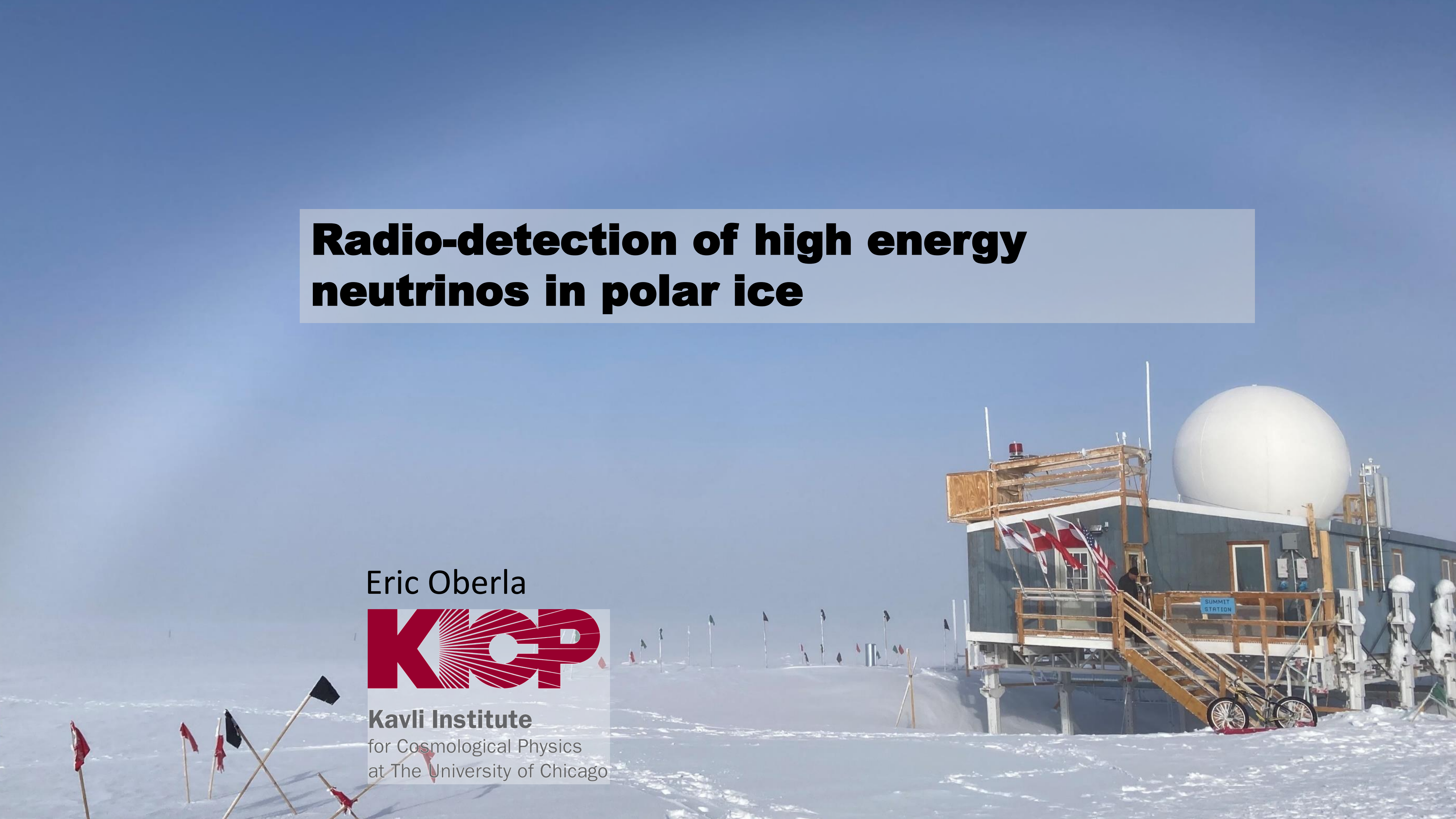
Radio-detection of high energy neutrinos in polar ice



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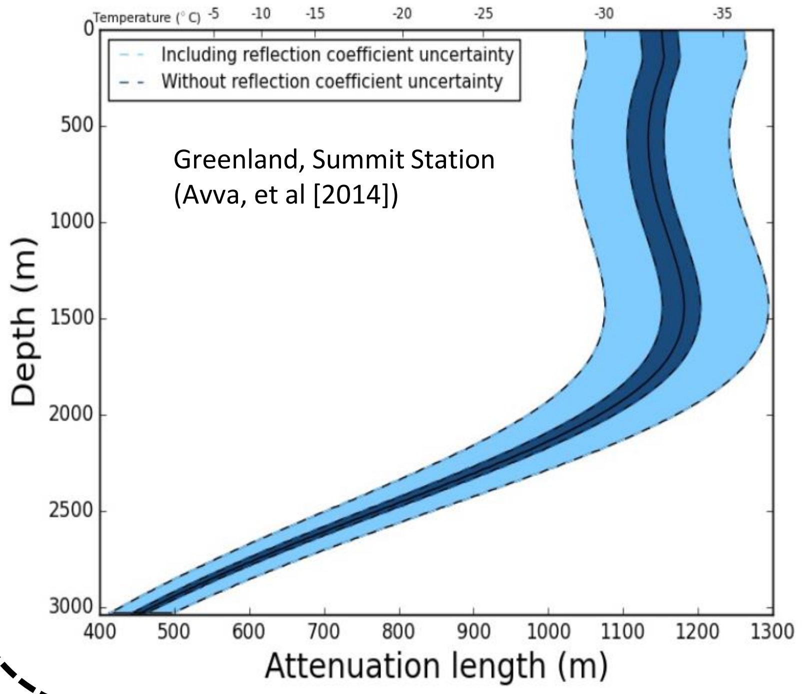
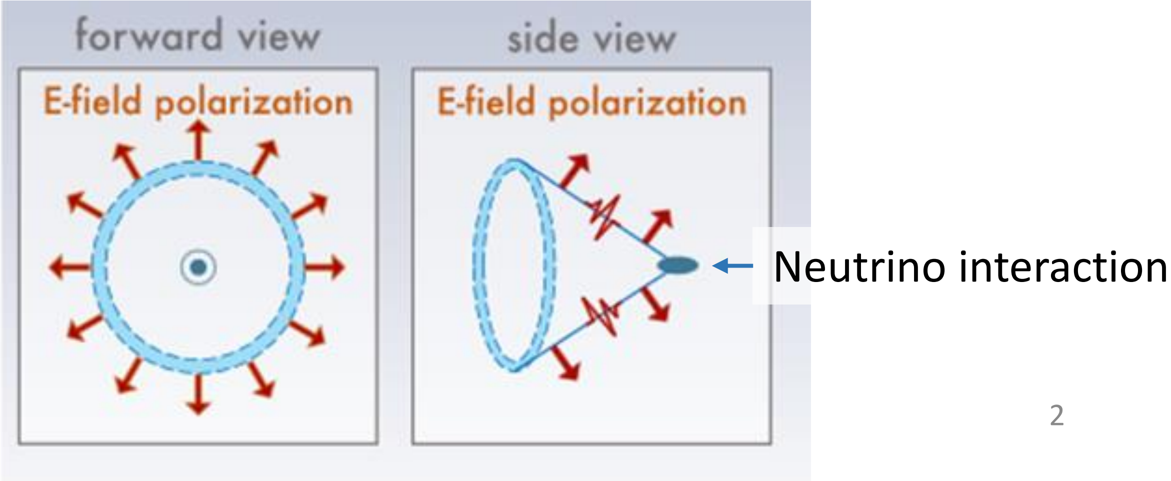
Askaryan Emission and Ultra-high energy neutrinos

- **Askaryan (charge-excess) radiation**: Fast-moving charge density in dielectric → coherent emission (~E^2) at long (radio) wavelengths
  - Charge excess from processes involving electronics in material (positron annihilation; Bhabha, Moller and Compton scattering)
  - At wavelengths larger than ~lateral width of shower, don't resolve individual charges
- *Nanosecond-scale* characteristic broadband impulses
- At neutrino-induced shower energies > 10PeV, radio emission stronger than optical.

