Simulations and Optimizations for Radio Neutrino Detectors

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IceCube Collaboration Meeting
Radio Pre-Meeting
April 28, 2019

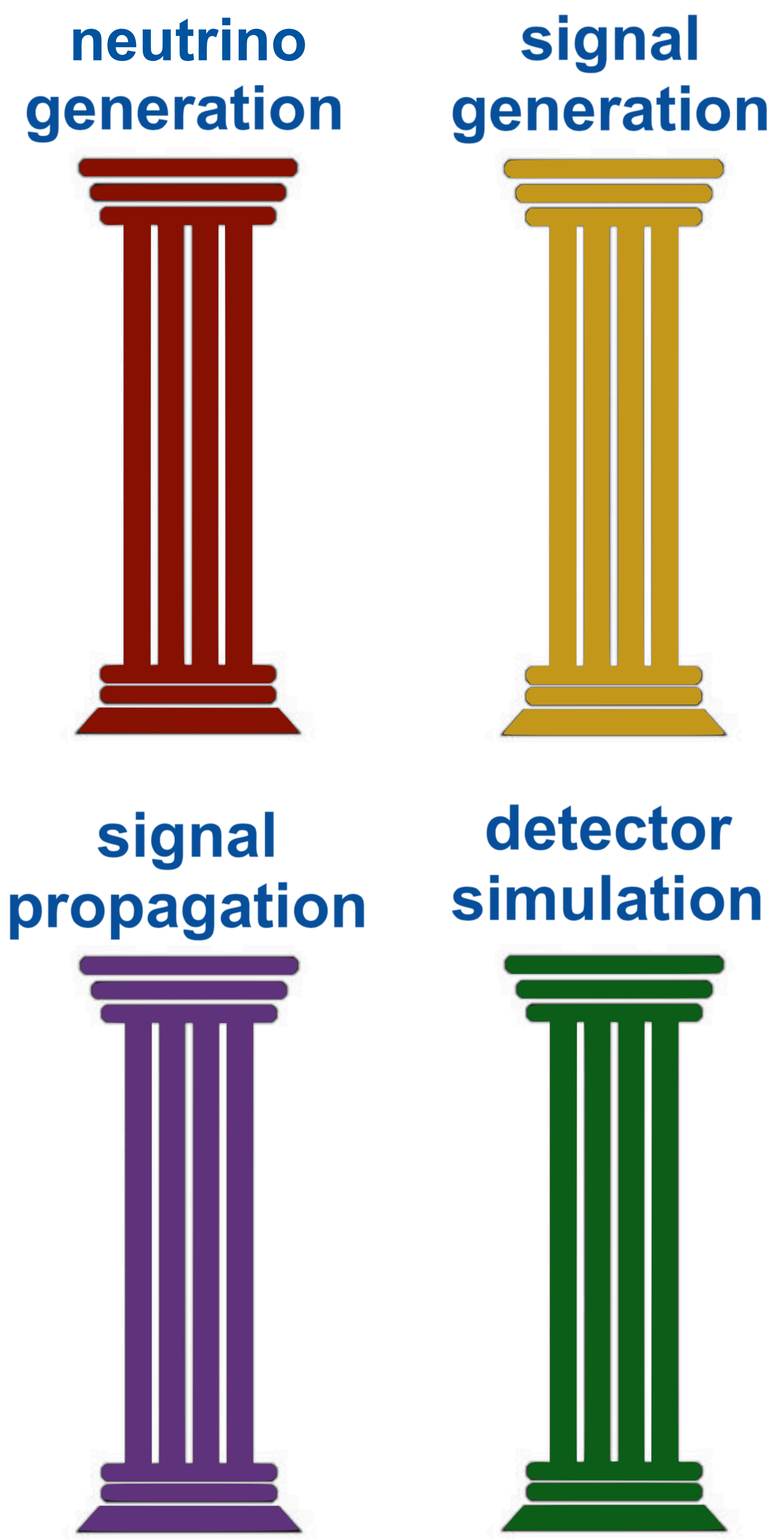
Simulation Development

- Radio simulation working group: InIceMC
  - ~15 members from the ARA and ARIANNA experiments
  - Foster collaboration and develop/maintain simulation tools
- Two new radio simulation packages developed as modern replacements for existing tools
  - PyREx https://github.com/bhokansonfasig/pyrex
  - NuRadioMC https://github.com/nu-radio/NuRadioMC
- New packages offer improvements in usability and physics accuracy
  - Flexible, modular implementations in Python
  - Updated Askaryan radiation models, antenna models, and signal propagation code

Simulation Features

- Neutrino event generation uniform in vertex position and shower direction, with weighting factors for Earth absorption and forced interaction
- Askaryan signal generation based on the latest models
- Signal propagation (ray tracing) from the interaction vertex to antenna locations
- Ice model with an exponential index of refraction profile and frequency-dependent attenuation length
- Flexible detector simulation with interfaces for a variety of antenna models, with antennas used by ARA and ARIANNA specifically implemented
- Simulation “steering” responsible for controlling the simulation chain

“4 Pillars of Monte Carlo”



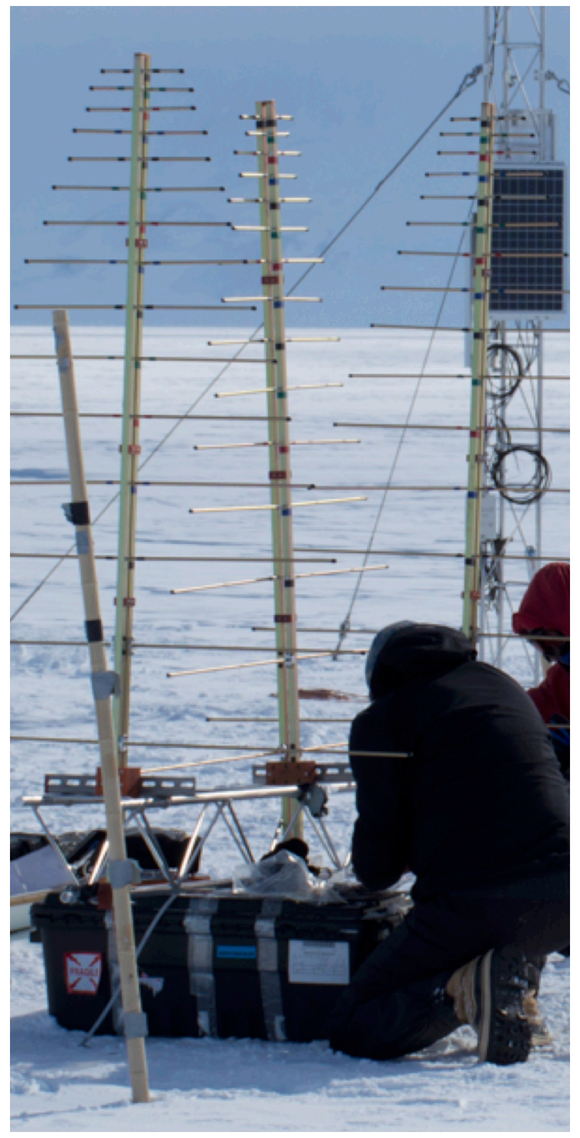
RNO Station Design

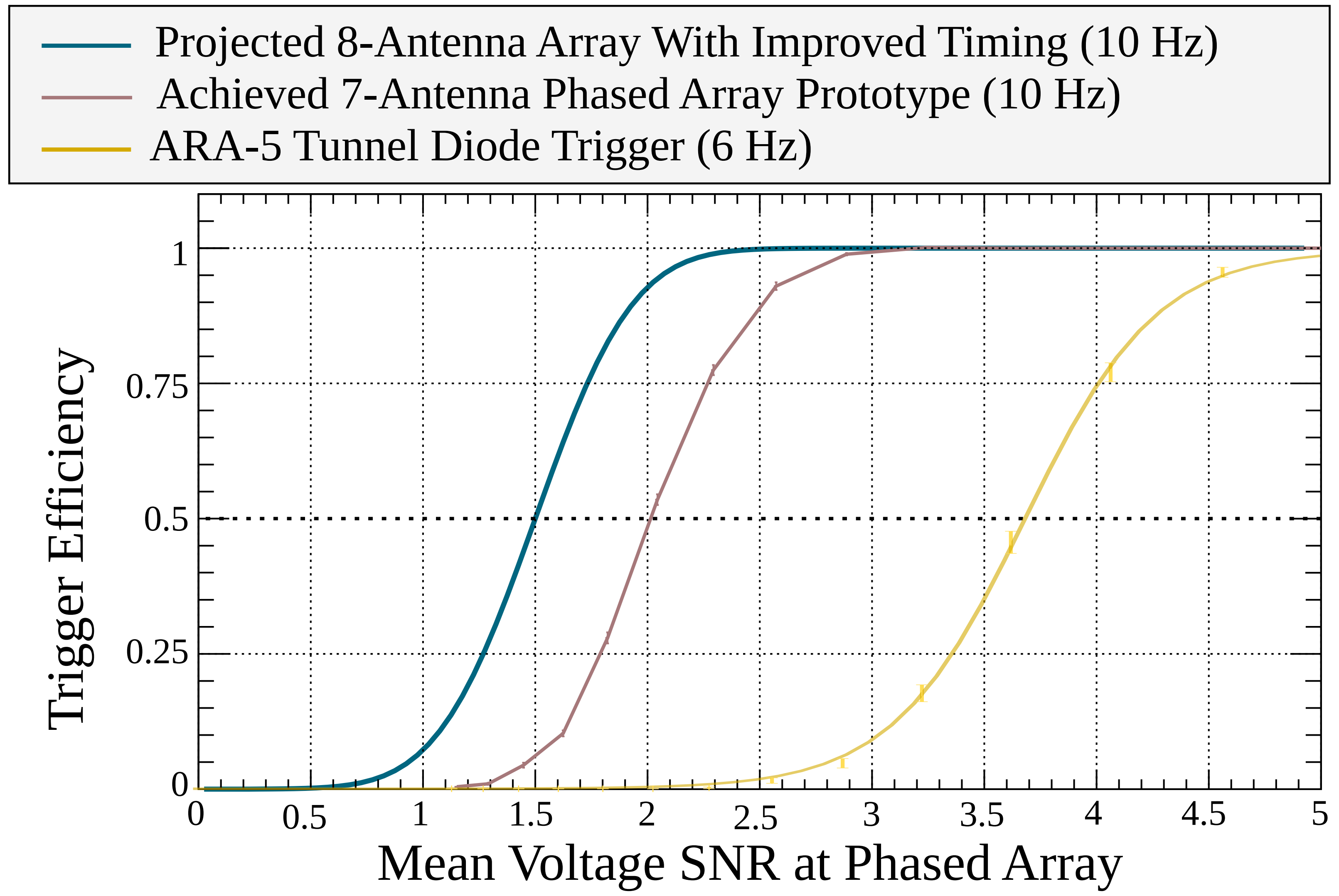
- Array of LPDAs deployed at or just below the surface, allowing unambiguous detection of nearby signals
  - Some LPDAs directed upward to reject cosmic ray signals
- Phased array string of bicone antennas deployed in the ice at some depth
  - Employs interferometry between the antennas to achieve low trigger thresholds
- Wider array of bicone and quad-slot antennas surrounding the phased array string to improve reconstruction of distant events
- Trigger on the phased array and the surface LPDAs

Bicone

Quad-Slot

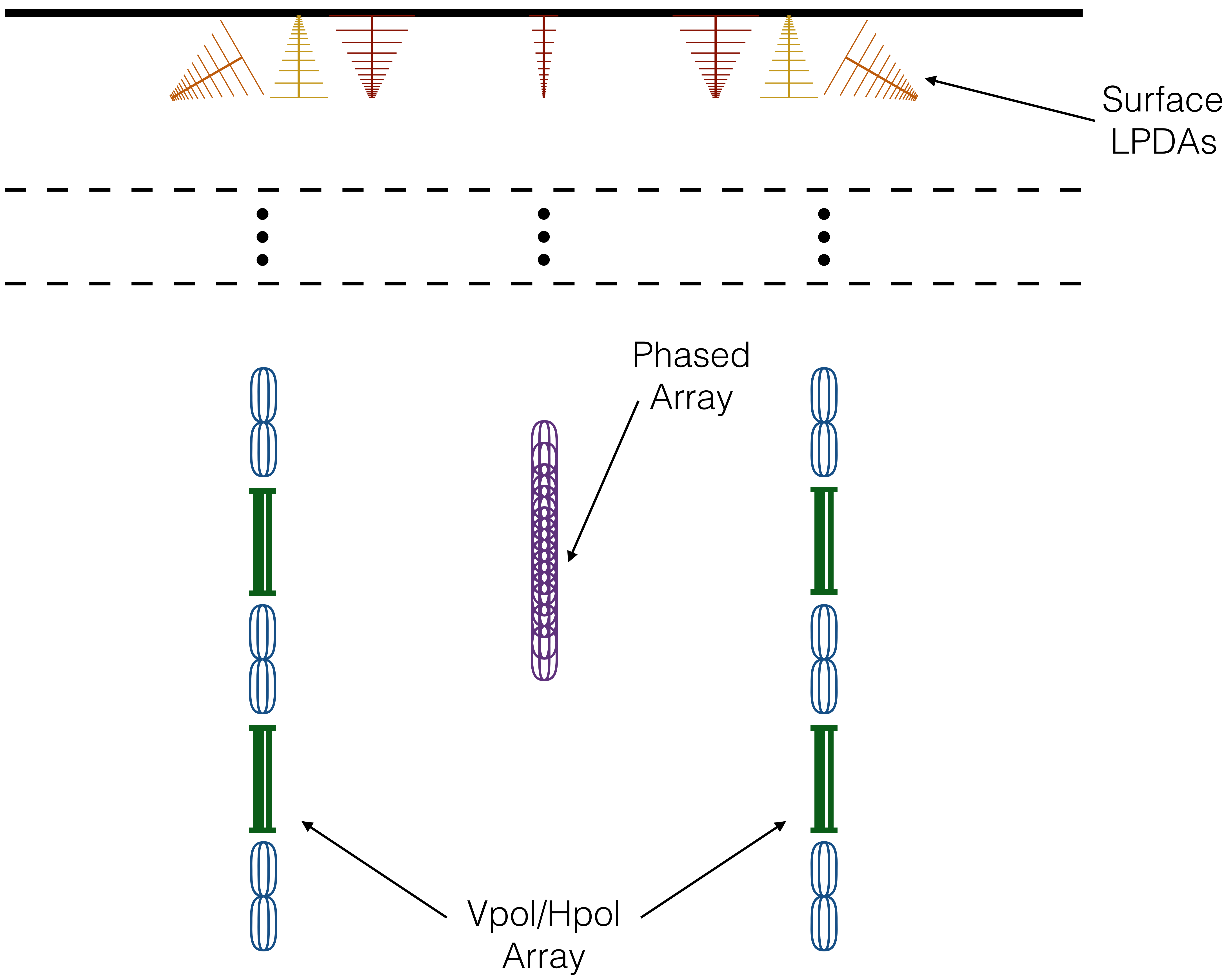
LPDA



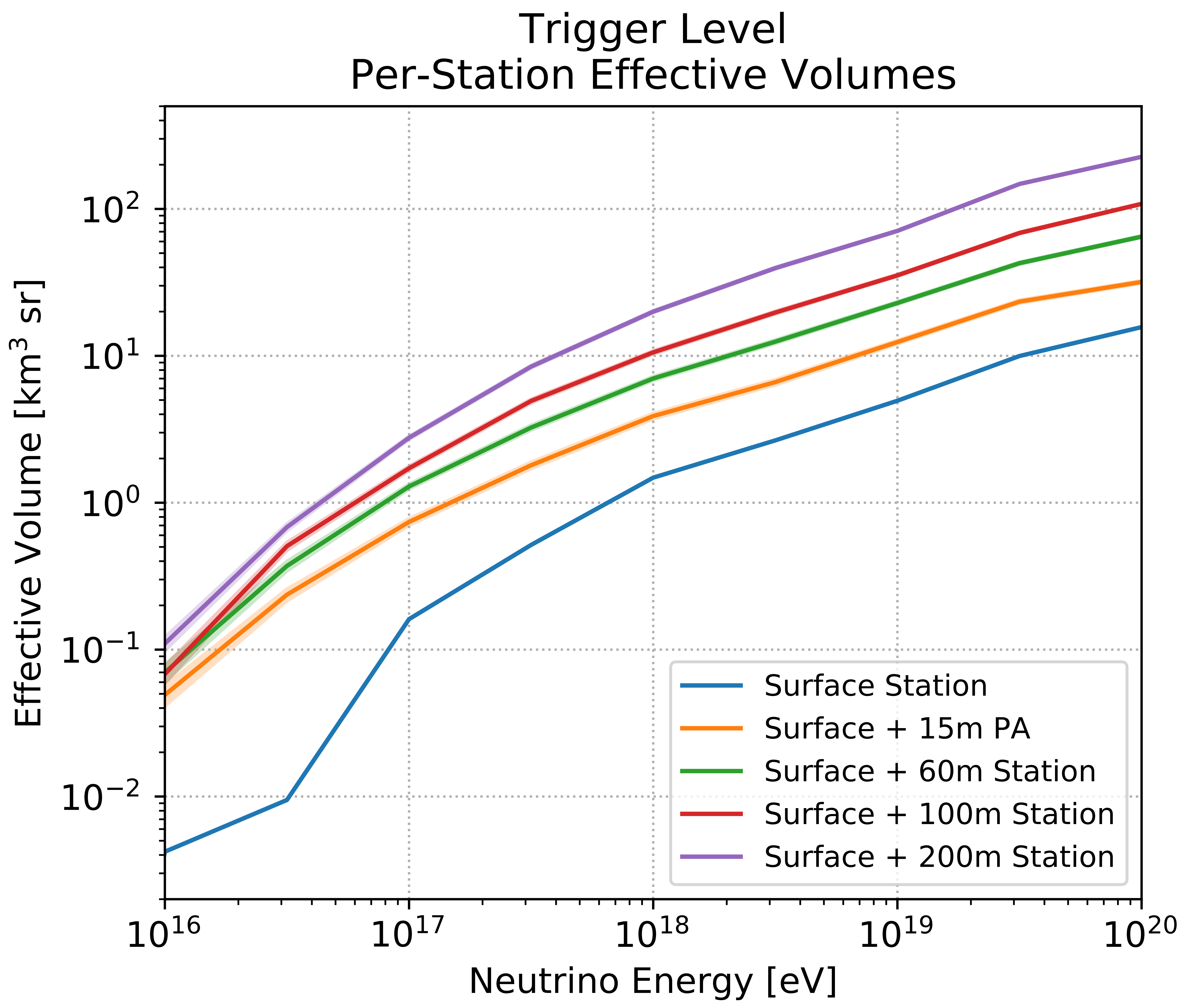


RNO Station Candidates to Compare

A. Surface LPDAs only
B. Surface LPDAs + 15m Phased Array
C. Surface LPDAs + 50m Phased Array
   + 60m Vpol/Hpol Array
D. Surface LPDAs + 85m Phased Array
   + 100m Vpol/Hpol Array
E. Surface LPDAs + 175m Phased Array
   + 200m Vpol/Hpol Array



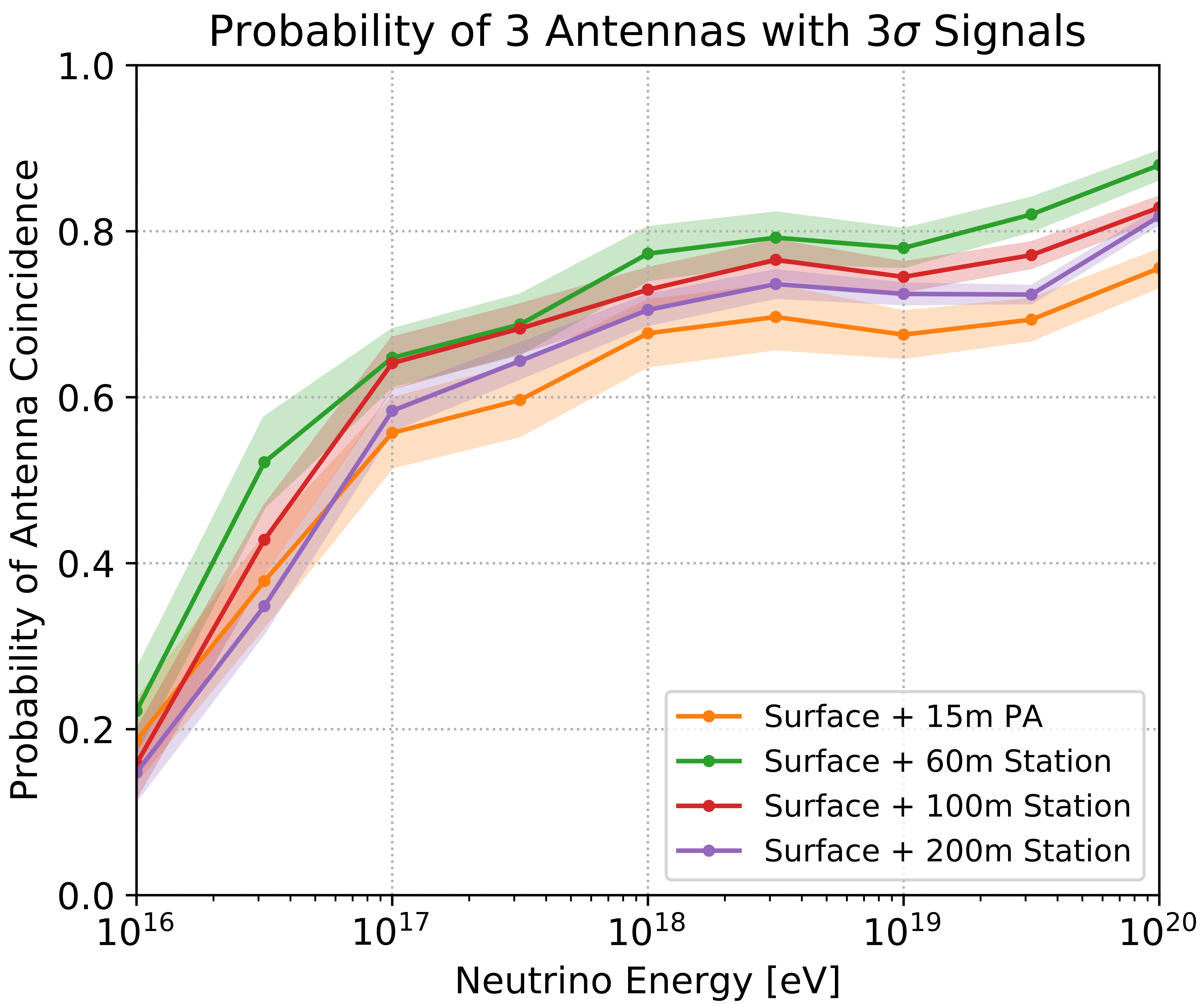
Effective Volumes of Station Varieties



Note: Design studies performed using PyREx version 1.8.1

- Trigger-level effective volumes improve as the sub-surface portion of the station is moved deeper
- Dominated by contributions from the phased array trigger
- At low energies, effective volumes from the phased array trigger are similar
- At high energies, effective volumes from the phased array trigger increase proportionally to the increased visible ice volume

