UHE Neutrino Radio Detectors

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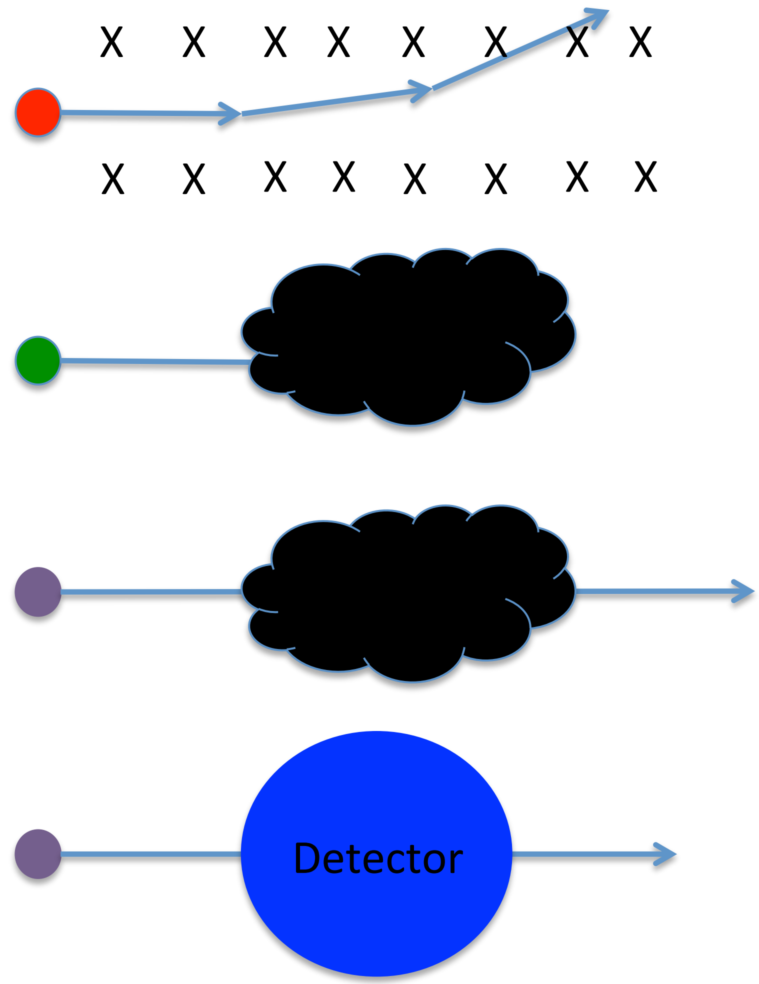
Cosmic Messages in Ghostly Bottles
February 27-28, 2014
Ohio State University Physics Department

Outline

- Introduction
- Balloon Experiments
  - **An**tarctic **I**mpulse **T**ransient **A**ntenna (ANITA)
  - **E**xa**V**olt **A**ntenna (EVA)
- *In situ* arrays
  - **R**adio **I**ce **C**herenkov **E**xperiment (RICE)
  - **A**skaryan **R**adio **A**rray (ARA)
  - **A**ntarctic **R**oss **I**ce-Shelf **AN**tenna **N**eutrino **A**rray (ARIANNA)
- Observables and Challenges
- Conclusions

Cosmic Messengers

- Cosmic rays
  - Charged - subject to magnetic deflection
  - Lose energy to GZK
- Gamma rays and other photons
  - Attenuation
- Neutrinos
  - No attenuation or deflection
  - Weakly interacting - difficult to observe
  - Only extraterrestrial sources
    - Sun, Supernova 1987A
    - new IceCube events



GZK Process and Sources

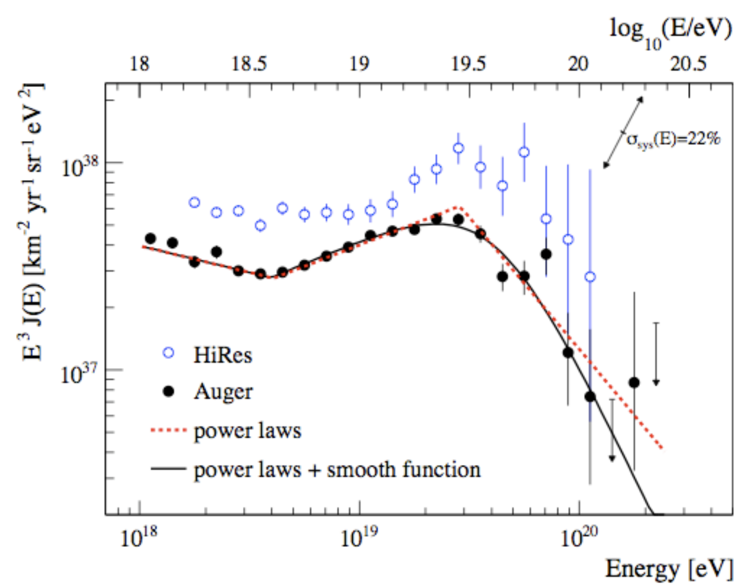
- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with E > $10^{19.5}$ eV interact with cosmic microwave background (CMB) photons
- Cosmic rays above this energy are limited to a range of ~75 MPc
- Process produces neutrinos, some at UHE
- Neutrinos are not subject to these successive interactions and happily continue on.
- UHE neutrinos could also be produced at a source location rather than through GZK
  - If observed, will trace back to source

$$\mathbf{p} + \gamma_{\mathrm{CMB}} \rightarrow \boldsymbol{\Delta}^* \rightarrow \mathbf{n} + \pi^+$$

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_{\mathbf{e}}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow \mathbf{e}^+ \bar{\nu}_\mu \nu_{\mathbf{e}}$$

