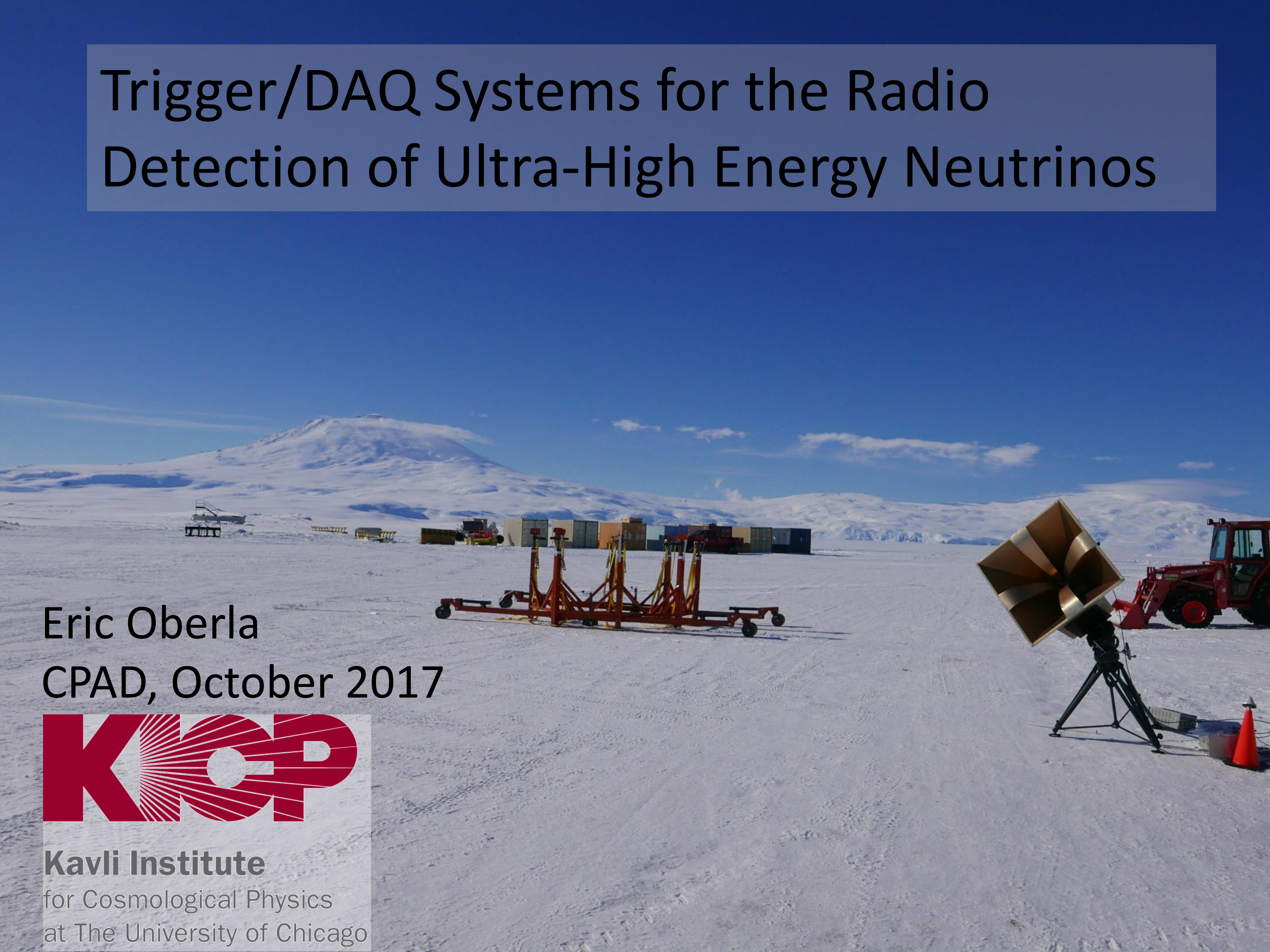
Trigger/DAQ Systems for the Radio Detection of Ultra-High Energy Neutrinos



Eric Oberla
CPAD, October 2017

KICP
Kavli Institute
for Cosmological Physics
at The University of Chicago

OUTLINE

- Background + detection mechanism
- Overview of the ANITA and ARA Trigger/DAQ systems
- Future directions: lowering the energy threshold of radio detectors with phased arrays

Neutrinos: An Ideal UHE Messenger

- The GZK process: Cosmic ray protons (E > $10^{19.5}$ eV) interact with CMB photons

$$
\begin{aligned}
p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} & \\
& \rightarrow \mu^{+} + \boxed{\nu_{\mu}} \\
& \quad \rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}}
\end{aligned}
$$

Neutrinos point directly back to sources

What type of detector is needed to discover these GZK neutrinos?

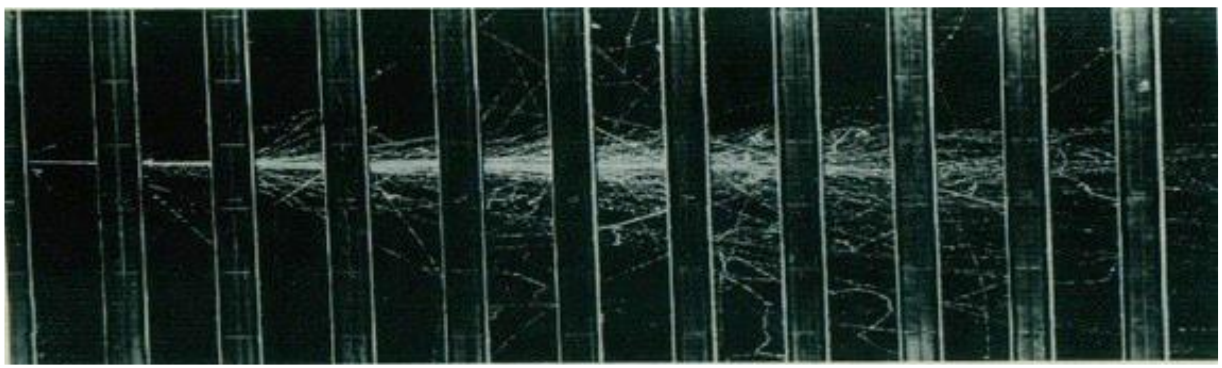
- ~1 GZK neutrino/km^2/year
- Lint ~ 300 km → 0.003 neutrinos/km^3/year
- Need a huge (>1000 km3), radio-transparent detector

→ Ice has long (>km) radio attenuation lengths

Detection Principle: The Askaryan Effect

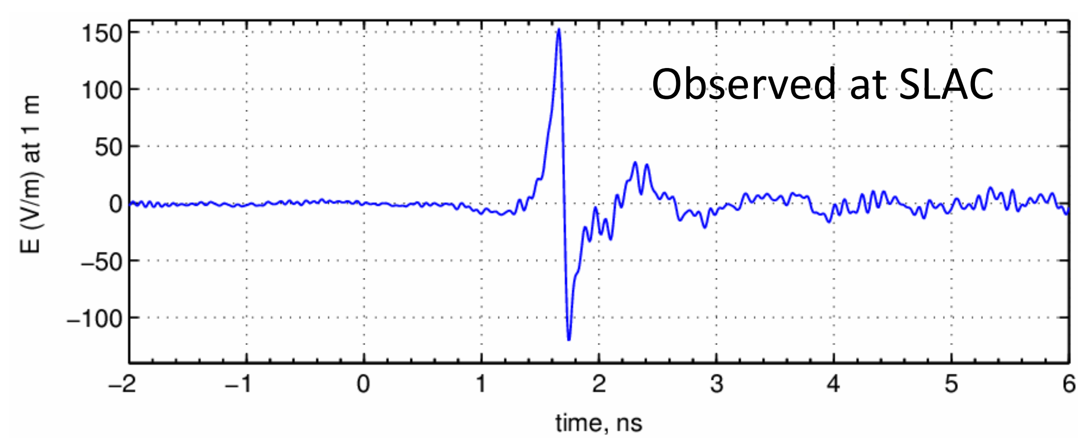
- EM shower in dielectric (i.e ice) creates fast moving negative charge excess
- Coherent radio Cherenkov radiation (P ~ E^2) if λ < Moliere radius

e^+, e^-, γ



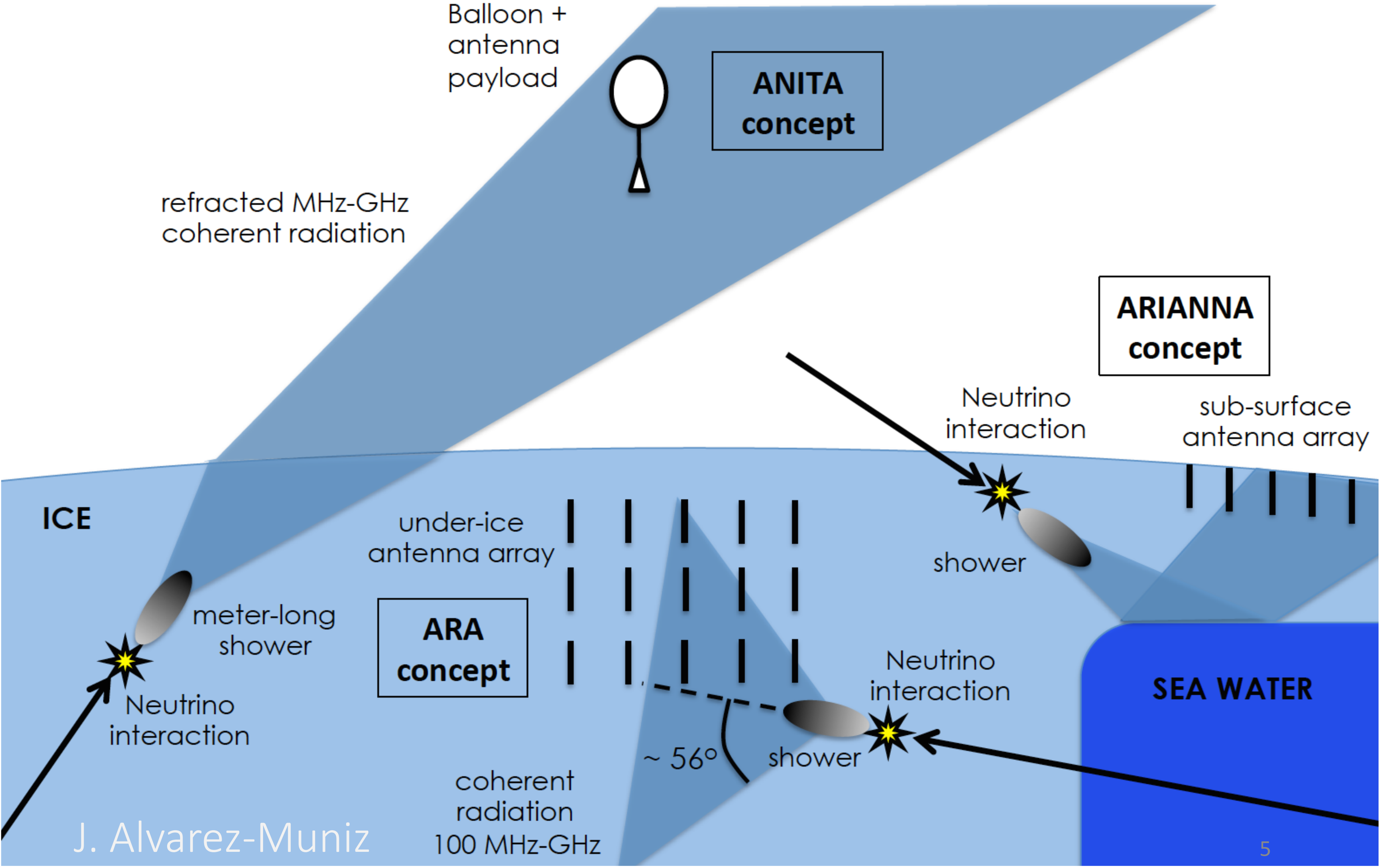
Typical scales:
L ~ 10 m
r ~ 10 cm

Radio emission stronger than optical for ultra-high energy (UHE) neutrino-induced showers



ANITA Collab., PRL 2007

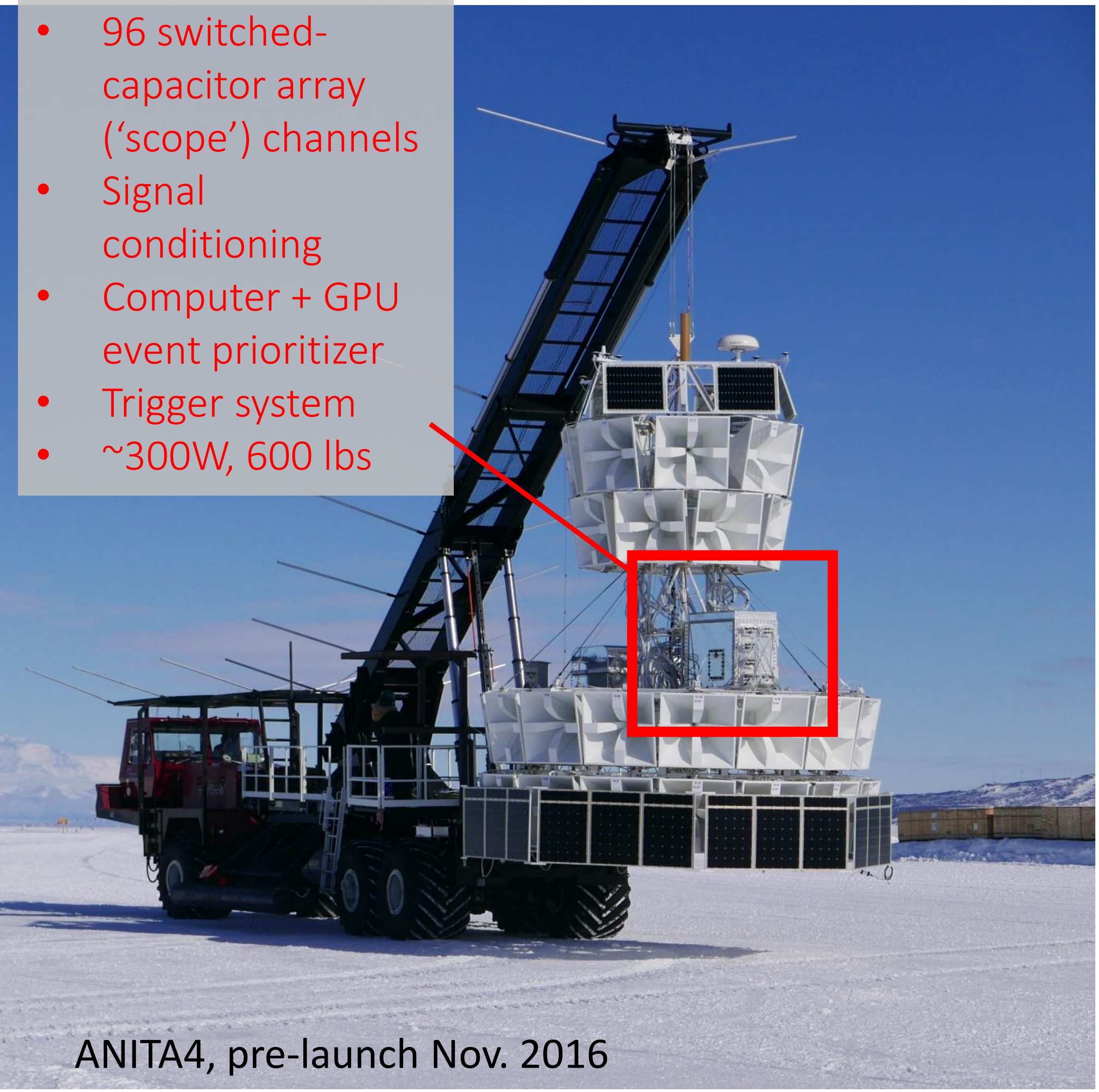
Radio Detectors using Dense Media: Ice



J. Alvarez-Muniz

ANITA

ANITA Instrument Box:
- 96 switched-capacitor array ('scope') channels
- Signal conditioning
- Computer + GPU event prioritizer
- Trigger system
- ~300W, 600 lbs

