RNO-G

Radio Neutrino Observatory - Greenland

THE QUEST FOR ULTRA HIGH ENERGY COSMIC NEUTRINOS

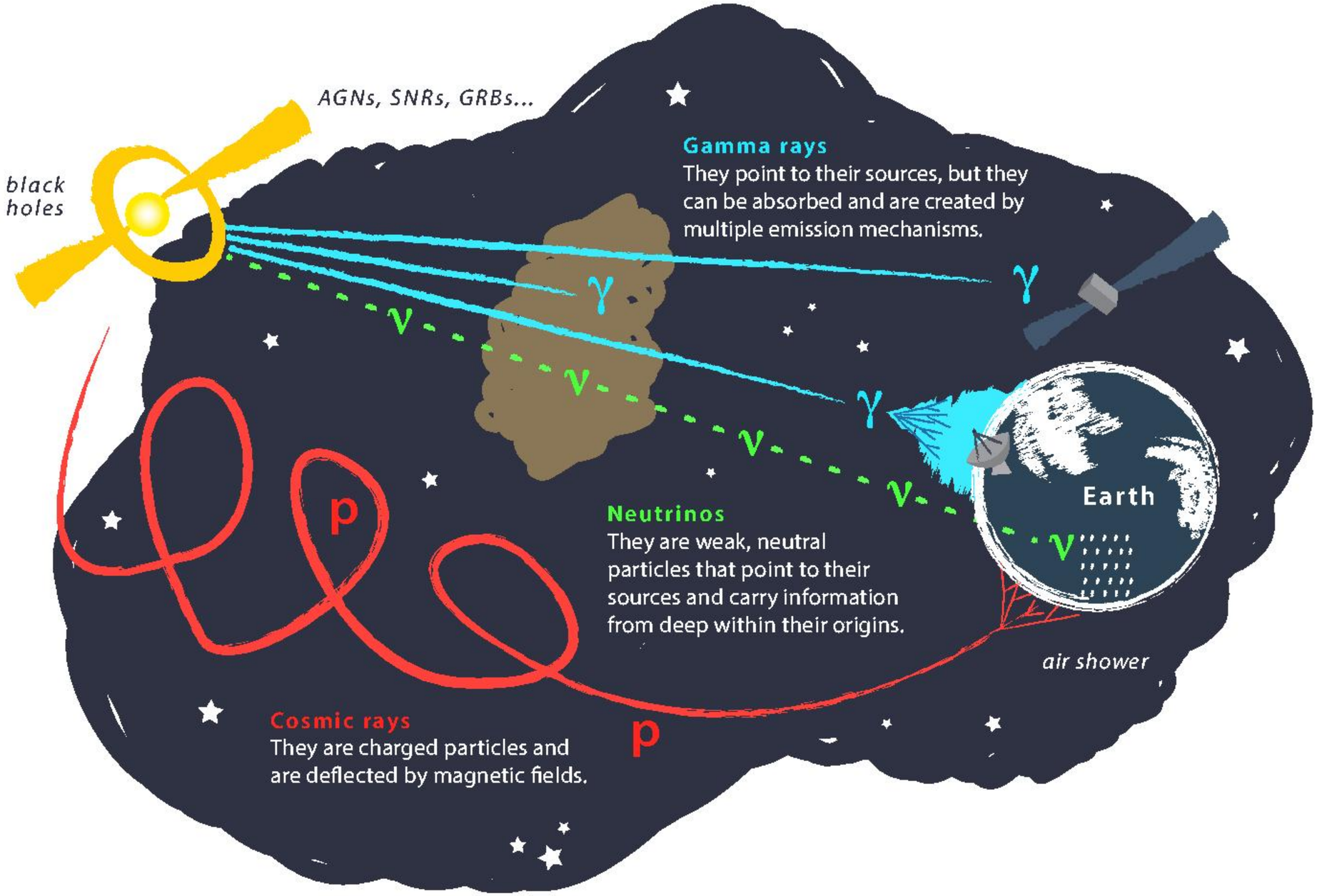
S. Toscano — IIHE-ULB
Simona.Toscano@ulb.be

be.HEP - December 22, 2021

OUTLOOK

- **Why neutrinos:** the multi messenger connection
- **In-ice radio detection**: a cost-effective way to build a teraton-scale neutrino detector.
- **Radio Neutrino Detector – Greenland (RNO-G)**: the new-generation Askaryan detector for ultra-high energy neutrinos.
- **The future of radio detection and neutrino astronomy**: IceCube-Gen2 (and its radio component).

Neutrino astronomy: the physics case



Neutrino astronomy: what kind of neutrinos are we hunting?

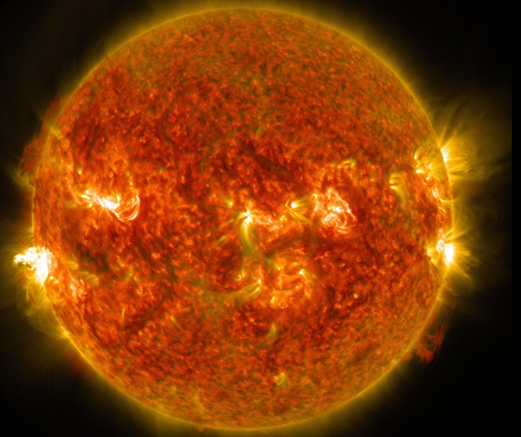
Solar/SN | **Atmospheric** | **Astrophysical** | **Cosmogenic**

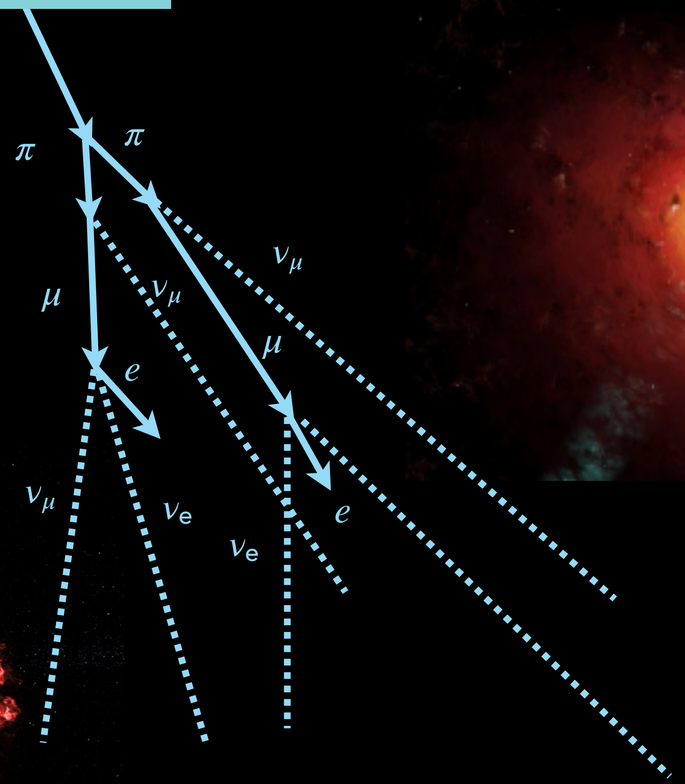
MeV

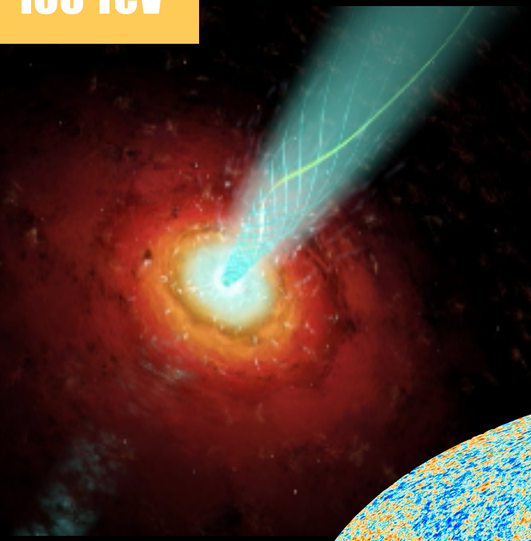
< 100 TeV

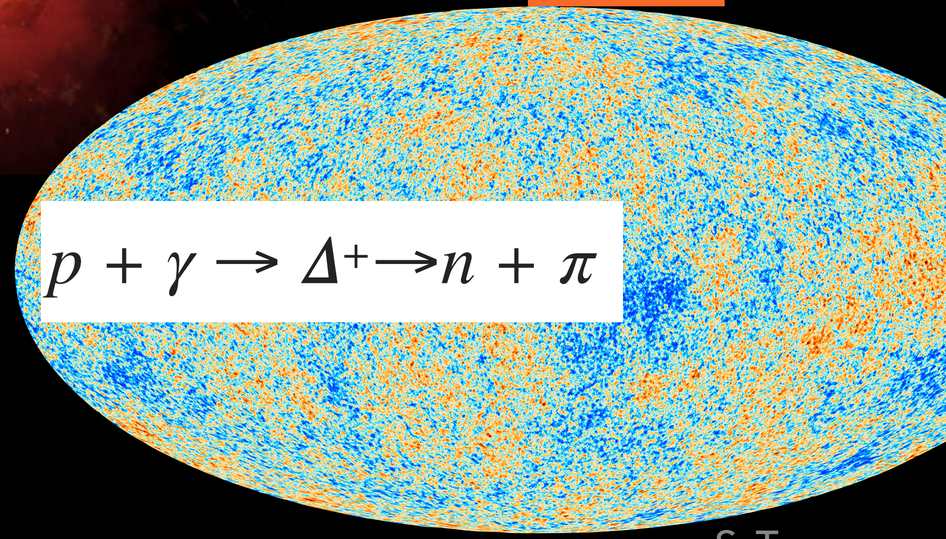
> 100 TeV

1 EeV









$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi$$

Neutrino astronomy: what kind of neutrinos are we hunting?

Solar/SN | **Atmospheric** | **Astrophysical** | **Cosmogenic**

MeV

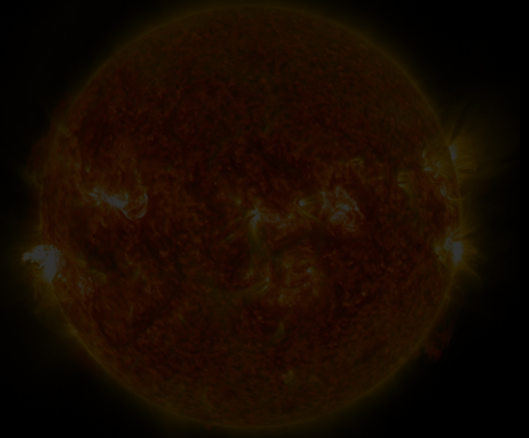
< 100 TeV

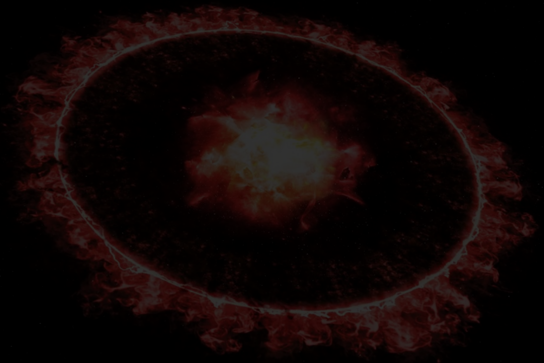
> 100 TeV

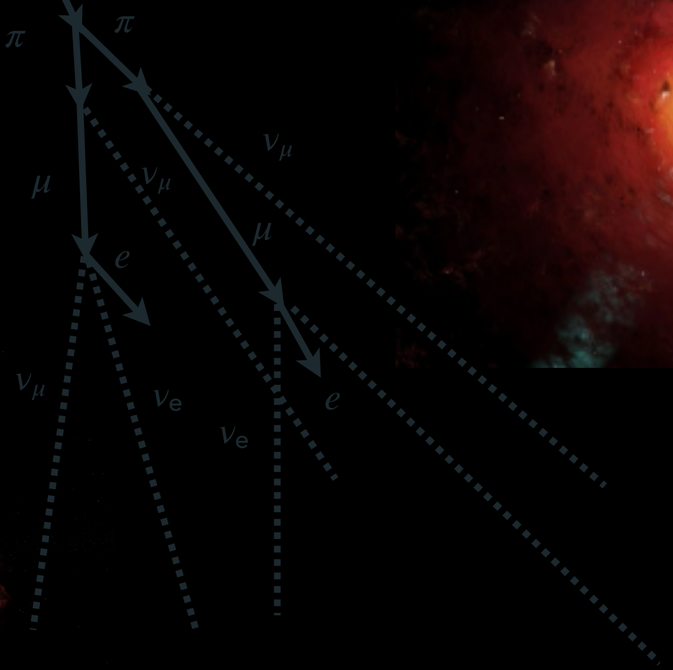
Discovered by IceCube

Guaranteed but not yet observed

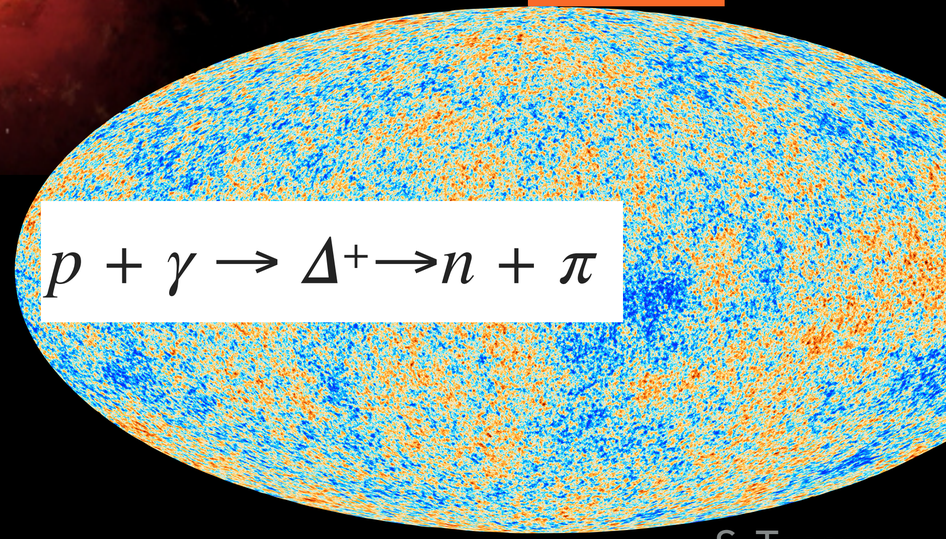
1 EeV





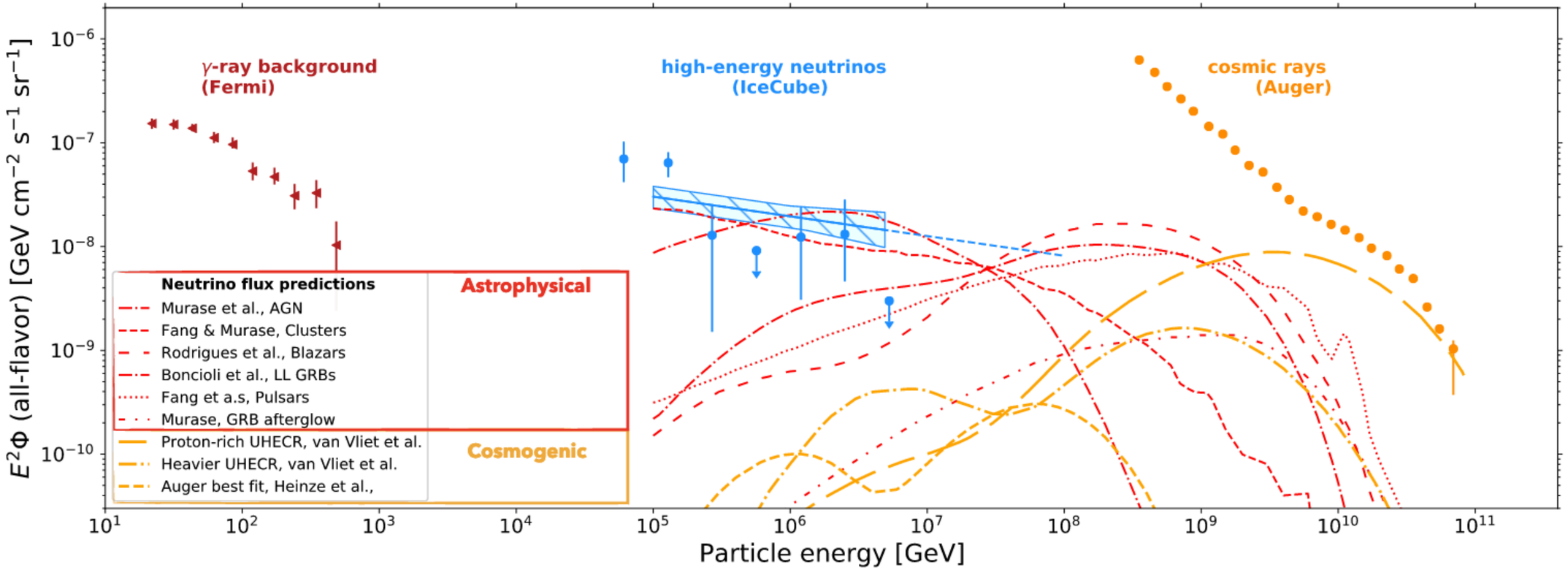


$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi$$



Neutrino astronomy: The multi-messenger connection

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

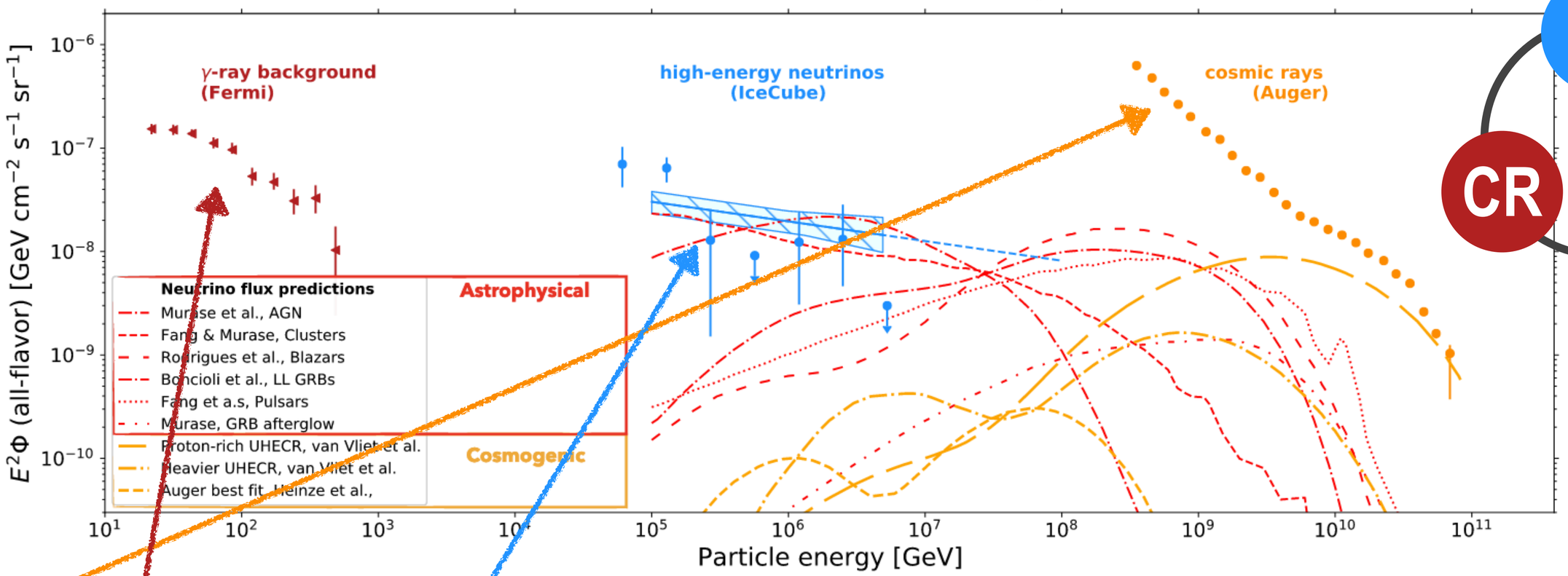
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \overline{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

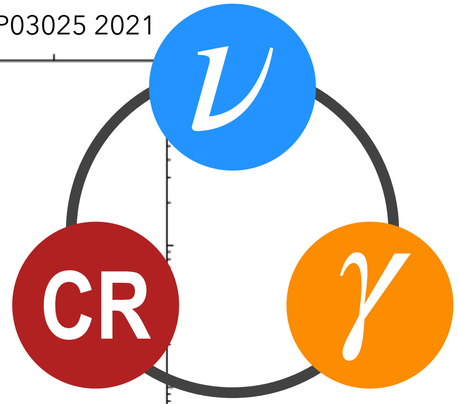
1 PeV **20 PeV**

Neutrino energy = Proton energy / 20

Neutrino astronomy: The multi-messenger connection

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021





$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

1 PeV **20 PeV**

Neutrino energy = Proton energy / 20

Neutrino astronomy: The next frontier

Astrophysical **Cosmogenic**

- Astrophysical: Revealing ν sky at PeV: Study of the astrophysical flux properties (cutoff, breaks).
- Cosmogenic: study of the source evolution and propagation mechanism, UHECR mass composition.

