

# Ultra high energy cosmic ray study results by radio emission technique at Yakutsk array

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# The Yakutsk array



58 stations with scintillation detectors;  
27 integral 3 track Cherenkov detectors;  
5 muon detectors.



Energy range:  $10^{15} - 10^{20} eV$

Area of the array:  $\sim 8 km^2$ .

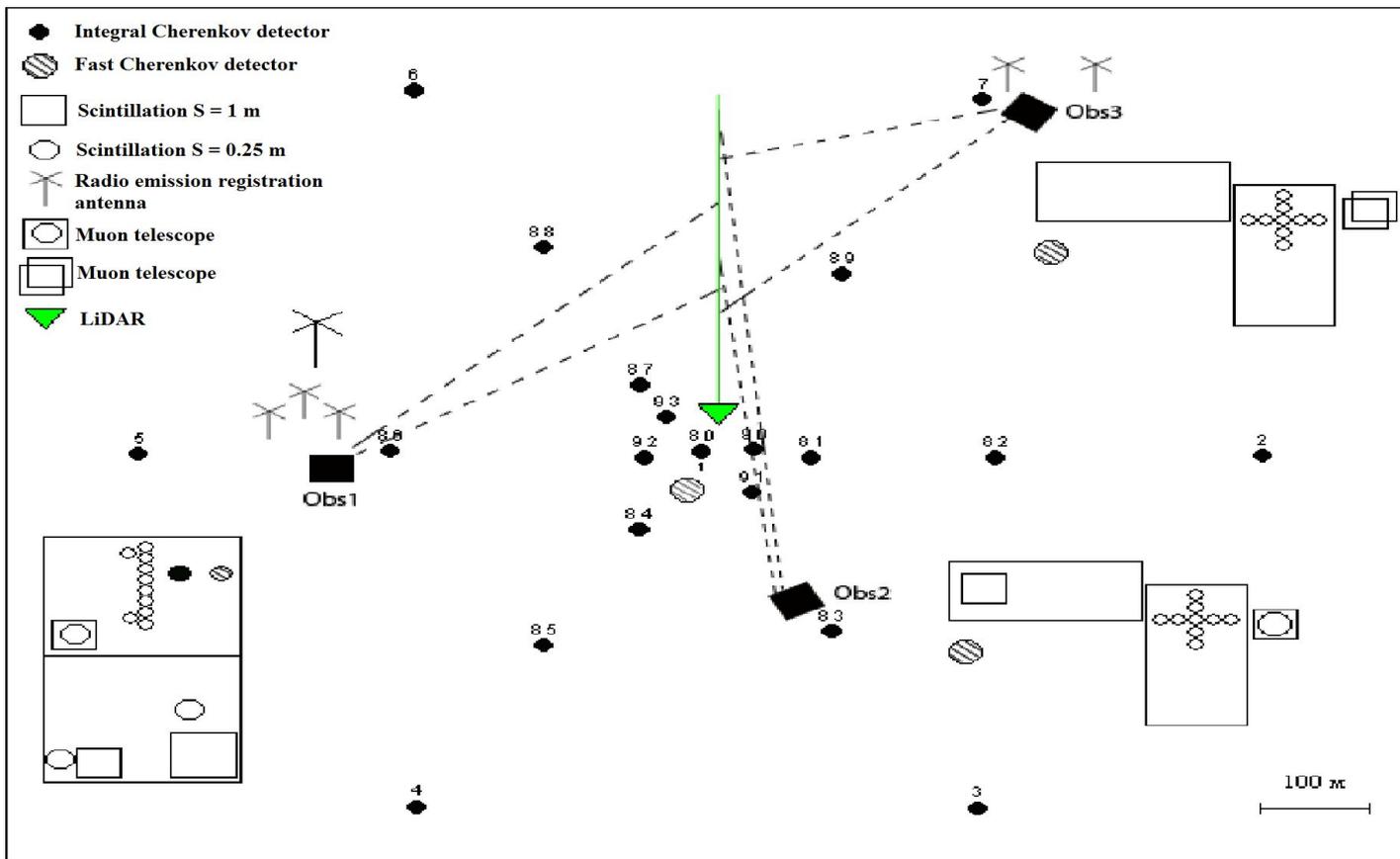
The array operates from September to April

