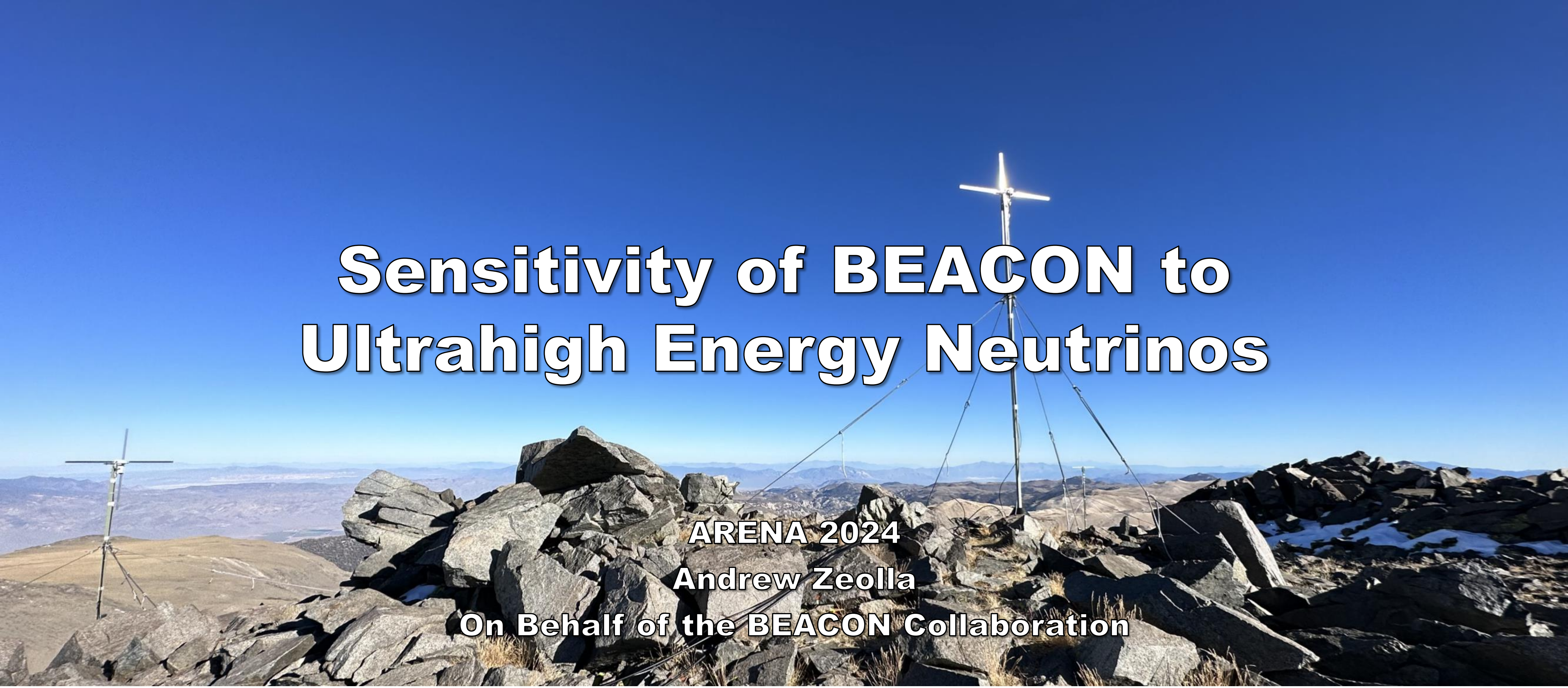
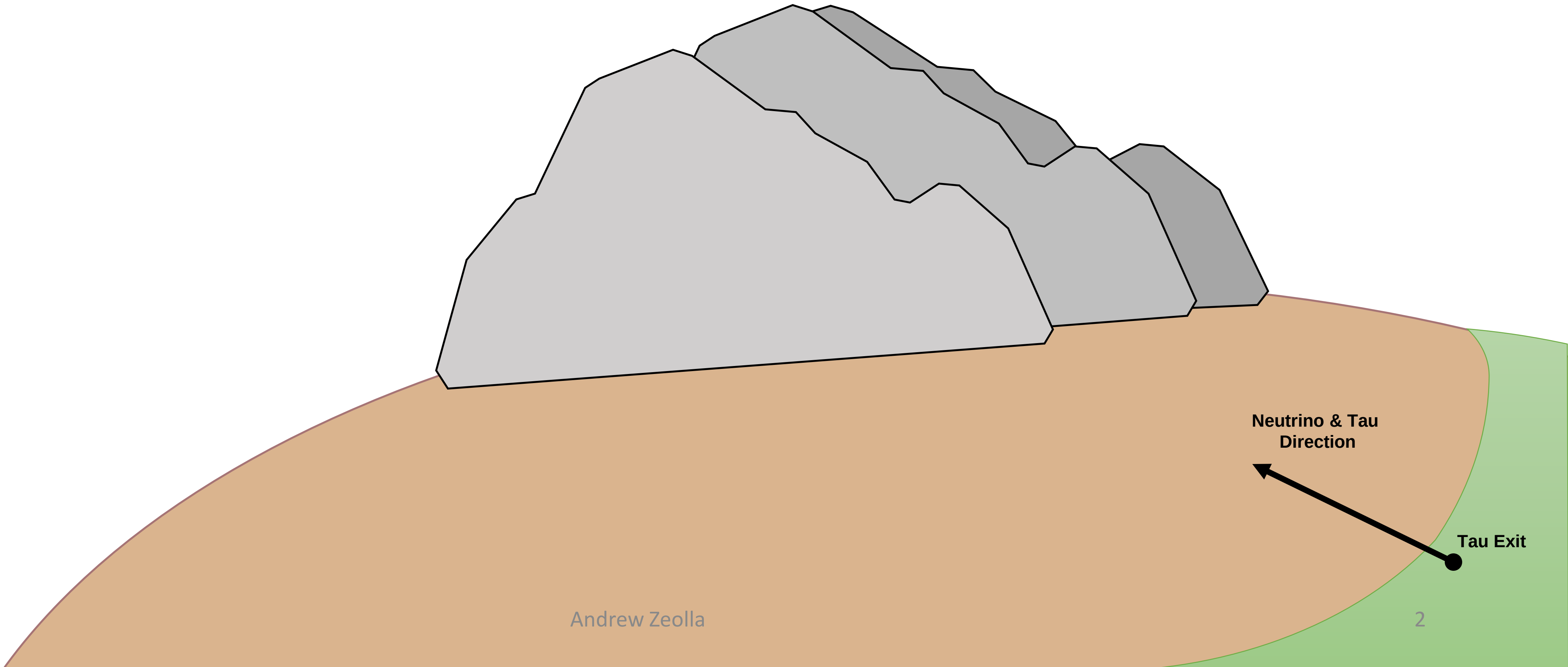


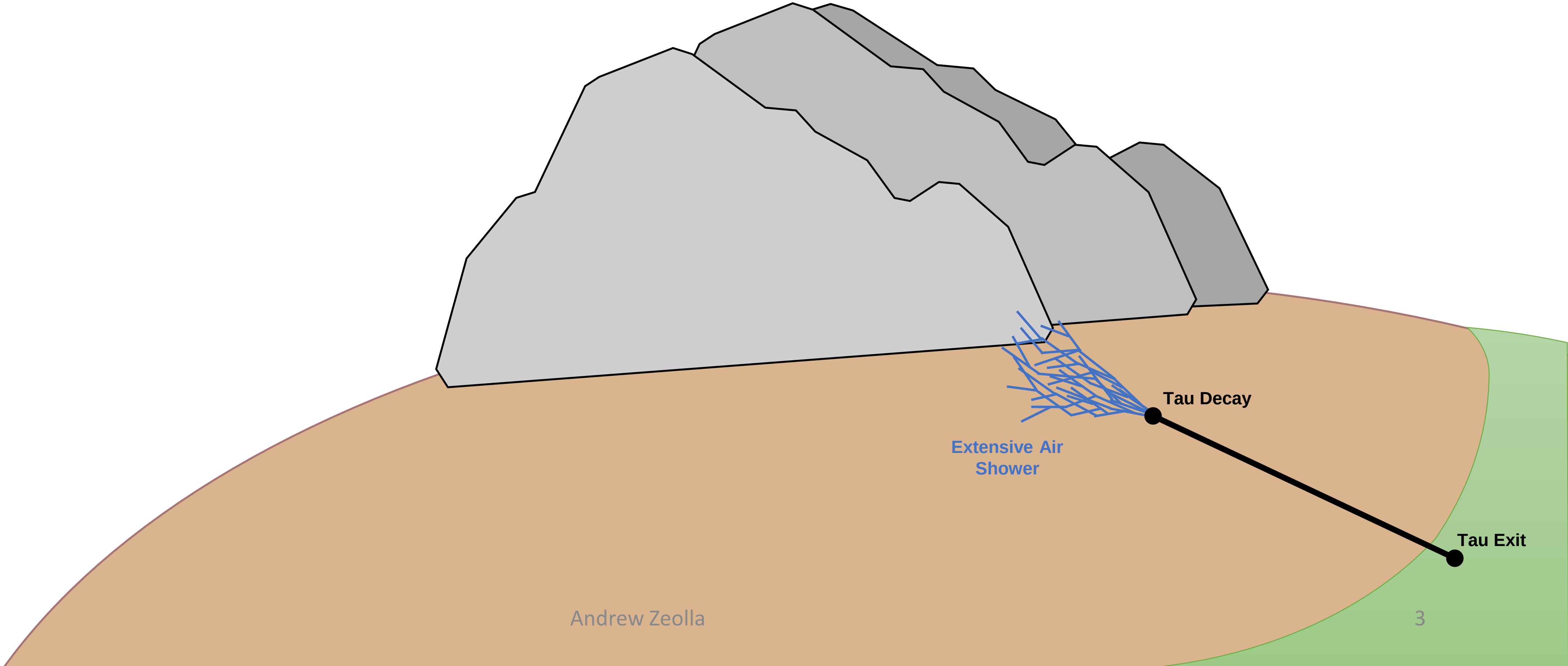
Sensitivity of BEACON to Ultrahigh Energy Neutrinos

ARENA 2024

Andrew Zeolla
On Behalf of the BEACON Collaboration

PennState
USC Universidade de Santiago de Compostela
The Ohio State University
Radboud Universiteit
JPL Jet Propulsion Laboratory California Institute of Technology
KICP Kavli Institute for Cosmological Physics at The University of Chicago
KU The University of Kansas
GSSI
White Mountain Research Center
NSF


