The Radio Neutrino Observatory - Greenland

Detecting ultra-high-energy neutrinos from the northern sky

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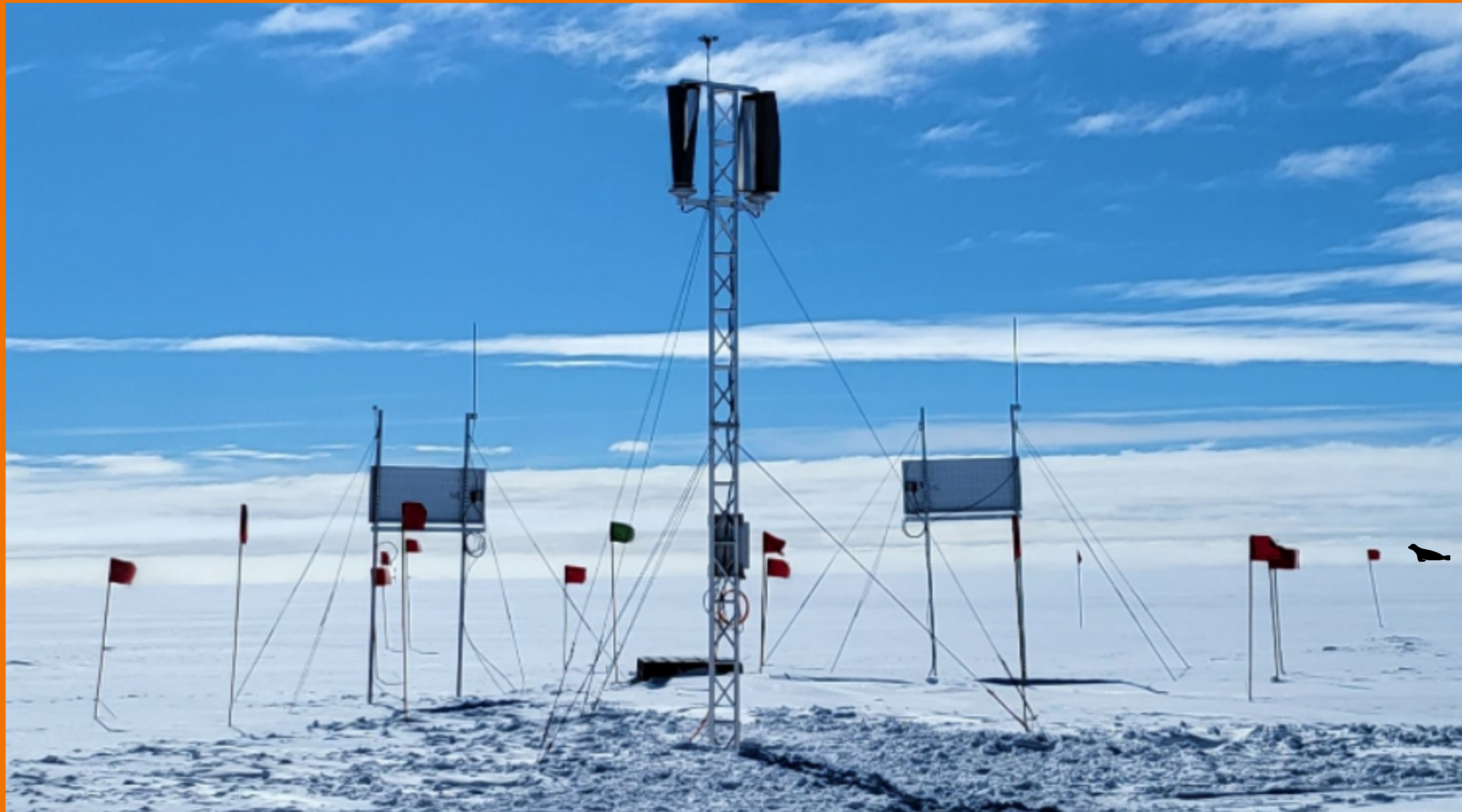
Chiba - 07.08.23



Outline

- Motivation
- The RNO-G detector
- Radio detection of UHE neutrinos
- RNO-G science potential
- Deployment and recent results

Check out our 10 contributions @ the ICRC 2023

Ultra-high-energy neutrinos

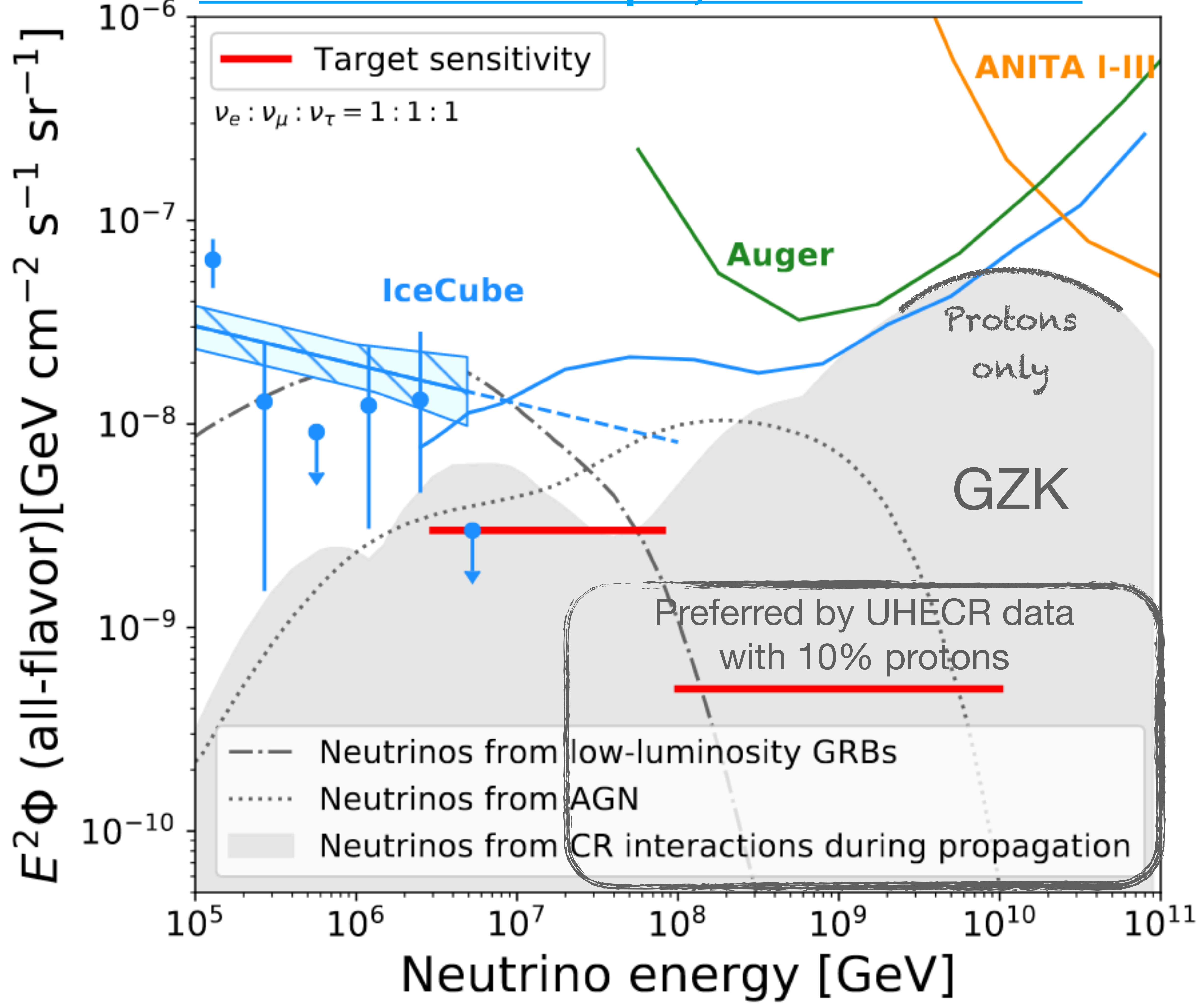
Not yet discovered!

- No measurements above 10 PeV
- Open questions:
  - Cutoff in astrophysical spectrum
  - Existence of 2. astrophysical component
  - Existence of cosmogenic GZK neutrino flux

➡ Requires IceCube x 10 - 100

➡ In-ice radio detectors target energy range: 100 PeV - 10 EeV

Astro2020 White Paper, arXiv:1903.04334

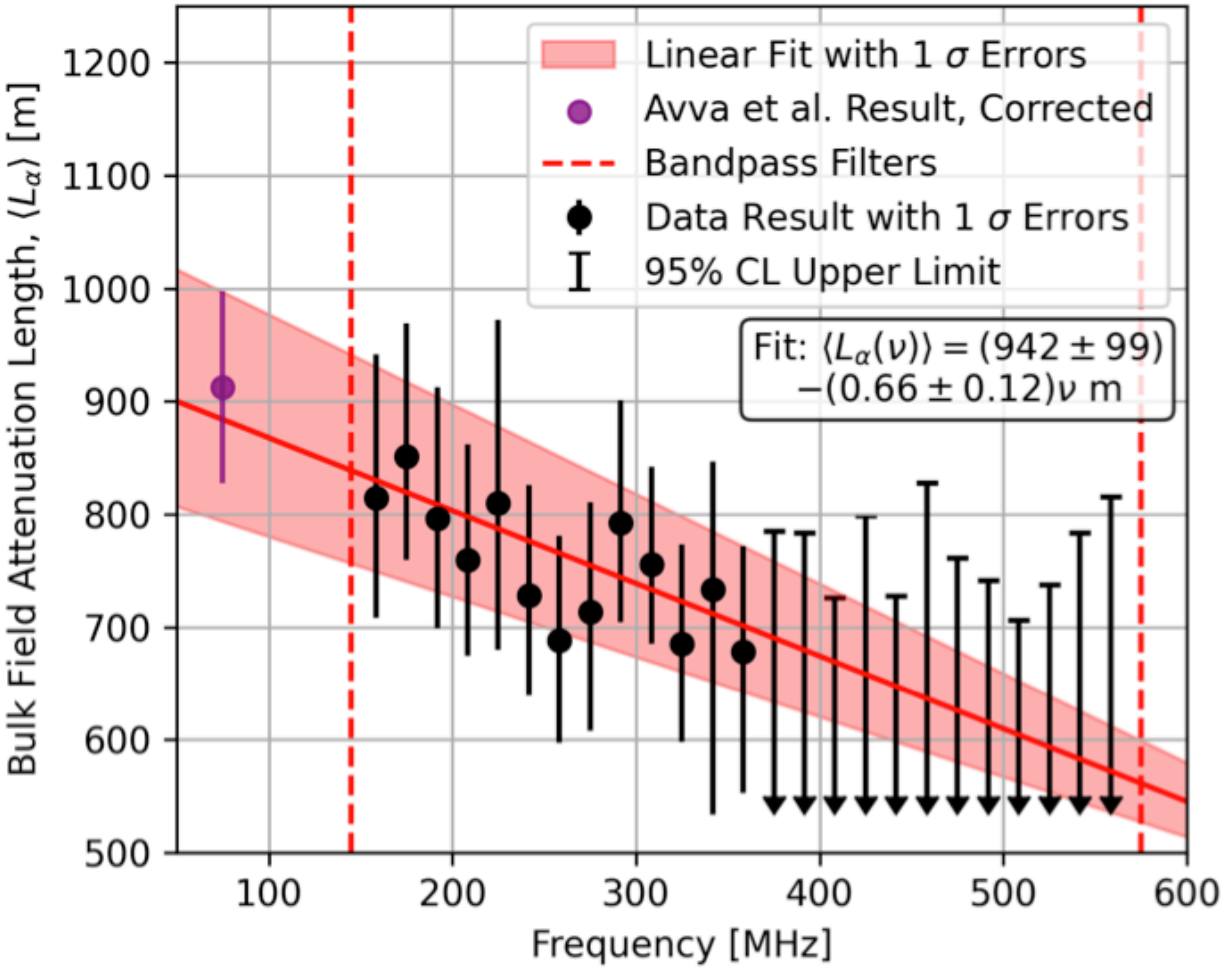


Radio detection of neutrinos

Why?

- Use natural glacier ice as target
- Radio waves are less attenuated in ice
  - A single radio station can monitor a cubic kilometer of ice
- Radio is a cost effective solution
  - In hardware & deployment (do not have to be deployed in 3 km depth; 100 - 200 m is sufficient)

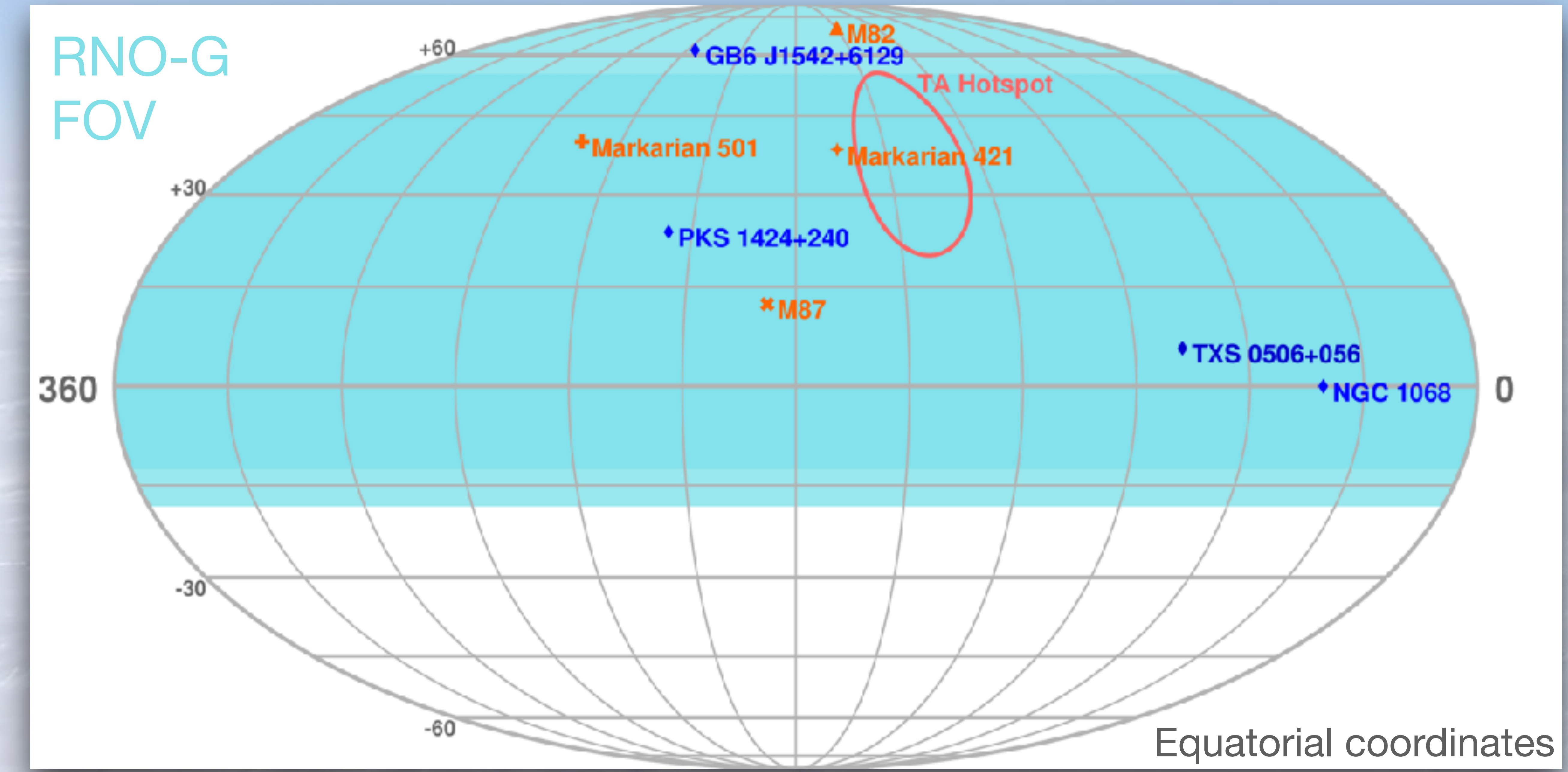
RNO-G, Journal of Glaciology



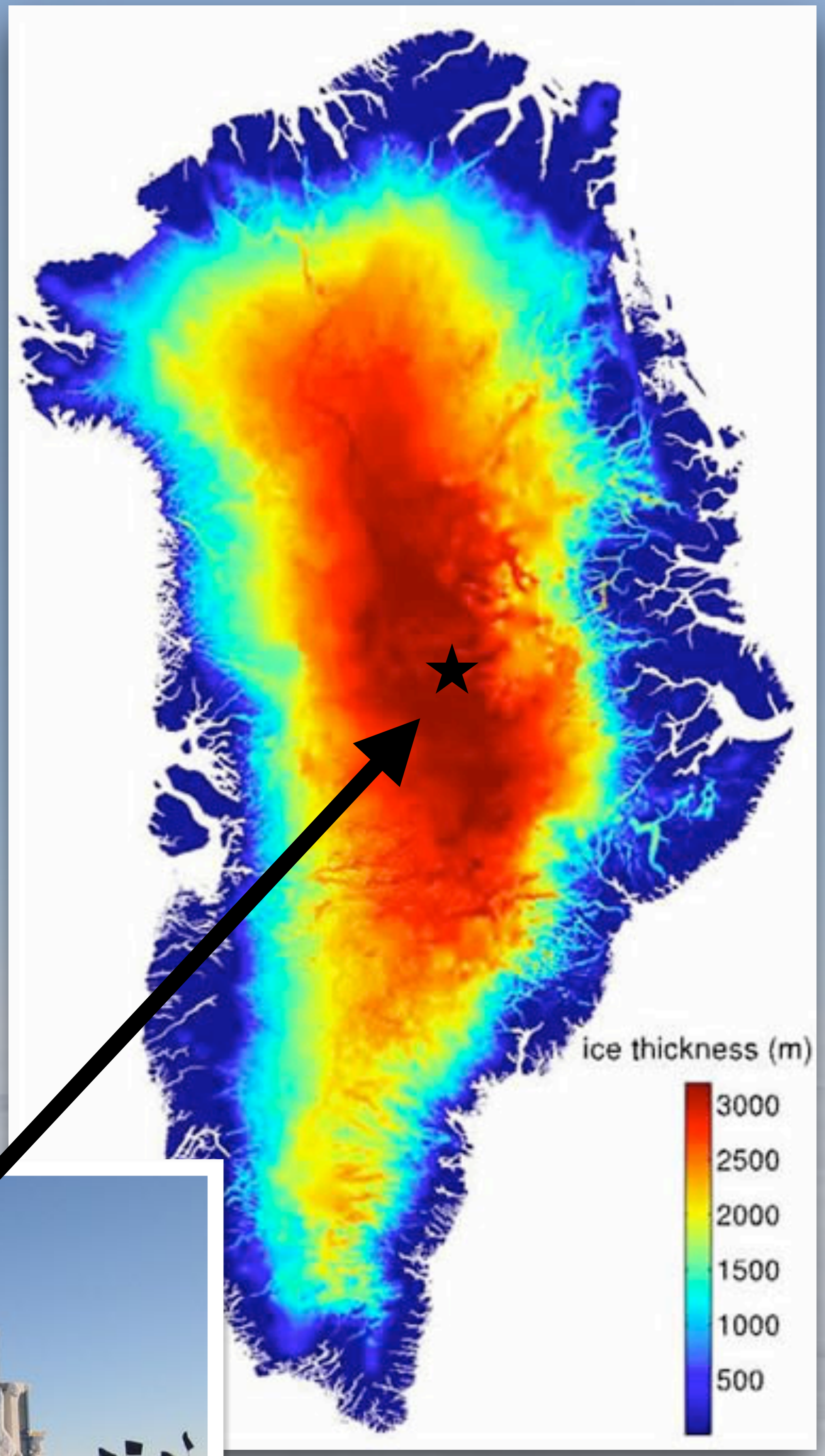
Radio detection of neutrinos

Where? **Greenland!**

- Existing infrastructure, 10 months of sunlight per year
- Field of view (FOV):
  - Overlapping with IceCube for TeV neutrinos
  - Complementary with future UHE observatory at South Pole



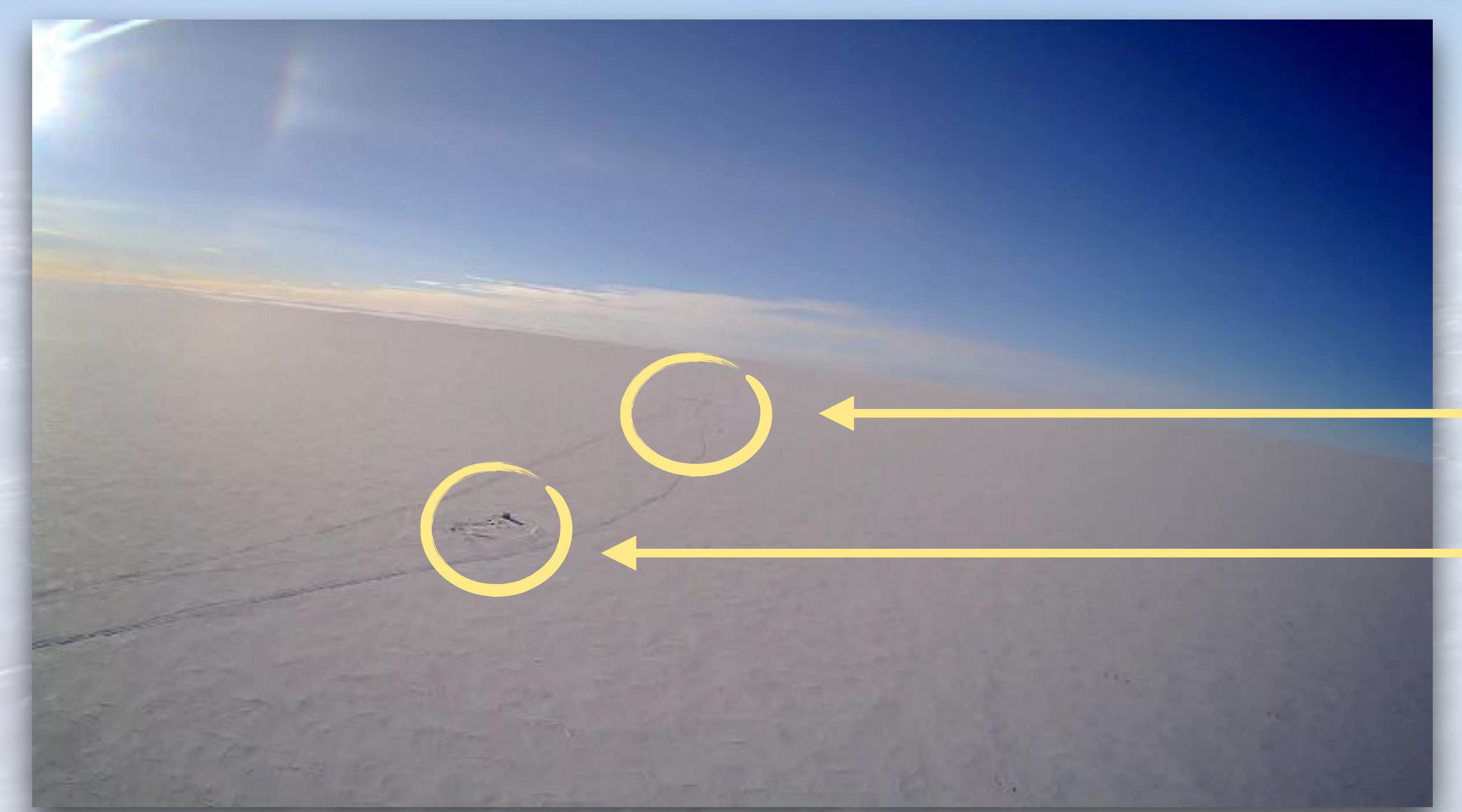
@ Summit Station



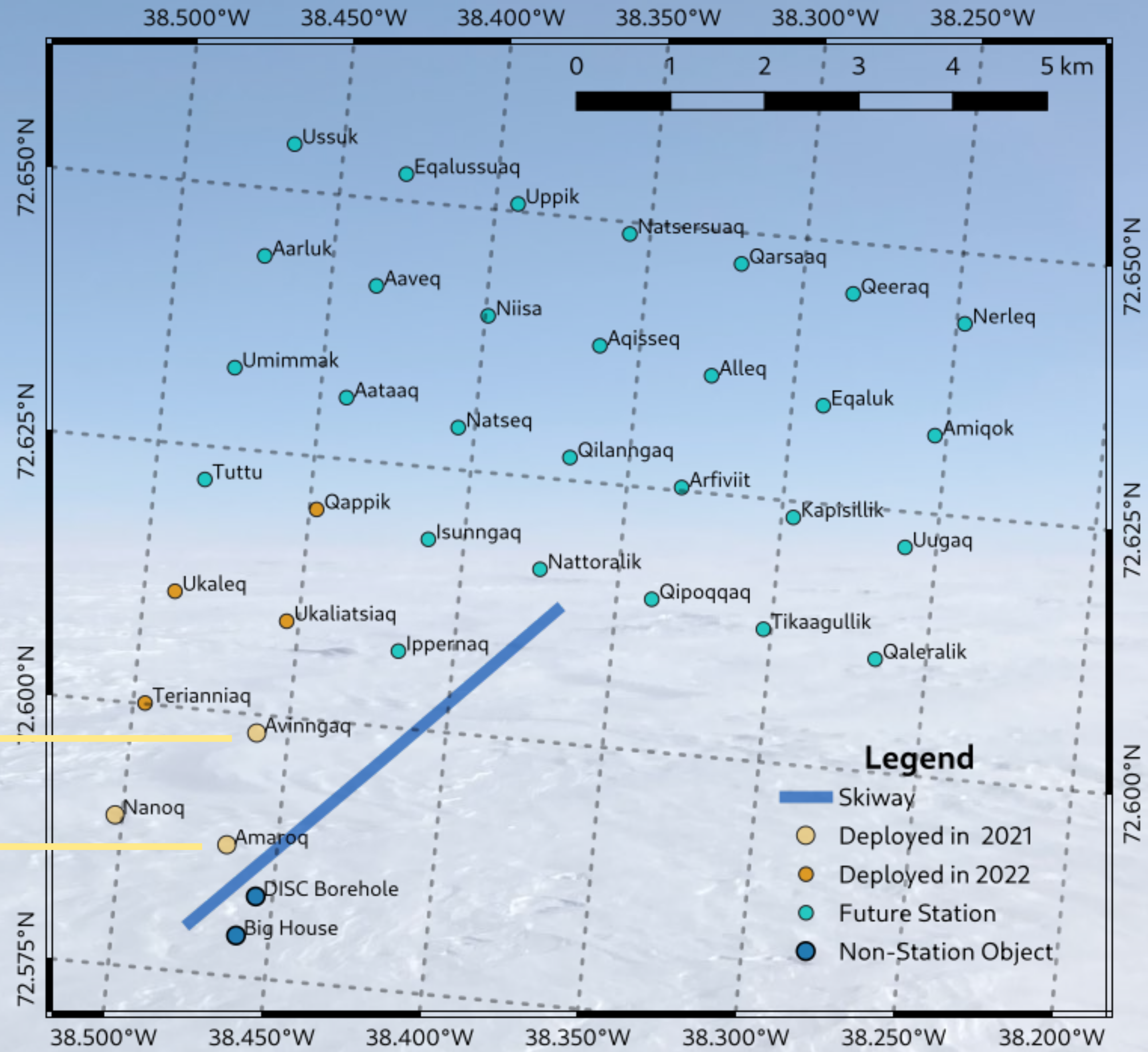
Radio Neutrino Observatory - Greenland

What?

- 35 stations on 1.25km grid
  - 7 already deployed & taking data
  - 3 - 4 more deployment seasons
- Stations are solar powered & communicate wireless



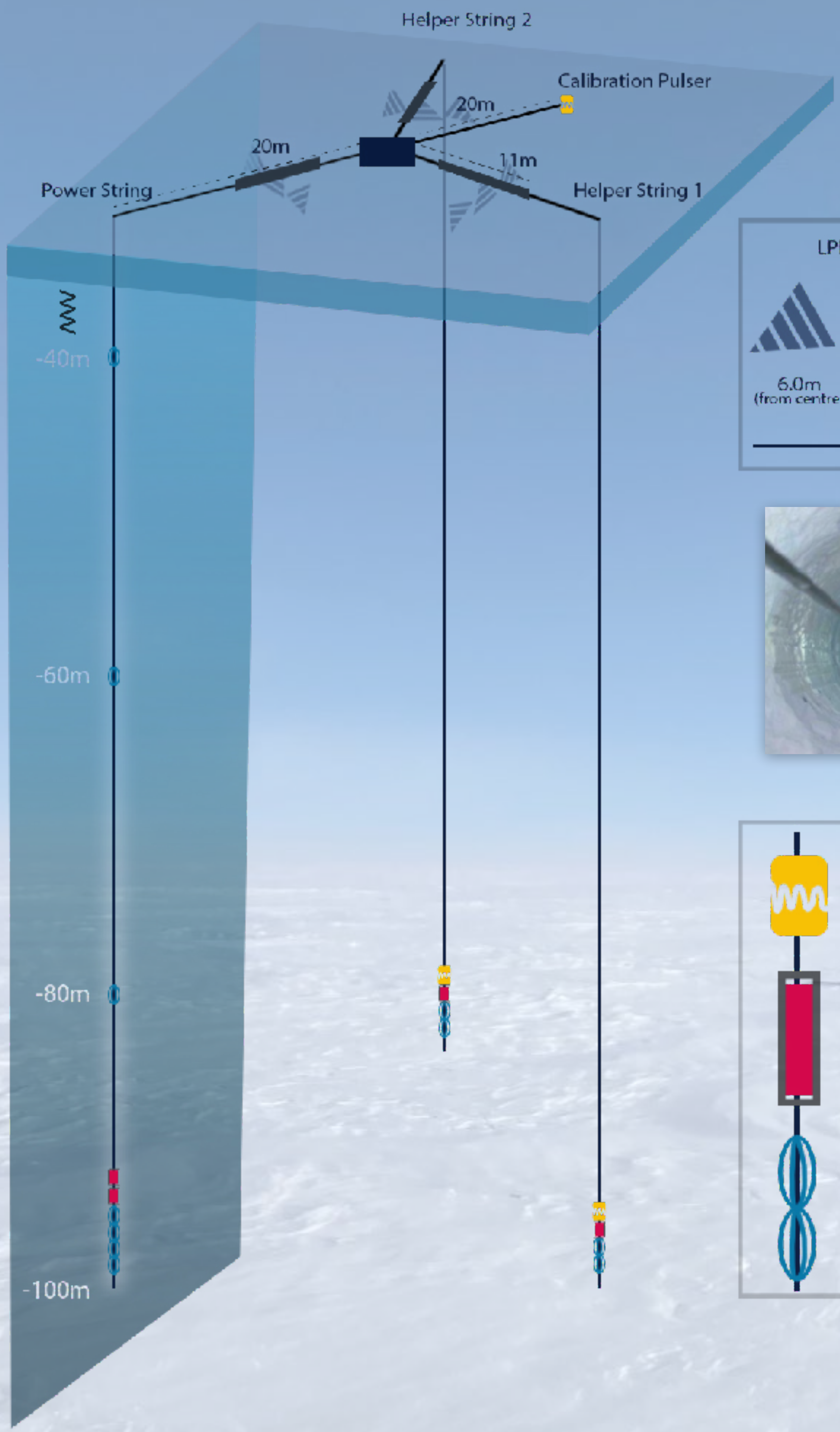
RNO-G Planned Layout

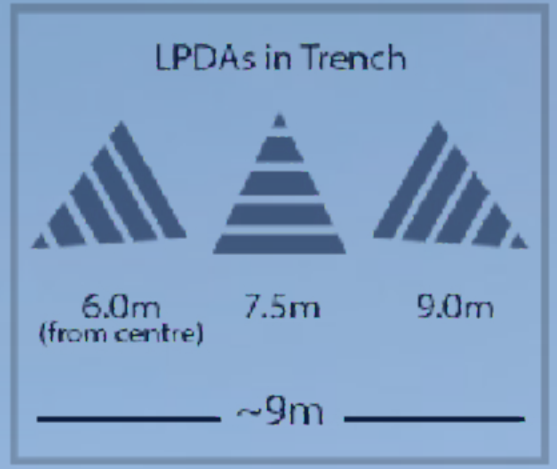


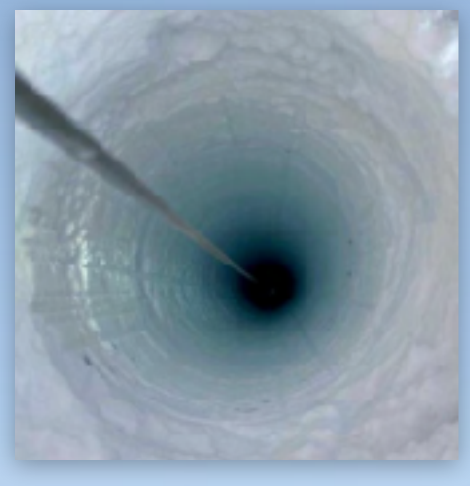
Station design

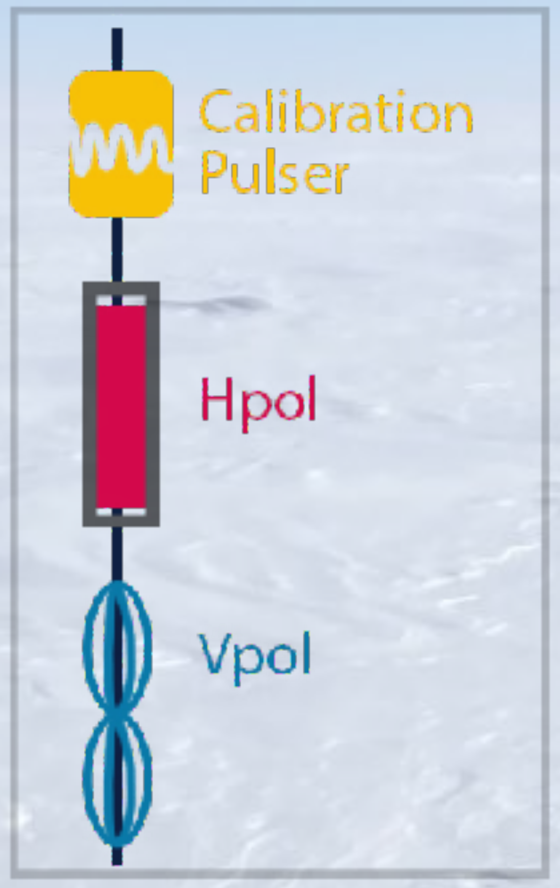
A hybrid concept

- 24 antennas
  - 3 types
  - ~ 80 - 650 MHz
- 3 calibration pulsar
- Informed by pilot experiments (ARA & ARIANNA)
- Will inform IceCube-Gen2 radio array design









