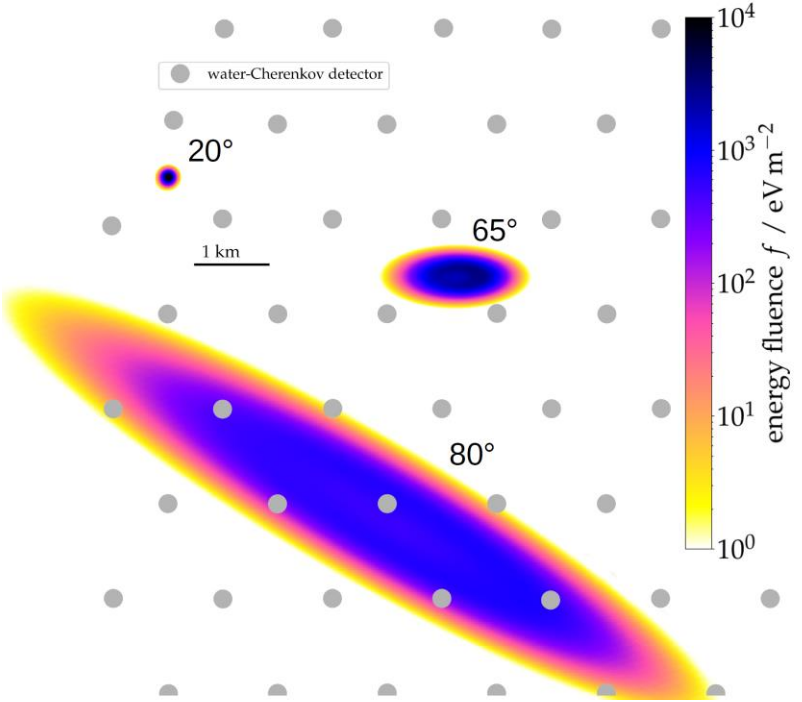
The Pierre Auger Radio Detector

Tim Huege (KIT & VUB

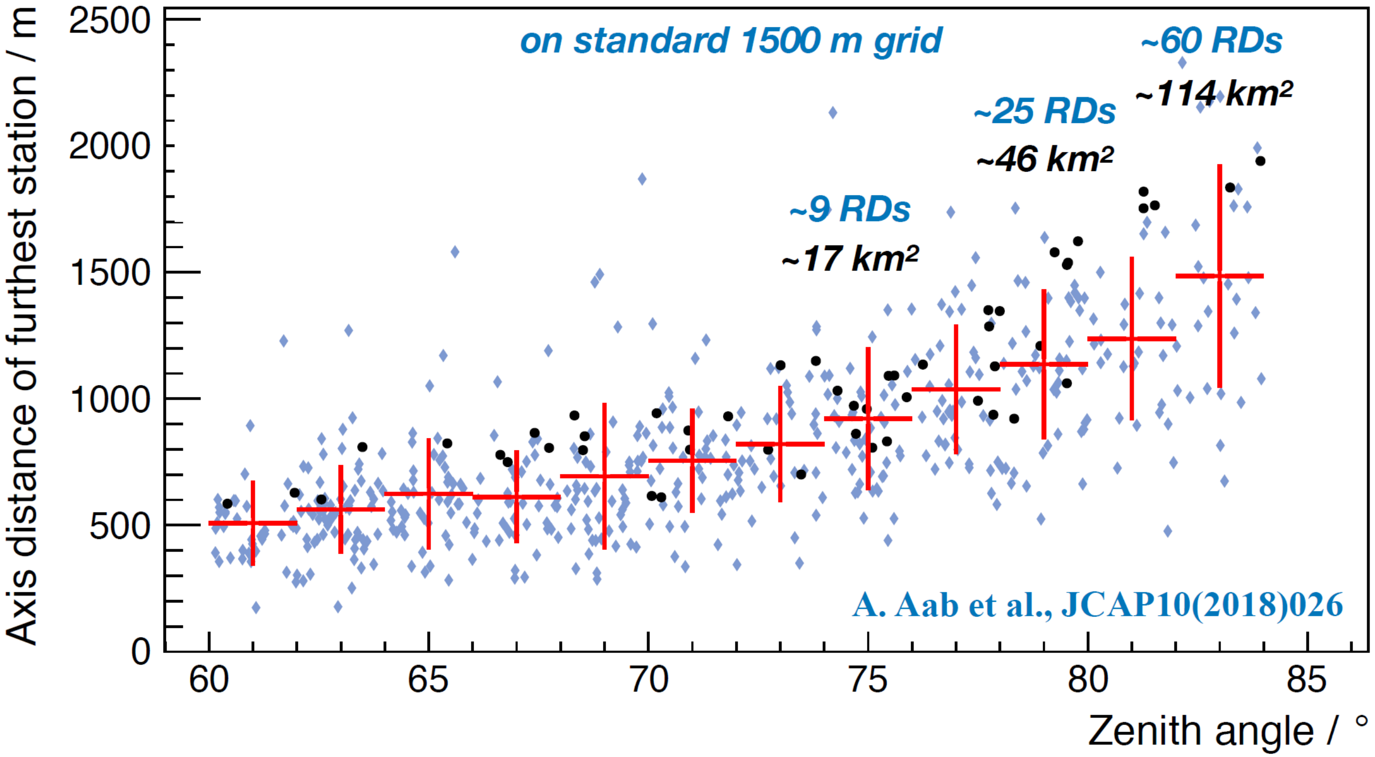
Radio detection of extensive air showers

- Provides calorimetric measurement of electromagnetic energy of air showers
- 100% duty cycle, atmosphere uncritical
- For vertical showers proven to provide Xmax information
- Zenith Angle ⇔ Spacing ⇔ CR energy
  - Vertical showers need dense arrays, access low energies
  - Inclined showers long predicted to be measurable with sparse arrays, access high energies

see T. Huege, A. Haungs, UHECR2014, arXiv:1507.07769

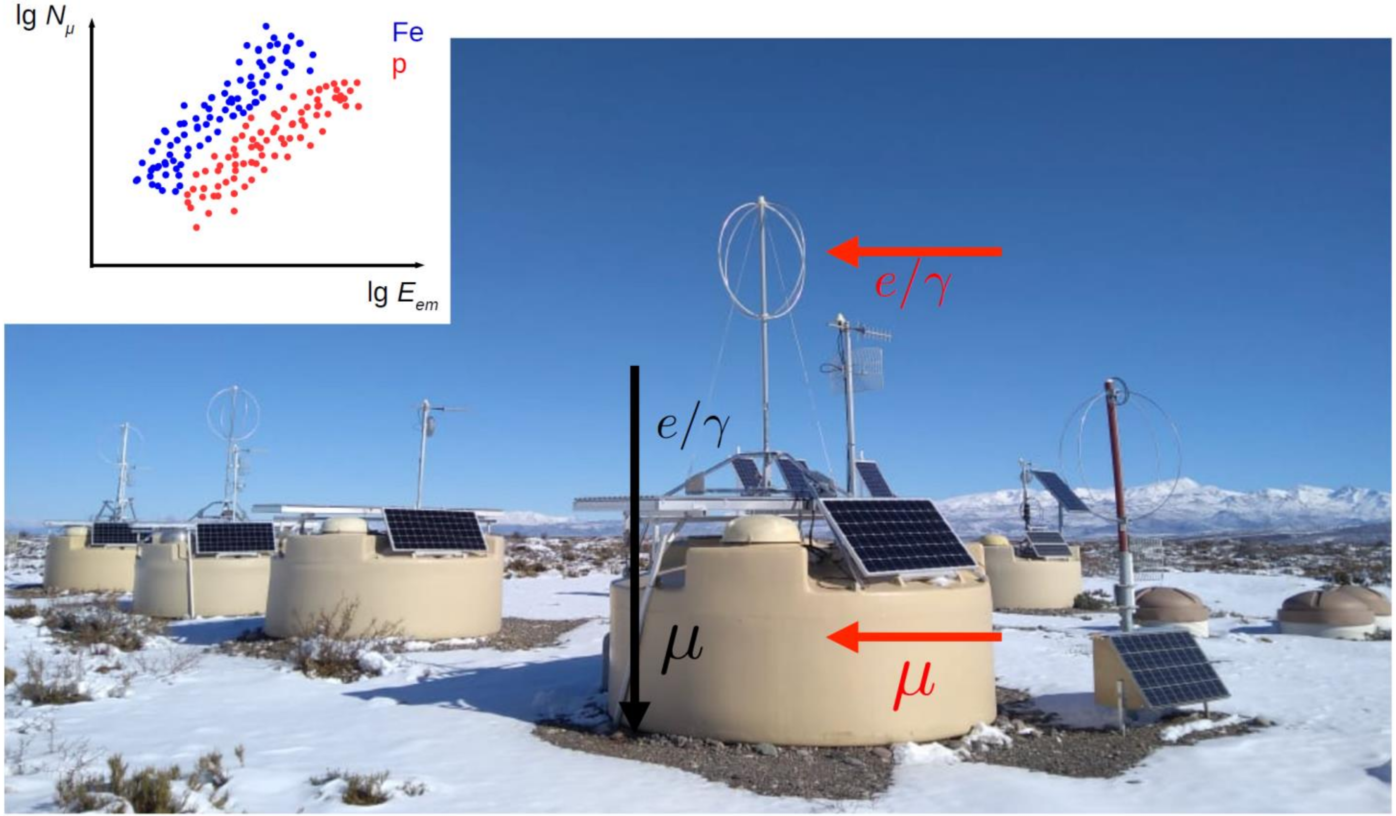


Auger Engineering Radio Array results



- Hundreds of inclined air showers detected with ~6 km^2 of AERA
- Inclined air showers indeed measurable with arrays with >1km spacing
- Can measure at highest energies with 1.5 km Auger grid