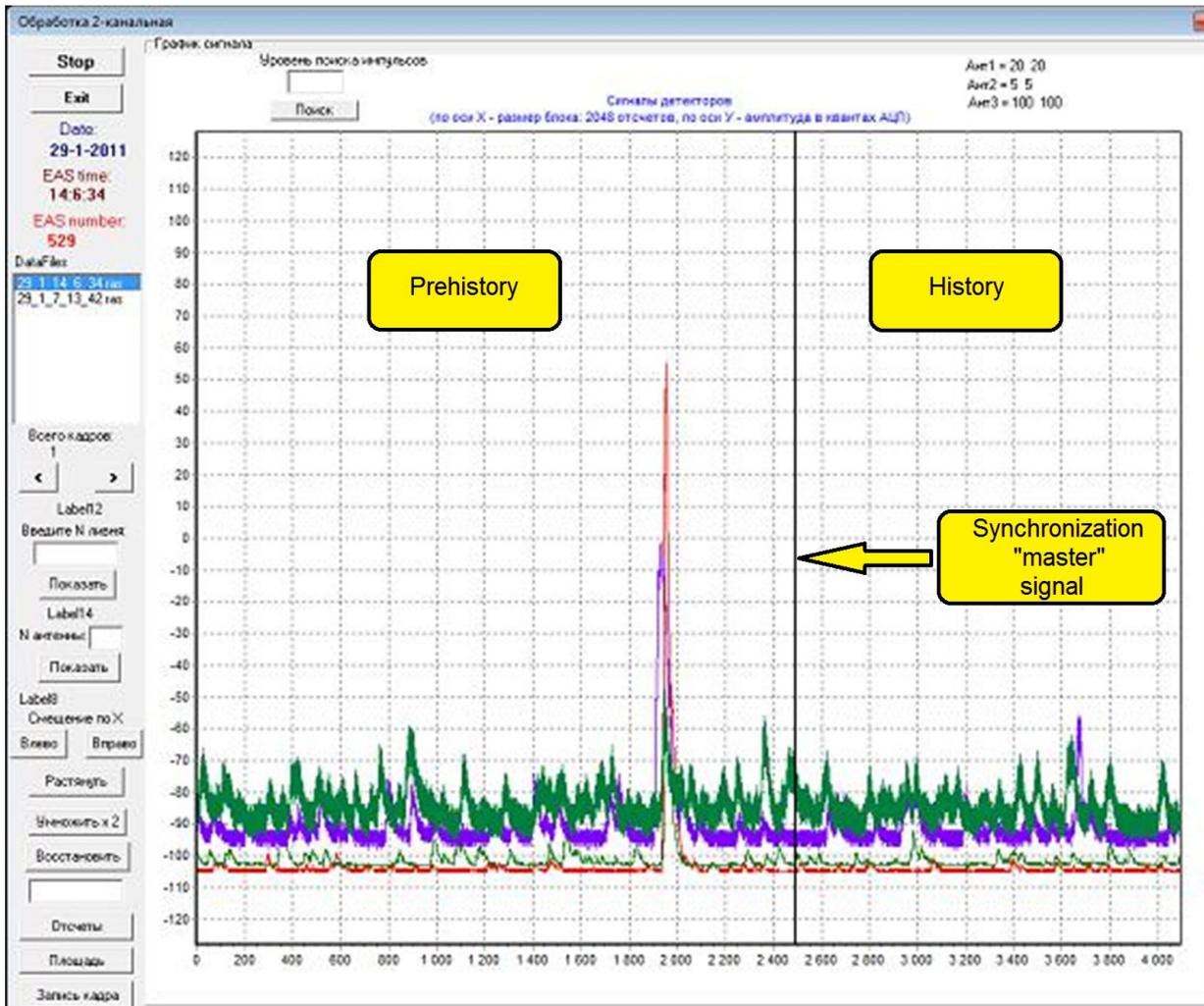
# Radio Emission Antennas at the Yakutsk Array



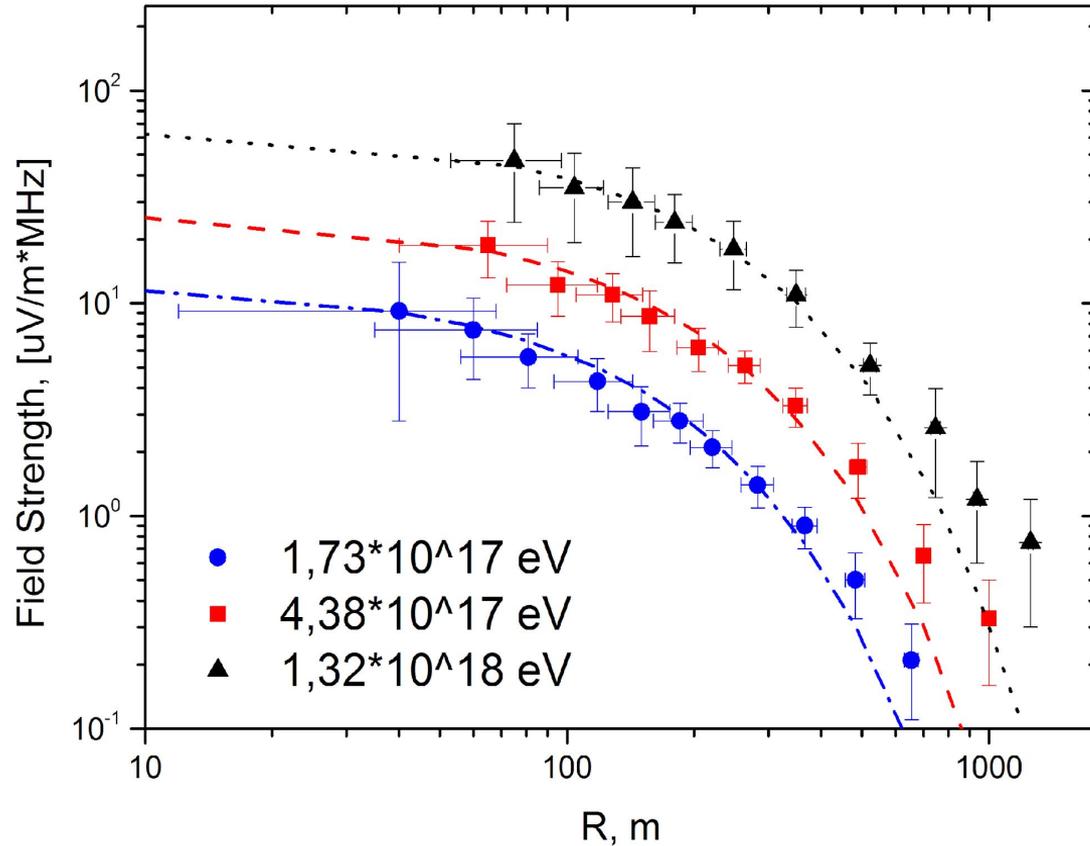
Yakutsk array  
measures:

