A Radio Phased Array for the Detection of High Energy Neutrinos

→ reducing the energy threshold

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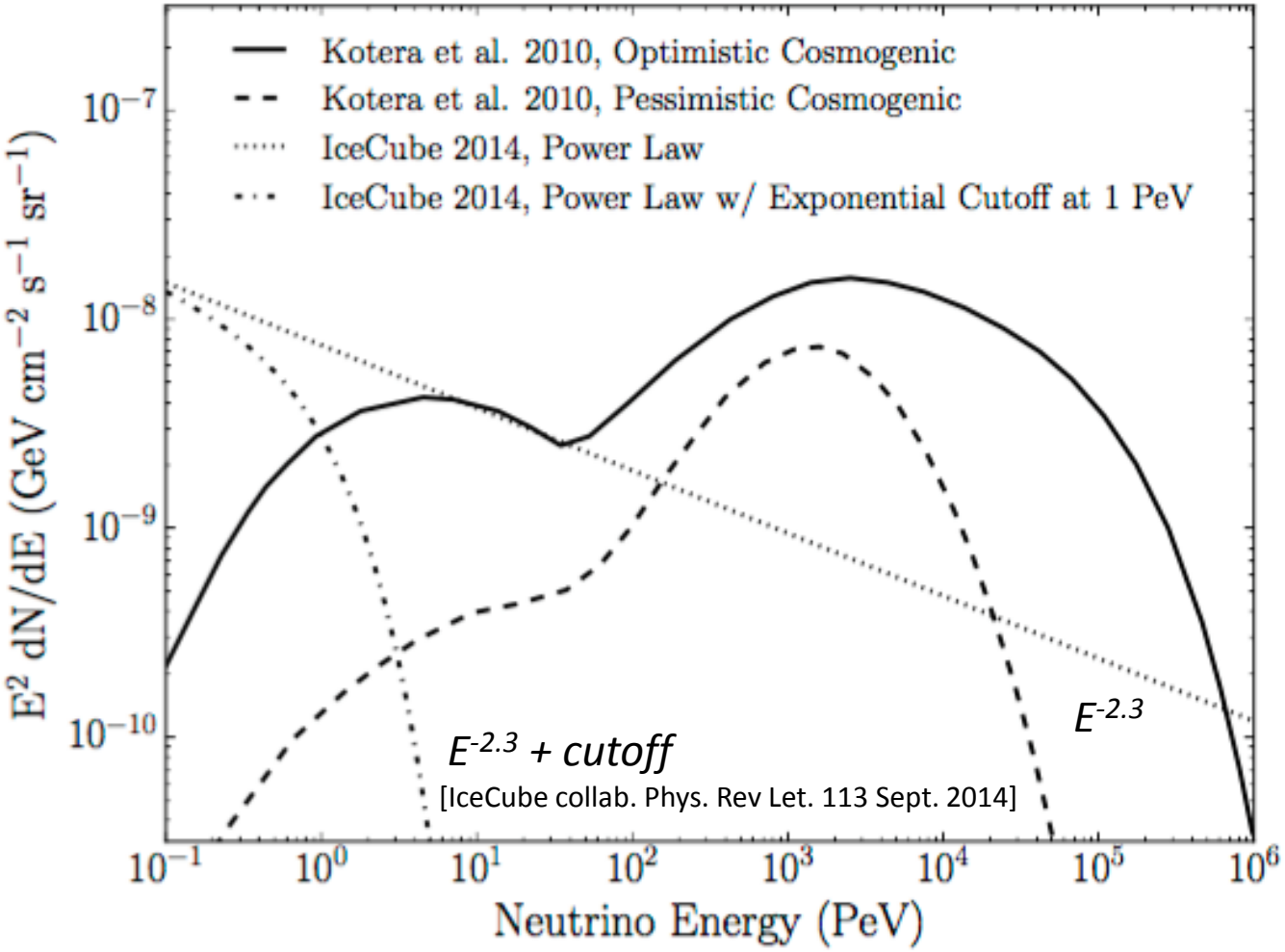
AT THE UNIVERSITY OF CHICAGO

Goal: A radio telescope for both Astrophysical and Cosmogenic *ν* populations



Concept paper: Vieregg, Bechtol, Romero-Wolf, JCAP 1602 (2016)

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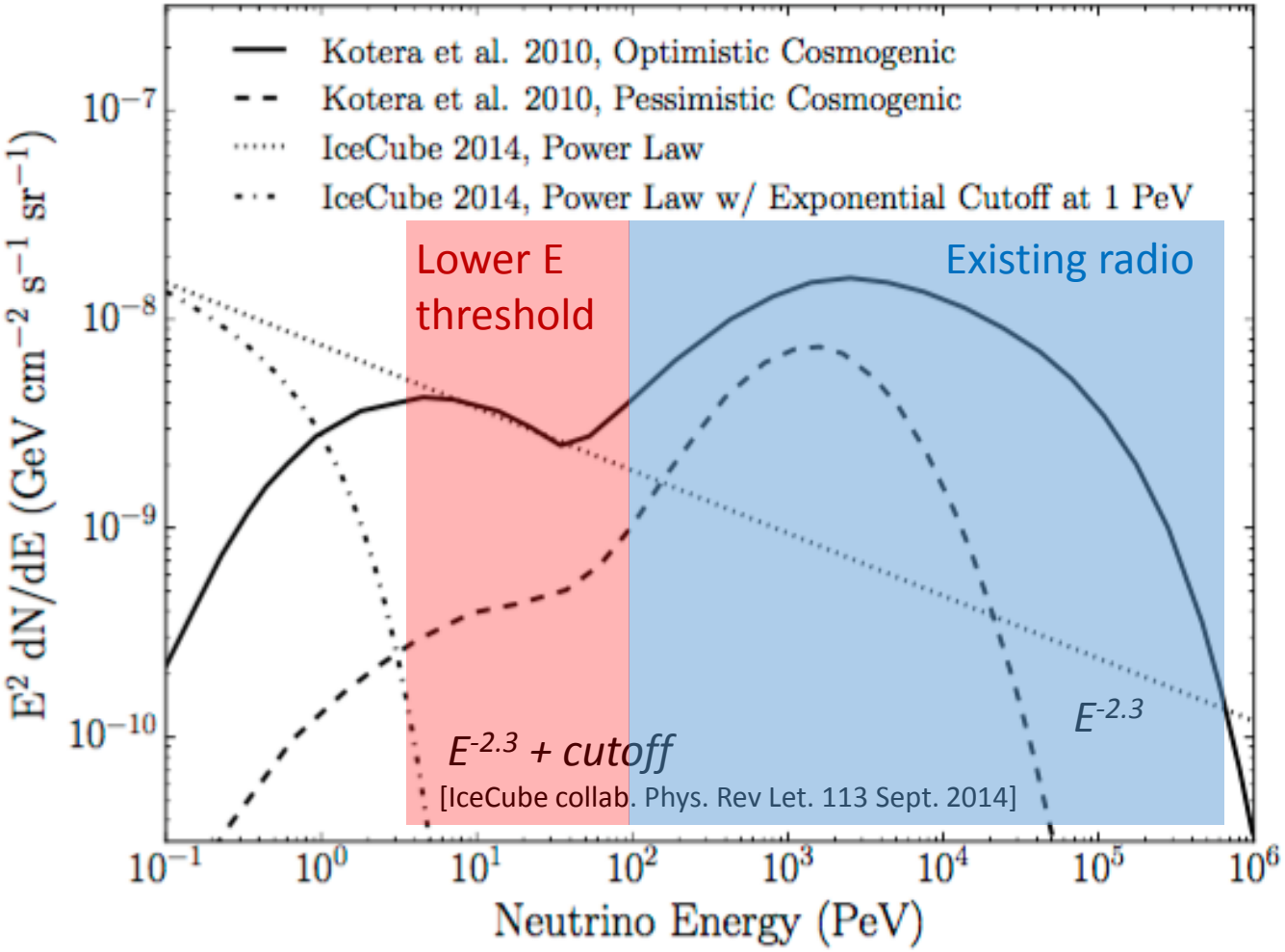

