Radio Detection of Astrophysical Neutrinos

Towards finding the sources of UHECRs

Anna Nelles

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

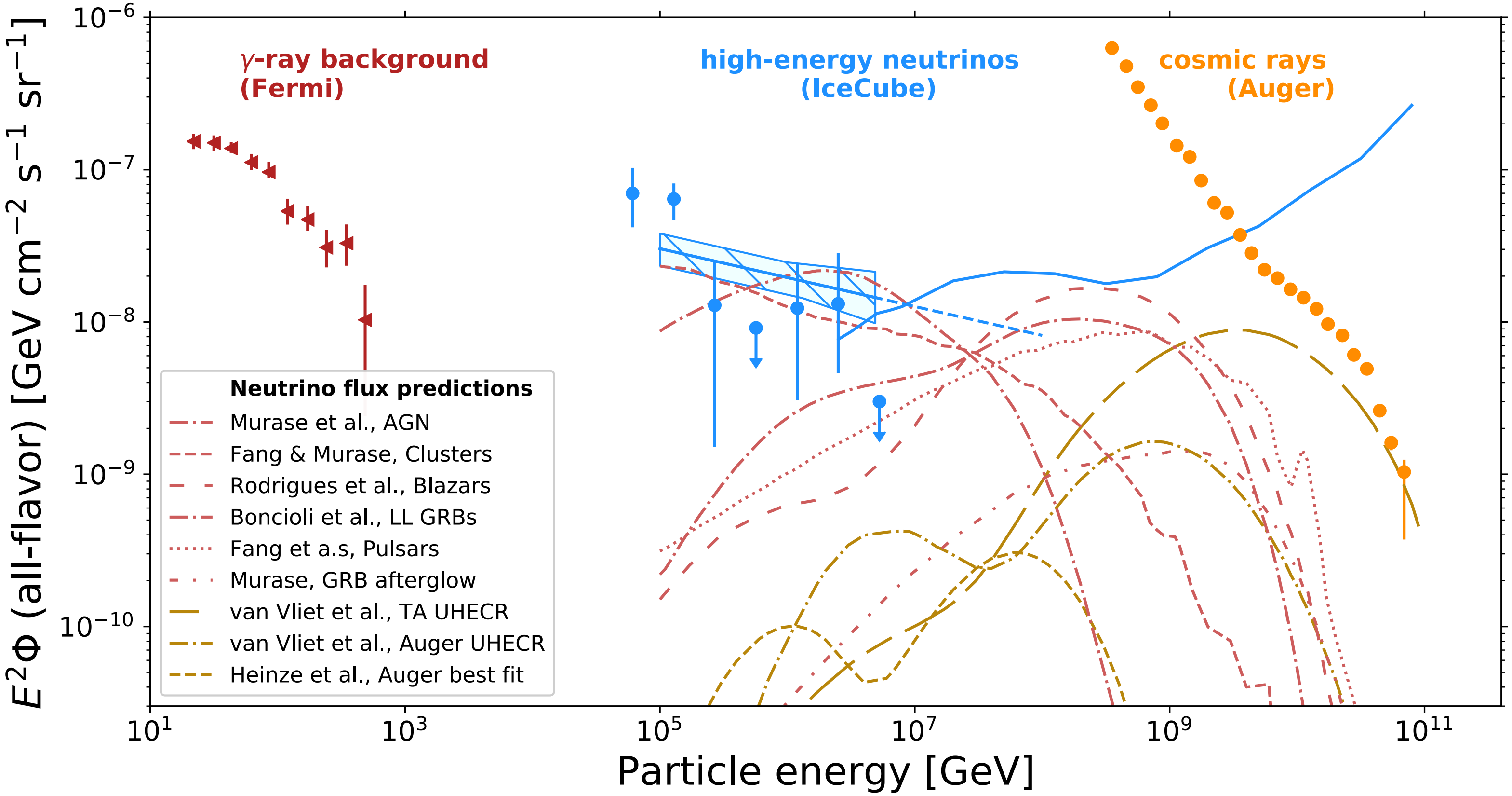
ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

DESY.

Scientific motivation

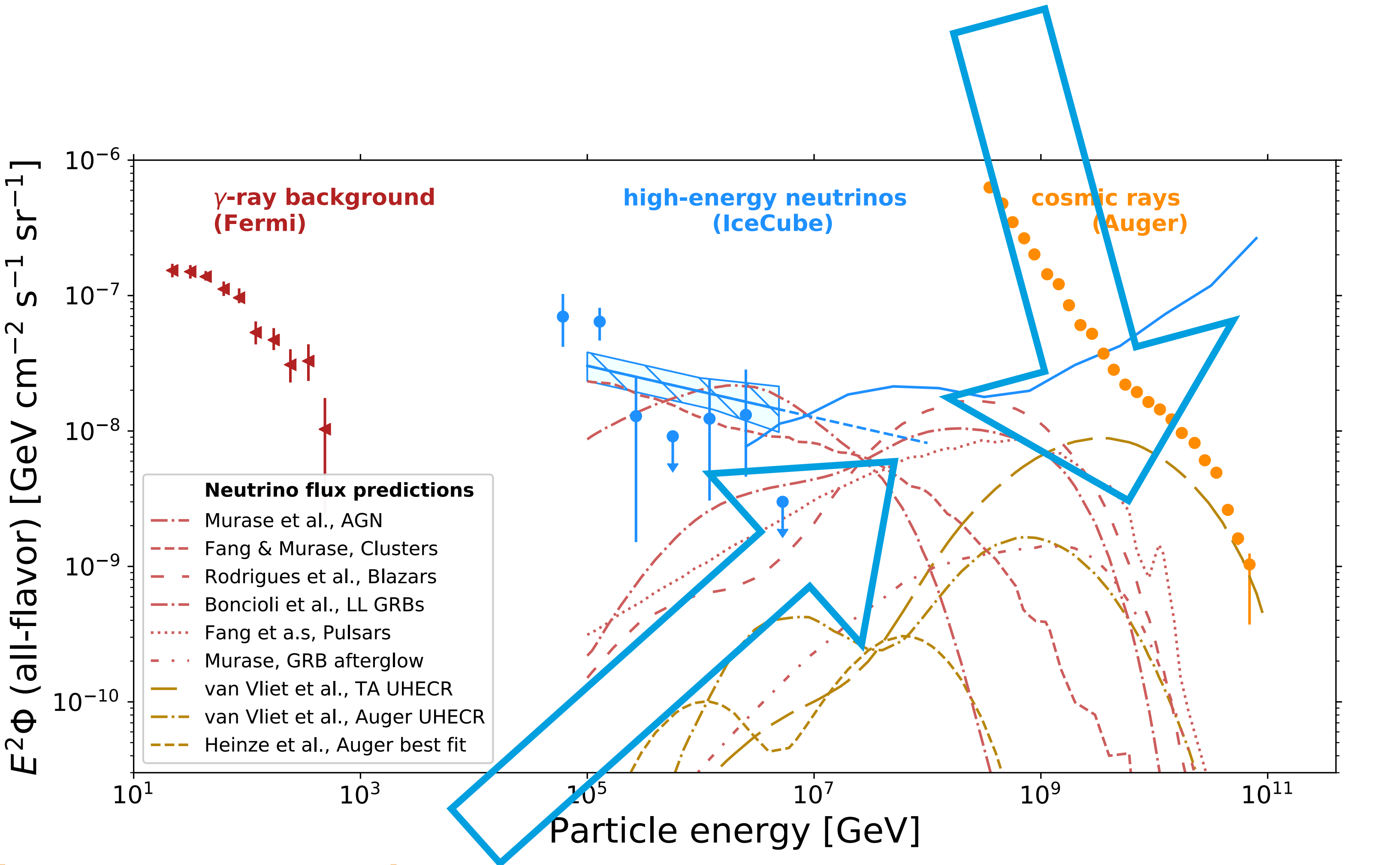
Where are ultra-high energy cosmic rays from?

Does the neutrino flux continue to higher energies?



How to address this?

