IceCube Particle Astrophysics Symposium
IPA 2026

Cosmic Ray Observations in BEACON using Coincident Radio and Scintillator Detection

Zachary Martin | UChicago
On Behalf of the BEACON Collaboration



BEACON

Kavli Institute for Cosmological Physics at The University of Chicago

PennState

White Mountain Research Center

USC Universidade de Santiago de Compostela

The Ohio State University

Radboud Universiteit

KU The University of Kansas

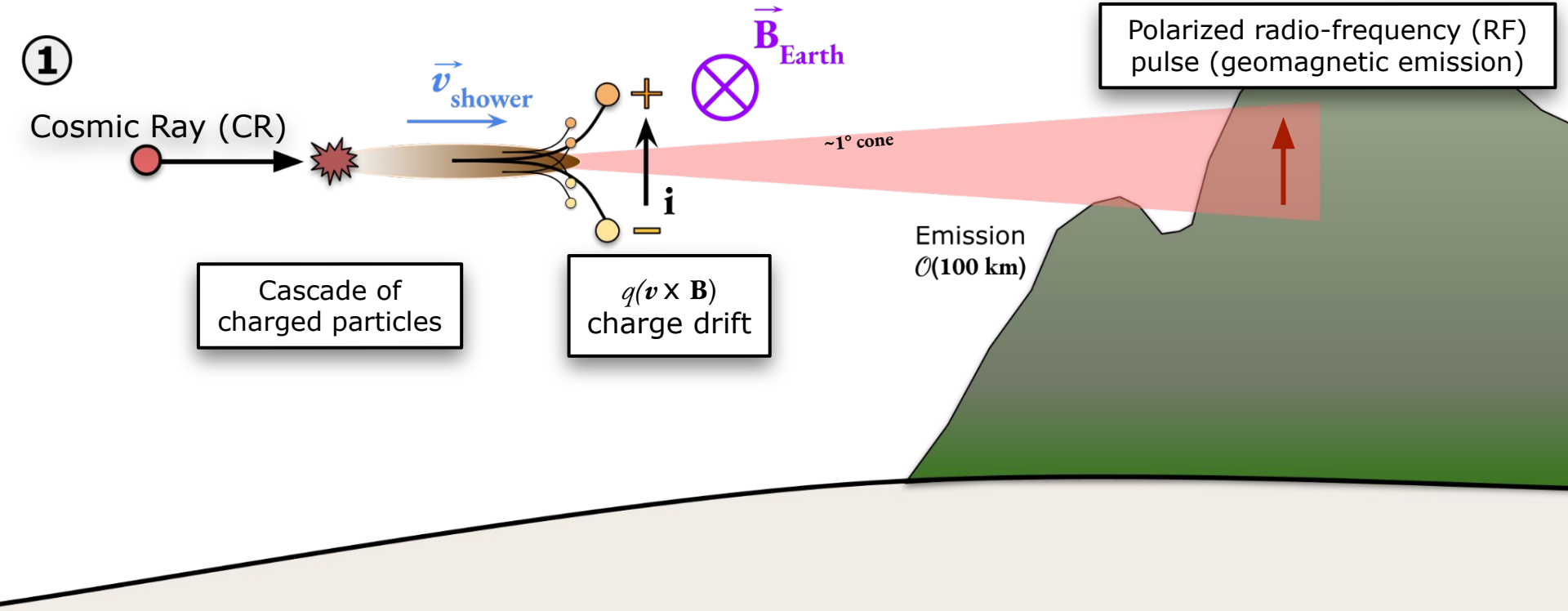
NSF

Overview

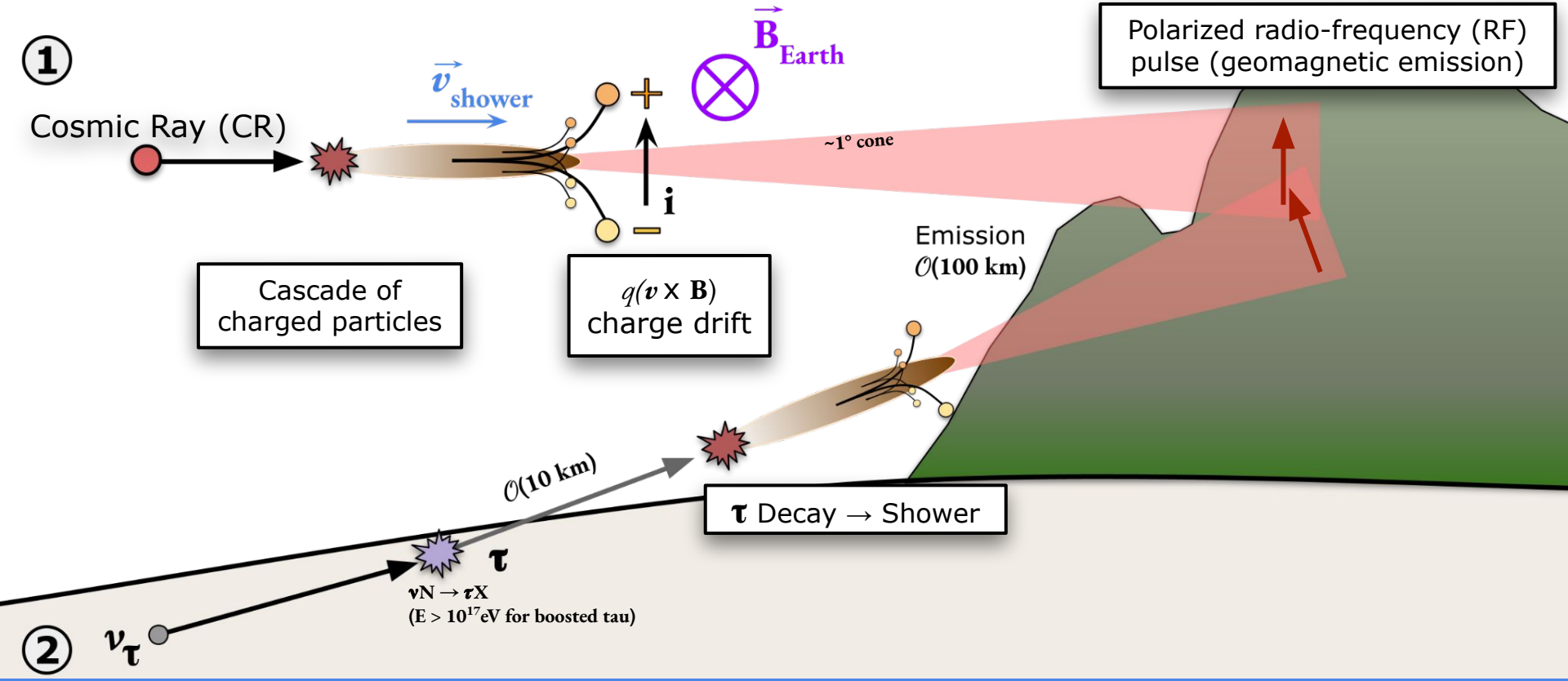
- Radio for Ultrahigh Energy Neutrino Detection
- BEACON Introduction & Prototype
- Cosmic Ray Search Analysis: Challenges & Strategy
- Candidate Cosmic Ray Events & Polarization Characterization

Zachary Martin | University of Chicago | zacharymartin@uchicago.edu

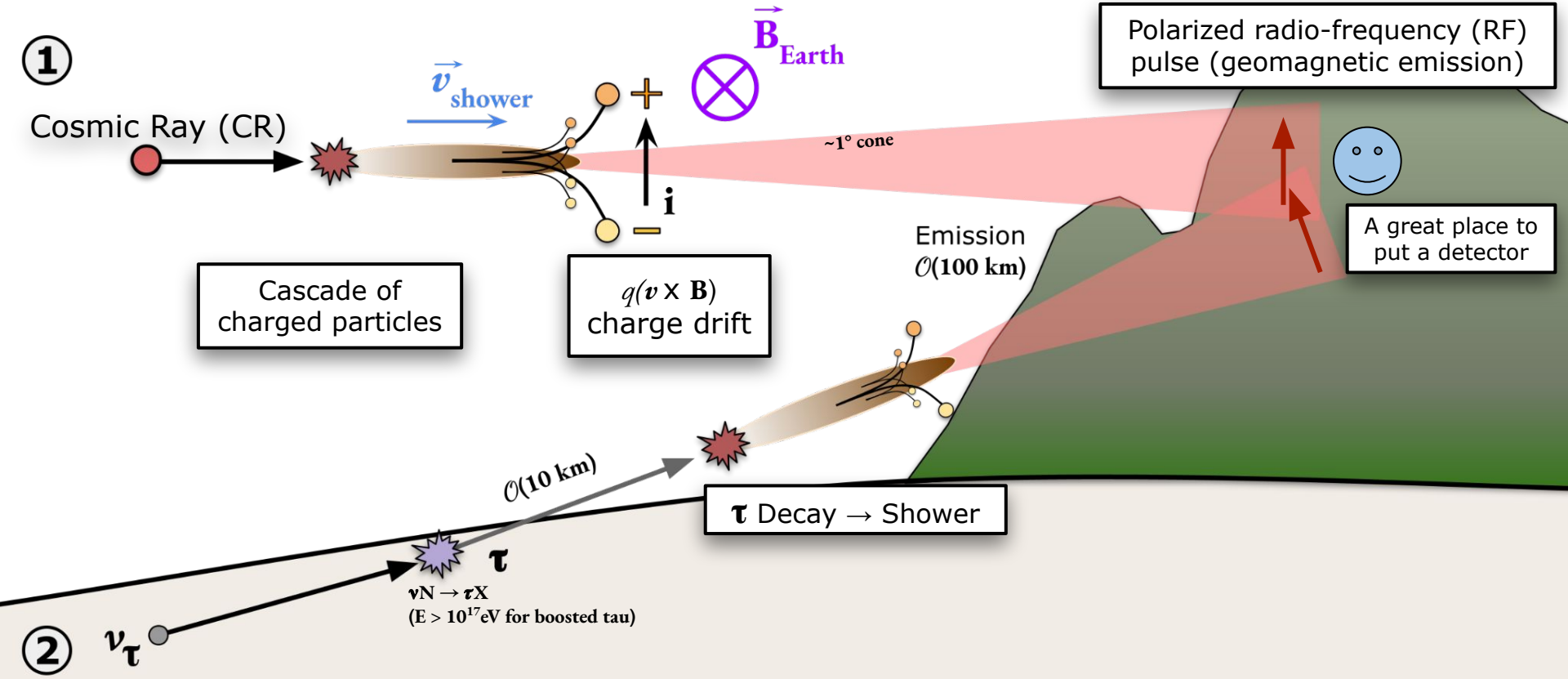
Radio Detection of Tau Neutrinos



Radio Detection of Tau Neutrinos



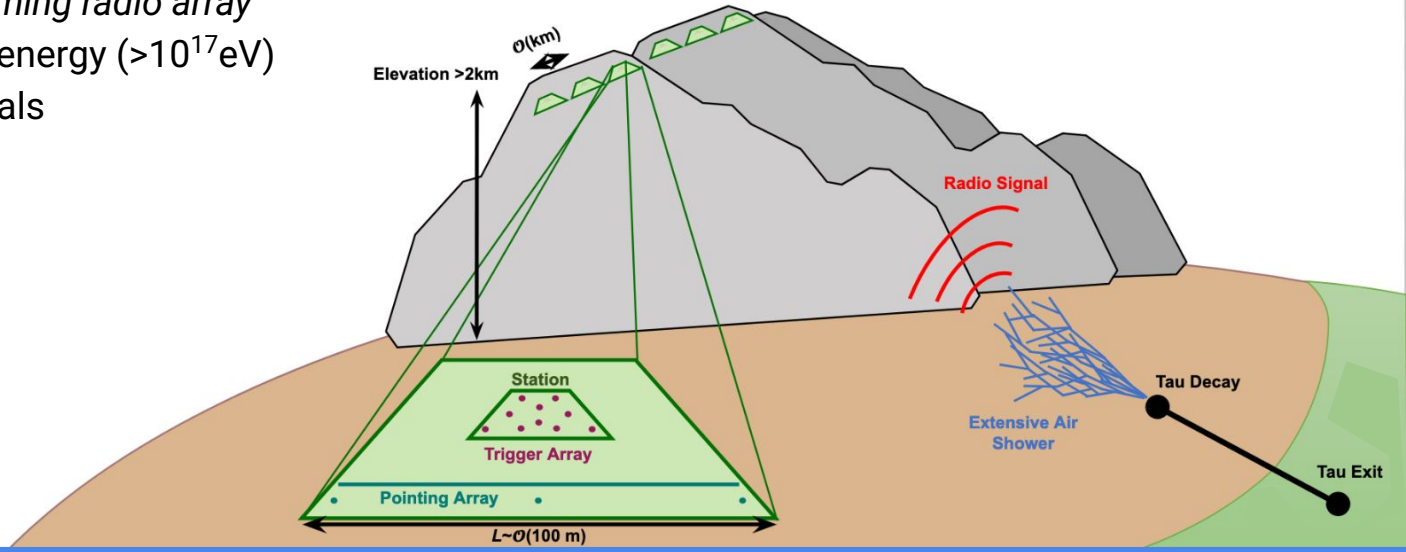
Radio Detection of Tau Neutrinos



BEACON Overview

Beamforming Elevated Array for COsmic Neutrinos (BEACON)

➔ Mountain-top *beamforming radio array* designed for ultrahigh energy (>10^{17}eV) tau-neutrino radio signals