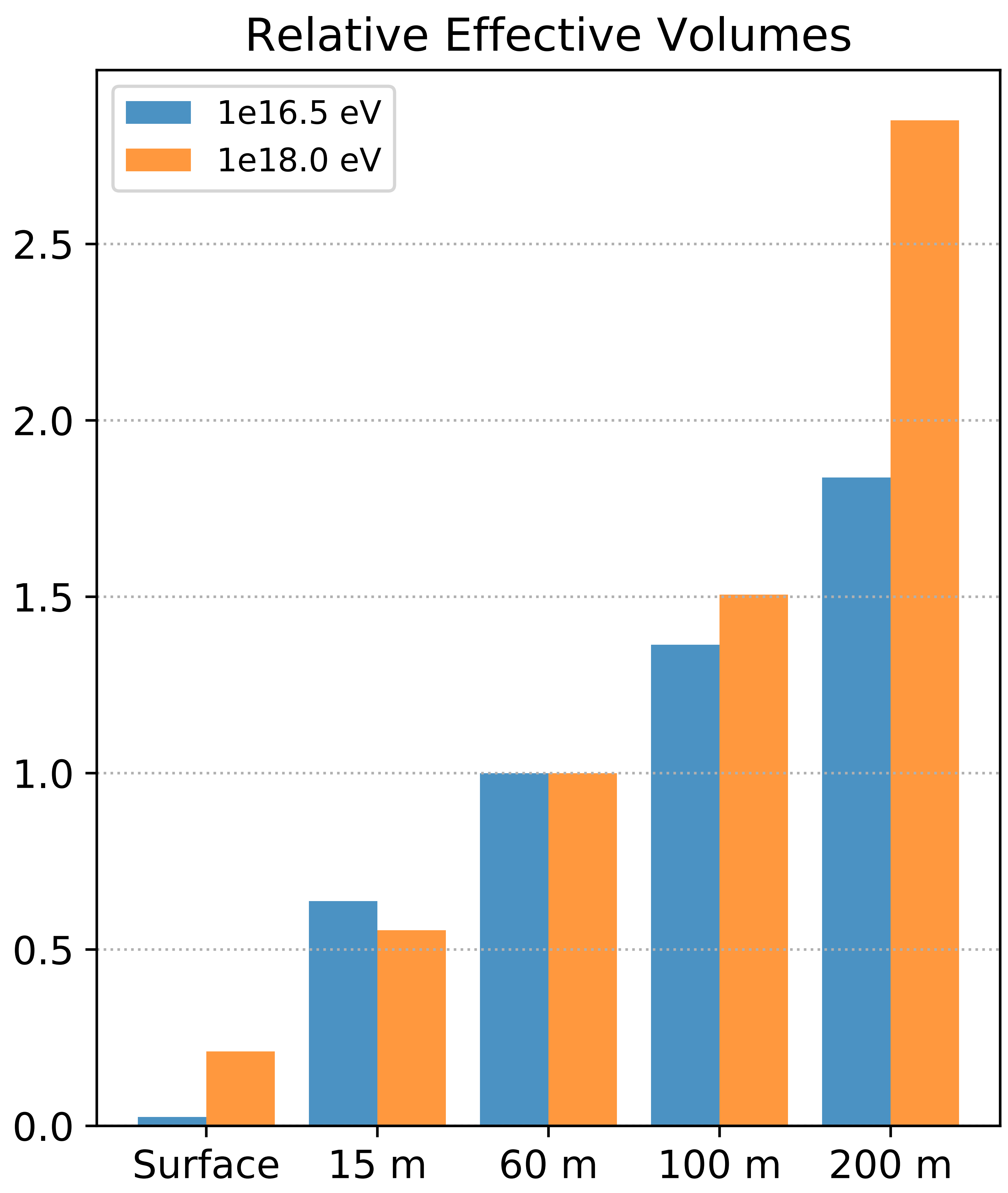
Analysis Proxy: 3-Antenna Coincidences



- Trigger-level effective volumes are informative, but analysis-level effective volumes will ultimately be more important
- Hard to tell the analysis cuts ahead of time, but we know that we will need at least 3 antennas with reasonably strong signals for a quality reconstruction of the event vertex
- Plot shows approximated analysis efficiencies for each station design, calculated as the probability for events which trigger the phased array at 1.5σ to also have 3 other antennas with signals above 3σ

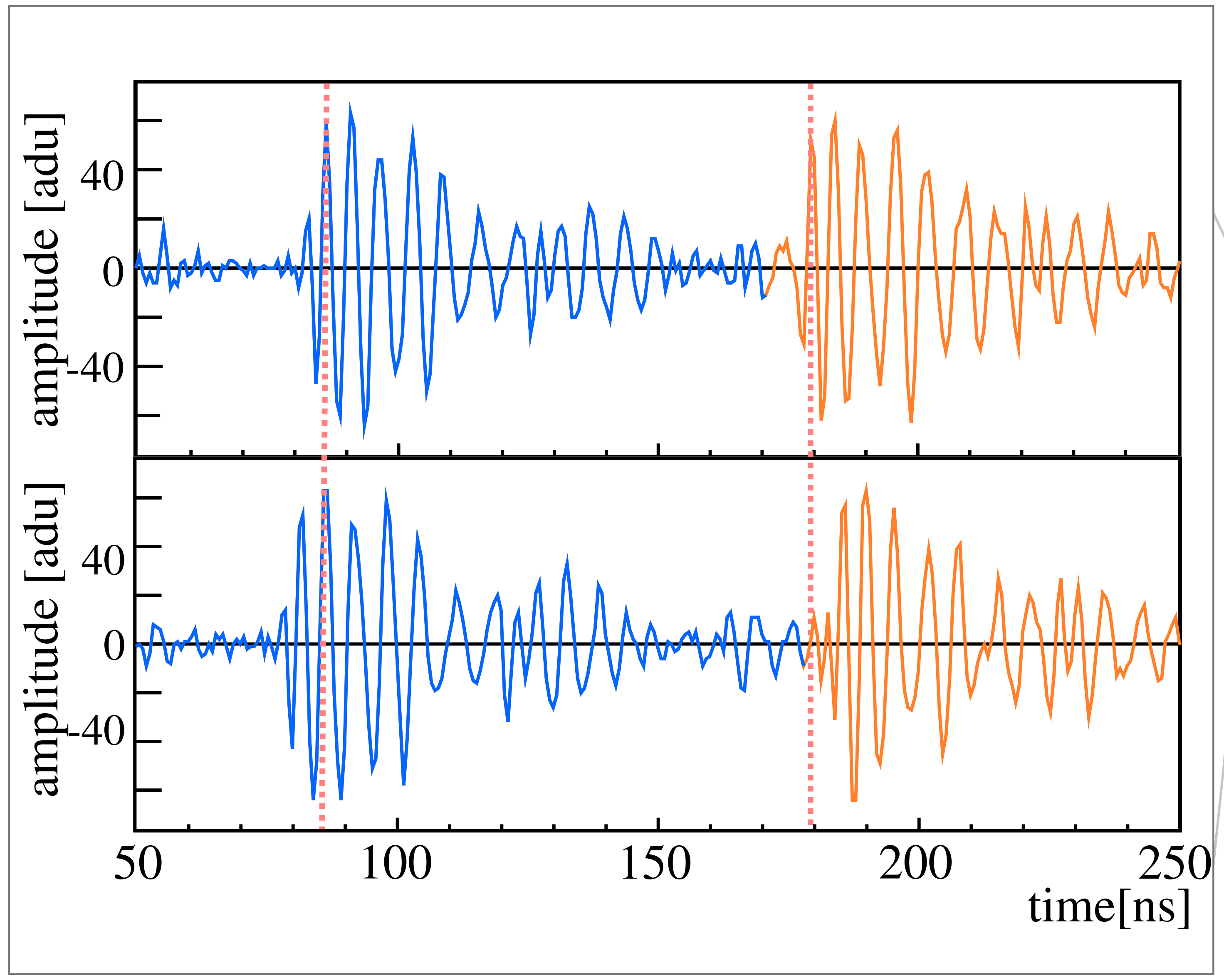
Relative Effective Volumes

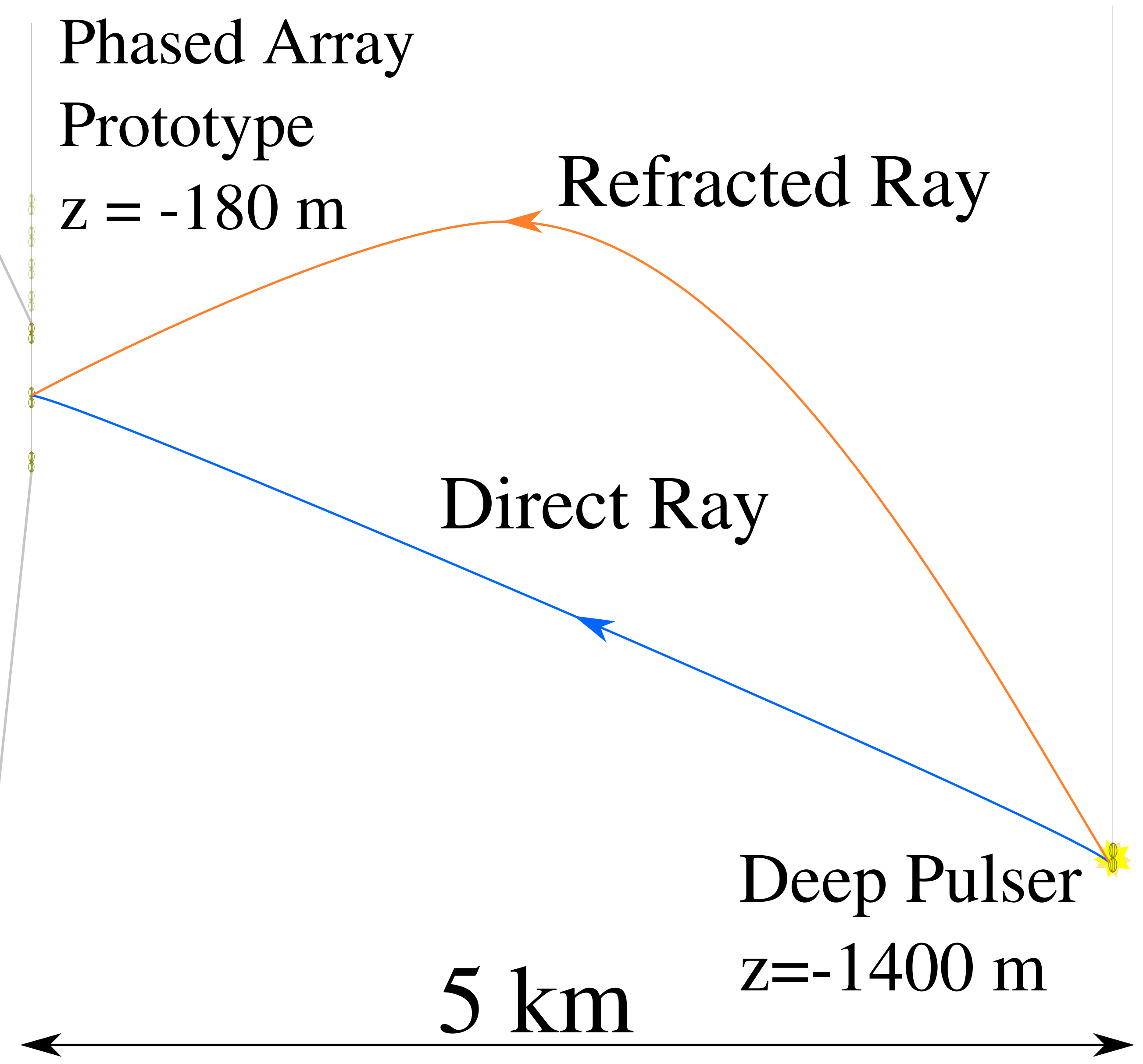
- For easier comparison of station varieties, can consider effective volumes (at trigger level) at a couple key energies:
  - 1e16.5 eV, where the RNO goal is to overlap the IceCube sensitivity
  - 1e18.0 eV, where the RNO goal is to have the world's best sensitivity
- Data for each energy is normalized separately here by the value for the 60 m station to show relative effective volumes

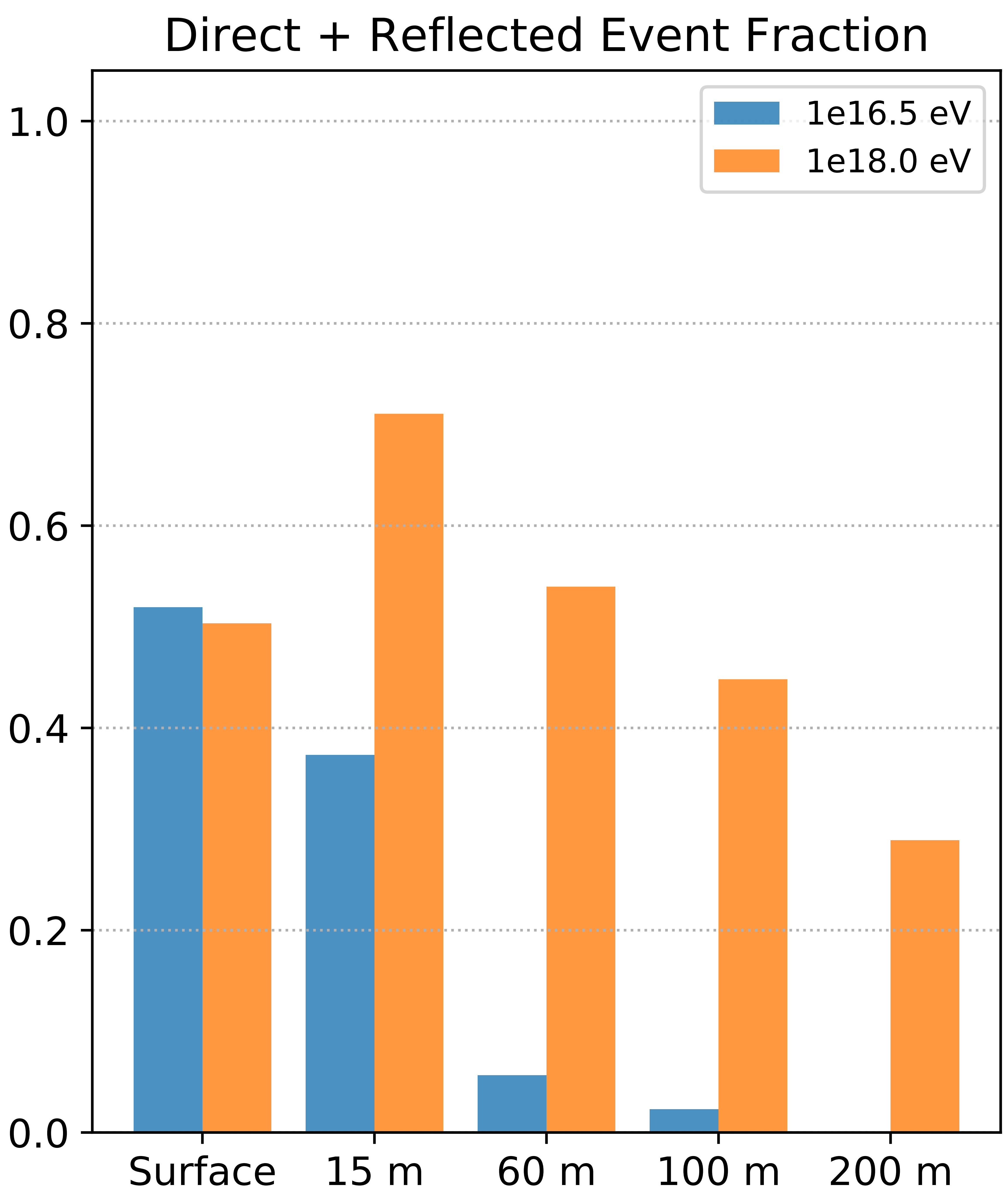


Double Pulse Event Fractions

- Events which have signal power received along both the direct and reflected paths are “golden” events
- The double-pulse signal structure makes events much easier to reconstruct, improving the physics abilities of the detector

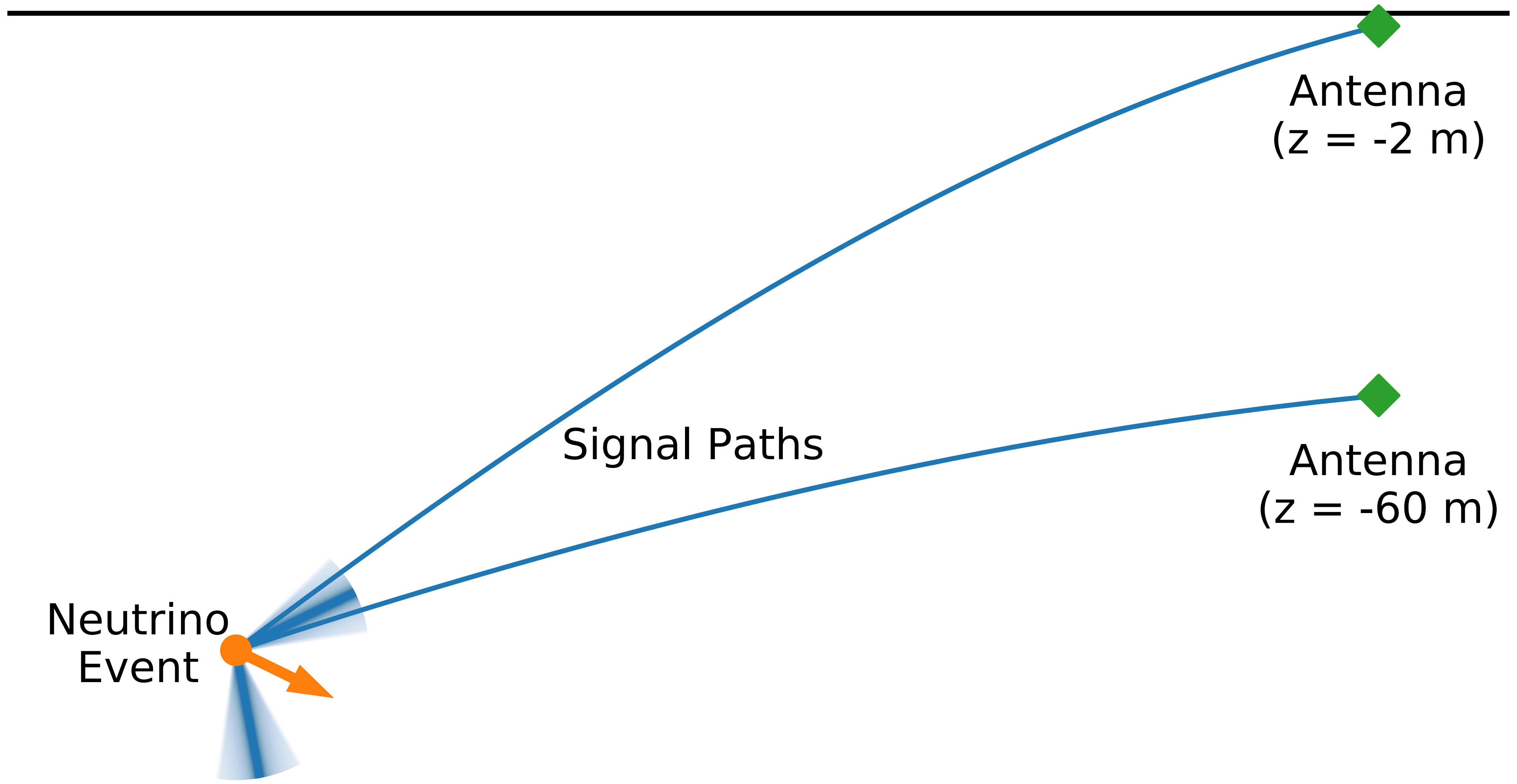


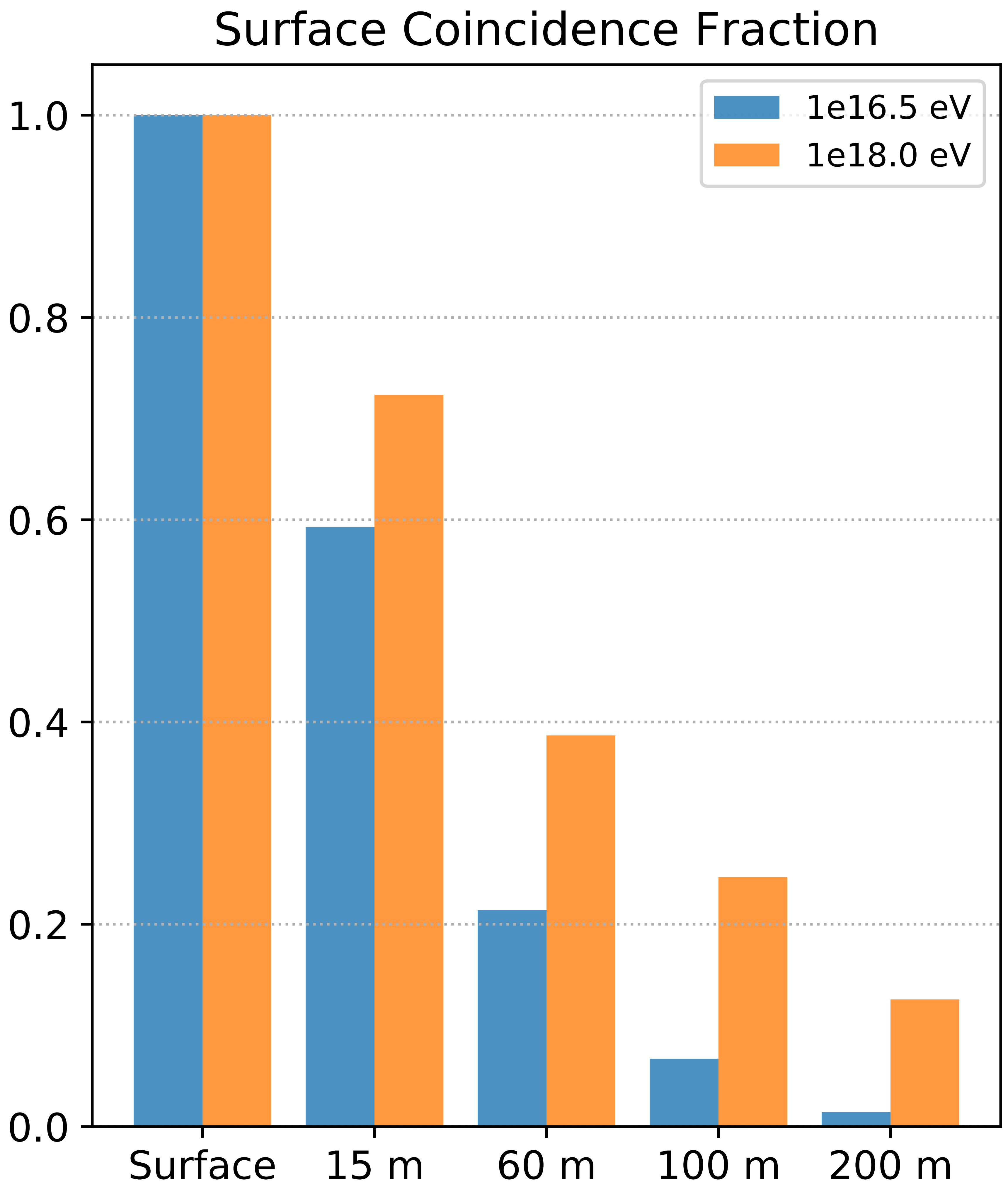




Surface Coincident Event Fractions

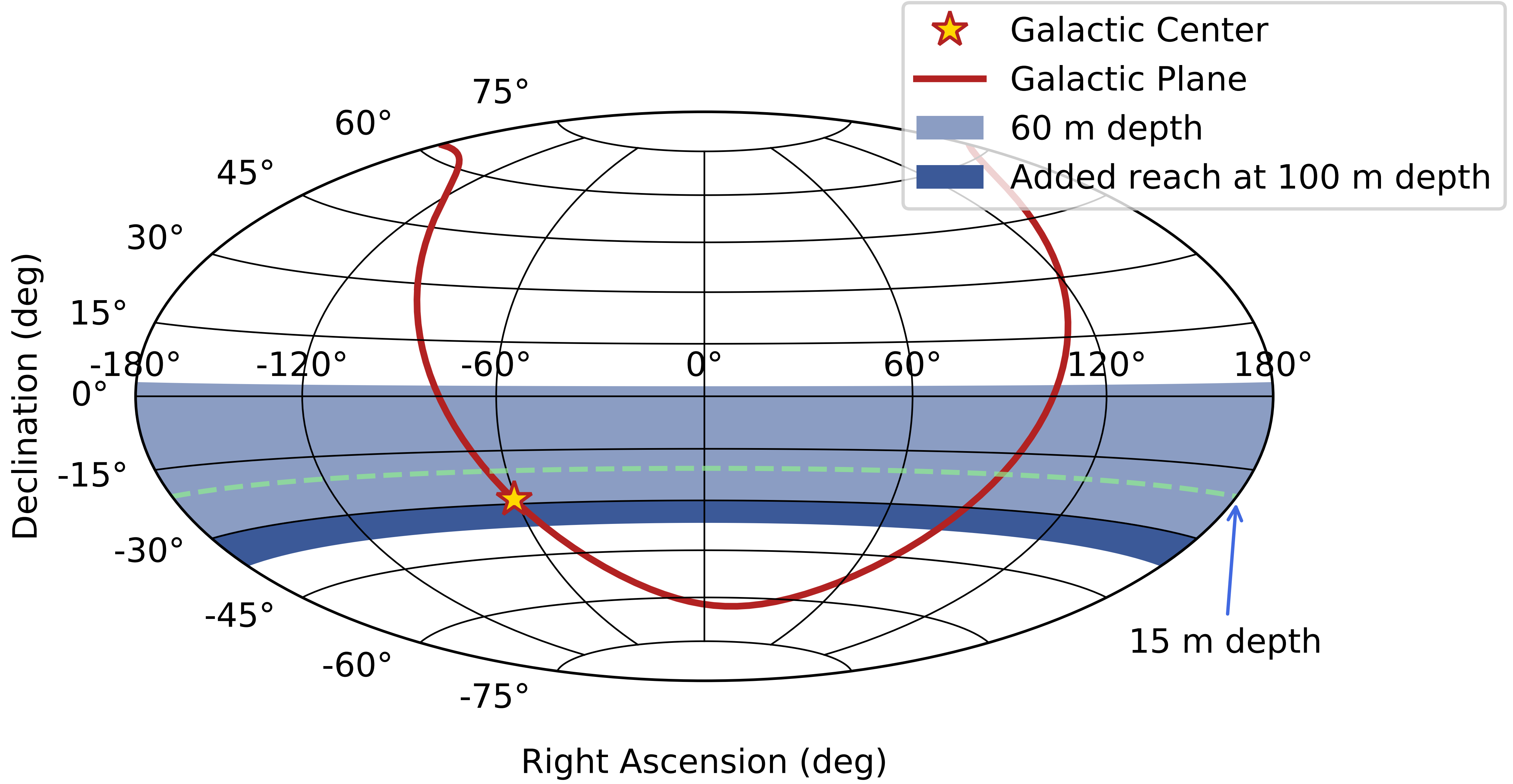
- Events which have signal power in both the surface and deep components of a station are also expected to be highly analyzable
- Again, events with these signal signatures will improve the reconstruction capabilities of the detector