Measure cosmic rays with better precision

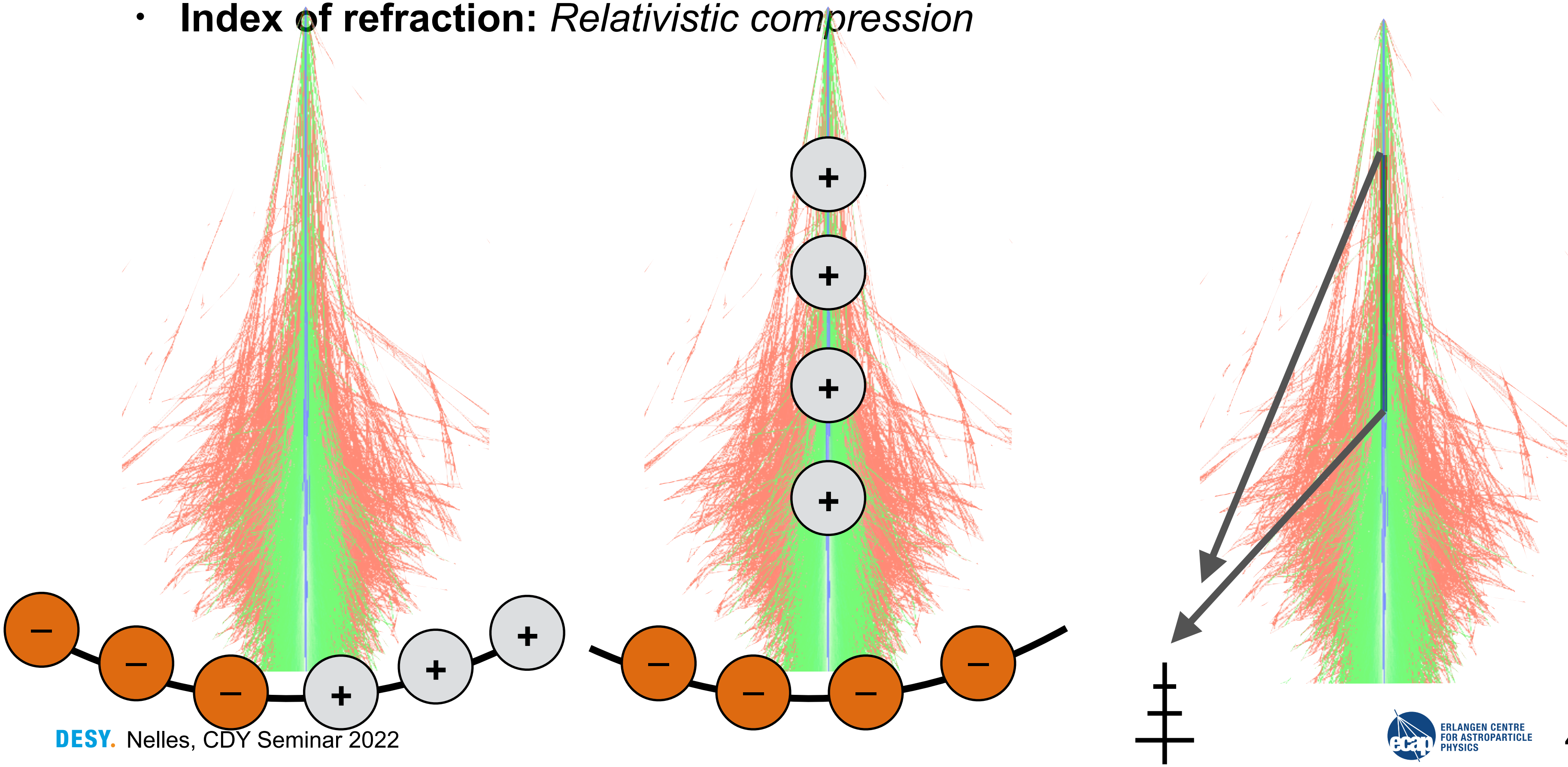


Measure more neutrinos

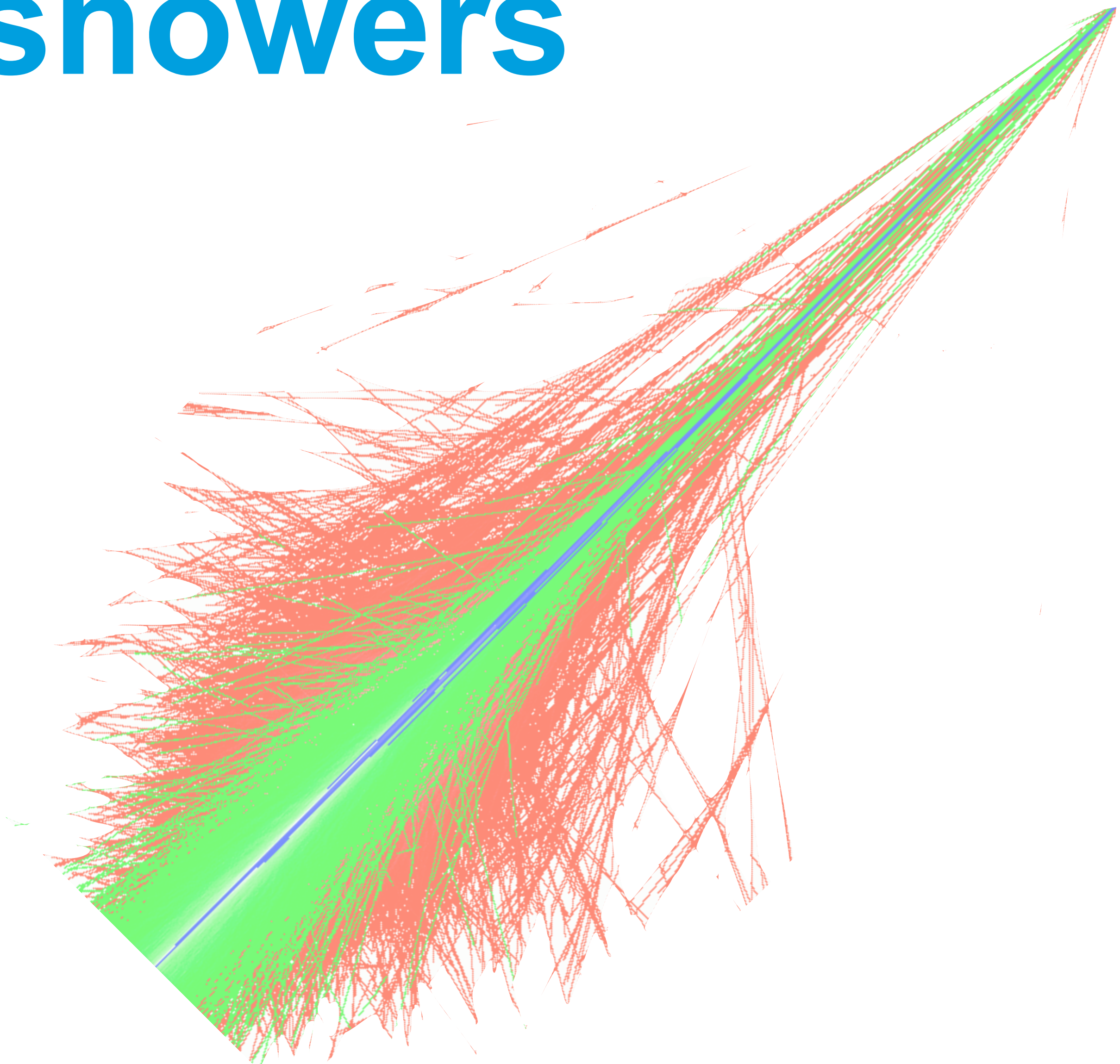
Radio emission of showers

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*



Air showers

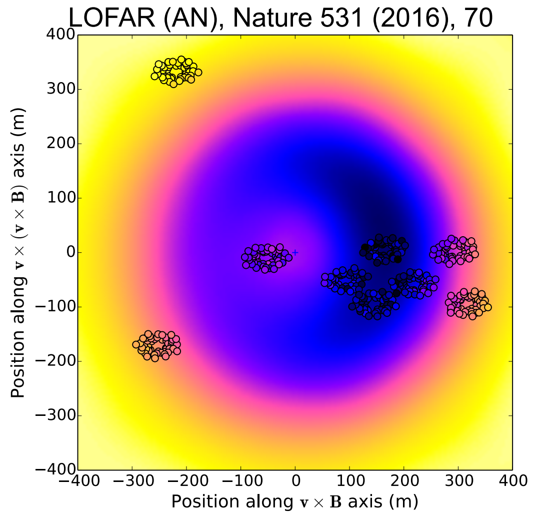


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

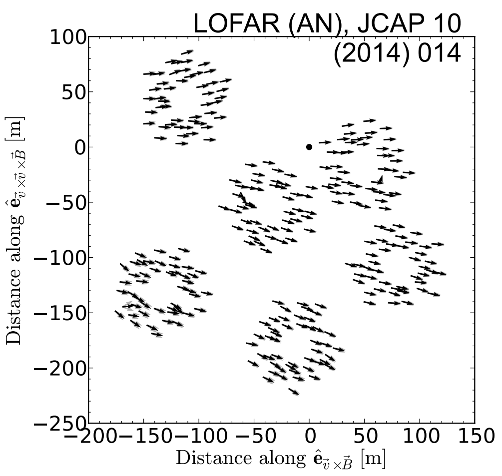
DESY.

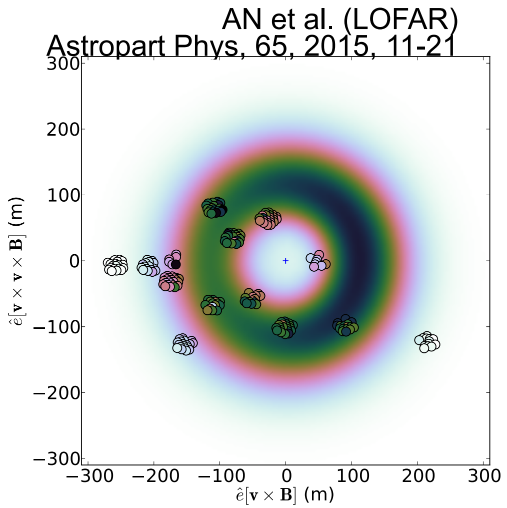
Are we really sure that we have understood this?

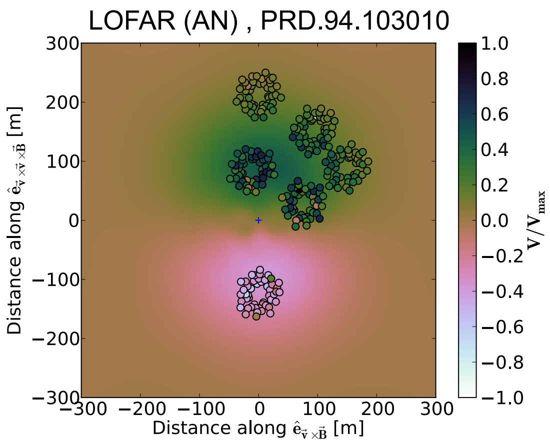
Quite a lot of experimental evidence:



- Signal distribution ✅
- Signal amplitude ✅
- Signal polarization ✅
- Signal frequency spectrum ✅
- Dependence on magnetic field ✅



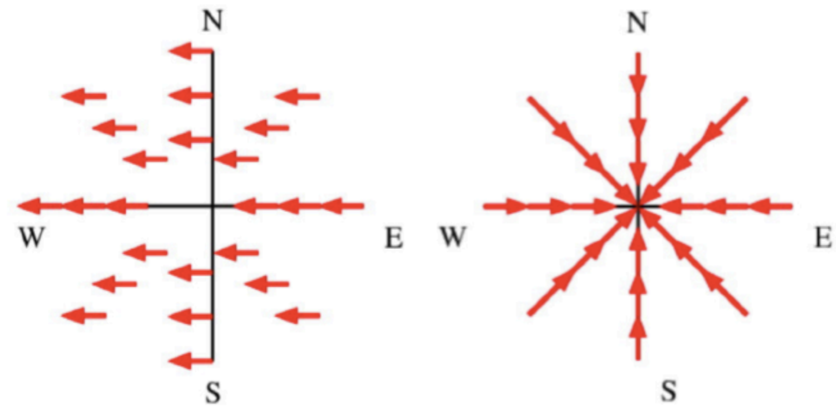


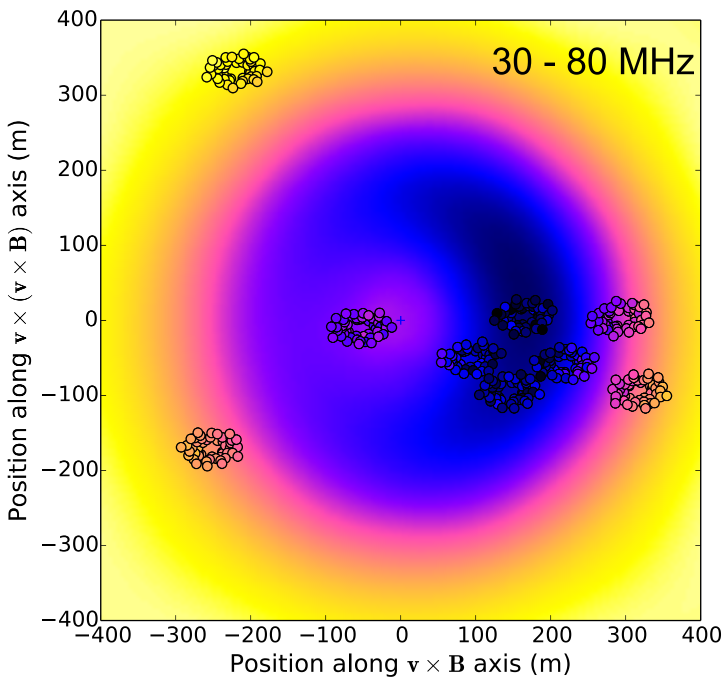


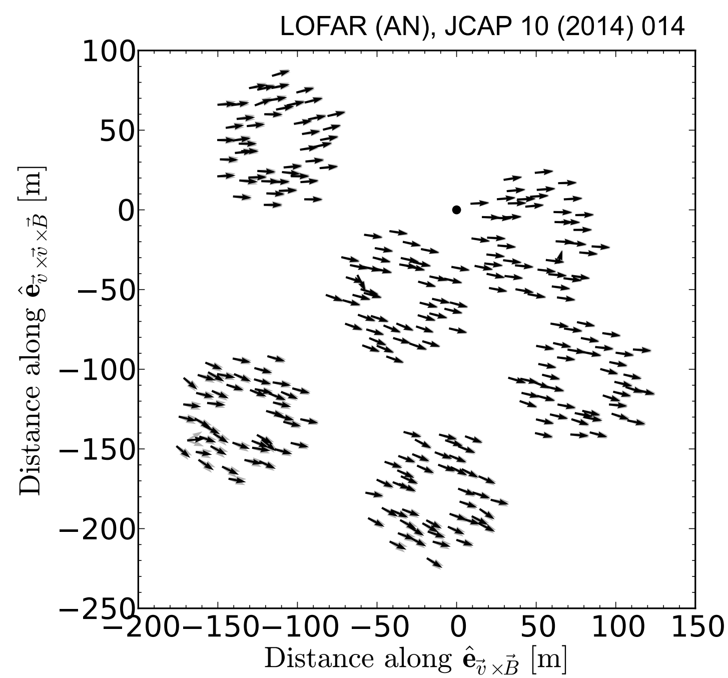
Radio emission of showers

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*



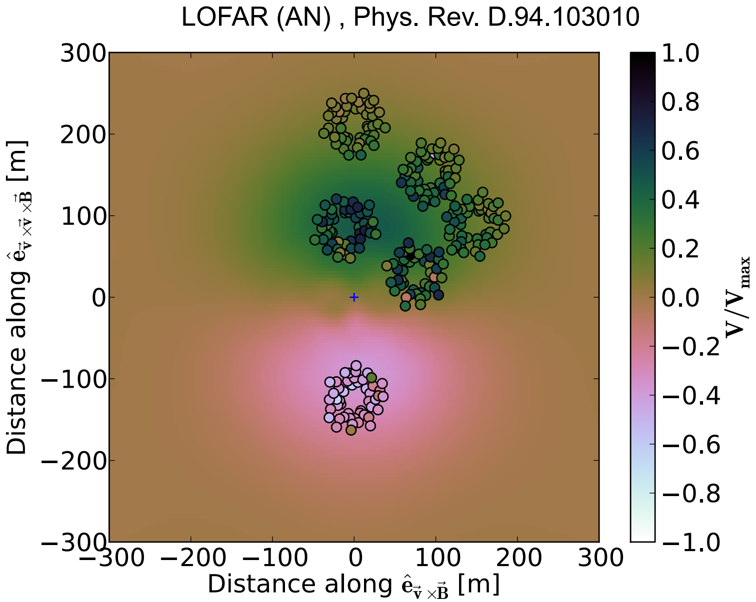




Radio emission of showers

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**



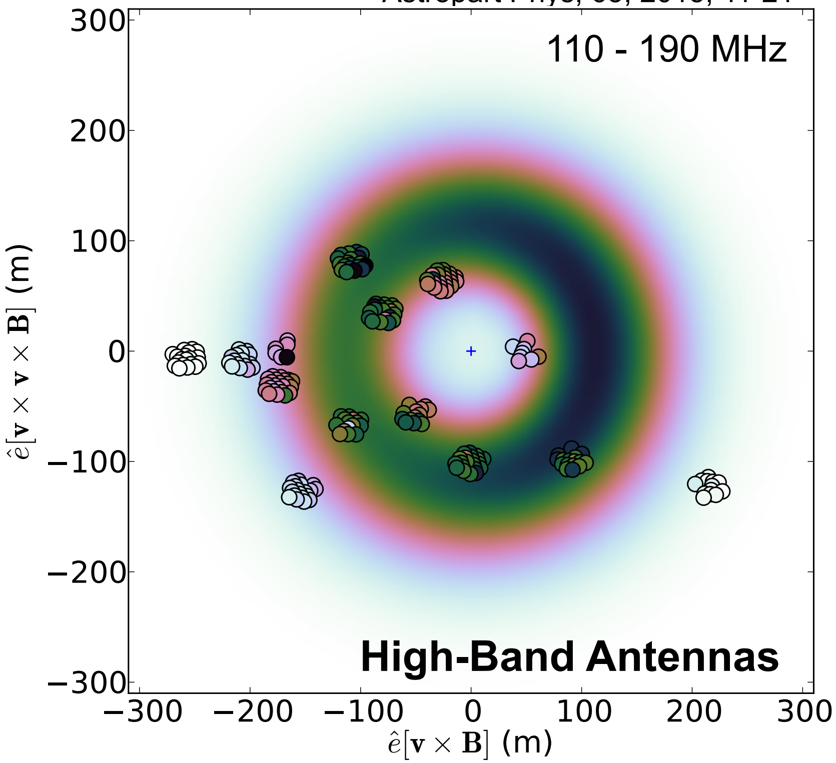
- Emission is due to **both geomagnetic emission** (dominant in air) and **Askaryan emission**
- Geosynchrotron radiation is a correction of < 1% to these effects

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

A.Nelles et al. (LOFAR)
Astropart Phys, 65, 2015, 11-21



We know all this from air showers

Are air showers still interesting?

