Radio Detection of Neutrinos and Cosmic Rays

A ‘new’ old method

Anna Nelles

Lecture Series, Modern Astro- and Astroparticlephysics, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
DESY.

Who am I?

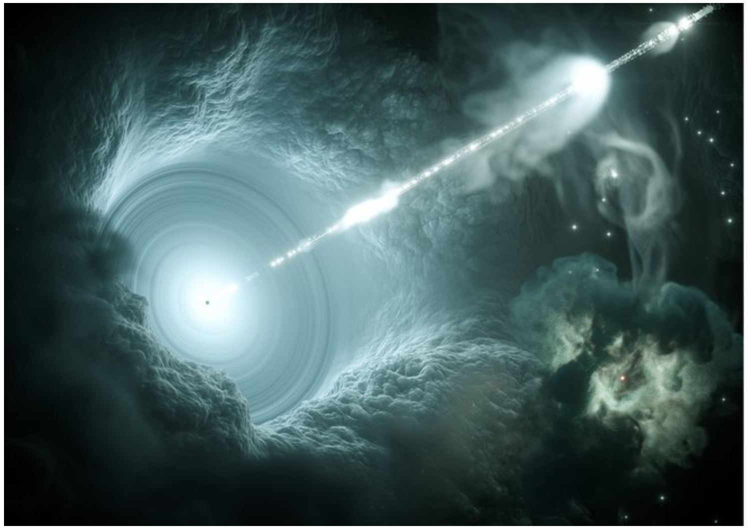
As far as one can do this online

- Currently: Professor of Astroparticle Physics at Friedrich-Alexander-University Erlangen-Nürnberg
- AND: Staff Scientist at DESY
- Brief CV:
  - Diploma in Physics from RWTH Aachen
  - (and Master in Business Studies)
  - PhD in Physics from Radboud University Nijmegen, The Netherlands
  - Post-Doc at University of California Irvine, USA
  - Emmy-Noether Group at Humboldt-University Berlin

Outline of today's lecture

Rough idea what will be covered

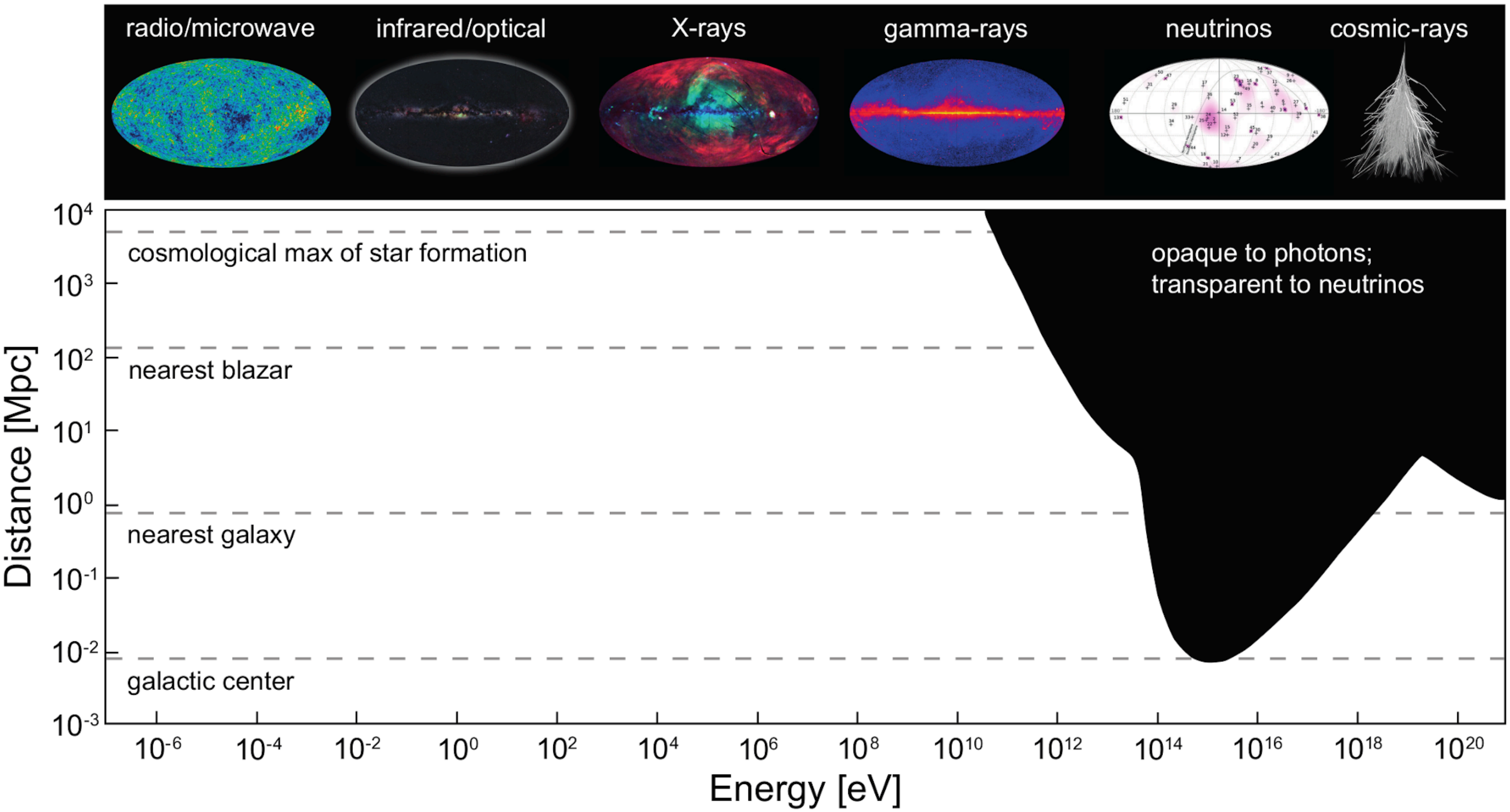
- Outline
  - Scientific motivation of radio detection of particle showers
  - Underlying physics of radio emission
  - Air shower experiments
  - Neutrino experiments



Multi-messenger Universe

Where are we at, at the moment?

see also Introduction by Karl-Heinz Kampert



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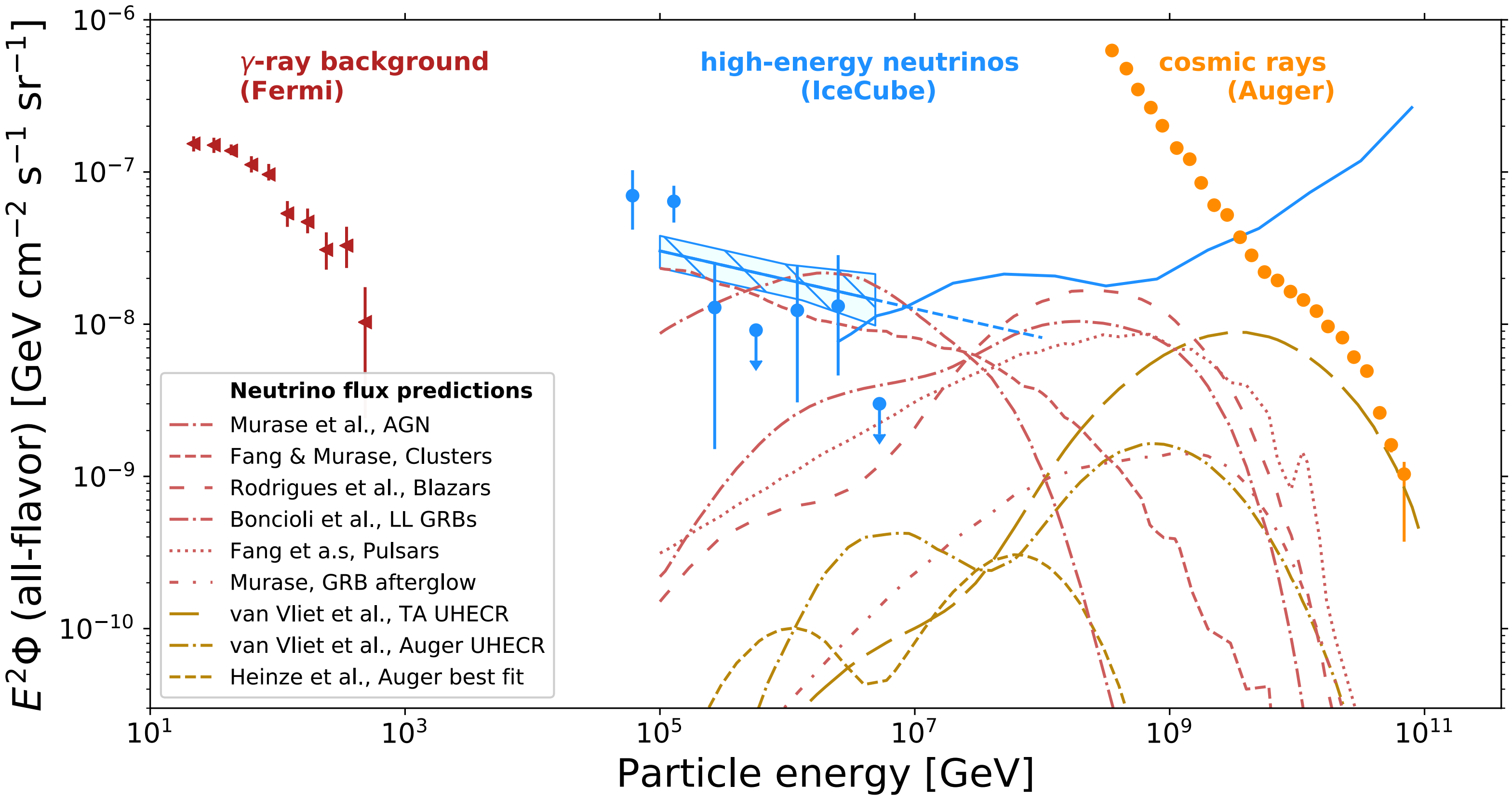


Radio detection of particle showers

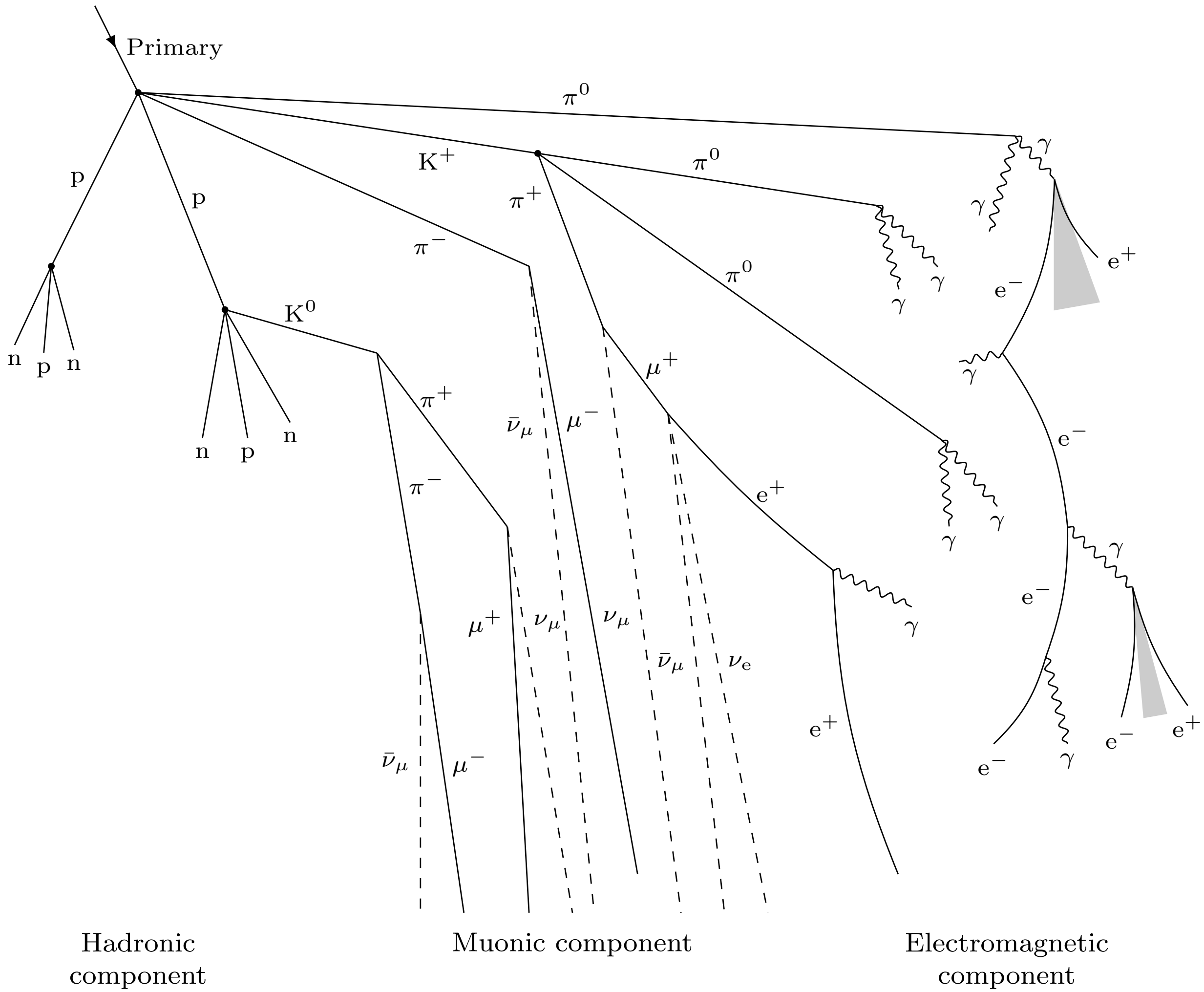
Basic idea, suggested already in the 1960s

- Particle showers create radio emission (see next slide)
- Radio waves are not attenuated in air/ice like light
- Radio antennas are cheap(er) than particle detectors
- One needs huge instrumented volumes to detect the low flux at the highest energies
- So measuring the radio emission of a shower sounds like a useful idea to instrument large volumes to detect air showers or neutrino induced showers

Radio signals

A theoretical introduction

- Highly energetic particles interact with medium and create shower of secondary particles
- Generally one distinguishes hadronic and electromagnetic showers
- Hadronic showers always have a electromagnetic component



Radio emission of particle showers

A theoretical introduction

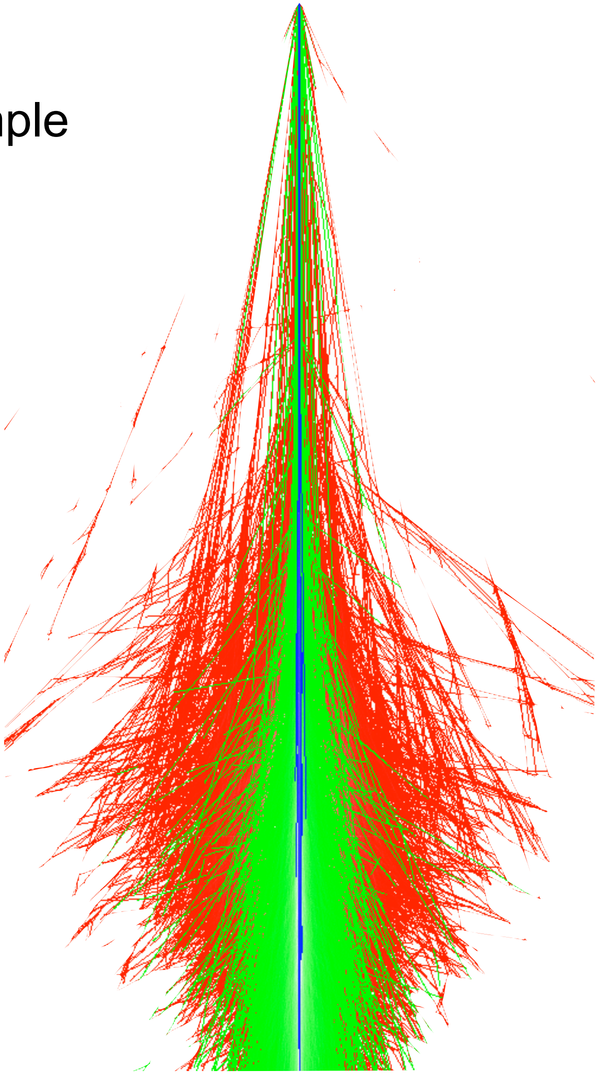
- Radio emission of showers can be explained from simple first principles

- Three ingredients:

  - **Magnetic field**
    (*Geomagnetic field, Lorentz-force*)

  - **Charge imbalance**
    (*Particle Physics processes*)

