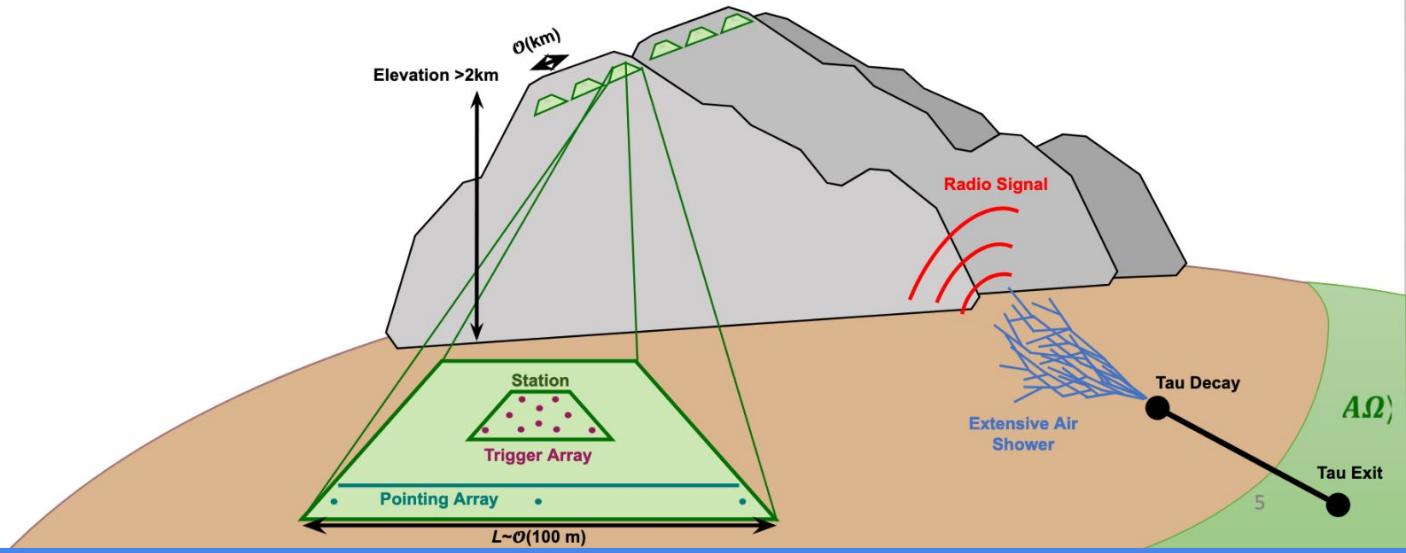
Searching for Cosmic Rays with the BEACON Prototype

Zachary Martin
On Behalf of the BEACON Collaboration

Overview

BEACON Prototype → *Goal* → Validate full instrument neutrino sensitivity



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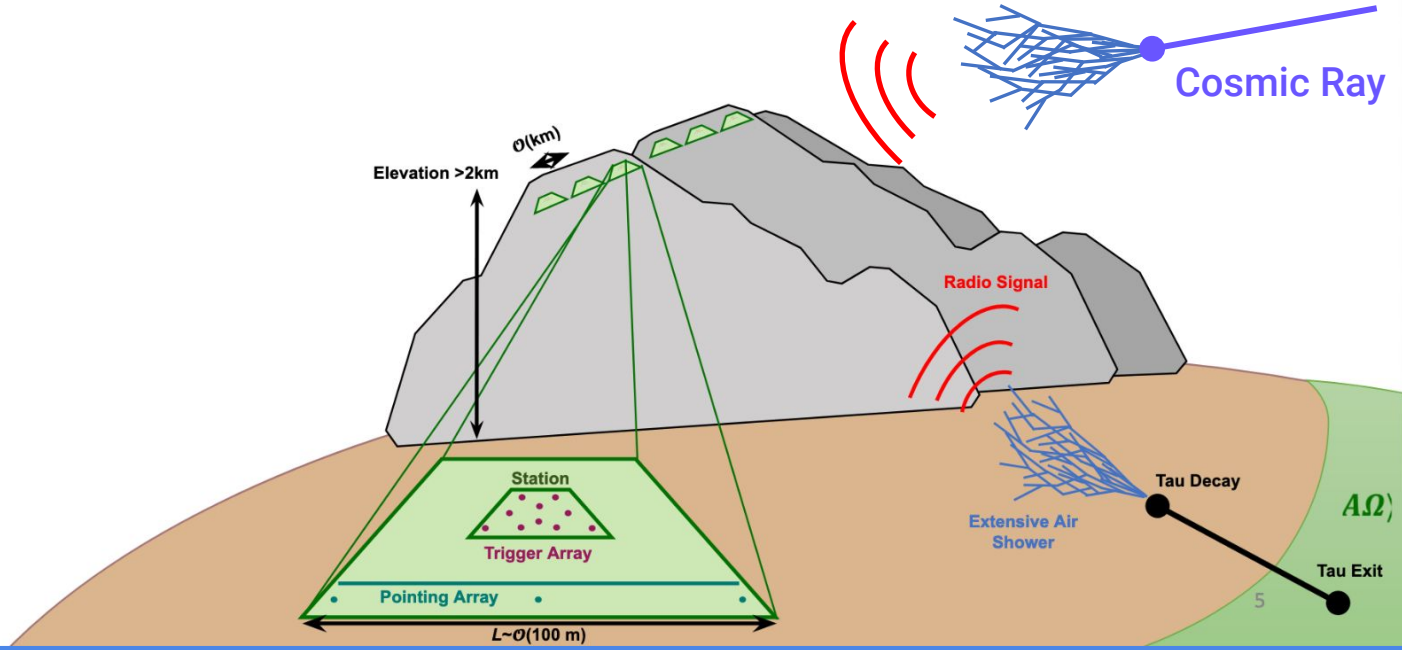
- *Goal* → Validate full instrument neutrino sensitivity
- *How* → Verify cosmic ray (CR) air shower radio flux



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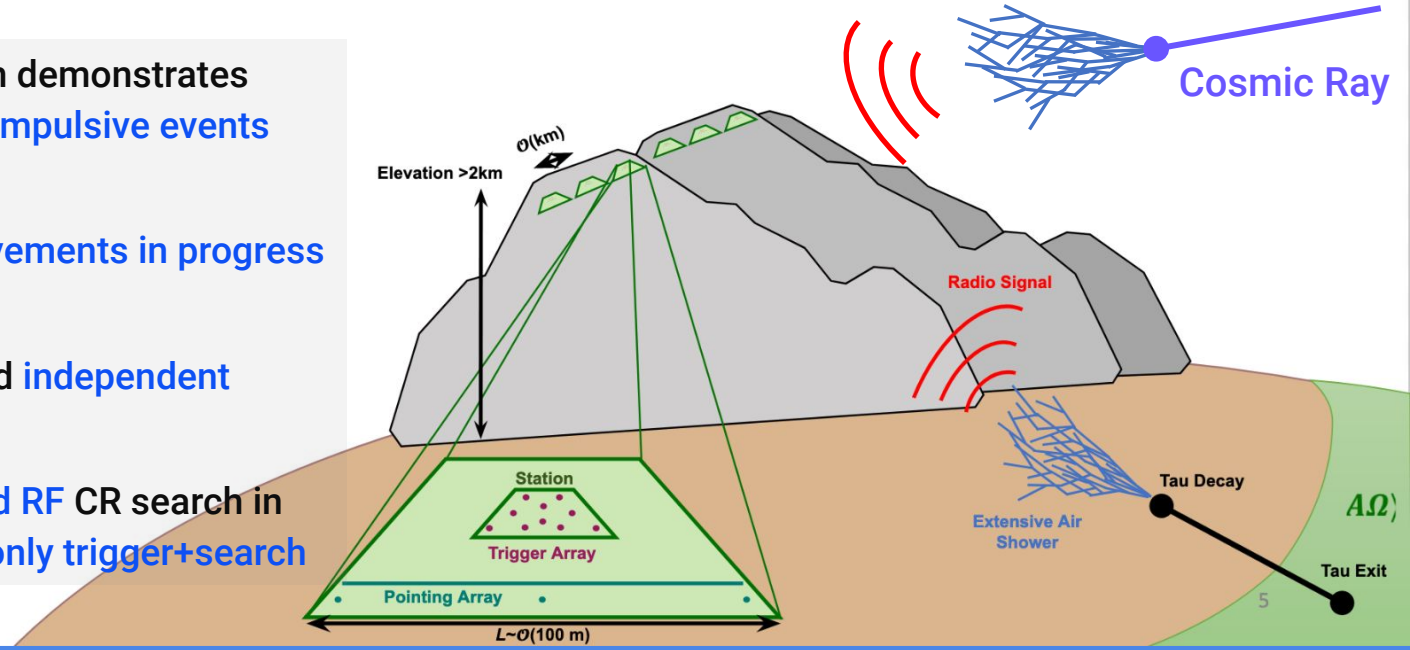
Presenting

- 2021 prototype CR search demonstrates capabilities to trigger on impulsive events (D. Southall)
- RF-only CR search improvements in progress (A. Zeolla)
- 2023 upgrades introduced independent scintillator array
- Coincident scintillator and RF CR search in progress to optimize RF-only trigger+search



BEACON 2021 Prototype

What are we working with?

BEACON 2021 Prototype

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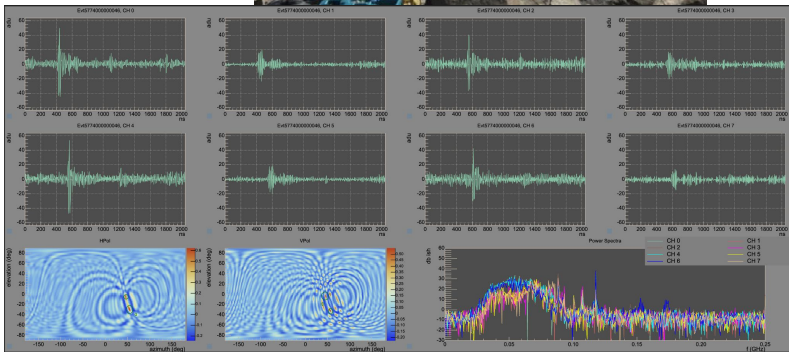
- 2.4 km prominence at White Mountain Research Station, CA

- Array of 4 Cross-Polarized Dipole Antennas (@ 30 - 80 MHz)

arXiv:2206.09660



"Monutau" Cosmin Deaconu (UChicago)

BEACON 2021 Prototype

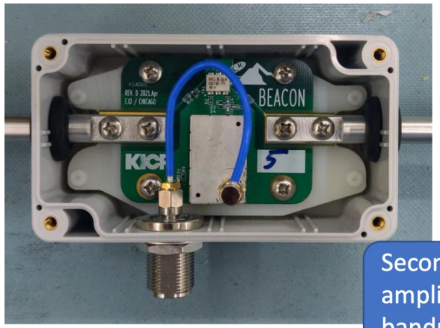
What are we working with?

