The Radio Neutrino Observatory - Greenland

Tuning in on ultra-high-energy neutrinos from the norther sky

Felix Schlüter for the RNO-G group @ IIHE

IIHE annual meeting - 15.11.23

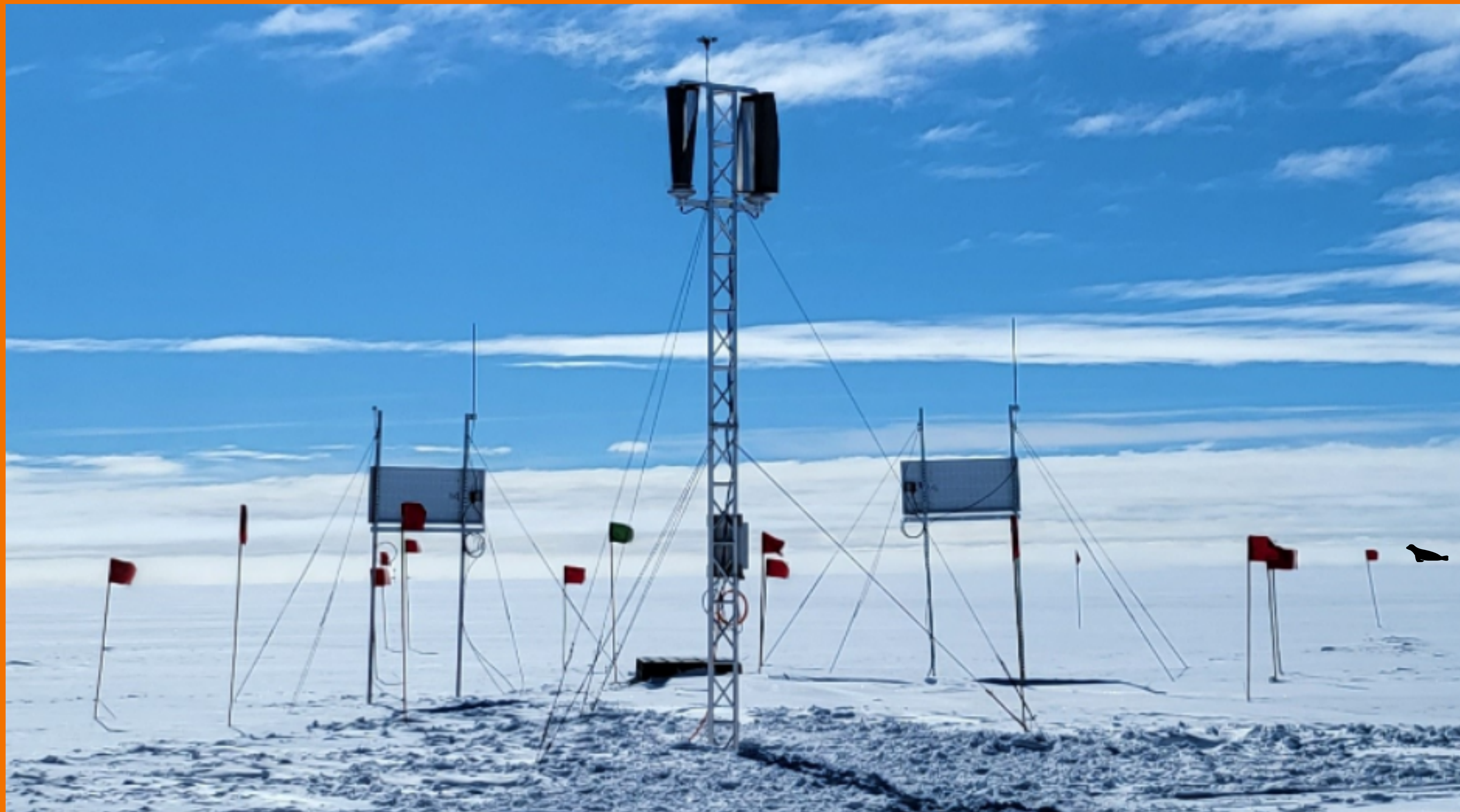

Illustration by Karen Teveer


the UHE-universe:
AGNs, SNRs, GRBs, ...
Common Sources:
Neutrinos are produced together with
gamma rays from UHE cosmic rays
gamma rays γ
Gamma rays
annihilate with CMB
neutrinos ν
Cosmic ray deflect in
magnetic fields
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Neutrinos are the
ideal messenger...
... but challenging
to measure!
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Particle cascades with E ≳ 10
PeV produce radio emission
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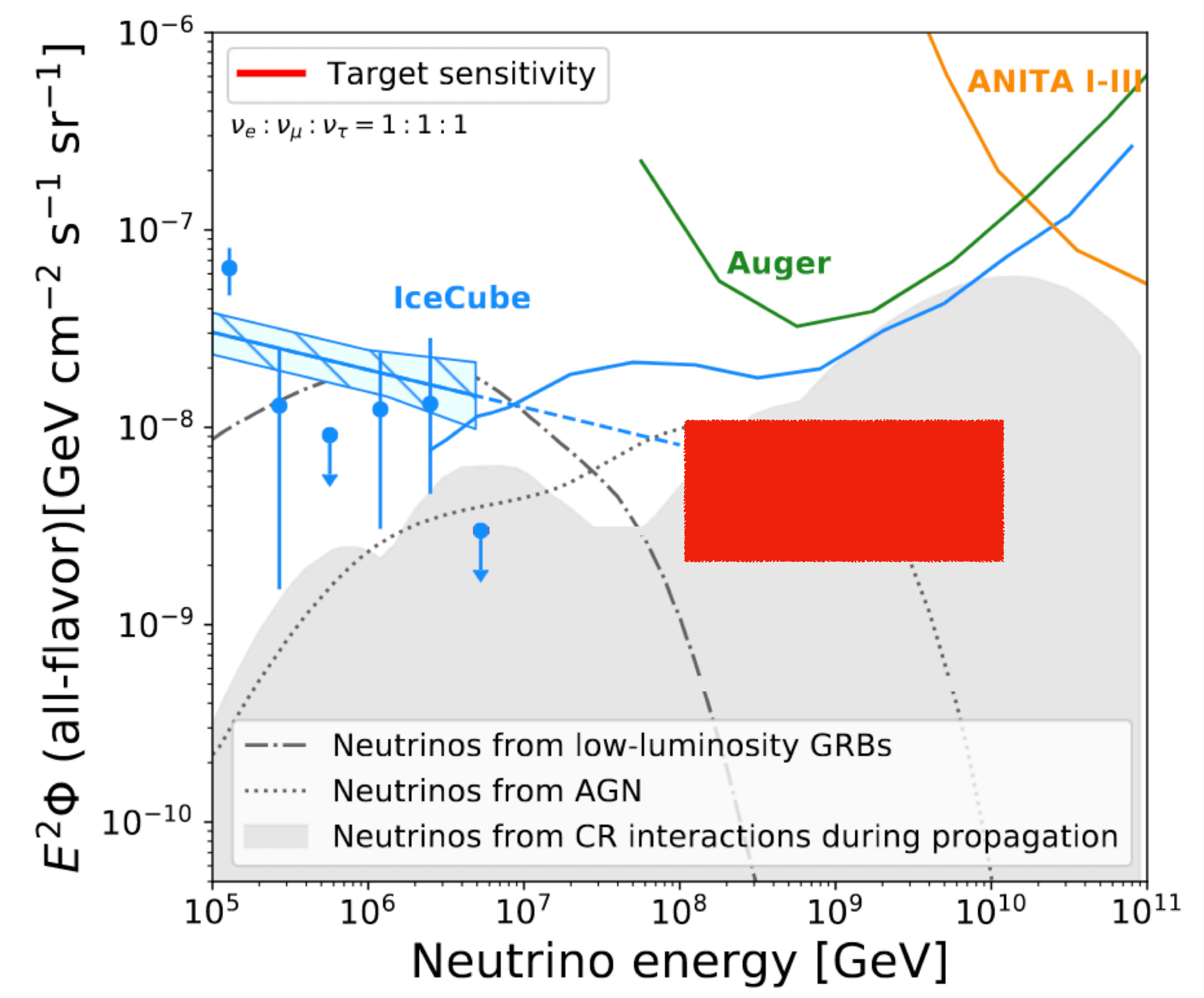
Attenuation length of radio $\mathcal{O}(1\,\mathrm{km})$
Askaryan-radiation
neutrino ν
interaction with ice
Particle cascades with $E \gtrsim 10$ PeV produce radio emission
Illustration by Karen Teveer

Ultra-high-energy neutrinos with RNO-G

- RNO-G targets 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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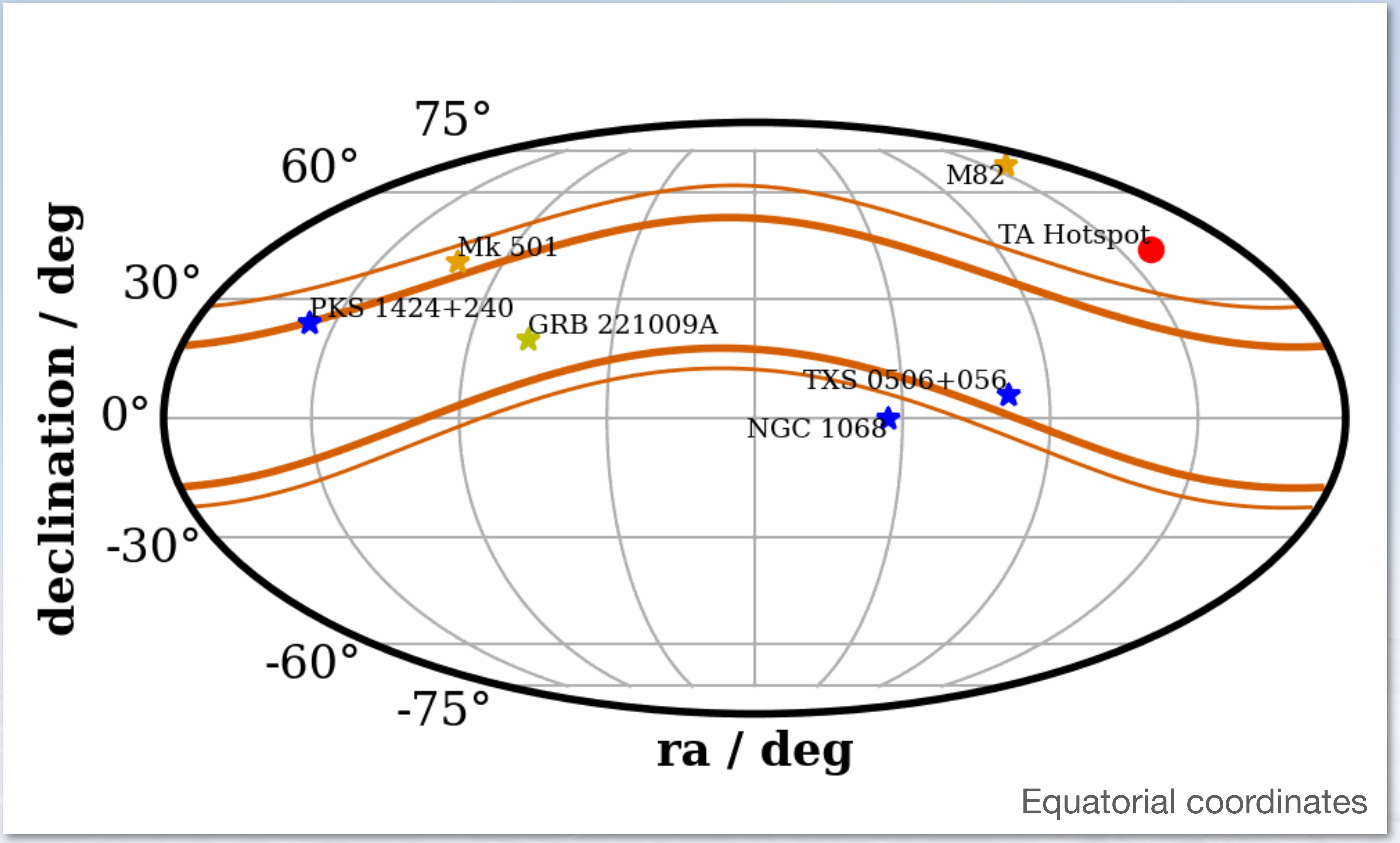
- UHE neutrinos in the Northern Hemisphere
  - Earth absorption matters above ~ 100 TeV
  - Complementary FOV to IceCube / South Pole
    - Extend energy range in Northern Hemisphere
    - Extend FOV for ultra-high energies to Northern Hemisphere



Neutrino sources (+ candidate)

Strong gamma ray sources

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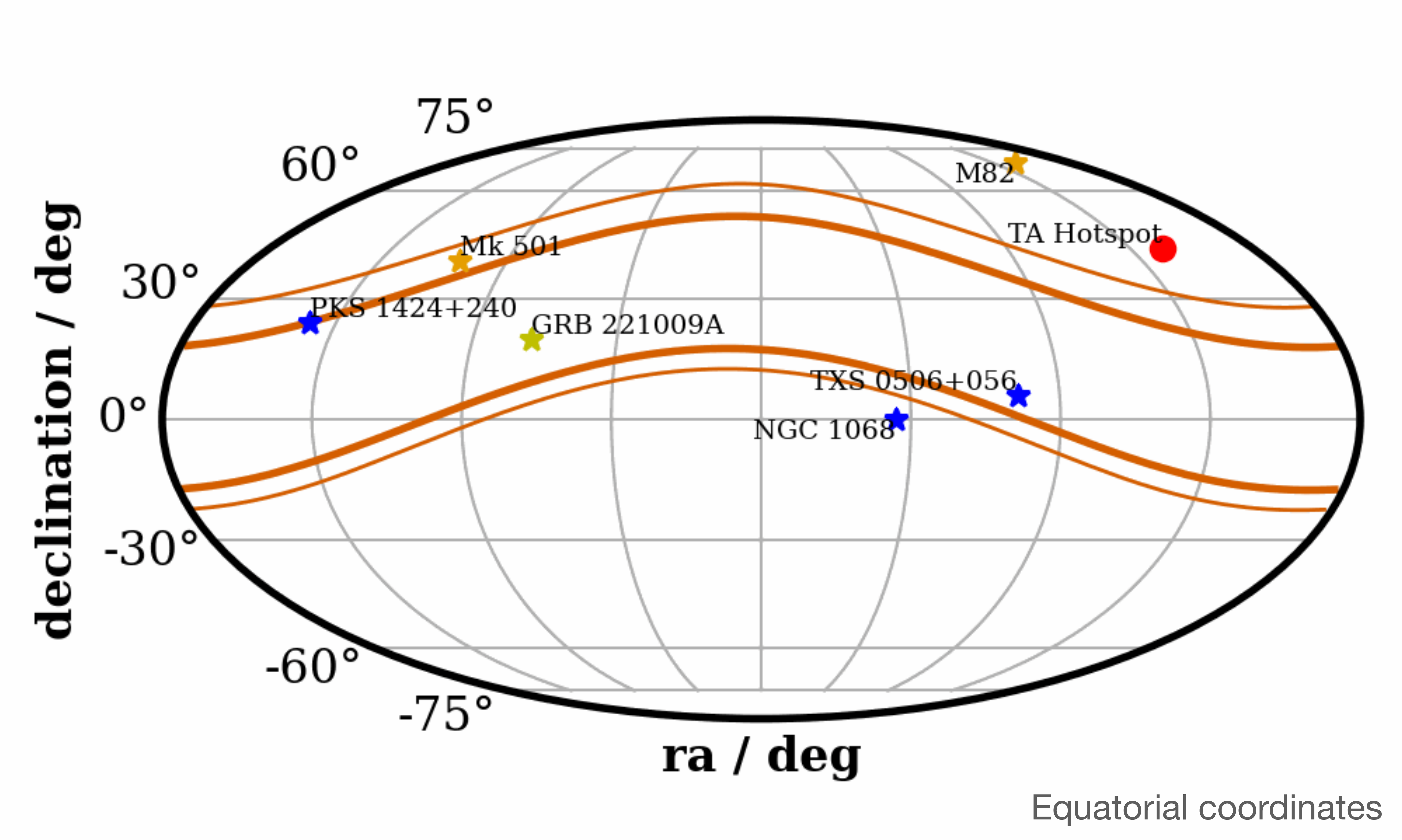
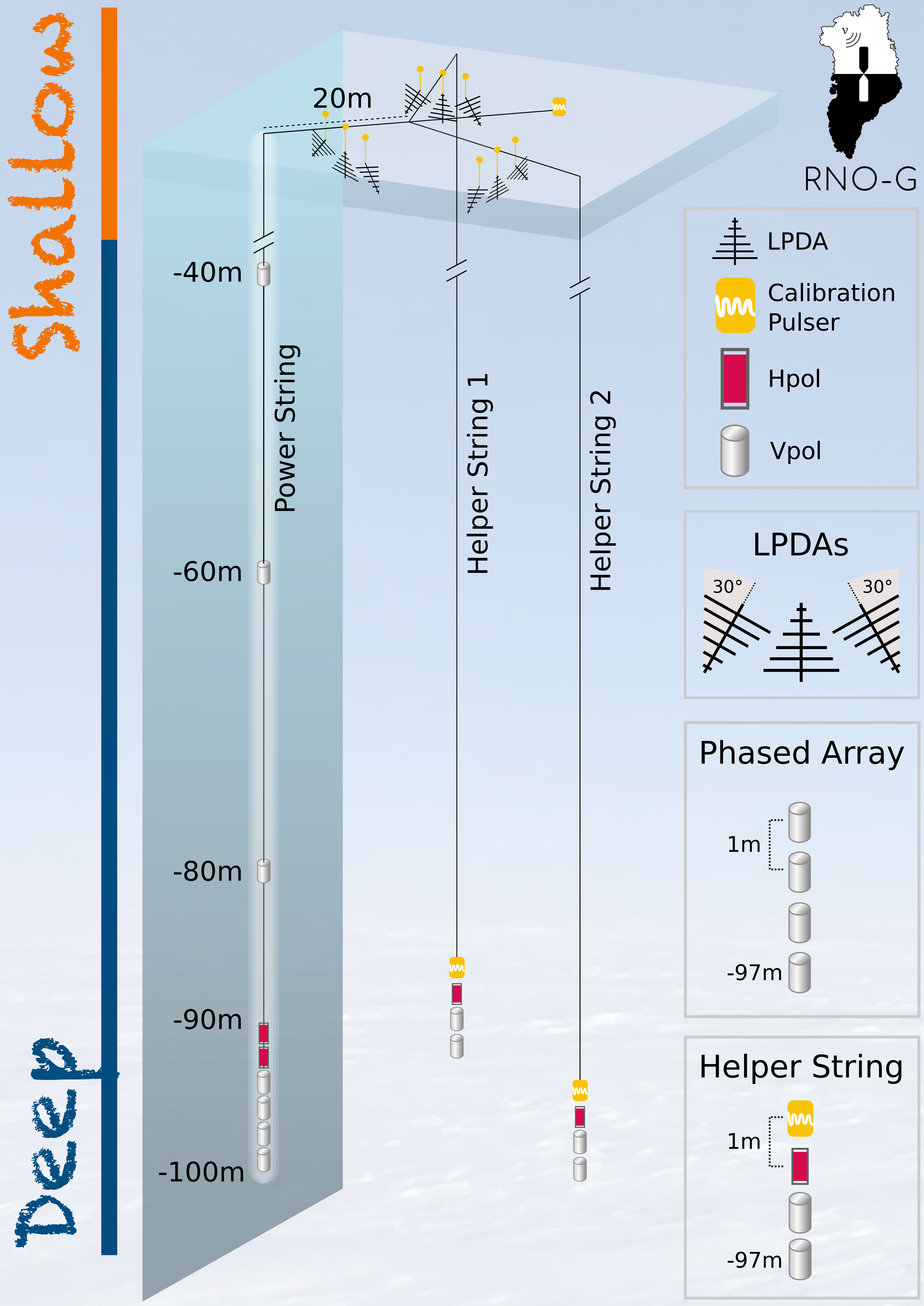


Neutrino sources (+ candidate)

Strong gamma ray sources

Radio Neutrino Observatory - Greenland

Hybrid station with 24 antennas



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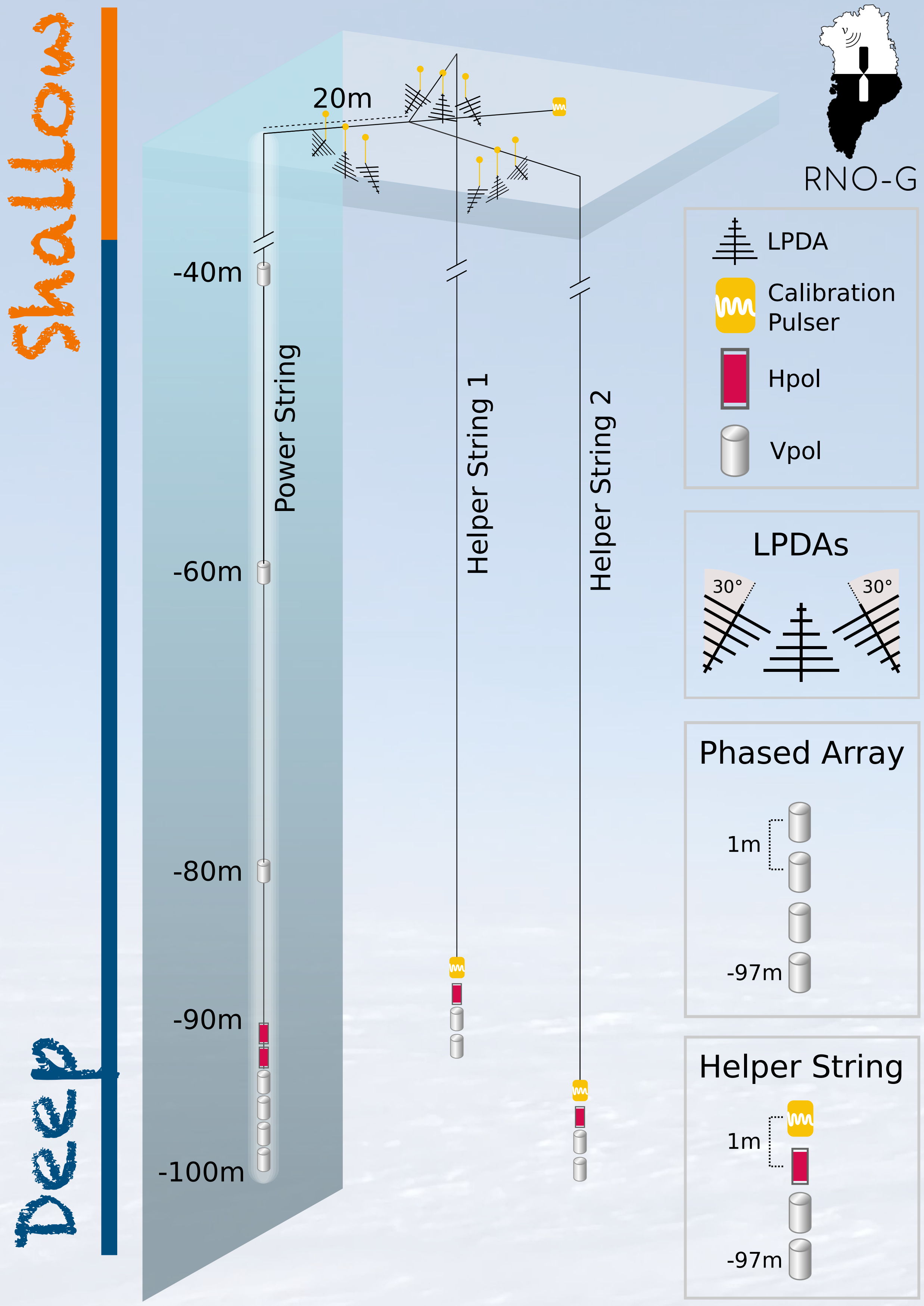
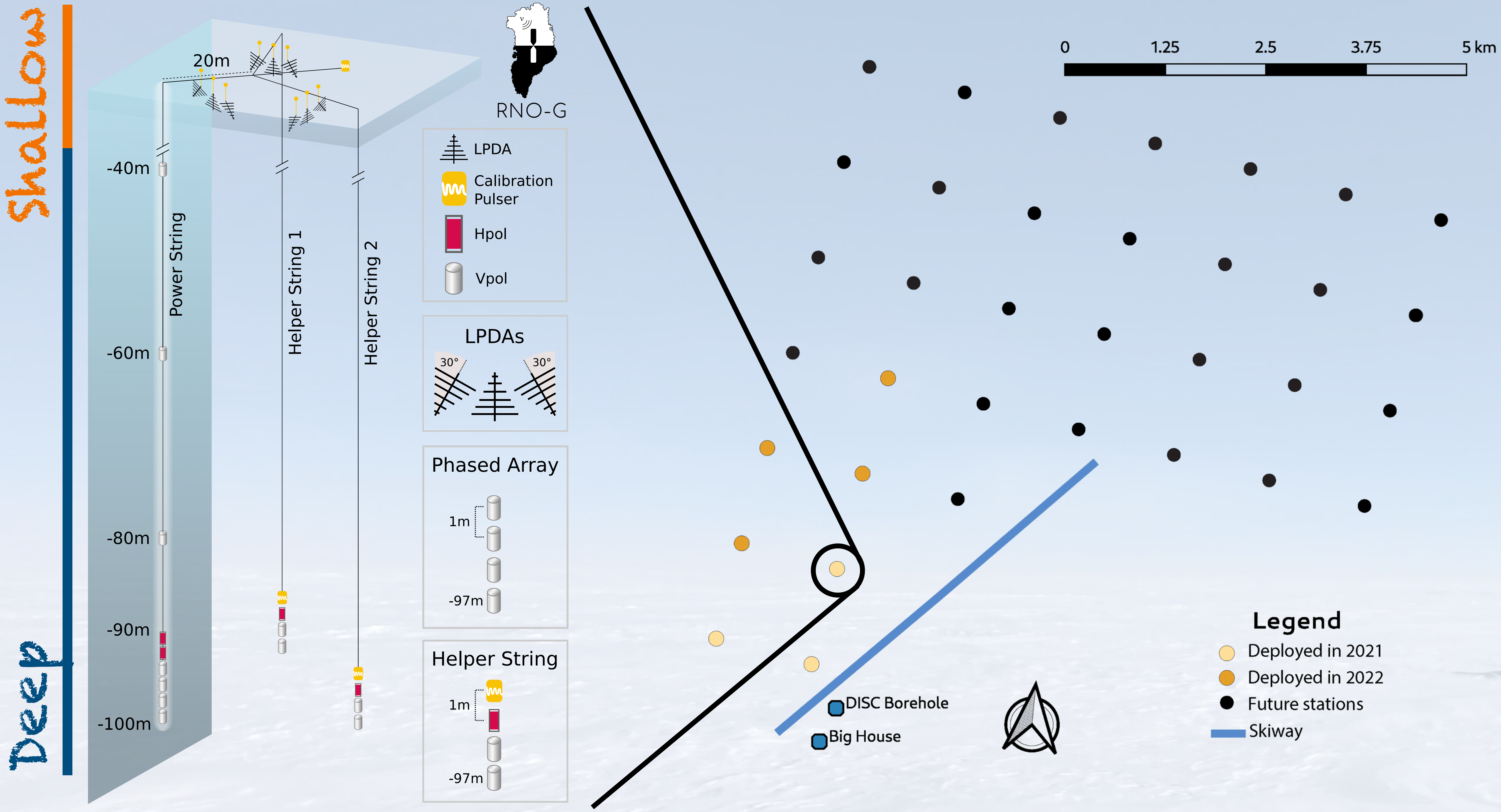


- Hybrid design with 24 antennas (3 different antenna types)
- Each station acts as independent detector

Radio Neutrino Observatory - Greenland

Hybrid station with 24 antennas

35 stations on 1.25 km grid



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- 7 stations already in operation
- Fully funded (3 more seasons)
- Solar powered & wireless communication

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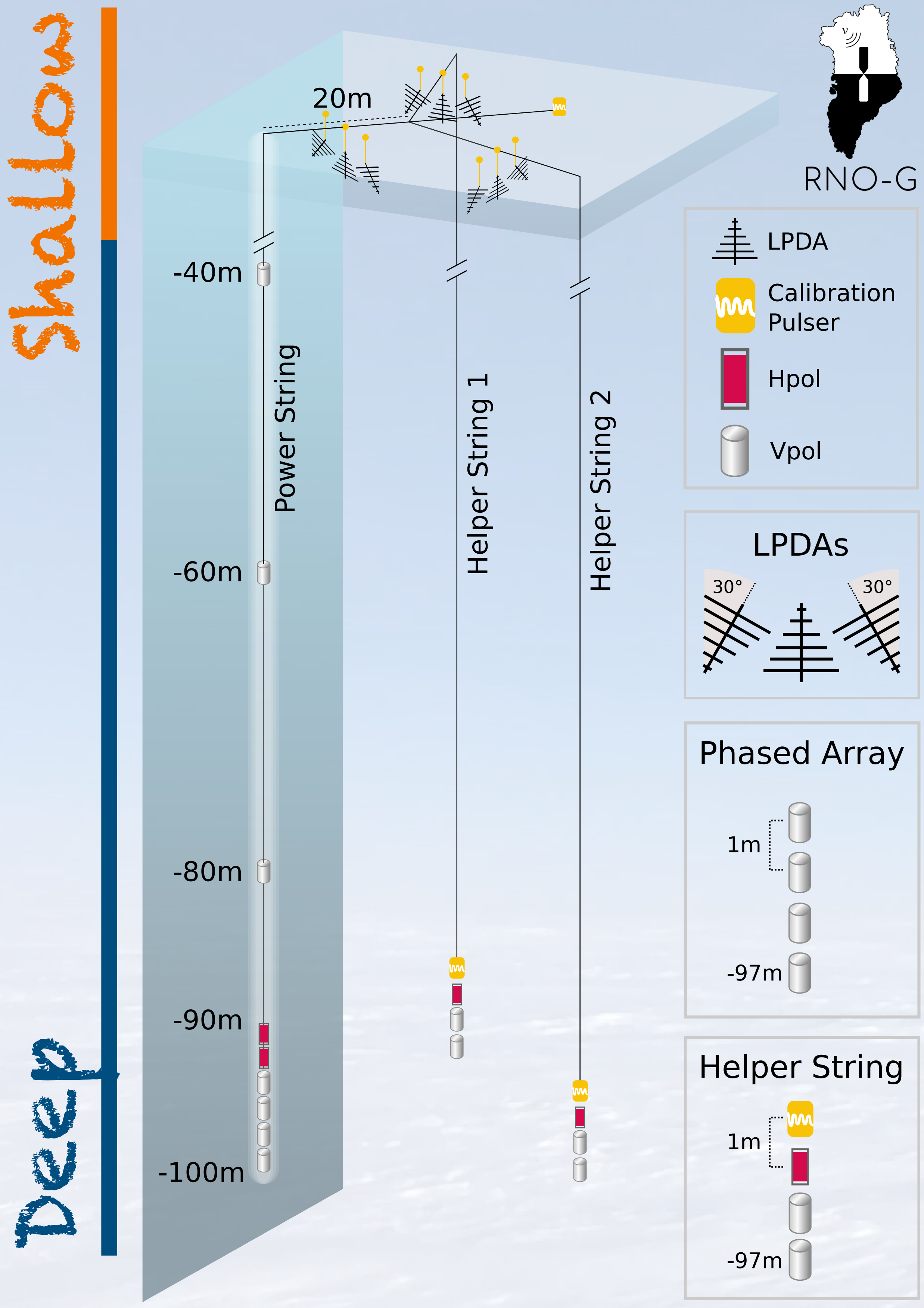

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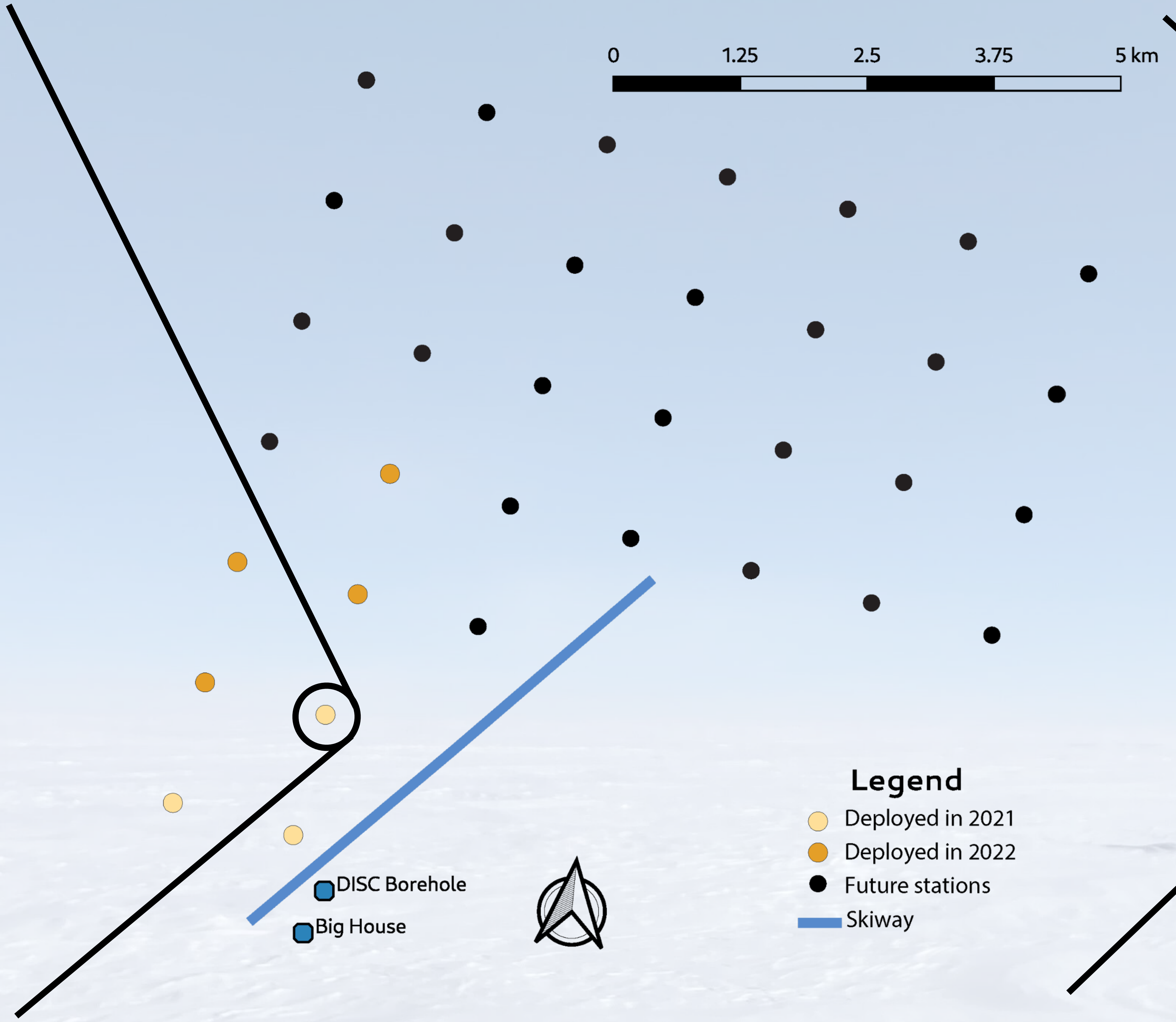

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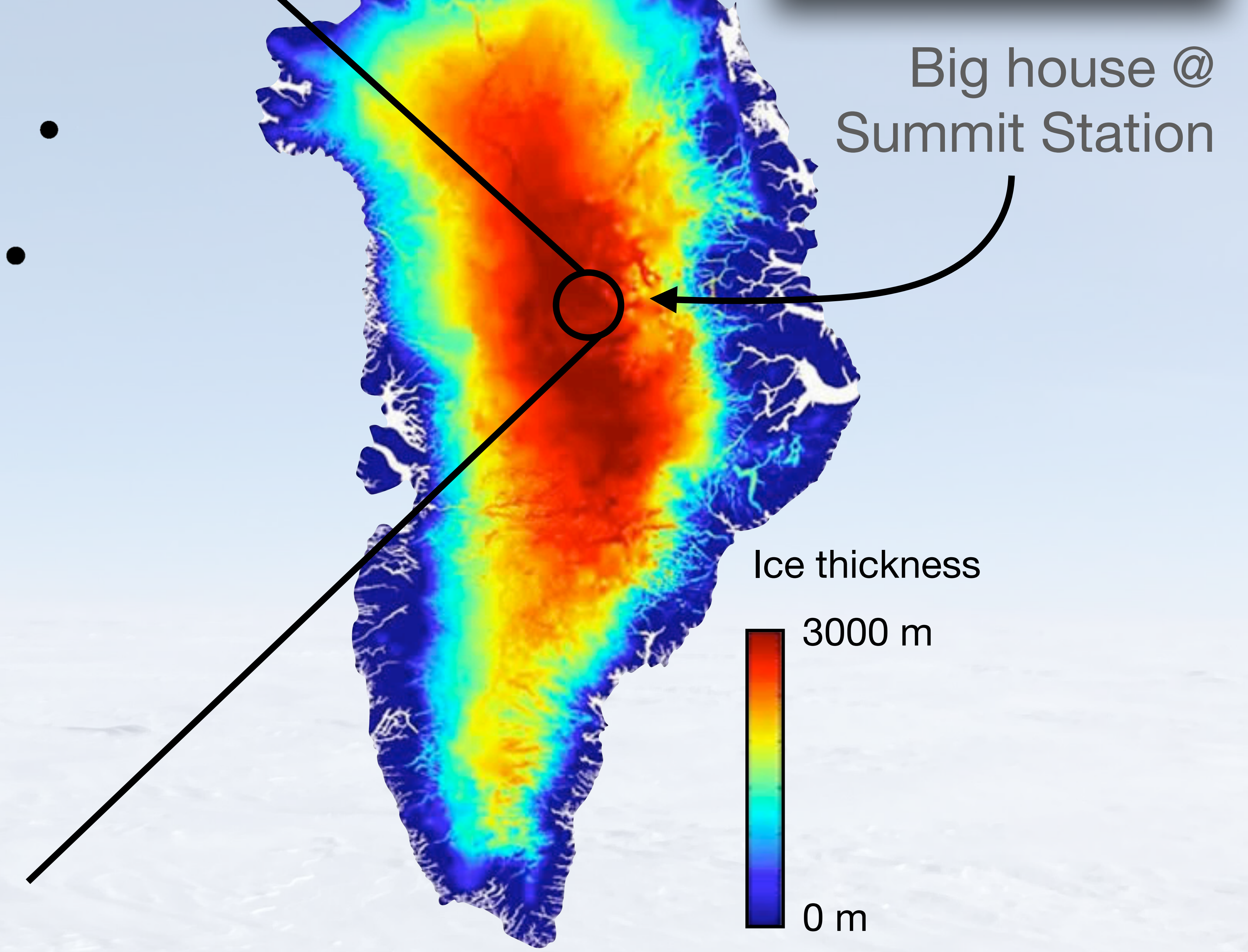
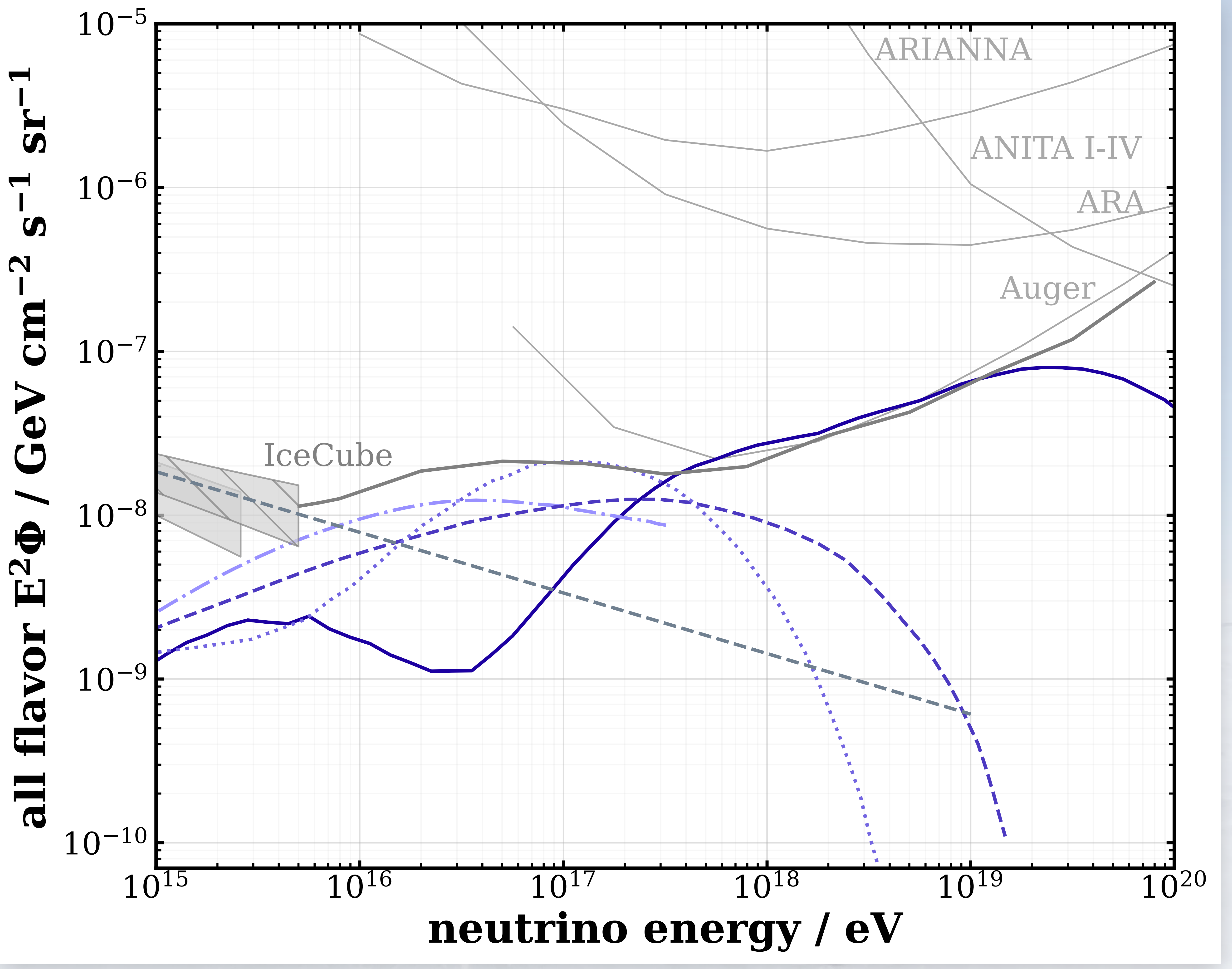
Greenland



- +3km of natural clean ice
- Existing infrastructure
- 10 months of sunlight per year

