‘A’ Radio Neutrino Observatory

The In-Ice approach

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PAHEN, August 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

What is new in in-ice radio detection?

A short outline

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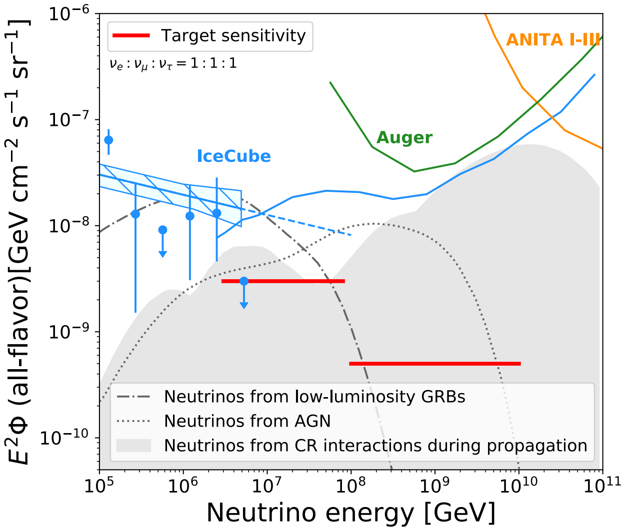
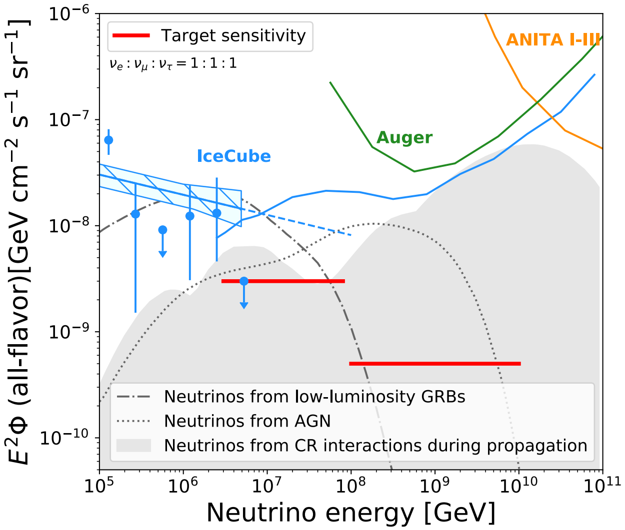


Emission mechanisms and scientific motivation

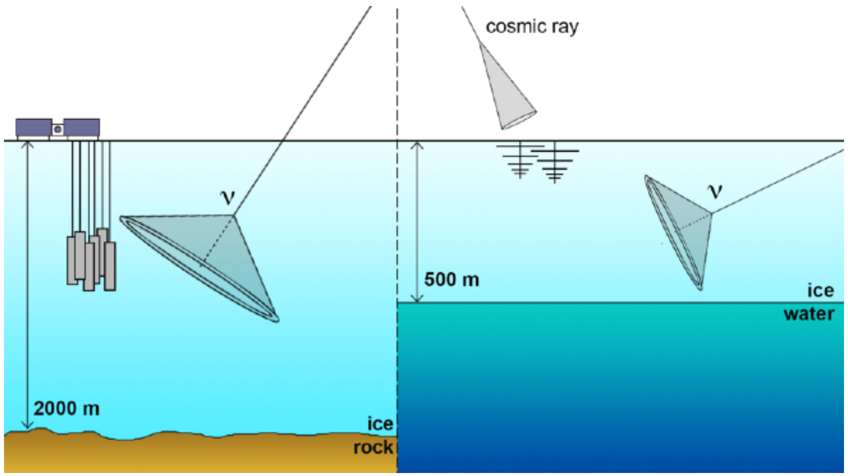
What is new in in-ice radio detection?

A short outline



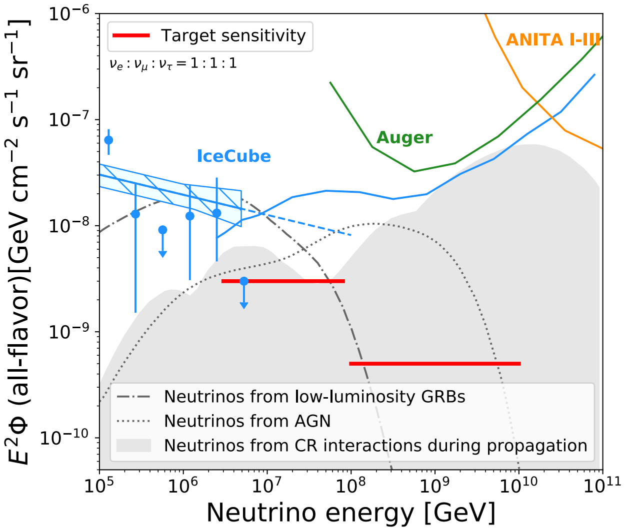
Emission mechanisms and scientific motivation

Experimental strategies

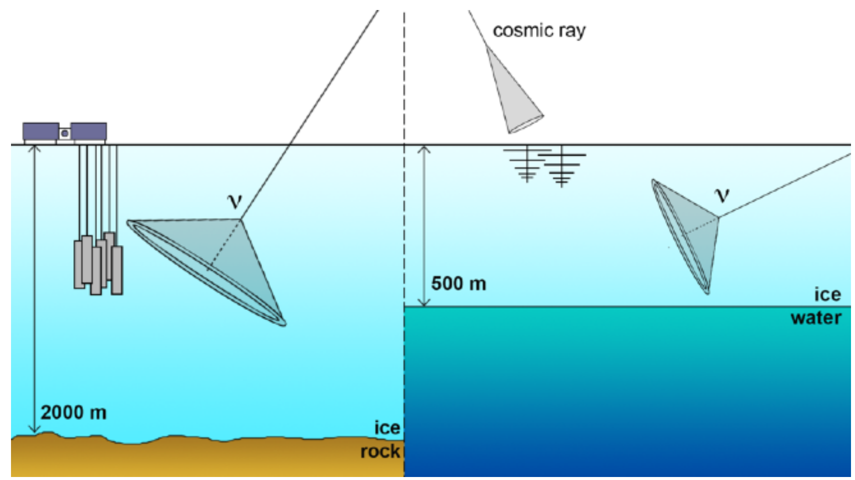


What is new in in-ice radio detection?

