Radio Extension of Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy

Dmitriy Kostunin for the Tunka-Rex Collaboration
September 26, 2017

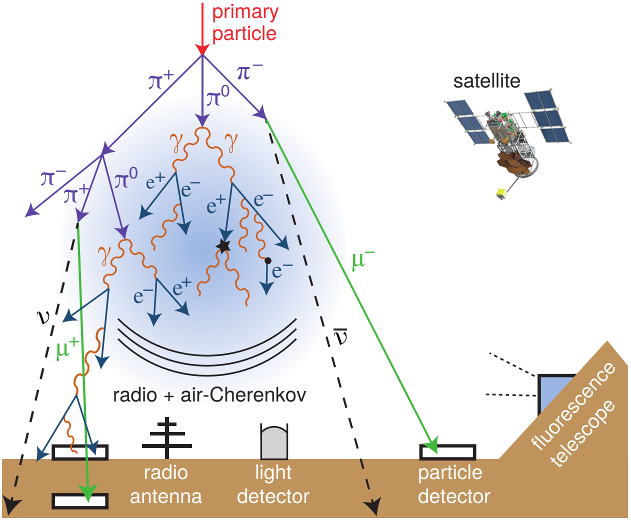
INSTITUT FÜR KERNPHYSIK

Outline

- General introduction in radio detection technique
- Review of historical and modern experiments
- Tunka Radio Extension as an example of large-scale array
- Radio detection of inclined air-showers and ultra-high energy neutrinos

General introduction in radio detection technique

Air-showers detection



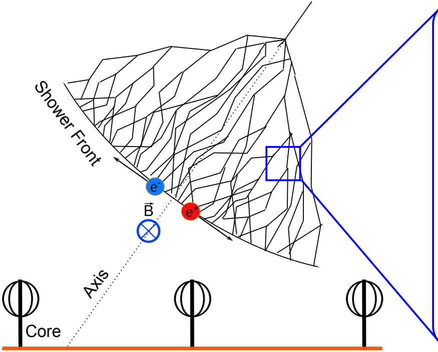
Radio emission processes

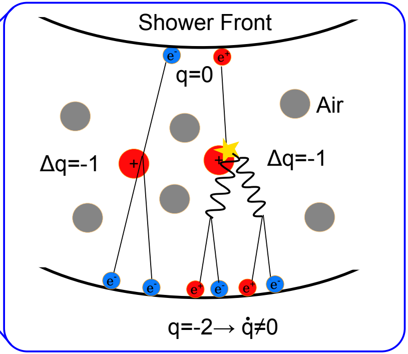
Geomagnetic effect

- Time-varying transverse currents
- Polarization along Lorentz force
- Dominant effect ($\sim \sin\alpha$)

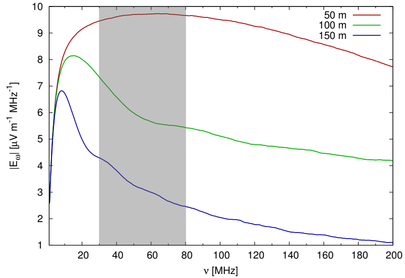
Askaryan effect

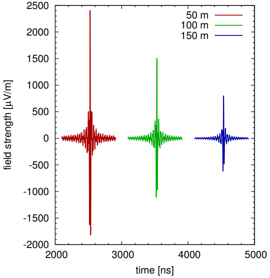
- Time-varying net charge
- Radial polarisation
- Second order effect ($\approx 10\%$)

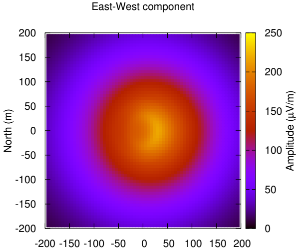


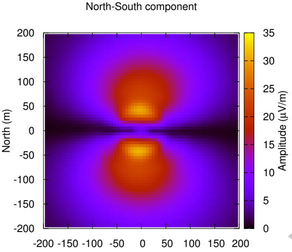


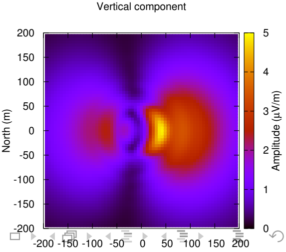
Properties of radio signal



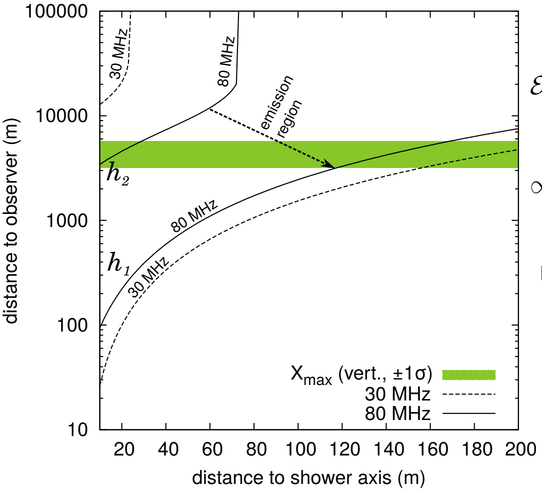








Coherence regions



$$\mathcal{E}_\nu(r) = \kappa \int_{h_1^\nu(r,n_r)}^{h_2^\nu(r,n_r)} \frac{N(h)}{h} \mathrm{d}h \propto$$

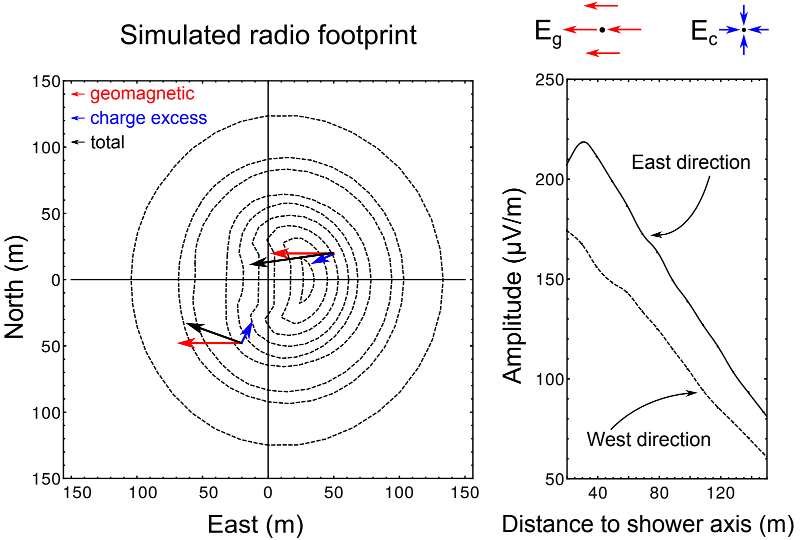
$$\propto \exp\left(-\frac{(r/r_0)^\alpha}{h_{\max}} f_{\mathrm{int}}(h_{\max}, \ldots)\right)$$