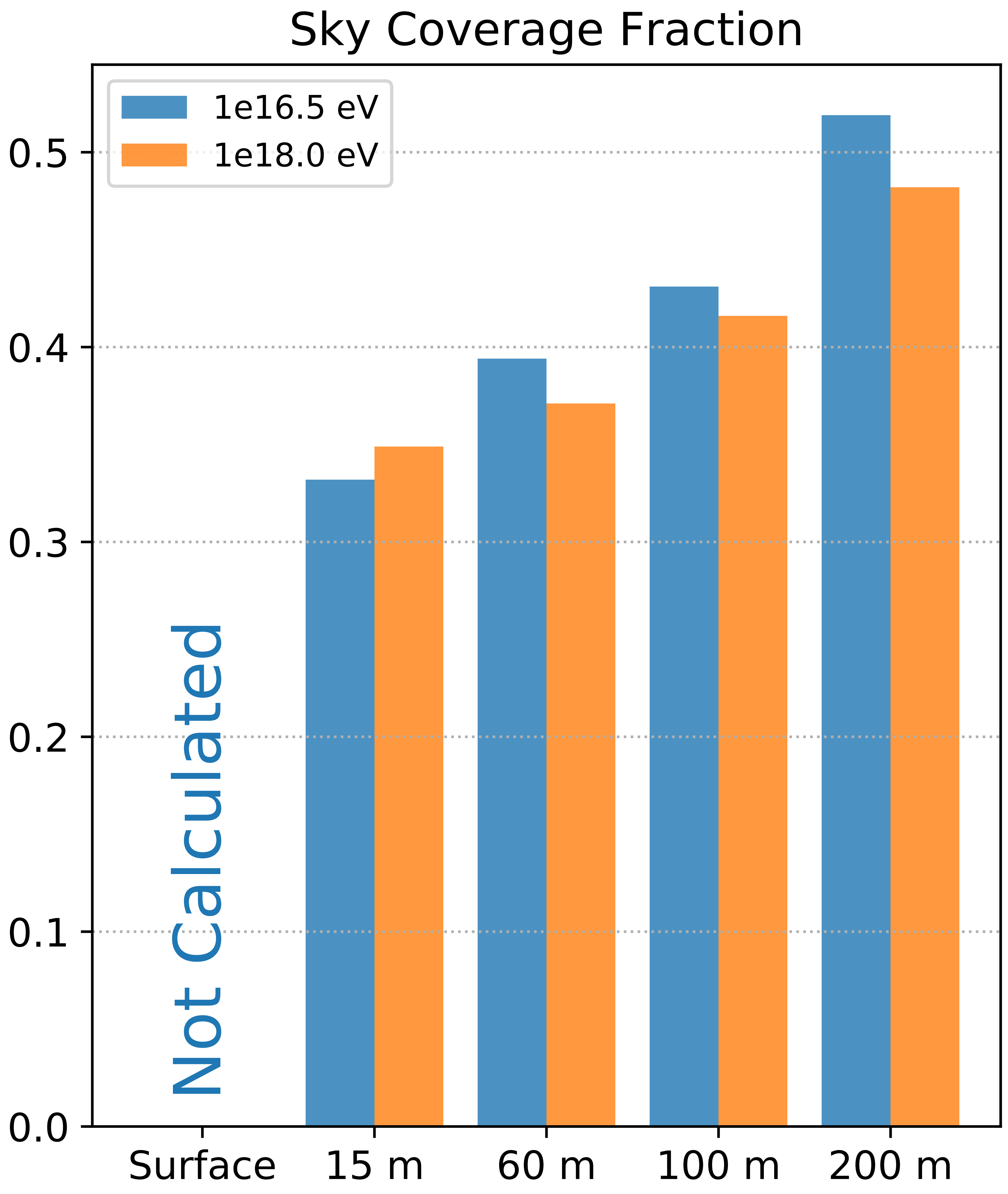




Sky Coverage

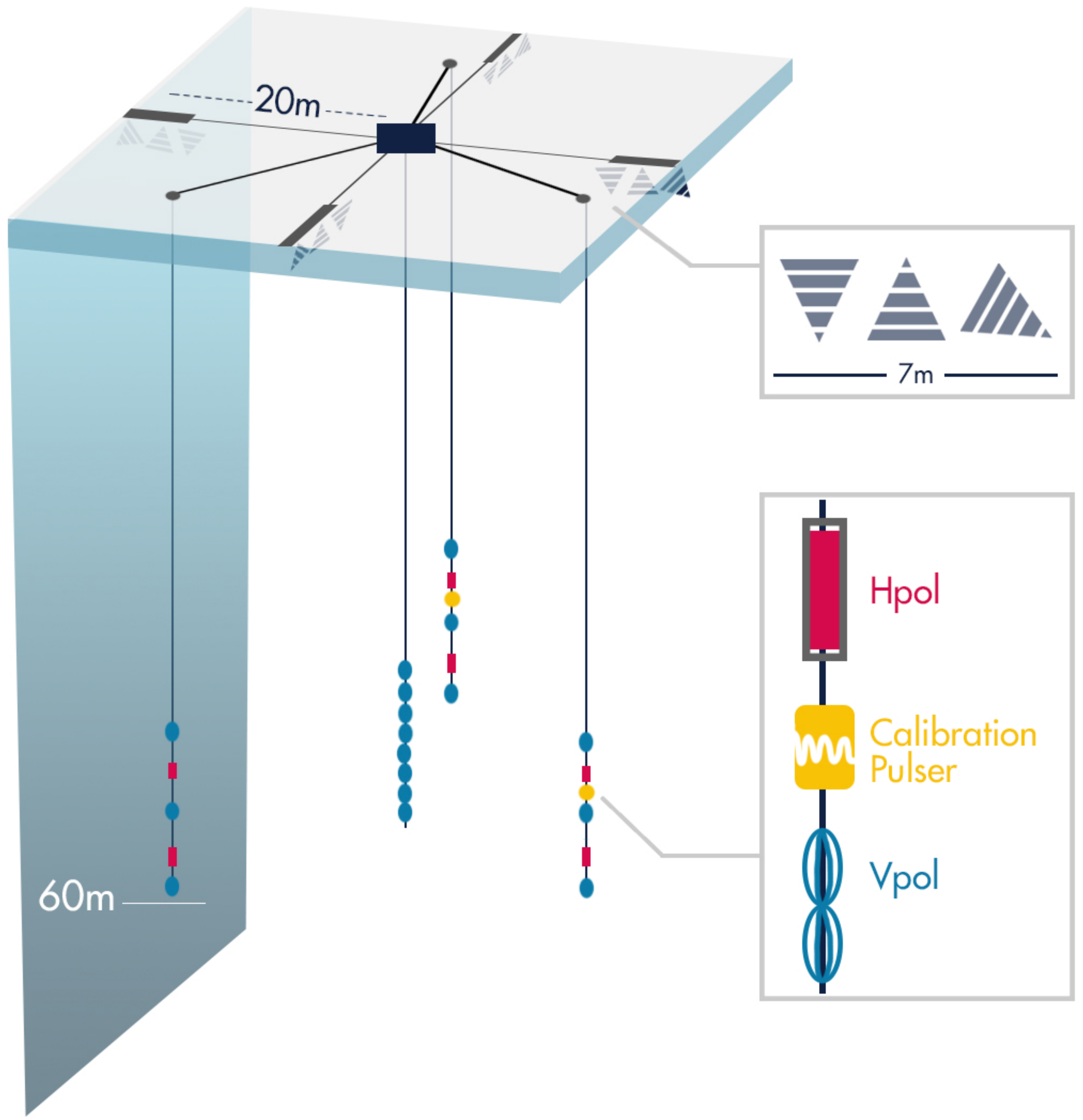
- The amount of sky visible by the detector is particularly important for multi-messenger astronomy
- Sky coverage fraction defined as the expected fraction of the whole sky that a station would see with at least 1% of the maximum exposure

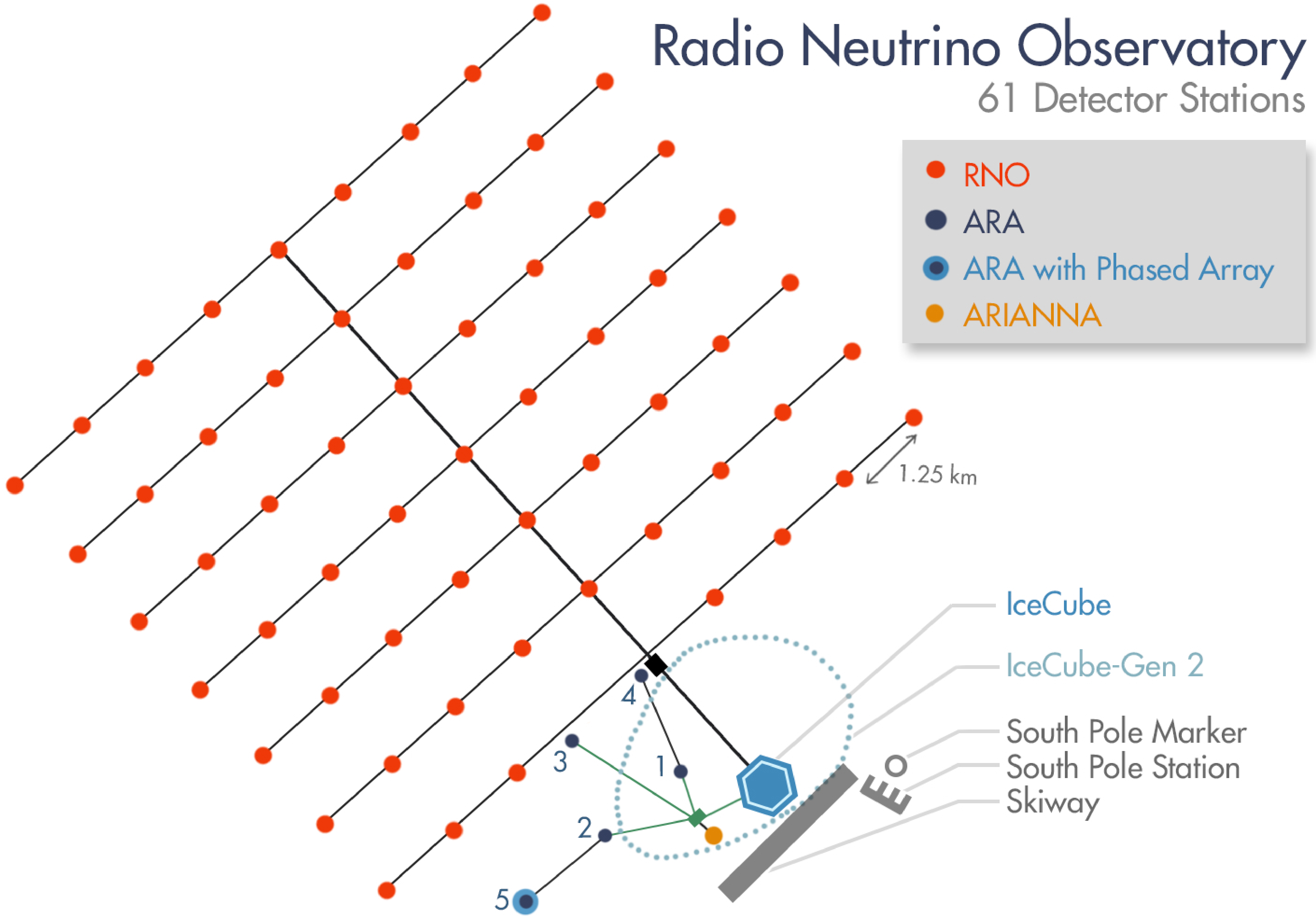




Final RNO Design Decision

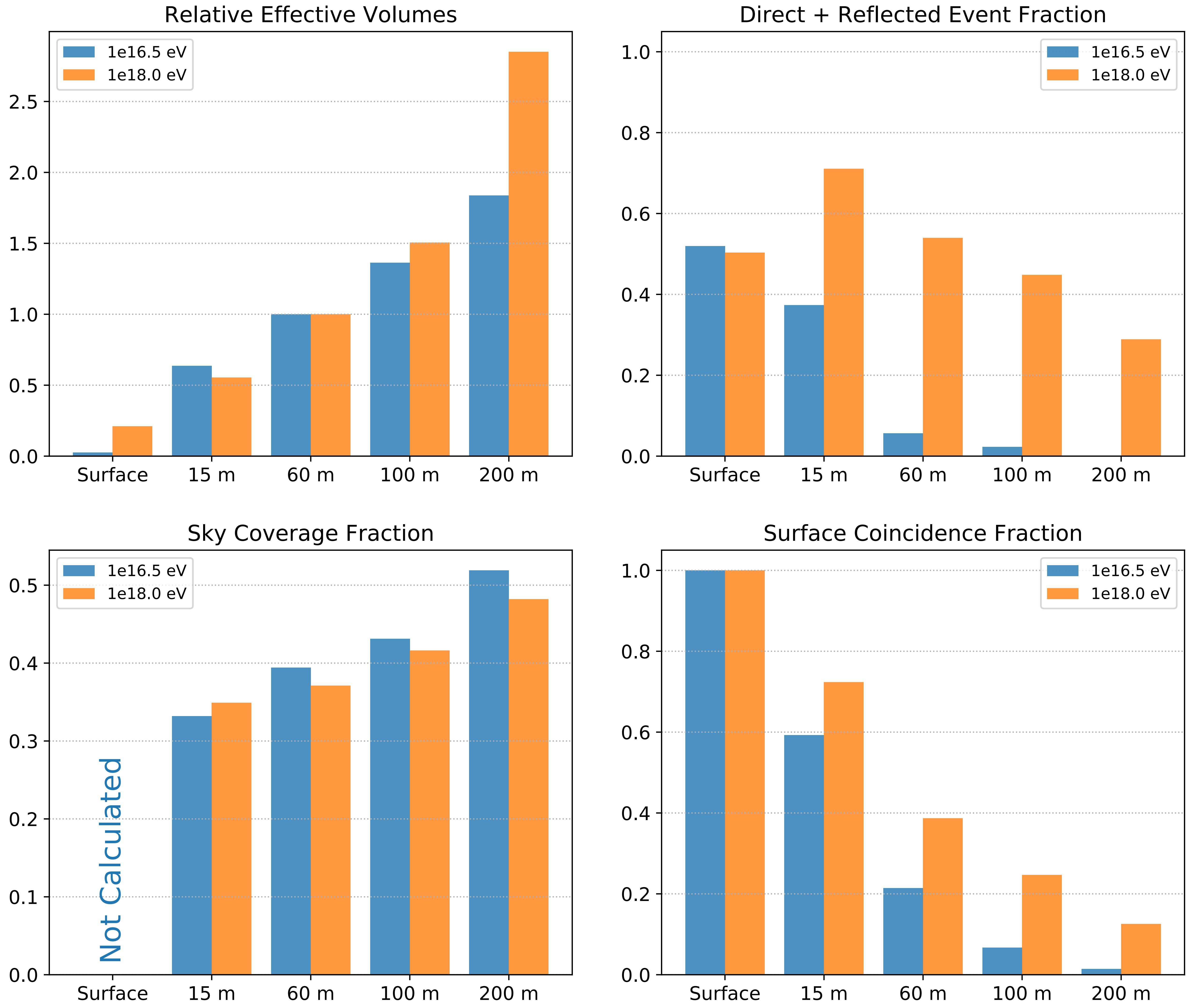
- Balancing of all factors led to the decision to propose the surface + 60 m station
- Consider deployment to 100 m if maximizing effective volume per station becomes the main driving design factor





Conclusions

- Simulation packages are ready and available for optimizing radio neutrino detectors
- RNO optimization pointed to stations with surface antennas and deep antennas down to 60 meter depth
- Parameter space for the optimization was limited to a fairly specific detector layout with surface antennas, a phased array, and outrigger strings
- More exotic detector designs may lead to different conclusions on the optimal deployment depth



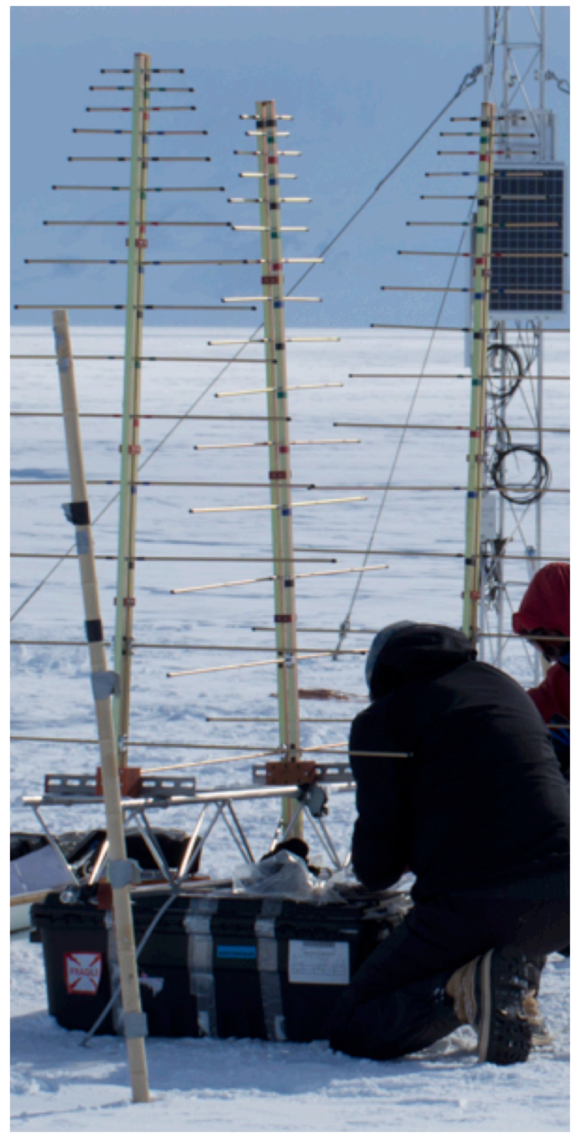
Backups

RNO Goals

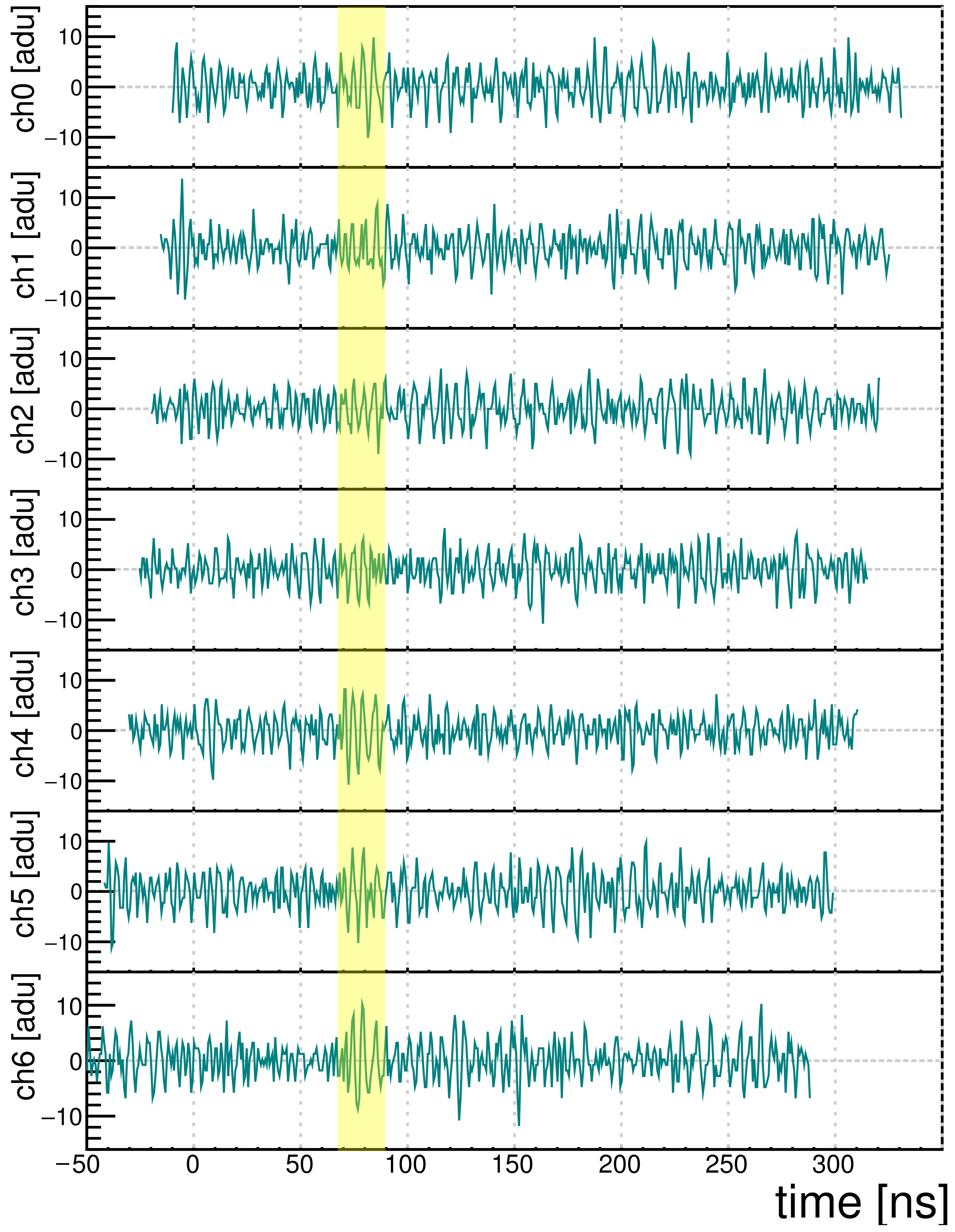
1. Achieve sensitivity to neutrinos across a broad range of energies to target both astrophysical and cosmogenic neutrino fluxes, which is best achieved with low trigger thresholds.
2. Achieve high livetimes critical for multi-messenger observations and improved sensitivity to diffuse neutrino fluxes. This requires powering the observatory using a power grid, rather than an autonomous power design, which in turn requires a minimal number of stations and therefore a high neutrino effective volume per station.
3. Provide high-quality energy and direction reconstruction of each neutrino event for multi-messenger studies, which is best achieved by comprehensive observations with both a surface and a deep component of a single station.
4. View a large fraction of the sky to enhance multi-messenger observations.
5. Enhance discovery potential by achieving a high reconstruction efficiency of triggered neutrino events and minimizing backgrounds.