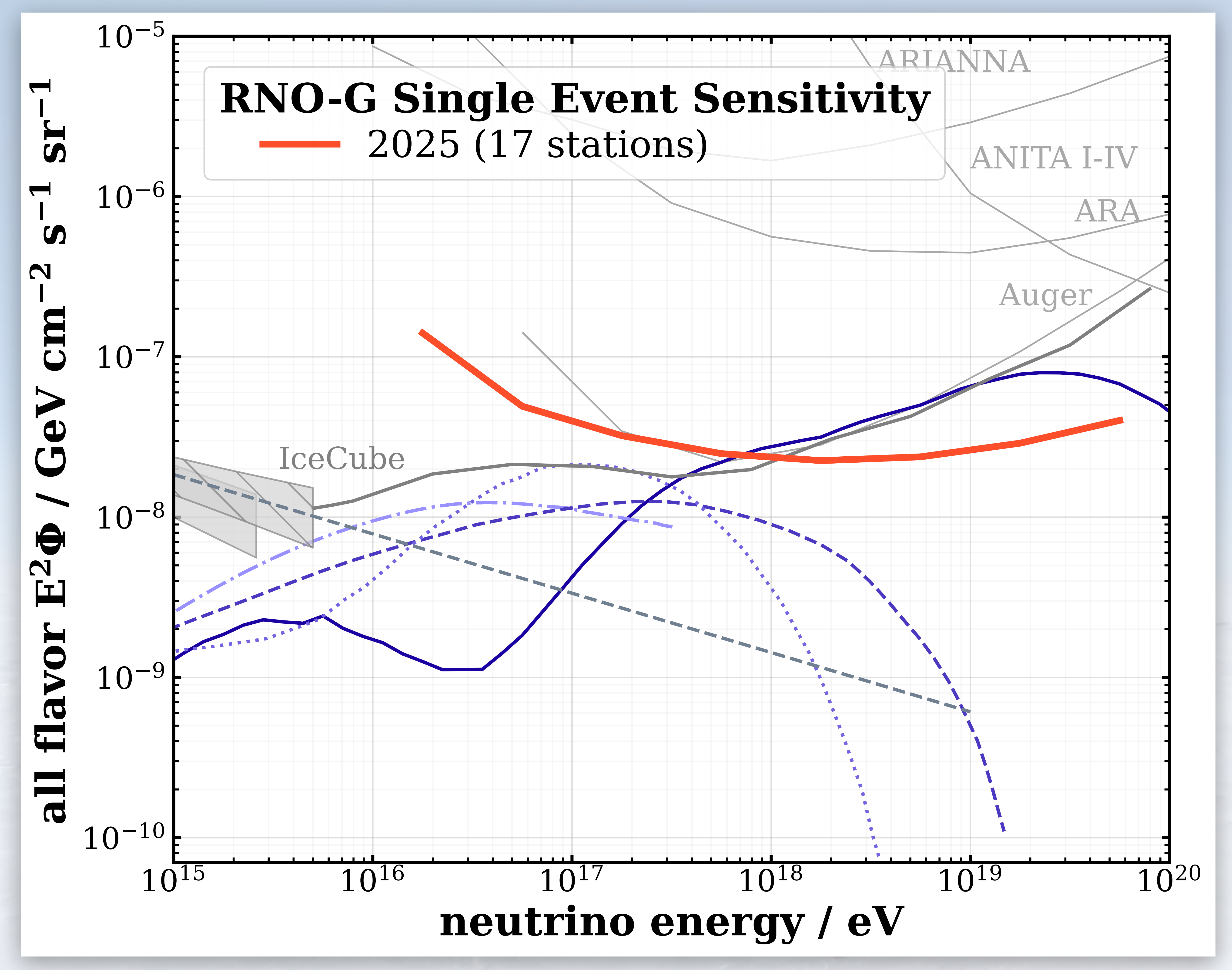
Sensitivity: Diffuse emission



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

Sensitivity: Diffuse emission

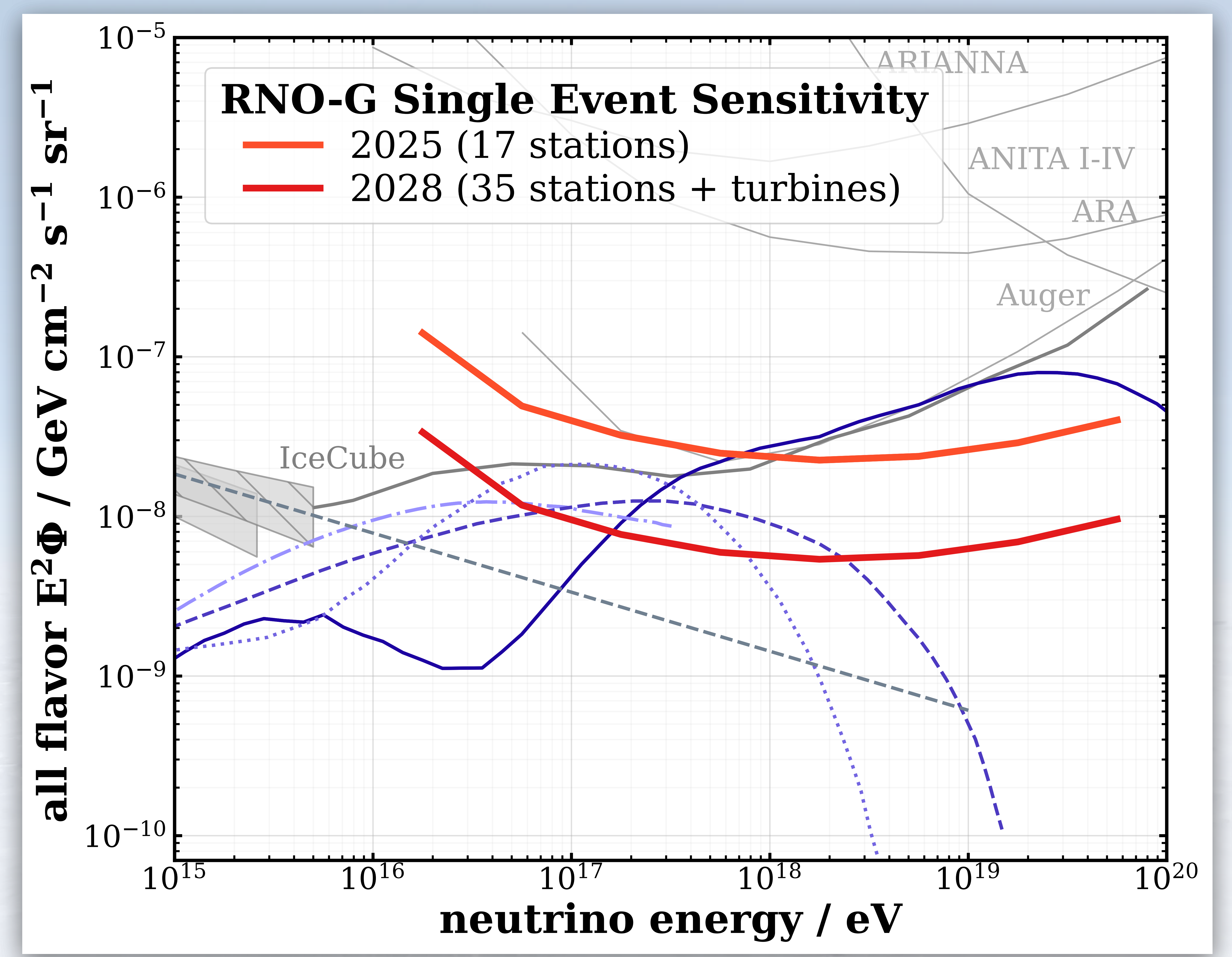
- Assuming no background



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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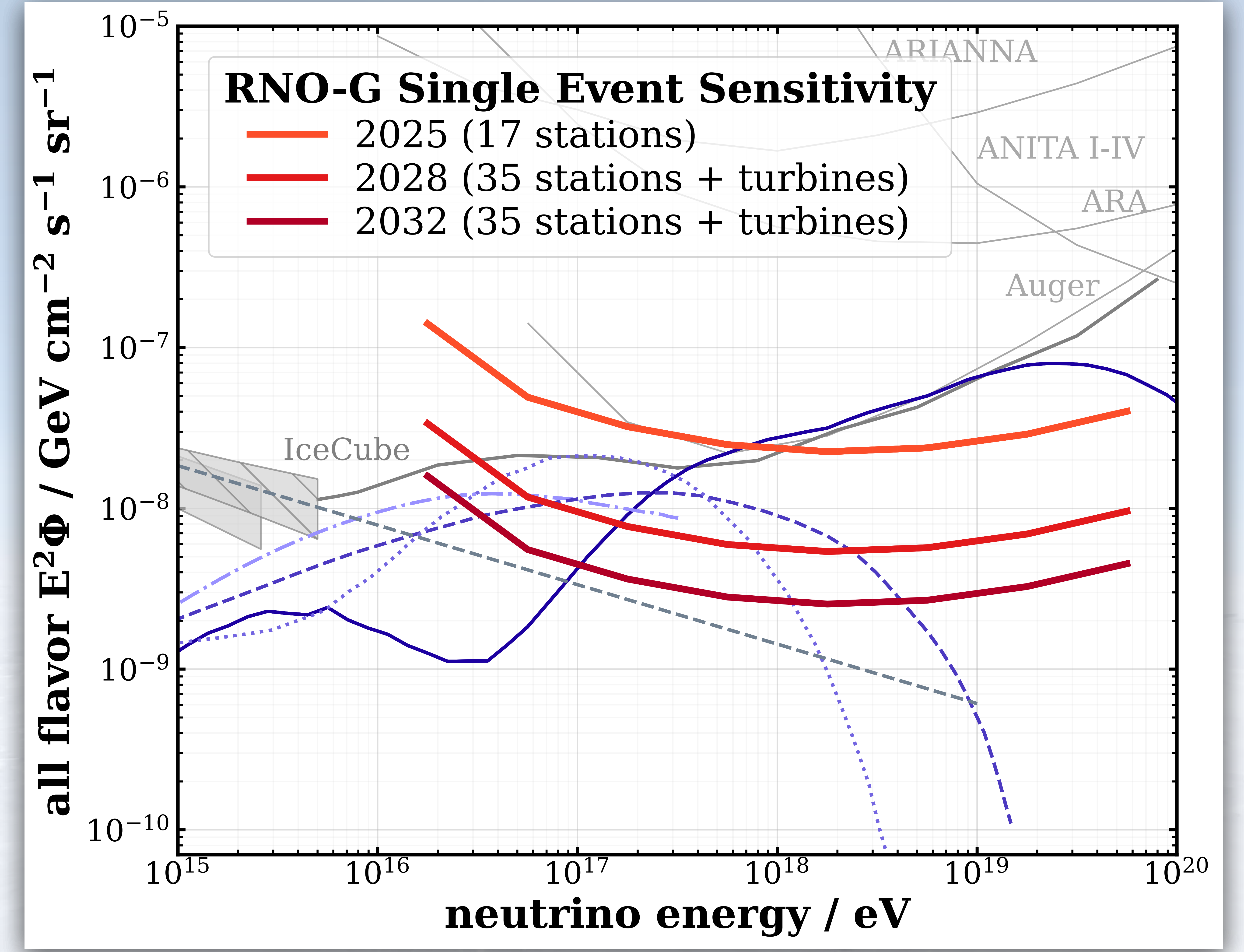

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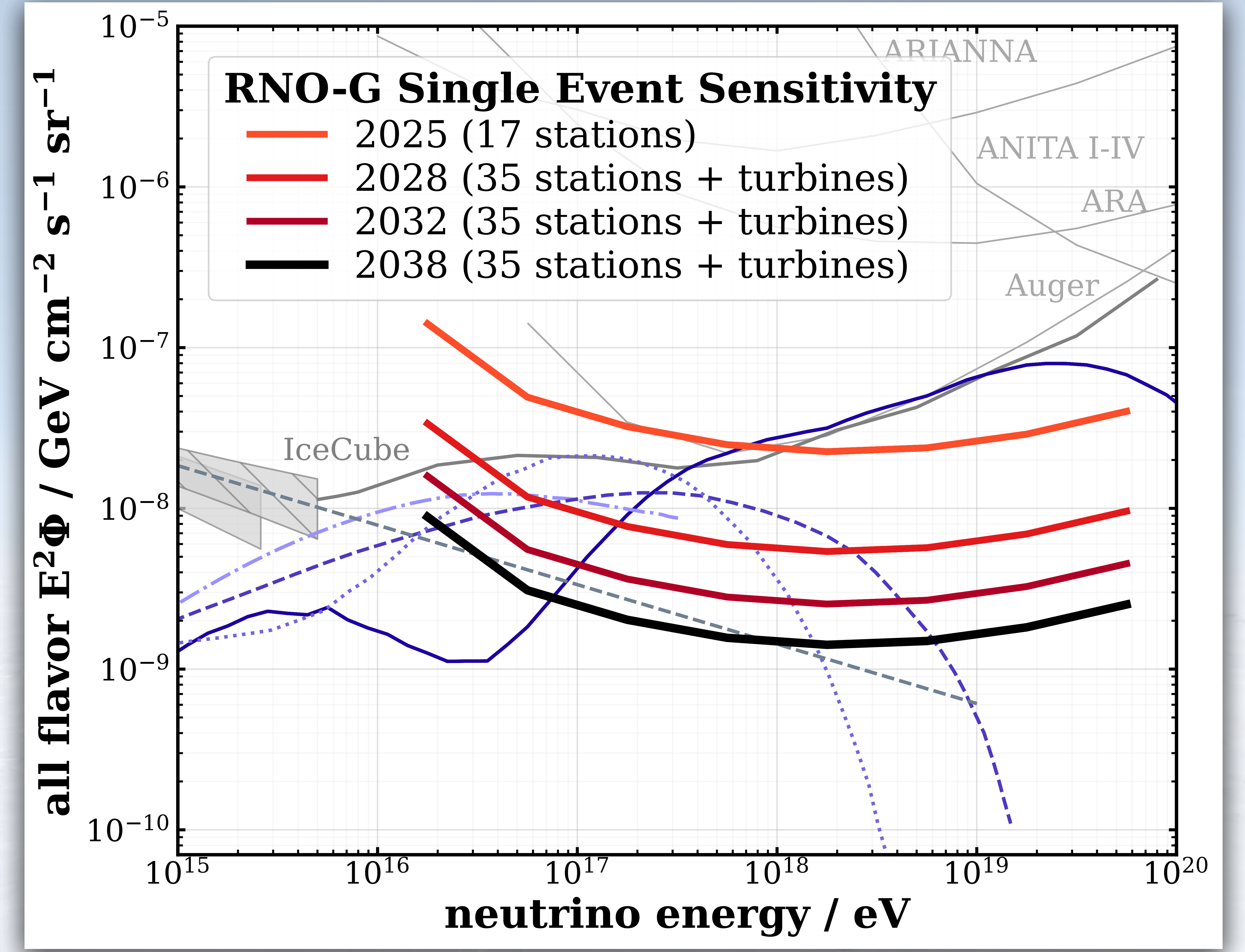
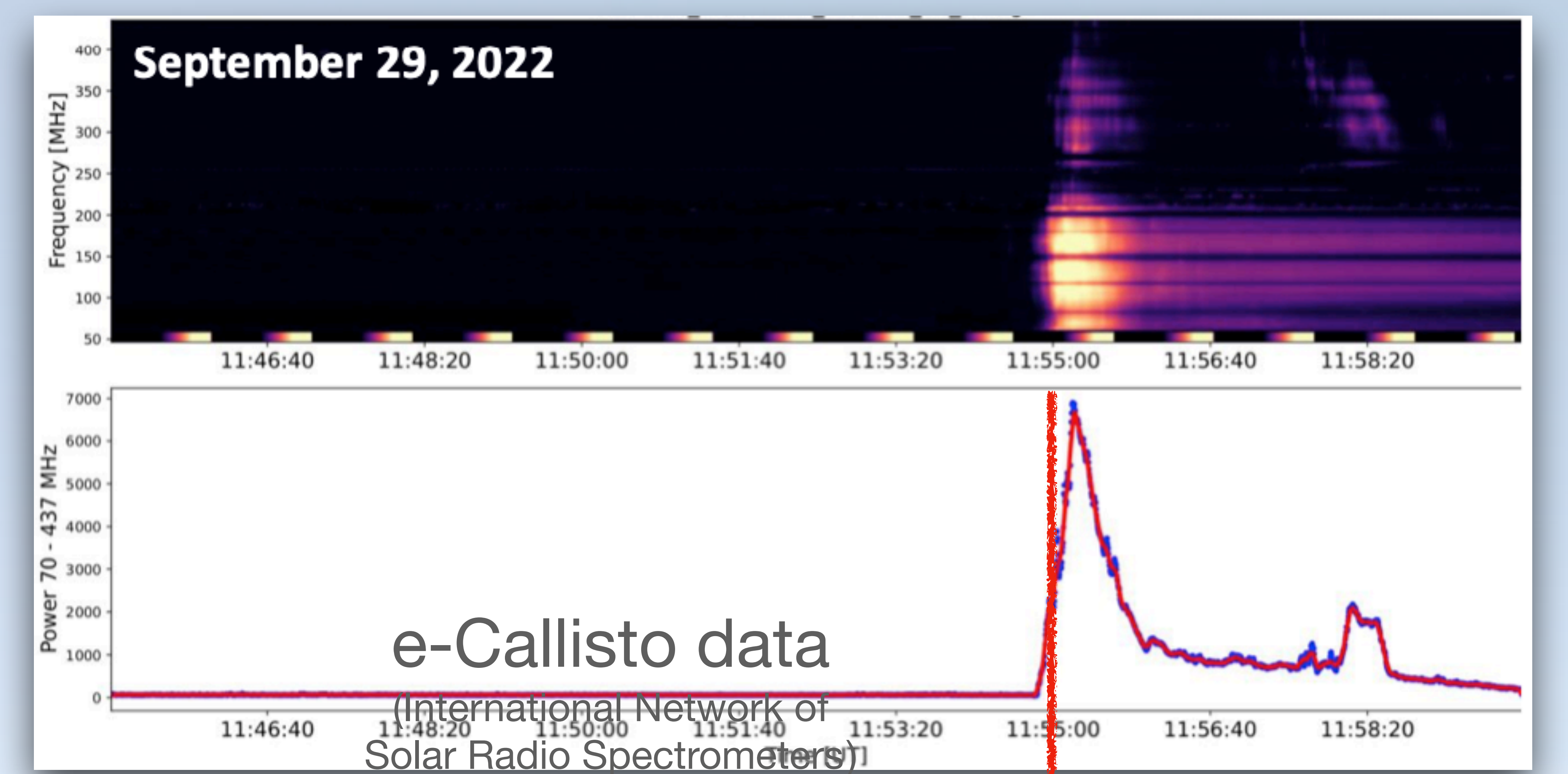
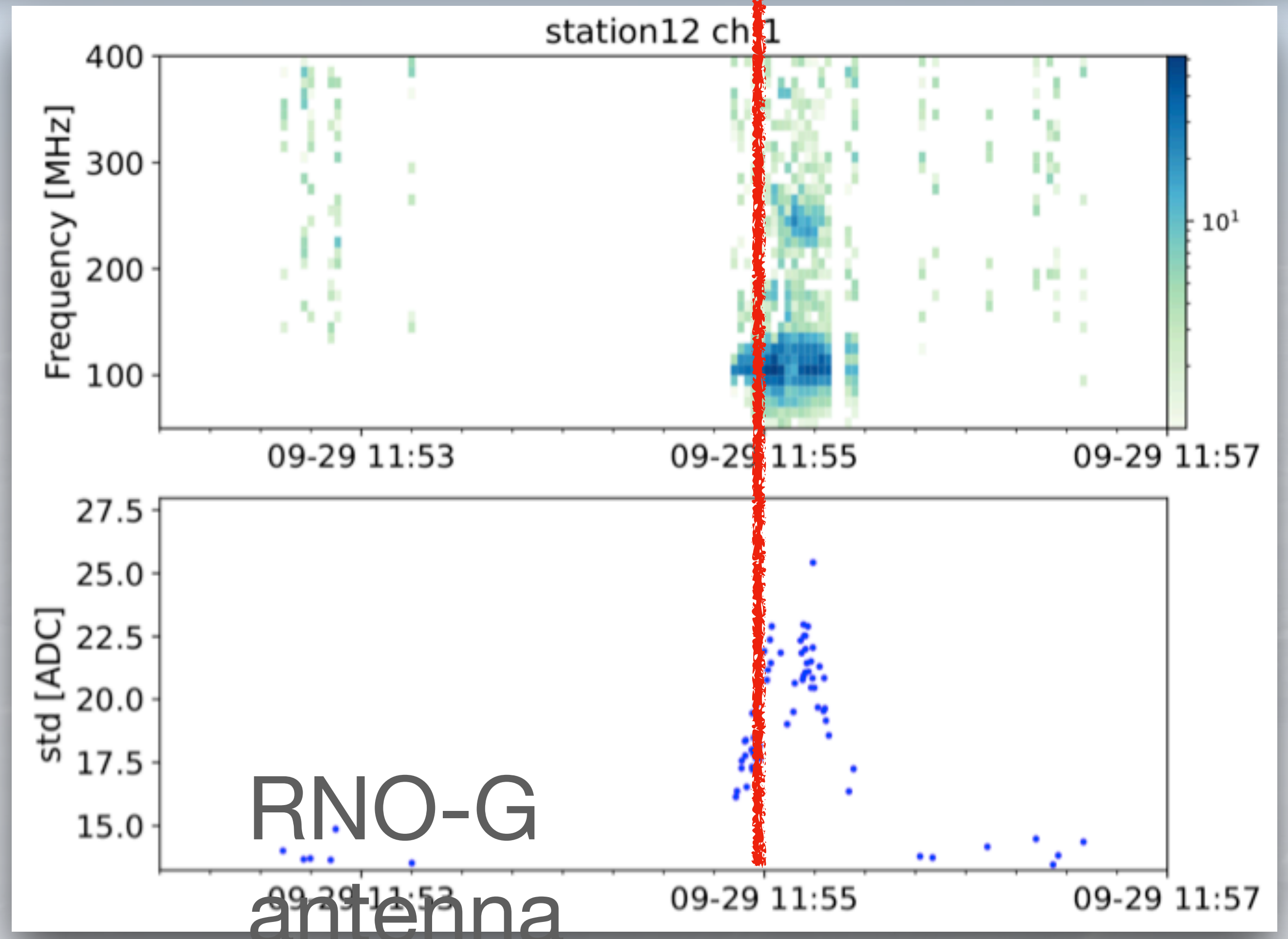
- Testing extension of astrophysical flux measured by IceCube



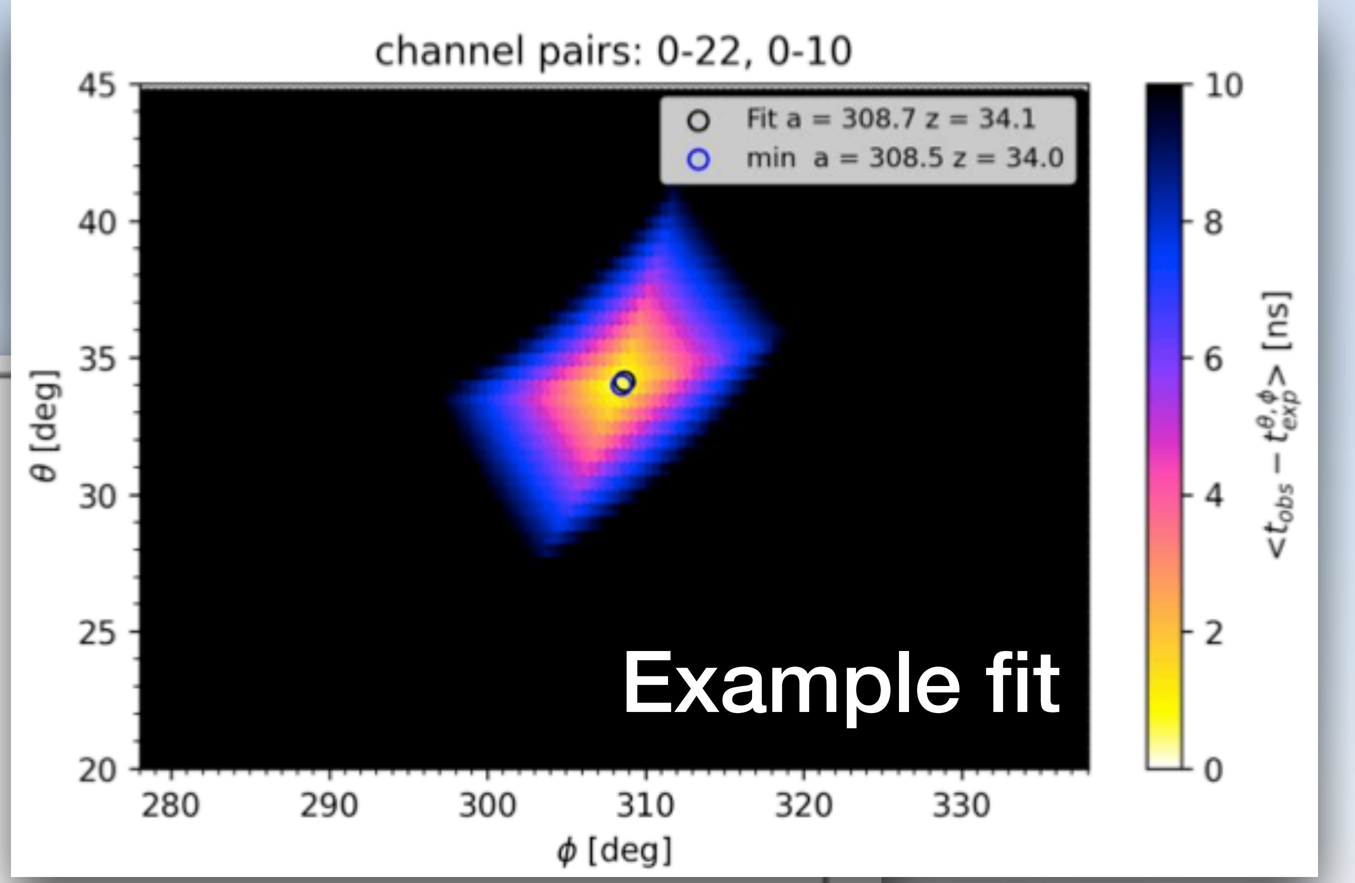
M. Muzio for RNO-G, PoS (ICRC23) 1485

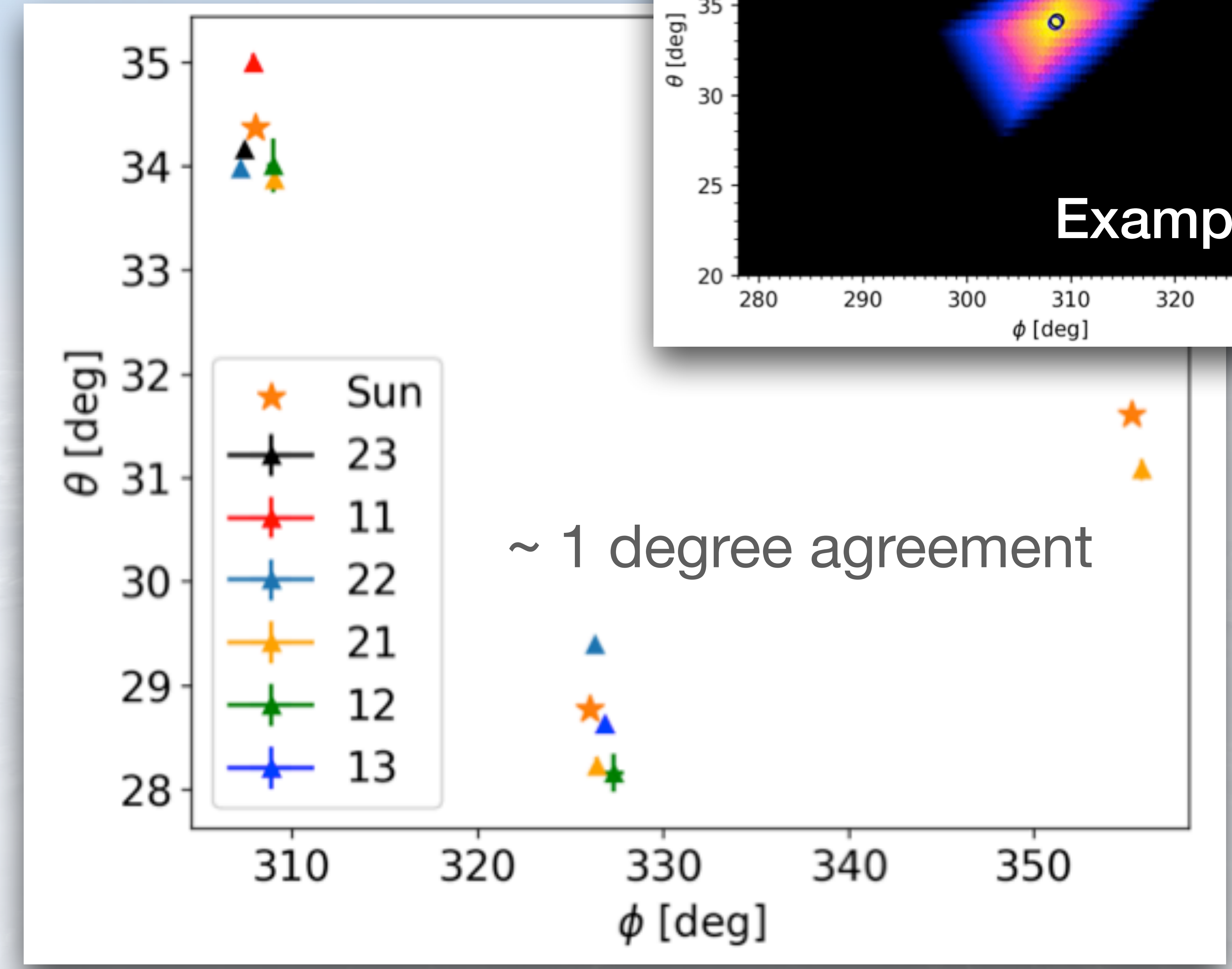
First look into the data: Solar flares





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

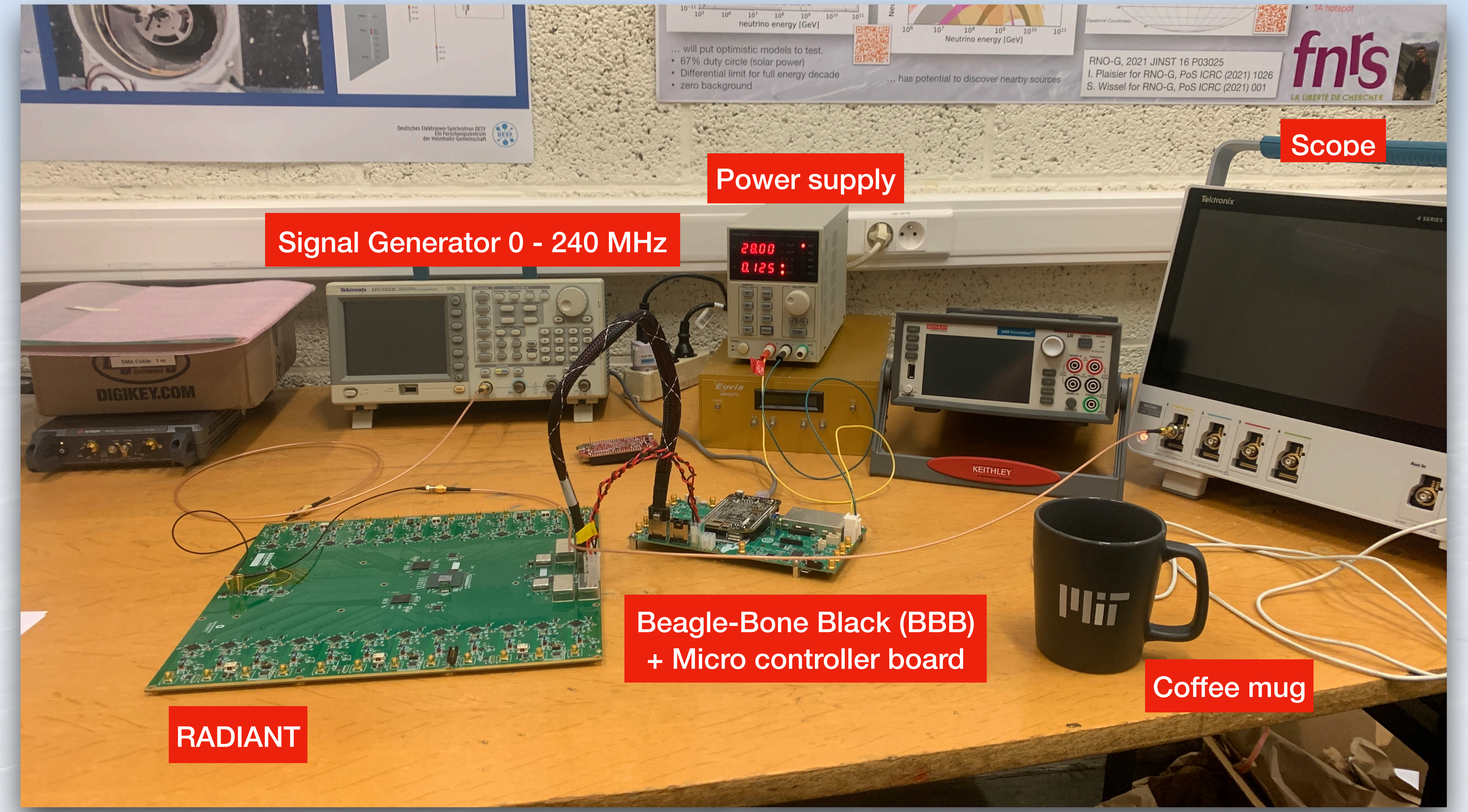


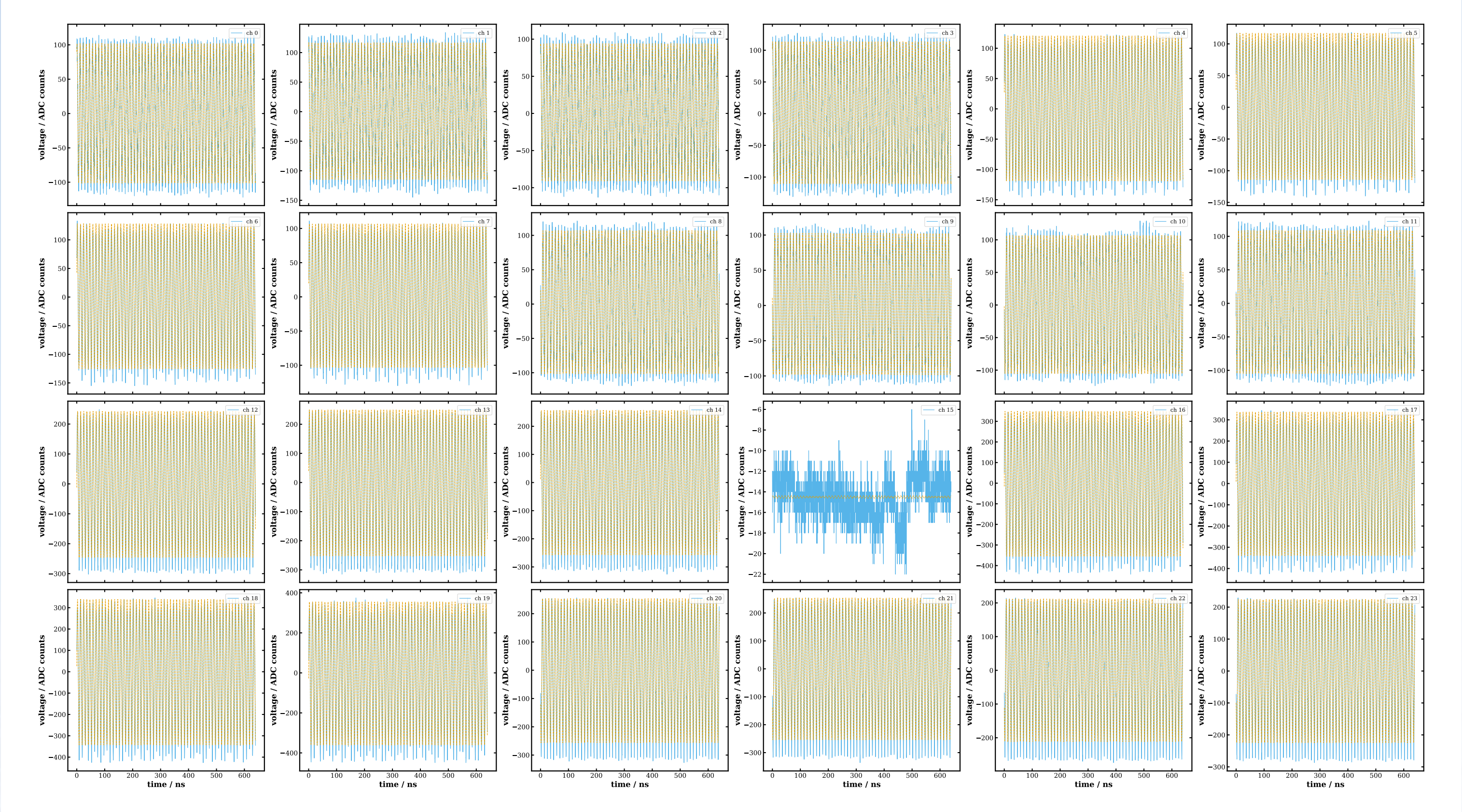


S. Hallmann for RNO-G, Pos (ICRC23) 1043

IIHE Efforts: Production of RADIANT boards

- 24 channel, low power, 3.2 GHz digitiser board
- Producing boards here in Belgium
- Currently producing and testing ~15 boards for next season





CH	result	290 < seam sample < 350	0 < slow sample < 290	rms < 100
0	FAIL	321.7 ps	314.7 ps	11.16 ps
1	FAIL	287.2 ps	311.6 ps	11.66 ps
2	FAIL	288.9 ps	305.6 ps	12.10 ps
3	FAIL	306.8 ps	313.9 ps	10.42 ps
4	FAIL	331.9 ps	309.7 ps	14.26 ps
5	FAIL	319.6 ps	321.1 ps	10.80 ps
6	FAIL	320.8 ps	330.0 ps	12.16 ps
7	FAIL	321.3 ps	326.3 ps	14.82 ps
8	FAIL	289.4 ps	332.9 ps	14.83 ps
9	FAIL	309.4 ps	329.5 ps	12.55 ps
10	FAIL	308.1 ps	324.7 ps	15.75 ps
11	FAIL	315.7 ps	327.8 ps	13.63 ps
12	FAIL	284.7 ps	323.8 ps	11.11 ps
13	FAIL	555.3 ps	192.0 ps	171.92 ps
14	FAIL	269.4 ps	320.6 ps	11.37 ps
15	FAIL	282.5 ps	318.7 ps	12.02 ps
16	FAIL	305.9 ps	315.1 ps	10.69 ps
17	FAIL	300.8 ps	326.3 ps	9.22 ps
18	FAIL	343.8 ps	295.7 ps	11.05 ps
19	FAIL	312.8 ps	323.1 ps	10.99 ps
20	FAIL	285.1 ps	330.8 ps	12.51 ps
21	FAIL	335.7 ps	304.9 ps	11.02 ps
22	FAIL	368.9 ps	317.7 ps	12.53 ps
23	FAIL	285.5 ps	324.4 ps	11.28 ps

Michael Korntheuer

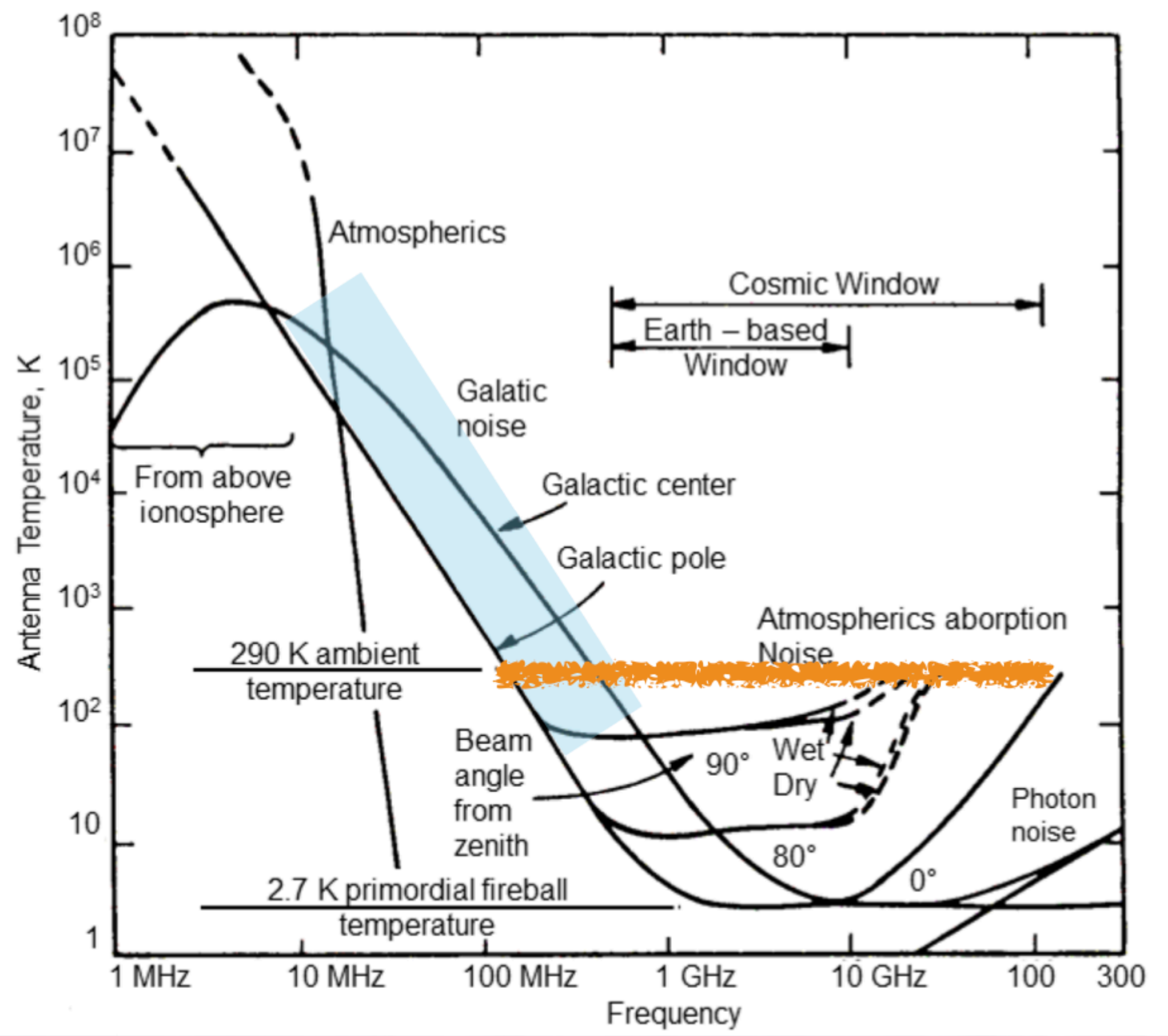
Abby Bishop
(visiting us from the US)

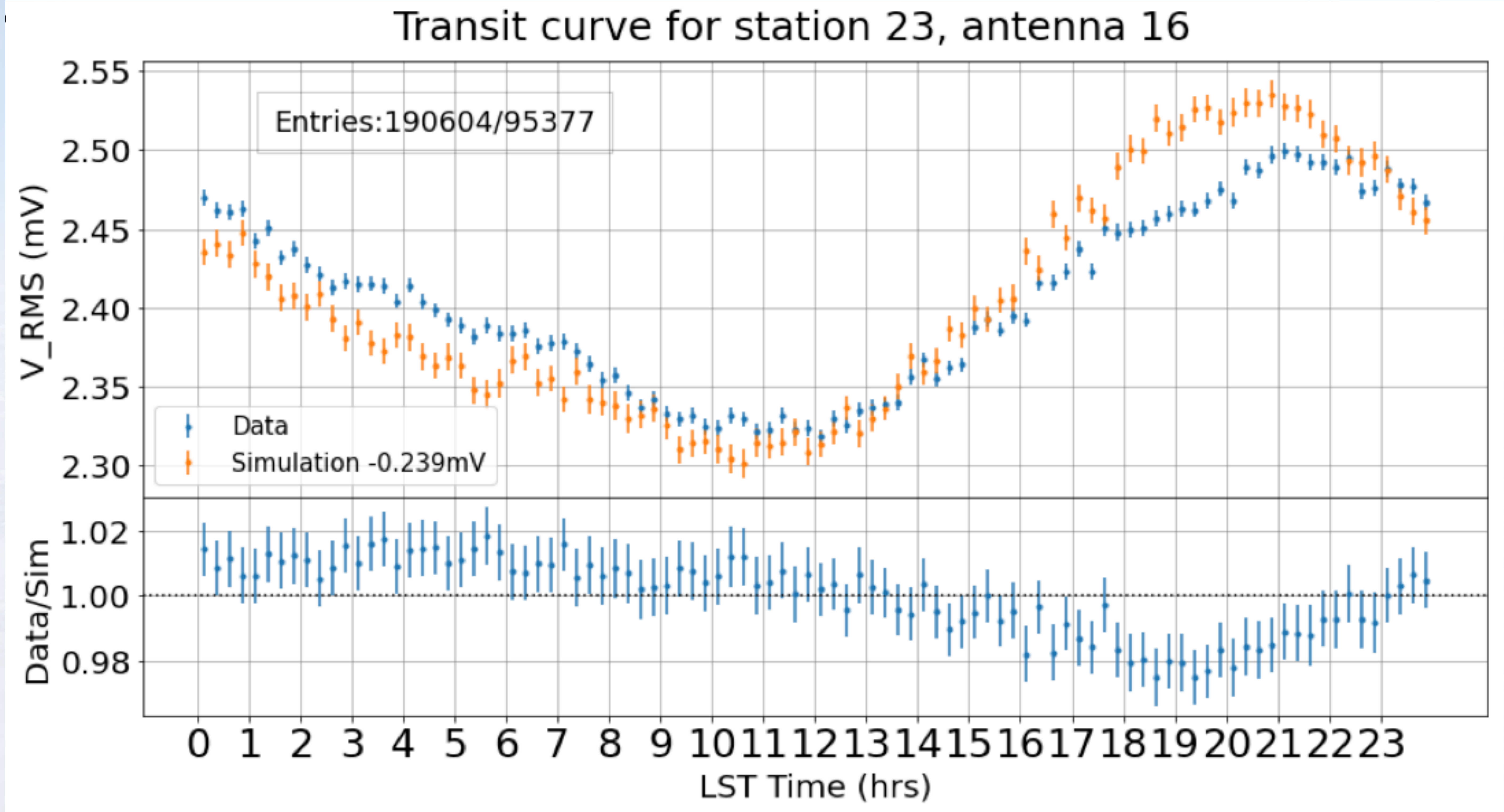
+ more people

IIHE Efforts: First look into the data

- Detecting the galactic emission with the upward facing antennas
  - Standard candle (only parts of plane visible at RNO-G)
  - Requires data cleaning and band-passing
  - Excess & modulation visible in the shallow upward facing antennas around 100 MHz
- "Proof of concept"

