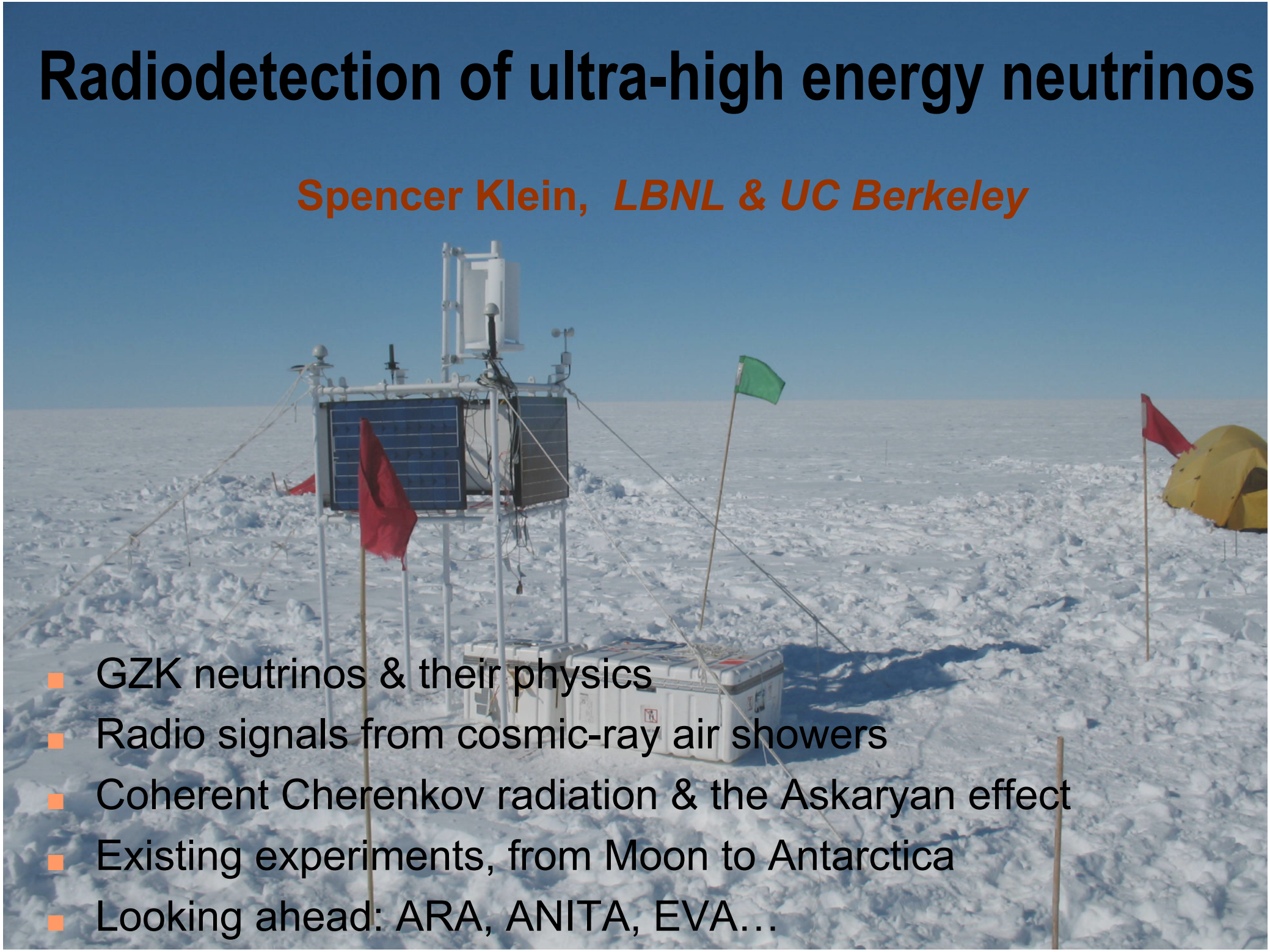
Radiodetection of ultra-high energy neutrinos

Spencer Klein, ***LBNL & UC Berkeley***



- GZK neutrinos & their physics
- Radio signals from cosmic-ray air showers
- Coherent Cherenkov radiation & the Askaryan effect
- Existing experiments, from Moon to Antarctica
- Looking ahead: ARA, ANITA, EVA…

Different techniques for different ν energies

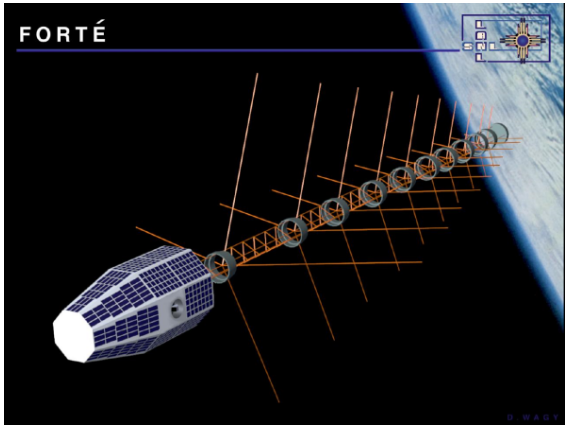
Larger target- antenna separations
Higher $E_{threshold}$
Larger targets

- The Moon -> radiotelescopes
- Greenland -> Satellite
  - FORTE
- Antarctica -> high altitude balloon
  - ANITA
- Antarctica/Greenland-> embedded antennas
  - RICE/ARA/ARIANNA
- Embedded antennas w/ interferometric triggers

New Physics

GZK neutrinos

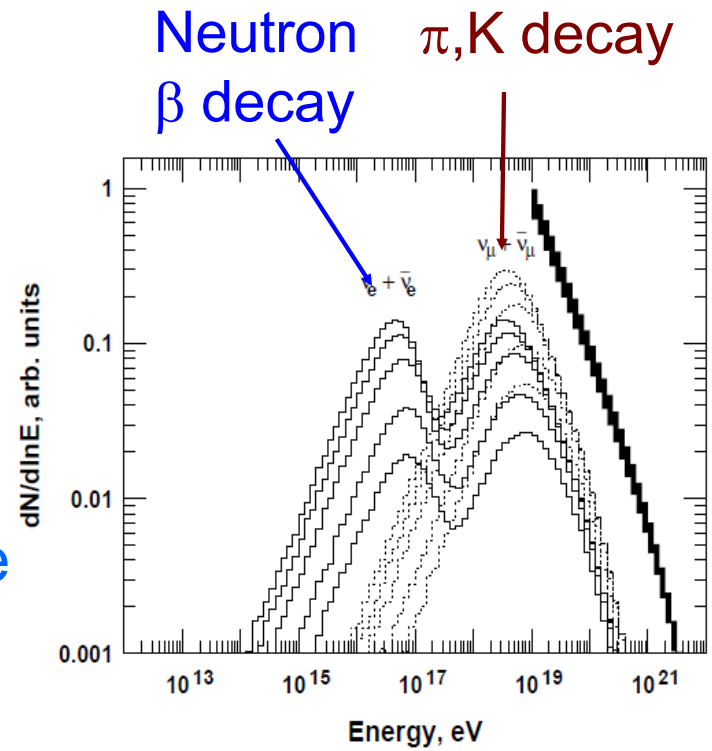
> PeV ν spectrum

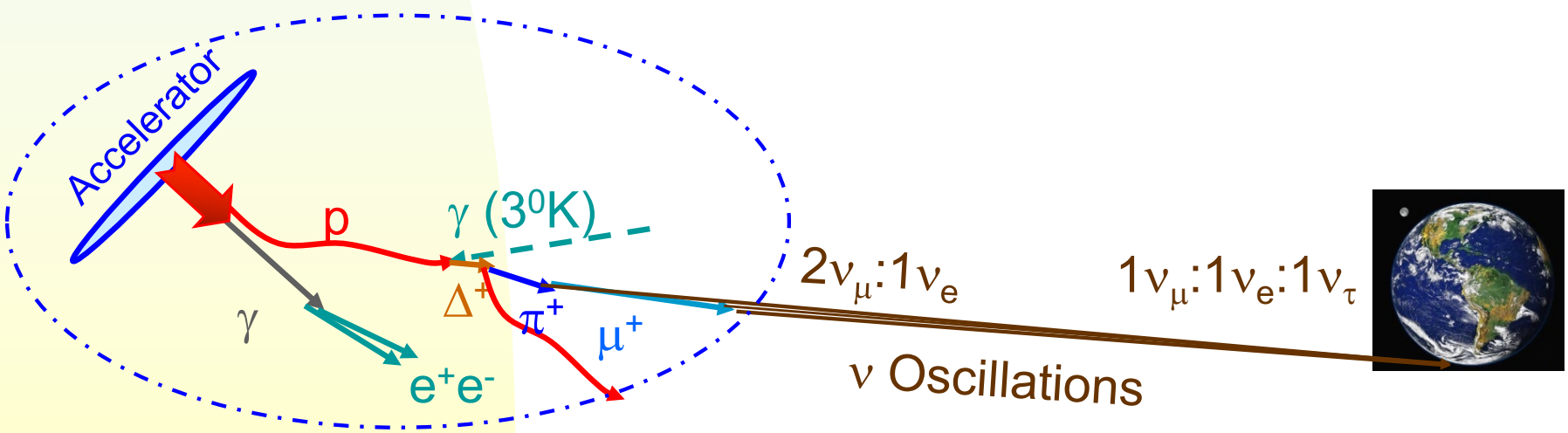


Overall Energy Dynamic range > 10^5

Greisen-Zatsepin-Kuzmin neutrinos

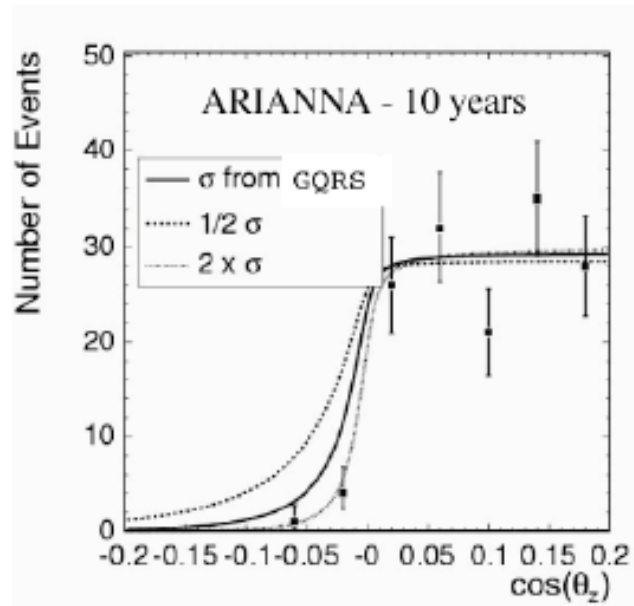
- At energies above $4*10^{19}$eV, protons interact with the 3^0K microwave background radiation
  - $p + \gamma_{3°K} \rightarrow \Delta^+ \rightarrow n\pi^+, \pi^+ \rightarrow \nu\mu, \mu \rightarrow e\nu\nu$
  - Neutrino energy range: 10^{17}-10^{20} eV
- ν flux depends on CR flux & composition
  - ν don't interact; distant sources contribute
    - Time evolution of sources matter; probe out to redshift of a few
- "Guaranteed" (*composition restrictions apply)