Using atmosphere n_r as input

$$h_1^\nu(r, n_r) = \left(\frac{r}{r_0(\nu)}\right)^{\alpha(\nu)}$$

$$h_2^\nu(r, n_r) \to \infty$$

Charge-excess asymmetry



Motivation for radio detection

Pros

- Cost-effective technique
- Almost full duty-cycle
- High precision for energy and shower maximum
- Sensitivity for inclined events

Cons

- Comparable high threshold ($>$100 PeV)
- Requires external trigger
- Sophisticated noise treatment and data analysis

Radio is ideal in combination with particle detector arrays

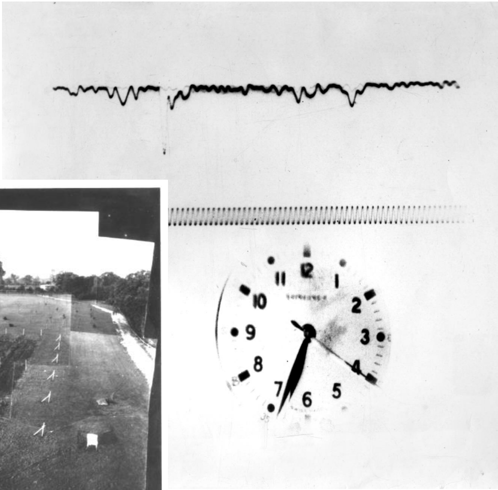
Science case: study of >EeV cosmic rays and neutrinos

Review of historical and modern experiments

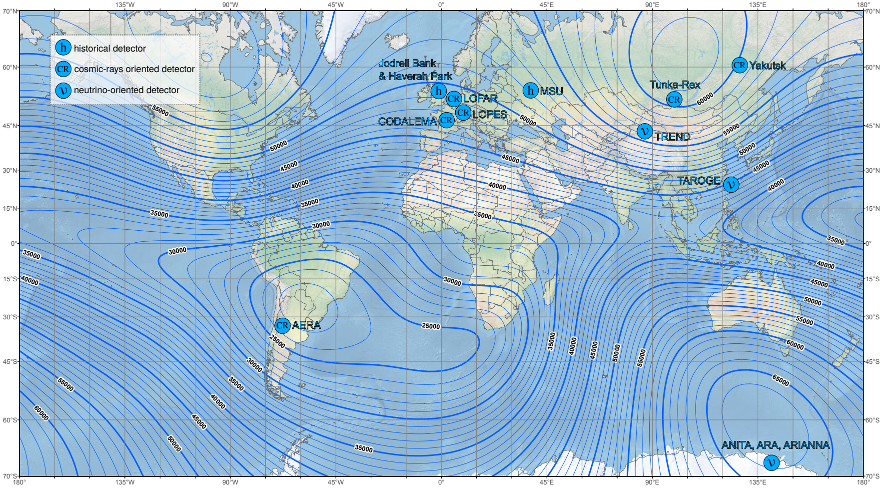
First detection

Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967

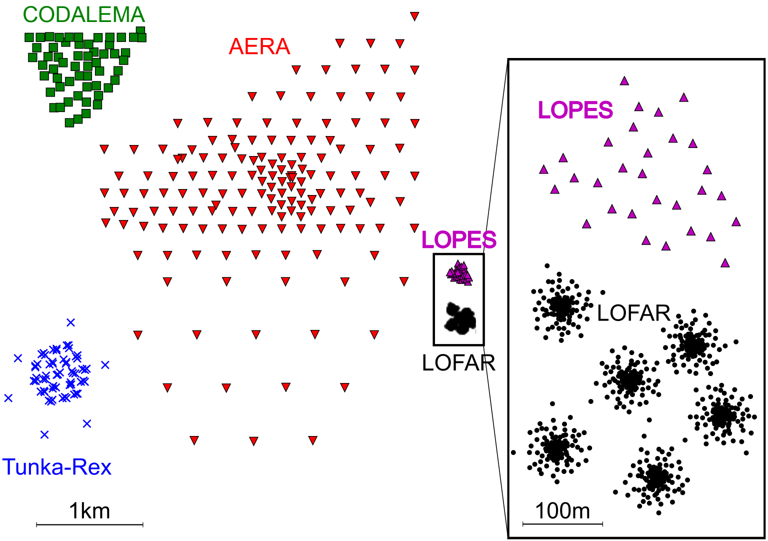
Jodrell Bank, England



Radio arrays since 1970



Modern cosmic-ray experiments



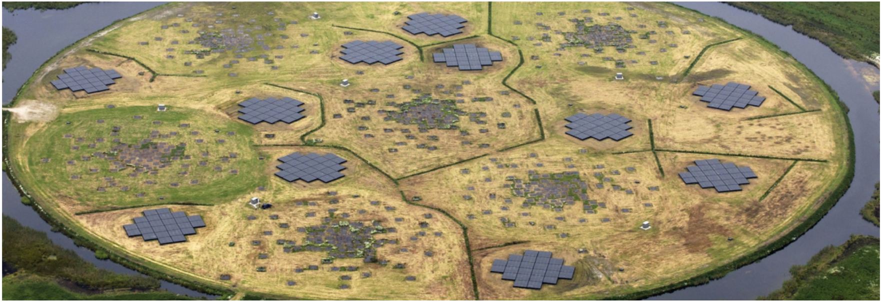
LOPES

LOfar PrototypE Station

- Digital interferometer
- **Proof-of-principle**
- 30 antennas
- Frequency band 40-80 MHz
- Triggered by KASCADE-Grande
- Operation years 2003-2013