- Air shower measurements were used to:
  - Provide the proof-of-principle for radio detection of particle showers
  - Confirm the emission mechanisms down to subtle features, agreement with Monte Carlo simulations astonishingly good
  - Develop methods of how to reconstruct data, remove the contribution of noise, understand antenna theory for impulsive events, …
- But a technique is only useful, if it can also contribute to advancing the astroparticle science case

Cosmic-ray energy spectrum

Air shower physics

Particle Physics

Acceleration

Sources of UHECR

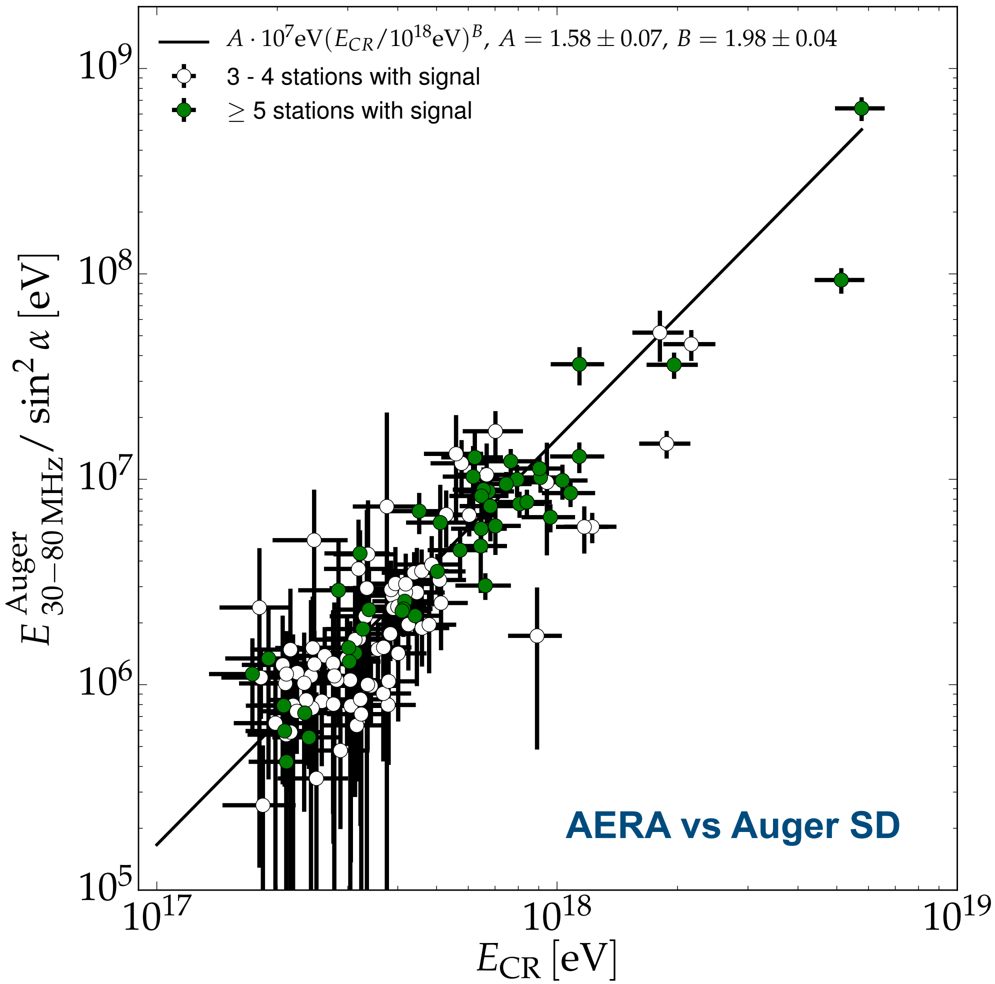
Cosmic-ray composition

Propagation

Detecting radio emission of air showers

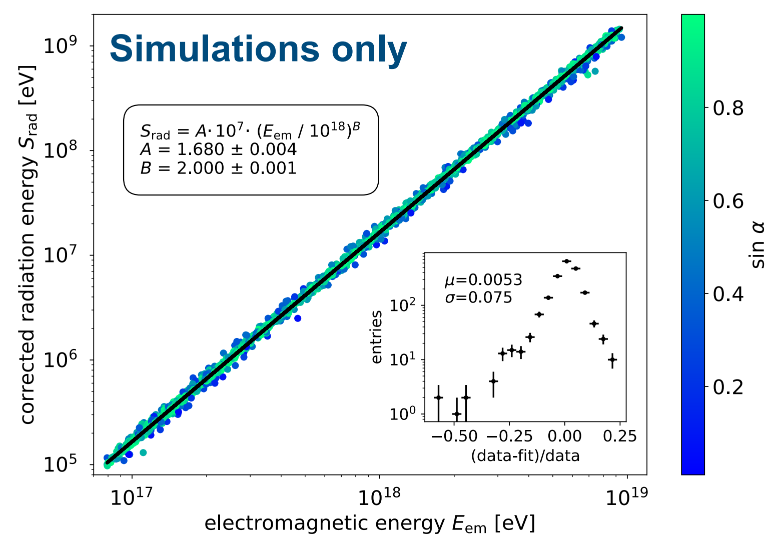
What is in it for the science?

A. Aab et al. (AN), PRL 116 (2016) 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



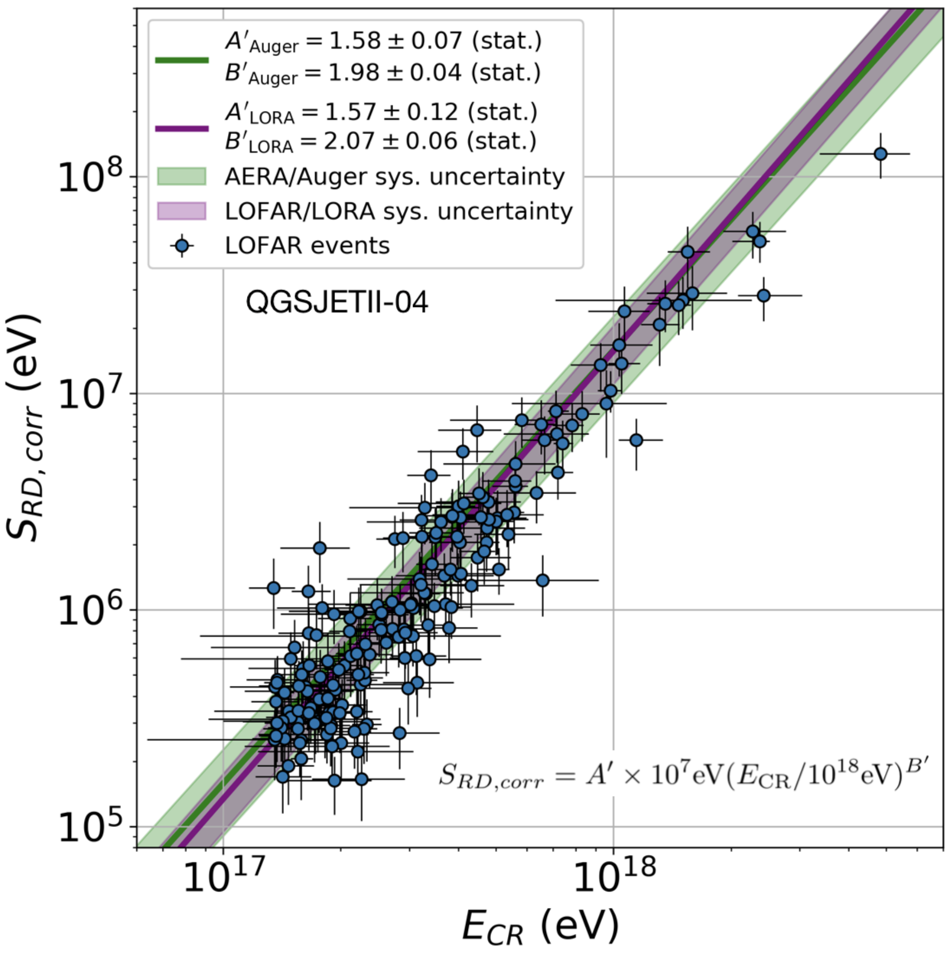
Detecting radio emission of air showers

What is in it for the science?

- **A radio energy estimate could reduce systematic uncertainties between observatories**
- Long standing issue in interpreting cosmic-ray data between observatories:

  Remove ad-hoc scaling, which has been impacting theory

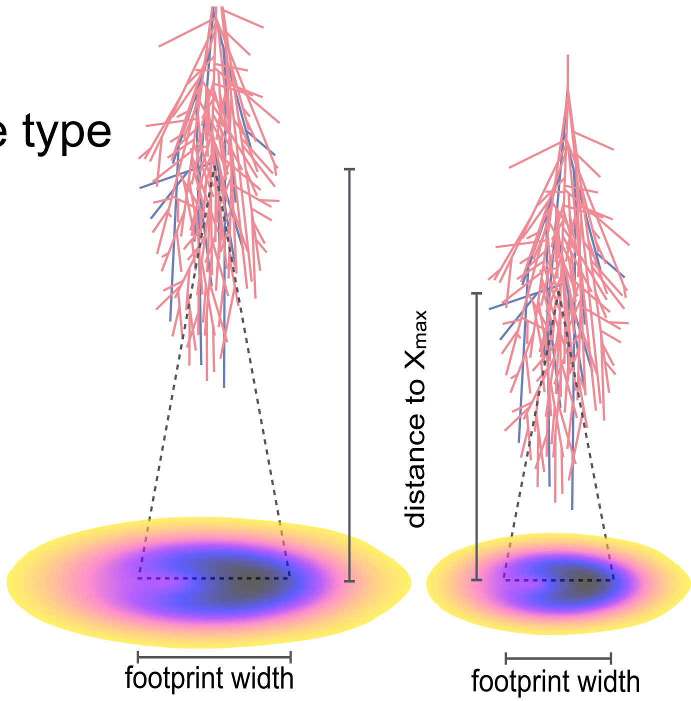
K.Mulrey et al. (AN) *JCAP* **2020** 017



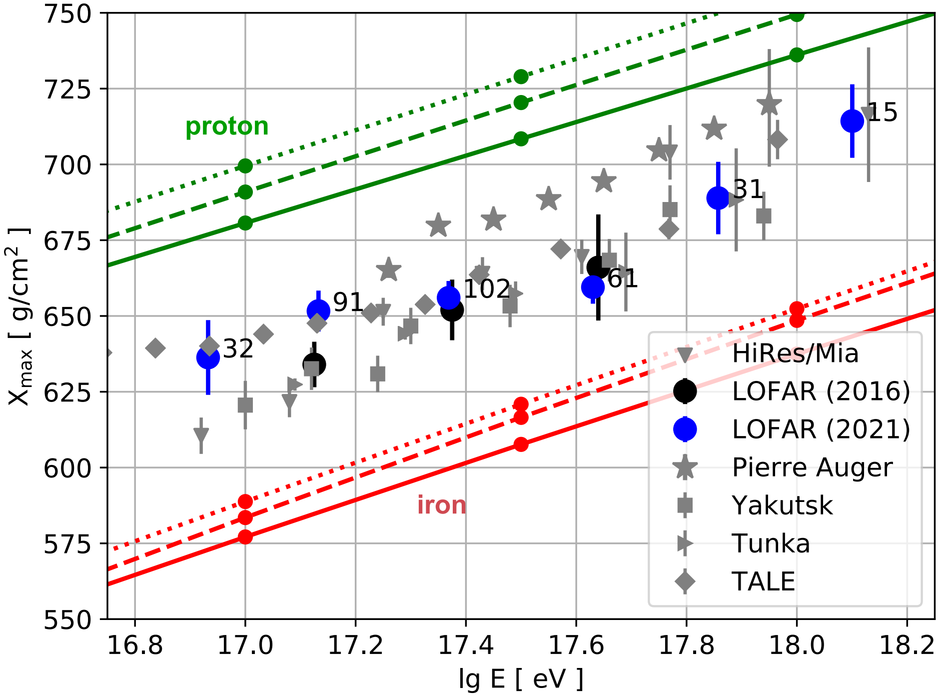
Detecting radio emission of air showers

What is in it for the science?

- Radio pattern is very sensitive to X_{max} = particle type



LOFAR (AN), Phys.Rev.D 103 (2021) 10



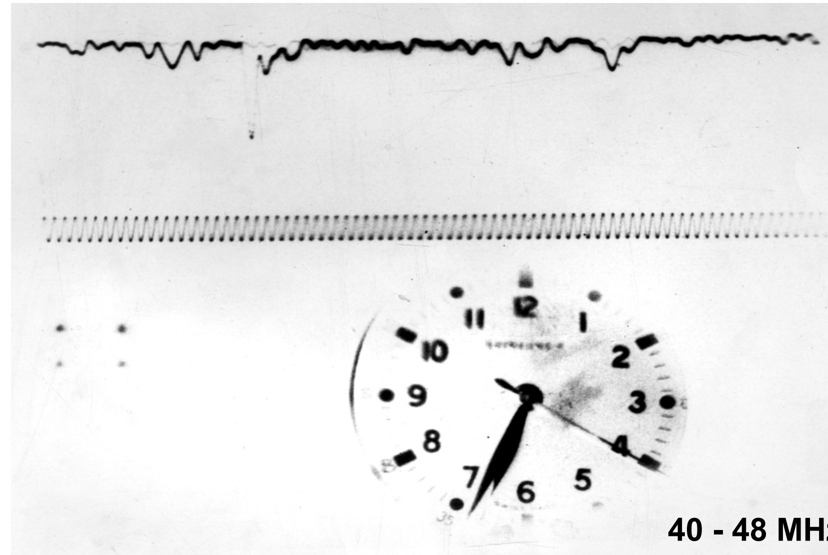
- Tension to Auger measurements, but agreement with Northern hemisphere experiments
- Potential for radio measurement on Southern hemisphere

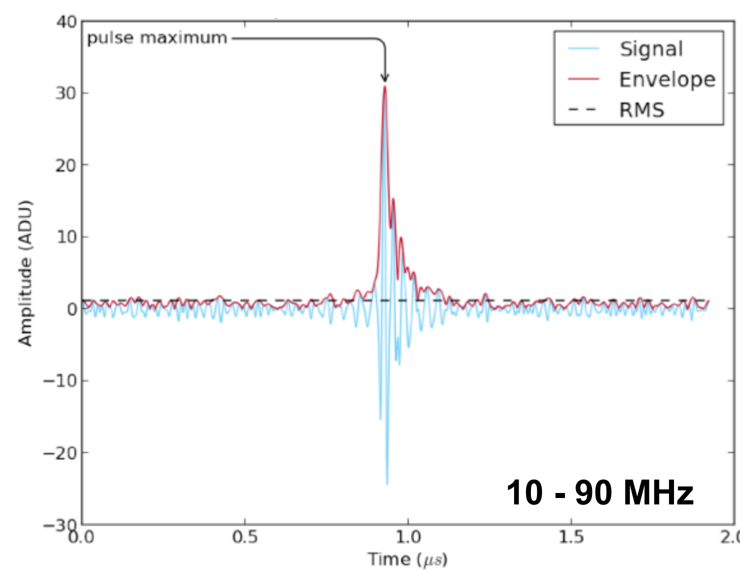
Detecting radio emission

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
- Extreme requirements for electronics:
  - Sampling speeds of at least 200 MHz, double-buffering
  - 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