Neutrino & Tau Direction
Tau Exit


Tau Decay
Extensive Air Shower
Tau Exit

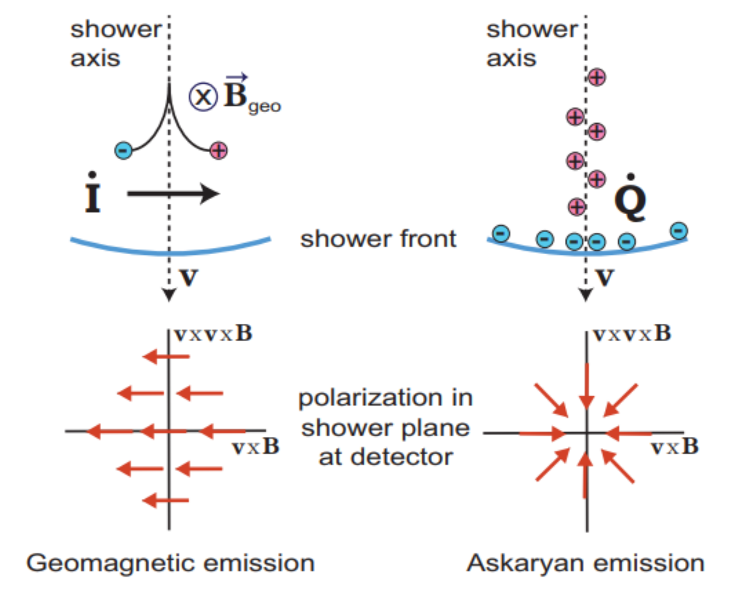
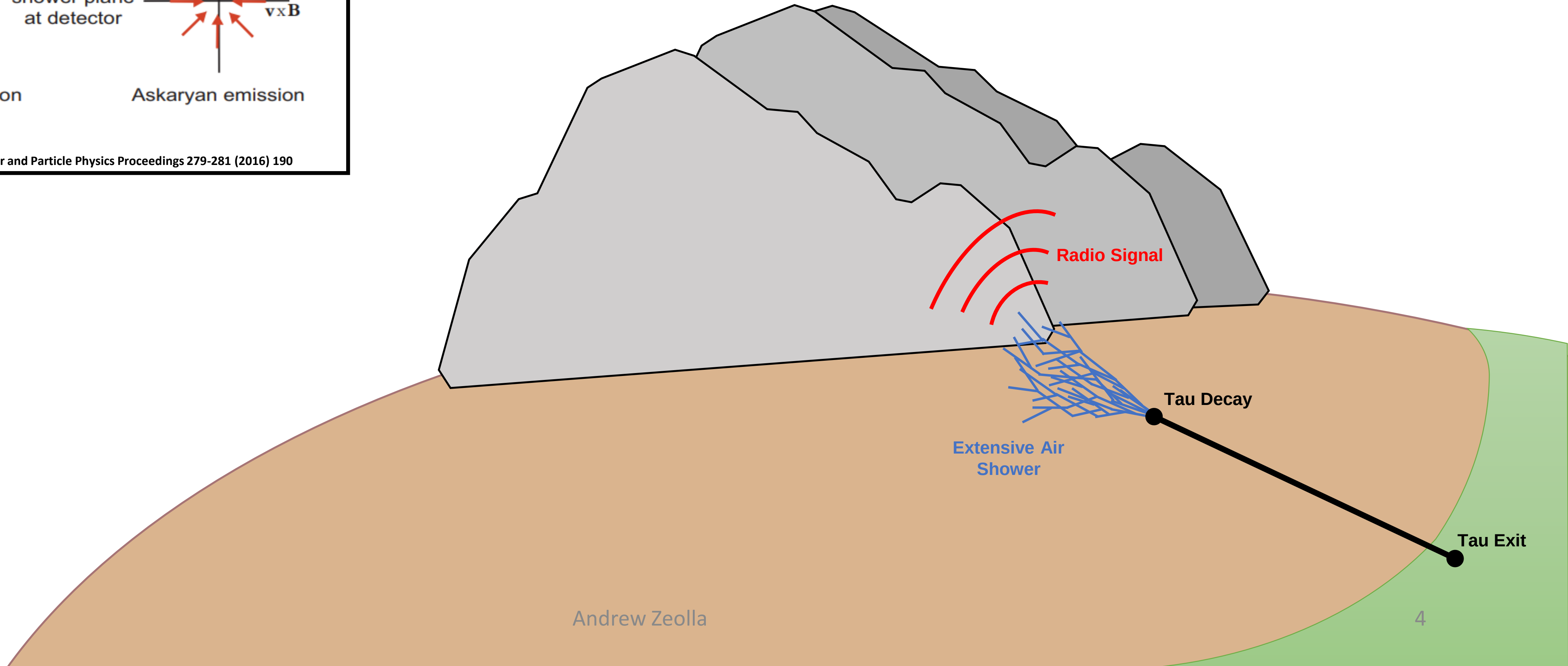


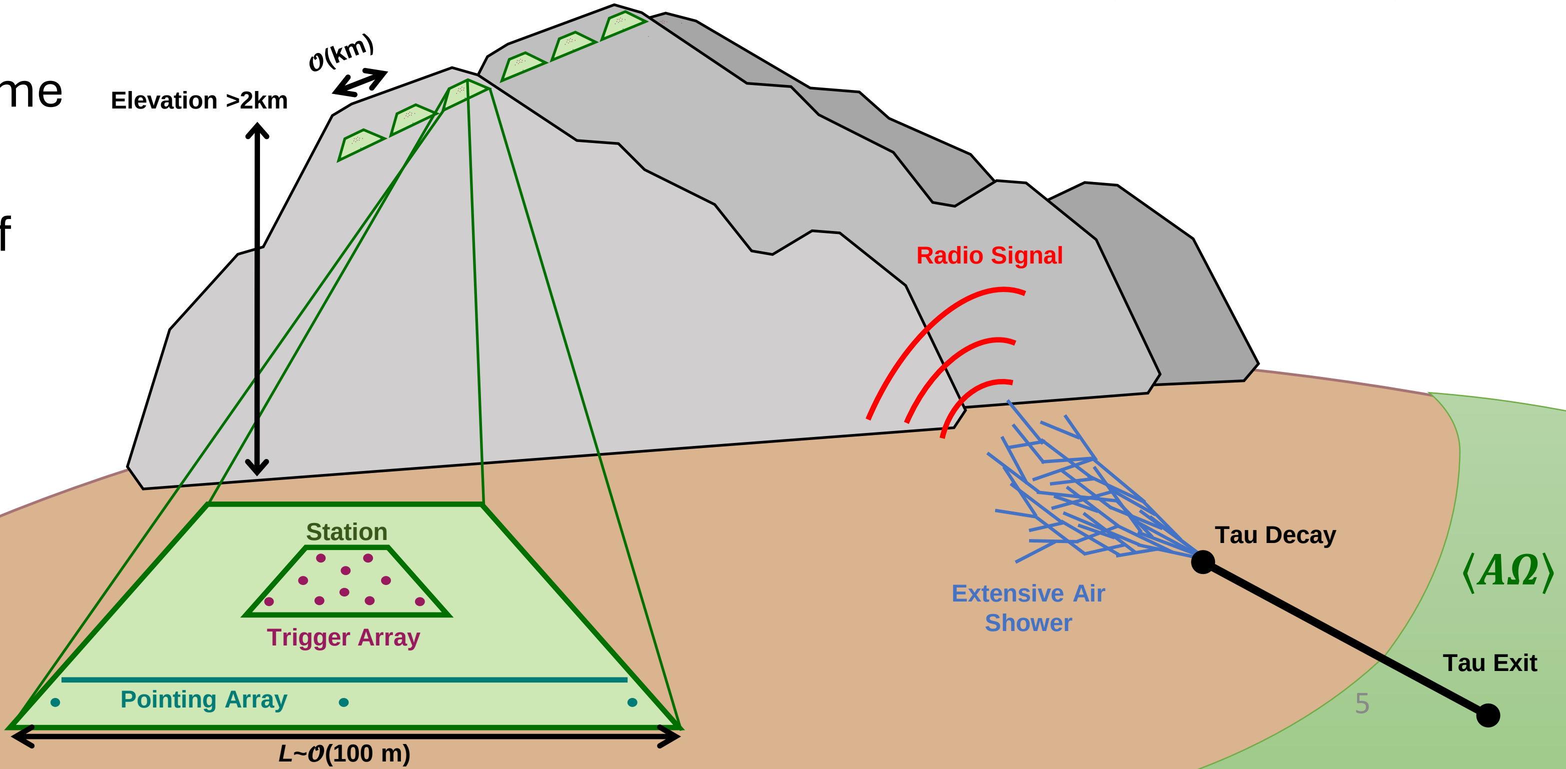
Figure from F.G. Schröder, Nuclear and Particle Physics Proceedings 279-281 (2016) 190



BEACON: Beamforming Elevated Array for COsmic Neutrinos

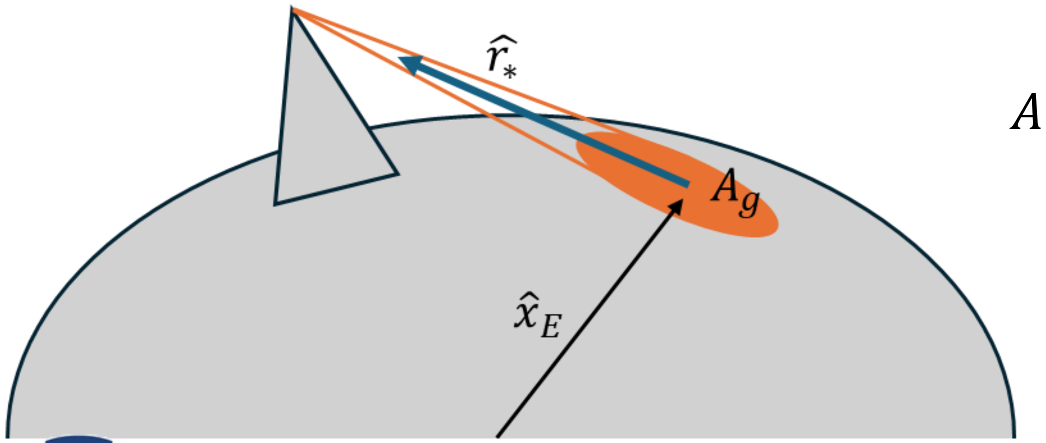
- Concept: $\mathcal{O}(1000)$ independent radio interferometers on mountaintops, designed to detect the radio emission of upgoing air showers created by earth-skimming ν_τ
- Goal: measure the flux of ν_τ at E > 100 PeV
- Advantages:
  - \+ radio = low cost, high duty cycle
  - \+ high elevation = large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

