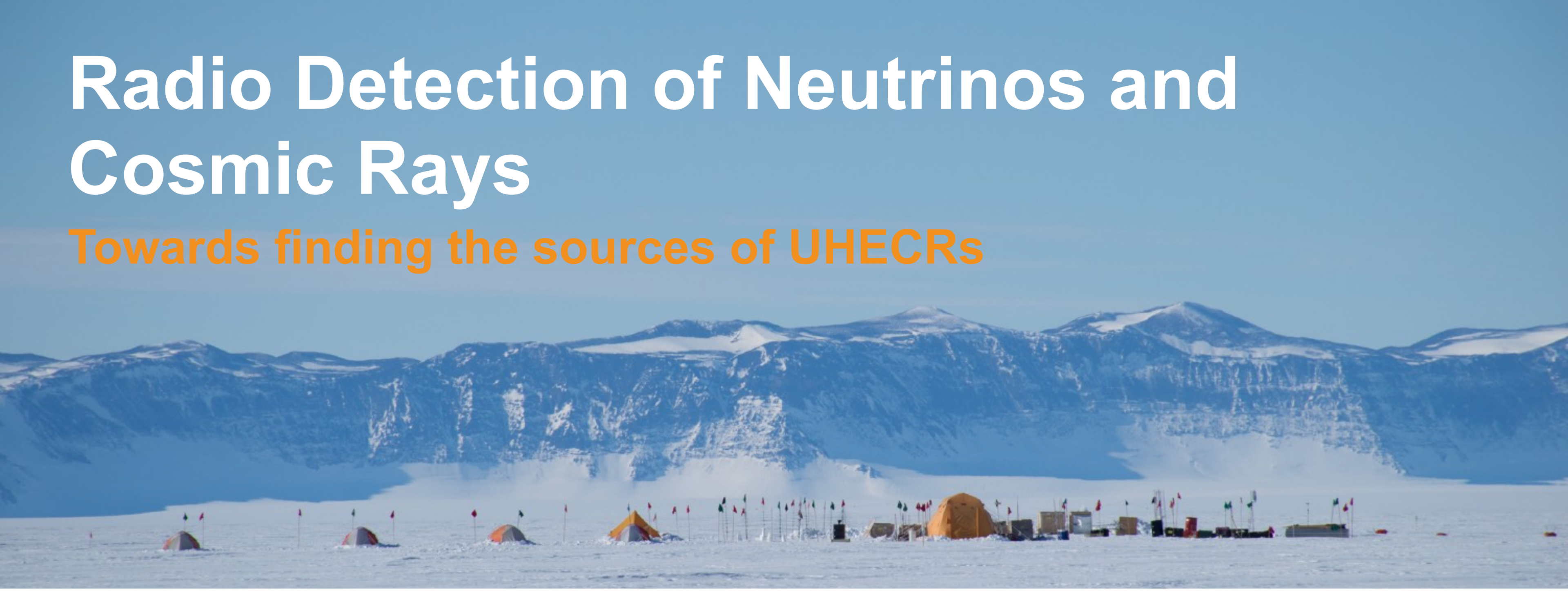
Radio Detection of Neutrinos and Cosmic Rays

Towards finding the sources of UHECRs



Anna Nelles

Cosmic Rays and Neutrinos in the Multi-Messenger Era (Online), December 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

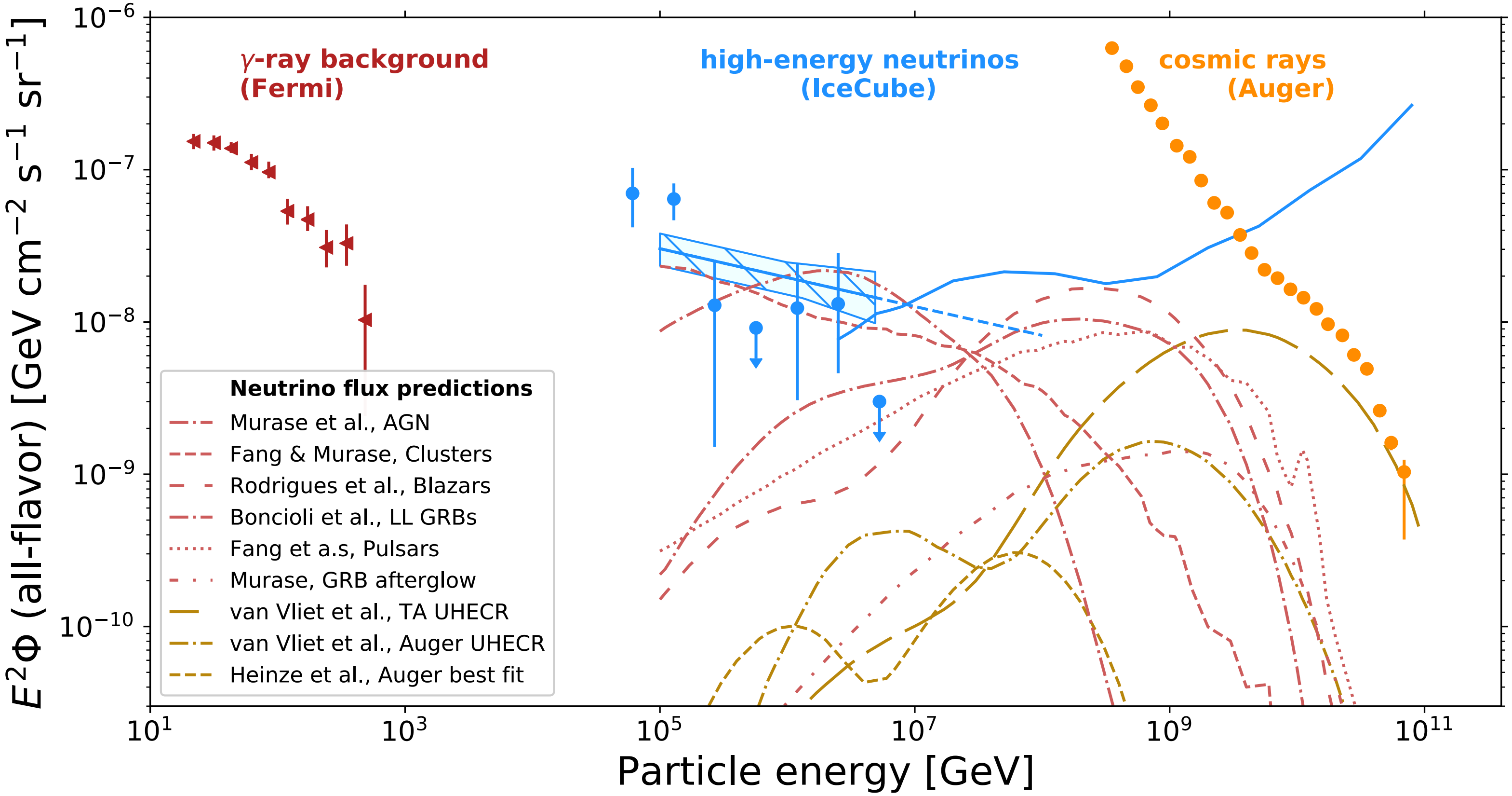
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

DESY.