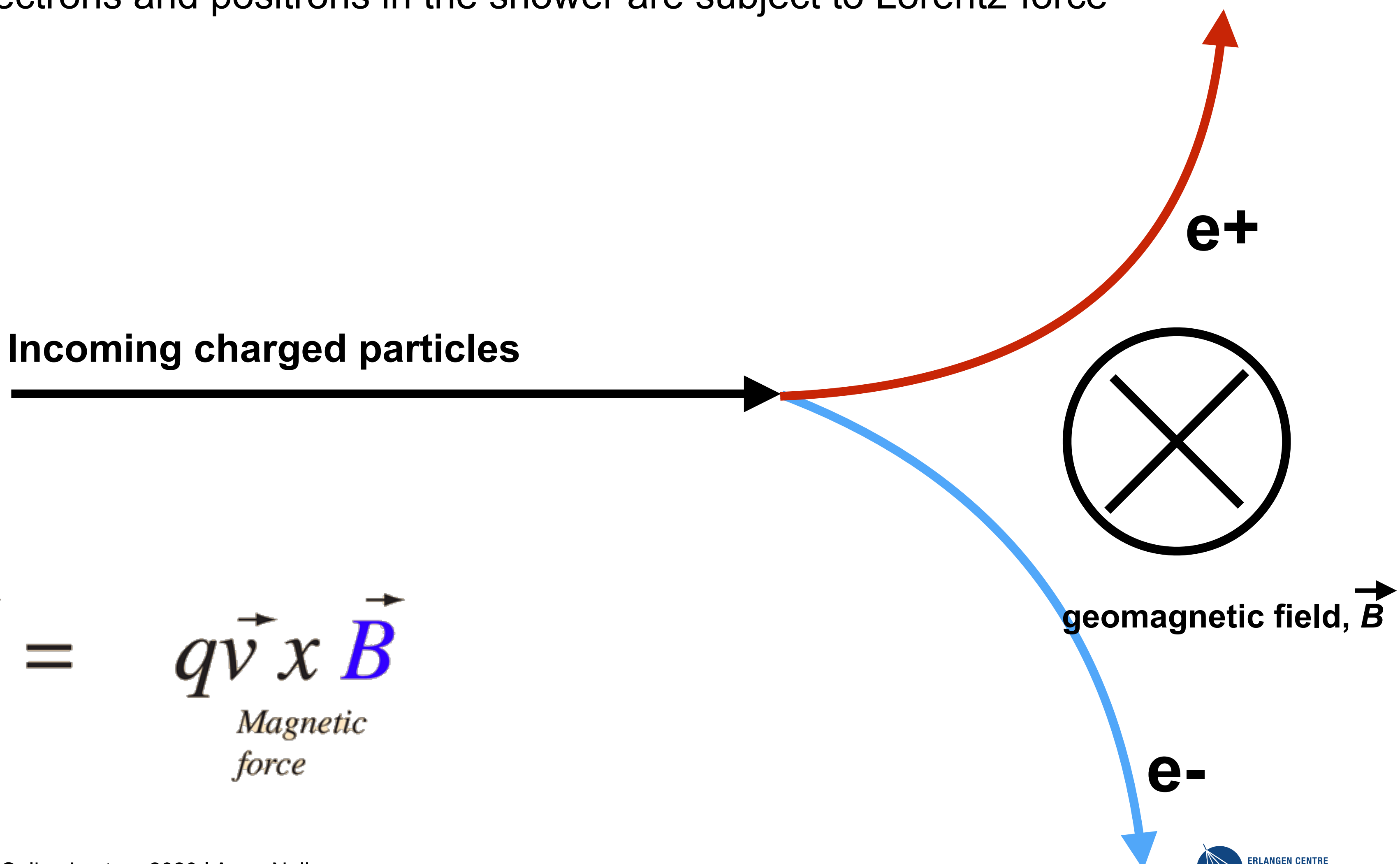
  - **Relativistic compression**
    (*Ray optics and relativity*)



Radio

Geomagnetic effect

- Electrons and positrons in the shower are subject to Lorentz-force



$$\vec{F} = q\vec{v} \; x \; \vec{B}$$

Magnetic force

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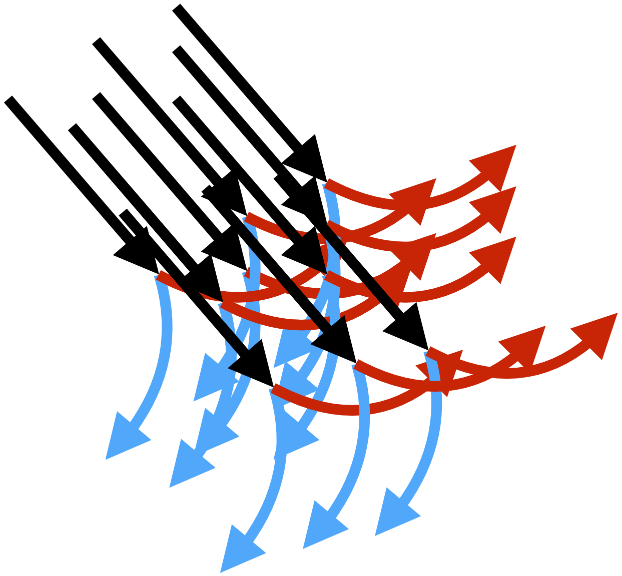
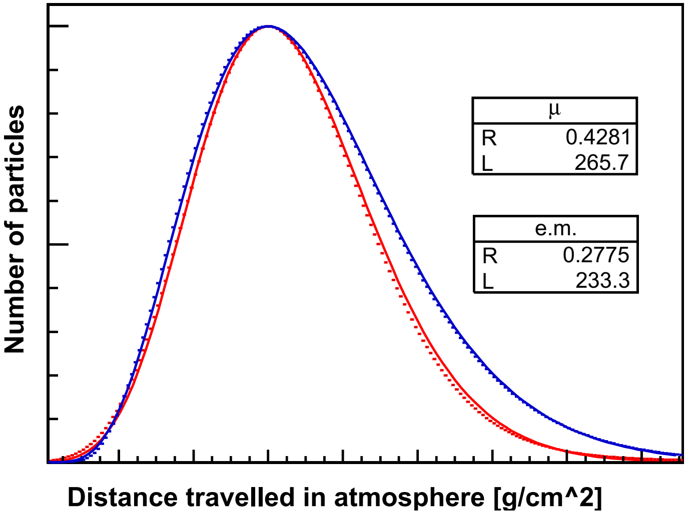
Radio

Geomagnetic effect

- In a shower: many particles
- Charge separation produces a current



- Number of particles is a function of height above ground



Radio

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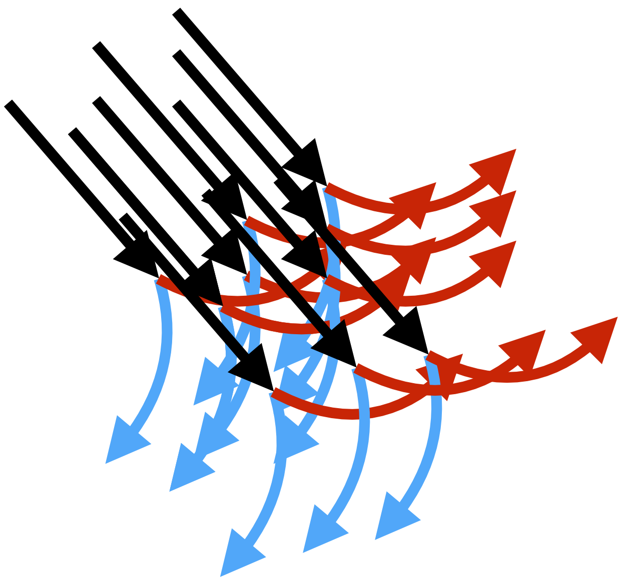

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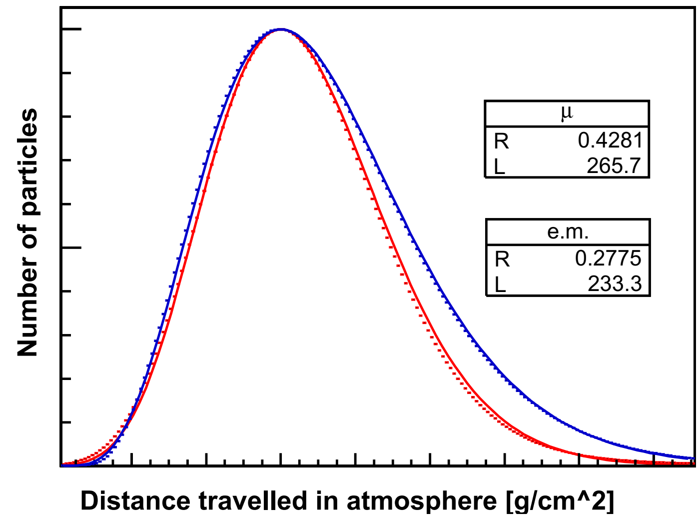
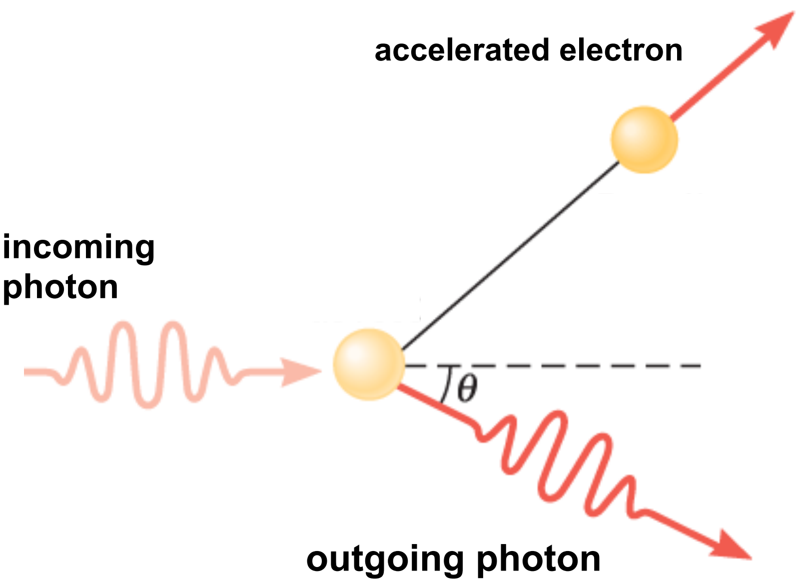


- The current changes as function of time/height
- A changing current causes electromagnetic emission

Radio emission of particle showers

Askaryan effect

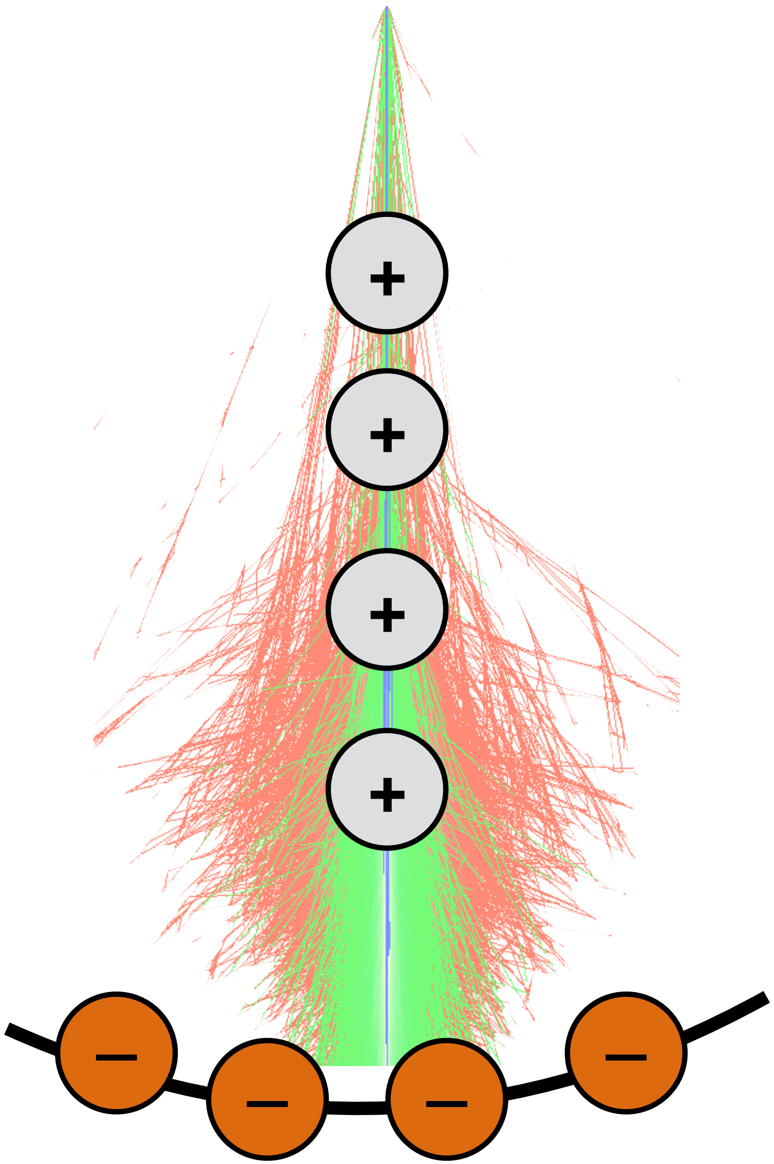
- Remember: numerous high energy photons, positrons electrons in shower
- In atmosphere: only electrons, no positrons
- Shower particles interact with particles in the atmosphere



Radio emission of particle showers

Askaryan effect

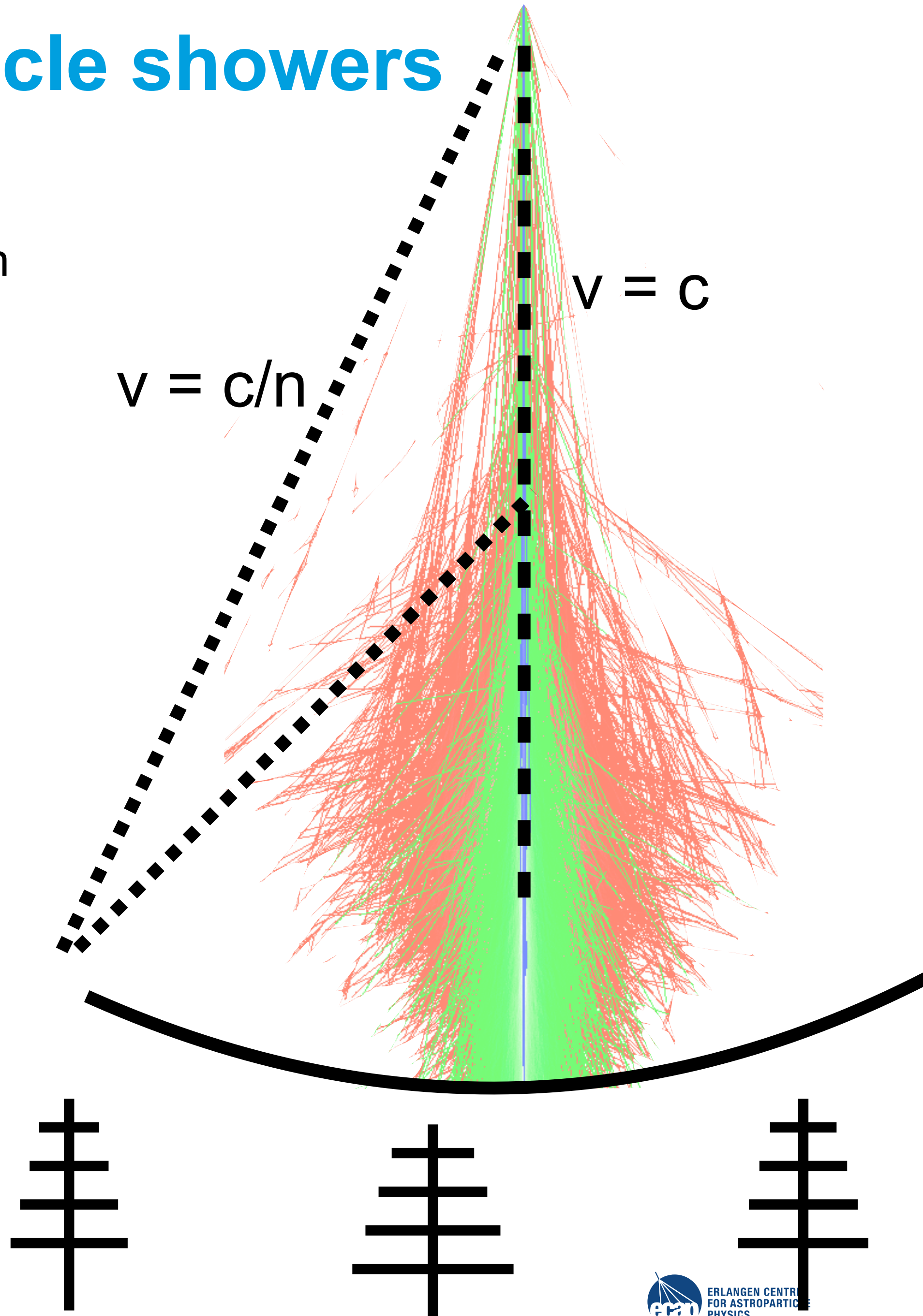
- Charge separation along axis
- Shower front is negative, axis positively charged
- Current along axis, changing as function of time/height
- Also here: changing current induces electric emission