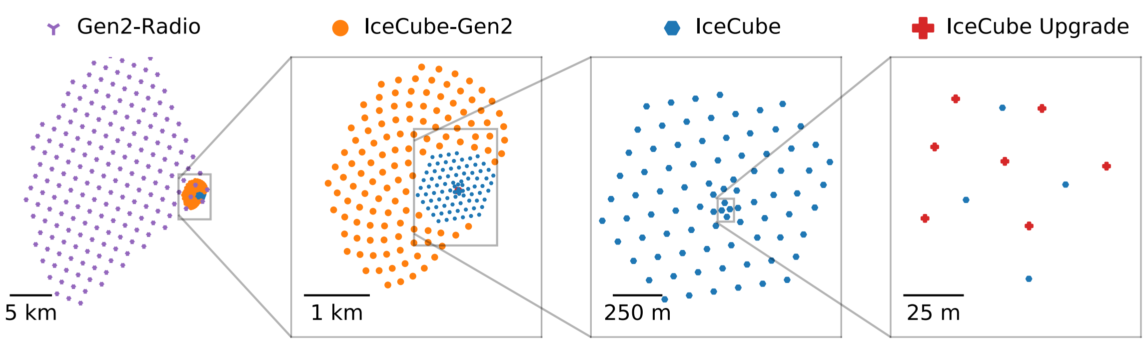
A short outline



Emission mechanisms and scientific motivation



Experimental strategies

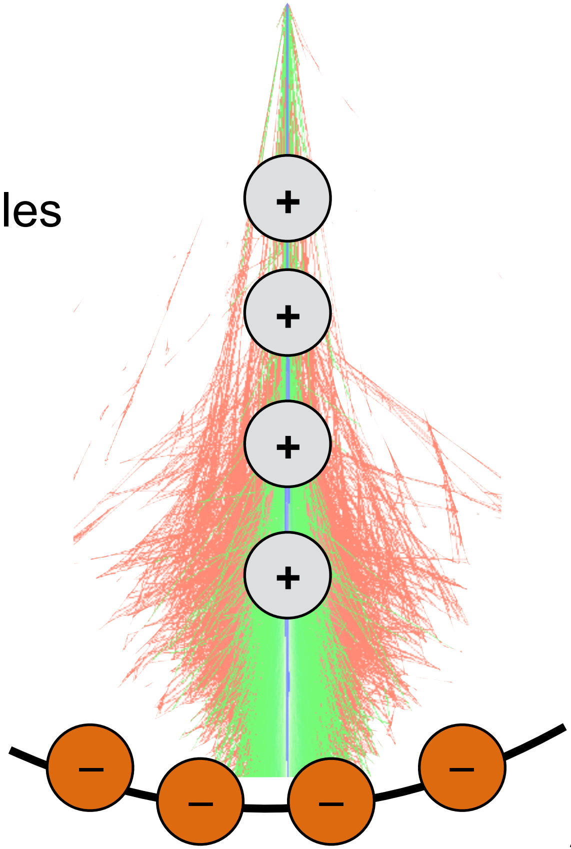


Concrete developments

Radio emission of neutrino (showers)

In a very small nutshell

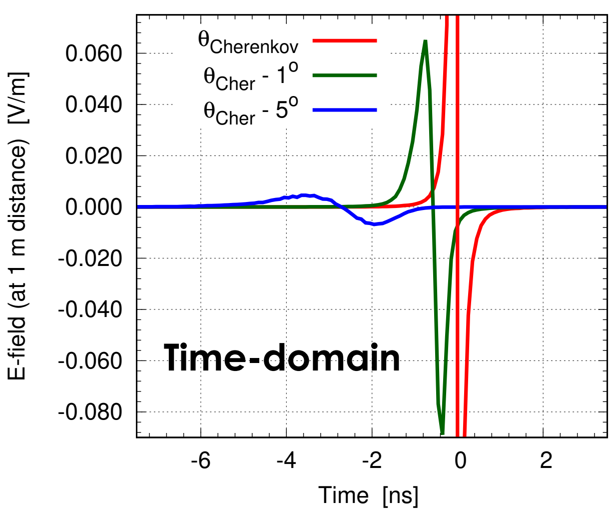
- Any electromagnetic shower (component) creates radio emission
- Shower front accumulates negative charge from surrounding material
- Macroscopically a changing current is induced (moving and changing net charge), this results in emission
- Emission is not caused by index of refraction, but
- Emission is added up coherently for all observer angles at which the emission arrives simultaneously: emission strongest at the Cherenkov angle