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Lowering the Energy Threshold

How to push down to a the 1-10 PeV range using the radio detection of Askaryan radiation?

- Put array as close as possible to the neutrino interaction

  → Put antenna array in the ice

  Ideally below the firn layer where refraction of the radio waves is most severe

- Increase the sensitivity of the receiving antennas

  → Deploy high gain antennas

Do both? High gain antennas have a large footprint and won't fit down boreholes, so build a phased array consisting of in-ice low gain dipole antennas to **synthesize** an high-gain receiver

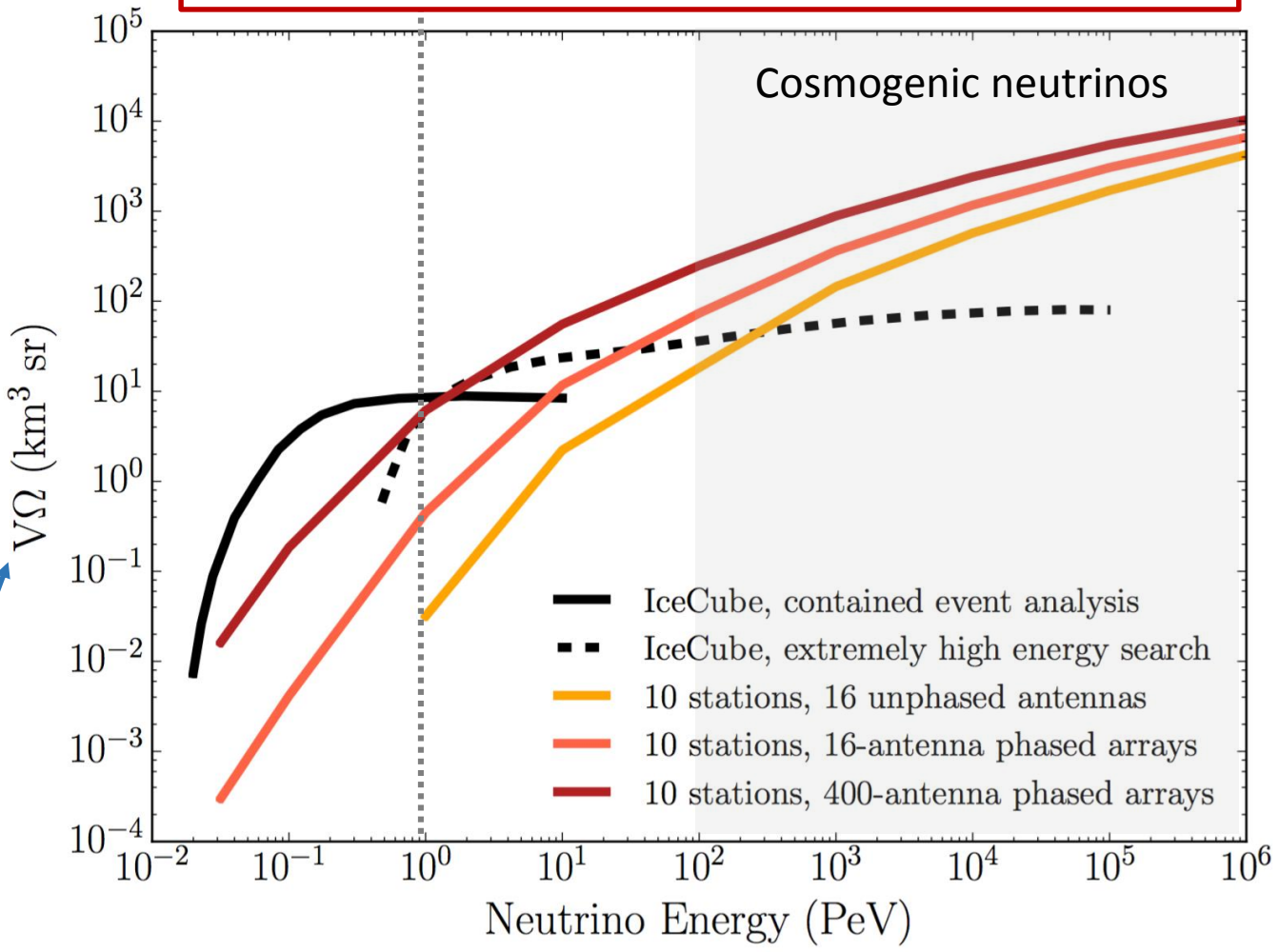
- Signal is correlated; noise is ideally uncorrelated --> increase the effective signal-to-noise ratio (SNR) as $\sqrt{N_{antenna}}$

Phased array sensitivity

- Factor of ~10x increase in sensitivity using ⦶10 phased antennas at 10 PeV
- 10+ stations of ⦶100 phased antennas required to complement IceCube high-energy searches around 10 PeV

