Radio Phased Arrays for the Detection of Ultra-High Energy Neutrinos

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A R E N A

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Phased array: synthesize higher gain antennas

- Deep in-ice antennas limited physical size by borehole dimensions, typically dipole or bicone type low-gain antennas
- Askaryan emission highly beamed

➔ Do interferometry at trigger level, push threshold down

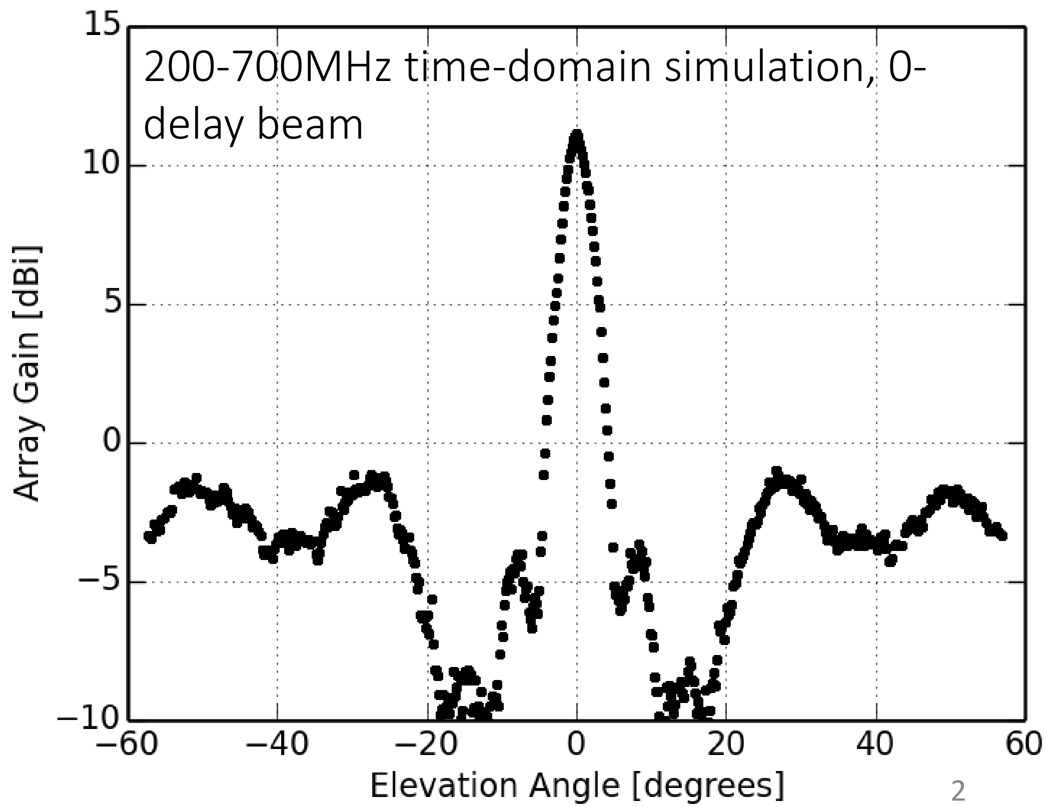
Antenna effective aperture:

$$A_{eff} = \frac{\lambda^2 G}{4\pi}$$

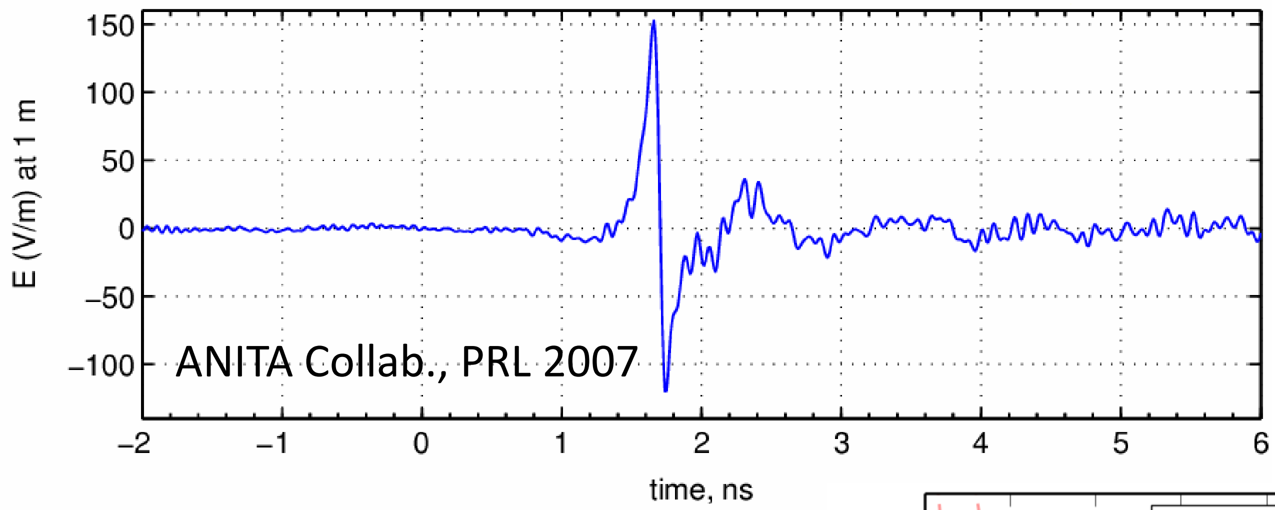
Linear phased array gain
(λ/2 element spacing):

$$G_{dBi} = 10\ \log_{10}(N\ G_{element})$$

For example, a linear phased array of 8 dipole antennas (G=1.64) has an array gain of 11 dBi, similar to a typical LPDA or ANITA horn antenna

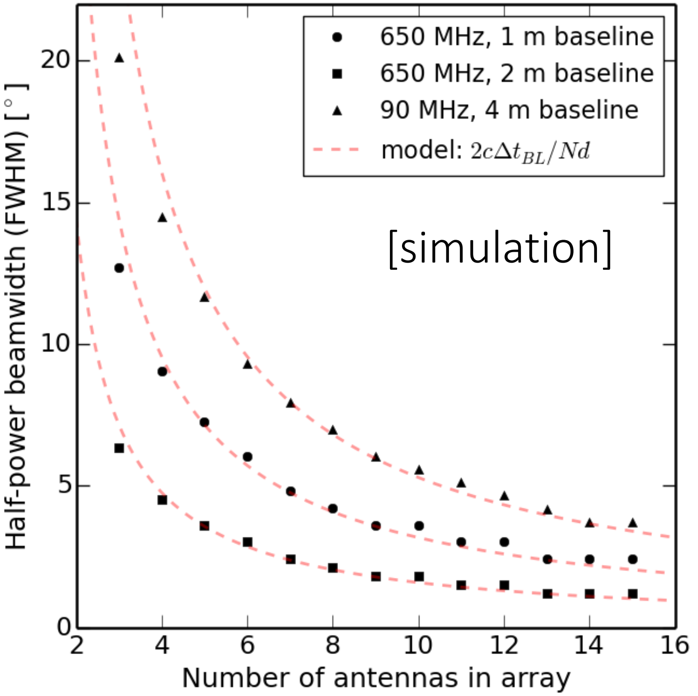


Askaryan signal + beamforming



- Askaryan signal extremely broadband: bandlimited signal in the detector
- Physical beamwidth of a time-domain summing array of bandlimited signals (characteristic time resolution $\Delta t_{BL} = 2\Delta\nu$) with uniform element spacing of *d*:

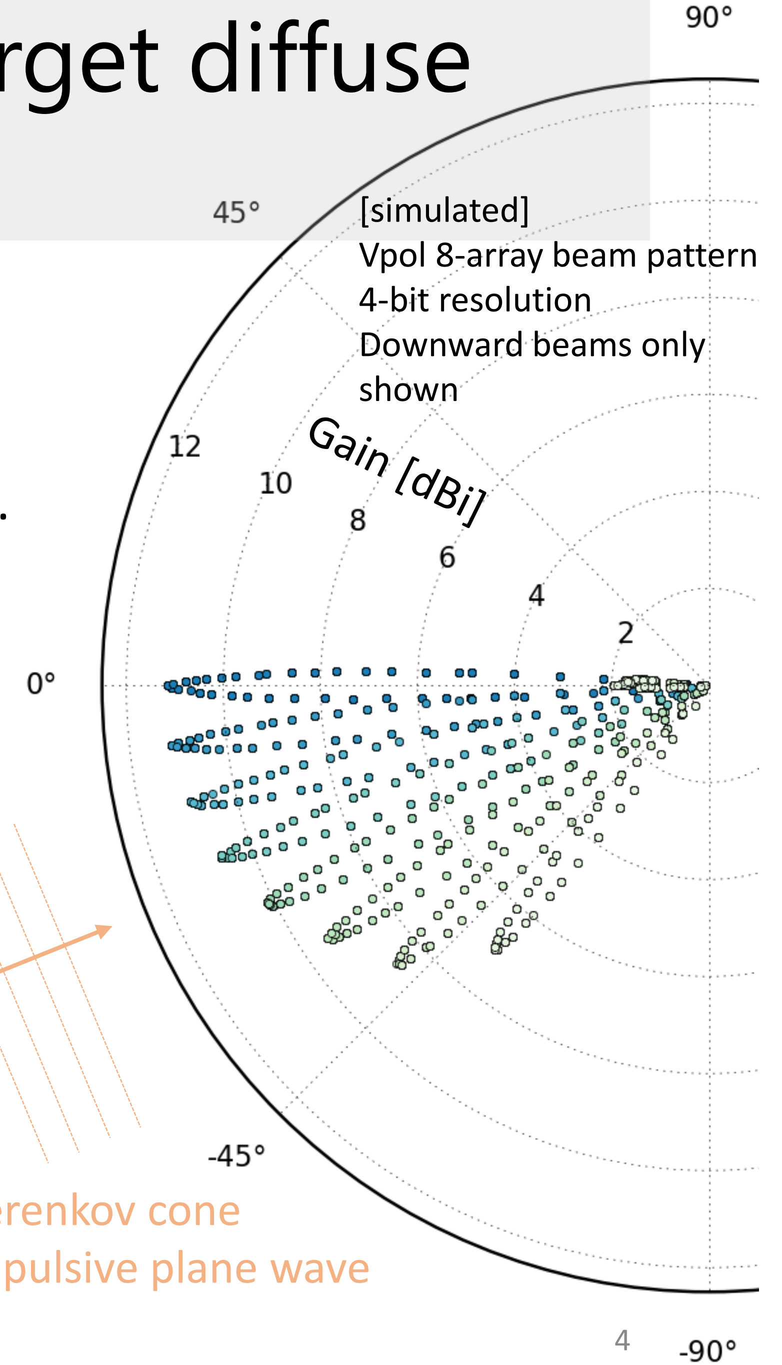
$$\Delta\theta \sim \frac{\lambda}{D} \rightarrow \frac{2\, c\, \Delta t_{BL}}{N_{ant}\, d}$$