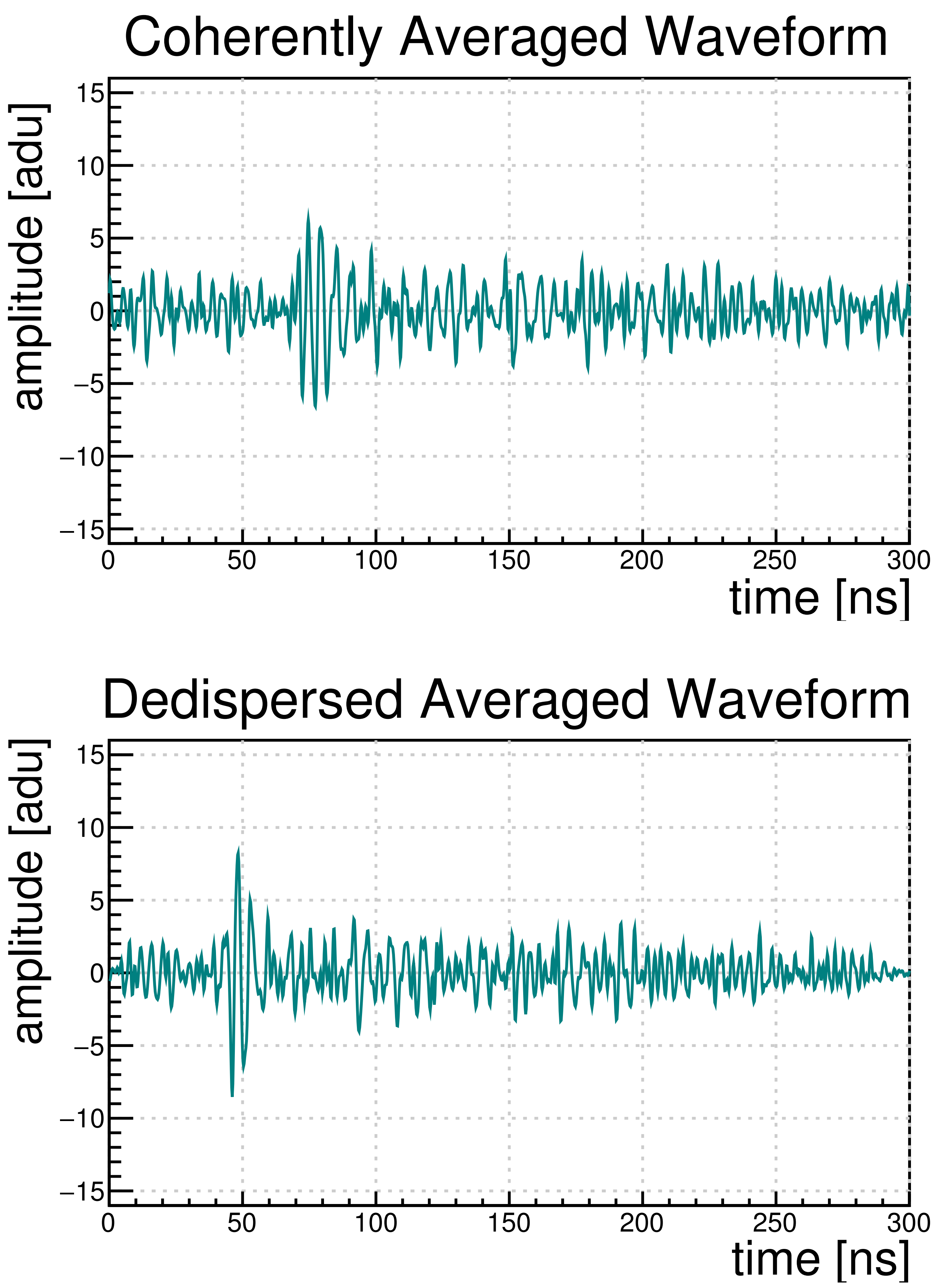
Available Antennas

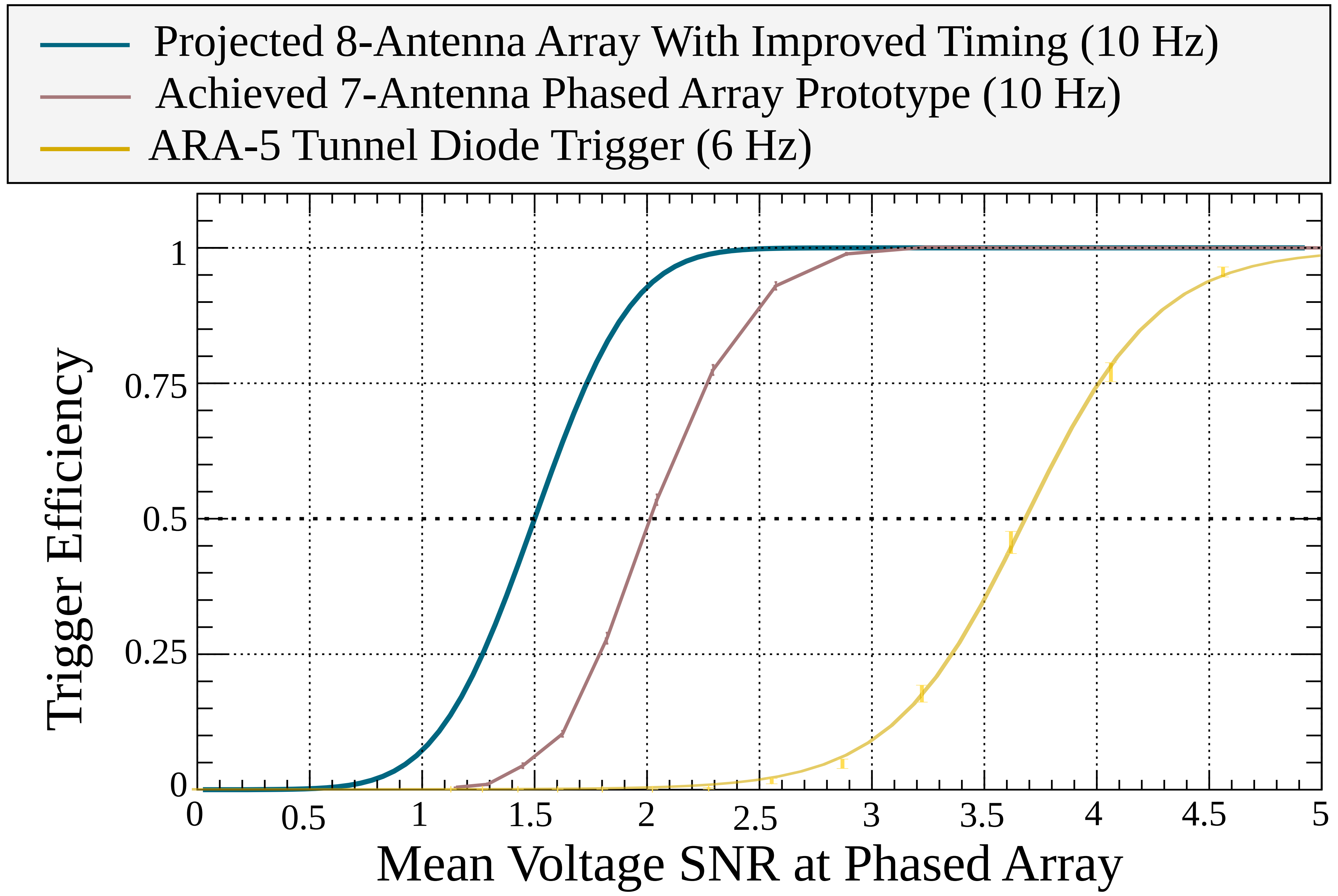
- ARA Bicone (Vpol) antennas
  - Minimally dispersive and sensitive to vertically polarized signals
  - Azimuthally symmetric
  - Narrow diameter (~6 inches) allowing down-hole deployment
- ARA Quad-Slot (Hpol) antennas
  - Sensitive to horizontally polarized signals in x and y
  - (Nearly) azimuthally symmetric
  - Narrow diameter (~6 inches) allowing down-hole deployment
- ARIANNA LPDA antennas
  - Highly sensitive to signals in a single plane, though dispersive
  - Too large to be realistically deployed more than a couple meters deep