Sensitivity to neutrino detection ~ detector volumetric acceptance

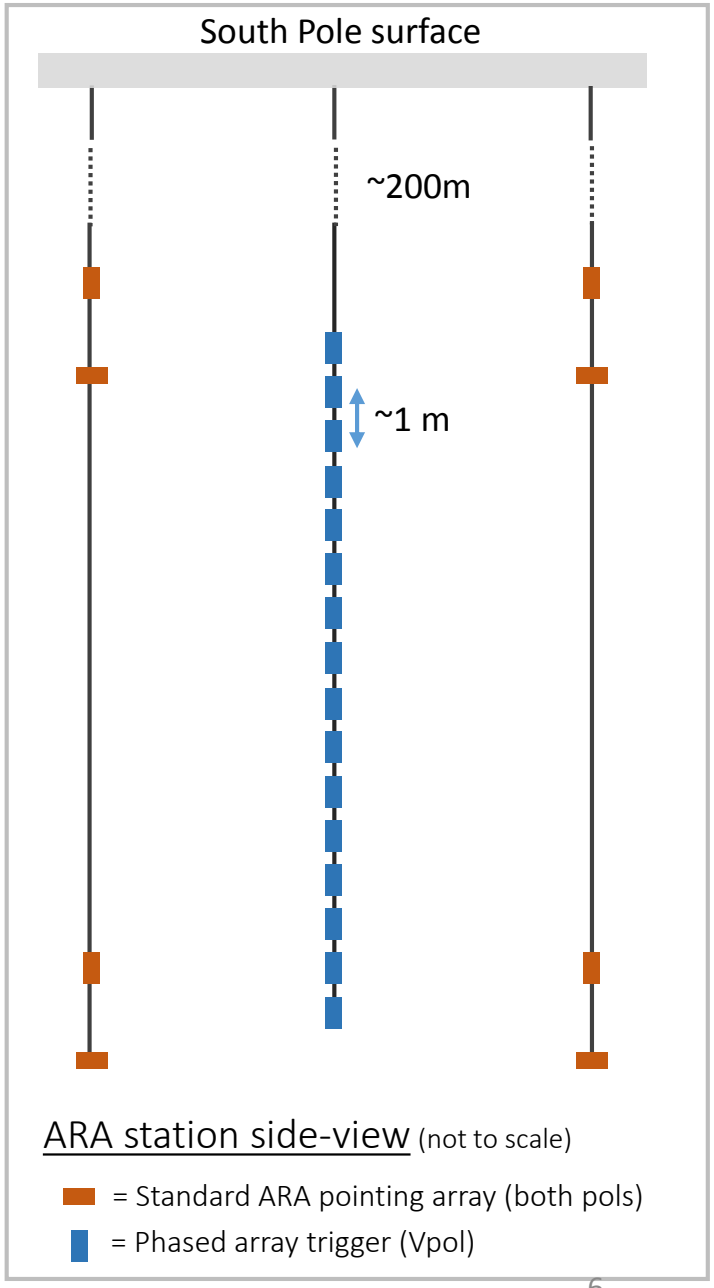
NOTE: Radio curves are shown at the trigger level and represent an ideal *in-ice* radio receiving array.



Vieregg, et al JCAP 1602 (2016)

A prototype phased array

- A 16 antenna array as an interferometric trigger system for an Askaryan Radio Array (ARA) station
- Digital processing and correlation:
  - Antenna signals digitized using streaming analog-to-digital converters
  - ‘Phasing’ on a Field-programmable gate array (FPGA) via delay-and-sum beamforming
  - Search for transient power in each formed beam
  - Set trigger rate in each beam direction, targeted to expected neutrino flux
- Deployment this season (2017/18) at the South Pole

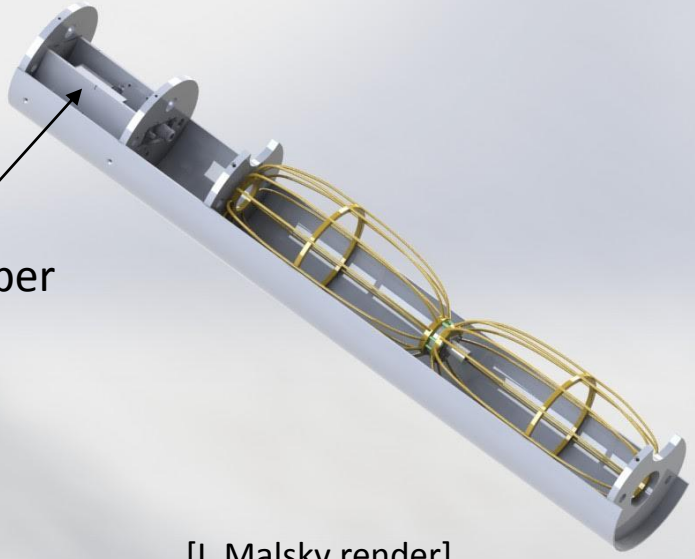


In-ice phased array

Planning a dual-polarization array: 8 of each horizontally (quad slot) and vertically (birdcage) polarized dipole antennas