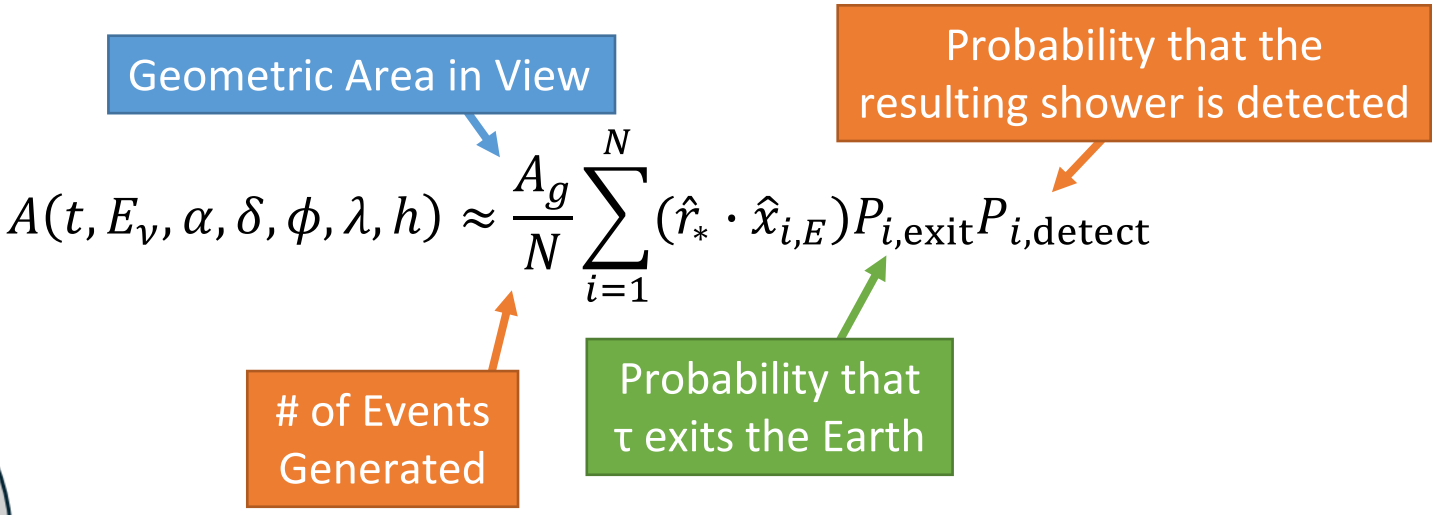
Concept paper: S. Wissel et al. JCAP11(2020)065



Monte Carlo Simulation

- **M**ultiple **A**ntenna A**r**rays on **Mo**untains **T**au **S**ensitivity
- Monte Carlo which calculates the effective area of any configuration of mountaintop phased arrays to point-sources of neutrinos
- Accounts for the effective areas of individual stations overlapping





Geometric Area in View

Probability that the resulting shower is detected

$$A(t, E_\nu, \alpha, \delta, \phi, \lambda, h) \approx \frac{A_g}{N} \sum_{i=1}^{N} (\hat{r}_* \cdot \hat{x}_{i,E}) P_{i,\mathrm{exit}} P_{i,\mathrm{detect}}$$

# of Events Generated

Probability that τ exits the Earth

From each station, find where a cone in the source direction ($-\hat{r}_*$) intersects Earth

→ Union of all the areas = A_g. Uniformly sample tau exit points ($\hat{x}_{i,E}$)

→ $P_{i,\mathrm{exit}}$ and τ energies from NuTauSim

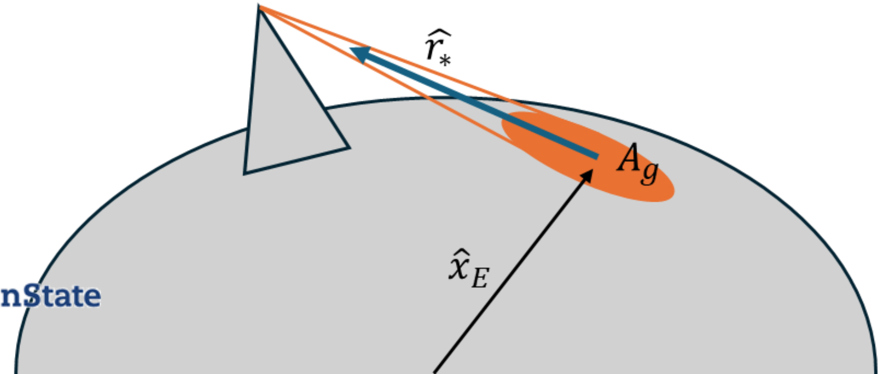
→ Decay distances from exponential distribution. Shower energies from PYTHIA

→ Electric Fields from ZHAireS radio-morphing

→ Peak voltages from simulated antenna gain and impedance

→ V_{rms} due to galactic and ground temperature

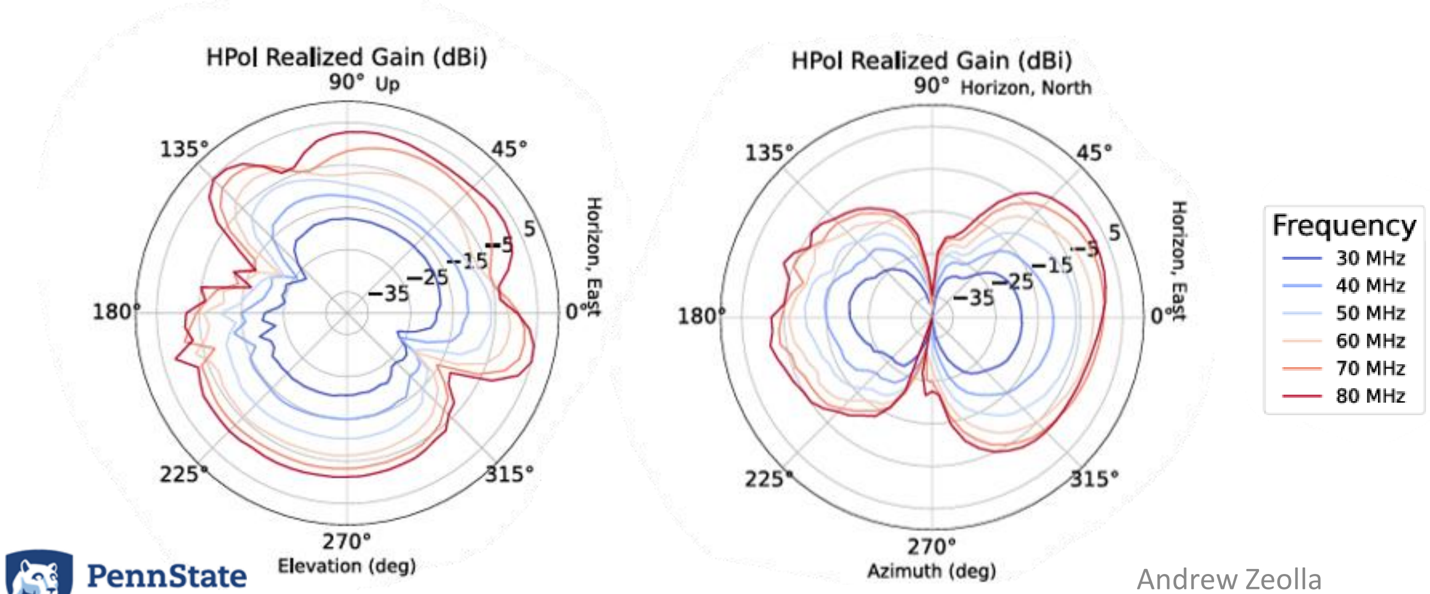
→ $\sqrt{N} \times (V/V_{rms}) > \sigma$ at any station ➔ $P_{i,\mathrm{detect}}$

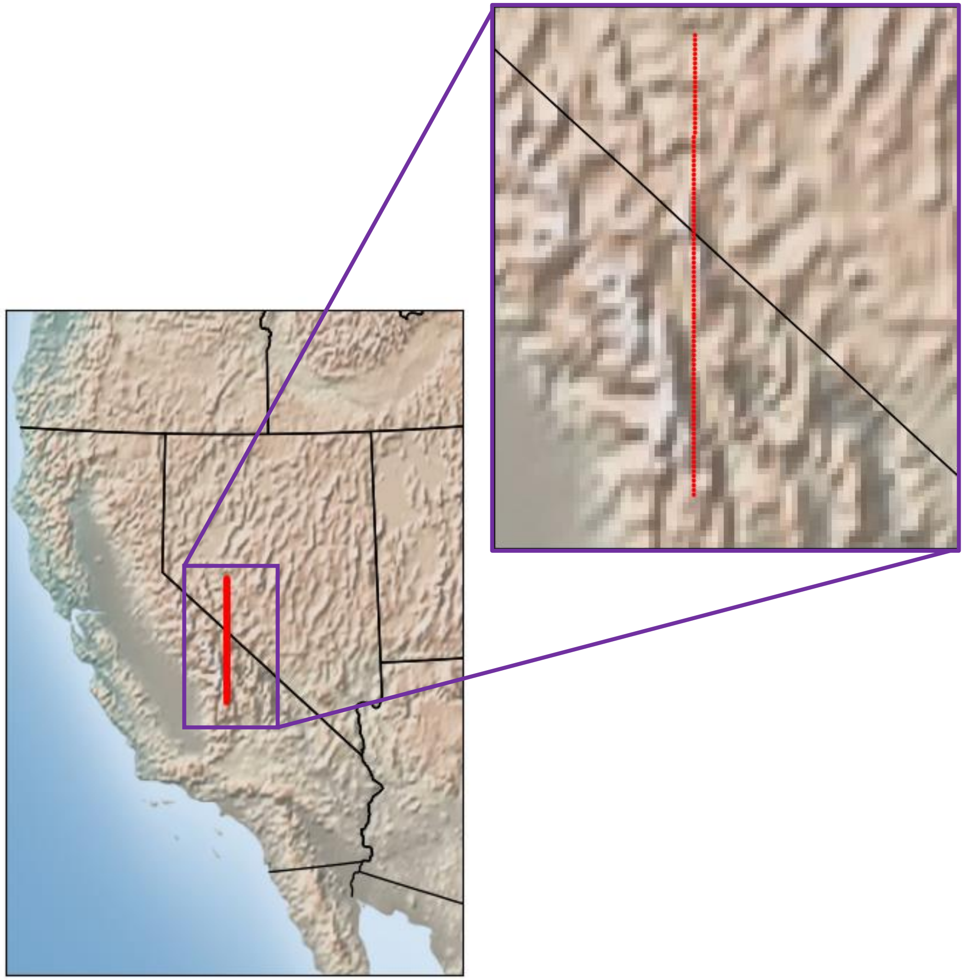


$$A(t, E_\nu, \alpha, \delta, \phi, \lambda, h) \approx \frac{A_g}{N} \sum_{i=1}^{N} (\hat{r}_* \cdot \hat{x}_{i,E}) P_{i,\mathrm{exit}} P_{i,\mathrm{detect}}$$