Charged component;  
Muon component;  
Cherenkov light;  
Radio emission.

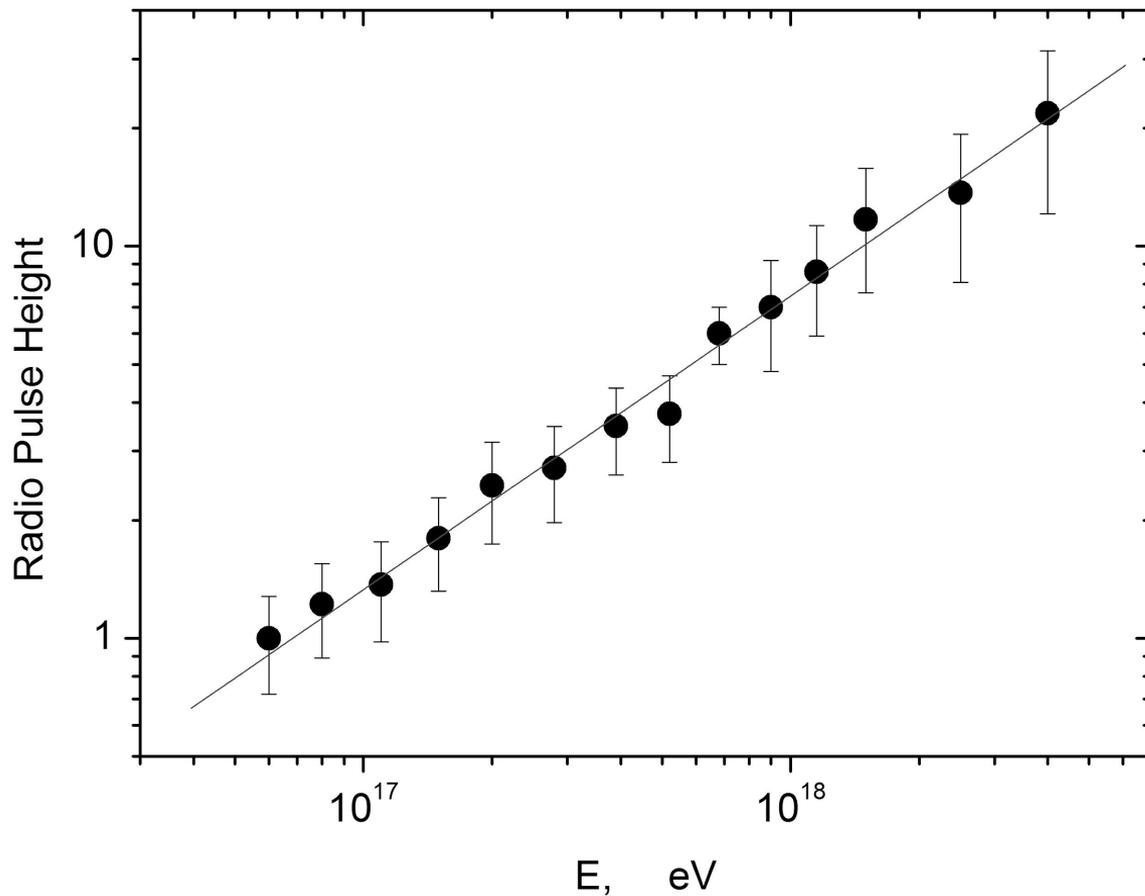




# LDF of Air Shower Radio Emission $E \geq 10^{17}$ eV



# Radio emission amplitude dependence on energy of the shower



# Air Shower Event with Energy $E > 10^{19}$ eV

Date:

22. 01. 2014

Time:

21:49:08

Zenith angle:

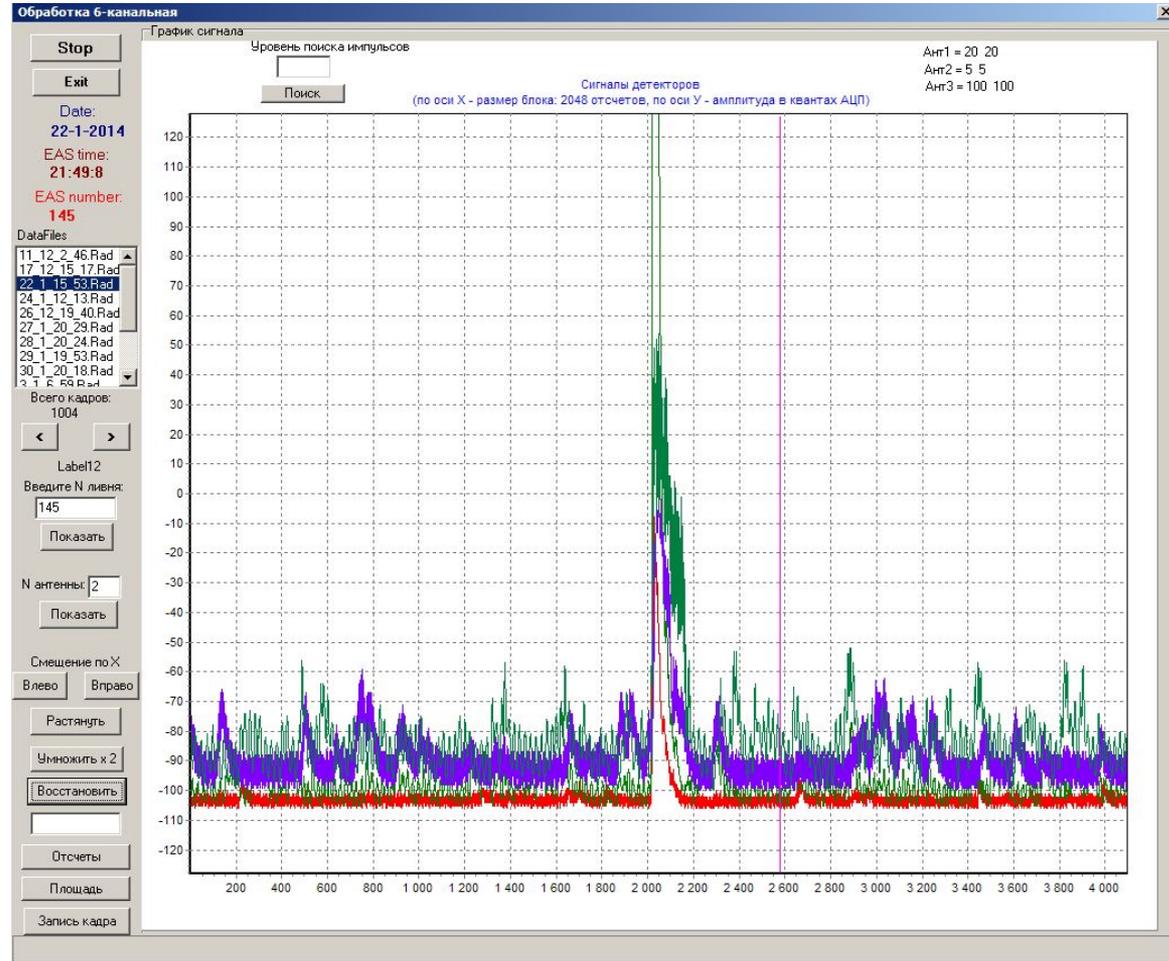
$\theta = 47^\circ$

Azimuth angle:

$\psi = 189^\circ$

Energy:

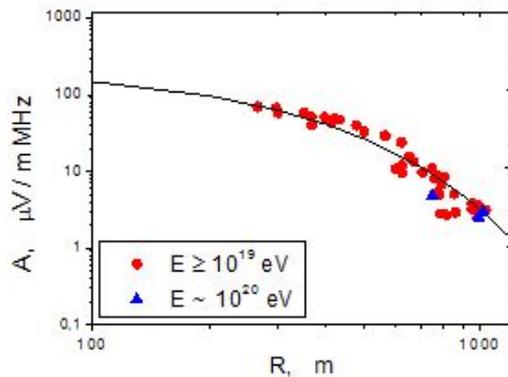
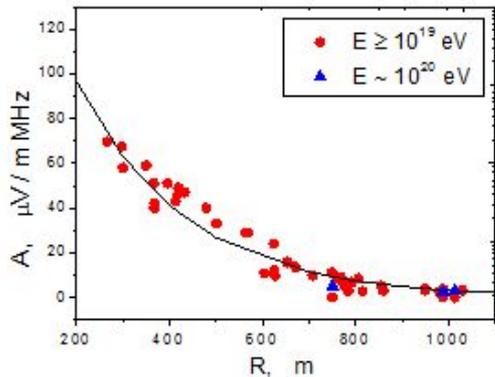
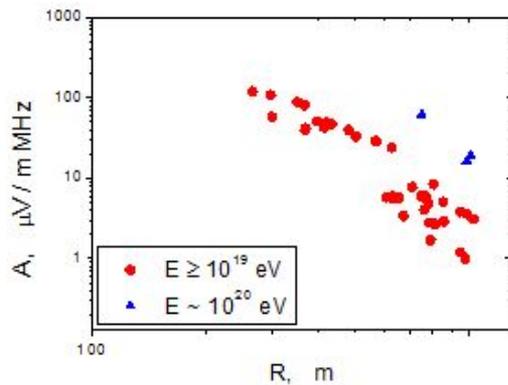
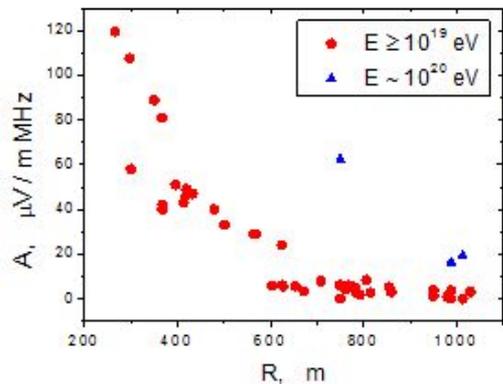
$E_0 = 1,11 \cdot 10^{19}$  eV