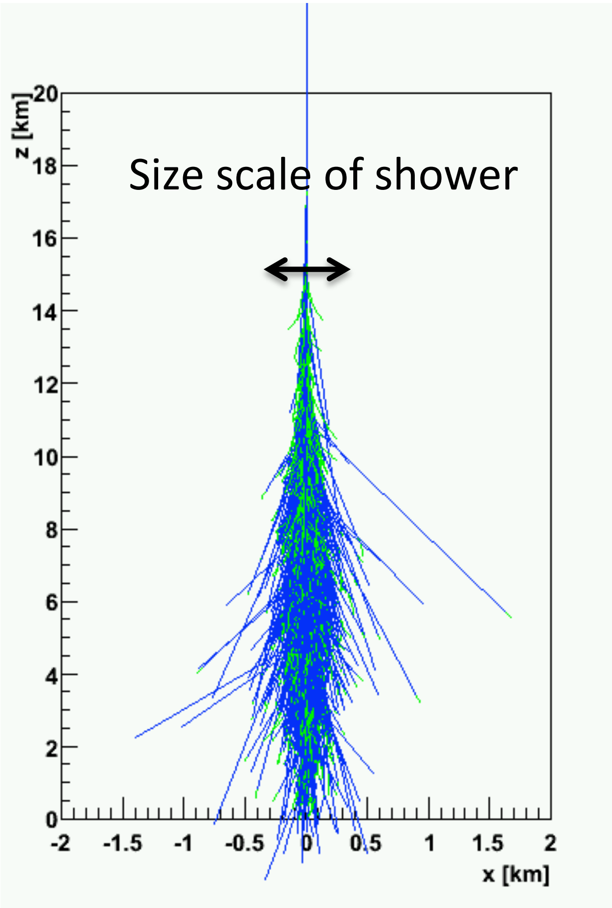


Large Volume Detectors

- Consider GZK models, Antarctic ice, earth shadowing, neutrino cross sections
  - Less than 1/km^3/year/energy decade
- IceCube – O(1 km^3) of ice – discovery scale
  - optical Cherenkov radiation – limited range, attenuates in ice
  - Better sensitivity at lower energies (more PeV, less EeV)
- ARA – O(100 km^3) of ice - sensitive to energies up to 10^{20} eV
  - This size needed for observatory-like detection of UHE neutrinos
- ANITA – O(1000000 km^3) of ice – 700 km to horizon
  - Balloon experiment - ~30 day flight time
  - Sensitive to higher energies than ARA but weaker at 1EeV

Detection technique

- How to get large-scale detection -
  - Brute force: make 100 IceCubes
  - Use a different approach – radio Cherenkov technique
- Coherent Cerenkov signal from net "current," instead of from individual tracks
  - A ~20% charge asymmetry develops in the shower
  - If $\lambda >> R_{Moliere}$ (radial size scale) → Coherent Emission
  - Hypothesized by Gurgen Askaryan, 1962
  - Observed in various dielectric media: ice, water, salt
  - Impulsive signal
- Attenuation of radio signal is considerably less than optical thus a signal detector unit has a far greater observable volume



E-M shower
(gamma ray in air)

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Balloons vs *in situ* Arrays

- Balloons
  - Large target volume, short flight time 30-40 days
  - Must be reconstructed after flight and "landing"
  - Good as a "discovery" instrument

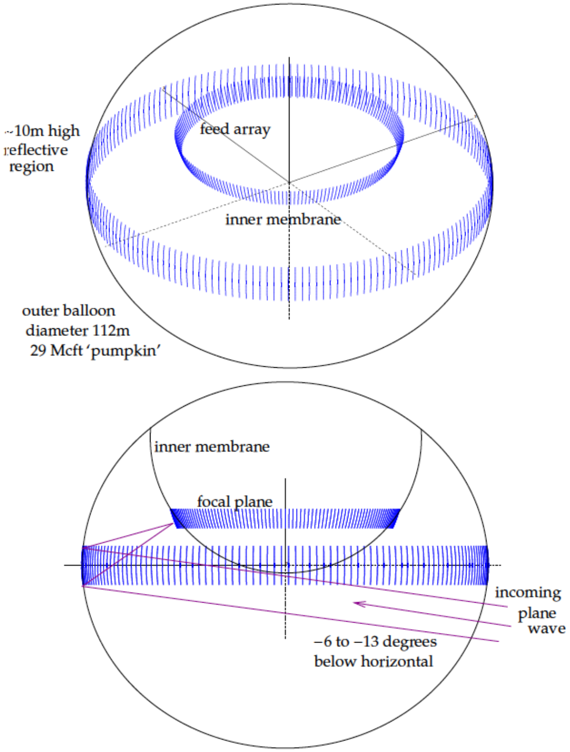
$$F = \frac{N}{At\Omega E}$$

- *In situ* arrays
  - Long operation time, "always on" but smaller observable volume
  - Environmental problems *in situ*
    - Need to model the environment
  - Good as an observatory – long term stability

Radio Cerenkov Balloon Experiments

ANITA

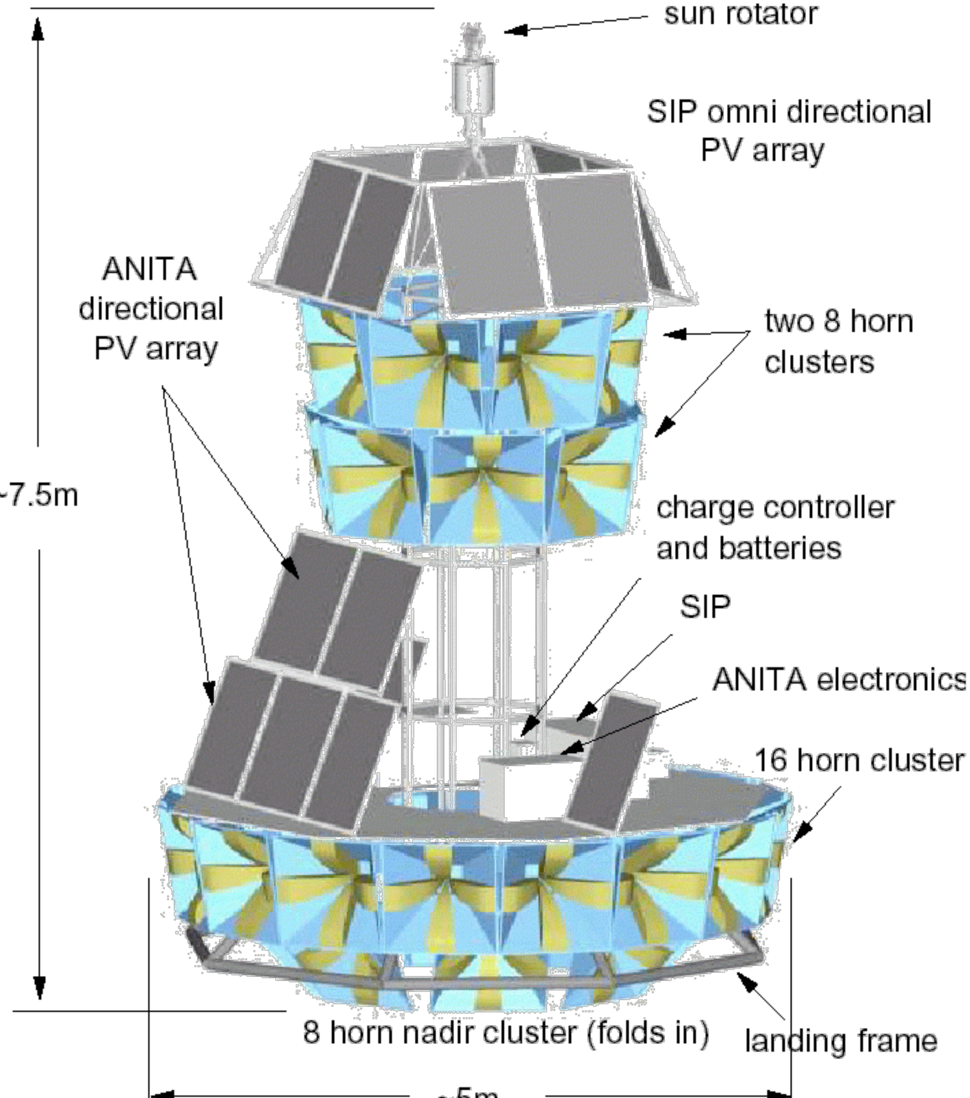
proposed ExaVolt Antenna (EVA)