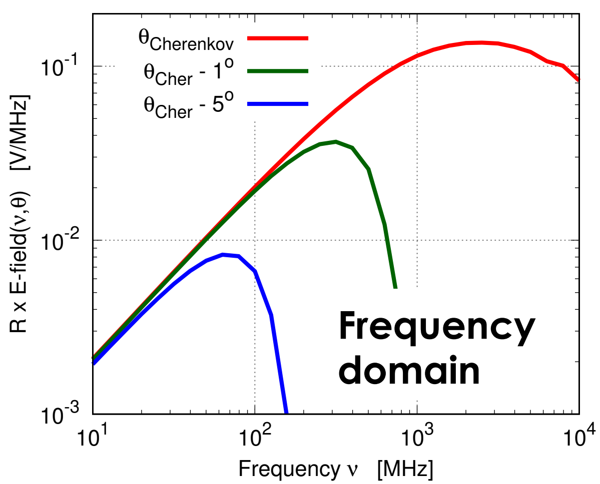


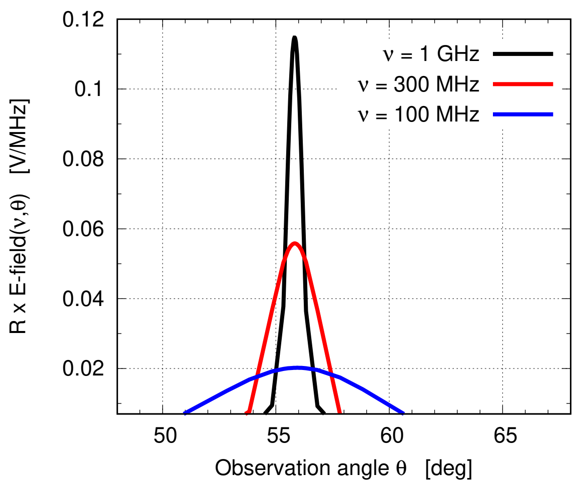
Radio emission of neutrino (showers)

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, …)



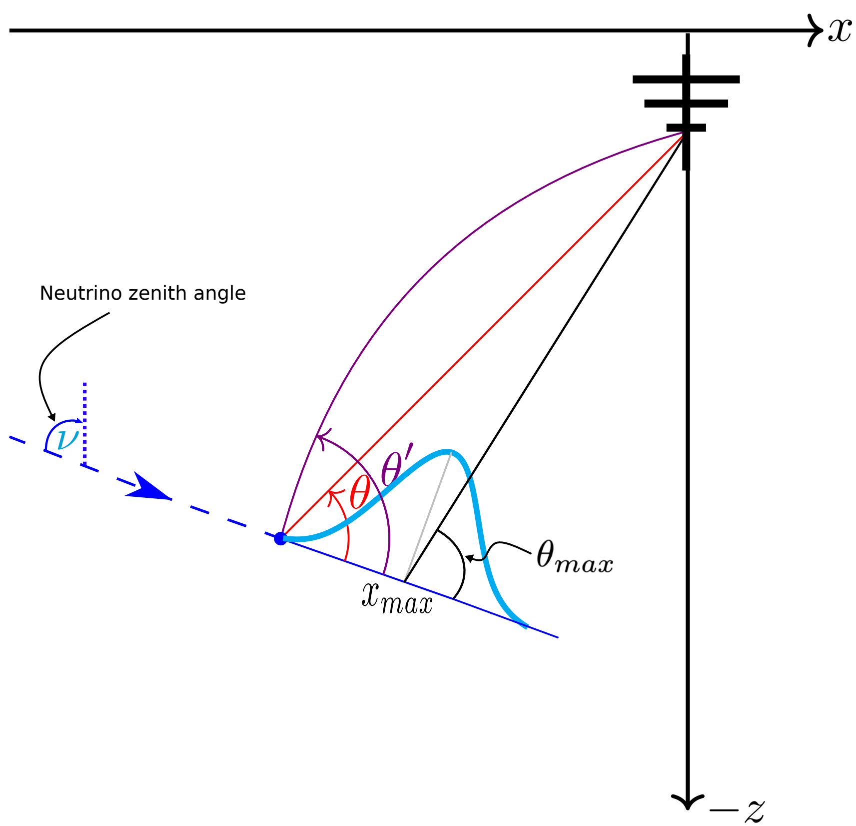




From: J. Alvarez-Muniz

How to detect a signal

The concept of radio detection

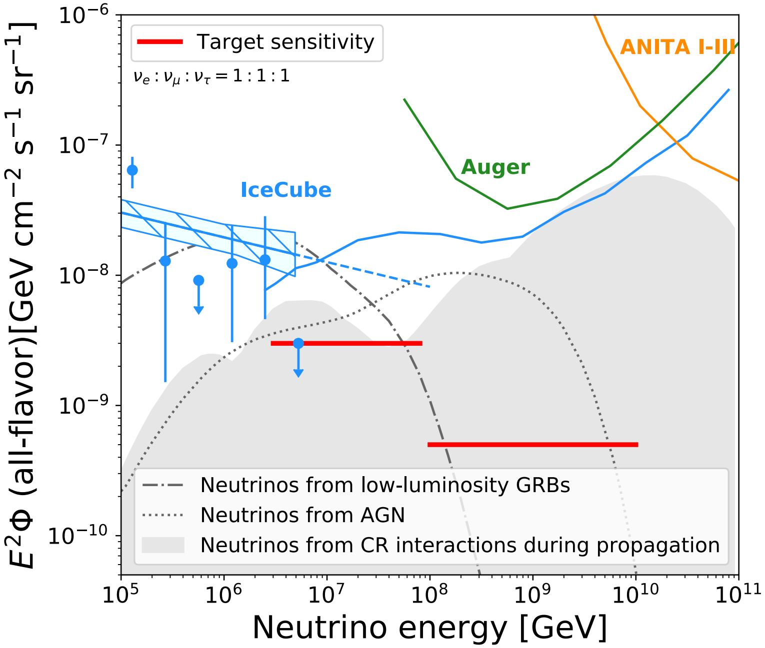


From Glaser et al, submitted, 1906.01670

- Neutrino interactions are measured at a distance
- Detection typically only by one cluster of antennas (= station)
- Signal parameters: arrival time, amplitude as function of frequency, polarization
- Attenuation length of cold ice ~ 1km
- Towards the surface, ice density gradient: signals travel on bent trajectories
- Every station monitors a block of roughly 1 km^3

Which science to target?

