Sensitivity Study of the 5-station Configuration of ARA

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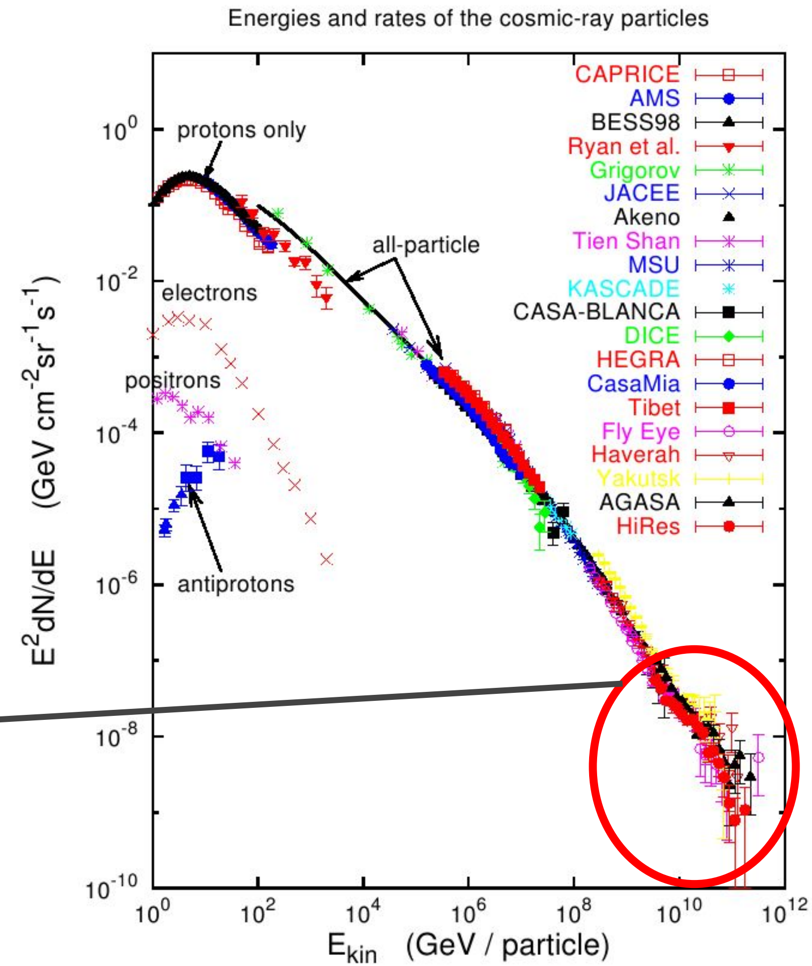
High-Energy Cosmic Rays

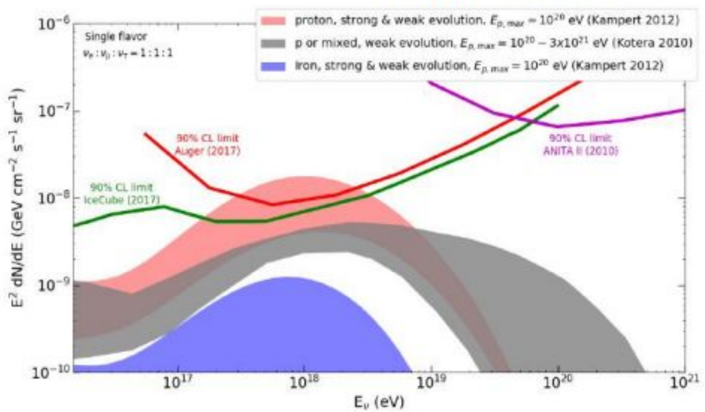
- Cosmic rays have been observed up to 10^{21} eV
- Origin not fully known
- Candidate Sources:
  - SN remnants
  - Active Galactic Nuclei
  - Gamma-Ray Bursts
  - Dark matter? Exotics?
- Cosmogenic neutrino flux:

$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$



Astronomy with cosmogenic neutrinos

High light talk at ICRC, Jaime

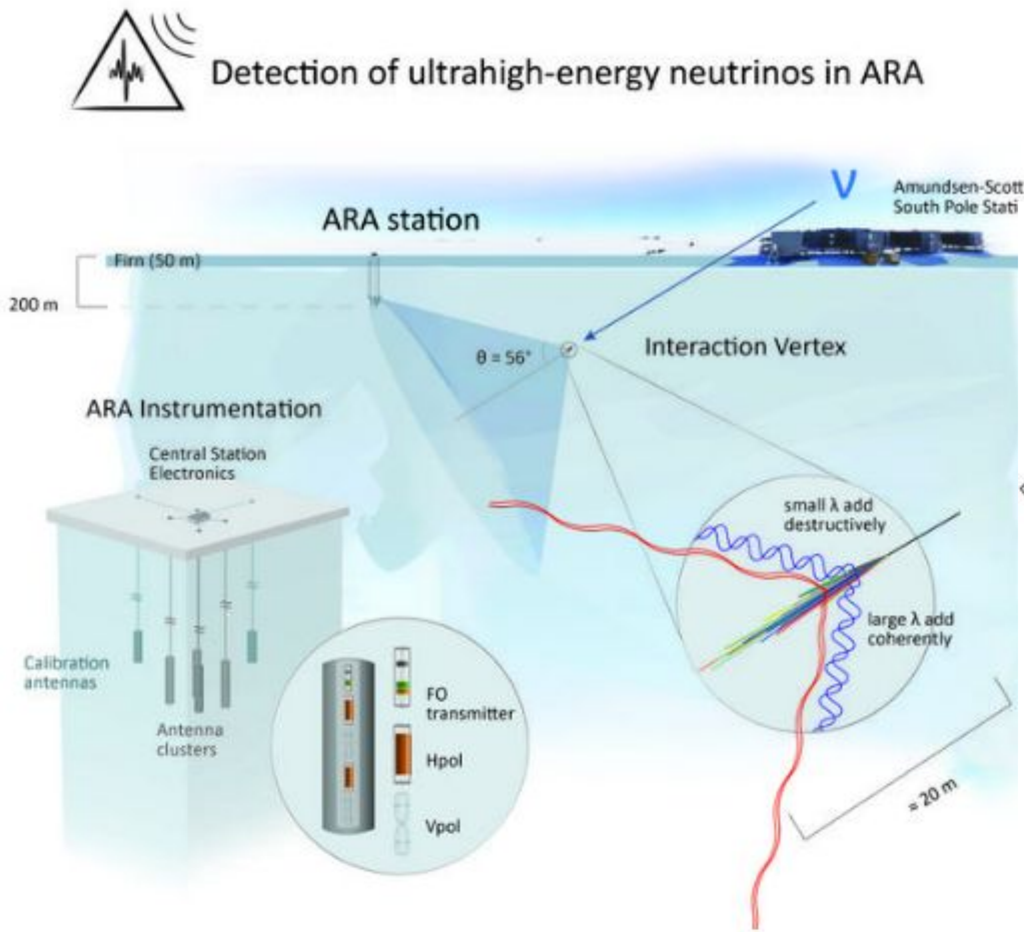


- Cosmogenic neutrino flux suitable for astronomy at Gpc distance scale
  - Mostly by default; difficult using other methods
- Cosmic accelerators at Gpc distance scale
- Cosmogenic neutrinos point back to UHECRs' sources, as distant as needed
- Also useful to study evolution and composition of UHECRs
- Fluxes are very low
- Large detection volume and large solid angle needed
- Neutrino target: Antarctic Ice sheet
- IceCube has a chance of seeing events. Needs larger and easier to scale technology (Gen-2)
- Or use radio detector to look into ice target