As part of AugerPrime: Auger Radio Detector



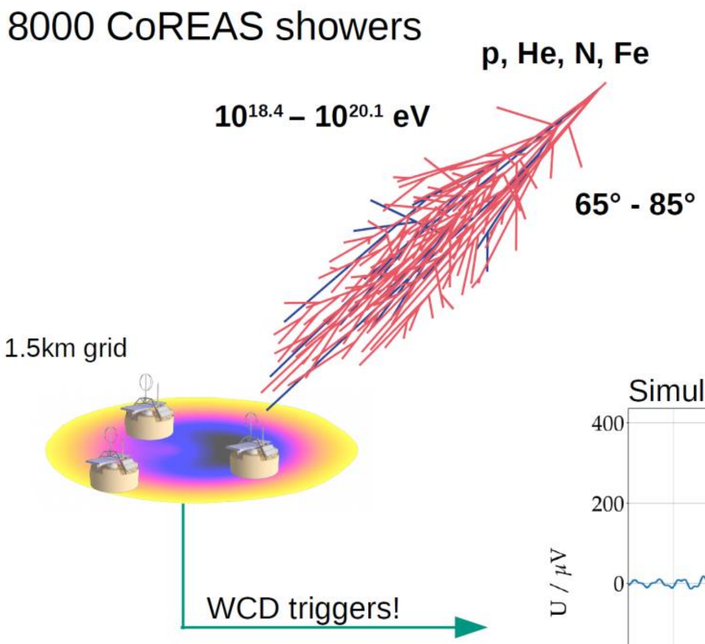
- Mount a dual-polarized radio antenna (30-80 MHz) on each SD station
- 1660 radio antennas over 3000 km^2
- Mass sensitivity for inclined air showers:
  - radio: em
  - WCD: muons
- Beautifully complementary to WCD/SSD

Expected Performance

see PoS(ICRC2021)228

 Tim Huege <tim.huege@kit.edu>

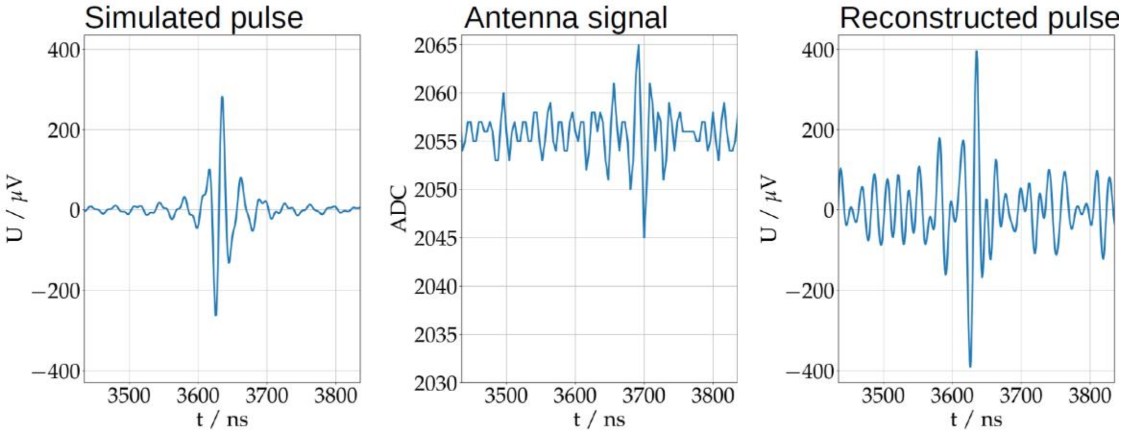
Fully realistic end-to-end simulation study



Simulate instrumental response

(directional response, analog gain, digitization, …..)

- Including uncertainties (σ_A = 5%)
- Measured noise



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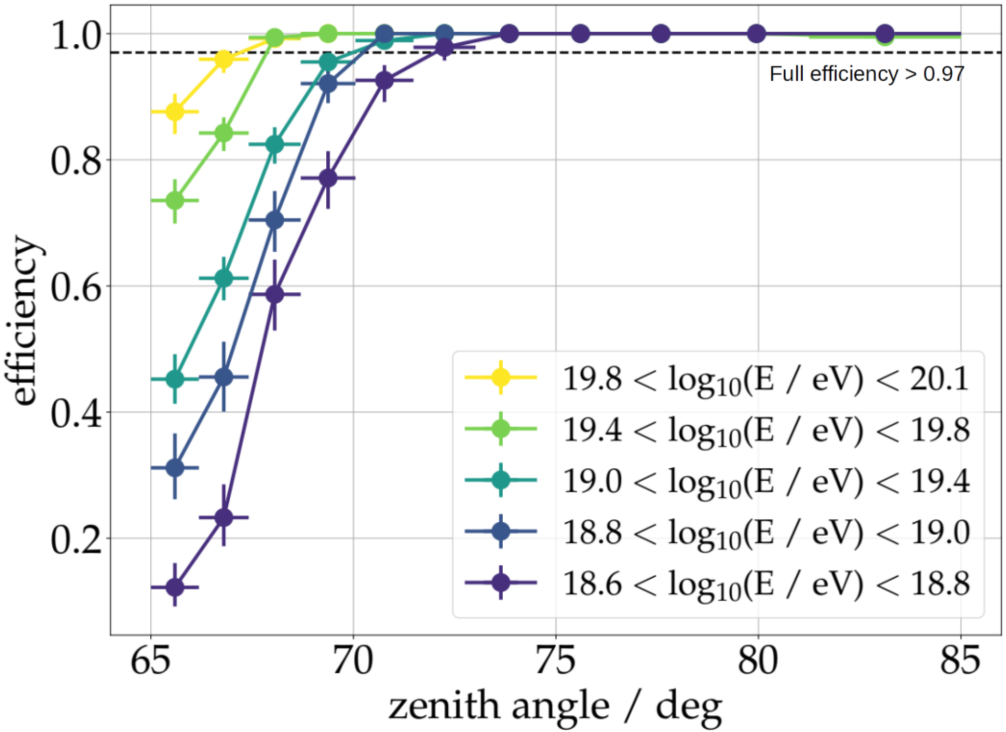
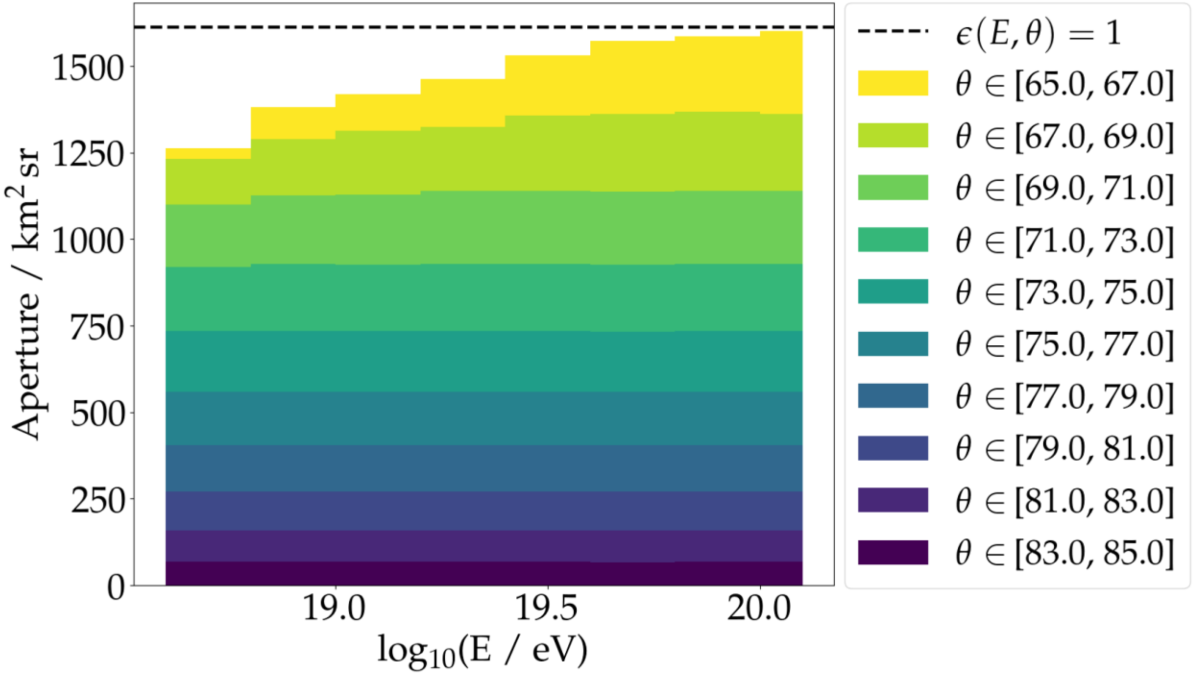
Detection efficiency

Karlsruhe Institute of Technology



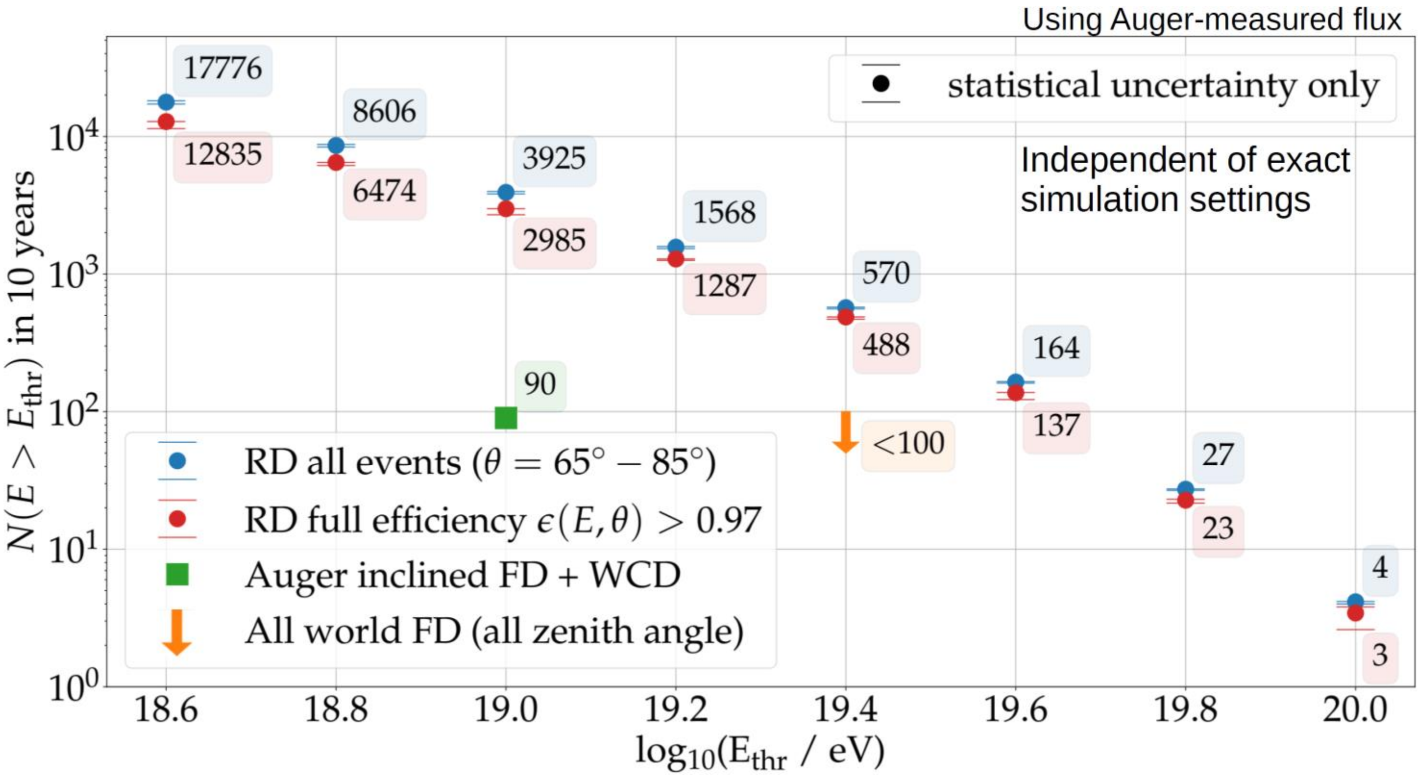
- Requires measurable signal in at least three radio antennas
- 100% efficiency for θ>70° and E>$10^{18.8}$ eV