Parameter space



From Ackermann et al.,
Decadal 2020, Whitepaper, 1903.04334

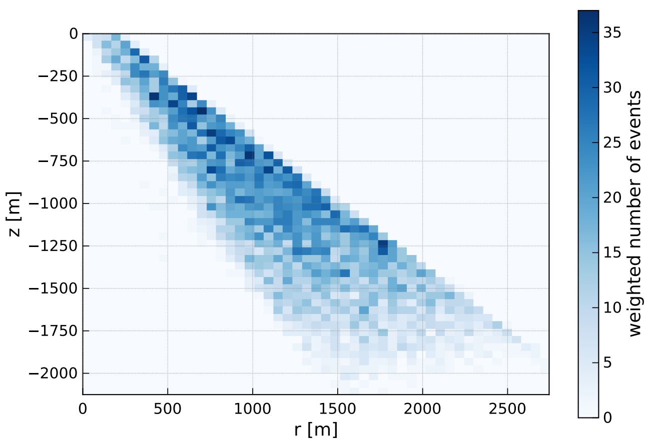
- The neutrino space above 100 PeV is unknown territory
- Experiments need very large effective areas
- Neutrinos can either be directly from sources (AGN, GRB, NS-NS merger, …)
- Or neutrinos can be from interaction of UHECR with photon background (CMB, EBL, …)
- Ideally experiments have sensitivity to measure continuation of IceCube flux to high energies

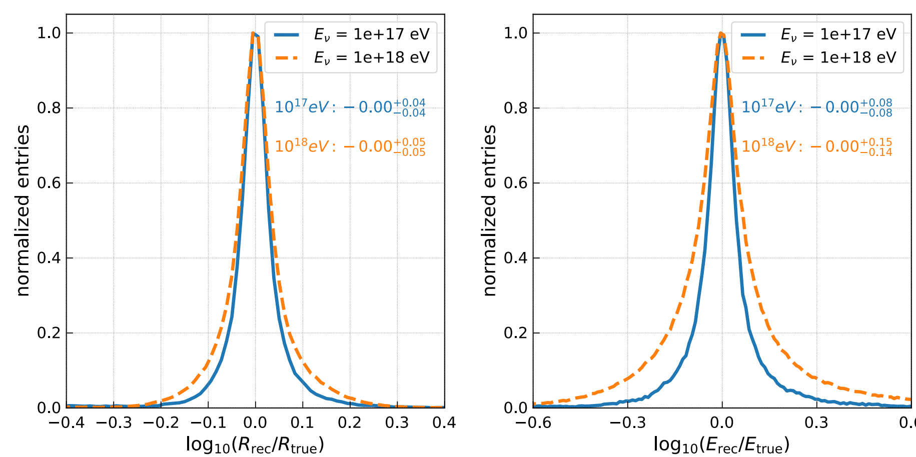
Which science to target?

Energy reconstruction

- Needed for spectrum measurement
- **Amplitude of pulse** scales with shower energy and **vertex distance**
- Reconstruction probably dominated by irreducible uncertainty from inelasticity distribution neutrino -> shower (see e.g. Glaser et al., 1909.02677)

$$\log_{10}(E_{\mathrm{sh}}/E_\nu) = \begin{cases} -0.12^{+0.11}_{-0.33} & \text{for astrophysical + cosmogenic spectrum} \\ -0.06^{+0.06}_{-0.22} & \text{at } 10^{17}\,\text{eV neutrino energy} \\ -0.25^{+0.18}_{-0.34} & \text{at } 10^{18}\,\text{eV neutrino energy} \\ -0.33^{+0.26}_{-0.49} & \text{at } 10^{19}\,\text{eV neutrino energy} \end{cases}$$



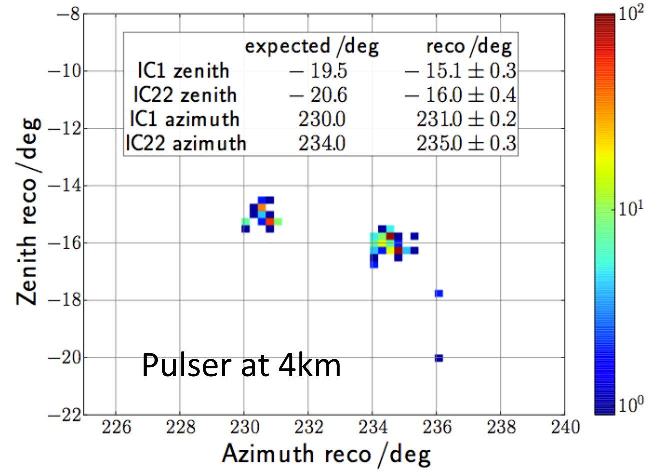


Which science to target?

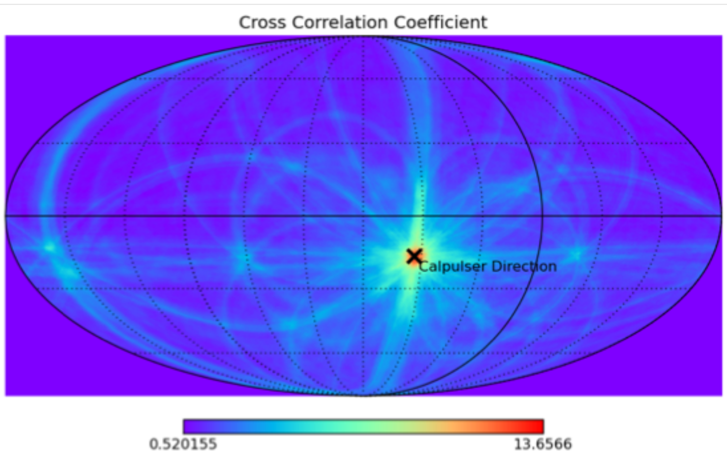
Reconstruction of arrival direction

- Needed for (multi-messenger) astronomy
- (1) mapping of Cherenkov cone, requires dense array, currently not in focus
- (2) measure arrival direction (**s**) and signal polarization (**p**) to determine axis (v): **v = s** x **p**
  current experimentally proven uncertainties:
  s < 1 deg, **p** <= 7 deg