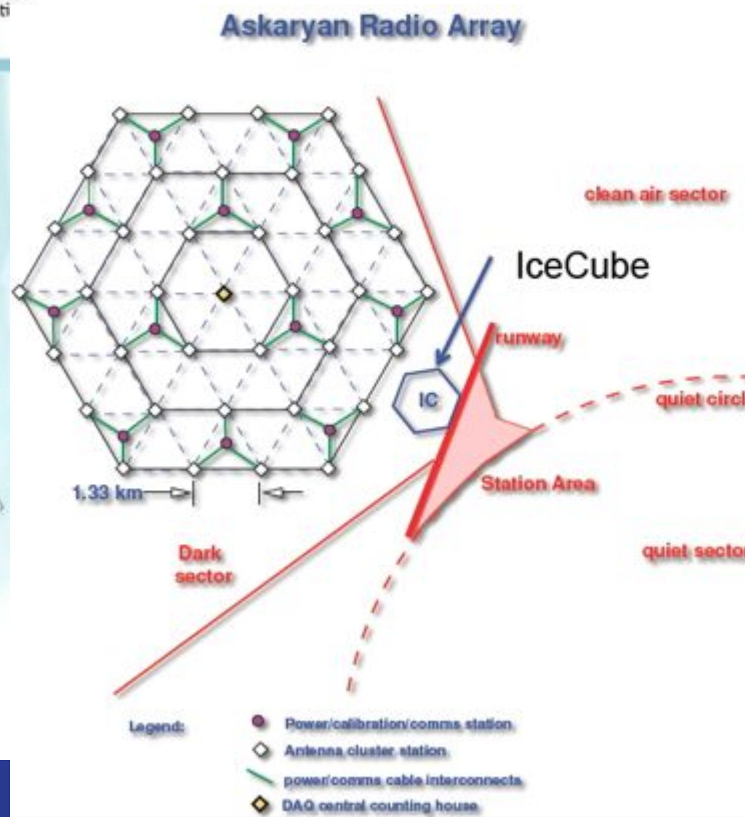
Askaryan Radio Array

- 12 institutions, ~50 authors
    - North America: California Polytechnic State University, University of Wisconsin–Madison, Kansas University, Ohio State University, University of Delaware, University of Maryland, University of Chicago, University of Nebraska-Lincoln
    - Europe: University College-London
    - Asia: Weizman Institute, National Taiwan University, Chiba University

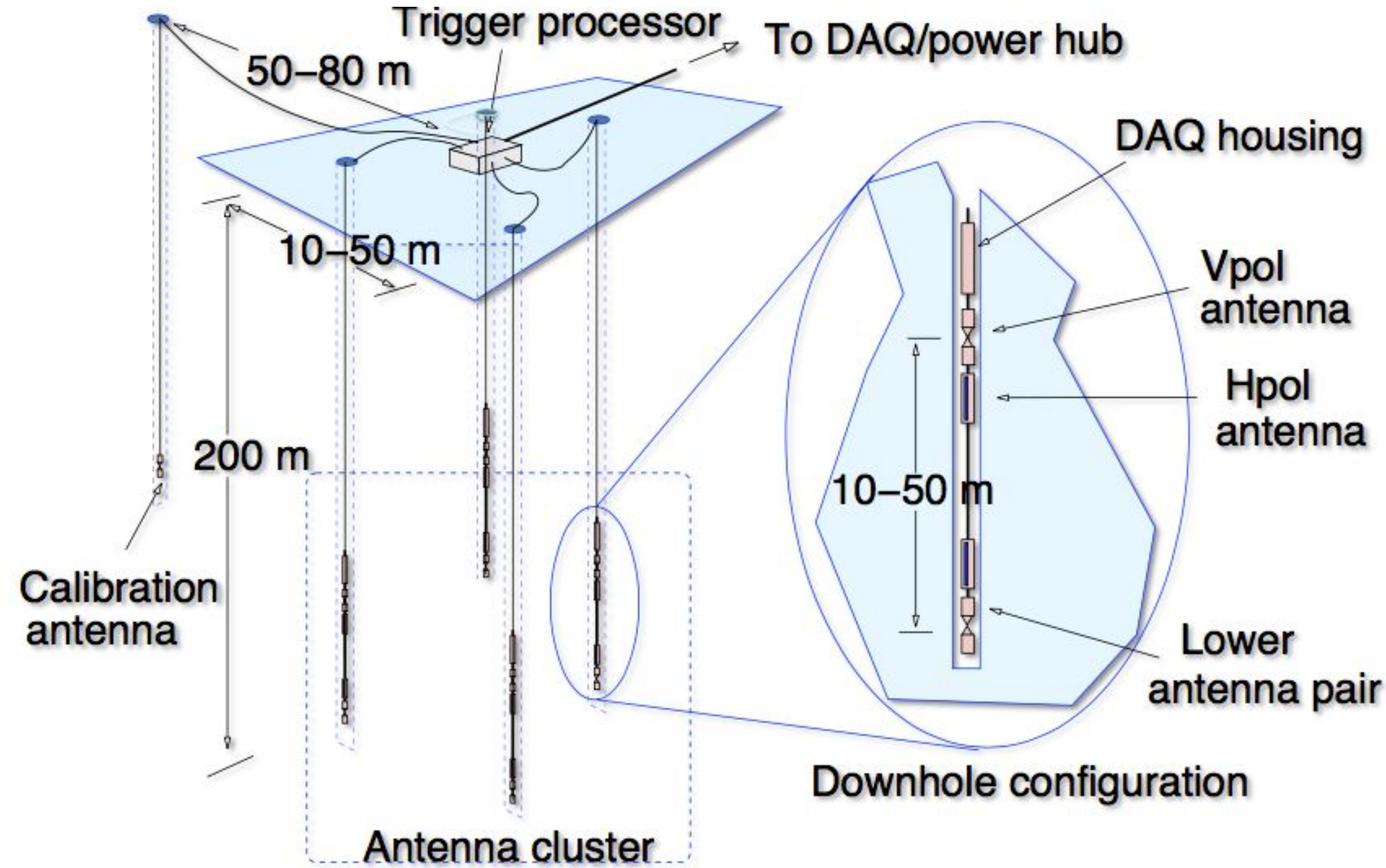
Askaryan Radio Array



- Deployed over 100 km^2
- Antennas are placed 200m deep in the ice
- Easier to make a bigger detector in an economical way