Predicted aperture



- Lower zenith angles make large contribution, but need high energy for full efficiency
- Higher zenith angles fully efficient, but make smaller contribution
  - contained events

Expected event statistics in 10 years

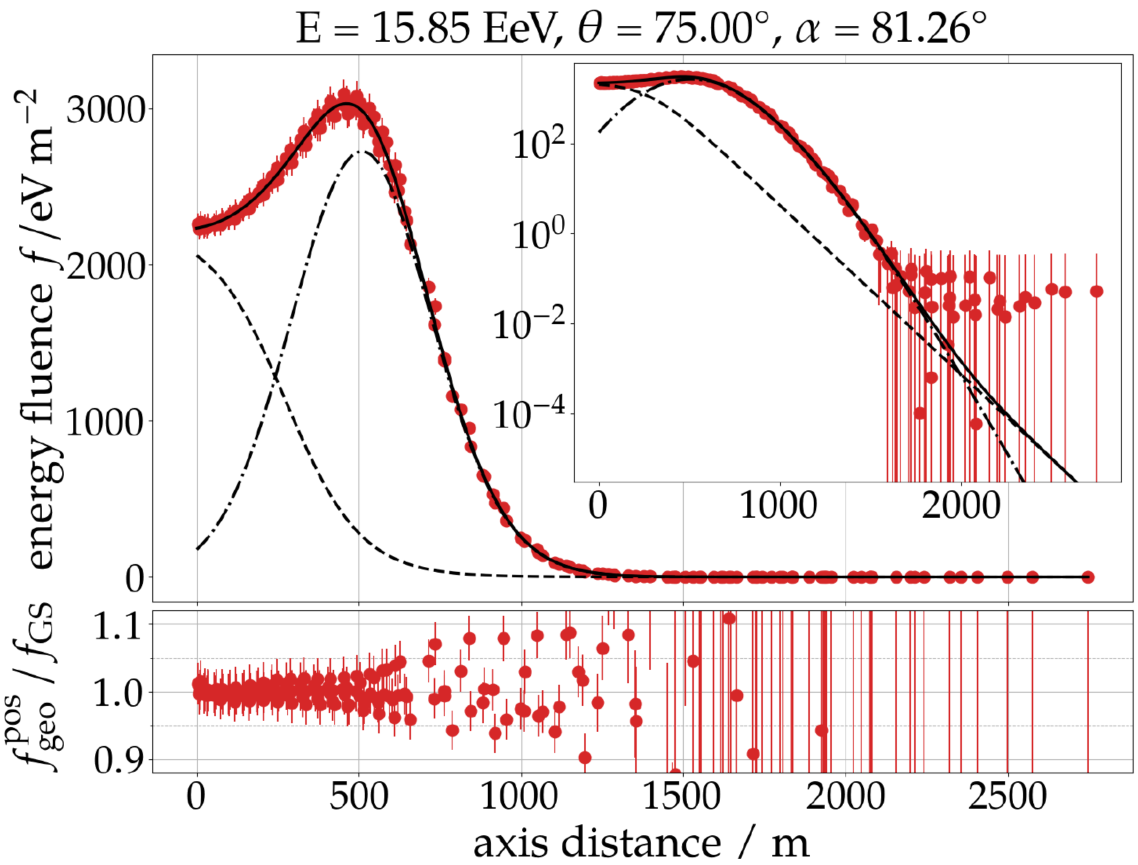


- Integral spectrum from folding flux with aperture
- Expect ~4000 events beyond 10^{19} eV

Event reconstruction

Newly developed LDF model*

- 2 parameter + core coordinates
- Derive start values from WCD (use radio rec. arrival direction)
- Integral yields energy estimator



* Signal model and event reconstruction for the radio detection of inclined air showers, F. Schlüter, T. Huege, JCAP

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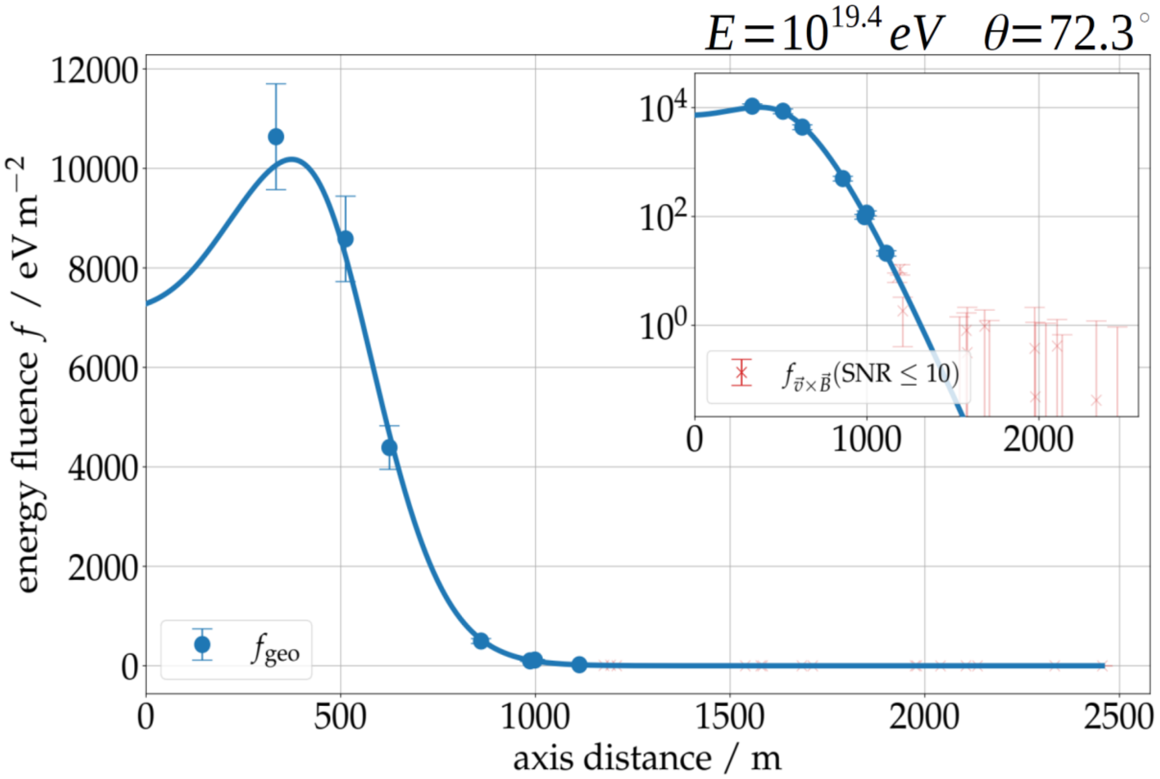


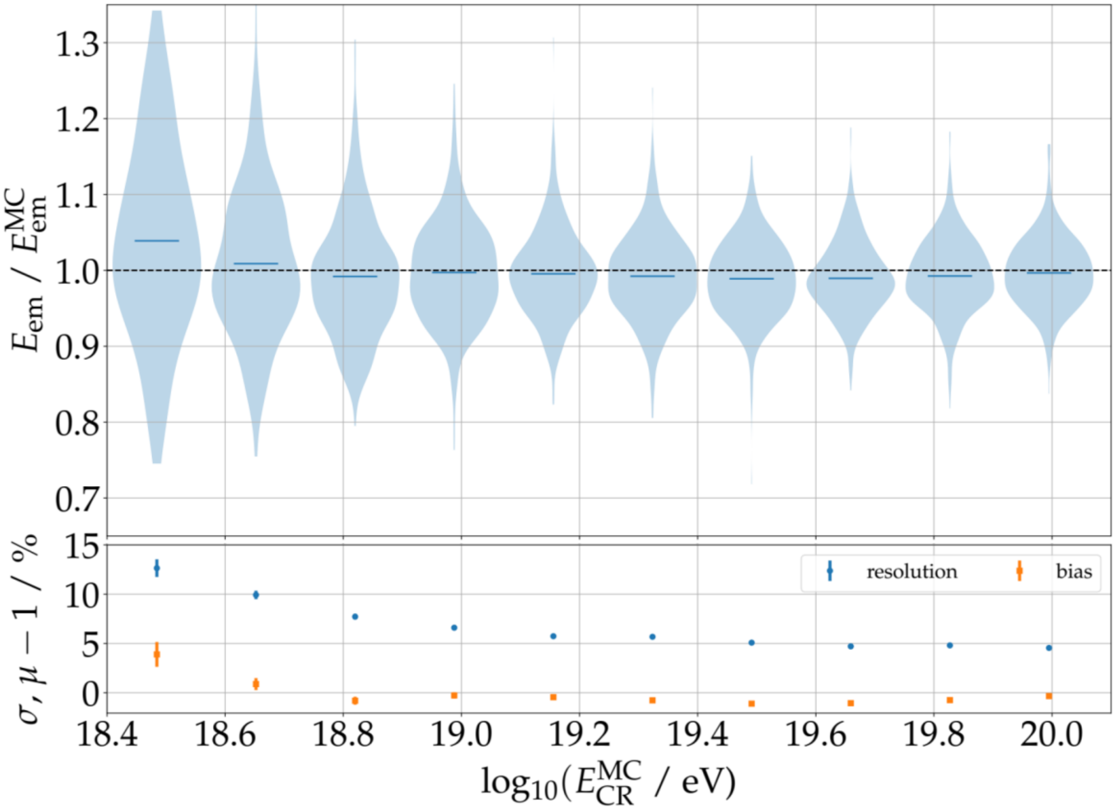
* Signal model and event reconstruction for the radio detection of inclined air showers, F. Schlüter, T. Huege, JCAP

Predicted energy resolution of Auger RD

Showers with at least 5 signal stations and θ > 68°

quality cuts: ~95% efficiency

Resolution improves with energy



Tim Huege <tim.huege@kit.edu>

Predicted energy resolution of Auger Radio Det.

