The Askaryan Radio Array: Challenges in Polarization Reconstruction

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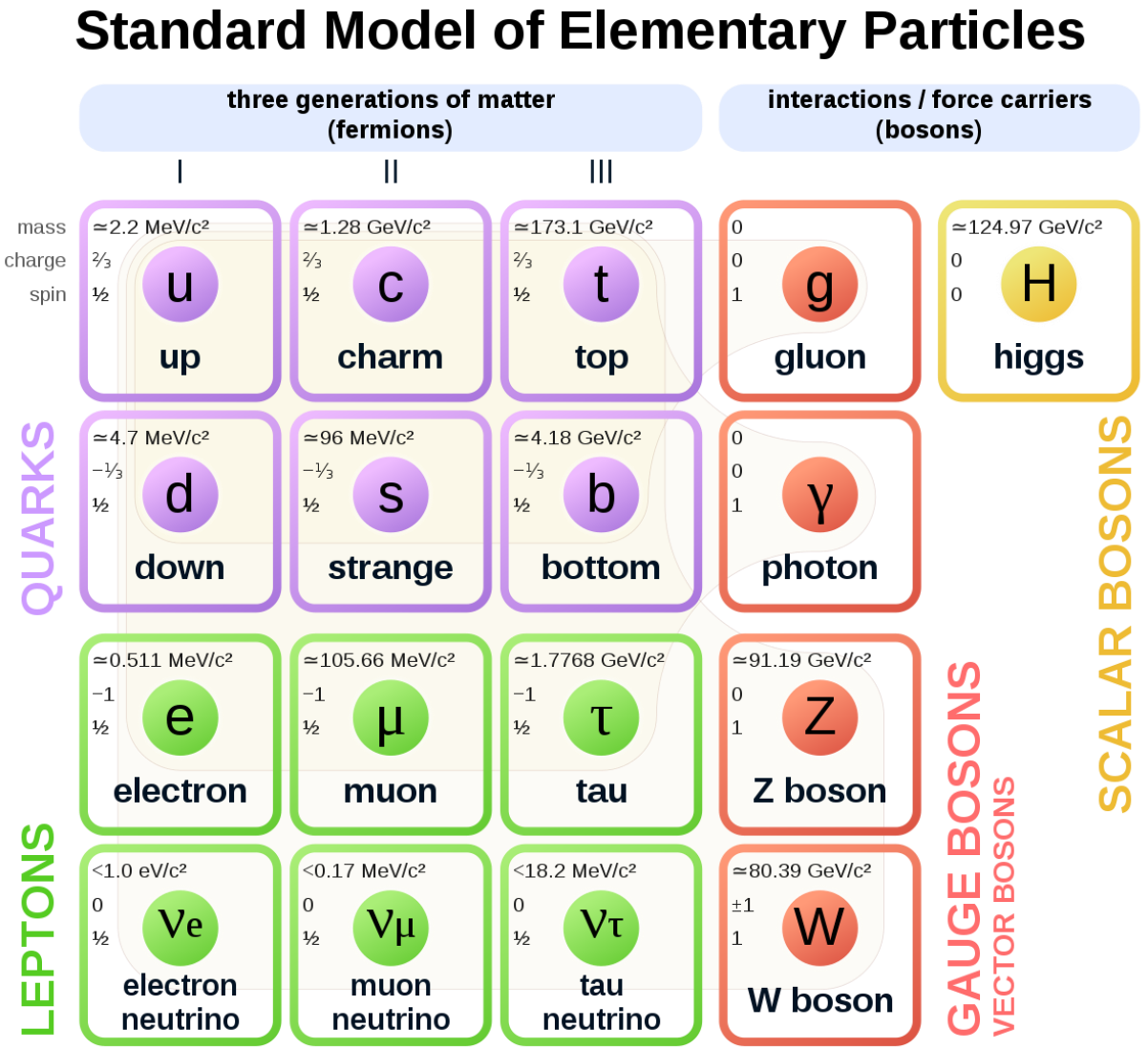
CCAPP Symposium 2025

Main Takeaway:

Polarization reconstruction is crucial for source searches.

What are Neutrinos?

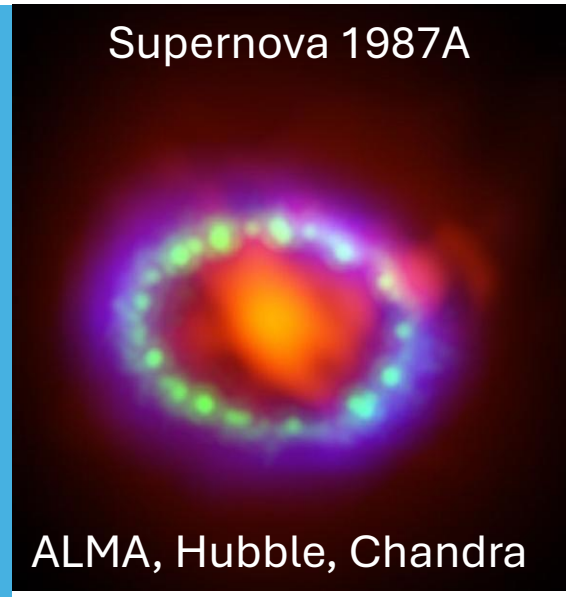
- One of the fundamental particles in the Standard Model.
- No charge and extremely small mass.
- Interacts via the Weak Force.
- Produced in nuclear reactions, including those in the Sun, supernovae, and other energetic cosmic events.
- **They're among the most abundant particles in the universe, but their weak interaction makes them difficult to detect.**

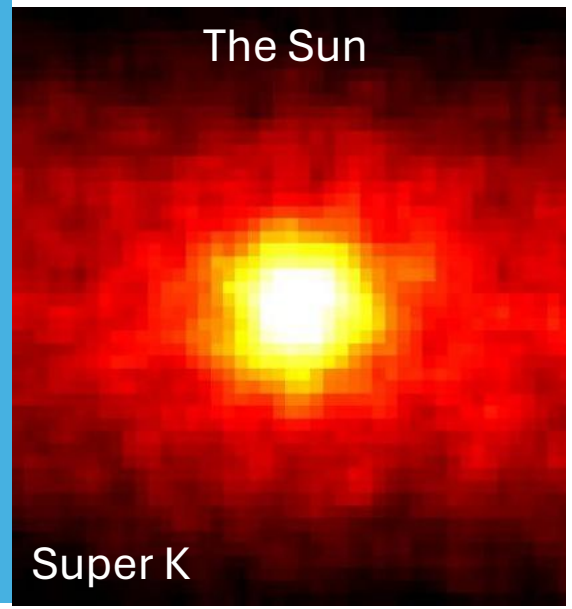


Courtesy: Particle Data Group

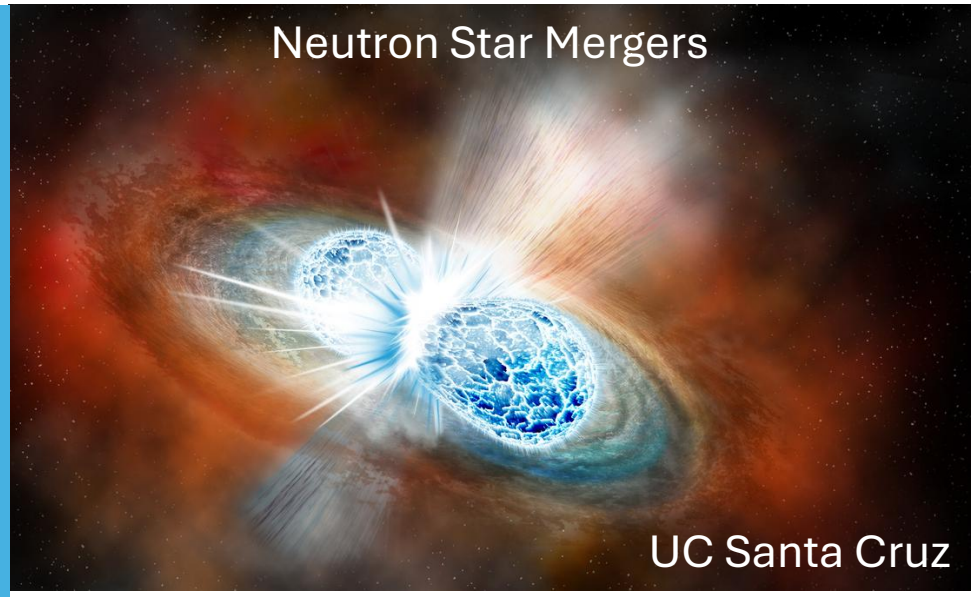
What Sources Can We Probe with Neutrinos?

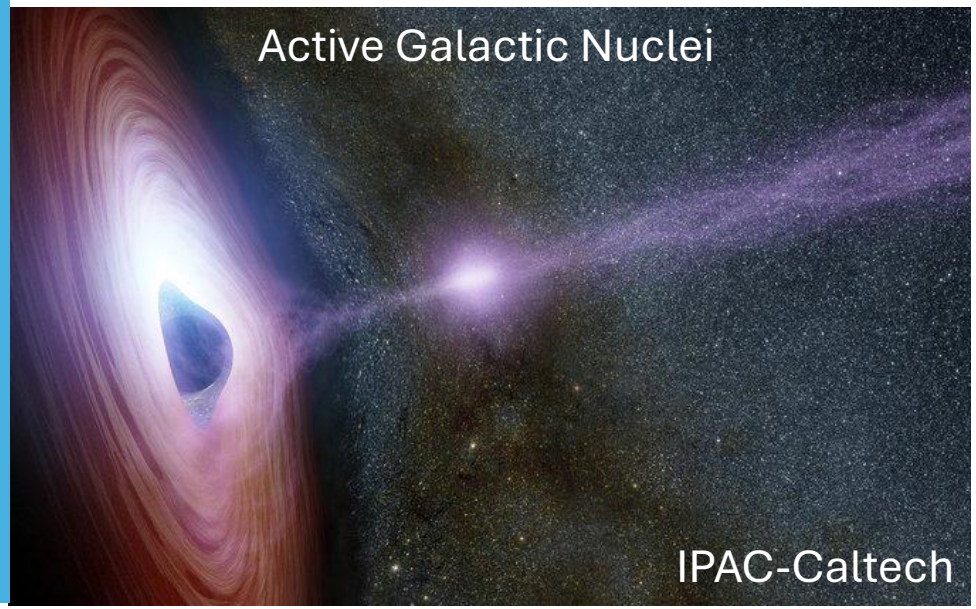
Low Energy

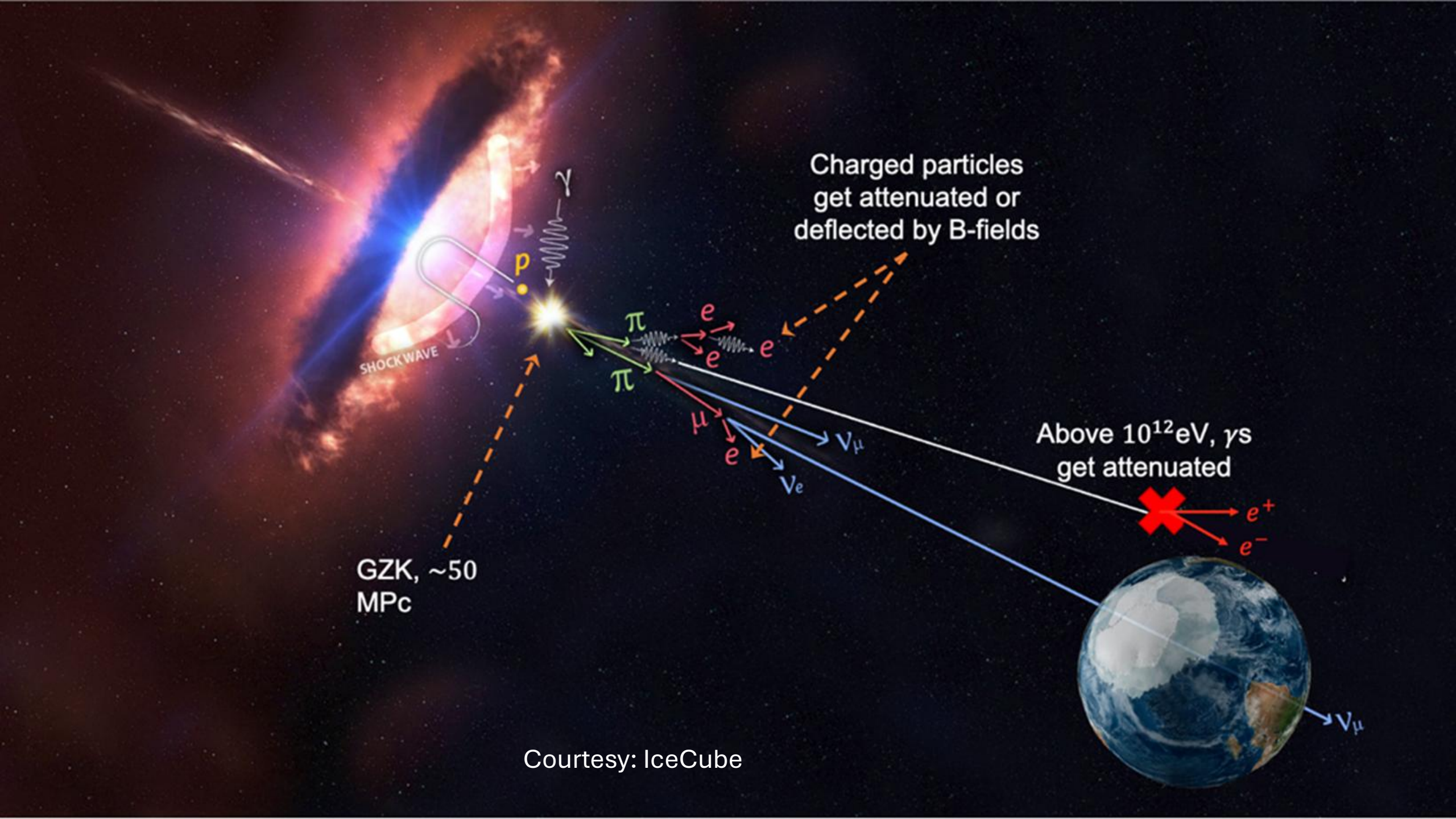




High Energy



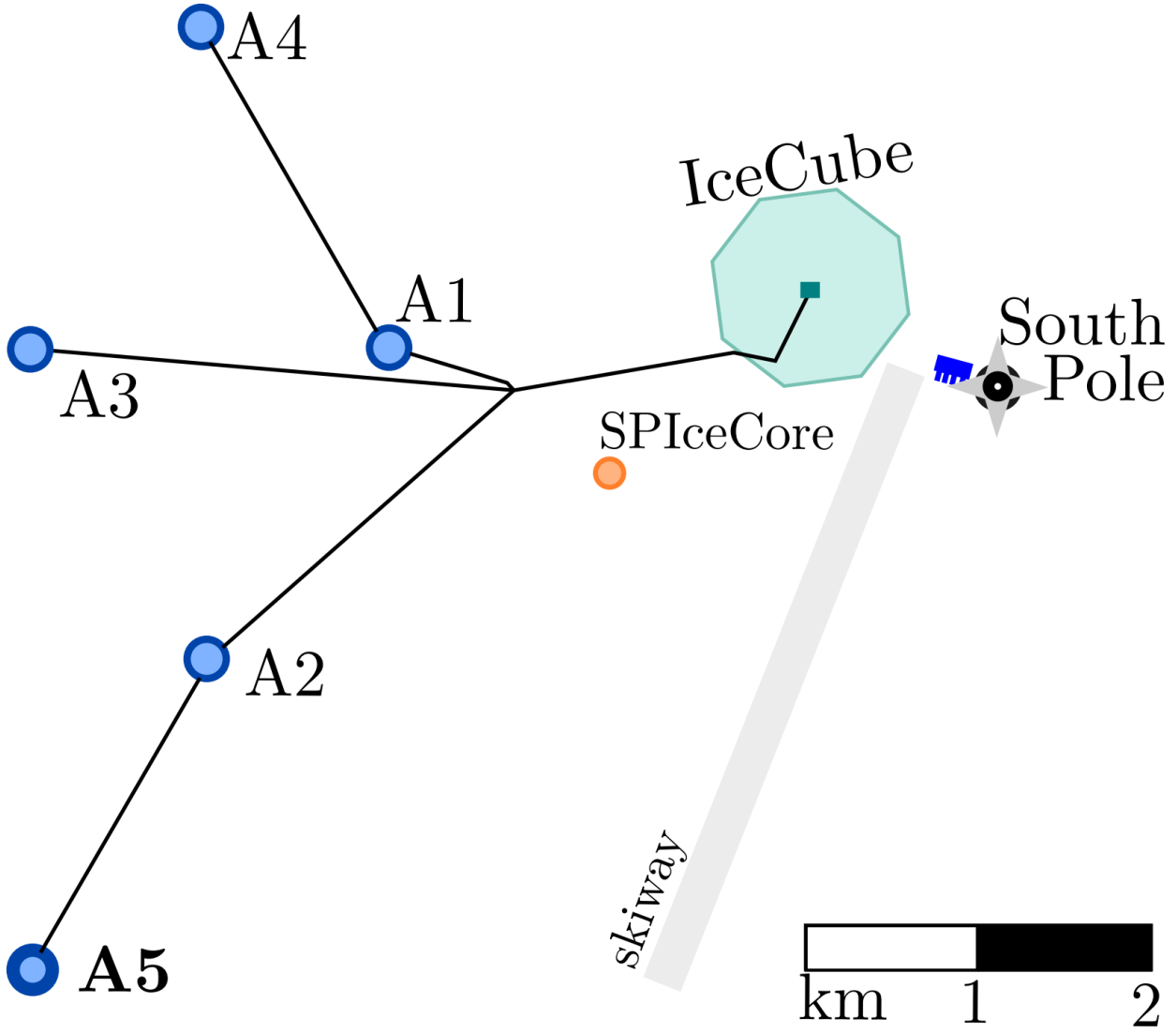




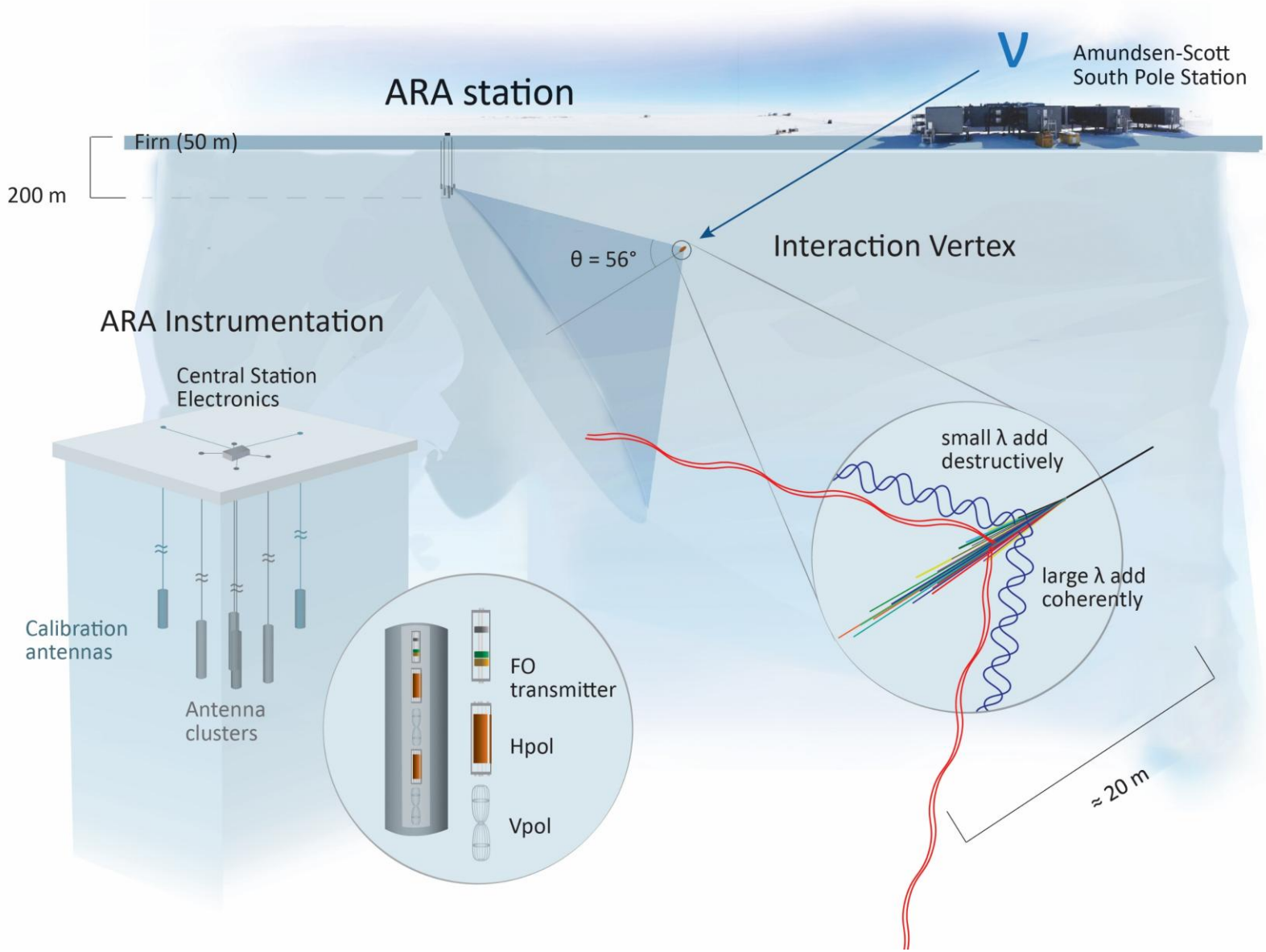
Courtesy: IceCube

The Askaryan Radio Array

- Searches for UHE neutrinos (> 10 PeV).
- Five stations separated by ~2 km, with first station installed in 2011.
- Each station has at least 4 strings of antennas.
- Currently undergoing comprehensive 5-station analysis:
  - See poster by Alan Salcedo Gomez and talk by Paramita Dasgupta.