Gorham *et al.* (2011)

ANITA Design

- Payload consists of an array of quad-ridge horn antennas
- Antennas aimed down 10° to view ice rather than sky
- 2.6 GHz data sampling and fast triggering electronics
  - Signal range = 150-1000 MHz

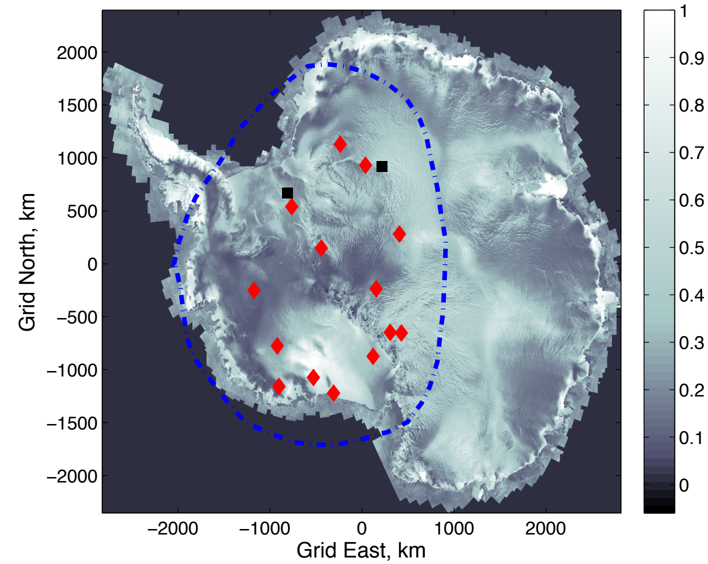


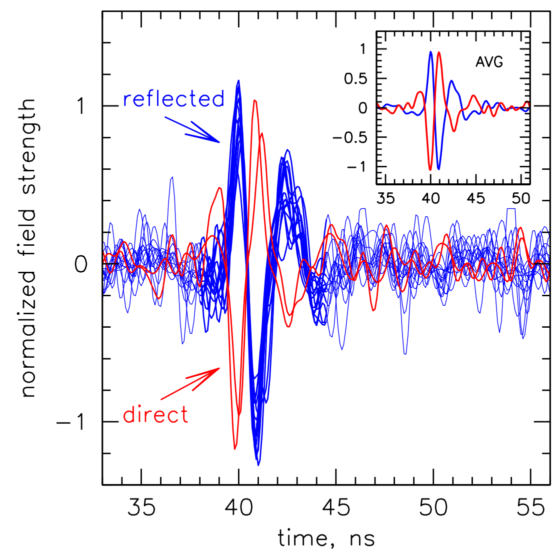
ANITA Flights and Differences

- ANITA-I – flew austral summer 2006-2007
  - 18 days good livetime, cosmic ray events observed
- ANITA-II – flew austral summer 2008-2009
  - Added 8 antennas over ANITA-I, optimized trigger
  - Lower noise amplification, directional mask
  - No h-pol trigger
- ANITA-III - planned for 2014-2015 pole season
  - Added 8 new antennas over ANITA-II
  - Optimized for neutrinos and cosmic rays

ANITA Results

- ANITA-I observed radio signals from 16 cosmic ray showers
  - Radio signals produced by geosynchrotron emission
  - Majority of events reflected from the ice surface
  - Some direct events
- No neutrinos but placed competitive limits above 1 EeV



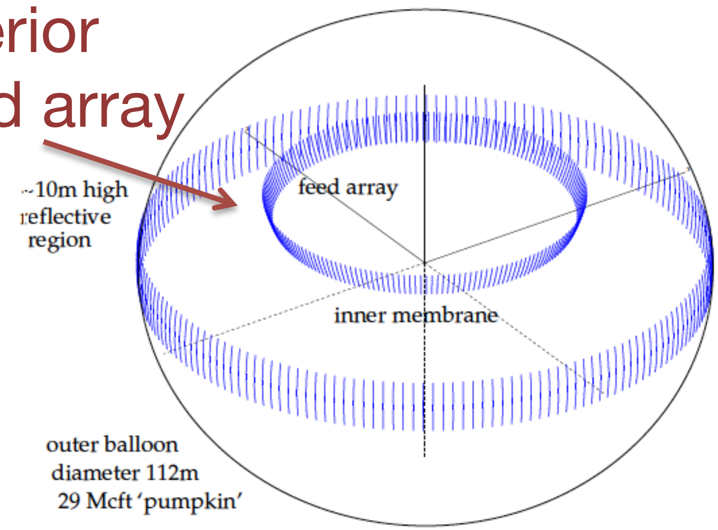


S. Hoover *et al.*

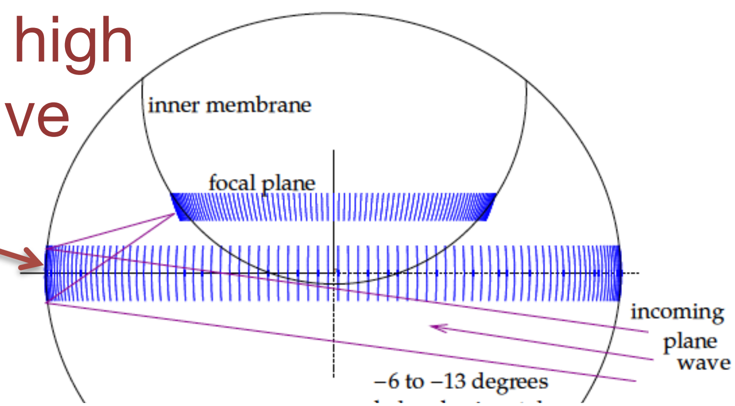
ExaVolt Antenna (EVA) concept

- Design balloon to be a apart of the detector
  - Put reflector on exterior to focus signal inwards
- Would be the world's largest aperture airborne telescope
  - 1000's of square meters
  - 150-600 MHz ($\lambda_{air} \approx 0.5$-2 m)
- 100X increase in sensitivity to radio signals
- Currently under development with 3 year NASA engineering study