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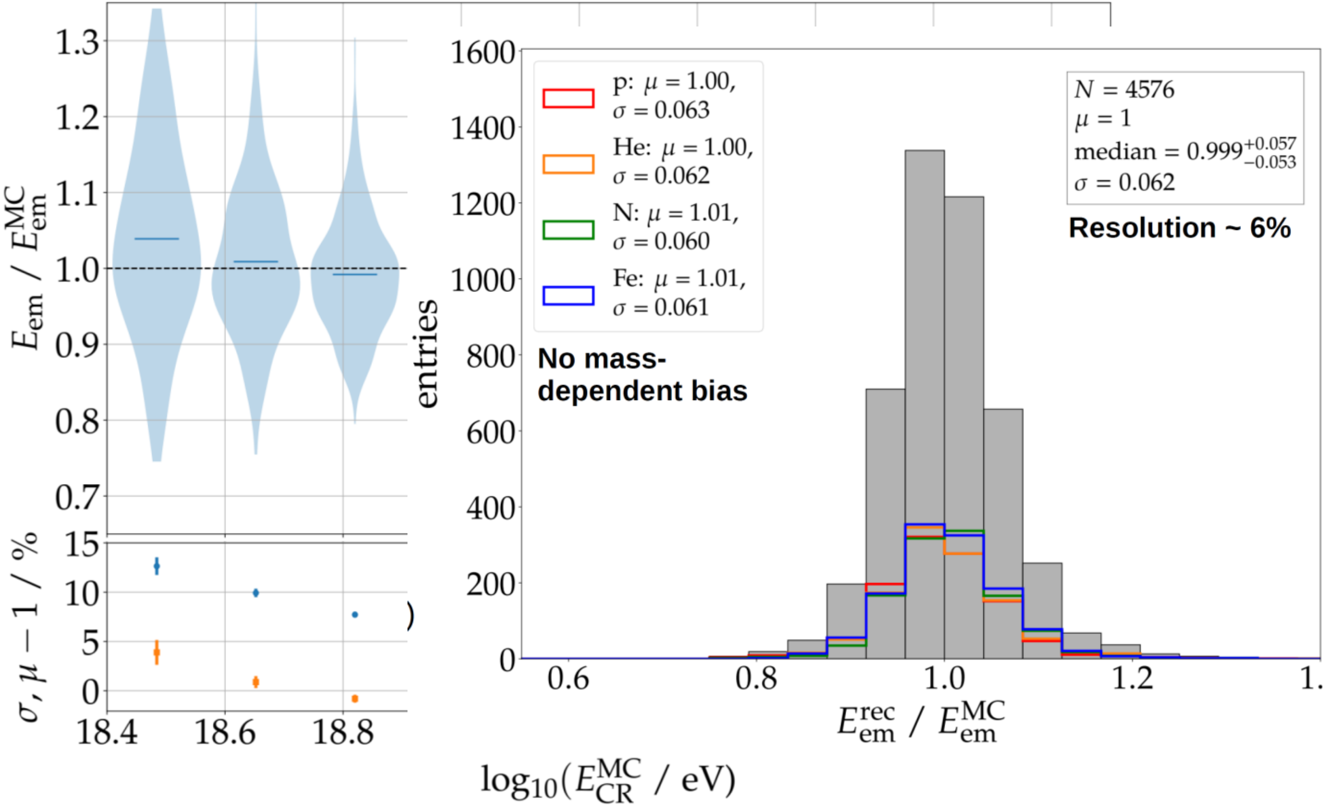


Mass composition sensitivity

50/50 p-Fe composition
with 10-year RD spectrum

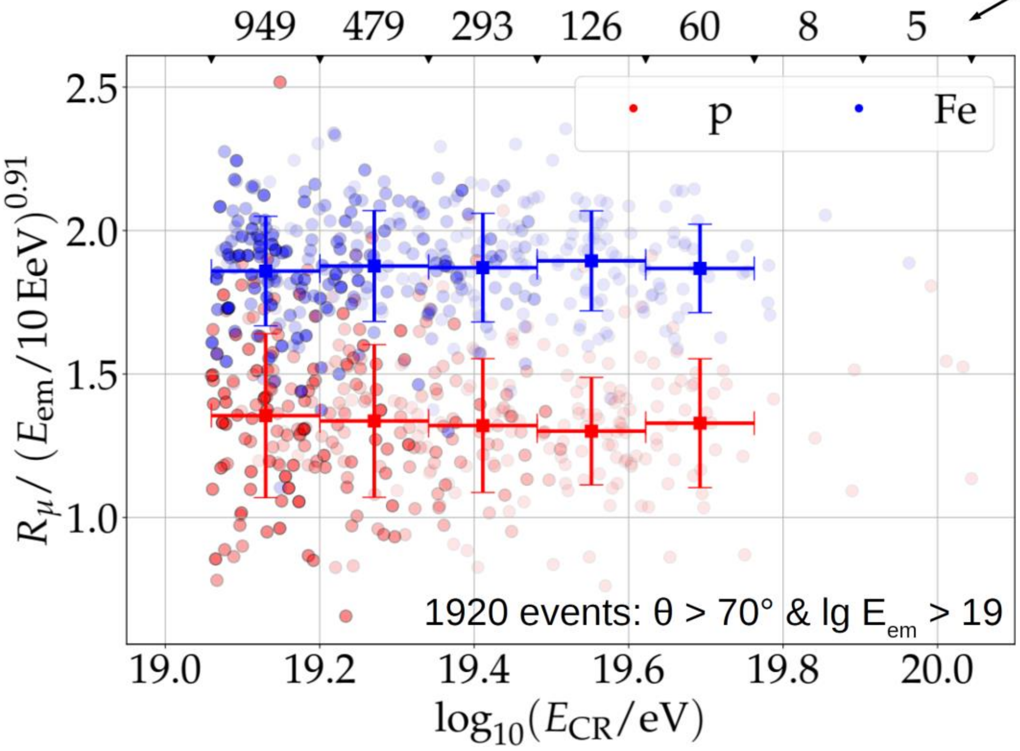


Figure of Merit:

$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma^2_{r_p} + \sigma^2_{r_{Fe}}}}$$

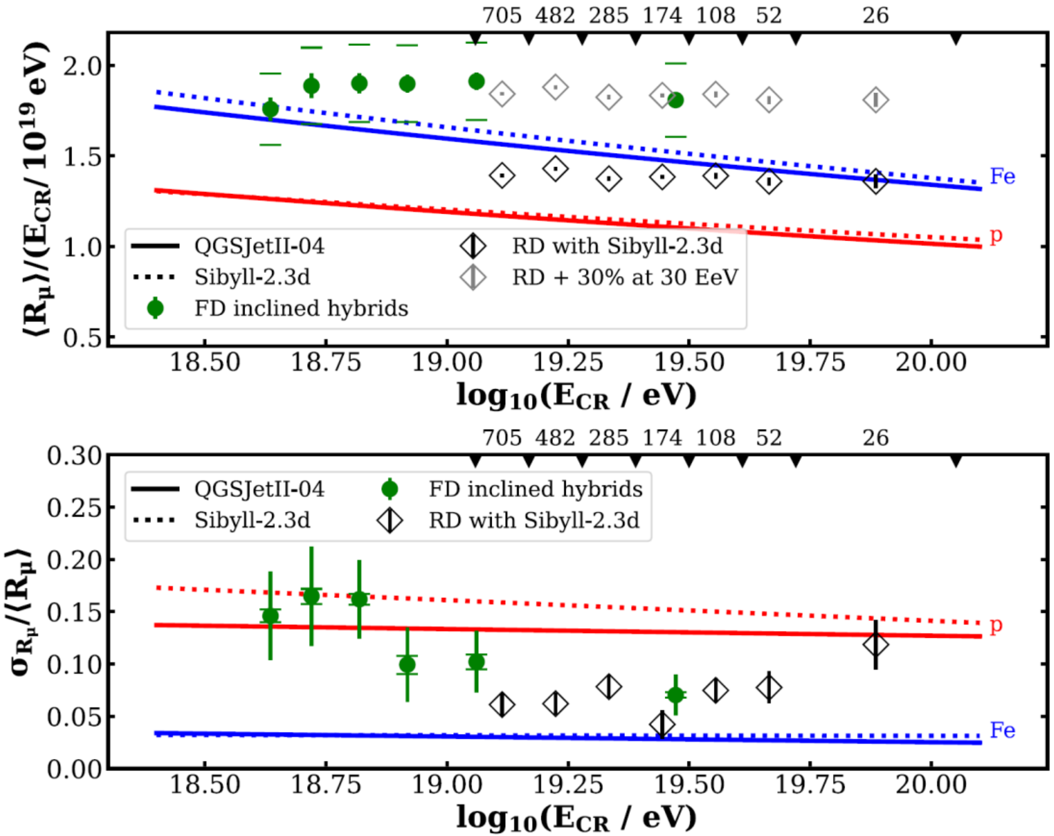
FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5

see also proof of principle study with AERA, PoS(ARENA2022)

Muon number measurements



- Very high-statistics measurements of muon number with WCD+RD at highest energies
- Especially measurement of the variation of the muon number with will be very powerful

Auger-RD Neutrino Aperture

On the middle panel of Fig. 4 we show the RDSim estimated aperture for ν_τ induced events. The apertures, even at the peak ($10^{18.5}$ eV), are just a small fraction of the apertures for the ν_e CC case. This is due to the extra propagation of the tau-lepton, which needs to decay above the ground to create a shower. Also, these showers develop much closer, decreasing their footprint size. Increasing the energy further decreases the probability of the τ creating a shower, e.g., at 85° and 100 EeV, the average distance to the decay is ~5000 km, and less than 1% of the created tau-leptons decay above ground. For the lowest energies, the probability of creating a shower increases, but the footprints get dimmer and are harder to detect.