# List of Air Showers with Energy $\geq 10^{19}$ eV Registered by Yakutsk array Antennas

Data	$\theta$ , deg	$\psi$ , deg	$E_0$ , $\text{эВ}$	$A_v$ , $\text{МКВ} \cdot \text{М}^{-1} \cdot \text{МГЦ}^{-1/2}$	R, M
16.11.86	74	180	$3.1 \cdot 10^{19}$	58.0	300
16.12.87	71	178	$3 \cdot 10^{19}$	40.0	367
21.02.88	70	210	$10^{19}$	3.1, 3.8	1030, 950
09.03.88	36	125	$9 \cdot 10^{18}$	6.2	792
07.05.89	59	168	$2 \cdot 10^{20}$	62.5	750
10.03.11	51	239	$1.1 \cdot 10^{19}$	89, 43, 5.8	350, 413, 604
16.05.11	69	99	$1.6 \cdot 10^{19}$	33, 29, 40	501, 564, 479
31.12.11	15	165	$1.1 \cdot 10^{19}$	1.2, 1.0, 2.9	950, 980, 860
12.04.12	8	222	$1.3 \cdot 10^{19}$	4.1, 2.8, 6.0	762, 785, 626
04.05.13	46	295	$1.1 \cdot 10^{19}$	5.3, 6.0, 12	776, 768, 368
12.12.13	15	297	$1.2 \cdot 10^{19}$	5.1, 8.4, 3.6	855, 806, 988
03.10.13	21	21	$1.1 \cdot 10^{19}$	9.1, 11, 2.7	419, 396, 815
22.03.13	46	4	$1.8 \cdot 10^{19}$	41, 48, 78	418, 432, 366
02.01.14	48	207	$1.0 \cdot 10^{20}$	16.3, 19.4	1013, 988
22.01.14	47	189	$1.1 \cdot 10^{19}$	107.6, 119.6	297, 266
05.02.14	26	343	$3.5 \cdot 10^{19}$	3.4, 5.6	671, 627
02.03.14	30	217	$1.2 \cdot 10^{19}$	4.9, 6.0, 7.8	782, 749, 708
04.01.18	26	211	$1.6 \cdot 10^{19}$	1.3	1038
05.01.18	45	303	$2.1 \cdot 10^{19}$	180, 150	106, 118

# LDF of Air Shower Radio Emission $E \geq 10^{19}$ eV



Linear scale

Logarithmic scale

Normalized to  
 $E = 1.54 \cdot 10^{19}$   
eV  
 $\langle \theta \rangle = 43.1^\circ$