Radio emission of particle showers

Cherenkov-like effects

- Shower is faster than its emission at n = 1.003



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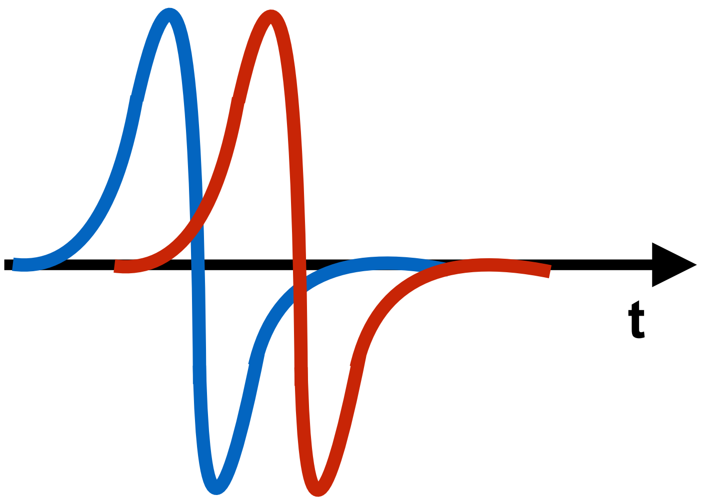
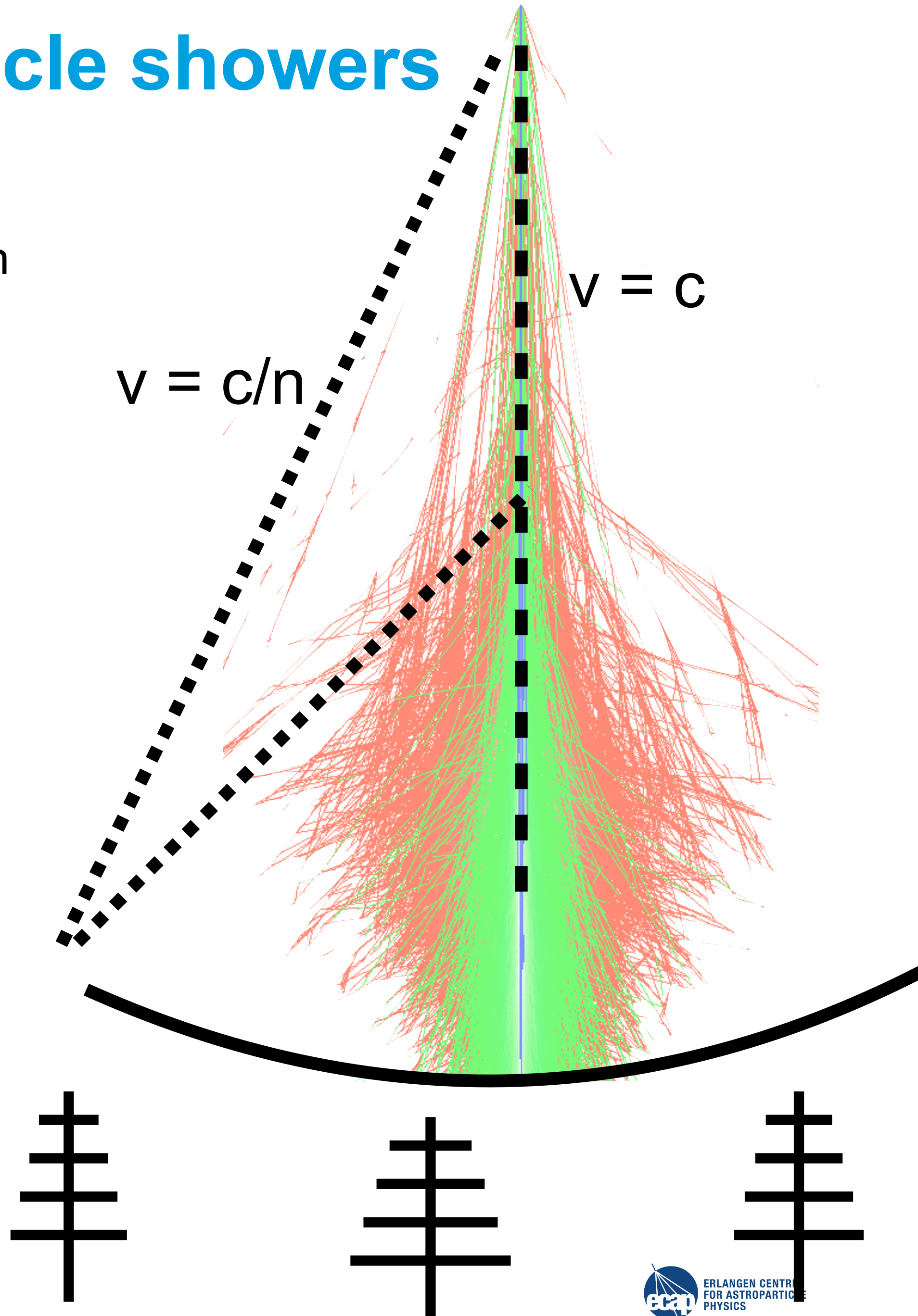


- Signal gets enhanced when it arrives in phase = coherence

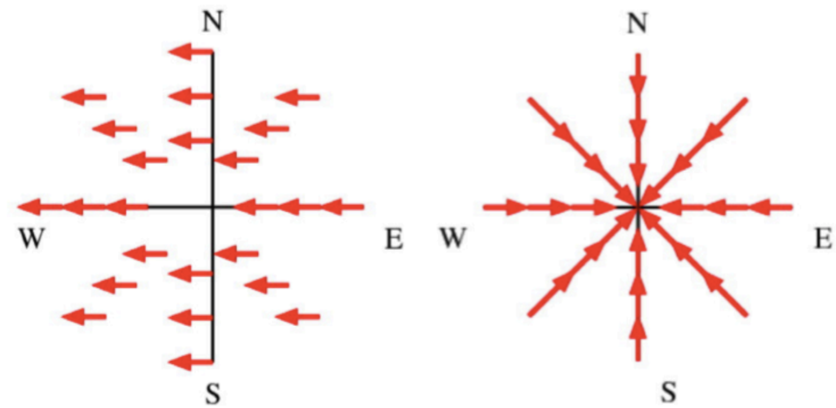
- Enhancement at the Cherenkov angle



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*



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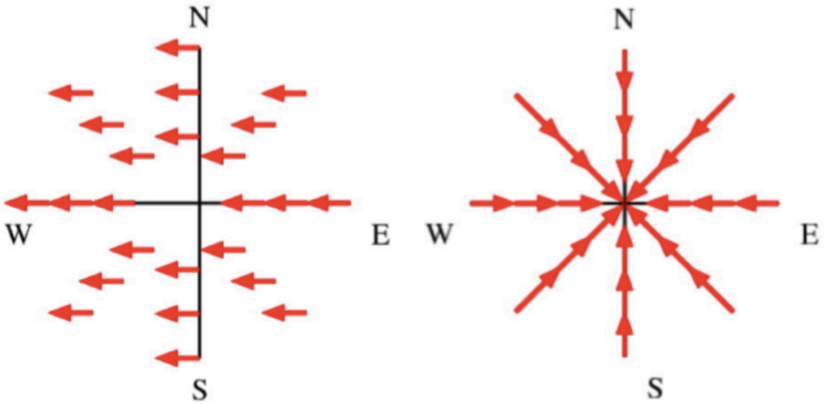
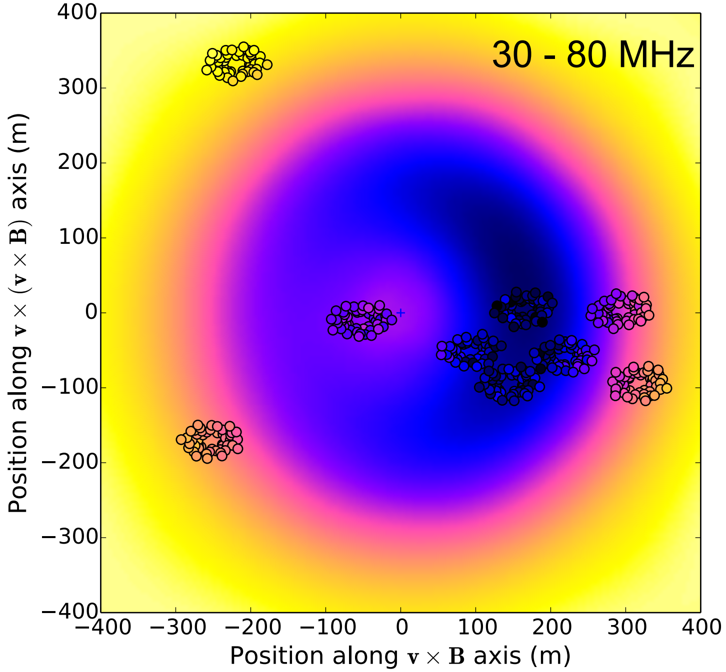
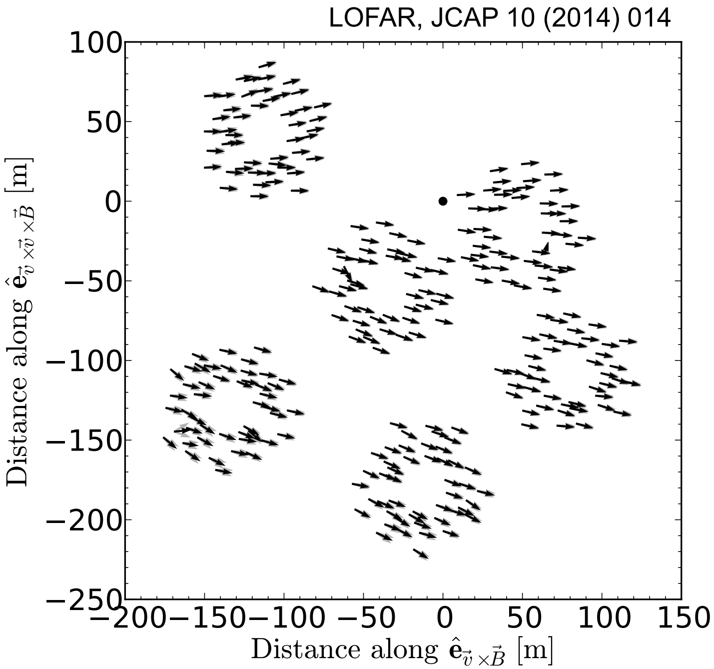






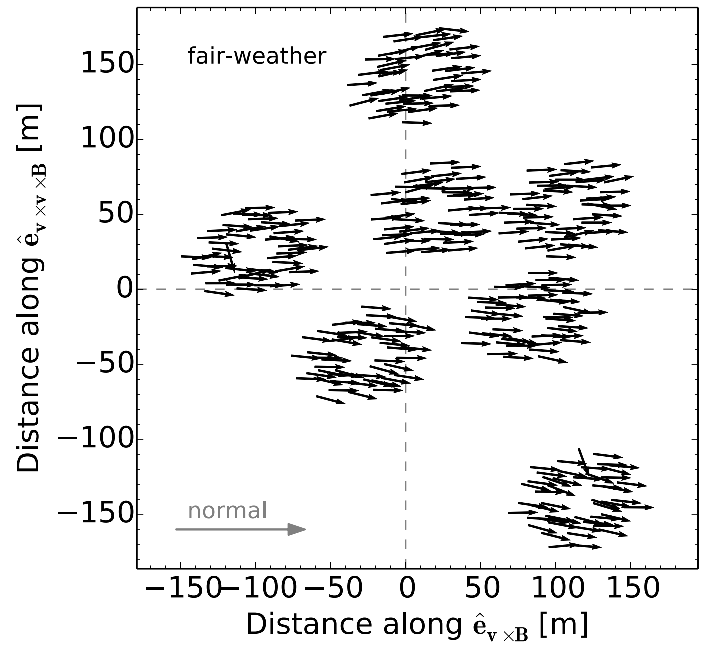
Radio emission of showers

How do we know this?

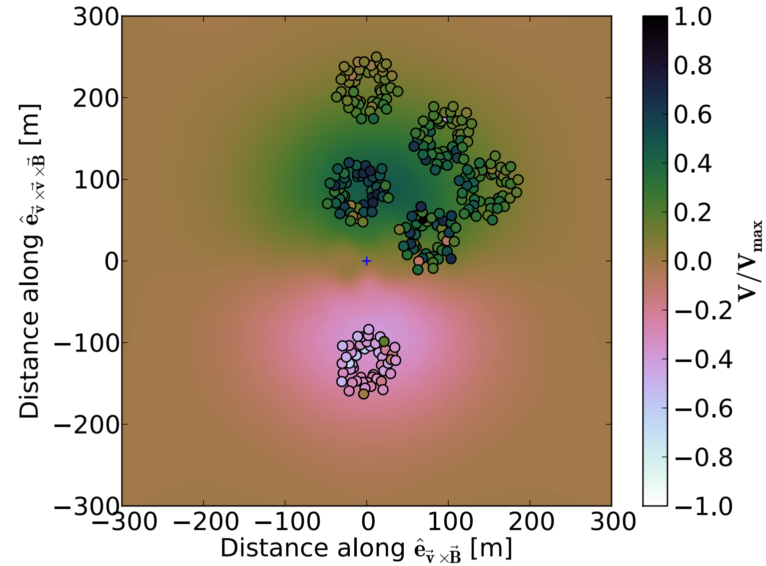
- Emission is due to **both geomagnetic emission** (dominant in air) and **Askaryan emission**

- **Pulse polarization follows geomagnetic effect and 15% charge excess correction**
  - The **two processes** stem from slightly different heights
  - Time difference = phase offset between two emission components
  - Leads to **circular polarization**

LOFAR, PRL 114, 165001 (2015)



LOFAR , Phys. Rev. D.94.103010

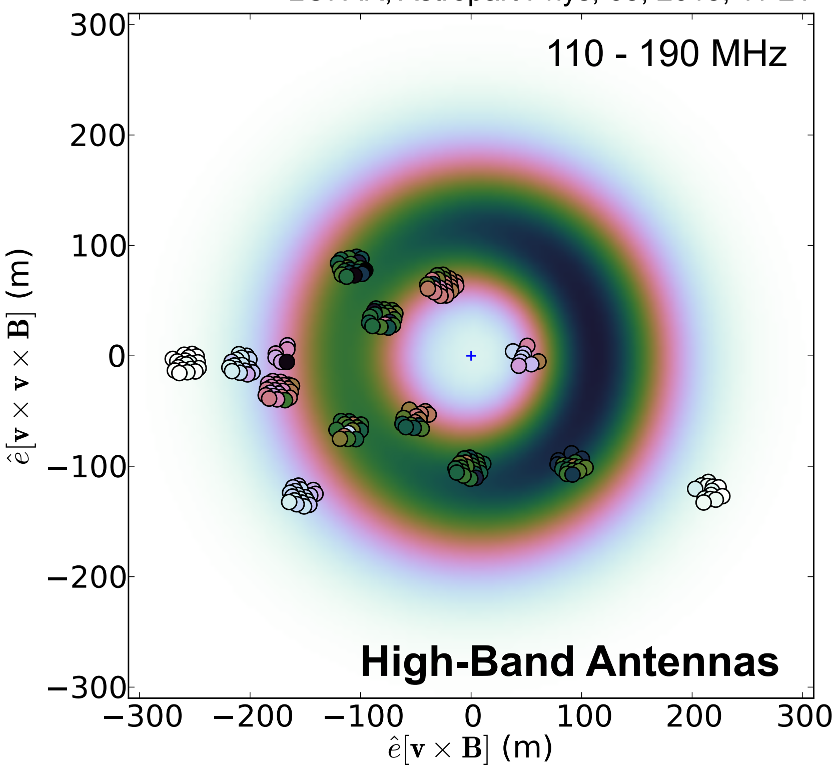


Radio emission of showers

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

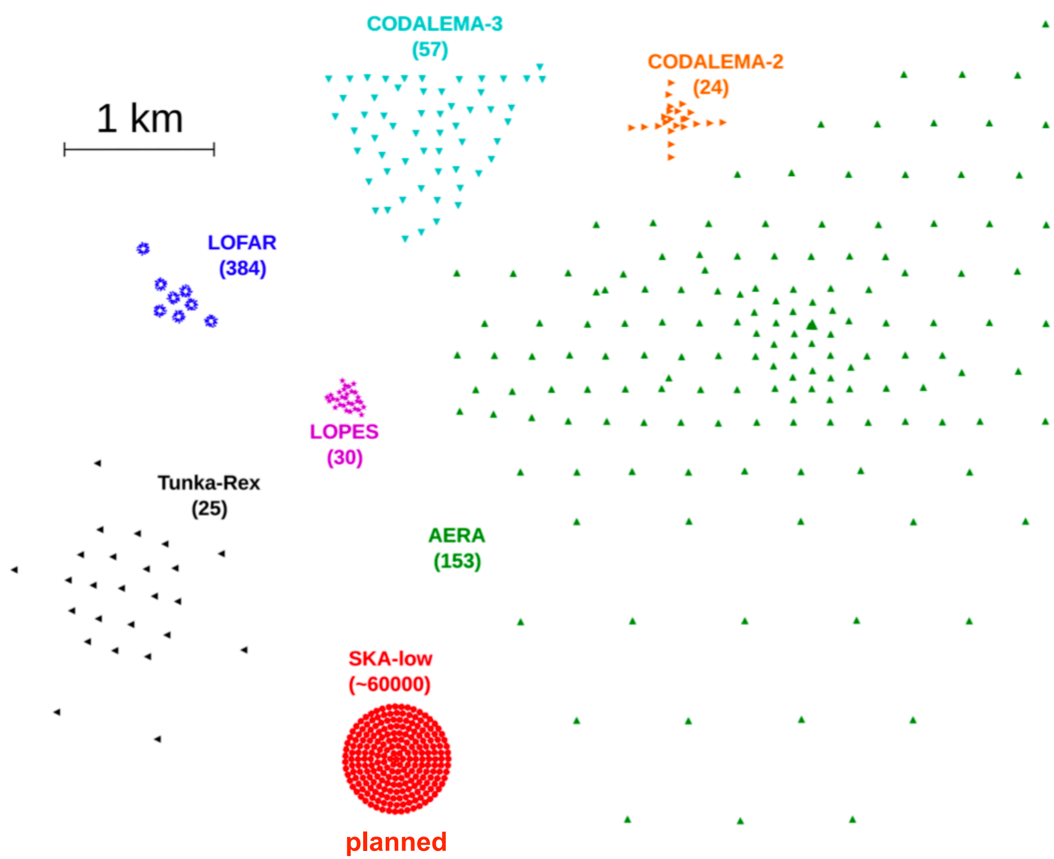


Detecting radio emission of air showers

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”
- Non-standard use of radio telescopes like LOFAR and SKA extremely successful

