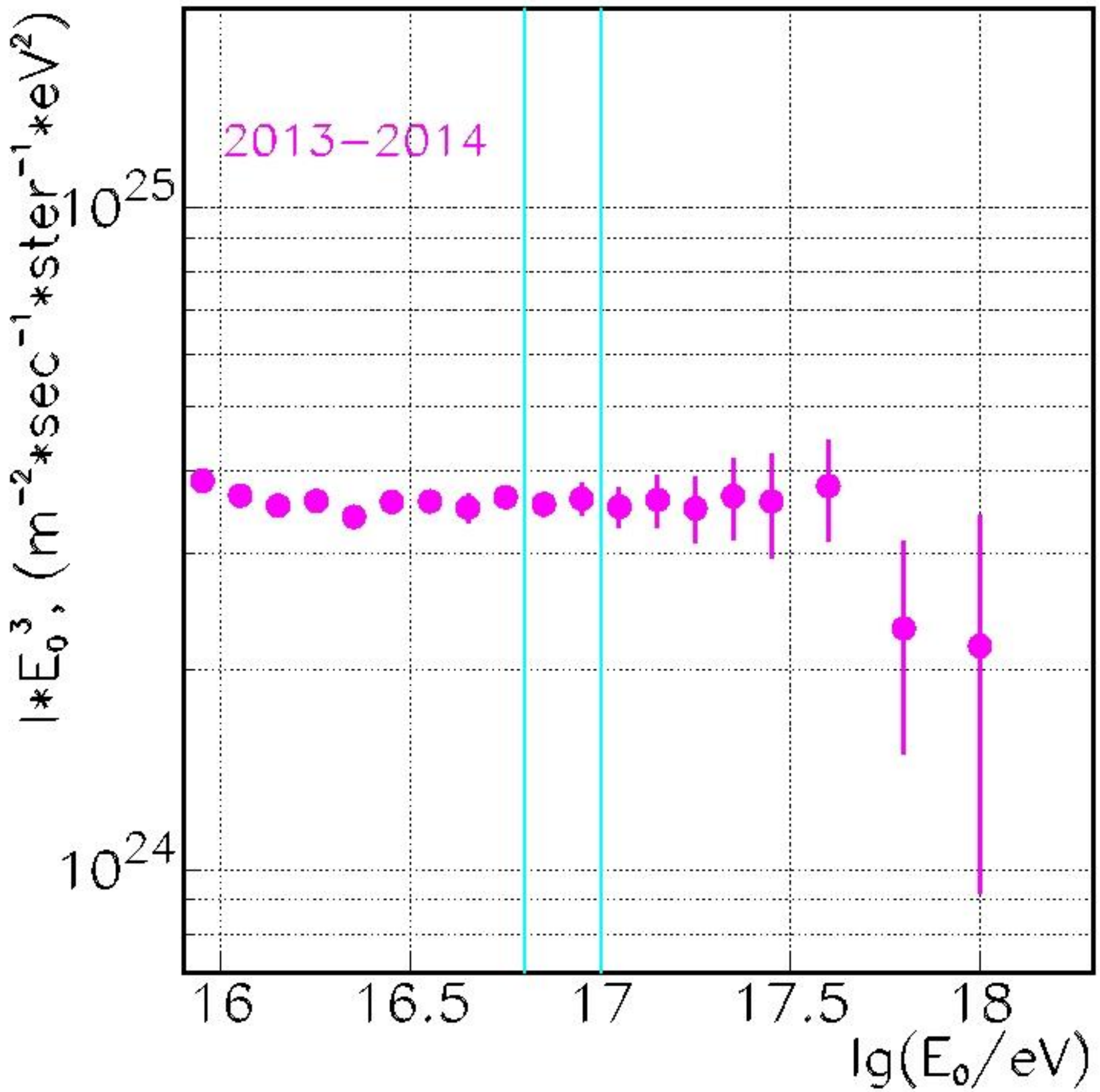
Single year spectrum



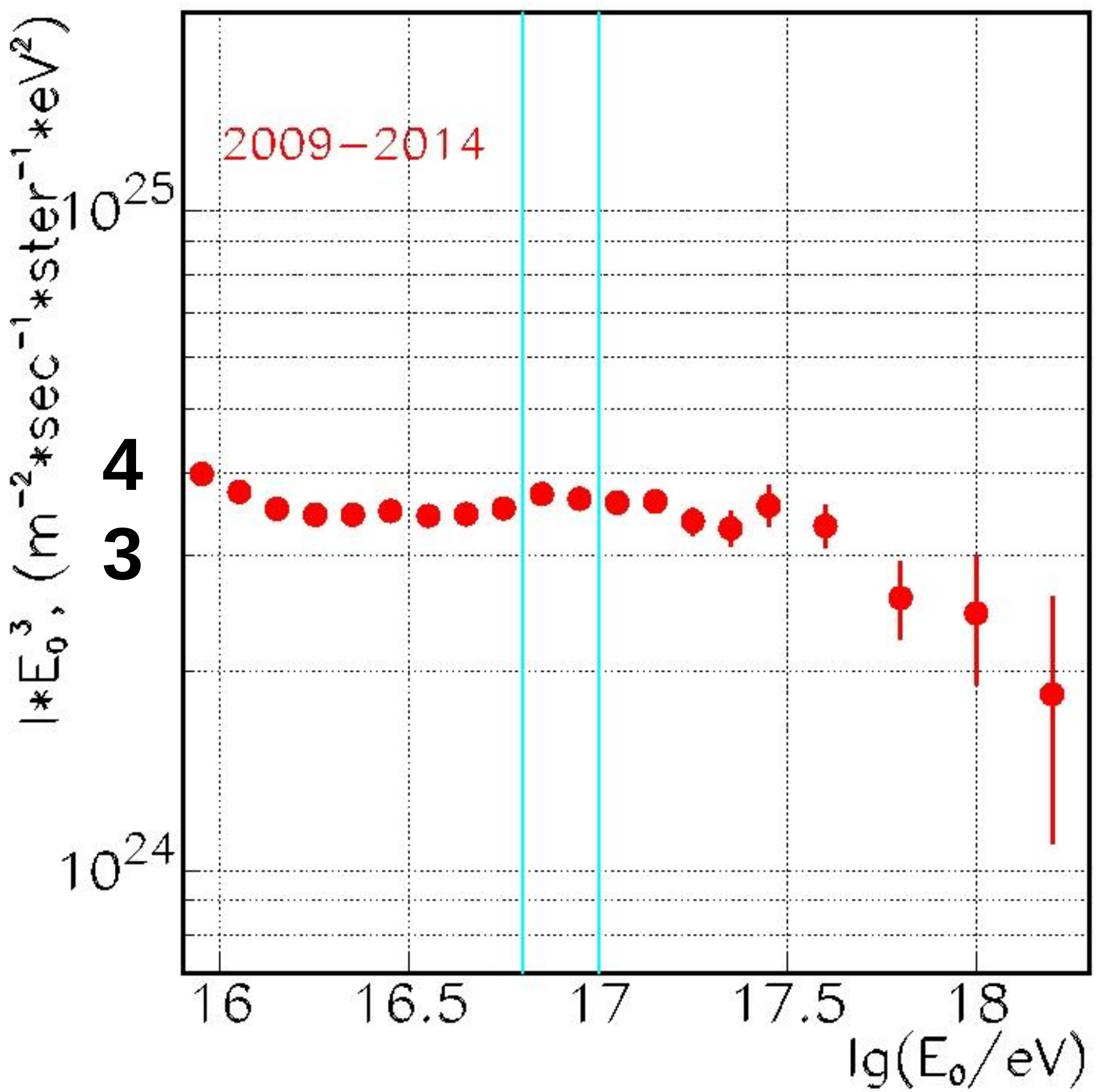
Single year spectrum



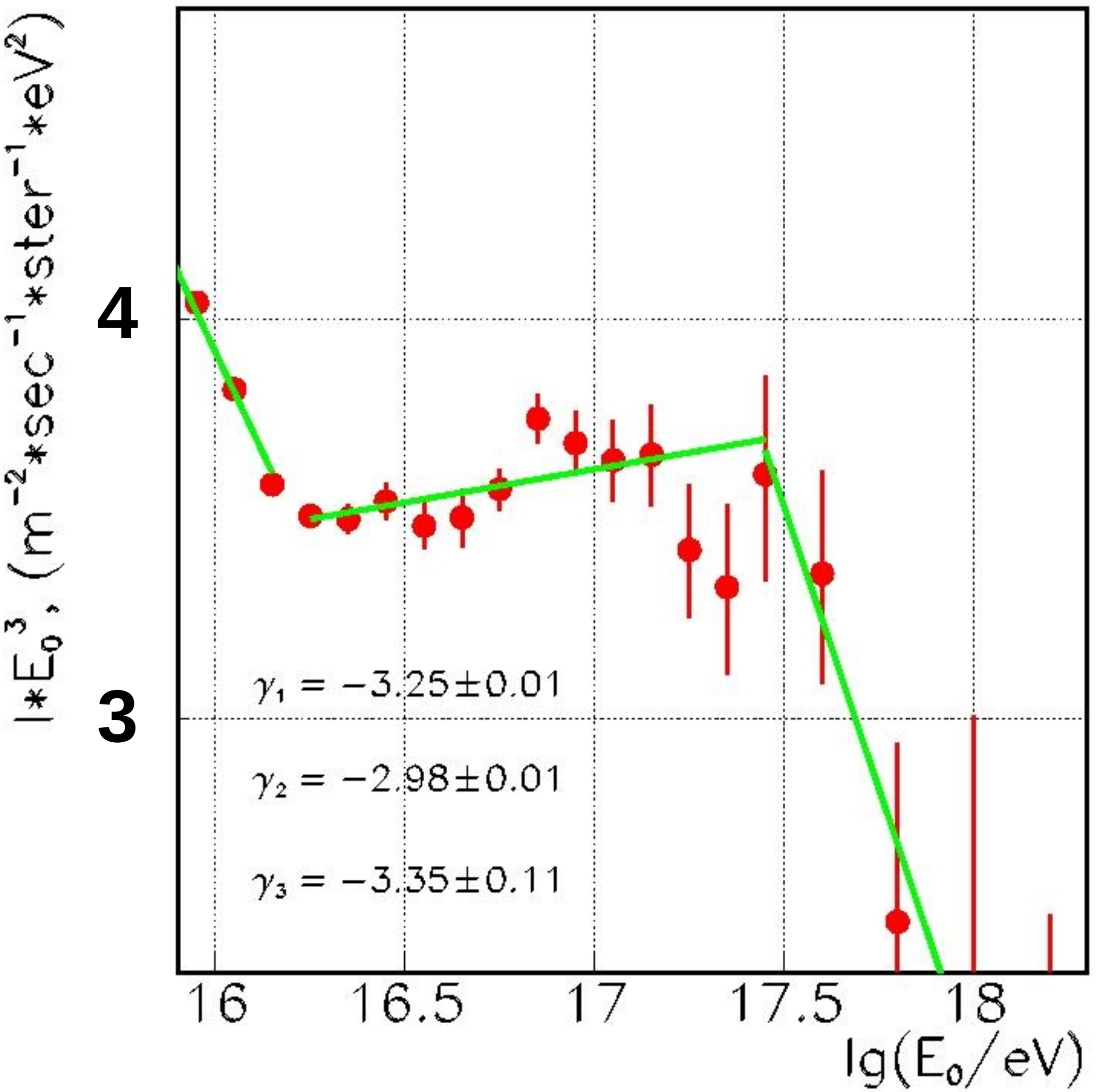
Single year spectrum



Five years summarized spectrum

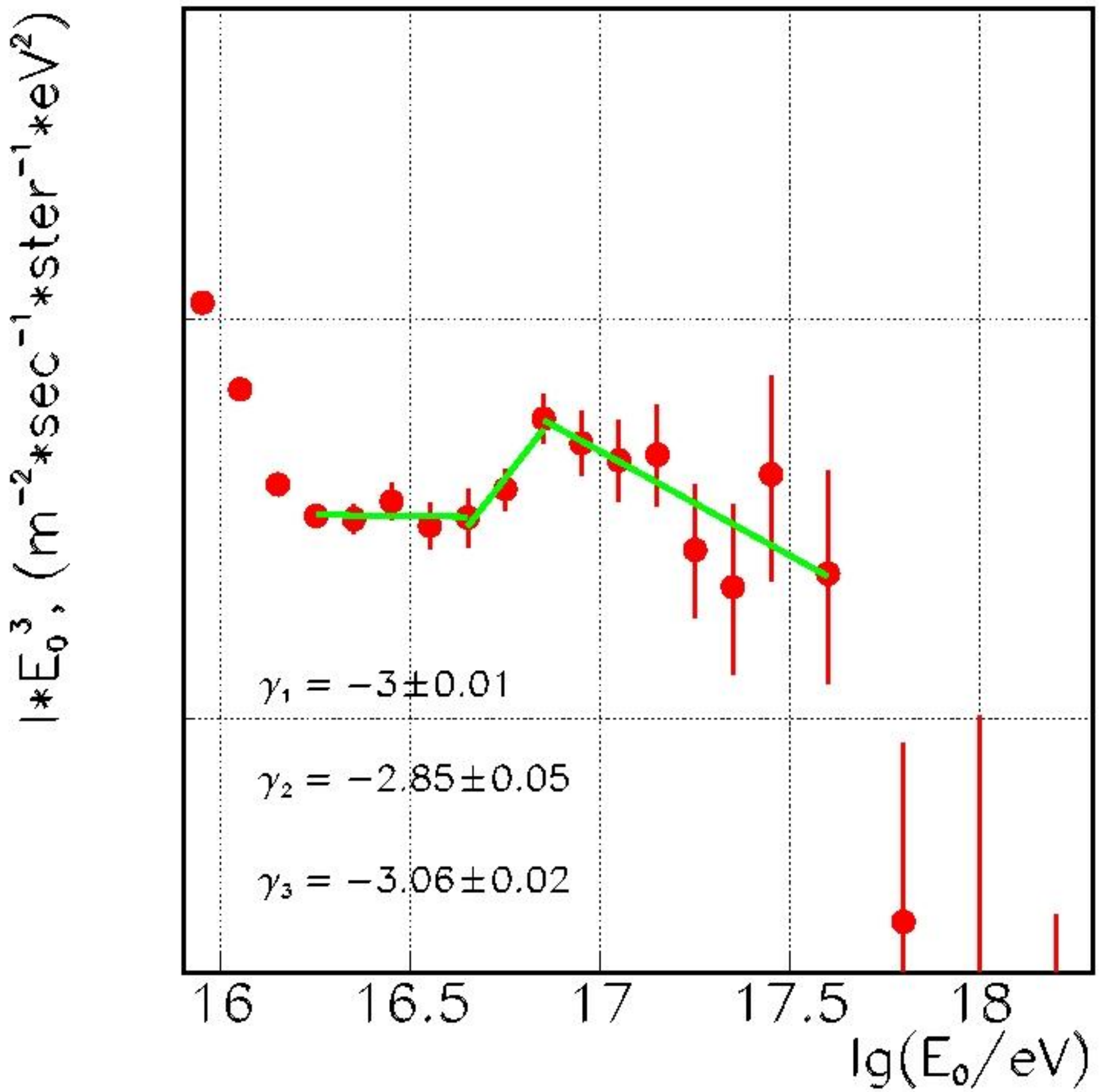