Simulation Setup

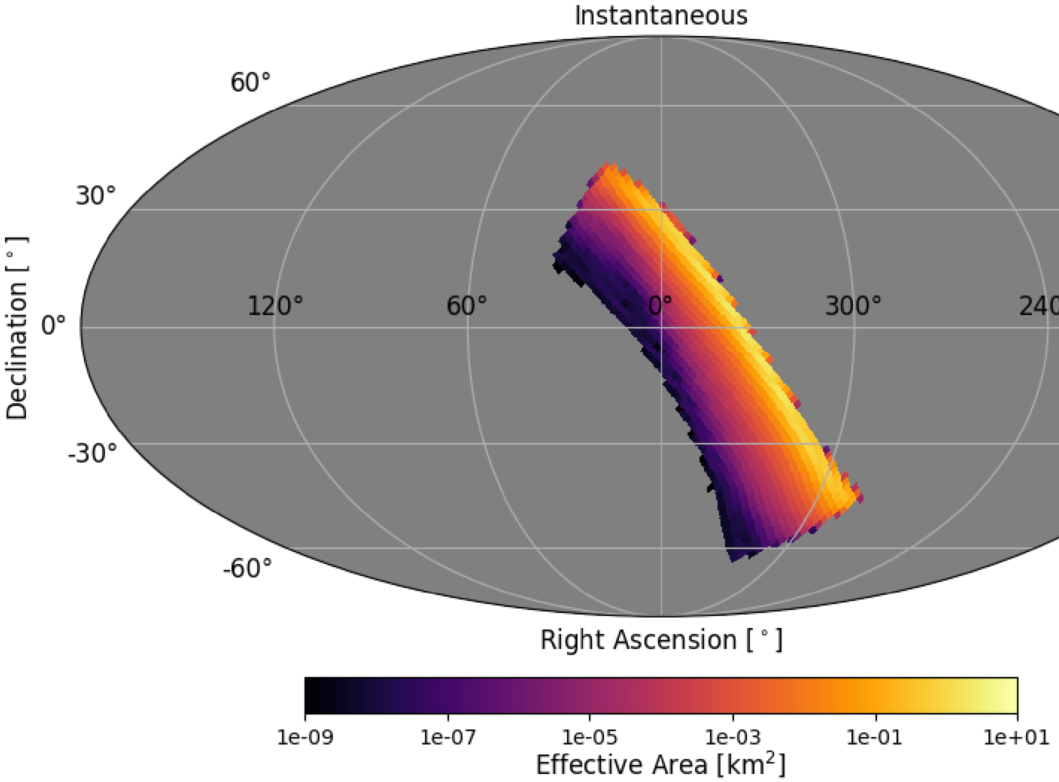
- 100 stations consisting of 10 phased antennas
- Spaced 3 km apart along same longitude, centered on location of BEACON Prototype
- 3 km altitude
- Facing East, 120° FoV
- SNR = 5 trigger

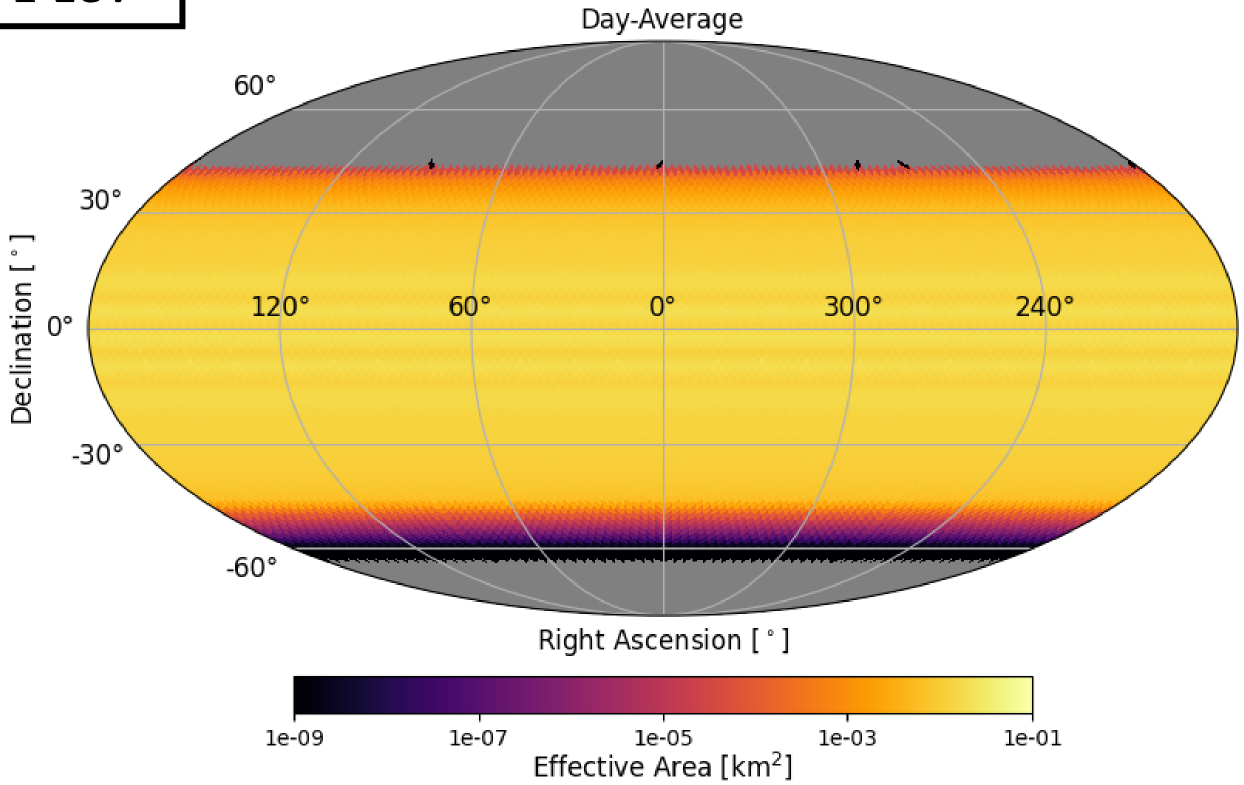




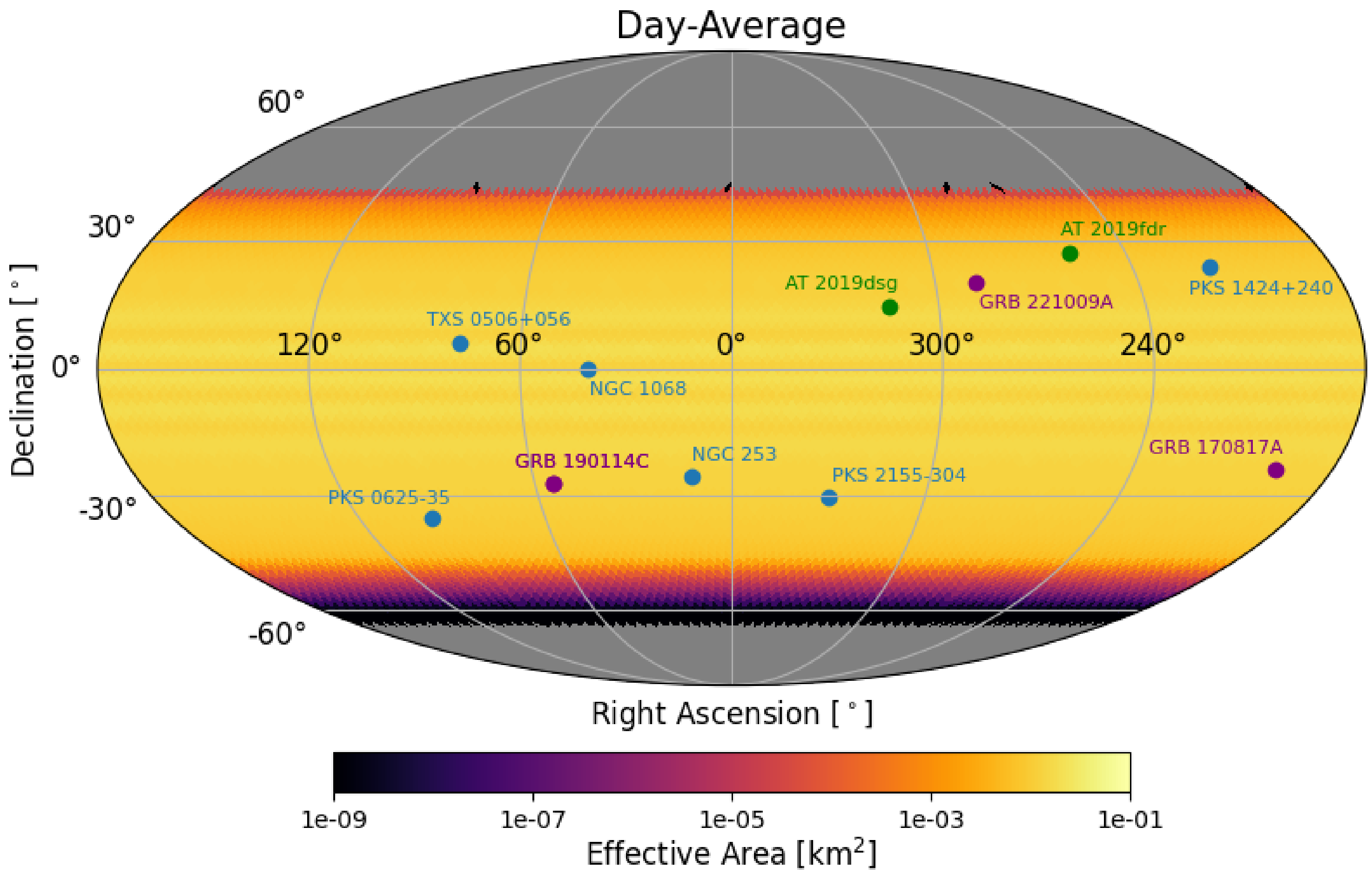
Effective Area (100 Stations)

