Experiment Tunka-Rex. Seven years of Tunka-Rex operation

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September 5, 2019

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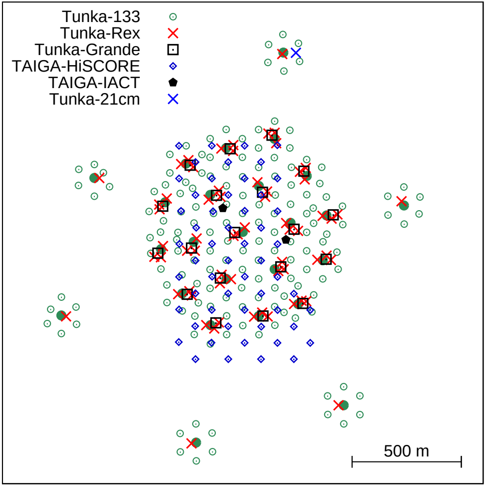
TAIGA

***T**unka **A**dvanced **I**nstrument for cosmic ray physics and **G**amma **A**stronomy*



= 3 km^2 covered by:

Cosmic ray detectors $<$EeV

- Tunka-133 air-Cherenkov
- **Tunka Radio Extension** (Tunka-Rex)
- Tunka-Grande scintillators

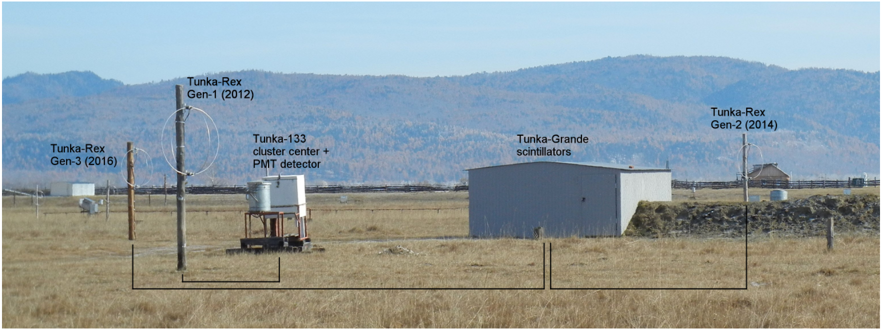
Gamma ray detectors $>$TeV

- HiSCORE
- IACTs

Ingeneering detectors

- Tunka-21cm

Single cluster of Tunka facility



- 7 Optical Modules
- 8 m^2 (on-ground) + 5 m^2 (underground) scintillators
- 3 antenna stations (2 polarizations, 30-80 MHz)

Total: 19 clusters

Gamma measurement

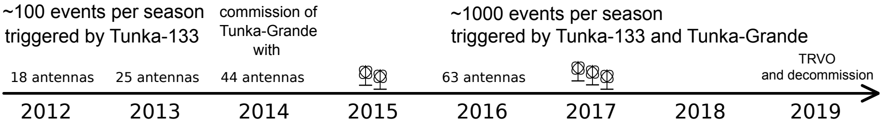
- Joint measurements with imaging and no-imaging atmospheric Cherenkov telescopes
- 4 PMT per TAIGA-HiSCORE station
- Mirror area of TAIGA-IACT – $10m^2$

Tunka-Rex

Tunka Radio Extension

- Tunka-Rex successfully operates since 2012
- Frequency band 30-80 MHz
- 63 antennas (2016)
- Energy range 10^{17} - 10^{18} eV
- Measurement season from October to April
- Duplex and triplex measurements with Tunka-133 and Tunka-Gande: $\gamma_{\mathrm{ch}}/\mu/e$ + radio
- Energy resolution of 10-15%, shower maximum resolution of 25–35 g/cm^2

Tunka-Rex detector timeline



Achievements:

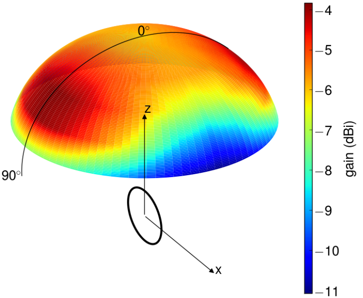
* Cross-calibration of radio and air-Cherenkov signal
* Precise reconstruction of energy and shower maximum
* Calibration of absolute energy scales of cosmic-ray experiments via radio extensions
* Estimation of aperture and exposure of radio array
* Mean shower maxima as function of primary energy

In Progress:

* Independent reconstruction with radio
* Joint reconstruction of electromagnetic and muon components of air showers
* Mass composition study
* Technologies for lowering the threshold
* Open-access to data and software
* Self-tirgger for radio

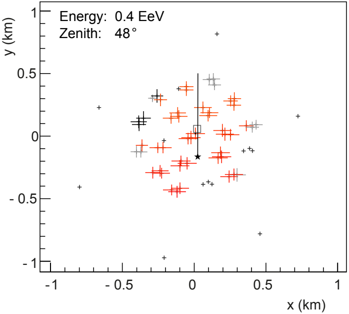
Amplitude calibration

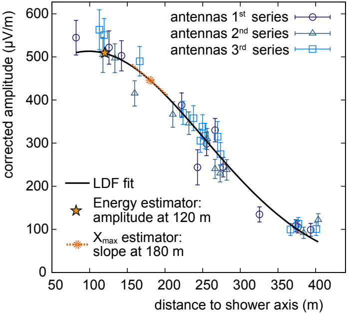
- Tunka-Rex, LOPES, LOFAR calibrated consistently with same source
- Calibration is used as normalization for simulated antenna pattern
- CoREAS amplitude scale confirmed (17%)