Long radio attenuation lengths in ice → sparse detectors to cover large detector volumes

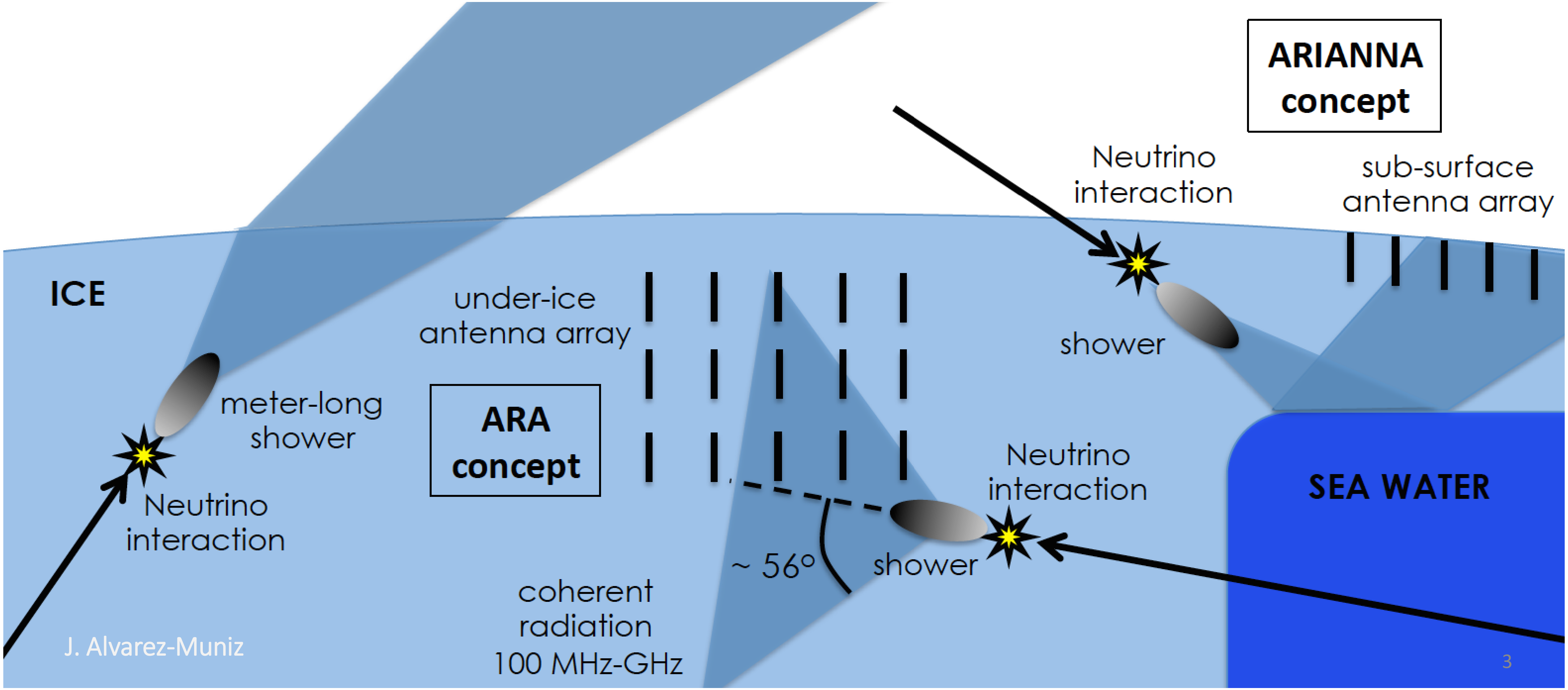


- Observables: Askaryan signal polarization, spectral content, and interferometric timing all important aspects to energy and event reconstruction
- **Askaryan detector design combines precision + low-noise VHF/UHF radio receivers with HEP-like baseband full-waveform digitization of triggered events.**



Antarctic Radio Detectors, currently operating

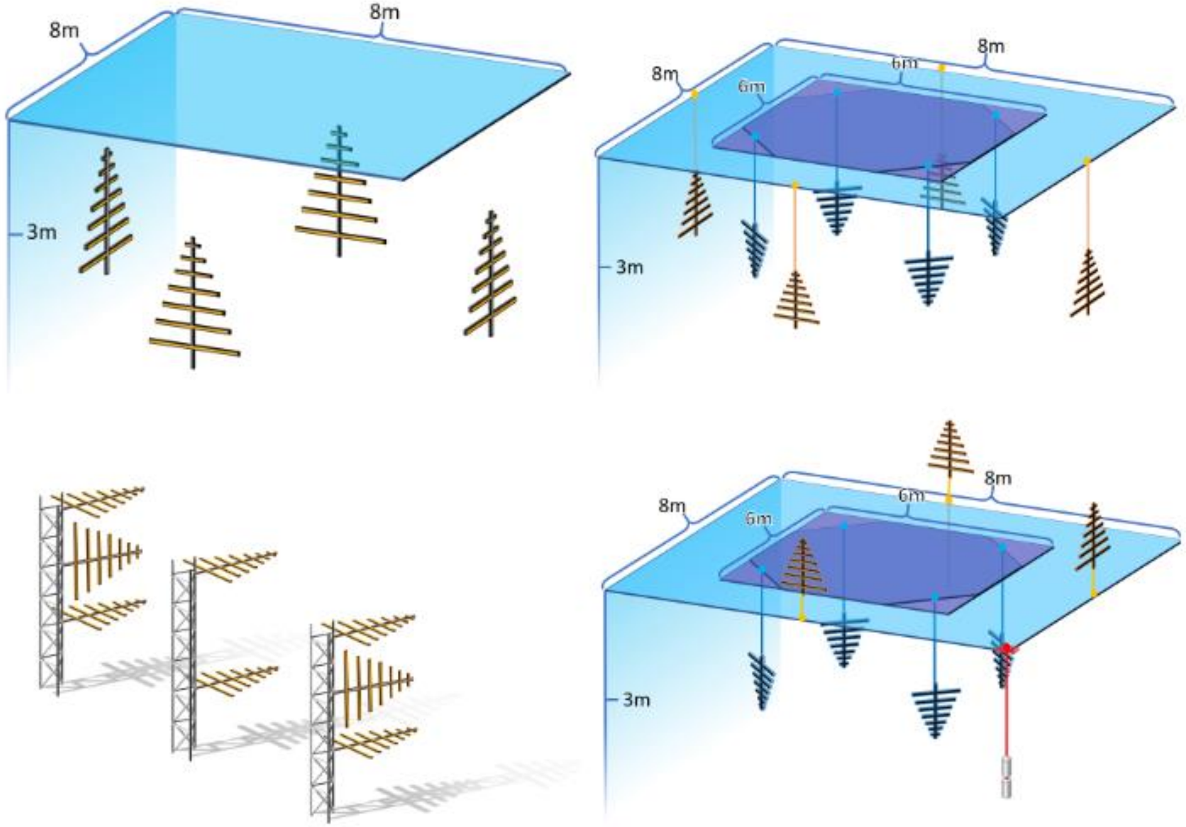
ARIANNA – Moore's Bay, shallow antennas, wireless low-bandwidth data transfer (Iridium)
ARA – South Pole, 200m deep antennas, wired high-bandwidth data transfer via IceCube Laboratory



ARIANNA

- Fully autonomous low-power station, (~5W), 4- or 8-channels, robust operation
- Primary site: Moore's Bay. Two test stations at South Pole
- Demonstrated detection of radio emission from cosmic rays.
- Demonstrated exceptional polarization resolution on impulse signal with LPDA surface antennas

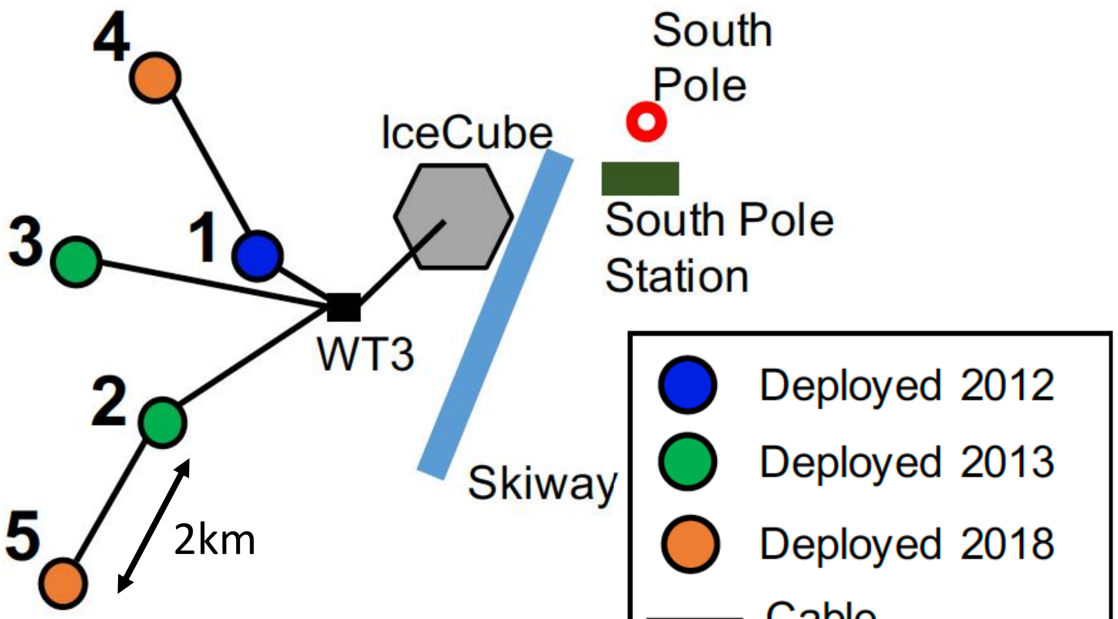
ARIANNA station topologies:

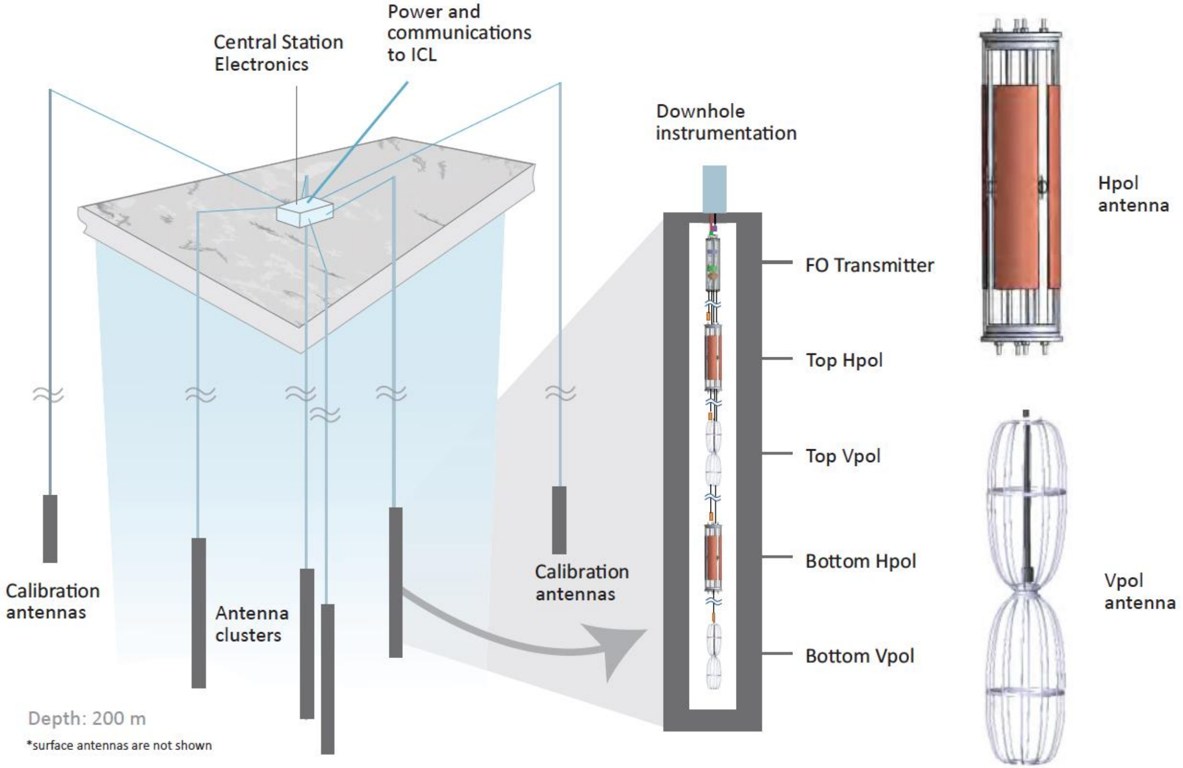


arXiv: 1903.01609, 2004.09841

ARA

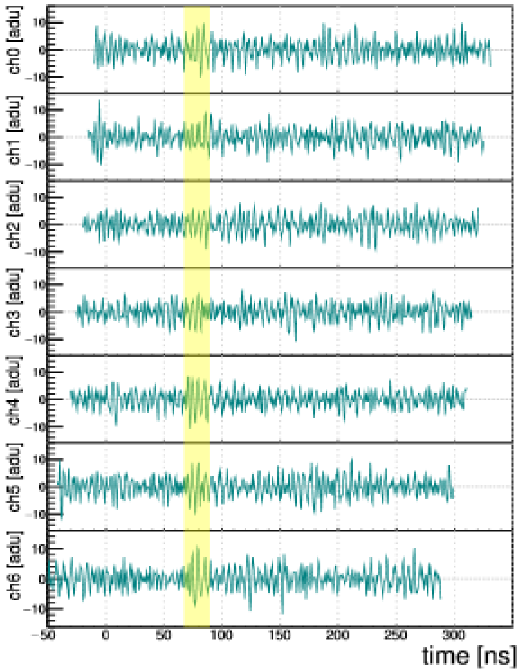
- 5-station array near South Pole Station
- Each station has 16 deep receivers (~200m) and 1-2 calibration pulsers
- Wired power and communications → year-round operation and higher trigger rates possible
- Most recent UHE neutrino limits: arXiv:1912.00987
- Approaching 10-year operation for the initial stations installed!

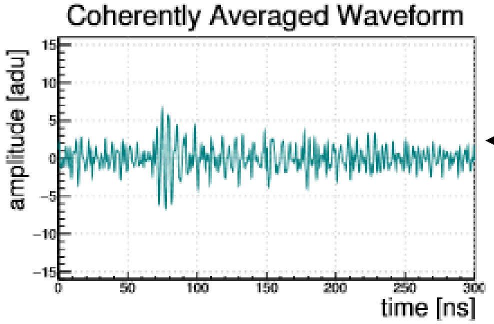


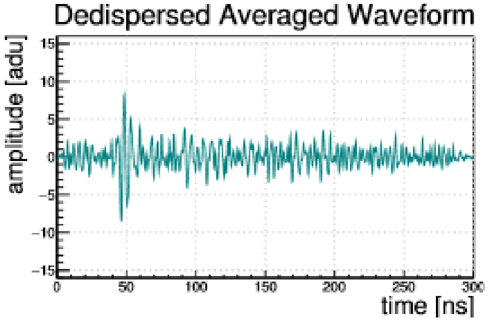


ARA – lowering triggering and analysis thresholds

- Demonstrated significant trigger threshold improvement with phased-array trigger system at the A5 station
  - Digital beamforming using an FPGA on a compact array of borehole antennas. Search for impulsive power over many beams simultaneously
- Recent work (K. Hughes) has demonstrated comparable improvement in the analysis efficiency near-threshold
- Lower the energy threshold for Askaryan detectors!

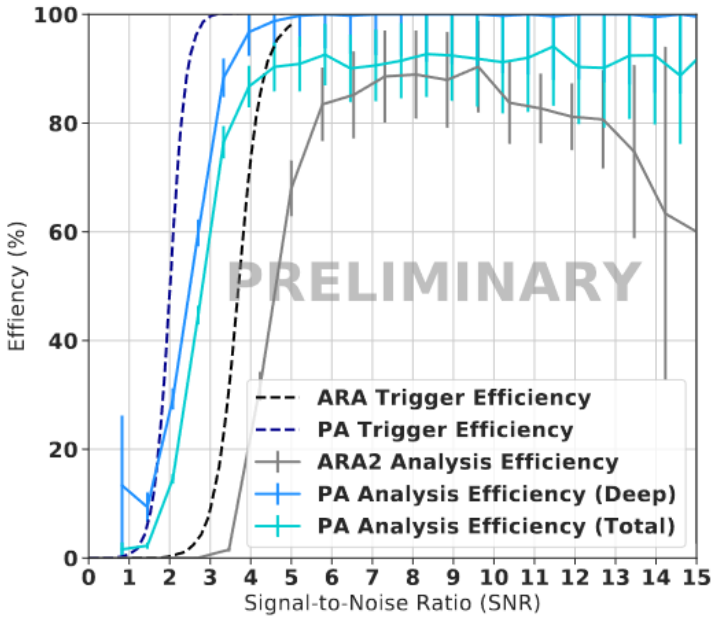




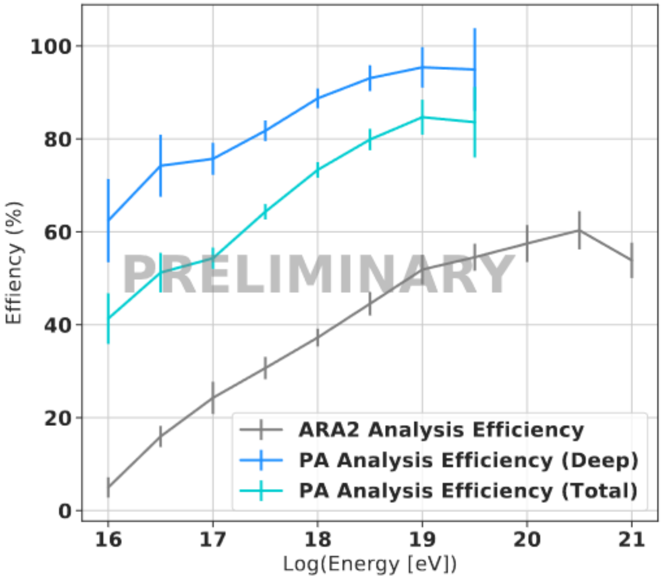


Triggered low SNR event

arXiv: 1809.04573, PoS(ICRC2021)1153



(b) Efficiency vs. SNR.