- 2.4 km prominence at White Mountain Research Station, CA

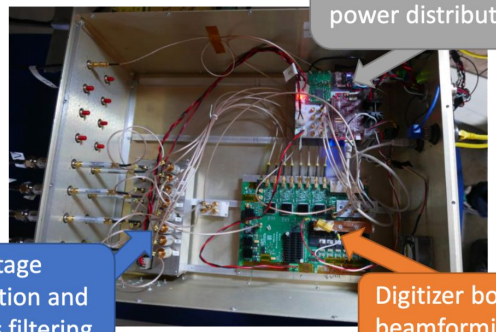
- Array of 4 Cross-Polarized Dipole Antennas (@ 30 - 80 MHz)
- Phased array RF triggers (Power+Direction thresholds)

→ CR search with RF only

(+Forced clock triggers for backgrounds)



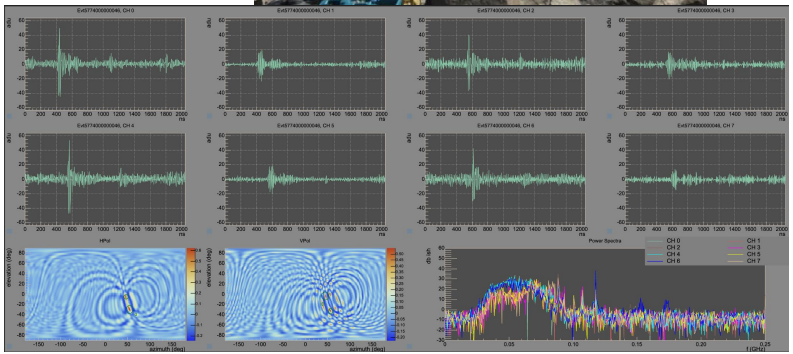
Second stage amplification and bandpass filtering



Single board computer, GPS clock, power distribution

Digitizer board and beamforming trigger

ARA DAQ



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RF Events & Simulation

What do we expect?

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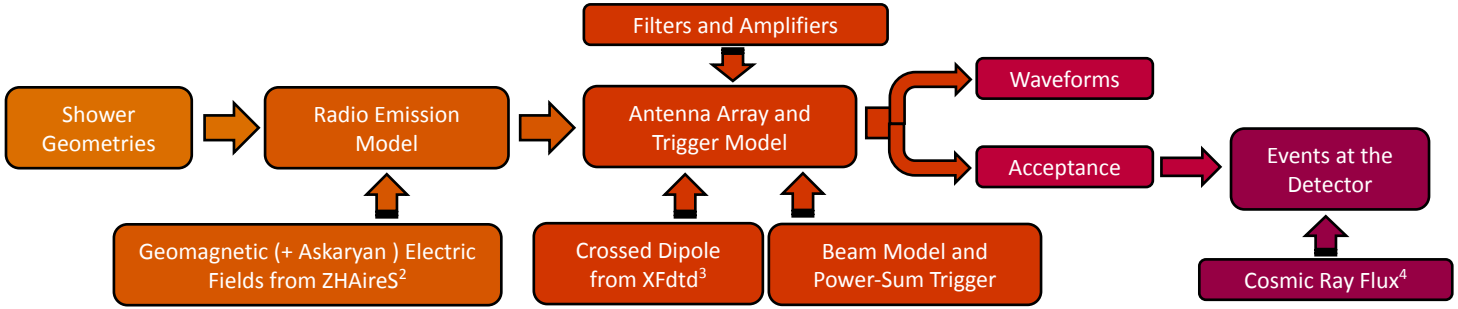
Expected **RF event distribution** obtained from Monte Carlo simulations using Cranberry

Cranberry[1]:



1) Nucl. Instrum. Methods Phys. Res. A 953, 163086

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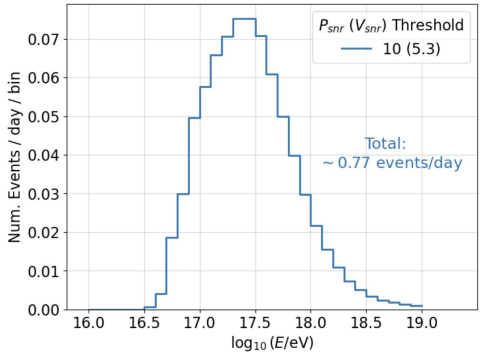
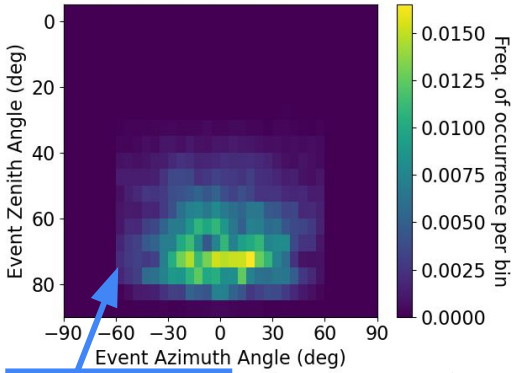
Expected CR Distributions from Simulation





Andrew Zeolla

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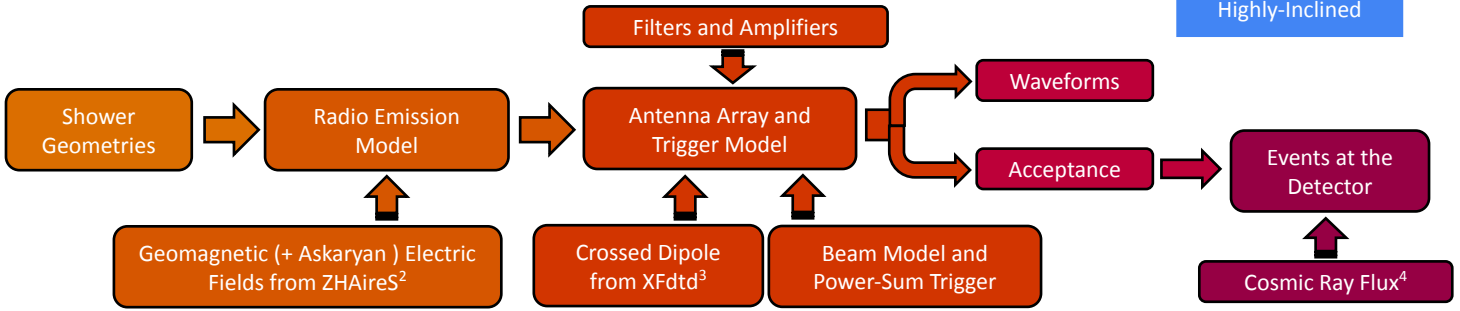

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Impulsive Events Search

What was found?

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112 days of data (expecting ~80 CR)

Cut Name	Number of Events Remaining	Fraction Cut Sequentially	Fraction Cut if Applied First
Full Data Set	96,483,288		
Elevation	1,830,144	0.98	0.98
Azimuth	1,145,593	0.37	0.0075
Time Delay Clustering, HPol	1,116,064	0.026	0.95
Time Delay Clustering, VPol	1,104,002	0.011	0.85
Peak-to-Sidelobe Ratio	201,926	0.82	0.065
Impulsivity	57,669	0.71	0.029
Cosmic Ray Template Correlation	42,184	0.27	0.028
Associated with Below-Horizon Sources	38,274	0.93	0.79
Signal Amplitude Differences	15,809	0.59	0.0038
Combined Normalized Map Peak Value	7,894	0.50	0.23
Combined Peak-to-Peak/(2 * Standard Deviation)	5,440	0.31	0.044
Hand-inspection breakdown of the 5,440 passing events:		Number of Events	Fraction of Events
Likely mis-reconstructions from below the horizon and Events with unstable amplifiers		4,081	0.75
Events associated with airplanes		1,323	0.24
Remaining above-horizon events		36	0.0066

Dan Southall (UChicago)

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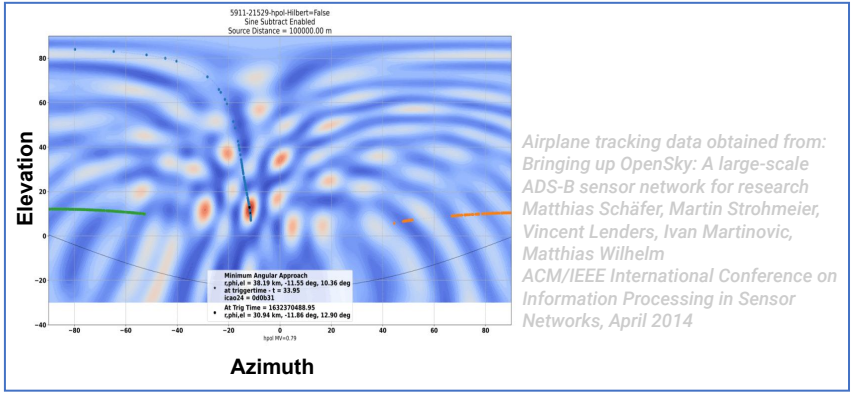

Airplane tracking data obtained from: Bringing up OpenSky: A large-scale ADS-B sensor network for research Matthias Schäfer, Martin Strohmeier, Vincent Lenders, Ivan Martinovic, Matthias Wilhelm ACM/IEEE International Conference on Information Processing in Sensor Networks, April 2014

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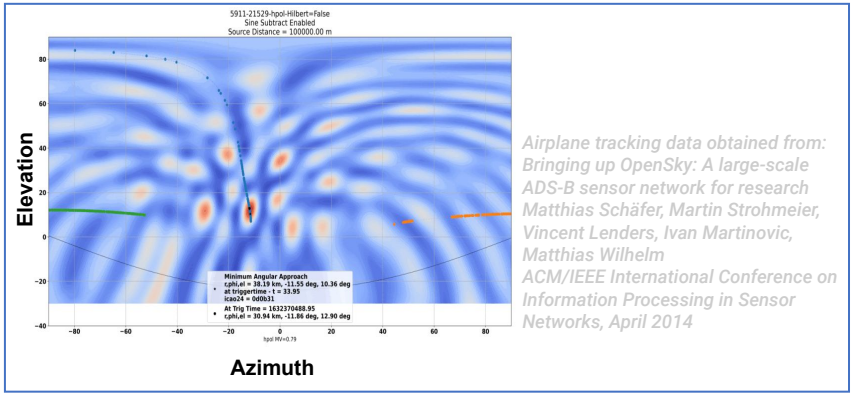

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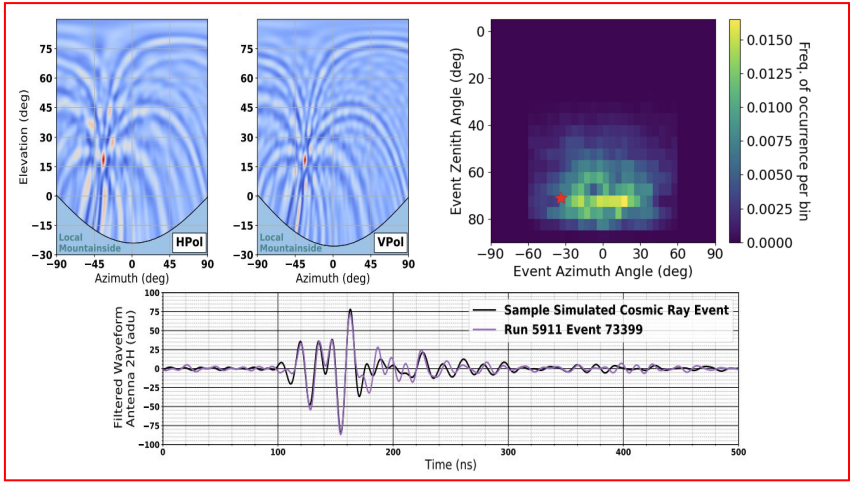


Cosmic-ray candidate event identified (by-eye)

Dan Southall (UChicago)

Improving CR Search from RF Using CNNs

How to do better?