Signal arrival direction

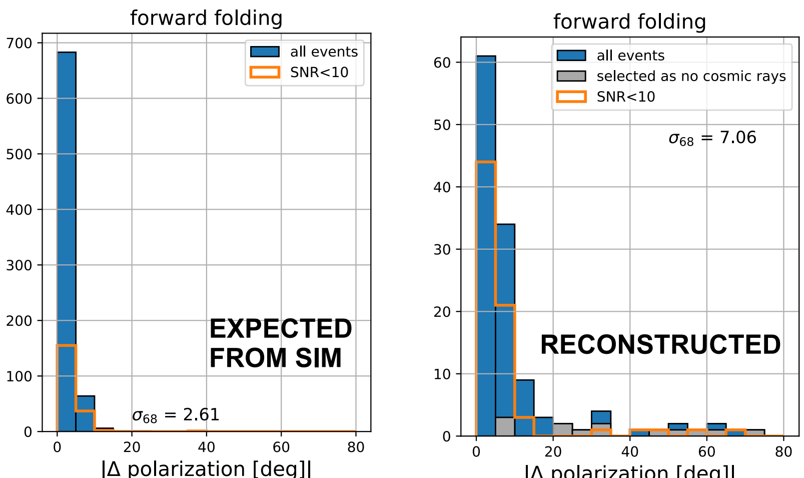


ARA Collaboration



Cosmic ray polarization

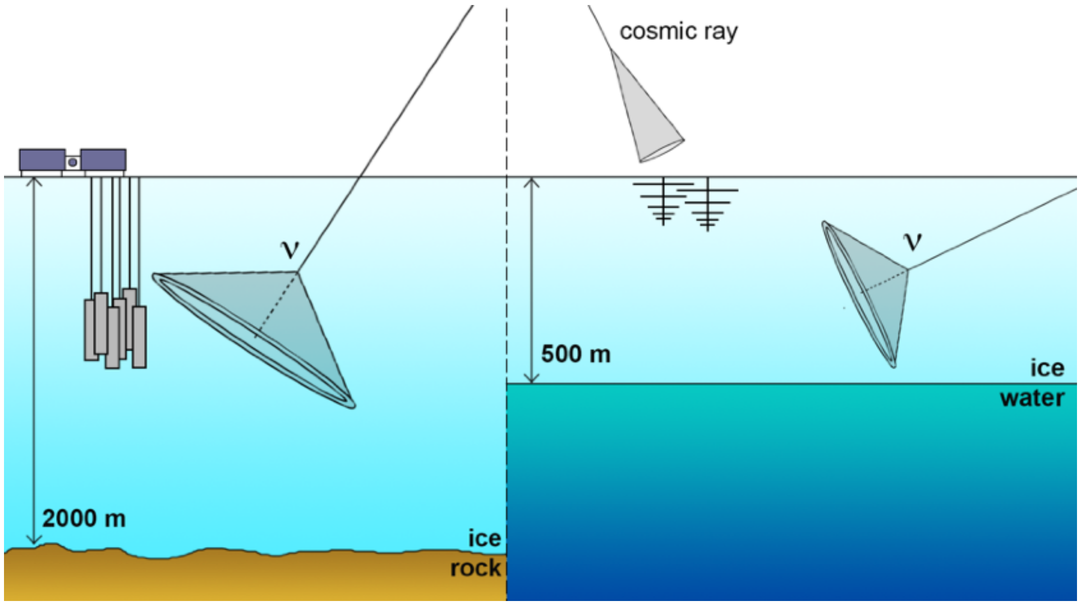
first results



ARIANNA Collaboration

Experimental strategies

What could one build?