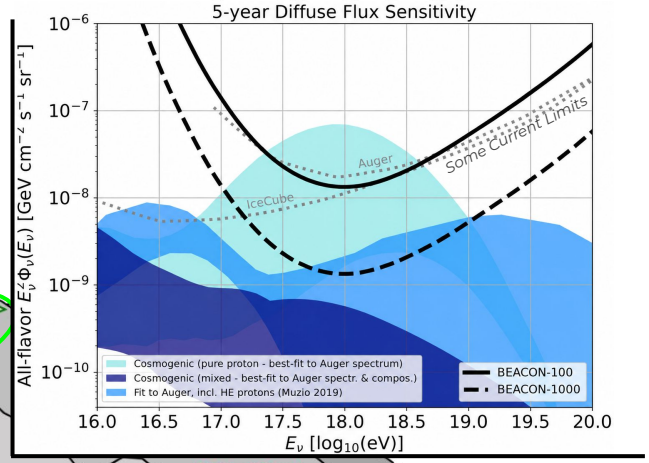


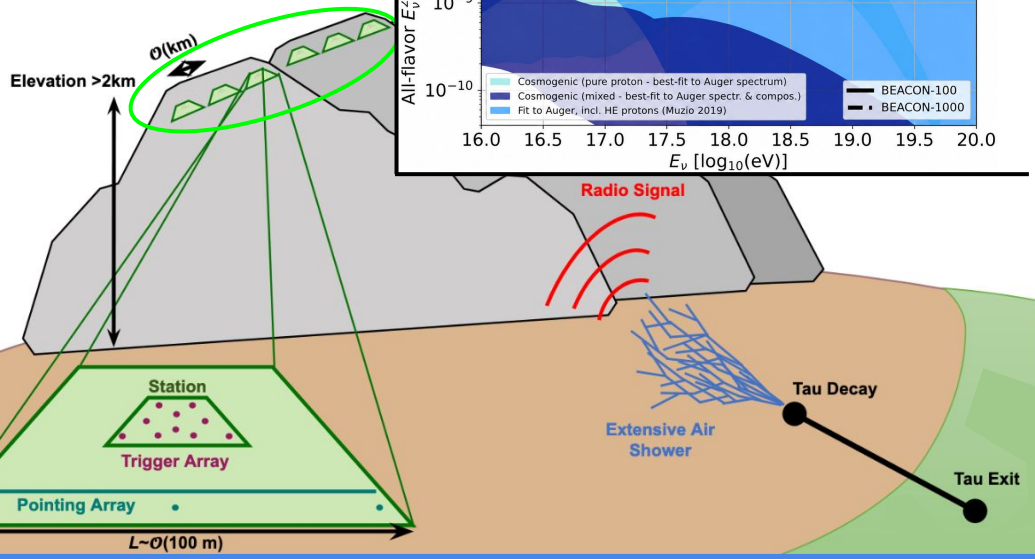
BEACON Overview

Beamforming Elevated Array for COsmic Neutrinos (BEACON)

- ➔ Mountain-top *beamforming radio array* designed for ultrahigh energy (>10^{17}eV) tau-neutrino radio signals
- ➔ Full scale 100 – 1,000 stations (~10 antennas per station)
  - ◆ Competitive sensitivity to diffuse ν flux and t < 1 day point sources

Andrew Zeolla, et al. "Sensitivity of BEACON to Ultra-High Energy Diffuse and Transient Neutrinos" arXiv:2504.13271 (Adapted)





Future Elevated Array: HERON (BEACON + GRAND)

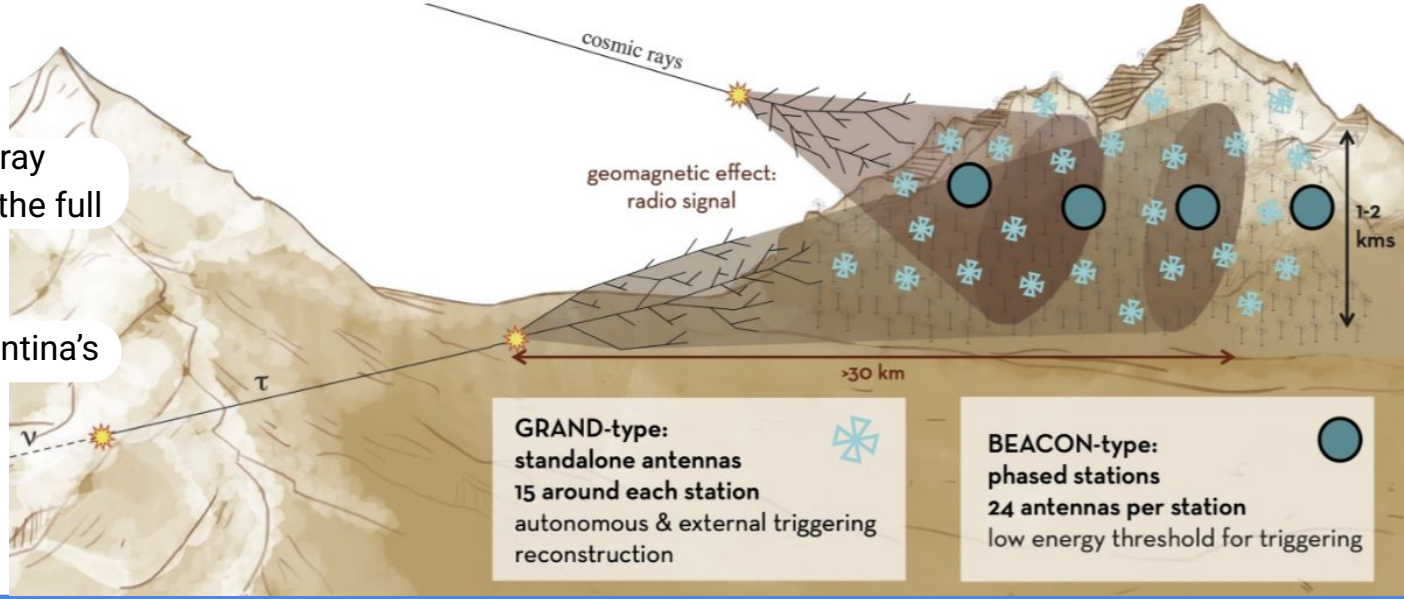
Beamforming Elevated Array for COsmic Neutrinos (BEACON)

Funded hybrid observatory combining the concepts of BEACON and the Giant Radio Array for Neutrino Detection (GRAND):

The Hybrid Elevated Radio Observatory for Neutrinos (HERON)

arXiv:2507.04382

- ➔ Extends beamforming array and sparse array across the full mountain range
- ➔ Installation plans in Argentina's San Juan province

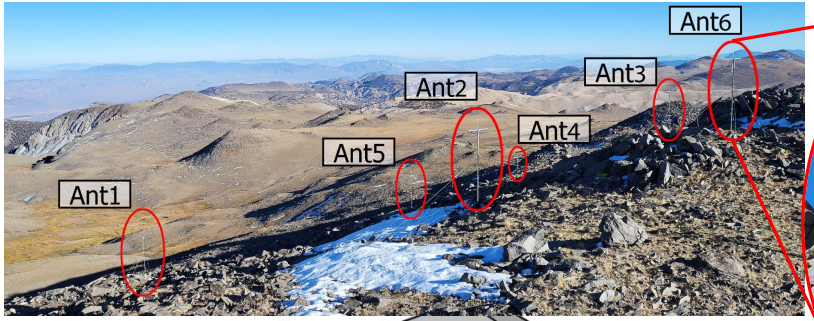


BEACON Prototype Overview

BEACON Prototype

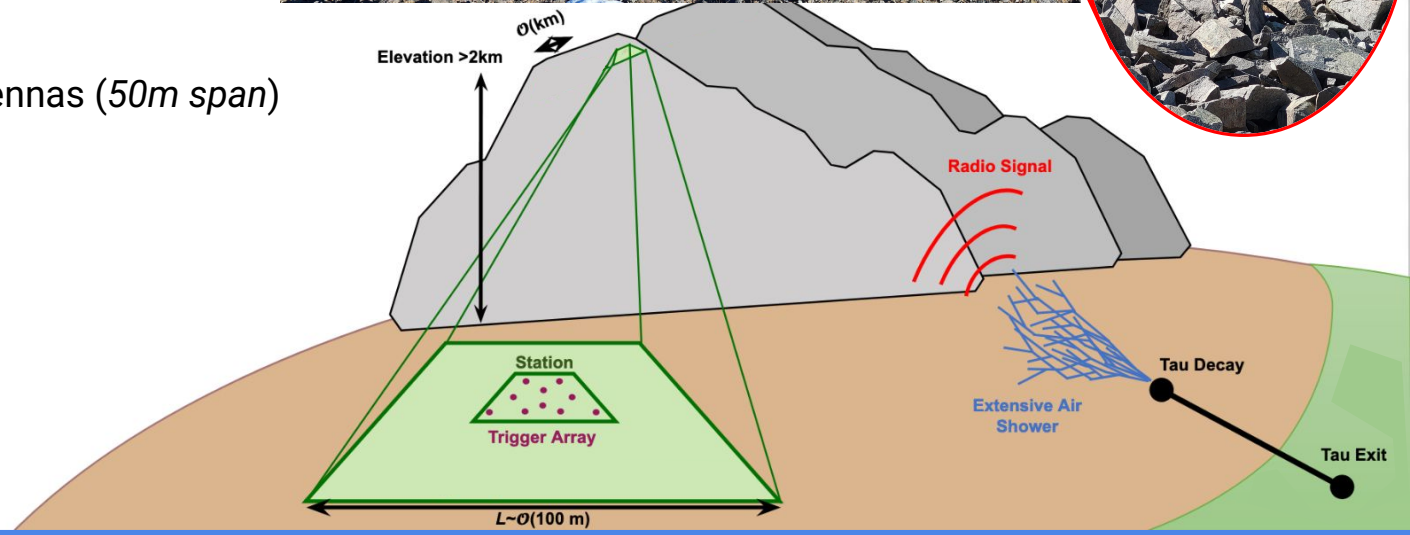
2018 – 2025

White Mountains, CA (*3.8km altitude*)





➔ Prototype (2023):
- 6 crossed-dipole antennas (*50m span*)

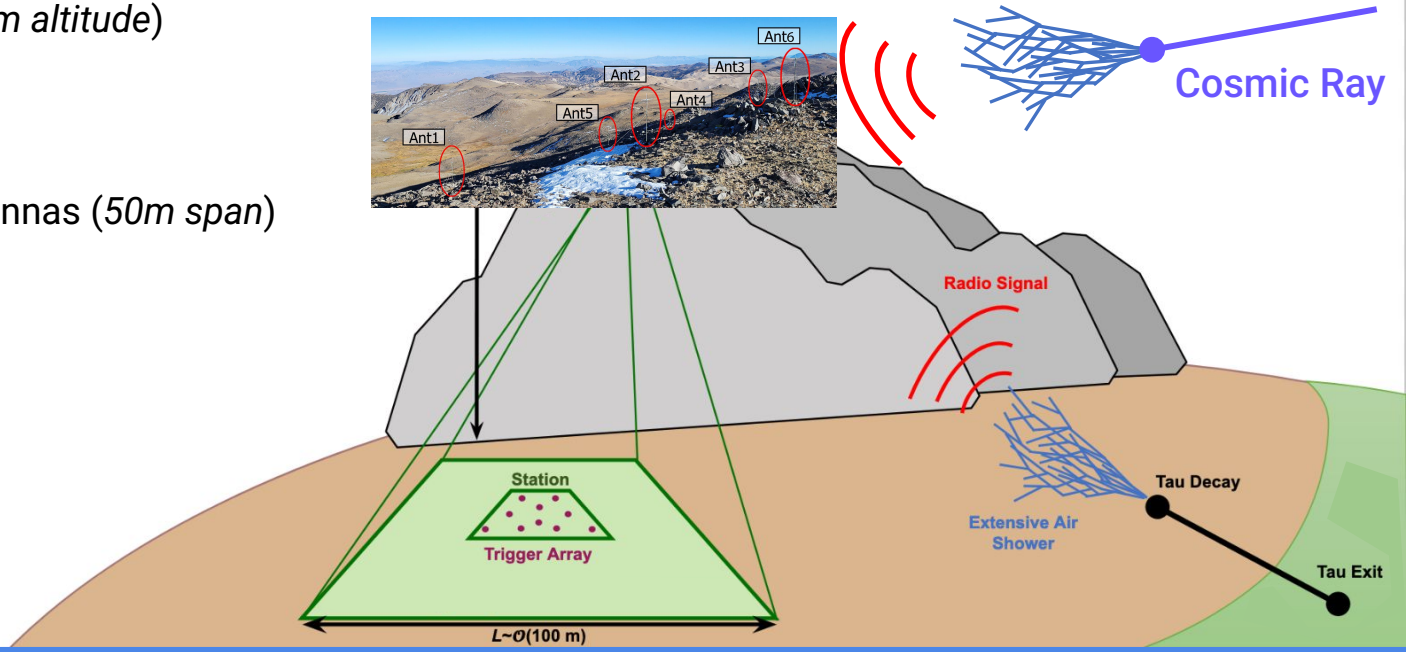


BEACON Prototype Overview

BEACON Prototype
2018 – 2025
White Mountains, CA (*3.8km altitude*)

Goal → Determine sensitivity to neutrinos
How → Verify instrument using cosmic rays (CR)

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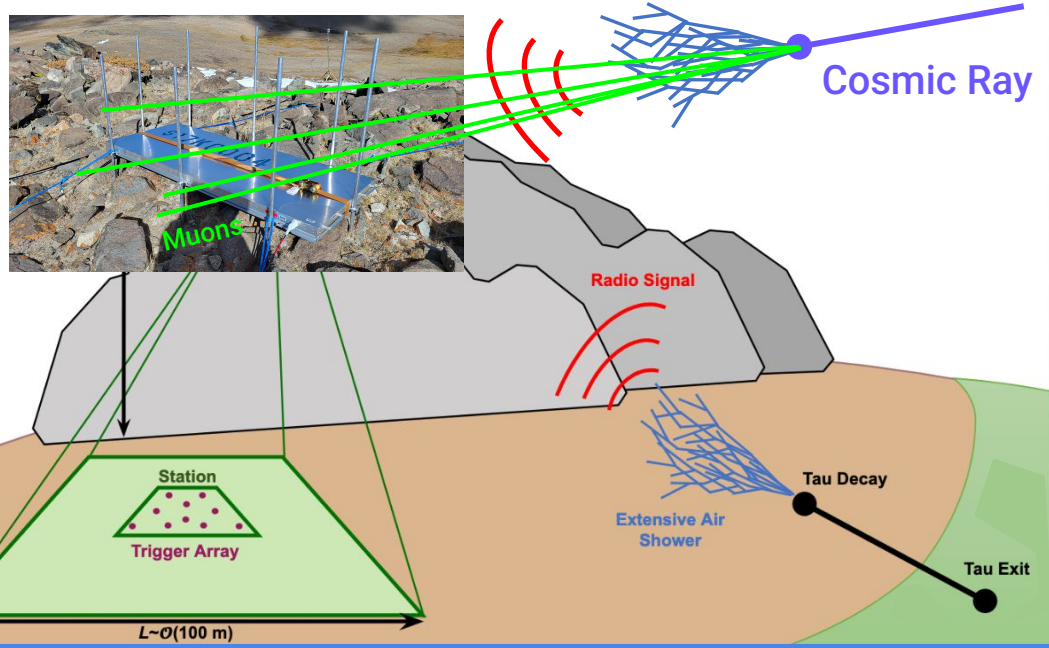
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Goal → Determine sensitivity to neutrinos
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➔ Prototype (2023):
- 6 crossed-dipole antennas (*50m span*)

➔ Scintillators:
- Array of 4 IceTop scintillators
- Cross-validate CR radio signals



Cosmic Ray Search

Goal: Identify radio-detectable cosmic rays triggered by the scintillators

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BEACON prototype acquires data based on two triggers:

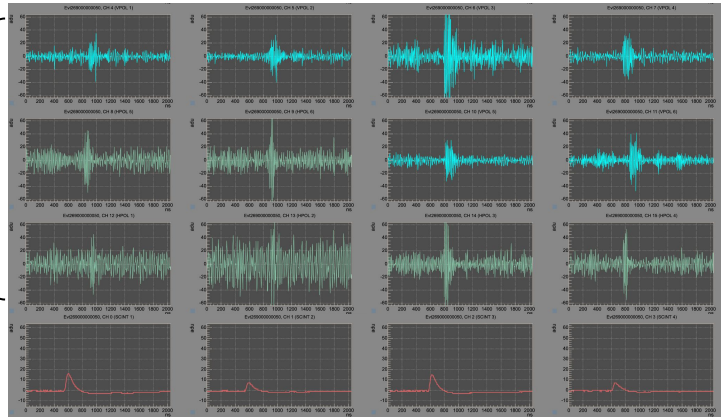
≥ 3 Scintillator Coincidence



Scintillator Triggered Event

RF

Scint



Cosmic Ray Search

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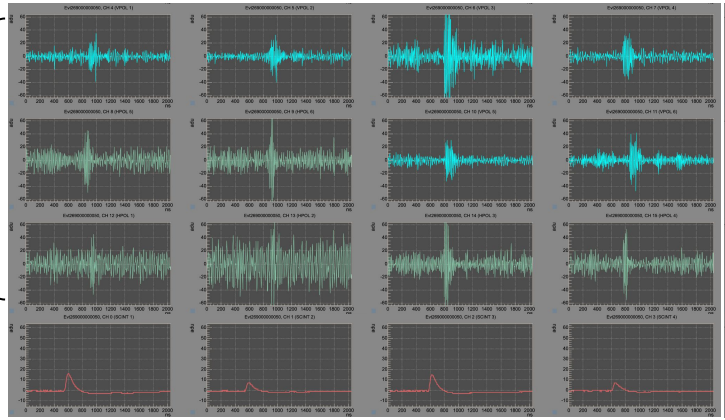
Fixed 2 Hz Software (SW) Trigger



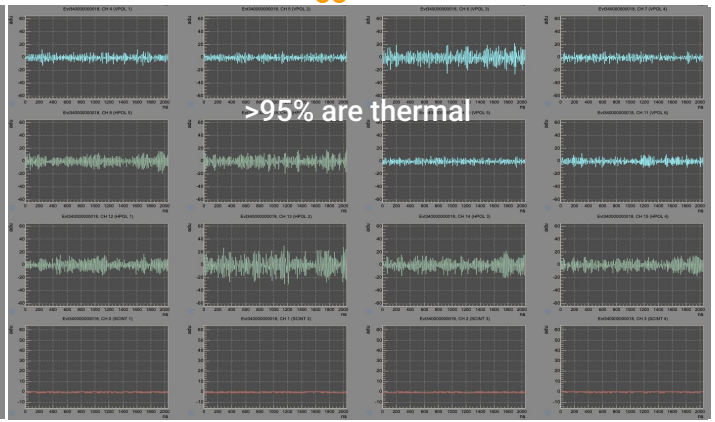
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Scintillator Triggered Event



SW Triggered Event



Cosmic Ray Search

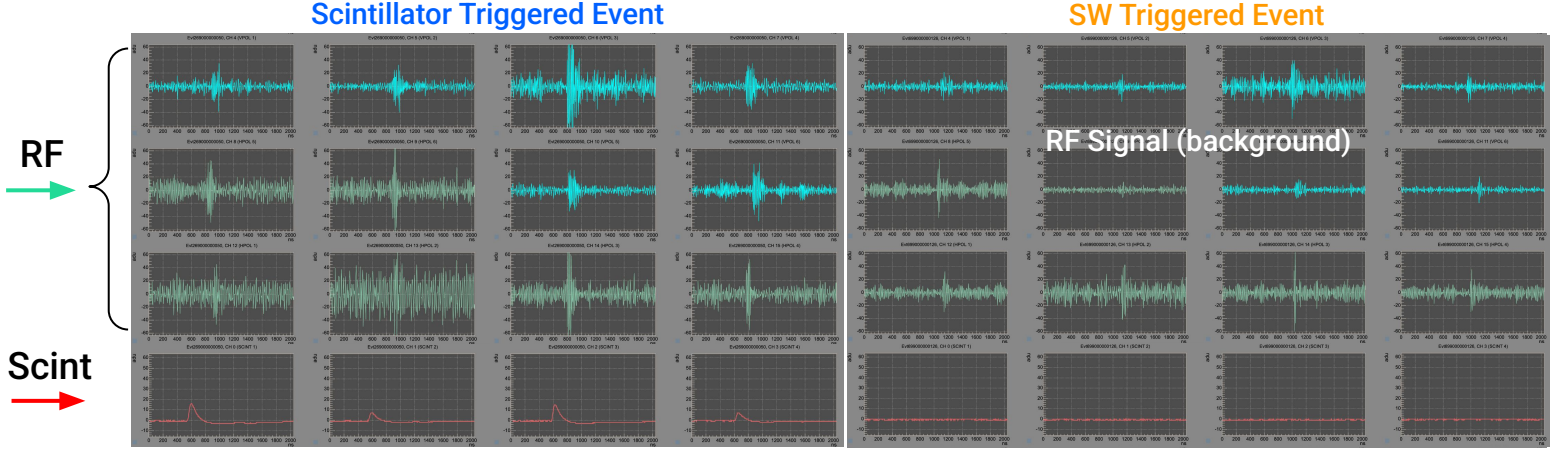
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Cosmic Ray Search

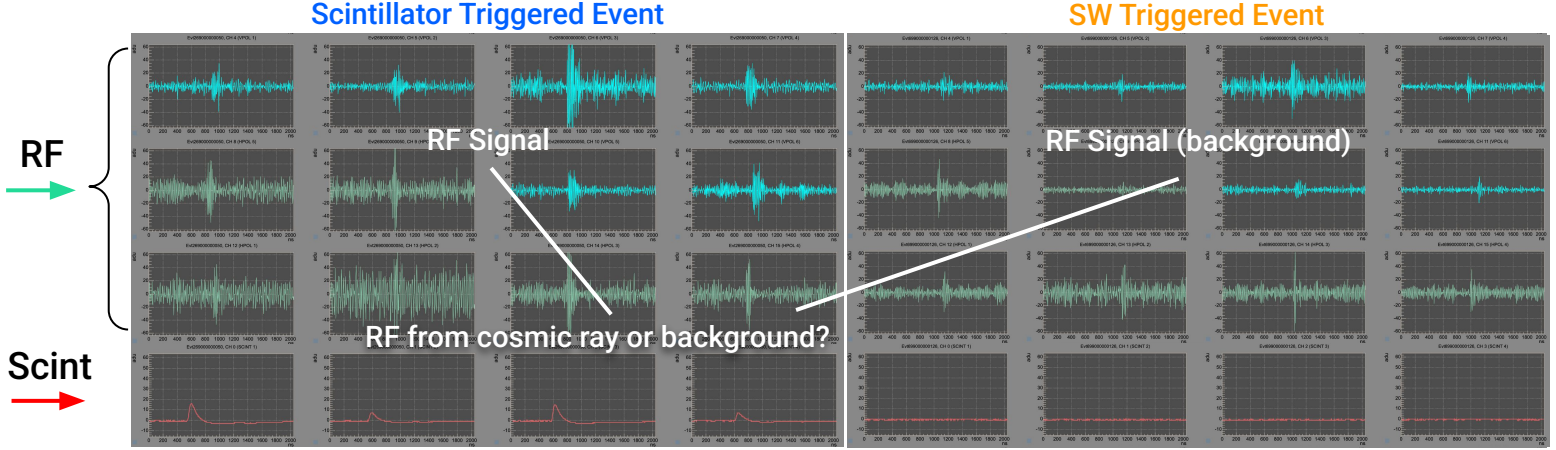
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BEACON prototype acquires data based on two triggers:

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Fixed 2 Hz Software (SW) Trigger





Characterize RF in SW dataset → Background RF discrimination

Cosmic Ray Search Characteristics of Interest

Let’s build some helpful characterizations of the data

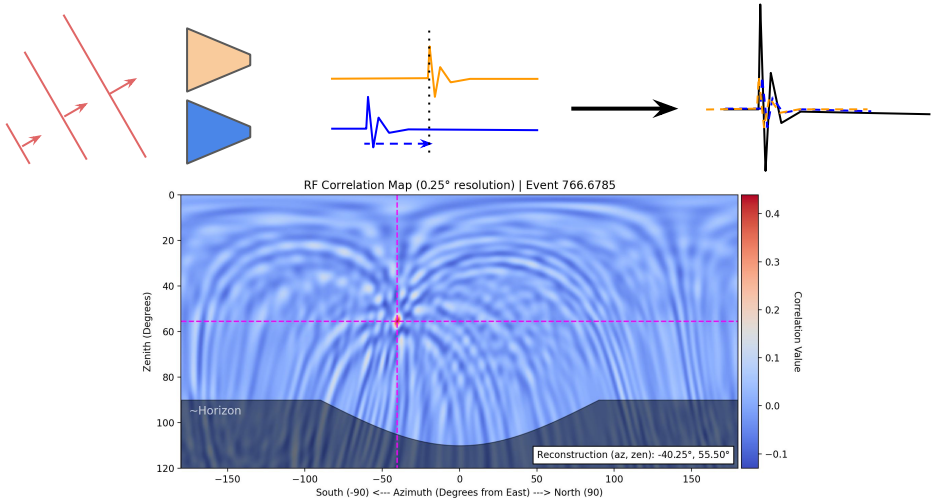
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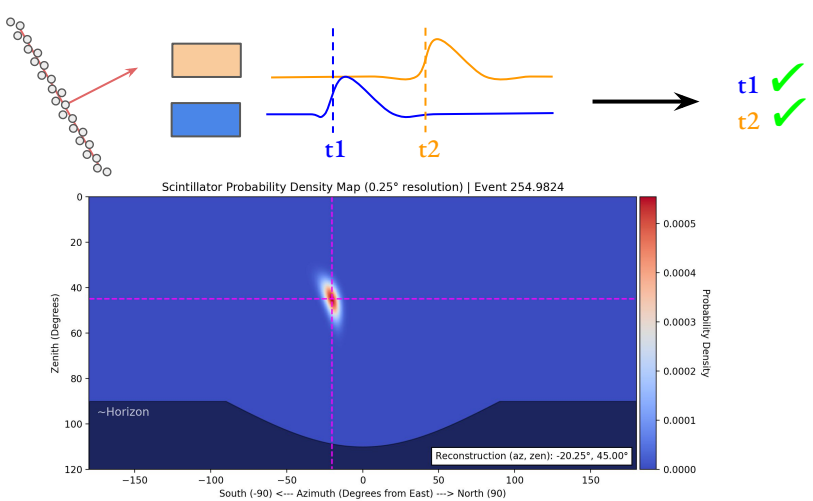
Reconstructed Source Direction

(Do they agree within 10°?)

RF: Cross-correlate antenna pairs



Scint: Fit expected arrival times to rising edges



Cosmic Ray Search Characteristics of Interest

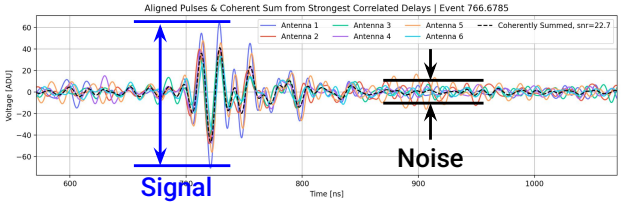
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Signal Behavior

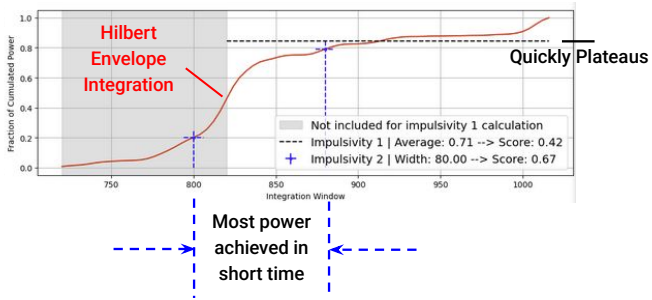
(Are the signals representative of high energy cosmic ray showers?)

RF

Strong
(High coherent SNR)



Impulsive
(Nanosecond duration)



Scint

Cosmic Ray Search Characteristics of Interest

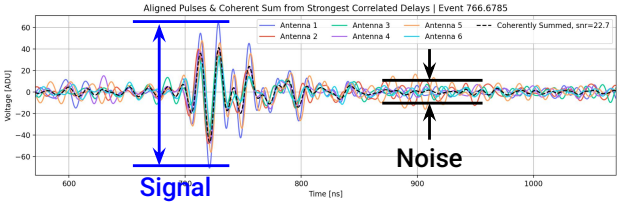
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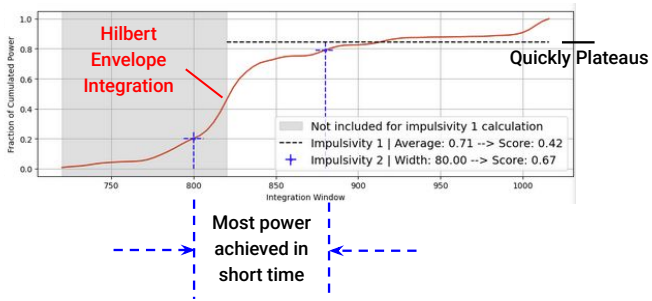
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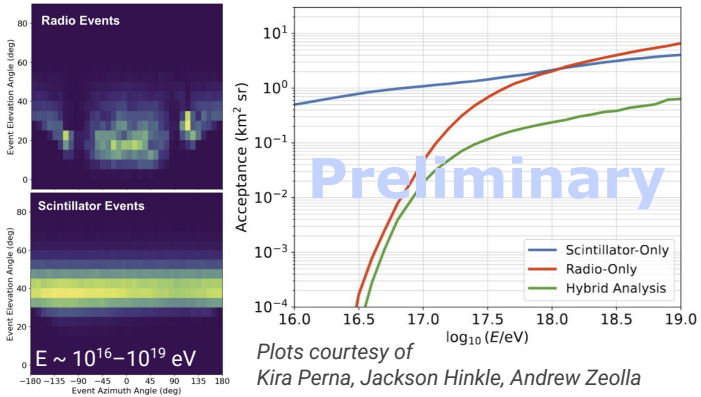
Impulsive
(Nanosecond duration)



Scint

Saturation

Detector acceptance & direction overlap in E > $10^{\sim 17}$eV
→ Detectable radio ~> scintillator saturation



Plots courtesy of
Kira Perna, Jackson Hinkle, Andrew Zeolla

(Ultimately used for optimized background rejection)

Cosmic Ray Search Characteristics of Interest

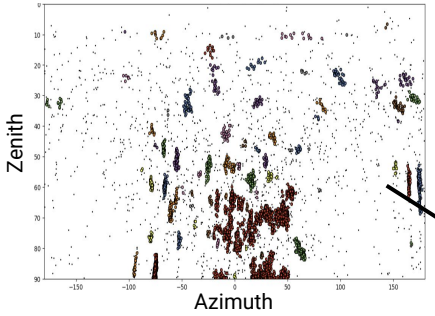
Let's build some helpful characterizations of the data

Background RFI Identification

(How do we avoid picking RFI events?)