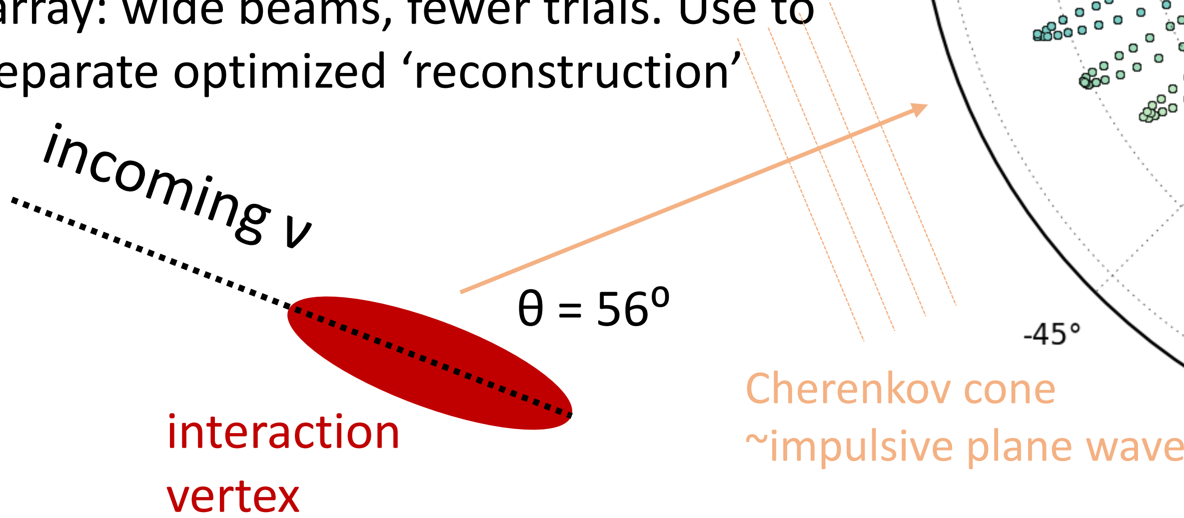


An in-ice phased array: target diffuse UHE neutrino flux

An electronically steered phased array can form multiple beams simultaneously over the volume of interest.

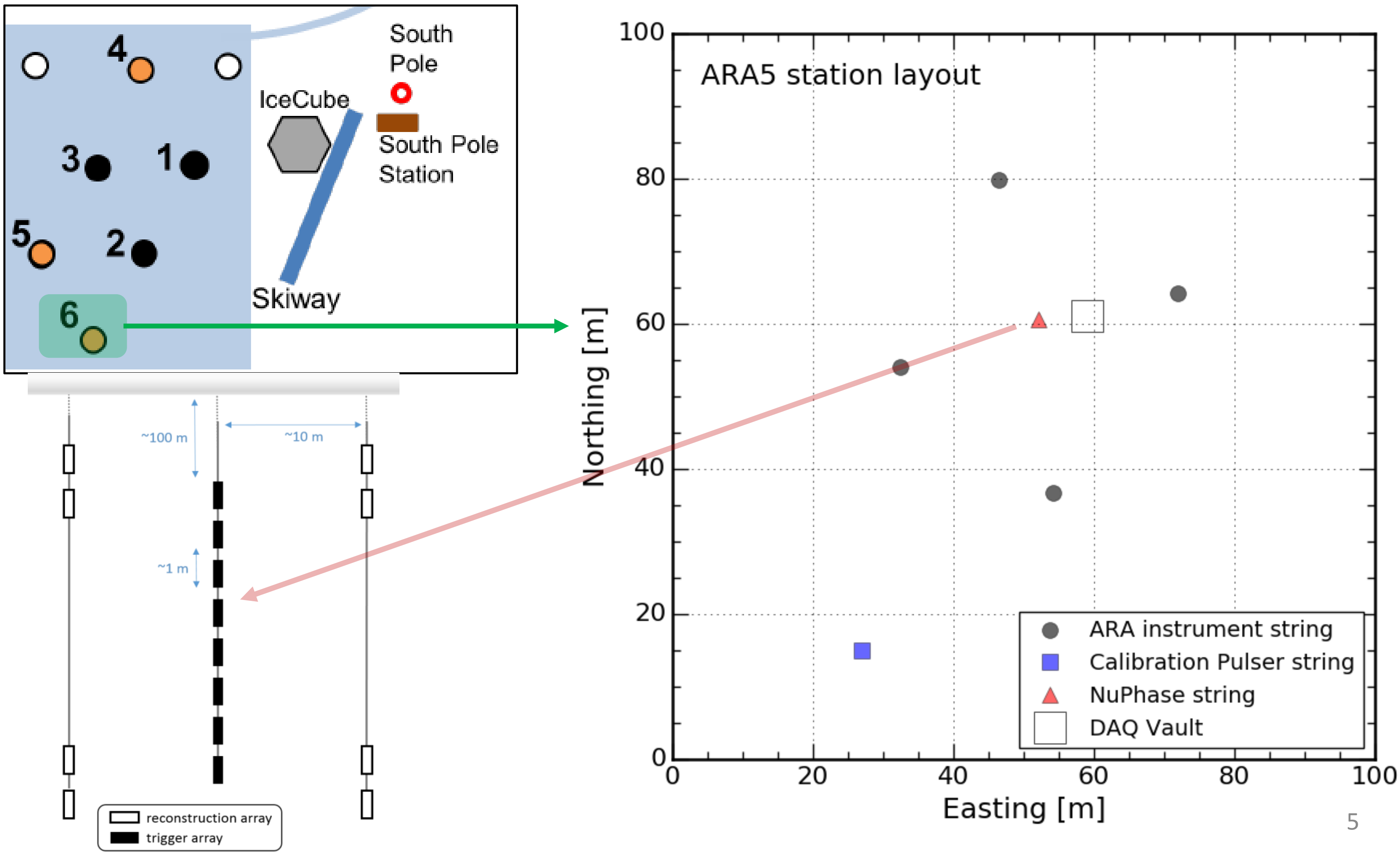
→ Each beam to is an independent trigger channel.
→ Directional triggering capability. Rate 'budget' can be allocated on the fly
→ In presence of uncorrelated thermal noise, coherent gain scales as $\sqrt{N_{antenna}}$.
→ Compact array: wide beams, fewer trials. Use to trigger a separate optimized 'reconstruction' array





Phased array string at ARA5

10-antenna array (8 Vpol + 2 Hpol) installed in the center of ARA5 at a depth of 185 m: 'NuPhase'. Commissioned in early 2018



Phased array string at ARA5

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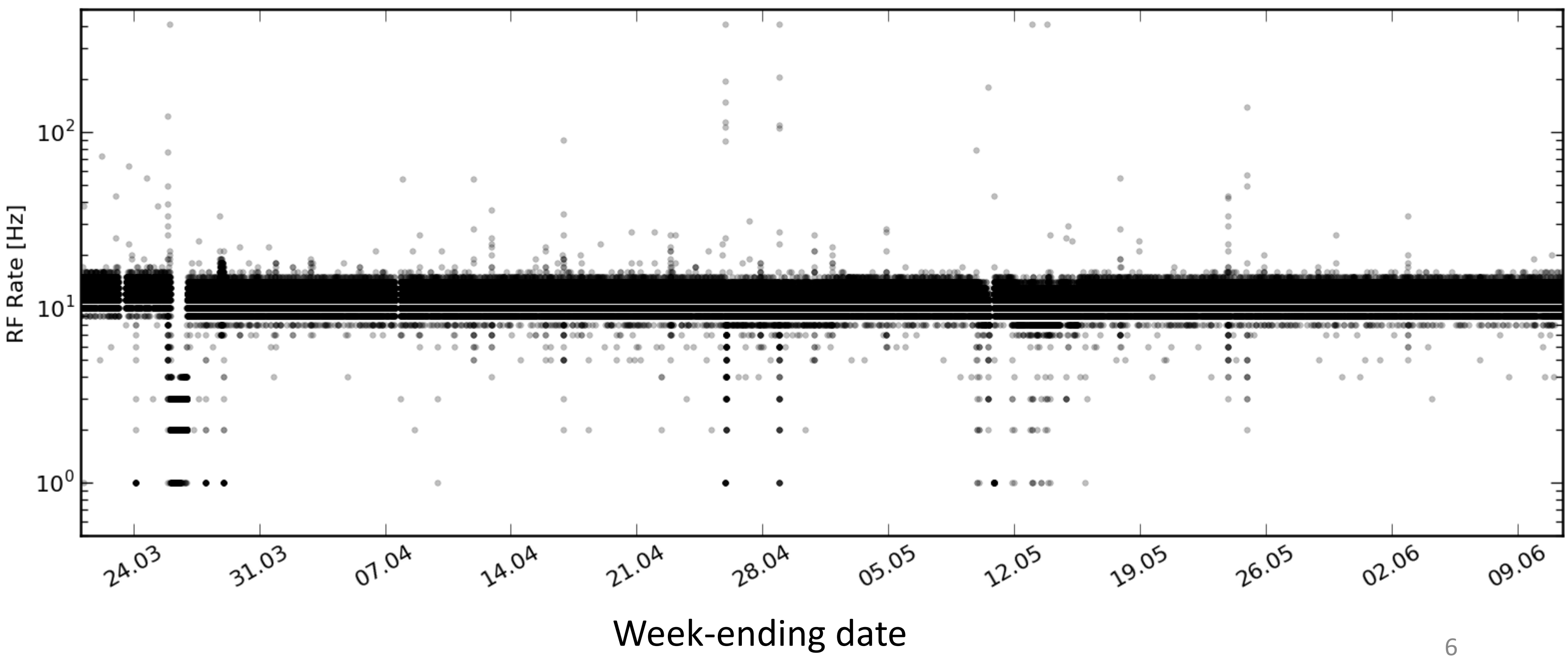
Steady triggering and data-taking at 10 Hz since February