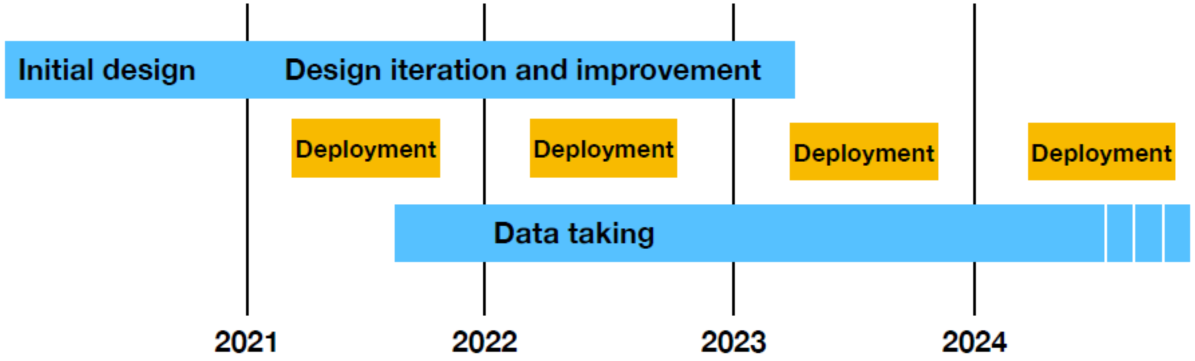


(a) Efficiency vs. Energy.

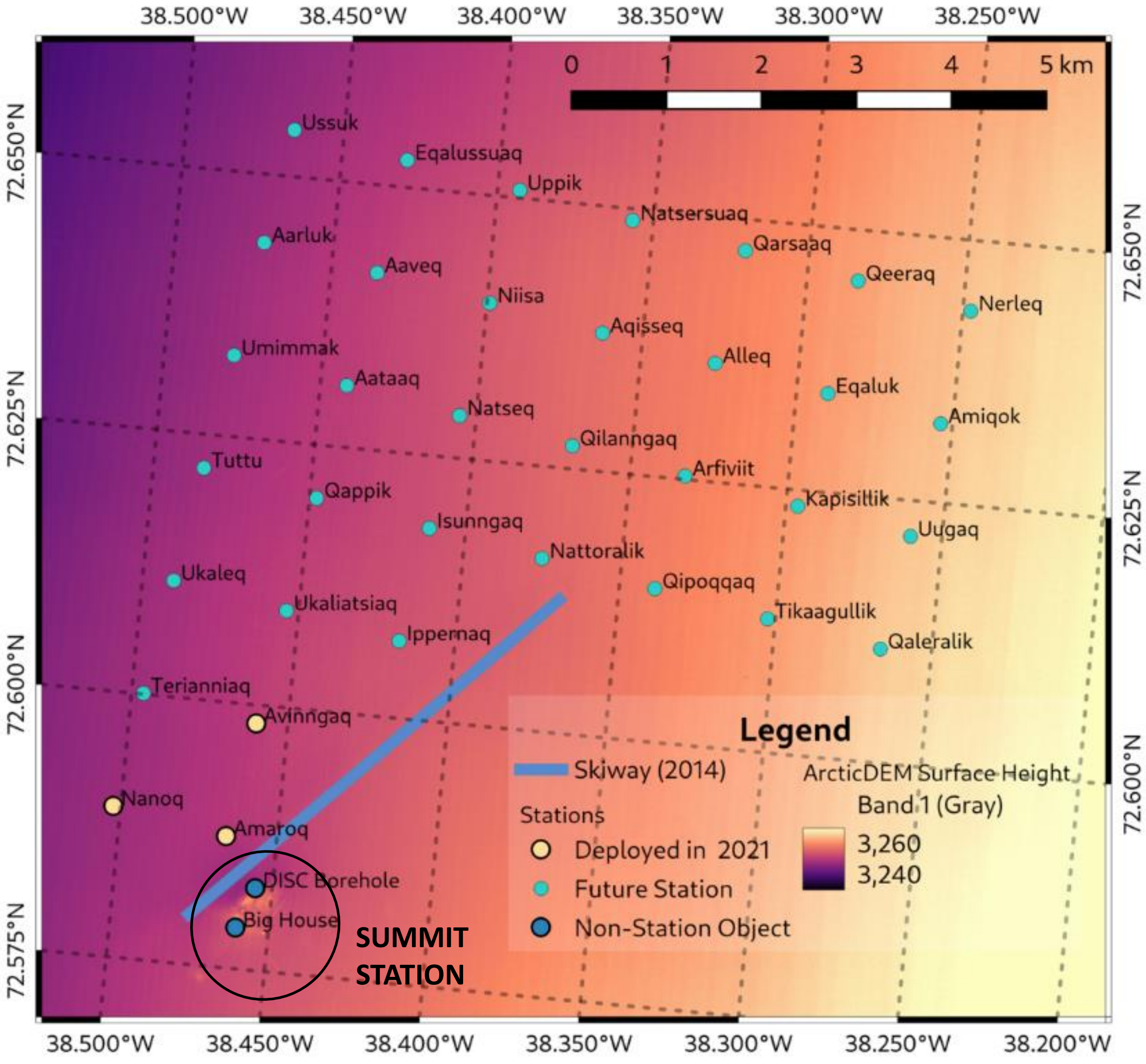
RNO-G

Radio Neutrino Observatory in Greenland

- 35 stations, 1.25km spacing. NSF Summit Station, Greenland
- Autonomous and scalable station design. Receiver bandwidth 80-750MHz.
- First three stations installed this summer, 2021. Currently taking data.
- Three more field seasons planned, with last deployment in 2024.
- First UHE radio observatory in the northern hemisphere. arXiv: 2010.12279



RNO-G Planned Layout



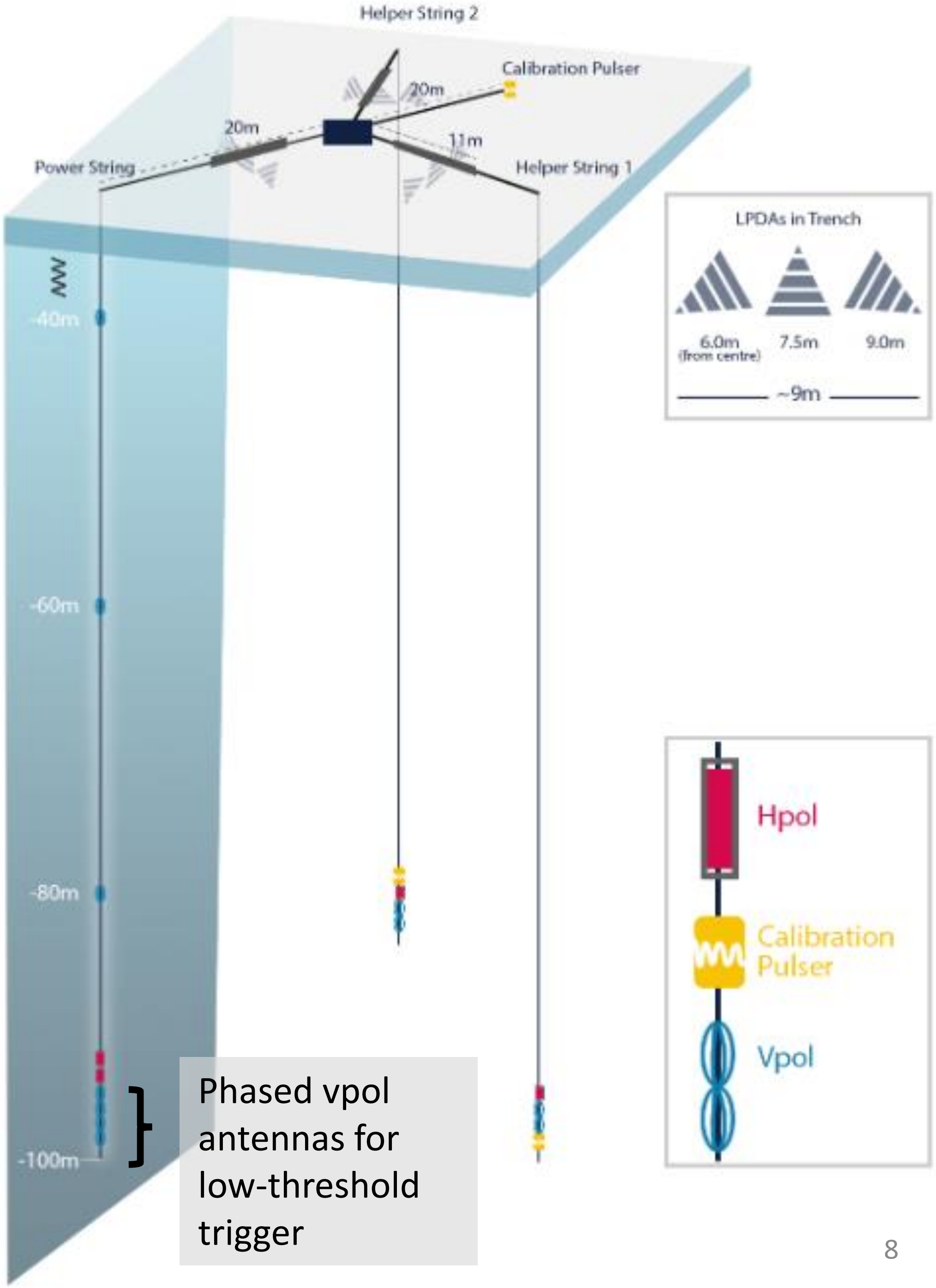
RNO-G Surface + Deep Receiver hybrid design

