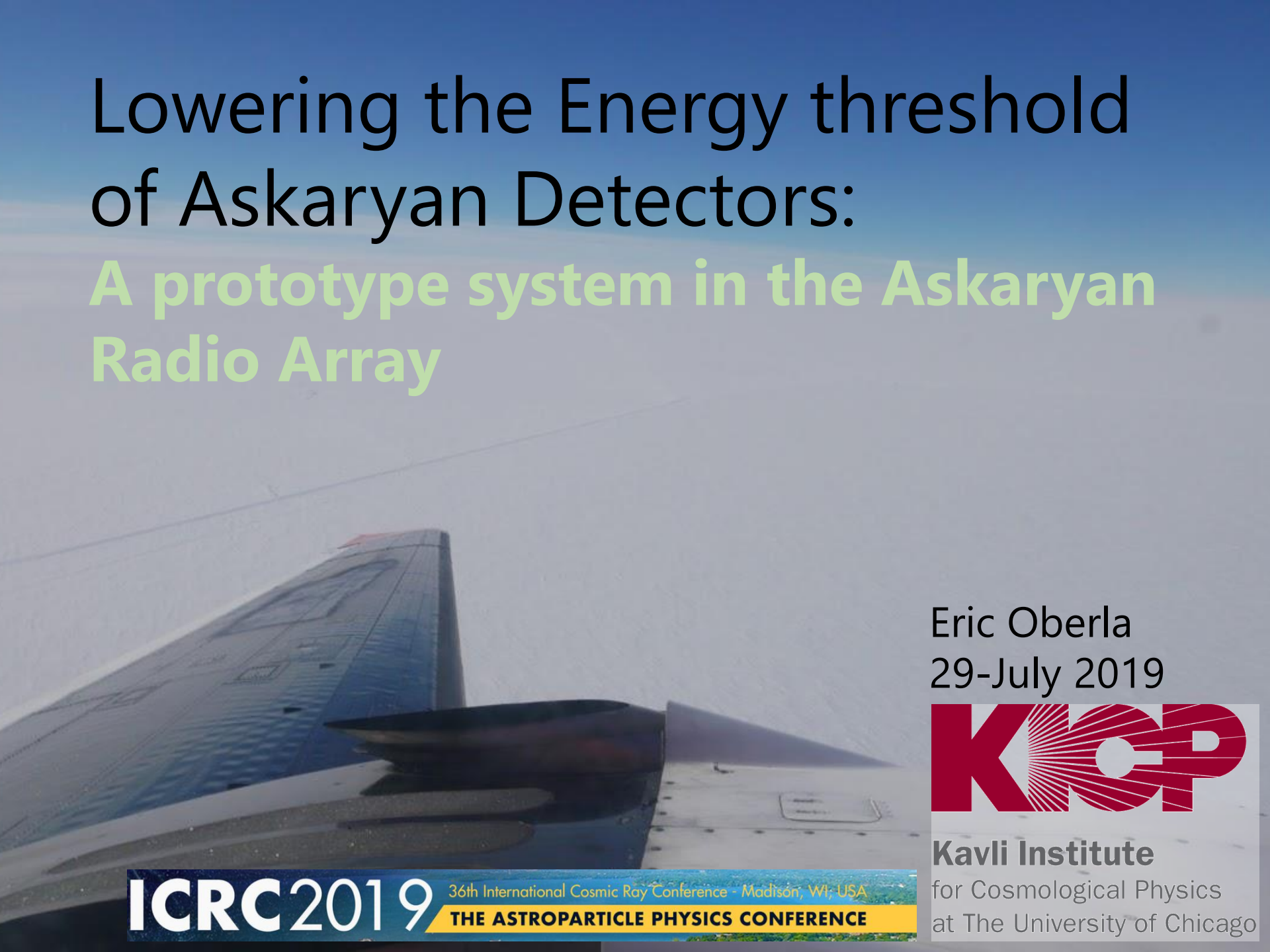
Lowering the Energy threshold of Askaryan Detectors:

A prototype system in the Askaryan Radio Array



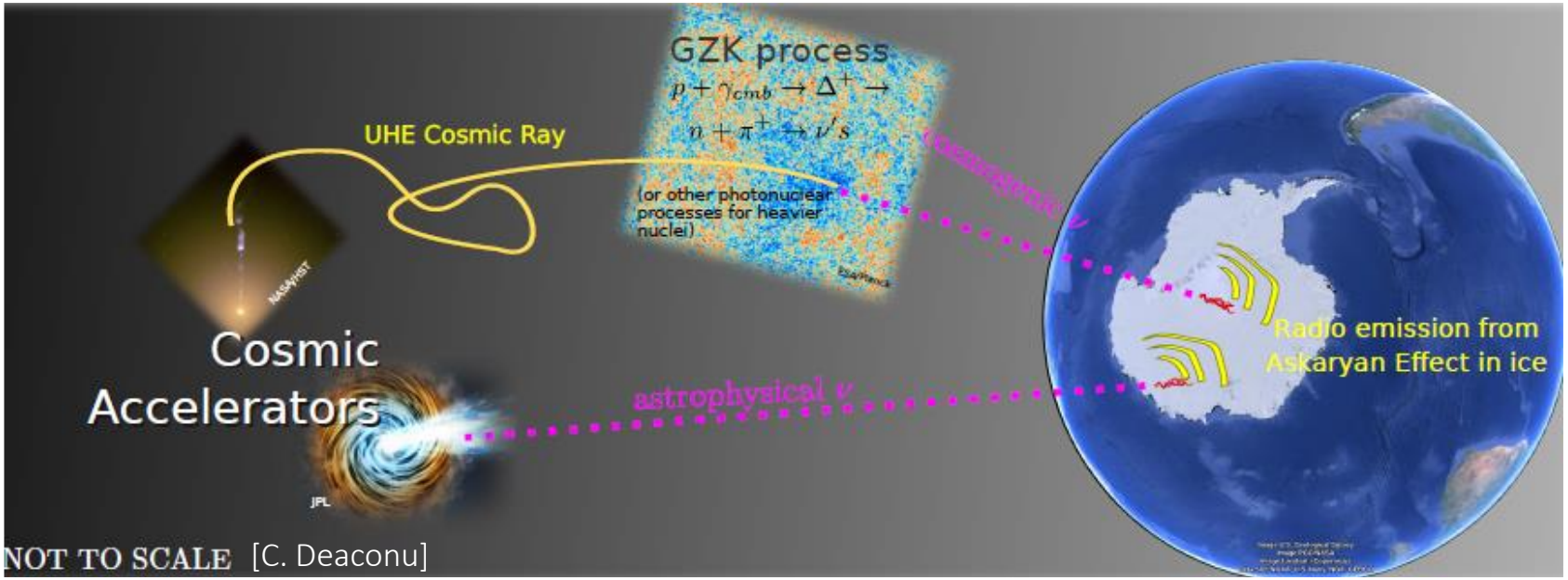
Eric Oberla

29-July 2019

ICRC2019 36th International Cosmic Ray Conference - Madison, WI, USA
THE ASTROPARTICLE PHYSICS CONFERENCE