$E_\nu = 1\ \text{EeV}$





Astrophysical Neutrino Sources



- **AGN/FSRQ/Blazars**
- **Tidal Disruption Events**
- **Gamma Ray Bursts**

Large Antenna FoV

+

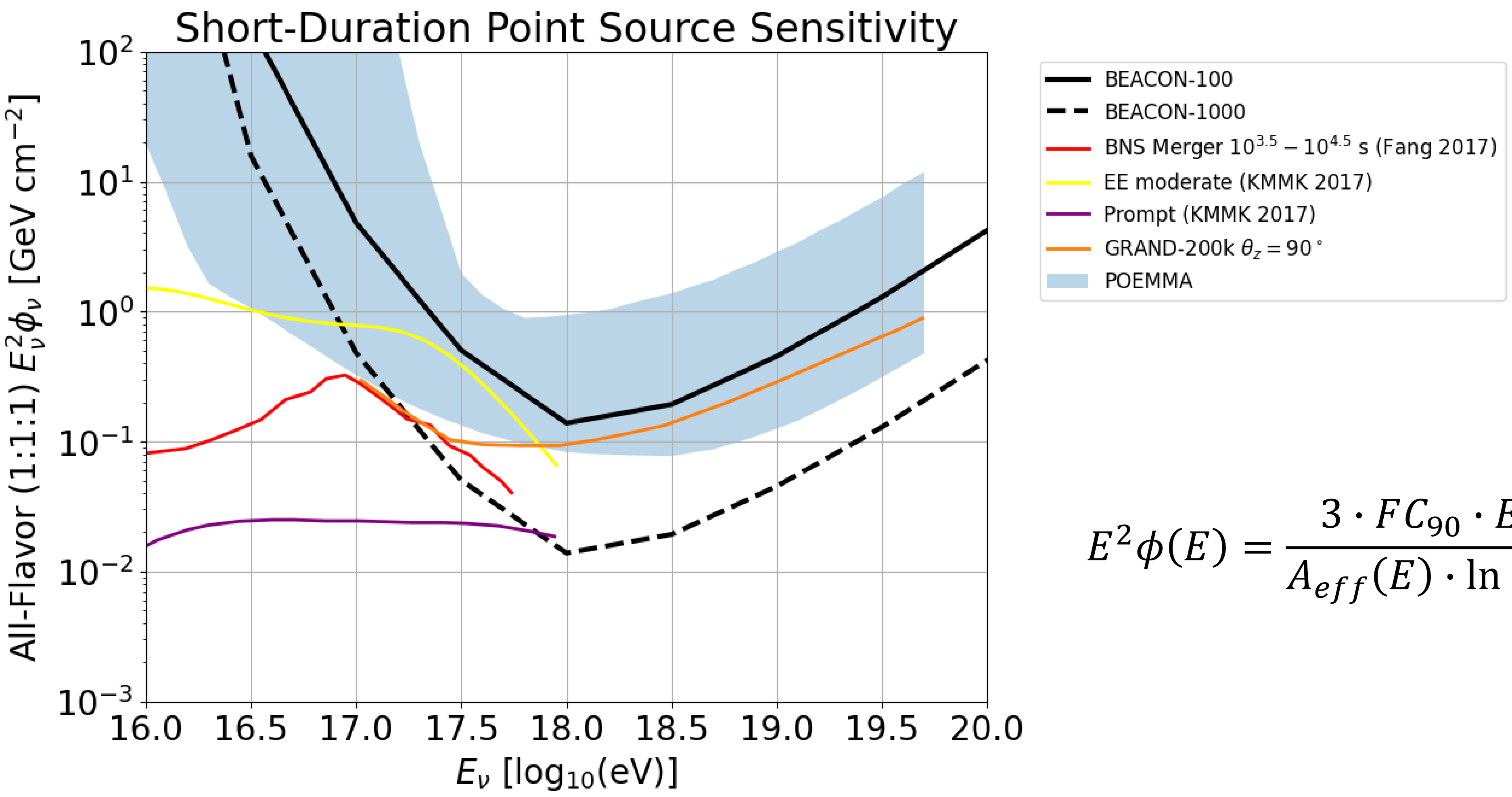
Position Near Equator

=

Many Sources Observed!