Vpol antenna units

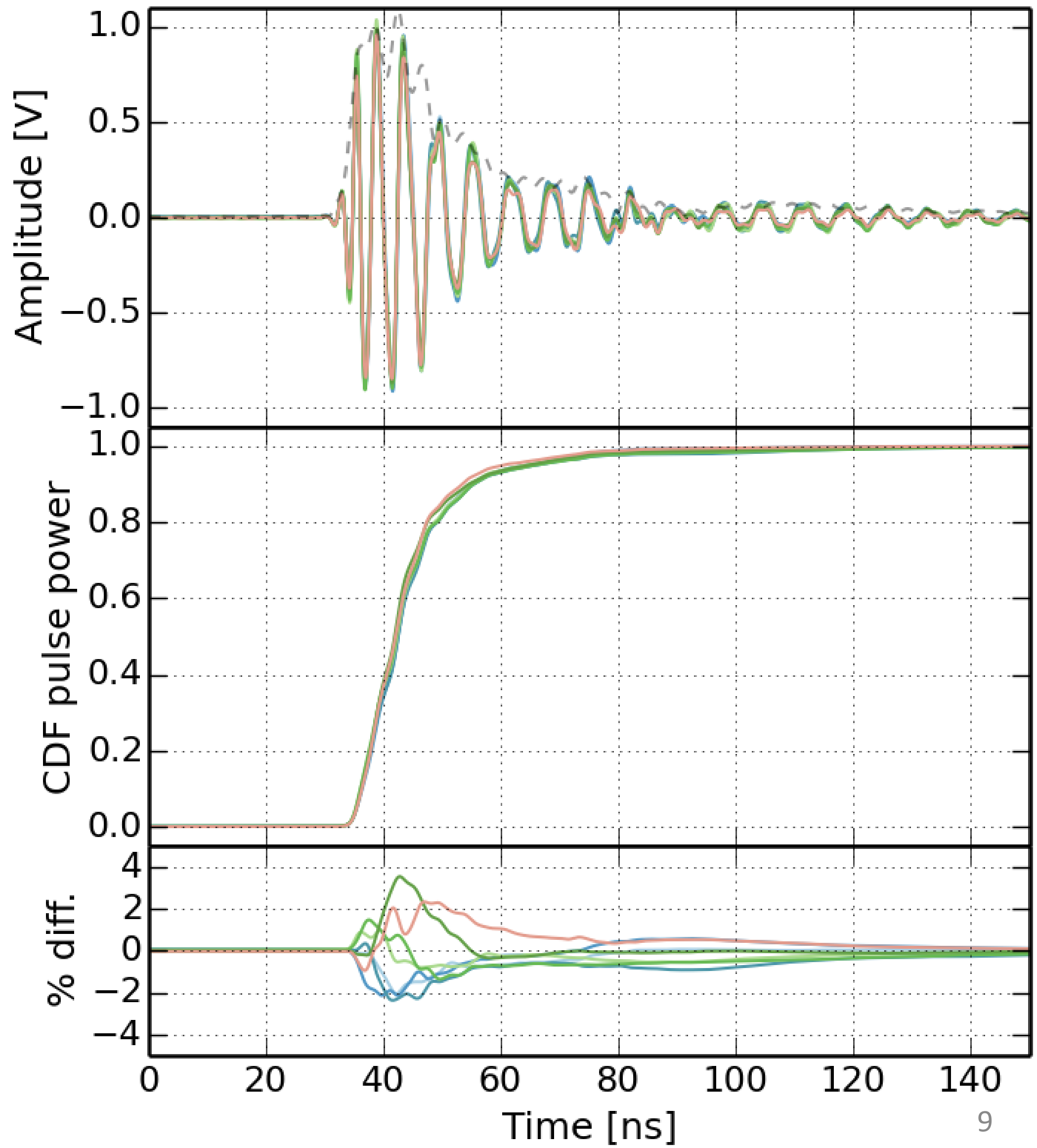
- Birdcage antennas (identical to ARA Vpol except for feed design)
- LNA + RFoF transmitter closely integrated, allowing close packing
- Signal sent up through the array over optical fiber. Single coaxial cable runs through array for power. Matching through-cabling was key design goal to match antenna responses
- Relative vertical spacing of antenna units known to ~1 cm

Fiber management

Vpol response

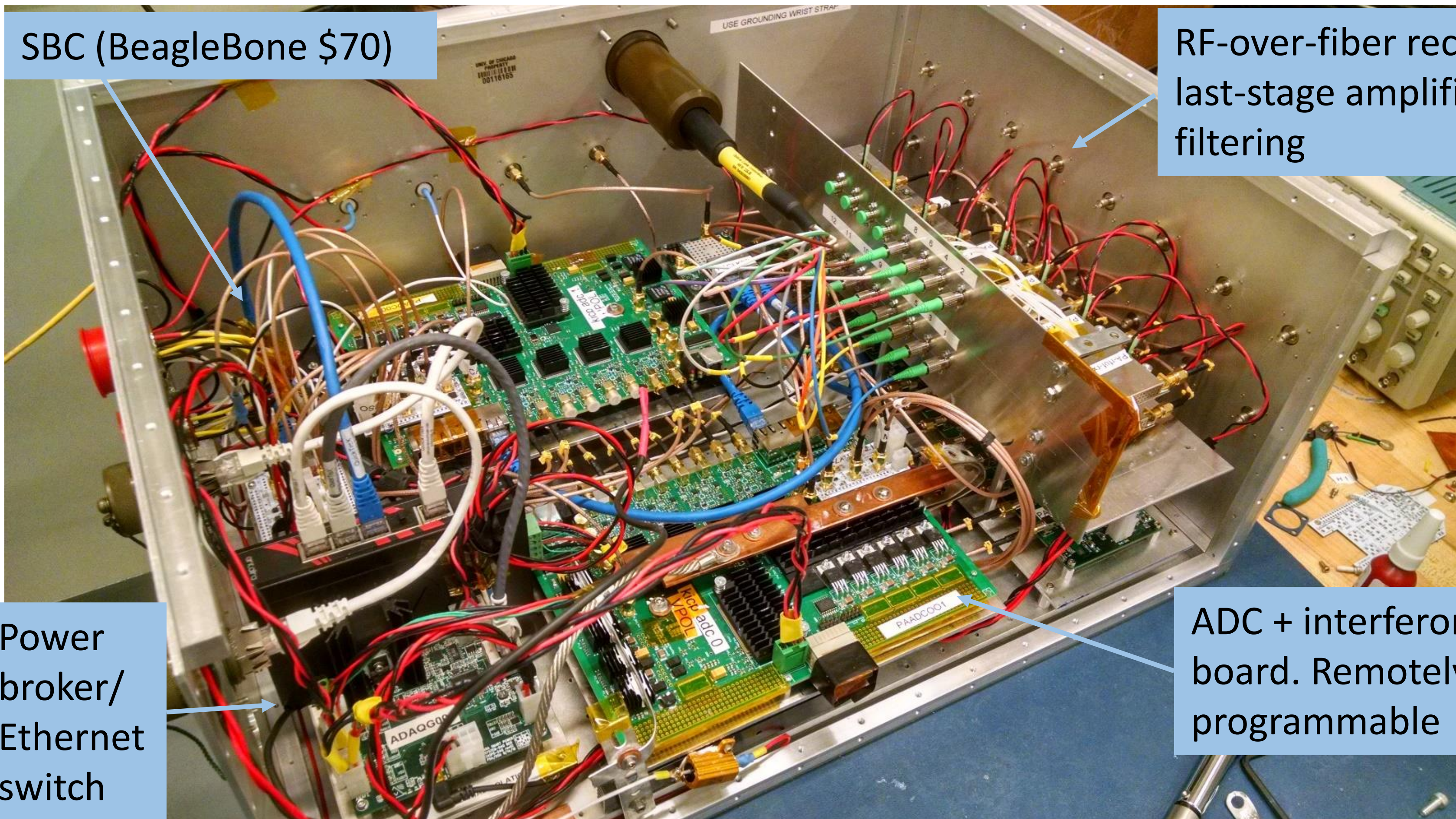
- Time-domain response of all Vpol channels using ARA5 calibration pulser (not de-convolved)
- Well matched between channels
  → Better than 5%
  → Important for coherent summing without expensive pre-processing

