TUNING INTO TAU NEUTRINOS

Stephanie Wissel
IIHE / ULB / VUB

BEACON Collaboration

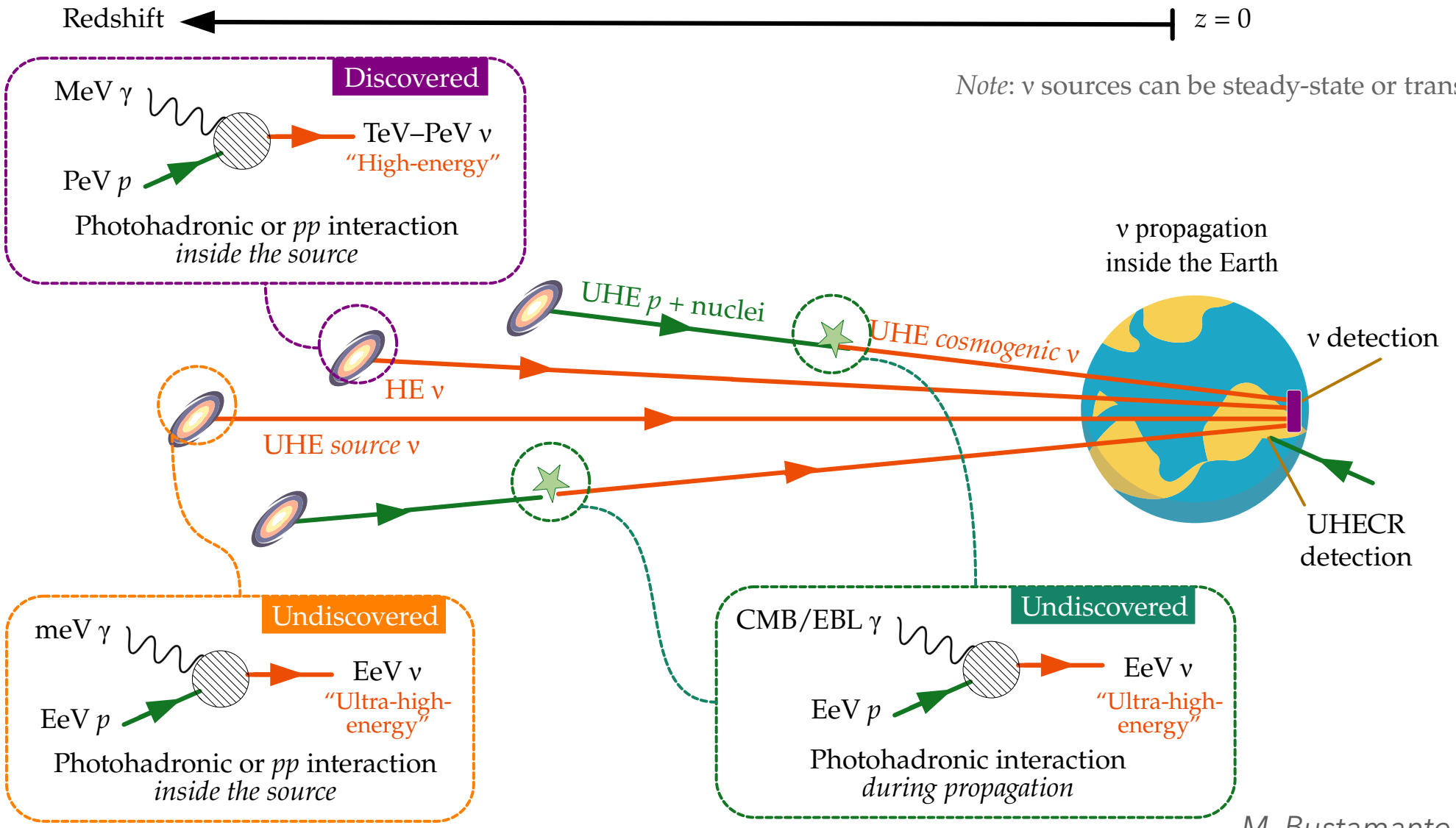
- Collaboration includes: Penn State, UChicago, University of Santiago Compostela, Ohio State, JPL, Radbound University
- Work presented here is largely due to three graduate students + one postdoc:

Andrew Zeolla, Penn State, soon to be at IAP

Dan Southall, UChicago, '22,

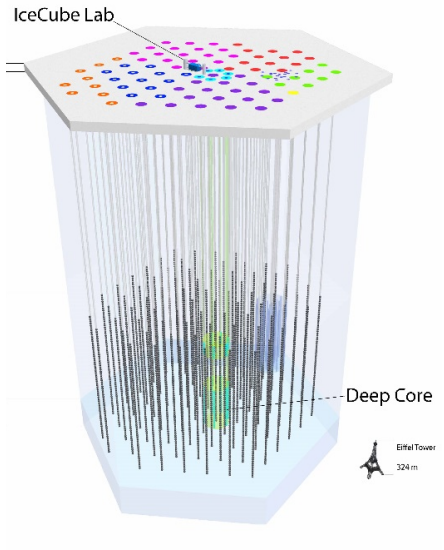
Austin Cummings, Penn State, postdoc

Zack Martin, UChicago


Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation

UHE ν's Need Large Exposures

The Challenge



IceCube 1 km^3

Interact rarely and the flux is low~E^{-2}

We need a bigger detector…

Cosmogenic neutrino rate

< 1 neutrino / km^2 sr / year

Interaction length ~ 300 km

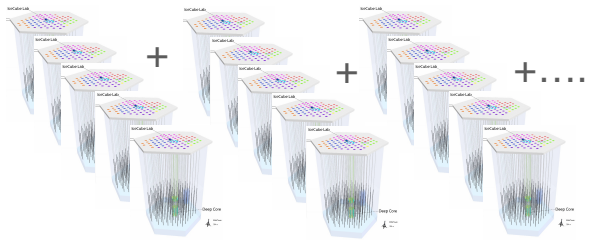
0.01 neutrino / km^3 sr / year

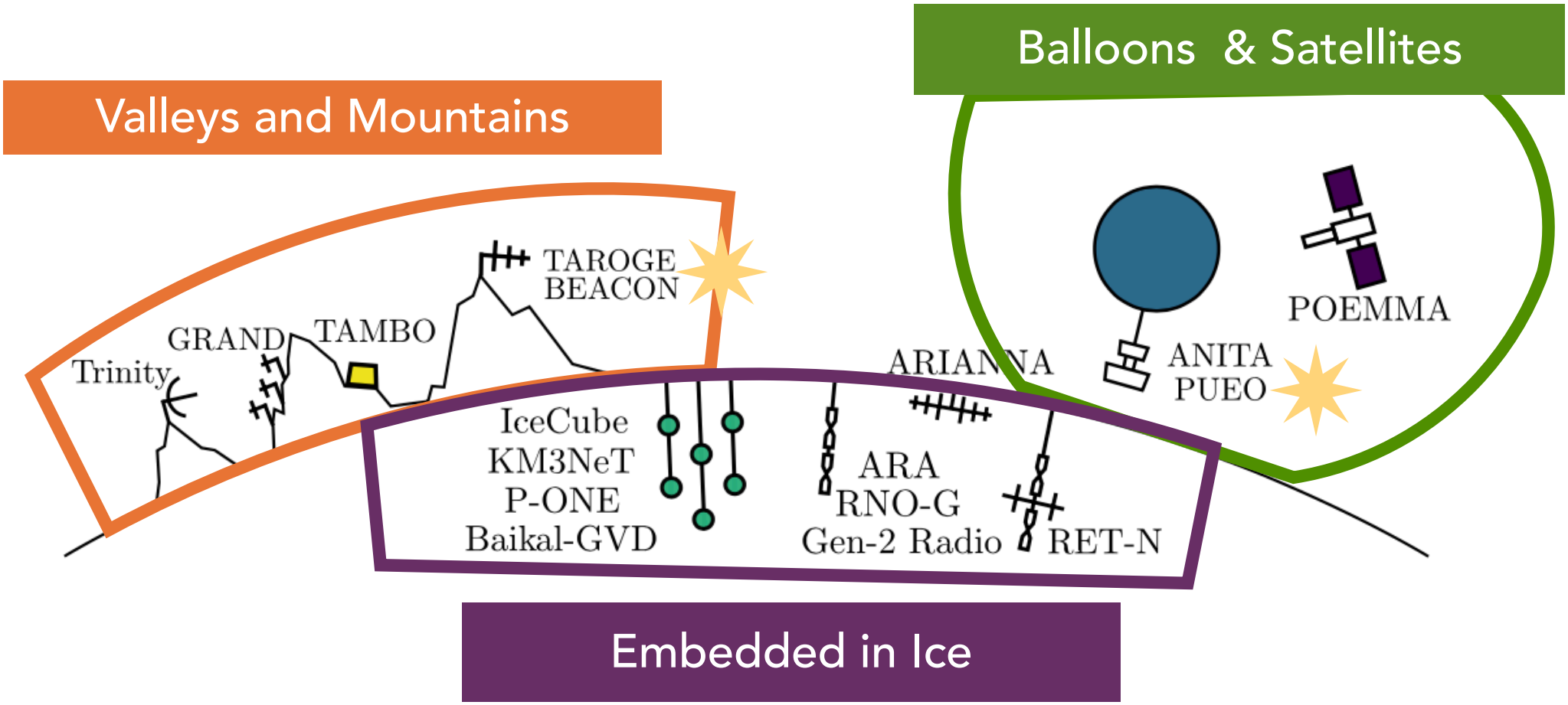
For 100 neutrinos:

1 km^3 × **100 years**

– or –

100 km^3 Detector Volume × **1 year**





Estaban, Prohira, Beacom 2022 arXiv:2205.09763

Why Radio?

- Long propagation lengths – $\mathcal{O}$(1-100's km)
- Low cost instrumentation – $\mathcal{O}$(\$1k) per channel
- Continuous data collection
- Polar ice and Earth's limb offer large natural neutrino targets

Large Detector with Minimal Instrumentation

In Ice

Balloons

Mountains

Several Options for Detector Geometries

Earth Skimming ν_τ

- Neutrino cross-section grows with energy. At ultrahigh energies, the Earth is opaque
- Due to flavor-mixing, an equal number of ν_e, ν_μ, ν_τ arrive at Earth
- UHE ν_τ can skim the Earth, interact within, and have the resulting τ-lepton decay just above the surface
- Earth acts as a filter for ν_τ
- The resulting extensive air shower produces a detectable radio impulse

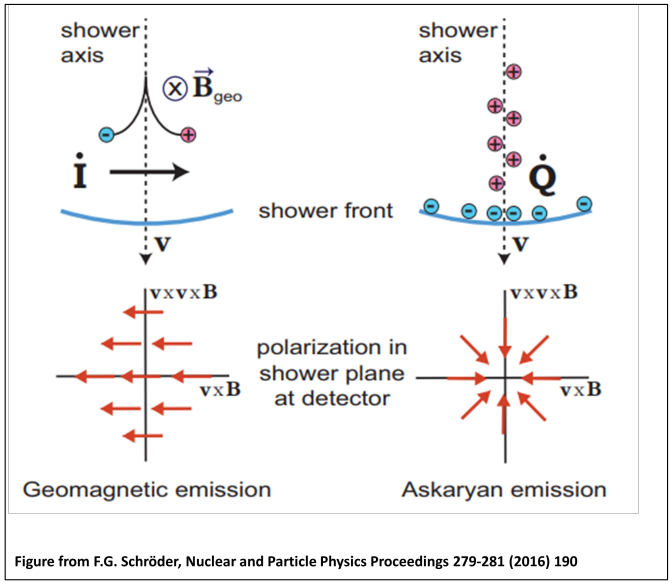
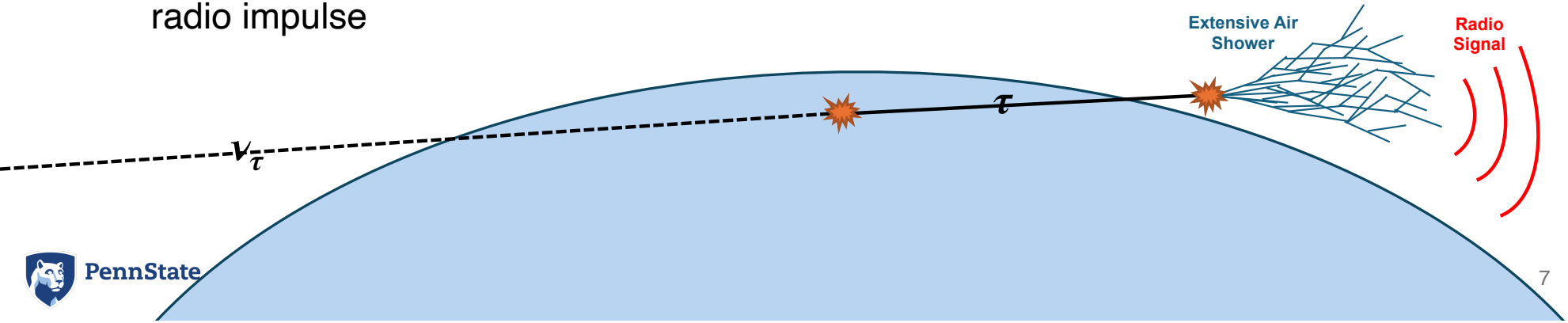
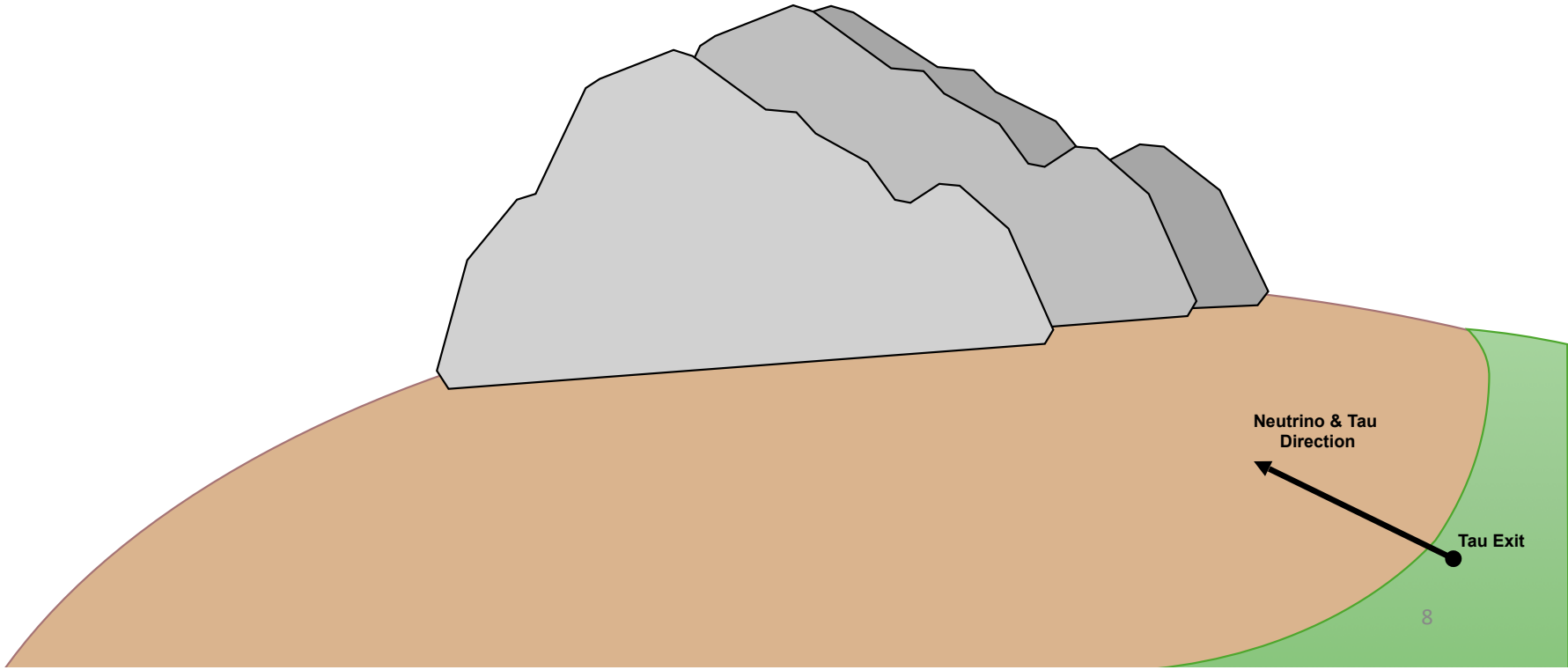
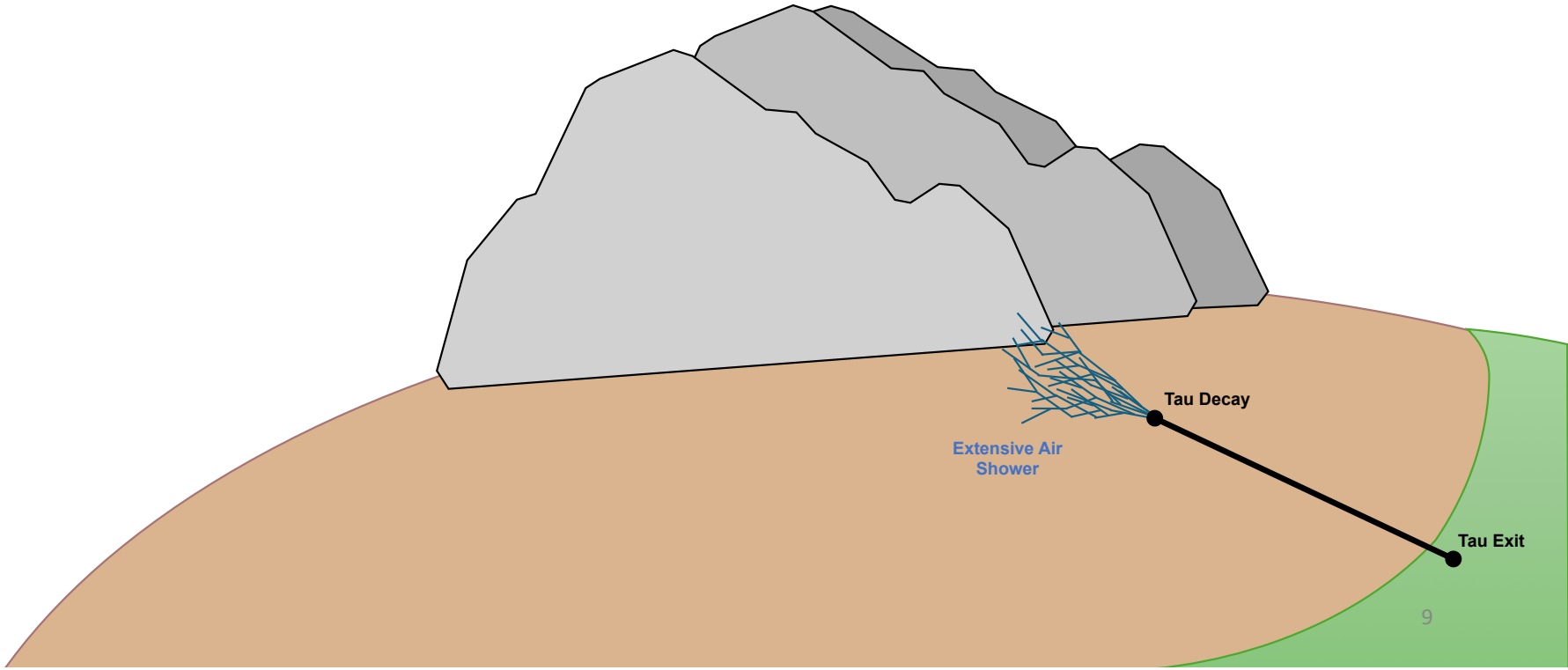


Figure from F.G. Schröder, Nuclear and Particle Physics Proceedings 279-281 (2016) 190





PennState



PennState

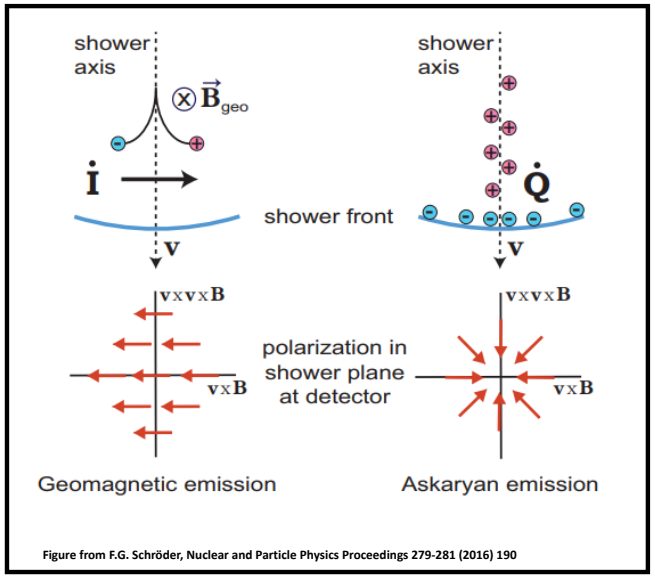
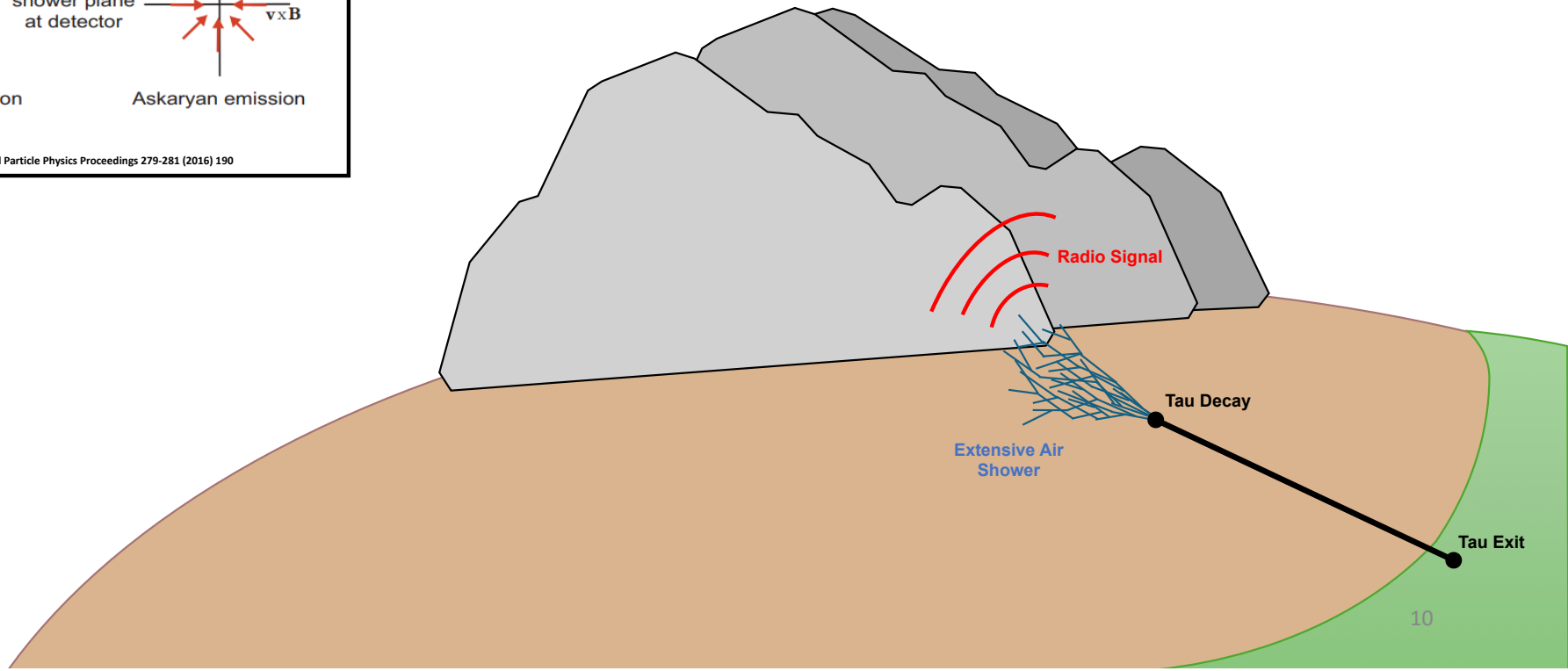
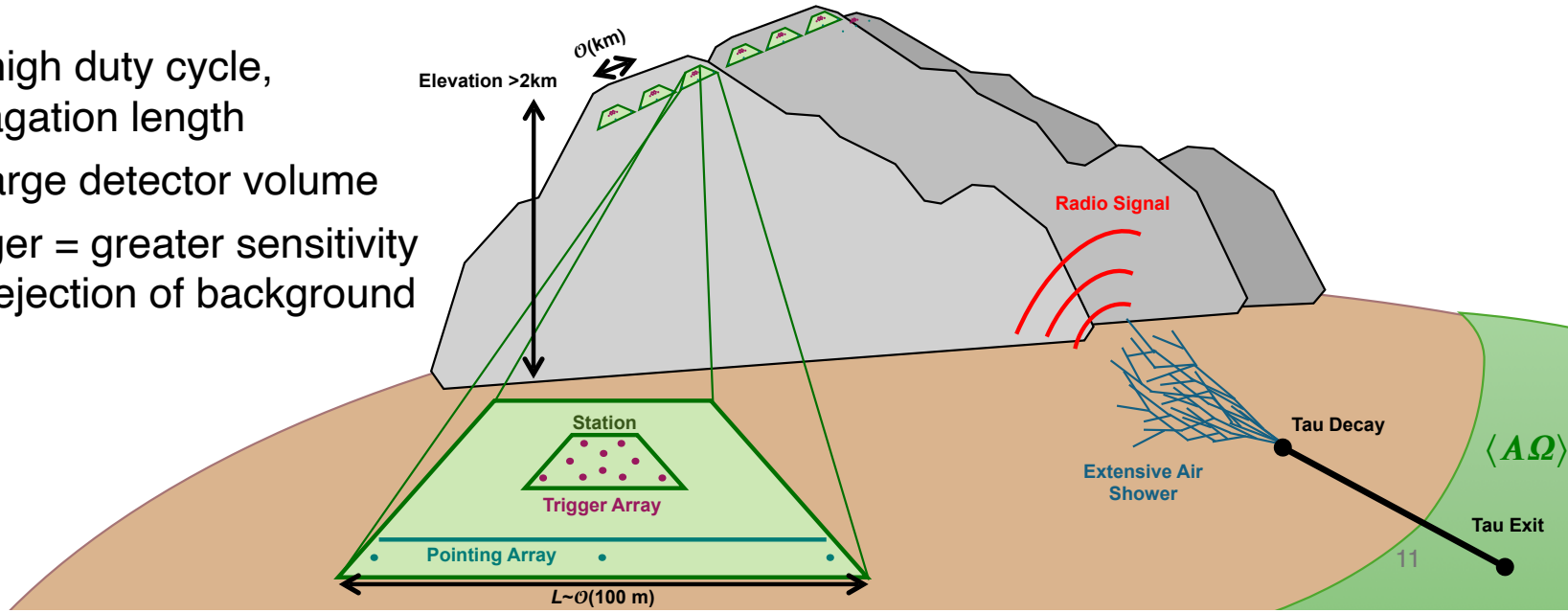