Short-Duration Point Source Sensitivity

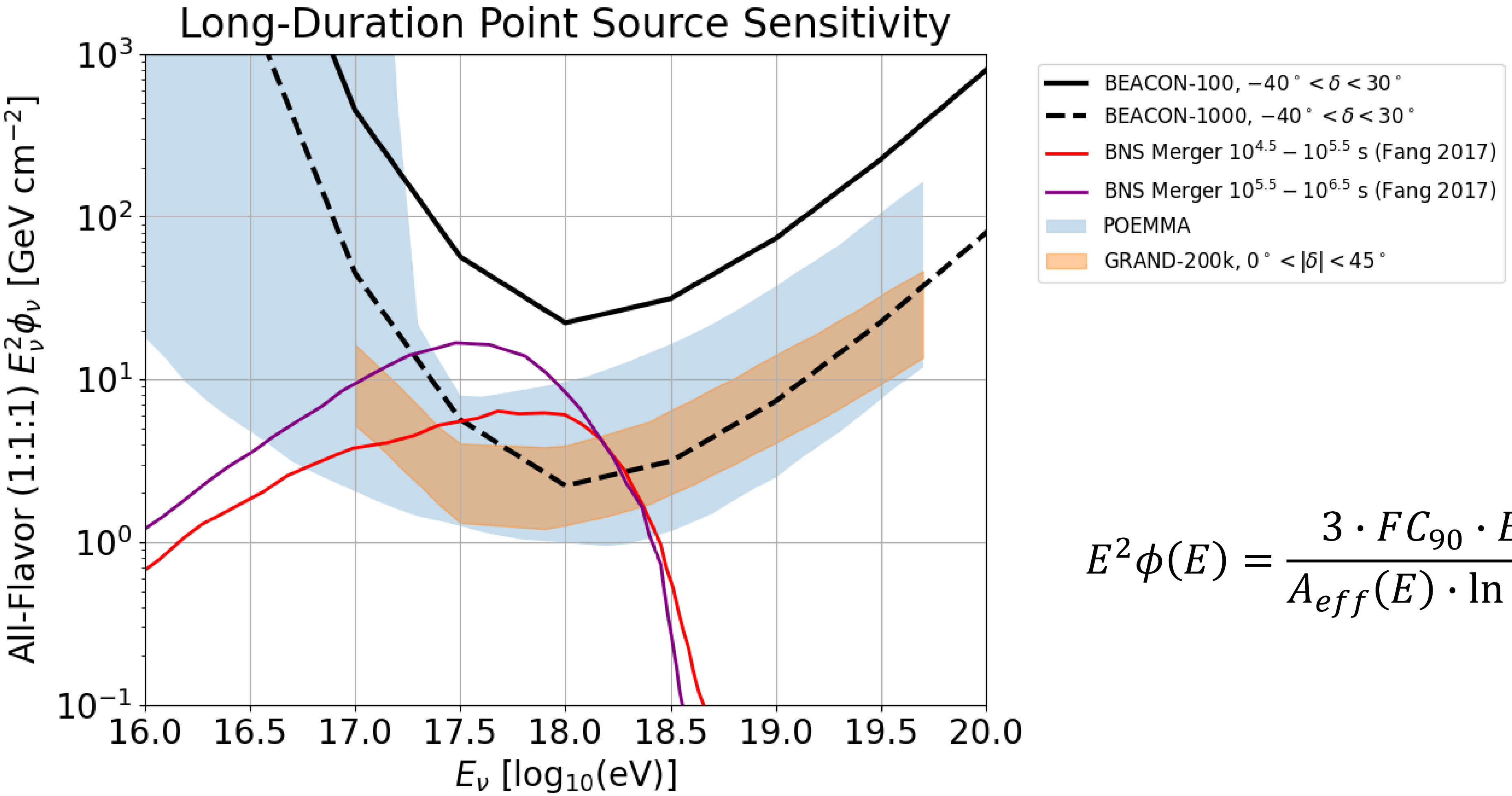
Maximum Instantaneous Effective Area



$$E^2\phi(E) = \frac{3 \cdot FC_{90} \cdot E}{A_{eff}(E) \cdot \ln 10}$$

Long-Duration Point Source Sensitivity

Day-Average Effective Area Averaged over δ

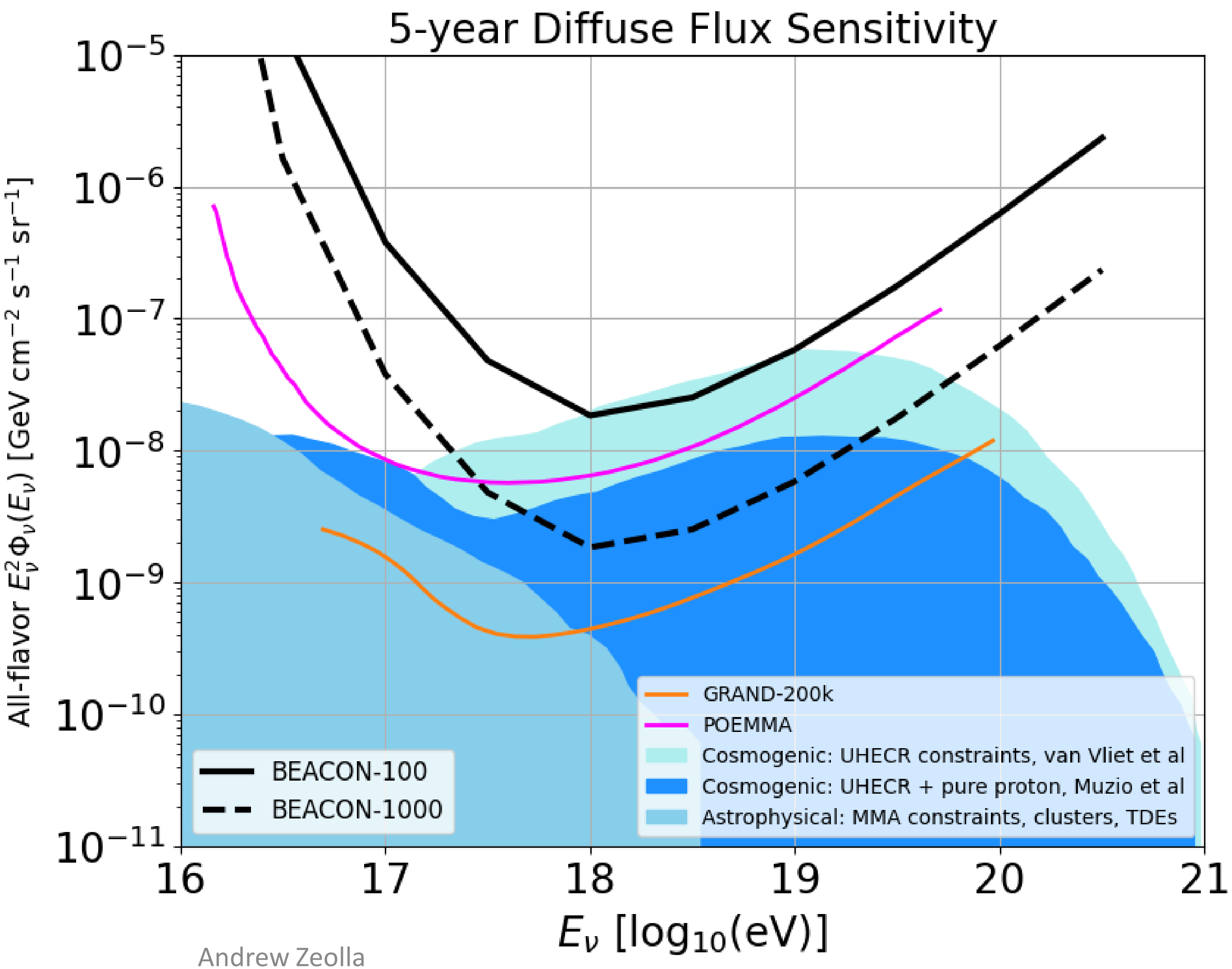


$$E^2\phi(E) = \frac{3 \cdot FC_{90} \cdot E}{A_{eff}(E) \cdot \ln 10}$$

Diffuse Flux Sensitivity

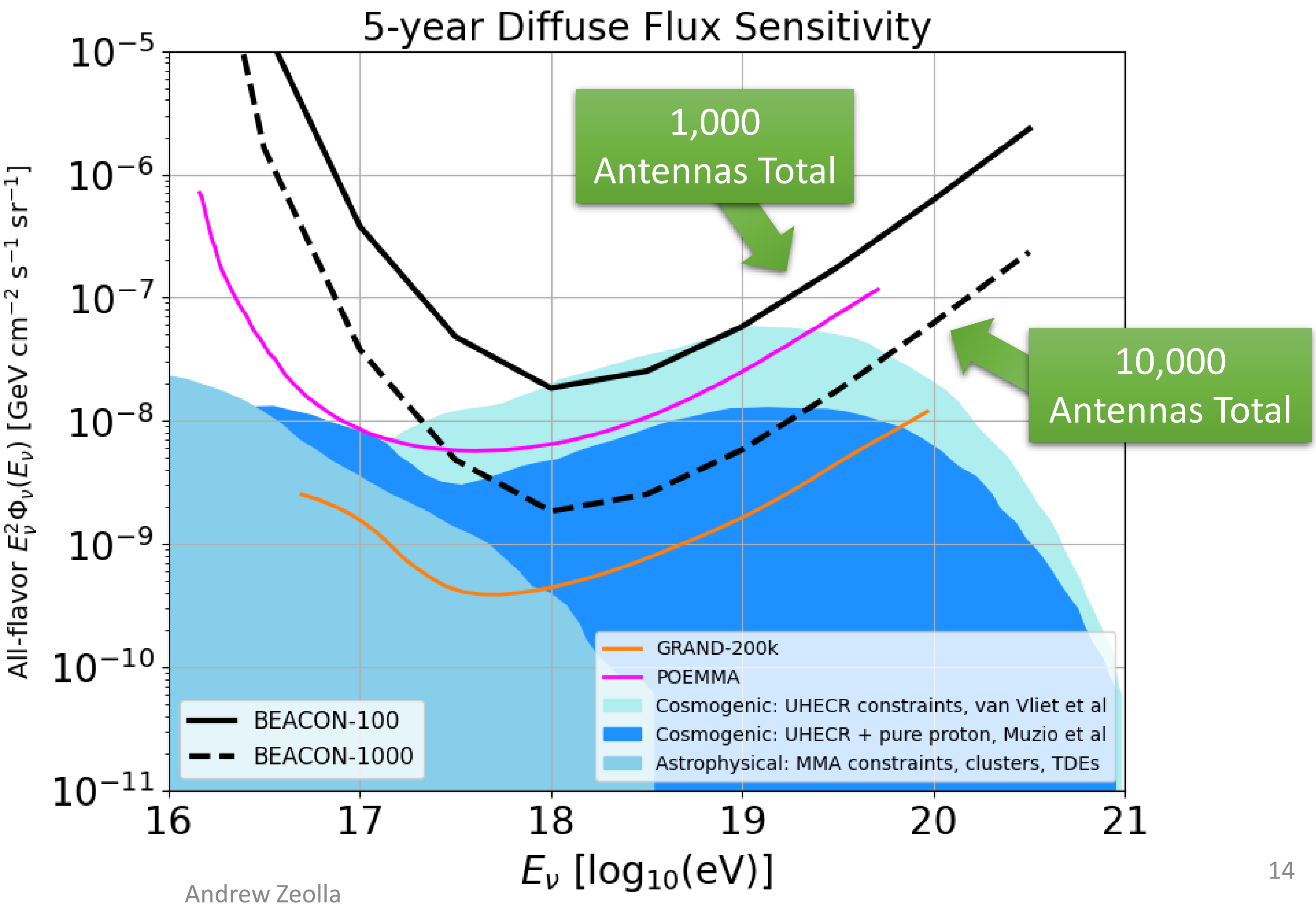
$$\int_0^{\pi} \sin(\theta) \int_0^{2\pi} A_{eff}(\phi, \theta)\, d\phi\, d\theta$$

$$E^2\phi(E) = \frac{3 \cdot FC_{90} \cdot E}{A\Omega(E) \cdot \ln 10 \cdot T}$$



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

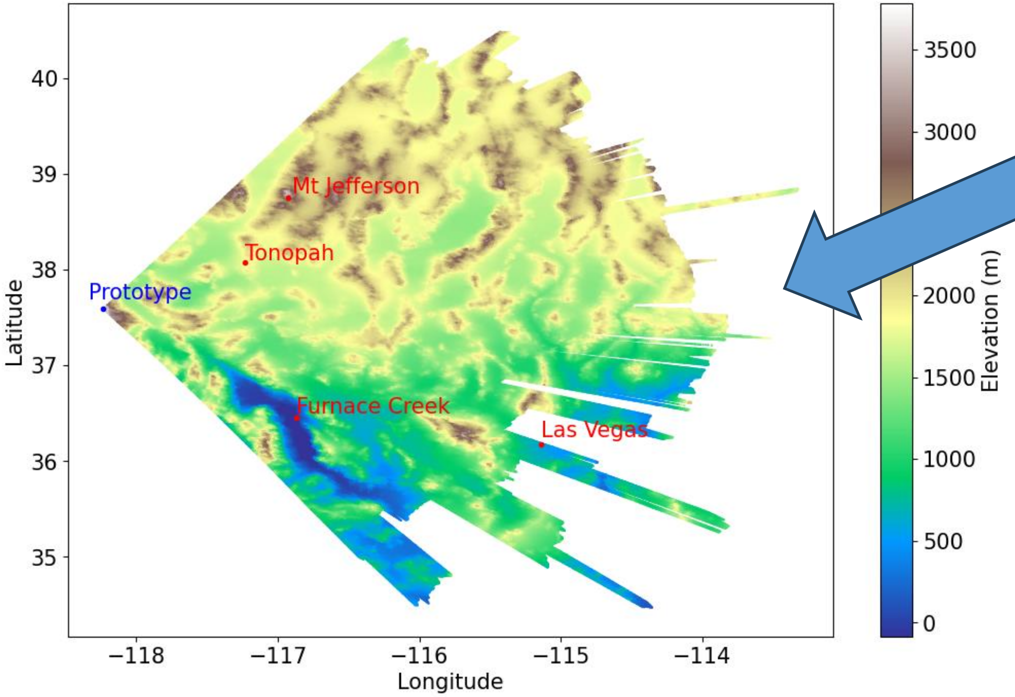


1,000 Antennas Total

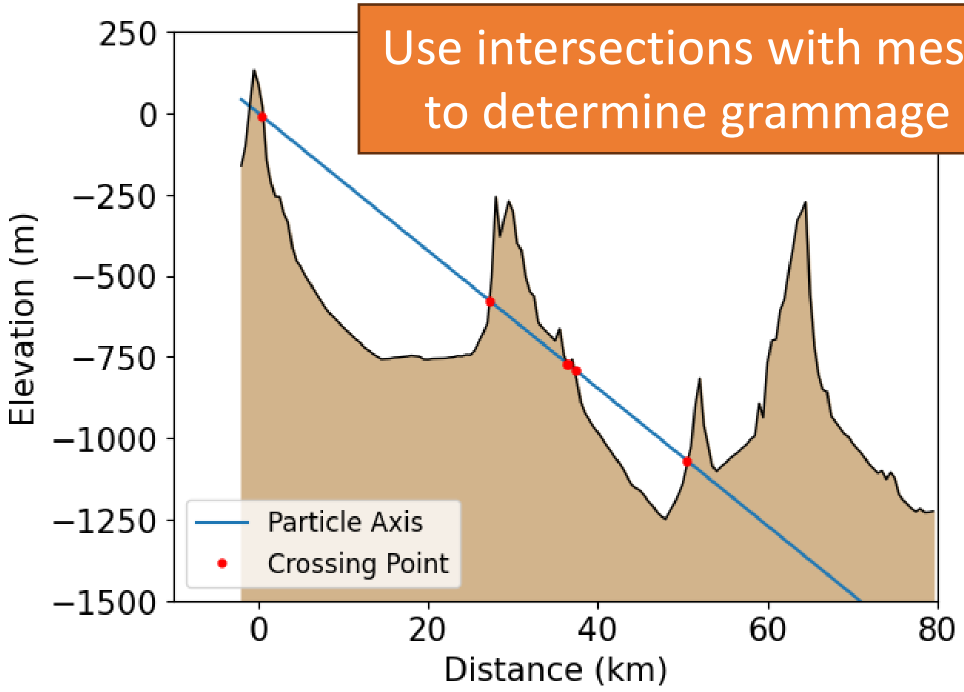
10,000 Antennas Total

Adding Topography to Marmots

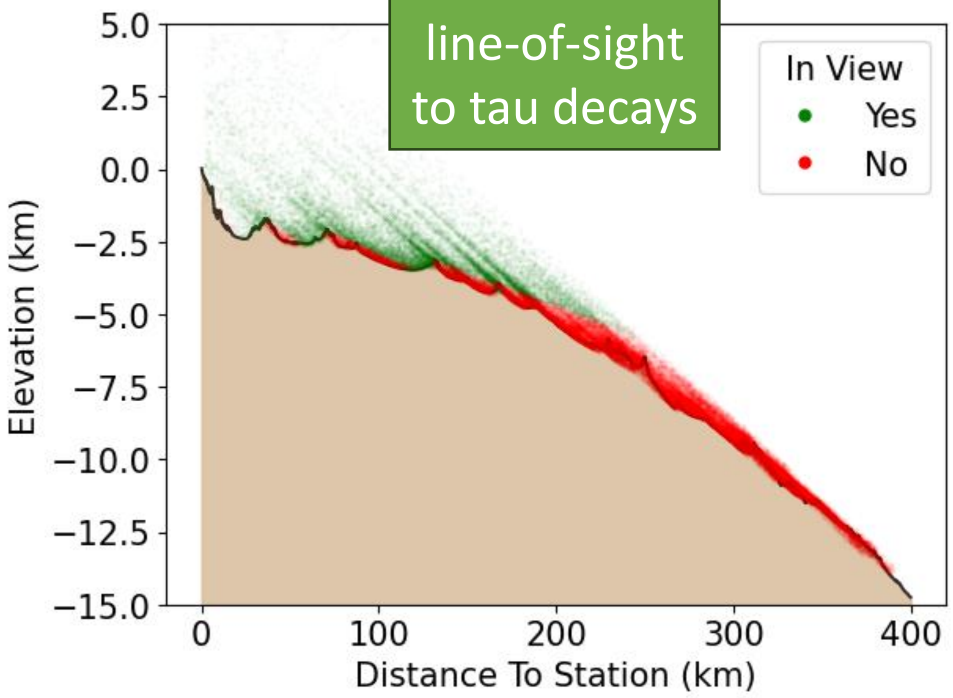
Does it help or hurt?



