Observation of In-ice Askaryan Radiation from High-Energy Cosmic Rays

TeVPA 2025

Nat Alden and Philipp Windischhofer for the ARA collaboration

arXiv: 2510.21104

SOUTH POLE
ASKARYAN RADIO ARRAY

THE UNIVERSITY OF CHICAGO

The Askaryan Radio Array (ARA)

Askaryan [radiation]

First described by Gurgen Askaryan in 1962
—Coherent Cherenkov-like radio emission from high-energy particle showers in a dielectric medium

↓

Has been measured at particle accelerators in sand, salt, and ice → Motivating ultra-high energy neutrino experiments such as RICE, ANITA, **ARA**, RNO-G, PUEO
(See plenary talk by Simona Toscano)

… And as a subdominant component of the signal from cosmic ray (CR) air showers (Auger, LOFAR, CODALEMA)

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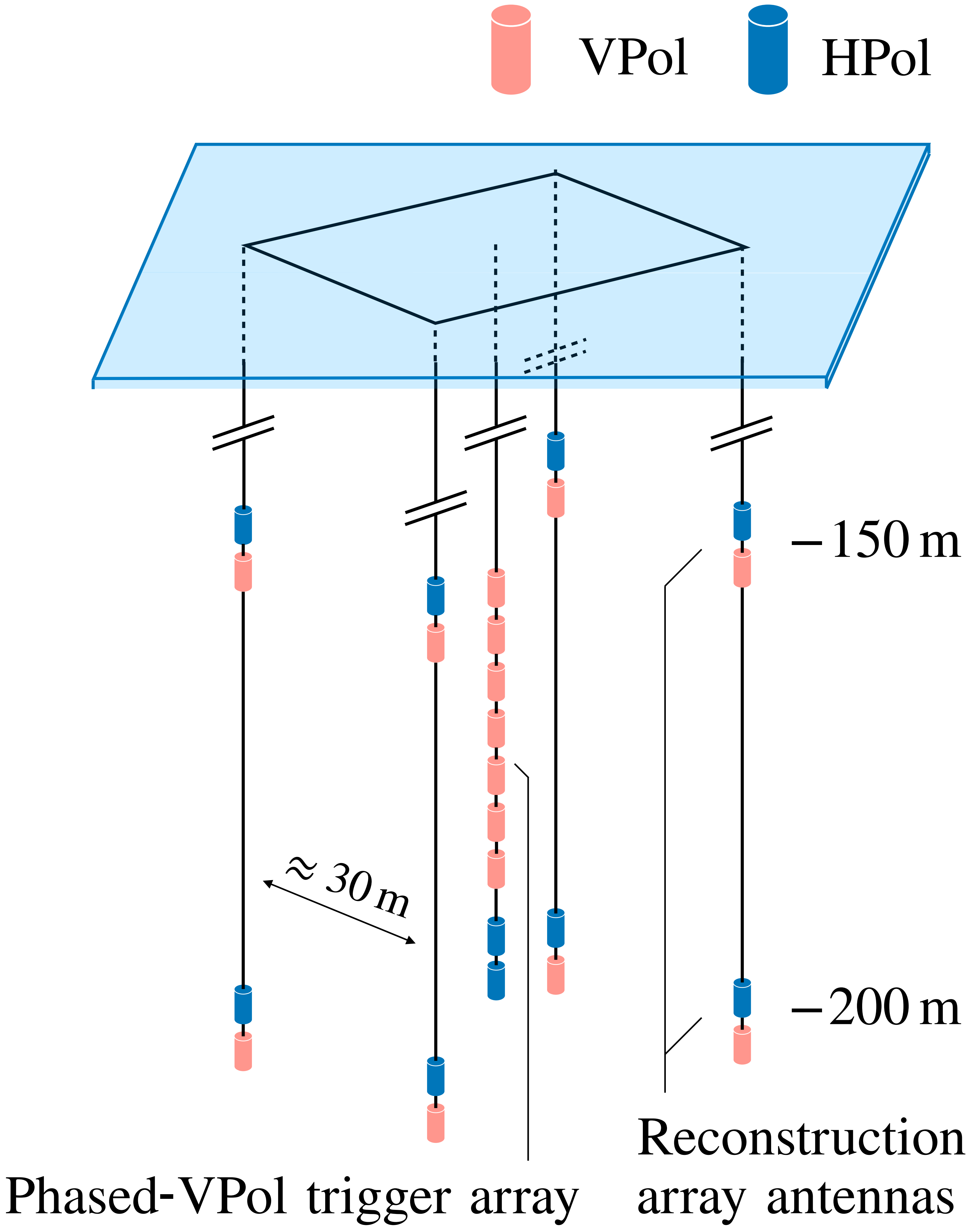
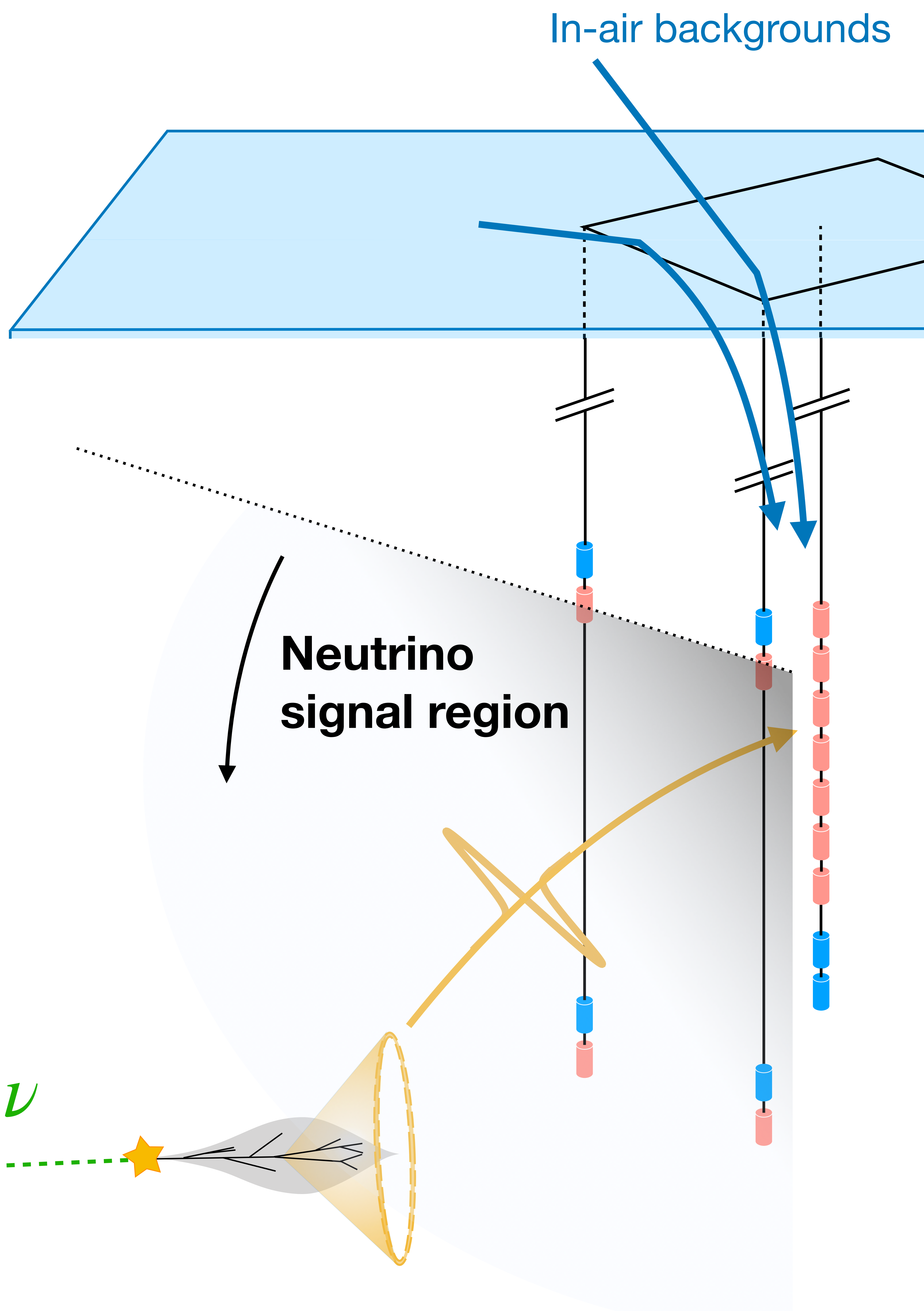
Radio Array



Event selection

A previous analysis searched for neutrinos coming from the deep ice [PRD 105, 122006 (2022)]

→*Removes backgrounds from near or above the surface*



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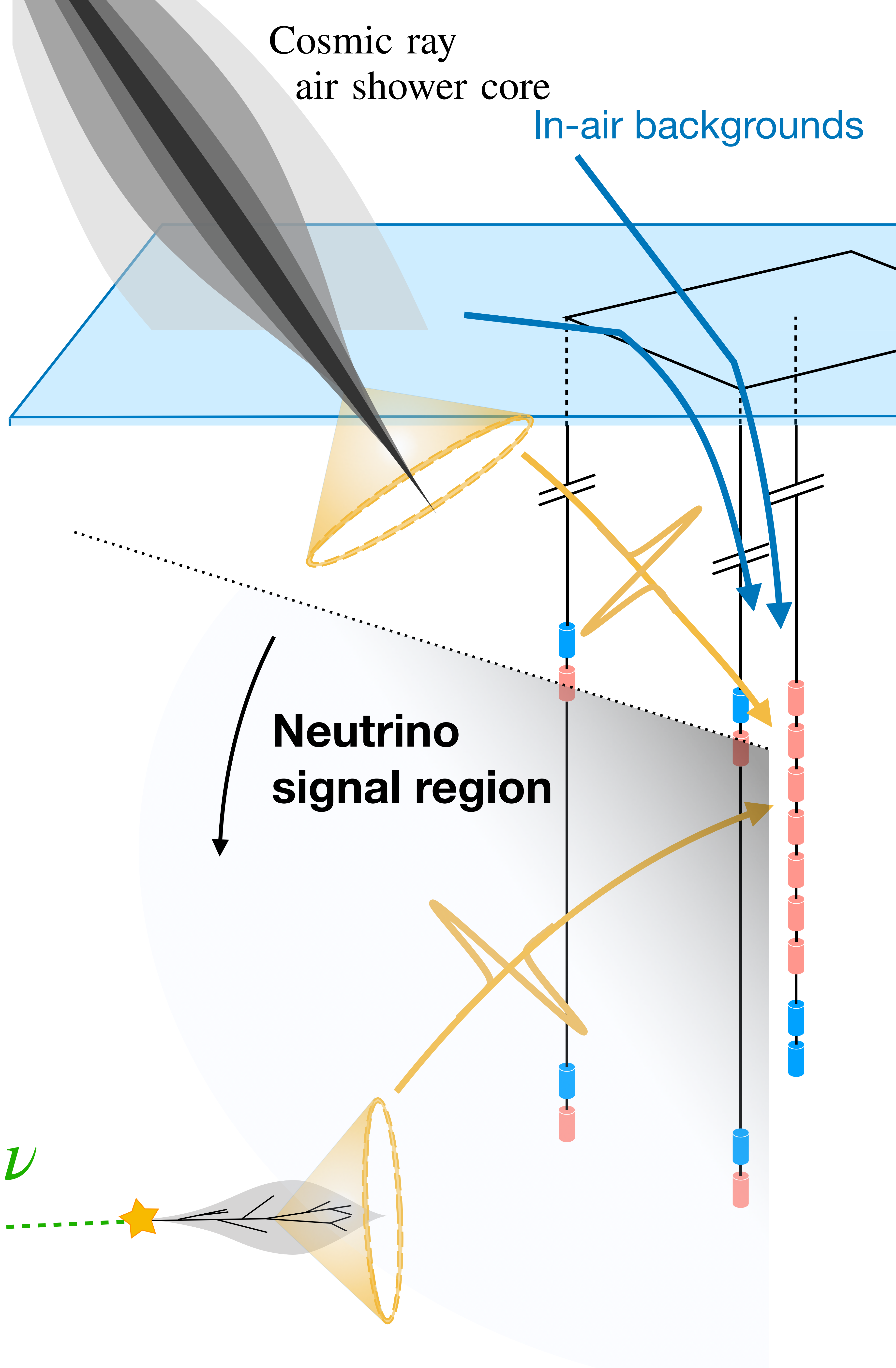
Cosmic rays also produce Askaryan radiation