The same spectrum with expanded scale



Expanded scale

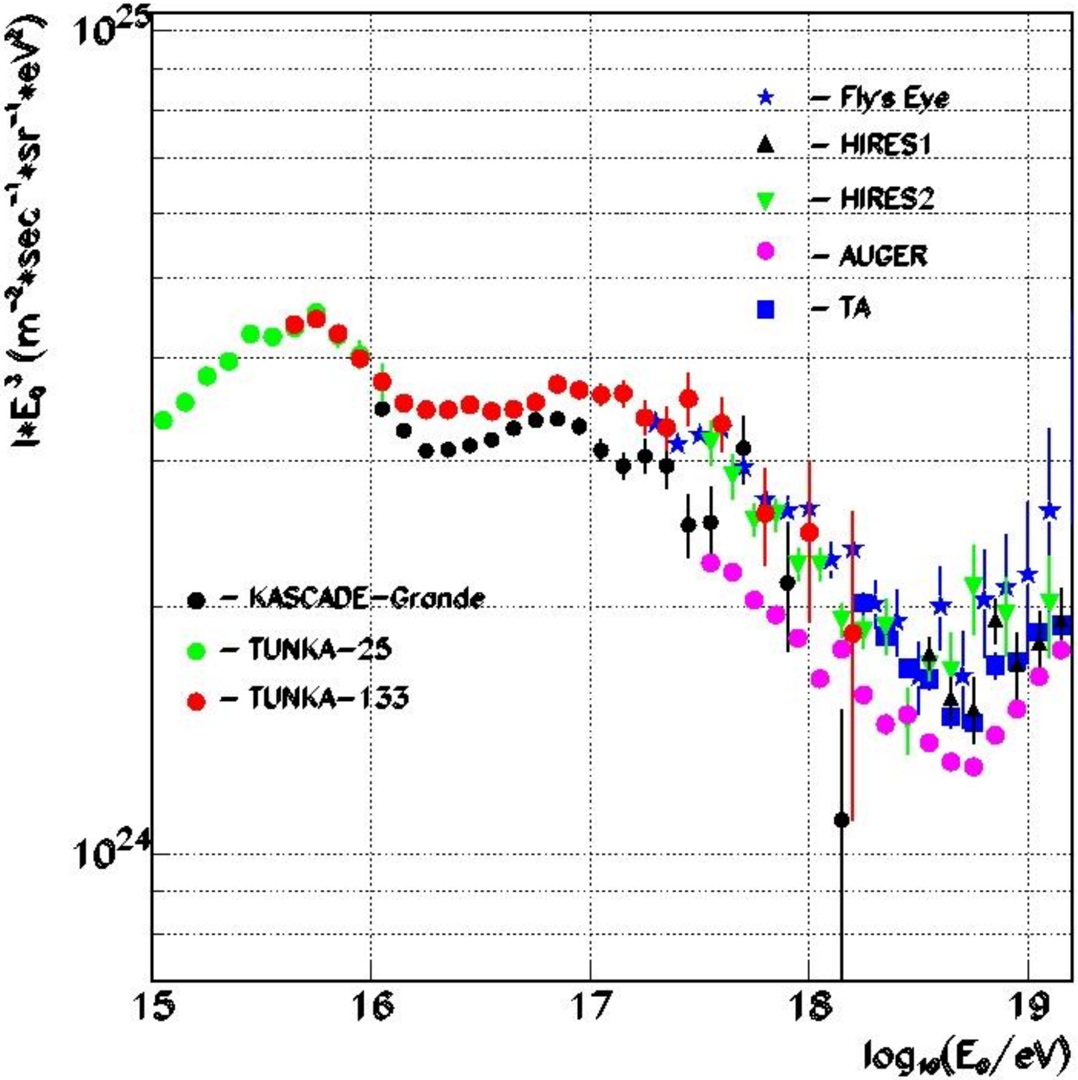
Possible interpretation – Structure of the "second" knee



To get much more data is the task for **Tunka-Grande SD** array.

The data taking rate will be **~10 times higher** than for Tunka-133