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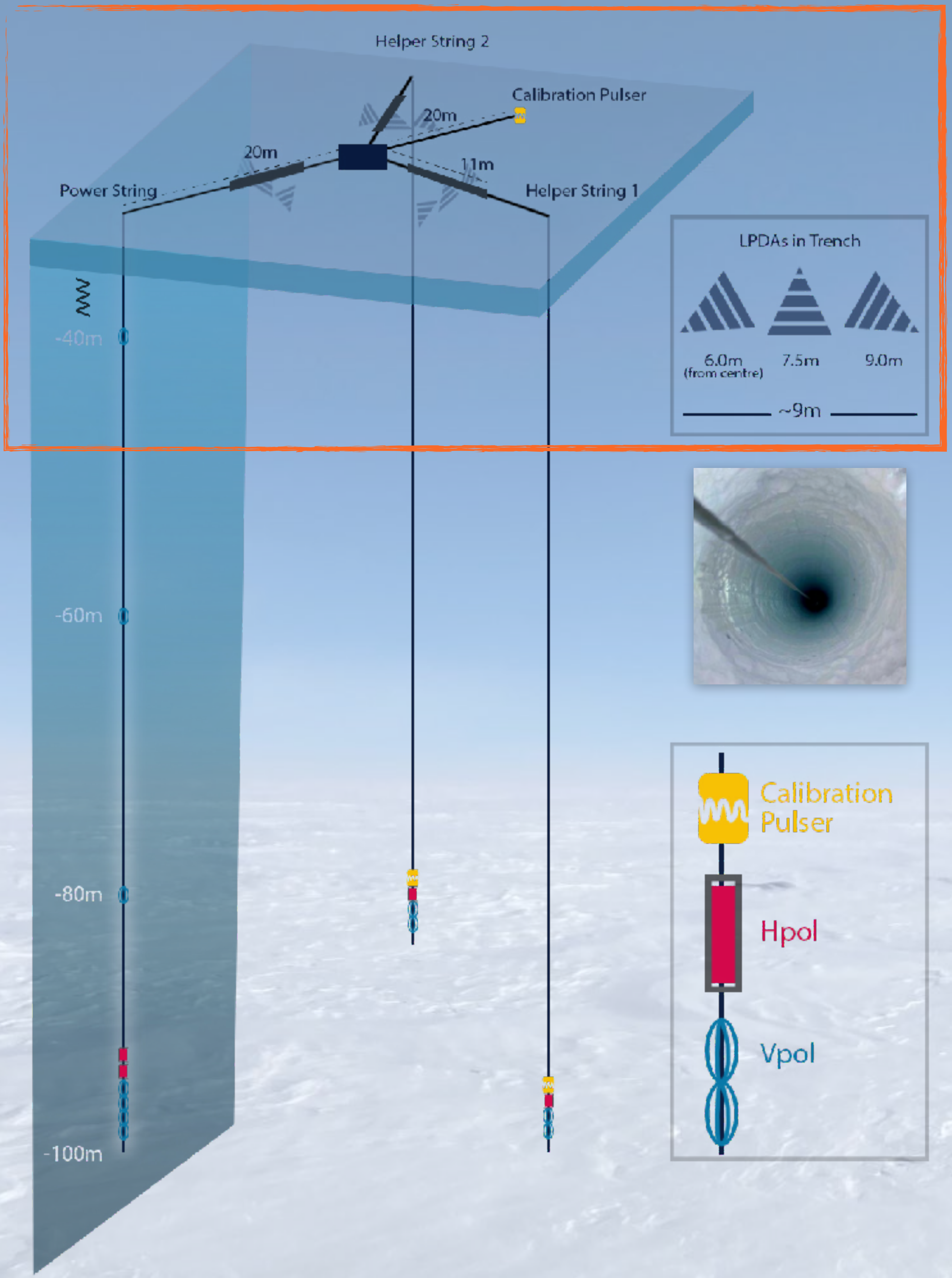

Shallow component

- Upward- & downward-facing LPDA antennas
- CR detection + veto
- Accurate polarisation reconstruction
- Multiple coincidence threshold trigger

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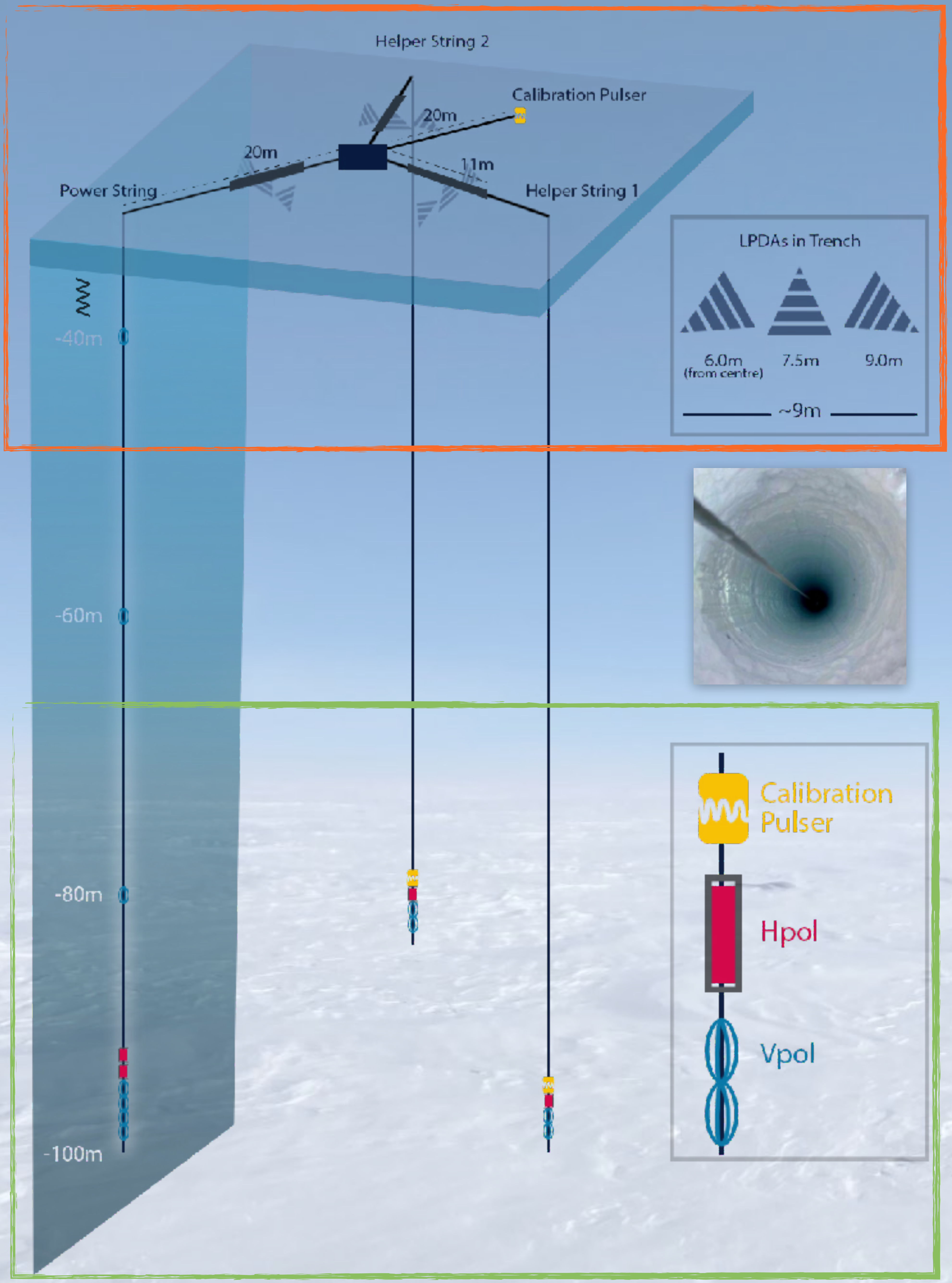

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Deep component

- 100m deep
- “Overlook” larger volume
- Low threshold trigger

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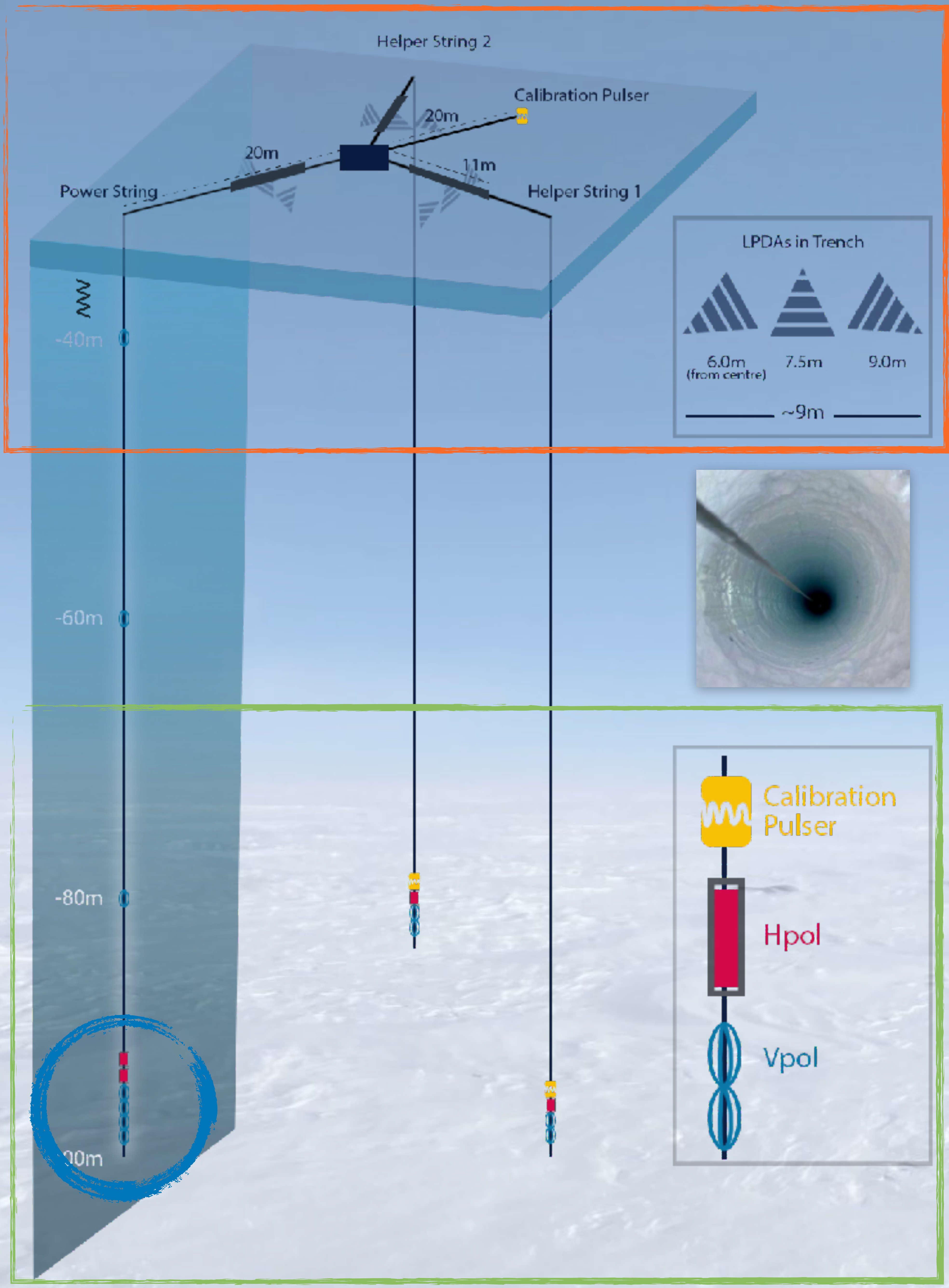
Phased array

- Signal of 4 Vpols combined by phasing into 8 beams in real time



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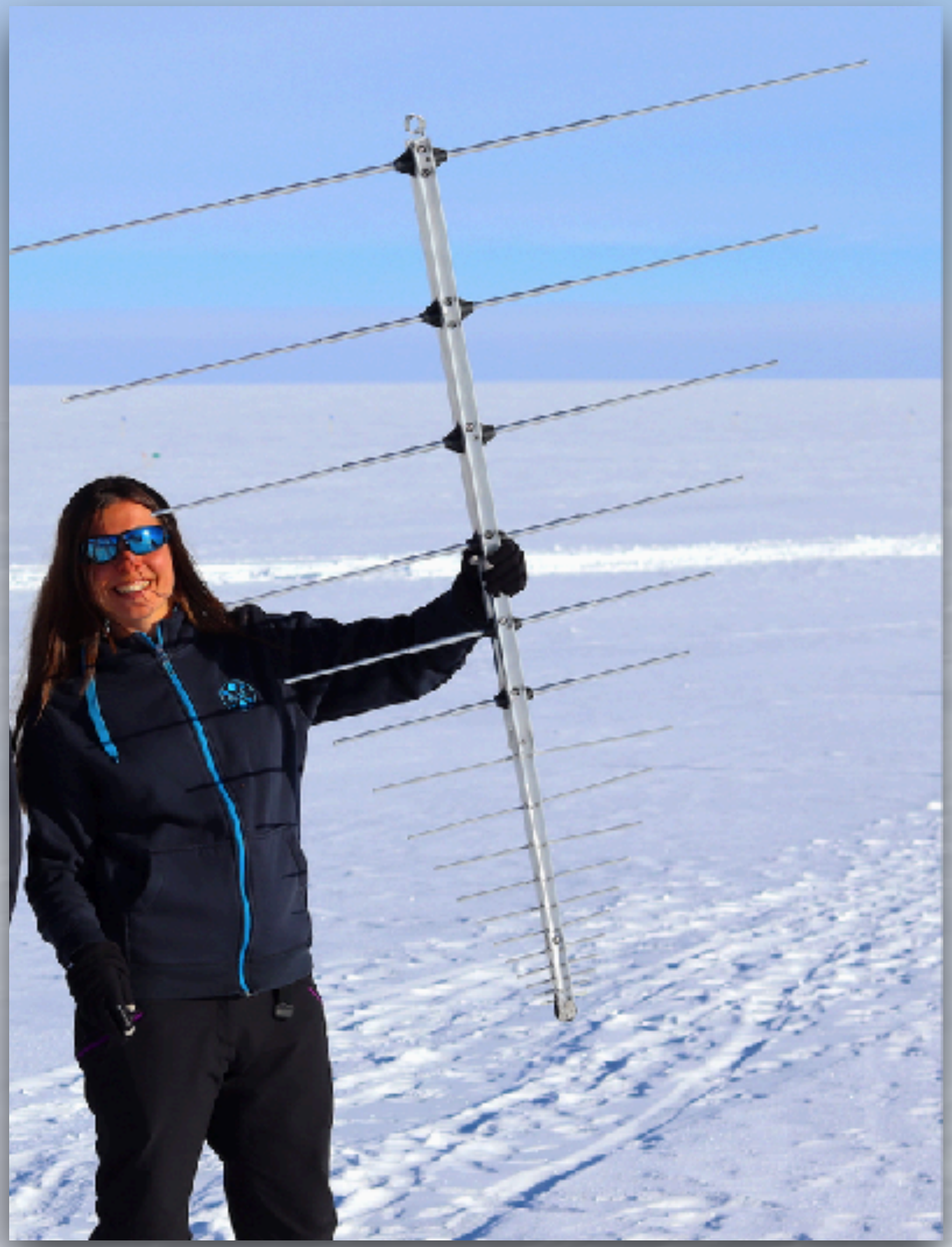
Antenna sensitivity

3 different antenna types

- LPDA is more sensitive but can not be deployed in borehole
  - 2 orthogonal LPDAs → Polarisation

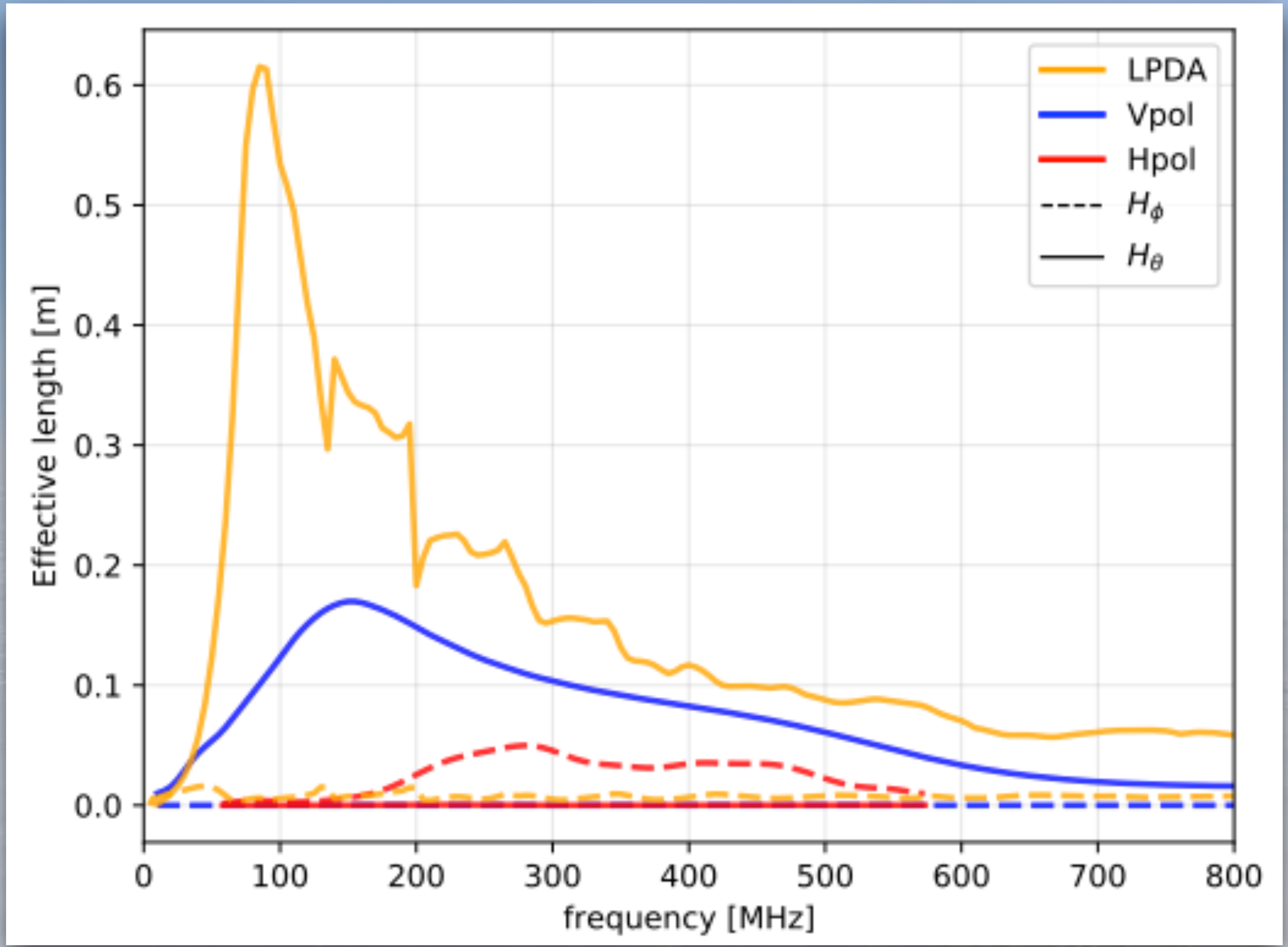
LPDA



Hpol

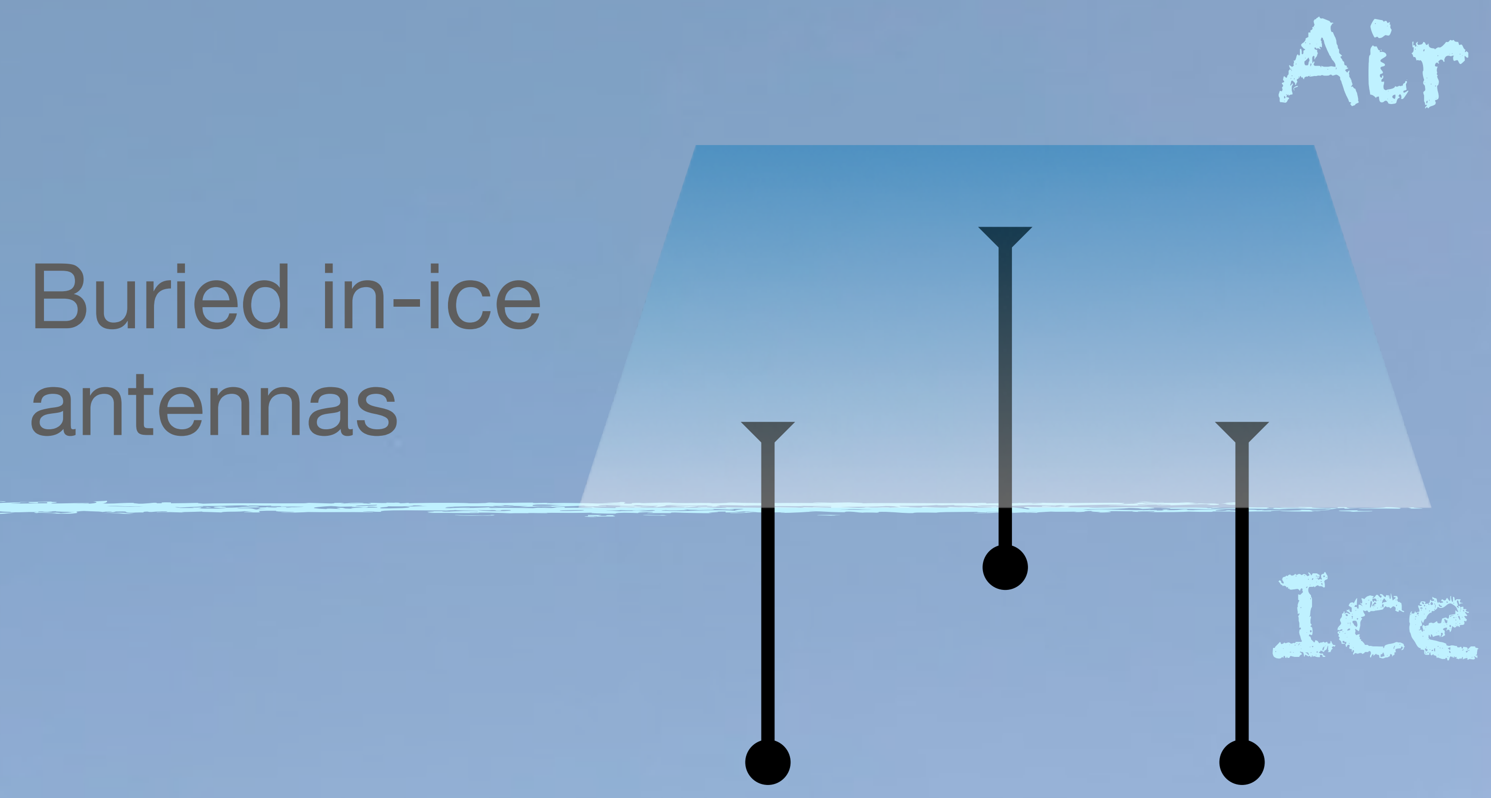
Vpol

- Combination of Vpol and Hpol gives polarisation
  - Hpols is less sensitive because of narrow diameter of borehole



Radio detection of neutrinos

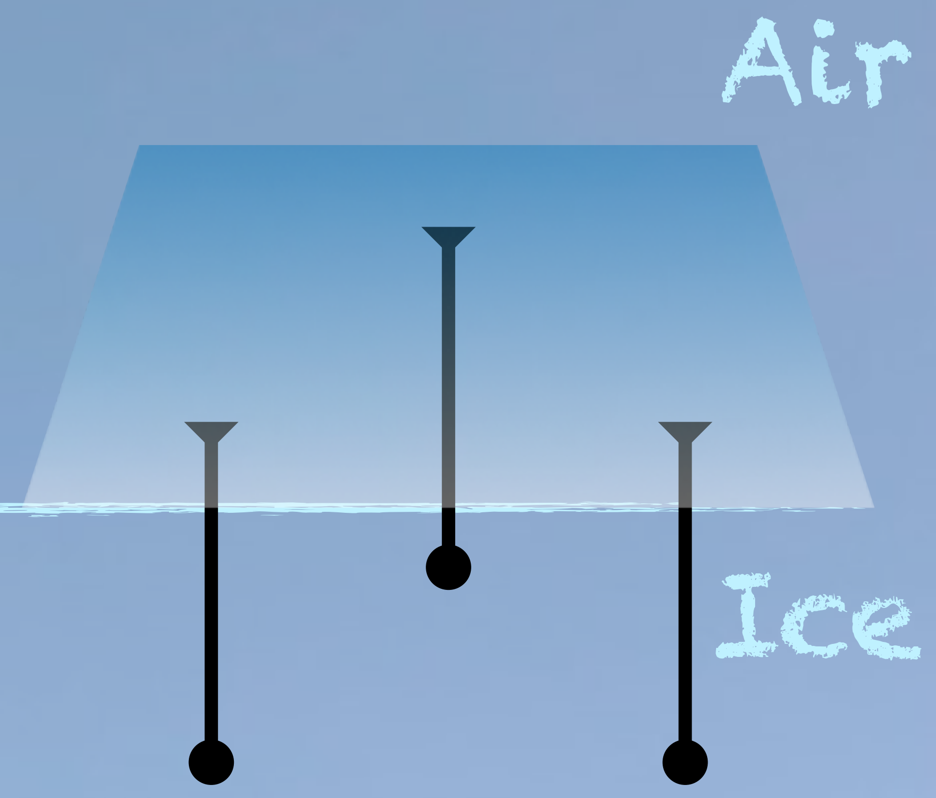
How?



Radio detection of neutrinos

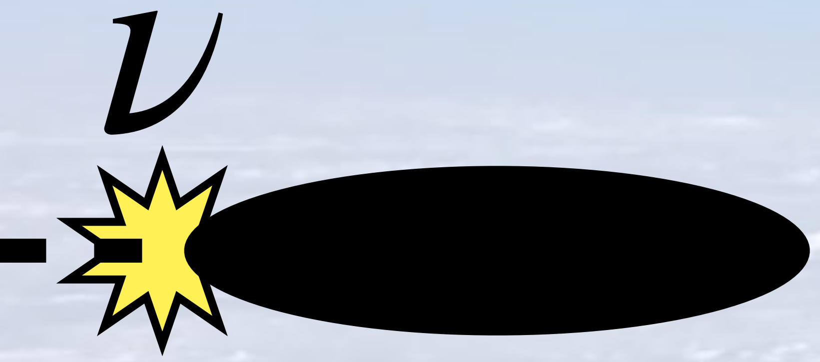
How?

Buried in-ice antennas



Particle cascade

E_{min} to detect radio emission $\gtrsim$ 1-10 PeV



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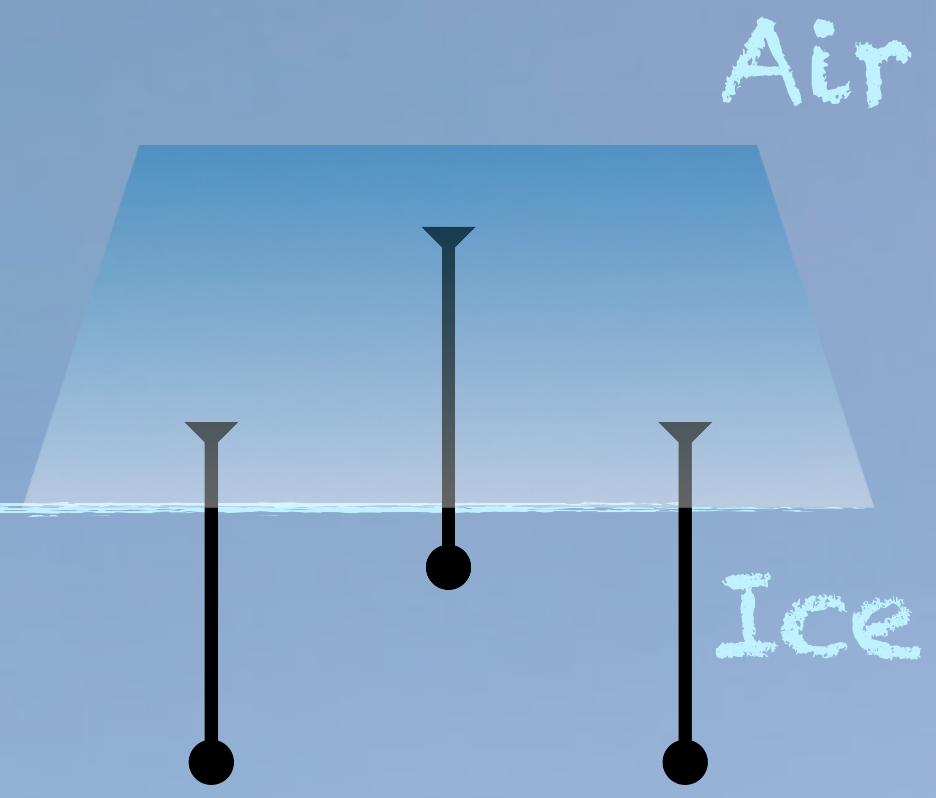

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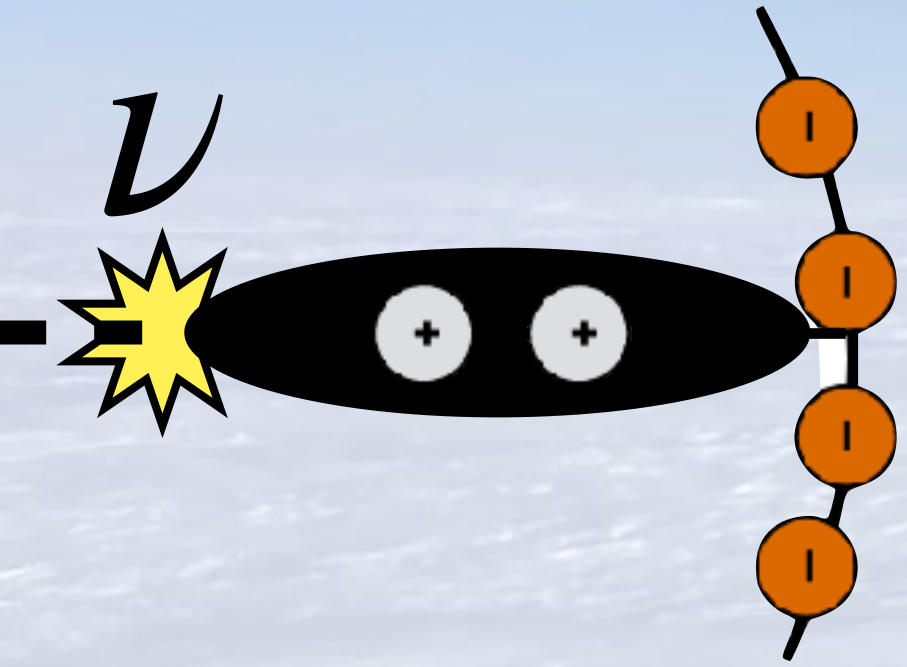

A negative charge-excess builds up (electrons are knocked out of ice) …

… and produces radio emission (Askaryan 1968)

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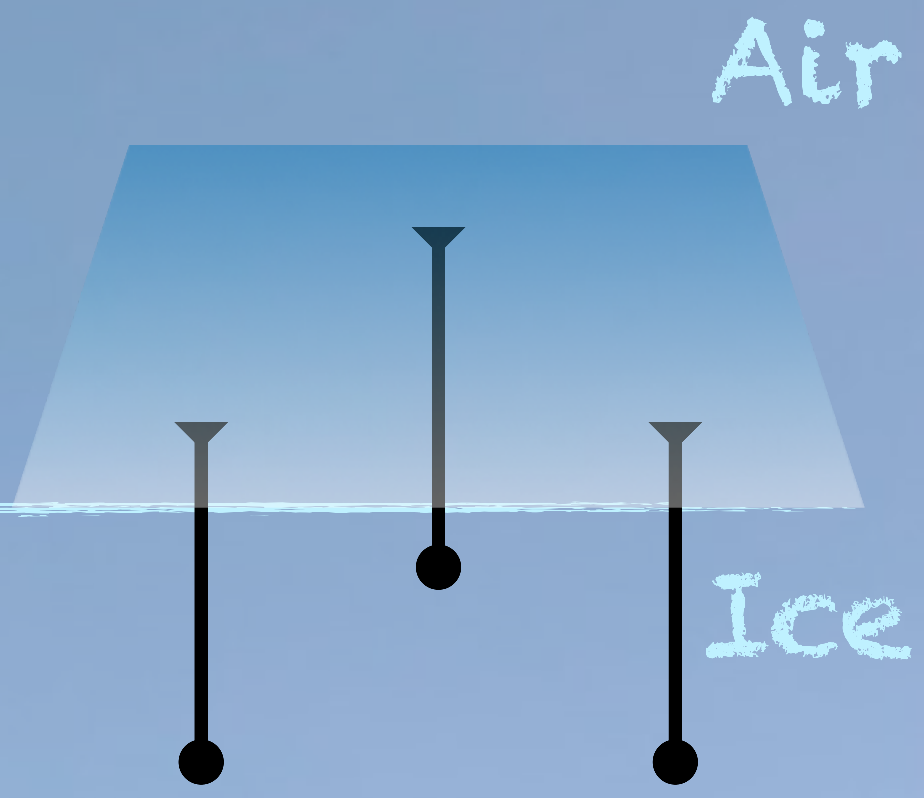