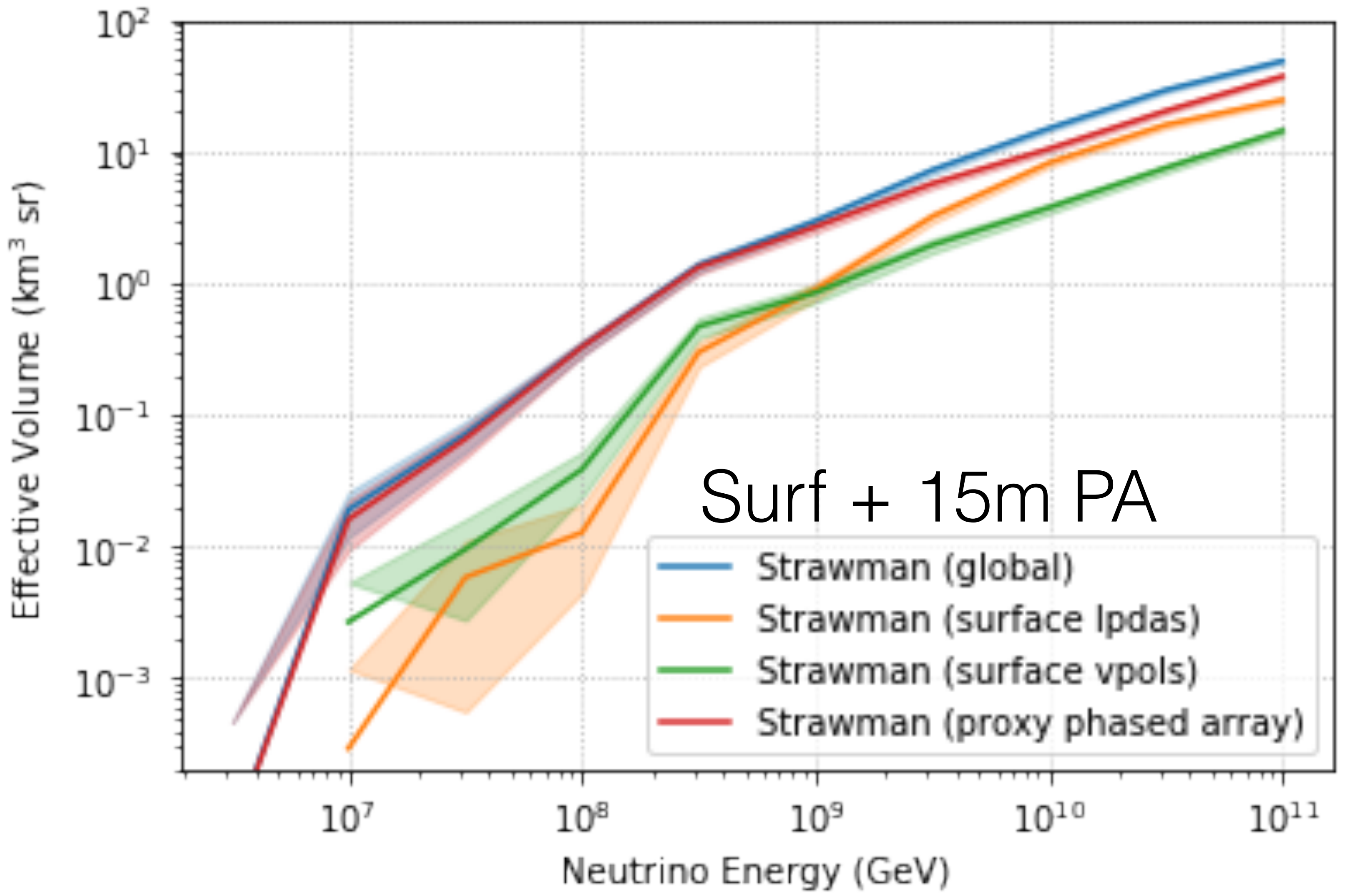
Phased Array Interferometry

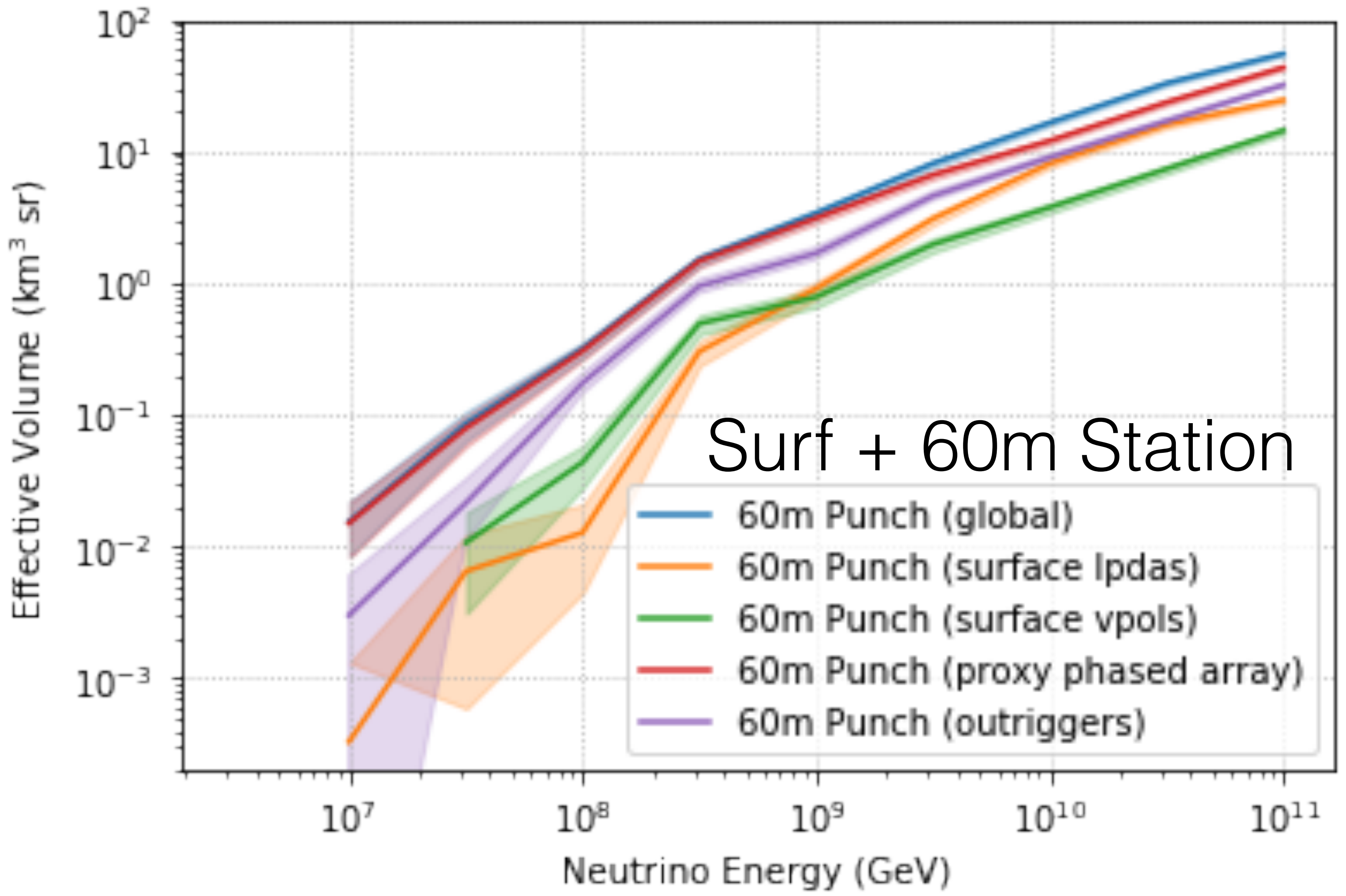


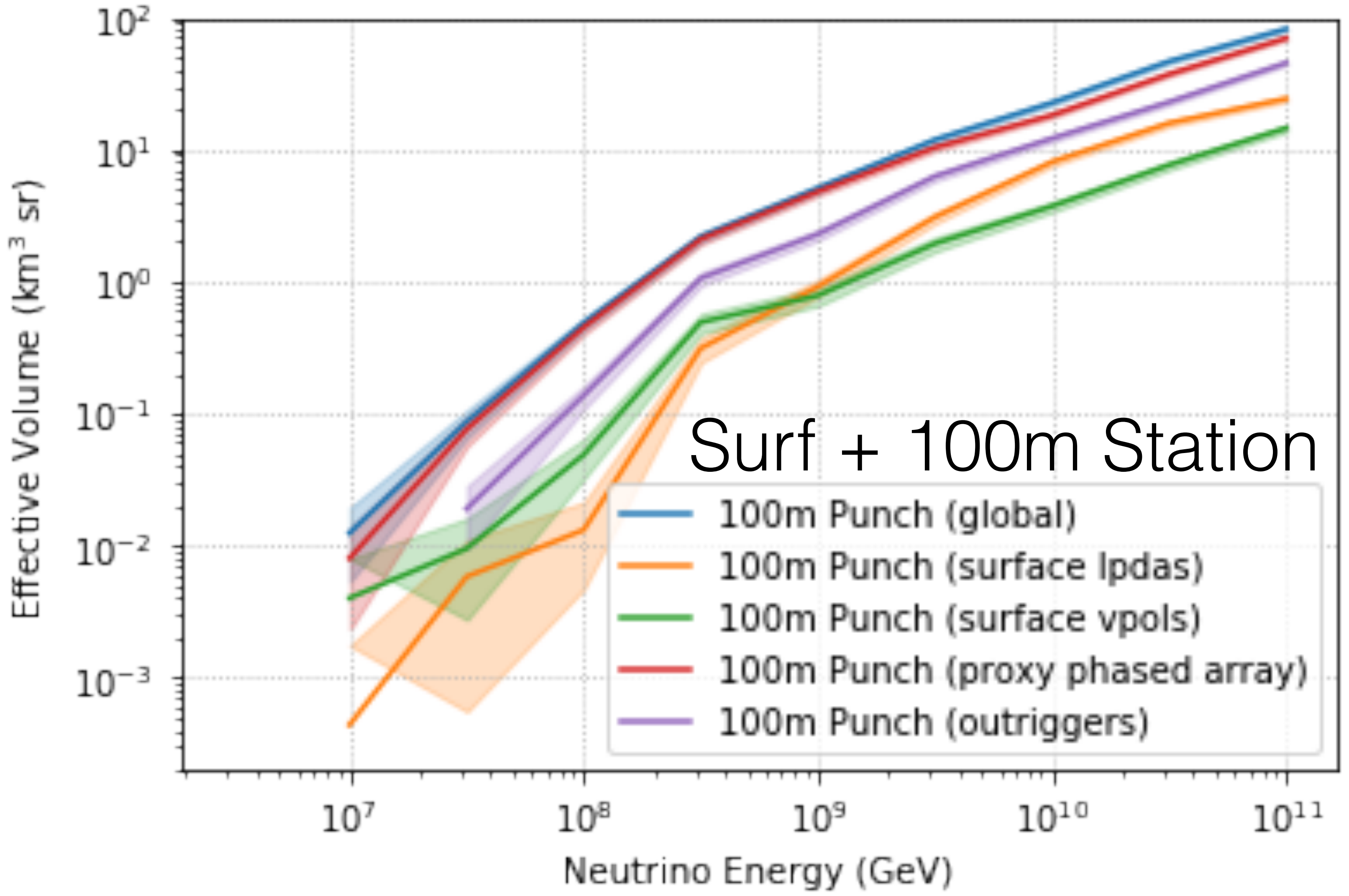




Effective Volume Components







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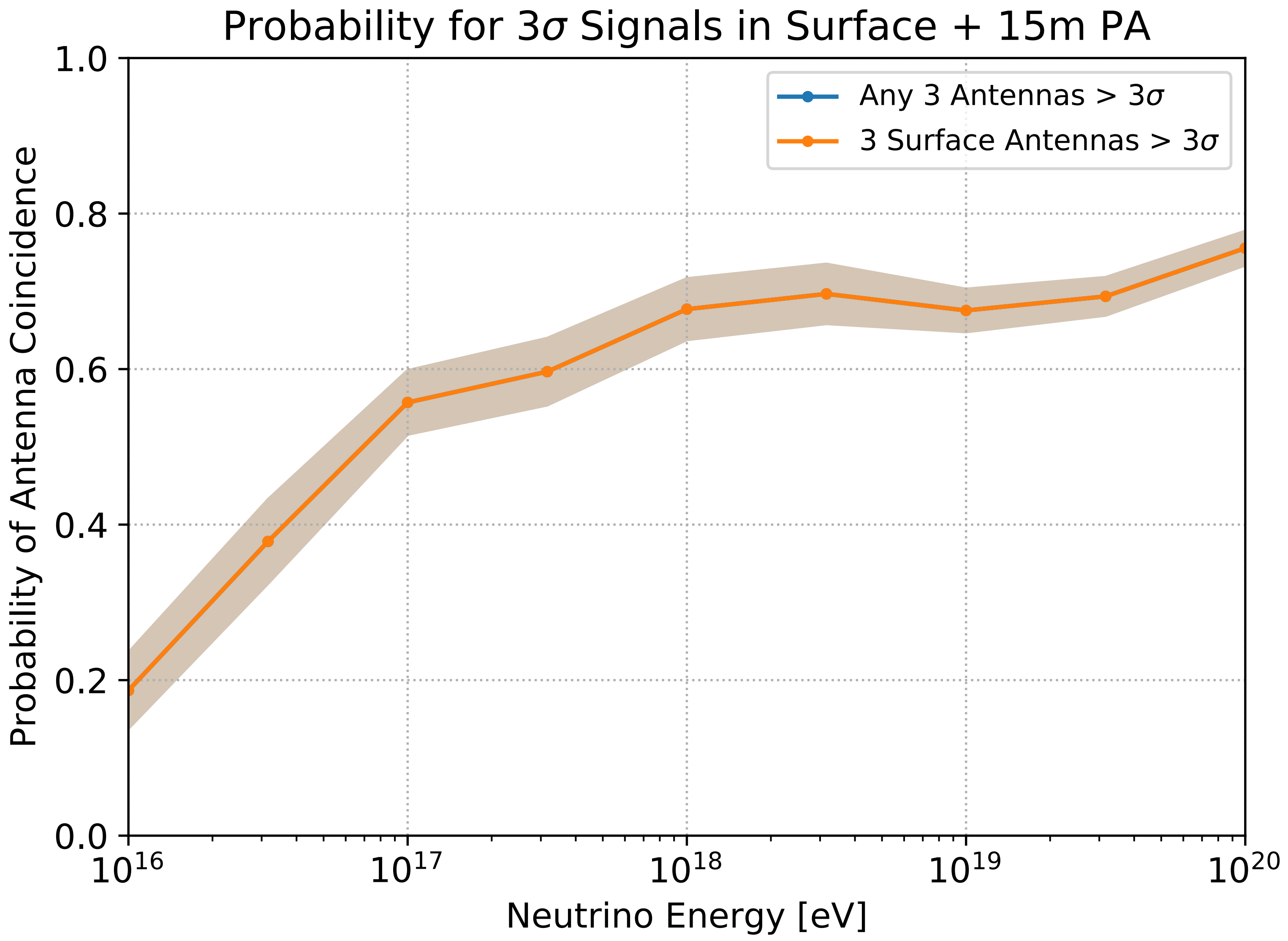
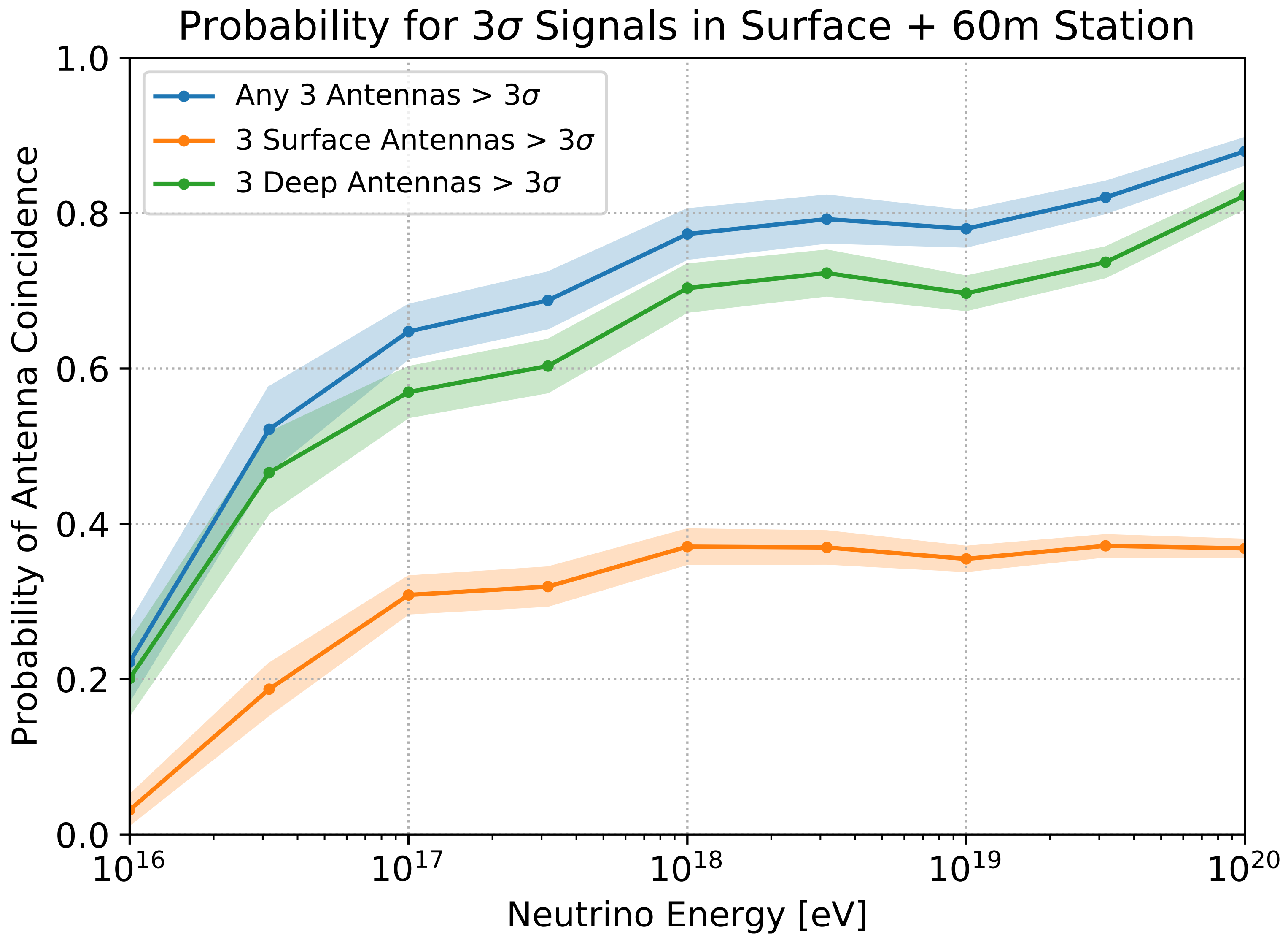
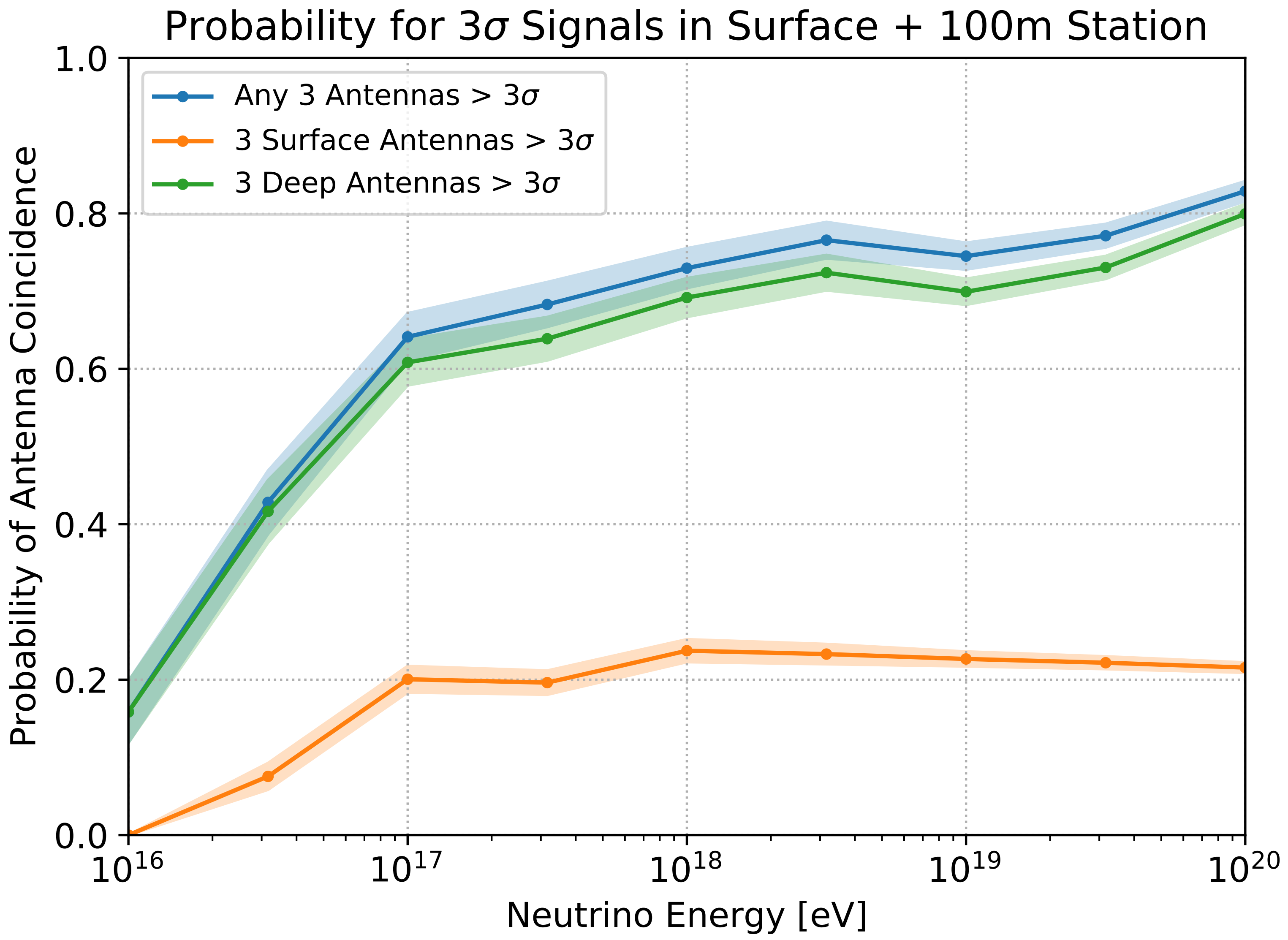
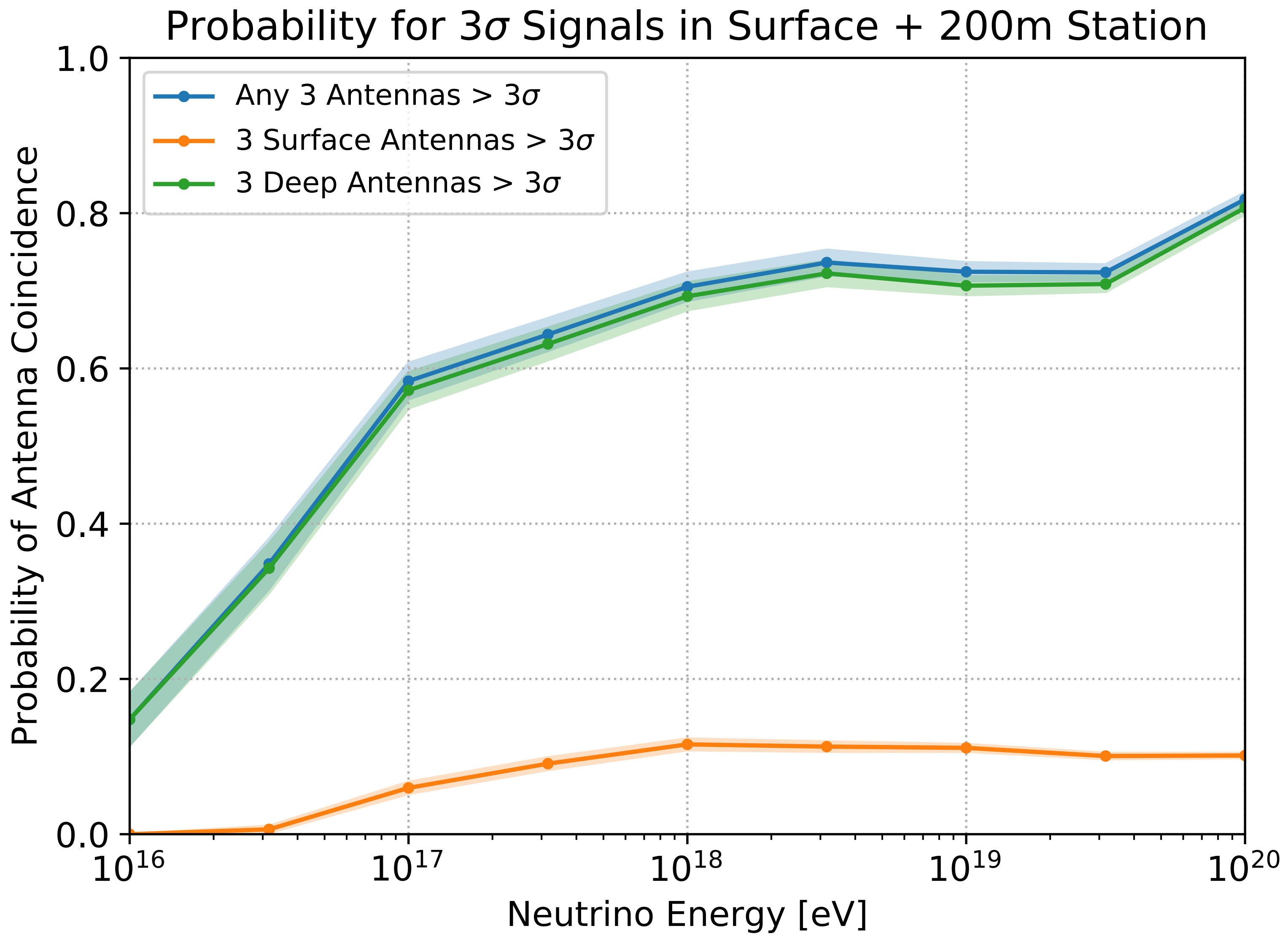








"Science Factor" Table

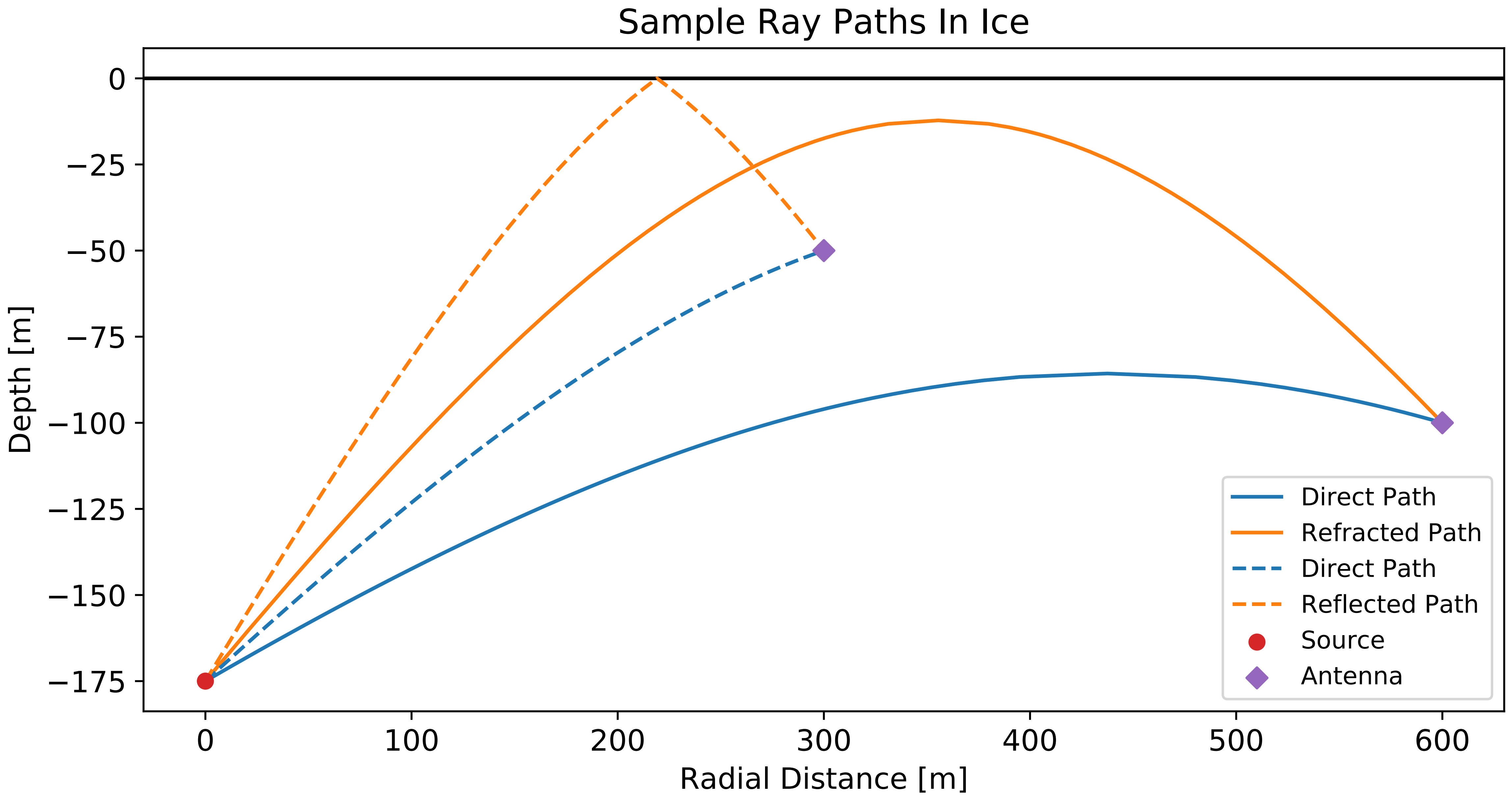
- Using approximate analysis-level effective volumes, we can produce a table that will summarize the relative effectiveness of each station
- To calculate the science factor, take the average of the approximate analysis-level effective volume for the two key energies (1e16.5 eV and 1e18 eV)
  - Analysis-level effective volumes calculated by multiplying the trigger-level effective volumes by the probability of meeting the 3@3σ condition shown on the previous slide
- The science factor between two station designs A and B should tell you approximately how many of station B need to be built to detect the same number of neutrinos as a single station A

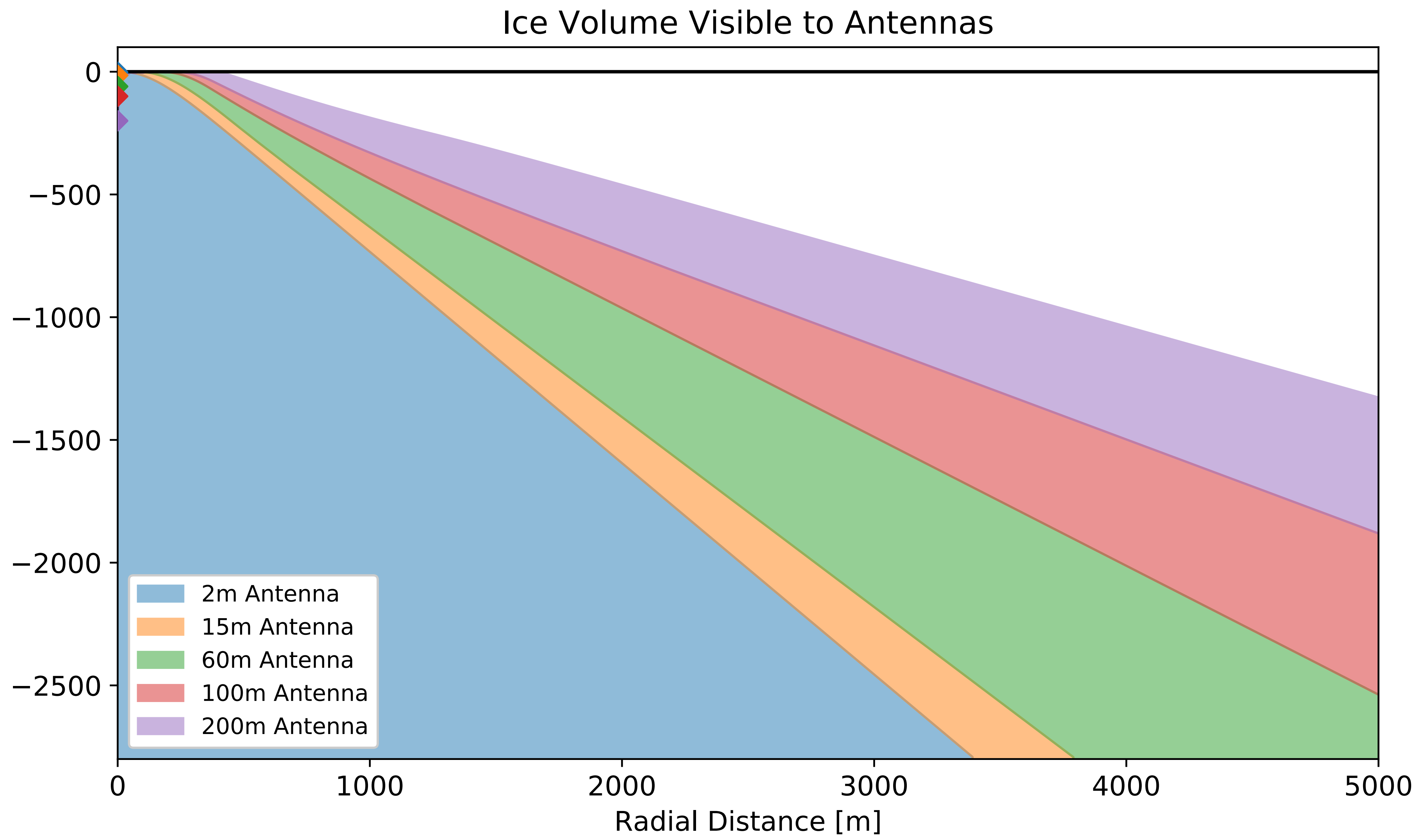
“Science Factor” Table

	Surface Only	Surface + 15m PA	Surface + 60m Station	Surface + 100m Station	Surface + 200m Station
Surface Only	1	2.00	4.54	6.18	7.21
Surface + 15m PA	0.50	1	2.27	3.09	3.61
Surface + 60m Station	0.22	0.44	1	1.31	1.64
Surface + 100m Station	0.16	0.32	0.76	1	1.13
Surface + 200m Station	0.14	0.28	0.61	0.88	1

Ray Bending in Shallow Ice

- Rapidly changing index of refraction of the shallow ice results in curved paths from a signal source in the ice to an antenna
- The curved paths and reflections off the surface allow for two possible paths from a source position to each antenna
- The curved paths also lead to a limit in the field of view of each antenna, beyond which source signals cannot reach the antenna





Effective Volumes

- For easier comparison, can consider effective volumes (at trigger level) at a couple key energies:
  - 1e16.5 eV, where the RNO goal is to overlap the IceCube sensitivity
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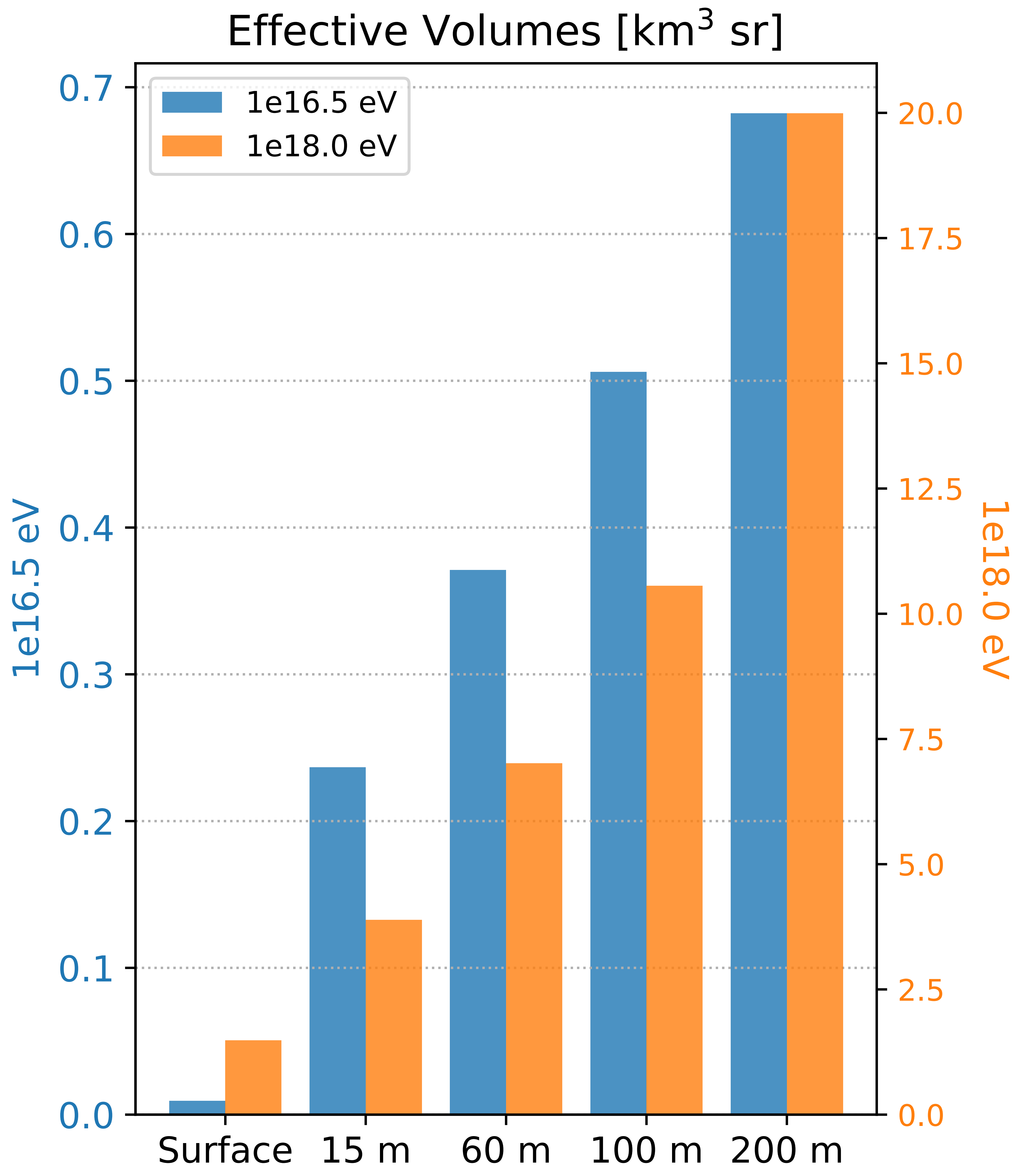
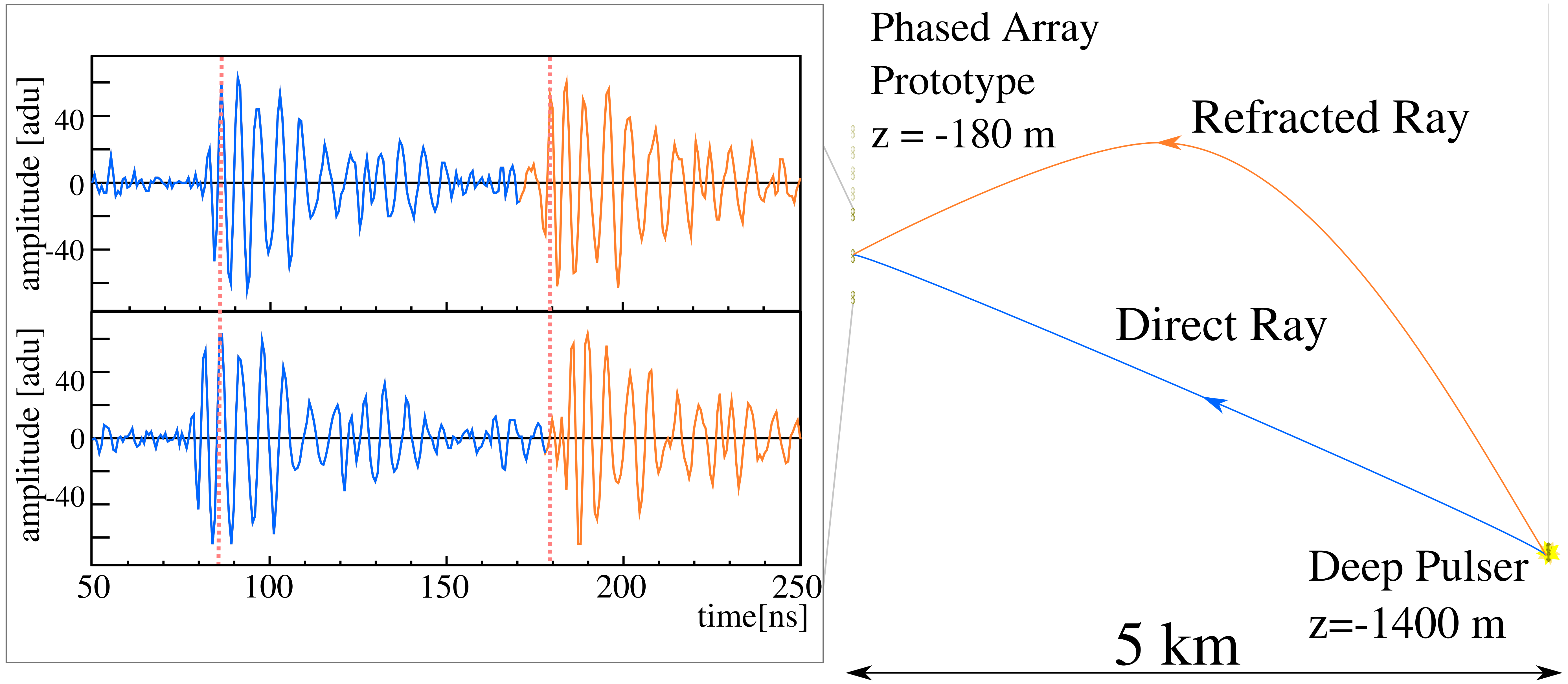
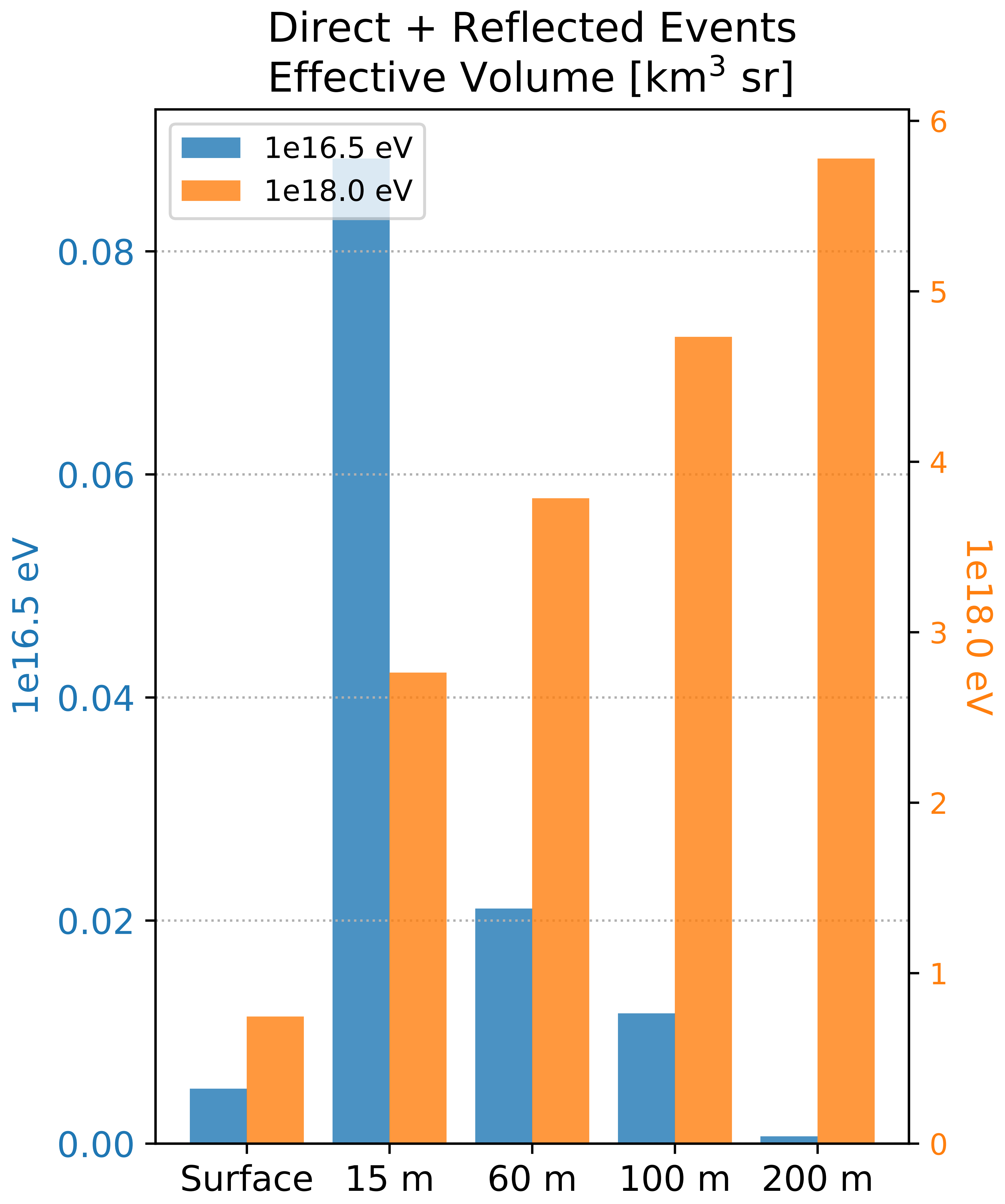
- Effective volumes shown here on separate linear axes to show the behavior of both energies together