Scientific motivation

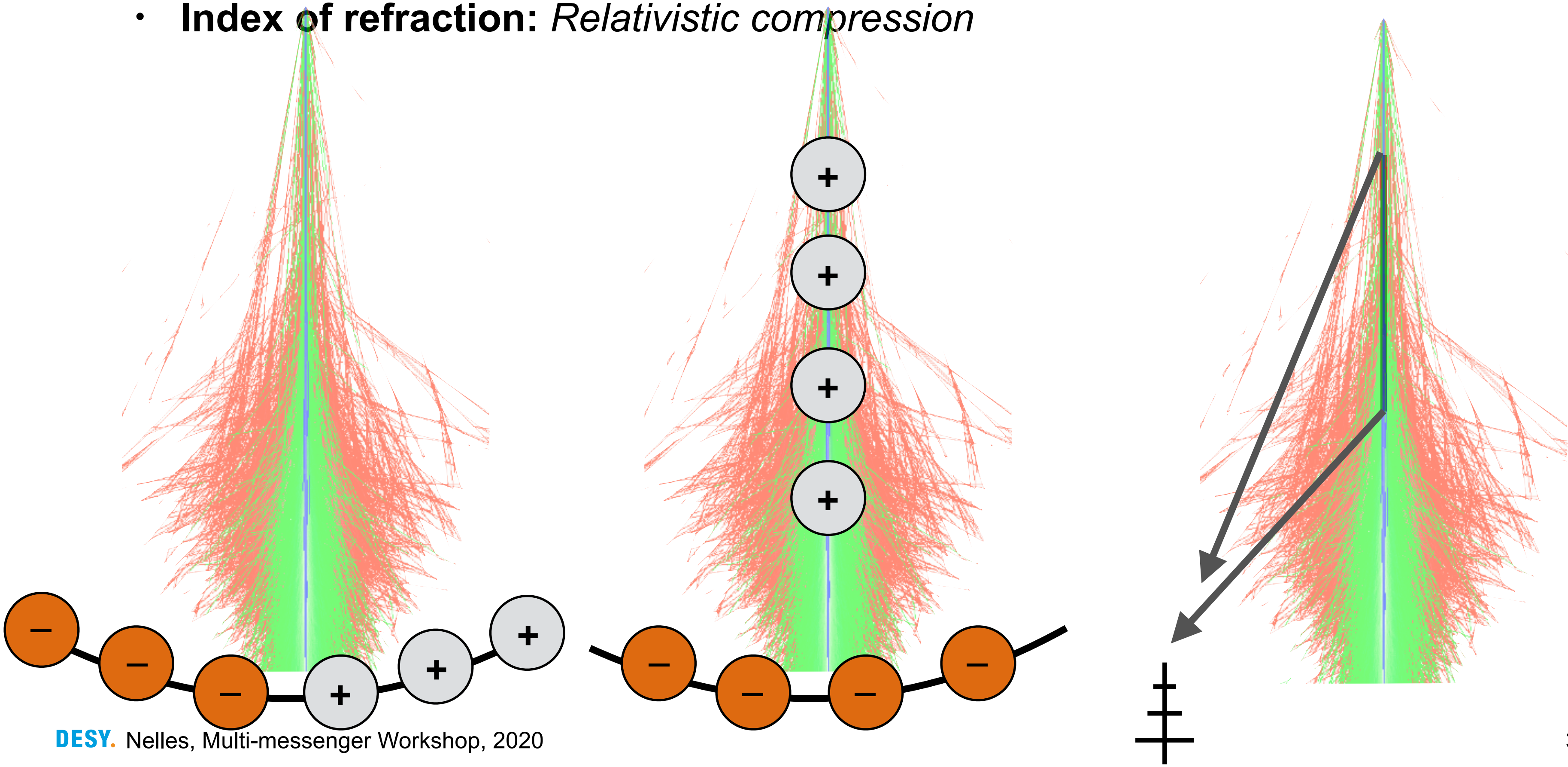
Thankfully all covered by Kumiko



Radio emission of showers

The story of the two effects and the refractive index

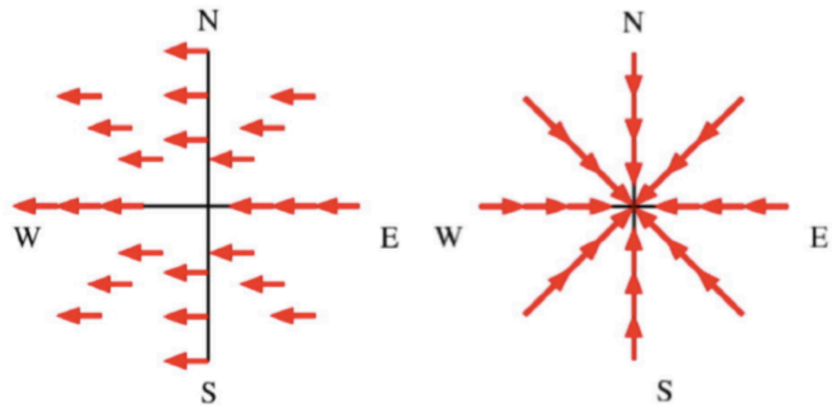
- Radio emission of showers can be explained from first principles and three aspects
  - **Magnetic field:** *Geomagnetic field, Lorentz-force*
  - **Charge imbalance:** *Particle Physics processes*
  - **Index of refraction:** *Relativistic compression*

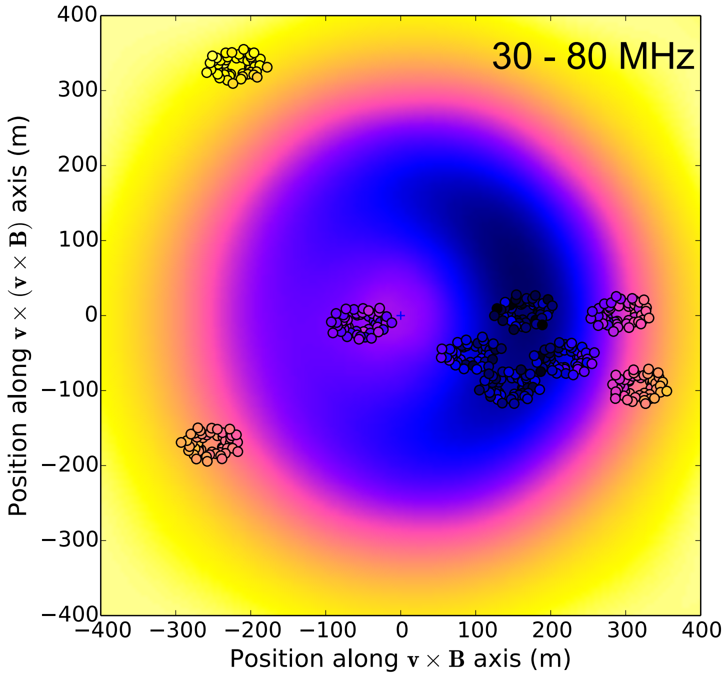


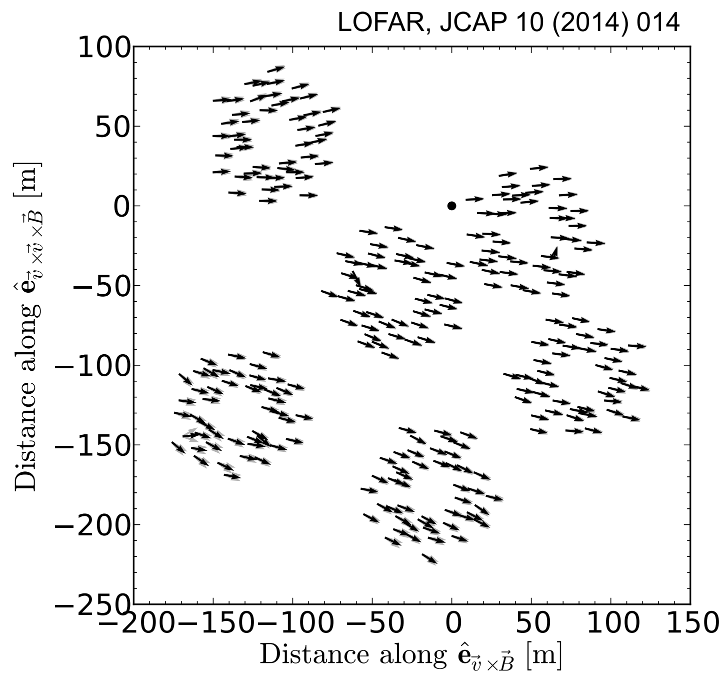
Radio emission of showers

How do we know this?

- The key evidence: **Polarization**
  - **Geomagnetic effect:** *Lorentz-force, polarization orthogonal to shower axis and magnetic field*
  - **Askaryan effect:** *Polarization points towards shower axis*



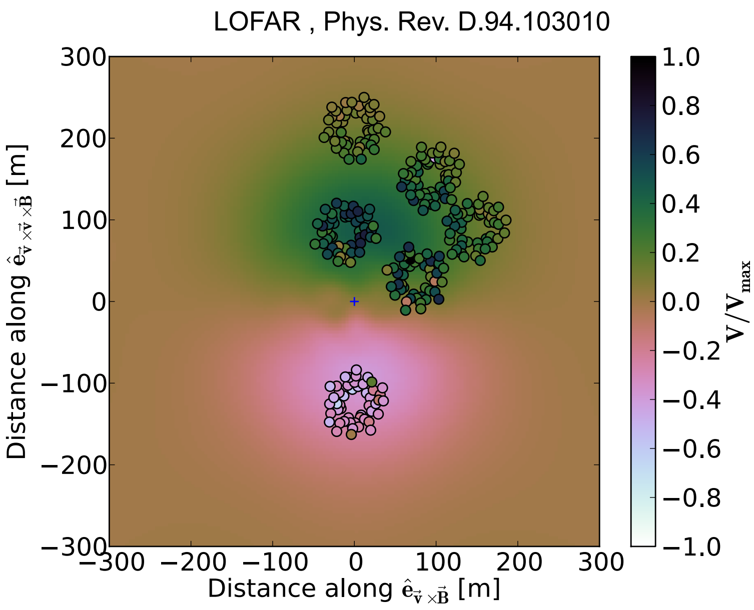




Radio emission of showers

How do we know this?