all vpol channels

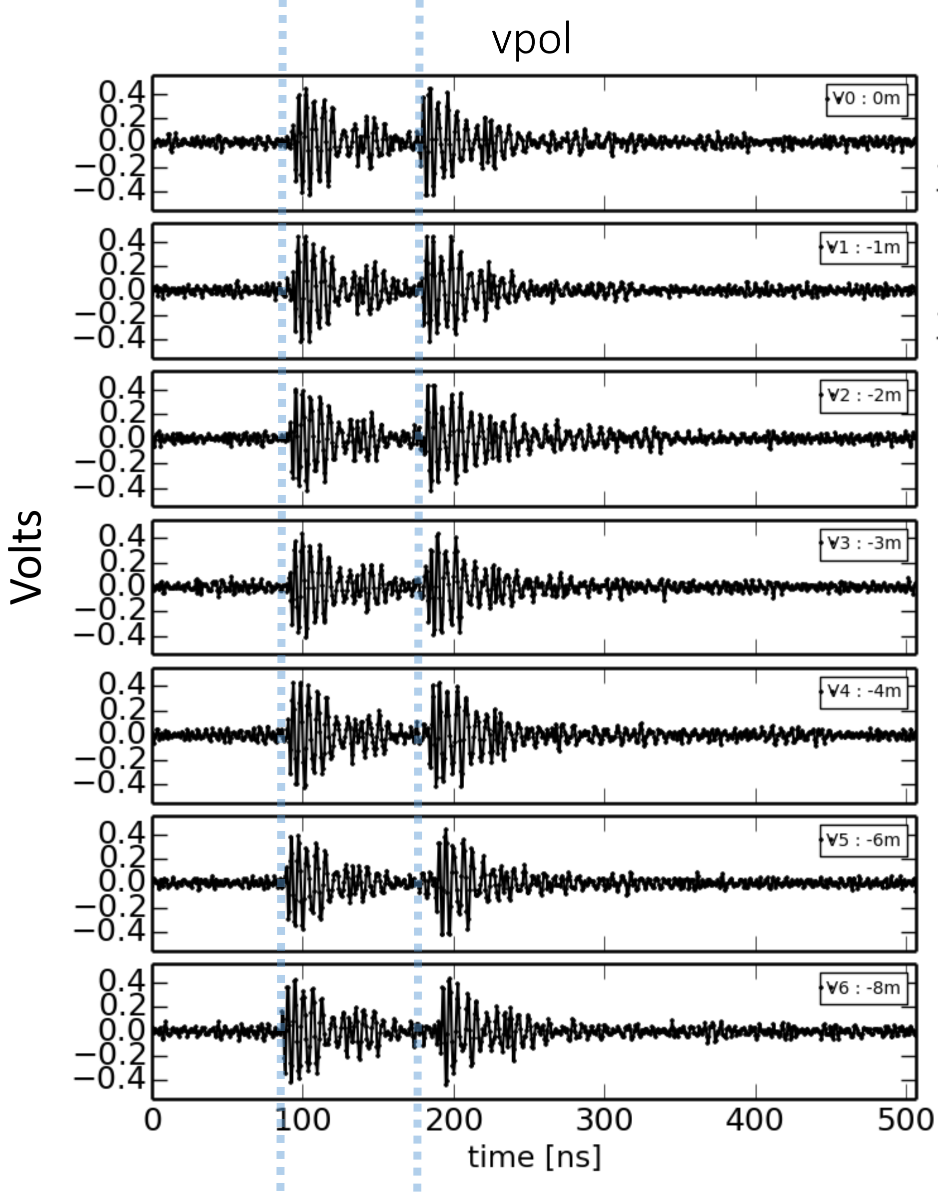


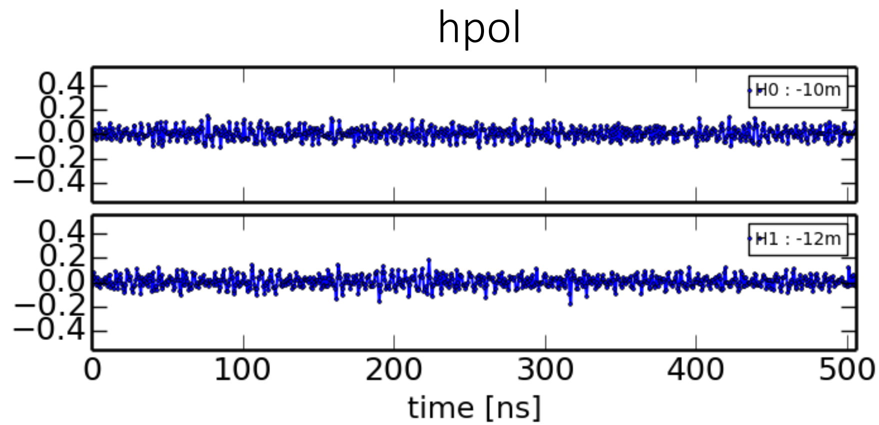
NuPhase DAQ + Trigger system

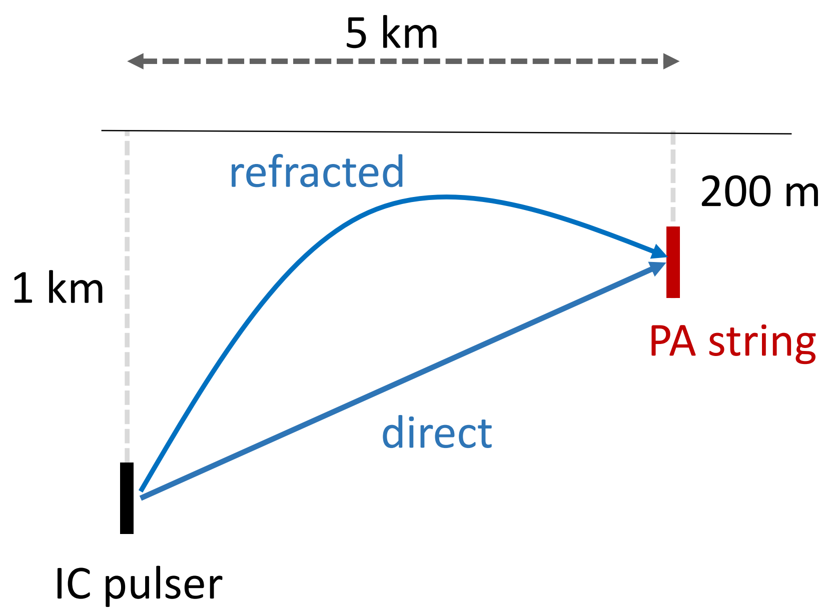
- Two 8-channel, 7-bit ADC boards running continuously at 1.5 GHz. Interferometry and other signal processing done on high-performance FPGAs
- Not just a trigger system: Full waveforms are also saved and sent over the network for storage. Multi-event buffering handles pileup, up to 2.4 microsecs/wfm.
- 100 W power consumption target; operable at <-40^{o}C ambient