Interior feed array



~10 m high reflective region

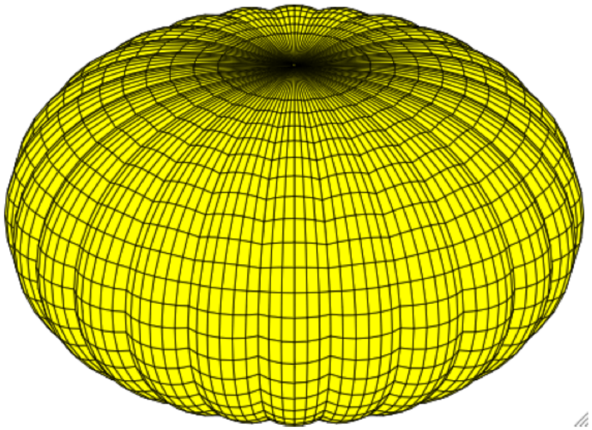


incoming plane wave at -6 to -13 degrees below horizontal

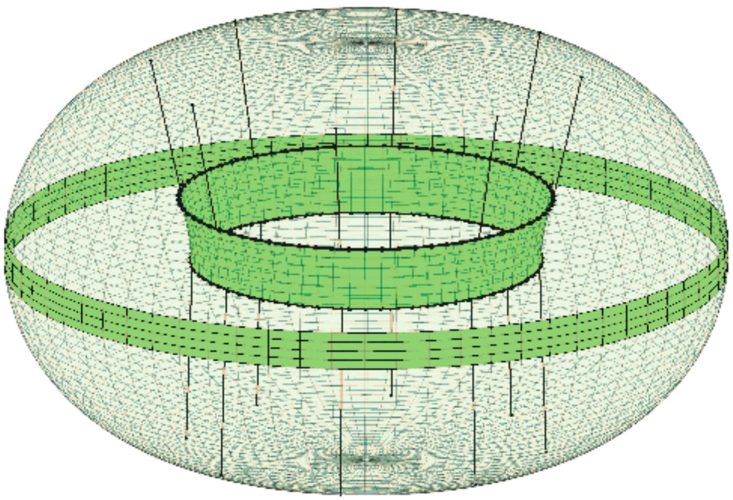
P. W. Gorham et al., 2011.

EVA Design

- Use a super pressure balloon (SPB) instead of standard zero pressure balloon
  - Maintains relatively consistent lobed geometry (like a pumpkin)
- Feed array on suspended surface within balloon
  - 3m high, 5 rows of total 1200 feed antennas
- Planned 1:20 scale hang test at Wallops Flight facility later this spring



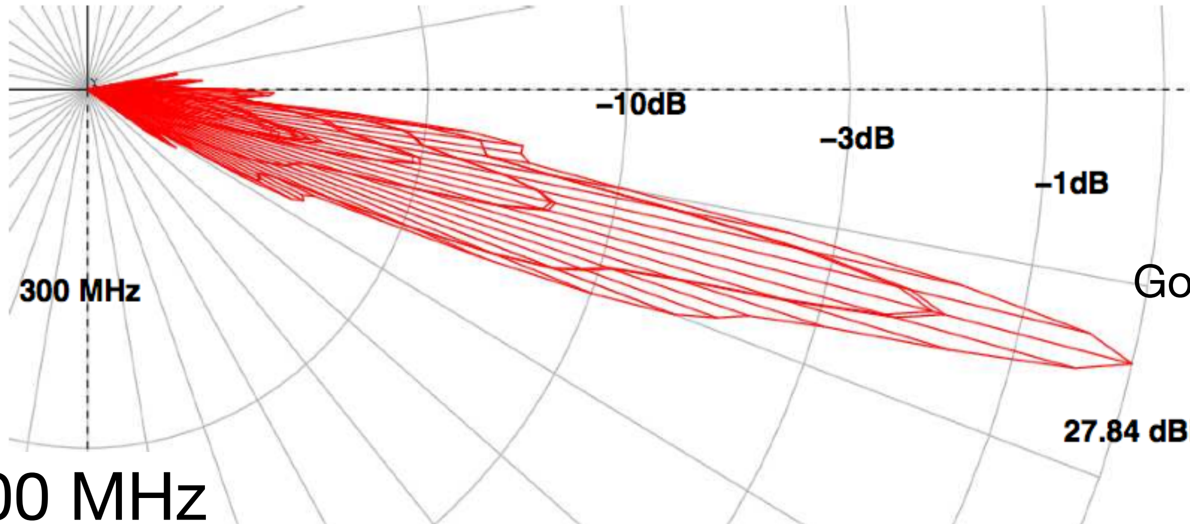
Gorham *et al.* 2011)



outer balloon diameter
112 m, 29 Mft^3

Gains

- Nec2 simulation of ± 25°, 11 m high reflector region
- For vertical polarization 200-500 MHz, gain exceeds ~500 times isotropic = 27 dBi



Gorham *et al.* (2011)

300 MHz

- x 100 in gain → ÷ 100 in power threshold → ÷ 10 in E field threshold → ÷ 10 in ν energy threshold
- For most GZK models, at least a factor of 10 increase in event rate over ANITA-II; could even reach mixed composition models

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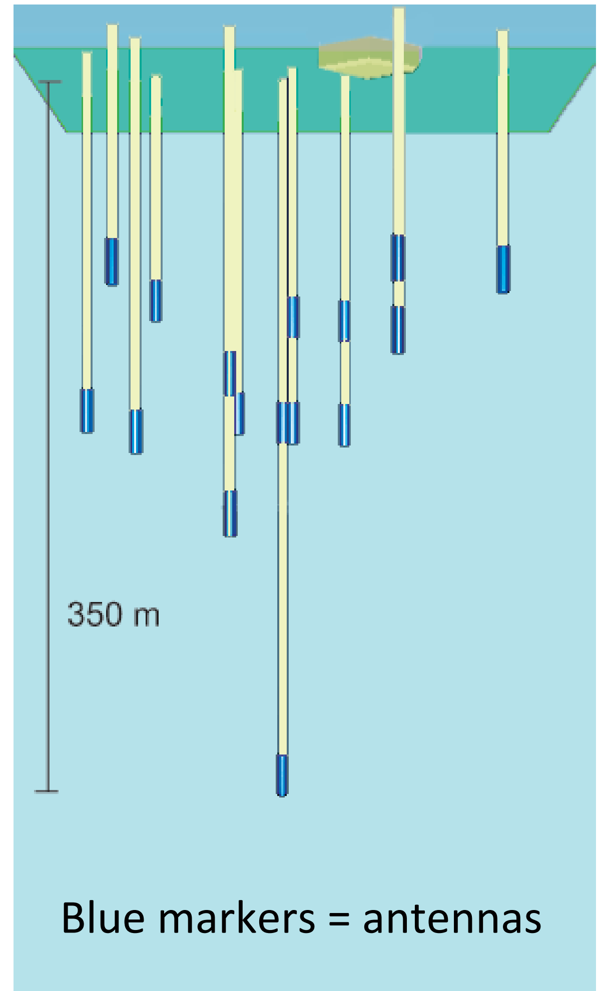
Radio Ice Cherenkov Experiment