Current 1 km^3 IceCube detector is too small for the low >PeV fluxes

➡ ~5 events ~PeV detected in 10 years → Need >100 times larger detector

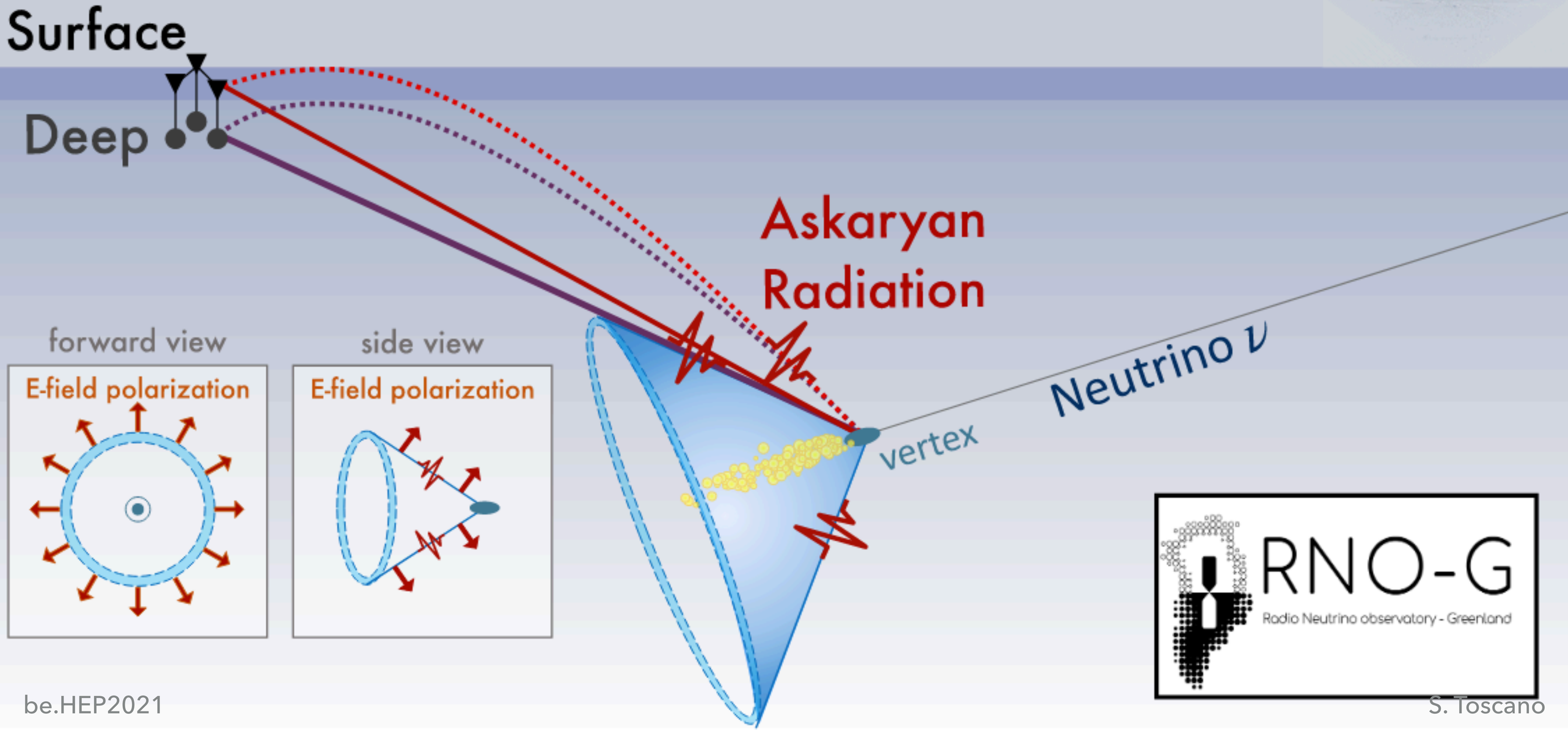
➡ λ_{att} ~ 200m for light → Amount of light sensors and drilling not feasible

INSTEAD USING RADIO SIGNAL OF ν SHOWERS

RADIO DETECTION OF NEUTRINOS

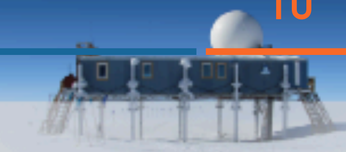
DETECTION PRINCIPLE

In-ice radio detection: Askaryan emission



RNO-G
Radio Neutrino observatory - Greenland

In-ice radio detection: Askaryan emission



We are looking for impulsive **nanosecond-scale** broadband (**10 MHz — 1 GHz**) signal

Surface

Deep

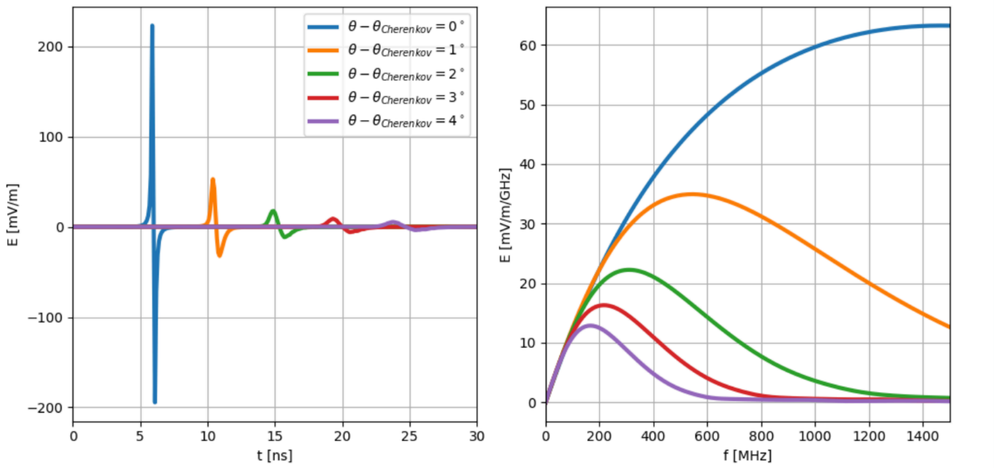
Askaryan Radiation

Neutrino ν

vertex

Emission strongest and higher frequency at Cherenkov angle

J. A. Aguilar et al. (RNO-G Collaboration), JINST 16 P03025 2021.



IMPULSIVE RADIO SIGNAL

BROADBAND PULSE

RNO-G

Radio Neutrino observatory - Greenland

RADIO DETECTION OF NEUTRINOS

WHY POLAR REGIONS?

RADIO DETECTION OF NEUTRINOS

WHY POLAR REGIONS?

- Big volume of dense target for neutrinos: **polar ice**
- RF transparent medium: **attenuation length ~ 500 m - 1km**

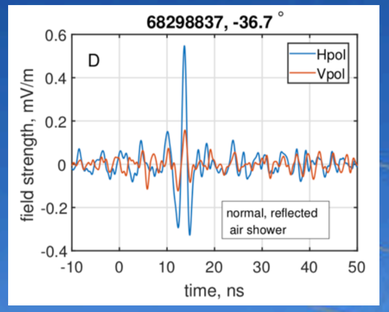
RADIO DETECTION OF NEUTRINOS

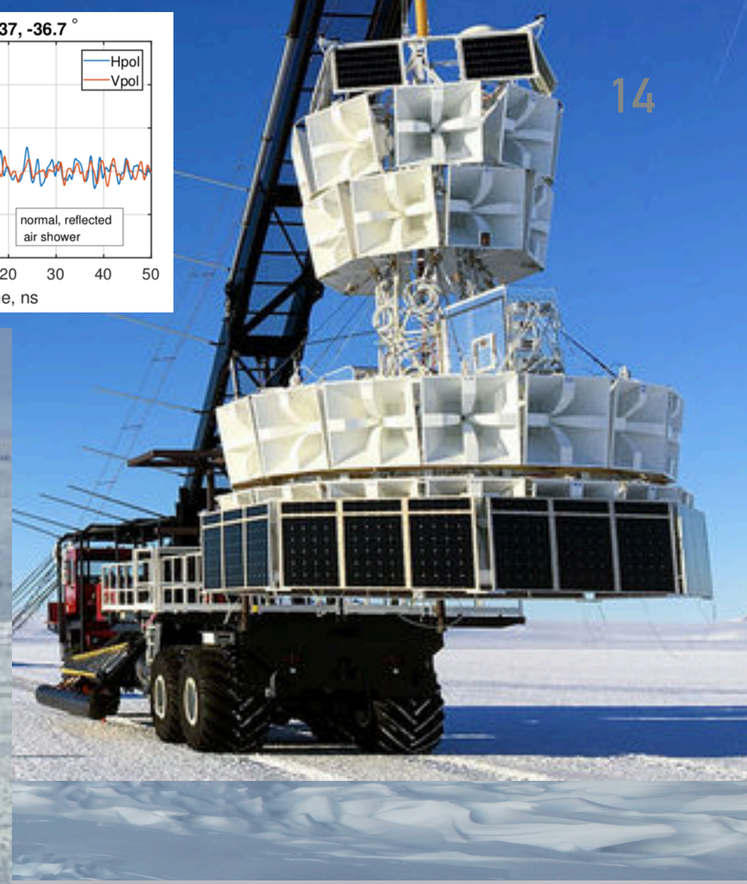
BIG EFFECTIVE VOLUME WITH SMALL NUMBER OF DETECTION UNIT (λ_{att} ~1 km)

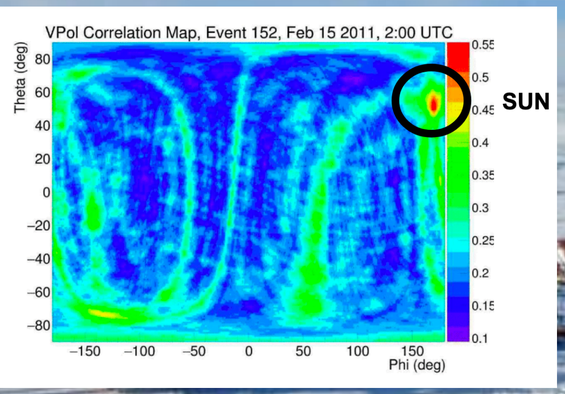
CHEAPEST OPTION (BOTH IN HARDWARE AND DEPLOYMENT)

In-ice radio detection: pilot arrays

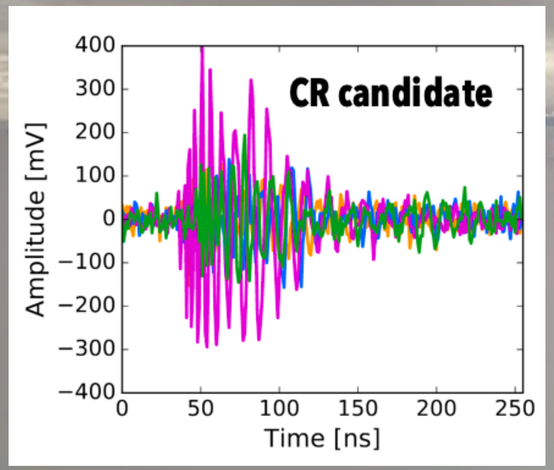
ANITA (Antarctica)







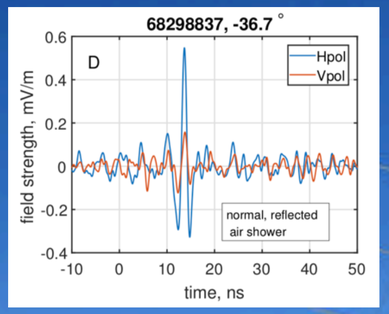
ARA (South Pole)

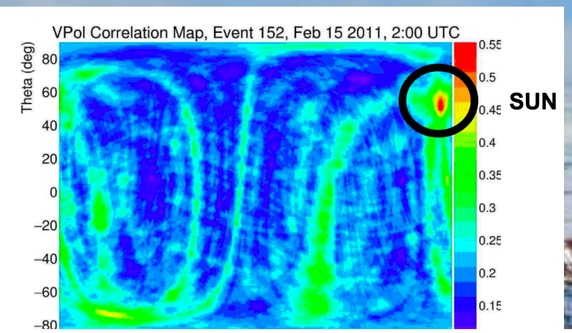


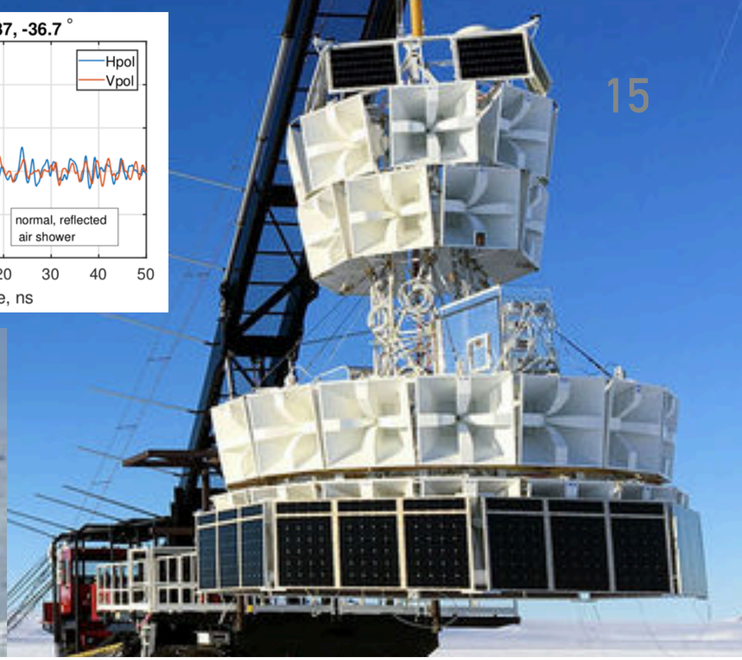
ARIANNA (Antarctica)

In-ice radio detection: pilot arrays

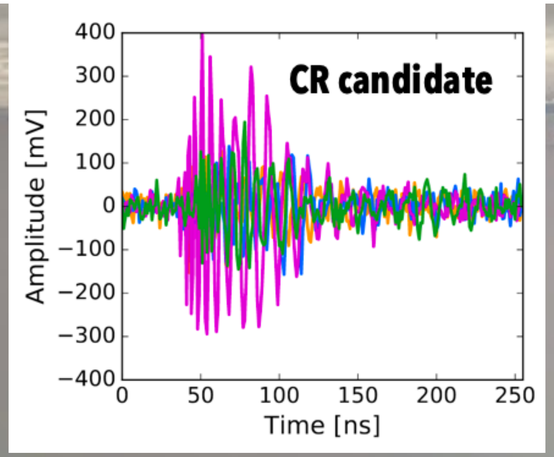
ANITA (Antarctica)







Radio detection of neutrinos in-ice works!



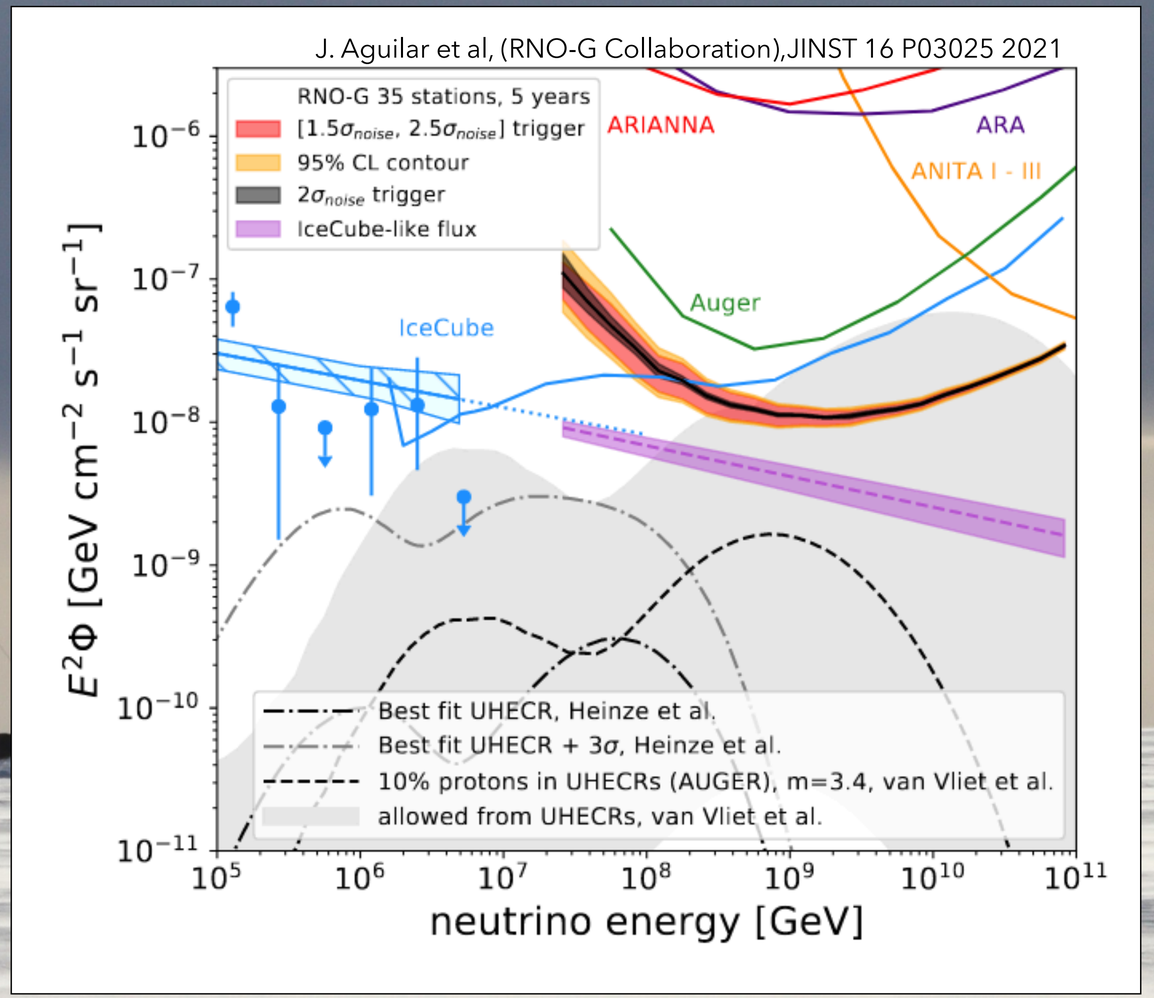
ARIANNA (Antarctica)

RNO-G

Radio Neutrino Observatory - Greenland

Mostly funded through FWO-IRI program

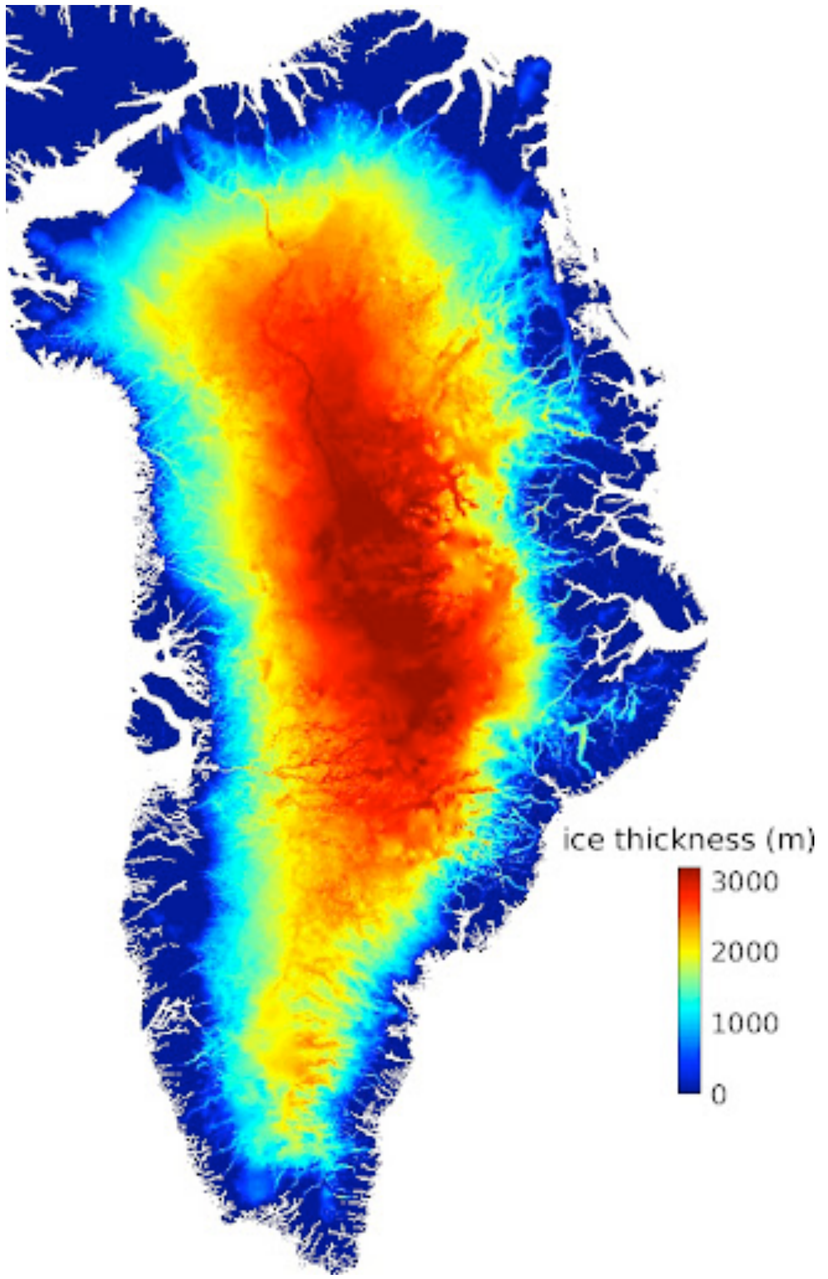
- A **mid-scale experiment** for **science** and testing.
- Scale-up from current arrays
- Hybrid design combines advantages of deep (ARA) and shallow (ARIANNA) stations:
  - ➡large effective volume
  - ➡cosmic ray veto
- Scalable to ~100 km^2 array:
  - ➡autonomous power



VRIJE UNIVERSITEIT BRUSSEL · GHENT UNIVERSITY · UPPSALA UNIVERSITET · UNIVERSITY OF DELAWARE · THE UNIVERSITY OF CHICAGO · MICHIGAN STATE UNIVERSITY · THE OHIO STATE UNIVERSITY · UNIVERSITÉ LIBRE DE BRUXELLES · DESY. · FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG · THE UNIVERSITY OF ALABAMA · WISCONSIN UNIVERSITY OF WISCONSIN-MADISON · PennState · KU · CAL POLY

In-ice radio detection: why Greenland?

