# BEACON Overview

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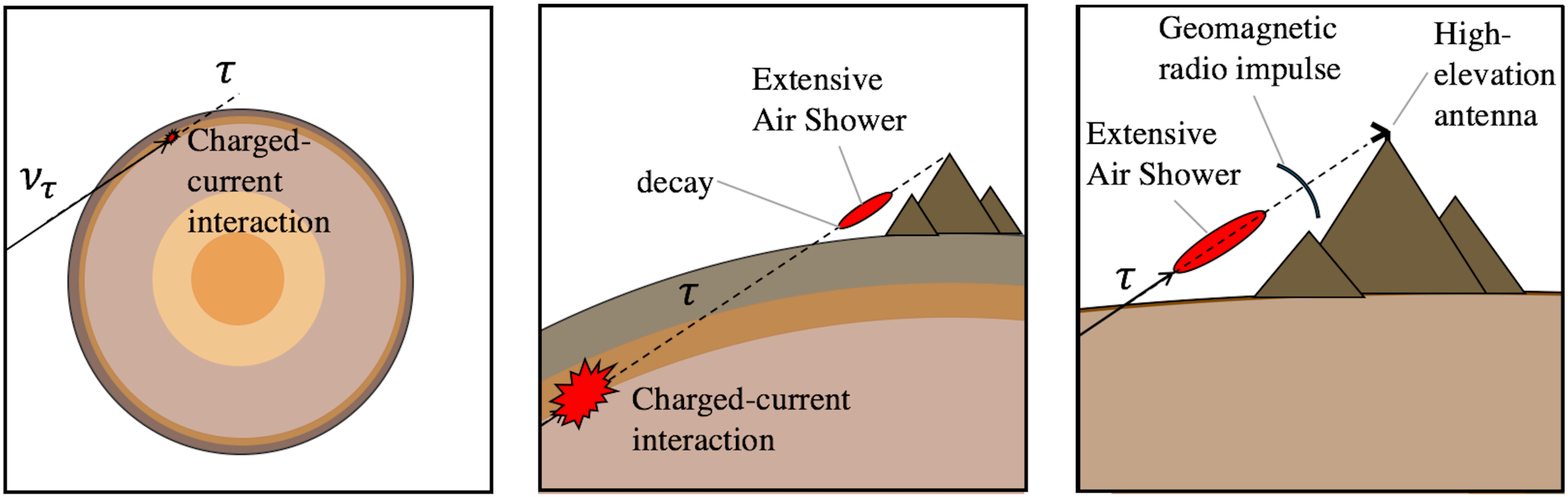
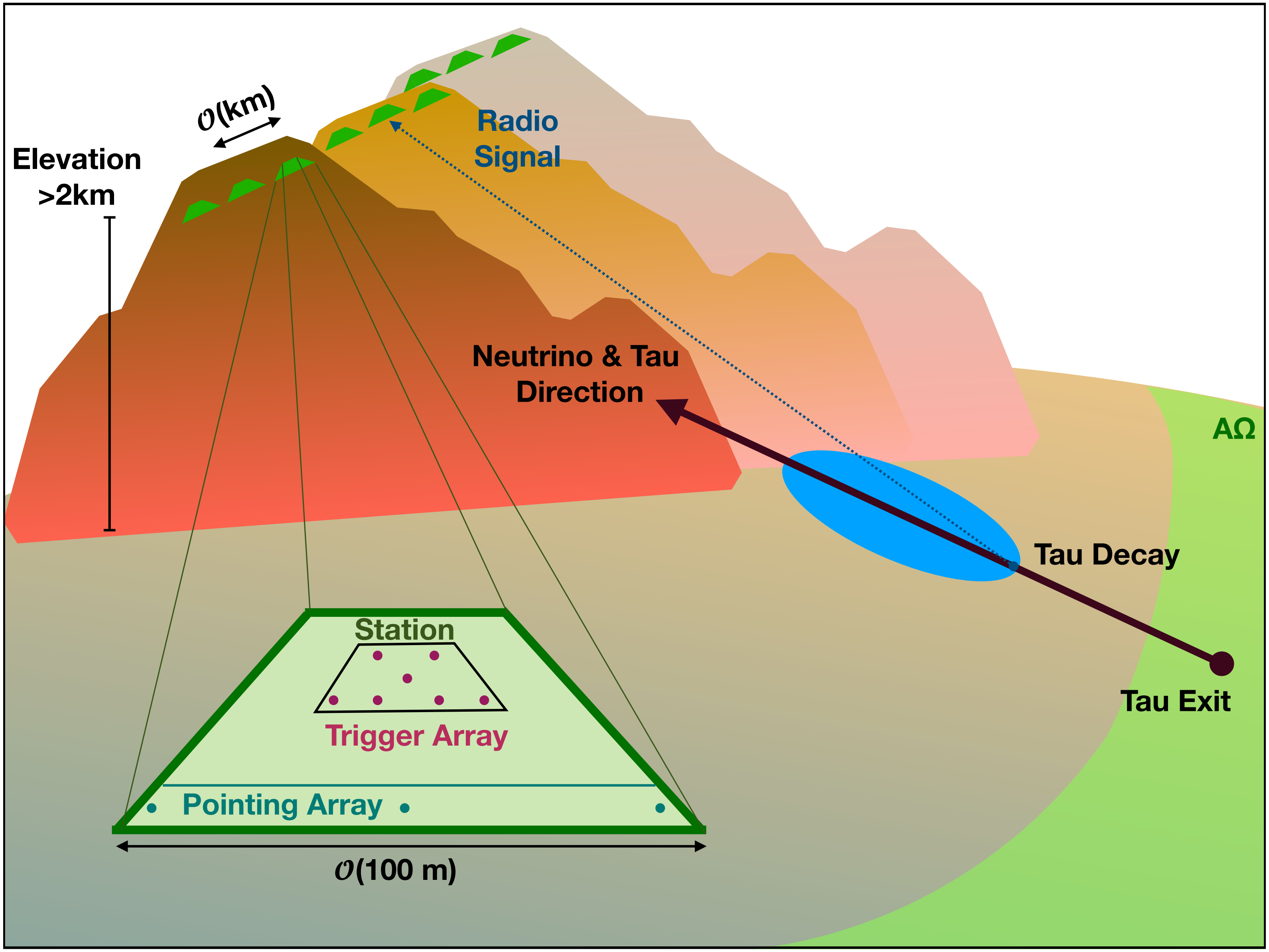
BEACON-GRAND Workshop

11 Jan 2024

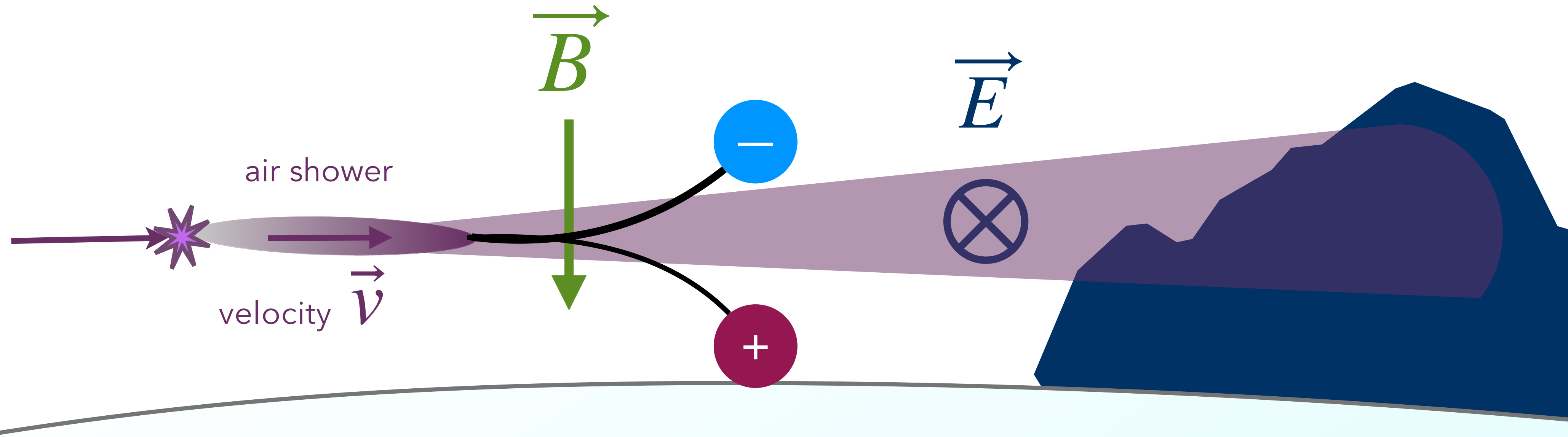
# BEACON: Beamforming Elevated Array for COsmic Neutrinos