Combined spectrum: comparison with some other works



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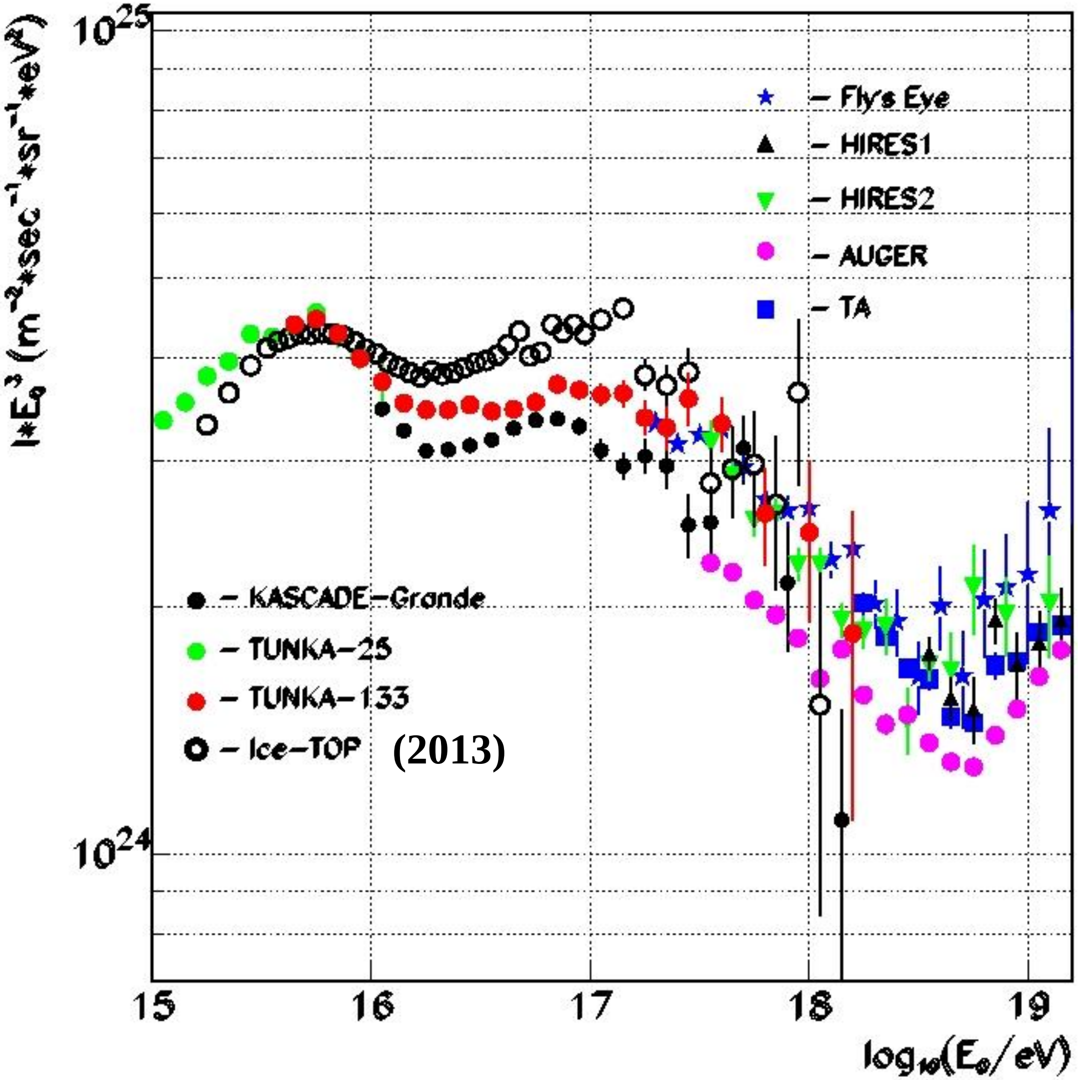
Agreement with KASCADE-Grande
Agreement with old Fly's Eye, HiRes and TA spectra.