Double Pulse Event Fractions

- Events which have signal power received along both the direct and reflected paths are “golden” events
- The double-pulse signal structure makes events much easier to reconstruct, improving the physics abilities of the detector





Surface Coincident Event Fractions

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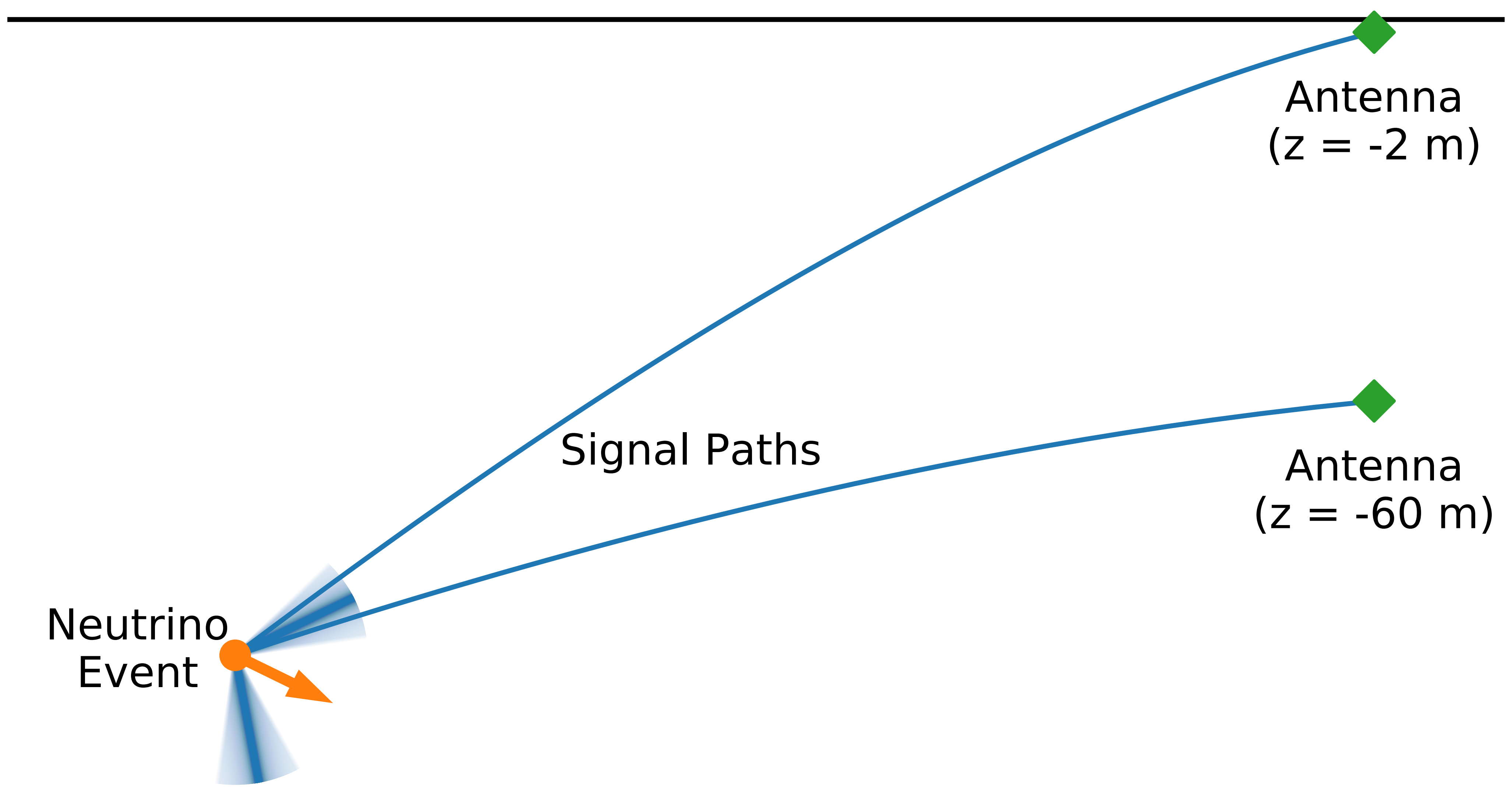
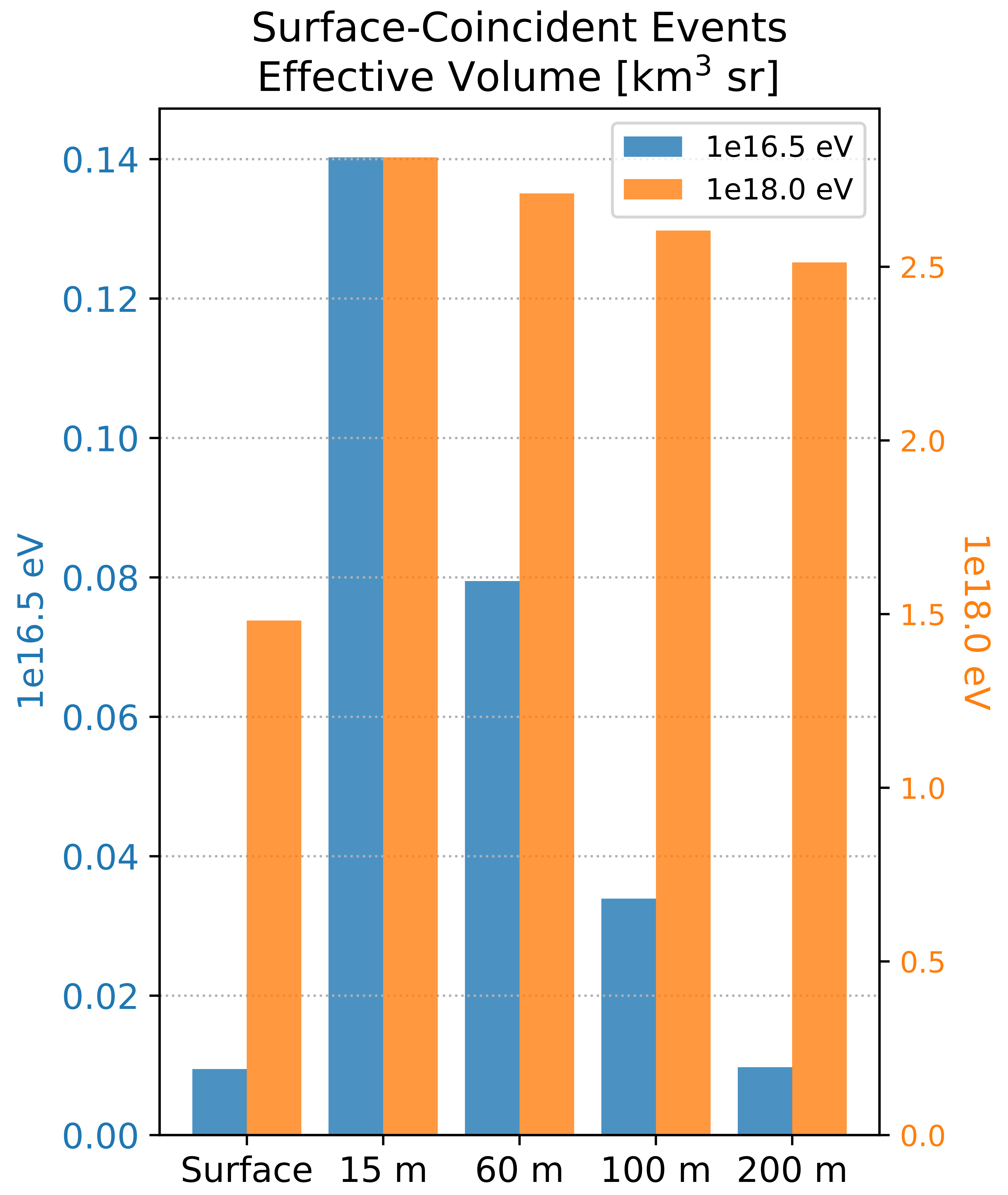
- Again, events with these signal signatures will improve the reconstruction capabilities of the detector





Sky Coverage

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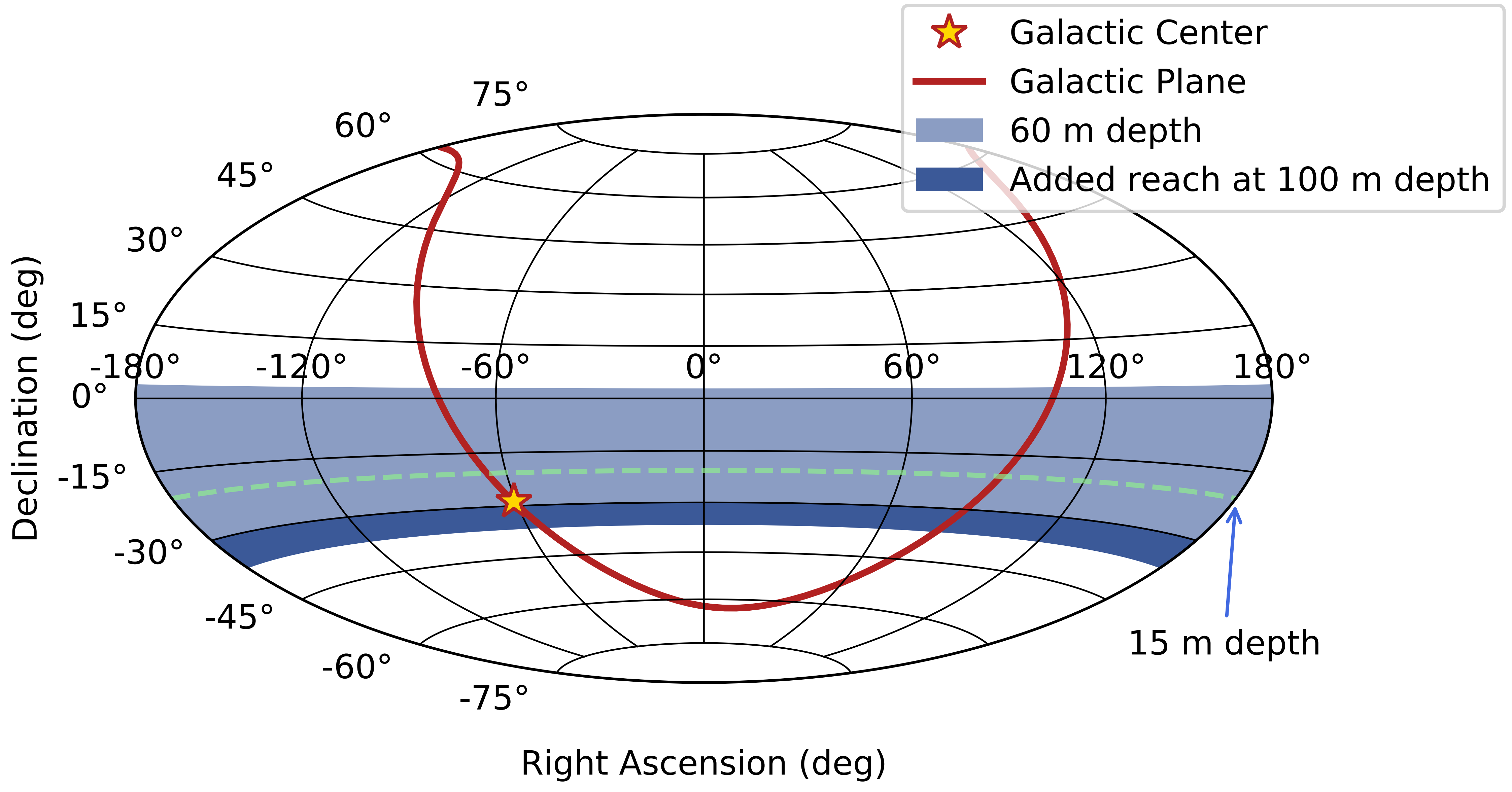
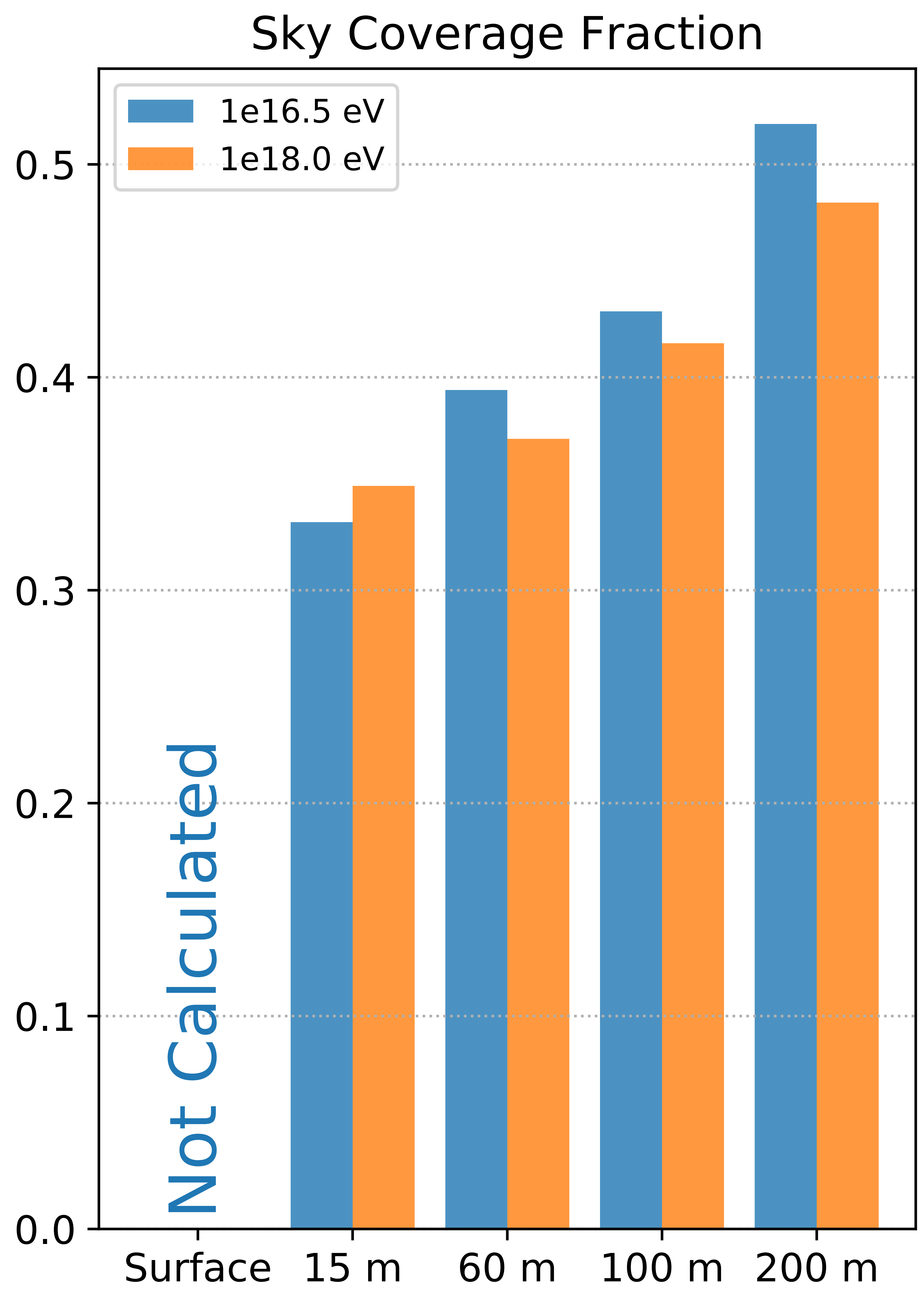
- Sky coverage fraction defined as the expected fraction of the whole sky that a station would see with at least 1% of the maximum exposure



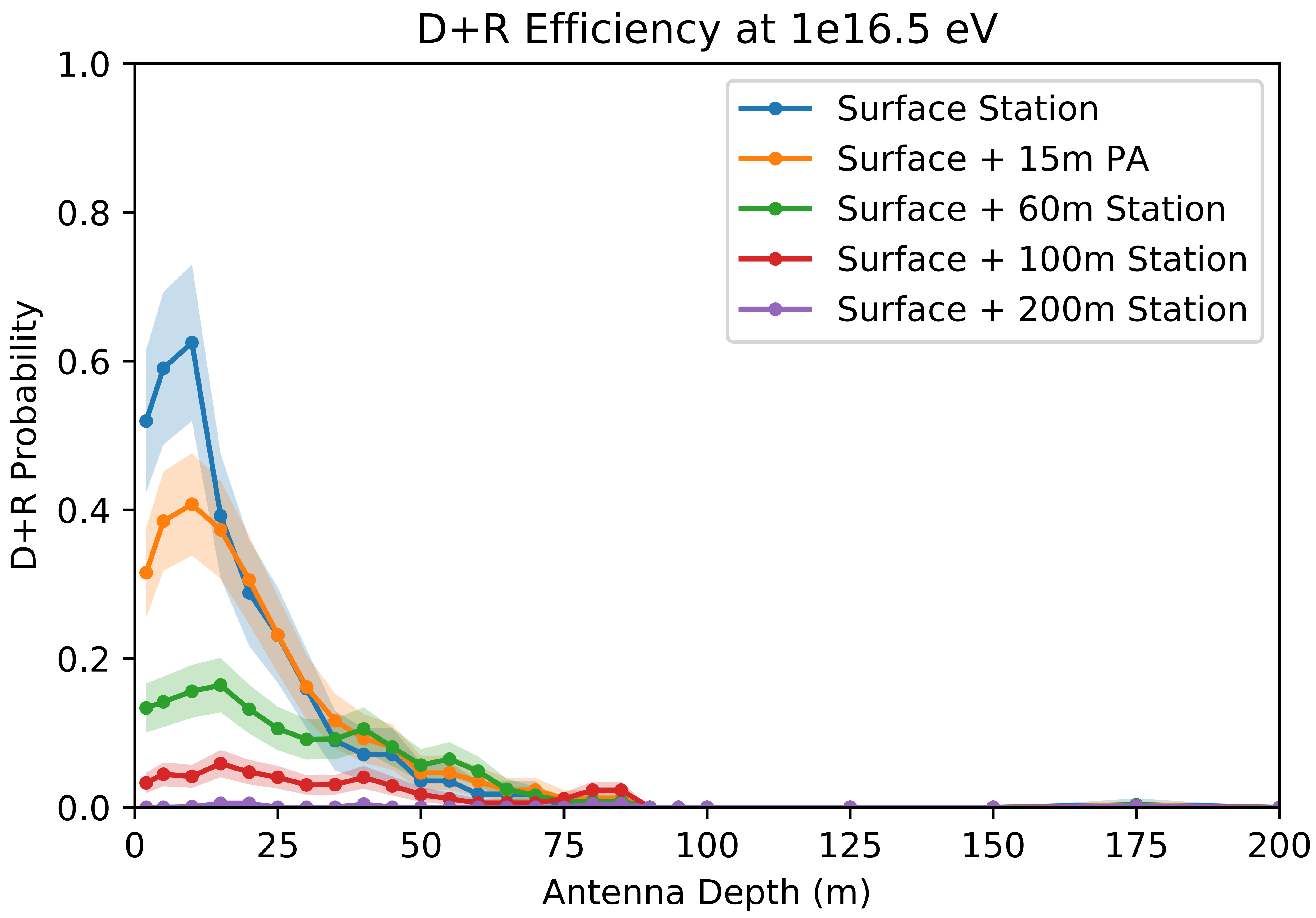


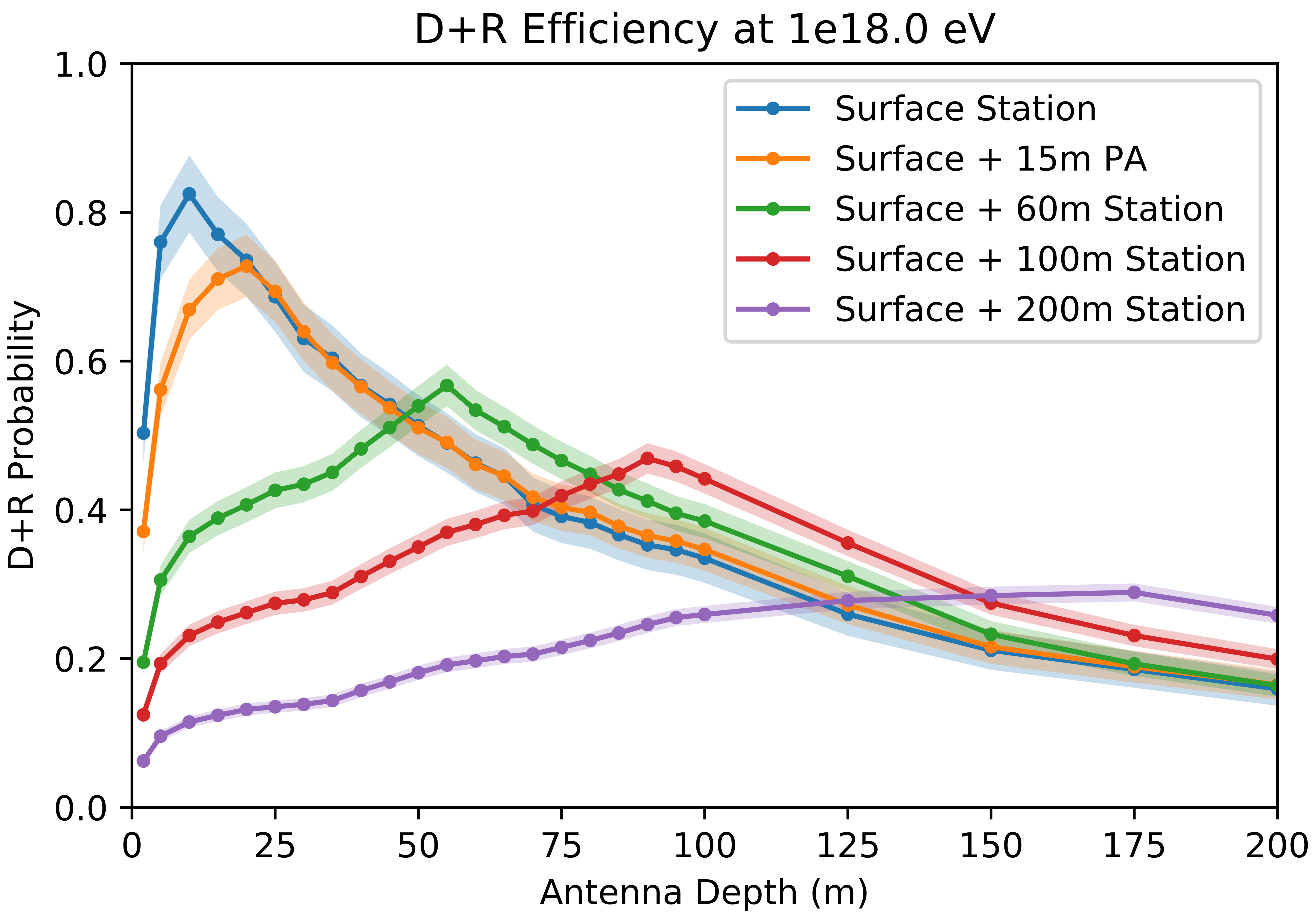
Direct + Reflected Event Fraction Method