Improving CR Search from RF Using CNNs

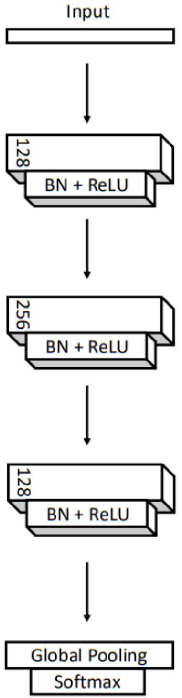
How to do better?

Convolutional Neural Networks (CNN) are deep learning models that can **extract features** of datasets based on weighted parameters determined from training

Has been applied to **Time Series Classification (TSC)** many times already (health care, earthquake detection, finance, etc.)

Z. Wang, W. Yan, T. Oates arXiv:1611.06455

General Example of CNN Layer Structure



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So, CNN can be **trained with CR simulations & triggered RF data** to classify data groups:

- Force-triggered events (**noise**)
- RF-triggered events (**background**)
- Cosmic rays (**simulated**)

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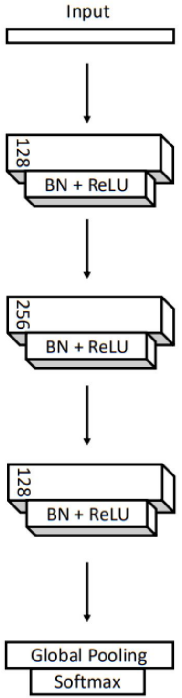

CR Search Flow and Results (WIP)

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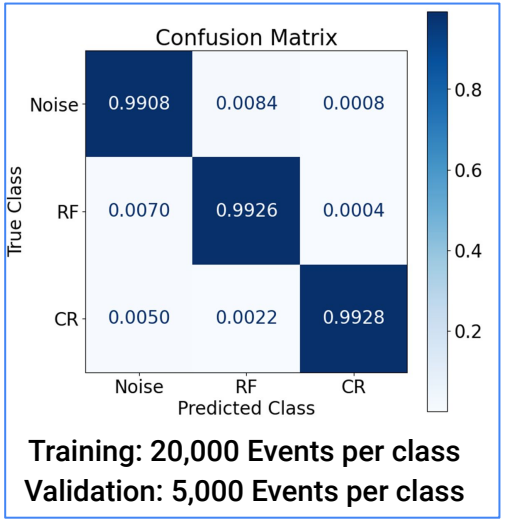
CNN Classification

RF vs CR-like



Training: 20,000 Events per class
Validation: 5,000 Events per class

Andrew Zeolla (PennState)

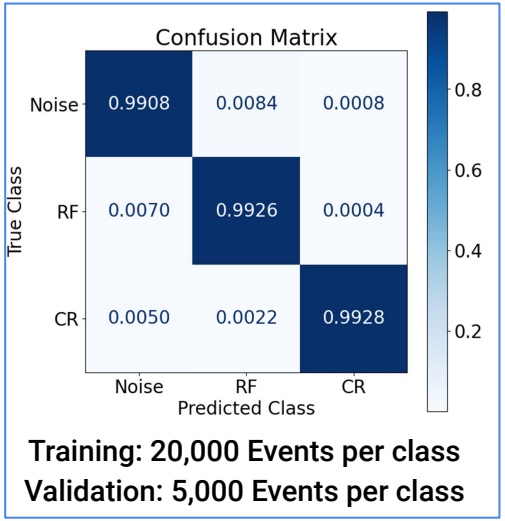
CR Search Flow and Results (WIP)

CNN Classification → CNN Denoiser → Event Reconstruction

RF vs CR-like

Noise Subtraction

Pointing with Waveform Correlation



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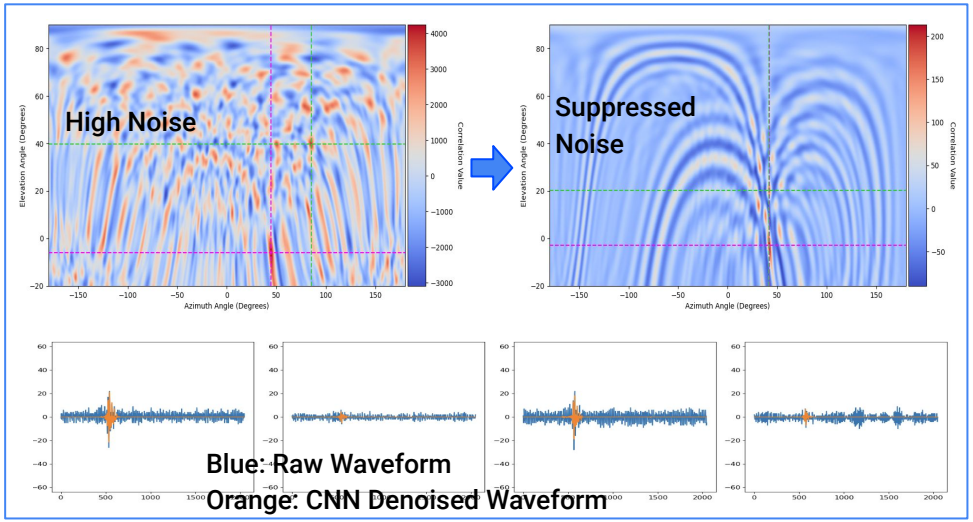


Blue: Raw Waveform

Orange: CNN Denoised Waveform

Andrew Zeolla (PennState)

CR Search Flow and Results (WIP)

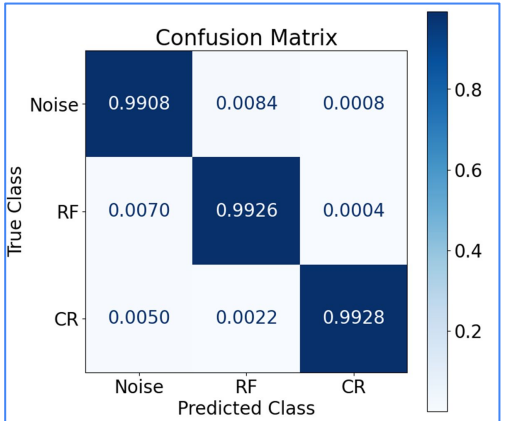
CNN Classification → CNN Denoiser → Event Reconstruction → Zenith & Azimuth Cuts

RF vs CR-like

Noise Subtraction

Pointing with Waveform Correlation

30 < Zen < 85
-60 < Az < 60



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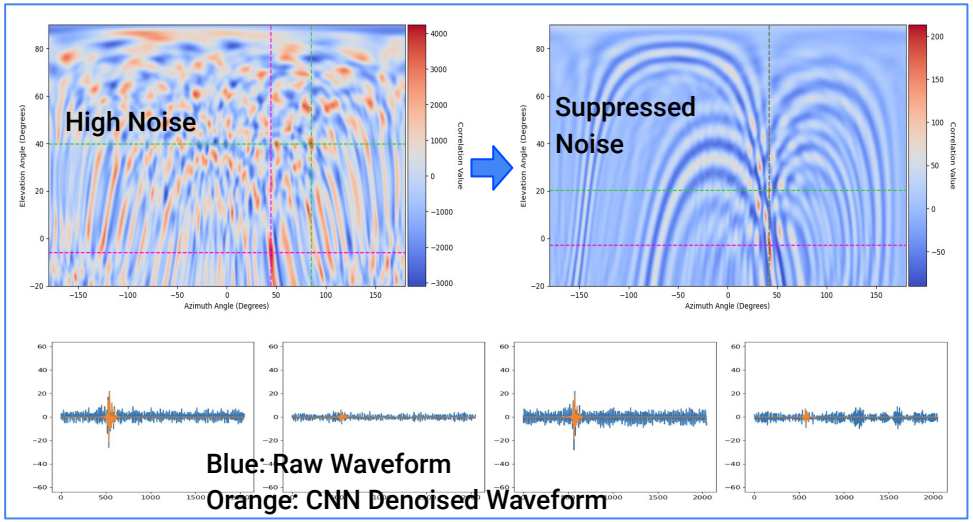

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CR Search Flow and Results (WIP)

CNN Classification → CNN Denoiser → Event Reconstruction → Zenith & Azimuth Cuts → Temporospatial Cuts (?) → ??? → Cosmic Ray Population

RF vs CR-like

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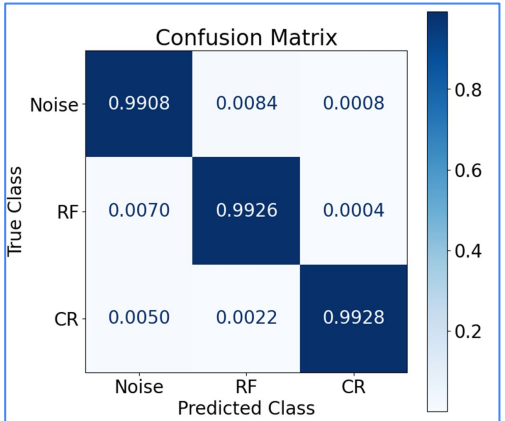
Clustering



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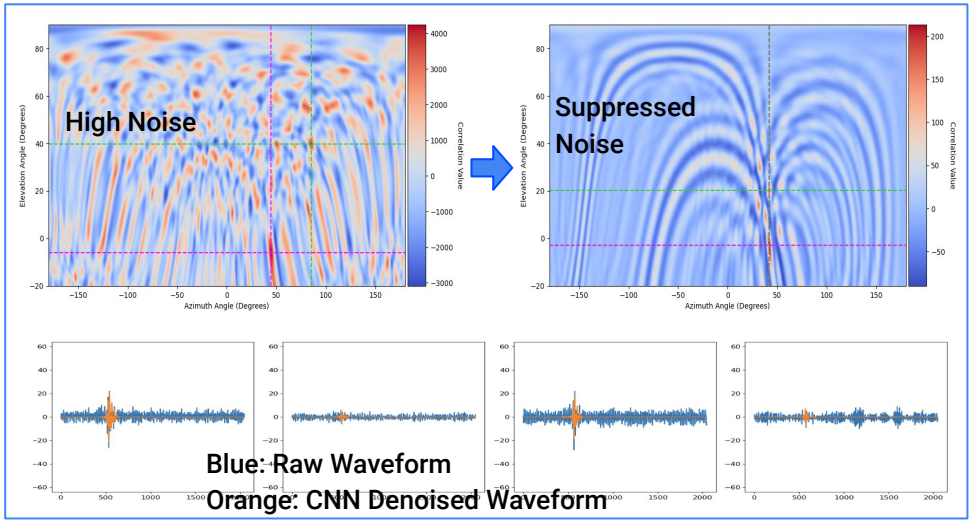
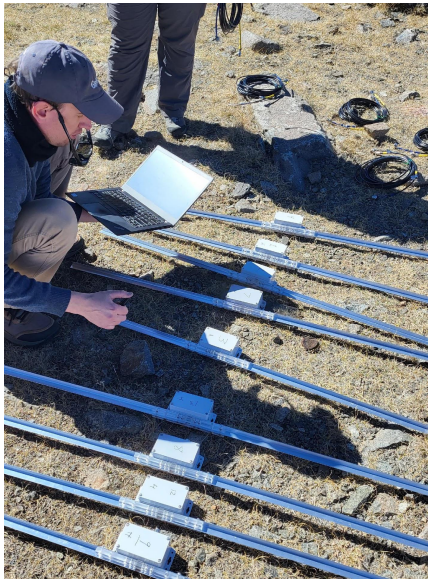


