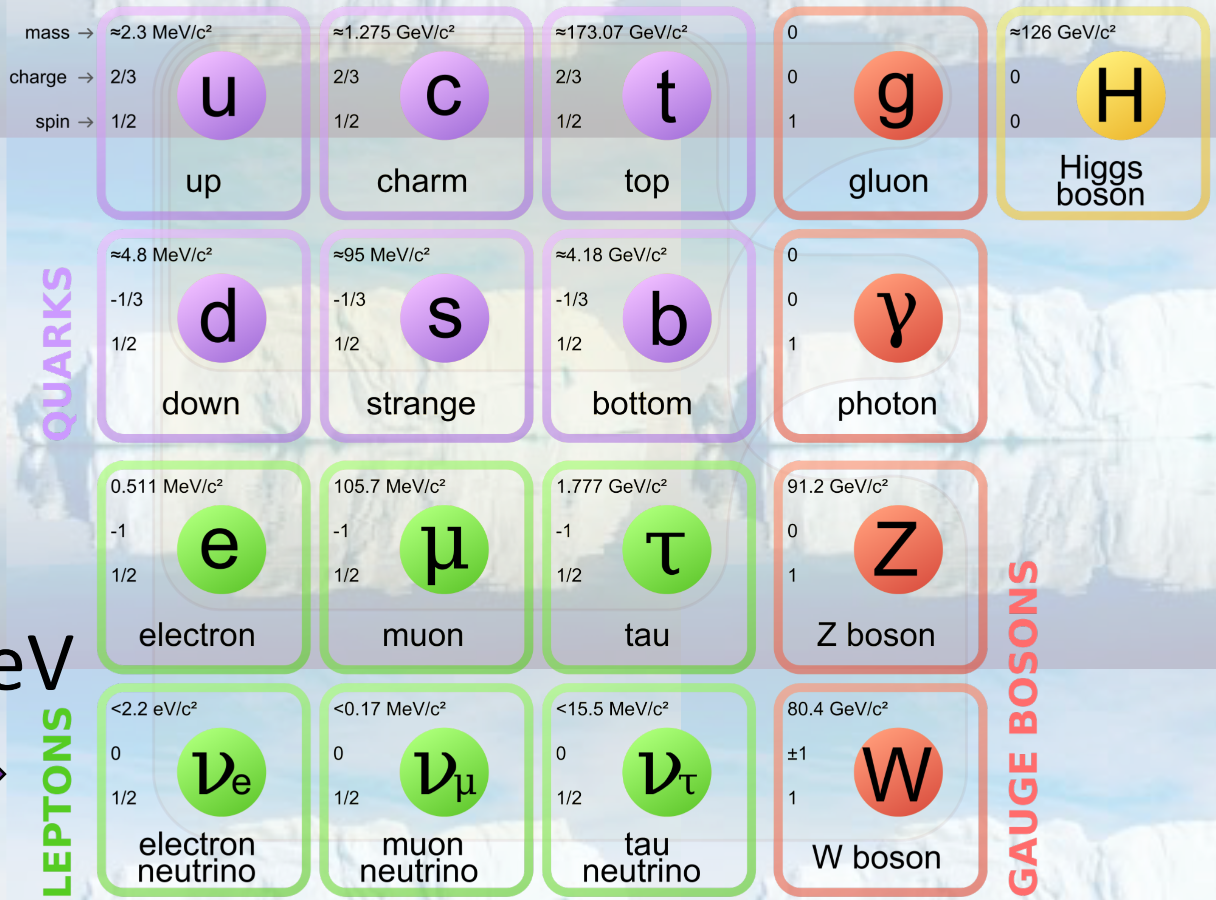
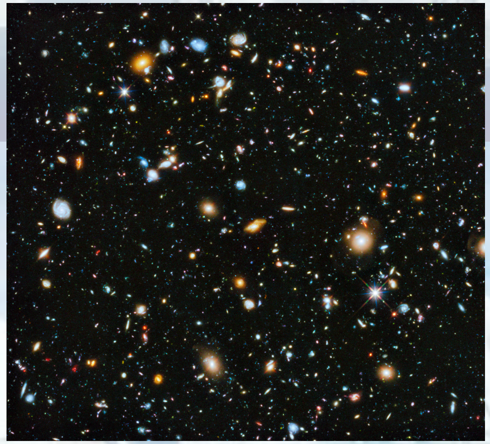
Ray Tracing in Radio Signal Detection of Neutrinos in Ice

SPOORTHI NAGASAMUDRAM

What are we looking for?

