Karlsruhe Institute of Technology

Tunka-Rex

Seven years of Tunka-Rex operation

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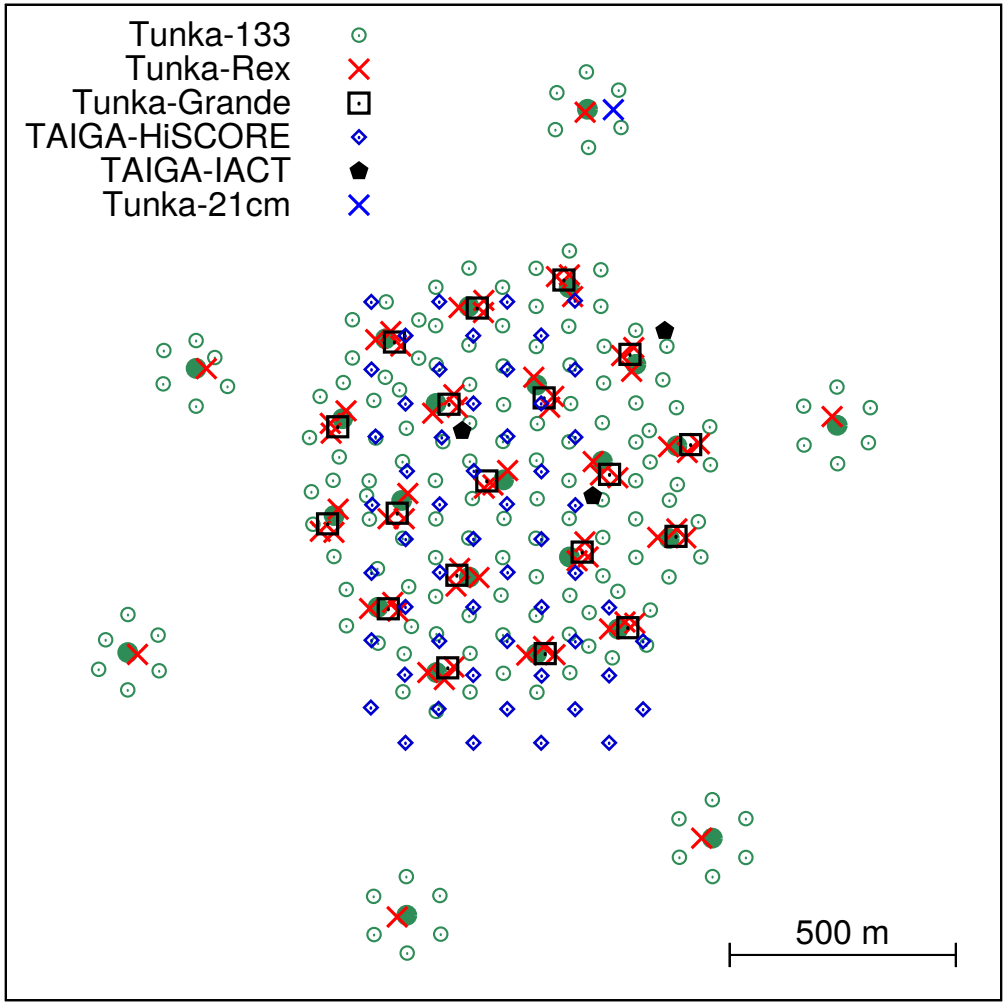
July 27, 2019

INSTITUTE FOR NUCLEAR PHYSICS

Tunka-133 → 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

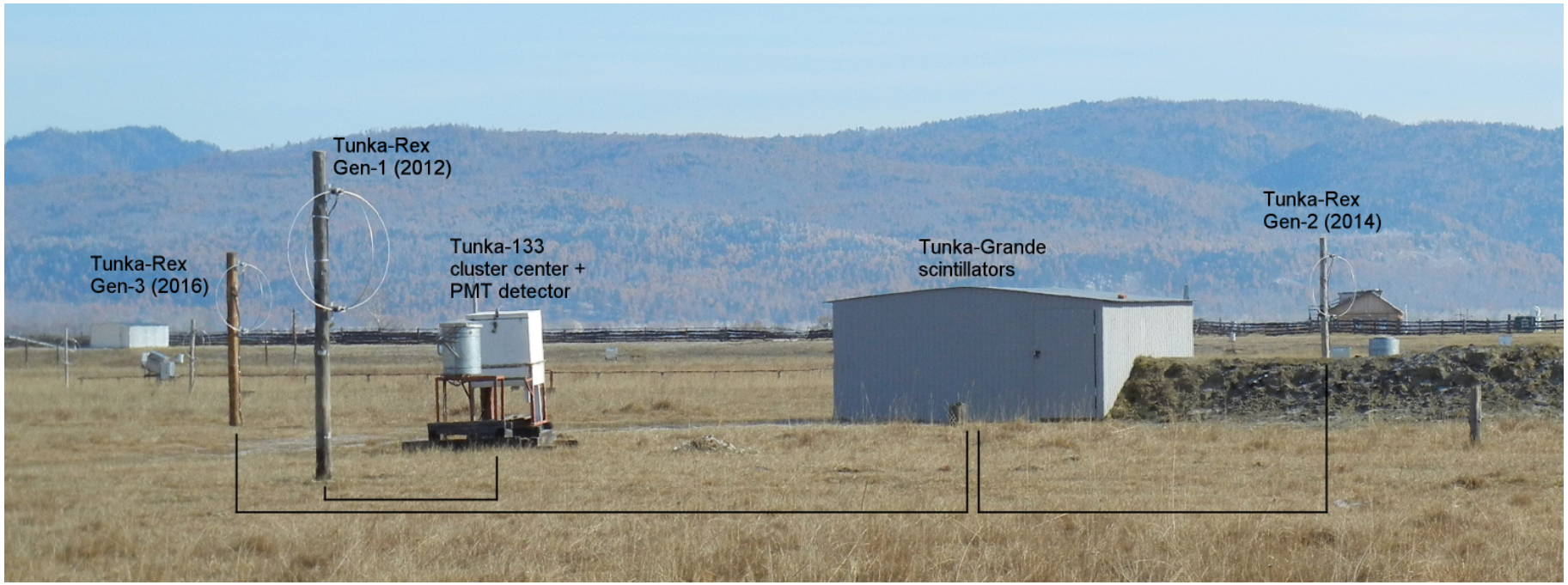
- Tunka-133 air-Cherenkov
- **Tunka Radio Extension** (Tunka-Rex)
- Tunka-Grande scintillators

Gamma ray detectors >TeV

- TAIGA-HiSCORE
- TAIGA-IACT

J.Phys.Conf.Ser. 1263 (2019) no.1, 012006

Single cluster



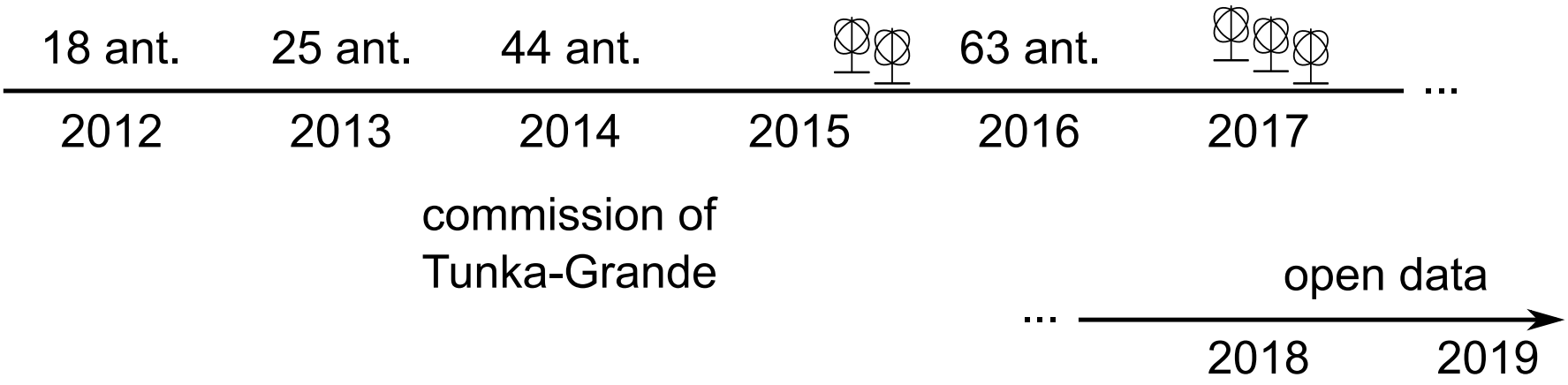
- 7 optical modules
- 8 m^2 (on-ground) + 5 m^2 (underground) scintillators
- 3 antenna stations (2 polarizations, 30–80 MHz)

Total: 19 (dense) + 6 (satellite) clusters

Tunka-Rex detector timeline

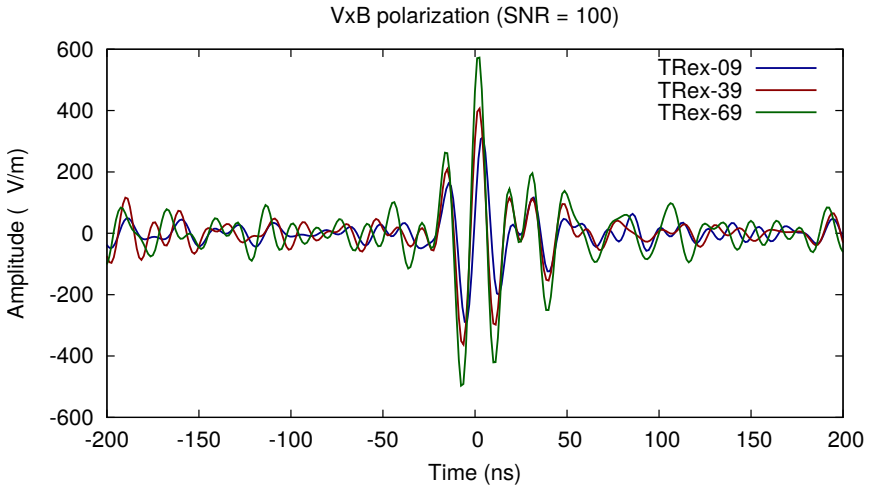
~100 events per season
triggered by Tunka-133