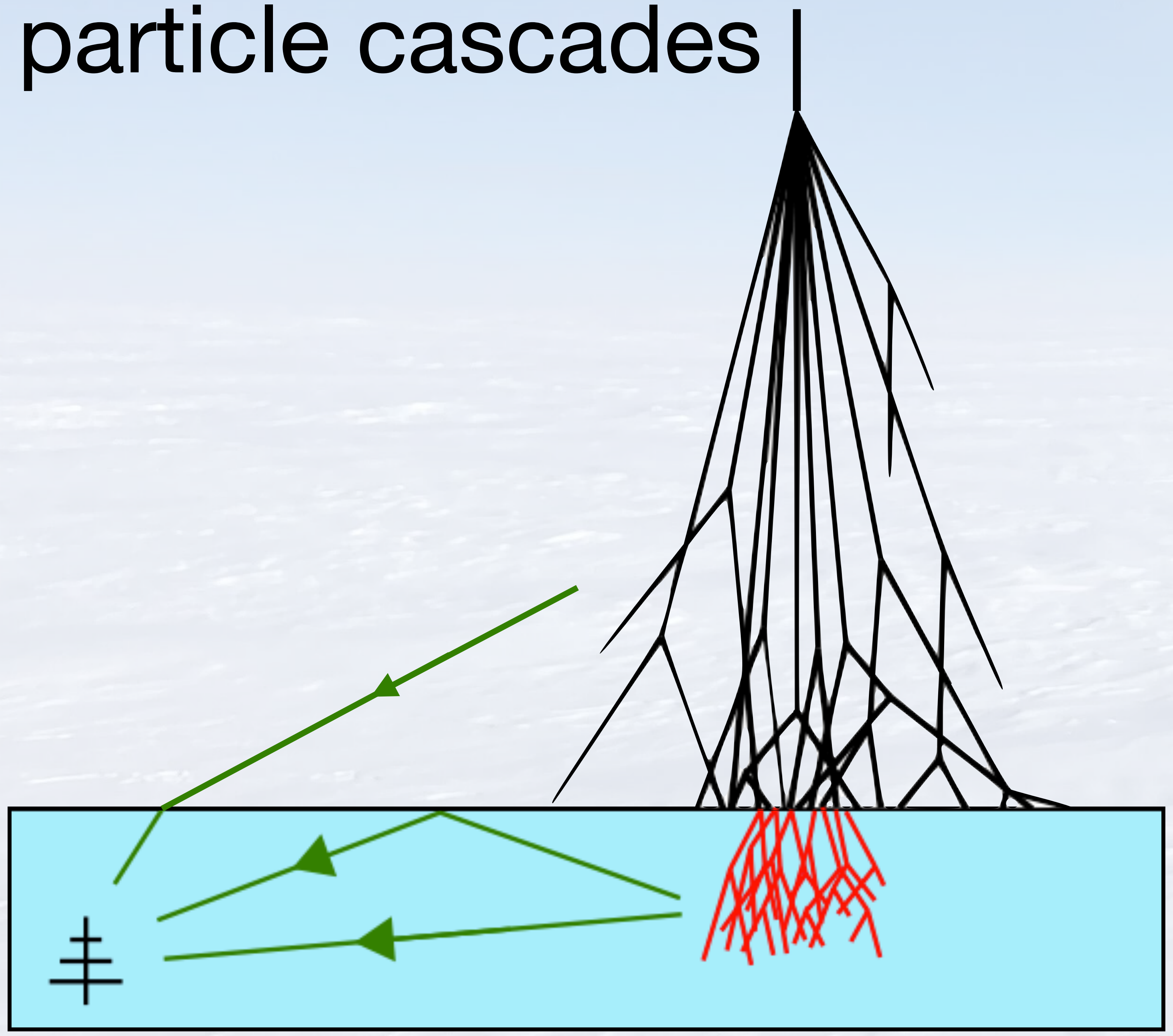
Jethro Stoffels

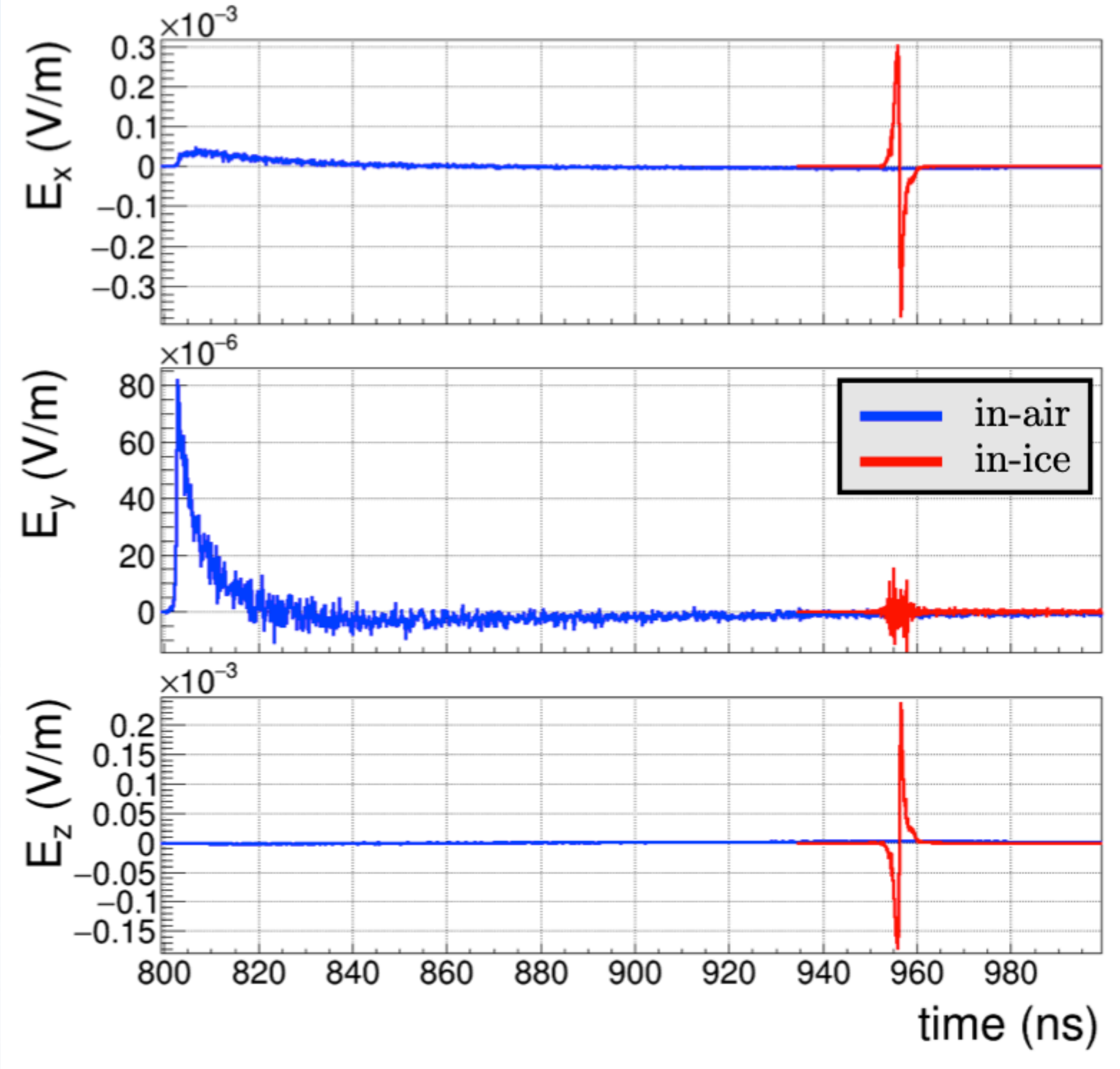


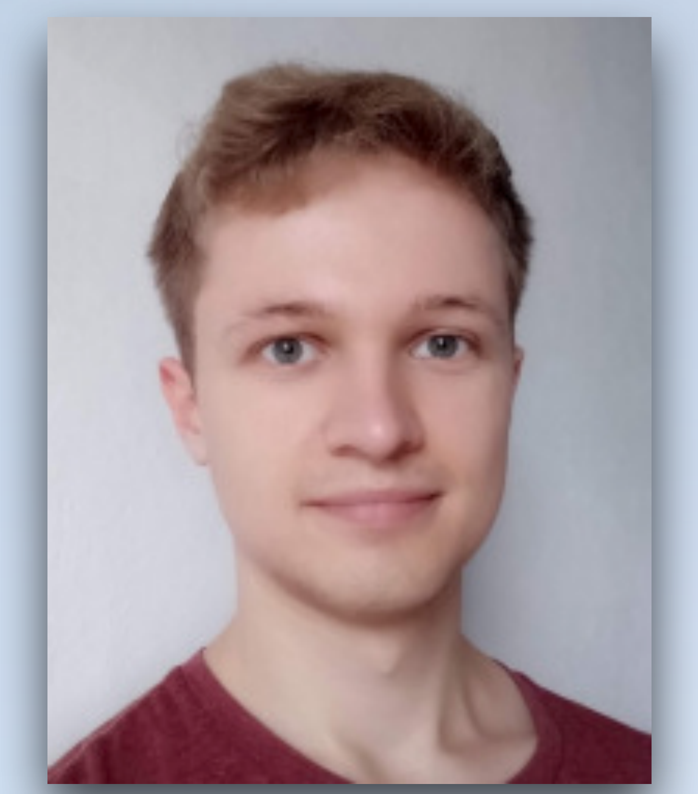


IIHE Efforts: Simulation of air showers

- First in-ice signals we will see
- Can be used to validate our detector and analysis techniques
- Develop a brand-new MC simulation code for in-ice particle cascades
  - Based on existing in-air code
  - Combine both code to simulated full event
- Overlap with RET-CR (next talk)







Simon De Kockere

Uzair Latif
(Moved to industry)

IIHE Efforts: Developing neutrino searches

fnrs
LA LIBERTÉ DE CHERCHER

- Lead of the Multi Messenger working group in RNO-G
- Develop a fast response analysis for transient alerts (as part of my FNRS grant)
- Current efforts: Developing event filtering

Case study: RNO-G sensitivity to a particular bright GRB

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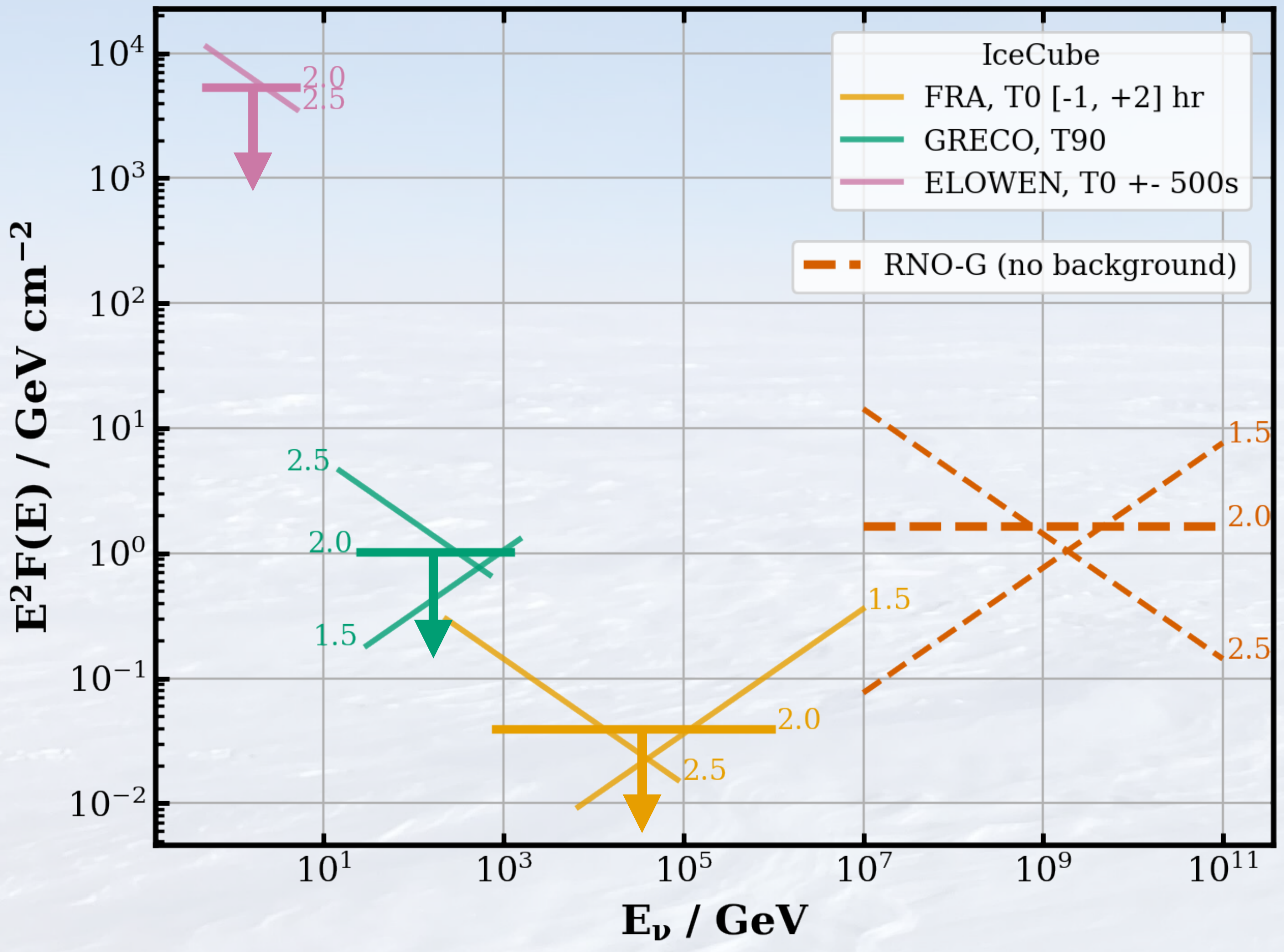

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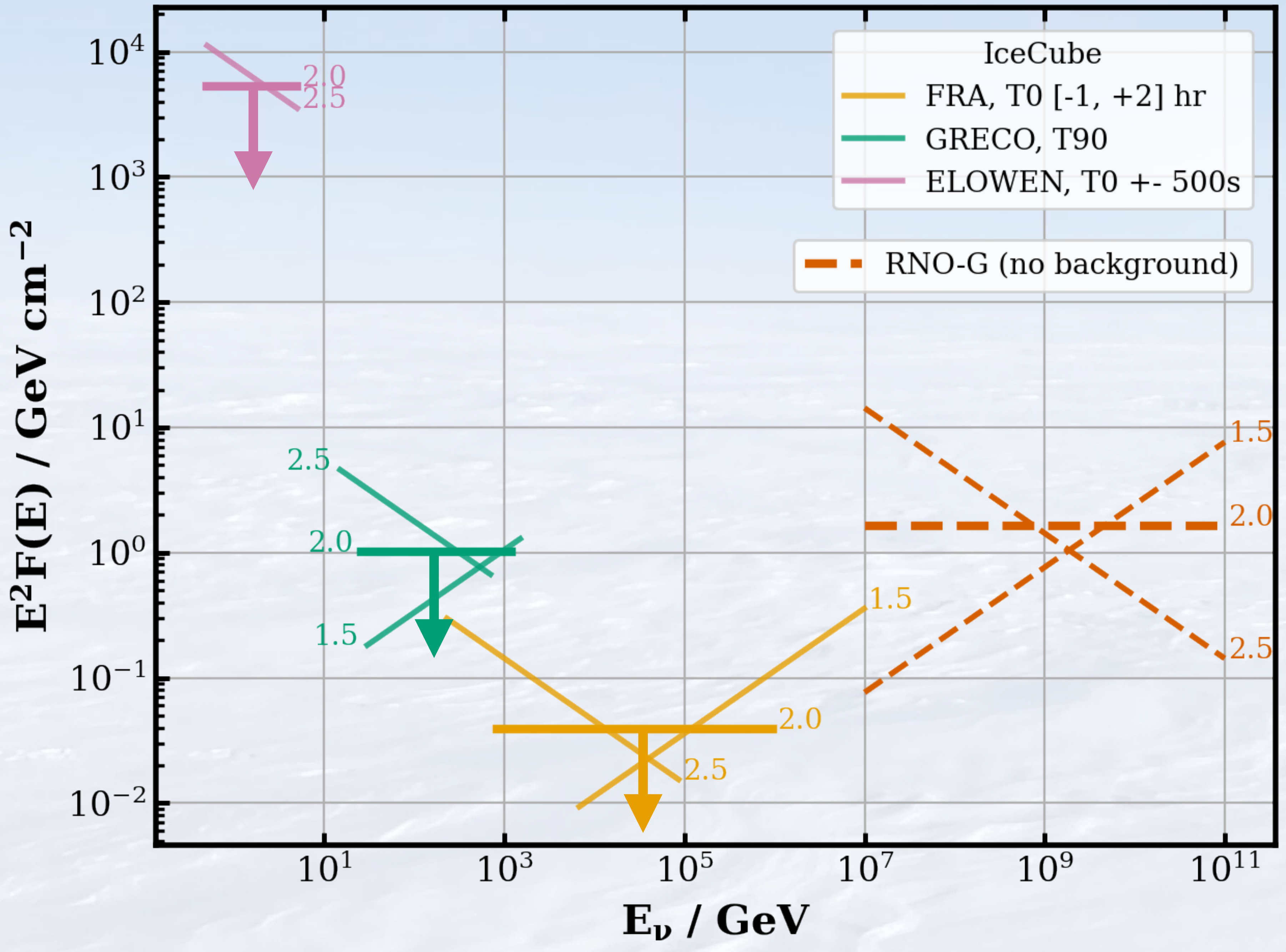
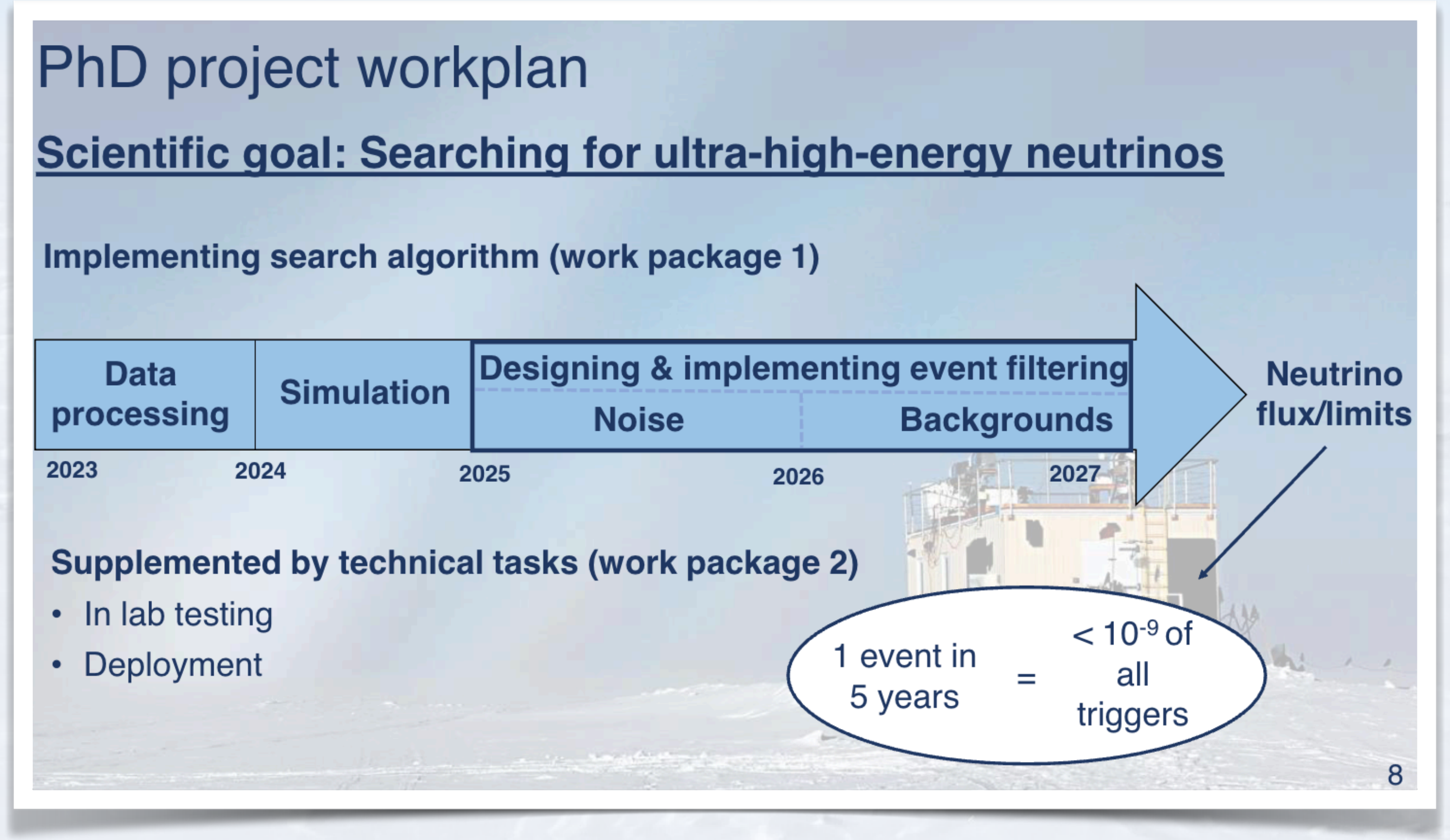


Excellent FRIA application (waiting for the result)

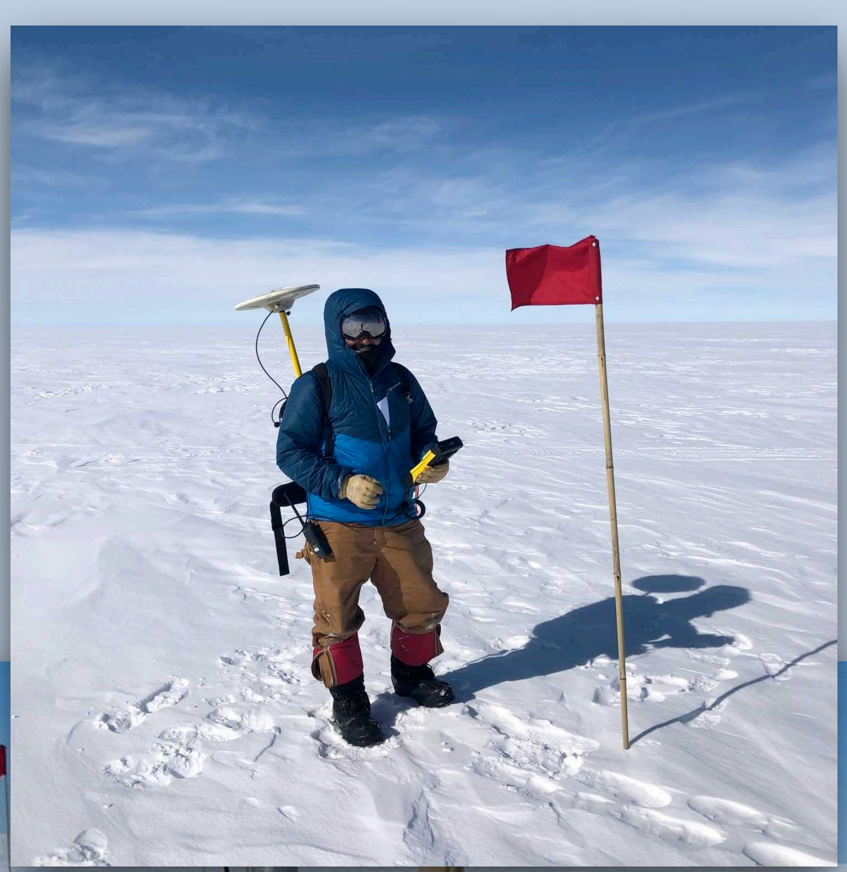


Ruben Camphyn

He already started! Data commissioning and calibration

IIHE Efforts: Deployment

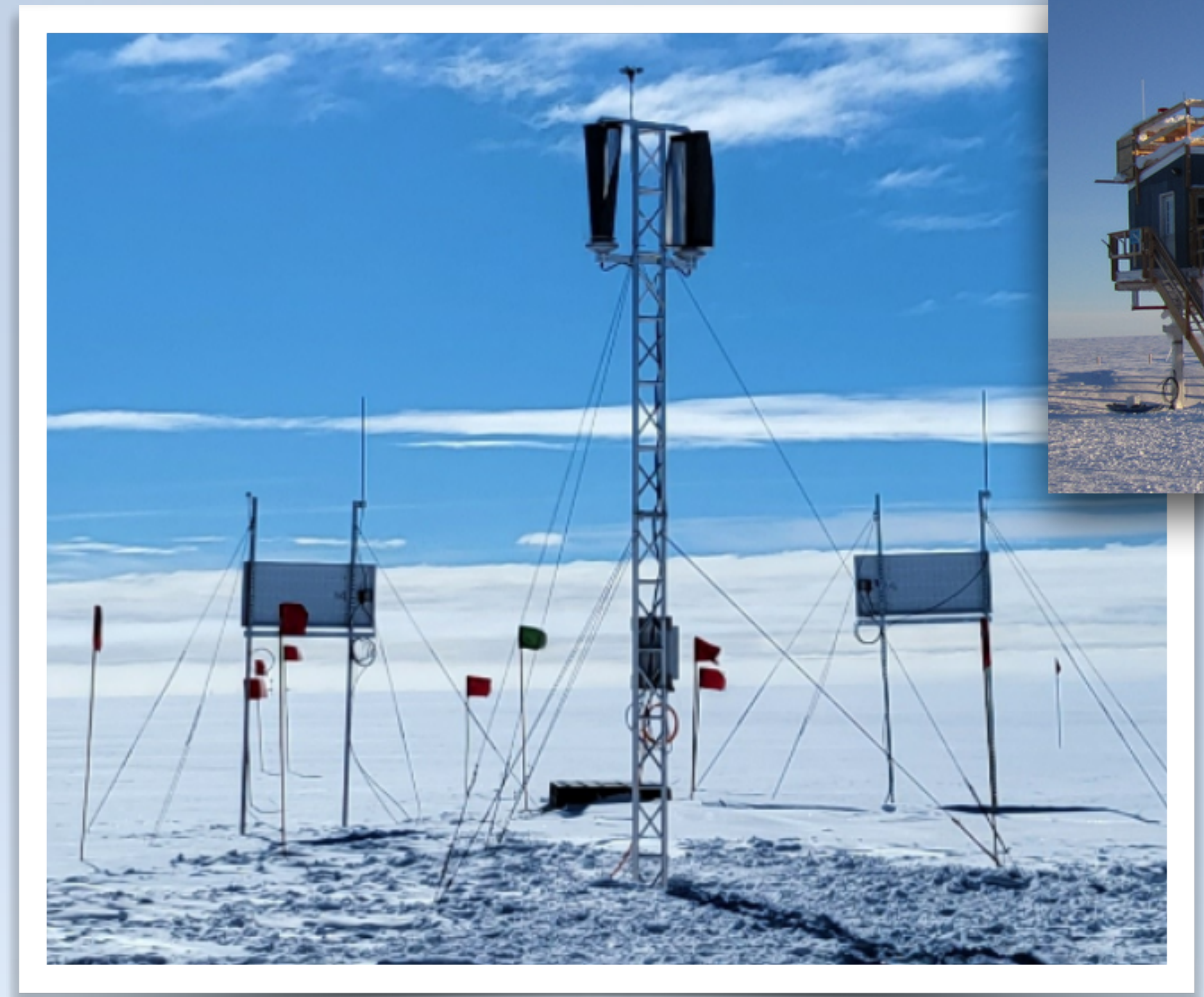
- Past seasons: Uzair, Simon, Paramita Dasgupta, Katie Mulrey
- Next Season: Felix, Jethro



Paramita Dasgupta
(Moved to Ohio State)

Katie Mulrey

Summary



- 7 station already in operation at Summit Station in Greenland and fully funded for in total 35 stations
- 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

- Strong group at IIHE lead by Nick & Simona
- Contributing to various activities:
  - Data analysis (Neutrino searches, ….)
  - Hardware production & testing
  - Deployment support
  - Commissioning


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

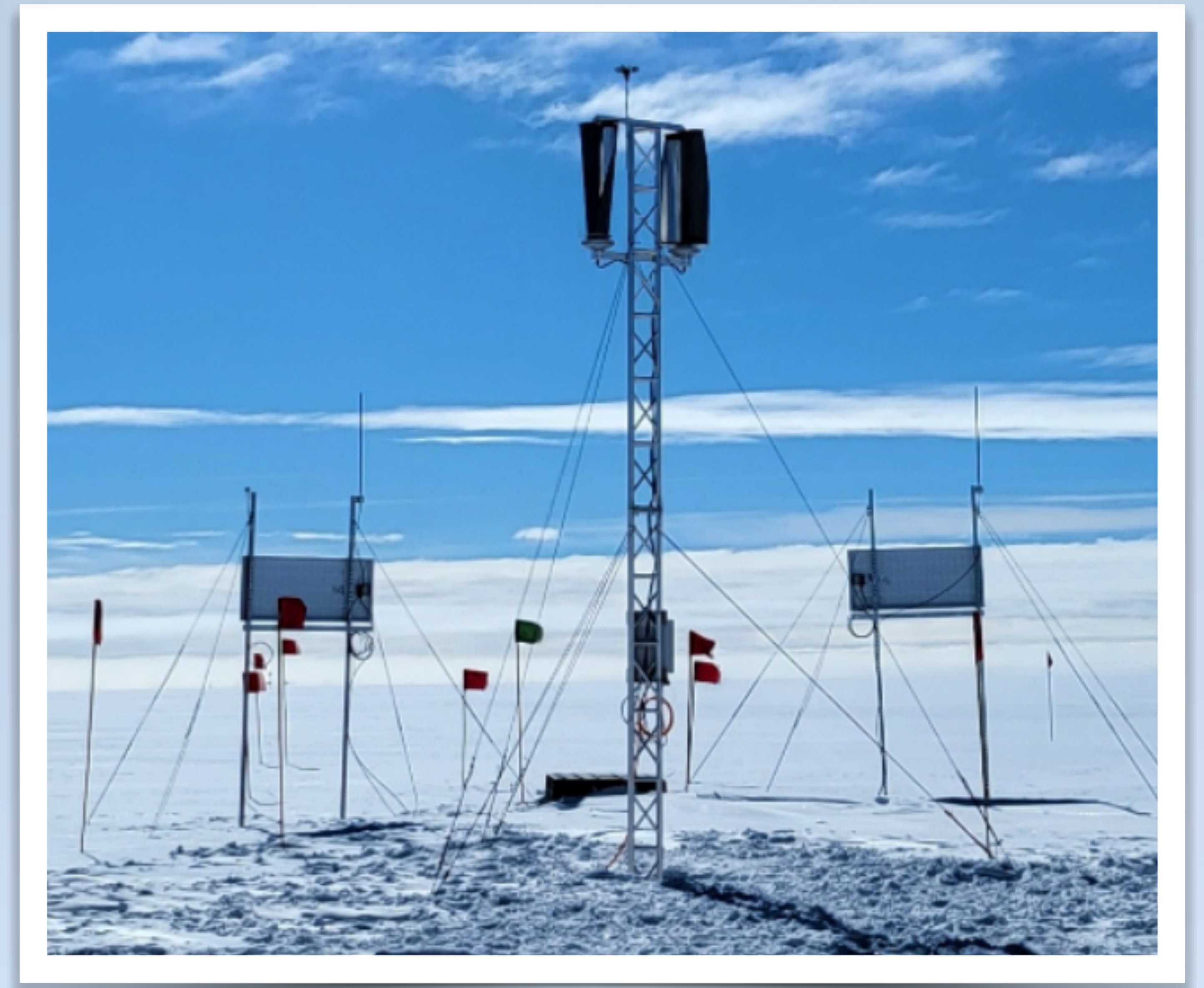
IIHE Efforts: Other tasks

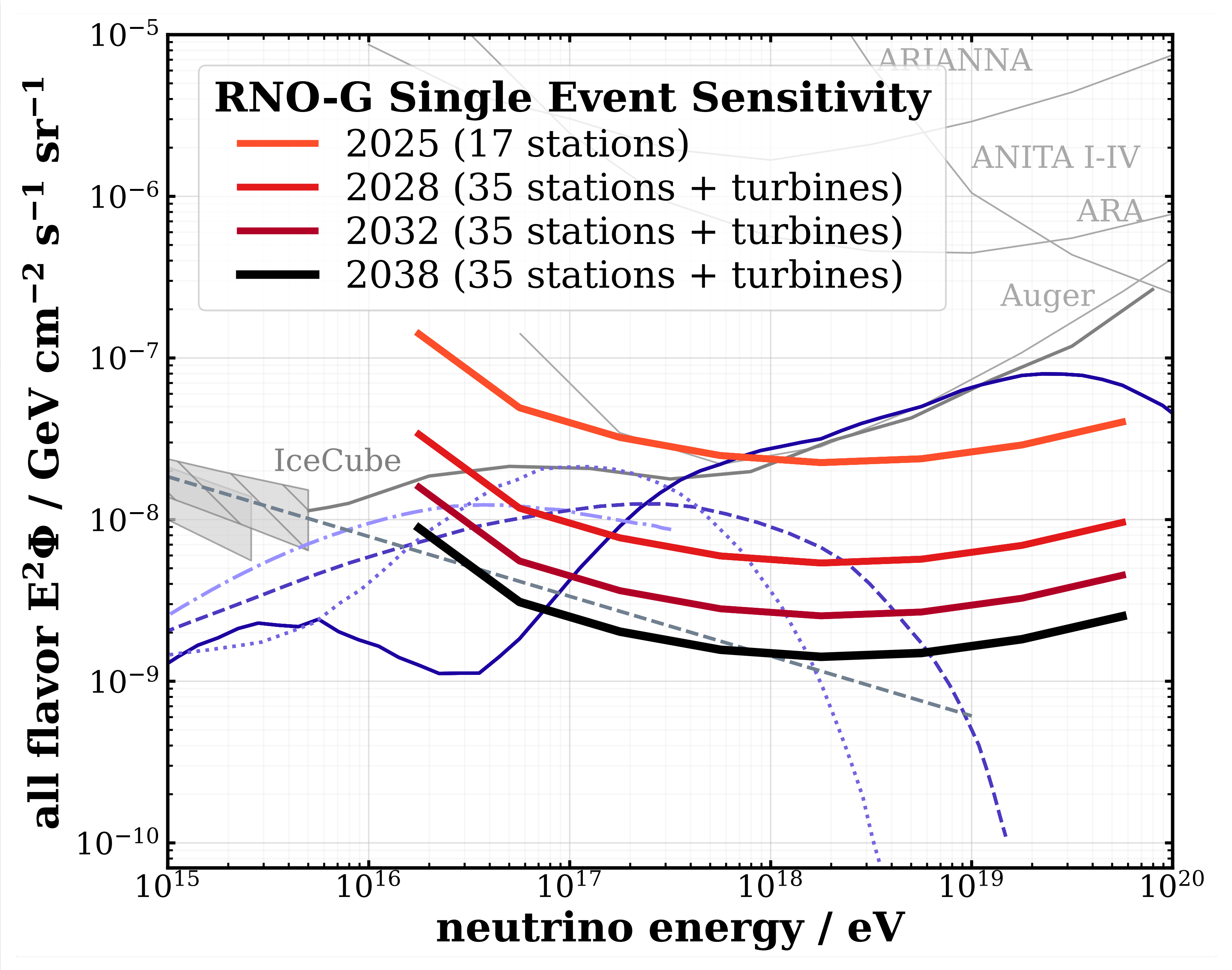
- Data commissioning
- Coding
- Voltage calibration
- ….

Backup

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]





Radio detection of neutrinos

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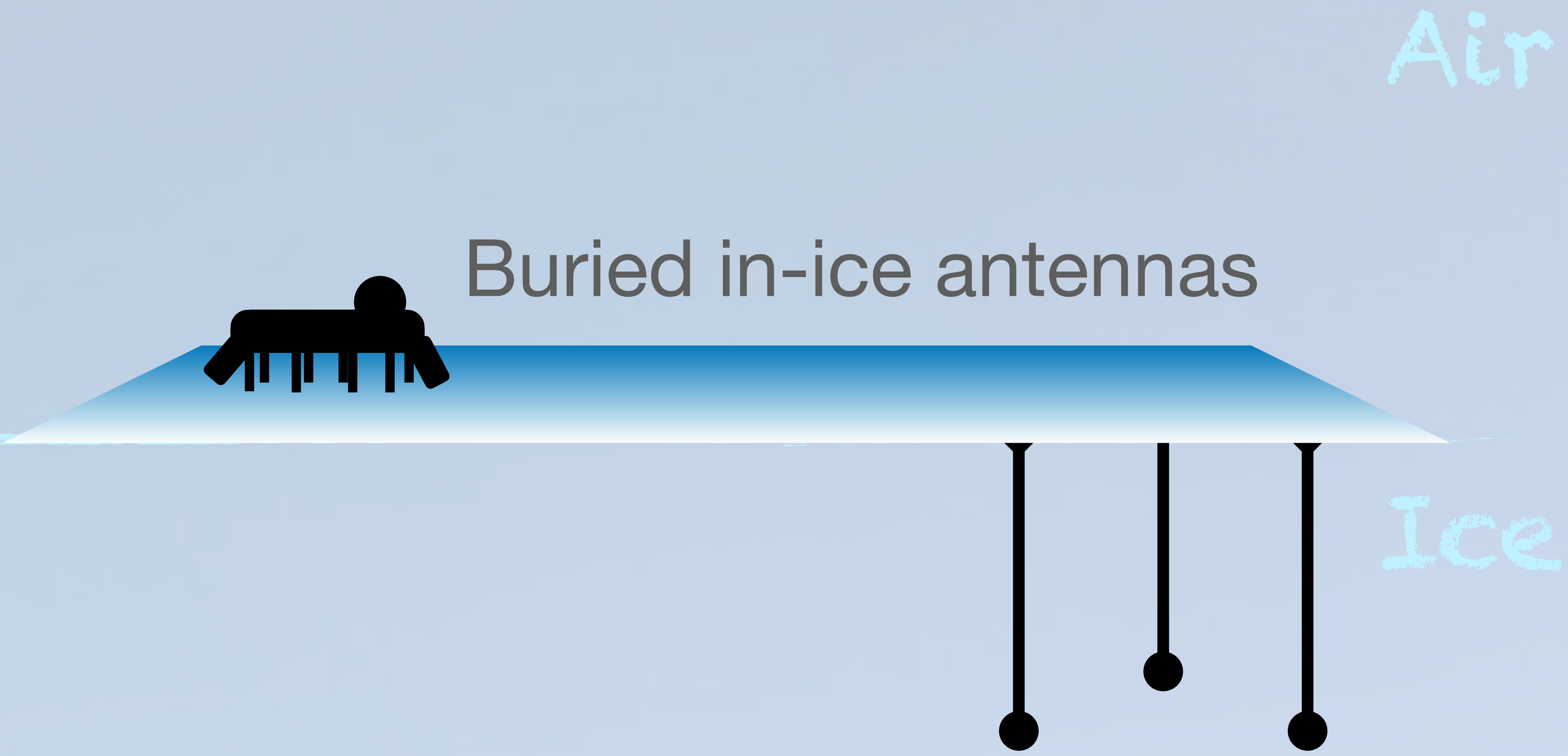
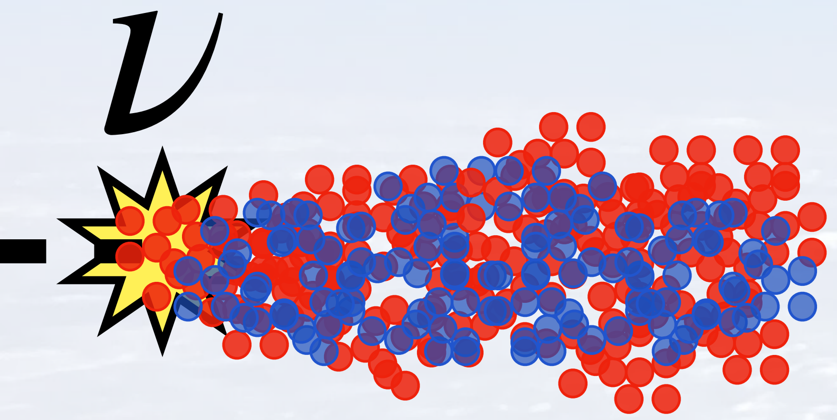


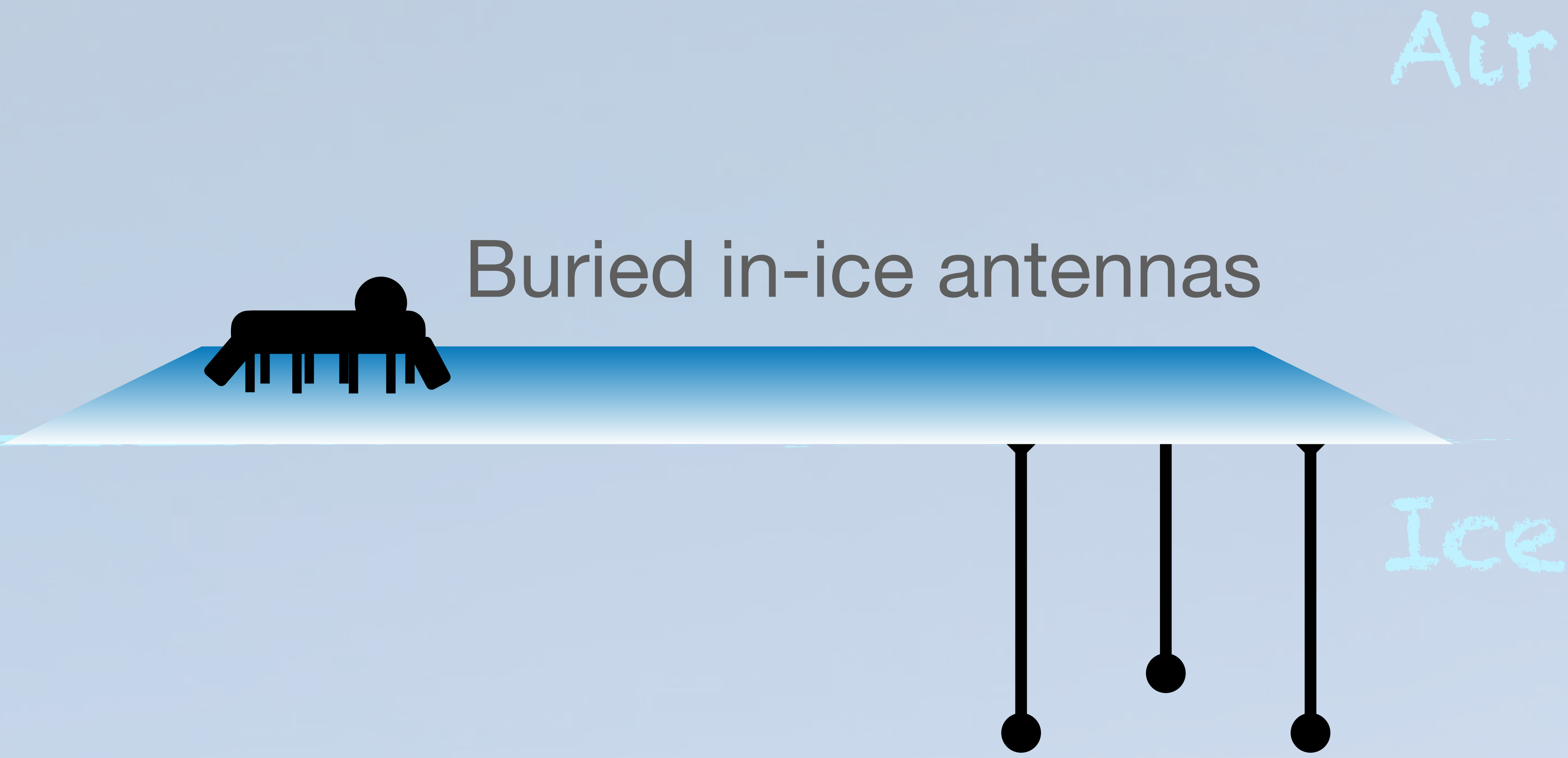
Particle cascade

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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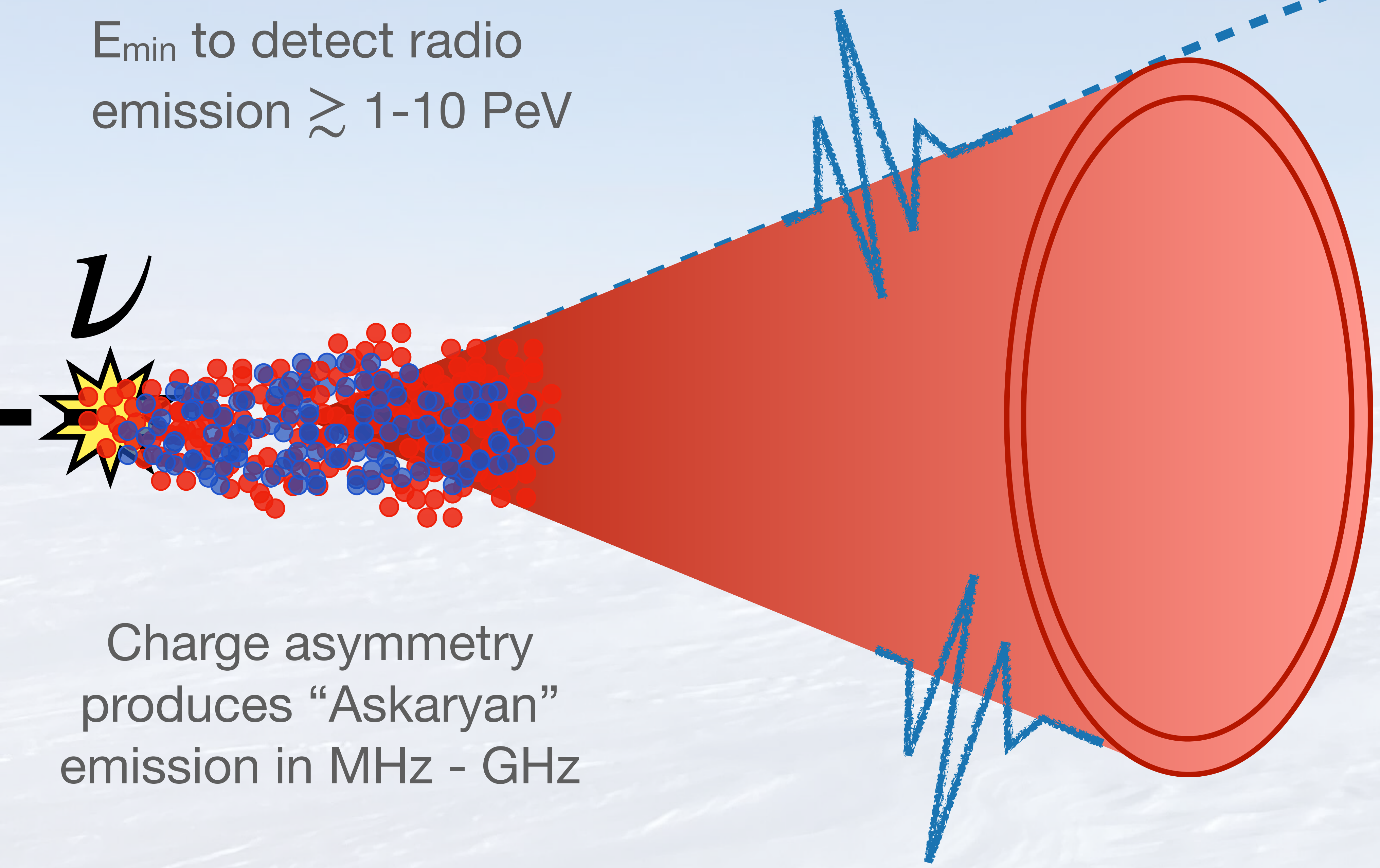