- The key evidence: Polarization
  - The **two processes** stem from slightly different heights
  - Time difference = phase offset between two emission components
  - Leads to **circular polarization**



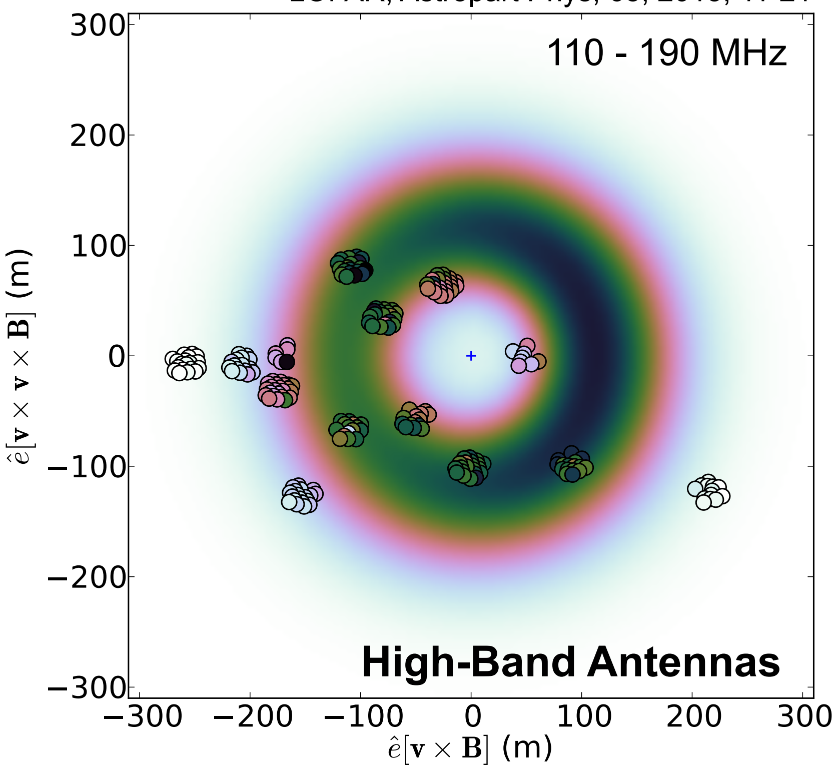
- Emission is due to **both geomagnetic emission** (dominant in air) and **Askaryan emission**
- Geosynchrotron radiation is a correction of < 1% to these effects

Radio emission of showers

There is also a Cherenkov ring but not Cherenkov emission

- The emission is only strong if it arrives coherently (at the same time for all frequencies, high frequencies more pronounced effect)
- At the Cherenkov angle, an enhancement is seen, in air this is very close to the shower axis
- Same effect for showers in ice, but here Cherekov angle ~ 52 degrees, so it looks much more like “Cherenkov radiation”, but it is not
- If one had the same shower development in vacuum, it would still radiate

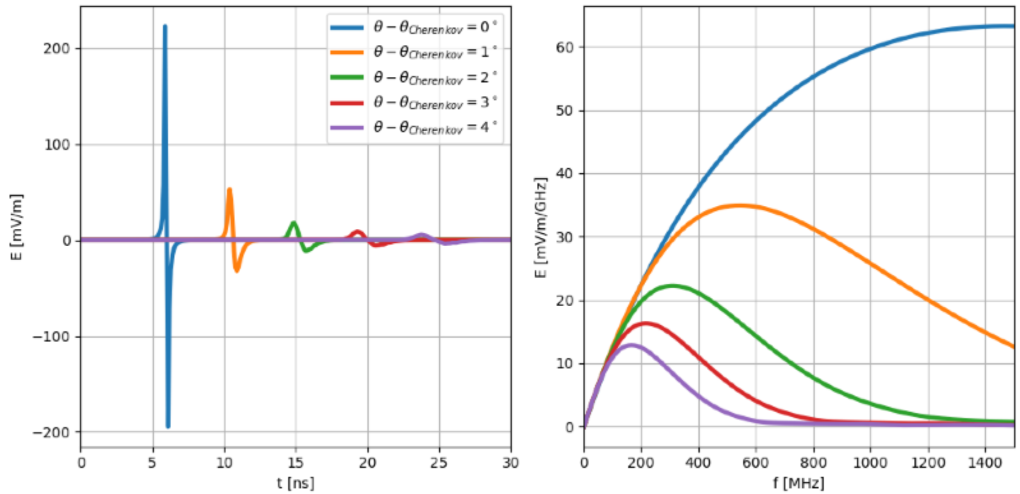
LOFAR, Astropart Phys, 65, 2015, 11-21

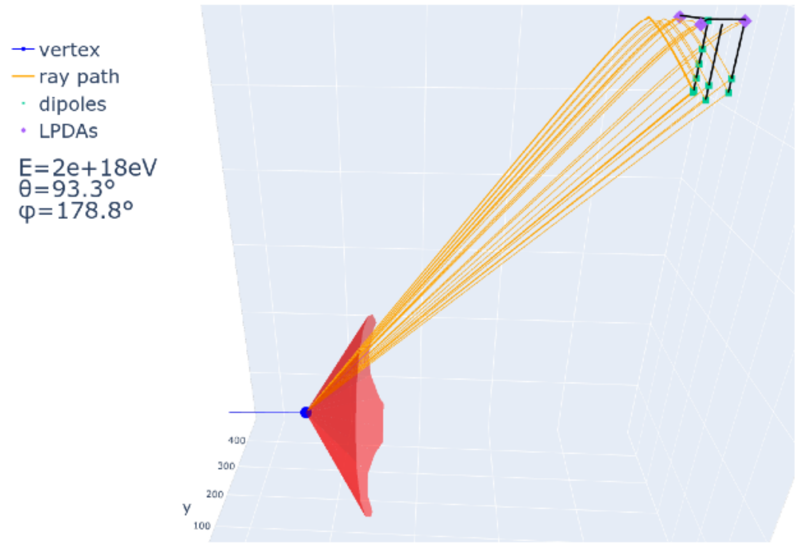


Radio emission of showers in dense media

A difference between detecting cosmic rays and neutrinos

- Showers in media are smaller, i.e. more intense charge imbalance and less influence of geomagnetic field
- Higher frequencies due to smaller size
- Index of refraction >> 1, Cherenkov cone, travel on non-straight lines with changing n
- Ice attenuates the signal, air does not



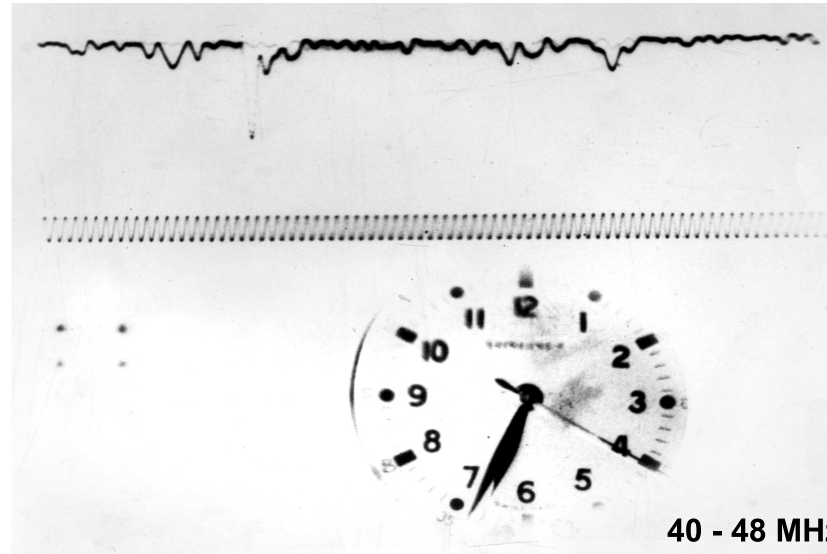


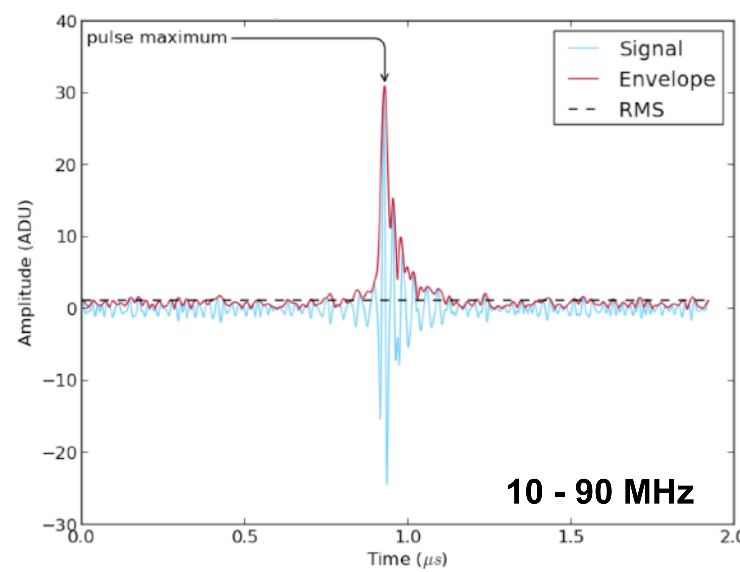
Detecting radio emission of air showers

Experimental challenges and opportunities

- Search for a very broad-band nanosecond scale pulse
- Detectable typically at shower energies > 10^{15} eV, i.e. rare signal
- Sampling speeds of at least 200 MHz
- Needs full waveform sampling for frequency content and polarization
- Preferably stations run independently at very low power
- Duty-cycle (almost) independent of weather

