Radio detection of high energy particles

Perspective of the past and next 10 years

Anna Nelles

20th Anniversary of the Foundation of the Pierre Auger Observatory

Malargue, Argentina

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.


Your GOLDEN TICKET
GOLDEN
COLORADO
VisitGolden.com
Scratch and Save UP TO 20% OFF AT PARTICIPATING GOLDEN MERCHANT
Auger
identification
muons and
Particles
i Auger
improved
Auger
Auger Turbo
Really Big
Suzanne
& Victor
"Auger Observatory"
Auger Prime
Primary
measurement
Auger
Muon


Your
GOLDEN TICKET
GOLDEN
COLORADO
VisitGolden.com
Scratch and Save
i Auger
improved
Auger
Auger Turbo
Really Big
Suzanne
& Victor
"Auger Observatory"
Auger Prime
Primary
measurement

Pimp Auger
Perfect Identification of Muons and Particles

iAuger
improved Auger

Auger Turbo
The Update of the Really Big Observatory

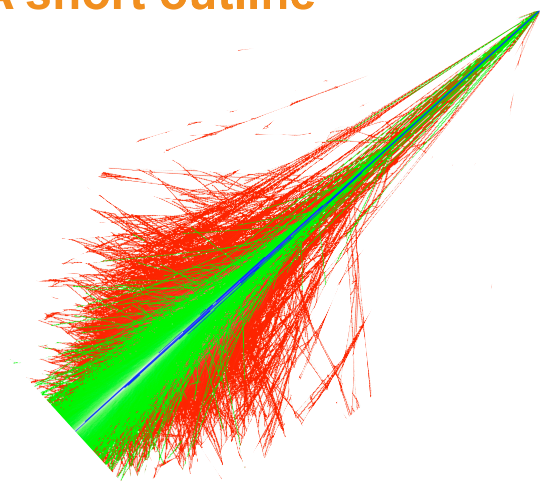
Suzanne & Victor
Auger Observatory

Auger Prime
Primary measurement

Miss Auger
Muon identification super station

Radio detection of high energy particles

A short outline



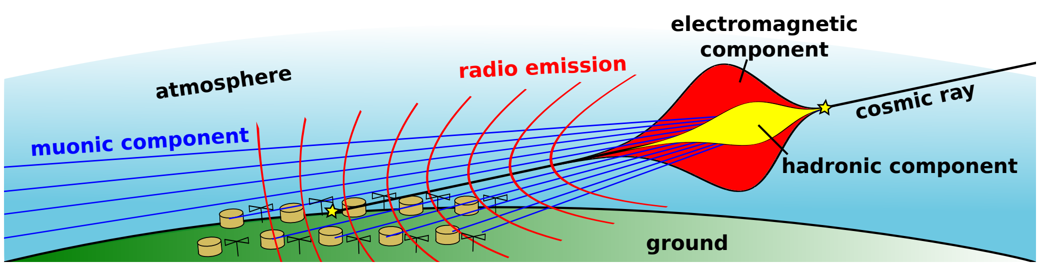
Emission mechanisms and scientific motivation

LOFAR

Current experimental results

AERA
Auger Engineering Radio Array

Tunka-Rex

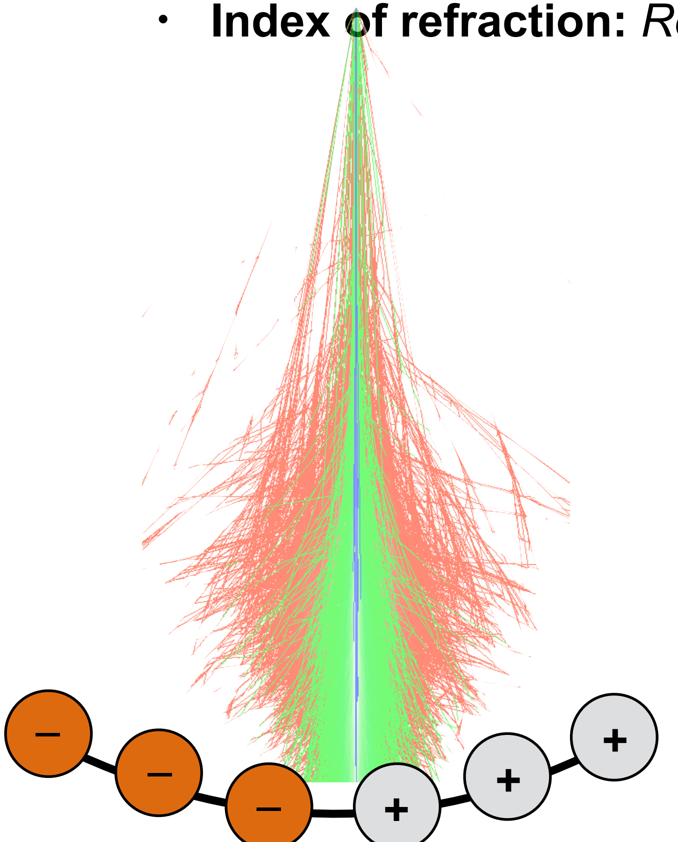


Future developments

Radio emission of showers

The story of the two effects and the refractive index

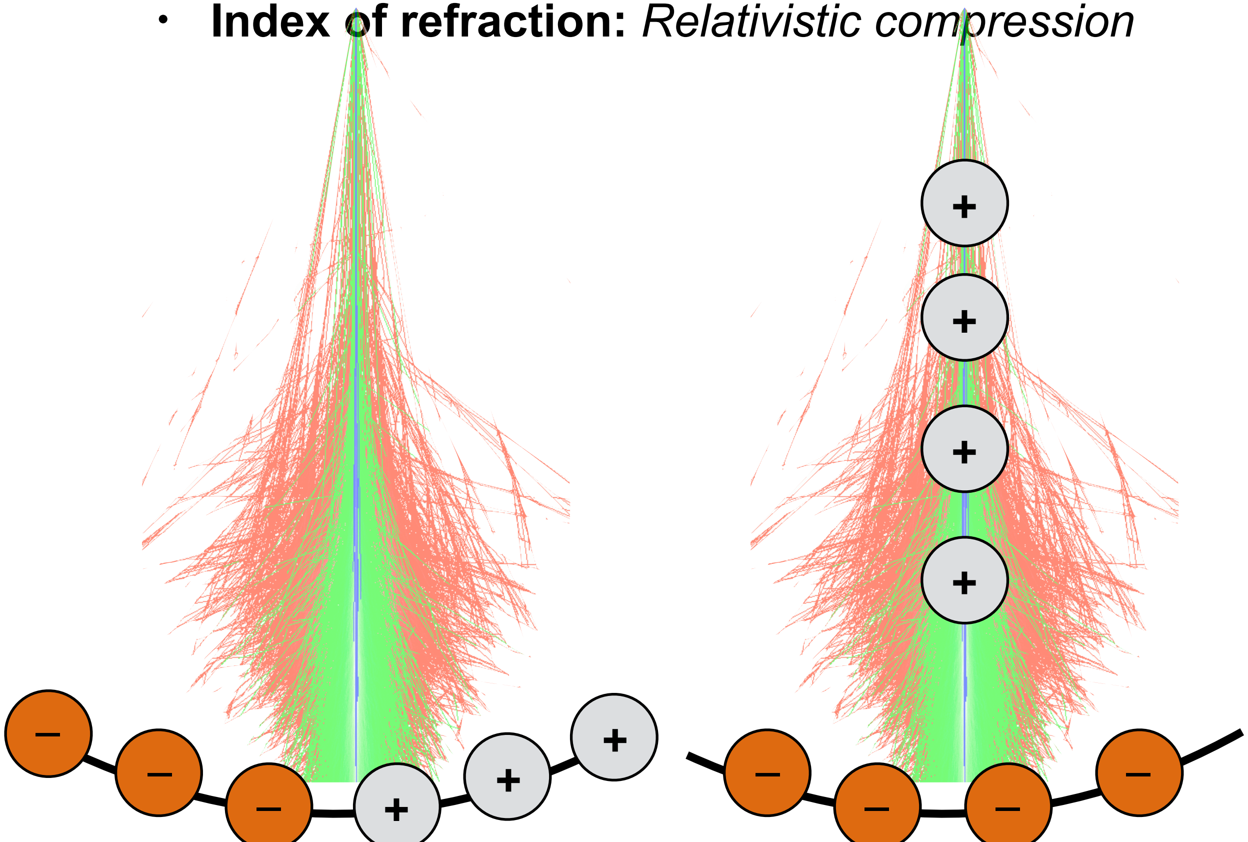
- Radio emission of showers can be explained from first principles and three aspects
  - **Magnetic field:** *Geomagnetic field, Lorentz-force*
  - **Charge imbalance:** *Particle Physics processes*
  - **Index of refraction:** *Relativistic compression*