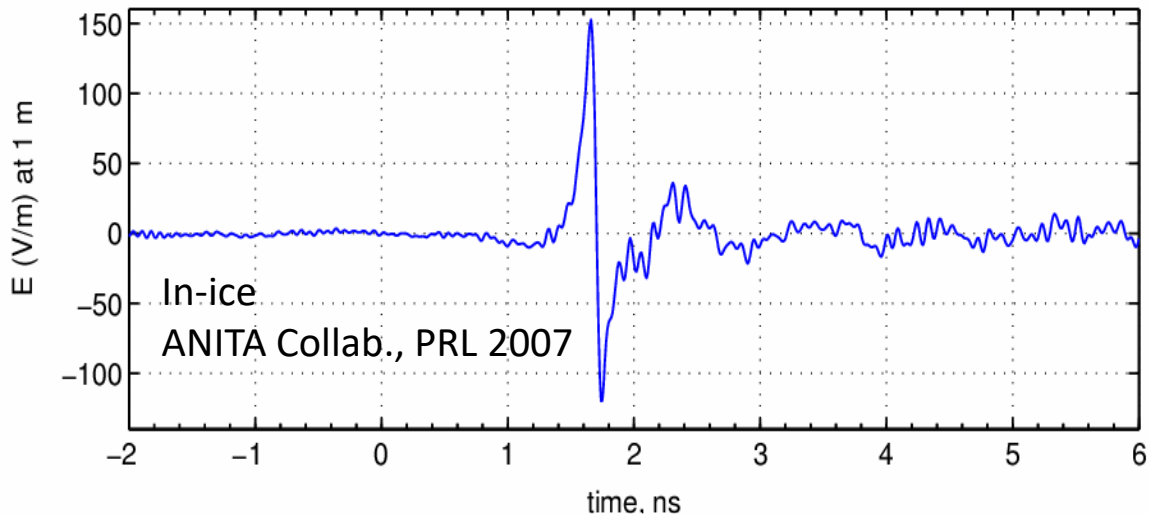
Kavli Institute
for Cosmological Physics
at The University of Chicago

Motivation



Enhance the sensitivity of the Askaryan radio-detection technique at lower energies (30-300 PeV) where there is tantalizing evidence (IceCube) of an astrophysically-sourced flux

Askaryan Radio Signal

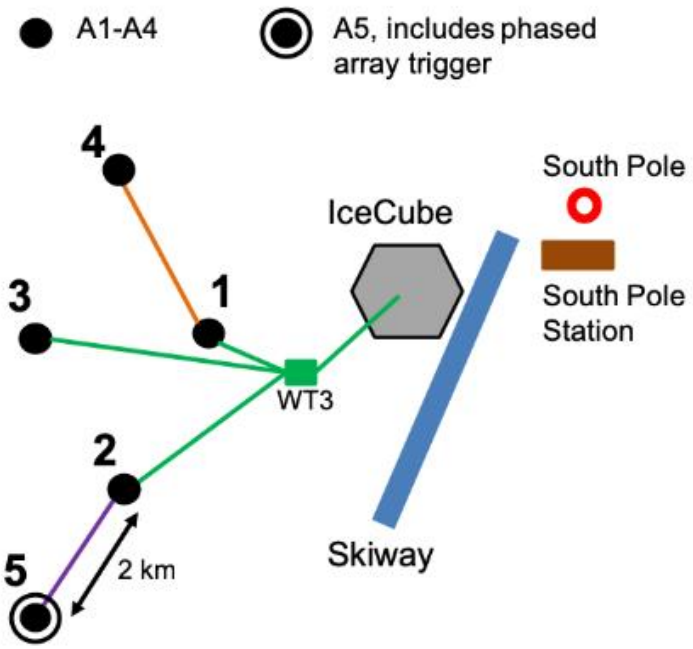


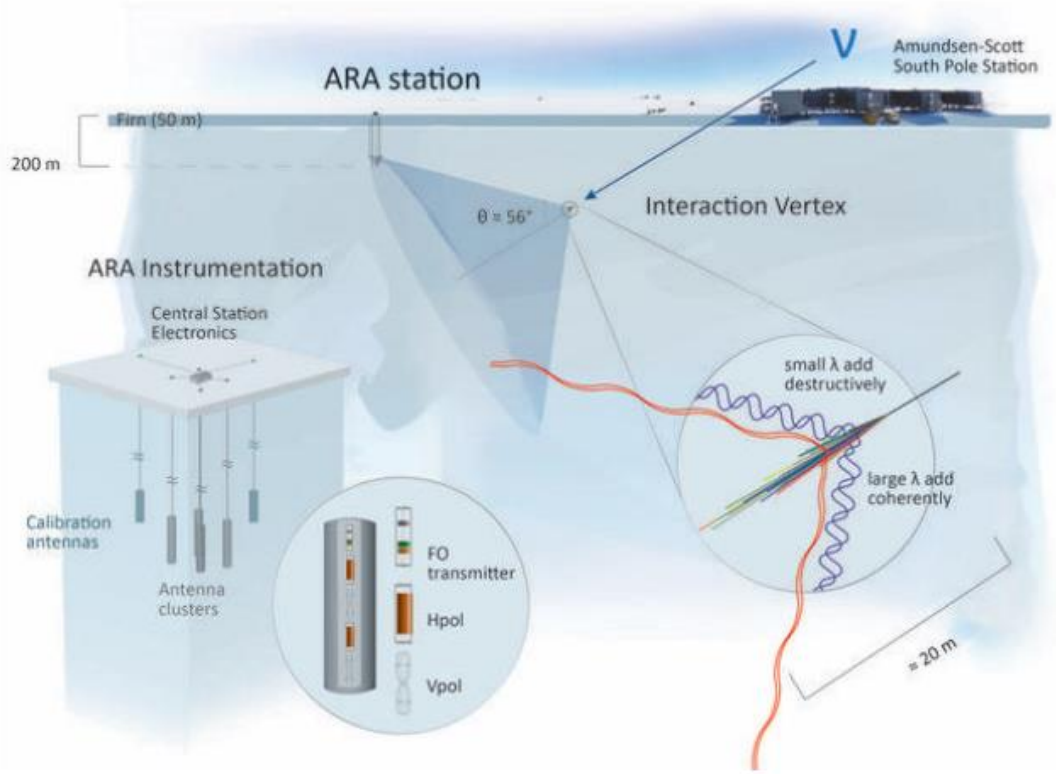
$\circledast$ Antenna + RF system response

- Askaryan signal extremely broadband → bandlimited signal in the detector
- To trigger on an UHE neutrino: build an radio impulse detection system and reject thermal noise (ice) and RFI backgrounds as best possible.
- To reconstruct an UHE neutrino:
  1) Relative timing between antennas ('pulse-phase interferometry') provides vertexing of the in-ice interaction
  2) Frequency and polarization content provides location on Cherenkov cone
  3) A good understanding of the detection medium; ice in our case

Askaryan Radio Array (ARA)

- Five stations of deep (200 m boreholes) low-gain antennas at the South Pole
- Standard trigger involves individual antenna thresholds + multi-antenna coincidence requirement
- Stations A4 and A5 deployed during 2017/18 season
- Utilizing IceCube infrastructure: stations are cabled (power + comms.) to the IceCube Laboratory