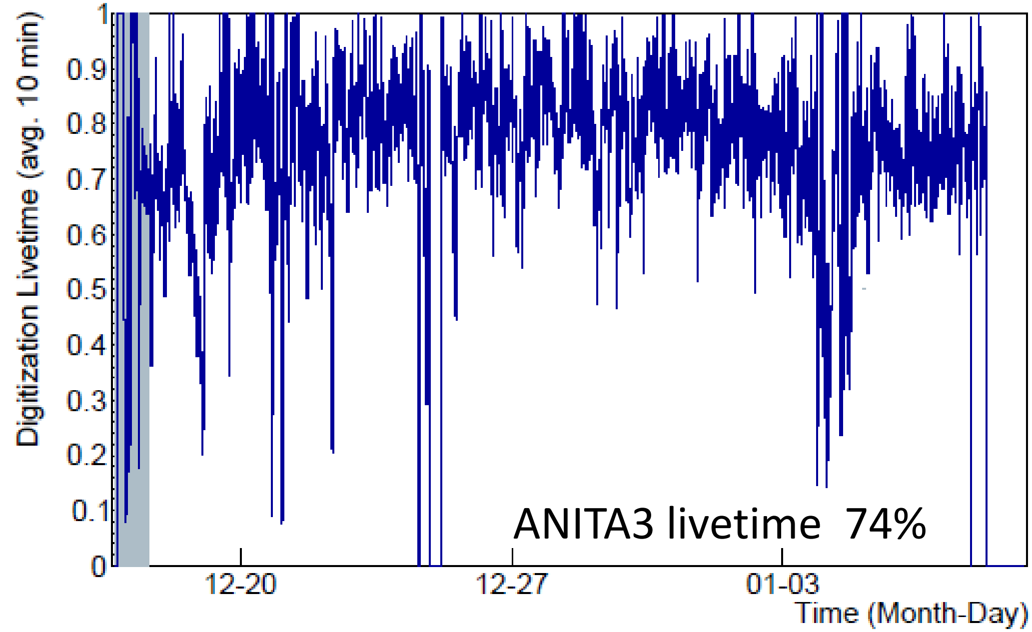


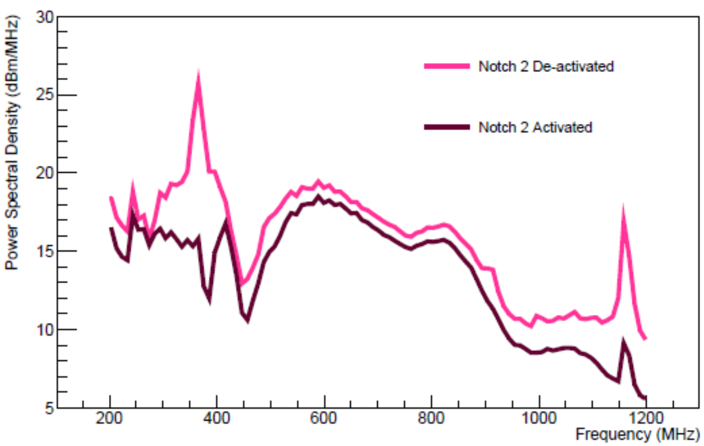
ANITA4, pre-launch Nov. 2016

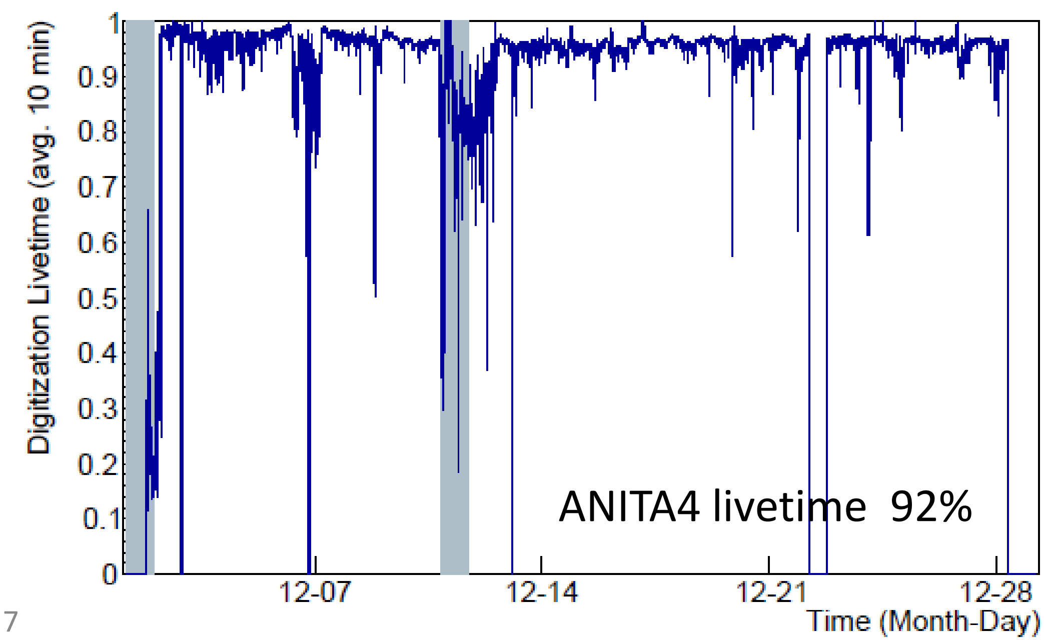
- NASA Long Duration Balloon Payload
- From float altitude (35-40 km), instruments ~10^6 km^3 of ice
- Four flights (2006,2008, 2013, 2016)
- 48 Quad-ridge horn antennas 200-1200 MHz
- Event reconstruction using timing delay between antennas (interferometry)
- Restrictive Power (~600W) and weight (~4000 lbs) budget

ANITA4 included dynamically tunable notch filters to reject satellite CW

- A large number of military satellites were launched between ANITA2 and the launch of ANITA3
- Serious interference at 260 MHz and ~380 MHz



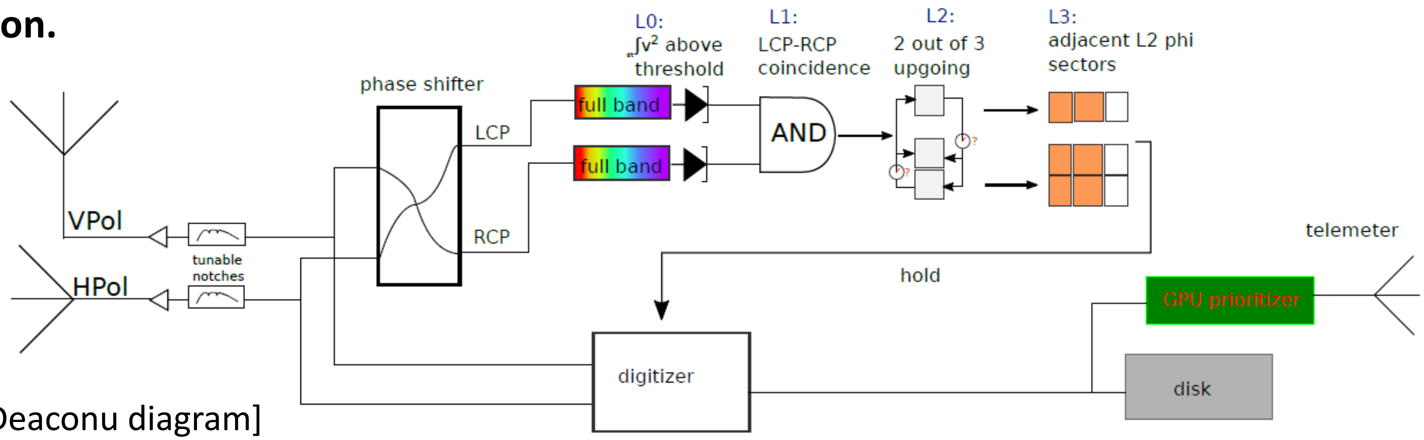




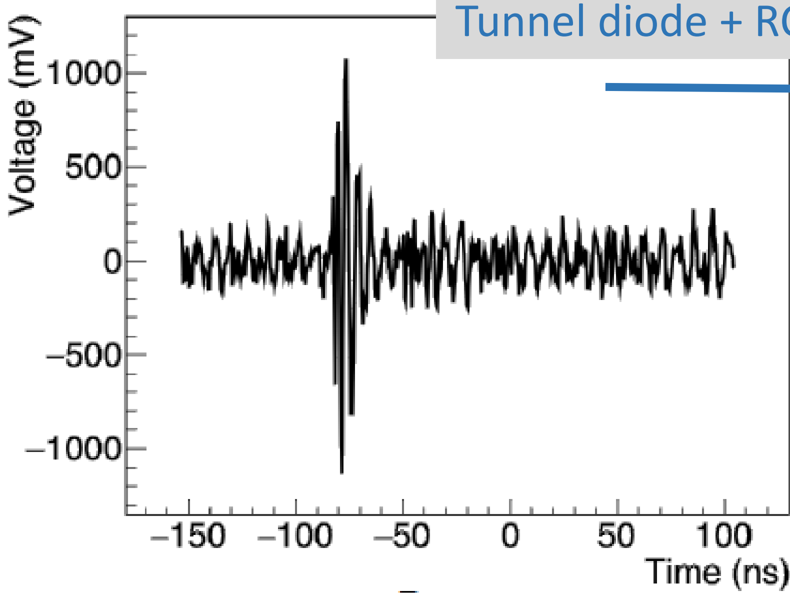
[P. Allison, O. Banerjee, ANITA collab., NIMA 869 46-55 2017]

The ANITA4 Trigger

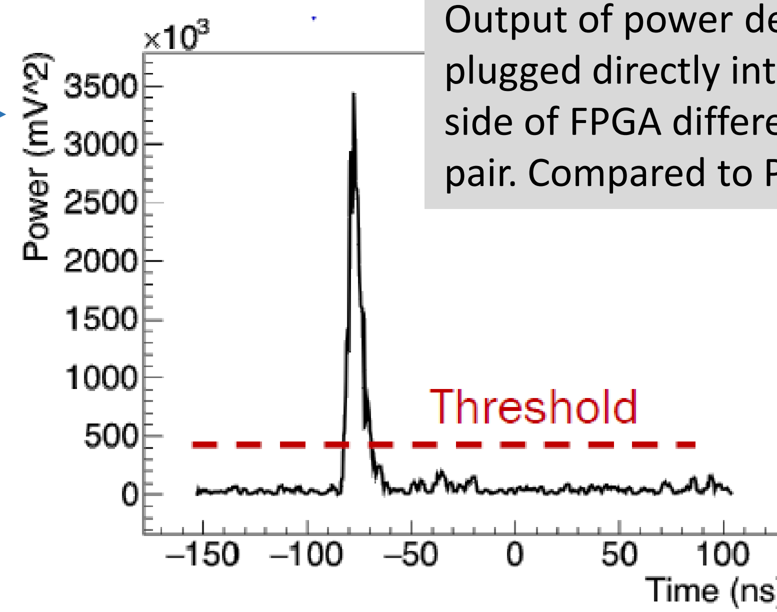
Horizontally and Vertically polarized signals sent through a coupler converting to Left and Right circular polarization, inserted into tunnel diode power detectors. Trigger requires coincidence of L and R power within a short time window: **an unbiased trigger on any linearly polarized signal while rejecting circular polarization.**



[C. Deaconu diagram]



Tunnel diode + RC



Output of power detector plugged directly into one side of FPGA differential pair. Compared to PWM DAC