Radio emission of showers

The story of the two effects and the refractive index

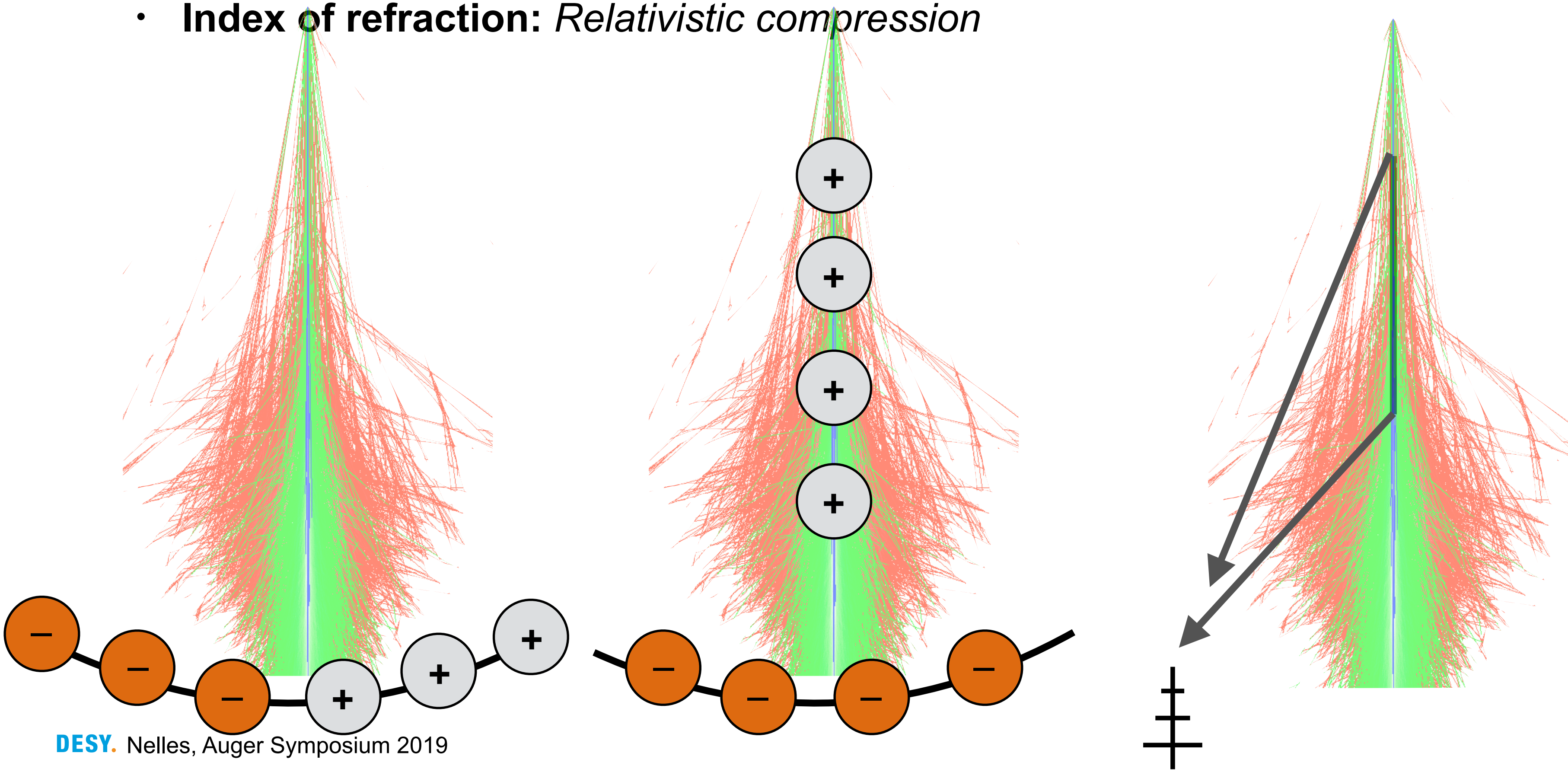
- Radio emission of showers can be explained from first principles and three aspects
  - **Magnetic field:** *Geomagnetic field, Lorentz-force*
  - **Charge imbalance:** *Particle Physics processes*
  - **Index of refraction:** *Relativistic compression*



Radio emission of showers

The story of the two effects and the refractive index

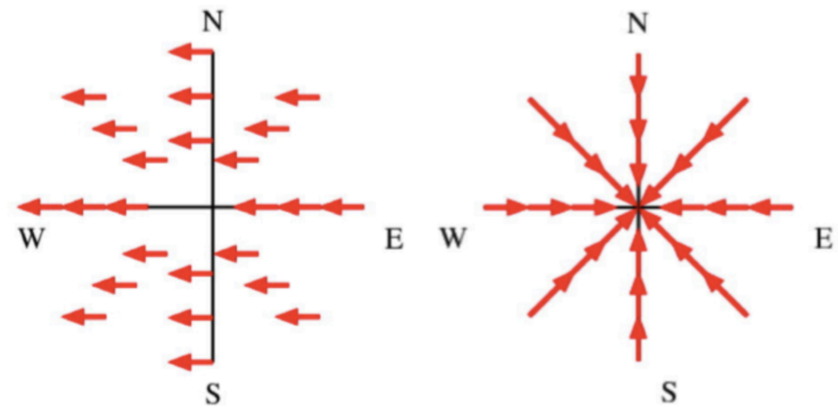
- Radio emission of showers can be explained from first principles and three aspects
  - **Magnetic field:** *Geomagnetic field, Lorentz-force*
  - **Charge imbalance:** *Particle Physics processes*
  - **Index of refraction:** *Relativistic compression*



Radio emission of showers

How do we know this?

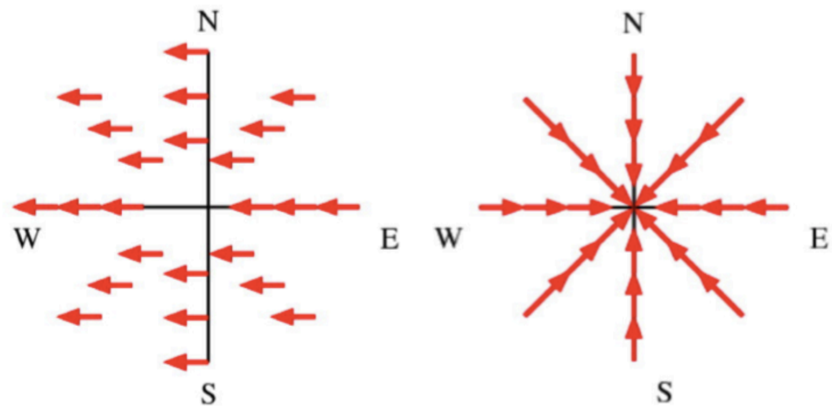
- The key evidence: **Polarization**
  - **Geomagnetic effect:** *Lorentz-force, polarization orthogonal to shower axis and magnetic field*
  - **Askaryan effect:** *Polarization points towards shower axis*

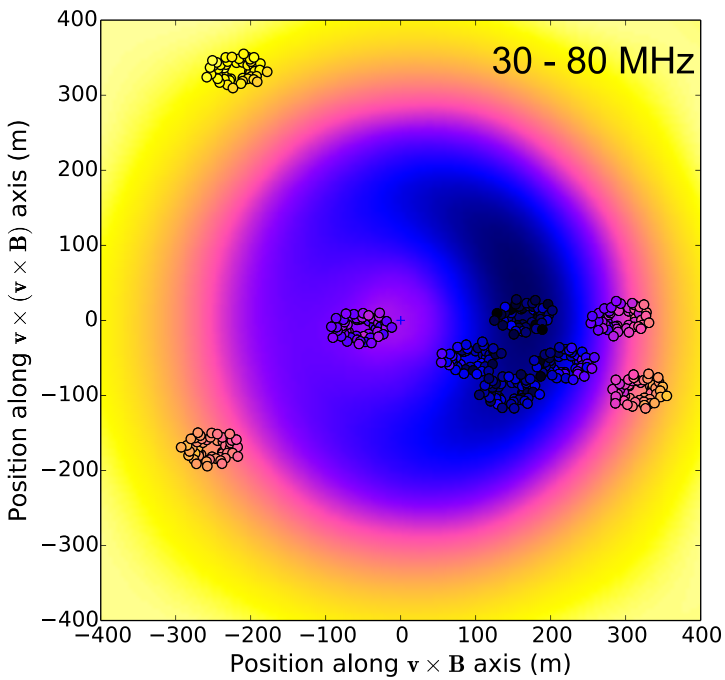


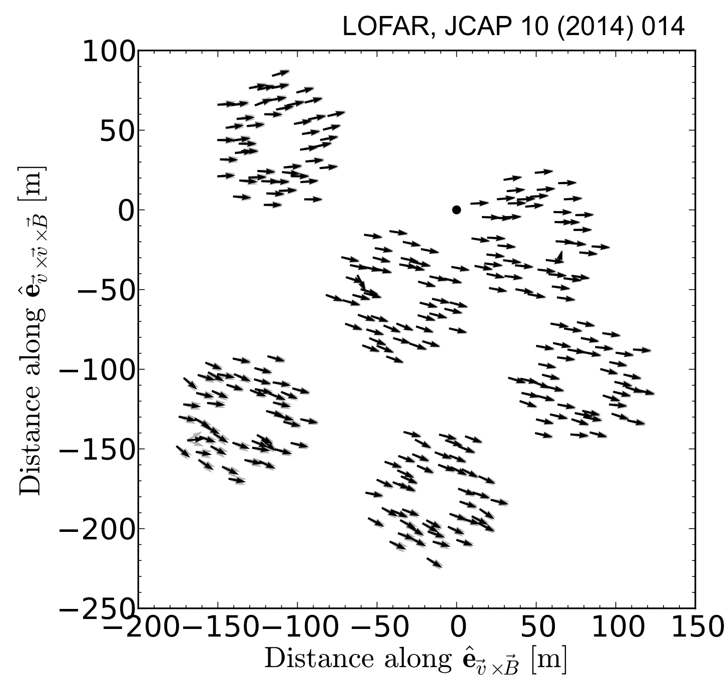
Radio emission of showers

How do we know this?