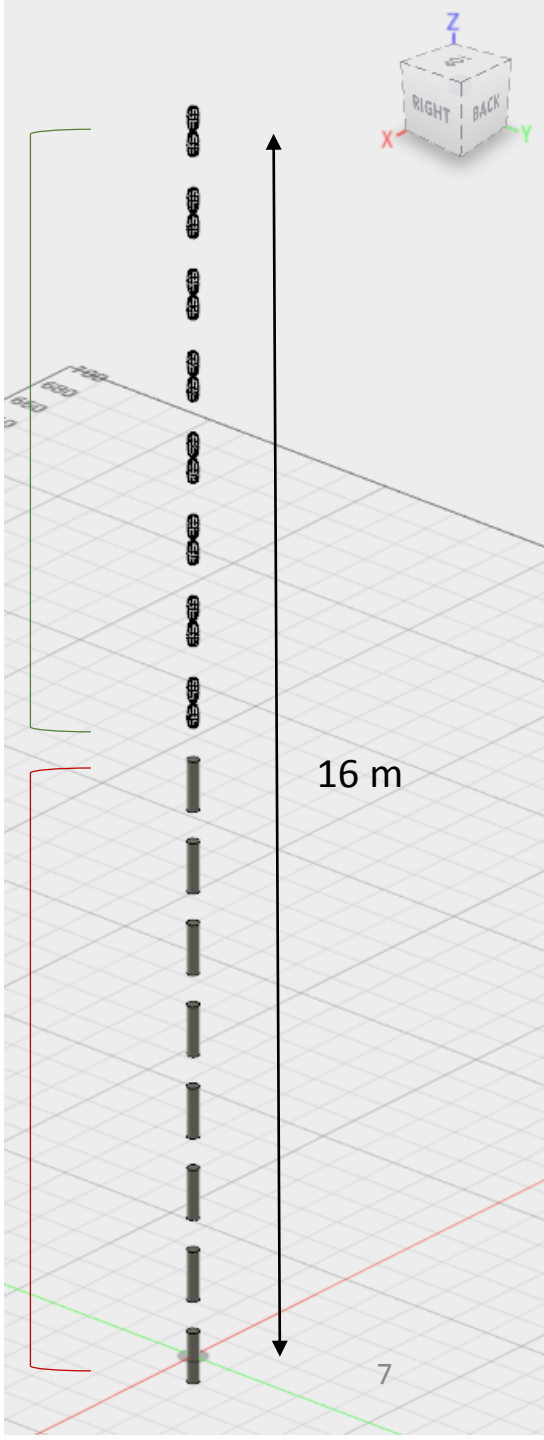
- Effectively two 8-antenna phased arrays
- Antennas designed and implemented by ARA [Astropart.Phys. 35 (2012) 457-477]

Vpol – repackaged to fit in 1 m spacing



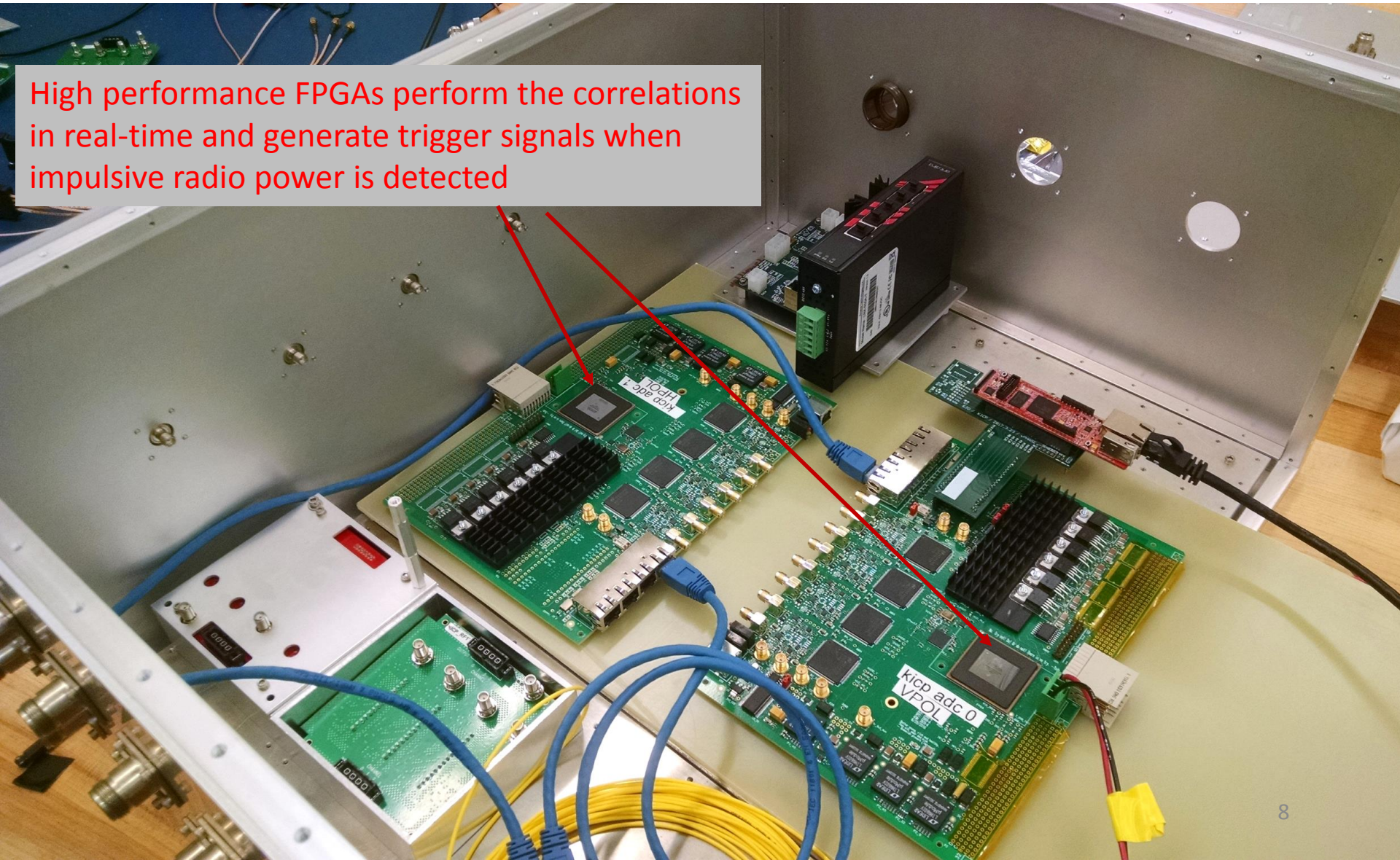
LNA+ RF-over-fiber transmiter

[I. Malsky render]