~1000 events per season
triggered by Tunka-133 & Tunka-Grande

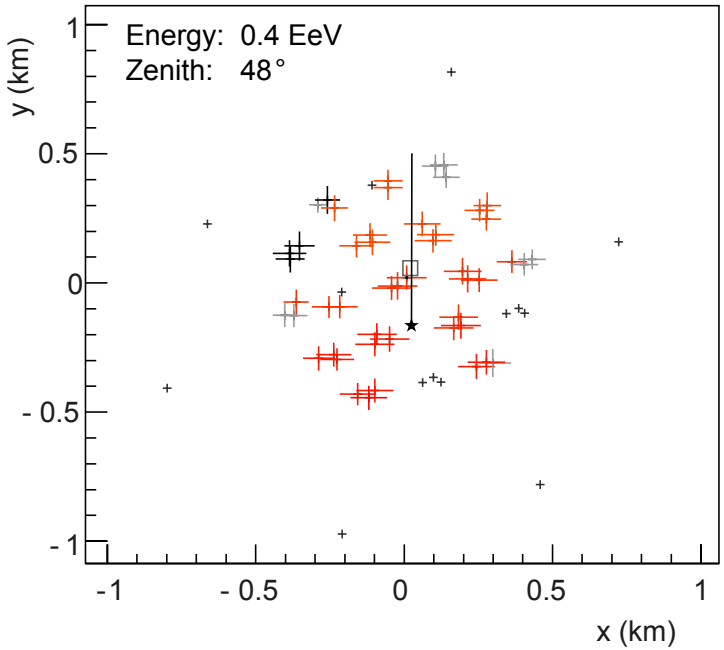


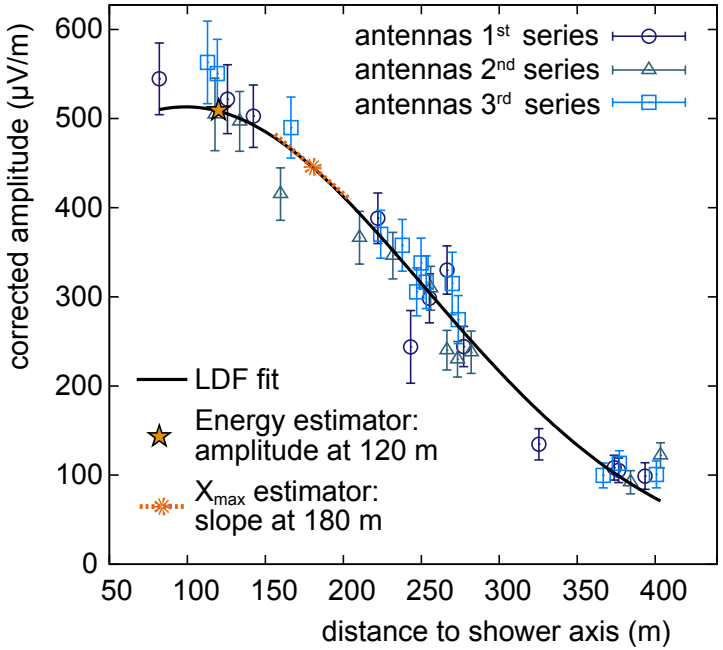
- Measurement season from October to April
- Starting from 2015 Tunka-Rex reached 85% uptime
- Currently **only** data with **Tunka-133 trigger** are used

