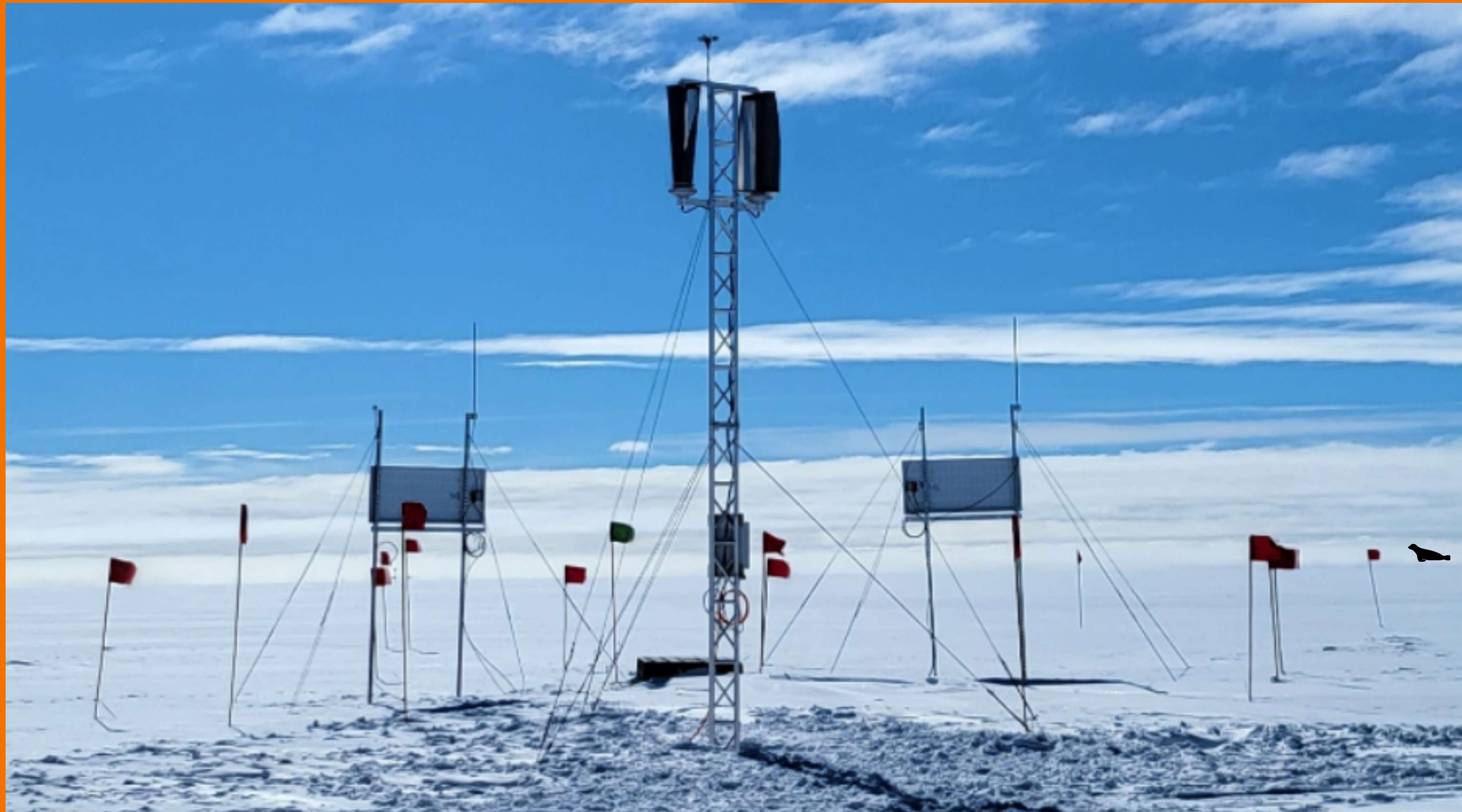
The Radio Neutrino Observatory - Greenland

Performance and Prospect

Felix Schlüter for the RNO-G collaboration

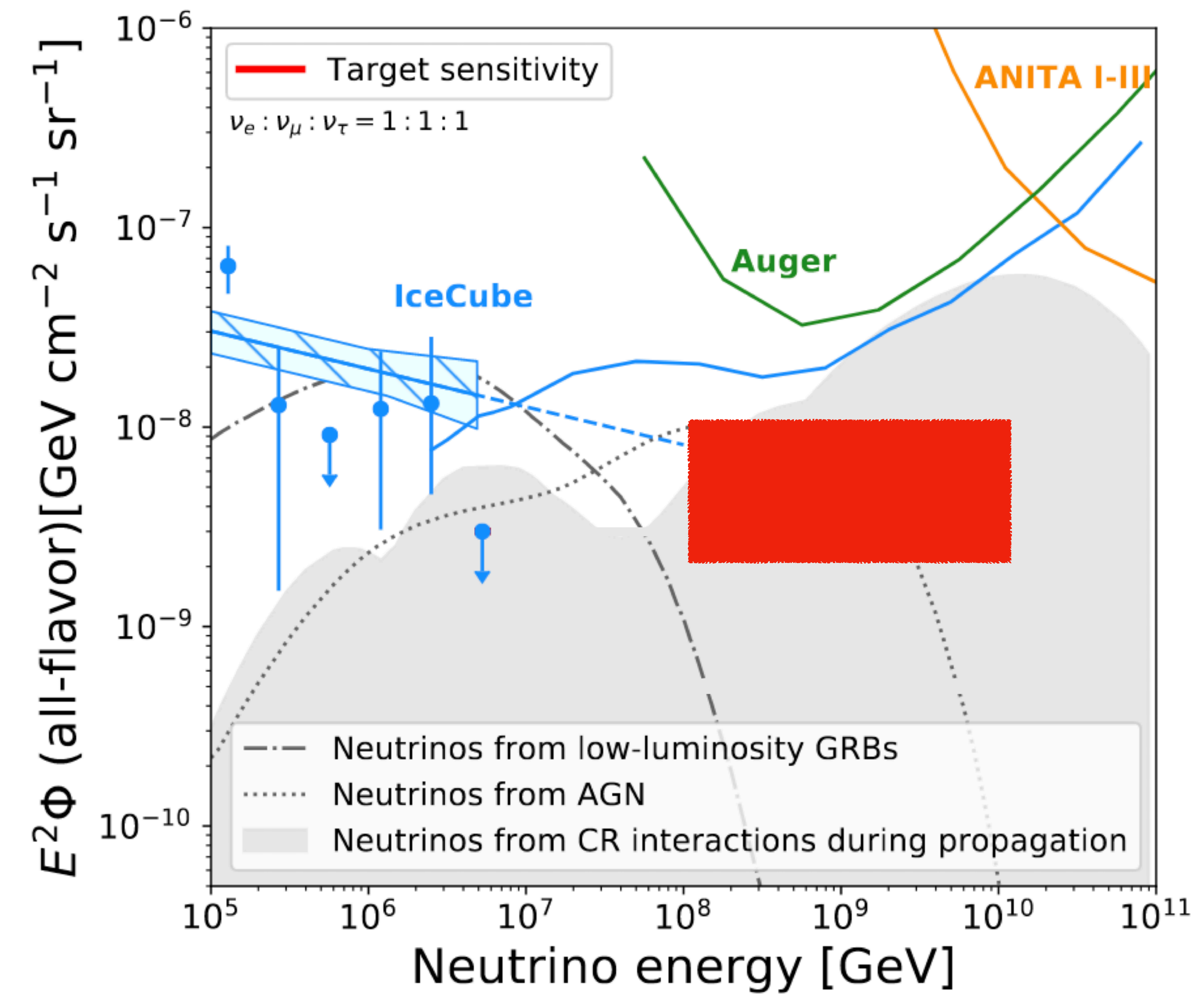
felix.schluter@icecube.wisc.edu

Neutrino Telescope 23, Venice - 25.10.23



Ultra-high-energy neutrinos with RNO-G

- RNO-G's best sensitivity at 100 PeV - 10 EeV
  - Cutoff in astrophysical spectrum
  - Test models of 2. astrophysical component
  - Test cosmogenic GZK neutrino flux



Astro2020 White Paper, arXiv:1903.04334 (modified)

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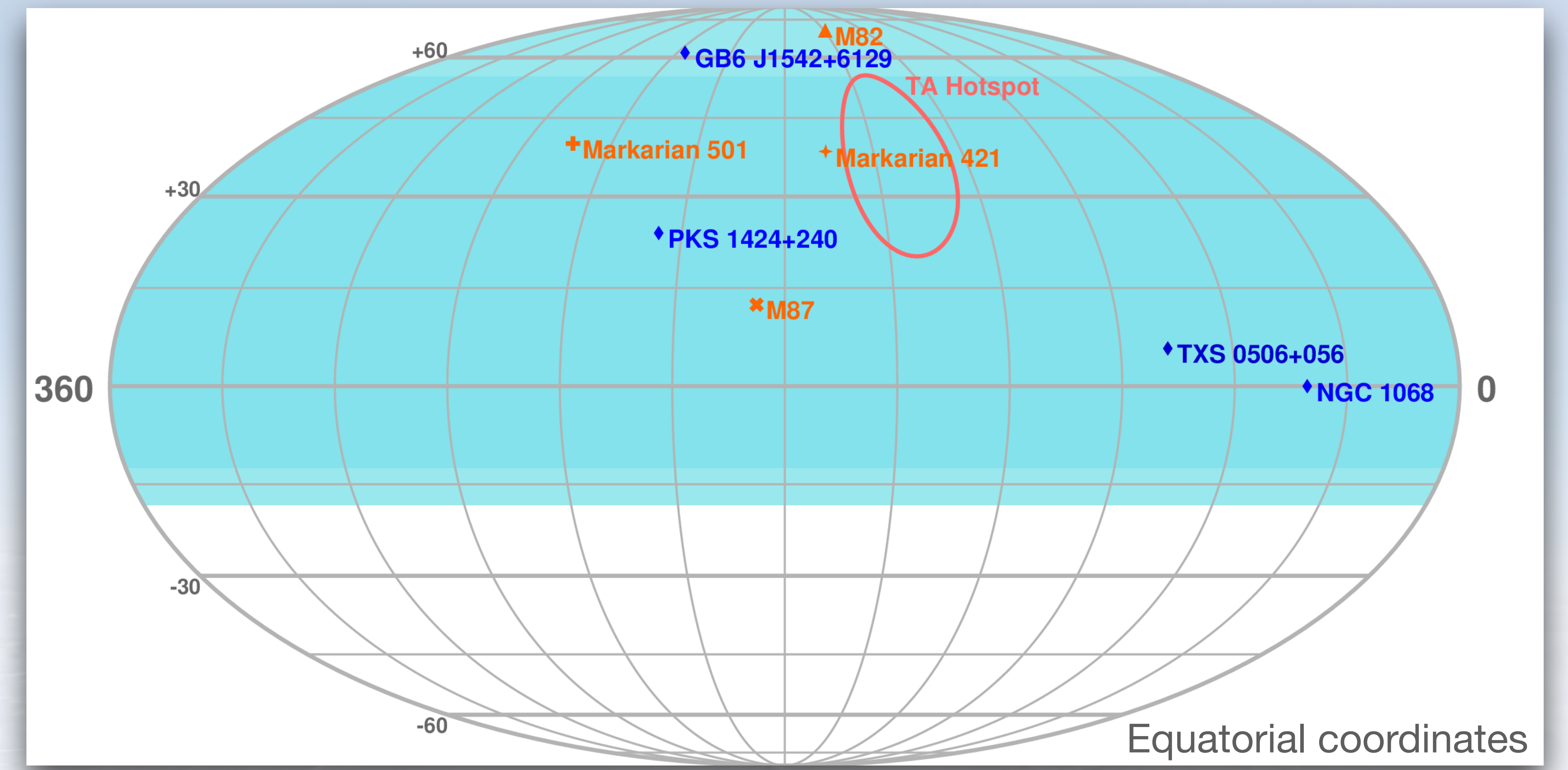
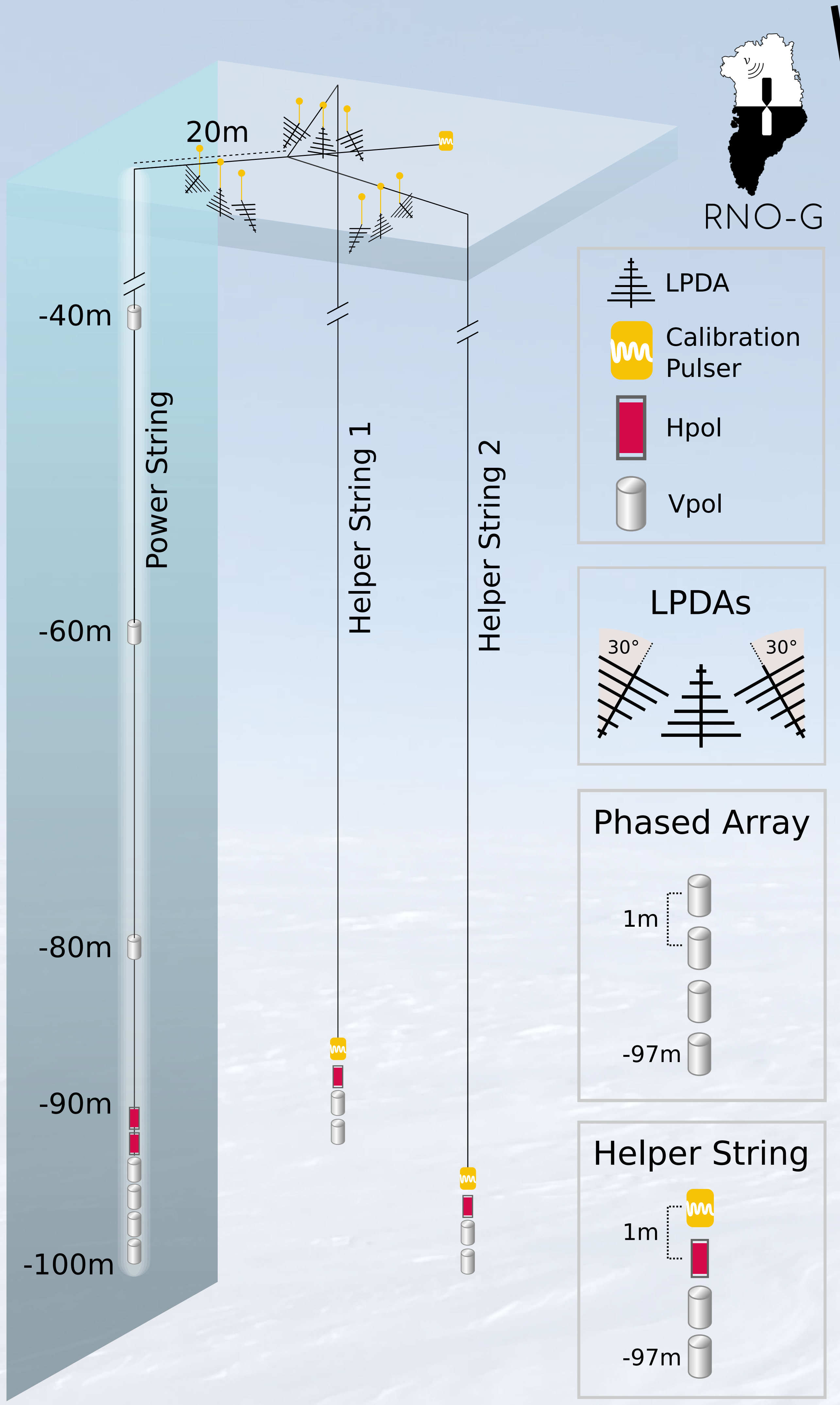
  - Cutoff in astrophysical spectrum
  - Test models of 2. astrophysical component
  - Test cosmogenic GZK neutrino flux
- UHE neutrinos in the northern hemisphere
  - Earth absorption above ~ 100 TeV
  - Complementary FOV to IceCube / South Pole
    - Extend energy range in Northern Hemisphere
    - Extend FOV for ultra-high energies to Northern Hemisphere

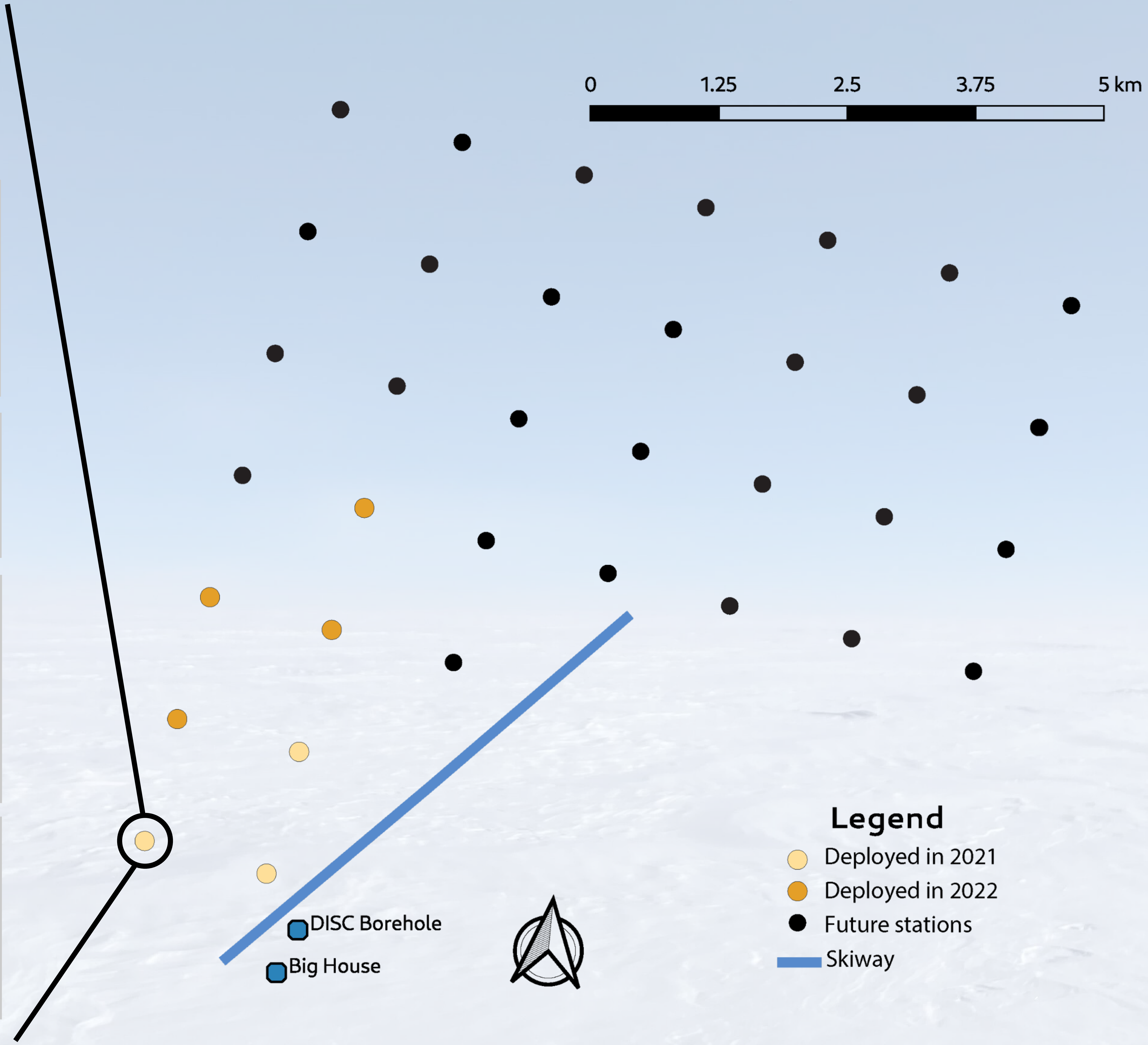


Radio Neutrino Observatory - Greenland

Hybrid station with 24 antennas



35 stations on 1.25 km grid

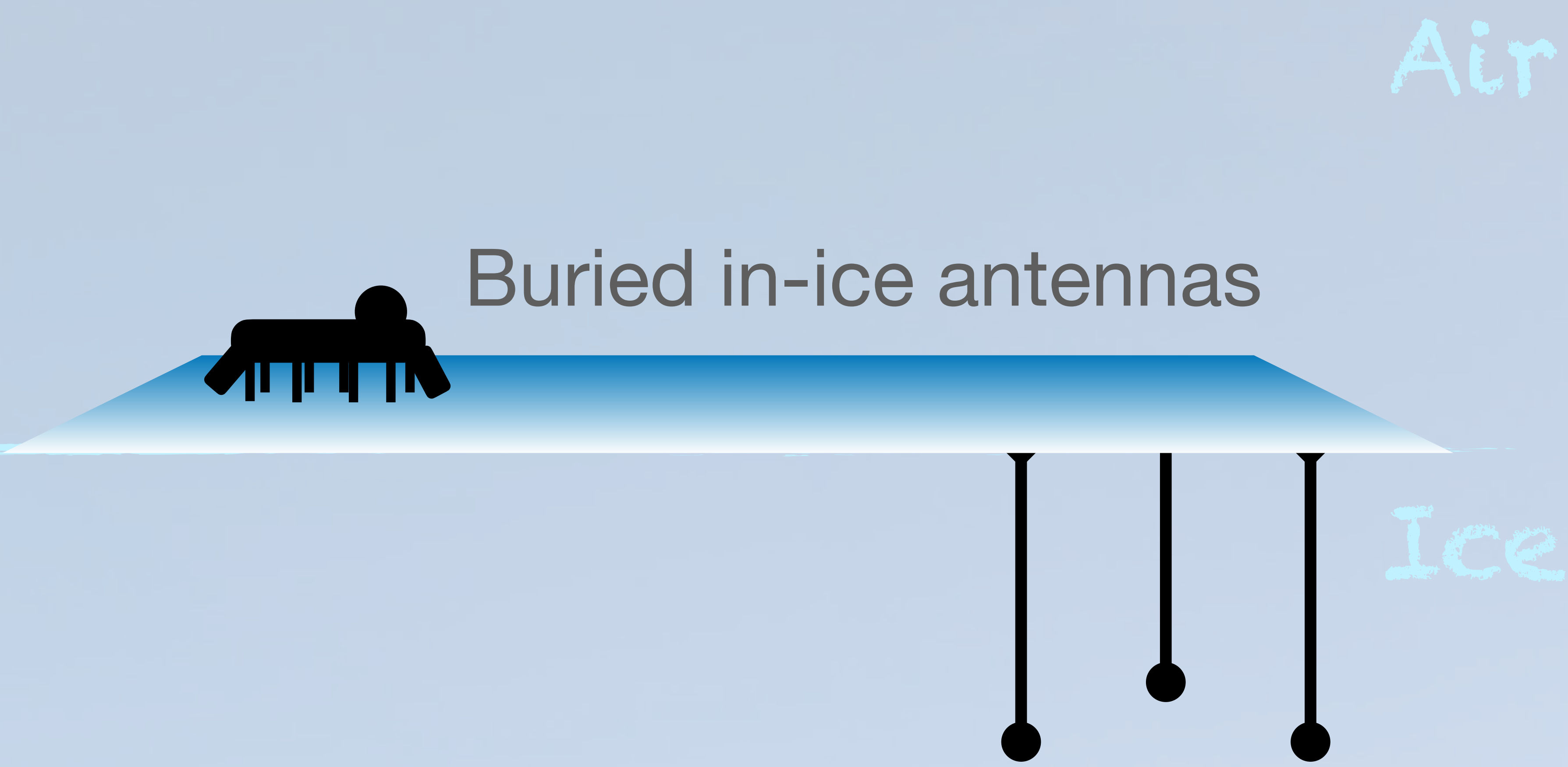


- Fully funded!
- 7 stations already deployed & taking data
- 3 (4) more deployment seasons
- Each station acts as independent detector

See previous talk by Delia Tosi

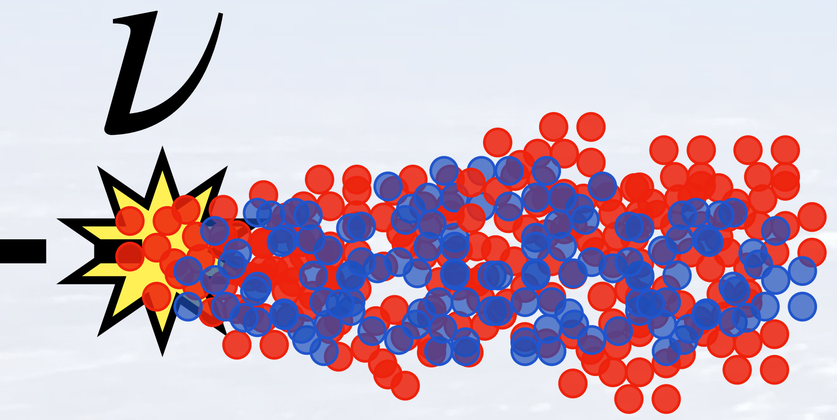
Radio detection of neutrinos

Radio detection of neutrinos



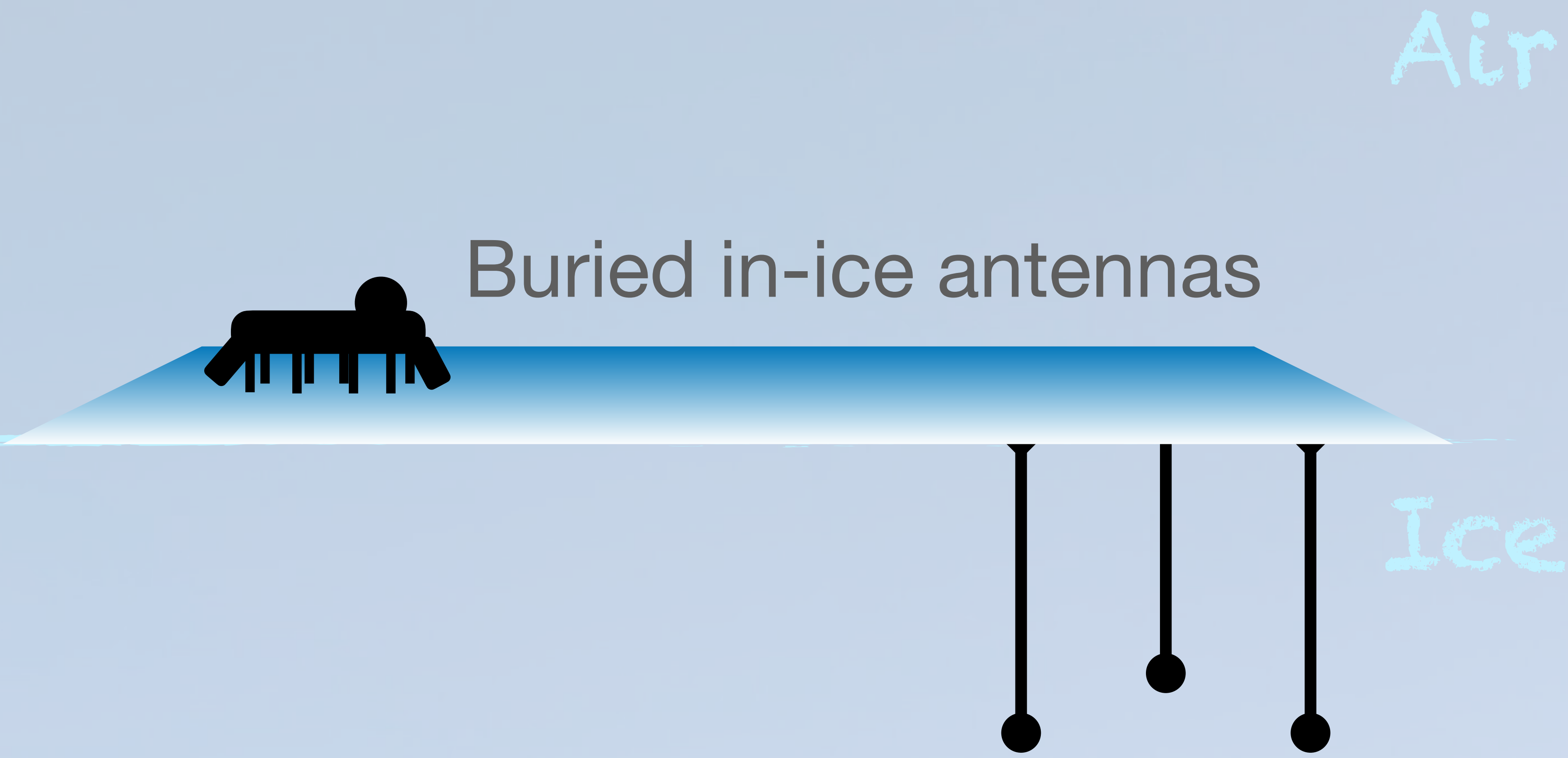
Particle cascade

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



Charge asymmetry produces “Askaryan” emission in MHz - GHz

Radio detection of neutrinos



Buried in-ice antennas

Radio emission pattern has cone shape due to interference

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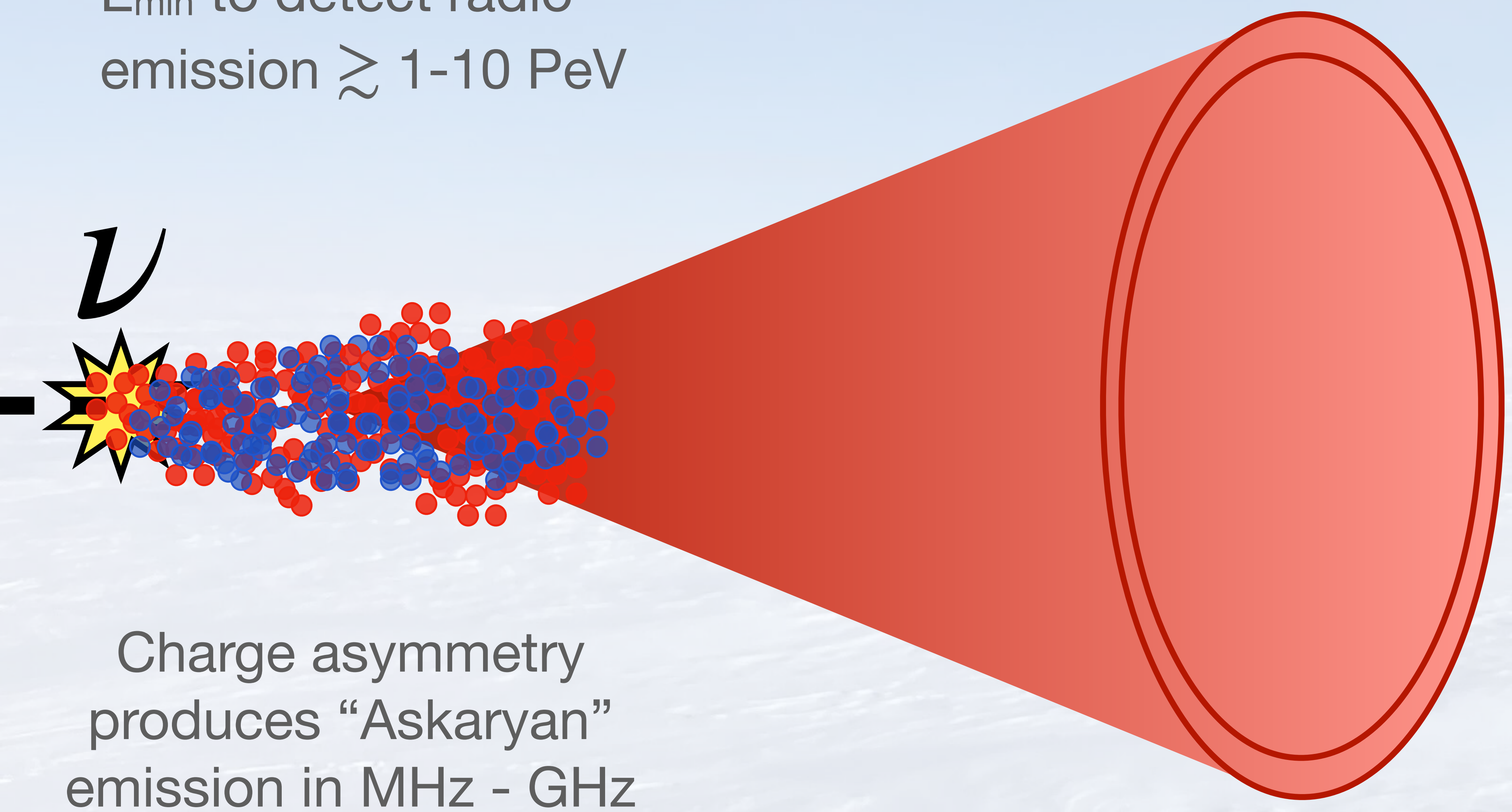

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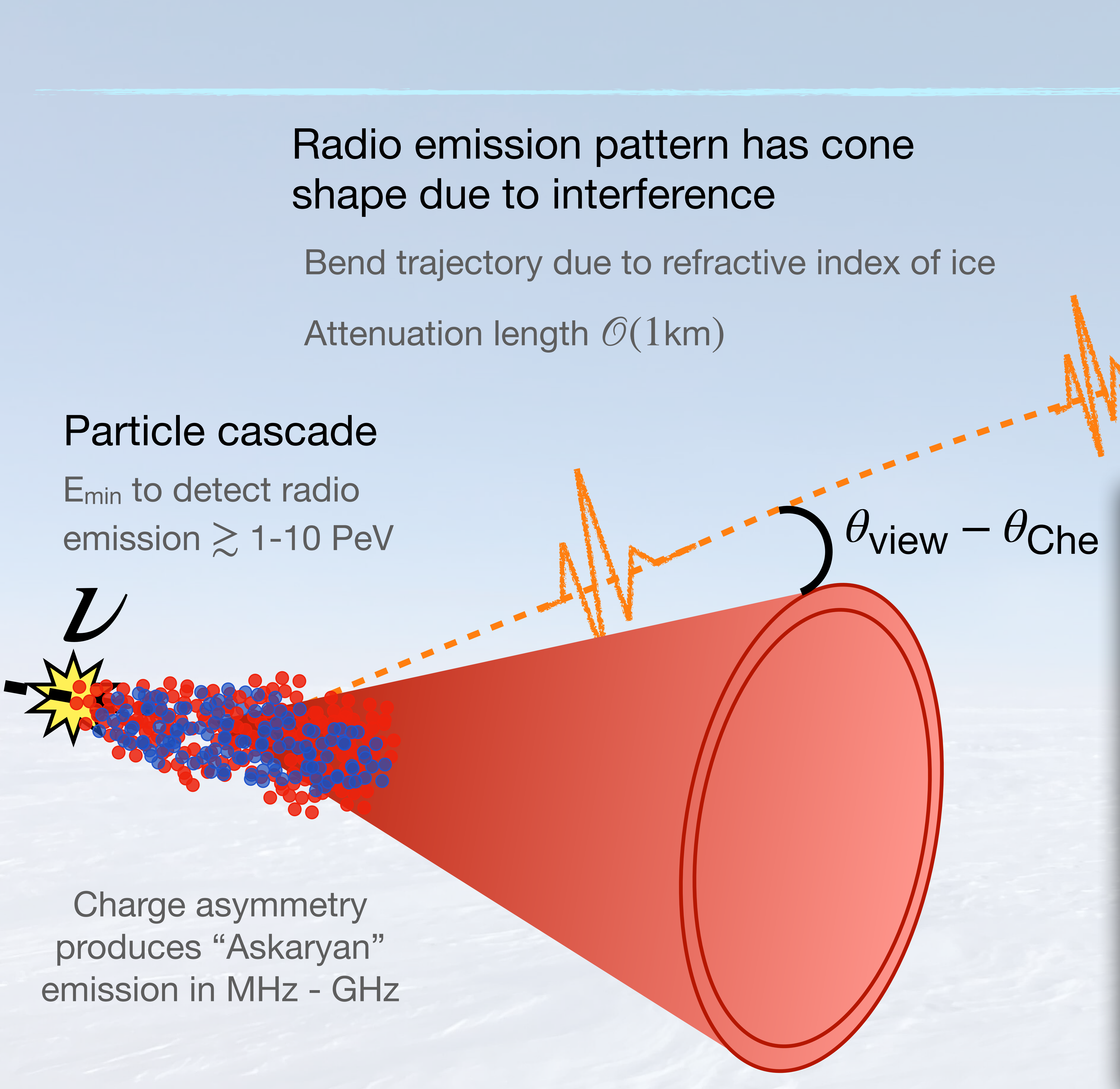

Radio emission pattern has cone shape due to interference

Bend trajectory due to refractive index of ice

Attenuation length $\mathcal{O}(1\text{km})$

Particle cascade

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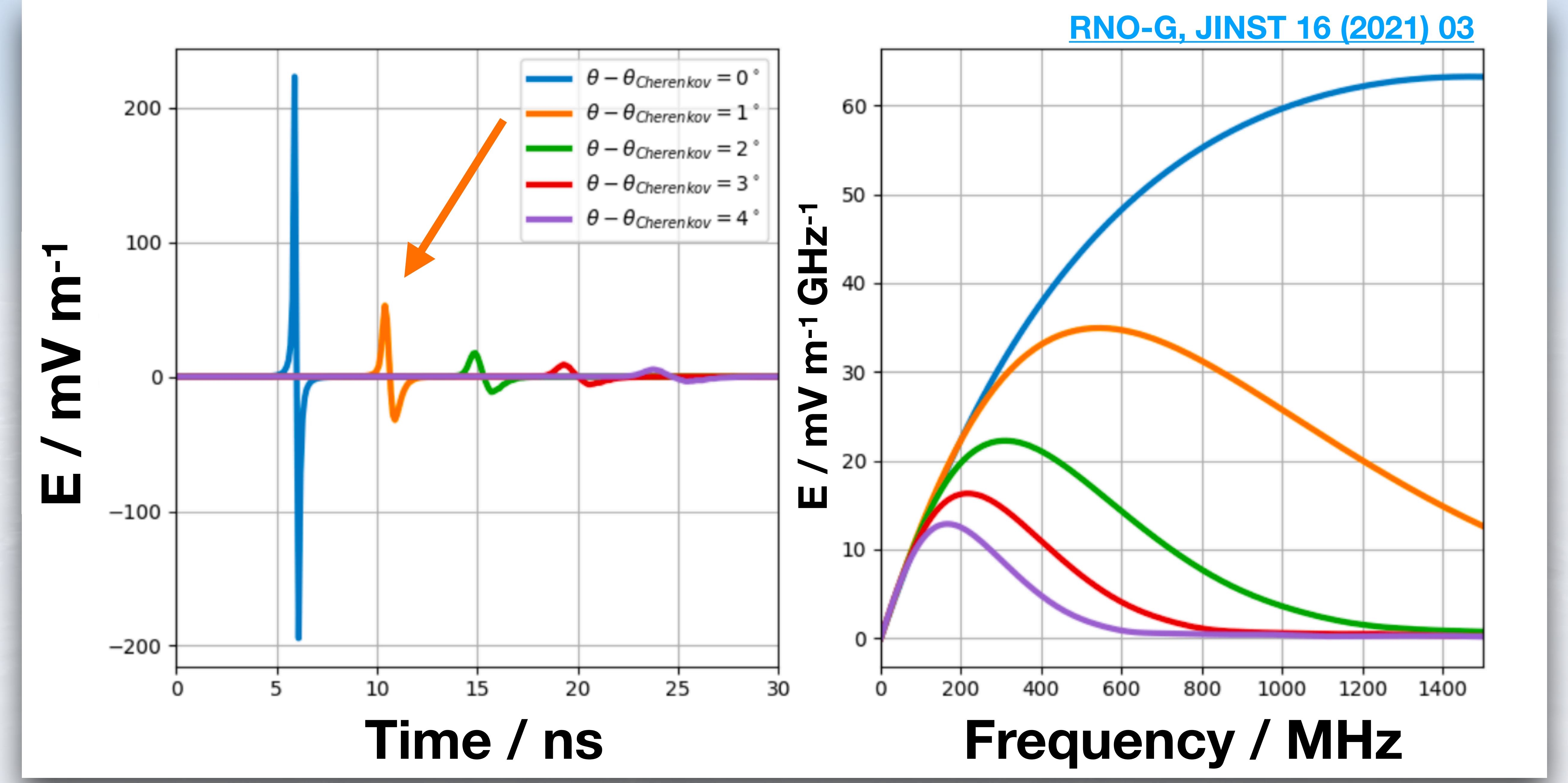
Charge asymmetry produces "Askaryan" emission in MHz - GHz

Change viewing angle θ_{view} reduces signal (higher frequencies vanish)