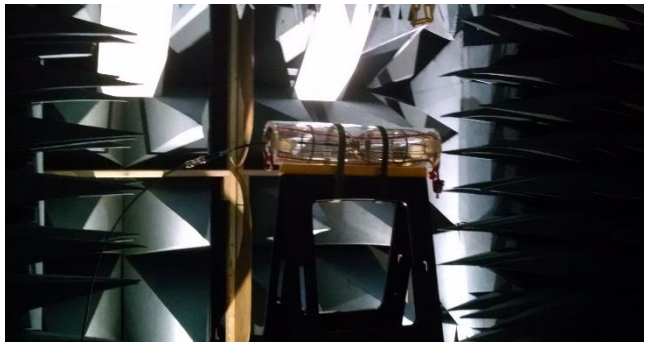
Beamforming and triggering electronics

16-channels, 1.5 Gigasample-per-second ADCs, running at 5 bit resolution



Proof of Principle

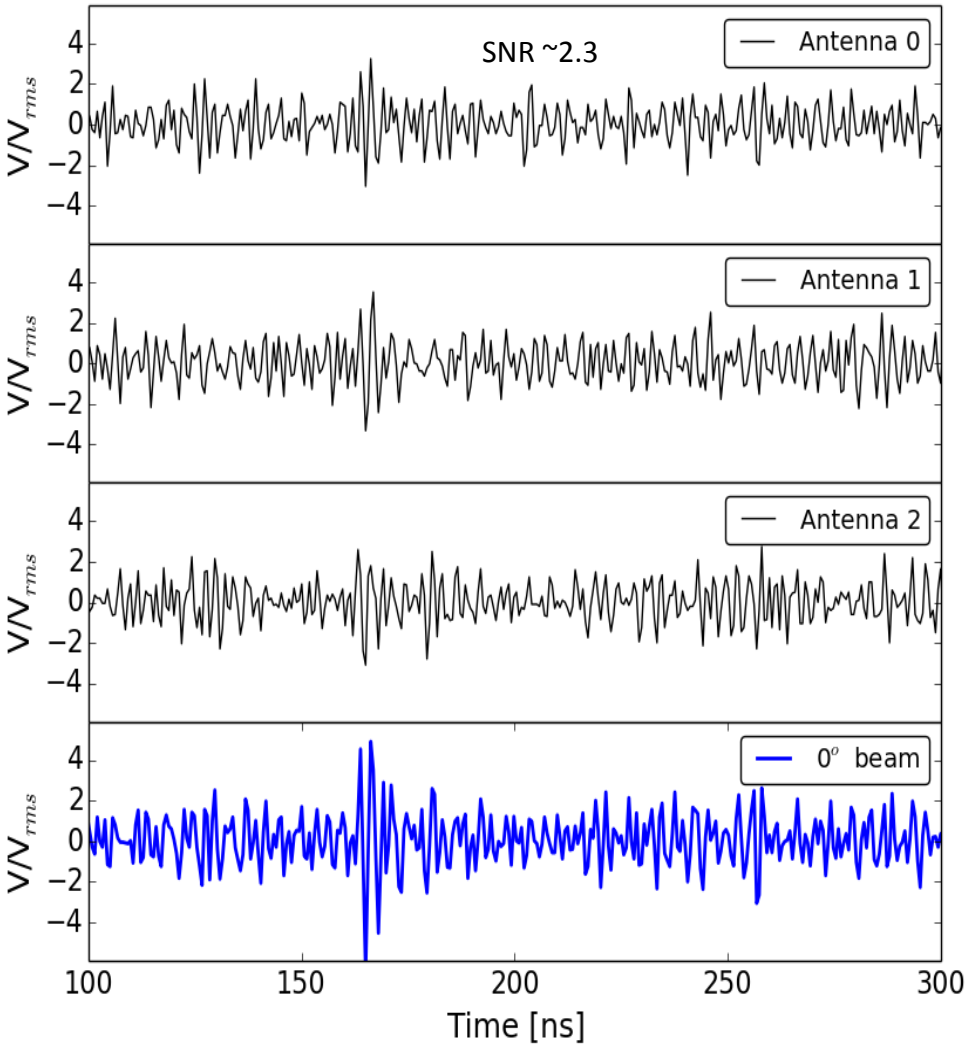
Transmitting antenna + variable attenuation



Few meters

Test receiver array of 3 antennas

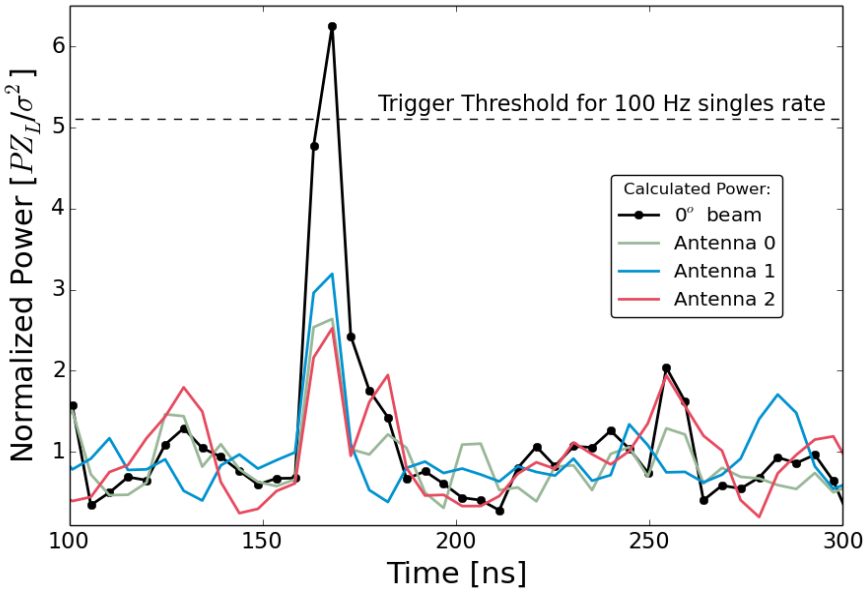
Antenna waveforms and one of the digitally-formed beams