Example of event

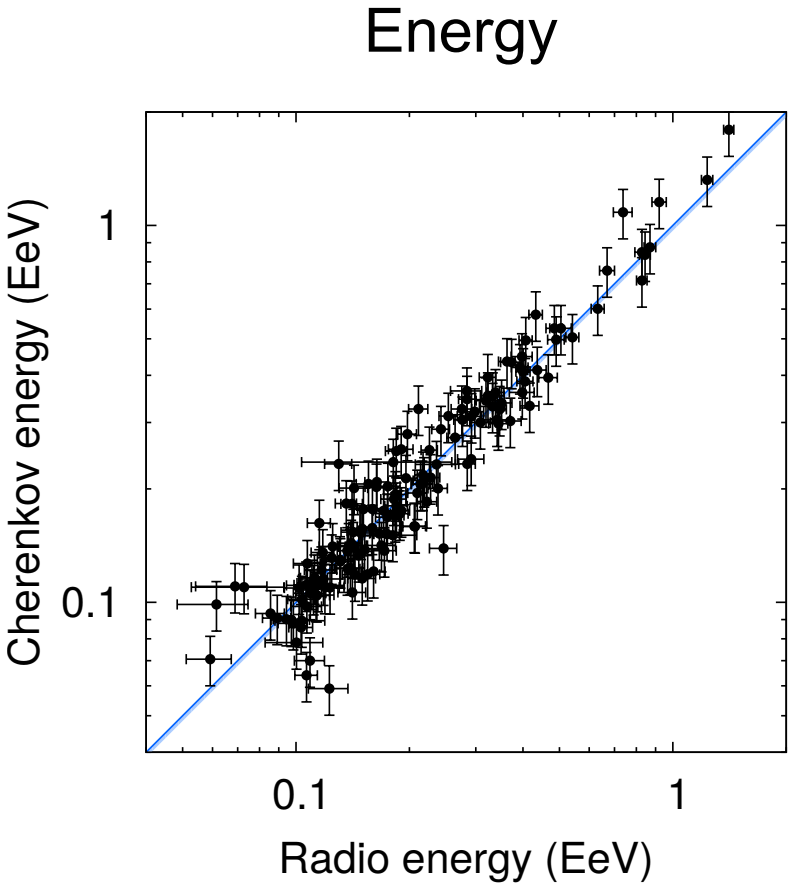


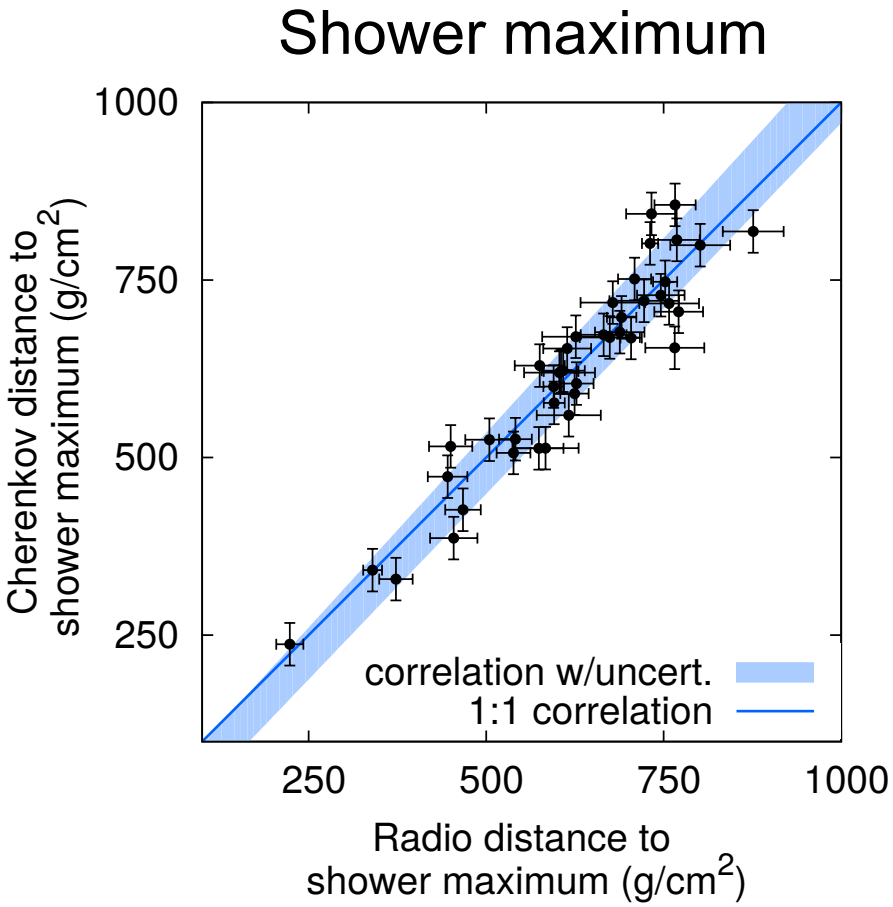
Asymmetry corrected LDF





Blind cross-check with Tunka-133





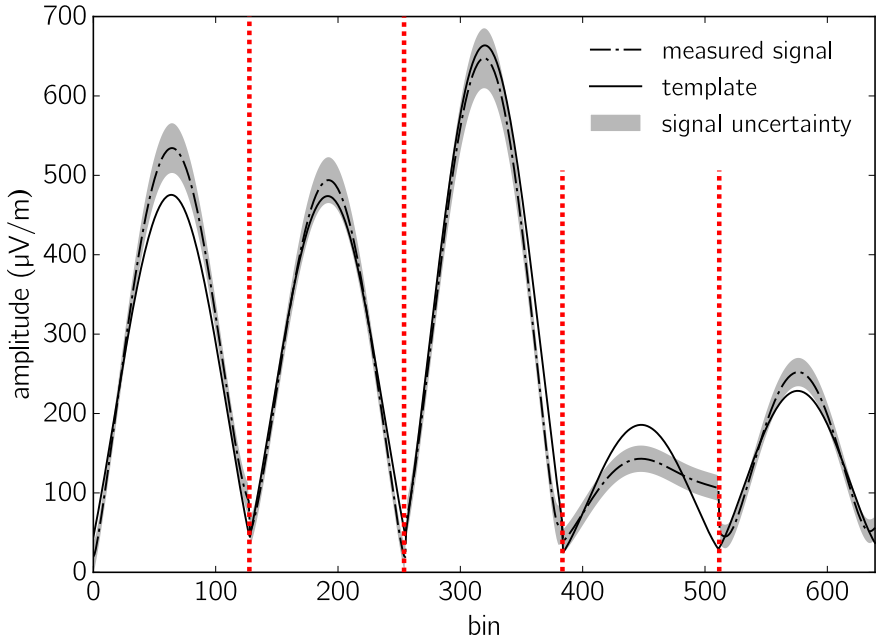
resolution: 15%

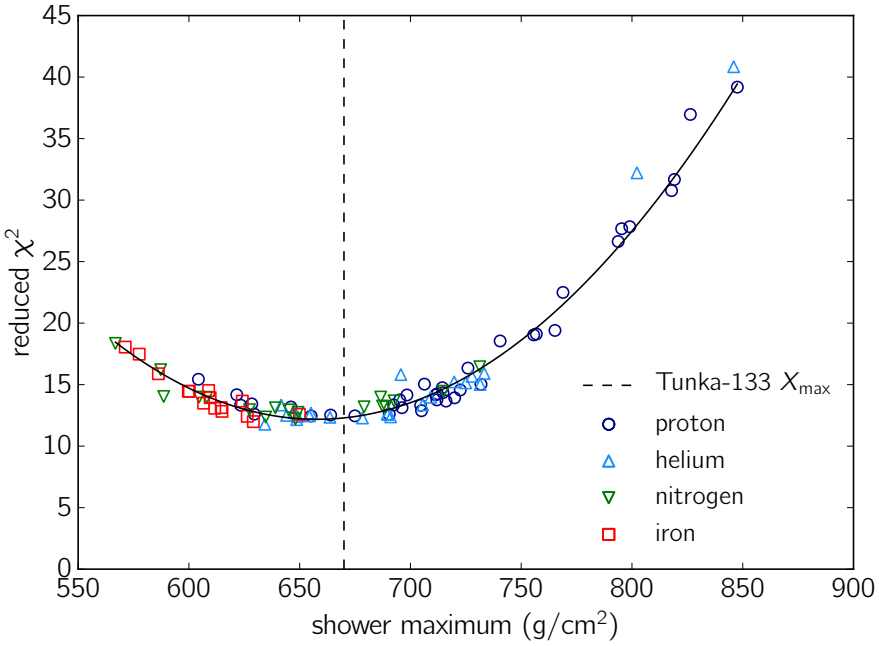
resolution: 38 g/cm^2

JCAP 1601 (2016) no.01, 052

Template fit method

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

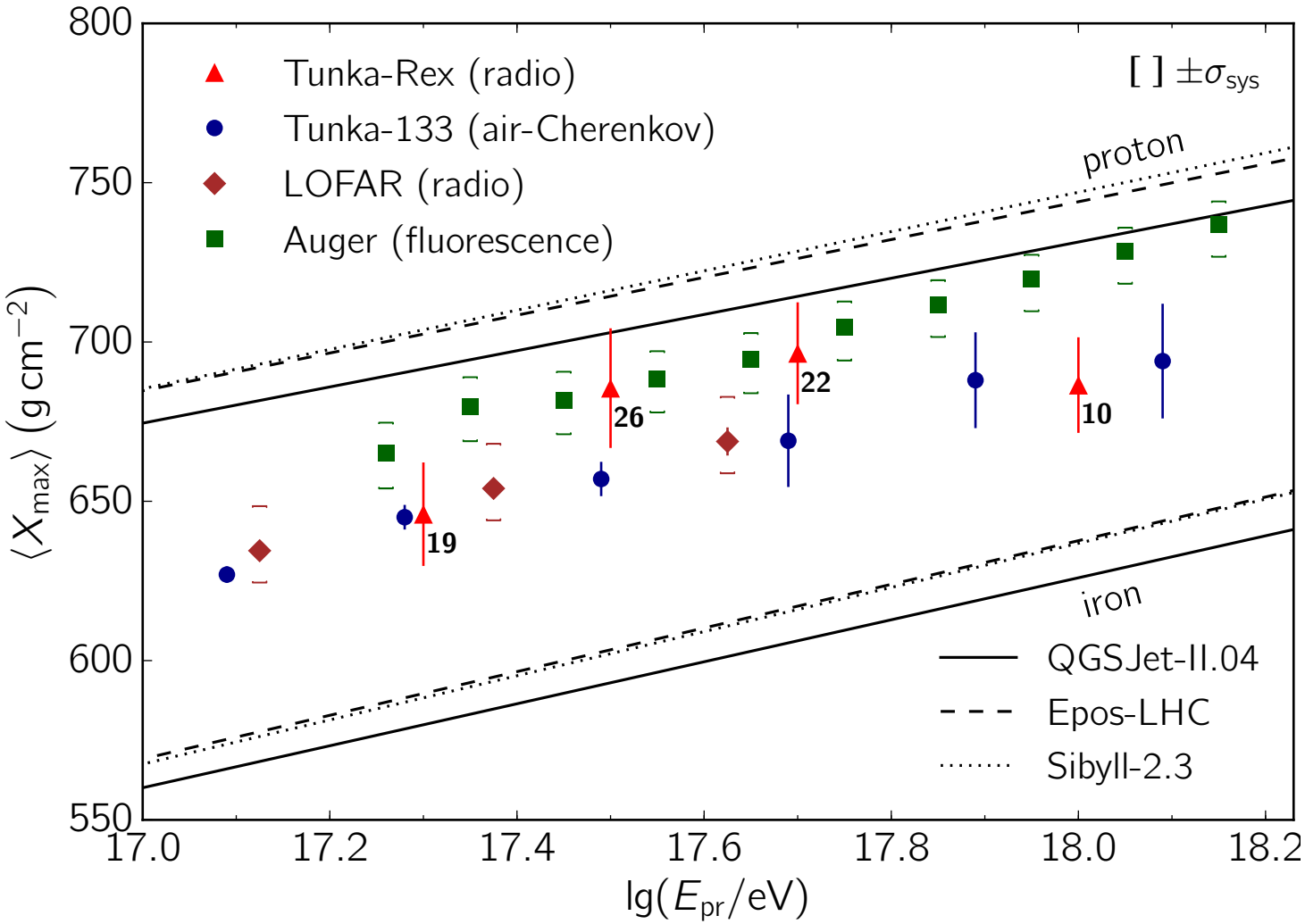




$X_{\max}$ resolution improved to 25-35 g/cm^2, E_{pr} resolution is 10%

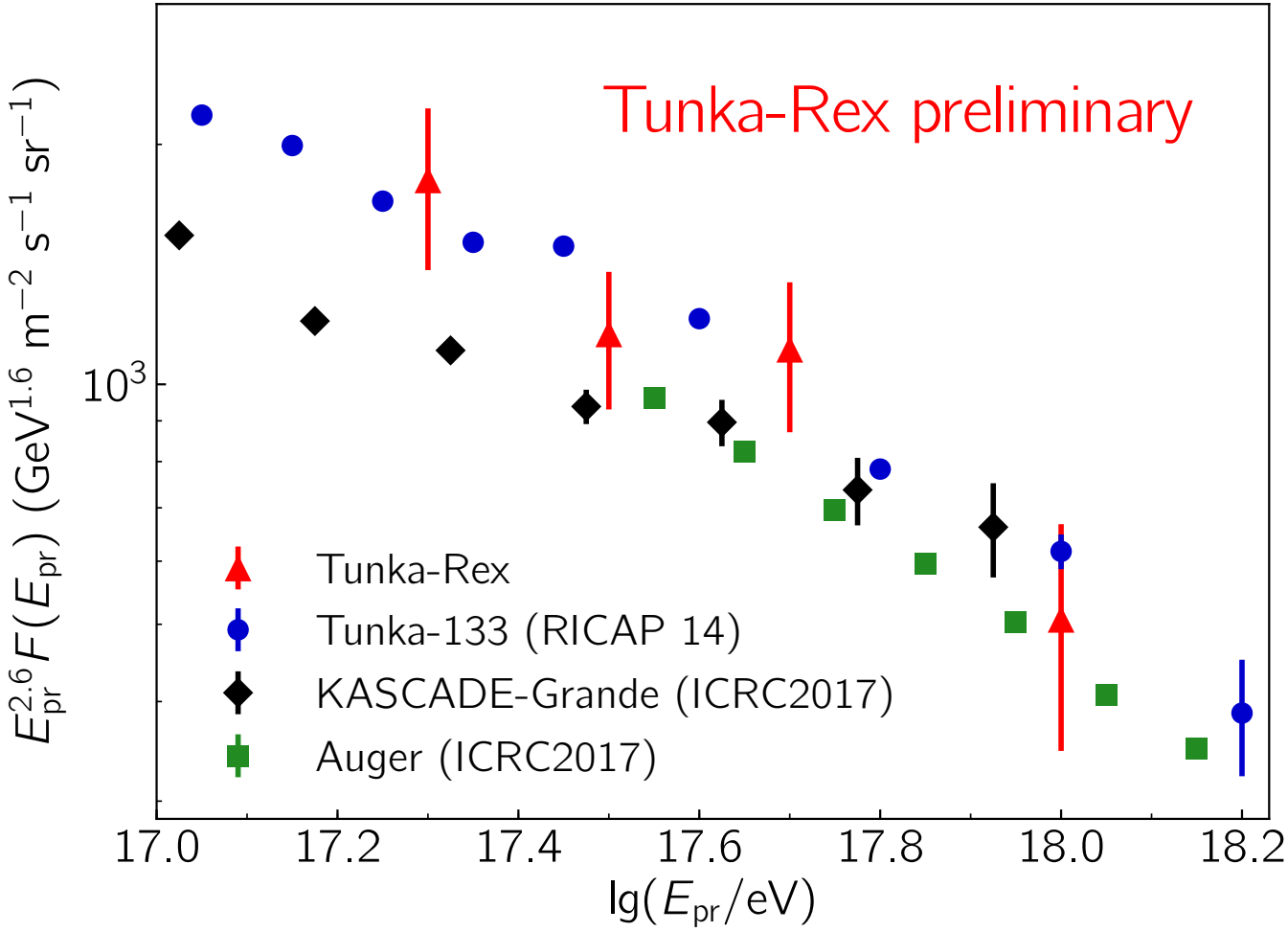