Exit points are now sampled on a triangulated mesh of Earth's surface



Use intersections with mesh to determine grammage



Determine line-of-sight to tau decays

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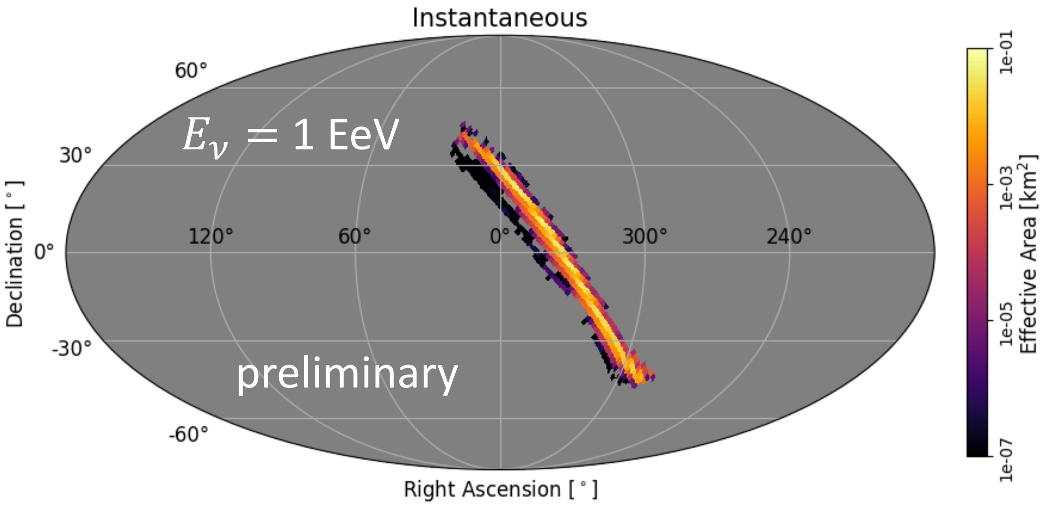
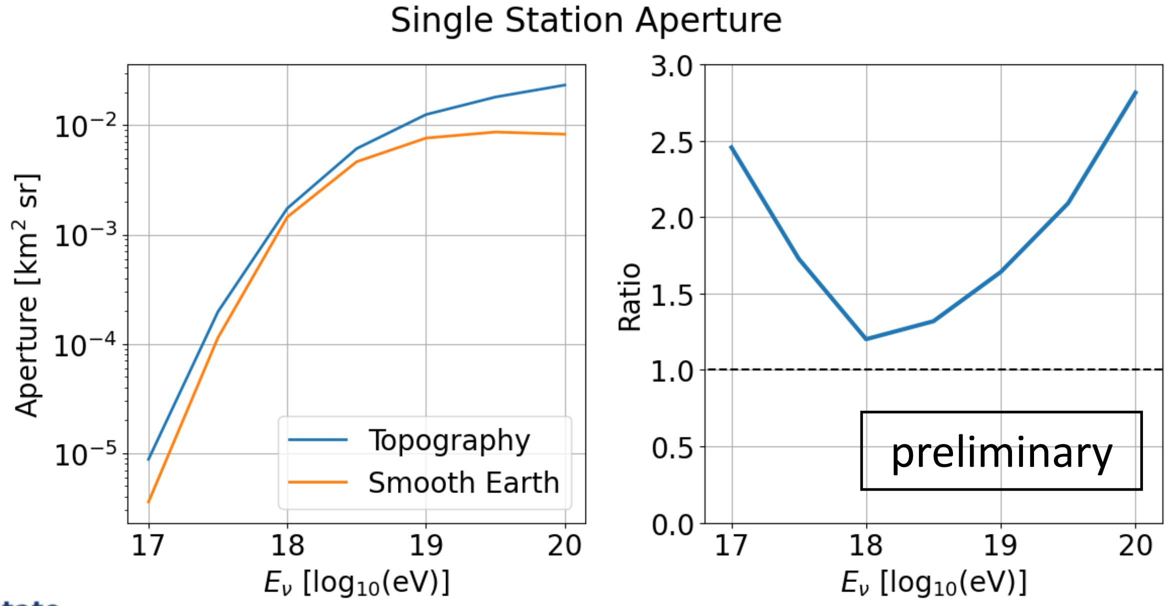
Effect of Topography at the Prototype Site





- **Factor of 1-3 increase** in effective area and aperture at the prototype site
- **Effect is site dependent.** Topography:
  - \+ Increases surface area
  - \+ Creates more targets for earth-skimming neutrinos
  - − Can block line-of-sight to taus

Conclusions

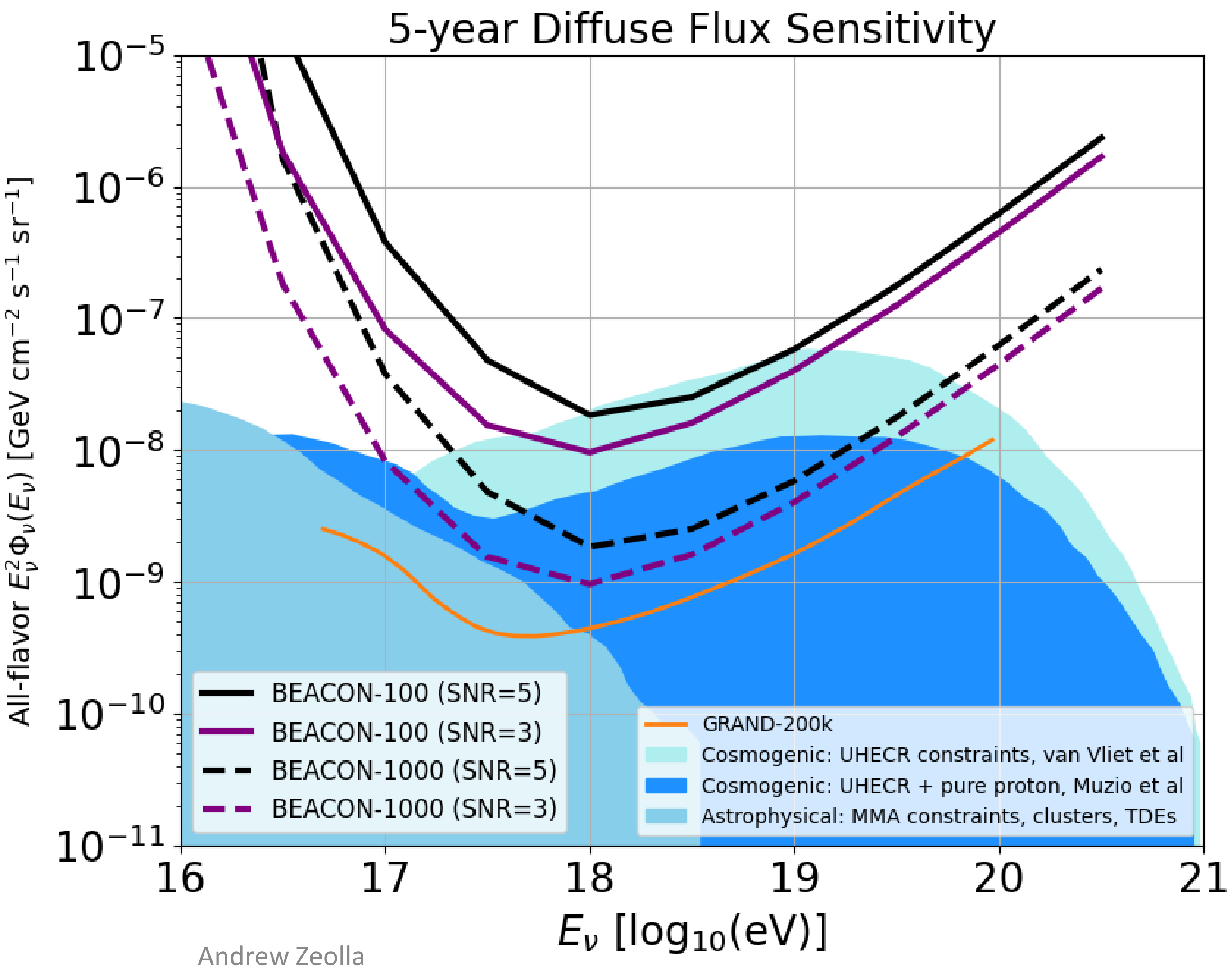
- BEACON is highly sensitive to transients that pass into its instantaneous field of view
- Large FoV and position near equator allows many sources to be observed over time
- High elevation sites coupled with phasing produce an efficient detector design
- Topography can further improve sensitivity