The ANITA4 Trigger

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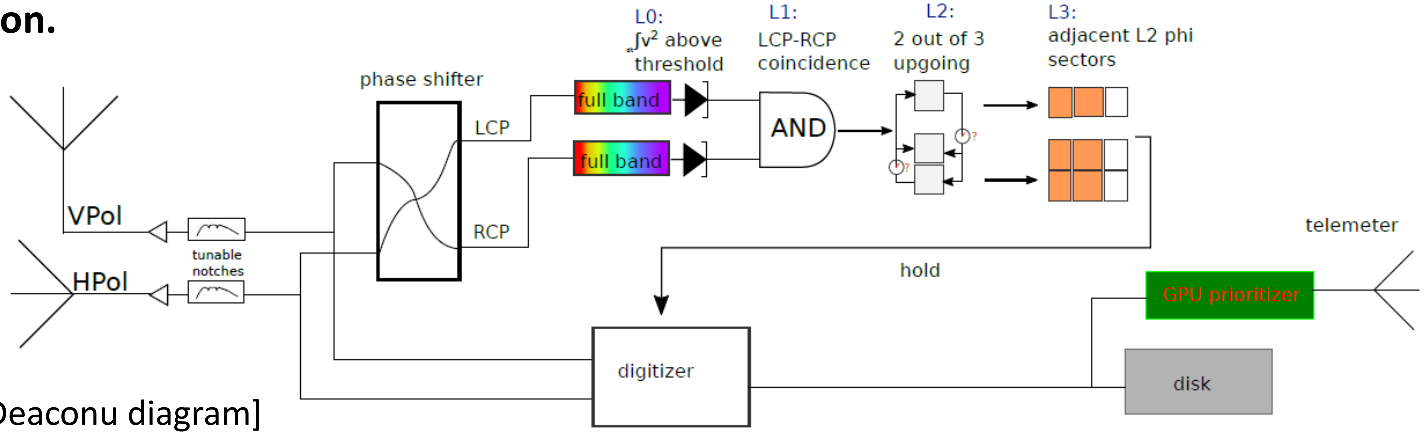
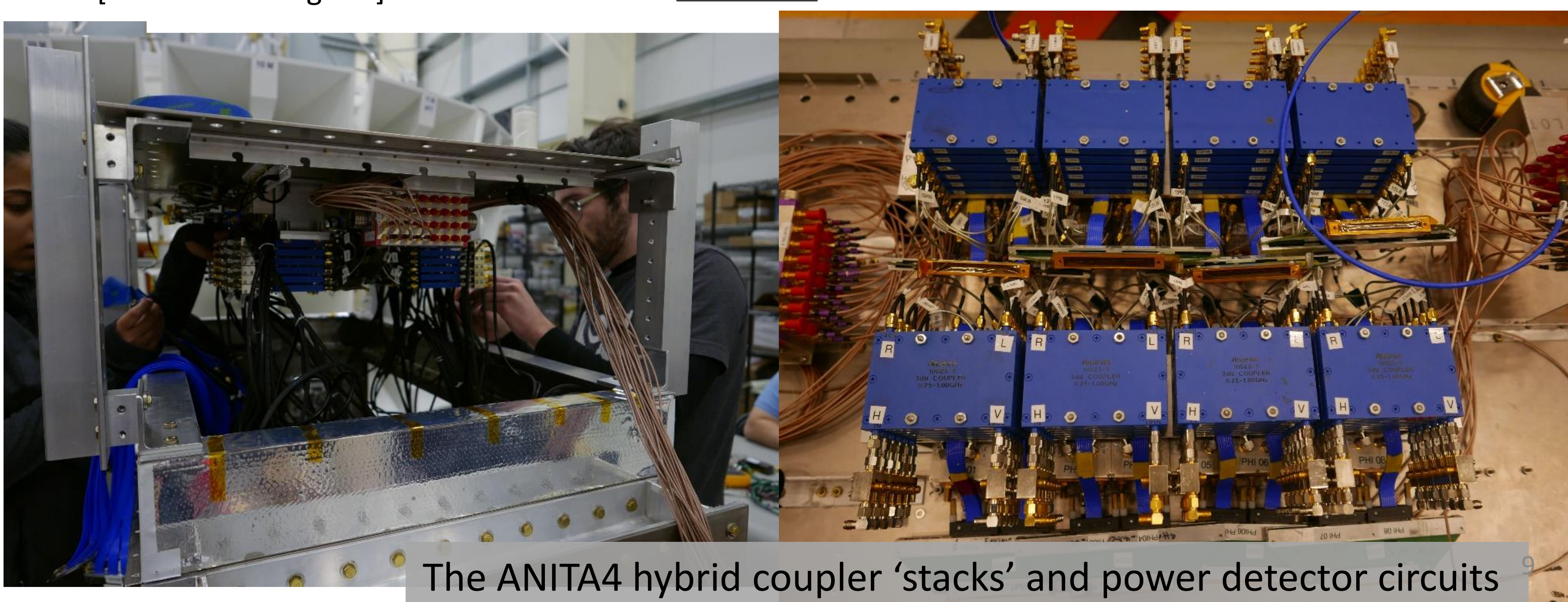


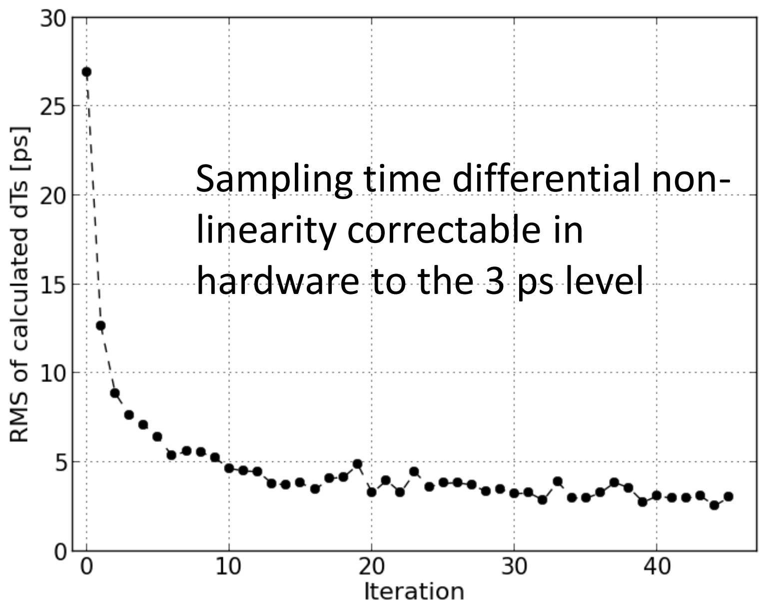
[C. Deaconu diagram]

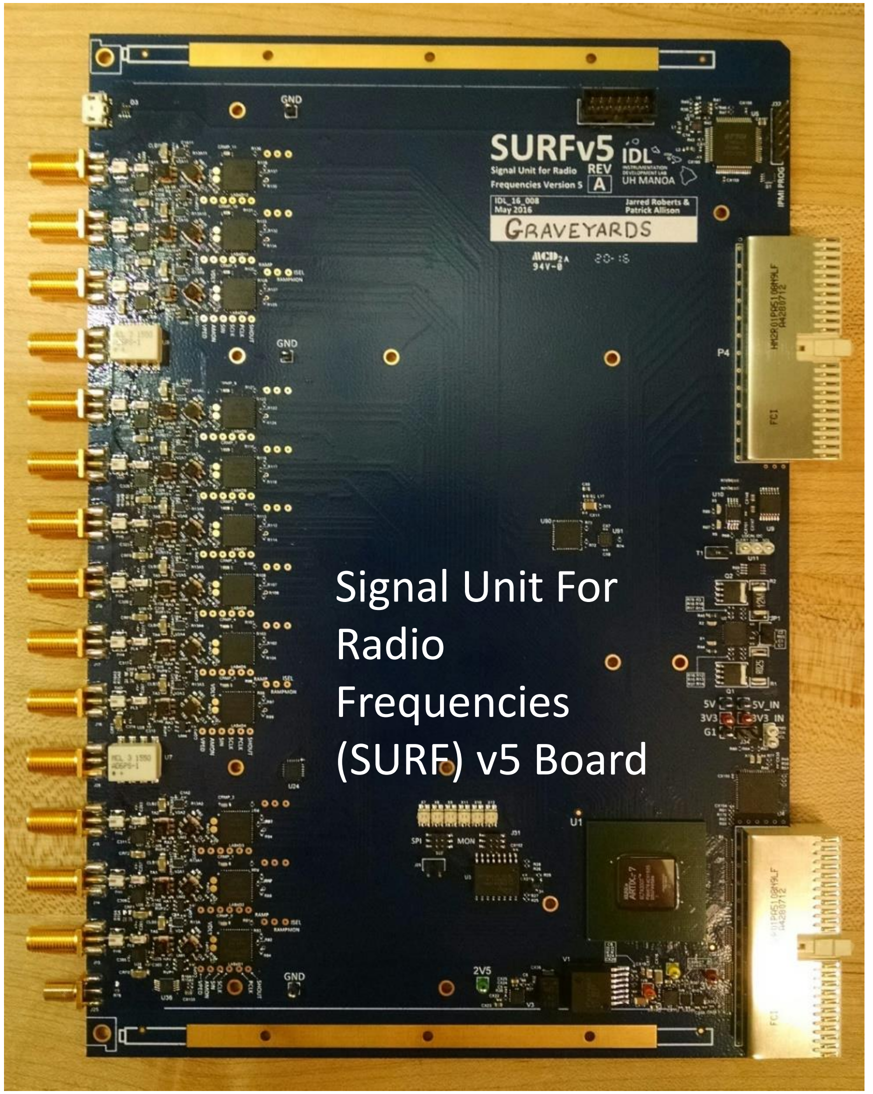


The ANITA4 hybrid coupler ‘stacks’ and power detector circuits

ANITA Data Acquisition

- ANITA flights 1-4 flew with the basically the same DAQ using the LABRADOR3 ASIC waveform sampler (2.6 GSa/s, 260 samples)
- A new system is ready for ANITA5 using the new LAB4D ASIC (Varner, UH)
  - 3.2+ GSa/s with 1024 samples per buffer and 4 buffers.
  - > 1 GHz analog bandwidth
  - Trim DACs on each sample allows for correcting sampling time non-linearity

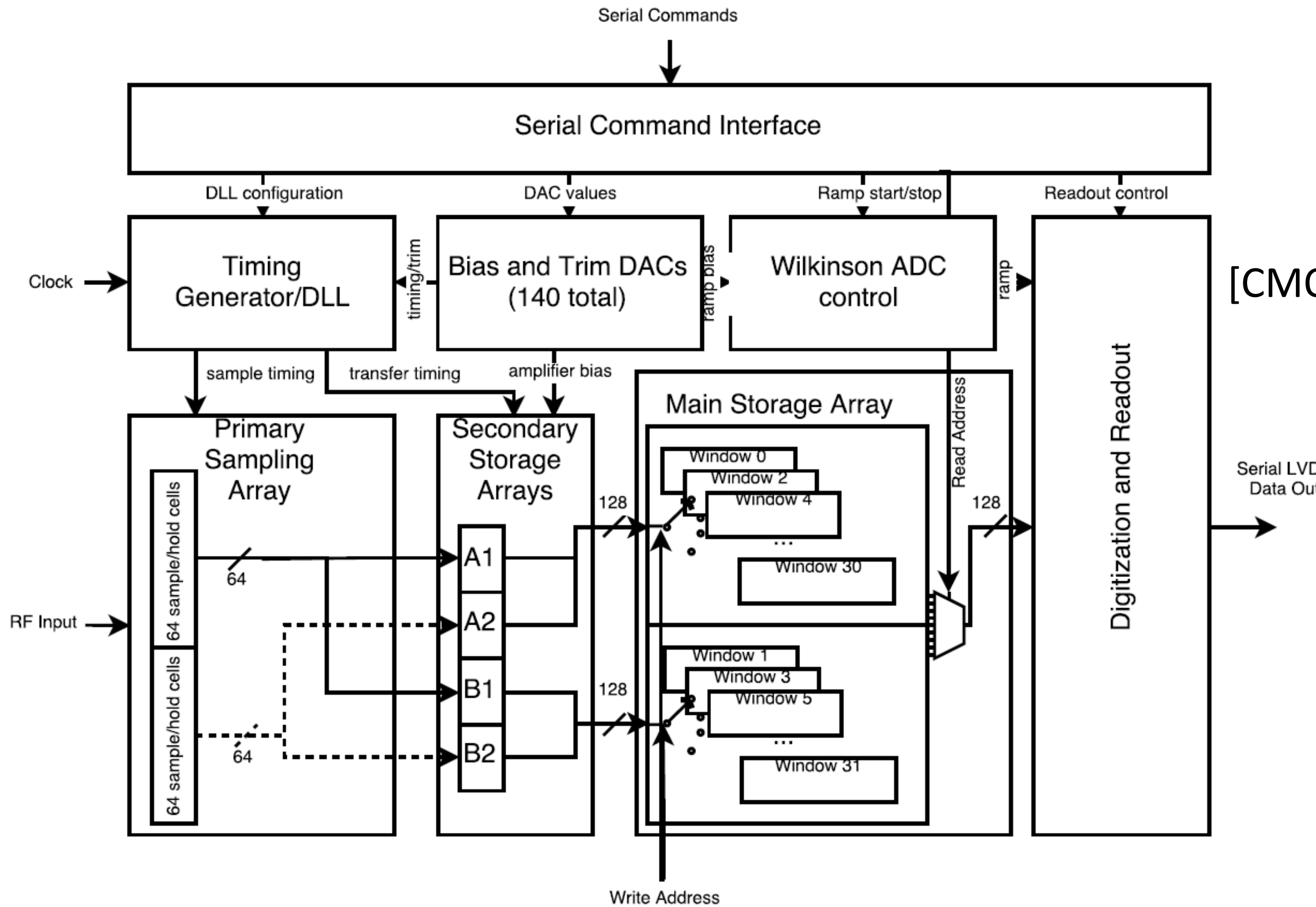




[Varner, et al NIMA 583 2007],
[P. Allison, EO, J. Roberts, G. Varner, in prep]

The LAB4D ASIC

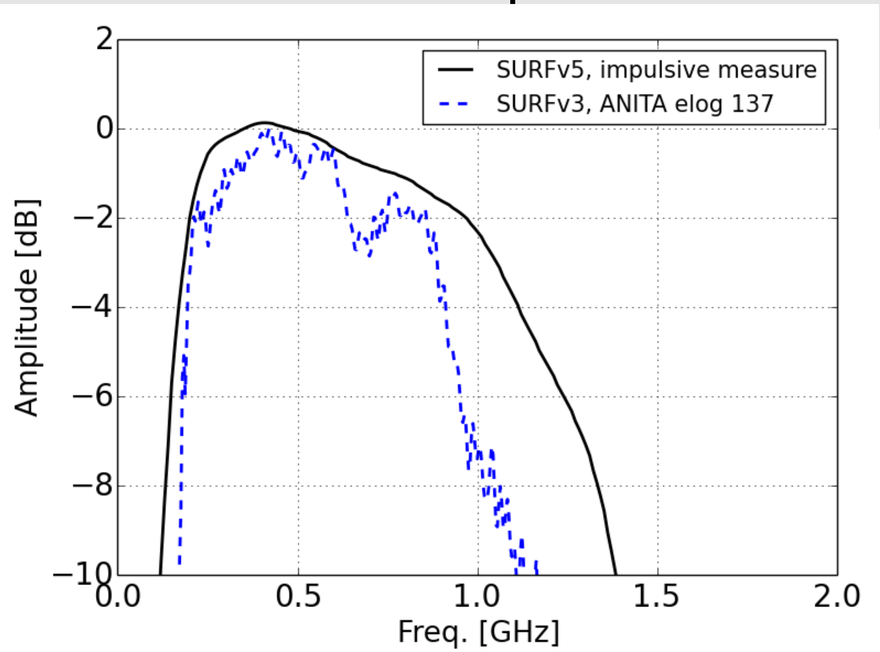
- Single channel per chip: allows for precision timebase tuning and eliminates on-chip crosstalk
- 48 pin QFN package. All analog biases generated internally
- 128 sample primary sampling array. Data are buffered to a 4096-sample deep storage array