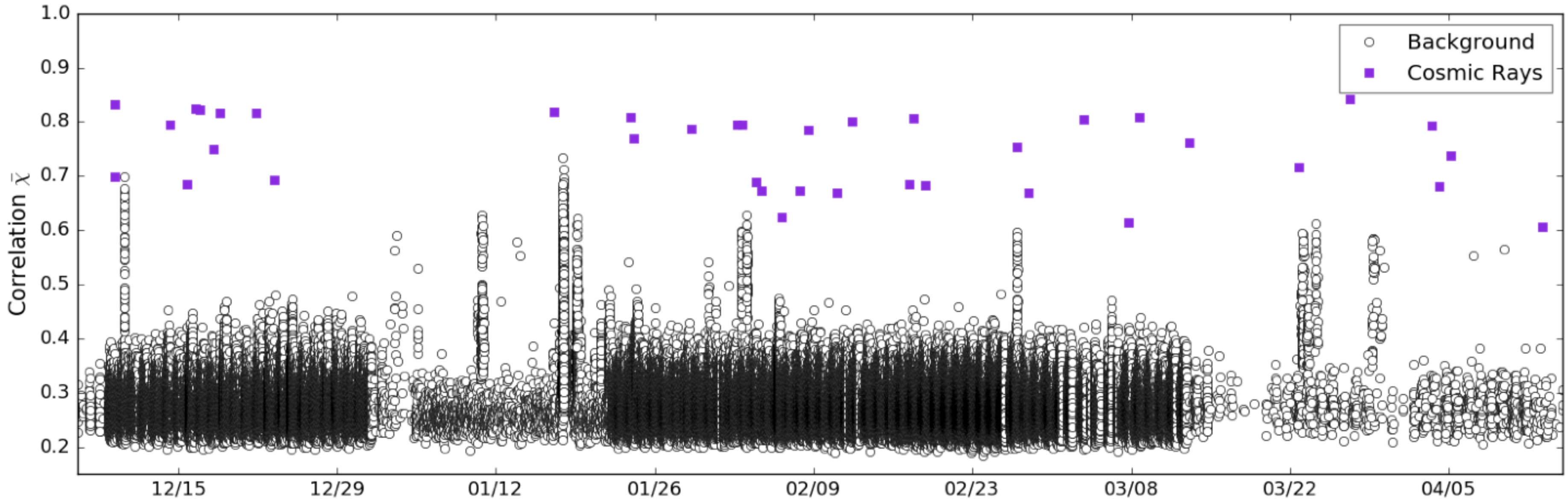


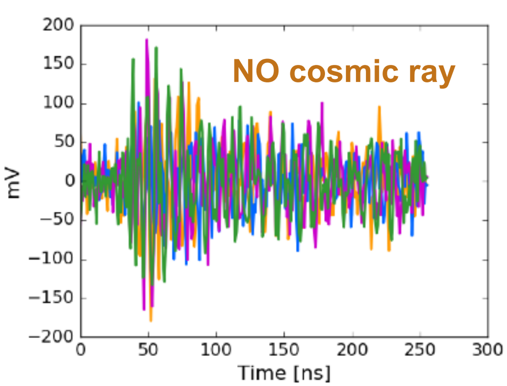


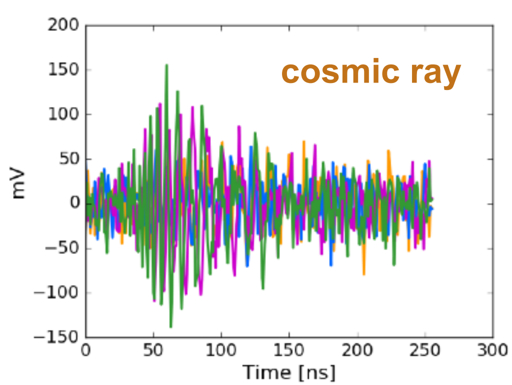
Detecting radio emission of air showers

Experimental challenges and opportunities

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

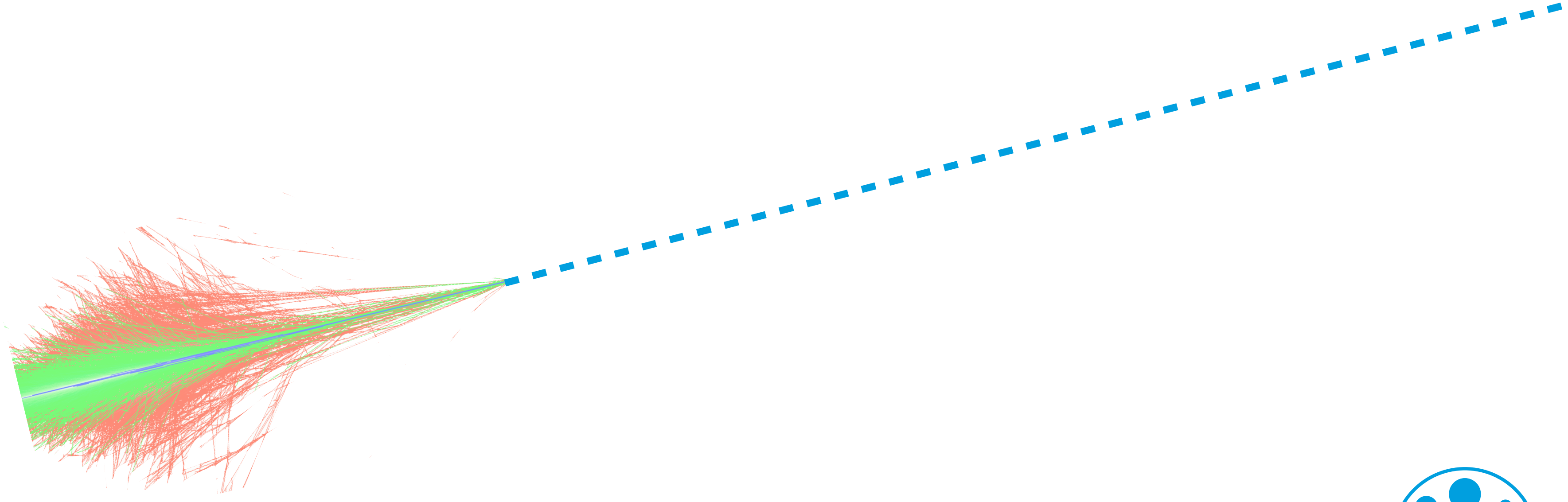






- Unfortunately, a lot of things make radio pulses
- Self-triggering and event identification remain a challenge
- New opportunities in modern data analysis methods

Neutrinos



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

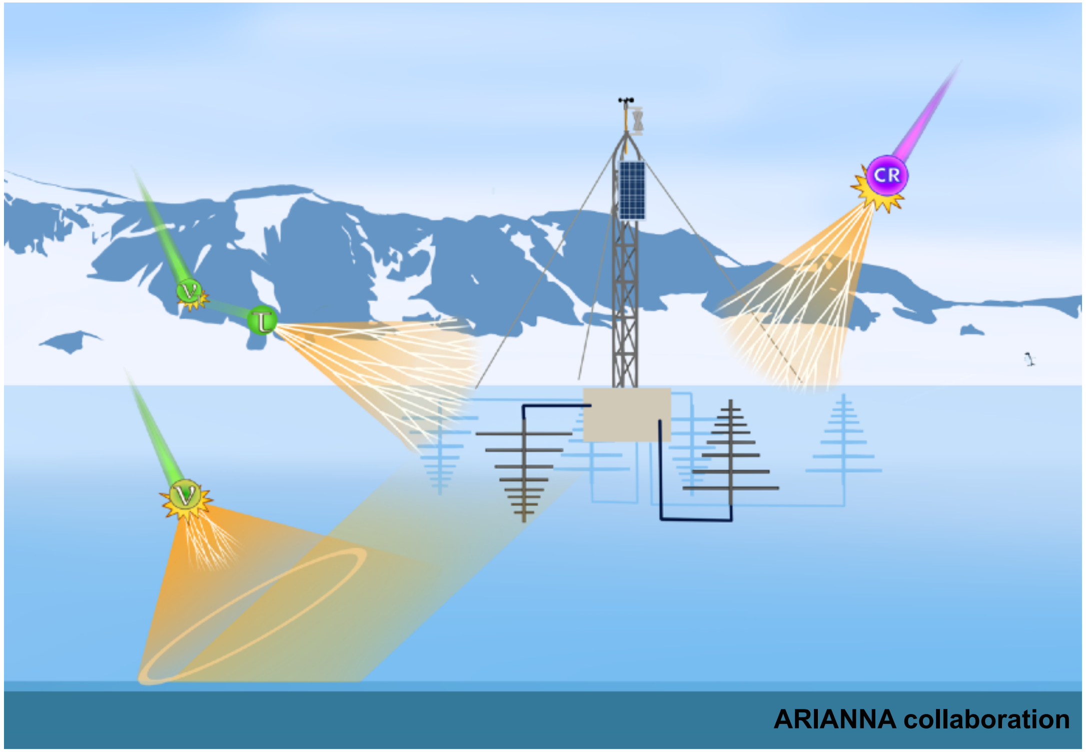
DESY.

Radio detection of neutrinos

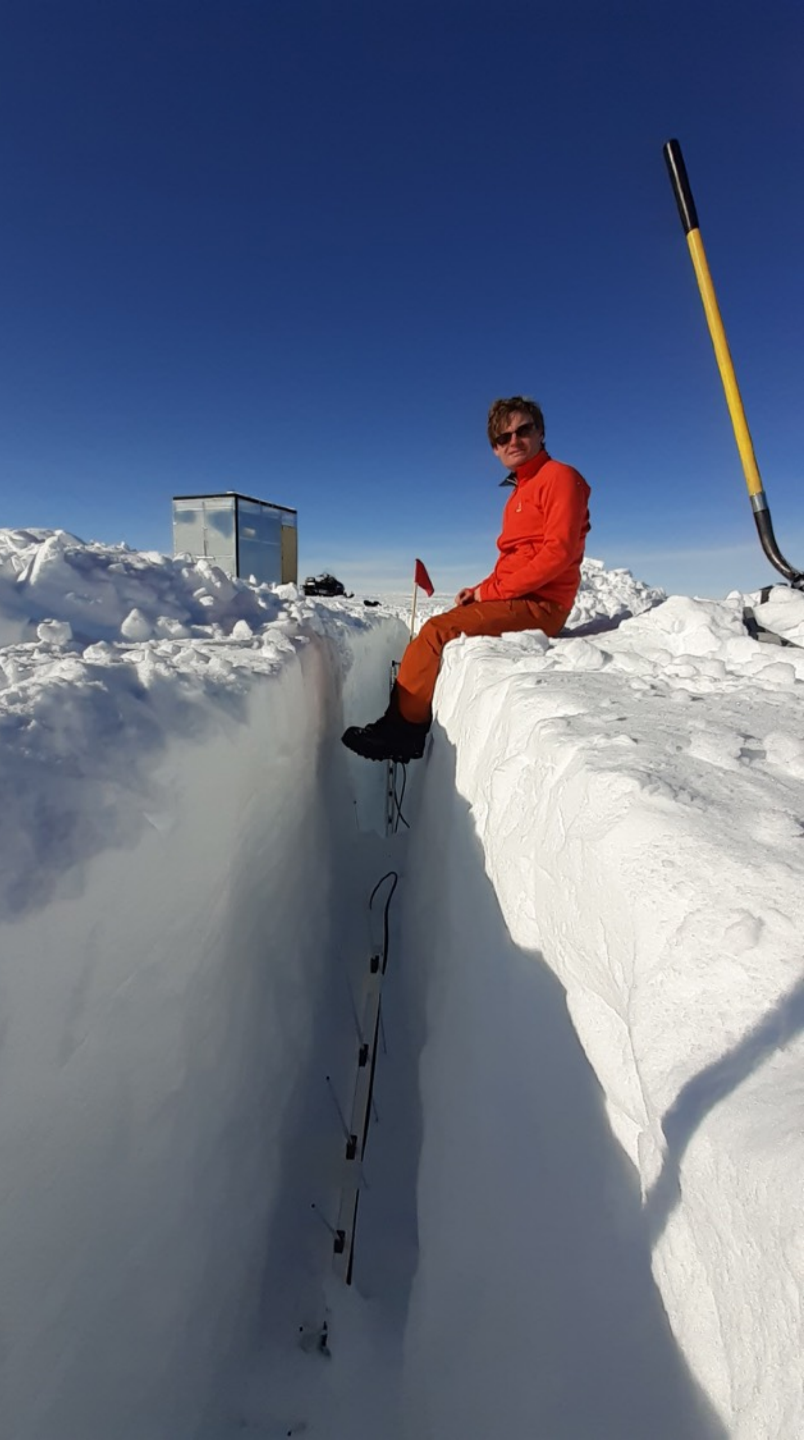
Why it is interesting for neutrinos?