Detecting GZK ν

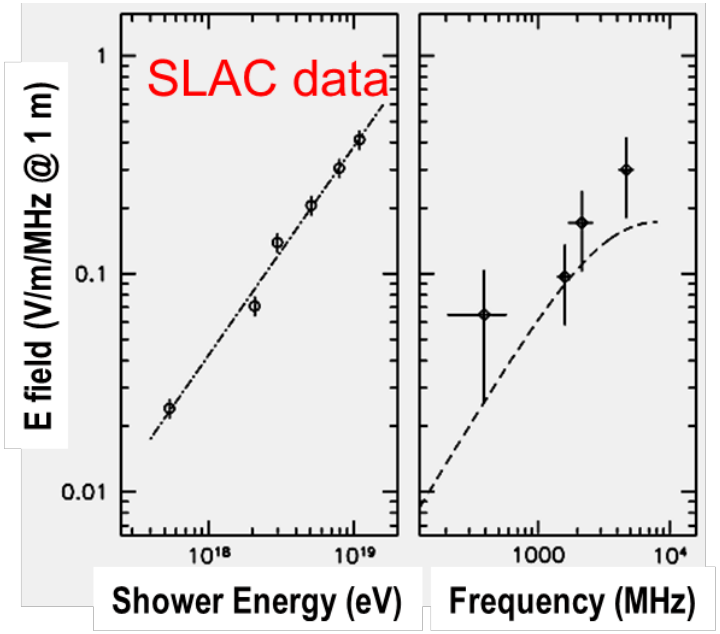
- Cross-sections rise with energy
  - Standard model $\sigma \sim 10^{-33}$ to 10^{-32} cm^2
    - Uncertainty from low-x (10^{-3} to 10^{-7}) high-Q^2 parton distributions
- ν are absorbed by the Earth
  - Horizontal or downgoing events
  - Zenith angle distribution probes $\sigma_{\nu N}$
    - Sensitive to new physics
      - Extra compact dimensions, leptoquarks, etc.
- Most sensitive to ν_e,
  - 80% of energy goes to EM shower from electron
    - LPM effect lengthens shower
      - Narrows Cherenkov radiation pattern
  - 20% of energy transferred to target nucleon
    - Hadronic shower
    - For all flavors CC & NC interactions
- ~ 100 km^3 needed to see 100 events in 3-5 years

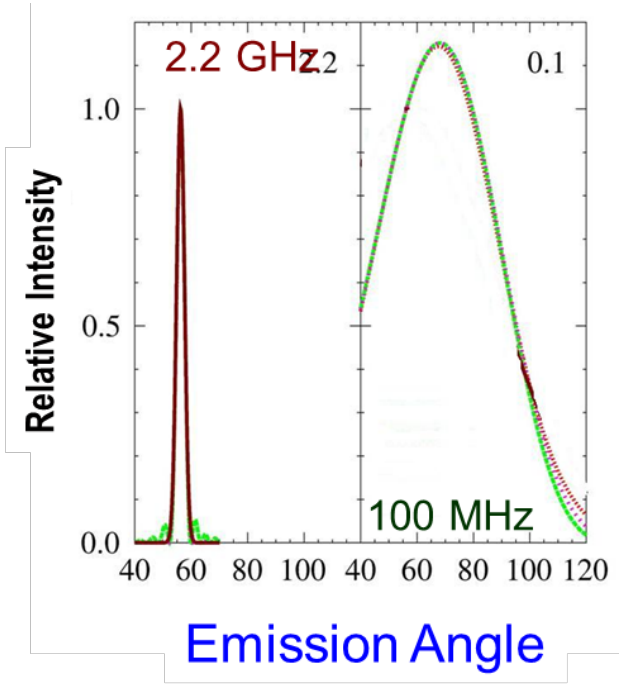


Plot by Amy Connolly

Radio-detection of ν

- ν induced showers emit radio pulses
- Showers contain ~ 20% more e^- than e^+
  - Compton scattering of atomic e^-
  - Shower e^+ annihilate on atomic e^-
- For wavelengths > transverse size of the shower, the net charge emits coherent Cherenkov radiation
  - Peak electric field ~ E_ν^2
  - Coherent at frequencies up to ~ 1 GHz in ice
  - Angular distribution depends on frequency
- Extensive studies with SLAC test beams

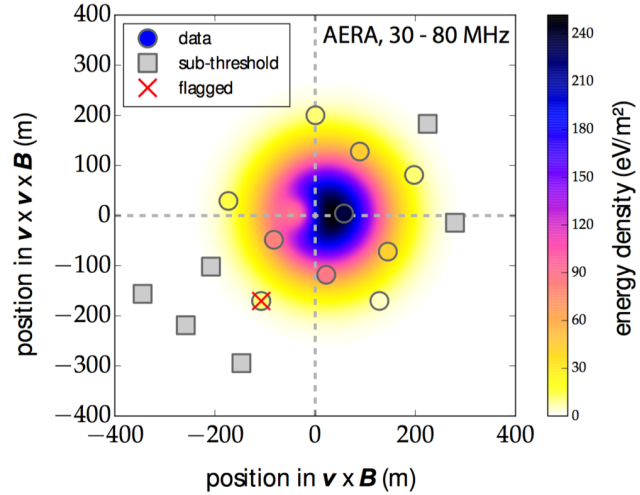


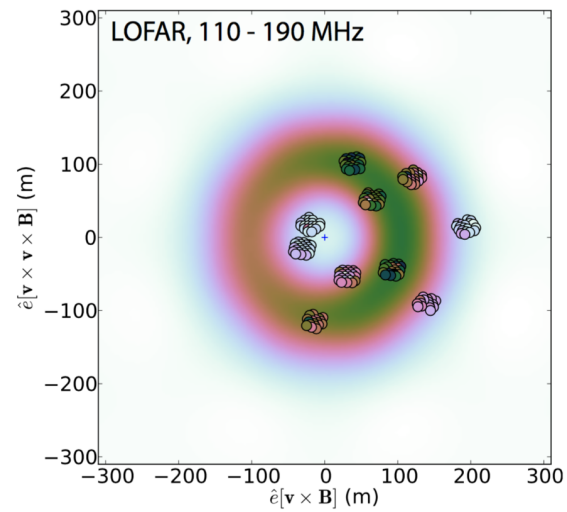


SLAC data:D. Saltzberg *et al.,* PRL **86**, 2802 (2001)
Angles: O. Scholten et al. J.Phys.Conf.Ser. **81**, 012004 (2007)

Radio signals from air showers

- Geomagnetic deflection of e^+ and e^- in opposite direction in Earths B field
- Coherent Cherenkov radiation contributes subdominantly
  - Interference between 2 components leads to asymmetric signals on ground
- Signal depends on shower orientation with respect to Earth's magnetic field
- Larger distance scales
  - Cherenkov angle is small, but altitudes are high
  - Lower frequencies except exactly on Cherenkov cone





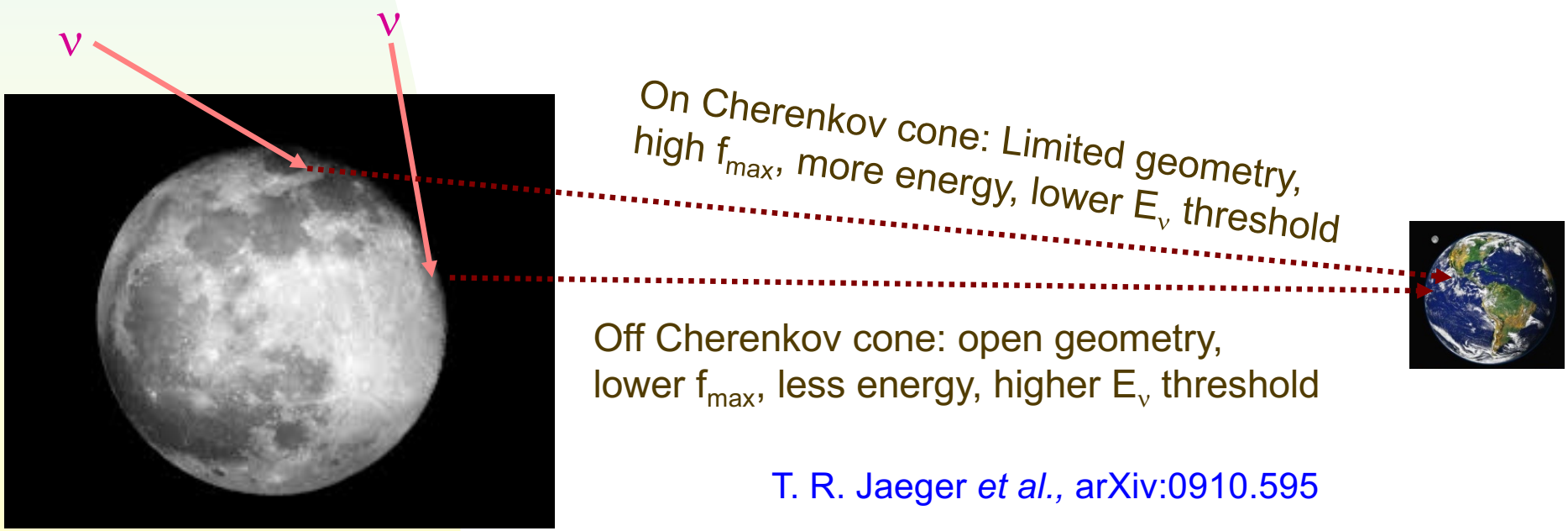
F. G. Schroeder, arXiv:1701.0596

Air Shower studies

- Useful signals for E> ~~ 10^{16} eV
- Recent codes show good agreement with data
  - COREAS & ZHAires
  - <20% energy resolution; could reach < 10%
    - Better than surface arrays
      - Radio samples well-understood EM component
- 1^0 angular resolution achievable
- Many applications
  - Energy calibration source for Auger
  - Composition studies via measurement of X_{max}
    - Radio arrays, especially LOFAR & TUNKA
      - $\sigma(X_{max}) \sim 20$ g/cm^2 for LOFAR
  - Calibrations for ν detectors
  - Proposed air shower veto (RASTA for IceCube)

Radio signals from the Moon

- Sensitive volume depends on frequency
  - Radio absorption length ~ 9 m/f(GHz) limits sensitive depth
  - High frequency searches see radio waves near the Cherenkov cone - near edge (limb) of moon
  - Lower frequency searches see a broader angular range
    - Larger active volume
- But… there is more radio energy at high frequencies
- Backgrounds from cosmic-ray moon showers
  - Not always distinguishable



T. R. Jaeger *et al.*, arXiv:0910.595

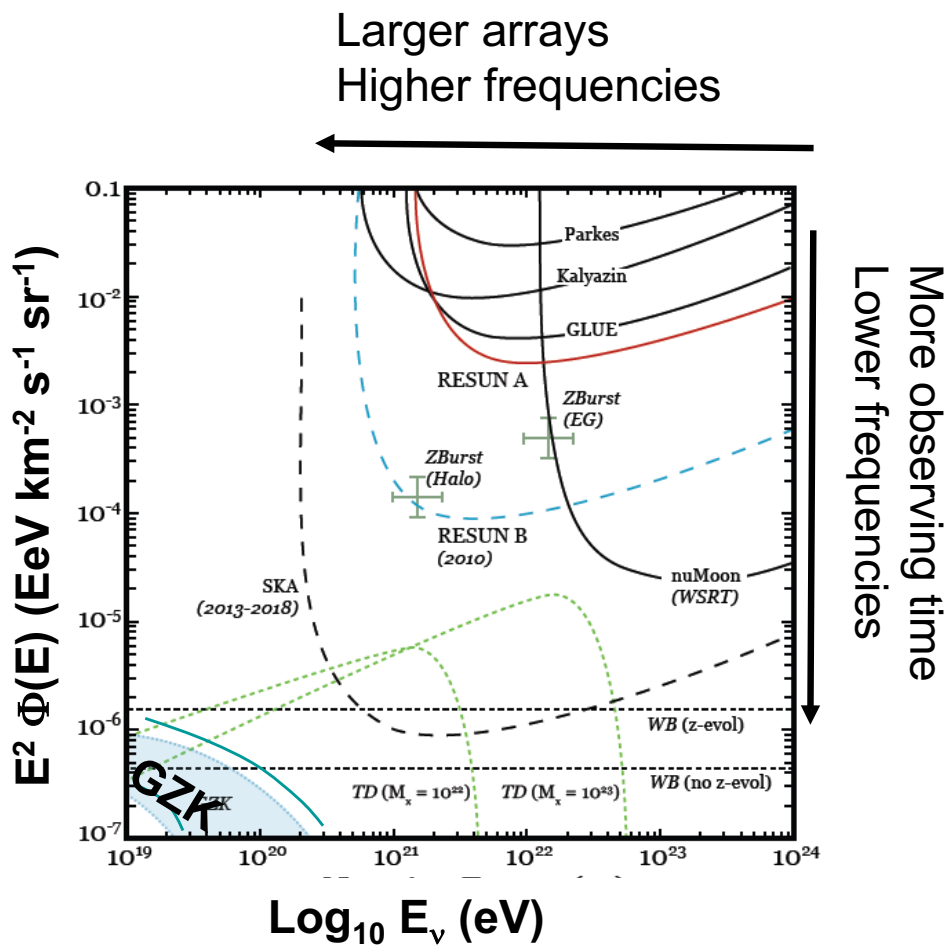
Radio detection

- NuMoon @ Westerbork 64 m dish
- Lunaska @ Australia Telescope Compact Array
  - 6 dishes
  - Wide bandwidth: de-dispersion filter
- Resun: 4 dishes of VLA array
- Low frequency array for radio astronomy (LOFAR)
  - 36 stations in Northwest Europe
- Square Kilometer Array - low
  - Proposed radio telescope array with 1 km^2 collecting area
  - 131,072 low-frequency antennas
  - Extensive beam forming in trigger