⟹ CRs are both a calibration source and a background source for neutrinos



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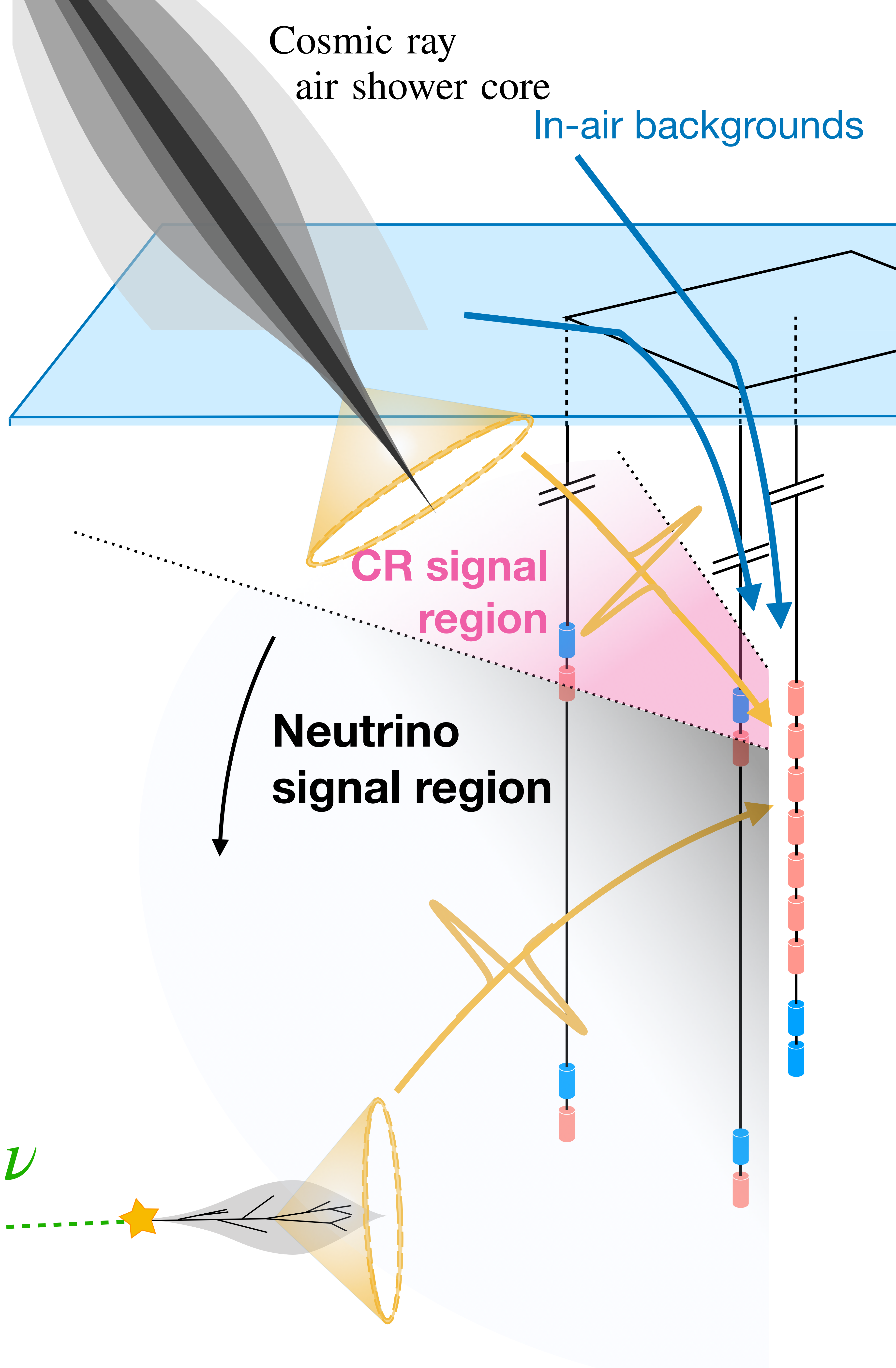
In this work:

Analyze the 13 events from the **"CR signal region"**: the zenith region where we can receive signals which originate in shallow ice, but **not in the air.**

→Suppresses anthropogenic backgrounds & geomagnetic emission

→This is the first observation of "natural" Askaryan emission in dense media:

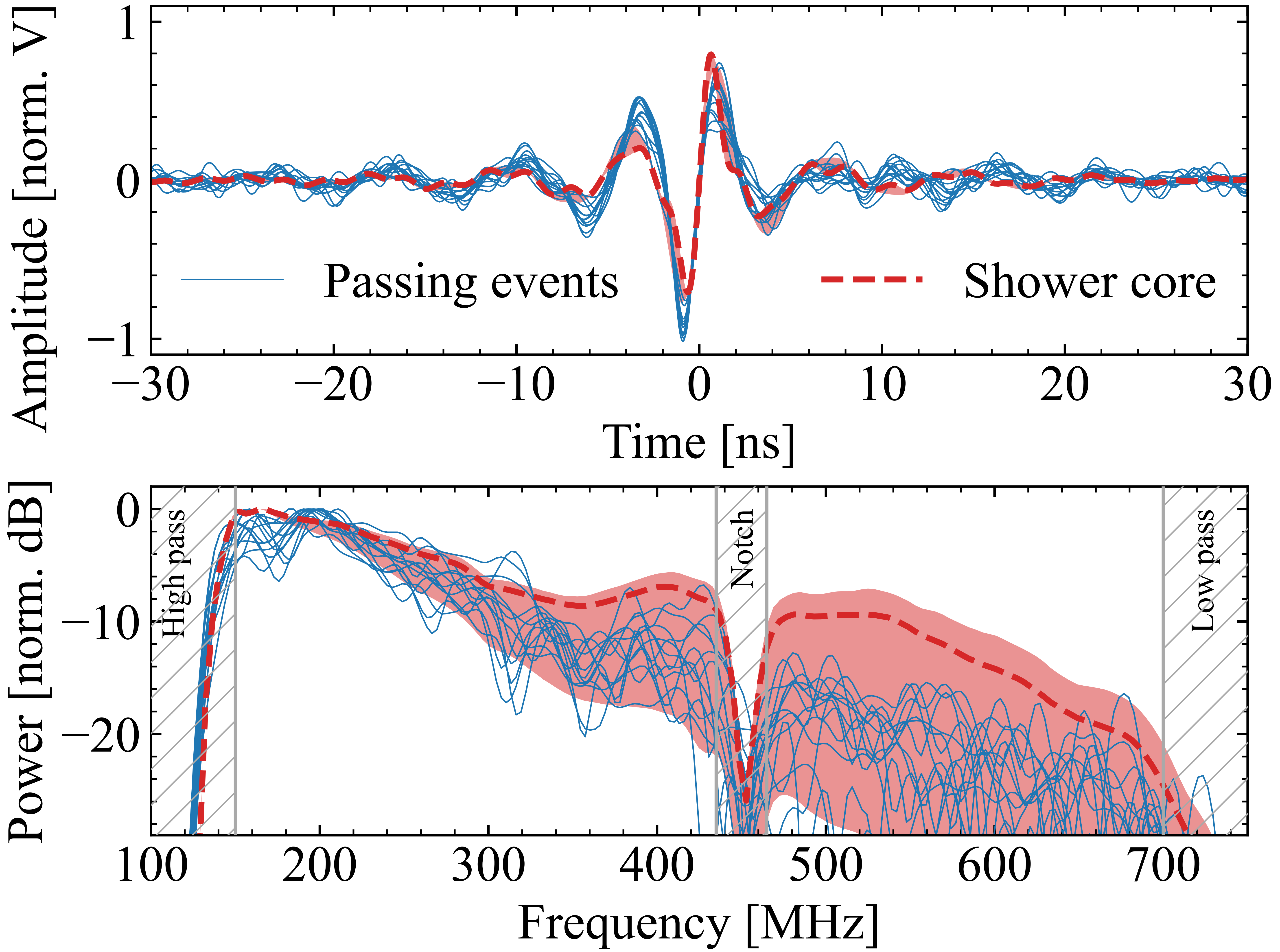
what does the signal look like?



Signal shape

Processing steps:
Remove instrumental phase response, reconstruct arrival direction to sum time-aligned waveforms.

All waveforms have same polarity and qualitatively similar shape



Microscopic simulations use CORSIKA 8 (particle cascades) and Eisvogel (full electrodynamics)

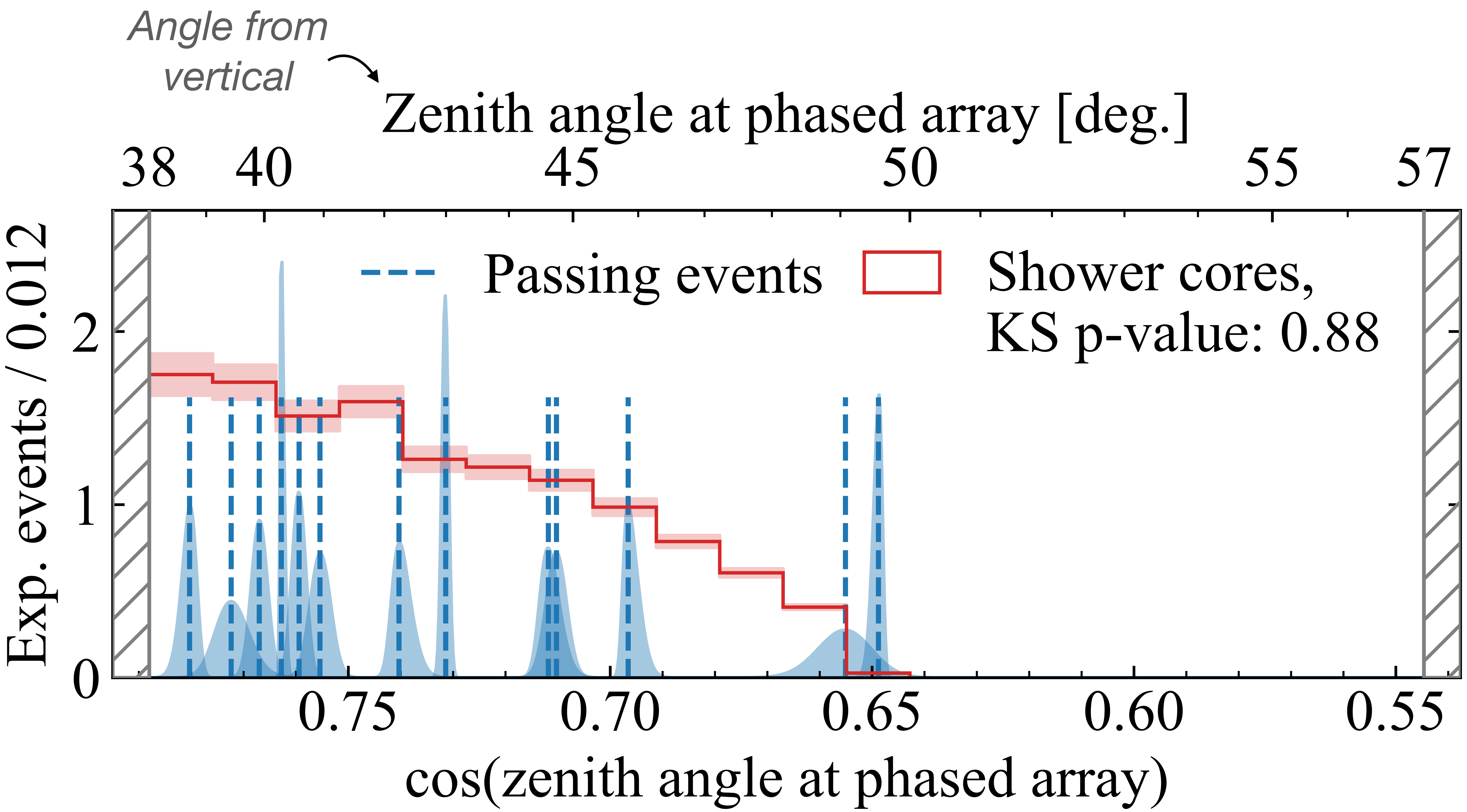
See talk by P. Windischhofer

Simulations span range of $0^{\circ} - 3^{\circ}$ off the Cherenkov cone, generated for a 10^{17} eV proton shower

Arrival directions

Agreement between data and simulation

Monte Carlo simulation generated using the procedure presented in Coleman et. al, Astropart. Phys. (2025) [link]