Detection of ultrahigh-energy neutrinos in ARA

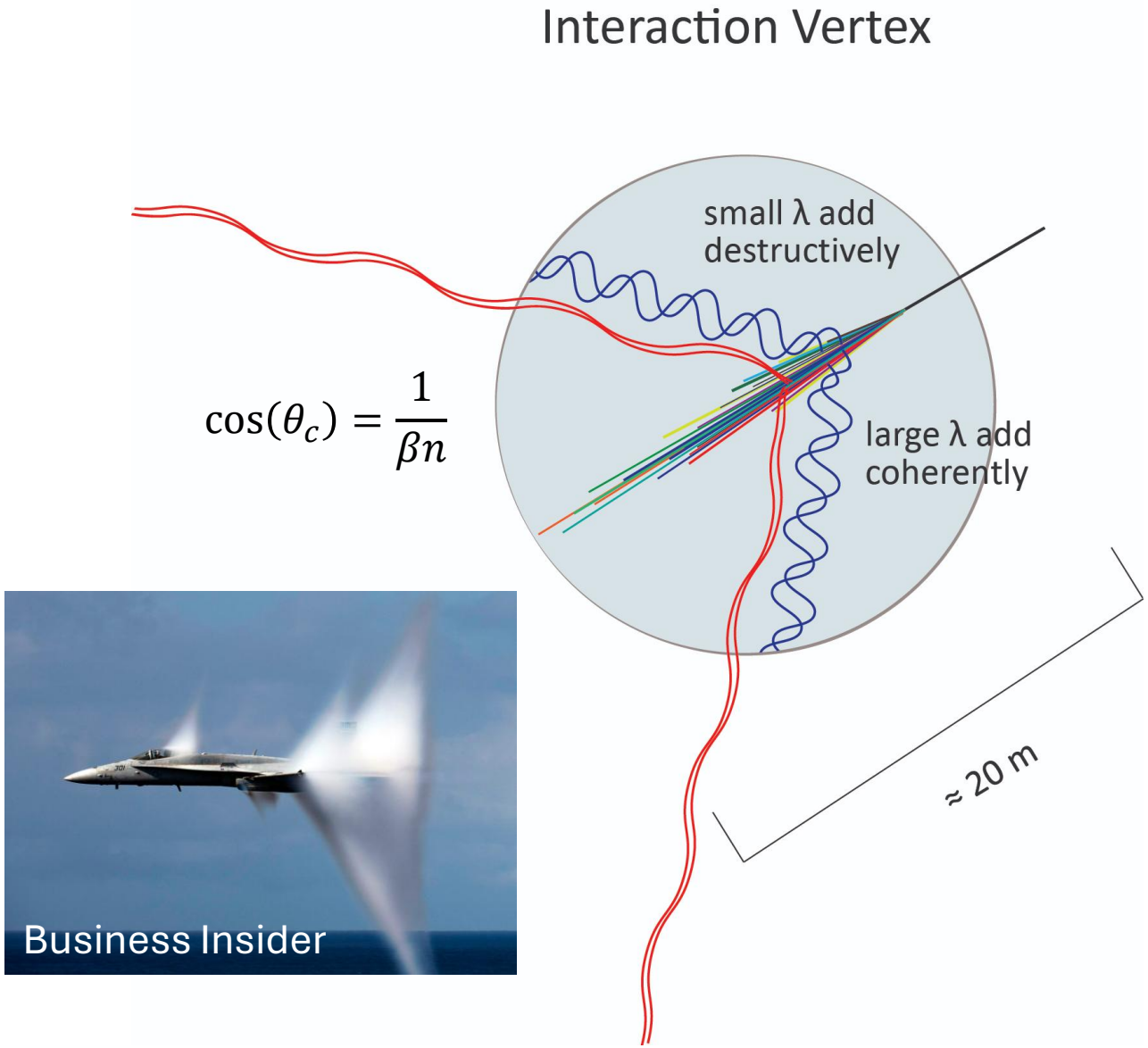


Detection of ultrahigh-energy neutrinos in ARA

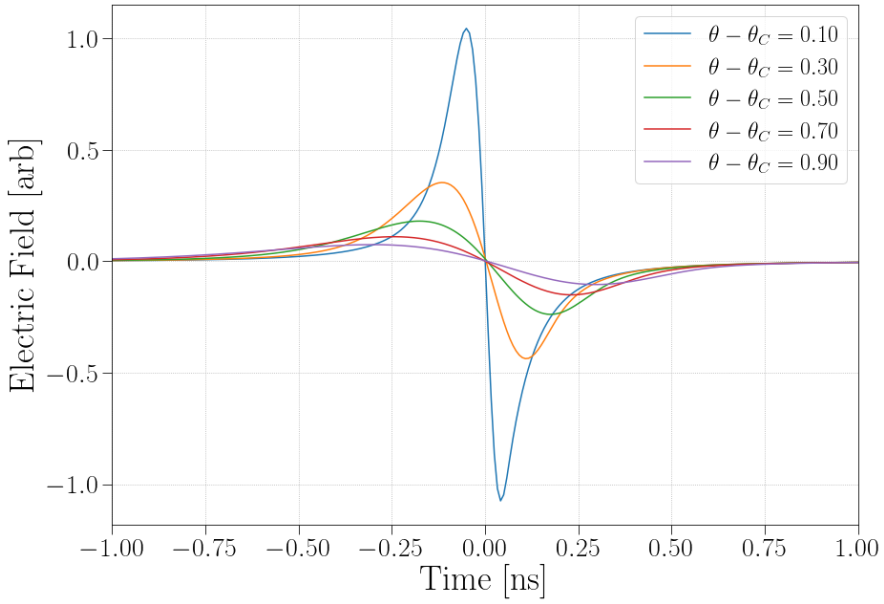
Detection of ultrahigh-energy neutrinos in ARA

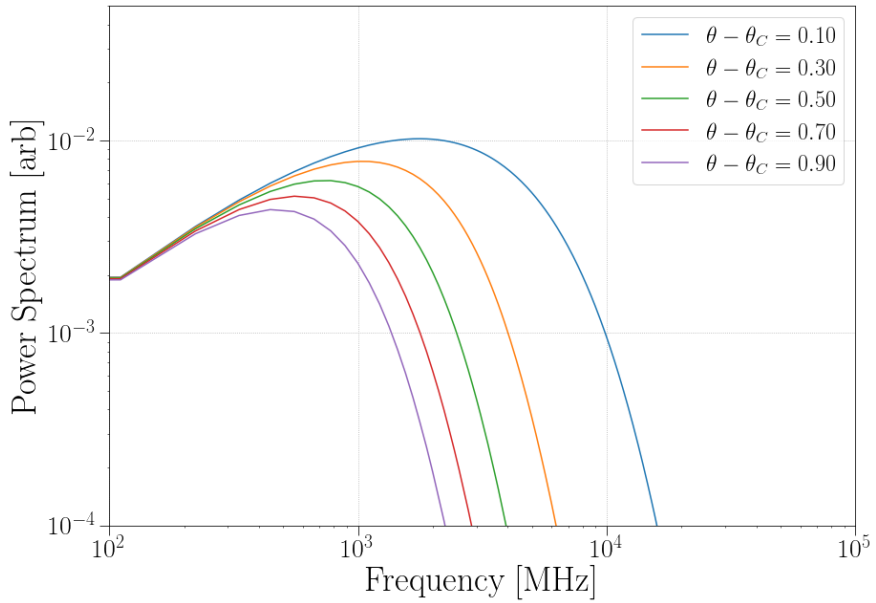
The Askaryan Effect:

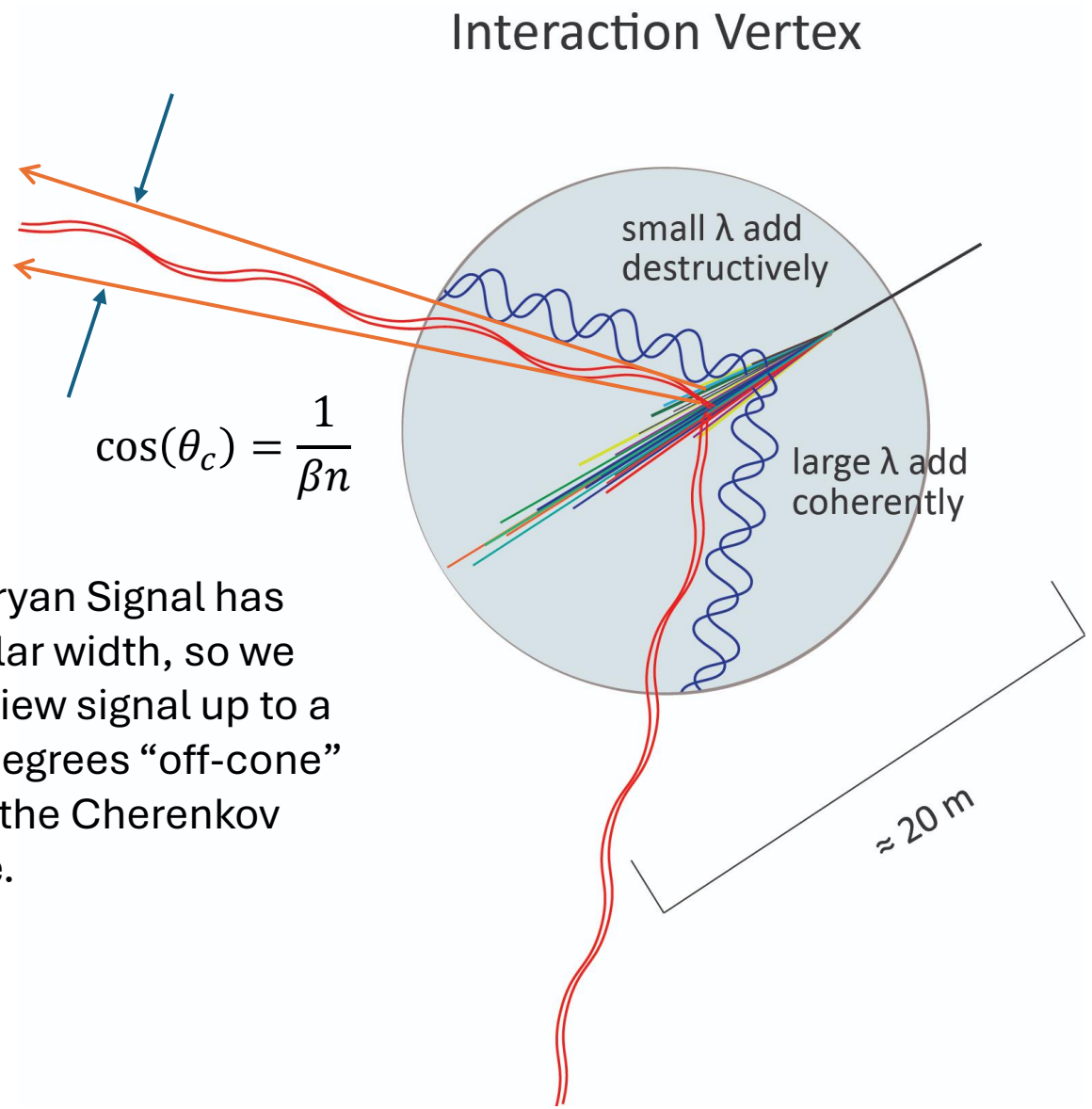
- The Askaryan effect offers a way to detect UHE neutrinos. When a neutrino interacts with a nucleus in a dense medium of refractive index n, it generates a particle shower that emits a cone of coherent Cherenkov radiation in the radio frequency range.
- This radio signal can propagate long distances in ice, making it ideal for detection.



$$\cos(\theta_c) = \frac{1}{\beta n}$$



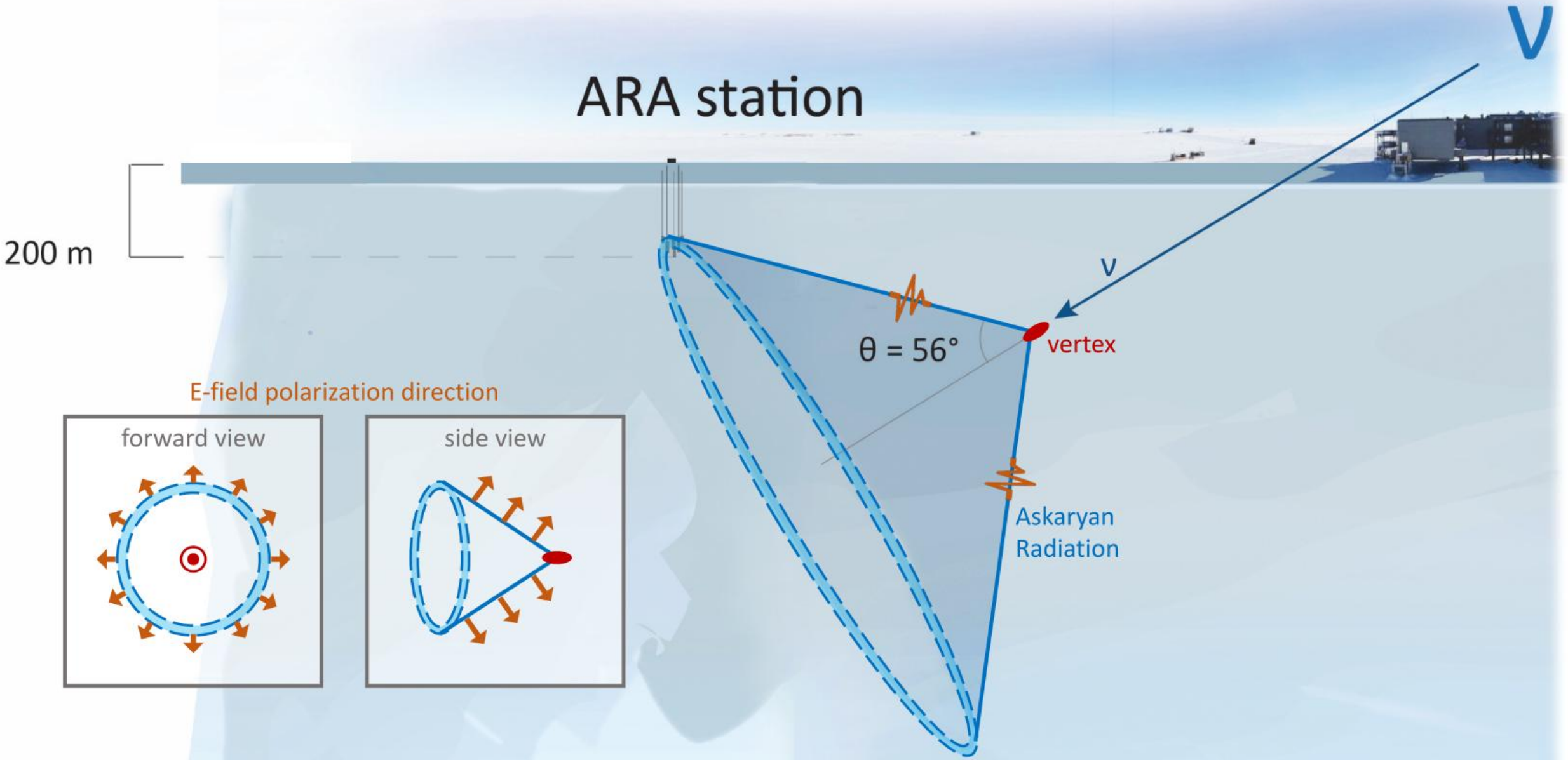




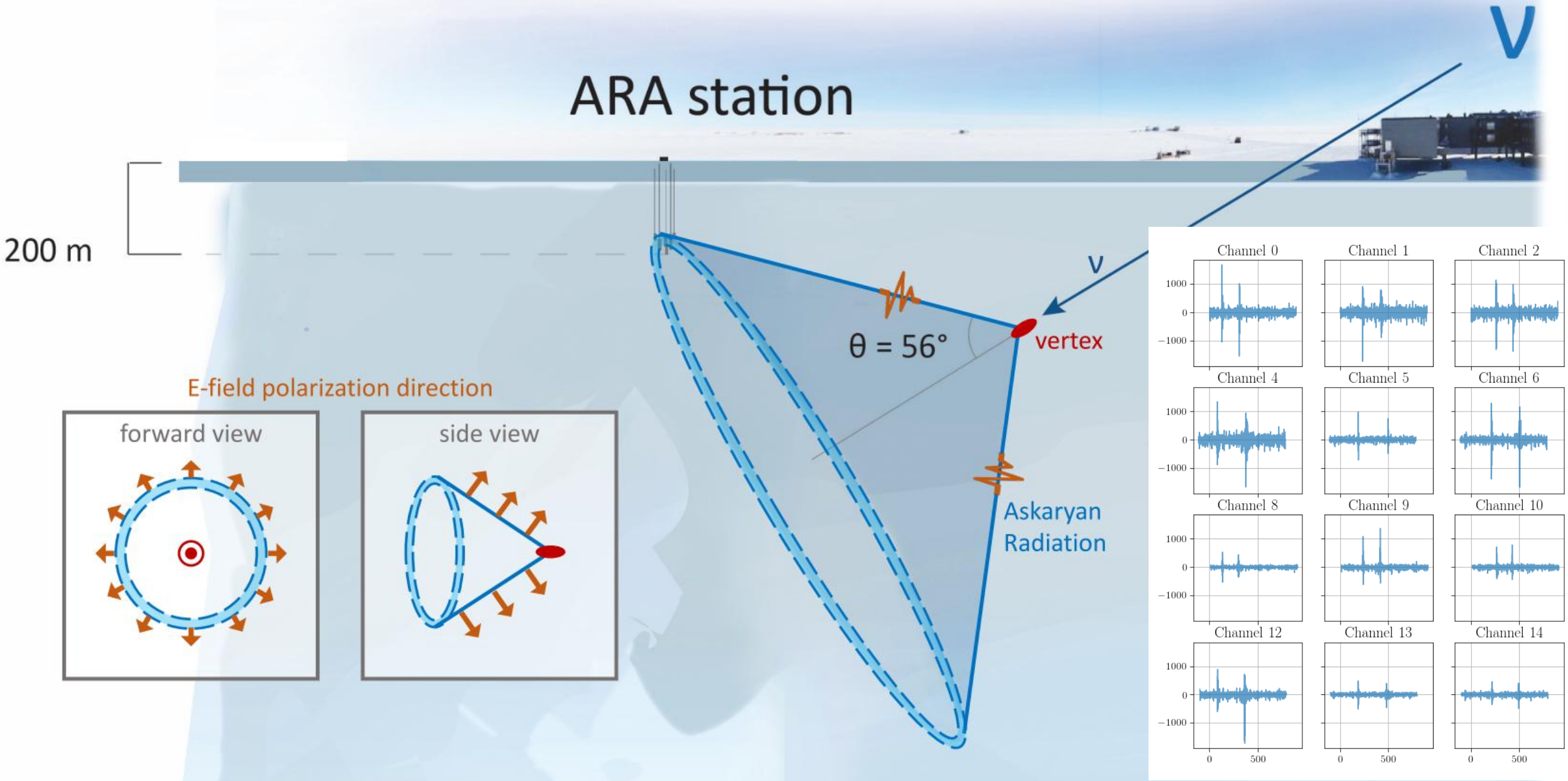
$$\cos(\theta_c) = \frac{1}{\beta n}$$

Askaryan Signal has angular width, so we can view signal up to a few degrees “off-cone” from the Cherenkov angle.