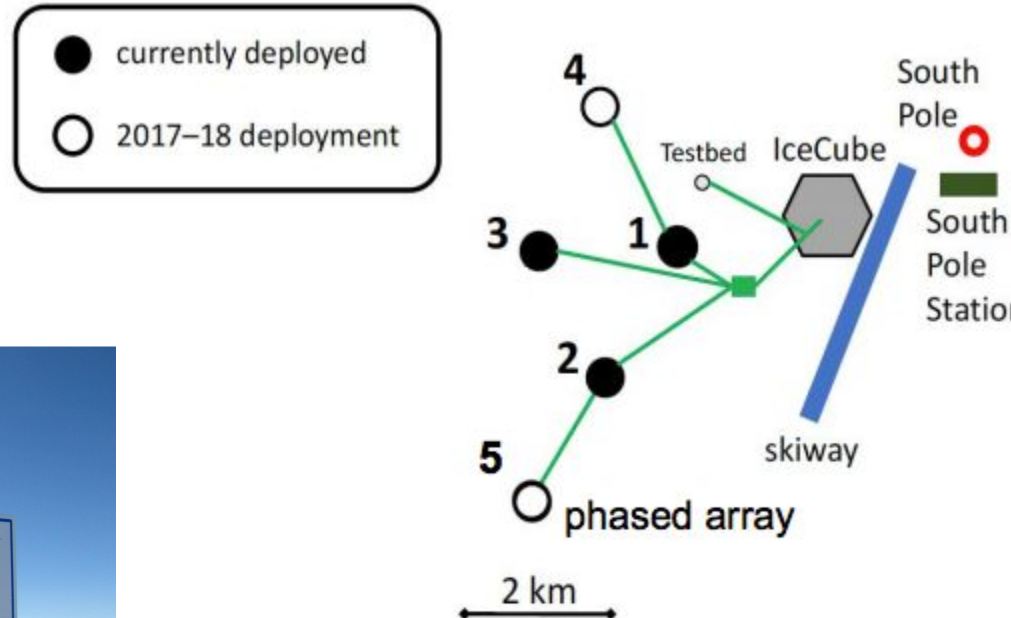


Askaryan Radio Array



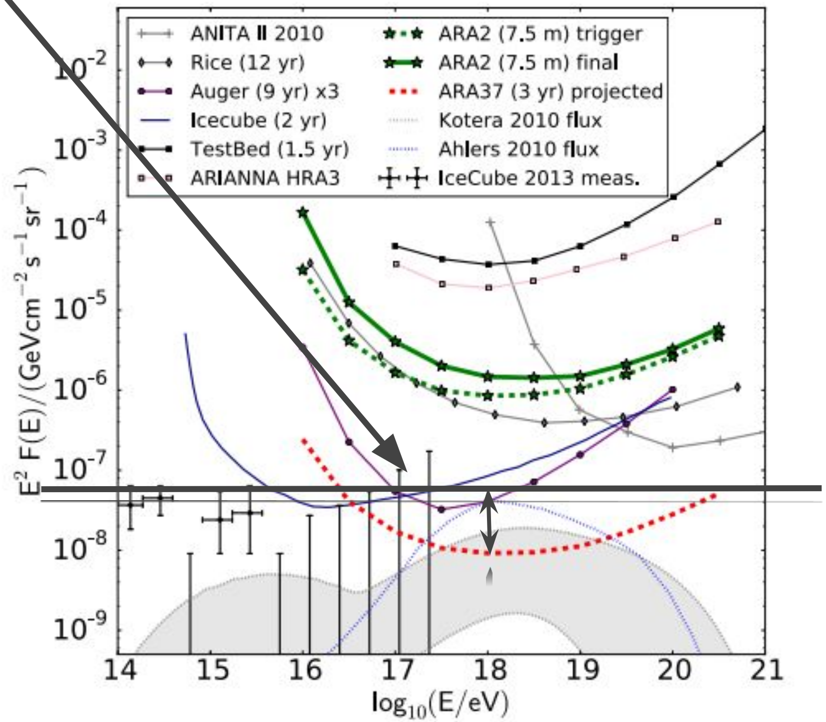
Current Status

- As of January 2018, 5 working stations
- Sensitivity comparable to IceCube at 10^{18} eV



Sensitivity of 5 stations

- Current claim is that sensitivity at 10^{18} eV is comparable to IceCube
  - Needs confirmation using simulations
- Simulations need to use proper antenna behavior
  - Reconstruction of neutrino energy and arrival direction
  - Misestimated antenna gain leads to shift in energy scale
- Analysis of in-situ antenna gain measurements improved with further data
  - Use results to develop antenna model over all angles and frequencies to be used in new simulations



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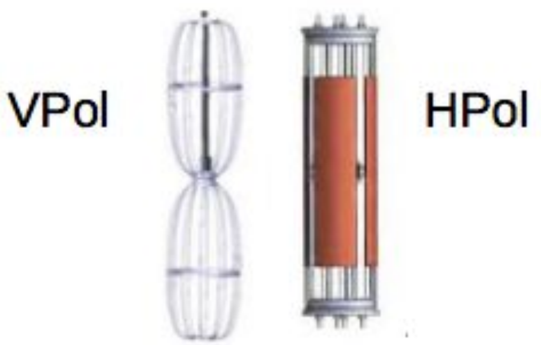
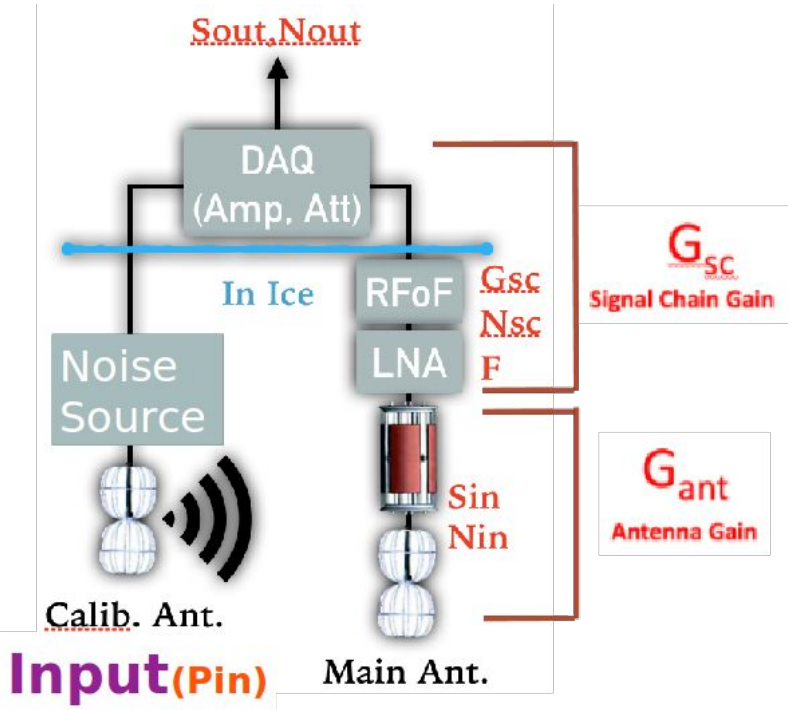
Understanding Antennas



- Different polarization to identify polarization of incoming signal
- Helps in neutrino reconstruction
- Requirements:
  - Broadband (150-850 MHz)
  - Azimuthal symmetry
  - Fit in hole
- VPol: birdcage dipoles
- HPol: ferrite-loaded quad-slot
- Described by XFDTD simulations

Understanding Antennas: In-Situ Calibration



- G_{Ant} : Antenna Gain
- P_{in} : Input power
- S_{out} : Signal output power
- S_{in} : Signal input power
- N_{out} : Noise output power
- N_{in} : Noise input power
- G_{sc} : Signal chain gain
- N_{sc} : Signal chain noise
- F : Noise figure
- R : Distance between Antennas