Class I: Persistent but Stationary

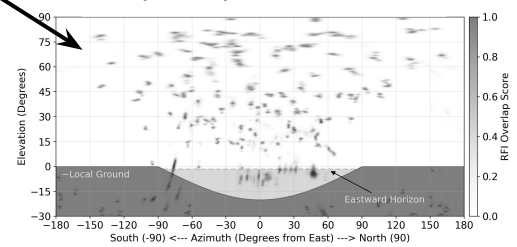
Clustering in SW dataset



DBScan: *Ester, M., H. P. Kriegel, J. Sander, and X. Xu, "A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise"*

Overlap with RFI sources scored by spatial distributions of strong, impulsive RF signals within the SW dataset

Points convolved with Gaussian point spread function



Class II:

Cosmic Ray Search Characteristics of Interest

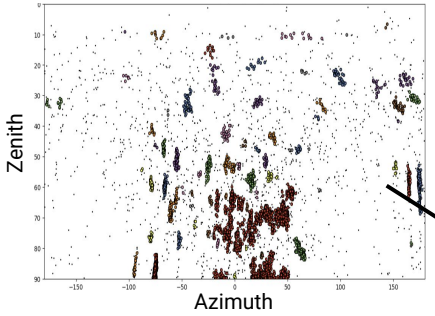
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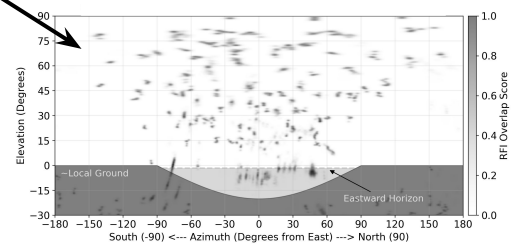
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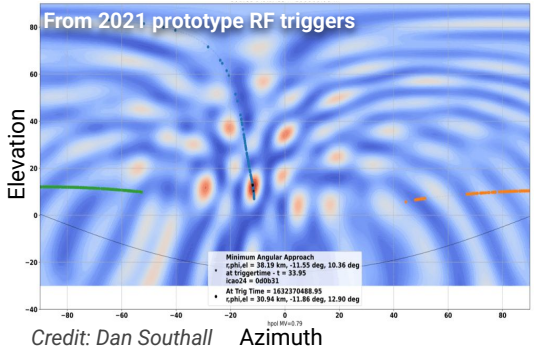
Overlap with RFI sources scored by spatial distributions of strong, impulsive RF signals within the SW dataset

Points convolved with Gaussian point spread function



Class II: Airplanes

Check *OpenSky Network* for airplanes within 5 deg, 1 minute window of event direction and timestamp



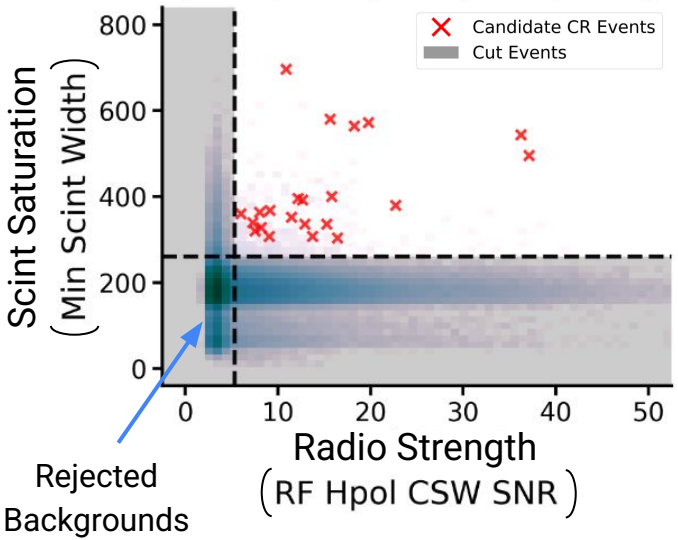
Credit: Dan Southall

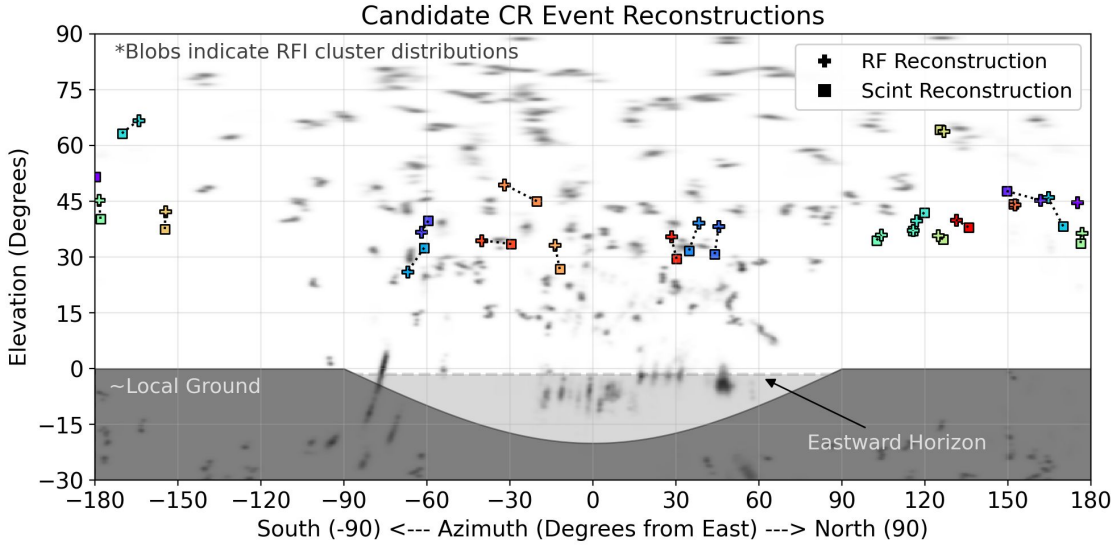
Airplane tracking data obtained from:
Matthias Schäfer, Martin Strohmeier, Vincent Lenders, Ivan Martinovic and Matthias Wilhelm. "Bringing Up OpenSky: A Large-scale ADS-B Sensor Network for Research". In Proceedings of the 13th IEEE/ACM International Symposium on Information Processing in Sensor Networks (IPSN), pages 83-94, April 2014.

(This operation is expensive, so we perform it after data selection cuts)

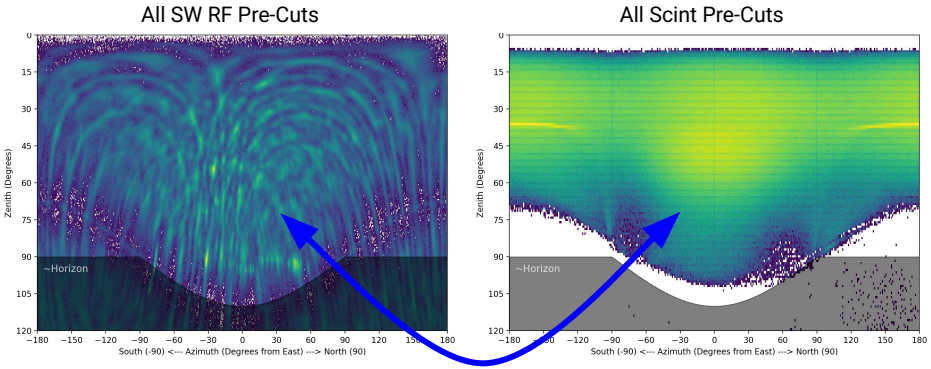
Cosmic Ray Search Results

After analysis cuts on characteristics of interest → ***22 Candidate Events***





Estimating Background to Cosmic Ray Search



Apply Cuts

Coincident radio and scintillator signals are random and truly unassociated

After 100,000 trials, background estimate from rate of random coincidences gives

22 cosmic ray candidate events over background of 0.1

Build datasets randomly pairing:

- RF channels from SW-triggered dataset
- Scintillator channels from scintillator-triggered dataset

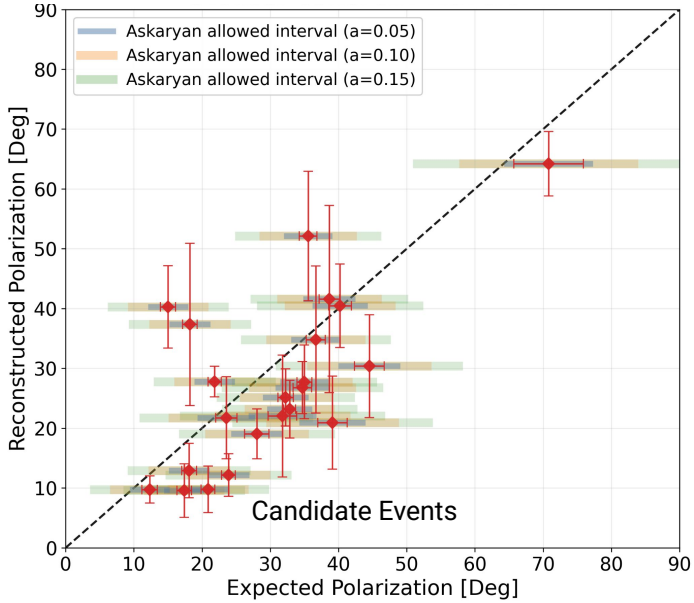
Polarization Reconstruction

Local E-fields obtained from deconvolving RF antennas and signal chain

Then polarization obtained via Stokes parameters:

Stokes

$$\left.\begin{aligned} Q &= \langle |\mathcal{E}\_az|^2 \rangle - \langle |\mathcal{E}\_zen|^2 \rangle \\ U &= 2\,\mathrm{Re}\{ \langle \mathcal{E}\_az\ \mathcal{E}^*\_zen \rangle \} \end{aligned}\right\} \rightarrow \psi = 0.5\ \mathrm{arctan2}(U, Q)$$



compared to pure-geomagnetic expectation

$$\sin^{-1}(|\,\hat{\mathbf{e}}_{\mathrm{geo}} \times \hat{\mathbf{e}}_{\mathrm{az}}\,|)$$

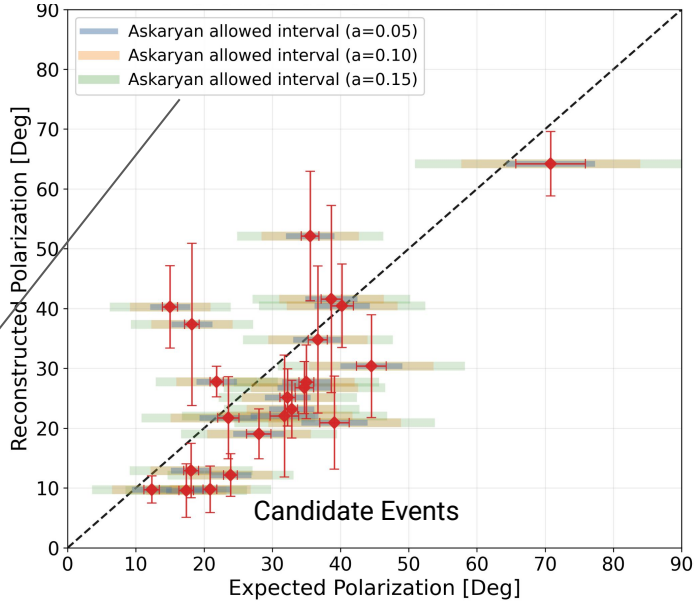
$$(\hat{\mathbf{v}} \times \hat{\mathbf{B}}) / |\hat{\mathbf{v}} \times \hat{\mathbf{B}}|$$

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Askaryan contribution deflect angle up to $|\delta|_{\max} = \sin^{-1}\left(\frac{a}{\sin\alpha}\right)$

$\left(a = \sin(\alpha)\frac{|E_{\mathrm{ask}}|}{|E_{\mathrm{geo}}|}\right.$, α = angle between shower and magnetic field$\left.\right)$

Improvements by reducing this degree of freedom requires sparse array for footprint reconstruction

compared to pure-geomagnetic expectation $\sin^{-1}(|\hat{\mathbf{e}}_{\mathrm{geo}} \times \hat{\mathbf{e}}_{\mathrm{az}}|)$

$(\hat{\mathbf{v}} \times \hat{\mathbf{B}}) / |\hat{\mathbf{v}} \times \hat{\mathbf{B}}|$



Summary

- BEACON measures geomagnetic emission to probe ultrahigh energy cosmic particles
- 2023 prototype uses scintillator array to trigger on for radio-detectable cosmic rays at a site with RFI
- We find 22 candidate CR events to 0.1 background events; Reconstructed polarization angles are compatible with CRs
- RFI discrimination in radio array can be improved with a reconstructed footprint from sparse array

Thank you!