C. W. James *et al.*, arXiv:1704.05336

Lunar results

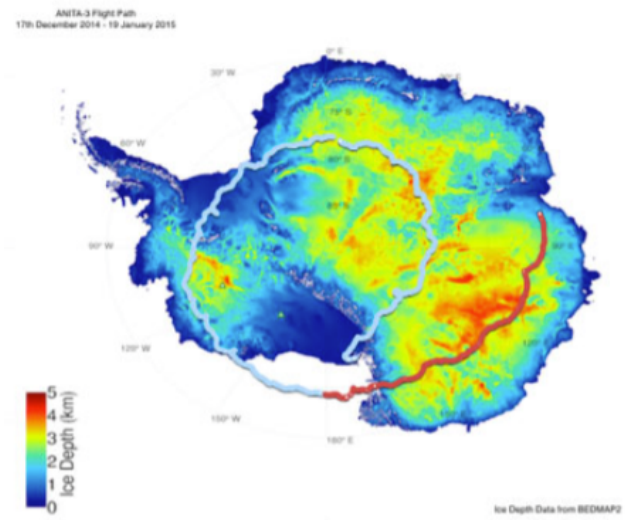
- Thresholds >> 10^{20} eV
  - Small fraction of GZK spectrum
  - Probes exotic models, like topological defects
- Multi-dish apparatus reach lower thresholds
  - SKA- will reach down to 10^{20} eV
- Lunaska (ATCA) presented two limits for different models of lunar surface roughness



O. Scholten *et al.*, PRL 103, 191301 (2009).

A balloon over Antarctica: ANITA

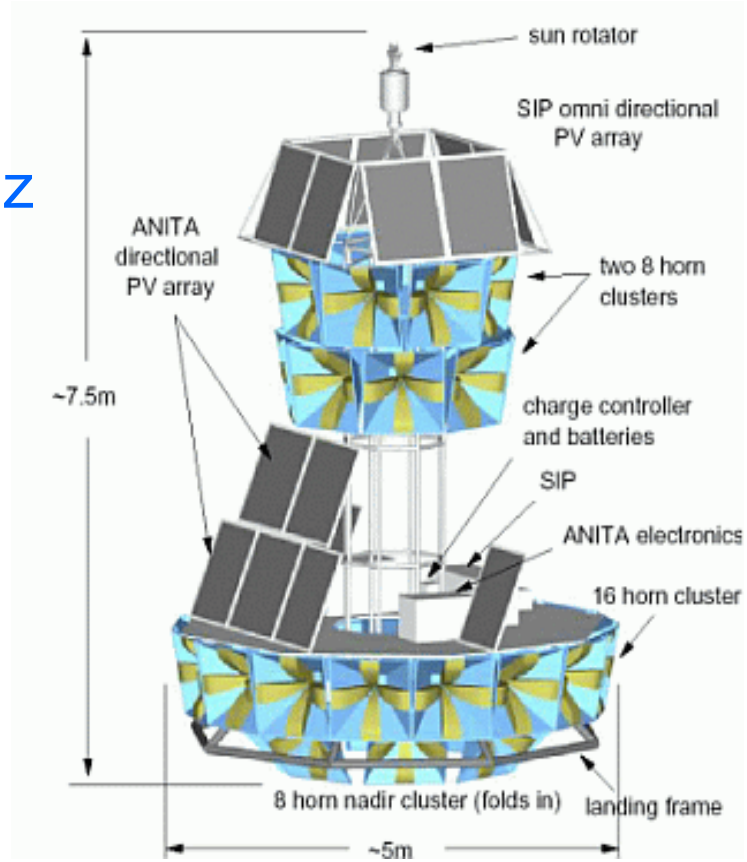
- Circled Antarctica, looking for radio pulses coming from the ice
  - Typical altitude ~ 35 km
    - Distance to horizon ~ 650 km
- 4 flights, from 2006/7 to 2016/2017
  - 22-35 days
  - At the mercy of the winds; flew over varying quality of ice
  - 5th flight requested
- Results from 1st 2 flights released



ANITA-3 flight path

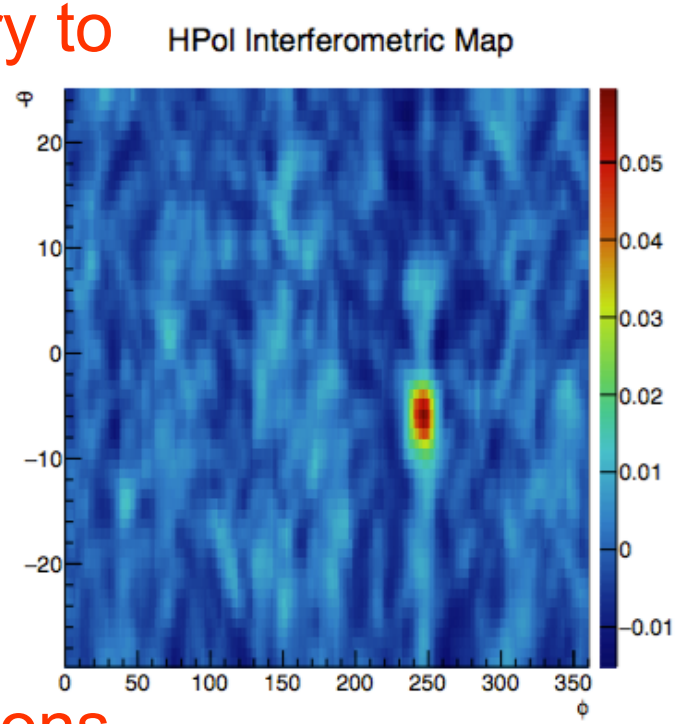
ANITA instrumentation

- 32/40/48 horn antennas
  - Separate channels for vertical (VPOL) and horizontal polarization (HPOL)
    - ν events should be VPOL
  - Frequency range roughly 200-1300 MHz
  - Read out with 2.6 GS/s switched capacitor array ADCs
- Sophisticated trigger
  - Tunnel-diode square law detectors
    - 1/channel
  - ANITA-IV includes notch filters
  - FPGA combines channels
- Calibrations from buried transmitters measure signal propagation through ice, firn and snow-air interface.



ANITA reconstruction & analysis

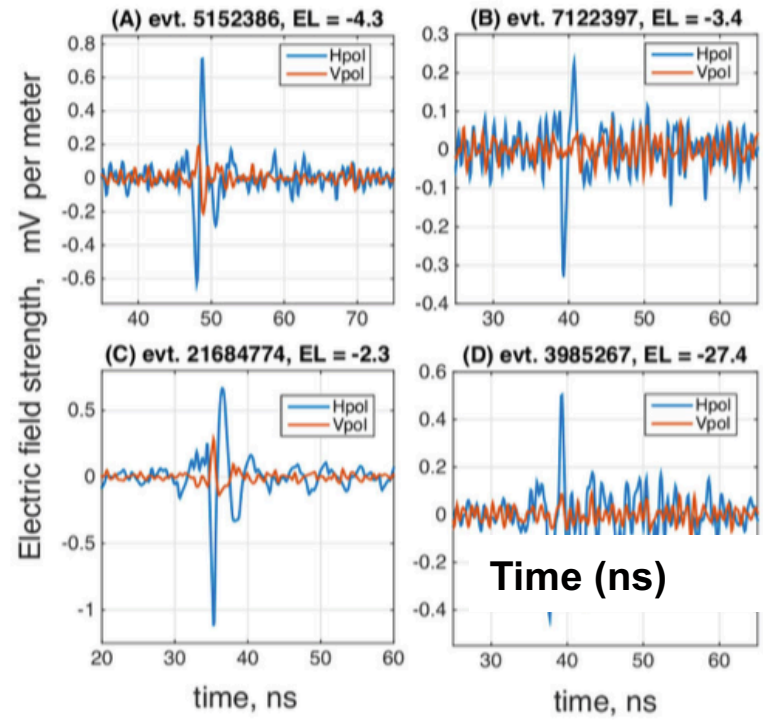
- Precise timing allows use of interferometry to reconstruct events
  - Like a phased-array radar
    - Multiple antennas act like a single larger one
  - Precise angular resolution
- Improved signal:noise ratio
- Cuts remove thermal, payload & anthropogenic noise, and misreconstructions
  - Anthropogenic noise cuts are stringent
  - Mostly vertical polarization
- 1 events remains after all cuts
  - Consistent with backgrounds
- Upper limit constrains 'interesting' GZK models



Cosmic-rays in ANITA

- Cuts similar to ν search
- Mostly HPOL
  - Earth's magnetic field is ~ vertical
- 16 events found in blind search
  - 3 background
  - 13 pulses from air showers which reflected off the ice surface
- Later found 4 more events
  - 3 events likely Earth-skimming cosmic-ray air showers
  - 1 event is consistent with an air shower coming from the Earth
    - τ or ν_τ event?
    - Unusual snow configuration?
    - Transition radiation?

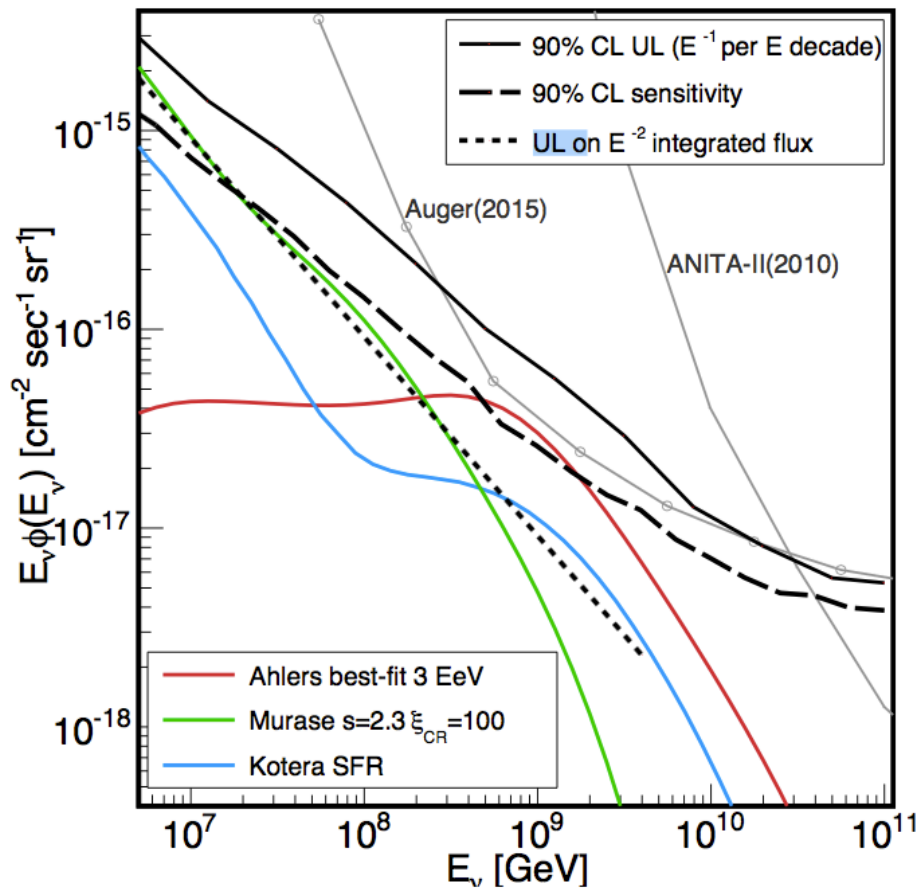
ANITA, PRL 117, 071010 (2016)



Waveforms from 3 (4?) air-shower candidates, with mostly horizontal polarization. The bottom left event appears to ceme from the Earth.