Buried in-ice antennas

Radio emission pattern has cone shape due to interference

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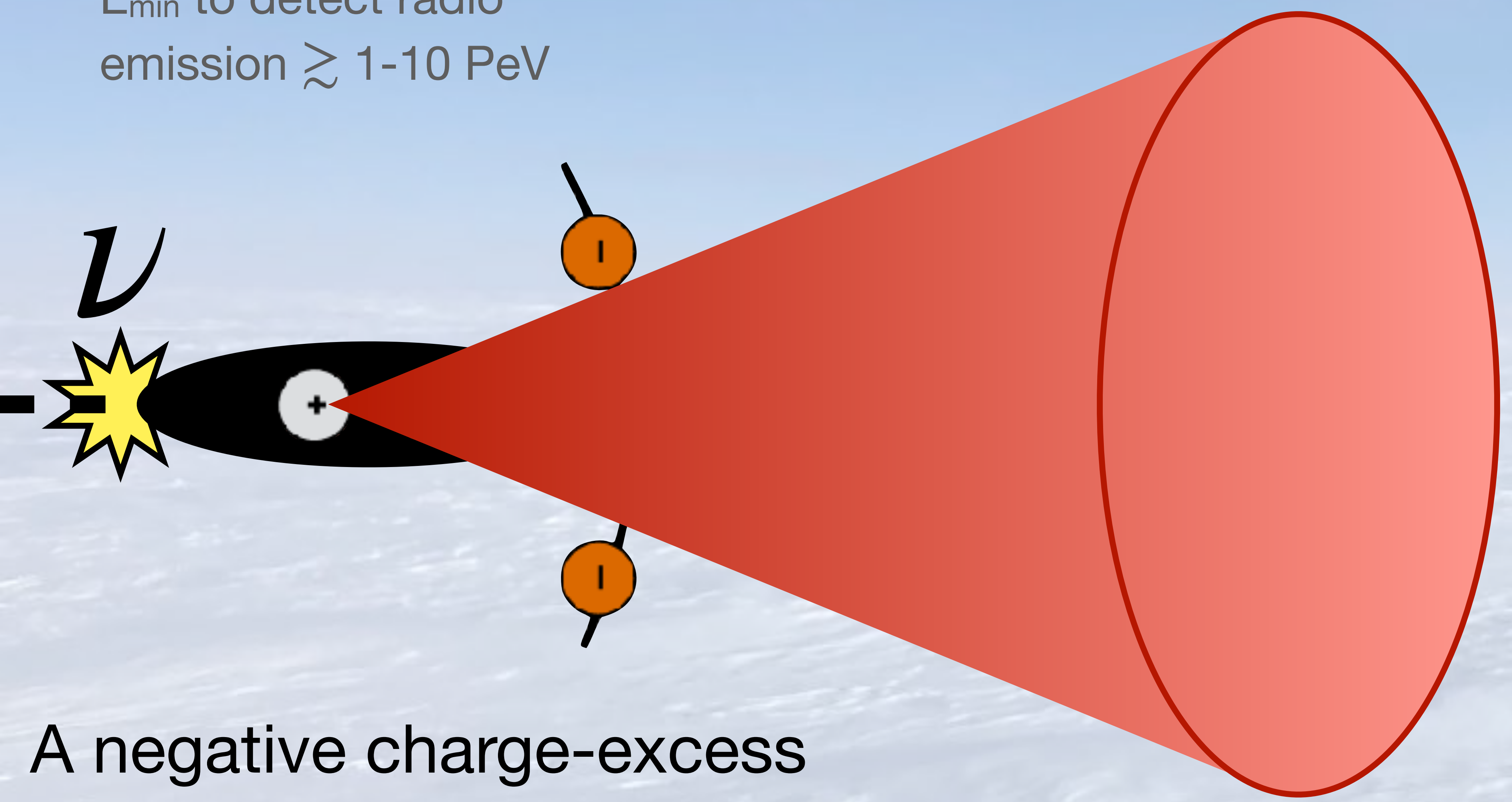

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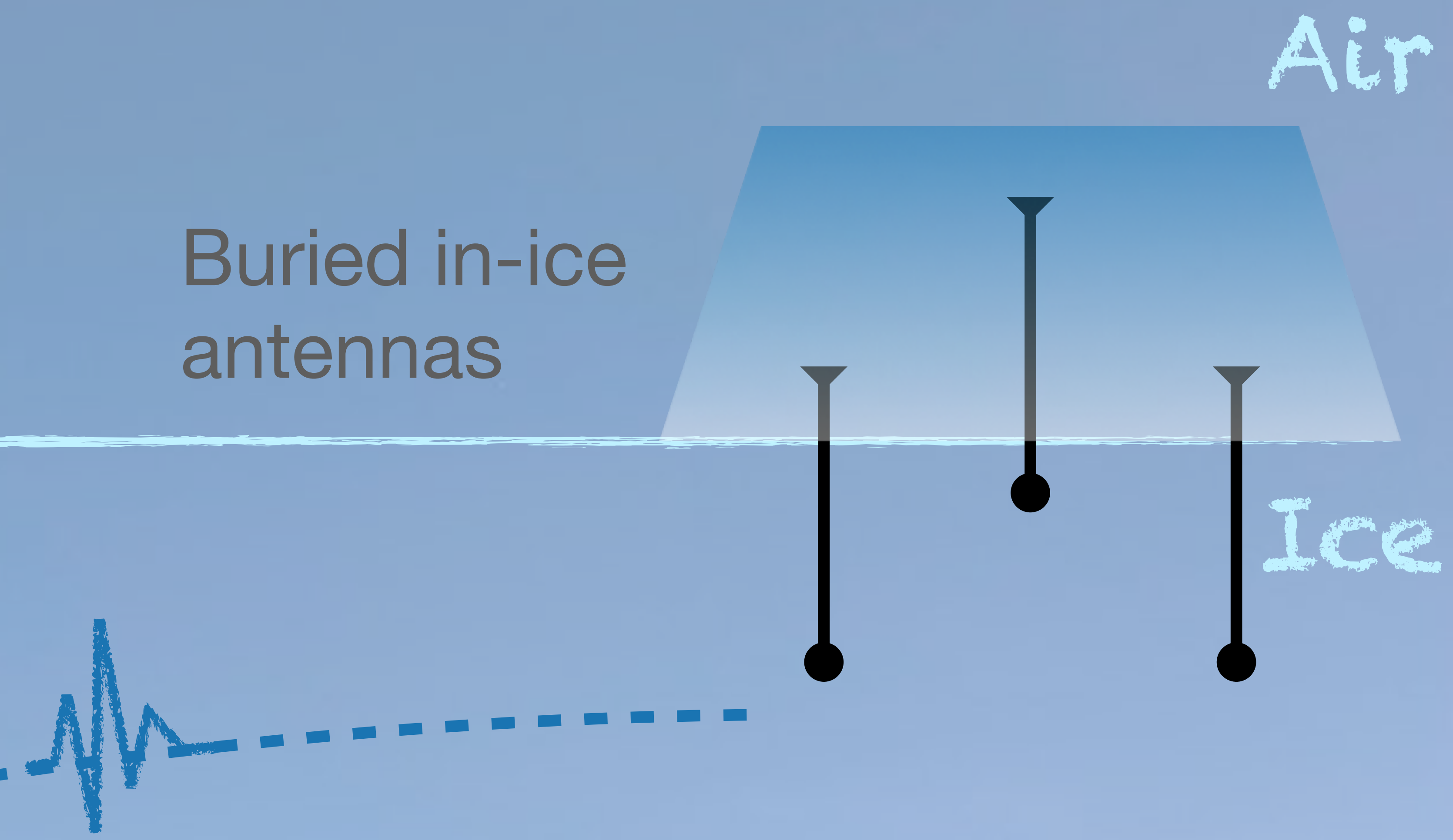

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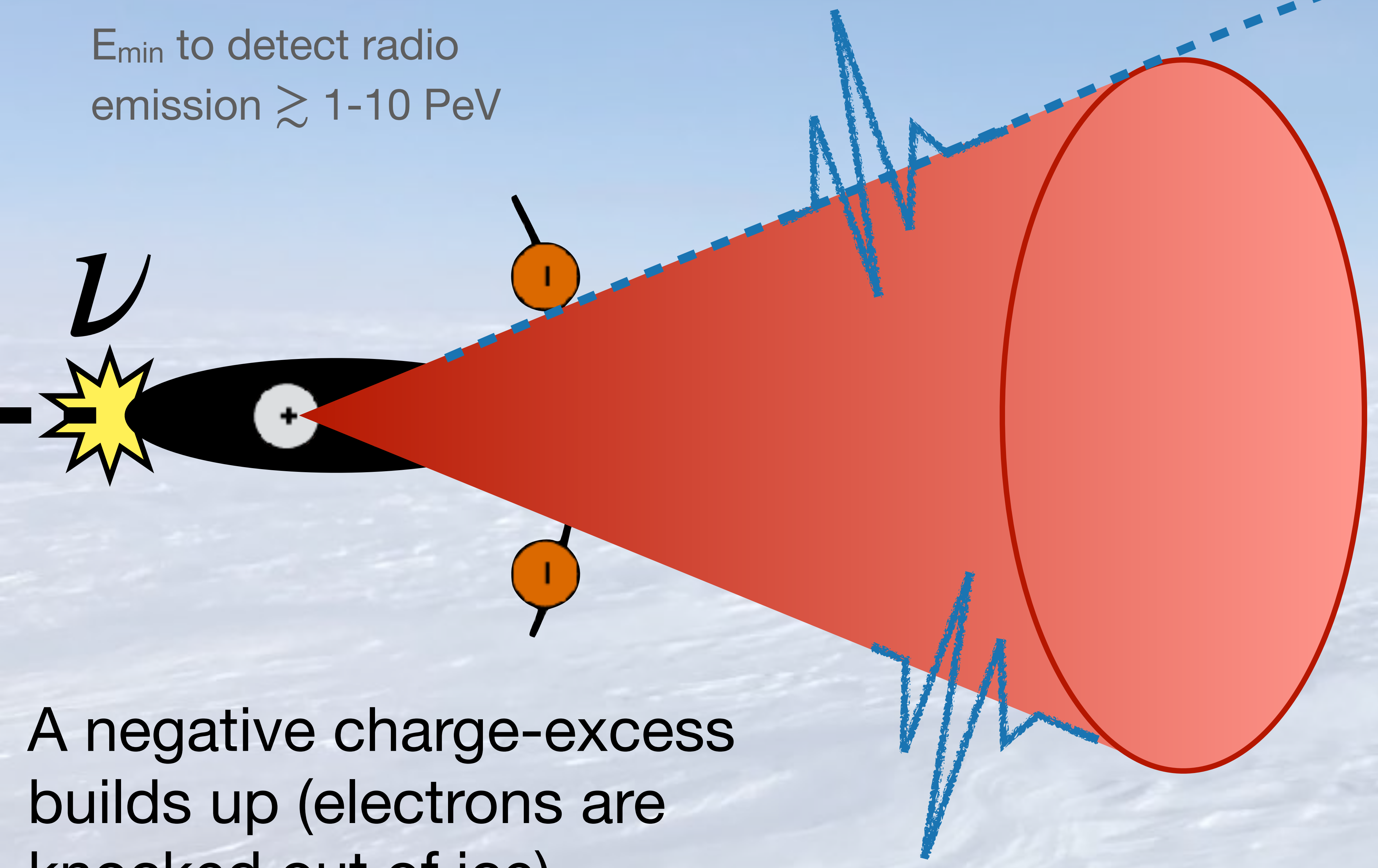

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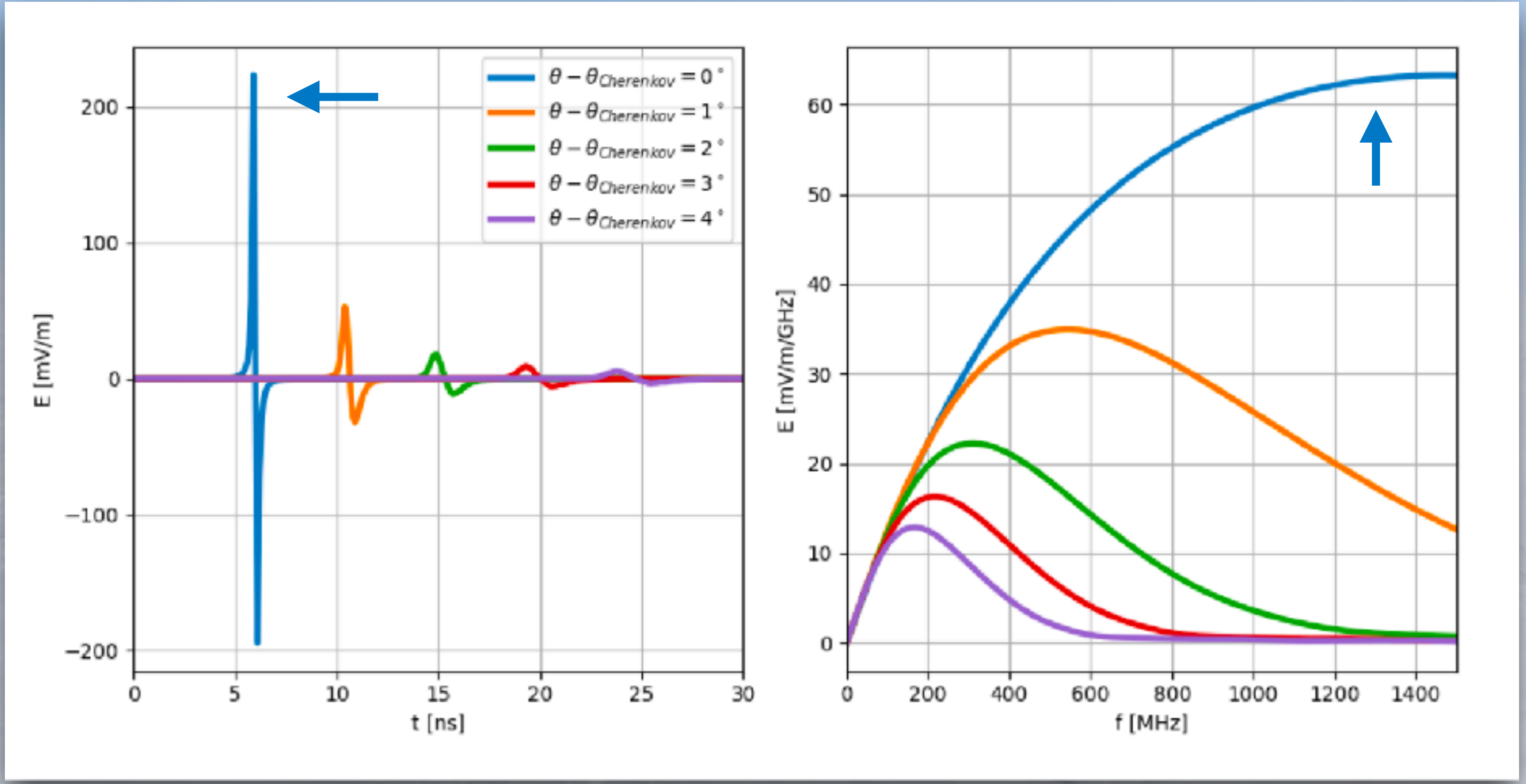
RNO-G, JINST 16 (2021) 03



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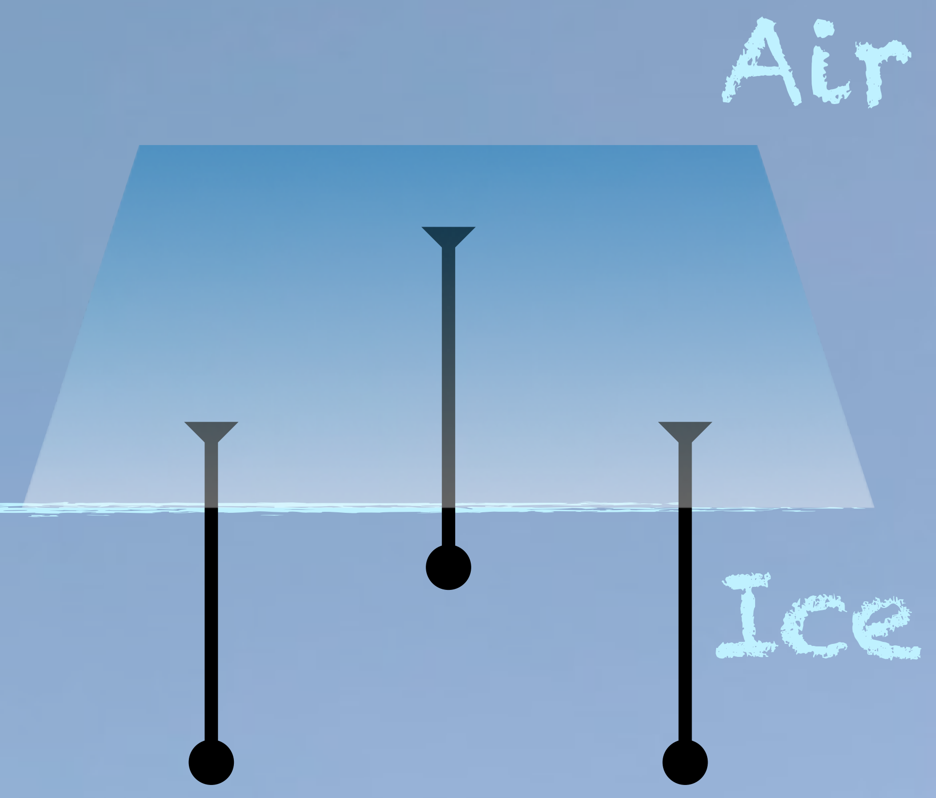

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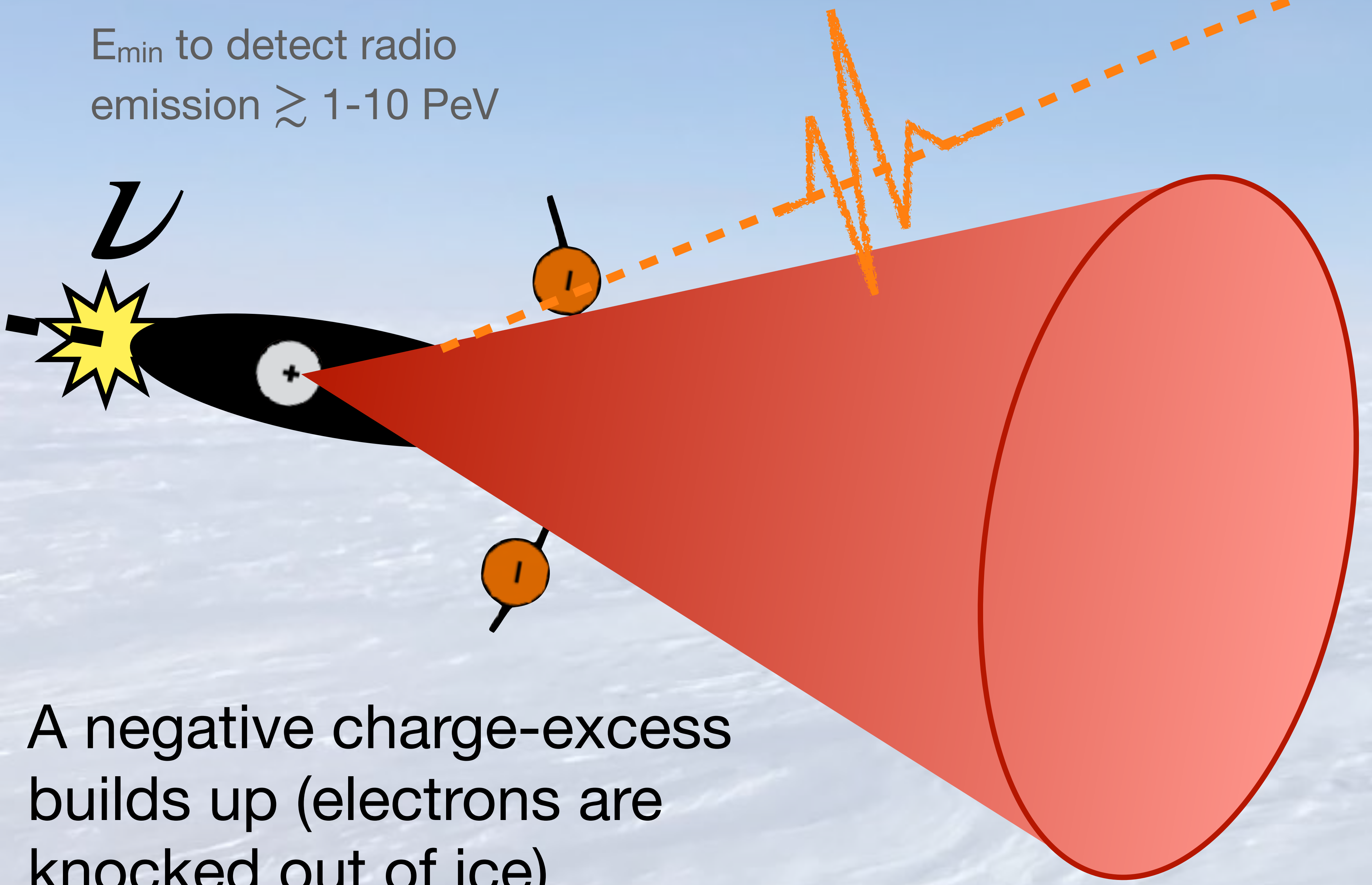
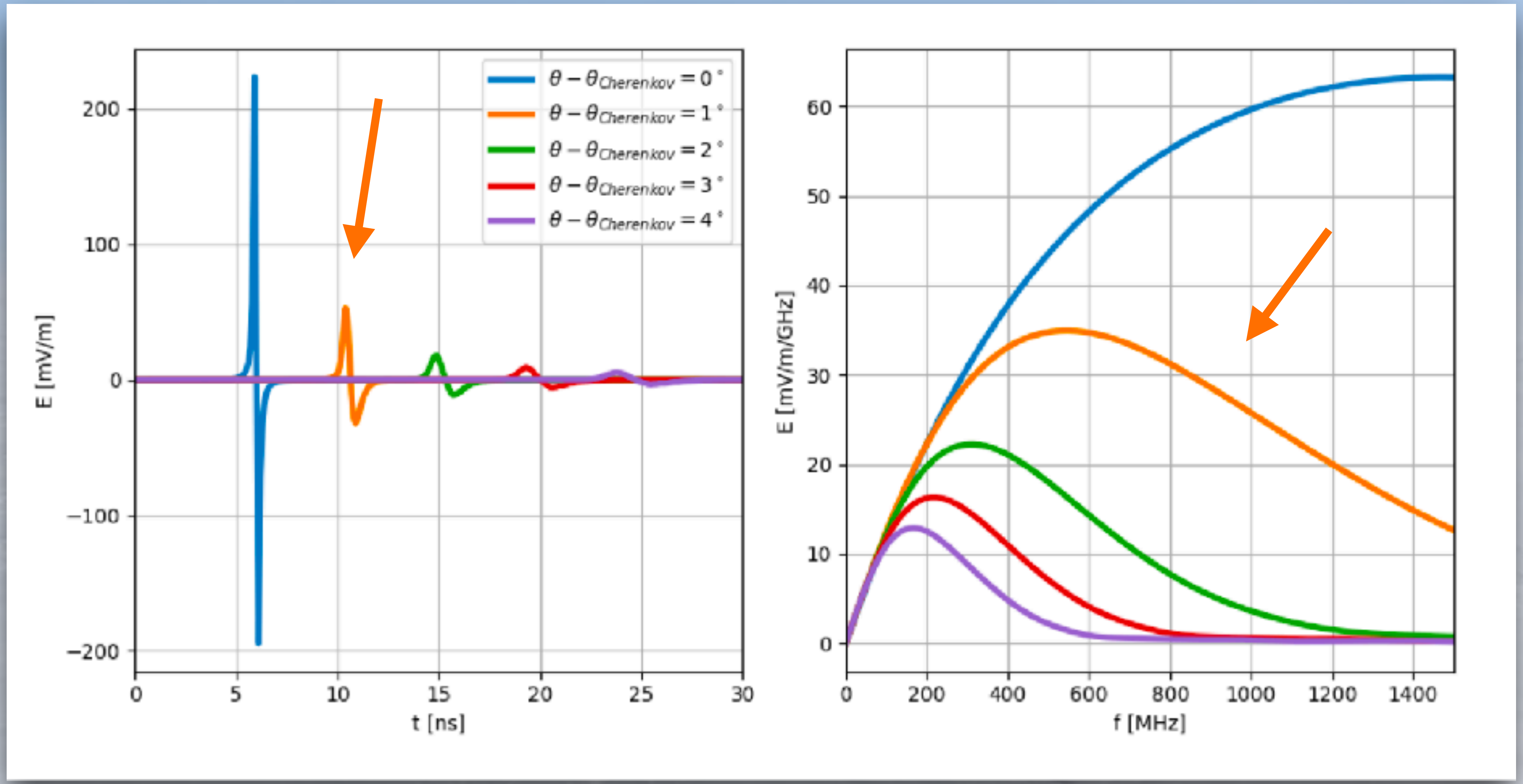


[RNO-G, JINST 16 (2021) 03](#)



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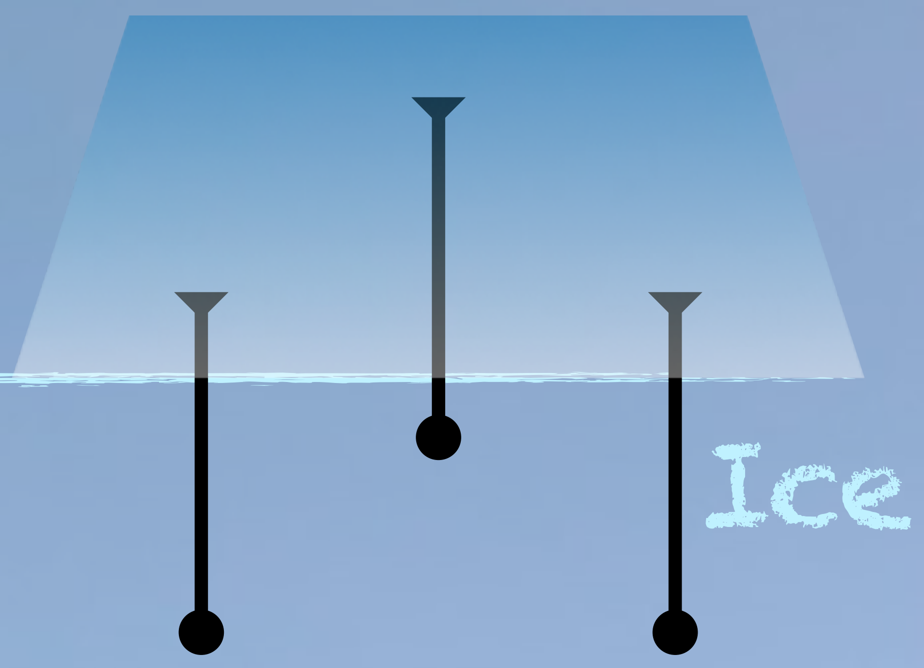

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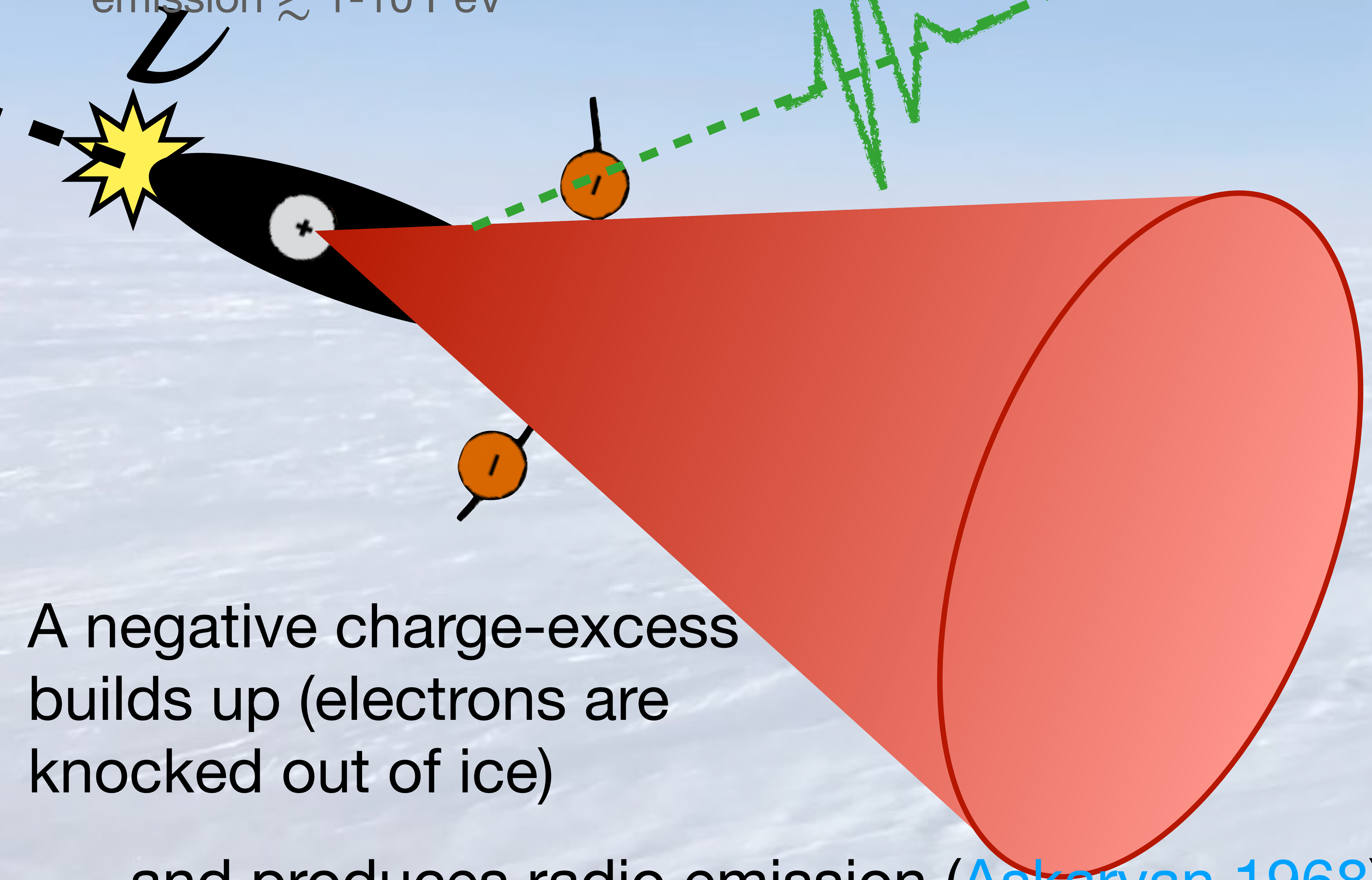

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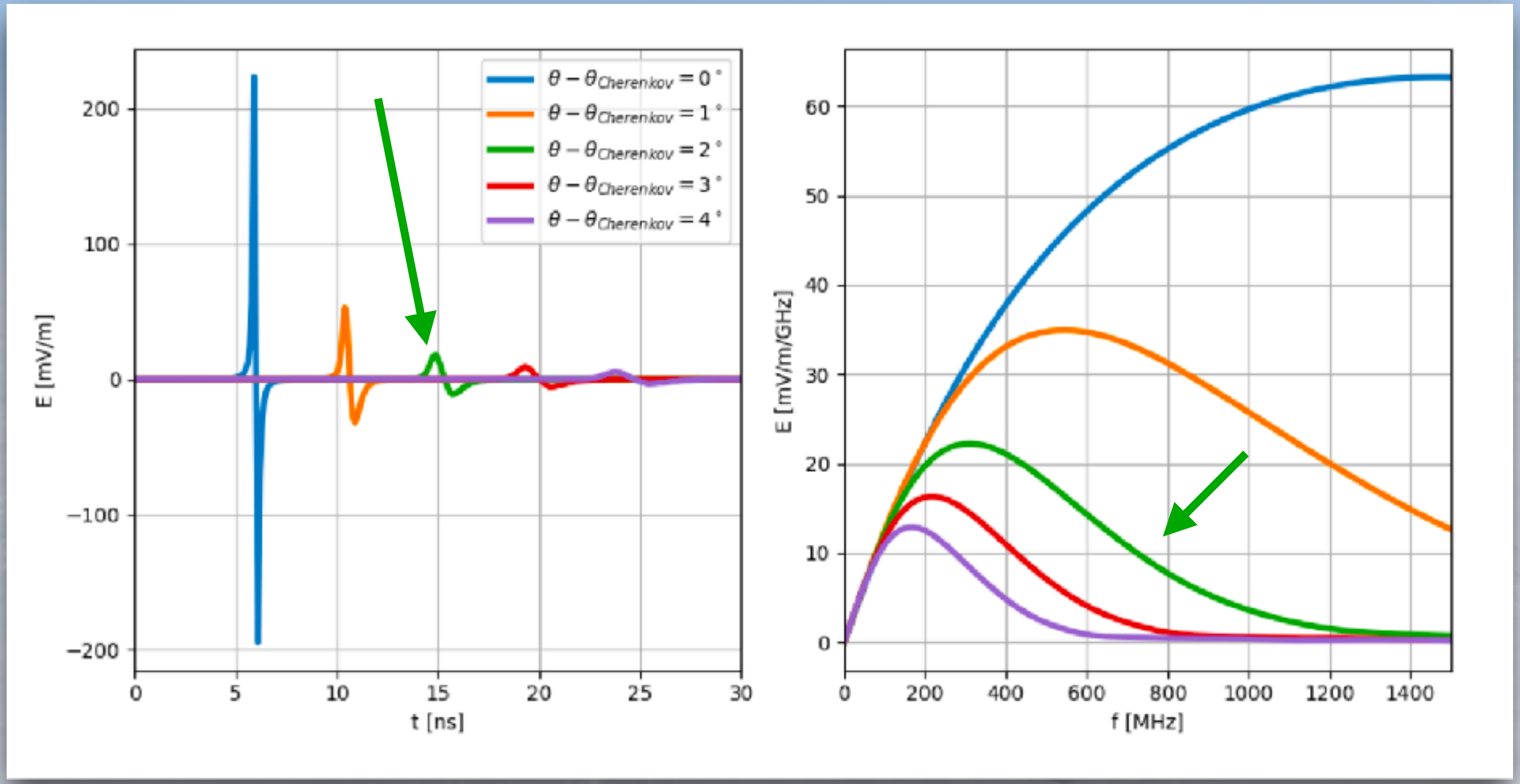

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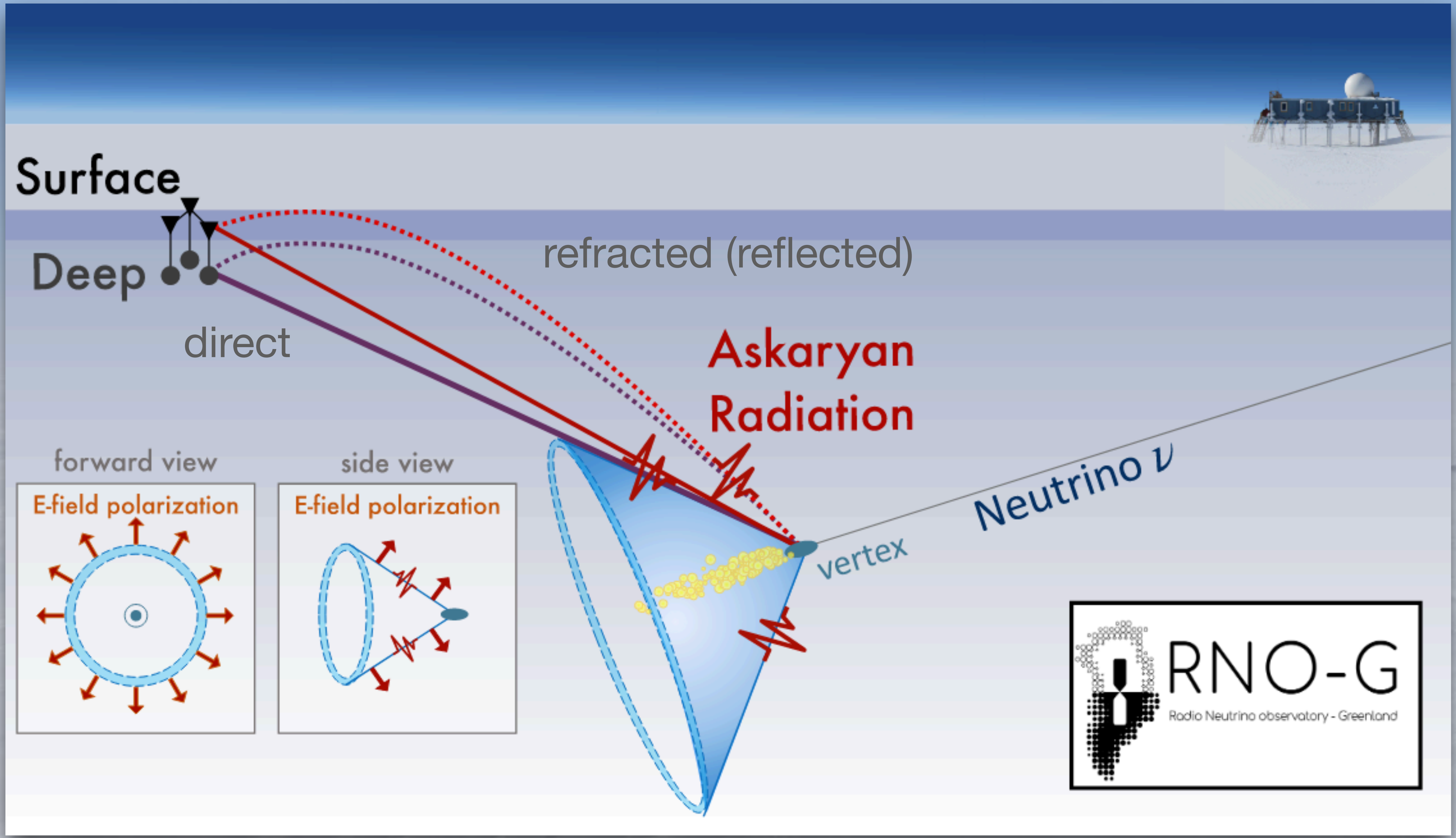
Radio detection of neutrinos

How?