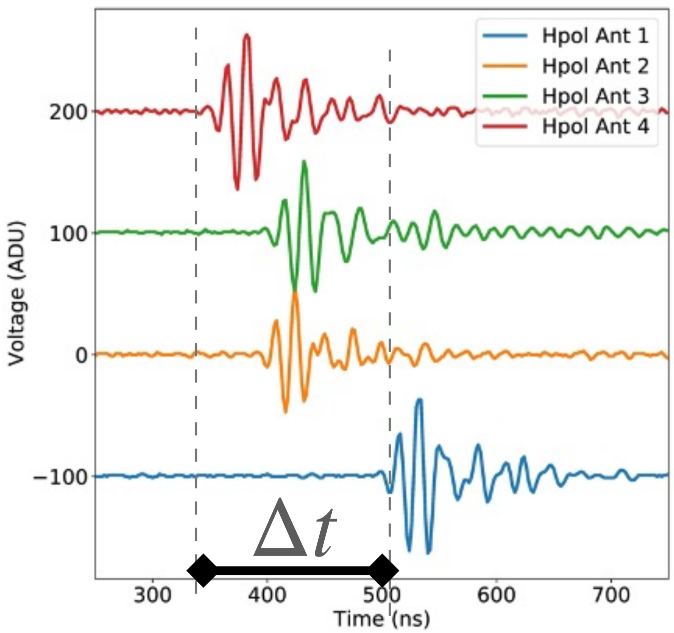

*Wissel*
*JCAP 2020*
*arXiv:2004:12718*

# Earth-Skimming Neutrino Radio Characteristics

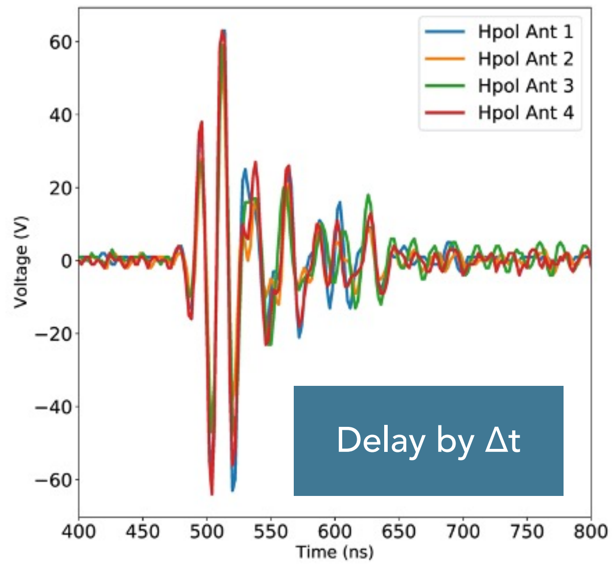


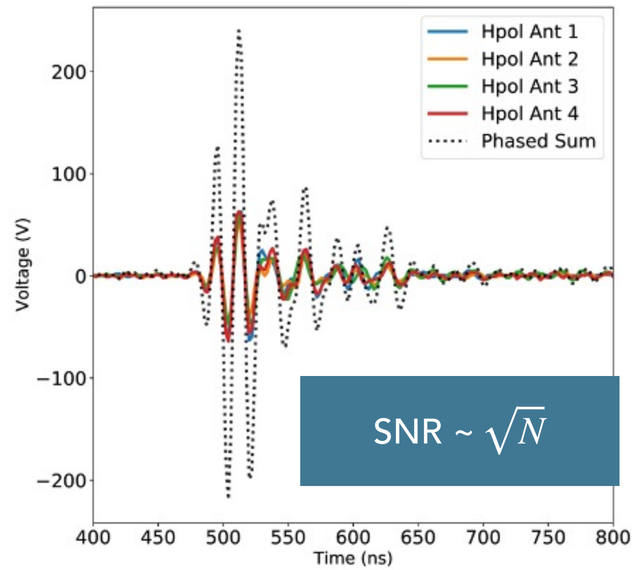

- **Geomagnetic emission:** separation of charges in shower due to Lorentz force. $\overrightarrow{E} \propto \vec{v} \times \overrightarrow{B}$
  - Polarization correlated with Earth's magnetic field
  - Also some radially polarized emission from charge excess in the shower → changes beam **("Askaryan radiation")**
- **Impulsive (fast and broadband)**: Strongest at low frequencies (<100 MHz); Signal peaks at Cherenkov angle at high frequencies (>100 MHz)
- Signal concentrated **near the horizon** due to exit probabilities

# Phased Arrays on a Mountain




"Phasing" a compact array increases SNR



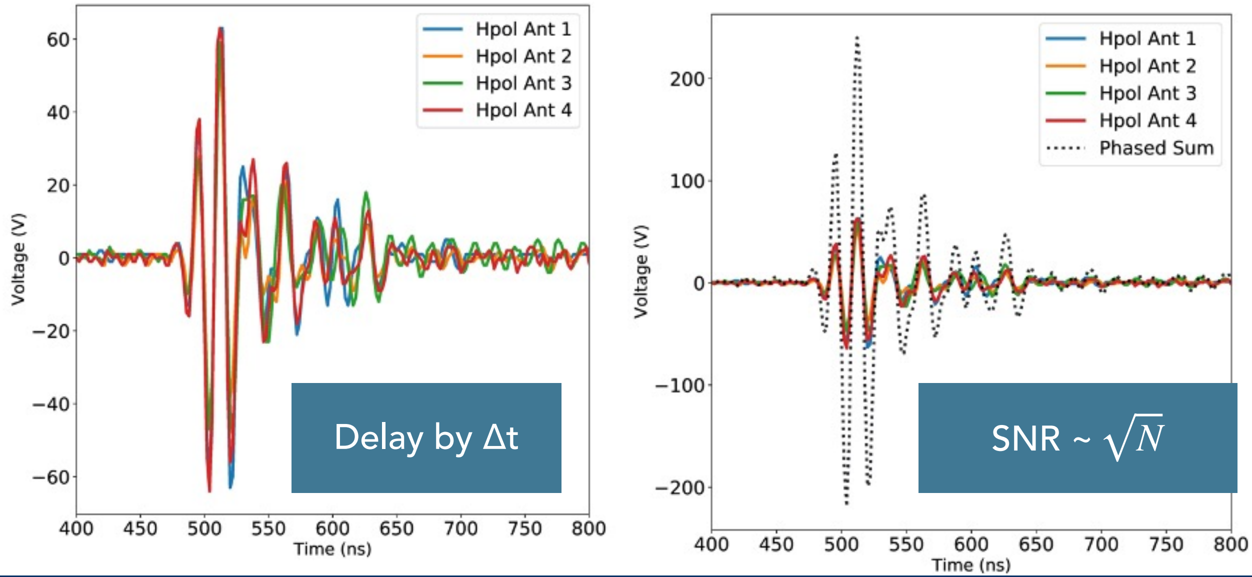



# PHASED ARRAYS ON A MOUNTAIN

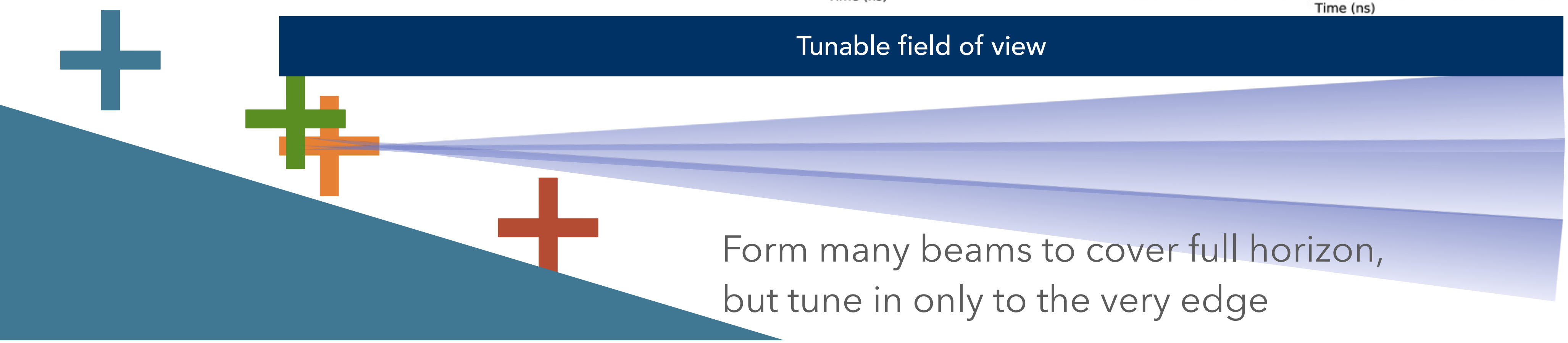
- Increase station gain by coherently summing multiple antennas