LOFAR (LOw Frequency ARray)

- Astronomical observations at radio-frequencies below 250 MHz
- Cosmic-ray detection triggered by particle array
- Biggest number of antennas and density
- Cosmic-ray studies at thunderstorms
- **Precise study of radio emission phenomena**



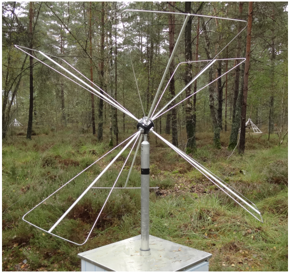
AERA

Karlsruhe Institute of Technology

Auger Engineering Radio Array

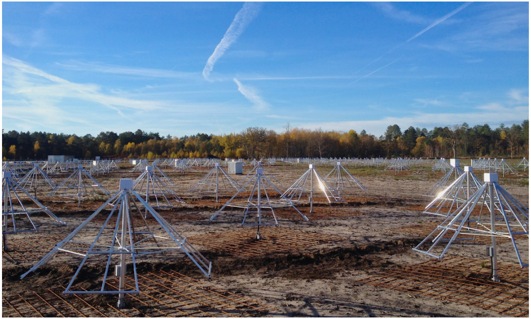
- Largest area (124 antennas on 23 km^2)
- Frequency band 30-80 MHz
- Hybrid and superhybrid detection: + particle & fluorescent detectors
- Inclined events
- **Proof-of-scalability**

CODALEMA



A swiss-knife for UHECR radio detection

- Wide frequency band (2 – 200 MHz)
- Multi-scale antenna densities
- Test bench for future projects



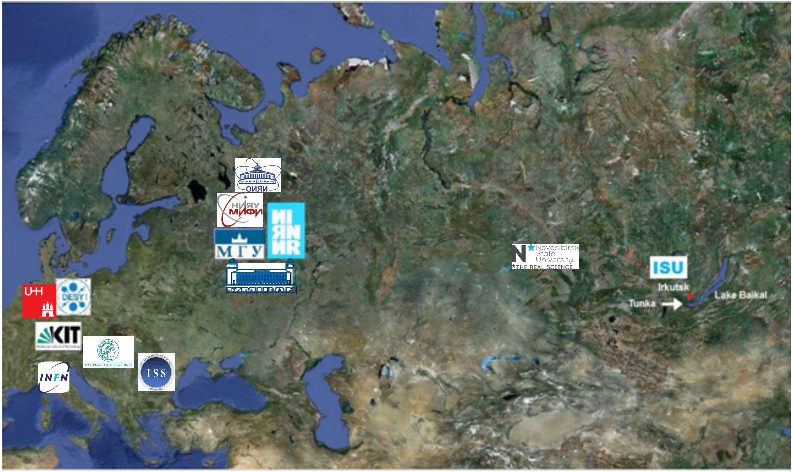
Tunka-Rex

Tunka Radio Extension

- Frequency band 30-80 MHz
- Cost-effective
- Duplex and triplex measurements: $\gamma_{\mathrm{ch}}/\mu/e$ + radio
- World-uniqe radio and air-Cherenkov cross-calibration
- First direct measurement of shower maximum with radio
- **Proof-of-feasible**

Tunka Radio Extension as an example of large-scale array

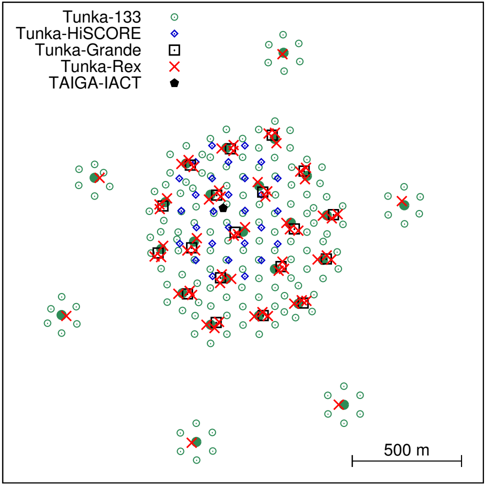
TAIGA Collaboration



13 institutes (EU + Russia), 76 people involved

Tunka-133 → TAIGA

__T__unka __A__dvanced __I__nstrument for cosmic ray physics and __G__amma __A__stronomy



= 3 km^2 covered by:

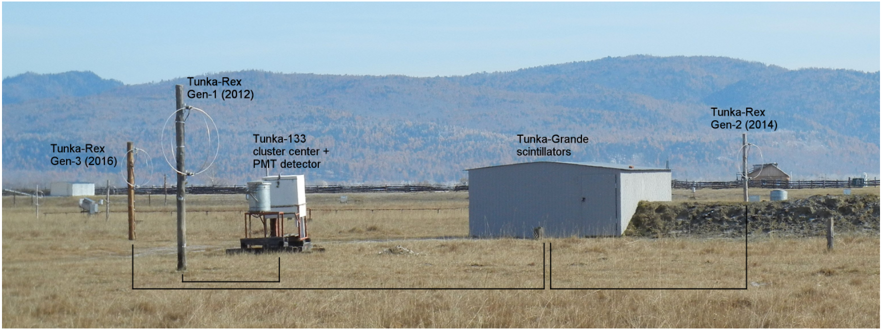
Cosmic ray detectors <EeV

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

Gamma ray detectors >TeV

- HiSCORE
- IACTs

Single cluster of Tunka facility

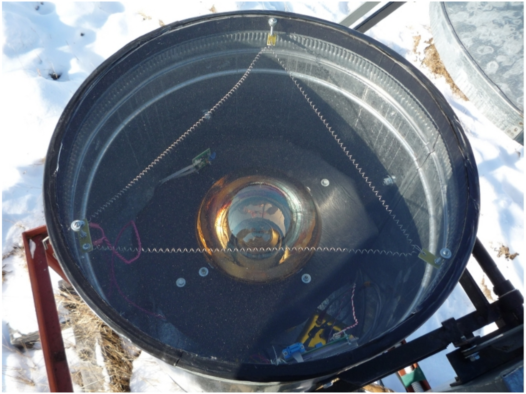


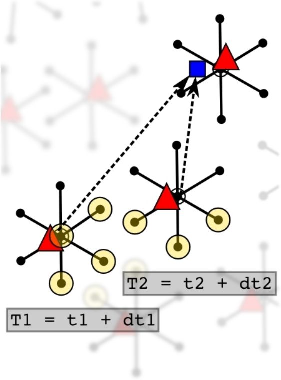
- 7 Optical Modules
- 8 m^2 (on-ground) + 5 m^2 (underground) scintillators
- 3 antenna stations (2 polarizations, 30-80 MHz)