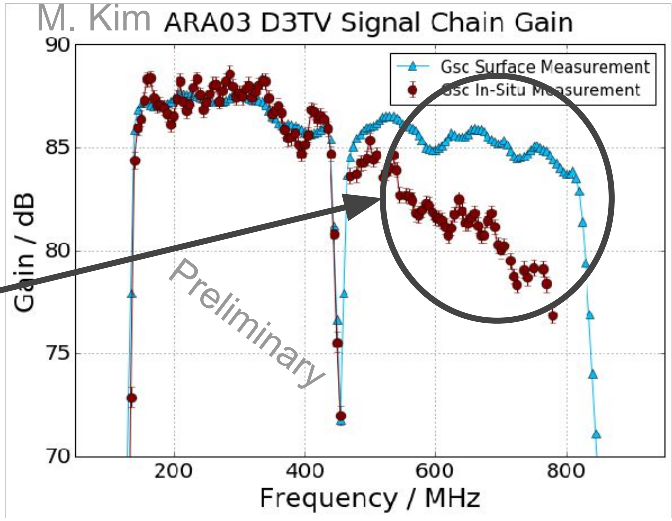
$$G_{tot} = G_{ant} \times G_{sc}$$

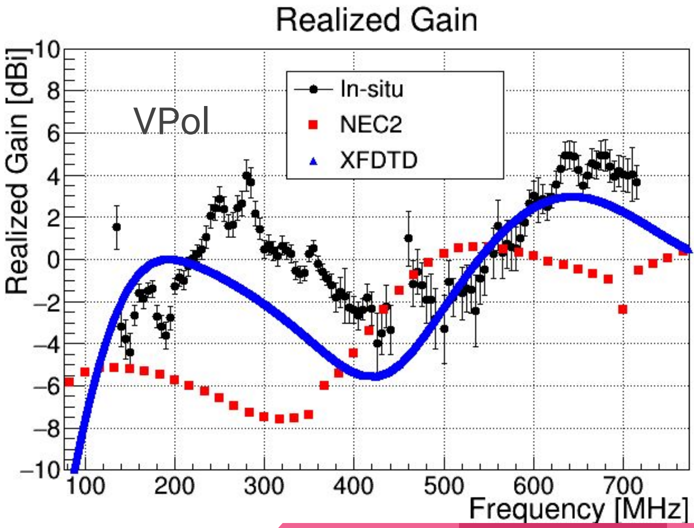
Total Gain

- Critical to the event reconstruction both for geometry and energy
- Calibration in-situ performed with the calibrated noise source
- Antenna gain and system gain are obtained
- Measurement performed by varying depth of calibration antenna
  - Allows to probe antenna response at different angles

In-Situ Calibration

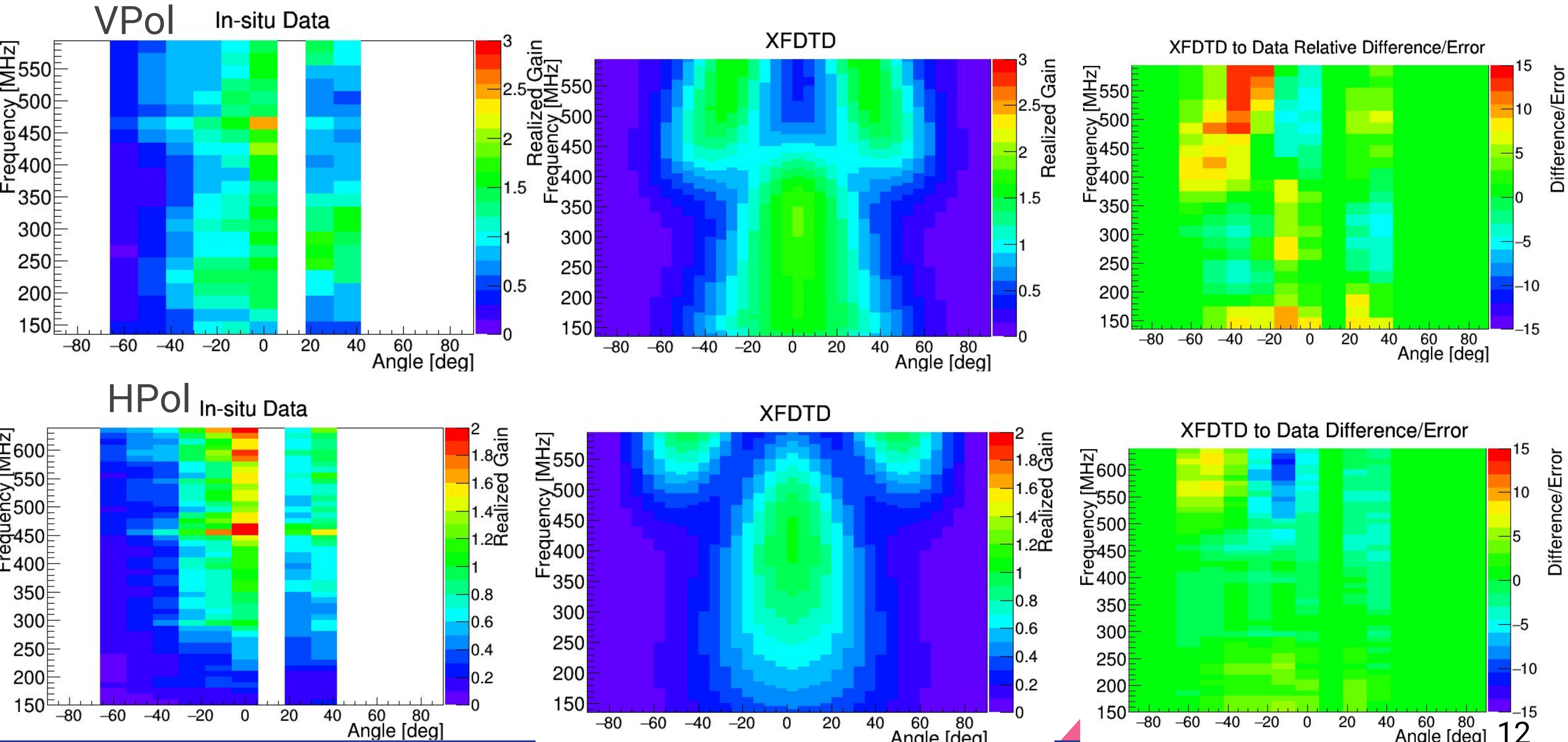
- Difference in high frequency. Due to DAQ response at high frequency
- Small systematic uncertainty (~20%-30%)
- Antenna realized gain is obtained, compared with in-ice simulations
- XFDTD simulations improve upon previous NEC2 version
  - Newer, more accurate antenna model