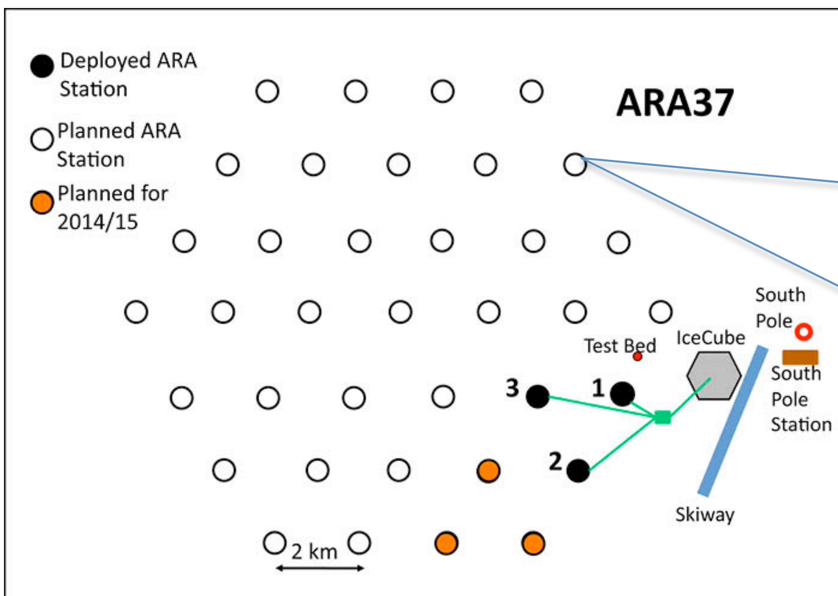
- Antennas deployed in AMANDA boreholes
- First in situ radio Cherenkov array
- Placed competitive limits on UHE neutrino flux



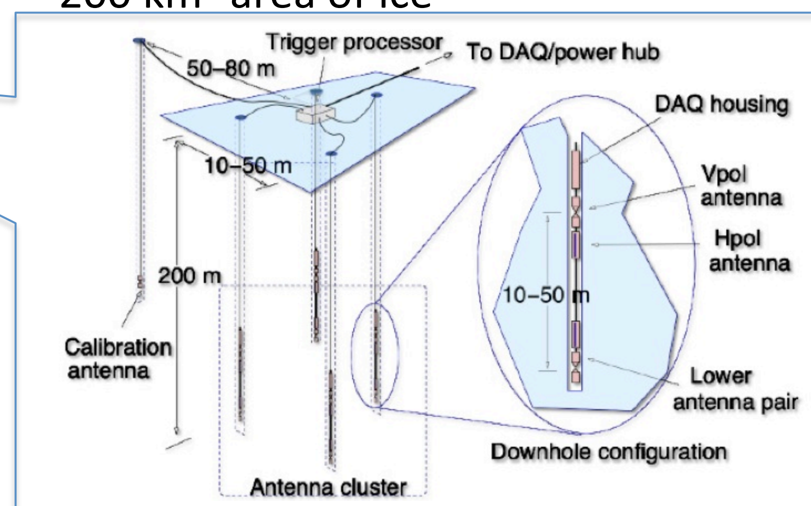
I Kravchenko *et al, 2011*

Askaryan Radio Array (ARA)

- Array of antennas designed to detect UHE neutrinos using radio Cherenkov technique (Askaryan effect) at South Pole
- Deployed a shallow TestBed prototype and 3 deep stations
  - 16 borehole antennas / station at 200MHz to 800MHz
    - 8 vertically polarized (Vpol), 8 horizontally polarized (Hpol)
  - Stations A2, A3 drilled to design depth of 200 m

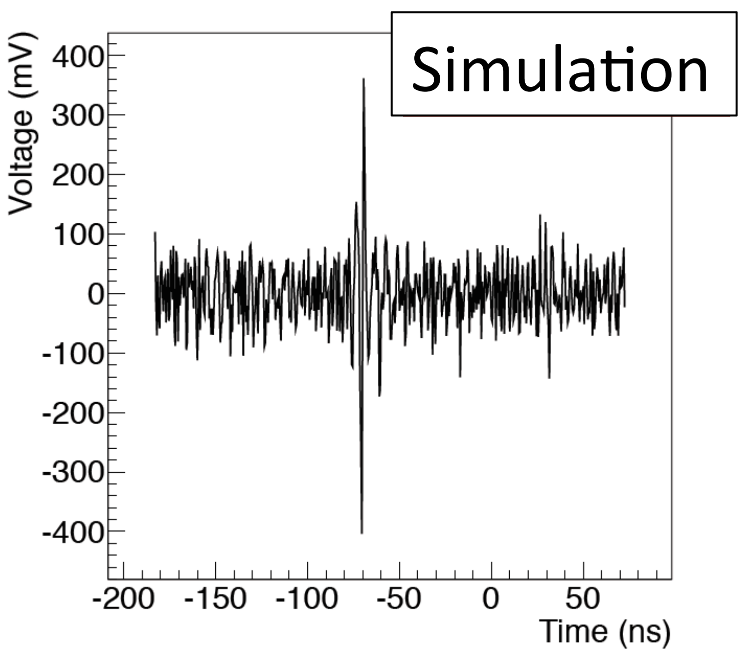


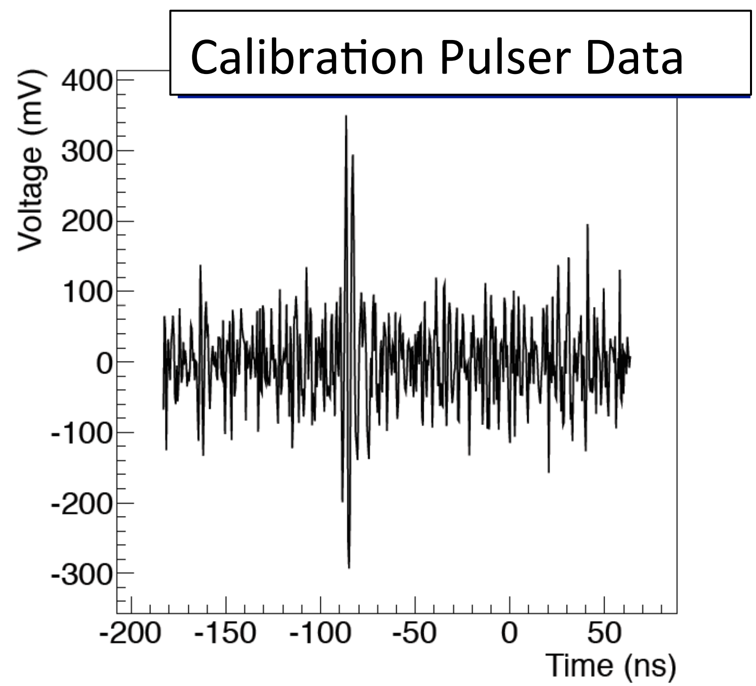
Proposed full 37-station array covering ~200 km^2 area of ice