Figure: Huege 2016

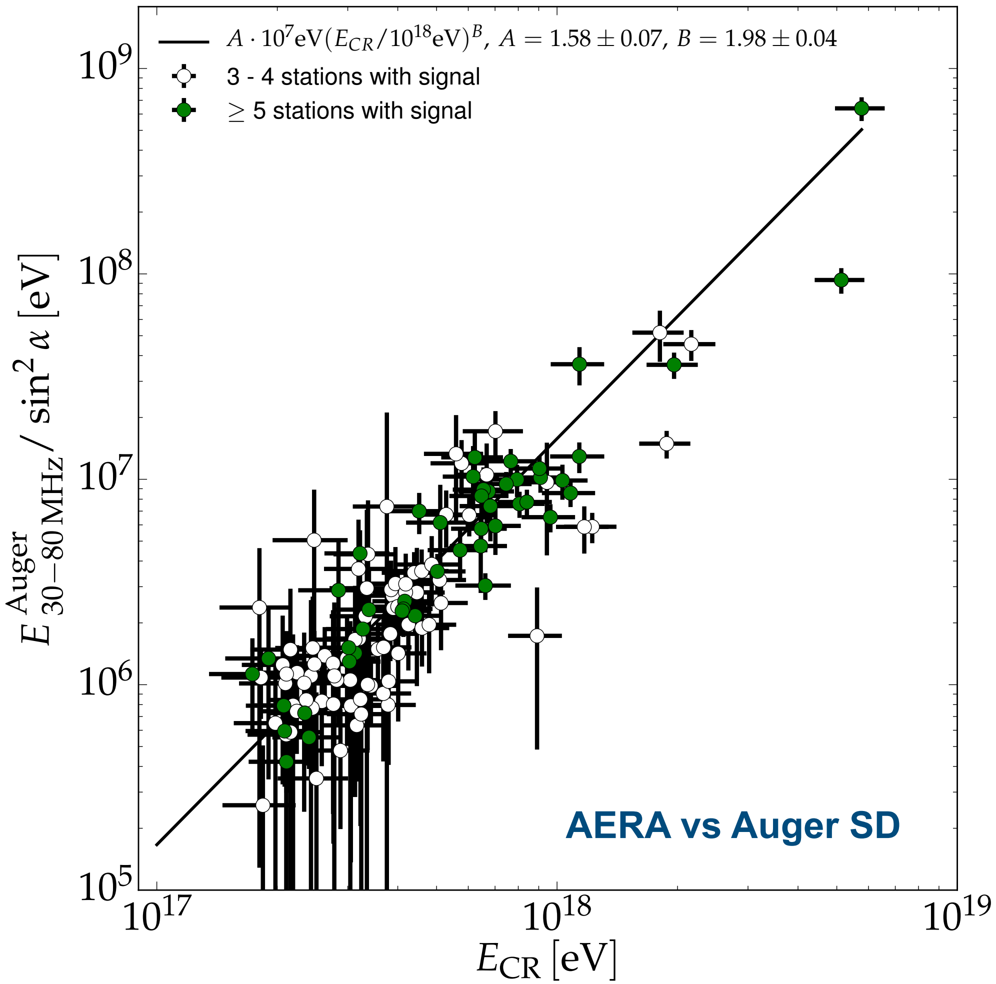


+neutrino detectors in ice
ARIANNA, ARA, IceTop, ..
+ANITA balloon

Detecting radio emission of air showers

What is in it for the science?

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



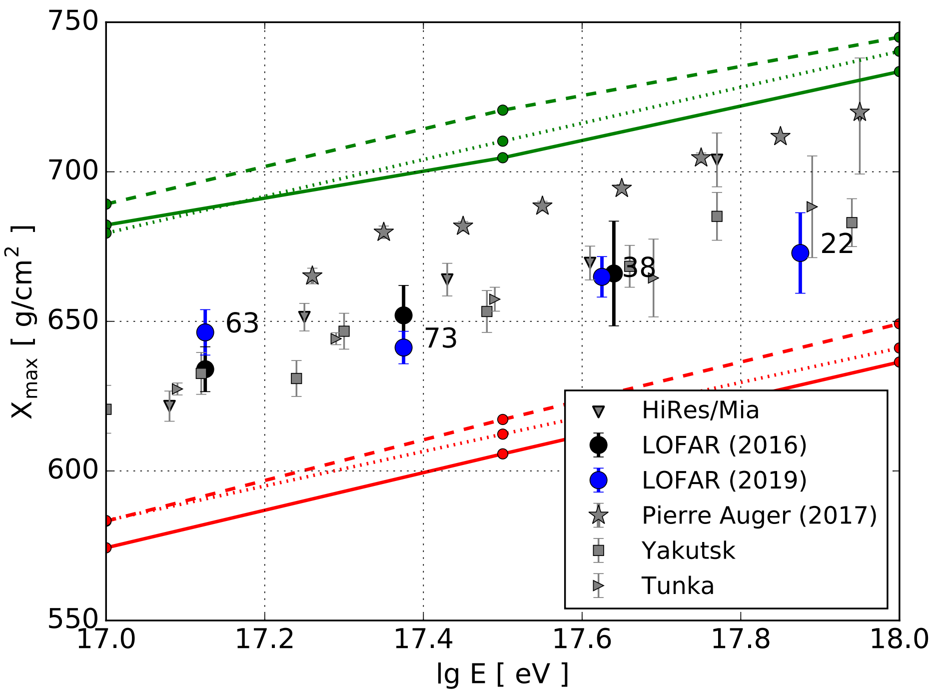
- Radio detection provides and excellent **energy estimator**
- **Coherent effect = pulse amplitude scales linearly with energy**
- This plot: proxy for pulse power on the y-axis
- Calculation from first principles
- Very little systematic uncertainties (< 5%) in method

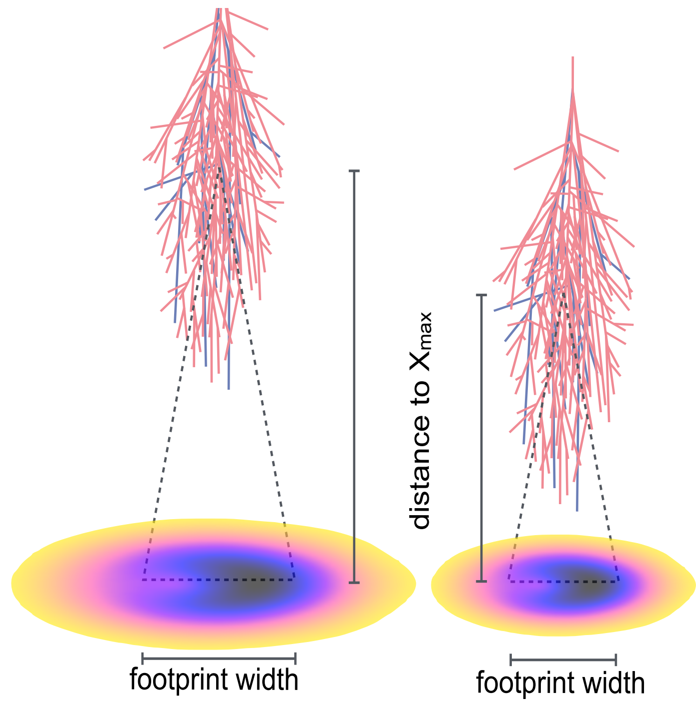
Detecting radio emission of air showers

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





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

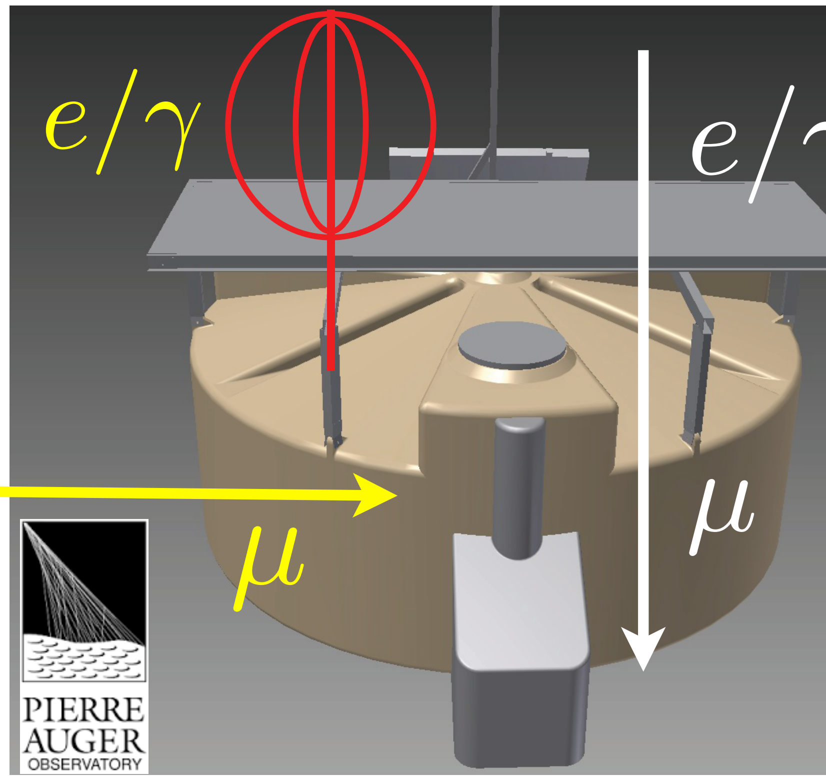
Radio detection of air showers

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

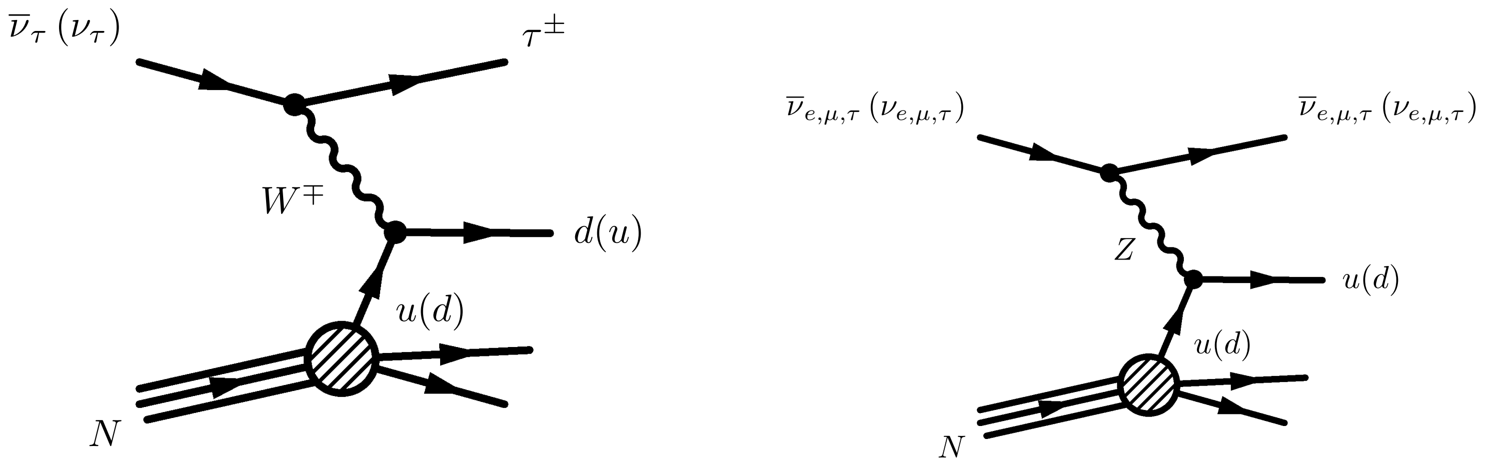
Equip ALL 1660 Water-Cherenkov tanks with radio antennas



in practice: different response to both components in both detectors: response matrix

Radio detection of neutrinos

No one has ever done this before

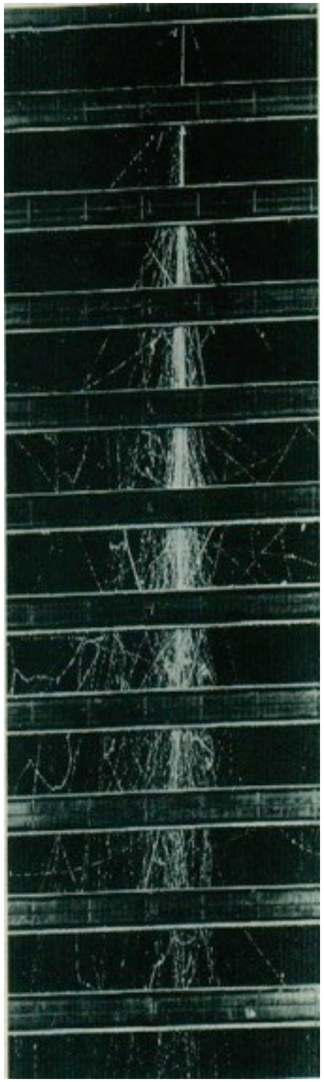


- Both charge current and neutral current interactions create “cascades”
- For radio emission: A shower in a dense medium also creates radio emission
- However: shower much shorter than in air
    - Short travel time in geomagnetic field
    - Larger charge excess in the shower front

Radio detection of showers in dense media

Seems to work as expected

- A shower from a neutrino interaction is subject to same emission mechanisms
- BUT: Showers shorter in ice, so reduced influence of geomagnetic field and enhanced charge excess
- Emission confirmed in accelerator experiments at SLAC, for both no magnetic field (Phys. Rev. D 72(2005)023002) and with magnetic field (PRL 116(2016)141103)
- **Simulations predict measurable neutrino signal > 10^{16} eV in radio above "normal" backgrounds**
- First detection of neutrino radio signal still to be done