Phys.Rev. D97 (2018) no.12, 122004

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

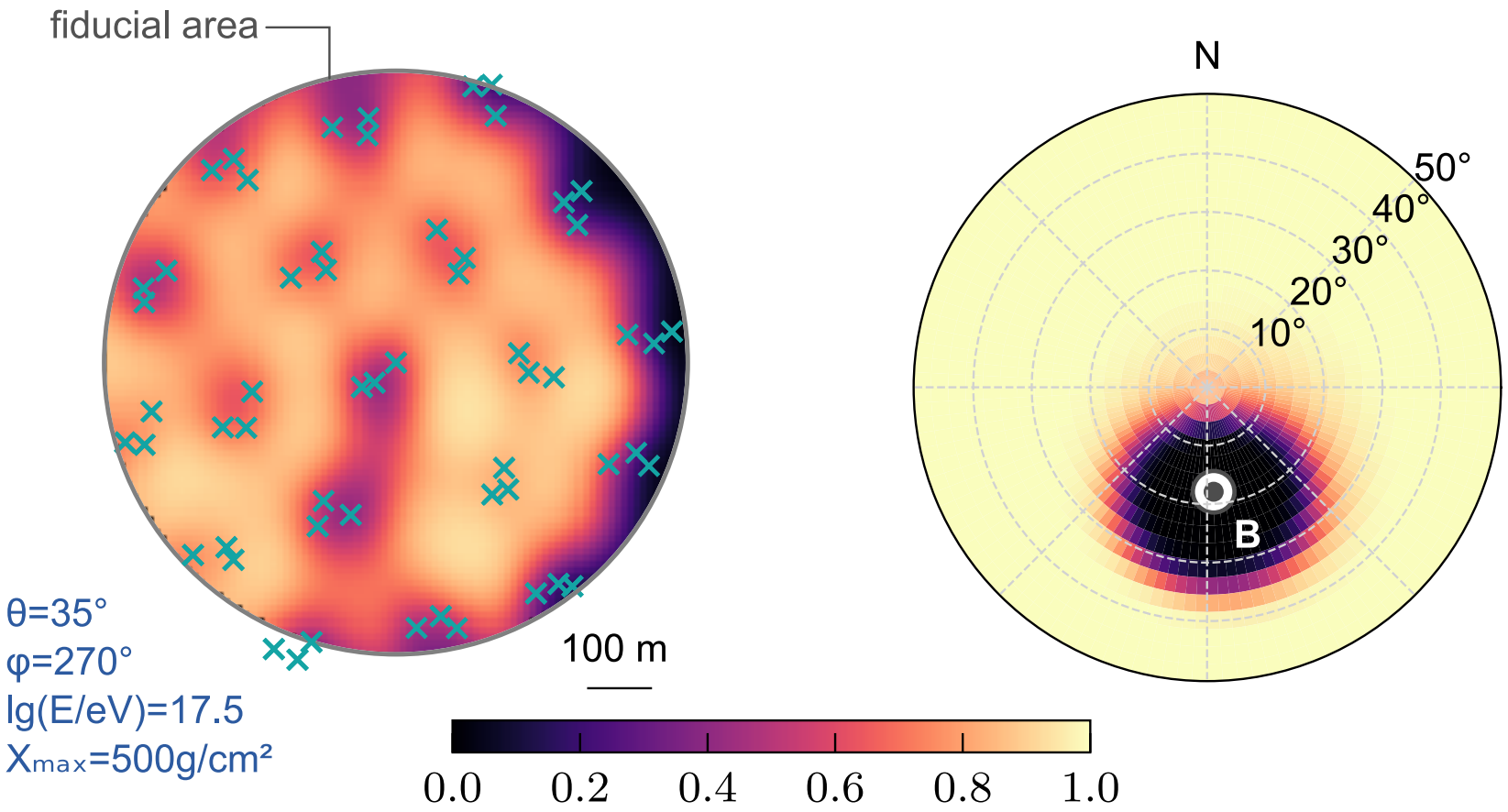


Phys.Rev. D97 (2018) no.12, 122004

Flux of cosmic rays



New estimation of efficiency

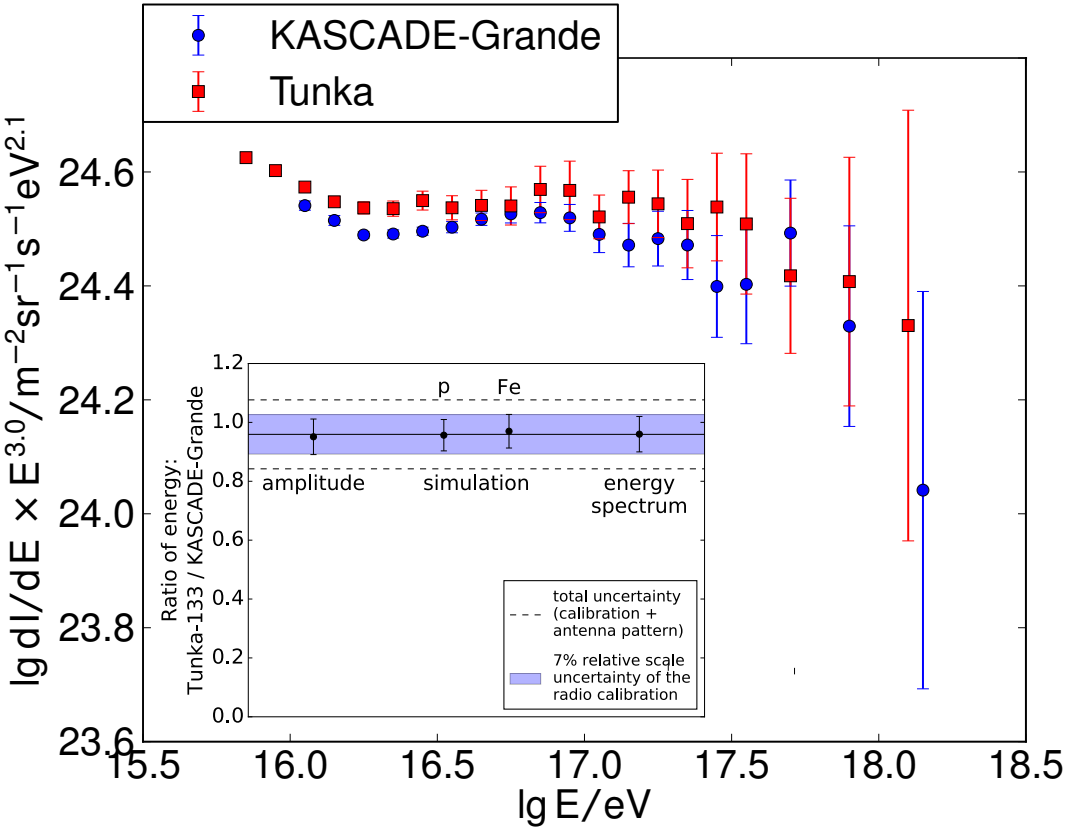


Predicted detection efficiency

see *PS3-182* and *PoS(ICRC2019)331*

Comparison of energy scales via radio

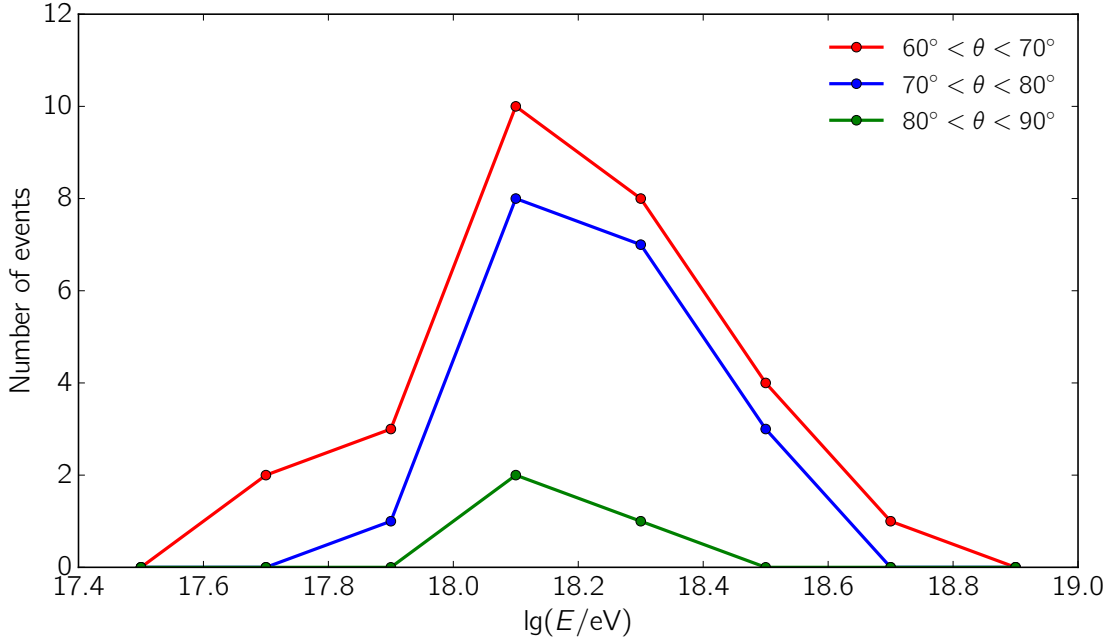
Independent check via LOPES and Tunka-Rex has shown that energy scales of KASCADE-Grande and Tunka-133 are consistent within 10%