- One of the biggest volume of transparent medium on Earth (the other one is in Antarctica):
  - 3km thick ice at Summit Station, with a water layer at bottom.
- Good infrastructure:
  - Summit station NSF-operated.
- Northern hemisphere:
  - Inverted season w.r.t. SP (no interference with IC Upgrade construction)
  - Same cargo planes.
- Sunlight 10 months/year:
  - Solar power.

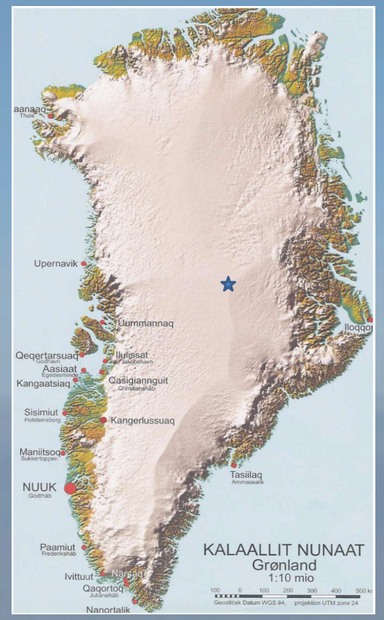


SUMMIT STATION

72.58°N, 38.46°W, 3256 M

OCTOBER 2017

POLAR FIELD



Skiway

Winter storage berms

North

Aircraft taxiway

SMG

SOB

MSF

Emergency generator

Power distribution hut

Fuel tanks

Snow mine

Green House, Berthing Module and Clinic (✚)

Microturbine

Snow melter

Big House

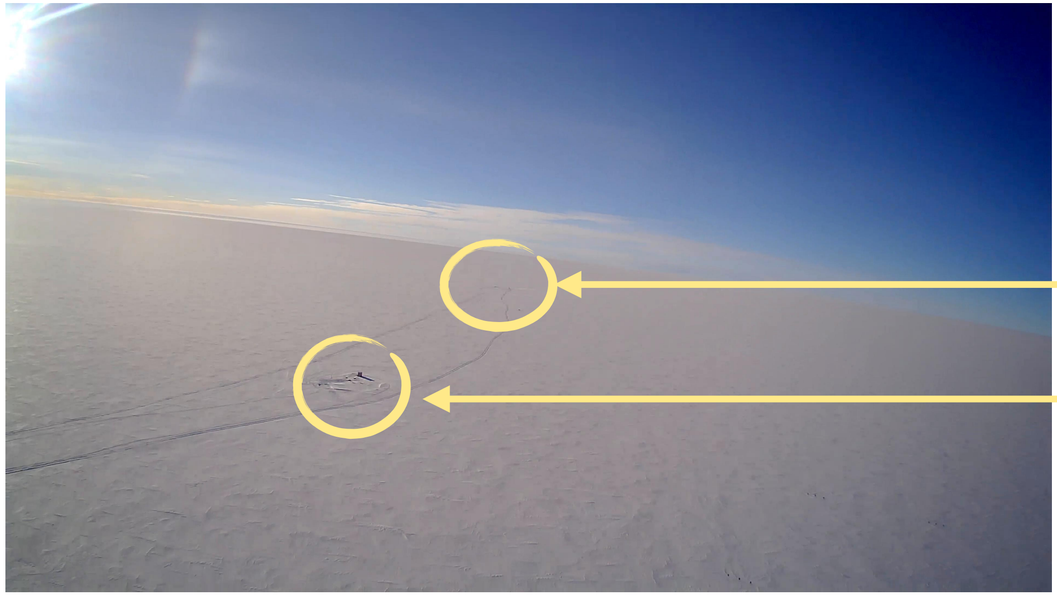
TAWO (700 m)

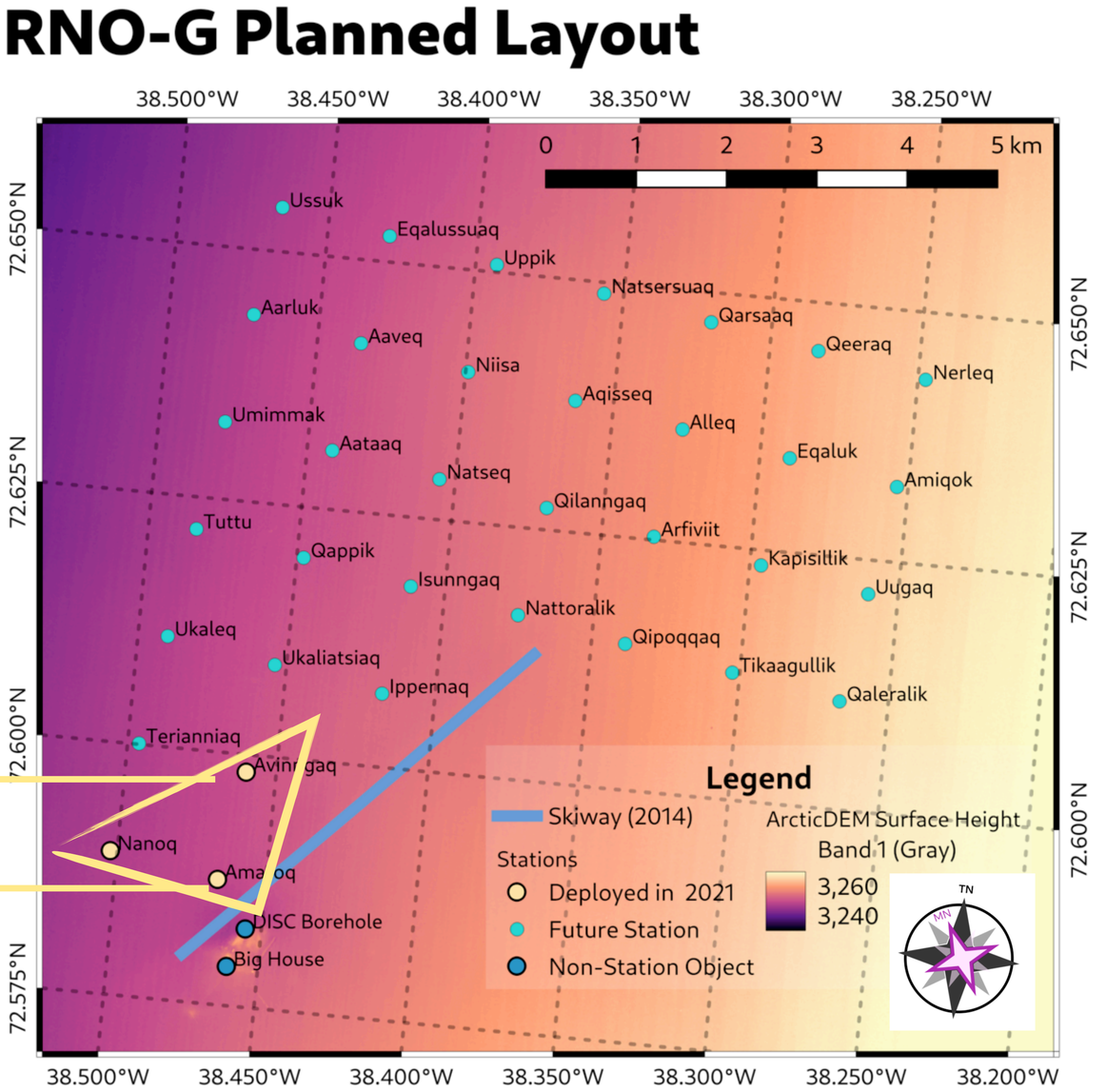
S. Toscano

Image: Sam Dorsi

Radio Neutrino Observatory — Greenland (RNO-G): status

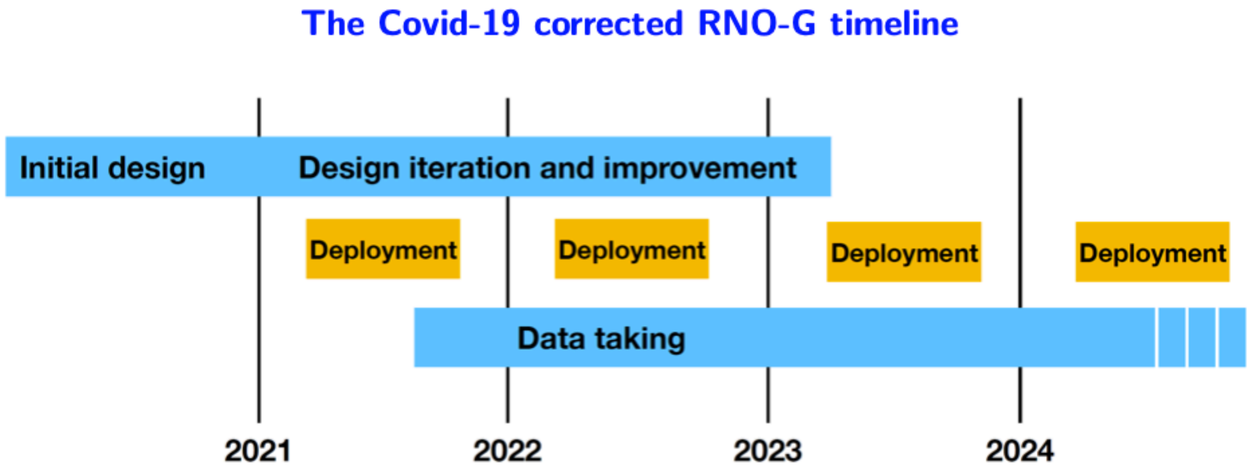
- 35 stations, 1.25 km spacing
  - Summit Station, Greenland
  - 3 stations deployed in Summer 2021

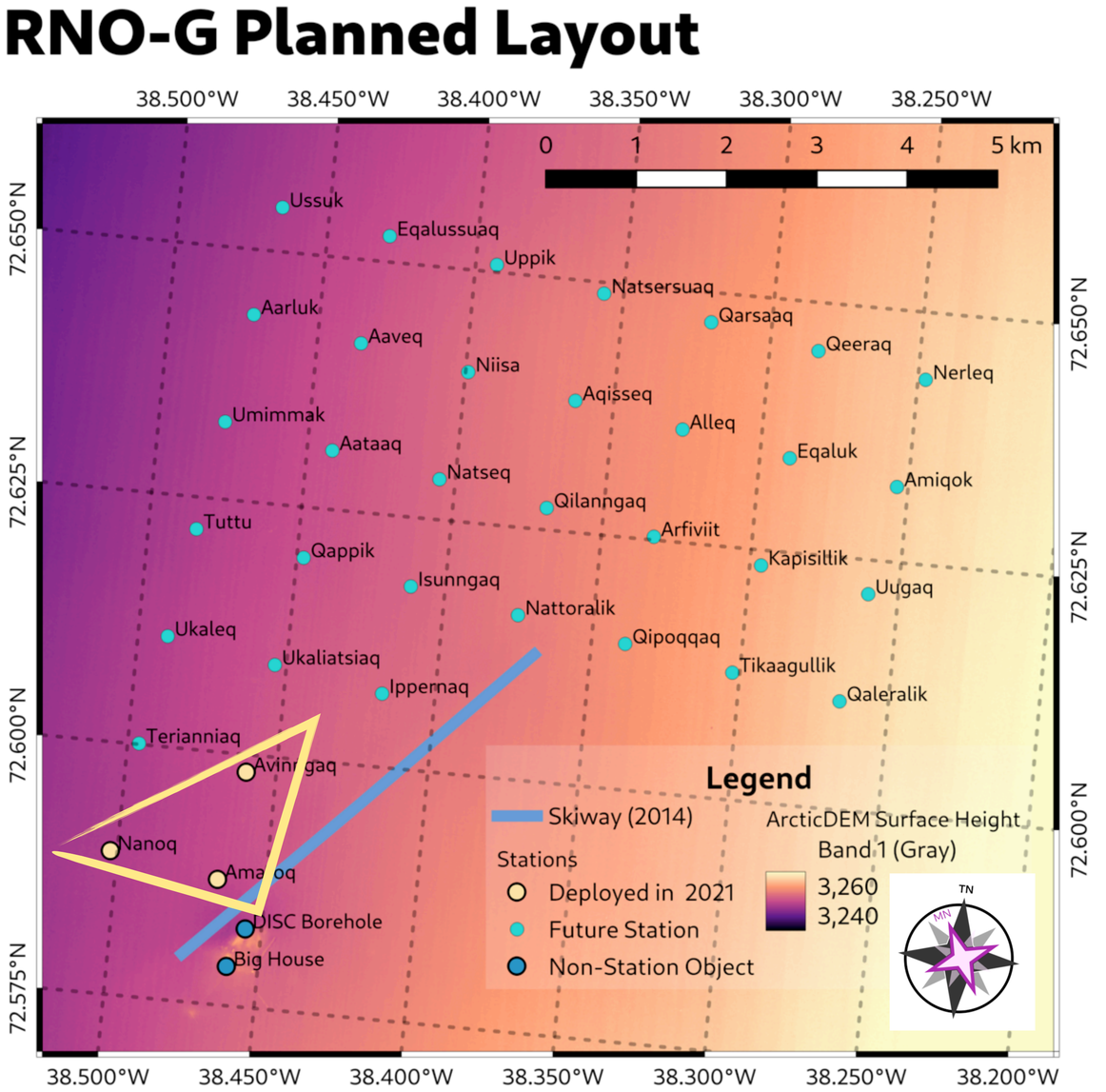




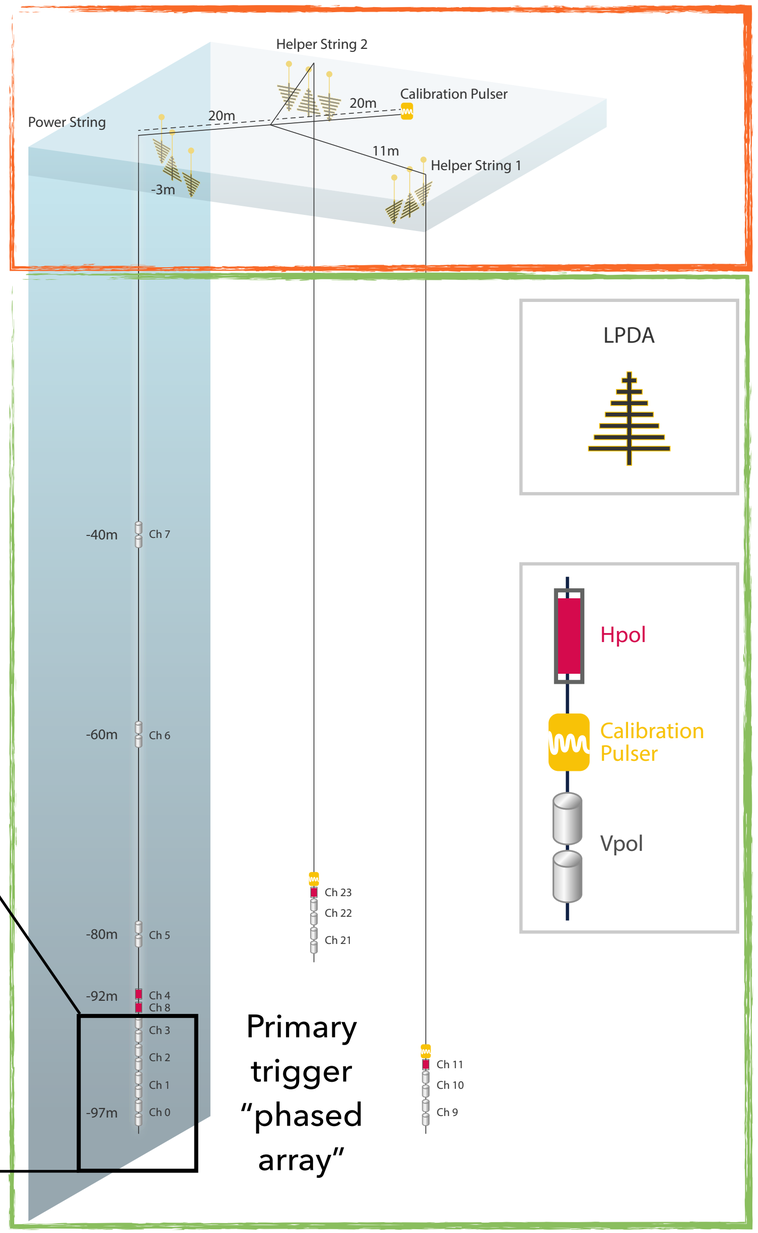
Radio Neutrino Observatory — Greenland (RNO-G): status

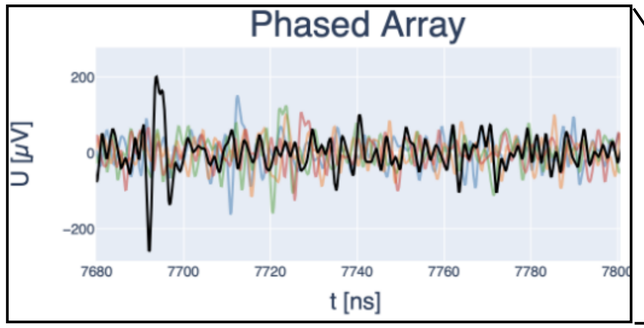
- 35 stations, 1.25 km spacing
  - Summit Station, Greenland
  - 3 stations deployed in Summer 2021
- Full array expected in 2024





RNO-G: station design





Shallow component

- ➡ CR detection.
- ➡ CR veto.
- ➡ additional channels for reconstruction.
- ➡ independent trigger.