Jelley et al, Nature 1965

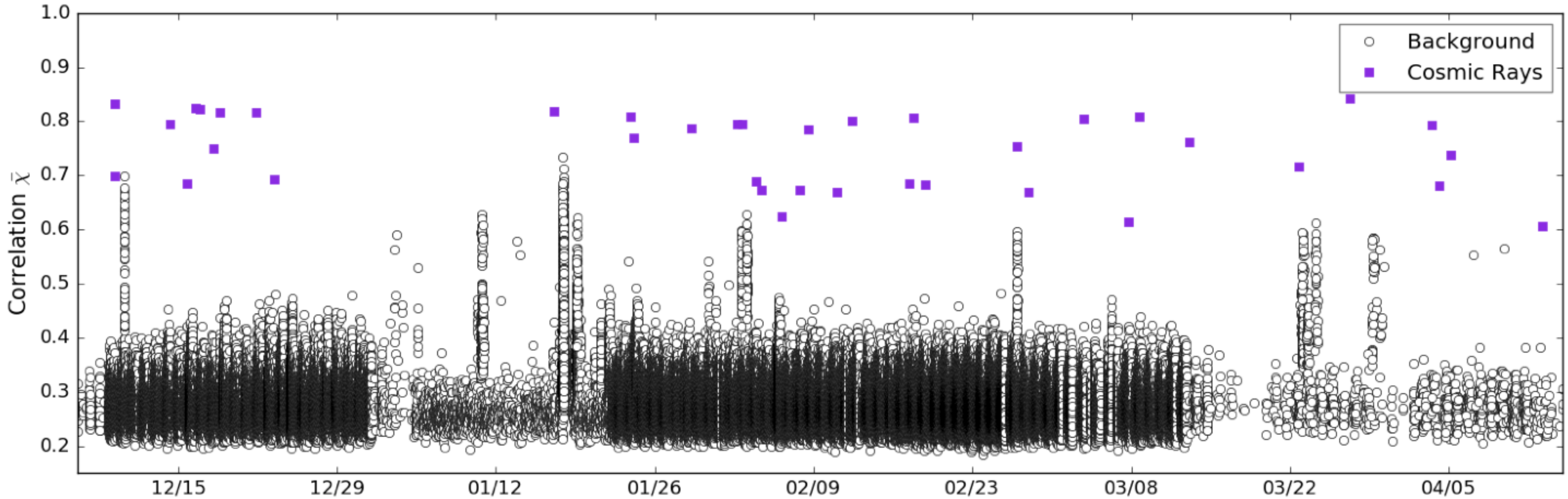


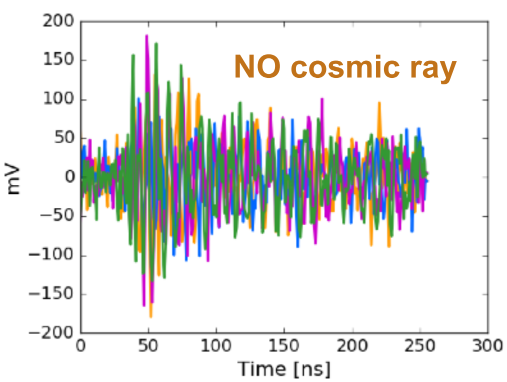


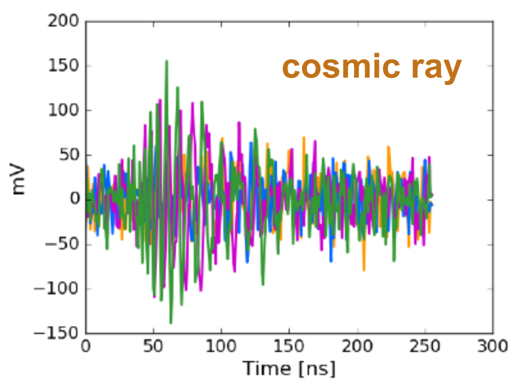
Detecting radio emission of air showers

Experimental challenges and opportunities

ARIANNA Coll., Astropart. Phys. 90 (2017) 50





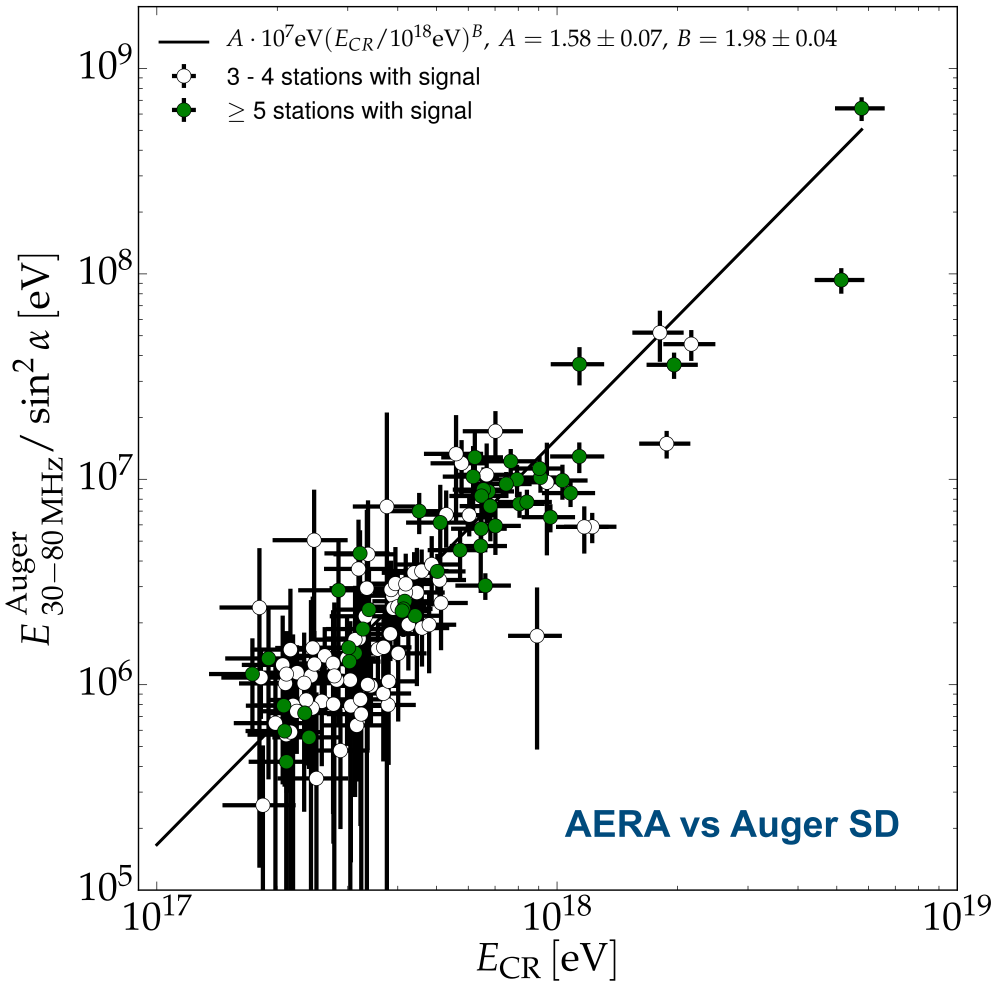


- Unfortunately, a lot of things make radio pulses
- Self-triggering and event identification remain a challenge
- Site quality important
- New opportunities in modern data analysis methods

Detecting radio emission of air showers

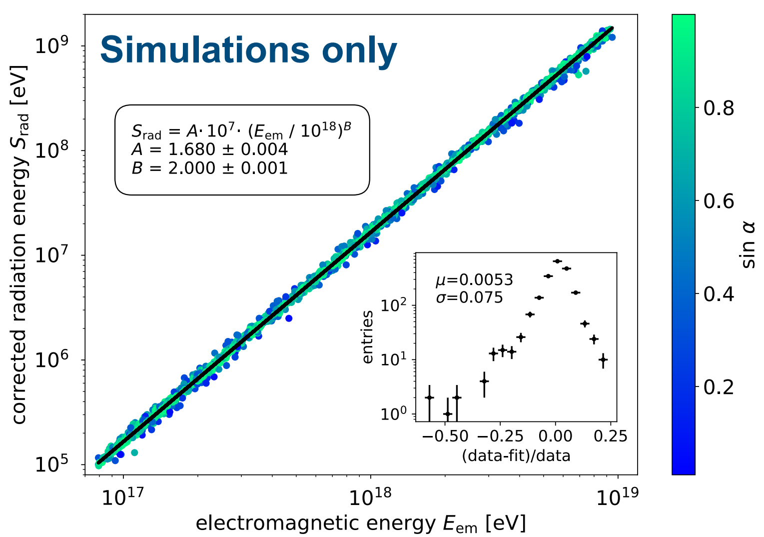
What is in it for the science?

A. Aab et al., PRL 116 (2016) no.24, 241101



- Radio detection provides and excellent **energy estimator**
- Calculation from first principles
- Very little systematic uncertainties (< 5%) in method