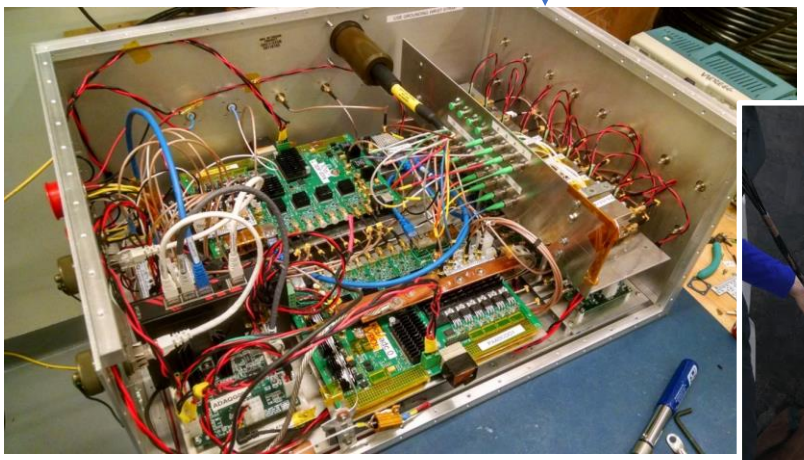




[ARA status and analysis: A. Connolly talk]