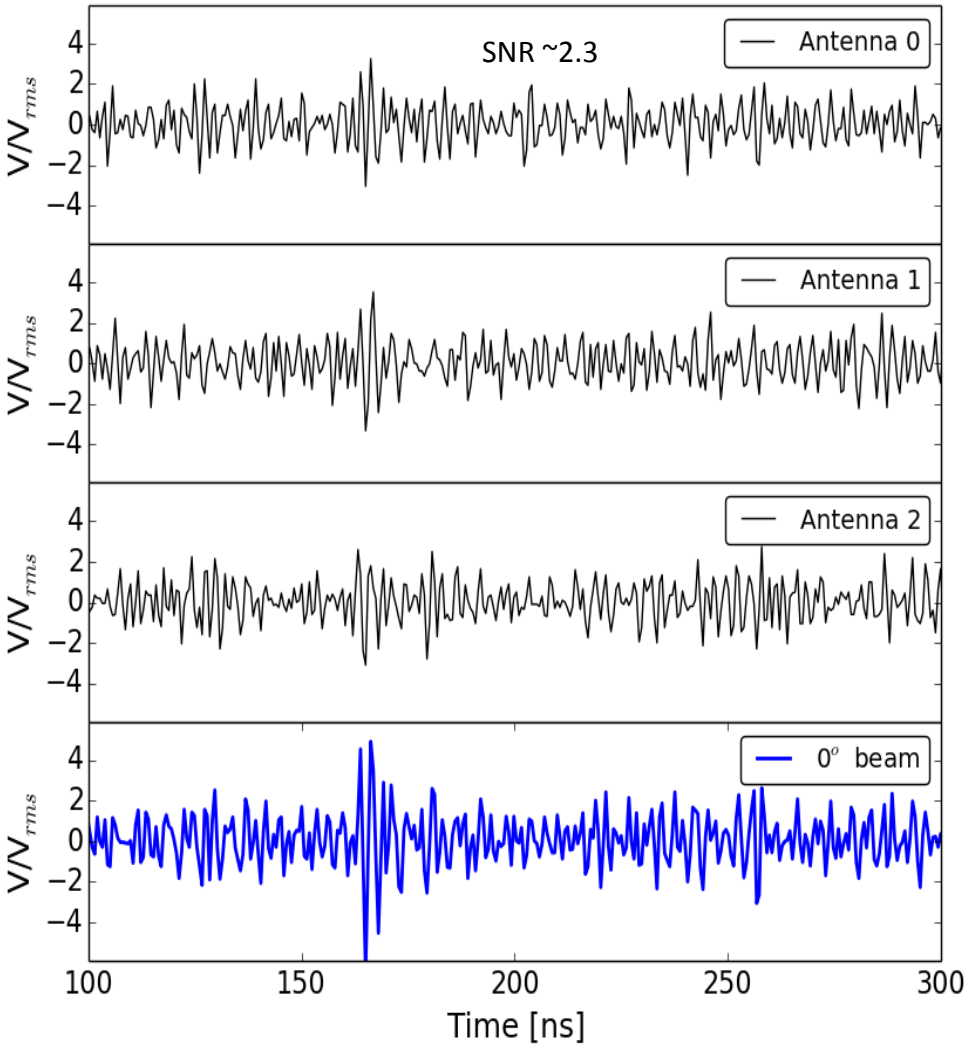
Proof of Principle

Transient power is calculated in a window of 16 samples

- Optimal window size depends on dispersion in system
- Best performance achieved if system response can be de-convolved *before* phasing

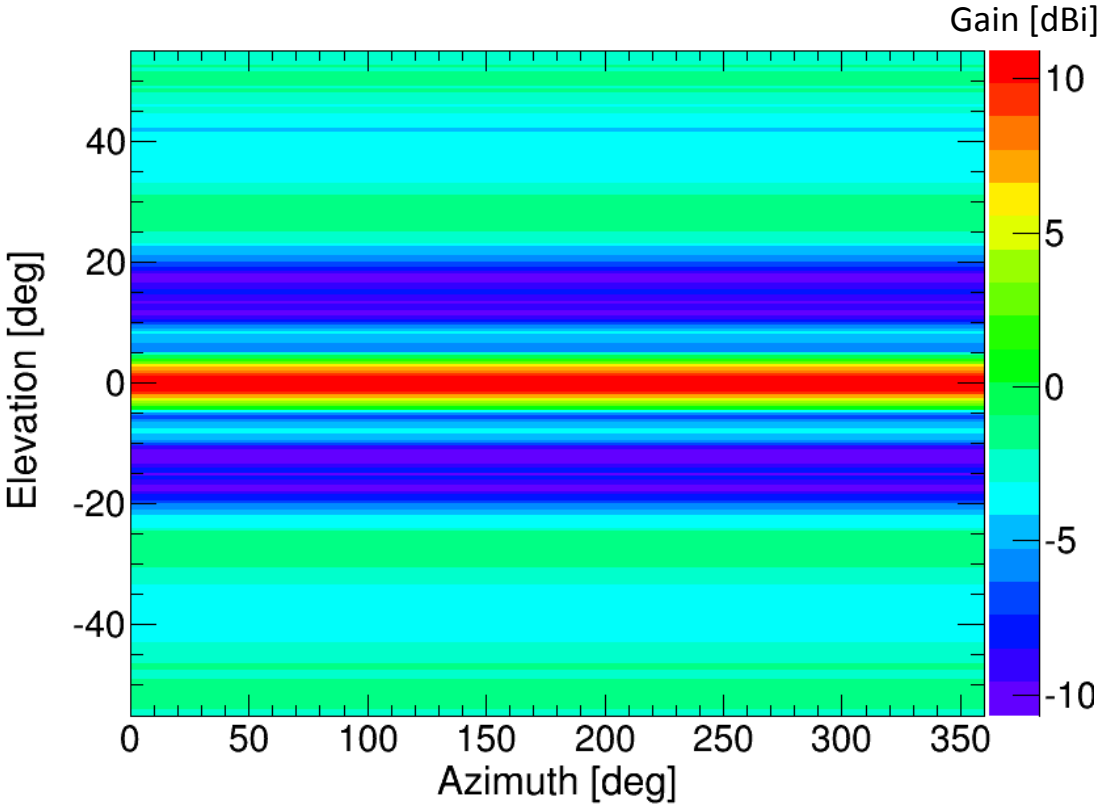


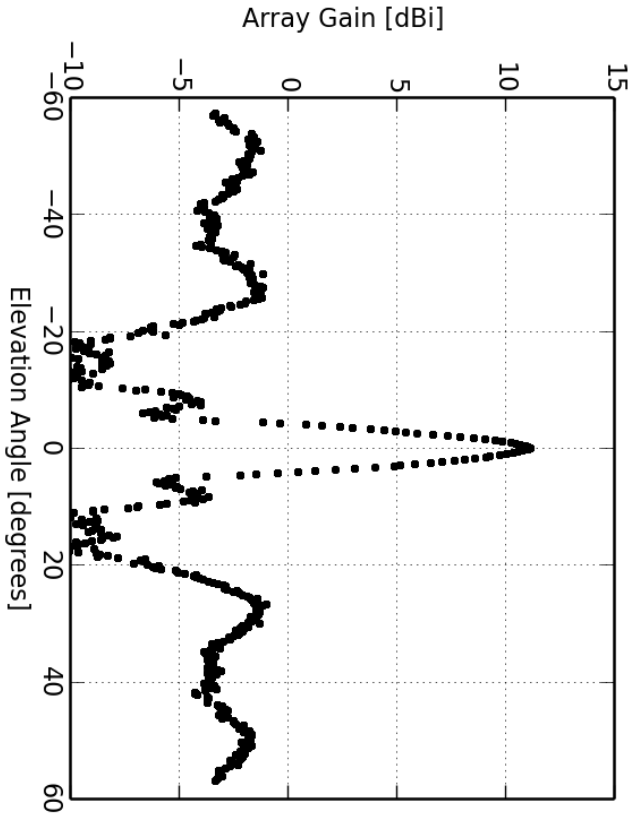
Antenna waveforms and one of the digitally-formed beams