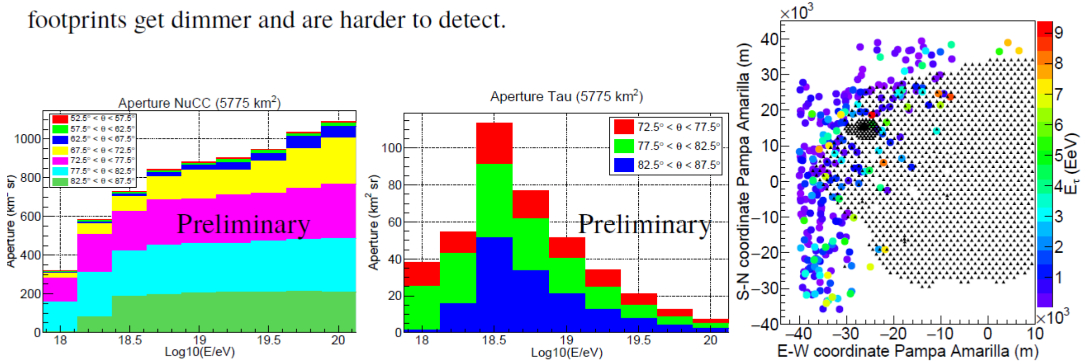


Figure 4: Left: Apertures for downgoing ν_e CC events at the Auger-RD estimated using RDSim. Middle: Same as left, but for ν_τ events. The displayed energy of both plots refers to shower energy. Right: Simulation of mountain τ events using RDSim, but without the actual detection simulation (see text).

Carvalho Jr. et al., PoS(ICRC2023)1097

Assuming neutrino interacts!

- Generally not looking good - detectors spaced too far and antennas not very sensitive at these zenith angles
- Mountain events very small zenith angle range, antenna insensitive
- Earth-skimming taus very unfavorable (high energy, too late decay)

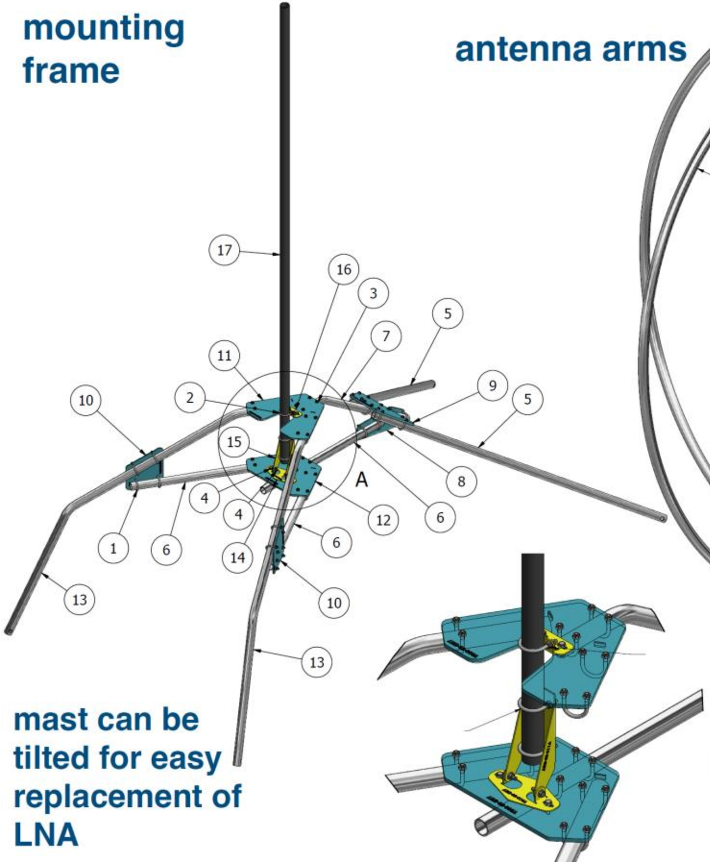
Hardware and Status

RD current status

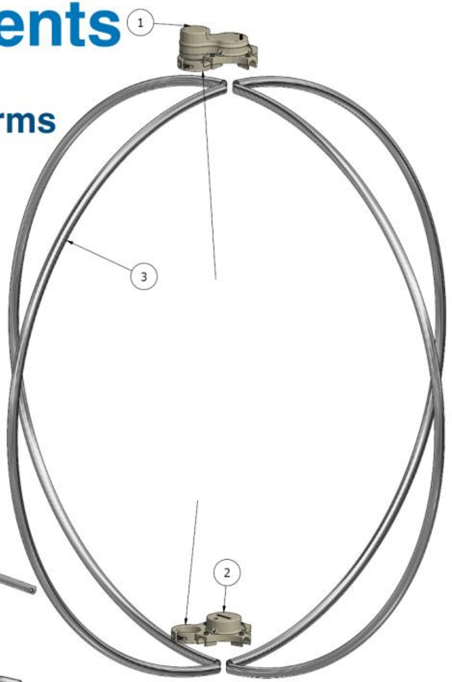
- January 2024: XX antennas in the field, YY operating
- Mechanical and electronics design mature and proven
- Trigger for now from WCD, but working on hybrid trigger

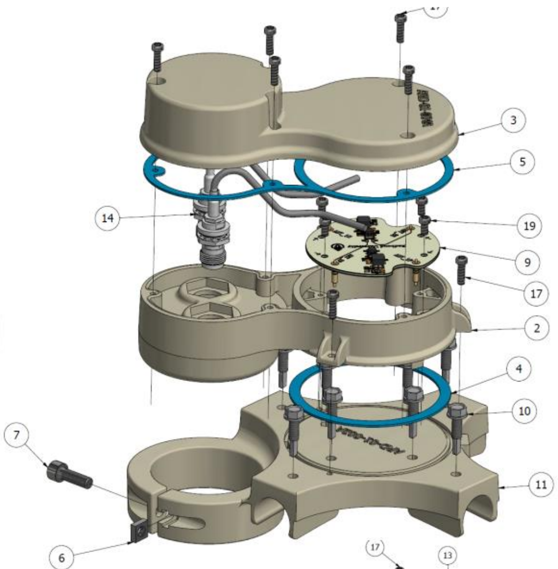
Mechanical components

mounting frame



antenna arms





housings for LNA and bottom load

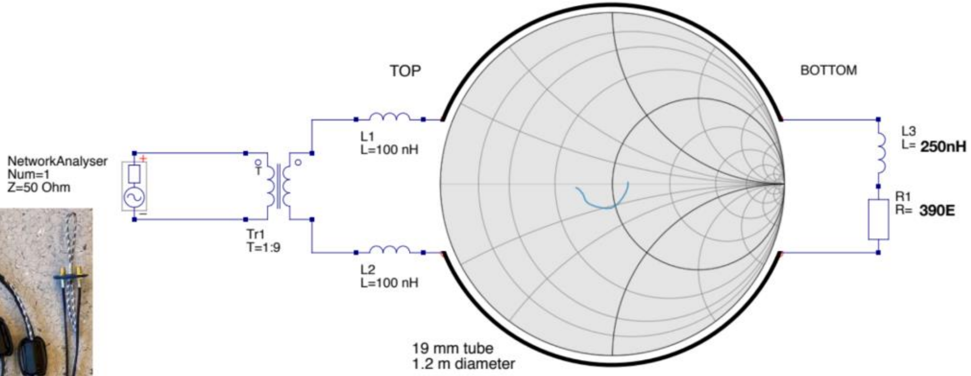
mast can be tilted for easy replacement of LNA

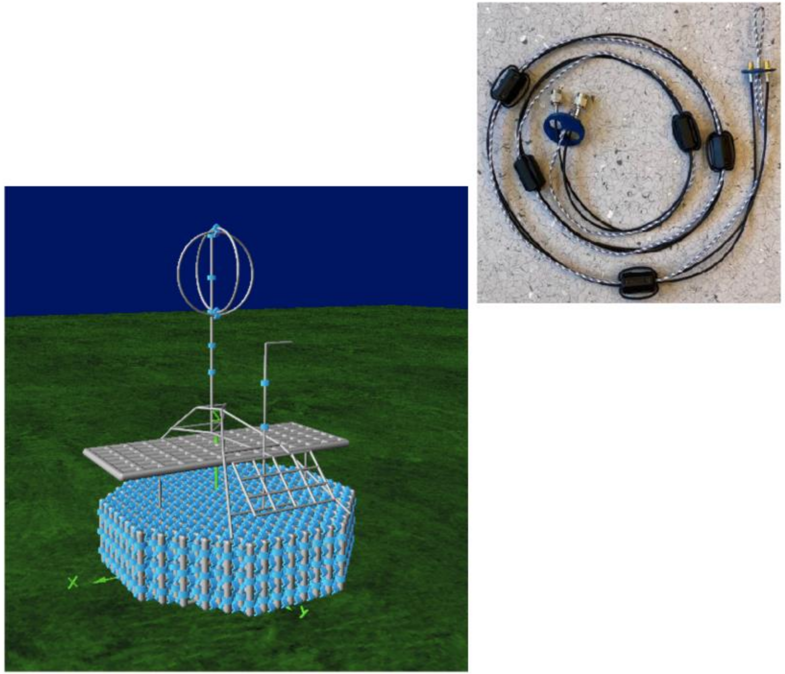
housings for digitizer

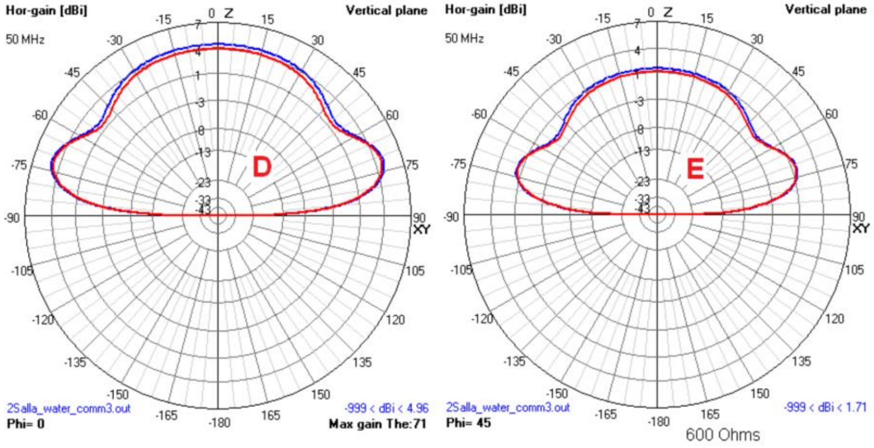
Tim Huege <tim.huege@kit.edu>

Short Aperiodic Loaded Loop Antenna

- bottom load to reduce influence of structures below antenna
- ferrites to reduce influence of cables on antenna pattern