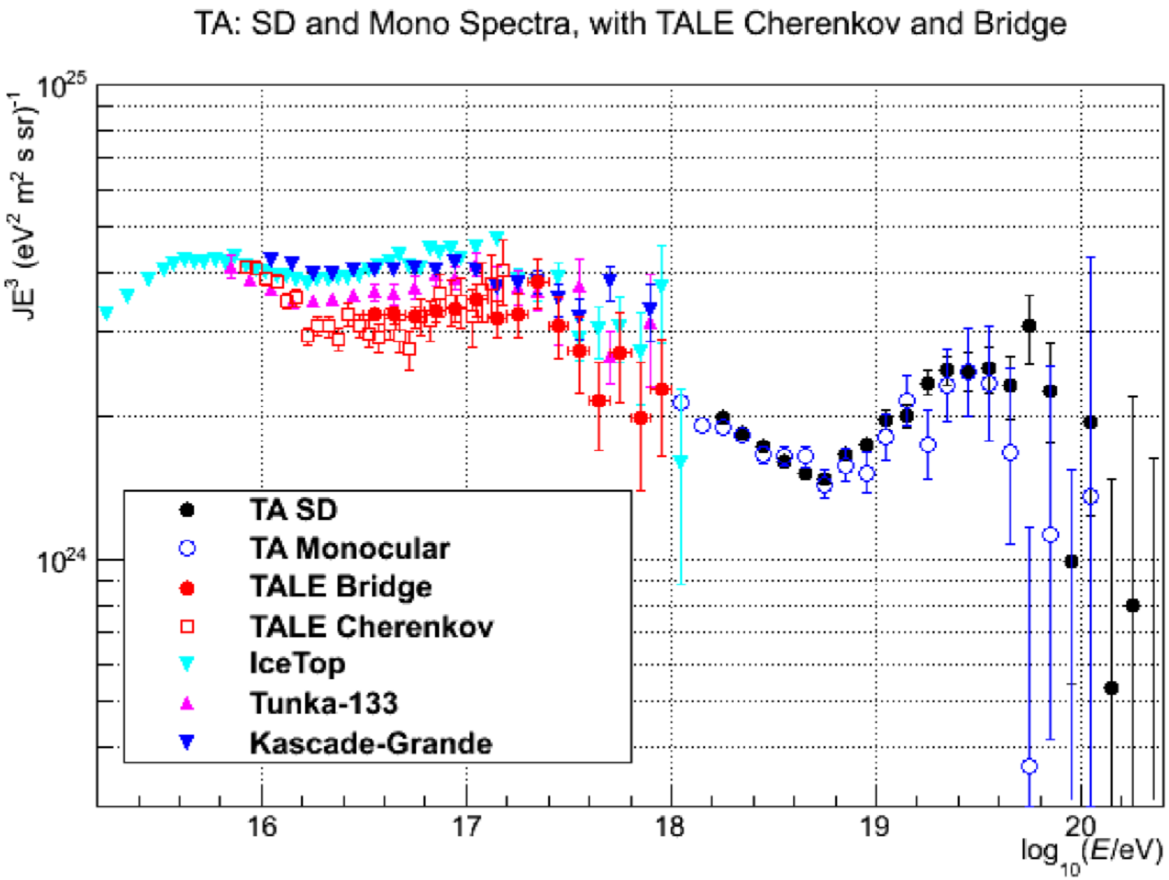
Combined spectrum: comparison with some other works



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

Agreement with Ice-TOP
Preliminary Ice-TOP (2014) points are closer to Tunka.

TA: TALE Cherenkov and Bridge
PRELIMINARY

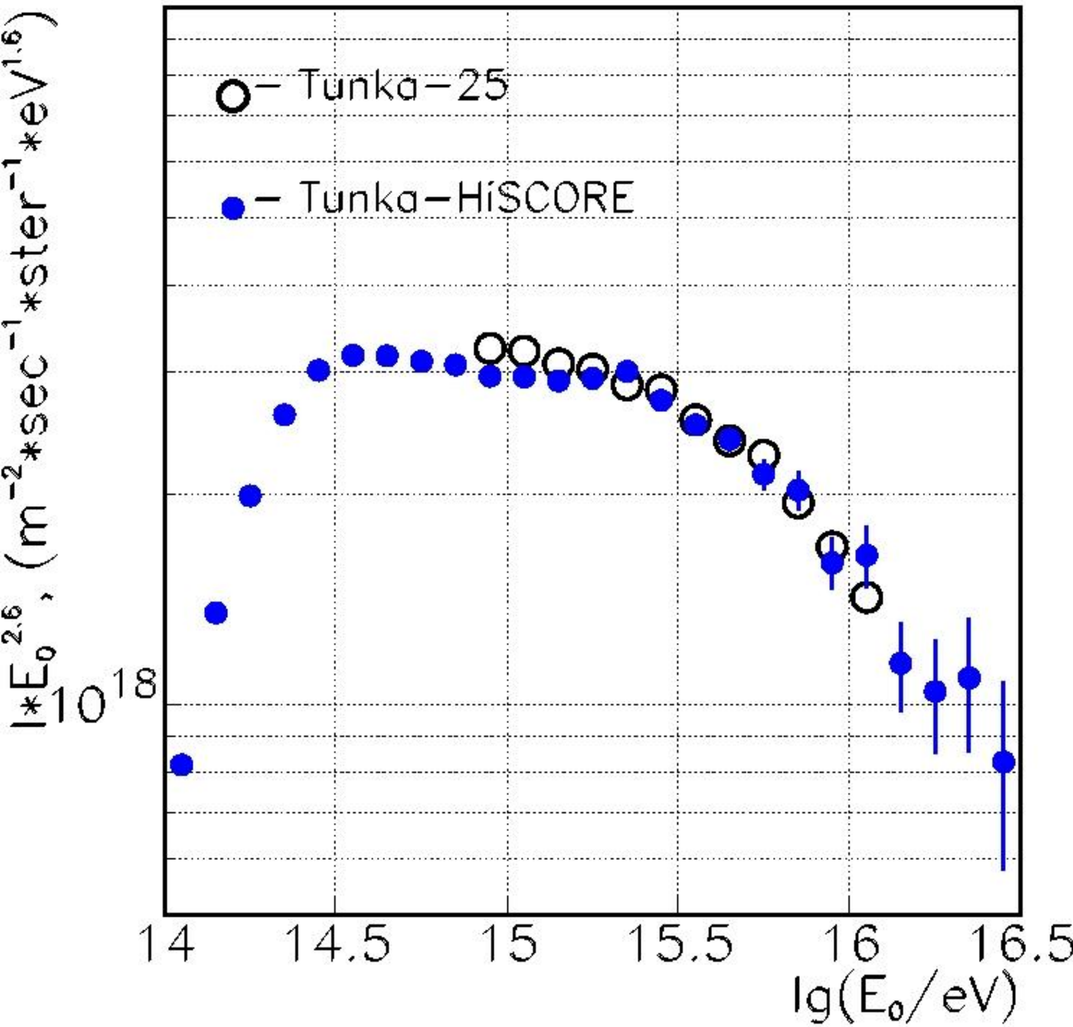


Tunka-HiSCORE:
as Expanding to the Lower Energy Range

We present here:
Processing of the Tunka-HiSCORE data with Tunka-133 algorithm only.