How did the CNN do? What features are not handled by the CNN? (WIP)

Andrew Zeolla (PennState)

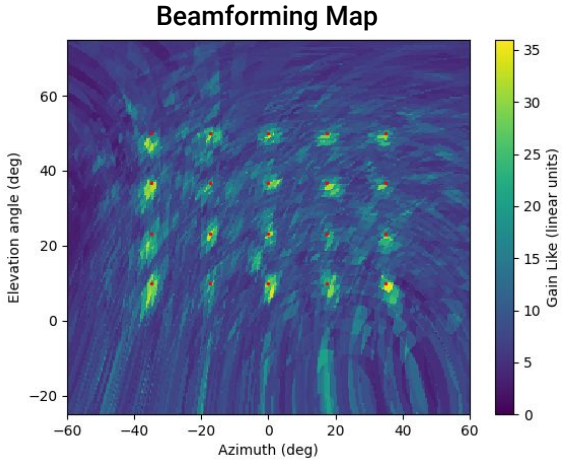
BEACON 2023 Upgrades



2023 Improved Antennas & DAQ

Antennas

- 4 antennas → 6 antennas
  (improved sensitivity & reconstruction)
- Side-mounted T-bar tines (greater strength)



Ryan Krebs (PennState)

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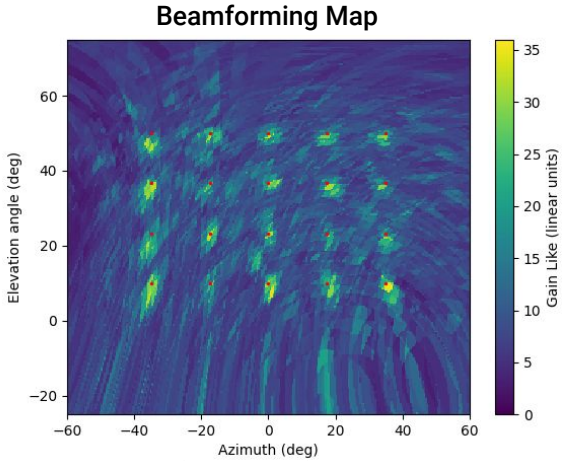
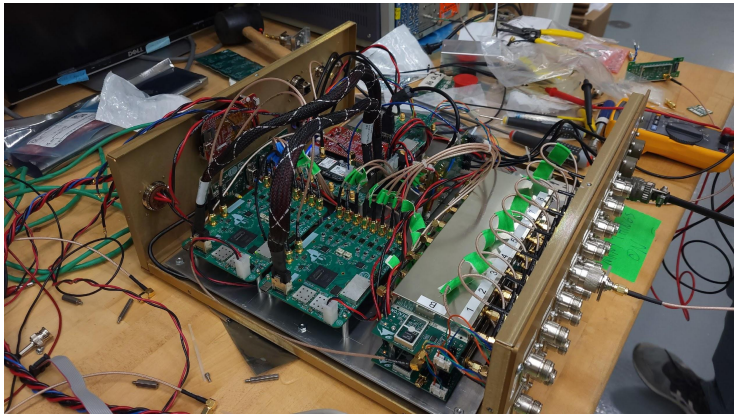


Ryan Krebs (PennState)

DAQ

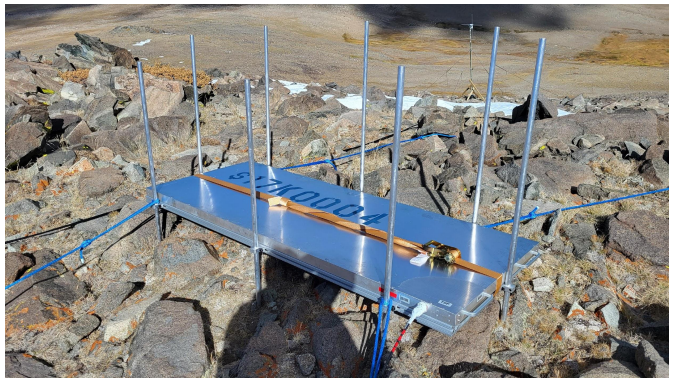
- 8 channels → 16 channels
- Modular FLOWER boards:
  - 8 ch/board, 500 GSa/s, onboard FPGA for phased array triggering
- Coincidence & Beamforming triggers



Eric Oberla (UChicago)

2023 Independent Scintillator Array

- New independent detector array of scintillators
    - CR population from muon flux
    - Verifies CR detection to assist RF trigger optimization



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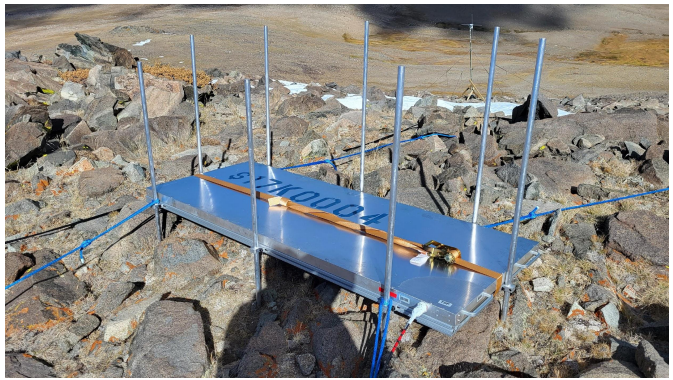

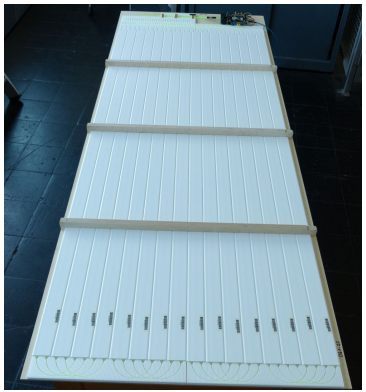

Scint Panels (B. Hoffmann, M. Oehler) IceCube Collaboration

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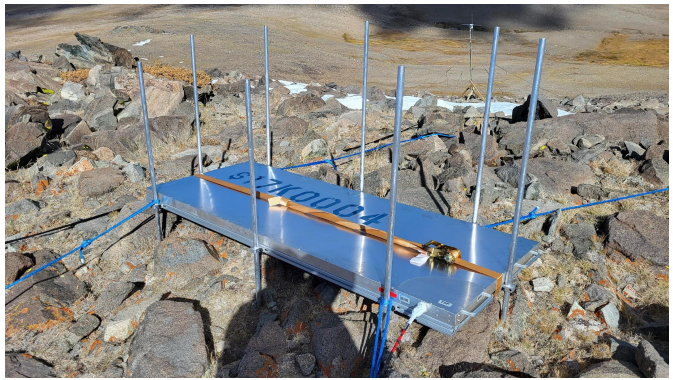

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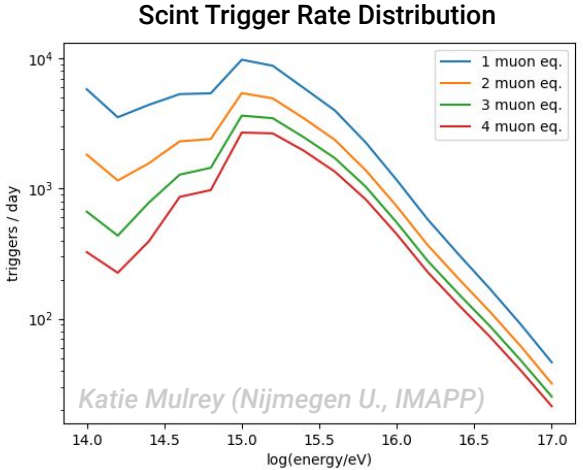
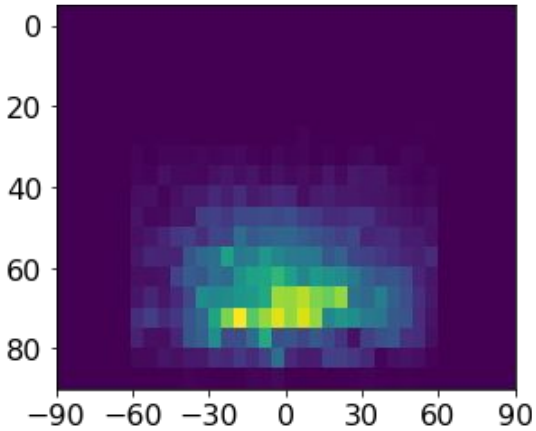


CORSIKA + GEANT-4 particle simulations give order of magnitude estimate trigger rate

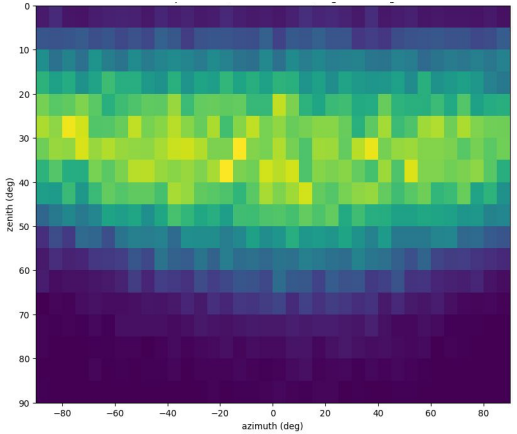
Expect **0.1-100 scint events per day in RF-sensitive energy region** (extrapolating to 10^{19}eV)