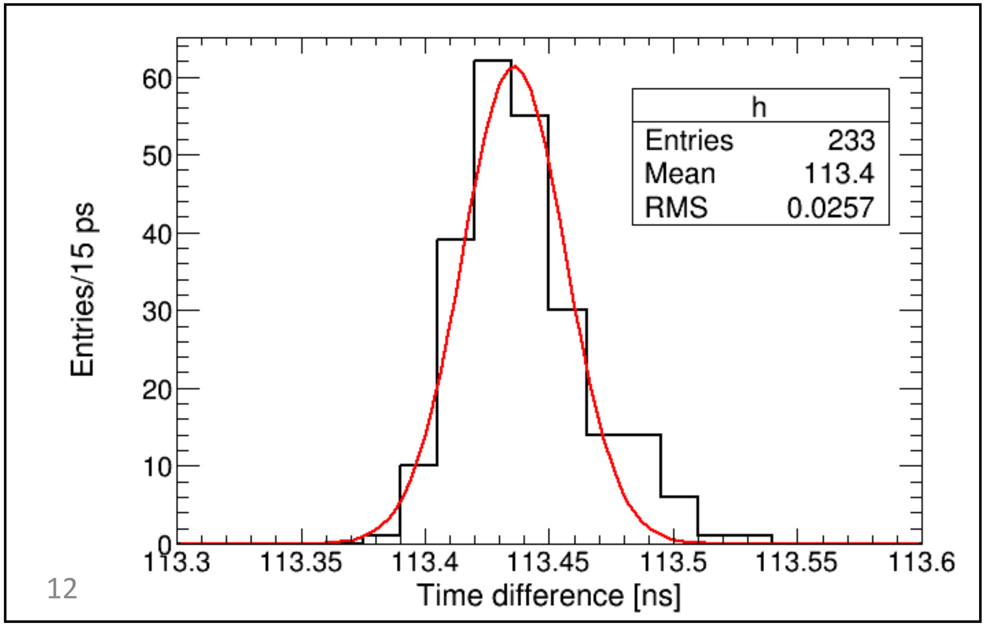
[CMOS 0.25 micron]

LAB4D ASIC – major improvements for a possible ANITA5 mission

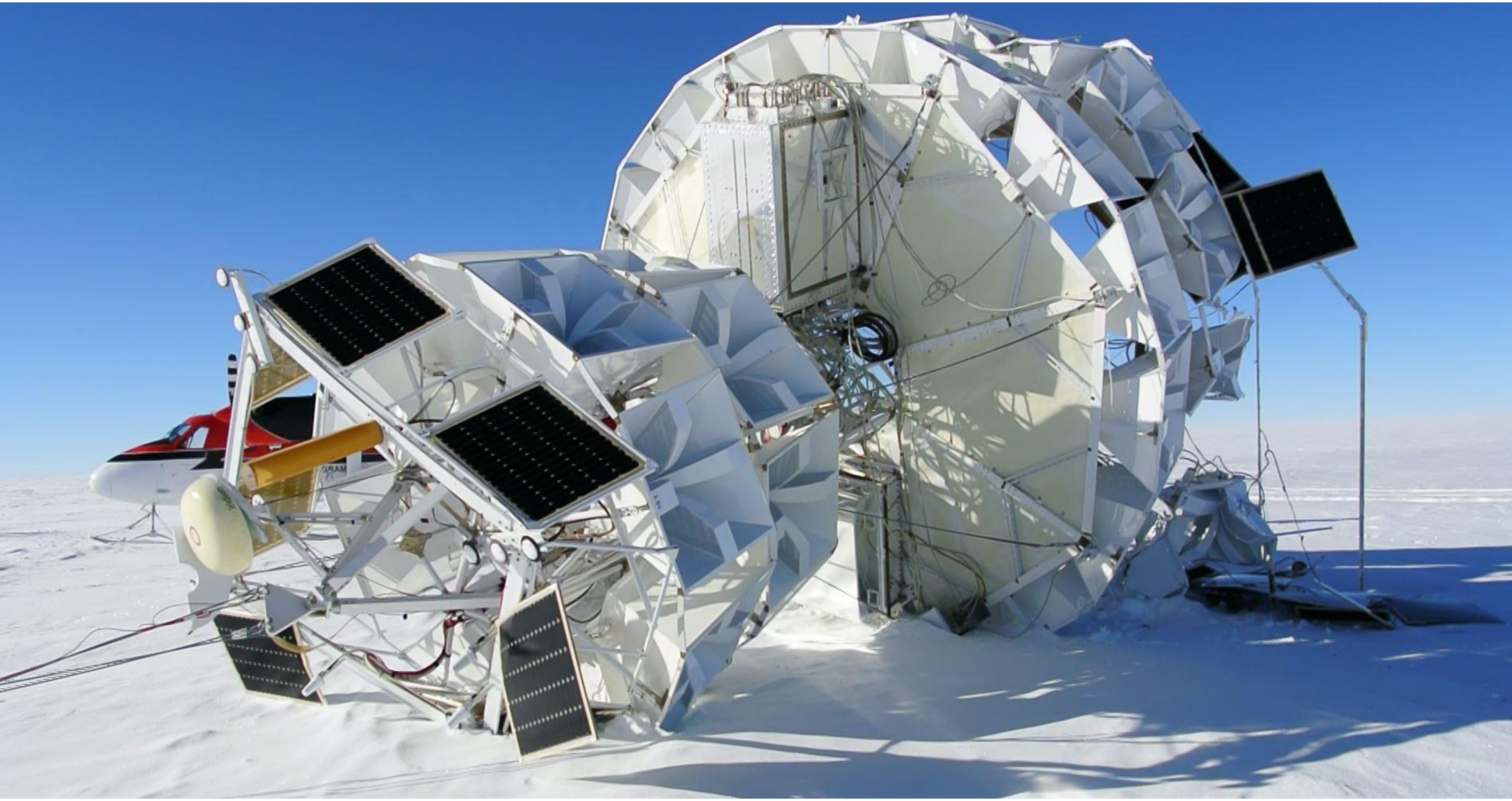
Analog Bandwidth > 1 GHz
(band defined by filters, not limited by the chip!)



Time-difference resolution better than 30 ps (on a baseline of ~110 ns) without any software corrections of timing or other non-linearities



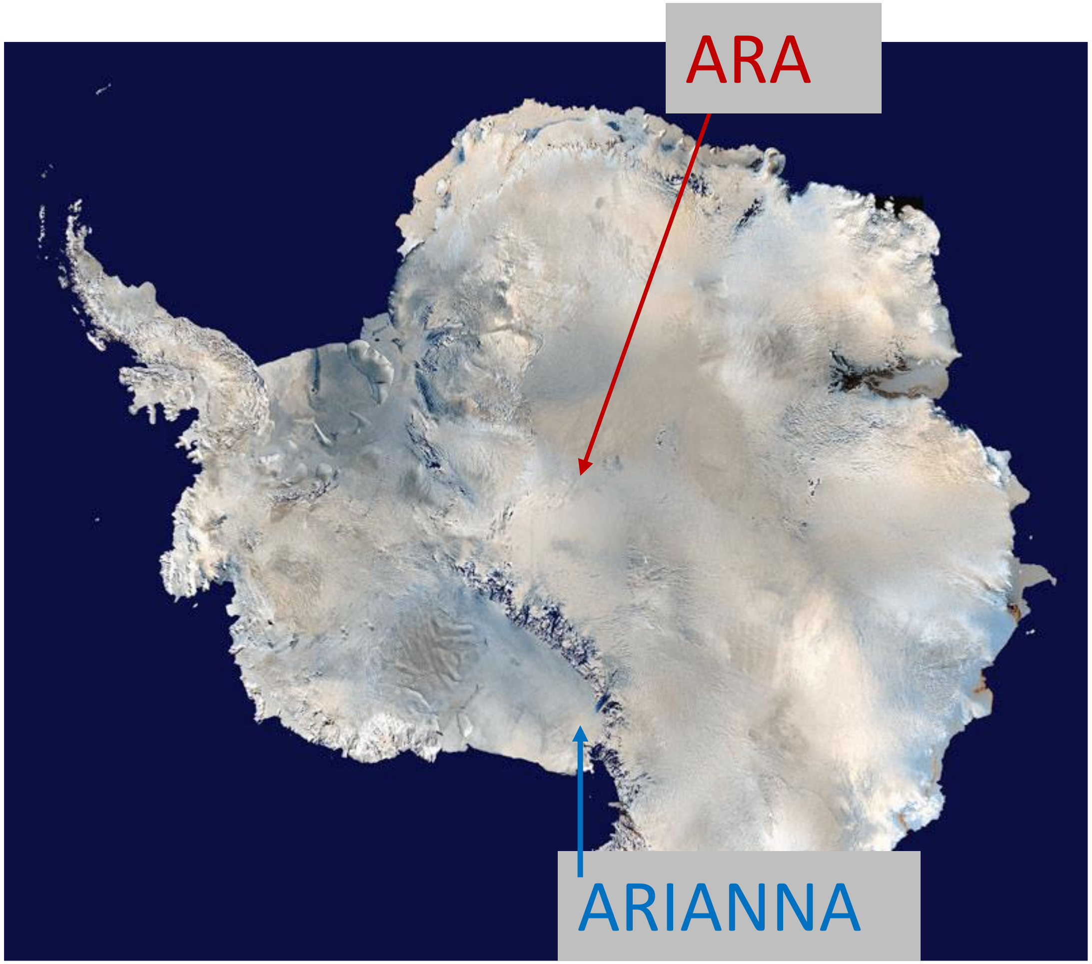
Going to ground-based detectors



[C. Miki photo, January 2017]

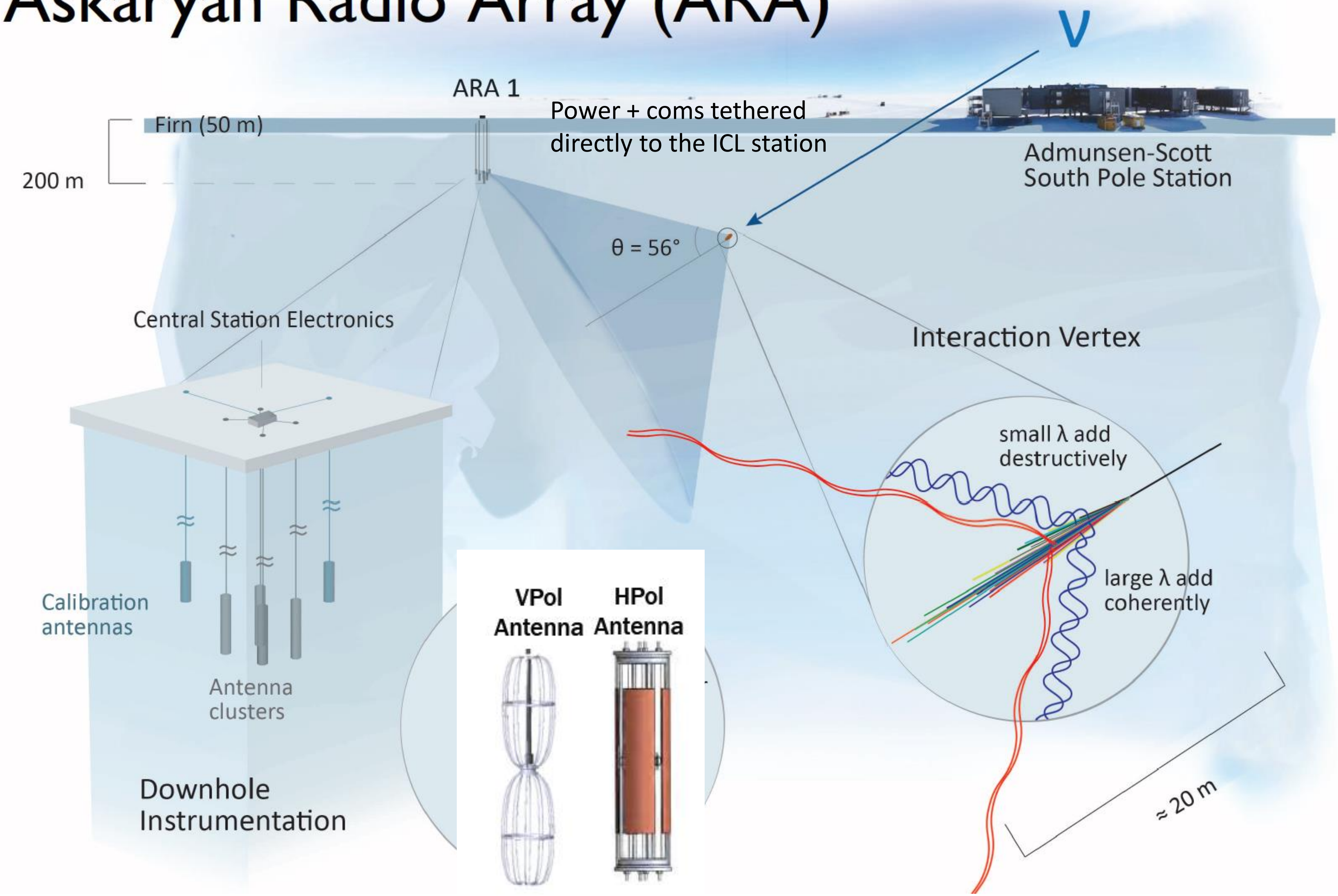
Discovering UHE with radio: Need ground-based detectors