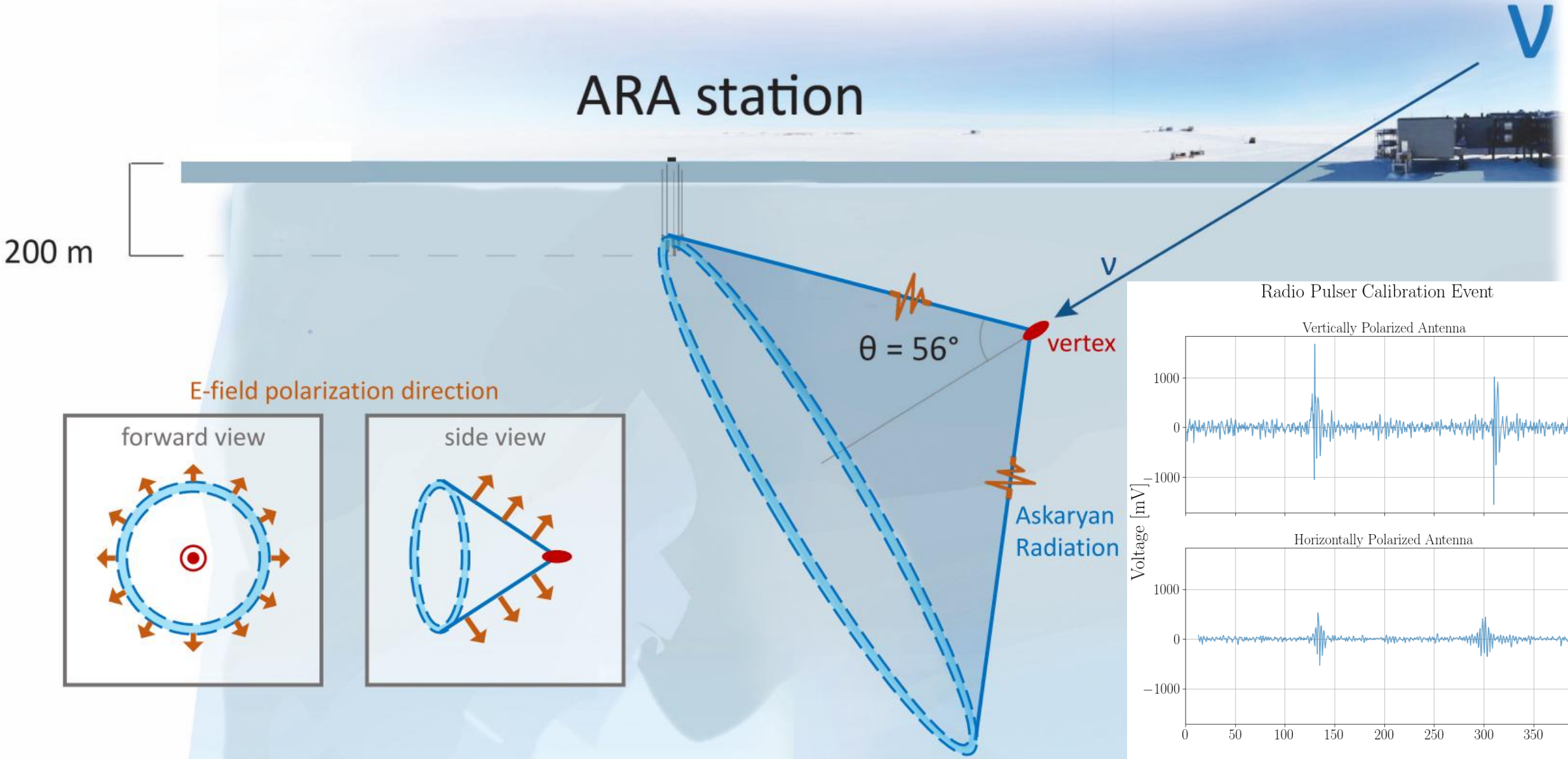
ARA station


ν
200 m
ν
θ = 56°
vertex
E-field polarization direction
forward view
side view
Askaryan
Radiation

ARA station

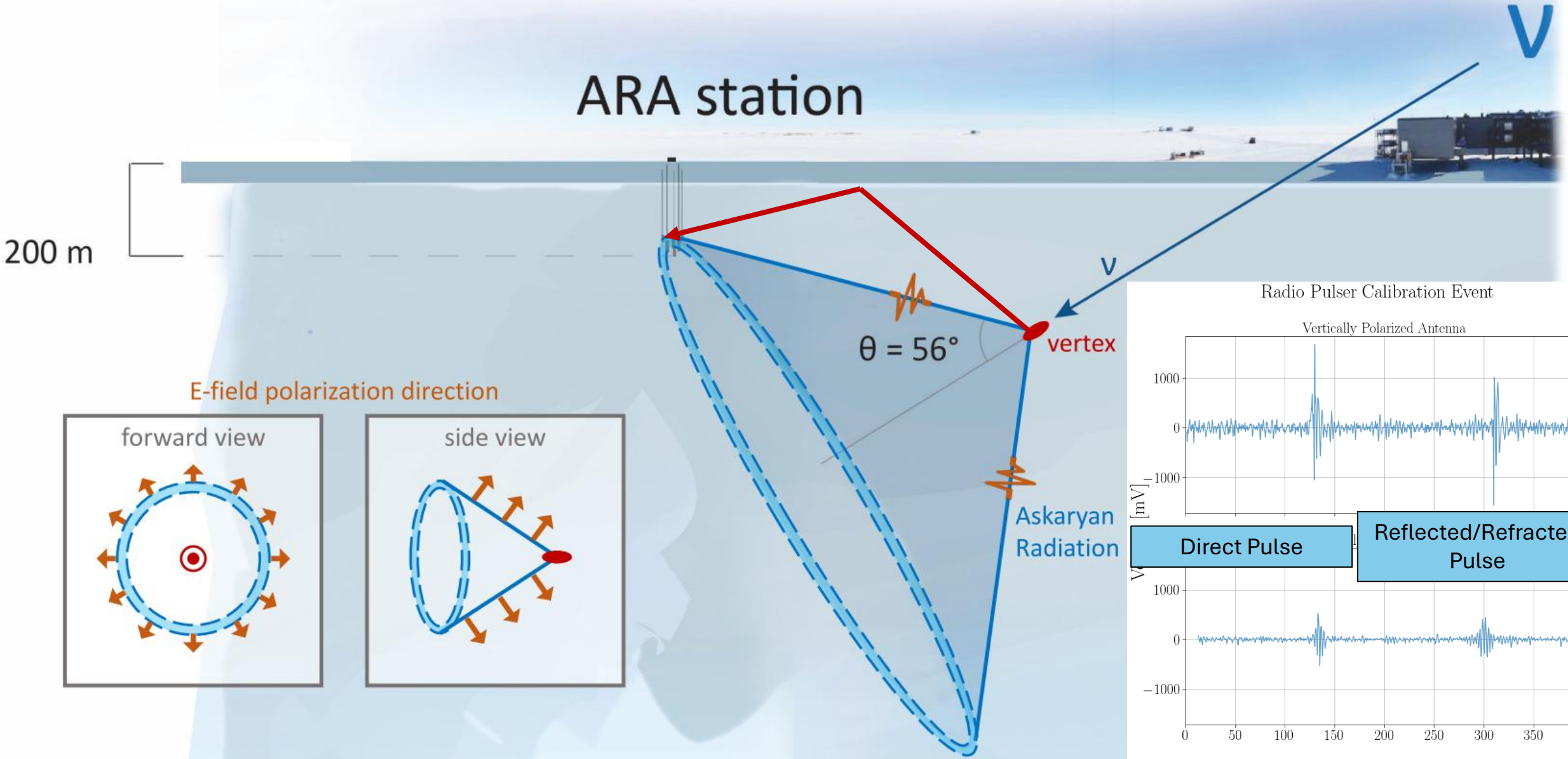

ν
200 m
θ = 56°
vertex
ν
Askaryan
Radiation
E-field polarization direction
forward view
side view
Channel 0
Channel 1
Channel 2
Channel 4
Channel 5
Channel 6
Channel 8
Channel 9
Channel 10
Channel 12
Channel 13
Channel 14
1000
0
−1000
0
500

ARA station

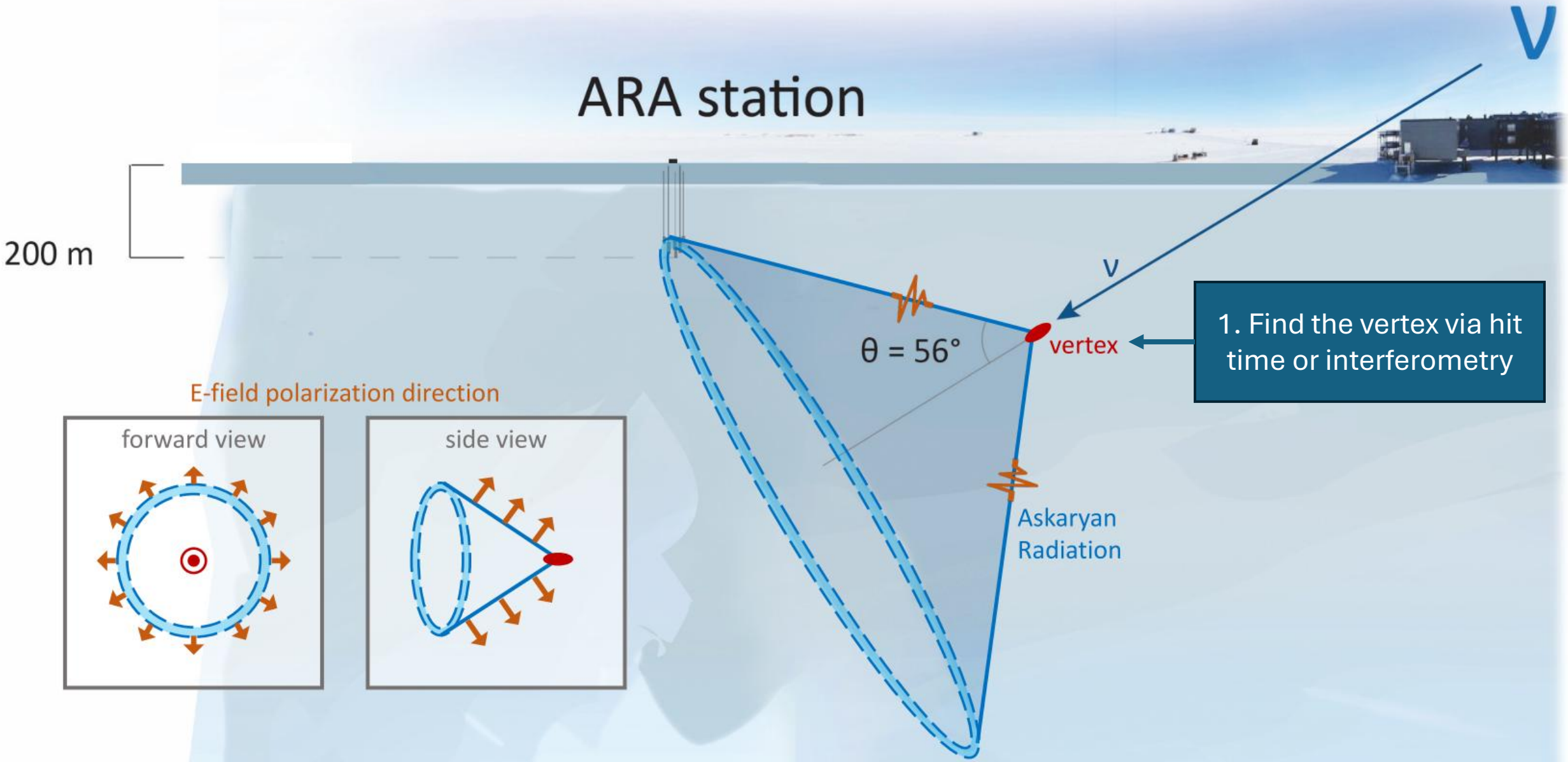

ν
200 m
ν
θ = 56°
vertex
Askaryan
Radiation
E-field polarization direction
forward view
side view

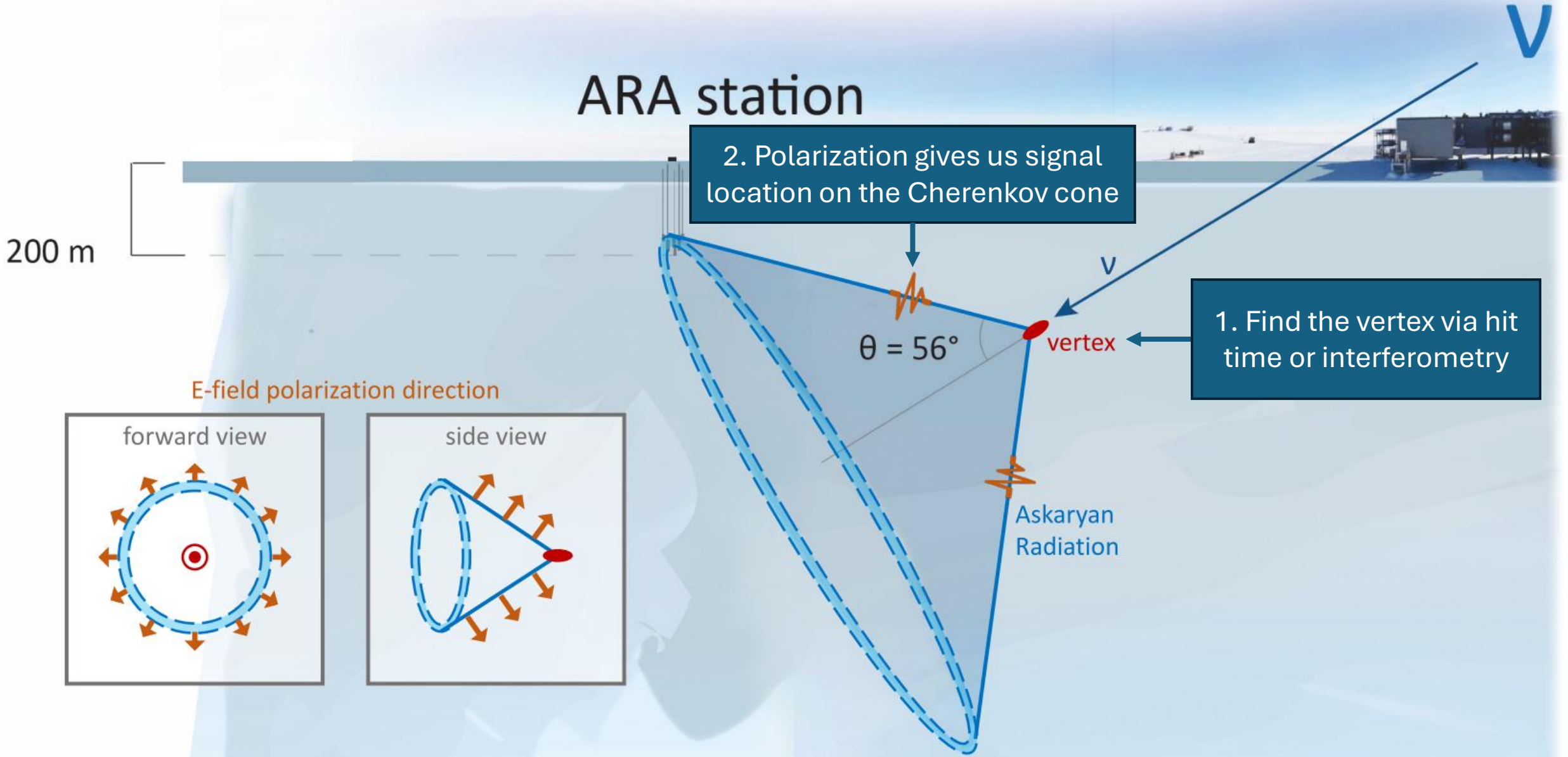
Radio Pulser Calibration Event
Vertically Polarized Antenna
Horizontally Polarized Antenna
Voltage [mV]
1000
0
−1000
0
50
100
150
200
250
300
350
400
Time [ns]

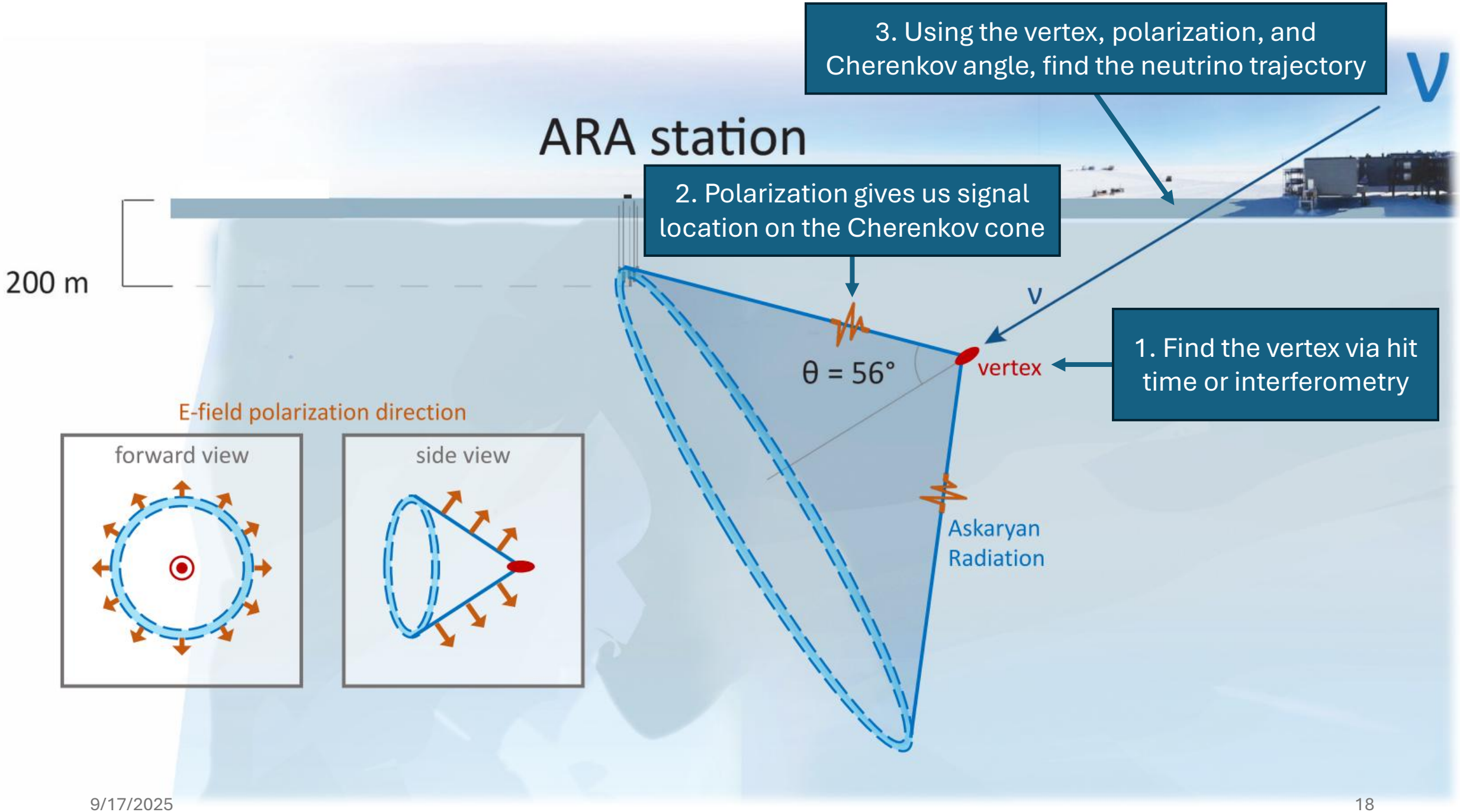
ARA station


ν
200 m
ν
θ = 56°
vertex
Askaryan
Radiation
E-field polarization direction
forward view
side view
Radio Pulser Calibration Event
Vertically Polarized Antenna
1000
0
−1000
[mV]
Direct Pulse
Reflected/Refracted
Pulse
1000
0
−1000
0
50
100
150
200
250
300
350
400
Time [ns]