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



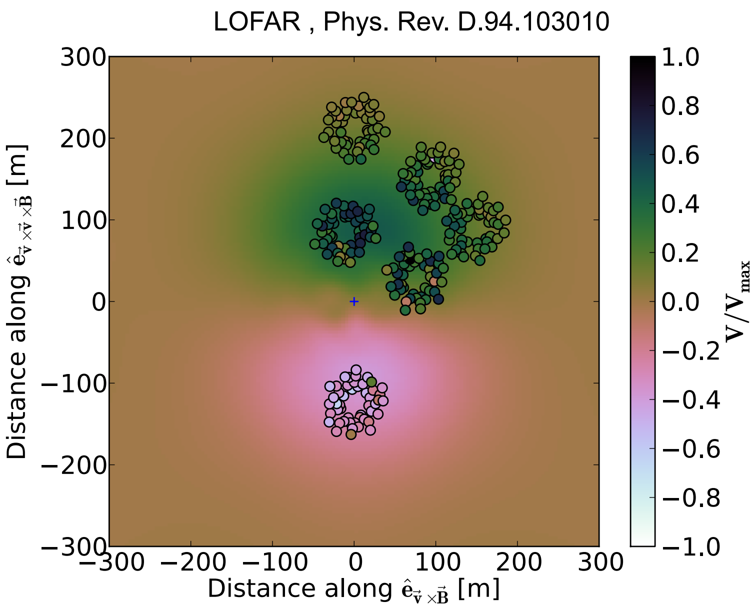




Radio emission of showers

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**



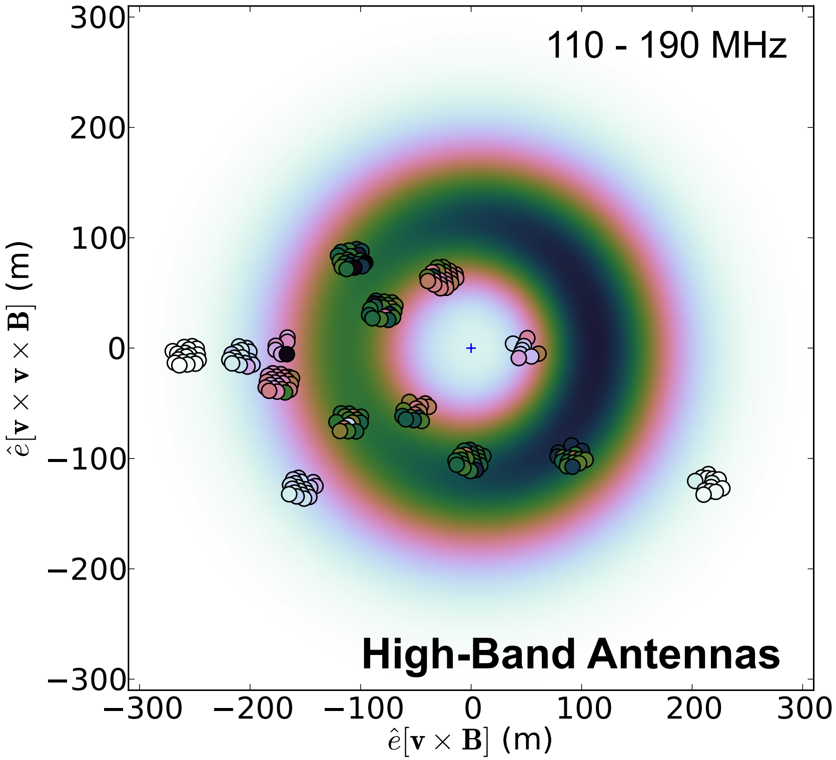
- Emission is due to **both geomagnetic emission** (dominant in air) and **Askaryan emission**
- Geosynchrotron radiation is a correction of < 1% to these effects