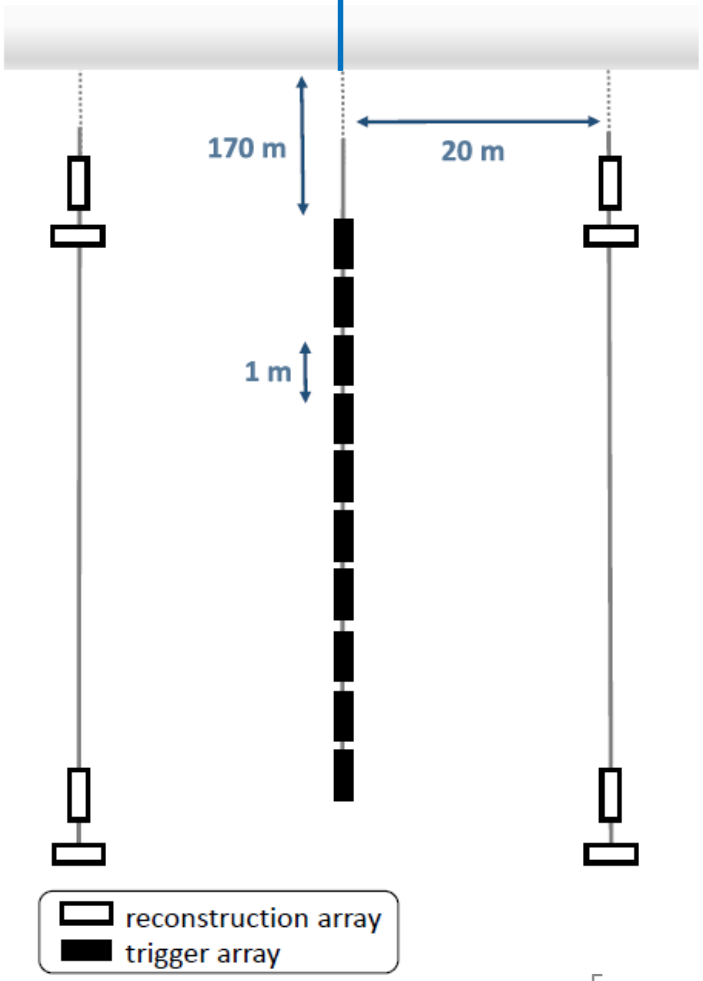
Low Threshold Trigger at A5

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



Trigger and recording DAQ for central NuPhase string

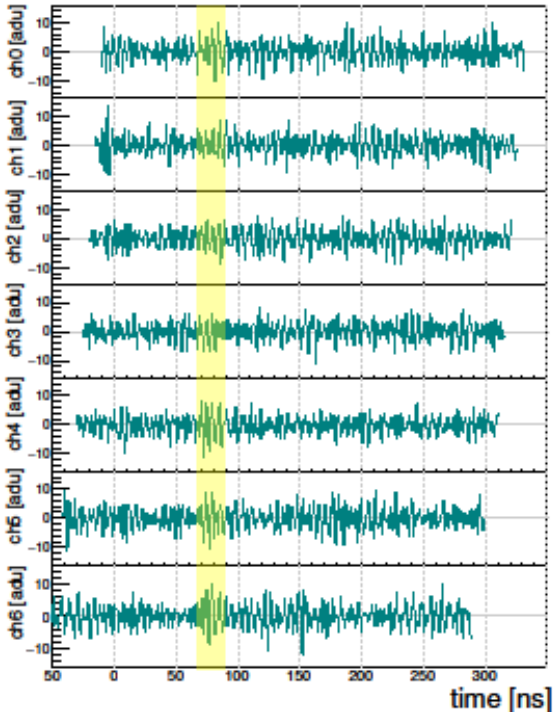
Vpol antenna + integrated RF front end



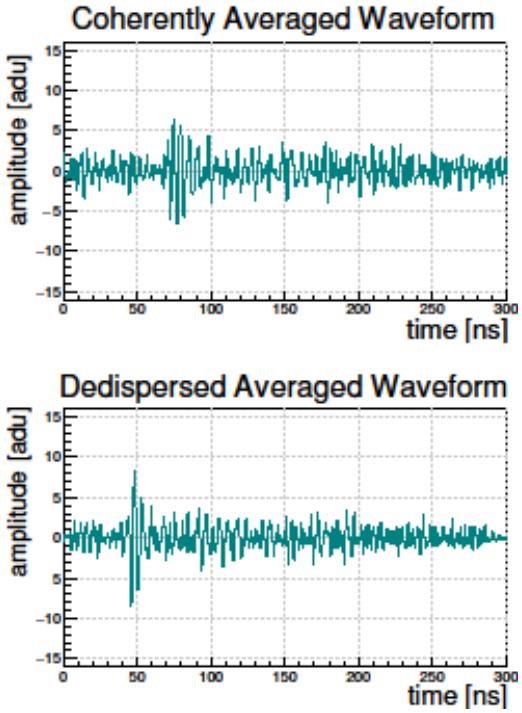
An in-ice phased array

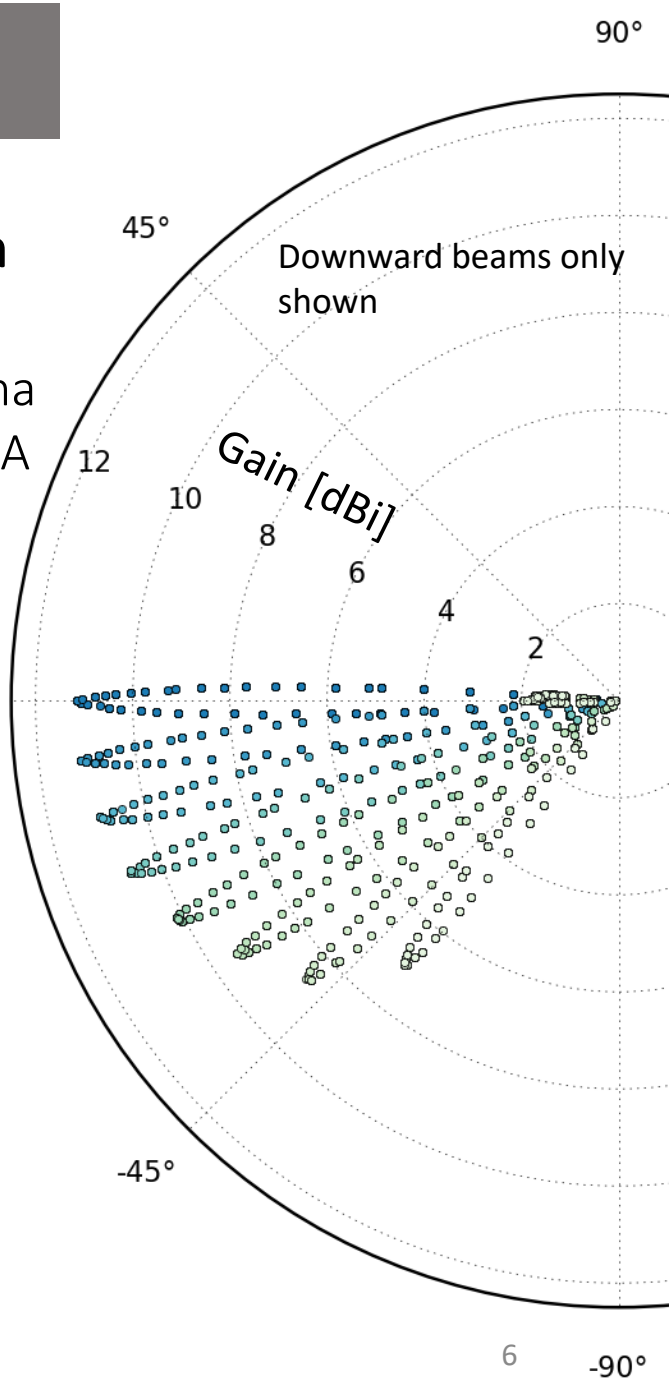
A digital interferometer can form multiple beams simultaneously over the volume of interest – **search for plane-waves at the trigger level**

- Real-time low-resolution digitization of trigger antenna signals. Stream data to digital beamformer on an FPGA
- In presence of uncorrelated thermal noise, coherent gain scales as $\sqrt{N_{antenna}}$.



Low SNR calibration pulser signal

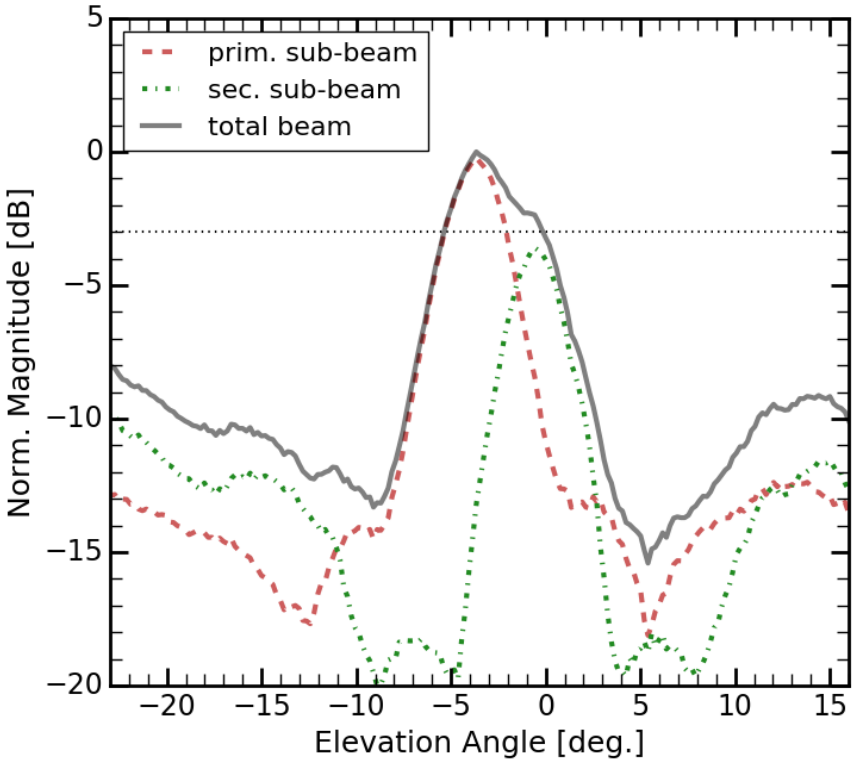




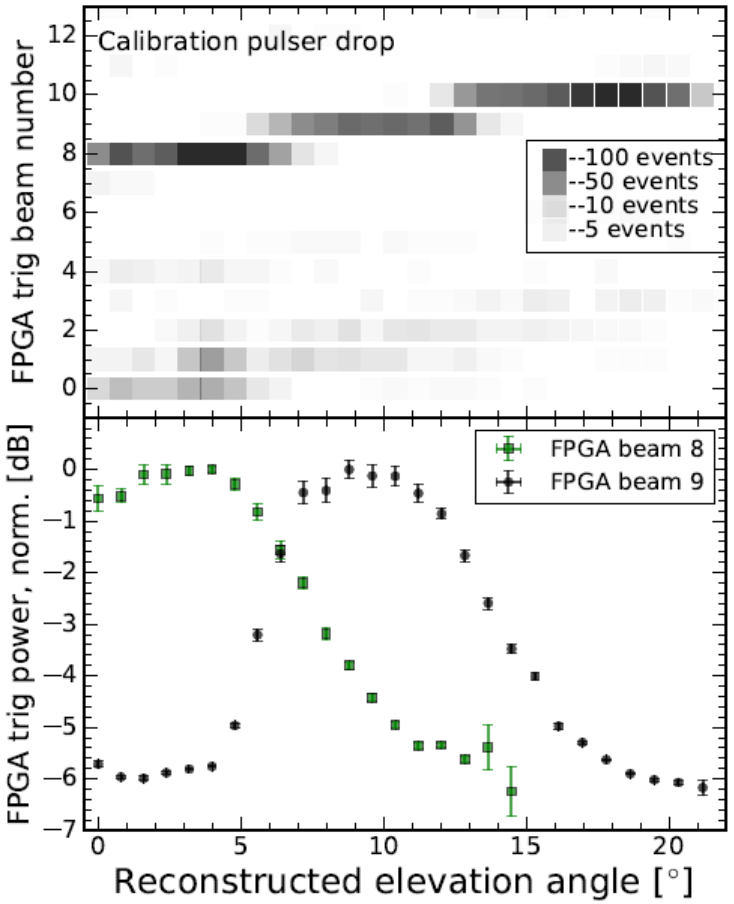
Beam Pattern

- Plane-wave coherent sums using 1 meter and 2 meter baseline antenna-pairs
- 10 ns binned power is calculated in each adjacent sum, each constituting a ‘beam’
- 15 beams formed simultaneously, covering 100° in elevation. Each an independent trigger channel with dedicated threshold
  - Possibility for directional background rejection in high-RFI environments [K. Hughes poster]