Special algorithms are designed now to decrease the energy threshold to about two times. They will be used later for gamma showers selection and reconstruction.

Tunka-HiSCORE:
All particle energy spectrum.
PRELIMINARY



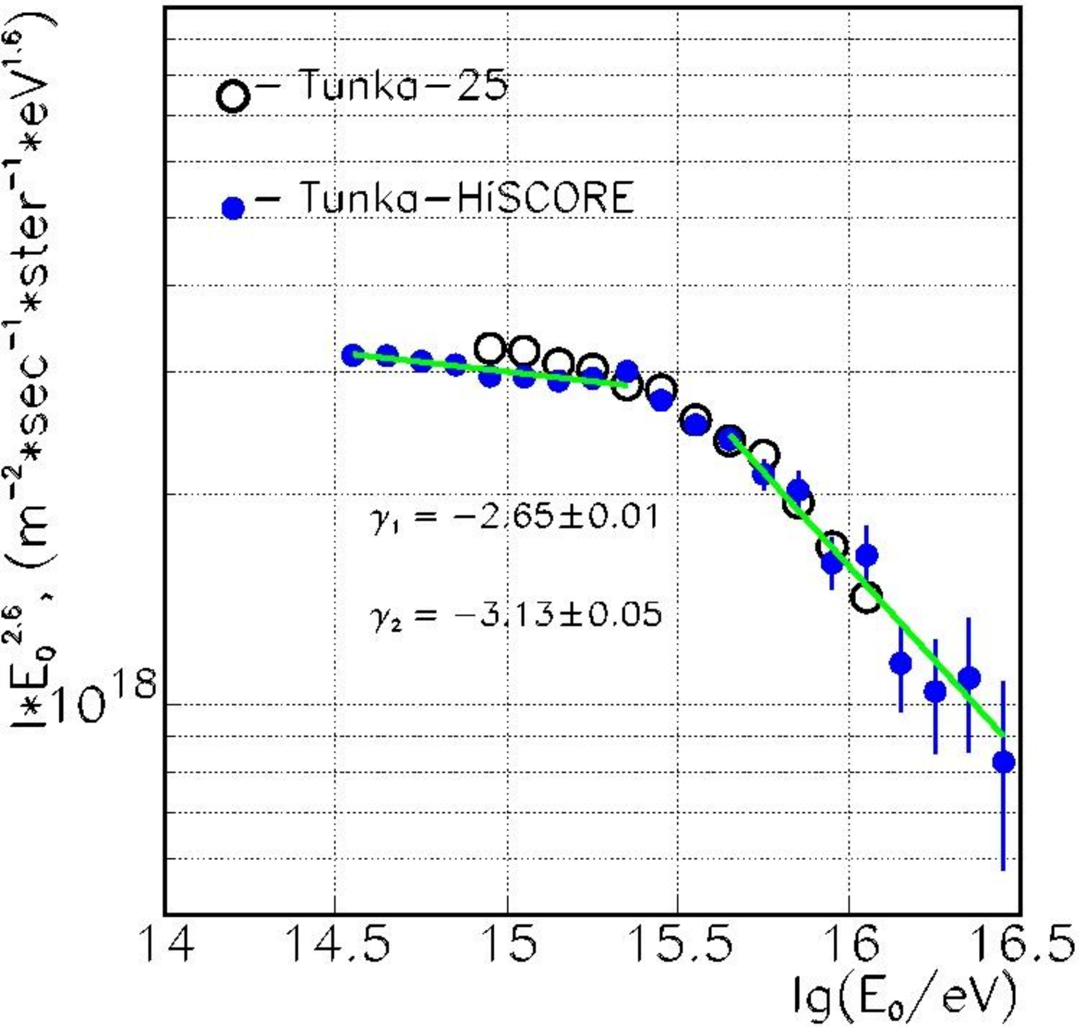
84 h during 13 clean moonless nights in February and March of 2014