BEACON

Kavli Institute for Cosmological Physics at The University of Chicago

PennState

White Mountain Research Center

USC Universidade de Santiago de Compostela

The Ohio State University

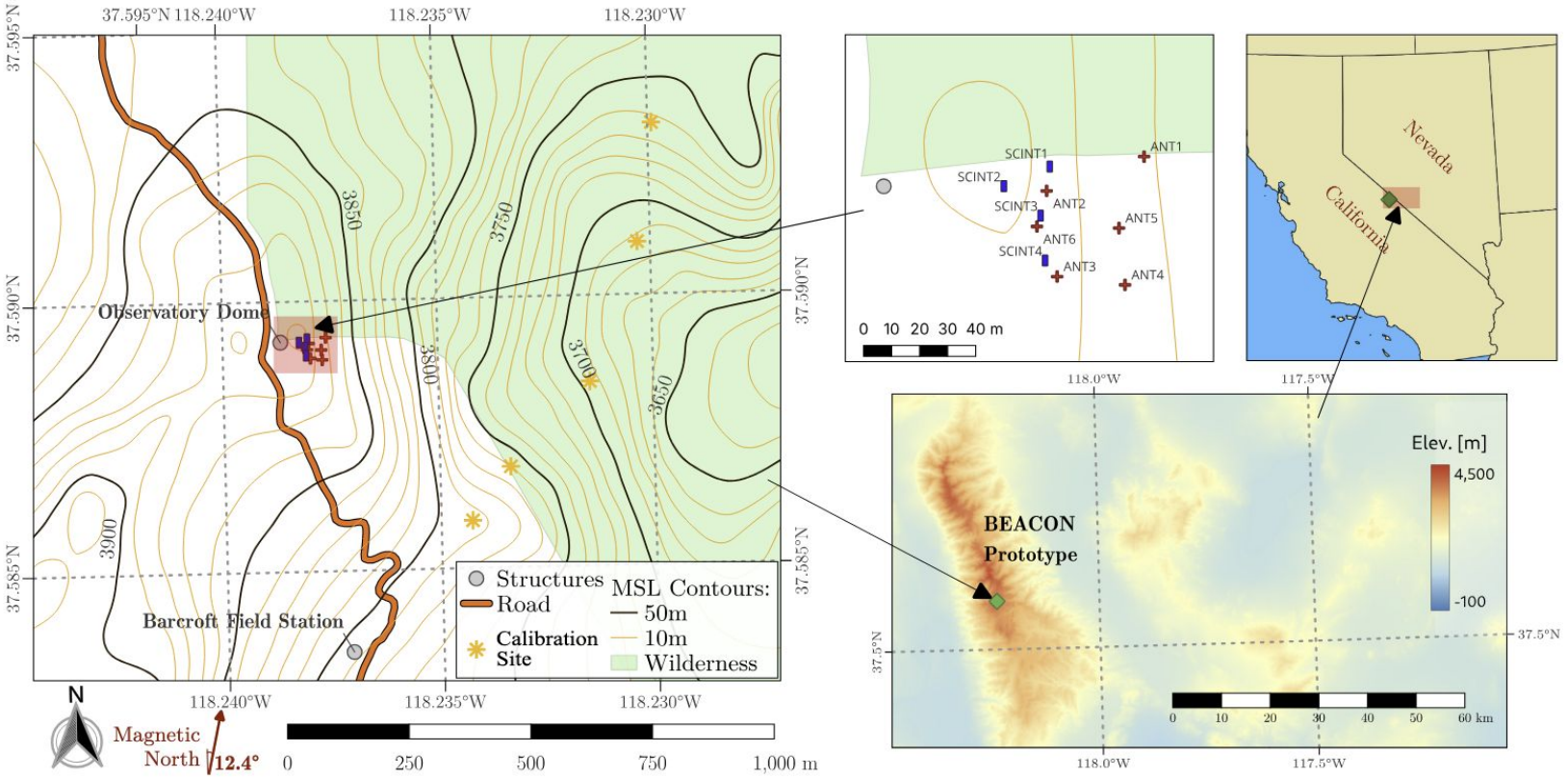
Radboud Universiteit

KU The University of Kansas

NSF

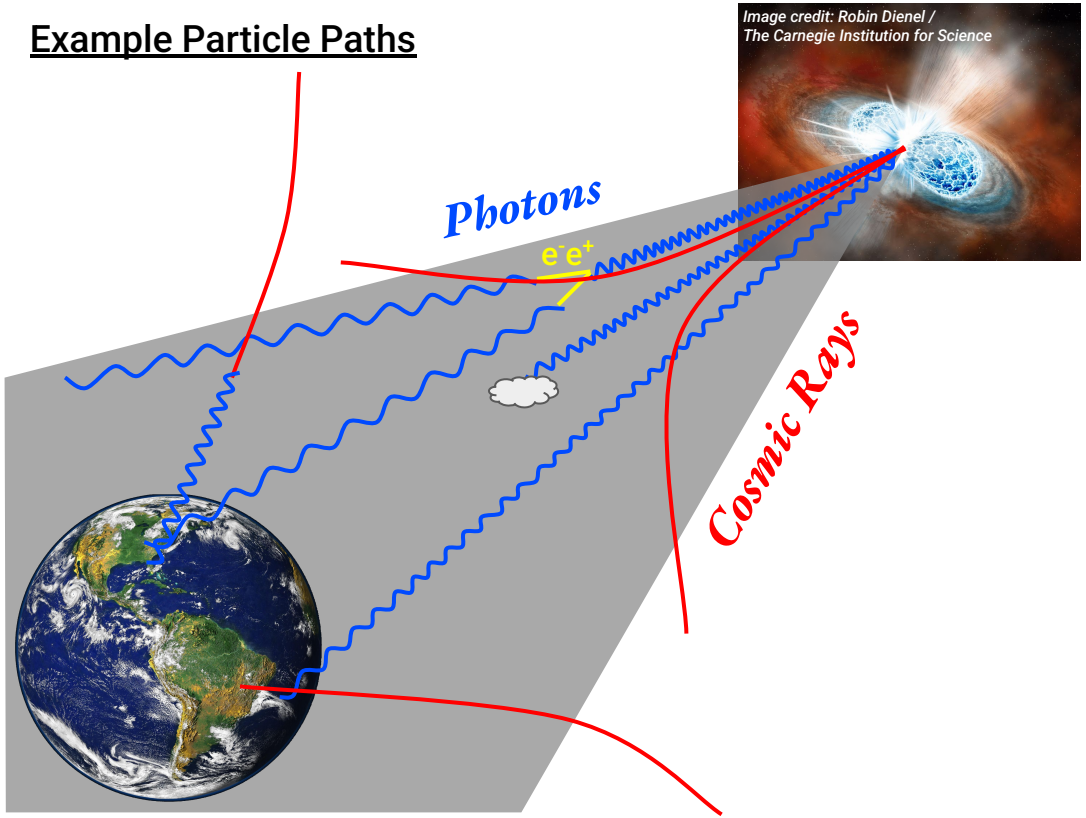
Supplementary Slides

Orientation

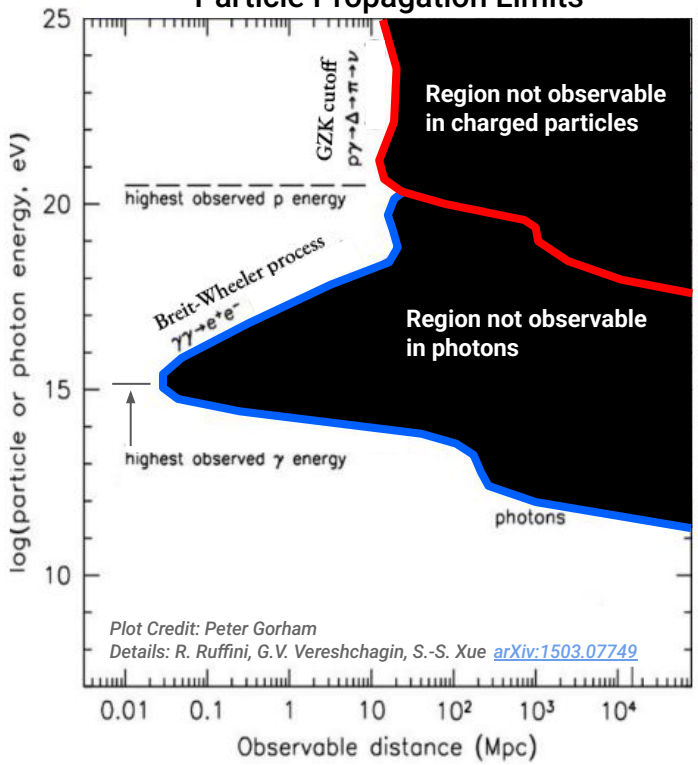


Neutrinos have advantages in multimessenger astrophysics

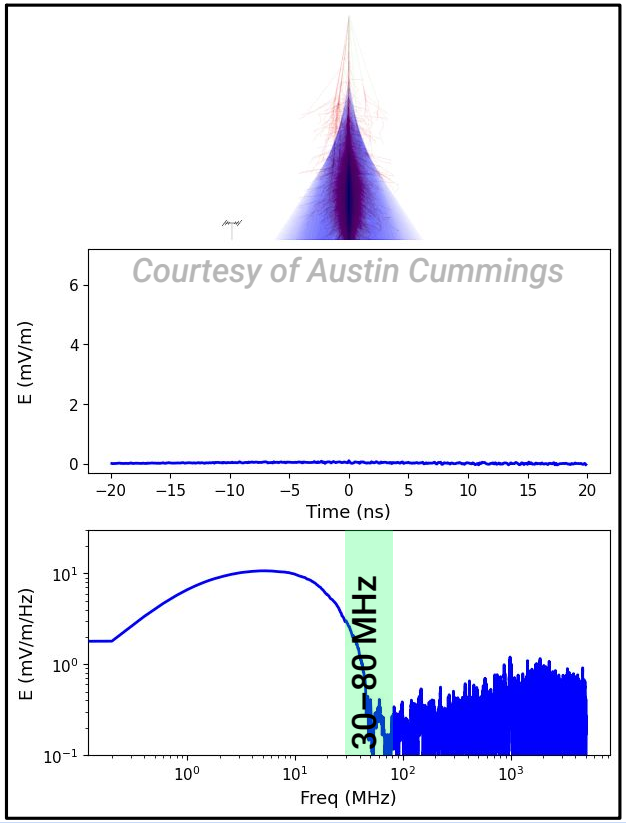
Example Particle Paths

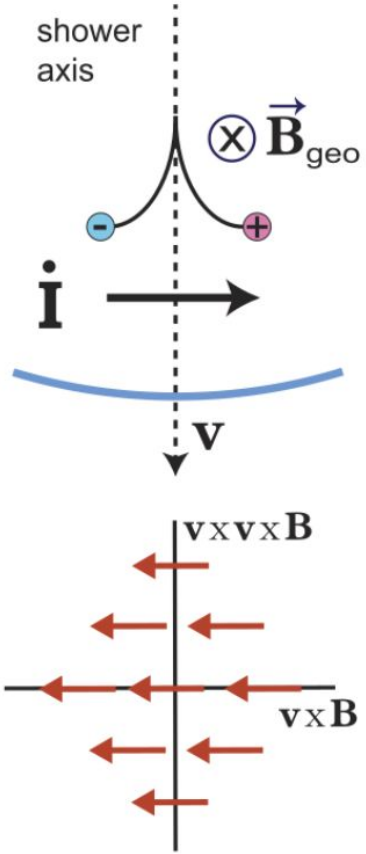


Particle Propagation Limits



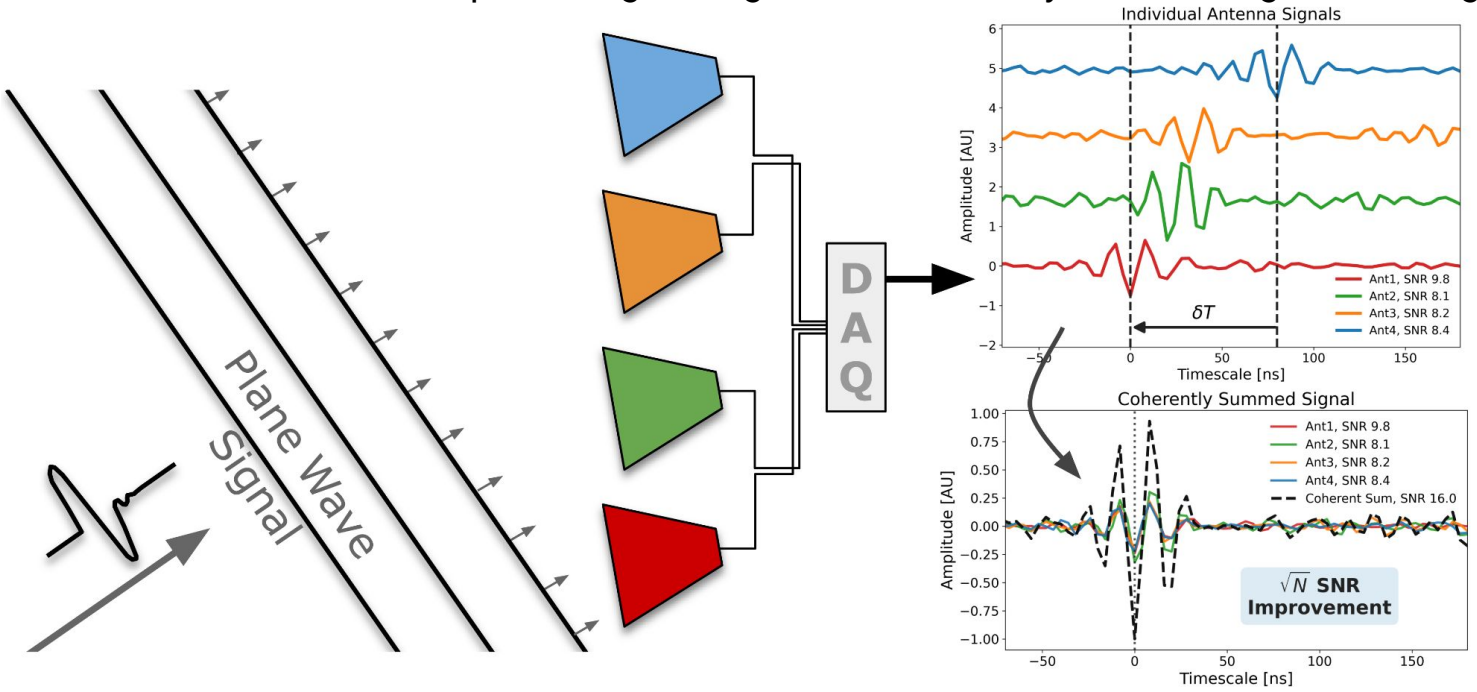
Geomagnetic Emission E-Field





How Beamforming Improves Detection Capabilities

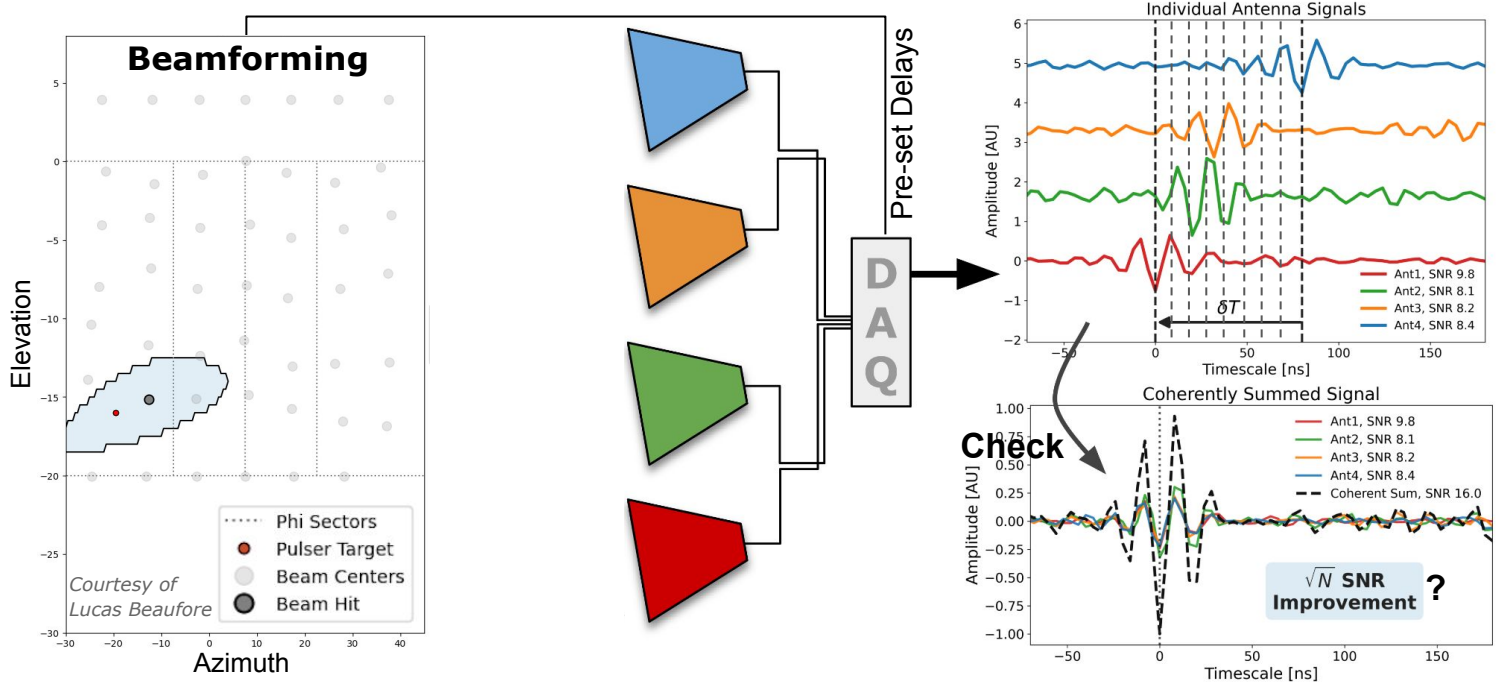
In Post: Specific directions → Specific Signal Alignment Time Delays → Alignment = High SNR*