Radio detection of neutrinos

Air

Buried in-ice antennas

Ice

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ν

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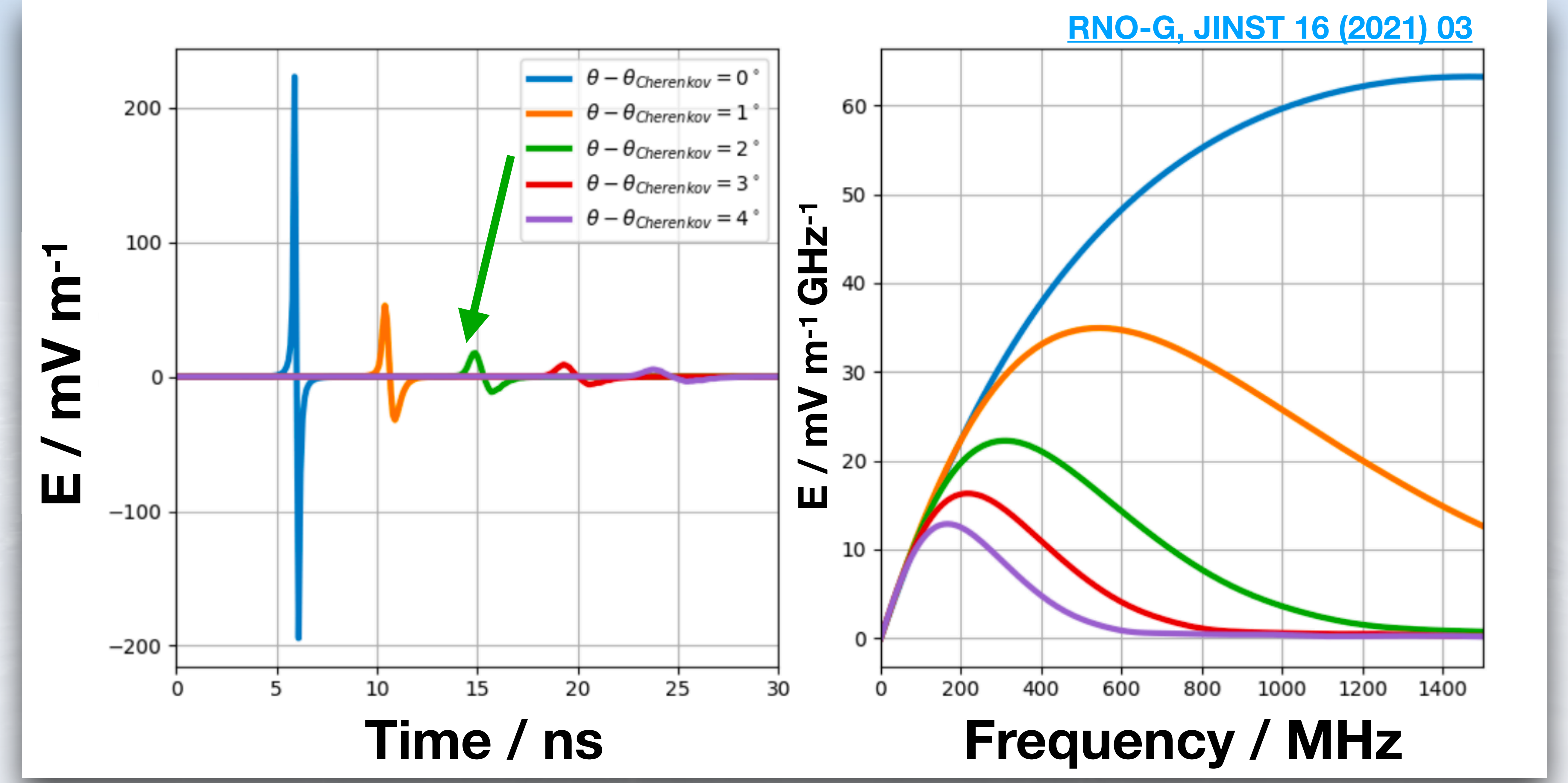

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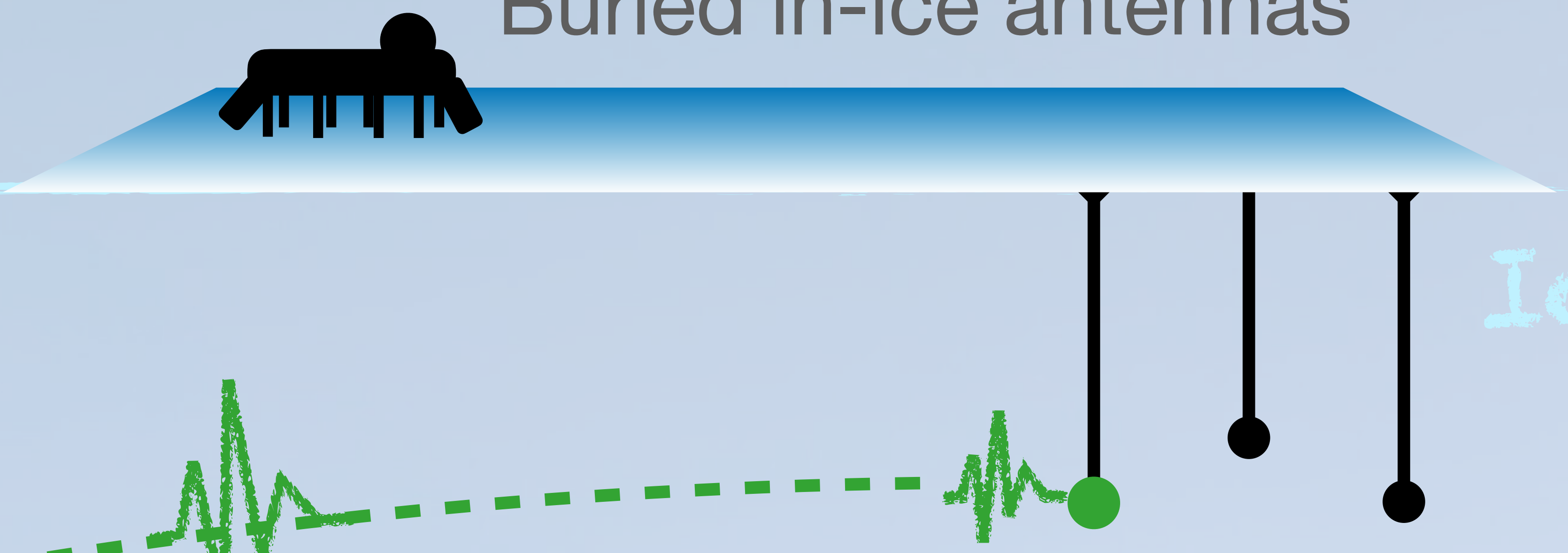

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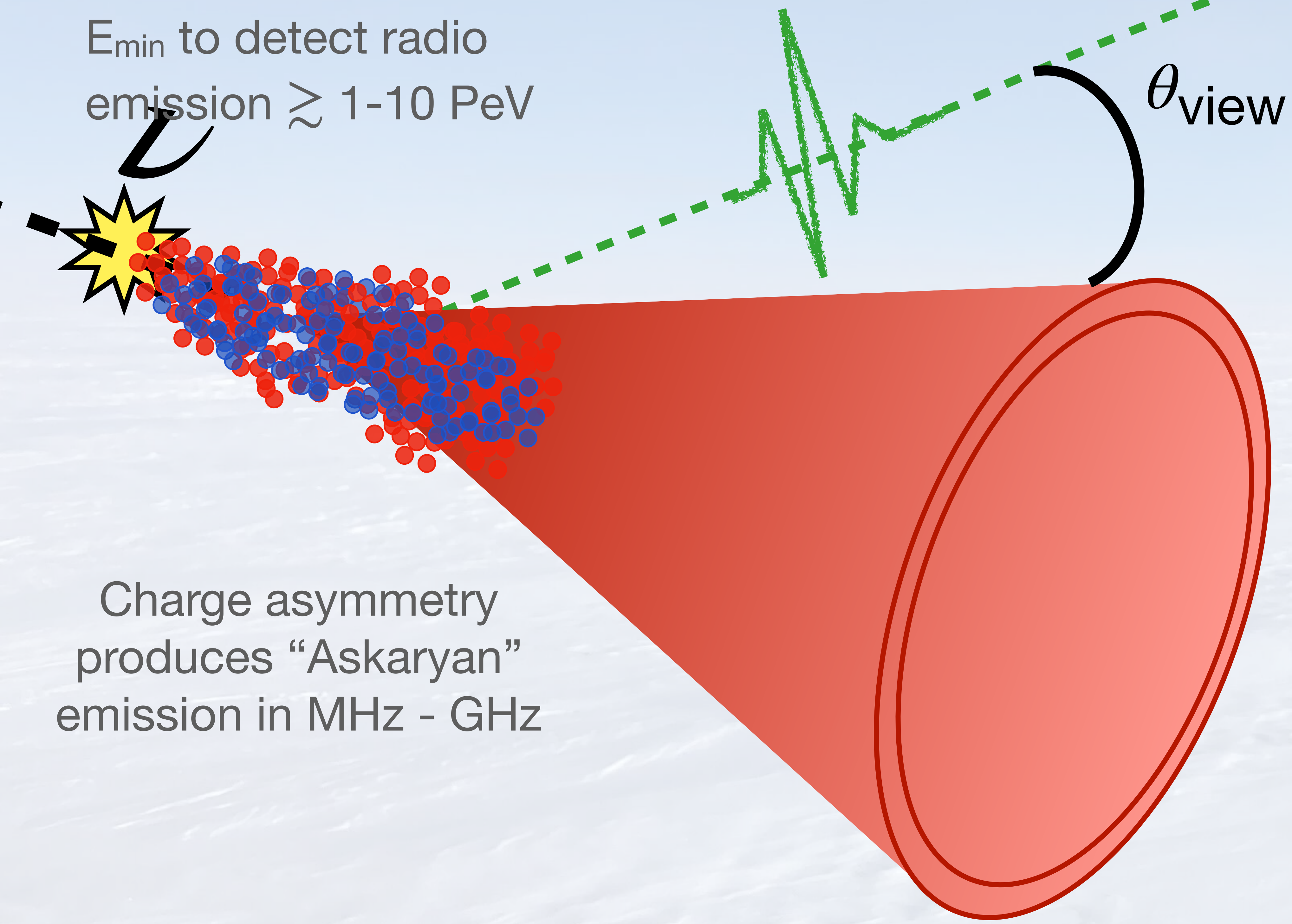
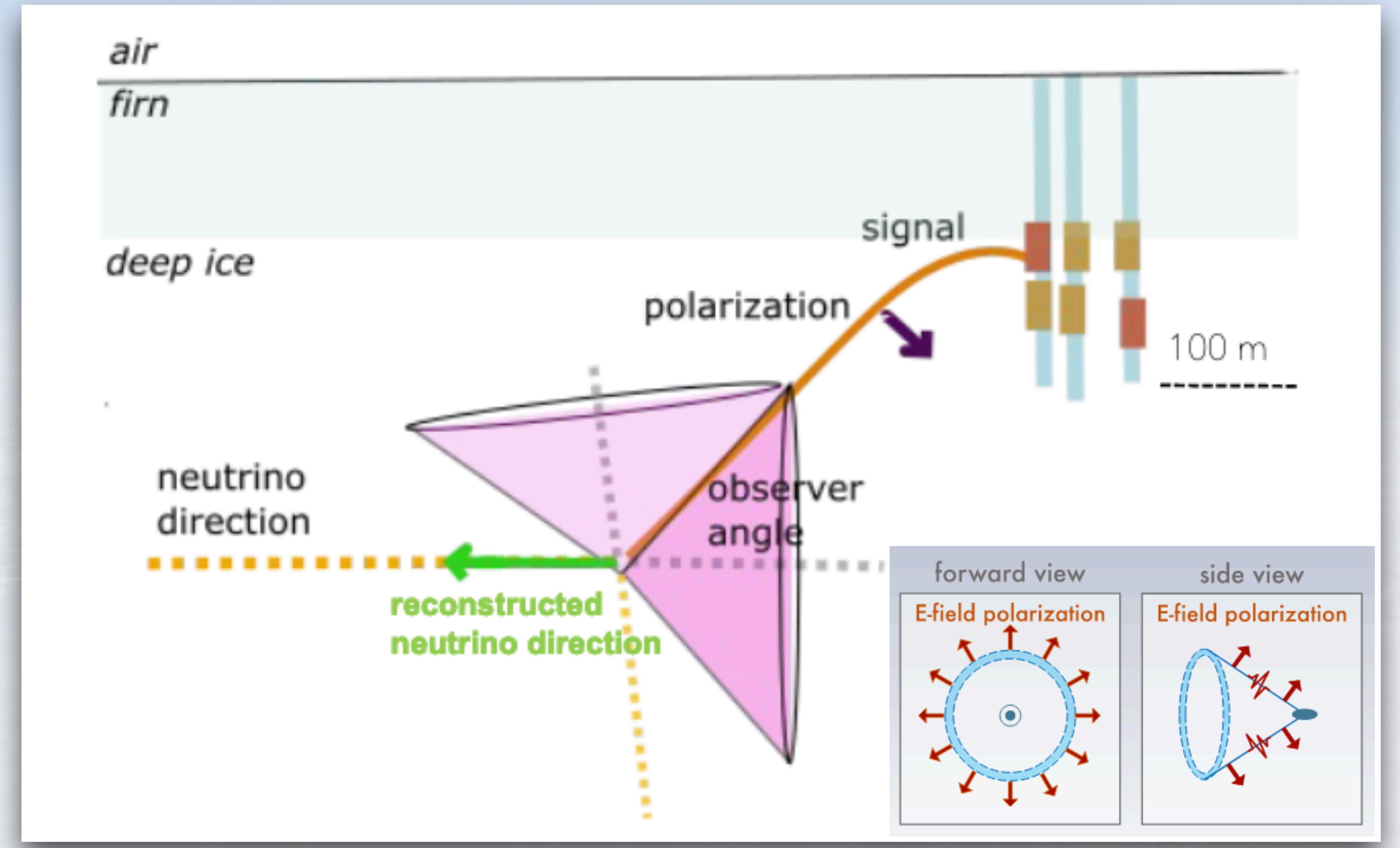
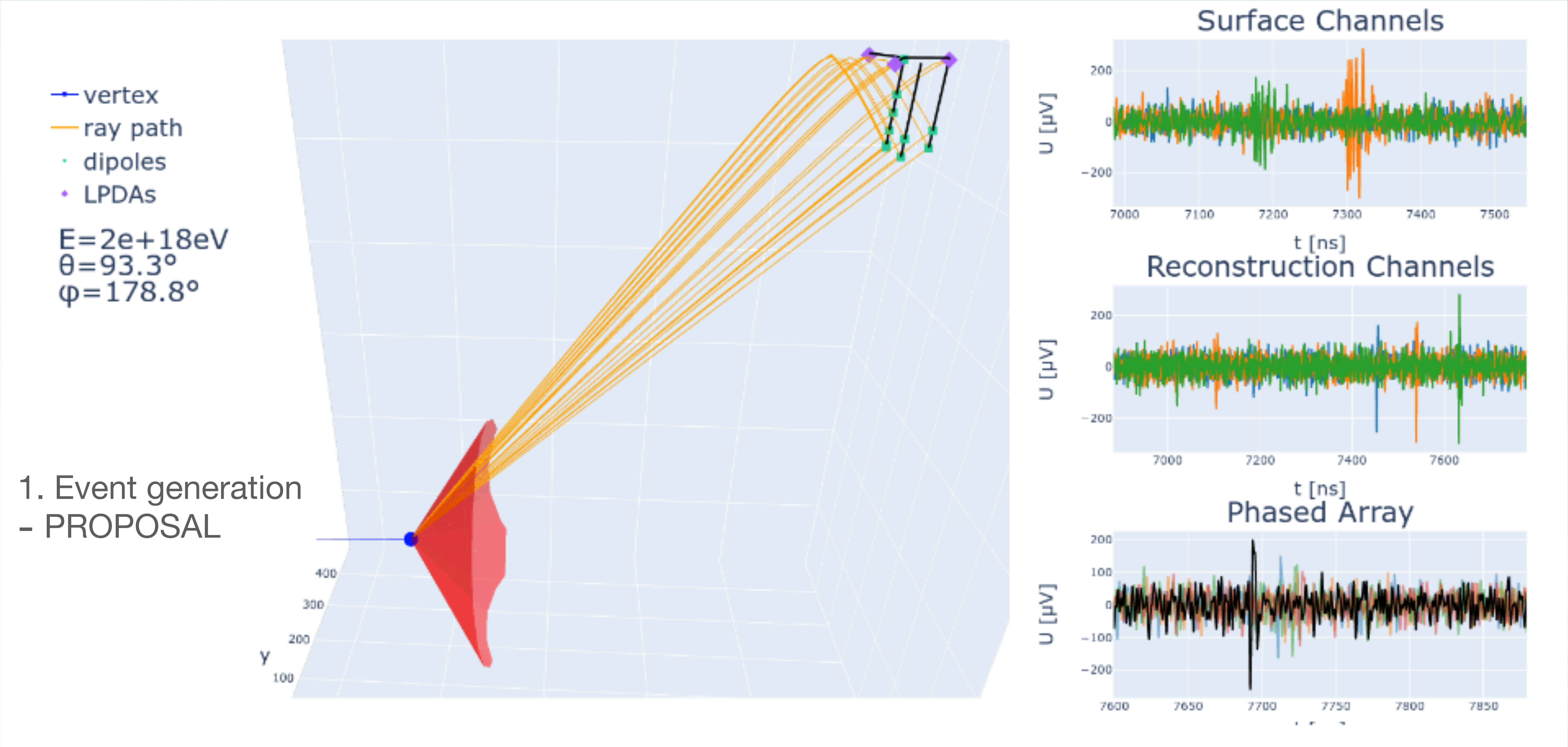


Charge asymmetry produces “Askaryan” emission in MHz - GHz

Signal polarisation reveals neutrino direction



Simulations with NuRadioMC



- Developed reconstructions
  - Energy (EPJC 82, 147 (2022)) & Arrival direction (EPJC 83 (2023) 5)
- Used to determine sensitivity

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

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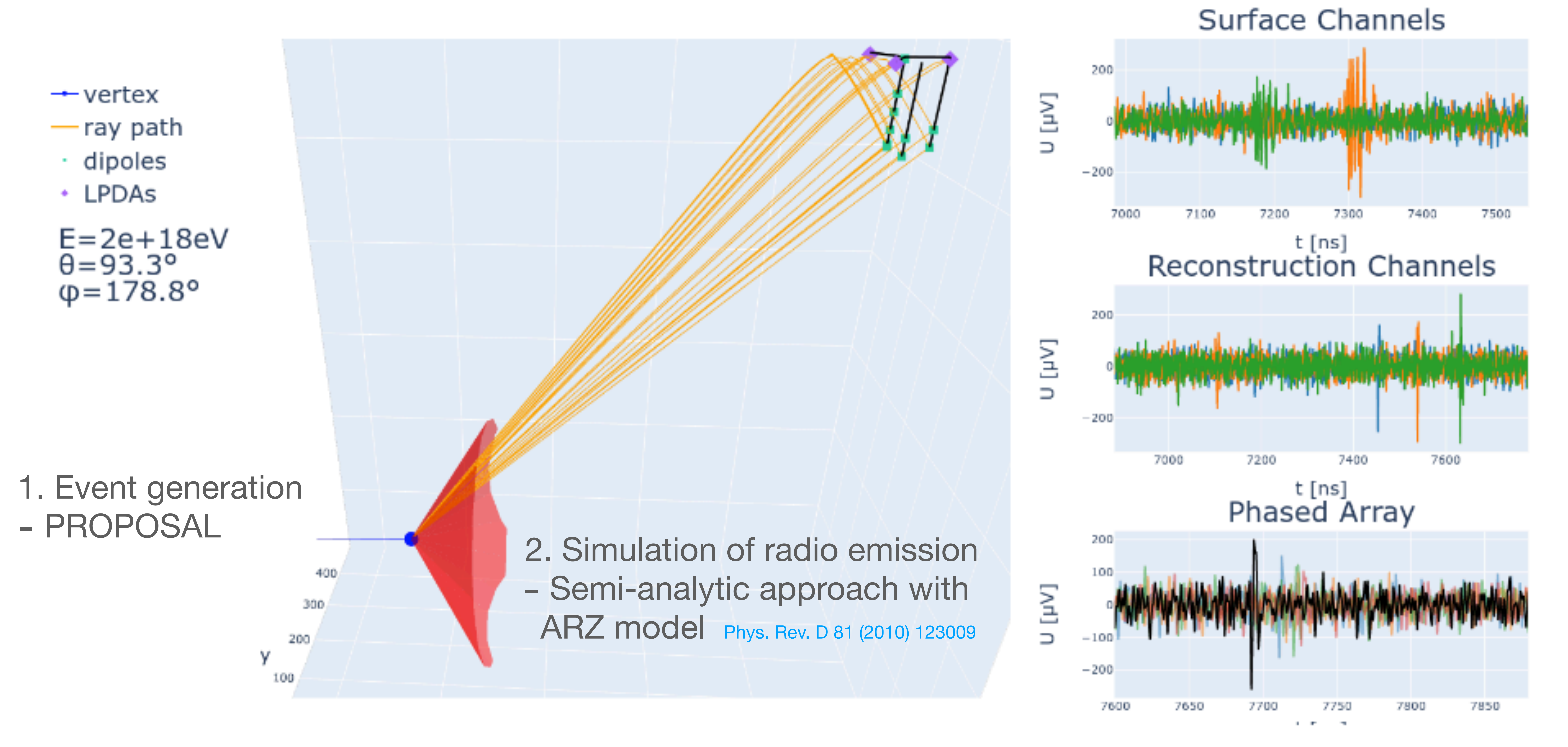

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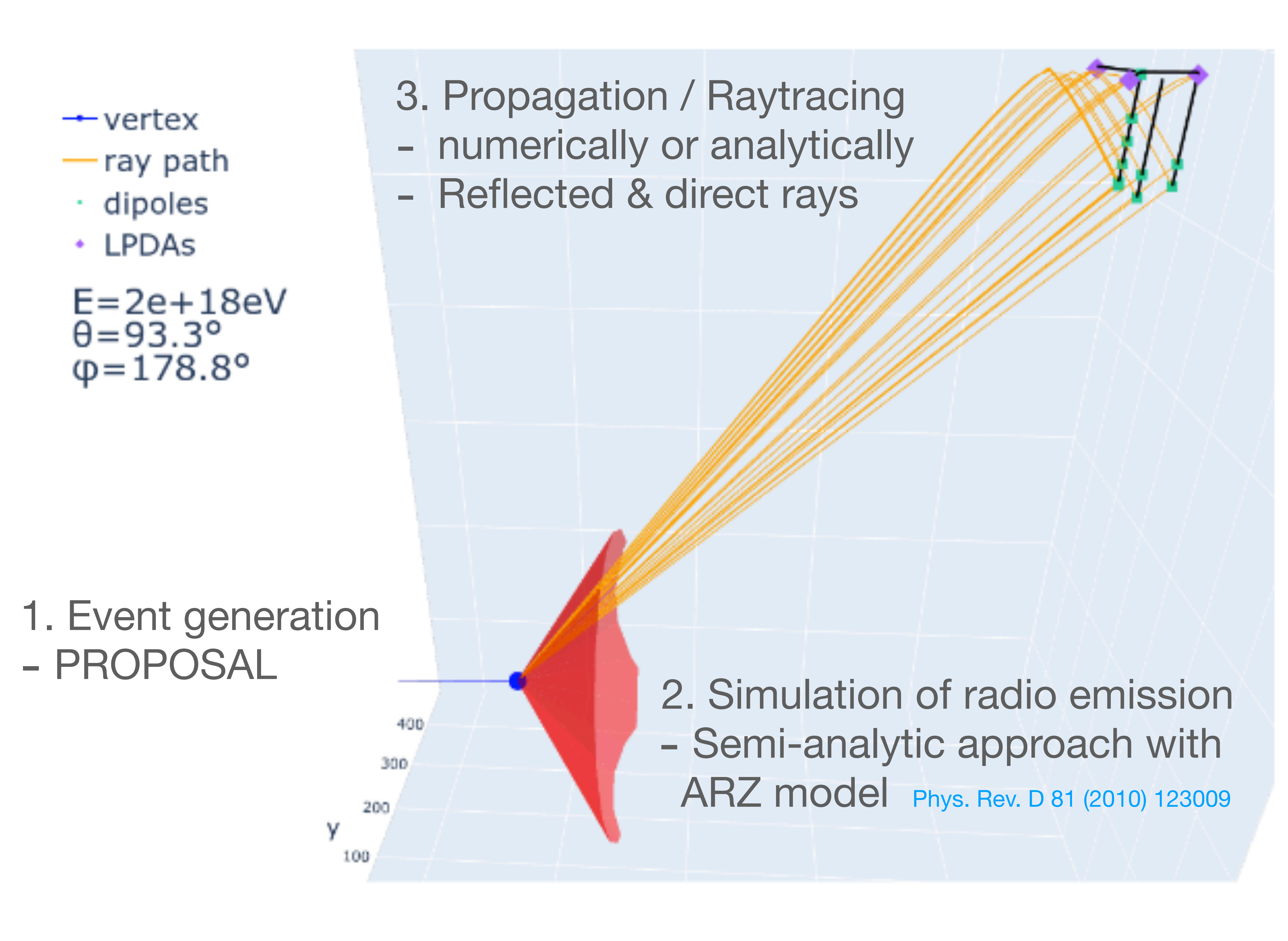

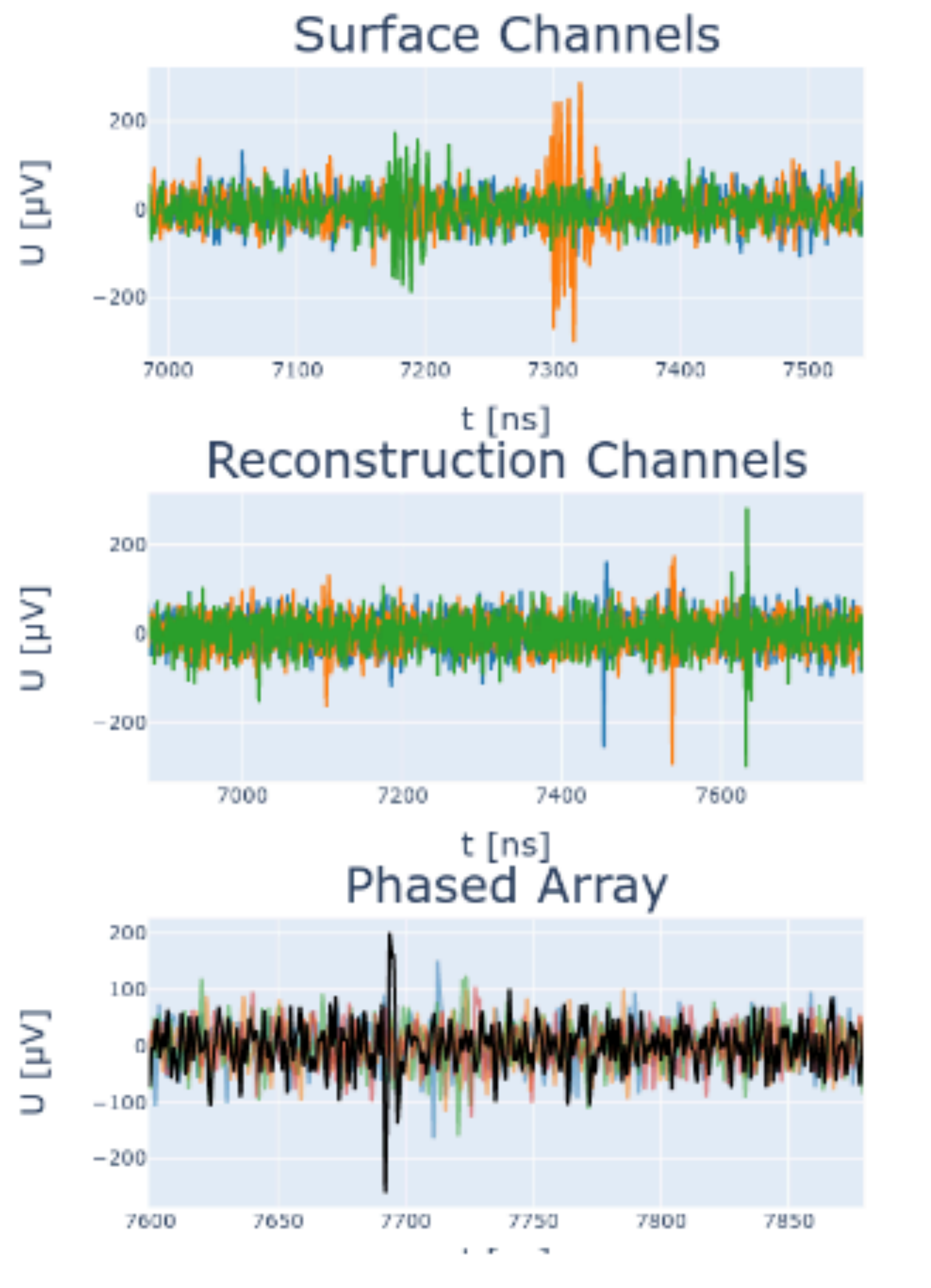

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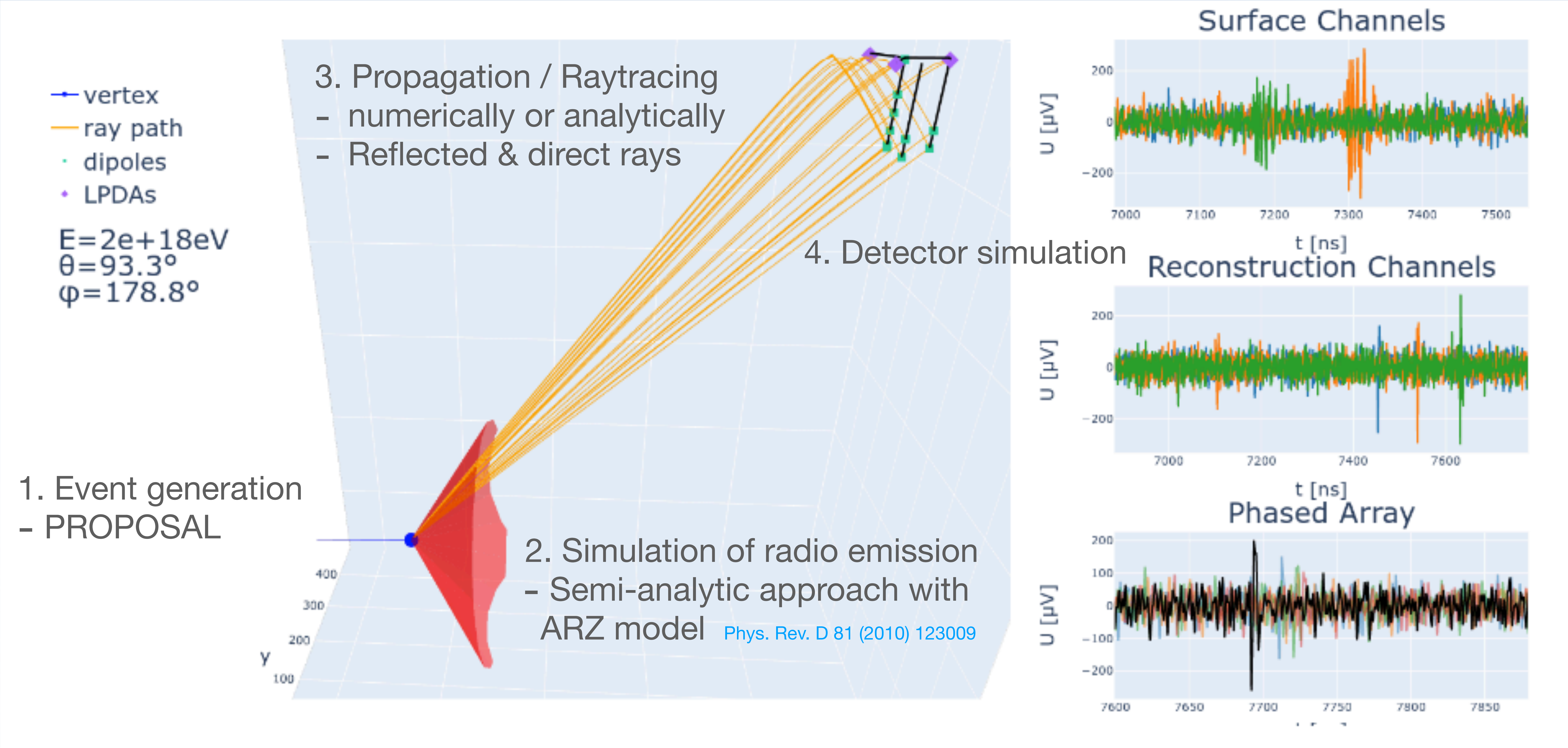

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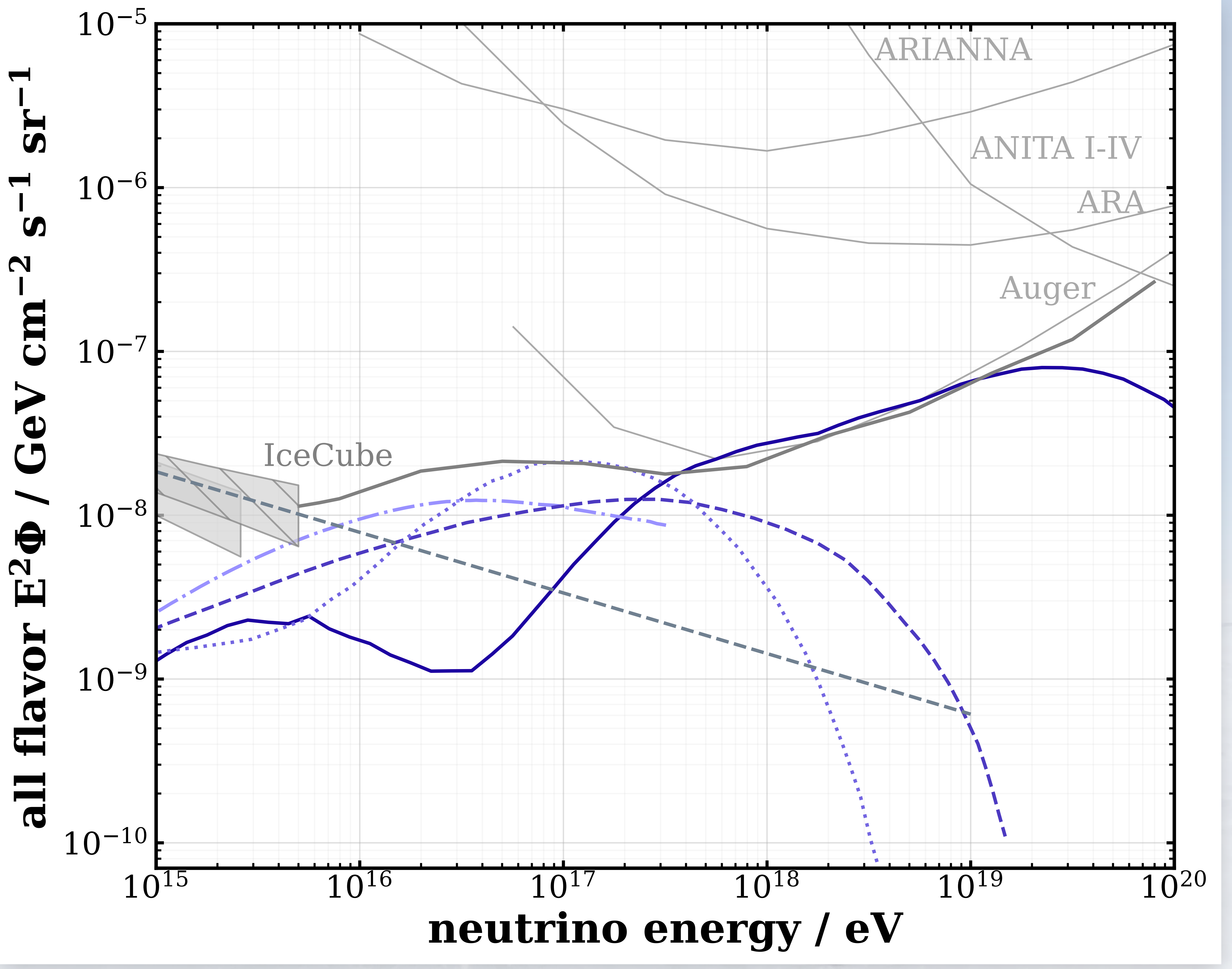
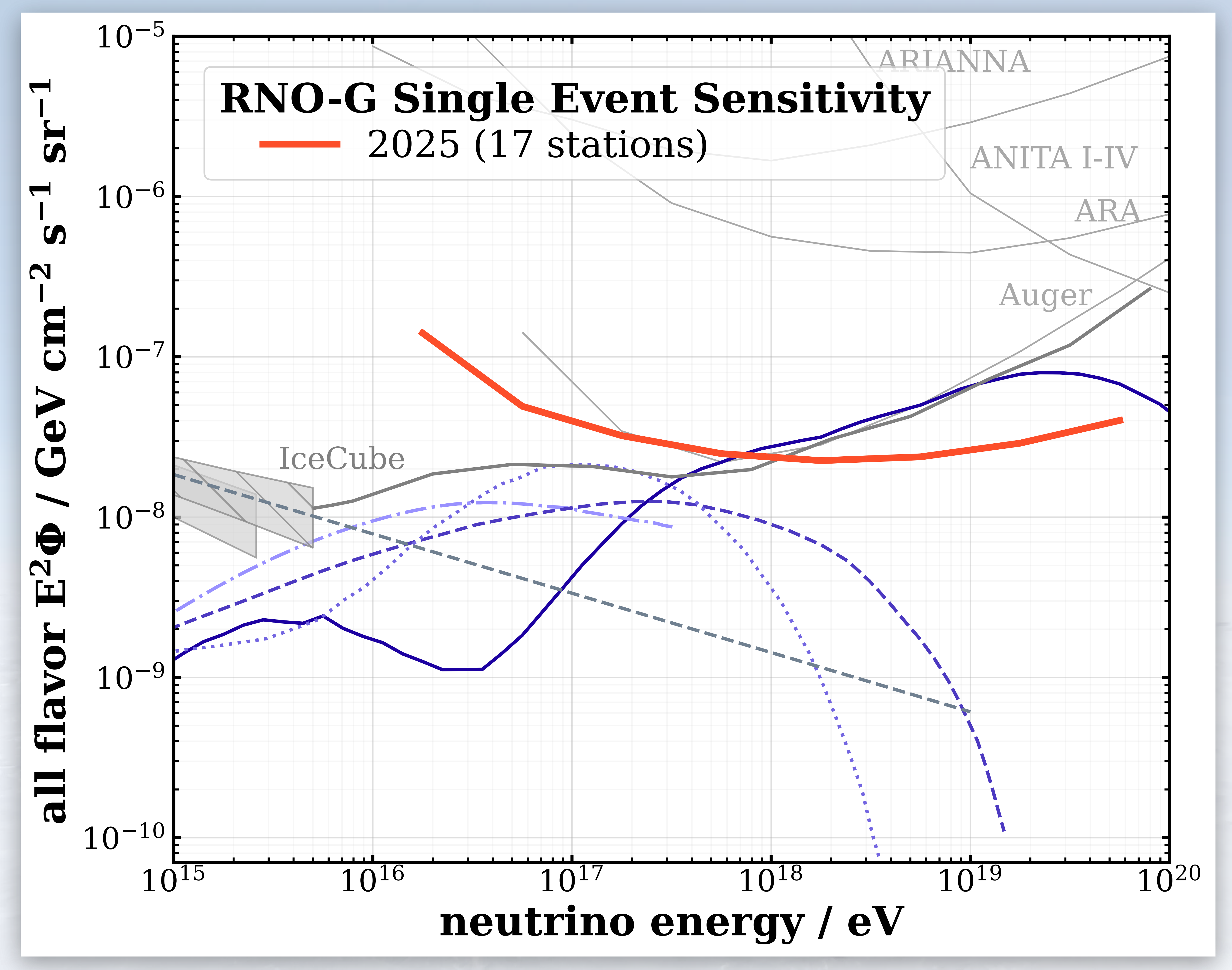
Sensitivity: Diffuse emission