RF-Scint Expectations

Simulated RF Event Distribution



Preliminary Scintillator Event Distribution

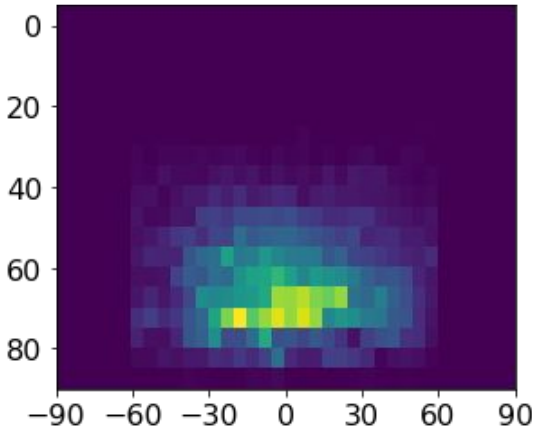


RF-Scint Expectations

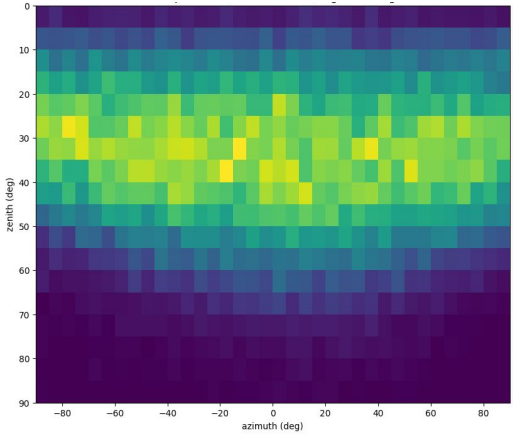
RF-Scint event overlap population depend on many aspects:

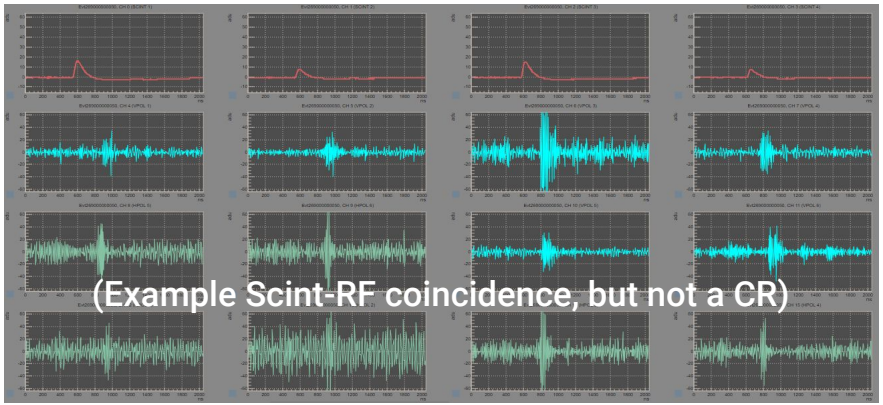
- High energy events
- Detector directional sensitivities
- RF vs Muon flux distributions

Simulated RF Event Distribution



Preliminary Scintillator Event Distribution





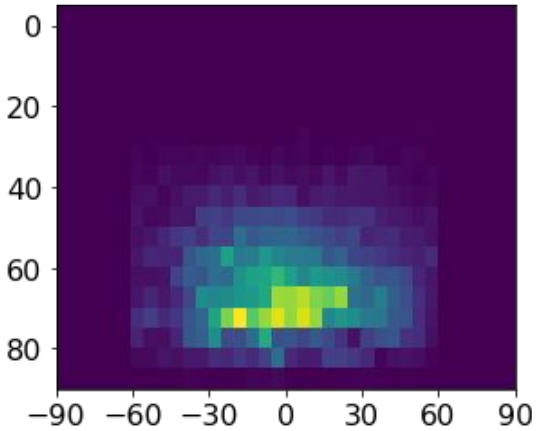
(Example Scint-RF coincidence, but not a CR)

RF-Scint Expectations

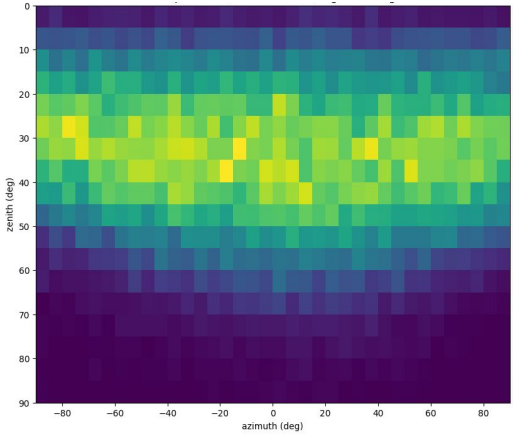
RF-Scint event overlap population depend on many aspects:

- High energy events
- Detector directional sensitivities
- RF vs Muon flux distributions

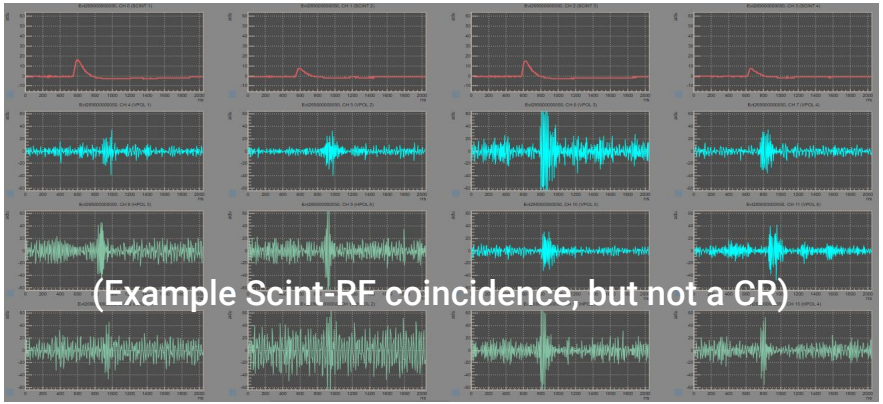
Simulated RF Event Distribution



Preliminary Scintillator Event Distribution



Scintillator implementation into Cranberry simulations will give an expected coincident event rate in both detectors (WIP)

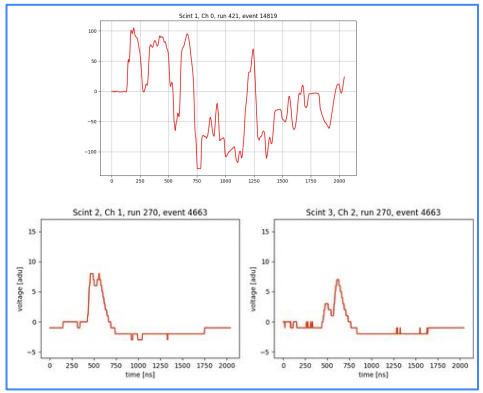


(Example Scint-RF coincidence, but not a CR)

Scintillator CR Search for RF Optimization

Scintillator CR Search for RF Optimization

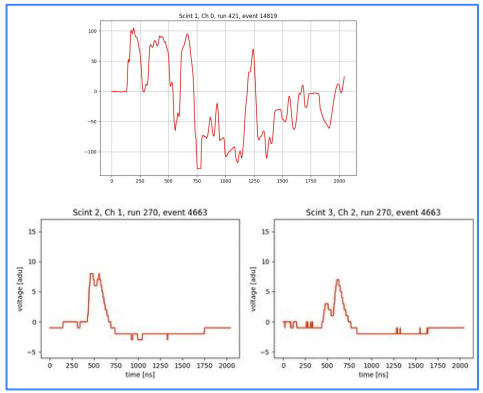
Scint Quality Cuts



Scintillator CR Search for RF Optimization

Scint Quality Cuts → Scint Characteristic Cuts

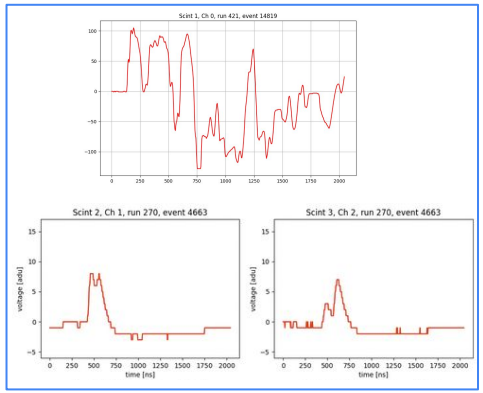
- Max Voltage
- Peaks
- Temporospatial Clustering
- etc.

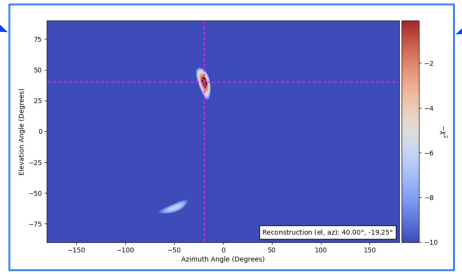


Scintillator CR Search for RF Optimization

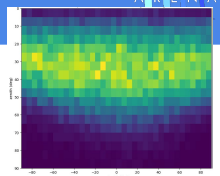
Scint Quality Cuts → Scint Characteristic Cuts → Scint Reconstruction → Scint Zenith/Azimuth Cuts

- Max Voltage
- Peaks
- Temporospatial Clustering
- etc.

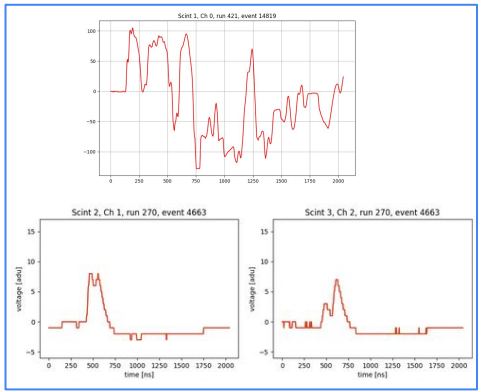




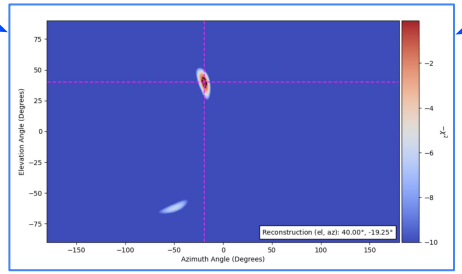
Scintillator CR Search for RF Optimization



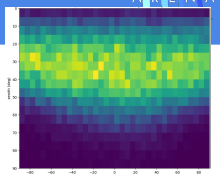
Scint Quality Cuts → Scint Characteristic Cuts → Scint Reconstruction → Scint Zenith/Azimuth Cuts → ??? → Scint CR Population



- Max Voltage
- Peaks
- Temporospatial Clustering
- etc.