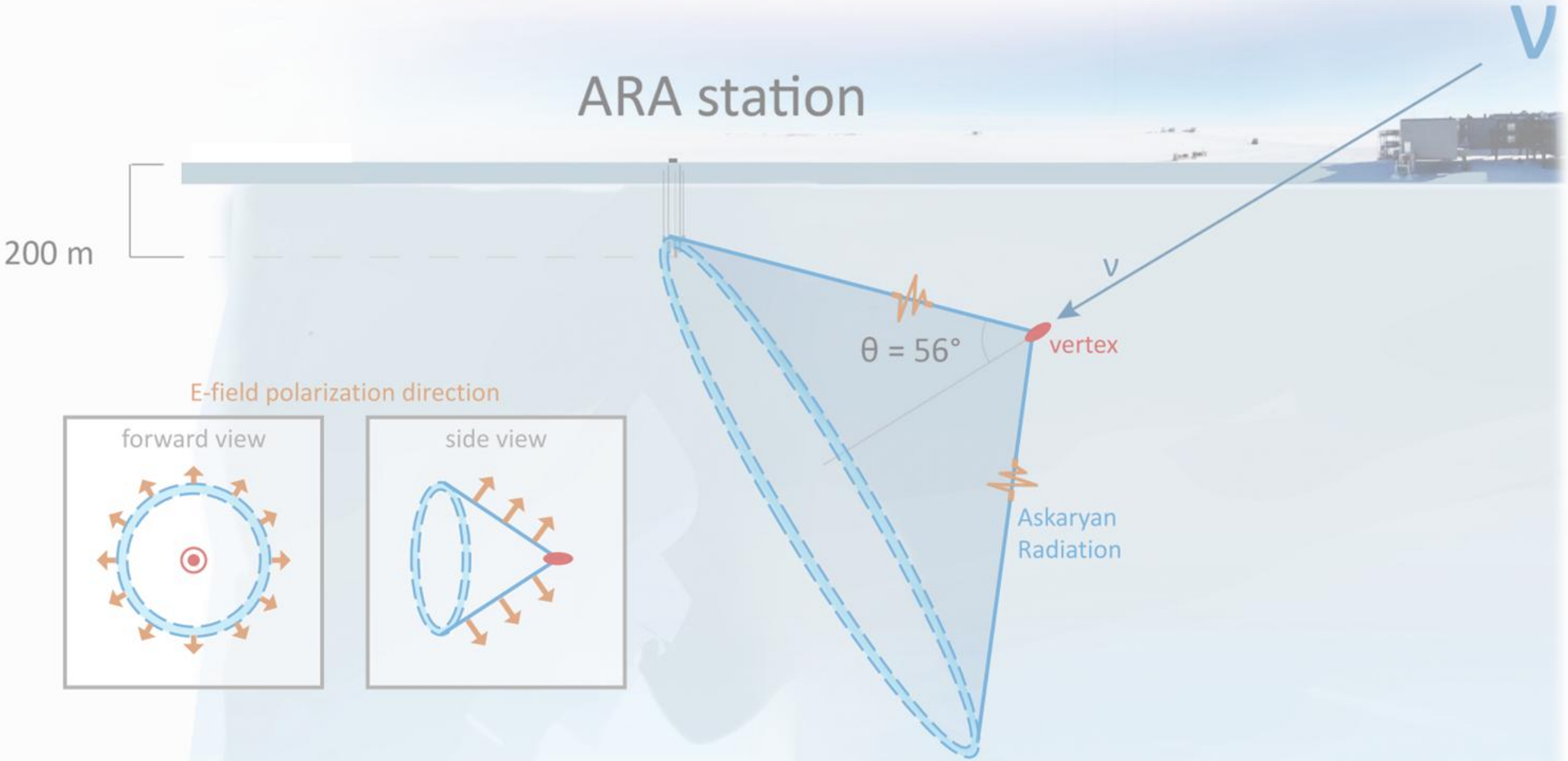
ARA station


ν
200 m
ν
θ = 56°
vertex
1. Find the vertex via hit time or interferometry
E-field polarization direction
forward view
side view
Askaryan Radiation

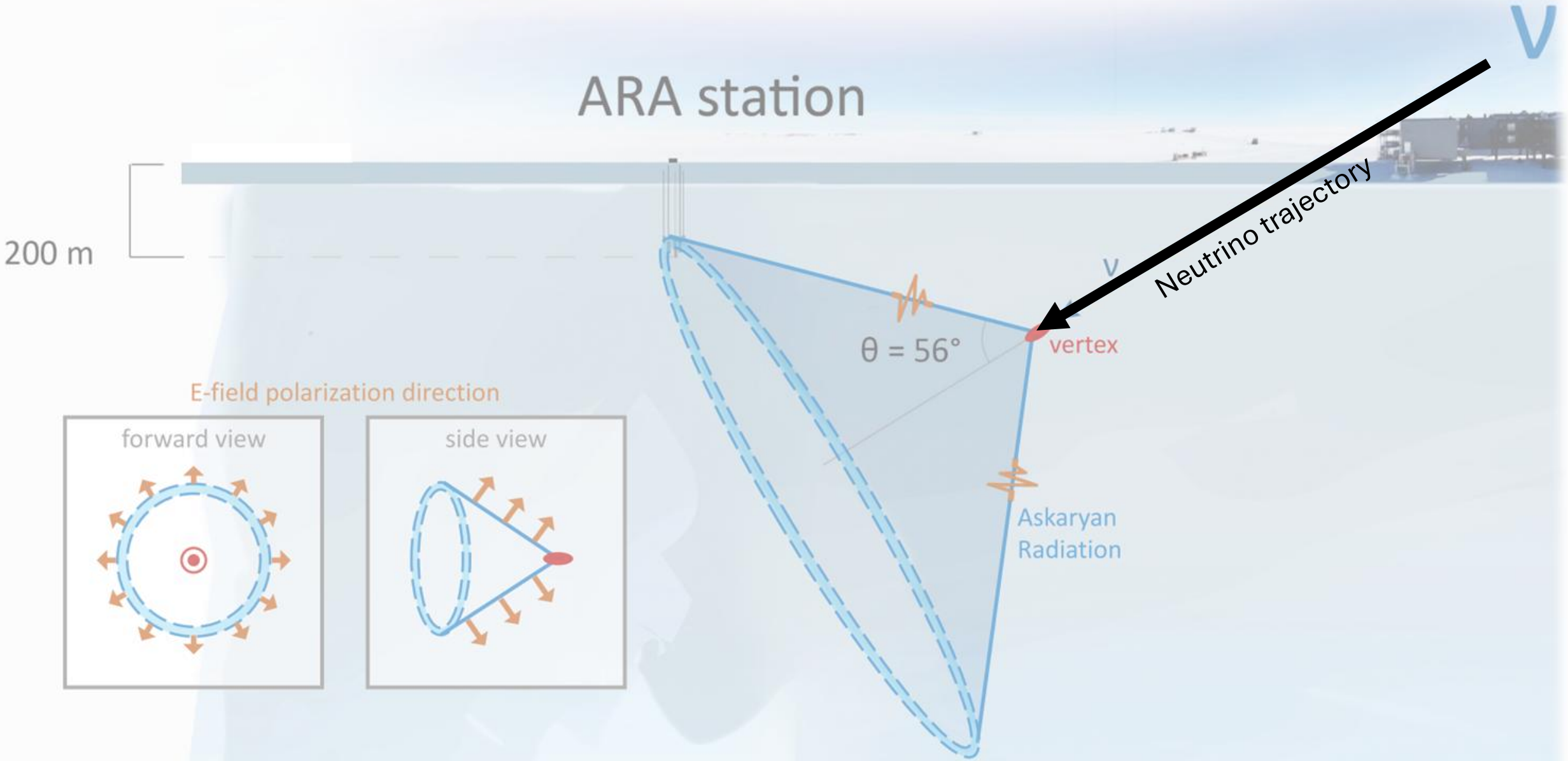

ν
ARA station
2. Polarization gives us signal location on the Cherenkov cone
200 m
ν
θ = 56°
vertex
1. Find the vertex via hit time or interferometry
E-field polarization direction
forward view
side view
Askaryan Radiation

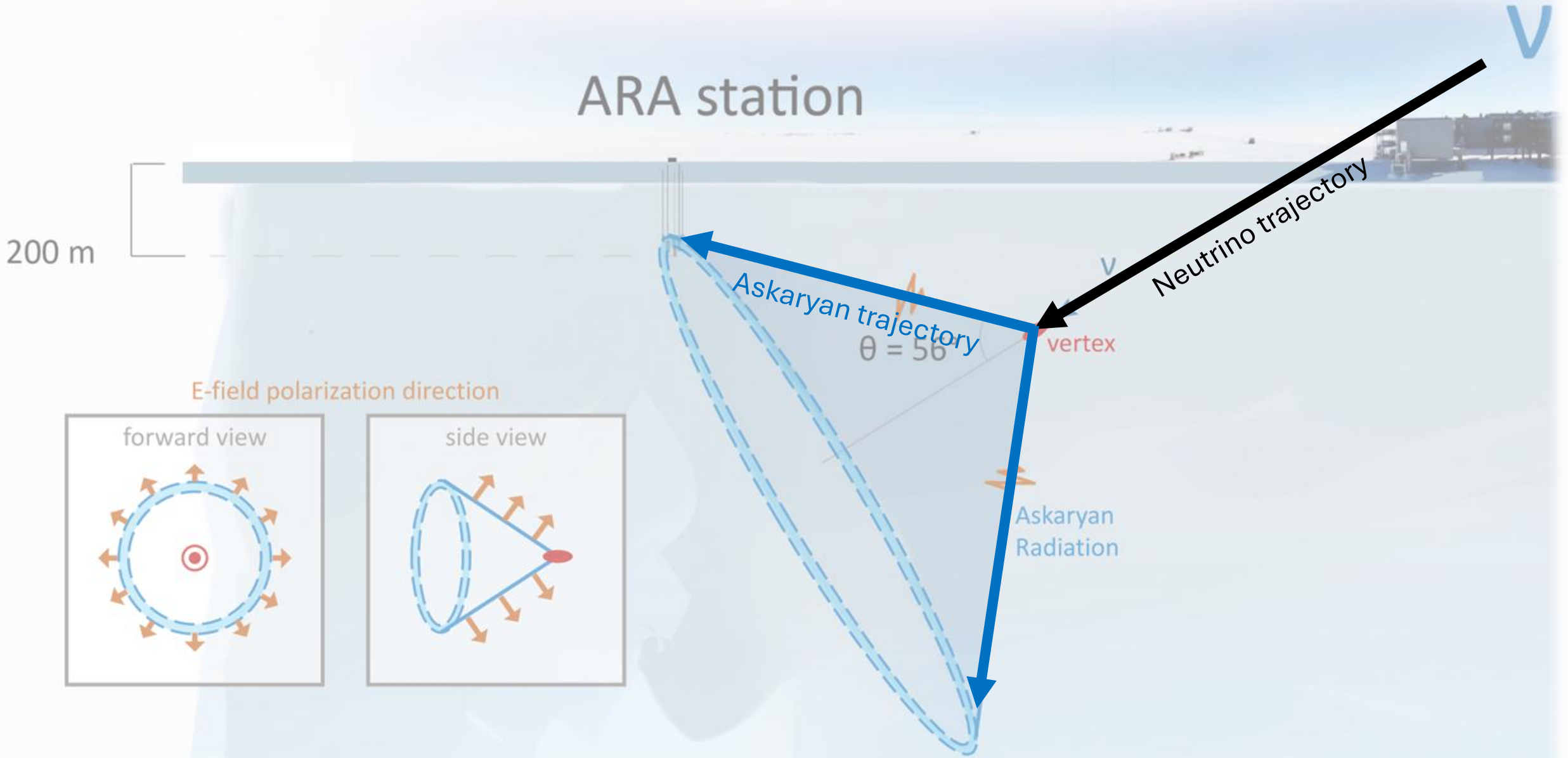

3. Using the vertex, polarization, and Cherenkov angle, find the neutrino trajectory
ν
ARA station
2. Polarization gives us signal location on the Cherenkov cone
200 m
ν
θ = 56°
vertex
1. Find the vertex via hit time or interferometry
E-field polarization direction
forward view
side view
Askaryan Radiation

ARA station


ν
200 m
ν
θ = 56°
vertex
E-field polarization direction
forward view
side view
Askaryan
Radiation

ARA station


ν
Neutrino trajectory
200 m
ν
θ = 56°
vertex
Askaryan
Radiation
E-field polarization direction
forward view
side view


ARA station
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E-field polarization direction
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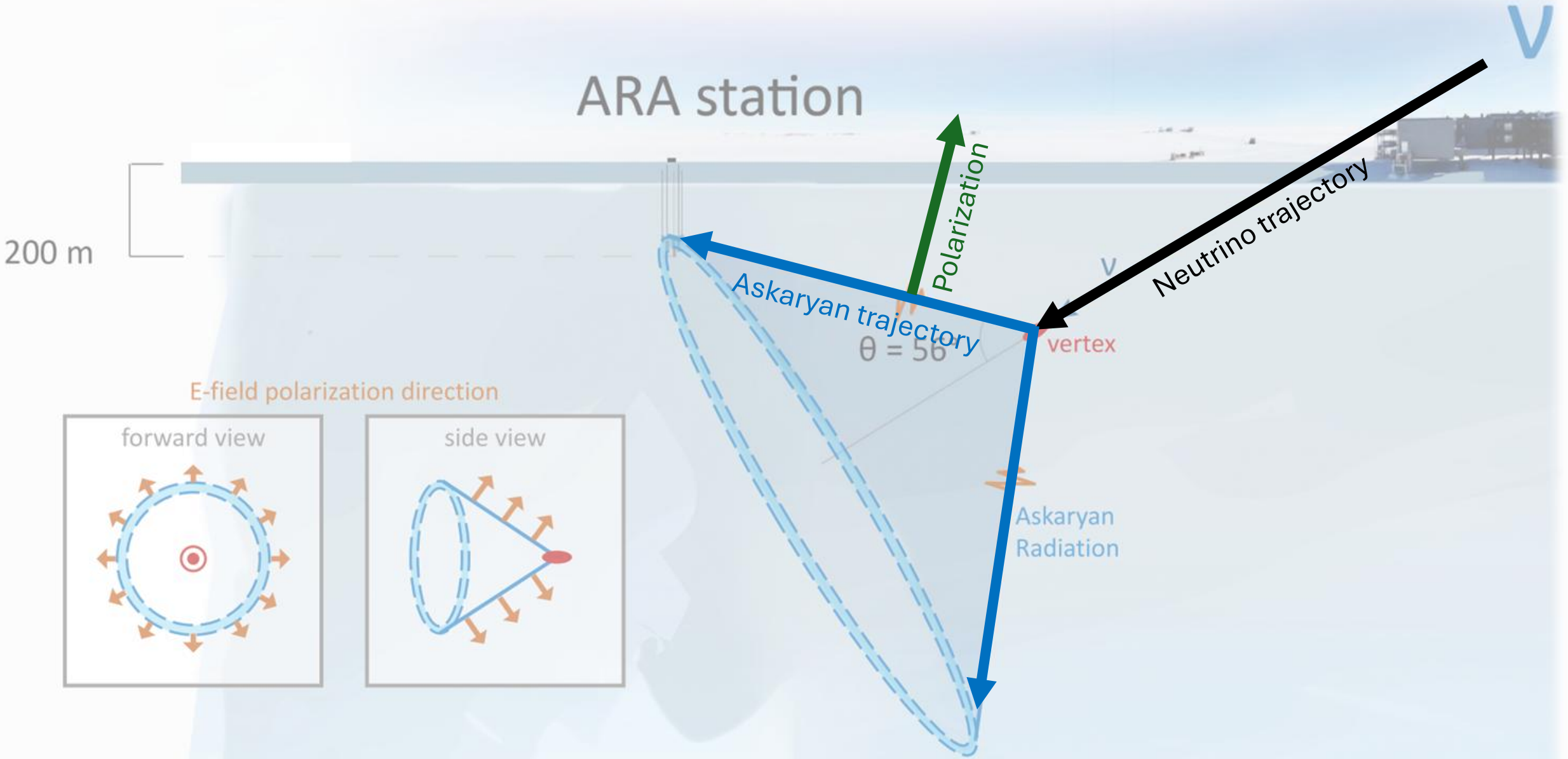
Askaryan
Radiation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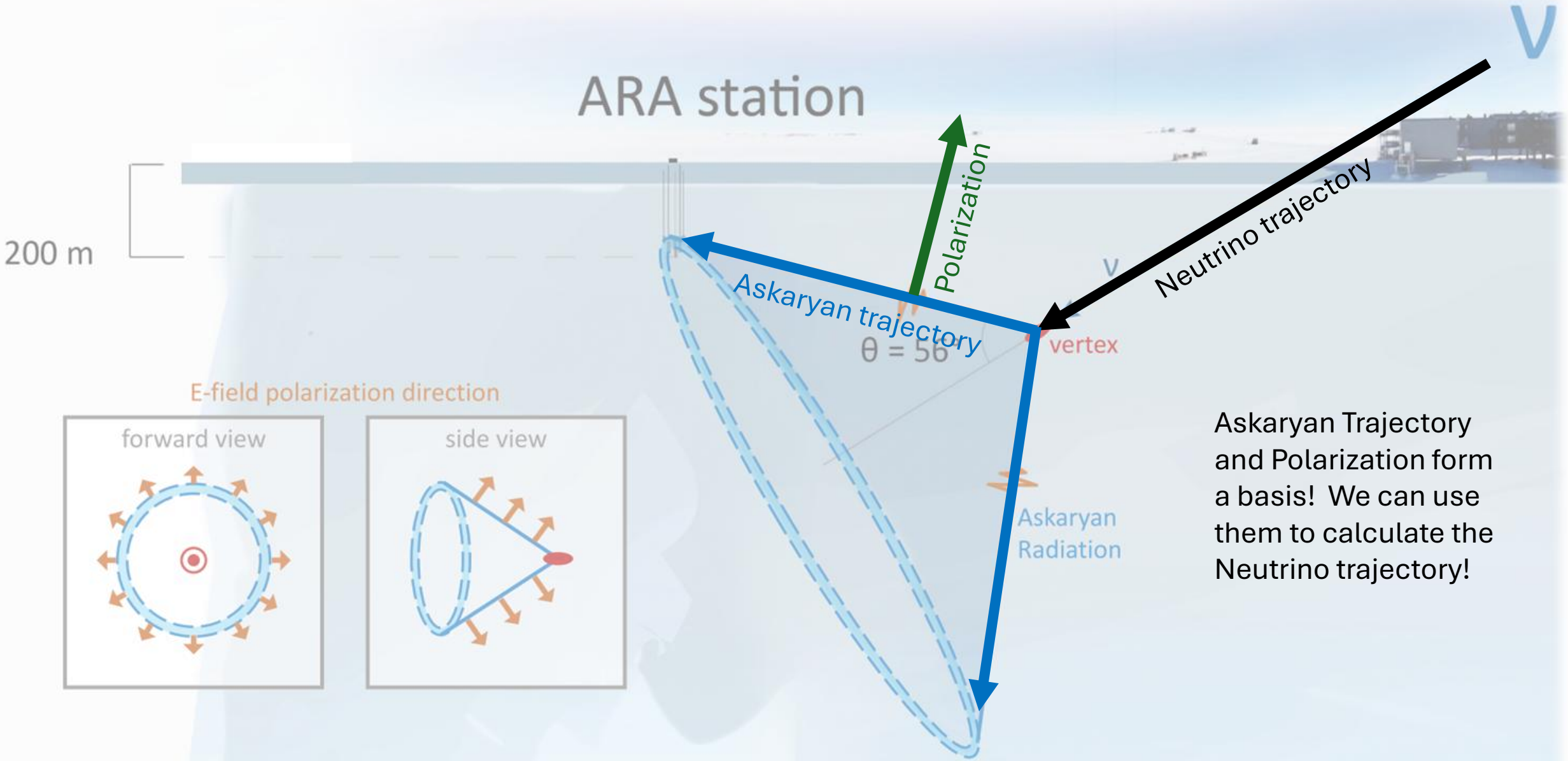
side view



Askaryan Trajectory and Polarization form a basis! We can use them to calculate the Neutrino trajectory!