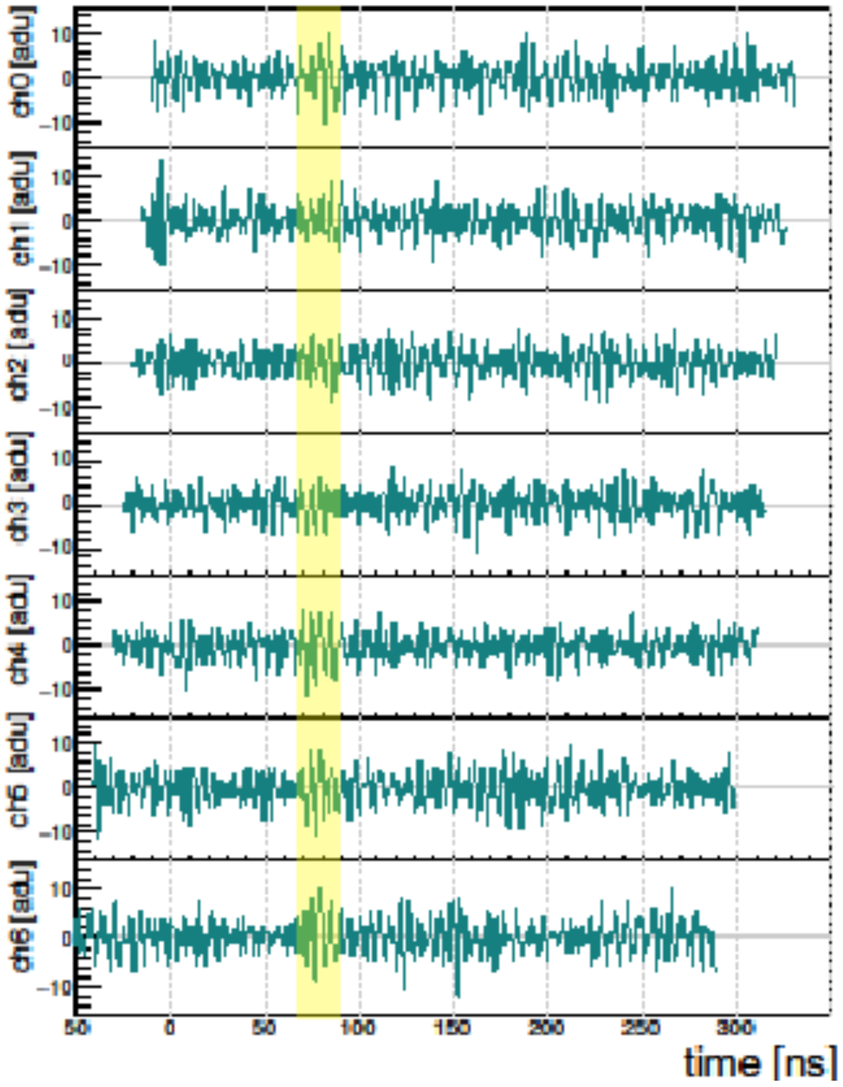
Deep component

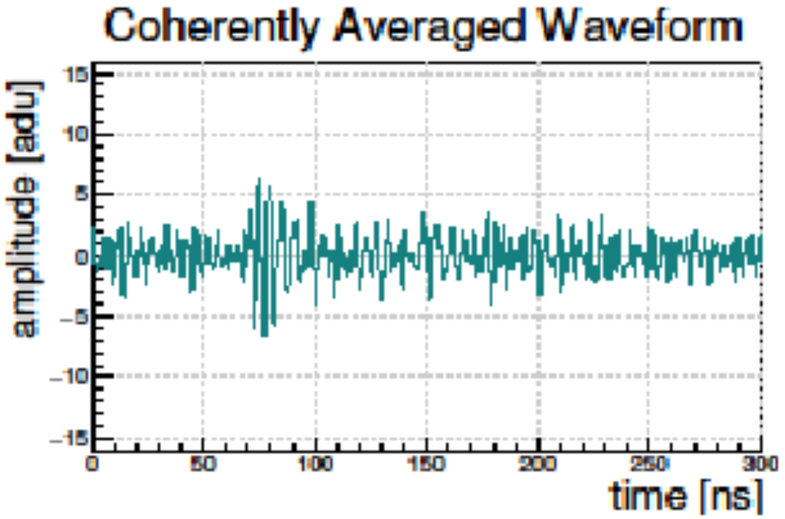
- ➡ Effective Volume.
- ➡ Low Threshold (2σ) trigger with compact phased array.
- ➡ Outrigger antennas enable reconstruction.

The phased trigger approach in ARA

[E. Oberla, ICRC 2019]

Low SNR calibration pulser signal

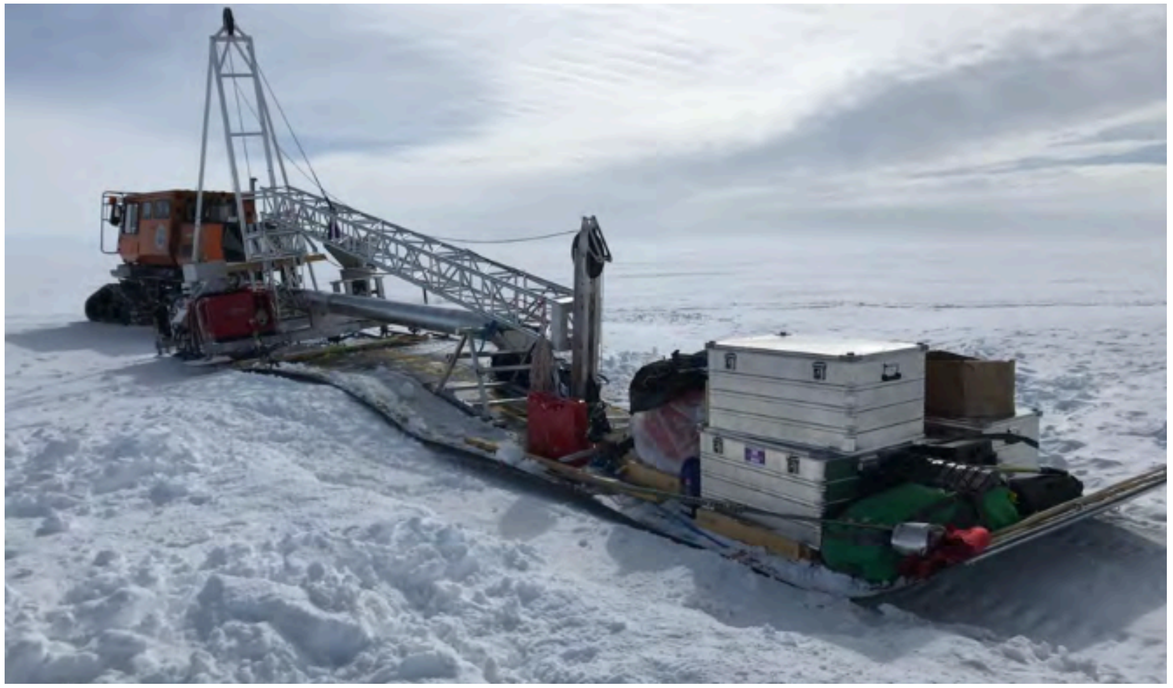


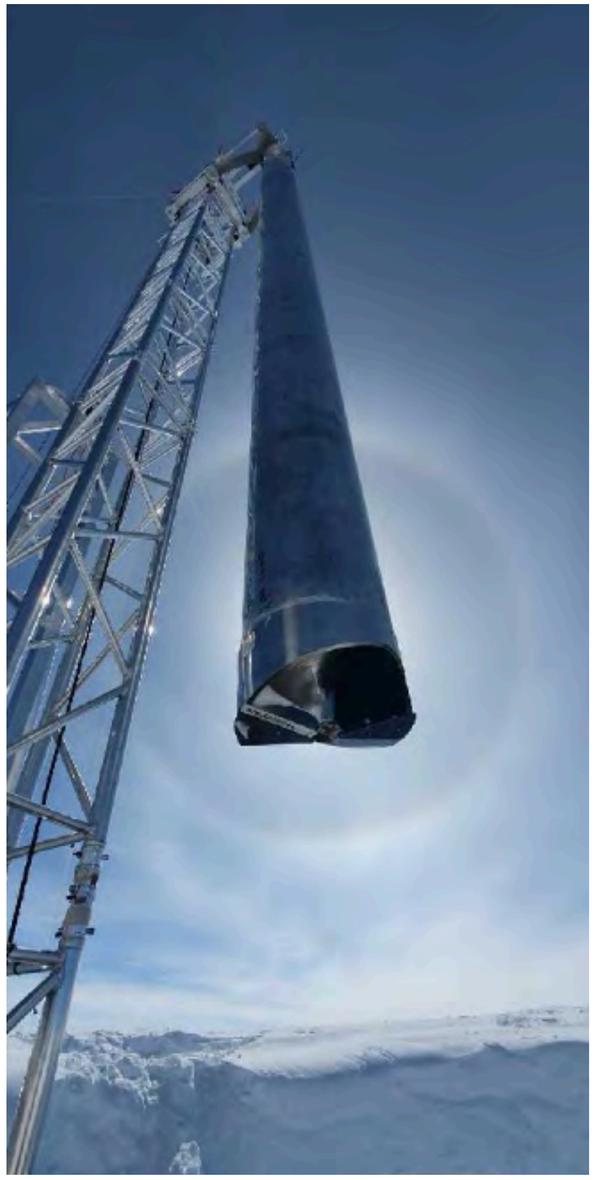


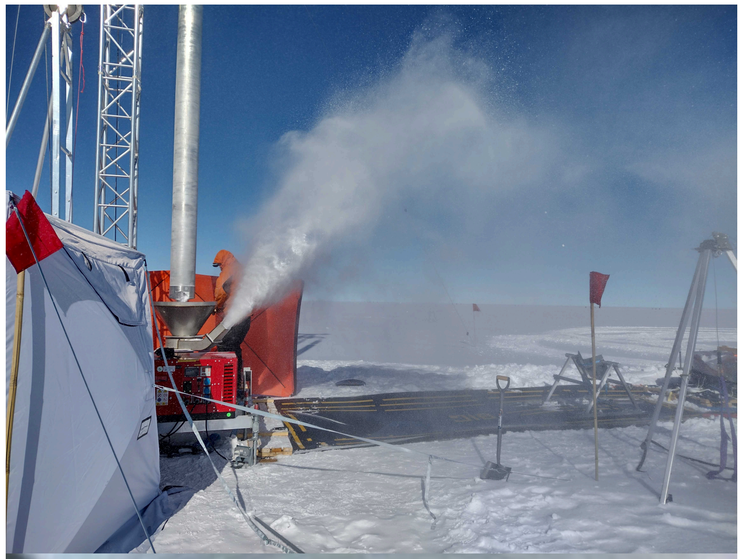
RNO-G: BAS BigRAID drill

Custom auger drill developed for RNO-G by the British Antarctic Survey:

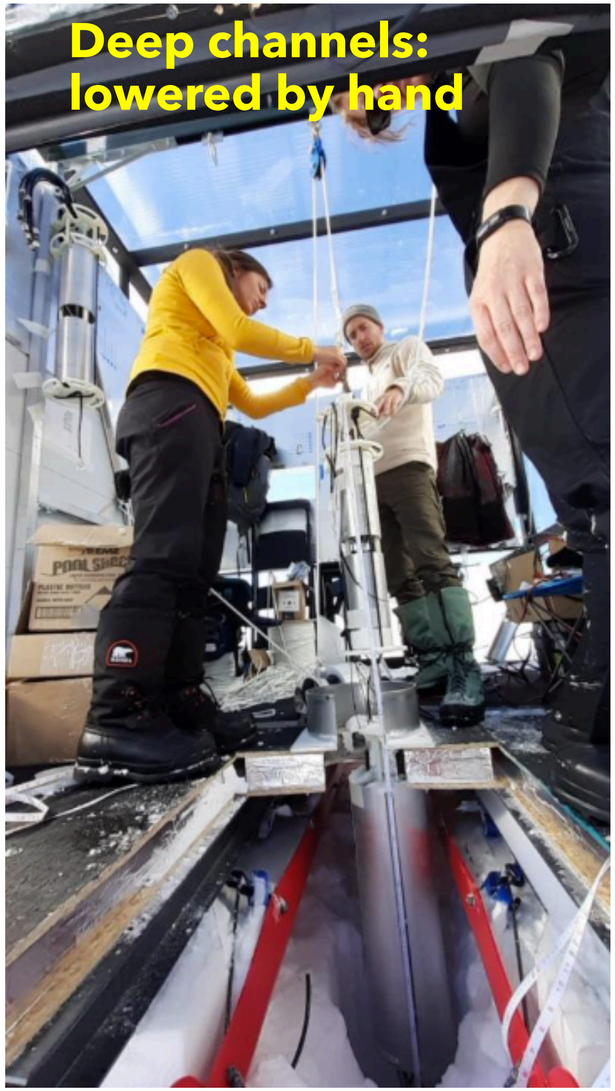
- ➡ 11-inch diameter holes
- ➡ Capable of drilling 1 hole to 100 m in 1 shift (2 people)
- ➡ Most holes drilled this season are 2 shifts / hole

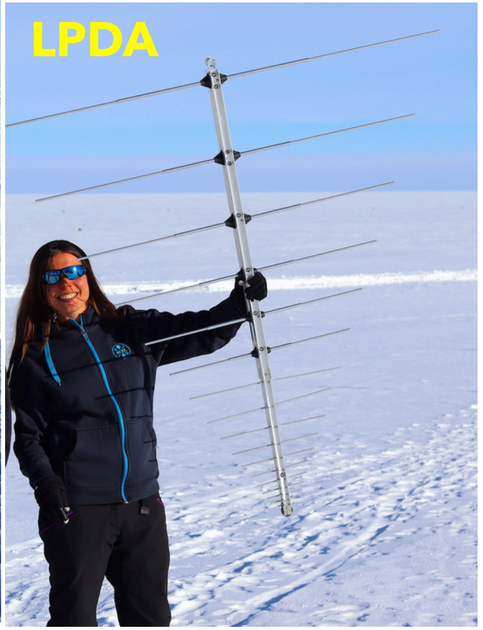






RNO-G: deployment — Season 2021



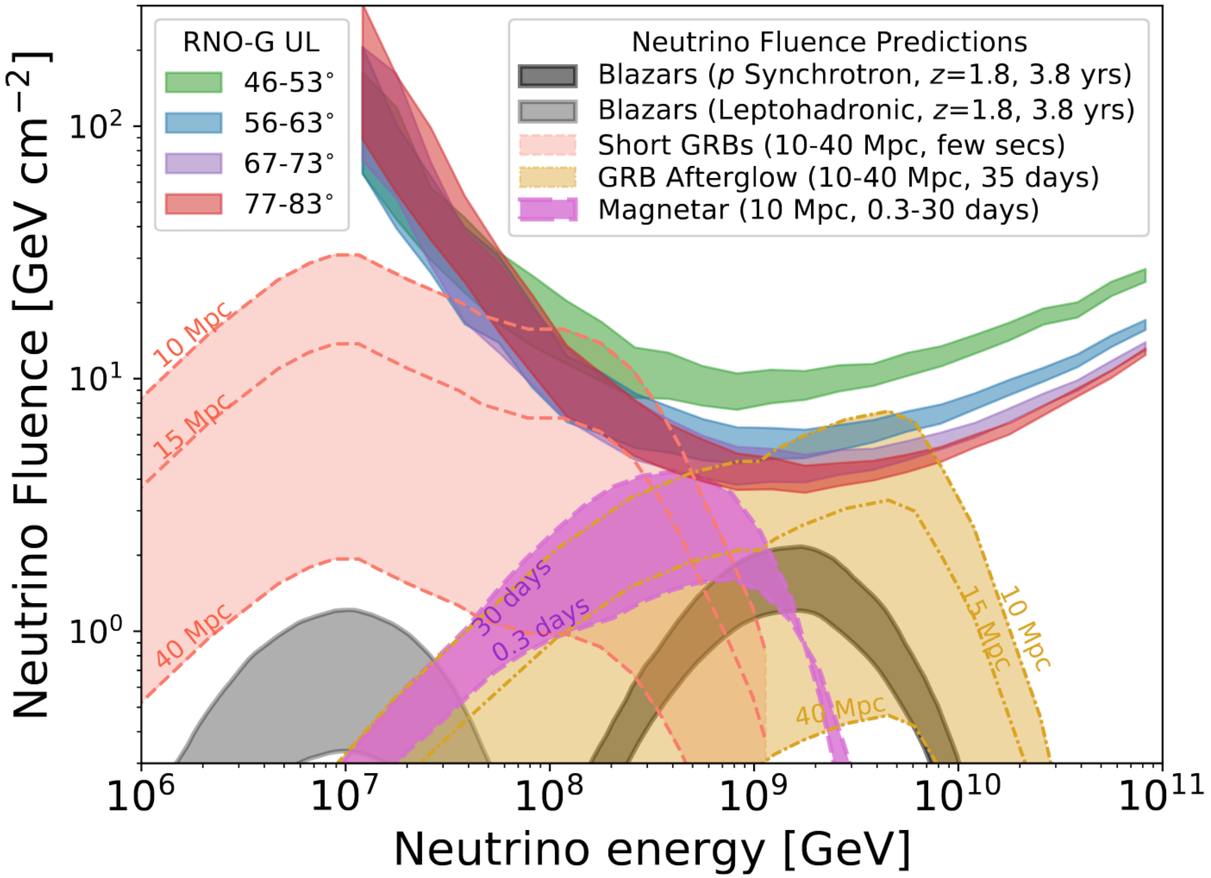


RNO-G: Autonomous power

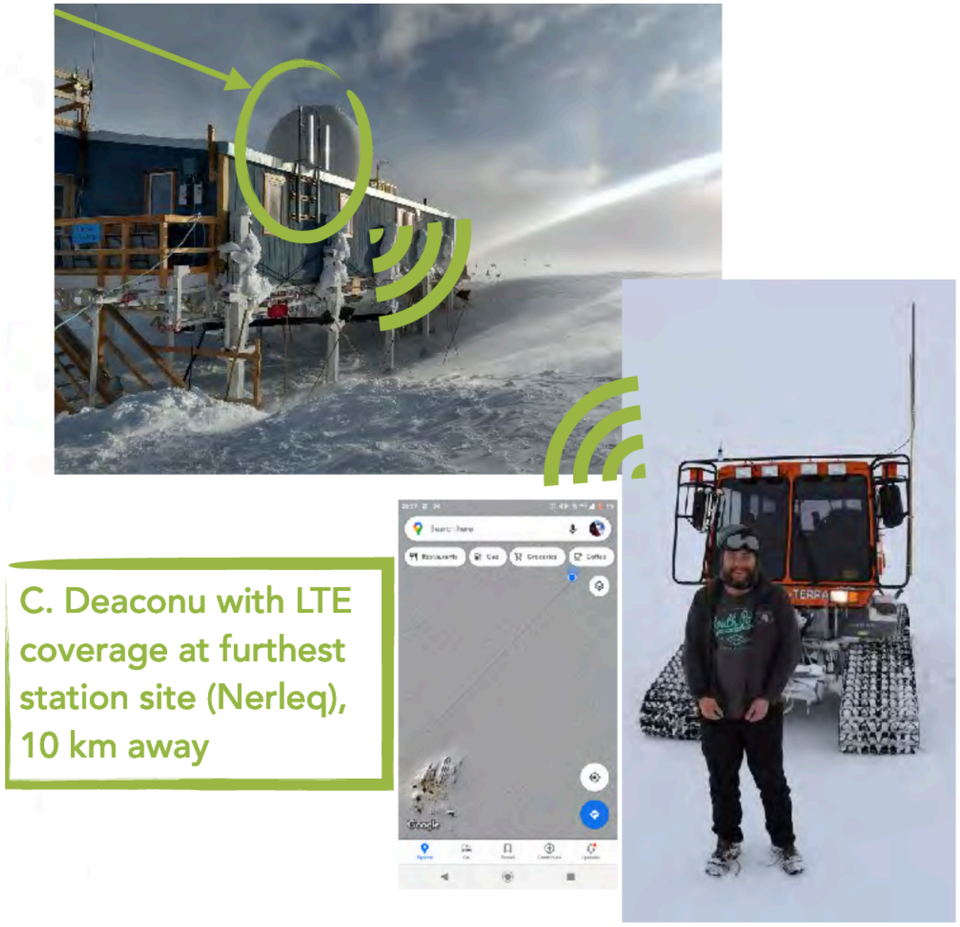
RNO-G: sensitivity to transient sources

- Unique capabilities to process alerts in nearly real time.
- Sensitive to nearby and/or transient events.