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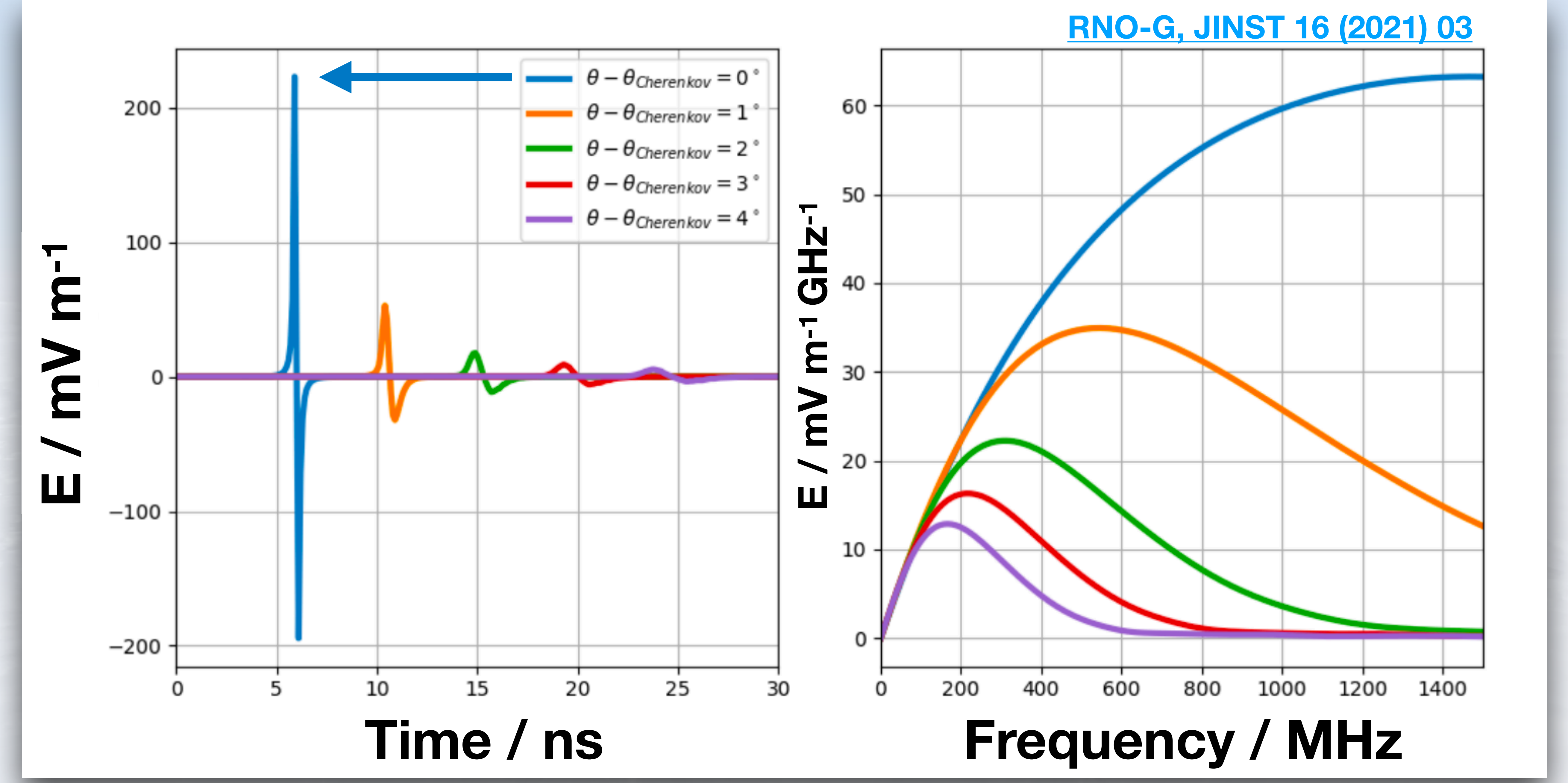

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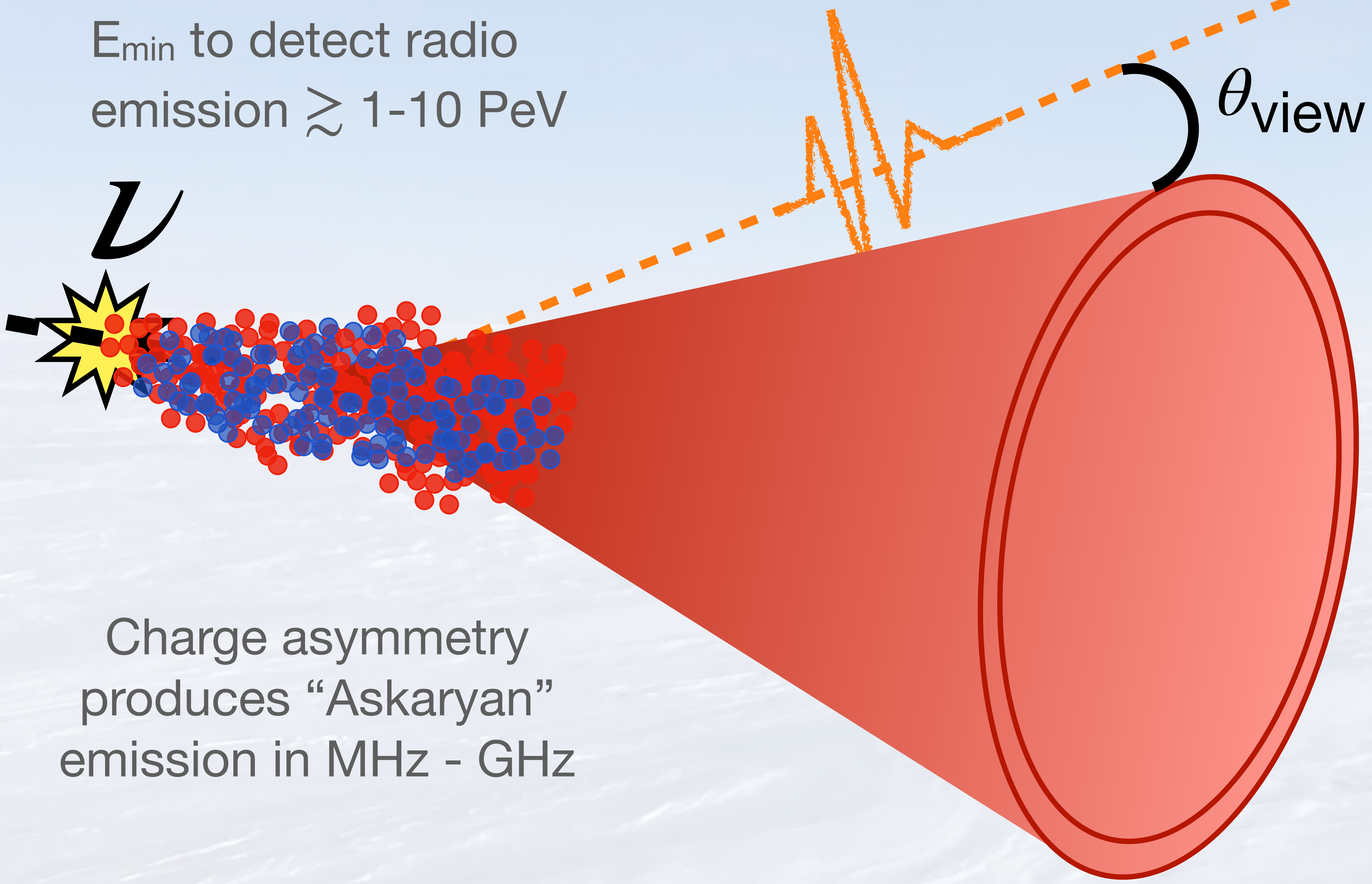
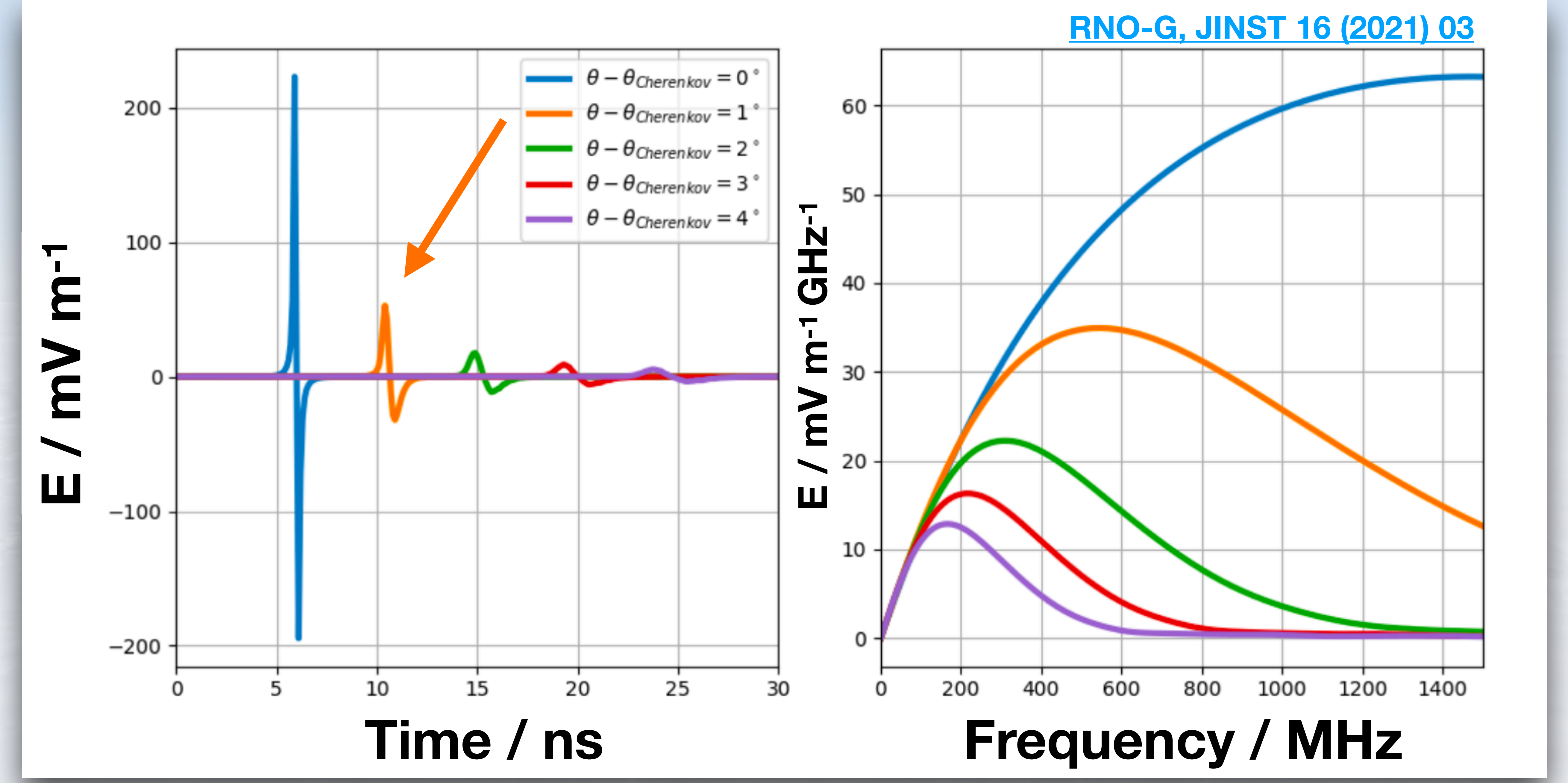


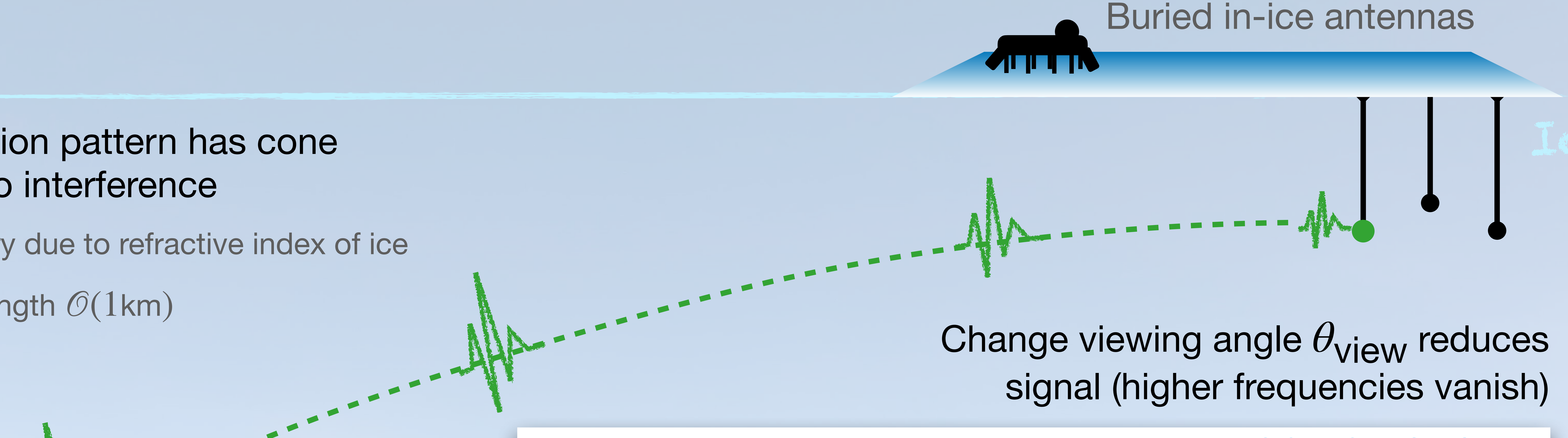


Radio detection of neutrinos

Air

Buried in-ice antennas

Ice



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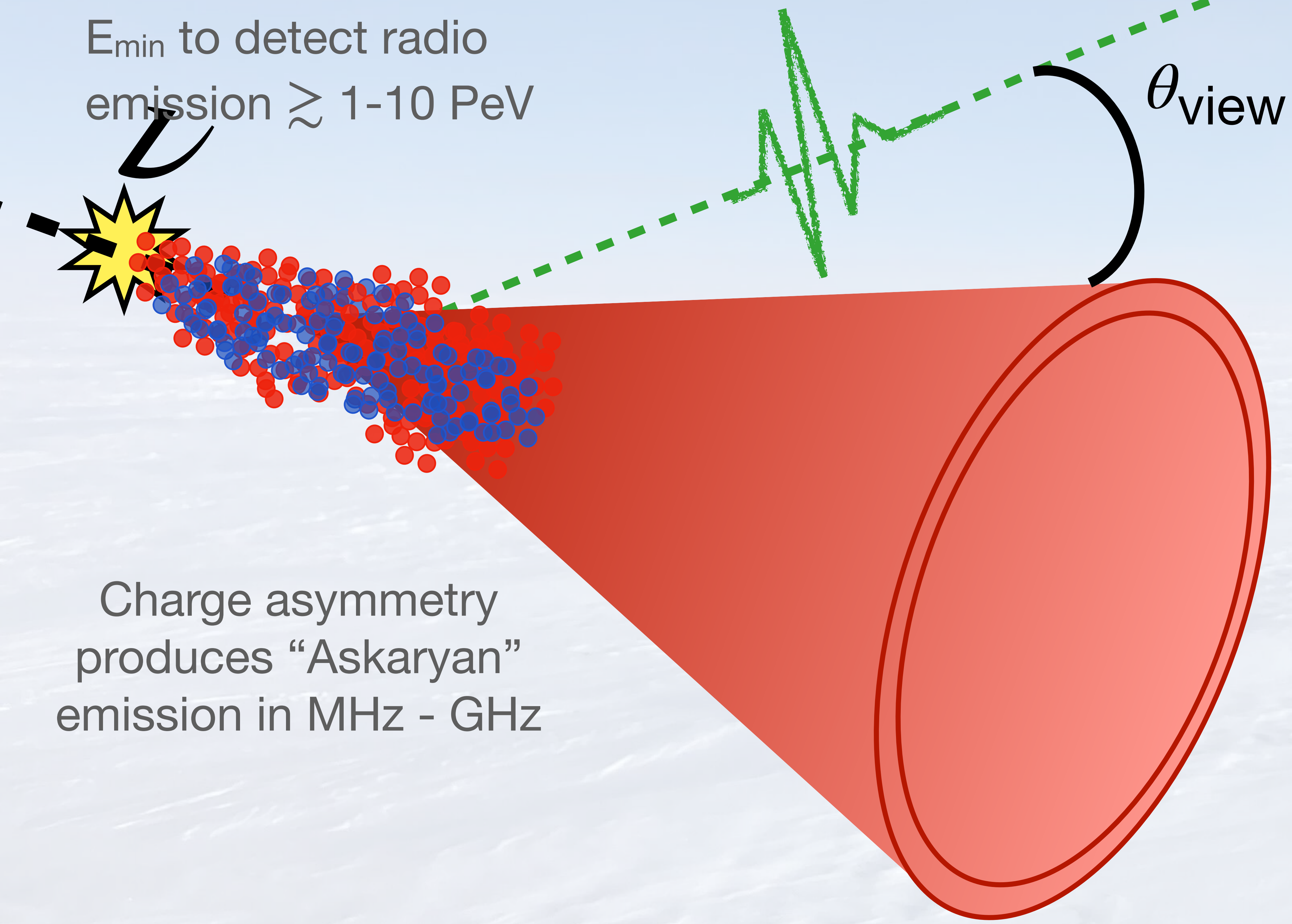

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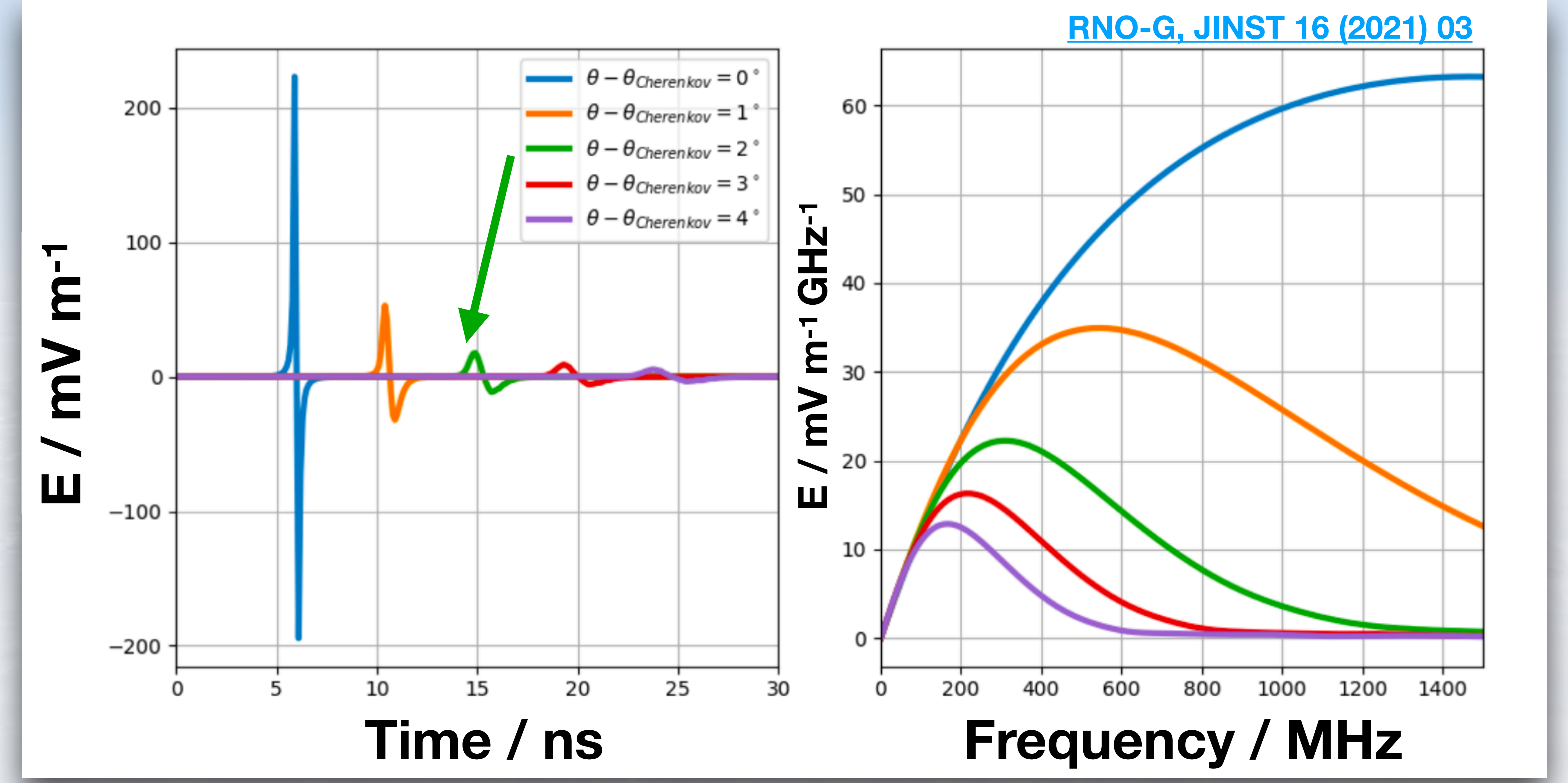

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$\theta_{\text{view}} - \theta_{\text{Che}}$

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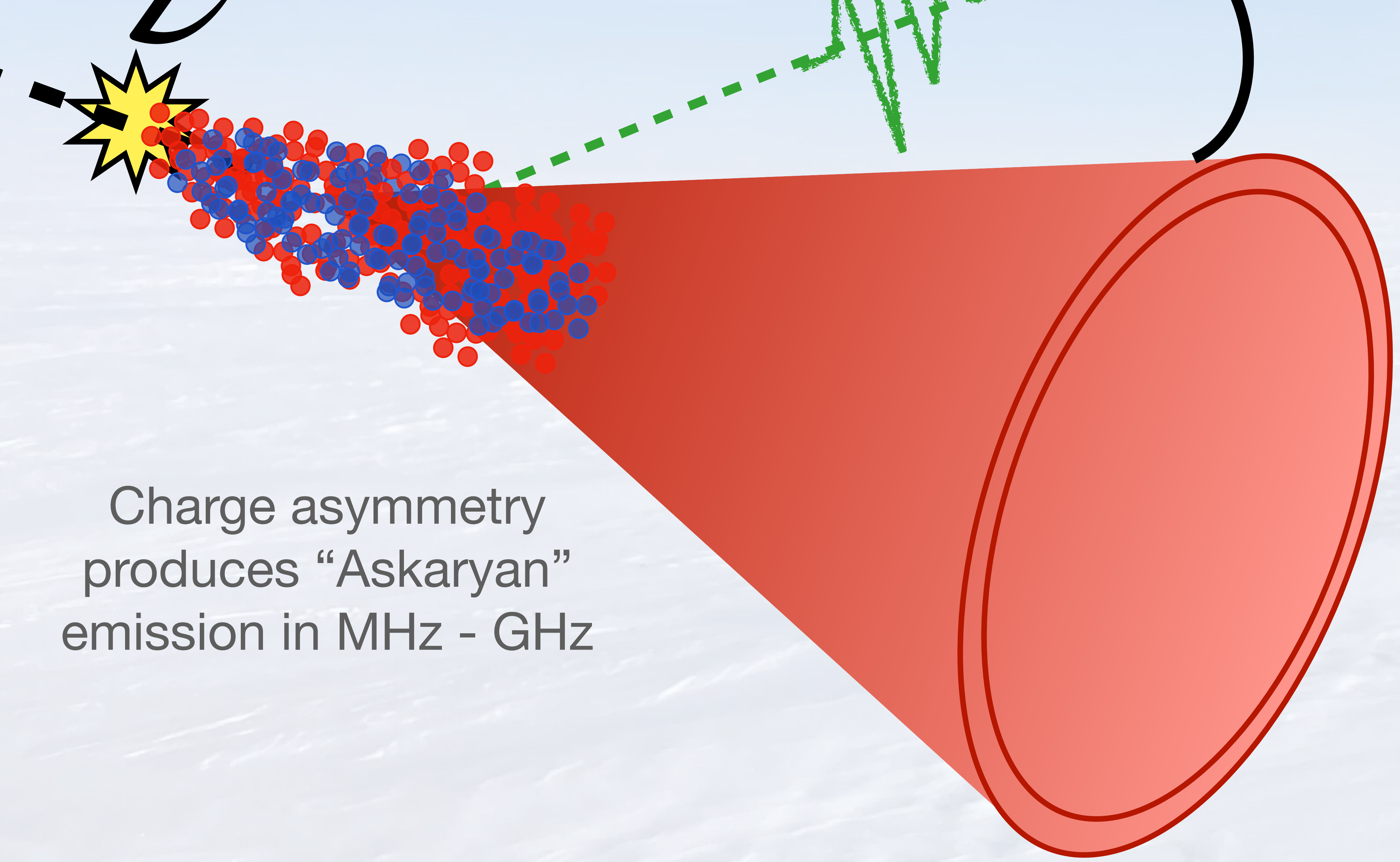
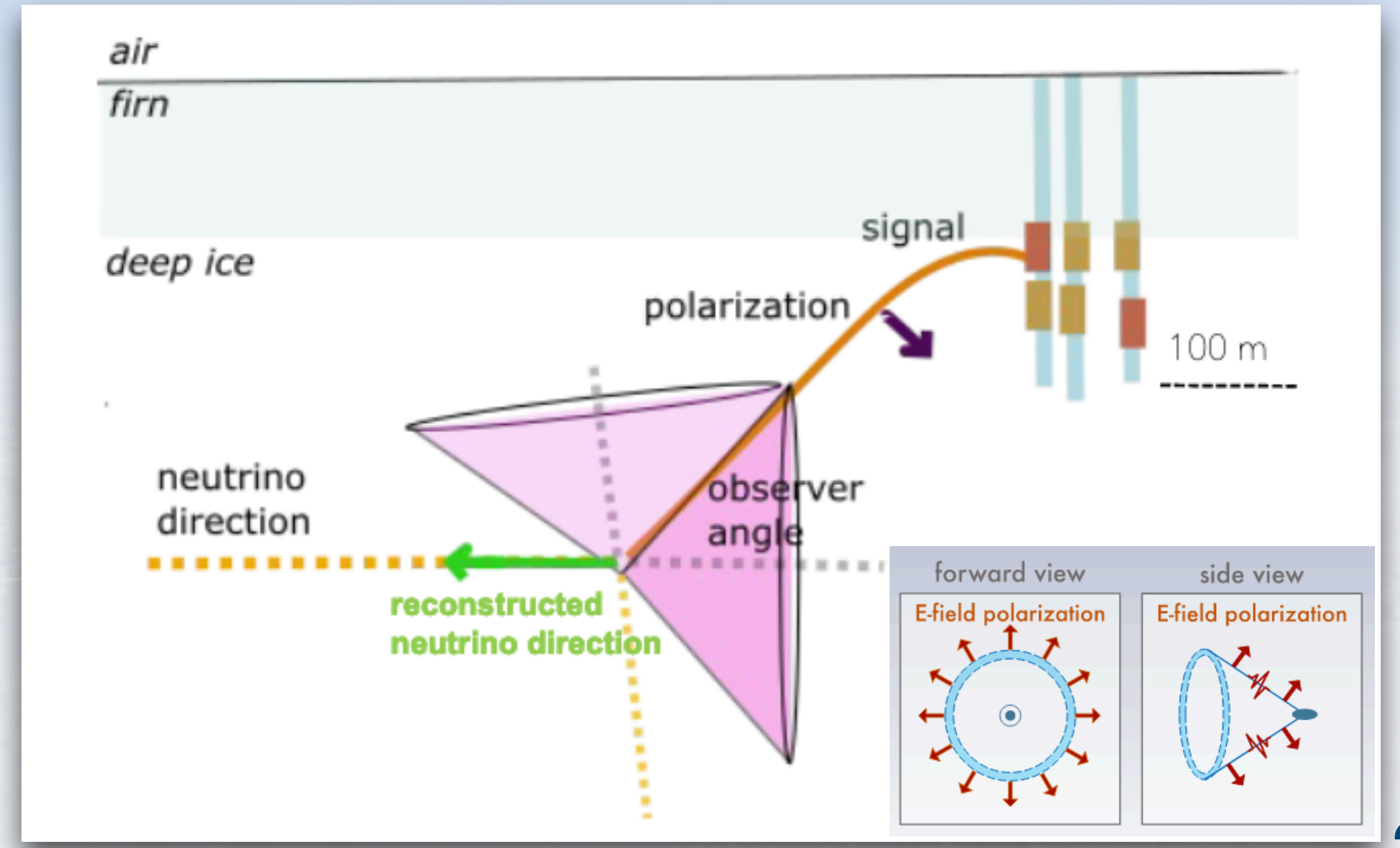
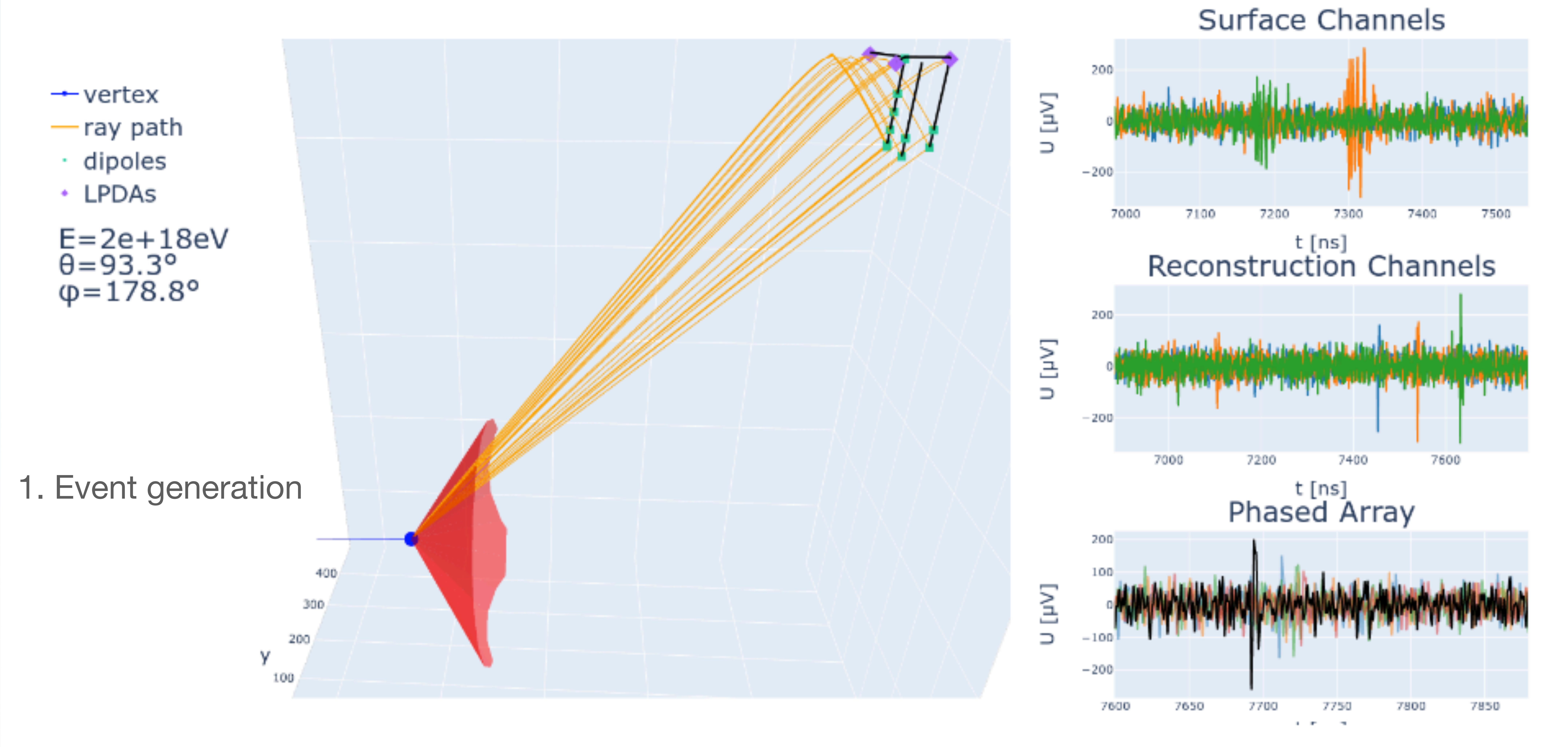


Charge asymmetry produces "Askaryan" emission in MHz - GHz

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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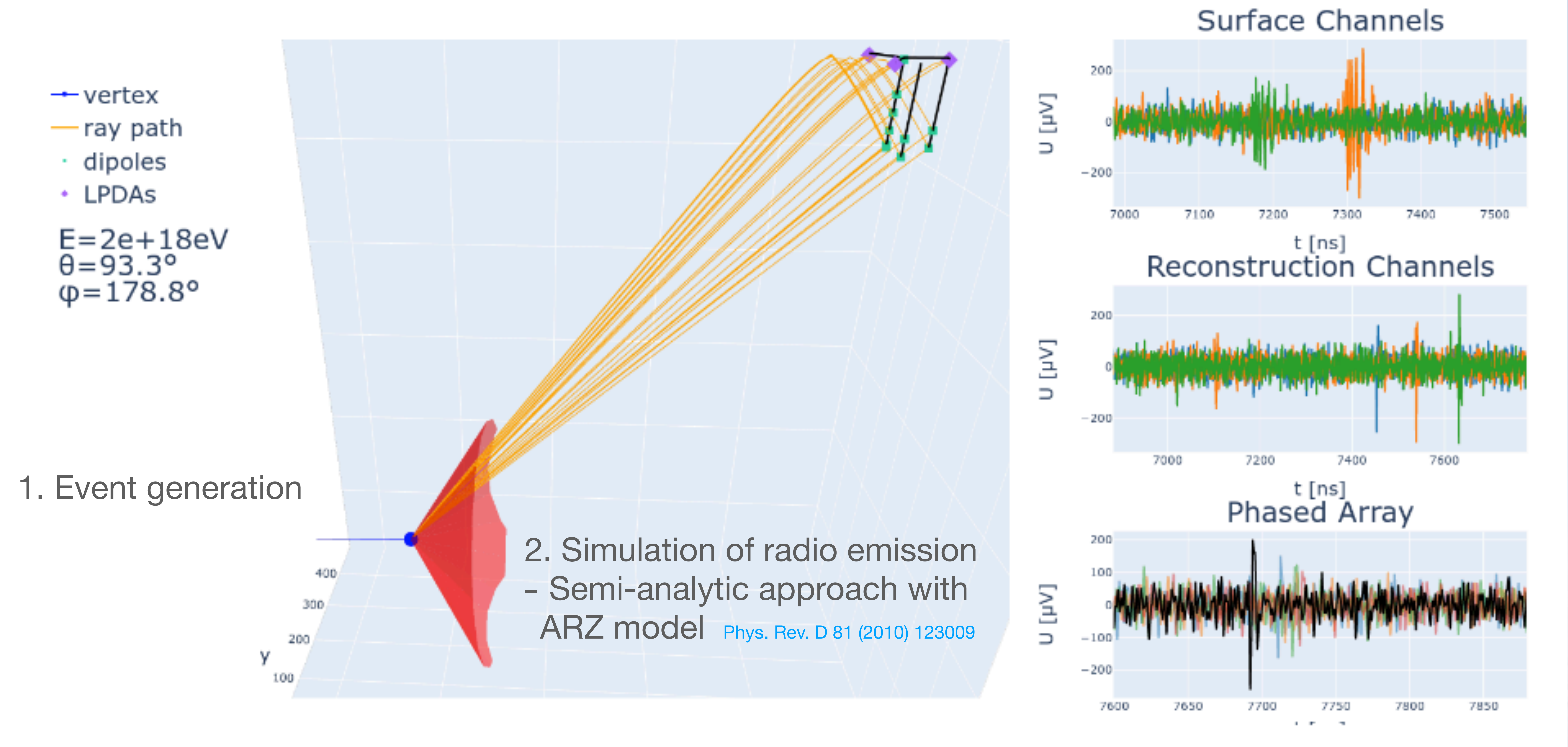

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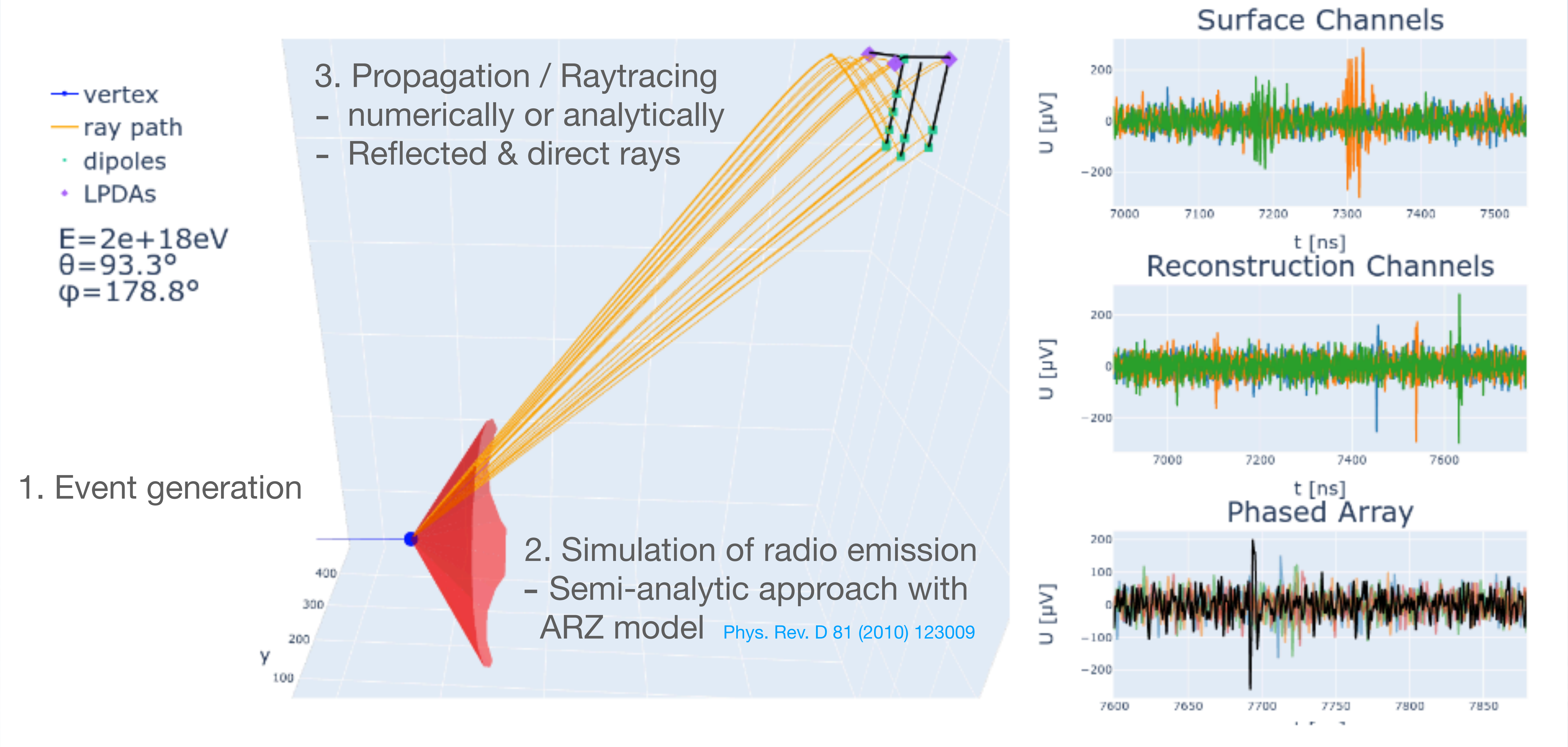

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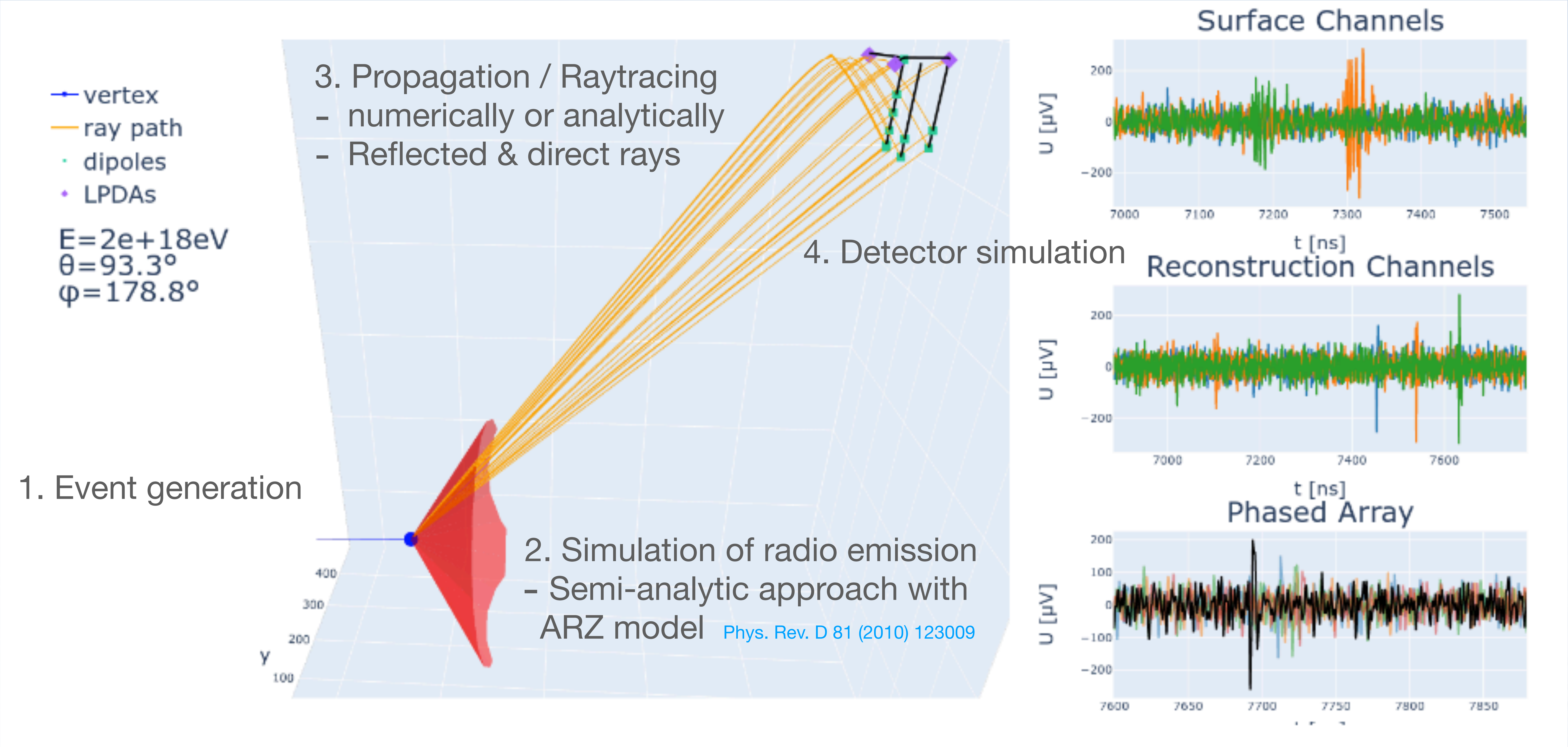