Figure from F.G. Schröder, Nuclear and Particle Physics Proceedings 279-281 (2016) 190



BEACON: Beamforming Elevated Array for COsmic Neutrinos

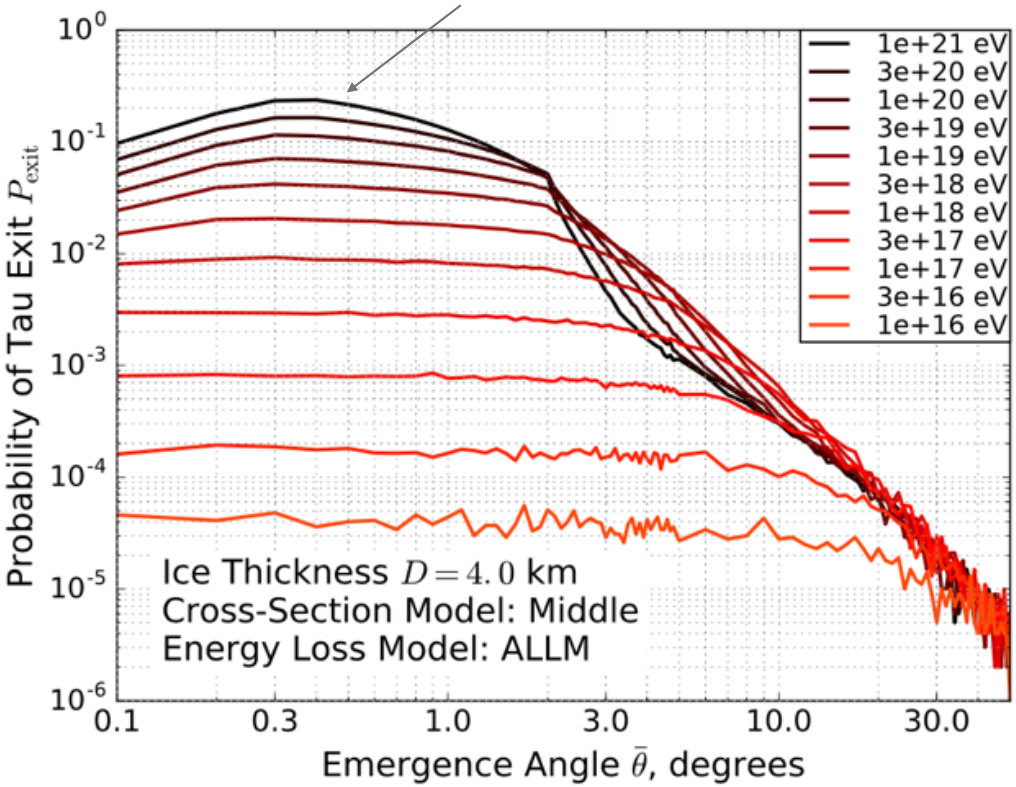
- Concept: $\mathcal{O}$(100-1000) independent radio interferometers on mountaintops, designed to detect the radio emission of upgoing air showers created by earth-skimming ν_τ
- Goal: measure the flux of ν_τ at E > 10^{17} eV
- Advantages:
  - + radio = low cost, high duty cycle, long propagation length
  - + high elevation = large detector volume
  - + phased array trigger = greater sensitivity & directional rejection of background



Concept paper:
S. Wissel et al.
JCAP11(2020)065

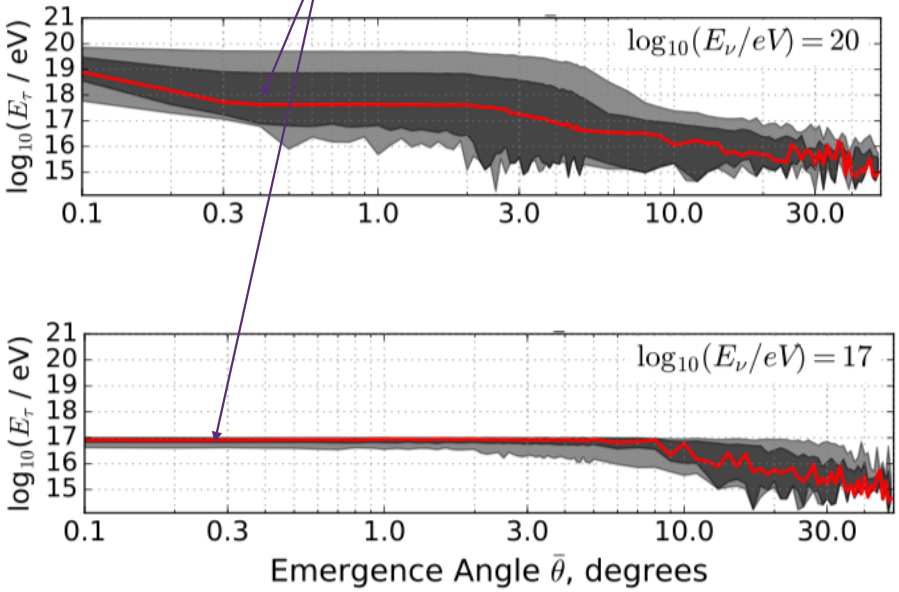
Exiting Taus

Most expected right at the horizon



Alvarez-Muñiz, et al. PRD 2017

Energy pile up at 10^{17} eV



What's the Best Elevation?

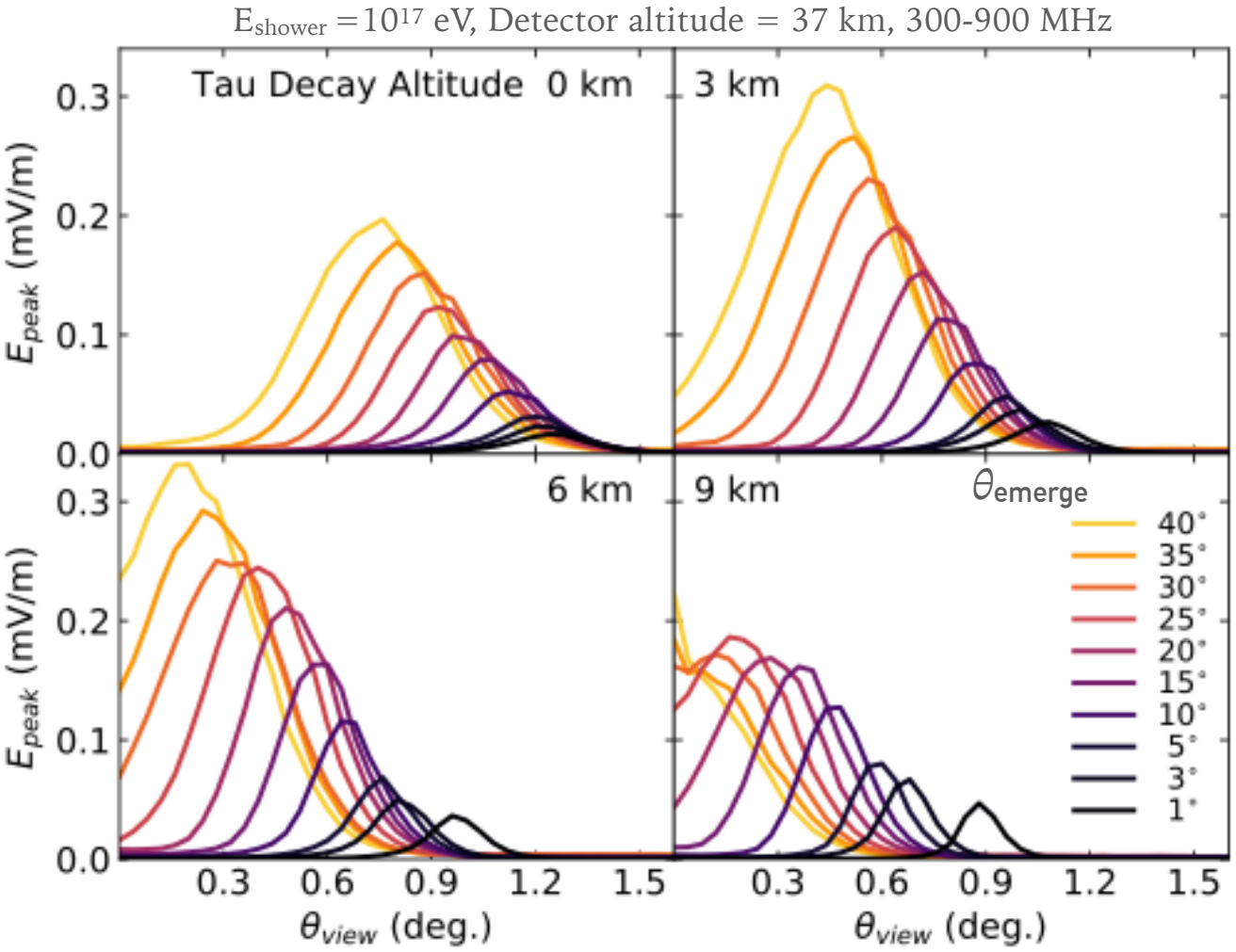
Mountain elevations

- Signal grows as shower moves closer to the detector

Balloon / Satellite elevations

- Area visible is larger, but signal decreases due to rarefied atmosphere

Signal grows up to 6 km

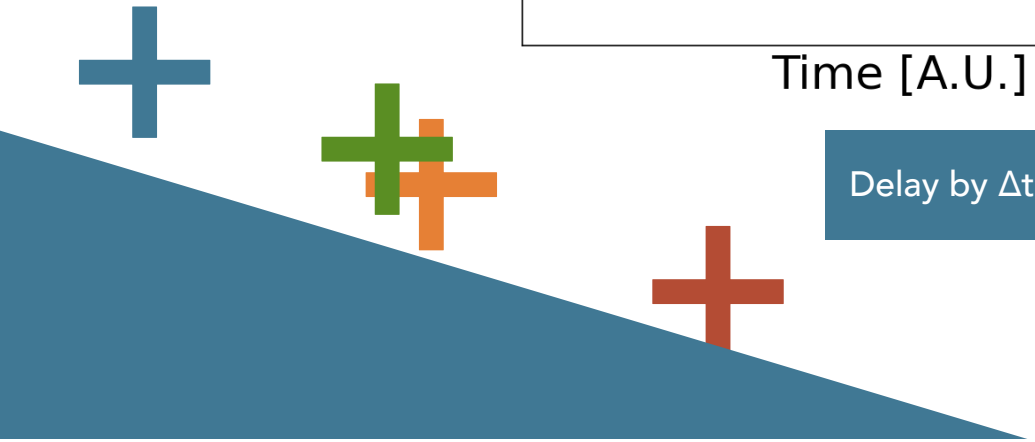


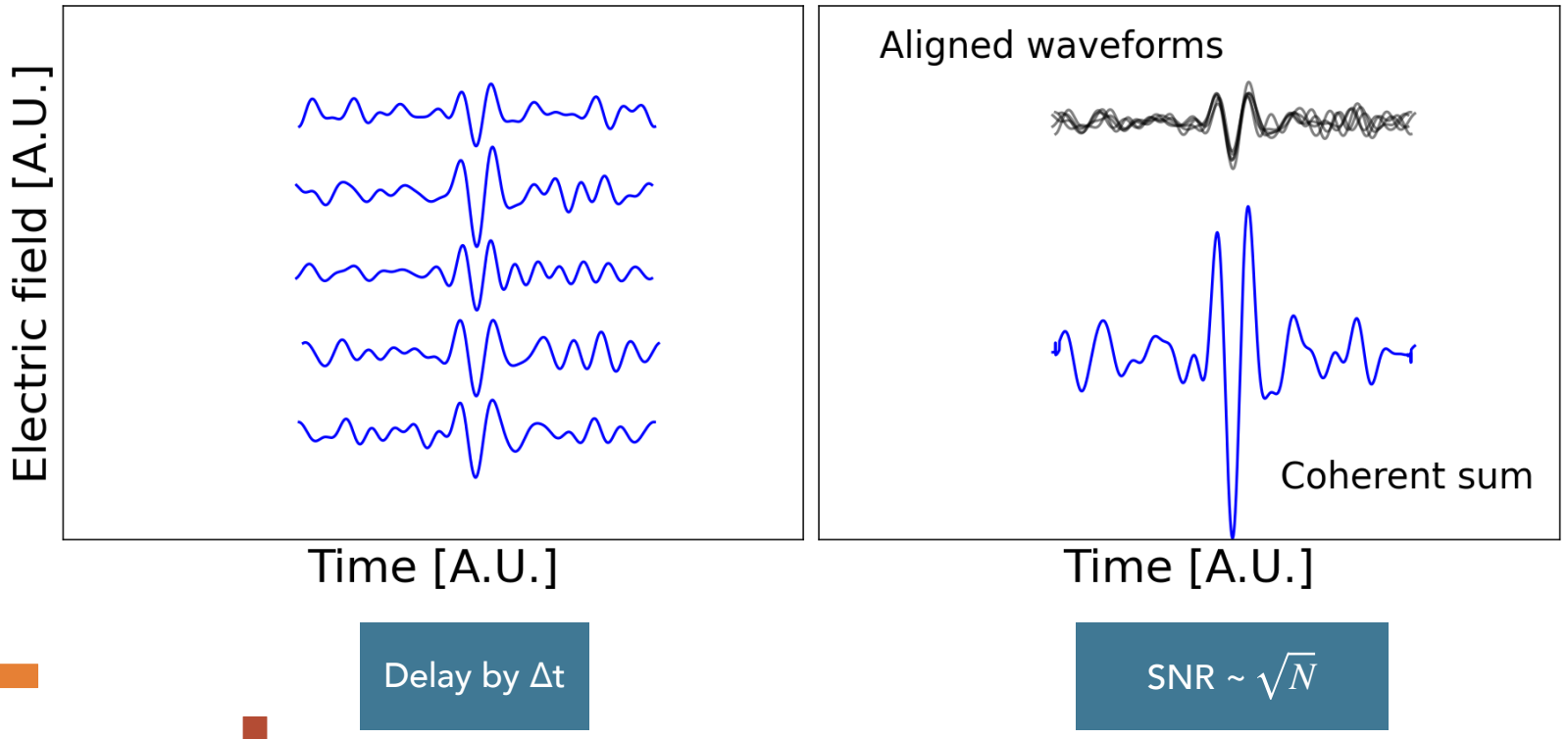
Romero-Wolf, SAW, ANITA PRD 2018

Phased Arrays on a Mountain

"Phasing" a compact array increases SNR

Multiple, N, antennas summed together increase the SNR by $\sqrt{N}$



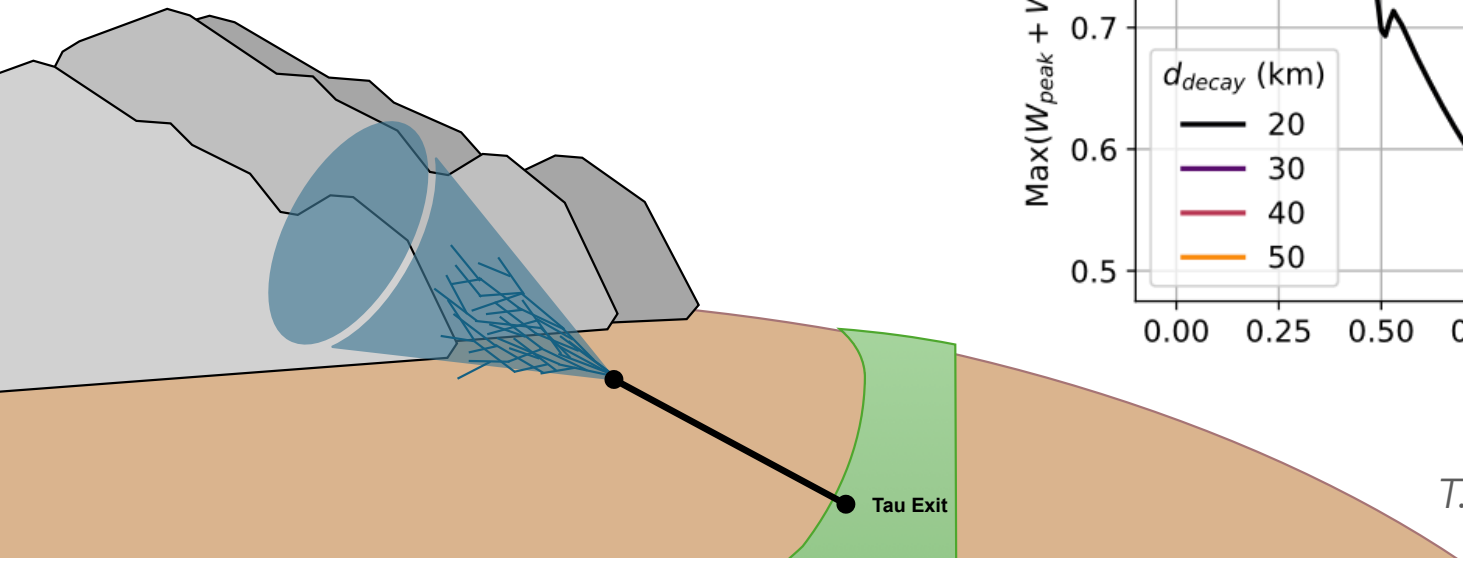


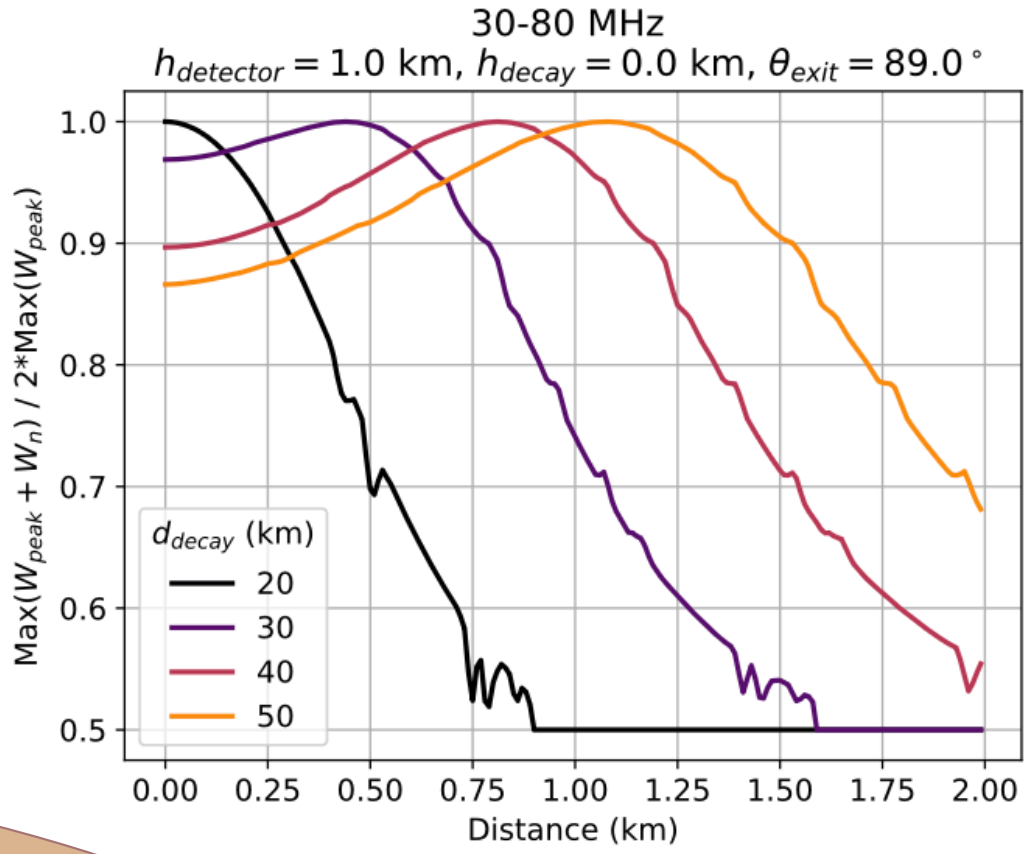
Delay by Δt

SNR ~ $\sqrt{N}$

How Compact?

- The phasing technique has the highest efficiency when viewing the same portion of the shower
- >80% phasing efficiency when antennas are spaced max of 250 m apart

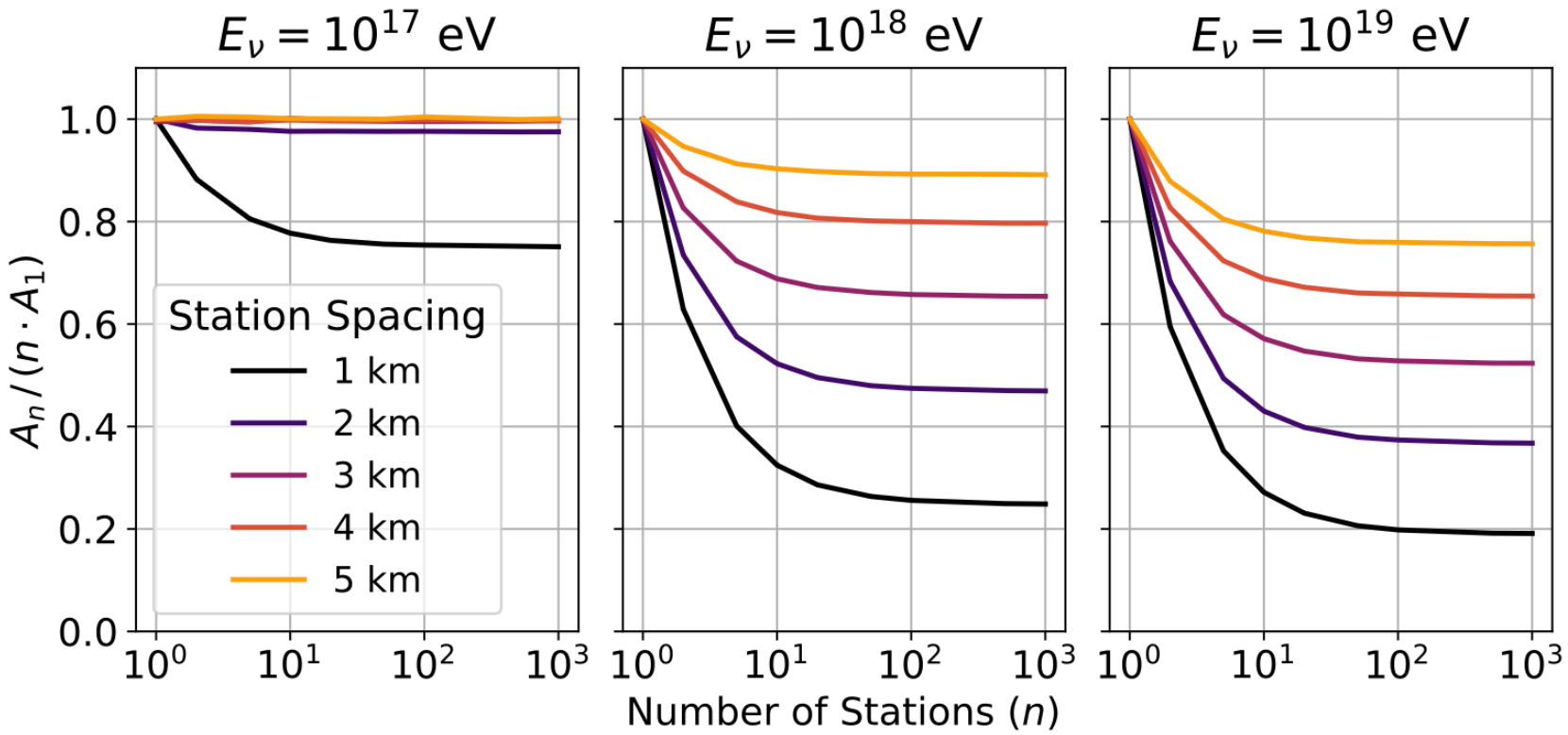




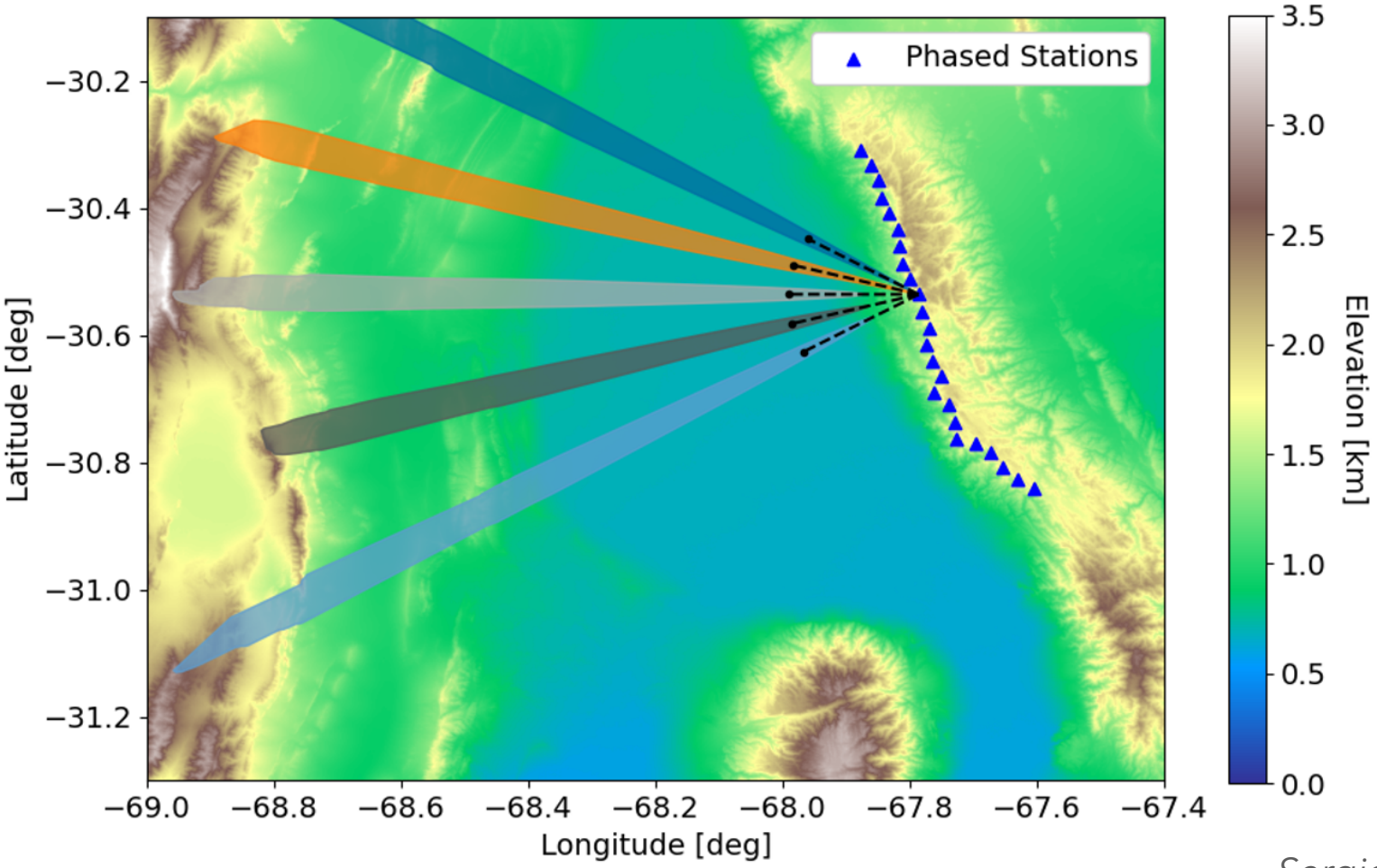
T. Radovic, HERON ICRC 2025

Station Spacing

- Effective area is maximized if stations view independent neutrino volumes
- At 3 km spacing, >70% of events are independent at 1 EeV → leaves possibility of "golden" coincident events