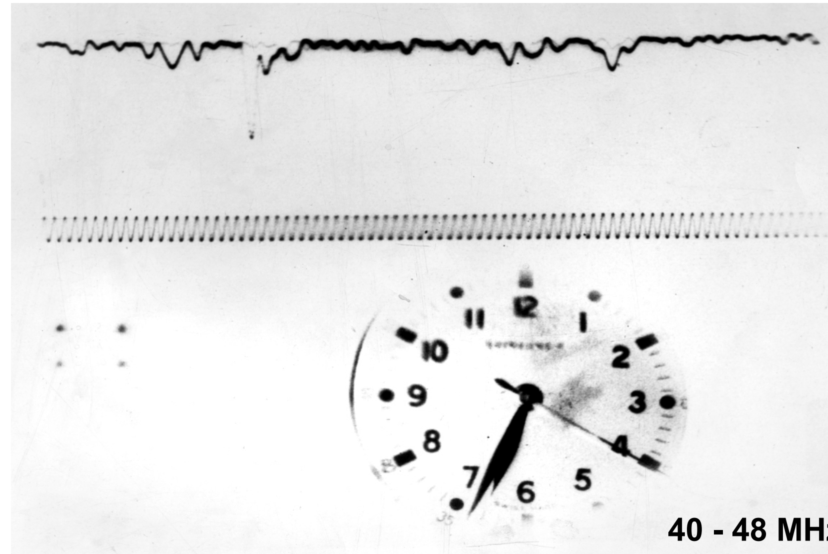


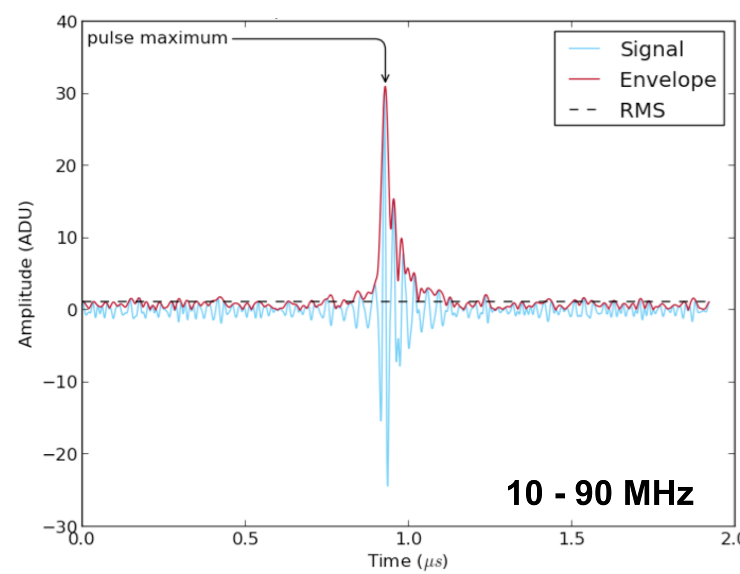
Detecting radio emission of air showers

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

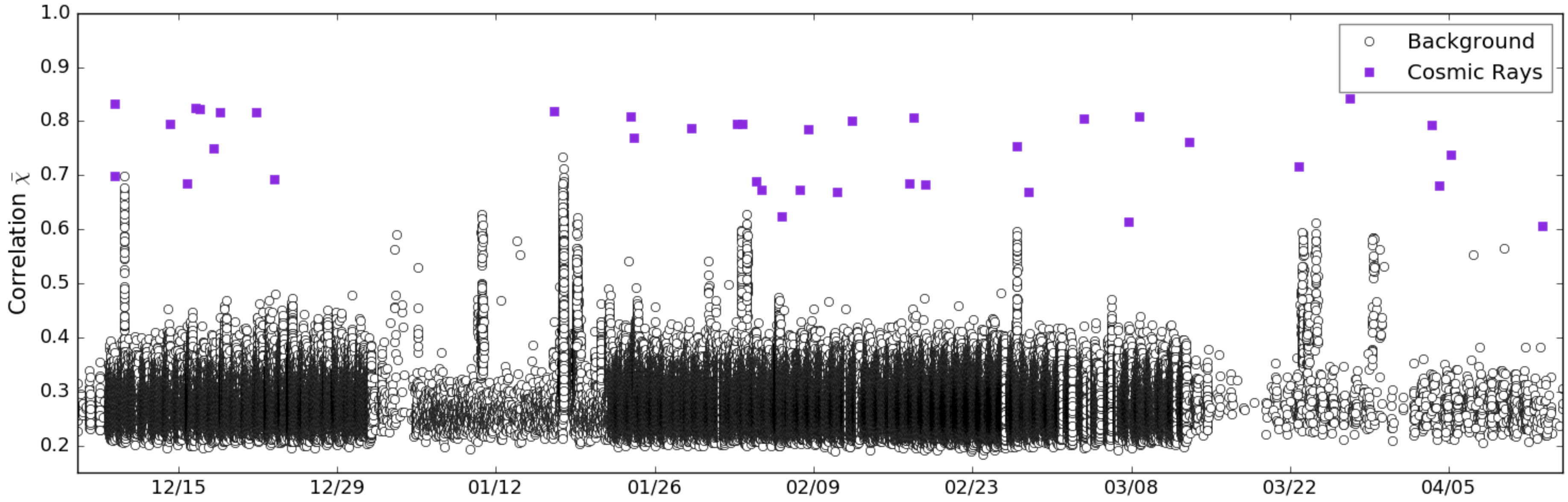


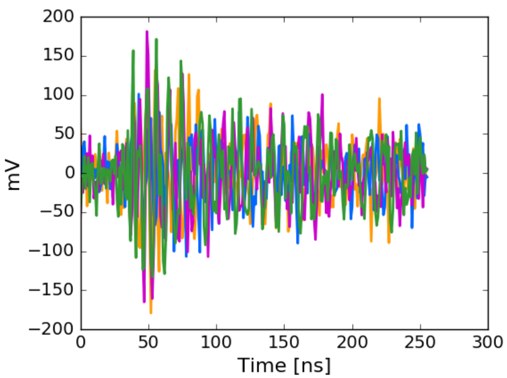


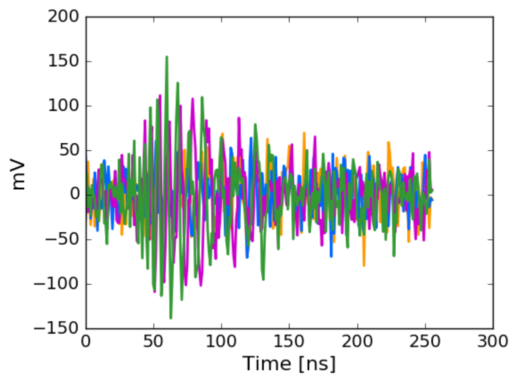
Detecting radio emission of air showers

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

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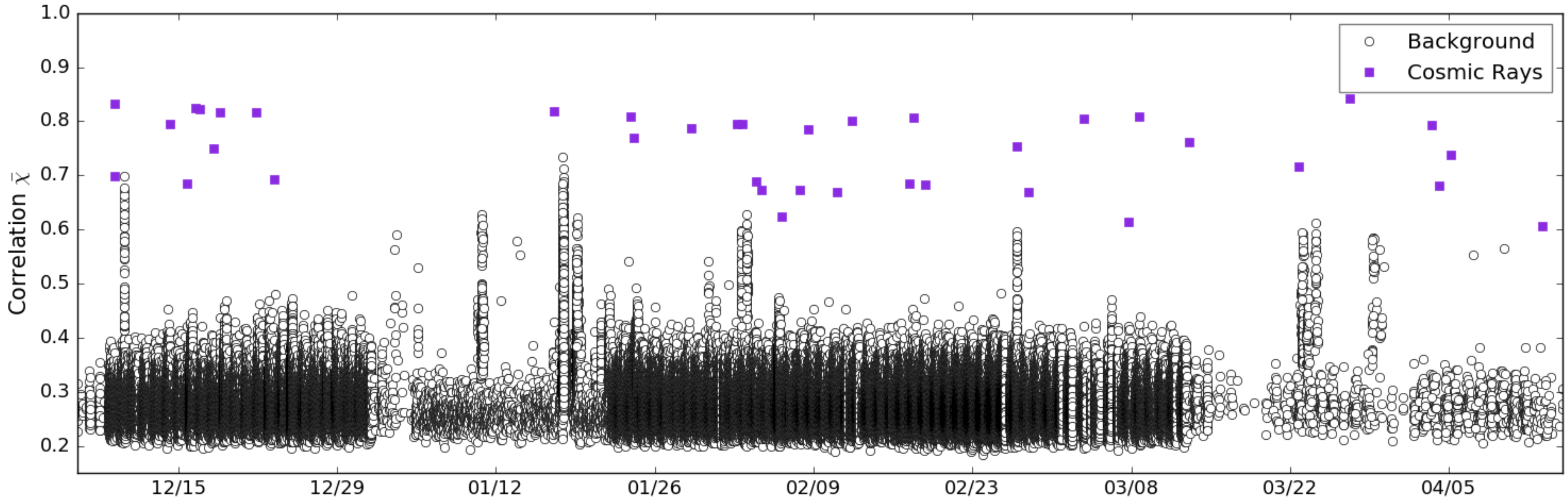

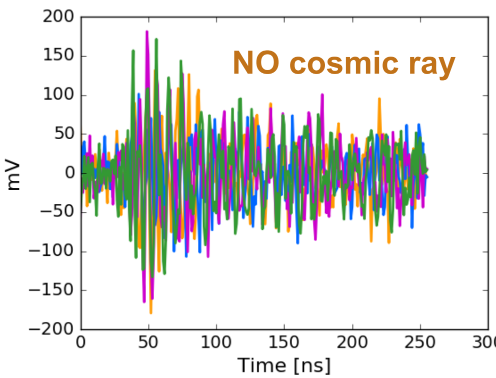

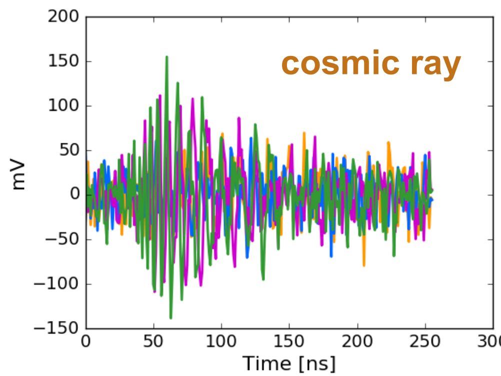

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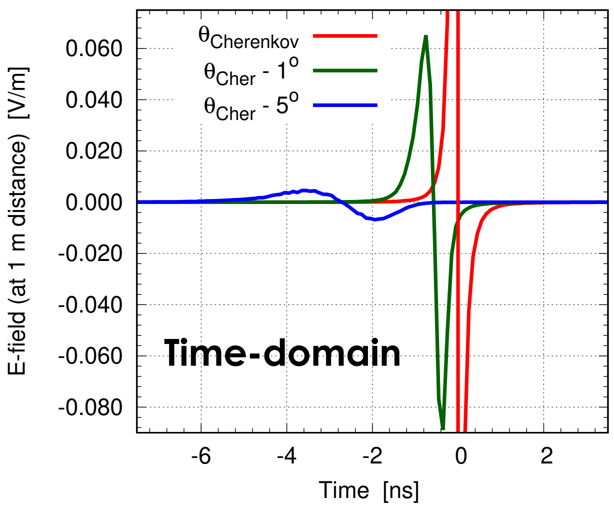
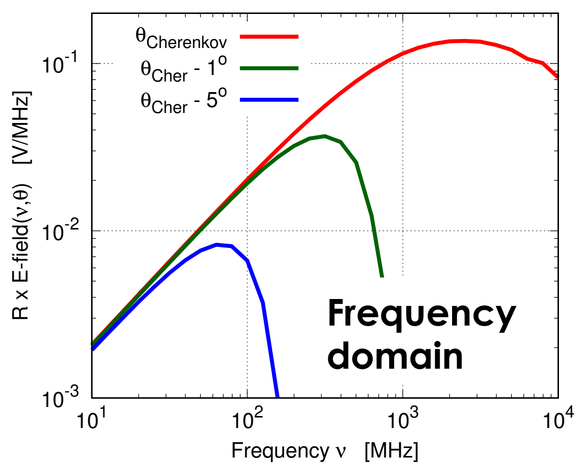
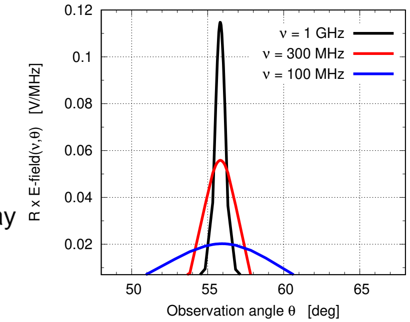
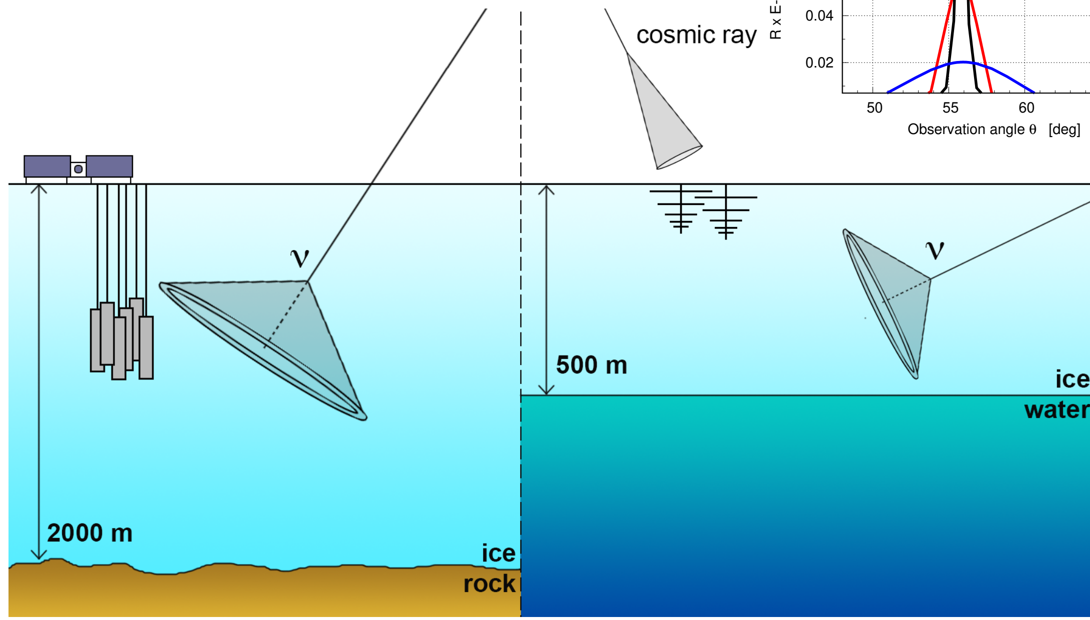
Radio detection in ice

Different concepts for the same case









- Short nano-second scale broad-band pulse
- Amplitude scales with energy of neutrino

Radio detection of neutrinos

Neutrino interactions in ice

- One can also fly a balloon above the ice to detect neutrinos
- ANITA is probably the experiment with the most news coverage of the radio community

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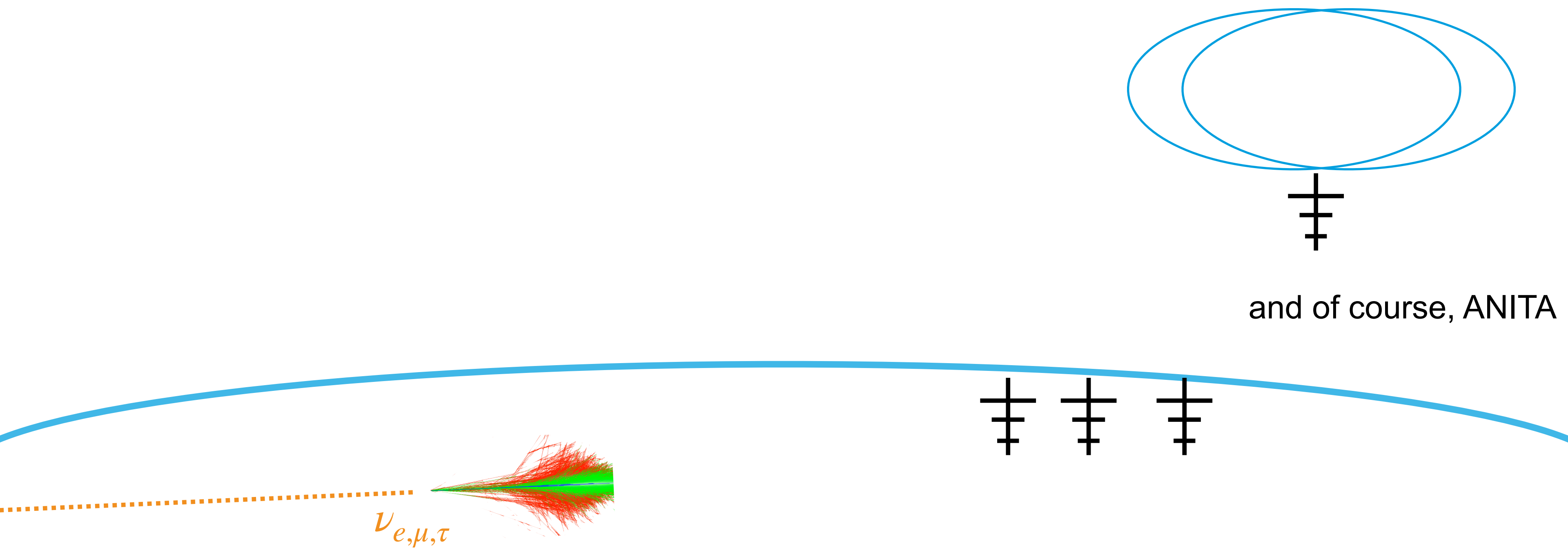

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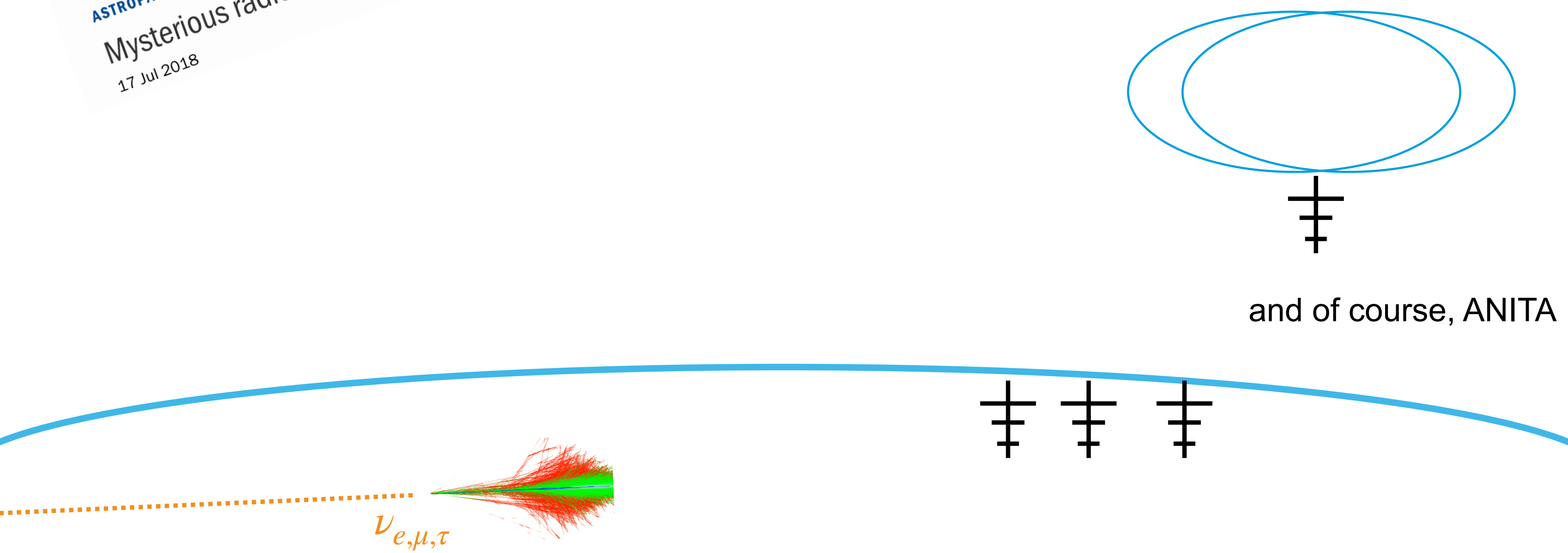
ASTROPARTICLE PHYSICS | RESEARCH UPDATE