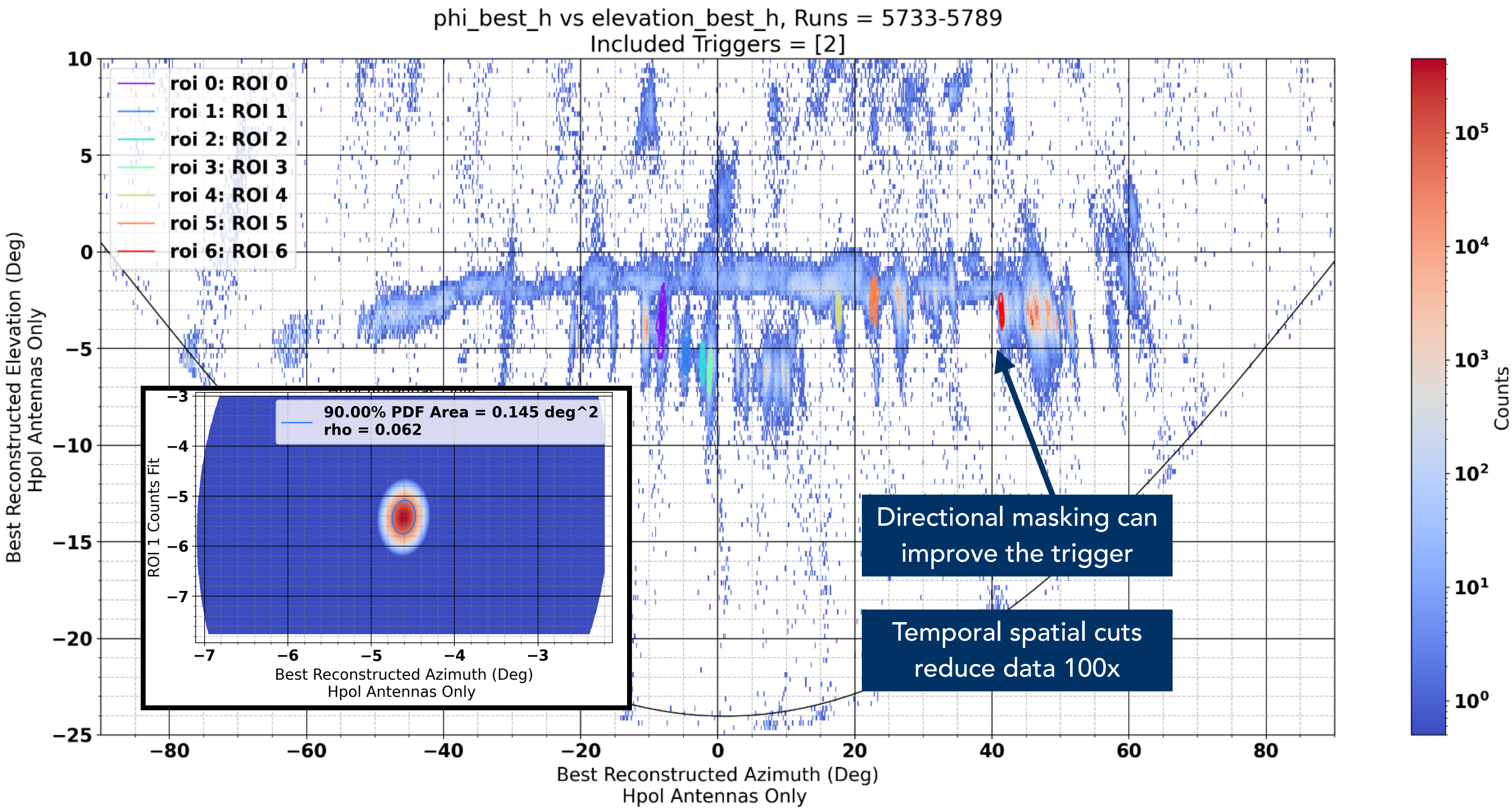
$$G = 10\log_{10}(N_{ant}) + G_{ant}$$

## "Phasing" a compact array increases SNR




## Tunable field of view






D. Southall, BEACON arXiv:2206.09660

# ADVANTAGES OF THE BEACON CONCEPT

- **Phasing**
  - Coherently summing signals in an array improves SNR by a factor of $\sqrt{N_{antennas}}$
  - Pointing allows for lower trigger thresholds, tunable beams at the horizon, ***and*** directional rejection of noise
  - *N.B. requires compact trigger arrays (spacing ~10's of meters)*

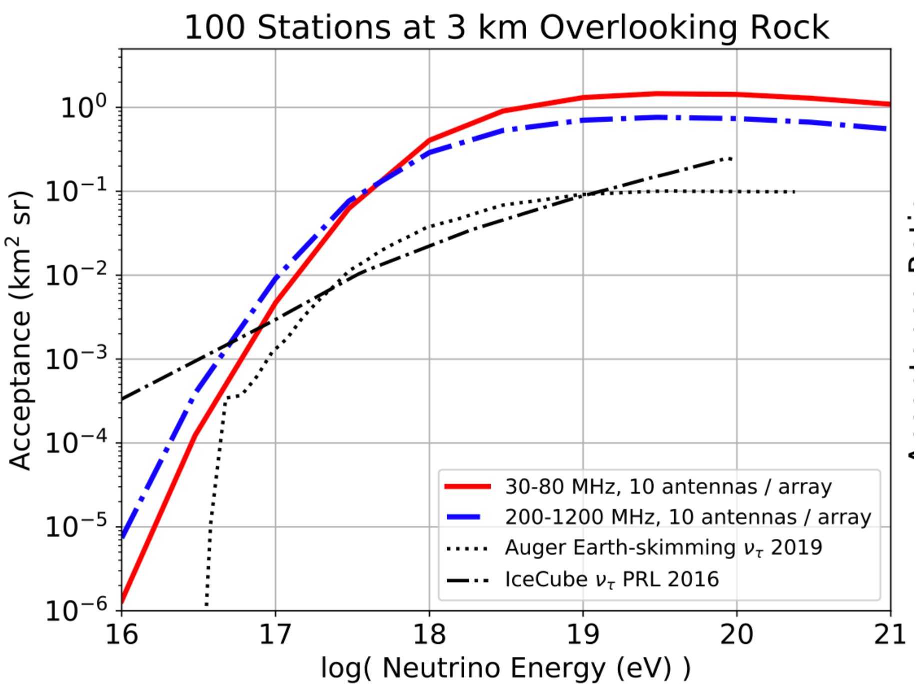
- **High elevation mountain ranges**
  - Increased viewing area
  - Multiple independent antenna arrays can be built to linearly improve the sensitivity
  - *N.B. requires large station spacings to be truly independent (6-7 km at 1 EeV for 10% overlap)*

- **Target energy range is an important design consideration**
  - 10 PeV to 1 EeV is a sweet spot between astrophysical and cosmogenic fluxes
  - Frequency range, elevation chosen depends on this
  - Can design different detectors for a broader – or more targeted – energy range

So how do I design my mountaintop phased array?