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

Tunka-133

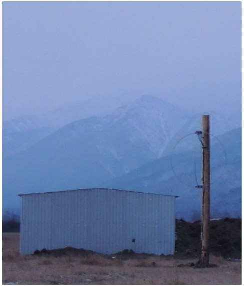
- 175 optical modules (7 per cluster, 25 clusters) on 3 km^2
- Independent trigger for cluster, syncronization via optic fibers
- Measurement during moonless winter nights





Tunka-Grande

- 19 scintillator stations with spacing 200 m on 1 km^2
- Each station consists of electron (8 m^2) and muon (5 m^2) detectors
- Independent trigger for station, syncronization via optic fibers
- Lower threshold, almost full duty-cycle



Tunka-Rex detector timeline

~100 events per season
triggered by Tunka-133

expected more than 2000 events per season
triggered by Tunka-133 and Tunka-Grande

2012	2013	2014	2015	2016	2017
18 antennas	25 antennas	44 antennas		63 antennas	

Tunka-Grande

Achievements:

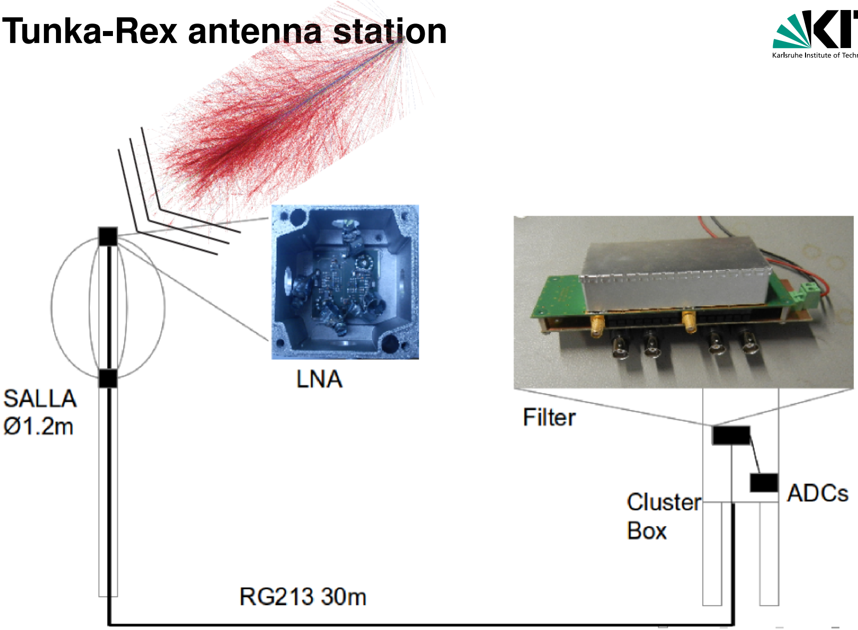
* Cross-calibration of radio and air-Cherenkov signal
* Determine precision of the radio technique

Plan:

* Core reconstruction with radio
* Joint reconstruction of electromagnetic (Tunka-Rex) and muon (Tunka-Grande) components of air showers
* Mass composition study

- Measurement season from October to April
- Starting from 2015 Tunka-Rex reached 85% uptime
- Expected event rate $>$2000 events per season
- Duplex and triplex measurements (e/μ, $\gamma_{\rm c}$, radio)

Tunka-Rex antenna station

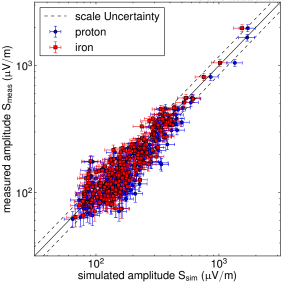


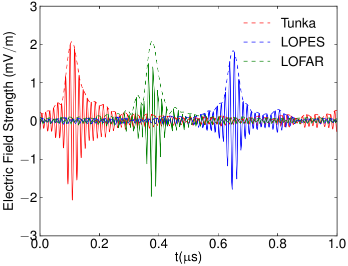
Amplitude calibration

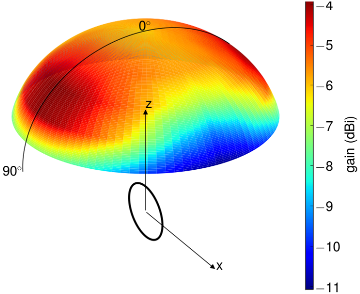
- Tunka-Rex, LOPES, LOFAR calibrated consistently with same source
- CoREAS amplitude scale confirmed (17%)
- Compare energy scales (10%)

Tunka-Rex Collaboration, NIM A, 802:89-96, 2015.