Mysterious radio signals could be from new type of neutrino

17 Jul 2018



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ASTROPARTICLE PHYSICS | RESEARCH UPDATE

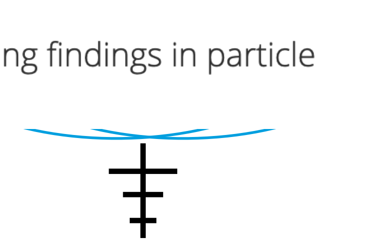
Mysterious radio signals could be from new type of neutrino

17 Jul 2018

Strange ice formations may have tricked physicists into seeing mysterious particles that weren't there

By Rafi Letzter - Staff Writer May 23, 2020

What if one of the strangest, most unsettling findings in particle physics turned out to be an illusion?



and of course, ANITA

Radio detection of neutrinos

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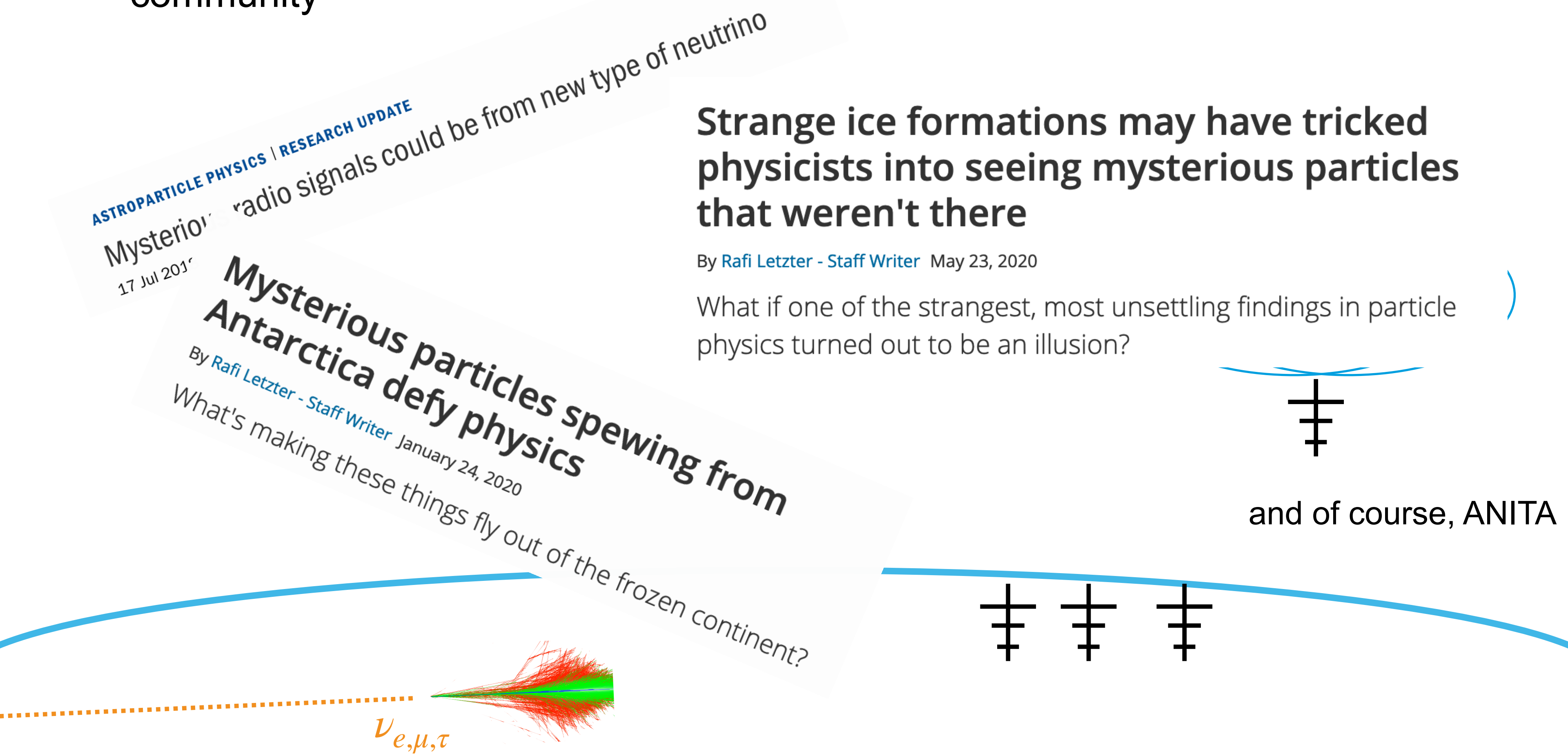
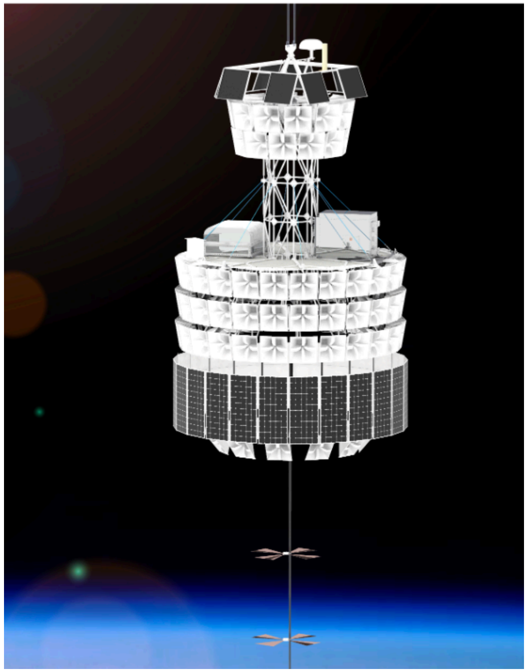


Radio detection of neutrinos

The above ice results

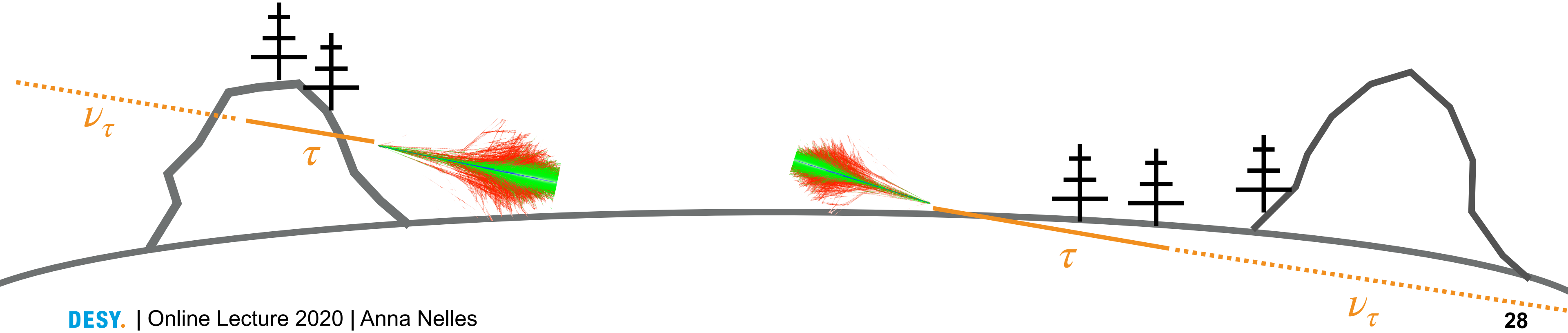
- ANITA I-III: Mystery events — behave like cosmic ray signals, but show signal polarization/polarity like neutrino from deep trough Earth
  - If truly neutrino: disagreement with IceCube limits, difficult to reconcile with Standard Model
  - Other explanations offered: ice, background, etc.
  - ANITA IV: again 4 events with inconsistent polarity, but near horizon, nothing 'mysteriously' steep arXiv:2008.05690
  - Follow-up experiment will fly in 2024 with better low energy sensitivity and more exposure: PUEO balloon arXiv:2010.02892
  - Hopefully we can then put the mystery rest



Radio detection of neutrinos

Tau neutrinos emerging from the Earth

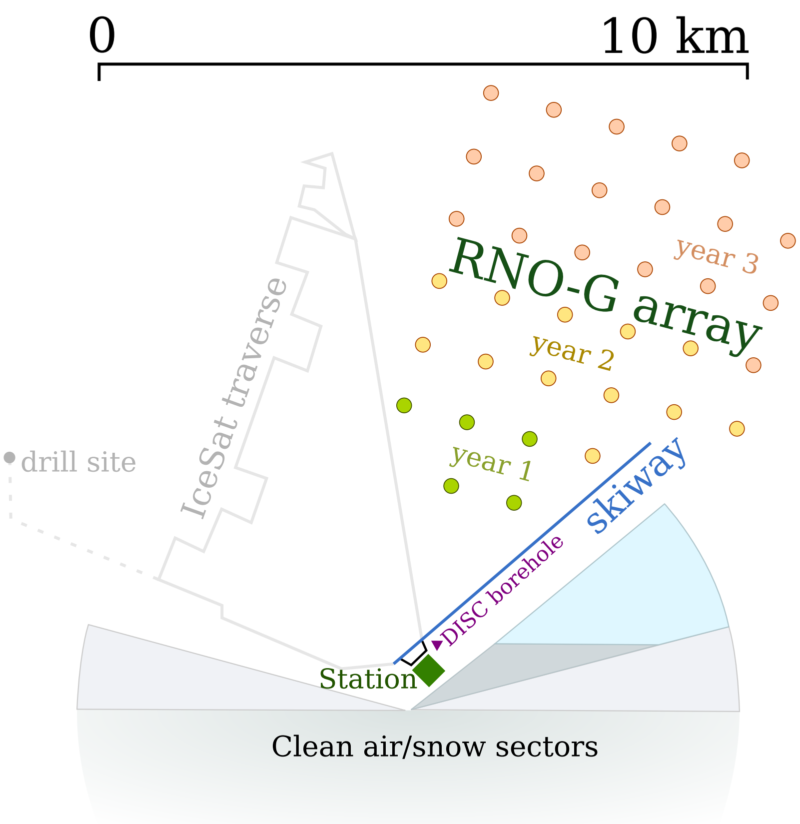
- Looking at tau's emerging from the Earth, creates large effective volumes for neutrinos, radio emission is (almost) not attenuated in air
- Radio detectors probably most effective, when they use mountainous terrain
- Have to exploit economies of scale for very cheap antenna stations
- Largest challenge: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

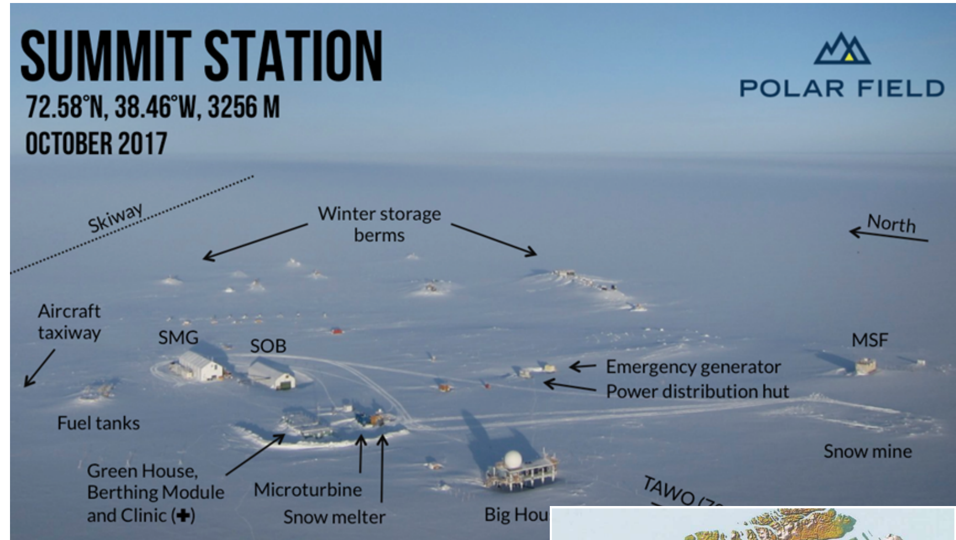


Radio detection of neutrinos

One particular highlight

Radio Neutrino Observatory

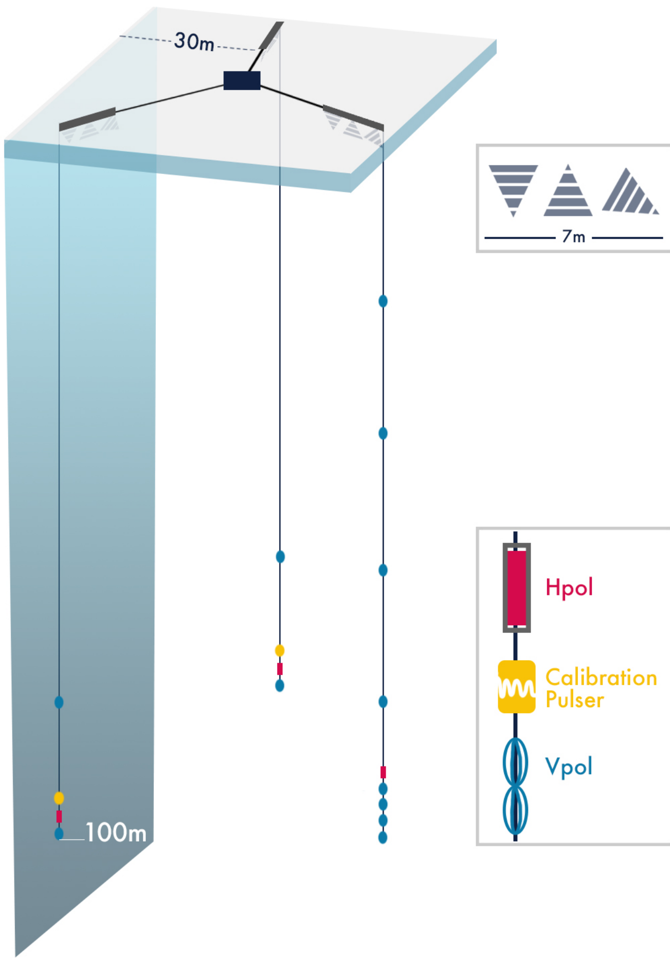




- After lots of proof-of principle experiments: first scale-up to large array

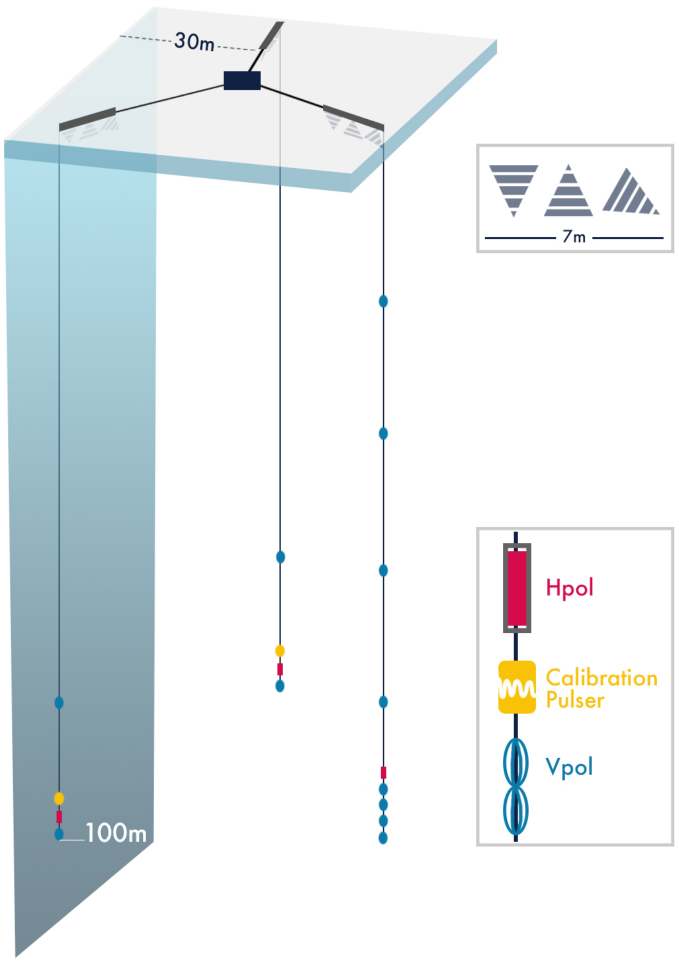
The RNO-G approach

What will be built



The RNO-G approach

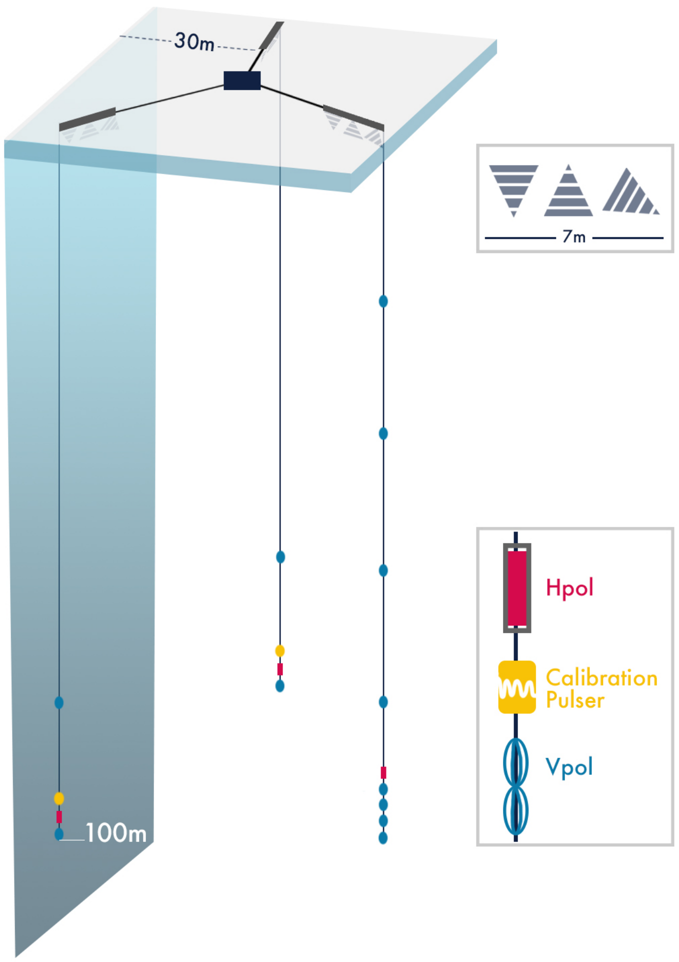
The single components



- Log-periodic dipole antennas (**LPDA**) at the surface:
- High-gain antennas with very good response to neutrino signals, but too big to fit in a hole
- At the surface subject to ray-bending = not all trajectories reach these antennas
- Antennas at the surface also act as cosmic ray veto
- 3x3 antennas to detect all arrival directions and polarizations