- Frequency Range
- Elevation
- Phased Trigger Design

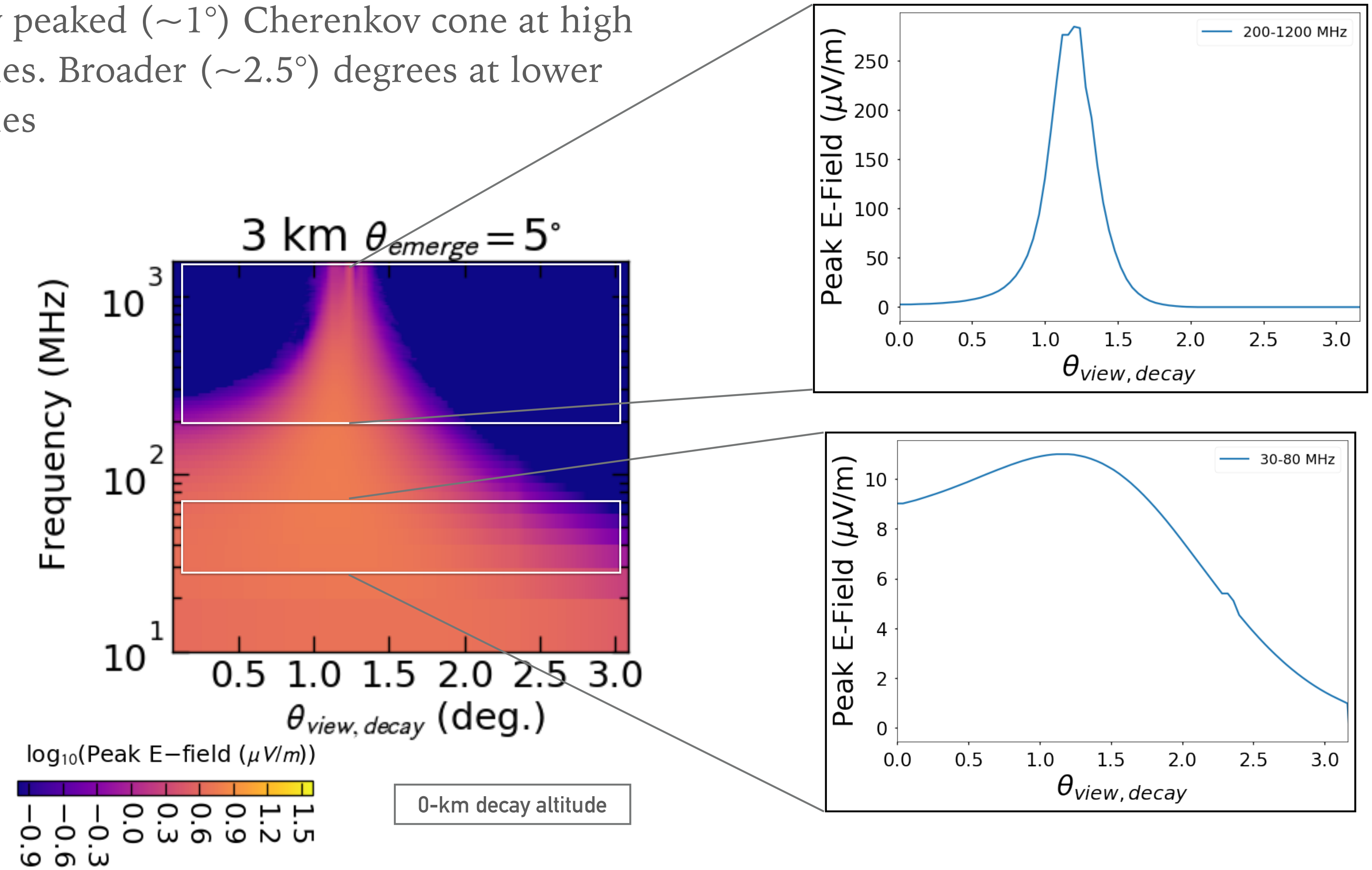
# BEACON Reference Designs



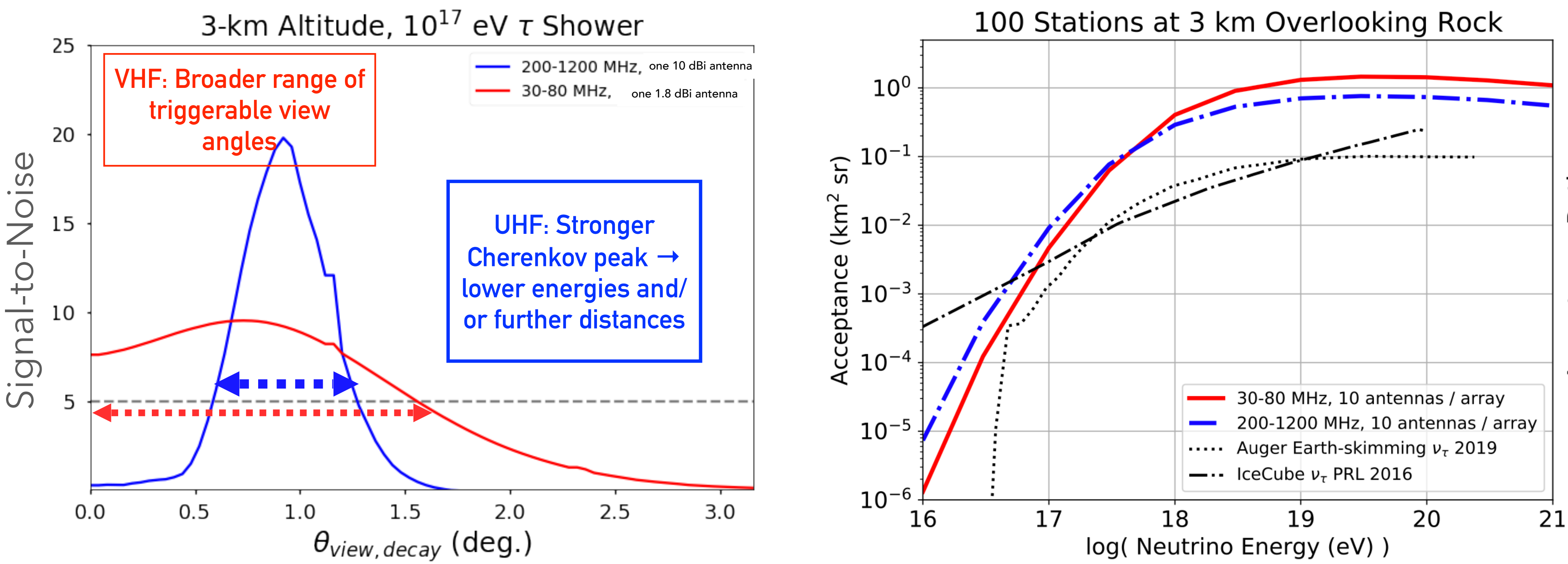

- 3 km Elevation, 120° FOV
- 30-80 MHz or 200-1200 MHz, depending on site RFI
  - 30-80 MHz: Electrically short dipoles 1.8 dBi, isotropic
  - 200-1200 MHz: High-gain broadband antennas (horns, LPDAs) 10 dBi, isotropic
- 10 phased antennas in the trigger per station
- Stations are spaced so that <10% overlap in effective volume

# Radio Footprint at Mountain Altitudes

Narrowly peaked (~1°) Cherenkov cone at high frequencies. Broader (~2.5°) degrees at lower frequencies



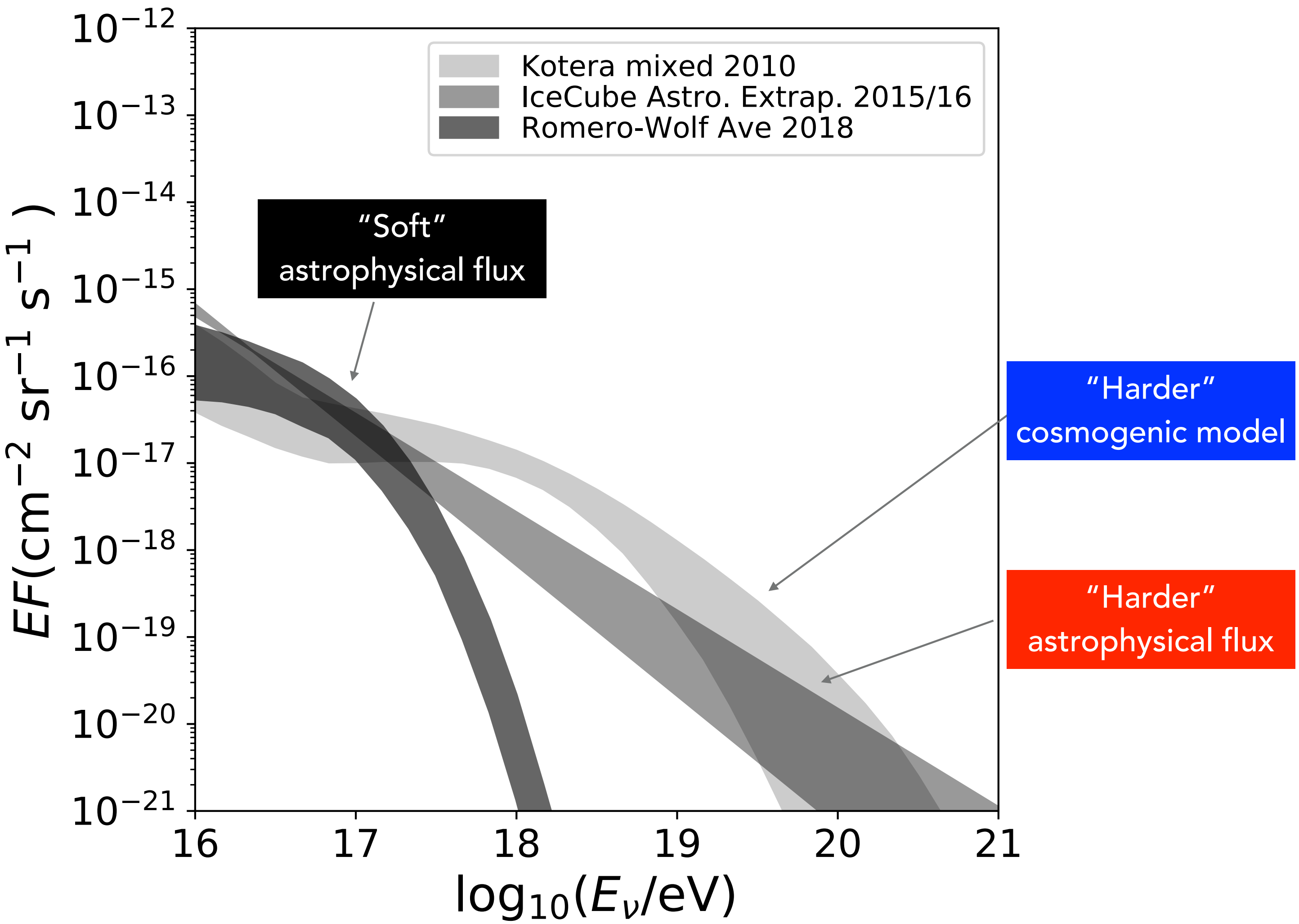
# Frequency Range Impact




- Comparable effective area for the two frequency bands, but lower frequencies are slightly better at high energies and high frequencies slightly better at threshold
- RFI at sites may determine optimal band (although 30-80 MHz typically cleaner)