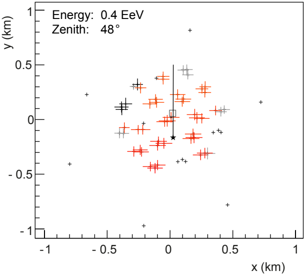
doi:10.1016/j.nima.2015.08.061

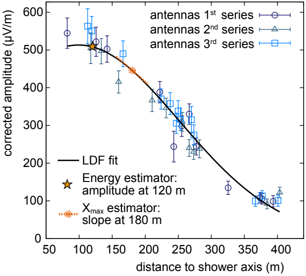


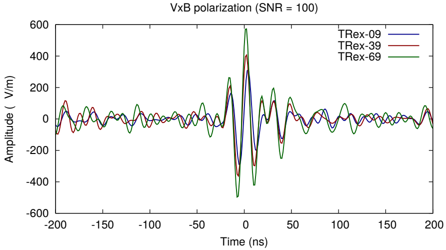




Example of event







Reconstruction pipeline

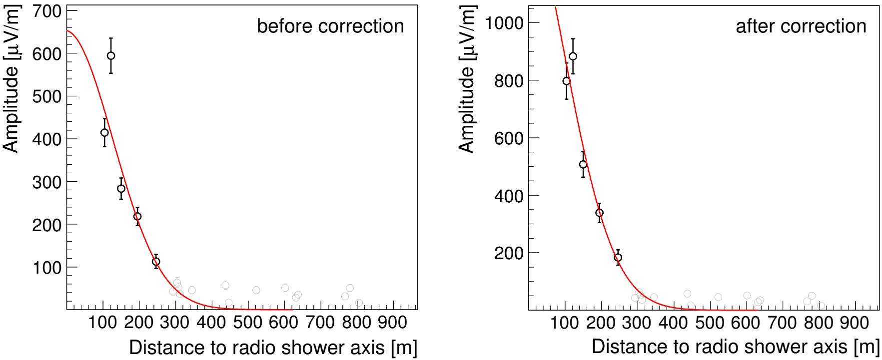
- Searching of the signal in power trace
  - Digital filtering
  - SNR$\geq$10
  - N_{ant} $\geq$3
- Rejecting false positive events
  - Reconstruction of arrival direction and core position
  - Comparison with Tunka-133/Tunka-Grande reconstruction ($\Delta\Omega < 5°$)
  - Rejecting outliers from the LDF
- Quality cuts (for X_{max} reconstruction)
  - at least one antenna at $d_{\mathrm{axis}} > 200$ m
  - fit uncertainty $\sigma(X_{\mathrm{max}}) < 50$ g/cm^2

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

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 $\alpha_\mathrm{g} > 0$

Air-shower reconstruction

Lateral distribution function (LDF)

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

Fixing quadratic term

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

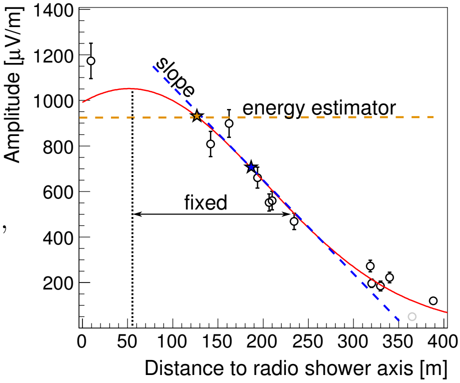
LDF slope

$$\eta = \frac{\mathcal{E}'}{\mathcal{E}}$$

Air-shower parameters

$$E_{\rm pr} = \kappa_L \mathcal{E}(r_{\rm e})$$

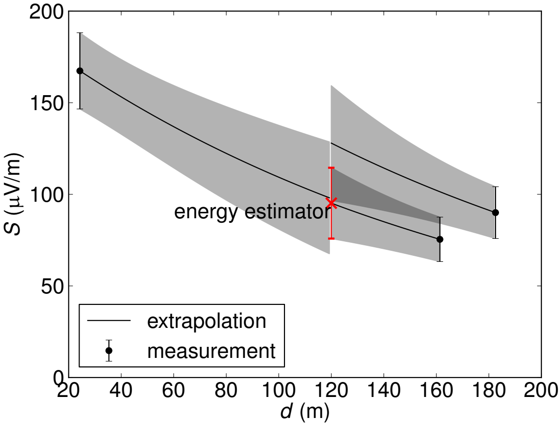
$$X_{\rm max} = X_0/\cos\theta-(A+B\log(\eta(r_{\rm x})+\bar{b}))$$



Model parameters from CoREAS simulations

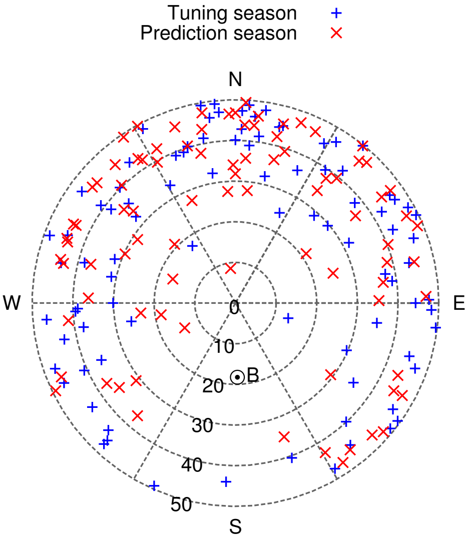
`doi:10.1016/j.astropartphys.2015.10.004`

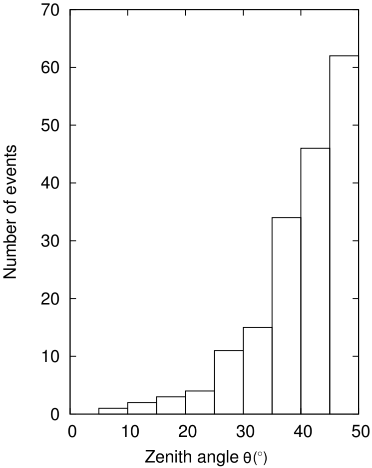
One-antenna analysis



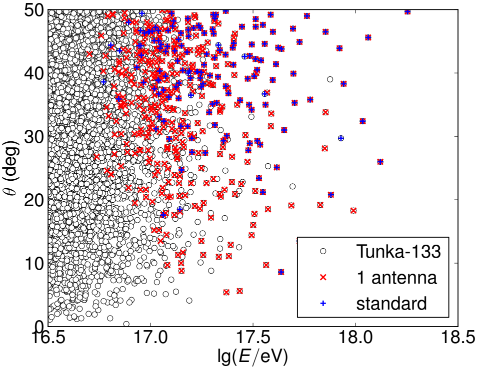
$$r_{\rm th}(E,\theta,\alpha) = r_0 + \frac{1}{\eta_0 \cos\theta} \ln \frac{E \cdot \sqrt{\sin^2\alpha + \varepsilon^2}}{\kappa \mathcal{E}_{\rm th}}$$