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



Multi-messenger follow-up enabled with continuous satellite coverage, beam-forming and LTE cellular comms networking

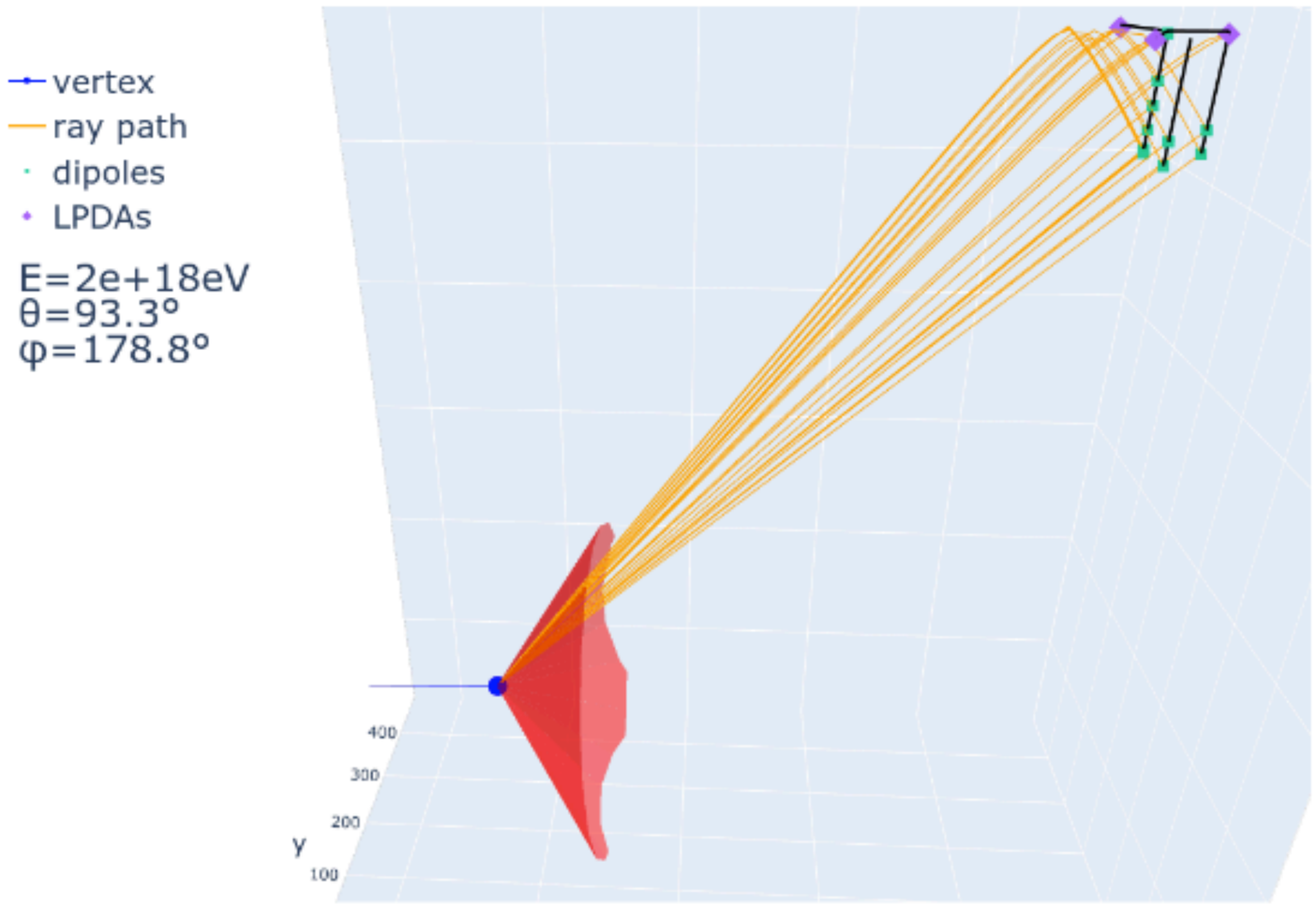


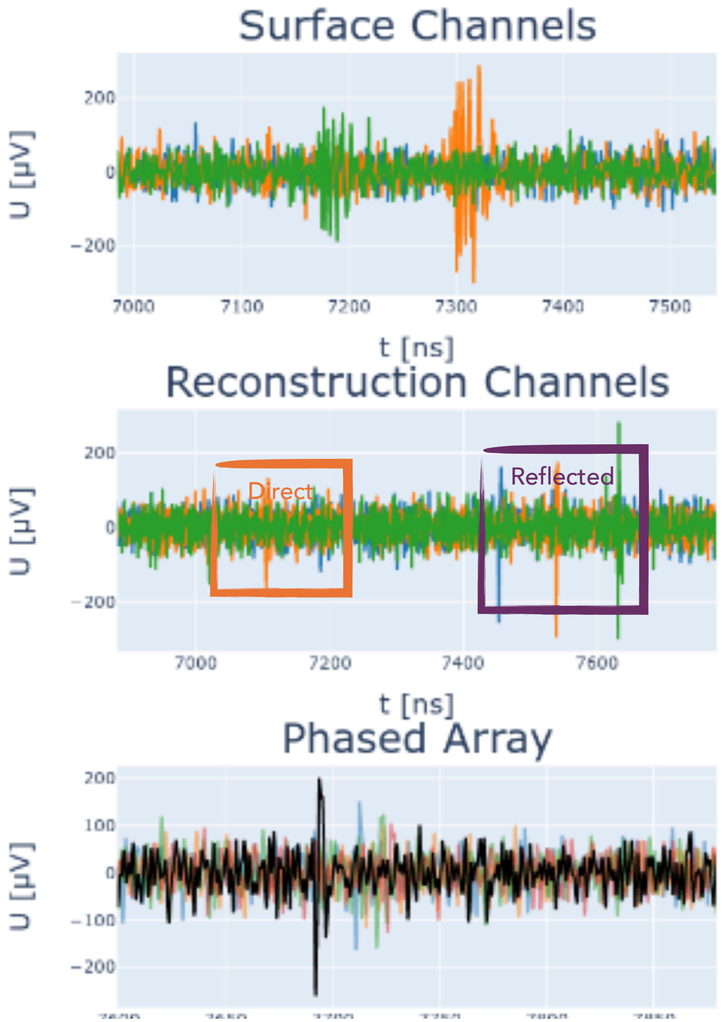
C. Deaconu with LTE coverage at furthest station site (Nerleq), 10 km away

First Station: Amaroq (Arctic Wolf)

Deployed June 2021

RNO-G: neutrino events - simulation





➤ **Two Types** of **Golden Events for Reconstruction:** (~20% each of the events at 10^{18} eV)

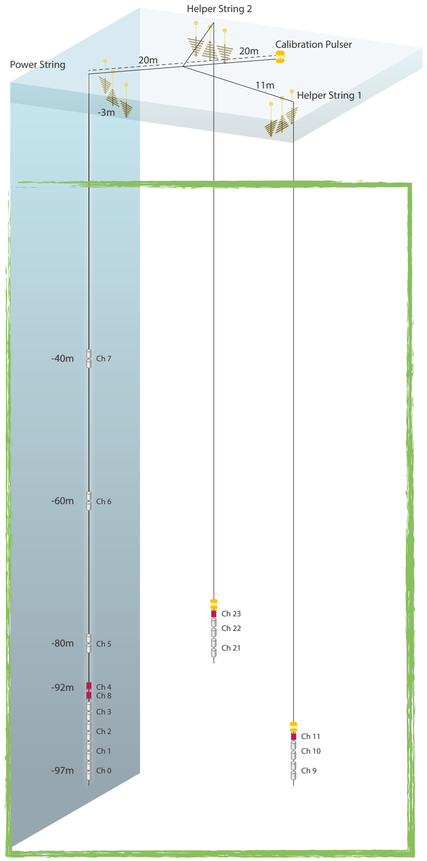
1. **Direct** *and* **reflected** signals on the downhole antennas
2. **Surface-Deep Coincident** Events

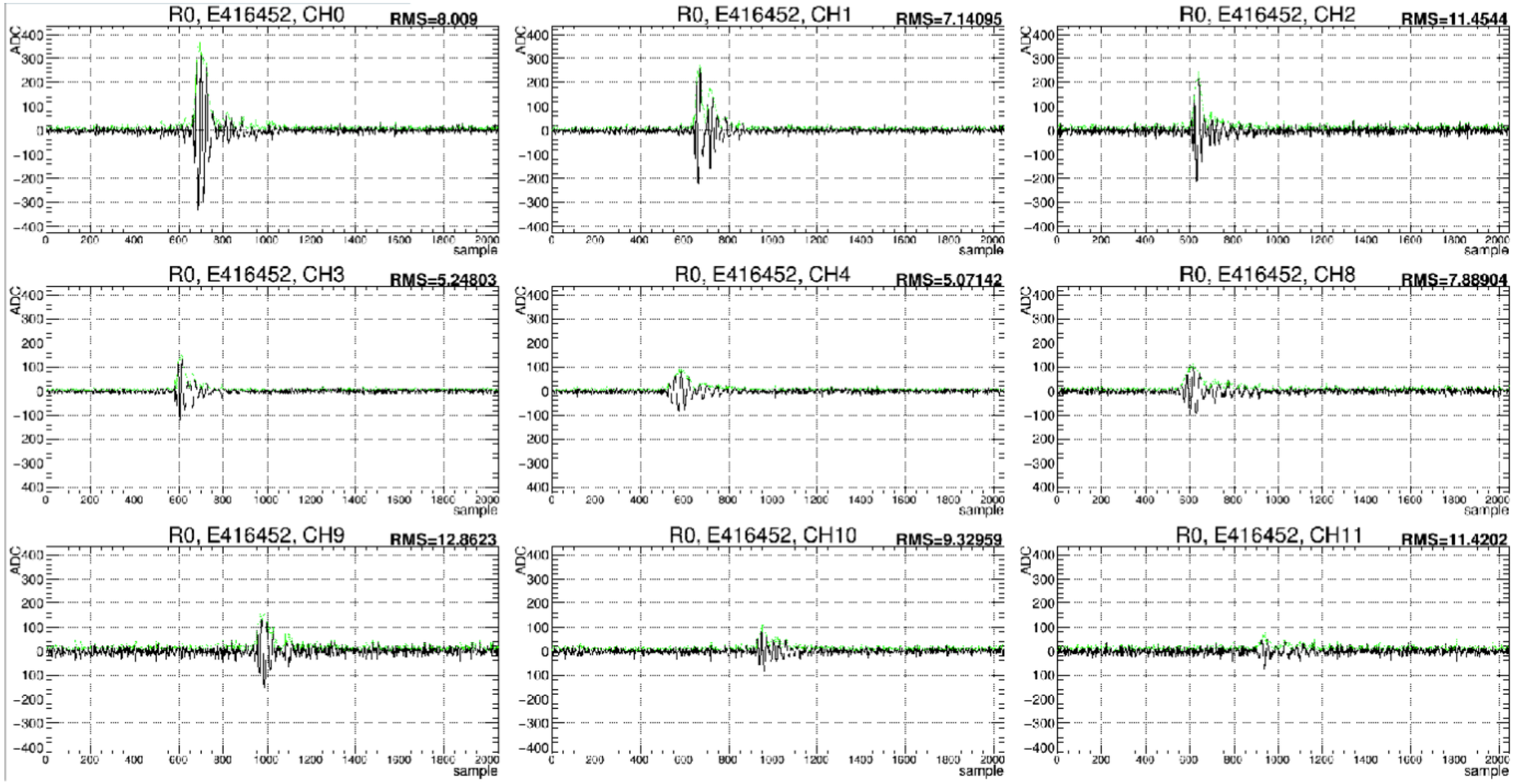
THIS EVENT HAS BOTH

S. Toscano

RNO-G: first deep events

Snowmobile lights up the deep channel.





RNO-G: potential backgrounds

1. Thermal noise
   - Dominates trigger rates but identification easy

2. Anthropogenic/environmental noise
   - Must come from the surface
   - Rejected by upward facing antennas (shallow)
   - Effects only small angular region (deep)

3. Rare physical backgrounds

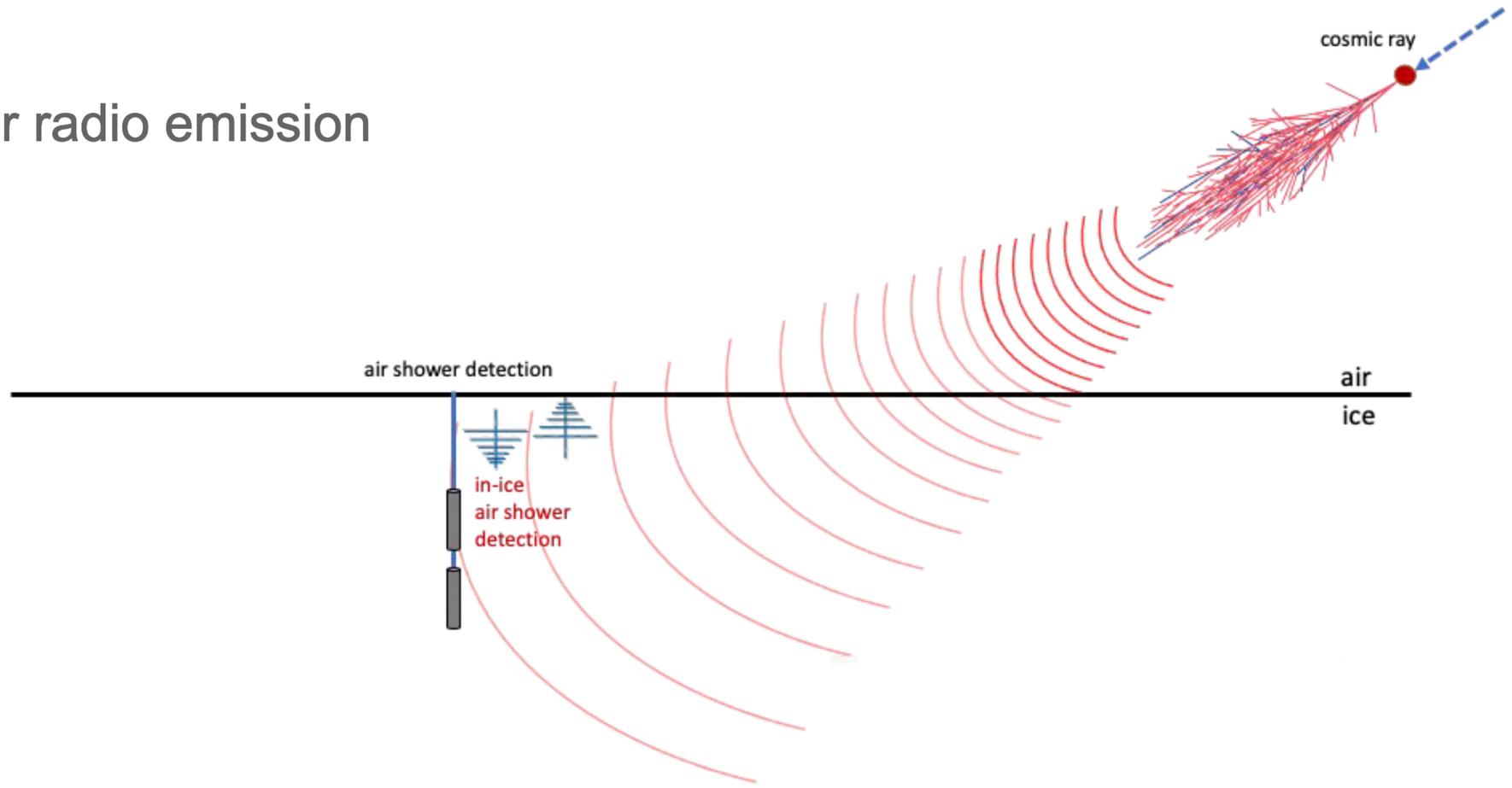
RNO-G: potential backgrounds

1. Thermal noise → Easy to reject
   - Dominates trigger rates but identification easy

2. Anthropogenic/environmental noise → Easy to reject
   - Must come from the surface
   - Rejected by upward facing antennas (shallow)
   - Effects only small angular region (deep)

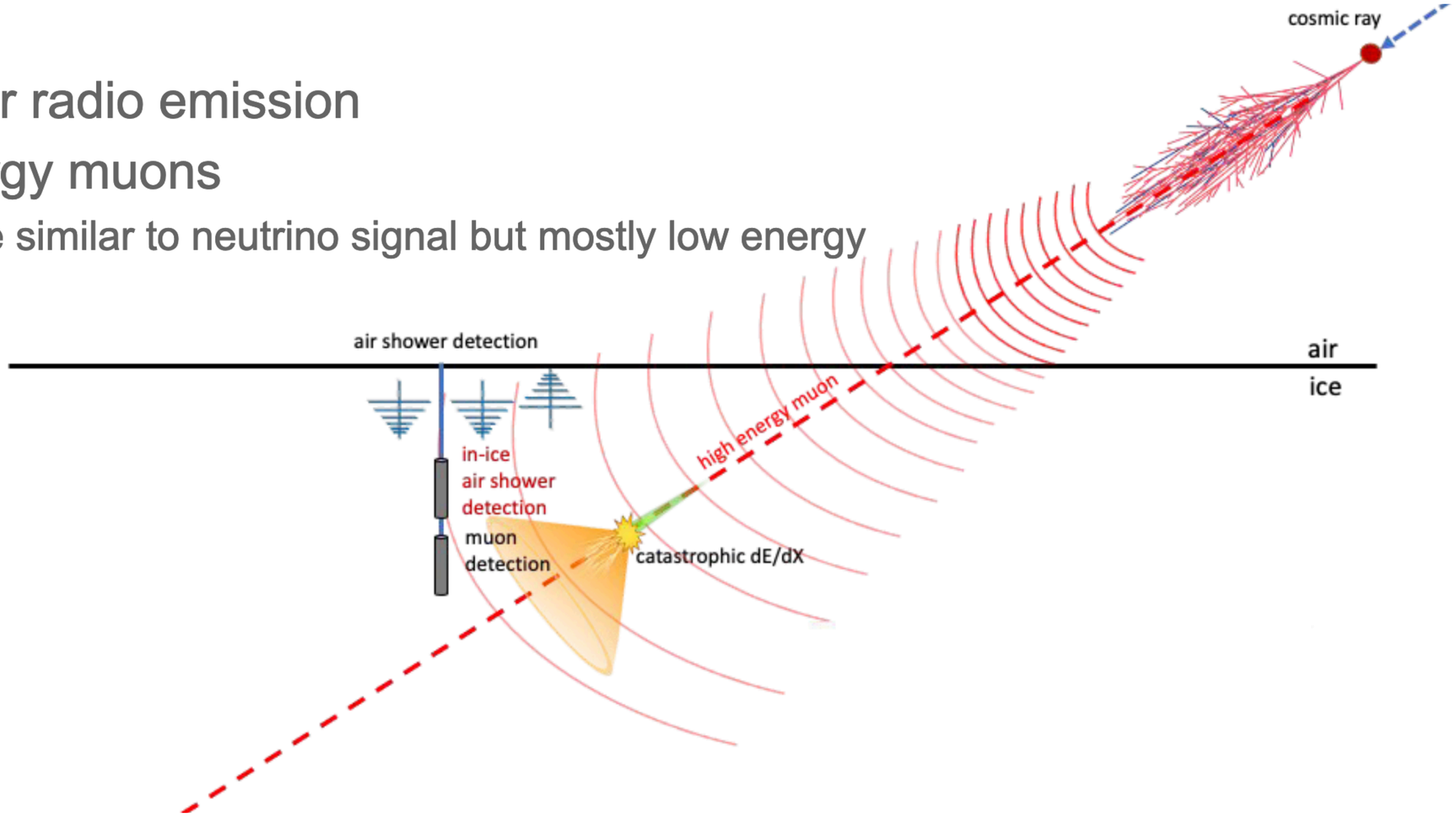
3. Rare physical background

1. Air shower radio emission



RNO-G: physical background

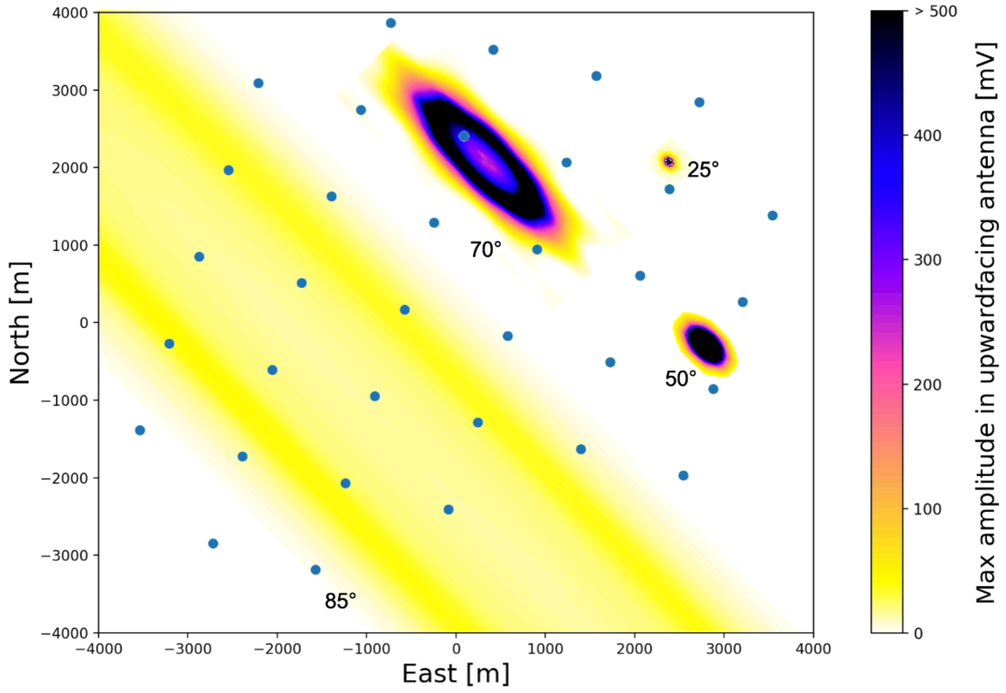
1. Air shower radio emission
2. High-energy muons
   a. signature similar to neutrino signal but mostly low energy