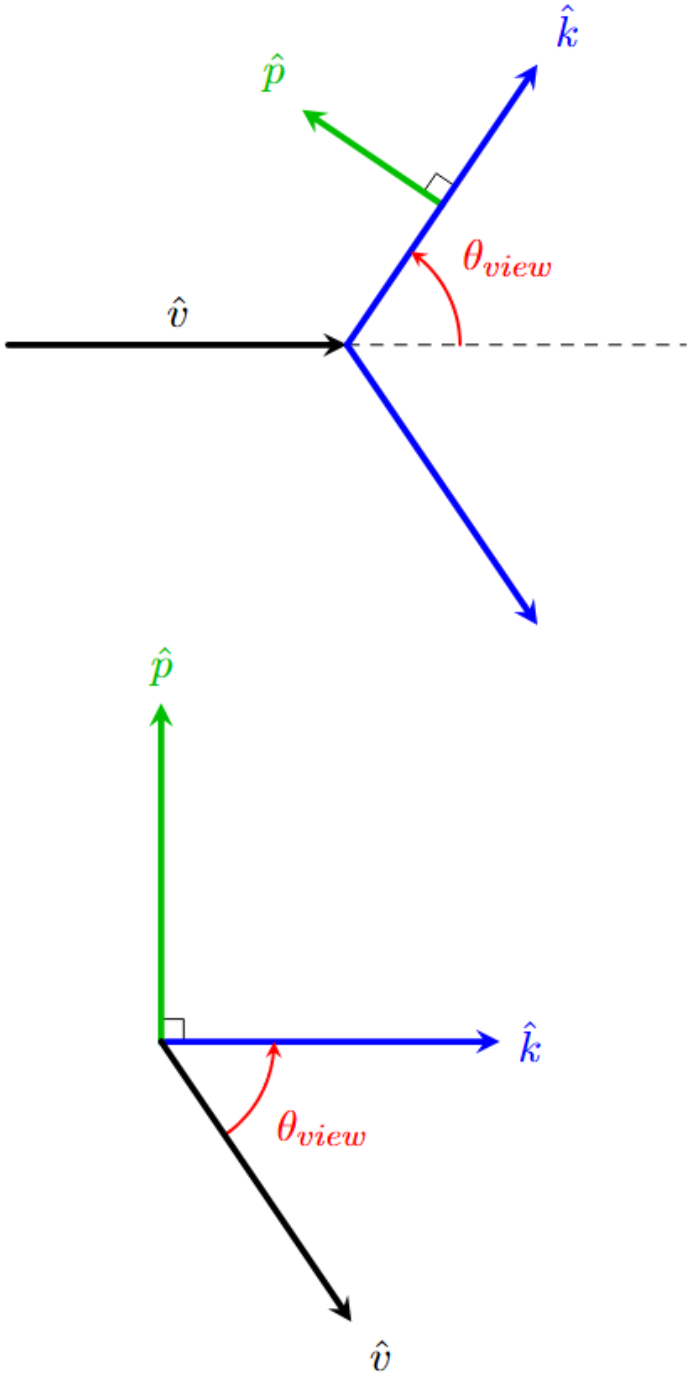
Simplified View of Trajectory Reconstruction

The Askaryan Radiation wavefront and the polarization form a basis that can be used to find the neutrino trajectory

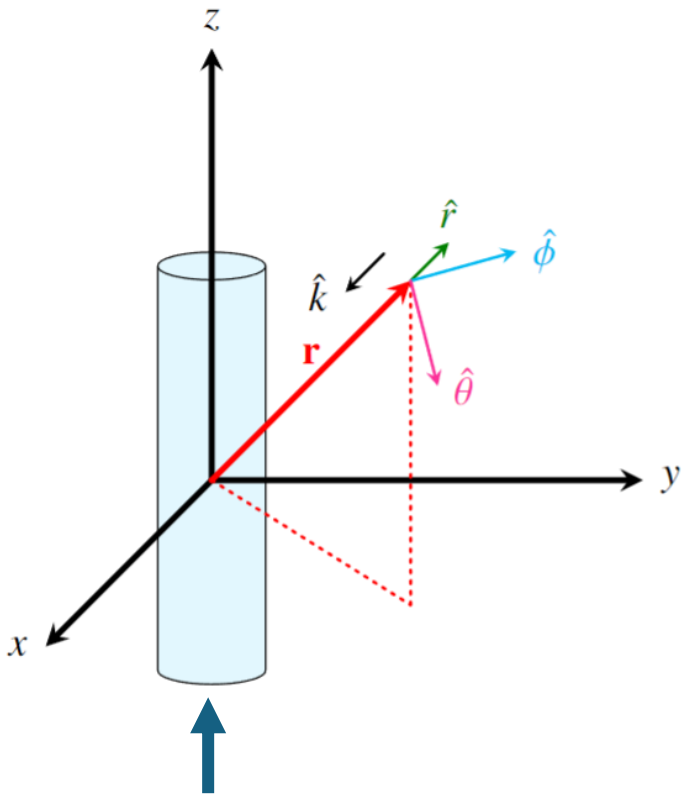
$$\hat{p} = \frac{1}{\sin\theta_{view}}\left(\hat{v} \times \hat{k}\right) \times \hat{k}$$

$$\hat{v} = \cos\theta_{view}\ \hat{k} - \sin\theta_{view}\,\hat{p}$$

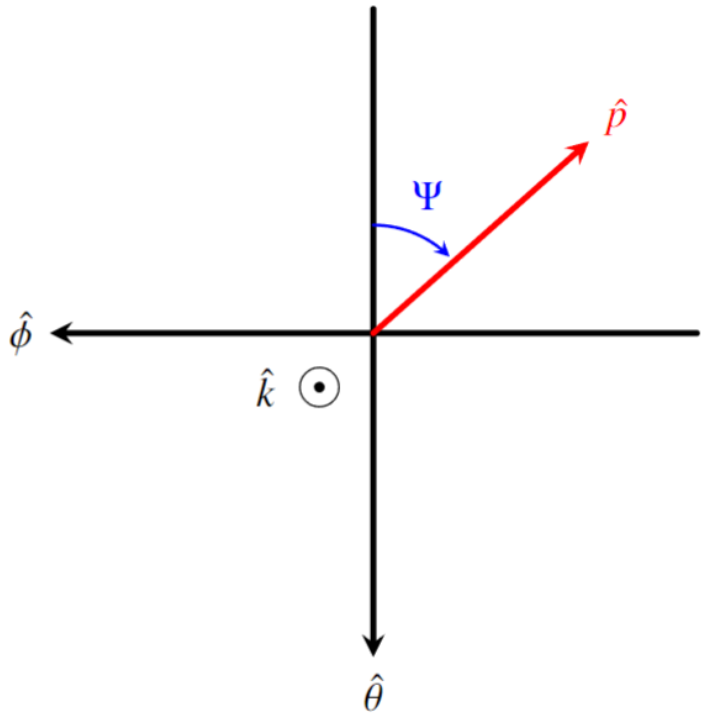
Thus, finding the direction of propagation (via ray tracing) and the reconstructing the polarization are crucial for finding the trajectory.



Reconstructing the Polarization



ARA
Antenna



We define the polarization angle in the plane of propagation $\hat{k}$.

$$\hat{p} = \begin{bmatrix} -\cos\psi\cos\theta\cos\phi + \sin\psi\sin\phi \\ -\cos\psi\cos\theta\sin\phi - \sin\psi\cos\phi \\ \cos\psi\sin\theta \end{bmatrix}$$

$$\psi = arctan\left(\frac{\hat{p}\cdot\hat{\phi}}{\hat{p}\cdot\hat{\theta}}\right)$$

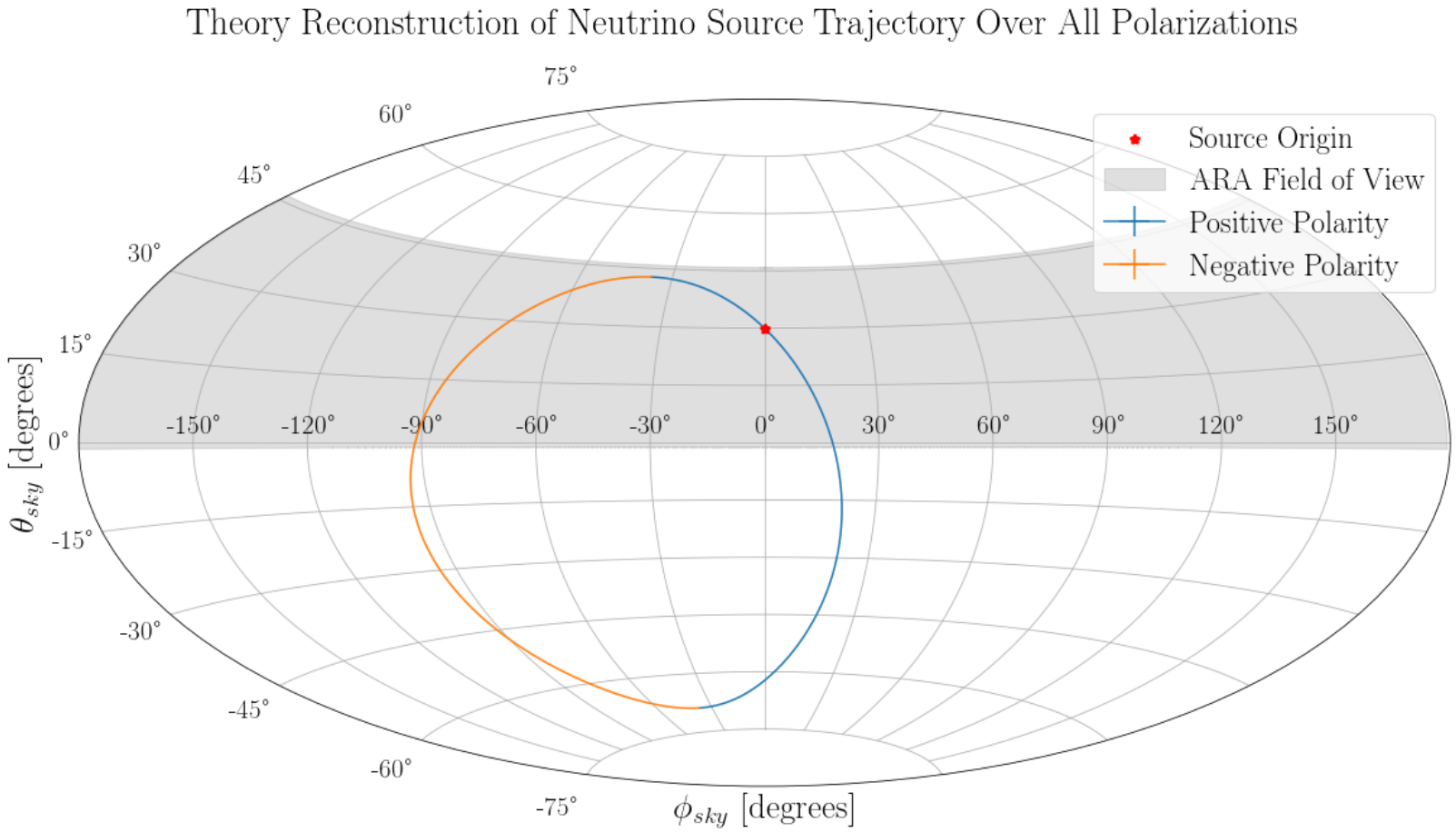
We focus on the domain of $\psi \in [0,90º]$, as polarity of signal is a separate study.

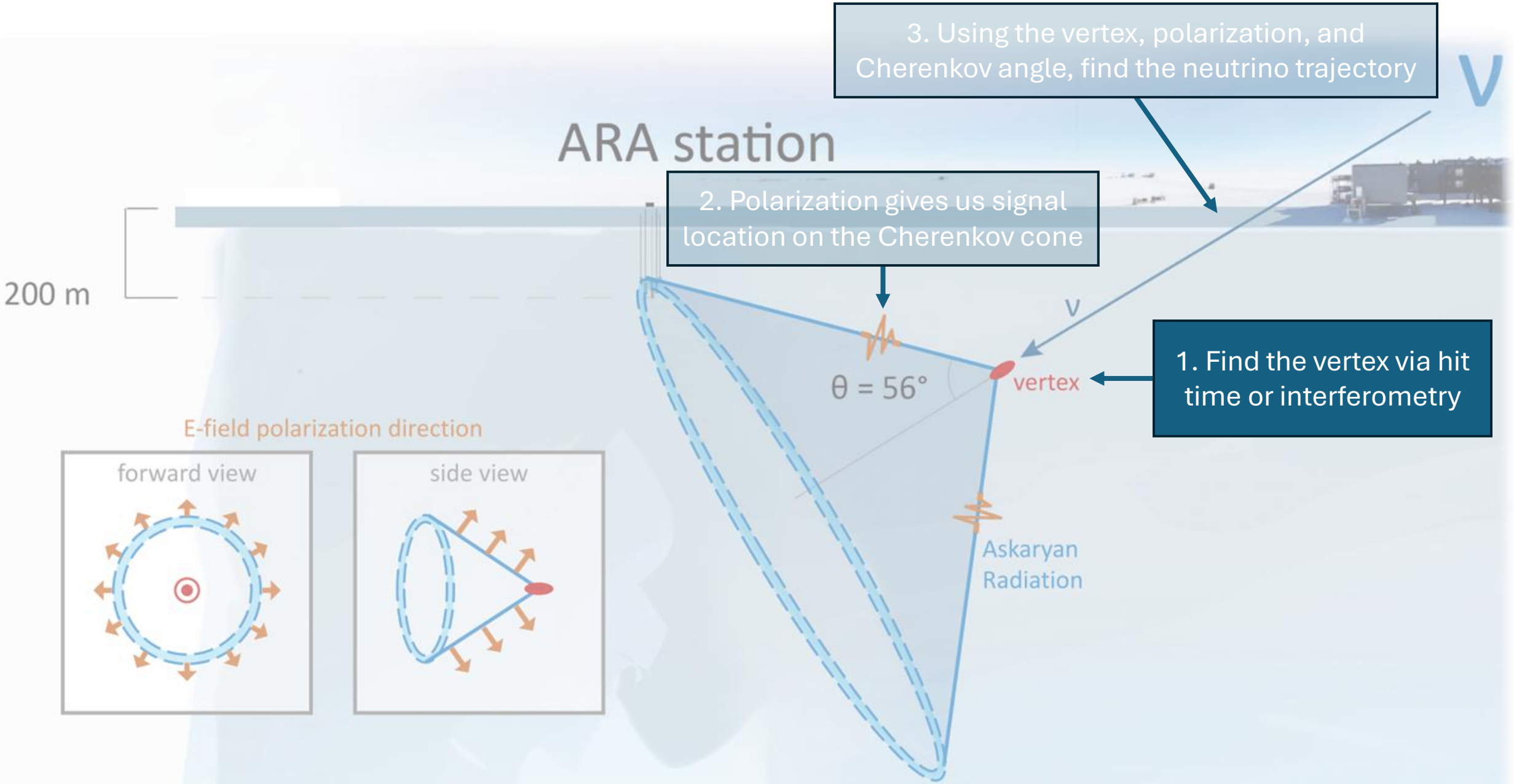
Trajectory Reconstruction

If we can't discern the polarization, our neutrino trajectory would form a large ring in the sky.

$$\hat{v} = \cos\theta_{view}\ \hat{k} - \sin\theta_{view}\,\hat{p}$$

Thus, polarization is important for source searches!

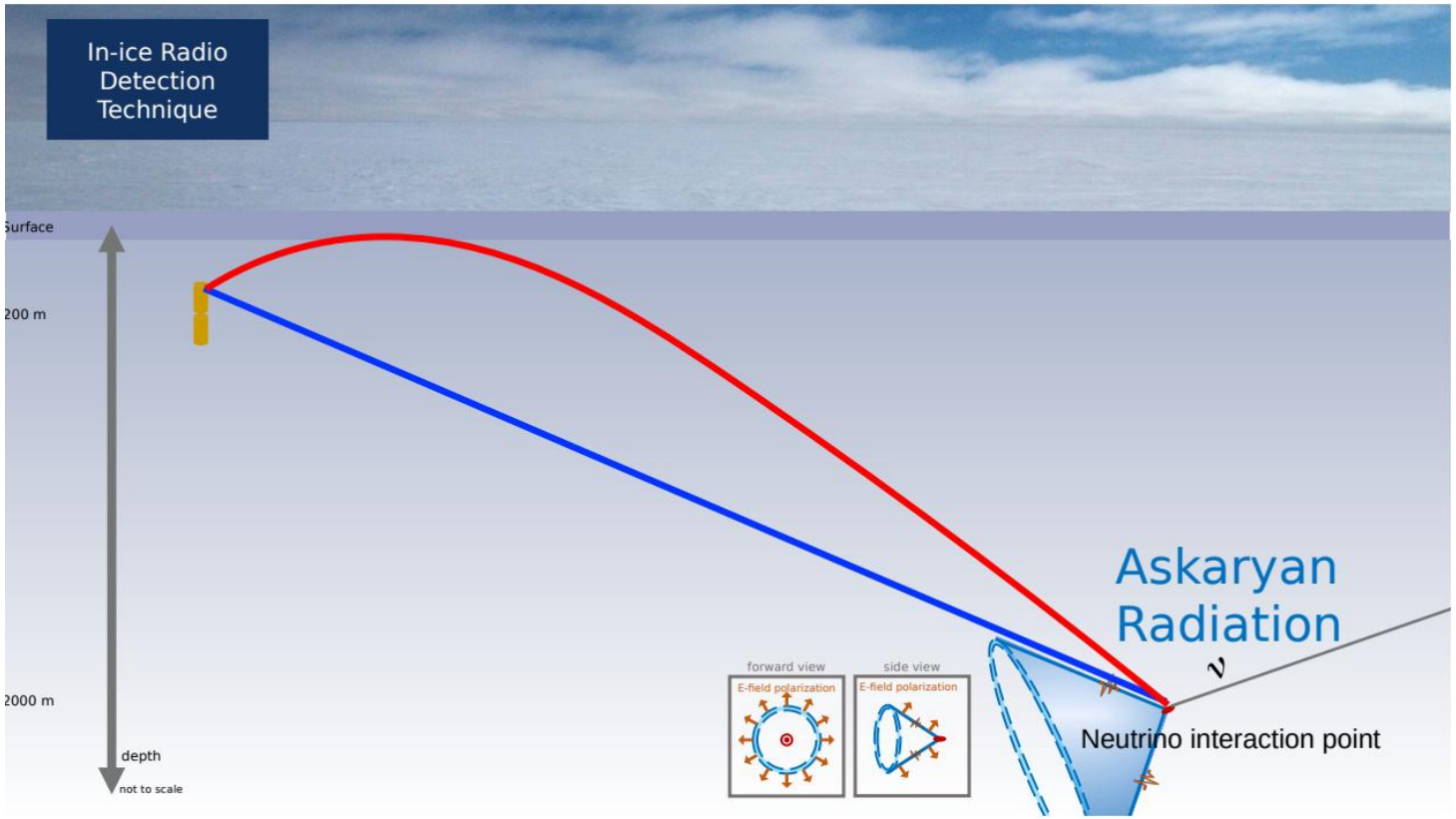



3. Using the vertex, polarization, and Cherenkov angle, find the neutrino trajectory
ν
ARA station
2. Polarization gives us signal location on the Cherenkov cone
200 m
ν
θ = 56°
vertex
1. Find the vertex via hit time or interferometry
E-field polarization direction
forward view
side view
Askaryan Radiation

Ray Tracing in the Antarctic Ice

- Radio signals bend in the Antarctic ice due to a depth-dependent index of refraction.
- This causes signals to follow an exponential curve.

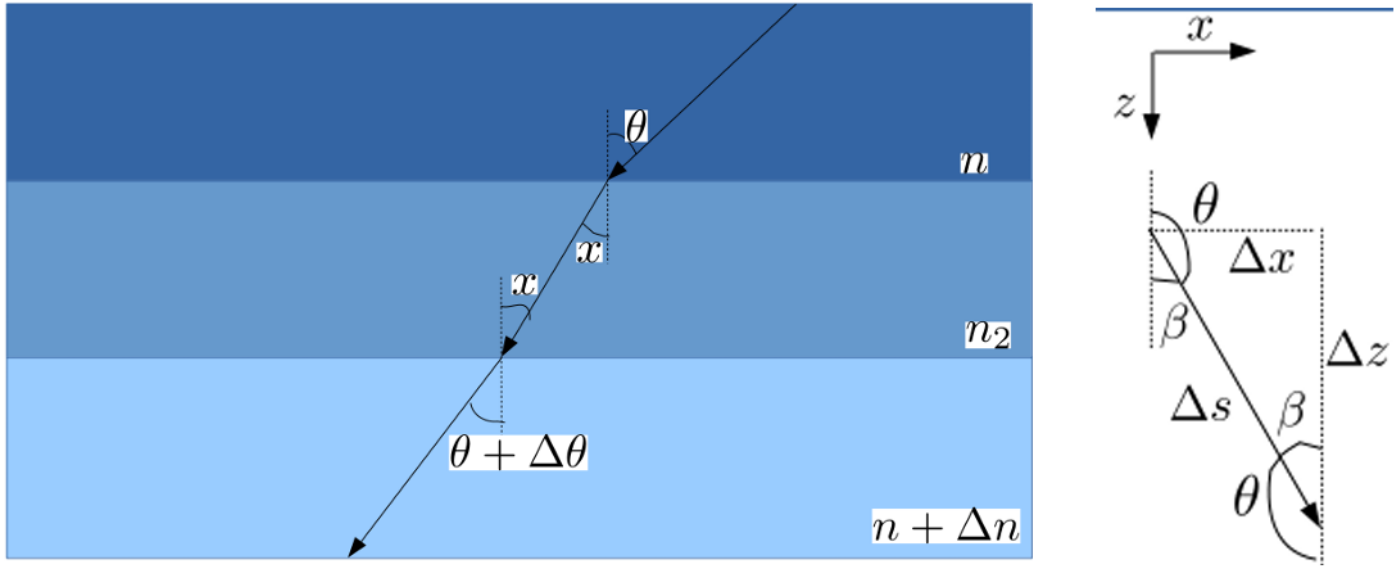
$$n(z) = n_d - (n_d - n_s)e^{\kappa z}$$



Ray Tracing in the Antarctic Ice

$$n(z) = n_d - (n_d - n_s)e^{\kappa z}$$

We handle this computationally by breaking the ice up into vertical slices and solving Snell's Law in steps.