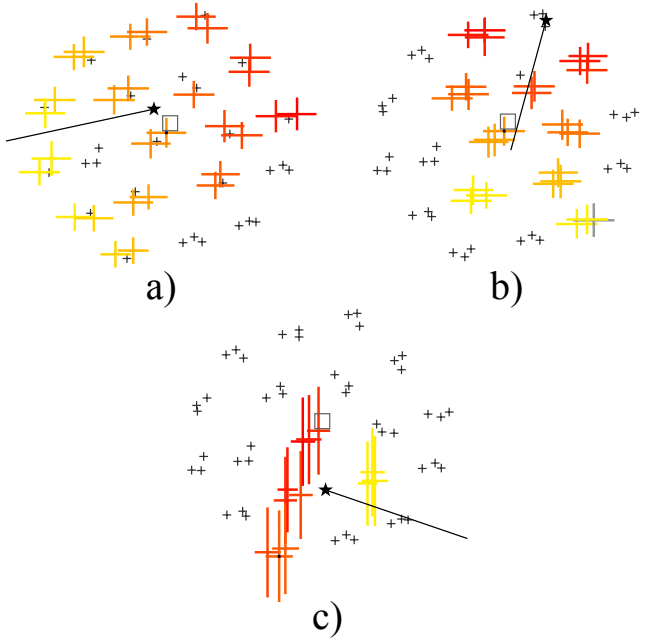


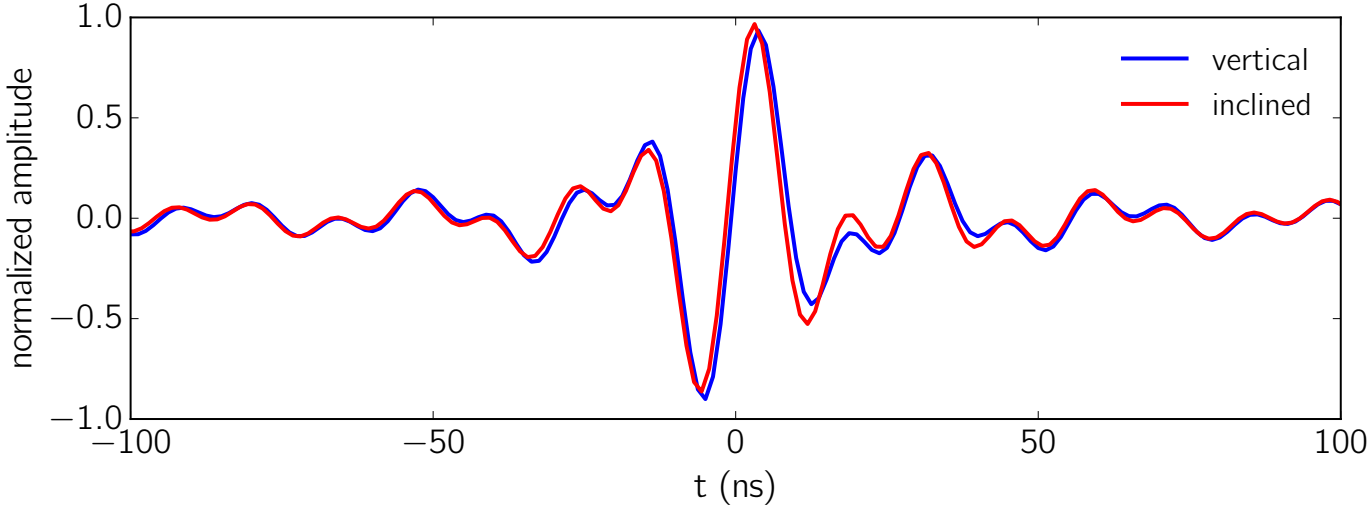
Phys.Lett. B763 (2016) 179-185

Developing techniques for the next-generation detectors

Detection of inclined air-showers





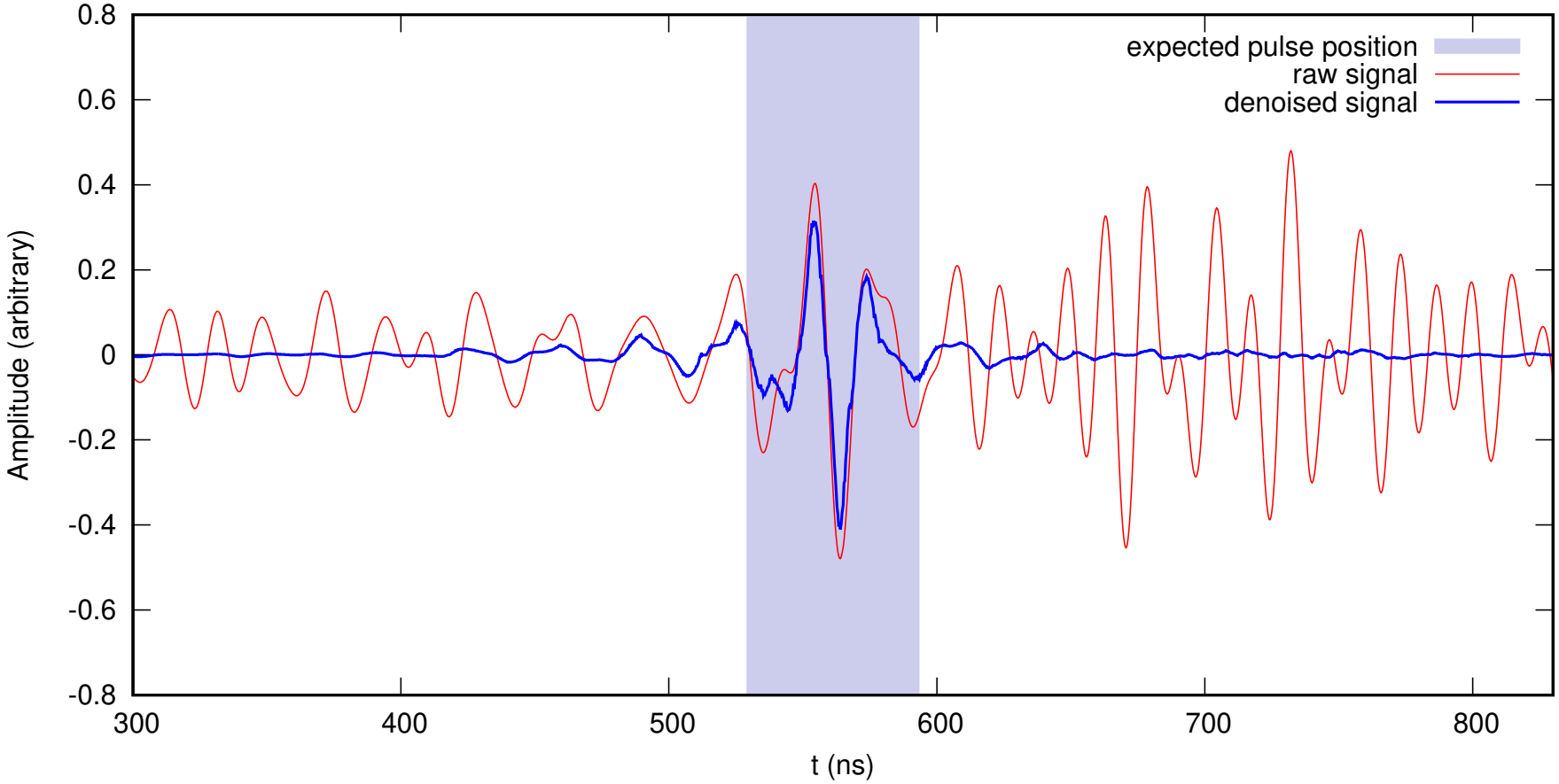


a) $60° - 70°$
b) $70° - 80°$
c) $80° - 90°$

arXiv:1812.03724

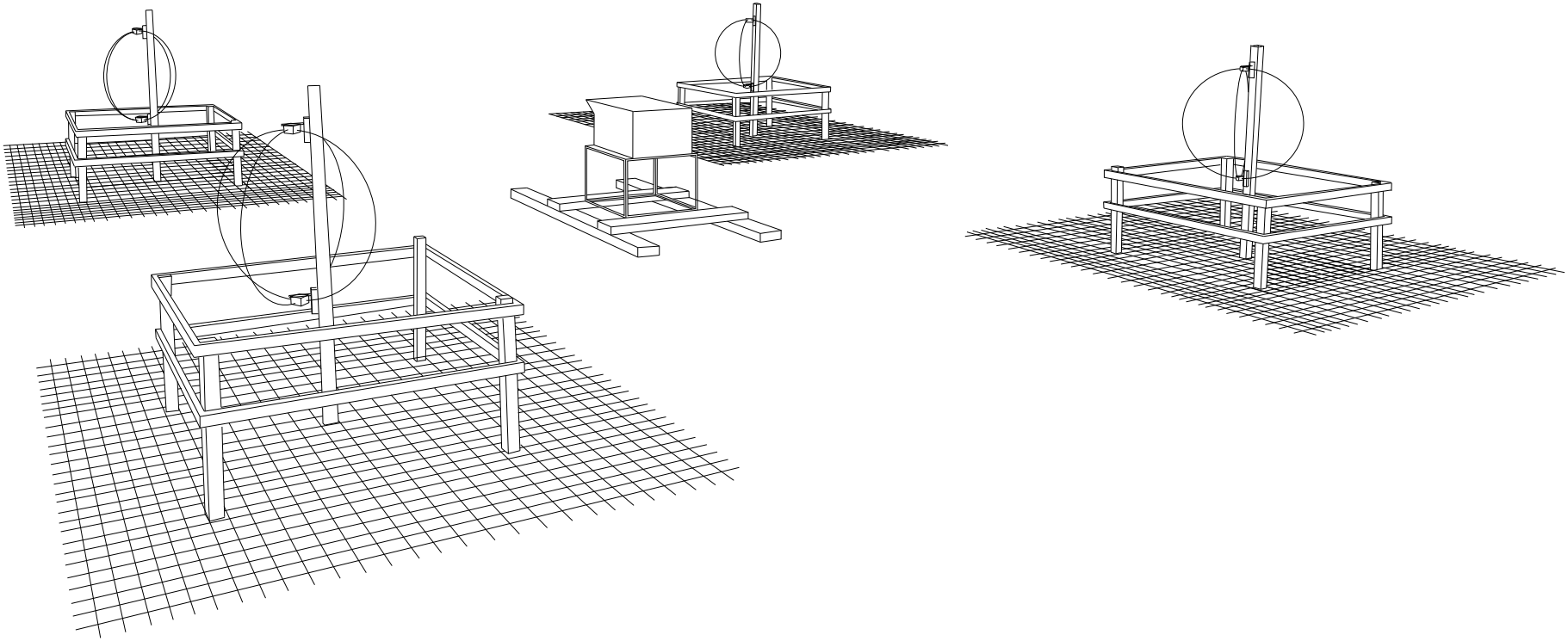
Deep learning for the signal denoising

Example of the autoencoder performance on a measured Tunka-Rex trace showing successful denoising of the typical RFI after the signal.



arXiv:1906.10947

Tunka-Rex based pathfinder arrays



- Engineering multi-purpose array for 21cm cosmology and self-trigger research — see *PoS(ICRC2019)320*
- High-altitude radio air-shower array @ Tien-Shan, Kazakhstan (3300 m a.s.l.) — first data

Summary and outlook

- Tunka-Rex smoothly 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 (PoS(ICRC2019)395)**

- 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

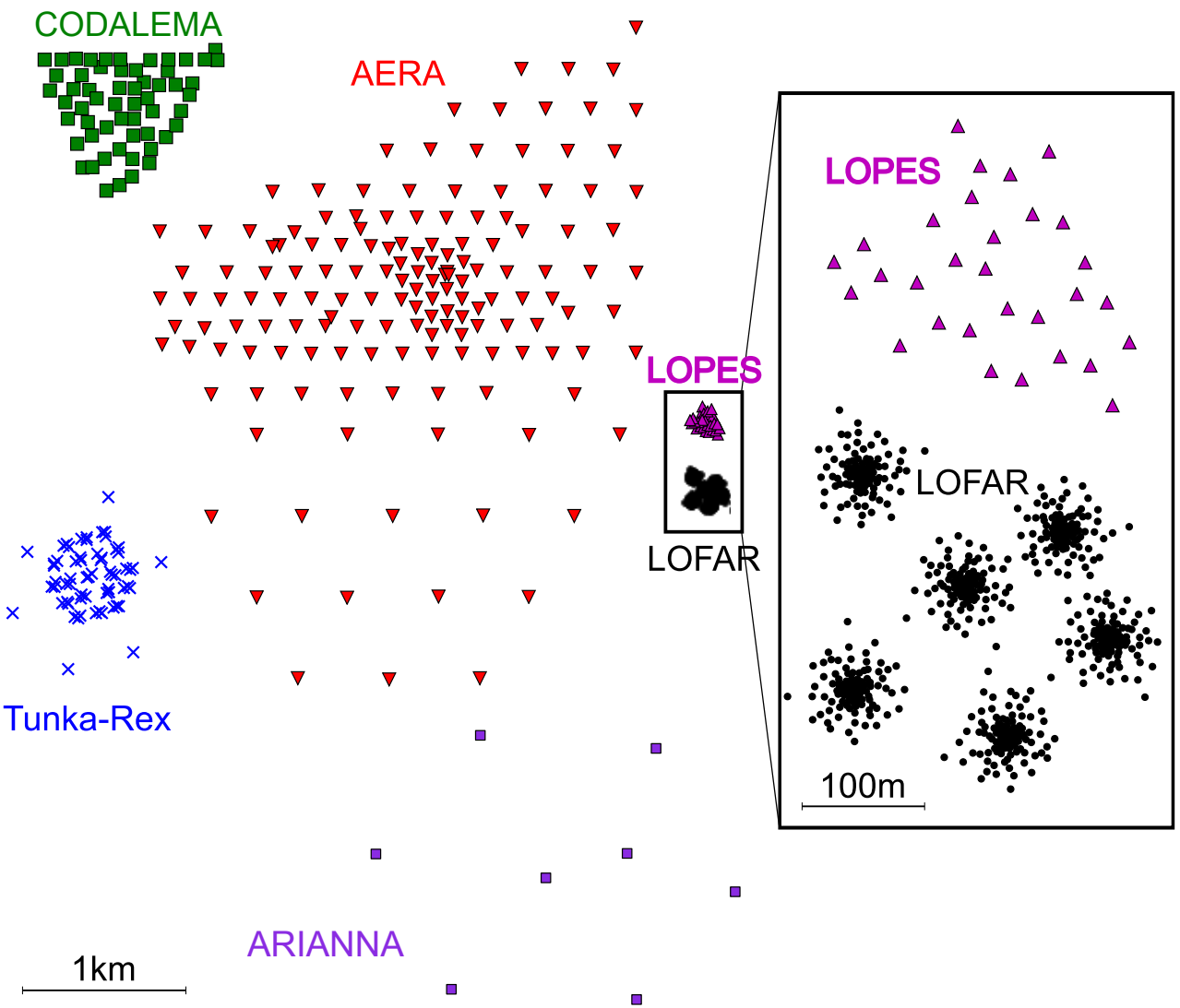
Open data and education (*arXiv:1906.10425*, *PoS(ICRC2019)284*)