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

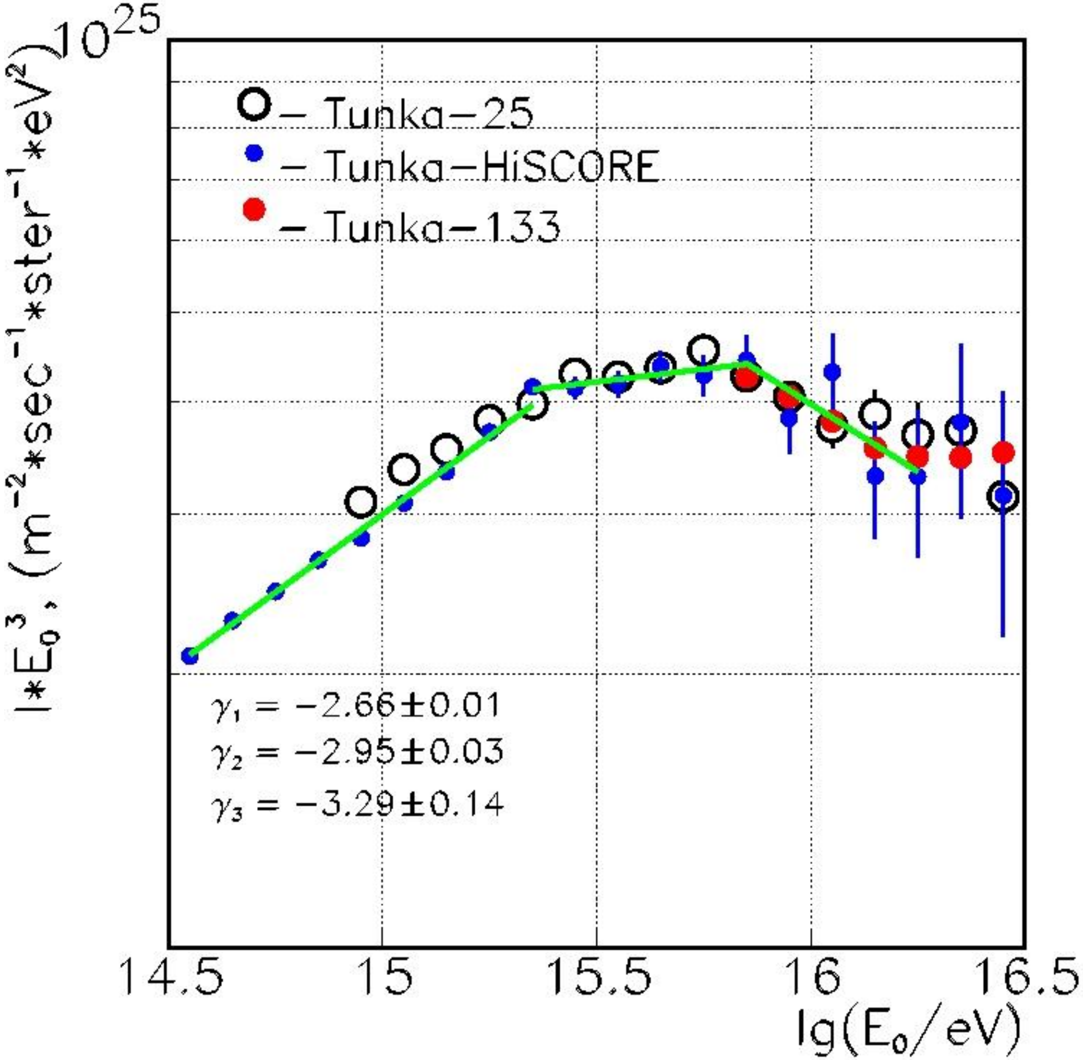
~ 21 000 events $E_0 > 10^{15}$ eV

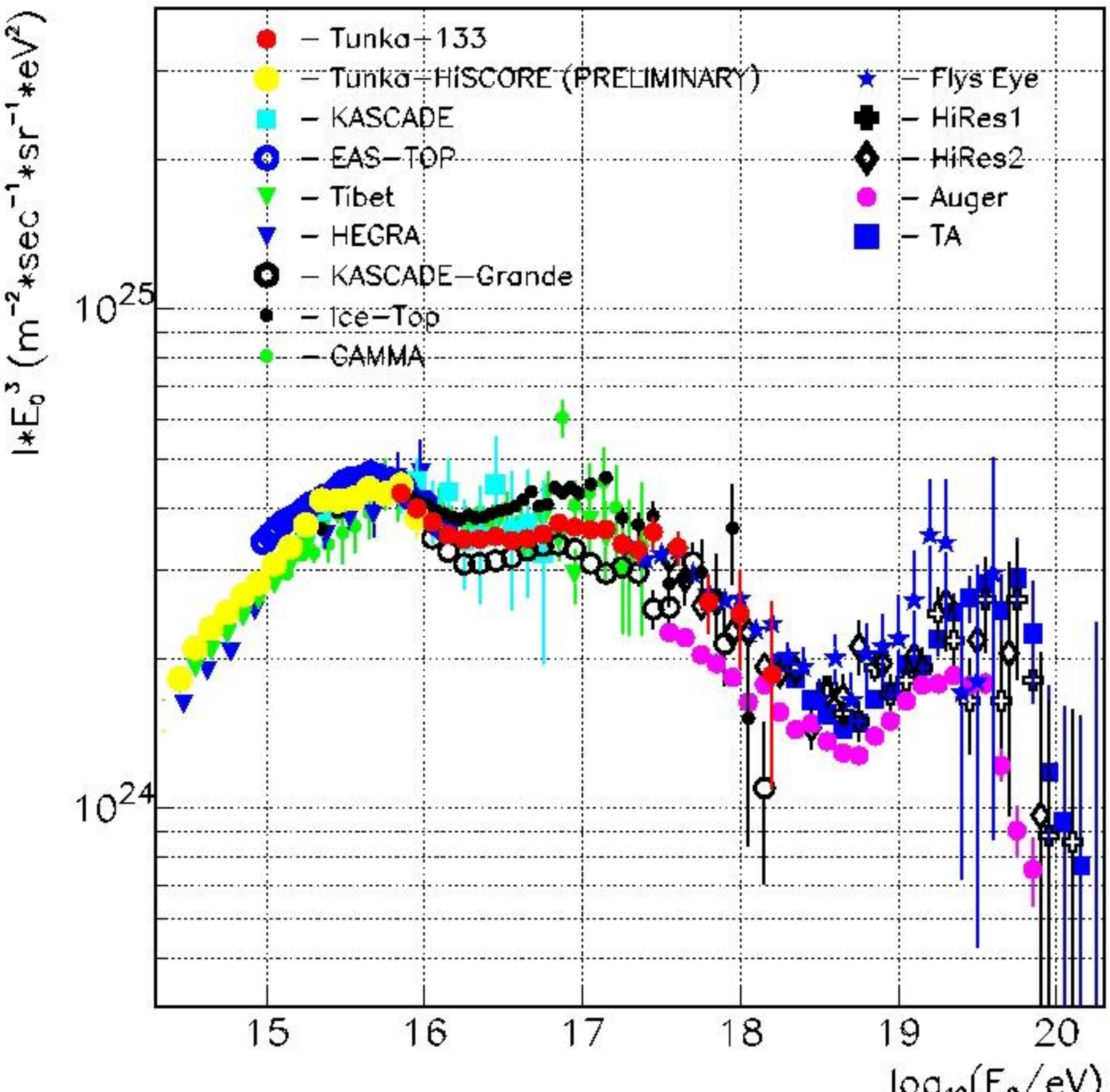
~ 200 events $E_0 > 10^{16}$ eV

Tunka-HiSCORE:
All particle energy spectrum.
PRELIMINARY



Spectrum Structure in the Knee



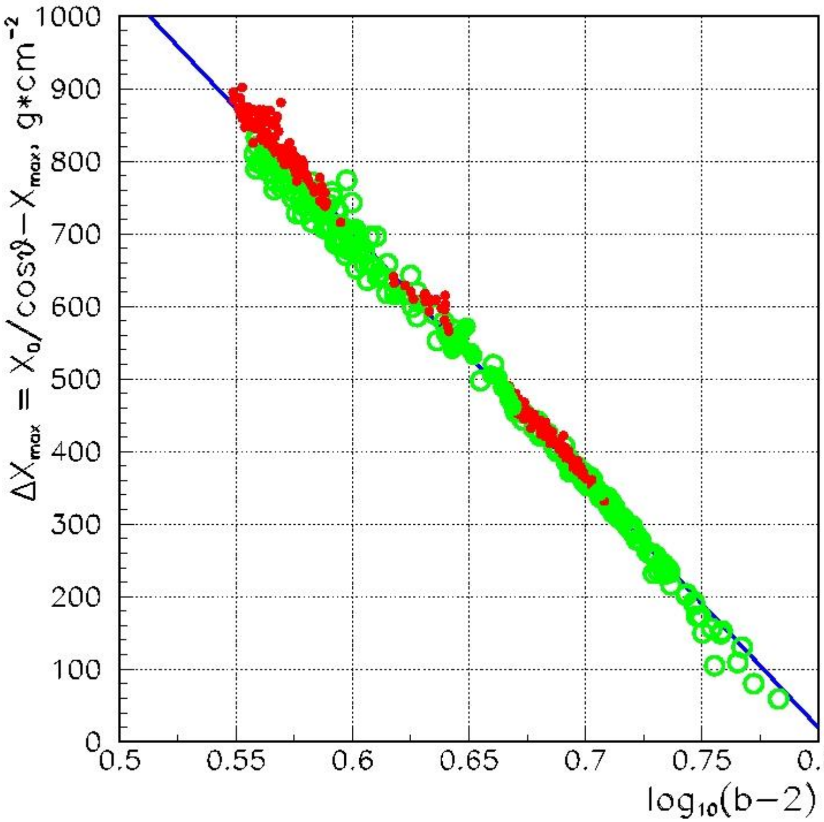


– Tunka-133
– Tunka-HiSCORE (PRELIMINARY)
– KASCADE
– EAS-TOP
– Tibet
– HEGRA
– KASCADE-Grande
– Ice-Top
– GAMMA
– Flys Eye
– HiRes1
– HiRes2
– Auger
– TA
$I*E_0^3$ ($m^{-2}*sec^{-1}*sr^{-1}*eV^2$)
10^{25}
10^{24}
15
16
17
18
19
20
$\log_{10}(E_0/eV)$