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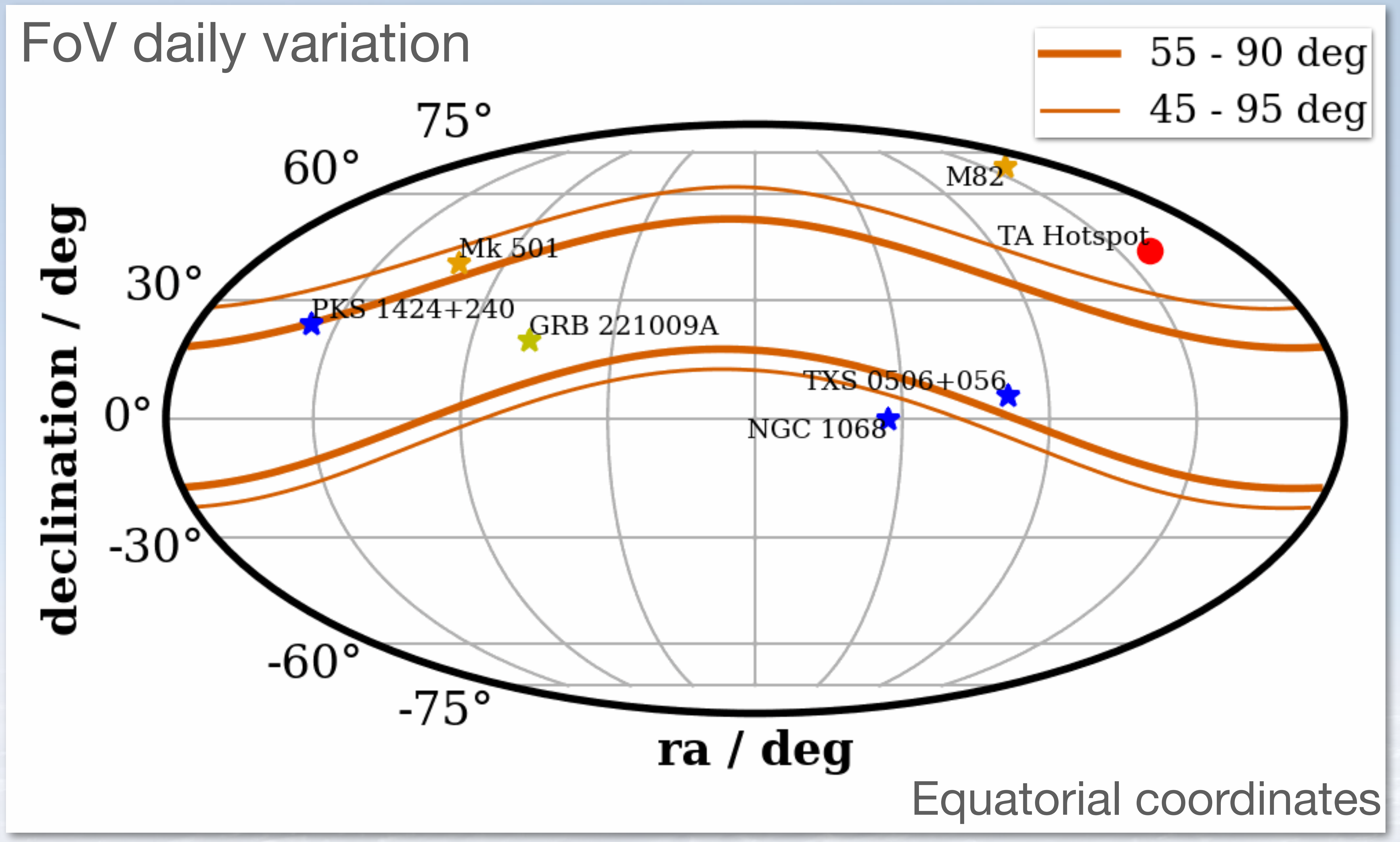
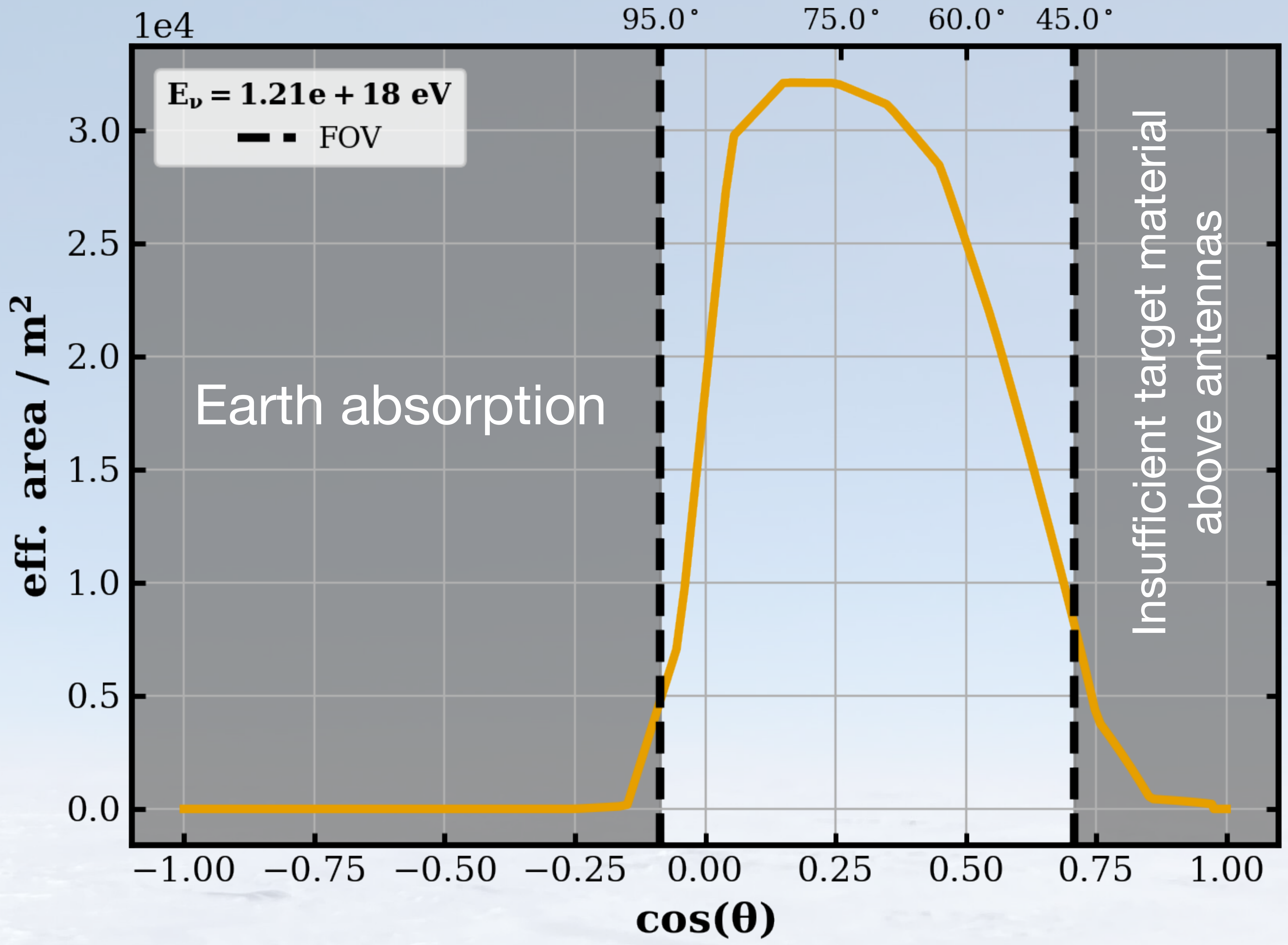
Eur. Phys. J. C 80, 77 (2020)

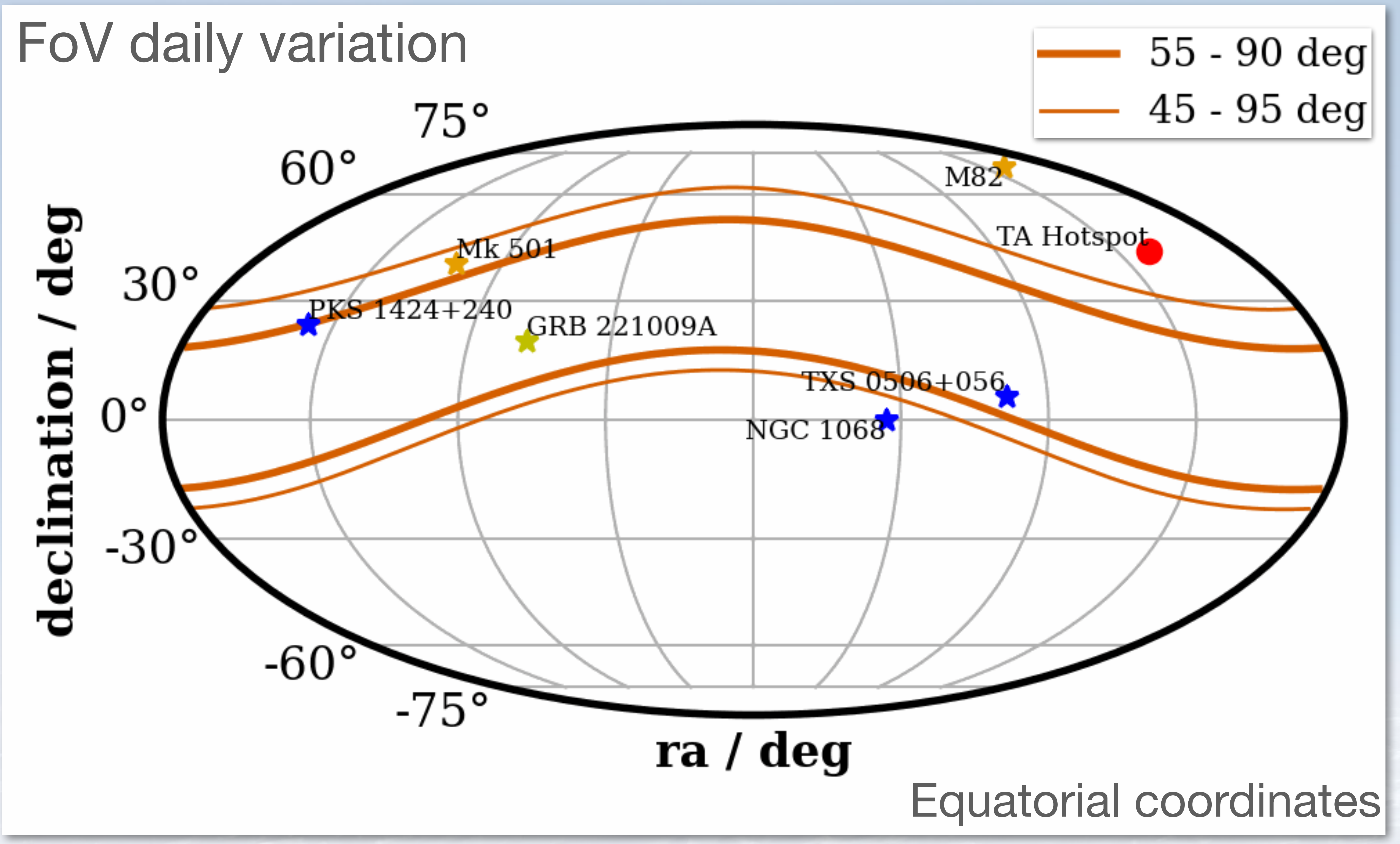
Neutrinos from the northern sky

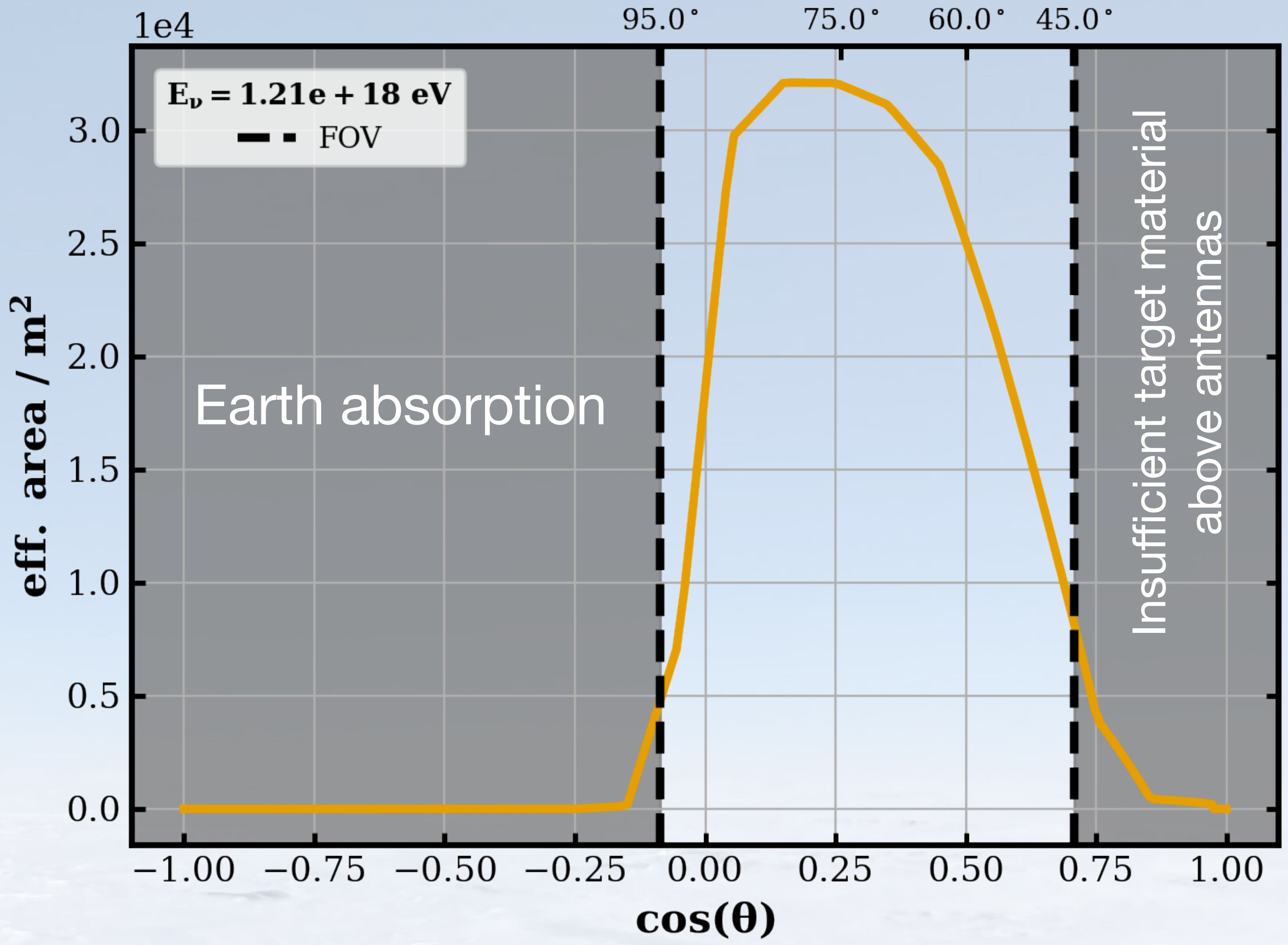




- Earth is opaque for UHE neutrinos
- Observatory in northern hemisphere relevant for multi-messenger observation!
- RNO-G eff. area for full 35 station array
- Largest aperture just above the horizon

Neutrinos from the northern sky





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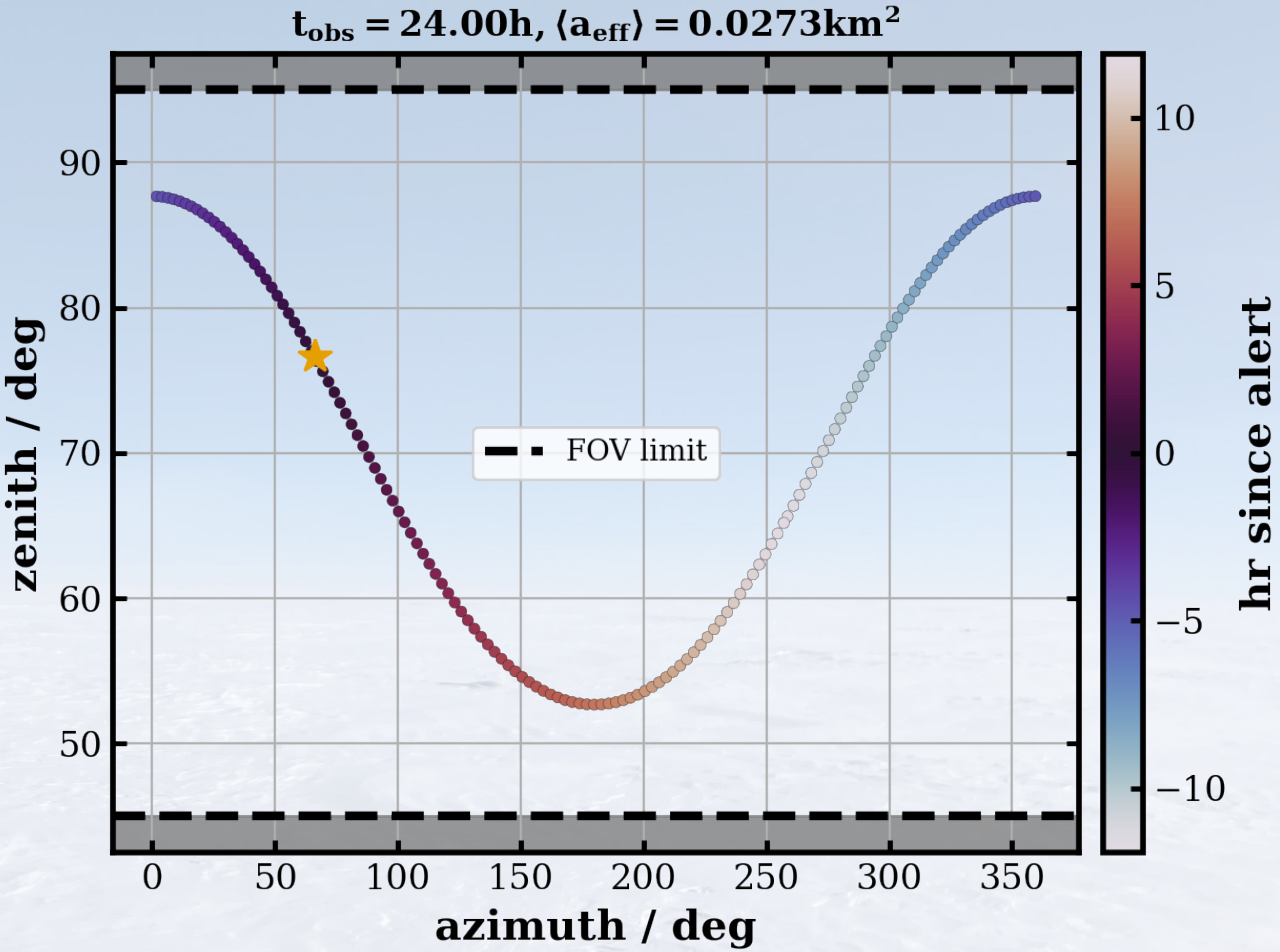
- RNO-G eff. area for full 35 station array
- Largest aperture just above the horizon

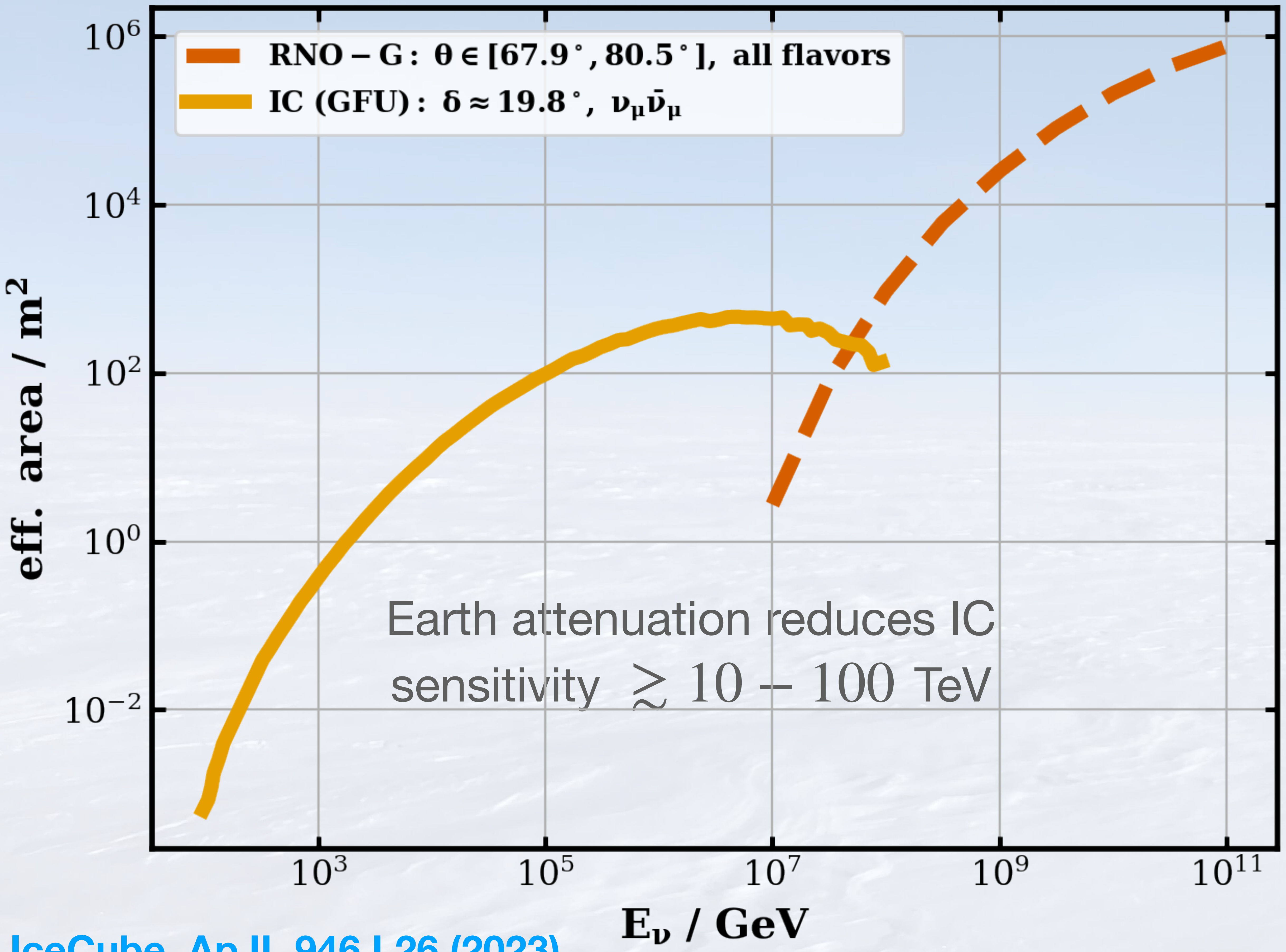
GRB 20221009A in the FOV of RNO-G

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



Sensitivity: GRB 20221009A

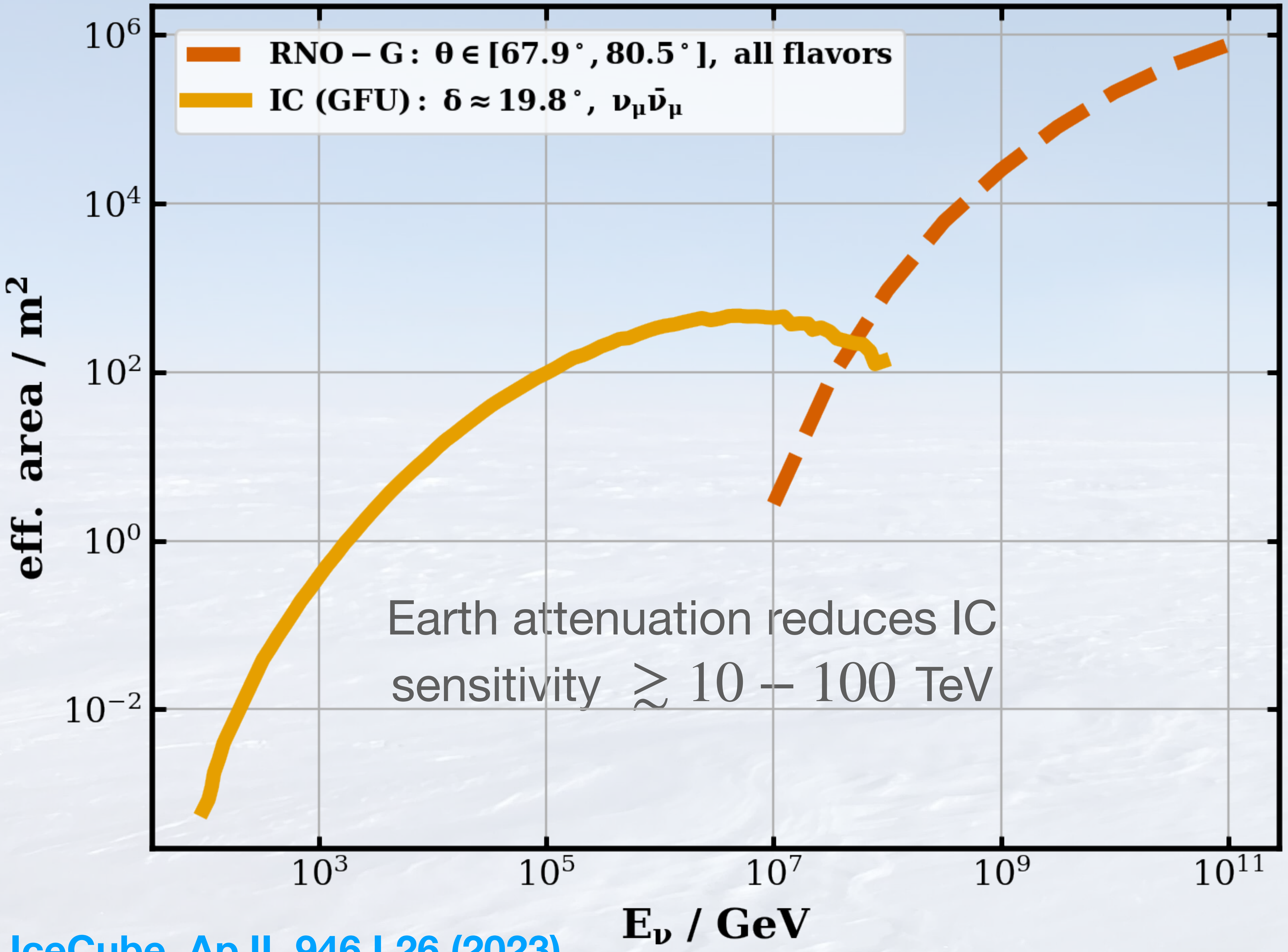
- RNO-G eff. area for 3h time window

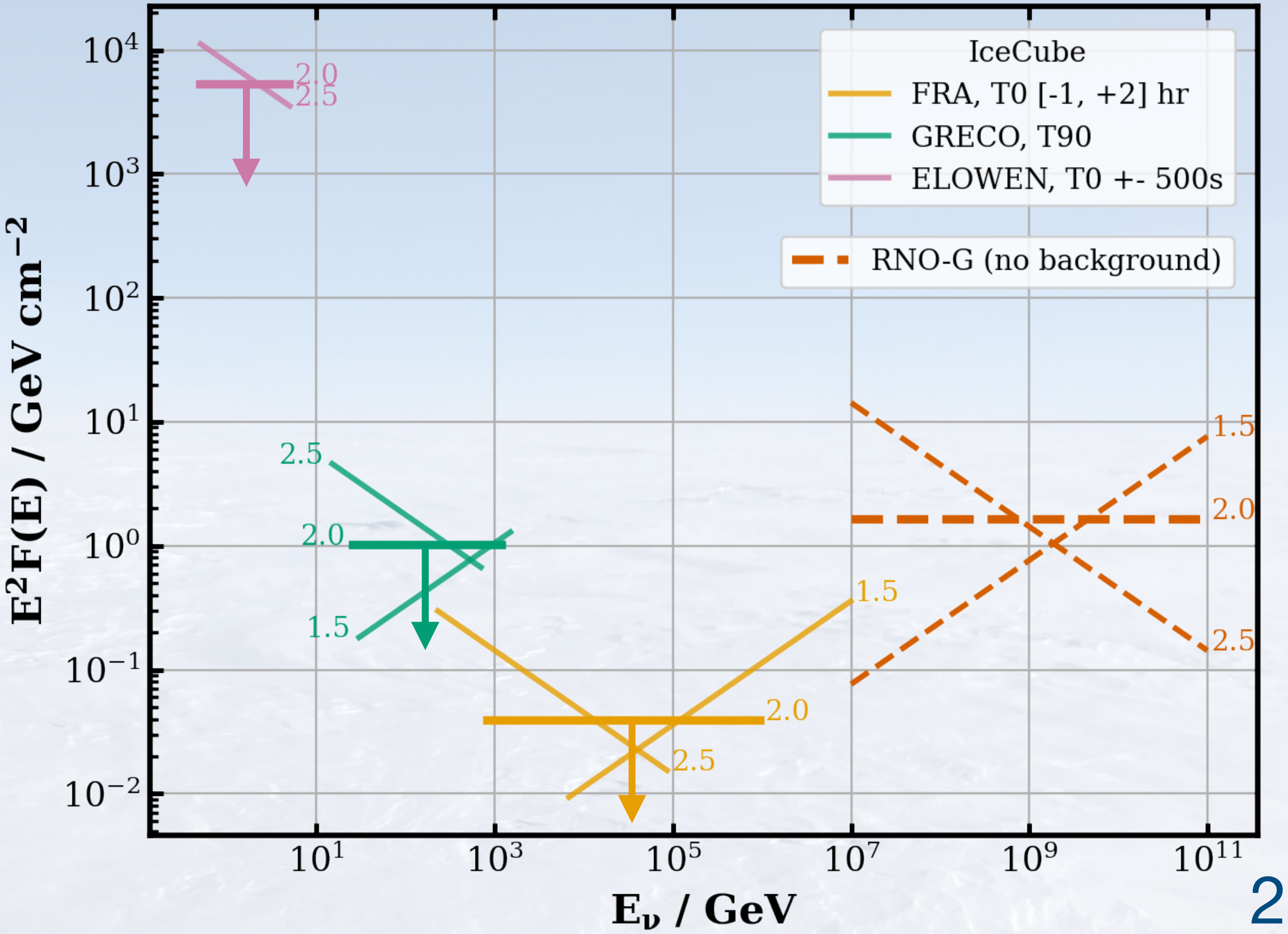


IceCube, ApJL 946 L26 (2023)

Sensitivity: GRB 20221009A

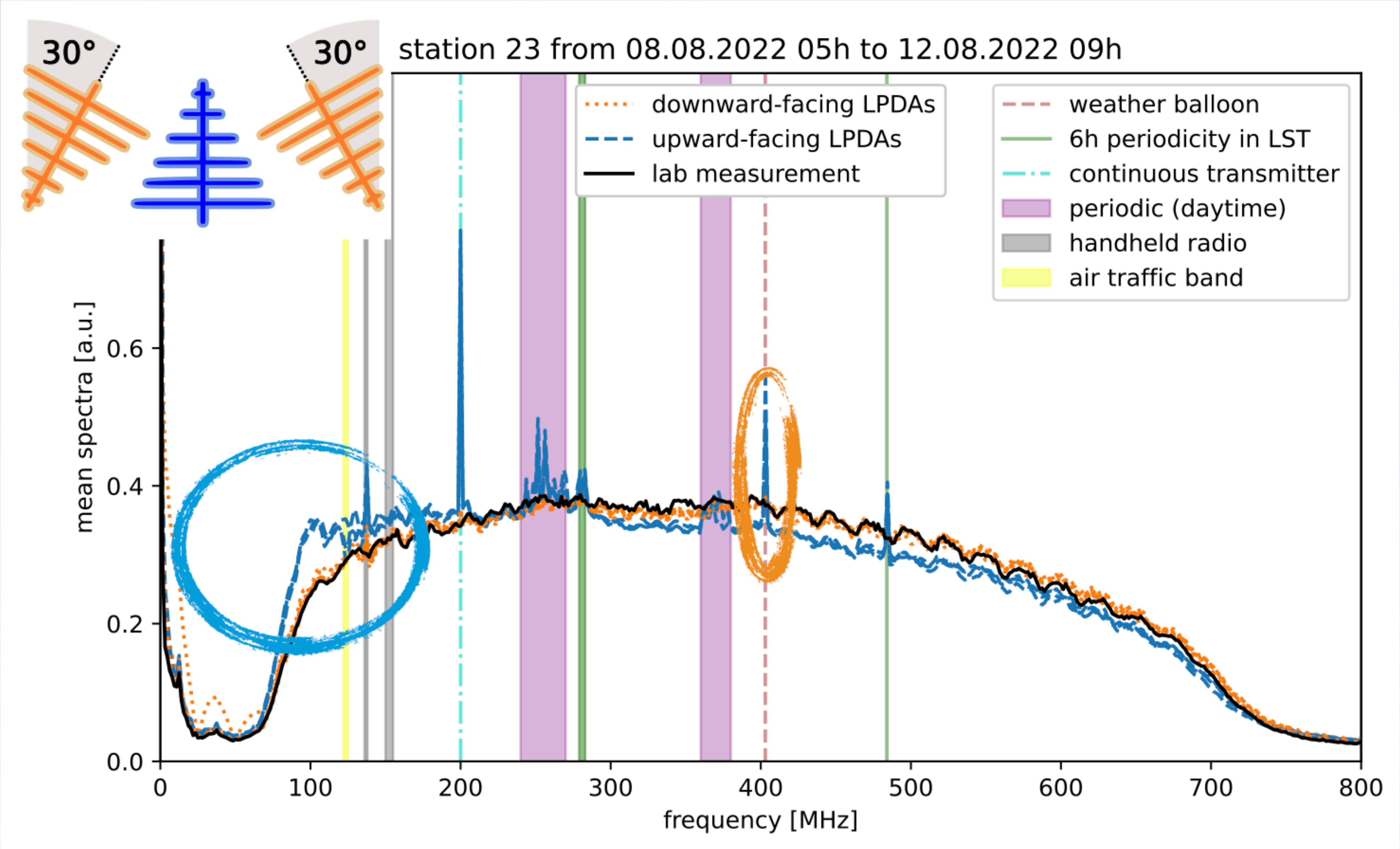
- RNO-G eff. area for 3h time window
- Sensitivity on time integrated E^{-2} flux over several decades in energy
  - RNO-G with competitive sensitivity at higher energies



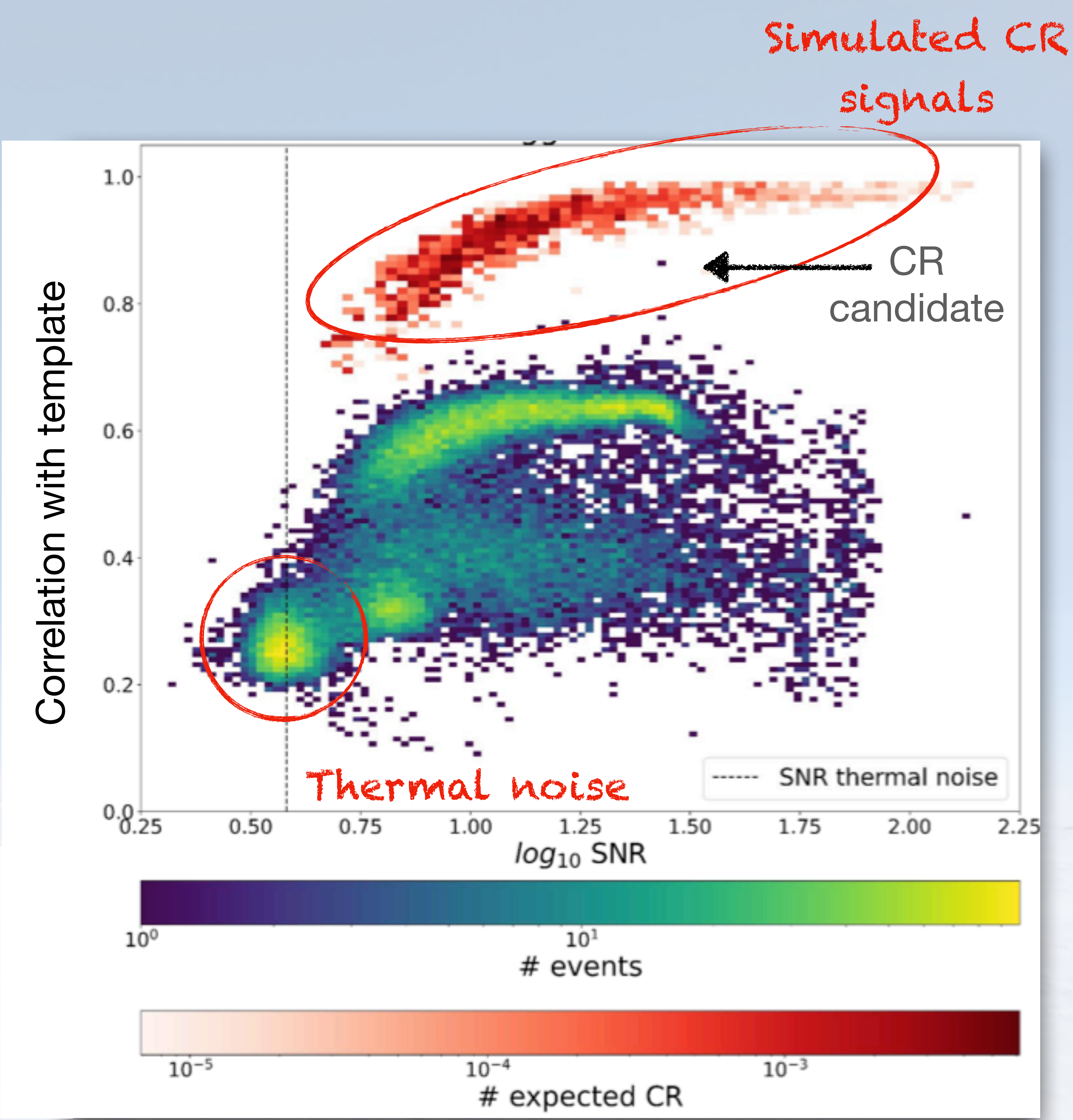


IceCube, ApJL 946 L26 (2023)

First look into the data



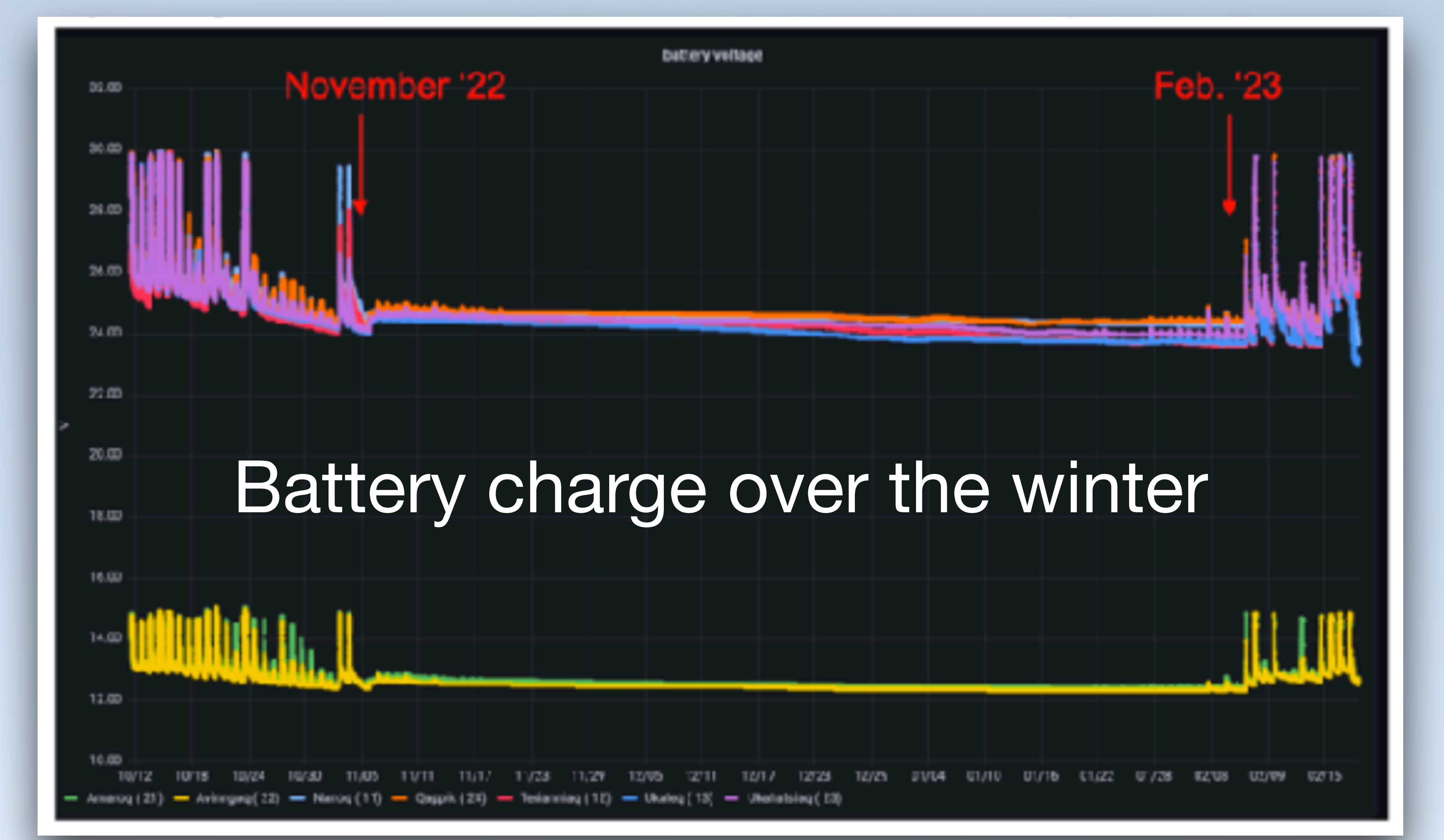
Excess in received power at lower frequencies for upward-facing LPDAs → Galactic emission

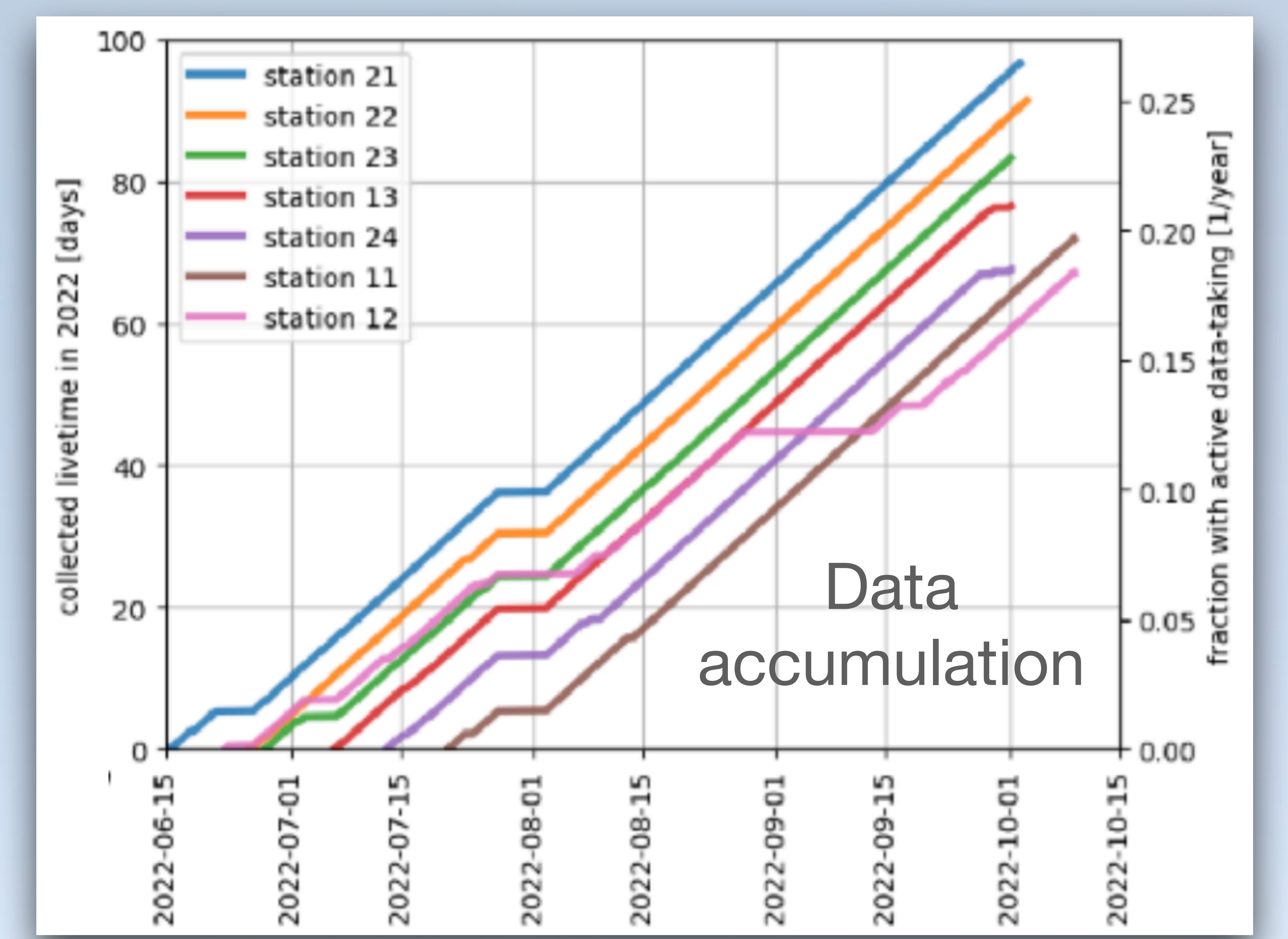


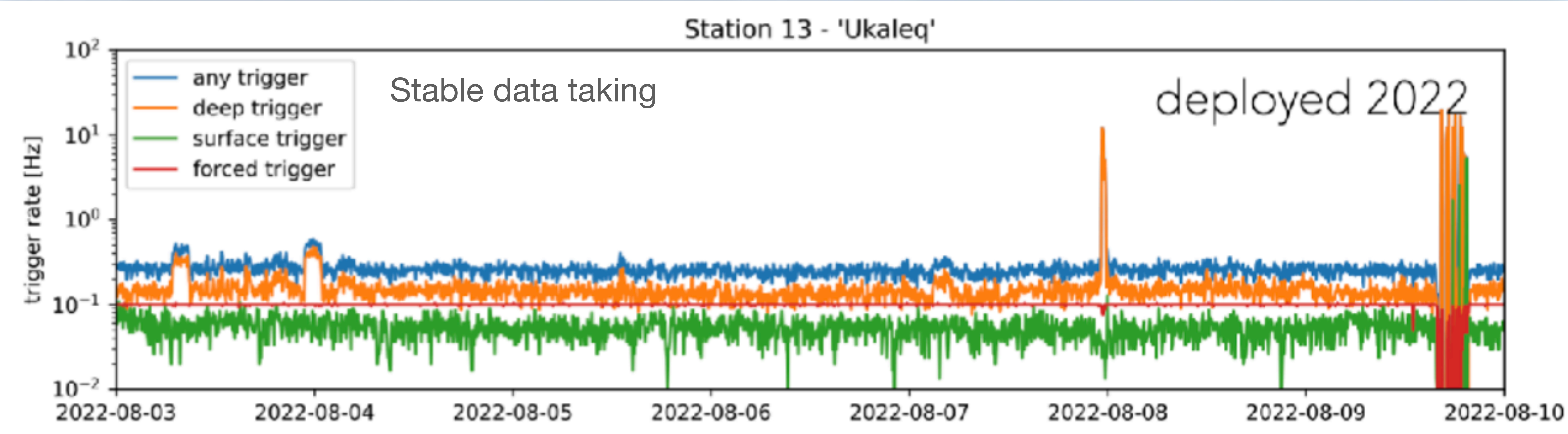
S. Hallmann for RNO-G, Pos (ICRC23) 1043