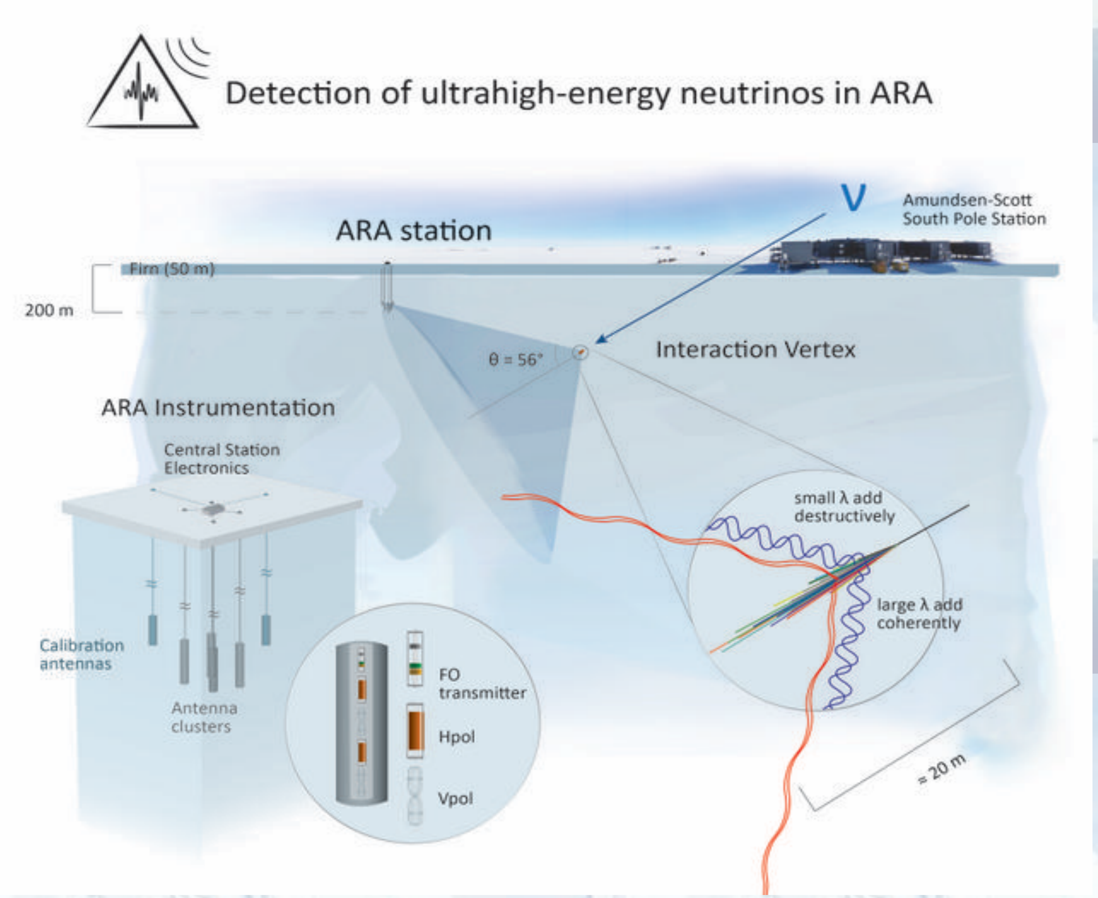
$10^{18} - 10^{22}$ eV





https://en.wikipedia.org/wiki/Hubble_Ultra-Deep_Field

Detection of UHE neutrinos



Depiction of neutrino detection by ARA
(https://ara.wipac.wisc.edu/home)