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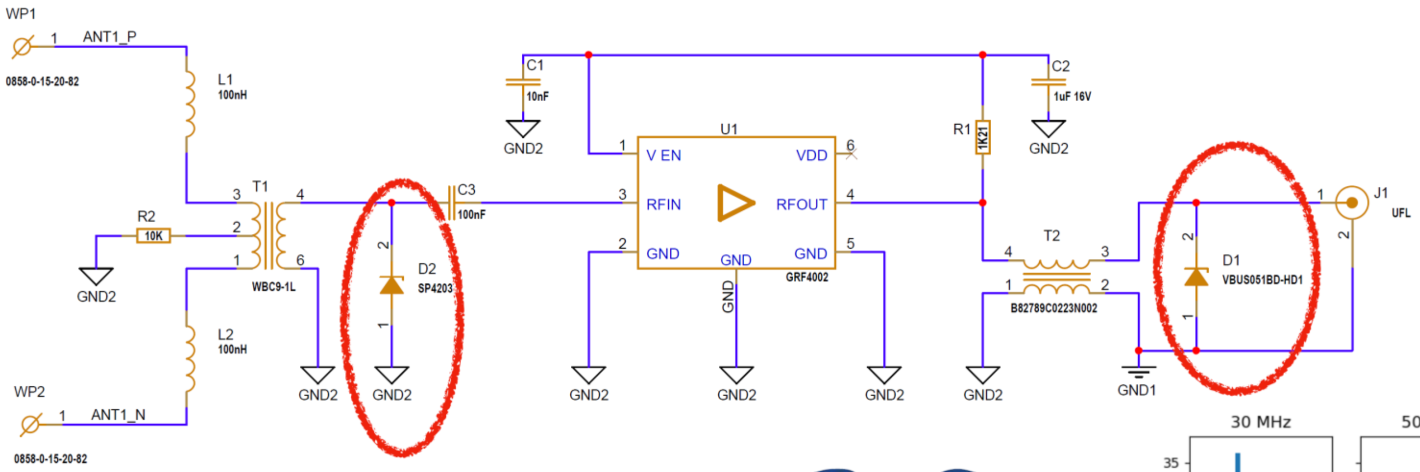
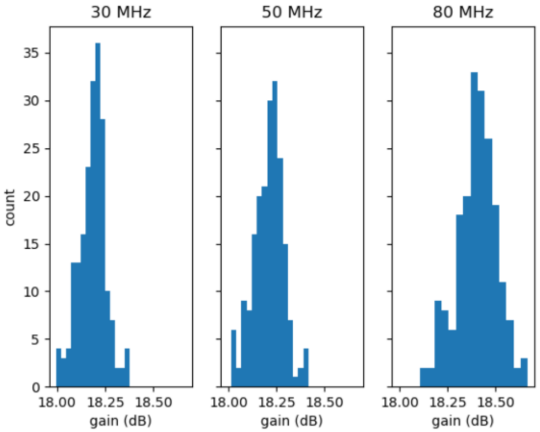
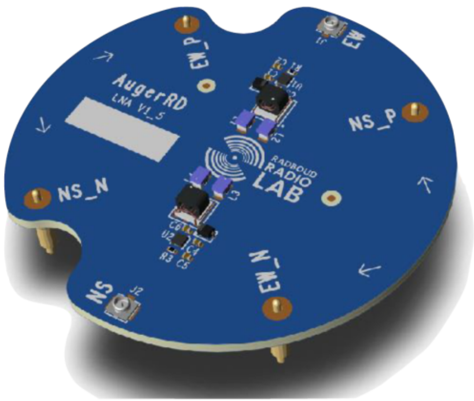
Low Noise Amplifier



~1% in voltage

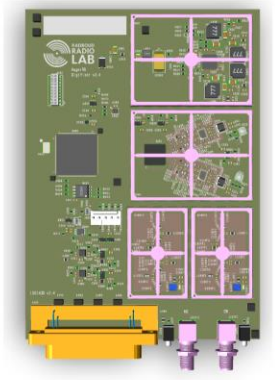


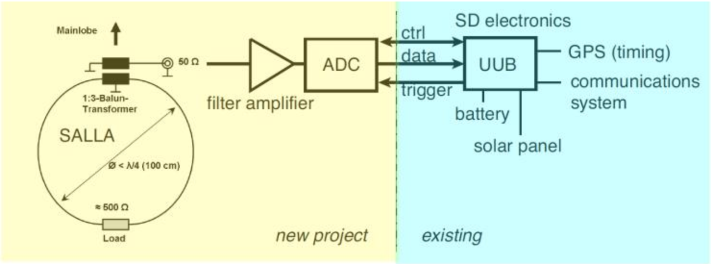
antenna is highest point of assembly
—> attractive for lightning
—> protection diodes
& design to allow easy maintenance



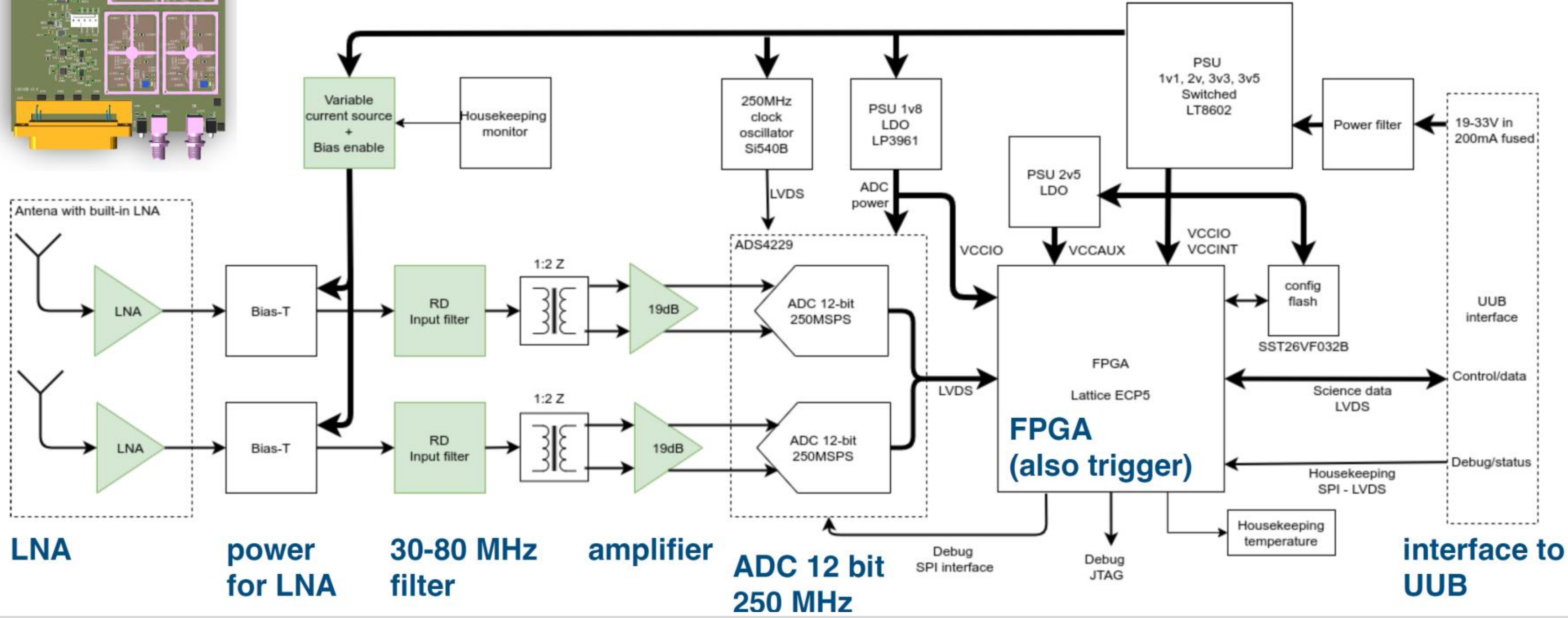
power consumption: 0,2 W

RD Digitizer



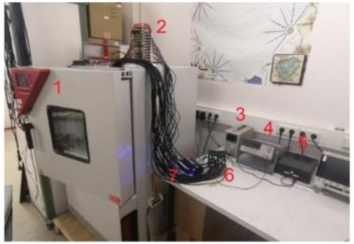


power consumption: 2,4 W

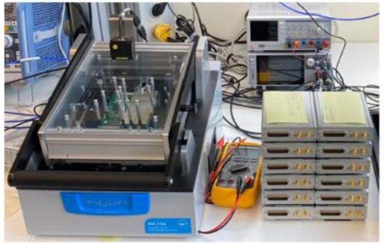


RD calibration concept

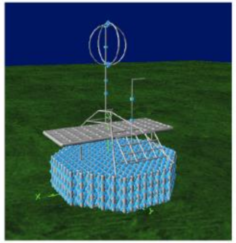
thermal cycling (aging) LNA & digitizer

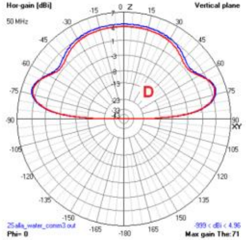


end-to-end calibration in lab LNA & digitizer

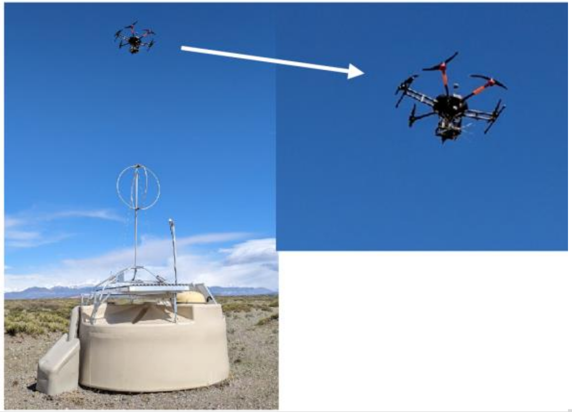


simulation of antenna pattern NEC

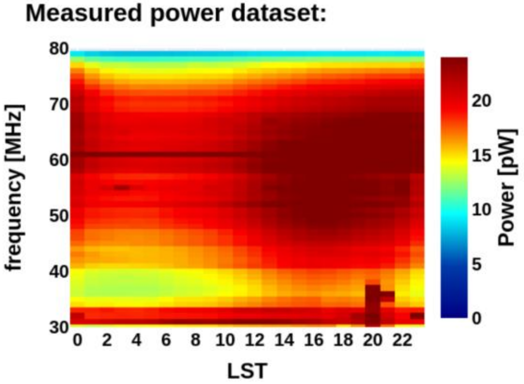




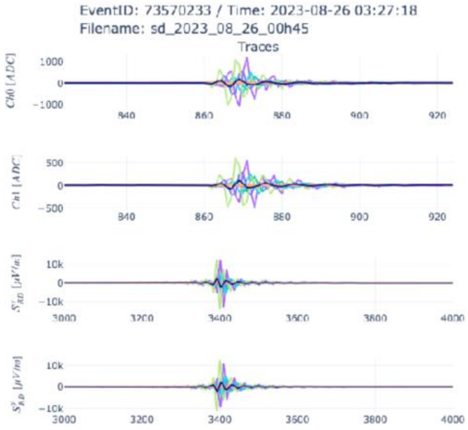
in-situ calibration with reference antenna