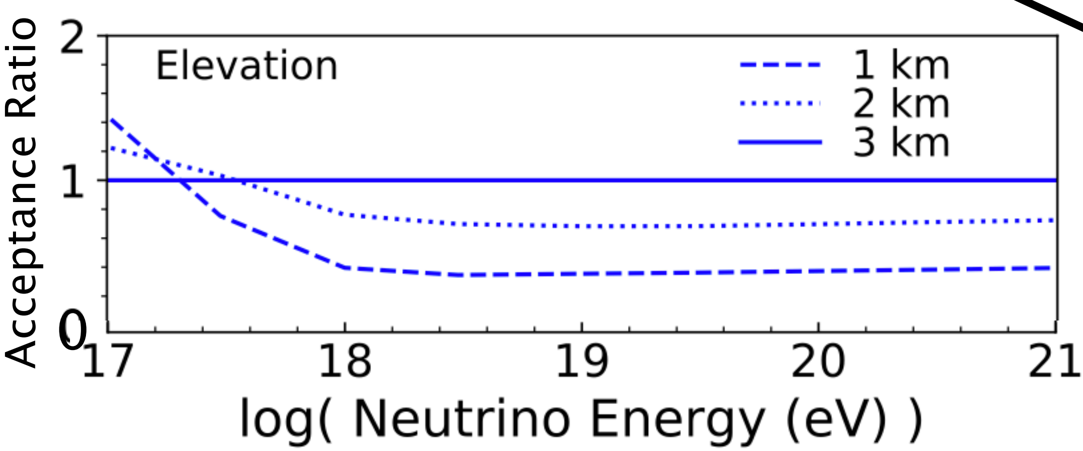
*Wissel JCAP 2020 arXiv:2004:12718*

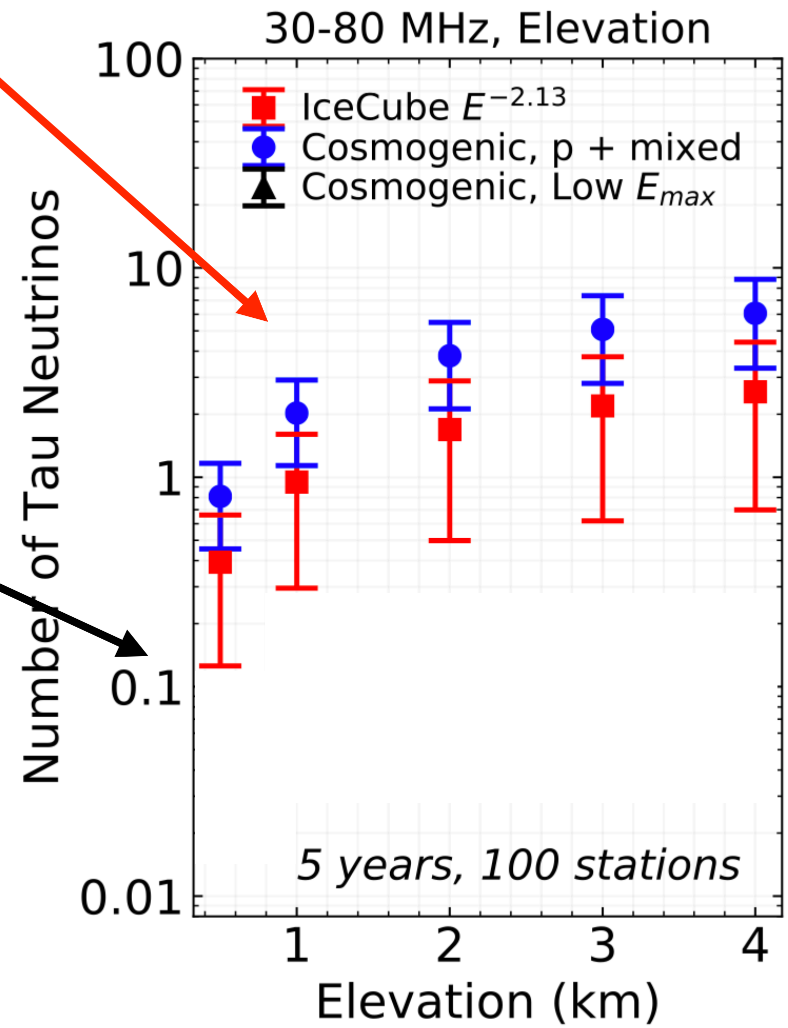
# Test Designs Against Flux Models



# How High?

- 2 km is a good balance between increased viewing area and threshold for higher energy models
- 1 km reduces the energy threshold
- Designs targeting <100 PeV are largely insensitive to elevation beyond 1 km (black curve)

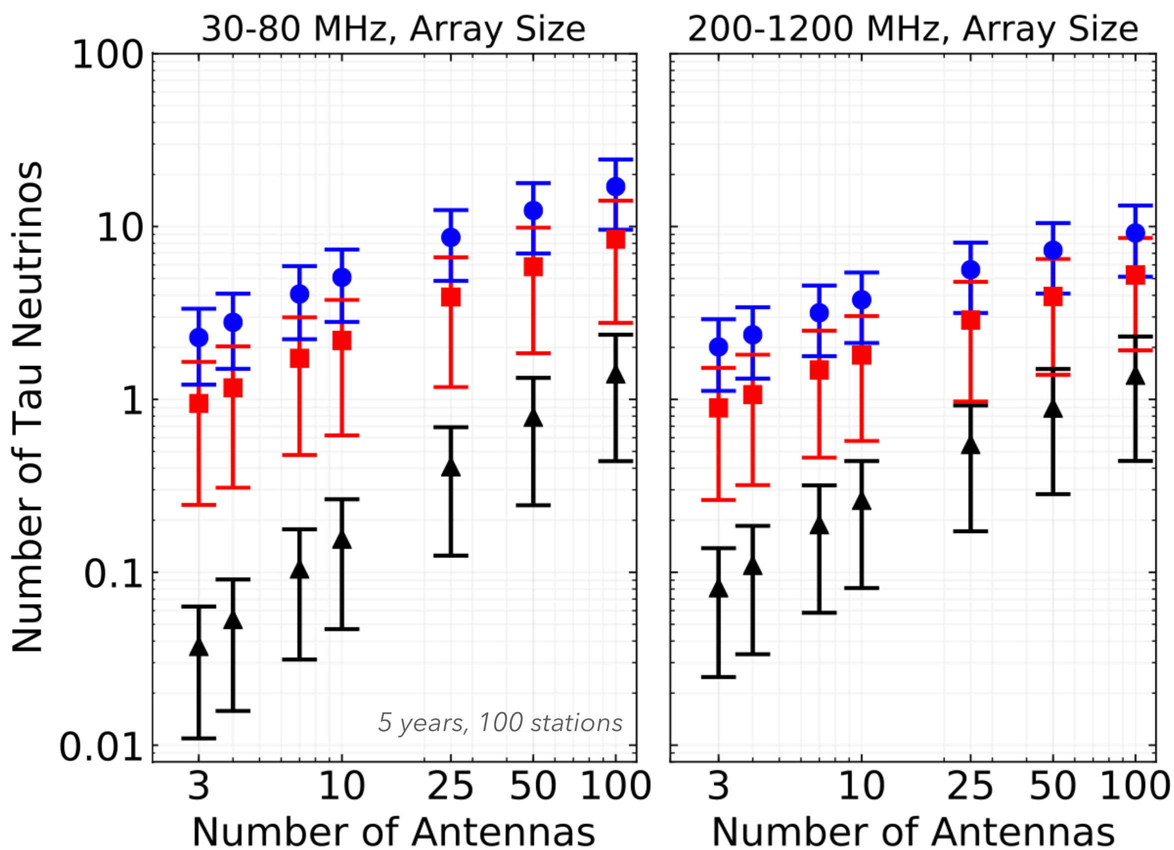


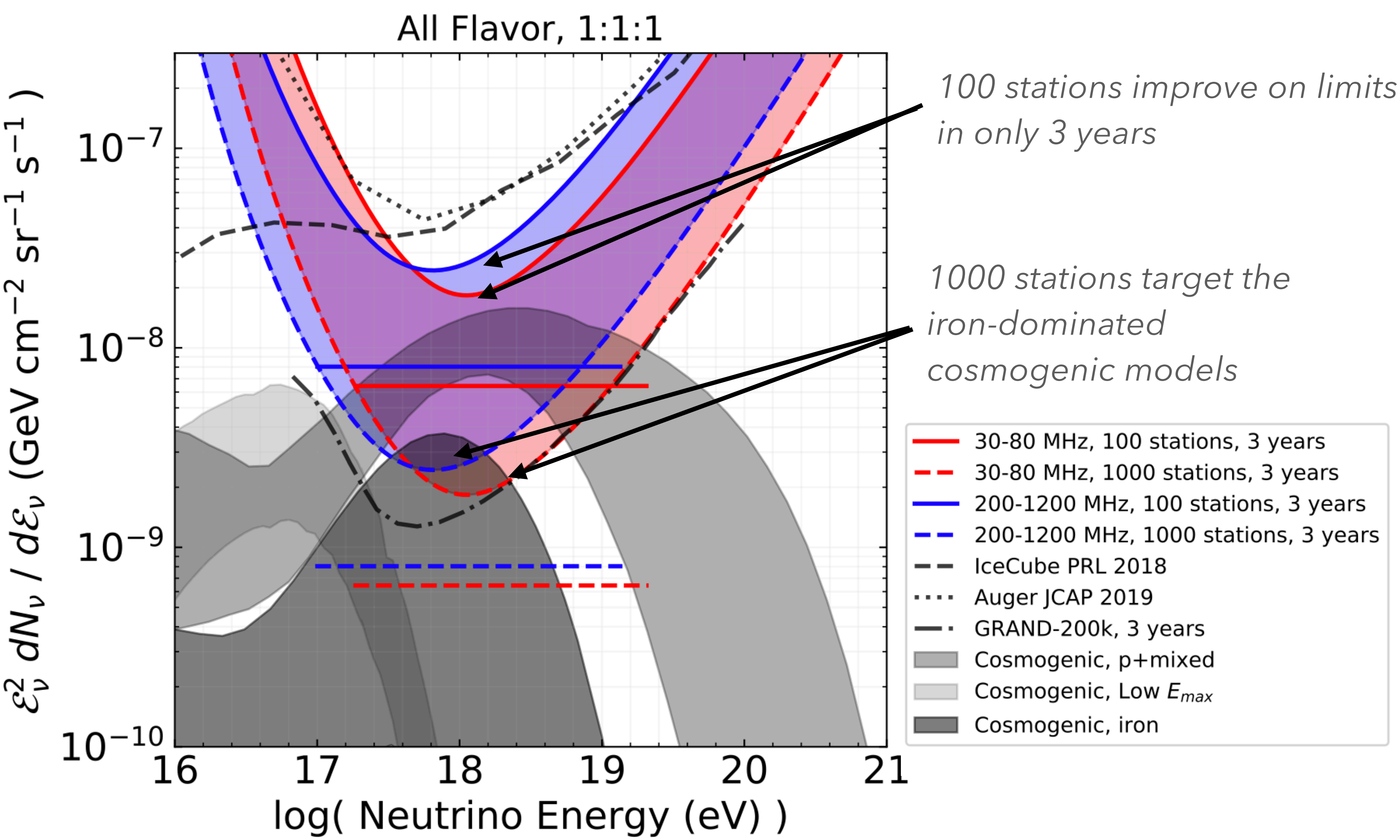
# How Many Antennas?