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

Sensitivity: Diffuse emission

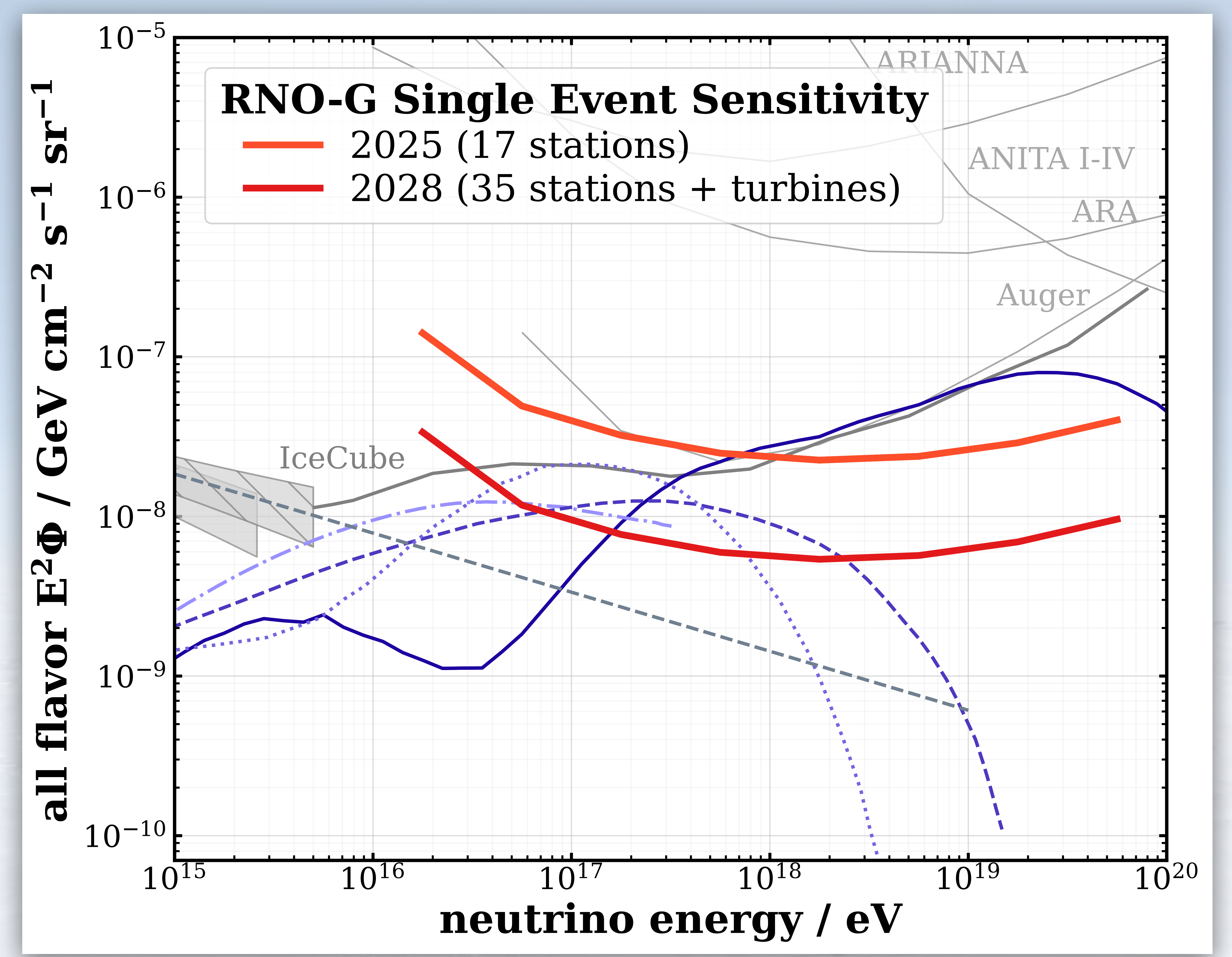
- Assuming no background



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

Sensitivity: Diffuse emission

- Assuming no background
- World leading sensitivity @ 1 EeV
- Testing 2. (hard) astrophysical component



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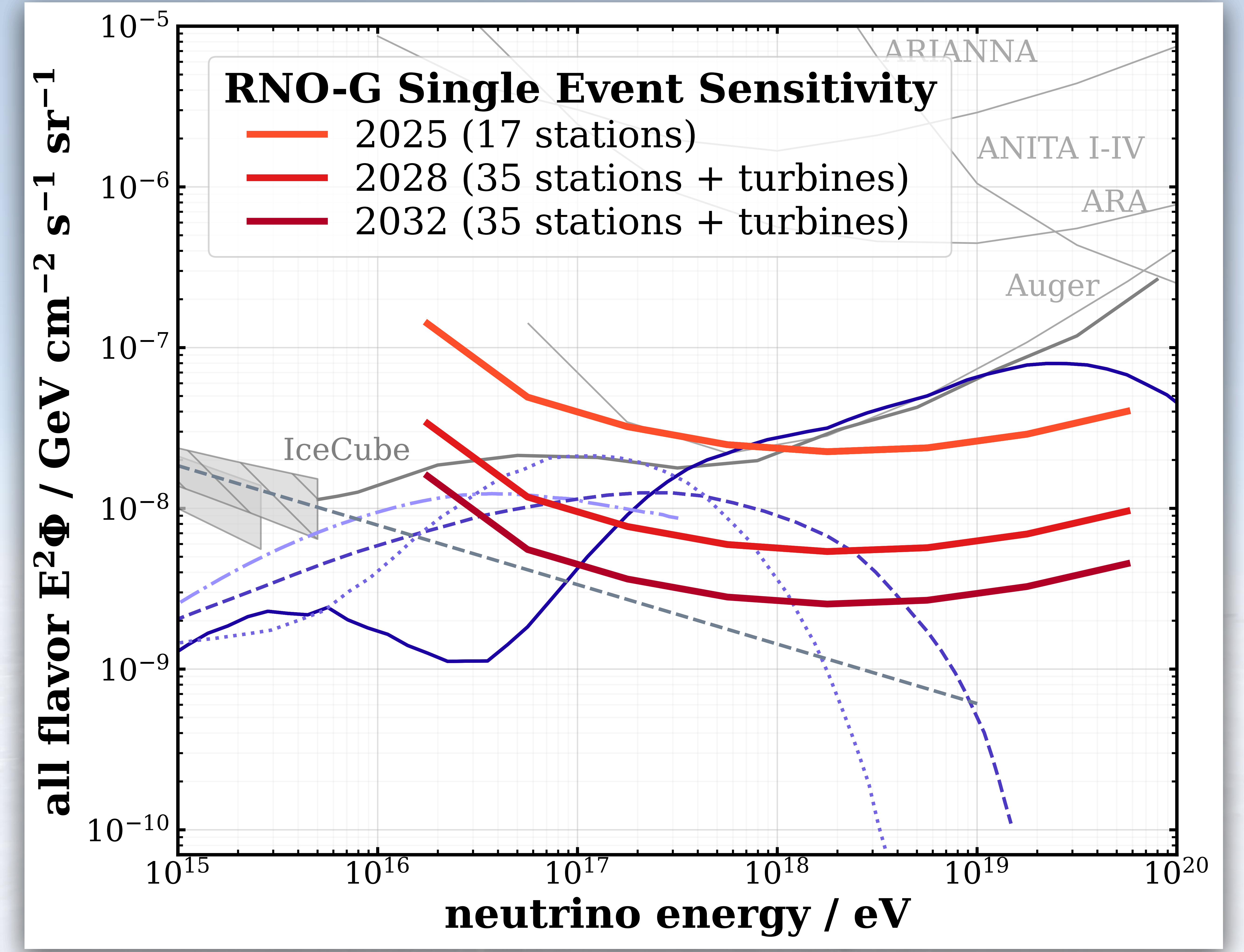

M. Muzio for RNO-G, PoS (ICRC23) 1485

Sensitivity: Diffuse emission

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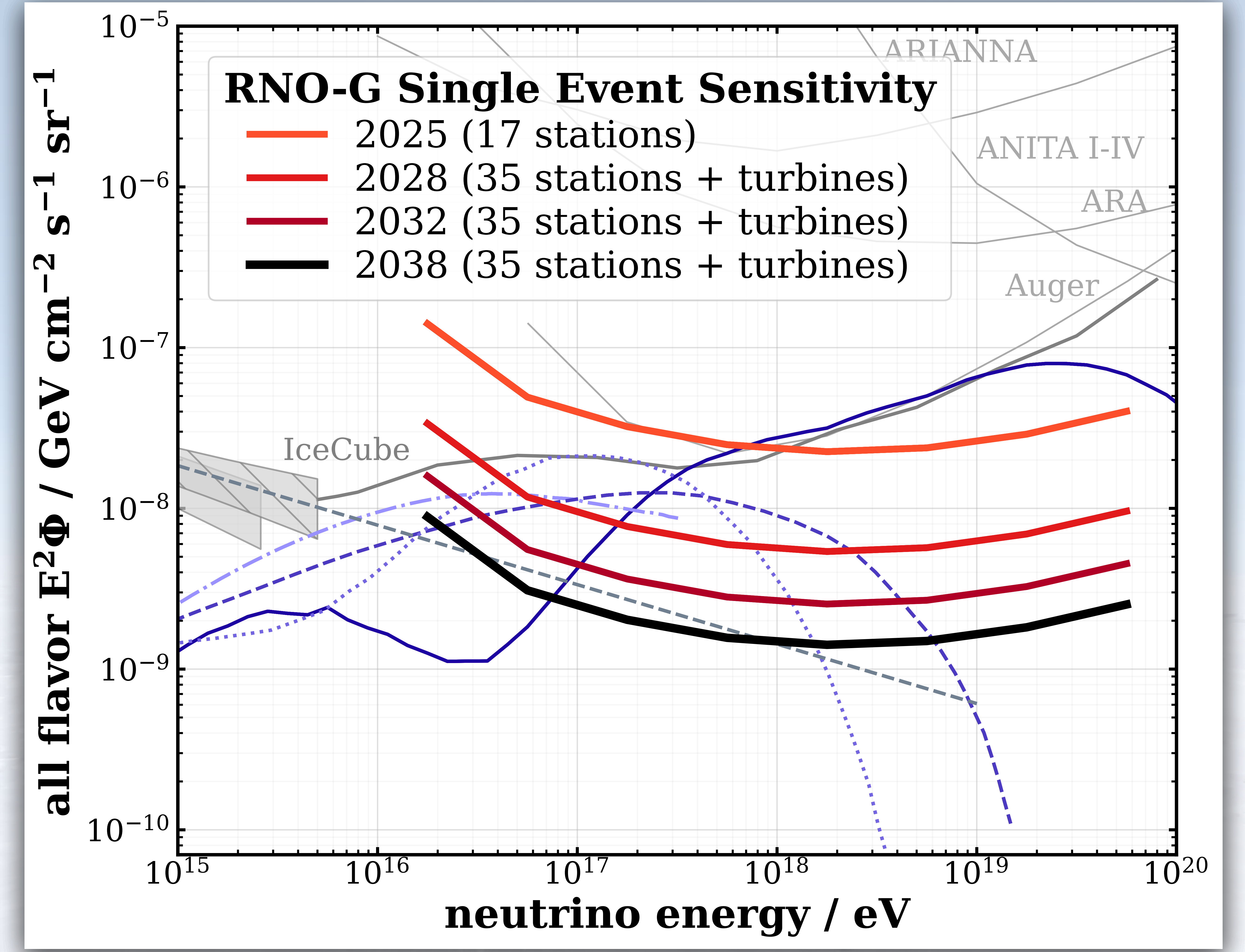
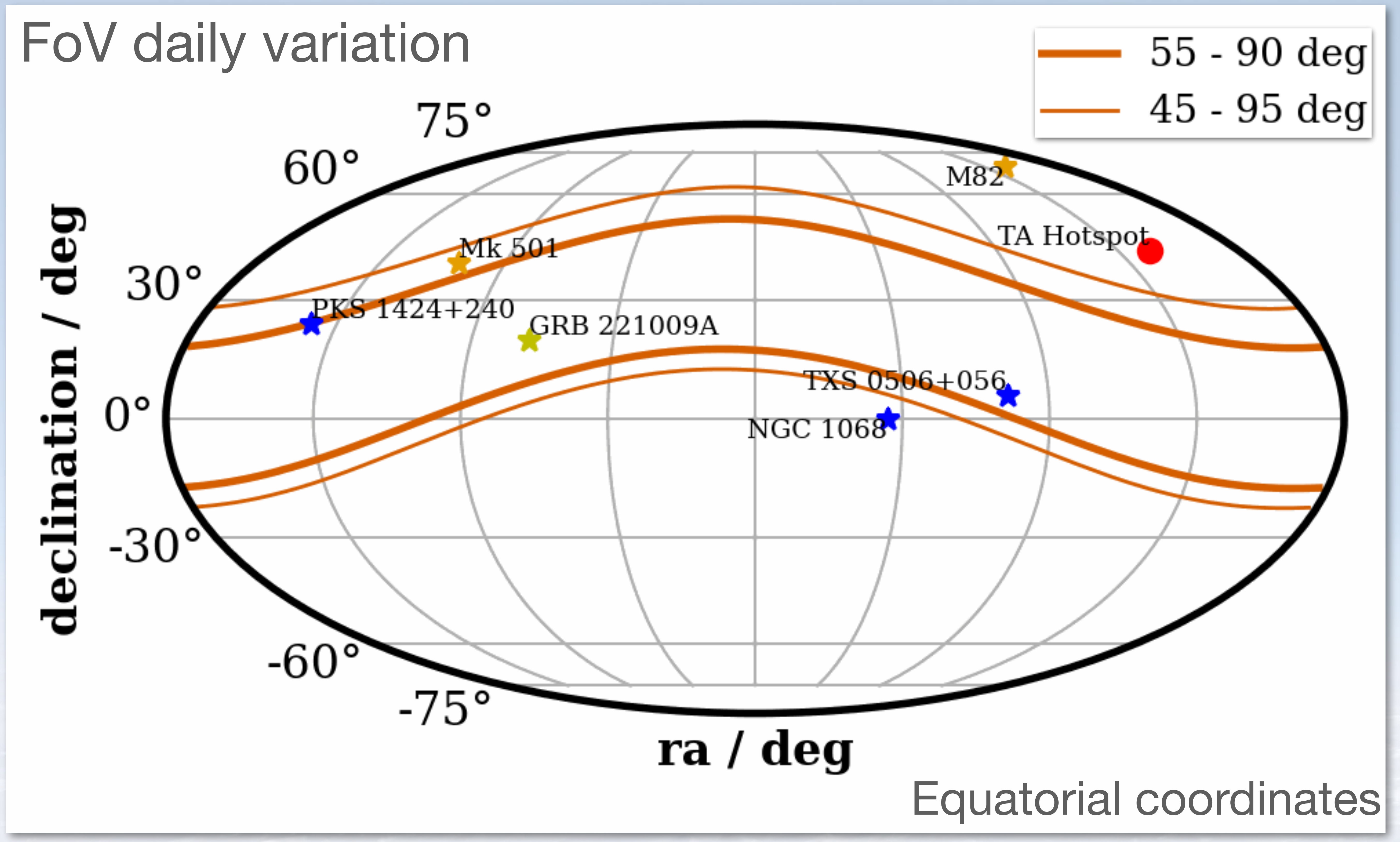
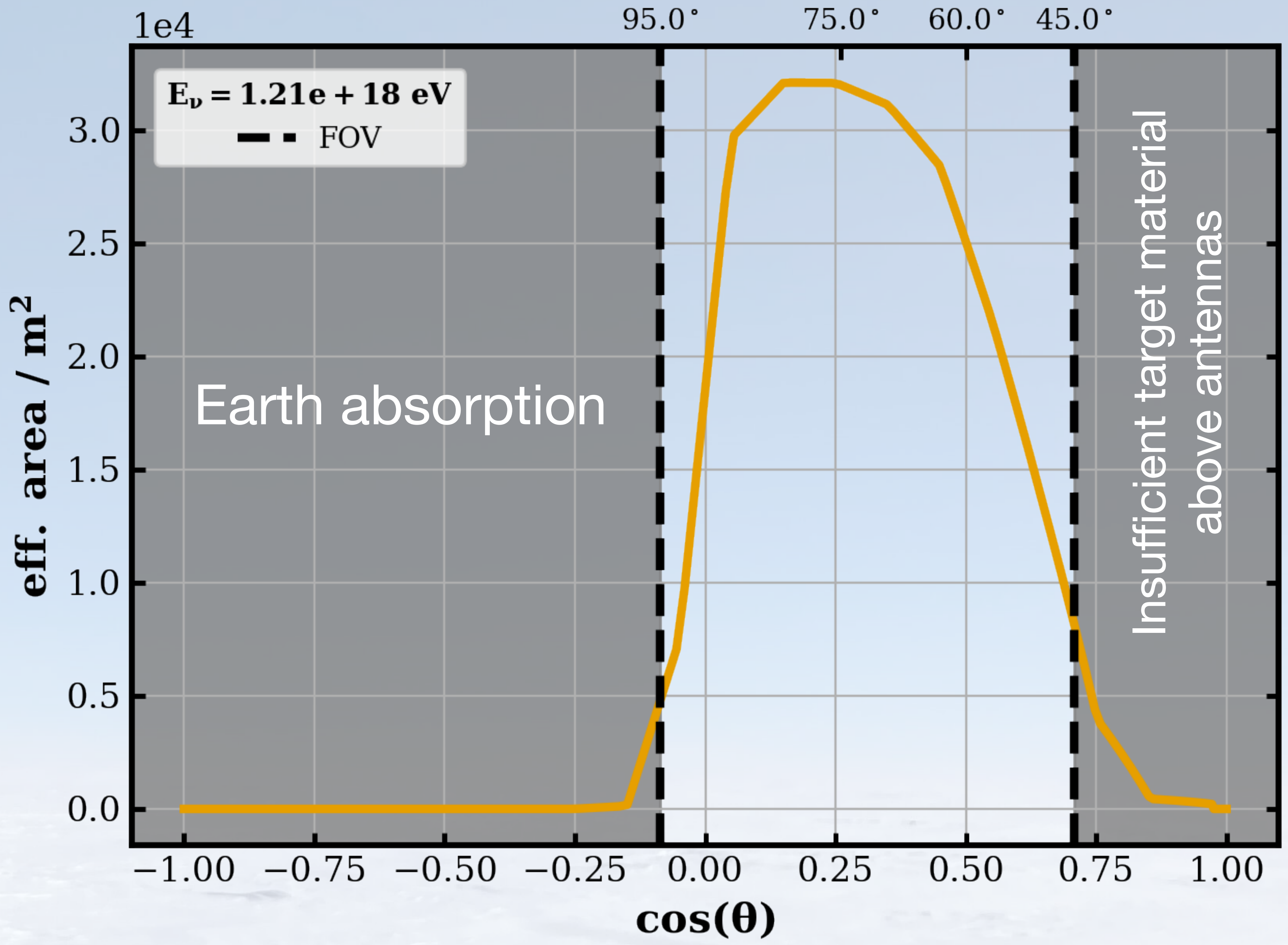
- Testing extension of astrophysical flux measured by IceCube



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

Neutrinos from the northern sky





- Earth is opaque for UHE neutrinos
- Observatory in northern hemisphere relevant for multi-messenger observation!
- RNO-G eff. area for full 35 station array
- Largest aperture just above the horizon

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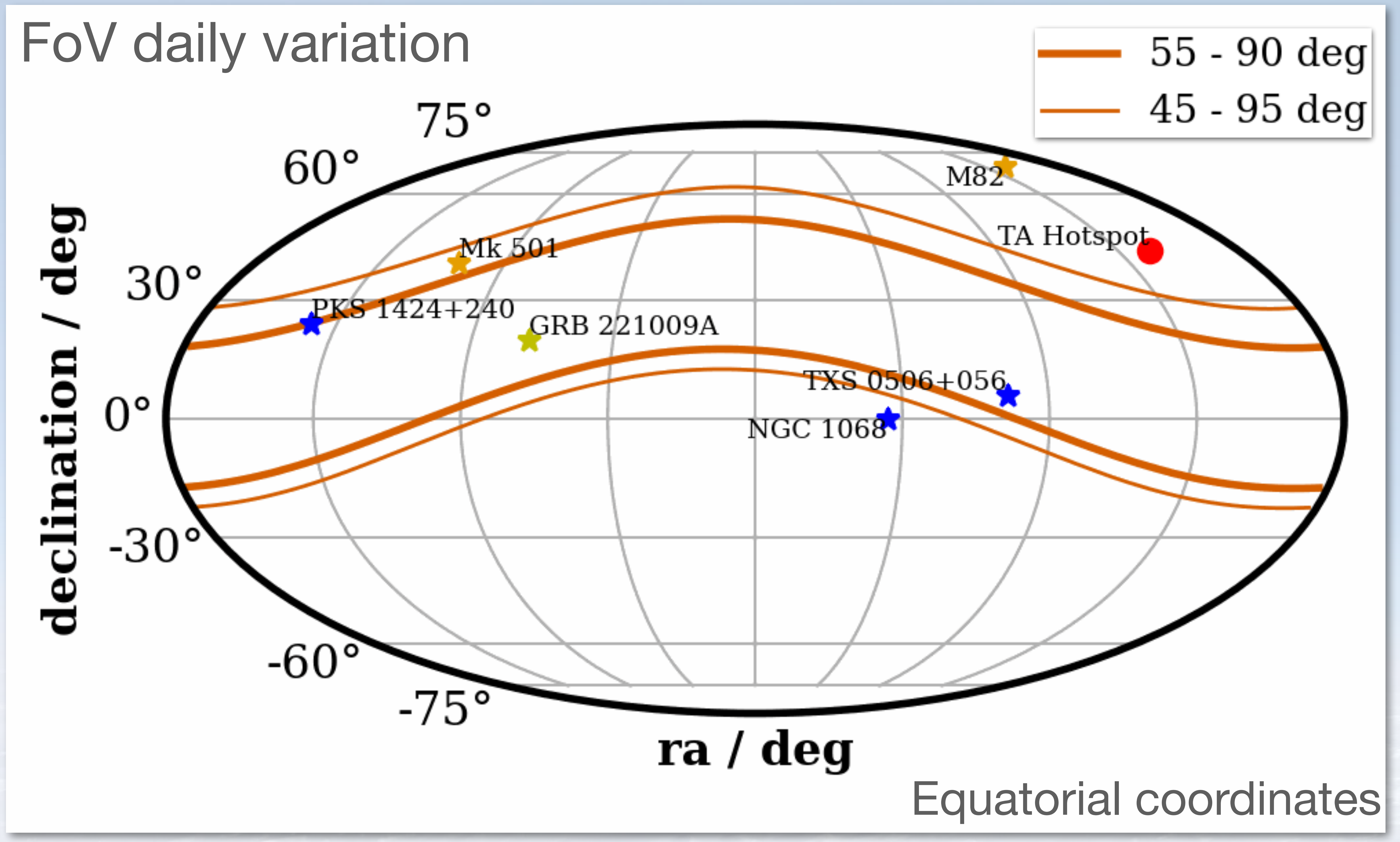

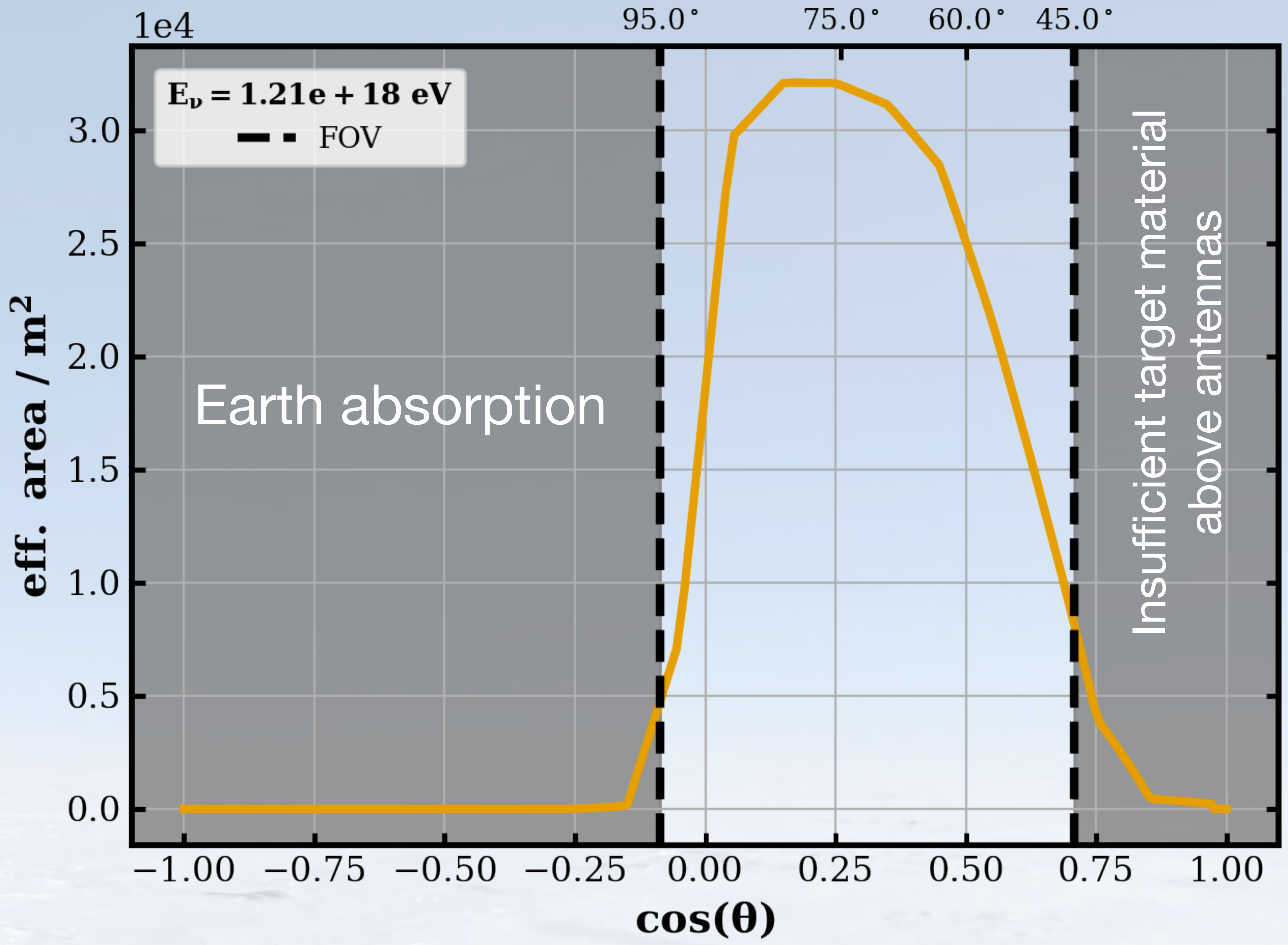

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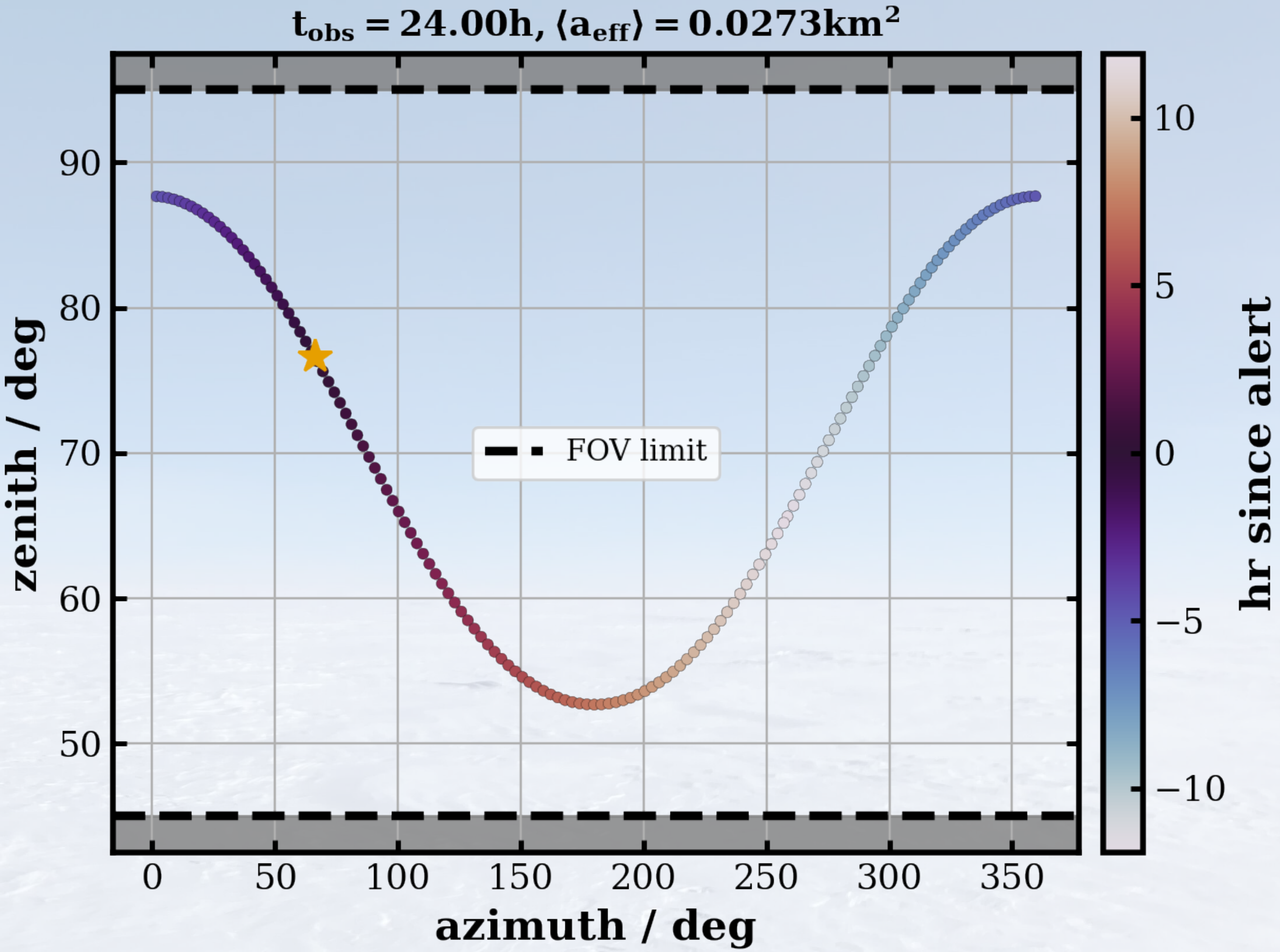
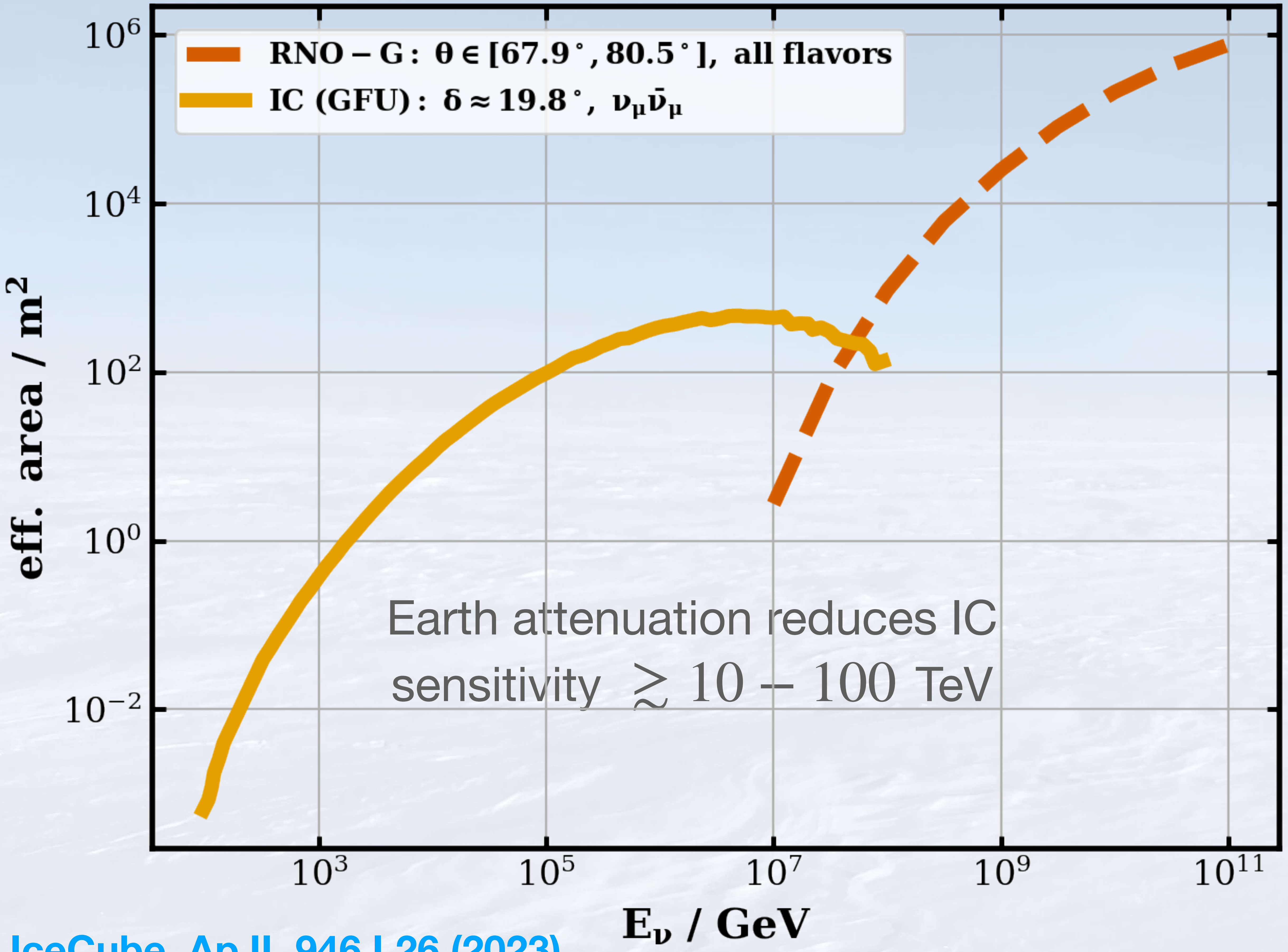
GRB 20221009A in the FOV of RNO-G

- Extremely bright GRB
- Perfectly in FOV of RNO-G
  - 24h visible, alert at favourable zenith angle band 70 - 80 deg
- Detector was off (winter mode) at that time!



Sensitivity: GRB 20221009A

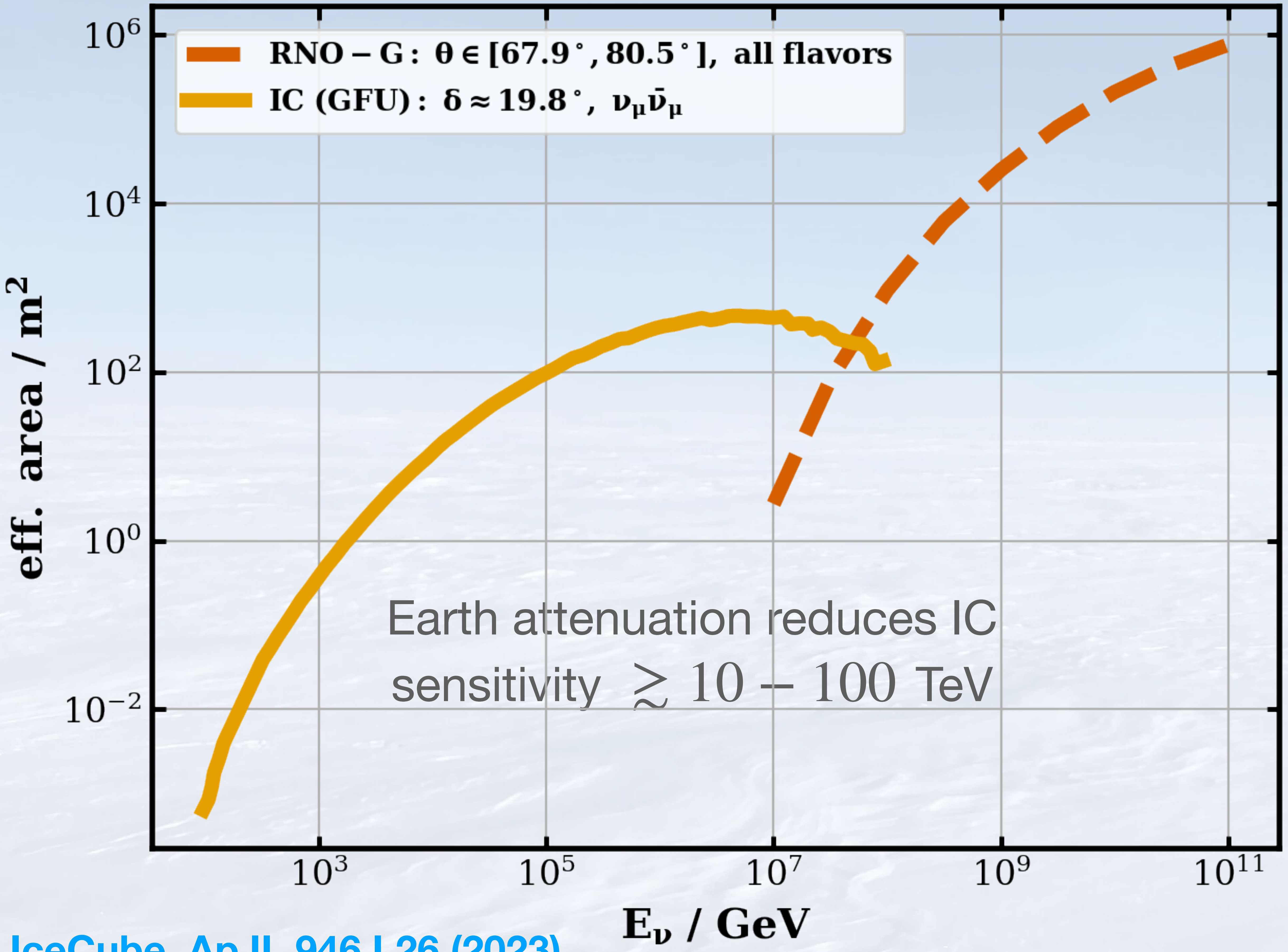
- RNO-G eff. area for 3h time window

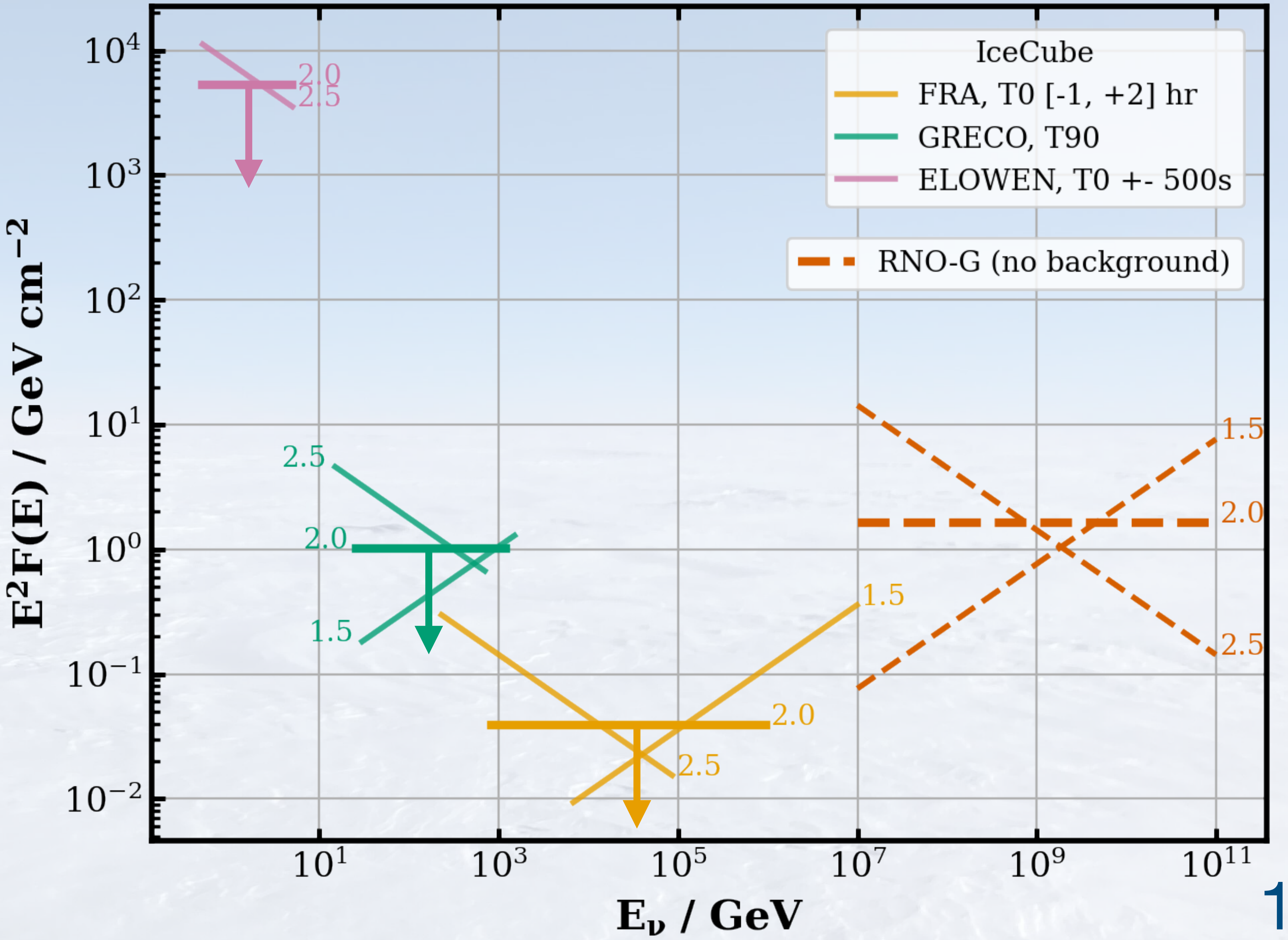


IceCube, ApJL 946 L26 (2023)