Scintillator CR Search for RF Optimization



Scint Quality Cuts → Scint Characteristic Cuts → Scint Reconstruction → Scint Zenith/Azimuth Cuts → ??? → Scint CR Population

- Max Voltage
- Peaks
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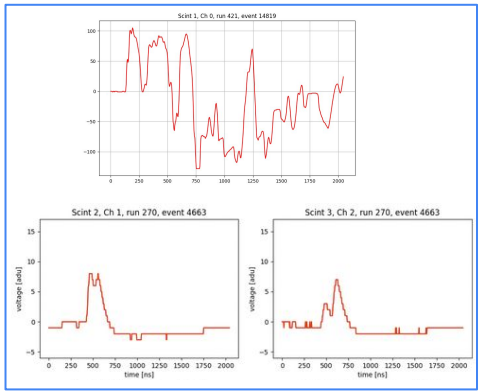
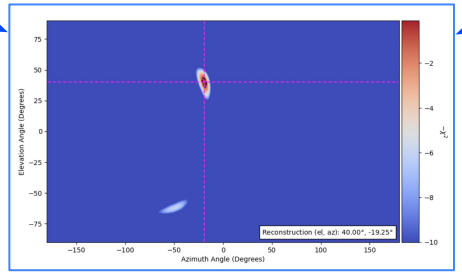
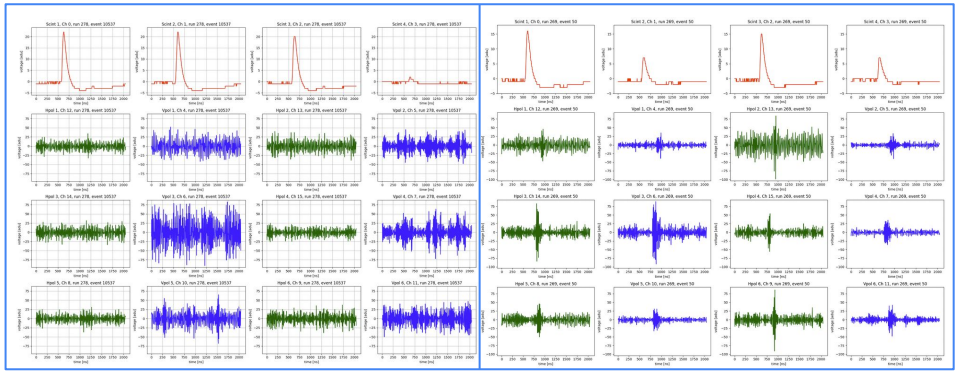
- etc.





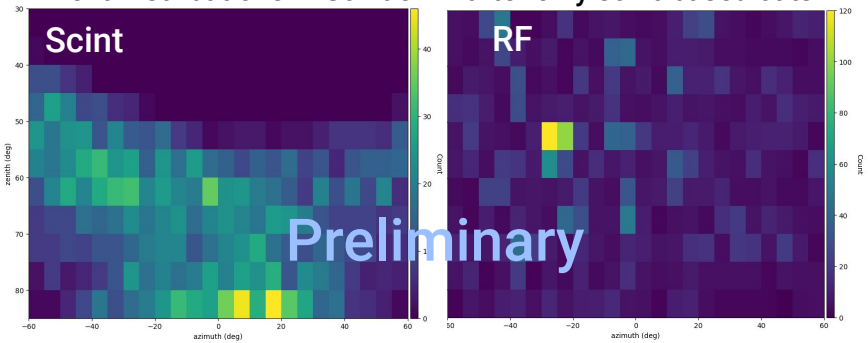


Scint CR Population → Conservative RF cuts → ??? → Scint-RF CR Population

Preliminary Results

Preliminary Scint & RF cuts result in a few events out of ~70 days of data

Event Distributions in Scint & RF after only scint-based cuts



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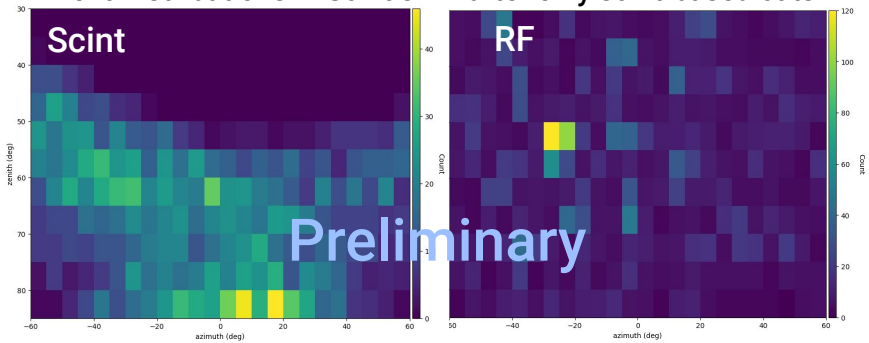
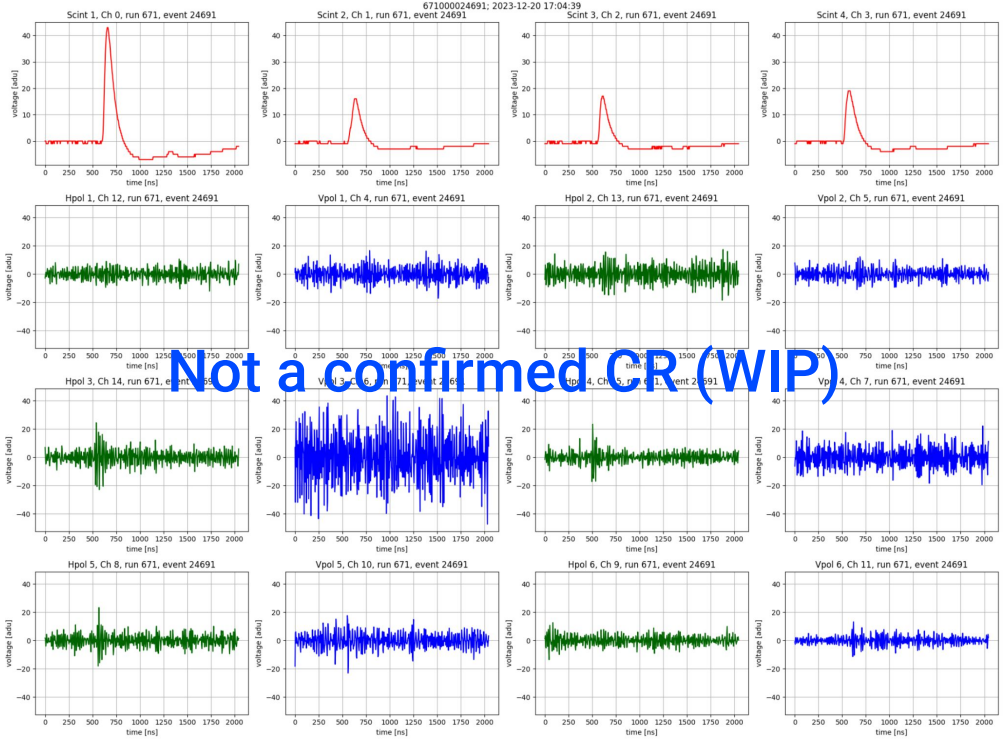




Not a confirmed CR (WIP)

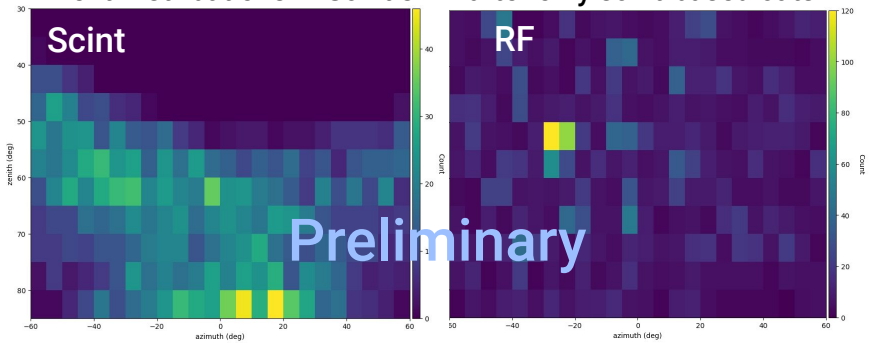
Preliminary Results

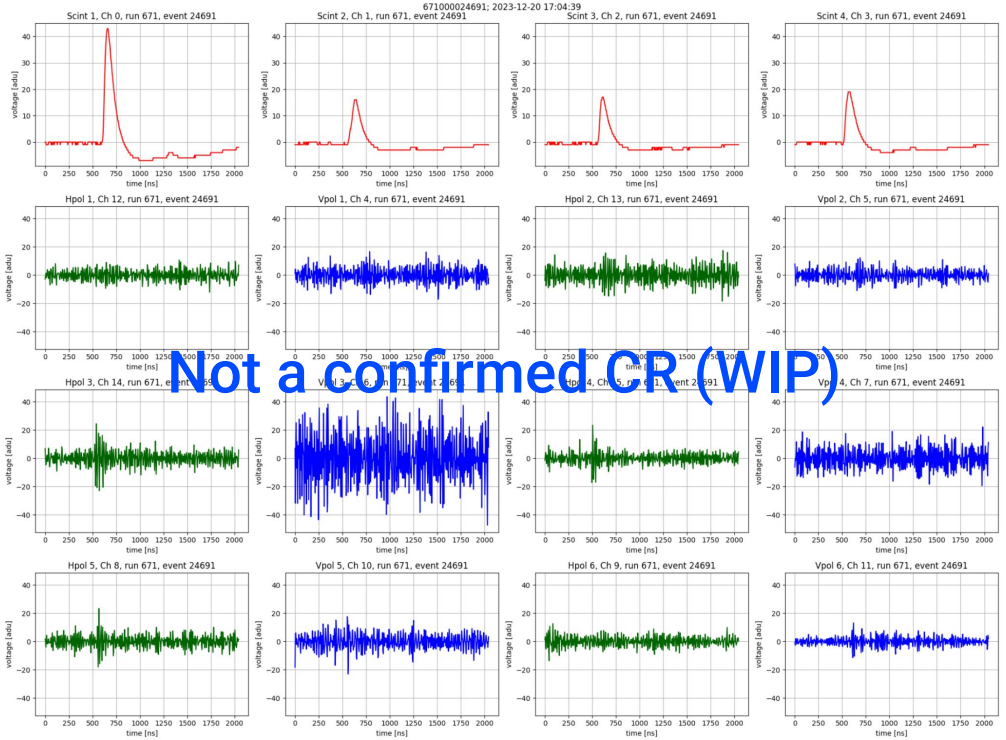
Preliminary Scint & RF cuts result in a few events out of ~70 days of data

Future:

- Confirm CR in RF using sims
- Iterate on analysis accuracy (backgrounds)
- Optimize RF search w/ RF-Scint CRs

Event Distributions in Scint & RF after only scint-based cuts





Not a confirmed CR (WIP)

Summary

- BEACON prototype sensitive to impulse events / CRs
- CR search will verify full BEACON sensitivity to ν's
- WIP for search improvements using RF
- WIP using independent scintillator array CR search to optimize RF-only search & trigger

BEACON

PennState

The Ohio State University

USC Universidade de Santiago de Compostela

KU The University of Kansas

Kavli Institute for Cosmological Physics at The University of Chicago

Radboud Universiteit

GSSI

JPL Jet Propulsion Laboratory California Institute of Technology

White Mountain Research Center

NSF

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USC Universidade de Santiago de Compostela