- Is it better to build ***bigger*** phased arrays or ***more*** independent stations?
  - Minimum 3 antennas for phased advantage
  - No. neutrinos linear with phased array gain
  - Harder models prefer lower frequency design
  - Softer models require large phased arrays $\mathcal{O}(100)$ for appreciable neutrino rate

- Conclude that $\mathcal{O}(10)$ **phased antennas** with 10x more independent stations is preferred



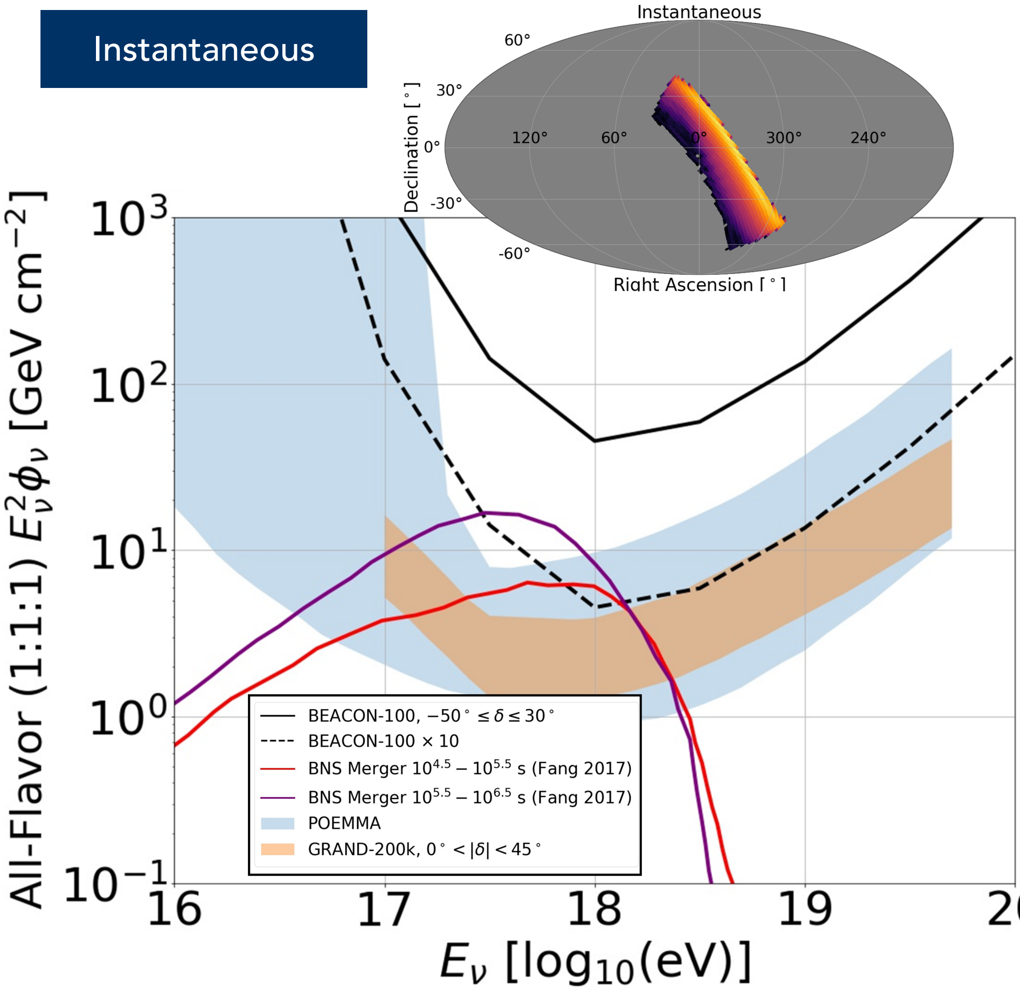
# BEACON IS AN EFFICIENT DESIGN



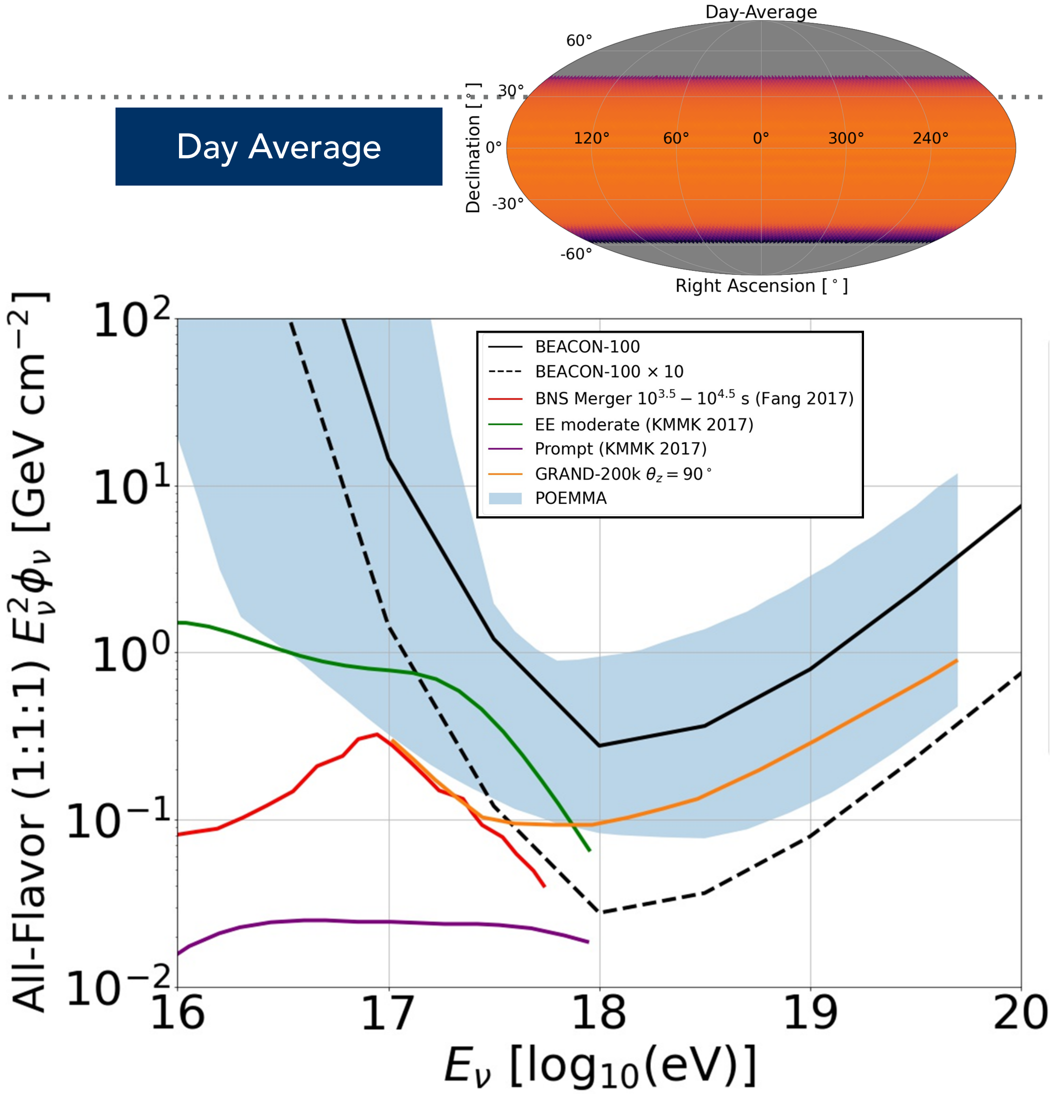

*Wissel*
*JCAP 2020*
*arXiv:2004:12718*

# BEACON Point Source Sensitivity

Instantaneous




Day Average



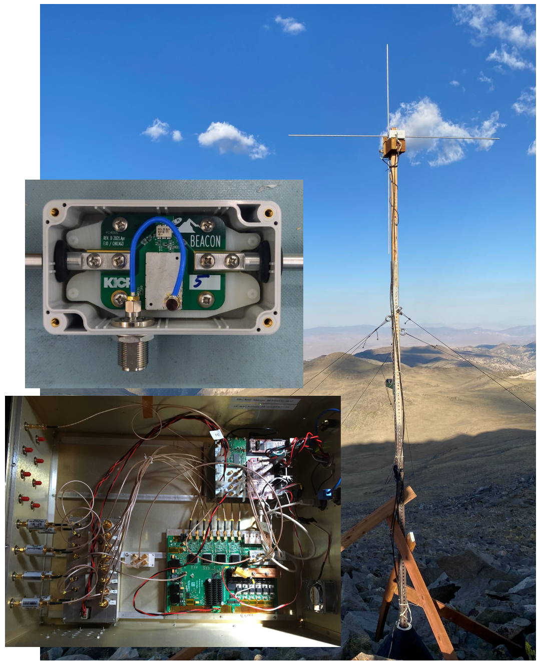

*30-80 MHz, including overlap, 3-km spacing, Zeolla ICRC 2023*

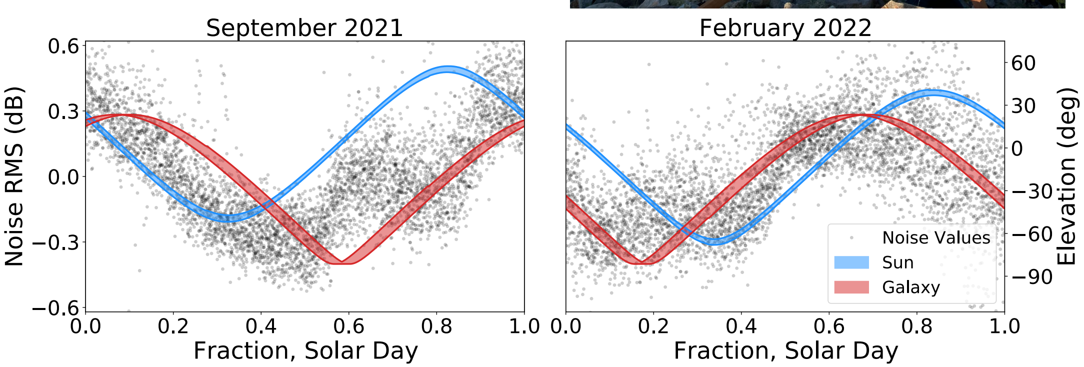
# BEACON Prototype Array

- Prototype at the White Mountain Research Station has been running since 2018 at 3.8 km (2.4 km prominence)
- Goals:
  - validate sensitivity estimates with cosmic ray search
  - test phased arrays at high elevation
  - manage backgrounds and operate continuously