Sensitivity: GRB 20221009A

- RNO-G eff. area for 3h time window
- Sensitivity on time integrated E^{-2} flux over several decades in energy
  - RNO-G with competitive sensitivity at higher energies

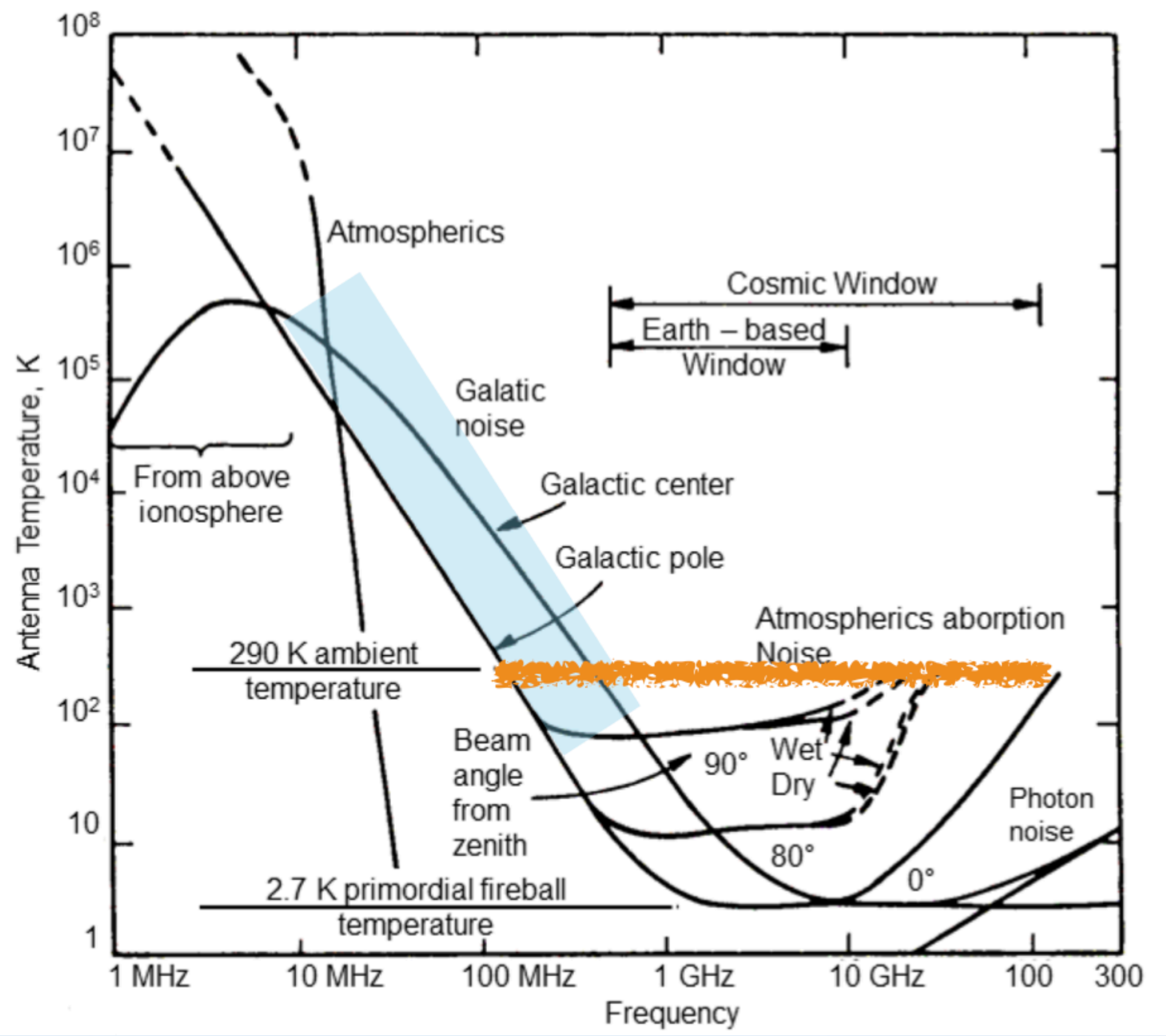


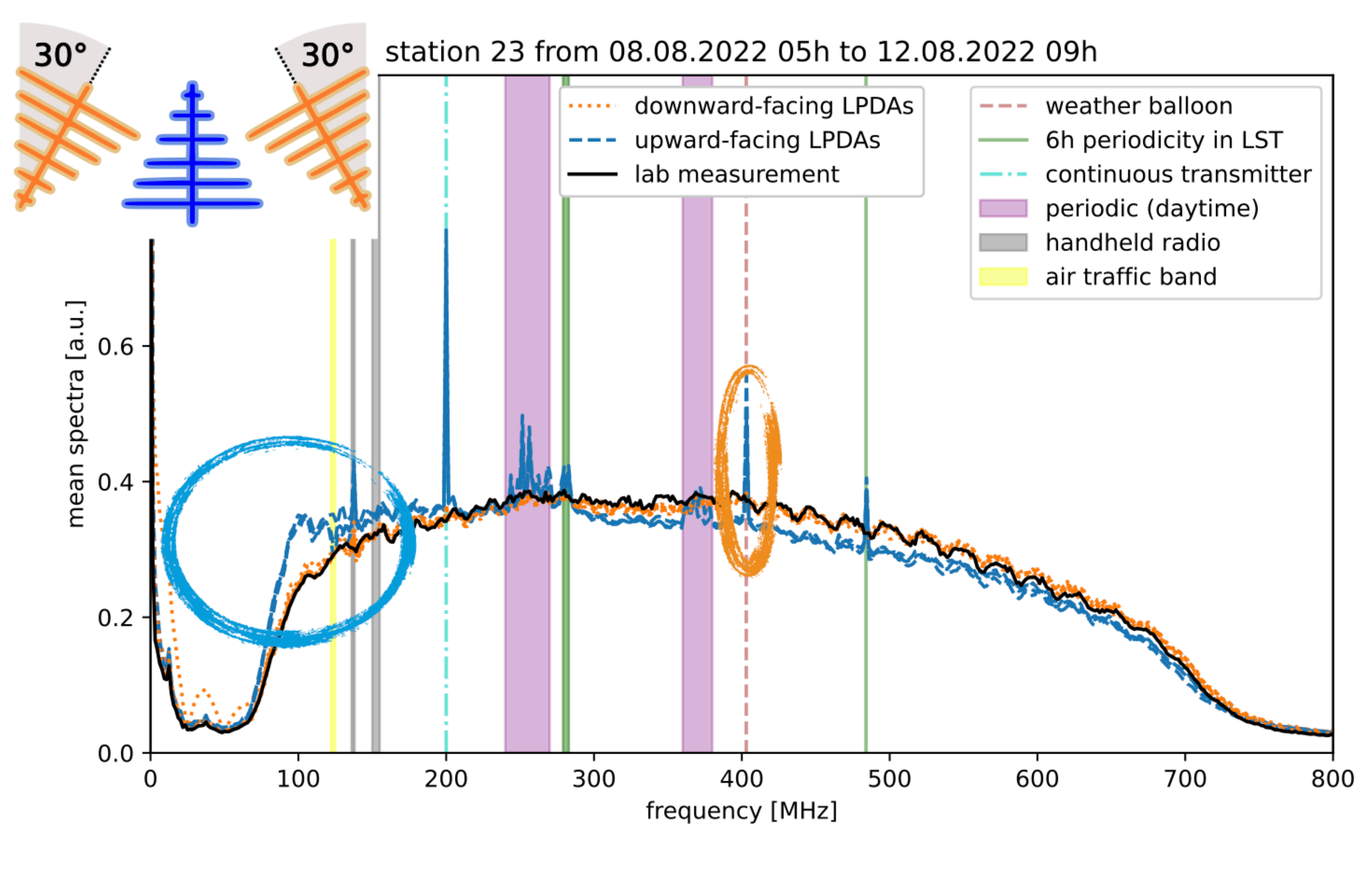


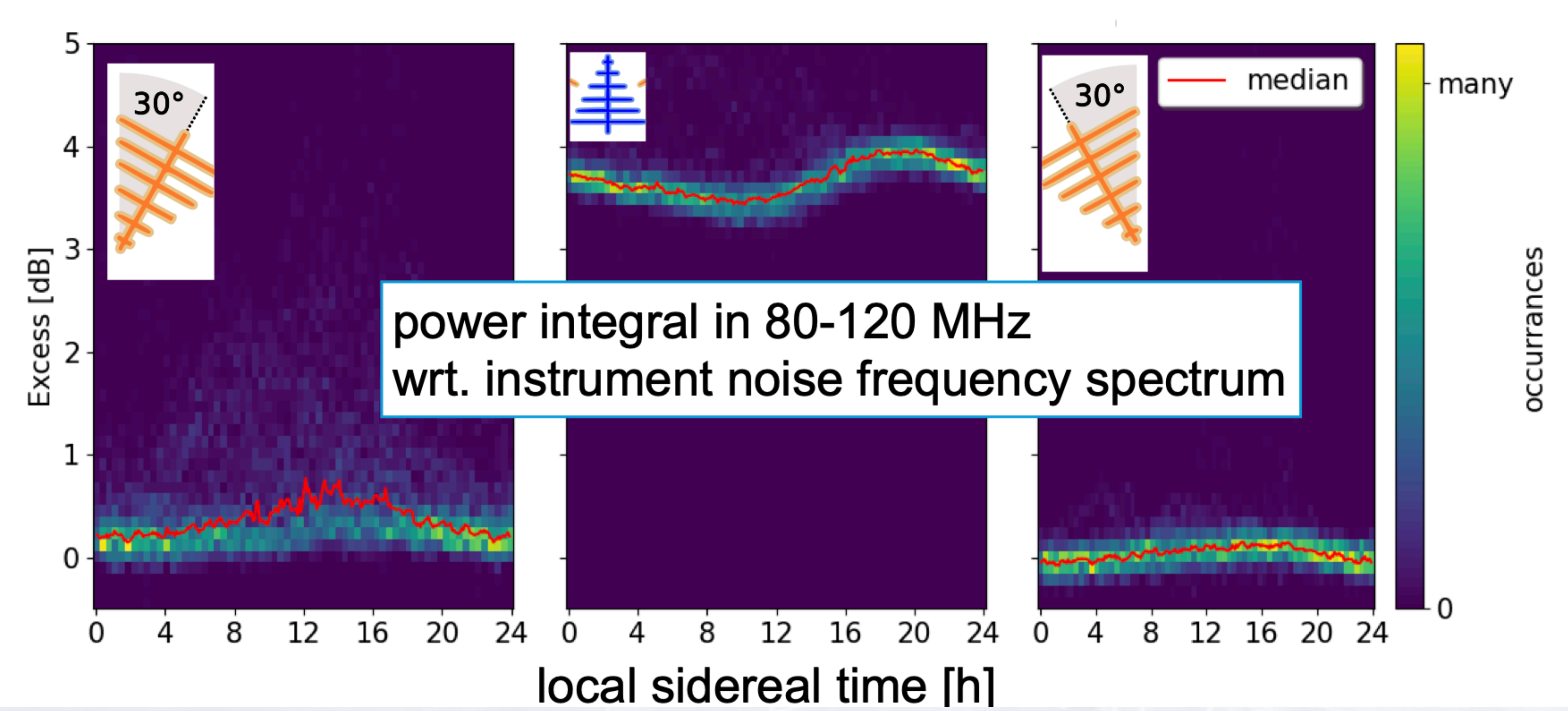
IceCube, ApJL 946 L26 (2023)

First look into the data: Galactic emission

- Standard candle (only parts of plane visible at RNO-G)
  - Excess visible in the shallow upward facing antennas around 100 MHz
  - Daily modulation seen as expected



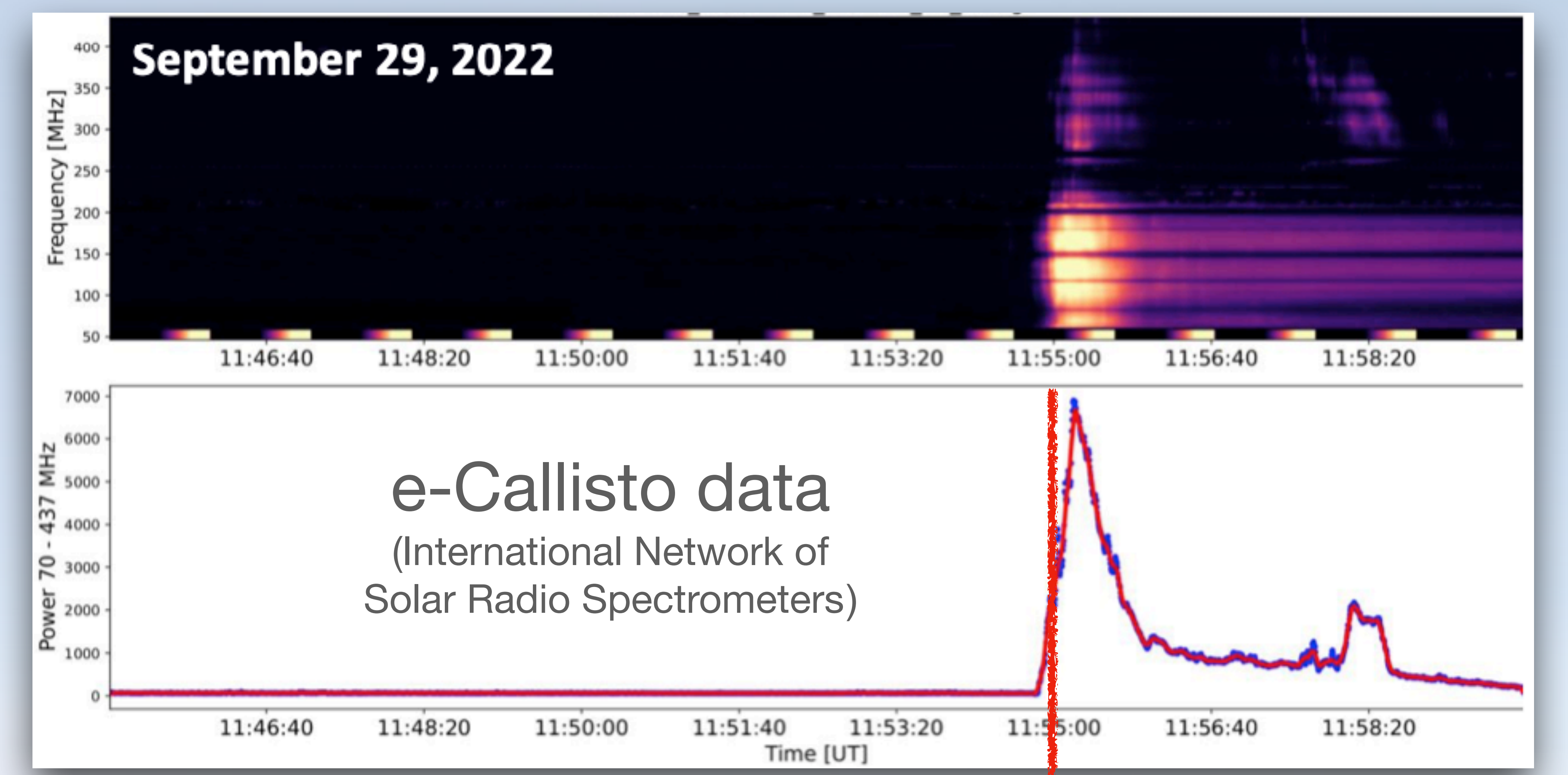


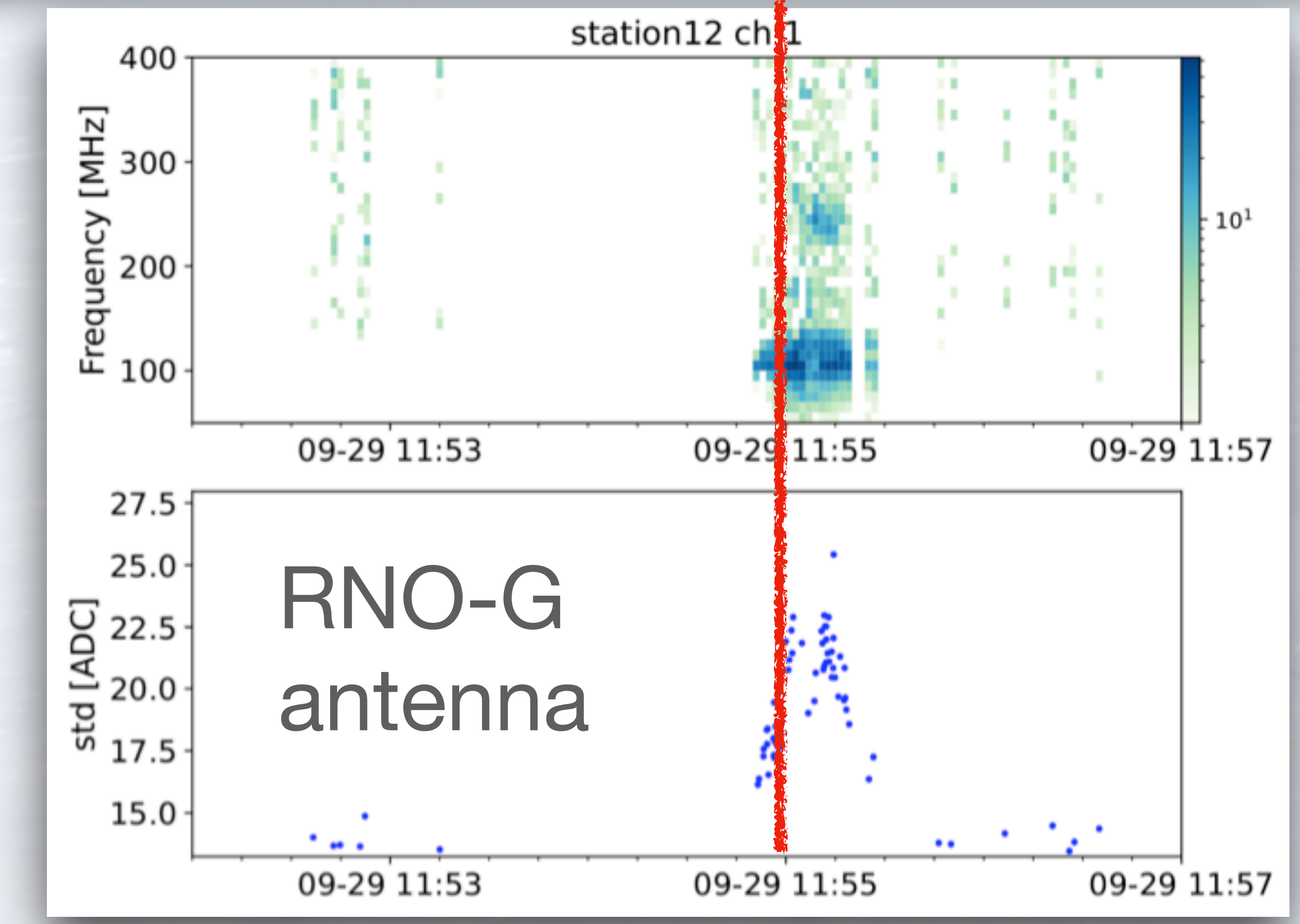


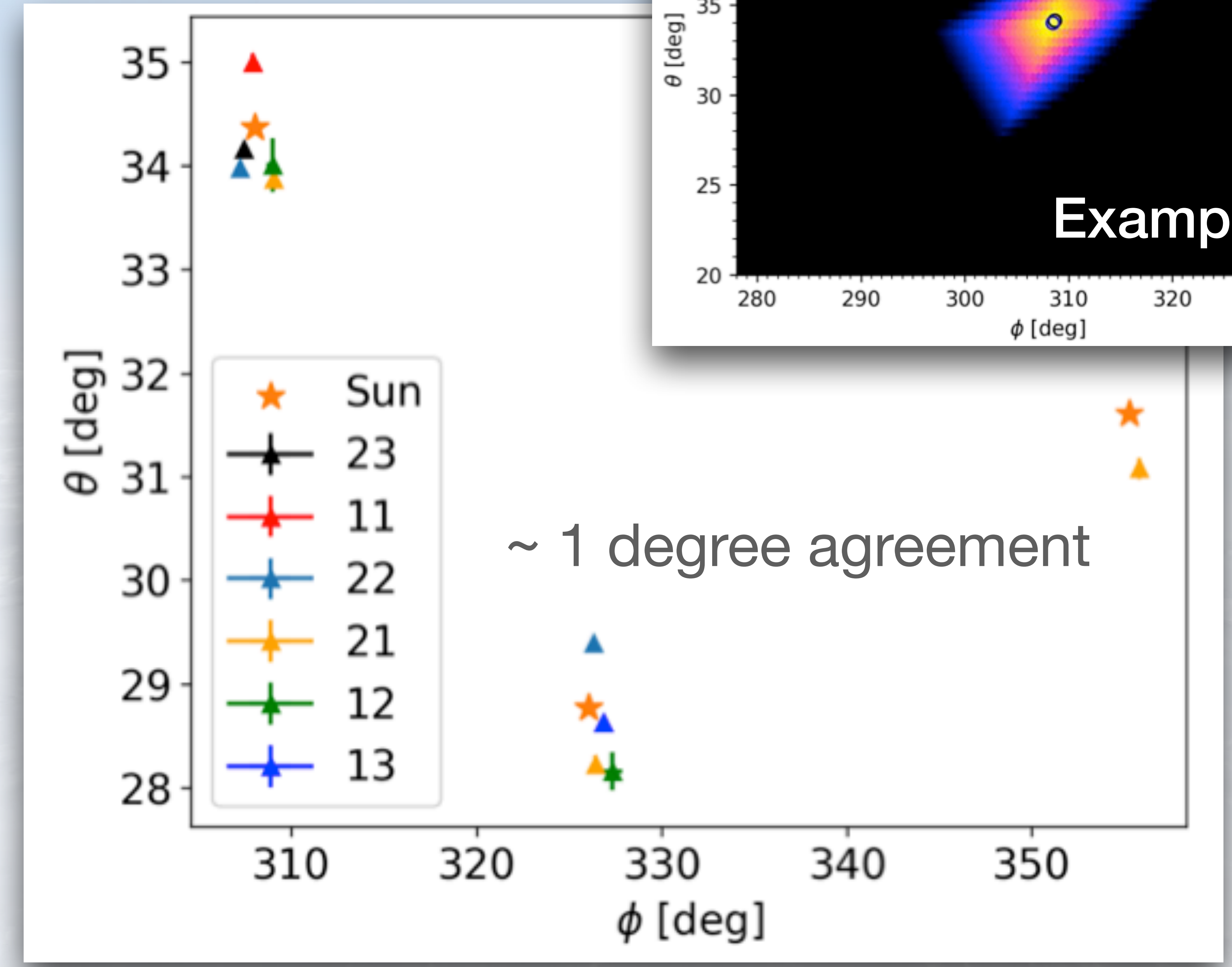
S. Hallmann for RNO-G, Pos (ICRC23) 1043

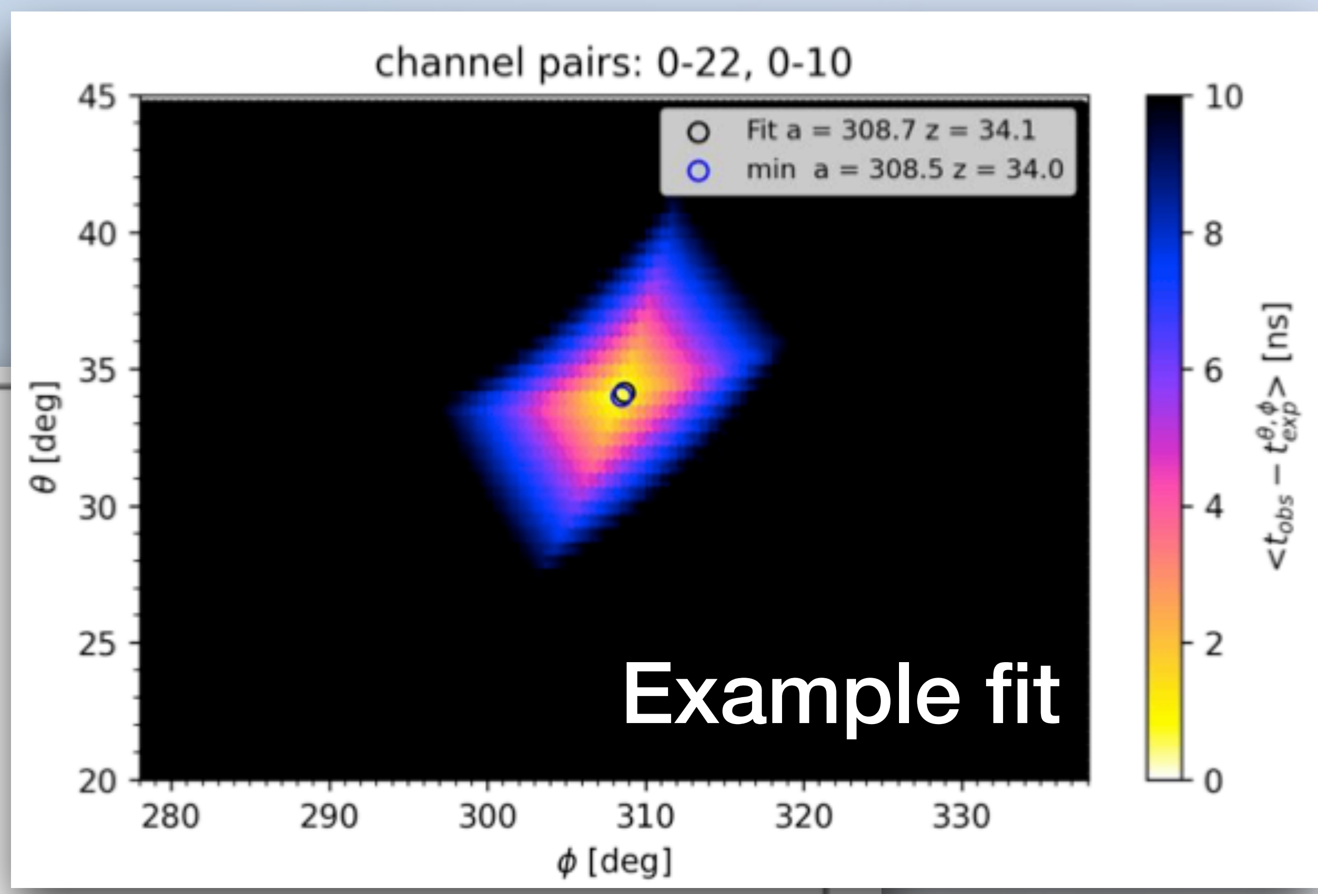
First look into the data: Solar flares

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



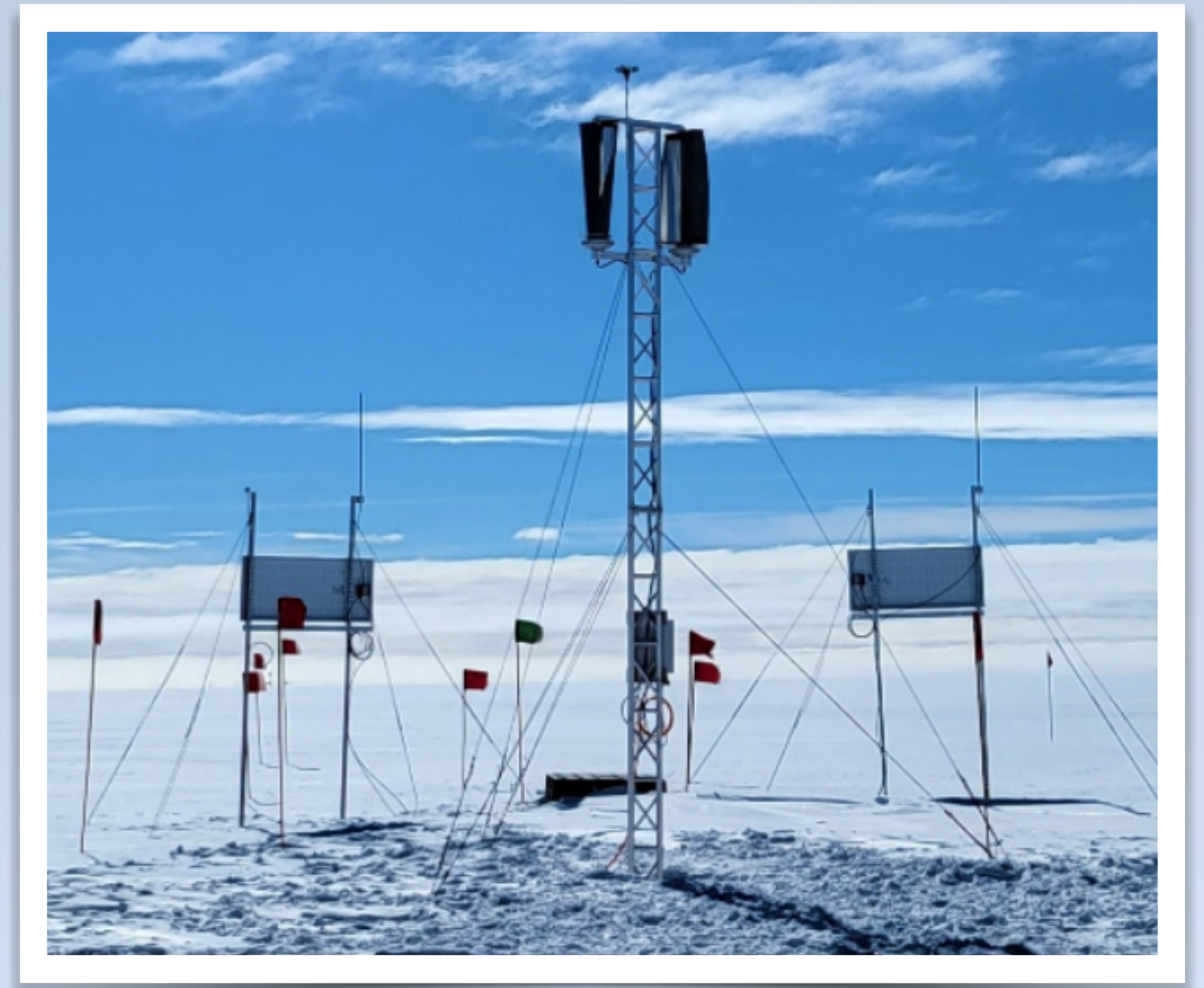


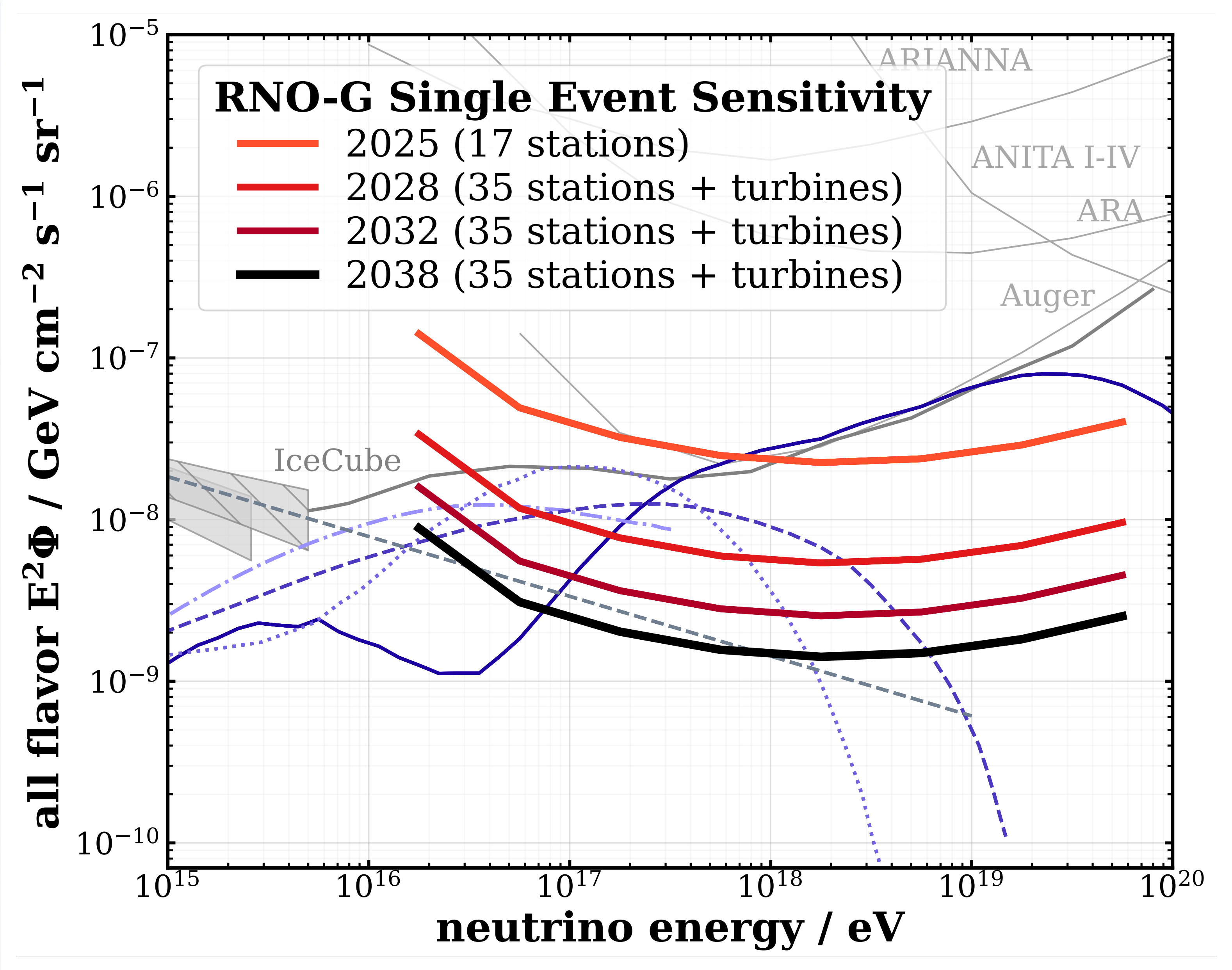




Summary & Outlook

- 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!
  - Developing a rapid follow up analysis
  - We have developed reconstruction algorithms
  - 10 contributions at ICRC23

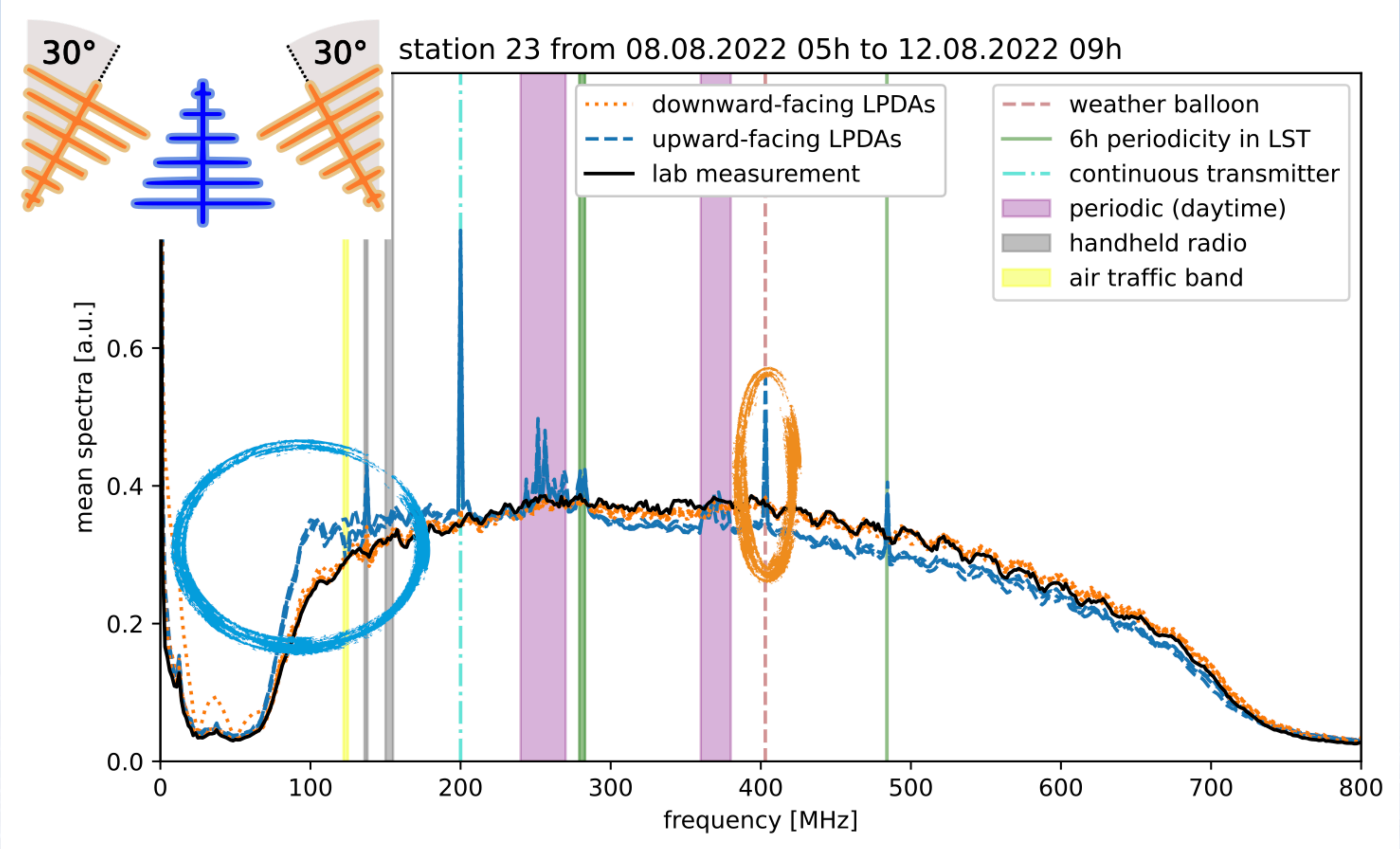




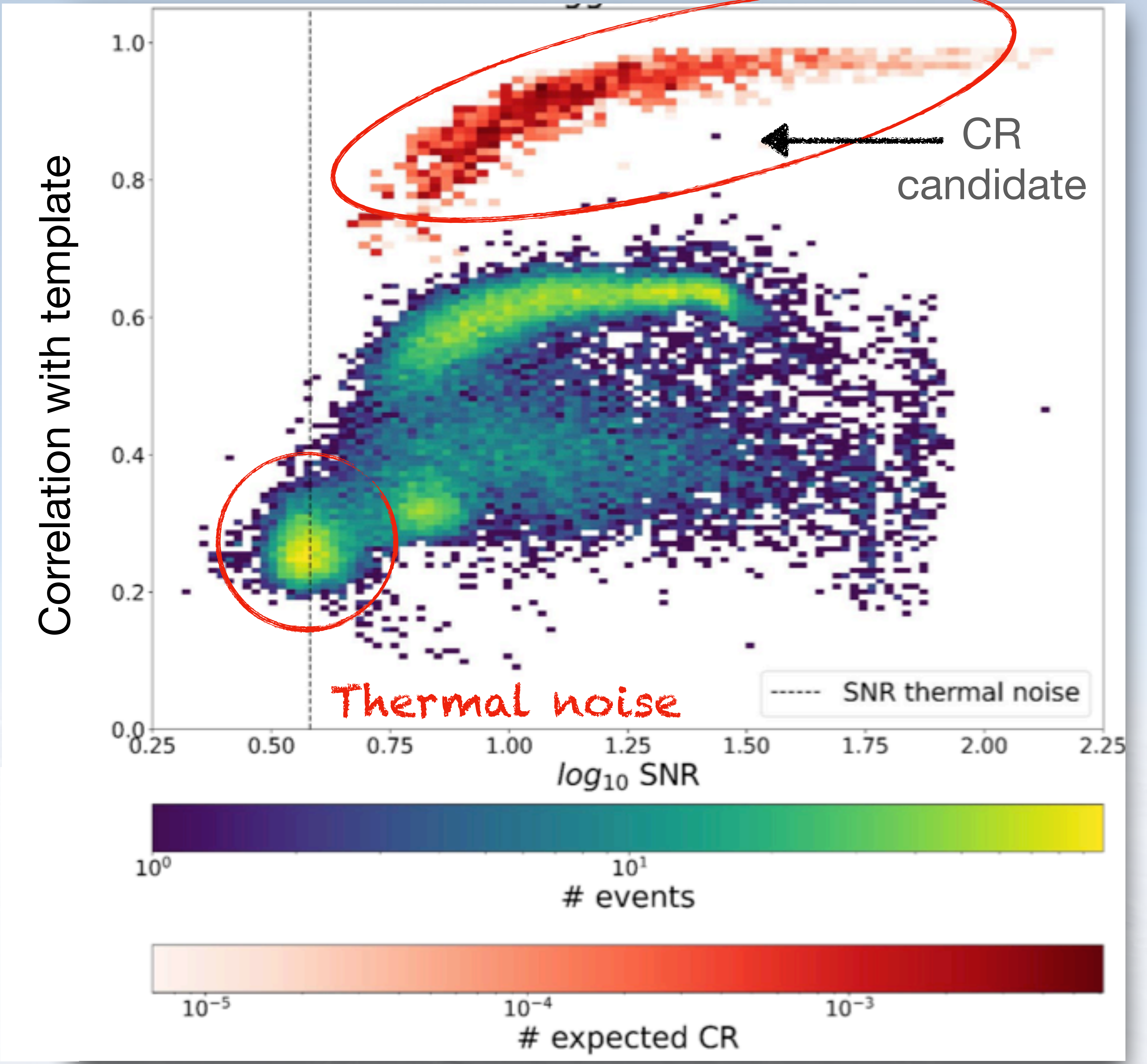
Whittier College
Summit Station
Uppsala University
DESY-Zeuthen
FAU-Erlangen
Radboud University
Université Libre de Bruxelles
Vrije Universiteit Brussels
Ghent University
University of Nebraska-Lincoln
University of Kansas
University of Wisconsin-Madison
University of Chicago
The Ohio State University
Pennsylvania State University
University of Alabama
University of Delaware
University of Maryland
RNO-G
Collaboration
February 2023
THE UNIVERSITY OF CHICAGO
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON
VUB
VRIJE UNIVERSITEIT BRUSSEL
ULB
UNIVERSITÉ LIBRE DE BRUXELLES
DESY.
FAU
Friedrich-Alexander-Universität Erlangen-Nürnberg
KU
THE UNIVERSITY OF KANSAS
PennState
THE OHIO STATE UNIVERSITY
THE UNIVERSITY OF ALABAMA
UNIVERSITY OF MARYLAND
UNIVERSITY OF DELAWARE
UPPSALA UNIVERSITET
Radboud University
WHITTIER COLLEGE
1887
GHENT UNIVERSITY
UNIVERSITY OF Nebraska Lincoln