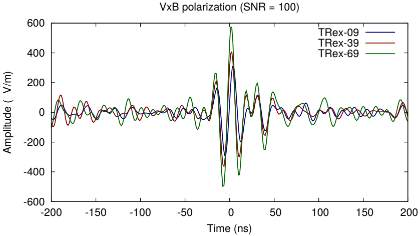


doi:10.1016/j.nima.2015.08.061

Example of event

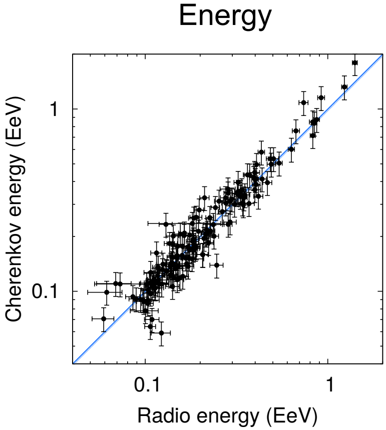


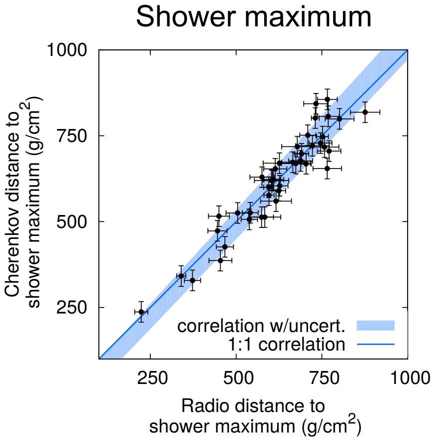




Asymmetry corrected LDF

Blind cross-check with Tunka-133





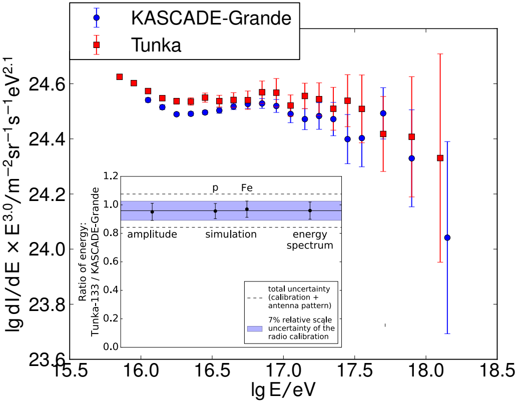
resolution: 15%

resolution: 38 g/cm^2

JCAP 1601 (2016) no.01, 052

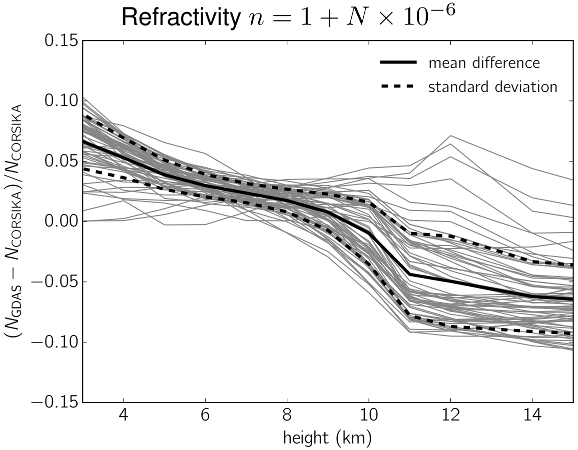
Comparison of energy scales via radio

Independent check via LOPES and Tunka-Rex has shown that
energy scales of KASCADE-Grande and Tunka-133 are consistent within 10%



Phys.Lett. B763 (2016) 179-185

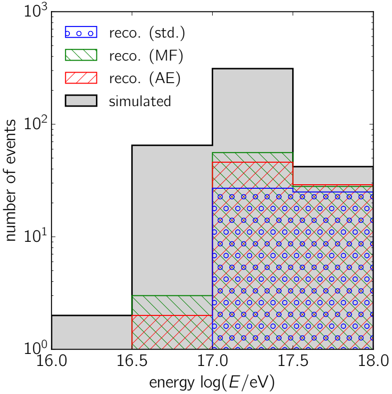
Influence of air refractivity

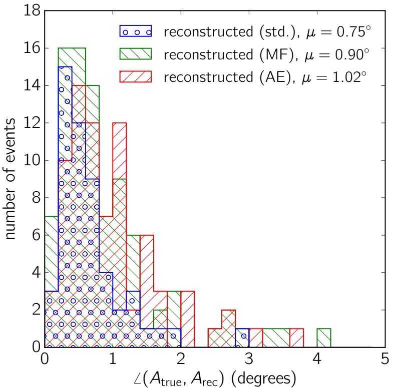


- Event-to-event uncertainty 3 g/cm^2 (refractivity variation of 2%)
- Systematic shift up to 5 g/cm^2 (refractivity difference of 5%)

EAS signal search

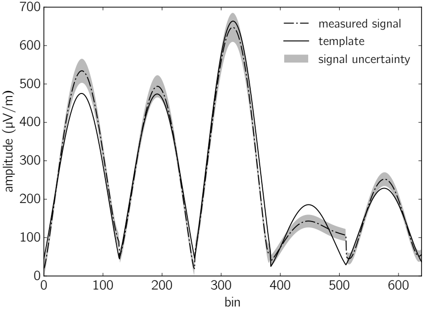
Autoencoder is binded with Tunka-Rex fork of Auger Offline
Reconstruction of CoREAS simulations (reproduction of 2012-2014 events)

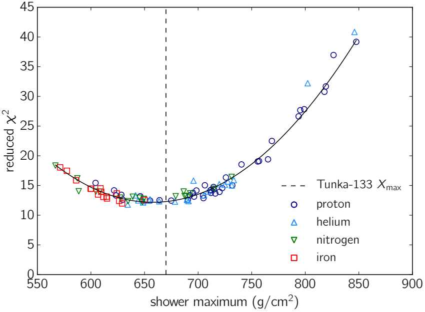




Template fit method

Chi-square fit of clipped envelopes **concatenated** to a single trace





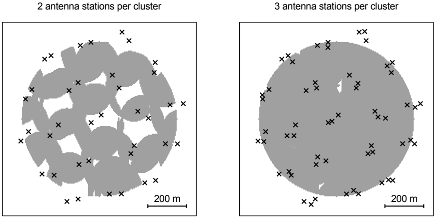
$X_{\max}$ resolution improved to 25-35 g/cm^2, E_{pr} resolution is 10%