- Cherenkov Radiation
  Radiation from particles traveling faster than the speed of light in the medium

- Askaryan Effect
  Wavelengths larger than the radius of the shower are coherent in the medium

- Askaryan radiation in ice is radio waves

Motivation to use Antarctic ice

- Large attenuation length of ice
- Radio clear
- Ice volumes on the order of 100 km^3

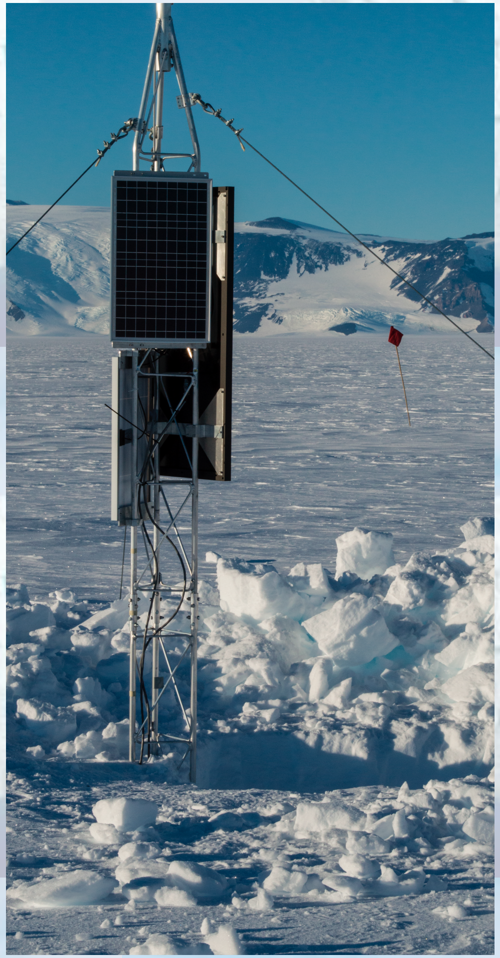
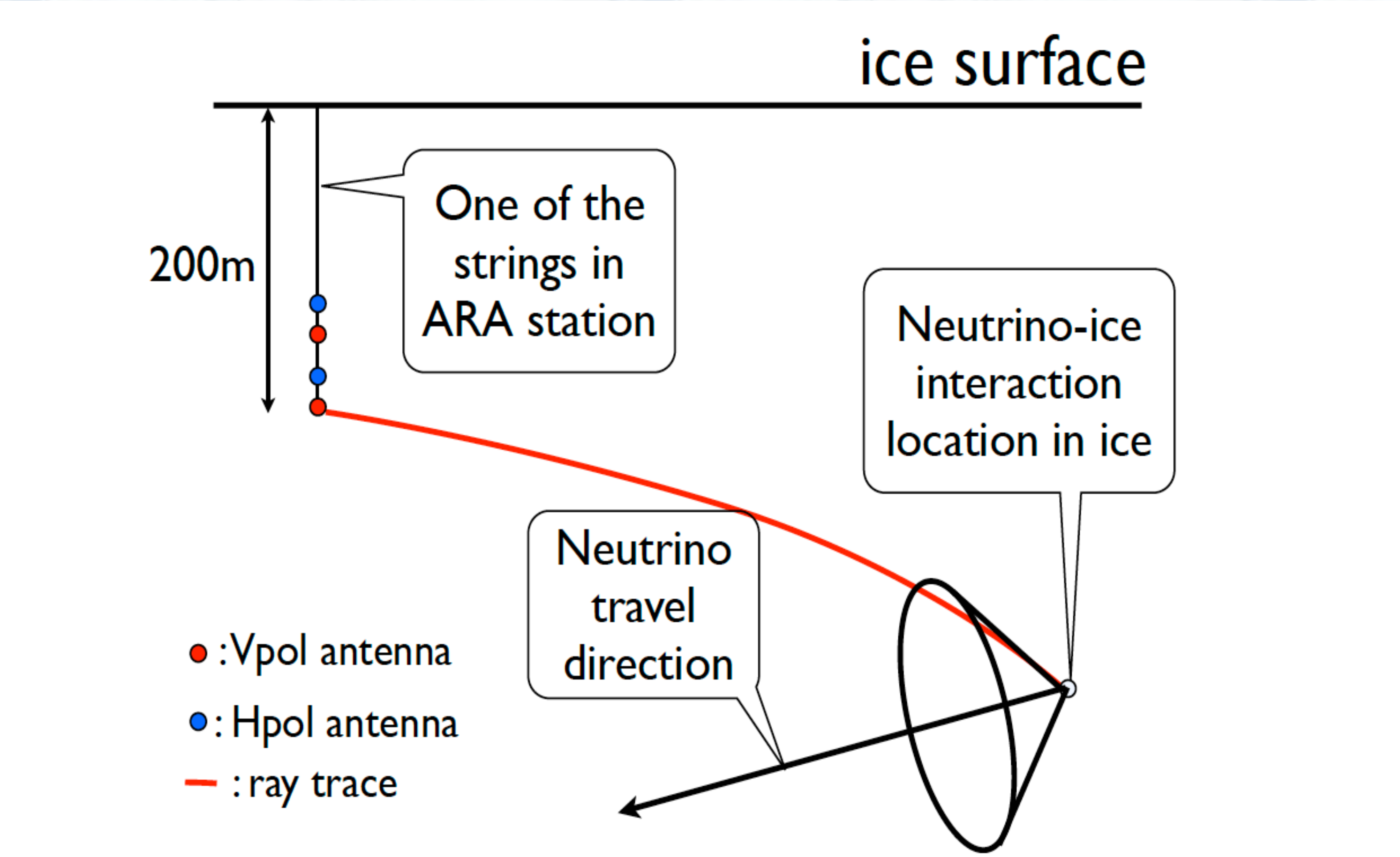