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

Hardware performance

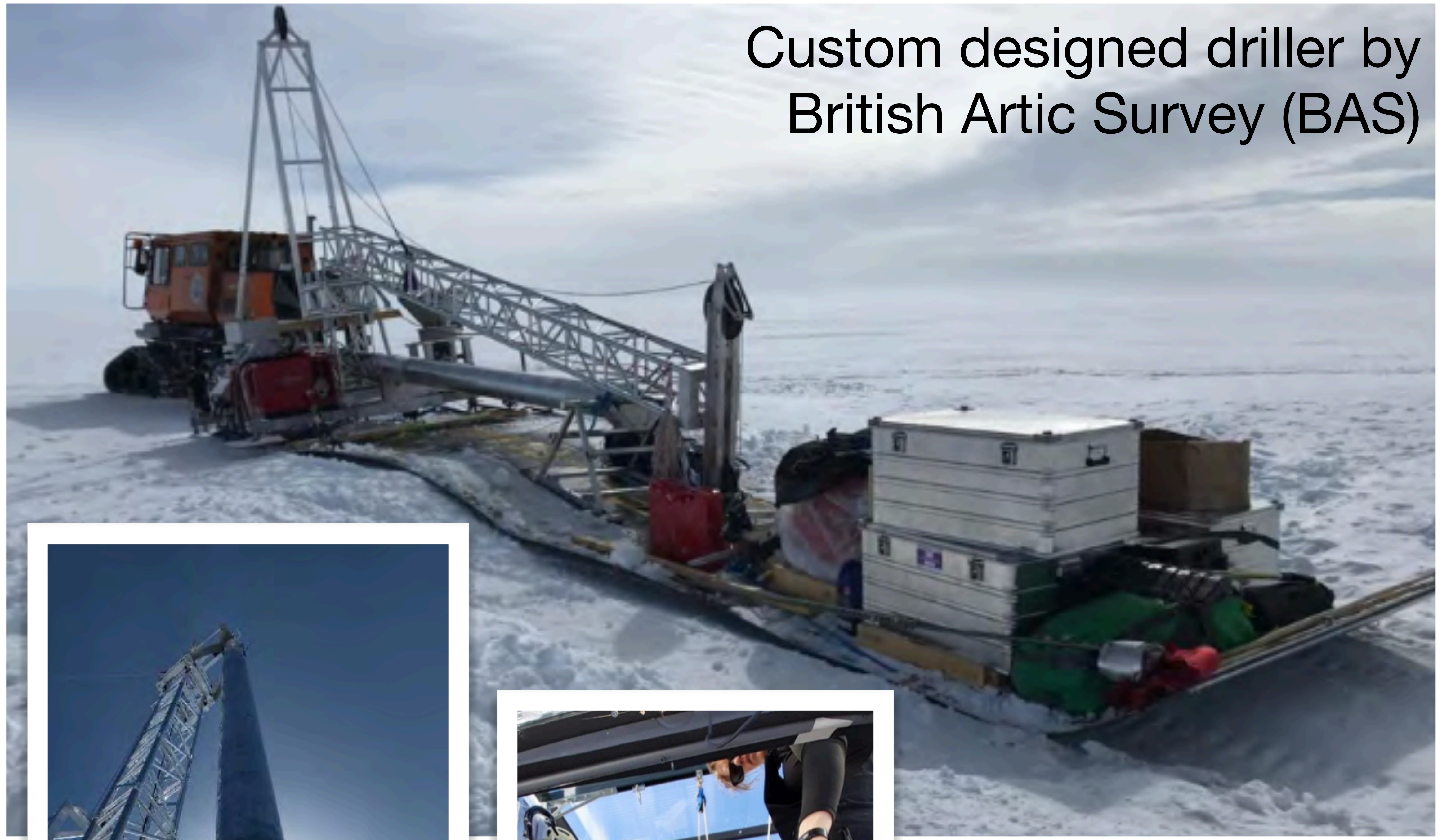




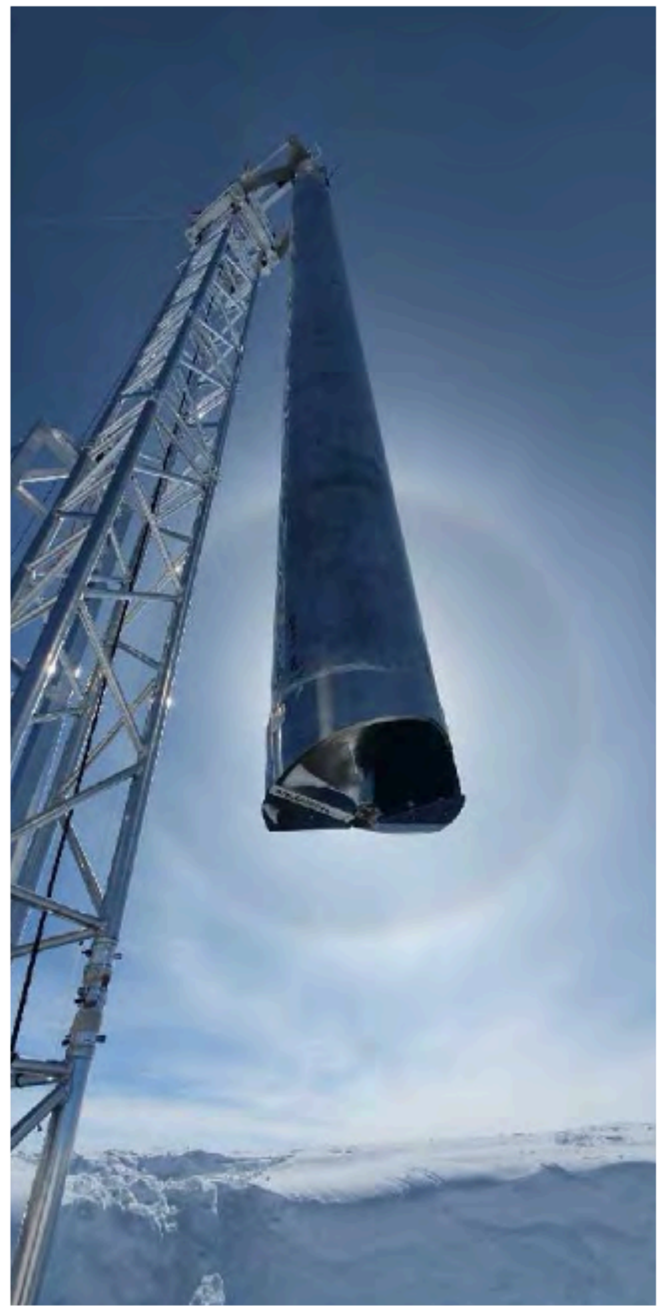


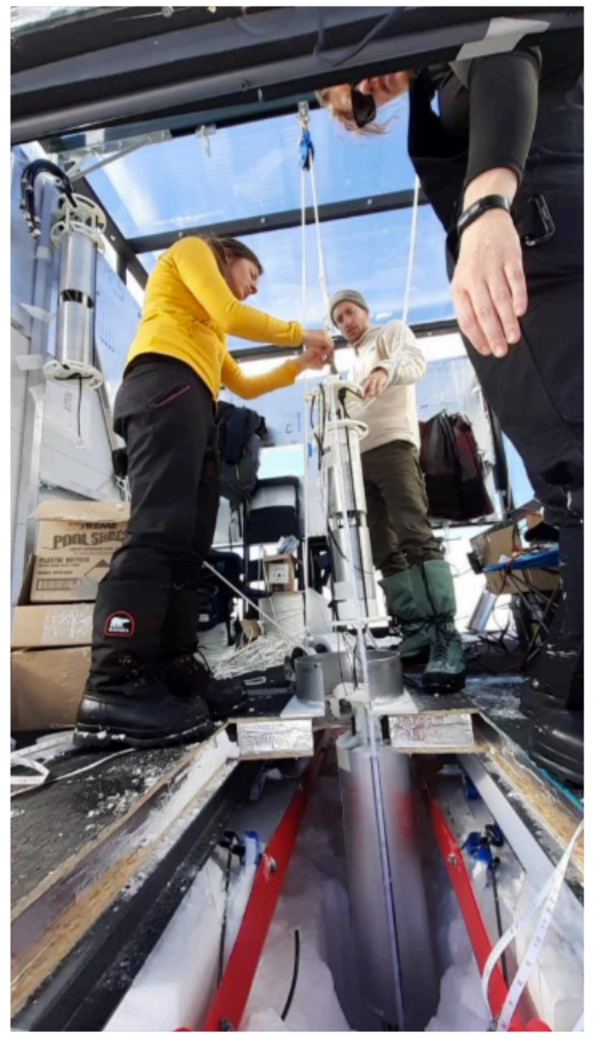
Deployment

Drilling 100m deep, 28 cm diameter hole



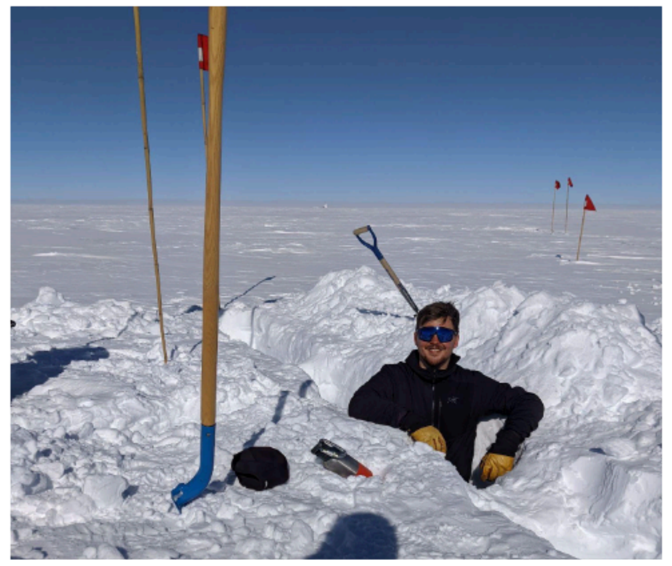
Custom designed driller by British Artic Survey (BAS)

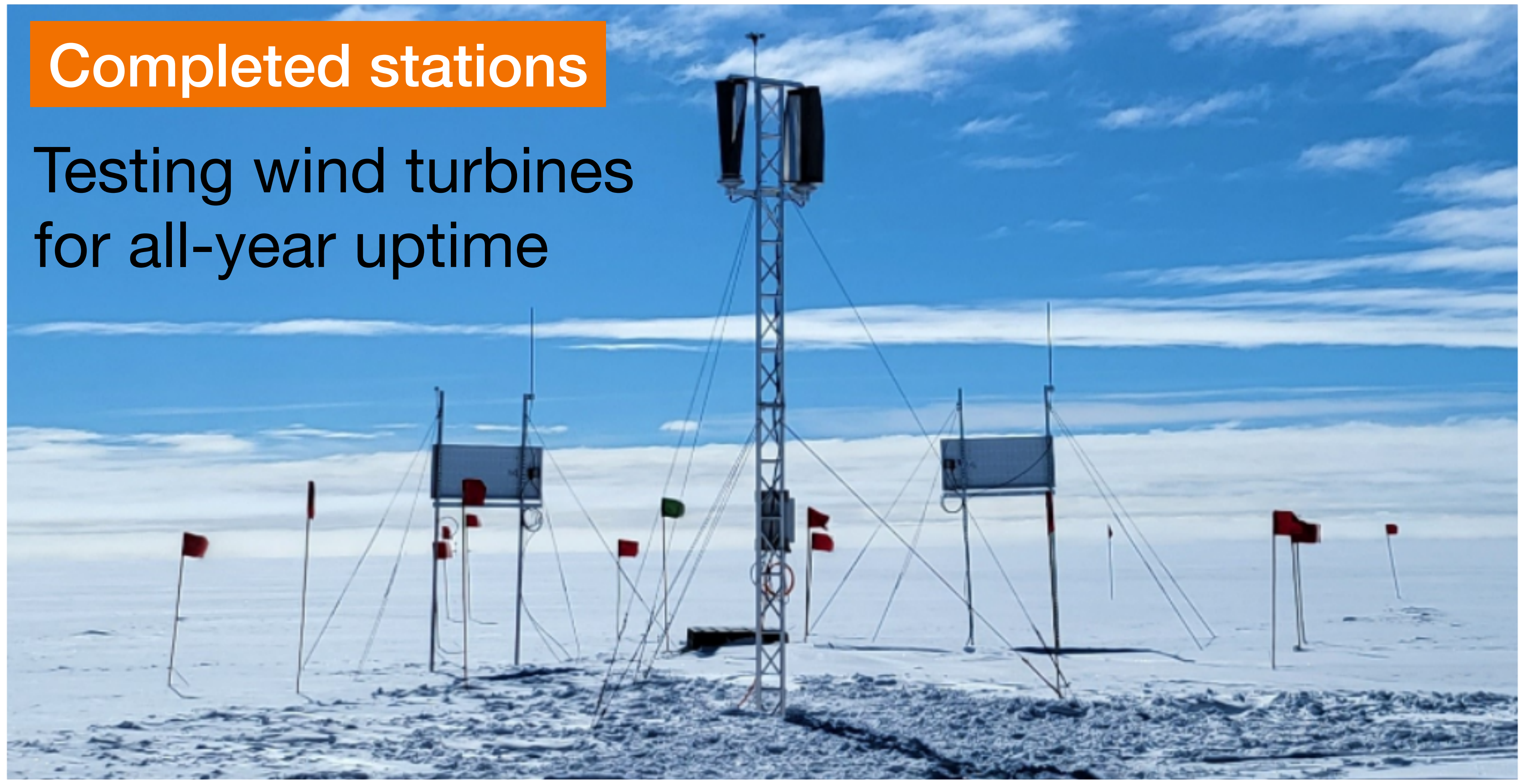




Shallow antennas are deployed in trenches …

… which we dig!





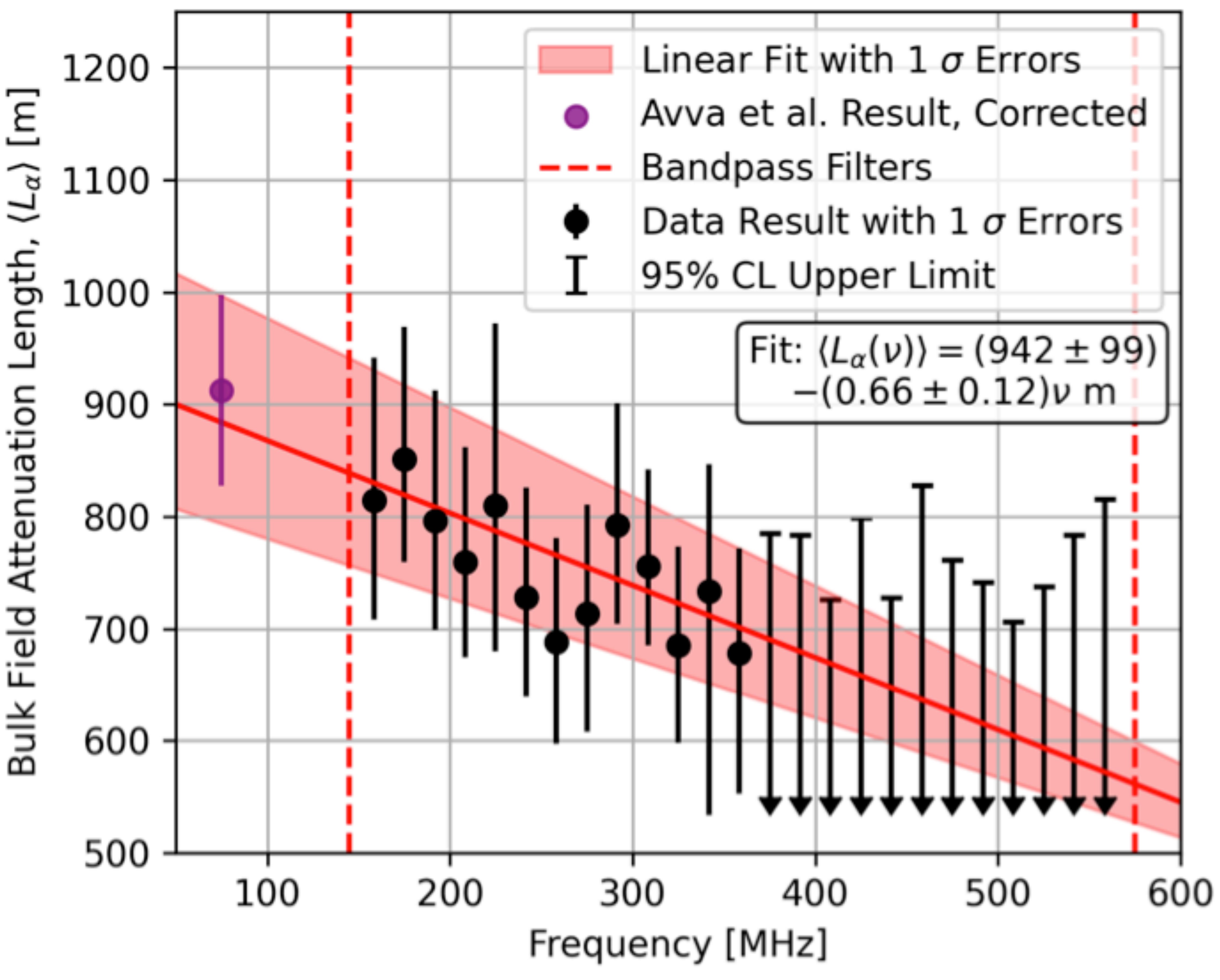
Completed stations

Testing wind turbines for all-year uptime

Radio detection of neutrinos

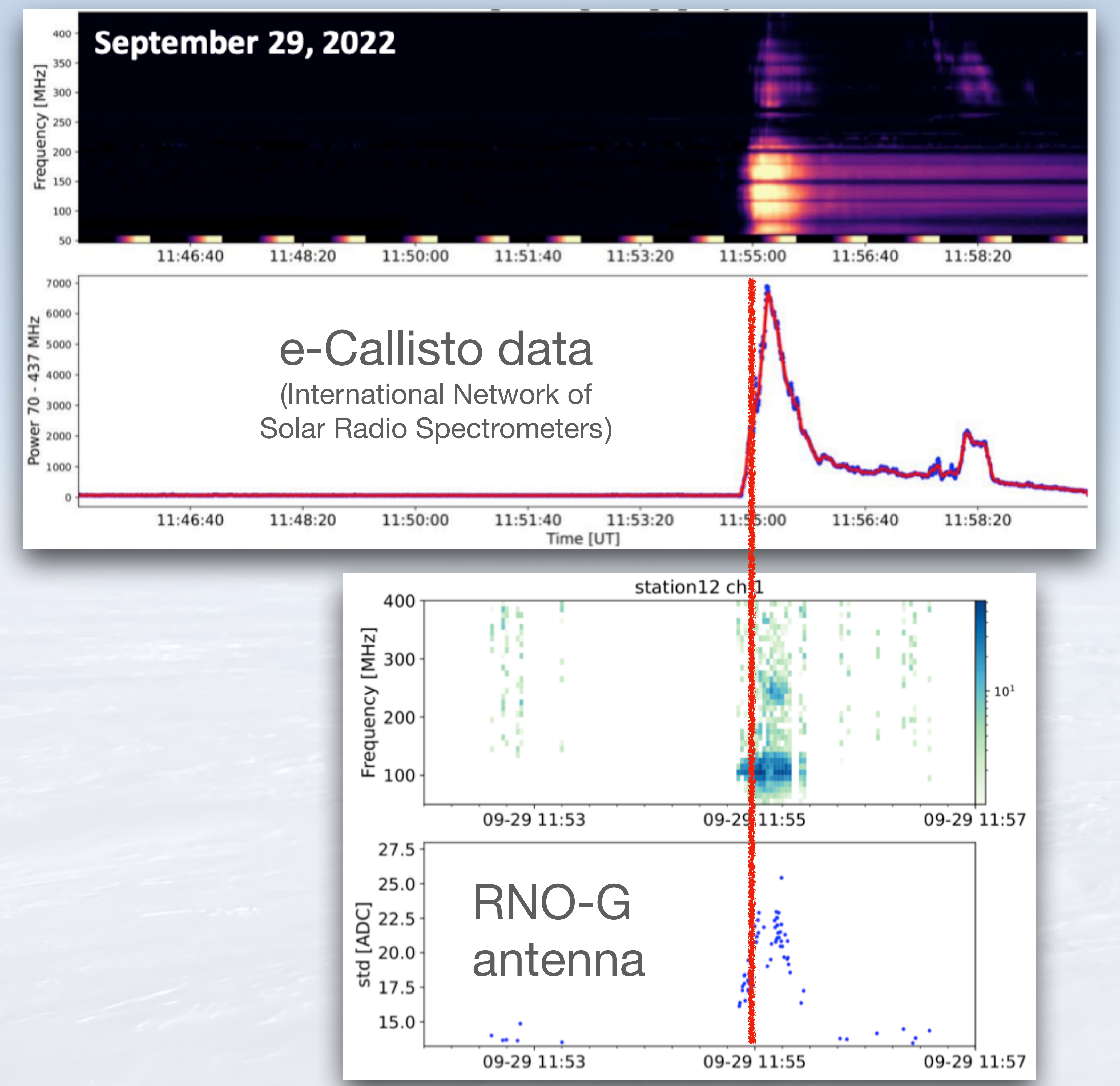
- Use natural glacier ice as target
- Radio waves are less attenuated in ice
  - A single radio station can monitor a cubic kilometer of ice
- Radio is a cost effective solution
  - In hardware & deployment
    (do not have to be deployed in
    3 km depth; 100 - 200 m is sufficient)

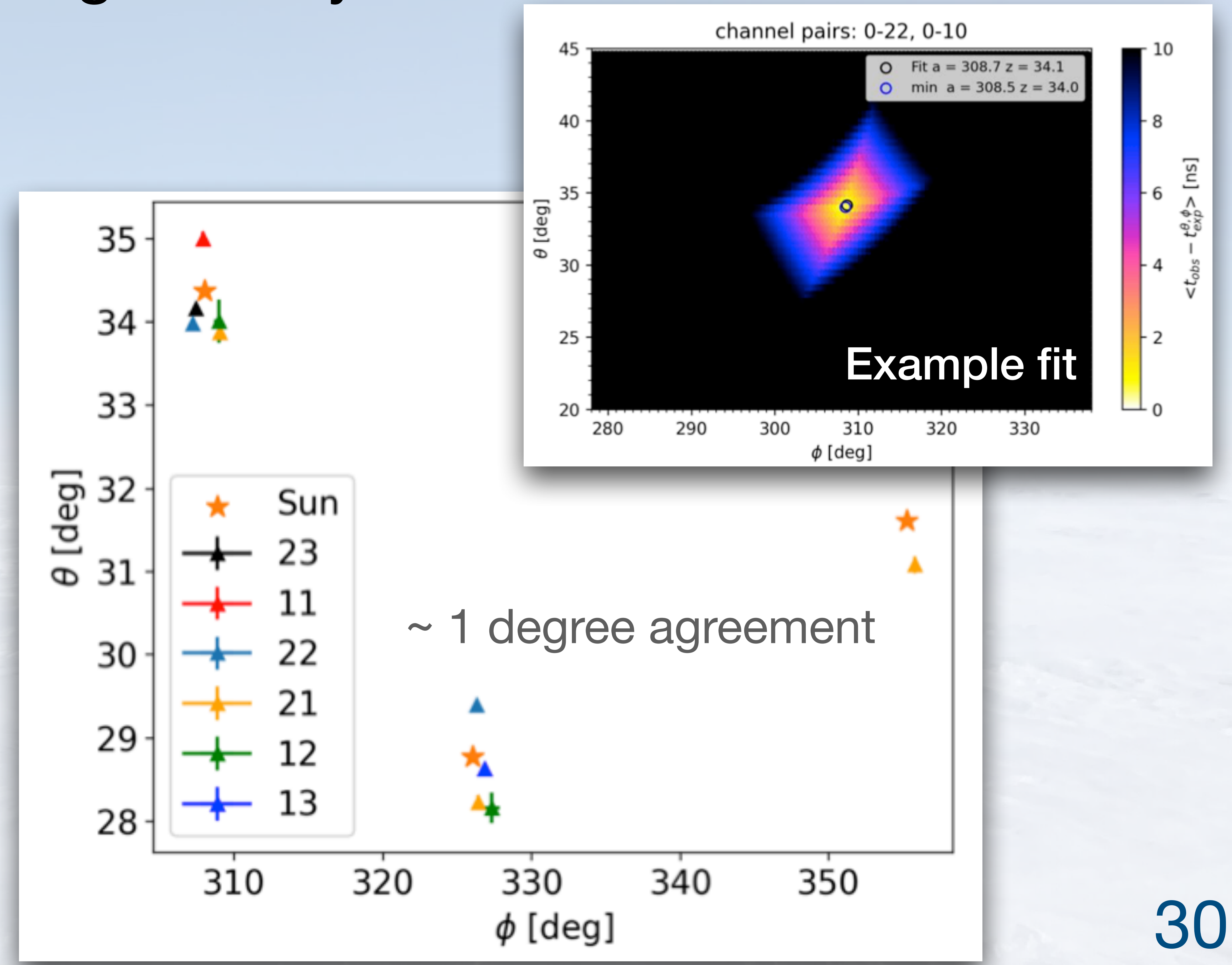
[RNO-G, Journal of Glaciology]



First look into the data: Solar flares

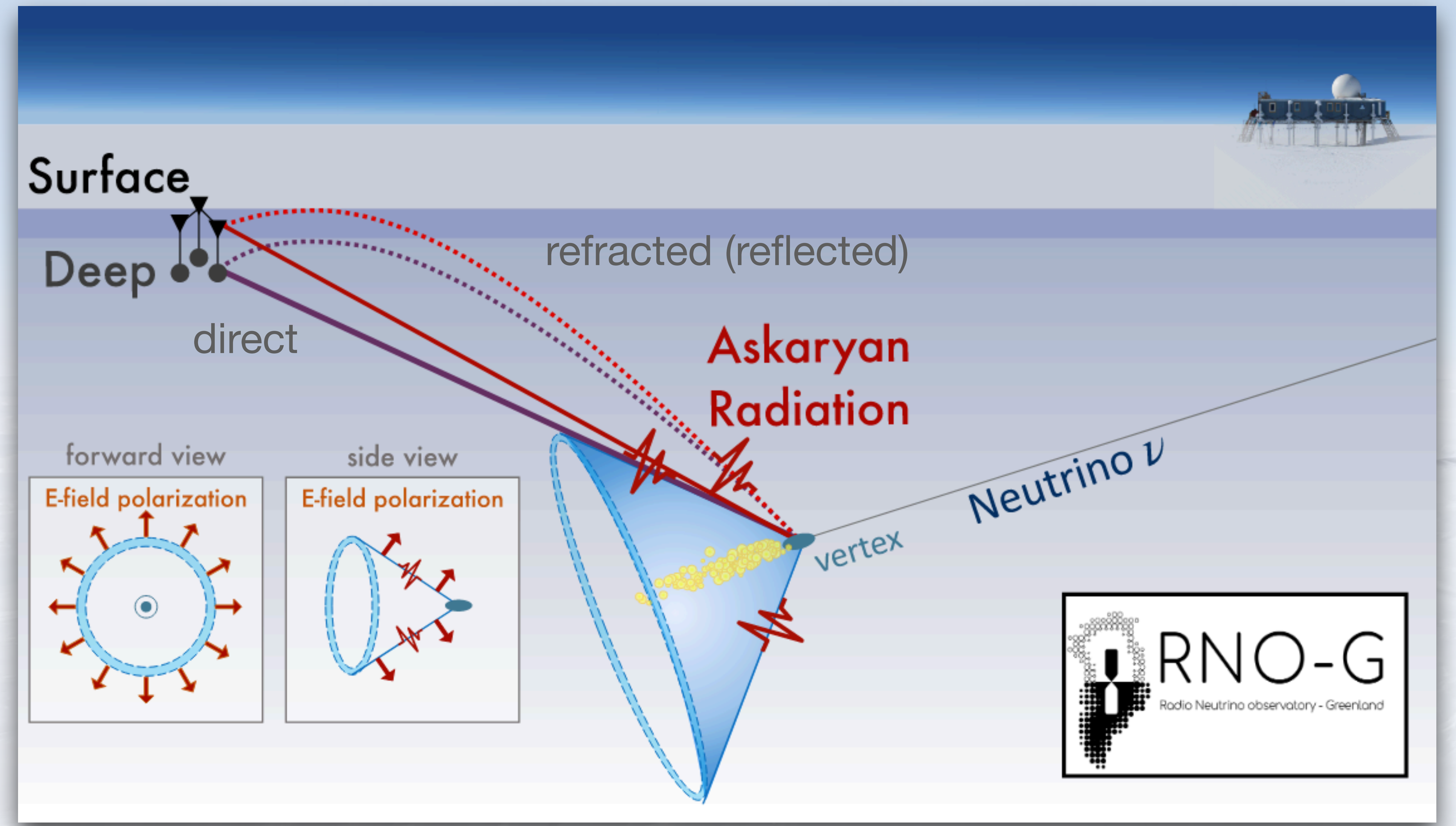
- For 3 solar flares, reconstruct position of Sun
- Allowed correction / calibration of station geometry





Radio detection of neutrinos

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



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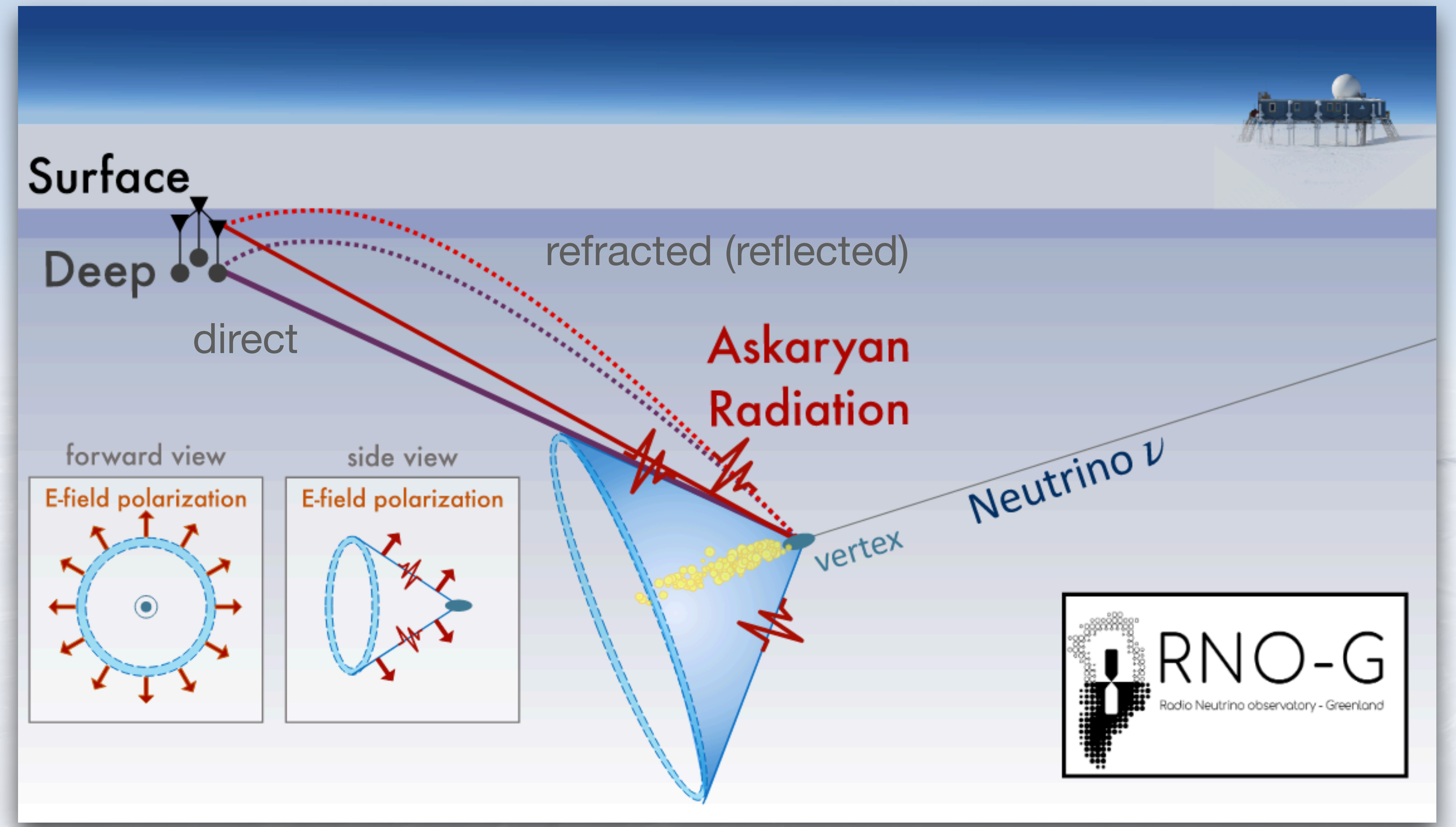
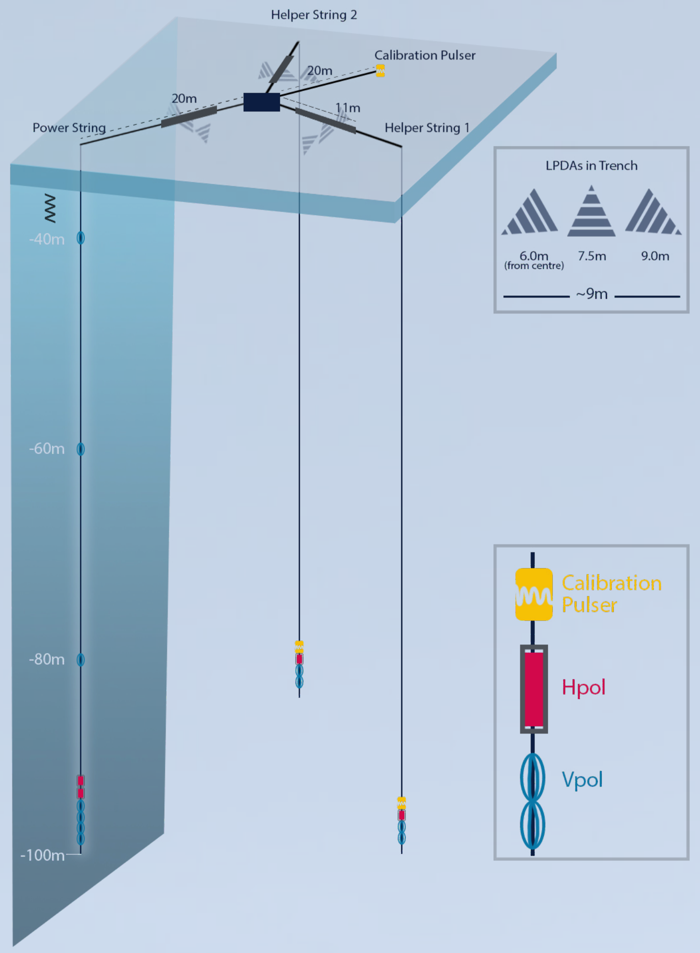


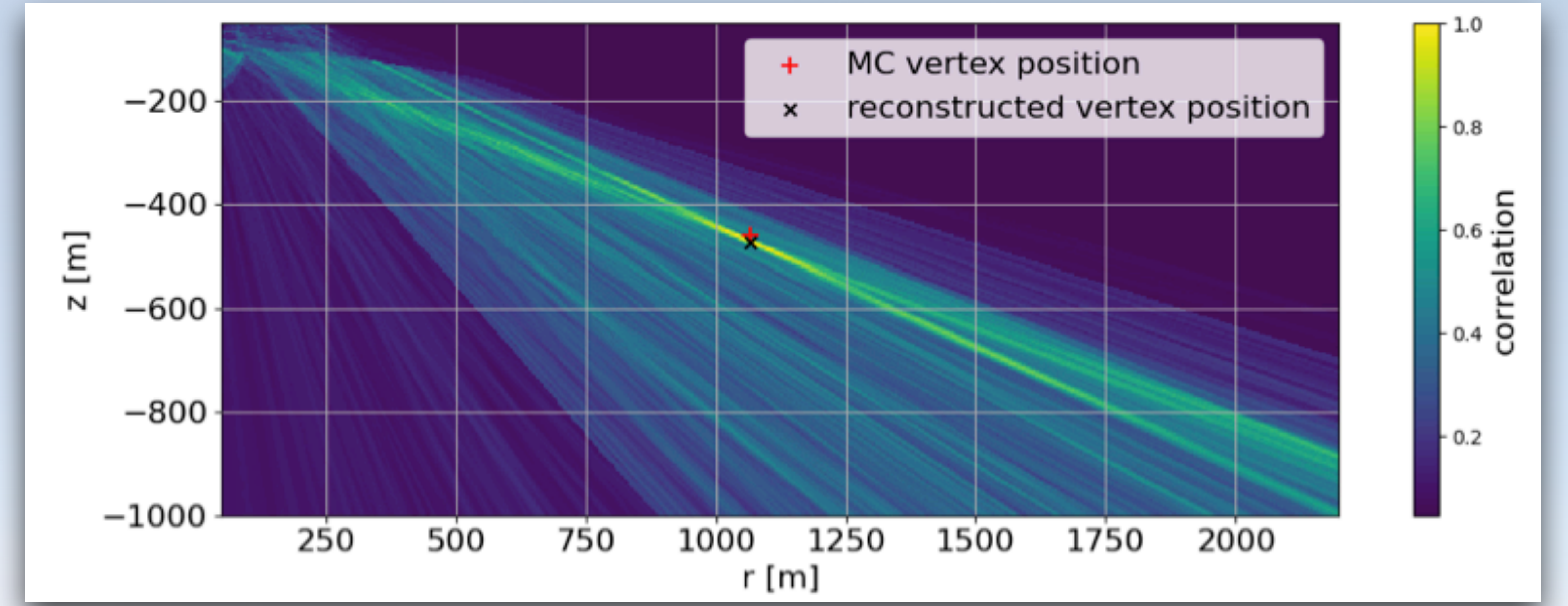
The radio emission …

- 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



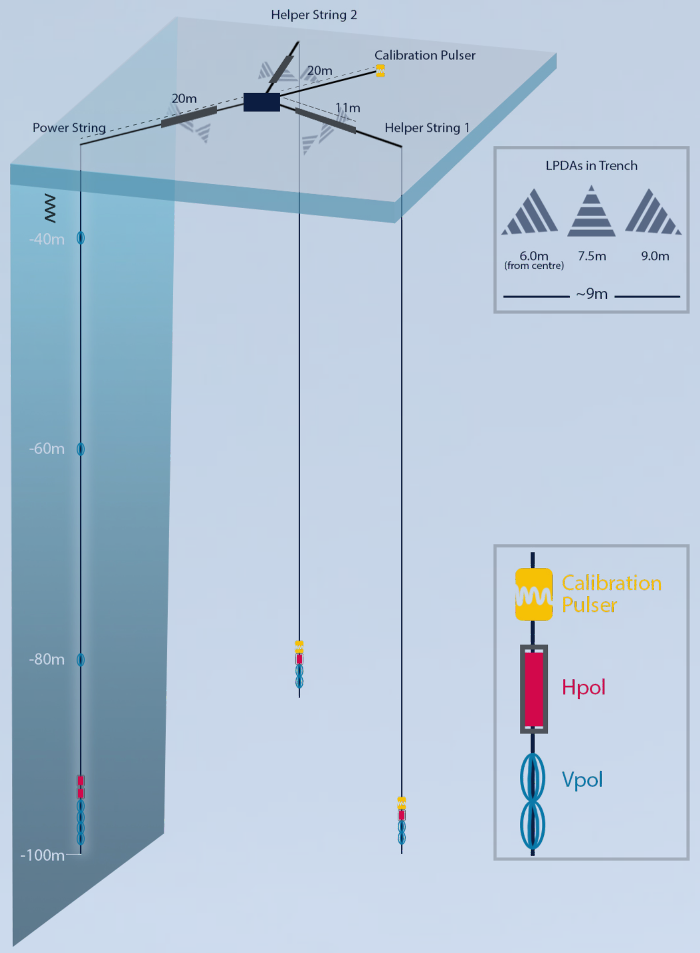
Using cross-correlation to determine signal (time) in each antenna.

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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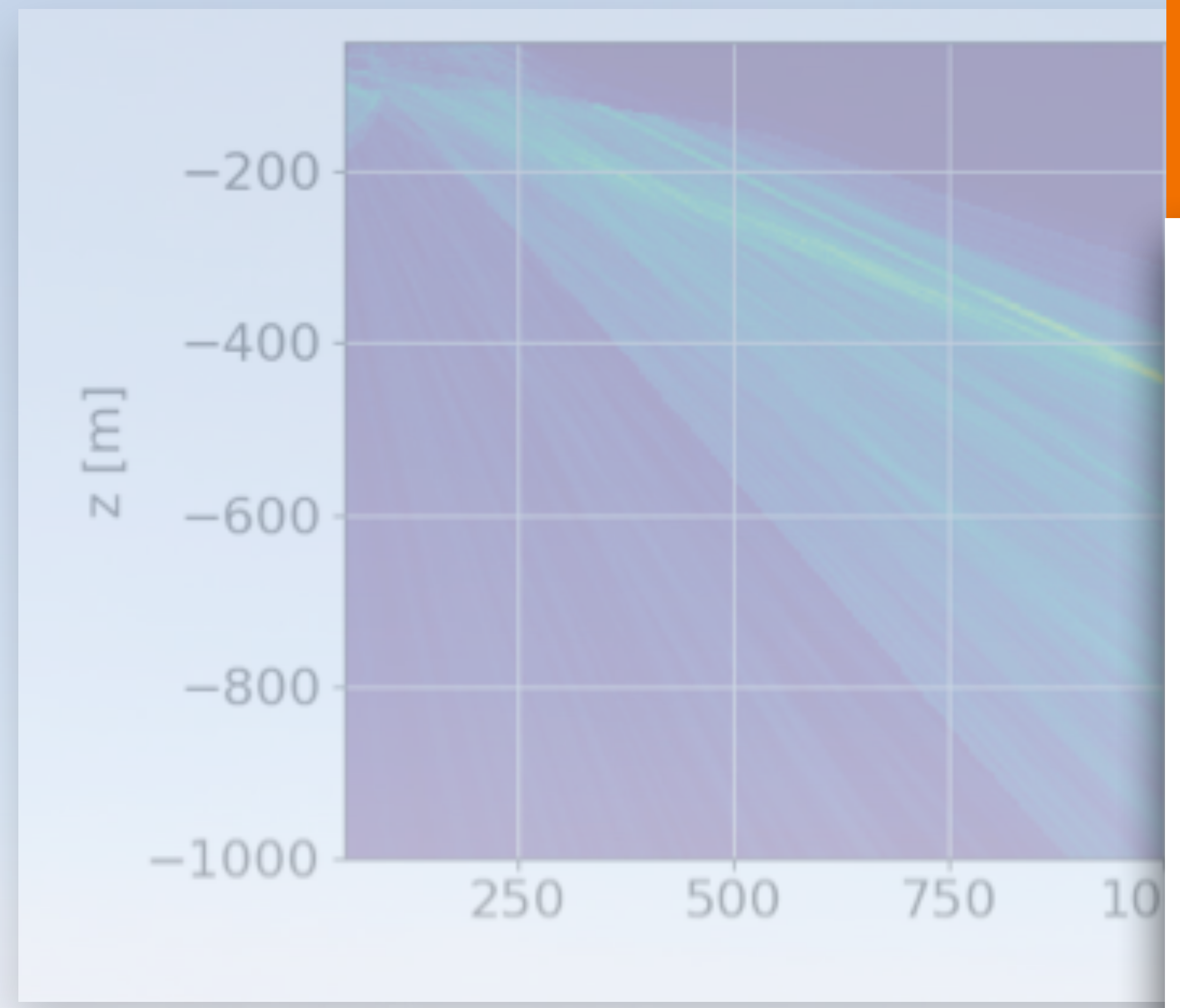

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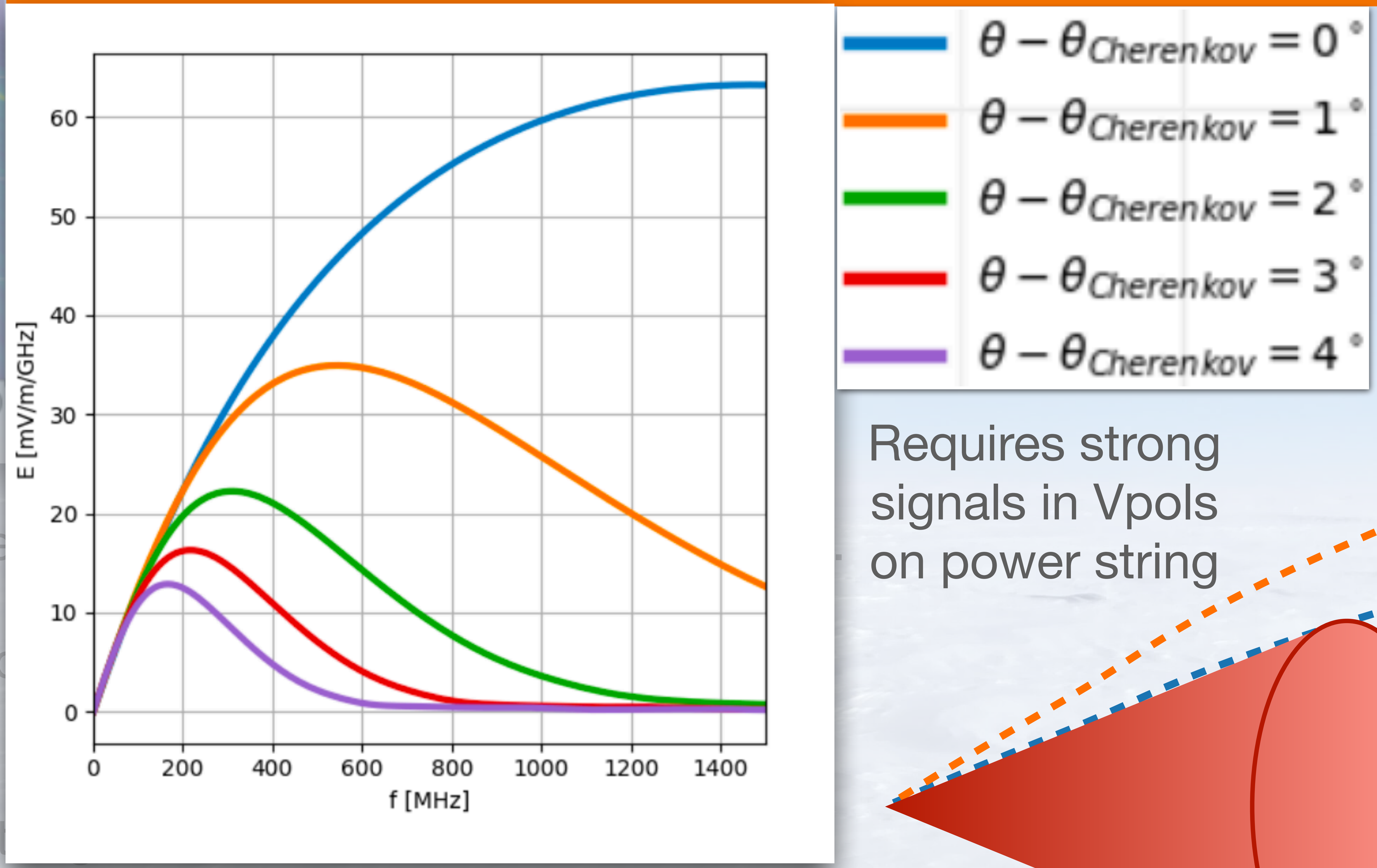
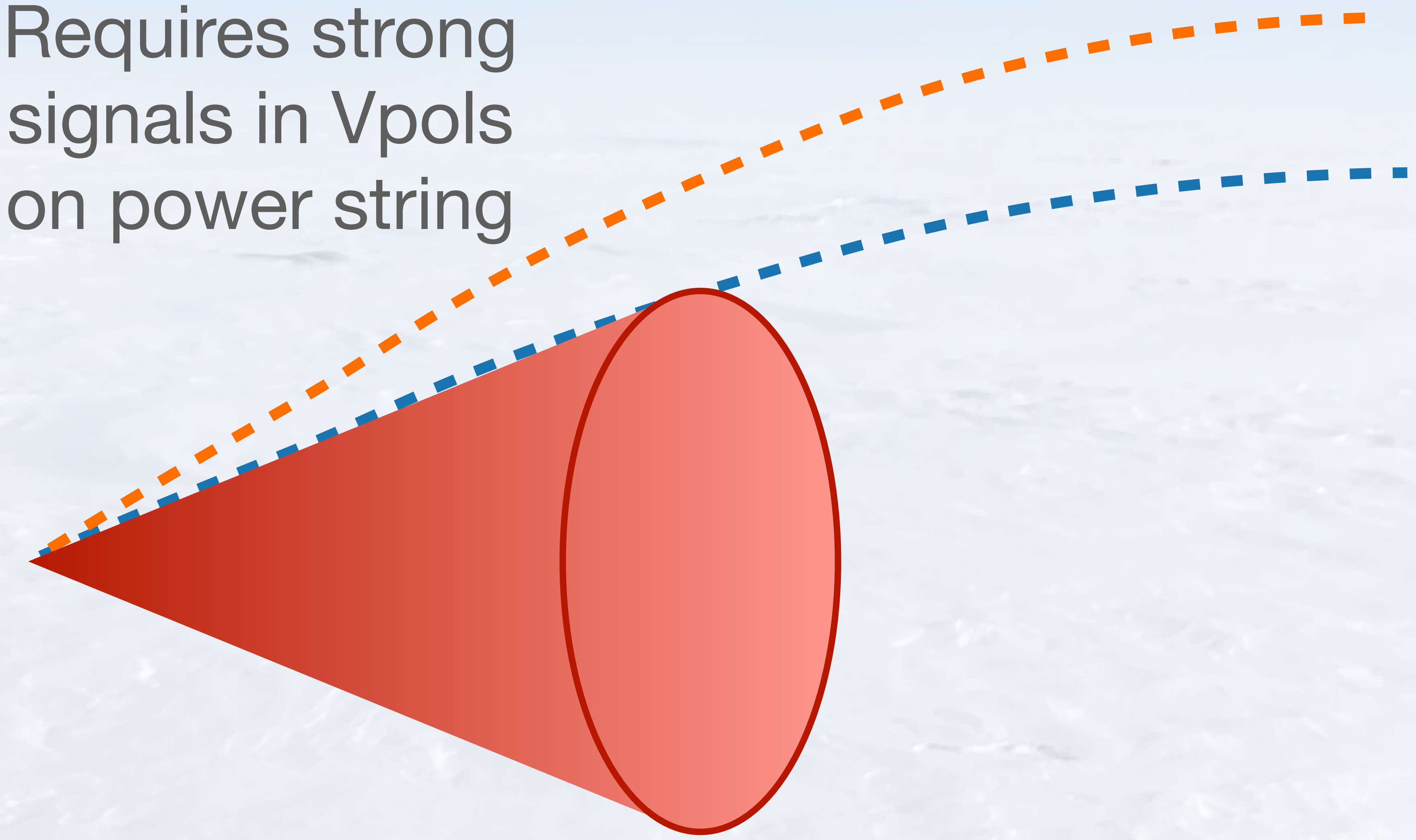