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

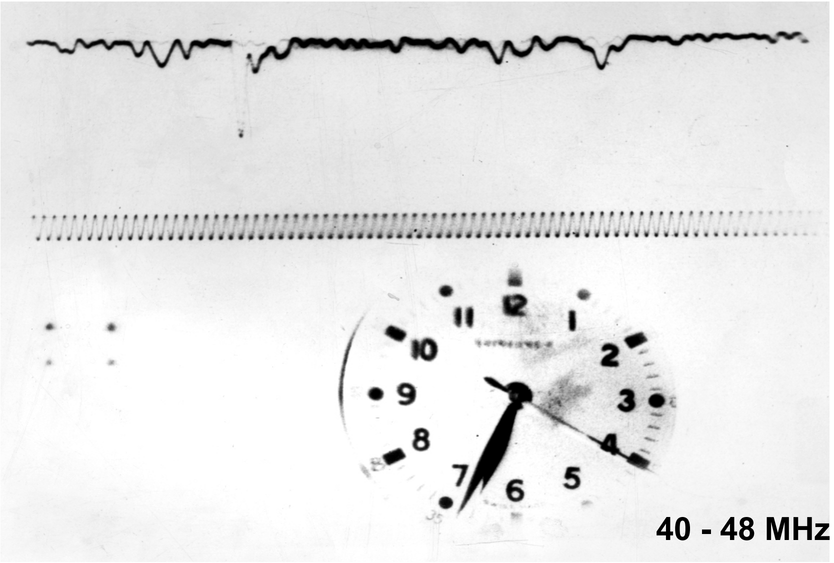


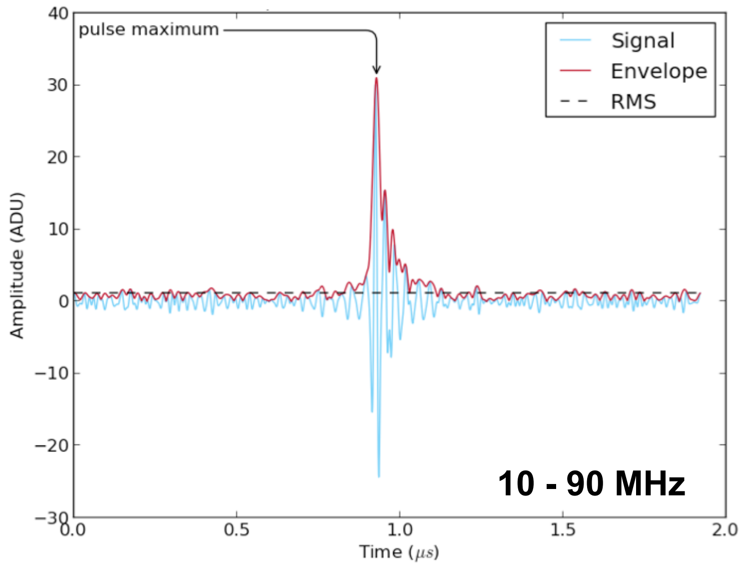
Detecting radio emission of air showers

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

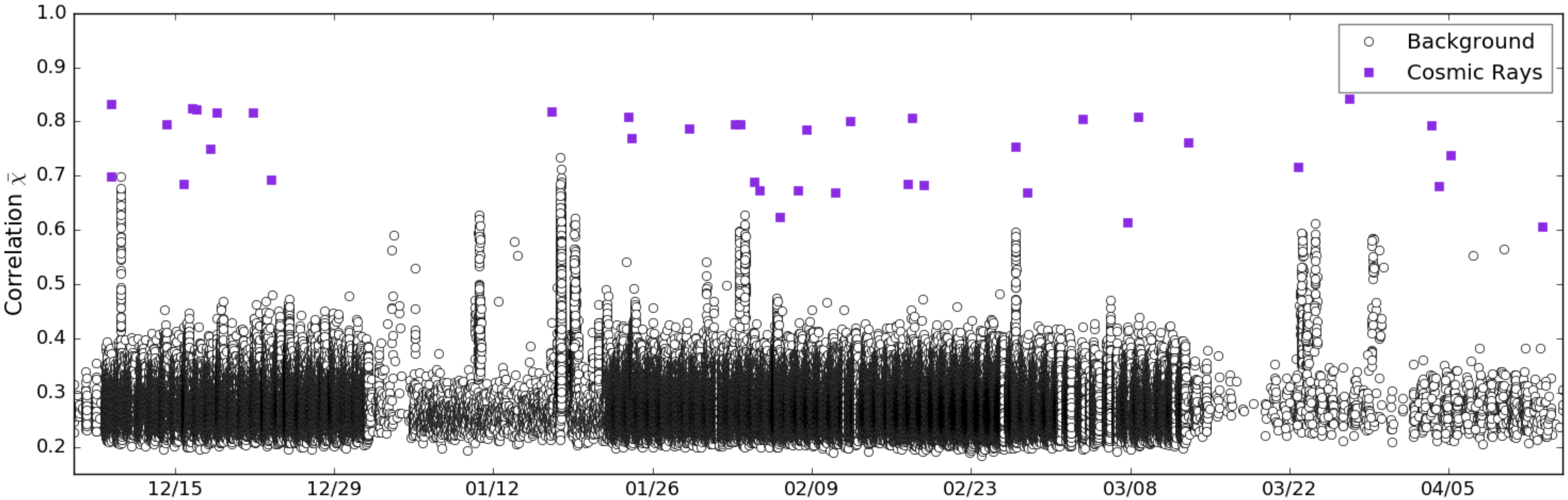


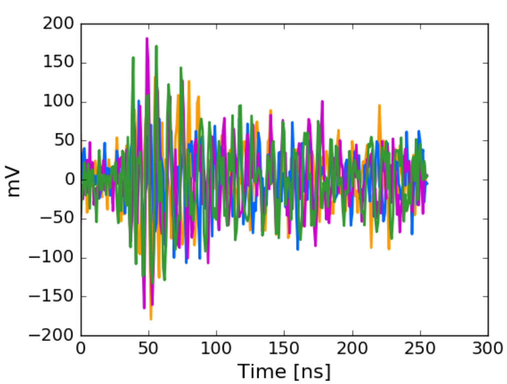


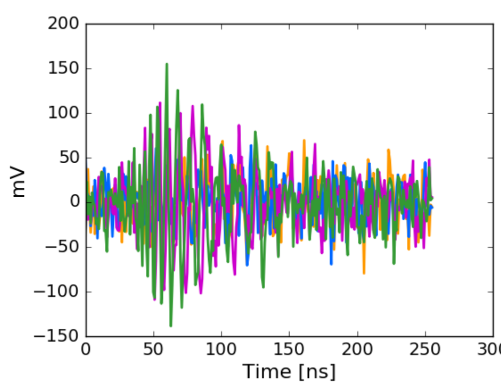
Detecting radio emission of air showers

Experimental challenges and opportunities

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





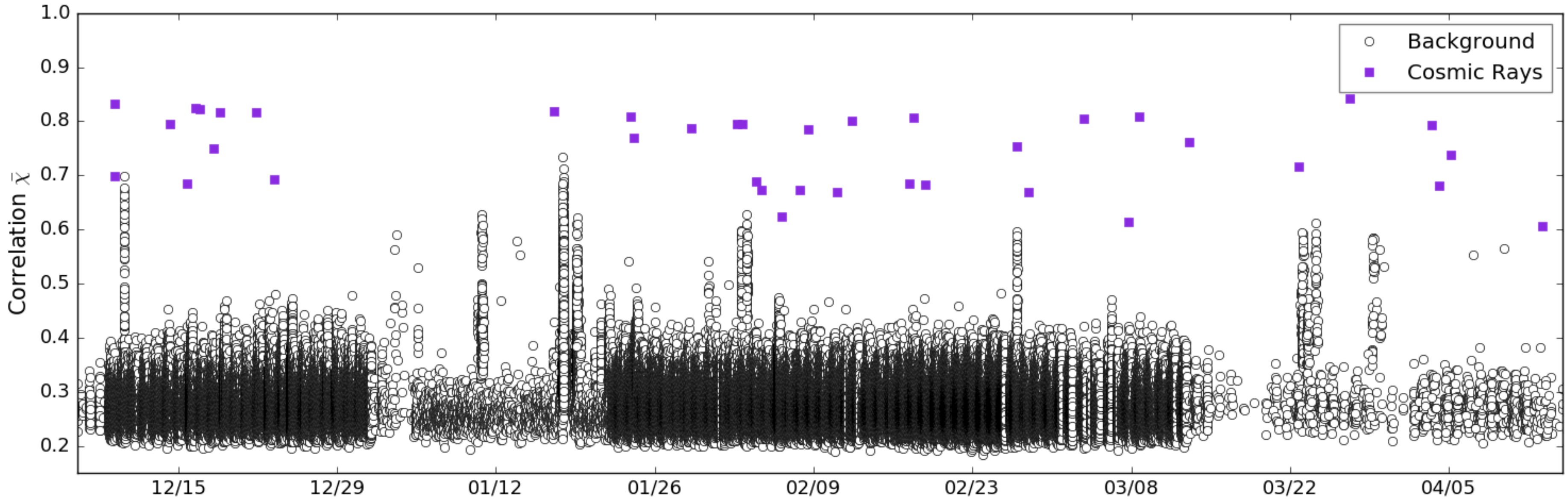


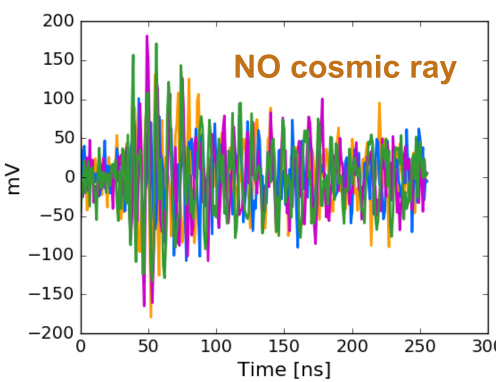
- Unfortunately, a lot of things make radio pulses
- Self-triggering and event identification remain a challenge
- Site quality important
- New opportunities in modern data analysis methods

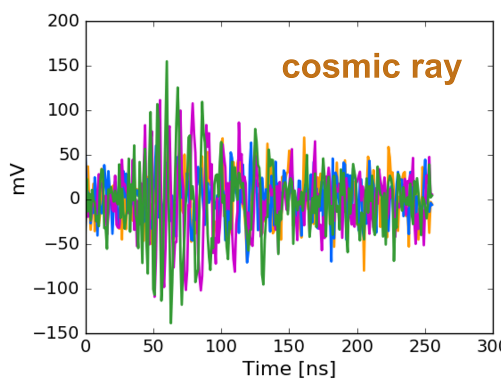
Detecting radio emission of air showers

Experimental challenges and opportunities

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





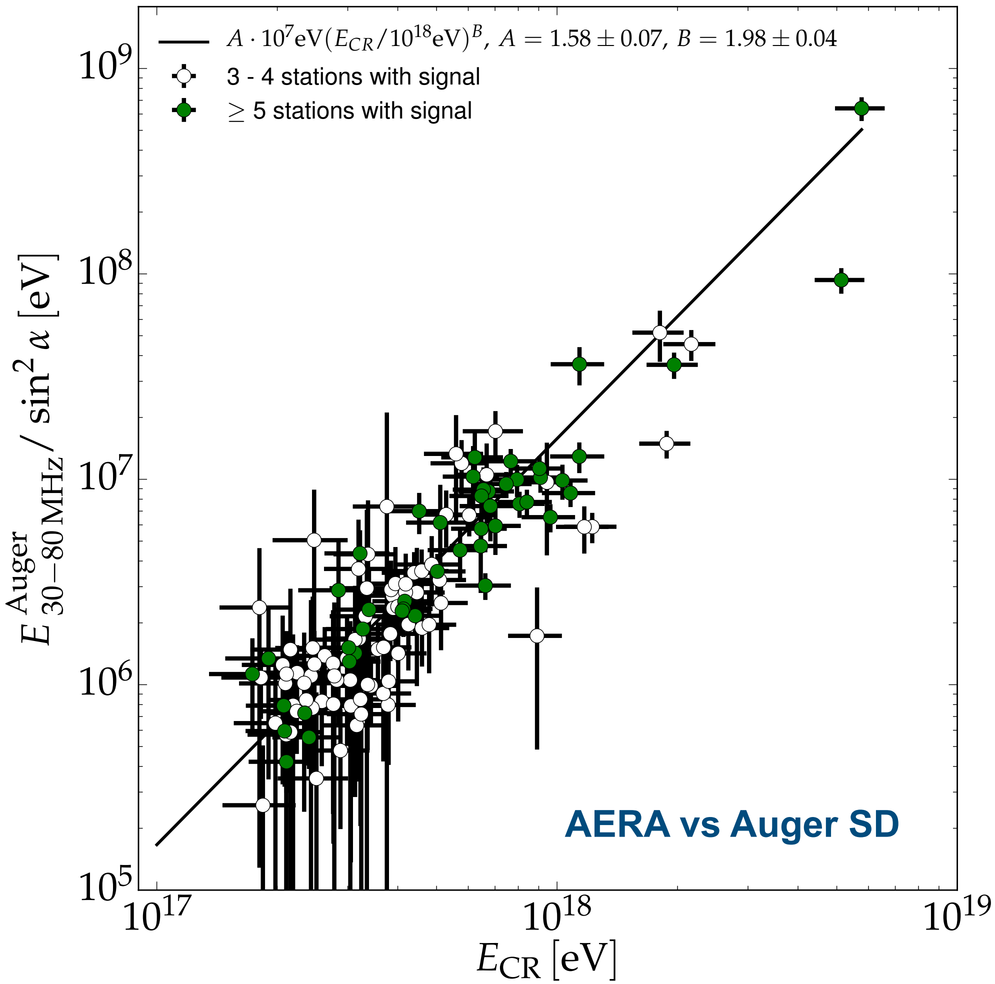


- Unfortunately, a lot of things make radio pulses
- Self-triggering and event identification remain a challenge
- Site quality important
- New opportunities in modern data analysis methods

Detecting radio emission of air showers

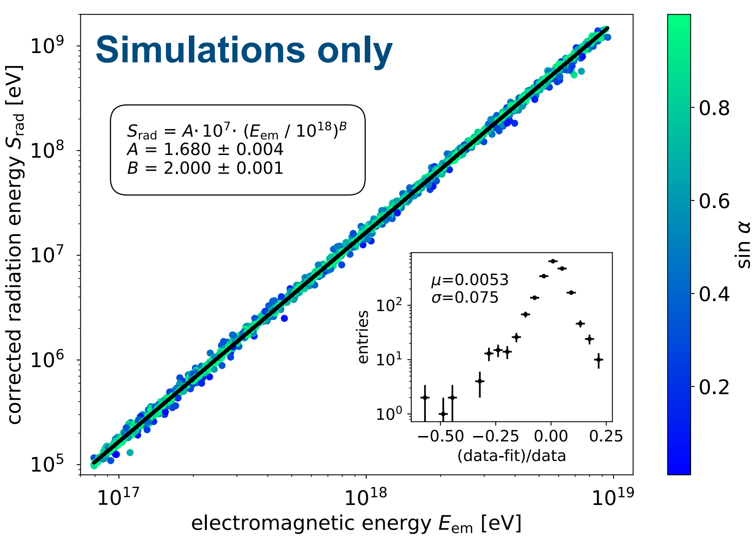
What is in it for the science?