Current limits

- ANITA (2 flights)
- IceCube
  - Tracks or cascades with very high light output
- Auger
  - Showers emerging from the Earth
  - Near-vertical & deeply interacting high-angle
- Current Limits touch on some GZK predictions
  - All protons
  - Favorable evolution



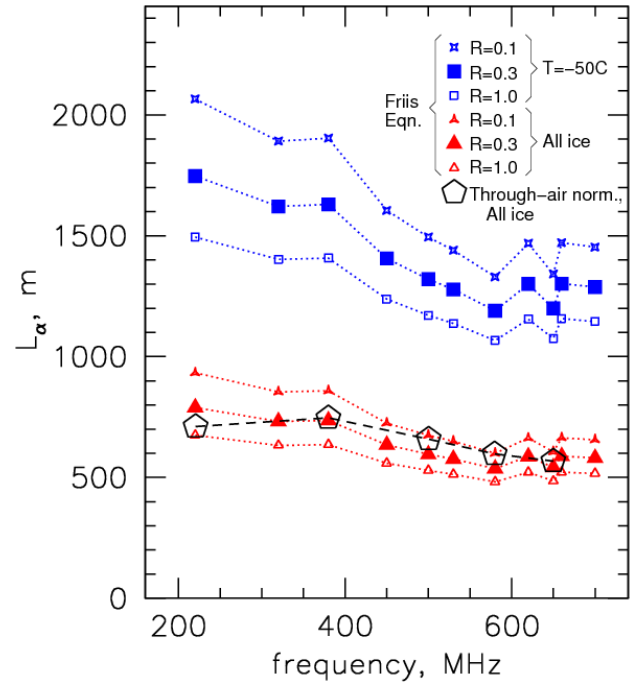
M. G. Aartsen *et al.,* PRL117, 241101 (2016);
A. Aab *et al.,* Phys. Rev. D91, 092008 (2015);
P. W. Gorham et al., Phys. Rev. D85, 049901 (2012)

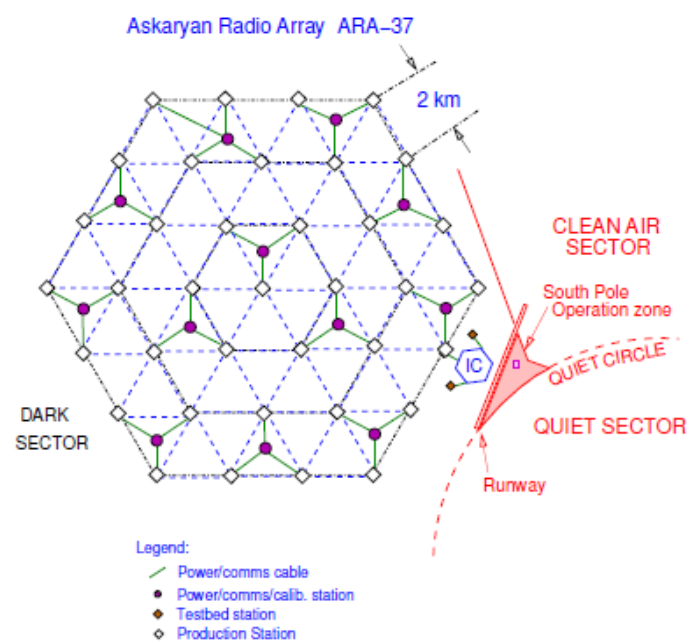
Looking ahead

- Most effort is focused on deploying antennas in Antarctic ice to reach ~ ~< 10^{17} eV thresholds to probe GZK ν and test IceCube spectral measurements at higher energies
  - No sharp threshold – turn-on is gradual
- Pioneered by the RICE Collaboration, which deployed antennas in AMANDA bore holes
- ARA & ARIANNA collaborations have deployed prototype arrays & published test limits
  - Both achieve few-degree angular resolution
  - Monte Carlo cross-checks show agreement there
  - Planned volume ~~ `100 km^3
- Other ideas : EVA balloon & tau-induced radio showers emerging from the Earth

ARA at the South Pole

- Clusters of radio antennas in 200 m deep holes
  - On a ~1-1.5 km triangular grid
  - VPOL + some HPOL
  - Radio Attenuation length 500-1500 m
    - Buried pulsers
    - Frequency & temperature dependent
- Surface detectors as monitors…
- ARA-37 proposal submitted

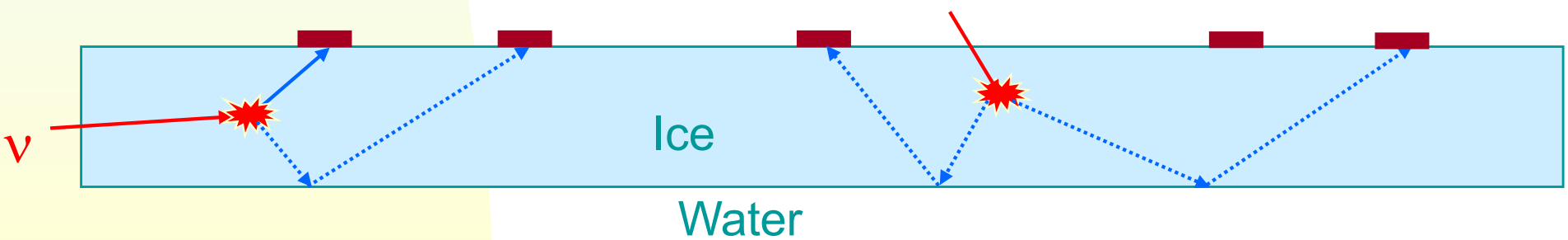




ARA Collaboration: Astropart Phys. **35**, 457 (2012)

ARIANNA in Moore's Bay

- 570 m of ice floating atop seawater
  - The smooth ice-water interface reflects radio like a mirror
  - Reflection increases solid angle
    - Sensitive to downward-going neutrinos
    - Latitude also increases sky coverage
- Surface stations avoid drilling costs & allows flexibility in antennas
  - ~ 8 antennas/station allow single-station reconstruction
- Clean radio environment – almost no anthropogenic noise
- Proposed 1300 stations array



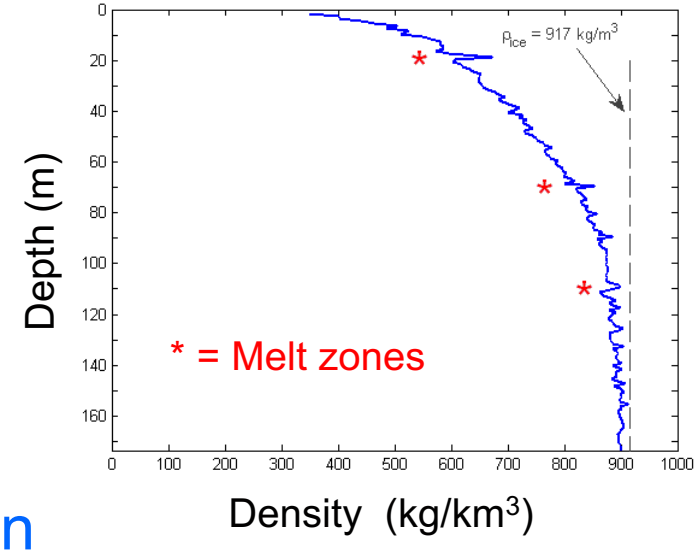
S. Barwick, tomorrow; SK ft. ARIANNA Collaboration: arXiv:1207.3846

ARA and ARIANNA

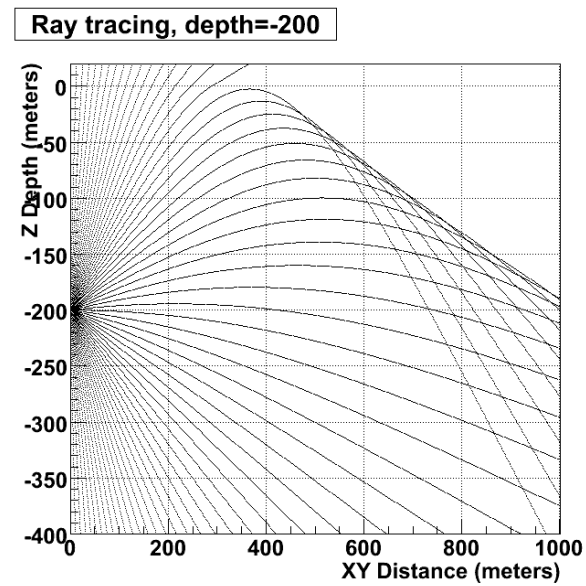
Factor	ARA	ARIANNA
Site	South Pole	Ross Ice Shelf
Ice Temperature	Colder	Warmer
Radio Atten. Length	820 m (avg.)	400 m (avg.)
Antenna Deployment	200 m deep narrow borehole	Surface
Acceptance	Horizontal	Horizontal + Downgoing
Anthropogenic Noise	South Pole Station	Little
Logistics Surface Temperature	South Pole Station, 2800 m elevation Winter power -20 to -40^{0}C	Green Field Site Near sea level Winter wind (maybe) Surface temp ~0 ^{0}C

Radio propagation in ice

- Ice density varies with depth
  - Solid at depths below ~ 100 m
  - Packed snow at surface; gradual increase in density with depth
  - Recent studies find non-uniform variation with depth
    - Layering, as seen in optical studies
- Index of refraction depends on density
  - Waves bend downward
    - Surface detectors have a limited field of view in smoothly varying firn
  - Density variations may produce channels which capture waves and transport them horizontally
    - How efficient is horizontal capture?



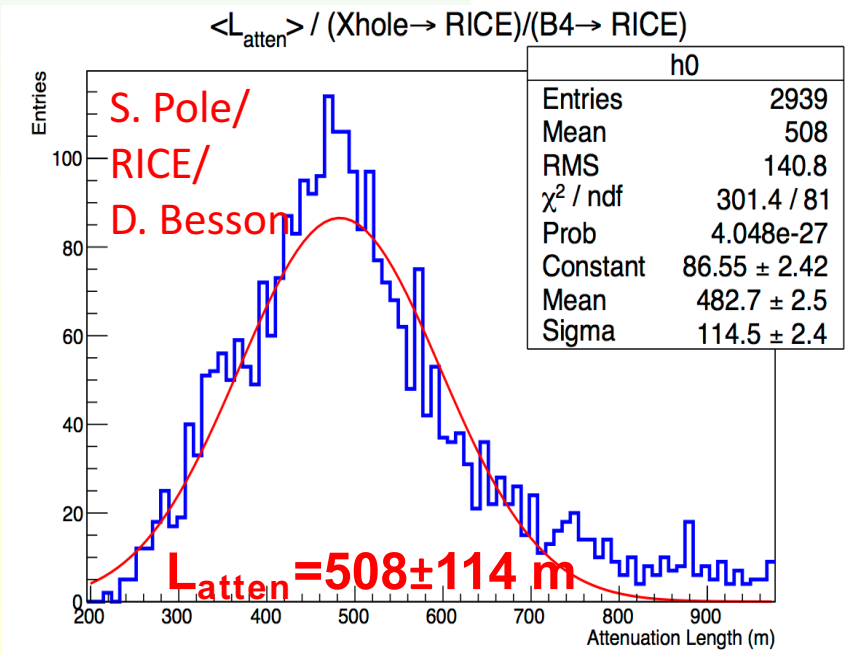
Density vs depth
DYE-3 core (Greenland)