Simulated beam



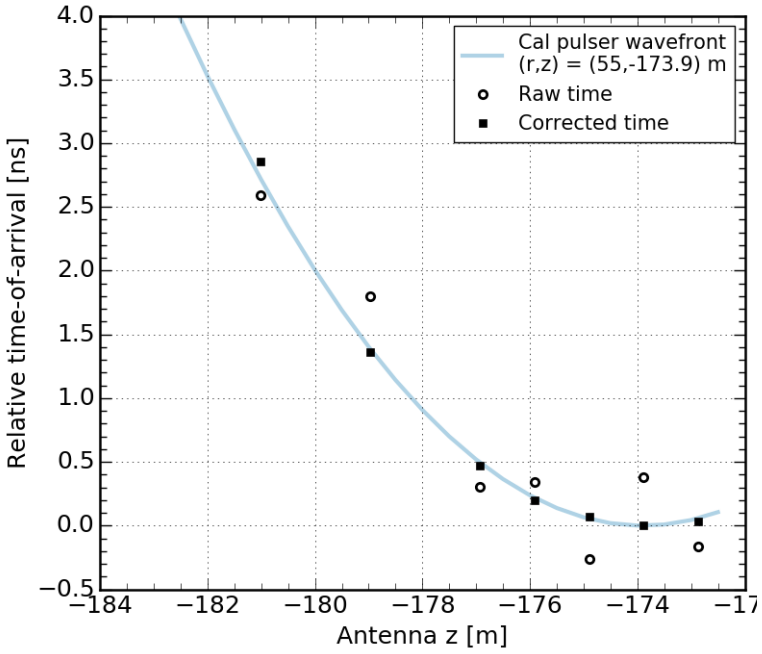
In-situ beam-mapping



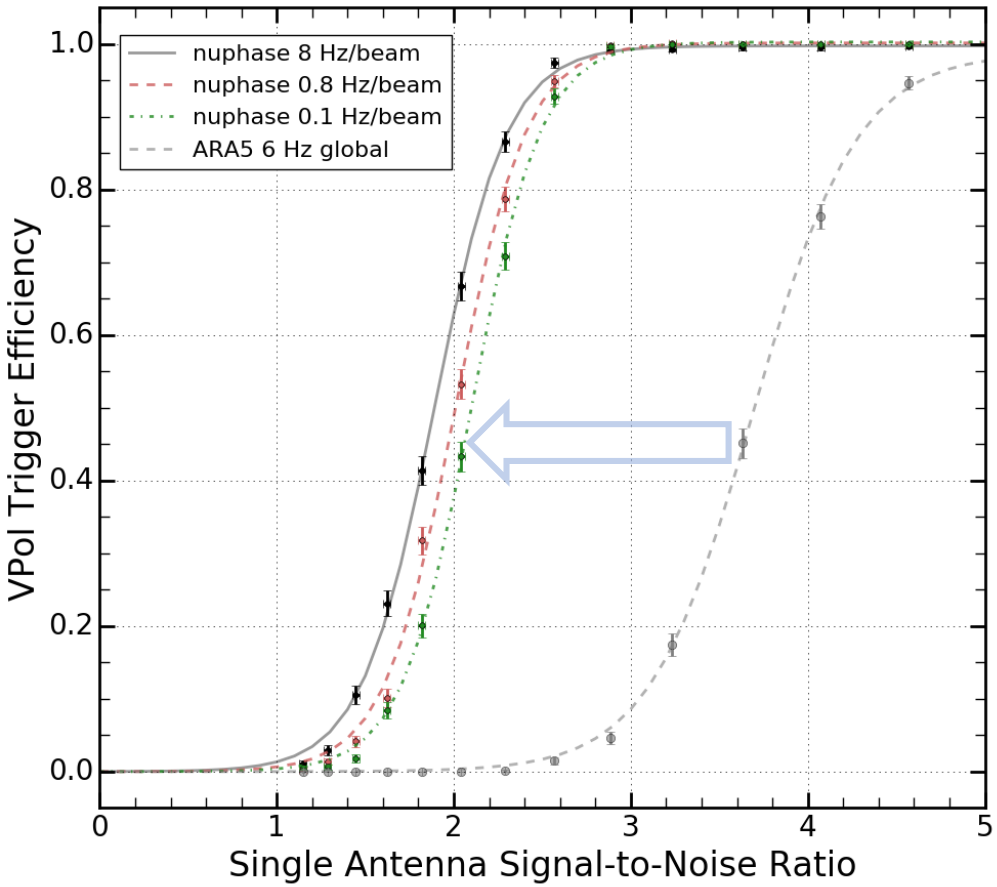
Lowering the Trigger Threshold

- In-situ measurements using A5 station calibration pulser, in the near field (spherical wave)
- Trigger threshold at voltage signal-to-noise ratios (VSNR) of 2.0 achieved
- Remains efficient at low (<1 Hz) global trigger rates

Calibration pulse wavefront timing at the phased array

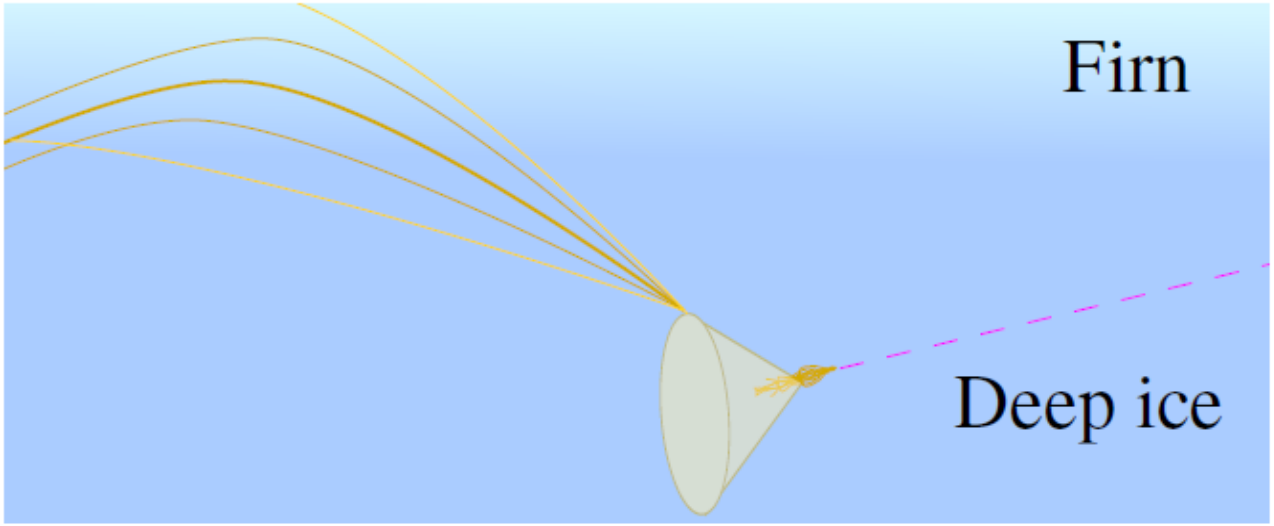


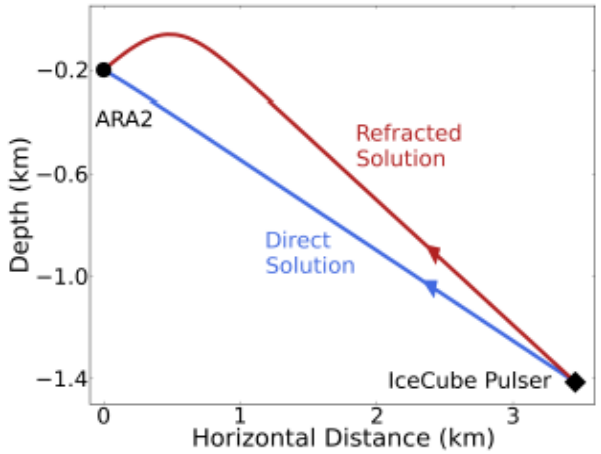
Trigger Efficiency on cal pulser signals