Antenna Model Development

- Why build a model?
  - Simulations don’t always match with data perfectly

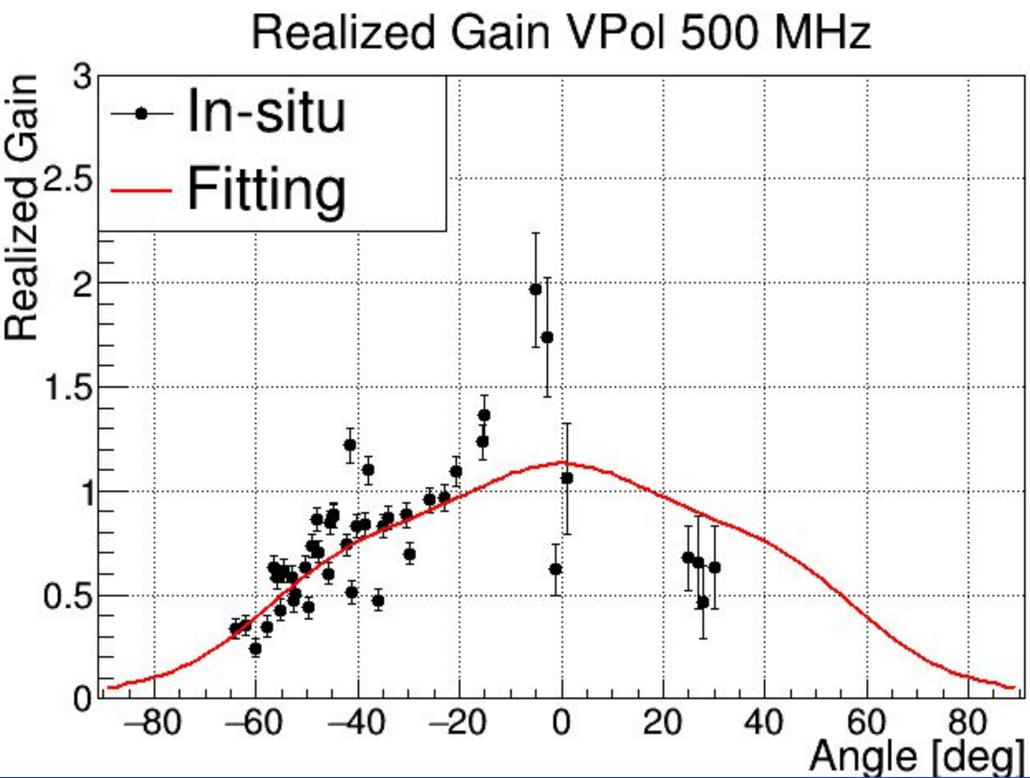


Antenna Model Development

- Why build a model?
  - Simulations don't always match with data perfectly
    - Especially for HPol
  - In-Situ measurements don't cover all angles
    - Serves as a basis for model construction
- How to build a model?
  - Following the idea of Legendre polynomials
  - A combination of which should always describe an antenna angular pattern
  - $A(f)\cos^2(B(f)\theta) + C(f)\sin^2(D(f)\theta)$

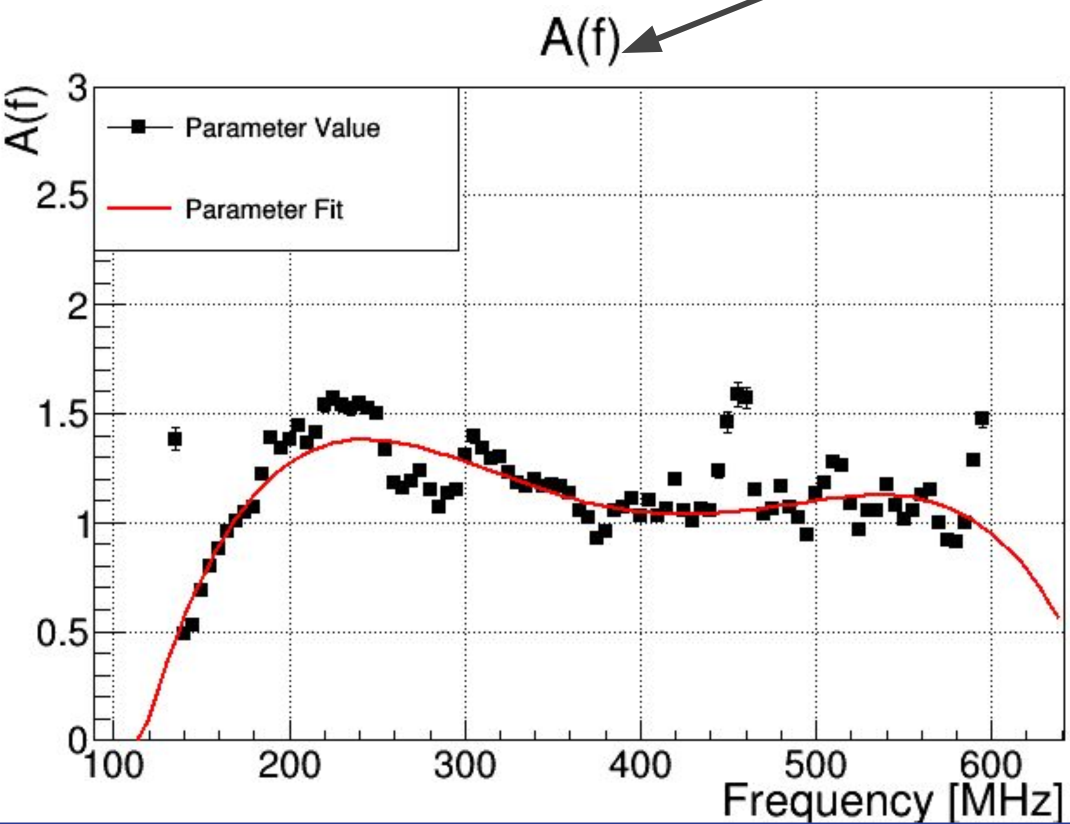
Antenna Model Development

1. Get angular realized gain distribution for each available angles, per frequency, from in-situ measurement
2. Fit each with $A\cos^2(B\theta) + C\sin^2(D\theta)$



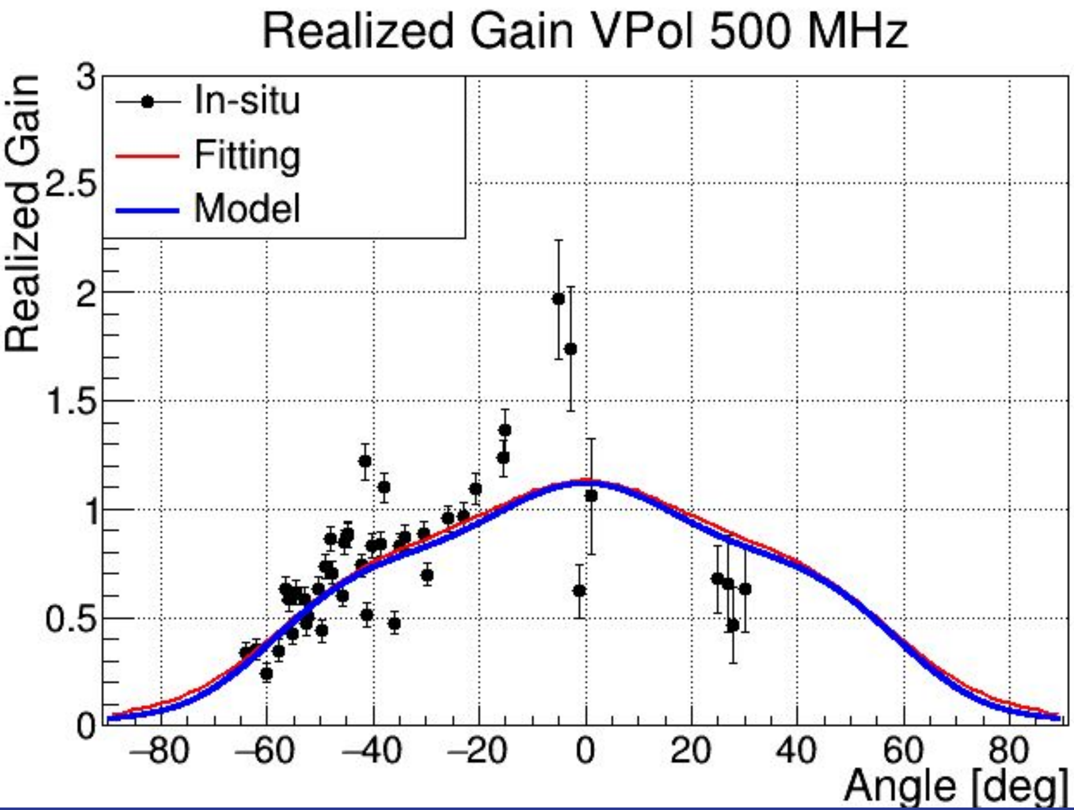
Antenna Model Development

3. Plot A, B, C and D for each frequency (from $A\cos^2(B\theta) + C\sin^2(D\theta)$)
4. Fit a 4-degree polynomial to each