# $X_{\max}$ estimation

Depth of  $X_{\max}$  is estimated by

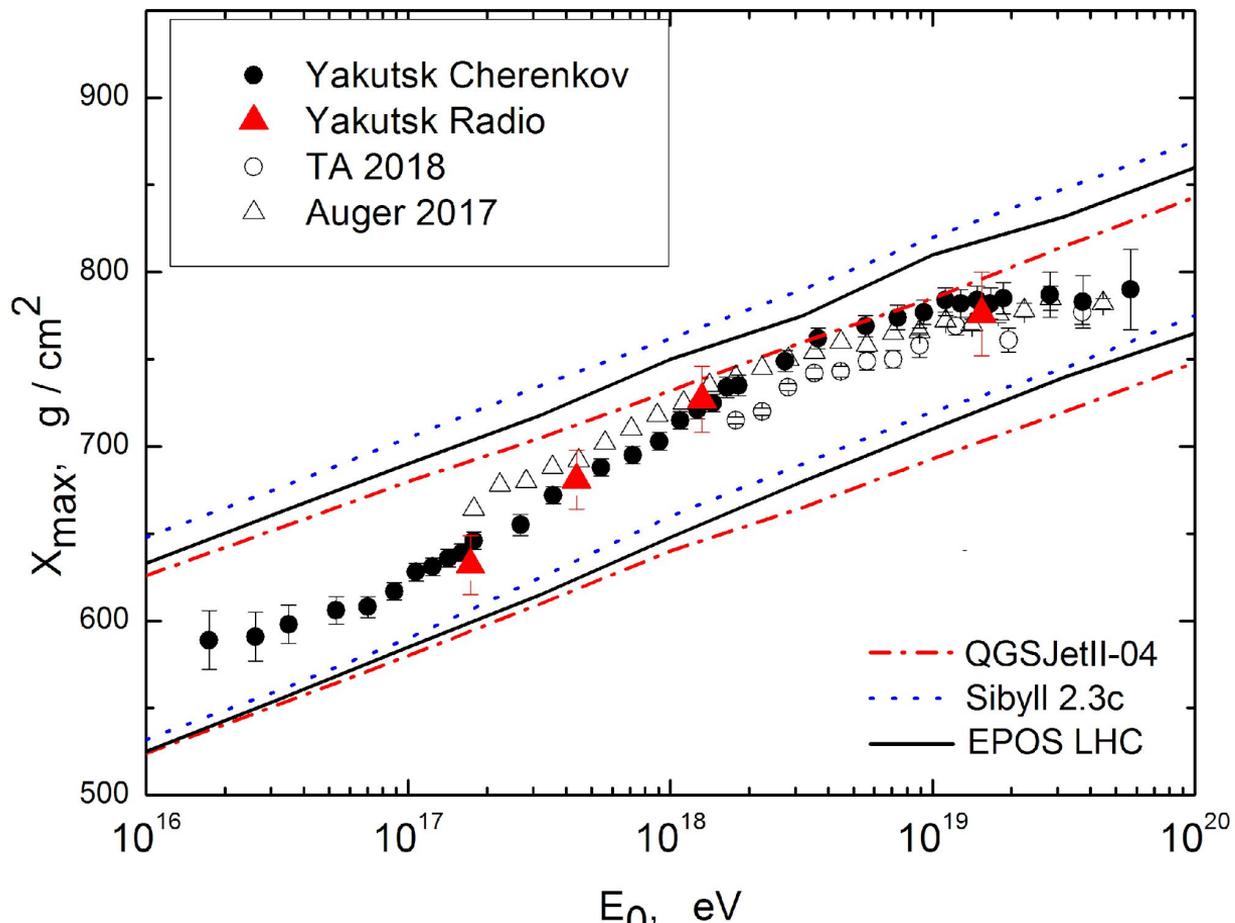
$$X_{\max} = (655 \pm 10) + (100 \pm 5) \left( \frac{P_1 - 3.01}{0.46} \right) \quad (1)$$

$$X_{\max} = (660 \pm 15) + (100 \pm 5) \left( \frac{P_2 - 11.5}{3} \right) \quad (2)$$