Impulsive Phased array beam pattern

- Simulated beam pattern of 8-antenna Vpol using the measured broadband 200-800 MHz impulse response. Zero degree beam shown
  FWHM ~ 5 degrees.
- Peak directional gain at ~11 dBi -- comparable to ANITA high-gain horn antenna
- Uniform coverage in azimuth since we are phasing only in 1 dimension along the vertical array axis





Multiple Beams

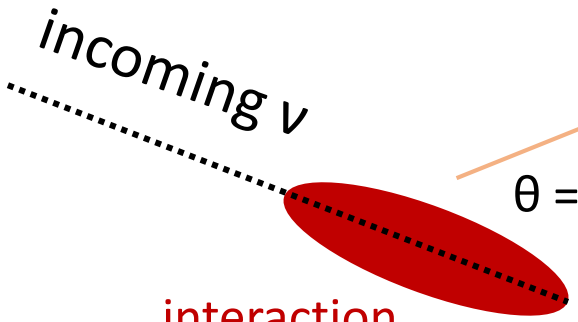
In addition to increased sensitivity, this `electronically steered' phased array can form multiple beams simultaneously over the volume of interest.

→ Each beam to is an independent trigger channel.

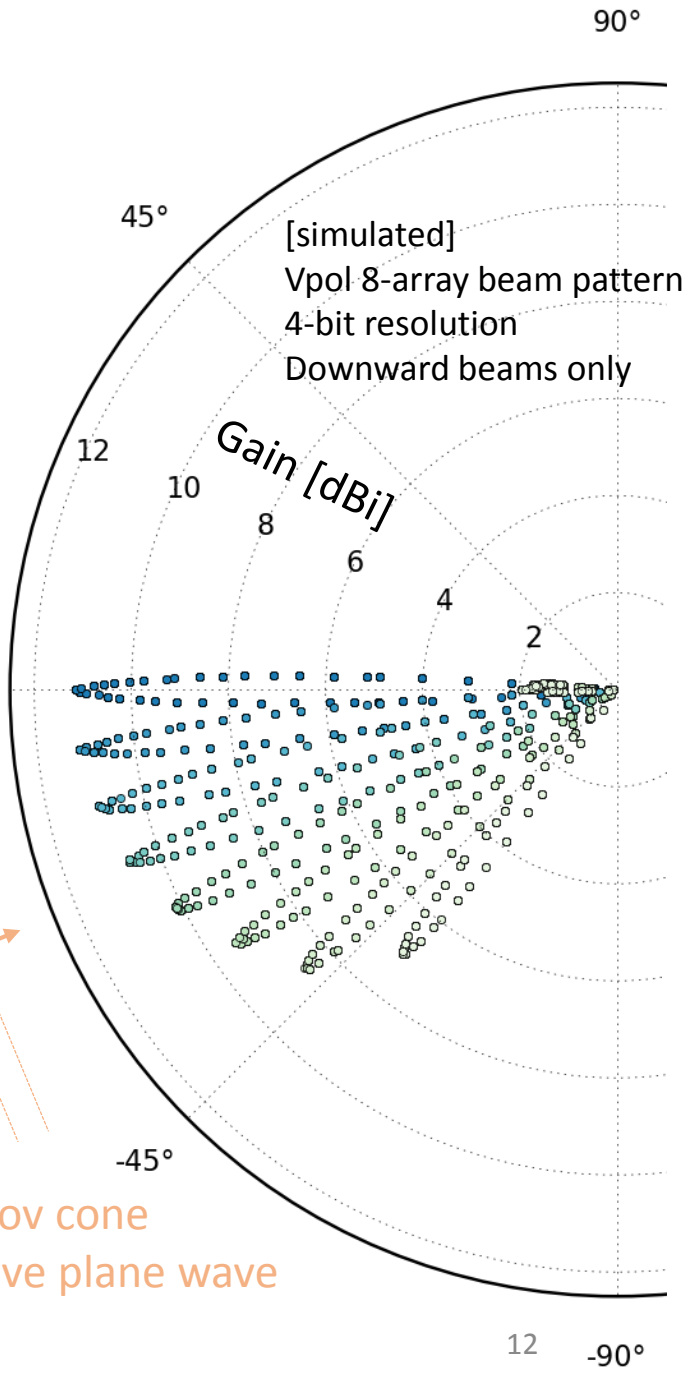
→ Set low thresholds for beams that cover the expected incoming Askaryan radiation directions

→ Set high thresholds for beams that point up and towards potential (anthropogenic) noise sources