Arrival directions

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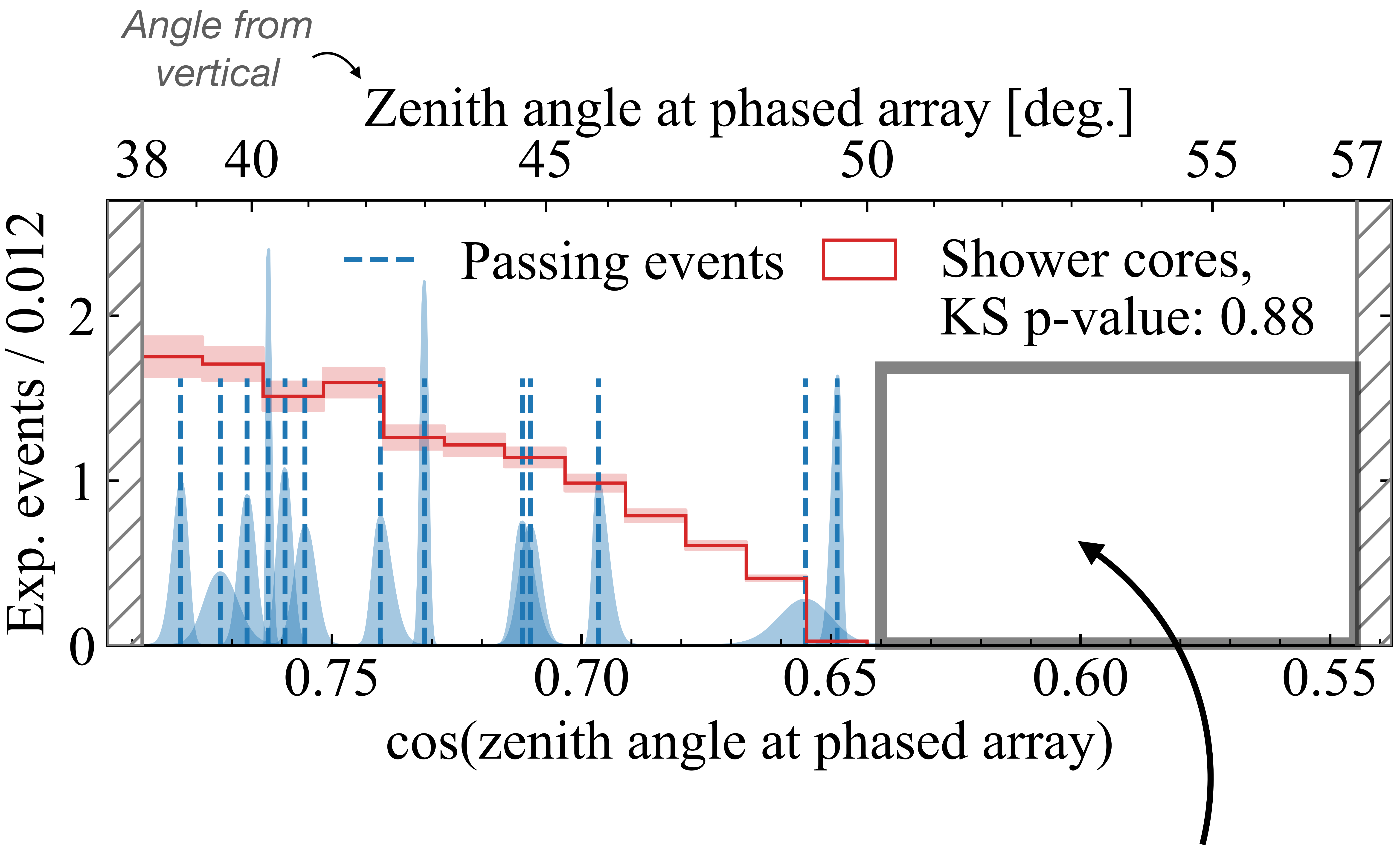
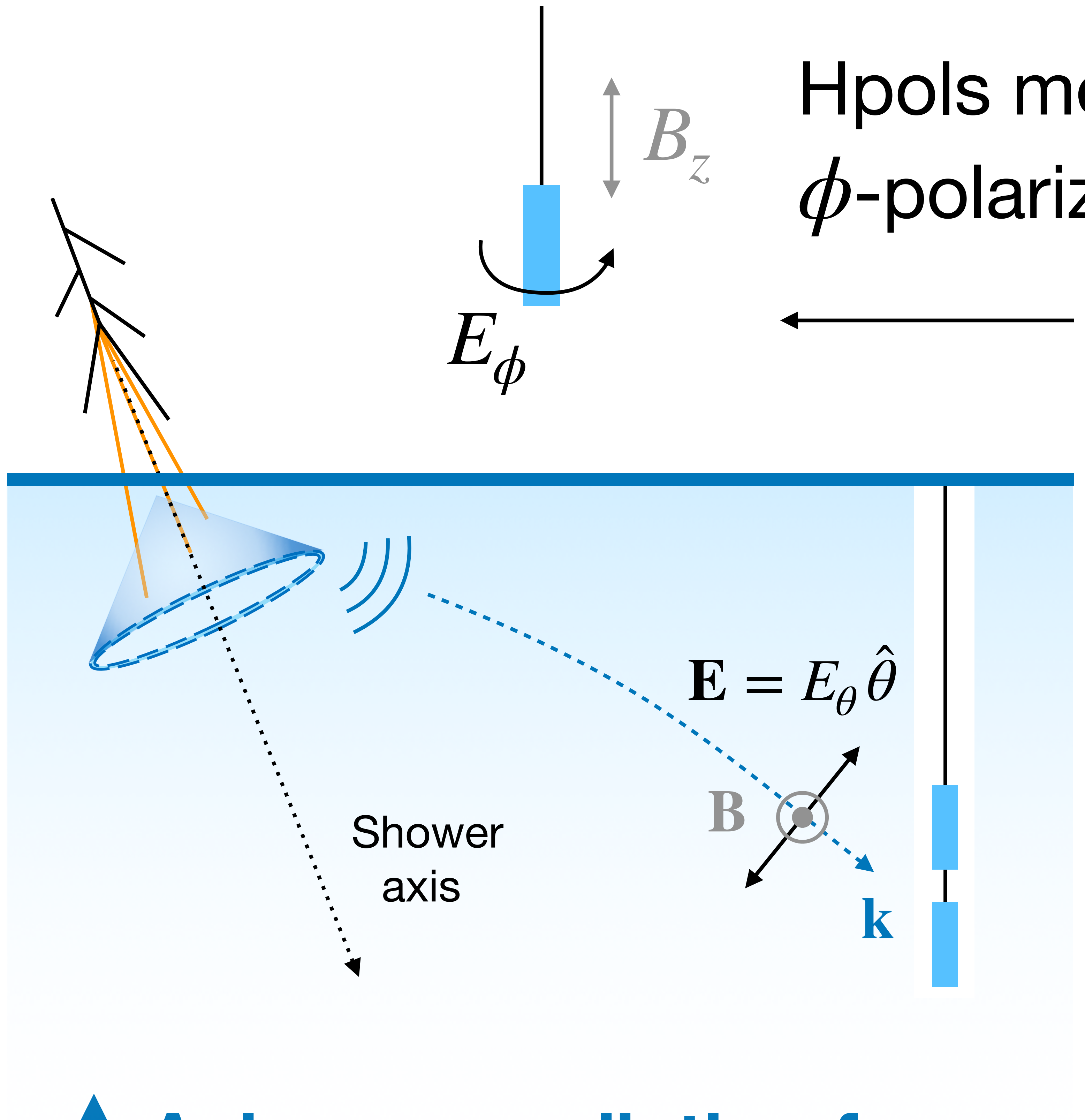
Arrival directions contain information about location and emission pattern of the source.



No events here ⟹ **evidence for emission in the near-surface ice**

Signal polarization



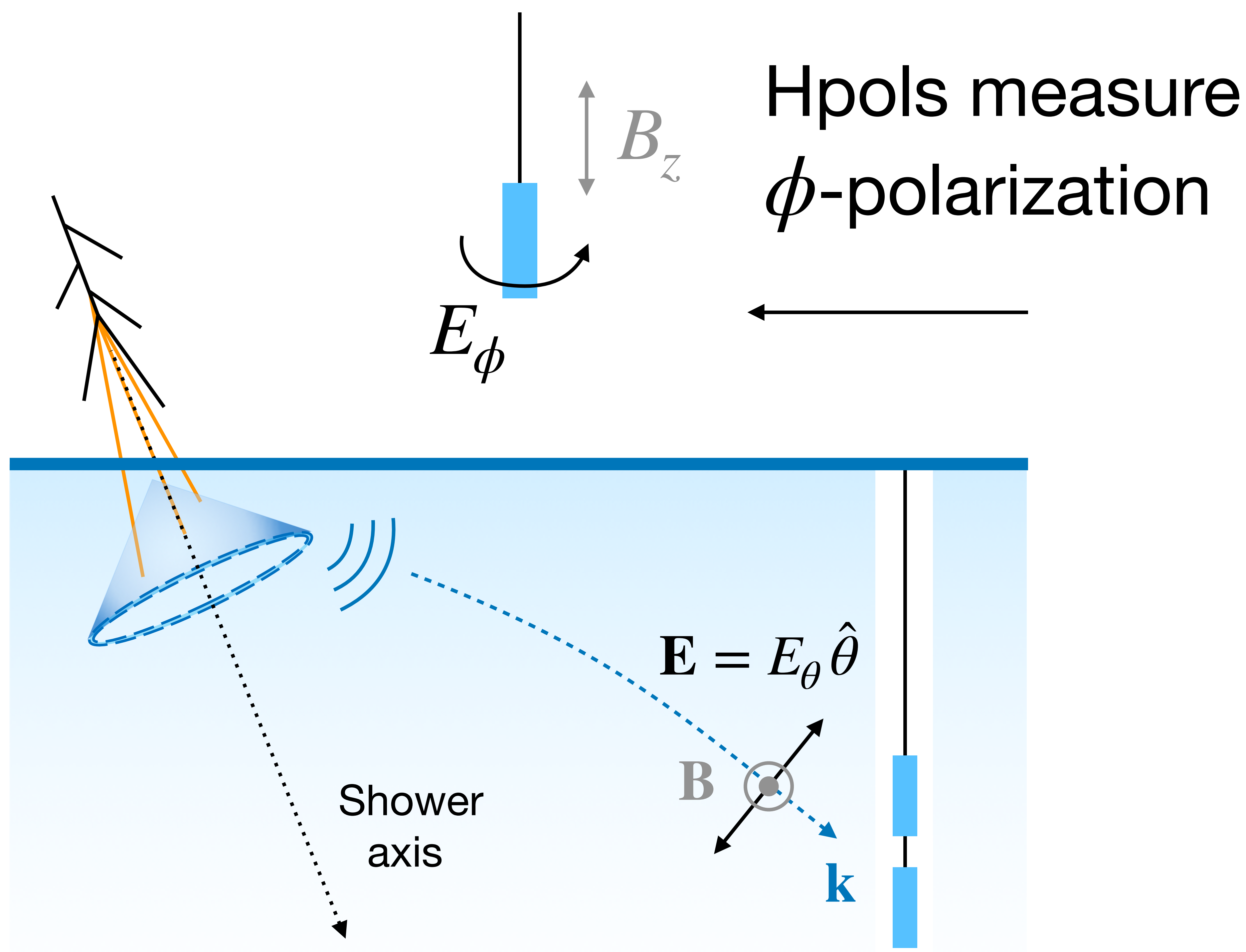
Hpols measure ϕ-polarization

Askaryan radiation from near-vertical showers is almost entirely θ-polarized

Tilting shower "out of the plane" produces E_ϕ

In-air geomagnetic: $\mathbf{v} \times \mathbf{B} \sim E_\phi$ at Pole

Signal polarization



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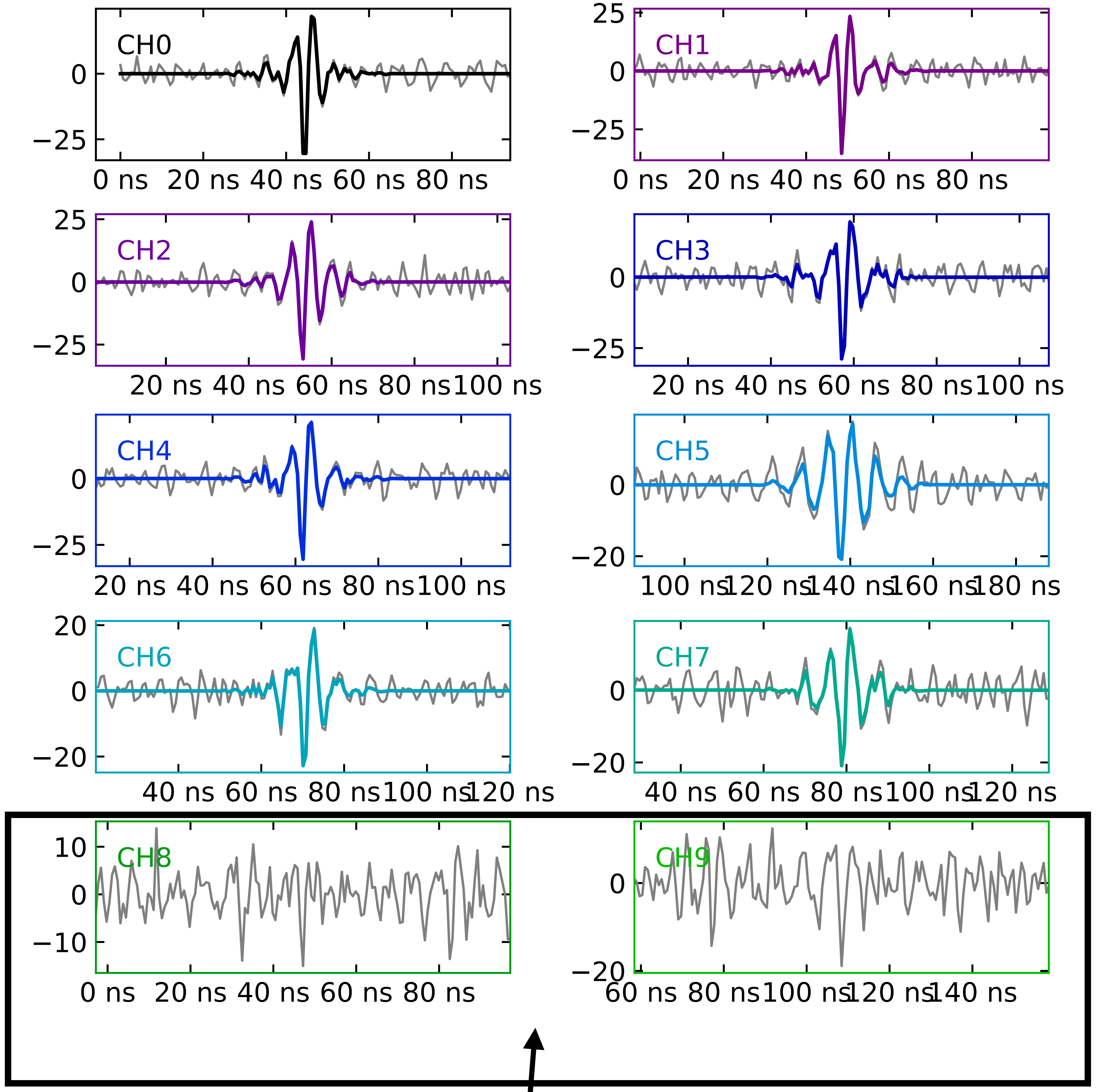
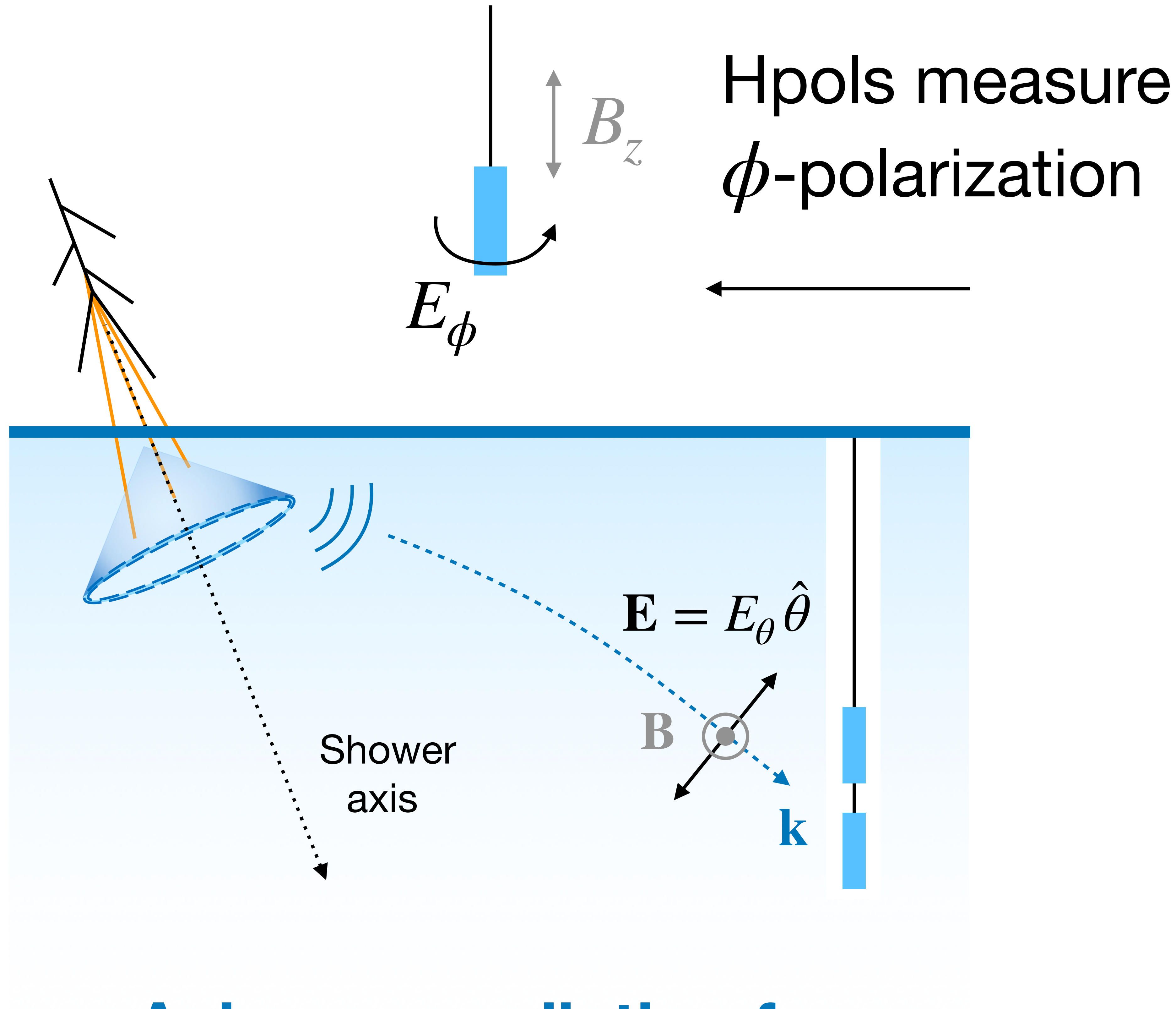