SURFACE component :

- High-gain off-the-shelf antennas
- Direct cabling to RF amplifiers
- Cosmic rays and RFI veto

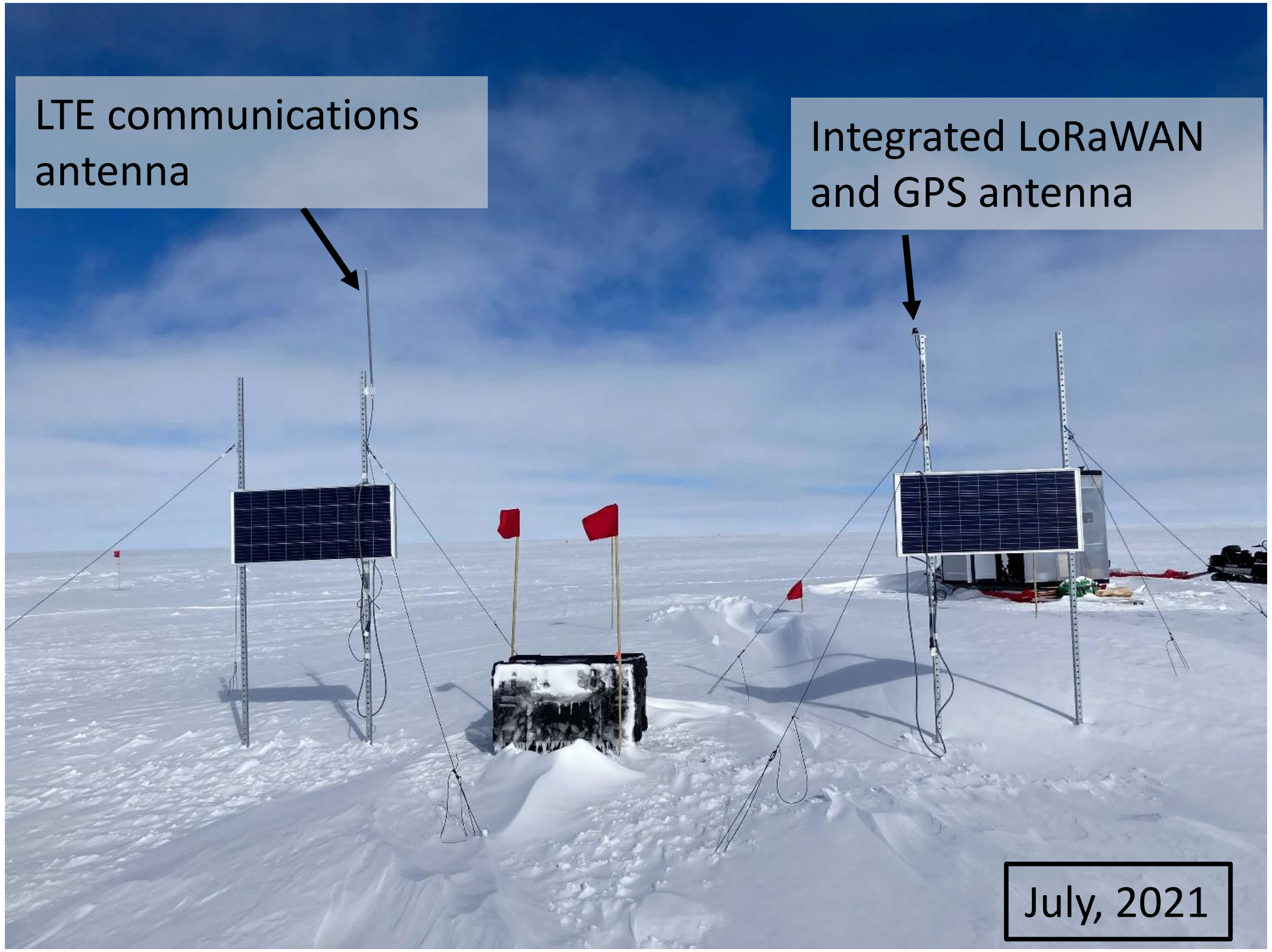
DEEP component :

- Custom borehole antennas (Hpol and Vpol)
- Signal transport over low-cost analog fiber links
- Effective neutrino volume and low-threshold trigger
- Large baselines for event reconstruction (interferometric + timing, signal frequency content)

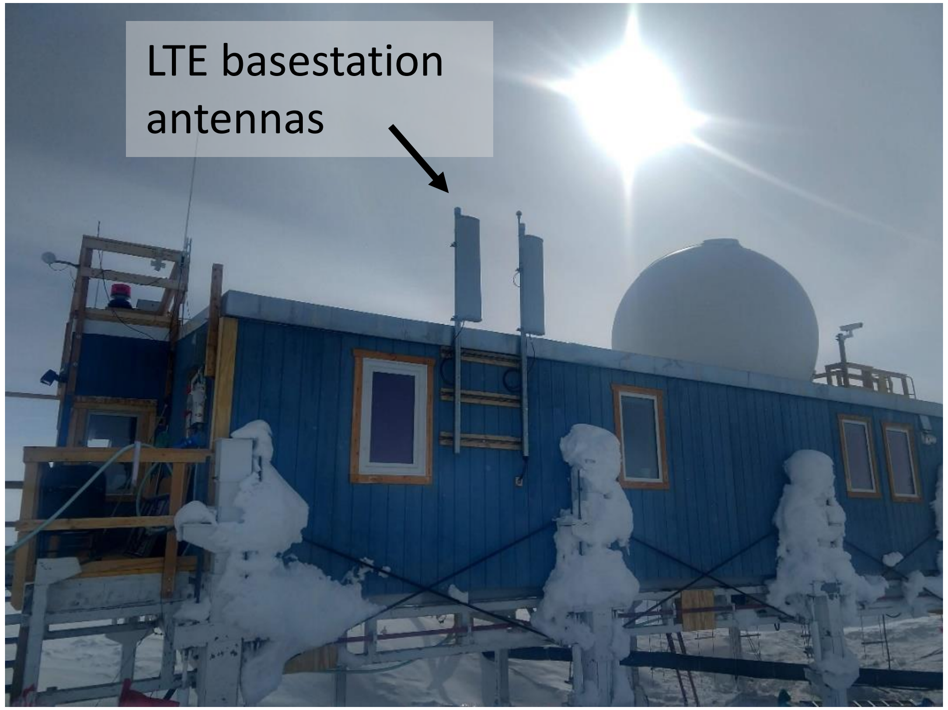


RNO-G: Autonomous Power + Wireless Communications

- **300W solar power system + battery bank with ~2.5kWh usable capacity →** ~7.5 month uptime at Summit latitude
- Future stations will be compatible with 24V wind turbines (Uppsala)