RNO-G: physical background

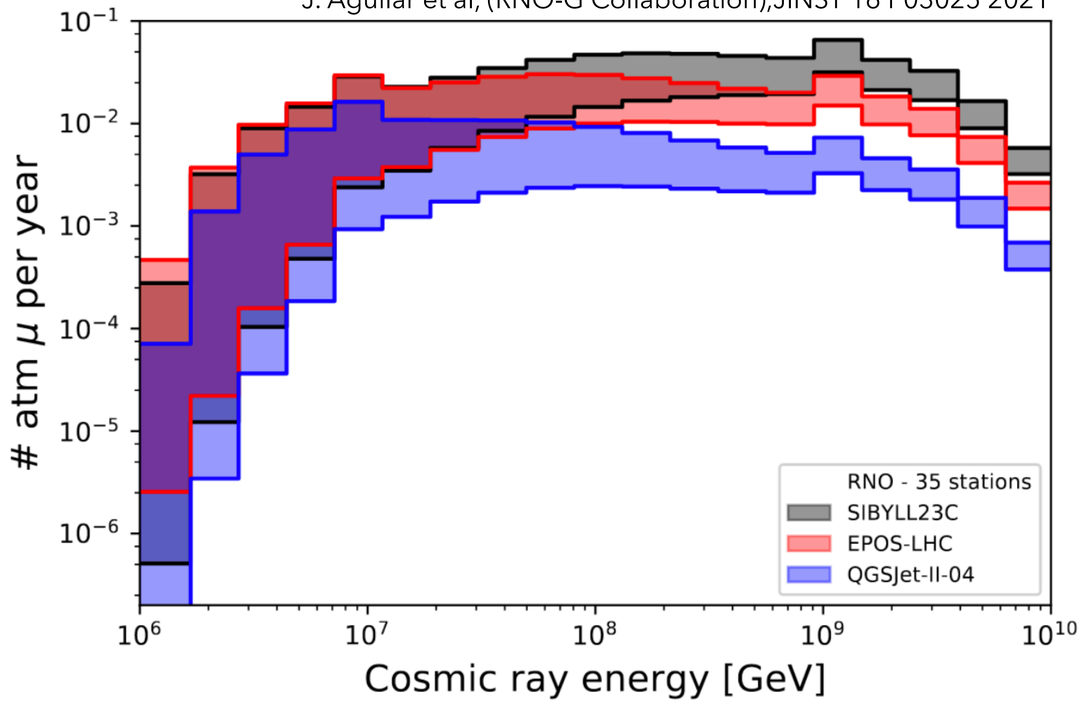
- Dangerous because can mimic a neutrino signal
- Shallow component vetoes both kinds
- Would otherwise be $\mathcal{O}(0.1-1)$ events per year for the array, comparable to possible neutrino event rates

Cosmic ray air showers



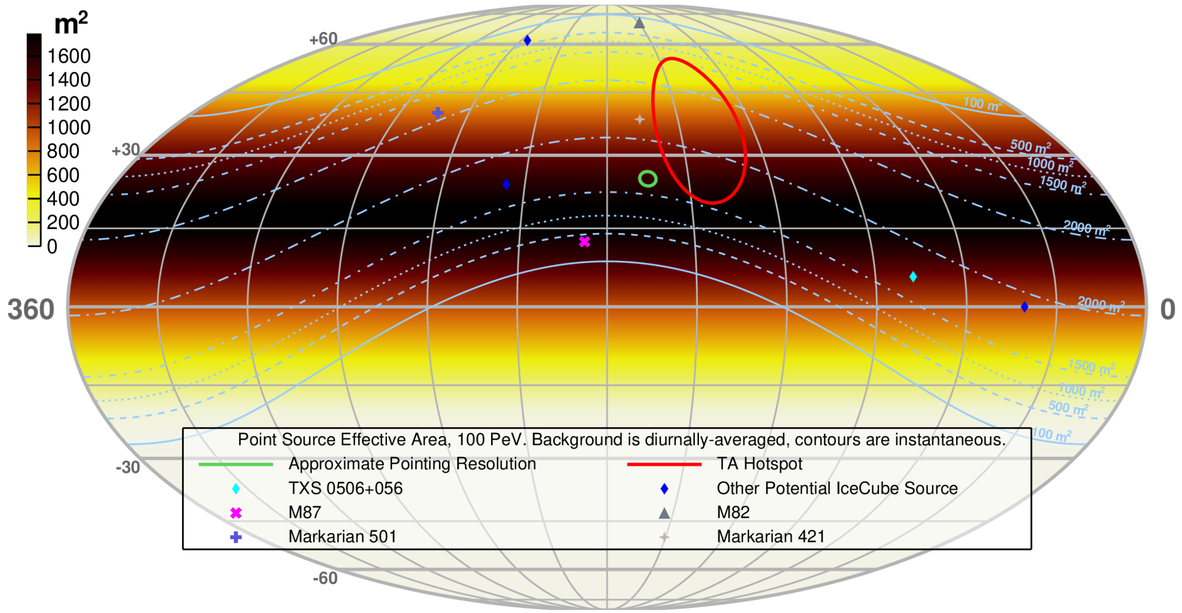
Penetrating muons

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



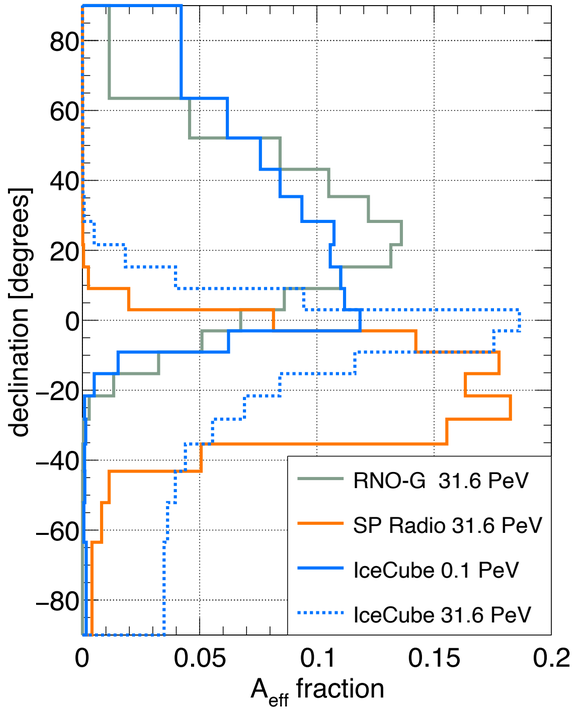
RNO-G: sky coverage for a Northern array

At UHE energies, primarily sensitive to down-going or Earth-skimming neutrinos

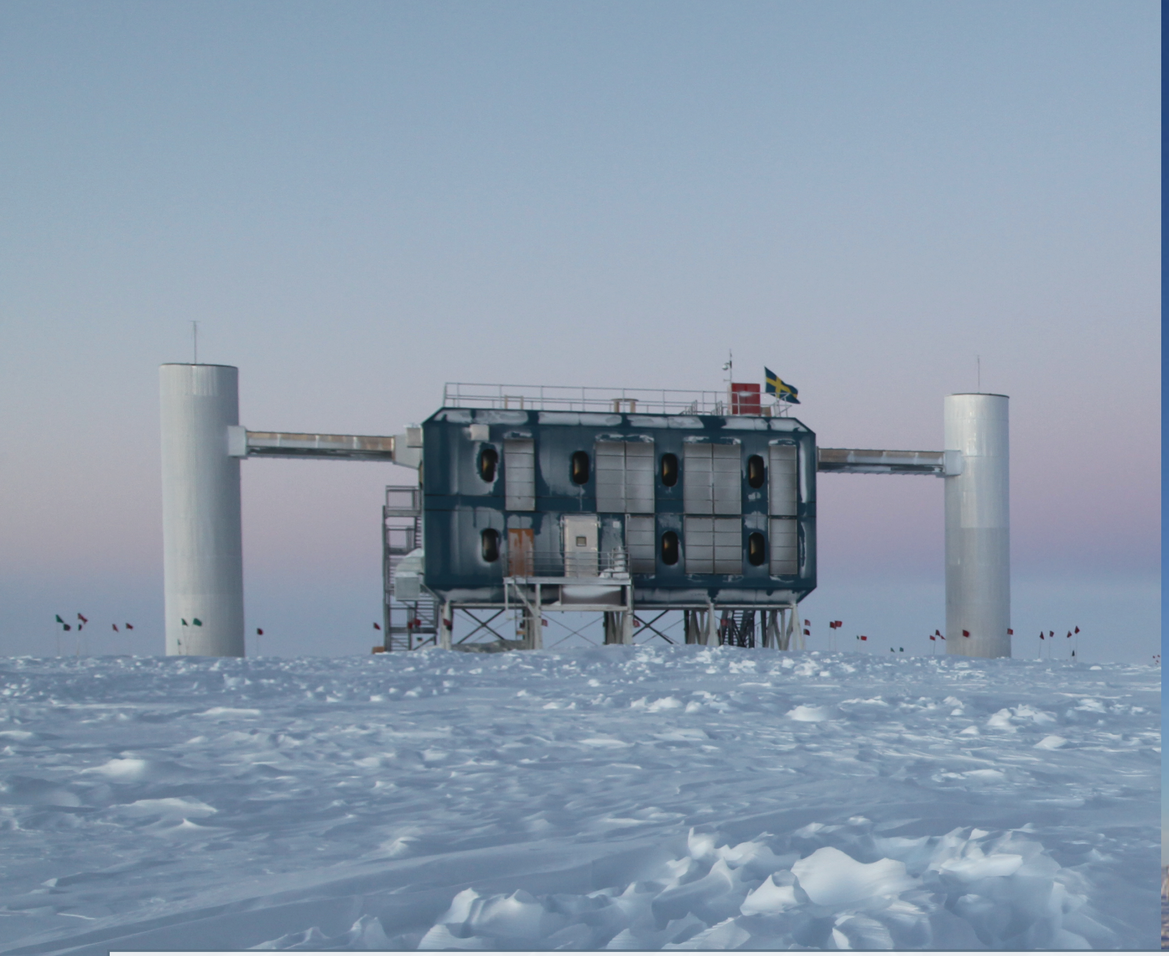


IceCube & TA Hotspots
atop RNO-G diurnally averaged sky coverage

RNO-G overlaps with IceCube at lower energies

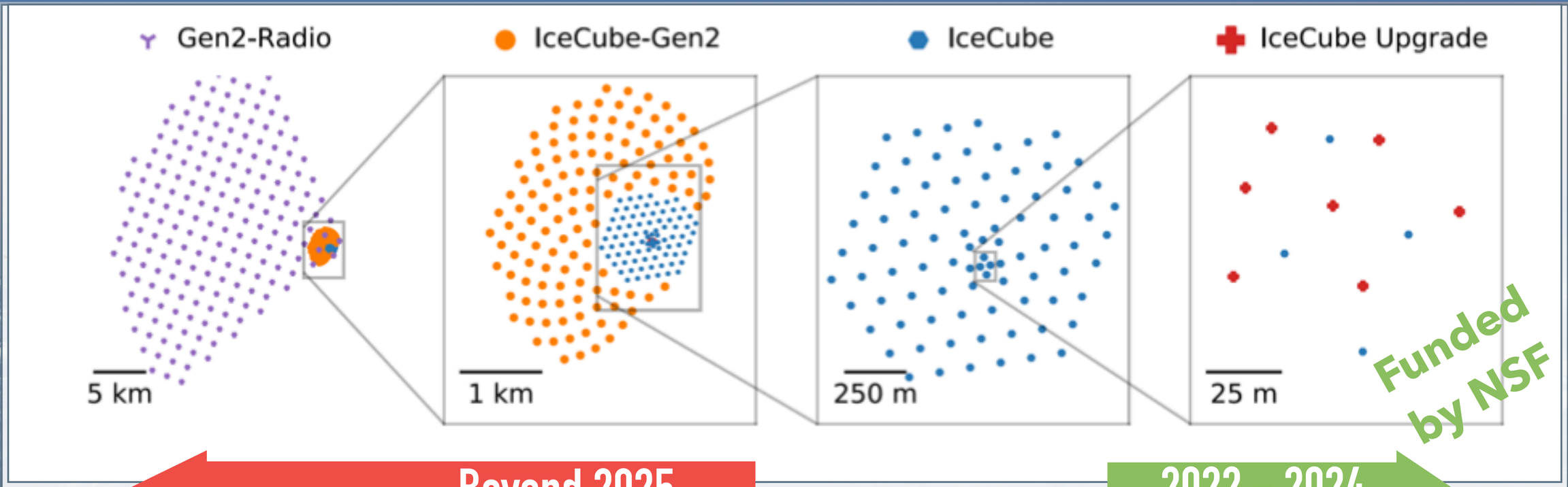


- Strong science case:
  - observing the same sky as IceCube but at higher energies allowing for **multi-energy (TeV to PeV)** observations of (steady and transient) sources
  - complementary to any Southern radio array in terms of FoV allowing for better sky coverage at PeV energy: synergy for **multimessenger neutrino alerts**.



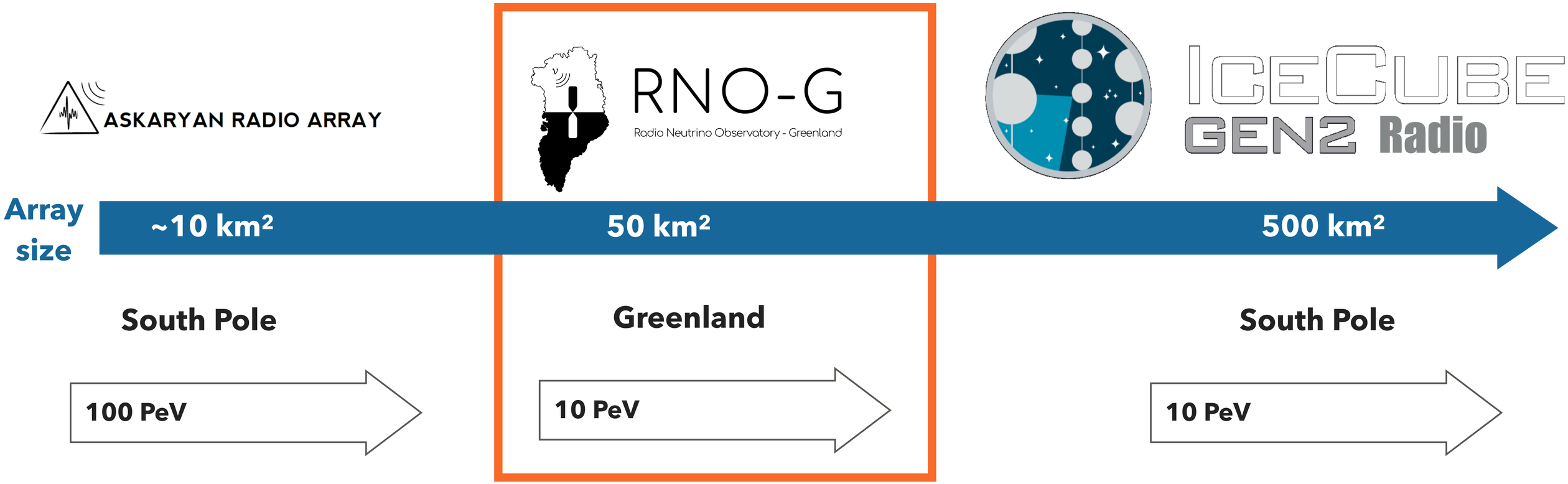
WHAT'S NEXT

FROM GREENLAND TO THE SOUTH POLE

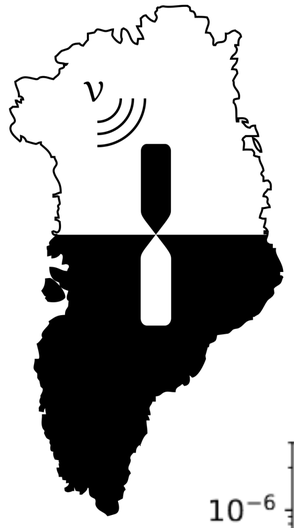


Radio community is working together towards a viable and scalable design.

RNO-G: the road towards Gen2-Radio



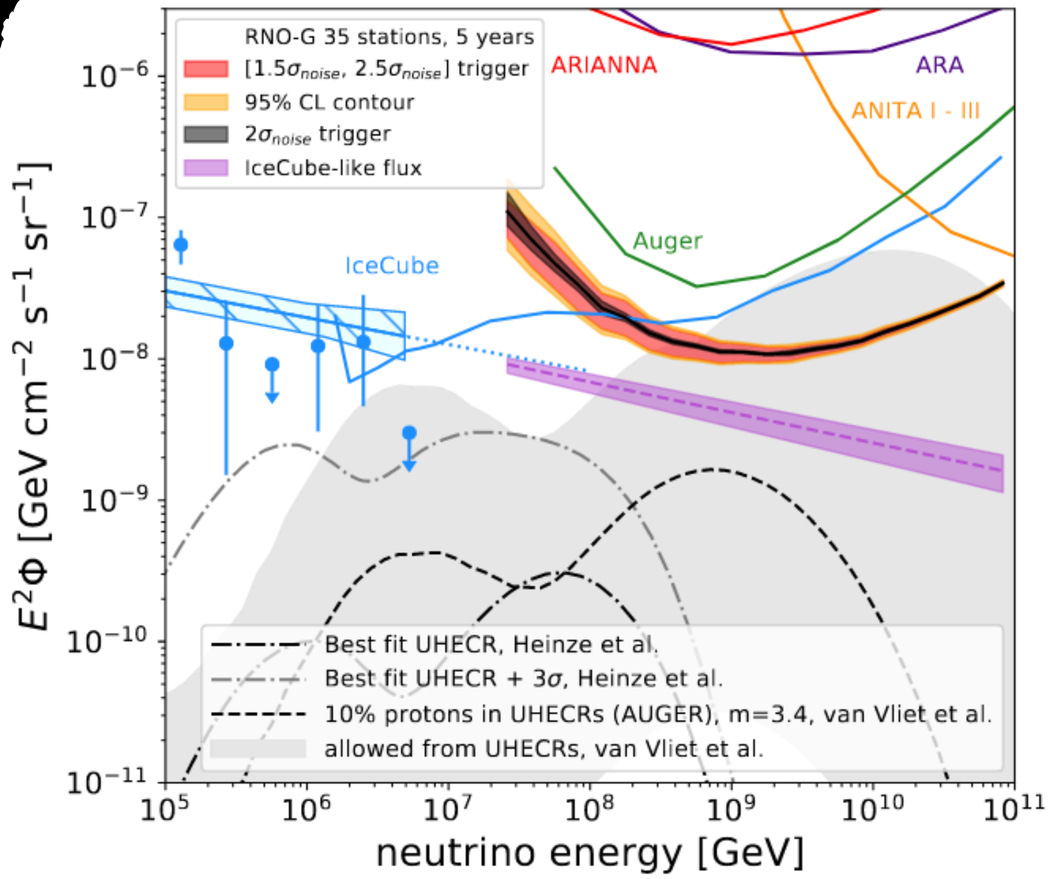
- RNO-G is a middle-scale **discovery** instrument
- RNO-G **design will inform** IceCube-Gen2 Radio design (now preparing for TDR).