→ Compact array: wide beams, fewer trials



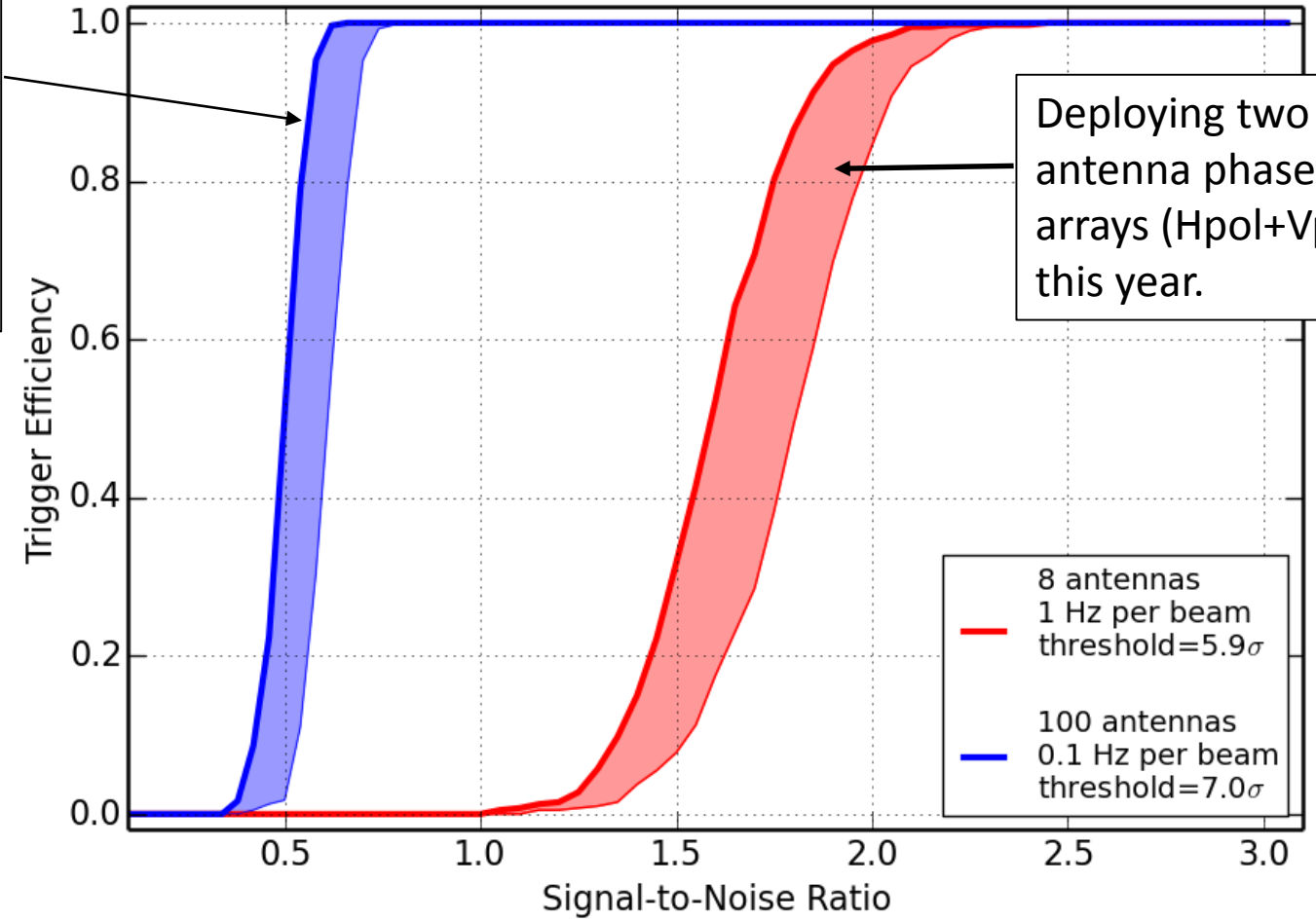
Cherenkov cone
~impulsive plane wave



Trigger Efficiency

Simulated, 4 bits at 1.5 GHz sampling and 10 Hz station trigger rate

100 antenna phased array = ability to trigger robustly on signals buried in thermal noise background

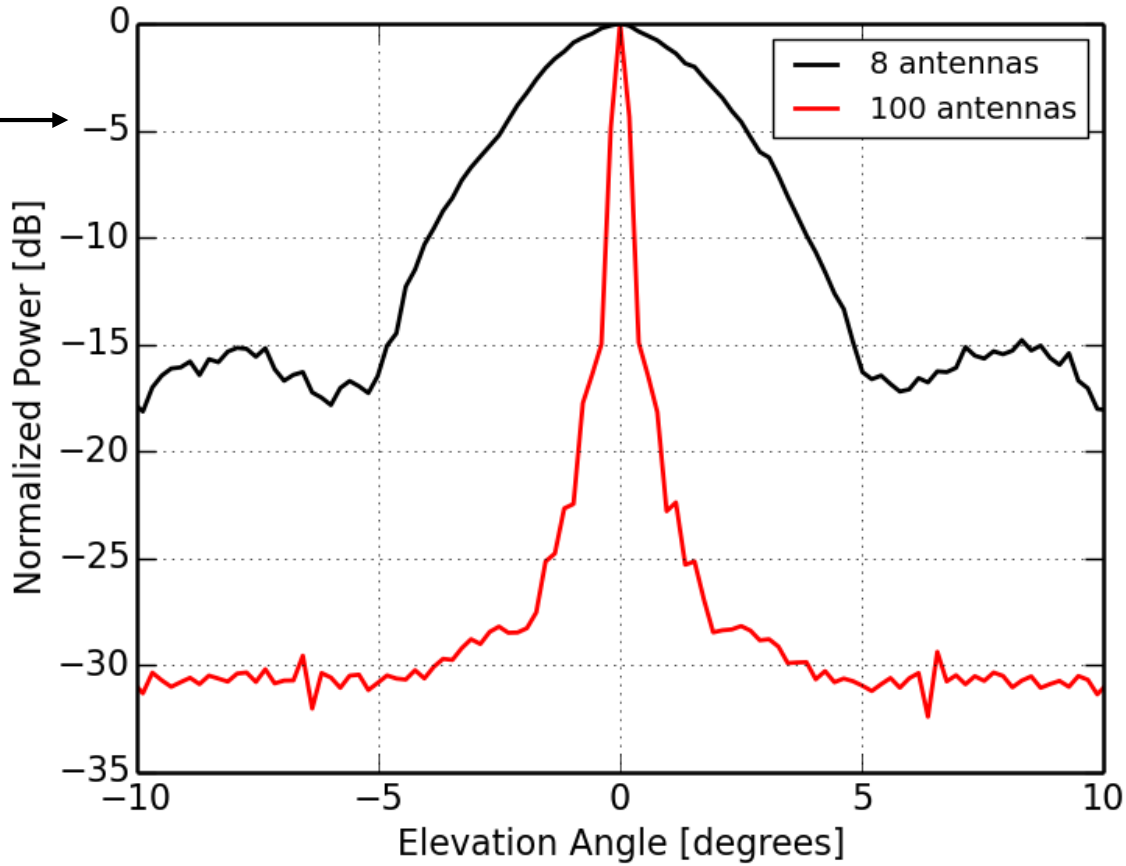


Deploying two 8 antenna phased arrays (Hpol+Vpol) this year.

(Pulse signal to noise ratio as measured at a single antenna in the array)

Scaling to 100's of phased antennas

- Beams become much narrower (sub degree) requiring more complicated FPGA designs



- 3D Array geometry: beamform in both elevation and azimuth.

- Power consumption and cost:

→ Move to front-end ASIC instead of commercial ADC chip
→ Combine analog and digital beamforming

Summary

- We are deploying a 16 channel phased array as a directional trigger system for impulsive radio signals this year with the ARA collaboration
- Radio phased arrays with ~100 antennas have the potential to complement IceCube's high-energy searches in the ~10-100 PeV regime.

[S. Wissel, Summit Station 2015]