Hpol signal small in most cases

Signal polarization



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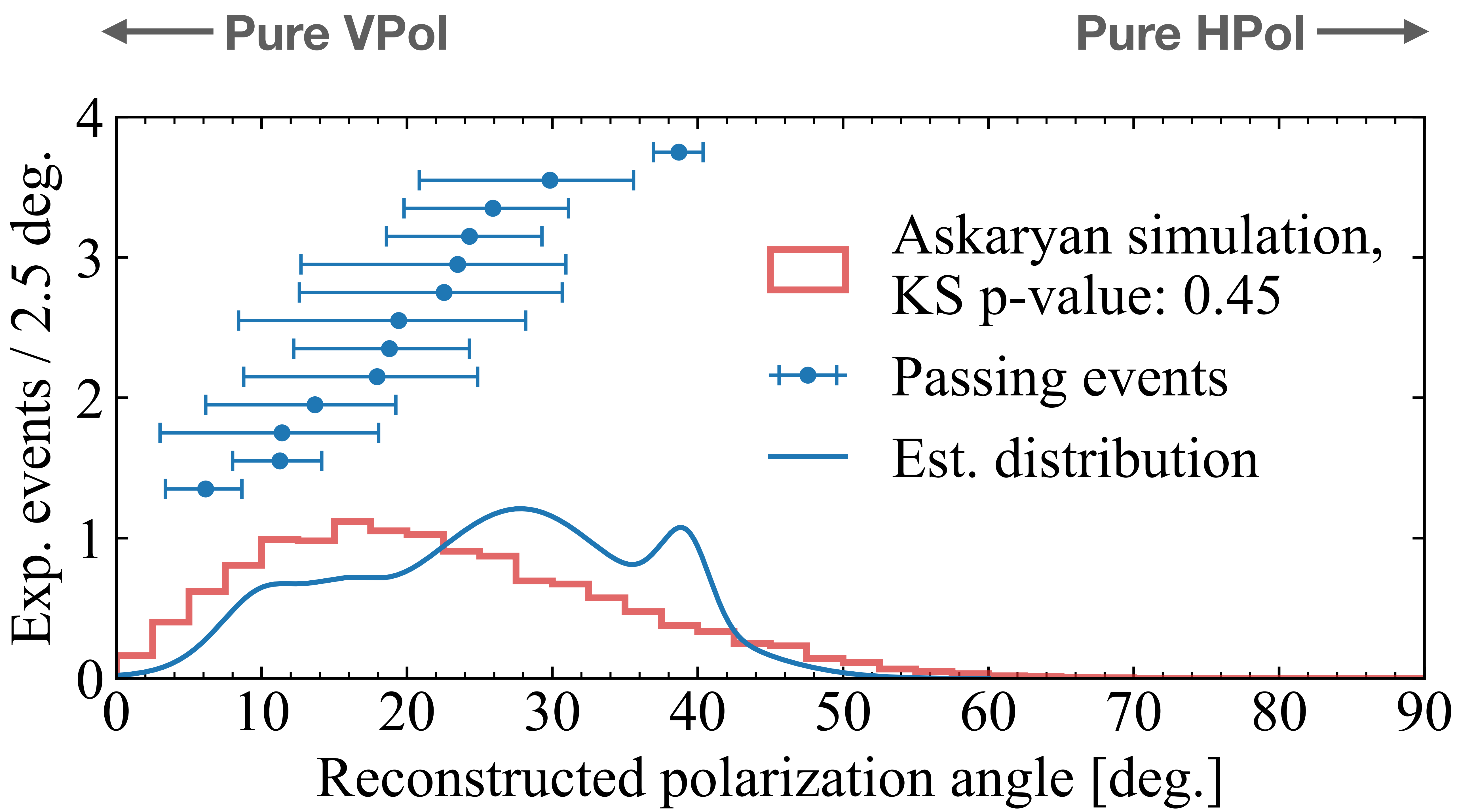

Measured polarization angles are consistent with simulation

Emission pattern

How can we use the emission pattern to learn about the source?

Reconstructing the Cherenkov cone would be ideal; in practice, this requires the use of polarization information and is difficult to do robustly…

But: can discriminate between emitters of different physical size using just the emission pattern

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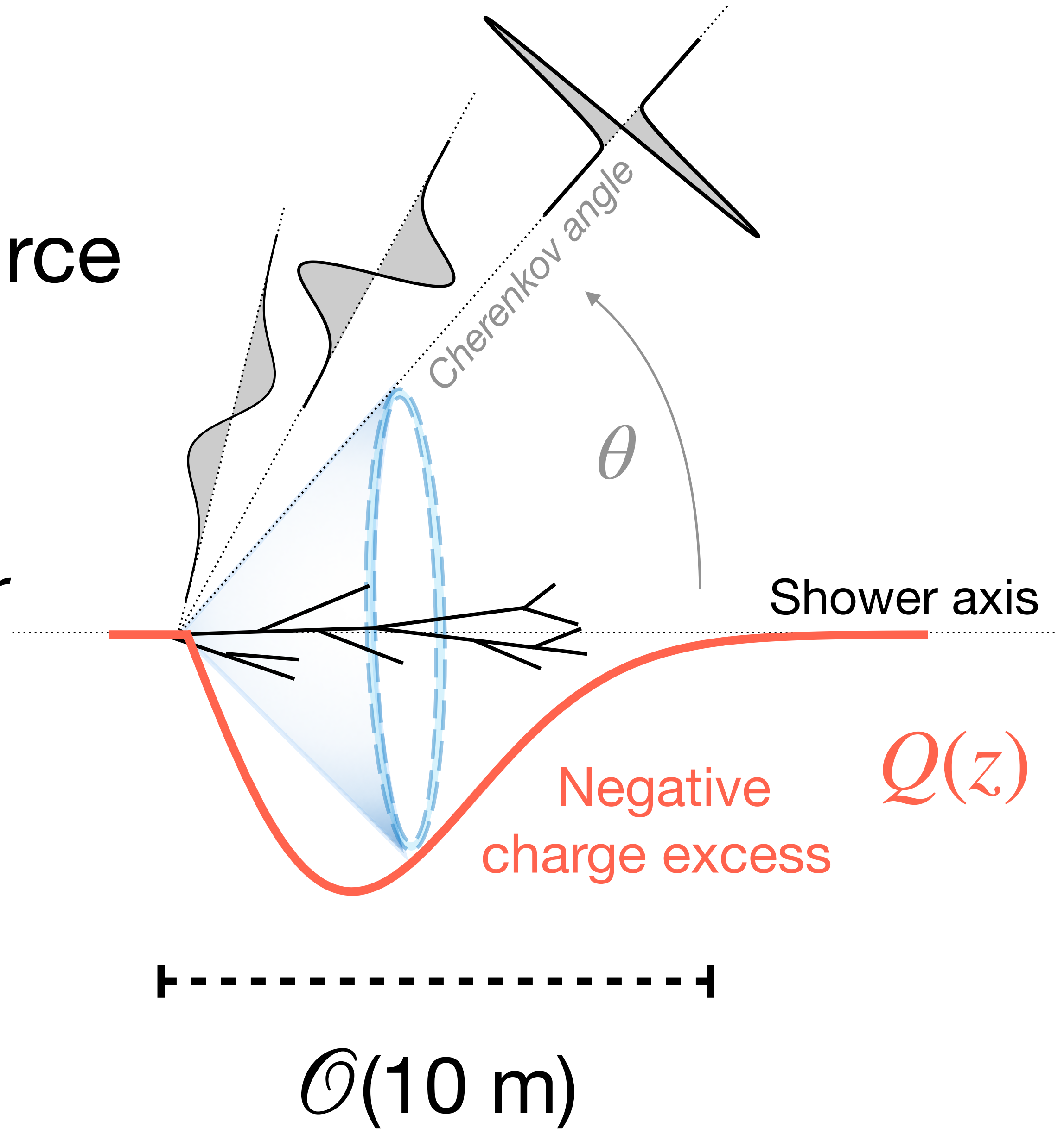
"Extended" source