The RNO-G approach

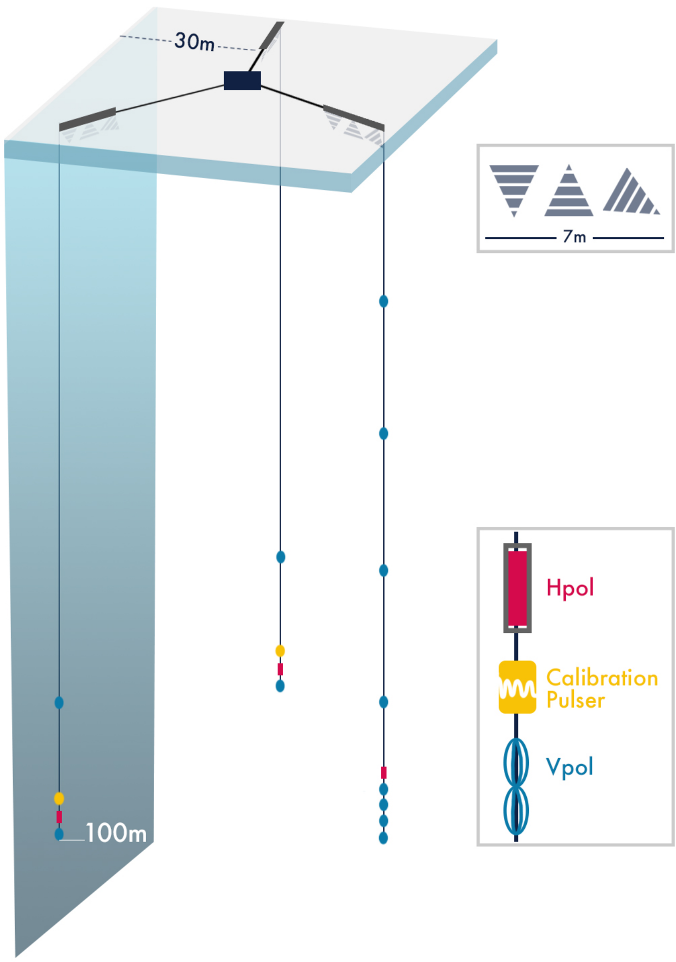
The single components



- Bicone antennas and quad-slot antennas in 100 meter deep holes
- the deeper the better (ray shadowing)
- 100 meters achievable with a fast mechanical drill (cheap)
- two different types of antennas to cover all polarizations
- small antennas have less gain and are typically less broad-band

The RNO-G approach

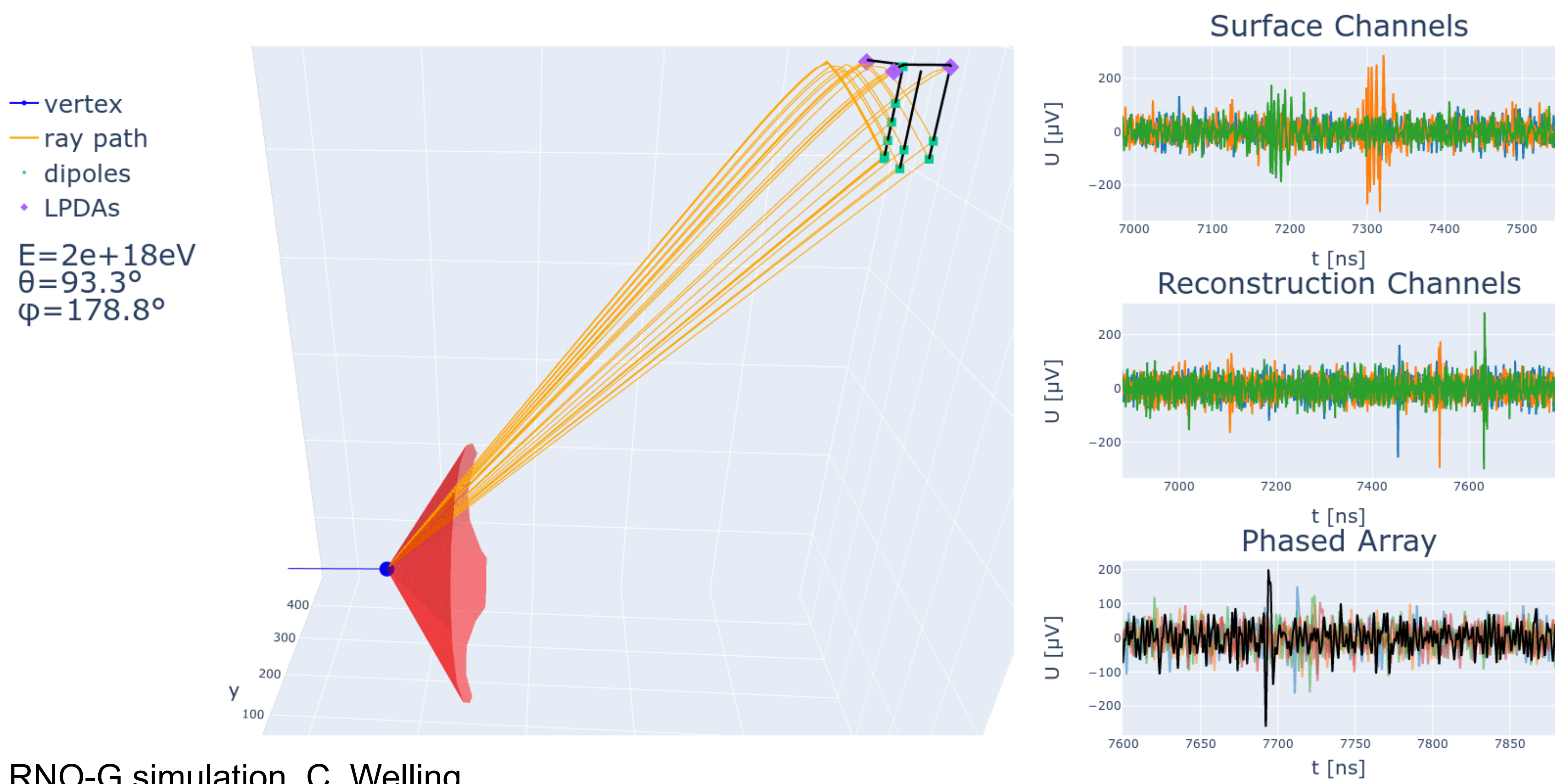
The single components



- Station geometry:
- Three strings to reconstruct arrival direction
- One string with many antennas to make the reconstruction of the vertex distance a one-dimensional problem
- String also hosts the phased array trigger
- The lower the threshold the better the sensitivity

The RNO-G approach

What do the signals look like

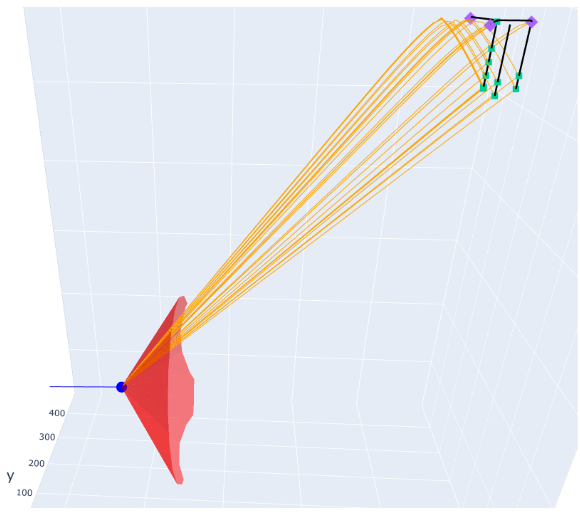


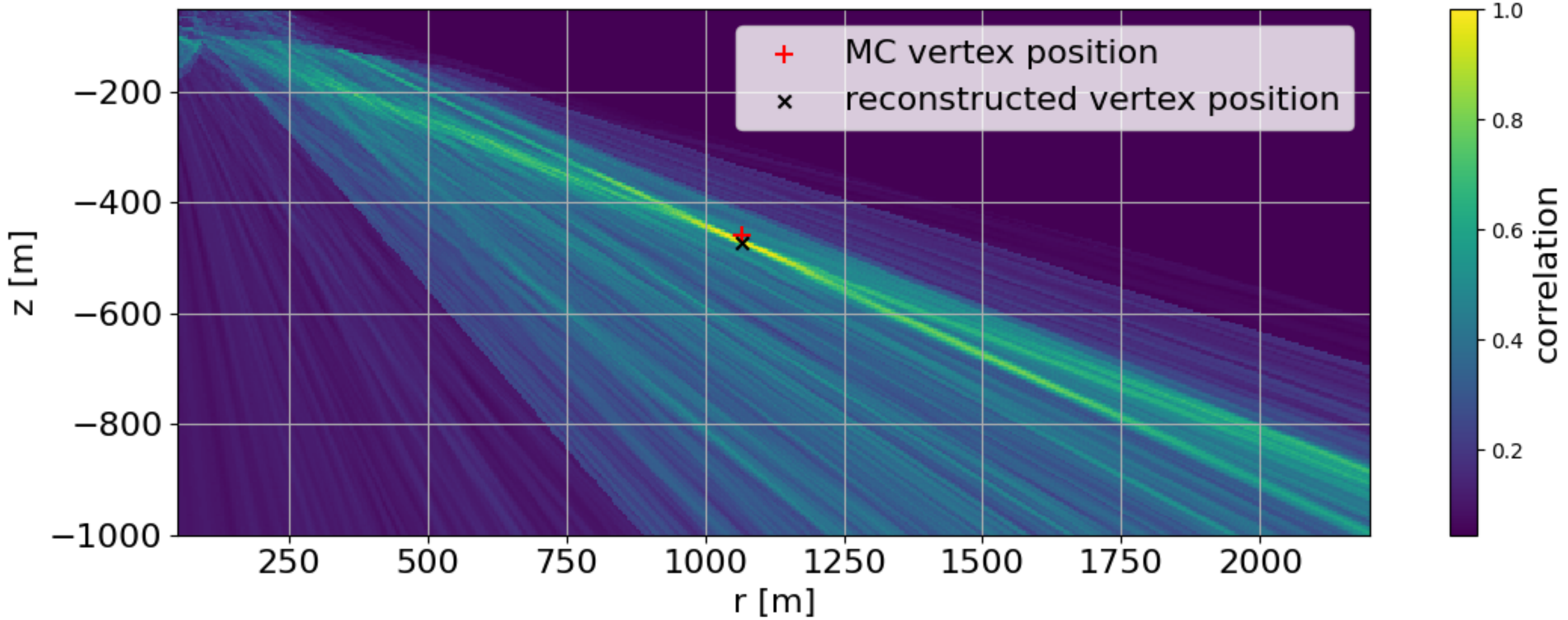
Full RNO-G simulation, C. Welling

Software development:
Always make nice visualization tools, increases the number of users

The RNO-G approach

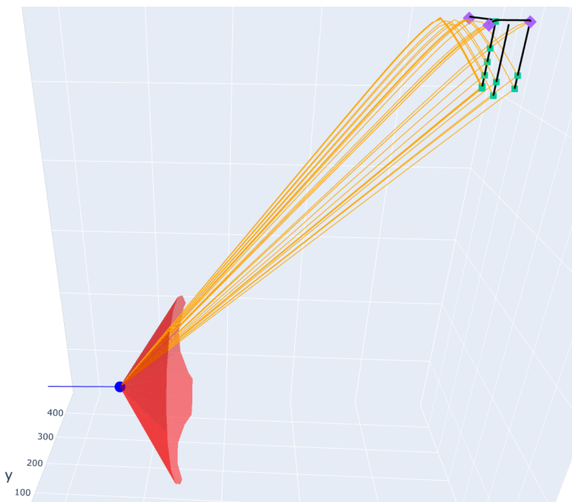
Excursus: How does one reconstruct this?

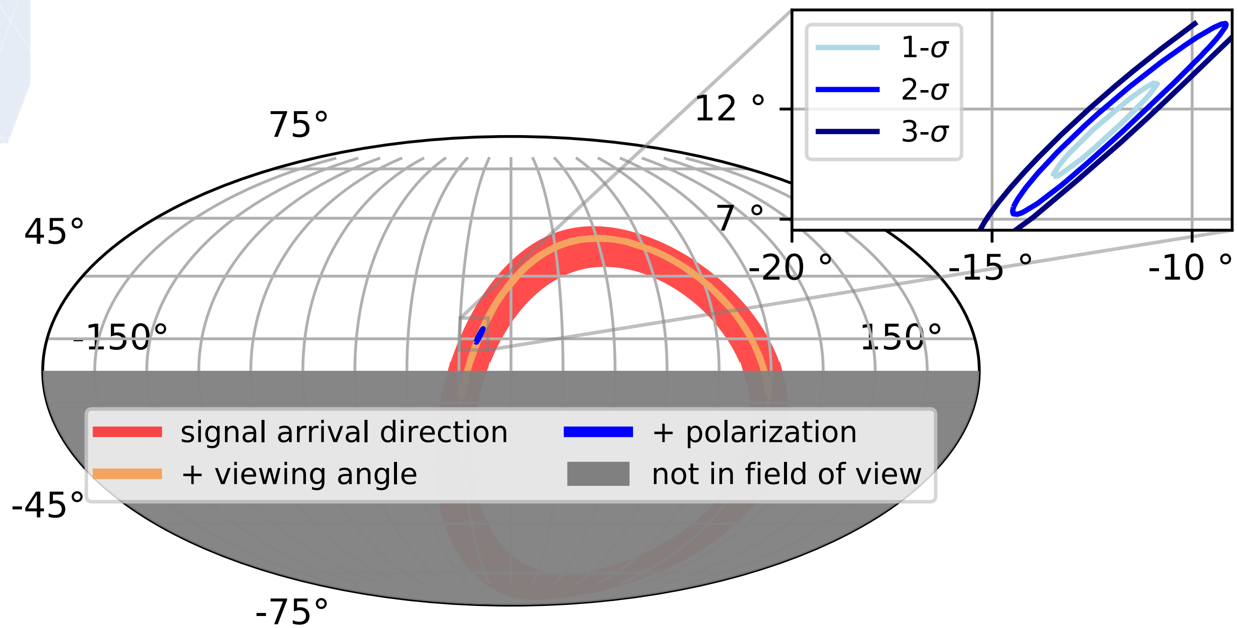




The RNO-G approach

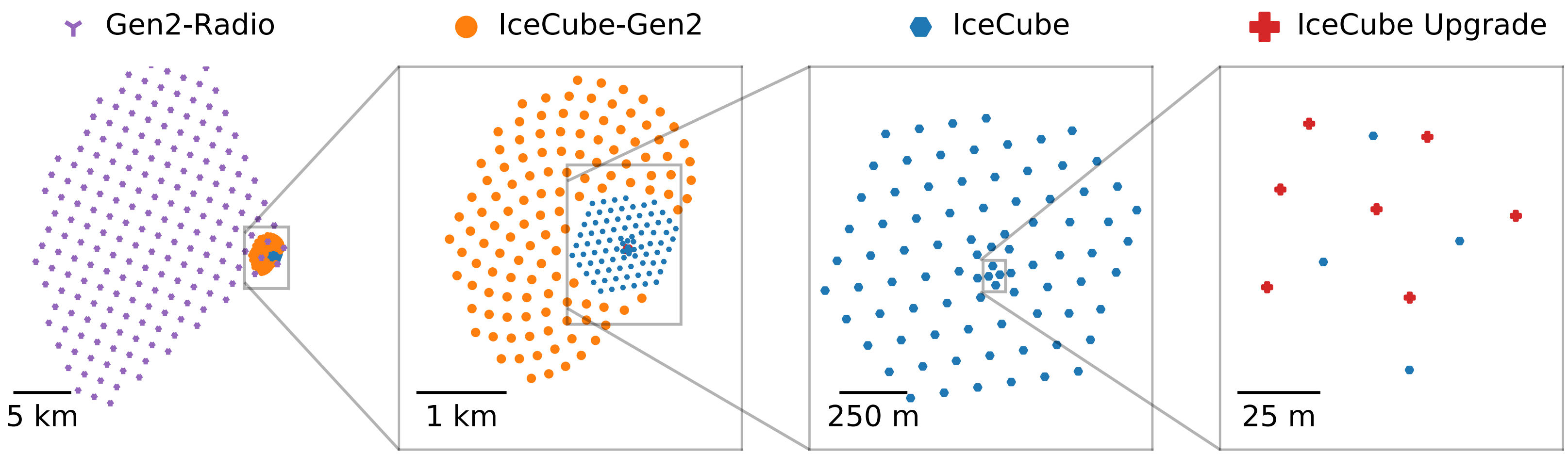
Excursus: How does one reconstruct this?