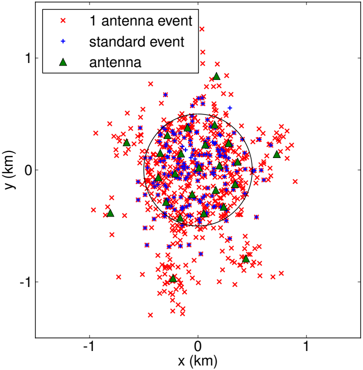
Angular distribution





Reconstructed events (2012-2014)

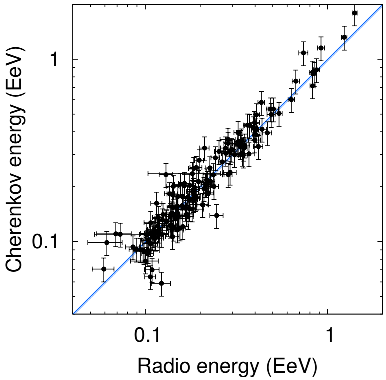




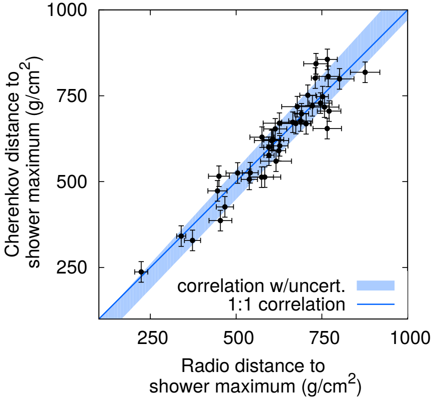
- One-antenna analysis: 606 events
- Standard analysis: 171 events
- High quality events ($X_{\max}$): 42

Cross-check with Tunka-133

Energy



Shower maximum



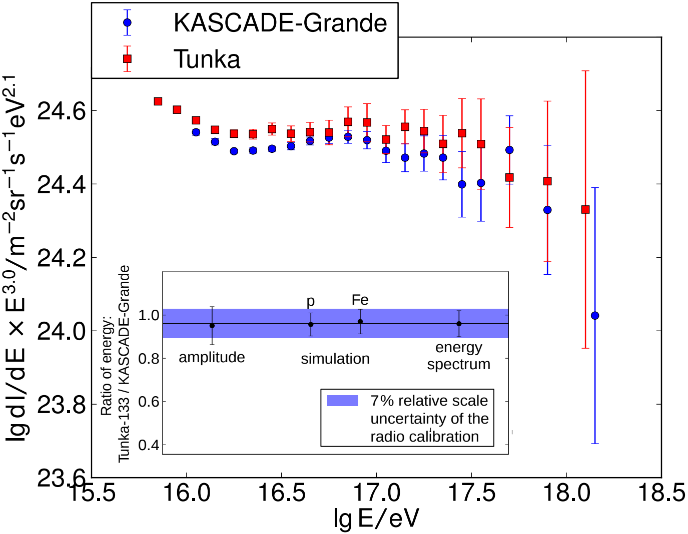
resolution: 15%

resolution: 38 g/cm^2

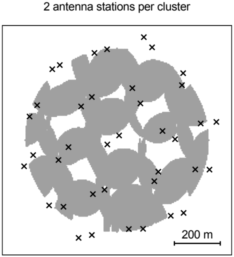
Tunka-Rex Collaboration, JCAP 1601 (2016) no.01, 052 [doi:10.1088/1475-7516/2016/01/052]

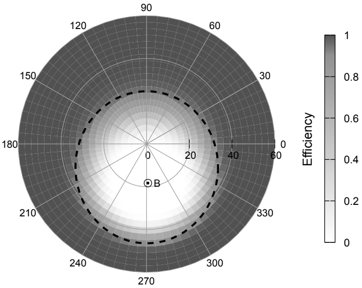
Energy scales of Tunka-133 and KASCADE-Grande via radio

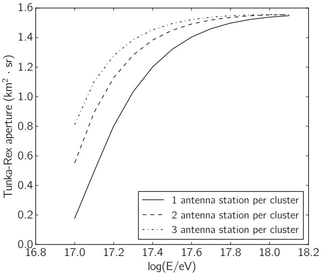
Karlsruhe Institute of Technology

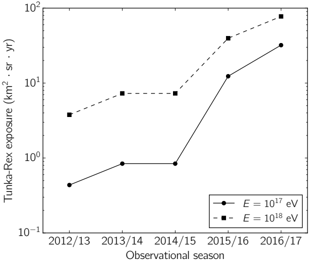


Towards energy spectrum with radio

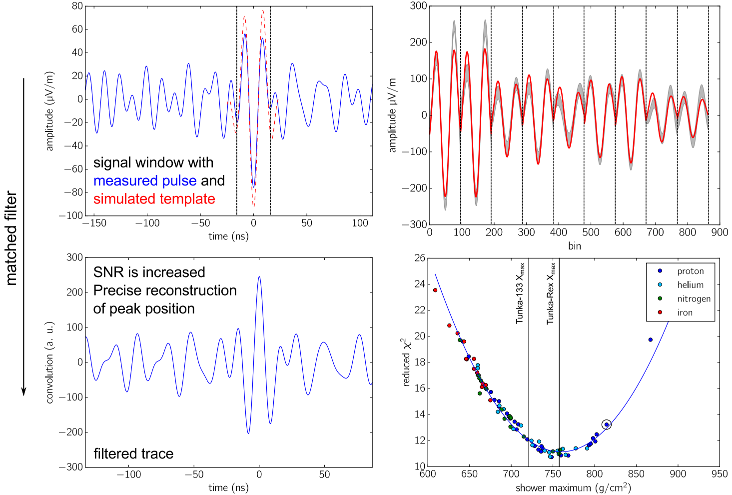








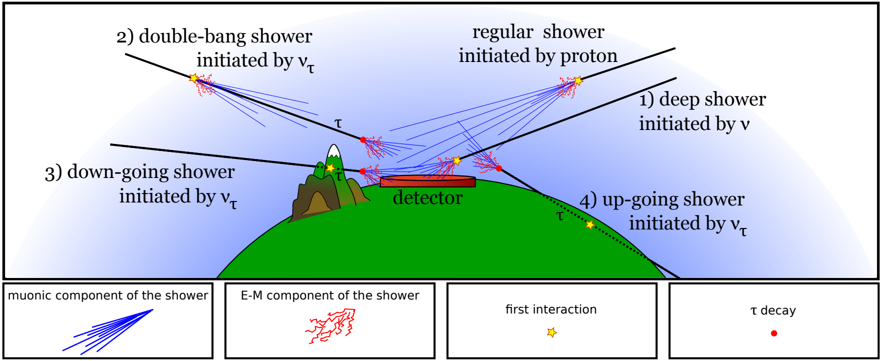
Towards ultra-precise reconstruction



Accurate calibration and broad band are required!