- More livetime: 300 days/year vs 30 days/3 year
- Lower energy threshold than a balloon experiment
- Not limited by a launch envelope: can deploy many more antennas
- But: smaller instrumented volume



I won’t have time to discuss the ARIANNA system: please see Kleinfelder, arXiv:1511.07525

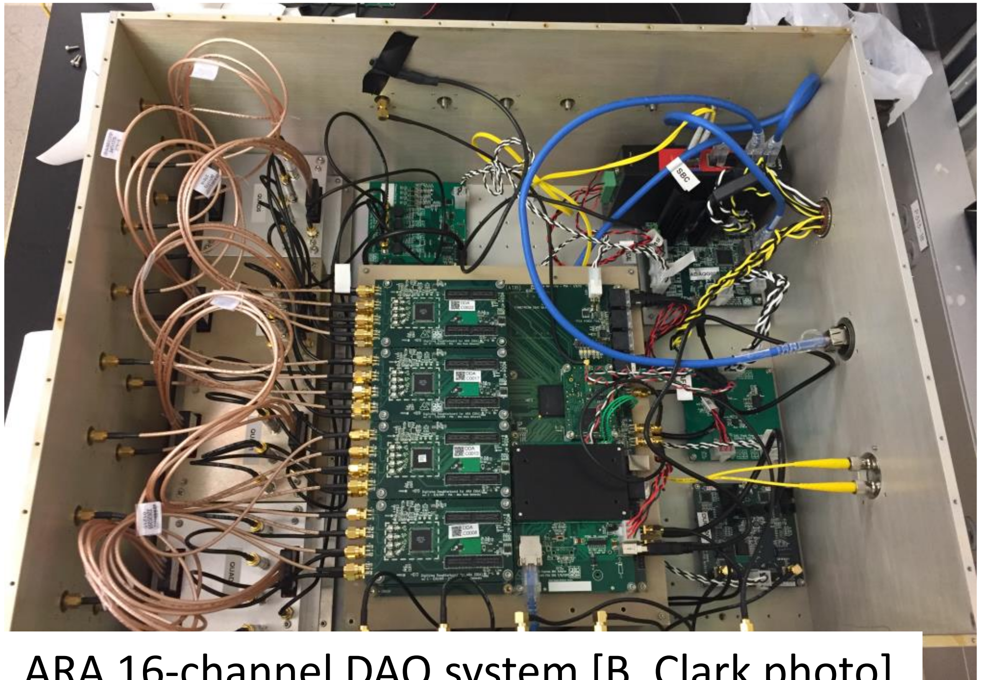
Askaryan Radio Array (ARA)



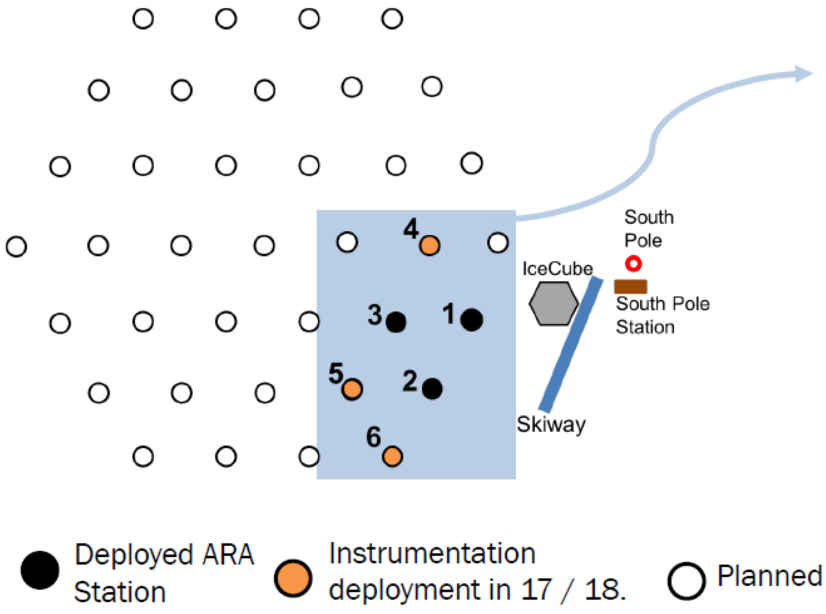
Each station has 8 Hpol slot and 8 Vpol bicone antennas at a depth of ~200m

ARA detector

- Currently 3 stations installed at the South Pole. Plan for 37 stations, each spaced ~2 km apart.
- Major deployment this year: 3 more stations with improved electronics and risk mitigation
- New stations tested at -40 C ambient conditions for weeks before shipping
- ARA trigger uses tunnel diode power detectors. Coincidence logic requires 3/8 antennas above threshold of same polarization in ~110 ns window
- Nominal continuous event rate is 7 Hz / station → 10^8 evts/year/station

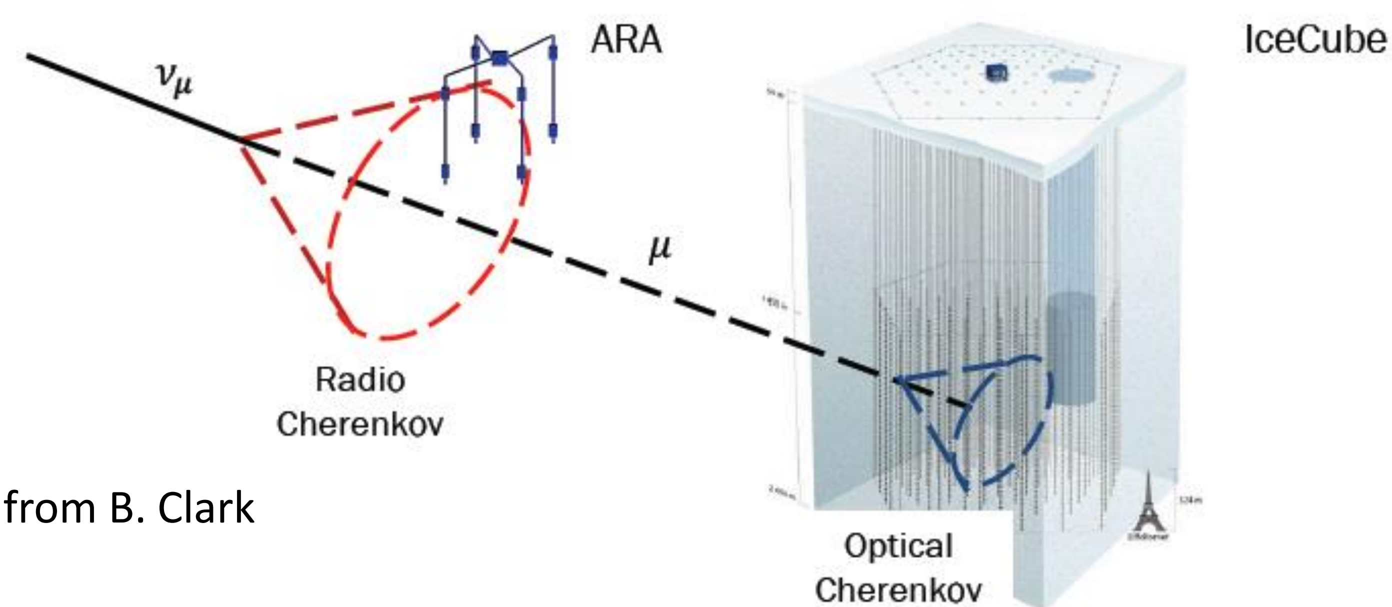


ARA 16-channel DAQ system [B. Clark photo]



New ARA stations equipped with Precision Time Protocol (PTP)

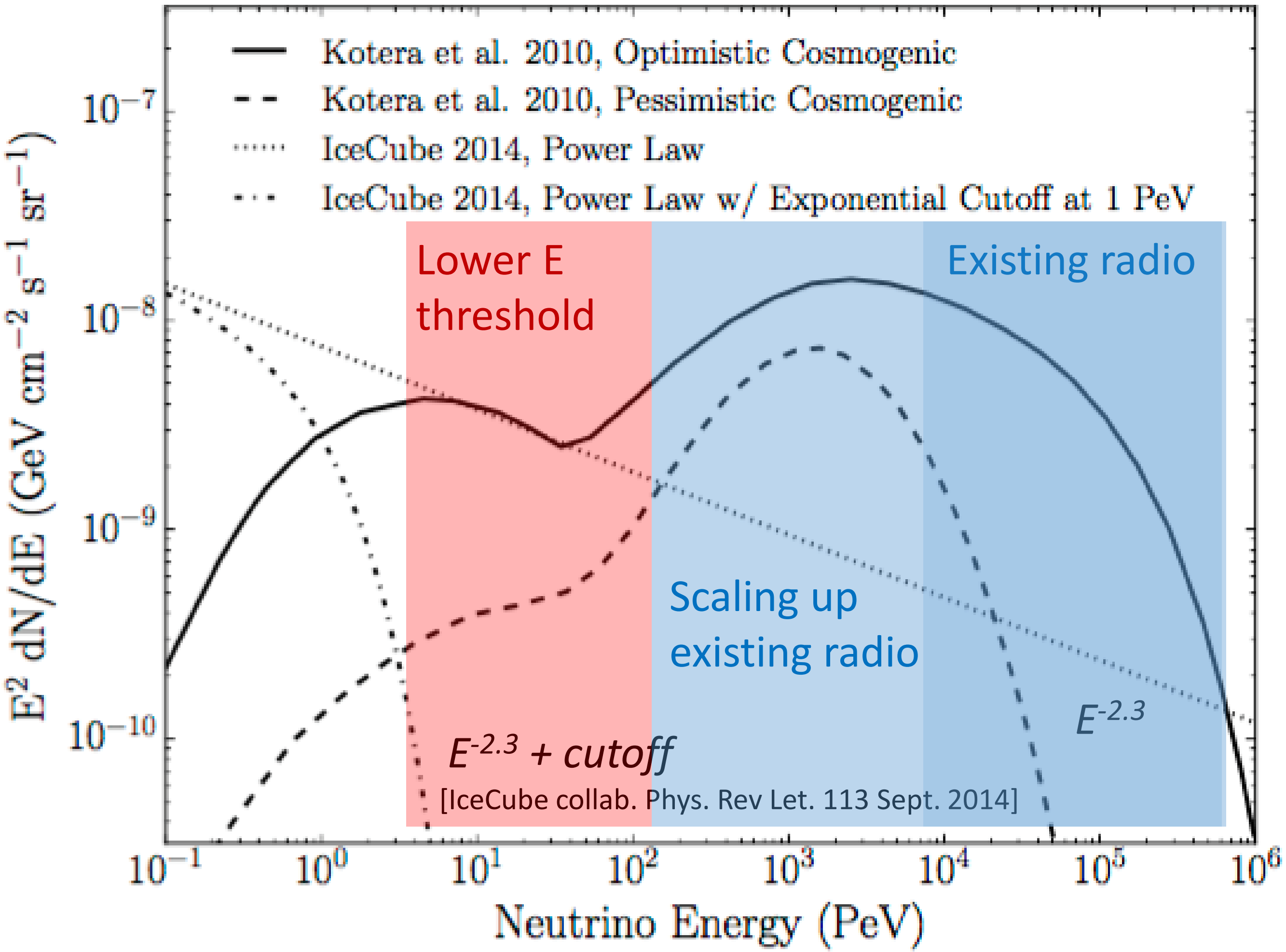
- Synchronization between ARA stations at the ~10 ns level
- Additional benefit: clock sync with IceCube White Rabbit system
    - At the analysis level, can search through data to find any concurrent IceCube events (far stretch, but high payoff)
- Work at OSU getting this ready for this deployment season



Slide adapted from B. Clark

Lowering the energy threshold: A radio telescope for both Astrophysical and Cosmogenic (GZK) ν populations

Can radio detectors be used to measure the astrophysical neutrinos discovered by IceCube?



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

Lowering the Energy Threshold : *NuPhase*

Current detectors have sensitivity for UHE neutrinos > 100 PeV 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

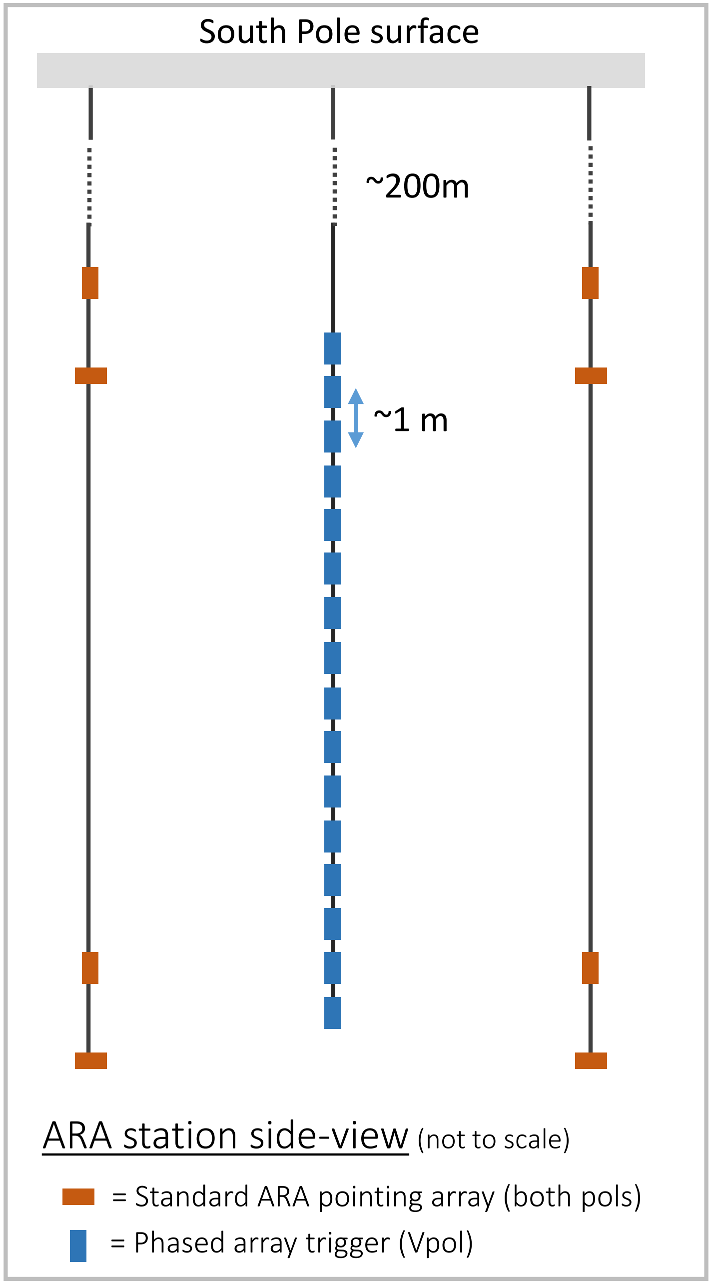
Do both? High gain antennas have a large footprint and won't fit down boreholes, so build a <u>phased array</u> consisting of in-ice low gain dipole antennas to **synthesize** an high-gain receiver