Antenna Model Development

5. Use fit results to obtain model:
   $A(f)\cos^2(B(f)\theta) + C(f)\sin^2(D(f)\theta)$

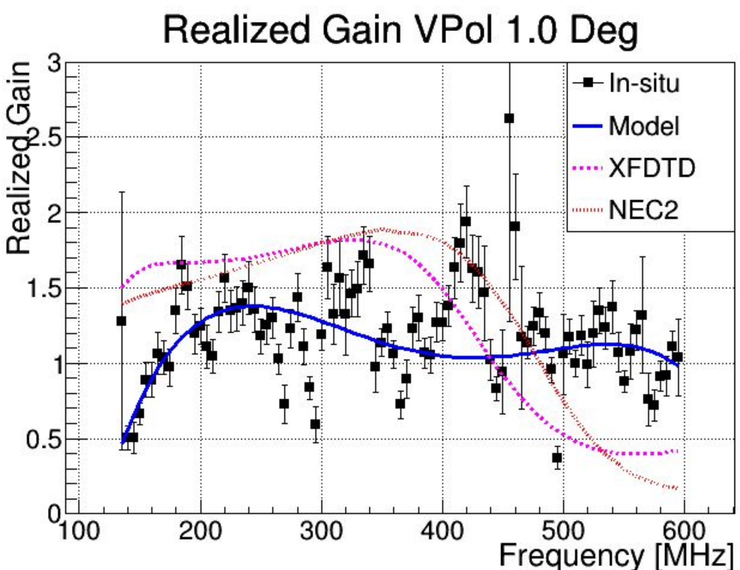


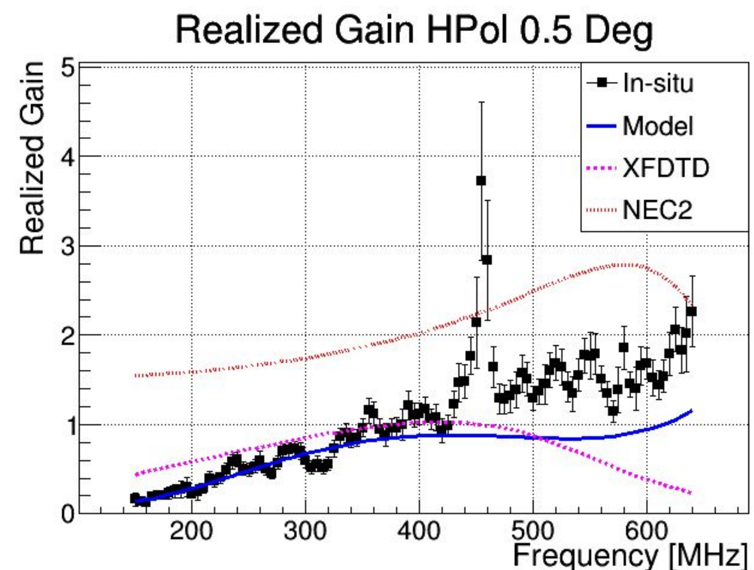
- Necessary steps to have one equation to use to determine gain for whatever frequency and angle

Antenna Model Development

- Averaging out data and model results to check agreement

	VPol	HPol
Model (Rel.Diff. average +/- Systematics / χ^2/NDF)	3.12% +/- 34% / 5.3	-3.11% +/- 40% / 4.0
XFDTD (Rel.Diff. average +/- Systematics / χ^2/NDF)	39.8% +/- 68% / 23.2	28.9% +/- 83% / 12.8

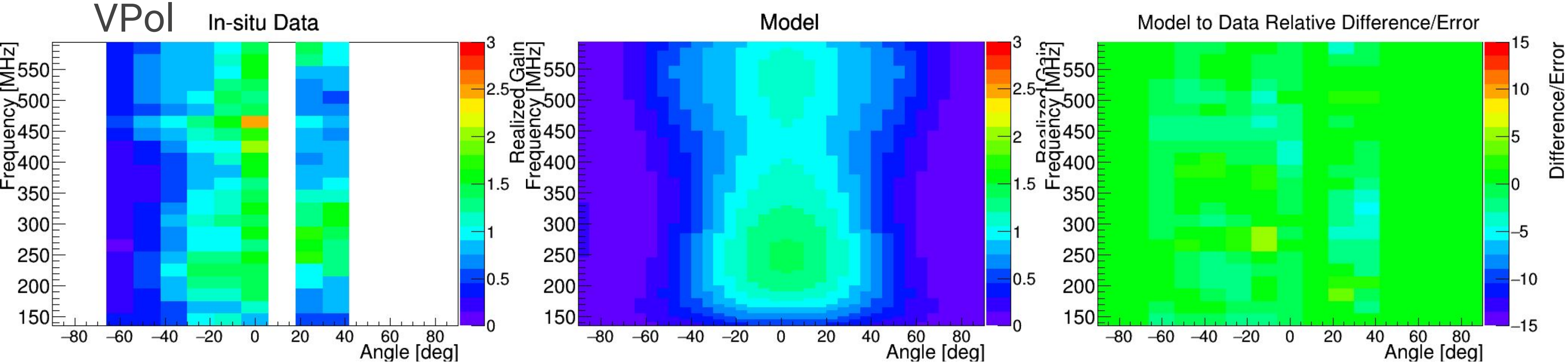




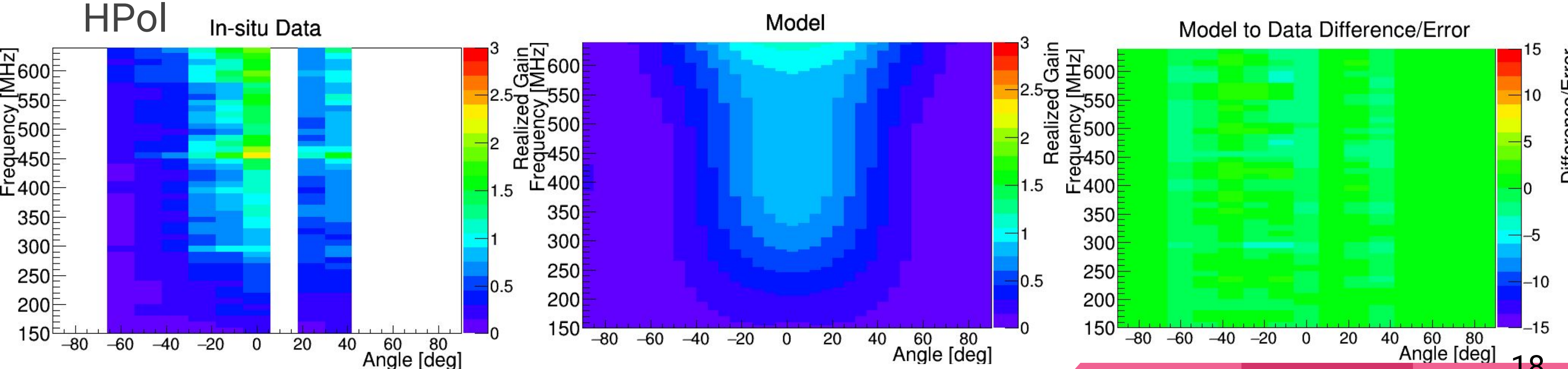
Antenna Model Development

- Improvement in 2D space?