Askaryan radiation from particle shower



Sharply beamed $\Longrightarrow$ diffraction effects

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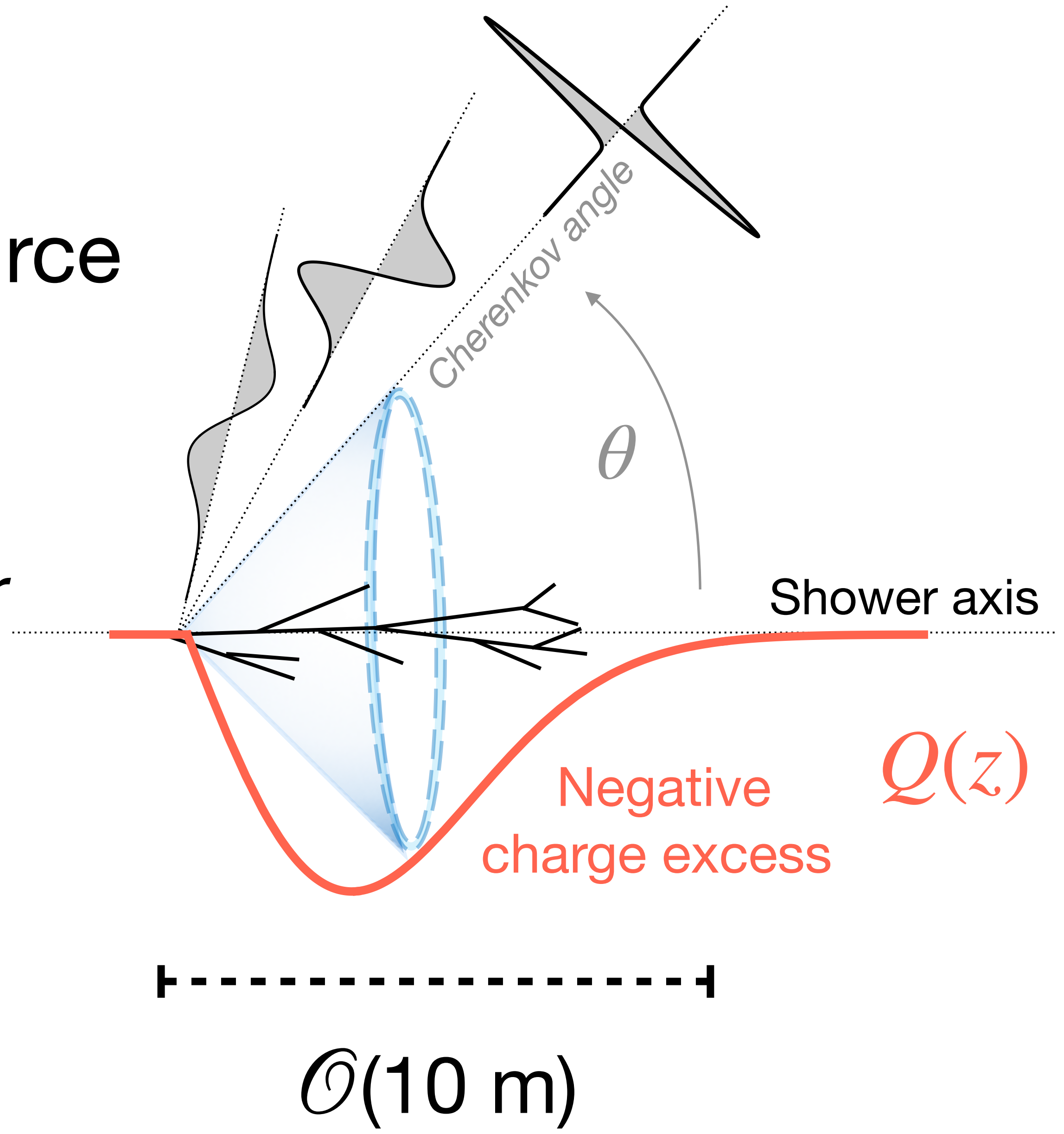
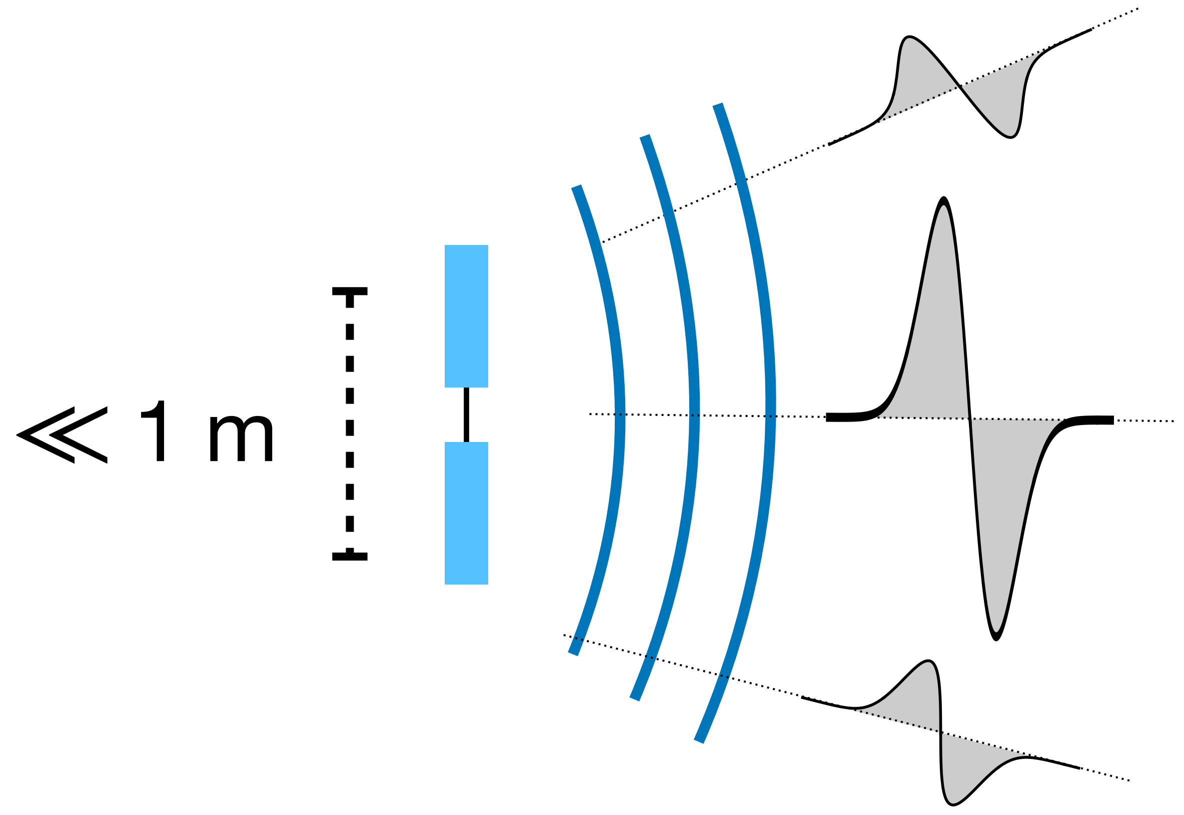




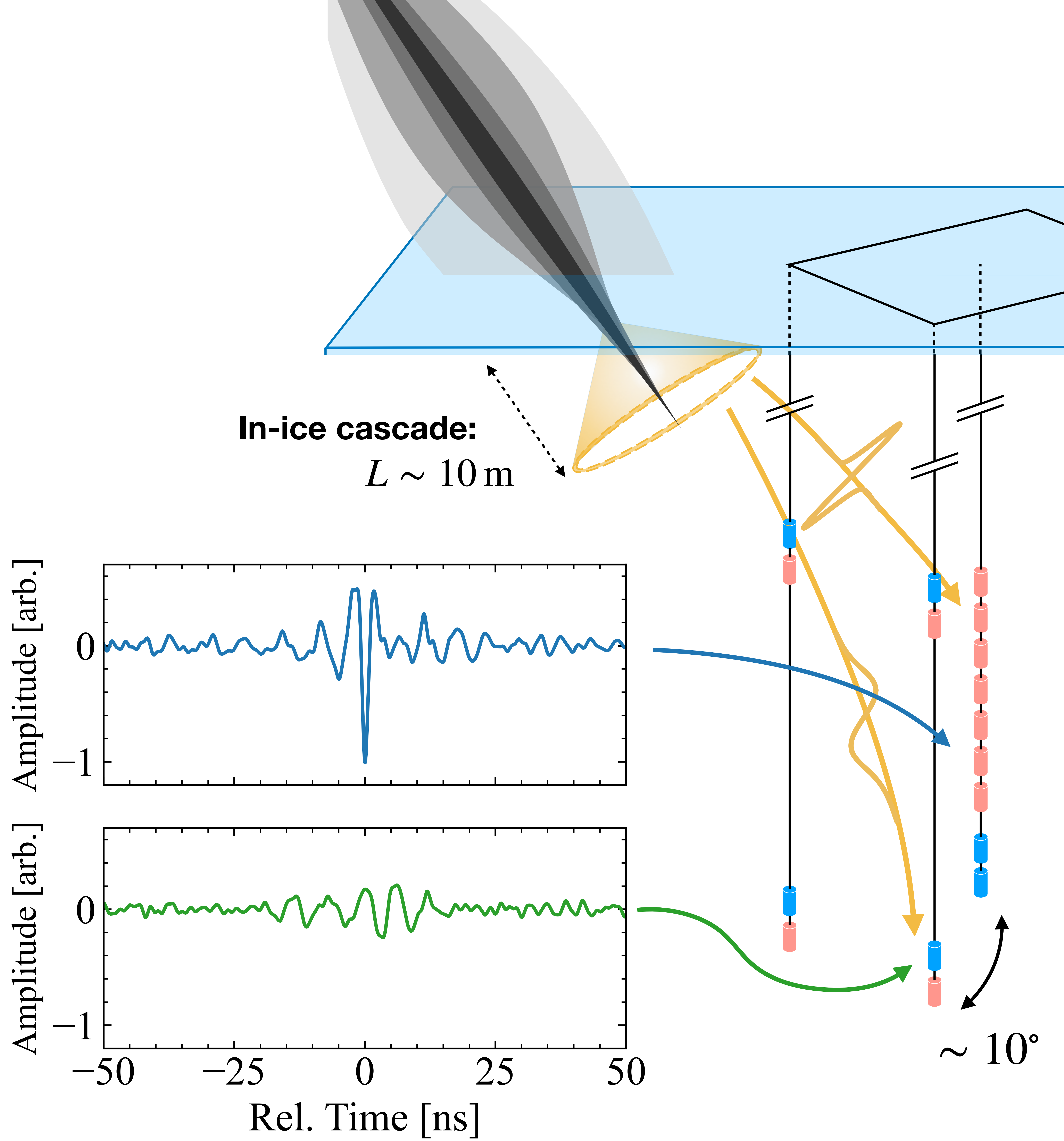
“Point-like” source

Single-mode antenna, spark, transition radiation from particle shower …

Sharply beamed $\Longrightarrow$ diffraction effects

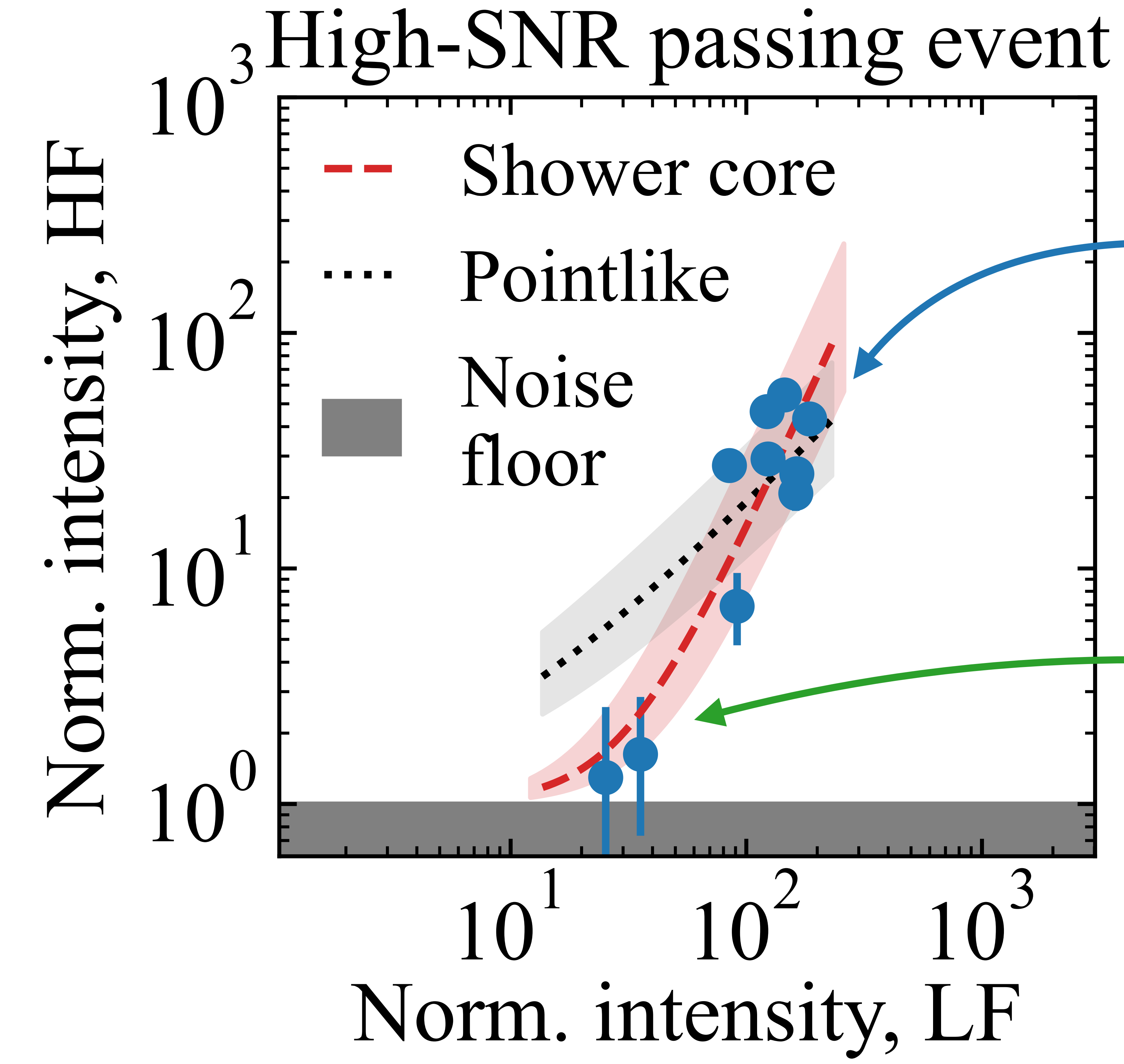
Wide beam pattern $\Longrightarrow$ diffraction effects are small to none