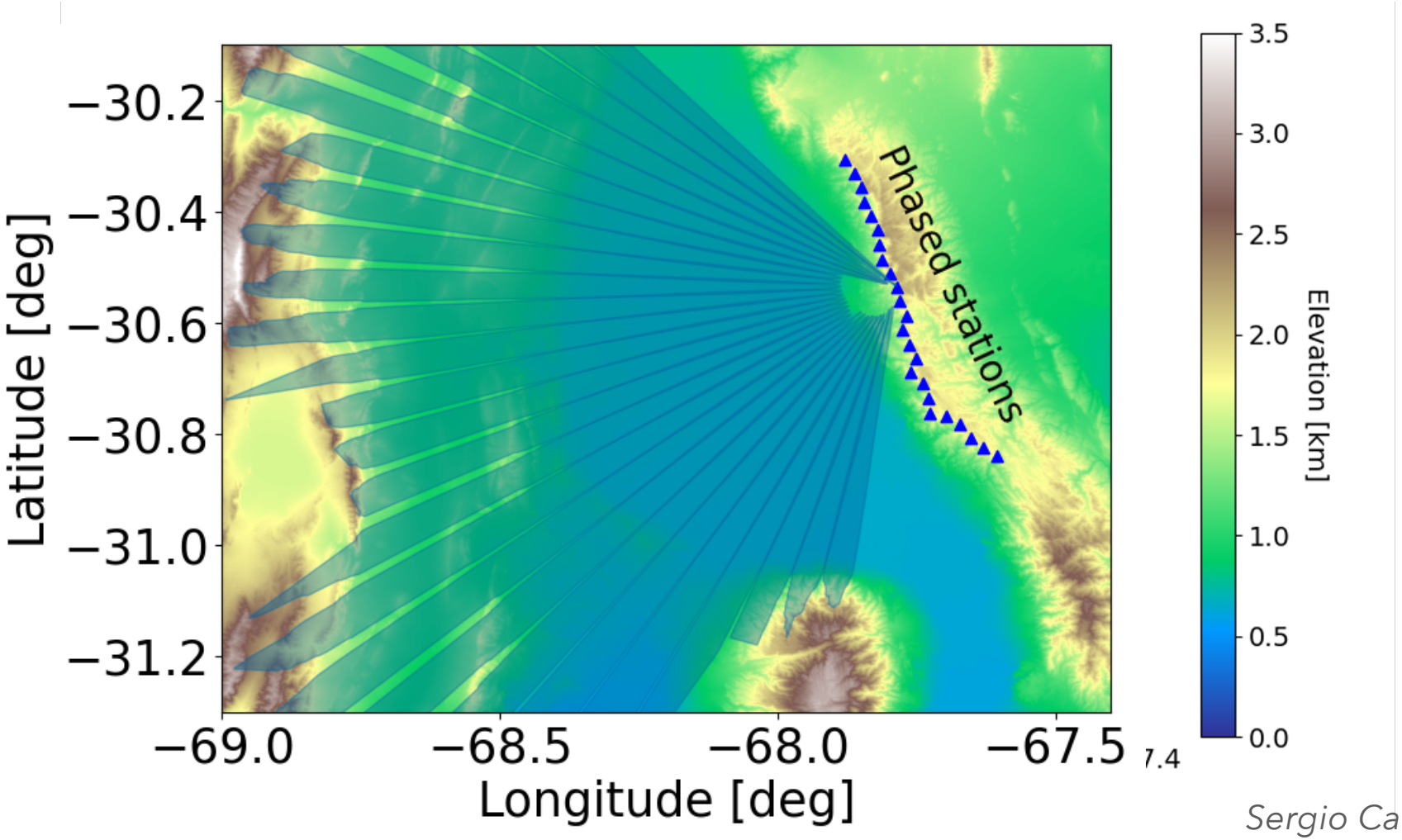


Beam Directions



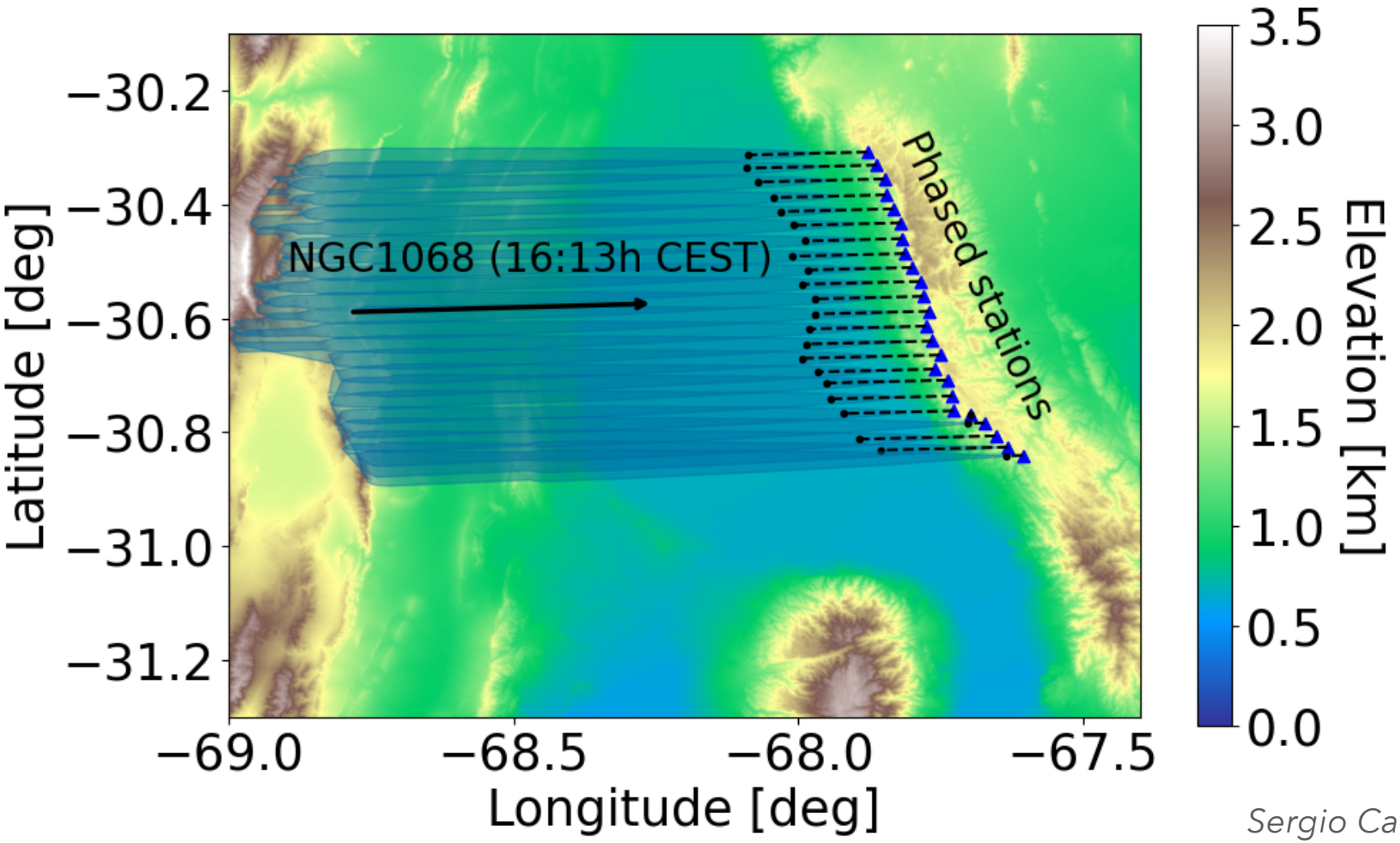
Sergio Cabana, USC

Beam Directions



Sergio Cabana, USC

Beam Directions

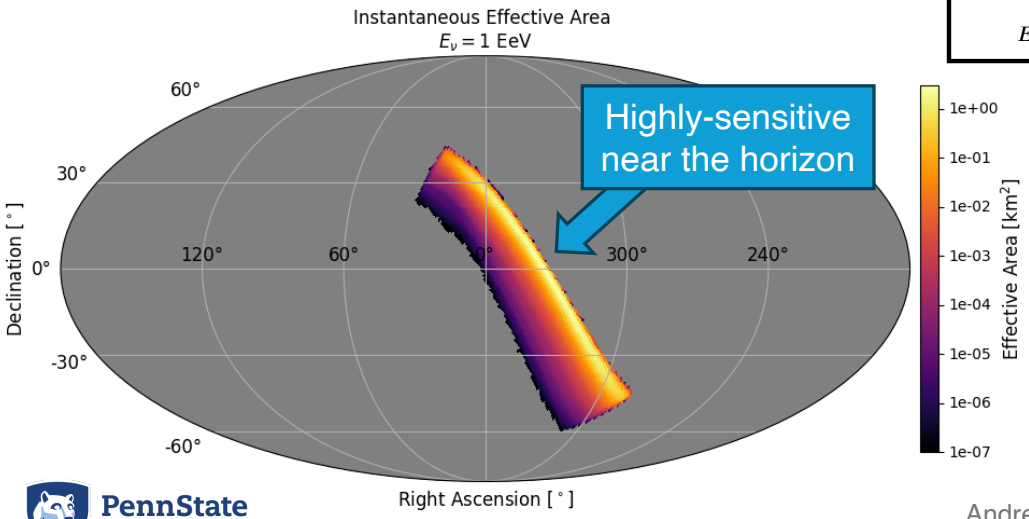


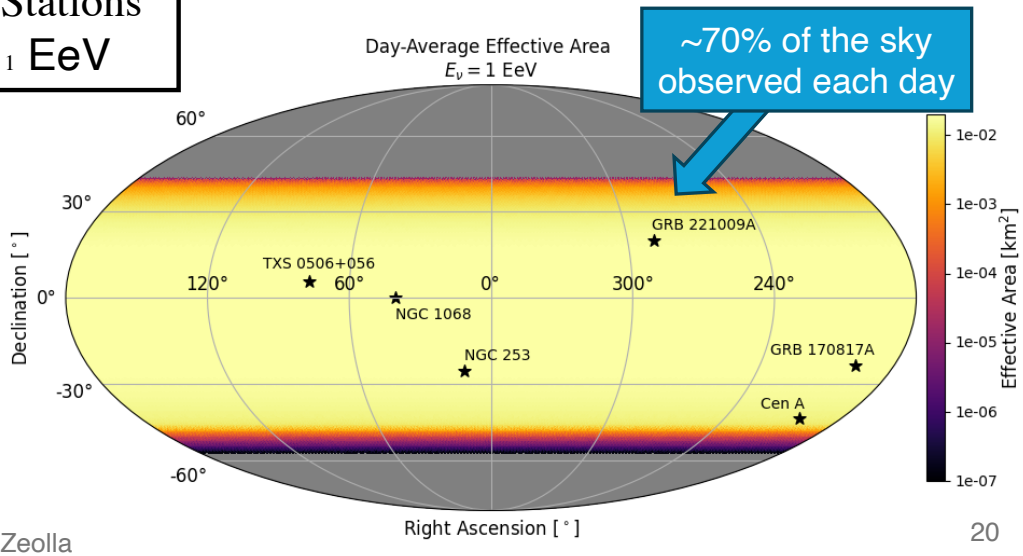
Sergio Cabana, USC

Predicting BEACON's Sensitivity

- Monte Carlo: **M**ultiple **A**ntenna A**r**rays on **Mo**untains **T**au **S**ensitivity
- Calculates the effective area of any configuration of mountaintop phased arrays to point-sources of neutrinos
- Uses simulations of tau propagation, shower development, radio emission, and detector response

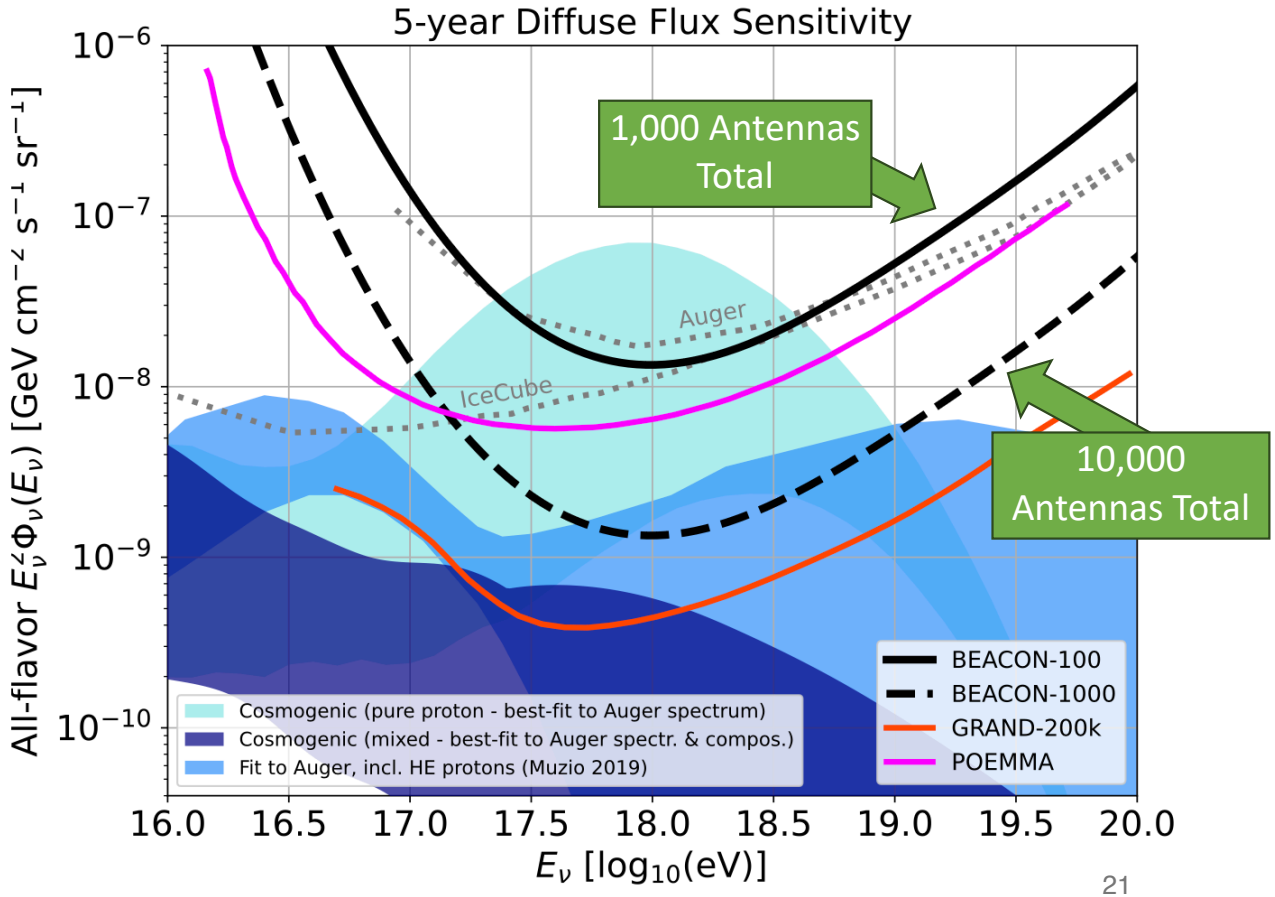
100 Stations
$E_\nu = 1$ EeV





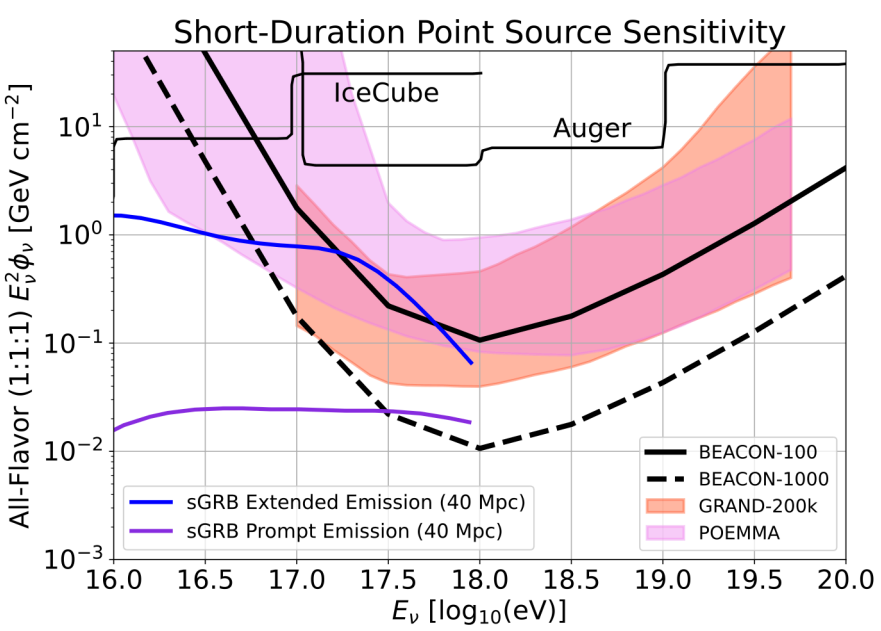
Diffuse Flux Sensitivity

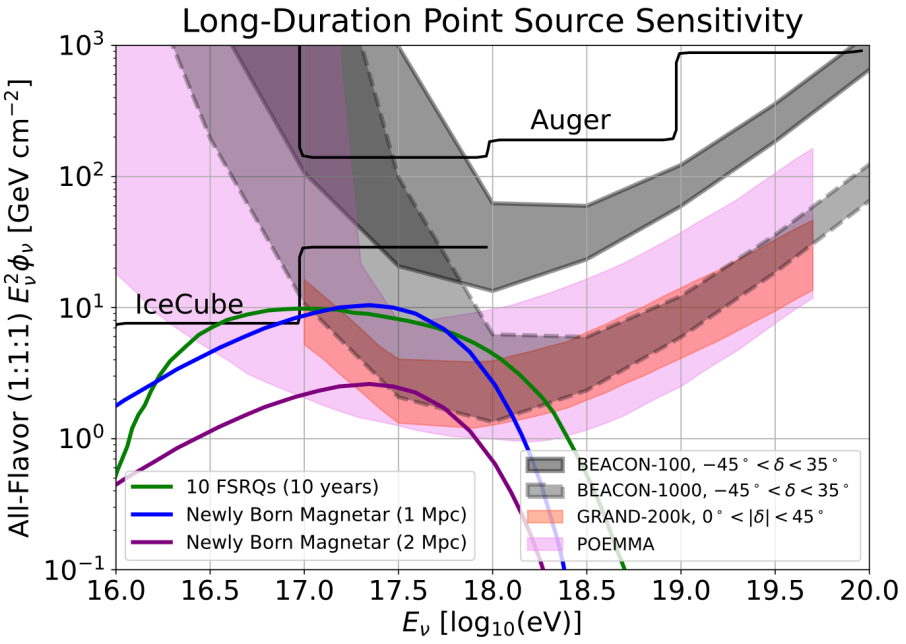
- With 100 stations and 5 years of data, BEACON can begin to constrain cosmogenic flux models
- High elevation sites and phasing create an efficient detector



Astrophysical Transient Sensitivity

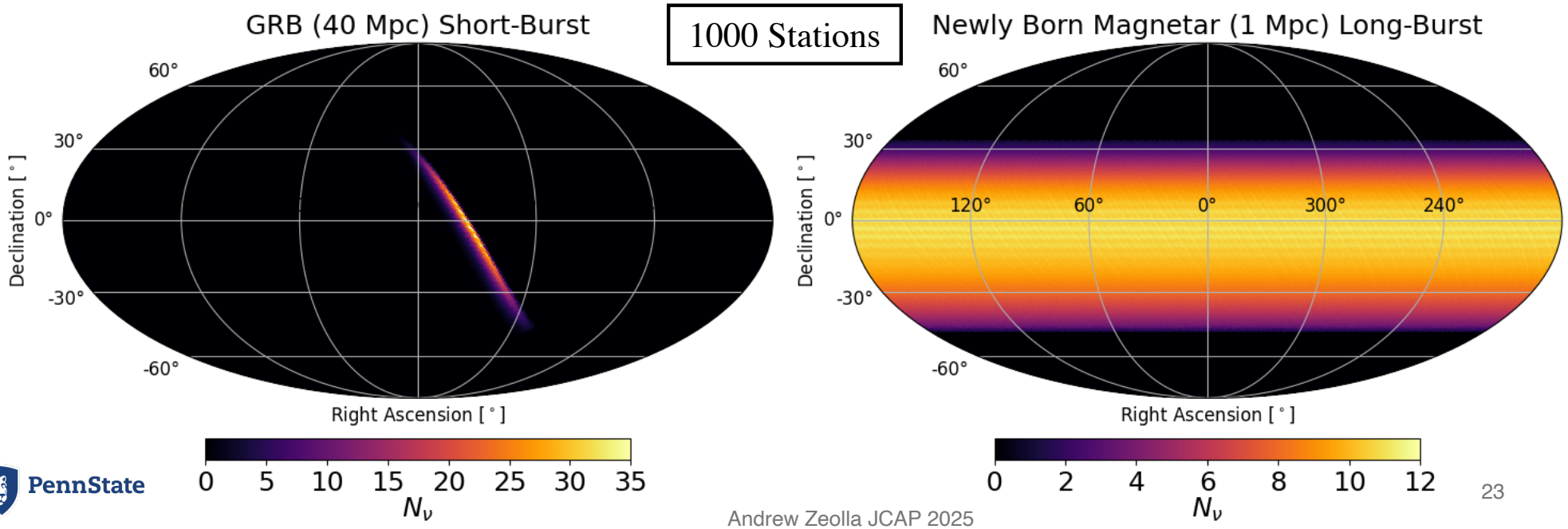
- BEACON is highly-sensitive to astrophysical transients
- With sub-degree pointing resolution, BEACON can serve as an ultrahigh energy neutrino telescope





Astrophysical Transient Sensitivity

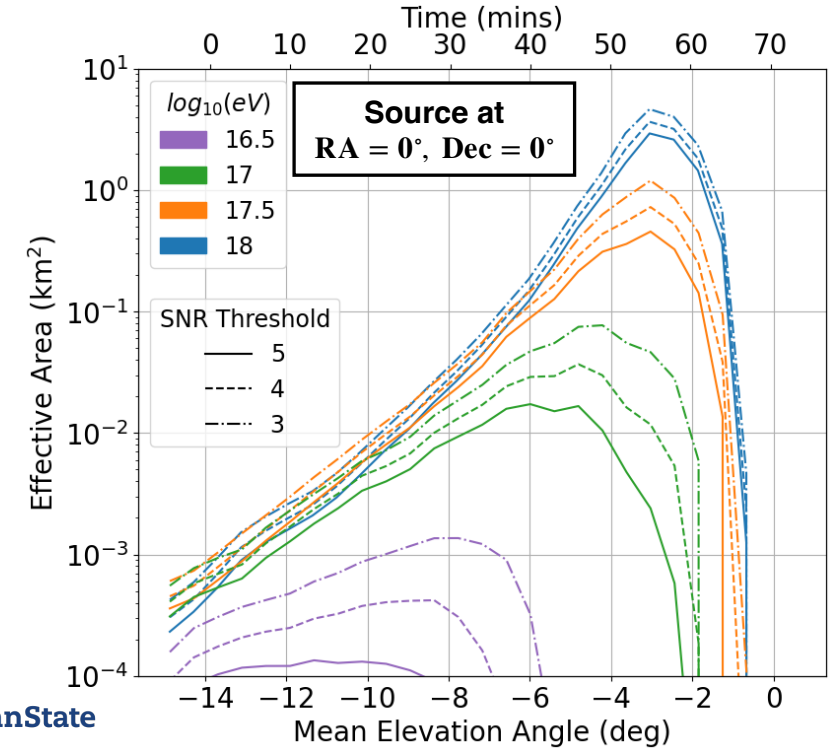
- BEACON is highly-sensitive to astrophysical transients
- With sub-degree pointing resolution, BEACON can serve as an ultrahigh energy neutrino telescope