Backup

First look into the data



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

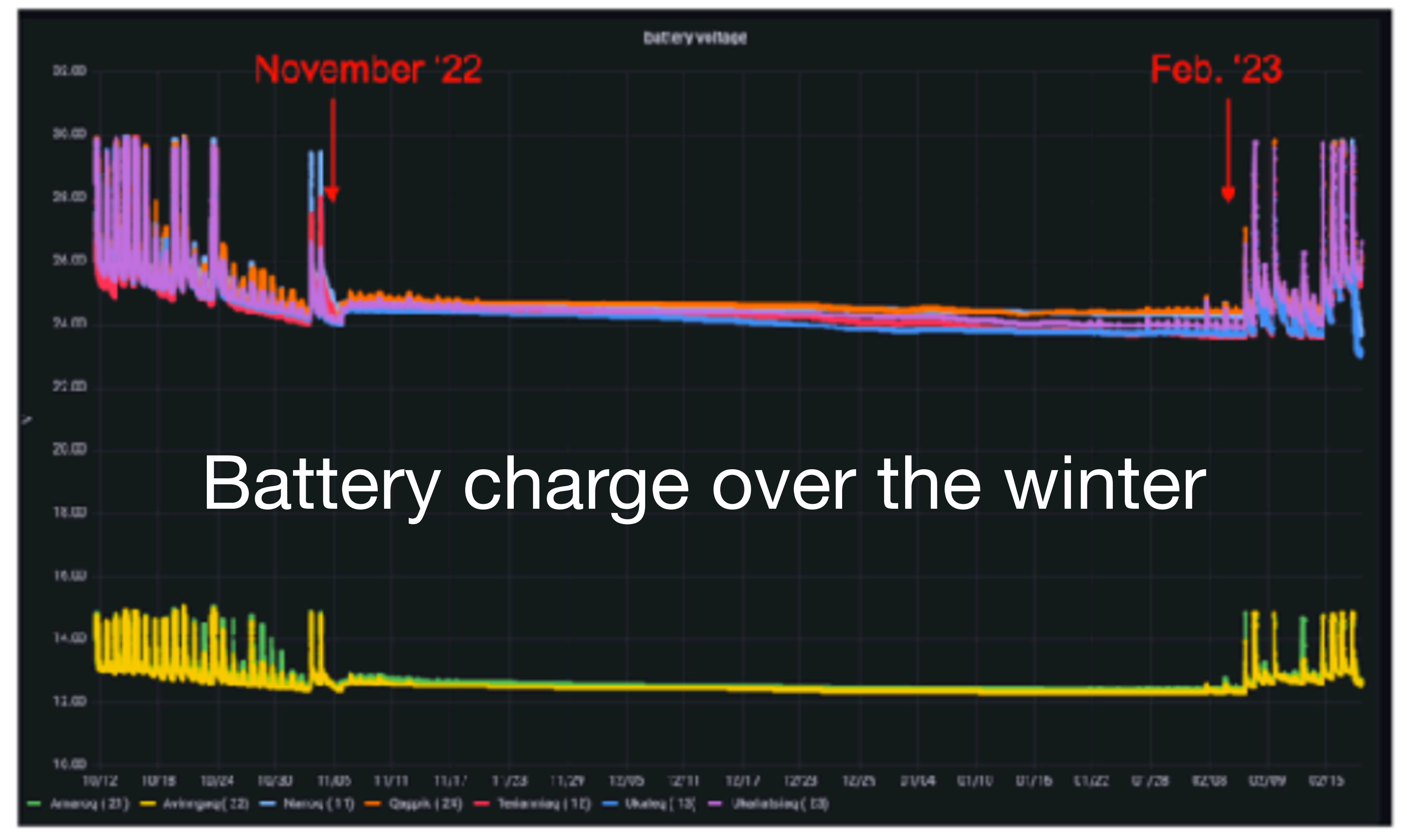


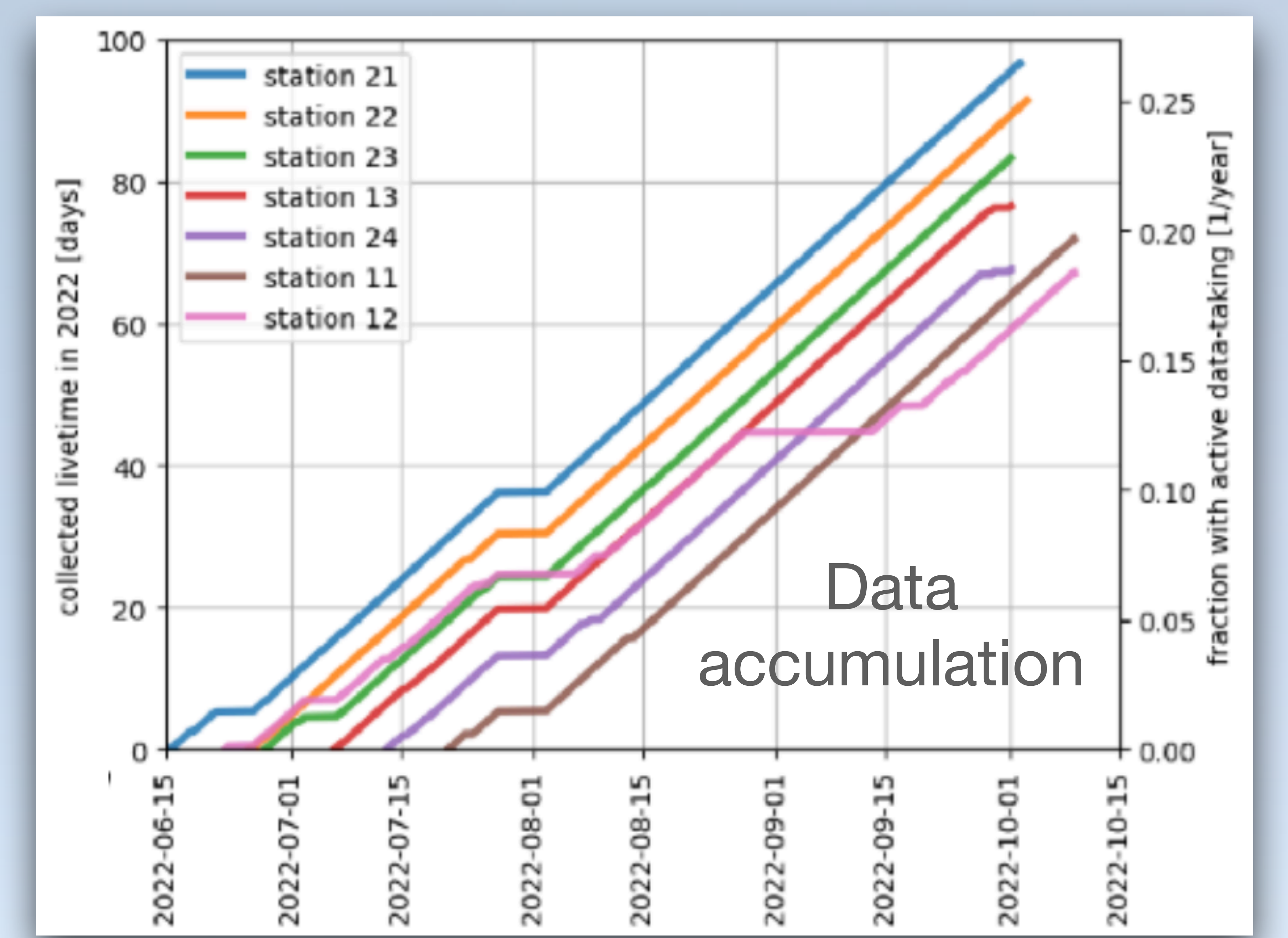
S. Hallmann for RNO-G, Pos (ICRC23) 1043

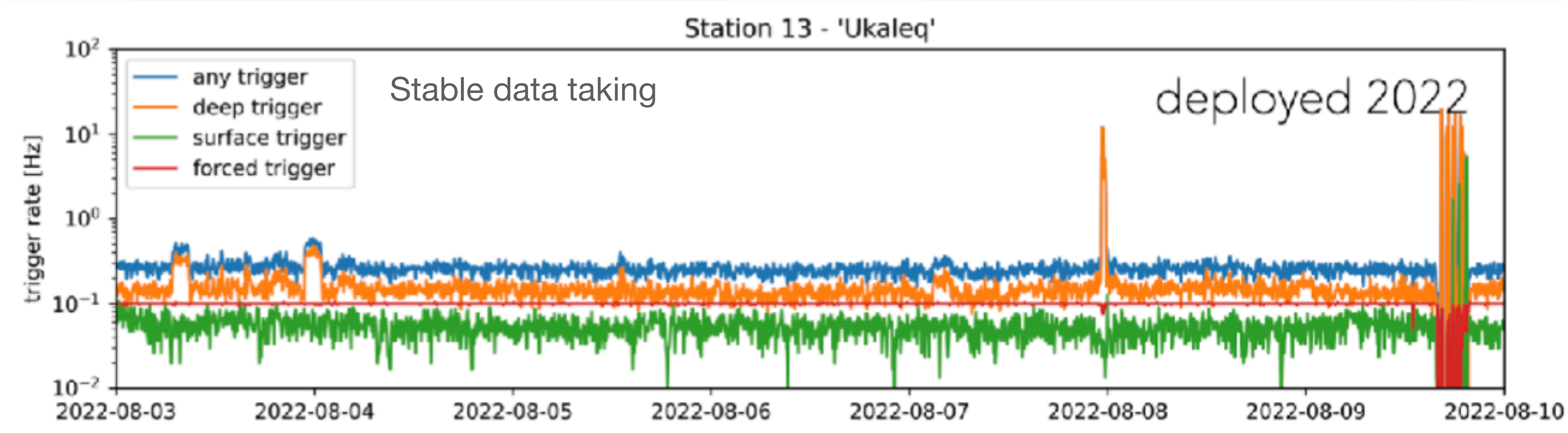
J. Henrichs and A. Nelles for RNO-G, Pos (ICRC23) 259

Hardware performance

Aka surviving the winter!

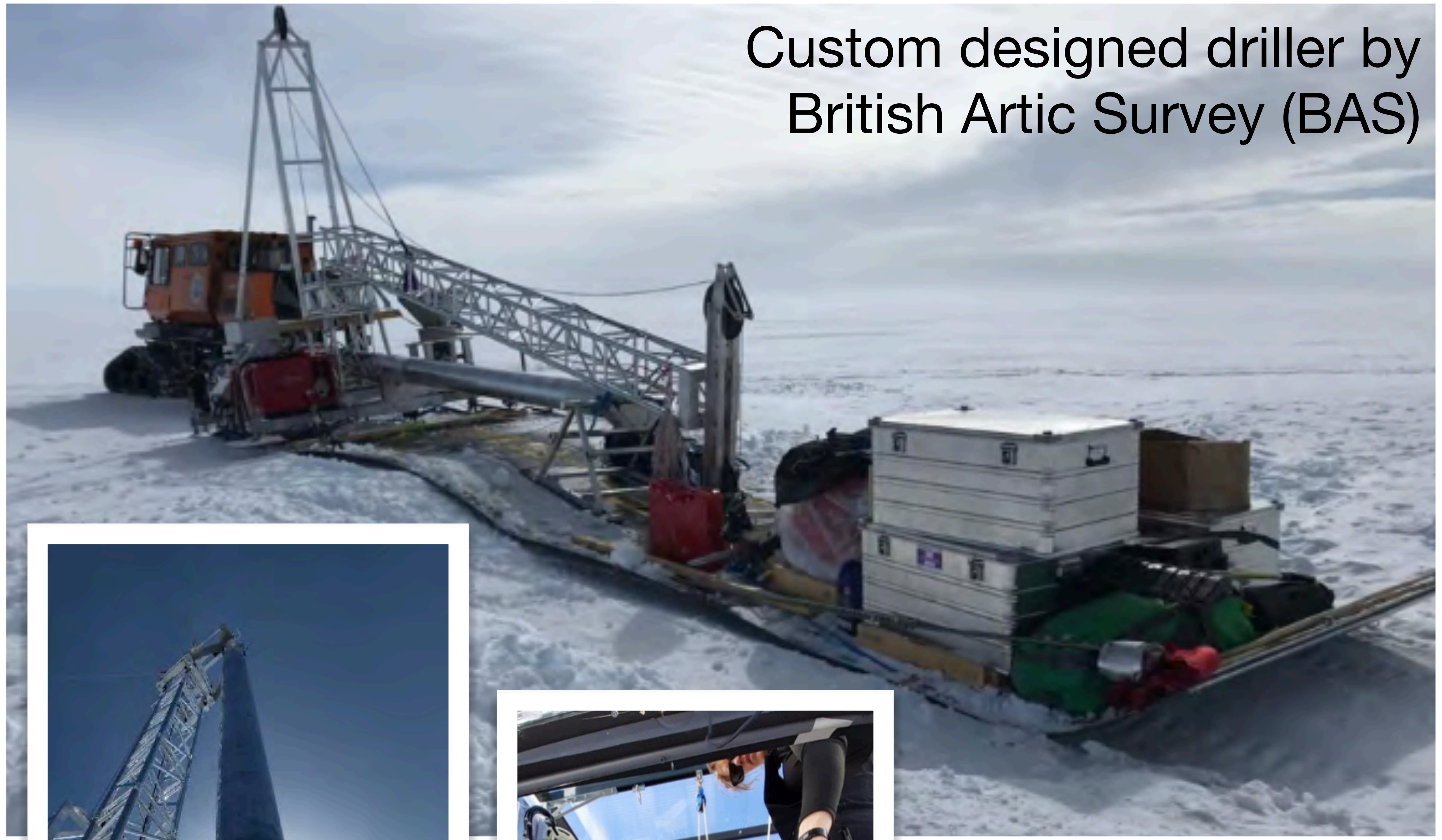




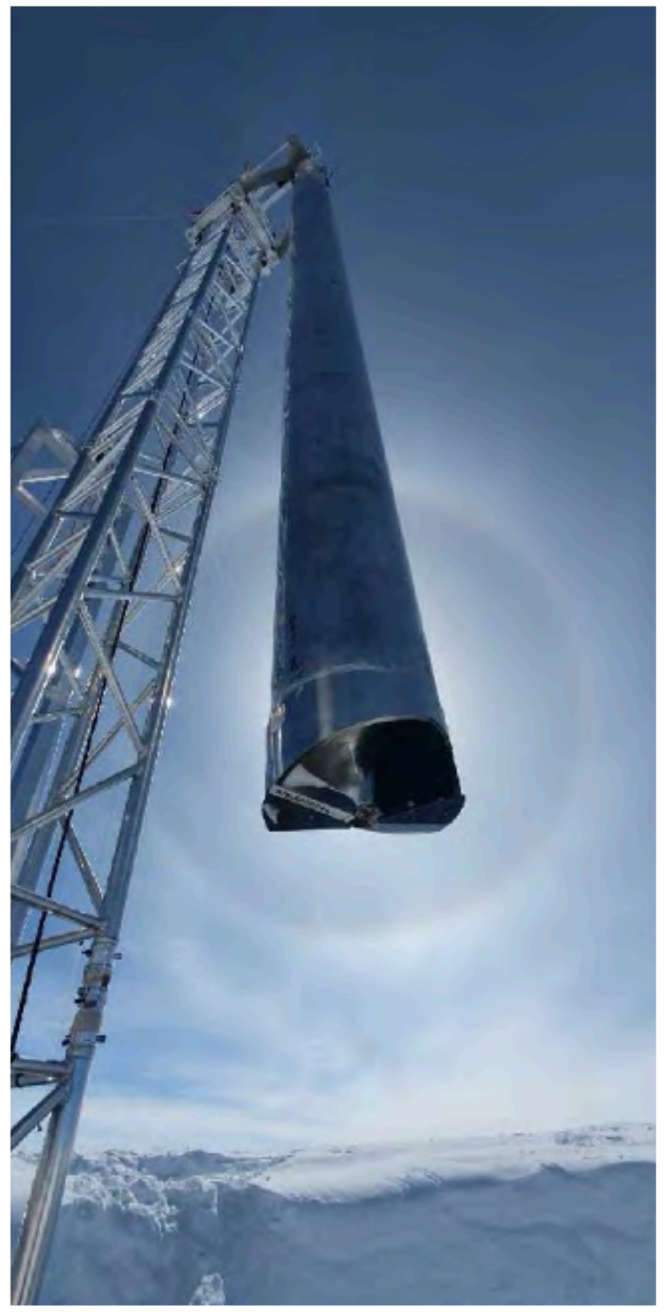


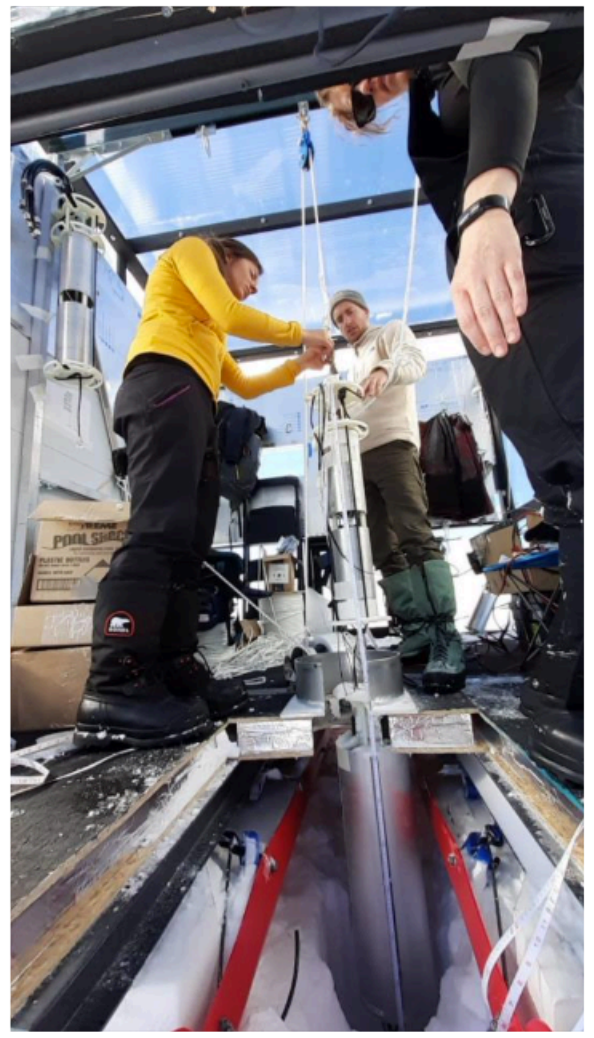
Deployment

Drilling 100m deep, 28 cm diameter hole



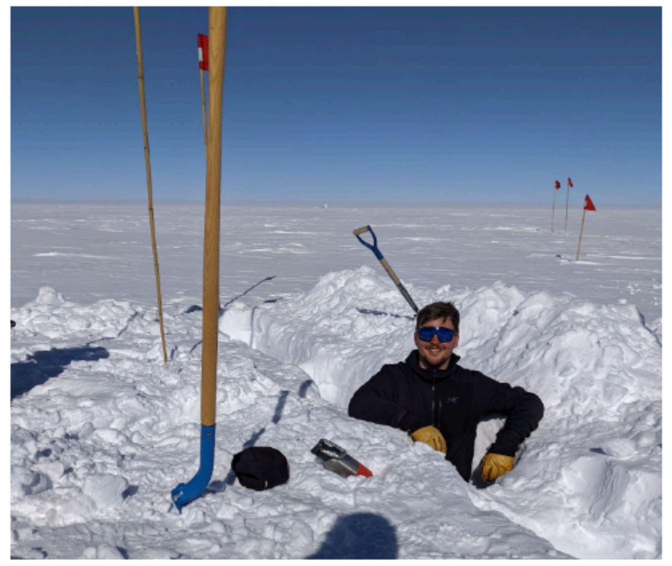
Custom designed driller by British Artic Survey (BAS)



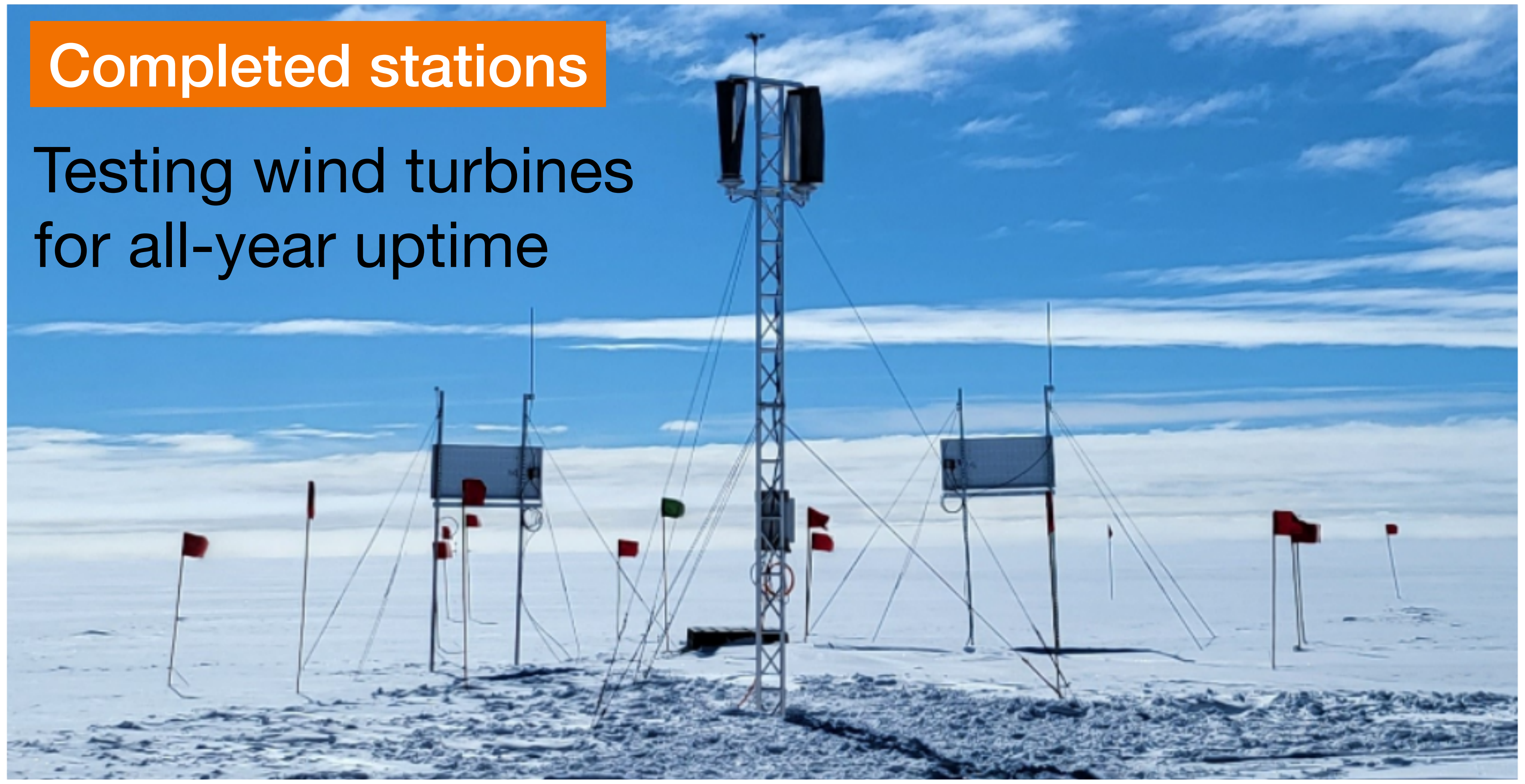


Shallow antennas are deployed in trenches …

… which we dig!



Completed stations



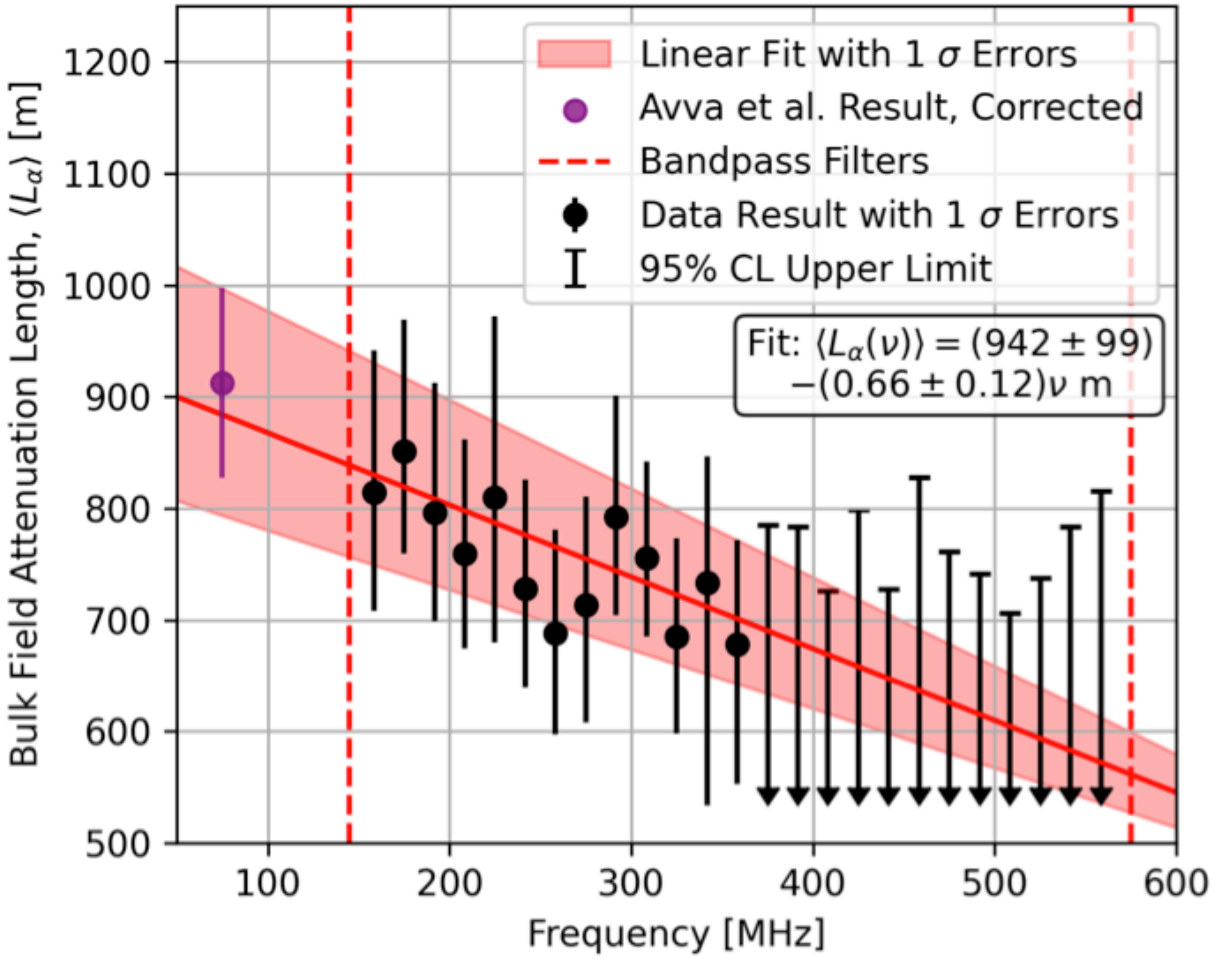
Testing wind turbines for all-year uptime

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)

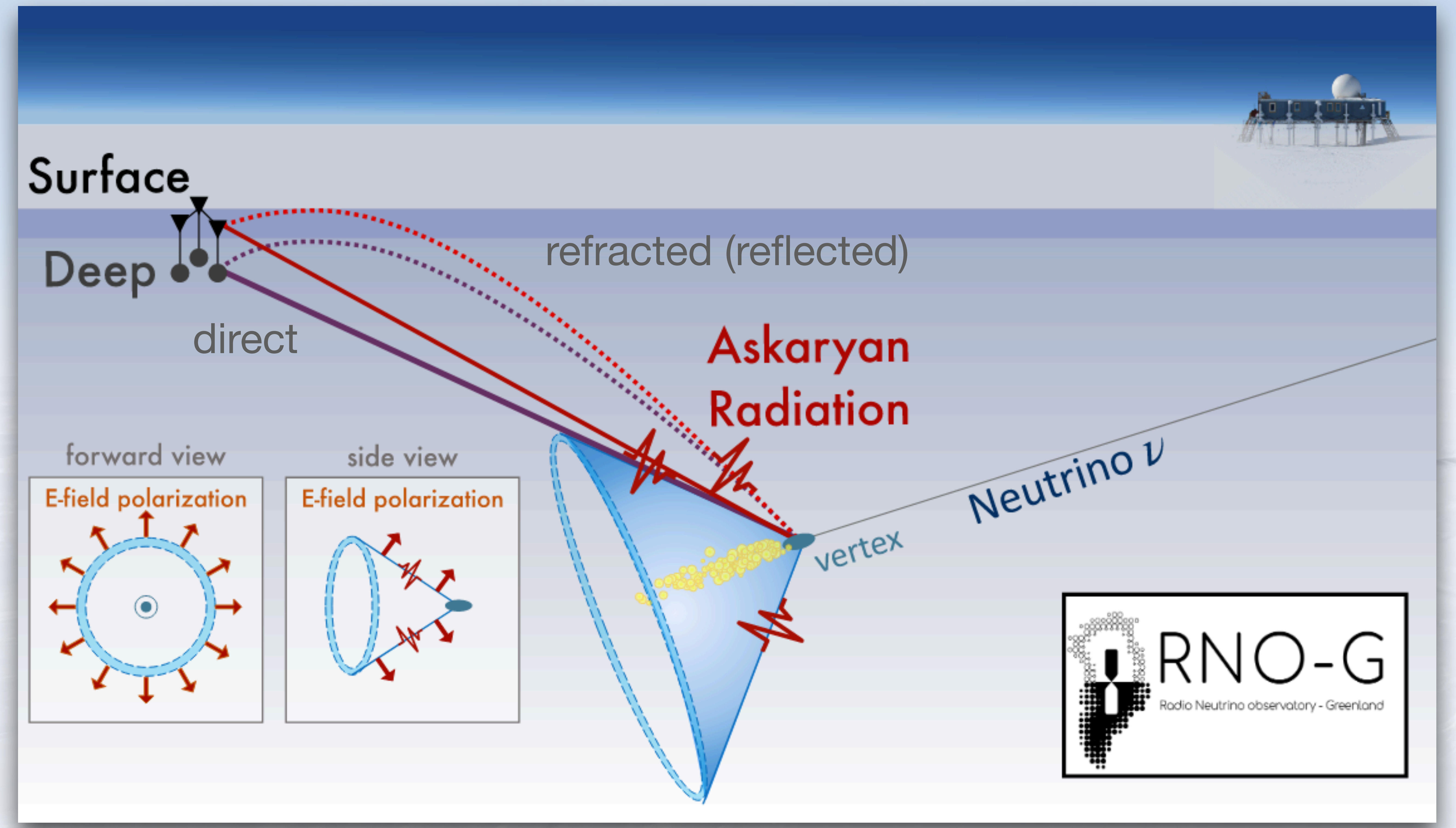
[RNO-G, Journal of Glaciology](#)



Radio detection of neutrinos

How?

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



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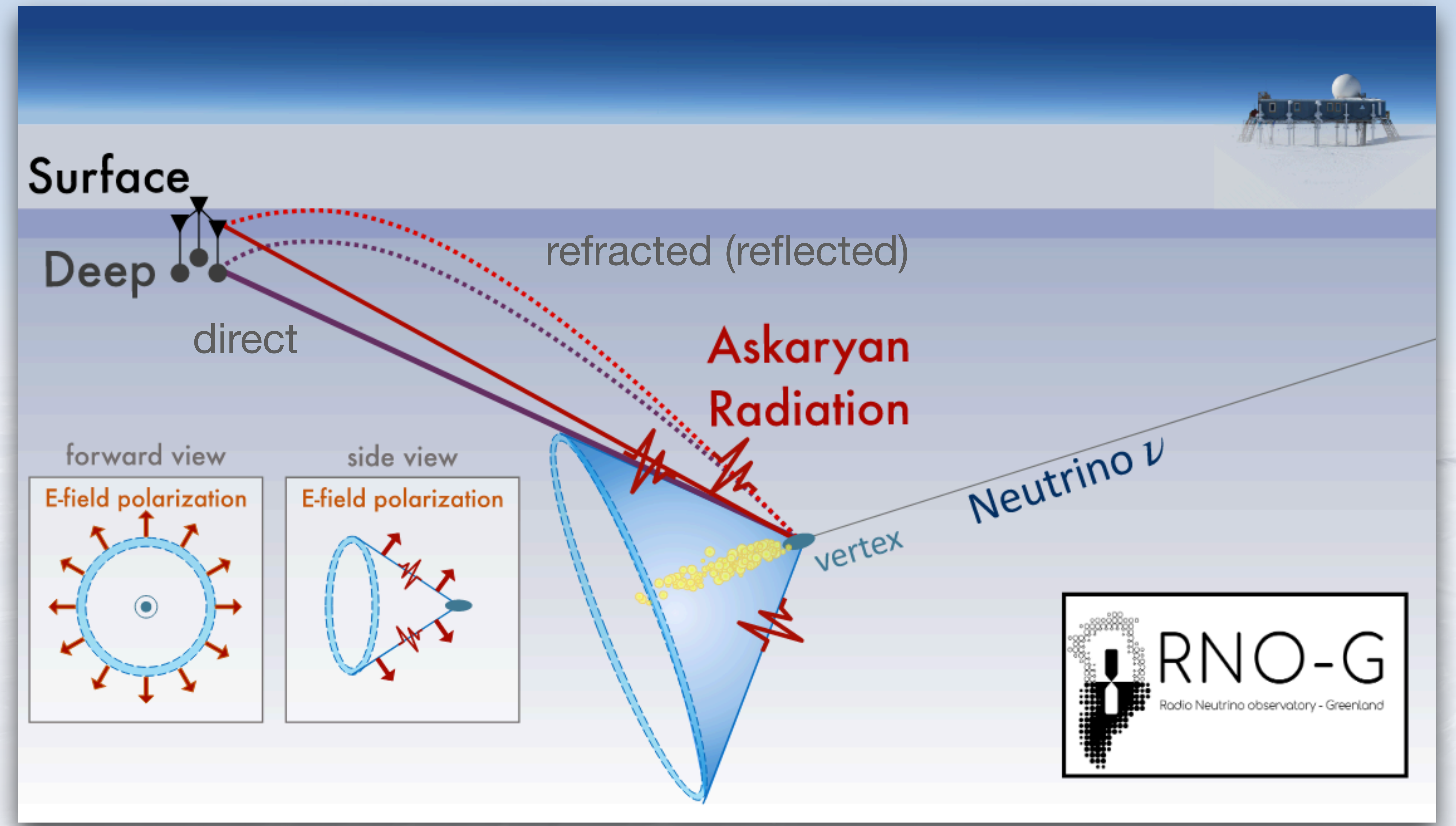
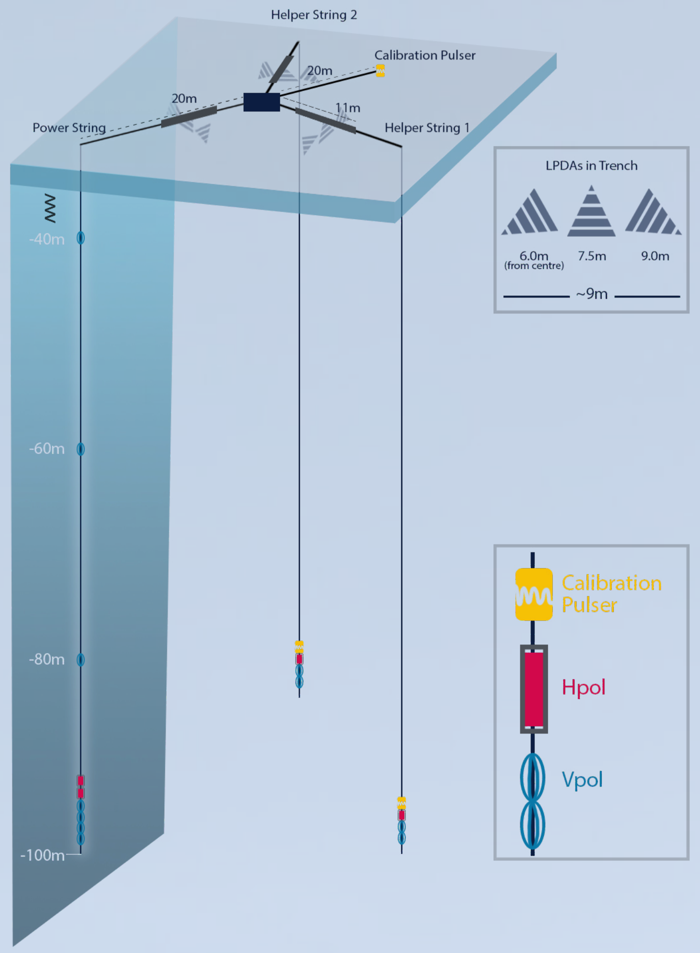
- Polarisation of electric field allows localisation on cone
- Several possible ray trajectories



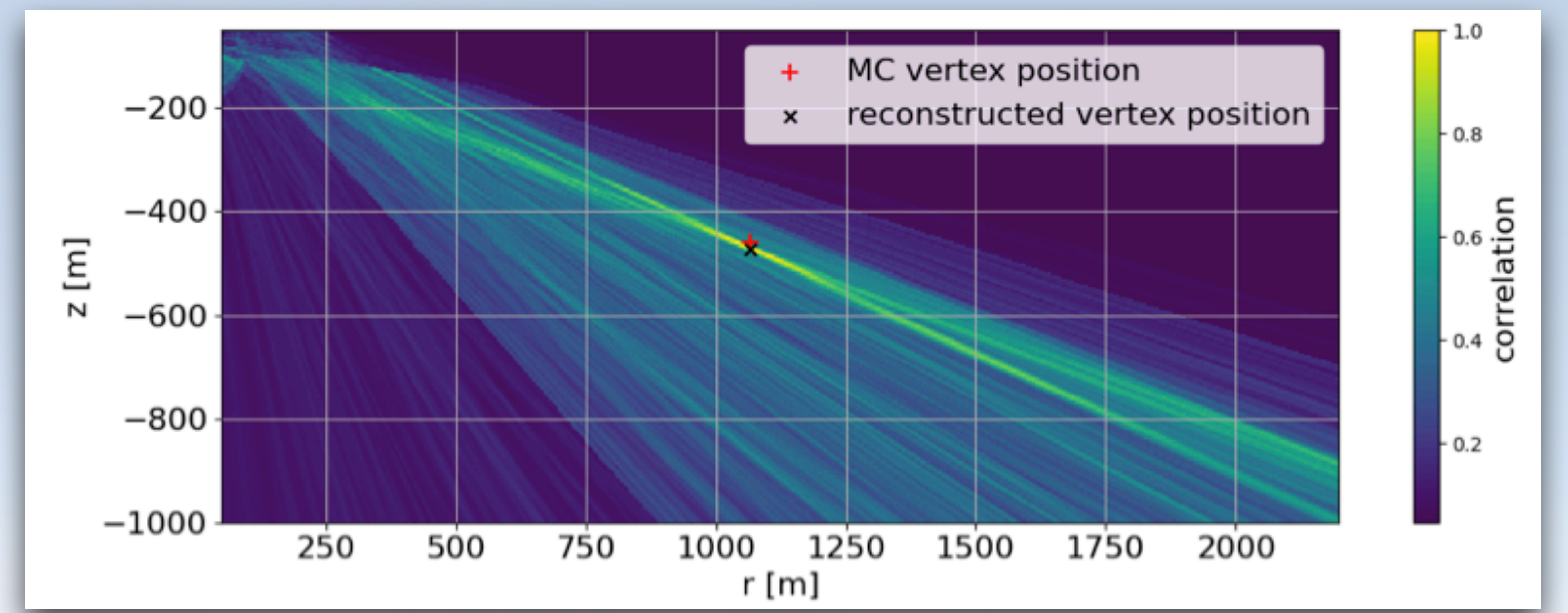
The radio emission …

- 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



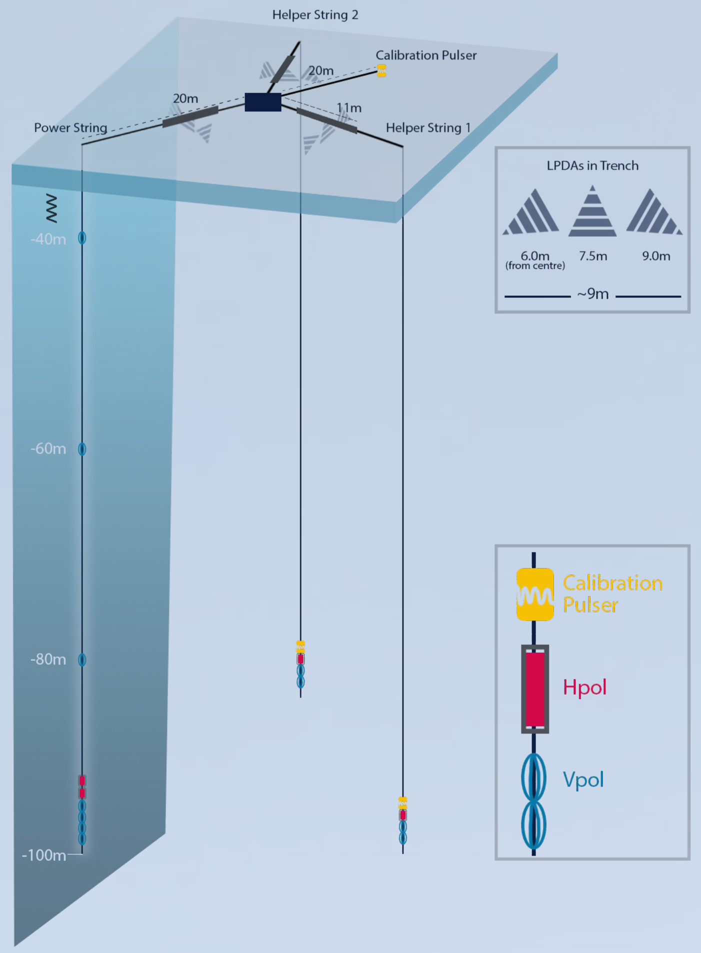
Using cross-correlation to determine signal (time) in each antenna.