Image of the ARIANNA station (Hong et al., 2013)

Raytracing in the Detection of UHE Neutrinos



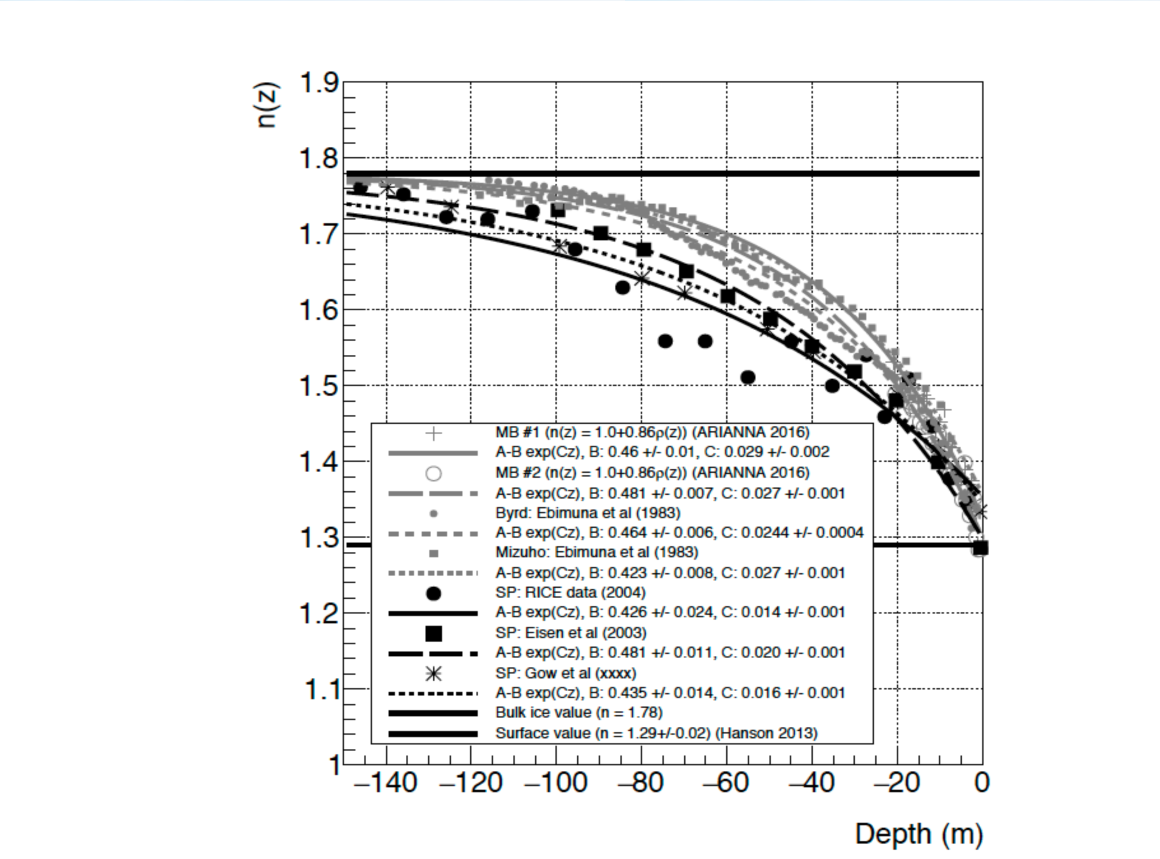
Basic Schematic of raytracing (Hong et al., 2013)