Tunka-Rex data + software 001 101 .10 astroparticle.online

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

BACKUP

Digital radio detection of air-showers



First generation:
LOPES
CODALEMA

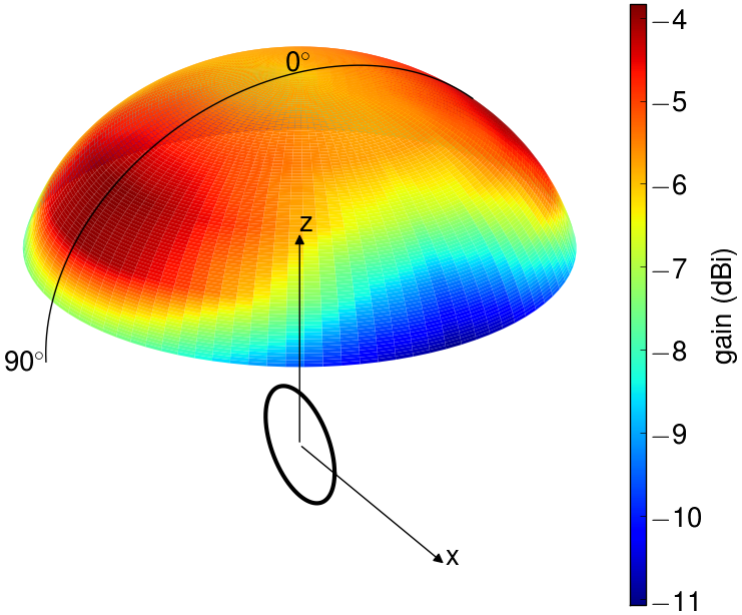
Second generation:
AERA
Tunka-Rex

Third generation:
ARIANNA
GRAND, Radio@SP

Radiotelescopes:
LOFAR
SKA

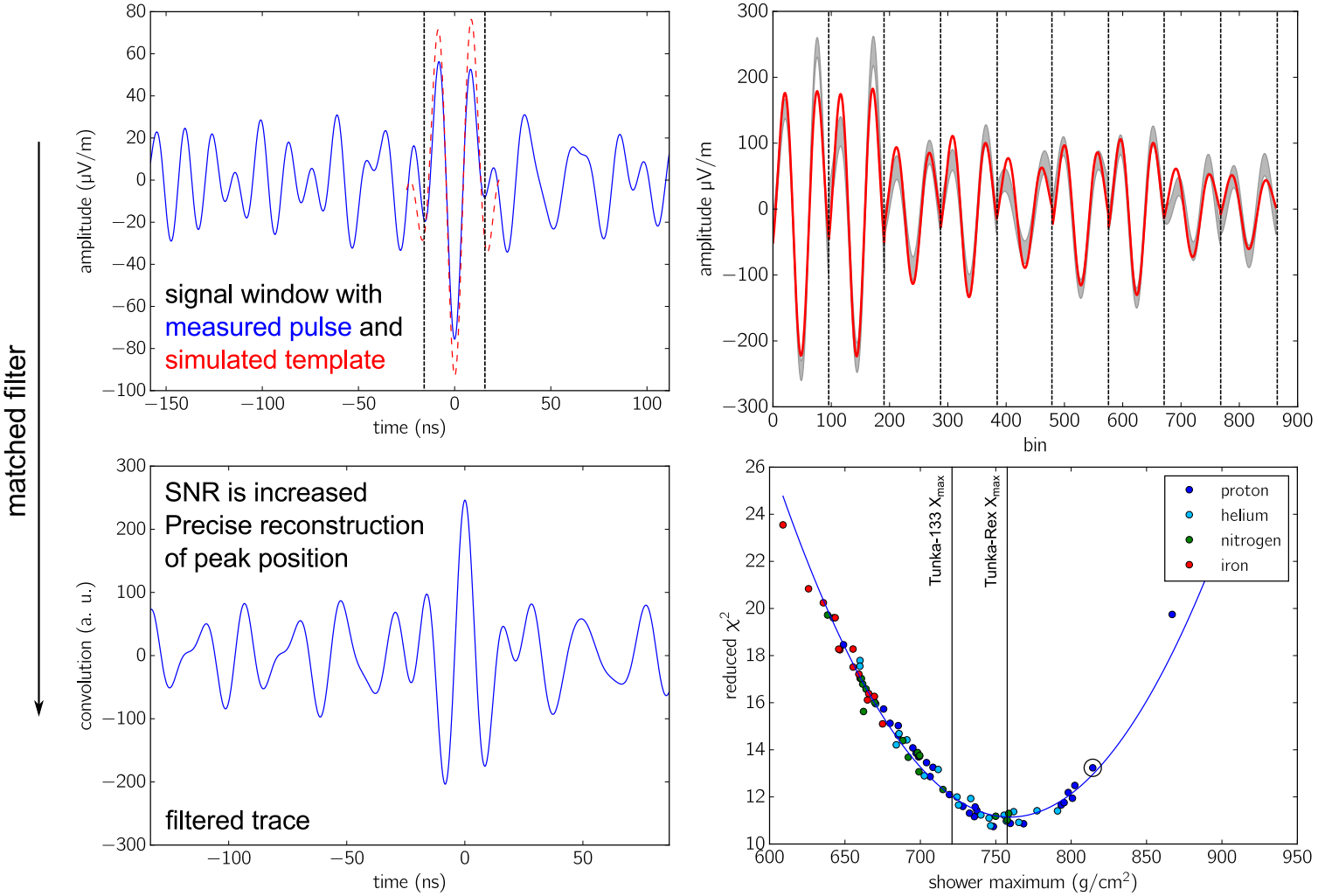
Amplitude calibration

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



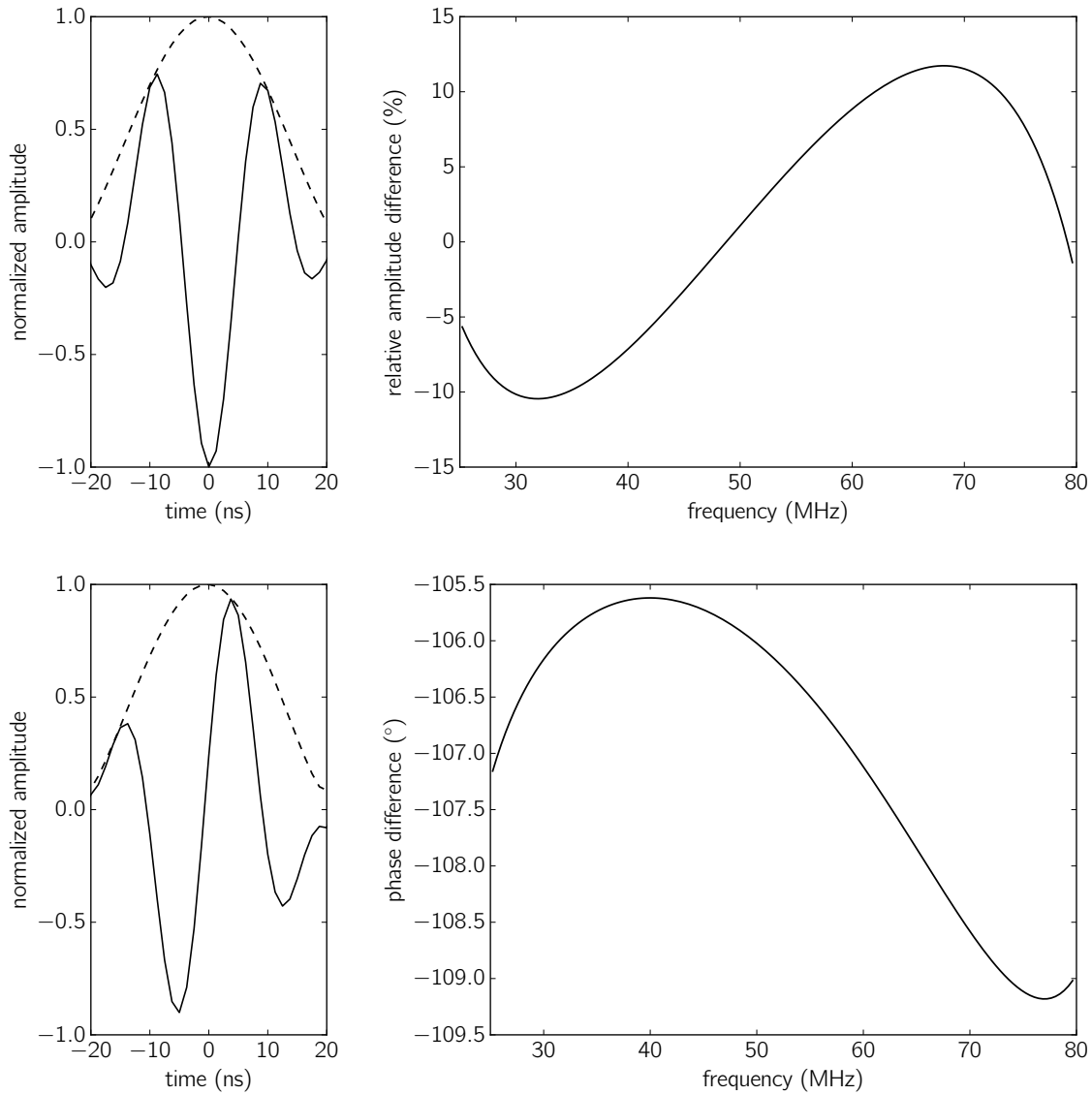
doi:10.1016/j.nima.2015.08.061

Towards ultra-precise reconstruction



Accurate calibration and broad band are required!

Difference between simulation and data



- Absolute scale is tested by direct measurements
- The small relative difference in spectra does not have significant impact on pulse shape
- The significant difference in phases changes pulse shape dramatically
- Envelopes of the measured and simulated signals are in very good agreement

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 ($\Delta\Omega < 5°$)
  - 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

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

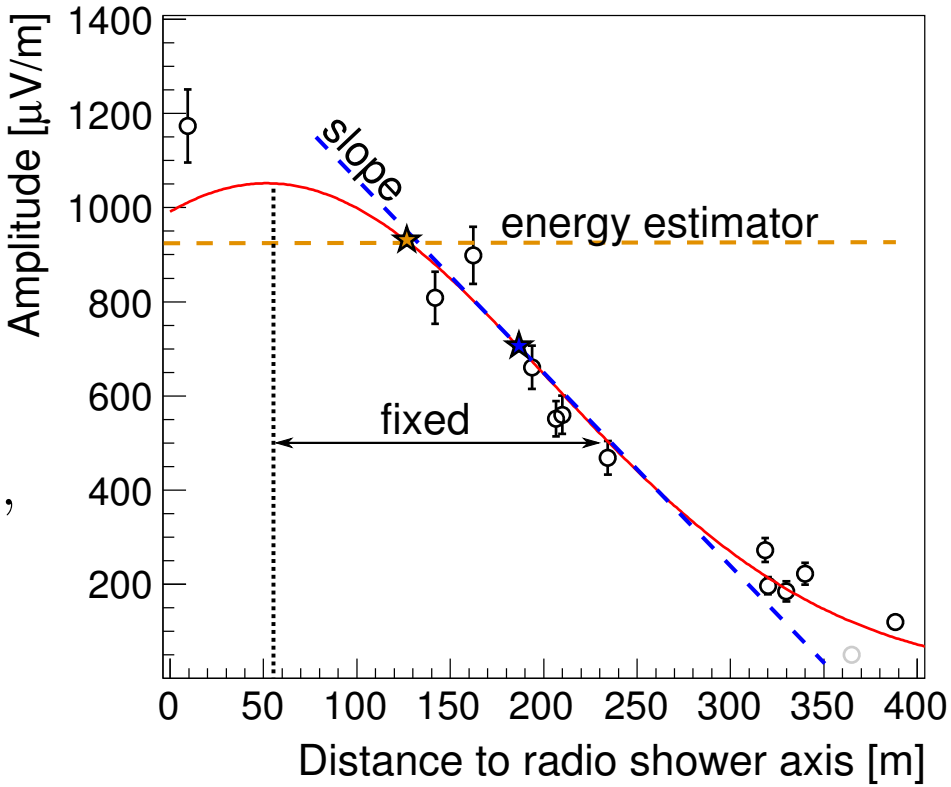
$$a_2(\theta, E_\mathrm{pr}^\mathrm{est}) = a_{20}(E_\mathrm{pr}^\mathrm{est})+a_{21}(E_\mathrm{pr}^\mathrm{est})\cos\theta\,,$$

Air-shower parameters

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

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

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

Signal processing

Signal reconstruction and adjustment

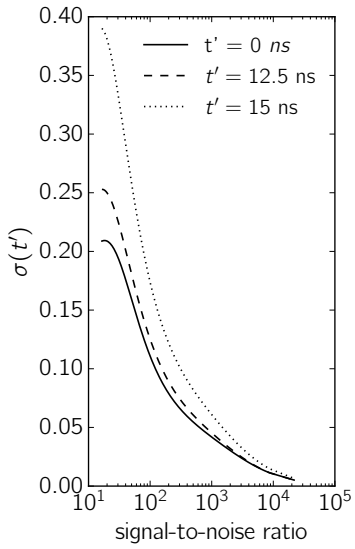
- Median filter
- Sliding noise window
- Total signal $u(t) = \sqrt{u^2_{\mathbf{v}\times\mathbf{B}}(t) + u^2_{\mathbf{v}\times\mathbf{v}\times\mathbf{B}}(t)}$
- Uncertainty $\sigma(t', \mathrm{SNR})$ and correction $u(t') \to u(t')(1 + f_c(t', \mathrm{SNR}))$

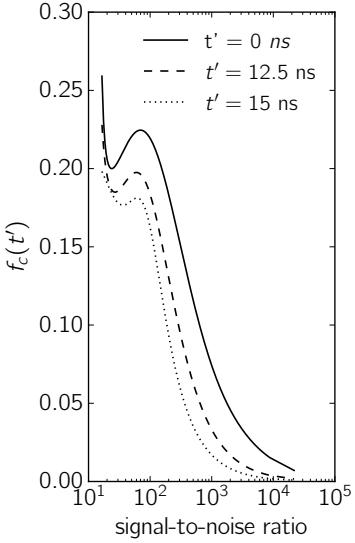
Quality cuts

- RFI rejection (see talk by D. Shipilov)
- Neighborhood SNR
- Full pulse width

$$\sigma, f_c(t', \mathrm{SNR}) = L_1^{\sigma, f_c}(t', \mathrm{SNR}) + L_2^{\sigma, f_c}(t', \mathrm{SNR})$$

$$L_{1,2}^{\sigma, f_c}(t', \mathrm{SNR}) = \frac{a_{1,2}^{\sigma, f_c}(t') \cdot \mathrm{SNR}}{\left(\mathrm{SNR} - b_{1,2}^{\sigma, f_c}(t')\right)^2 + c_{1,2}^{\sigma, f_c}(t')}$$