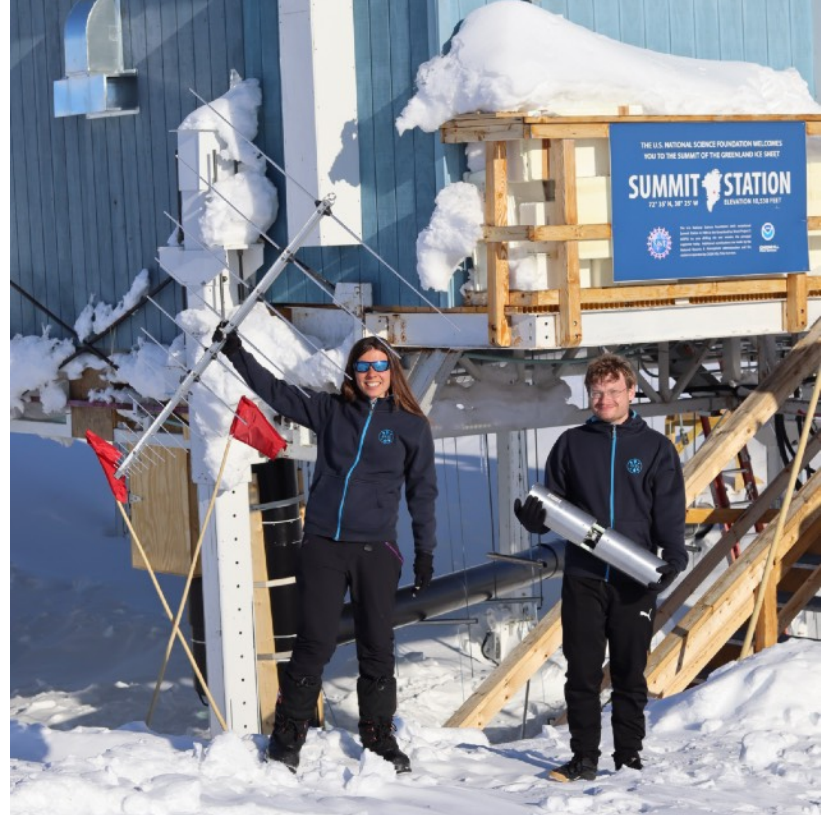
- Any shower containing an electro-magnetic cascade creates radio emission
- A similar experimental approach for:
  - air showers from **cosmic rays**
  - air showers from **neutrino induced tau decays**
  - **in ice showers** following a **neutrino** interaction

All radio neutrino detectors are also air shower detectors



- But something denser than air is needed to provide a decent target
- Ice: kilometer-scale attenuation length

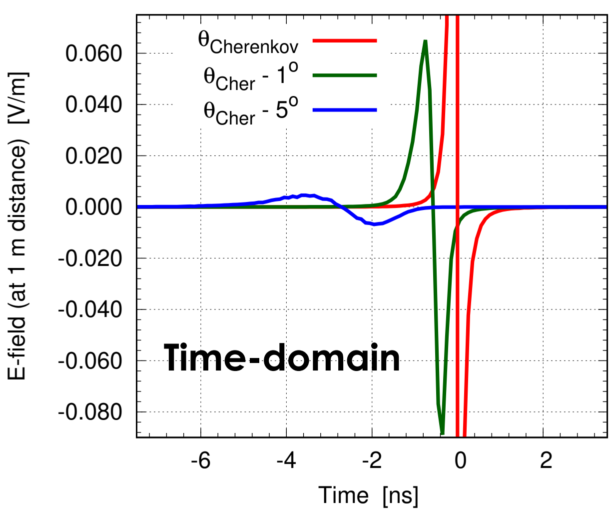


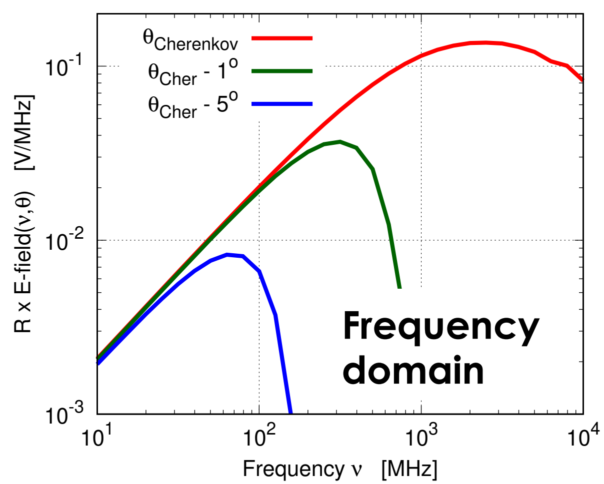

THE U.S. NATIONAL SCIENCE FOUNDATION WELCOMES
YOU TO THE SUMMIT OF THE GREENLAND ICE SHEET
SUMMIT STATION

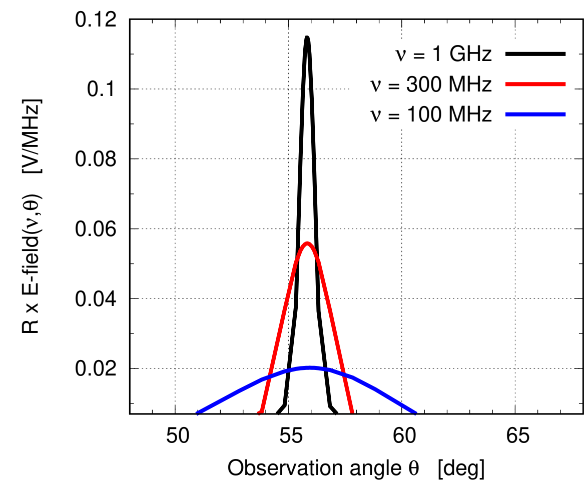
Radio emission of neutrino (showers)

In a very small nutshell

- We are looking for non-repeating nanosecond-scale pulses
- Caused by every shower following an interaction (multiple-pulses per shower possible)
- Detection threshold: pulse amplitude scales linear with shower energy, pulse needs to be detected above background (thermal noise, Galactic radio emission, human-made radio emission, …)







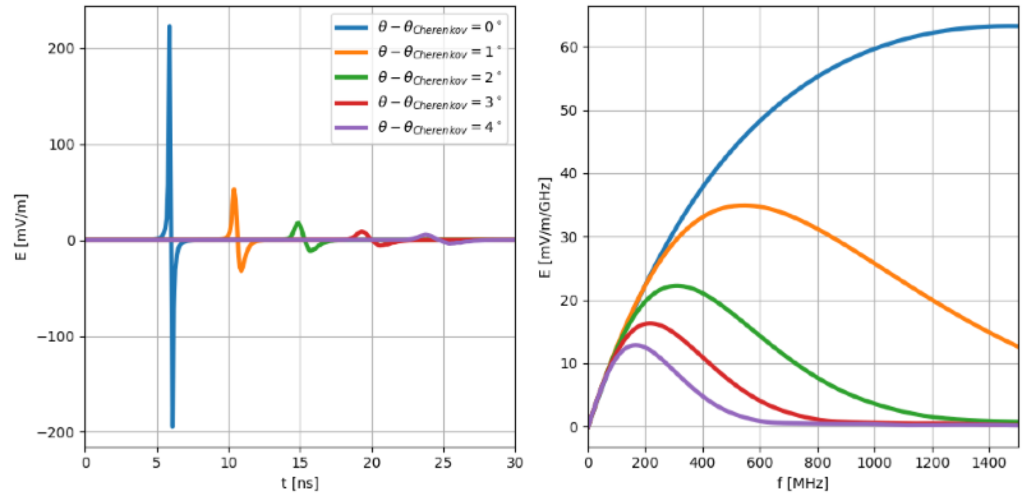
From: J. Alvarez-Muniz

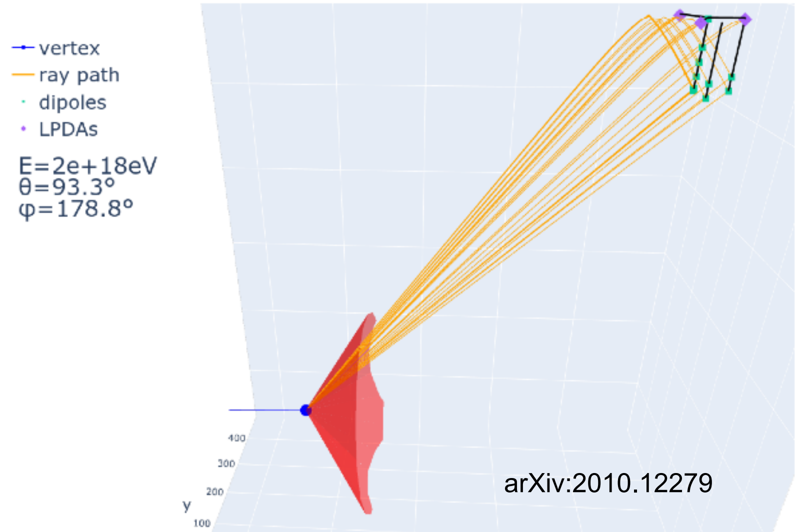
Radio emission of showers in dense media

A difference between detecting cosmic rays and neutrinos

NuRadioMC, Eur. Phys. J. C 80, 77 (2020)

- 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





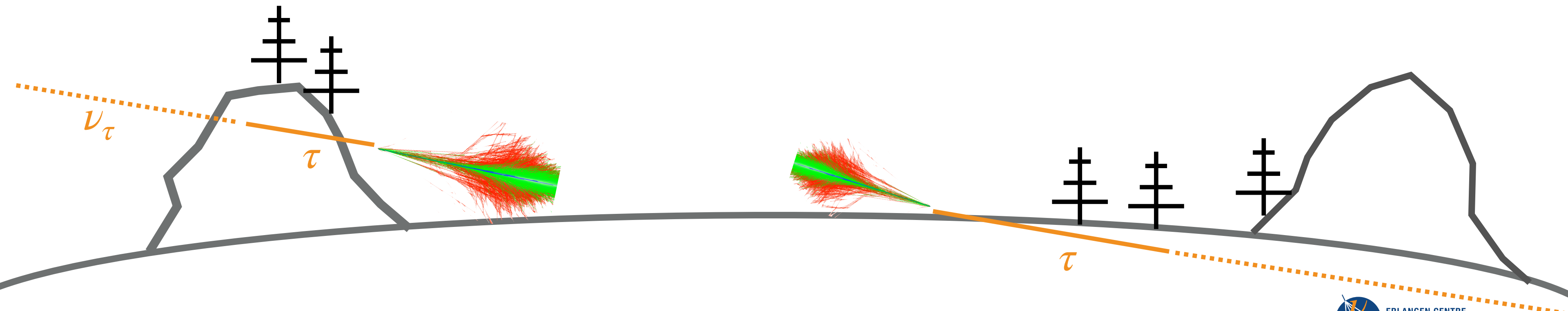
arXiv:2010.12279

*All results powered by NuRadioMC
https://github.com/nu-radio/NuRadioMC
AN and group: core development team

Radio detection of neutrinos

Tau neutrinos emerging from the Earth

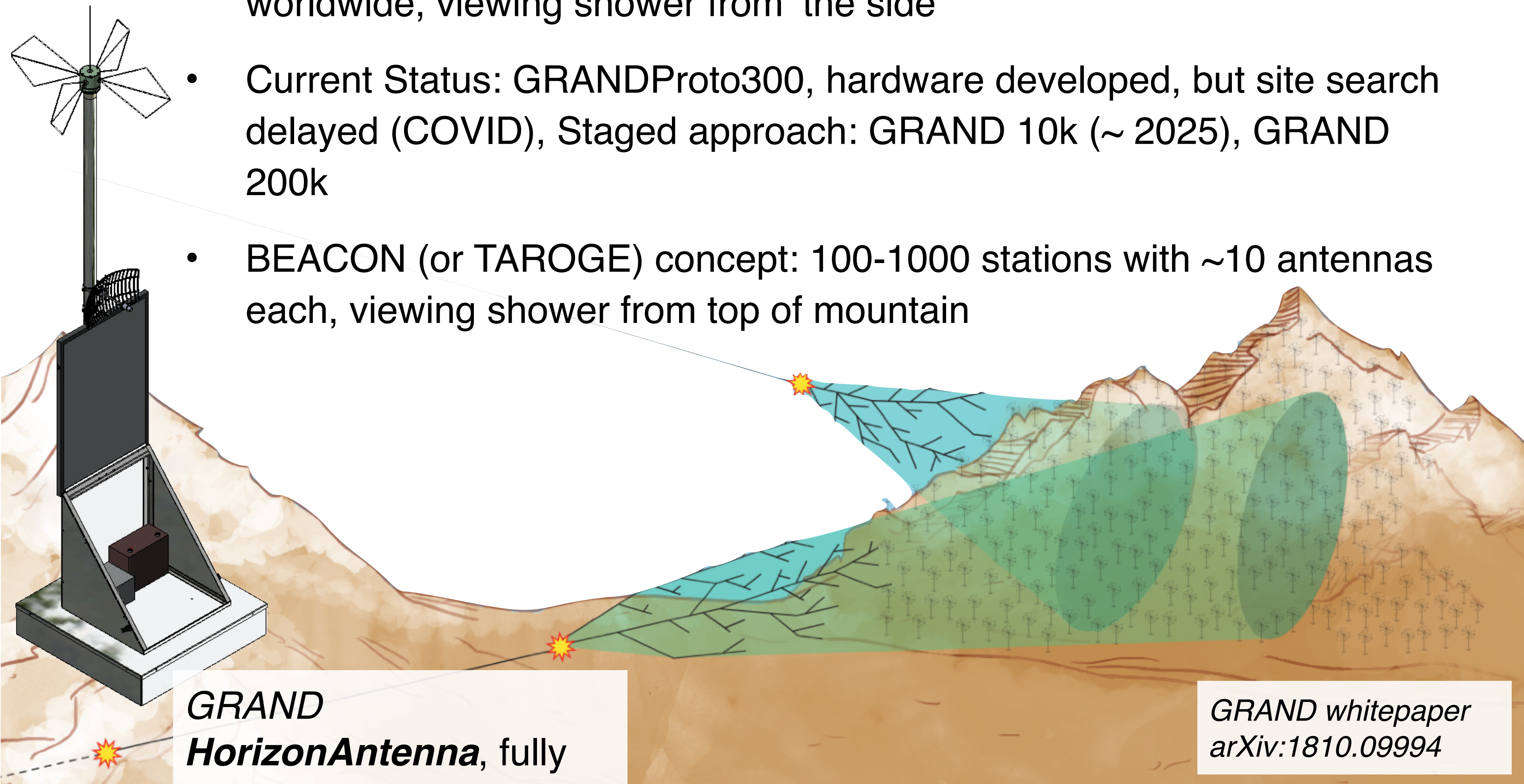
- Looking at tau’s emerging from the Earth, creates large effective volumes for neutrinos, radio emission is (almost) not attenuated in air
- Radio detectors probably most effective, when they use mountainous terrain
- Have to exploit economies of scale for very cheap antenna stations
- Largest challenge: 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