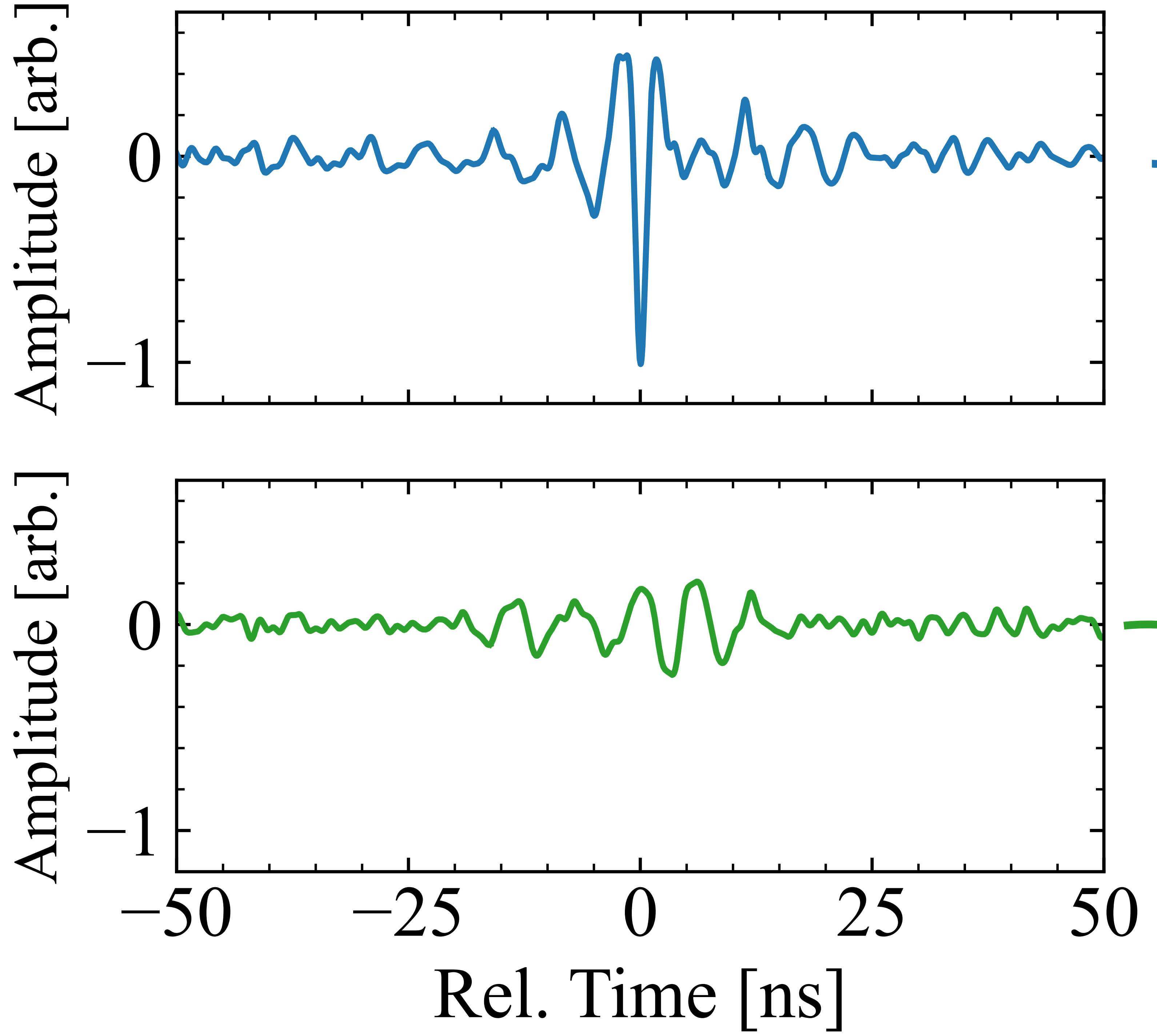
Emission pattern

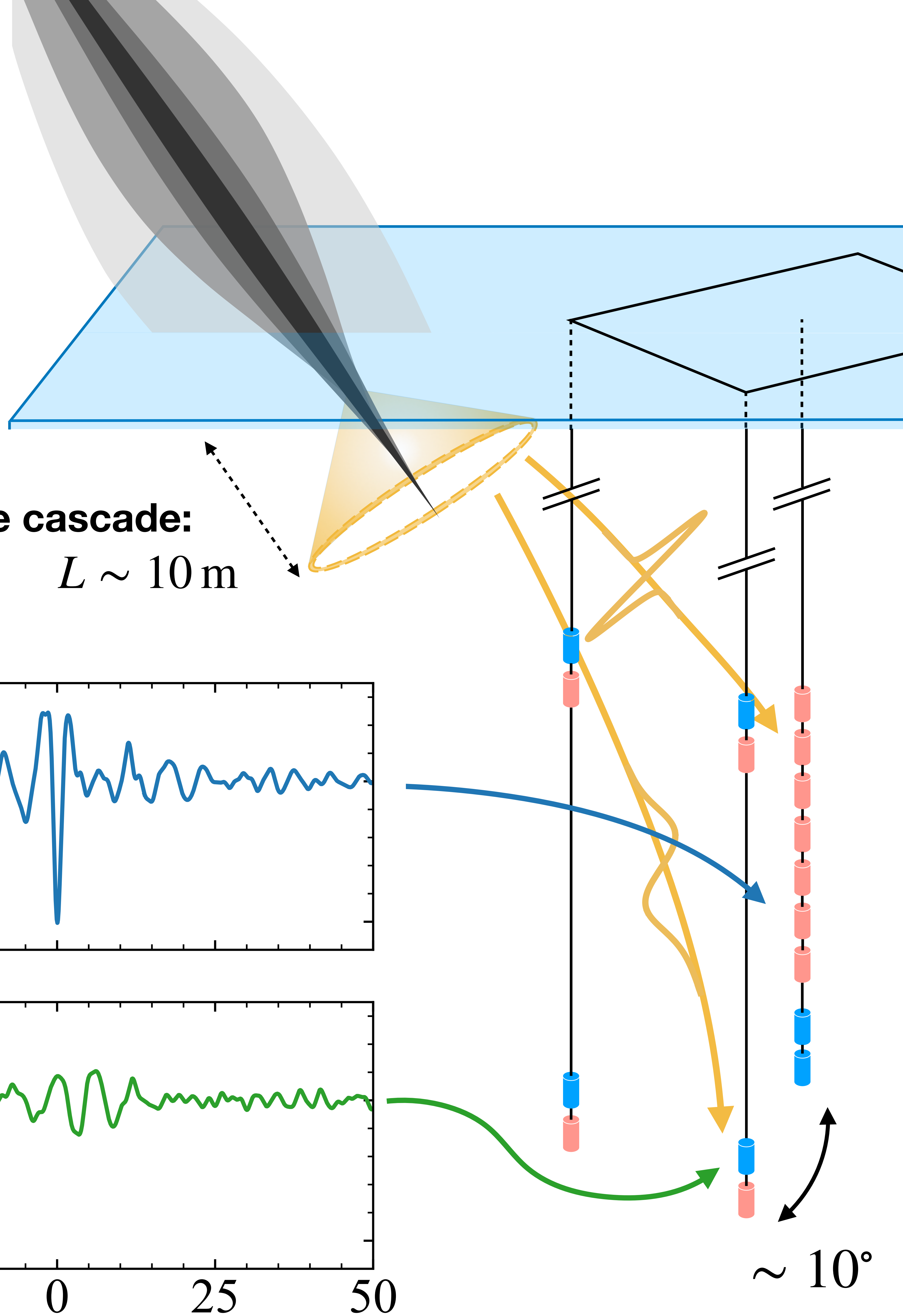


Emission pattern

Better agreement with shower core hypothesis!







Summary and looking forward

The 13 passing events are consistent with the signal shape, arrival directions, polarization, and emission pattern expected for Askaryan radiation from impacting cosmic rays. *For more details see arXiv 2510.21104*

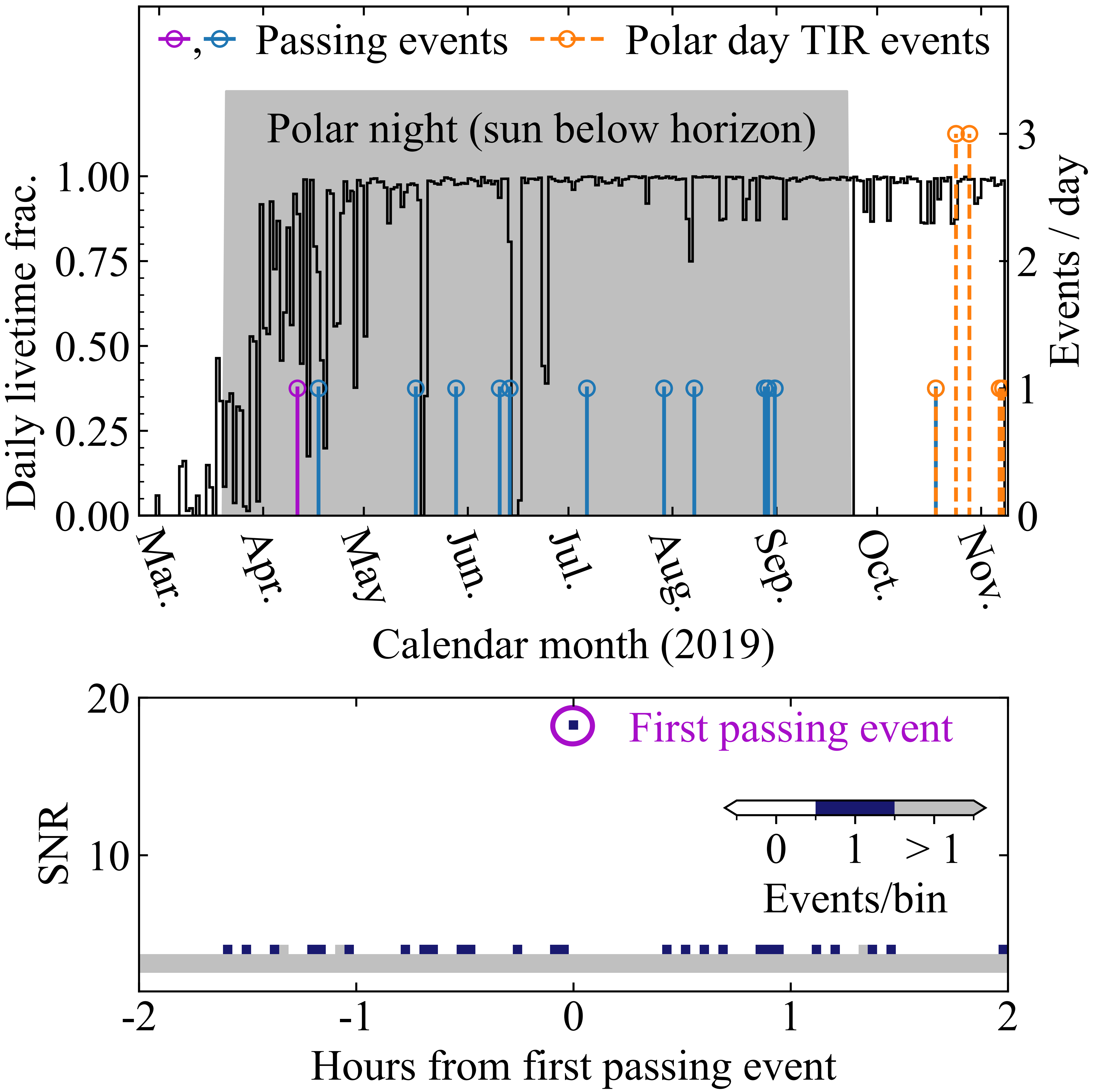
Cosmic rays are useful tools:
-to understand the trigger and analysis efficiencies
-as a testbed for event reconstruction

Cosmic rays are also a background to neutrinos:
If reflected off of layers in the ice, a down-going signal can appear to be up-going

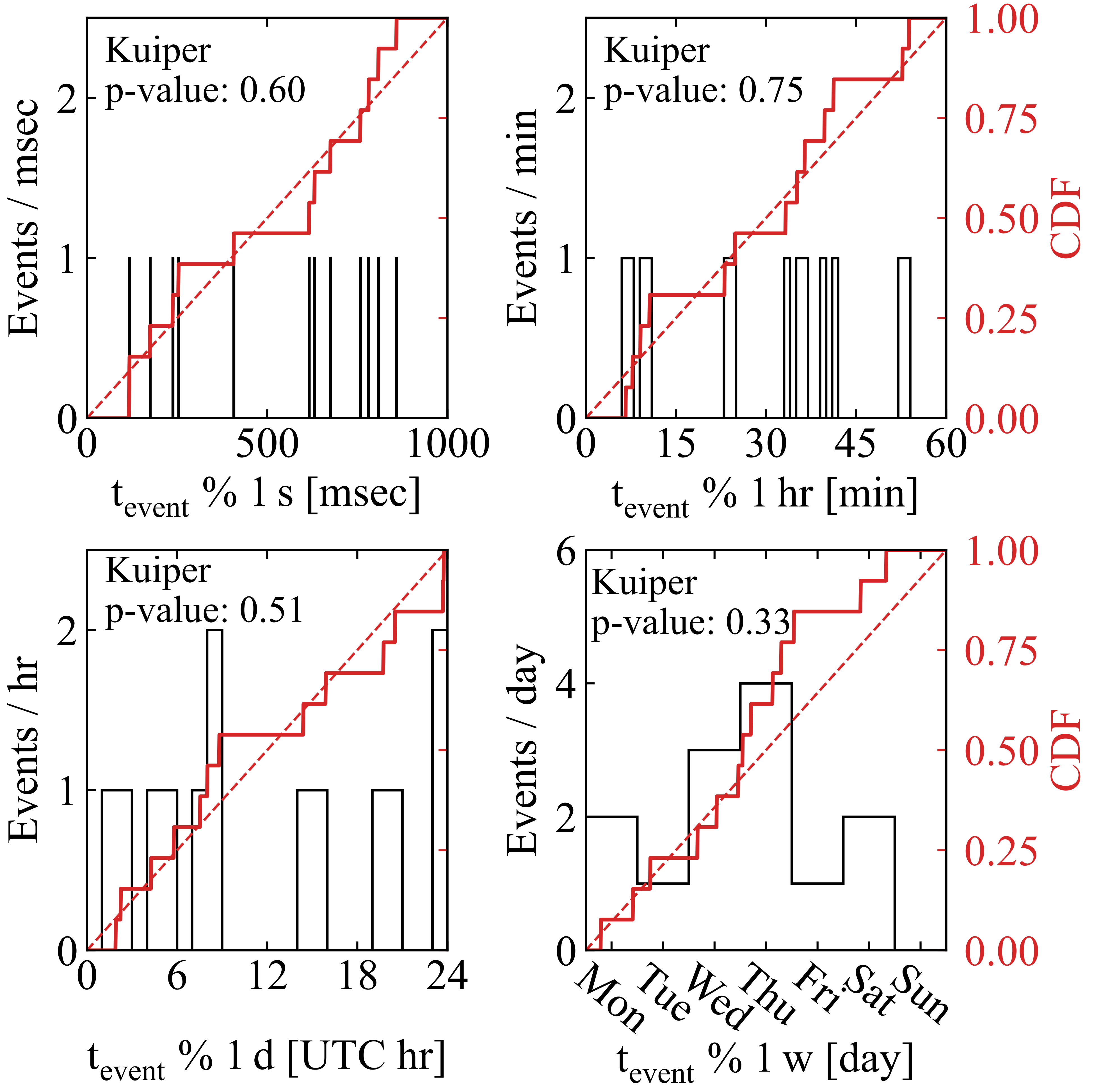
In the future:
-further validate **end-to-end simulation pipelines**
-use for **data-driven studies of the cosmic ray background in a neutrino search**