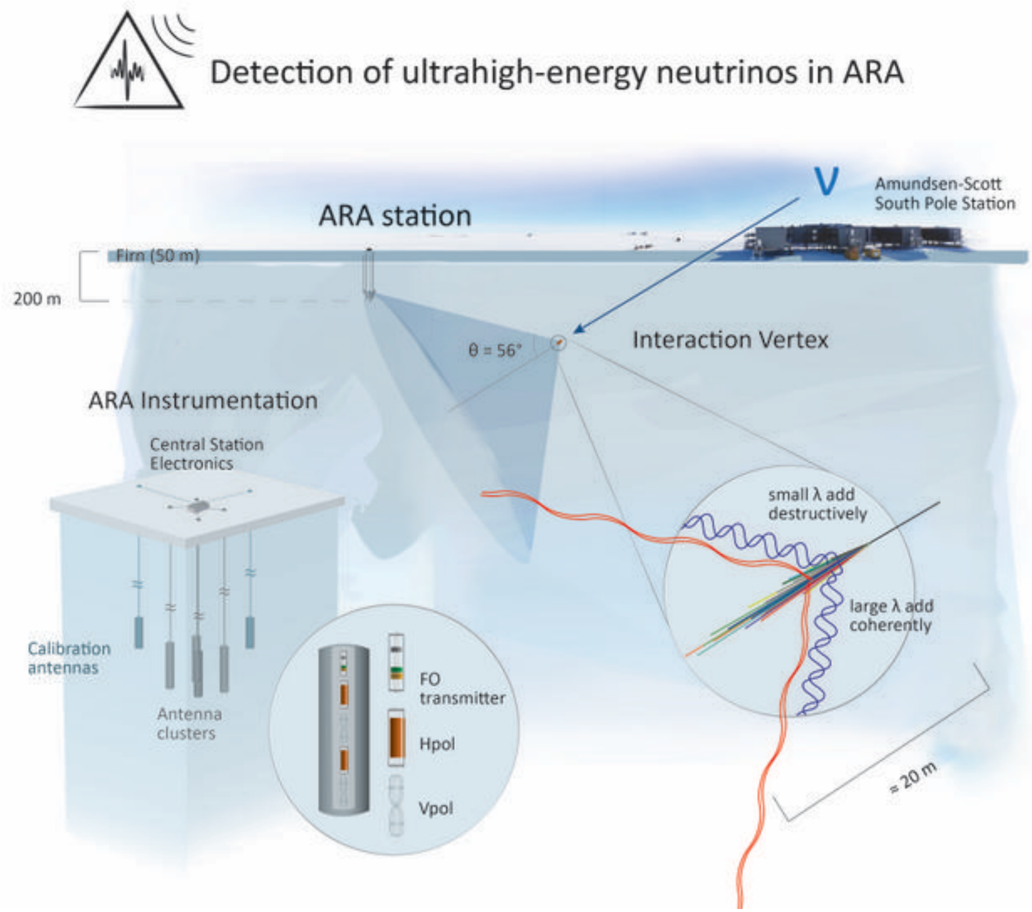


- Several approaches have been tried
- Many important proof-of-principle measurements with RICE, ARA, and ARIANNA and affiliated experiments
- Next step is a pathfinder array that shows the scale-up of technology and viability of large scale array

Experimental strategies

What has been done so far: ARA

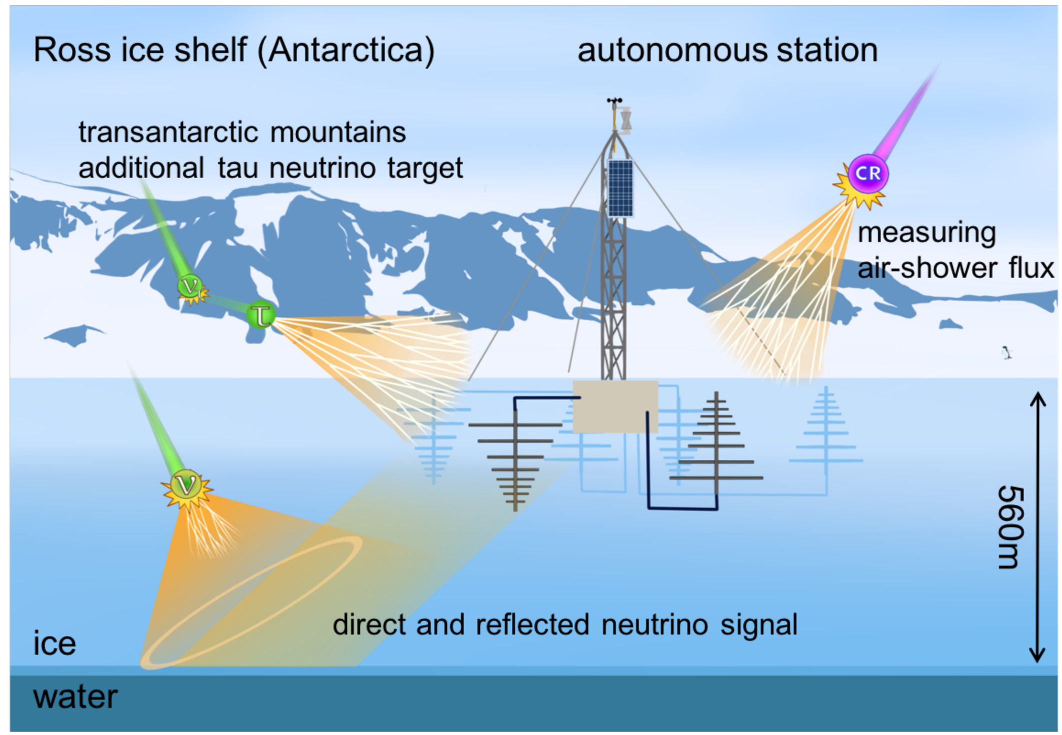
- Has been running in various configurations since 2010
- At 200 meters depth, compact ice, wide field of view, shielding from man-made noise at surface
- Powered by South Pole station, 100% up-time
- Data-transfer to station, low trigger thresholds, high data-volumes, analysis offline
- Design restricted by bore-hole geometry



Experimental strategies

What has been done so far: ARIANNA

- Has been running in various configurations since 2012
- Stations are deployed close to the surface for maximum flexibility in antenna and station design
- Autonomous, light-weight stations with minimal data transferred via Iridium
- Isolated on Ross Ice-Shelf reduced man-made background
- Air showers unique calibration signal



Experimental strategies

Deep vs shallow

Deep

- Detector below the firn = reduced ray bending = large field of view
- Detector deep = less human-generated noise
- Increased logistical overhead in drilling and deploying
- Antenna geometry restricted by borehole, difficult to build broad-band, high-gain antennas for horizontal polarization