*SNR = Signal-to-Noise Ratio

How Beamforming Improves Detection Capabilities

In Post: Specific directions → Specific Signal Alignment Time Delays → Alignment = High SNR*

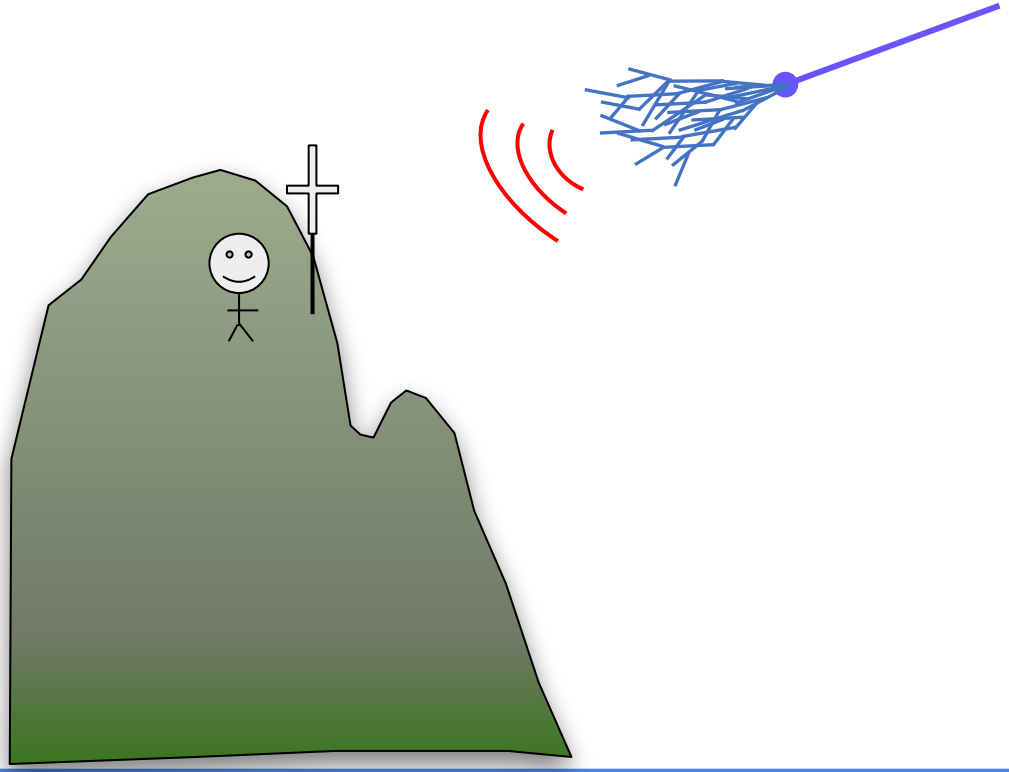


In Real Time: Delays at Many Directions → High SNR for Real Signals → Improved Trigger Threshold

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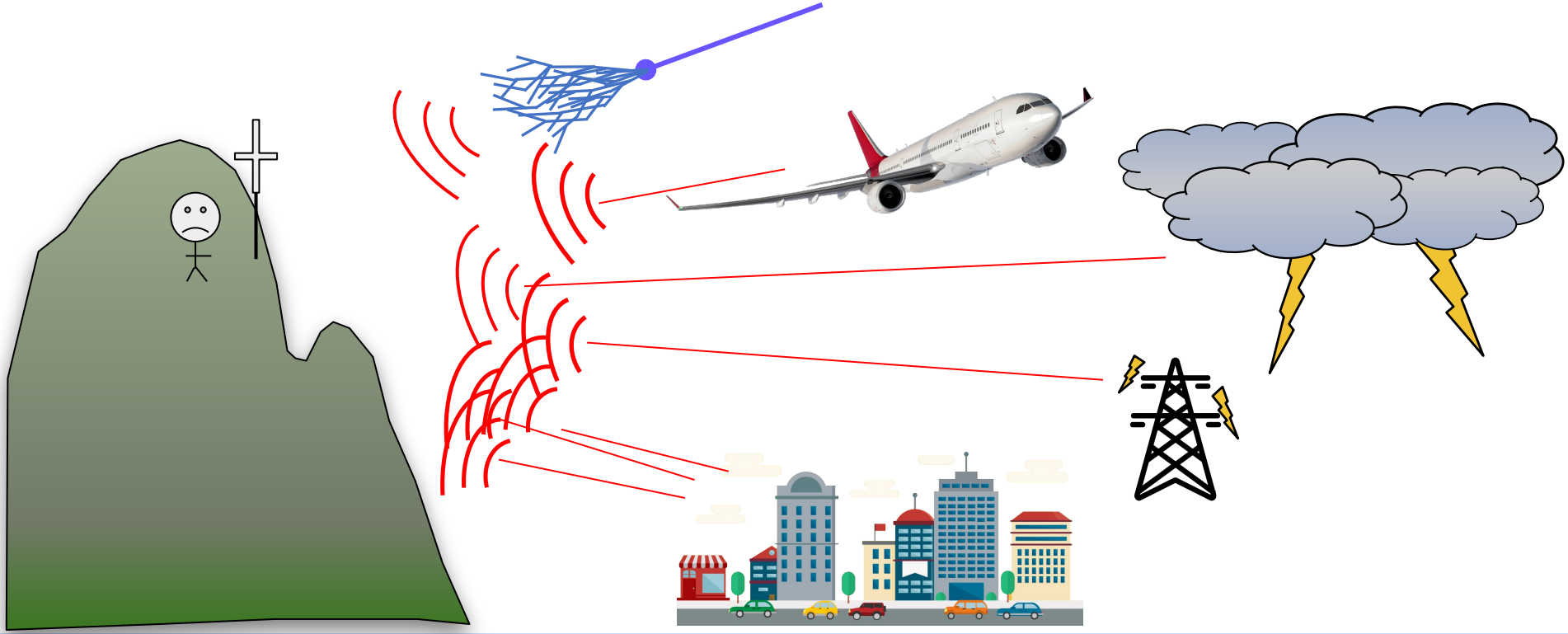
*SNR = Signal-to-Noise Ratio

Why Have Scintillators as a Cross-Validation Detector?



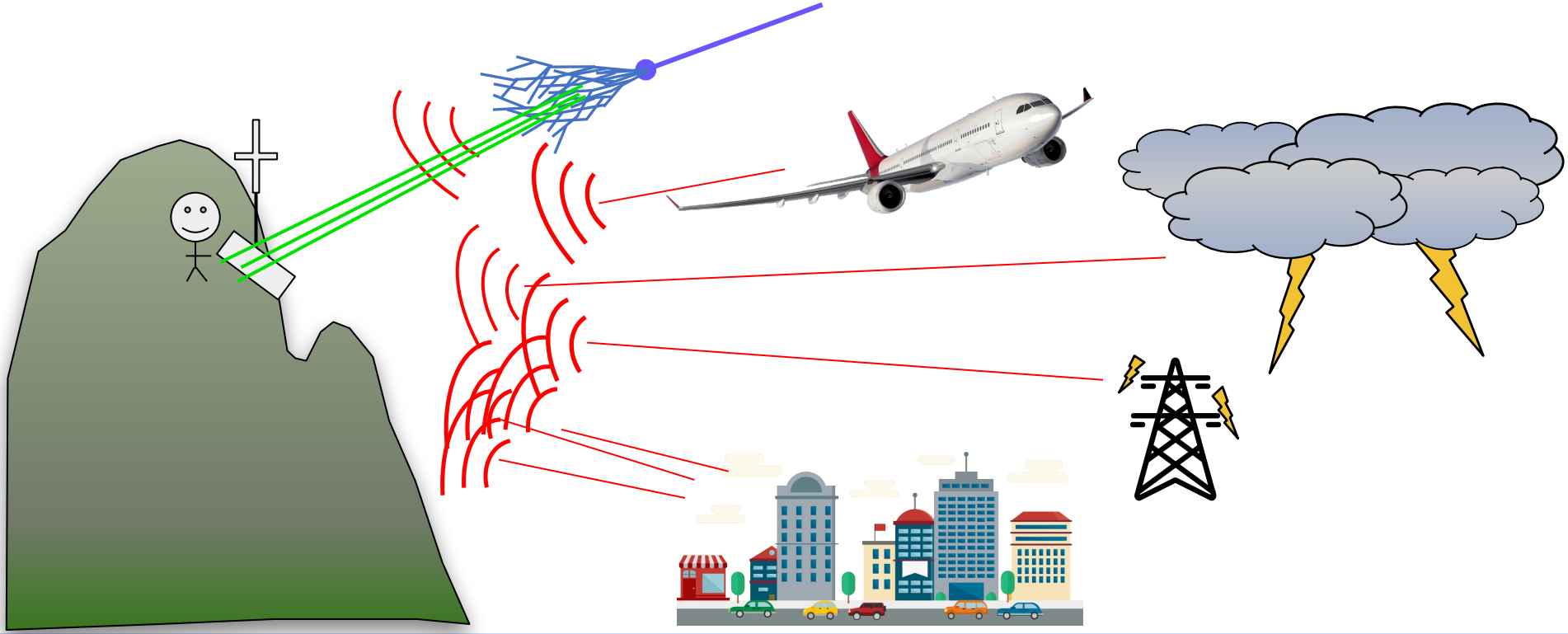
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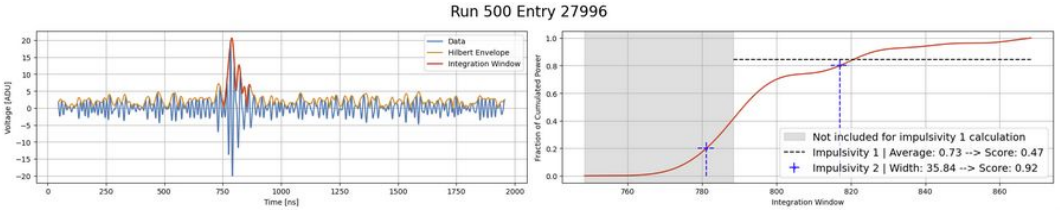
Why Have Scintillators as a Cross-Validation Detector?

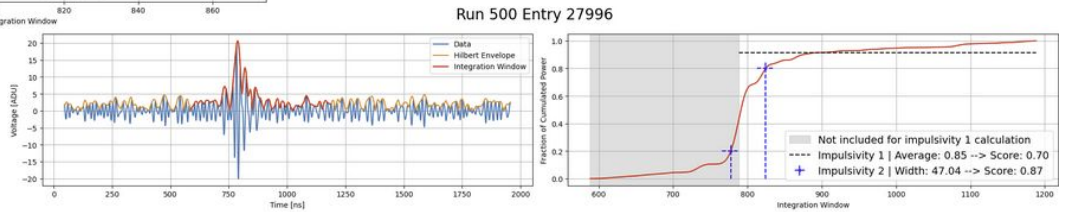


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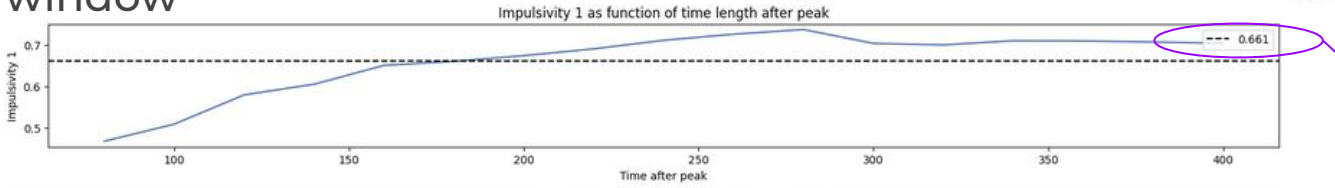
Impulsivity Details

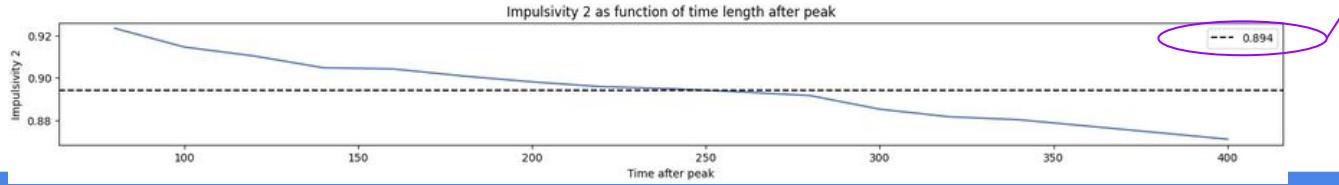
Impulsivity 1 = Average post-peak; Impulsivity 2: Time width from 20-80%