ARA

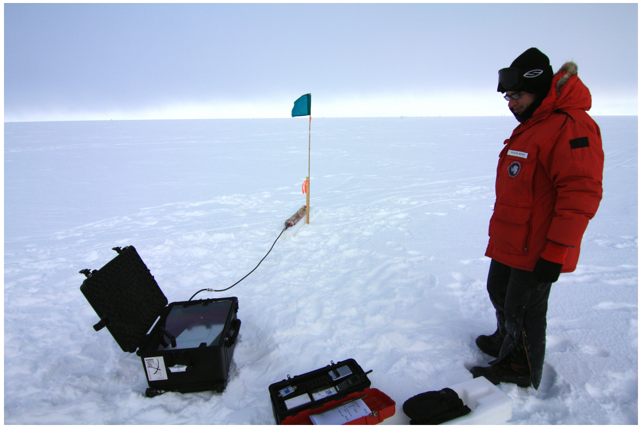
- 2 GHz data sampling and fast triggering
- 3 out of 8 (Hpol or Vpol) antennas pass power threshold within 110 ns
  - Signal expected to be dominated by one or the other polarization
- Currently finalizing first analyses of TestBed data taken from 2011-2012
  - Beginning to extend analysis to A2, A3
- Developing rigorous detector simulation (AraSim)
  - Want to include entire signal chain from shower development to digitized RF waveform

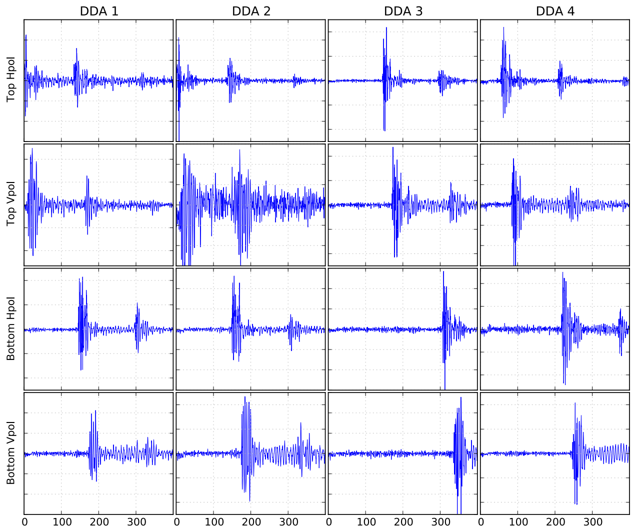




ARA (continued)

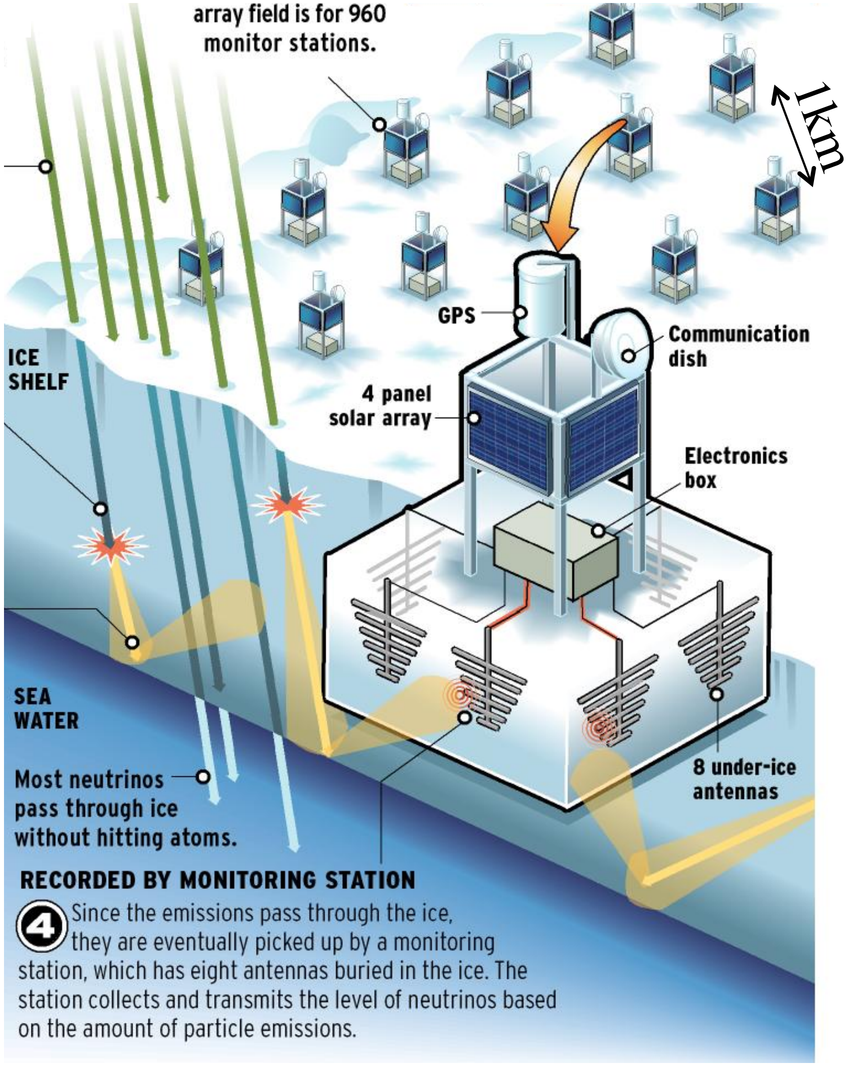
- Calibration
  - ICL pulser
  - In-ice calibration pulsers
  - Surface pulsers (2013-2014 season)
- Backgrounds – radio is very active even at Pole!
  - Continuous wave (single frequency)
    - weather balloons
    - communications frequencies – filter at 450 MHz
  - Impulsive – SPS, other man-made sources on ice, static discharges
- Reject events that point to repeated locations, known source locations





ARIANNA

- Array of antennas on the surface of Ross Ice Shelf in Antarctica
  - Antennas buried just under the ice surface
- Recently completed a hexagonal array of stations
- Radio Cherenkov signals reflected from the bottom of the ice sheet
  - Could potentially see more “down-going” events
  - Relies on detailed knowledge of ice sheet