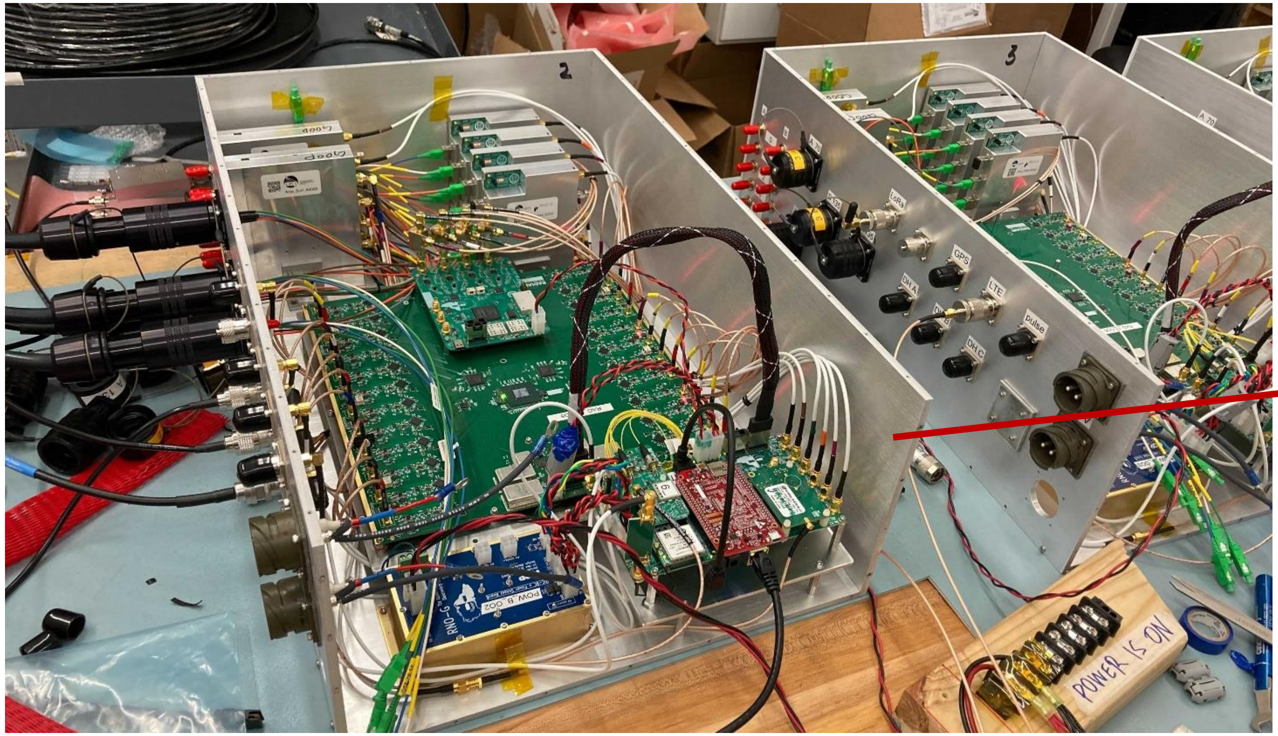


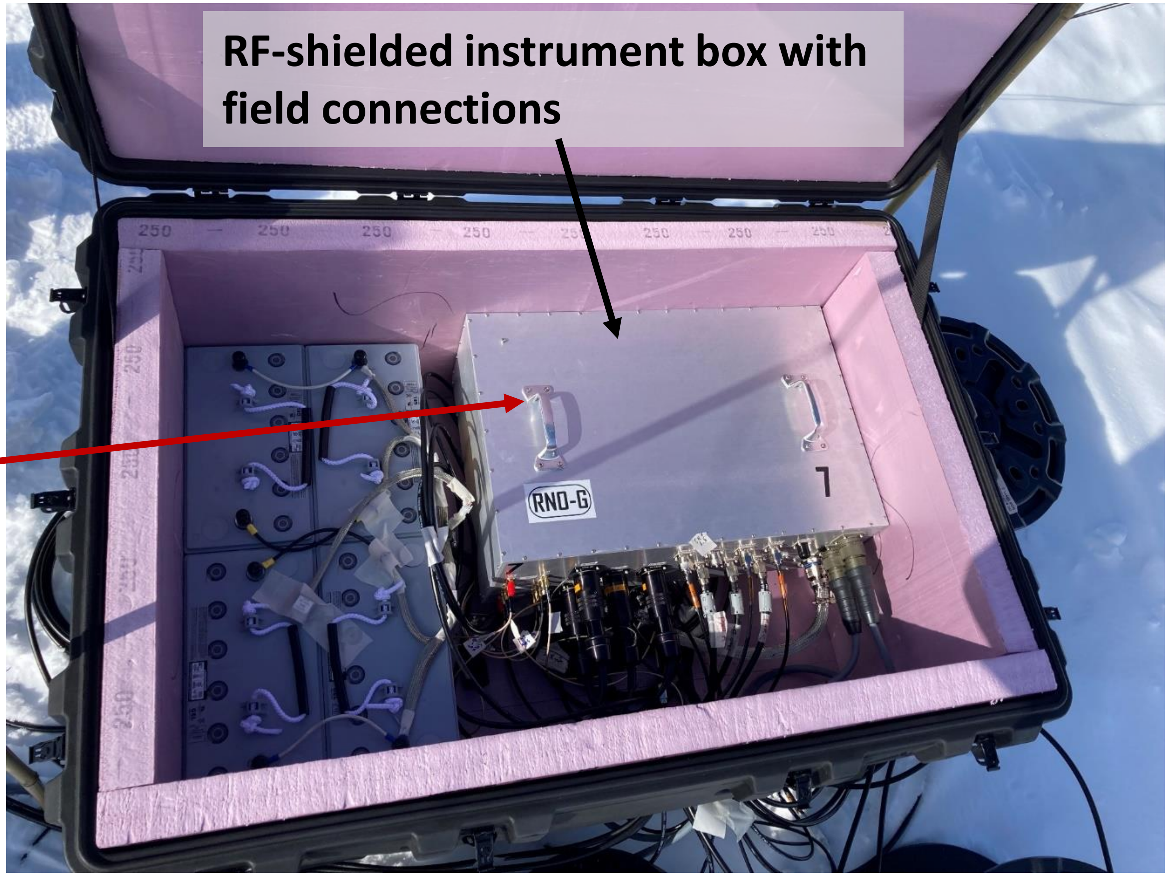
- **Primary data link using commercial LTE basestation. GSM Band 8.**
  - 880-915 MHz uplink / 925-960MHz downlink
  - 1-2 Mbps per station possible. Nominal data rate is ~500-600 kbps → 1Hz trigger rate
- Low-power (1W avg) cell modem used on individual stations
- LoRaWAN is used as a secondary low-bandwidth wireless link (ultra low power, primarily for station housekeeping)



Data Acquisition Hardware

- 24 channel readout board using a custom 'oscilloscope-on-chip' ASIC (LAB4D). 2048 samples per event at ~3 Gigasamples/second sample rate, 12-bit vertical resolution.
- Low-threshold deep trigger system using 4-channel ADC board on lowest ~150MHz of signal bandwidth
- Auxiliary surface antenna trigger (i.e. cosmic rays) using programmable coincidence detection
- 25 Watts in fully-functional operation mode. 'Winter' power-down mode <100mW, retains LoRaWAN communications link