Why study ray propagation?

- Arrival angles
- Attenuation length calculations
- Determining background
- Deeper understanding of how radio signals propagate in a medium

Modeling the firn

- Changing index of refraction of ice in the firn
- Fit to data is exponential
- Depth-dependent
- Location in antarctica
- Various experiments use different firn models



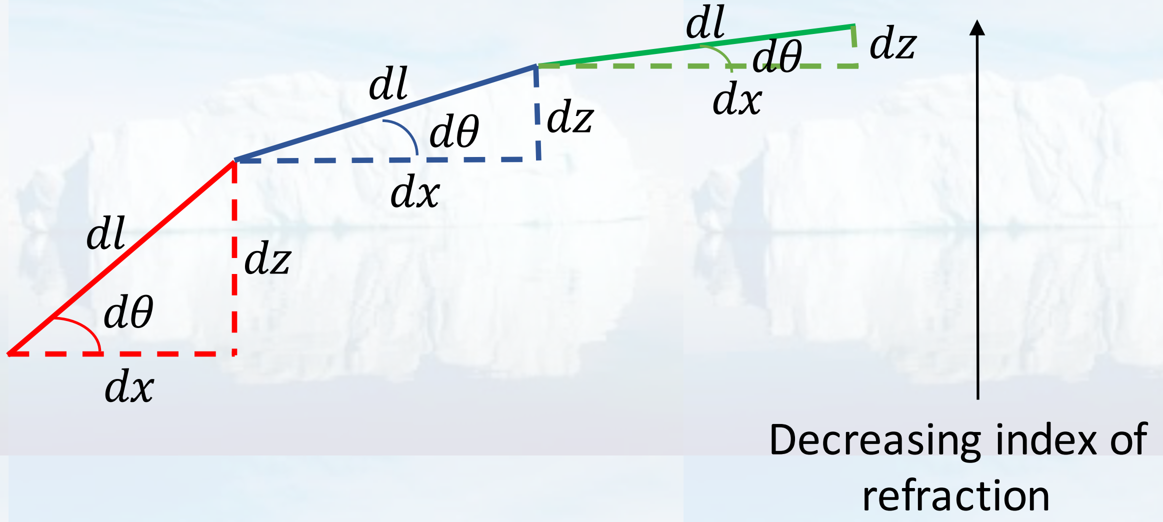
Firn index vs. depth

Non South Pole Fit
Non South Pole Data
South Pole Fit
South Pole Data

Ray Tracing Procedure

$$dx = \cos(\theta) \times dt \times \frac{c_0}{n}$$

$$dz = \sin(\theta) \times dt \times \frac{c_0}{n}$$



$\alpha = n(z)\cos\theta$ is constant (Snell's Law)