Shallow

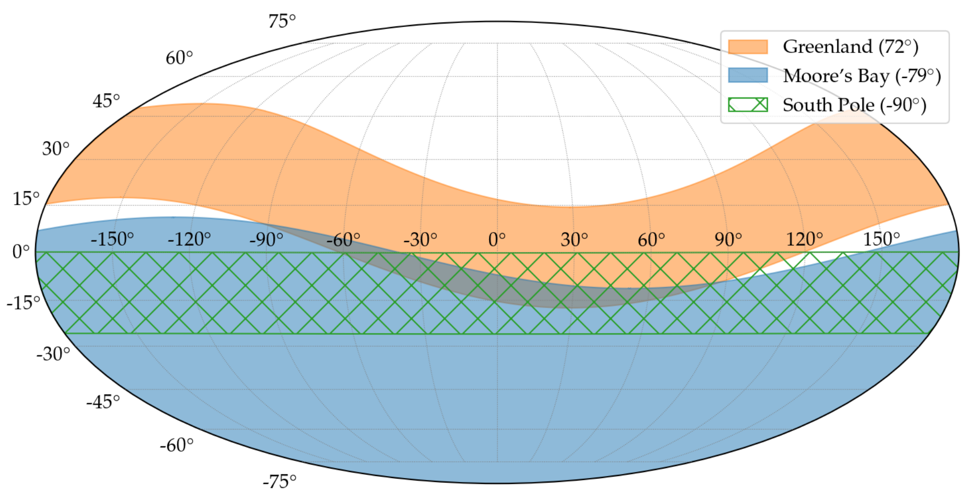
- Challenging propagation geometry at surface
- Cosmic-ray self-veto (detect radio emission in air)
- Easy accessibility and deployment
- Large antennas = Large gain = low energy threshold

Most likely a comparable cost/effective area ratio

Experimental strategies

Which site to choose

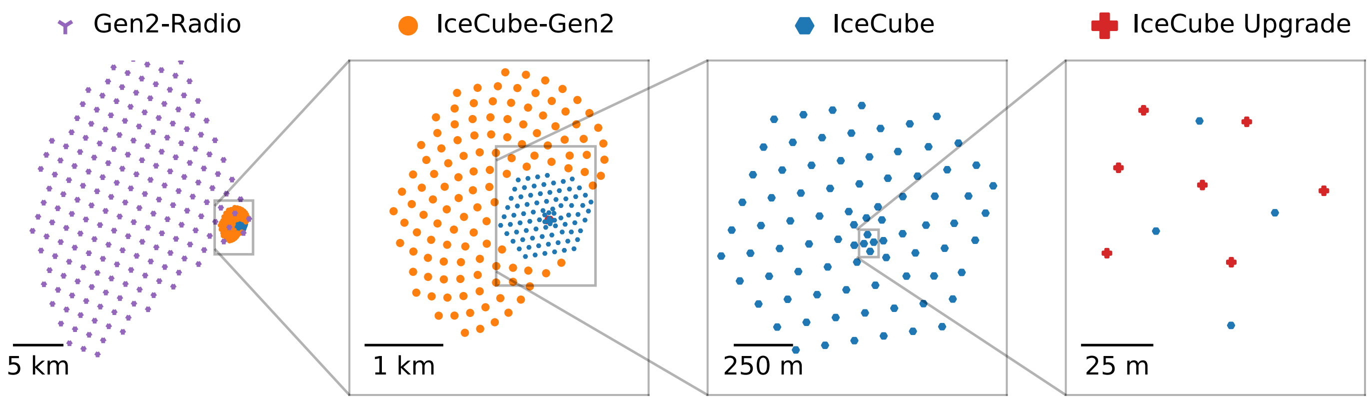
- ARA site: South Pole, excellent logistical support, but constraints from IceCube, excellent ice quality
- ARIANNA site: Ross Ice-Shelf, good logistical support from McMurdo, very remote, decent ice quality with extra reflections
- Greenland: Summit station, commercial and NSF support, very flexible, good ice quality



Instantaneous sky coverage: All three sites almost complimentary

What to do next?

Pathfinders towards IceCube-Gen2



- Goal: O(200) stations as part of IceCube-Gen2
- Provide up to two orders of magnitude improvement over current diffuse neutrino sensitivities at the highest energies
- Severely constrain cosmic ray composition, provide deep real-time sensitivity for explosive events and probe unknown parameter space for new physic
- Construction to begin beyond 2025

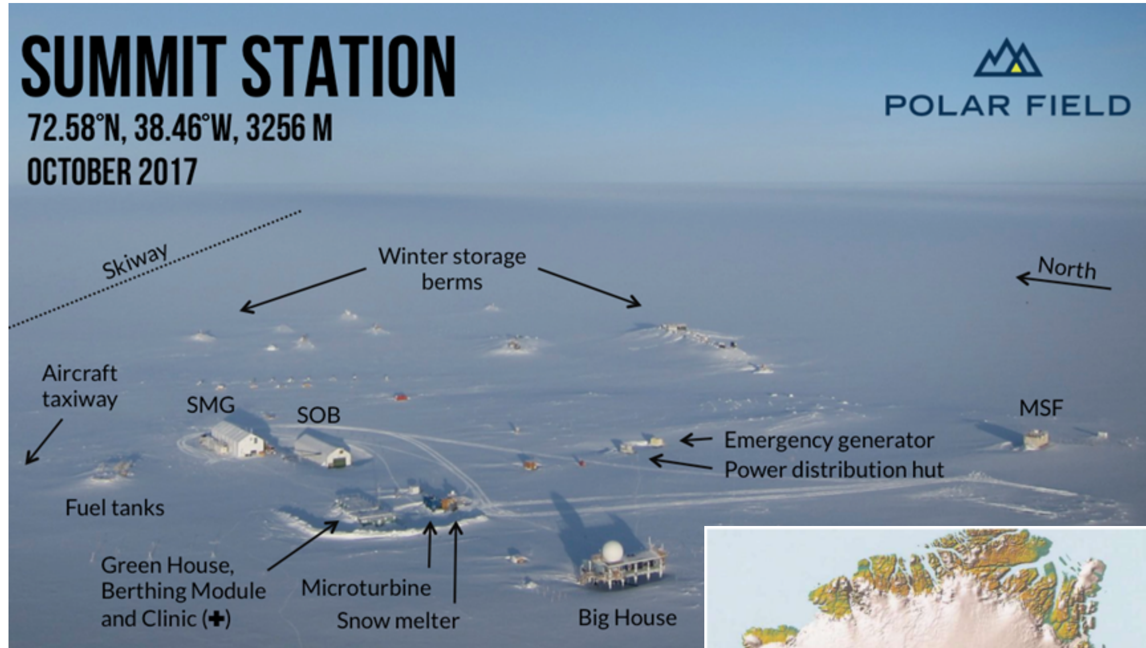
What next?