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

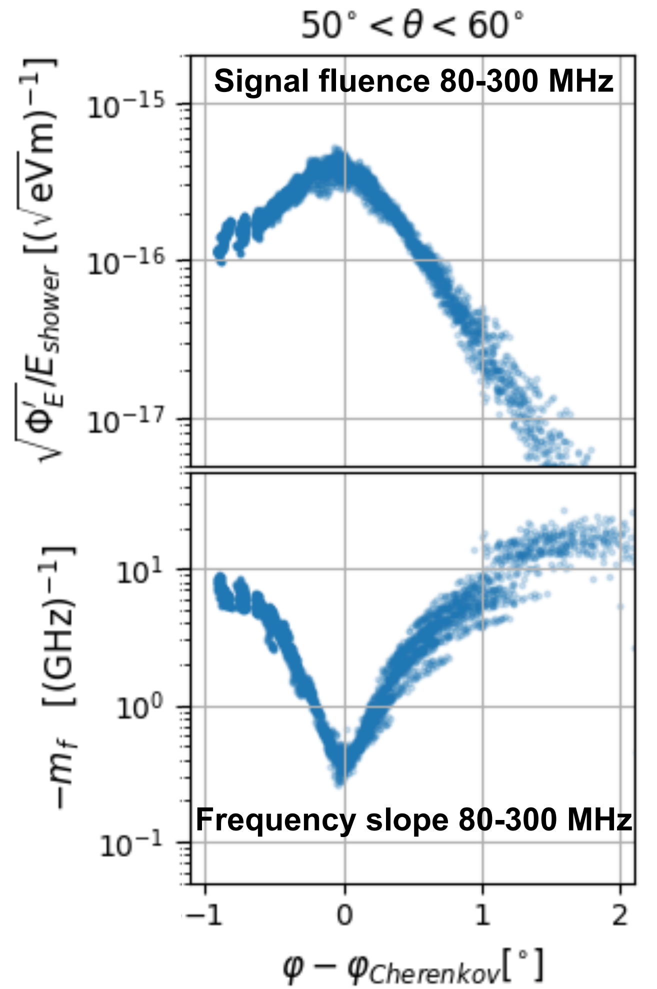


Detecting radio emission of air showers

What is in it for the science?

C.Welling et al, JCAP10(2019)075

- The radio signal contains more than its power
- Using its frequency content allows to measure the energy of a shower from a single detection to better than 15% accuracy (no detector uncertainties)
- Negligible corrections due to atmospheric effects
- 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**