KU The University of Kansas

NSF

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Radboud Universiteit

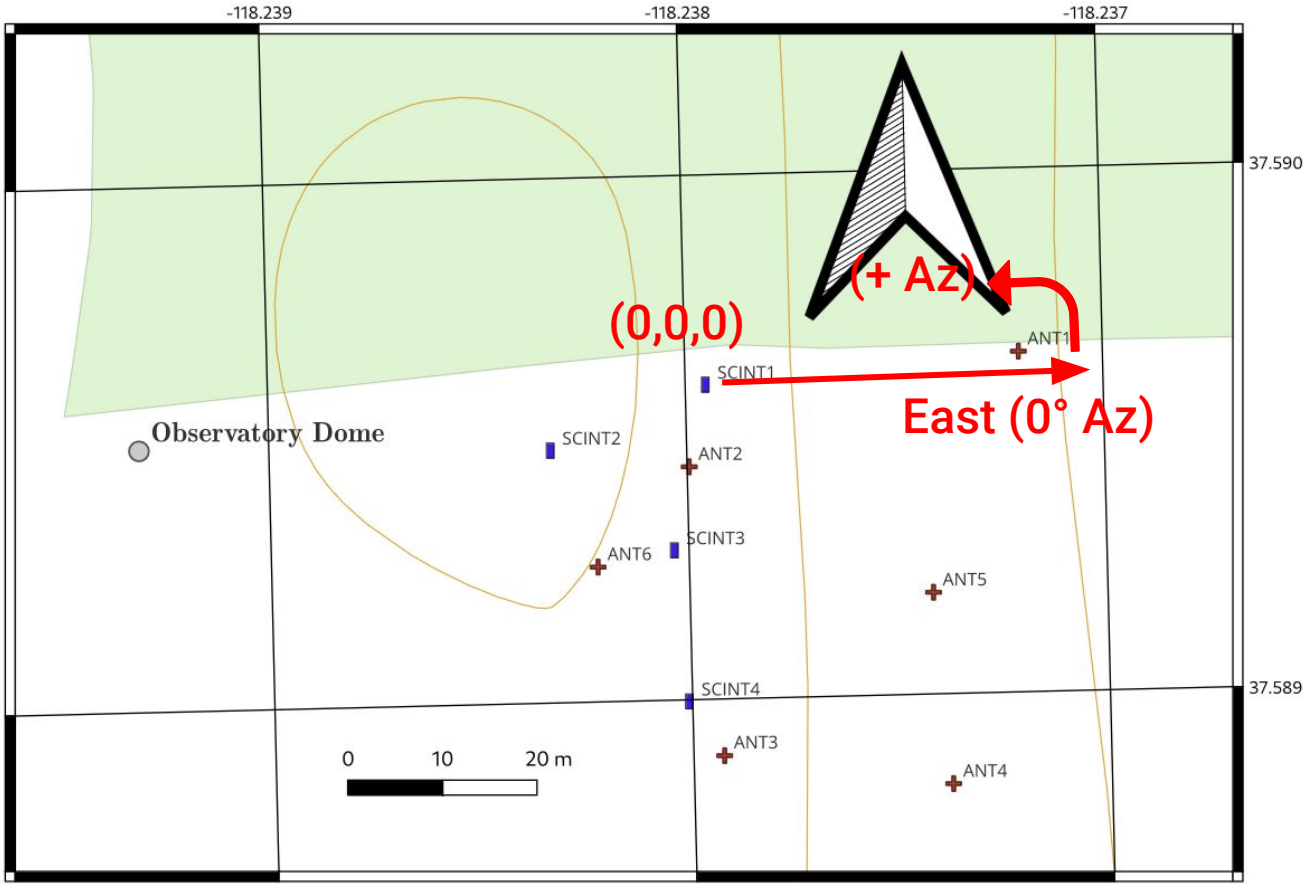
GSSI

JPL Jet Propulsion Laboratory California Institute of Technology

White Mountain Research Center

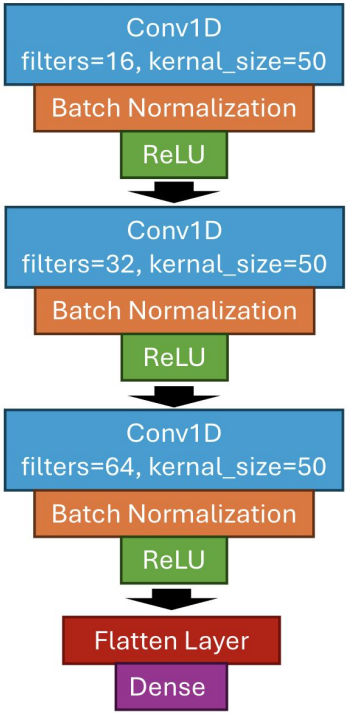
Backup/Extra Slides

Orientation

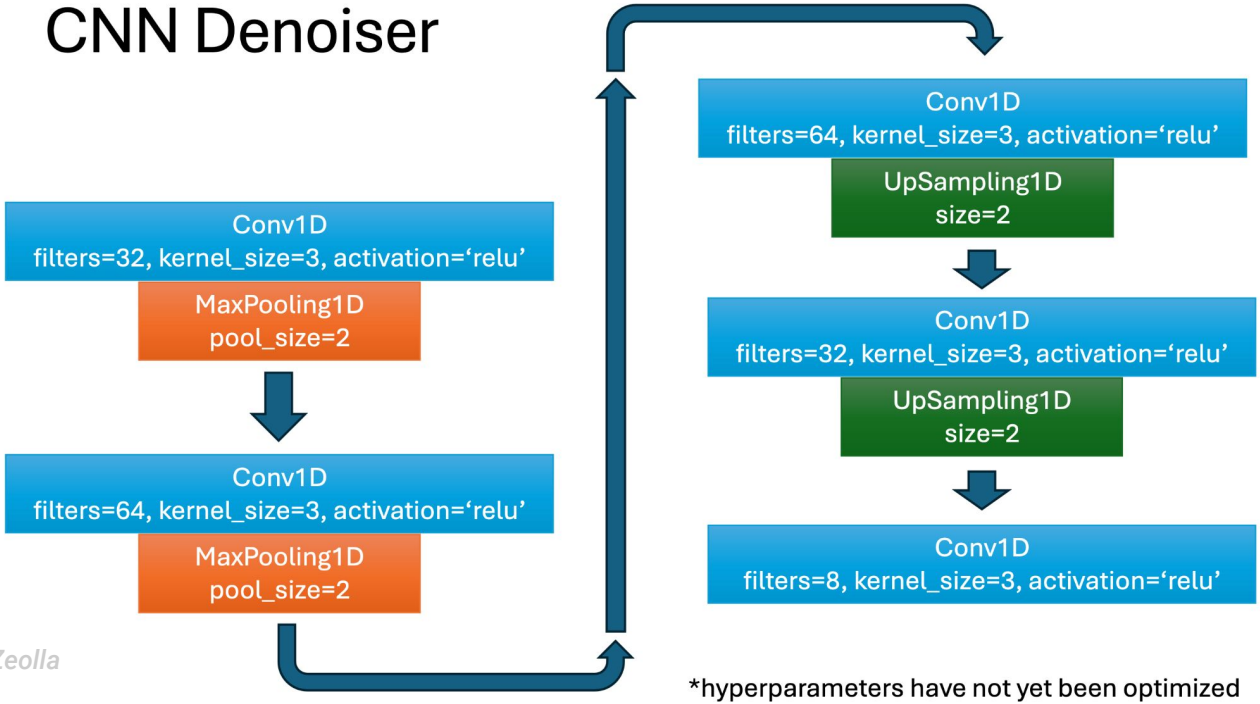


CNN Structures

CNN Classifier



CNN Denoiser



Andrew Zeolla

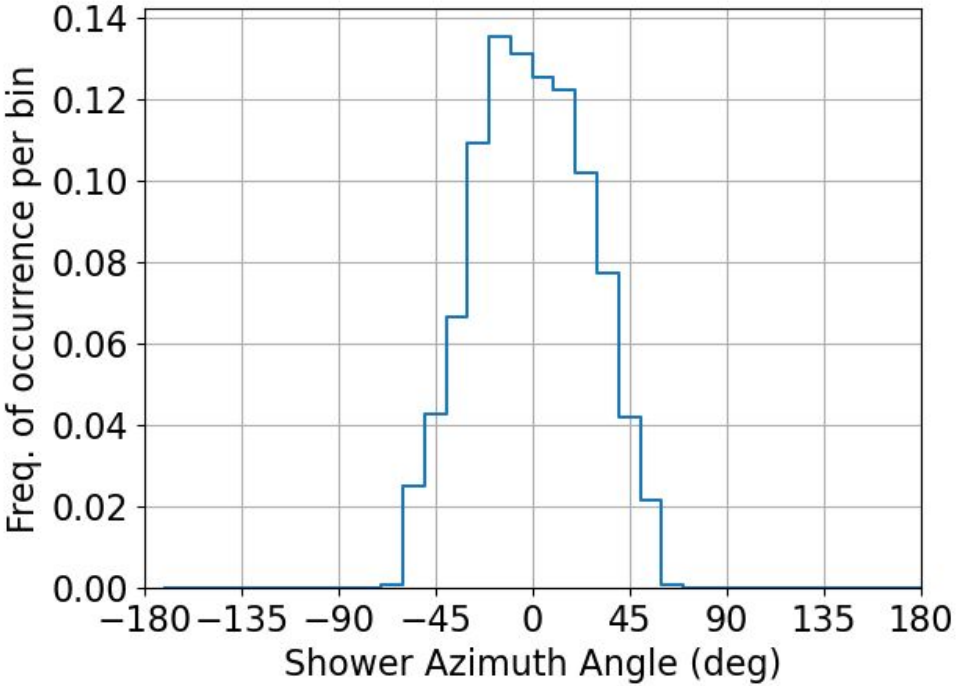
*hyperparameters have not yet been optimized

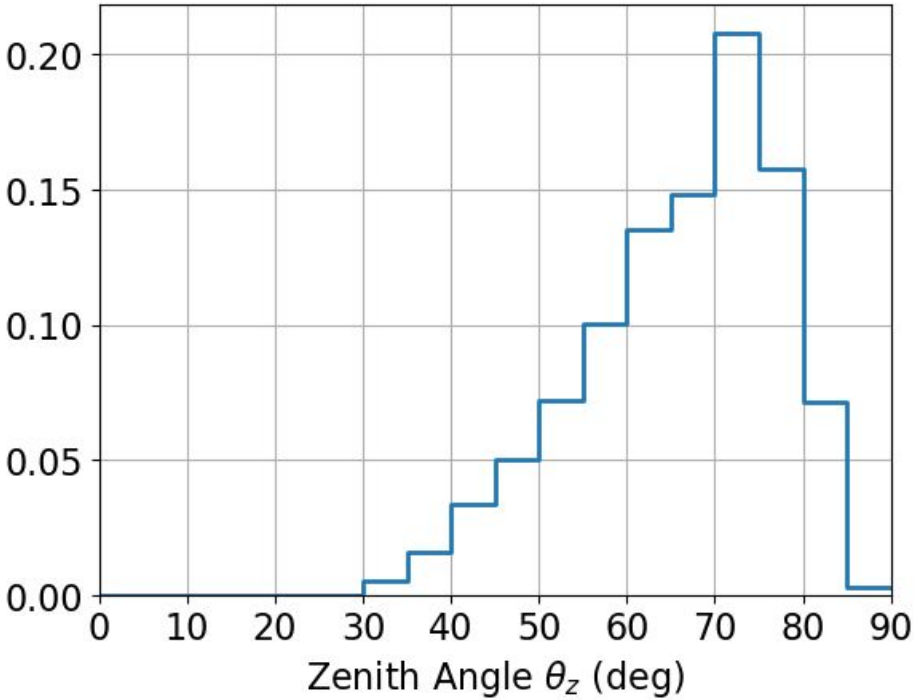
CNN Classification Cut

p_{CR} Cutc	Events Remaining	% of Events Cut
0.5	17,092	99.85%
0.75	12,263	99.89%
0.9	9,050	99.92%
0.95	7,452	99.94%
0.99	5,203	99.95%