- Simulate neutrino events with a fixed energy uniform in event vertex and direction, traveling to antenna at a given depth
  - 2 m deep antenna for surface-only, phased array depth for other stations
  - Antennas used were ARA bicones with a simplified front-end, producing a noise rms (σ) of 9.86 microvolts
- DnR event requires both direct and reflected signals above **1.5σ** and arrival time difference larger than **5 ns**
- Trigger condition requires a single signal above **1.5σ**
- Event fraction is the ratio of DnR events to triggered events
- To calculate effective volume of DnR events, multiply each event fraction by the corresponding effective volume

Double Pulse Event Fractions

- Explore the probability of an antenna at some depth receiving direct and reflected signals above **1.5σ** given a station trigger (phased array at 1.5σ)
- DnR event fraction will be the point on each curve at the phased array (or at the surface for surface-only station)



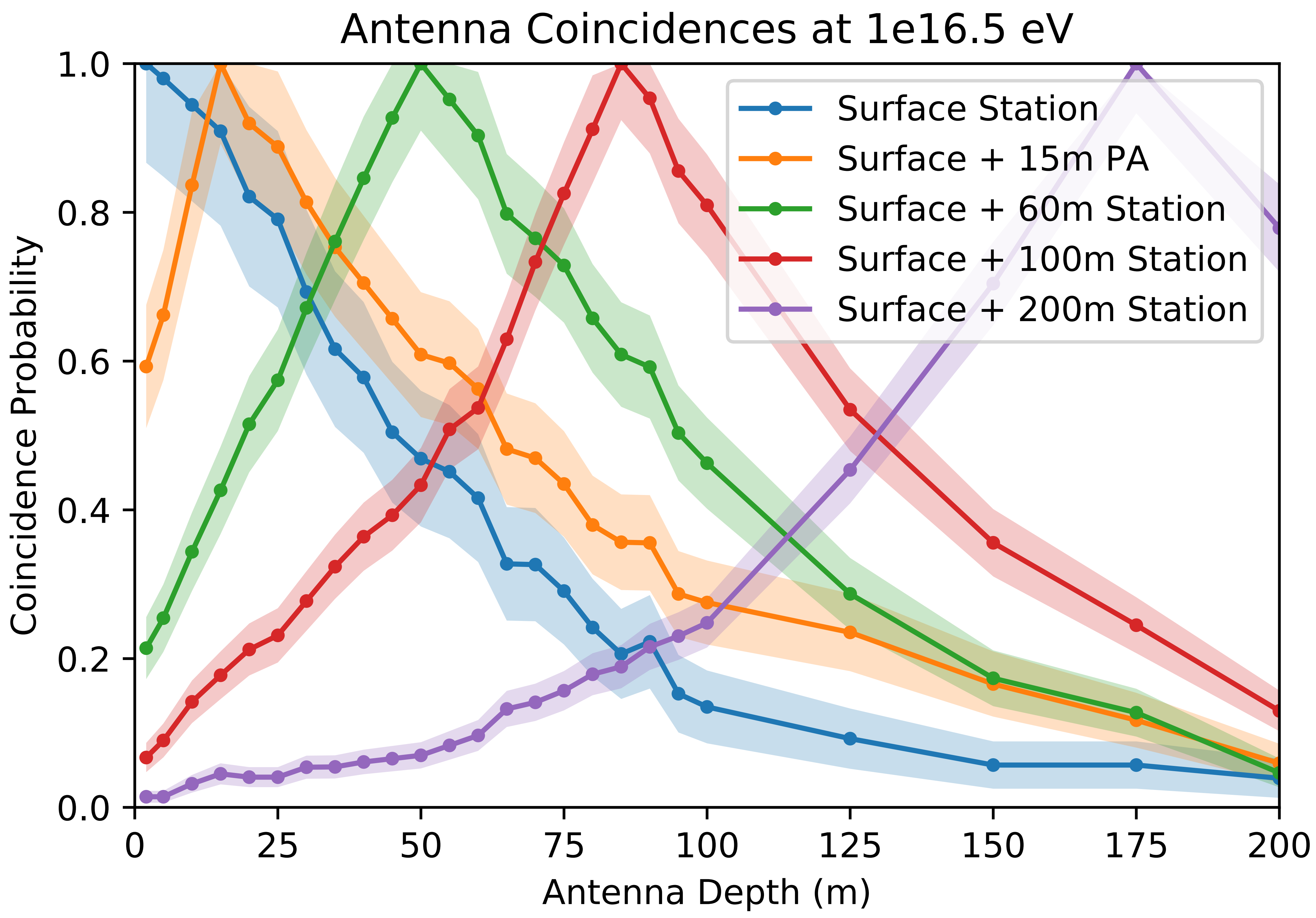


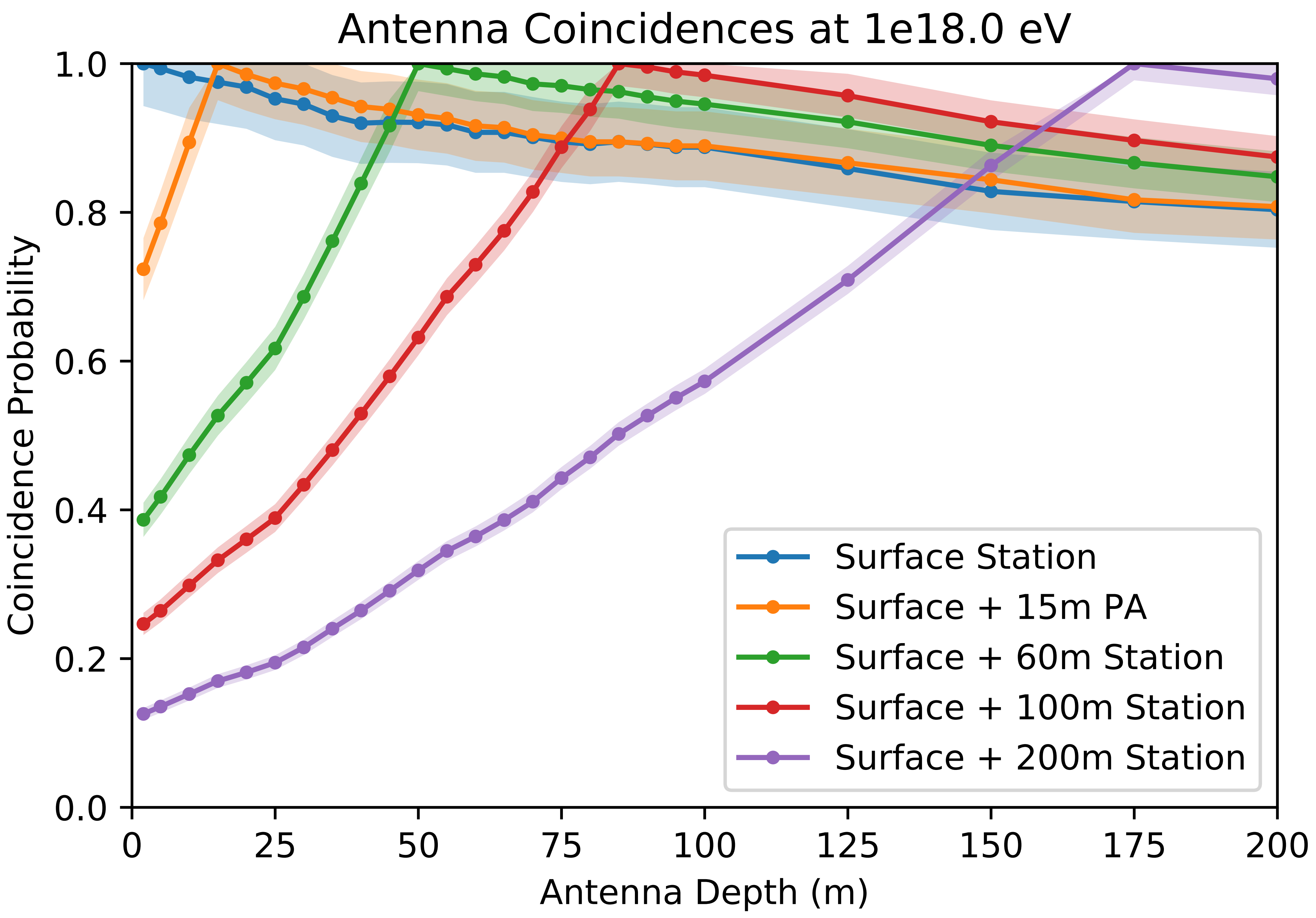
Surface-Coincident Event Fraction Method

- Simulate neutrino events with a fixed energy uniform in event vertex and direction, traveling to antennas at representative depths
  - 2 m deep antenna for surface + antenna at phased array depth
  - Antennas used were ARA bicones with a simplified front-end, producing a noise rms (σ) of 9.86 microvolts
- Surface-coincident event requires triggering the phased array antenna at **1.5σ** and a signal in the surface antenna at **1.5σ**
  - For surface-only station, trigger requirement in the surface antenna rather than phased array
- Trigger condition requires a signal in the phased array antenna above **1.5σ**
- Event fraction is the ratio of surface-coincident events to triggered events
- To calculate effective volume of surface-coincident events, multiply each event fraction by the corresponding effective volume

Surface-Coincident Event Fractions

- Explore the probability of an antenna at some depth receiving a signal above **1.5σ** given a station trigger (phased array at 1.5σ)
- Surface coincidence probability will be the value of the leftmost point on each curve

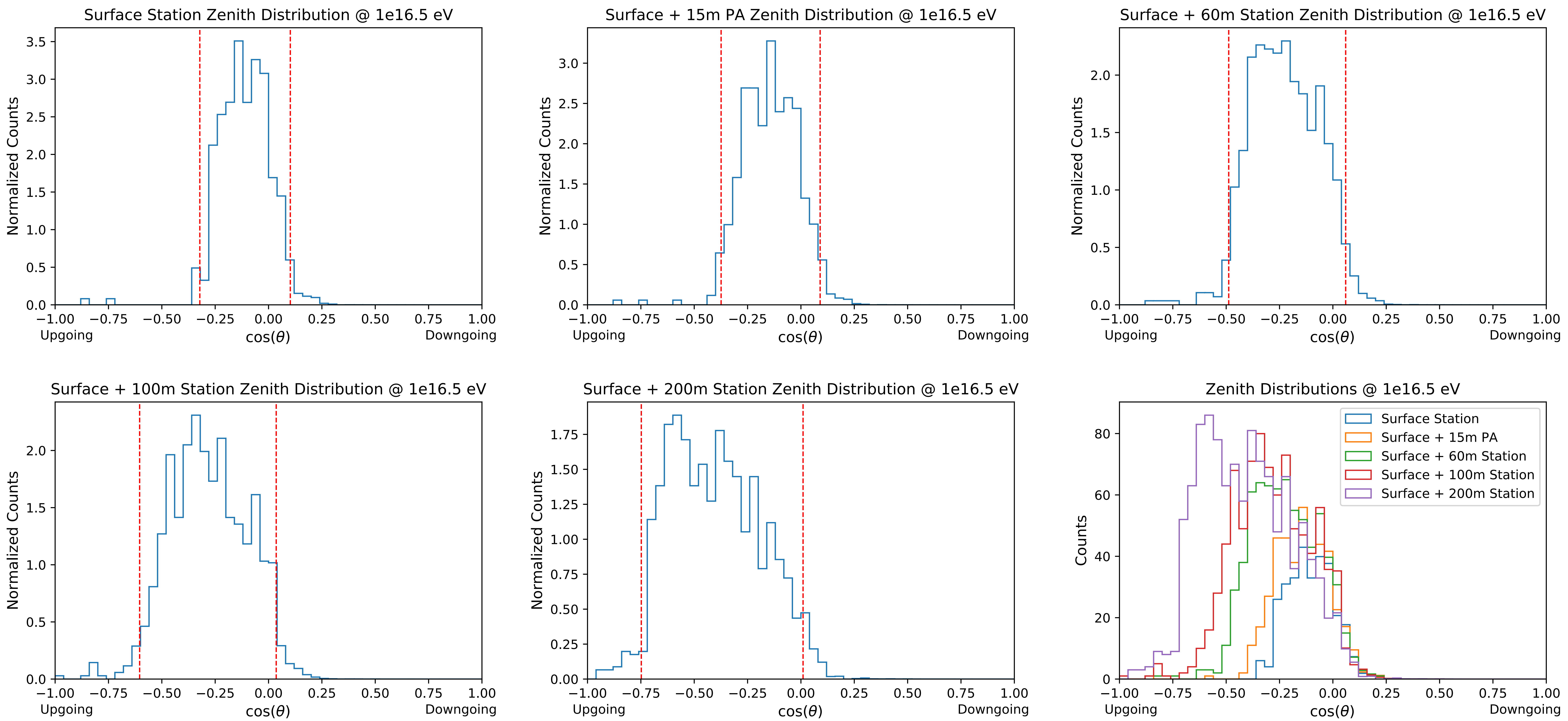




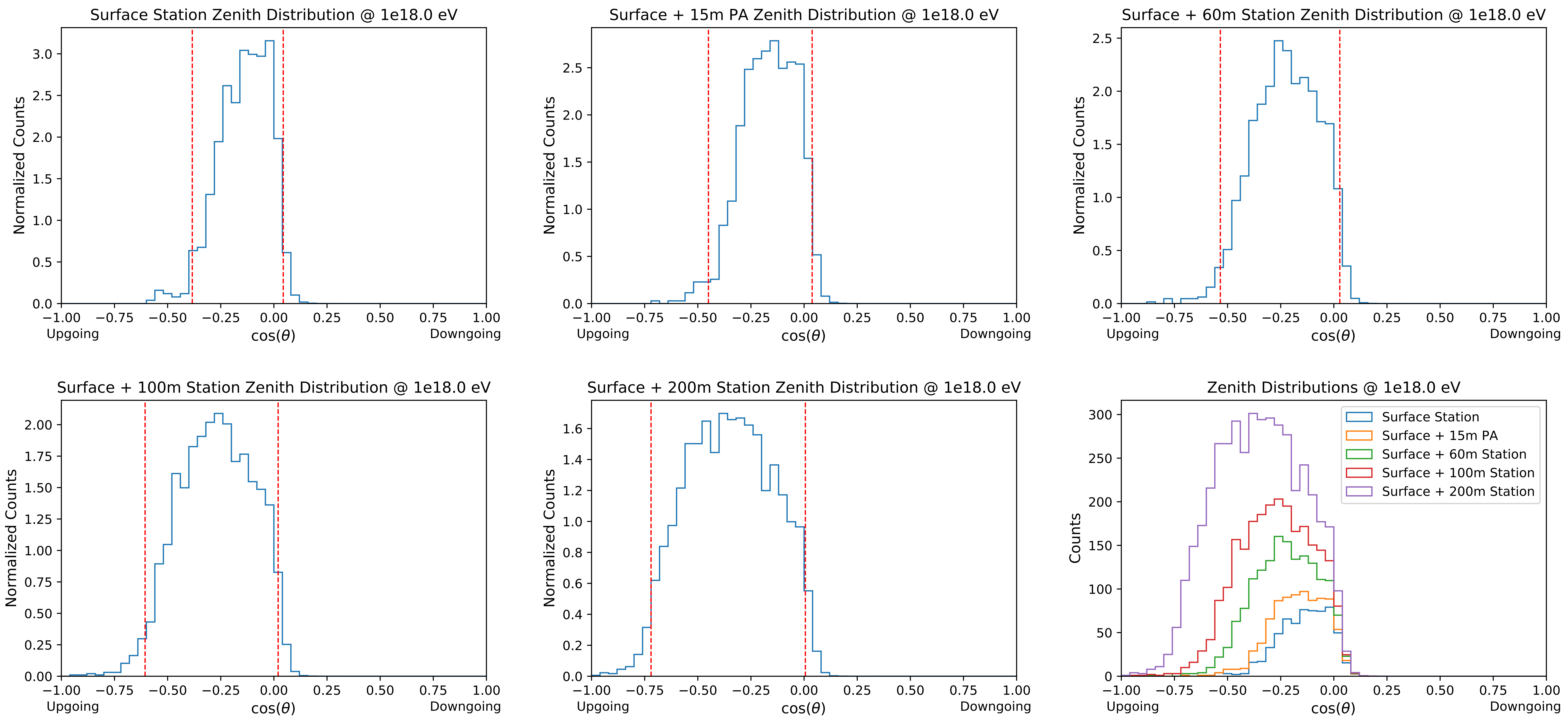
Sky Coverage Fraction Method

- Simulate neutrino events with a fixed energy uniform in event vertex and direction, traveling to antennas at representative depths
  - 2 m deep antenna for surface + antenna at phased array depth
  - Antennas used were ARA bicones with a simplified front-end, producing a noise rms (σ) of 9.86 microvolts
- Trigger condition requires a signal in the phased array antenna above **1.5σ**
- Determine the minimum and maximum zenith angles which achieve **95% containment** of the events (i.e. 2.5% above the maximum and 2.5% below the minimum)
  - Convert this zenith angle range into the visible solid angle of sky (assuming full azimuthal visibility)
  - Sky coverage fraction is the visible solid angle divided by 4π

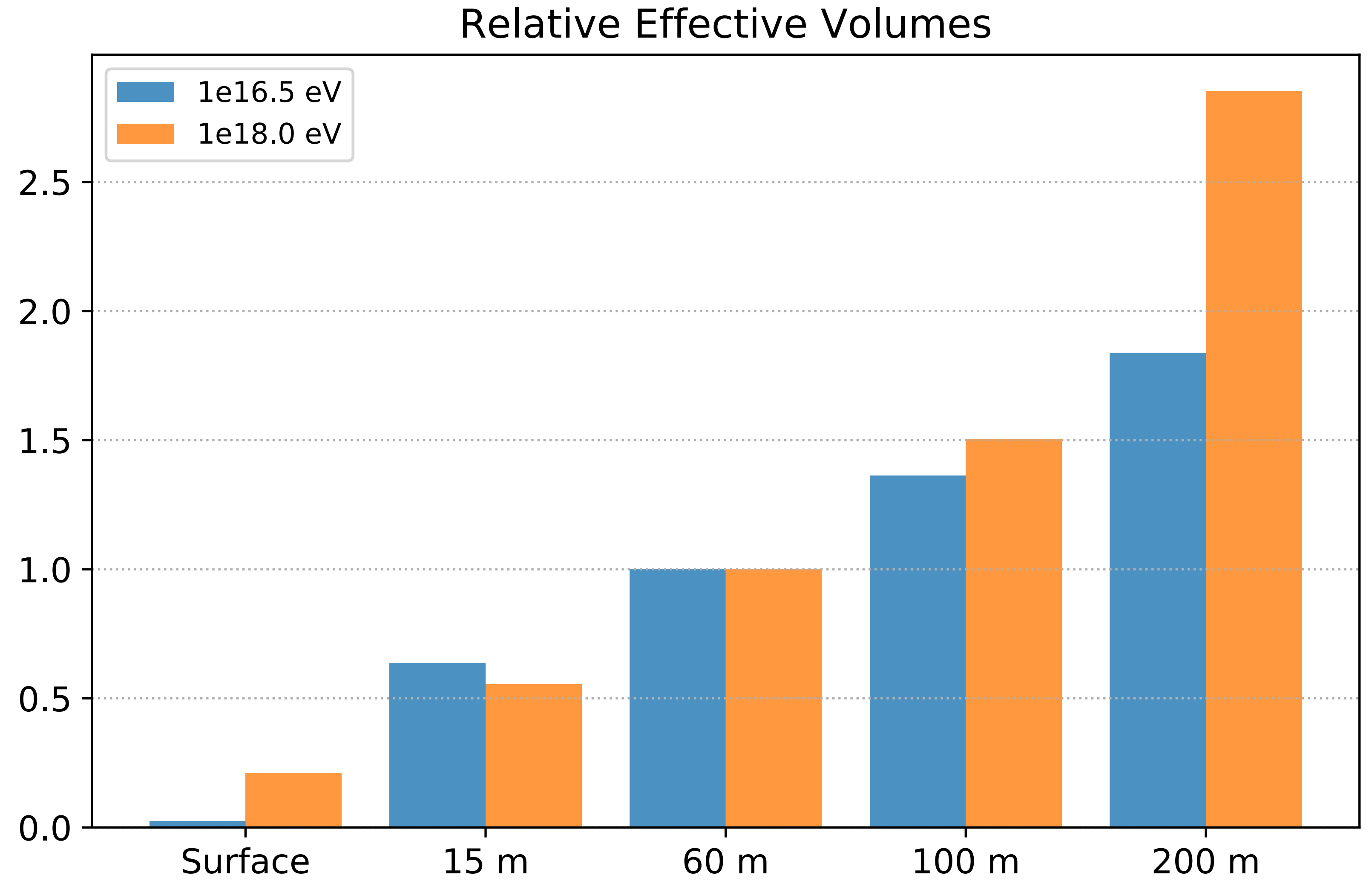
Sky Coverage Calculation Zenith Distributions