- Polarisation of electric field allows localisation on cone
- Several possible ray trajectories



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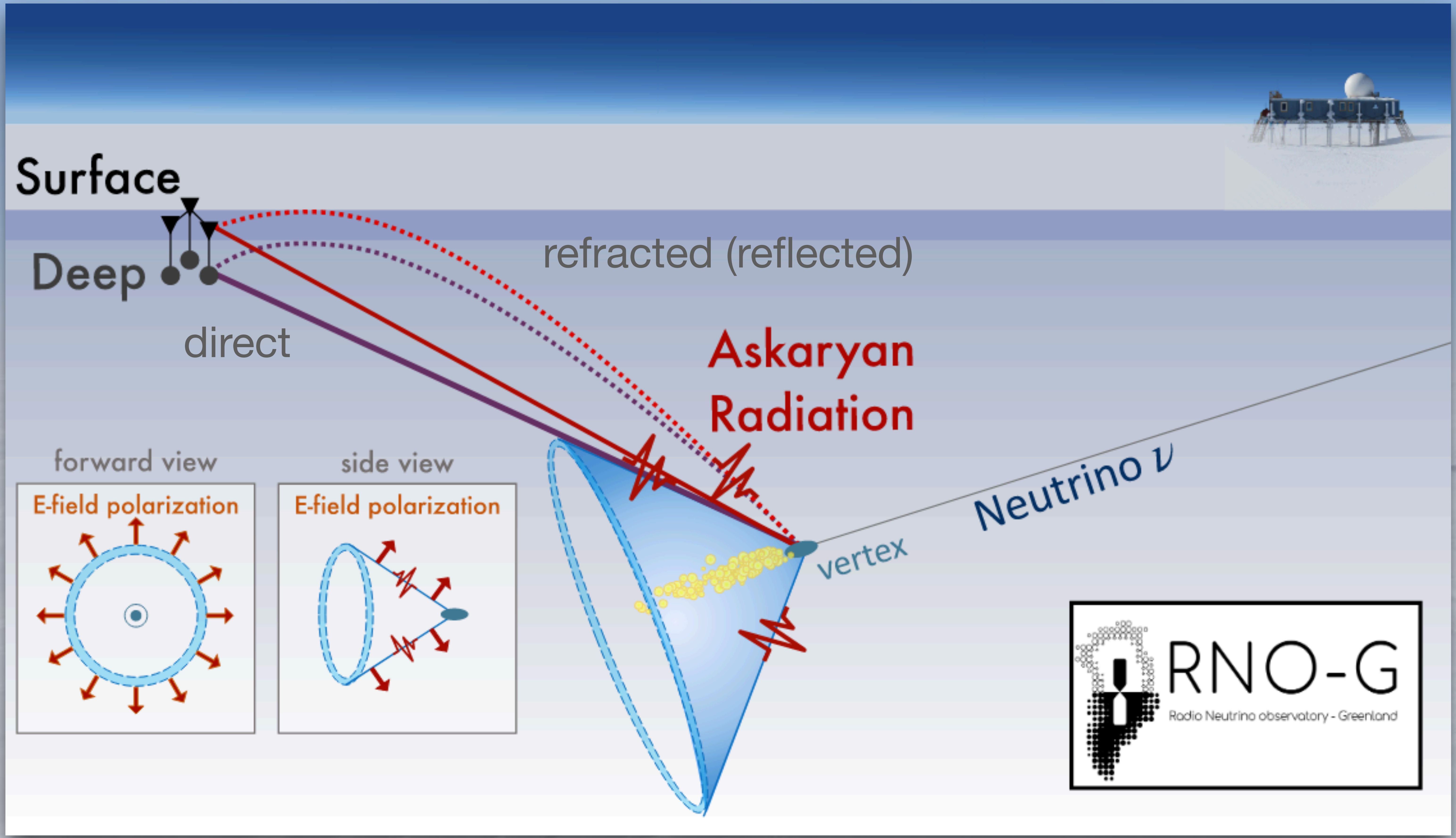
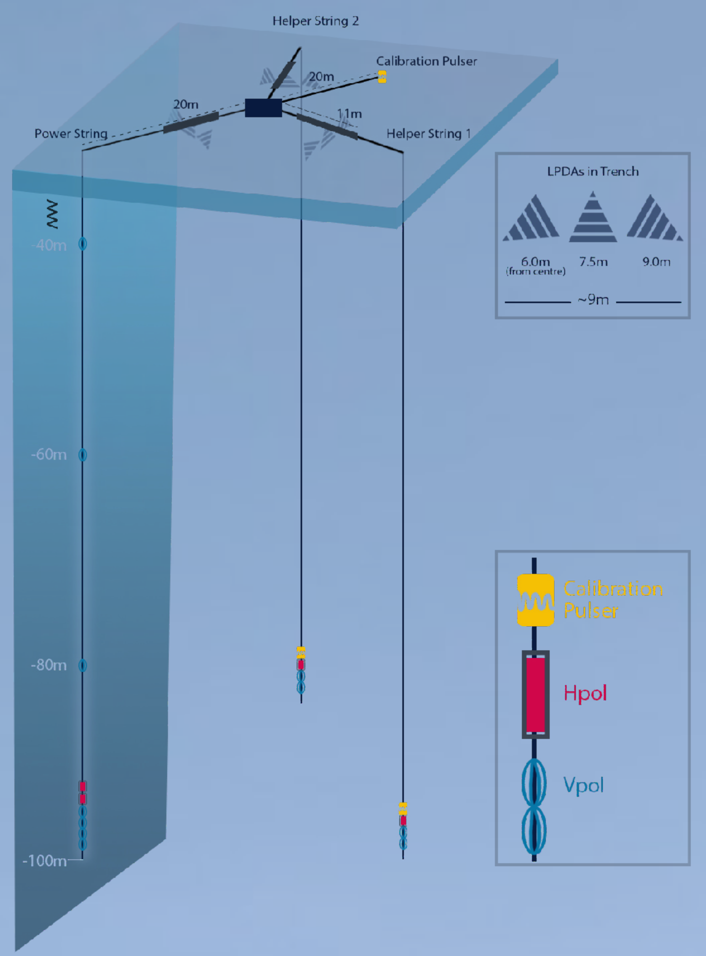


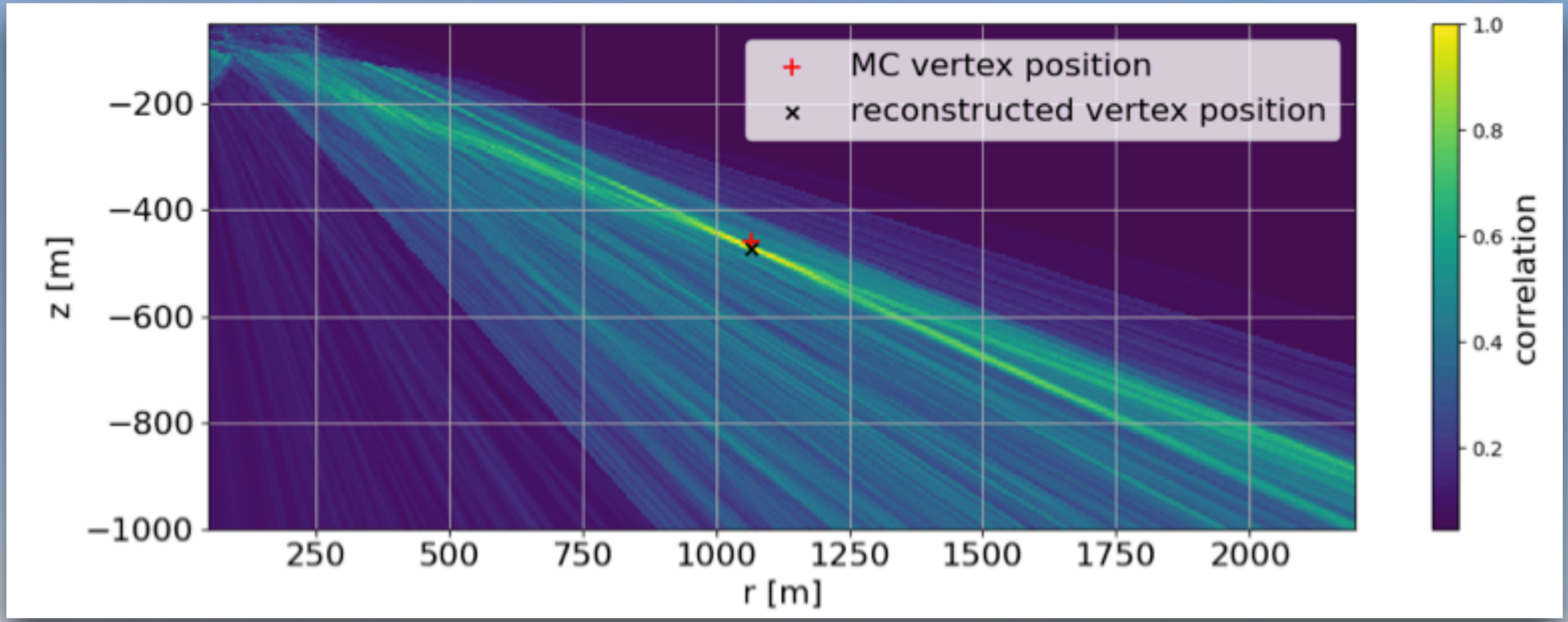
The radio emission …

- is produced by >PeV cascades
- illuminates a spherical (Cherenkov) cone
- gets bend in shallow ice
- propagates over km distances
- Signal features (frequency spectrum polarisation) allow to reconstruct neutrino properties

Arrival direction reconstruction



1. Reconstruct vertex position / signal arrival direction from triangulation



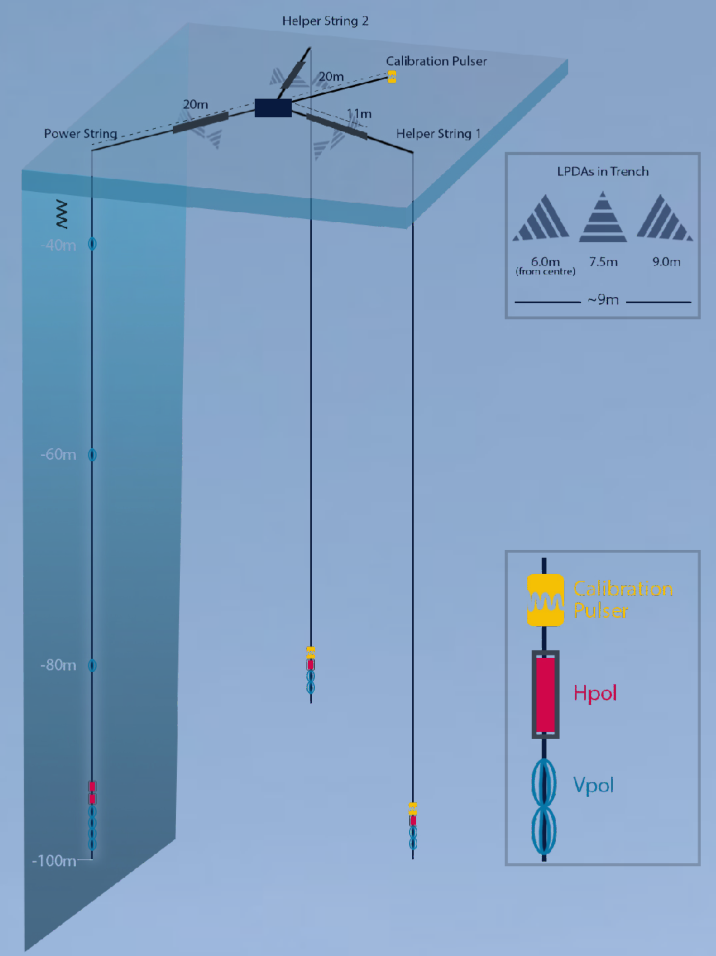
Using cross-correlation to determine signal (time) in each antenna.

Using forward folding technique to determine vertex position / signal arrival direction.

Requires signals in several strings

S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045 I. Plaisier et.al., EPJC 83 (2023) 5

Arrival direction reconstruction



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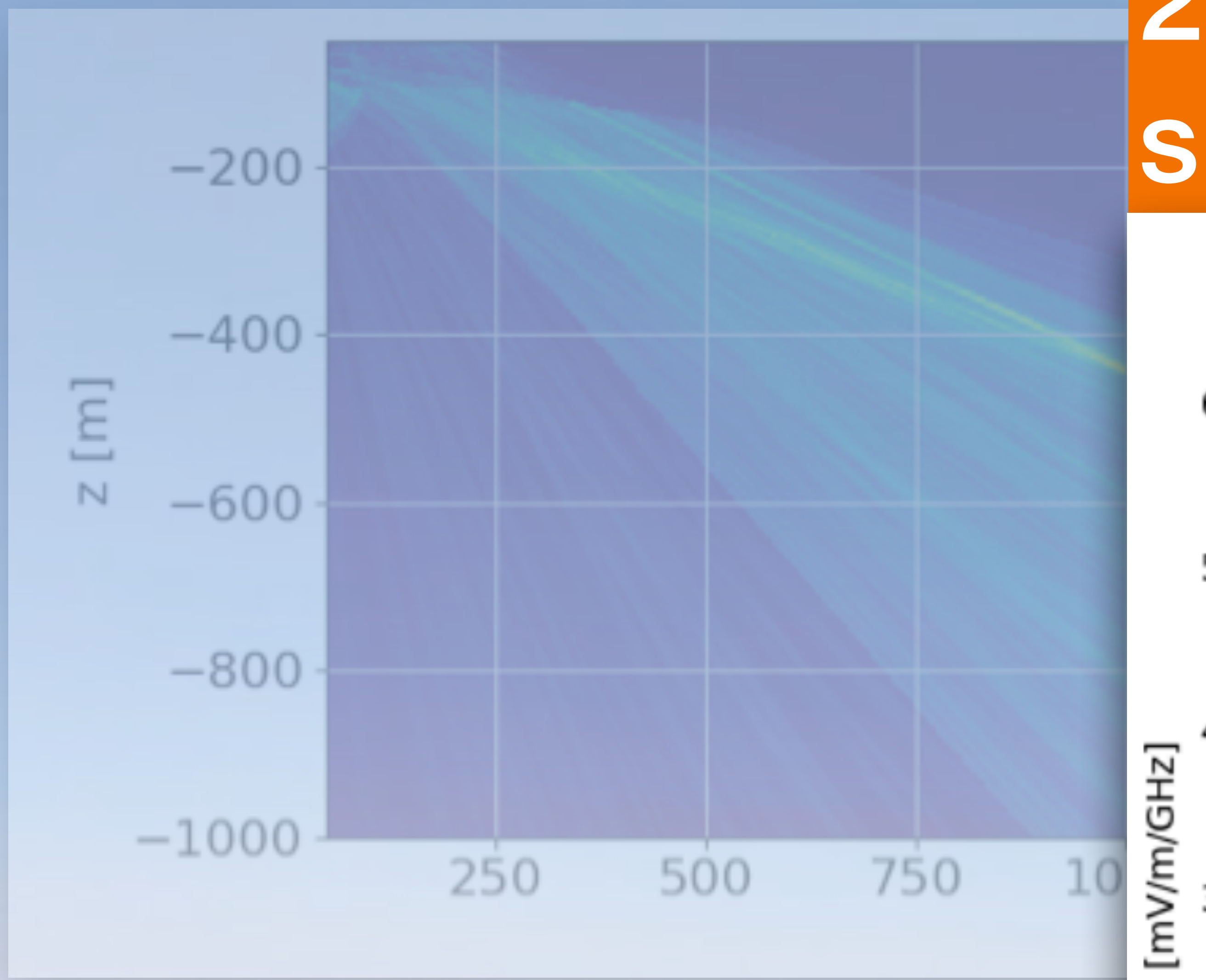

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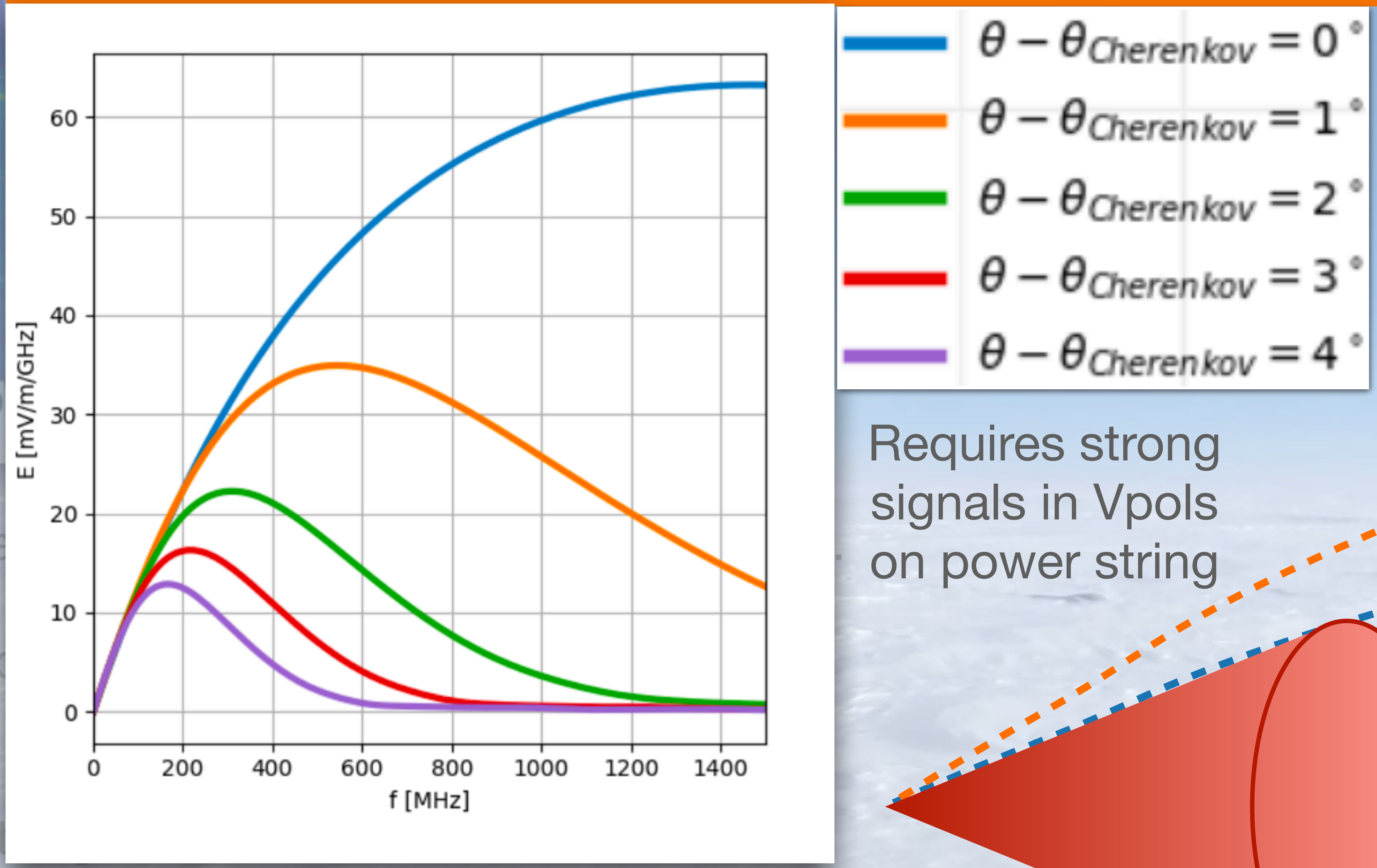
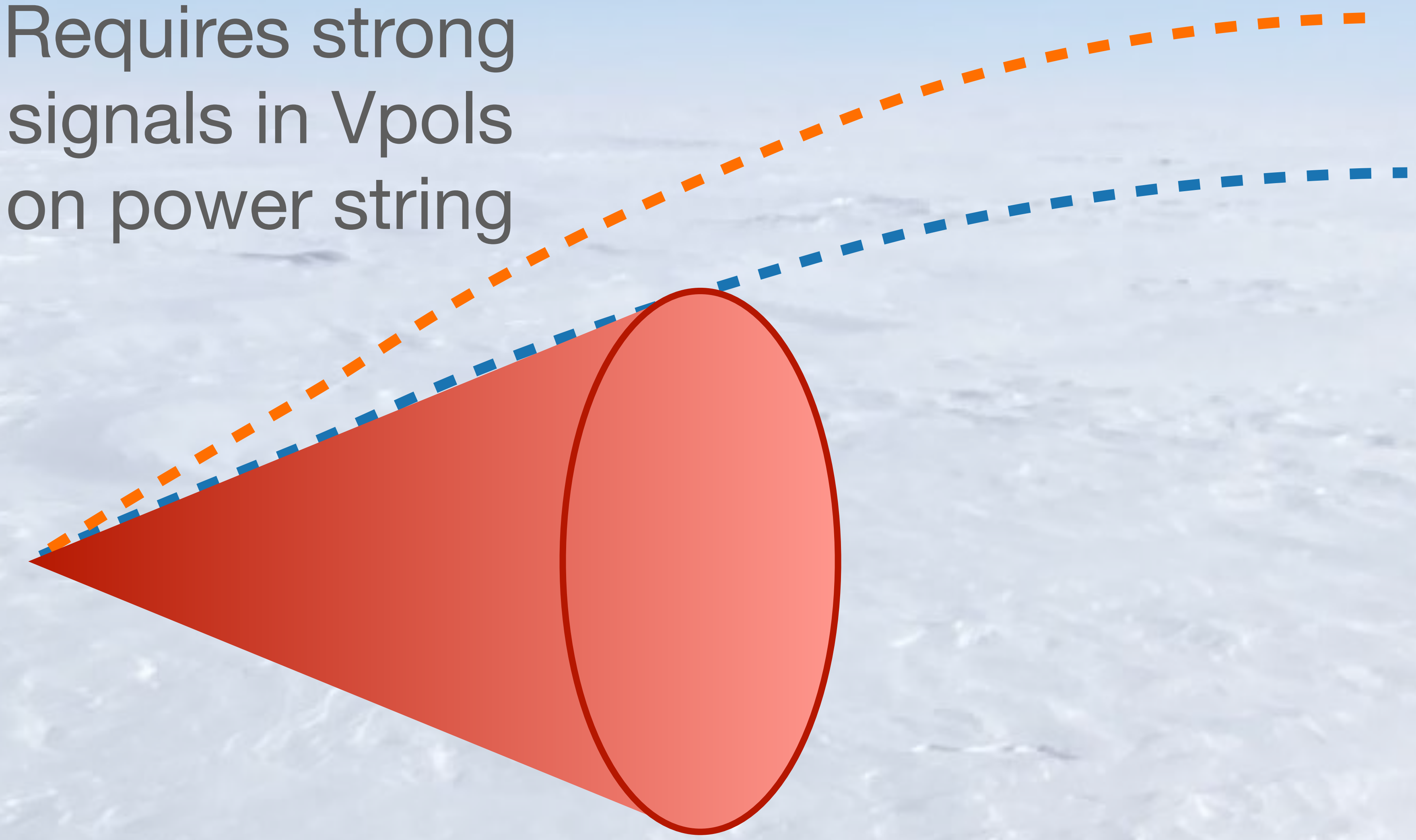
2. Reconstruct viewing angle from frequency spectrum



Requires strong signals in Vpols on power string



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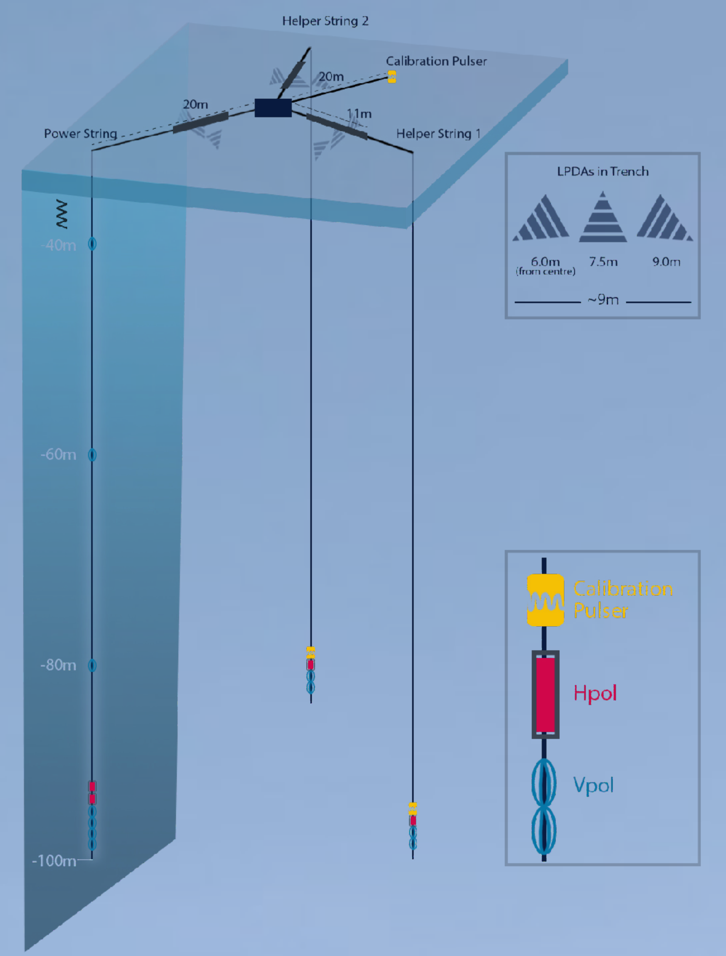

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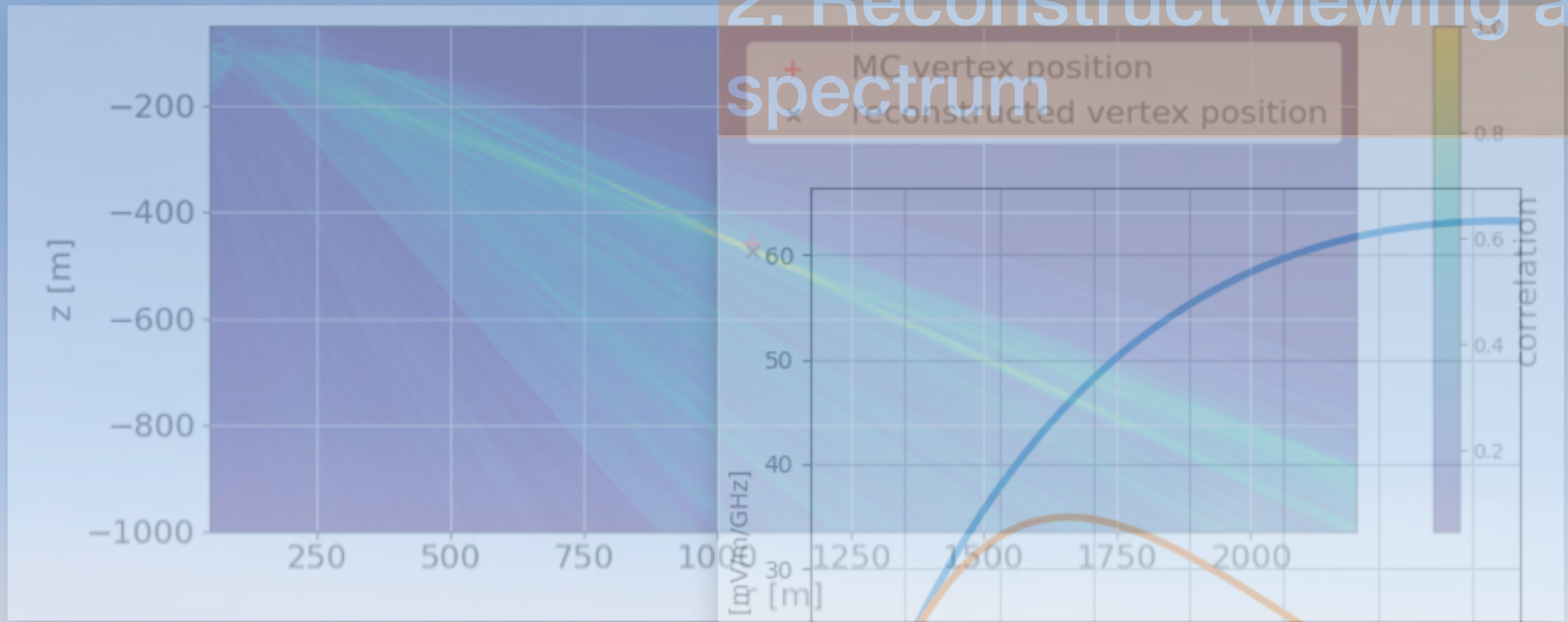

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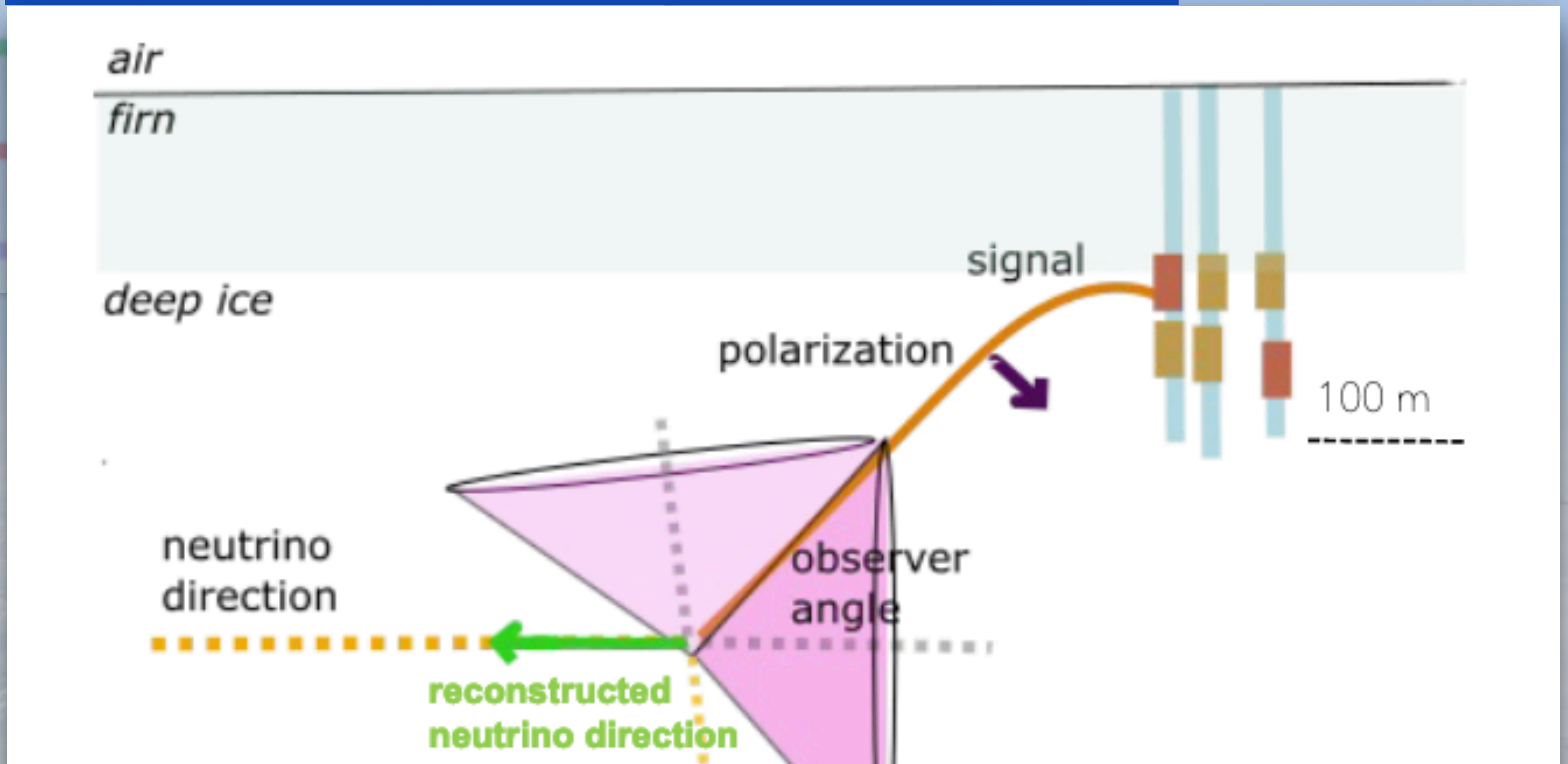
2. Reconstruct viewing angle from frequency spectrum