Phys.Rev. D97 (2018) no.12, 122004

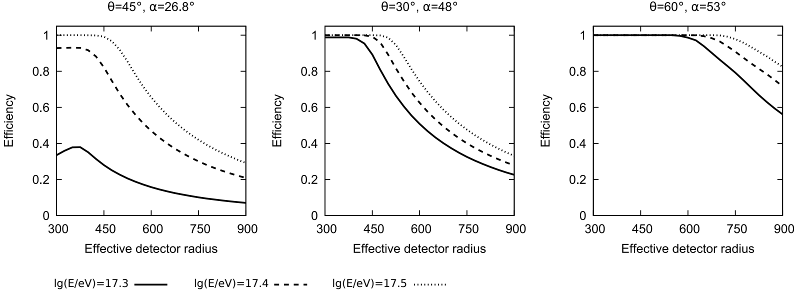
Effective radius of Tunka-Rex

$$\varepsilon = \frac{N_{detected}}{N_{total}}$$

$$\varepsilon_R = \Theta\left(R^2\left(E,\theta,\alpha\right) - x^2 - y^2\right)$$

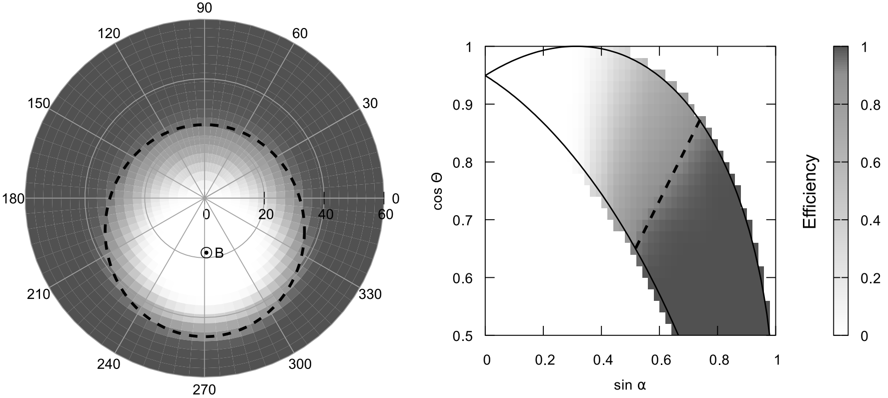


$\theta = 45°$, $\alpha = 27°$, $\lg(E/\text{eV}) = 17.3$



Angular efficiency

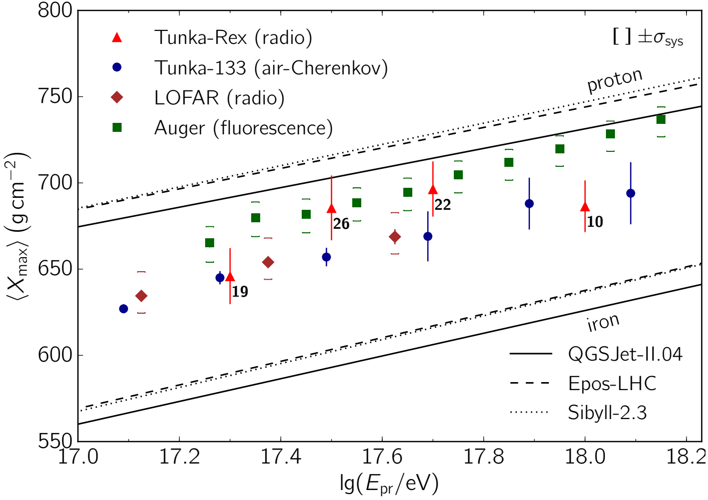
$\lg(E/\text{eV}) = 17.4$



(θ, ϕ) $(\cos\theta, \sin\alpha)$

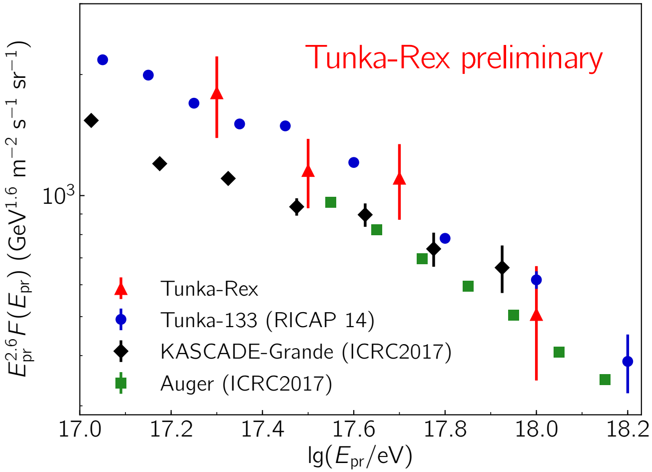
[arXiv:1712.00974]

$\langle X_{\max} \rangle$ as function of energy

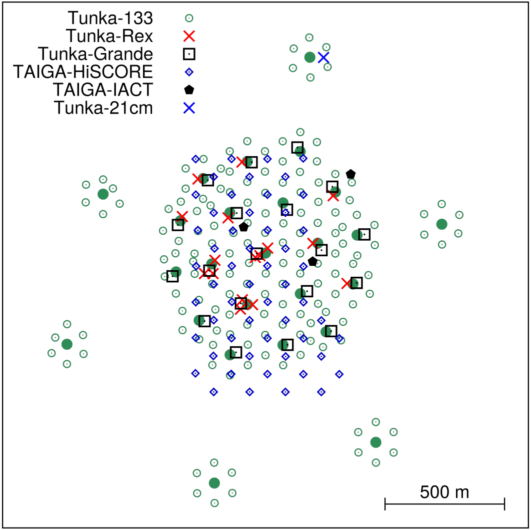


Phys.Rev. D97 (2018) no.12, 122004

Flux of cosmic rays



Tunka-Rex decommission



Tunka-Rex based pathfinder arrays

- Engineering multi-purpose array for 21cm cosmology

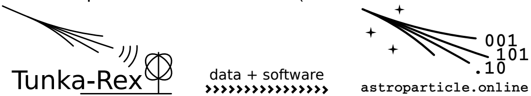
Summary and outlook

- Tunka-Rex successfully operates since 2012
- Energy resolution of 10-15%, shower maximum resolution of 25–35 g/cm^2

- **Ideal tool for energy scale calibration between CR experiments (KG + Tunka-133)**
- **SALLA will be used in the radio upgrade of the Pierre Auger Observatory**

- More detailed calibration and study of systematics
- Mass composition study combining radio (E_{pr} + $X_{\max}$) and particles (Tunka-Grande e/μ)
- Study of inclined air-showers
- Small engineering arrays
- Development of self-trigger for radio

Open data and education (*arXiv:1906.10425*



Making data, software, knowledge and experience publicly accessible
(Tunka-Rex Virtual Observatory)

backup

Air-shower reconstruction (phenom.)

Lateral distribution function

$$\mathcal{E}(r) = \mathcal{E}_{r_0} \exp(a_1(r-r_0)+a_2(r-r_0)^2)\,,$$

$$r_0 = (r_{\mathrm{e}}\,, r_{\mathrm{x}}),\;\; \eta = \mathcal{E}'/\mathcal{E}$$