M. Gottowik et al. Astropart. Phys. 103 (2018) 87

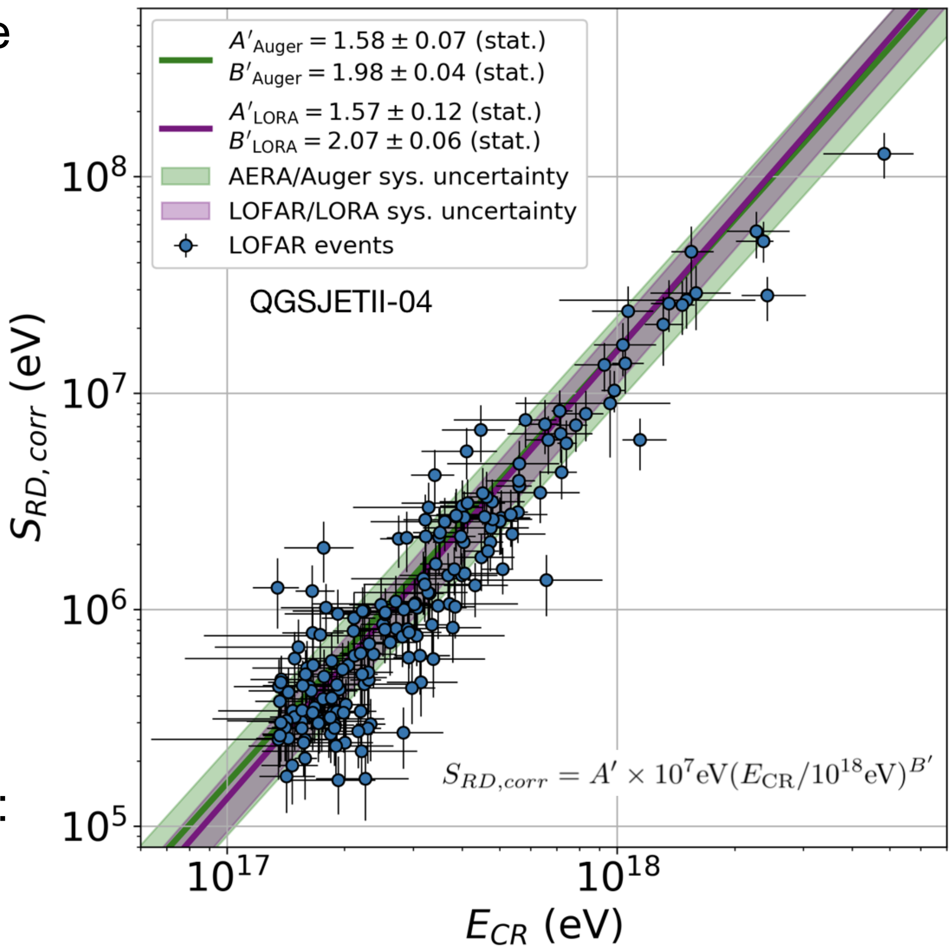


Detecting radio emission of air showers

What is in it for the science?

- Negligible corrections due to atmospheric effects on energy-scale
- Auger has so far shown the most thorough detector calibration, obtaining an absolute scale uncertainty of 14 %
- **A radio energy estimate could reduce systematic uncertainties between observatories with modest experimental efforts**
- First try: LOFAR vs. Auger, comparing Auger Surface Detector to LORA scintillator array at LOFAR: $E_{CR LORA}/E_{CR Auger}$= 1.06±0.20

K.Mulrey et al. *JCAP* **2020** 017

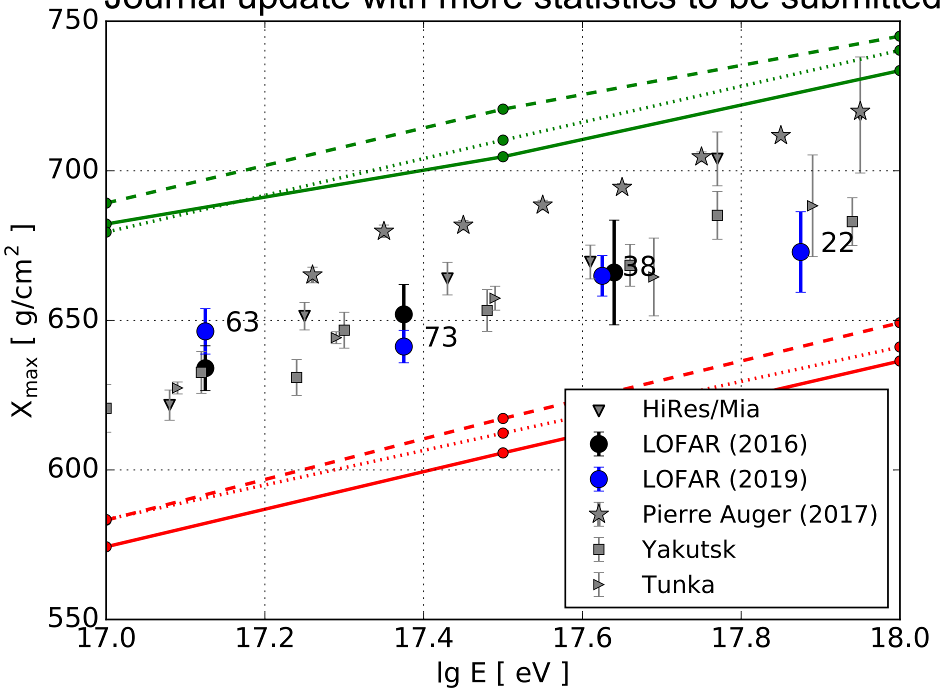


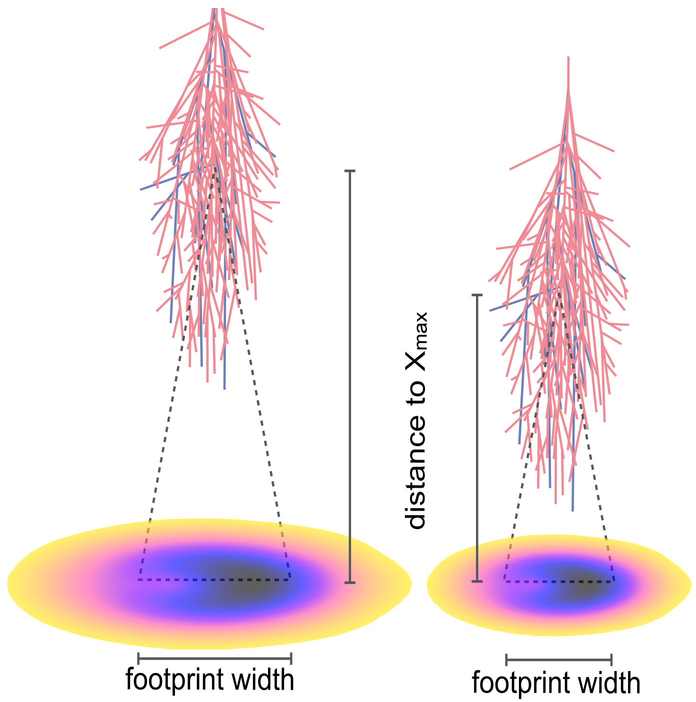
Detecting radio emission of air showers

What is in it for the science?

- Radio pattern is very sensitive to X_{max}
- LOFAR has presented high precisions X_{max} measurements, $\sigma_{X_{max}}$ = 17 g/cm^2

PhD Thesis A. Corstanje, Update to Nature 2016
Journal update with more statistics to be submitted





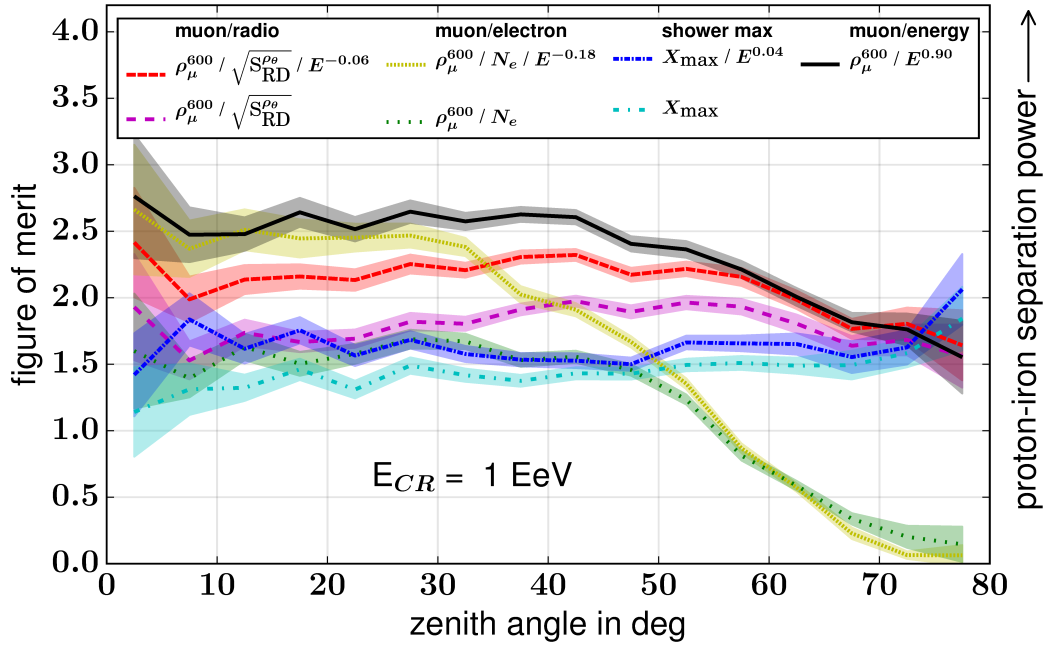
- Tension to Auger FD measurements
- Eagerly awaiting RD/FD hybrid study to possibly resolve this

Detecting radio emission of air showers

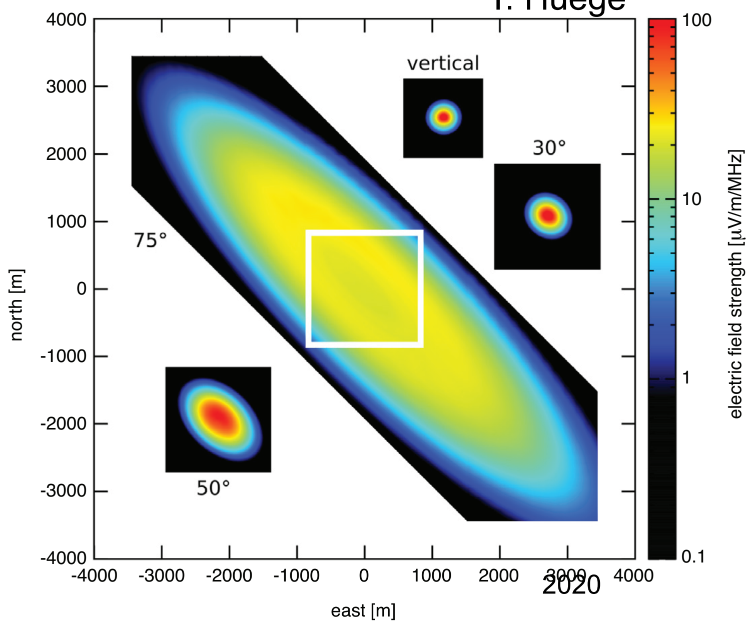
What is in it for the science?