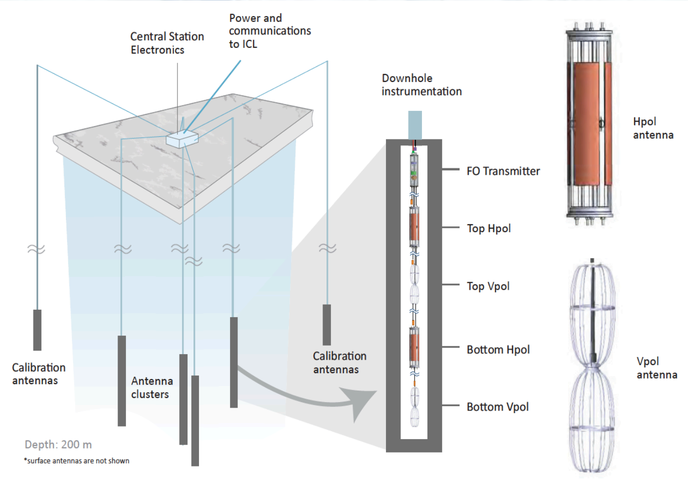
$$\Rightarrow \frac{d\alpha}{dl} = 0 = \frac{dn}{dl}\cos\theta - n\sin\theta\,\frac{d\theta}{dl}$$

$$d\theta = \cos\theta \times \frac{c}{n^2} \cdot \frac{dn}{dz} \times dt$$

Two different neutrino detection experiments

Askaryan Radio Array (ARA)

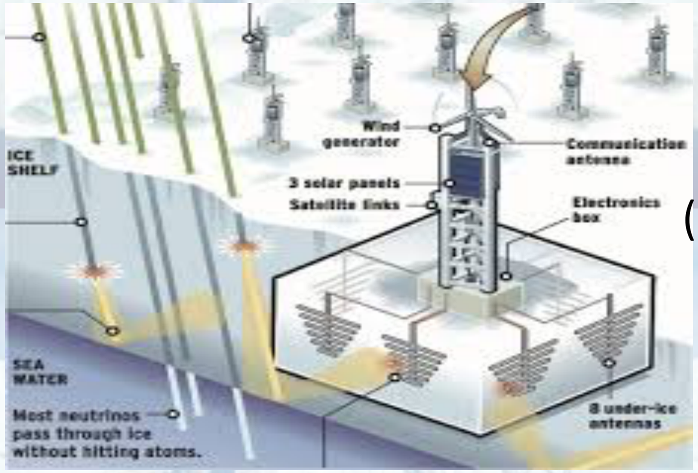
- South Pole
- Antennas 200m deep



ARA station (https://inspirehep.net/record/1385863/plots)

Antarctic Ross Ice-Shelf Antenna Neutrino Array (ARIANNA)