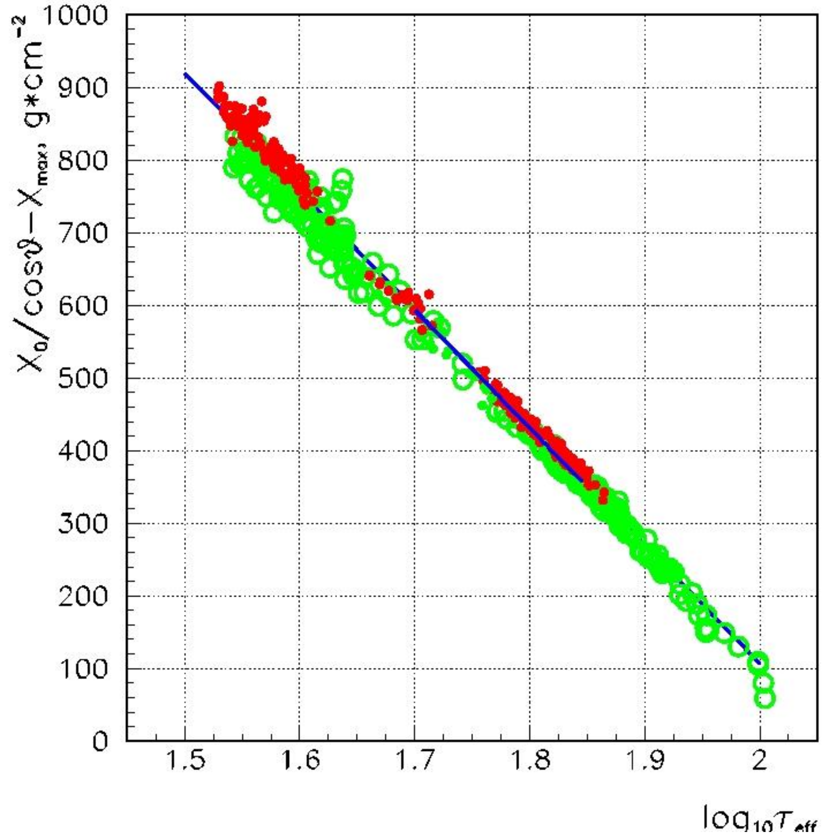
CORSIKA

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

ΔX_{max} vs. b_A



ΔX_{max} vs. $\tau_{eff}(400)$

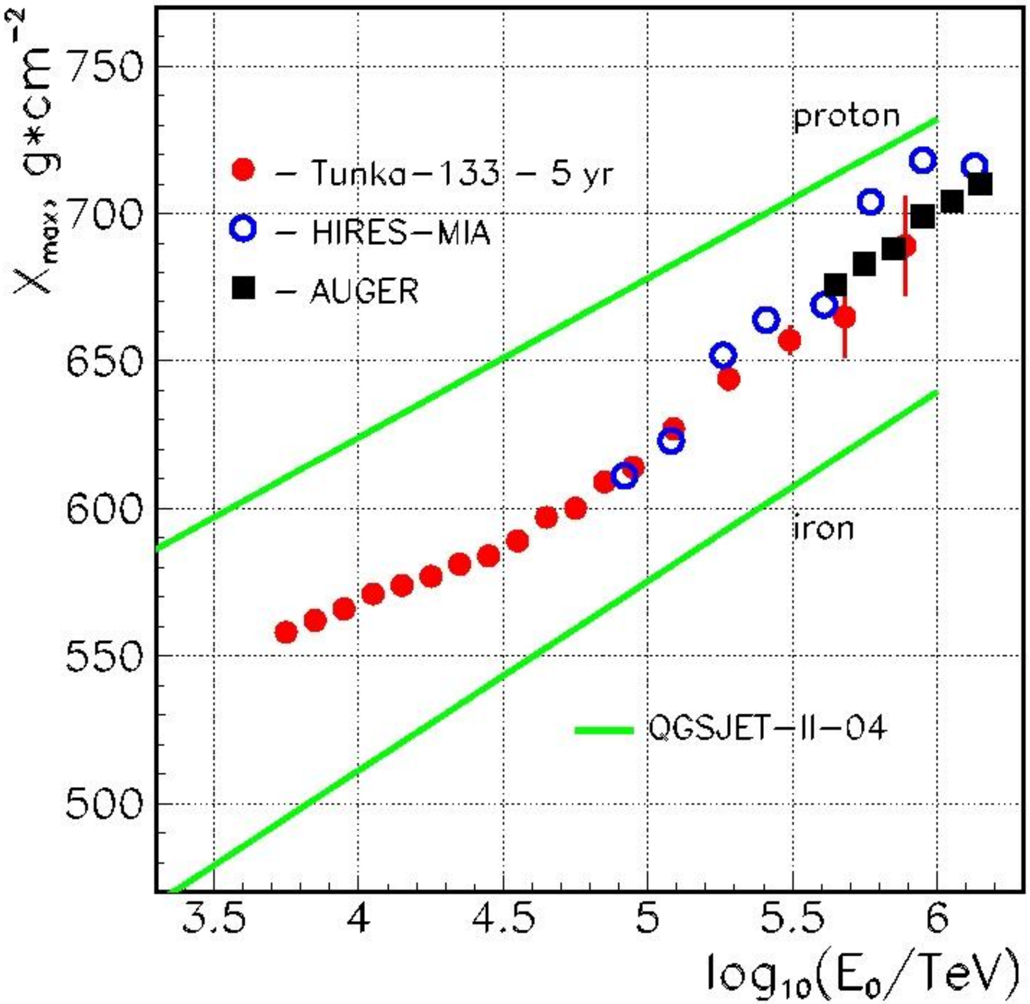


~ 500 events – 10^7 GeV < E_0 <10^8 GeV, θ = 0°, 30°, 45°

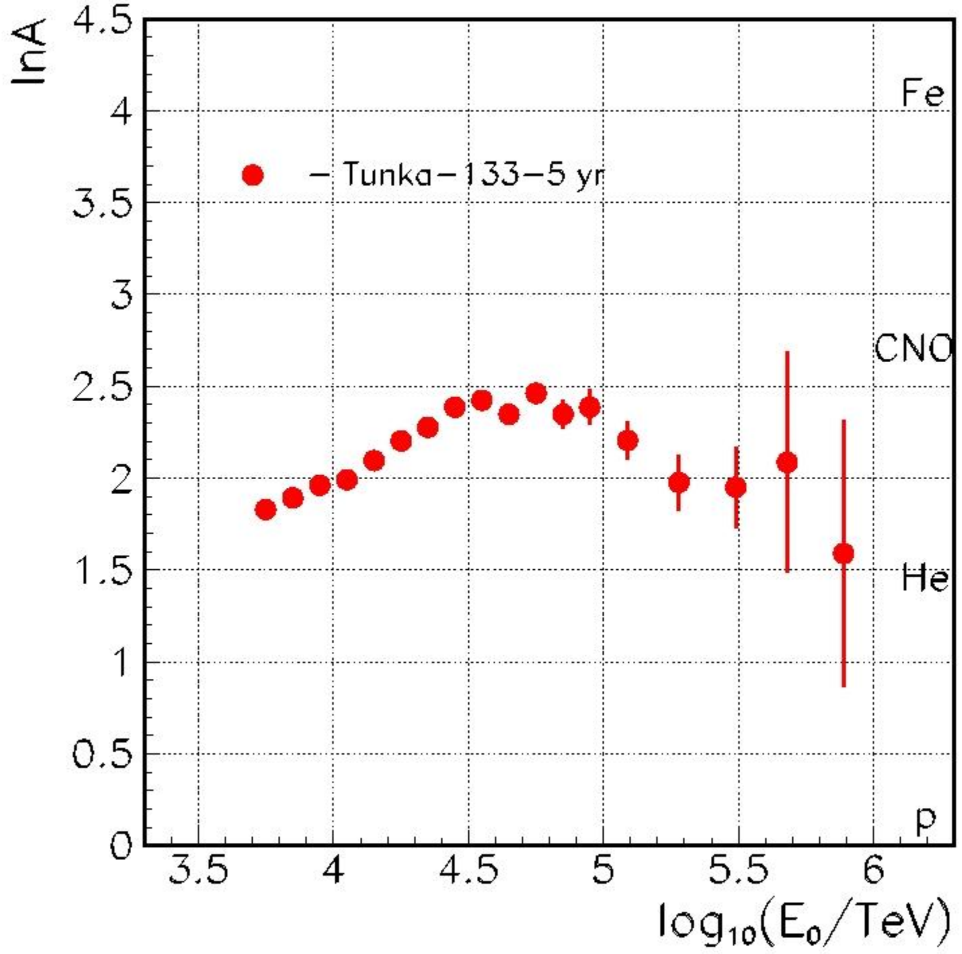
green – p, red – Fe

$<X_{max}>$ vs. E_0

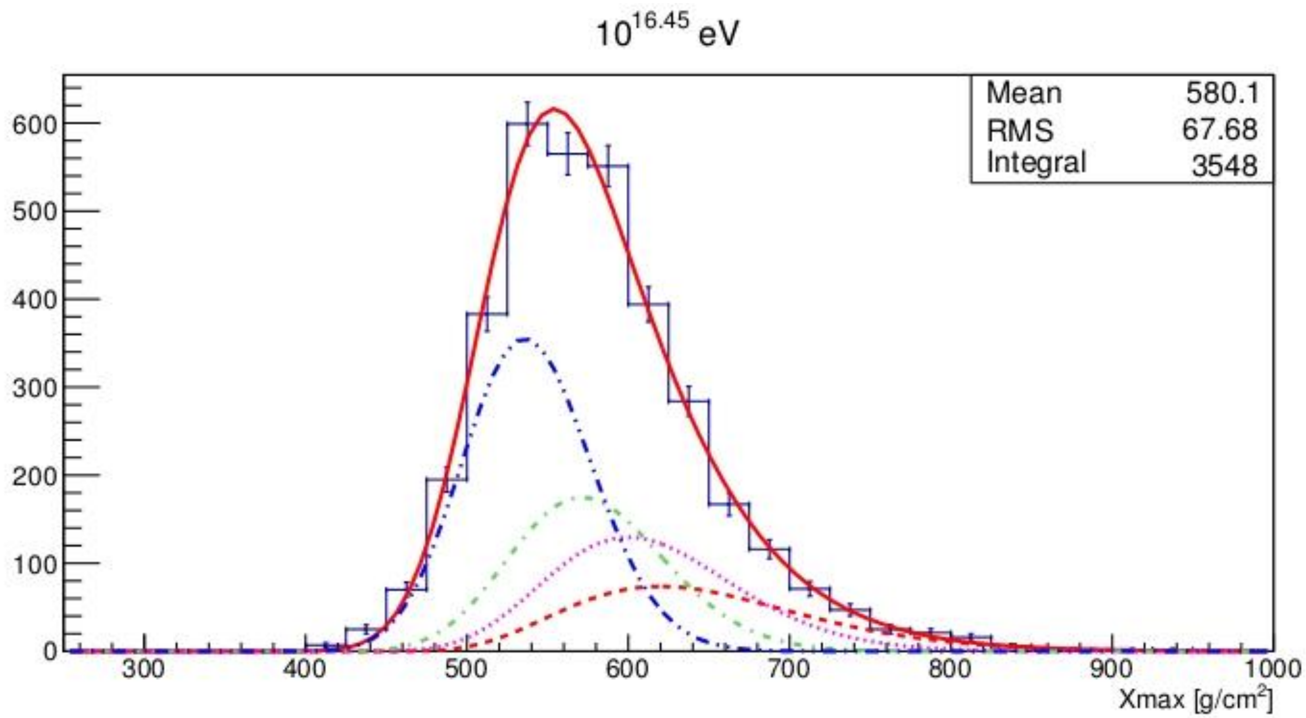
Agreement with HiRes-MIA and Auger results at $10^{17} – 10^{18}$ eV