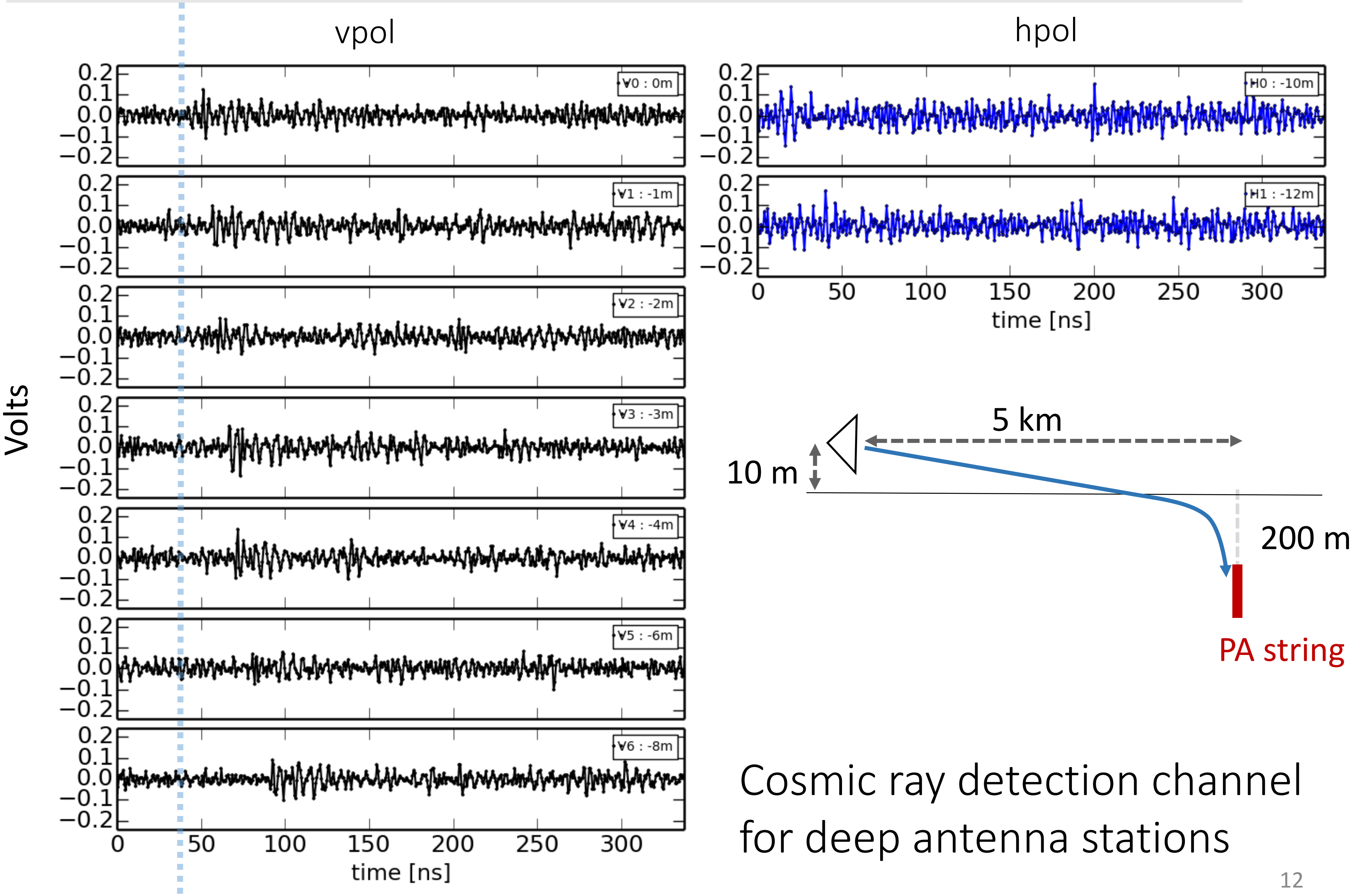
IceCube Deep Pulser







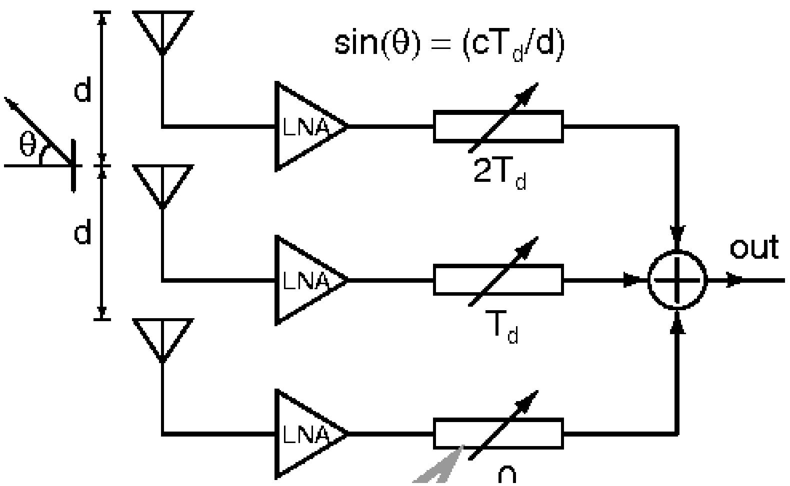
IceCube Lab Rooftop Pulser



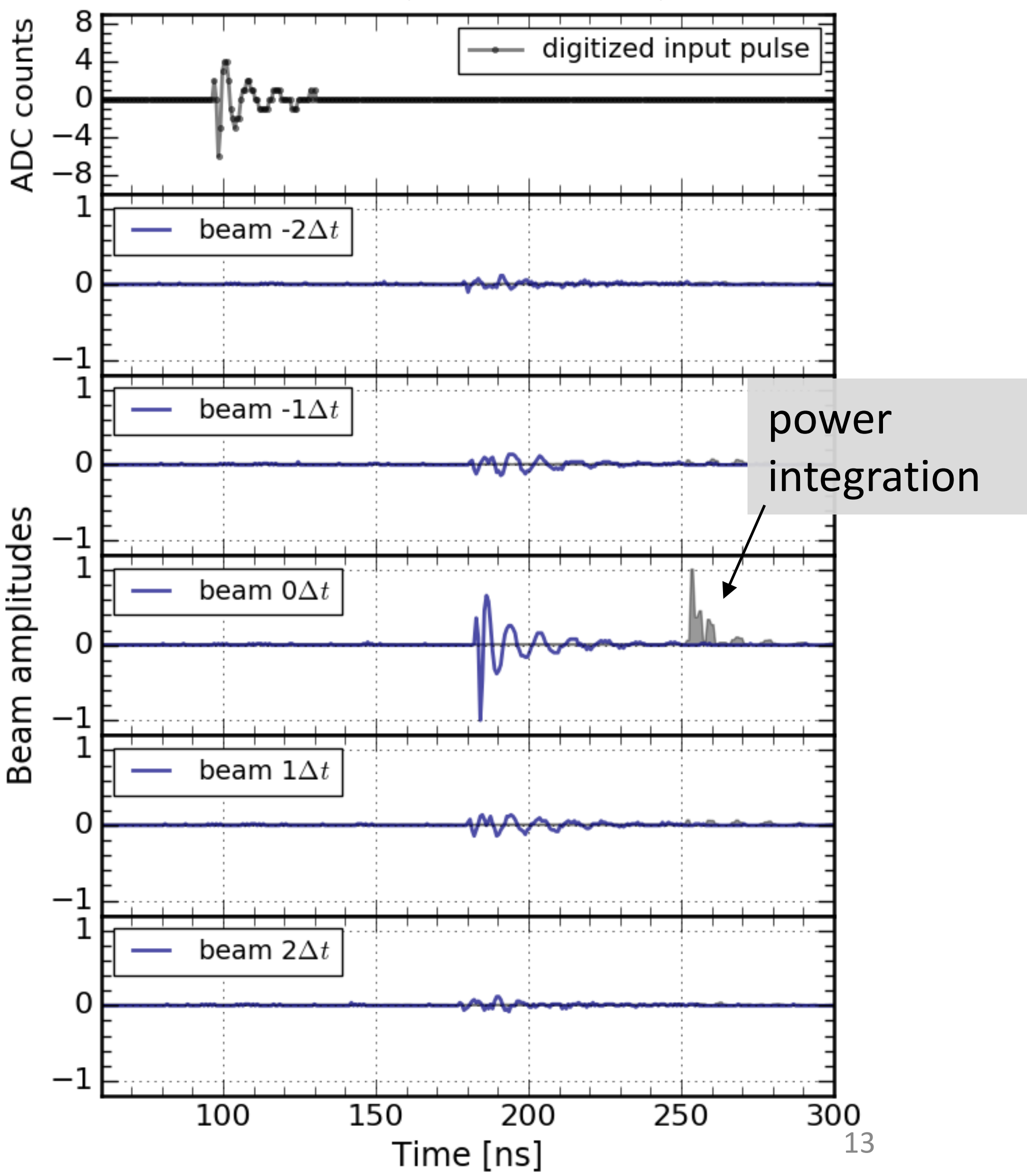
Cosmic ray detection channel for deep antenna stations

Delay-and-sum beamforming trigger

- Beamformer uses 5 bits for each channel.
- Calculate coherent sums covering a wide range of angles (blue traces)
- Integrate power in each coherent sum in ~10 ns bins (programmable), compare to threshold
- If multiple beams simultaneously exceed threshold, trigger only on maximum power
- Steering granularity in a digital beamformer given by the sampling rate



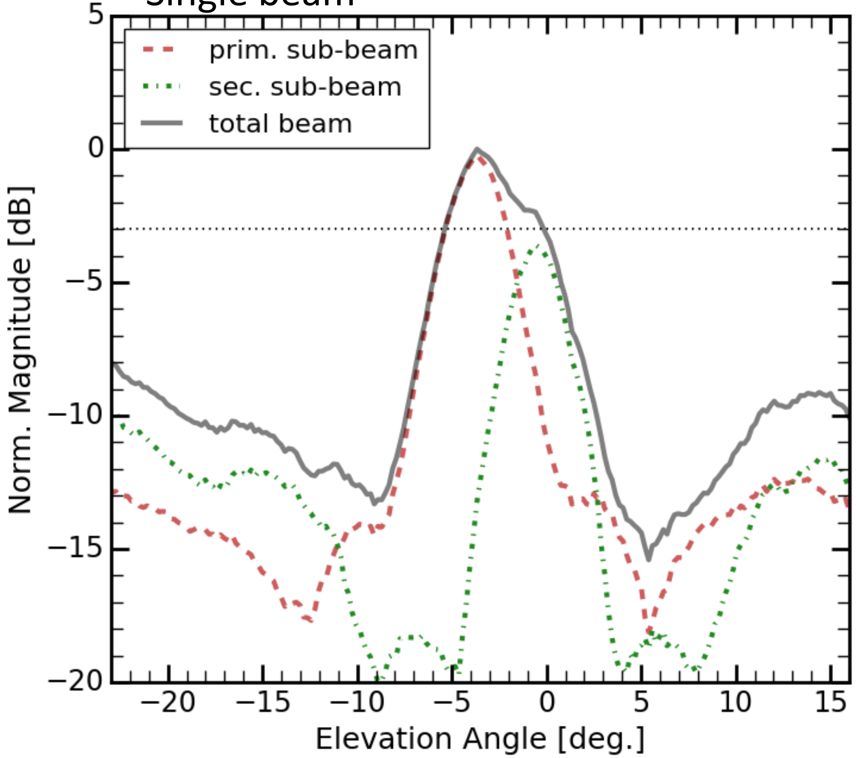
test-bench outputs of FPGA system



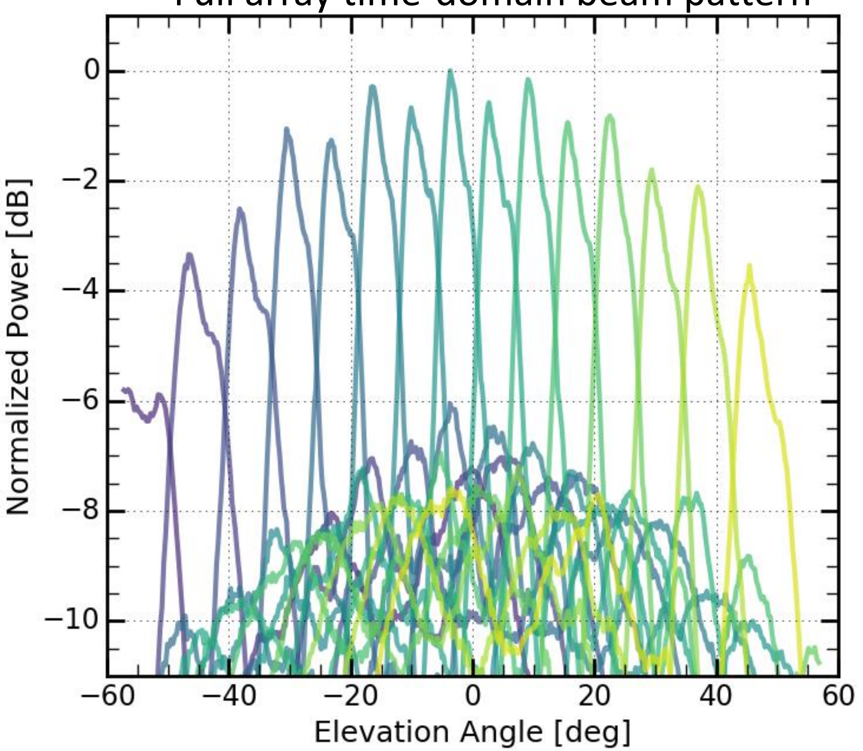
Beam pattern

- Plane-wave coherent sums using 1 m (7 antennas) and 2 m (5 antennas) baselines.
- 10 ns binned power is calculated in each adjacent sum, added together = NuPhase 'beam'. Roughly 7° FWHM.
- 15 beams formed simultaneously, covering 100° in elevation. Each an independent trigger channel with dedicated threshold