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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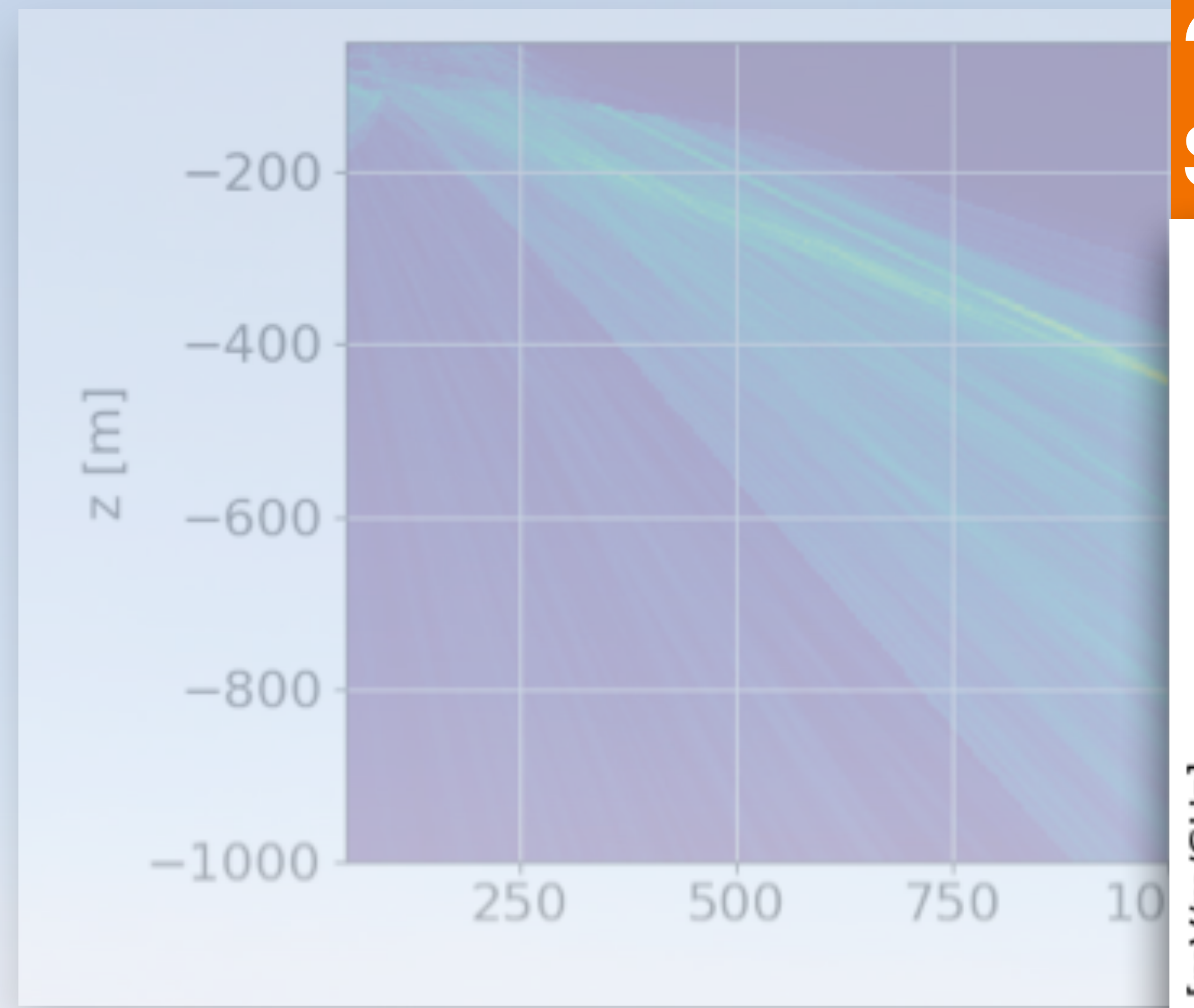

Using cross-correlation to de

Using forward folding techni
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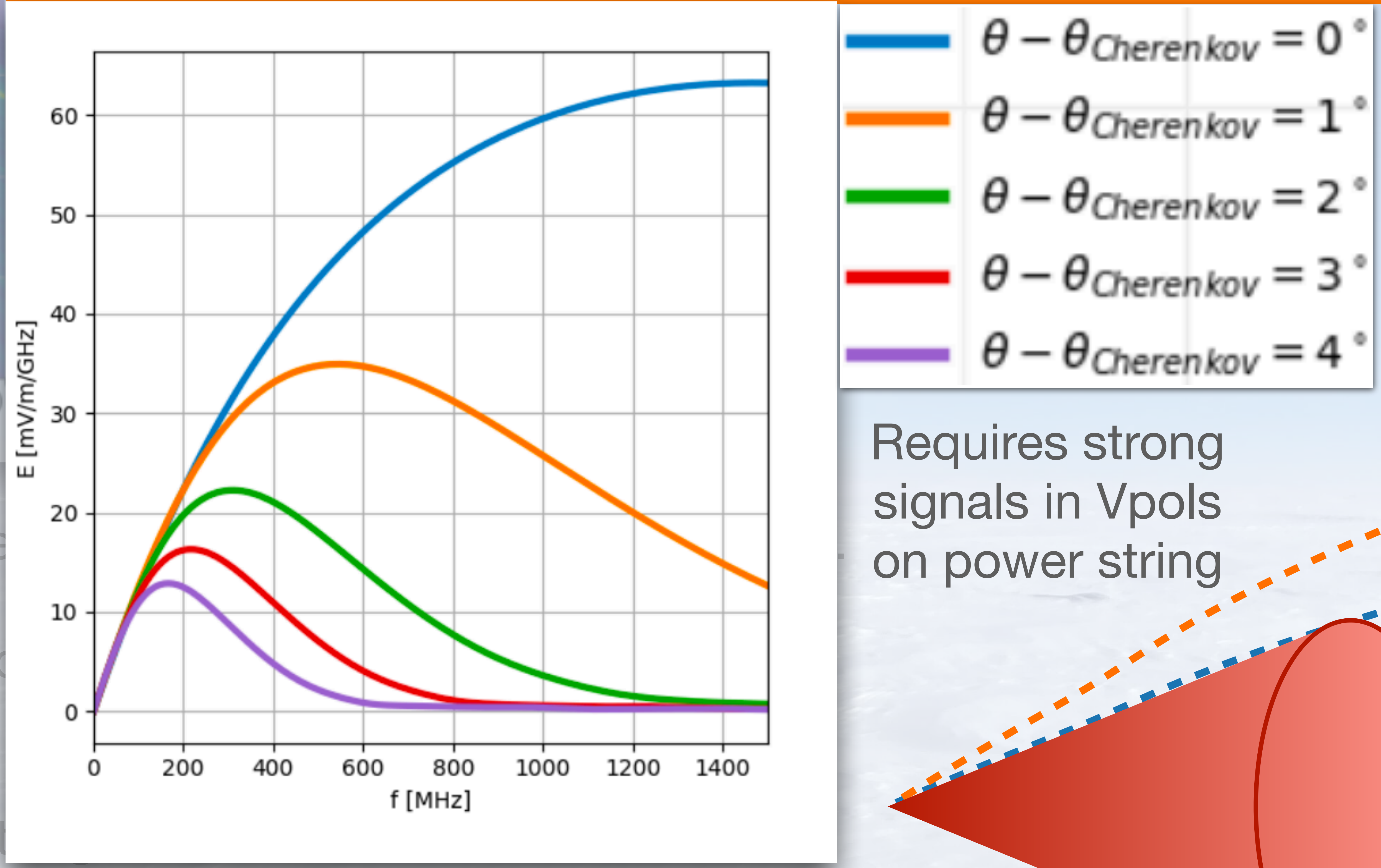
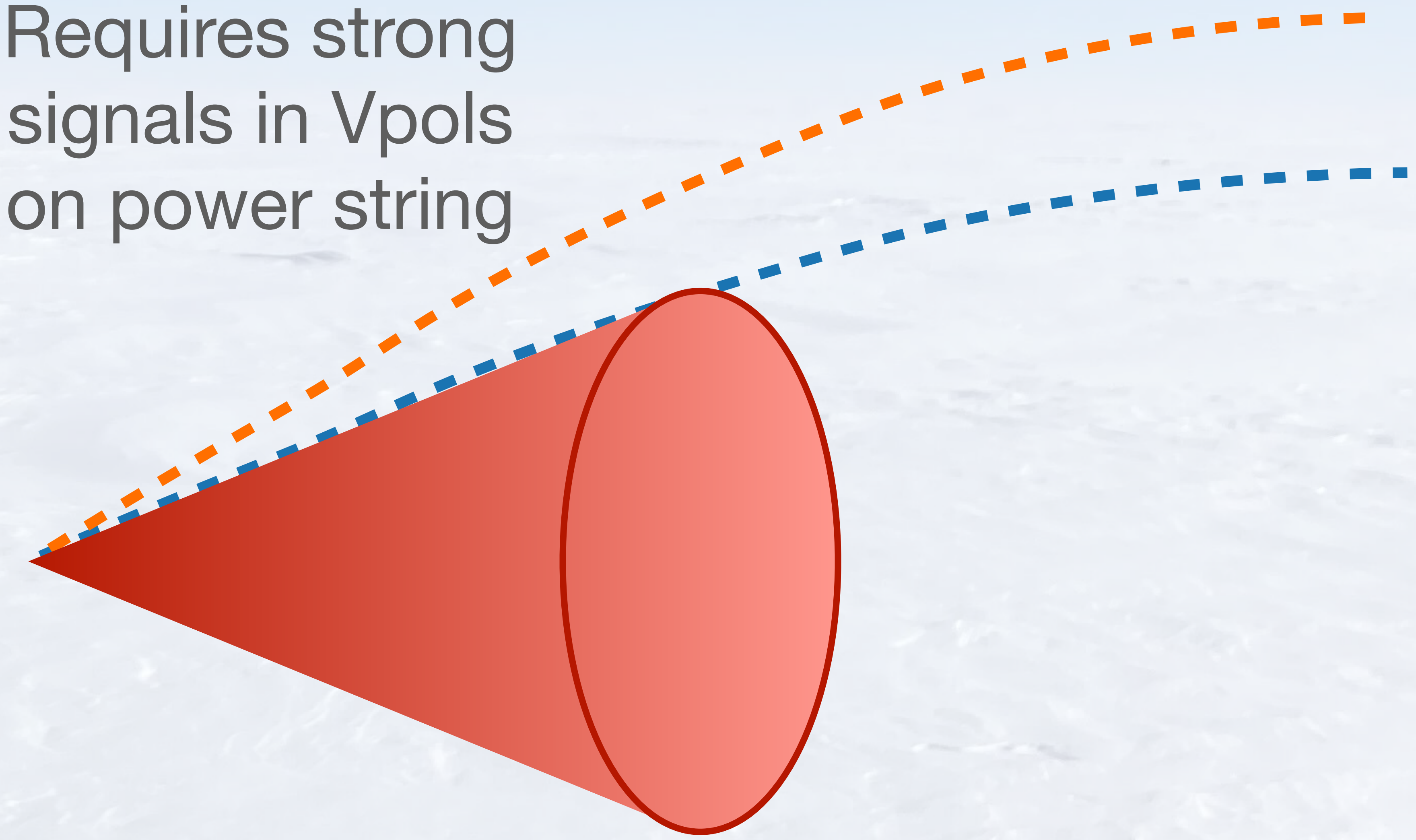
Requires signals in several st

2. Reconstruct viewing angle from frequency spectrum

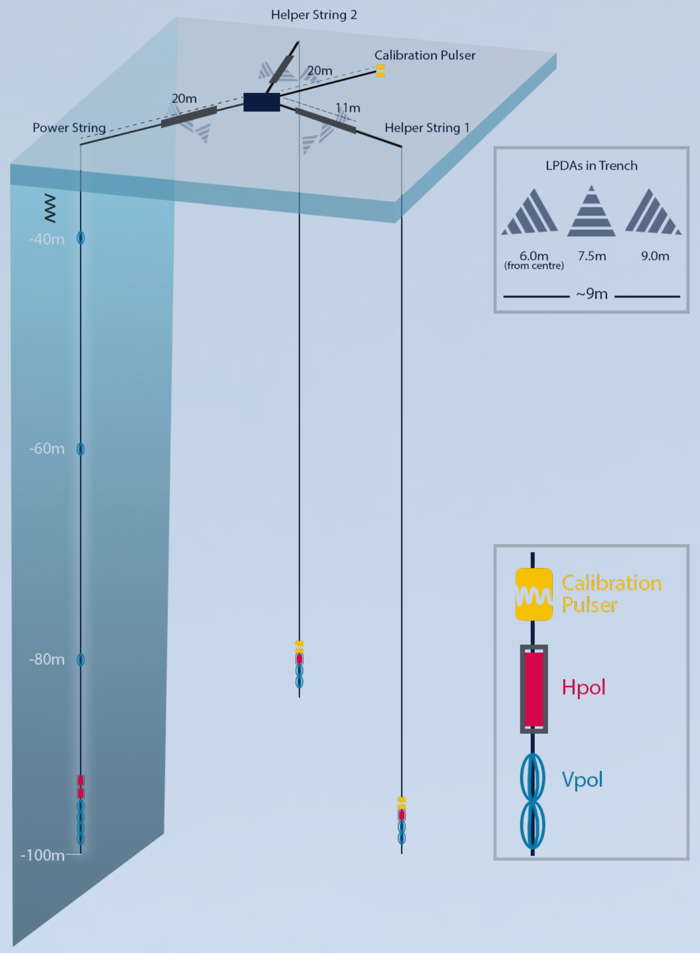


Requires strong signals in Vpols on power string



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

Arrival direction reconstruction



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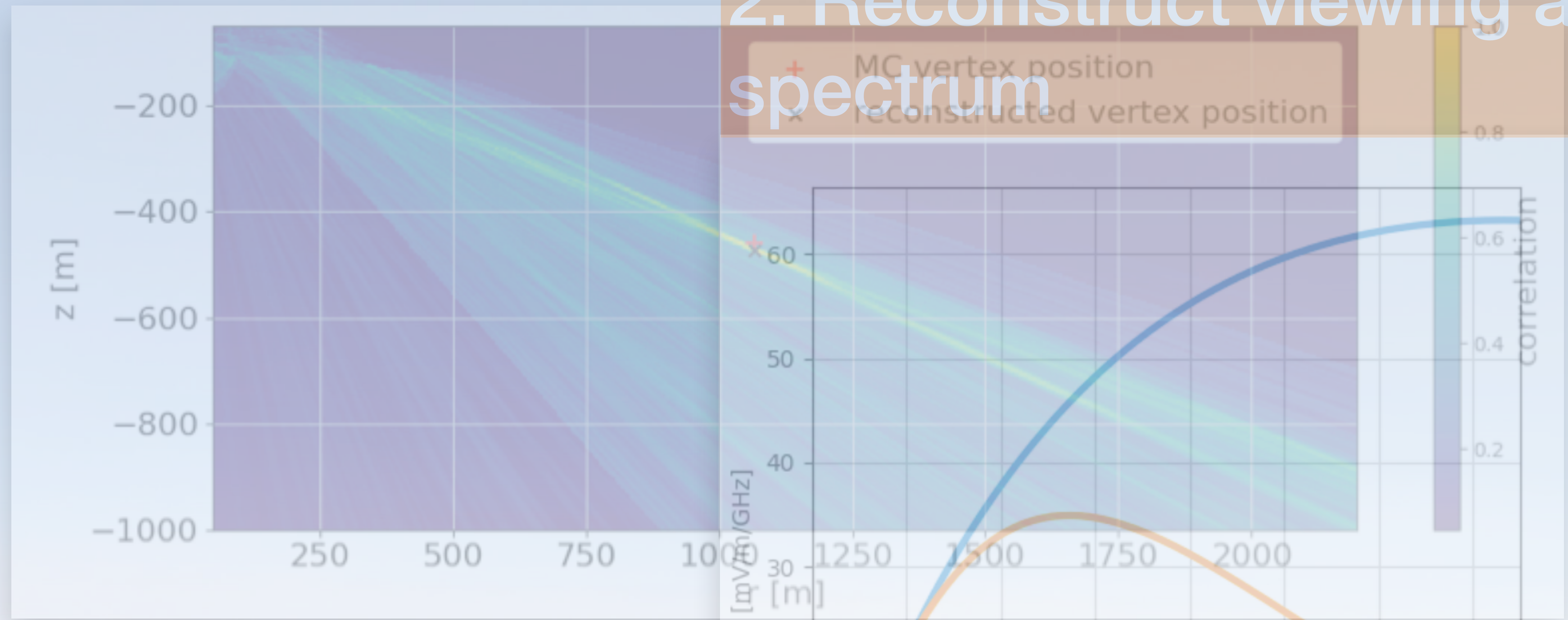

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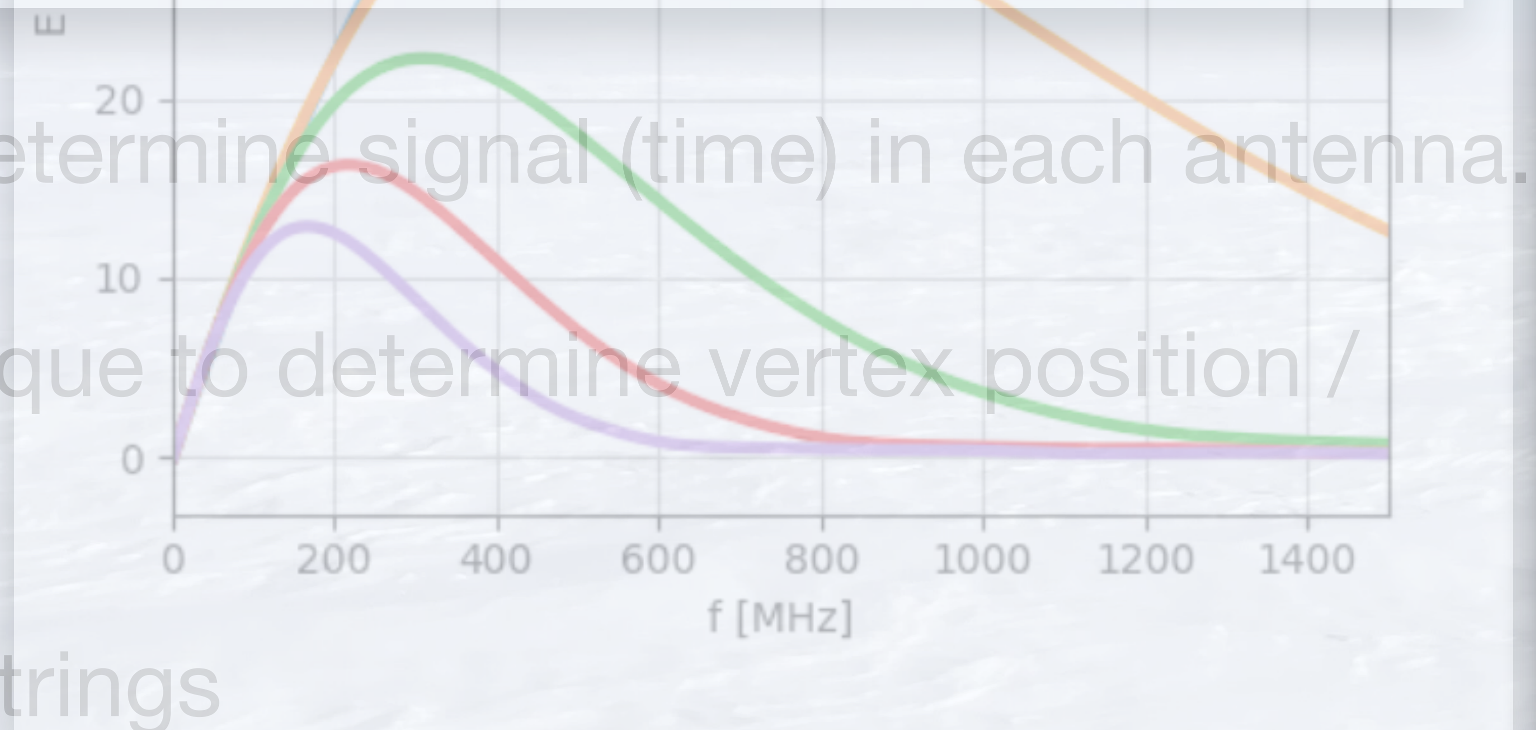
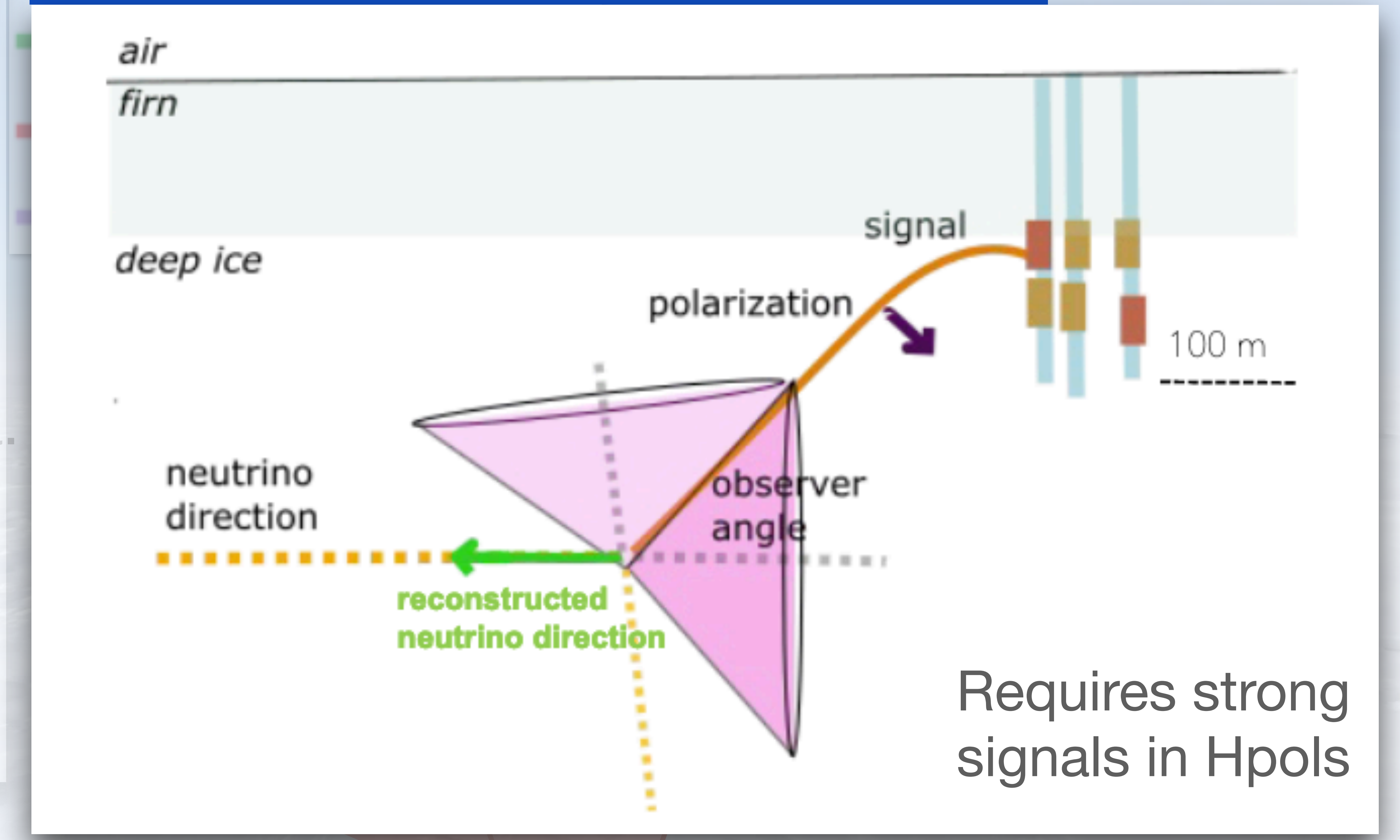


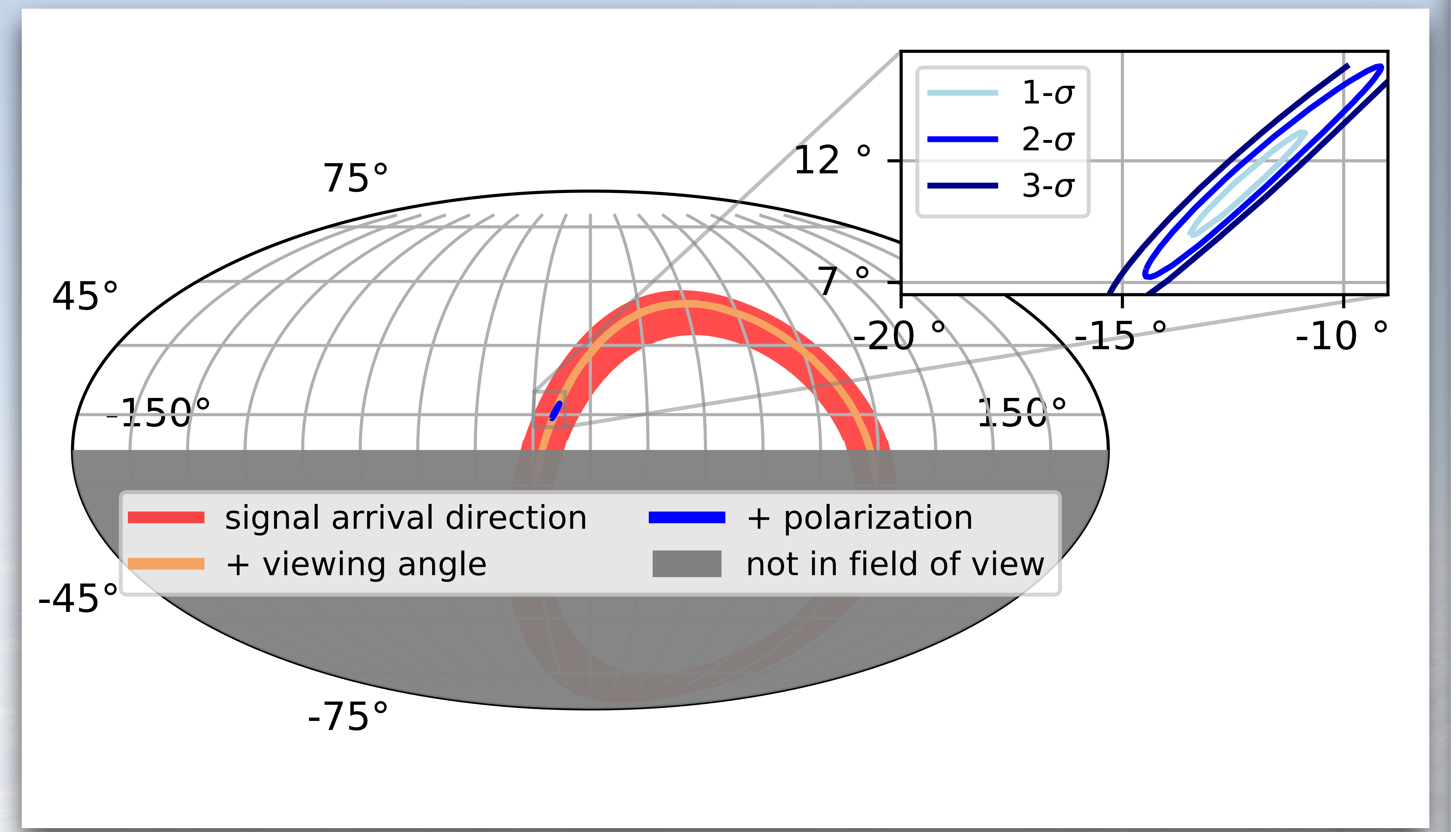
3. Reconstruct polarisation

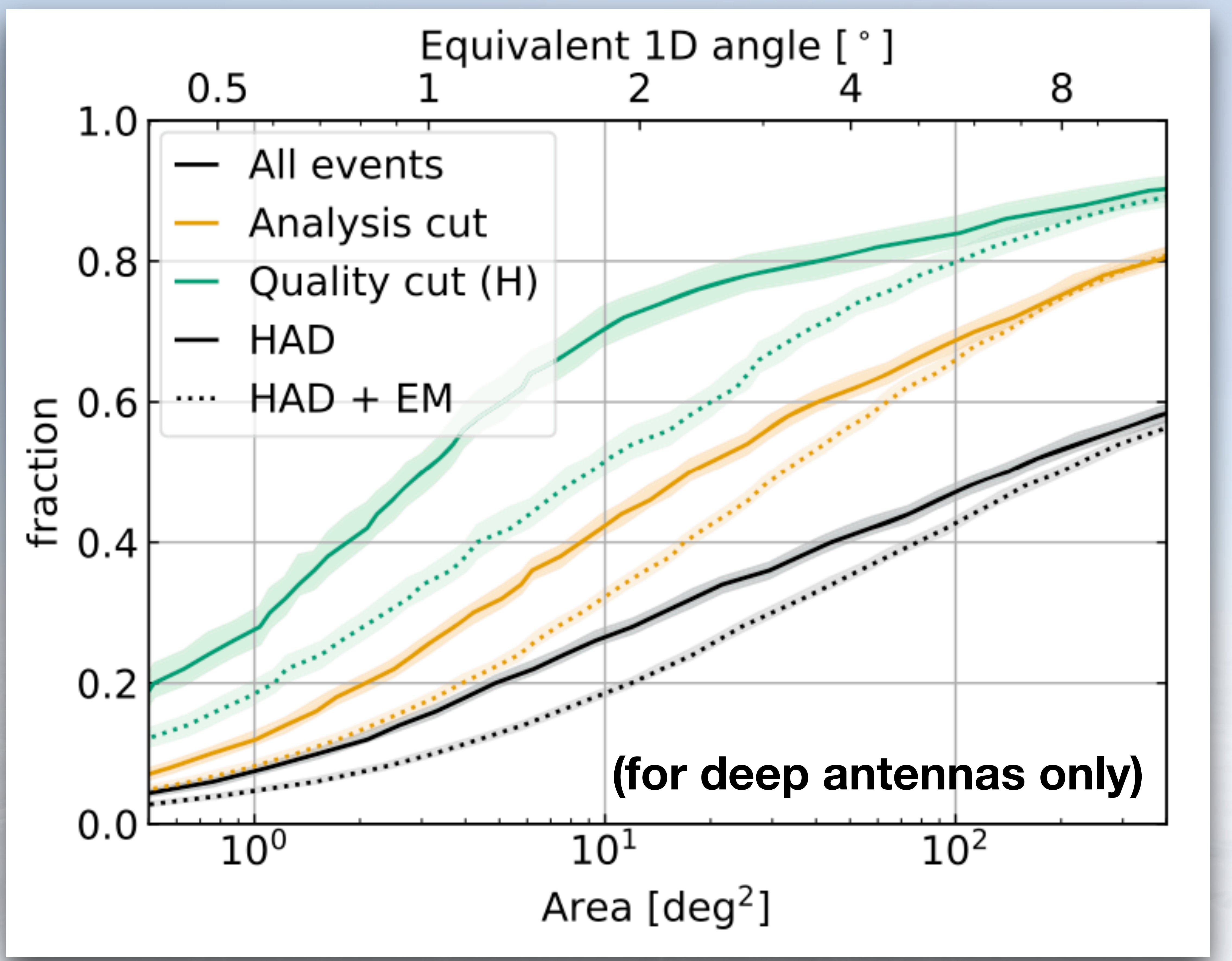


Requires strong signals in Hpols

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

Arrival direction reconstruction





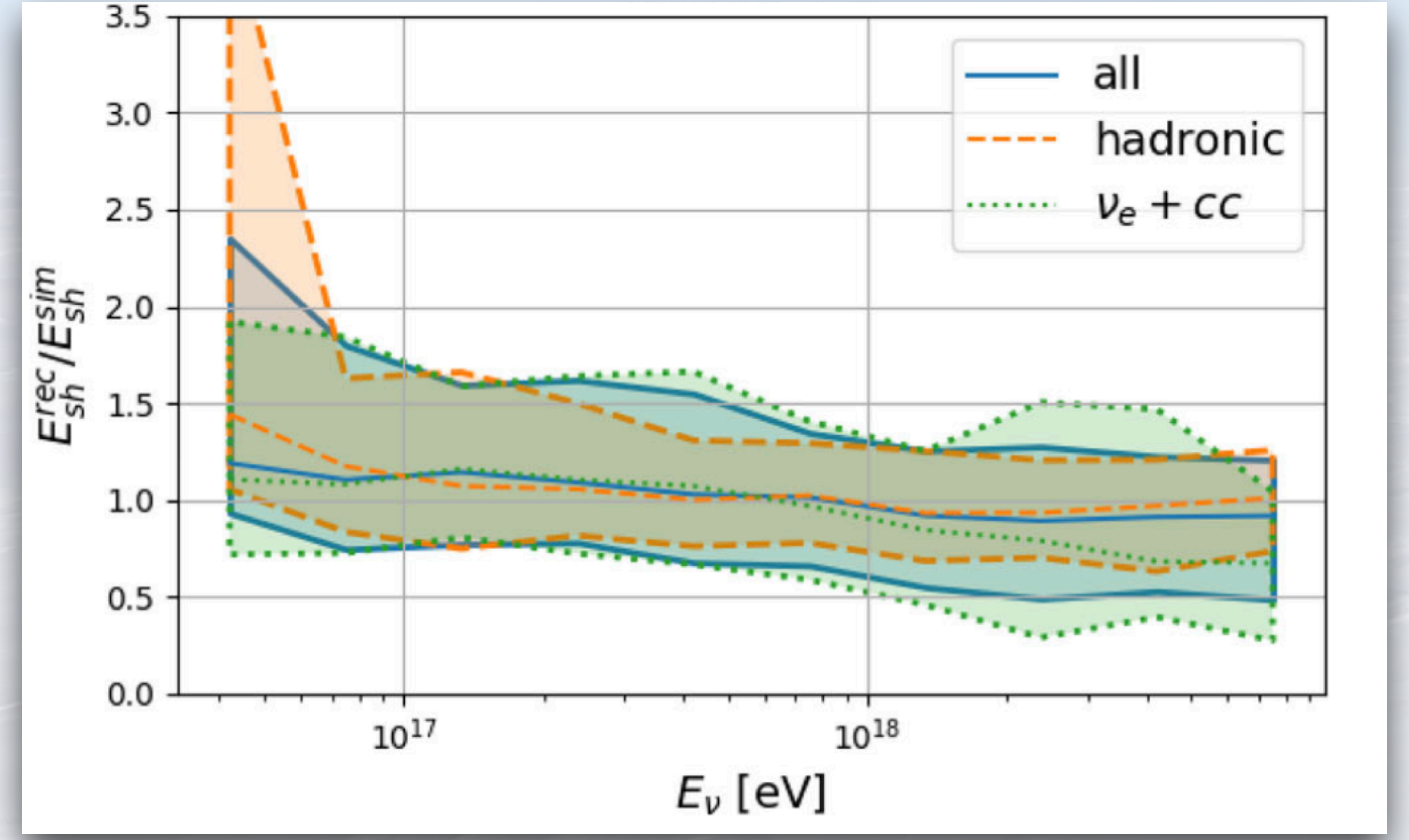
S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045   I. Plaisier et.al., EPJC 83 (2023) 5