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

NuPhase deployment in December, 2017

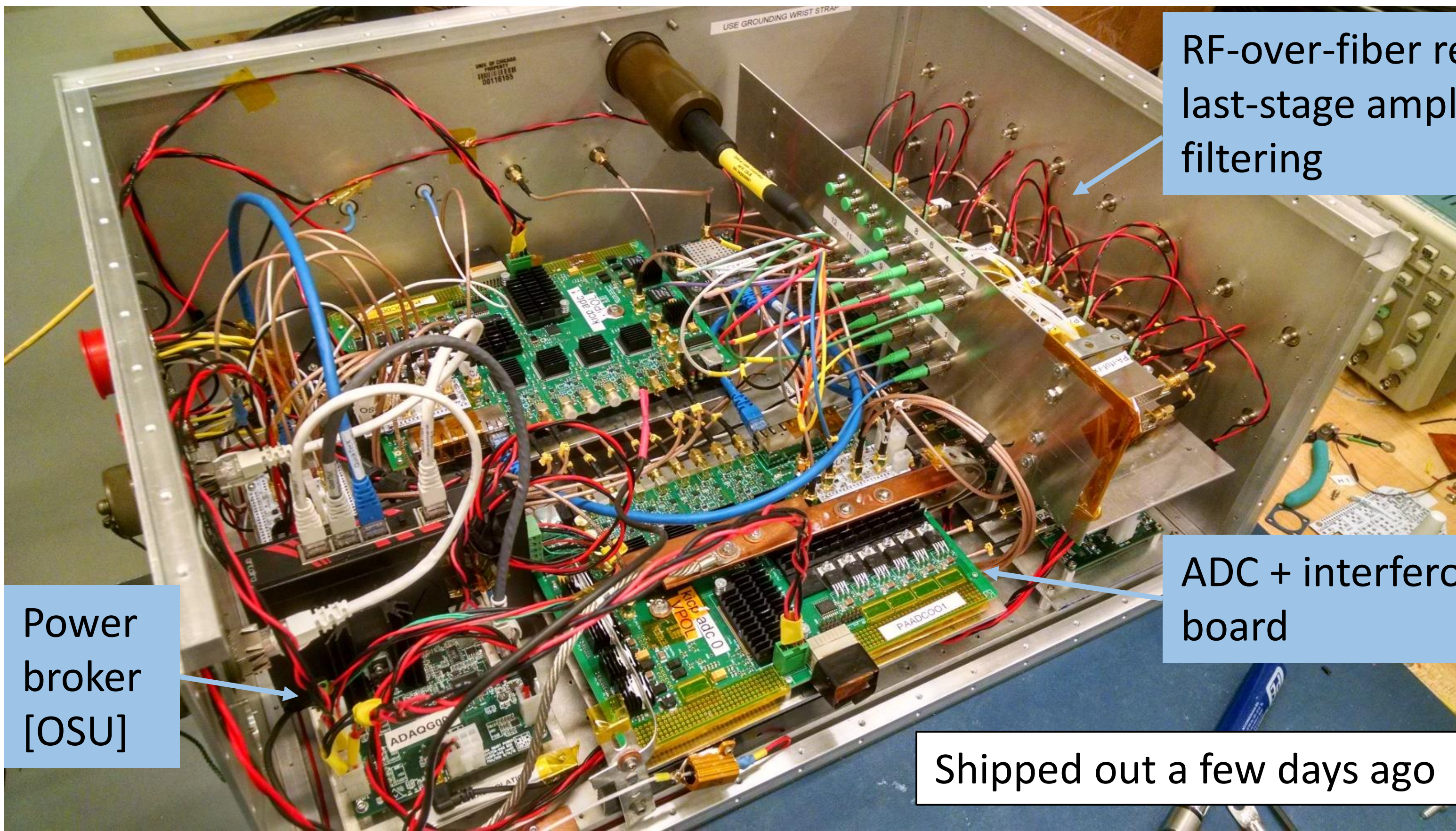
- An 8 antenna phased array as an interferometric trigger system for an Askaryan Radio Array (ARA) station
- An additional 4 Vpol and Hpol receivers
- Digital processing and correlation:
  - Antenna signals digitized using streaming analog-to-digital converters
  - ‘Phasing’ on a Field-programmable gate array (FPGA) via delay-and-sum beamforming
  - Search for ~10-ns binned transient power in each beam

Vpol antenna + low-noise amplifier package



NuPhase DAQ + Trigger system

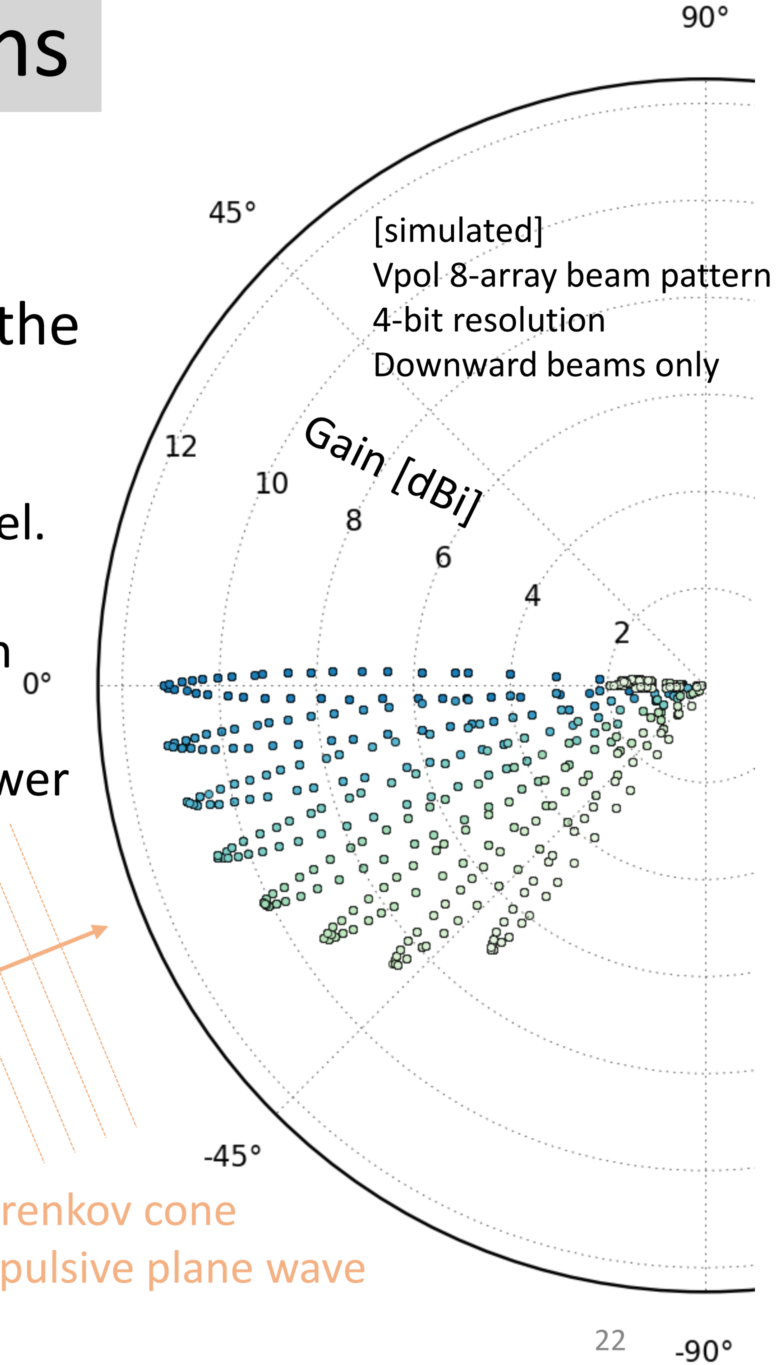
- Two 8-channel, 7-bit ADC boards running continuously at 1.5 GHz. Interferometry and other signal processing done on high-performance Arria V Altera (Intel) FPGAs
- Not just a trigger system: Full waveforms are also saved and sent over the network for storage. System includes an industrially-rated BeagleBone Black single-board computer + SPI interface to FPGAs
- Power consumption was not a major design consideration for this first system. Replace commercial ADC with custom low-resolution streaming ADC ASIC for future scaling up

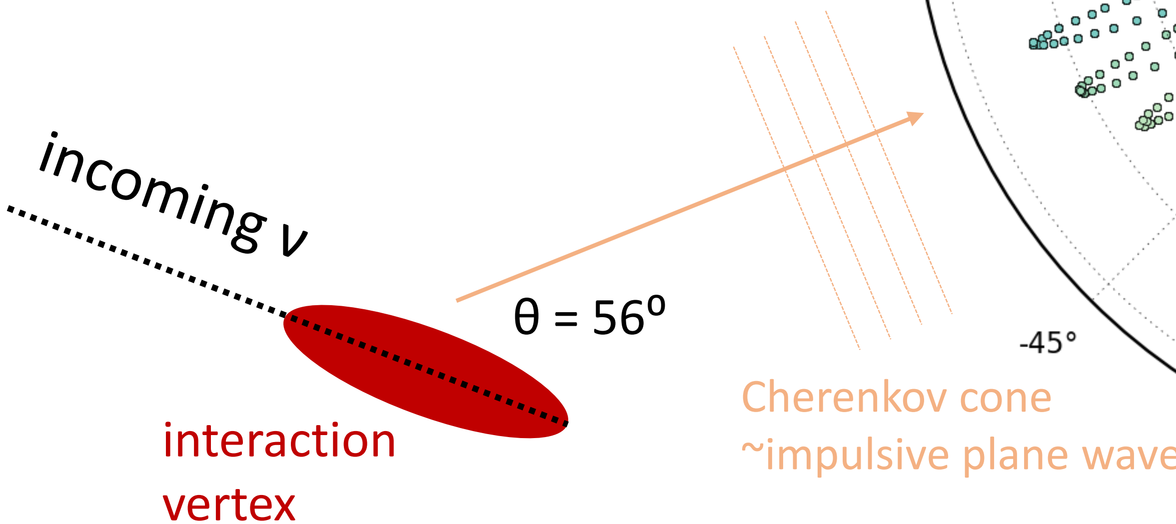


Multiple Independent Beams

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

→ Each ~5° beam is an independent trigger channel.
→ Optimize trigger rate budget such that beams cover the expected incoming Askaryan radiation directions
→ Compact array: form widest possible beams, fewer trials



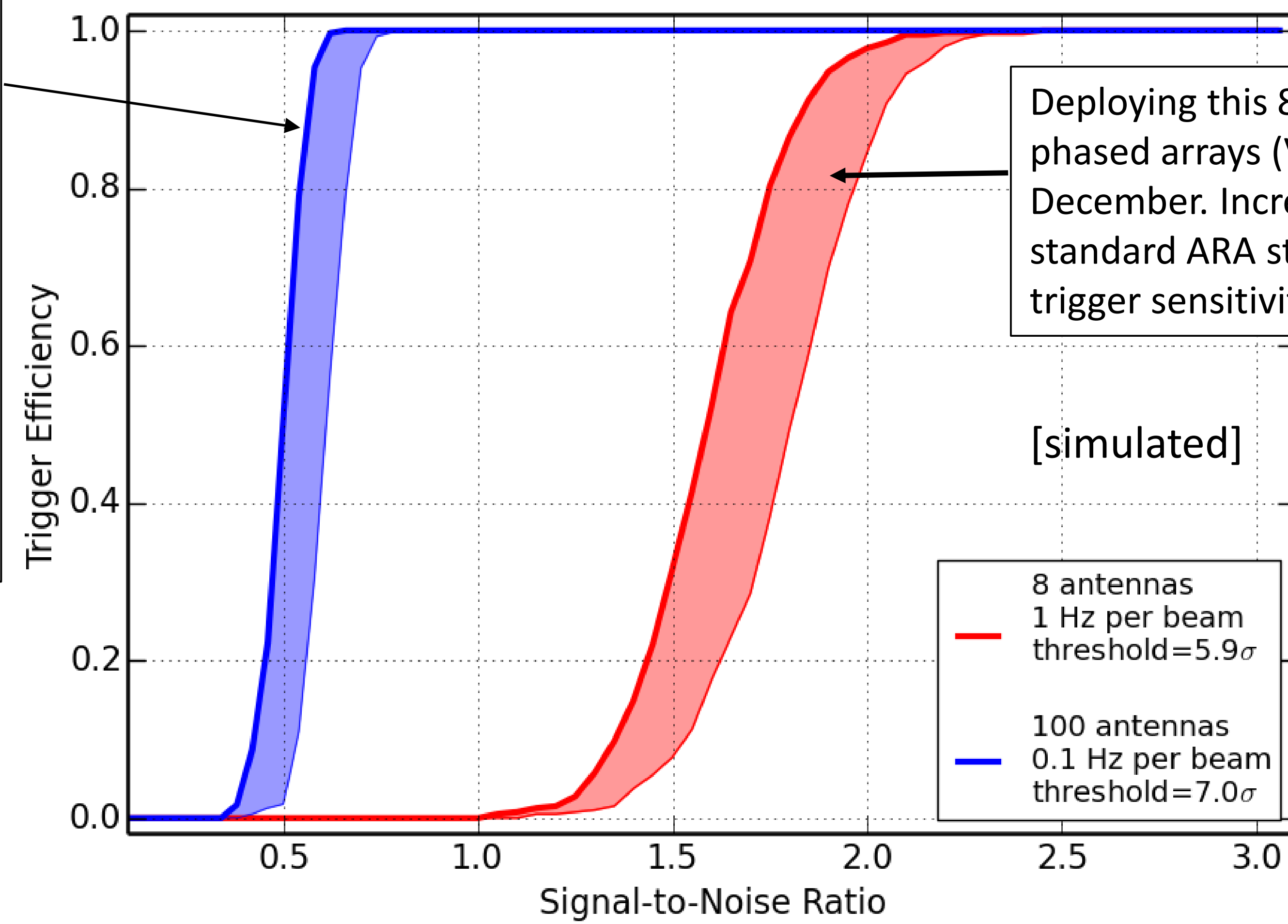


Trigger Efficiency of a Phased Array for Transients

4 bits at 1.5 GHz sampling and <u>10 Hz total station event rate</u>

100 antenna phased array = ability to trigger robustly on signals buried in thermal noise background. *This is roughly the number of phased antennas to reach down to the ~10 PeV level*