- Moore's Bay, Antarctica
- Different index of refraction model

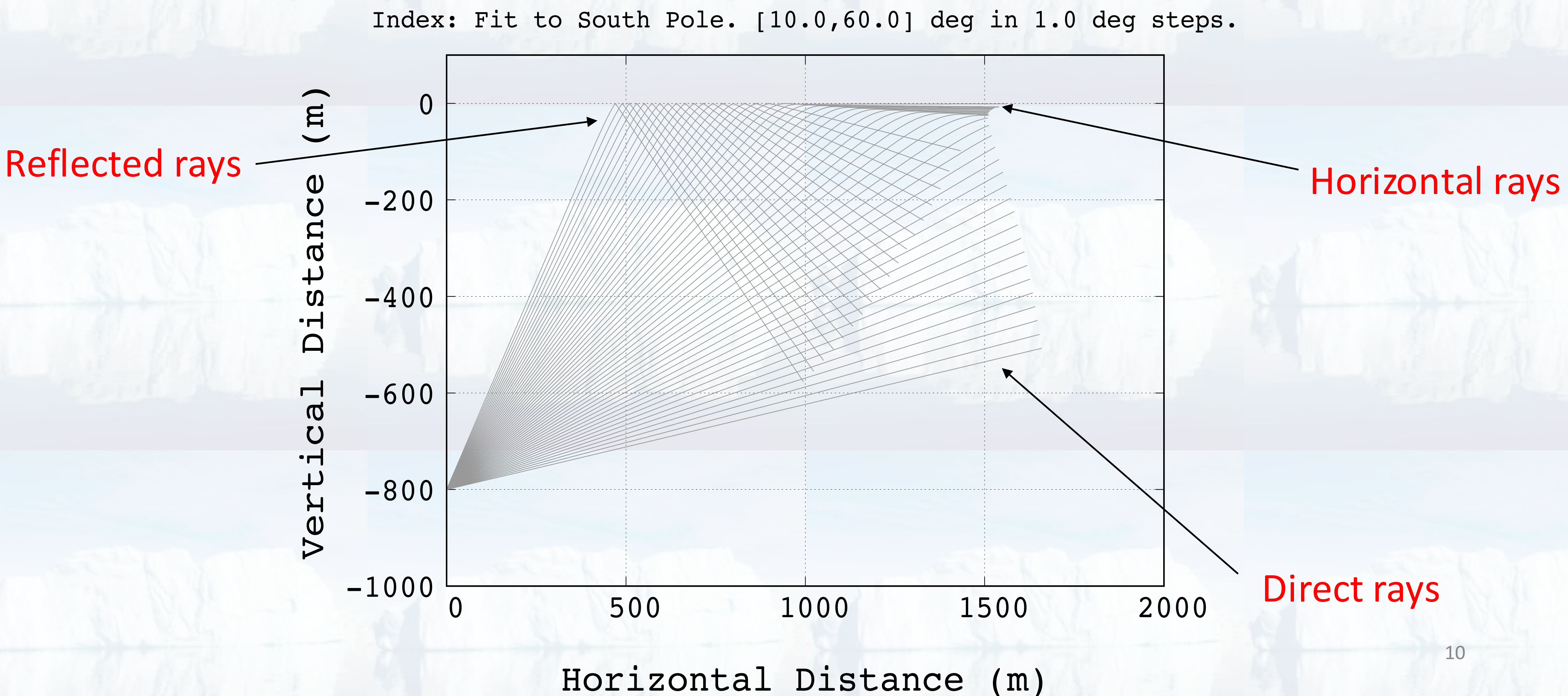


ARIANNA station (https://arianna.ps.uci.edu/science)

Reasons to develop a new ray tracing code

- New data reveals horizontal ray propagation may be possible.
- Multiple reflecting layers in ice possible.
- A flexible code that works in both the ARA and ARIANNA simulations.

Raytracing results from the new code



Finding solutions

- Find the ray that hits closest to a given target location.
- In order to do this, we scan many rays to see which ones make it and which ones do not.
- Then we find some of the characteristics of these rays such as:

1. initial angle,
2. receipt angle,
3. arrival time at antenna,
4. length of the path traversed
5. angle at which ray reflects off the ice surface

Finding solutions as roots

- Scan through a range of initial angles .
- Calculate the vertical miss distance from the target.
- Interpolate vertical miss distance, z, as a function of initial angle.
- Find the angle that satisfies the equation z = 0.
- Two solutions possible, one for direct rays and one for reflected.