3. Reconstruct polarisation



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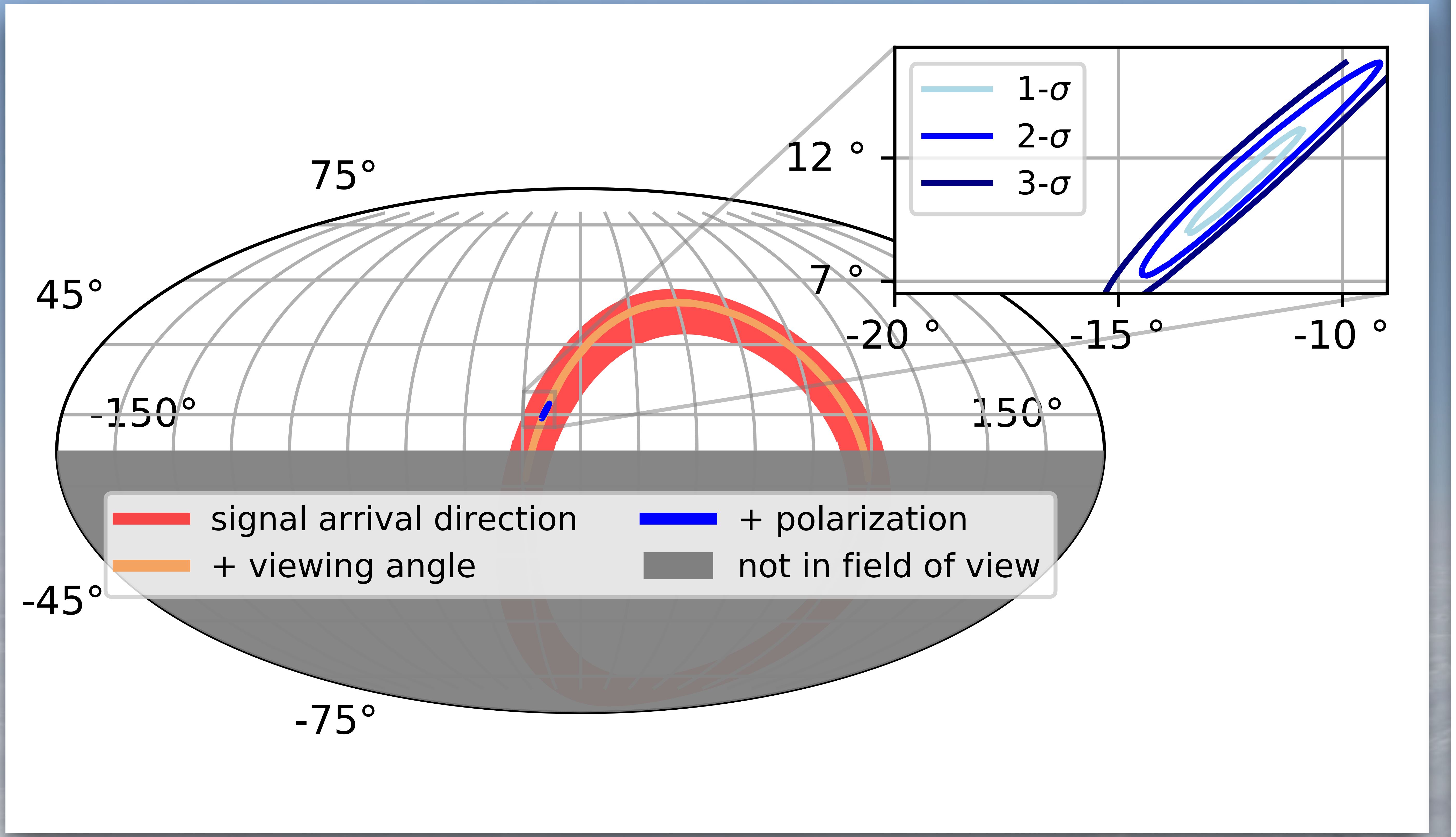

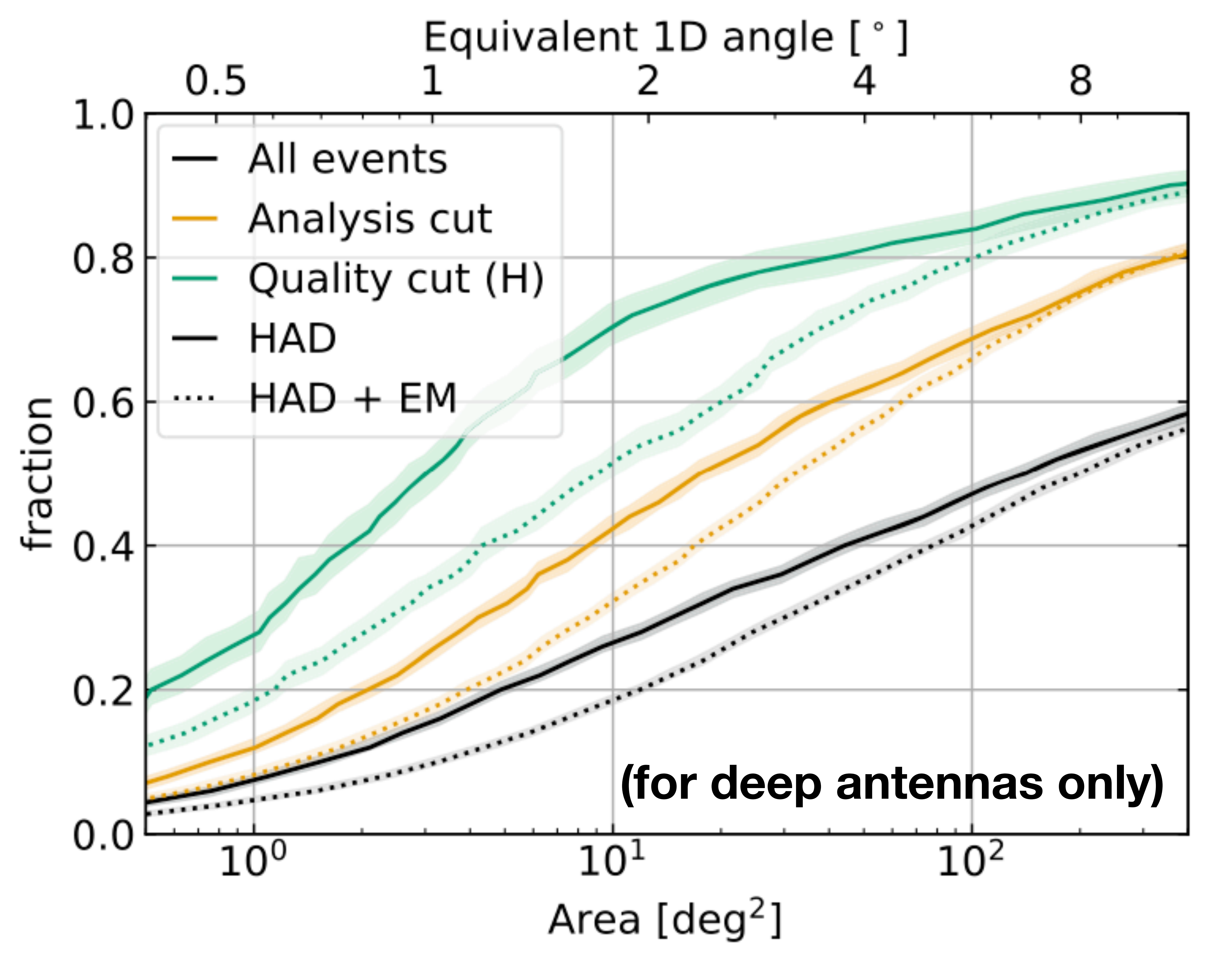

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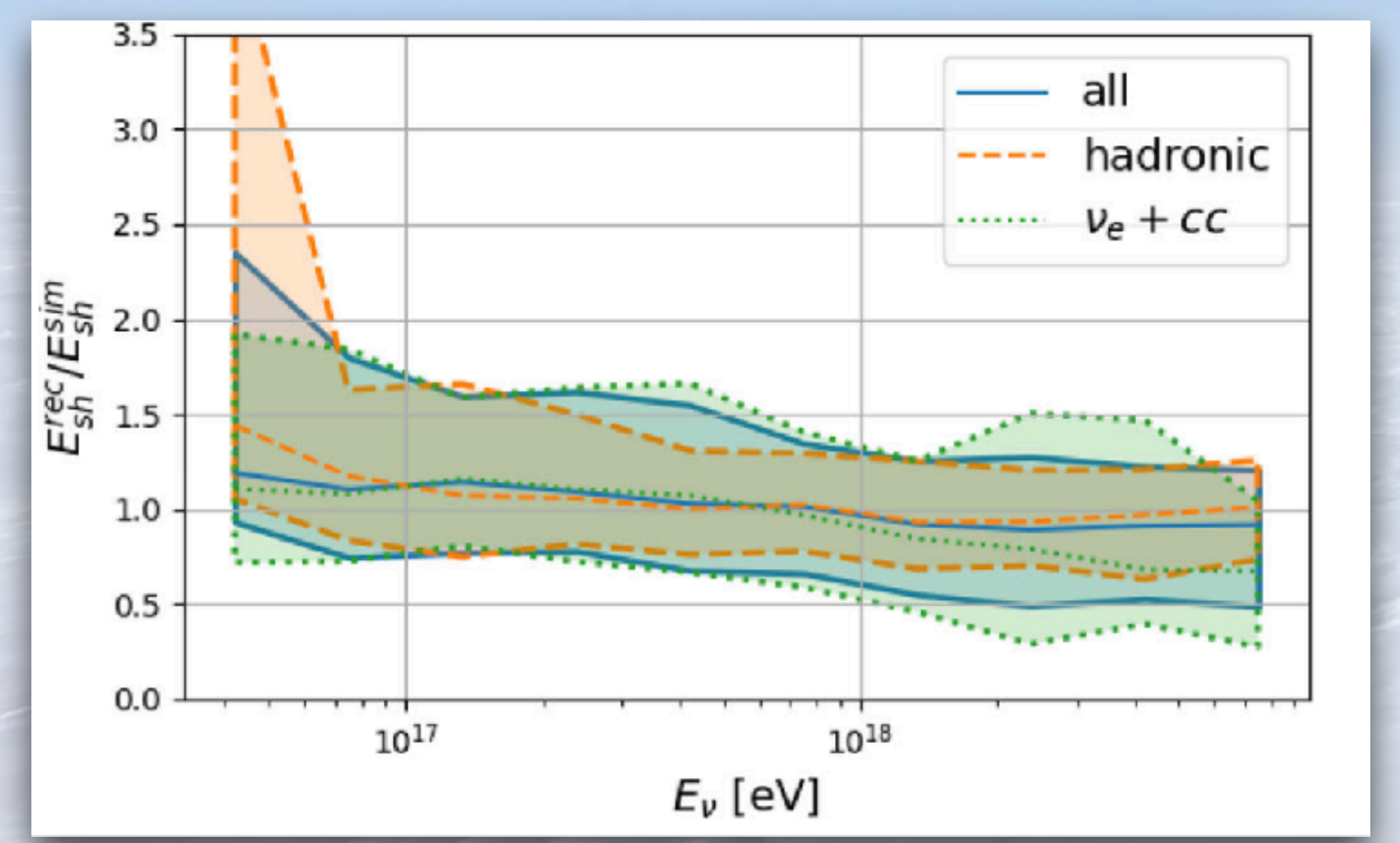
Energy reconstruction

[RNO-G, EPJC 82, 147 (2022)](#) [RNO-G, JINST 16 (2021) 03](#)

Observed Field — Viewing angle — Vertex Distance — Polarization

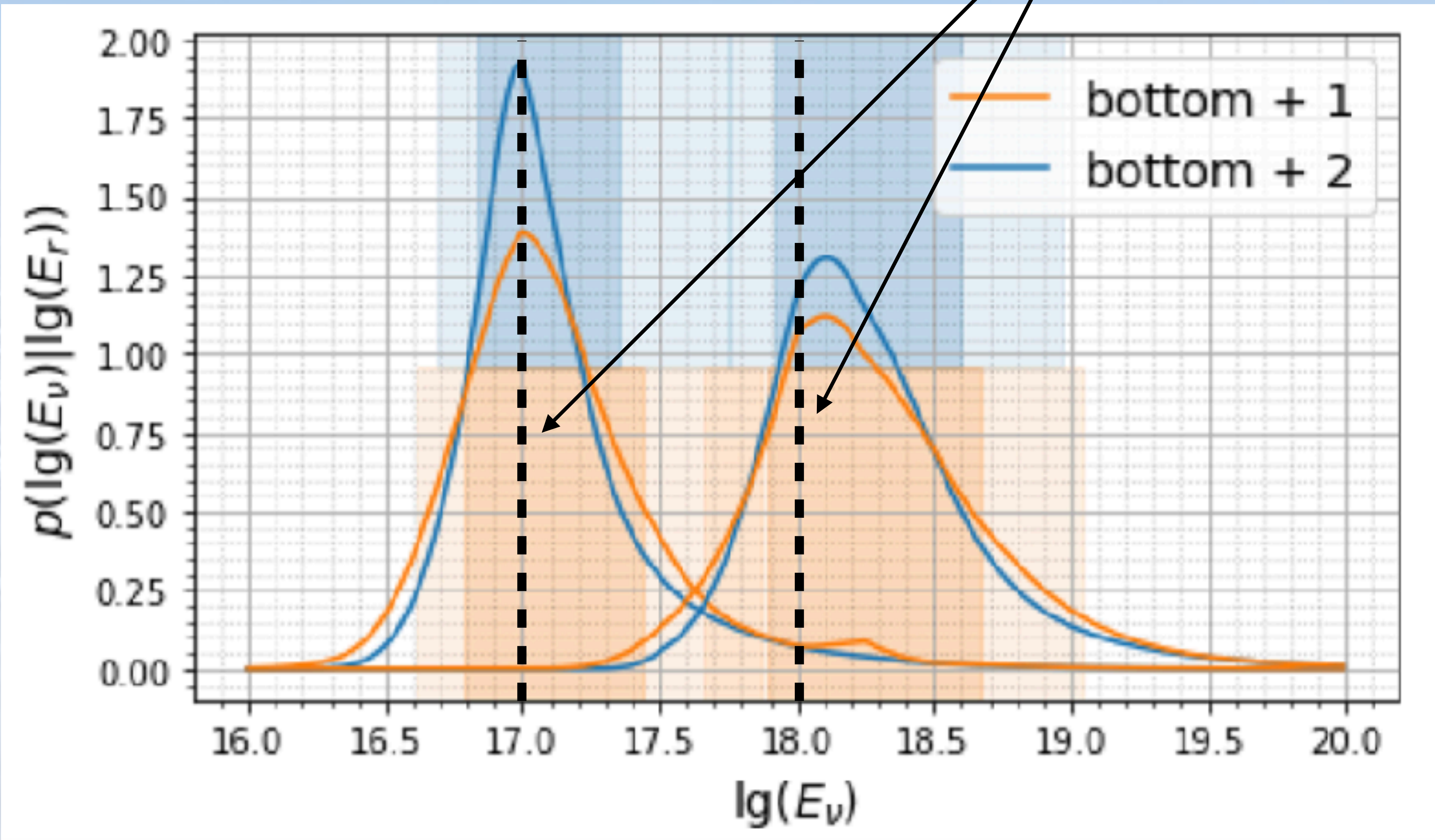
$$\vec{\mathcal{E}}(f) \propto (1-y)E_\nu \; \exp\left[-\frac{1}{2}\left(\frac{\theta-\theta_c}{\sigma(E_{sh},f)}\right)^2\right] \; \frac{1}{R}\exp\left(\frac{-R}{L(f)}\right) \; \vec{\ell}\times(\vec{v}_\nu\times\vec{\ell})$$

Shower energy



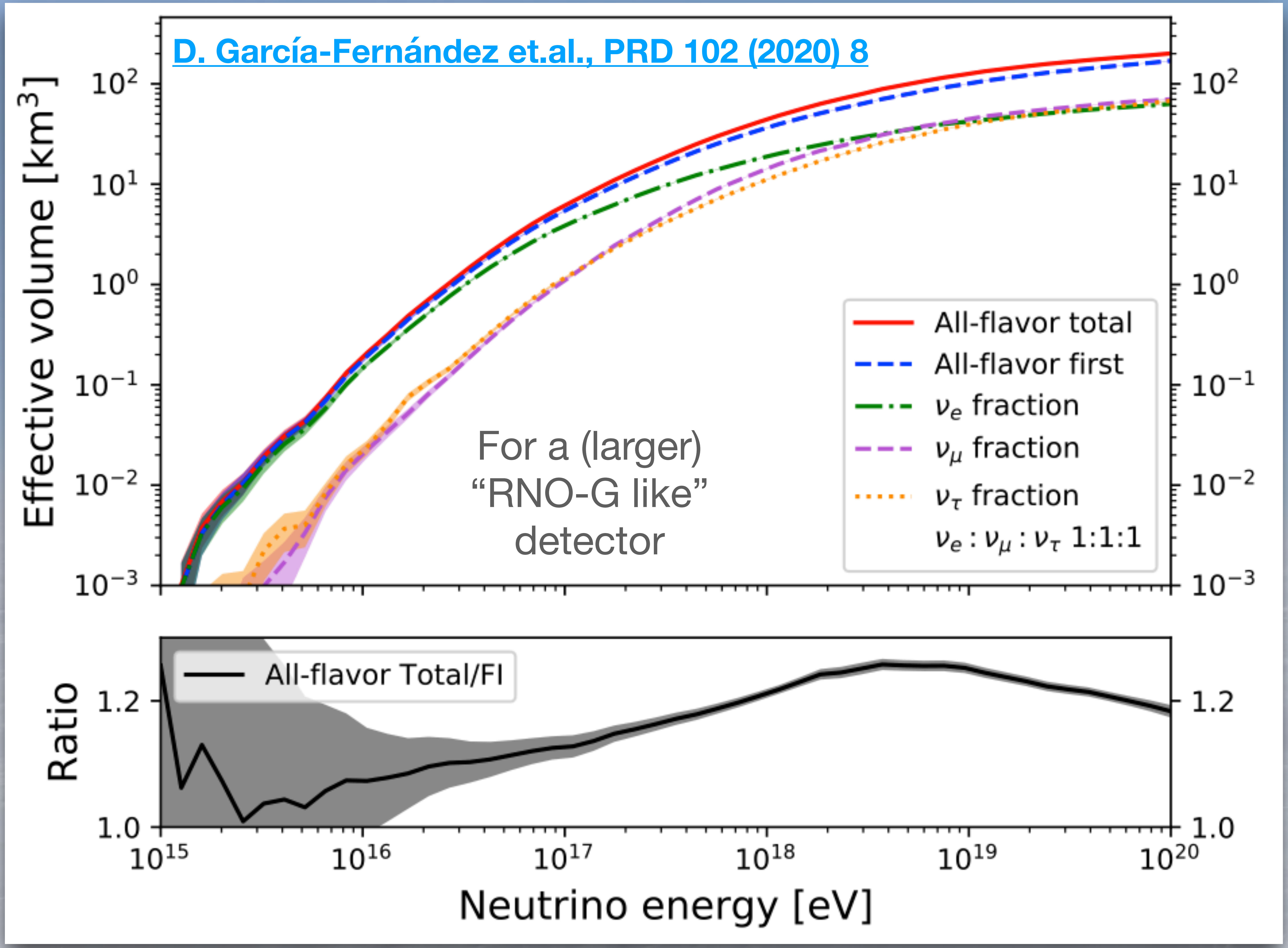
Neutrino energy

True energy



Detecting neutrinos with RNO-G

Effective area

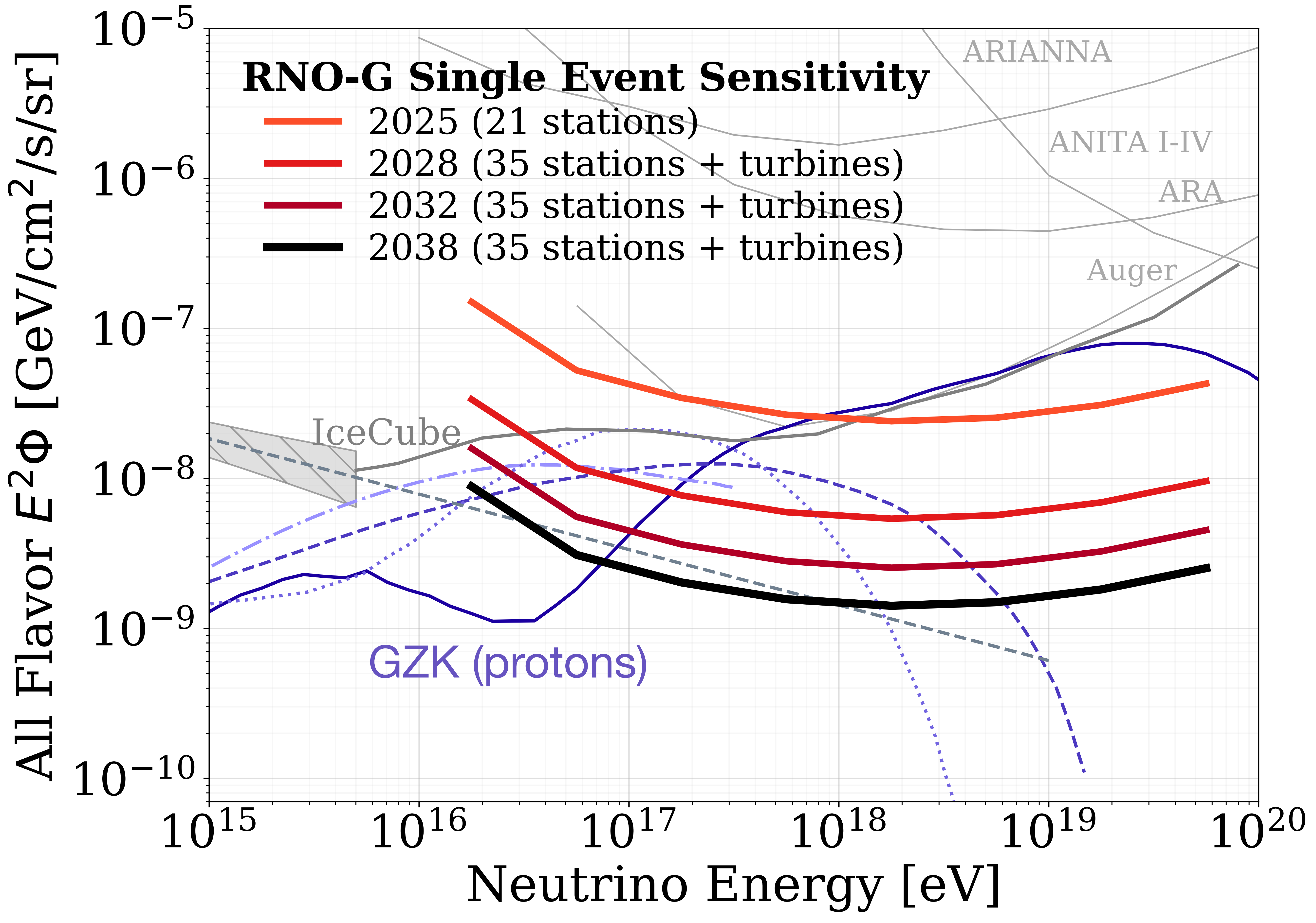


- At lower energies: Sensitivity from electron neutrinos
  - Strong(er) electromagnetic cascades in CC interactions
- At higher energies: Similar sensitivity across all flavours
  - LPM effect "hurts" radio signal in very high energy em cascades
  - Muon and tau leptons undergo catastrophic energy losses which can trigger the radio detector

Sensitivity

to a diffuse emission

- World leading sensitivity @ 1 EeV
- Cosmogenic neutrinos from proton interactions with the CMB (GZK cutoff)
  - Not discovered yet
  - RNO-G will confirm or reject the most promising flux expectations
- Unresolved point source
  - Extension of astrophysical flux measured by IceCube
  - Potential to discover a hardening
- Expect low background



M. Muzio for RNO-G, PoS (ICRC23) 1485

Detecting neutrinos with RNO-G

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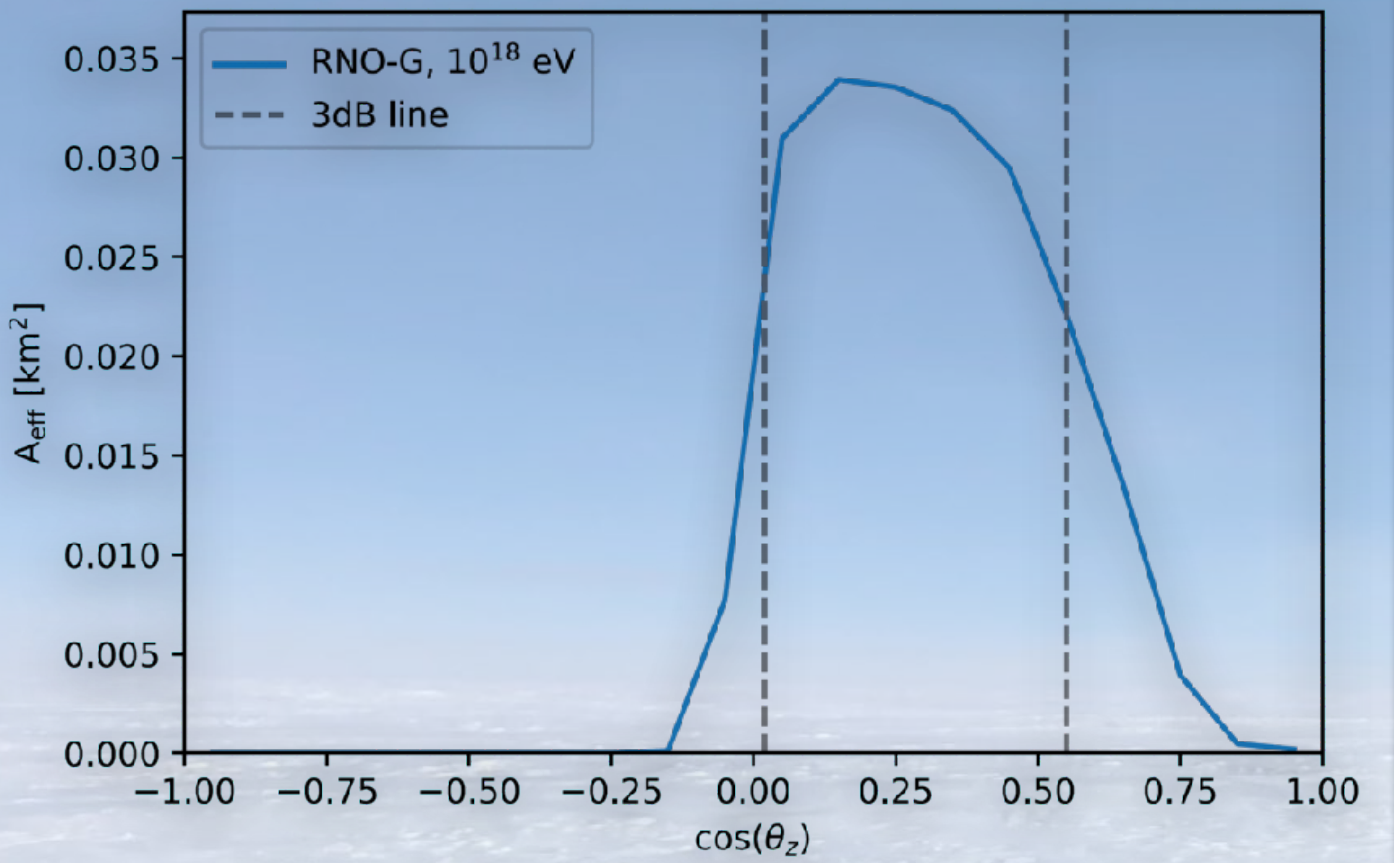

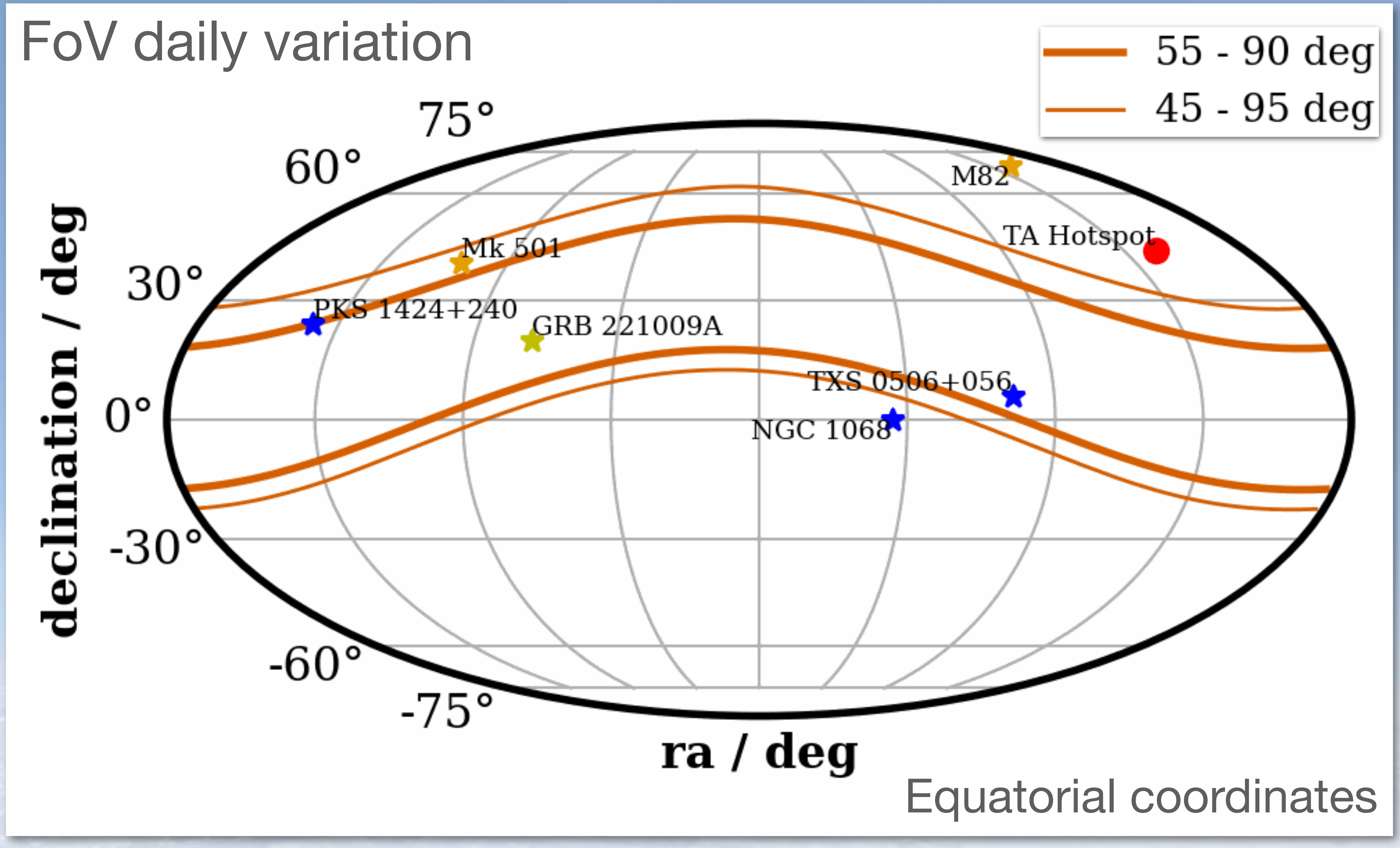

- Largest aperture just above the horizon
- Earth is opaque for UHE neutrinos
- Observatory in northern hemisphere relevant for multi-messenger observation!