Backup

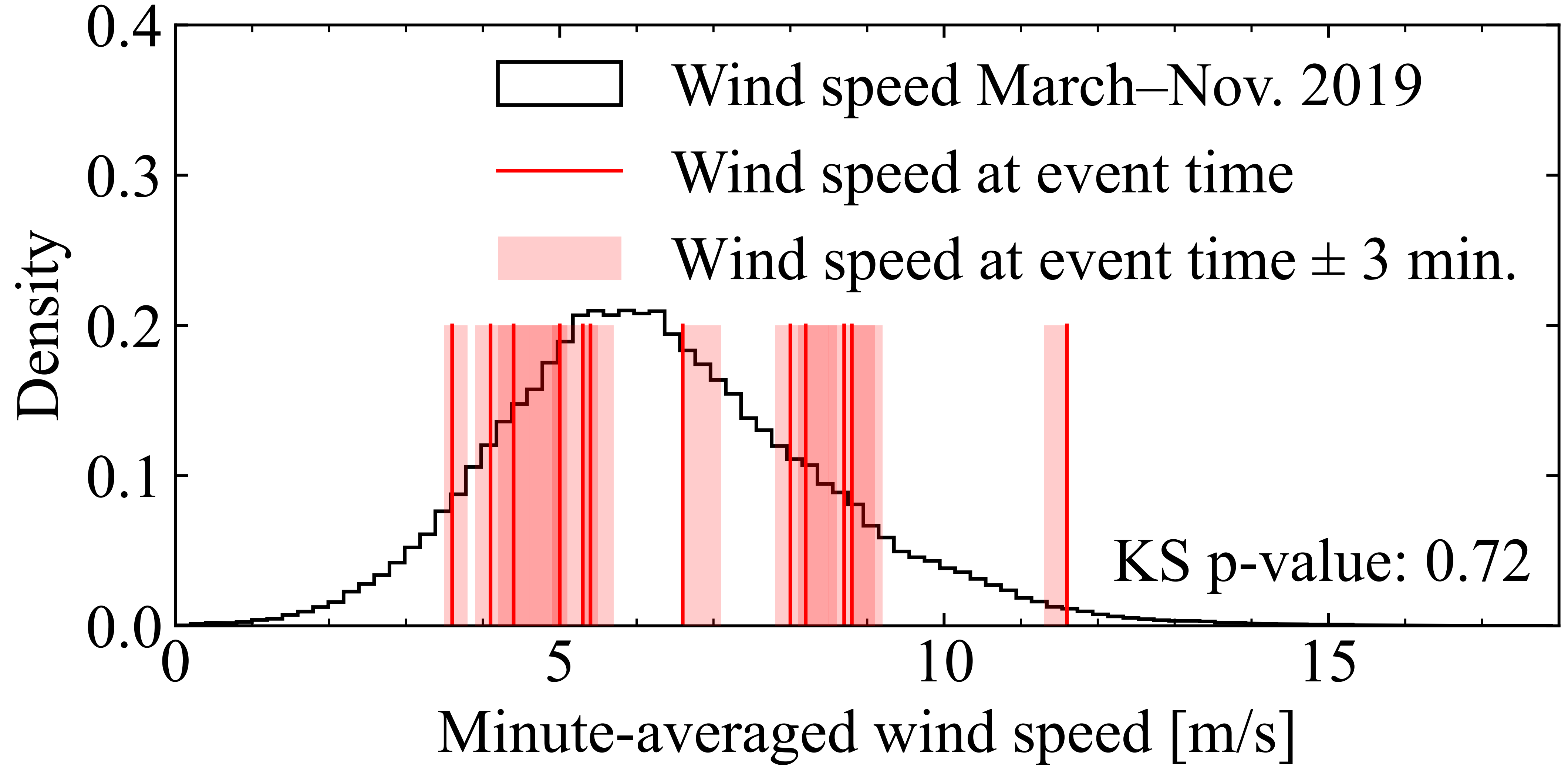
Time isolation



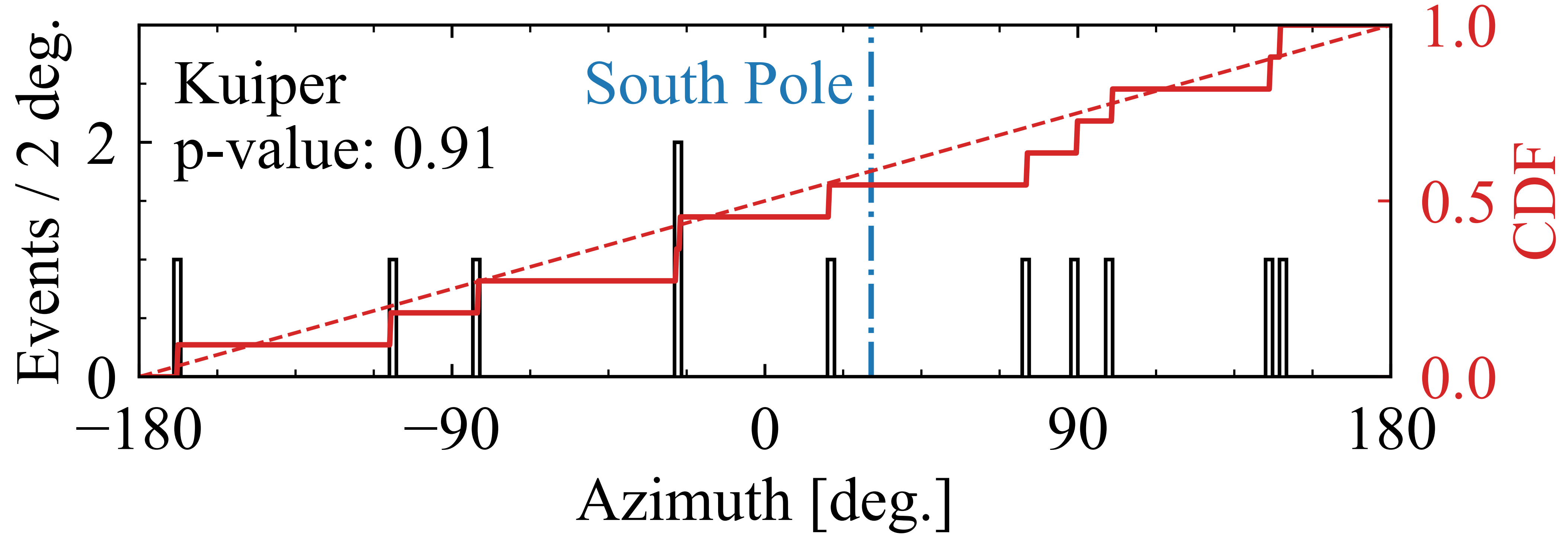
Background checks



No evidence of periodicity on human time scales.



Consistent with wind-speed-independent mechanism



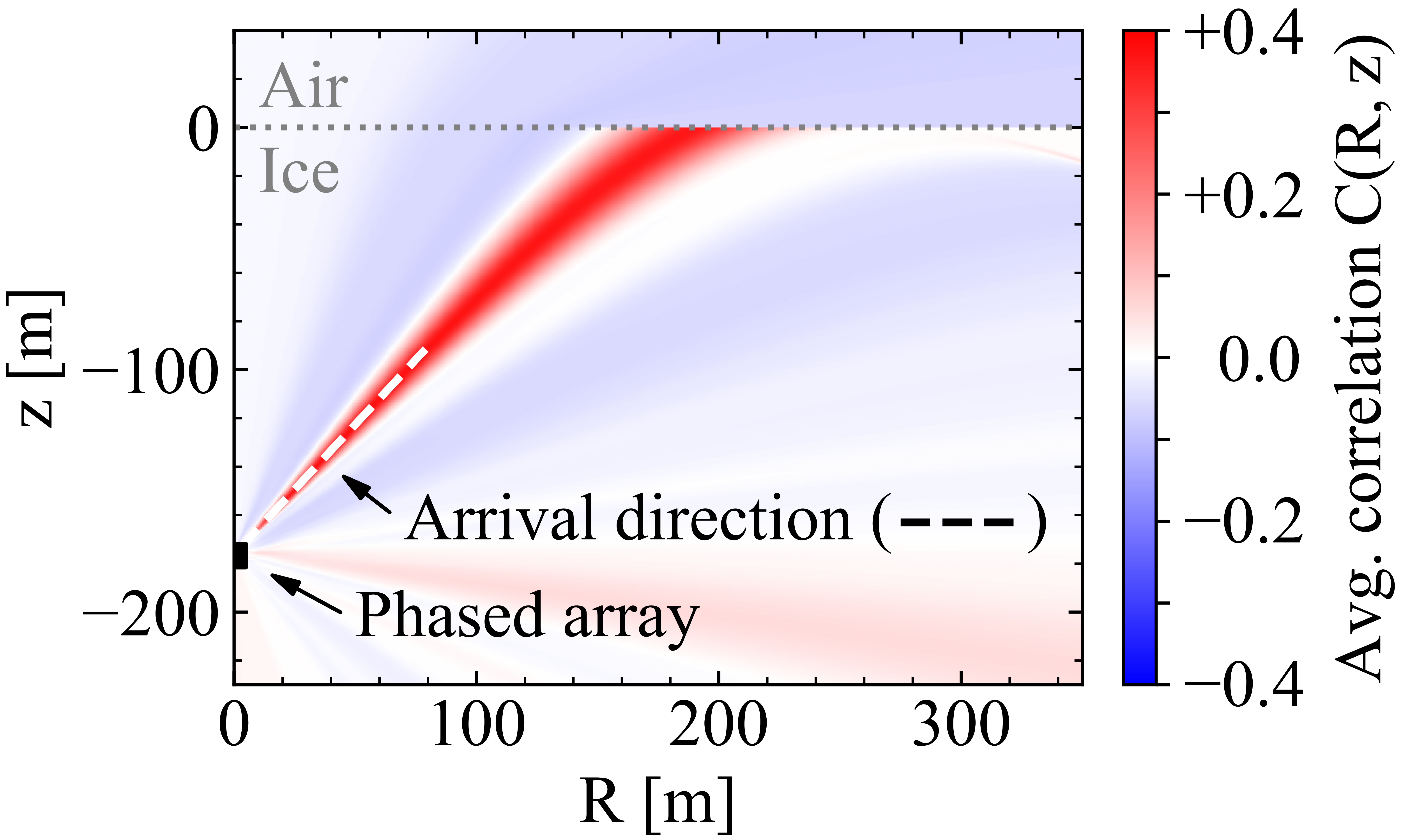
Consistent with uniformity in azimuth.

Reconstruction

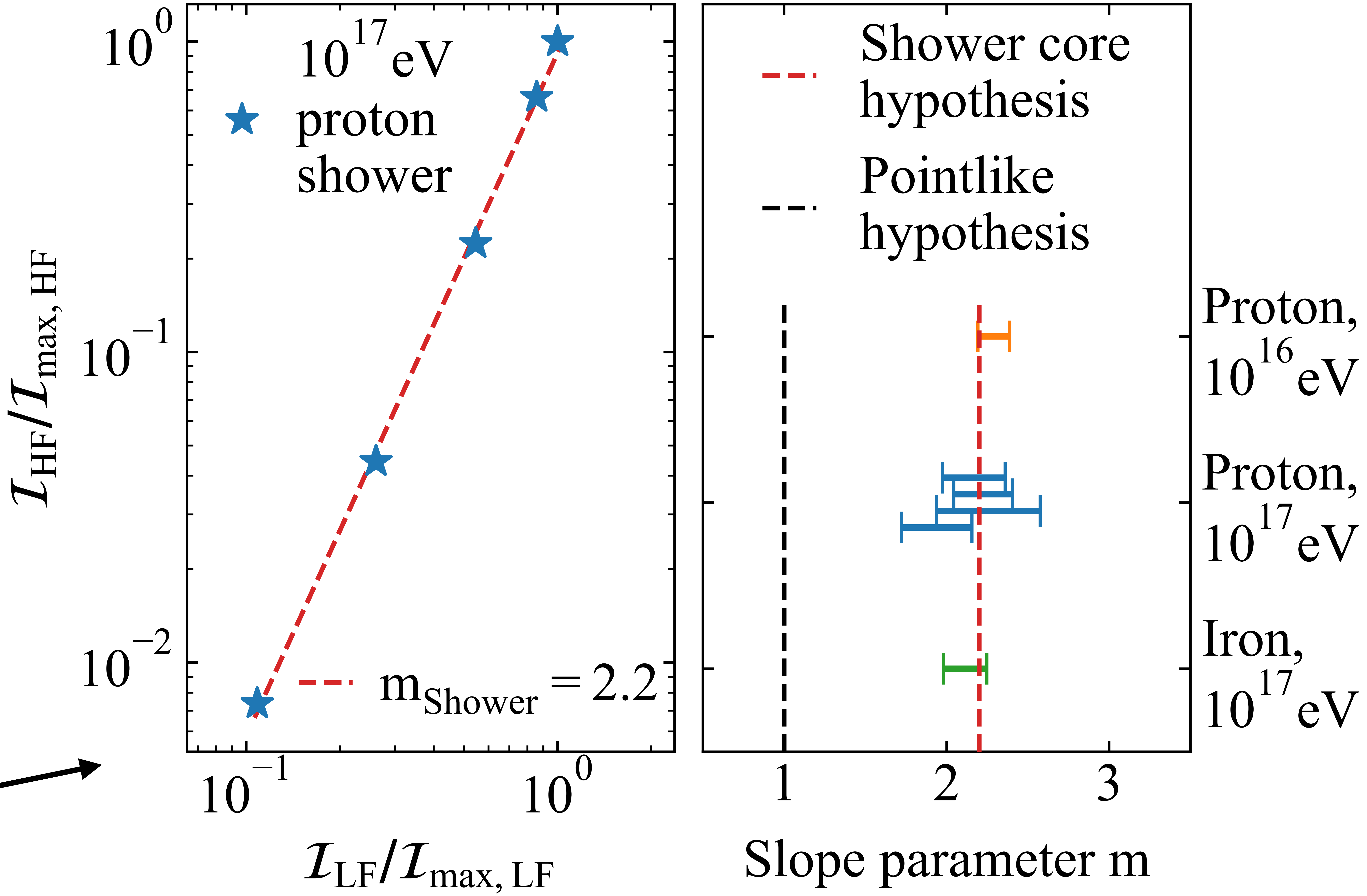
Reconstruct using the Eikonal method to make a travel time map for each antenna (in a 2D slice)