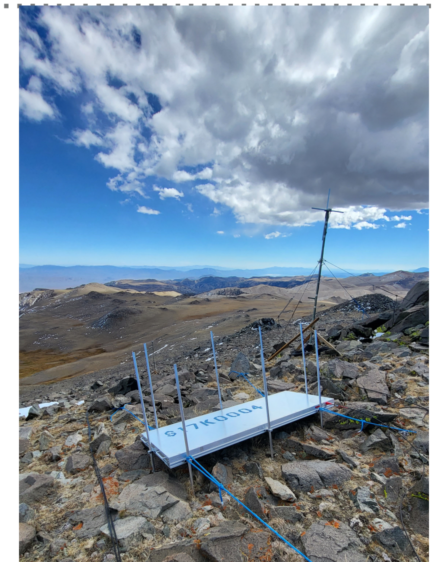
# BEACON's Prototypes

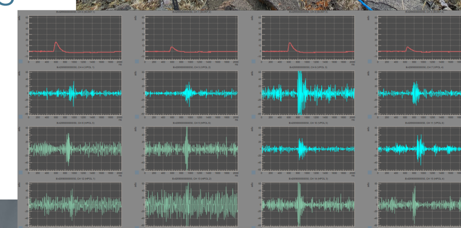
- 2018: LWA antennas
- 2019-2022: custom dipoles + 7-bit 1GSa/s phased array DAQ
- 8 antennas (H&V) on 4 masts
- Power ~50 W

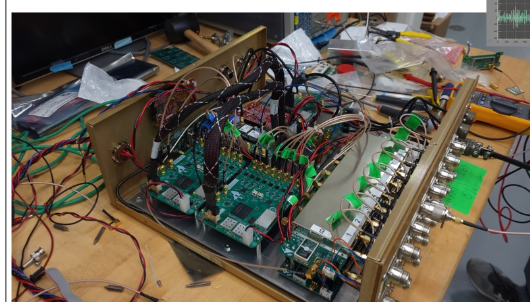





- 2023
- Custom dipoles with built in differential GPS
- 12 antennas (H&V) on 6 masts
- 4 scintillators
- Custom 500 MSa/s 4-channel DAQ with onboard phasing and coincidence triggering
- Power draw ~25 W



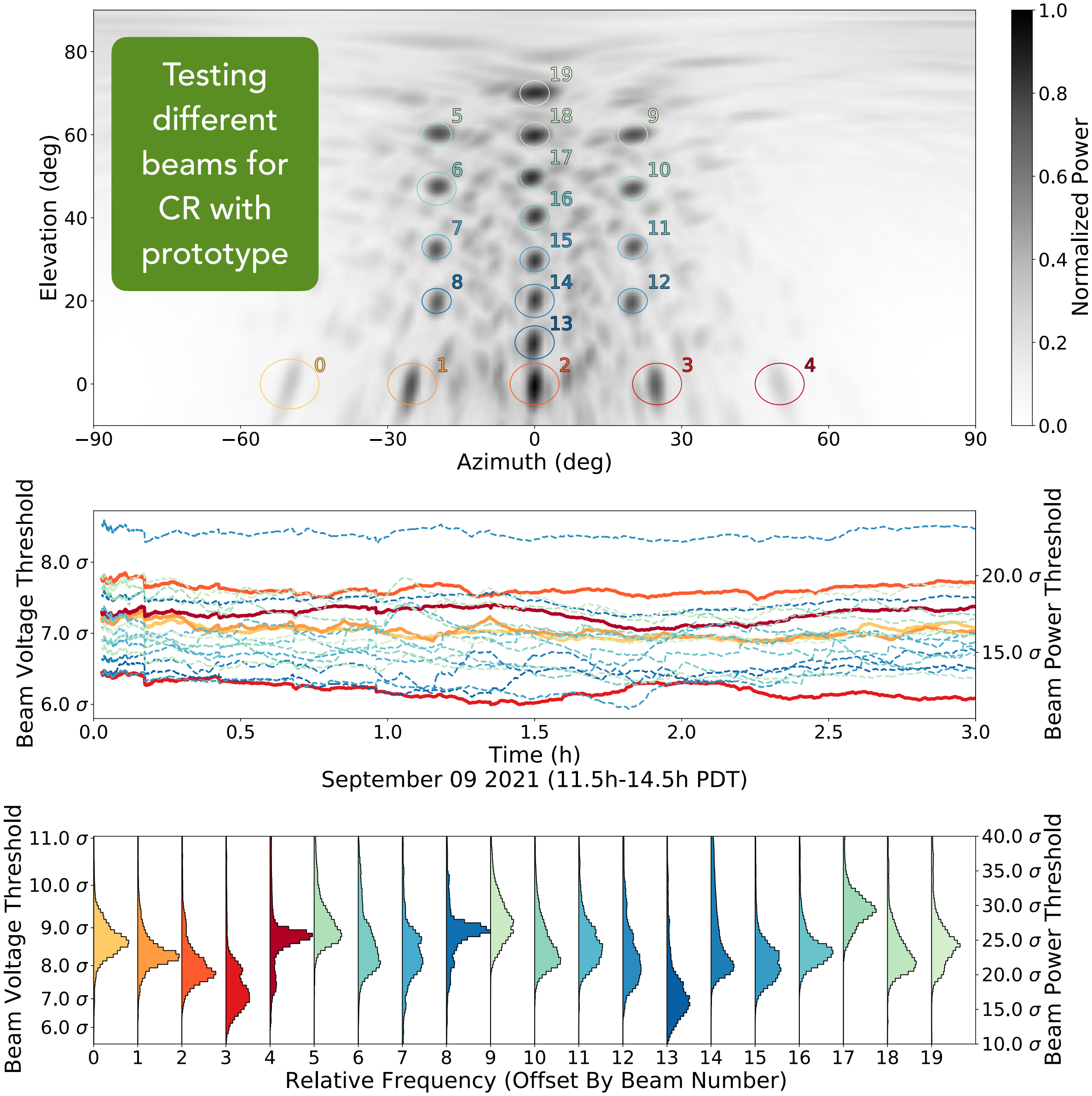




# BEAMFORMING *IN SITU*

- 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

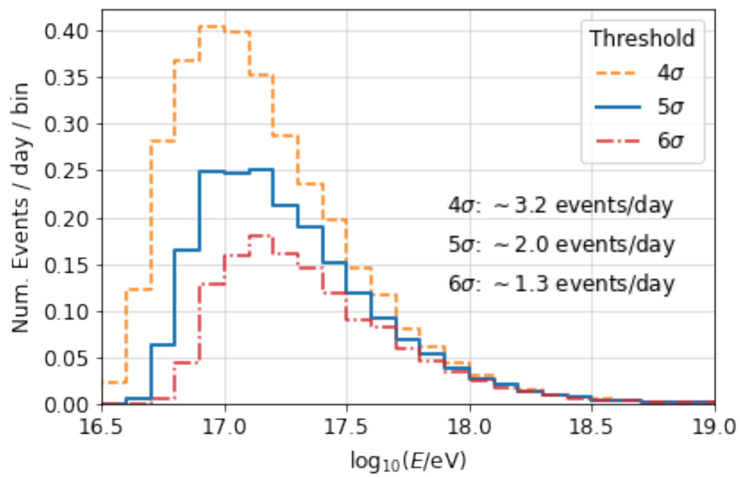



> **<u>Thresholds</u>**: Many beams at thresholds ***approaching*** level assumed in neutrino sims

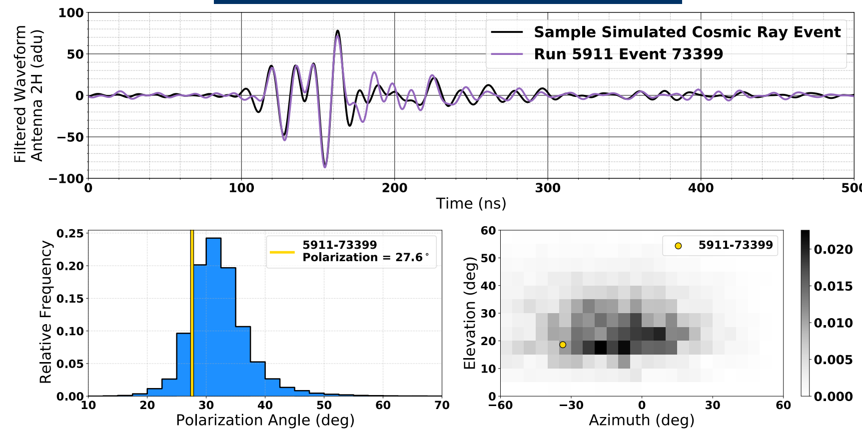
*D. Southall, V. Decoene, A. Zeolla, BEACON arXiv:2206.09660*