Detecting neutrinos with RNO-G

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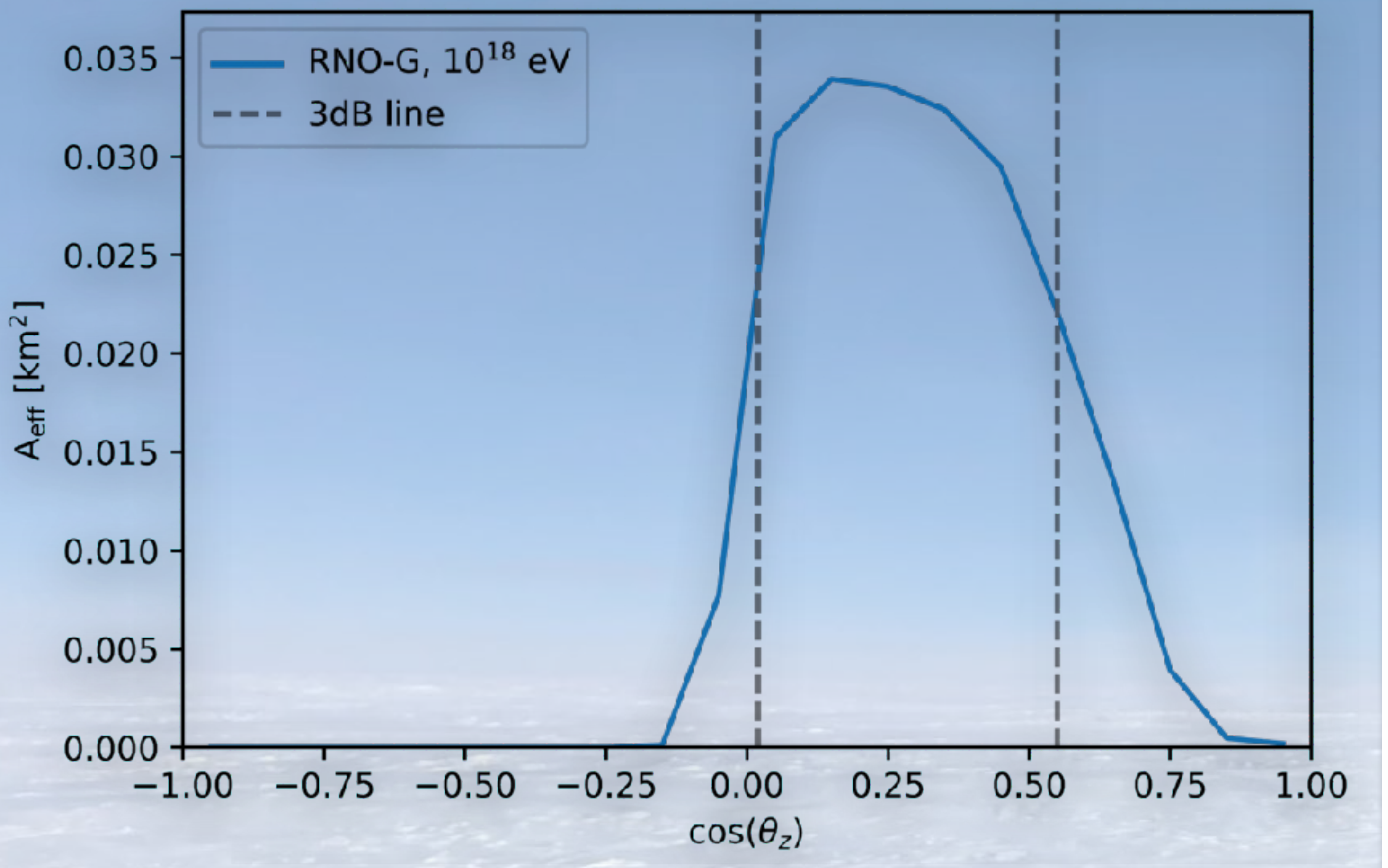

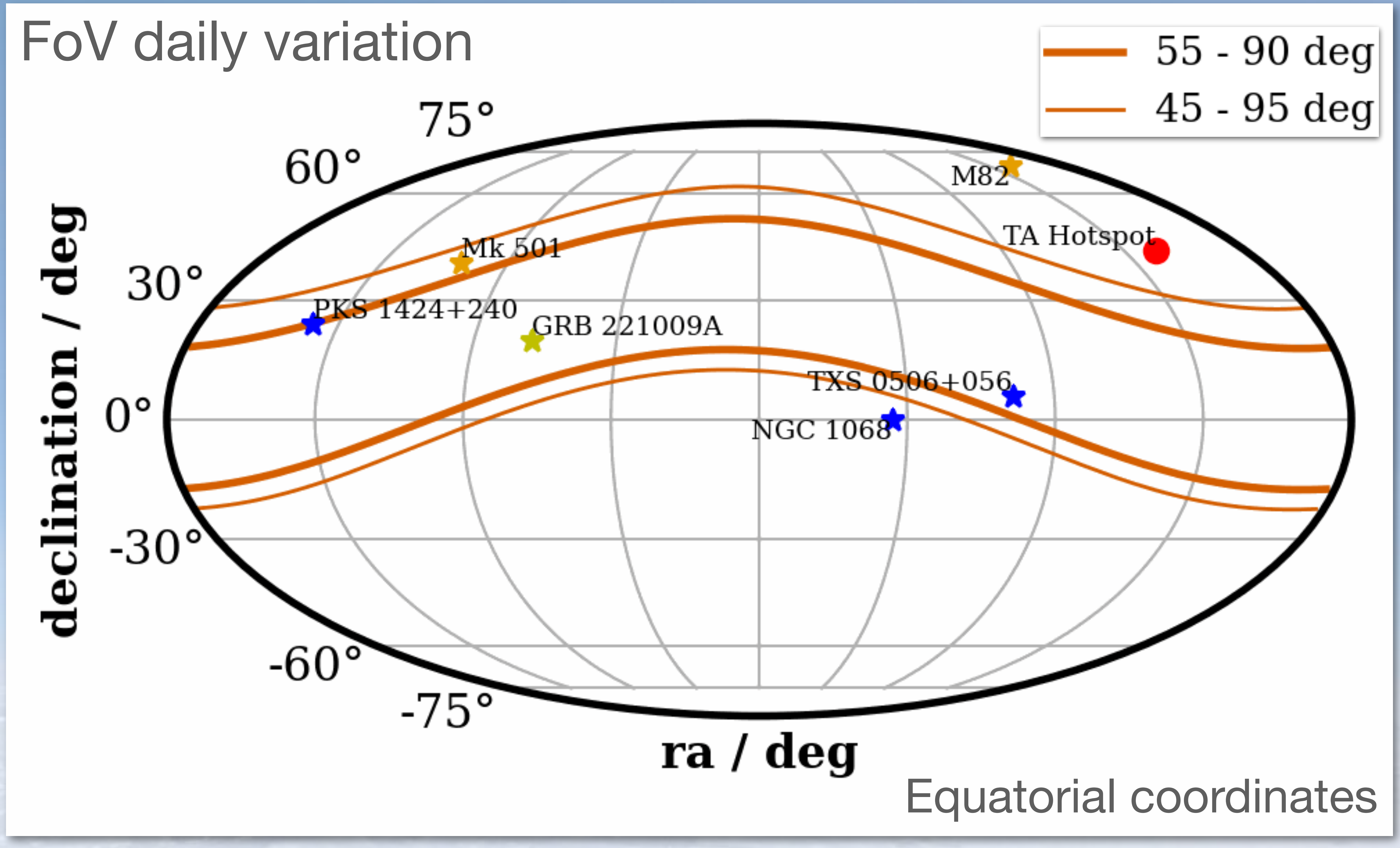

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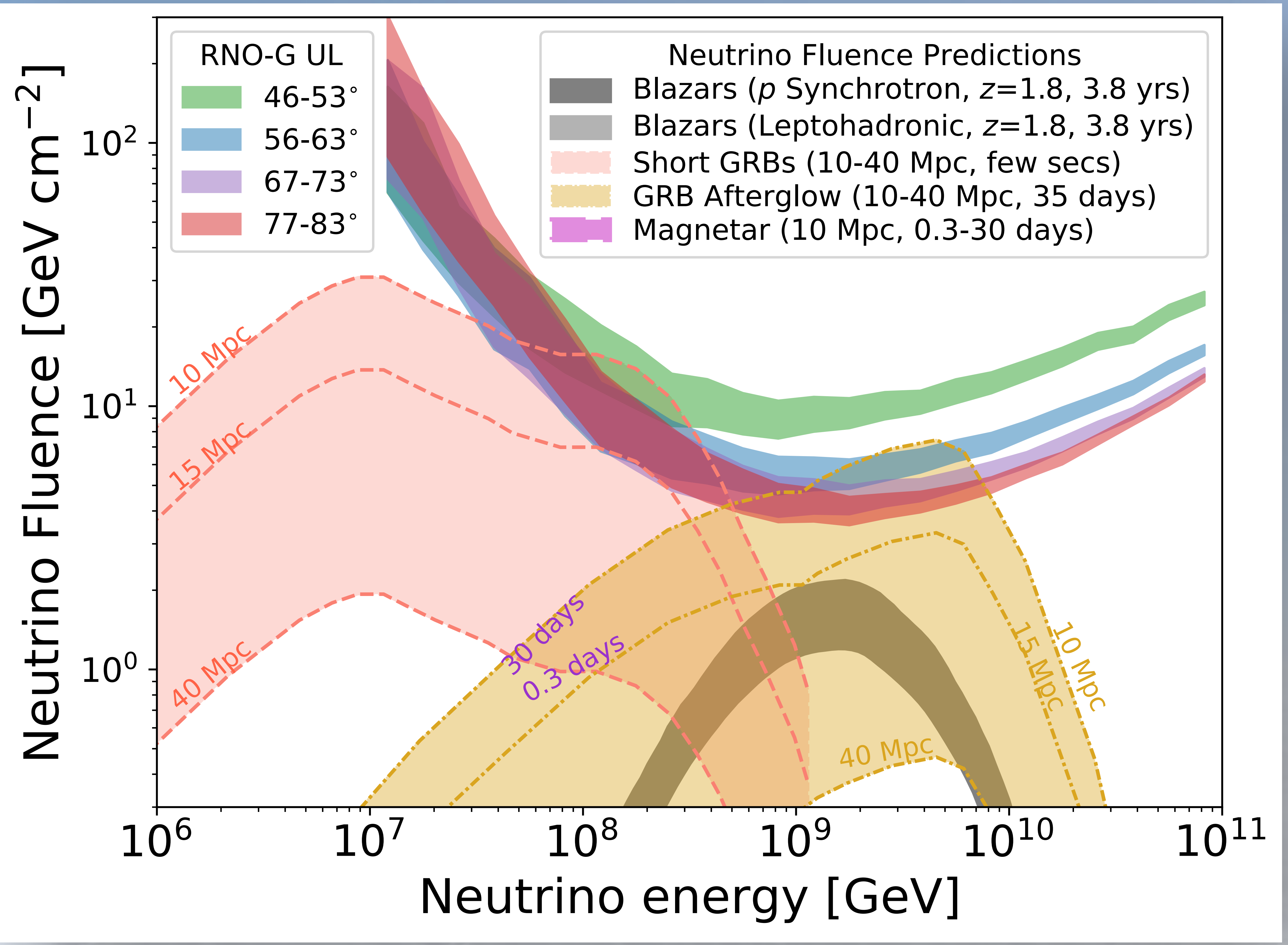
Sensitivity

to transient events

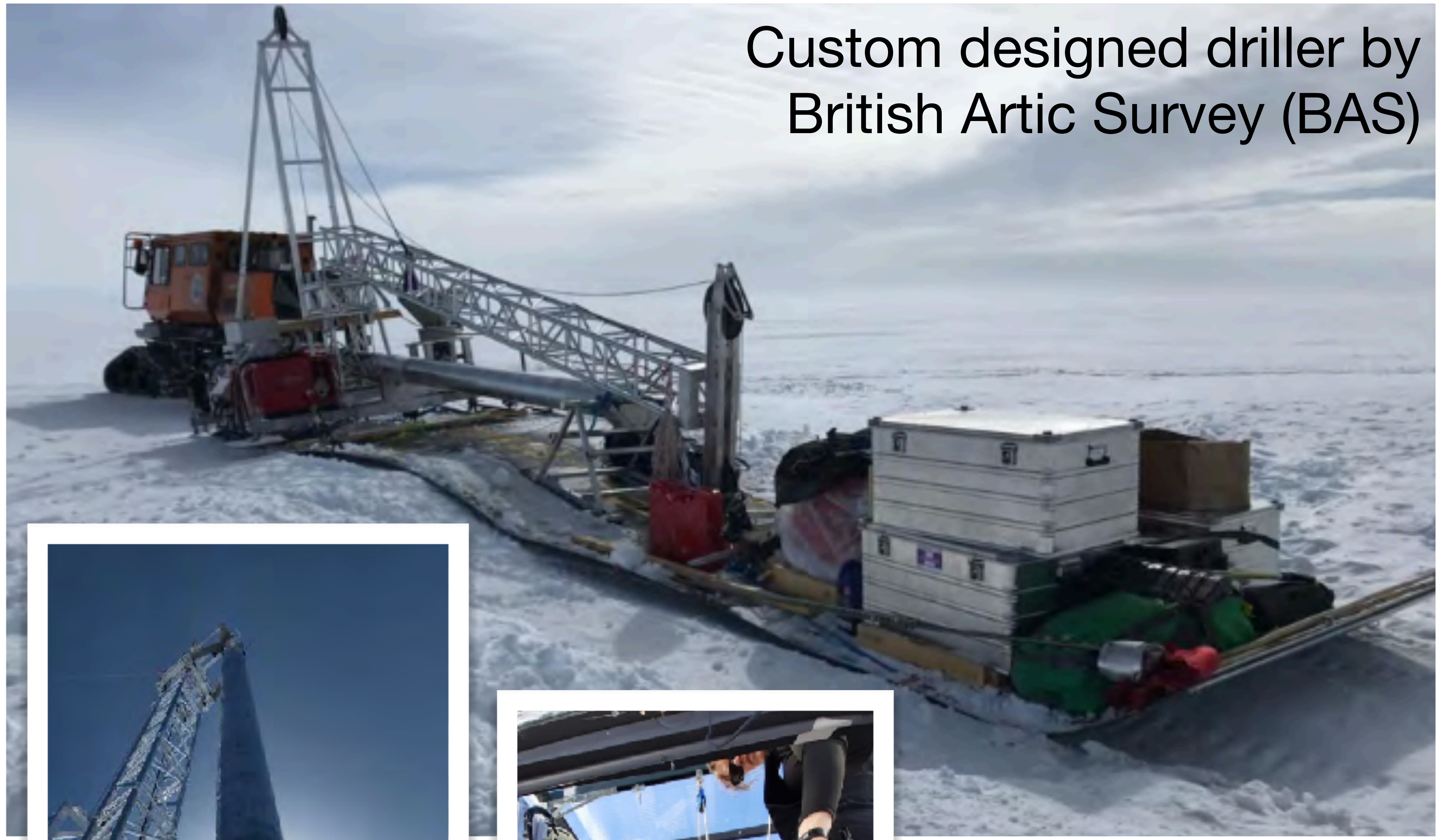
- Able to observe nearby GRBs
- Contributor for multi-messenger search also with IceCube-Gen2 in the south

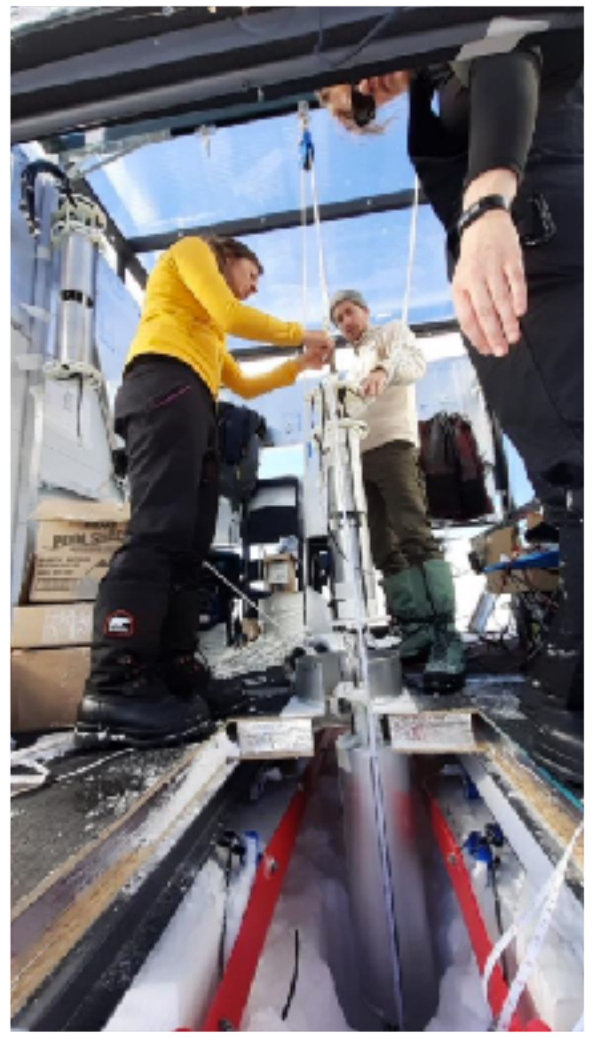


RNO-G, JINST 16 (2021) 03

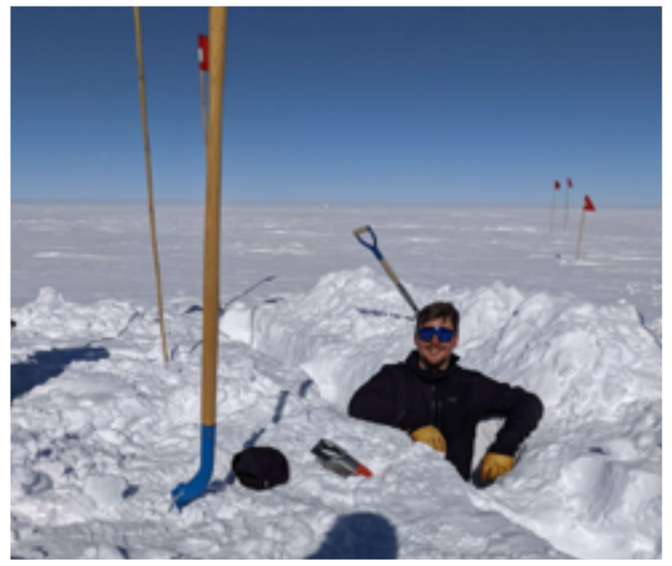
Deployment

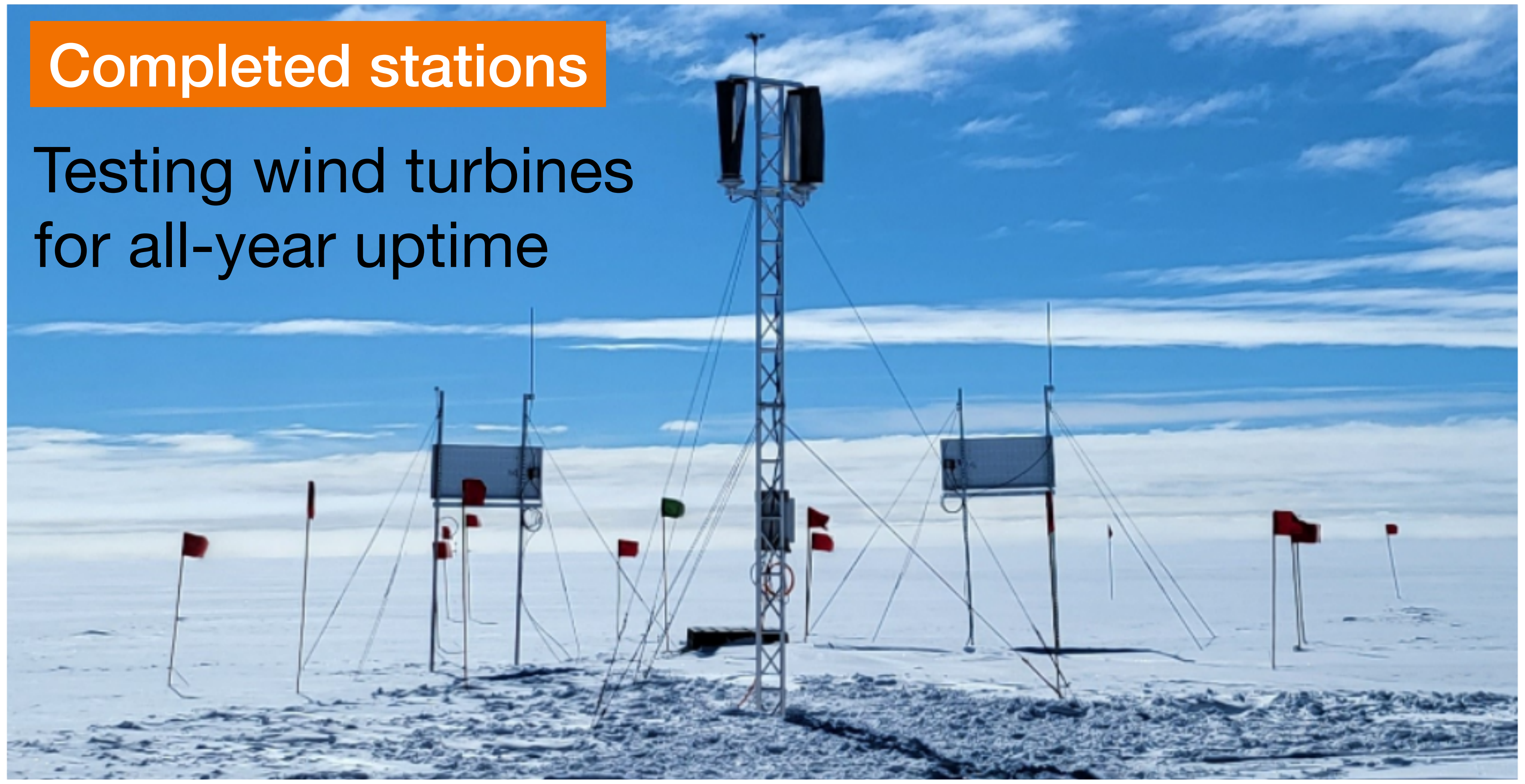
Drilling 100m deep, 28 cm diameter hole





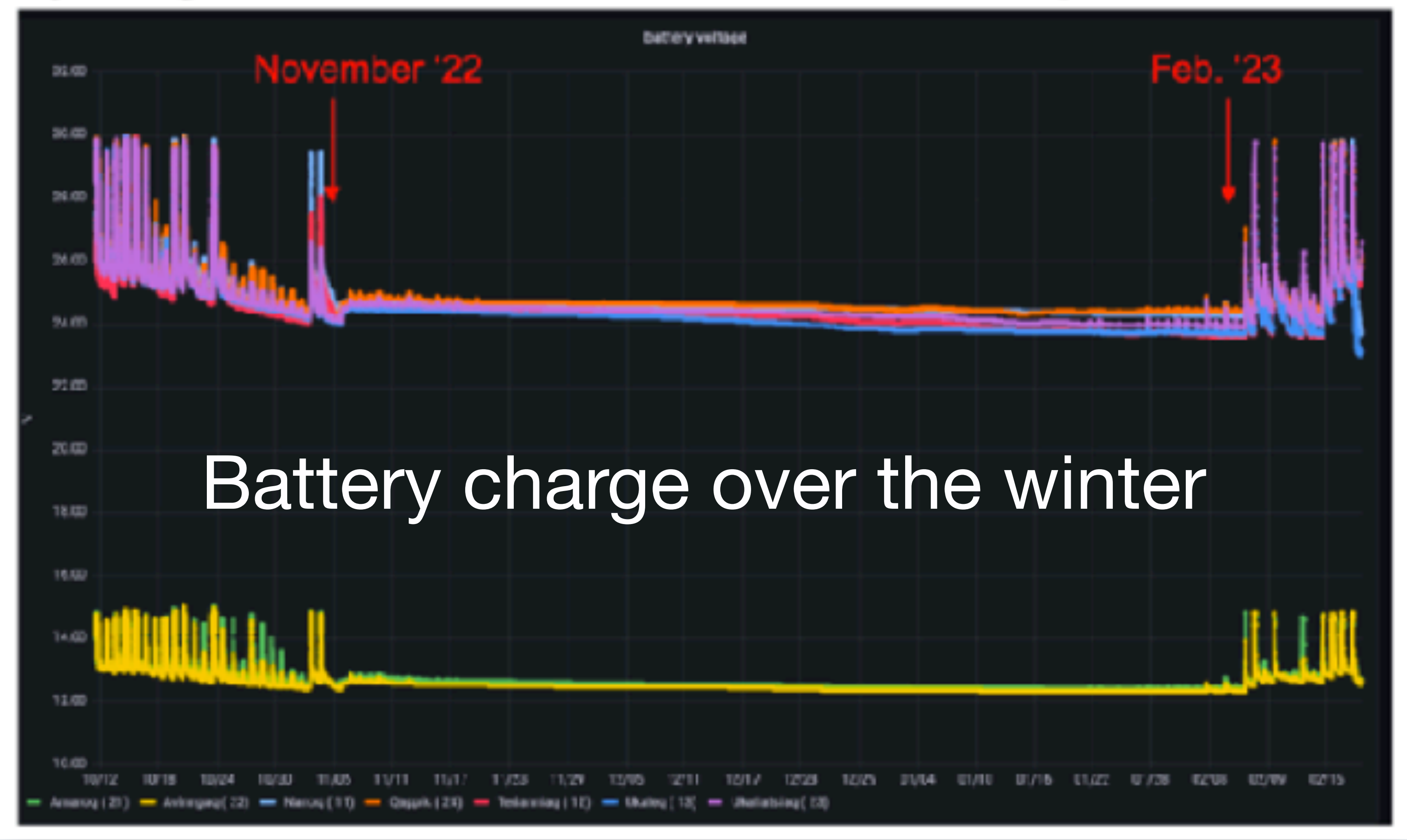
Shallow antennas are deployed in trenches …

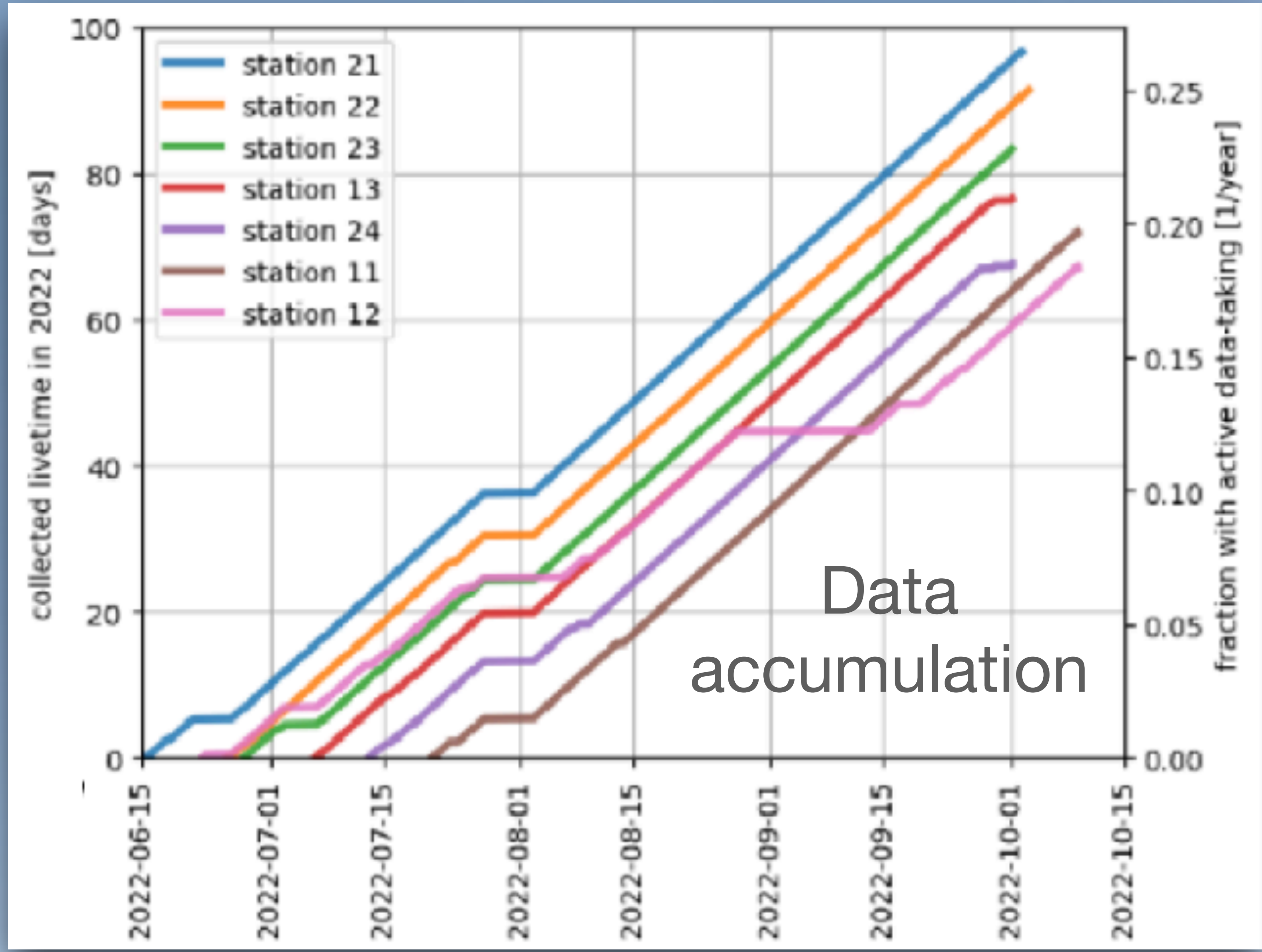


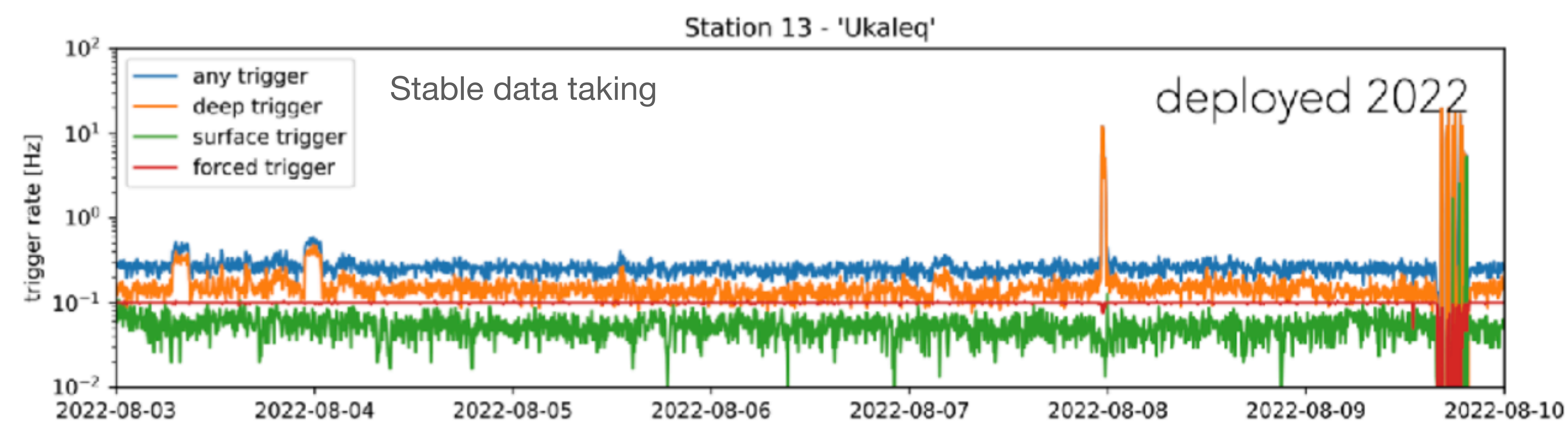


Hardware performance

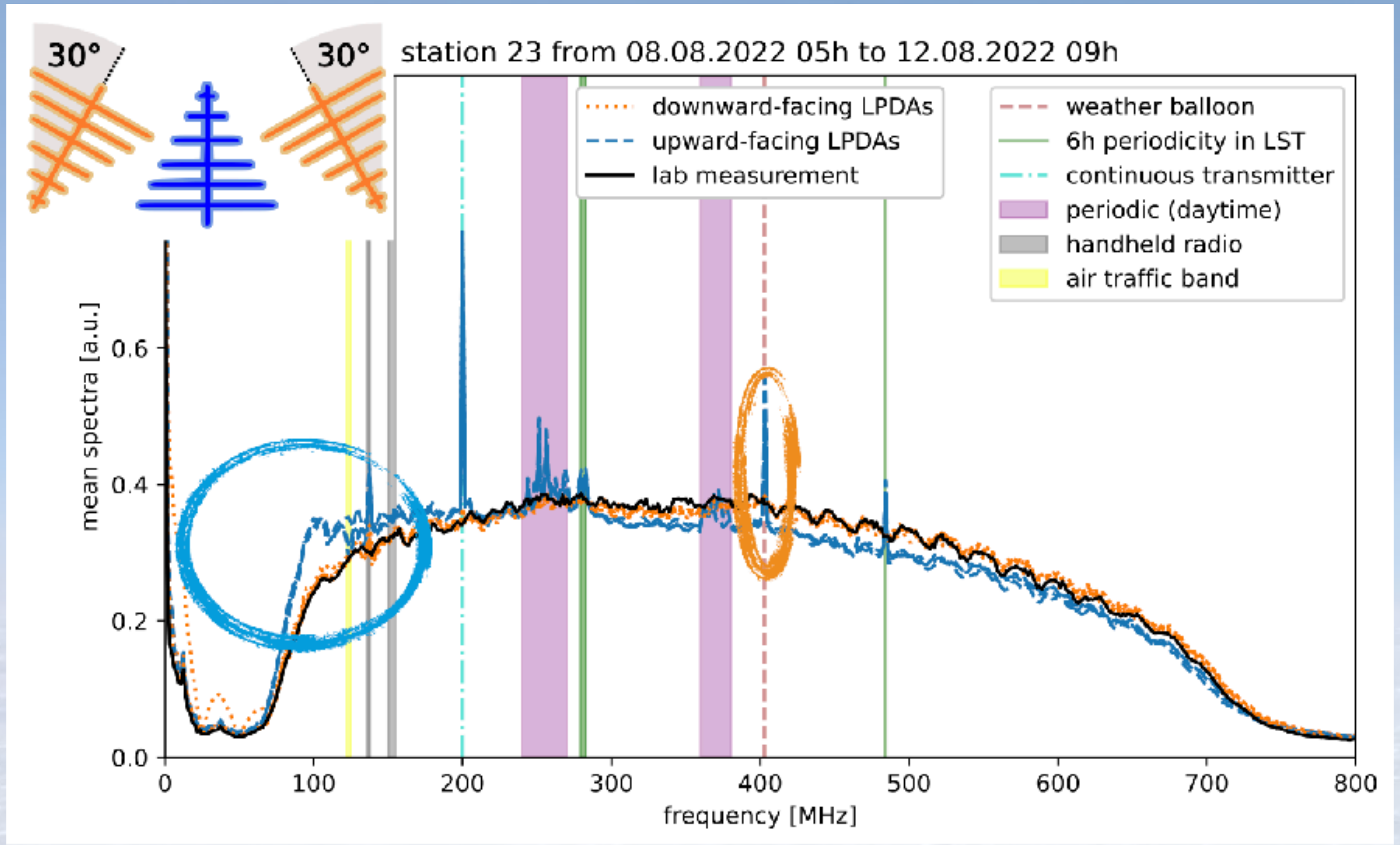
Aka surviving the winter!