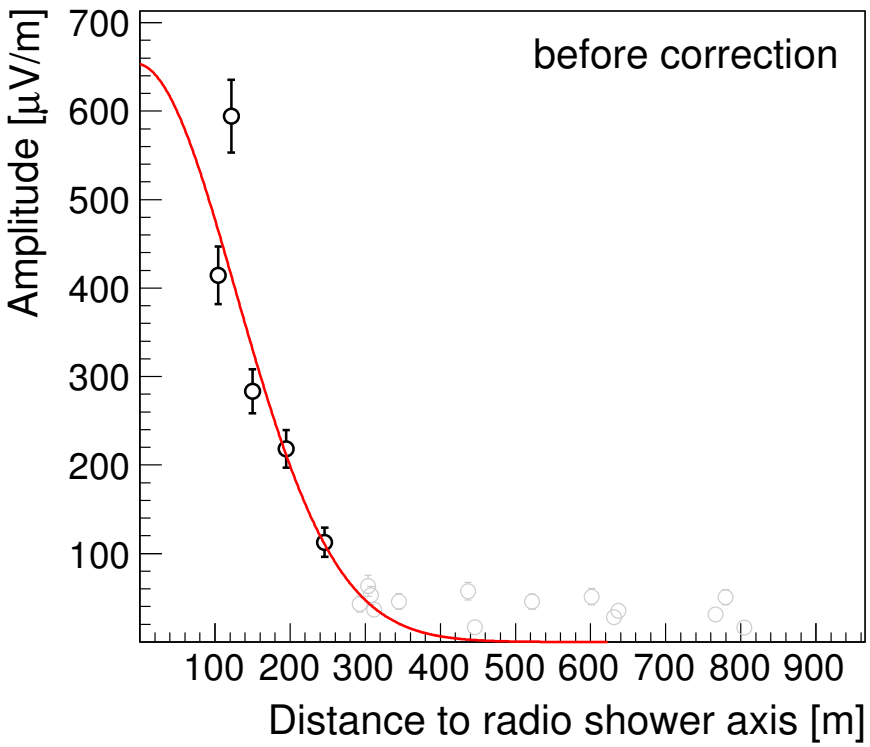


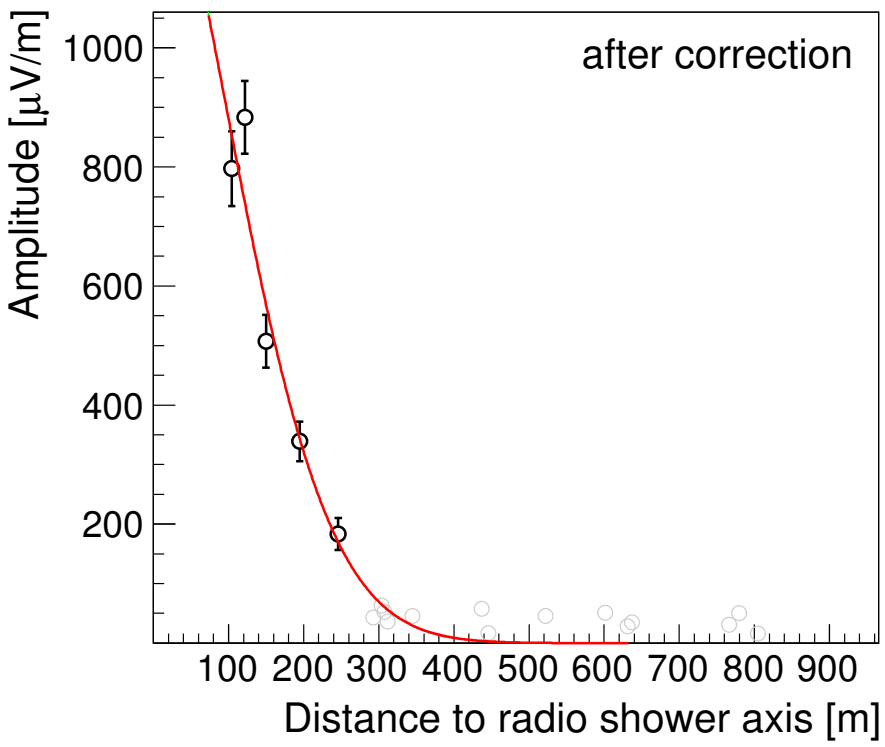


Asymmetry correction of LDF

Correction operator $\hat{\mathrm{K}} = \left(\varepsilon^2 + 2\varepsilon\cos\phi_\mathrm{g}\sin\alpha_\mathrm{g} + \sin^2\alpha_\mathrm{g}\right)^{-\frac{1}{2}}$

α_g is geomagnetic angle, $\varepsilon = 0.085$ is asymmetry, ϕ_g is azimuth of antenna





Slope (η) sensitivity to shower maximum $\delta\eta \Leftrightarrow \delta X_\mathrm{max} \lesssim 70$ g/cm^2

Energy estimator works for all $\alpha_\mathrm{g} > 0$

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 $\varepsilon(\phi) \neq \mathrm{const}$

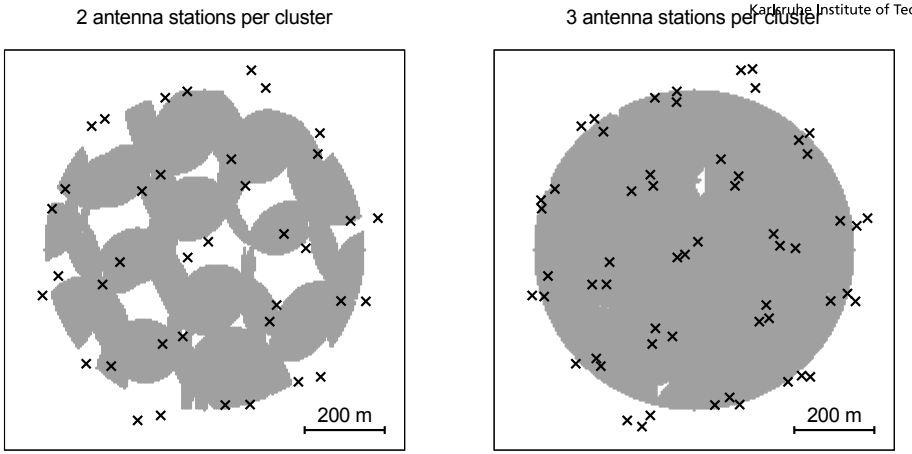
$$(\theta,\phi) \to (\theta,\alpha) : \varepsilon = \varepsilon(E,t,\theta,\alpha,x,y), \quad \alpha = \alpha(\theta,\phi,\theta_{\mathbf{B}},\phi_{\mathbf{B}})$$