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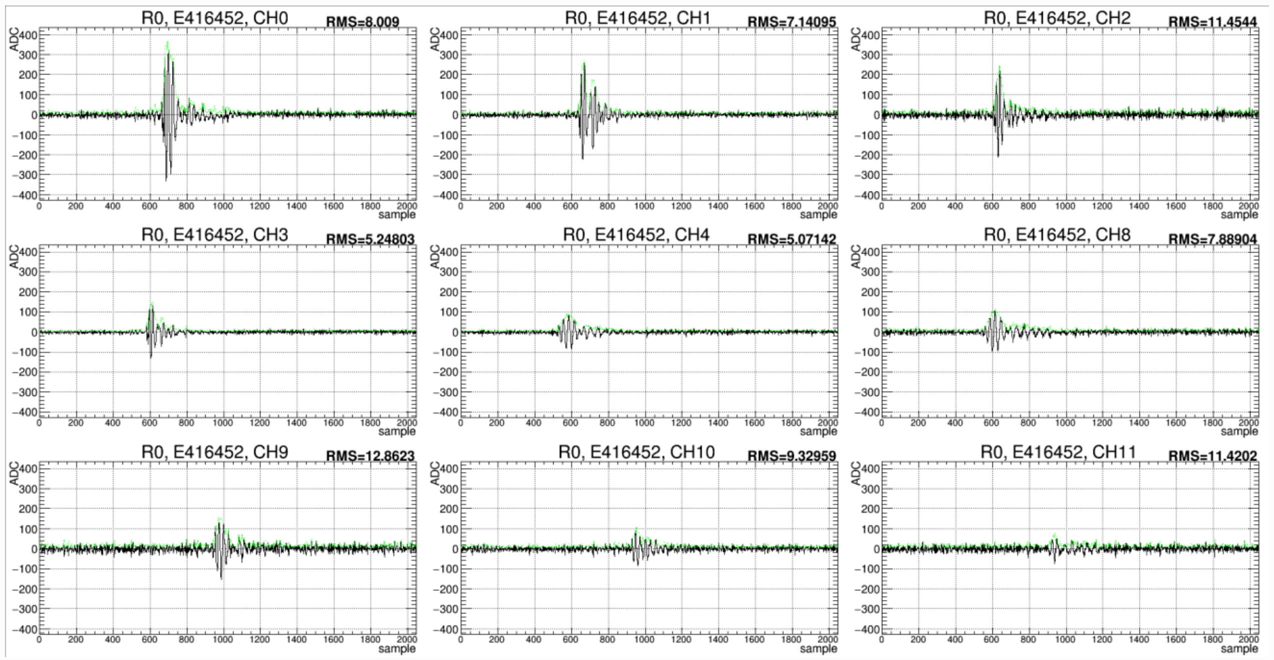
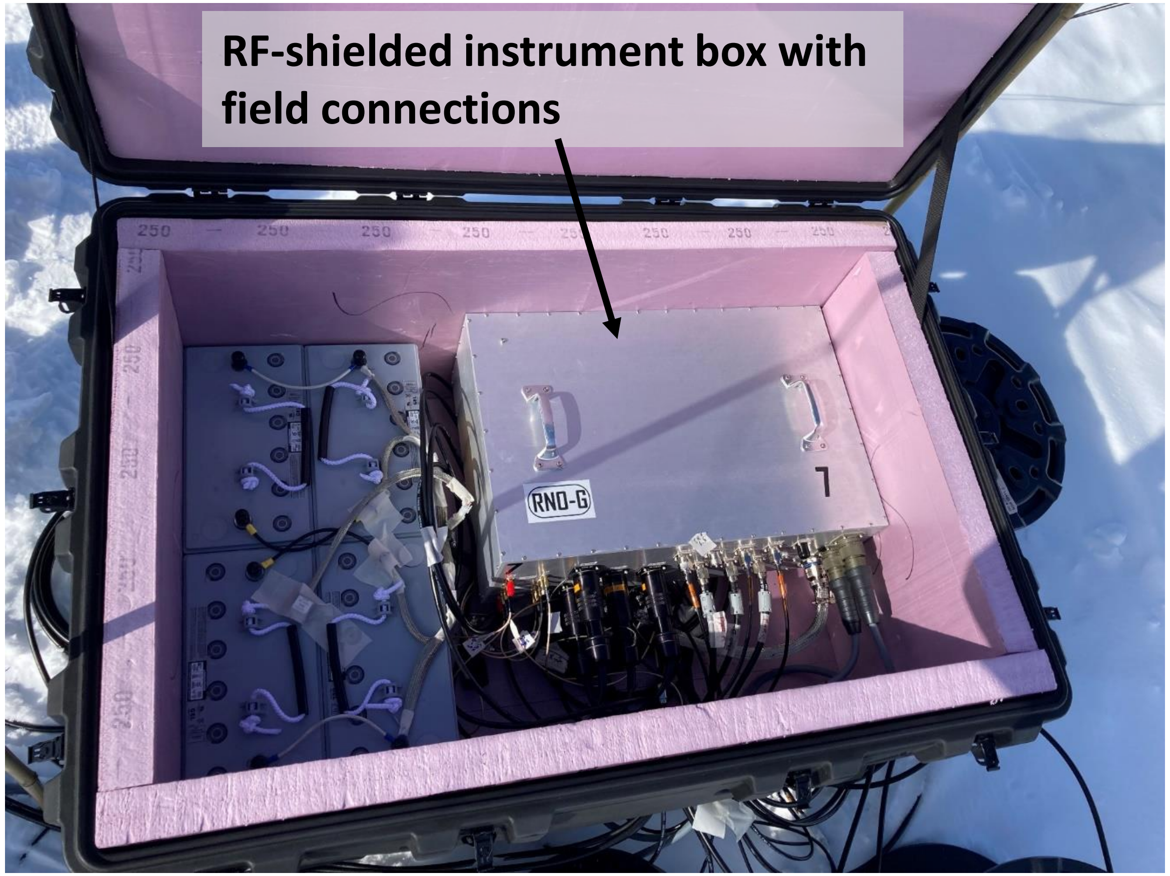
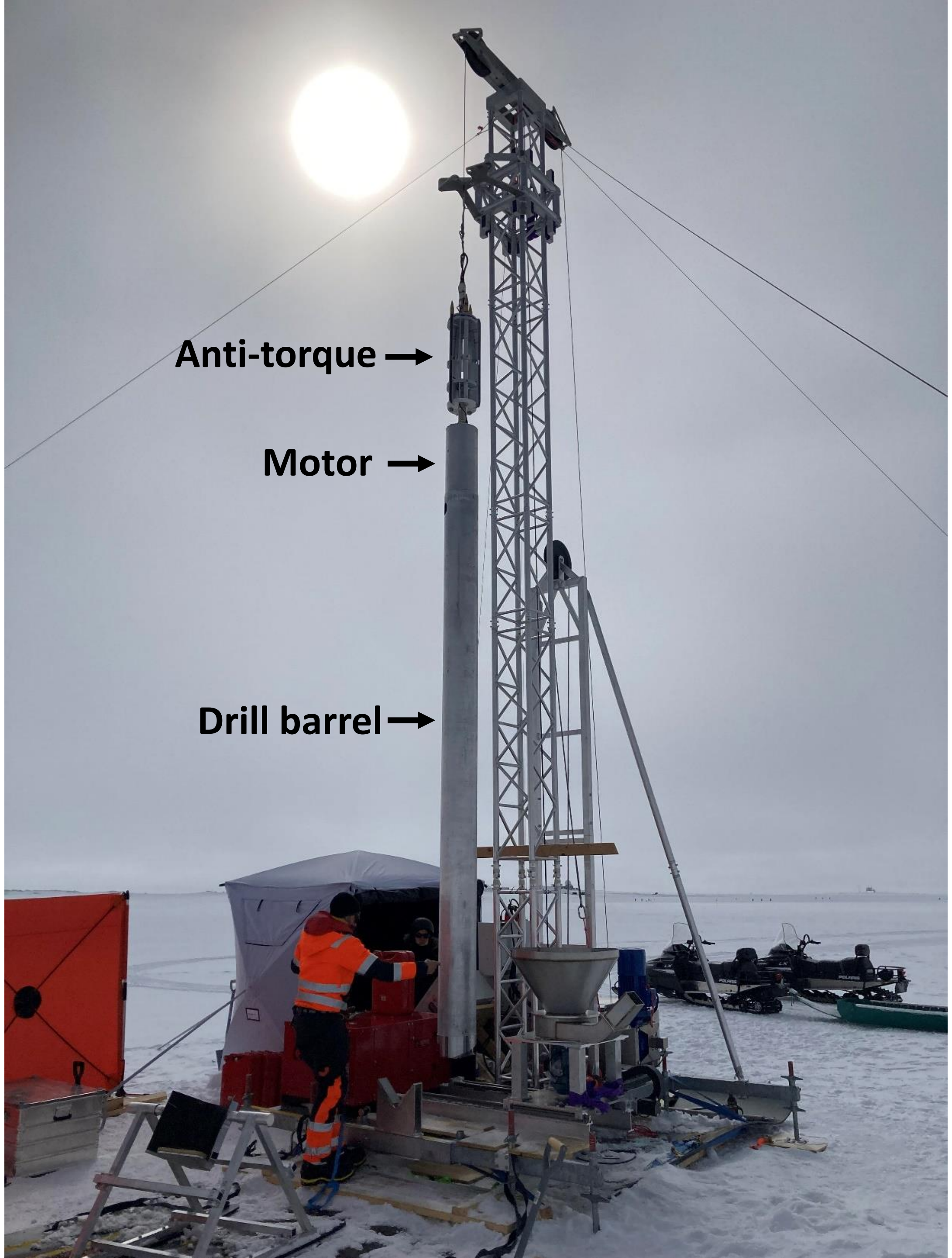
Background event (snowmobile) seen in 9 deep Vpol channels





Drilling

- British Antarctic Survey auger **BigRAID drill**
- 11 inch diameter holes
- Demonstrated drilling of 100m hole in 1 shift (2 people)
  - Though most 2021 holes were done in 2 shifts
- Ongoing development to make the drill fully automatic during drilling operations



RNO-G Deployment Strategy

- Pre-fab deployment hut with gantry towable by snowmobile
- Full station installation in 3-4 days with a four-person field team crew

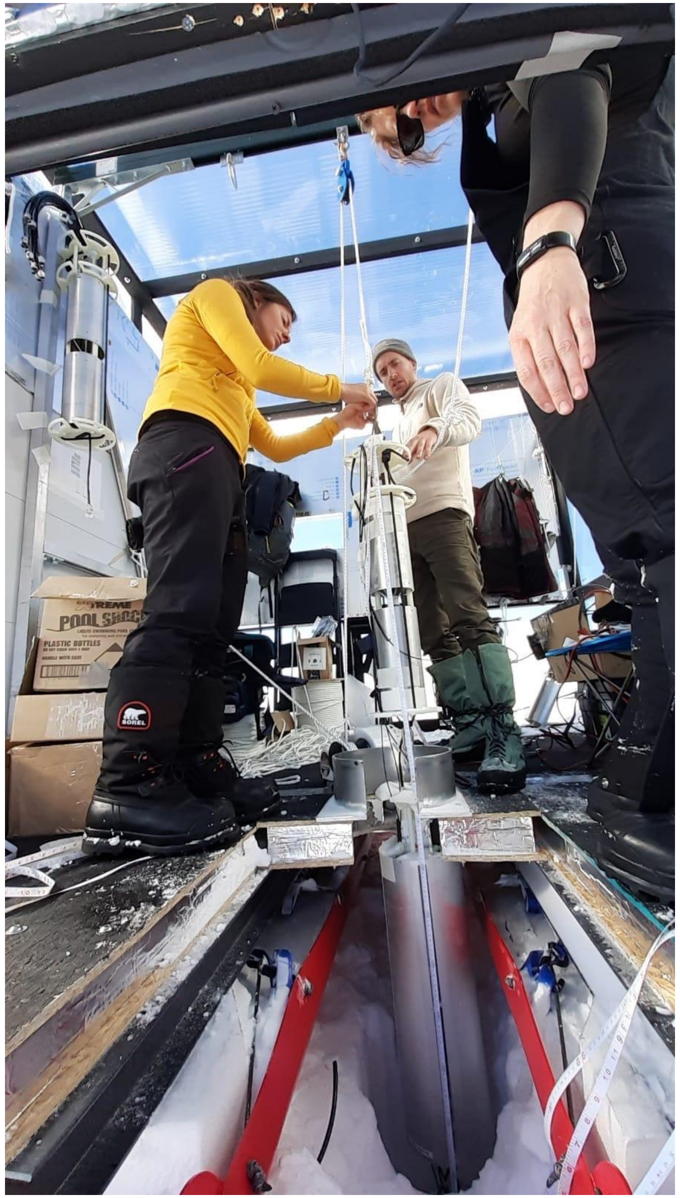
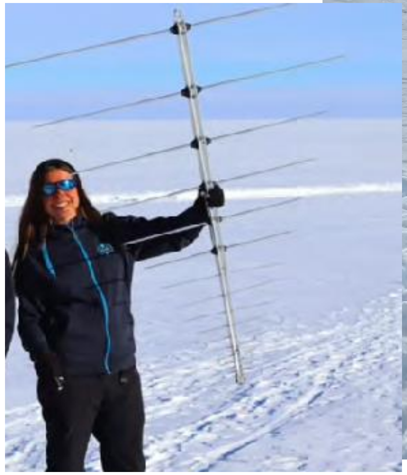