The long-term plan

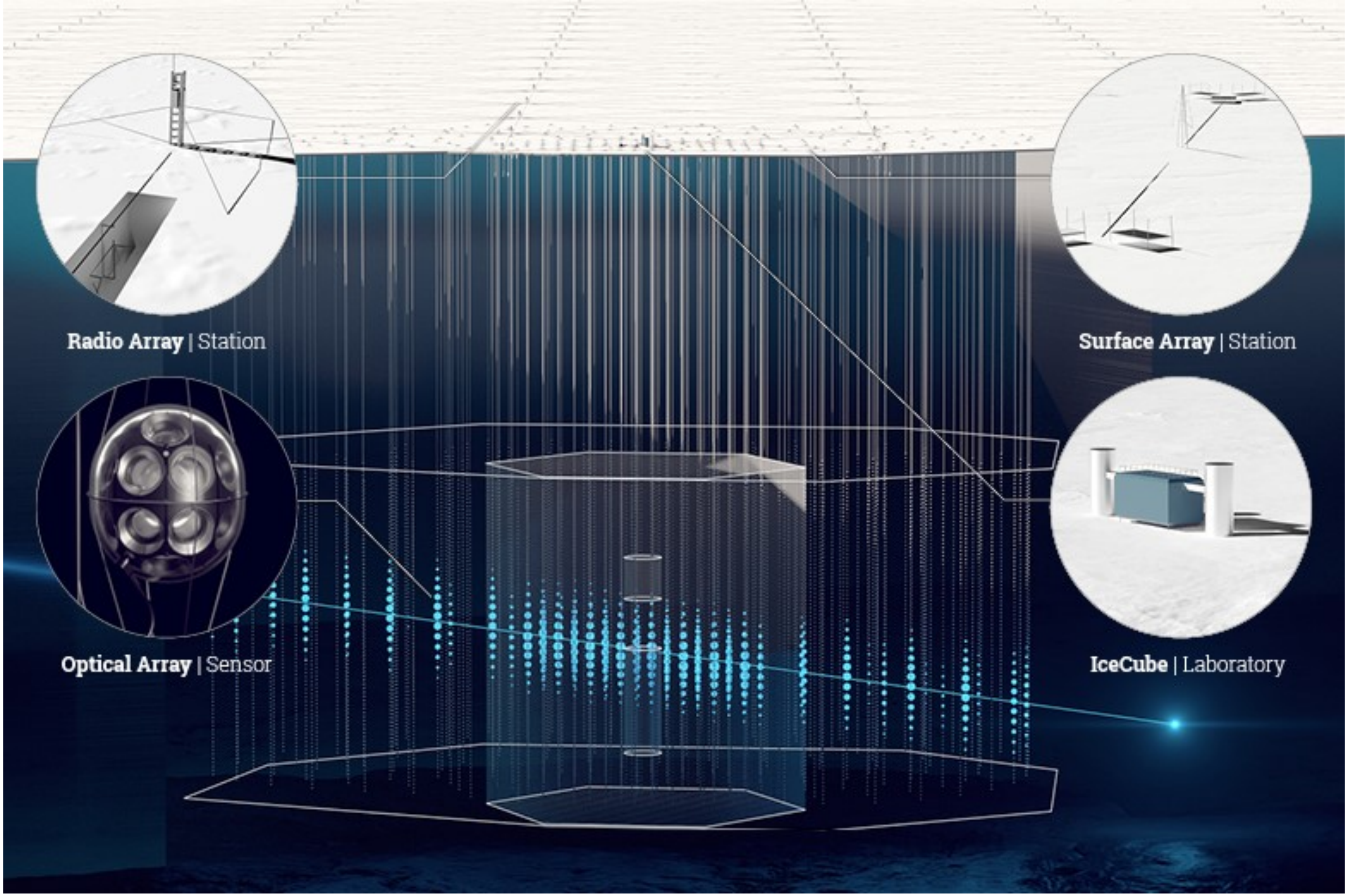
What after we are done with RNO-G



- Beyond 2024 the Gen2 Collaboration is planning to build IceCube-Gen2 at South Pole
- NSF lead project with major contributions from International Partners
- Radio array will be a BIG part of IceCube-Gen2

IceCube-Gen2

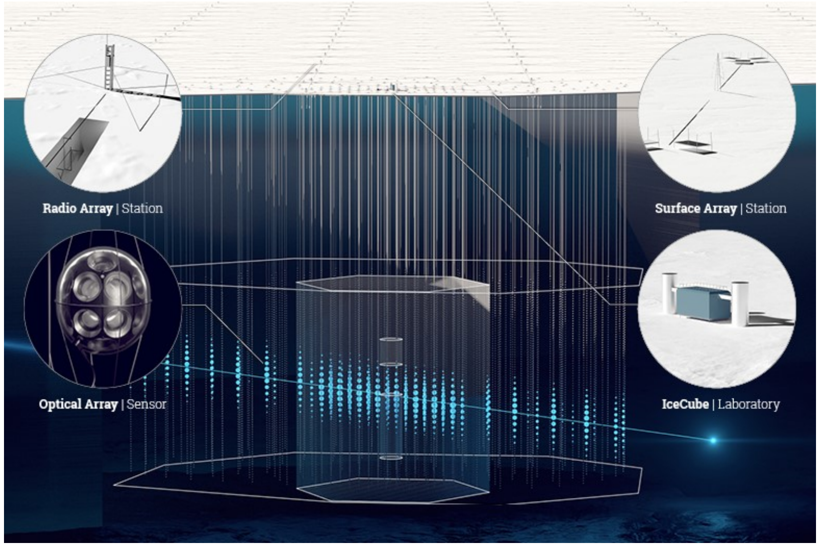
The window to the extreme Universe

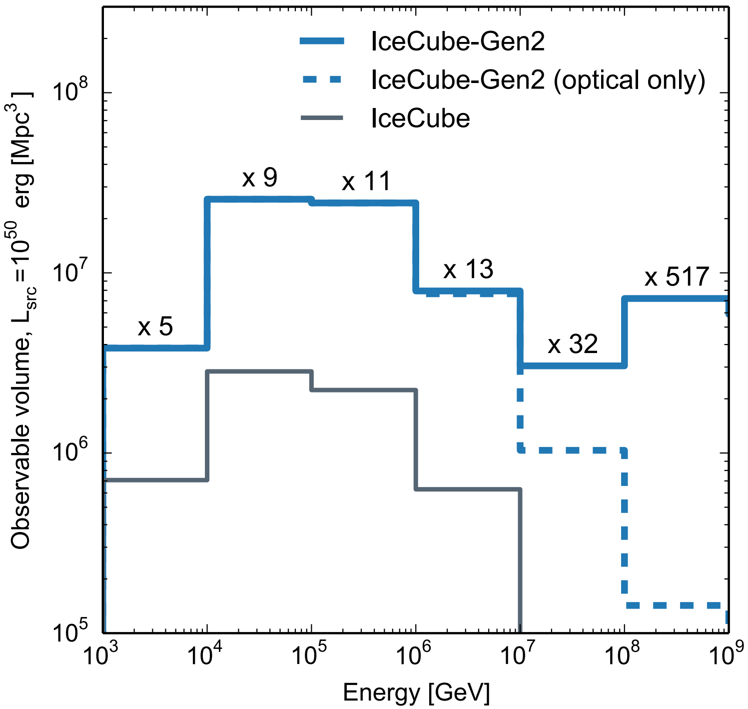


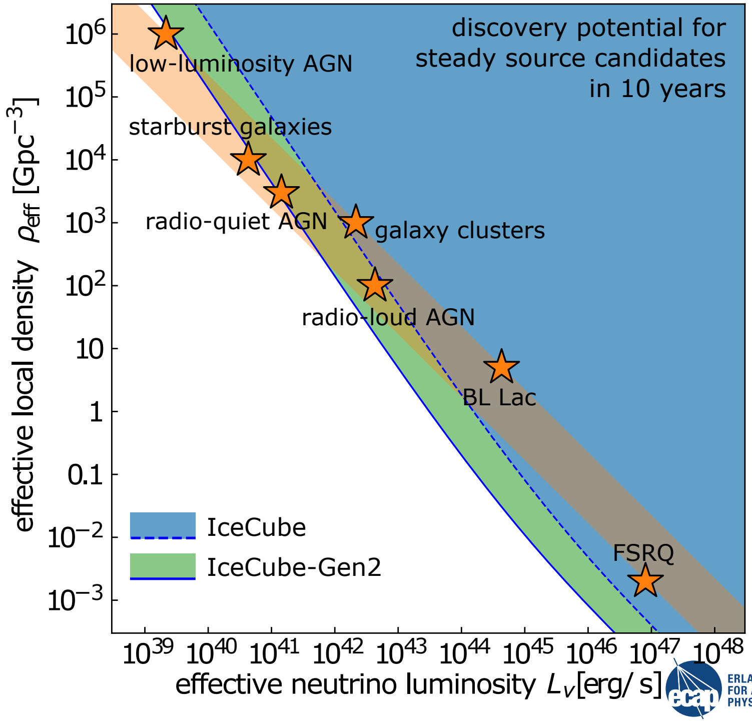
IceCube-Gen2

The window to the extreme Universe

- The next generation of IceCube
- Many more discoveries







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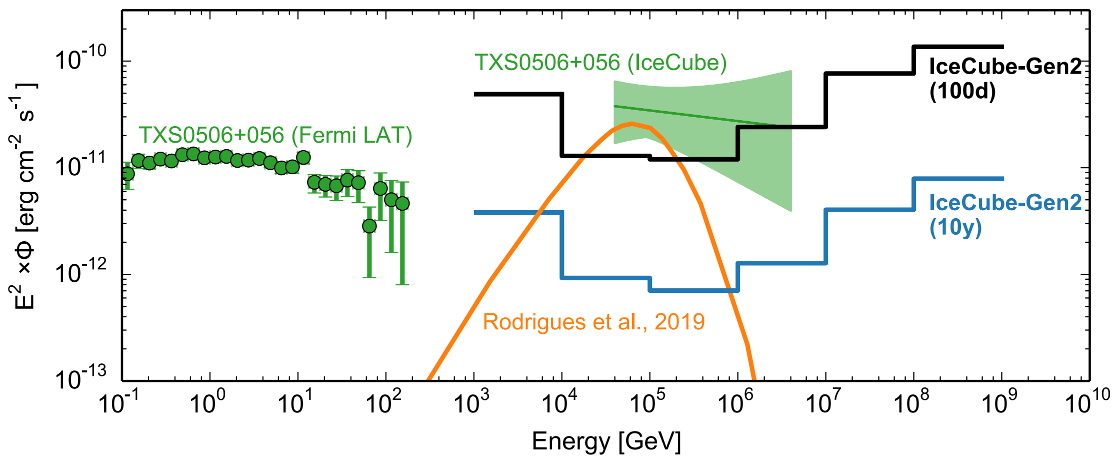
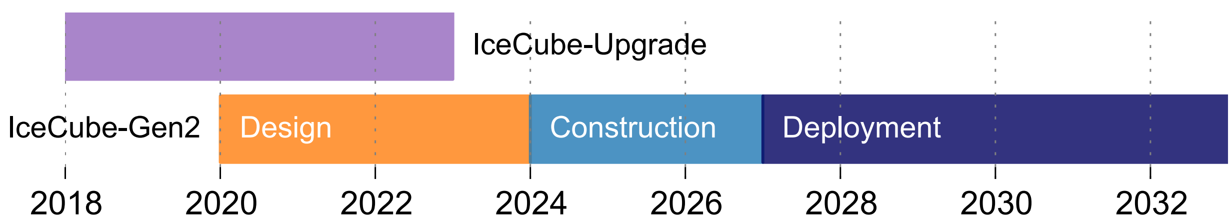
IceCube-Gen2

The window to the extreme Universe



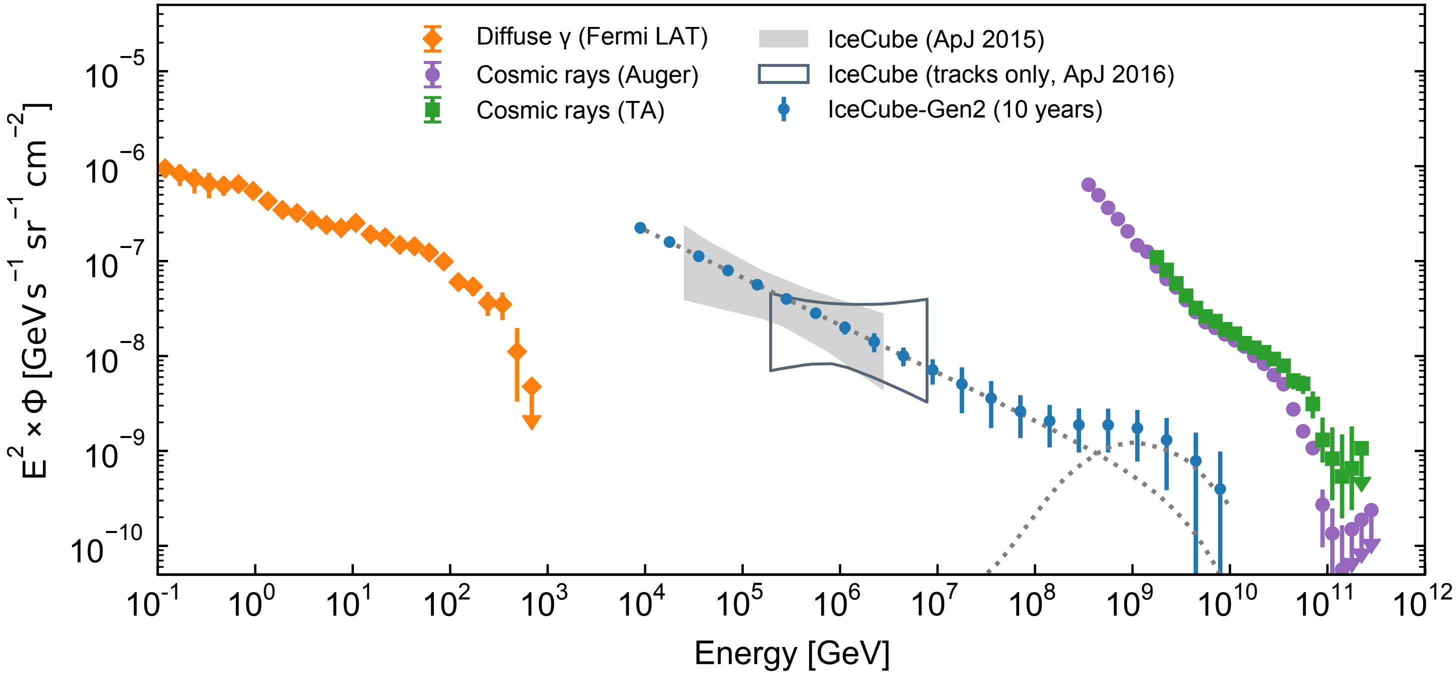
- Integrated observatory of more optical sensors and large radio array
- Upgrade is being built now, Gen2 will follow



IceCube-Gen2

Read more about it in 85 pages of whitepaper

“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, Journal of Physics G, in press

Conclusions

Radio detection of air showers and neutrinos

- Radio detection theory has a solid foundation through measurements of air showers
- Radio detection of air showers very sensitive to composition, will help improve air shower arrays and teach us about shower development
- Radio detection of neutrinos is a promising way to target the highest energies and find the sources of ultra-high energy cosmic rays
- RNO-G and IceCube-Gen2 will be large arrays targeting neutrinos above 10 PeV