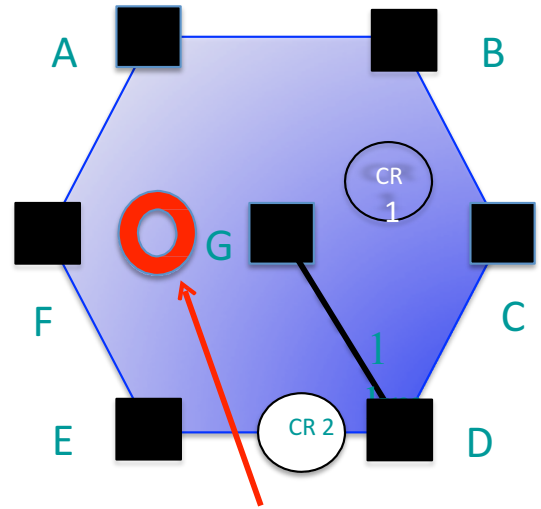


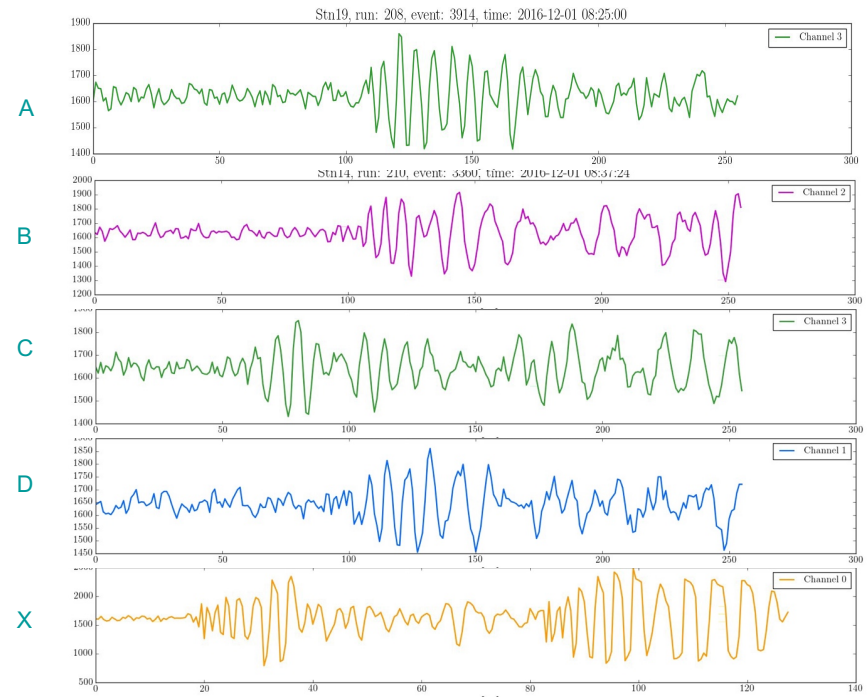
http://www.iceandclimate.nbi.ku.dk/research/flowofice/densification/

Horizontal propagation

- ARIANNA test (Ross Ice Shelf)
  - Signals from a 20 m deep VPOL dipole pulser seen up to 1.5 km away
    - Impossible in smoothly varying firn
  - Timing shows direct propagation
- South Pole study (D. Besson)
  - Older data from RICE
  - Attenuation length ~ 500 m







Antenna Tradeoffs

- **Surface**
- VPOL+HPOL
- Many choices, including with gain
- Simpler design
- Limited field of view, unless channeling is highly efficient

- **Buried**
- Mostly VPOL
  - Must fit in small hole
- Full field of view

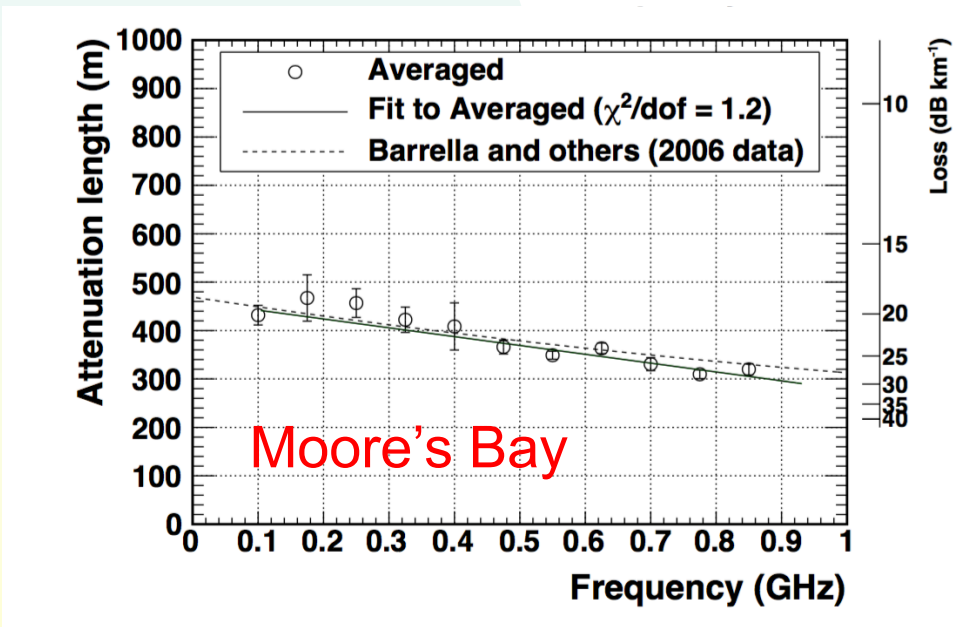
Hpol antenna

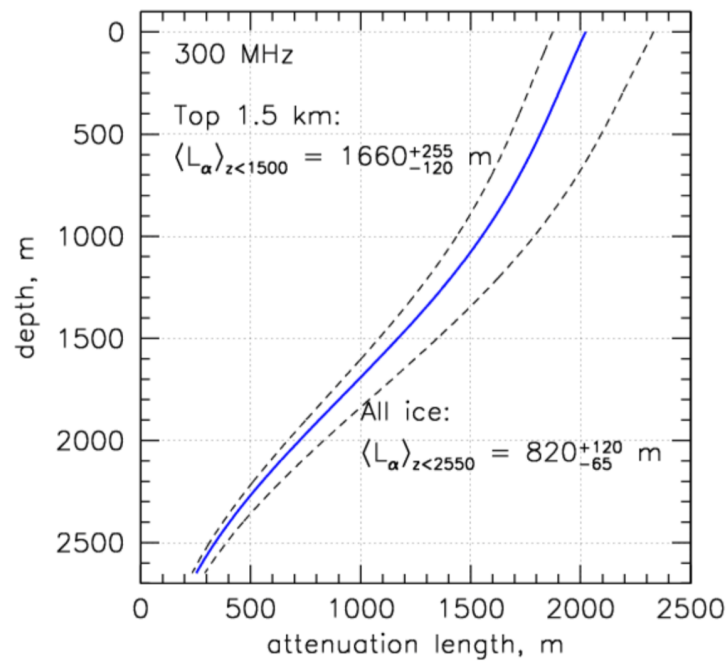
Vpol antenna

Ice Comparison

- Moore's Bay
  - Ice is warmer
  - Measured by reflecting signals off bottom
- <Λ> ~ 400 m

- South Pole
  - Ice is colder
  - Measured w/ buried transmitter
- <Λ> ~ 820 m
  - Better near surface
  - Big advantage for higher E_ν

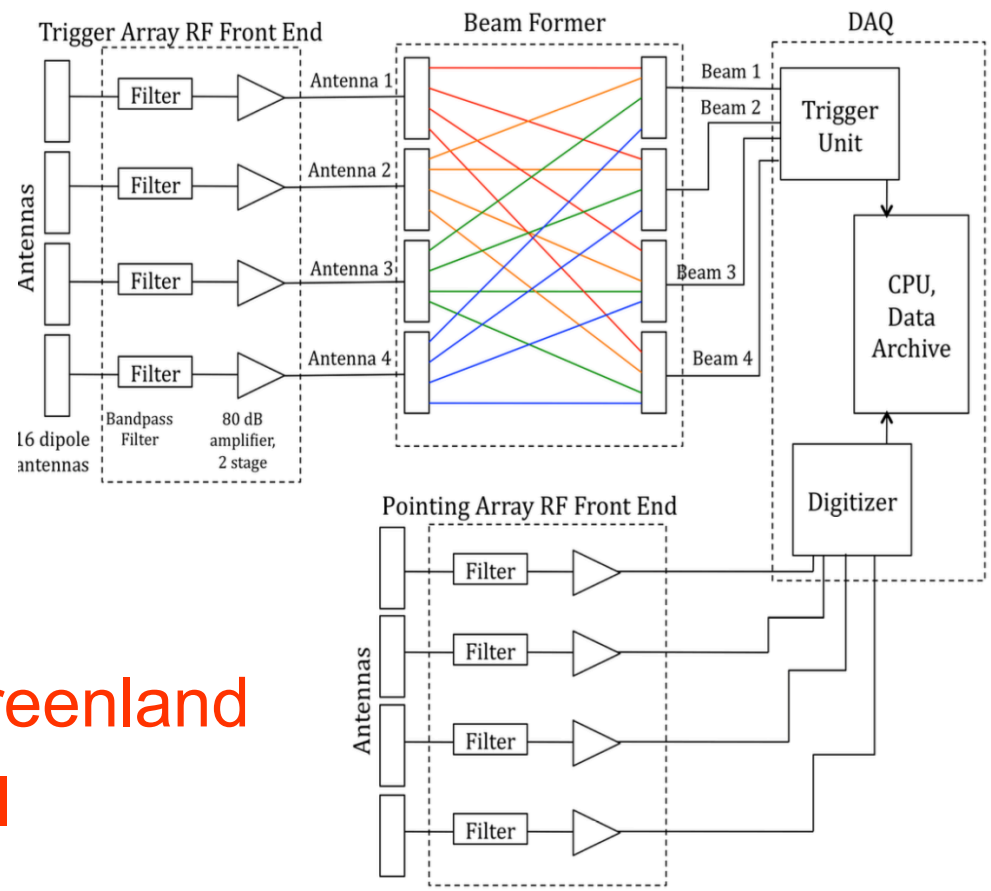




ARIANNA: S Barwick et al., J. Glaciol. 61, 227 (2015)
ARA: P. Allison et al., Astropart. Phys. 35, 457 (2012)

Interferometric detection

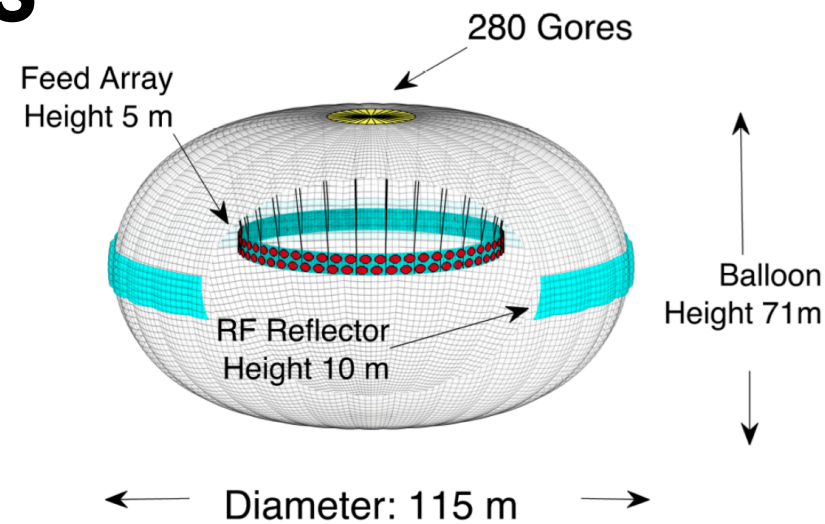
- With interferometric techniques
  - Signal ~$N_{ant.}$
  - Noise ~ $\sqrt{N_{ant.}}$
  - Threshold scales ~ $1/\sqrt{N_{ant.}}$
- Beam-former needs $N_{ant.}^2$ elements to cover all directions
  - Complicates trigger
    - Power
- 4-antenna system tested in Greenland
- ARA tests planned this Austral summer
- 'Factor of several' threshold reduction
  - Attractive for studies of Icecube ν flux



A. Vieregg

Other ideas

- In EVA (Exavolt antenna), part of the surface of an 115 m diameter balloon would serve as a radio reflector
  - Large area -> 10^{17} eV threshold
  - 1/20 scale model built & being tested
- Multiple groups are considering experiments to look for ν_τ interactions in mountains (or shallow Earth)
  - The τ emerges and then decays.
  - Optical methods for $10^{15\text{-}17}$ eV
  - Radio at higher energy
    - Chinese 21 cm array (right)
    - TAROGEE (Taiwan)



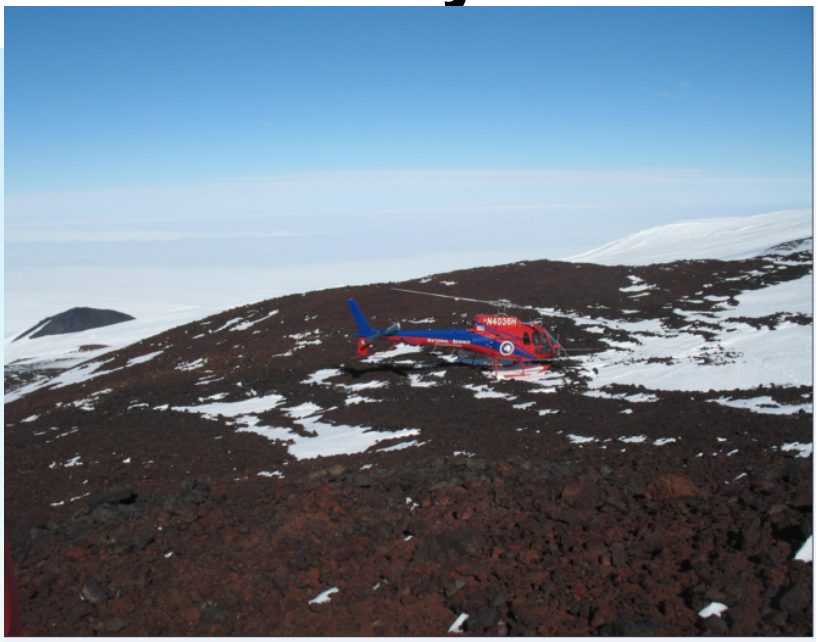
Whither radio?