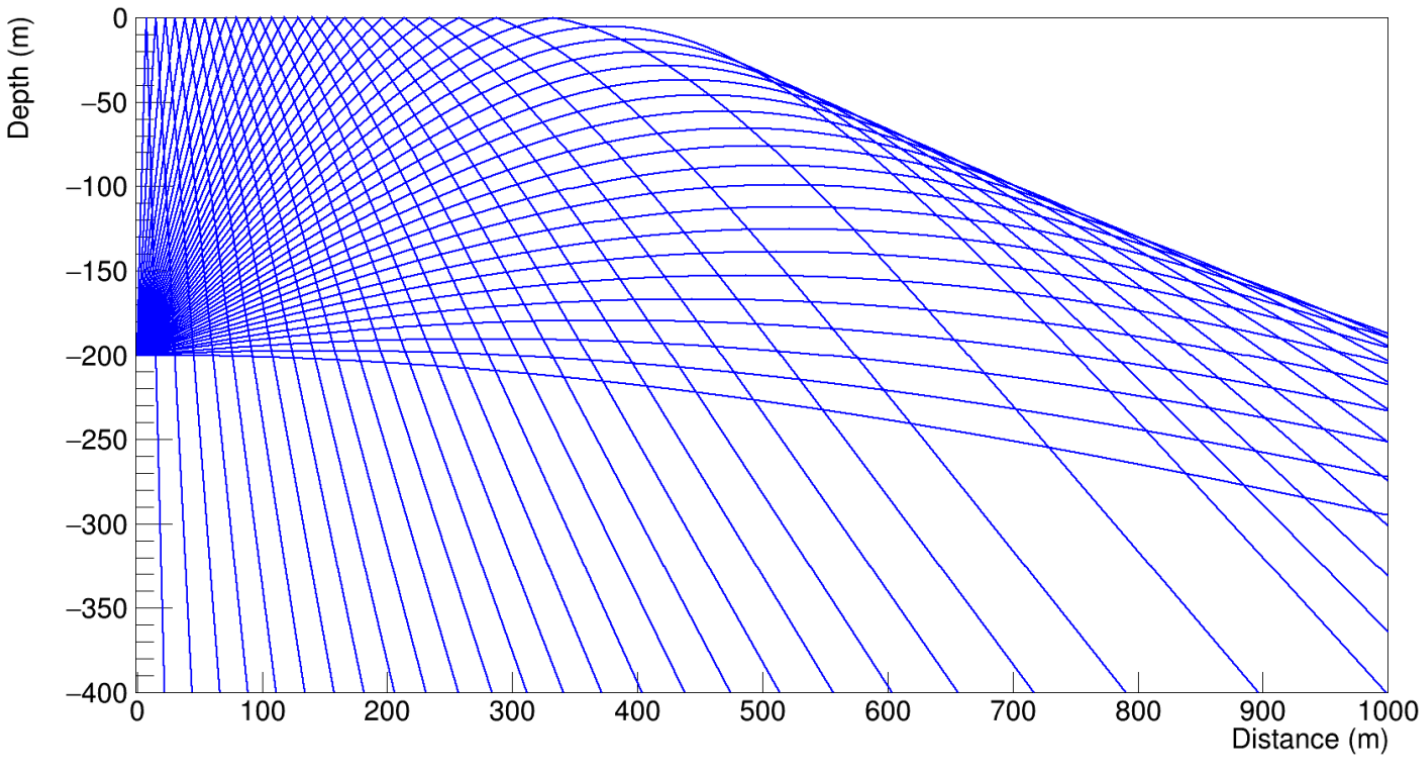
Courtesy: Uzair Latif

Ray Tracing in the Antarctic Ice

$$n(z) = n_d - (n_d - n_s)e^{\kappa z}$$

This can lead to areas where we have one, two, or zero ray tracing solutions.

Rays Launched from Antenna at 200 m Depth at 1º Increments



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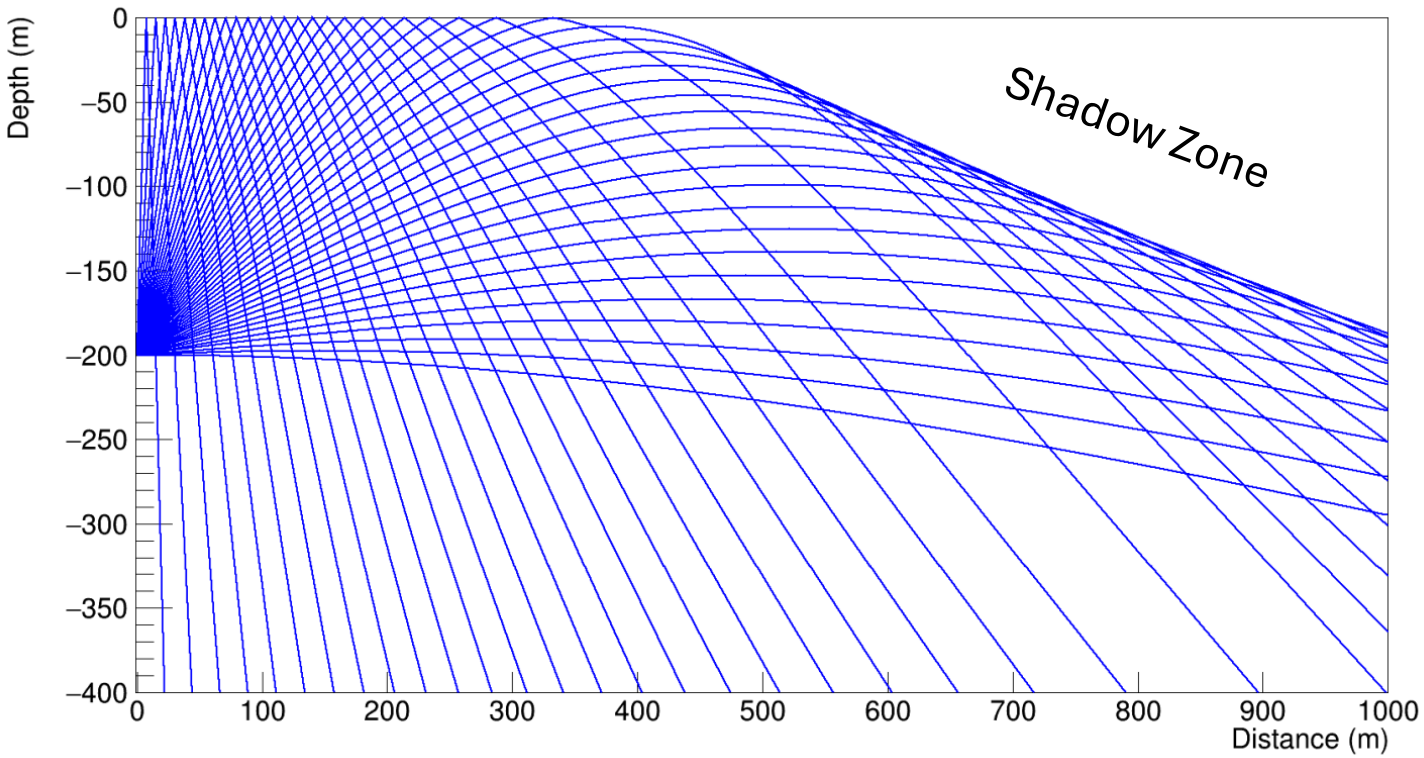
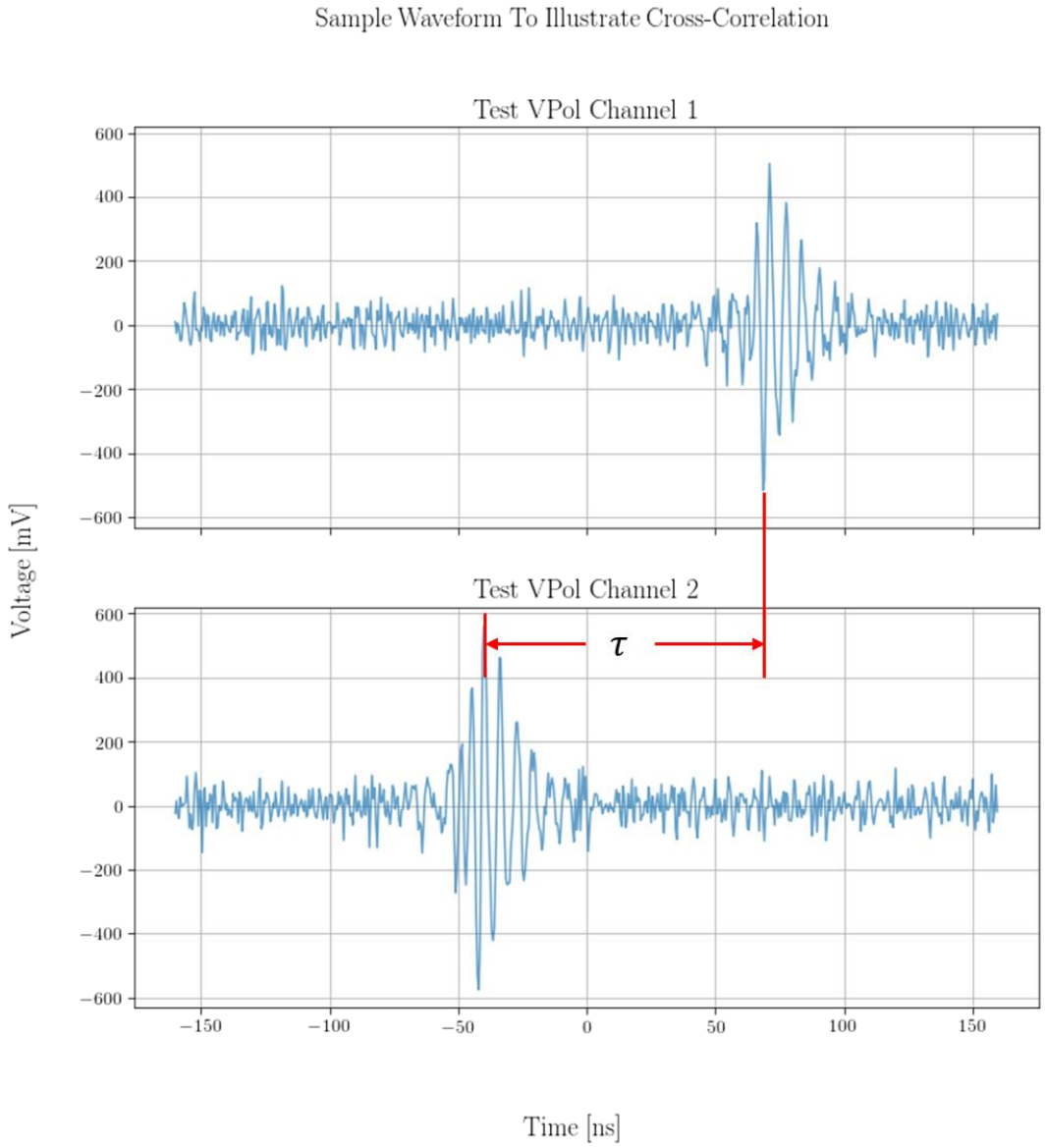


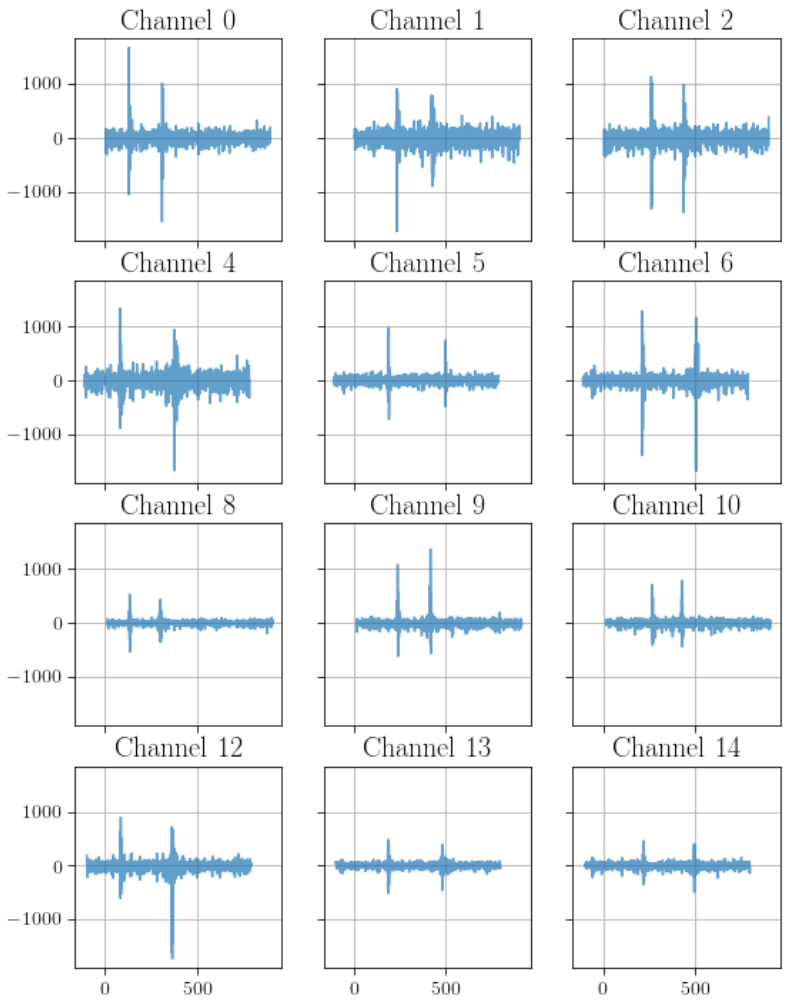
Courtesy: Uzair Latif

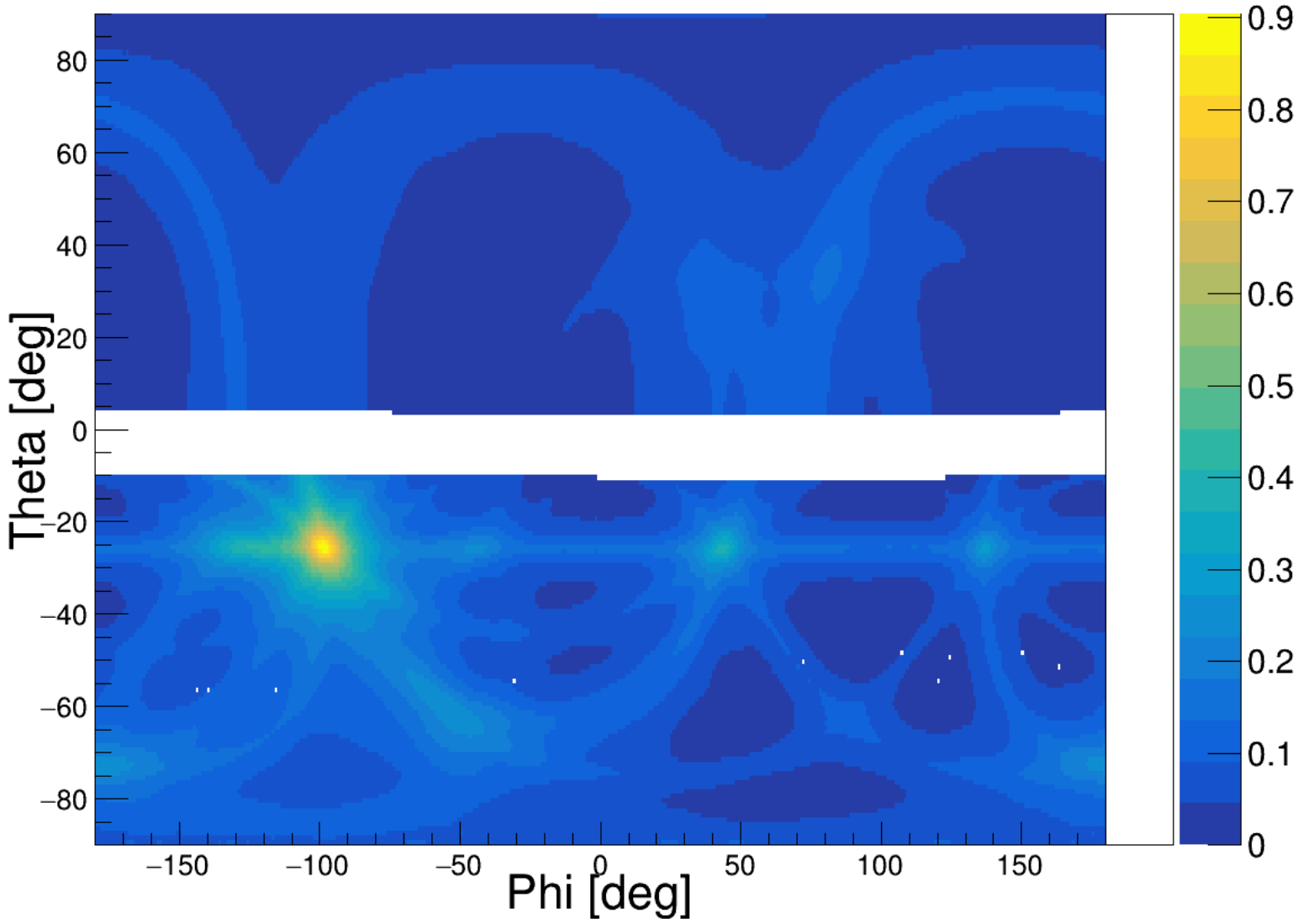
Ray Tracing Tables and Cross-Correlation

- To speed up computation, we do the ray tracing ahead of time for all directions around the antenna.
- This gives us a 3D mesh of solutions, each bin containing information for the launch and arrival directions of the ray, as well as arrival time.
- This arrival time is used to cross-correlate the channels, where we essentially triangulate the position of the vertex using the arrival time.



Example of Vertex Reconstruction of Calibration Event via Cross-Correlation





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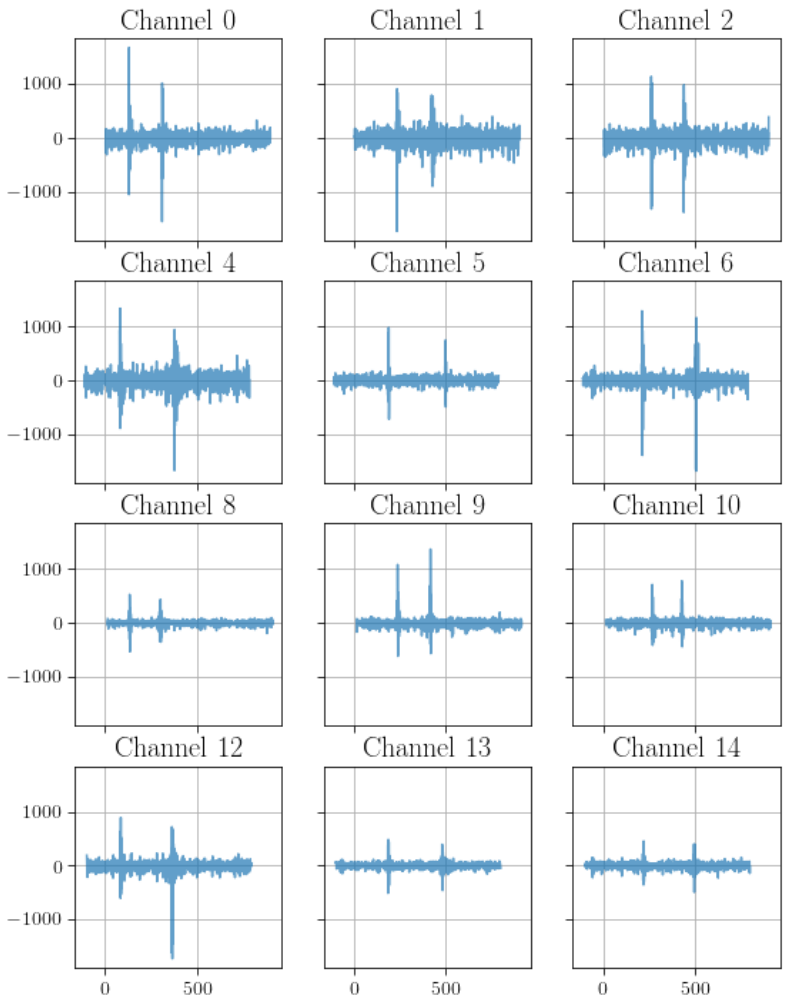
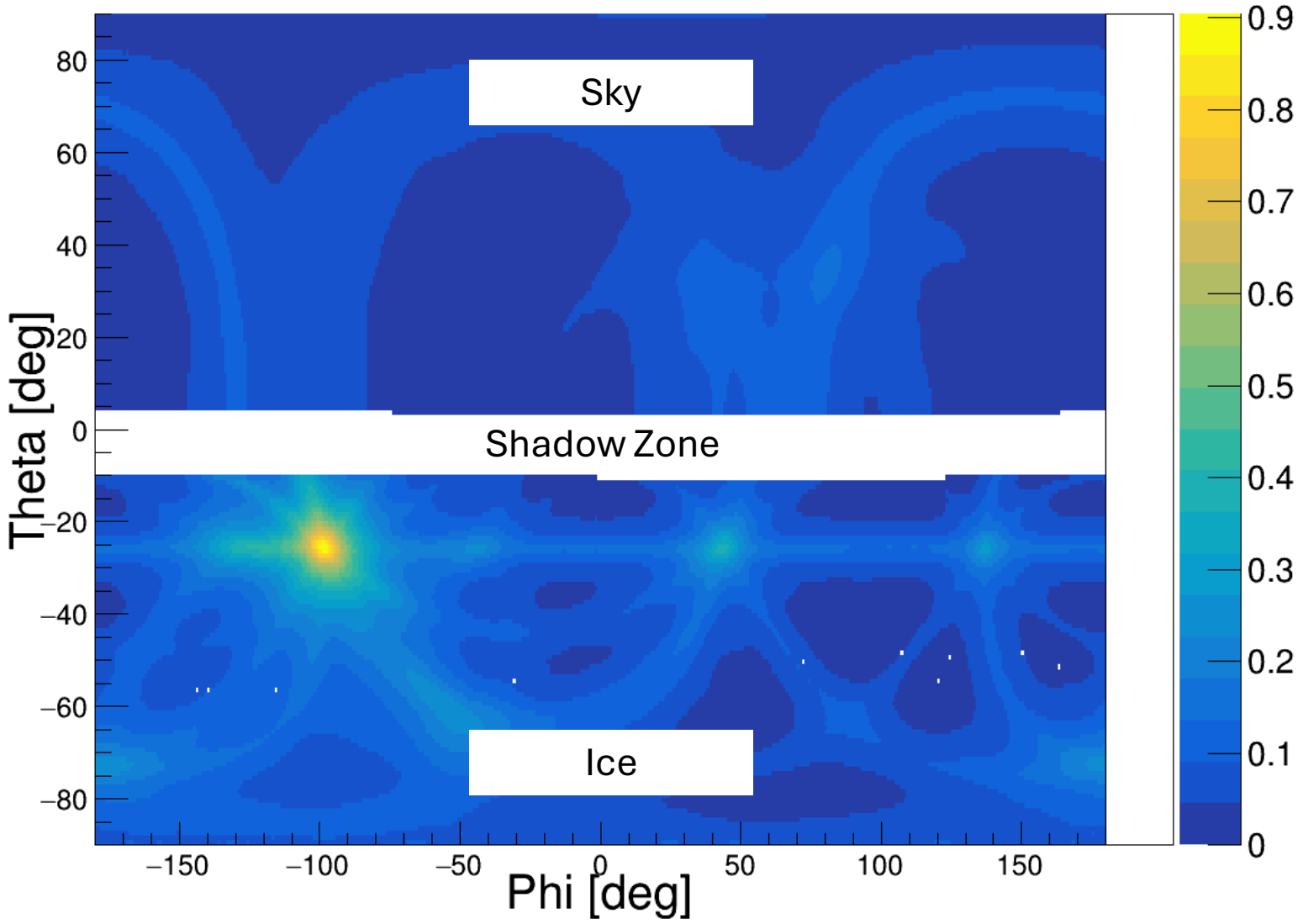