Plot of z as a function of initial angle

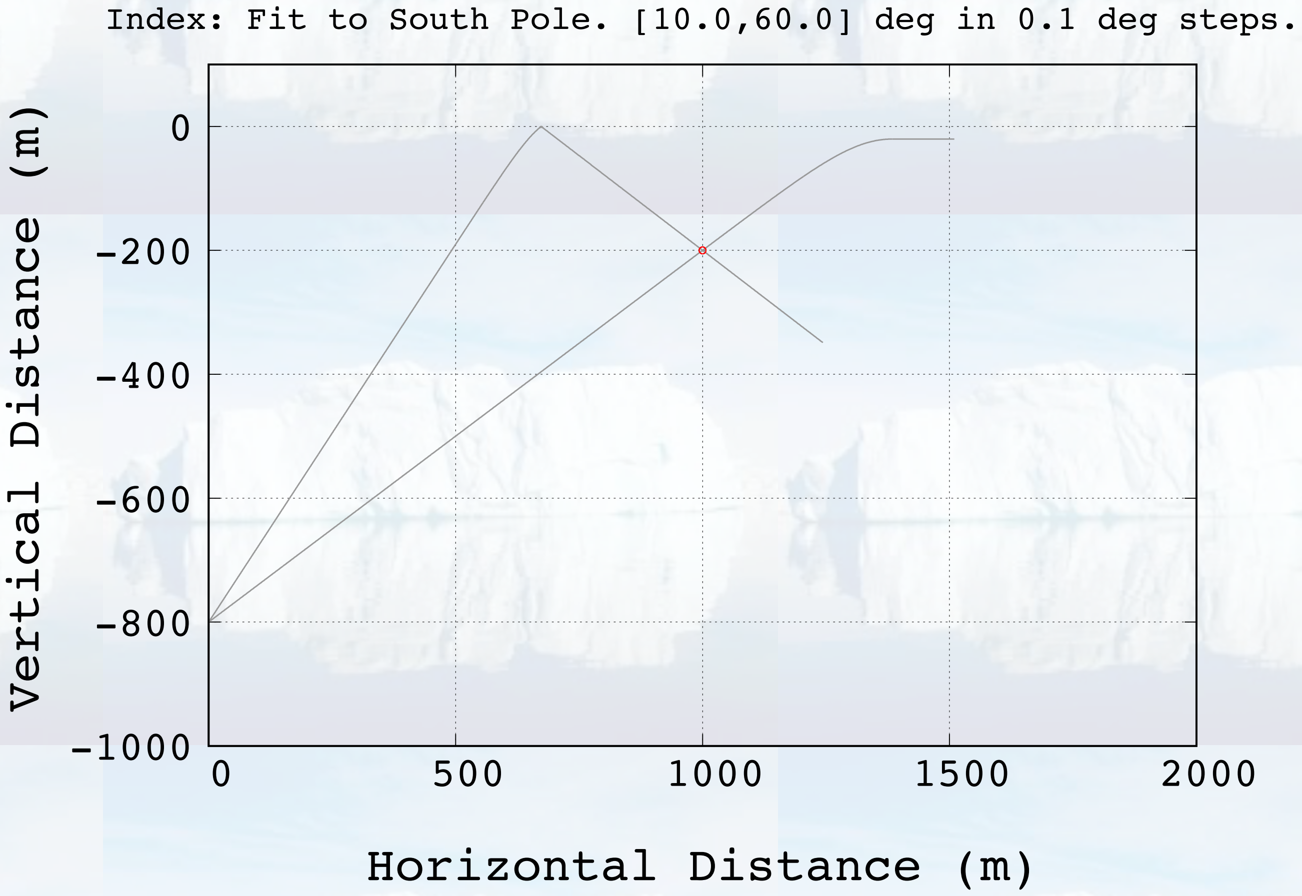
Results

- Two ray solutions found as expected!

- Miss distances found to be on the order of cm, which is reasonable.

- Sample output of the program:

```
Initial angle: 50.6513
Receipt angle: -31.4535
Arrival time: 8307.86
Surface reflection angle: 31.4869
Path length: 1429.54
```



Conclusions/Further work

- Ray tracing is important to determine antenna gain functions, attenuation lengths and background
- Need for a more flexible ray tracing code which incorporates new findings

Further work:

- Use the new ray tracing code in AraSim and see how it performs
- Add attenuation length characteristics in the new code
- Calculate the total power transmitted to antenna by all solutions

References

1. Connolly, A. L., & Vieregg, A. G. (2017). Radio Detection of High Energy Neutrinos. *Neutrino Astronomy: Current Status, Future Prospects*, 217.
2. HONG, E., CONNOLLY, A., & PFENDNER11, C. G. Simulation of the ARA Experiment for the Detection of Ultrahigh Energy Neu-trinos.

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