# Cosmic Rays help Validate the Performance

- Cosmic ray rate depends strongly on instrument threshold

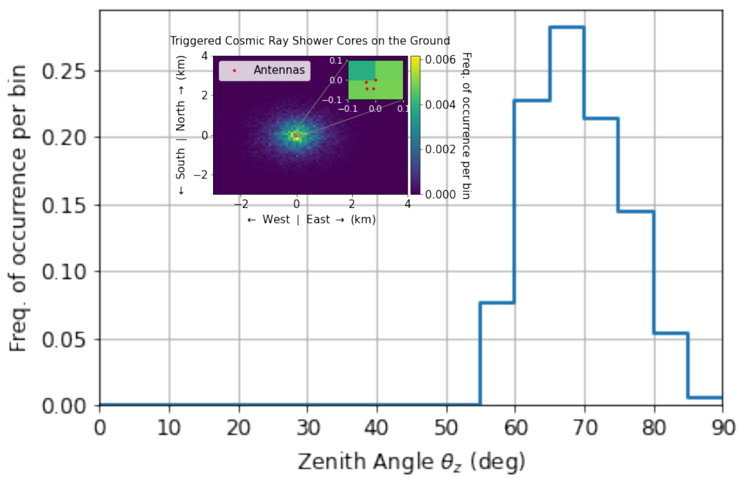



CR Candidate




*D. Southall, BEACON arXiv:2206.09660*

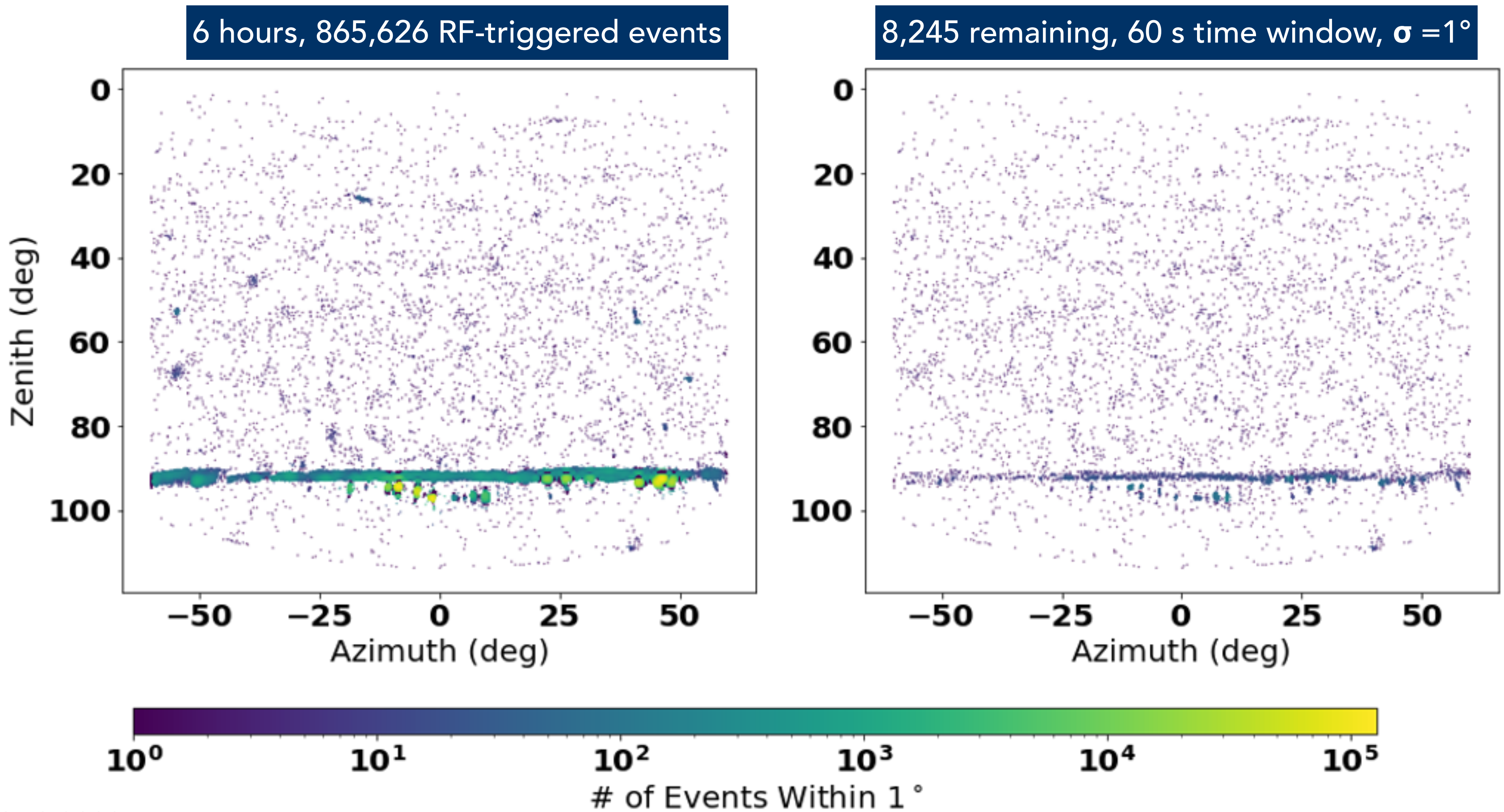
- Geometry is predominately sensitive to highly inclined, distant air showers




*A. Zeolla ICRC 2023, 2021, ARENA 2022*

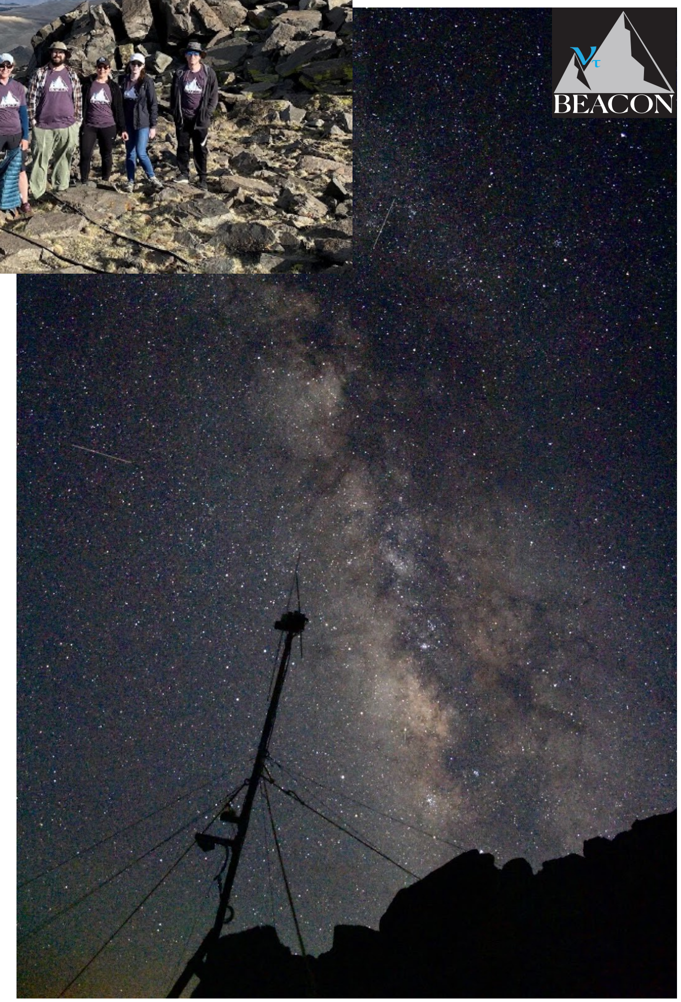
# Temporalspatial Cuts for CR Search

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



# Conclusions

- **Thresholds**
  - Trigger Threshold reduction is key to making an efficient detector
  - Lower energy threshold also preferable!
  - Prototype achieving >6σ thresholds with 4 antennas
  - Can we improve RF-only trigger based on scintillator inputs and/or machine learning?
- **Array Configurations**
  - Building 1000 independent stations is a large fraction of the Earth!
  - Higher energy models prefer high elevations with ~ 10 antennas
  - Lower energy models suggest that we should phase more antennas at any. (i.e. could be lower) elevation
- **Event Reconstruction**
  - More work is needed here!!
  - Key design goal is: better than 1° precision in zenith
  - Combinations of UHF & VHF may help with event reconstruction (direction, Xmax, energy)



# Bonus Slides

# Choice of Frequency Bands

## 30-80 MHz VHF Design

- Commonly available active electrically short antennas
  - e.g. 1.8 dBi Dipole Antennas

**Advantage** Broader beam at low frequencies → wider solid angle in acceptance

**Noise**
- Dominated by sky noise, $V_{rms} \sim 10\ \mu V$

## 200-1200 MHz UHF Design

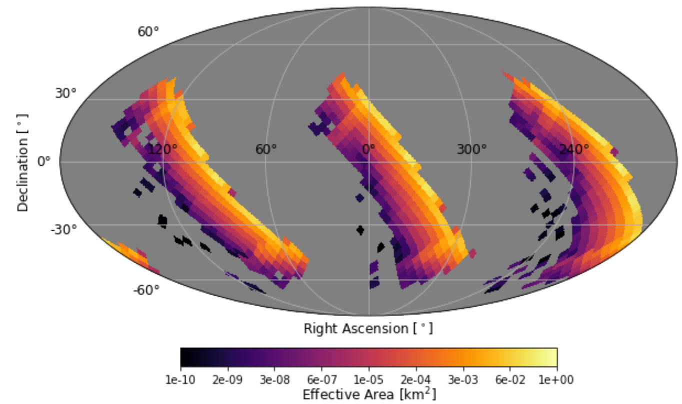
- Readily available, high-gain antennas
  - e.g. ~10 dBi quad-ridged horns, LPDAS

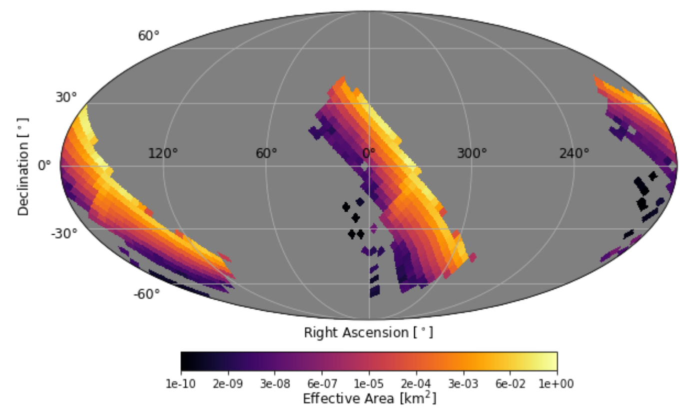
ANITA PRD 2009

**Advantage**
- Easier to find higher gain antennas at UHF frequencies, smaller resonant antennas

**Noise**
- Dominated by thermal noise
- $V_{rms} \sim 14\ \mu V$

**Combination of VHF & UHF:**
One or the other may be better for trigger;
Both advantageous for event reconstruction


60°
30°
0°
-30°
-60°
120°
60°
0°
300°
240°
Declination [ ° ]
Right Ascension [ ° ]
1e-10
2e-09
3e-08
6e-07
1e-05
2e-04
3e-03
6e-02
1e+00
Effective Area [km²]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