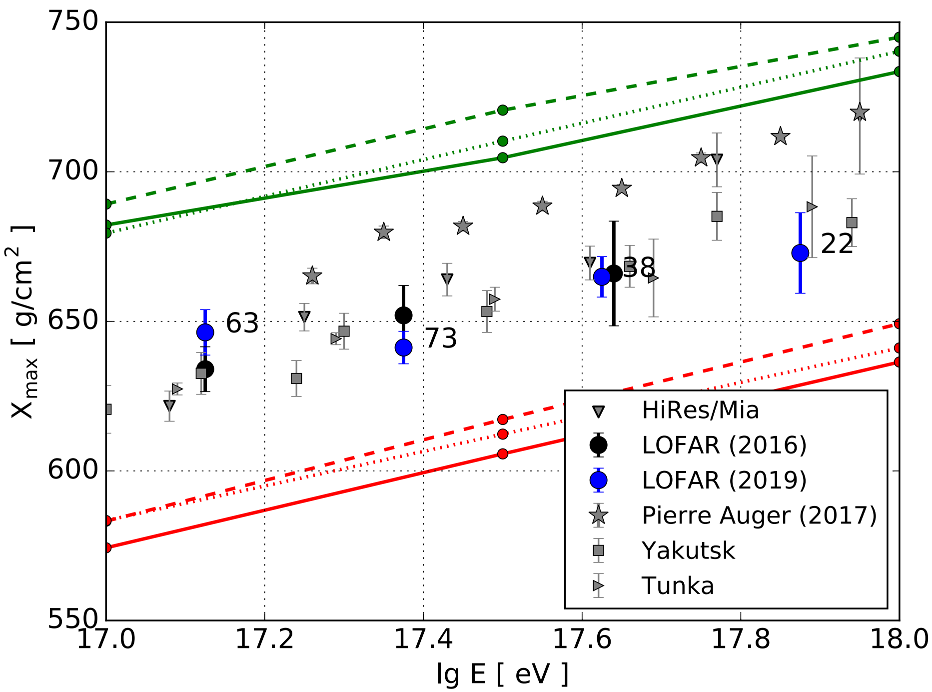


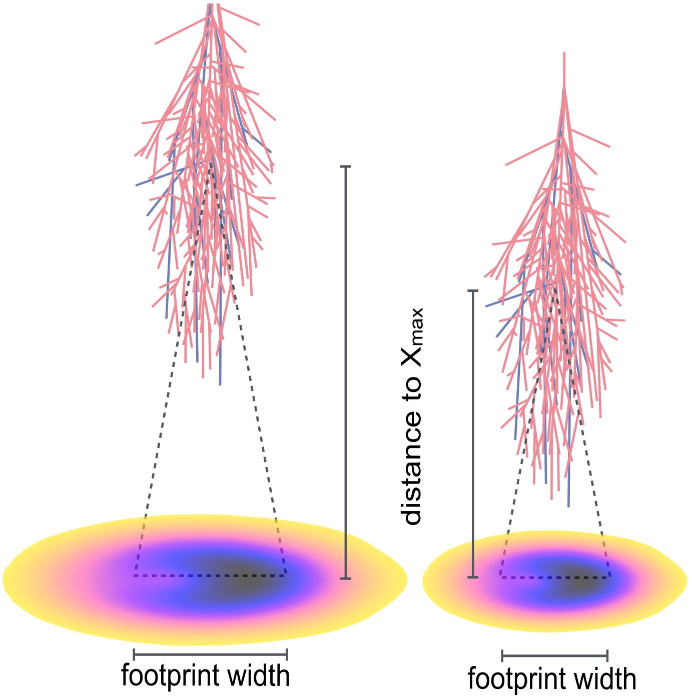
Detecting radio emission of air showers

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/cm²

PhD Thesis A. Corstanje, Update to Nature 2016



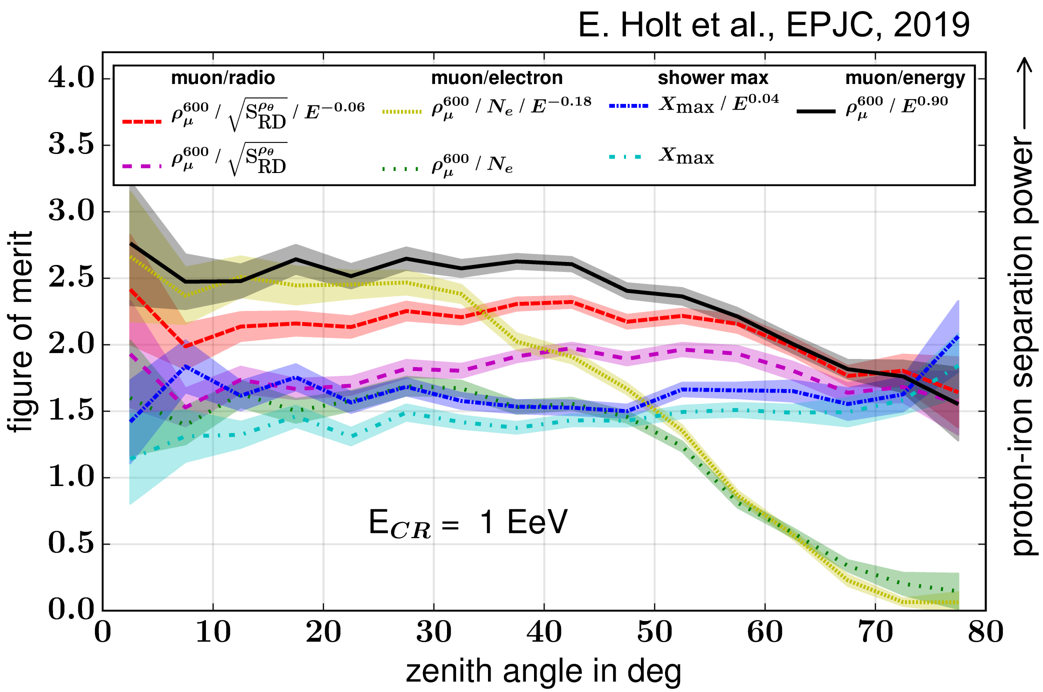


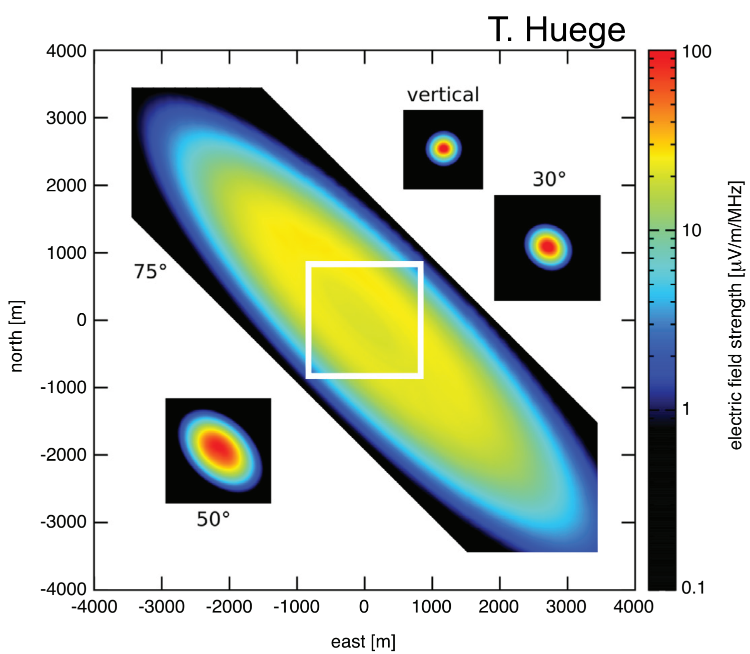
- Tension to Auger FD measurements
- Eagerly awaiting RD/FD hybrid study to possibly resolve this

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





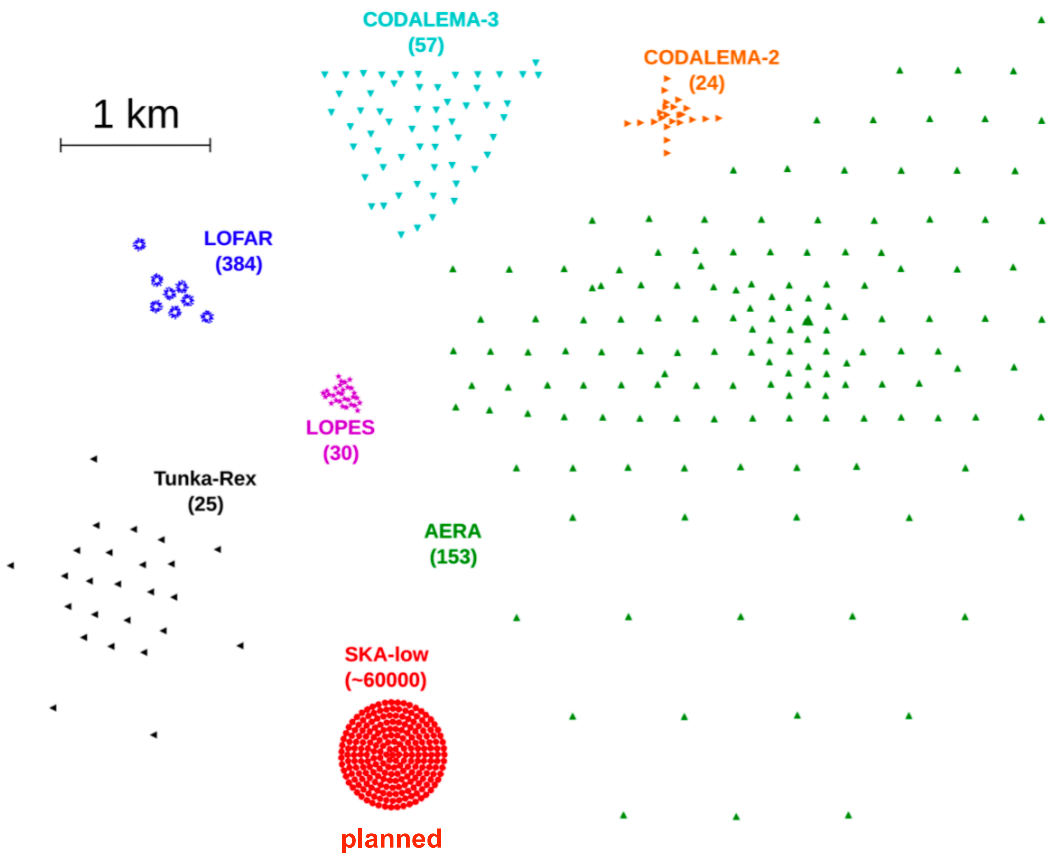
- Combining muon measurements with radio antennas provide a different handle on composition

Detecting radio emission of air showers

The global neighborhood

- Multitude of air shower arrays
- Many of the in hybrid configuration, tuned at different purposes
- Radio emission of air showers is considered a “standard tool”

Figure: Huege 2016

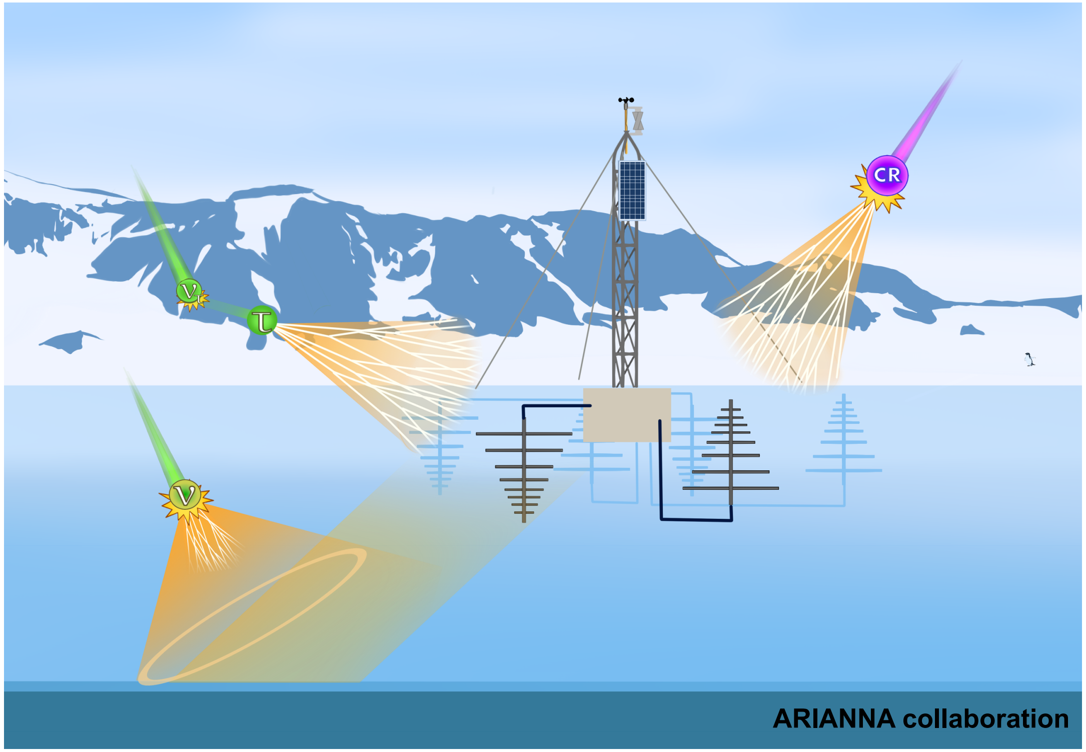


+ neutrino detectors in ice ARIANNA, ARA, IceTop, ..
+ ANITA balloon

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

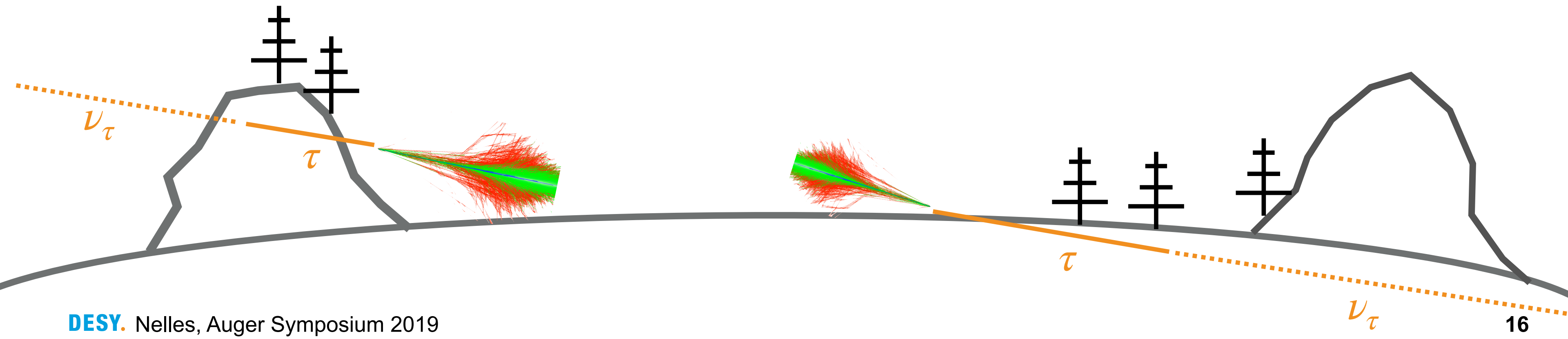


- All utilize negligible radio attenuation in air and kilometer-scale attenuation length in ice