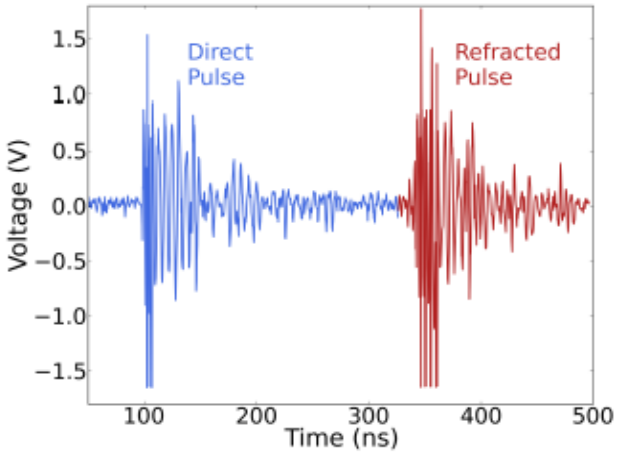


Ice considerations

- Top layer of ice ('firn') has density gradient → index of refraction gradient leads to loss of effective volume for shallower antenna installations
- Multiple signal paths from source to detector: 'direct' and 'refracted'







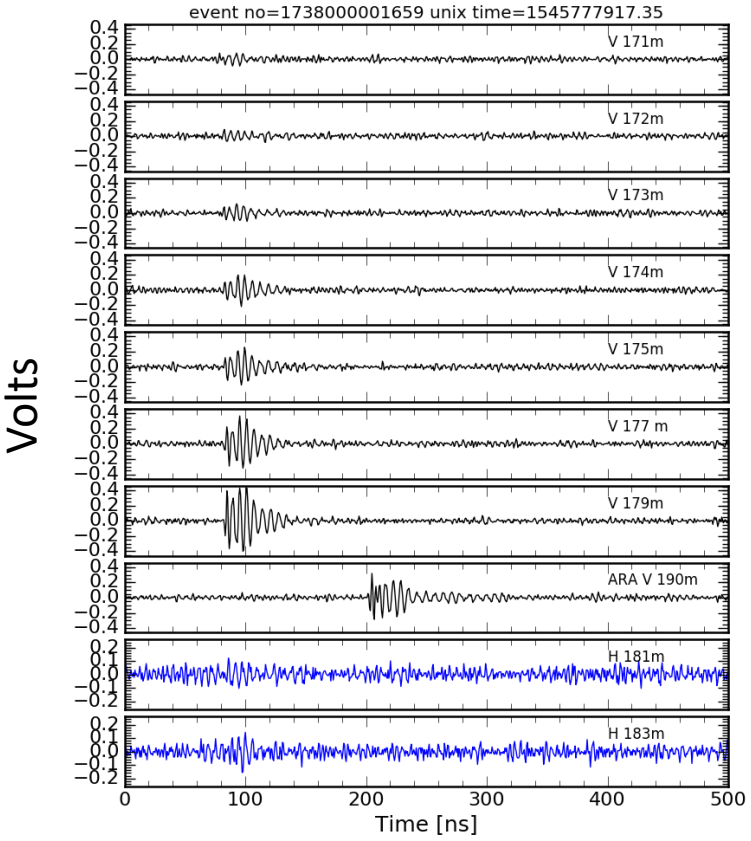
SPIceCore 2018/2019

- Radio pulser campaign using the South Pole Ice Core (SPIceCore) hole
- Pulser dropped from surface to 1500 m deep, a distance of ~5km from A5