Requires strong signals in Vpols on power string



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

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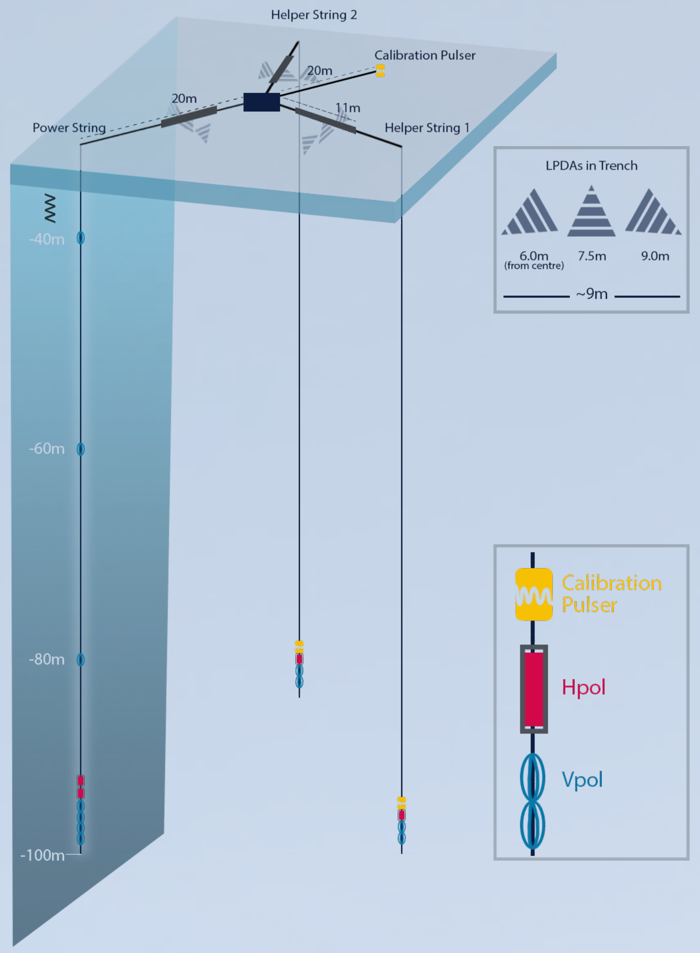

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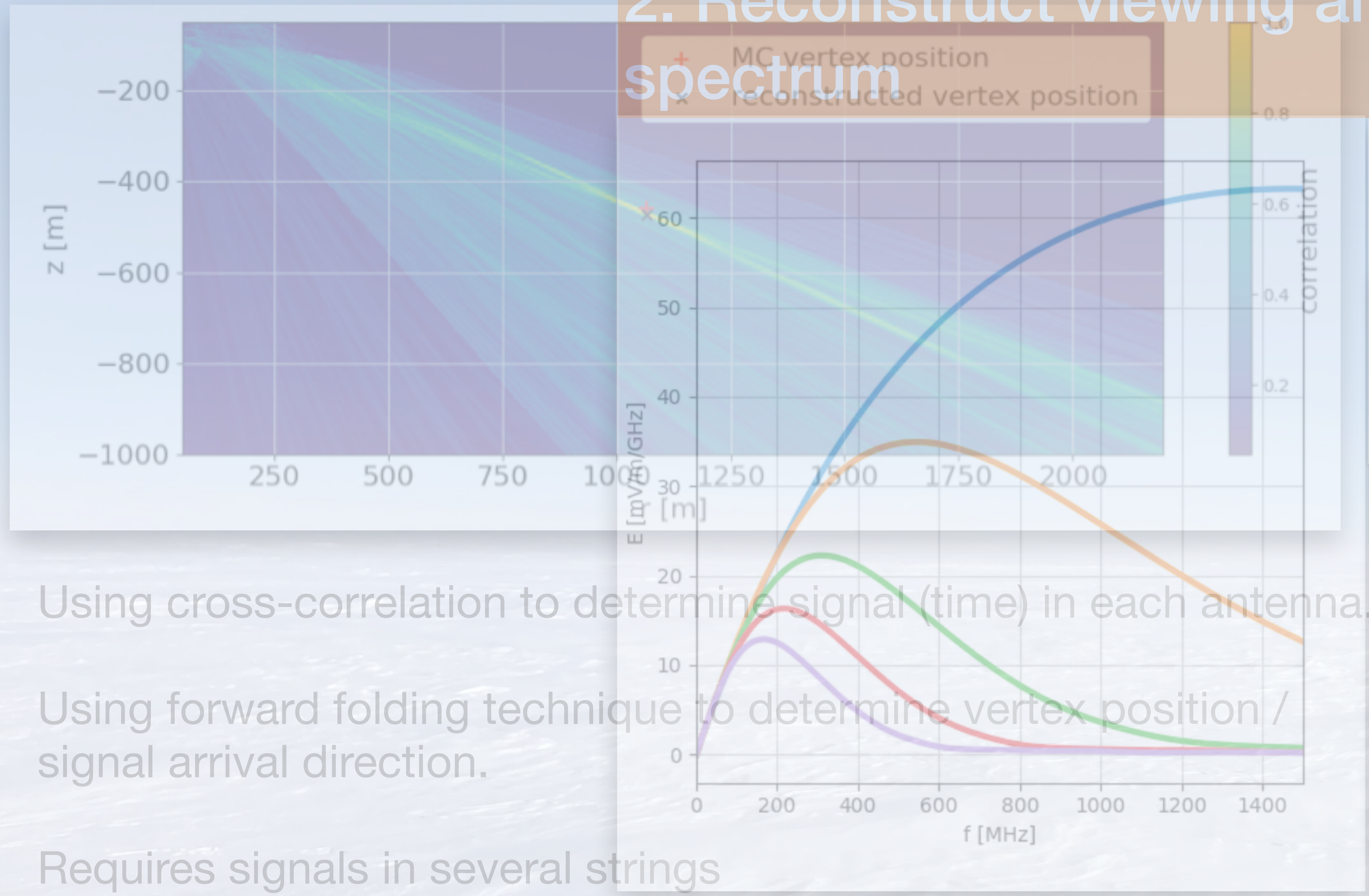


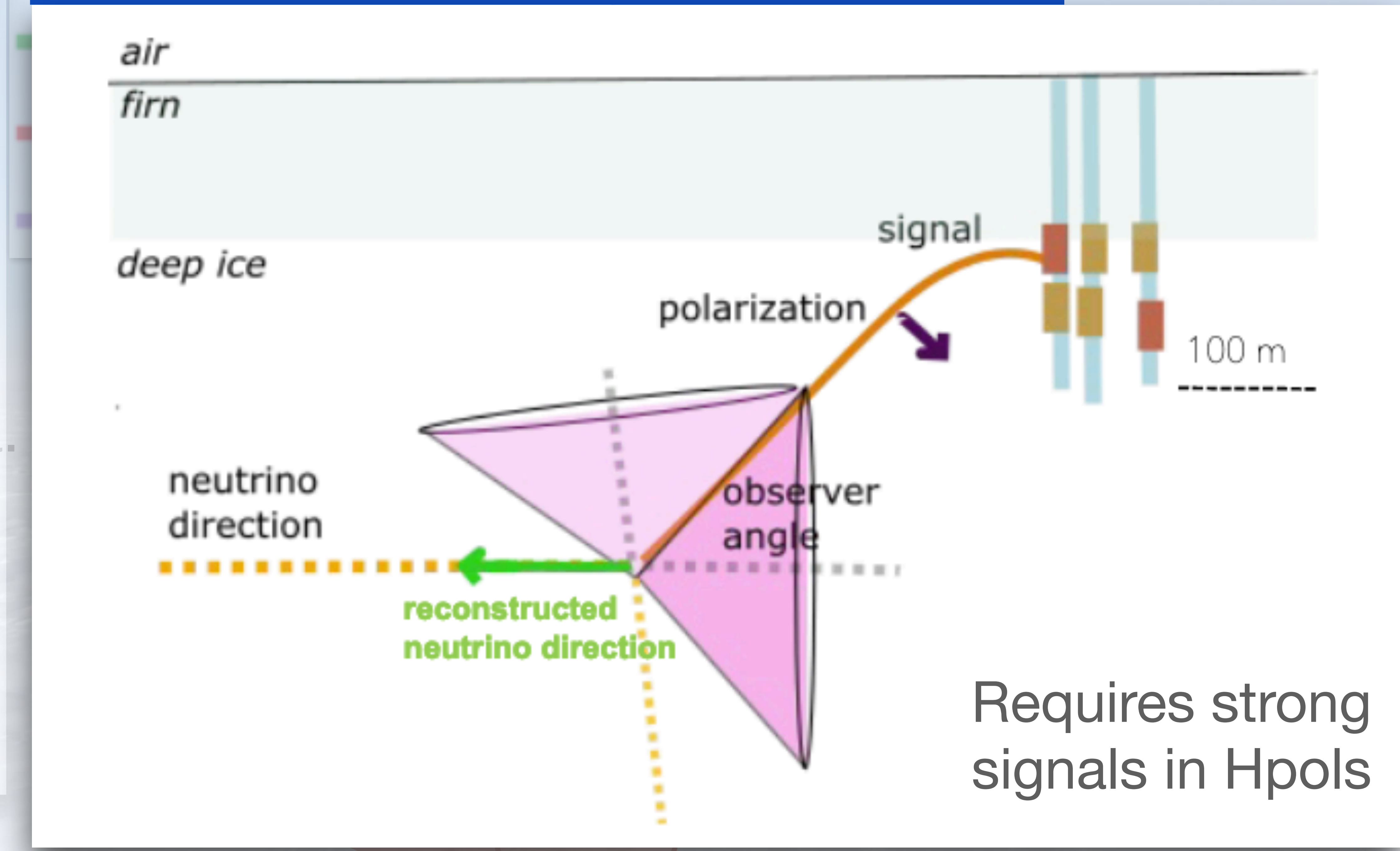
2. Reconstruct viewing angle from frequency spectrum

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

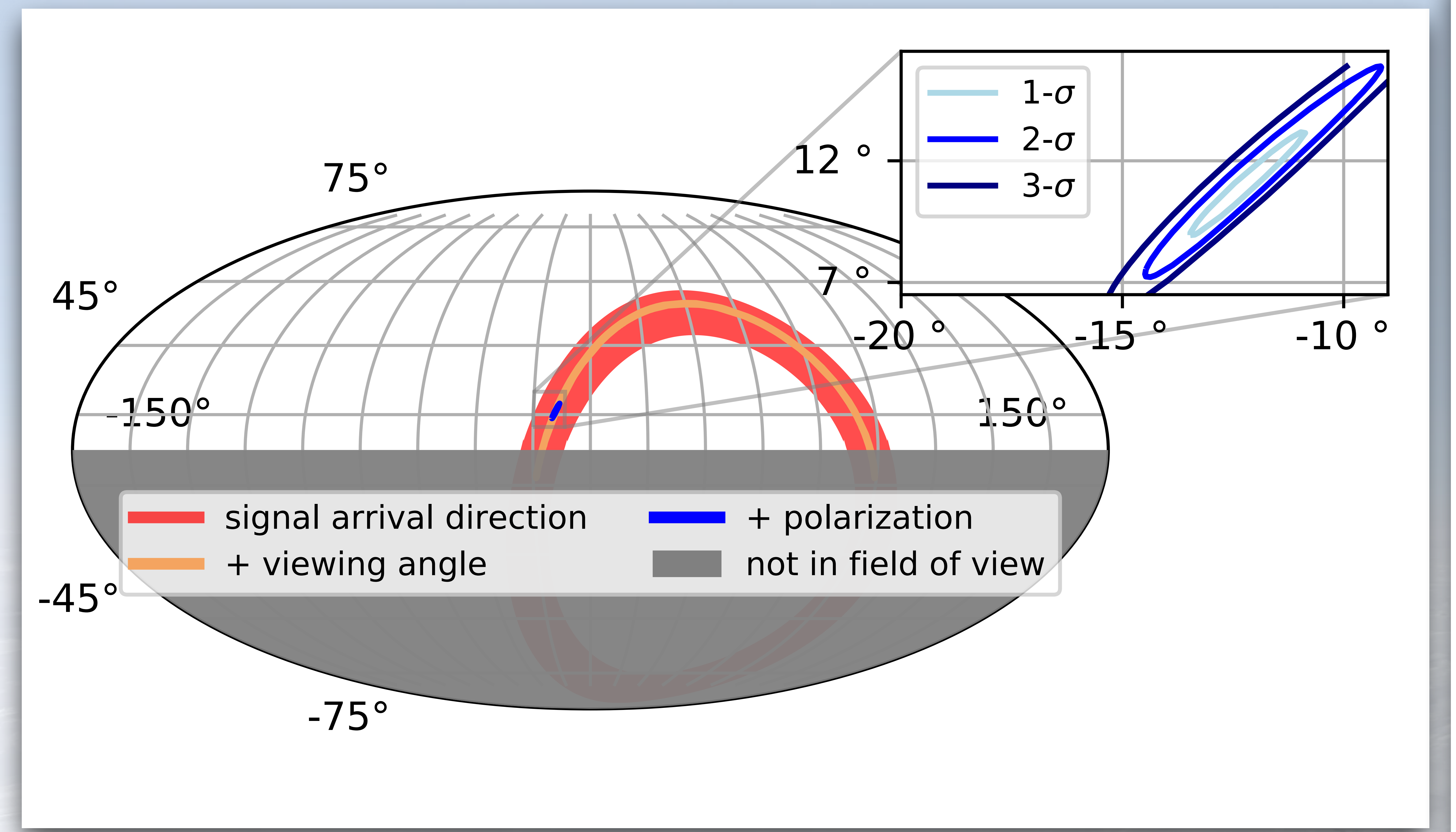
3. Reconstruct polarisation

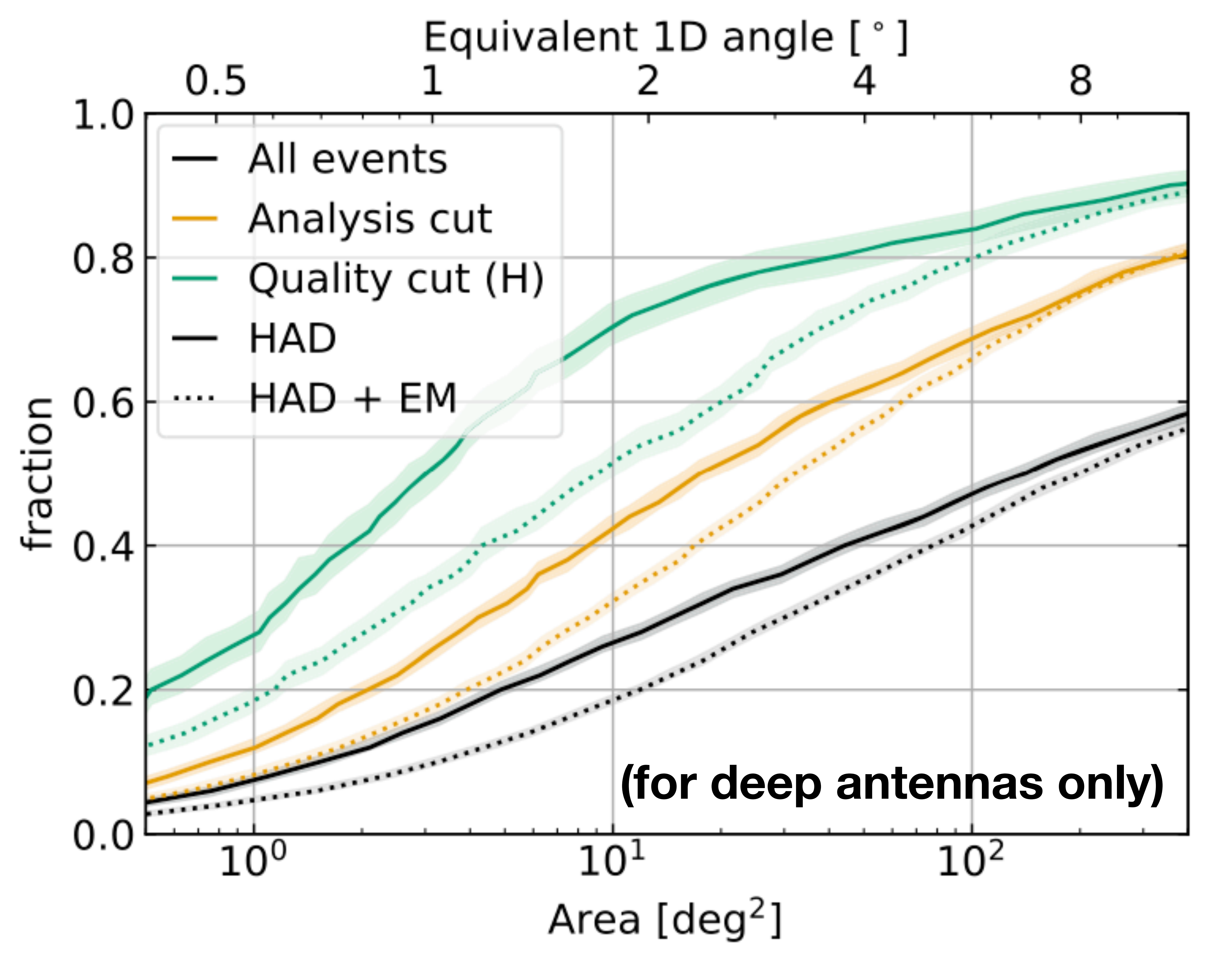


Requires strong signals in Hpols

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](#)

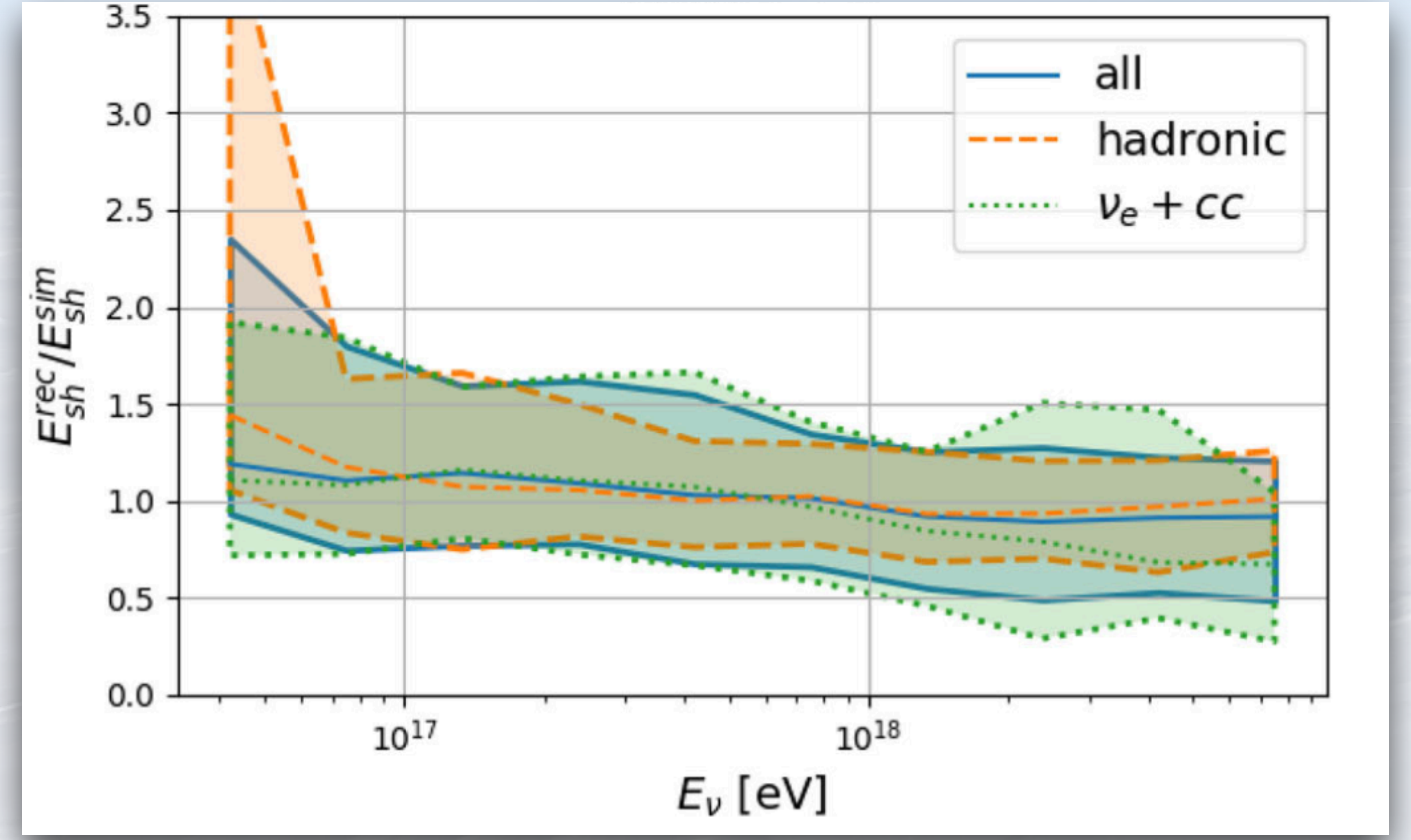
Energy reconstruction

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

Observed Field · Viewing angle · Vertex Distance · Polarization

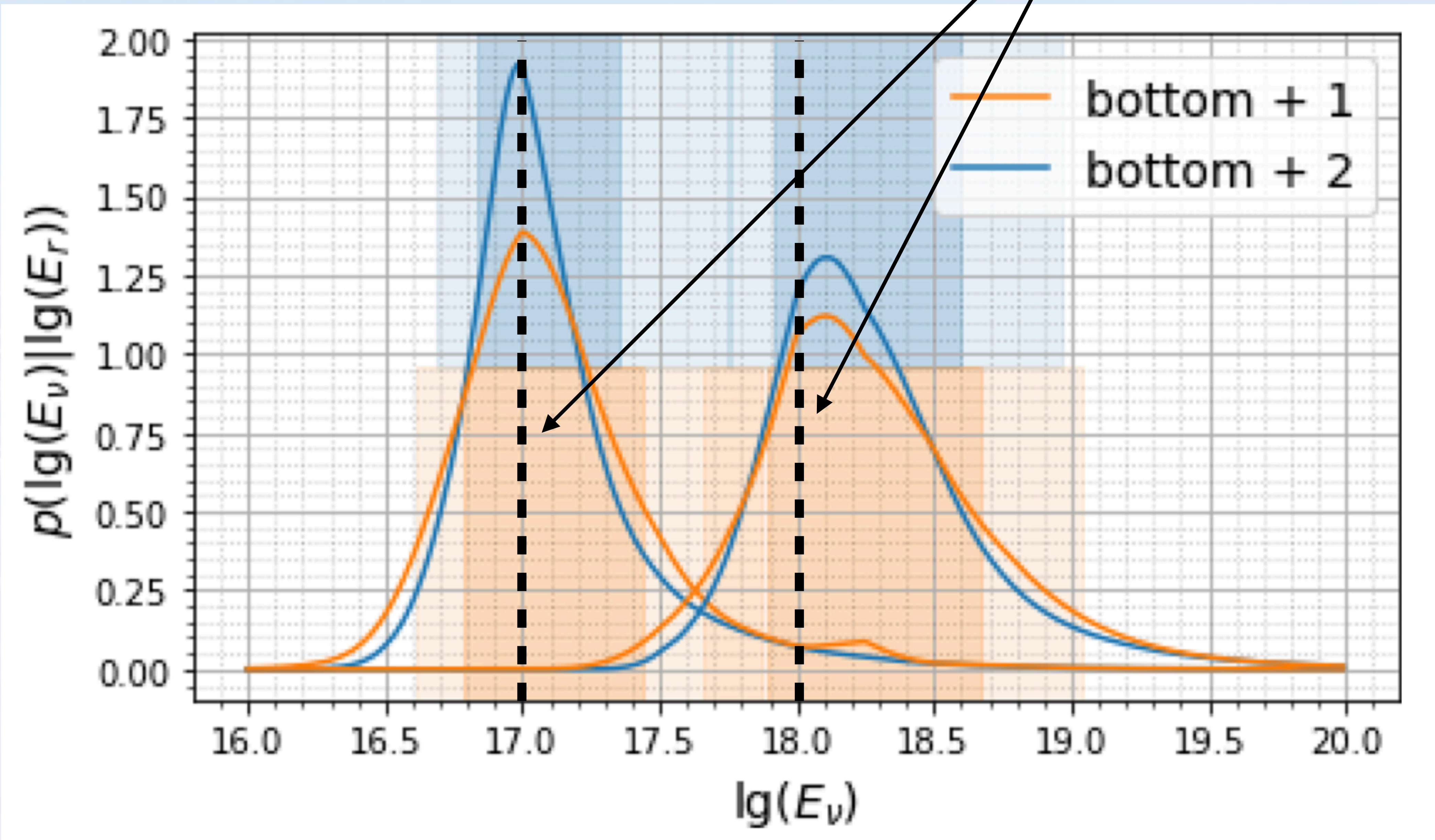
$$\vec{\mathcal{E}}(f) \propto (1-y)E_\nu \exp\left[-\frac{1}{2}\left(\frac{\theta-\theta_c}{\sigma(E_{sh}, f)}\right)^2\right] \frac{1}{R}\exp\left(\frac{-R}{L(f)}\right) \vec{\ell} \times (\vec{v}_\nu \times \vec{\ell})$$

Shower energy



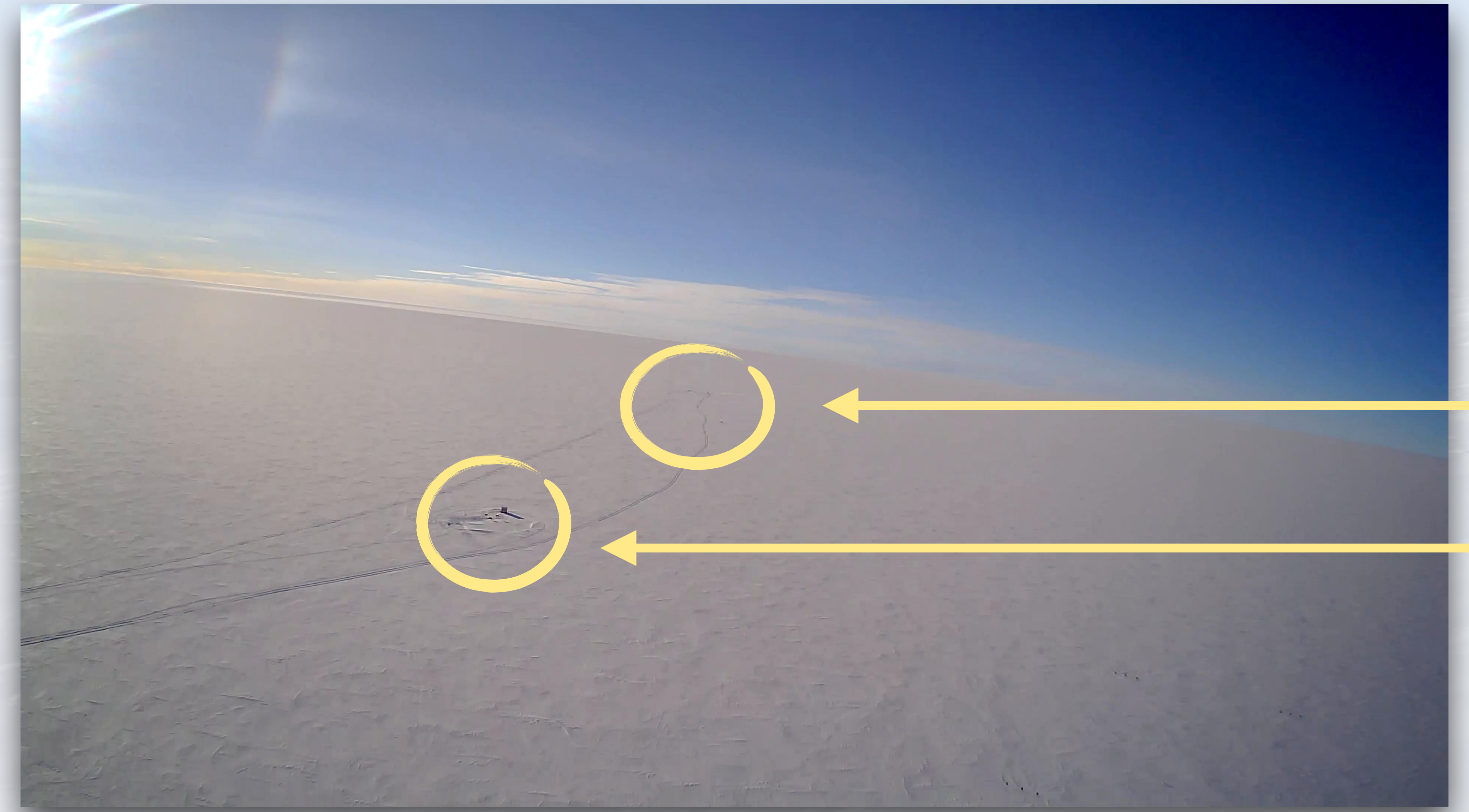
Neutrino energy

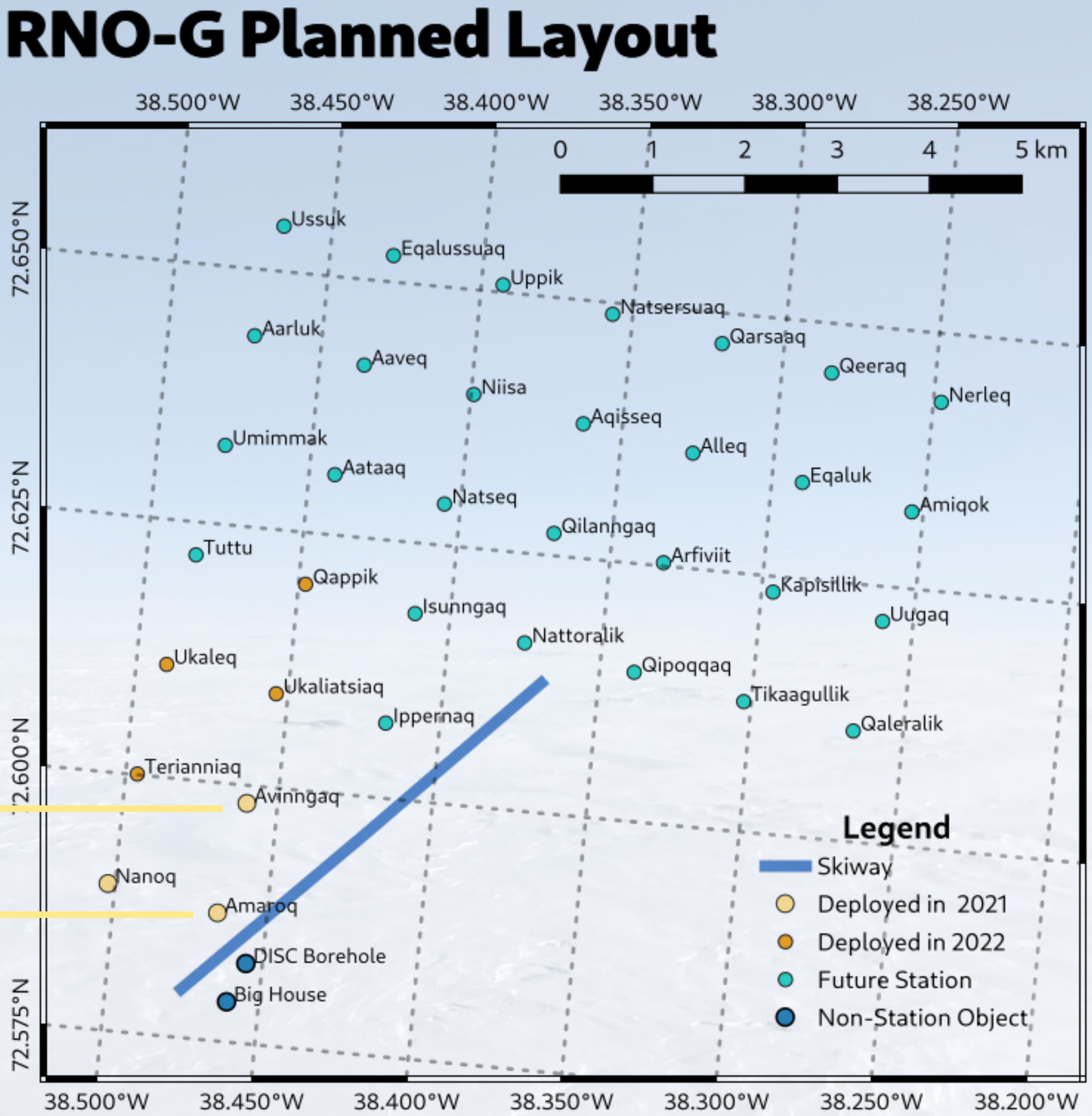
True energy



Radio Neutrino Observatory - Greenland

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

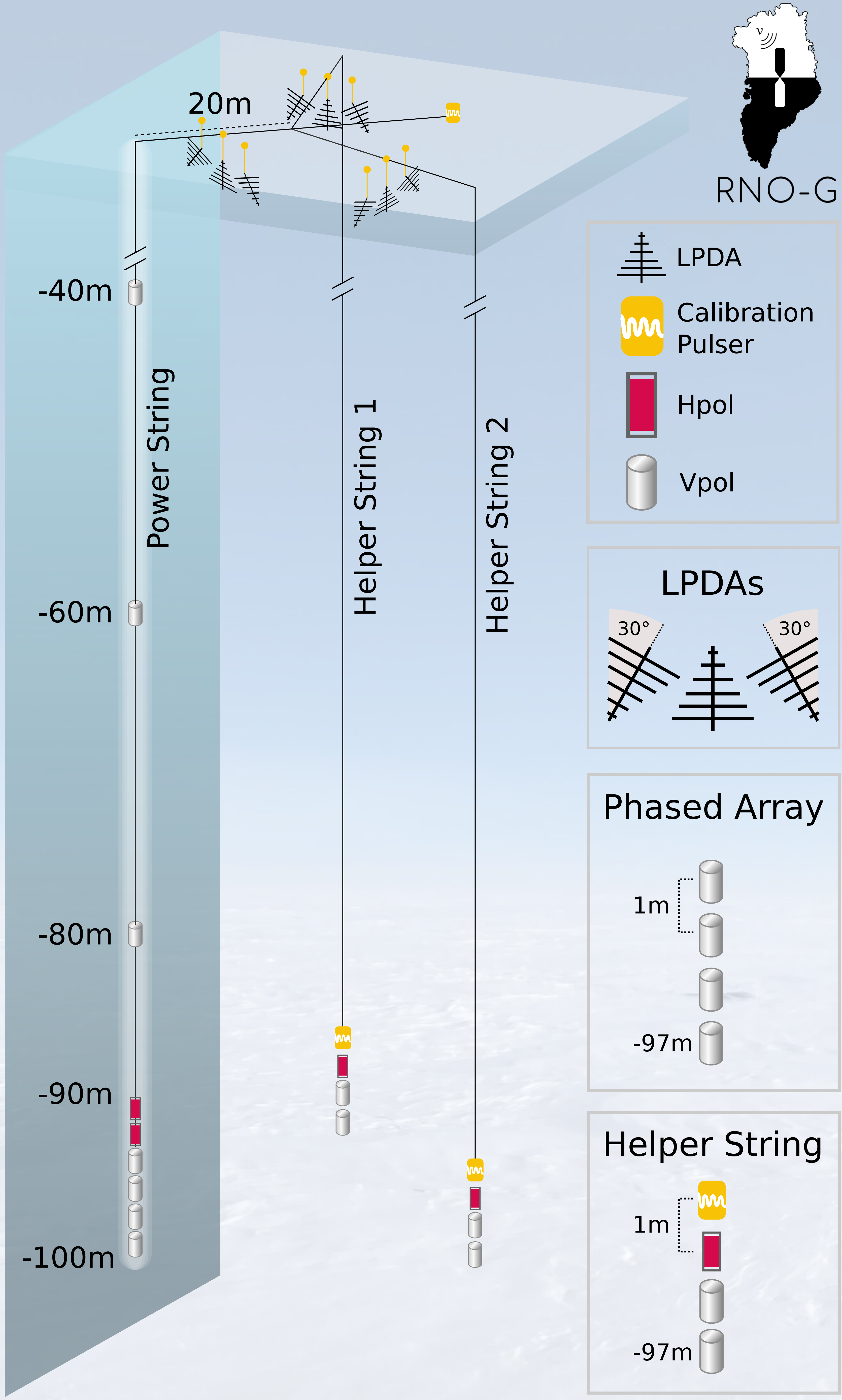




Station design

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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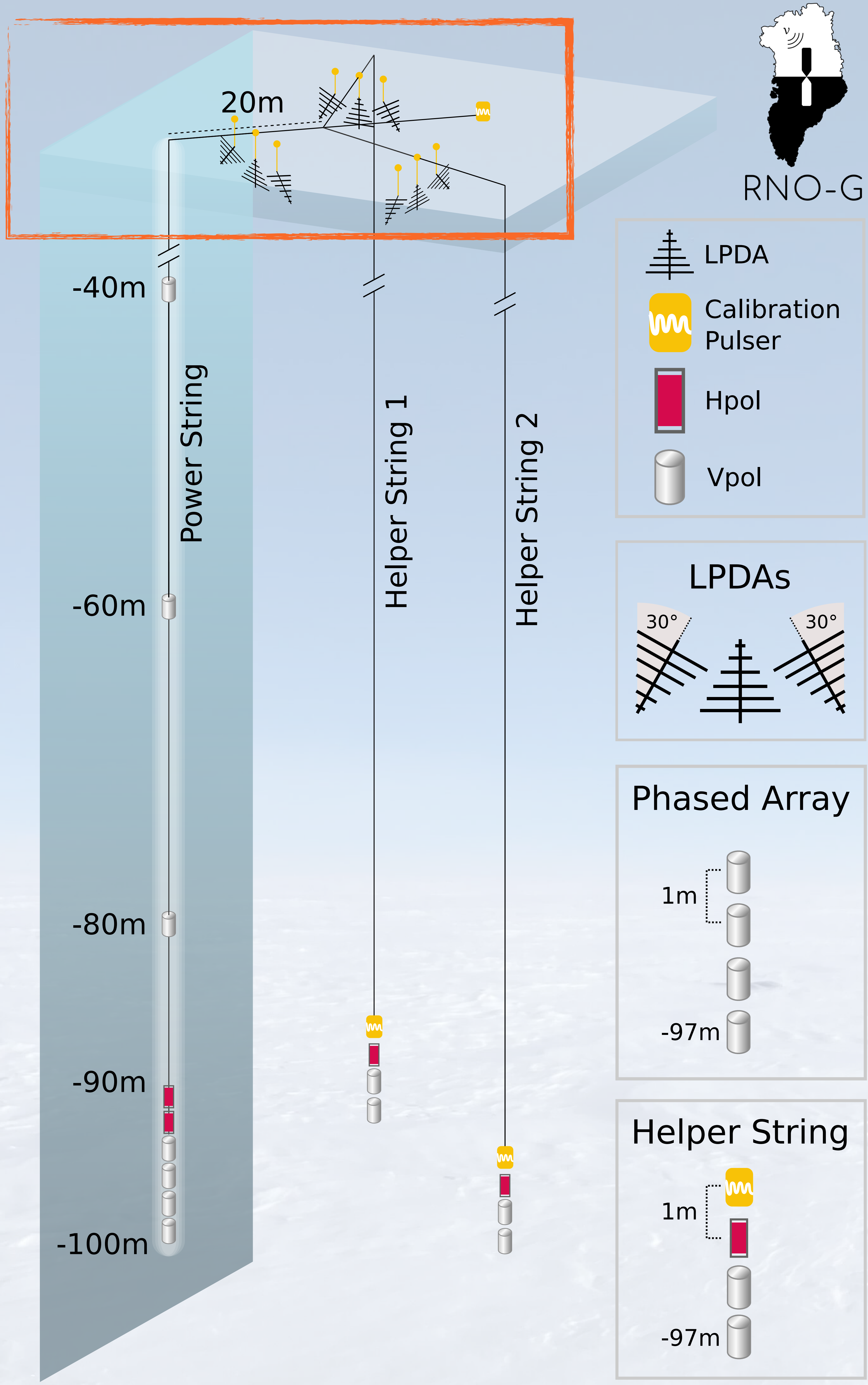

Shallow component

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

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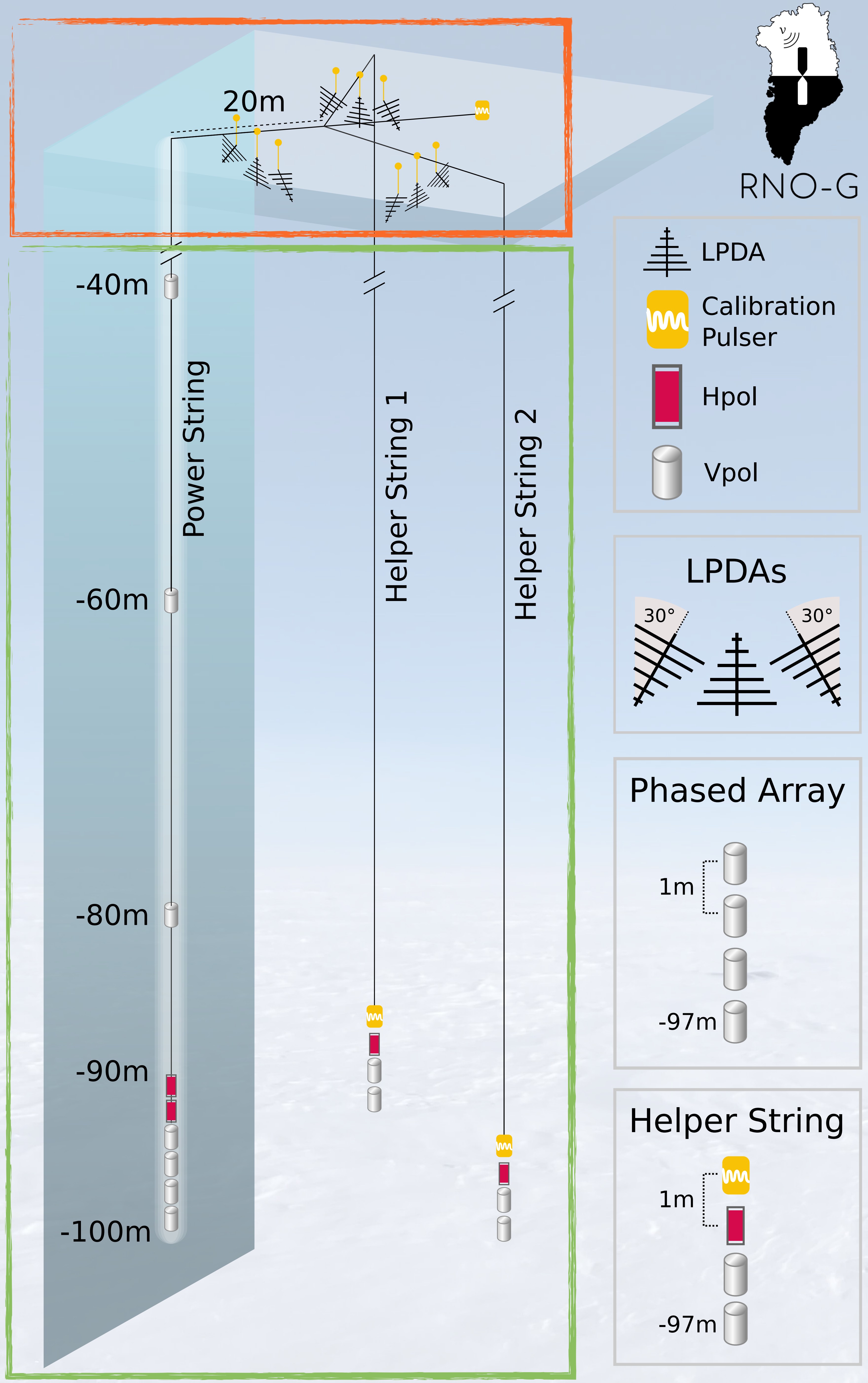