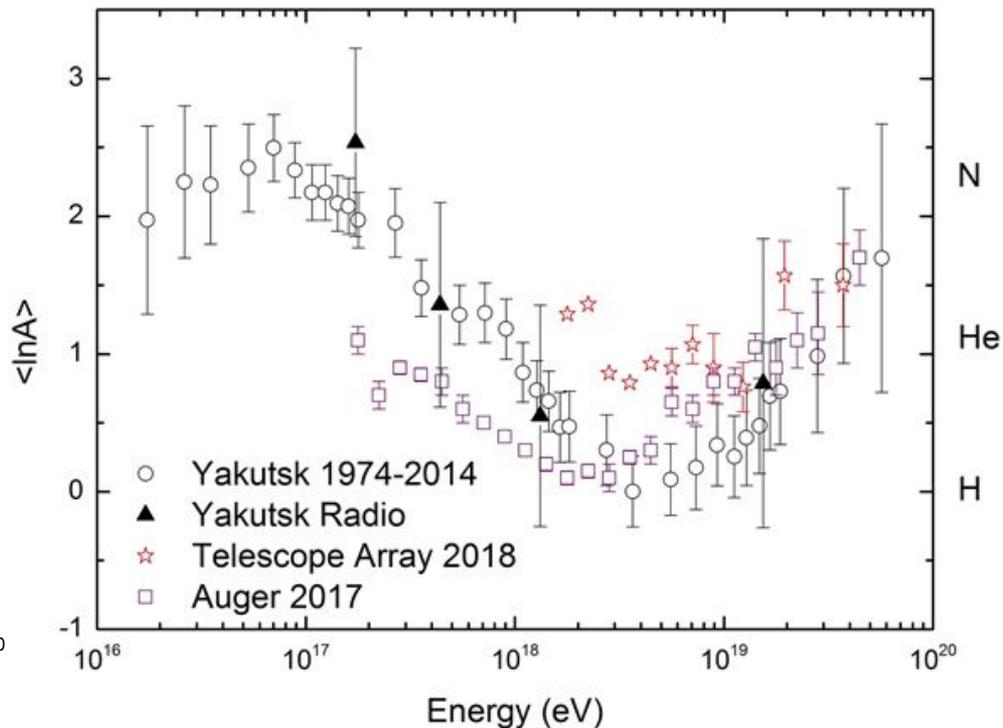
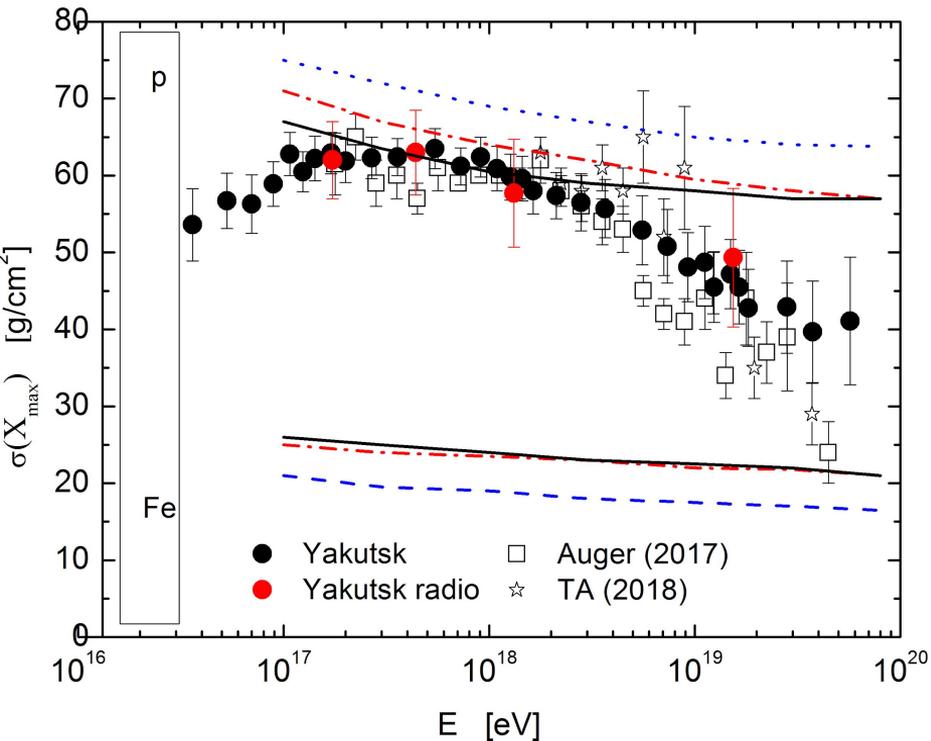
Eq. (1) is used for air showers with energy  $< 3 \cdot 10^{18}$  eV