Example waveforms

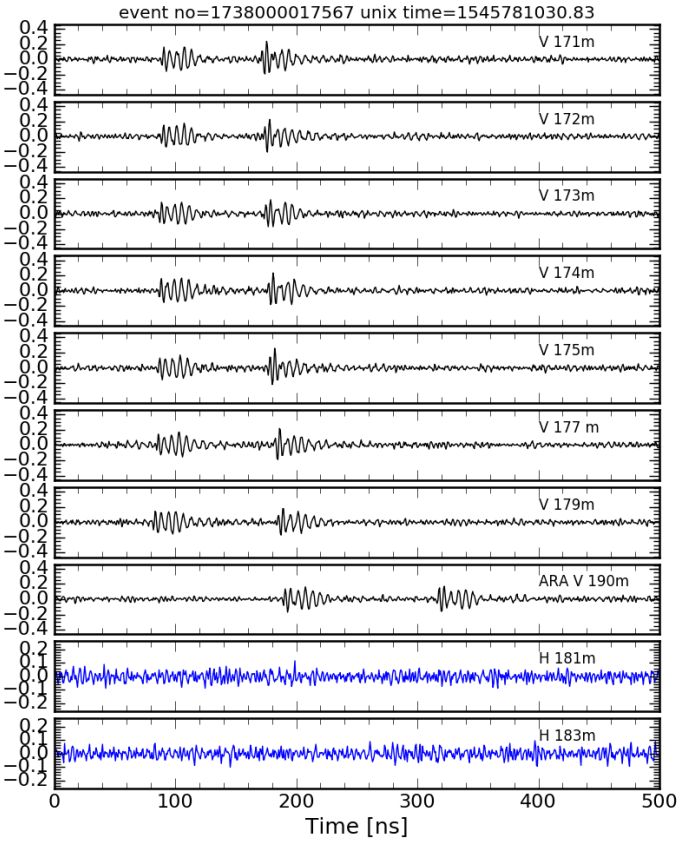
Tx depth ~ -550m

Steep amplitude gradient across the array as first triggers are recorded

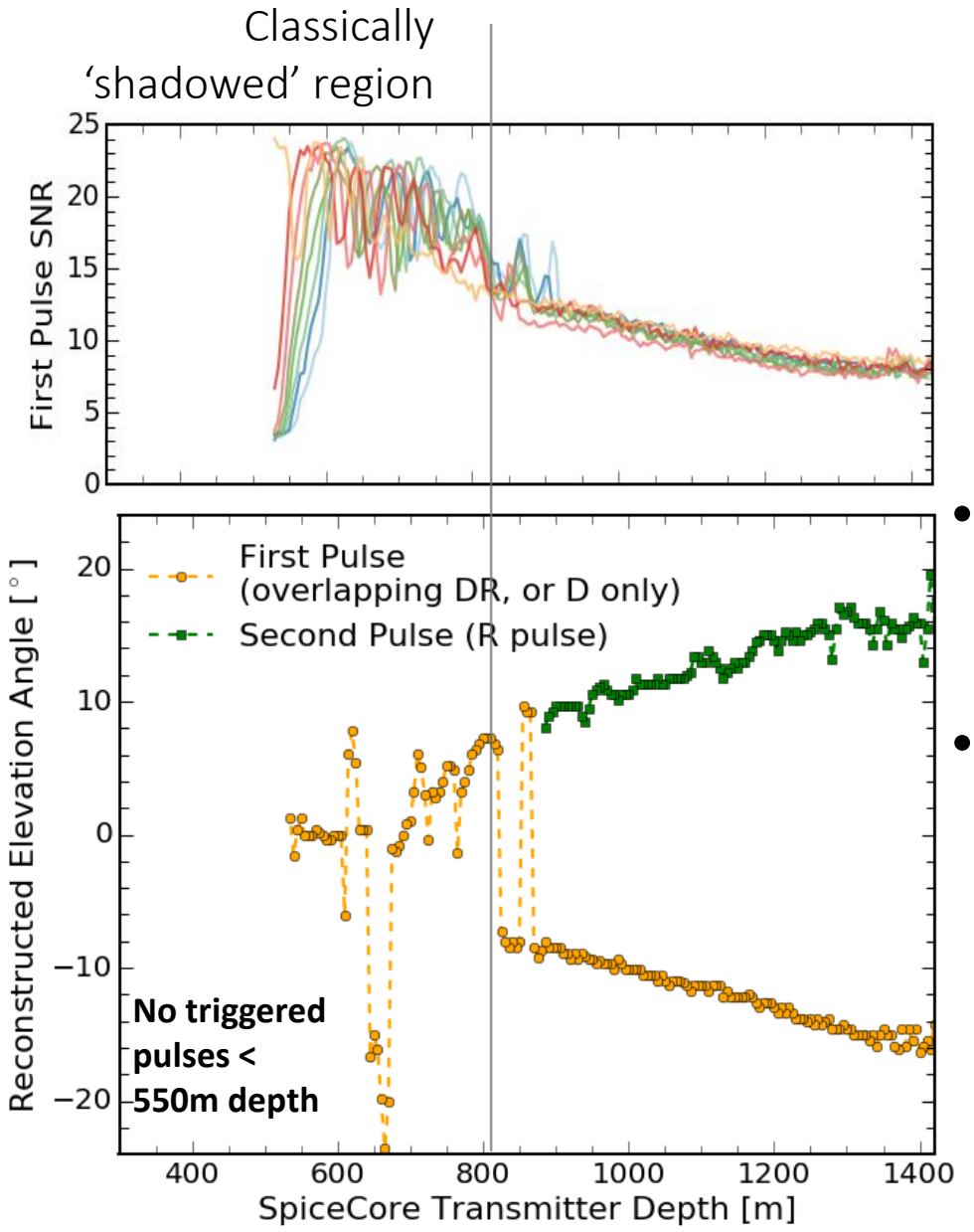


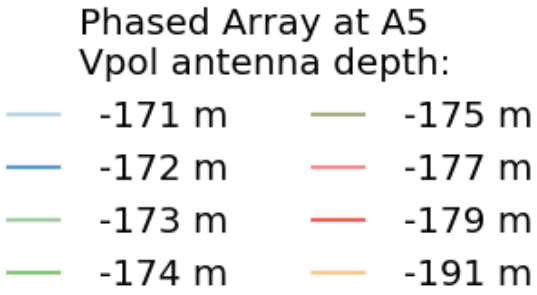
Tx depth ~ -1100m

Distinct DR pulses



Using the phased array/ARA to probe ice properties





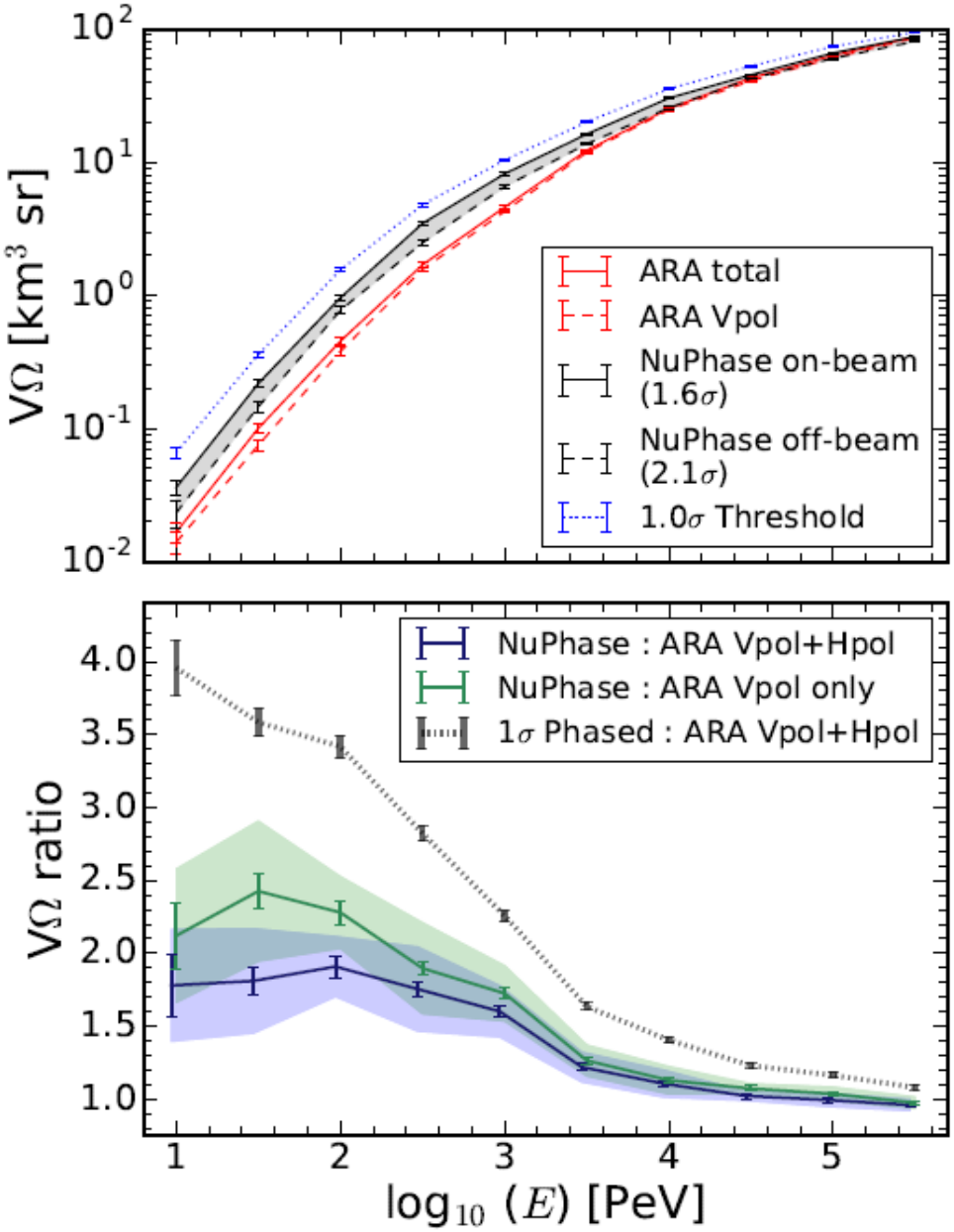
- Signal observed in the regions expected to be shadowed in conventional ray-tracing
- These 'shadowed' pulses exhibit interesting behavior:
  - large amplitude variations, on ~1 m scales
  - Erratic directional reconstruction
  - Ongoing studies..

Effective Volume

Measured performance of the ARA NuPhase trigger added to the ARASim detector simulation package

Demonstrated ~2x increase in per-station trigger-level effective volume at 10-300 PeV

Also studied an enhanced trigger system with lower threshold at VSNR=1.