Single beam



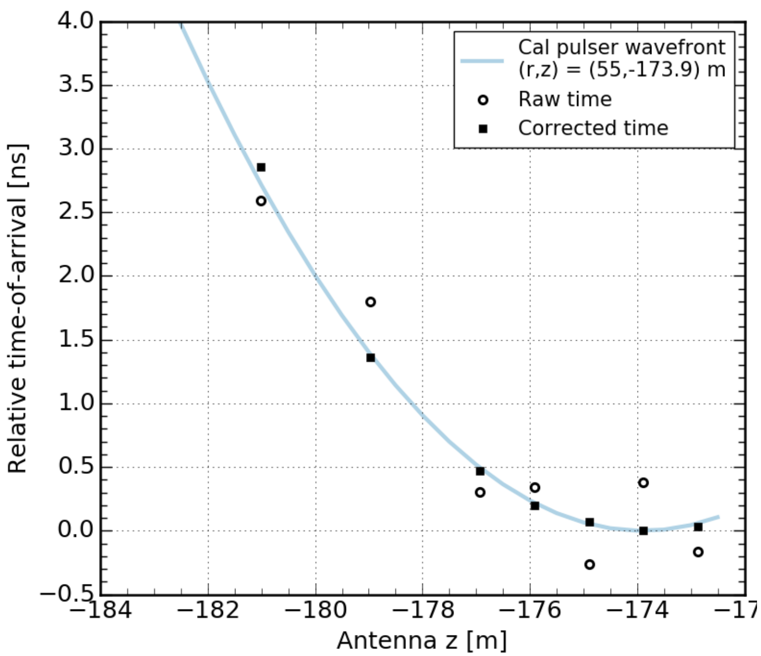
Full array time-domain beam pattern



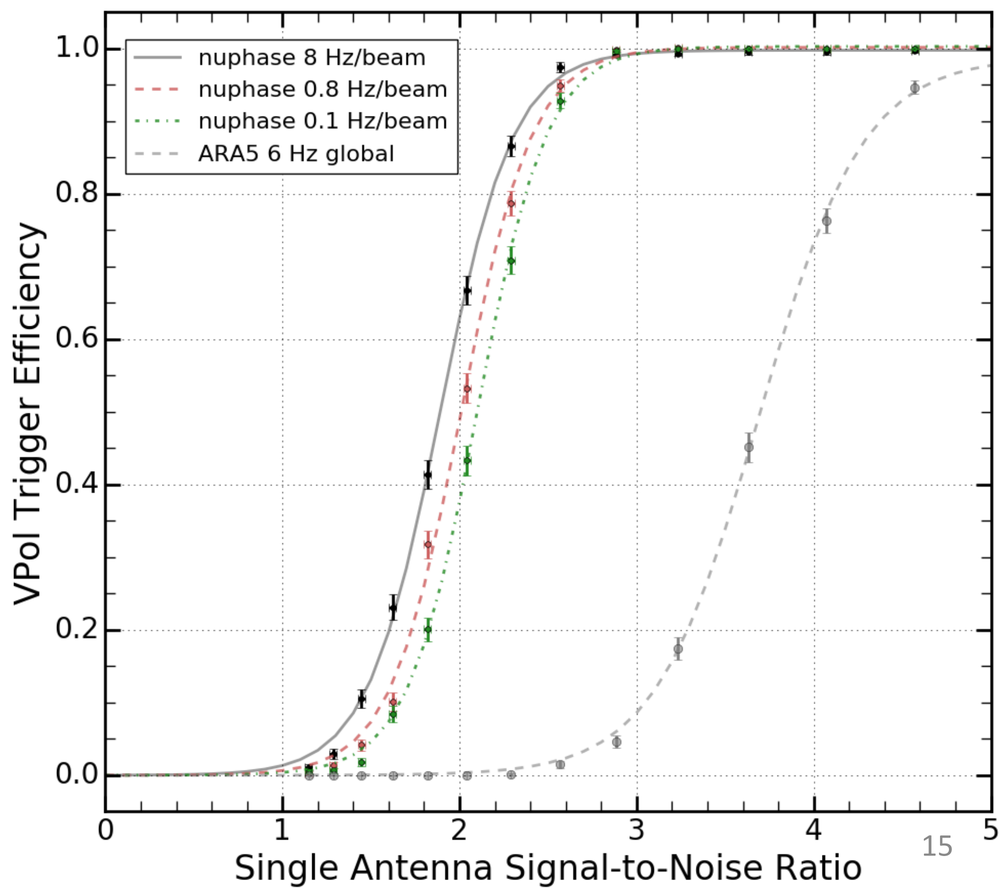
Trigger Efficiency

- Using ARA5 calibration pulser, in the near field (spherical wave)
- 50% trigger efficiency at SNR = 2.0 [$V_{pp}/(2\sigma)$] at 10 Hz global event rate
- Remains efficient at <1 Hz global rate

Time of received pulse at antenna



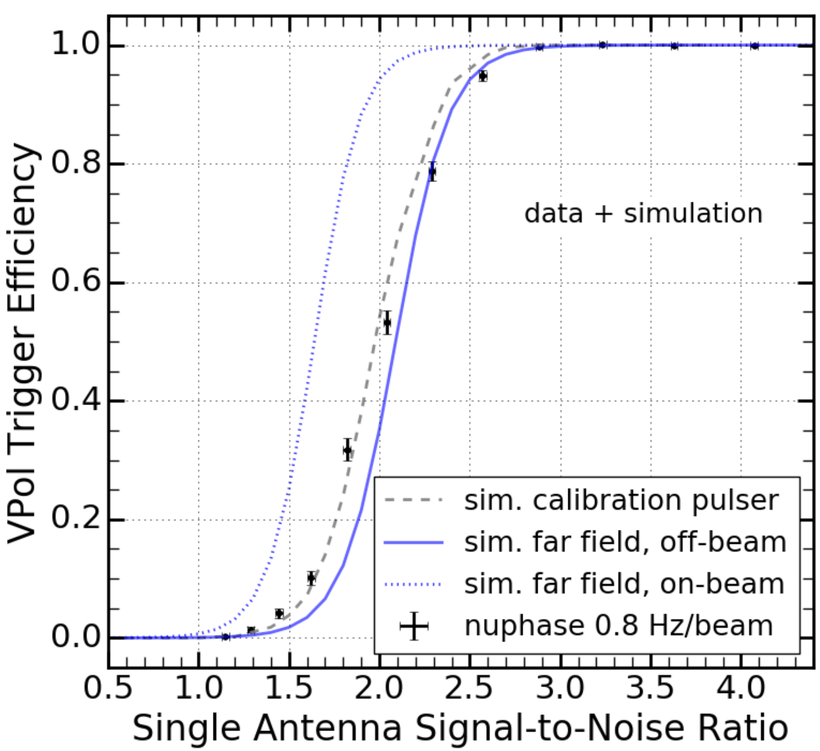
Efficiency on cal pulser signals



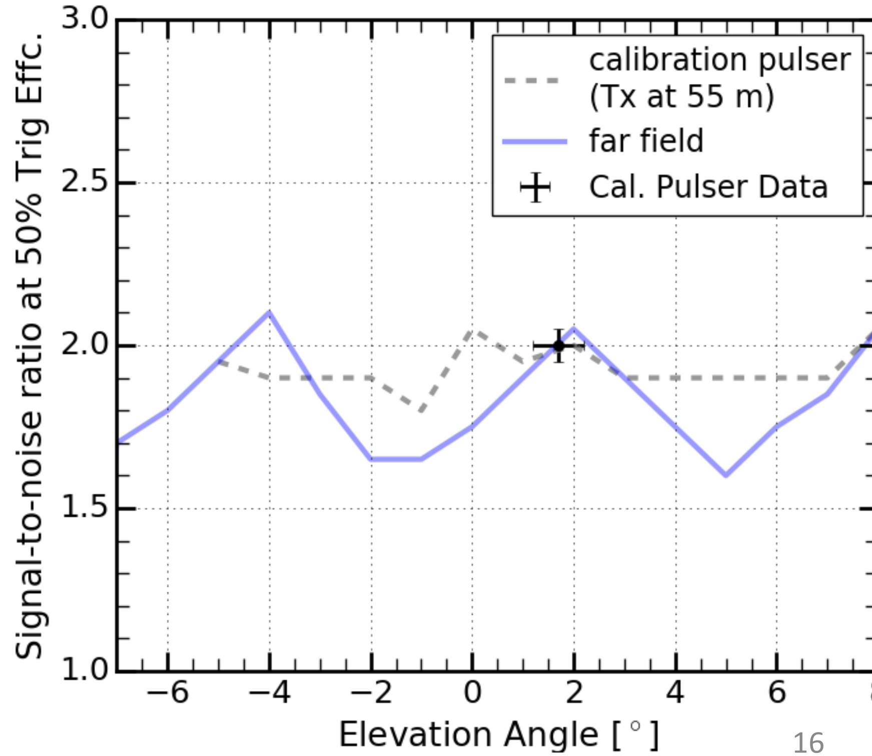
Detailed hardware-level simulation

- Important to understand FPGA processing + array sensitivity as a function of elevation angle and wavefront properties
- Some dependence on elevation angle due to beam patterns. Trigger efficiency at 50% varies between 1.6 and 2.1 for far-field plane waves
- Agrees well with measurements