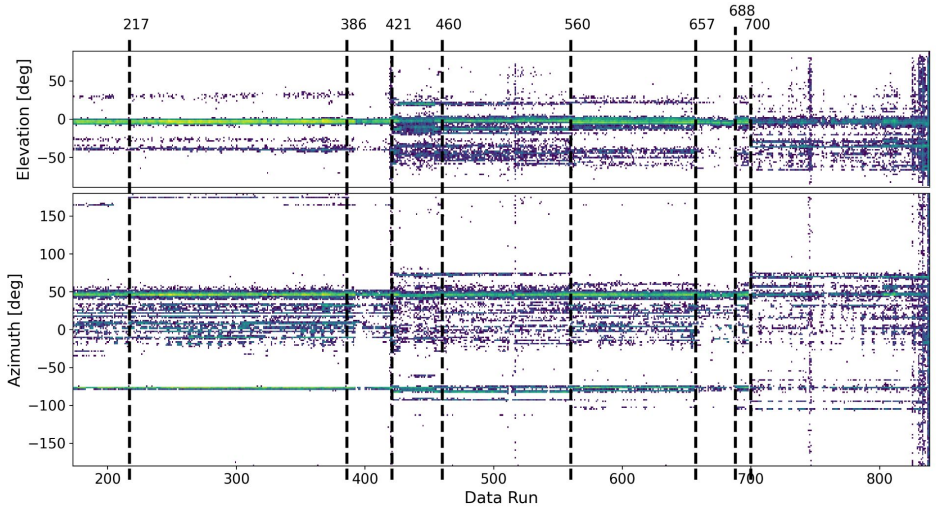
Average across multiple window lengths

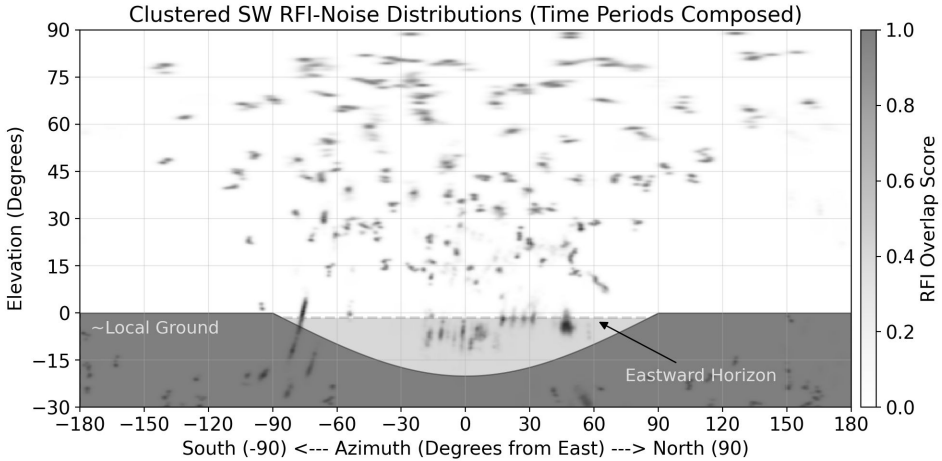




New total impulsivity is average of these

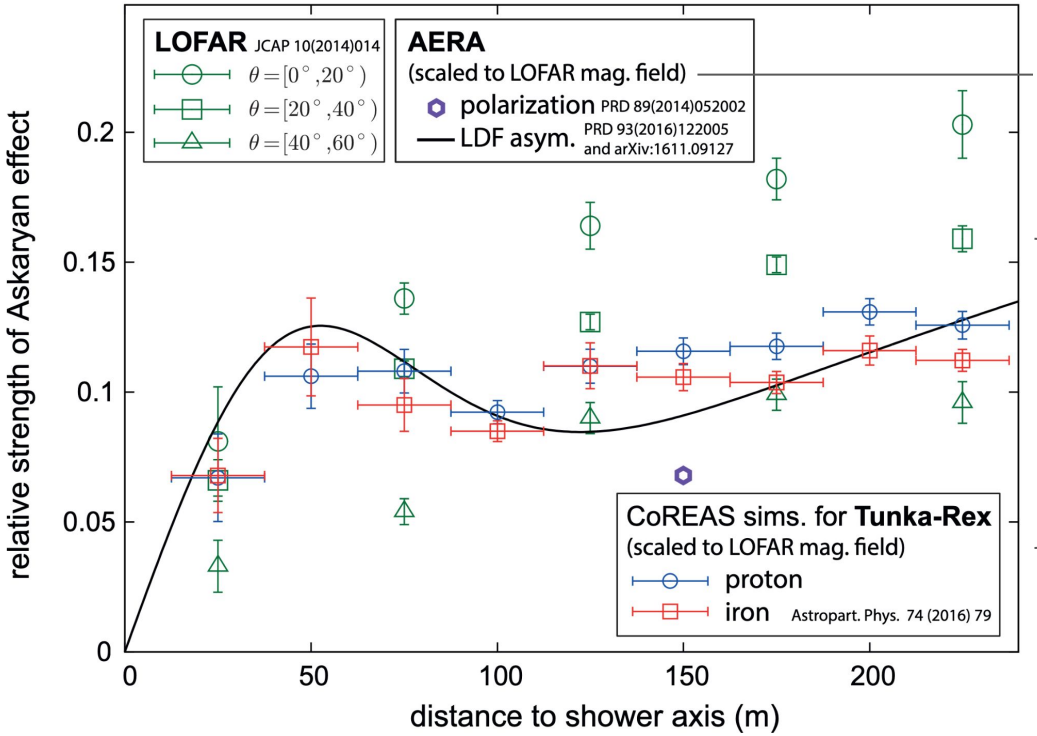
More on BEACON RFI Clustering





Askaryan Intervals

Choosing the Askaryan relative strength parameter, a

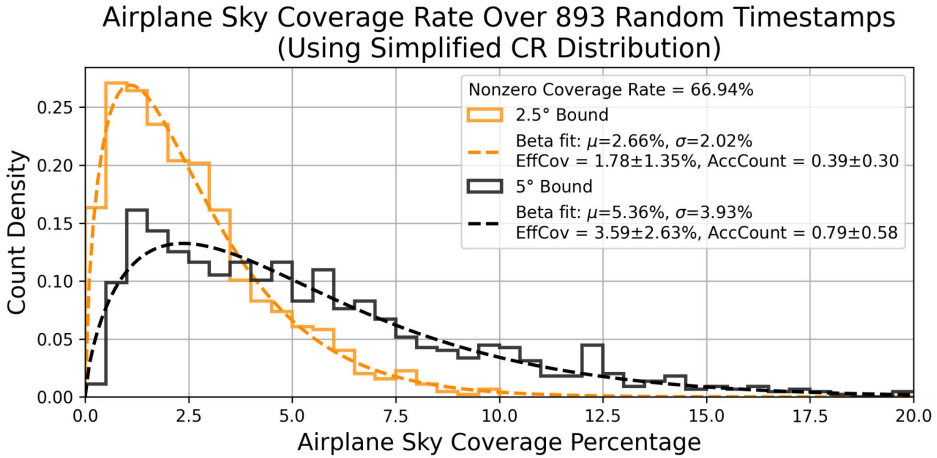


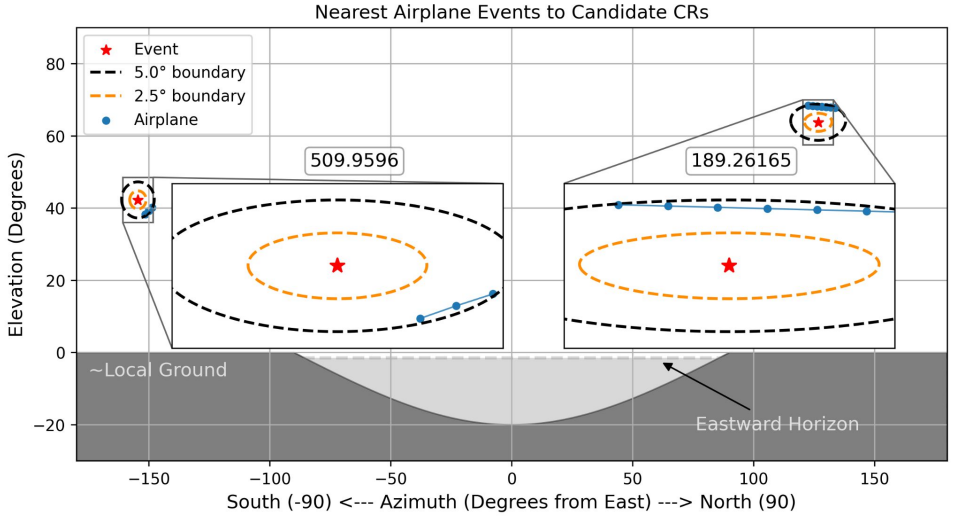
For |B| ~ 49 uT (Same as BEACON)

So I choose, a = 0.05, 0.10, 0.15

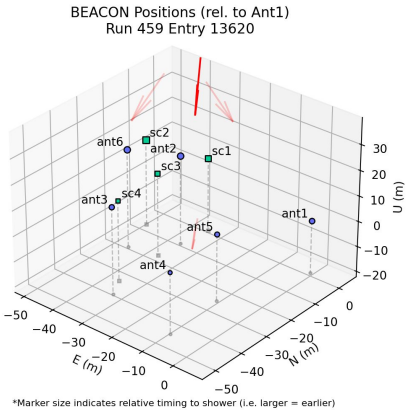
Schröder (arXiv:1607.08781)

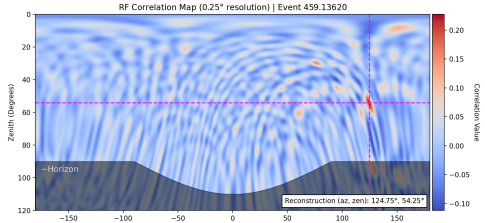
More on BEACON Airplane Background

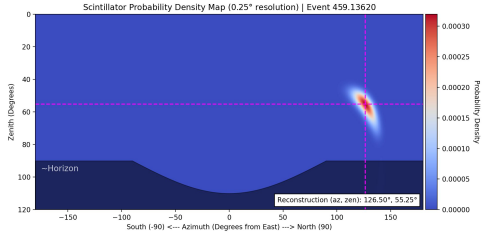


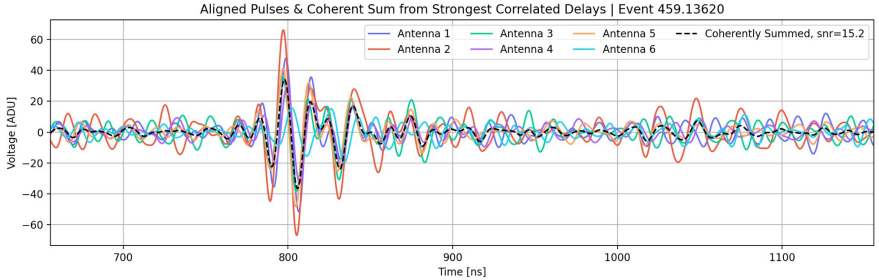


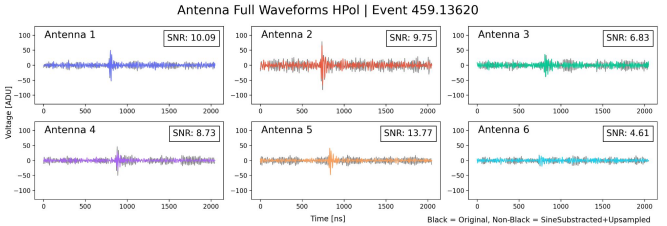
Example BEACON CR Event

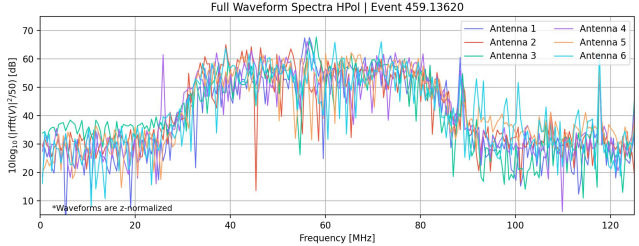


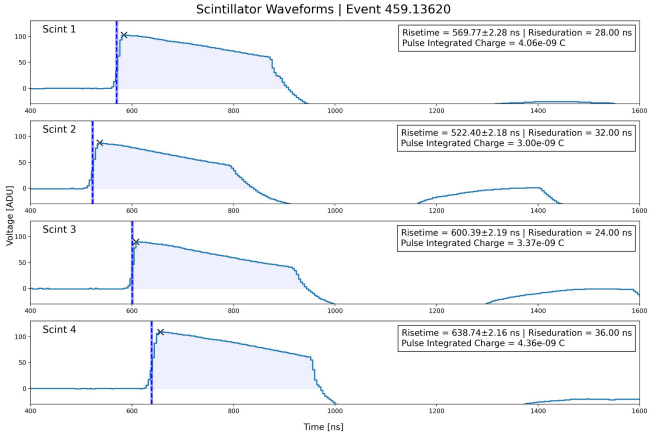










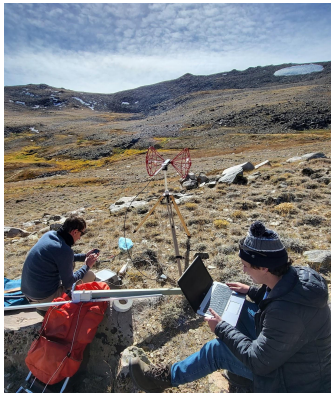


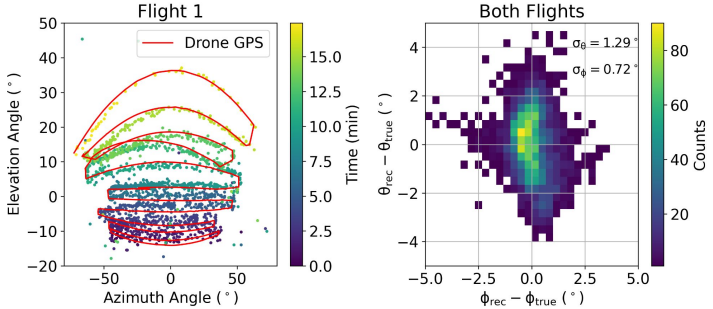
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BEACON Prototype 2023 Field Calibration