RNO-G

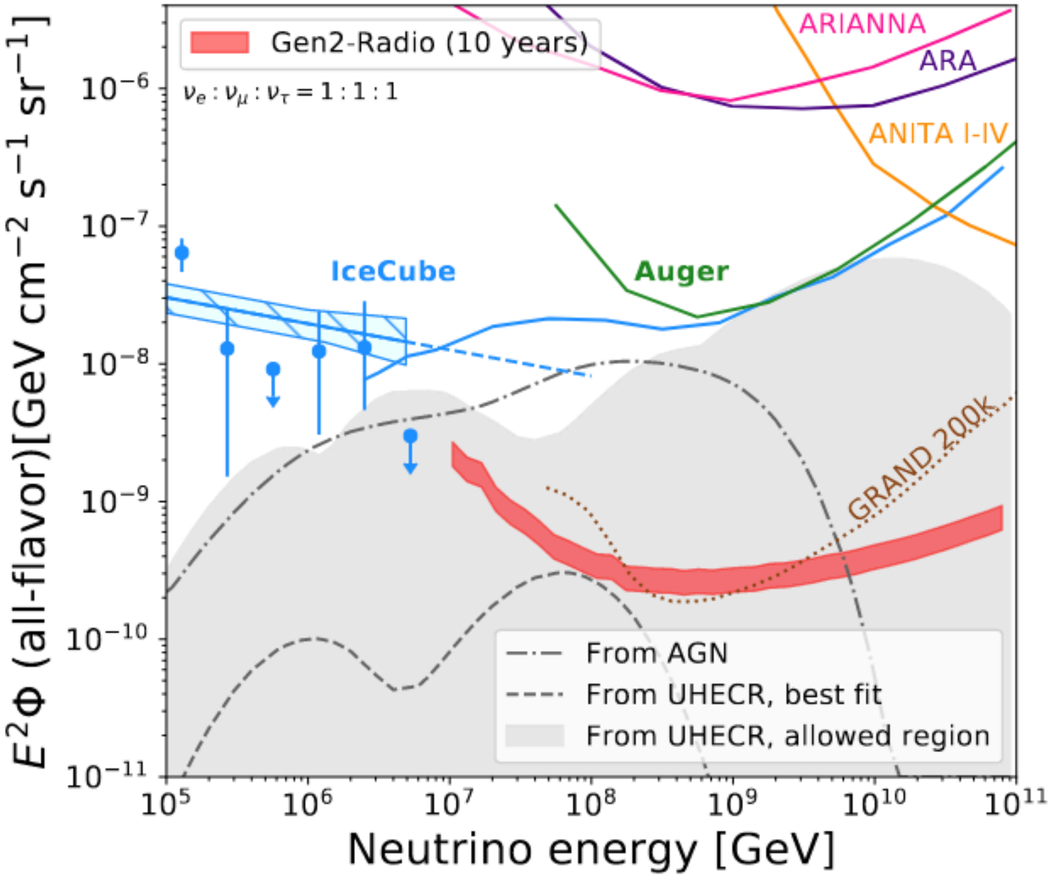
Radio Neutrino Observatory - Greenland

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



IceCube GEN2 Radio

Aartsen et al., (IceCubee-Gen2 Collaboration), arXiv:2008.04323



@RNO_Greenland

SUMMARY

- **Neutrino astronomy** has delivered on its premises (detection of cosmic neutrinos).
- **UHE neutrinos** missing piece to study the astrophysical flux and UHE cosmic ray (astro)physics.
- **Radio detection** is mature and the only feasible path to study the neutrino flux at E > 10 PeV.
- **RNO-G is the first science-level instrument** to target the UHE cosmic neutrino sky in the North
- **RNO-G is <u>important</u> R&D** for IceCube-Gen2

BACKUP

RNO-G: the phased array trigger approach

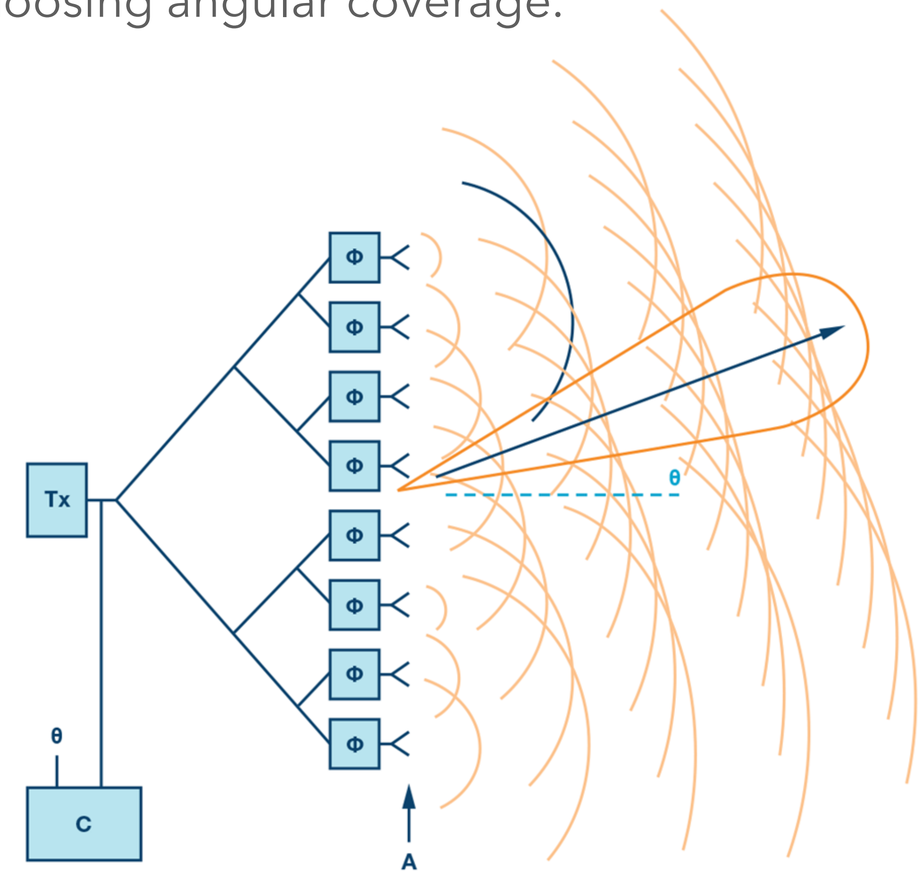
Beamforming technique

➡ Similar for receiving signals (commonly used radio astronomy)

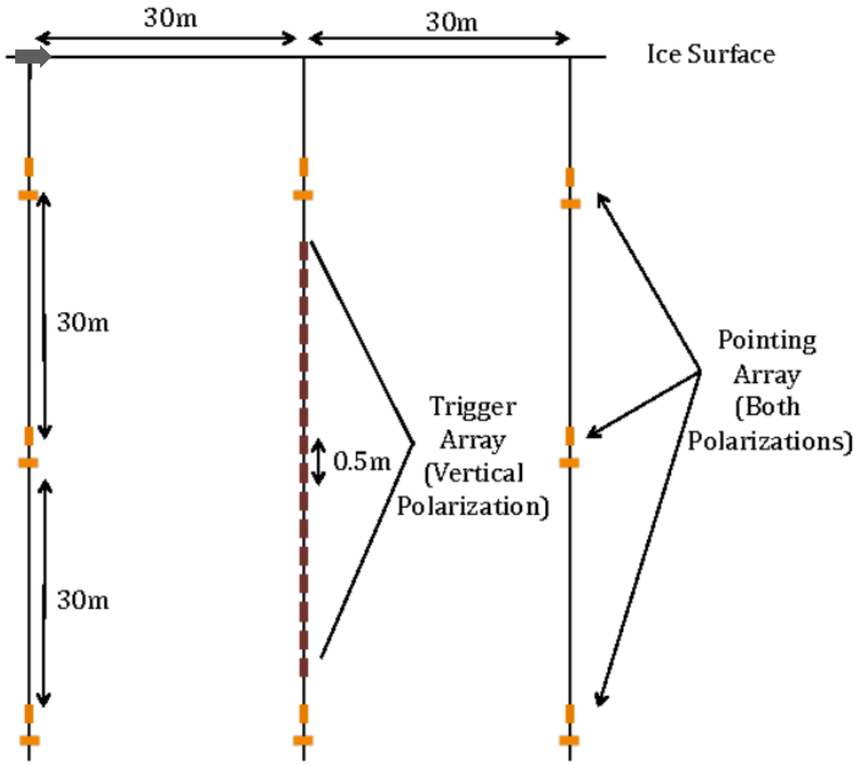
➡ Using multiple beams: high gain without loosing angular coverage.

➡In presence of uncorrelated thermal noise, coherent gain scales as $\sqrt{N_{antenna}}$.

➡Lower threshold for v detection.



Beamforming technique in ARA



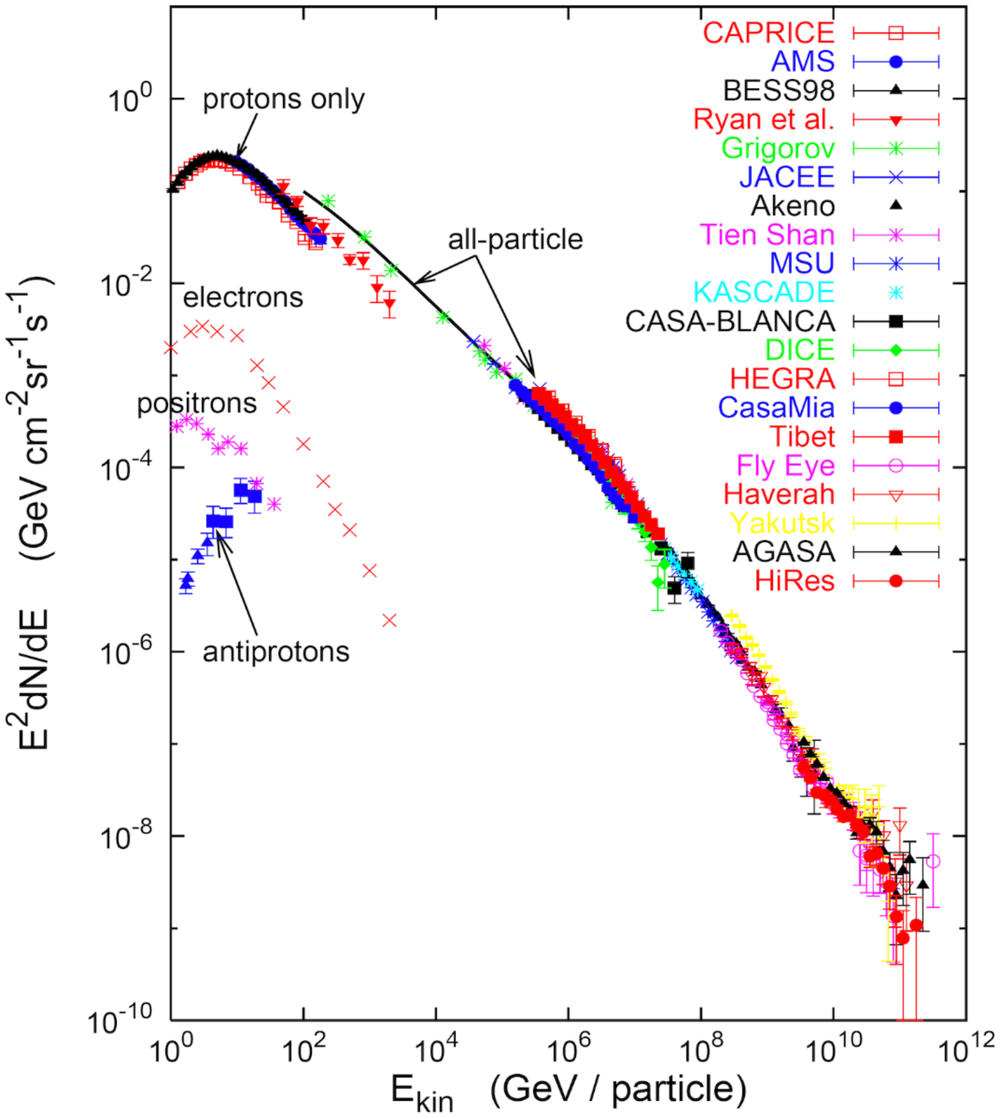
Cosmic rays: origin still unknown

- Cosmic rays discovered by Victor Hess more than a century ago (1912).
- Power law spectrum spanning over 10 decades in energy and more than 30 orders of magnitude in flux.
- Origin still unknown.
- **Strong connection with neutrinos and high-energy gamma rays.**

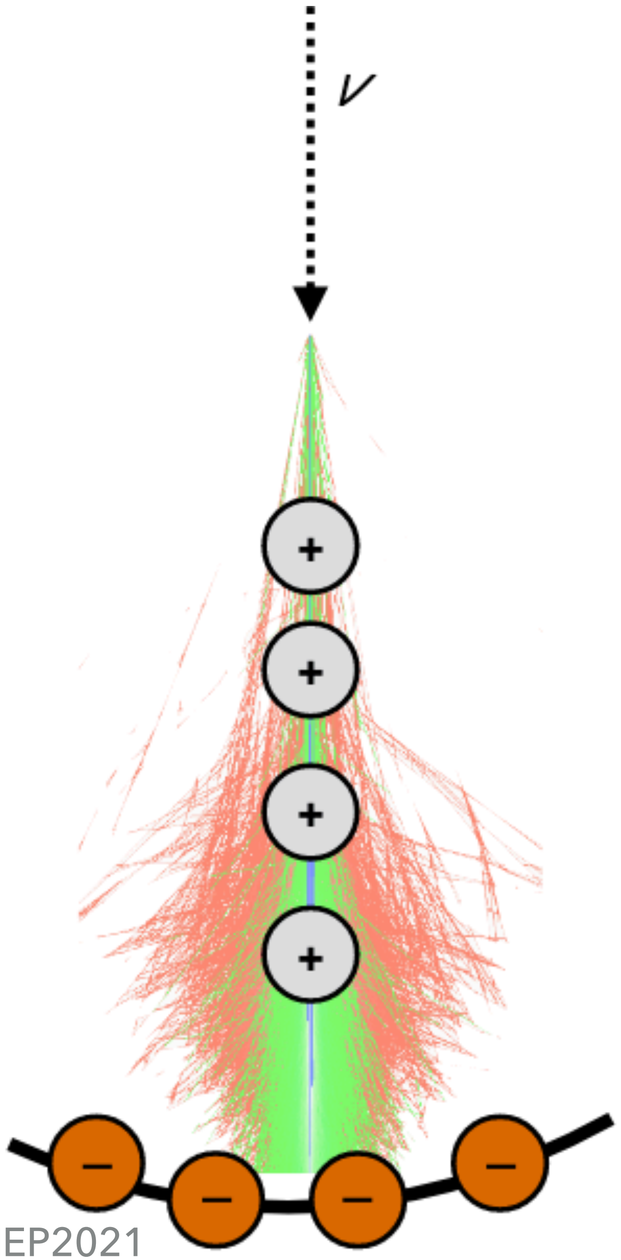
$$p + \gamma_{target} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \overline{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$



In-ice Radio Neutrino Detection: the Askaryan effect



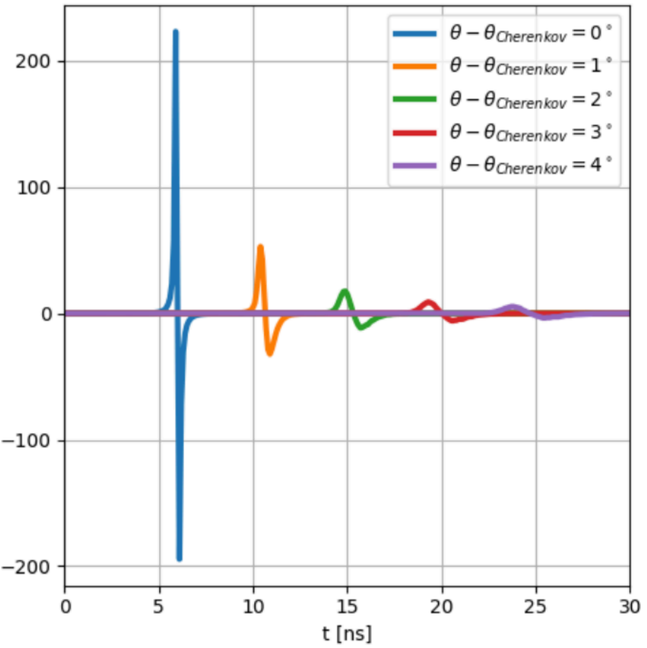
Neutrino-nucleon interaction creates electromagnetic or hadronic

- Shower develops a negative charge excess (Compton scattering and pair production).
- A moving charge creates currents and a current varying with time creates electromagnetic emission.
- Radio waves move in ice slower than the relativistically moving particle front (v > c / n) ->**Cherenkov** compression
- $\lambda > R_{Moliere}$ add coherently ($P \propto E^2$), producing a characteristic **broadband** (200 MHz - 1 GHz), **bipolar, impulsive** radio signal**.**

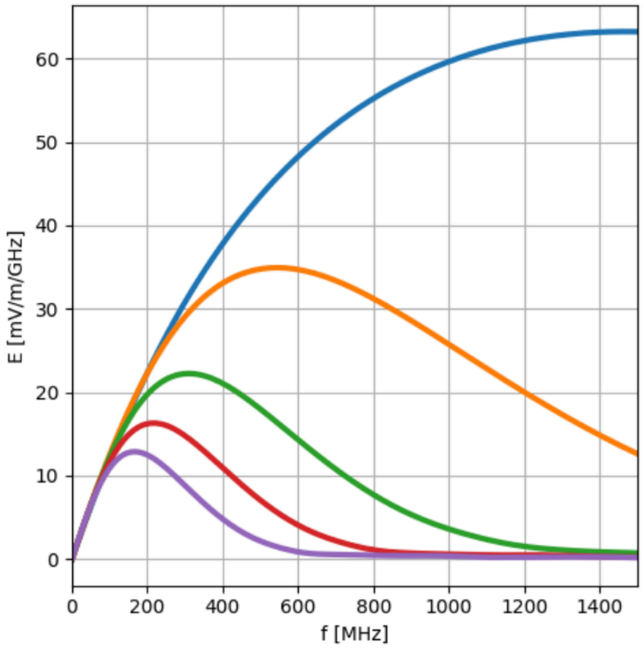
In-ice radio detection: Askaryan emission

We are looking for impulsive **nanosecond-scale** broadband (**10 MHz — 1 GHz**) signal

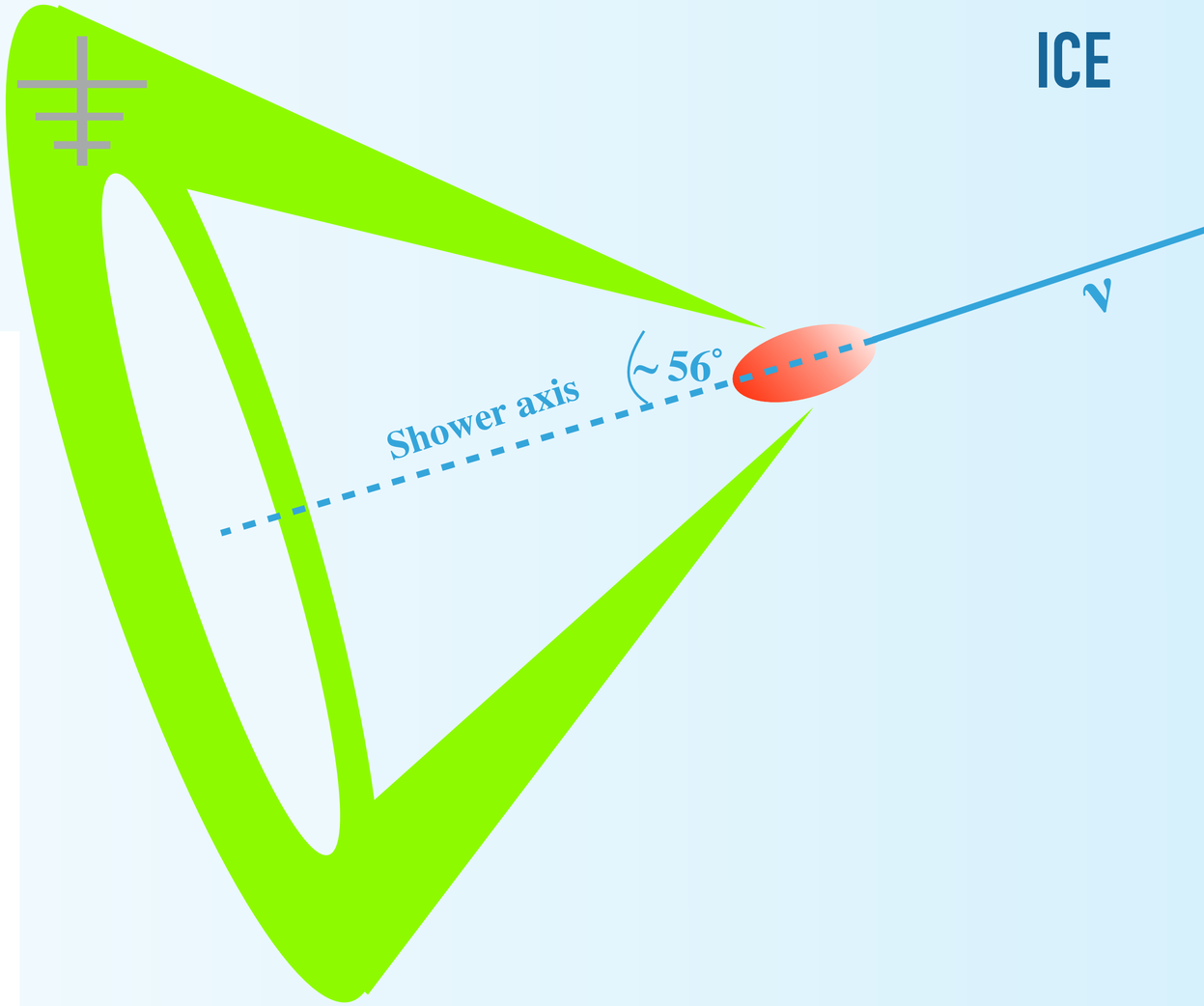
J. A. Aguilar et al. (RNO-G Collaboration), JINST 16 P03025 2021.