- There is a strong physics case and much interest in a large radio array. One should be built.
  - Non-detection of GZK ν would also be very interesting.
- Both ARA and ARIANNA are modular. Performance scales fairly directly with $$$
  - So, no performance projection comparisons
- We want to maximize physics/cost
  - Logistics are a main component of cost
  - I don't know which has a better overall ratio
- ARA and ARIANNA have many differences. We should mix & match to use the best site & design ideas.
  - This future radio effort might be part of IceCube Gen2
- A large array might cost in the $10-25 M range

Conclusions

- GZK neutrinos are a guaranteed* (if UHECR are mostly protons), but as-yet unseen source of UHE neutrinos. A ~ 100 km^3 detector should observe GZK ν
- Over the past ~ decade, radio-detection of neutrinos has become an accepted technique.
- Radio-telescopes searching for ν interactions in the Moon have set limits on ν flux for E > (>>) 10^{20} eV.
- The ANITA balloon experiment has put limits on ν with energies above ~ 10^{19} eV.
- Next-generation experiments are focusing on arrays of embedded antennas, leading to a threshold of order 10^{17} eV.
  - These experiments will either see GZK neutrinos, or rule out models with significant UHECR proton content. They will also probe the IceCube ν flux at higher energies.

Thank you



Any questions?

Backup Slides

Measuring $\sigma_{\nu N}$

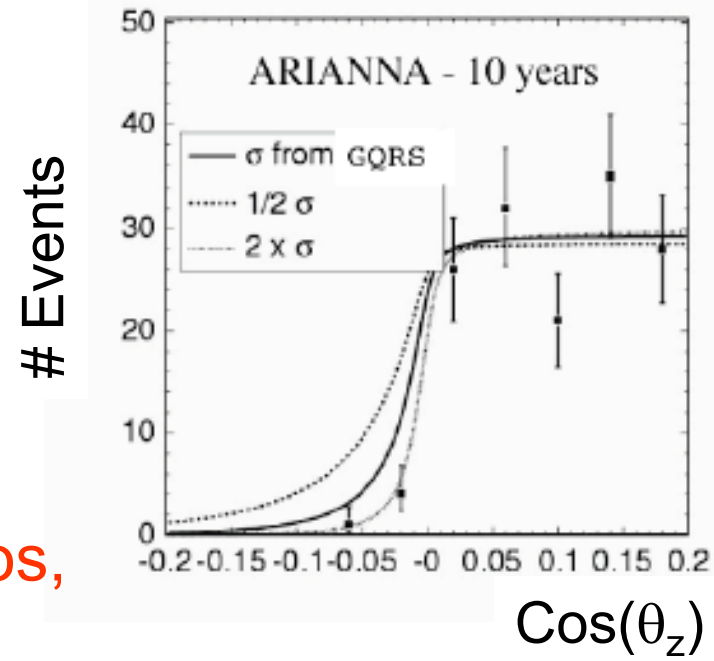
- Measure the neutrino flux as a function of energy and zenith angle
  - Absorption increases with zenith angle
- Self-normalizing
- At >10^{17}eV, the Earth is opaque to neutrinos, so all of the action is at the horizon
- Proposed detectors can measure $\sigma_{\nu N}$ at ~ 10^{18} eV to a factor of ~ 2 in 10 years
- Can't tell what type of interaction (charged or neutral current) caused the absorption

  Measure σ as a multiple of the standard model

  Not an issue for extra-dimension studies

  Tau regeneration is also a complication

IceCube has measured neutrino absorption in the Earth &, with it $\sigma_{\nu N}$!

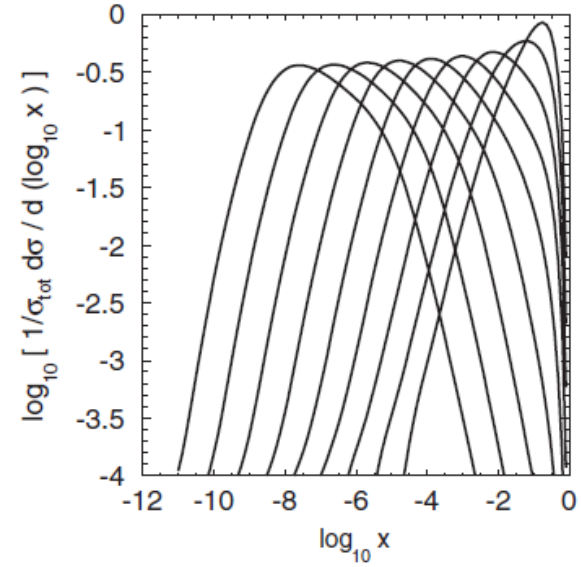


Plot by Amy Connolly

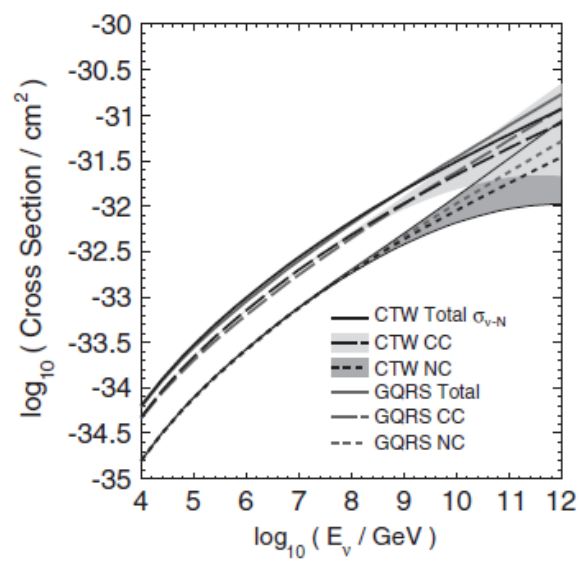
Gary Binder
Next talk

Theoretical issues, and the competition

- σ_{SM} has ~ 50% uncertainties at 10^{19} eV, mostly from the poorly known low-x gluon distributions
  - MSTW 2008 PDFs
- For $E_\nu = 10^{19}$ eV, $x_{typ.} \sim 10^{-6}$.
  - Uncertainty not dissimilar to the expected statistical errors.
- The LHC can do similar studies, but GZK ν reach higher energies. A 10^{19} eV ν has a νp center of mass energy of 140 TeV - 10 times that at the LHC
  - N.b. ν energy should be compared to parton energy



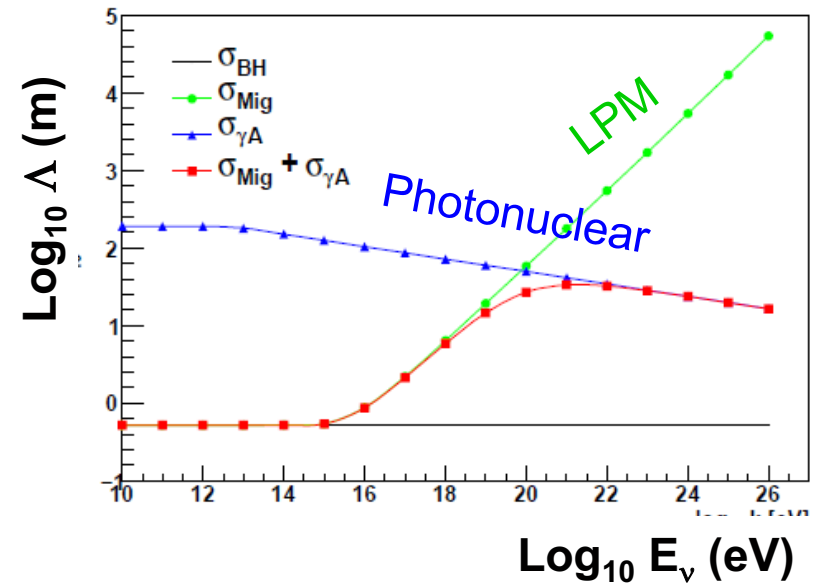
Bjorken x values of the tar
For $E_\nu = 10^4 \ldots 10^{12}$ GeV

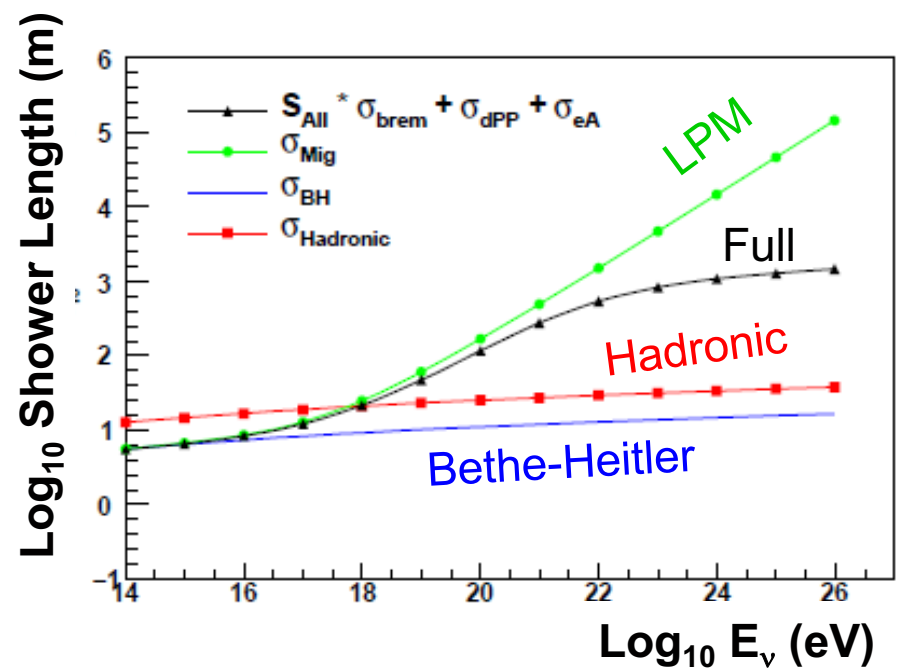


A. Connoly, R. S. Thorne & David Waters, PRD 83, 113009 (2011)

Neutrino Induced Showers

- Focus on ν_e, since that is most detectable
  - 20% of E_ν goes into a hadronic shower
  - 80% of E_ν goes into an electromagnetic shower
  - EM showers are elongated by LPM effect
    - Many higher energy (>10^{20} eV) experiments ignore ν_e showers
- For $E_\nu > 10^{20}$ eV, e & γ interact hadronically, limiting growth in shower length
  - Muons in showers