Drone & Ground Calibration Pulsing

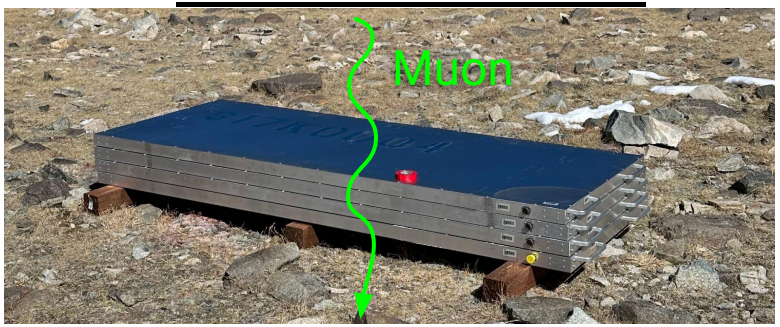


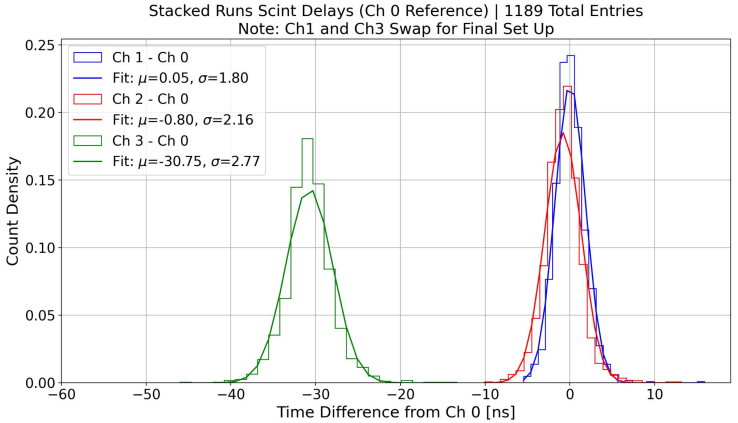




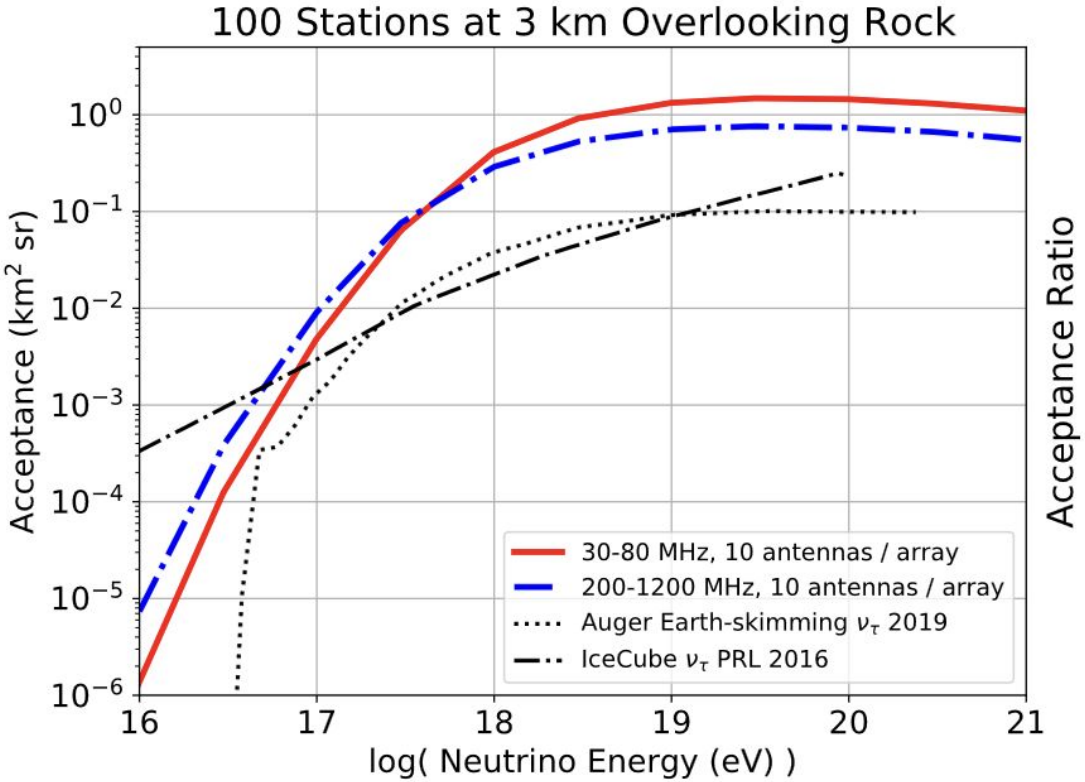
Work by Andrew Zeolla

Scintillator Calibration

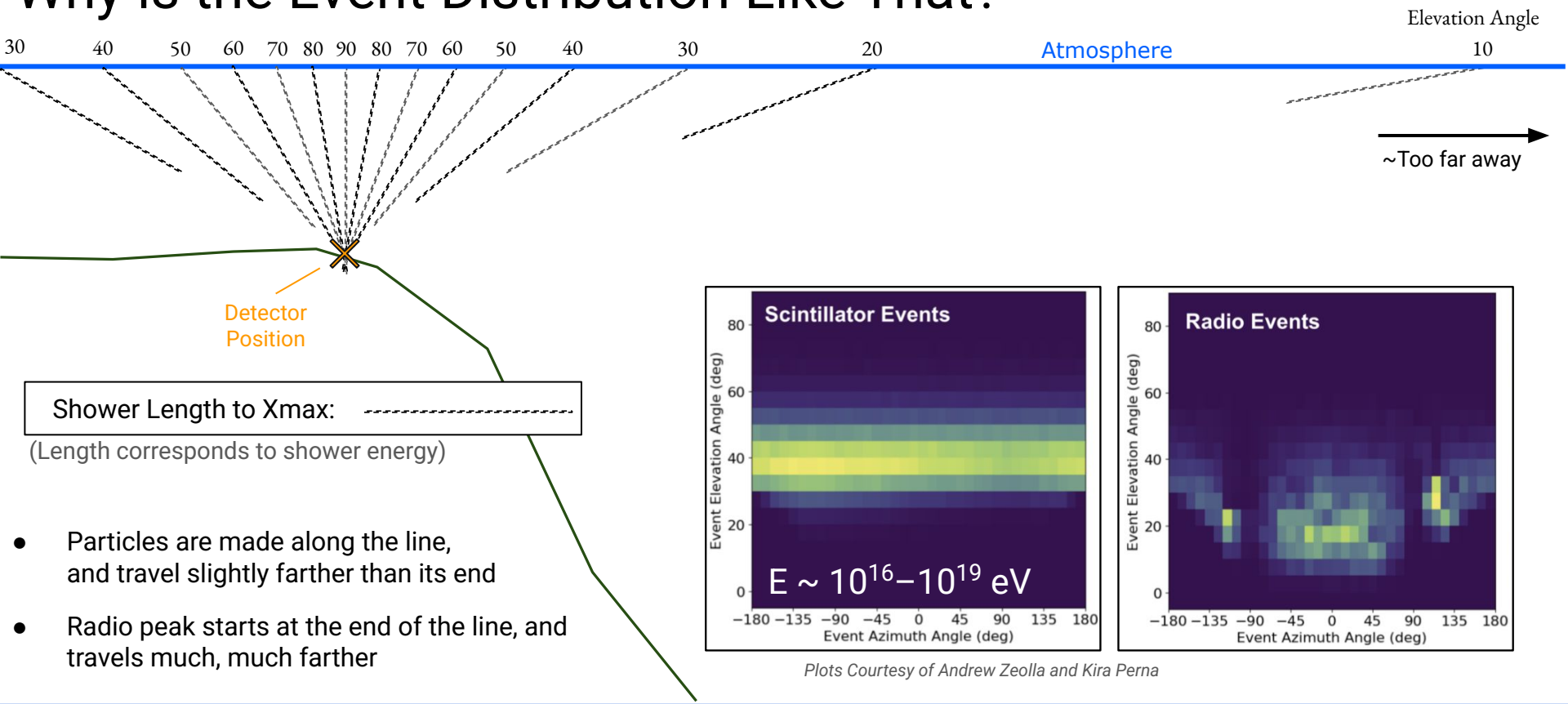




BEACON Low-Freq vs High-Freq



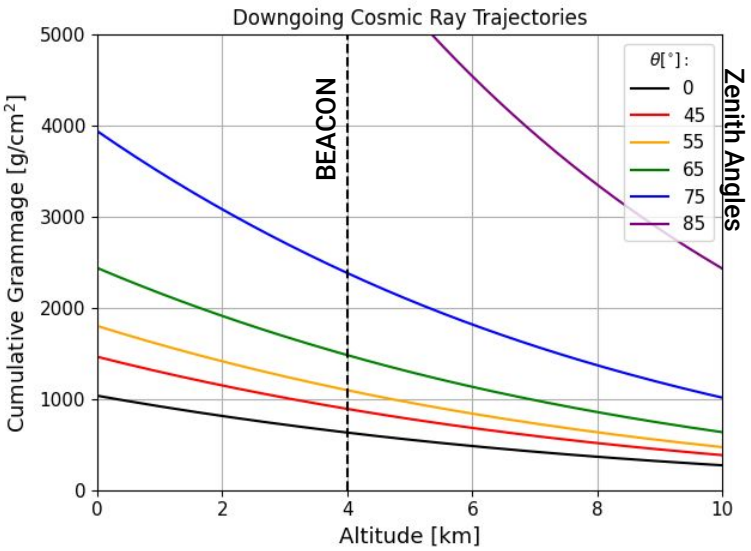
Why is the Event Distribution Like That?



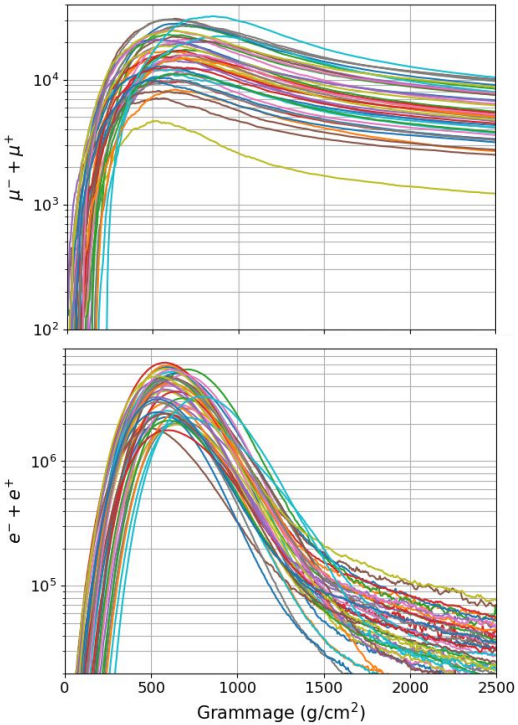
- Particles are made along the line, and travel slightly farther than its end
- Radio peak starts at the end of the line, and travels much, much farther

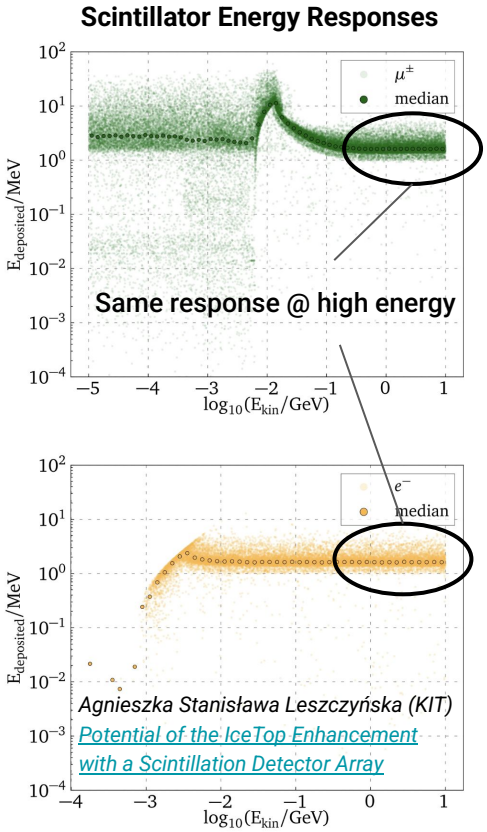
Plots Courtesy of Andrew Zeolla and Kira Perna

CR Particle Signatures in Xmax Perspective



Grammage Plots
Courtesy of Austin Cummings

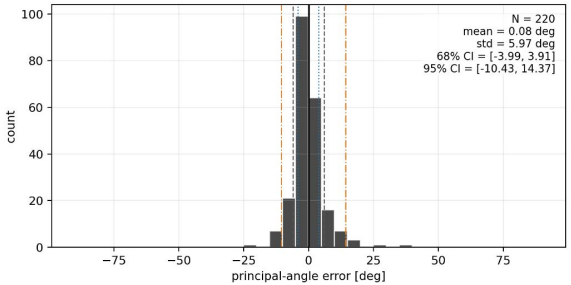




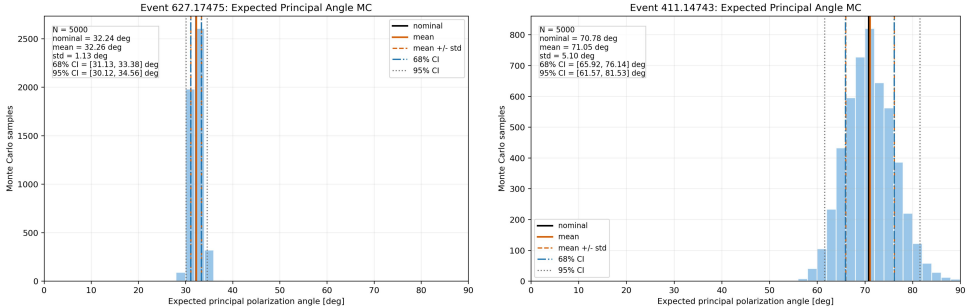
Agnieszka Stanisława Leszczyńska (KIT)
Potential of the IceTop Enhancement with a Scintillation Detector Array

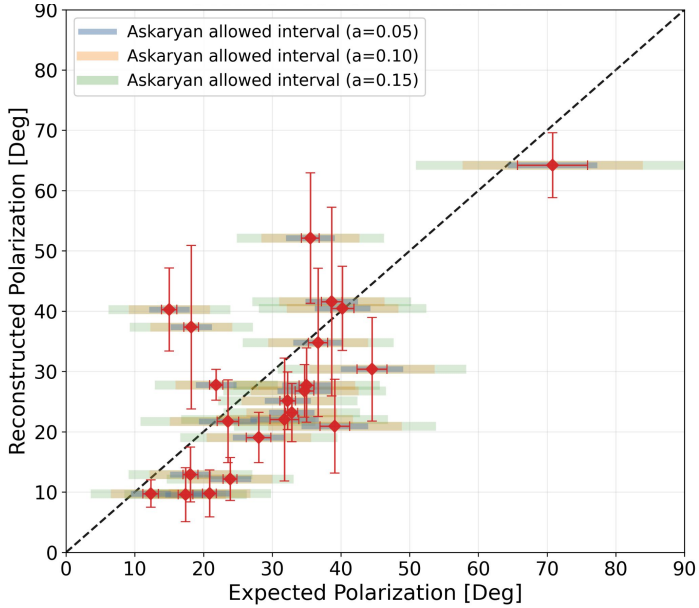
Polarization Reconstruction Uncertainties

Uncertainties on reconstruction are built from Monte Carlo on modeled impulsive E-fields, and includes SNR dependence and empirical antenna response uncertainties



Uncertainties on expected geomagnetic polarization built from sampled directions around event direction, and using world magnetic model data





Polarization Reconstruction vs Backgrounds

Candidate cosmic ray events agree much better than reconstructed polarization angles on background classes (a good sign!)