BEACON

Backup Slides

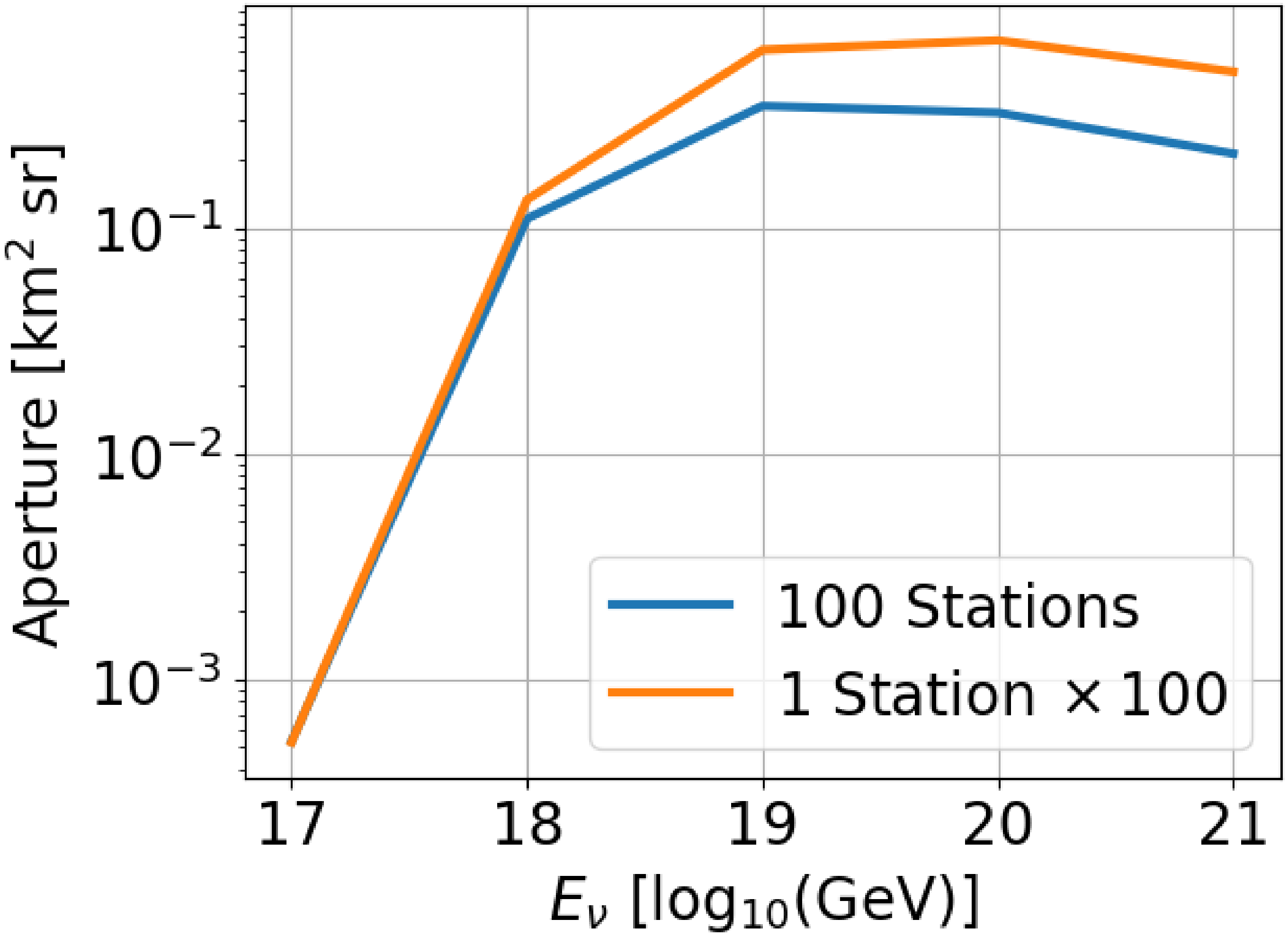
Diffuse Flux Sensitivity

- Lowering our trigger threshold increases our aperture by a factor of 5 at 100 PeV.



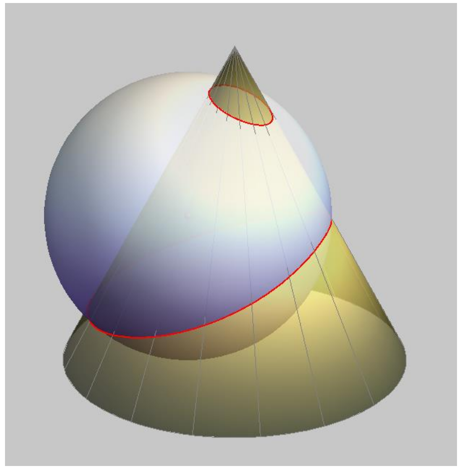
Accounting for Overlap

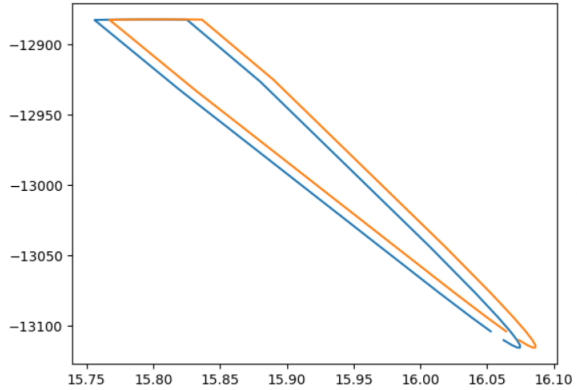
- Unless there is zero overlap between the effective areas of each station, linear scaling cannot be assumed
- Stations must be spaced far apart (>10 km) for zero overlap to occur
- The effect is energy dependent

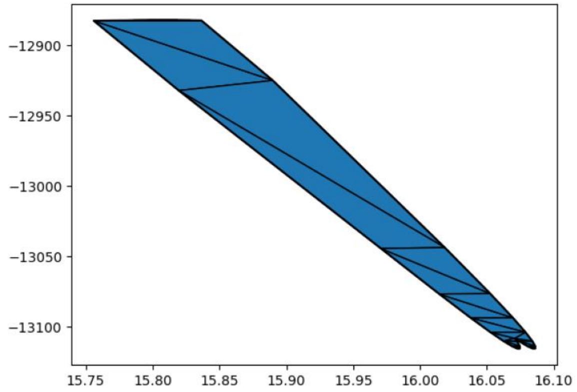


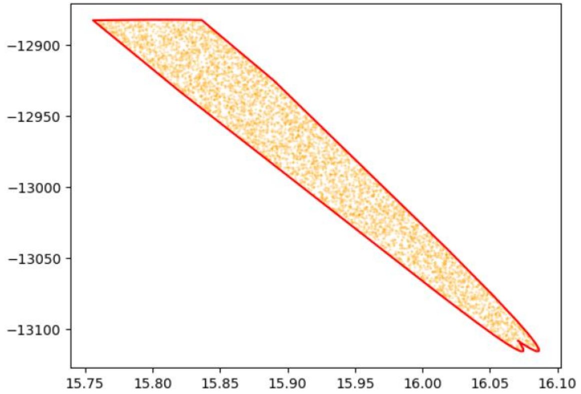
Geometric Area

1) Direction to source = shower-axis
2) Create cone of vectors around shower-axis, with the vertex at each station
3) Find where vectors intersect a sphere (an ellipse).
4) Sinusoidally project intersection points (3D → 2D while conserving area)
5) Find the union of all the polygons (Shapely). Find the total area (A_g)
6) Uniformly sample points within the total area via Constrained Delaunay Triangulation
7) Inverse projection









P_{exit}

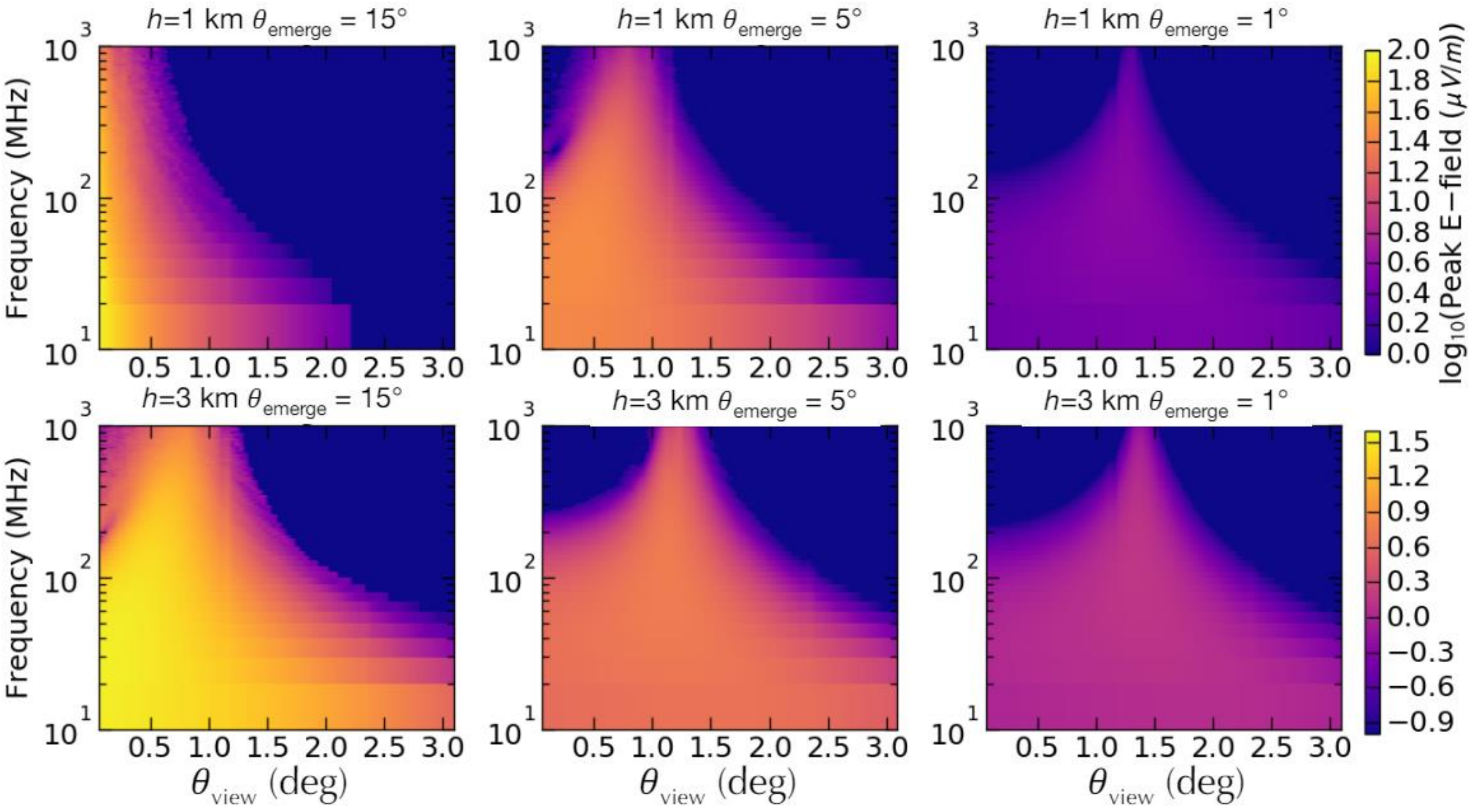
- The probability for each event to have exited the Earth, as well the energy of the resulting τ, is determined by the interpolation of a LUT generated using NuTauSim
- The decay point of the τ is randomly sampled from an exponential decay distribution. The energy of the resulting shower is determined by decay distributions generated using PYTHIA.

Electric Field

- Any event lying outside of a station’s viewing area is assumed undetectable
- An interpolation of a LUT is used to determine the peak electric field as a function of frequency for an event given it’s view angle, exit zenith angle, and decay altitude.
- The peak electric field is also scaled to account for energy, distance to decay, and the differing geomagnetic field

$$E_{event}(f) = E_{sim}(f) * \frac{\varepsilon_{event}}{\varepsilon_{sim}} * \frac{D_{sim}}{D_{event}} * \frac{B_{event}}{B_{sim}} * \frac{\sin(\hat{v} \times \hat{B})_{event}}{\sin(\hat{v} \times \hat{B})_{sim}}$$

Electric Field



Voltage and Trigger

- The electric field is then converted to voltage given the gain (θ, ϕ) and impedance of the BEACON antennas (XFdtd), or by assuming an isotropic gain and a perfectly matched antenna.
- V_{rms} is assumed to be due to galactic noise (Dulk parameterization) and the ground (300 K)
- The SNR: $\sqrt{N} \times {}^{V}\!/_{V_{rms}}$ is then calculated, and if it exceeds a chosen threshold a trigger occurs
- An event is considered detected if any station triggers on it → P_{detect}