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

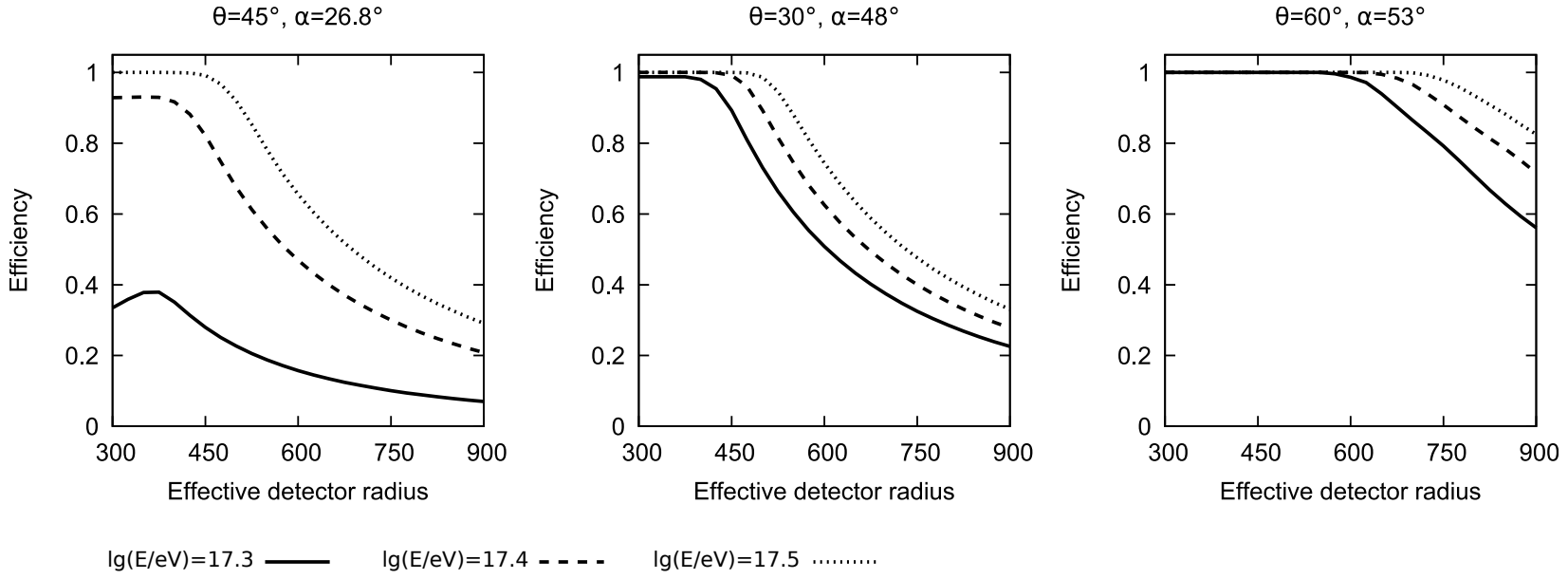
Effective radius of Tunka-Rex

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

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

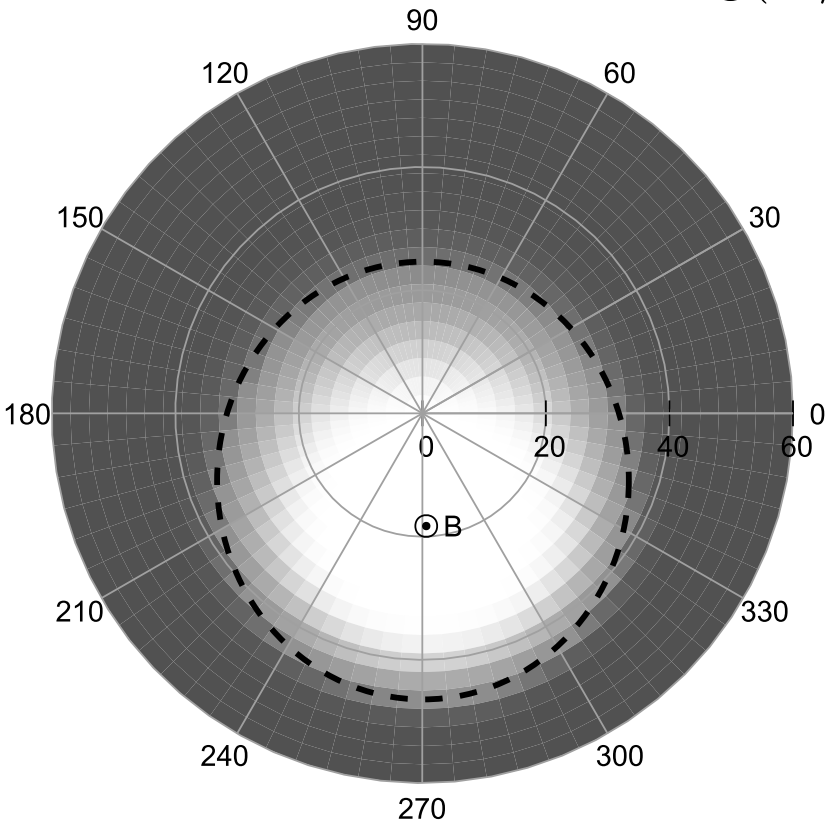


$$\theta = 45^\circ, \alpha = 27^\circ, \lg(E/\text{eV}) = 17.3$$

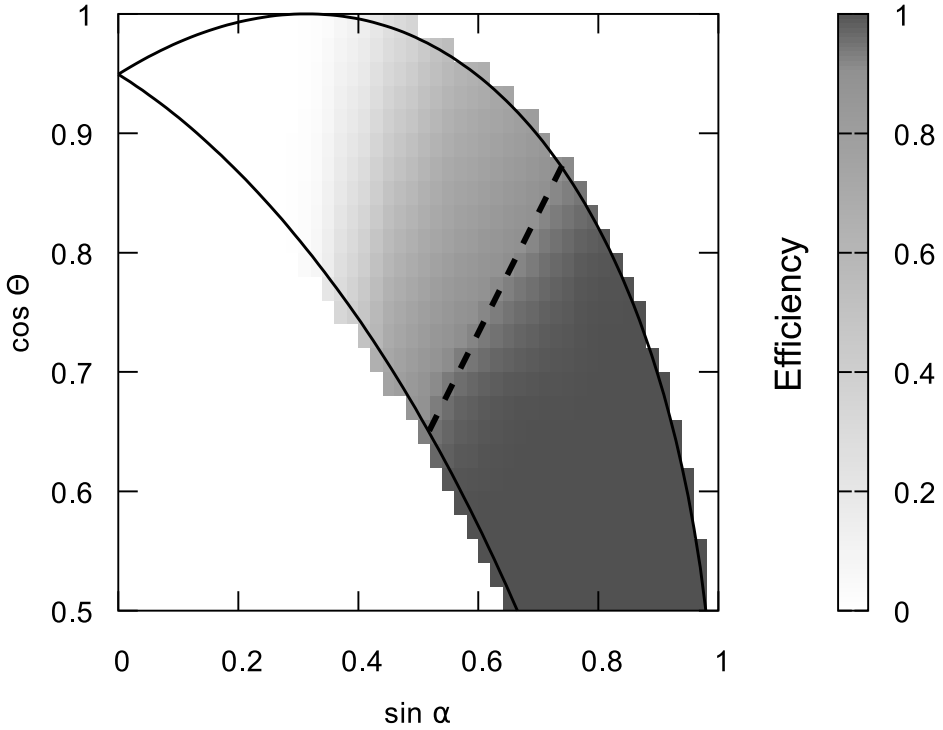


Angular efficiency

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



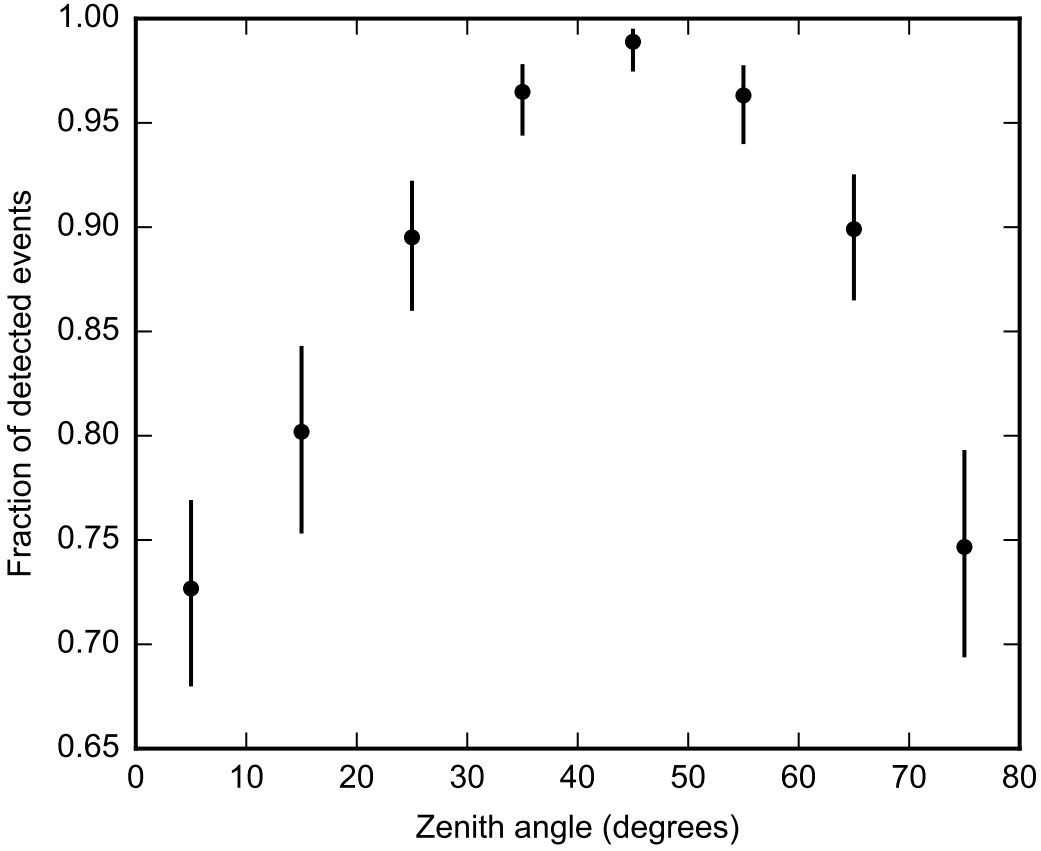
(θ, ϕ)



$(\cos\theta, \sin\alpha)$

[arXiv:1712.00974]

Comparison with simulations



- Model is tuned against data, agreement in range 30–60°
- Need dependence on antenna pattern and distance to source

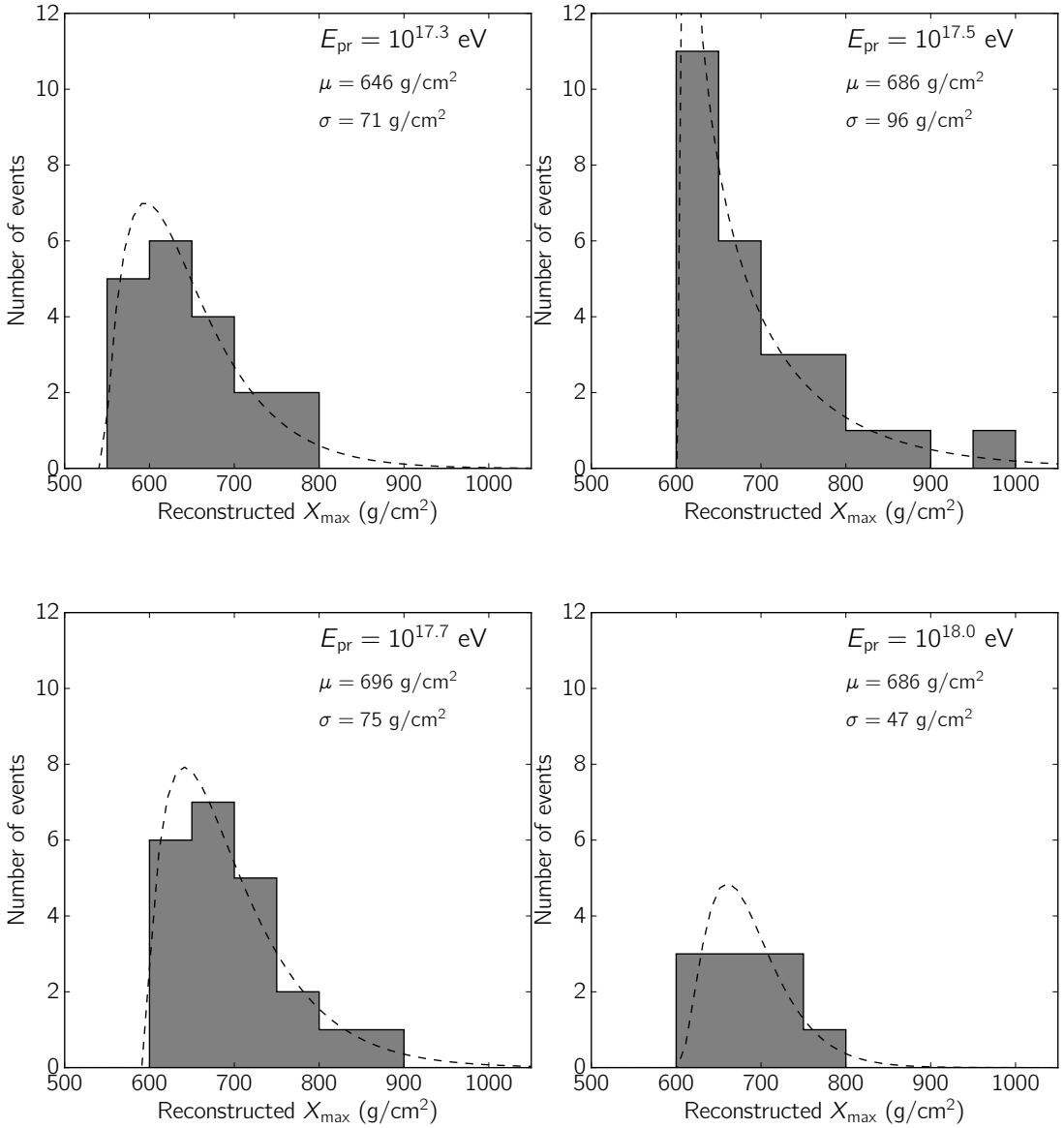
Benchmark of efficiency model

Calculation of 90% efficiency for mass composition study

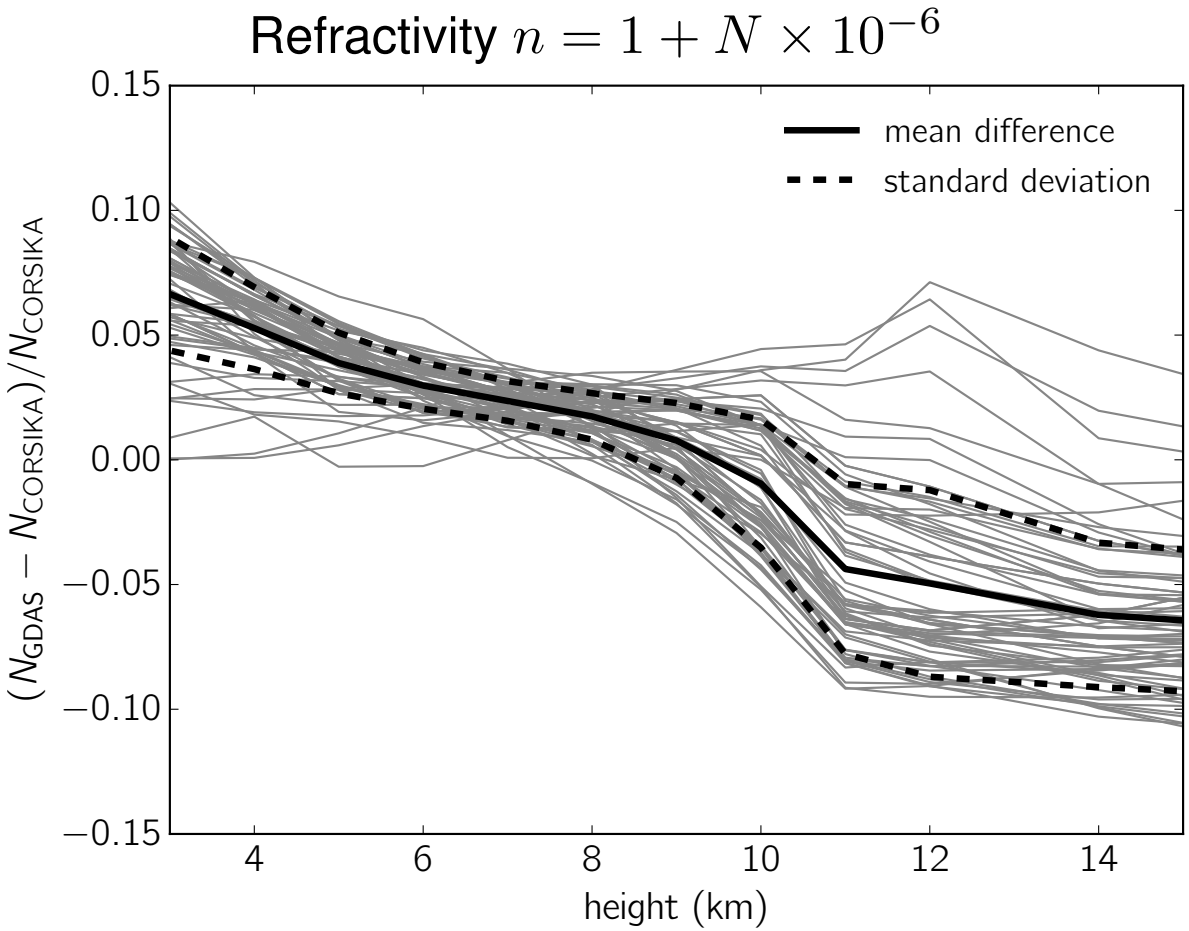
Gen.	Years	Number of antennas	Expected events	Detected events	Efficiency
1a	2012/13	18	23	20	$0.85^{+0.05}_{-0.09}$
1b	2013/14	25	28	27	$0.96^{+0.02}_{-0.05}$
2	2015/16	44	14	14	$1.00^{+0.00}_{-0.07}$
3	2016/17	63	17	16	$0.94^{+0.04}_{-0.08}$
		Total	82	77	$0.94^{+0.02}_{-0.03}$

- 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

Distribution of selected events



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%)