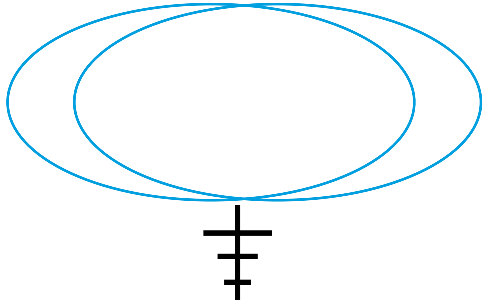
GRAND ***HorizonAntenna***, fully

GRAND whitepaper arXiv:1810.09994

Radio detection of neutrinos

Neutrino interactions in ice

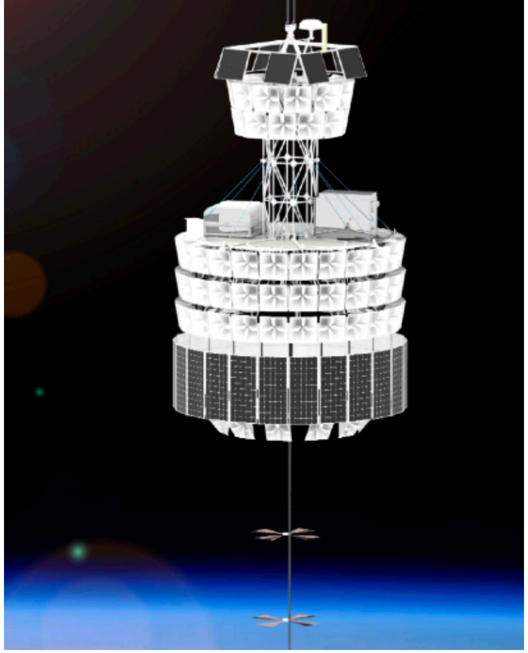
- Cold polar ice has attenuation length in the order of kilometers
- One radio station can typically monitor 1 km^3 of ice (= the size of IceCube)
- Detection threshold around 10 PeV shower energy, determined not by array spacing but pulse height above thermal noise
- > 100 km^3 needed to obtain sensitivity 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

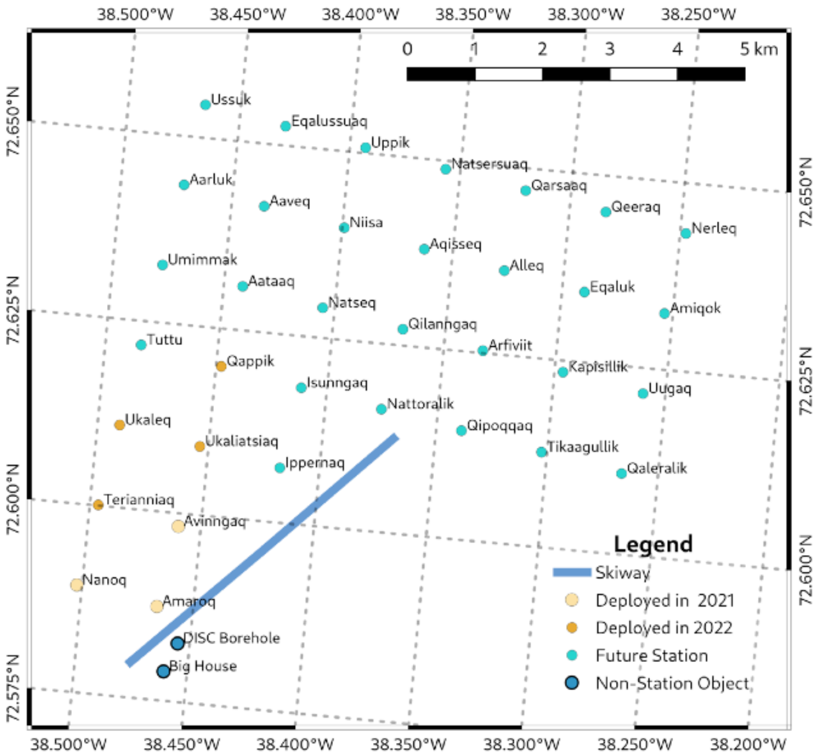


- Neutrino limits from radio detection of neutrinos towards high energies, not competitive to IceCube below 10^{10} GeV
- So far: experiments focussed on proof-of-concept, reconstruction and performance
- Exception: ANITA I-III: Mystery events — behave like cosmic ray signals, but show signal polarization/polarity 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 with better low energy sensitivity and more exposure: PUEO balloon arXiv:2010.02892

Radio detection of neutrinos

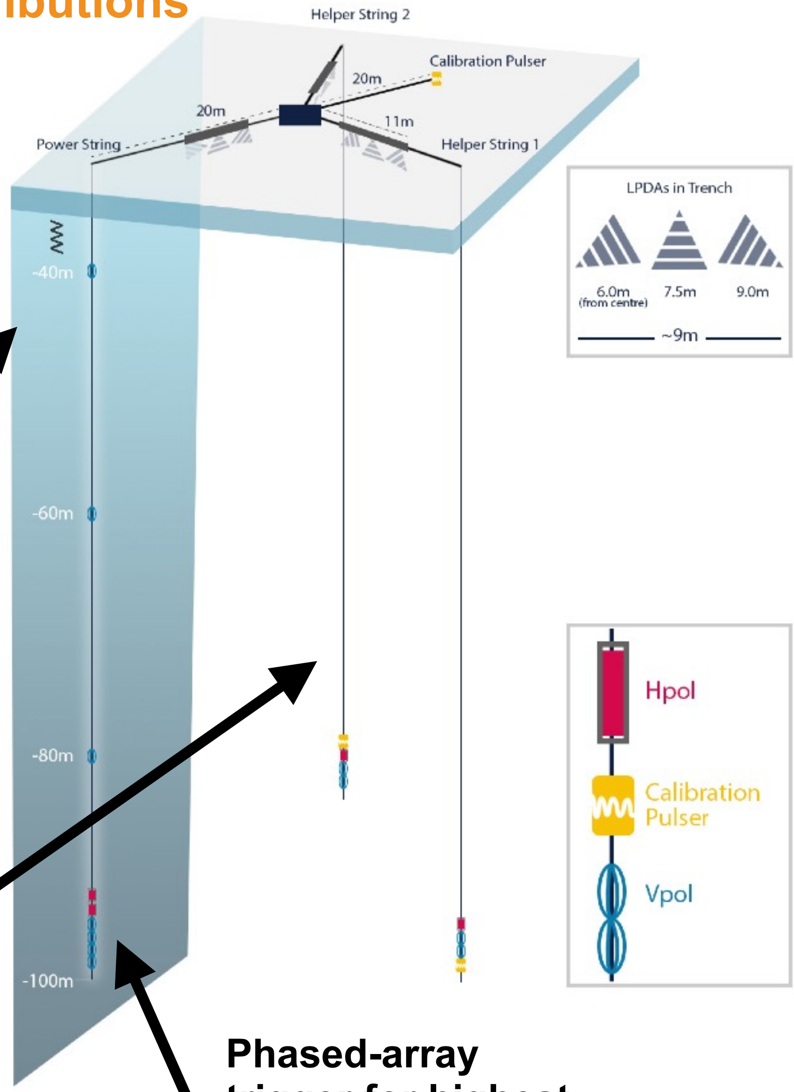
Radio Neutrino Observatory Greenland (RNO-G)

- RNO-G: Construction started in 2021
- 35 stations as first production scale implementation for neutrino detection
- Deployment in Greenland allows for fast development turn-around
- Largest yearly neutrino sensitivity > 10 PeV
- Lead institutions:
  Chicago, DESY,
  Brussels, PennState, Madison
- Concept and design paper:
  JINST 16 (2021) 03, P03025,
  arXiv:2010.12279



RNO-G

The details and contributions



Cosmic ray tagging and high-fidelity reconstruction

Antennas distributed for neutrino vertex reconstruction

Combination of antennas for reconstruction of full electric-field

RFover Fibre strings, for high signal quality and signal reconstruction

Phased-array trigger for highest effective volume

RNO-G Status

Where do we stand?

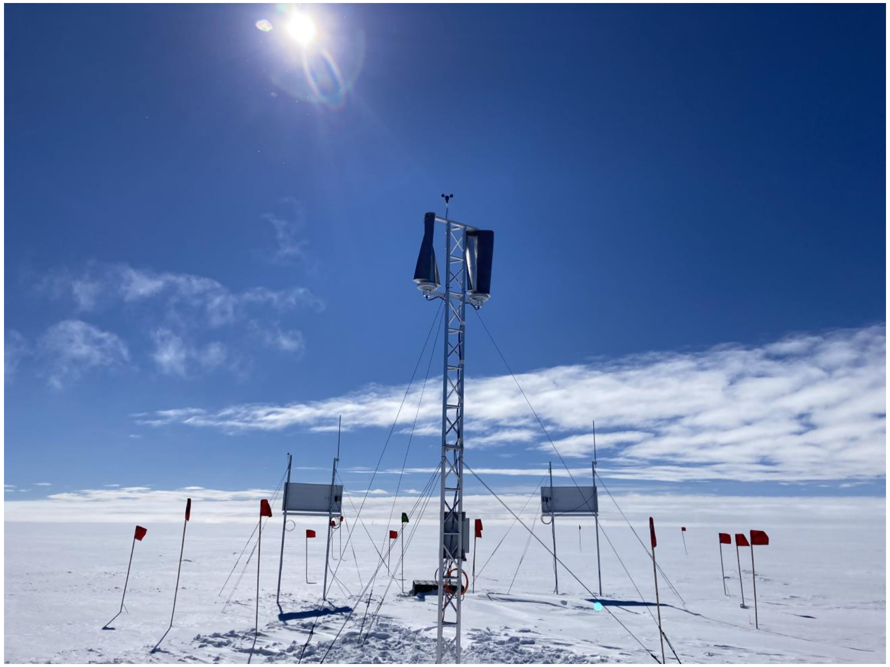
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

I. Plaisier, PhD student @ FAU

- 2021: Installed first 3 stations
  (with very little lab testing due to COVID)
- 2022: Installed 4 additional stations, upgraded existing ones, started to install wind-turbines

RNO-G Status

What is still to do?



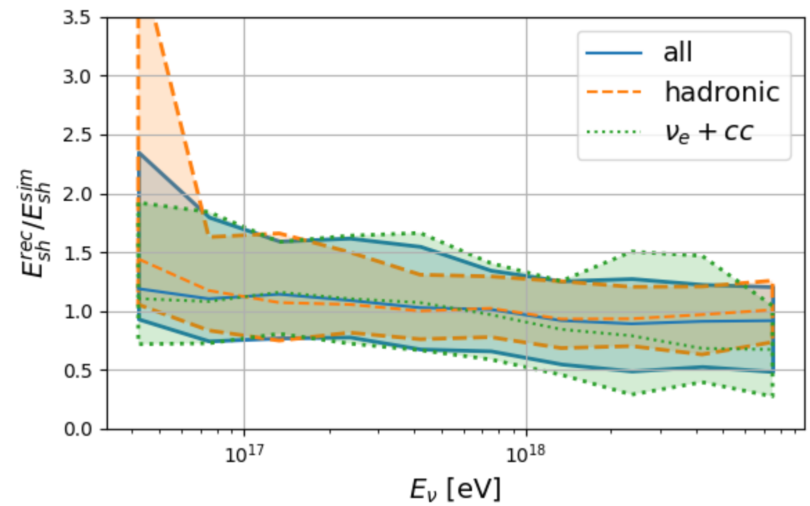
- 2023: Upgrade stations to ‘final’ version of hardware, install remaining wind-turbines, add cosmic-ray verification set-up
- 2024 + 2025 + 2026: Install 10 (+/-2) stations each year
- Perform ice calibration measurements and potentially install enhancements

- Operate at least until 2031 (or until IceCube-Gen2 supersedes RNO-G)

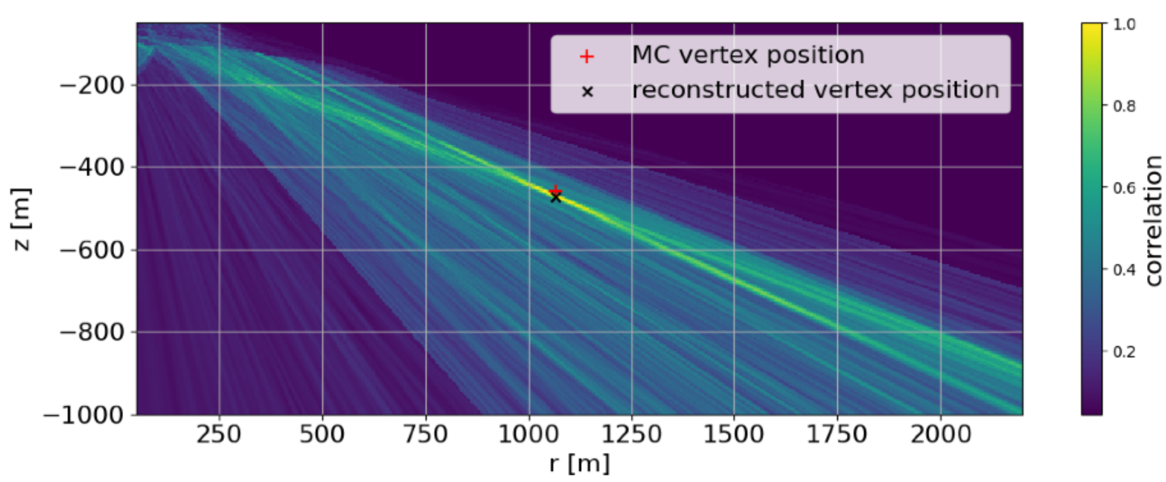
Radio detection of neutrinos

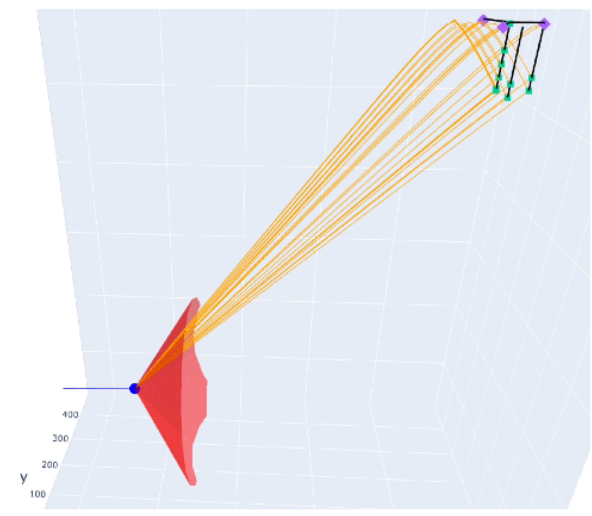
Reconstructing the energy

RNO-G, Eur. Phys. J. C (2022) 82: 147



- Radio detection a mixture of “radio interferometry” in a medium and particle physics
- Ingredients: vertex distance (scaling with distance and attenuation), signal fluency (scales quadratically with energy), neutrino inelasticity
- Energy resolution very good on shower basis, dominating uncertainty is neutrino inelasticity