Efficiency curves: nearby transmitter + far-field



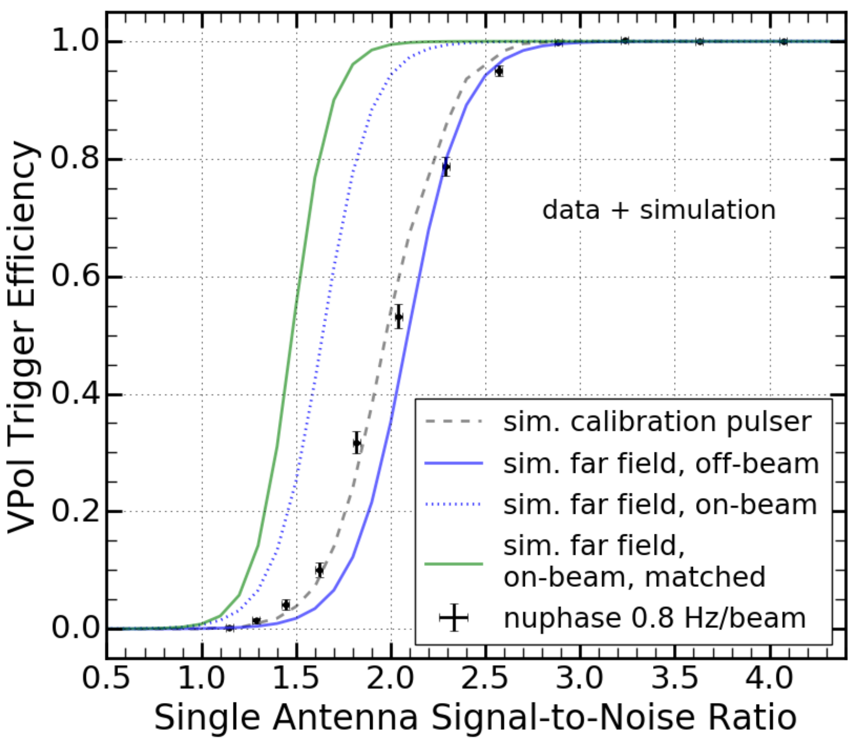
Incident angle dependence



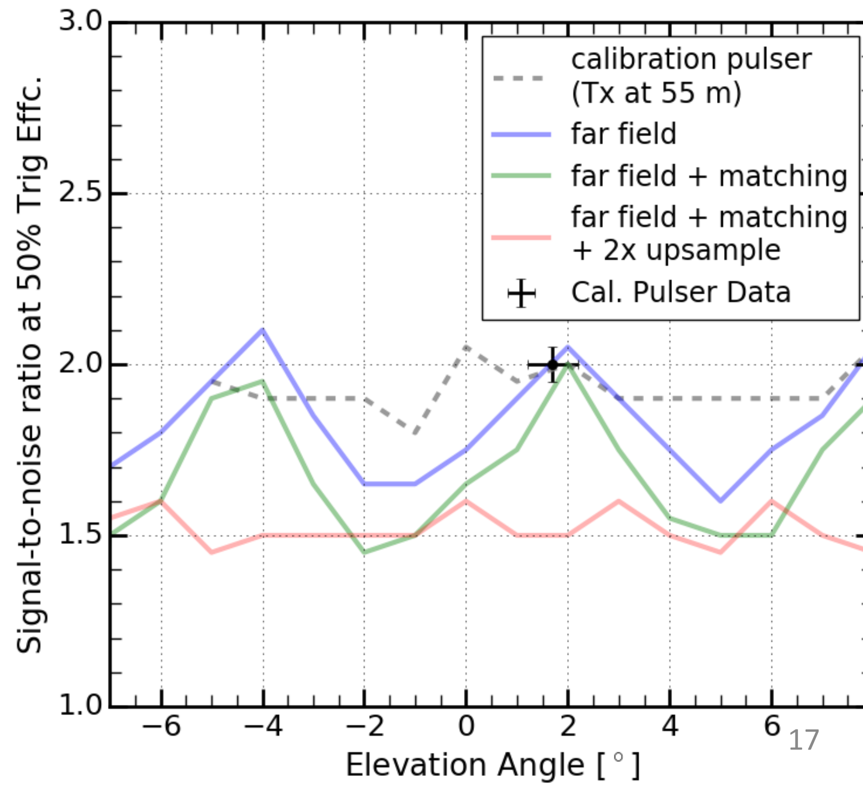
Improvements possible with current system

- Main sensitivity loss due to systematic timing mismatches between channels (~100 ps level), and due to array beam pattern
- Solution: upsampling on the FPGA!
  - Form an additional set of beams to fill gaps + fractional delays to correct channel-to-channel timing
  - Can reach 50% trigger efficiency at SNR = 1.6, uniform over angle
- However, increases trigger latency, perhaps not within requirements of ARA DAQ.

Efficiency curves: nearby transmitter + far-field

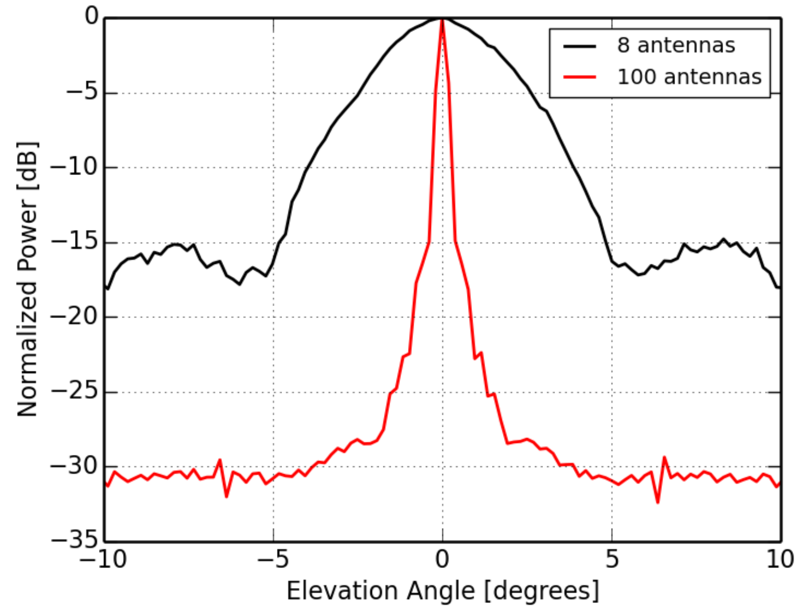


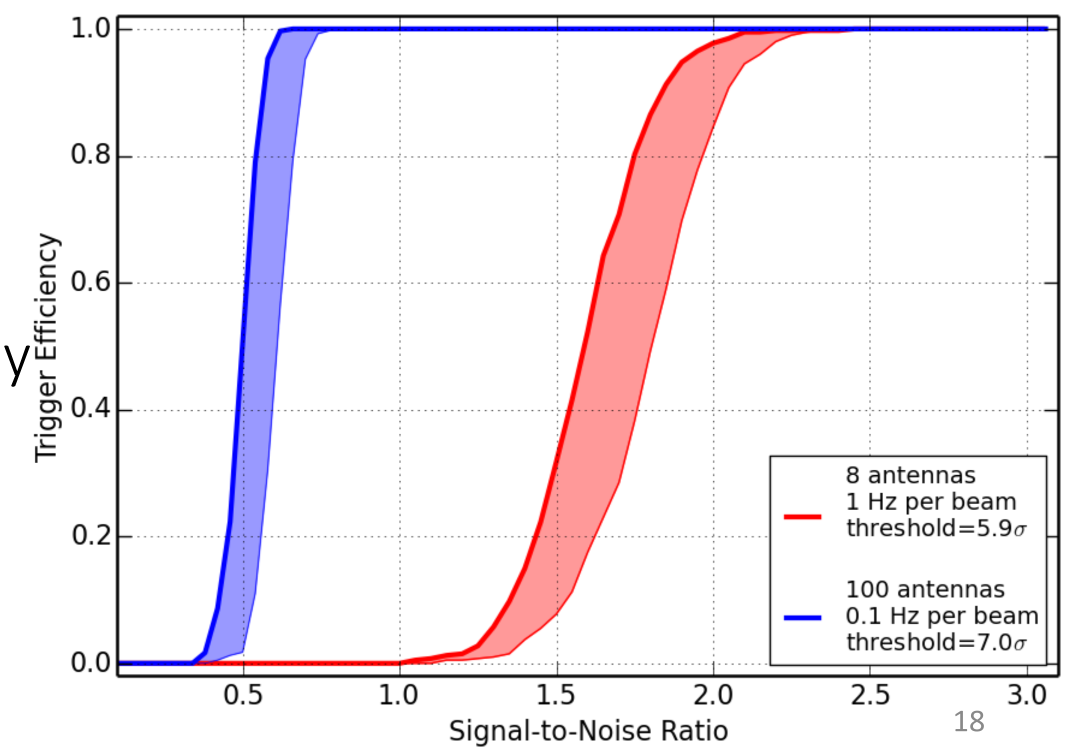
Incident angle dependence



Scaling up?

- Arrays of 16-24 antennas reach the SNR = 1.0 level
- 100 antennas required to push to ~PeV scale [Vieregg et al JCAP 2016:02]
- Scaling to 100 antennas may not be feasible, but envelope correlations or simple coincidences between multiple phased strings could be natural way to extend trigger
- Mixed polarization (add Hpol)





Summary

- Full phased array trigger system deployed at South Pole in 2017/18 season in collaboration with ARA
- Trigger efficient on Vpol signals with SNR ≥ 2.0
- Room for improvement in current system with additional firmware features.
- BEACON deployment will serve as testbed for further FPGA development for RFI mitigation, etc. (see Stephanie Wissel talk)

- Path towards scaling up includes optimizing the antenna array (number, frequency, and polarization) and lowering power consumption for potential autonomous stations.
    - An 8-channel phased array possible within 15W?

- Streaming digitization, even at low resolution, is an asset to any radio detector

Backup

Power reduction: autonomous station possibility?

- NuPhase made with mostly off-the-shelf components (ADC chip, RFoF system, etc) = quick fielding
- Per-channel power budget:

[LNA = 0.4 W] + [RFoF system = 6 W] + [2nd stage amp = 0.25W] + [ADC / FPGA data receivers + initial processing= 2.5W] ~ **10 W/ch**

- Commercial RFoF system is overdesigned for our purposes, custom design possible for 1-2W
- ASIC digitizer, fewer bits, push ADC/FPGA per channel consumption to <1W
- Likely possible to push down to <**3W/channel**

Lower Frequency band? i.e. 250MHz

- Power scales linearly with sampling rate → **1.5-2W/channel**

Integrate with a modular trigger/DAQ

Presently, NuPhase is a separate instrument.