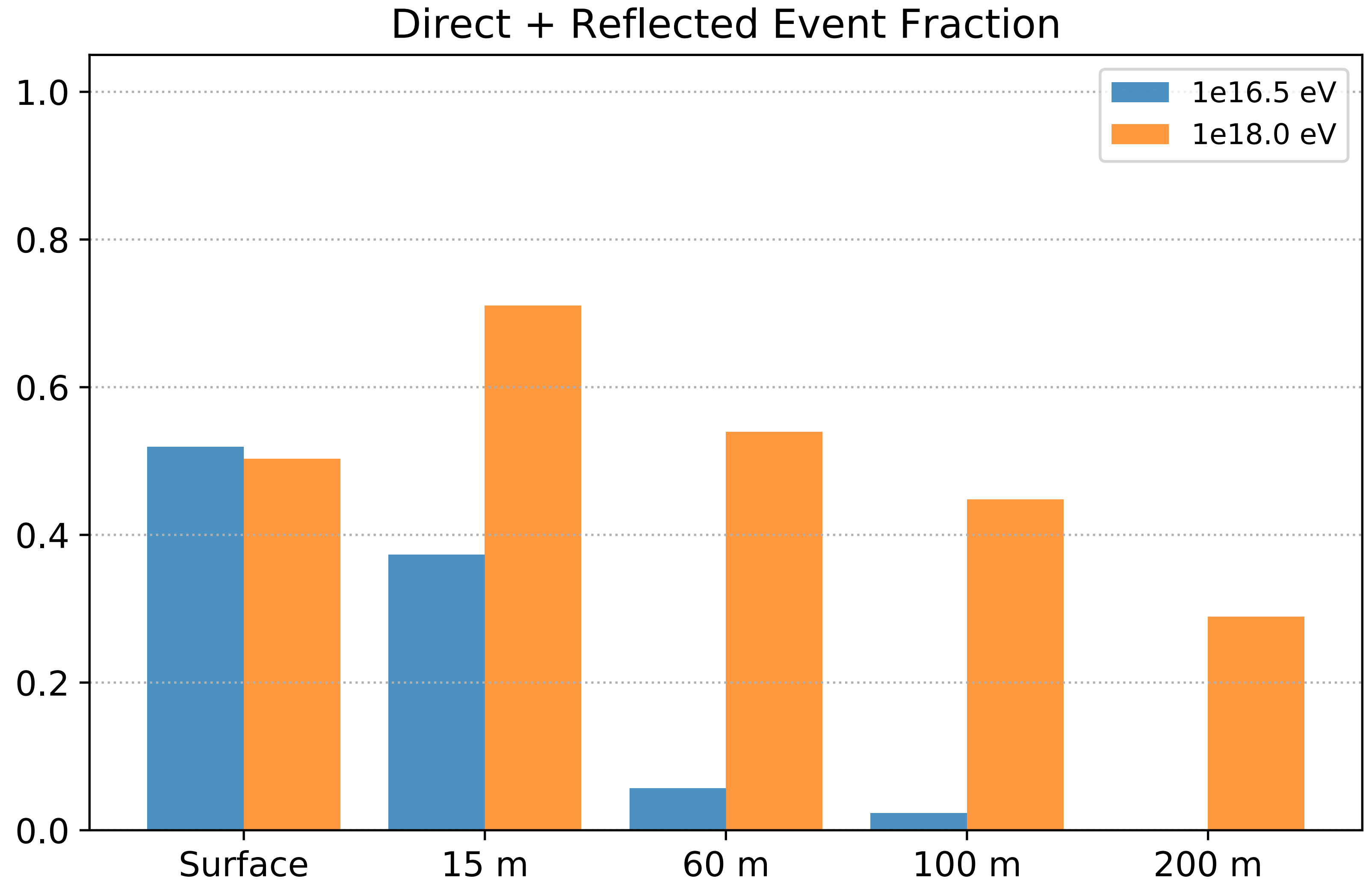


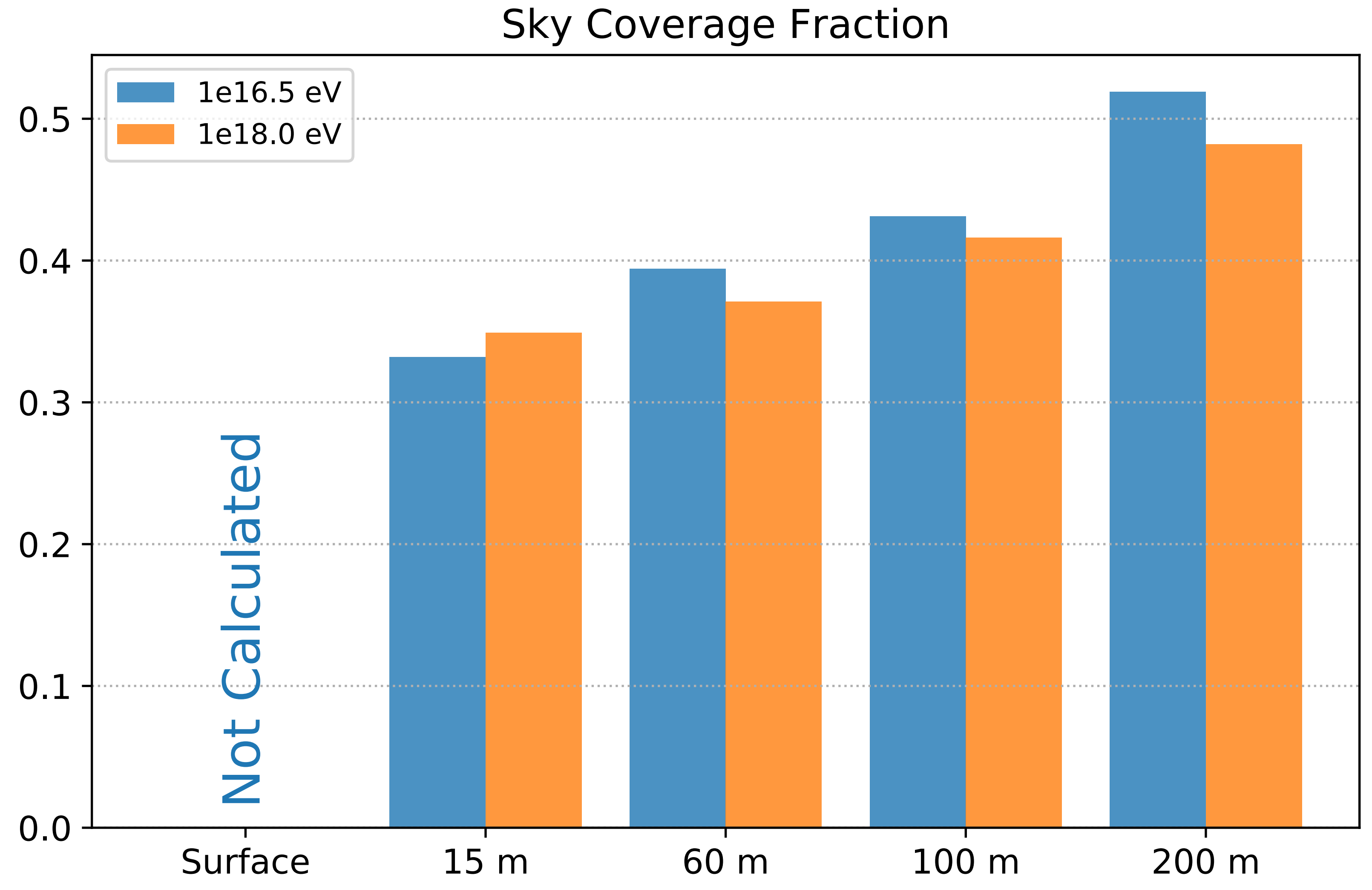
Sky Coverage Calculation Zenith Distributions

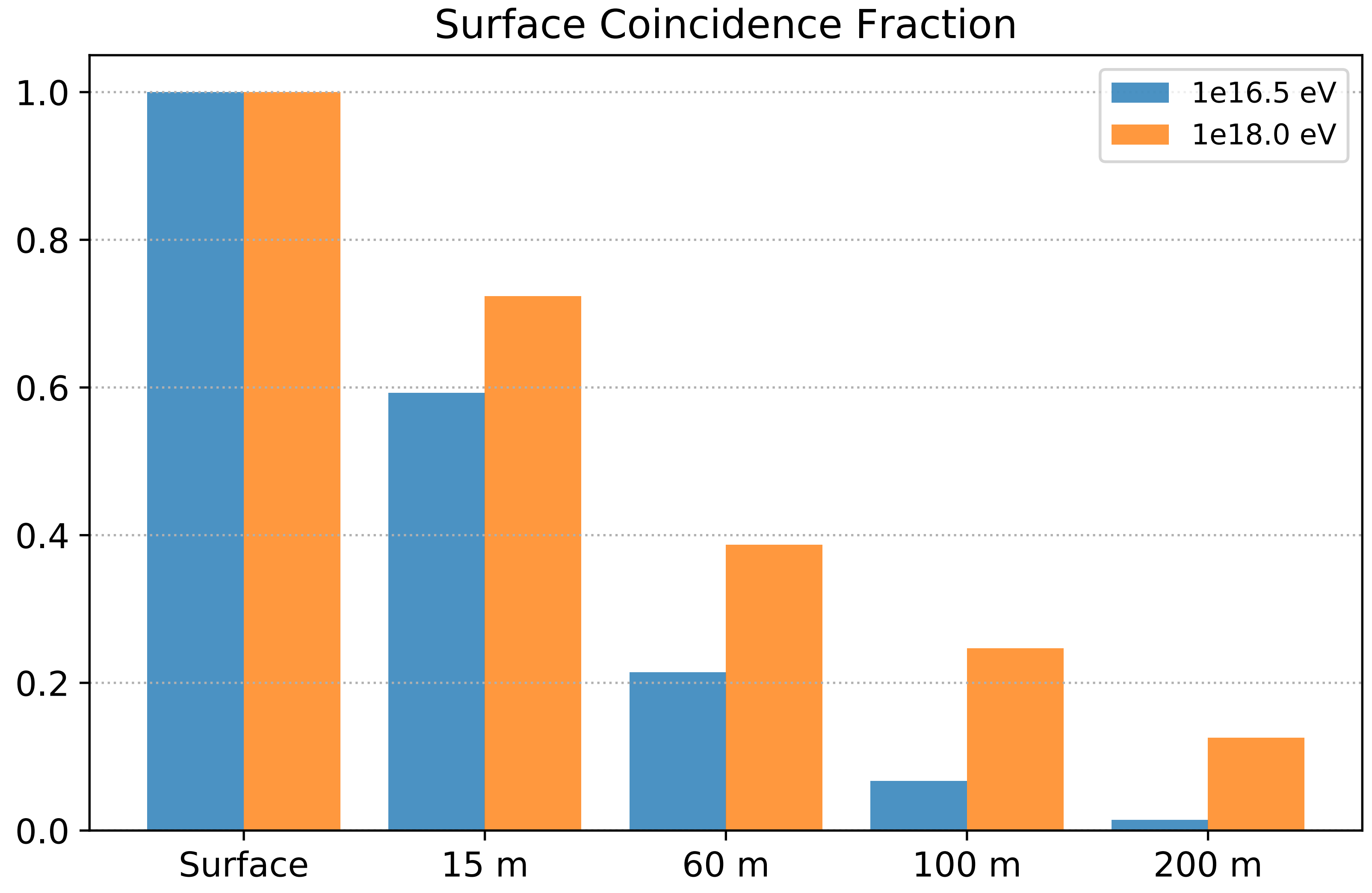


Summary of Design Studies









Design studies performed using PyREx version 1.8.1

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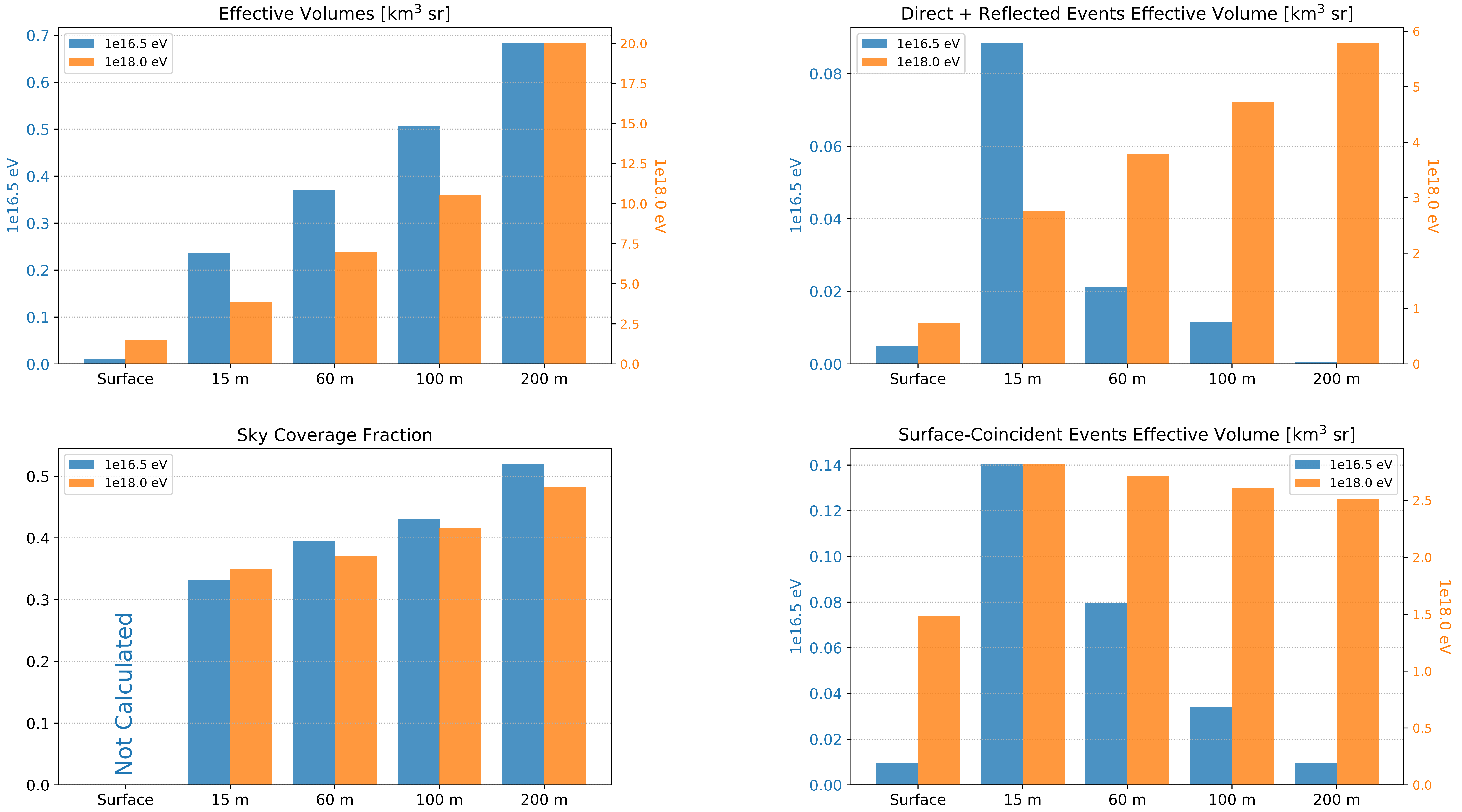
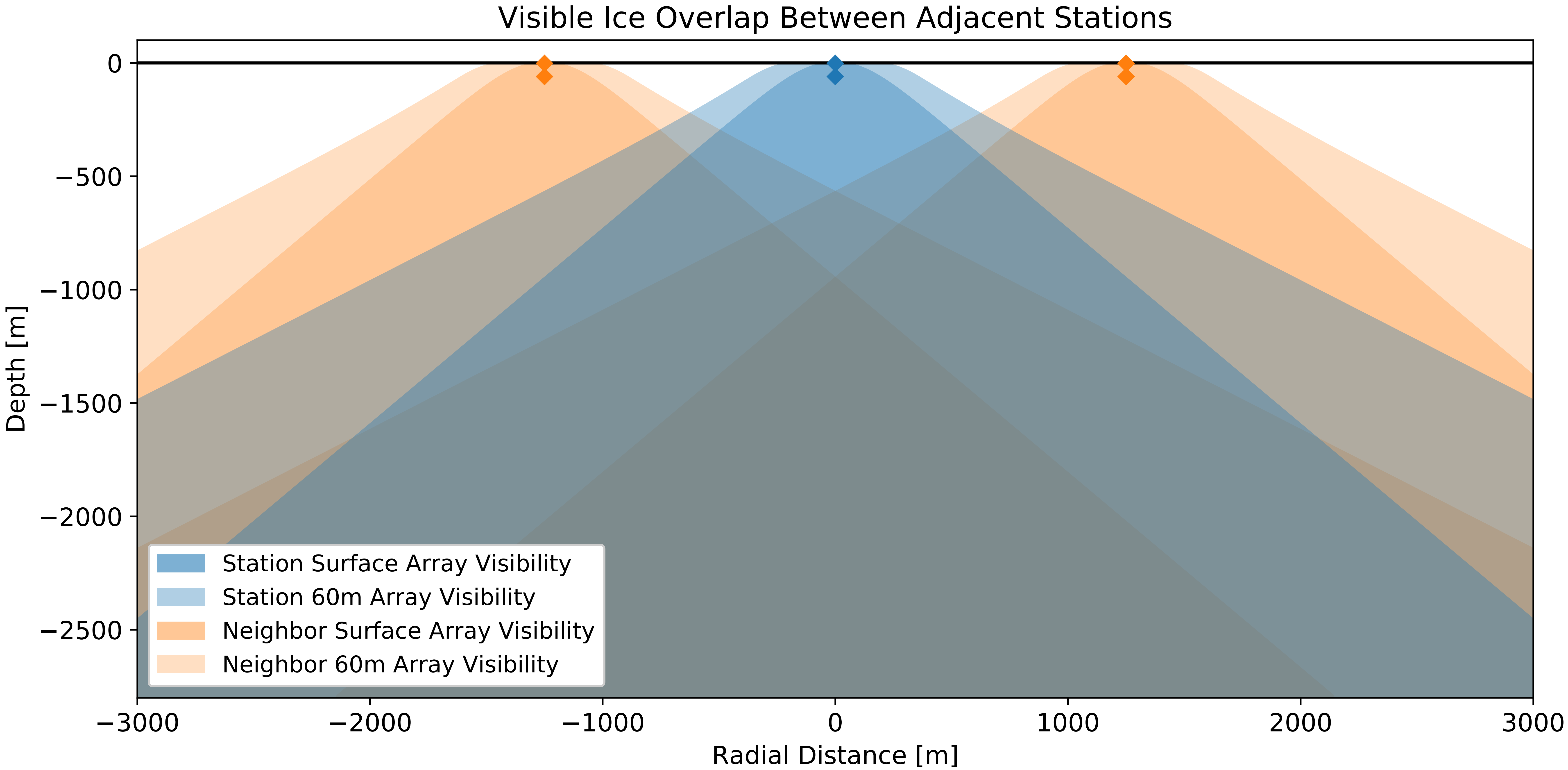


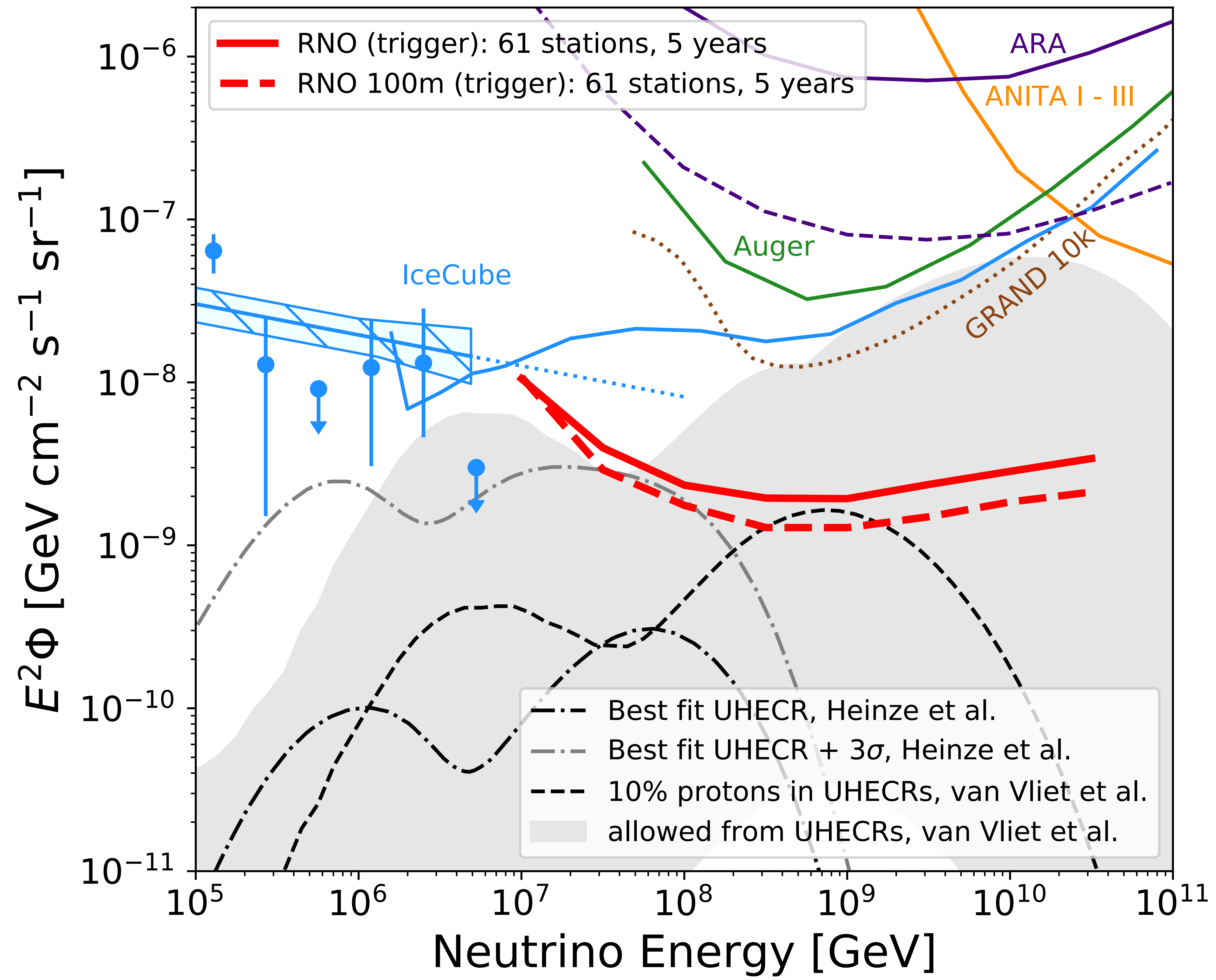
Design studies performed using PyREx version 1.8.1

Station Spacing

- A station spacing of around 1.25 km provides good ice coverage, reaching as far as possible while minimizing non-visible regions
- Event fraction seen by multiple stations is being explored

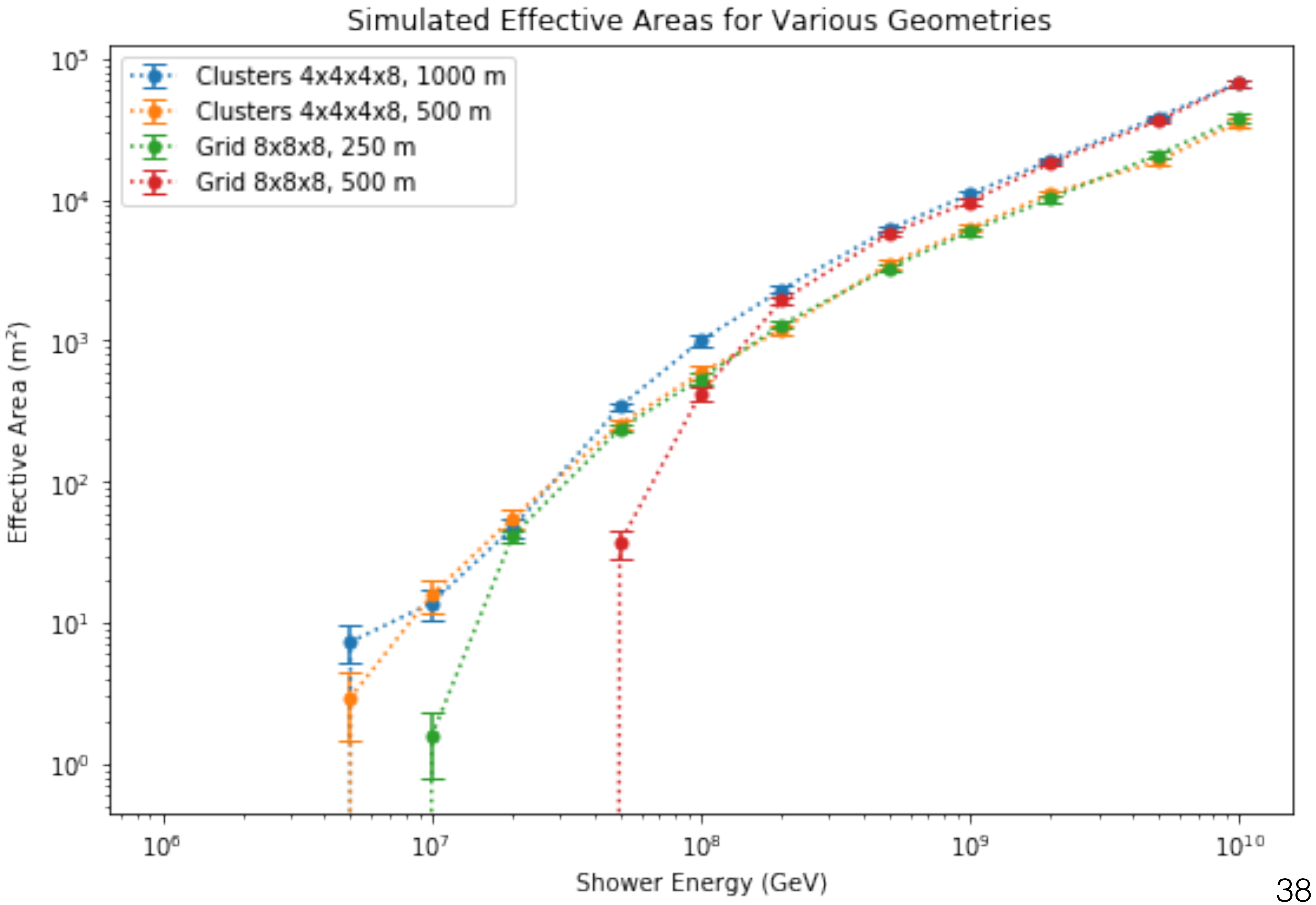


RNO Expected Sensitivity



Detector Geometries - Previous Study

- Explored the effective areas to compare the efficiencies of station geometries (like ARA) to string-grid geometries (like IceCube)
- Kept the number of strings and number of antennas constant between geometries
- The tested variations have 512 antennas, 64 strings, 8 antennas per string 10 m apart from -25 to -95 m
- Trigger condition requires 4 antenna triggers across 3 strings
- In the string grids the strings are spaced 250 and 500 m apart
- In the station ("cluster") geometries there are 4 strings per station with a diameter of 50 m, with stations spaced 500 and 1000 m apart



Detector Geometries - Previous Study

- Explored the effective areas to compare the efficiencies of station geometries (like ARA) to string-grid geometries (like IceCube)
- Kept the number of strings and number of antennas constant between geometries
- Grid geometries lose effective volume at low energies
- Station geometries have better low-energy effective areas due to the close spacing within the stations
- High-energy effective areas scale with the instrumented area