Fixing quadratic term

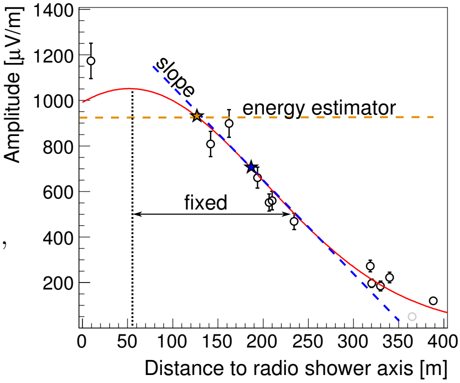
$$a_2(\theta, E_{\mathrm{pr}}^{\mathrm{est}}) = a_{20}(E_{\mathrm{pr}}^{\mathrm{est}})+a_{21}(E_{\mathrm{pr}}^{\mathrm{est}})\cos\theta\,,$$

Air-shower parameters

$$E_{\mathrm{pr}} = \kappa_L \mathcal{E}(r_{\mathrm{e}})\,,\;\; E_{\mathrm{pr}} = \kappa_I \int_0^\infty \mathcal{E}(r)\mathrm{d}r$$

$$X_{\max} = X_0/\cos\theta - (A + B\log(\eta(r_{\mathrm{x}})+\bar{b}))$$

Model: A, B, $\bar{b}$, r_{x}, κ_I, (r_{e}, κ_L)
Free: E_{r_0}, a_1



Model parameters from CoREAS simulations

doi:10.1016/j.astropartphys.2015.10.004

Reconstruction pipeline

- Station-level analysis
  - Digital filtering
  - RFI rejection
  - SNR cuts
- Event-level analysis
  - $N_{\mathrm{ant}} \geq 3$
  - Reconstruction of arrival direction and core position
  - Comparison with Tunka-133/Tunka-Grande reconstruction ($\Delta\Omega < 5^{\circ}$)
  - Signal correction (adjustment $f_c(t', \mathrm{SNR})$, $V \times V \times B$ correction)
  - Amplitude fits
  - Energy and shower maximum reconstruction
- Statistical analysis
  - Quality and efficiency cuts
  - Aperture and exposure estimation

For part of the analysis we use the Auger Offline software
Pierre Auger Collaboration, NIM A 635 (2011) 92

Aperture and exposure

Cosmic-ray flux

$$J(E) = \frac{\mathrm{d}^4 N}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}t} \approx \frac{\Delta N_{sel}(E)}{\Delta E}\frac{1}{\mathcal{E}(E)}$$

Estimation of exposure

$$\mathcal{E}(E) = \int_T \int_\Omega \int_S \varepsilon(E, t, \theta, \phi, x, y) \cos\theta \,\mathrm{d}S\,\mathrm{d}\Omega\,\mathrm{d}t = \int_T \mathcal{A}(E, t)\,\mathrm{d}t$$

$$\mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi, \quad \mathrm{d}S = \mathrm{d}x\,\mathrm{d}y$$

In case of radio measurements $\varepsilon(\phi) \neq \mathrm{const}$

$$(\theta, \phi) \to (\theta, \alpha) : \varepsilon = \varepsilon(E, t, \theta, \alpha, x, y), \quad \alpha = \alpha(\theta, \phi, \theta_{\mathbf{B}}, \phi_{\mathbf{B}})$$

$$\varepsilon = \varepsilon_R(E, \theta, \alpha, x, y)\,\varepsilon_a(E, \theta, \alpha)\,\varepsilon_i(E, x, y, t)$$

Benchmark of efficiency model

Calculation of 90% efficiency for mass composition study

Gen.	Years	Number of antennas	Expected events	Detected events	Efficiency
1a	2012/13	18	23	20	$0.85^{+0.05}_{-0.09}$
1b	2013/14	25	28	27	$0.96^{+0.02}_{-0.05}$
2	2015/16	44	14	14	$1.00^{+0.00}_{-0.07}$
3	2016/17	63	17	16	$0.94^{+0.04}_{-0.08}$
		Total	82	77	$0.94^{+0.02}_{-0.03}$

- Sufficient large footprint $\Rightarrow$ no bias due to deep protons
- Model gives reasonable predictions for all three generations of Tunka-Rex array
- Perfect agreement with measurements of full-efficient Tunka-133