From OC Register 2012

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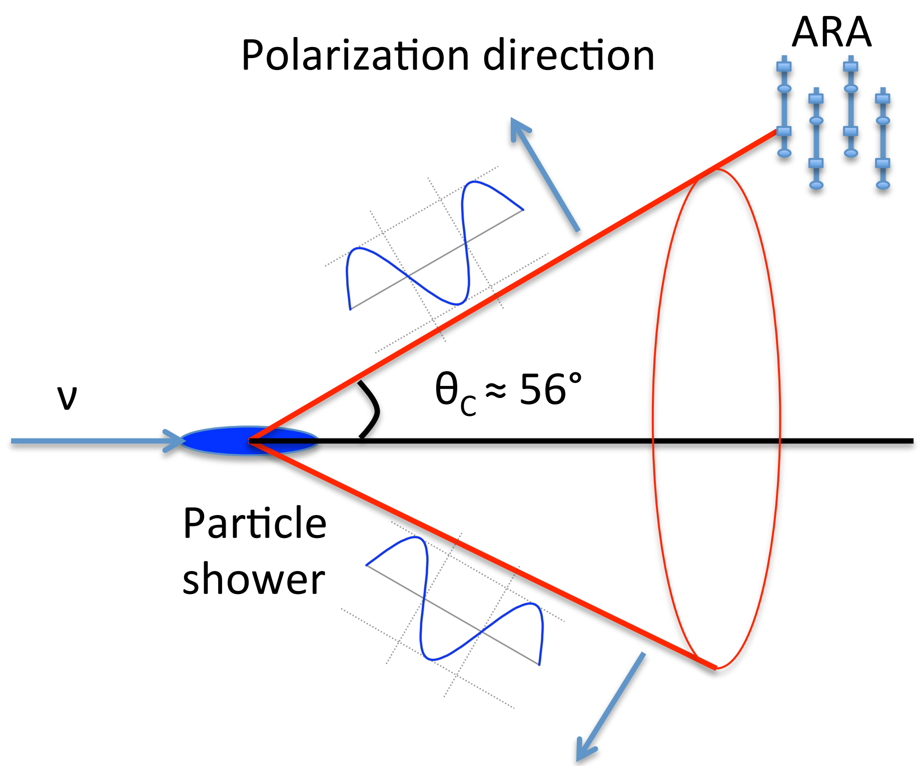
Observables

- What information about the neutrino do we want to extract?
  - Energy, pointing direction, flavor
- How do we get there?
  - received radio signals -> information about neutrino
  - Must interpret the radio signal
    - relative timing, shape, amplitude, polarization
  - Need refined modeling of radio Cherenkov signal
    - Shower emission model, ice model, LPM effect

Pointing Direction

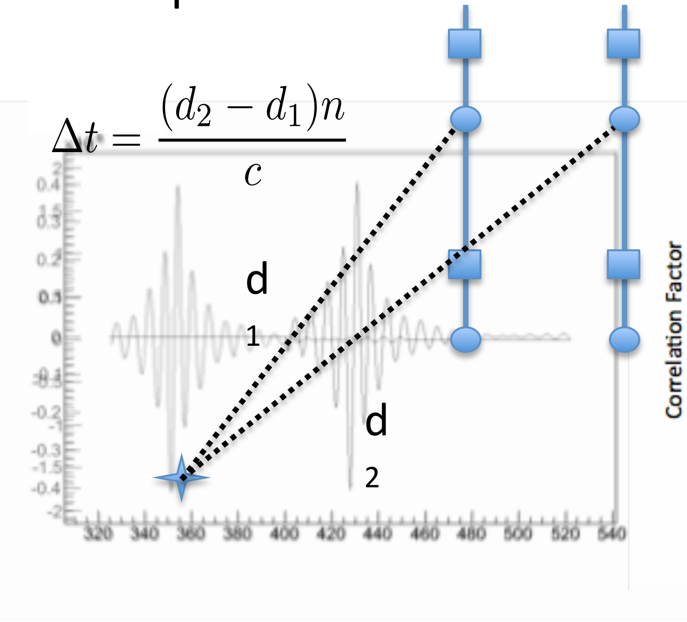
- Want to trace events back to a point in the sky
  - Source? Diffuse?
- Pointing direction of incoming neutrino needs
  - Reconstructed position
  - Polarization
  - Known Cherenkov angle (~56°)
- Cherenkov ring depends on direction of shower/incident neutrino
- Rejection of known sources and clusters of events
  - South Pole Station, weather balloons, etc.

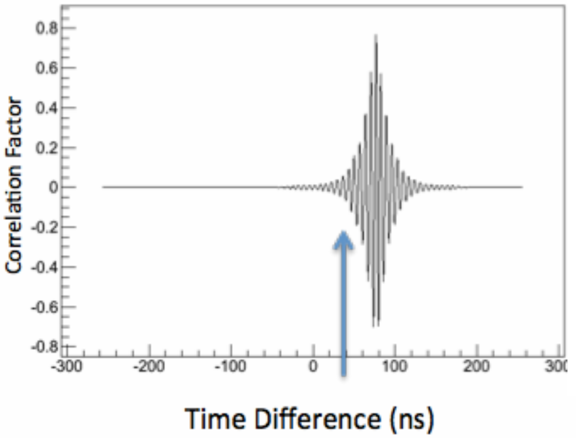


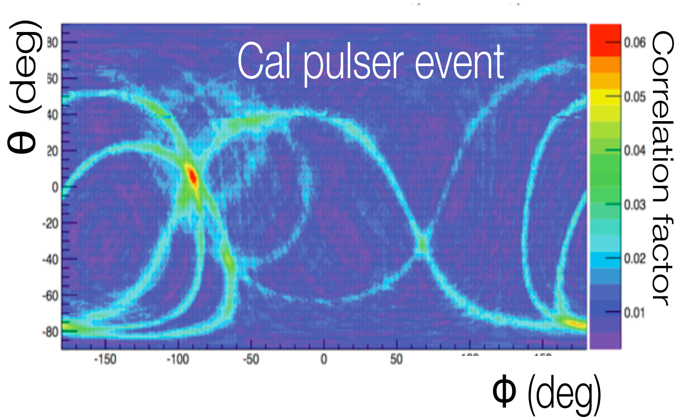
Position Reconstruction

- Impulsive waveform – ~1-10 ns time scale
- Correlation factor - Convolution of the two waveforms including a timing offset
- Only Vpol-to-Vpol comparison and Hpol-to-Hpol comparison
- Calculate timing delays for all angles of approach
- Sample correlation plot at these delays
- Many positions will produce the same timing delays for a pair of antennas
- Solution: Use more antennas - Add up all the correlation values from all the pairs of antennas