Energy reconstruction

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

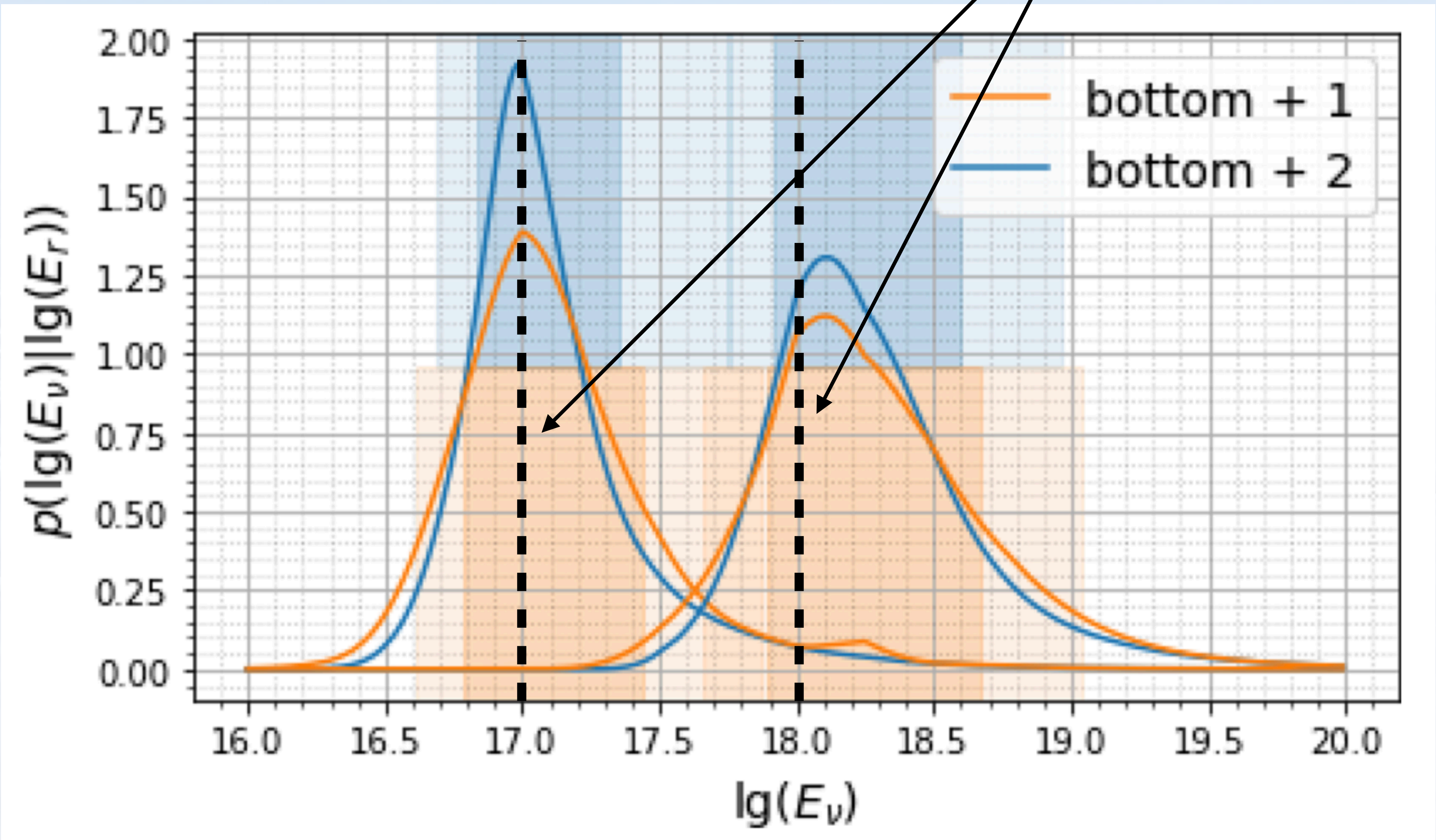
$$\underbrace{\vec{\mathcal{E}}(f)}_{\text{Observed Field}} \propto \underbrace{(1-y)E_\nu}_{\text{Shower energy}} \exp\left[-\frac{1}{2}\underbrace{\left(\frac{\theta-\theta_c}{\sigma(E_{sh},f)}\right)^2}_{\text{Viewing angle}}\right] \underbrace{\frac{1}{R}\exp\left(\frac{-R}{L(f)}\right)}_{\text{Vertex Distance}} \underbrace{\vec{\ell}\times(\vec{v}_\nu \times \vec{\ell})}_{\text{Polarization}}$$

Shower energy



Neutrino energy

True energy

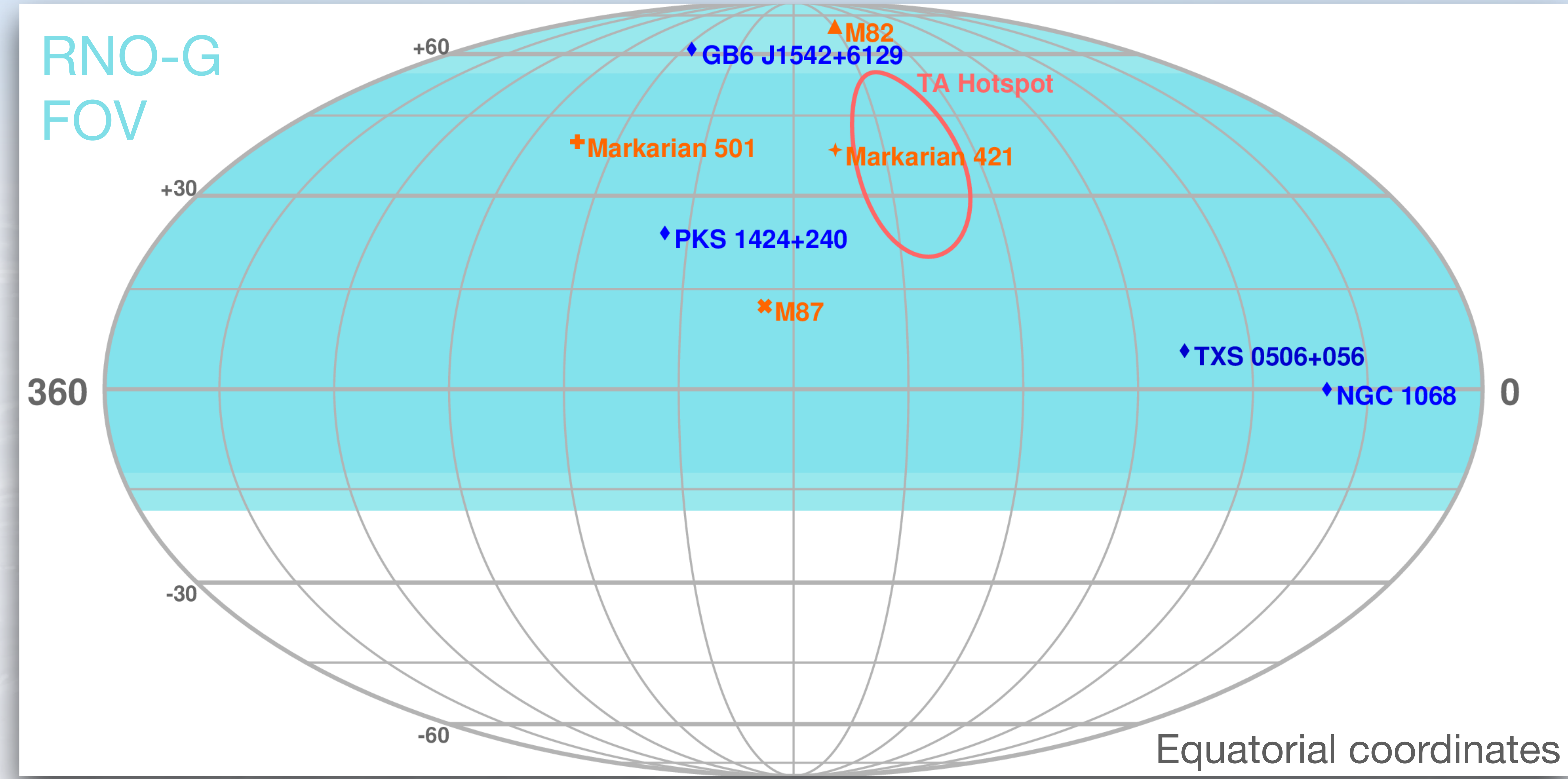


Radio detection of neutrinos

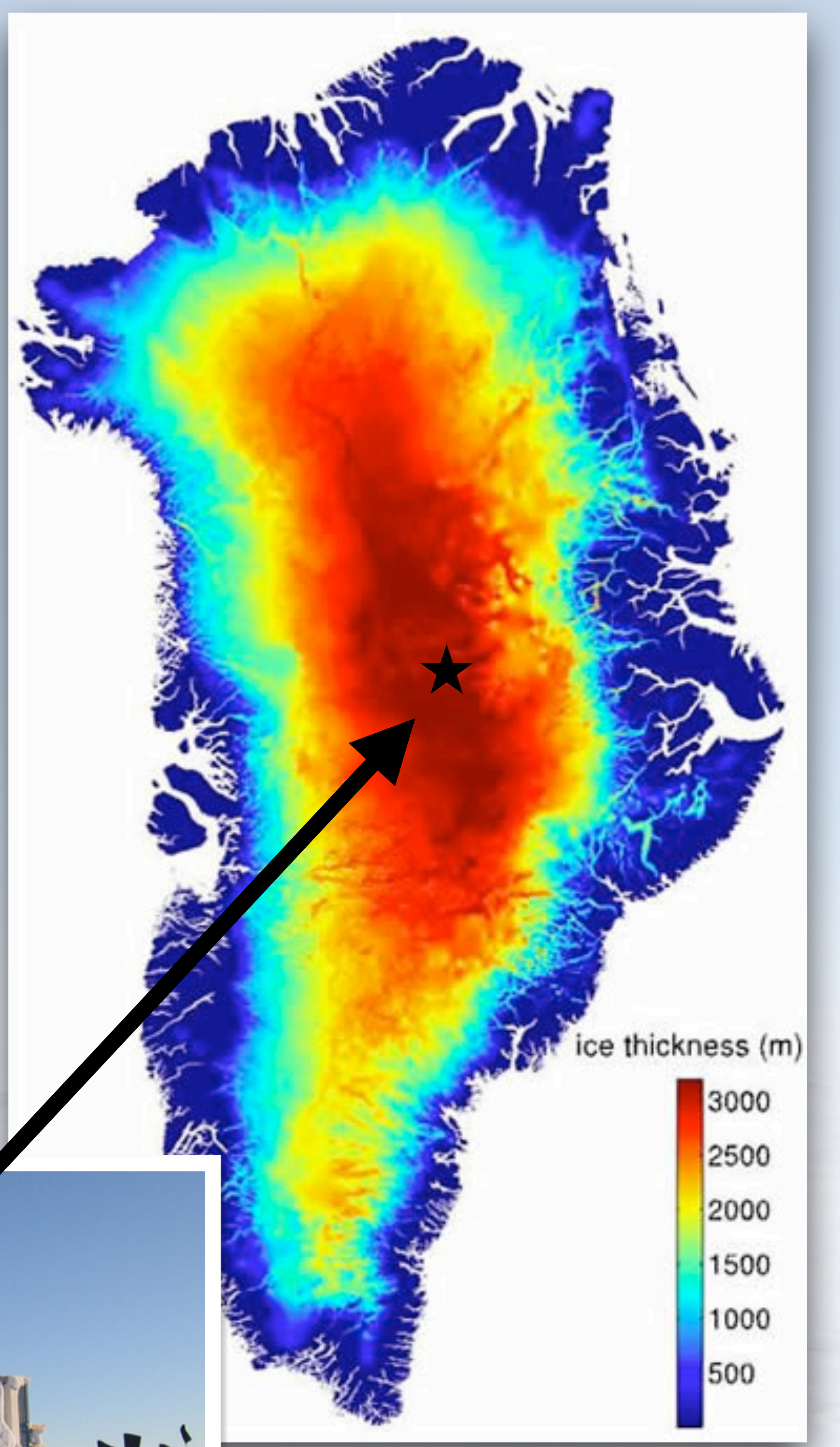
Where?

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



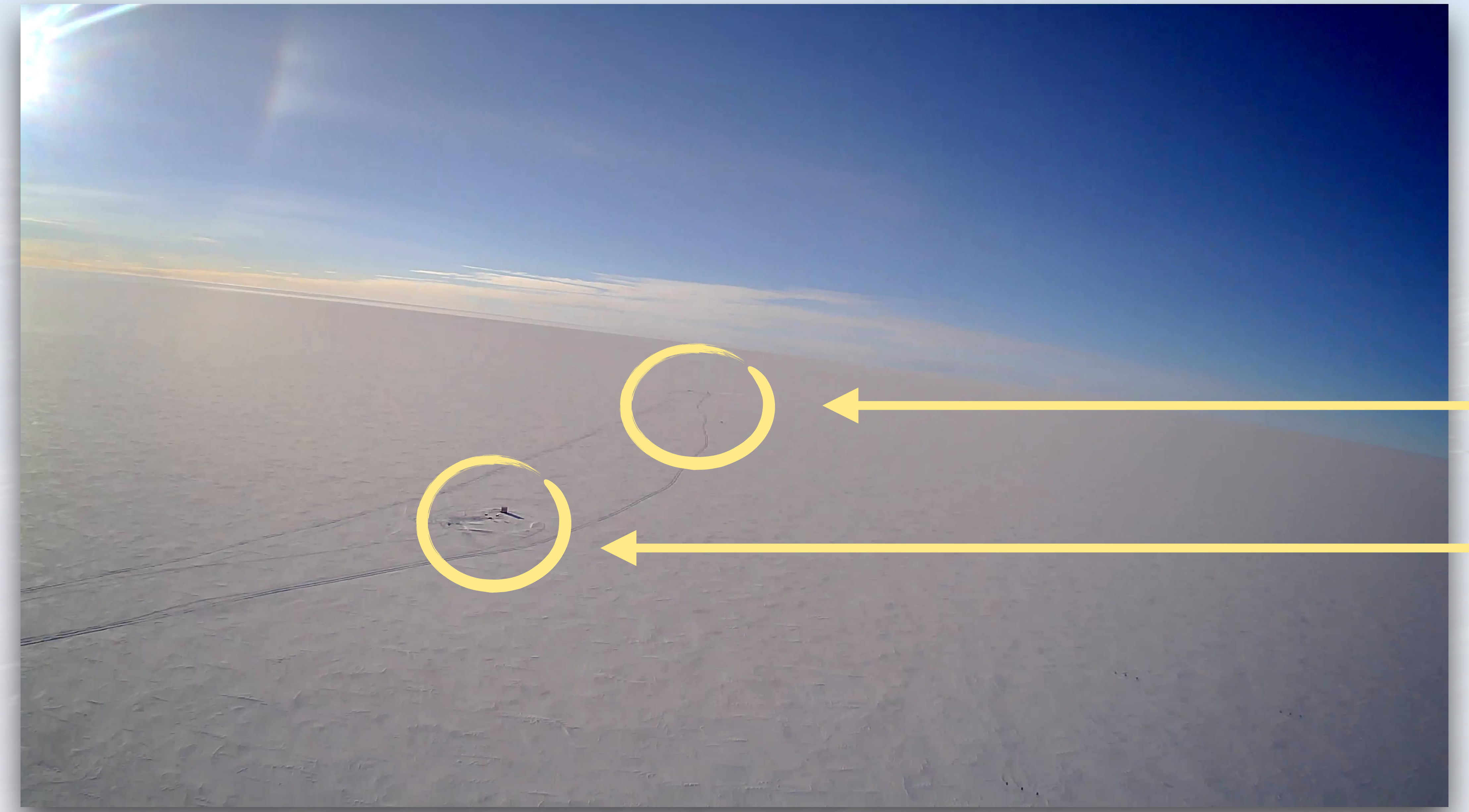
@ Summit Station



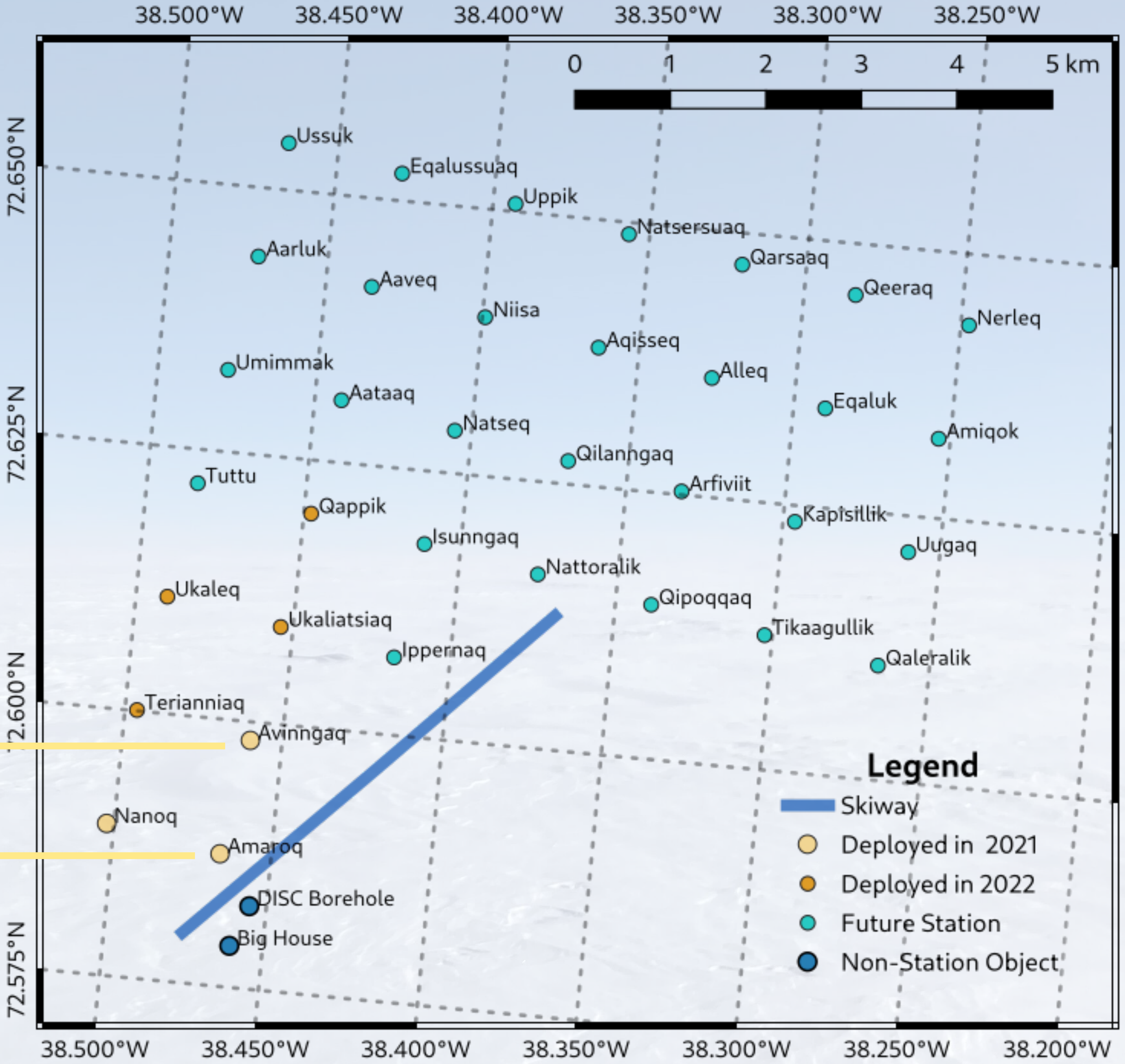
Radio Neutrino Observatory - Greenland

What?

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



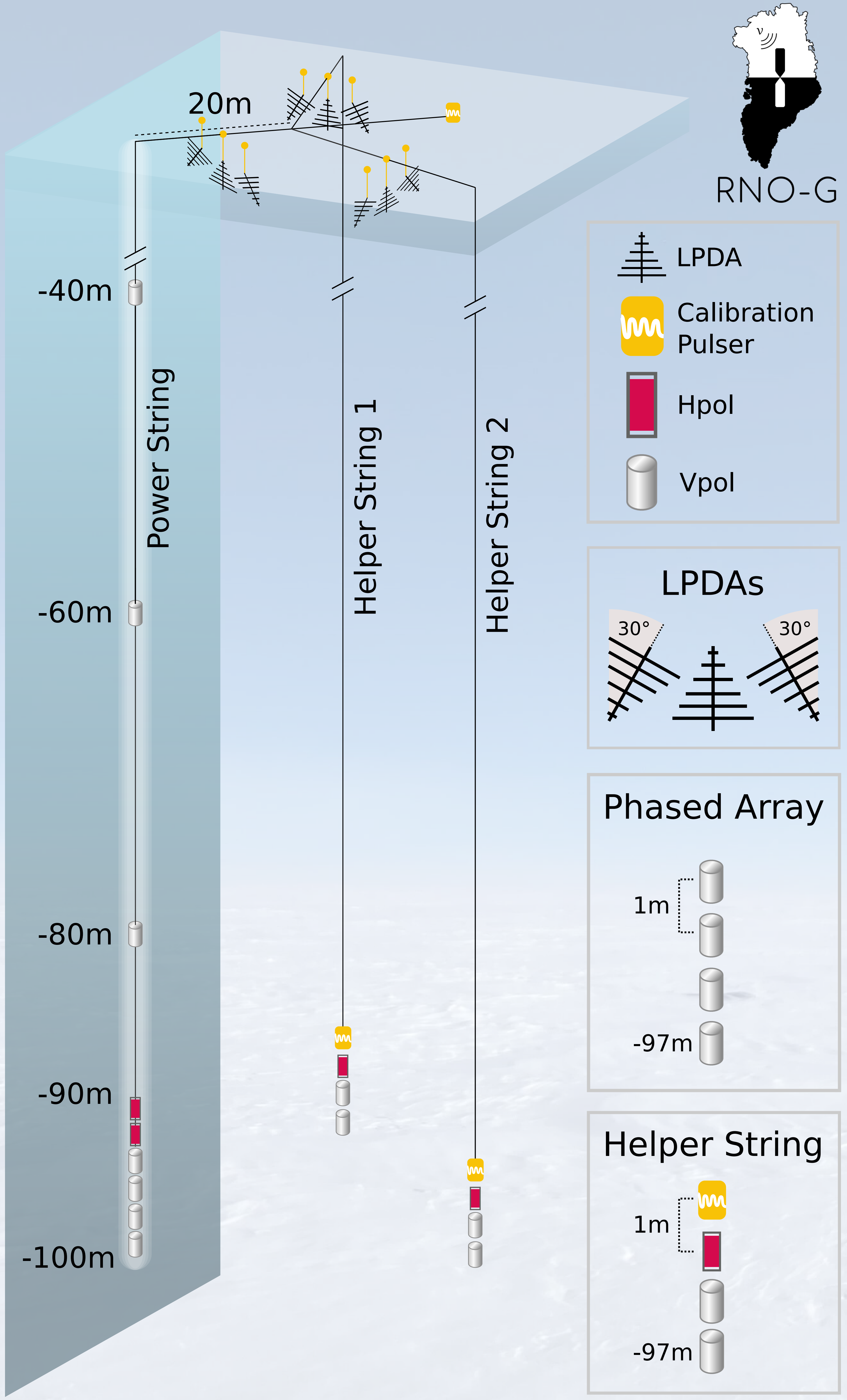
RNO-G Planned Layout



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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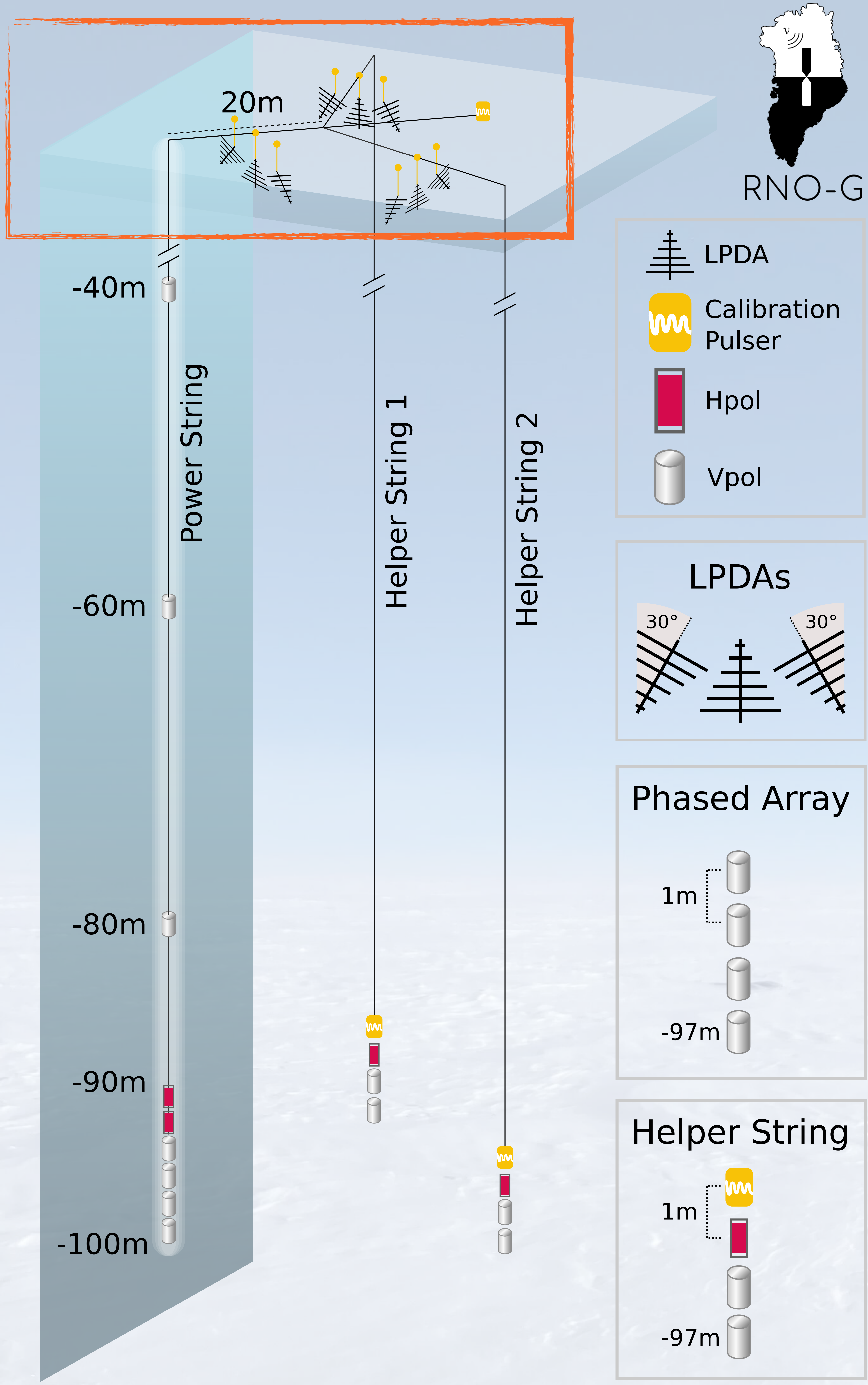

Shallow component

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

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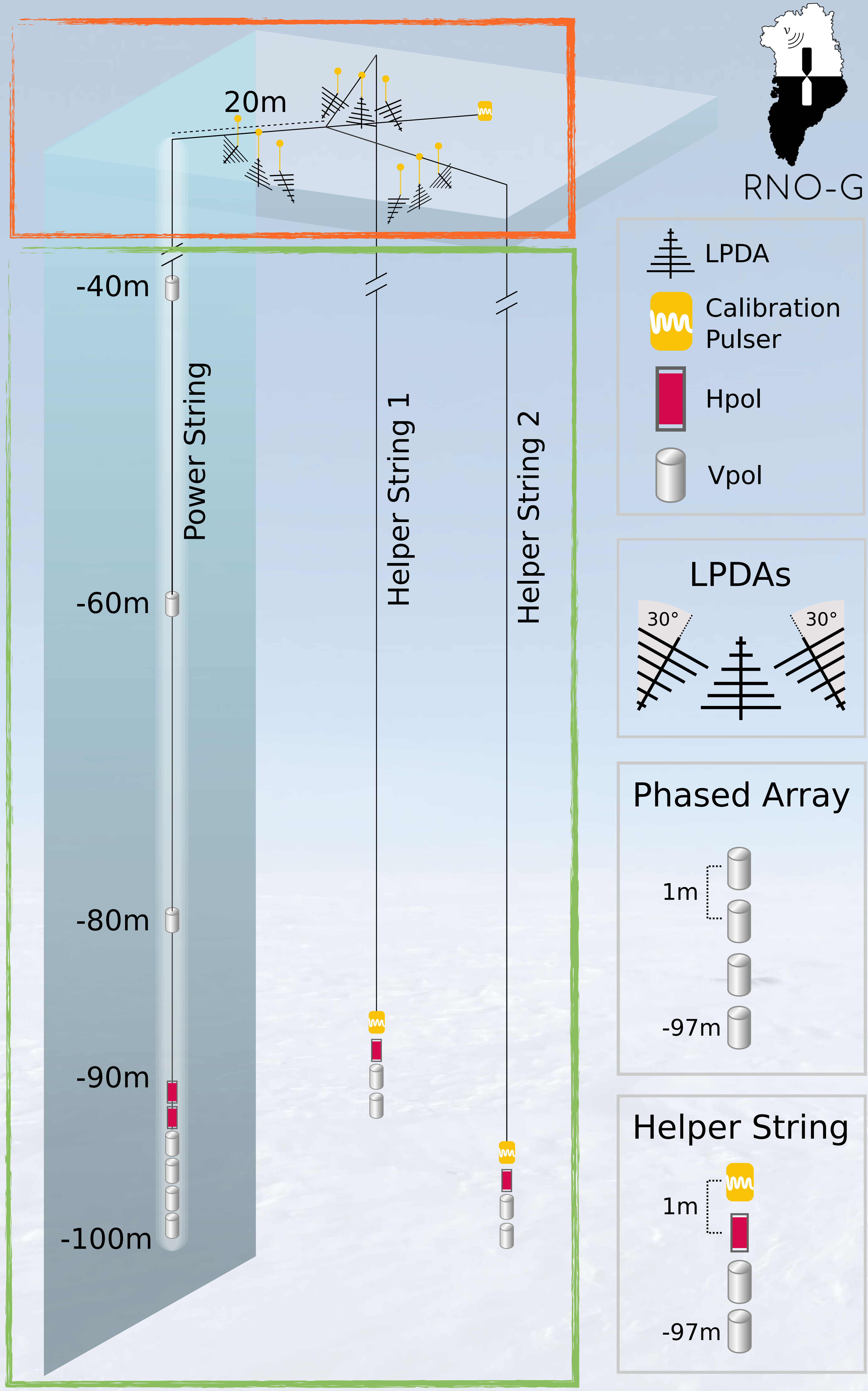

Shallow component

- Upward- & downward-facing LPDA antennas
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- Multiple coincidence threshold trigger

Deep component

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

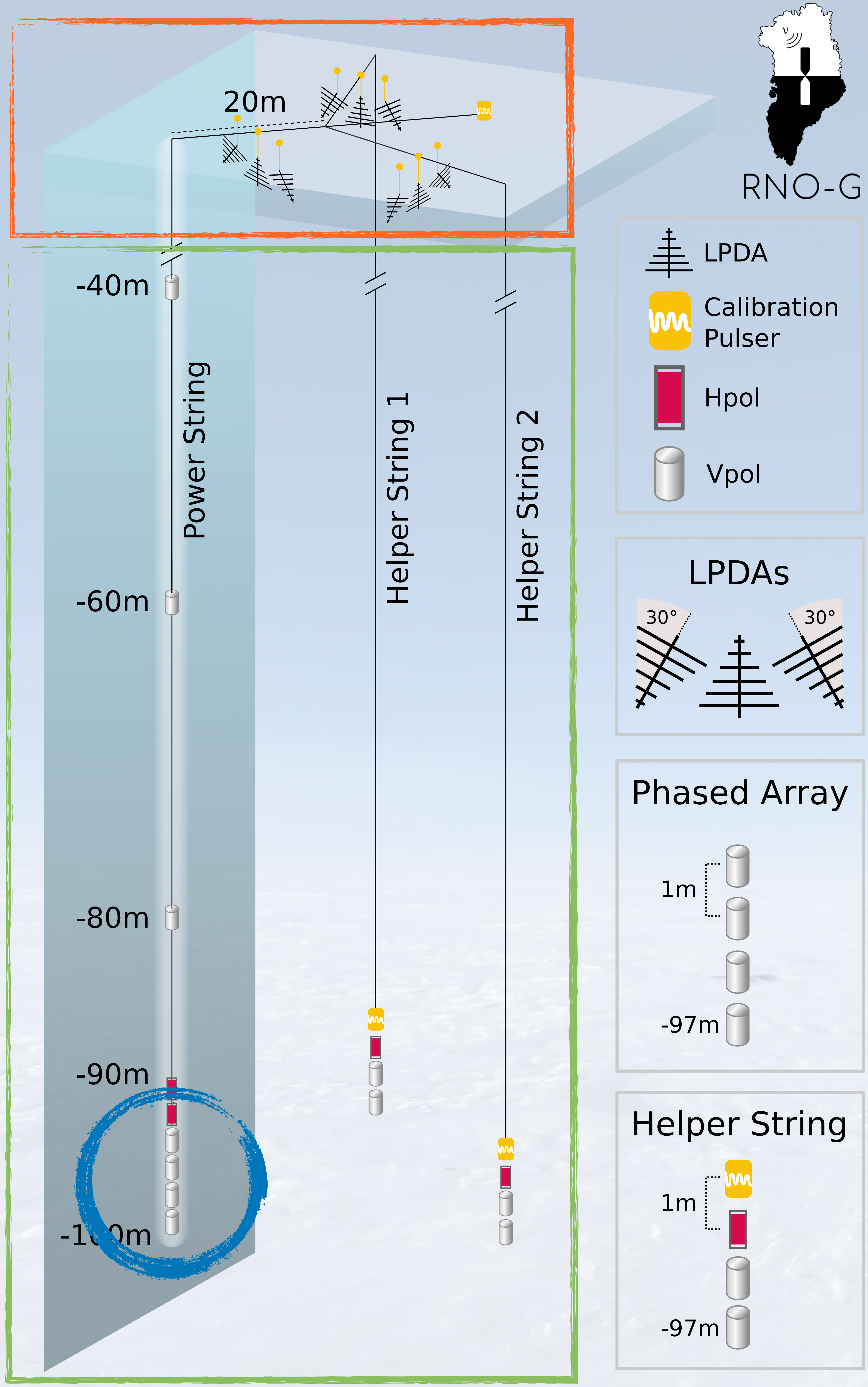
Station design

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

Phased array

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



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- Upward- & downward-facing LPDA antennas
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Deep component

- 100m deep
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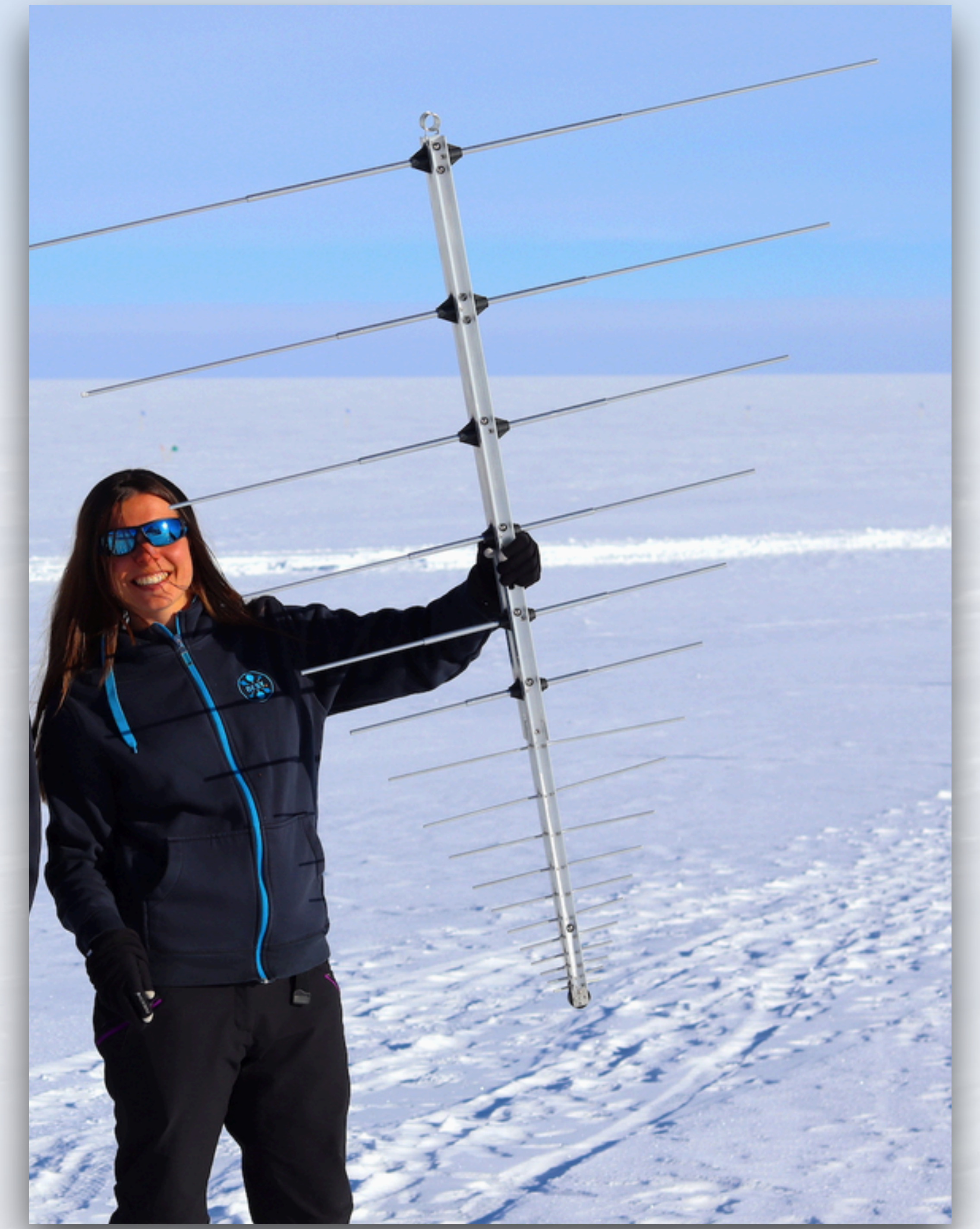
Antenna sensitivity

3 different antenna types

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

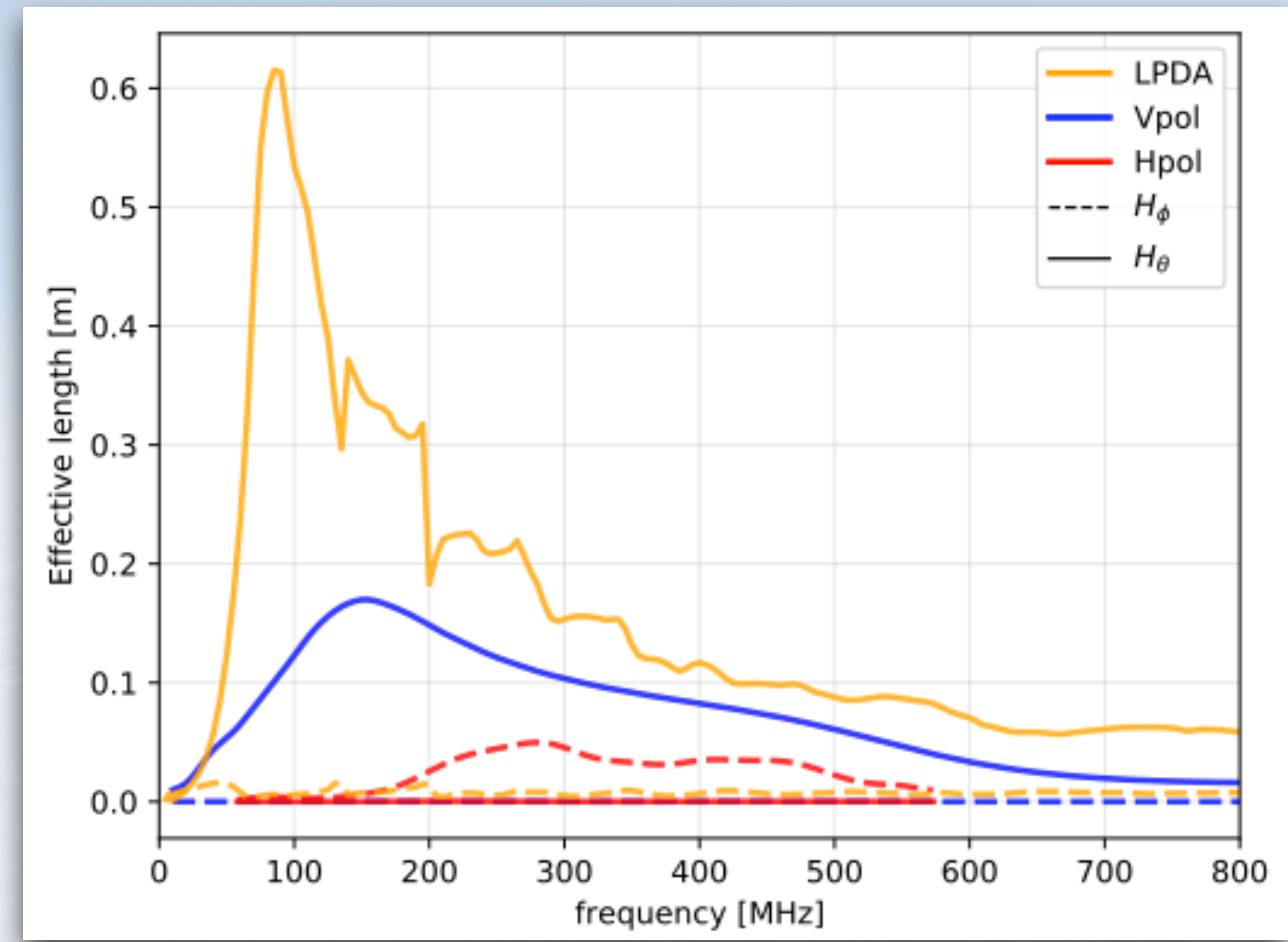
- Combination of Vpol and Hpol gives polarisation
  - Hpols is less sensitive because of narrow diameter of borehole

LPDA



Hpol

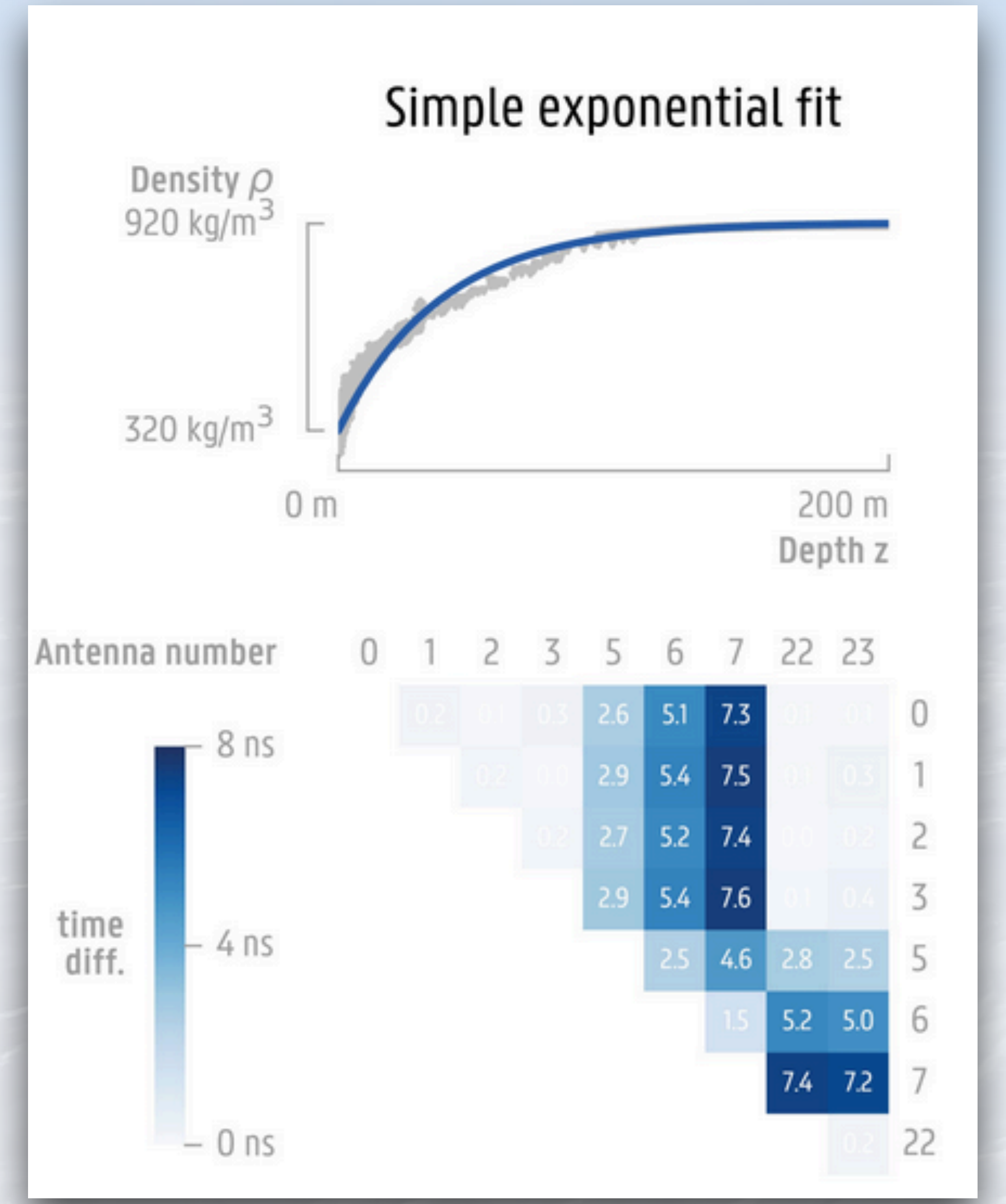
Vpol



Calibration

Current effort!