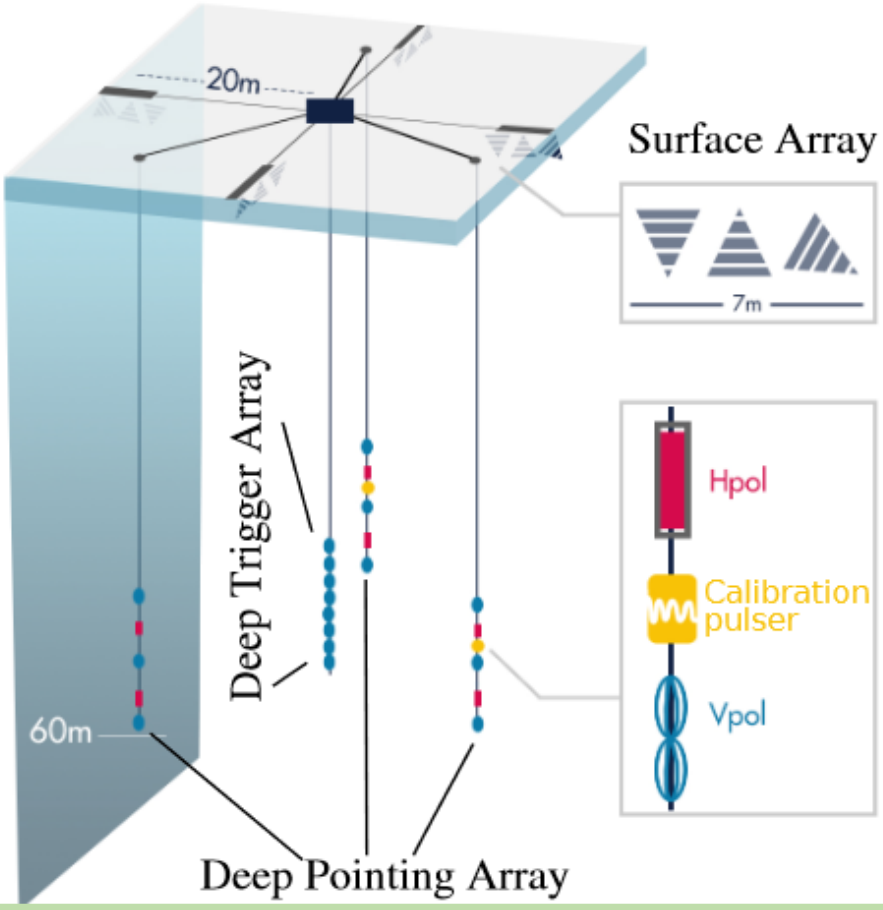


Future w/ phased triggers

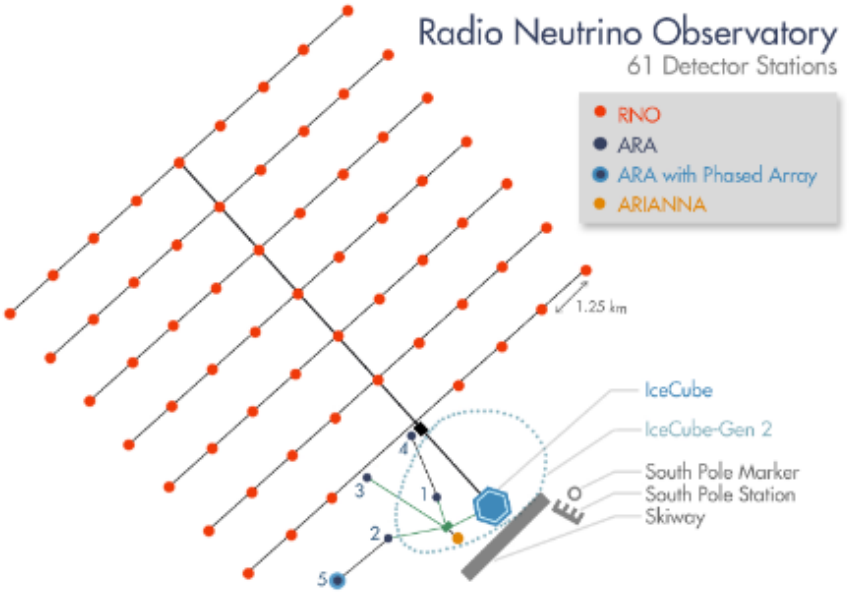
Radio Neutrino Observatory design studies

[See B. Hokanson-Fasig poster]

RNO design



61 Stations, each with a surface (LPDA) and deep (VPol bicone + HPol slot) component, combining elements of both ARA and ARIANNA stations.



Future w/ phased triggers

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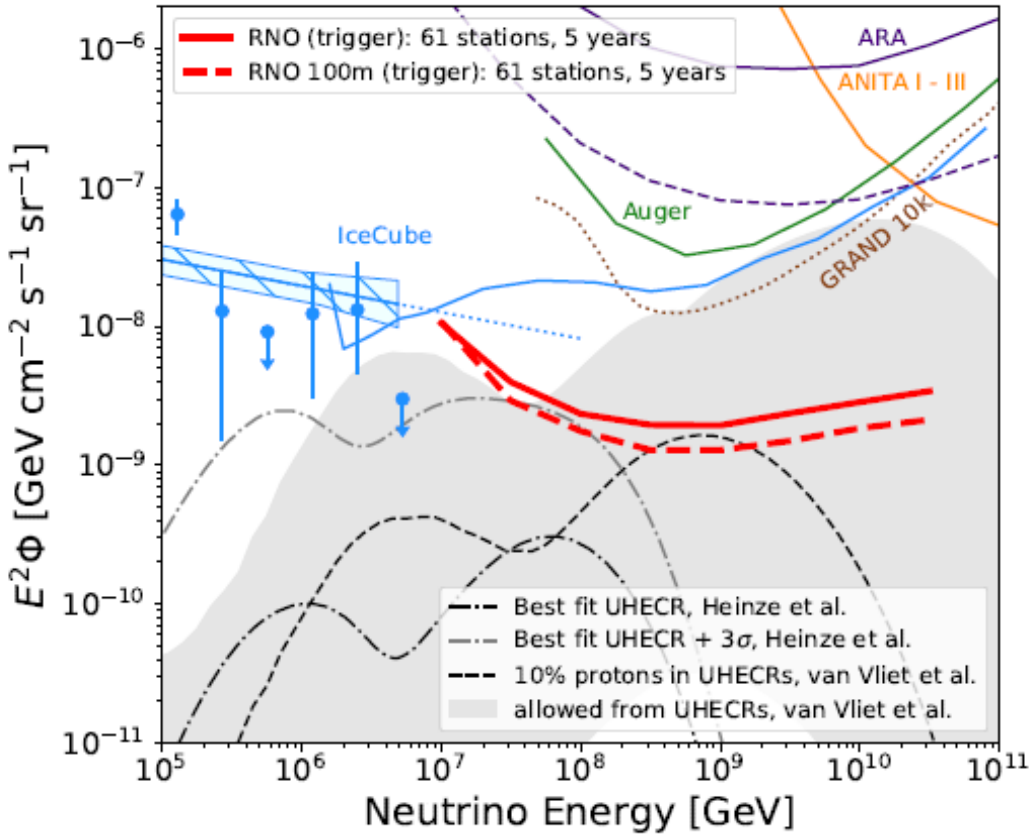
Projected sensitivity, trigger-level* w/ 61 phased-array equipped stations



Additionally, ongoing hardware R&D towards low-power implementations of this trigger system and integration with a flexible station design capable of running either in a wired or autonomous configuration.

Target deployments:
Greenland (ground-based R&D) & PUEO (next-generation balloon payload)

Takeaways

- A low-threshold beamforming trigger installed at an ARA station
- Hardware performance shows 2x boost in trigger sensitivity in the 30-300 PeV range
- ~1 station-year of A5 data stored, science analysis underway as well as development of improved analysis tools to increase efficiency at lower thresholds
- Developing a lower power version of the phased-trigger system for future Askaryan radio detectors