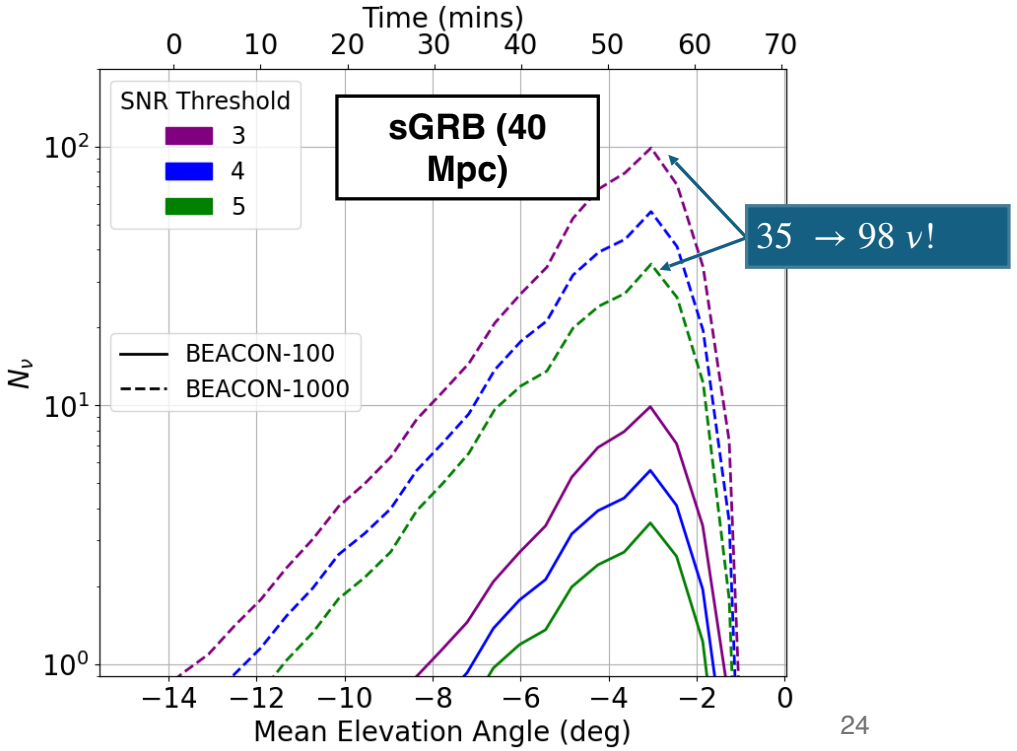


Multi-Messenger Astronomy

- Beamforming allows the trigger threshold in a specific direction to be adjusted

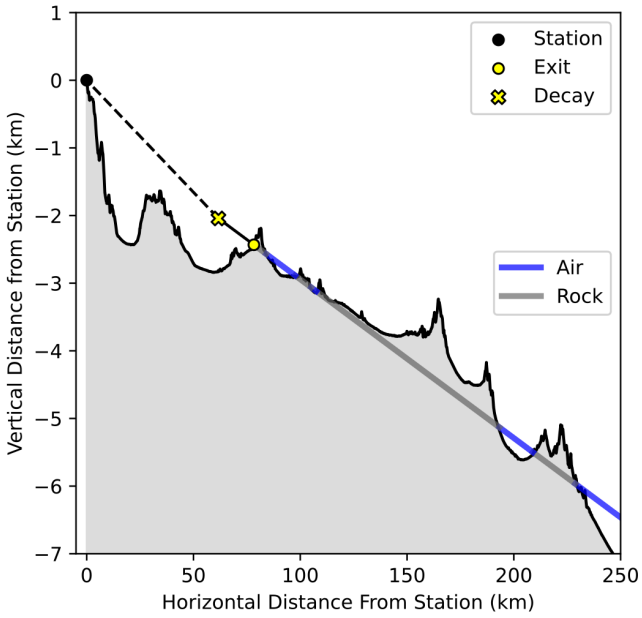
➔ Threshold can be decreased in the direction of MMA alerts

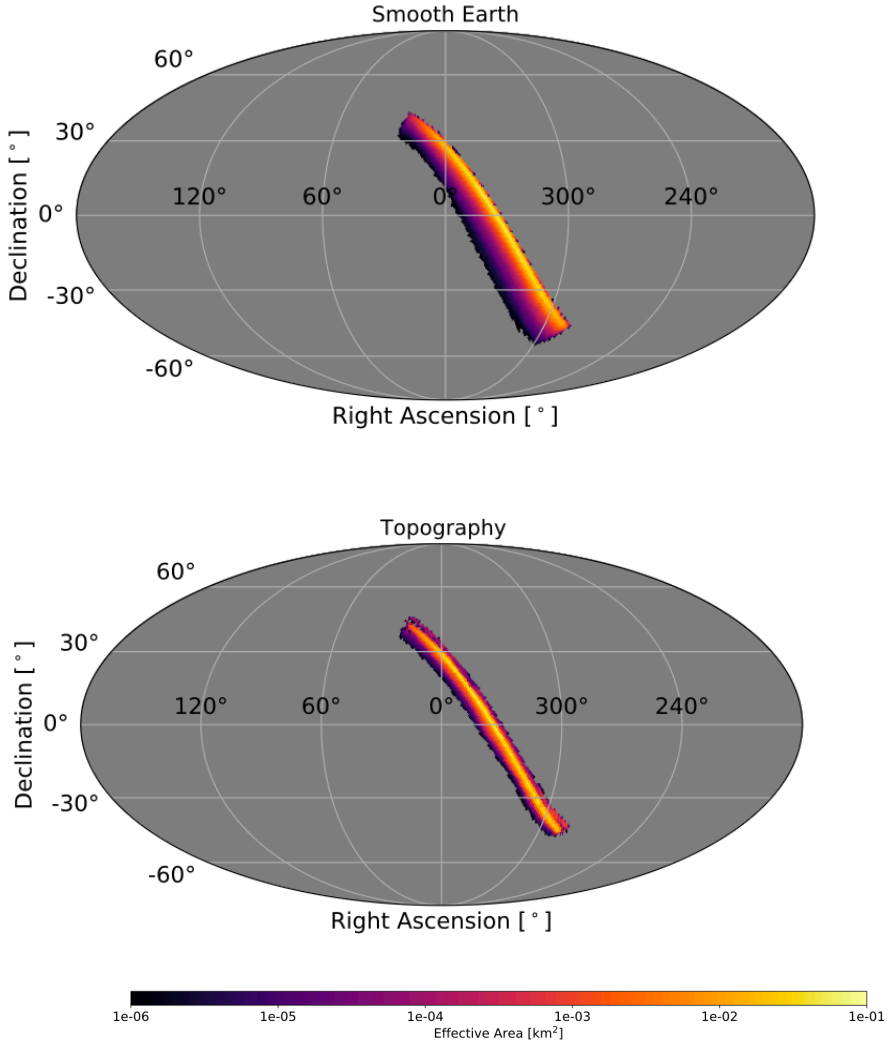




Topography

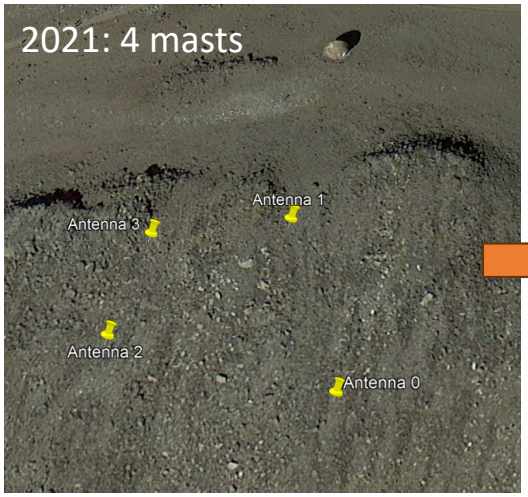
- Topography of a given site can impact effective area by either offering more target volume (✅) or by blocking radio (❌)
- At BEACON prototype site, topography improves effective area by factor of ~2





BEACON Prototype

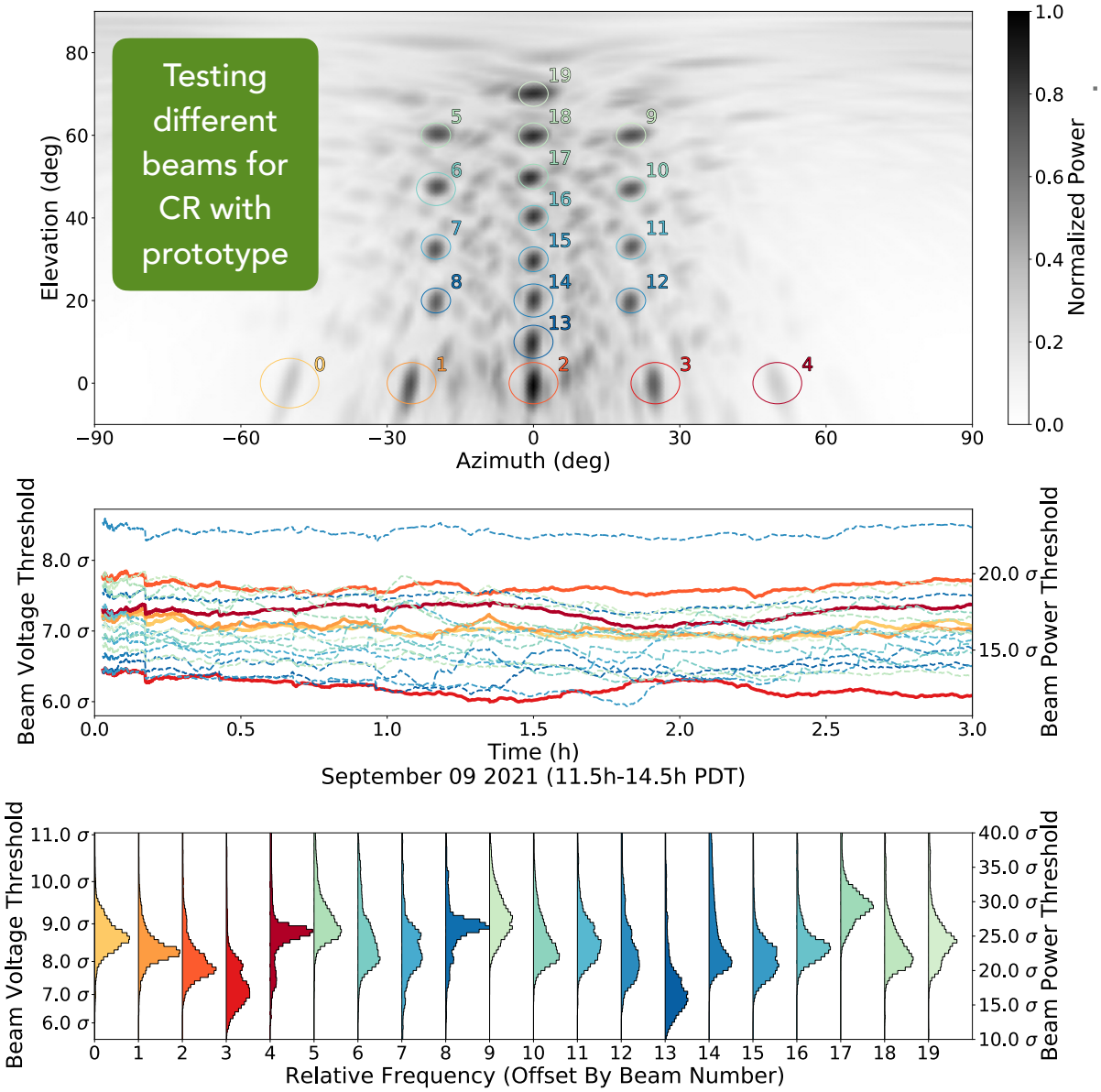
- Located within the White Mountains of California, 3.8 km (12,500 feet) elevation
- Array of cross-polarized dipole antennas and a beamforming DAQ
- 4 masts (2021) → 6 masts (2023)
- Array of 4 scintillators added in 2023, for cosmic ray detection validation



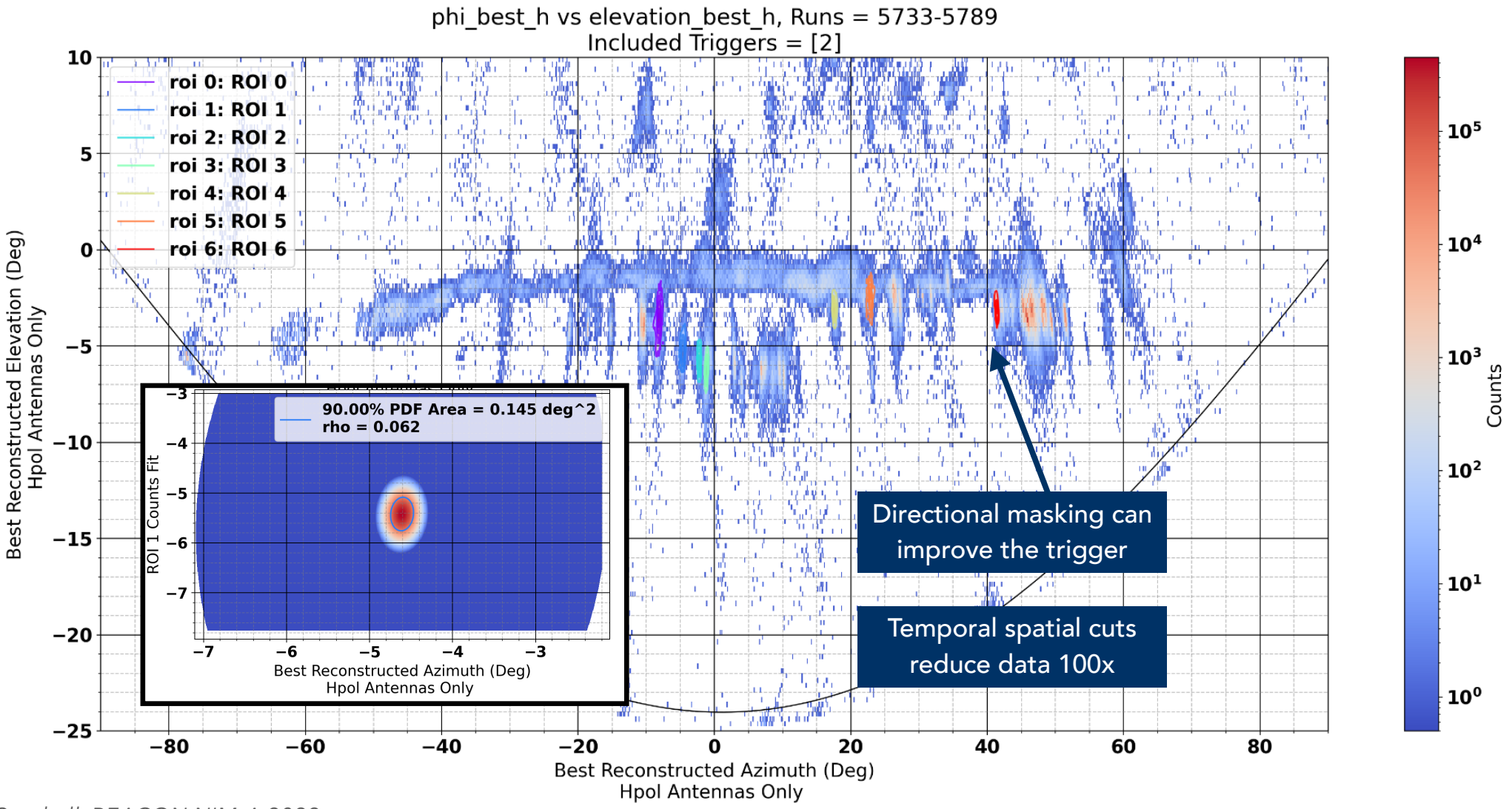
BEAMFORMING *IN SITU*

- Form beams that cover your full solid angle
- Noise-riding threshold automatically adjusts the thresholds in "noisy beams" so the backgrounds do not dominate

Thresholds: Many beams at thresholds ***approaching*** level assumed in neutrino sims



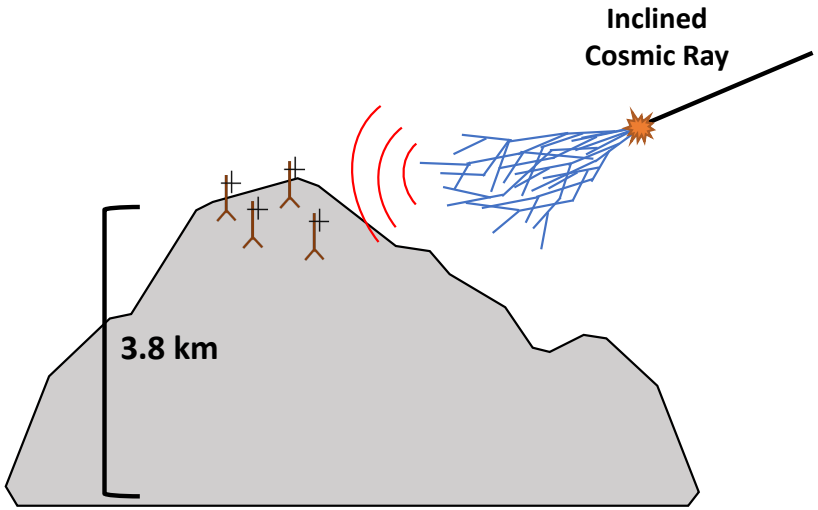
D. Southall, V. Decoene, A. Zeolla, BEACON arXiv:2206.09660

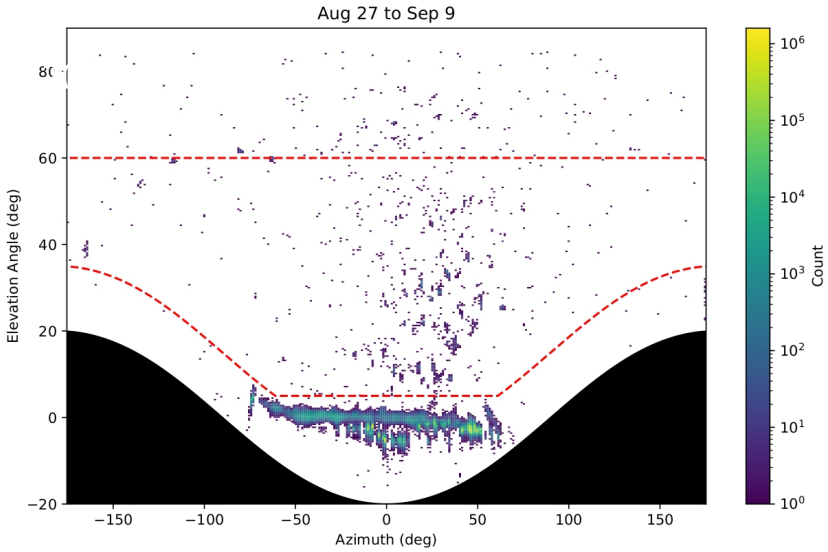


D. Southall, BEACON NIM-A 2022

Cosmic Ray Search

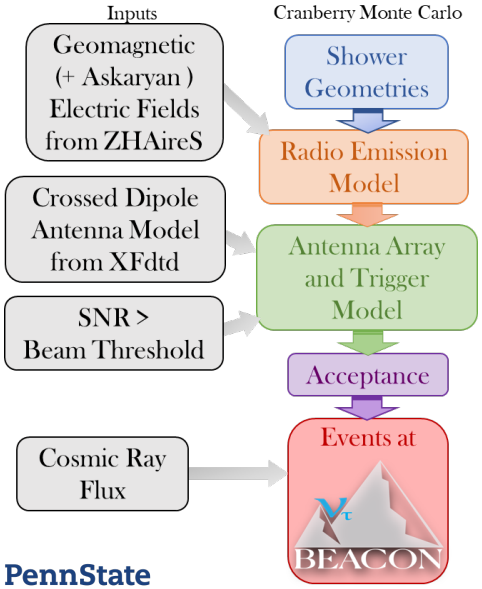
- Goal: demonstrate the ability to detect extensive air showers with an elevated phased array via an unblinded cosmic ray search
- Use the measured cosmic ray flux to determine BEACON's energy threshold
- August 27 to December 18, 2021 (113 days) ➔ **~100 million** phased array triggers

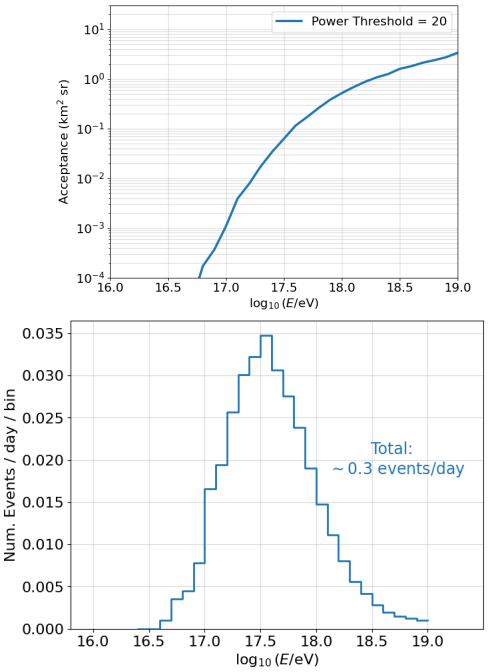


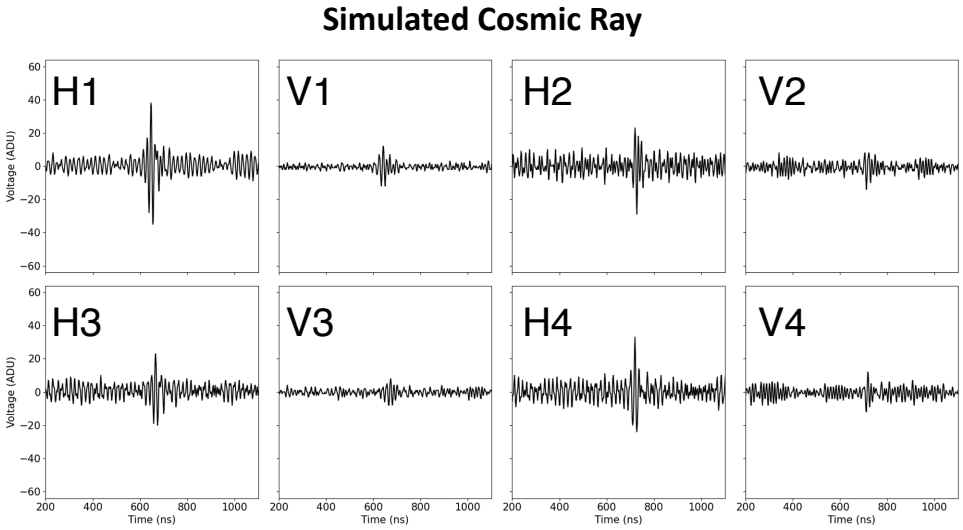


Simulations

- Monte Carlo CRANBERRY predicts cosmic ray acceptance and generates simulated cosmic rays
- Simulated cosmic ray = electric field from ZHAireS, convolved with antenna response and signal chain, added to real noise

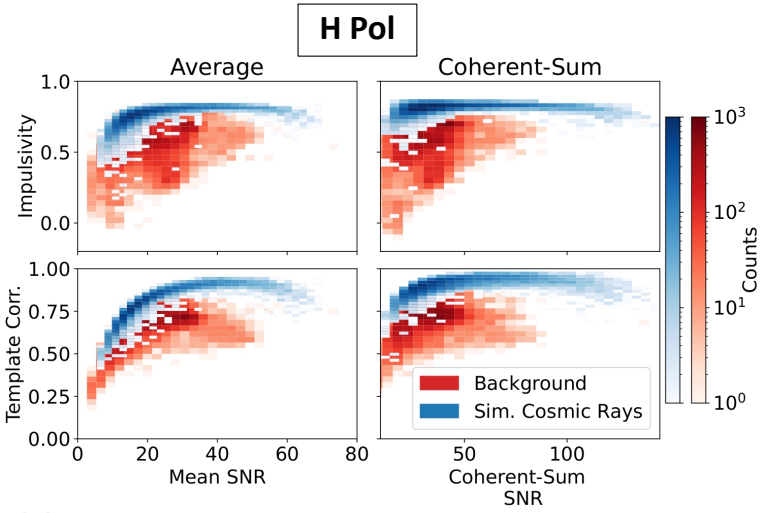


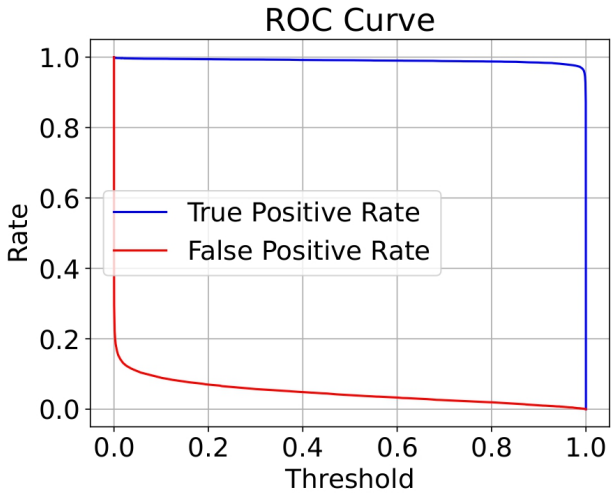


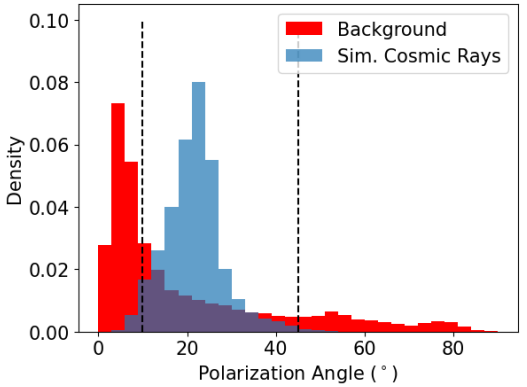


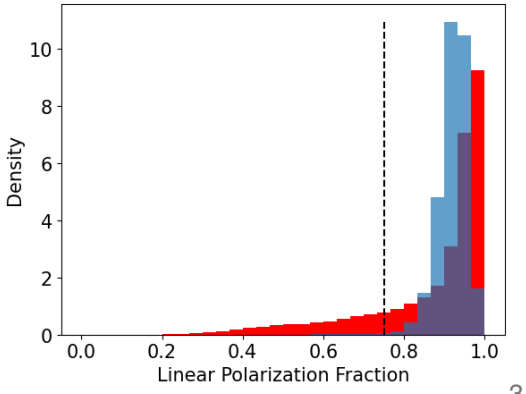
Cosmic-Ray-Like Cuts

- Linear Discriminant Analysis (LDA) trained on Hpol and Vpol impulsivity, template correlation, and voltage signal-to-noise ratio
  - Average across channels and coherent sum
  - 12 parameters total
- Additional cuts on polarization and linear polarization fraction