VPol

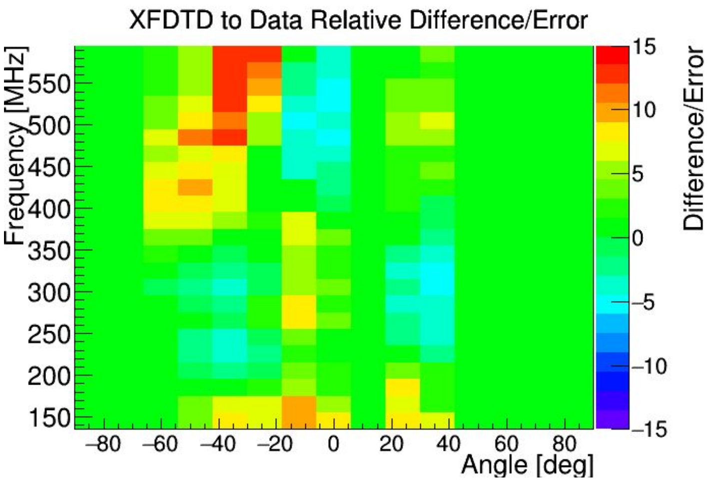


HPol

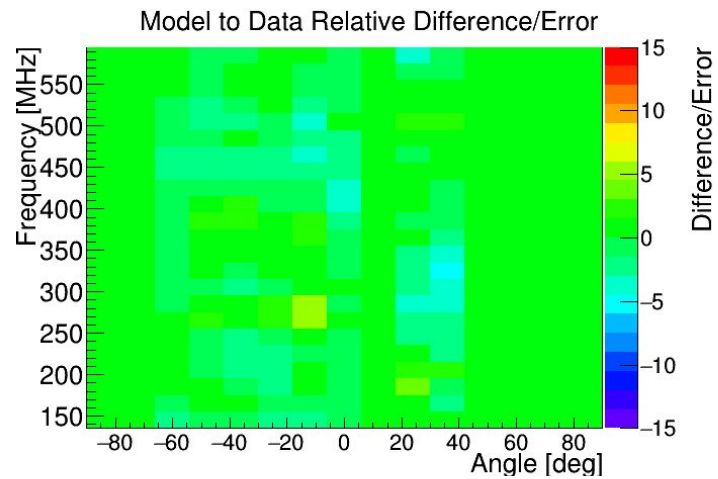


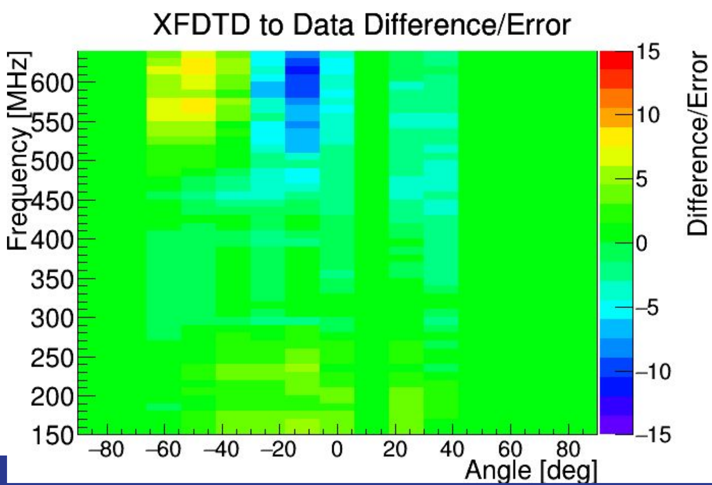
Antenna Model Development

- How does it fare against data when compared to XFDTD?