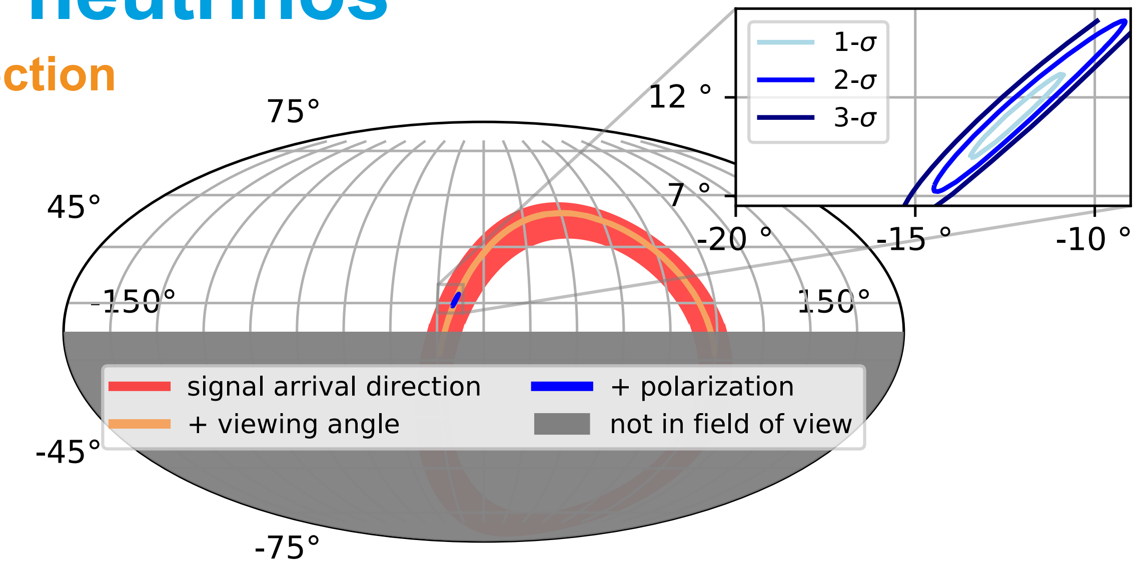


Radio detection of neutrinos

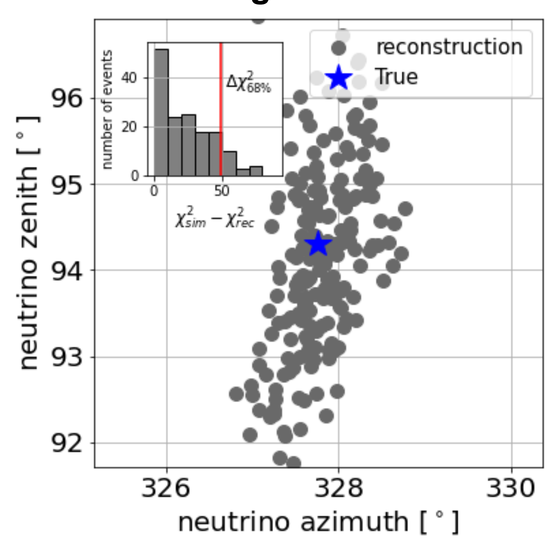
Reconstructing the arrival direction

PhD thesis, Ilse Plaisier, 2022

- A signal contains:
  - Timing, i.e. signal arrival direction
  - Frequency content, i.e. angle to Cherenkov angle
  - Polarization, i.e. radial angle on Cherenkov cone
- All need to be combined for arrival direction
- Working towards multi-messenger astronomy with UHE neutrinos



Single event contour



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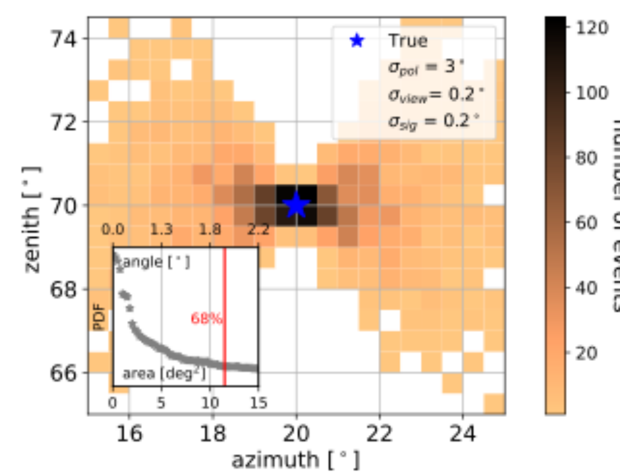
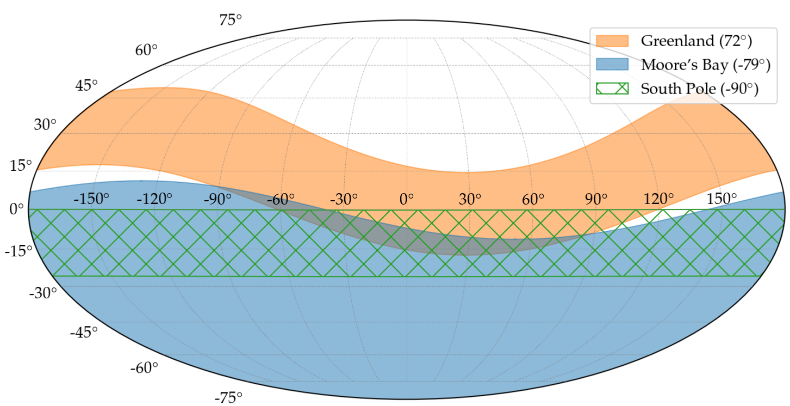


Plaisier et al., in prep

RNO-G

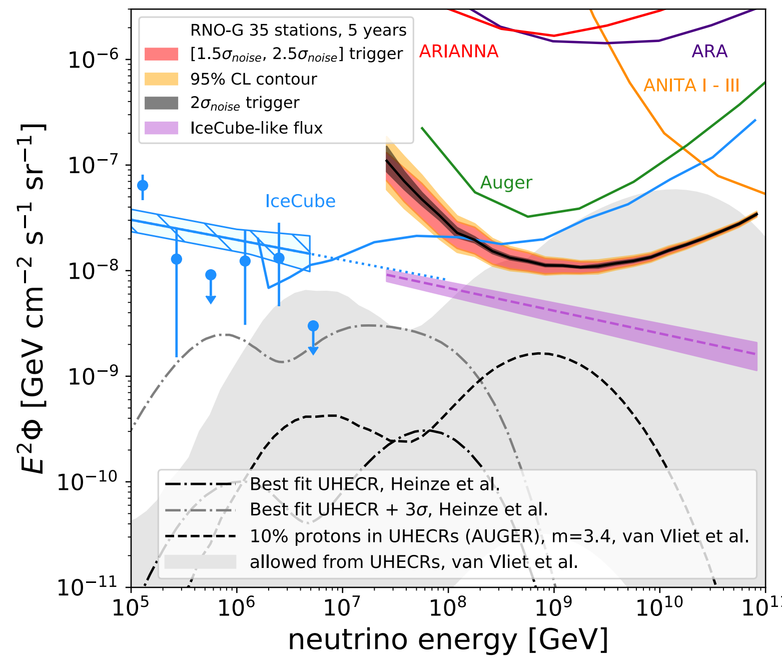
The science

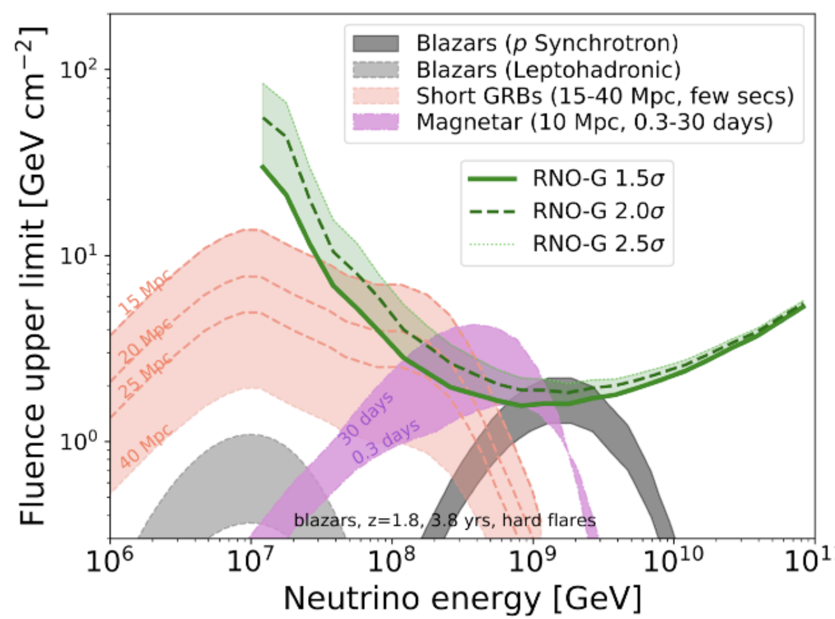
- RNO-G ‘big’ enough to have a reasonable chance to detect a continuation of the diffuse IceCube neutrino flux
- Somewhat optimistic chance to detect transient events, nice complimentary Northern hemisphere sensitivity



- Discovering > PeV neutrinos would be simply exciting
- Absence problematic for theory

arXiv:2010.12279



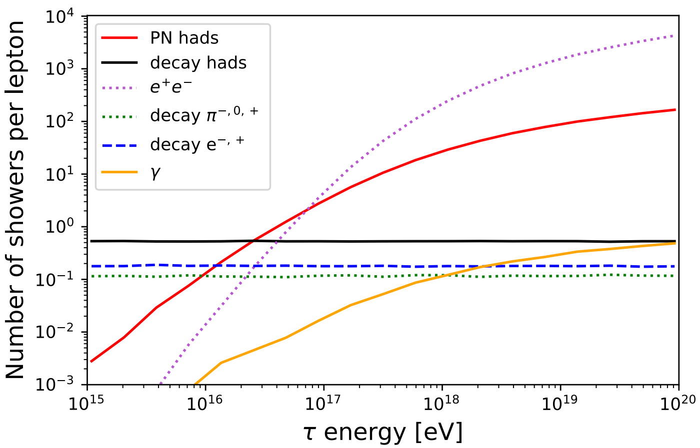


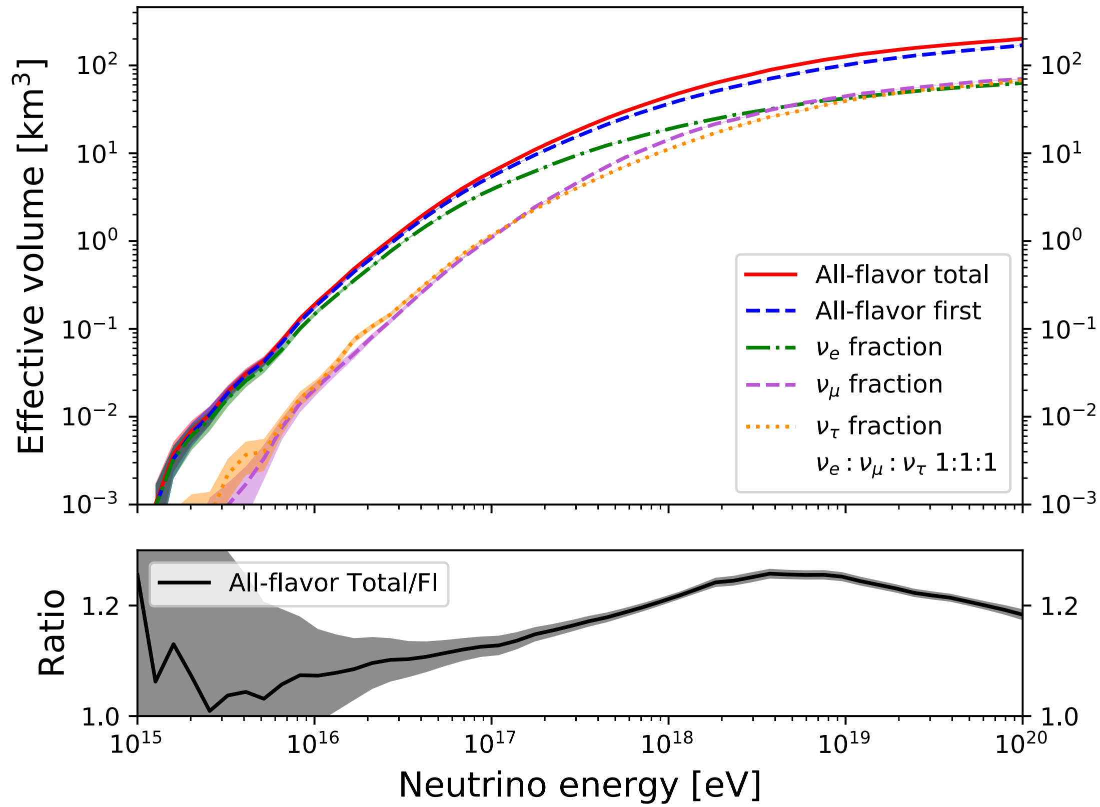
Radio detection of neutrinos

Neutrino sensitivity

- RNO-G sensitive to all 3 neutrino flavors (NC and CC, > 10 PeV)
- 20% of all detections are from interactions of secondary muons or taus
- Flavor-tagging relevant for both particle physics and astrophysics