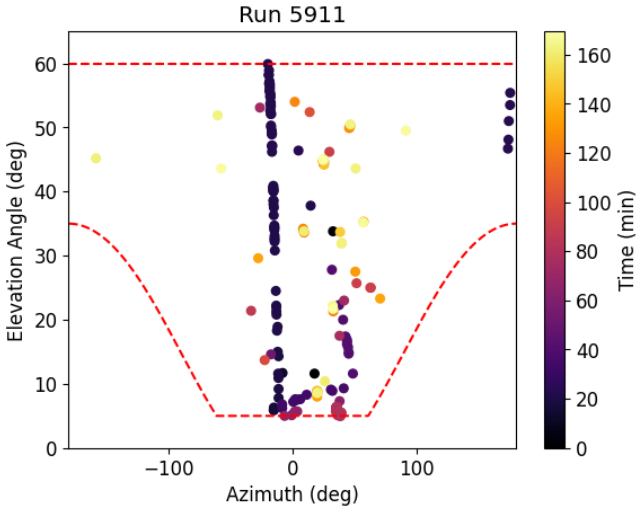


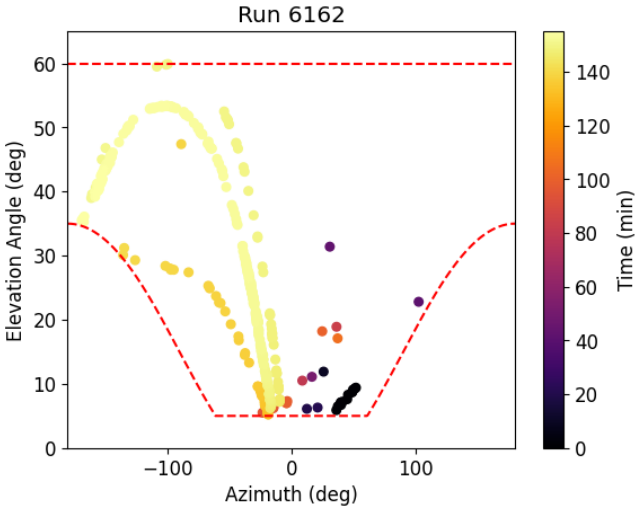


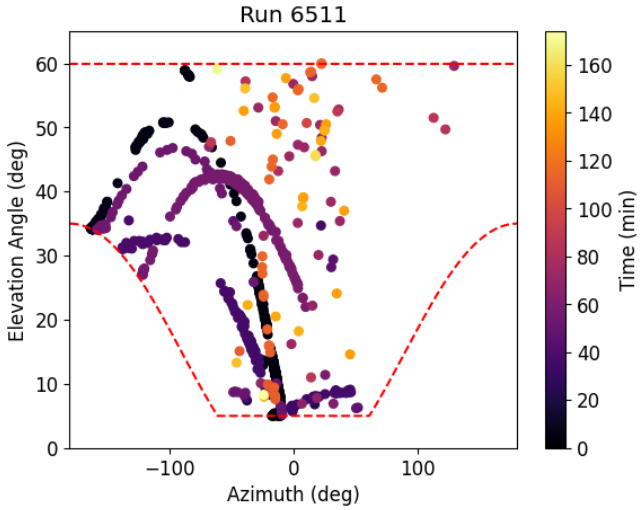
PennState

Temporospatial Clustering

- Airplanes are a prominent above-horizon impulsive background
- Mis-reconstructions tend to cluster
- Temporospatial cut removes events which occur within 20° in a 10-minute window
- Overall, 90.4% of events are clustered

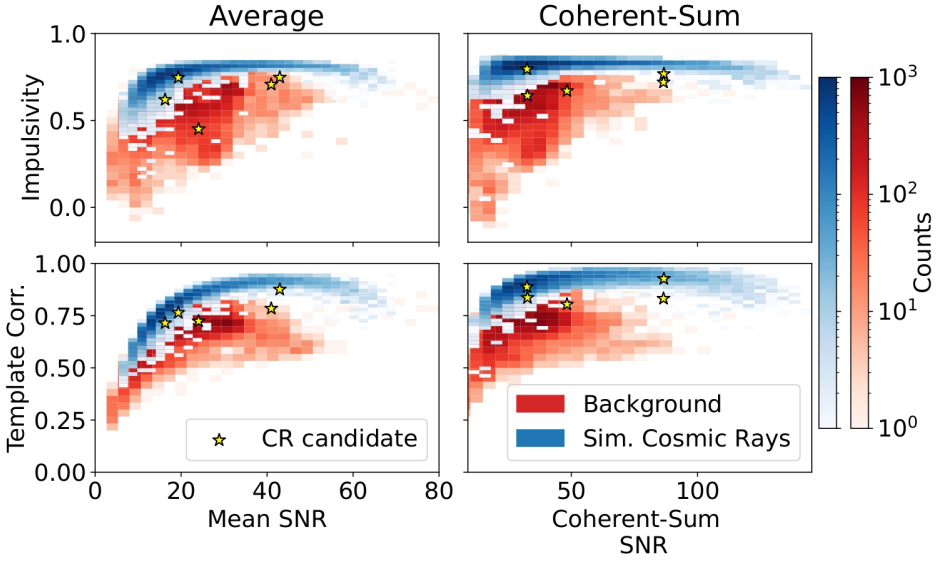


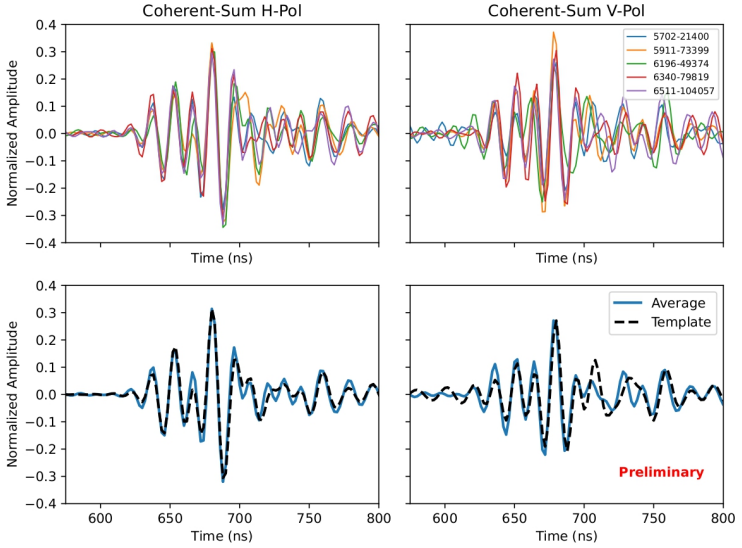




Results

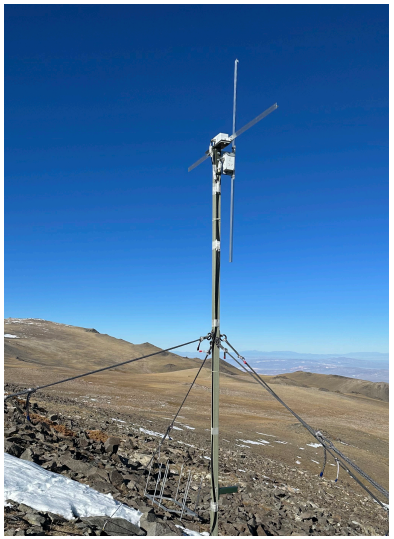
- Overall, just 16 events are both cosmic-ray-like and isolated
- At least 5 appear to be promising CR candidates after removing misreconstructinos
- Validation against airplane database & signal characteristics and final background estimate nearly complete

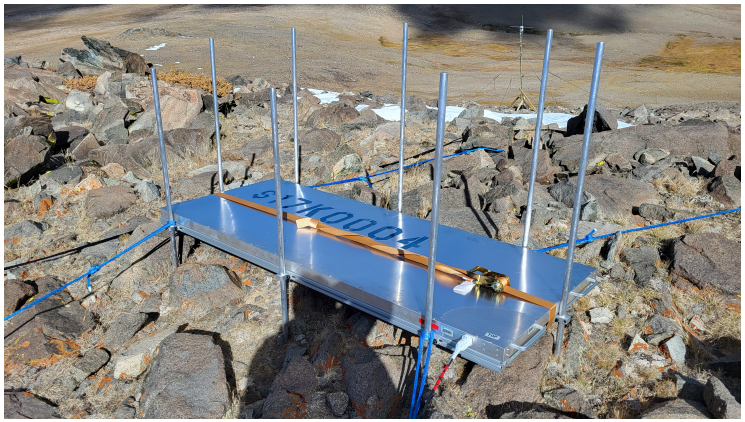


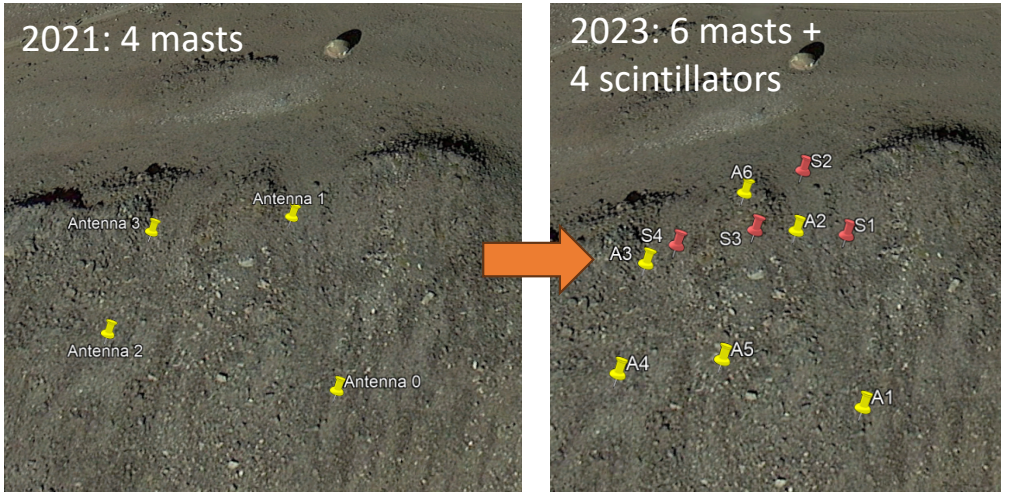


BEACON Prototype (2023)

- 2023 upgrade: reinforced antenna design, improved shielding non-conductive antenna mast
- Two additional antenna masts (12 RF channels total)
- Addition of four IceTop scintillators



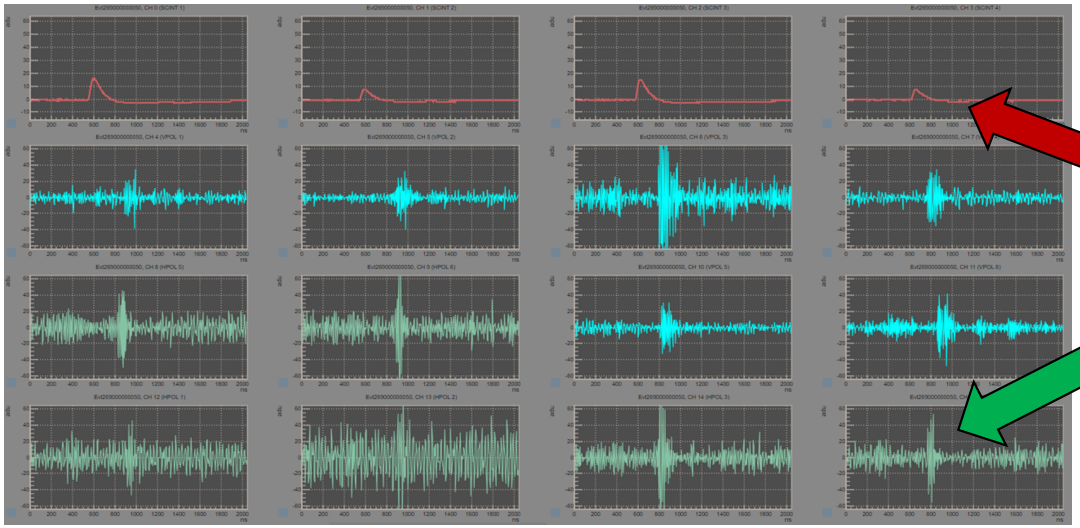




Scint. + Radio Cosmic Ray Search

- 3/4 scintillator-coincidence trigger saves radio data as well
- Goal: use scintillator triggers to confirm cosmic ray detection, study radio to improve radio-only phased array trigger
- Radio-Scintillator coincidence search: October 19, 2023 to March 2, 2024

➔ **~25 million** scintillator-triggered events



Scintillator Trigger

+

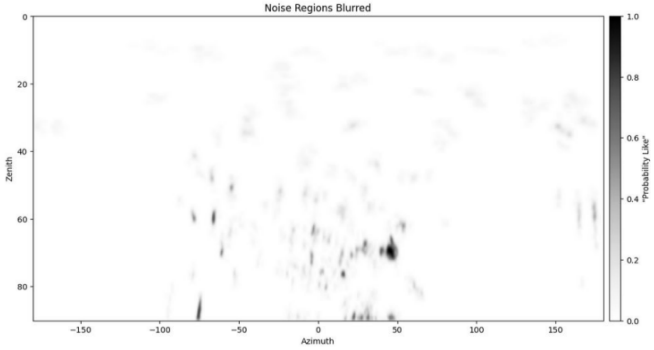
Radio Impulse

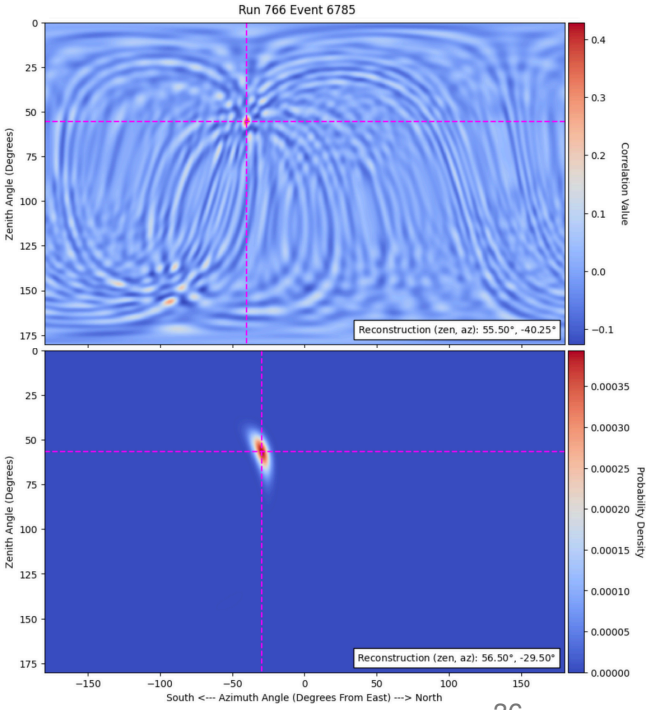
Analysis

- Cuts are designed to identify impulsive, above-horizon radio present in scintillator-triggered events
- Events which reconstruct near prominent noise clusters are removed
- Radio and scintillators must agree on direction to within 10°

➔ **15 remaining events**

	Cut Name	Restriction	Remaining Events	Cut % (Sequential)	Cut % (as first)
0	Full	None	25,209,347	0.00%	0.00%
1	RF H Zenith	$x < 90^{\circ}$	11,549,103	54.19%	28.12%
2	RF H Hilb. Peak	$0.01 > x > 0.9$	9,355,980	18.99%	4.51%
3	RF H Impulsivity	$x > 0.6$	36,768	99.61%	19.19%
4	RF H SNR	$5 > x > 25$	29,592	19.52%	0.01%
5	Wind Speed	$x < 8$mph	25,691	13.18%	0.01%
6	RF Noise-Like	$x < 0.01$	1,310	94.90%	0.05%
7	RF-Scint Distance	$x < 10$	15	98.85%	0.002%



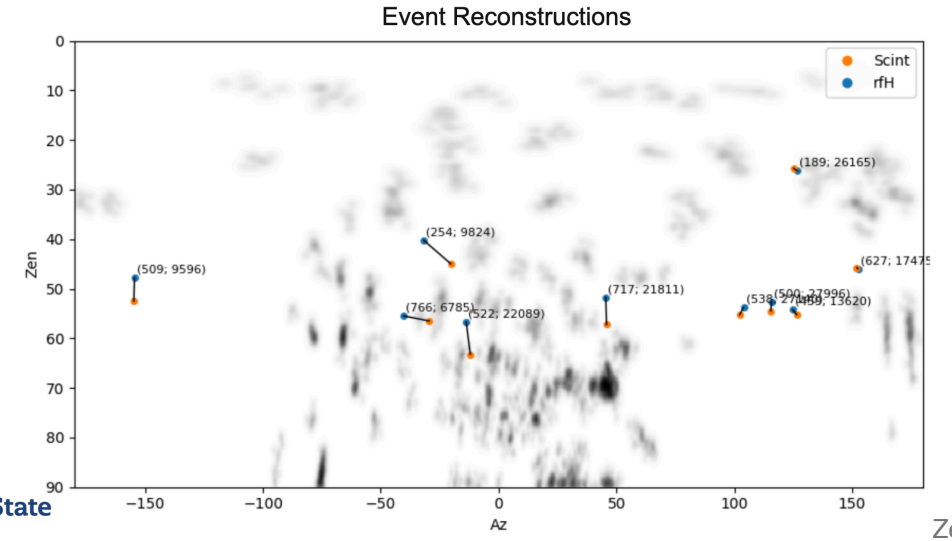


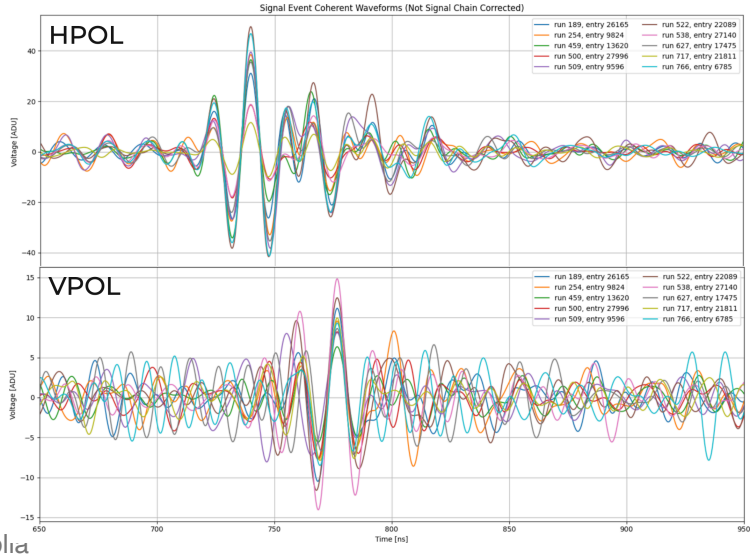
Results

- Background is estimated by randomly pairing force-triggered radio data with scint-triggered scint data and calculating the rate at which cuts are passed by chance

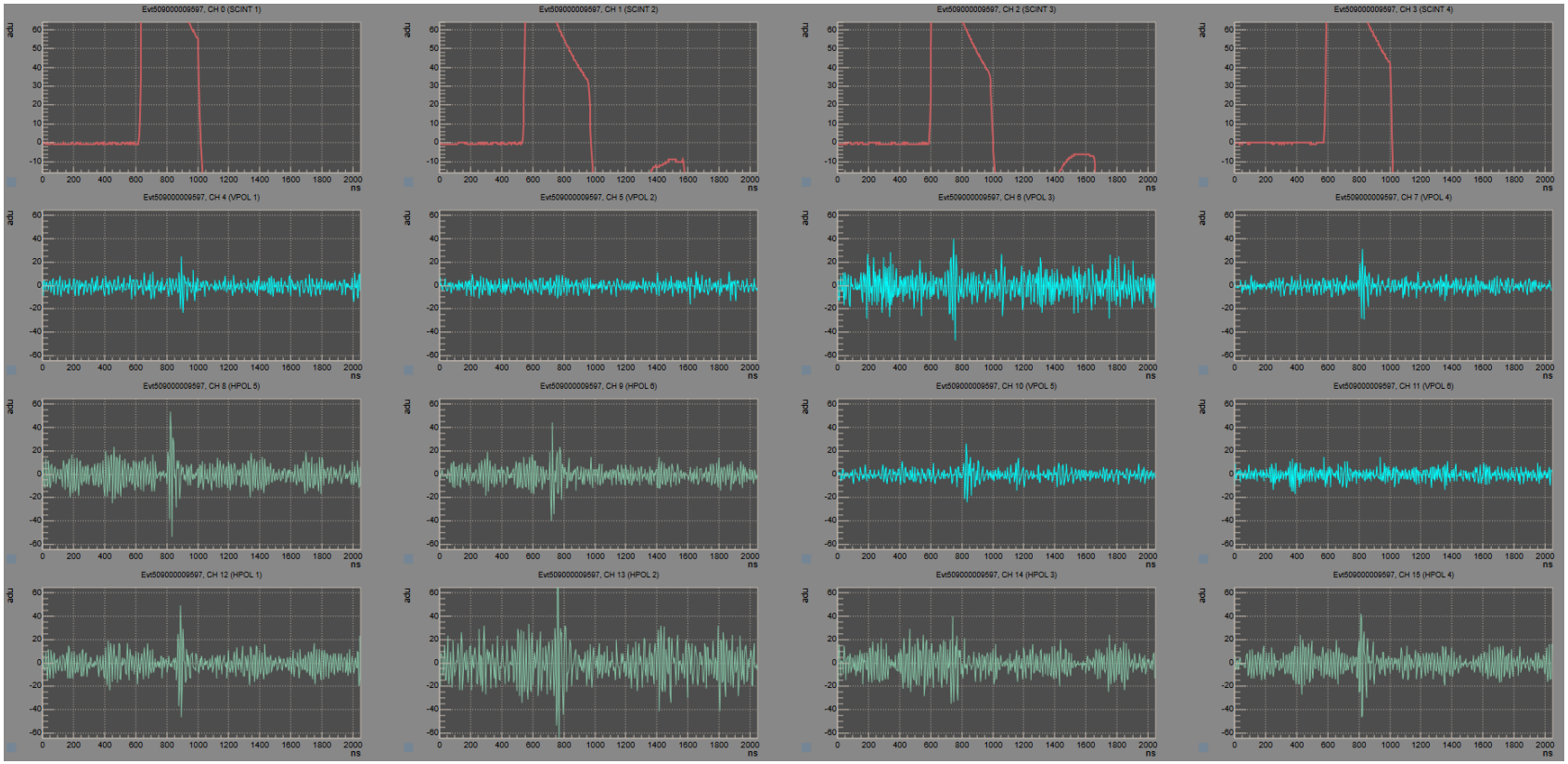
➔ 15 events on a background of 8 ± 1

- 10 of the 15 candidates have saturated scintillator signals. Only 6.8% of all events are saturated. Evidence of high energy cosmic rays?
- Requiring that the scintillators are saturated reduces the background estimate to 1





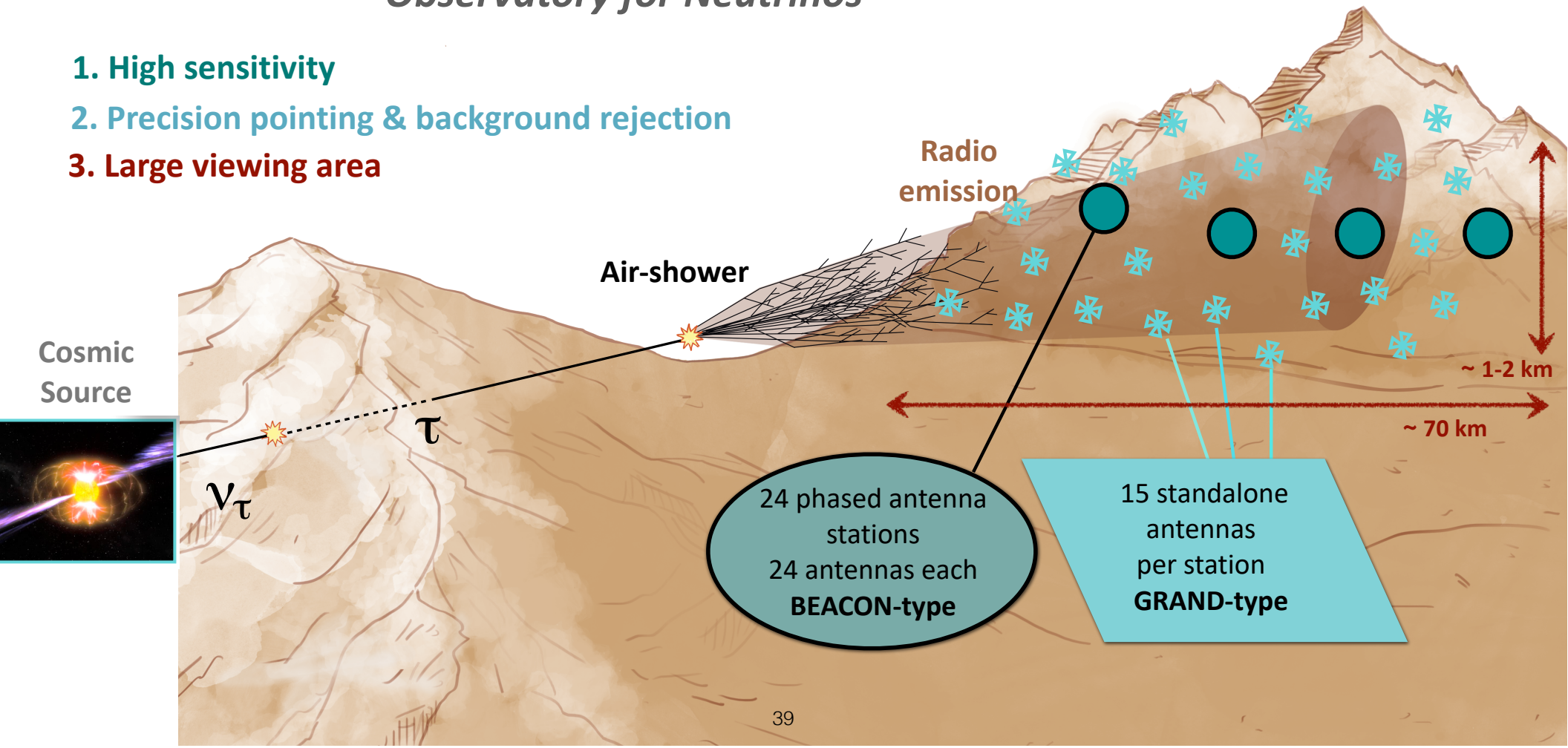
Cosmic-ray-like Radio + Saturated Scints