Eq. (2) is used for air showers with energy  $\geq 3 \cdot 10^{18}$  eV

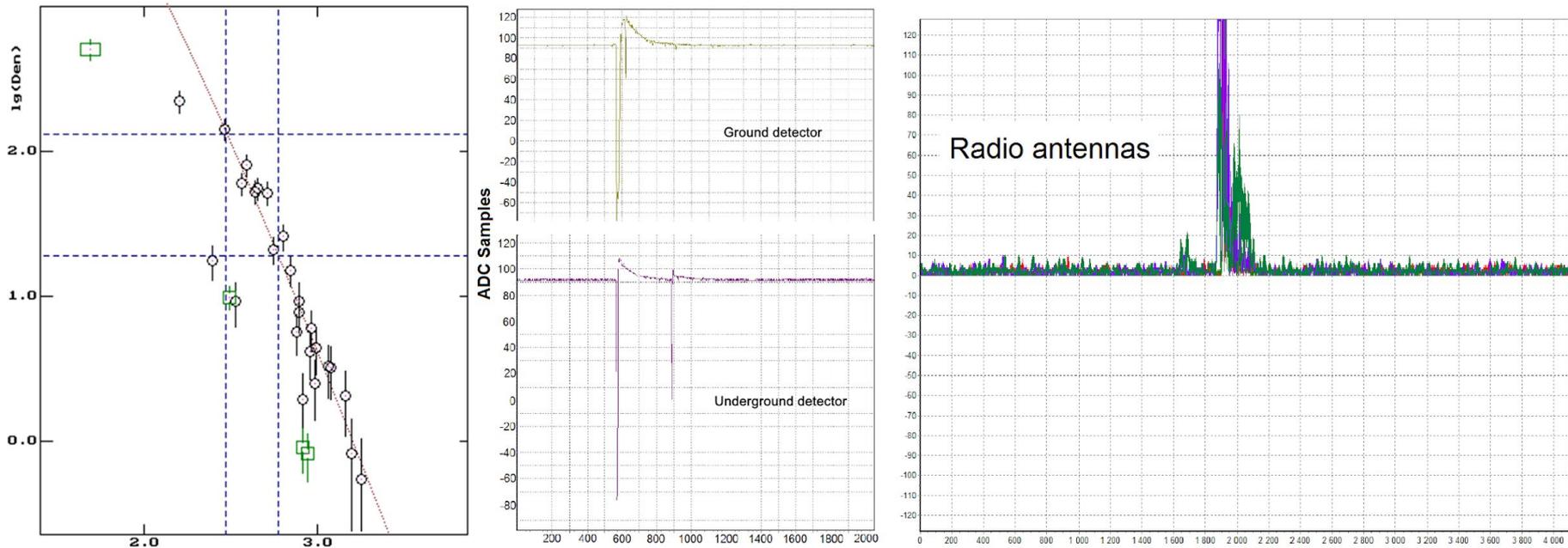
# $\langle X_{\max} \rangle$ vs $E_0$



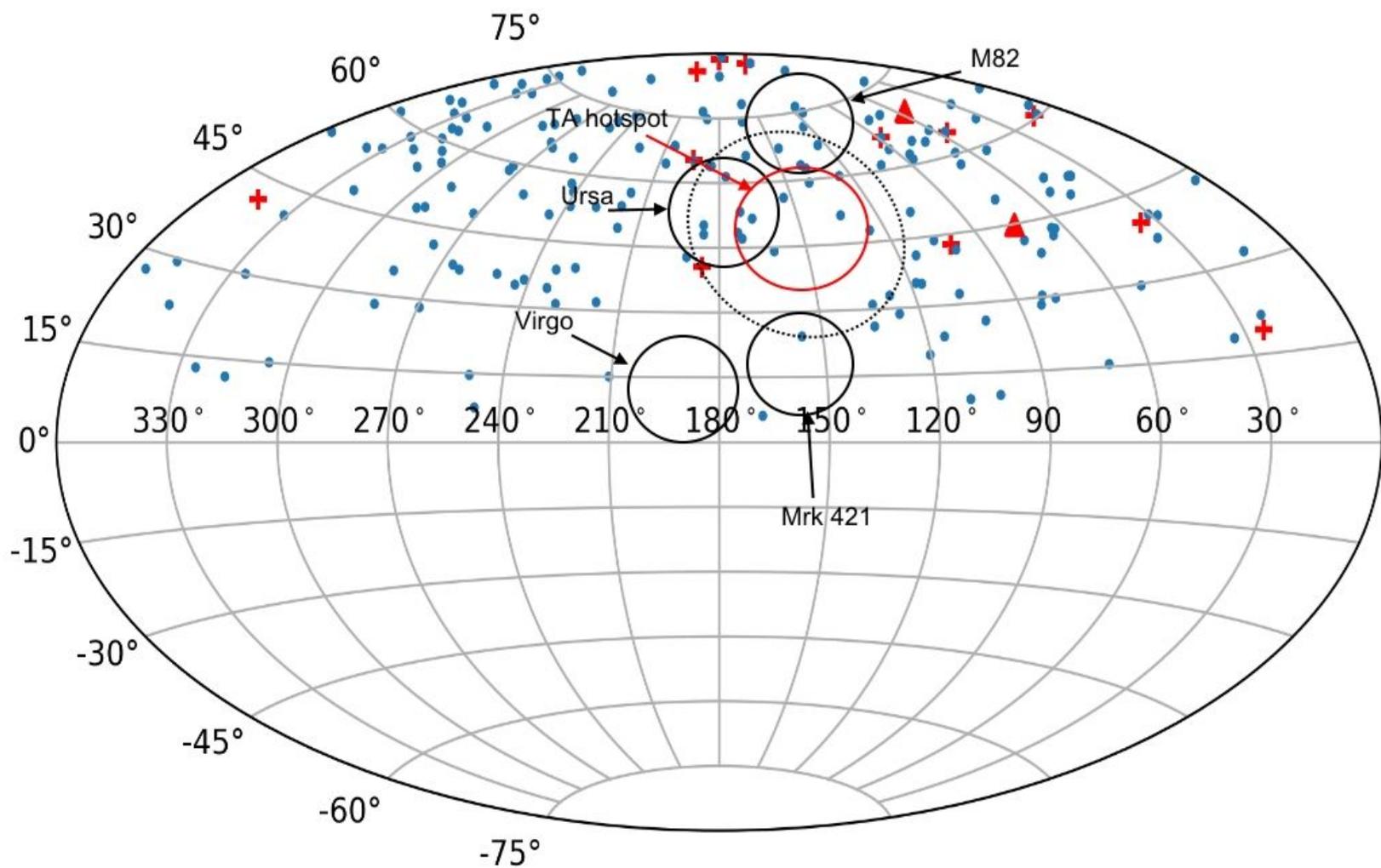
# Fluctuations of $X_{\max}$ vs $E_0$ and MC



# Air shower event with $E_0 > 10^{19}$ eV



Energy:  $E = 1.8 \cdot 10^{19}$  eV, Azimuth angle:  $\psi = 303^\circ$   
Zenith angle:  $\theta = 45^\circ$



# Conclusion

Radio experiments expands the possibilities of experimentally studying the characteristics of air showers;

Energy of the showers was determined by radio emission signal amplitude and depth of maximum by ratio of amplitudes at different distances;

Depths of maximum development estimated for 4 different energies by radio measurements are in agreement with depths of maximum development estimated by optical methods;

By radio emission measurements it is possible to search for the sources of ultra-high energy particles.

**Thank you for your attention!**