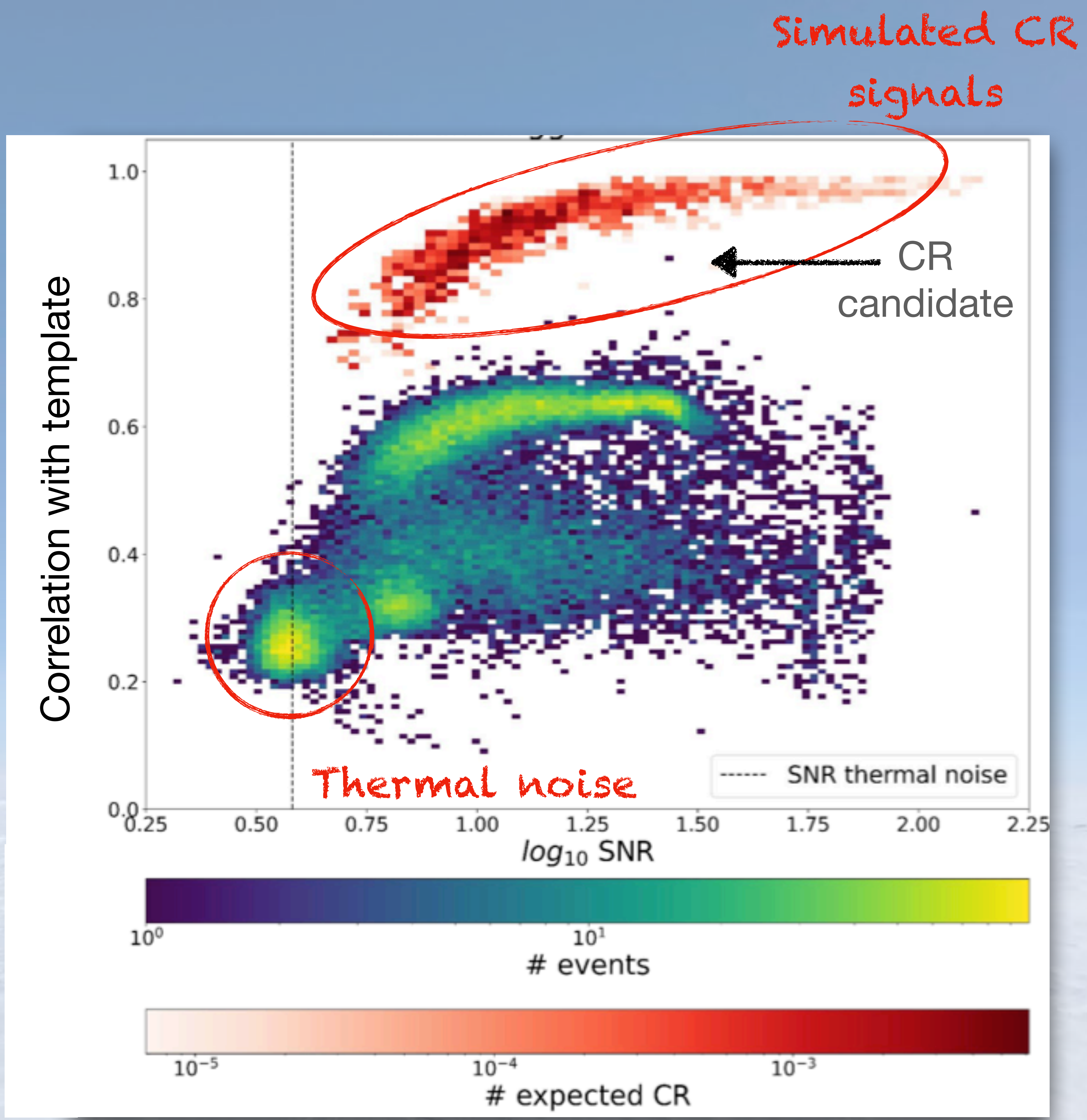




First look into the data



Excess in received power at lower frequencies for upward-facing LPDAs → Galactic emission



S. Hallmann for RNO-G, Pos (ICRC23) 1043

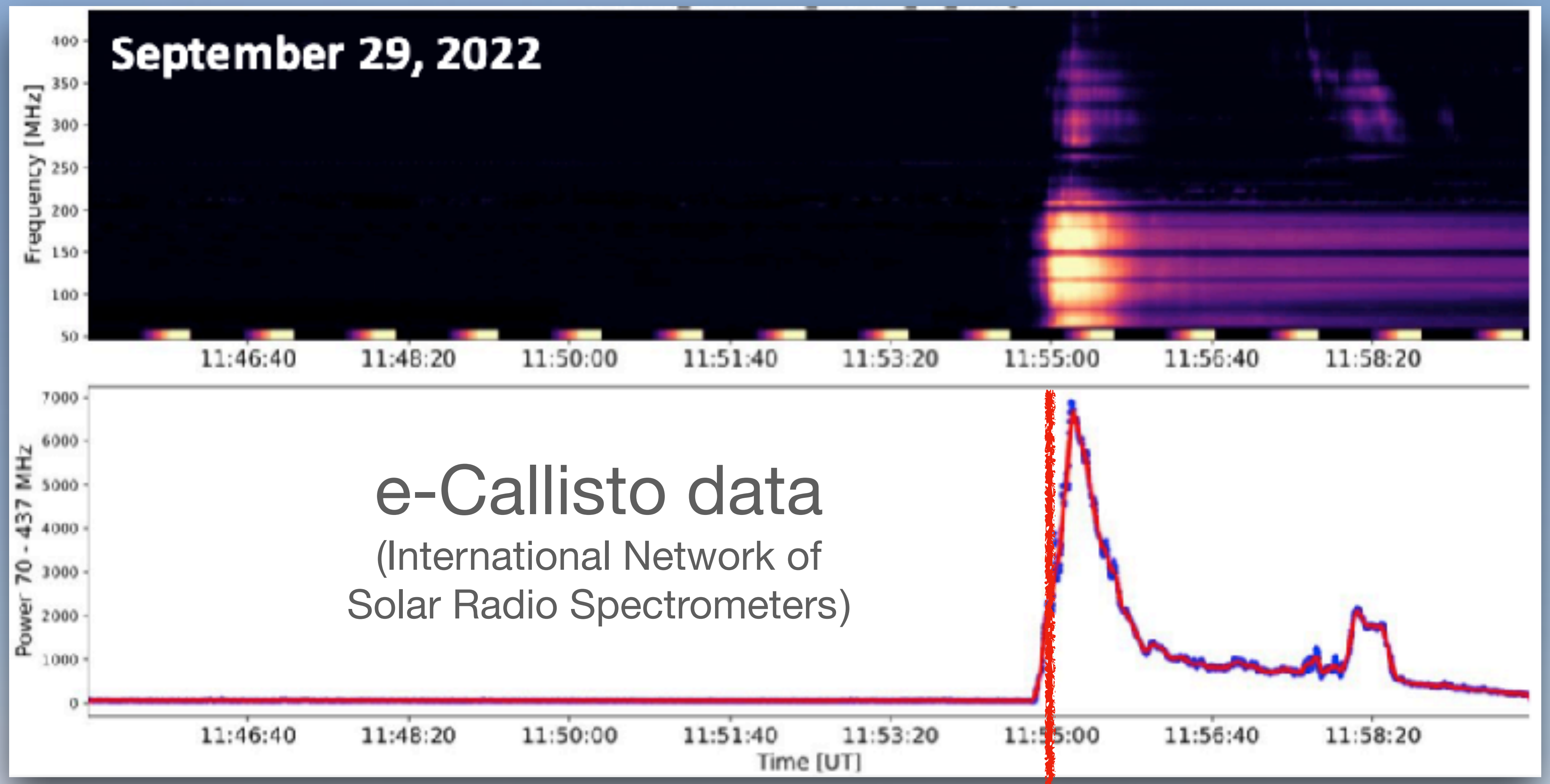
J. Henrichs and A. Nelles for RNO-G, Pos (ICRC23) 259

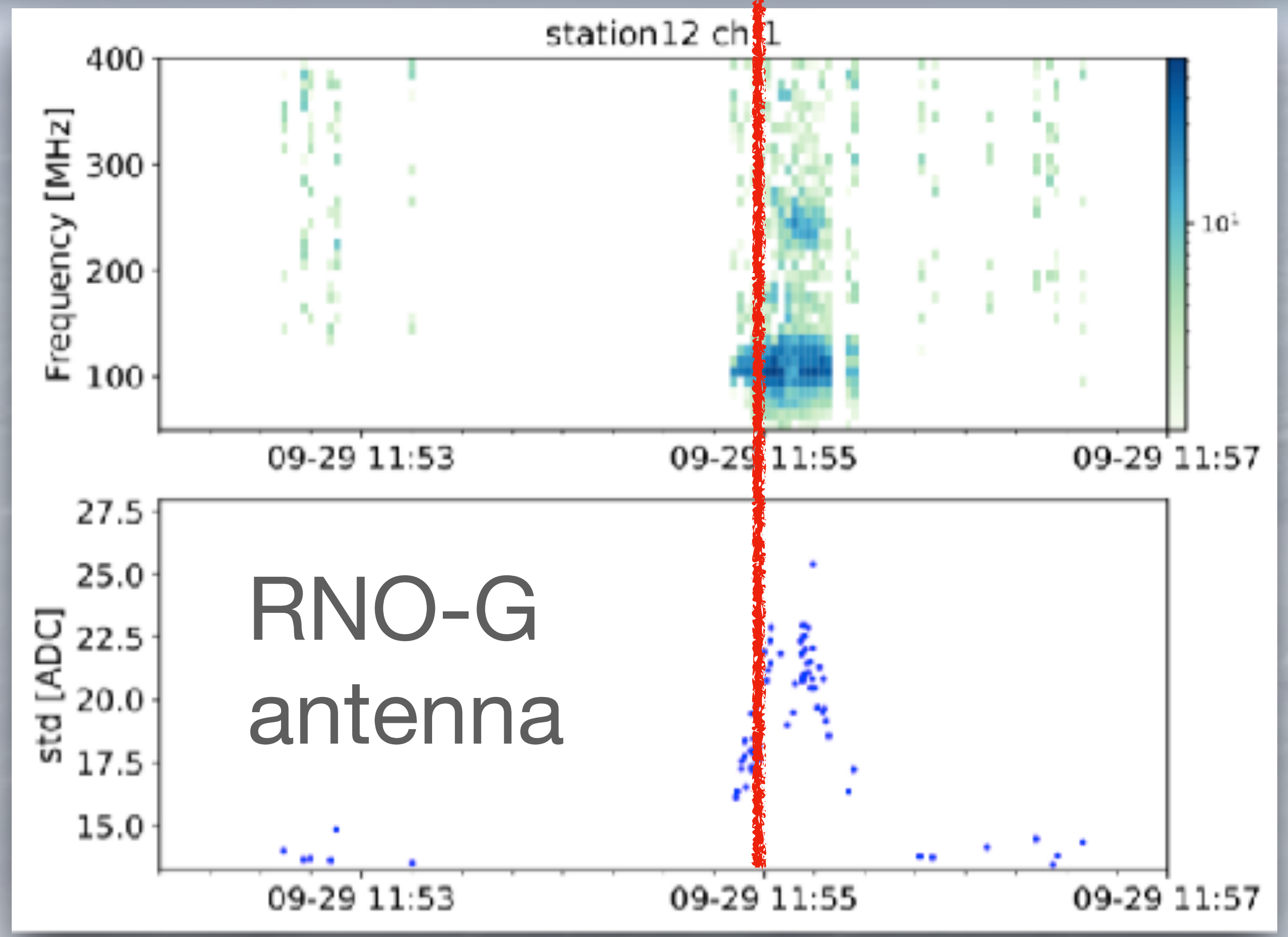
First look into the data

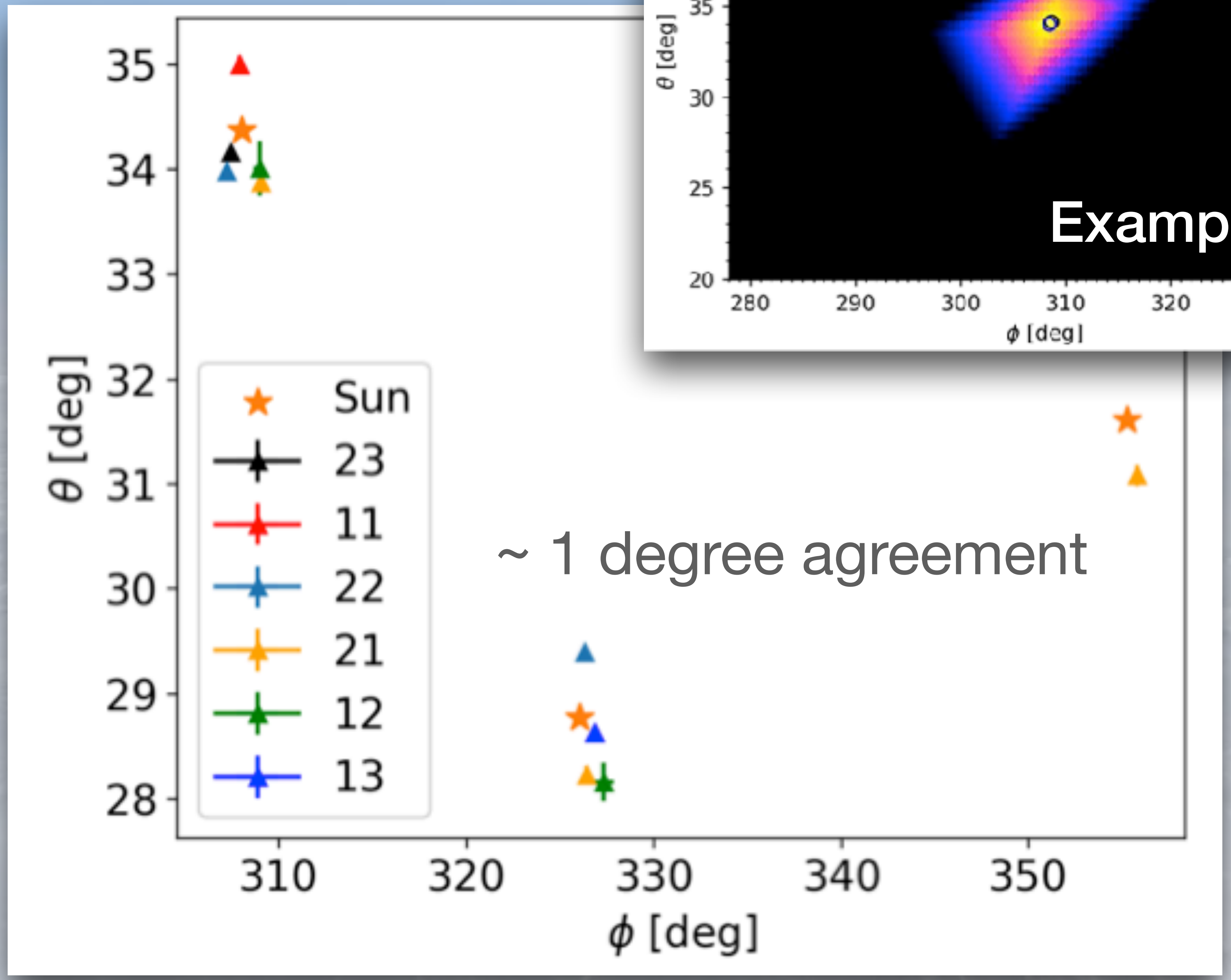
S. Hallmann for RNO-G, Pos (ICRC23) 1043

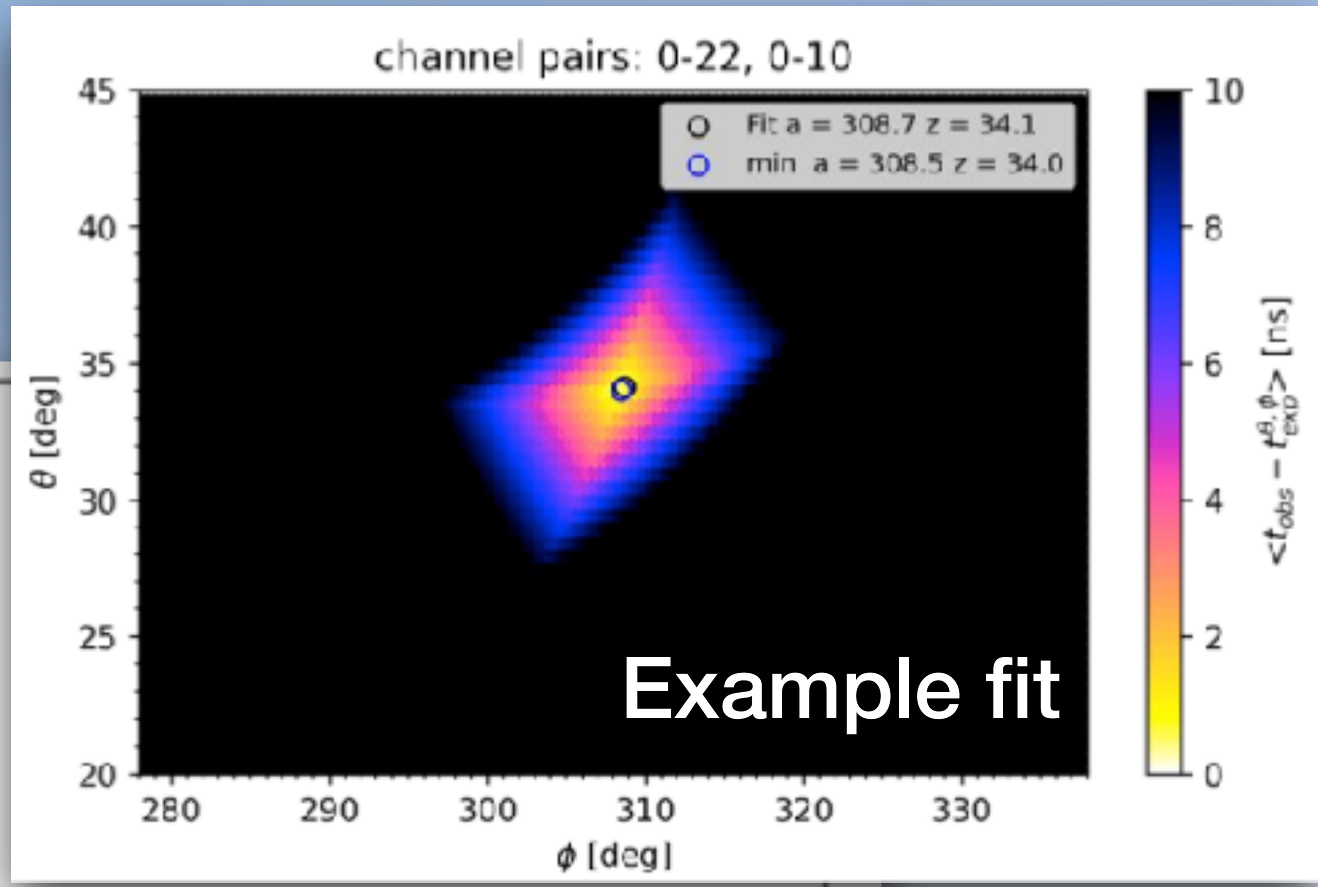
Correlation with solar flare

- For 3 solar flares, reconstruct position of Sun
- Allowed correction / calibration of station geometry



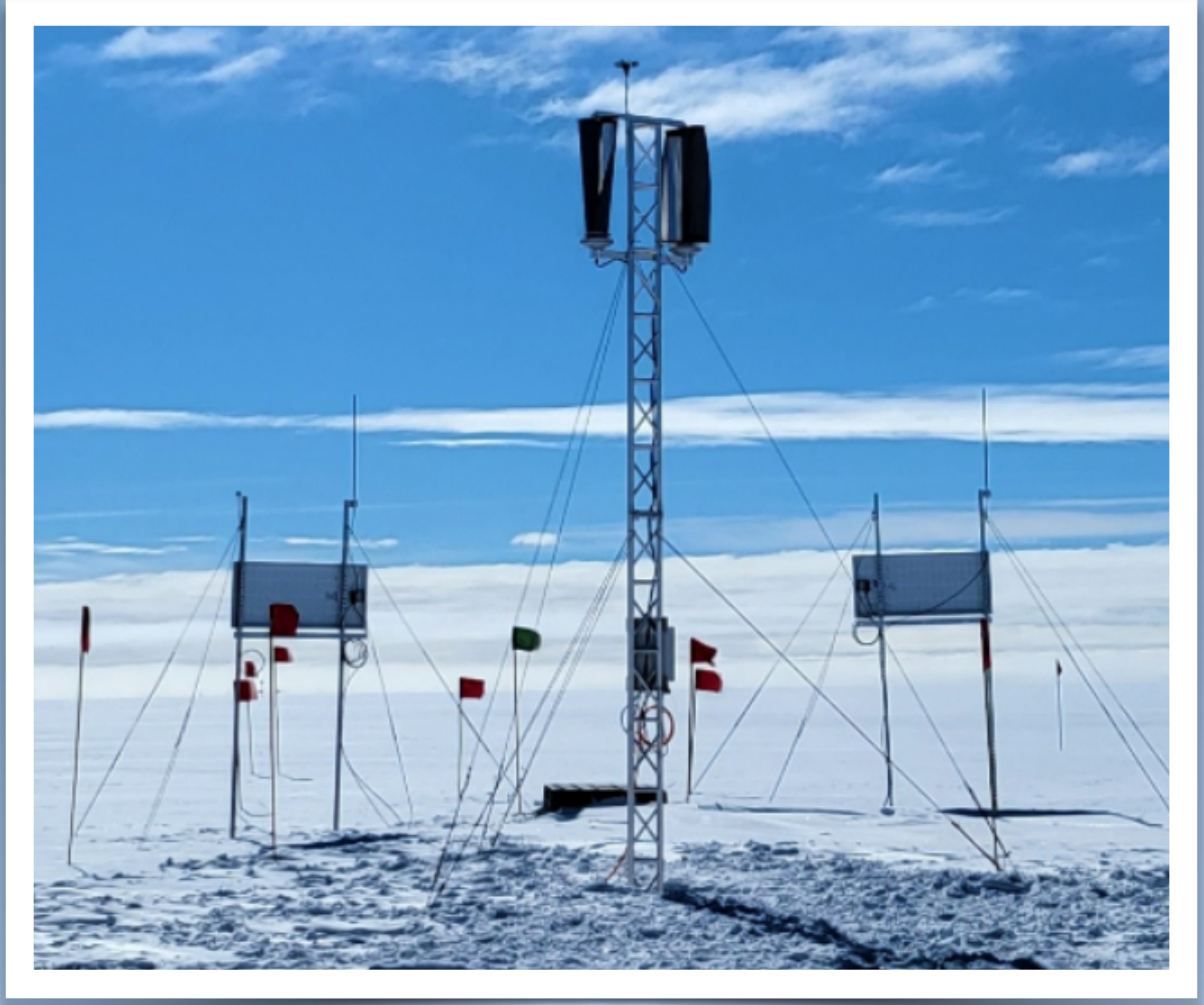


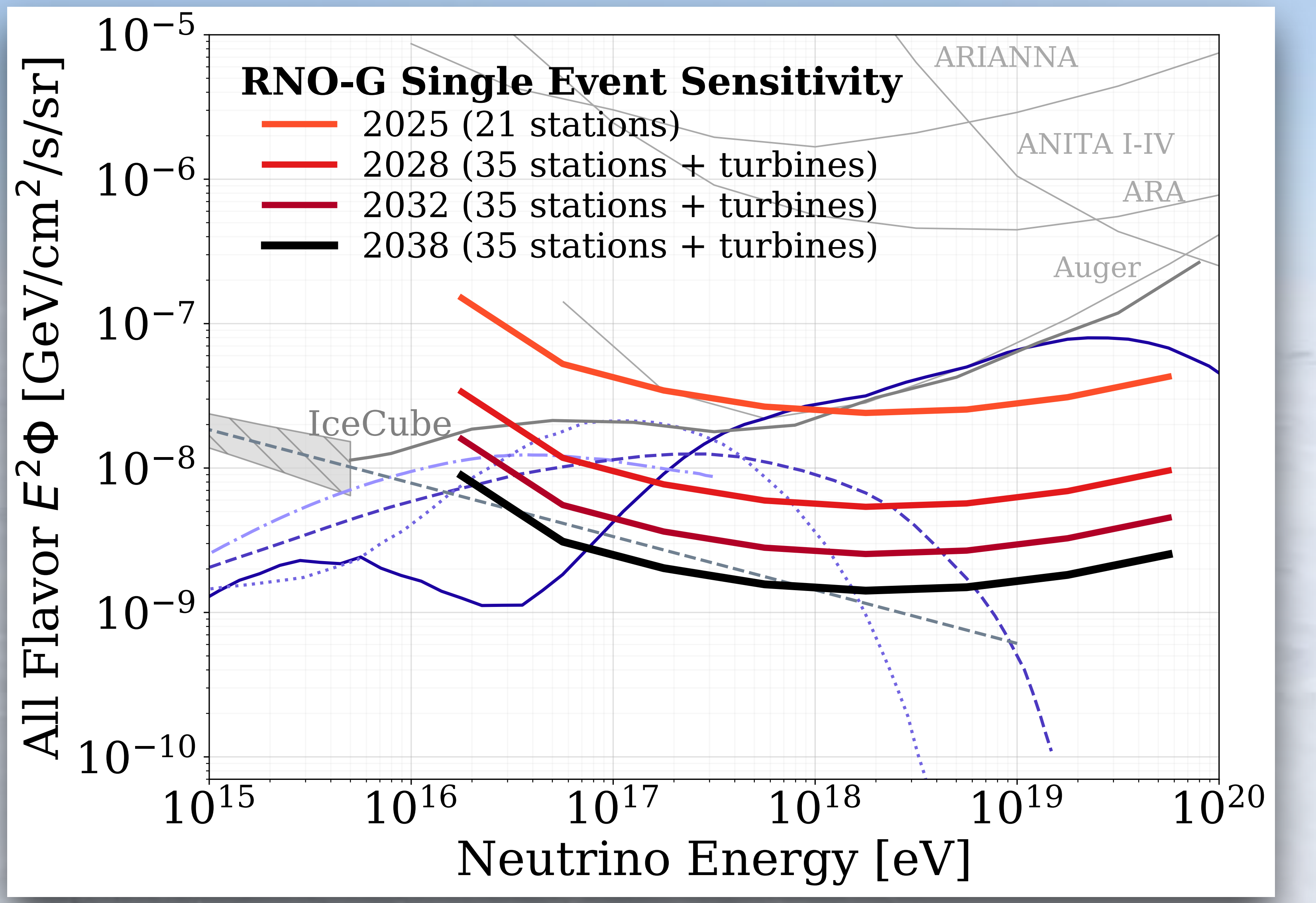




Summary & Outlook

- RNO-G is currently deploying at Summit Station in Greenland
- When completed, RNO-G will have world leading sensitivity for 1 EeV neutrinos
  - Potential to discover the first UHE neutrino!
- RNO-G will be contributing with UHE neutrino observation to multi-messenger campaigns in the Northern Hemisphere
- Current efforts focus on calibration & commissioning
- We are preparing for neutrino searches!
  - We have developed reconstruction algorithms
  - 10 contributions at ICRC23





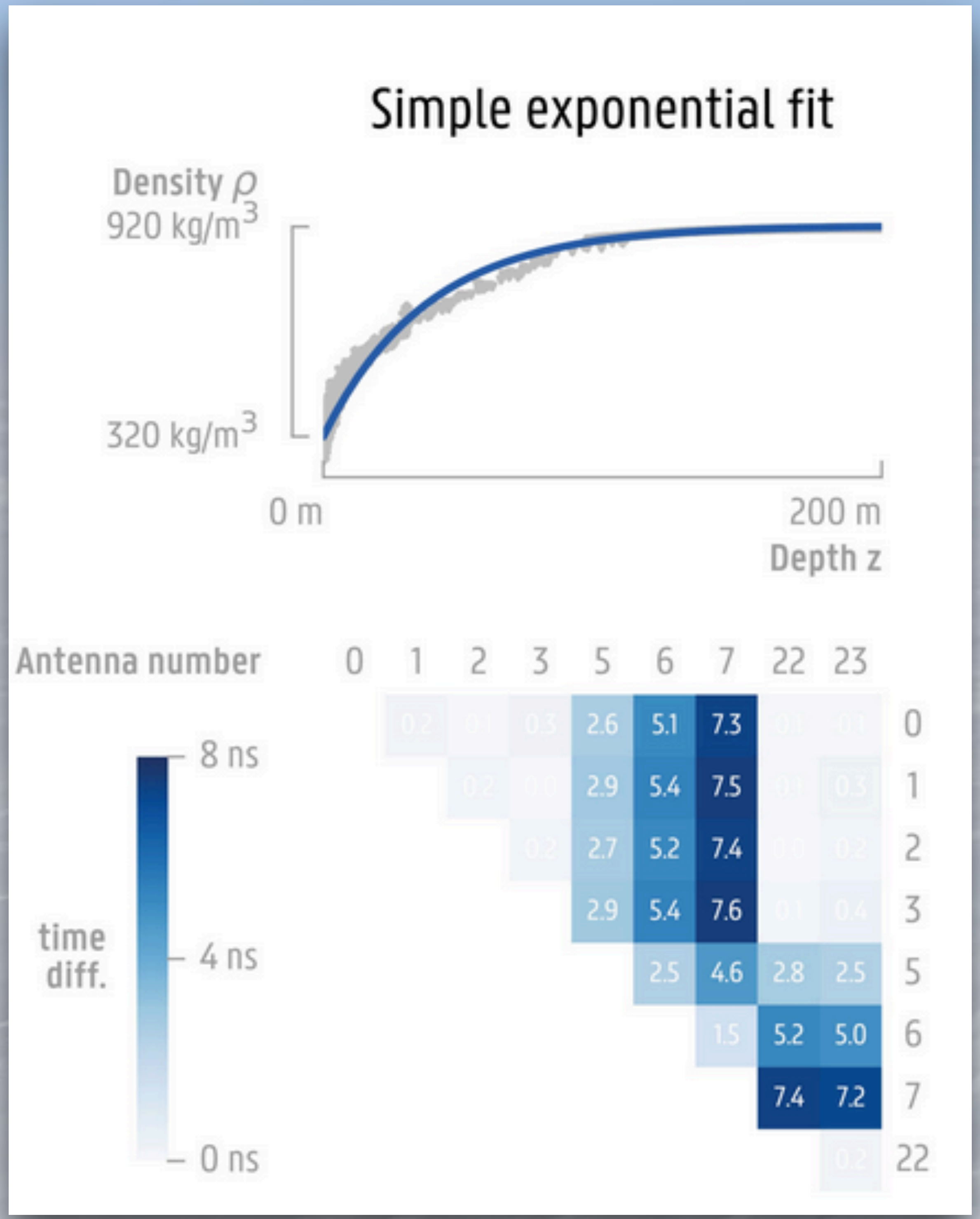
Summit Station
Whittier College
University of Nebraska-Lincoln
University of Kansas
University of Wisconsin-Madison
University of Chicago
The Ohio State University
Pennsylvania State University
University of Alabama
University of Delaware
University of Maryland
Uppsala University
DESY-Zeuthen
FAU-Erlangen
Radboud University
Université Libre de Bruxelles
Vrije Universiteit Brussels
Ghent University
RNO-G
Collaboration
February 2023

Backup

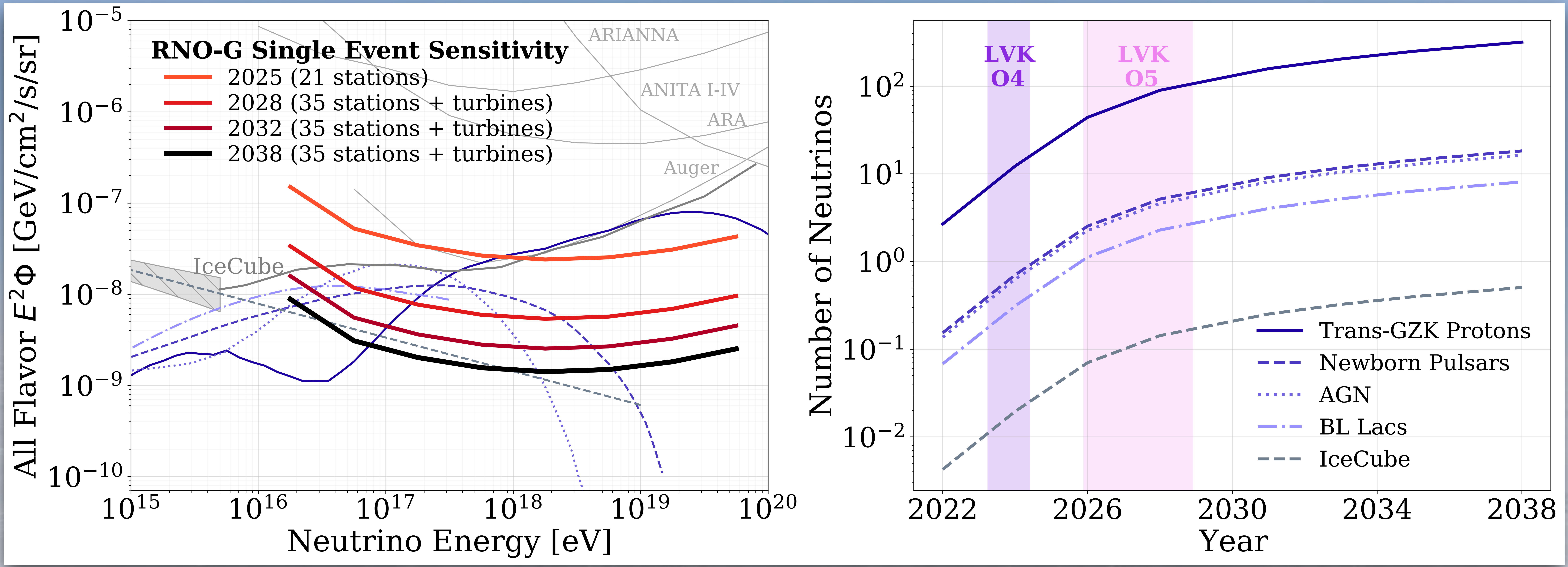
Calibration

Current effort!