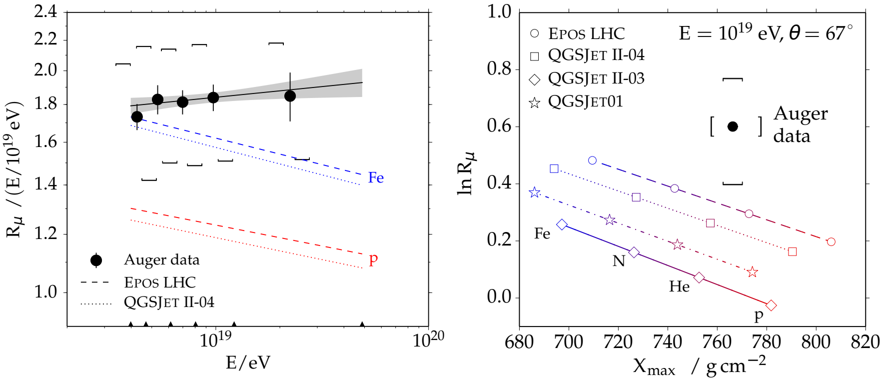
Radio detection of inclined air-showers and ultra-high energy neutrinos

Types of inclined events



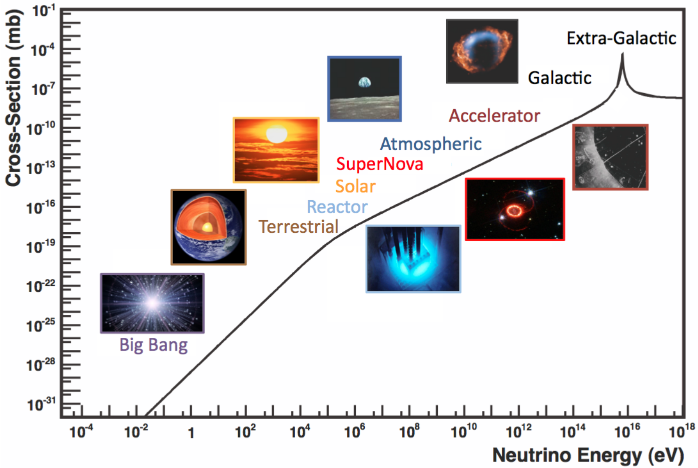
sketch by Javier Tiffenberg

Muon anomaly

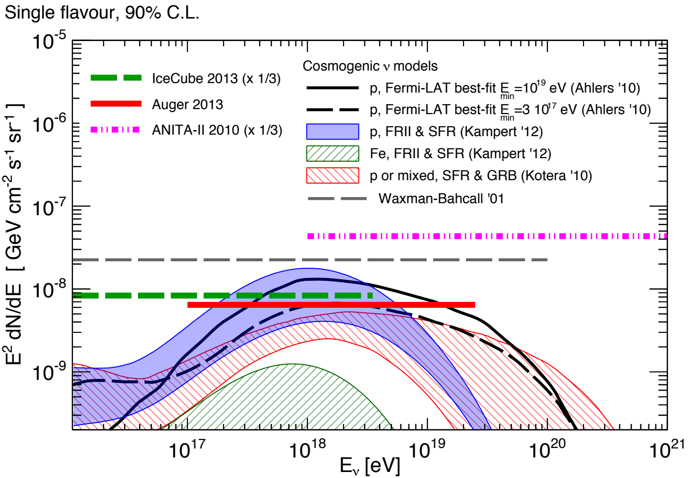


Pierre Auger Collaboration, Phys. Rev. D 91, 032003 (2015)

Ultra-high energy neutrinos

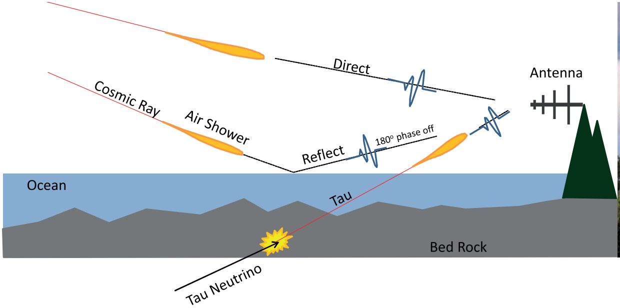


Ultra-high energy neutrinos



TAROGE

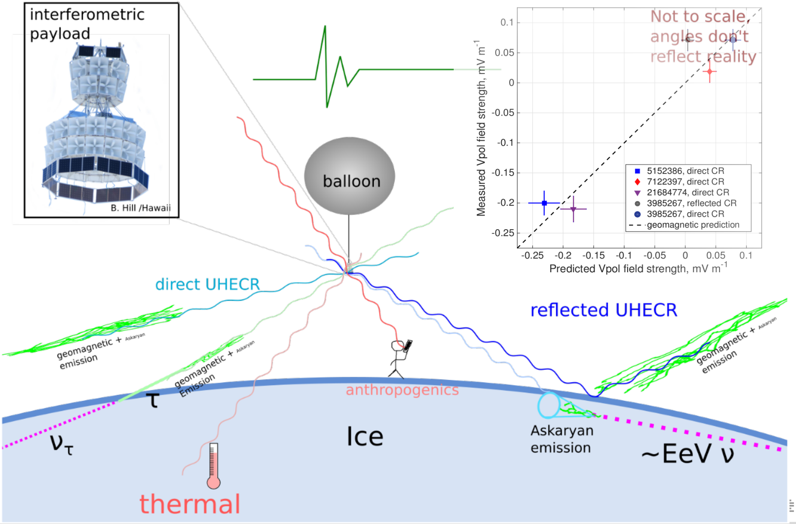
Taiwan astroparticle radiowave observatory for geo-synchrotron emissions