- Radio emission stems from the electro-magnetic component of the shower
- Attenuation in the atmosphere is negligible, radio emission of horizontal showers still accessible

E. Holt et al., EPJC, 2019



T. Huege



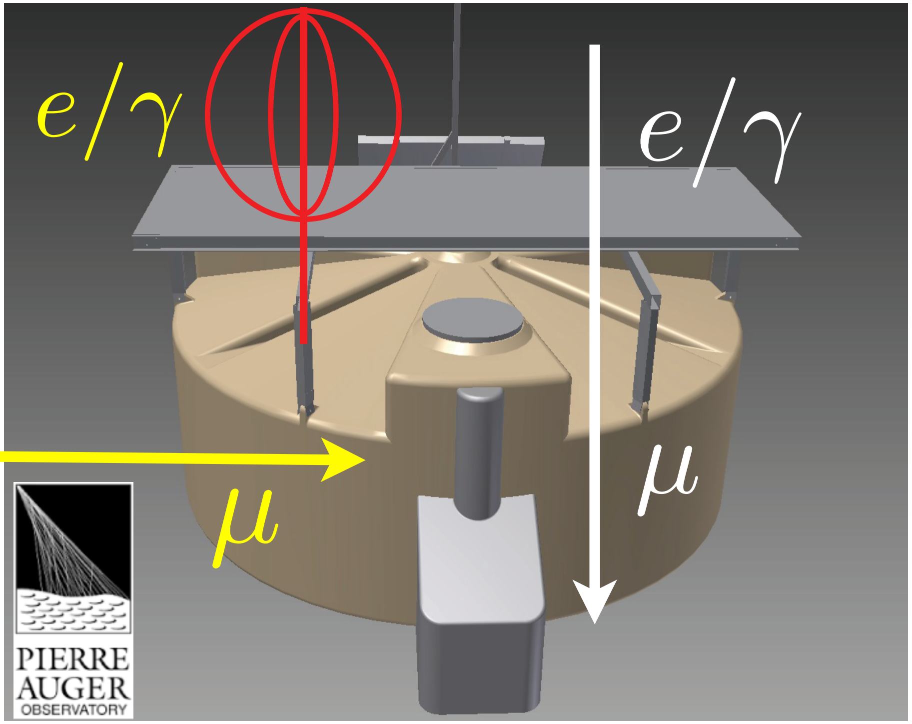
- Combining muon measurements with radio antennas provide a different handle on composition

Radio detection of air showers

Where will it go next?

- Equipping every Auger SD station with a radio antenna and scintillator
- The first truly large-scale implementation of the radio technique
- First chance to access the radio emission of showers of the highest energies
- Combination of many ways of air shower detection, will lower systematics on all parameters

Upgrade of the Pierre Auger Observatory

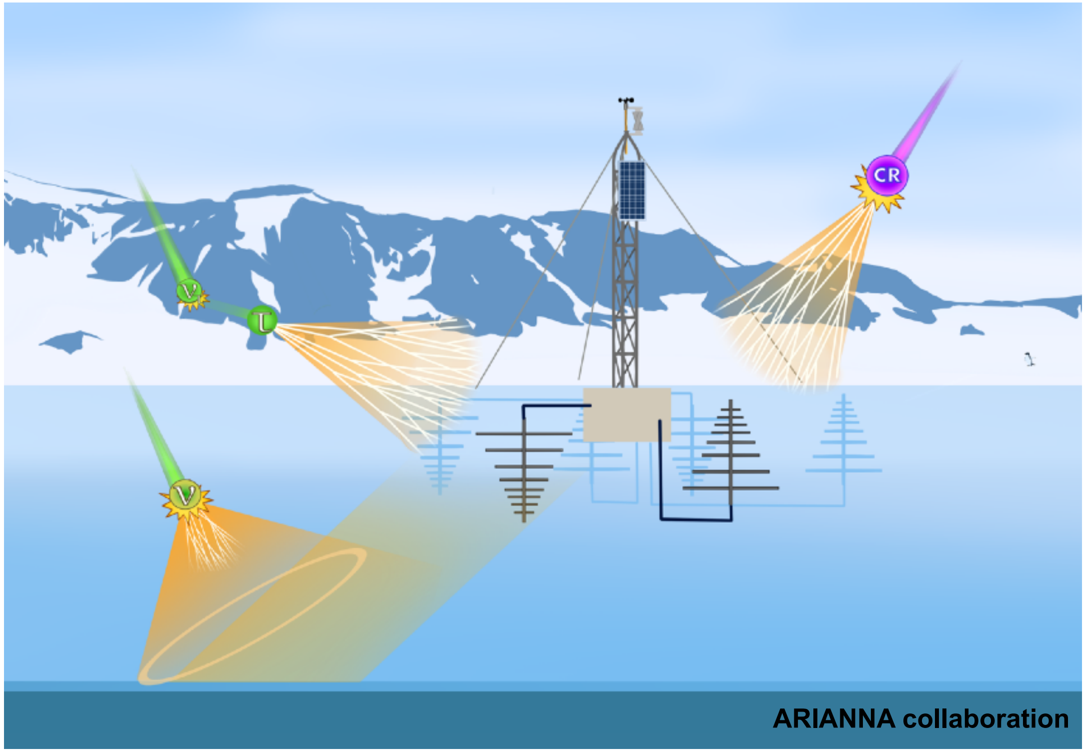


- Mean-time: Many new/improved methods for reconstruction and simulations
  - Interferometry (Schoorlemmer, Carvalho), single-station energy reconstruction (Welling et al.), template synthesis (Butler et al.), index of refraction corrections (Schlüter et al.), simulation interpolations (Tueros, Zilles), …

Radio detection of other particles

Why it is interesting for neutrinos?

- Any shower containing an electro-magnetic cascade creates radio emission
- A similar experimental approach for:
  - air showers from cosmic rays
  - air showers from neutrino induces tau decays
  - in ice showers following a neutrino interaction

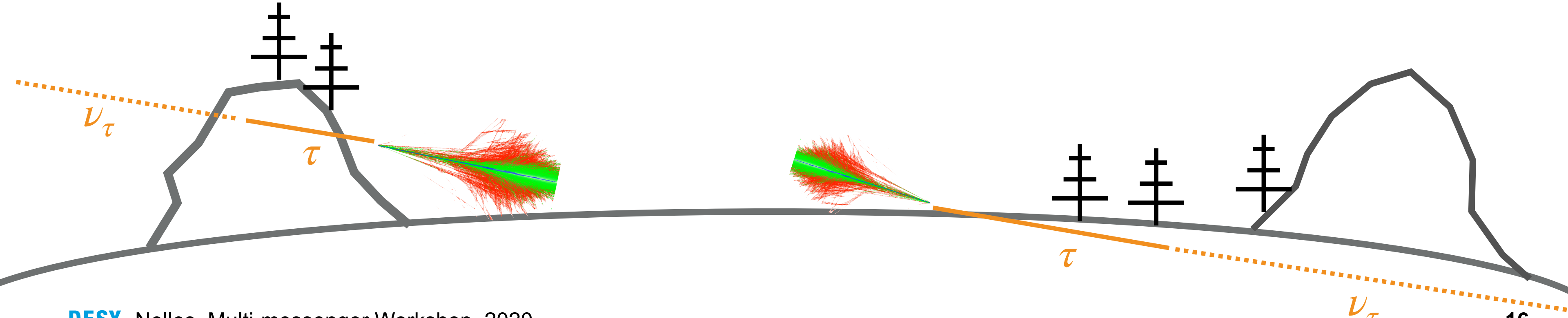


- All experiments utilize negligible radio attenuation in air and kilometer-scale attenuation length in ice