Andrew Zeolla

RF (Simulated) 1D Distributions

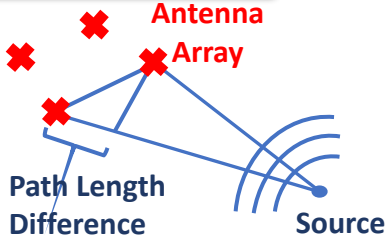




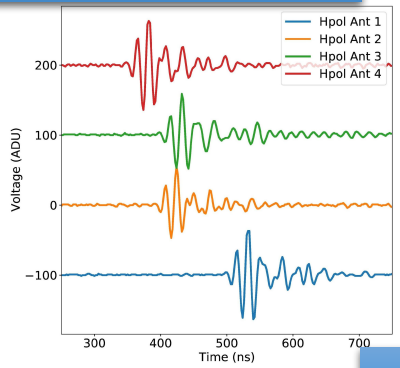
Andrew Zeolla

RF Pointing

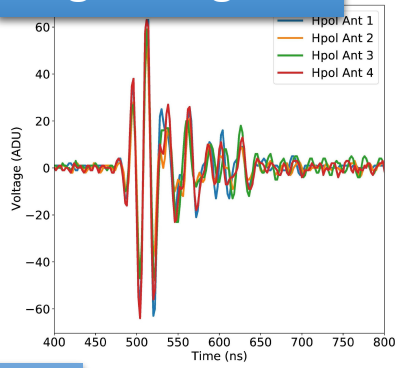
Geometry



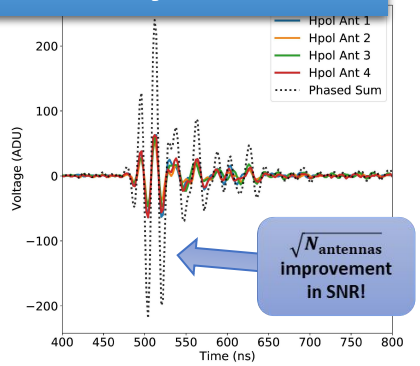
Received Signals



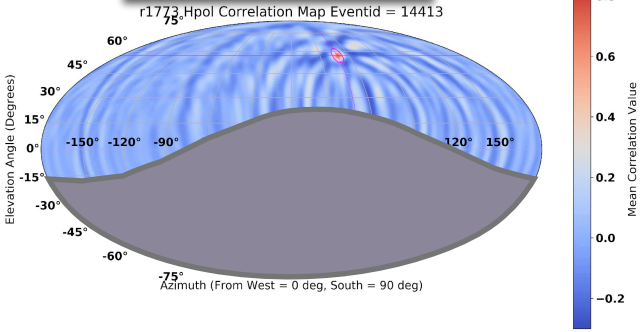
Aligned Signals



Coherently Summed

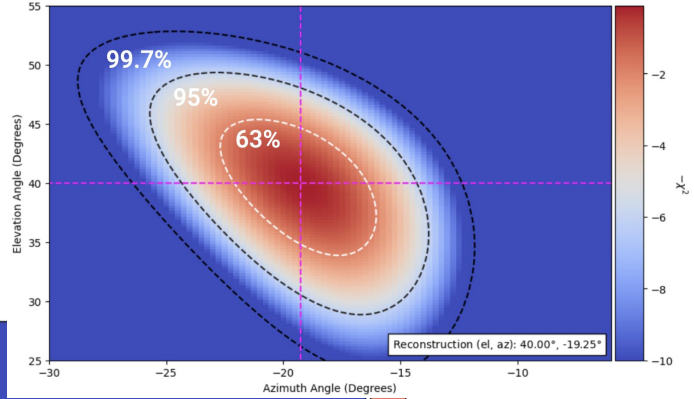


Pointing



Scint Pointing

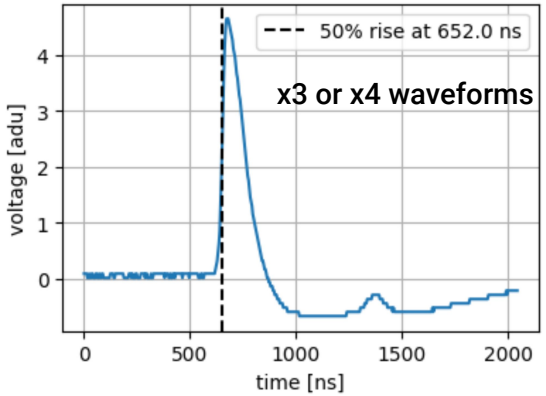
Likelihood curves give confidence intervals: exp(-□²/2)

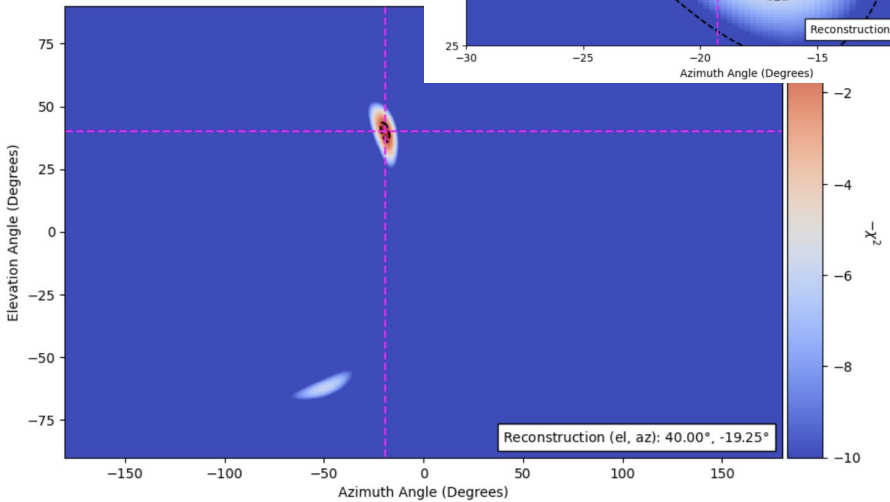


Minimizes 3 or 4 scints fitted to a plane wave

$$\chi(\theta, \varphi)^2 = \Sigma_{ij}(t_{meas,ij}(\theta, \varphi) - t_{exp,ij}(\theta, \varphi))^2 / \delta t_{ij}(\theta, \varphi)^2$$

Method: $t_{meas,ij}(\theta, \varphi)$ = 50% rise time





Cuts

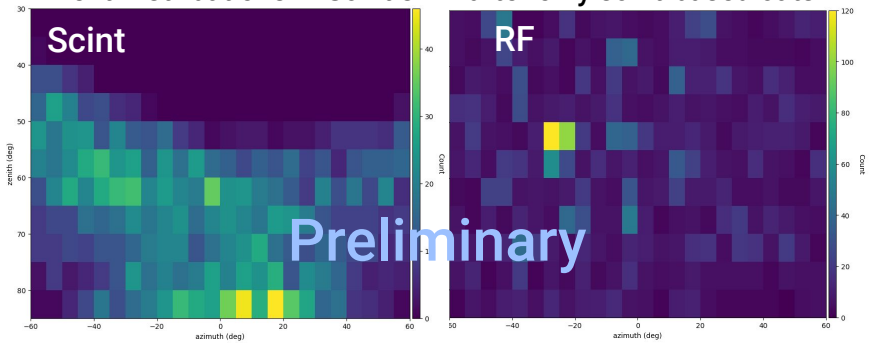
~70 days of data

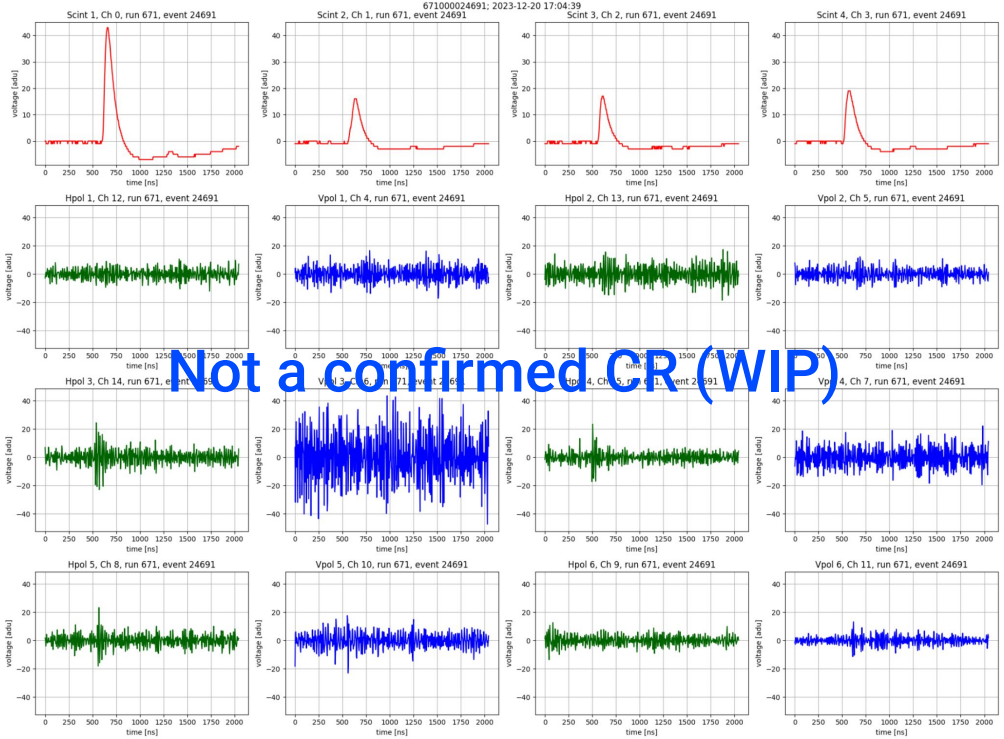
Scints

- Scint Triggered (4 scints)
- $\chi^2(\theta,\varphi) < 1$
- 10 ADU <= Vmax <= 120 ADU (max 127)
- 1 <= Peaks <= 4
- 30 < zenith < 85; -60 < Az < 60

- RF: Recon dist < 20 deg; SNR > 5; Pulse within 200ns

Event Distributions in Scint & RF after only scint-based cuts





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