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
- A couple of pathfinder projects on-going: GRAND, BEACON, TAROGE, …
- Largest challenge: suppress (human-made) background close to the horizon



Radio detection of neutrinos

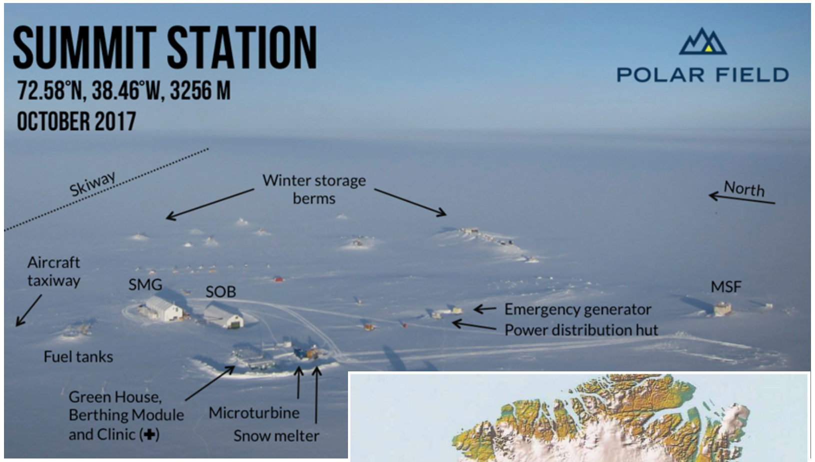
Neutrino interactions in ice

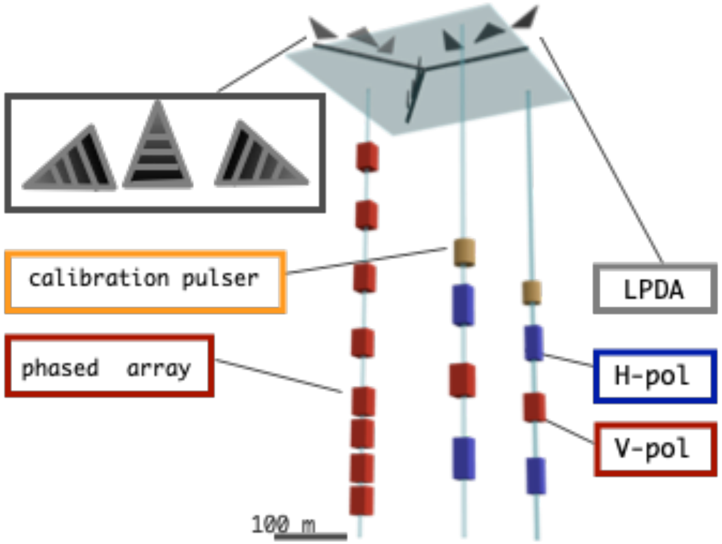
- Cold polar ice has attenuation length in the order of kilometers
- One radio station can typically monitor 1 km^3 of ice (= the size of IceCube)
- Detection threshold around 10 PeV shower energy, determined not by array spacing but pulse height above thermal noise
- > 100 km^3 needed to obtain sensitivity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

Radio detection of neutrinos

Where will it go next?

- Start construction of pathfinder array in summer 2020
- Technology will built on ARA and ARIANNA experience
- Deployment in Greenland allows for fast development turn-around in a less restricted environment
- Funding secured for hardware in Europe O(40) stations
- Proposal for US contribution to be submitted

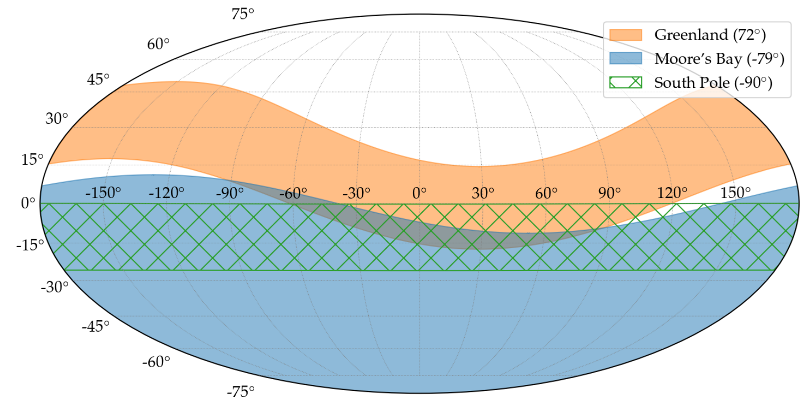


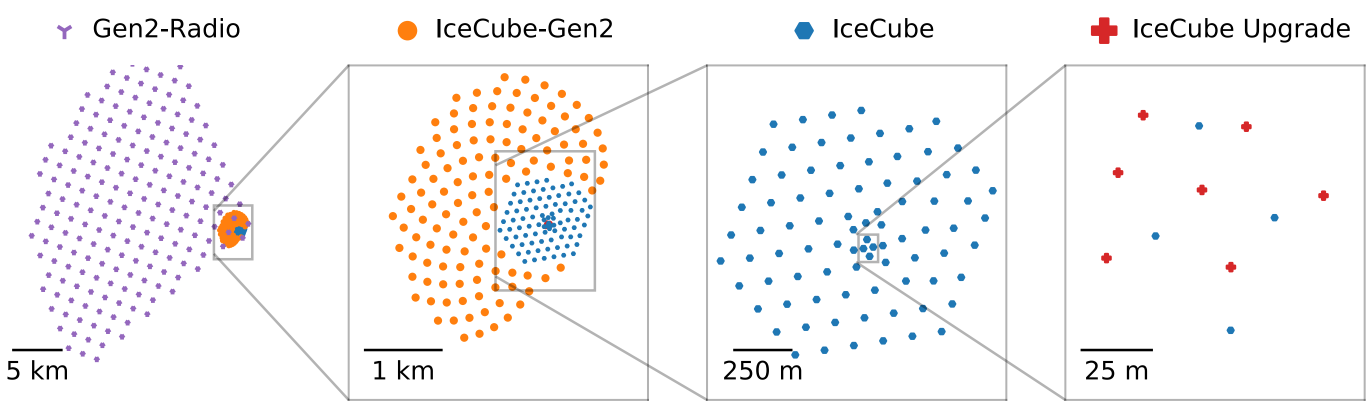


Radio detection of neutrinos

Where will it go next?

- IceCube Collaboration has put forward a baseline design for IceCube-Gen2 that will include a large radio array
- Greenland array will serve as pathfinder
- Possibly additional pathfinders to be proposed
- Sky coverage of locations complimentary