Radio detection of neutrinos

Tau neutrinos emerging from the Earth

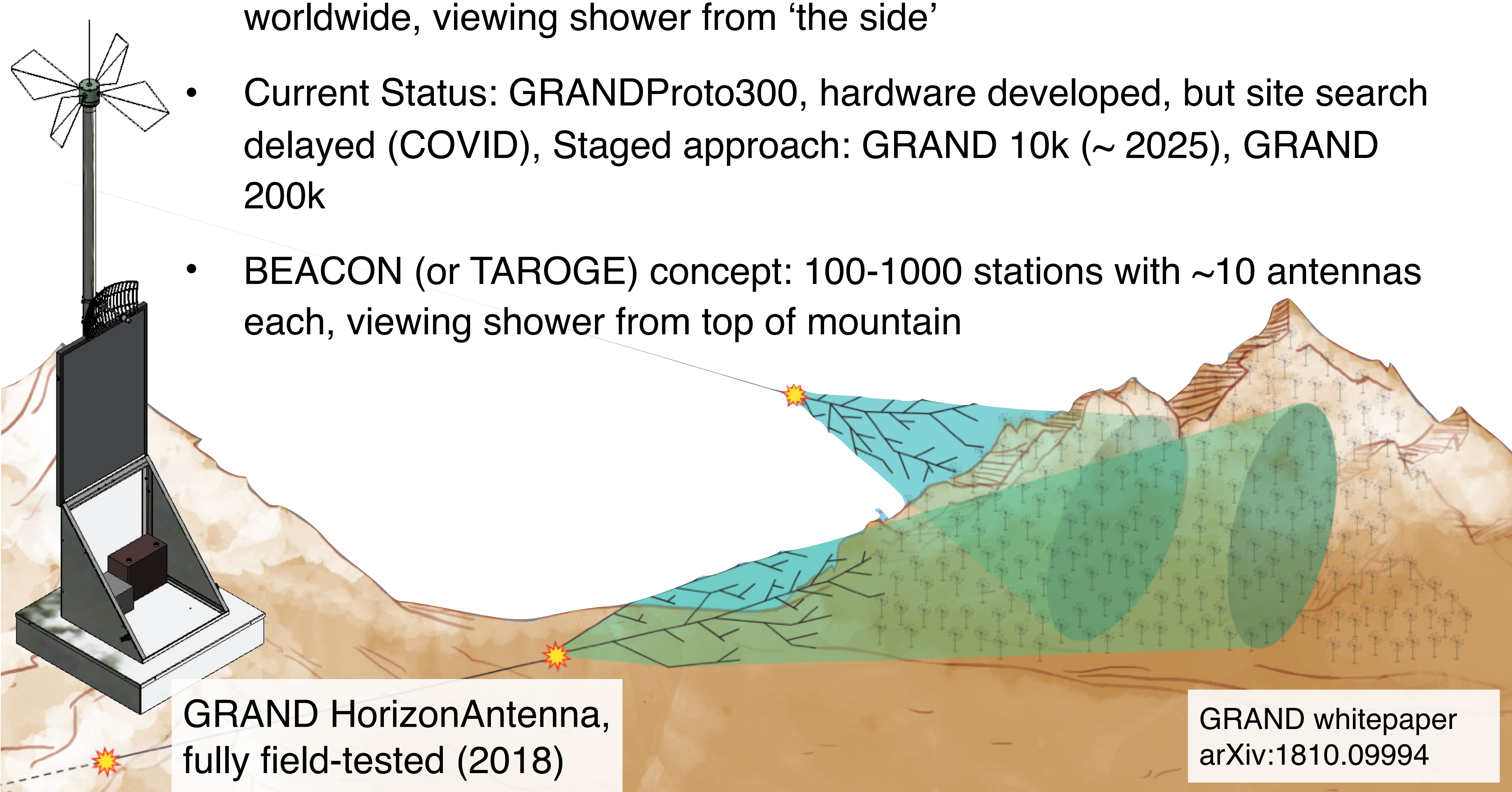
- Looking at tau's emerging from the Earth, creates large effective volumes for neutrinos, radio emission is (almost) not attenuated in air
- Radio detectors probably most effective, when they use mountainous terrain
- Have to exploit economies of scale for very cheap antenna stations
- Largest challenge: suppress (human-made) background close to the horizon
- A couple of projects on-going or proposed,
  e.g. GRAND, BEACON, TARGOE (radio),
  TAMBO (water-Cherenkov), TRINITY (air-Cherenkov), …



Radio detection of (tau)-neutrinos

Looking for air showers but stemming from neutrinos

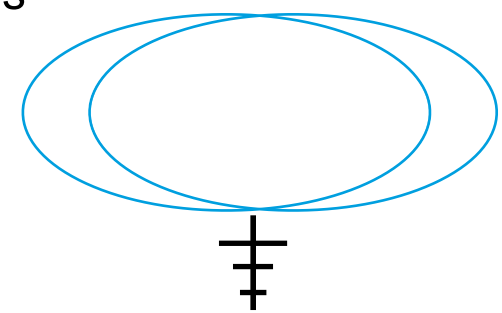
- GRAND: concept: 200’000 radio antennas over 200'000 km^2, i.e.~ 20 hotspots of 10'000 antennas over favorable sites in China and worldwide, viewing shower from ‘the side’
- Current Status: GRANDProto300, hardware developed, but site search delayed (COVID), Staged approach: GRAND 10k (~ 2025), GRAND 200k
- BEACON (or TAROGE) concept: 100-1000 stations with ~10 antennas each, viewing shower from top of mountain



Radio detection of neutrinos

Neutrino interactions in ice

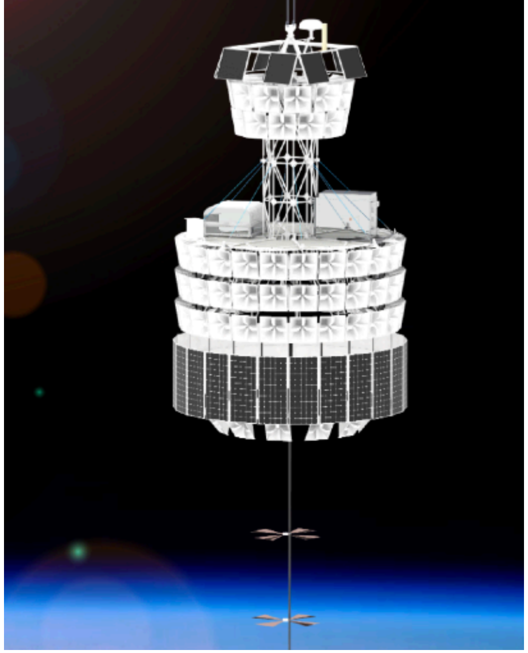
- Cold polar ice has attenuation length in the order of kilometers
- One radio station can typically monitor 1 km^3 of ice (= the size of IceCube)
- Detection threshold around 10 PeV shower energy, determined not by array spacing but pulse height above thermal noise
- > 100 km^3 needed to obtain sensitivity for cosmogenic neutrinos, neutrinos from UHECR with CMB, if very few protons at highest energies
- Human-made background typically smaller in polar regions, event identification and self-trigger less challenging
- Many early experiments:
  RICE, ARA, ARIANNA, …



and of course, ANITA

Radio detection of neutrinos

Results so far

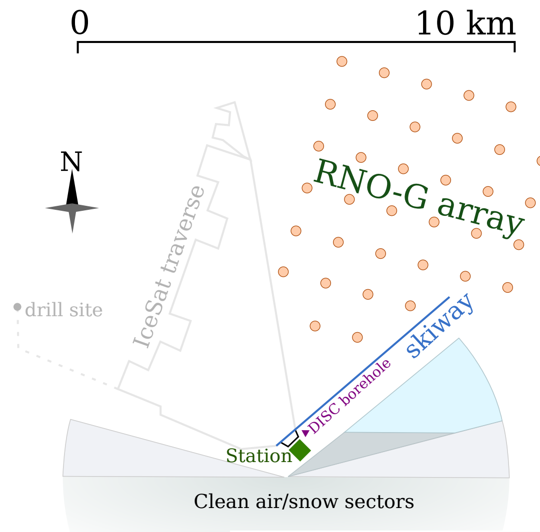


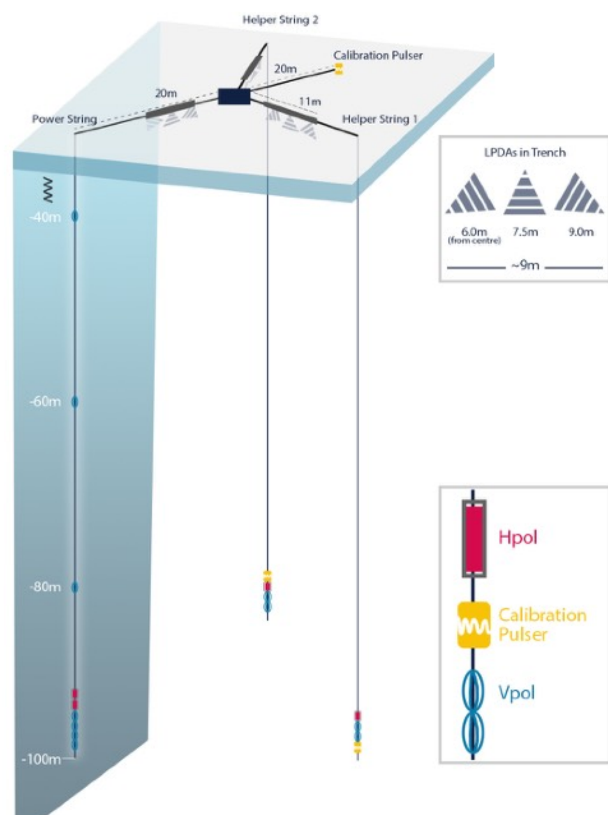
- Neutrino limits from radio detection of neutrinos towards high energies, not competitive to IceCube below 10^{10} GeV
- So far: experiments focussed on proof-of-concept, reconstruction and performance
- Exception: ANITA I-III: Mystery events — behave like cosmic ray signals, but show signal polarization/polarity like neutrino from deep trough Earth
  - If truly neutrino: disagreement with IceCube limits, difficult to reconcile with Standard Model
  - Other explanations offered: ice, background, etc.
  - ANITA IV: again 4 events with inconsistent polarity, but near horizon, nothing ‘mysteriously’ steep arXiv:2008.05690
  - Follow-up experiment proposed with better low energy sensitivity and more exposure: PUEO balloon arXiv:2010.02892

Radio detection of neutrinos

Where will it go next?