Other sites

- Radio-community will work together as part of IceCube-Gen2 towards a viable and scalable design
- Preparatory smaller scale R&D at South Pole needed
- Possibly proposal for a surface-only array at Moore’s Bay
- Pathfinder array in Greenland

What next?

Greenland



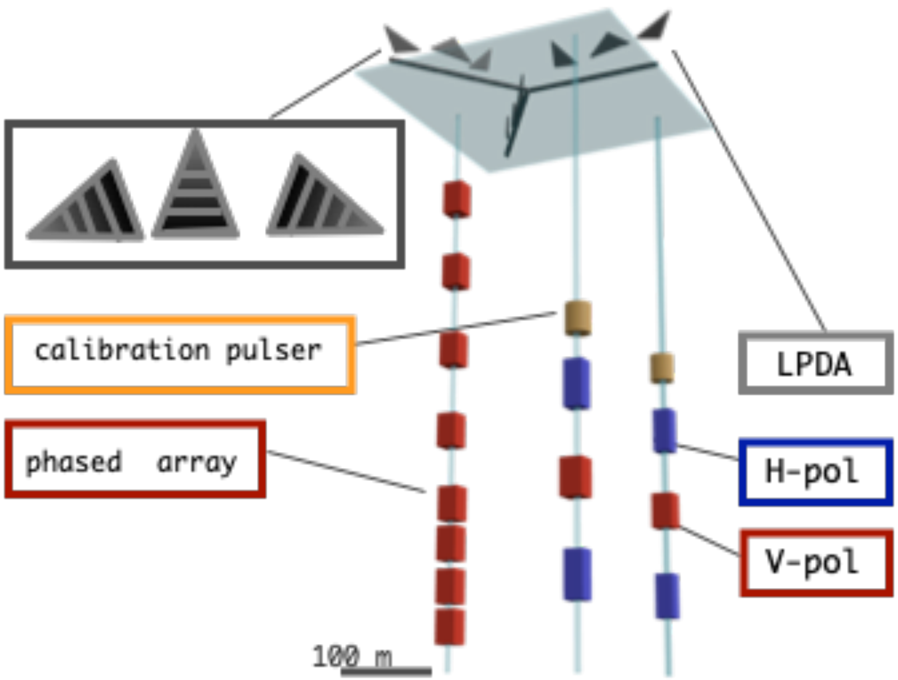
- Starting a pathfinder array as R&D towards IceCube-Gen2 as early as 2020
- Technology will built on ARA and ARIANNA experience
- Combination of strong points of both experiments
- Deployment in Greenland allows for fast development turn-around in a less restricted environment
- Site has been previously explored for neutrino detection by GNO project
- Funding secured for O(40) stations

What next?

Greenland

Current design concept

- phased-array at 100m with 4 antennas for triggering
- one main string with phased array and additional antennas for vertex reconstruction
- two outrigger strings with V-Pol and H-Pol antennas for polarization and arrival direction reconstruction
- surface antennas for cosmic ray veto, additional neutrino volume, and high-gain polarization data



What next?
Greenland

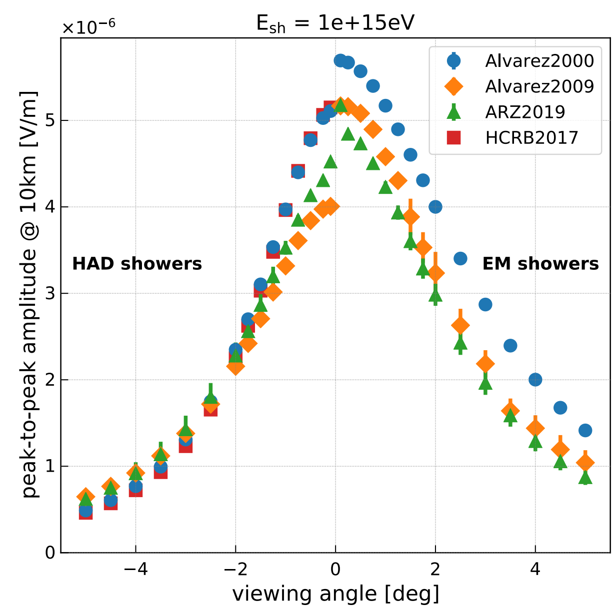
Current concept

- fully autonomous stations (solar power, possibly fuel cells or wind-turbines)
- no cabled connection, new concepts for data transfer (cell phone technology, satellite communications, …)
- drilling with mechanical ASIG drills, possibly melting drills
- development of efficient deployment methods

What next?

Common simulation framework

- InIceMC working group (ARA and ARIANNA members) redeveloped a simulation code for radio detection of neutrinos
- Extensive comparison of assumptions and parameterizations
- Modular approach to be able to simulate ALL types of detector and ice configurations
- Modern coding language, database support for large scale deployments
- Open to contributions and usage: **https://github.com/nu-radio/NuRadioMC**



From Glaser et al, submitted, 1906.01670

Conclusions

Things are happening, stay tuned

- Radio detection of neutrinos cost-effective way to access energies beyond 10 PeV
- ARA, and ARIANNA have laid a foundation, now the time to study scaling of technology
- Several projects as R&D towards IceCube-Gen2 considered
- A pathfinder array will start construction in 2020 in Greenland
- An array in Greenland will have complimentary sky coverage to IceCube