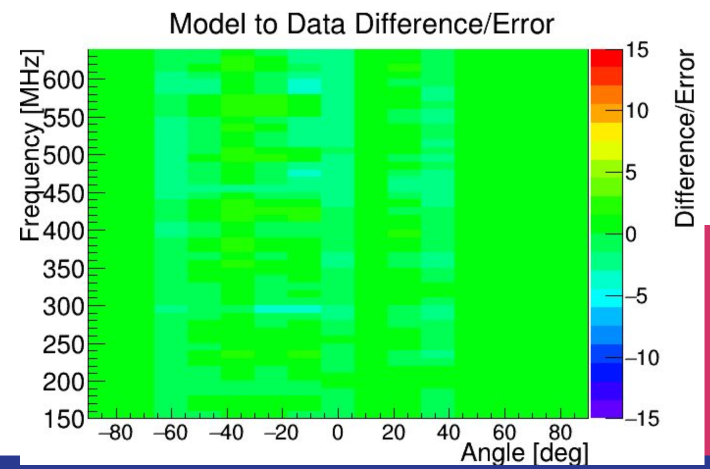


VPol

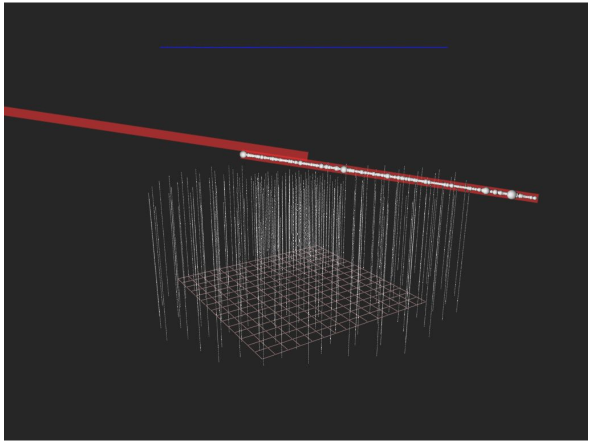




HPol



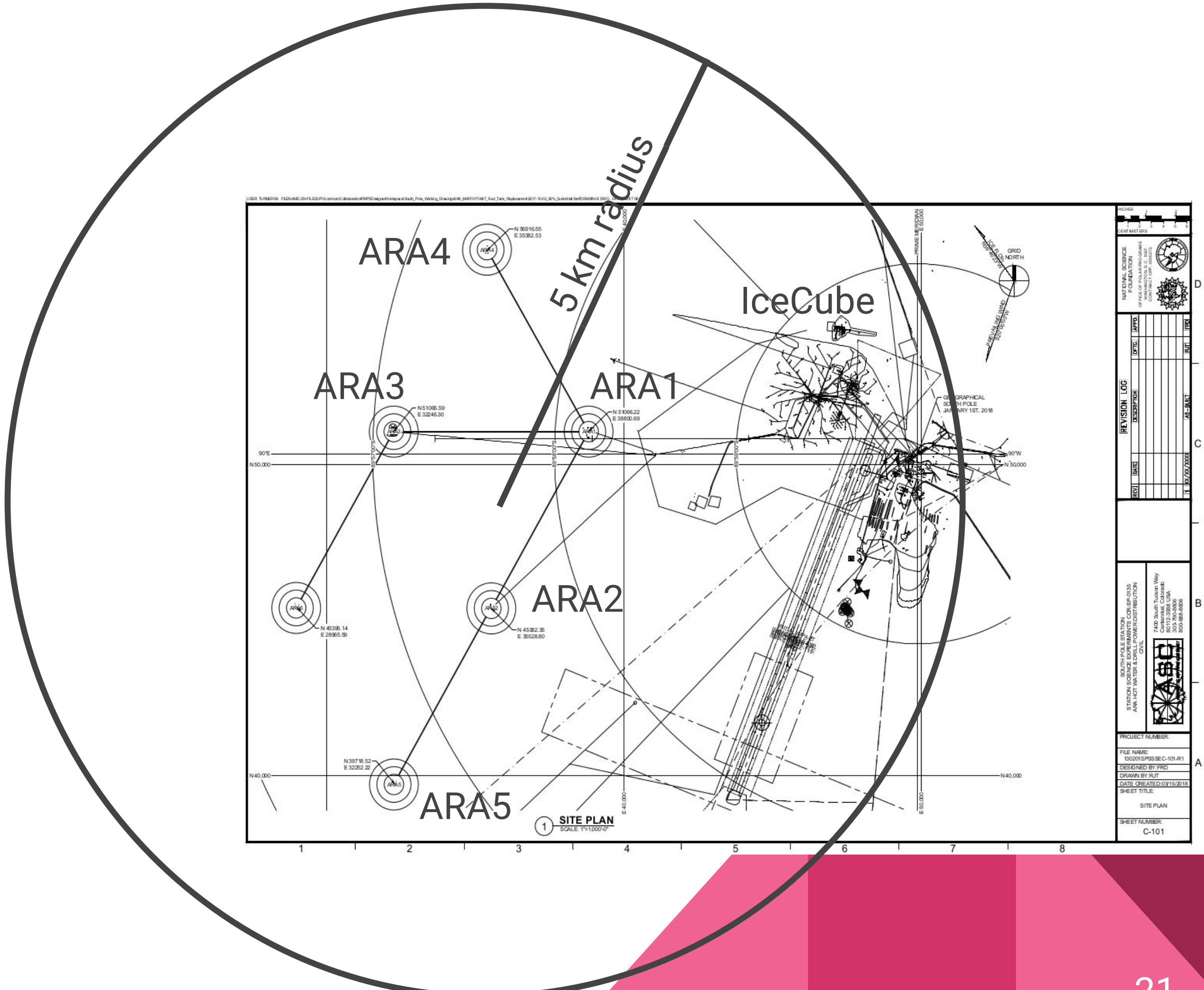
New ARA Simulation



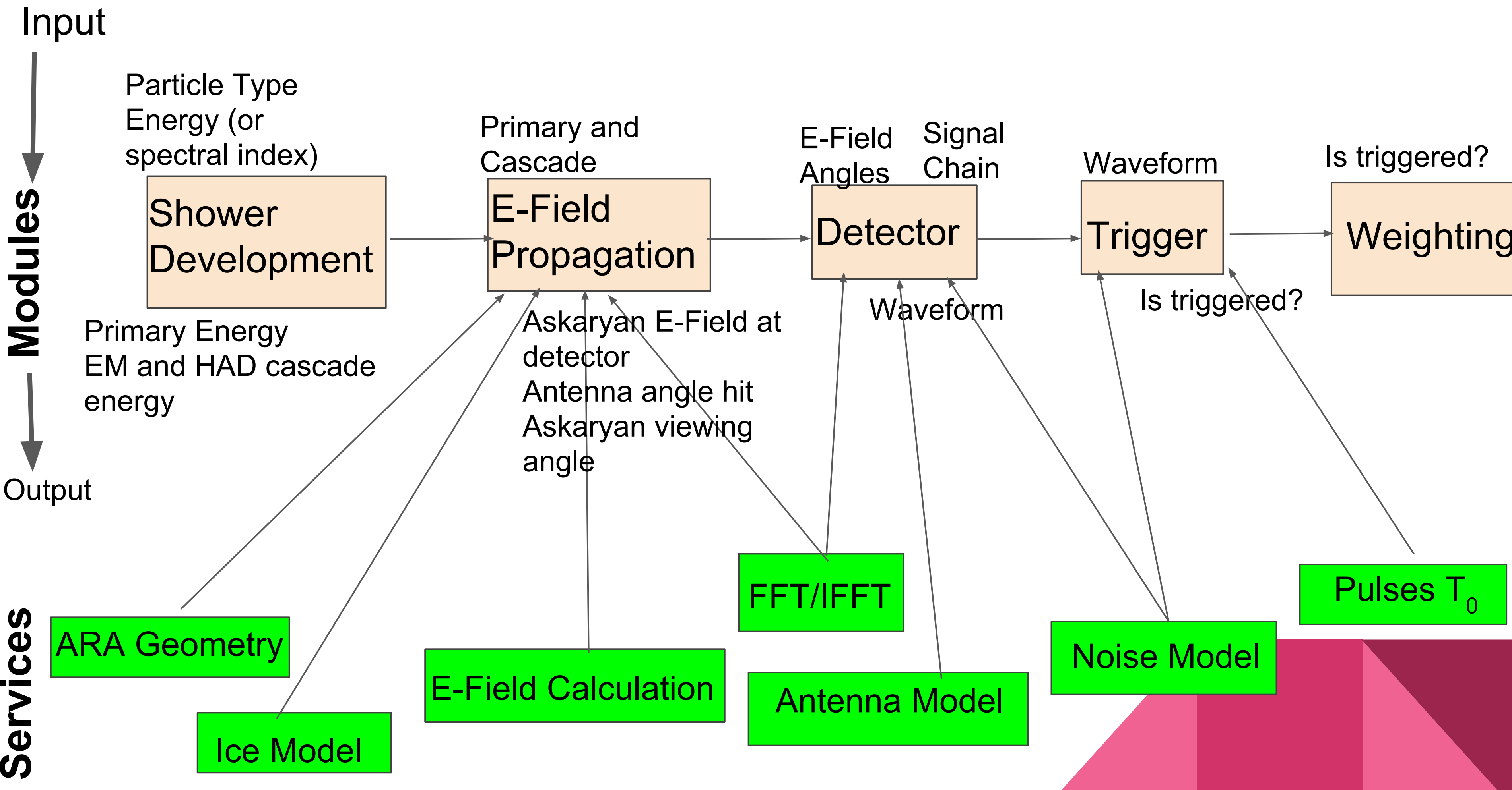
- Using IceCube modular structure (icetray)
- Motivation:
  - New, independent simulation
    - Good for cross-checks
  - Can be used in conjunction with IceCube simulations for checking:
    - Coincidence events
    - Overall sensitivity
  - Eventually used to investigate muon showers
    - Stochastic behavior of muons; multiple shower along the track
    - Potential background to be understood
    - Can confirm energy scale

New Geometry

- Using new geometry for 5 stations
    - Provided by surveyor
- Generating events in 5 km radius from defined center easily includes IceCube



New ARA Simulation



Summary

- ARA is looking for radio-detection of cosmogenic neutrinos interacting in Antarctic ice
- Current configuration is of 5 stations with a phased array
- Understanding the behavior of antennas is important for neutrino energy estimation and direction reconstruction
- New antenna model has been developed based on in-situ measurement results
- Will be implemented in new simulation, using IceCube modular structure
- Will obtain ARA-5 sensitivity, as well as study coincidence events with IceCube

Back-up

Understantind Antennas: Simulation

- Done with XFDTD licensed software
- Runs on Finite-Difference Time-Domain algorithm
  - Simulation is performed over region of space, with the antenna in the center
  - The space is divided into a grid of 3-D cells
    - Number of cells: wavelength of measurement, size of components, etc.
  - Each cell is defined with a material
    - Outside volume is free space
  - Propagate E-M wave through each cell in the region of interest.
  - Maxwell's equation are solved in each cell, as time advances
  - Once E-Field calculated in the far-field, calculates relevant quantities, i.e. realized gain