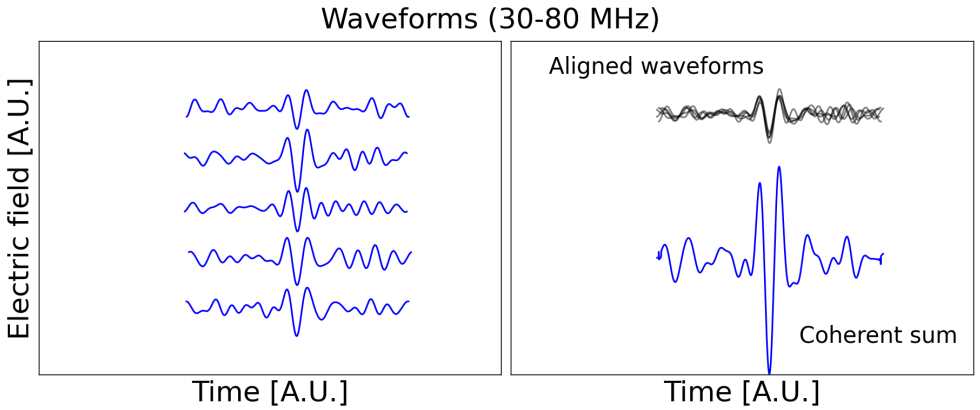
What's Next? HERON:

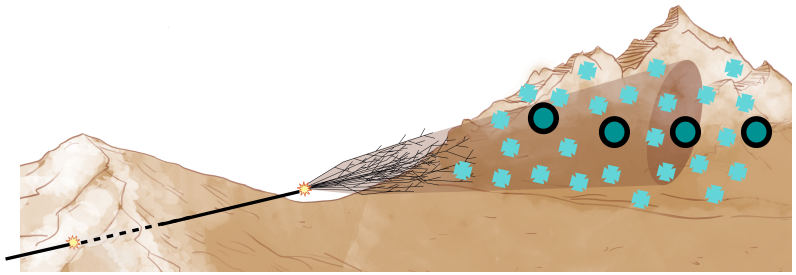
Hybrid Elevated Radio Observatory for Neutrinos

1. High sensitivity
2. Precision pointing & background rejection
3. Large viewing area



HERON: Hybrid Instrument (Part 1: trigger)



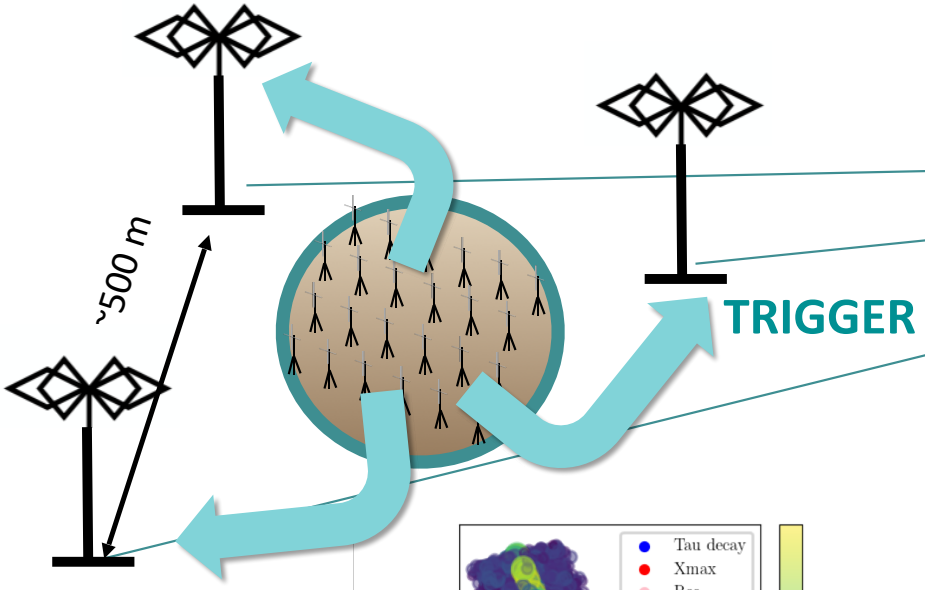


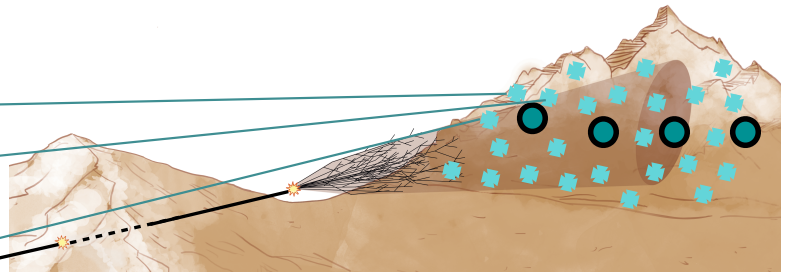
Signal phasing for trigger & reconstruction of transient radio signals

On phased arrays:
for trigger along beams
signal to noise ~ √N (N = 24 antennas)
improved threshold over huge effective area

SW, JA, JCAP 2025
KK, JA, OM, SW, ICRC 2025

HERON: Hybrid Instrument (part 2 reconstruction)





Signal phasing for trigger & reconstruction of transient radio signals

On phased arrays: **SW, JA,** JCAP 2025 **KK, JA, OM, SW,** ICRC 2025

for trigger along beams

signal to noise ~ √N (N = 24 antennas)

improved threshold over huge effective area

On standalone antennas: Falcke et al., Nature 2005; Schoorlemmer et al., (incl **AJ**), 2023, 2025

offline shower tomography

excellent background rejection

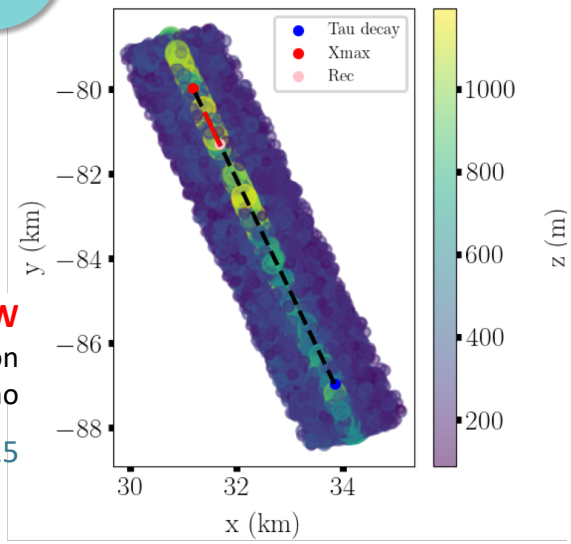
excellent direction reconstruction (σ < 0.4°)

➔ ***Neutrino astronomy***

NEW

HERON simulation for a 10^{18} eV neutrino

KK, JA, OM, SW, ICRC 2025

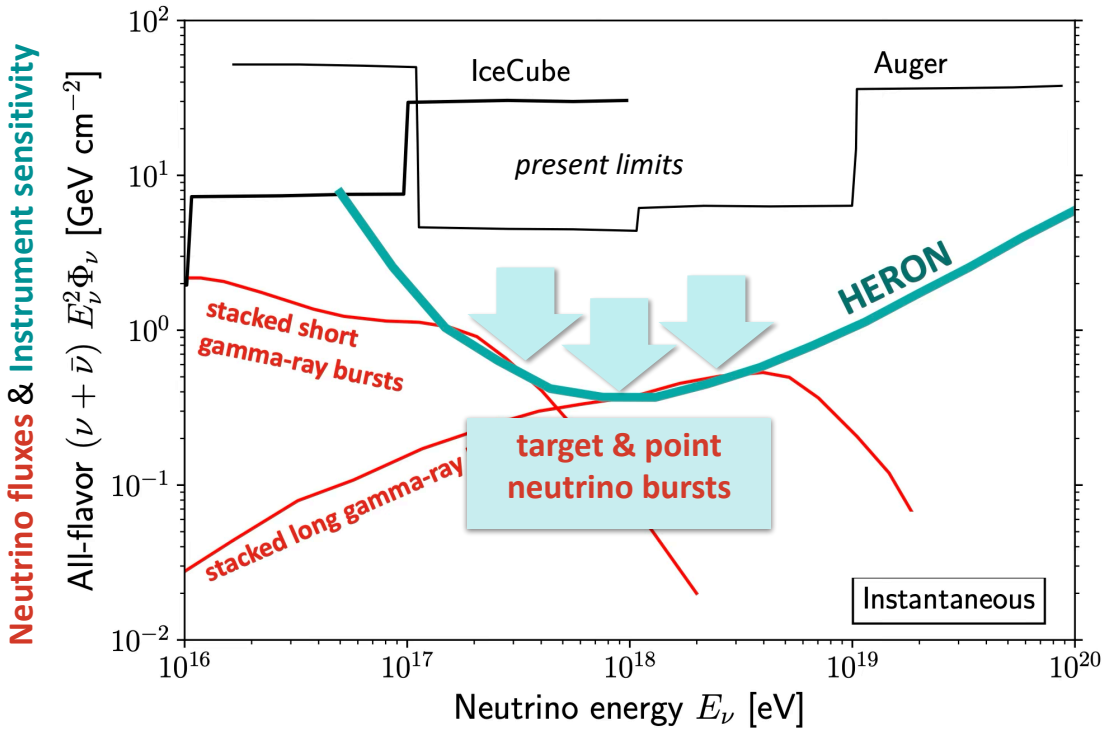


HERON's Sensitivity

HERON's Goals

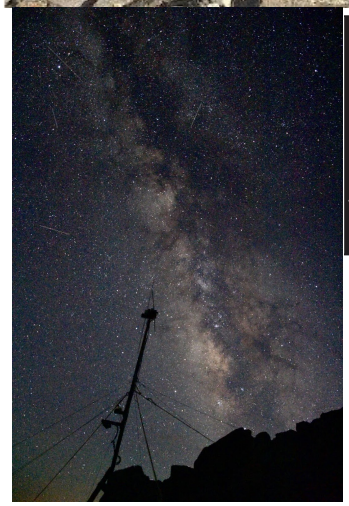
- Aim for UHE Neutrinos (> 10^{17} eV)
- Sub-degree angular resolution
- Targeted & Deep View of the Universe

KK, …, **OM**, **SW**, …, JCAP subm.
SW, KK, OM, JA, ICRC 2025



Conclusions

- High-elevation radio detectors are sensitive to particle showers
- **BEACON**
  - Promising approach for searching for Earth-skimming tau neutrinos
  - Candidate cosmic rays identified in radio-only and scintillator triggers
  - Can be used to finalize the expected thresholds & sensitivity
- **HERON**
  - Proposed combination of the BEACON and GRAND concepts that could have high sensitivity and excellent pointing resolution



BEACON

HERON

Conclusions and Outlook

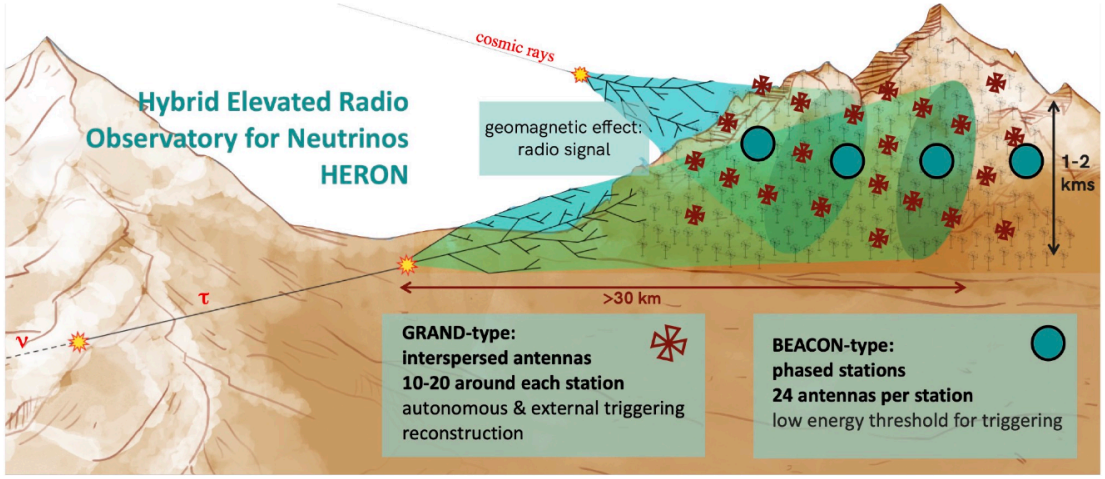
- 2021 radio-only cosmic ray search
  - 5 cosmic ray candidates, with further investigation needed
  - Once finalized, will be used to estimate BEACON's energy threshold
- 2023 scint + radio cosmic ray search
  - 15 candidates on a background of 8 ± 1
  - 10 candidates on a background of 1 if we require scintillator saturation
  - Future work will focus on finding cosmic rays below the radio threshold, with the goal of improving the radio trigger
  - Monte Carlo will explore expected radio + scint. overlap

What Next?

HERON

Optimize for 100 PeV neutrinos with long baseline array for reconstruction

Detecting the most violent astrophysical sources with HERON.



Nominal:

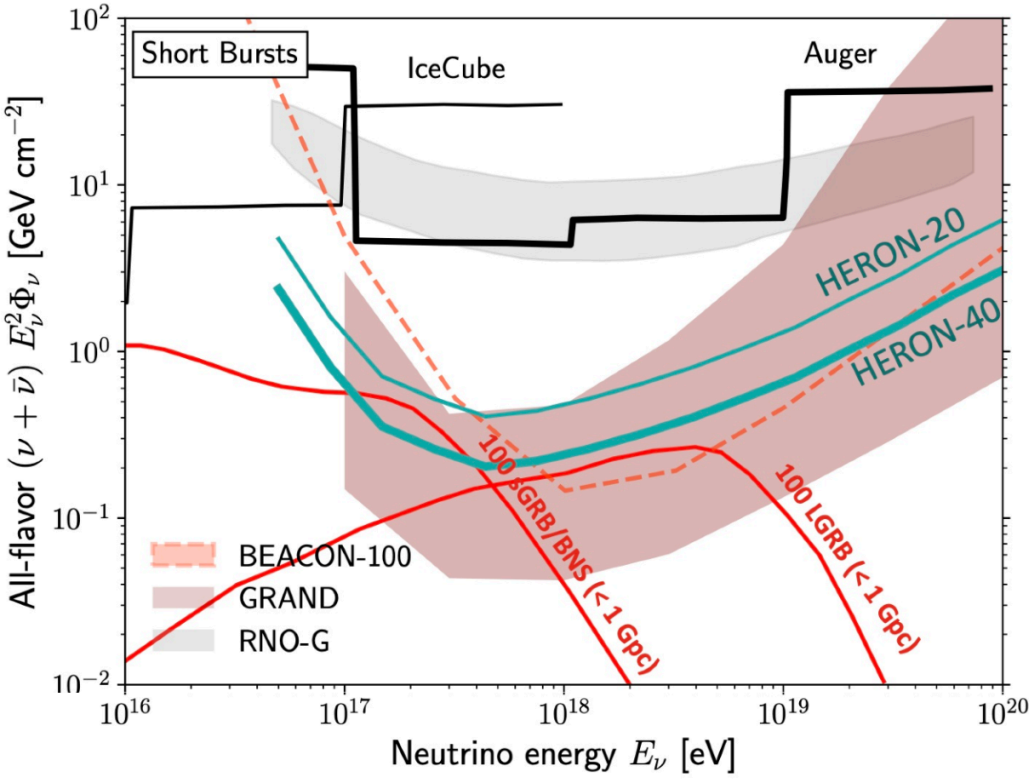
- 30-80 MHz frequency range
- Phased arrays: 1 km altitude, separated by 3 km, 24 channels (<200 m spacing)
- $\mathcal{O}(10)$ sparse antennas evenly spaced above and below 1 km

A. Zeolla

- **Trigger and Low-Energy Array:** 24 phased stations in a line along mountain ridge at 1 km
- **Reconstruction and High-Energy Array:** Single autonomous antennas for higher energies, long baselines for reconstruction, RFI rejection between 500 m and 1500 m

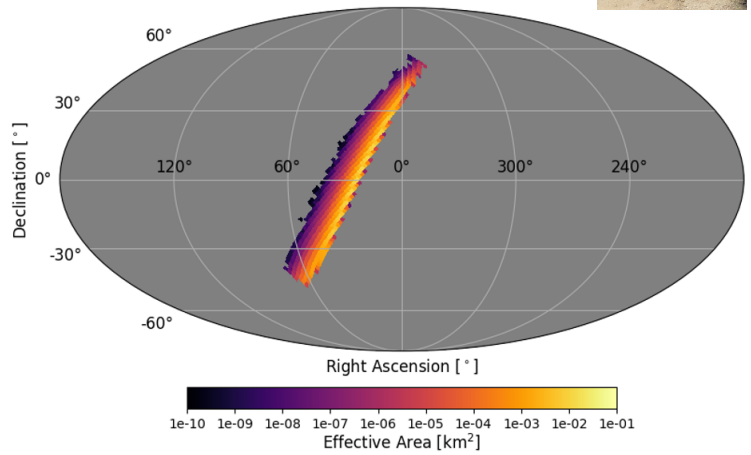
S.Wissel et al ARENA 2024

Short Burst Discovery Instrument

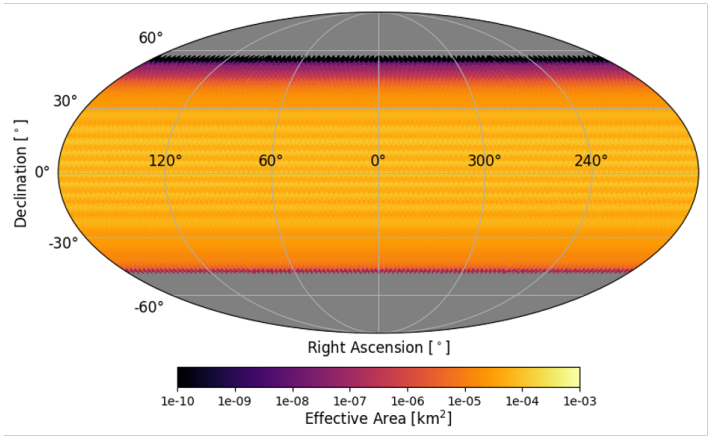


reliminary

Instantaneous FoV



Daily averaged FoV

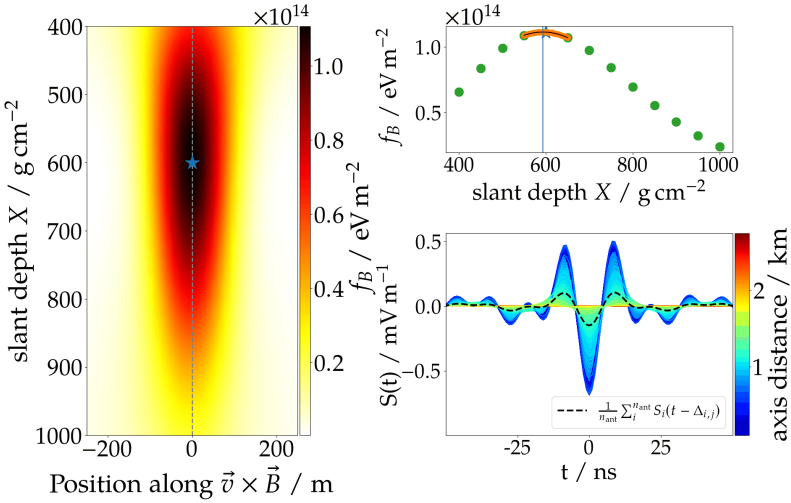


S.Wissel et al ARENA 2024

Sparse Array

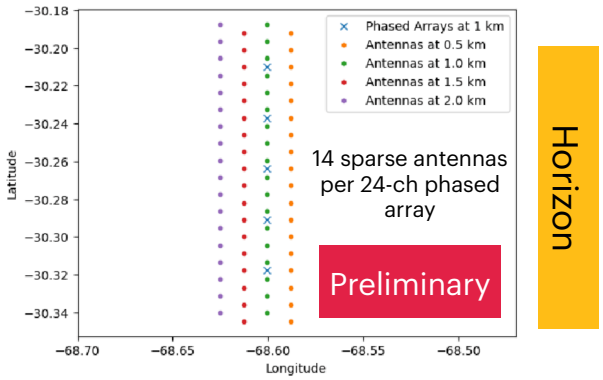
Reconstruction & RFI Rejection

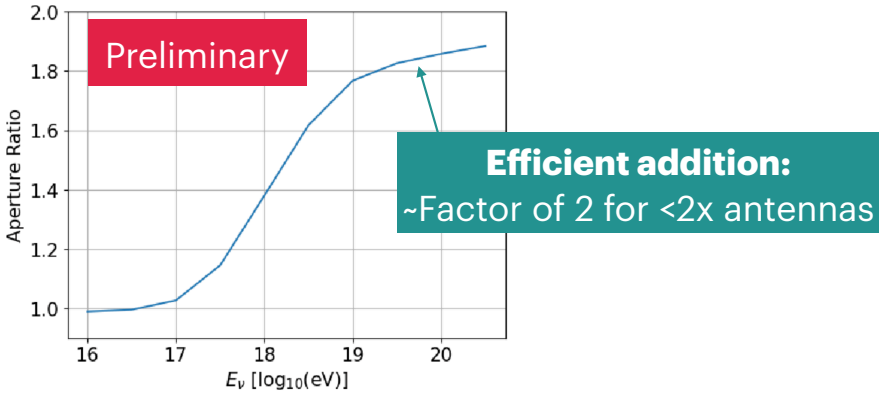
- **External Trigger:** Weak (< 1 σ) signals triggered from phased arrays
- **Interferometric reconstruction** can dig out the signal from the noise
  - Enables reconstruction of distance & energy
    → essential for CR/ν discrimination
  - To be verified with GRAND-BEACON layout + antenna design with noise present



Schoorlemmer & Carvalho arXiv:2006.10348
Schlüter & Huege arXiv:2102.13577

- **Autonomous Trigger:** Large sparse array builds sensitive at high energies



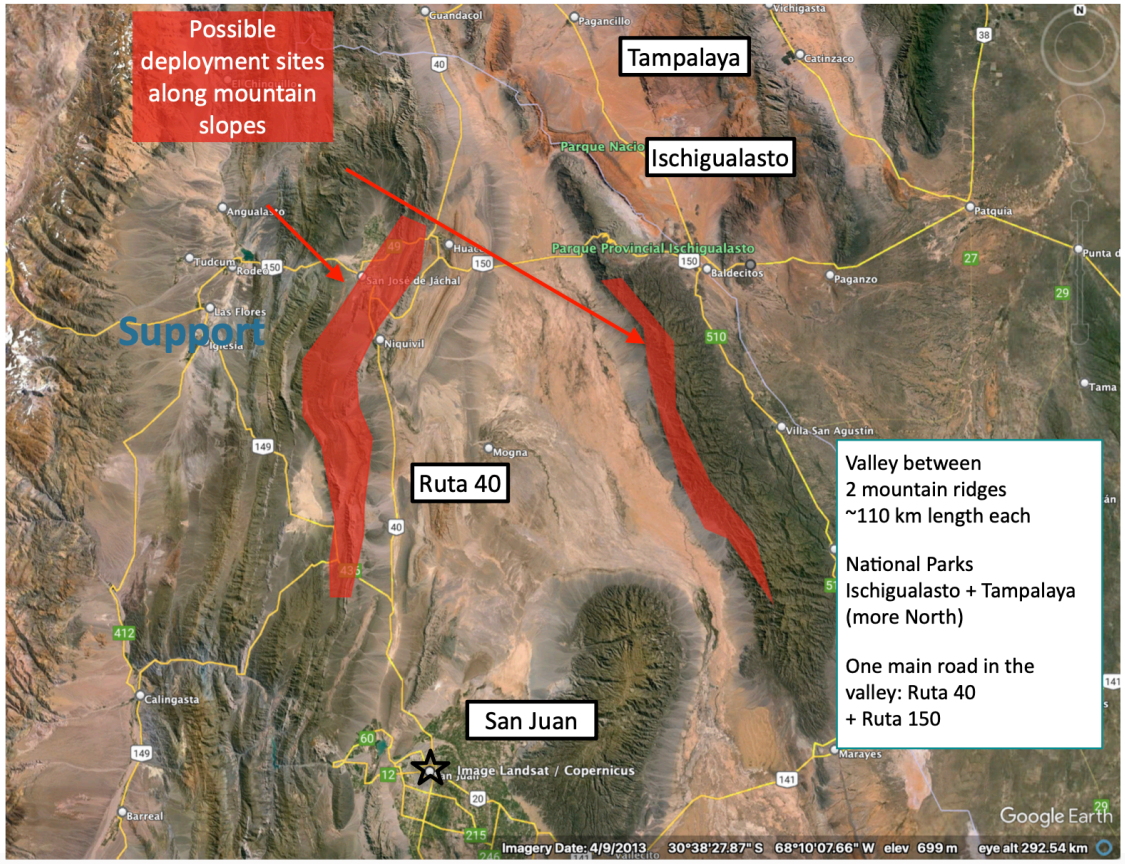


- Time synchronization & external trigger sent via beacon transmitter [demonstrated with AERA]

S.Wissel et al ARENA 2024

ARGENTINIAN SITE

- **Site Survey in San Juan mountains on going**



Requirements:

- a non-populated valley surrounded by 2 mountains of elevation > 1000 m, of 30-60 km wide
- radio-quiet environment (no power lines, no industries, no big road, no major town)
- possibility to establish a base near the site, to deploy our antennas, access, dig holes & pour concrete to install antennas.