3. Using the vertex, polarization, and Cherenkov angle, find the neutrino trajectory

ν

ARA station

2. Polarization gives us signal location on the Cherenkov cone

200 m

ν

✓

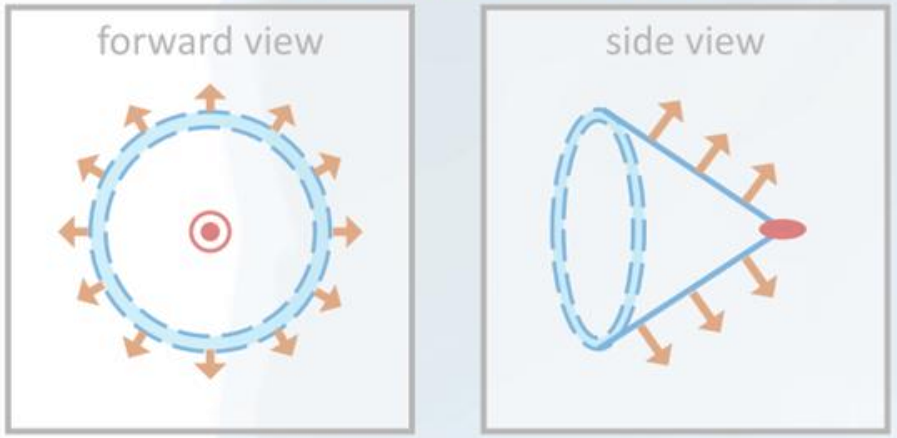
θ = 56°

vertex

1. Find the vertex via hit time or interferometry

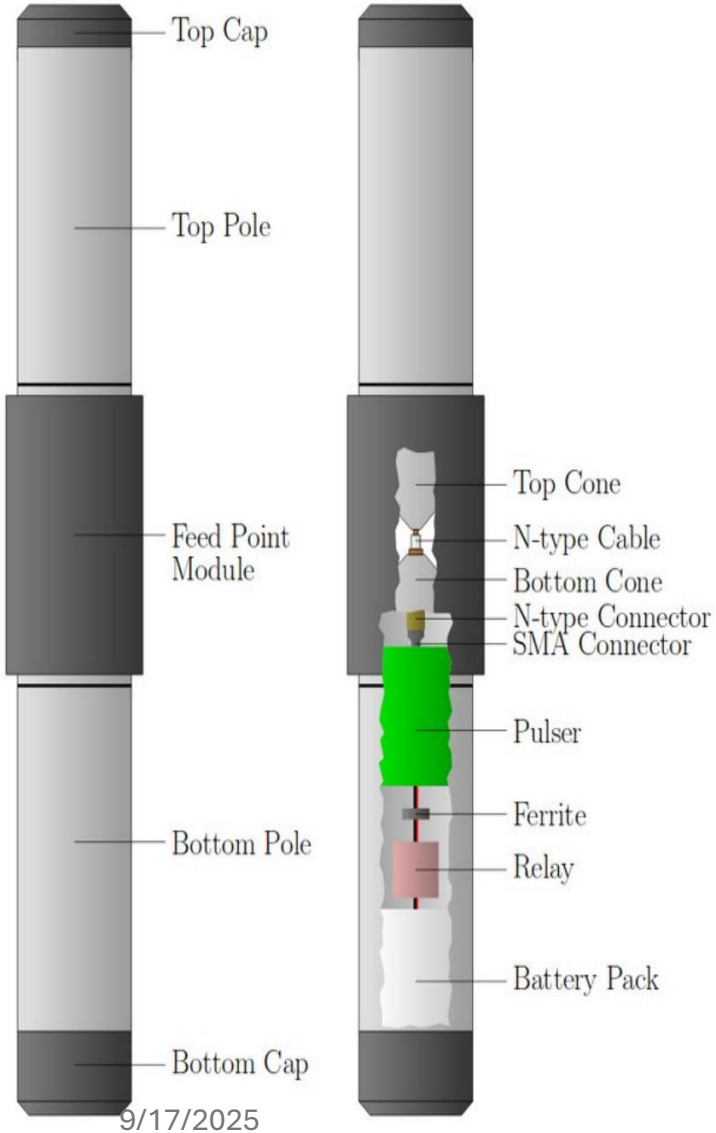
Askaryan Radiation

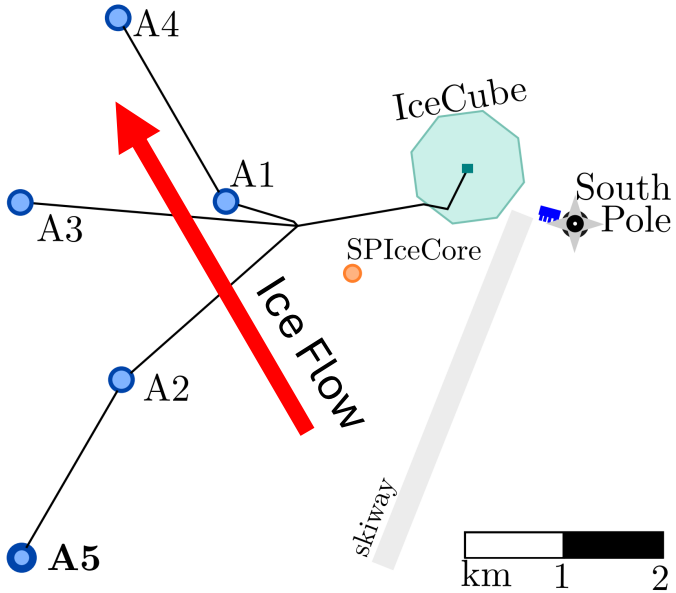
E-field polarization direction



How do we study polarization without neutrinos?

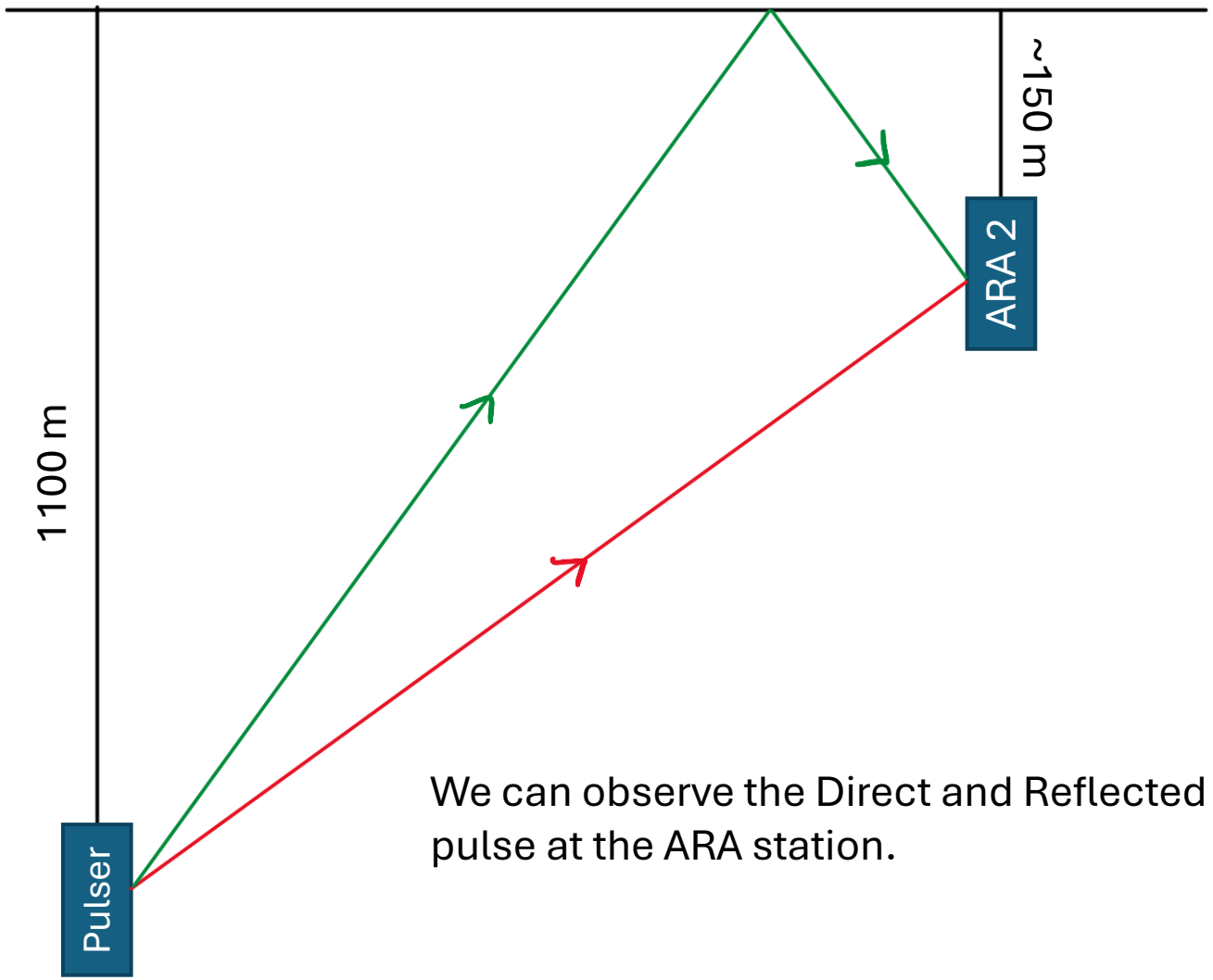
With Calibration Pulsers!



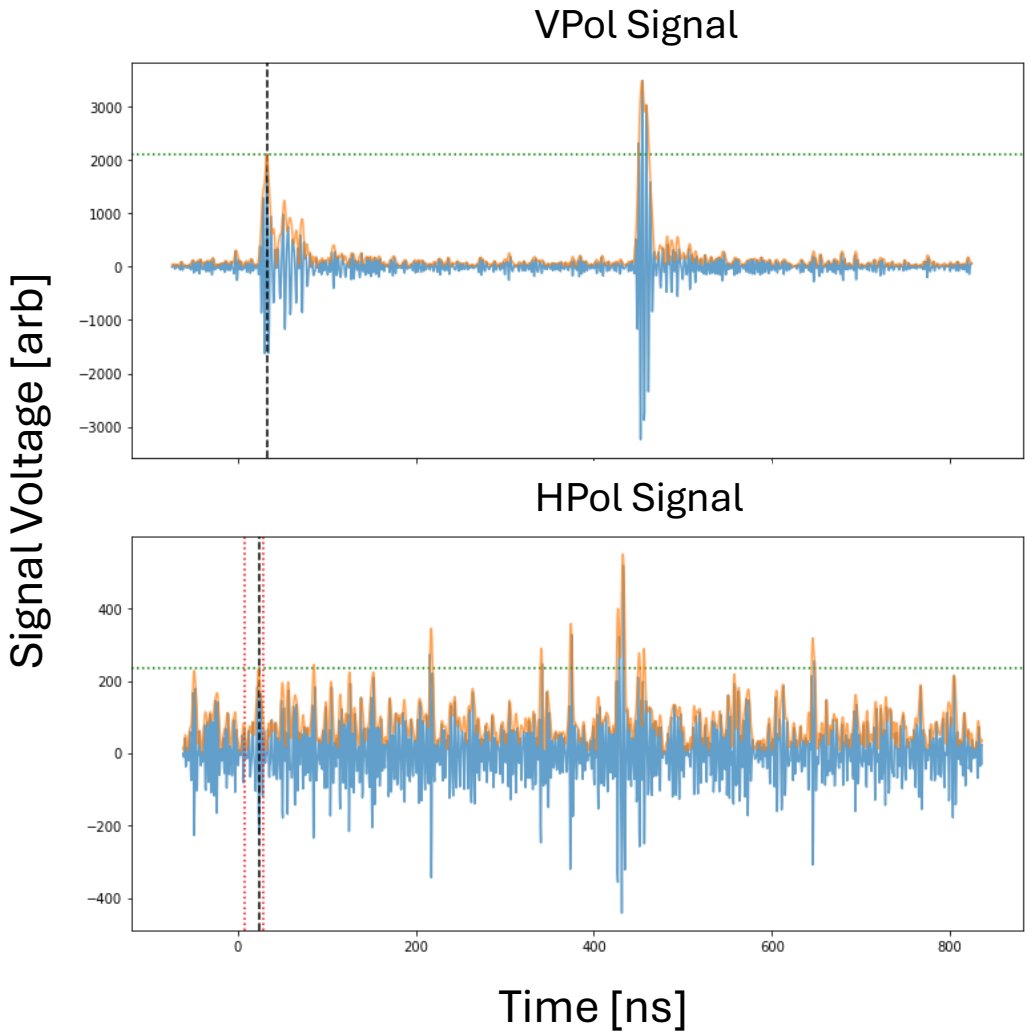


A radio pulser was into South Pole Ice Core Experiment (SPICE) borehole.

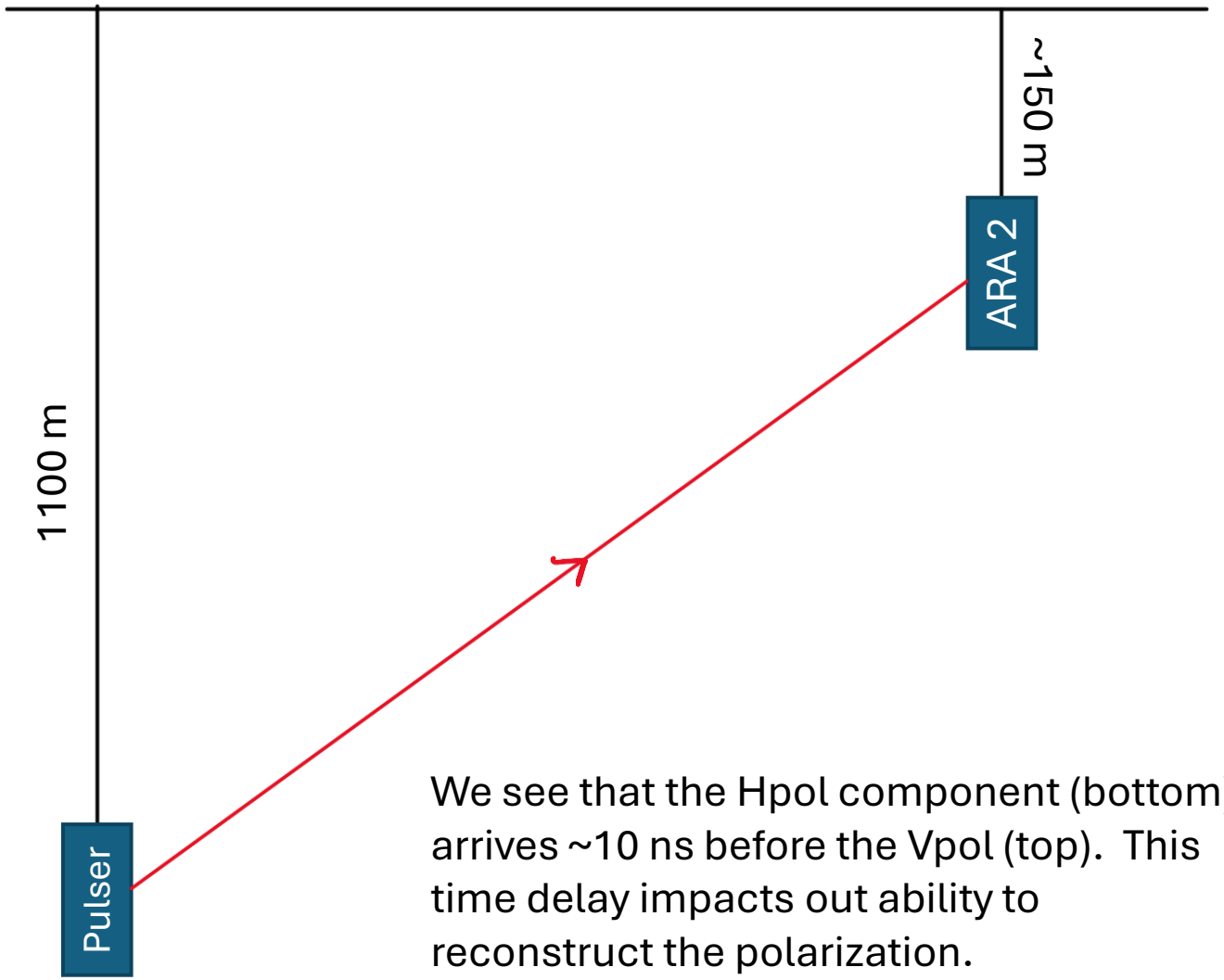
Observed event from SPICE



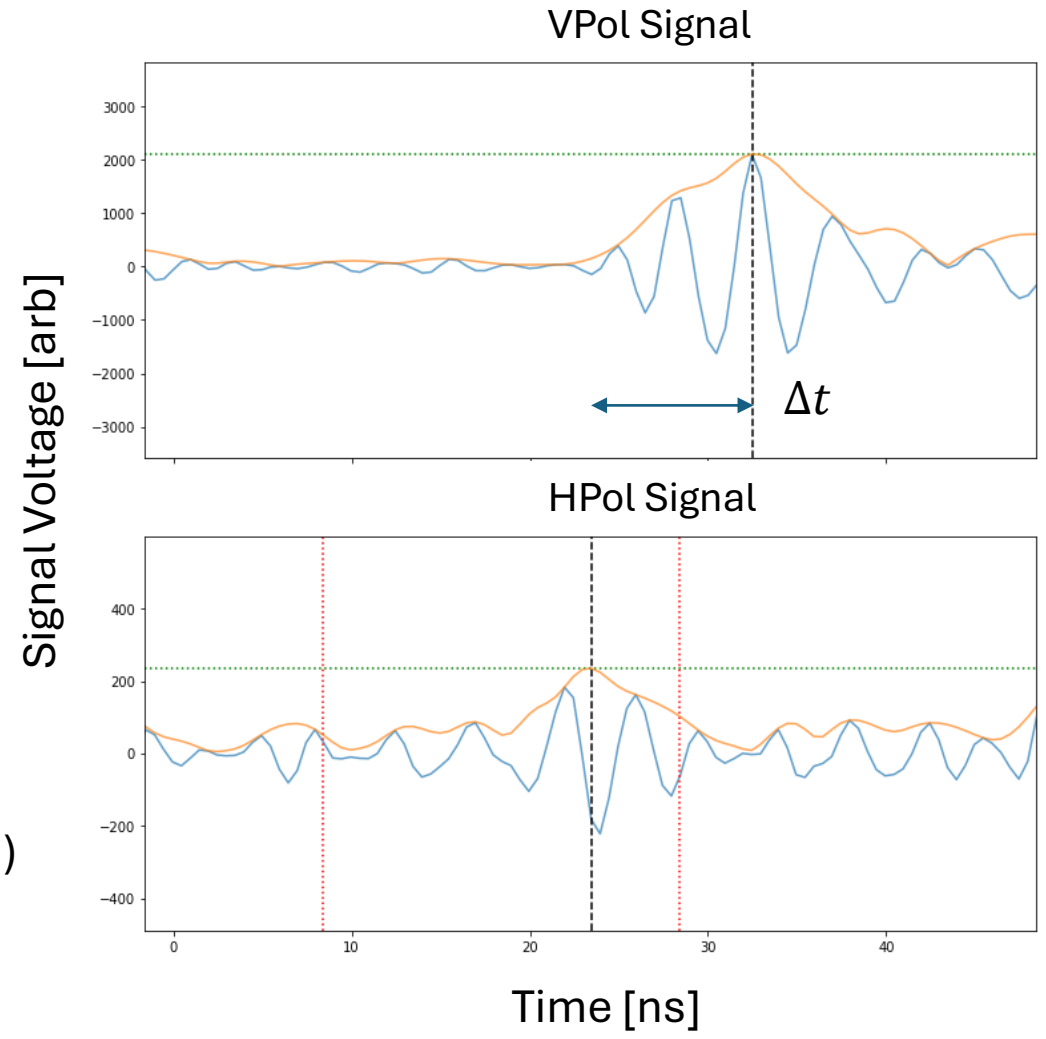
We can observe the Direct and Reflected pulse at the ARA station.