Shallow component

- Upward- & downward-facing LPDA antennas
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Deep component

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

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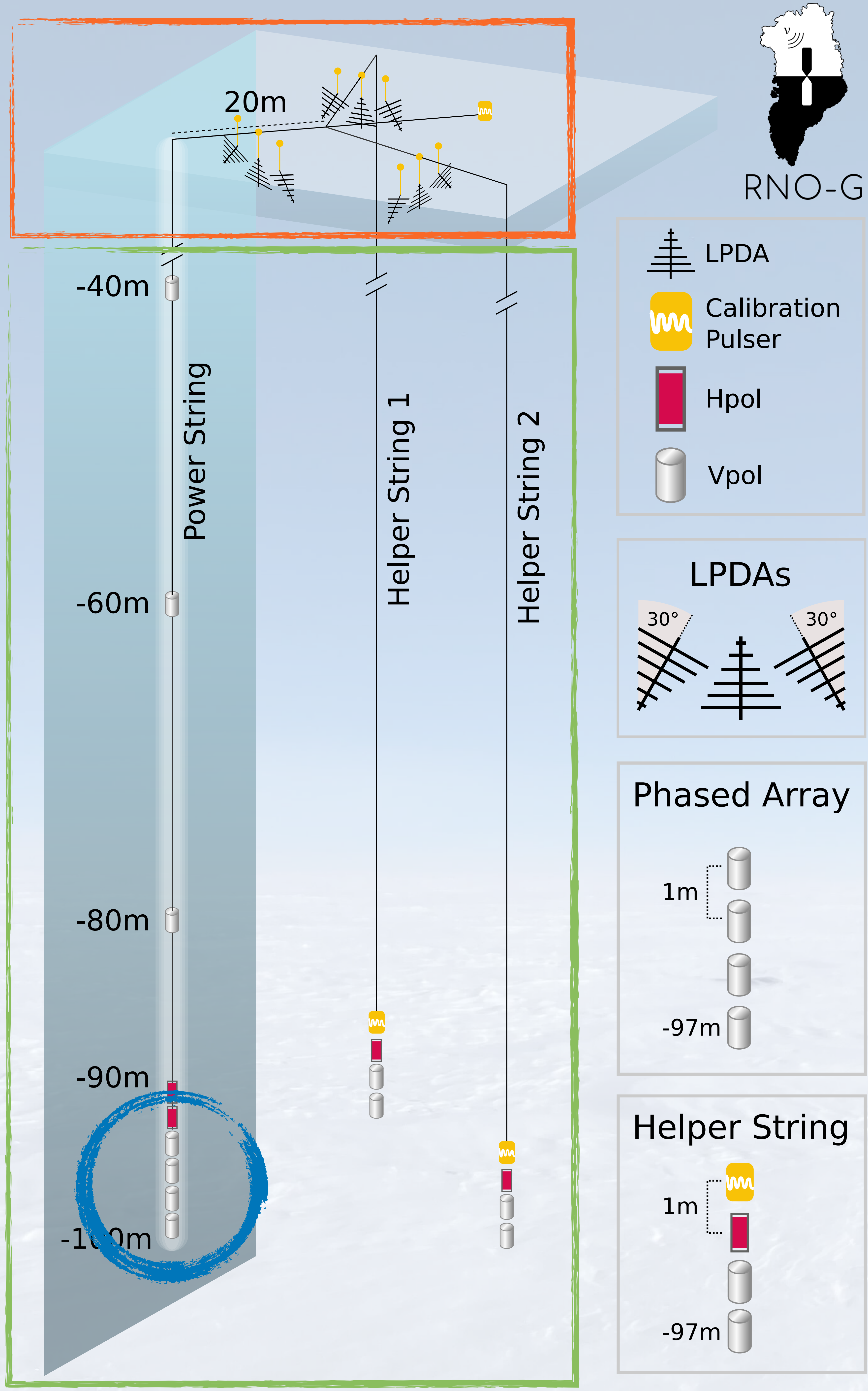


Phased array

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

Shallow component

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

Deep component

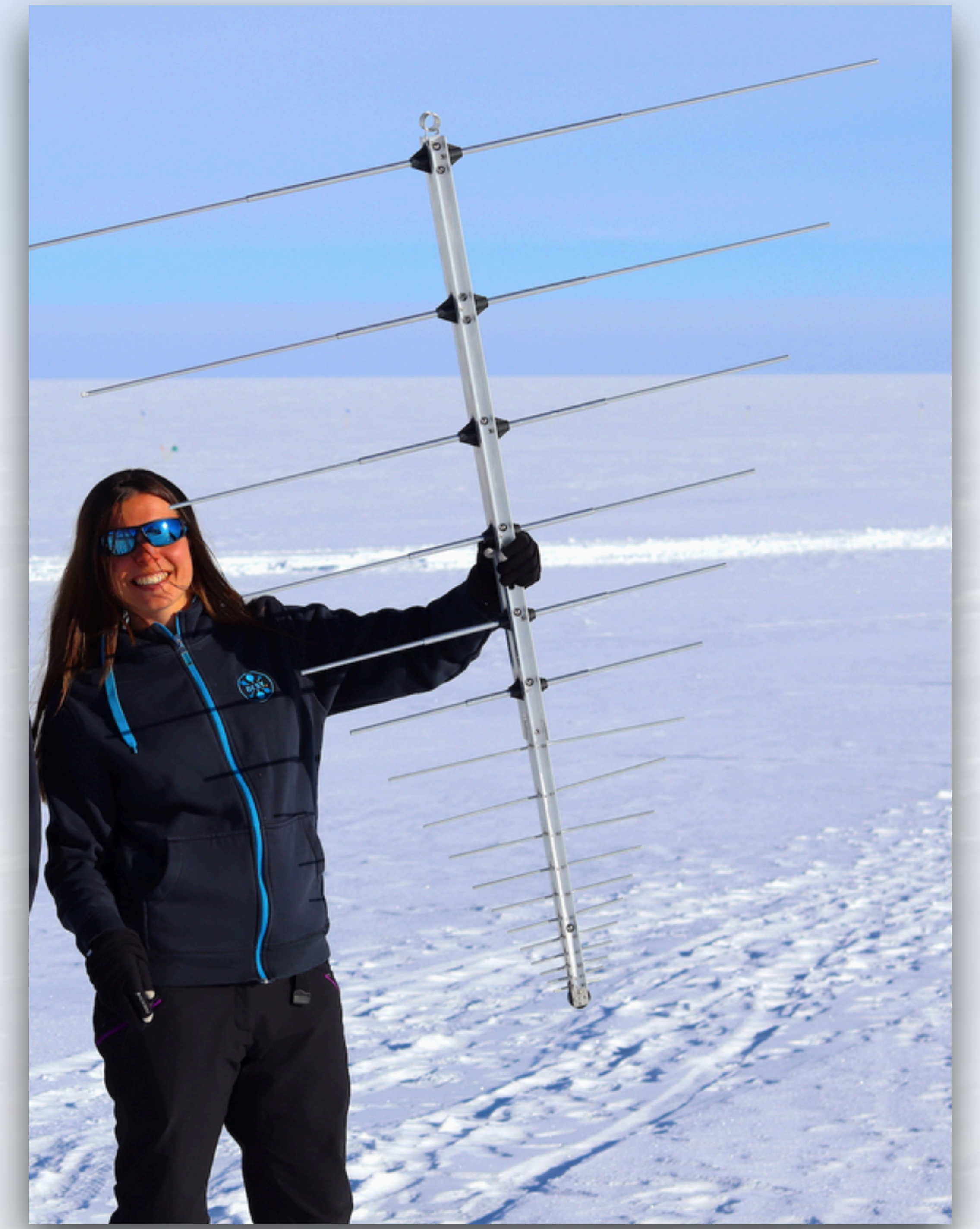
- 100m deep
- “Overlook” larger volume
- Low threshold trigger

Antenna sensitivity

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

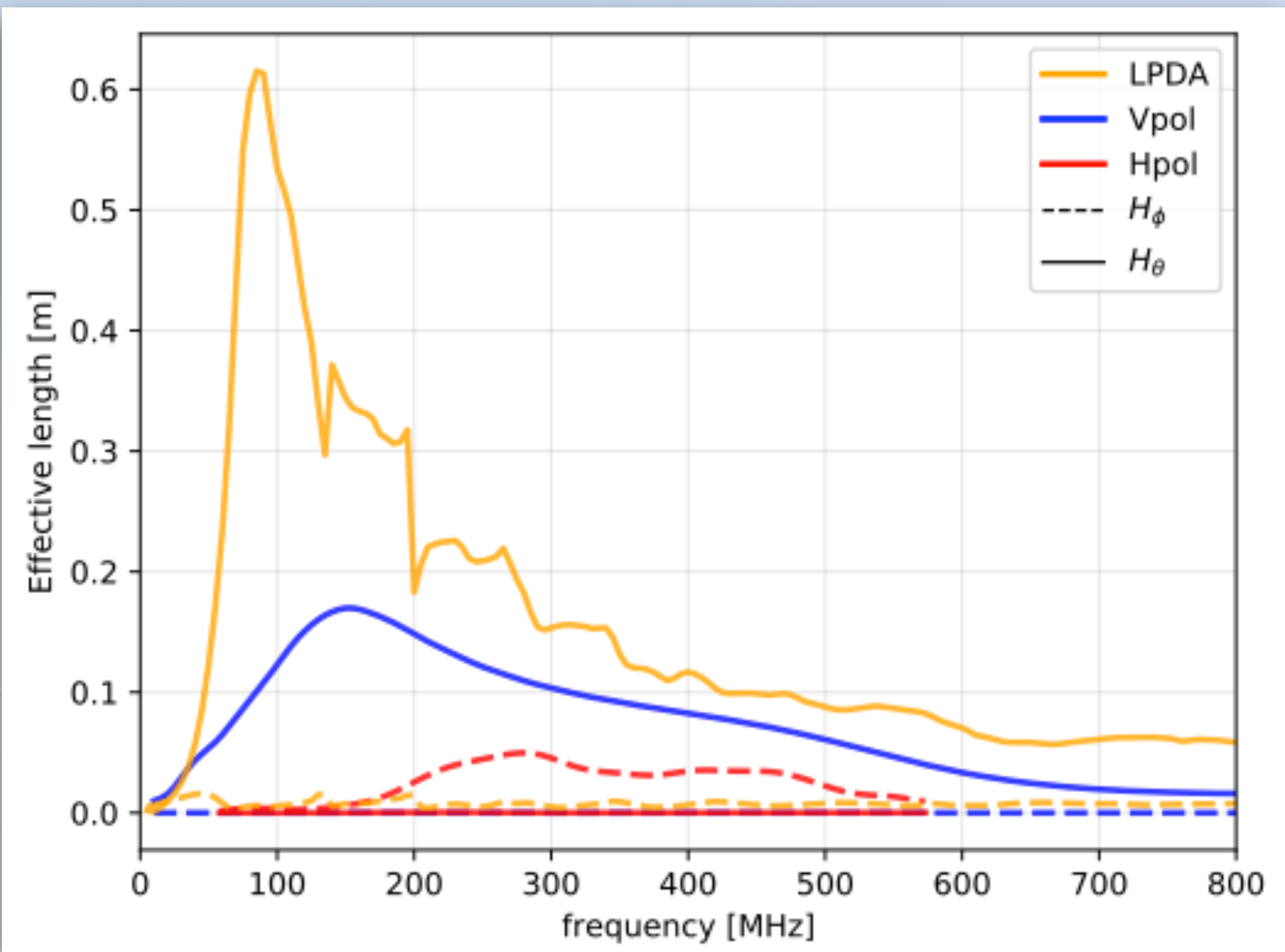
- Combination of Vpol and Hpol gives polarisation
  - Hpols is less sensitive because of narrow diameter of borehole

LPDA



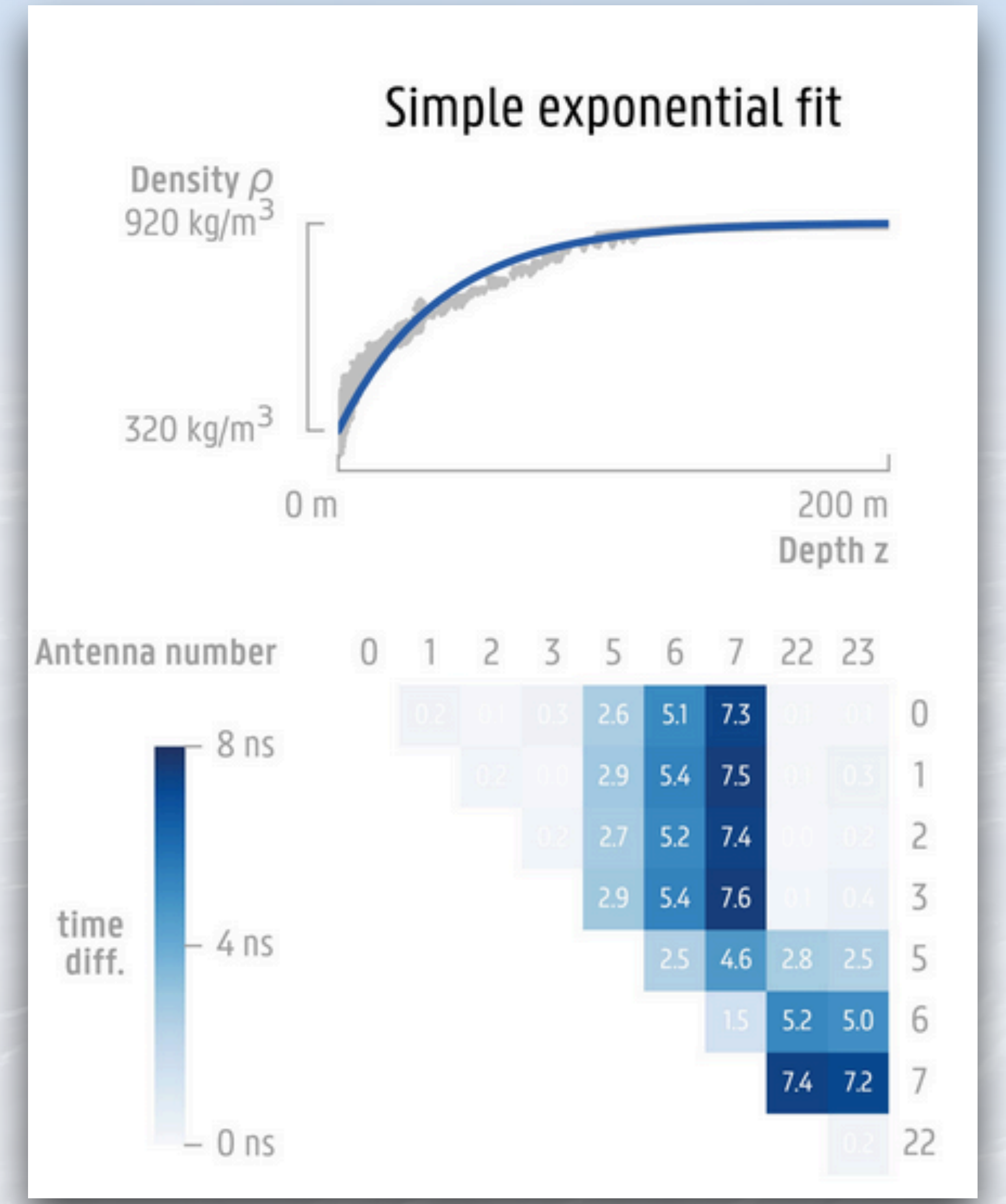
Hpol

Vpol



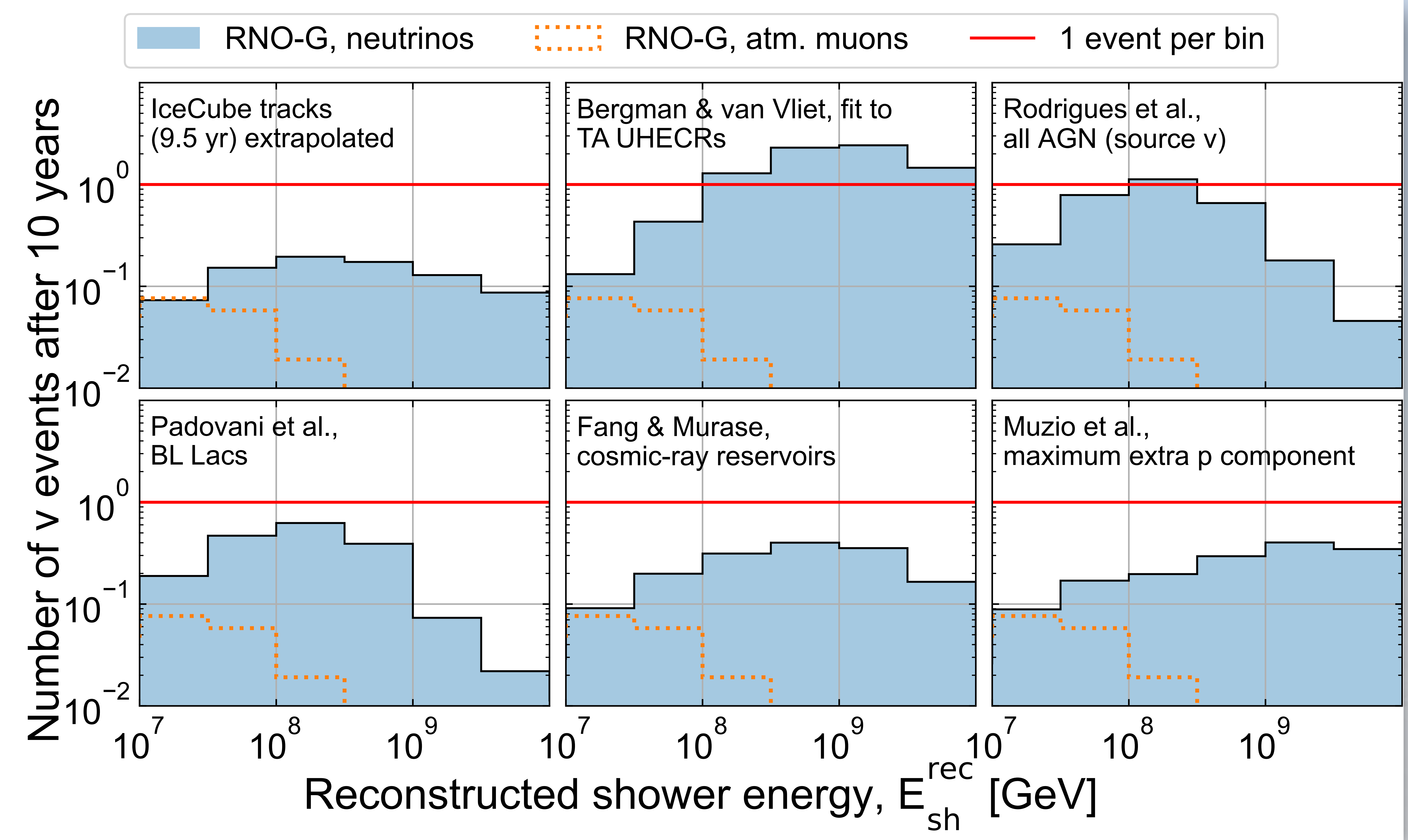
Calibration

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



Expected number of neutrinos

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

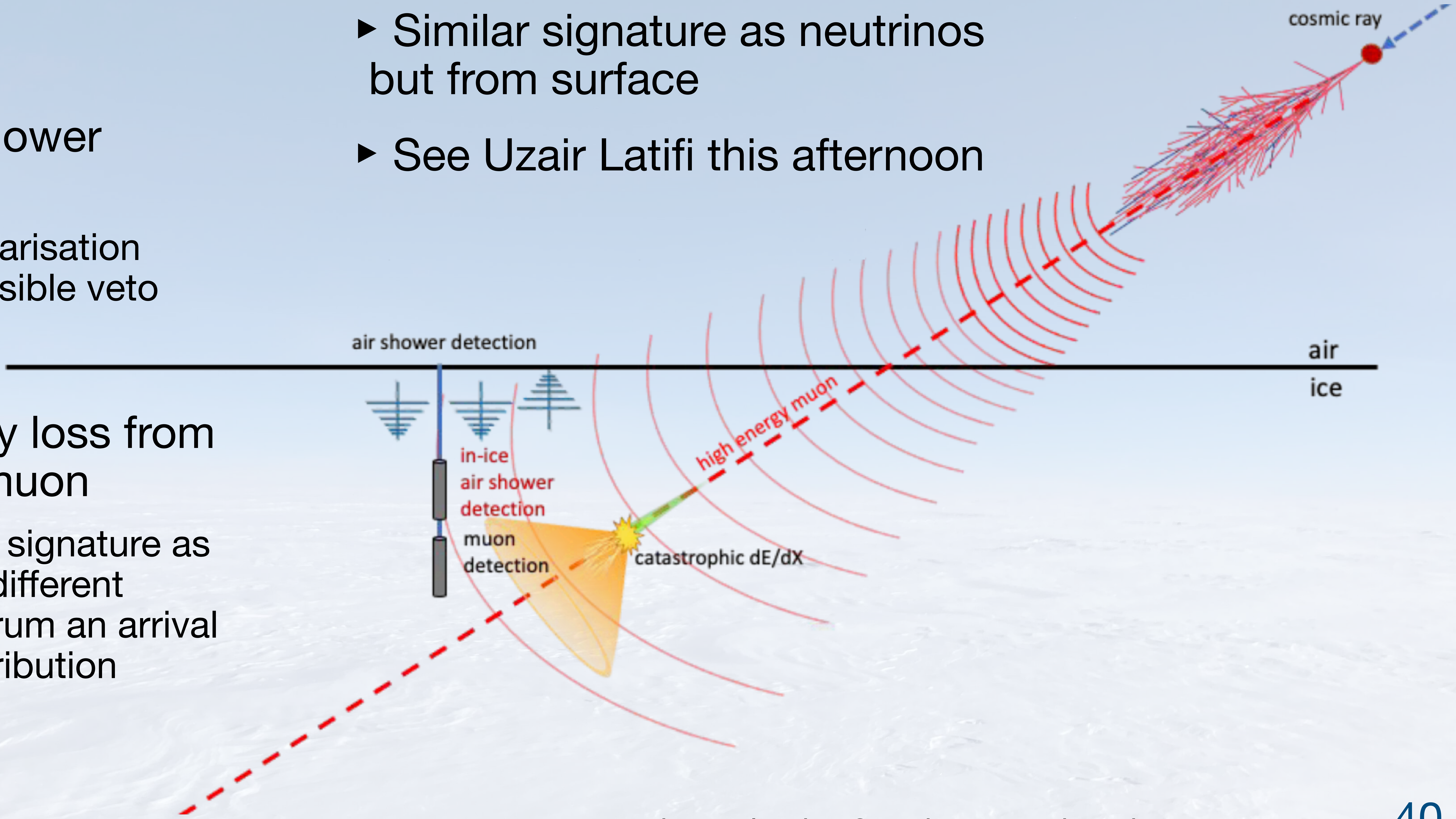


Background

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

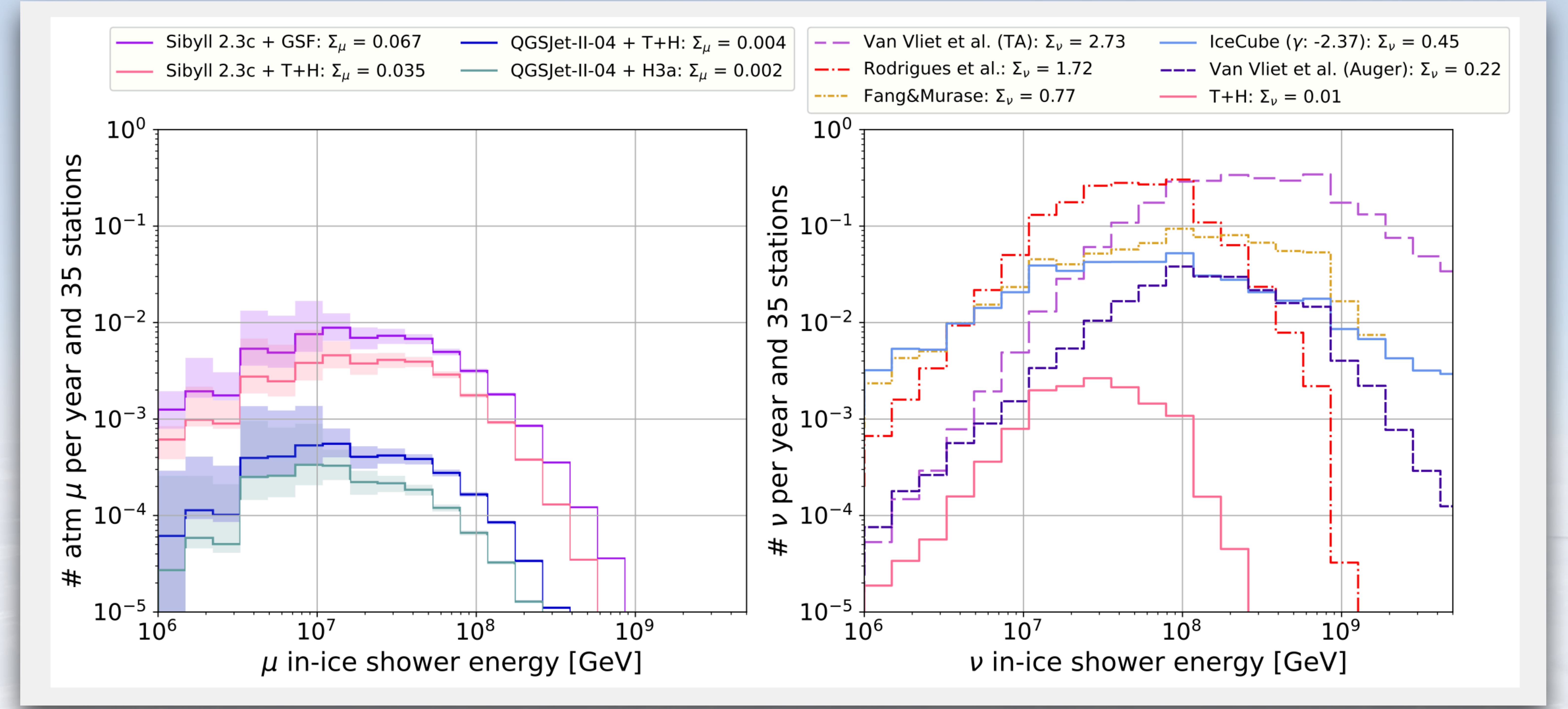
2. Huge energy loss from high energy muon
   - Same signal signature as neutrino but different energy spectrum an arrival direction distribution

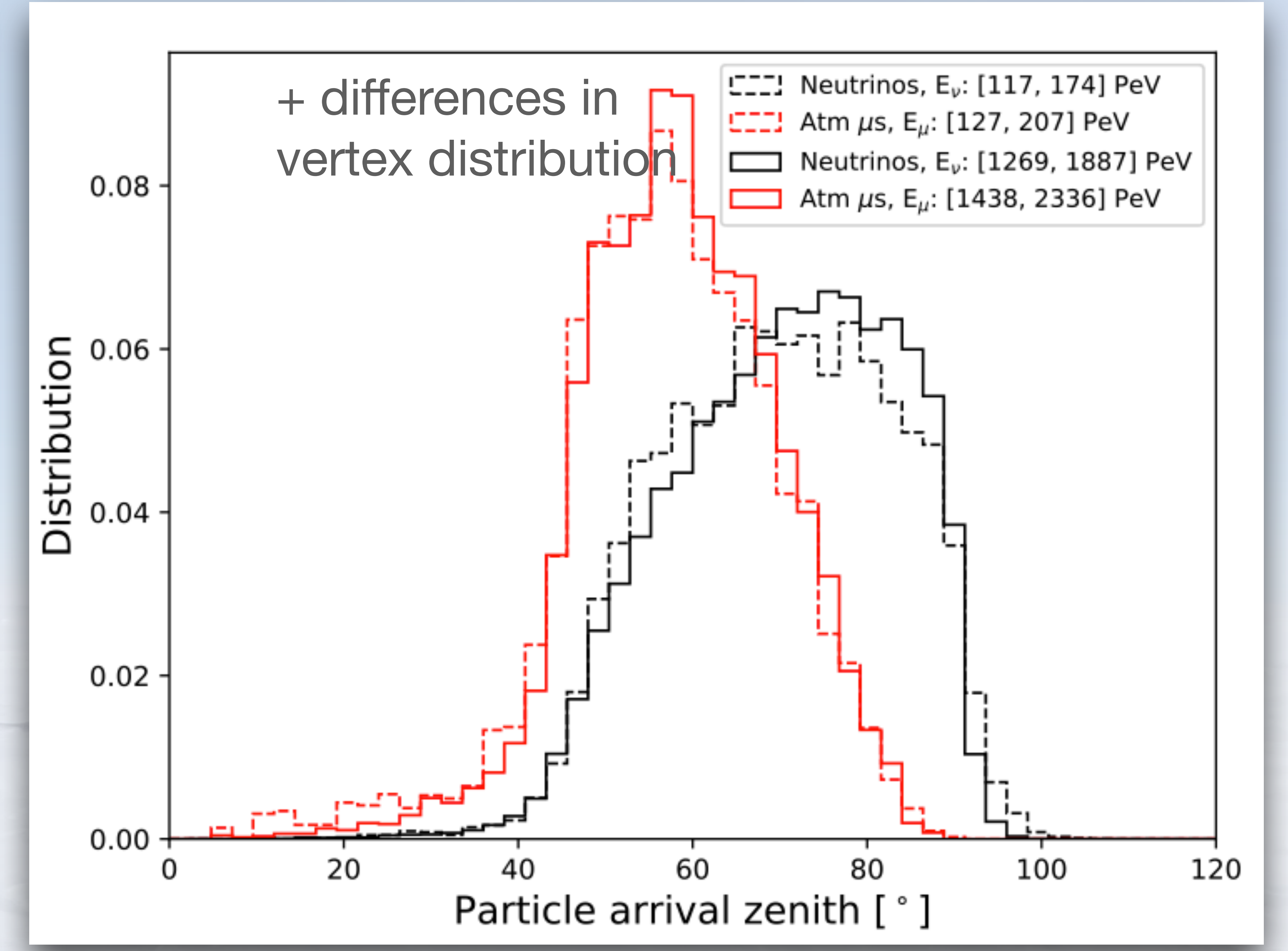
3. In-ice emission if air shower particles reach ice
   - Similar signature as neutrinos but from surface
   - See Uzair Latifi this afternoon



+ thermal noise & anthropogenic noise

Background



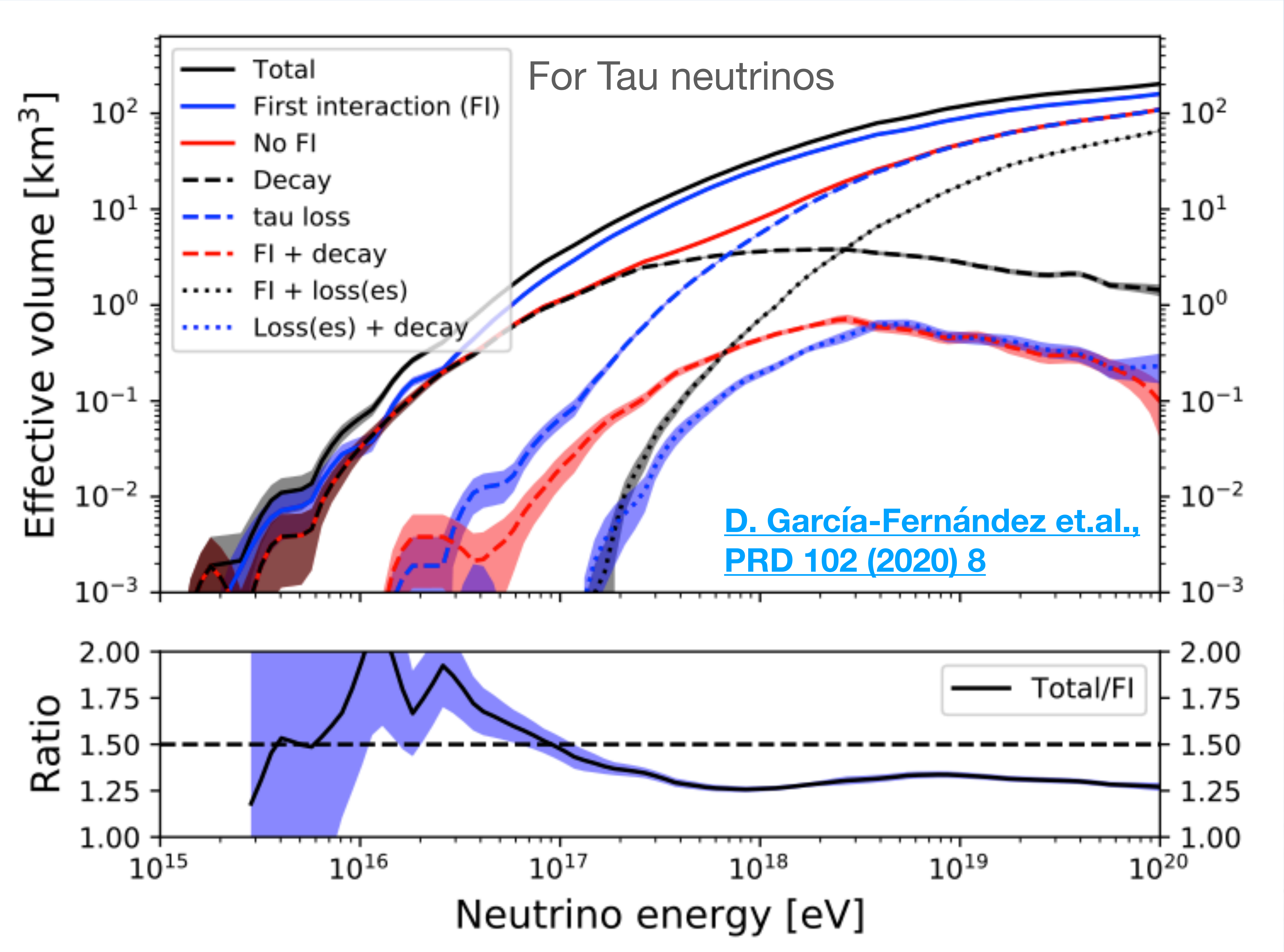


L. Pyras et al. PoS (ICRC2023) 1076 + arxiv

Ice Properties

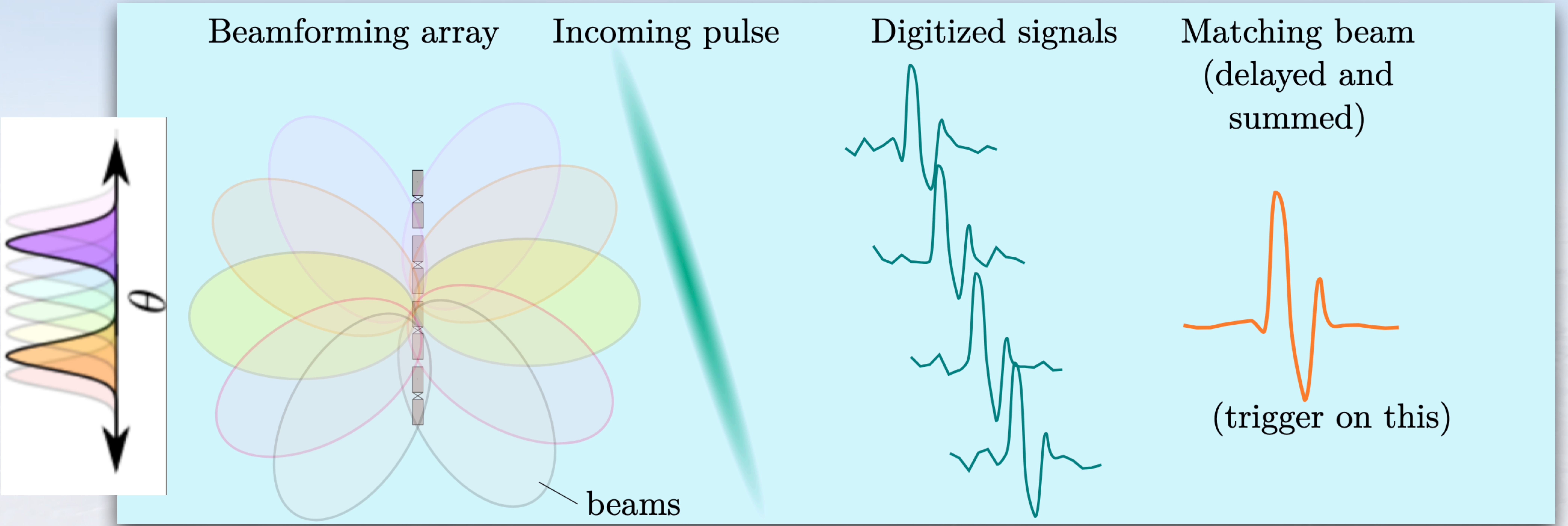
- Part of the detector -> needs to be calibrated

Signals from secondary leptons

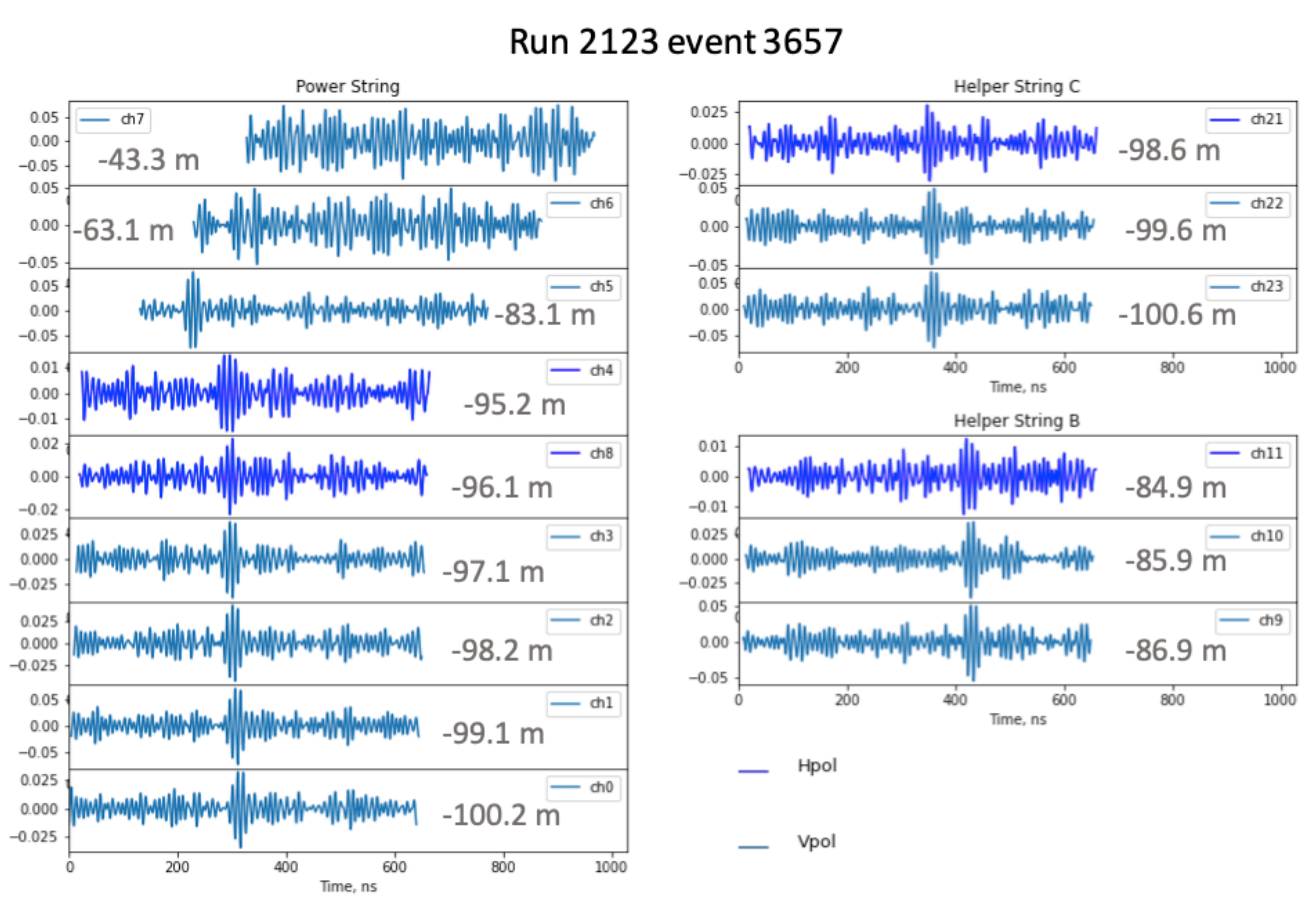


Phased array

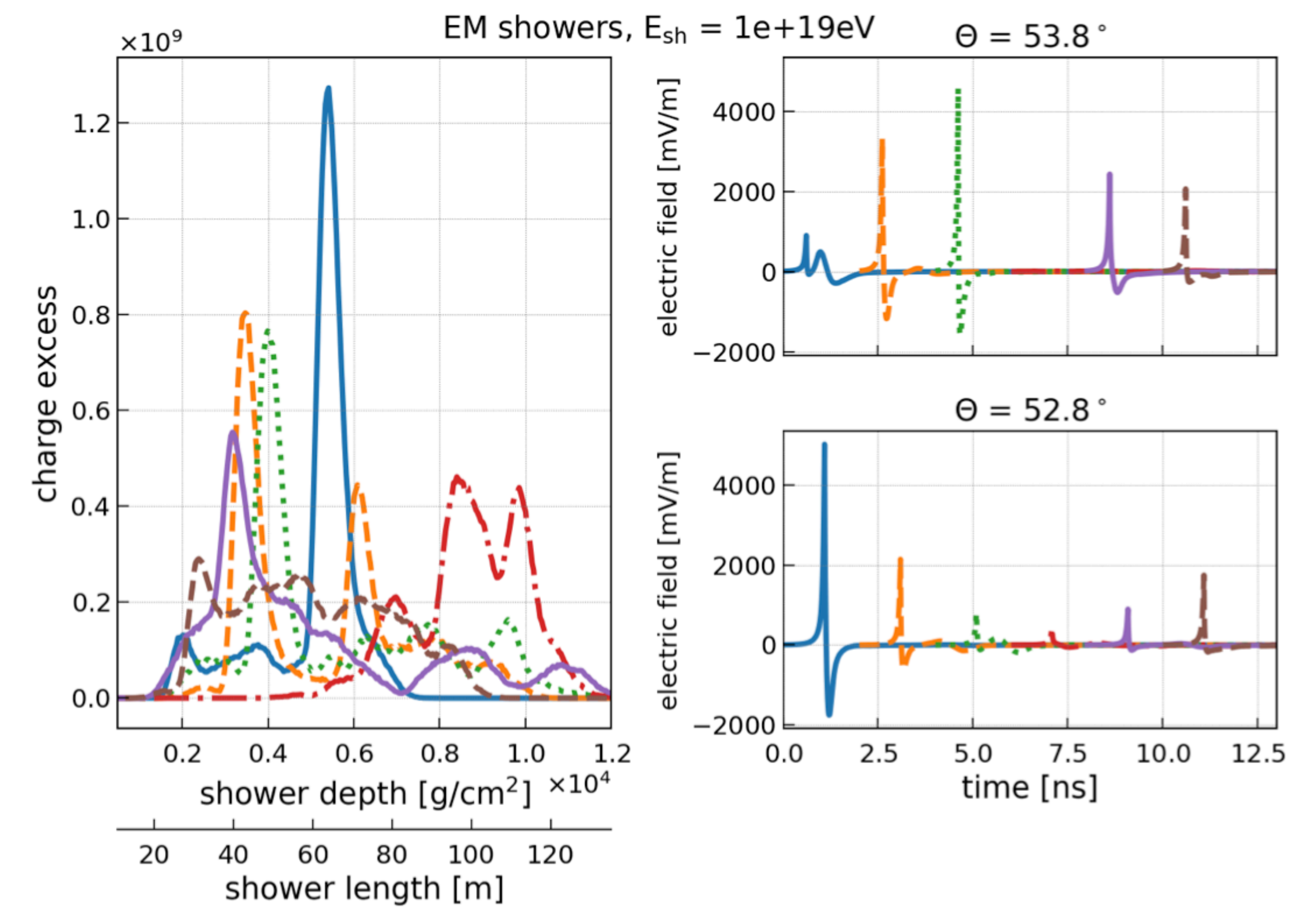
- Trigger runs on lower bandwidth (< 250 MHz), 8 beams are formed
- Design goal for threshold: amplitude_signal / sigma_noise = 2
- Technique demonstrated at South Pole by ARA [ARA, PRD 105]



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

LPM effect



EM showers, E_{sh} = 1e+19eV
×10⁹
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/cm²] ×10⁴
20 40 60 80 100 120
shower length [m]
Θ = 53.8 °
electric field [mV/m]
4000
2000
0
−2000
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