Conclusions

- Radio Detection of the the Highest Energy Neutrinos
  - Enhance sensitivity to beyond the PeV scale
  - Combine CR and neutrino observations

- Deep exposure instruments like PUEO and BEACON highly sensitive to bursts of UHE neutrinos

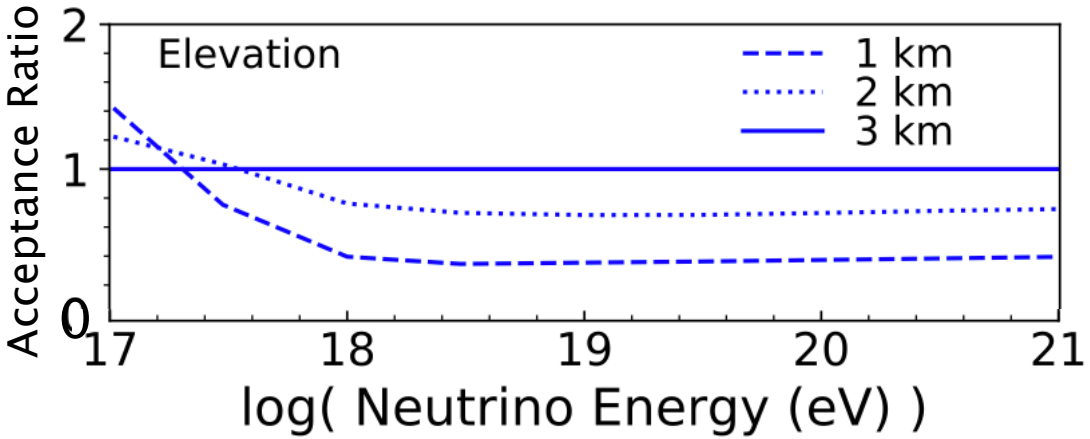
- PUEO can constrain or measure the flux at the **highest energy end**
  - the air shower channel offers **possible tau channel and** improved **background characterization**
- **BEACON / HERON** can measure the tau neutrino flux in a new energy range

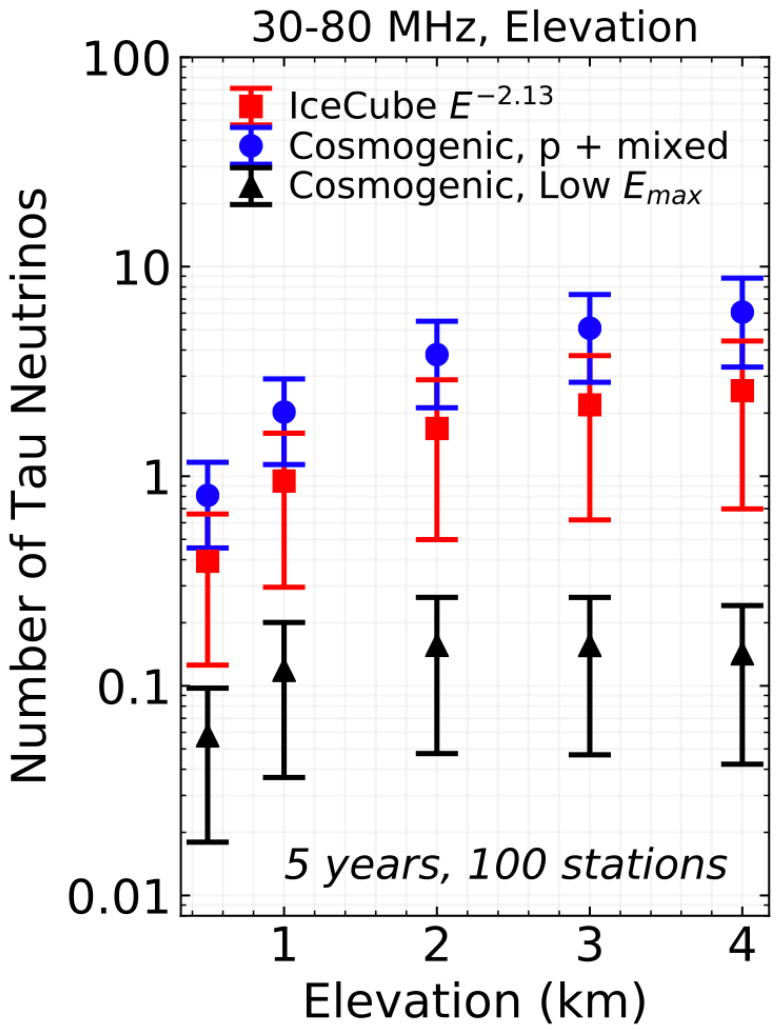
The Future is Radio Bright!

NSF BEACON IceCube GEN2 South Pole Askaryan Radio Array RNO-G Radio Neutrino Observatory - Greenland PUEO NASA

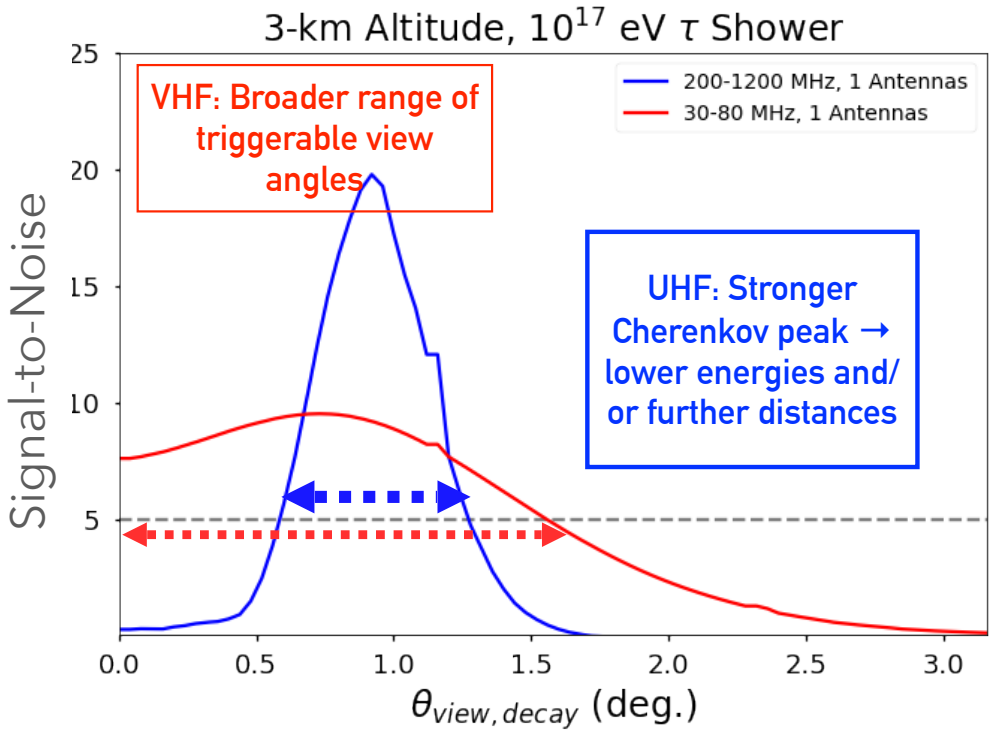
How High?

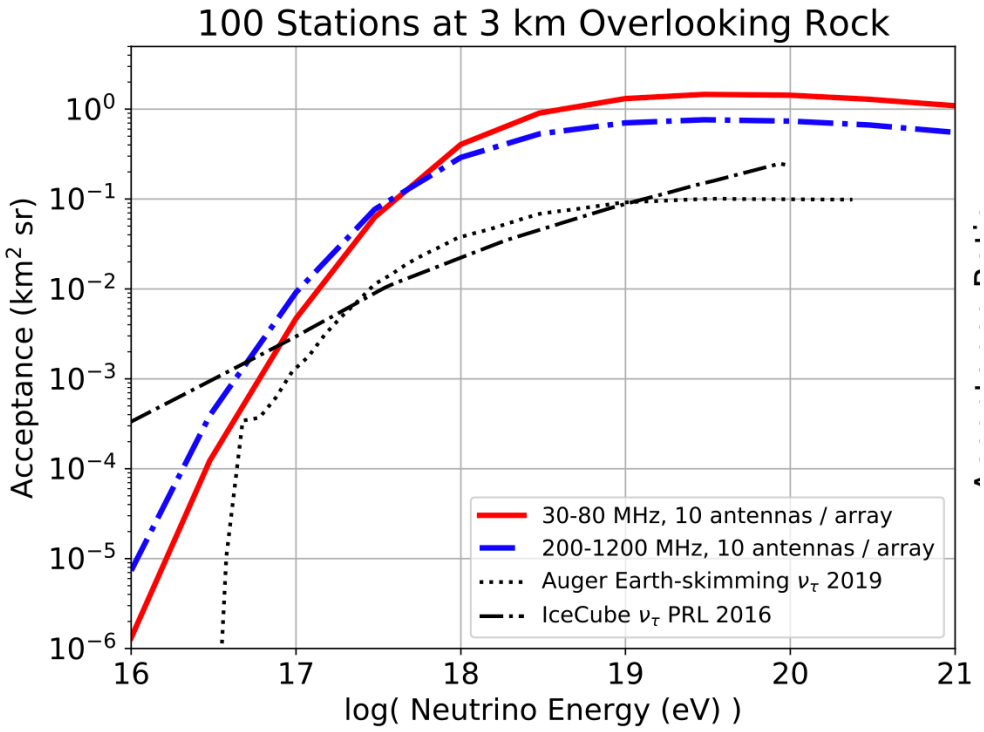
- 2 km is a good balance between increased viewing area and threshold





Frequency Range Impact

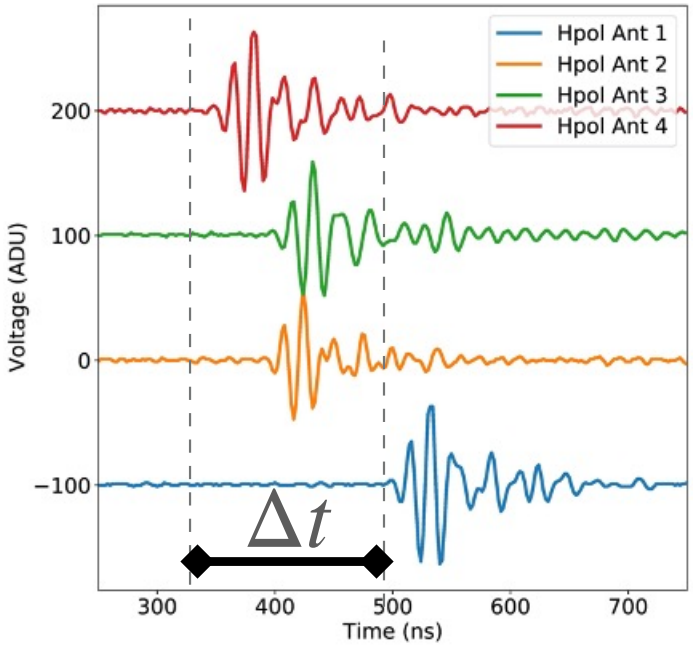




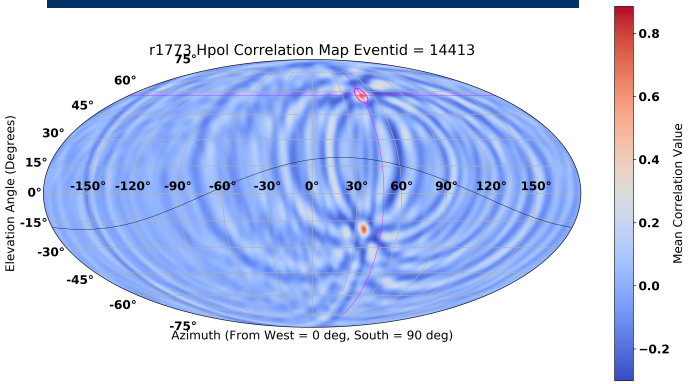
Wissel
JCAP 2020
arXiv:2004:12718

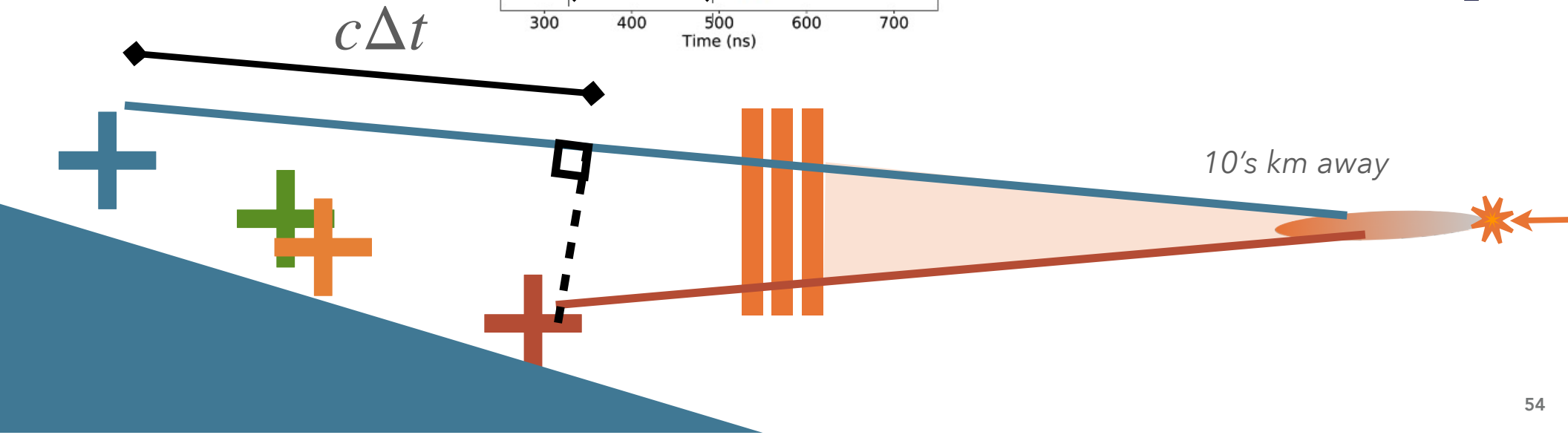
INTERFEROMETRY

Signals arrive at different antennas delayed by the Δt determined by the path length difference

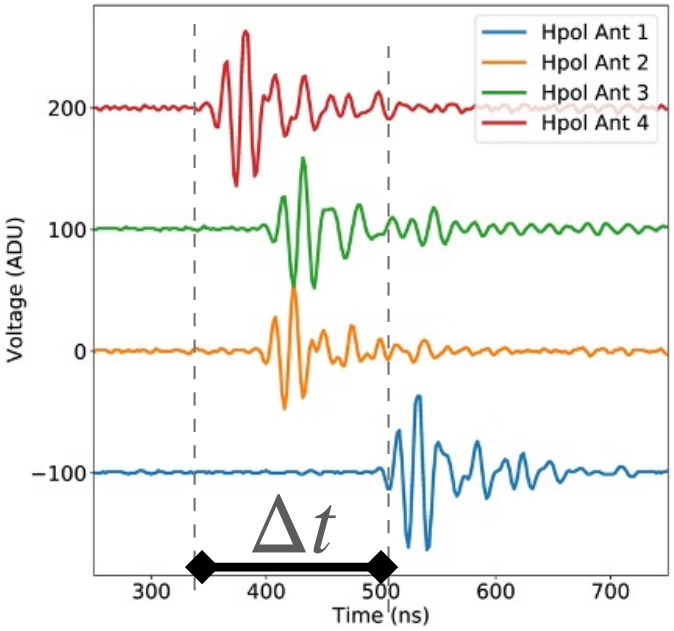


Δt's gives you direction

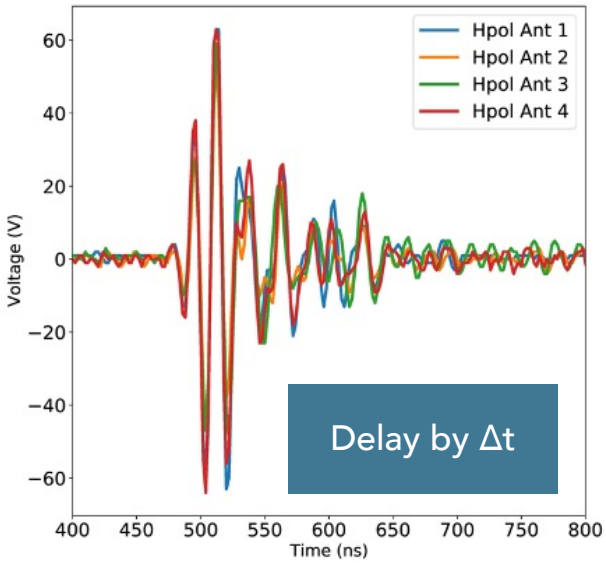


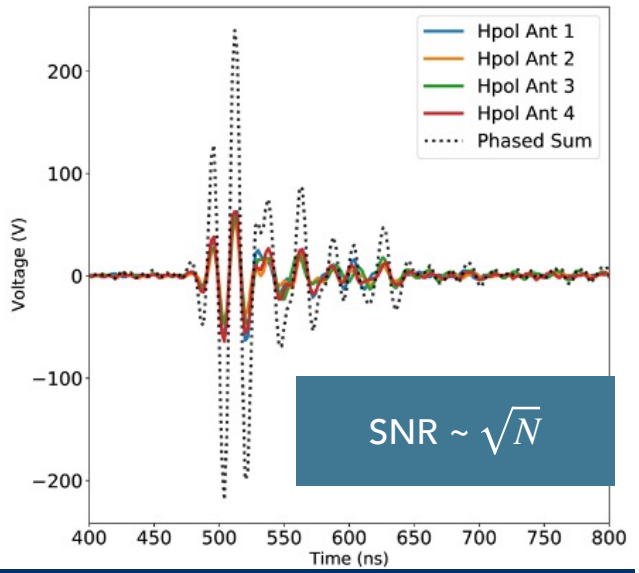


Phased Arrays on a Mountain

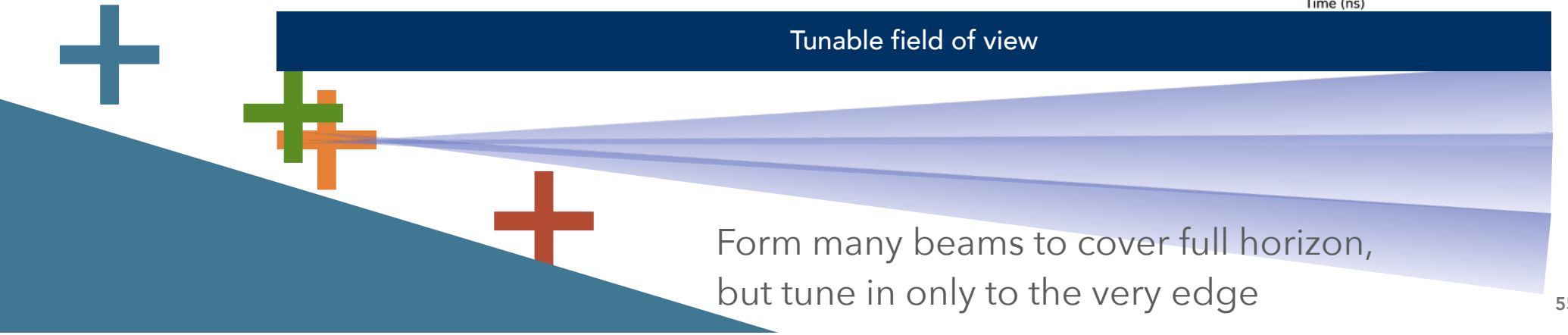


"Phasing" increases SNR



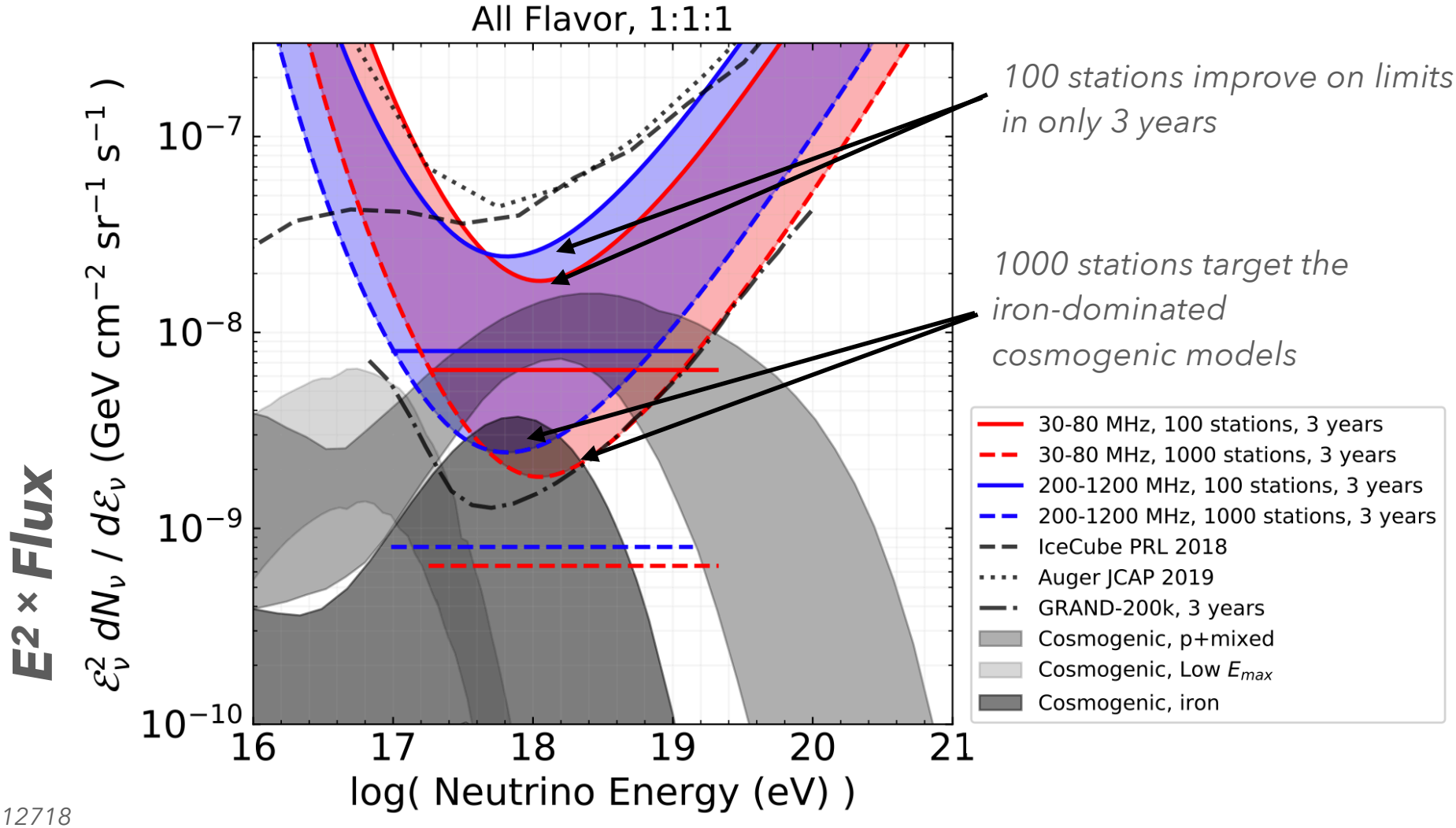


Tunable field of view



Form many beams to cover full horizon, but tune in only to the very edge

BEACON is an Efficient Design



Wissel
JCAP 2020
arXiv:2004:12718

Advantages of the BEACON Concept

- **Phasing**
  - Coherently summing signals in an array improves SNR by a factor of $\sqrt{N_{antennas}}$
  - Pointing allows for directional rejection of noise and a low trigger threshold

- **High elevation mountain ranges**
  - Increased viewing area
  - Multiple independent antenna arrays can be built to linearly improve the sensitivity

If we validate the sensitivity experimentally,
then we will have a **very efficient** tau neutrino experiment

BEACON Prototype Array

- Prototype at the White Mountain Research Station has been running since 2018 at 3.8 km
- Goals:
  - validate sensitivity estimates with cosmic ray search
  - test phased arrays at high elevation
  - manage backgrounds and operate continuously

BEACON Prototype Array

- Prototype at the White Mountain Research Station has been running since 2018 at 3.8 km
- Goals:
  - validate sensitivity estimates with cosmic ray search
  - test phased arrays at high elevation
  - manage backgrounds and operate continuously

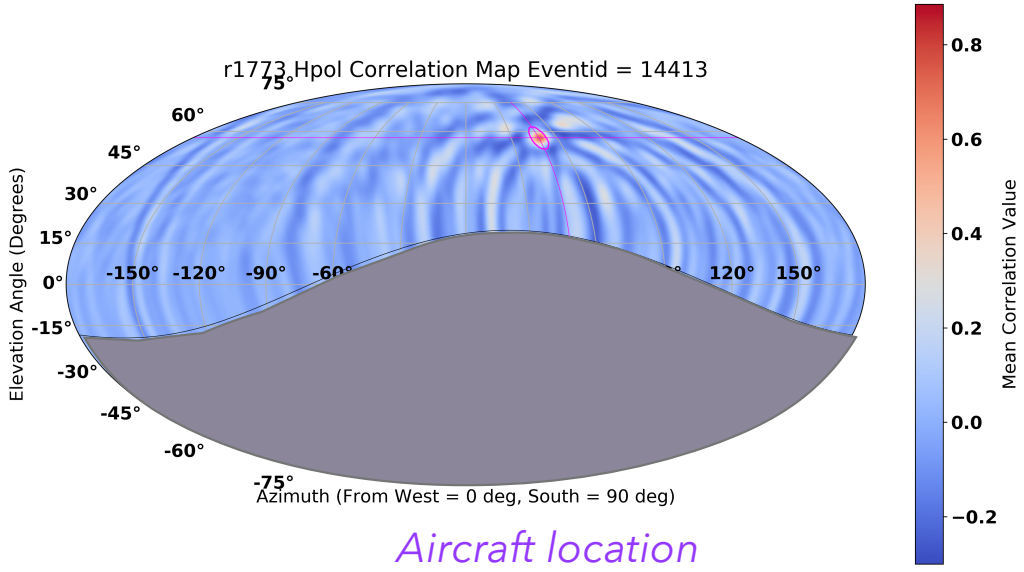
- Need to demonstrate that we **(1)** can trigger on **impulsive signals** with **(2) thresholds** comparable to 5 x thermal noise level in voltage

1. **Impulsive triggers**: demo RF-only trigger
2. **Thresholds**: understand what thresholds are achievable