Observed event from SPICE

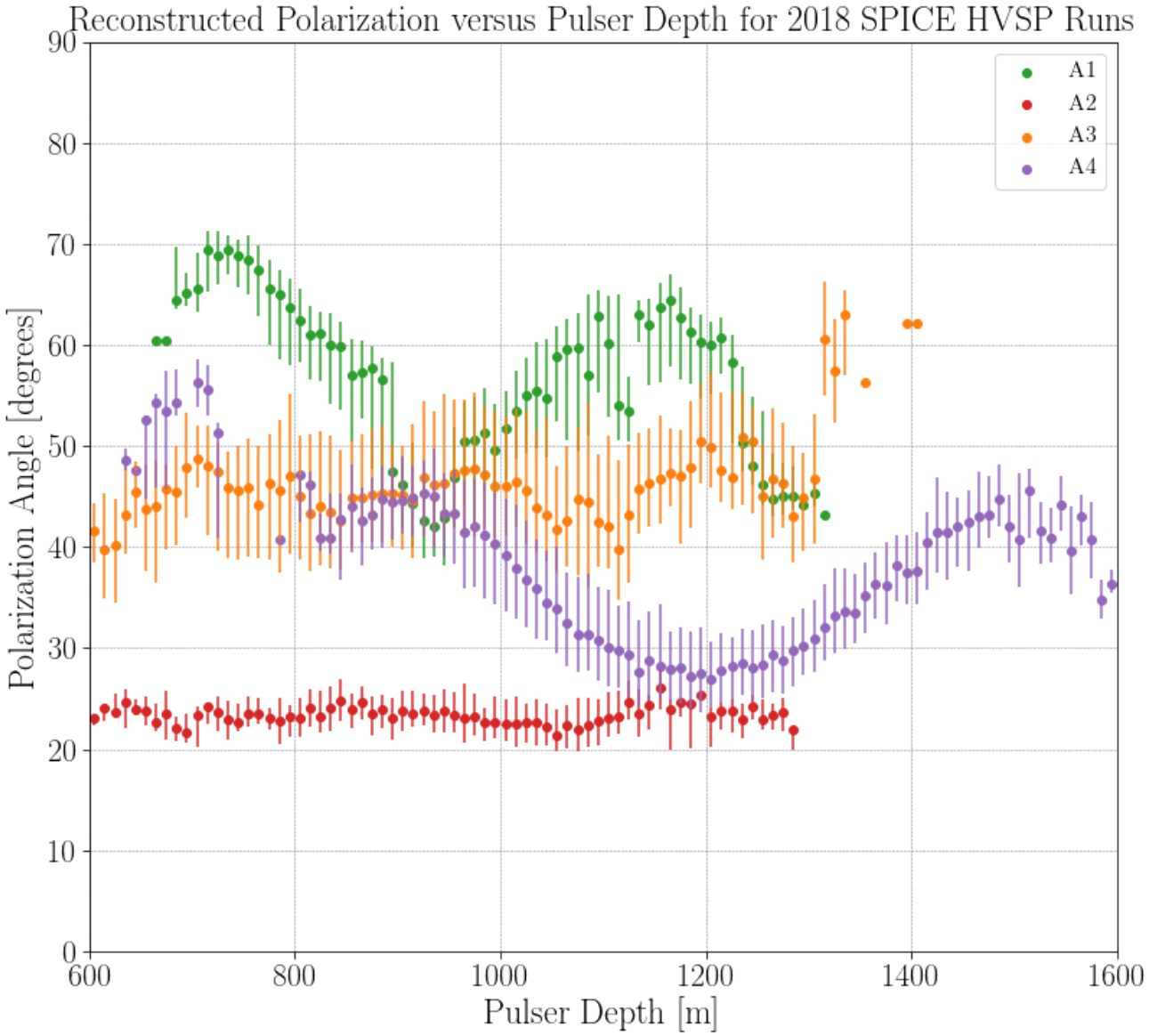


We see that the Hpol component (bottom) arrives ~10 ns before the Vpol (top). This time delay impacts out ability to reconstruct the polarization.



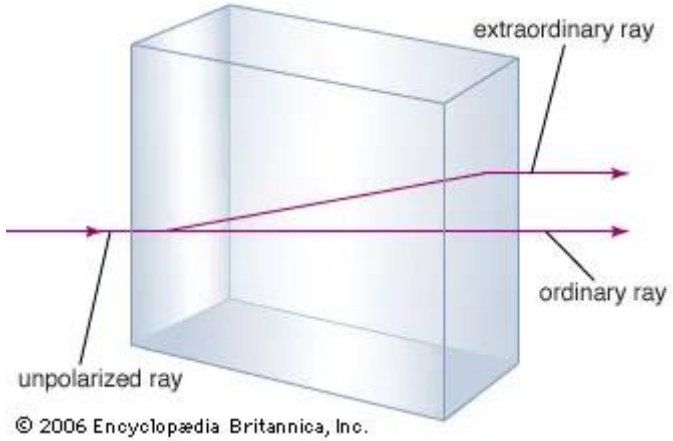
SPICE Reconstruction Results

- If we reconstruct SPICE events at varying depths across multiple stations, we see conflicting behavior in the polarization reconstruction.
- Birefringence in the current hypothesis for this behavior.



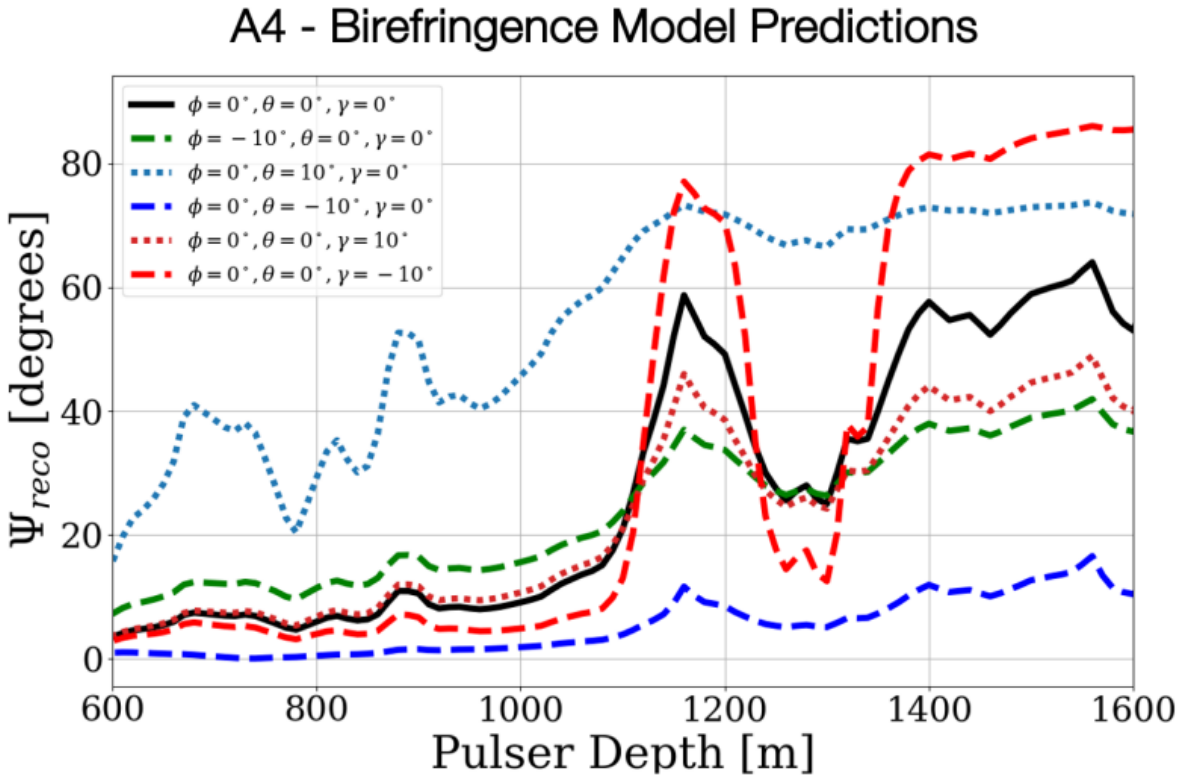
What is Birefringence?

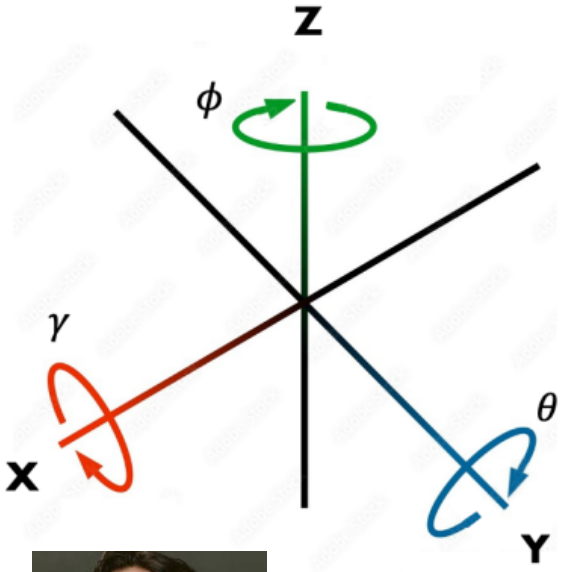
- A phenomenon where a crystal structure can have a polarization-dependent index of refraction.
- Causes a ray to be split into two based on the initial polarization.
- Most notable features in our context:
  - A net rotation in polarization
  - A time-delay between polarization components

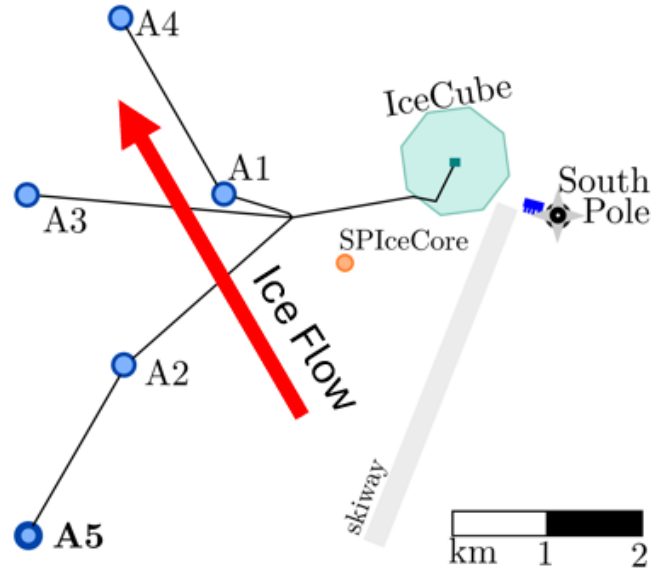


Birefringence Model is Sensitive to Crystal Orientation

- Glaciology studies have shown that the crystal fabric can be tilted by up to ten degrees.
- Alan Salcedo-Gomez has shown how impactful this effect is for Station A4 using a model by Amy Connolly.



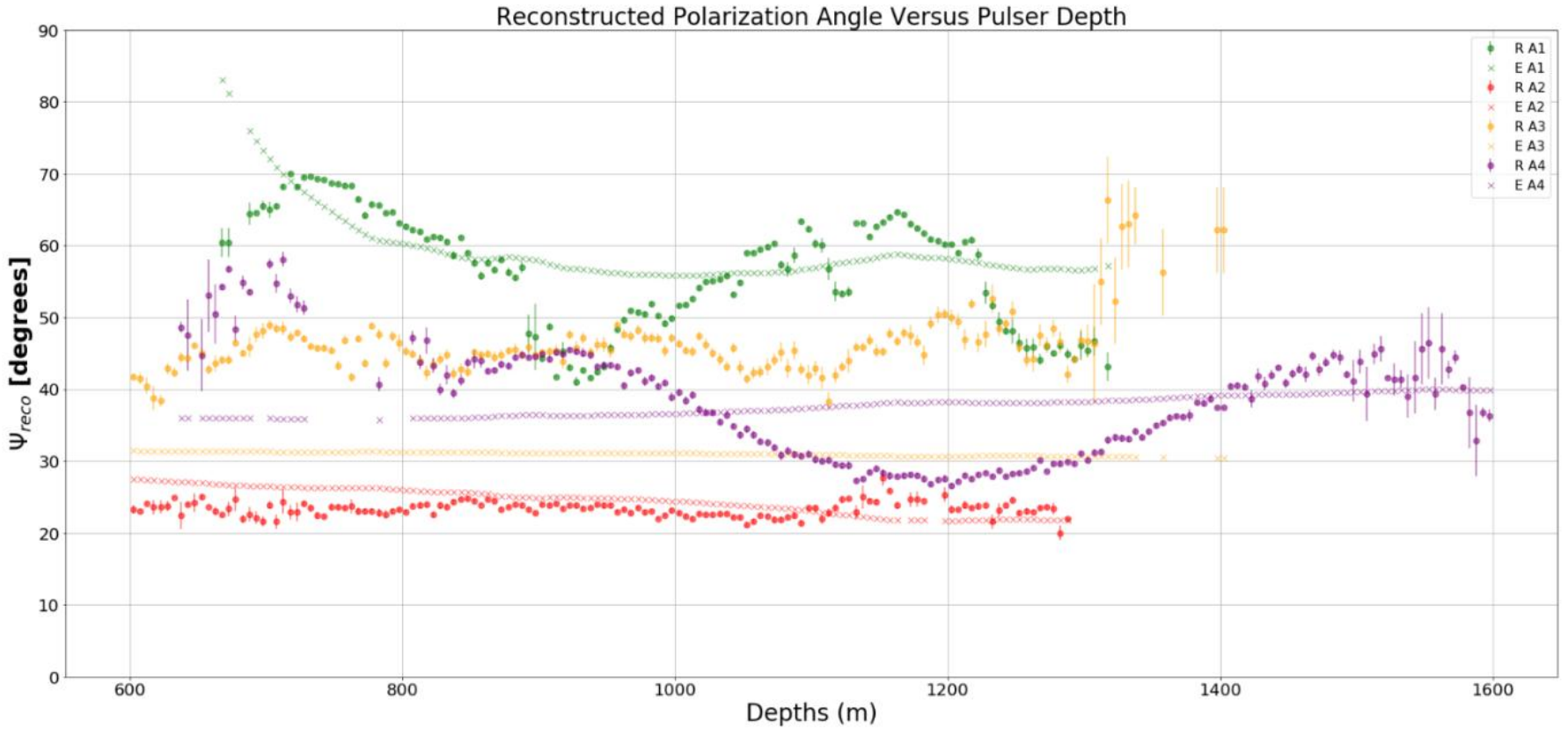




Courtesy: Alan Salcedo-Gomez

Fitting the Birefringence Model

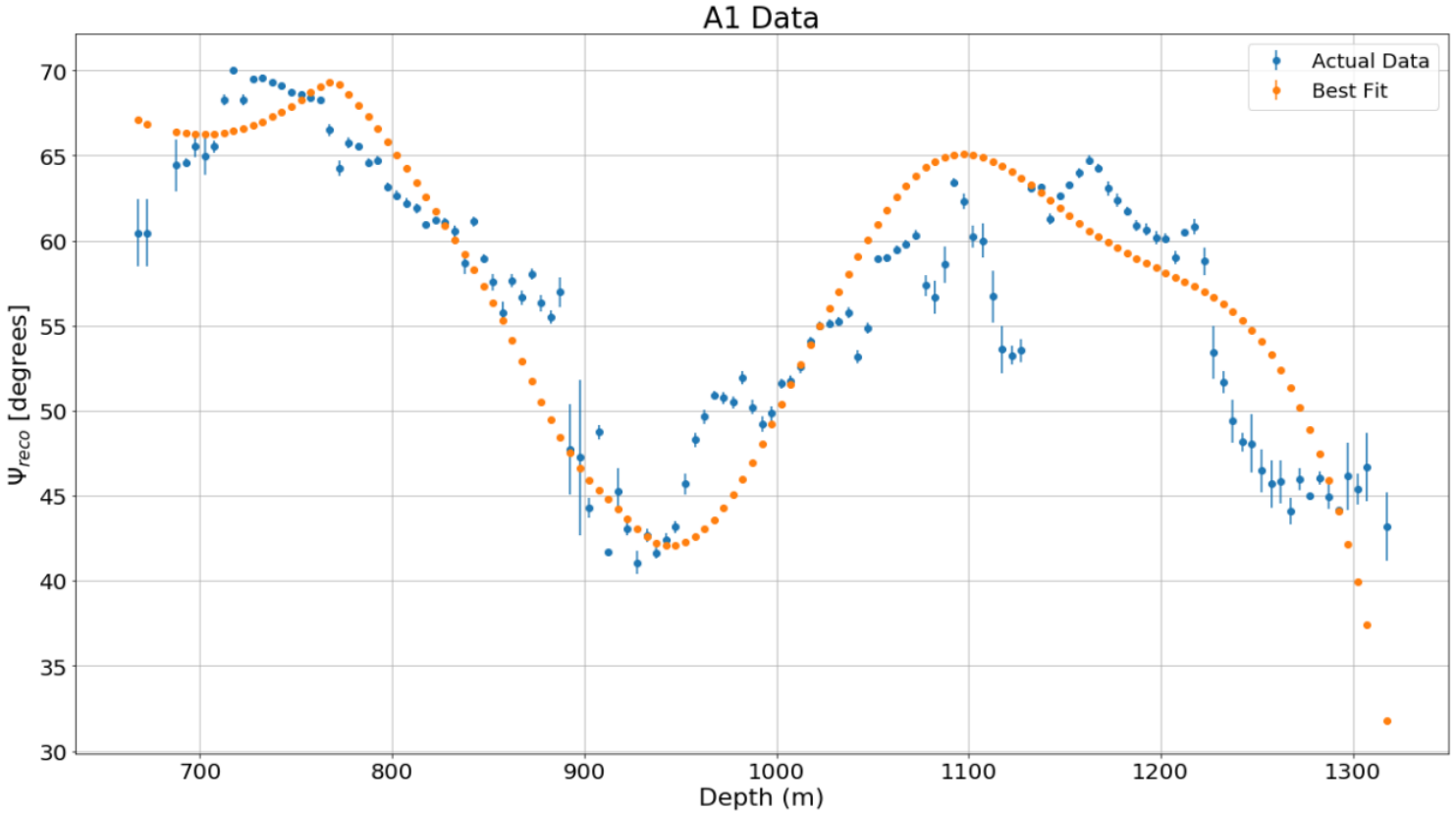
- Alex Machtay working on fitting reconstructed SPICE data using genetic algorithms to find the optimal parameters for the COF of the ice.



Courtesy: Alex Machtay

Fitting the Birefringence Model

- When fitting to a single station, the features are promising. However, ice properties should not be station specific.
- Work is still ongoing.



Courtesy: Alex Machtay

Closing Statements

- At present, ARA can reconstruct polarization within 2.7 degrees.
- Polarization of radio emissions in South Pole ice exhibit behavior hypothesized to be birefringence.
- Resolving the ice model is crucial to conduct source searches.
- Alan Salcedo Gomez, Alex Machtay, and Jacob Weiler have been continuing this work.

Questions?