- RNO-G: Start construction in 2021
- 35 stations as first production scale implementation for neutrino detection
- Deployment in Greenland allows for fast development turn-around
- Europe-led experiment with members from all previous in-ice experiments
- Largest yearly neutrino sensitivity > 10 PeV
- Concept and design paper: arXiv:2010.12279



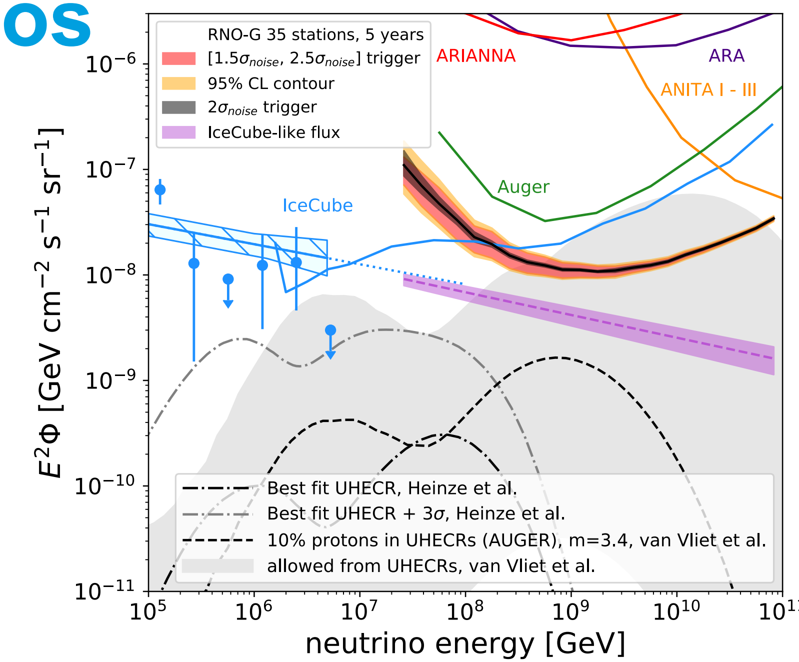


arXiv:2010.12279

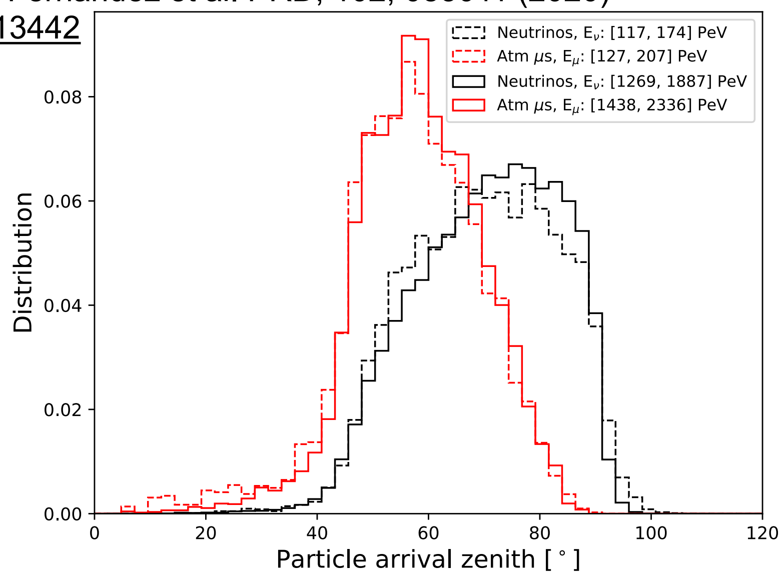
Radio detection of neutrinos

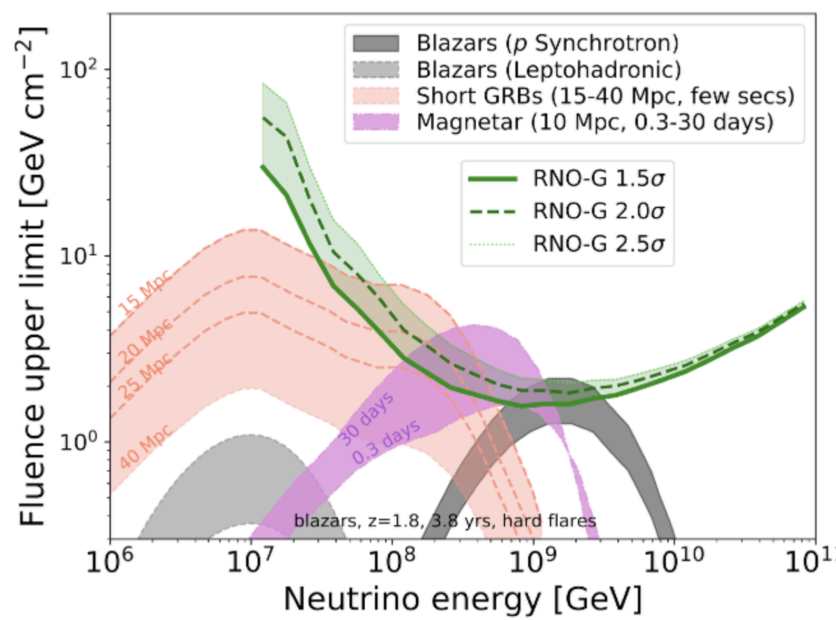
Where will it go next?

- RNO-G interesting sensitivities to transients and diffuse flux above 10 PeV
- Sensitive to all 3 flavors (NC and CC) with flavor-sensitivity under study
- Muon background may become interesting depending on hadronic interaction models



Garcia-Fernandez et al. PRD, 102, 083011 (2020)
2003.13442

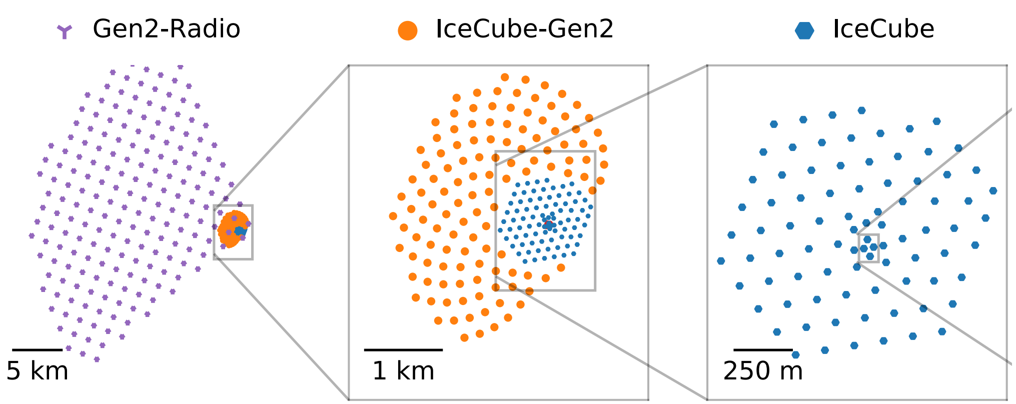


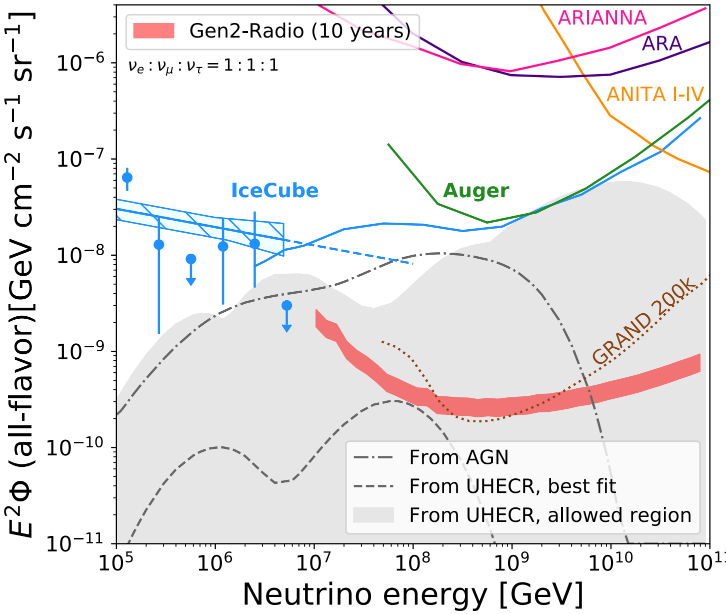


Radio detection of neutrinos

Where will it go next?

- IceCube Collaboration has put forward a baseline design for IceCube-Gen2 that includes a large radio array: arXiv:2008.04323
- Sky coverage of South Pole complimentary to Greenland
- Exact experimental design currently under review at IceCube-Gen2 working group
- Preliminary Design Review expected for fall 2021





Conclusions

Exciting past, hopefully even more exciting future

- 10 years ago the knowledge about emission mechanisms and potential of the radio technique was limited
- Community has established a solid theory and has shown the measurements to support it for both air showers and neutrinos
- Both air shower and neutrino experiments are embracing radio detection as a tool to answer the question about the origin of ultra-high energy cosmic rays
- Many exciting experiment being constructed using radio detection