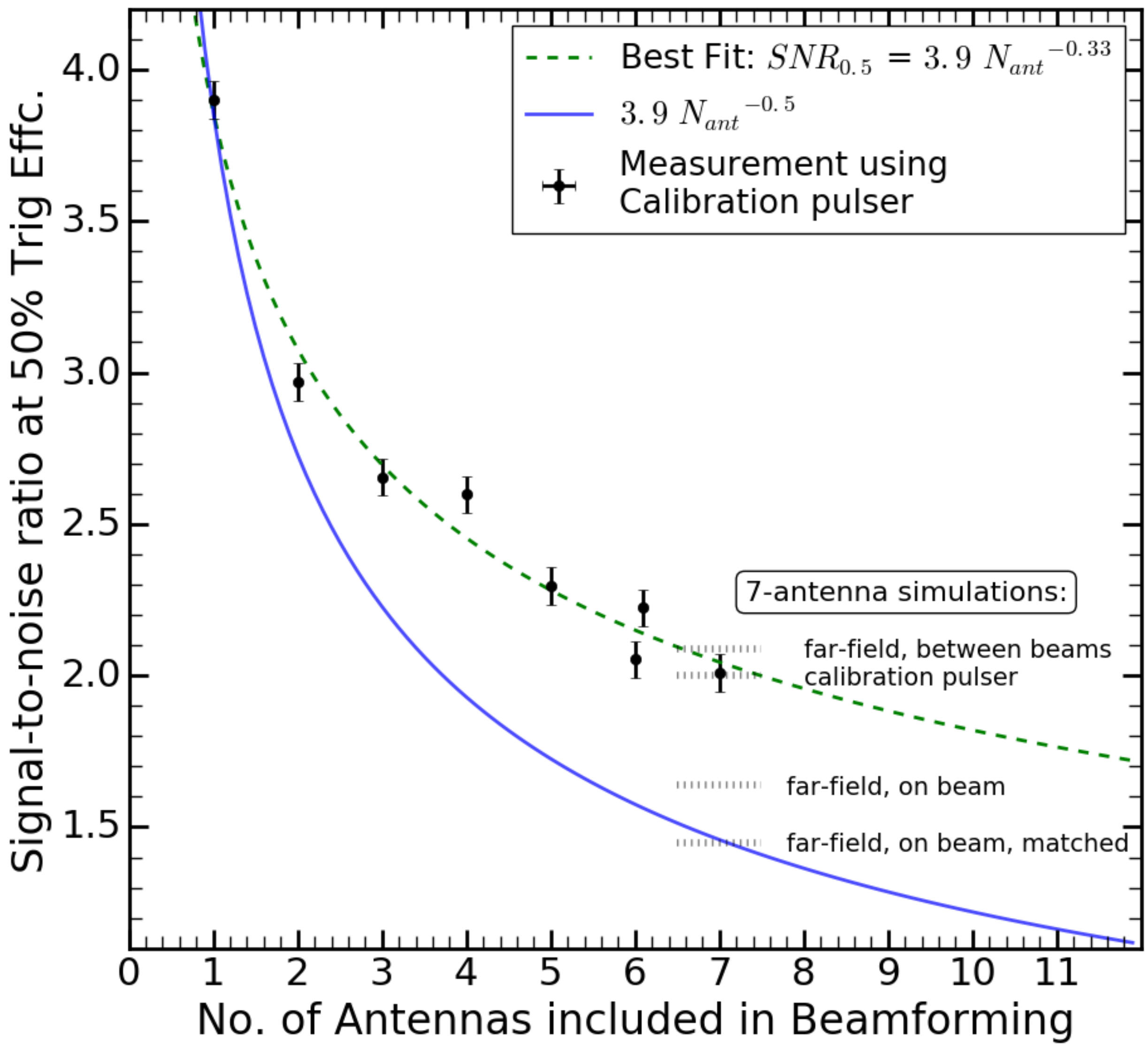
A modular DAQ system could incorporate a standard switched-capacitor array sampling ASIC and tunnel diode trigger, with option for ‘plugging’ in a phased array system

For an autonomous system, the DAQ could decide which trigger to run based on power availability

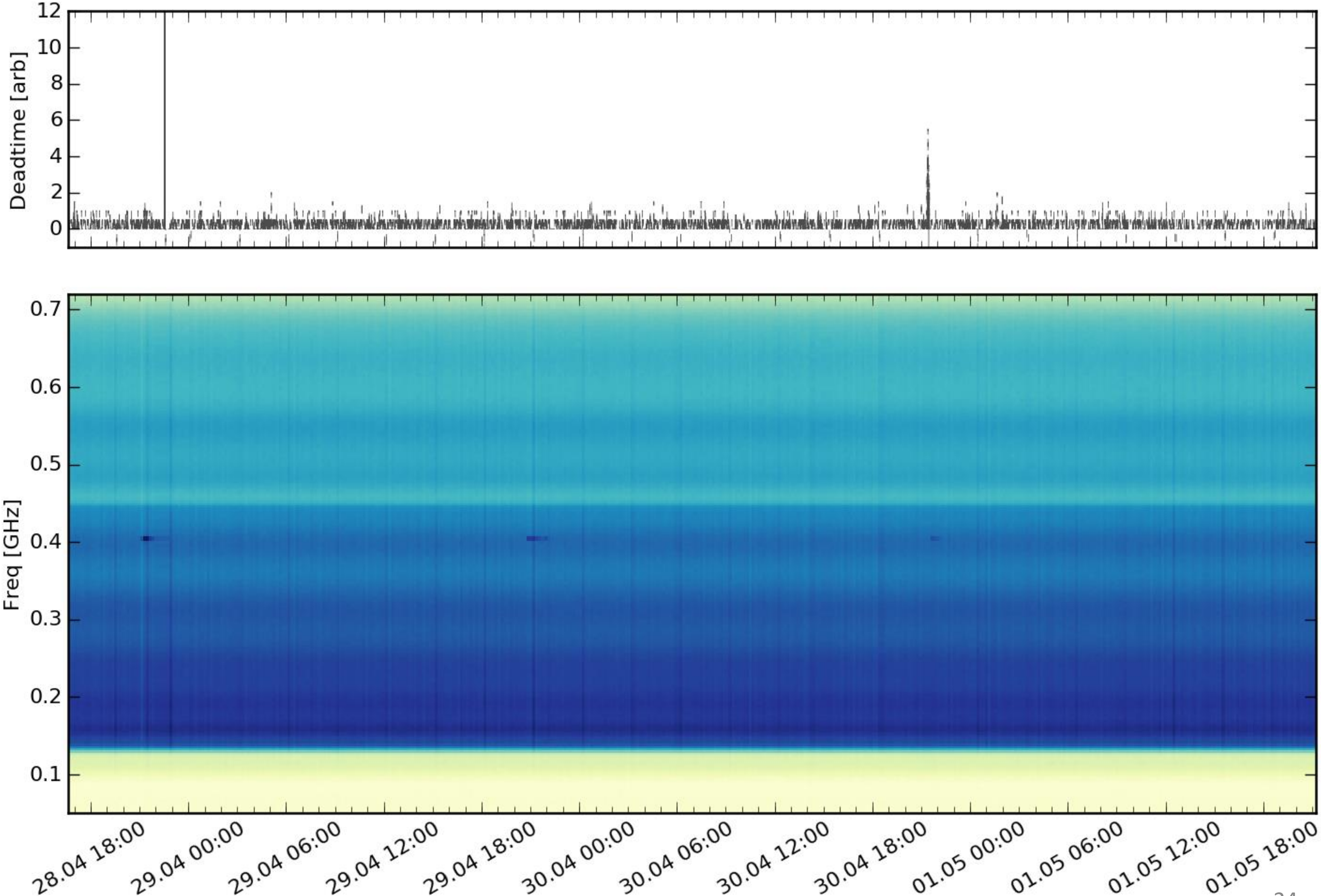
New multi-buffer ASICs, with record lengths > 1000 samples, and sampling rates > 2GSa/s

- LAB4D – 1 CH/chip, 4096 samples, hardware timebase trimming [arxiv:1803.04600]
- PSEC4A – 8 CH/chip, 1056 samples, sampling rates 1-10 GSa/s

Coherent gain vs number of antennas included in beamforming

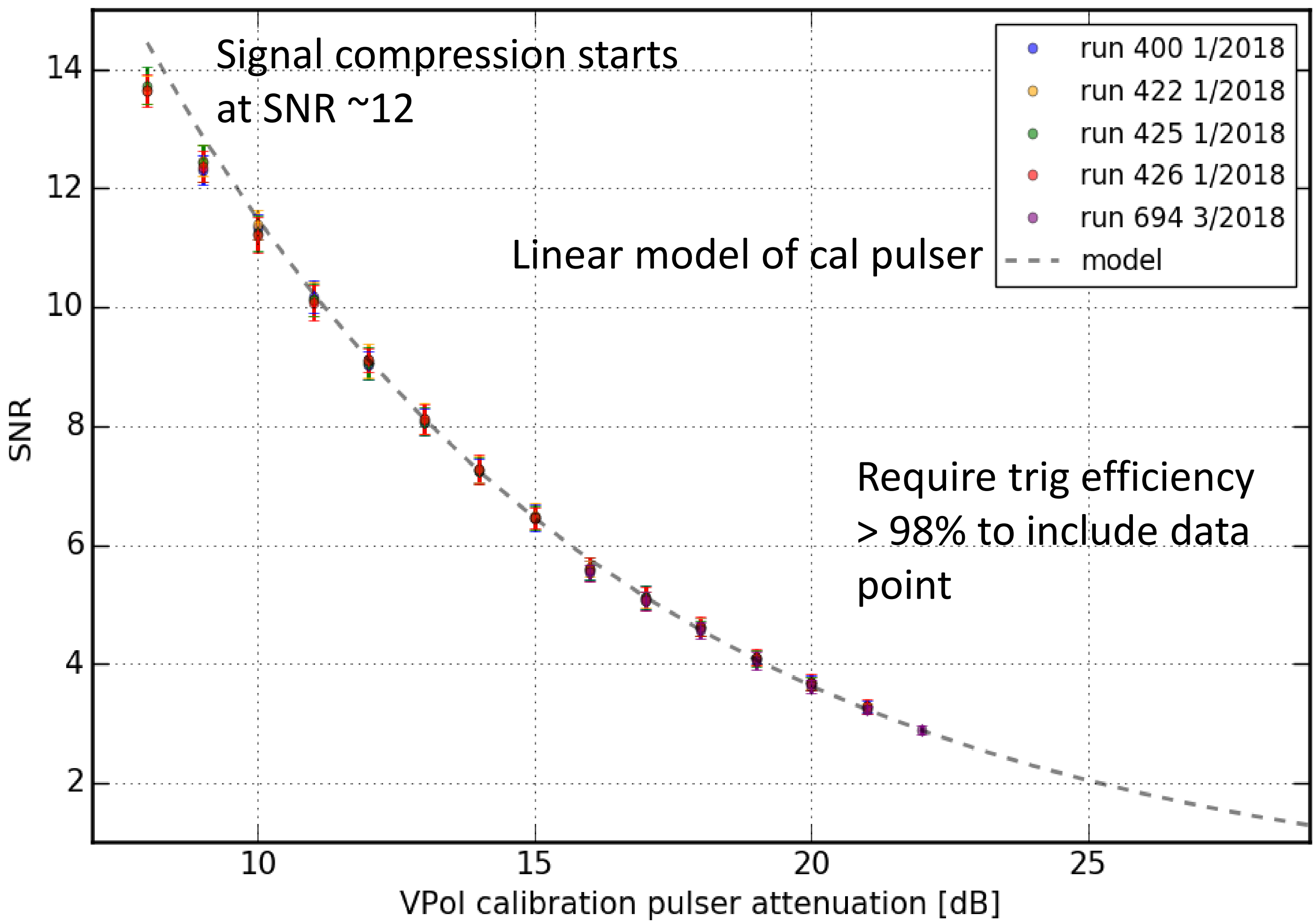


RFI environment / NuPhase livetime



Linearity / dynamic range

Using attenuation sweep of ARA5 Vpol calibration pulser



Trigger rates / thresholds