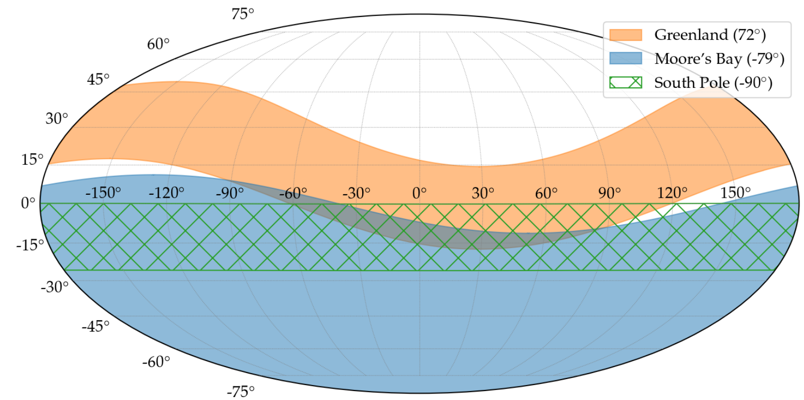


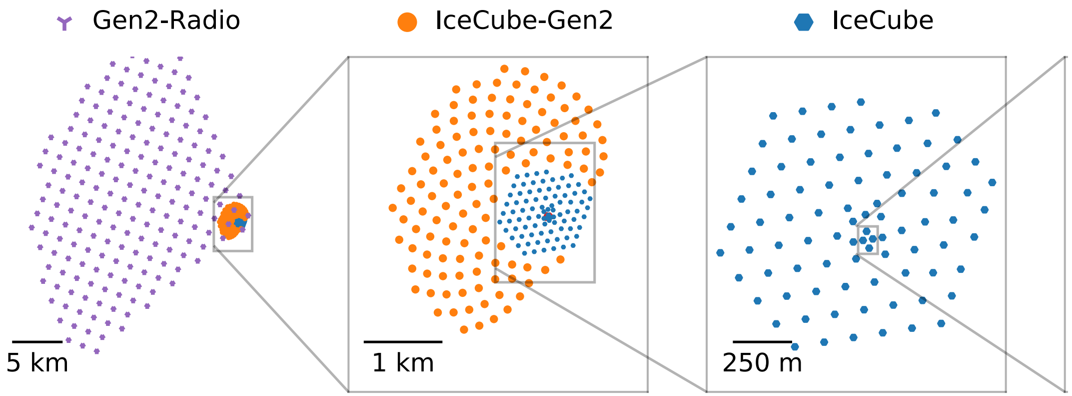


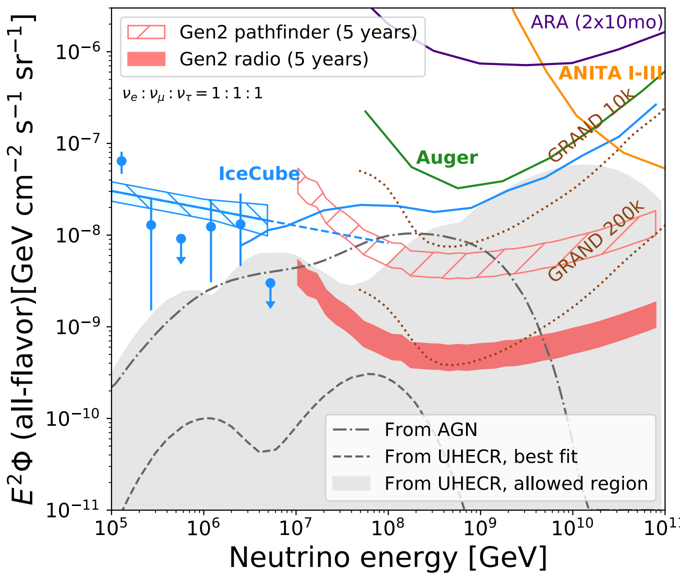
Radio detection of neutrinos

Where will it go next?

- IceCube Collaboration has put forward a baseline design for IceCube-Gen2 that will include a large radio array
- Greenland array will serve as pathfinder
- Possibly additional pathfinders to be proposed
- Sky coverage of locations complimentary





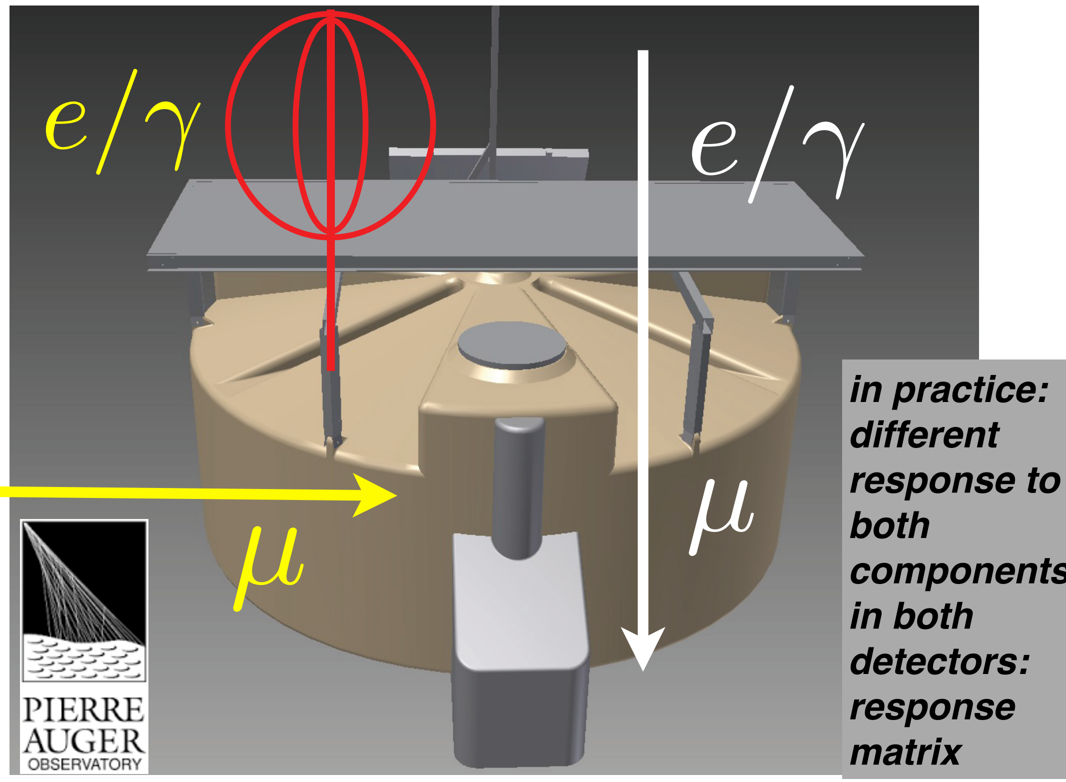


Radio detection of air showers

Where will it go next?

- 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 detecting air showers
- Targeting: What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?

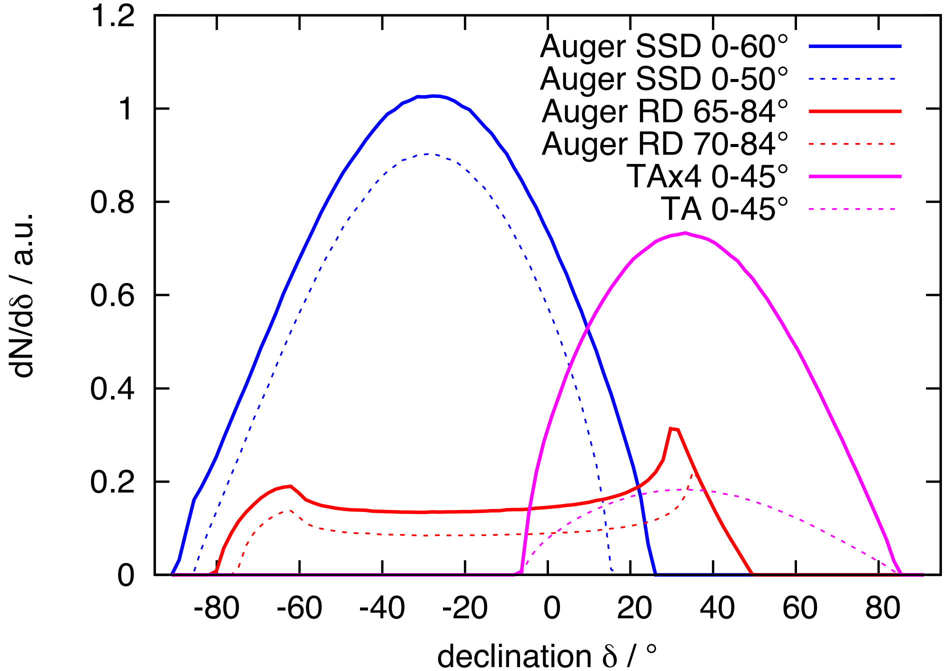
Upgrade of the Pierre Auger Observatory

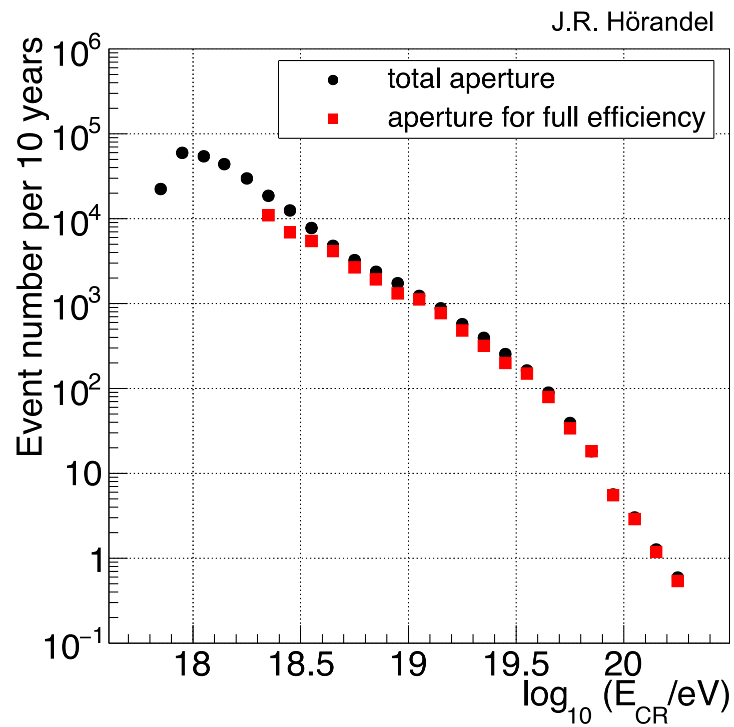


Radio detection of air showers

Where will it go next?

- Auger Radio Upgrade will provide a handle on composition for a large fraction of showers
- Due to horizontal sensitivity, access to a different fraction of the sky
- Different systematics than other detectors of the observatory





Conclusions

Exciting past 10 years, hopefully even more exciting next 10 years

- 10 years ago the knowledge about emission mechanisms and potential of the technique was limited
- Community has established a solid theory and has shown the measurements to support it
- 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