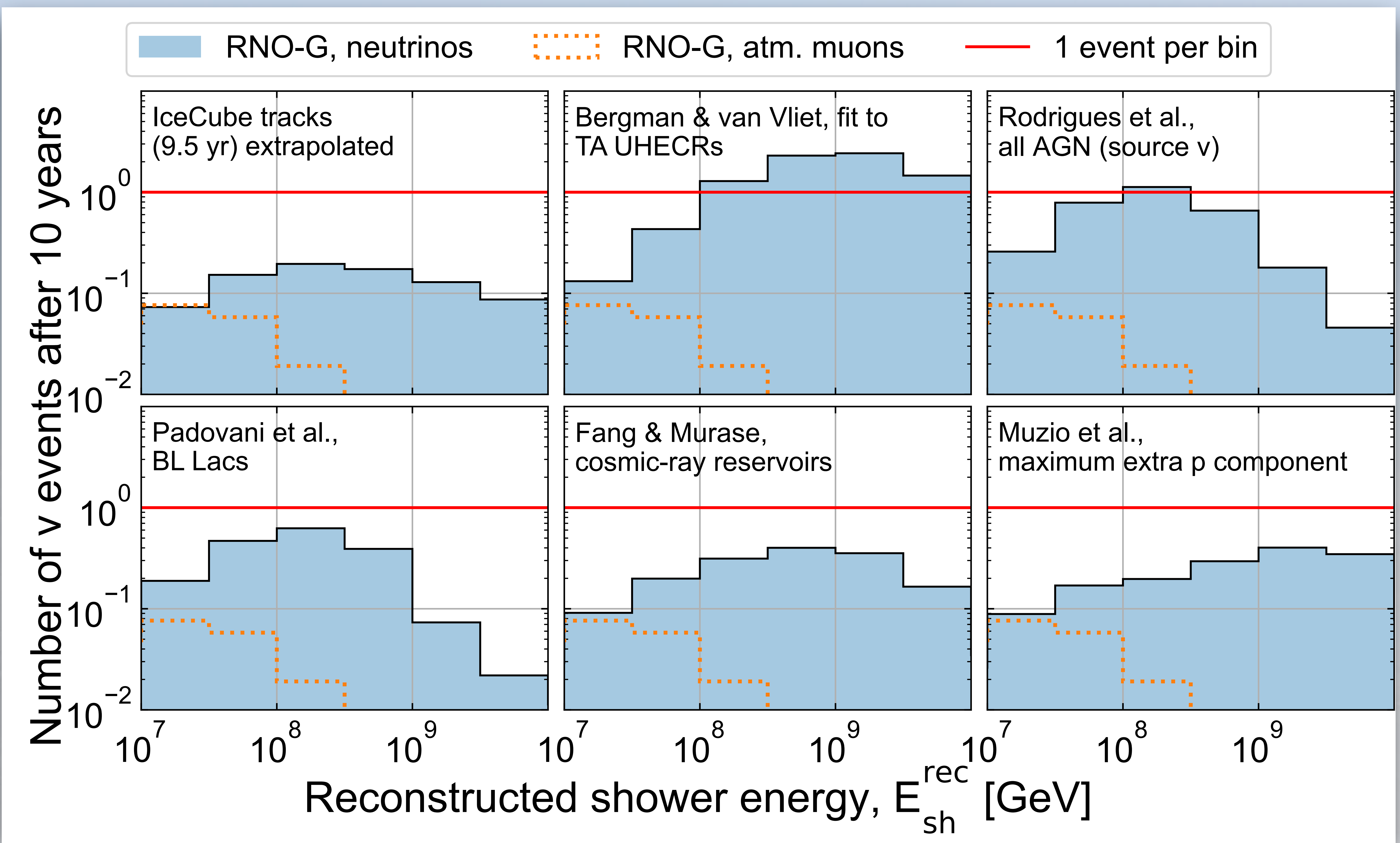
- The ice is part of our detector
  - Refractive index profile of crucial importance
  - ➡ See Talk by Bob Oeyen this afternoon



Expected number of neutrinos

For different flux models

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



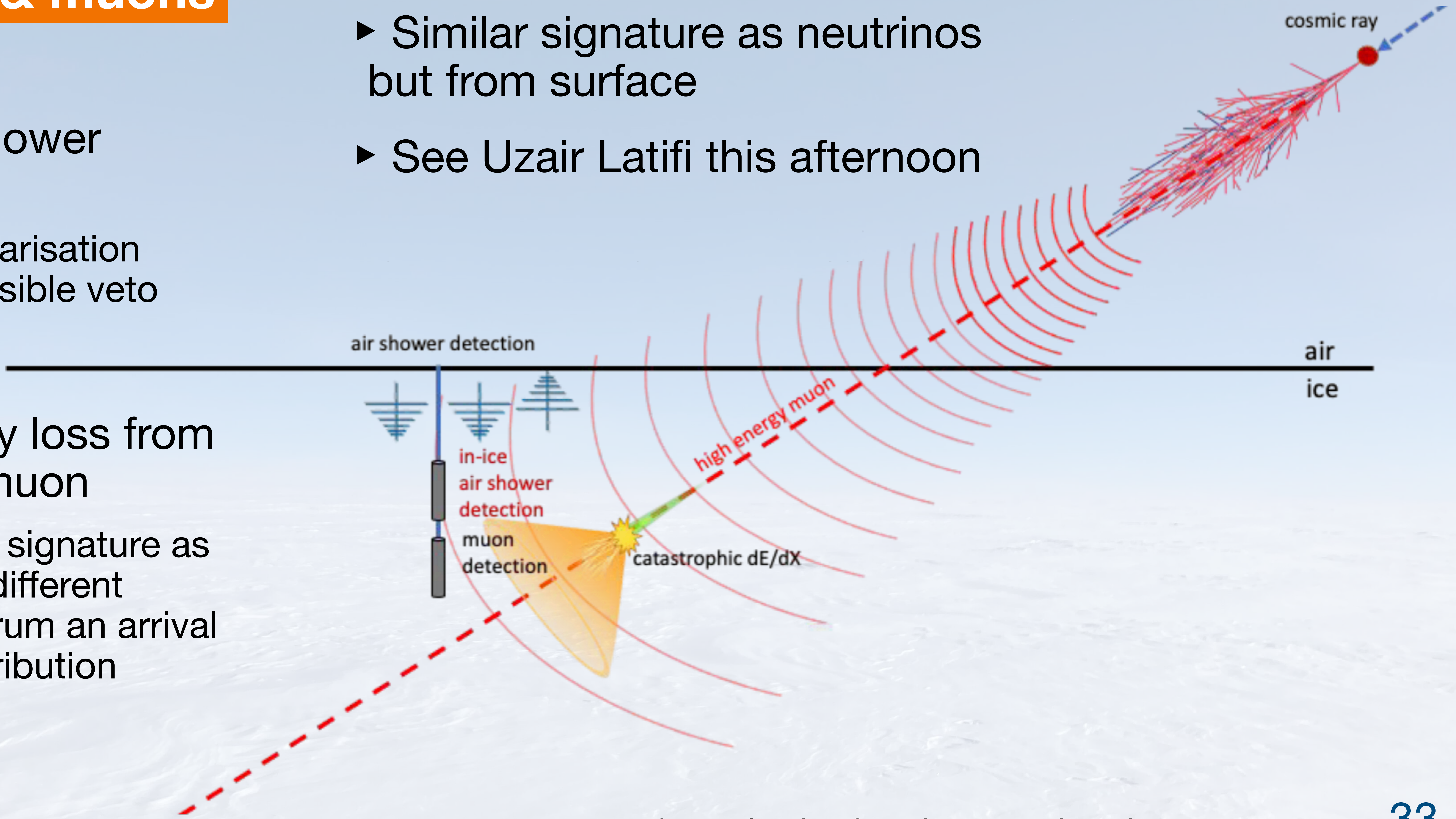
Background

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

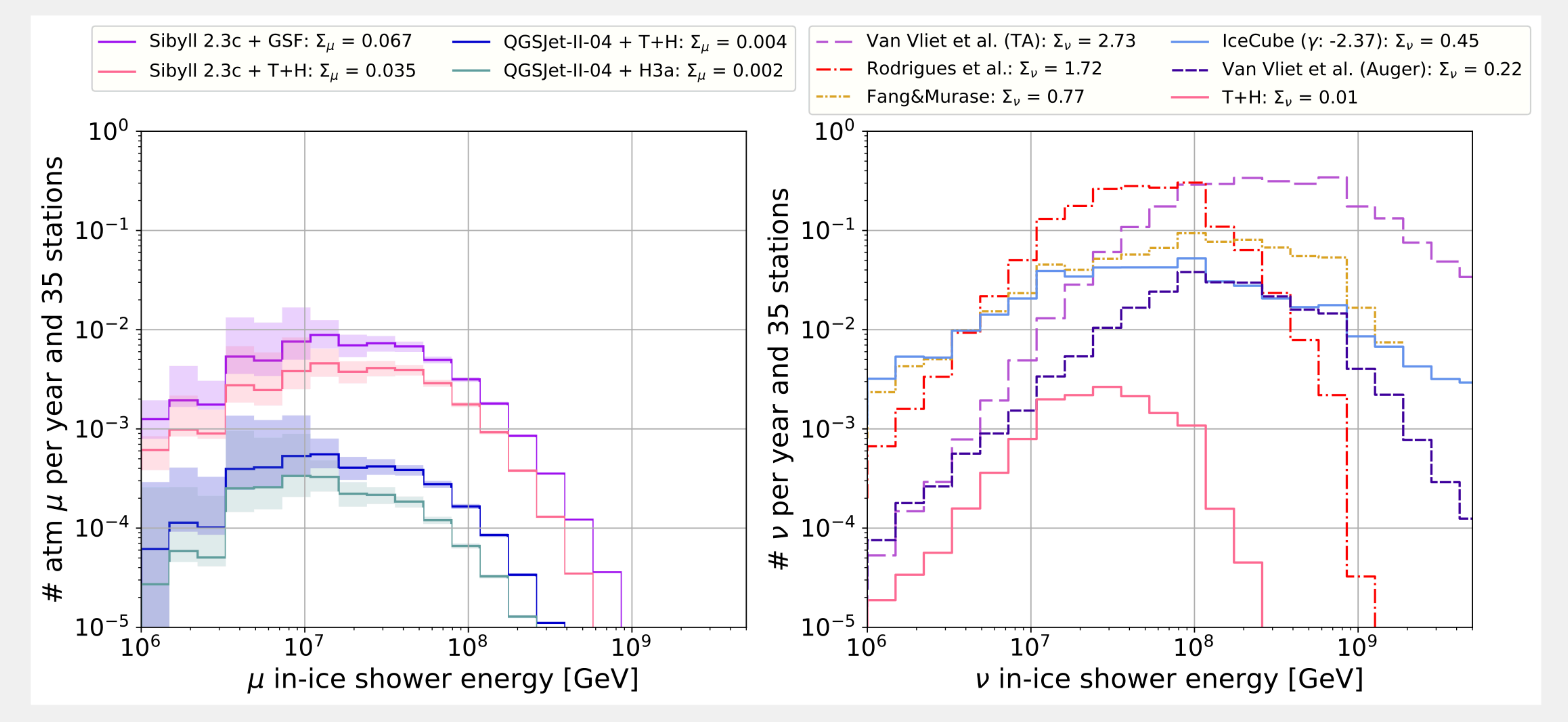
3. In-ice emission if air shower particles reach ice
   - Similar signature as neutrinos but from surface
   - See Uzair Latifi this afternoon

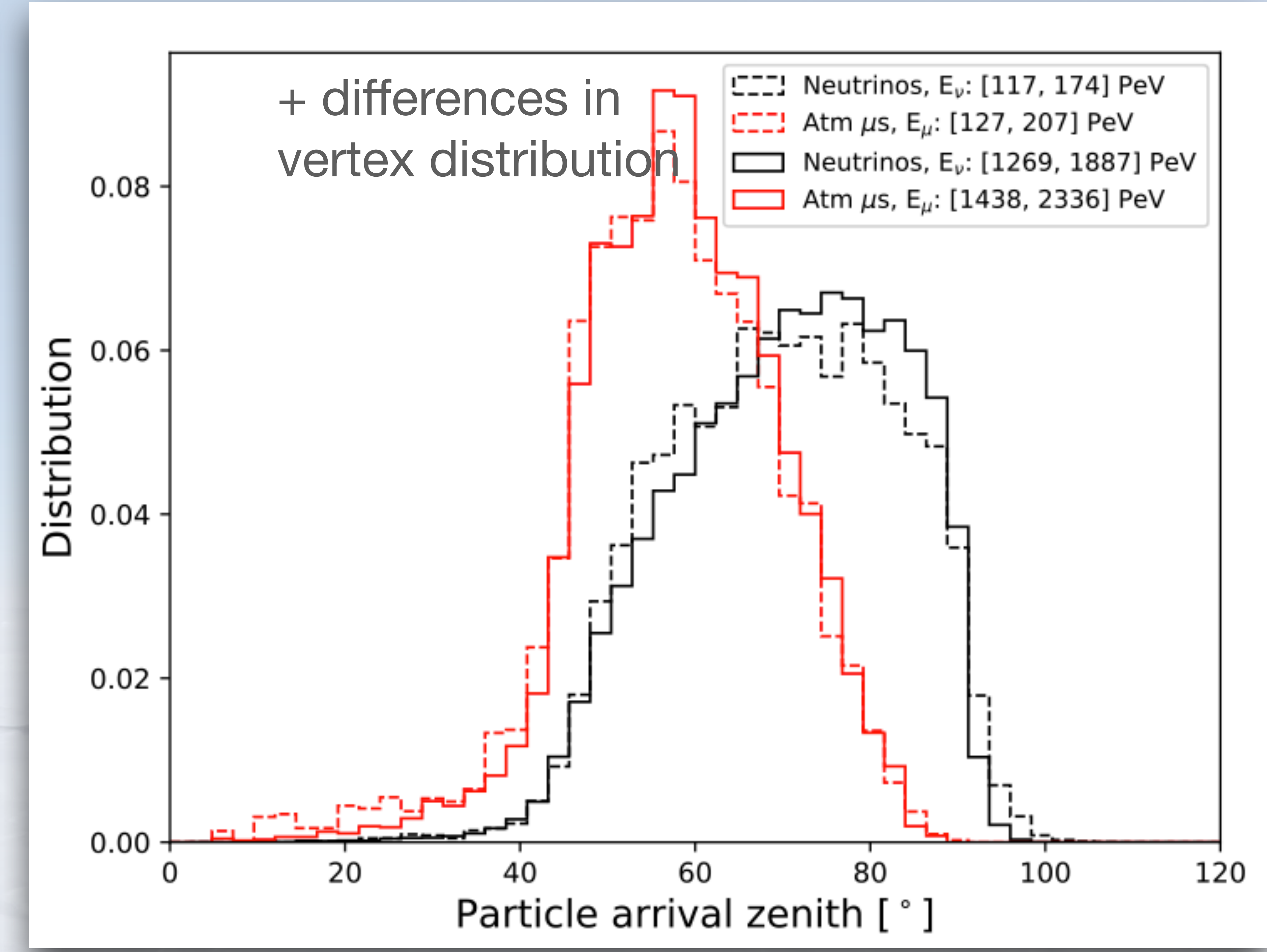


+ thermal noise & anthropogenic noise

Background

Air showers & muons





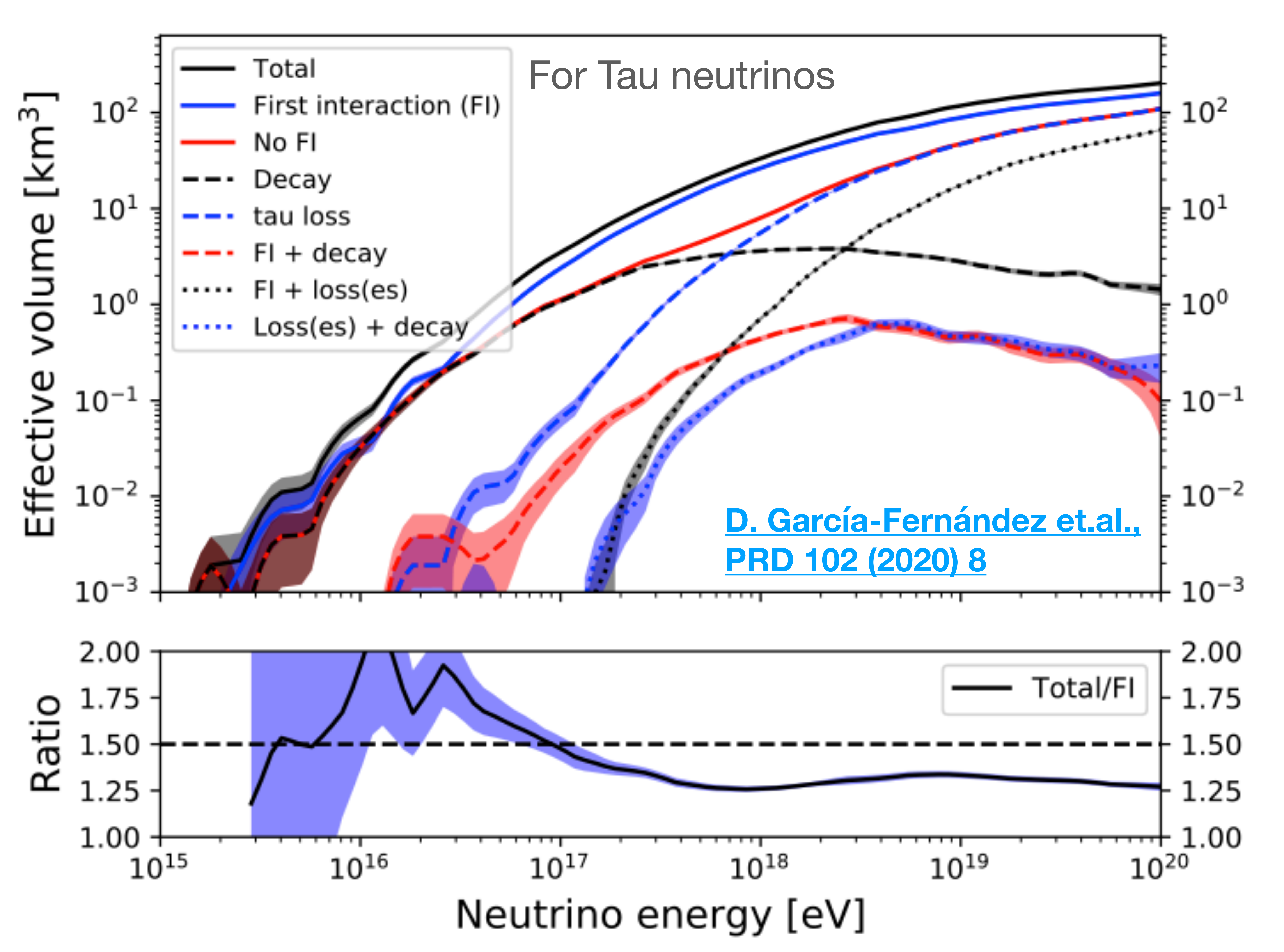
L. Pyras et al. PoS (ICRC2023) 1076   + arxiv

Ice Properties

- Part of the detector -> needs to be calibrated

Signals from secondary leptons

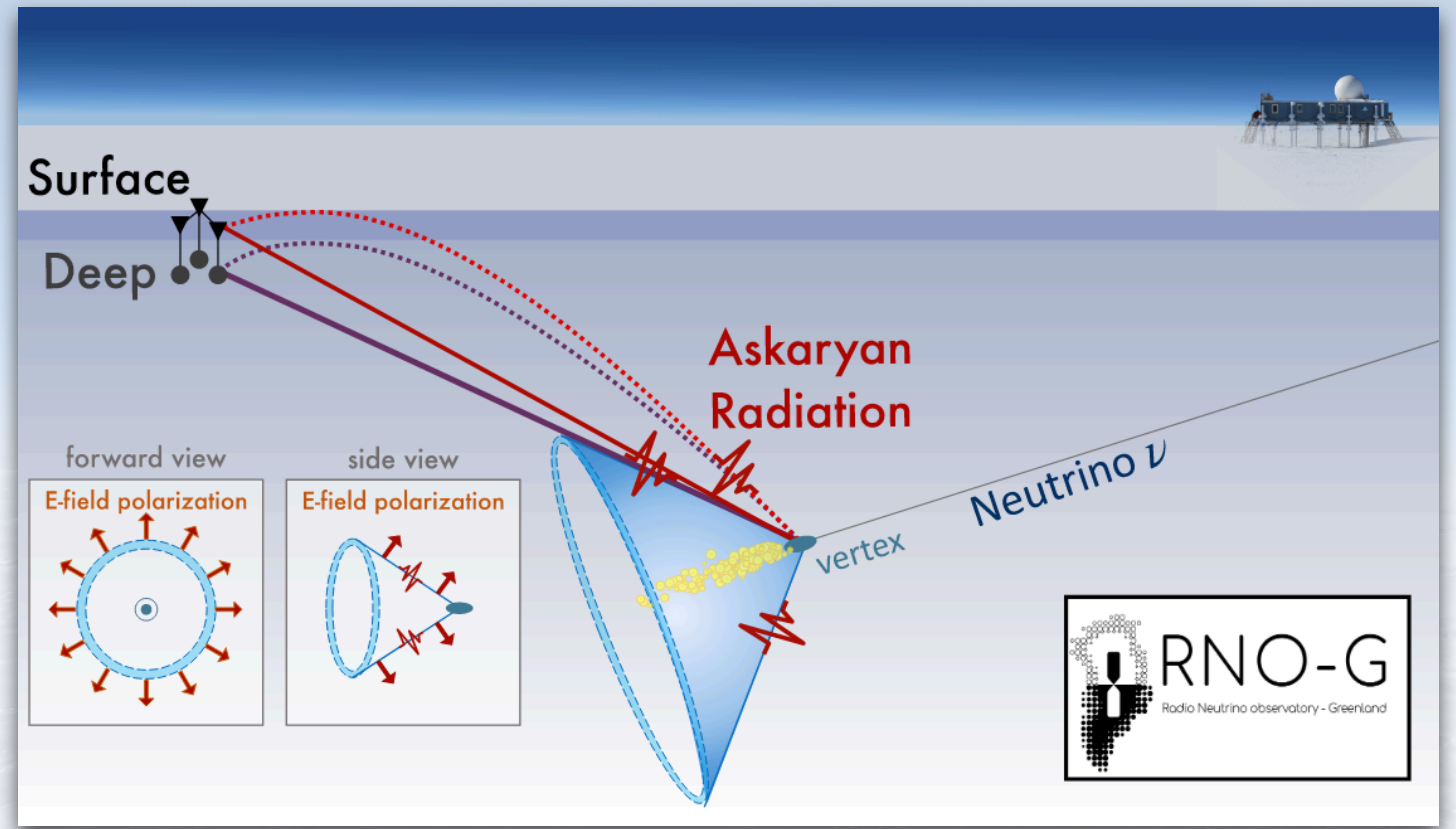
Which undergo catastrophic energy losses



D. García-Fernández et.al., PRD 102 (2020) 8

Askaryan Radiation

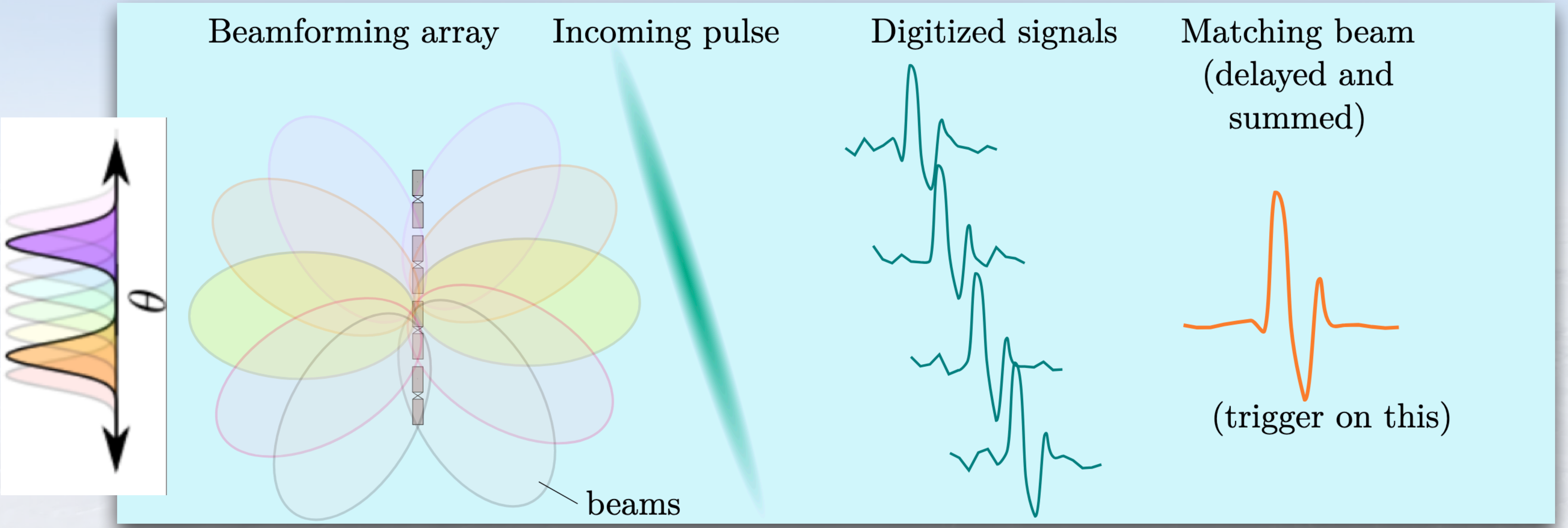
Specific polarisation pattern



Phased array

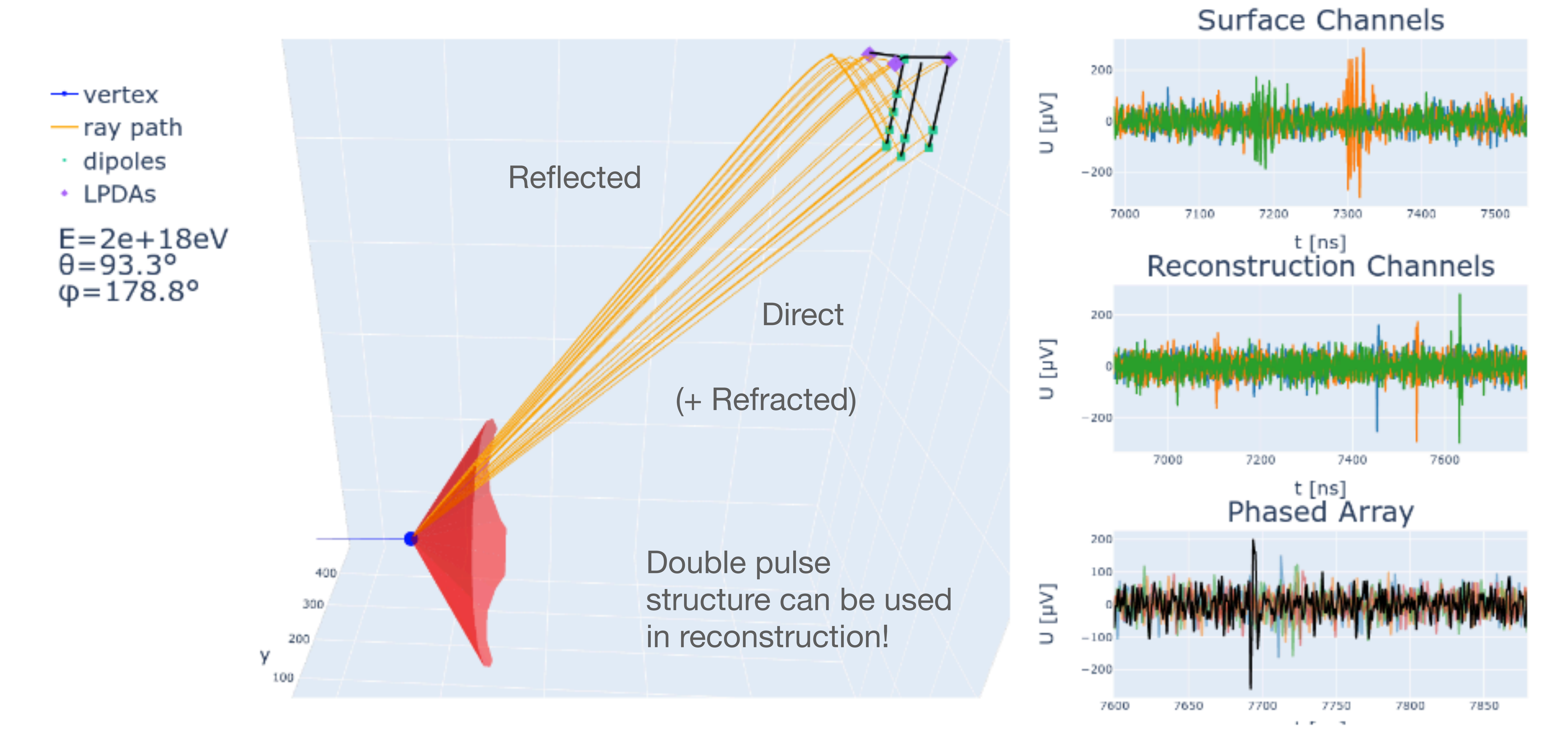
For triggering and reconstruction

- 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

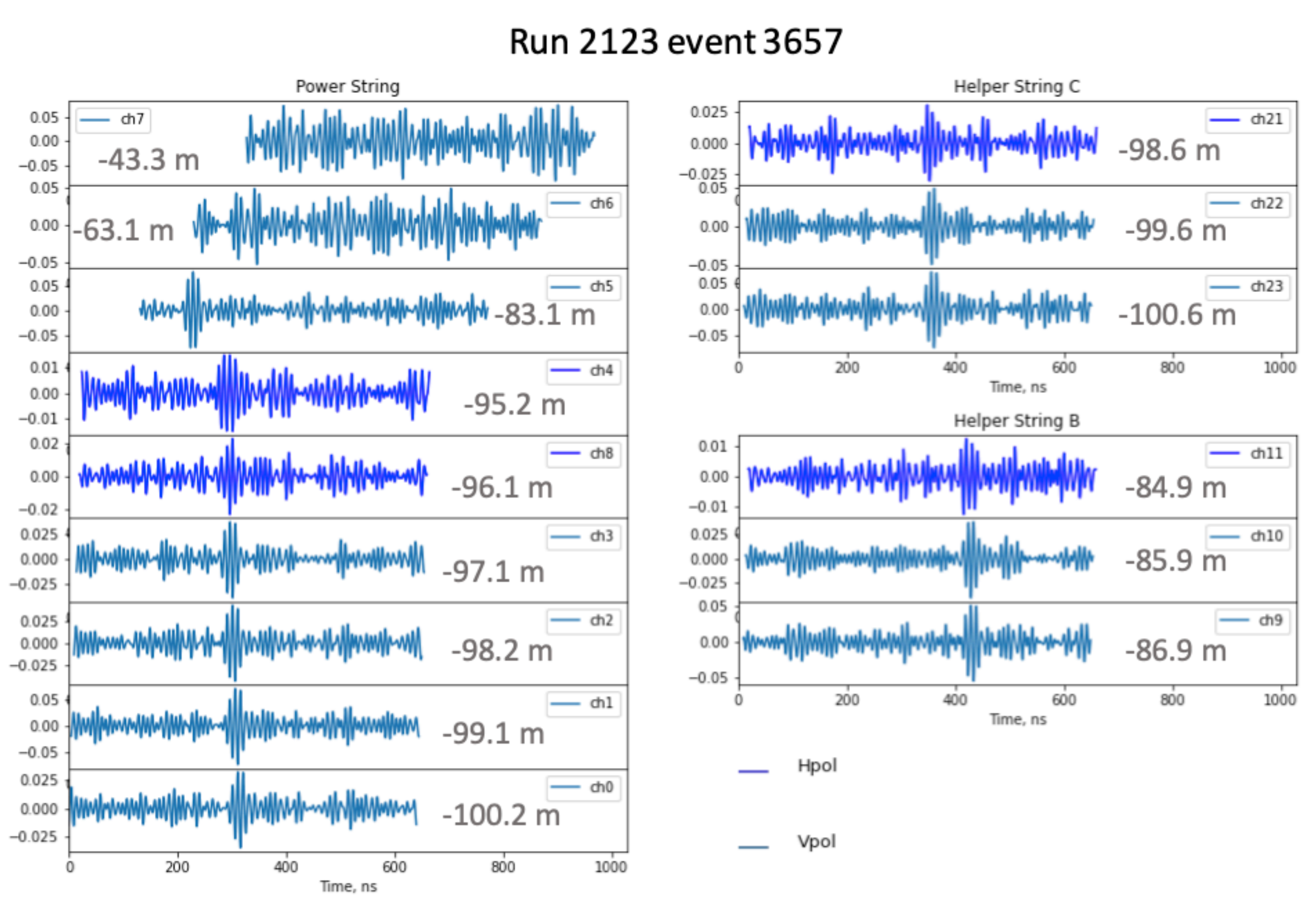


Propagation

Signal can reach antennas on different trajectories!

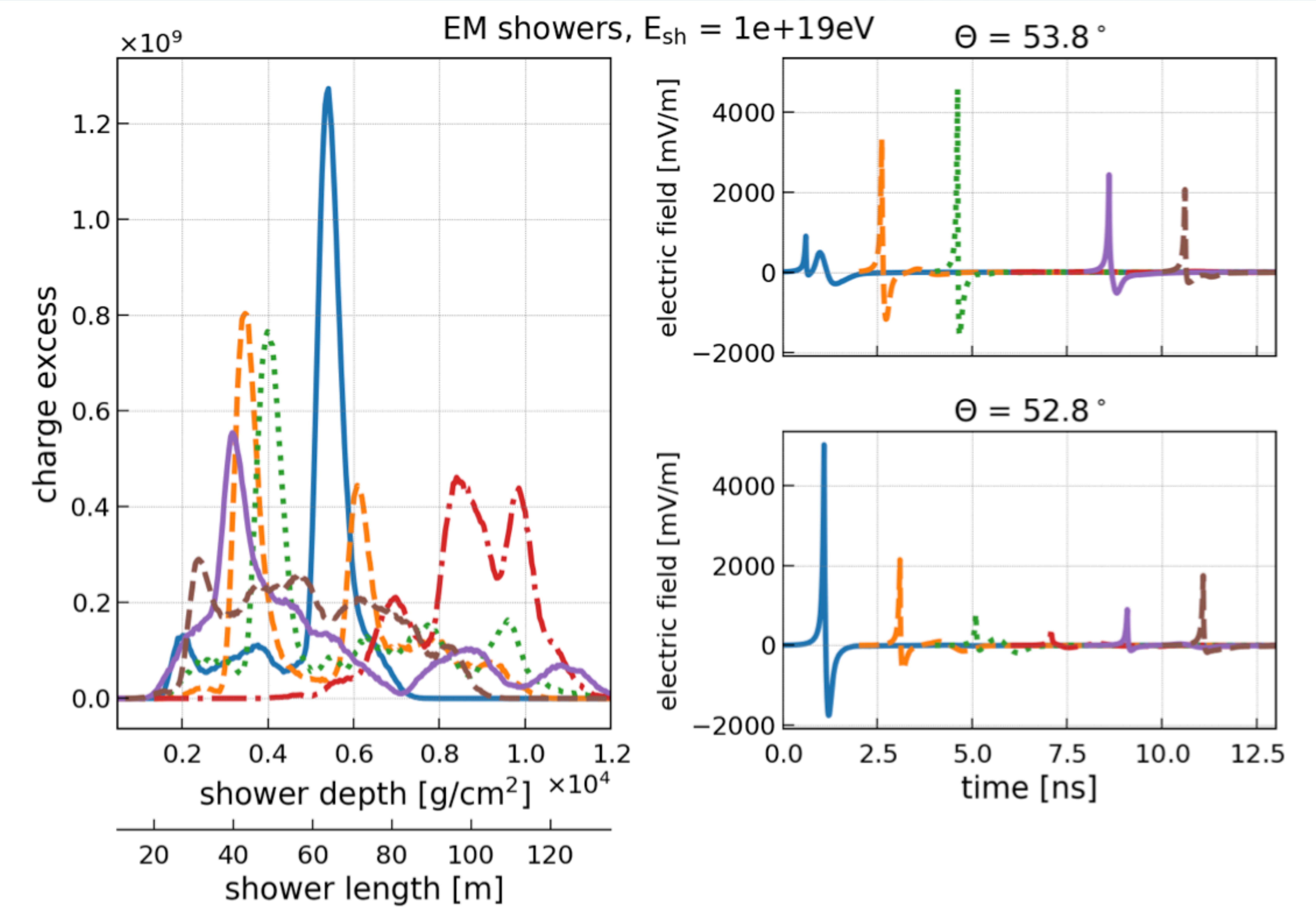


Solar flare



Run 2123 event 3657
Power String
Helper String C
Helper String B
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
ch21
-98.6 m
ch22
-99.6 m
ch23
-100.6 m
ch11
-84.9 m
ch10
-85.9 m
ch9
-86.9 m
Time, ns
Hpol
Vpol

LPM effect



EM showers, E_{sh} = 1e+19eV
$\times 10^9$
charge excess
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2 0.4 0.6 0.8 1.0 1.2
shower depth [g/cm^2] $\times 10^4$
20 40 60 80 100 120
shower length [m]
Θ = 53.8°
Θ = 52.8°
electric field [mV/m]
4000
2000
0
−2000
0.0 2.5 5.0 7.5 10.0 12.5
time [ns]

Earth attenuation