Deploying this 8 antenna phased arrays (Vpol) in December. Increase standard ARA station trigger sensitivity by ~10x



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

SUMMARY

- ANITA 4 flight last year with improved trigger and filtering, ANITA 3+4 results out soon. LAB4D a promising ASIC for radio applications

- Ground-based detectors are promising way forward. Both ARIANNA and ARA with deployments this year (including collaborative effort installing ARIANNA station at the Pole)

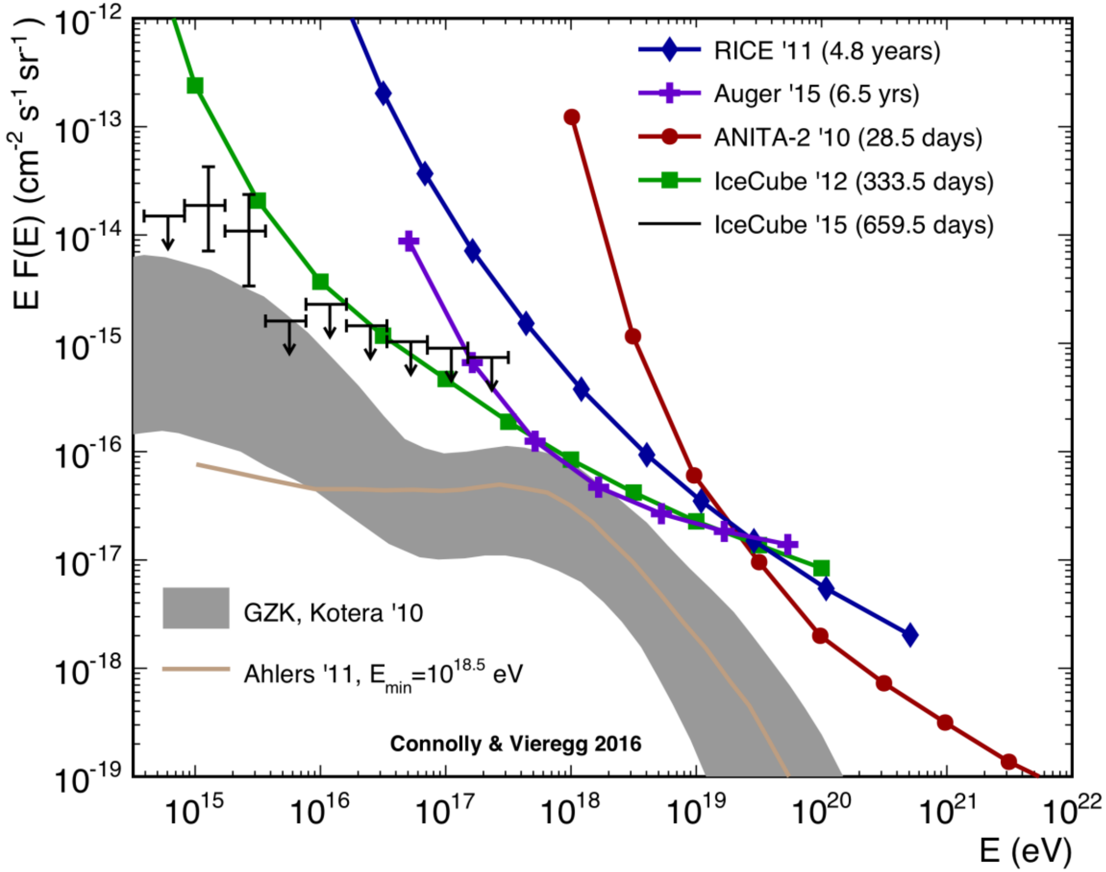
- First UHE neutrino phased array detector system installed this year. Our goal is to operate novel hardware to lower the energy threshold of the radio detection technique

Current Status and Constraints

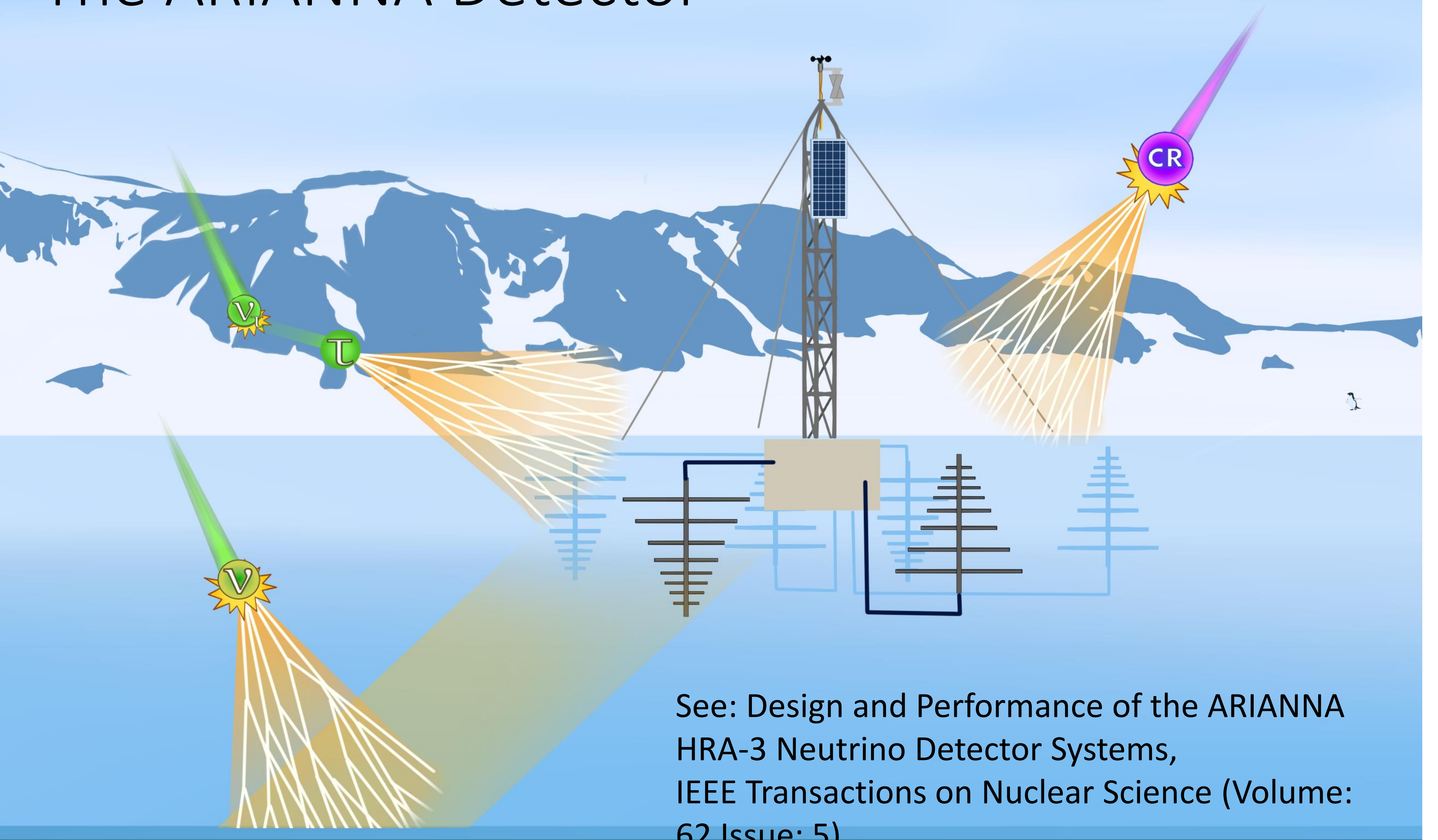
<u>Best Current Limits on UHE neutrinos:</u>

- > $10^{19.5}$ eV: Radio Detection (ANITA)
- < $10^{19.5}$ eV: Optical Detection (IceCube) and Earth-skimming airshowers (Auger)

There is a floor to the GZK-produced neutrino flux predictions!



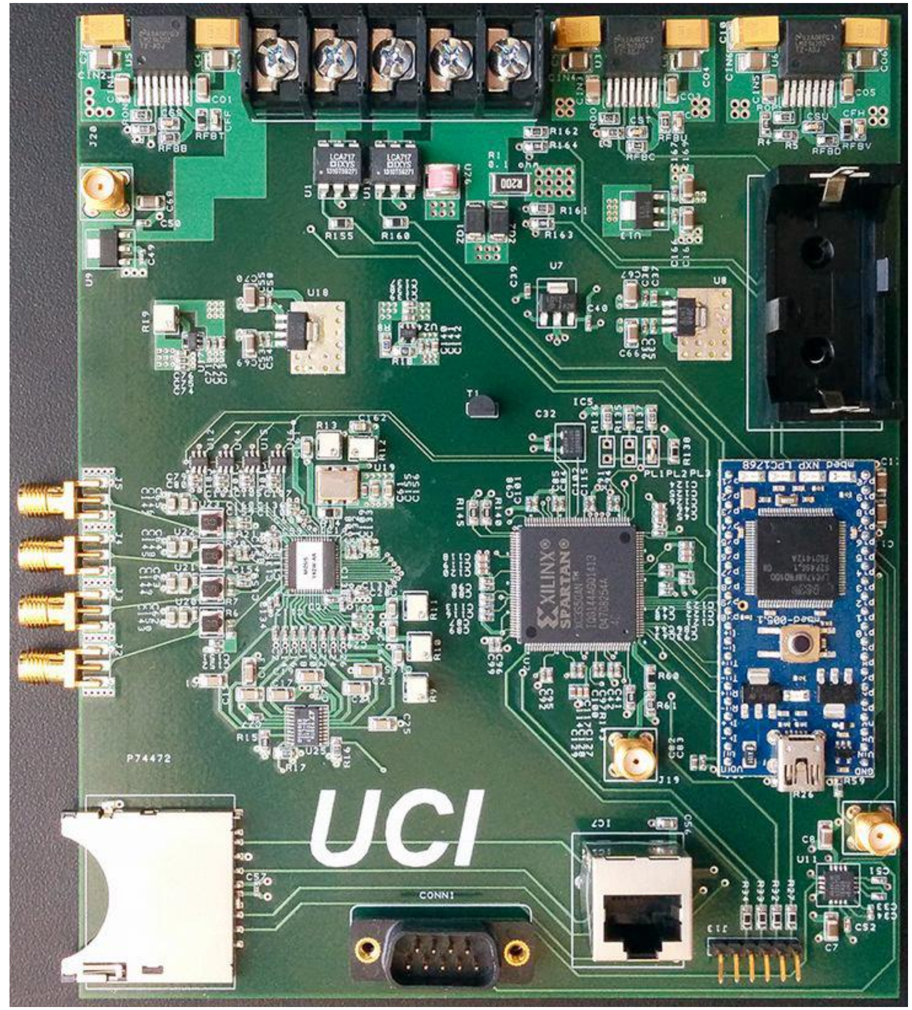
The ARIANNA Detector



See: Design and Performance of the ARIANNA HRA-3 Neutrino Detector Systems, IEEE Transactions on Nuclear Science (Volume: 62 Issue: 5)

The ARIANNA DAQ

- Full planned array includes 1296+ stations at Moore's Bay
- Extreme power limitations: each station solar powered ~20 W: for now running only during the Austral summer
- ~0.1 Hz event rate
- New 'SST' waveform sampling ASIC
  - 2GSa/s, 256 samples
  - 1.5 GHz bandwidth
  - 32 mW / channel
  - Built-in trigger system using coincidence of upper and lower thresholds on a bipolar pulse



Kleinfelder, *Design of the Second-Generation ARIANNA Ultra-High-Energy Neutrino Detector Systems*, IEEEE. arXiv:1511.07525