- The ice is part of our detector
  - Refractive index profile of crucial importance
  - ➡ See Talk by Bob Oeyen this afternoon



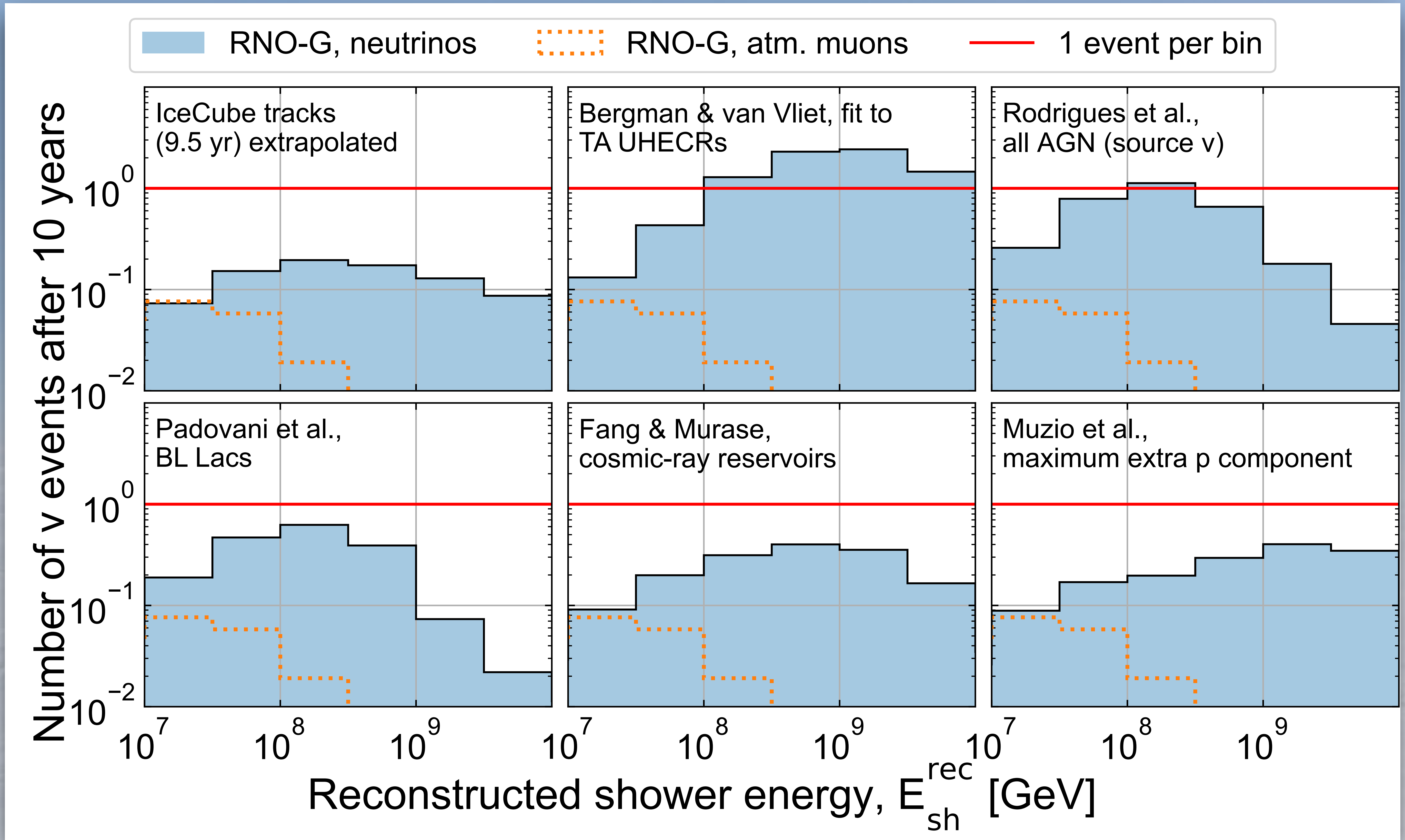
Sensitivity to different sources



Expected number of neutrinos

For different flux models

- Several models predict at least one neutrino when integrating over the energy



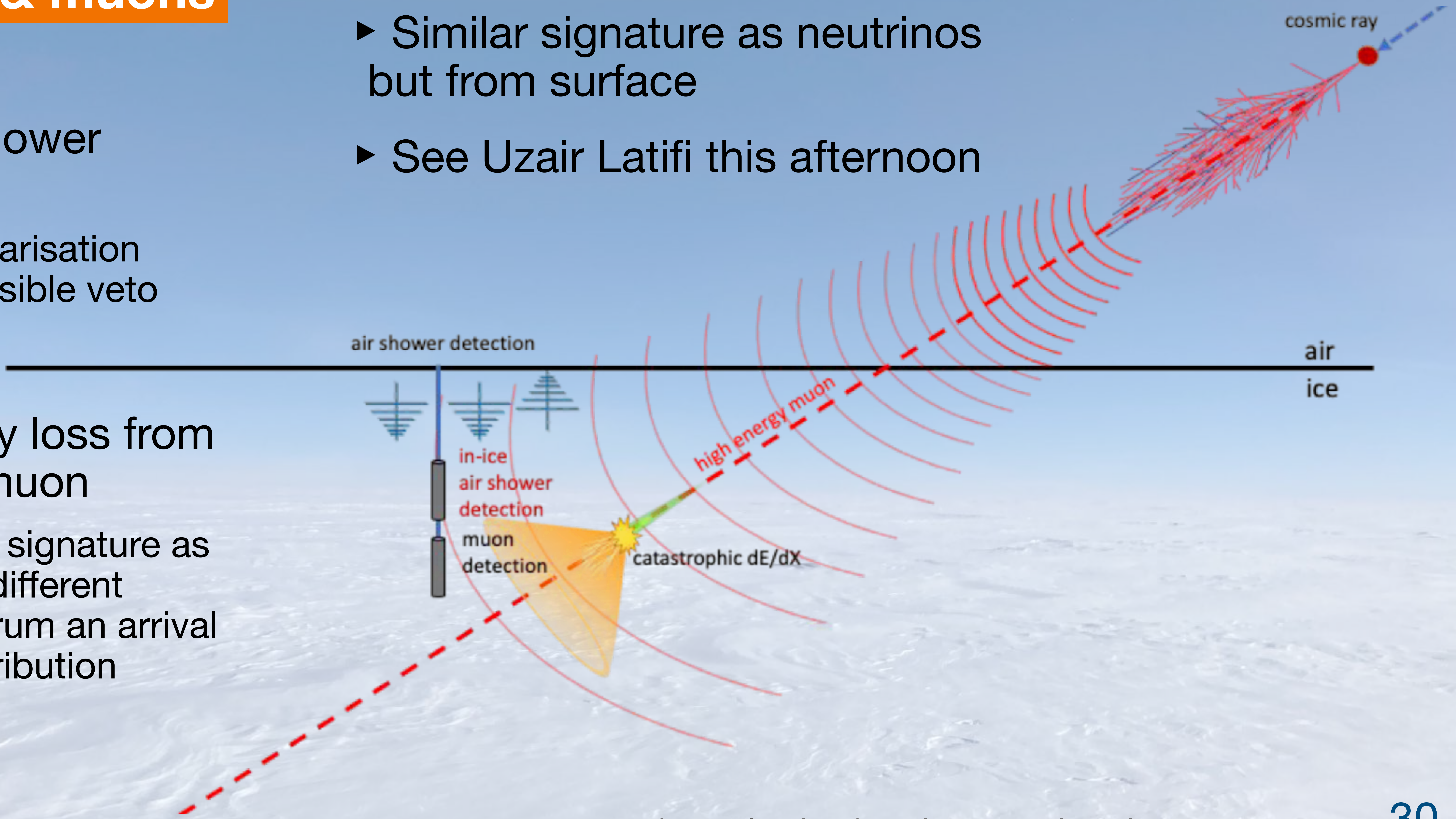
Background

Air showers & muons

1. Direct air shower emission
   - Different polarisation pattern, possible veto

2. Huge energy loss from high energy muon
   - Same signal signature as neutrino but different energy spectrum an arrival direction distribution

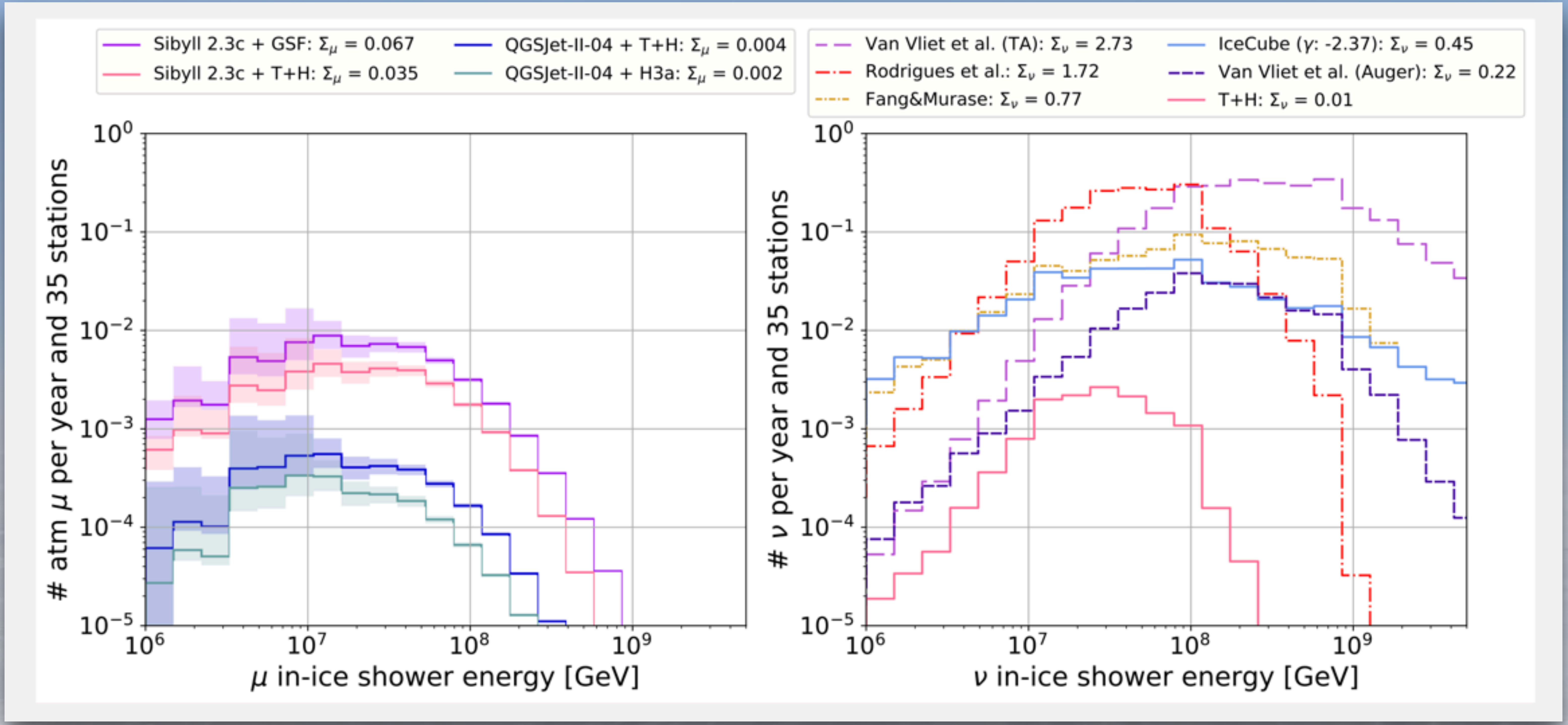
3. In-ice emission if air shower particles reach ice
   - Similar signature as neutrinos but from surface
   - See Uzair Latifi this afternoon

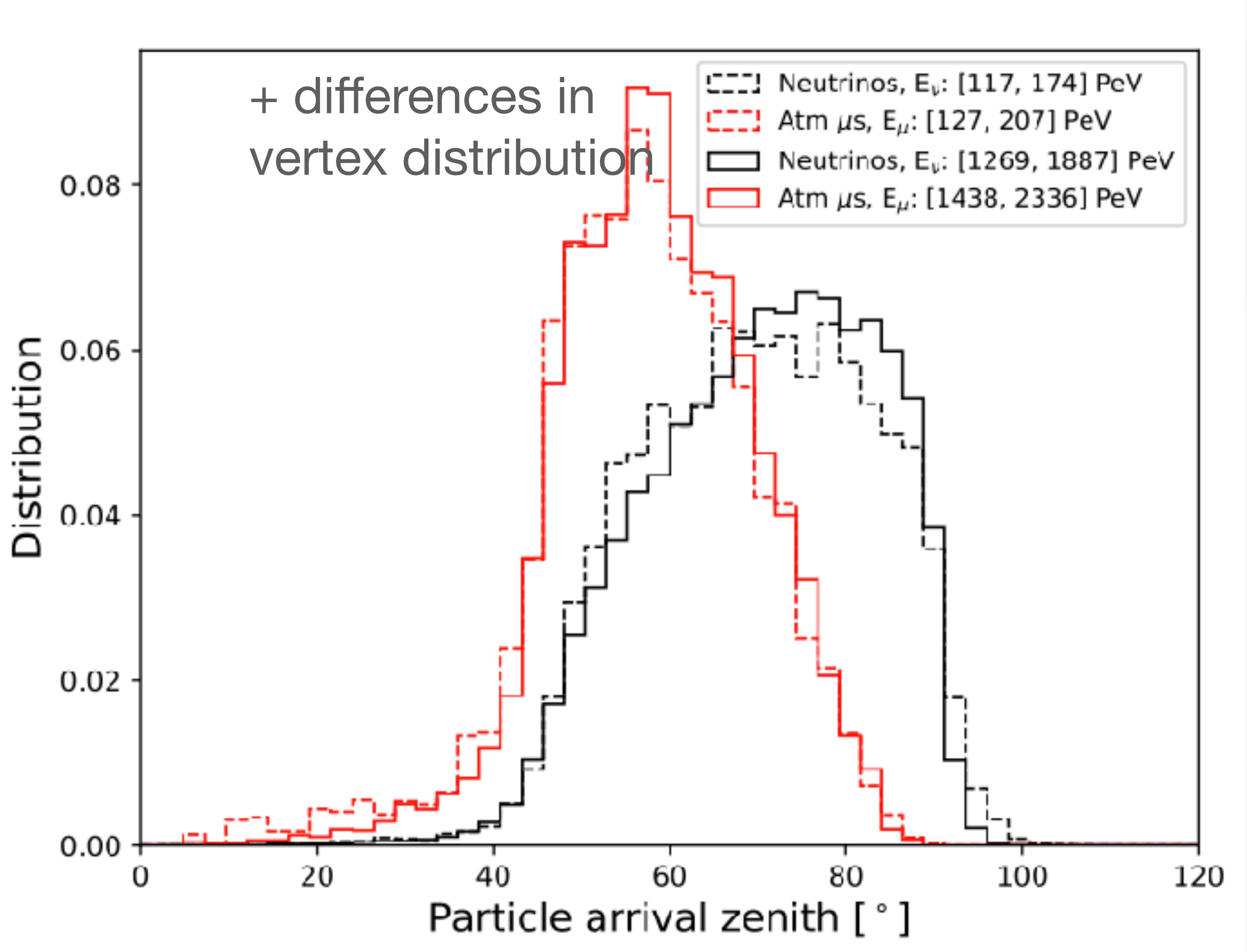


+ thermal noise & anthropogenic noise

Background

Air showers & muons





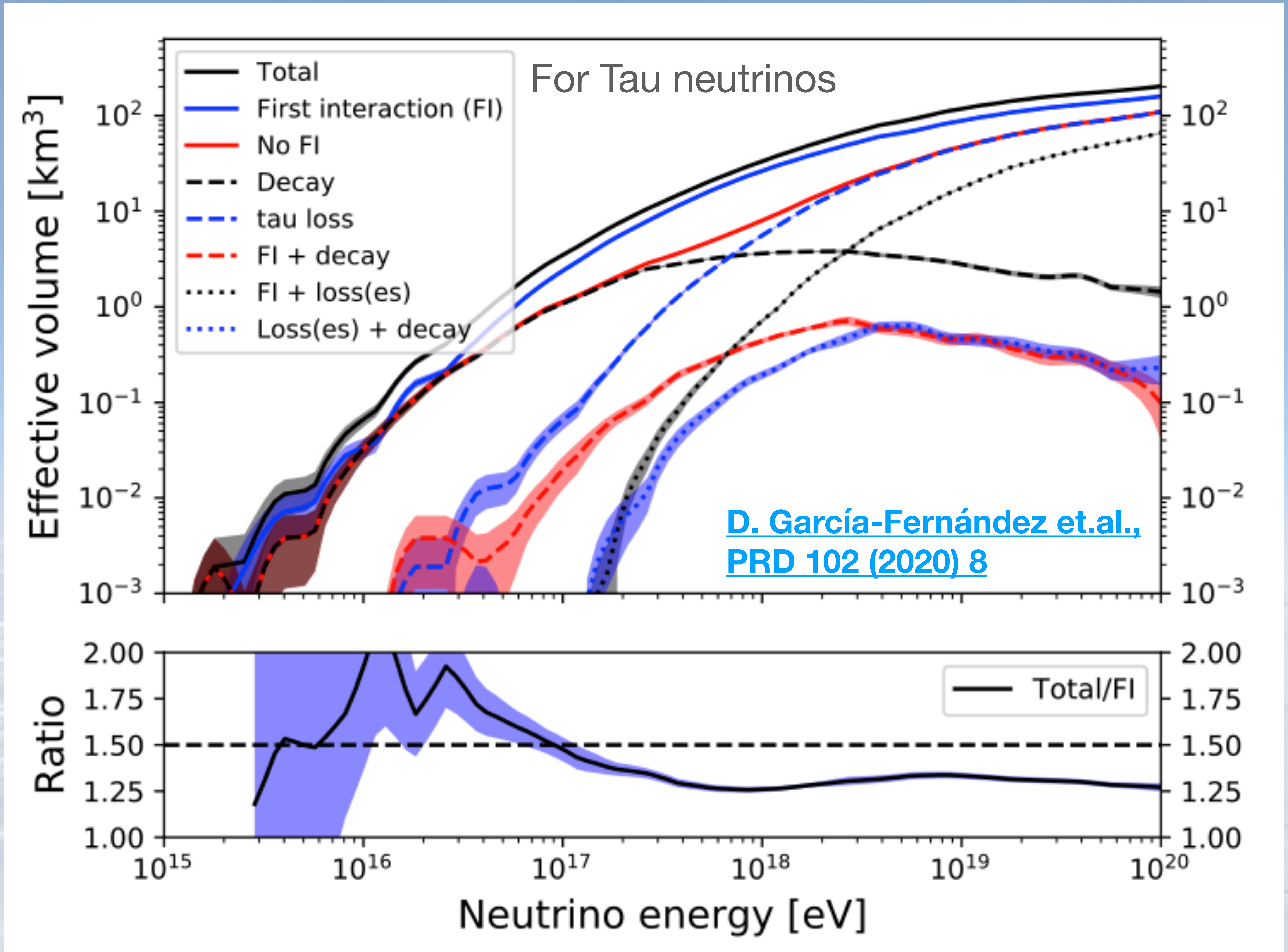
L. Pyras et al. PoS (ICRC2023) 1076 + arxiv

Ice Properties

- Part of the detector -> needs to be calibrated

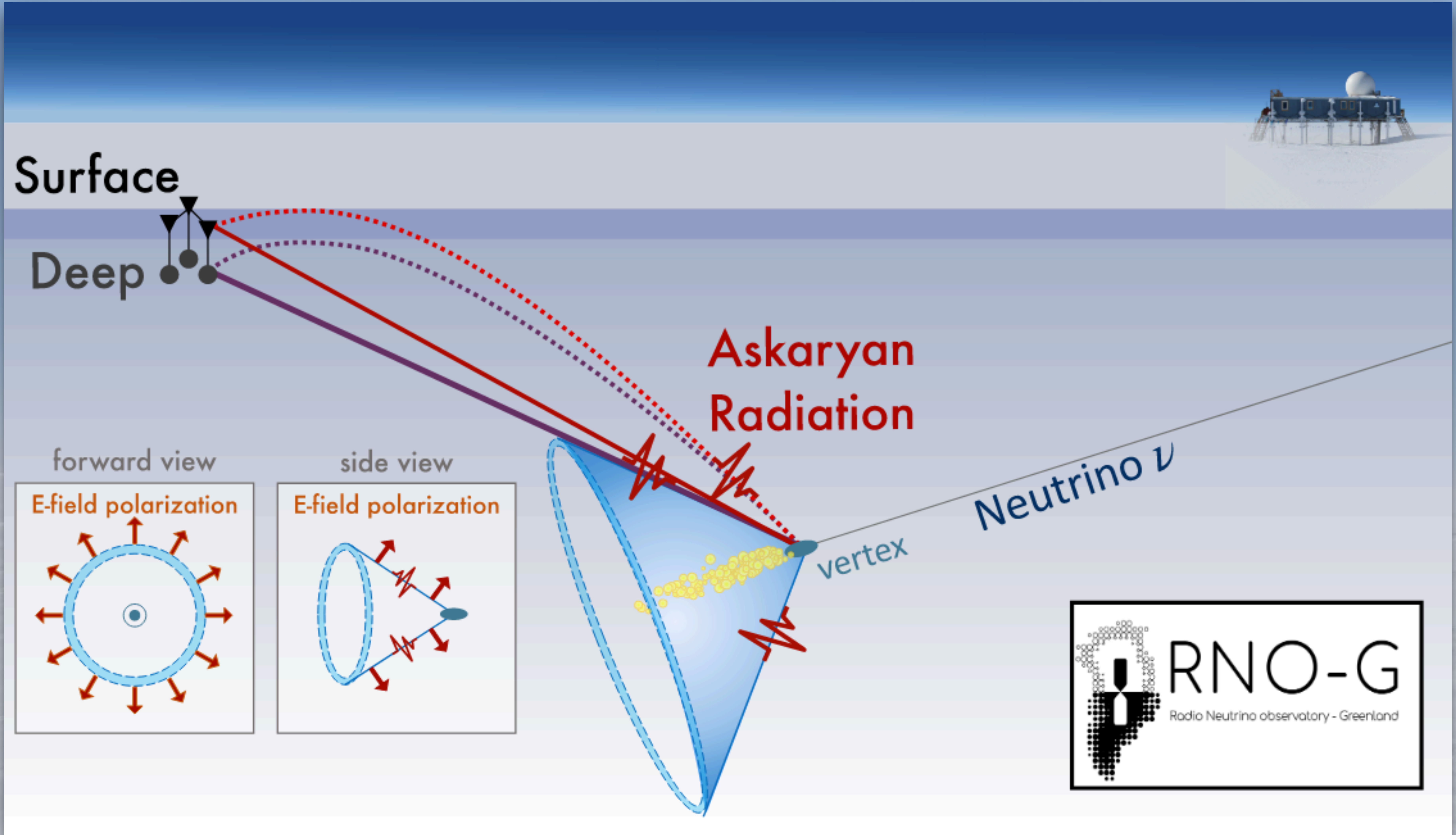
Signals from secondary leptons

Which undergo catastrophic energy losses



Askaryan Radiation

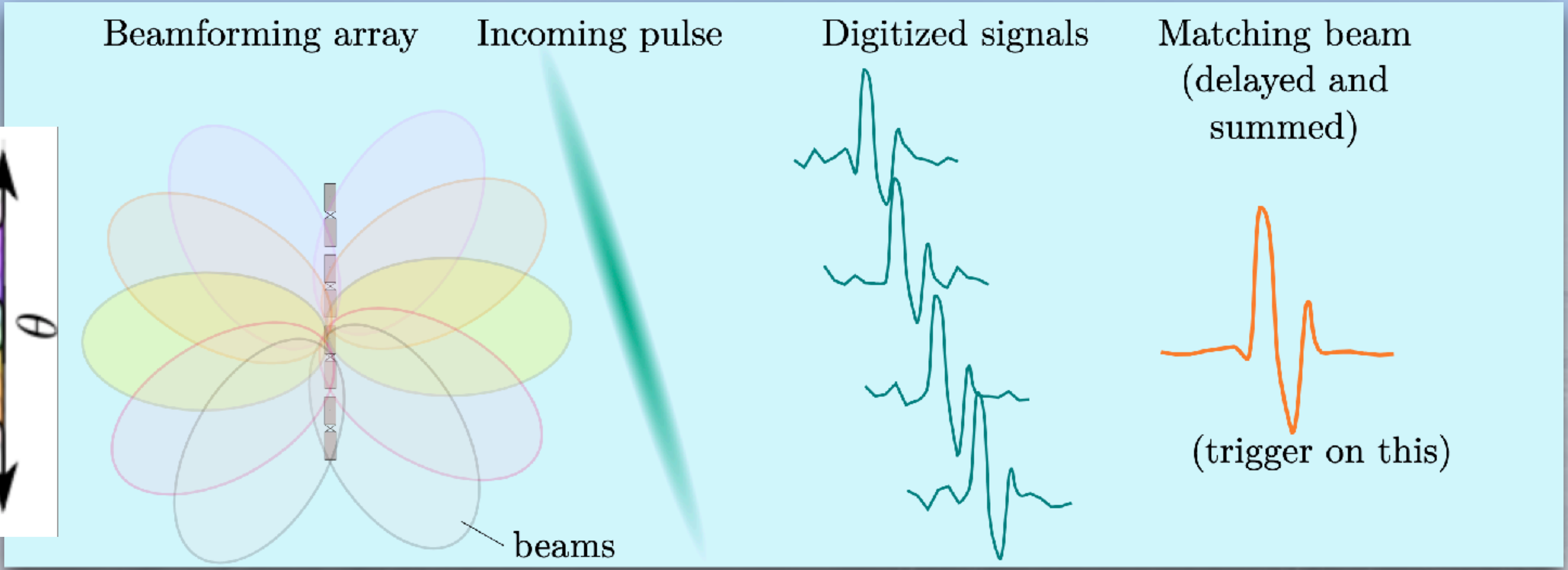
Specific polarisation pattern



Phased array

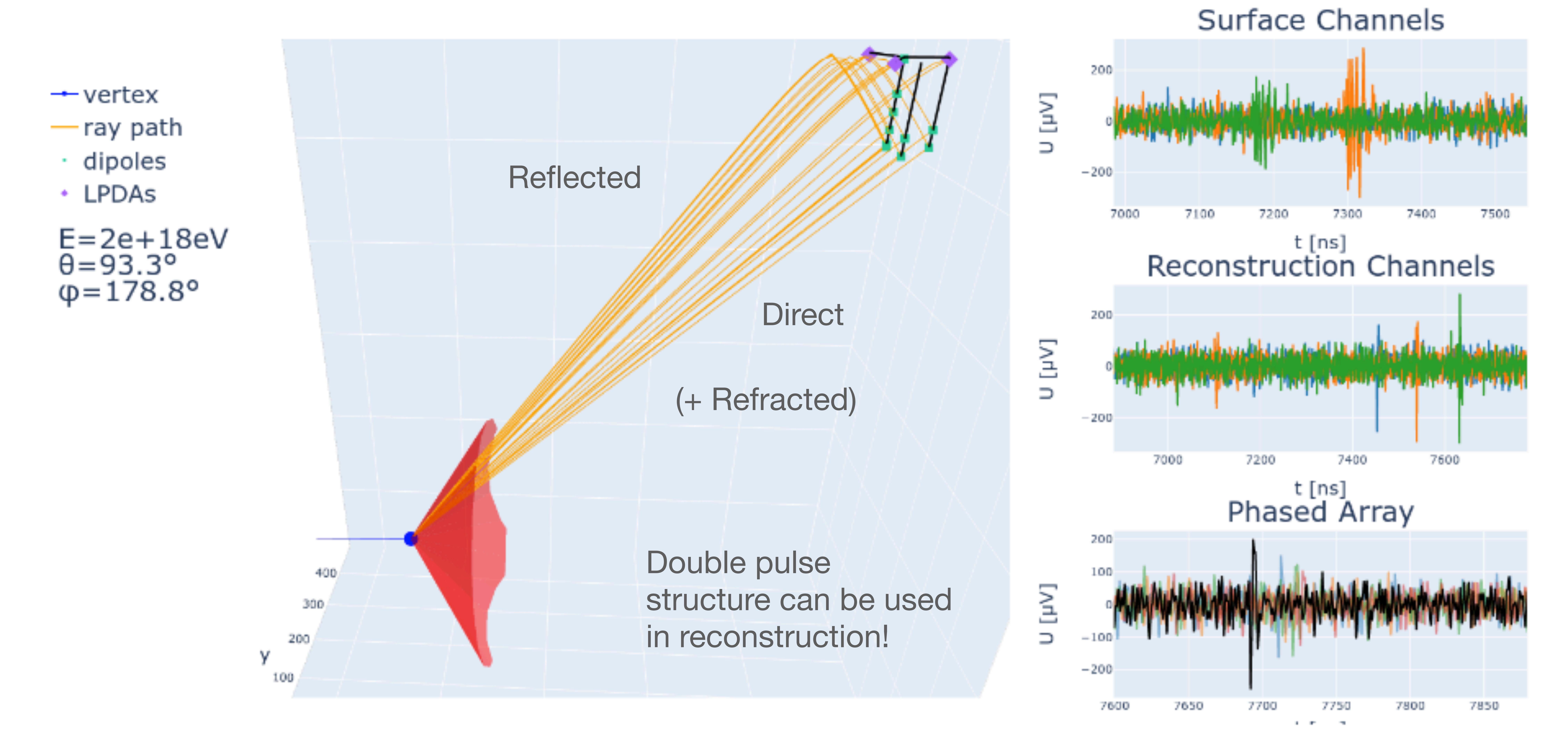
For triggering and reconstruction

- Trigger runs on lower bandwidth (< 250 MHz), 8 beams are formed
- Design goal for threshold: amplitude_signal / sigma_noise = 2
- Technique demonstrated at South Pole by ARA   ARA, PRD 105

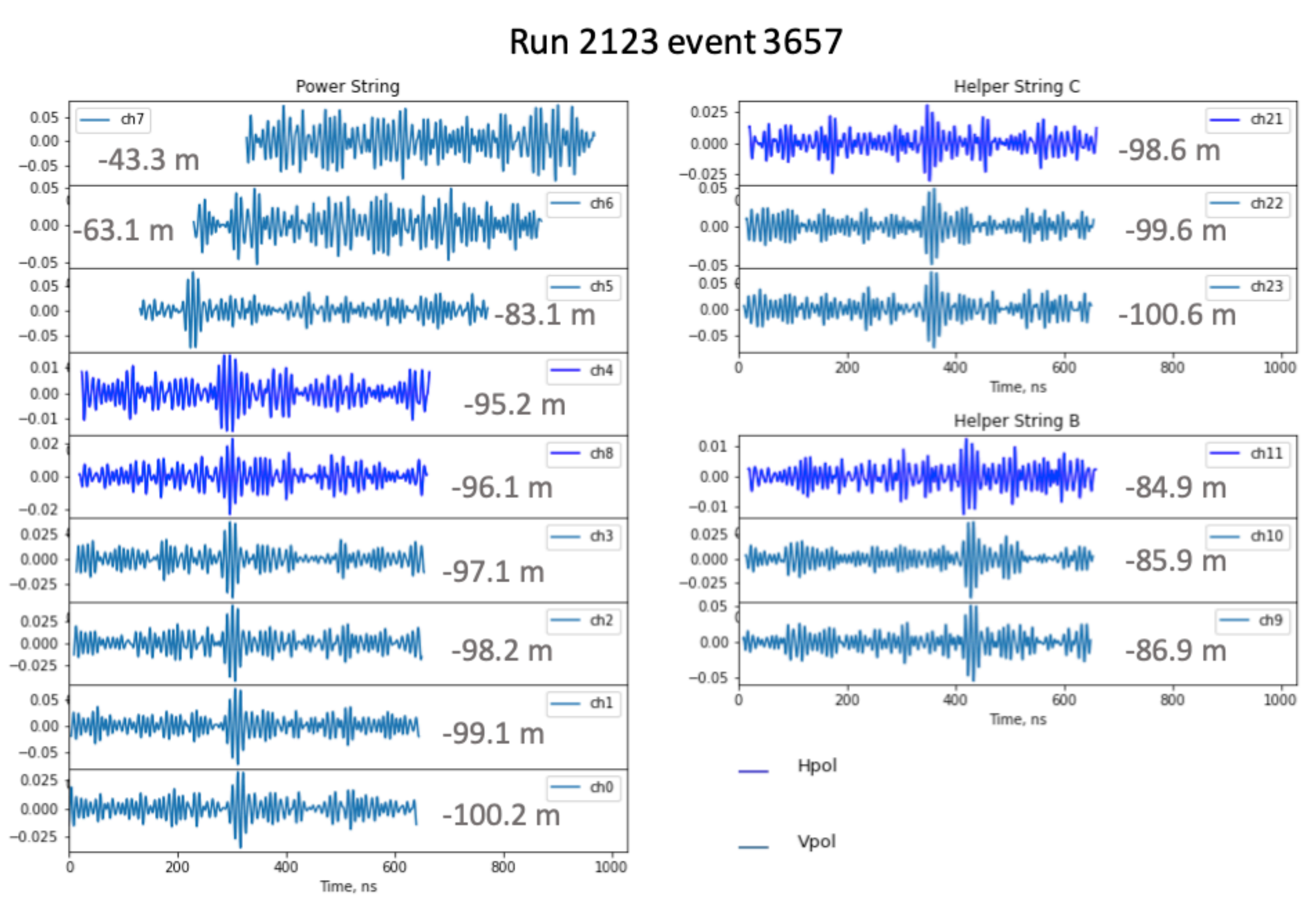


Propagation

Signal can reach antennas on different trajectories!



Solar flare



Run 2123 event 3657
Power String
ch7
-43.3 m
ch6
-63.1 m
ch5
-83.1 m
ch4
-95.2 m
ch8
-96.1 m
ch3
-97.1 m
ch2
-98.2 m
ch1
-99.1 m
ch0
-100.2 m
Time, ns
Helper String C
ch21
-98.6 m
ch22
-99.6 m
ch23
-100.6 m
Time, ns
Helper String B
ch11
-84.9 m
ch10
-85.9 m
ch9
-86.9 m
Time, ns
Hpol
Vpol