Galactic emission

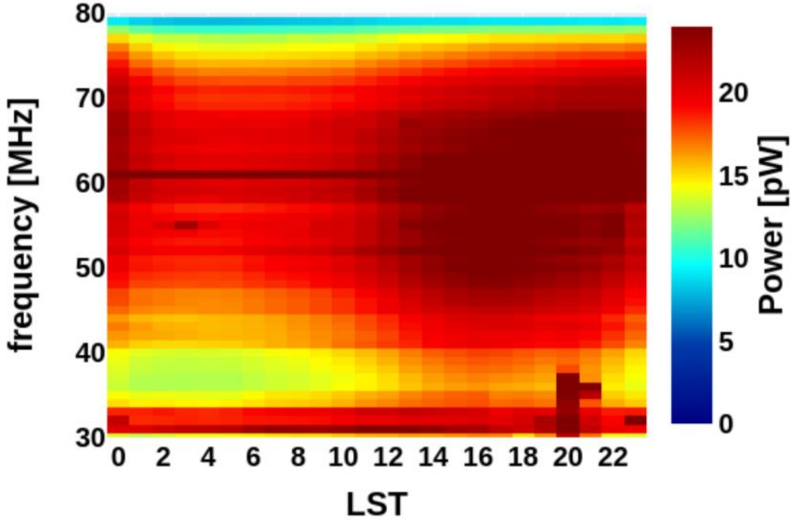


absolutely calibrated signals

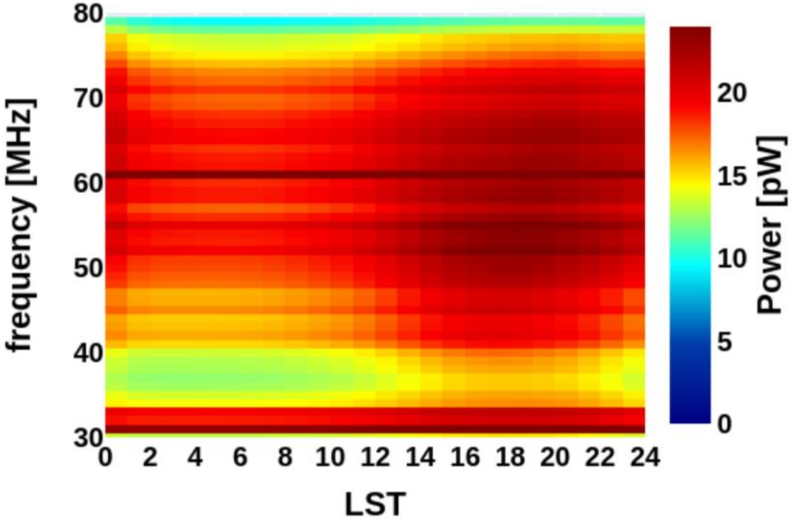


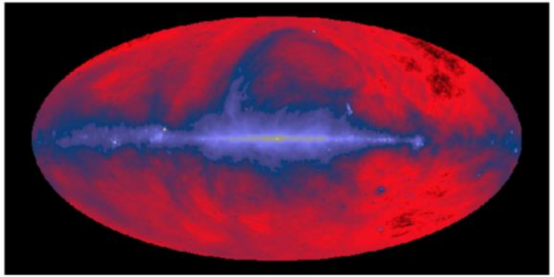
Measurement of Galactic emission

Measured power dataset:



Simulated dataset + fitted noise





—> the „muon peak" for radio
—> in-situ calibration
(implemented on FPGA)

systematic uncertainty ~10%

Aside: Uncertainties of using Galaxy as calibrator

Karlsruhe Institute of Technology

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Astronomy & Astrophysics

Uncertainties of the 30–408 MHz Galactic emission as a calibration source for radio detectors in astroparticle physics

M. Büsken[1,2], T. Fodran[3], and T. Huege[4,5]

[1] Institute of Experimental Particle Physics, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
e-mail: max.buesken@kit.edu
[2] Instituto de Tecnologías en Detección y Astropartículas, Universidad Nacional de San Martín, Av. General Paz 1555 (B1630KNA), San Martín, Buenos Aires, Argentina
[3] Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands
e-mail: t.fodran@science.ru.nl
[4] Institute for Astroparticle Physics, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
e-mail: tim.huege@kit.edu
[5] Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

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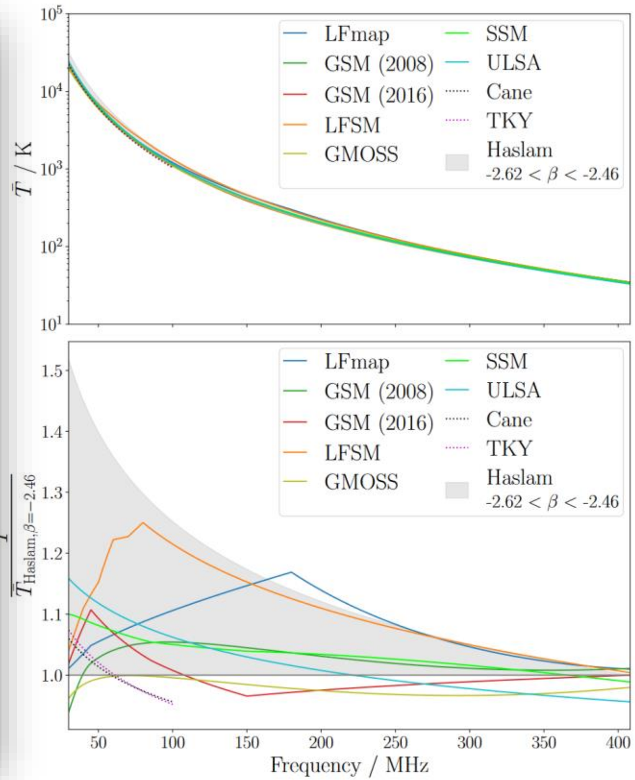
ABSTRACT

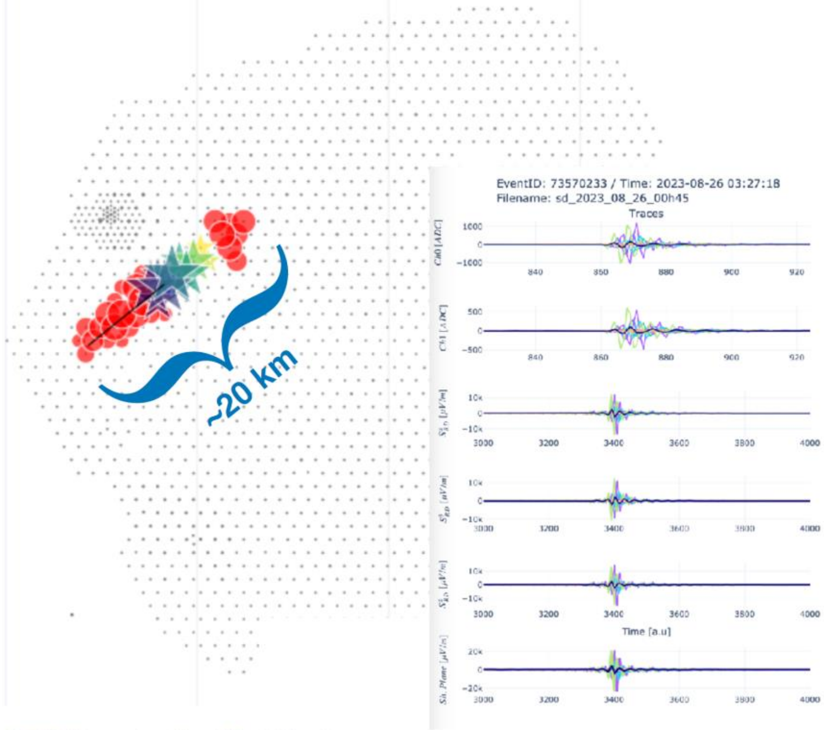
Context. Arrays of radio antennas have proven to be successful in astroparticle physics with the observation of extensive air showers initiated by high-energy cosmic rays in the Earth's atmosphere. Accurate determination of the energy scale of the primary particles' energies requires an absolute calibration of the radio antennas for which, in recent years, the utilization of the Galactic emission as a reference source has emerged as a potential standard.
Aims. To apply the "Galactic calibration," a proper estimation of the systematic uncertainties on the prediction of the Galactic emission from sky models is necessary, which we aim to quantify on a global level and for the specific cases of selected radio arrays. We further aim to determine the influence of additional natural radio sources on the Galactic calibration.
Methods. We compared seven different sky models that predict the full-sky Galactic emission in the frequency range from 30 to 408 MHz. We made an inventory of the reference maps on which they rely and used the output of the models to determine their global level of agreement. We subsequently took typical sky exposures and the frequency bands of selected radio arrays into account and repeated the comparison for each of them. Finally, we studied and discuss the relative influence of the quiet Sun, the ionosphere, and Jupiter.
Results. We find a systematic uncertainty of 14.3% on the predicted power from the Galactic emission, which scales to approximately half of that value as the uncertainty on the determination of the energy of cosmic particles. When looking at the selected radio arrays, the uncertainty on the predicted power varies between 11.7% and 21.5%. The influence of the quiet Sun turns out to be insignificant at the lowest frequencies but increases to a relative contribution of ~30% around 400 MHz.