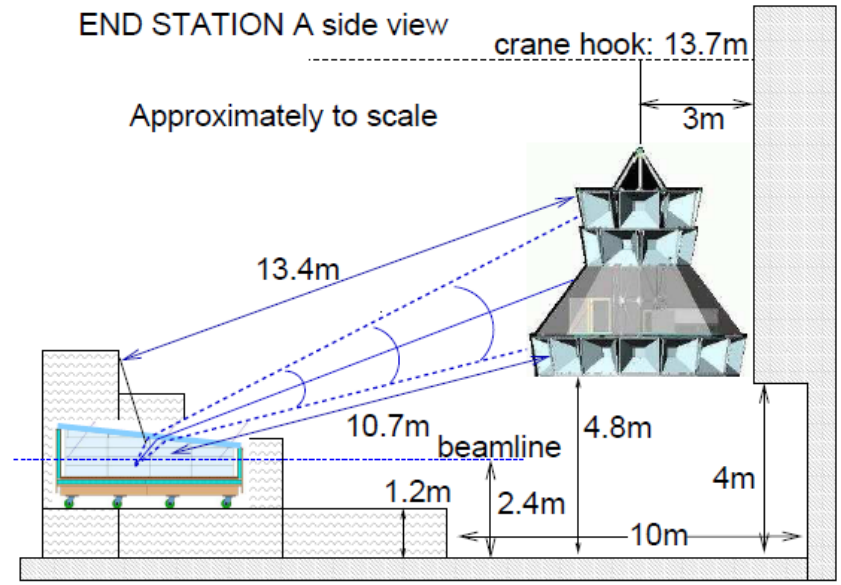


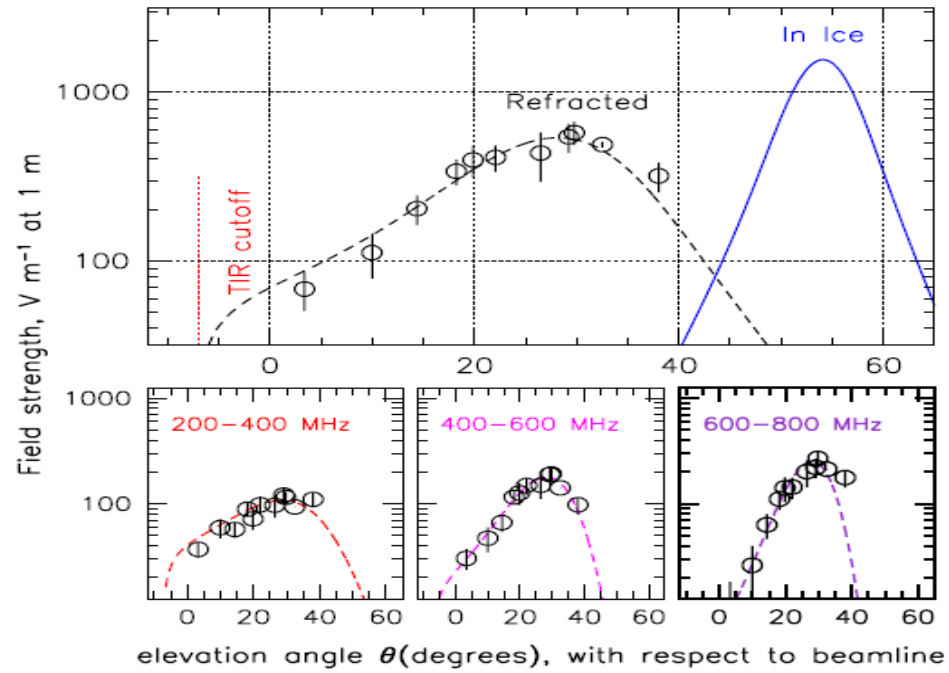


L. Gerhardt & SK, 2010

Shower Studies @ SLAC

- Pulses of 10^{10} 25 GeV e- were directed into a large cube of ice
  - Radiation studied by ANITA detector
- Frequency & angular distributions matched theory
  - Refraction affects angular dist.
- Previous expts. with salt and sand targets

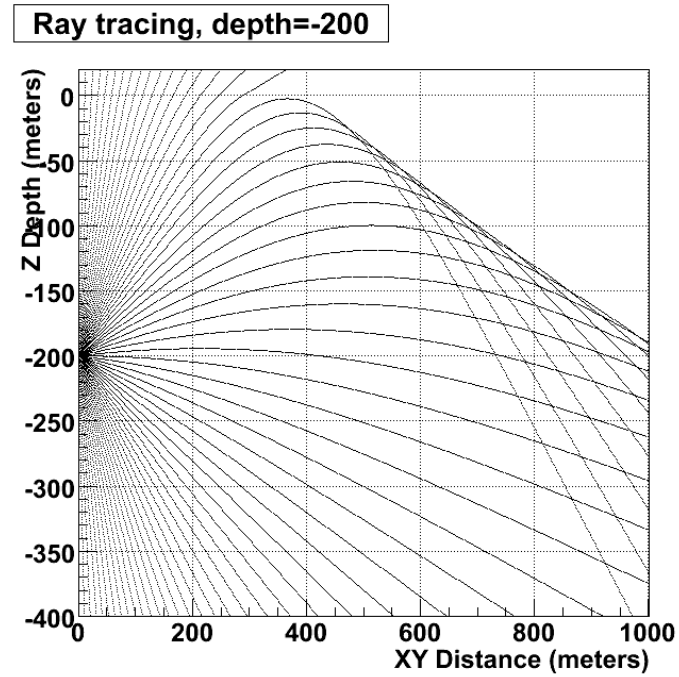




ANITA Collab., 2007

Ray Tracing in Antarctic Ice

- The varying density near the surface causes radio waves to refract
- Density profile measured with boreholes.
- Slowest transition to ice in central Antarc



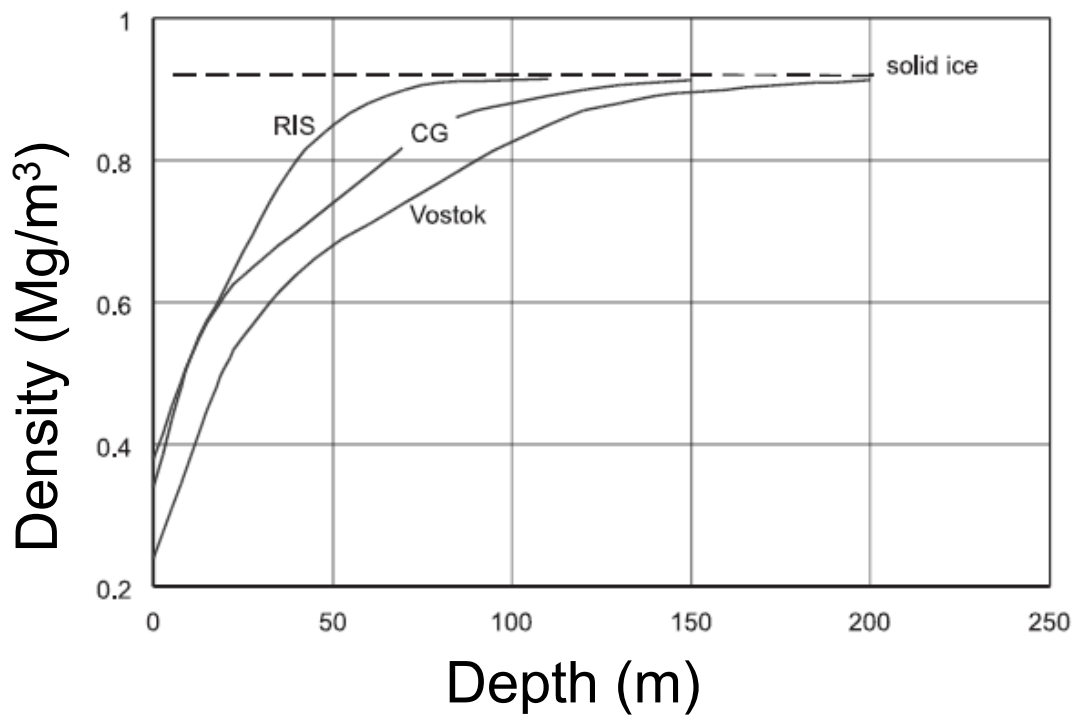
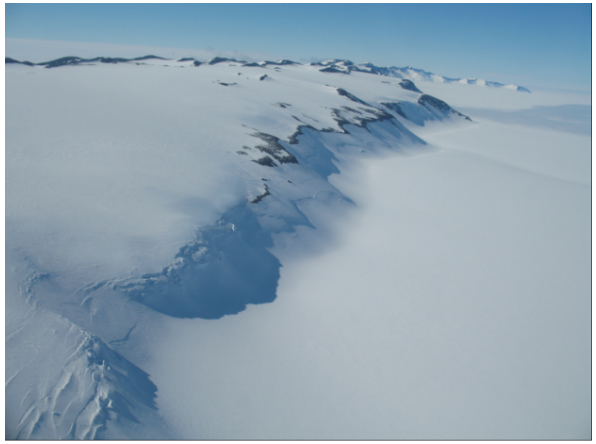
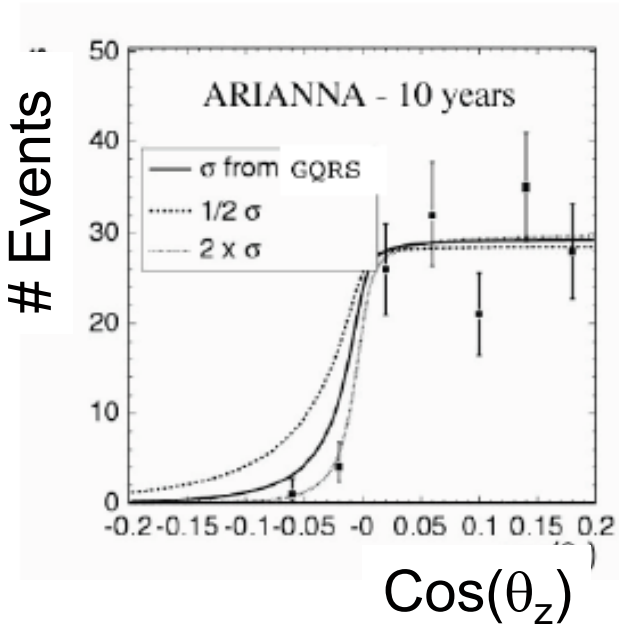


Figure 2. Firn density versus depth at three polar locations: the Ross Ice Shelf (RIS) and Vostok Station in Antarctica and Central Greenland (CG).

The ARIANNA proposal

- Each station is autonomous
  - Local trigger & intelligence
  - Spacing is a tradeoff between maximum volume/cost vs. seeing events with multiple stations
- Stations with 8 antennas
  - Antennas are in shallow trenches
  - Autonomous data acquisition
- Site is 110 km from McMurdo station, shielded by Minna bluff from anthropogenic noise
- Wide angular range allows measurement of neutrino-nucleon cross-section, independent of flux