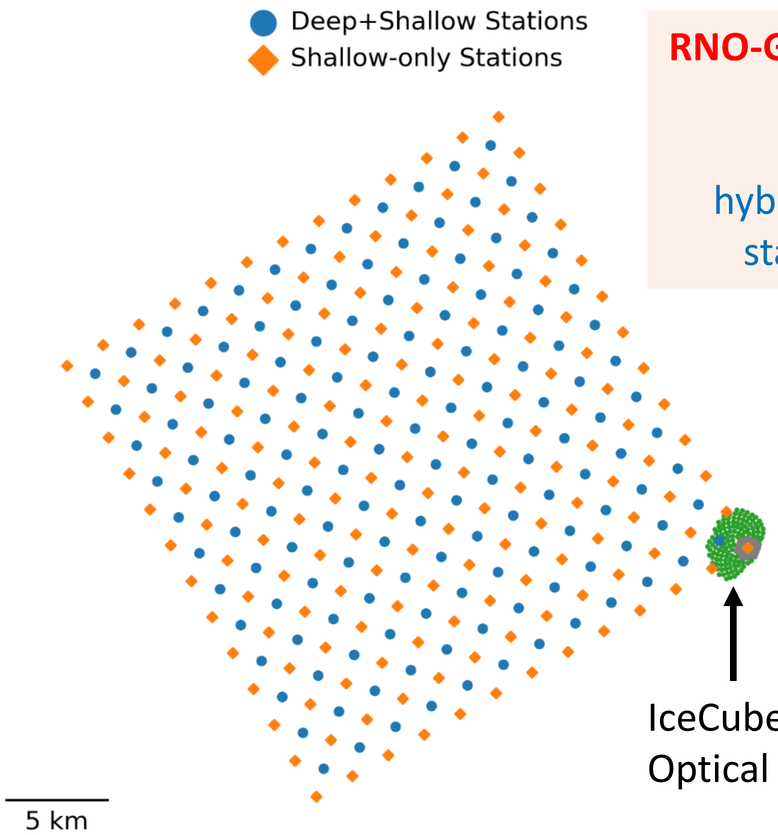
photo credits: C. Welling & C. Deaconu

- Surface antennas (LPDAs) installed by hand in ~1.5m trenches
- All gear transported to remote sites via snowmobile + cargo sled

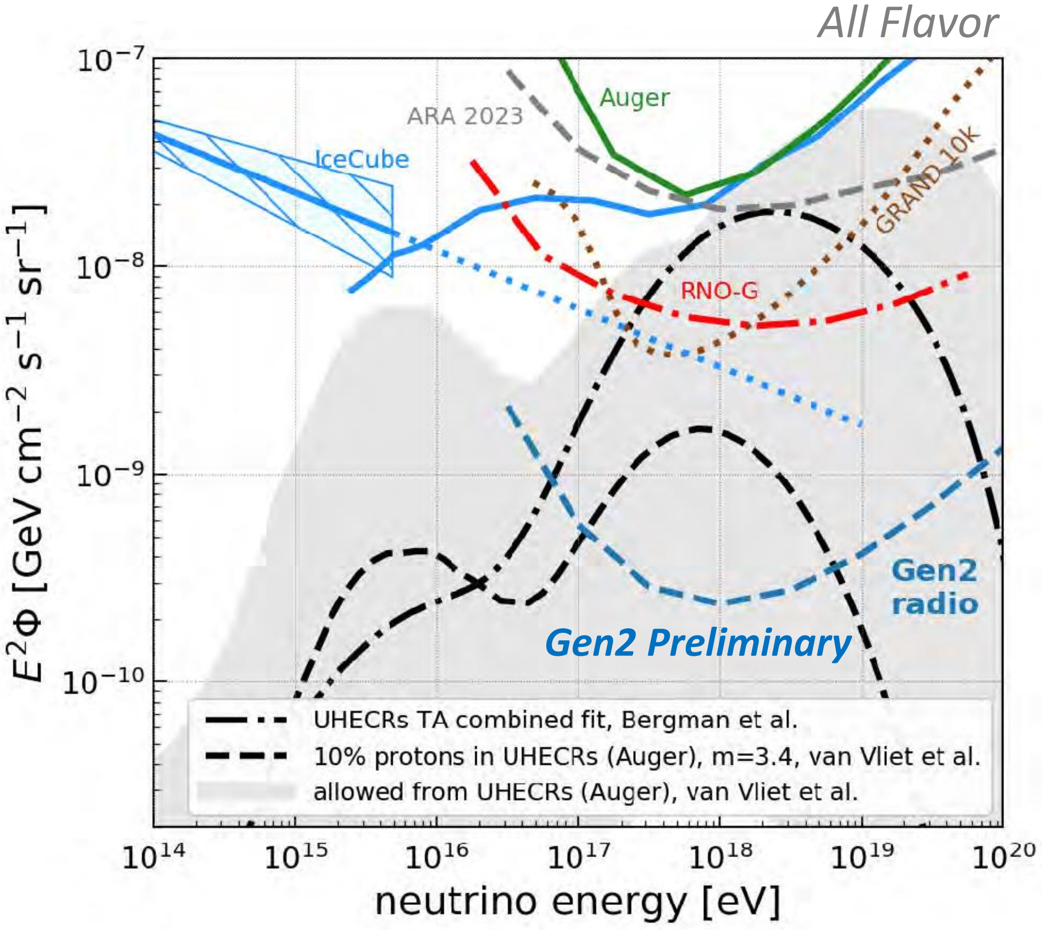


Towards the IceCube Gen2 Radio Array

- RNO-G as a mid-scale detector informs the hybrid station design for the Gen2 Radio Array component
- Gen2 radio array design will detect between 20 (Auger best fit) and 240 (TA best fit) GZK cosmological neutrinos. Another ~75 neutrinos from IceCube astrophysical flux (assuming unbroken spectrum). Plus transient source sensitivity.



RNO-G sensitivity : 35 stations, 5-years at 70% uptime
Gen2 radio concept: 144 hybrid stations + 169 surface stations, 10-year operation

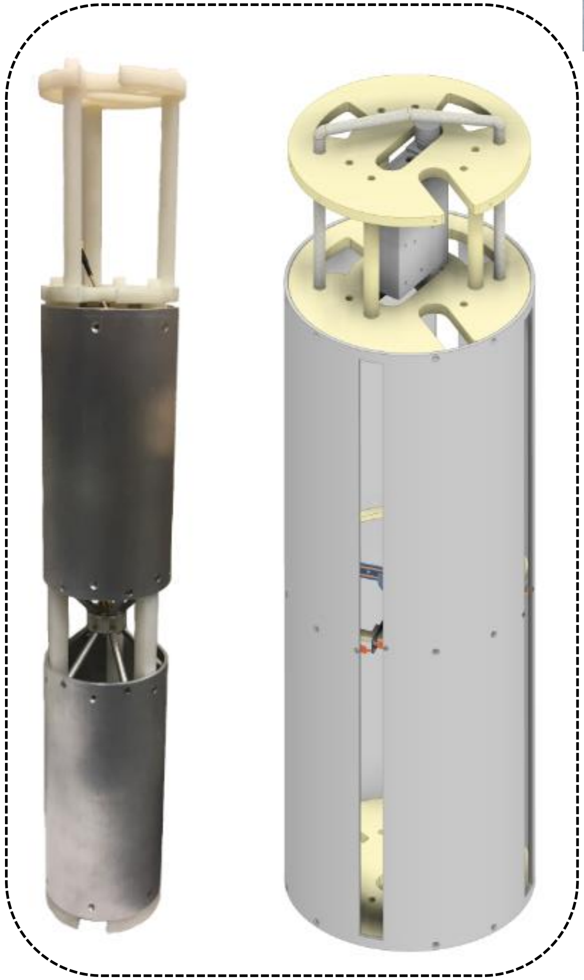


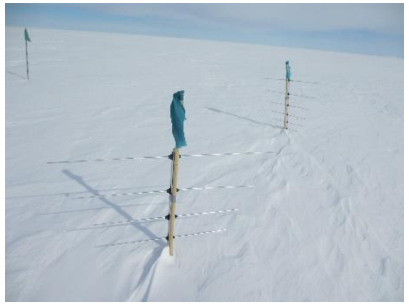

Thanks!

RNO-G Station Design

Receiver Frequency Range: 80-750MHz

Borehole antennas:
Vpol -- Fat dipole
Hpol -- Quad slot





Surface antennas:
commercial LPDAs

~100m custom Analog fiber links