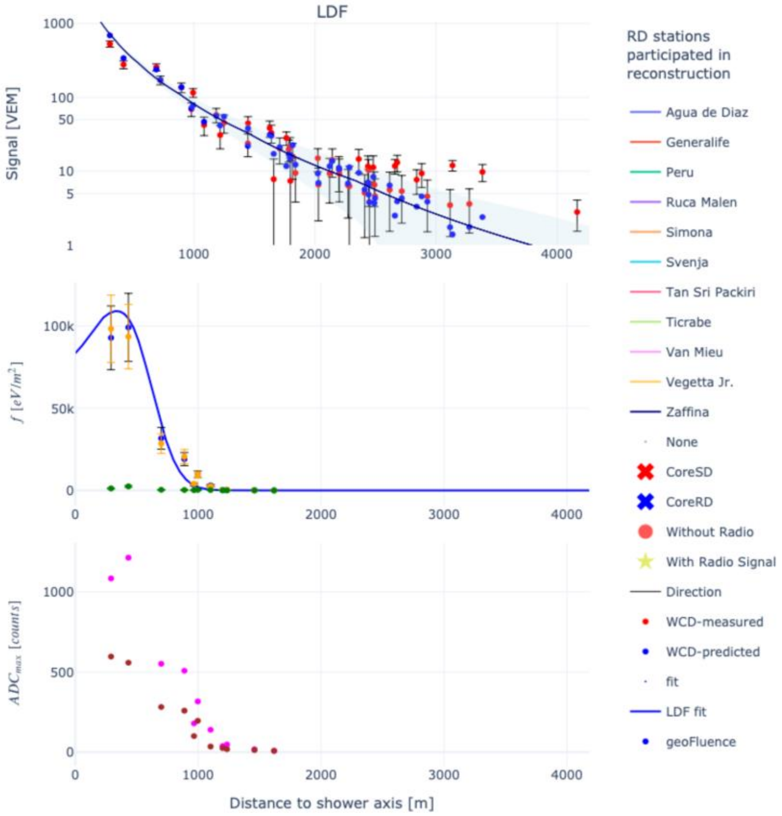
Key words. astroparticle physics – methods: miscellaneous – radio continuum: general – Sun: radio radiation



- Comparison of 7 sky models
- Assessment of agreement
- Relevance of quiet Sun (~11% at 400 MHz)

A measured air shower





WCD Reconstruction (52 stations)

$E_{SD} = 74.30 \pm 3.4\ EeV$

$\theta_{SD} = 74.7 \pm 0.0\ deg$

$\phi_{SD} = 217.2 \pm 0.1\ deg$

$N_{19} = 12.1 \pm 0.5$

RD Reconstruction (11 stations)

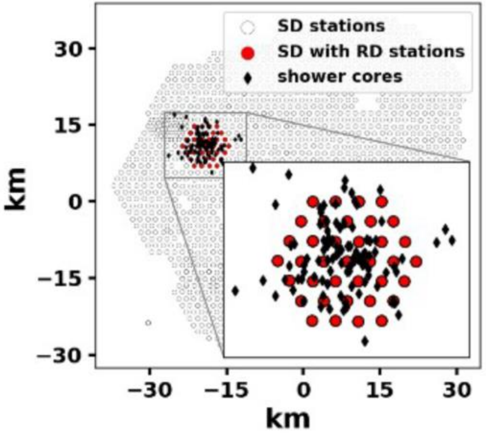
$E_{RD} = 80.62 \pm 7.0\ EeV$

$\theta_{RD} = 74.6 \pm 0.1\ deg$

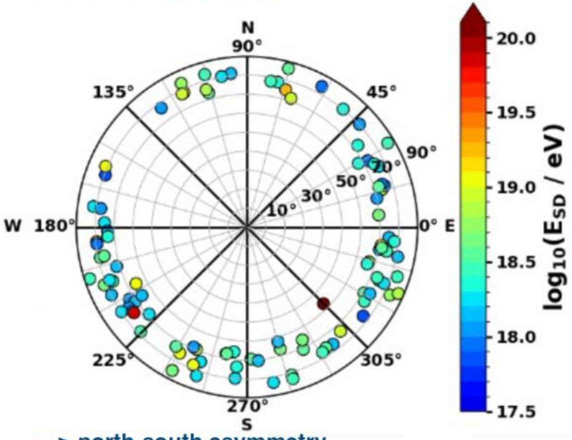
$\phi_{RD} = 217.1 \pm 0.0\ deg$

RD - look at 1st data

location of EAS axes

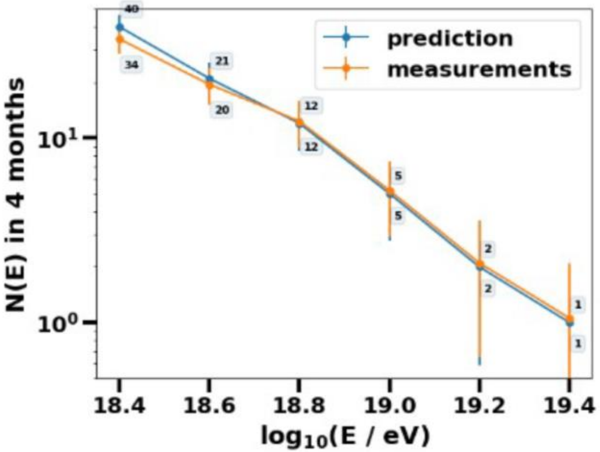


arrival direction

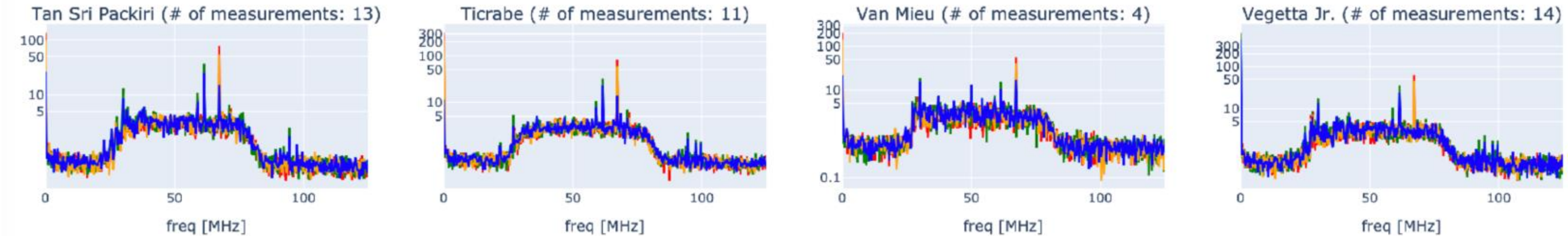


—> north-south asymmetry
—> emission mechanism vxB

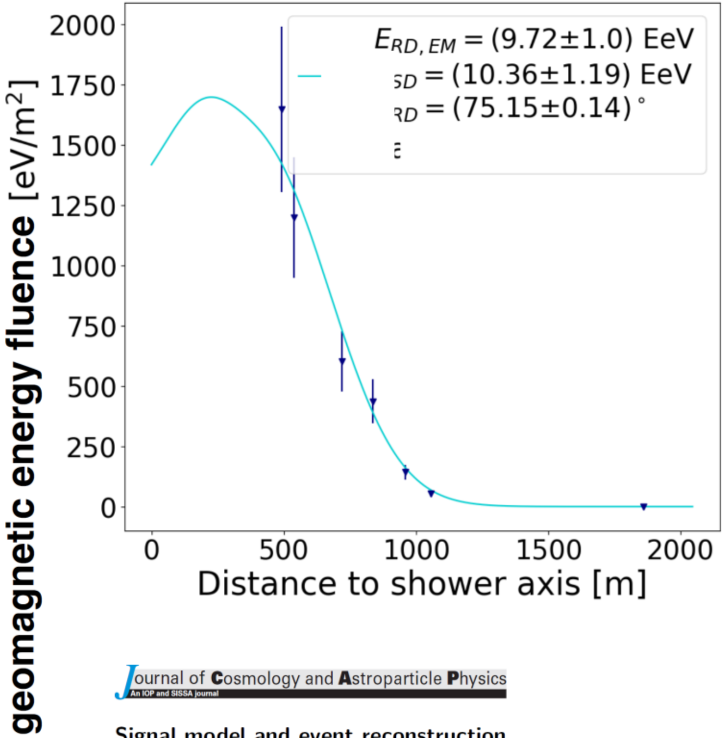
of measured cosmic rays

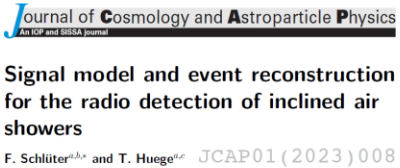


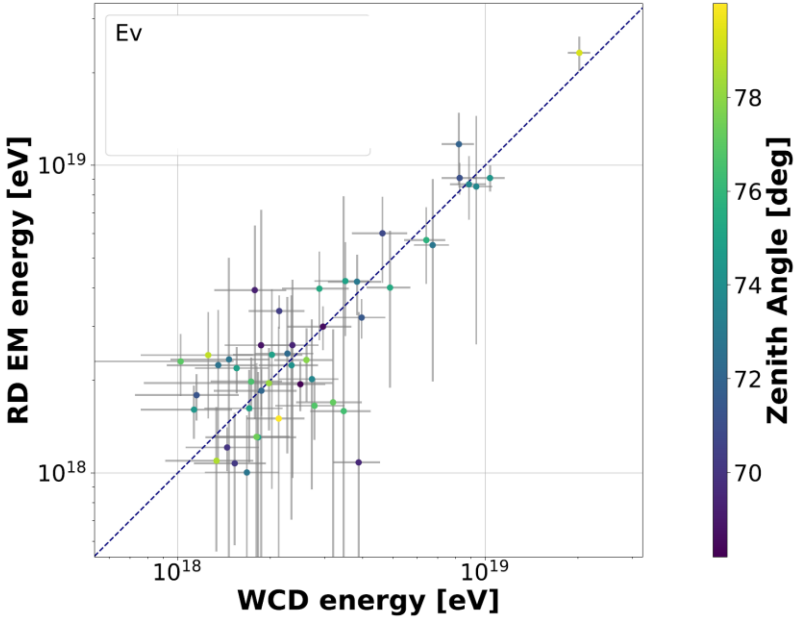
frequency spectra



Hybrid measurements RD-WCD







measurement of e/m energy by RD

—> full end-to-end verification of complete chain

Summary

- We are equipping the whole of Auger with 1660 radio antennas
- This will allow mass-sensitive measurements of inclined air showers
- Expected performance from end-to-end simulation study
  - ~4000 events measurable beyond 10^{19} eV in 10 years
  - Expect electromagnetic energy resolution of ~6%
  - Very good mass composition sensitivity/muon number measurements
- Design proven, mass production ongoing, deployment complete in 2024
- Future opportunitie
  - Use radio information for triggering, improve photon detection
  - Time-synchronize RD antennas to 1 ns, use interferometry