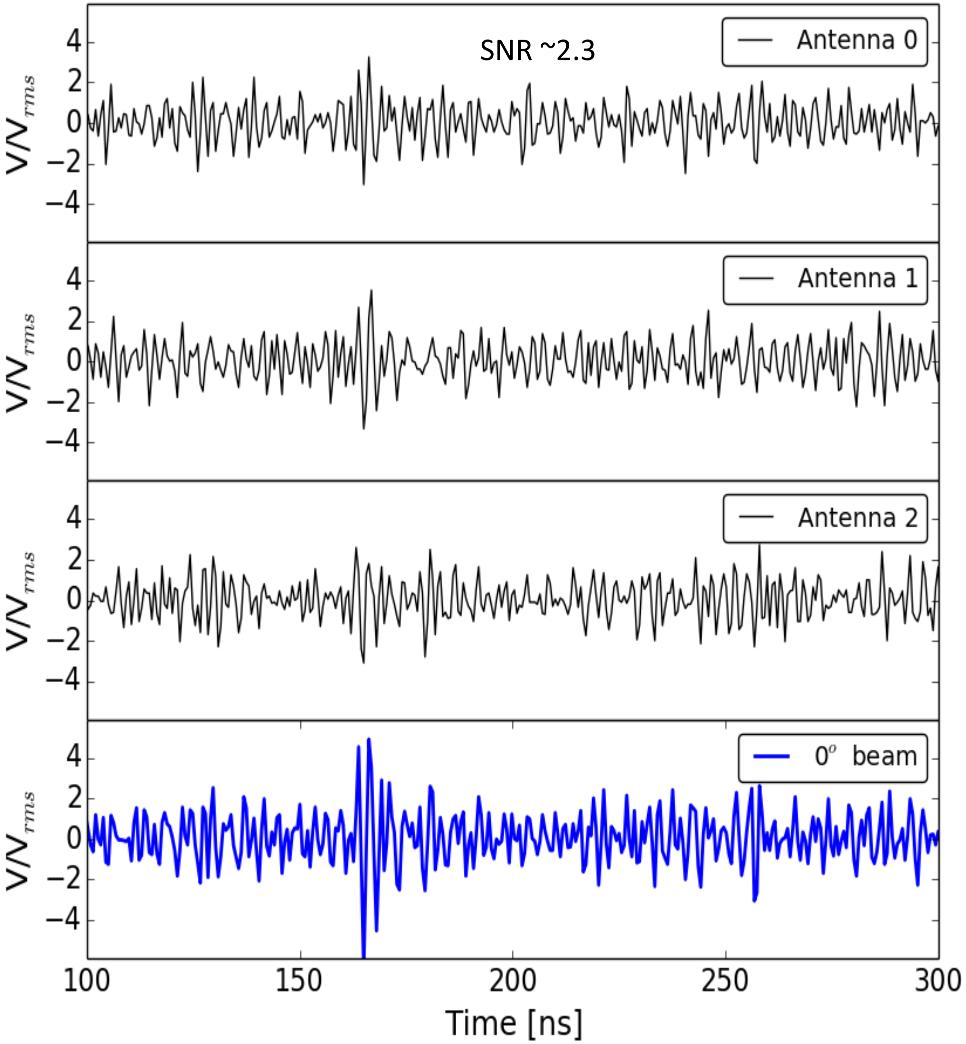
Proof of Principle

Transmitting antenna + variable attenuation

Few meters

Test receiver array of 3 antennas

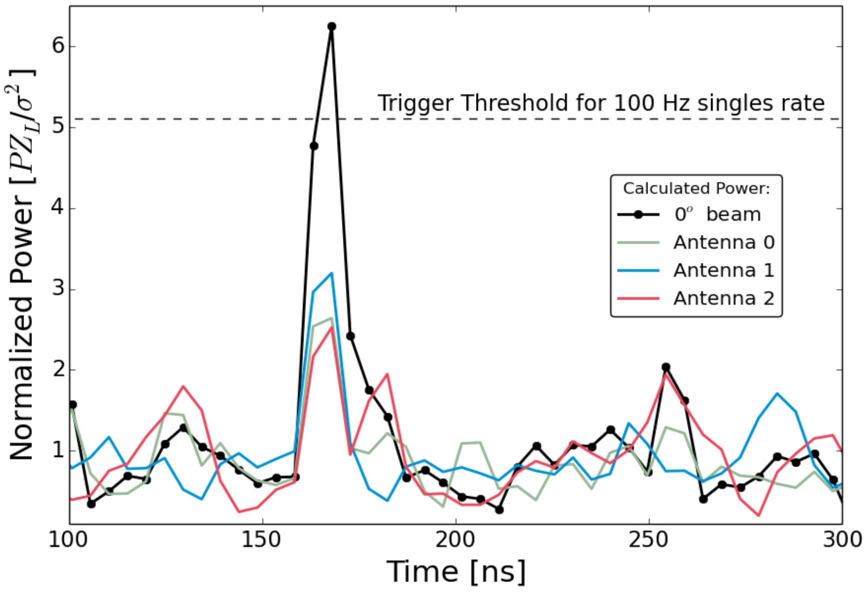
Antenna waveforms and one of the digitally-formed beams



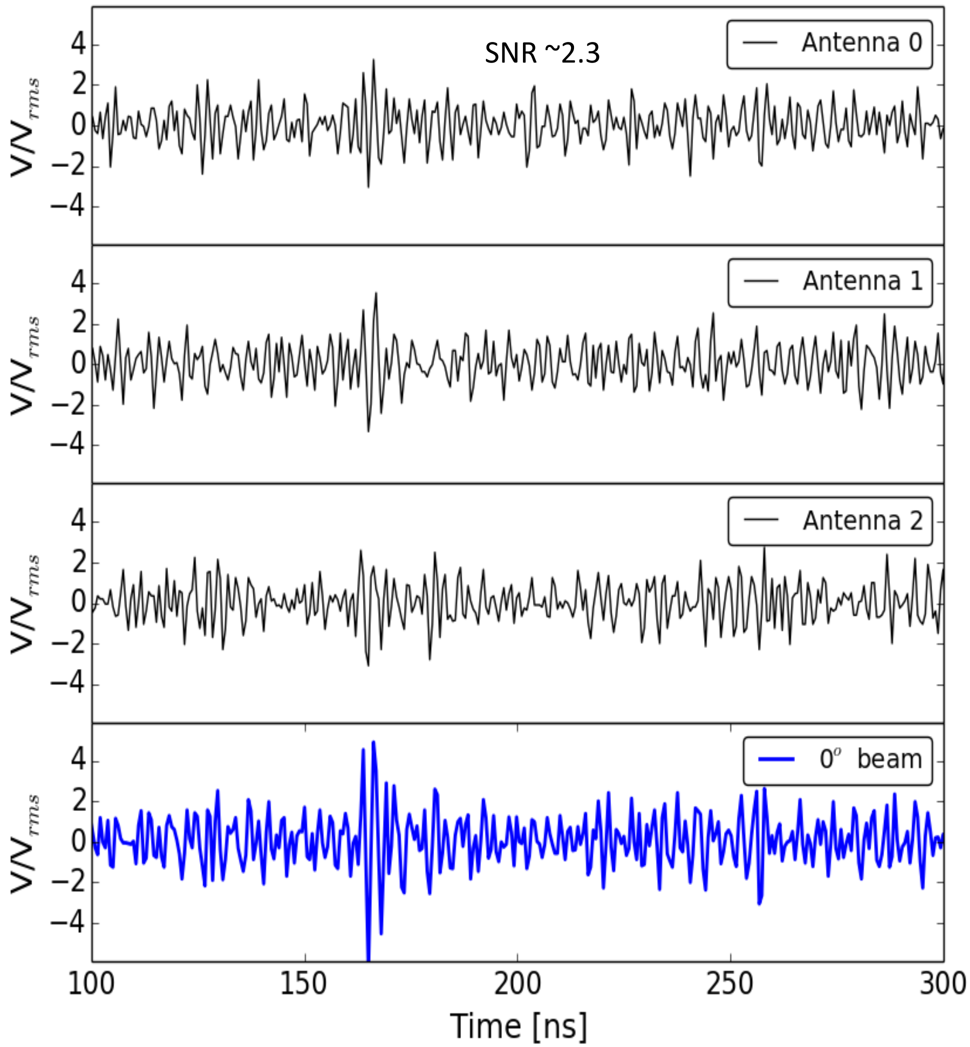
Proof of Principle

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

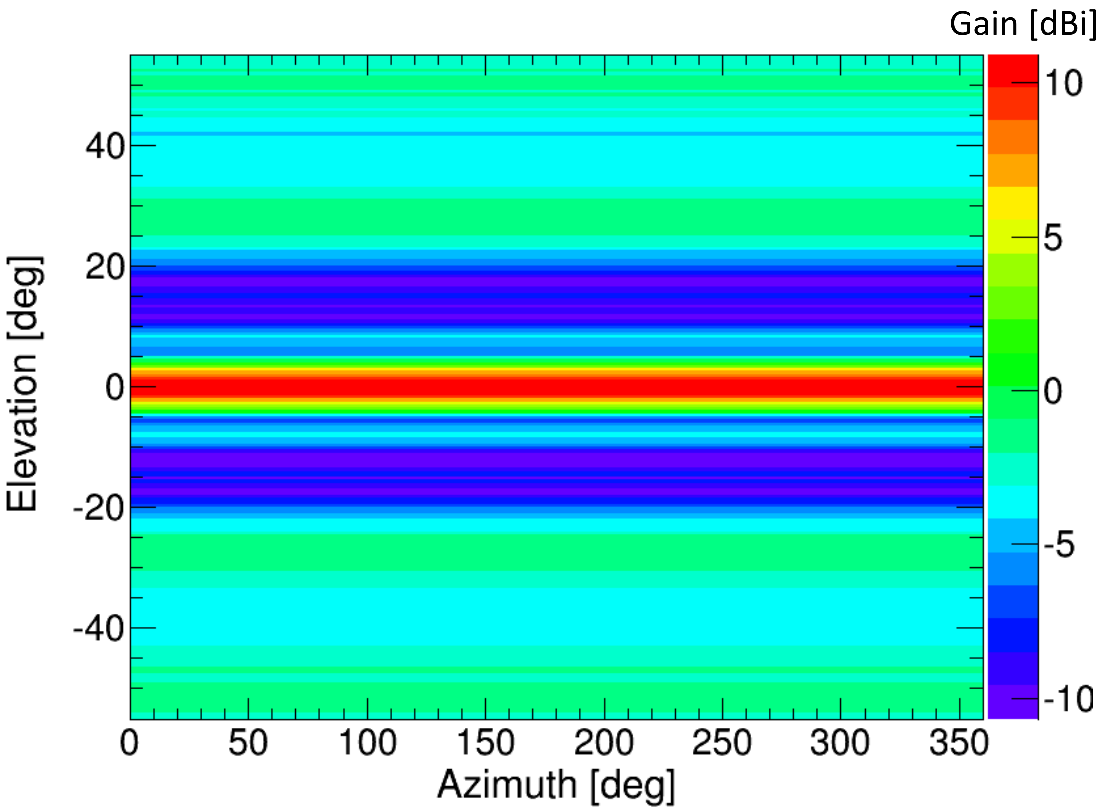


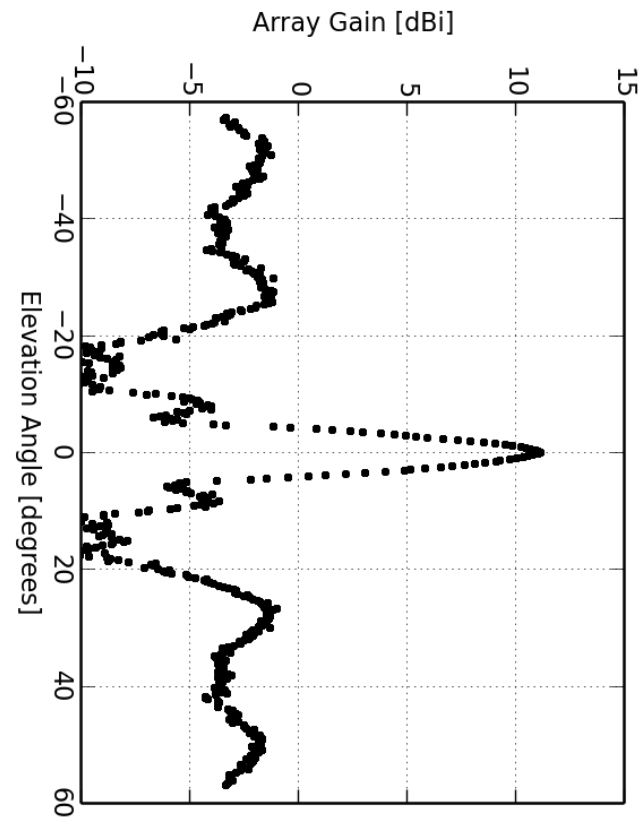
Antenna waveforms and one of the digitally-formed beams



Impulsive Phased array beam pattern

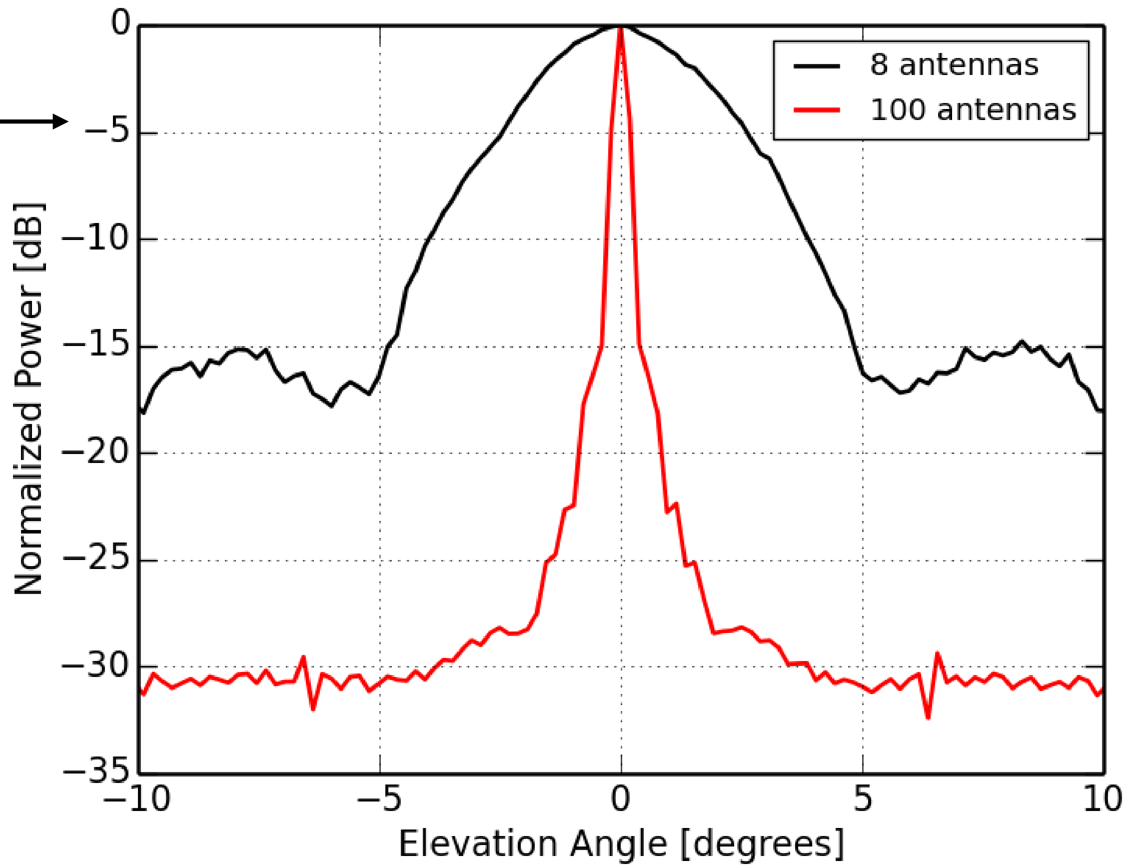
- Simulated beam pattern of 8-antenna Vpol using the measured broadband 200-800 MHz impulse response. Zero degree beam shown
  FWHM ~ 5 degrees.
- Peak directional gain at ~11 dBi -- comparable to ANITA high-gain horn antenna
- Uniform coverage in azimuth since we are phasing only in 1 dimension along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





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