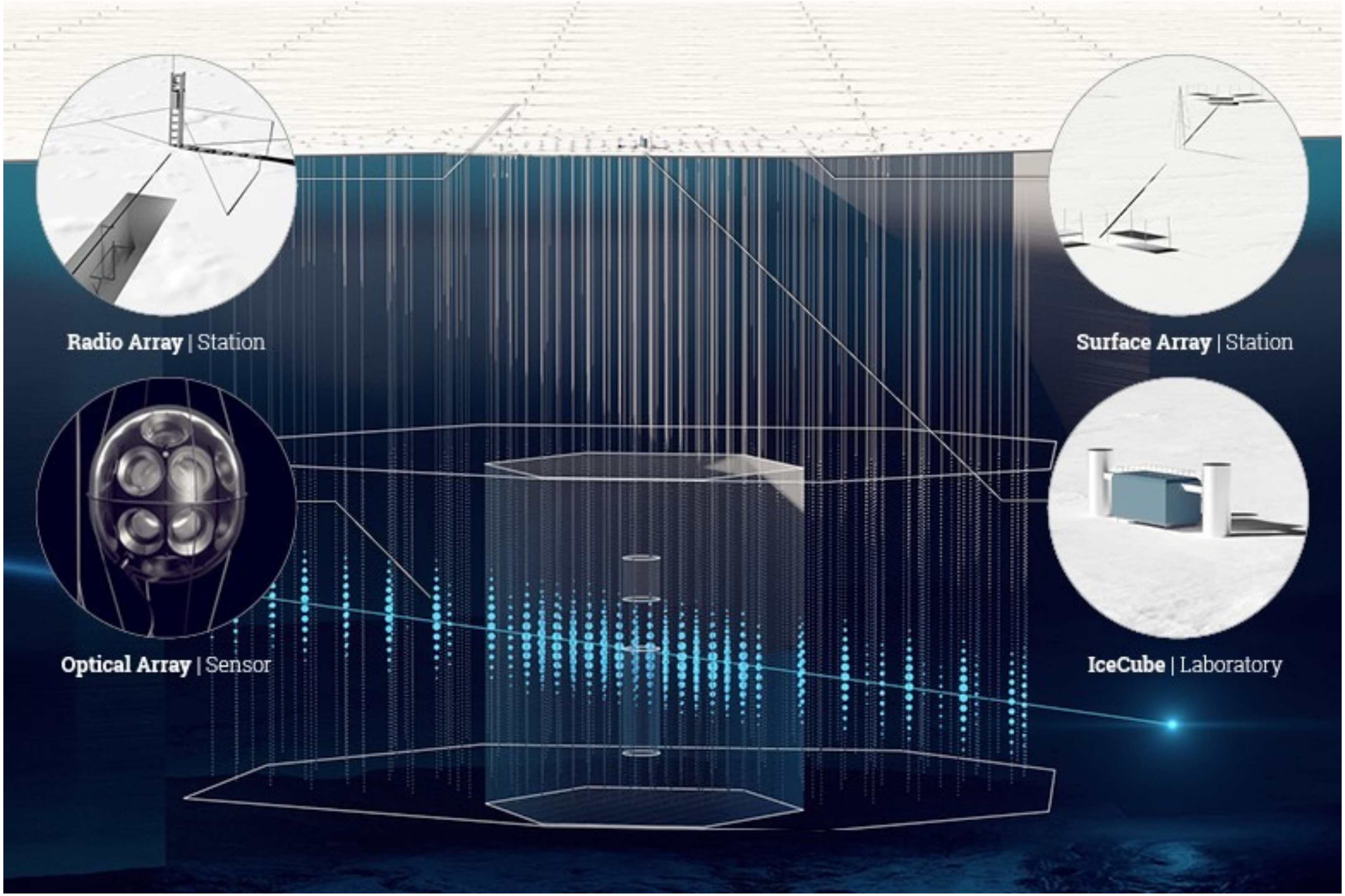
Garcia-Fernandez et al. (AN), Phys. Rev. D 102, 083011 (2020)





Radio detection of neutrinos

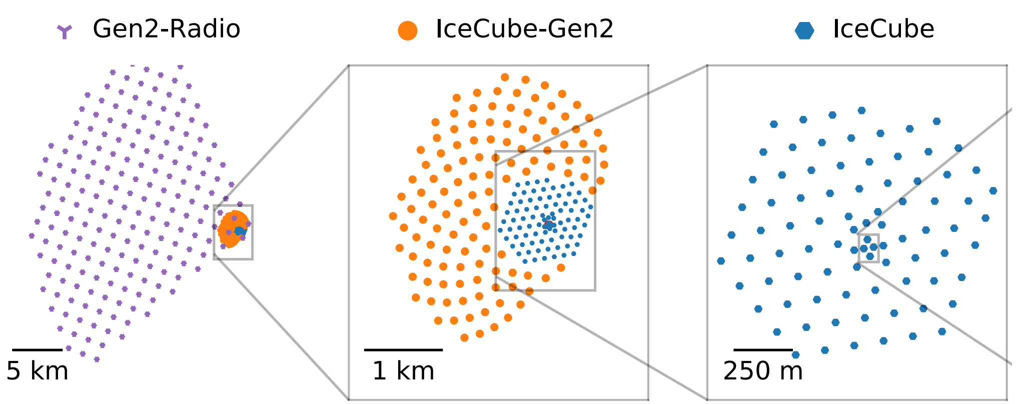
Where to after? IceCube-Gen2

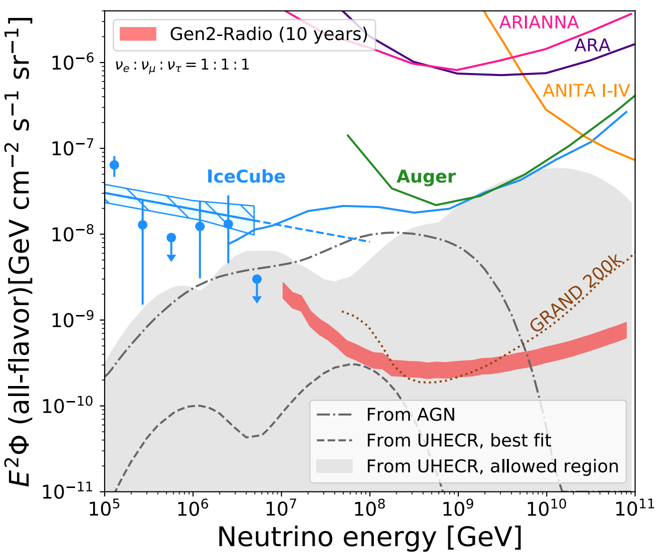


Radio detection of neutrinos

IceCube-Gen2

- Baseline design for IceCube-Gen2 includes a large radio array
- Experimental design based on RNO-G technology
- ‘Roughly’ a factor 10 more stations than RNO-G
- Collaboration is currently defining details in Technical Design Report
- **First milestone: favorably reviewed in Astro 2020 US Decadal Survey**



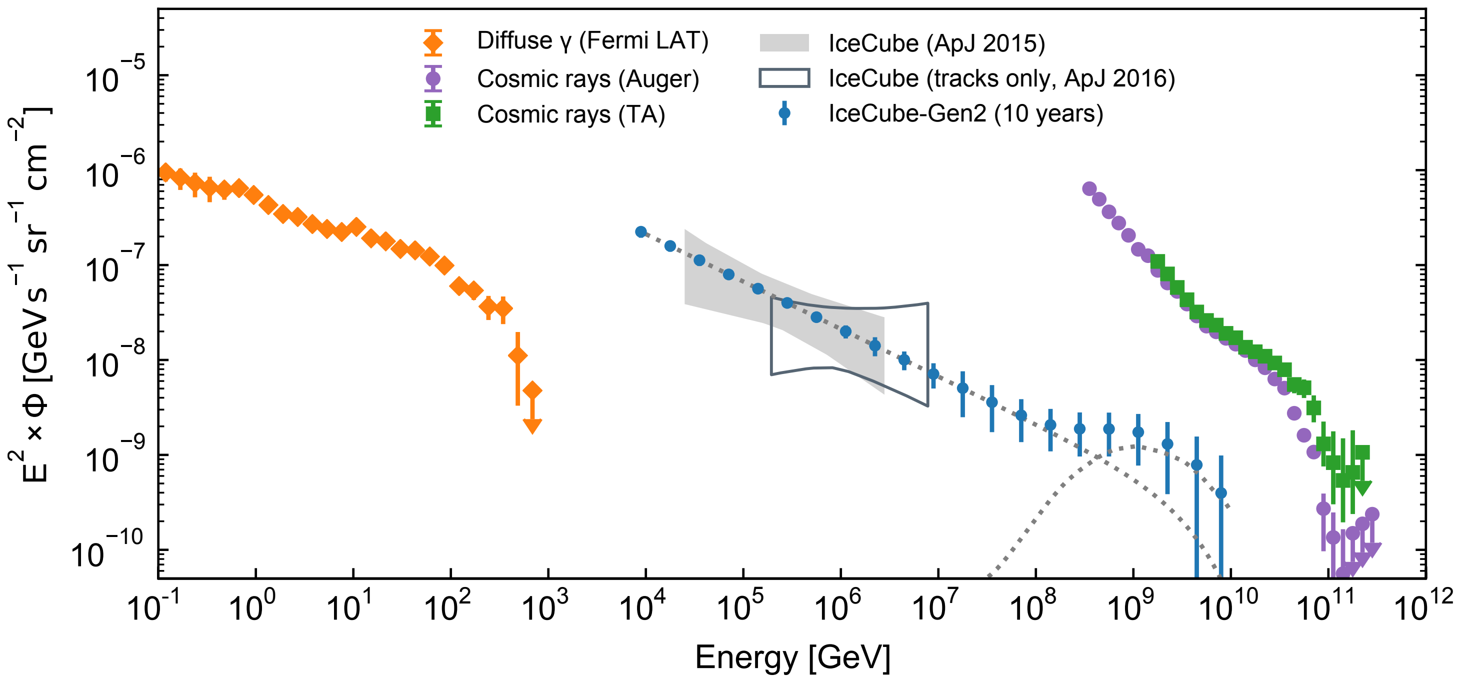


Radio detection of neutrinos

IceCube-Gen2

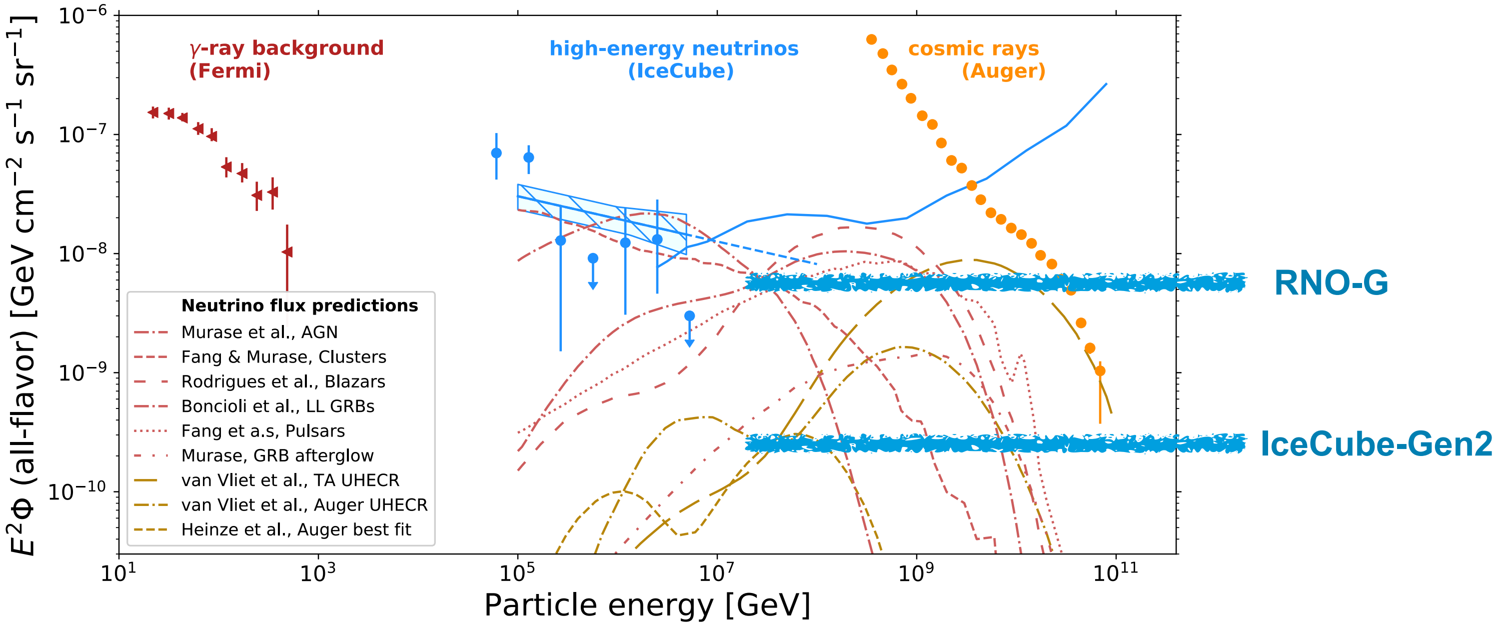
"IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy universe."

IceCube-Gen2: The Window to the Extreme Universe , https://arxiv.org/abs/2008.04323, *J.Phys.G* 48 (2021) 6, 060501



Conclusions

How to tackle the puzzle of the sources of ultra-high energy cosmic rays?



- **Neutrinos:**
  - Many ideas to go to > PeV energies using radio
  - In-ice technology **now** mature, **RNO-G** first large scale implementation at > PeV energies
  - **Next step**: **IceCube-Gen2** neutrino physics at all astrophysical energies with > factor 10 improved sensitivity