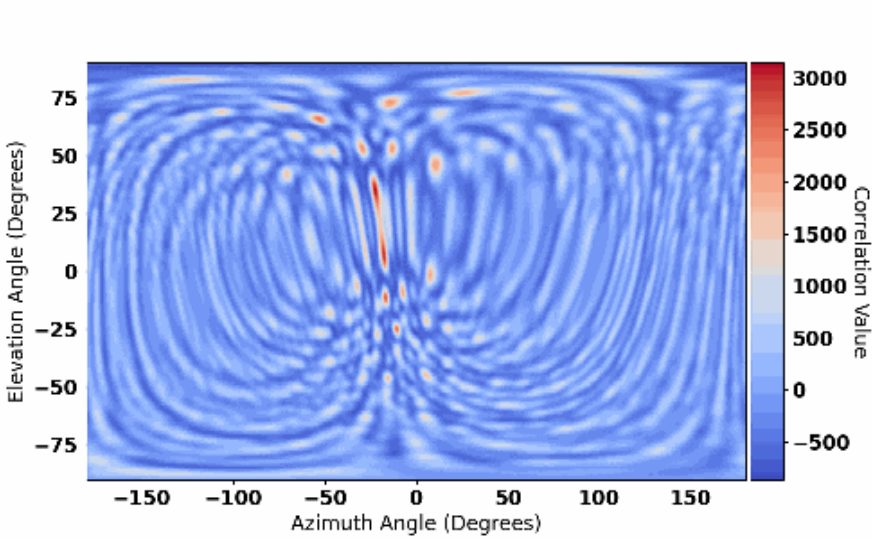
IMPULSIVE TRIGGERS

Impulsive triggers:

Aircraft and impulsive calibration sources



Aircraft location



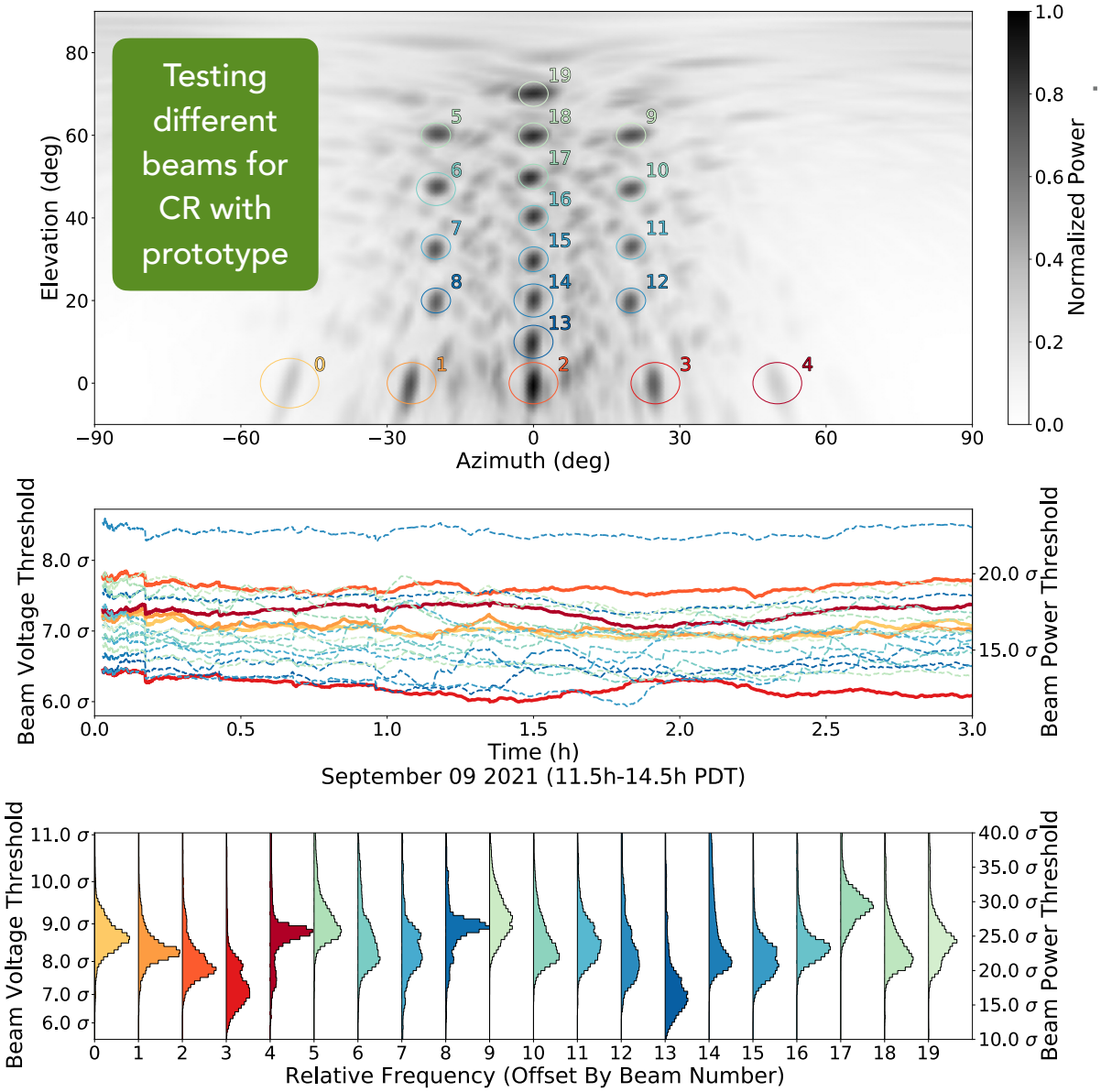
D. Southall, BEACON arXiv:2206.09660, A. Zeolla

BEAMFORMING *IN SITU*

- Form beams that cover your full solid angle
  - Full scale BEACON would fill the solid angle near horizon, and only point in a ring near the horizon
- Noise-riding threshold automatically adjusts the thresholds in "noisy beams" so the backgrounds do not dominate

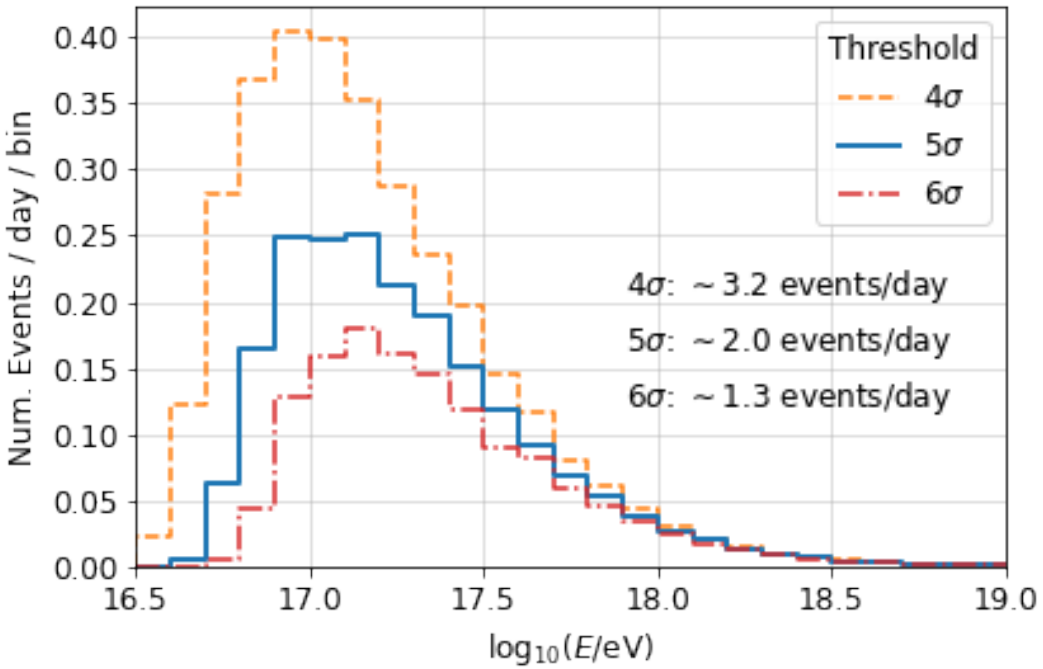
Thresholds: Many beams at thresholds ***approaching*** level assumed in neutrino sims

D. Southall, BEACON arXiv:2206.09660

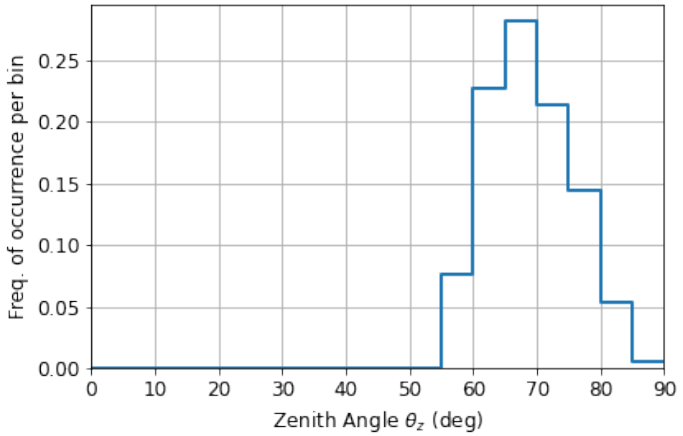


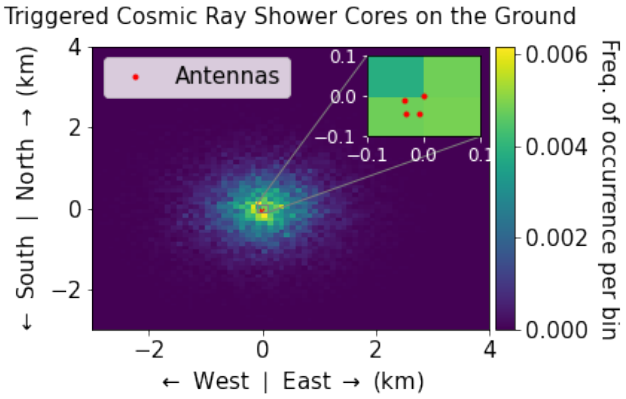
Cosmic Rays help Validate the Performance

- Cosmic ray rate depends strongly on instrument threshold

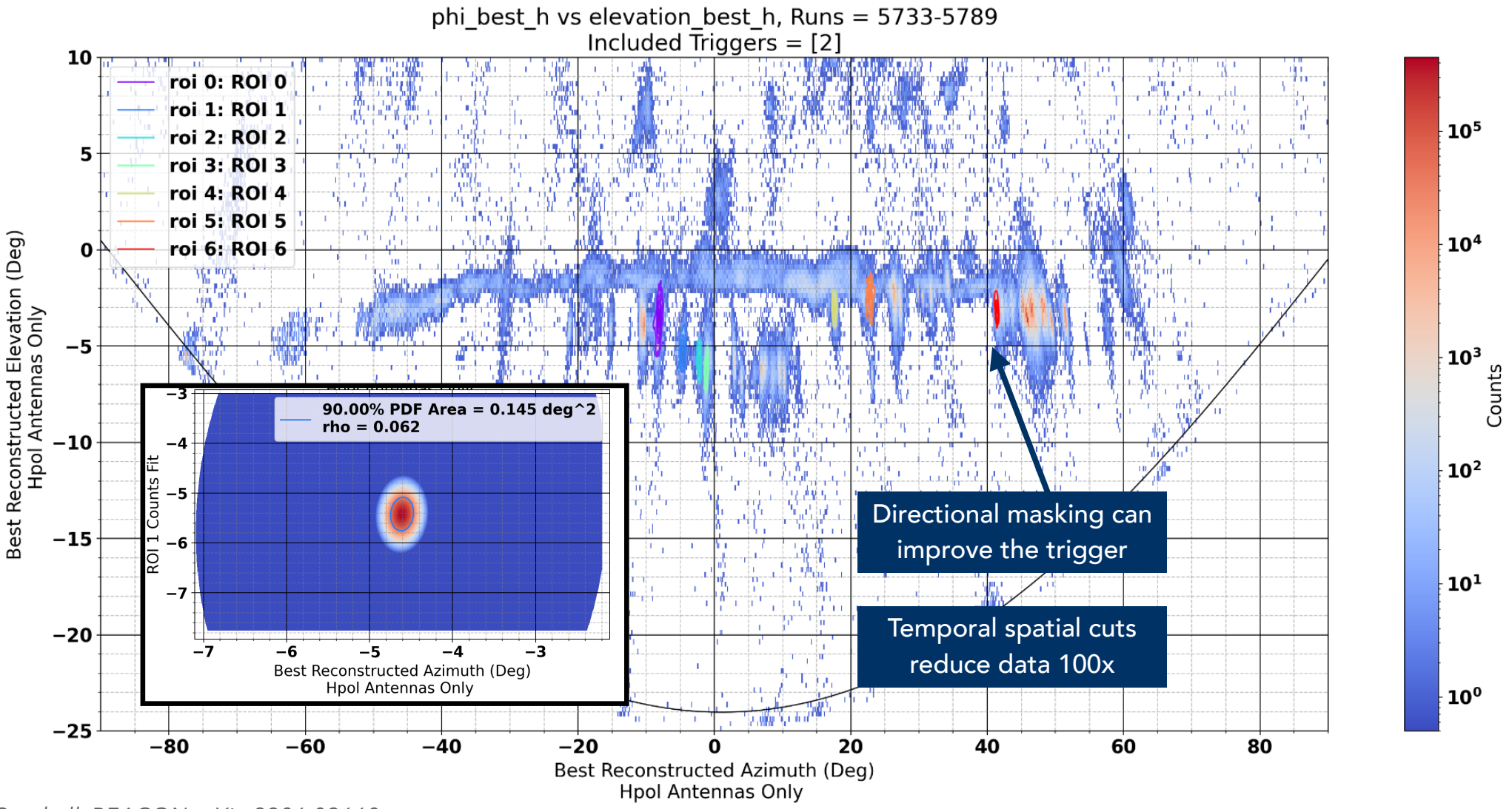


- Geometry is sensitive to highly inclined, distant air showers





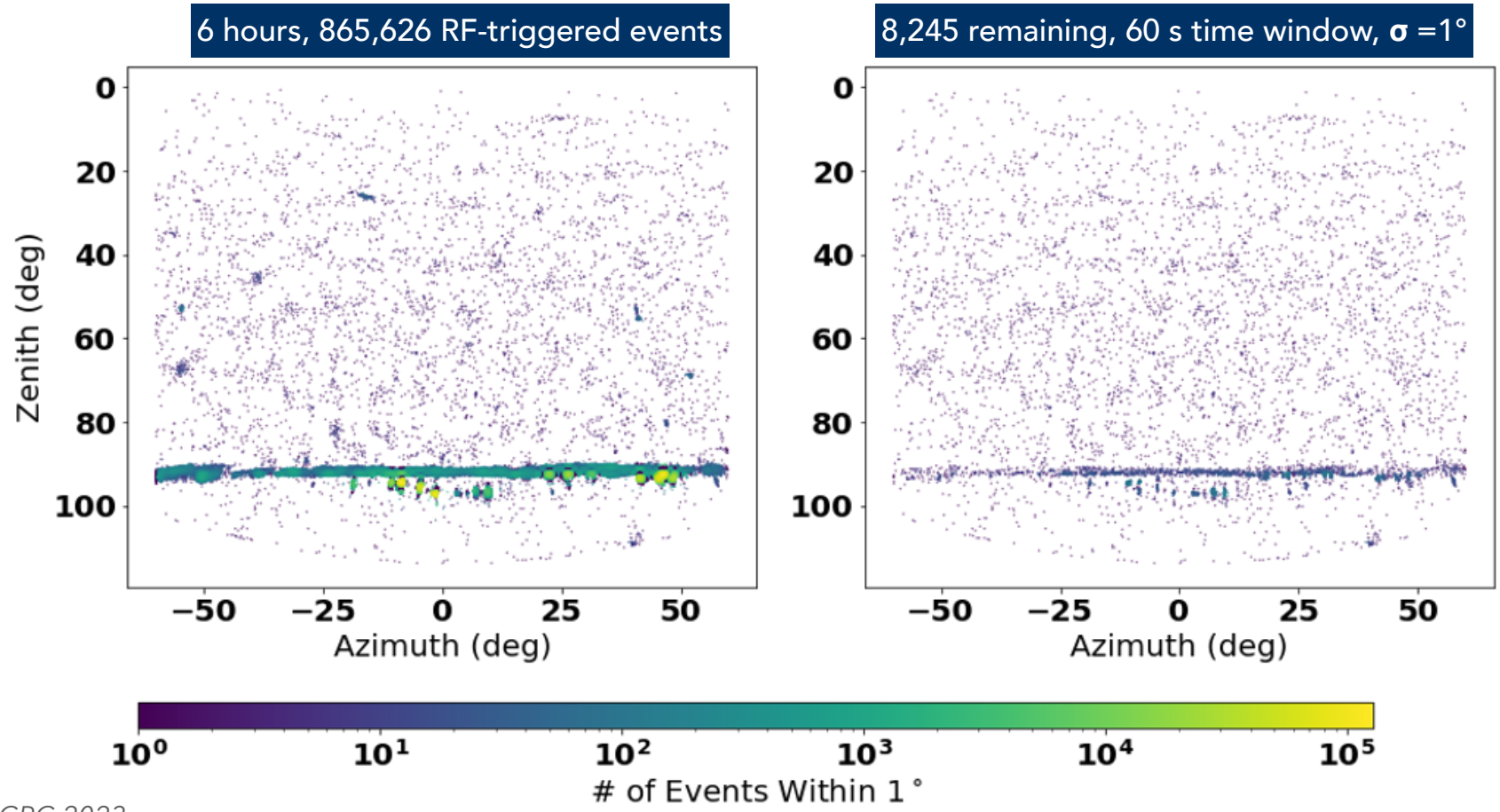
A. Zeolla ICRC 2023, 2021, ARENA 2022



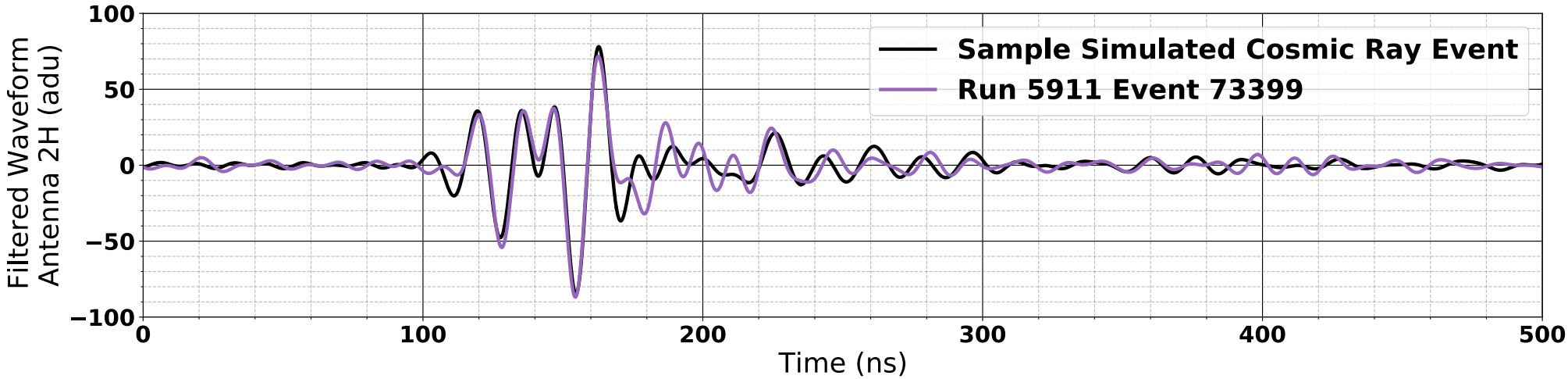
D. Southall, BEACON arXiv:2206.09660

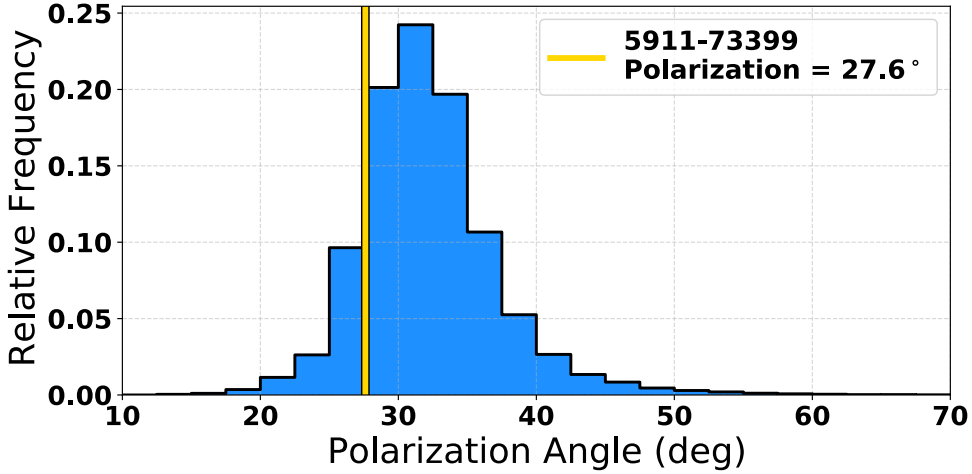
TEMPORALSPATIAL CUTS FOR CR SEARCH

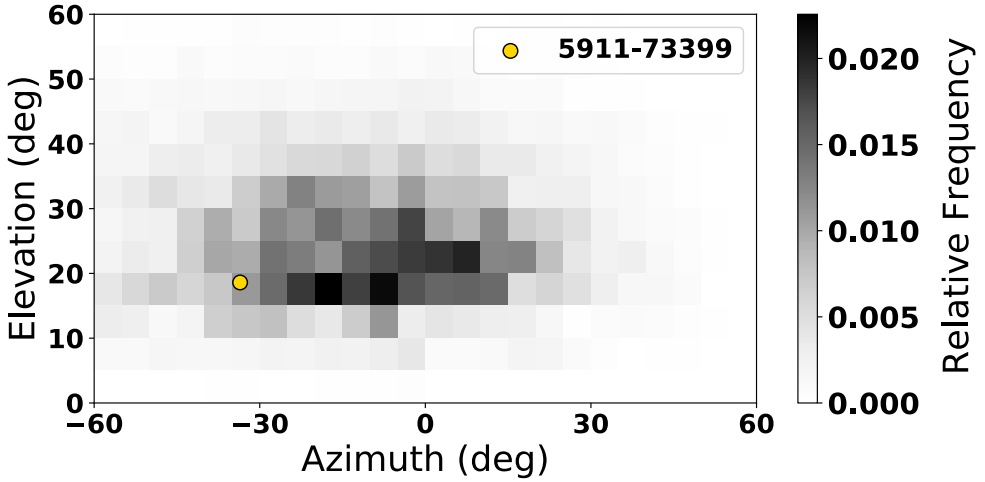
$$-2\log\left(L_{ij}\right) = \left(\frac{\theta_i - \theta_j}{\sigma_\theta}\right)^2 + \left(\frac{\phi_i - \phi_j}{\sigma_\phi}\right)^2$$



Promising CR Candidate



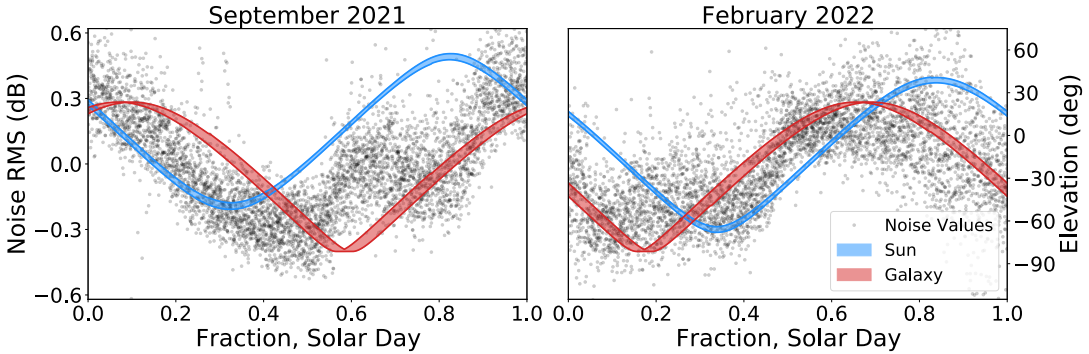




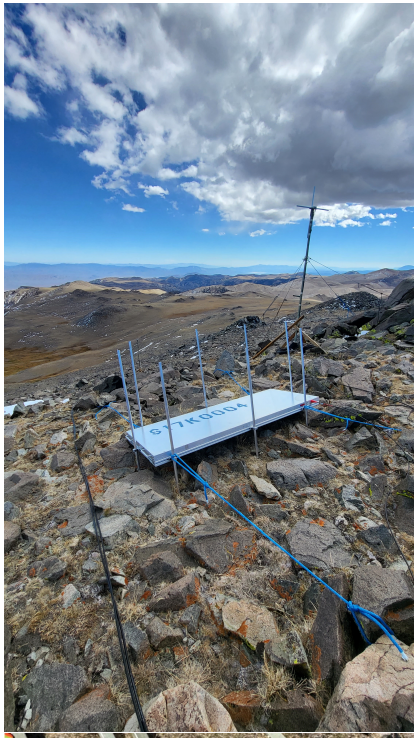
D. Southall, BEACON arXiv:2206.09660

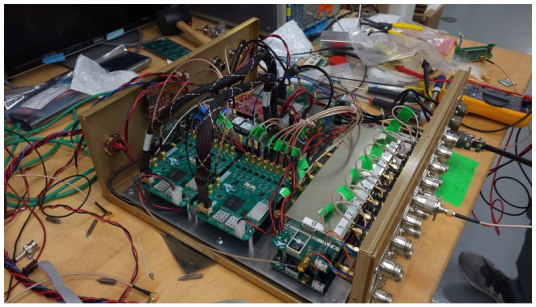
BEACON's Prototypes

- 2018: LWA antennas
- 2019-2022: custom dipoles + 7-bit 1 GSa/s MSa/s phased array DAQ
- 8 antennas (H&V) on 4 masts
- Power ~50 W



- 2023
- Custom dipoles with built in differential GPS
- 12 antennas (H&V) on 6 masts
- 4 scintillators
- Custom 500 MSa/s 4-channel DAQ with onboard phasing and coincidence triggering
- Power draw ~25 W





Conclusions

- High-elevation radio detectors are sensitive to particle showers
  - Neutrinos via Askaryan & Earth-skimming taus
  - Cosmic rays
    → instrument validation & backgrounds
- **PUEO LF**
  - Large low-freuquency deployable array
  - Tau neutrino search, background estimate improvement, & ANITA follow-up
- **BEACON**
  - Promising approach for searching for Earth-skimming tau neutrinos
  - CR search underway and recent upgrades
- **Stay tuned**