↓

At each point, calculate the average normalized cross-correlation score between each pair of antennas



Simulation



Generated with CORSIKA 8 + Eisvogel

Event rate and background estimate

Event rate and **background estimate** were not discussed here (see paper for more details). Briefly:

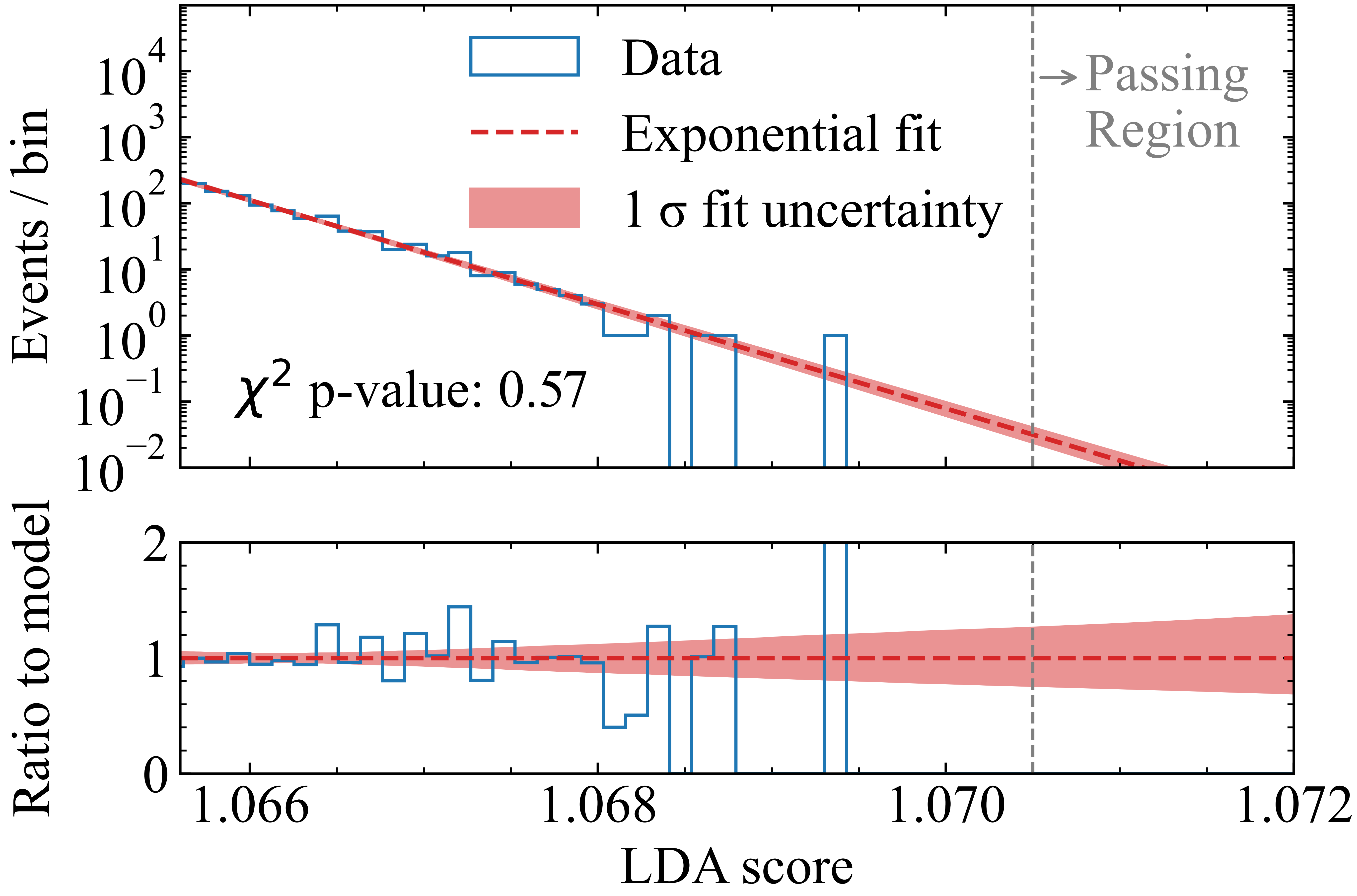
The event rate from our Monte Carlo simulation is calculated to be $8-34\ \mathrm{yr}^{-1}$, compared with an observed rate of $22.9^{+8.2}_{-6.2}\ \mathrm{yr}^{-1}$

The background estimate incorporates three types of backgrounds: thermal noise, distant near-horizon sources, and nearby on-surface sources.

We calculate a discovery significance of 5.1σ

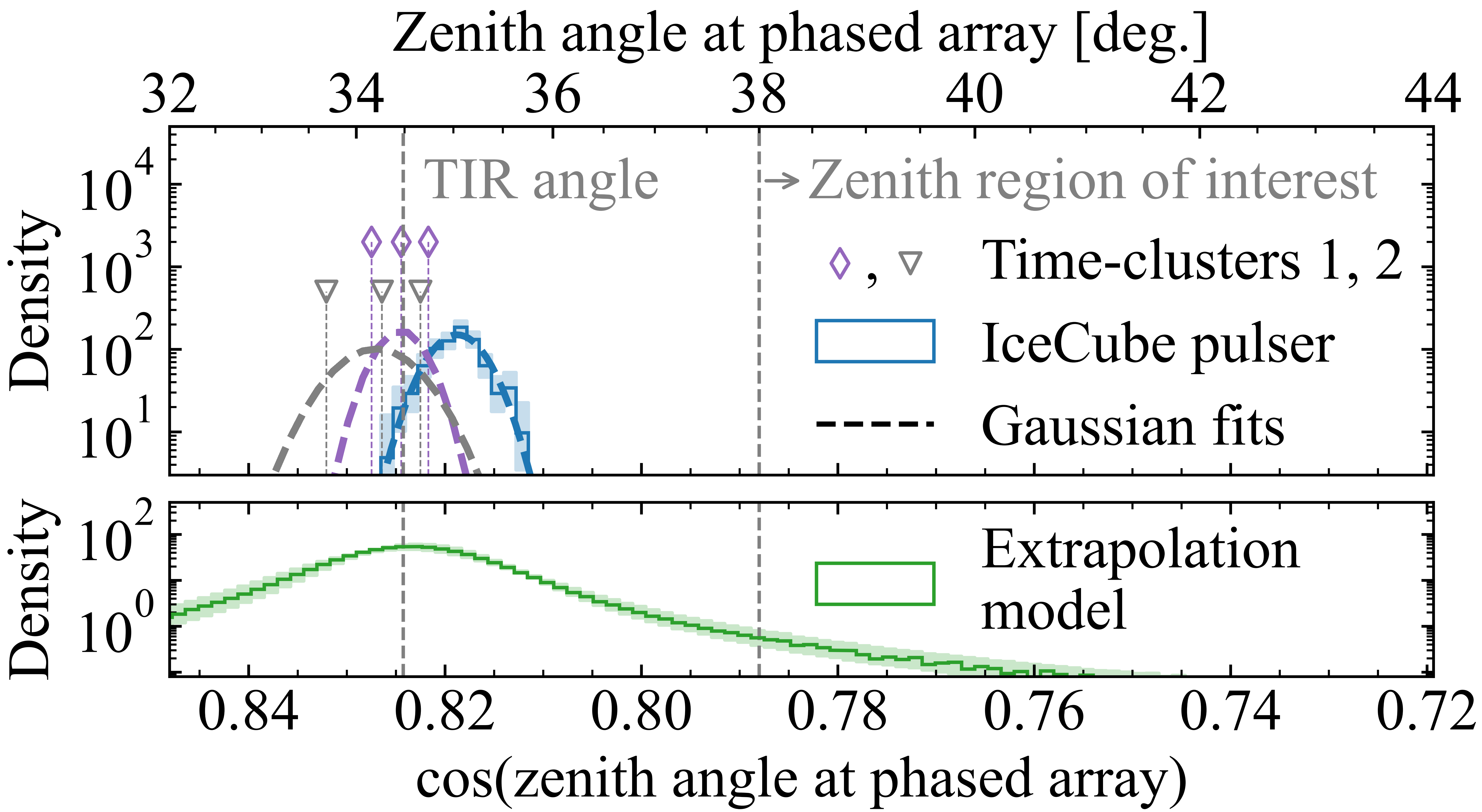
Thermal background

Extrapolate into the signal region by fitting the tail of the thermal noise distribution



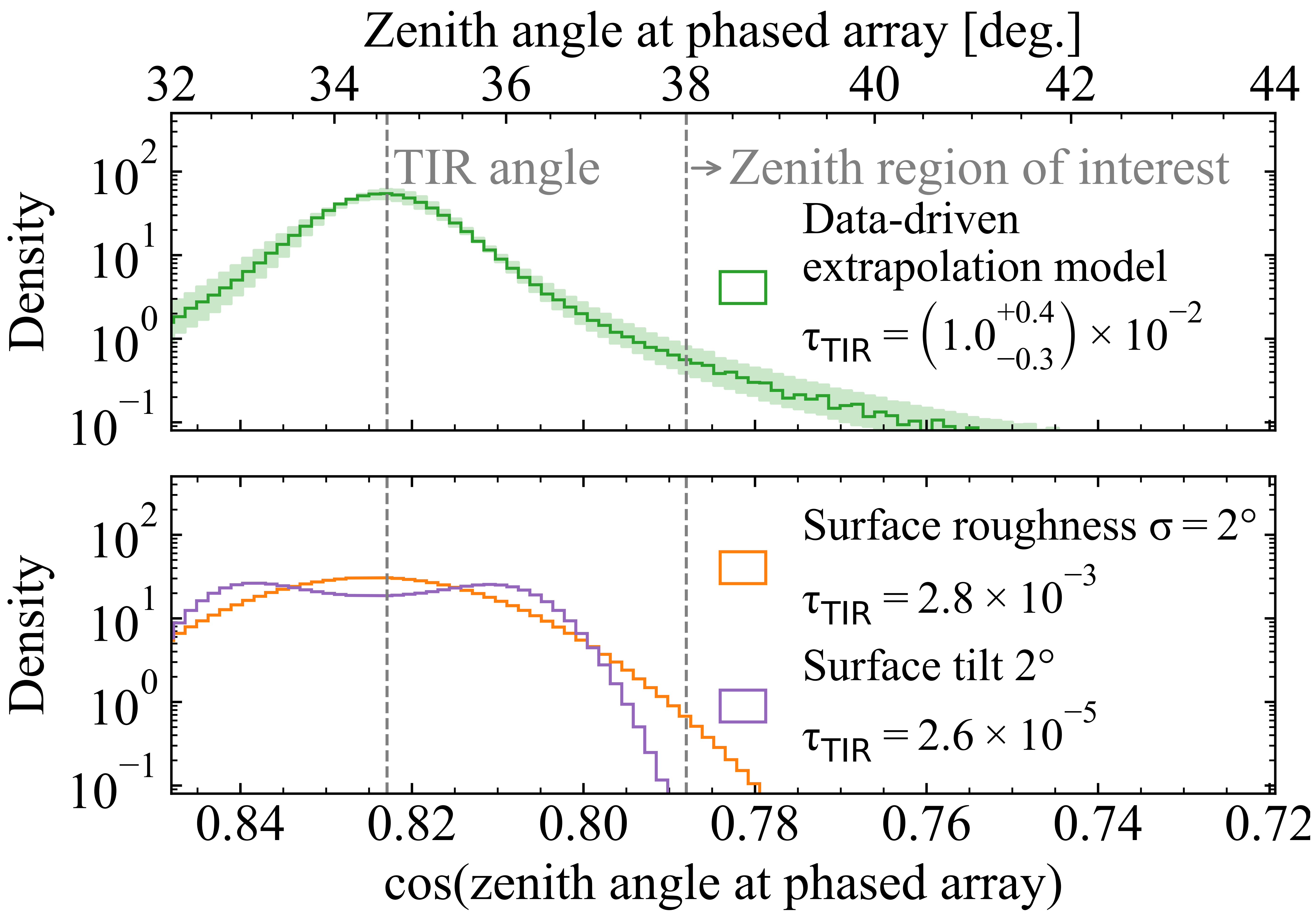
Distant near-horizon background

Extrapolate into the signal region by model the true distribution (in zenith) of near-horizon sources with a fat-tailed distribution



Distant near-horizon background

The chosen extrapolation distribution is conservative when compared with realistic modeling-based distributions



Nearby on-surface background

We use the fact that backgrounds typically cluster in time and extrapolate from clustered to unclustered using a control zenith region centered on the TIR angle, where we expect increased anthropogenic noise.

We also use the fact that the signals are much more impulsive than even the most impulsive observed anthropogenic sources (see top panel)