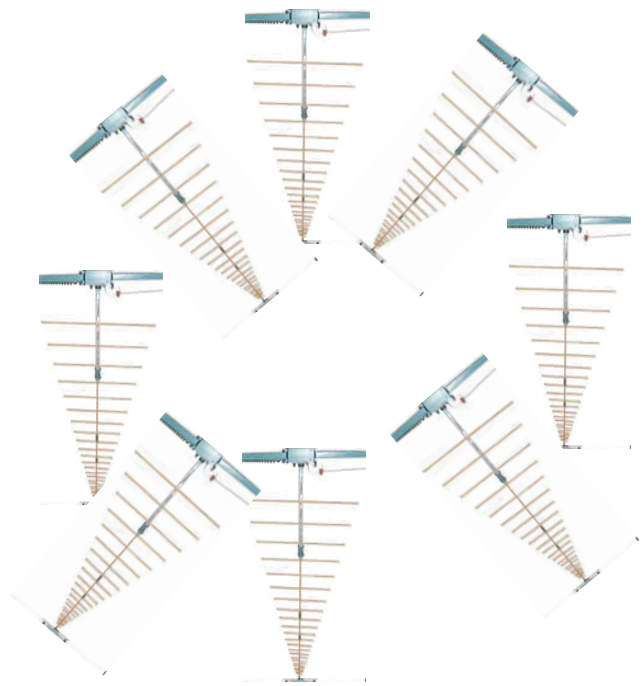


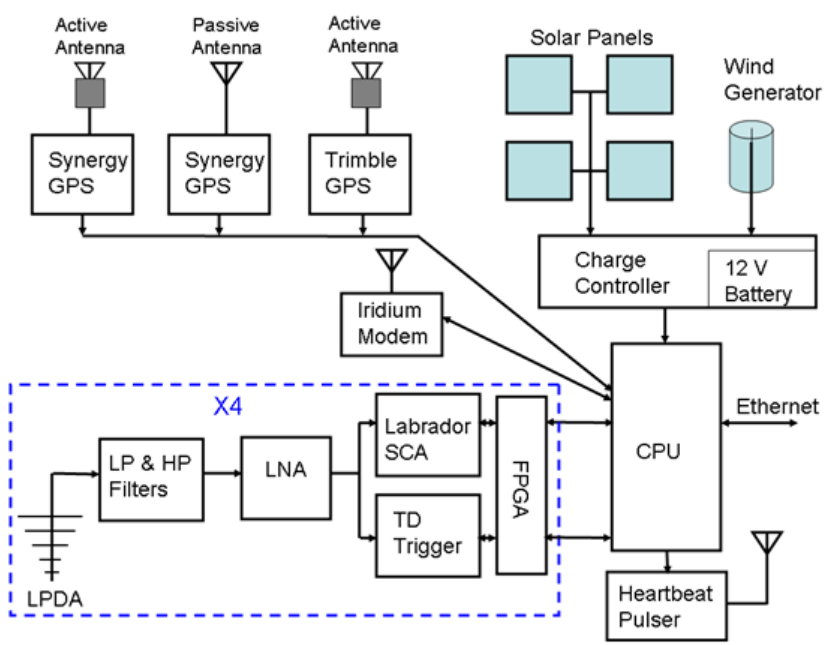


Plot by Amy Connolly

The ARIANNA detector

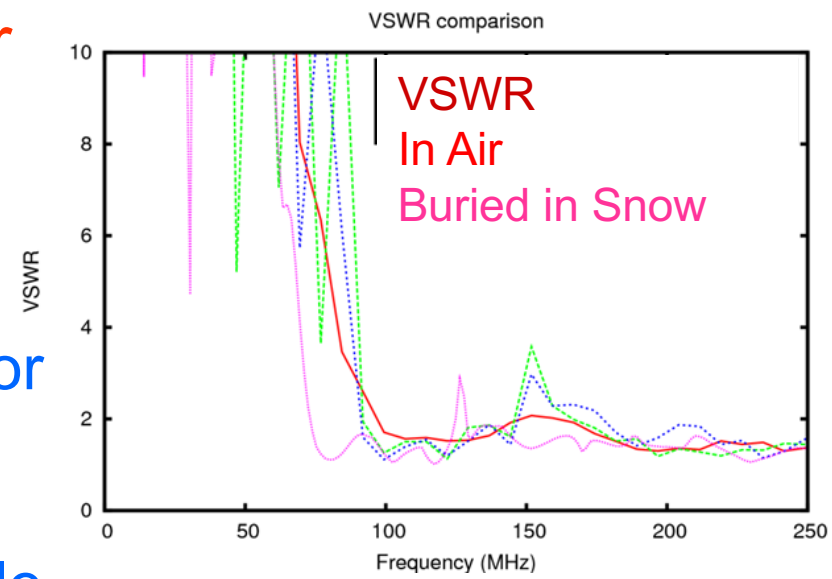
- 900 stations on a 1 km grid
  - Stations trigger independently
- 8 log—periodic dipole antennas/station
  - Response in ice from 80 MHz – 1 GHz
  - All pointed downward
  - Separation 2-4 m
    - Δt from opposing pairs gives zenith angle
  - Amplitudes from 45^0 pairs gives polarization (azimuthal angle)
- Trigger on 2-3 antenna above threshold
- Digitize signals at 2 GS/s with a switched capacitor array
- Irridium modem & internet communication
- Solar + wind/wired power





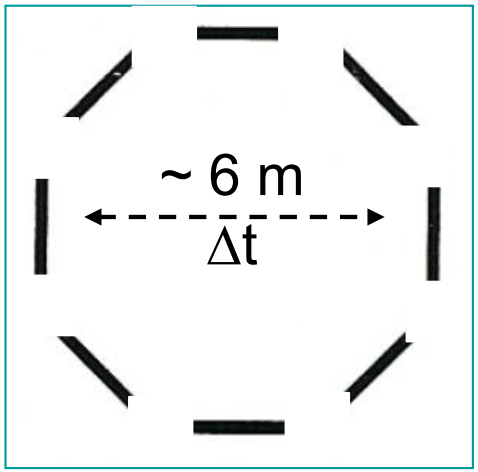
Signal Detection Hardware

- Log Periodic Dipole Antenna
  - Good directionality & polarization sensitivity
  - 105-1300 MHz in air
    - In ice, index of refraction n> 1
    - Wavelength Λ = c/nf is shorter
  - Antenna impedance is altered, shifted to slightly lower frequencies
- Low noise pre-amp & switch capacitor array ADC + trigger system
- GPS for timing
- Solar power (summer)
  - Wind generators under investigation for winter
    - Not much wind at site
  - Central power station + cables possible

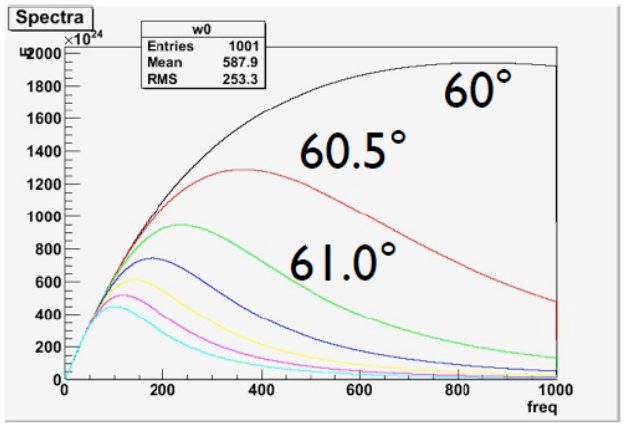


Stuart Kleinfelder will discuss the ARIANNA DAQ system on Thurs. morning

Directional determination

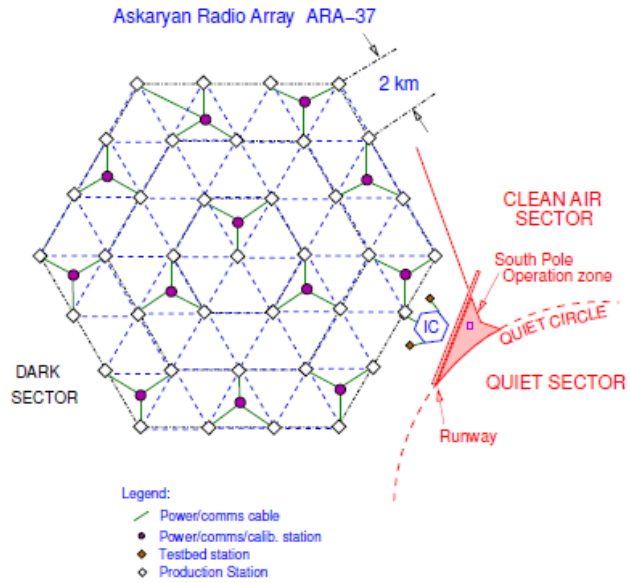


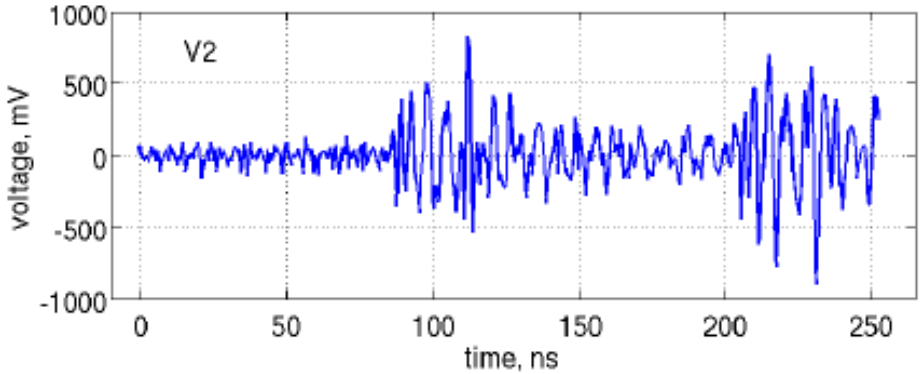
- The octagonal antenna arrangement allows us to determine ν direction from a single station.
- The direction from the station to the ν (*D*) interaction is found from the paired time differences from opposing antennas
  - Two angles
- Two angles determine ν arrival direction
  - The RF signal is linearly polarized in the plane containing the n direction and *D*
  - The frequency spectrum tells how far *D* is off the Cherenkov cone.
- 4-fold ambiguity in direction (2/angle)
  - (8-fold w/ only 4 antennas)



ARA hardware

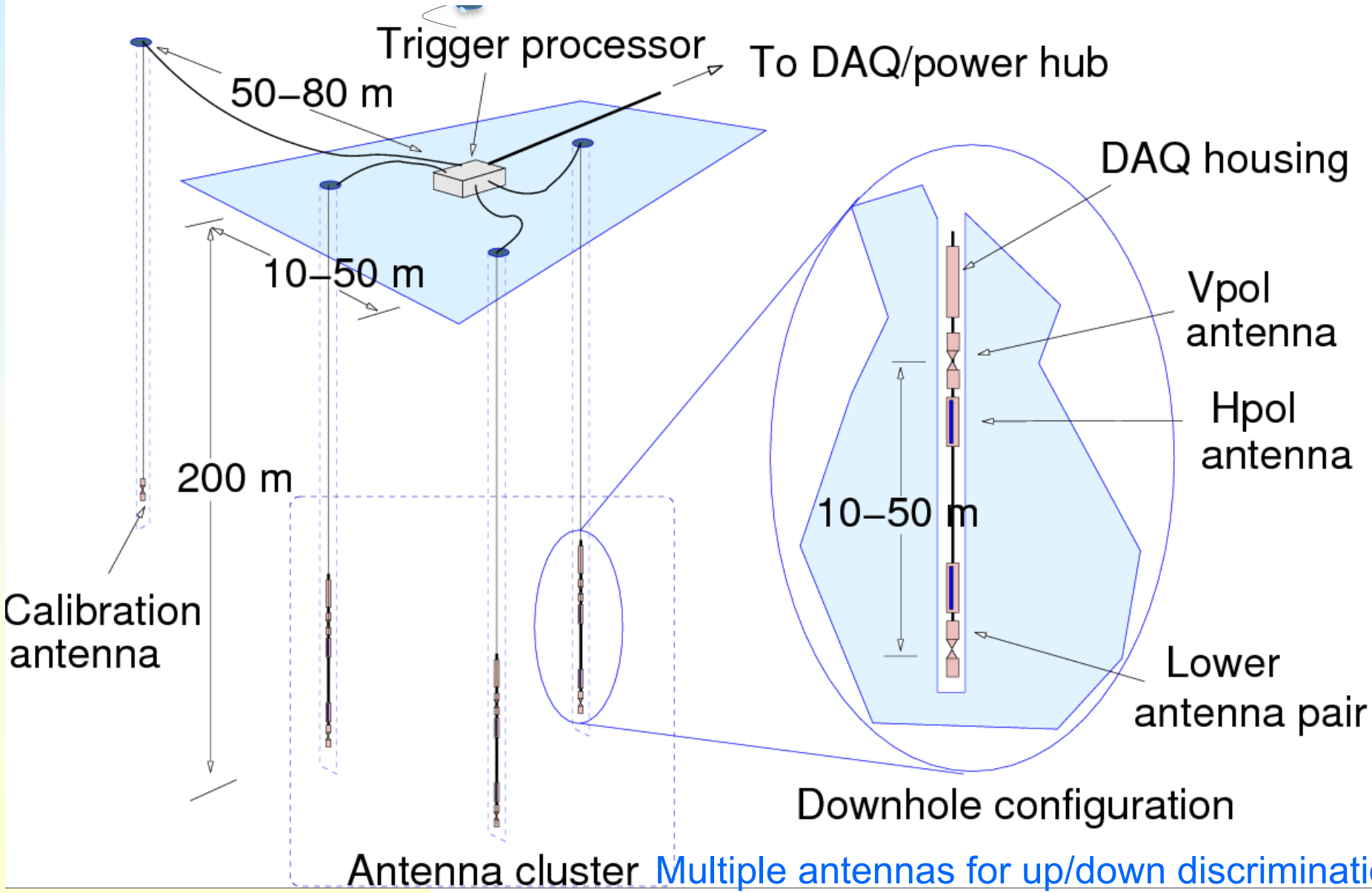
- Receivers are deployed in ~ 200 m deep 4 inch diameter boreholes
  - 4 receiver + 1 calibration string/cluster
- 150-850 MHz bicone antennas for vertical polarization
- 200-850 MHz quad-slotted cylinders for horizontal polarization.
- Single string trigger
- Waveform digitization at 2GS/s
- Some reflection observed from surface
-





ARA stations and antenna clusters

4 receiver strings + 1 buried calibration transmitter/cluster
Prototype Development in progress



Multiple antennas for up/down discrimination