EXPERIMENT: MEAN <lnA> vs. E_0

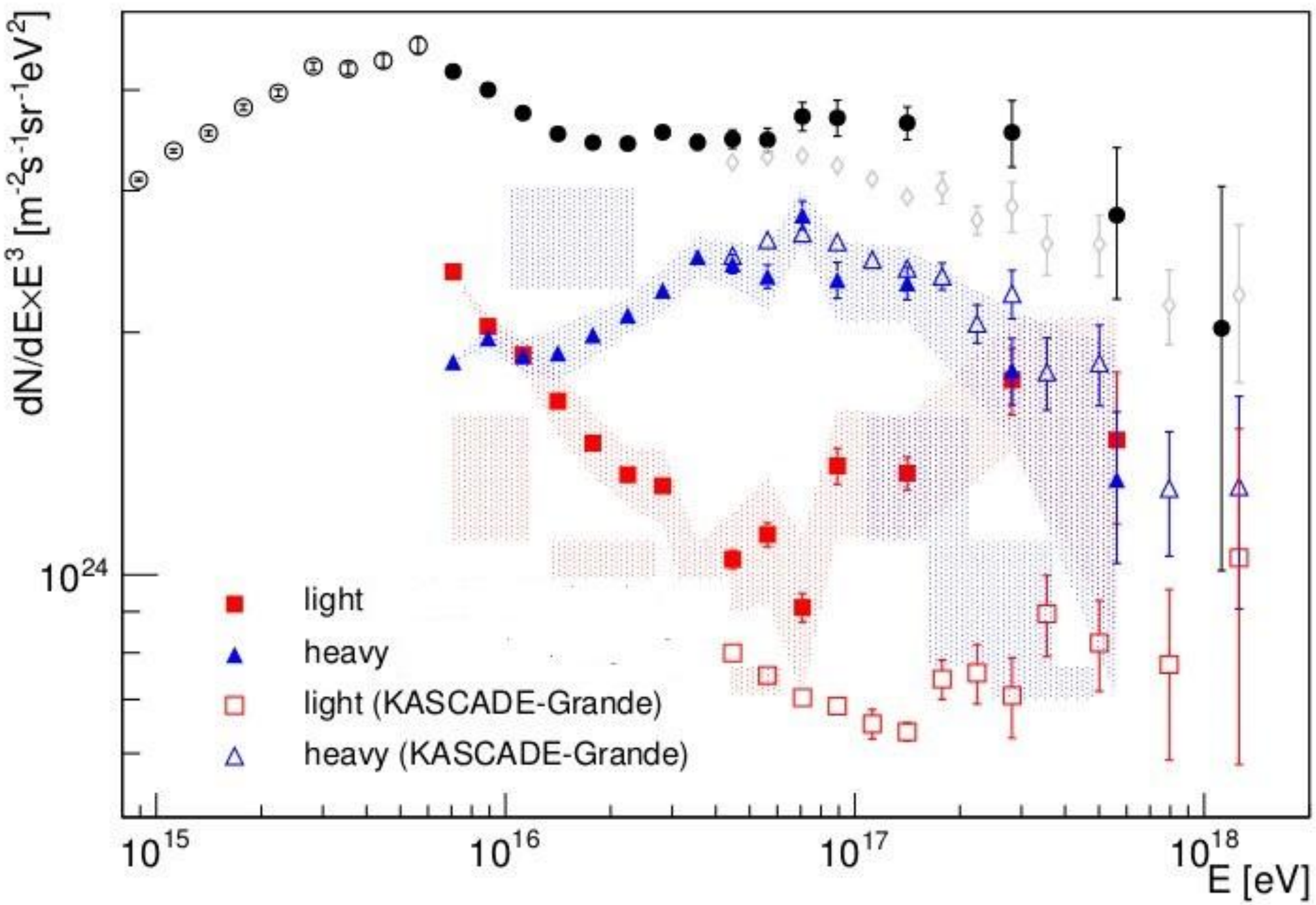


ANALYSIS of X_{max} DISTRIBUTIONS (2013)PRELIMINARY



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:

   $\gamma = 3.25 \pm 0.01$ — $5 \cdot 10^{15} < E_0 < 2 \cdot 10^{16}$ 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.

6. Possible double structures in the first and the second knees has to be investigated with more statistics.

Thank you!