IMPULSIVE RADIO SIGNAL



BROADBAND PULSE



Emission strongest and higher frequency at Cherenkov angle

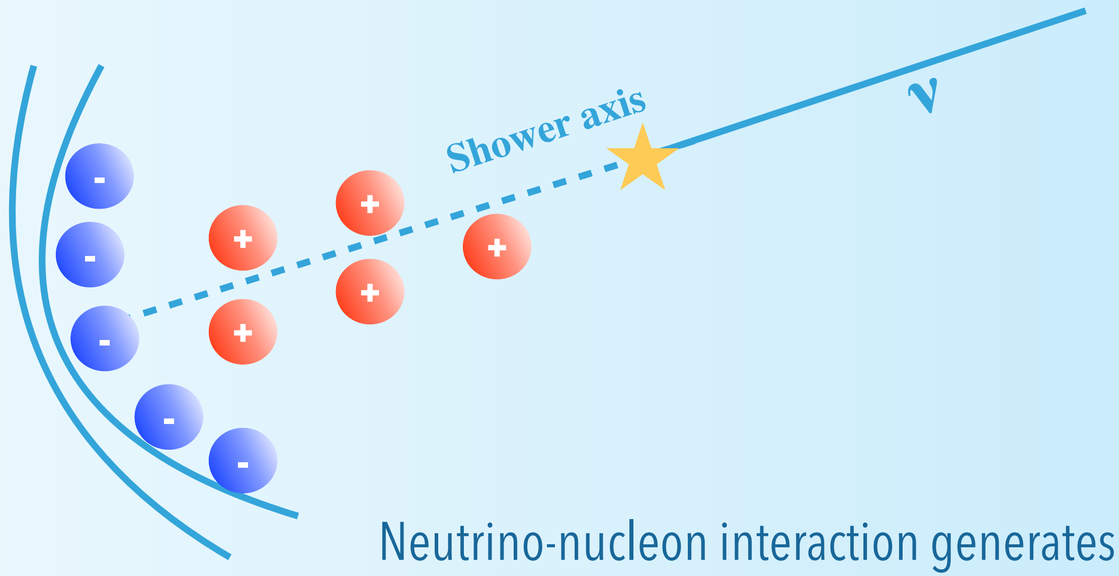
SUMMARY

@RNO_Greenland

- **Neutrino astronomy** has delivered on its premises (detection of cosmic neutrinos).
- **UHE neutrinos** missing piece to study the astrophysical flux and UHE cosmic ray (astro)physics.
- **Radio detection** is mature and the only feasible path to study the neutrino flux at E > 10 PeV.
- **RNO-G is the first science-level instrument to target the UHE cosmic neutrino sky in the North**
  - ➡ Plans are underway to build 35 stations in ~ 3 years
  - ➡ Multi-energy observation to study neutrino spectrum and multi-messenger campaign.
- **RNO-G is <u>important</u> R&D for IceCube-Gen2**
  - ➡ Autonomous, low power, low threshold stations
  - ➡ Combined surface & deep channels
  - ➡ Tests of deployment strategies, hardware improvements at large scale

In-ice radio detection: Askaryan emission

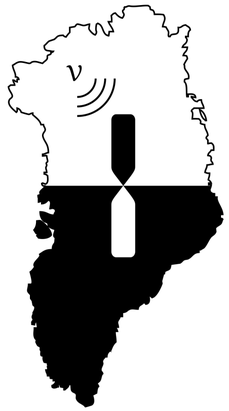
- Shower develops a negative charge excess (Compton scattering and pair production).
- A moving charge creates currents and a current varying with time creates electromagnetic emission.
- Radio waves move in ice slower than the relativistically moving particle front (v > c / n) ->**Cherenkov** compression
- $\lambda > R_{Moliere}$ add coherently ($P \propto E^2$), producing a characteristic **broadband** (200 MHz - 1 GHz), **bipolar, impulsive** radio signal**.**

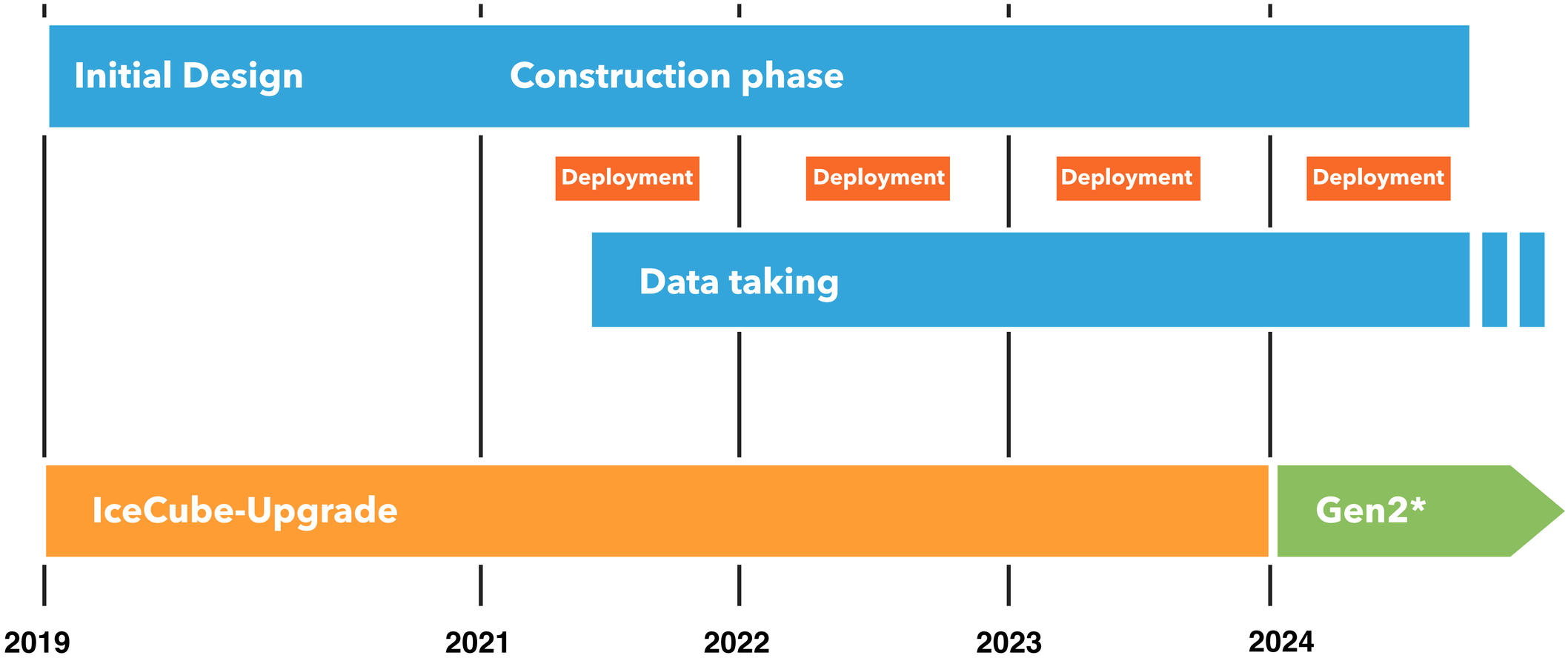


Neutrino-nucleon interaction generates hadronic/electromagnetic shower

RNO-G and IceCube-Gen2 radio: timeline / COVID-19 corrected

No interference with the Upgrade construction but still supported by NSF.

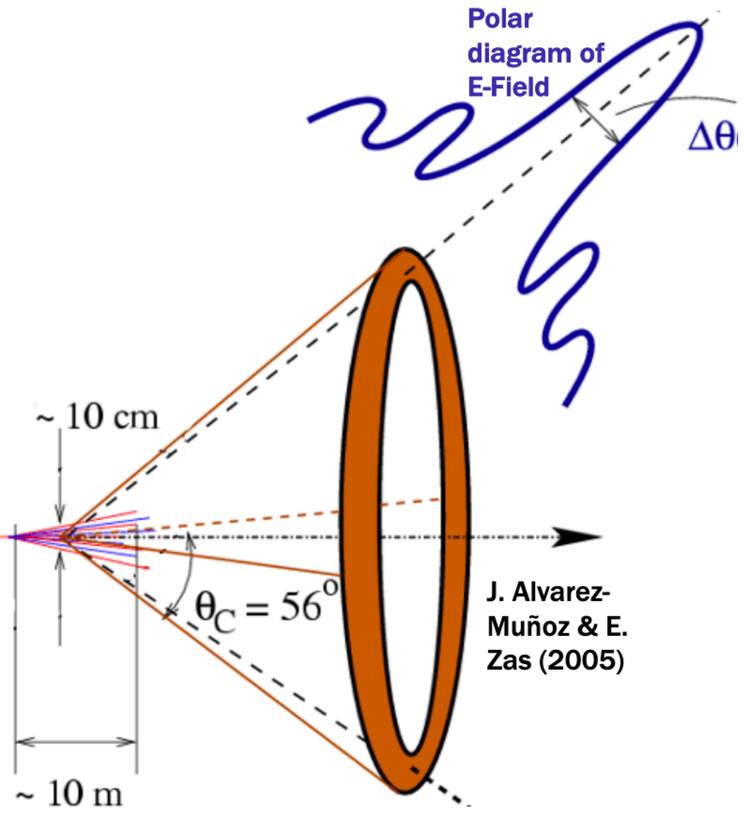




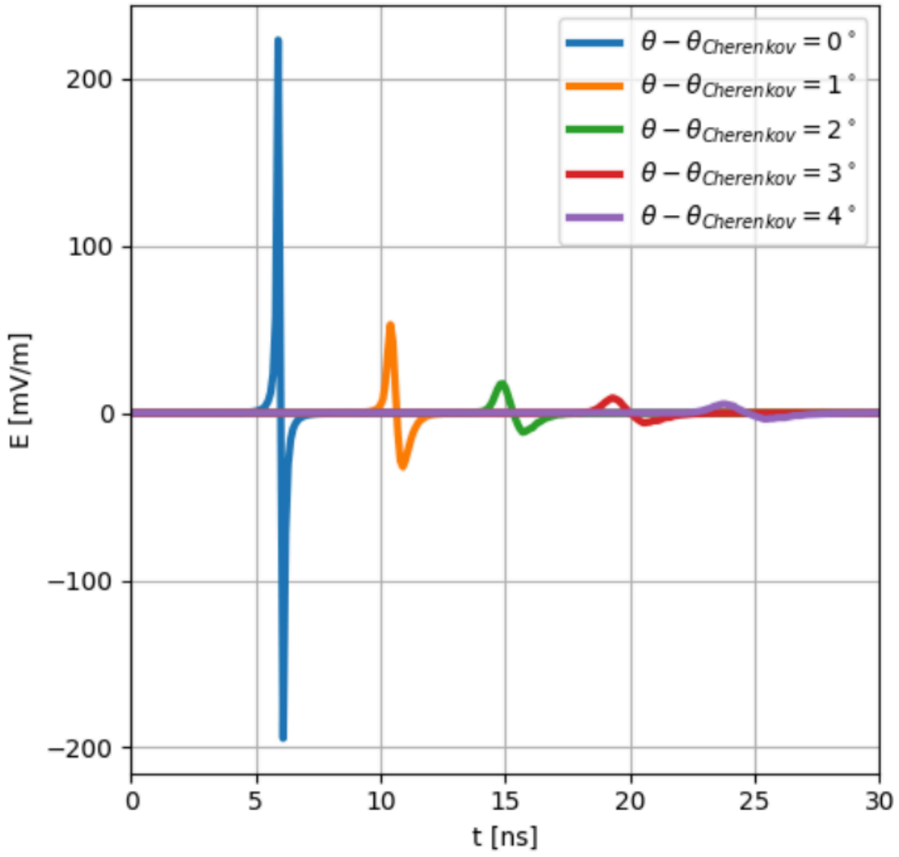
* Including optical and radio detectors

In-ice Radio Neutrino Detection: the Askaryan effect

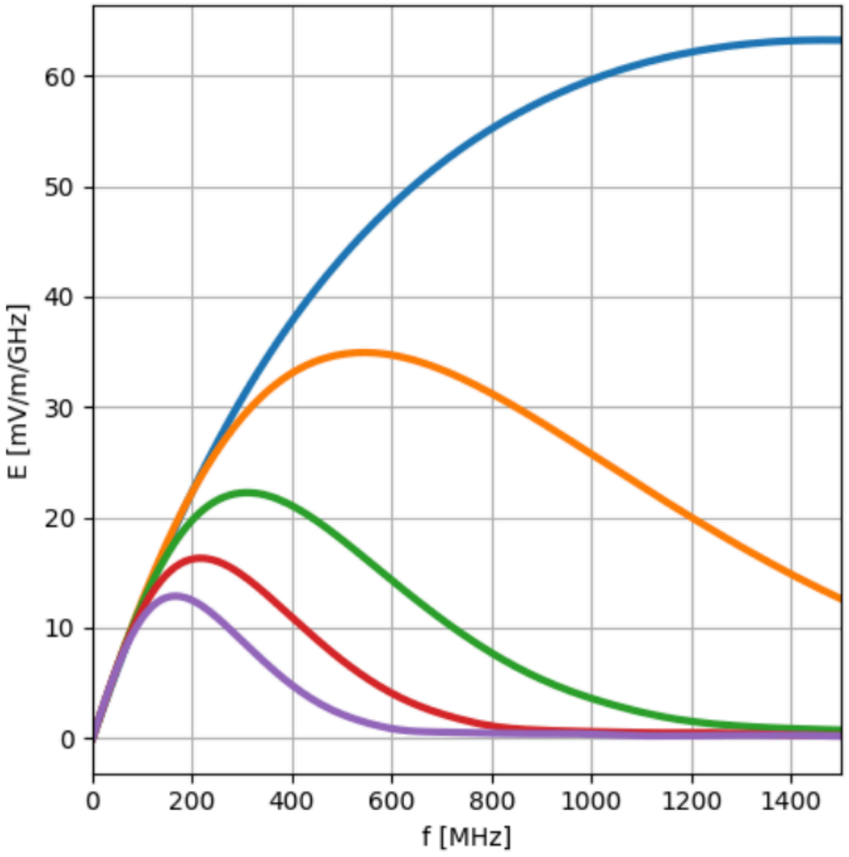
- Conical emission: strongest on Cherenkov cone



IMPULSIVE RADIO SIGNAL



BROADBAND PULSE

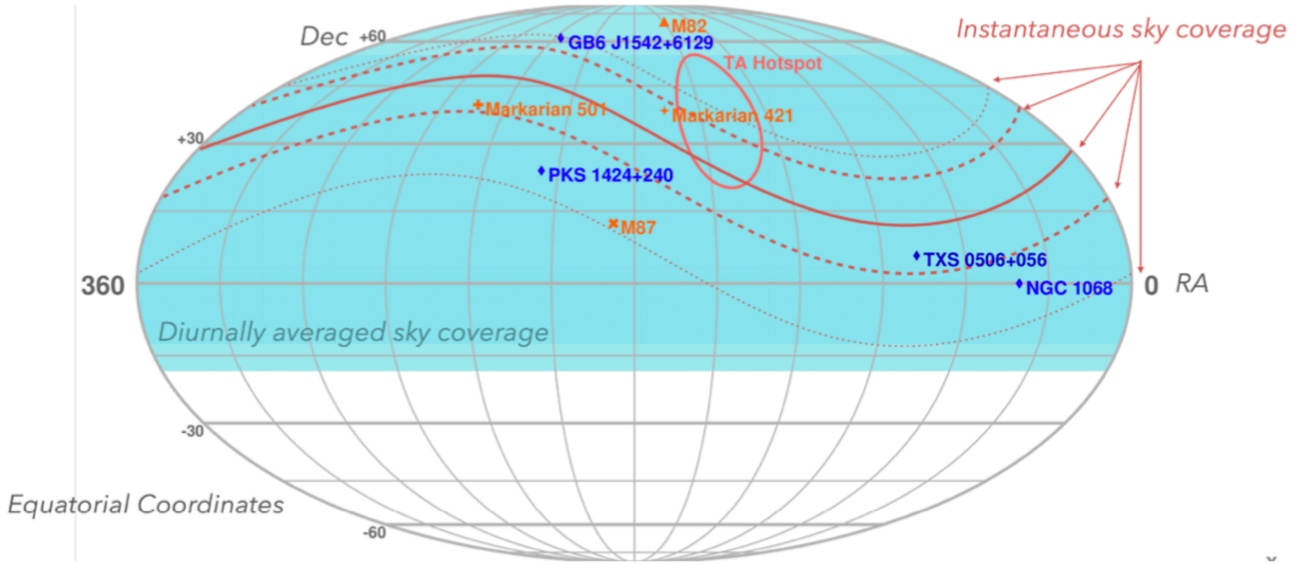


[J. Alvarez-Muñoz, A. Romero-Wolf and E. Zas, Phys. Rev. D84 (2011) 103003]

RNO-G: sky coverage for a Northern array

At UHE energies, primarily sensitive to down-going or Earth-skimming neutrinos

- Strong science case:
  - observing the same sky as IceCube but at higher energies allowing for multi-energy (TeV to PeV) observations of (steady and transient) sources
  - complementary to IceCube-Gen2 radio in terms of FoV allowing for better sky coverage at PeV energy: synergy for multimessenger neutrino alerts



Because of the different neutrino energies RNO-G and IceCube can look at the same sources (Northern sky) at TeV and PeV.

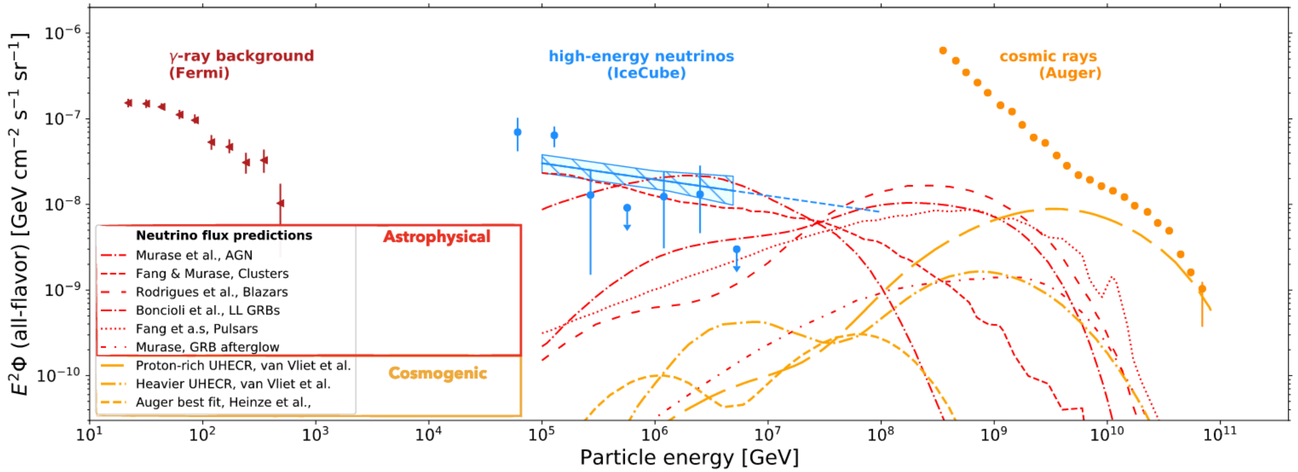
Cosmic neutrinos: science reach

They are key to answering two major questions

ASTROPHYSICS: WHAT MAKES THE MOST ENERGETIC PARTICLES WE DETECT?

PARTICLE PHYSICS: HOW DOES PARTICLE PHYSICS LOOK AT THESE ENERGIES?

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



Ackermann et al, Astro2020 1903.04333