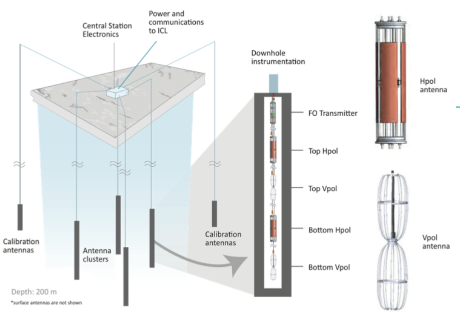
TAROGE-1

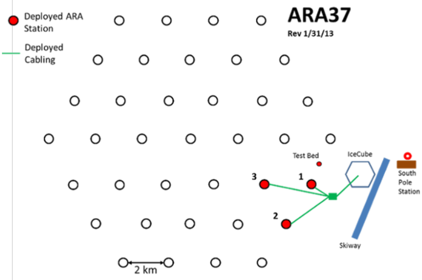
ANITA

ANtarctic Impulse Transient Antenna



ARA (Askaryan radio array)

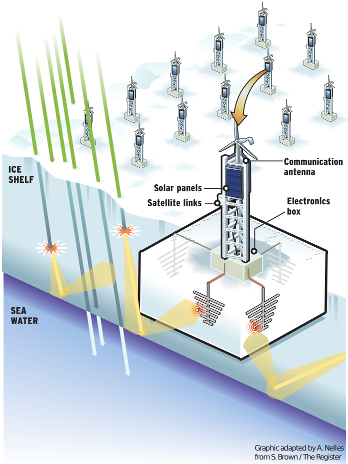




ARIANNA

Antarctic Ross Ice Shelf antenna neutrino array

- On ice-shelf: Ice-water boundary **almost perfect reflector** for radio emission
- **Independent antenna stations** can be installed at low costs on the surface
- Real-time data transfer via satellite
- Solar and wind power possible
- **High gain antennas (50 - 1000 MHz)** can be used to instrument a large volume
- Array of about 1200 antennas needed: ~ 30 Million USD

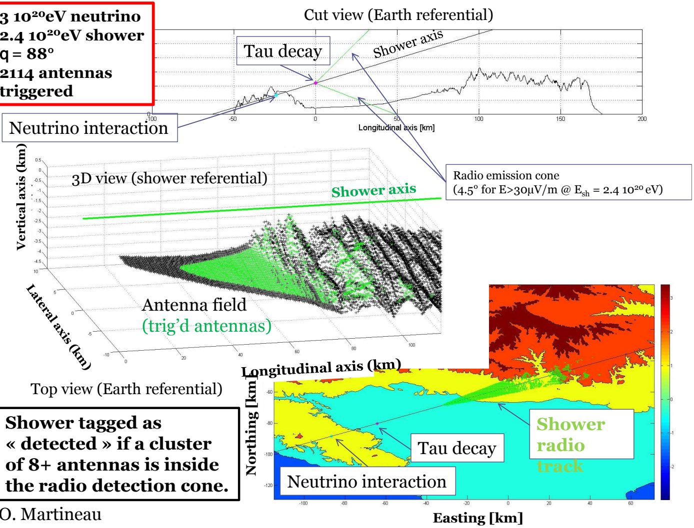


3 Anna Nelles, ARENA 2016

TREND → GRAND

Karlsruhe Institute of Technology

3 10^{20}eV neutrino
2.4 10^{20}eV shower
q = 88°
2114 antennas triggered



Shower tagged as « detected » if a cluster of 8+ antennas is inside the radio detection cone.

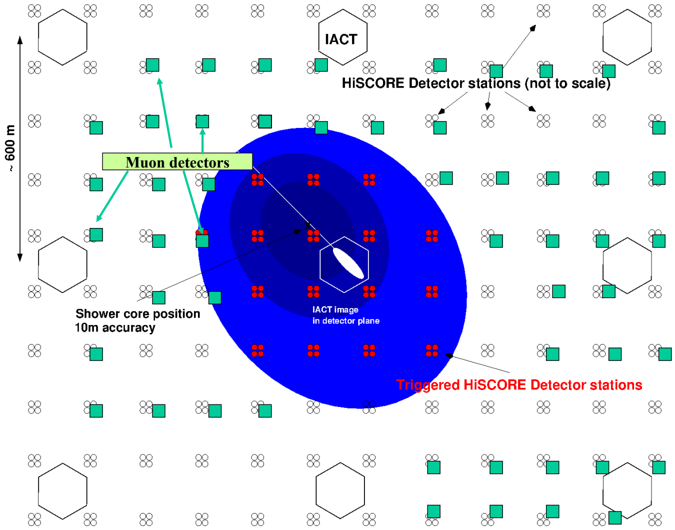
O. Martineau

Summary

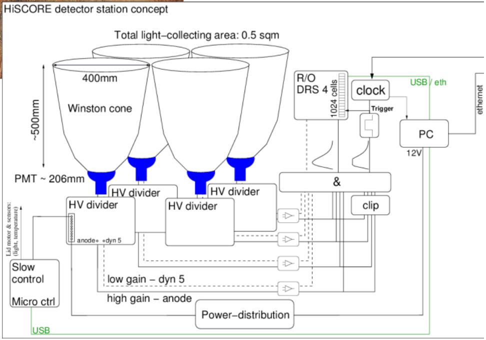
- Radio has shown its feasibility and competitiveness for high-energy cosmic-ray detection
- One of the successfull radio detectors is build and taking data in Tunka, Siberia
- The next science case for radio arrays is the inclined events study and detection of ultra-high energy neutrinos

BACKUP

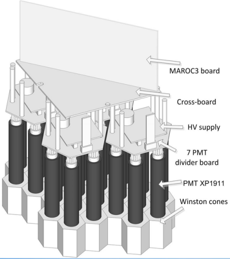
TAIGA concept

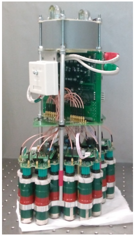


HiSCORE design



IACT design


MAROC3 board
Cross-board
HV supply
7 PMT
divider board
PMT XP1911
Winston cones

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