$$\Delta t = \frac{(d_2 - d_1)n}{c}$$

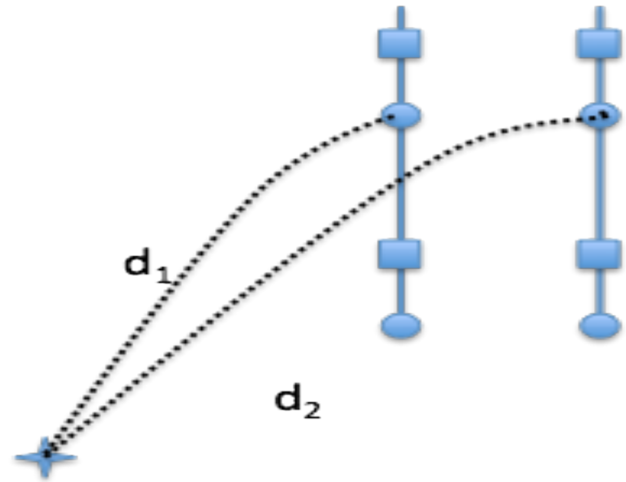


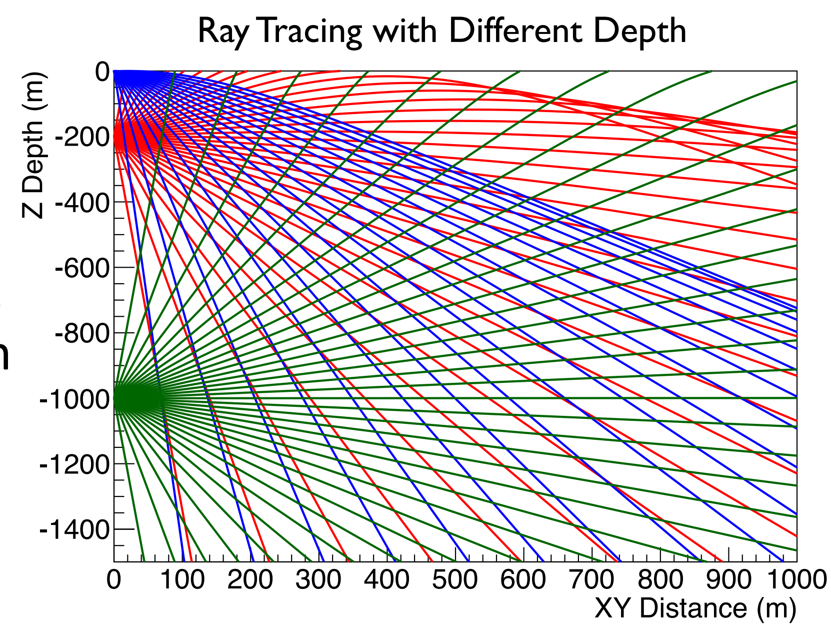




Concerns for Reconstruction

- Anything that affects timing delays will affect the correlation map
- The index of refraction of the ice
  - The values themselves
  - How they change in the ice
    - First 150 m "firn" – rapidly changing n
    - Changing n -> Snell's law
    - Curvature in path
    - Some areas excluded
- Electronics delays - measure them
- Use calibration pulser, surface pulsers, ICL pulser to get additional timing information
- Geometric assumptions - plane-wave vs spherical vs other (ray tracing)
- Also noise over the signal can severely wash out the correlation



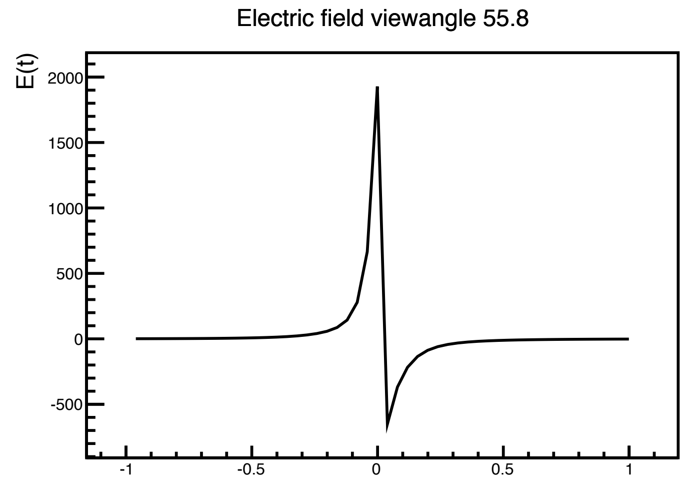


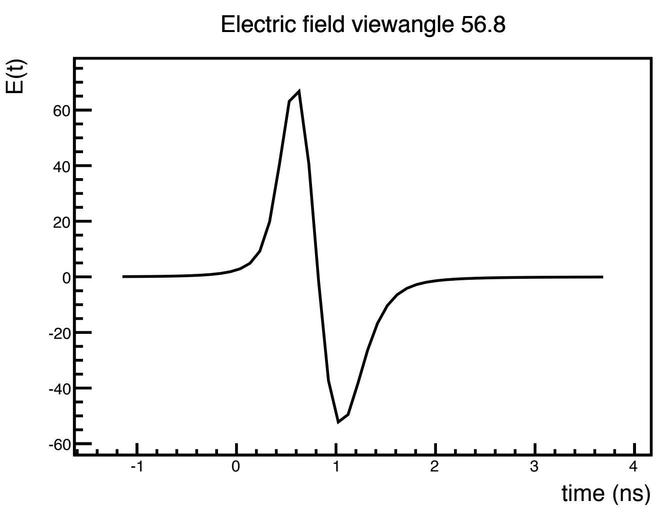
Energy of Primary

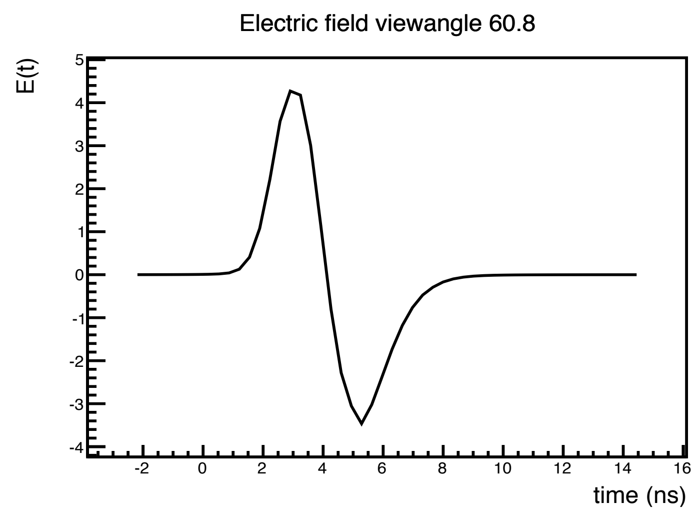
- Primary → shower development → viewing angle → received radio signal
- Energy reconstruction will depend on
  - signal strength, signal shape
  - Reconstruction information
- Shape and amplitude of the signal depend on
  - Energy of primary – proportional to charge in shower
  - Charge excess profile of particle shower
  - Deviation from Cherenkov angle
    - Also dependent on ice model

Cherenkov angle

- Viewing angle relative to the Cherenkov angle changes the shape and magnitude of the signal
  - Faster signal at Cherenkov angle
  - Can also be examined in frequency domain

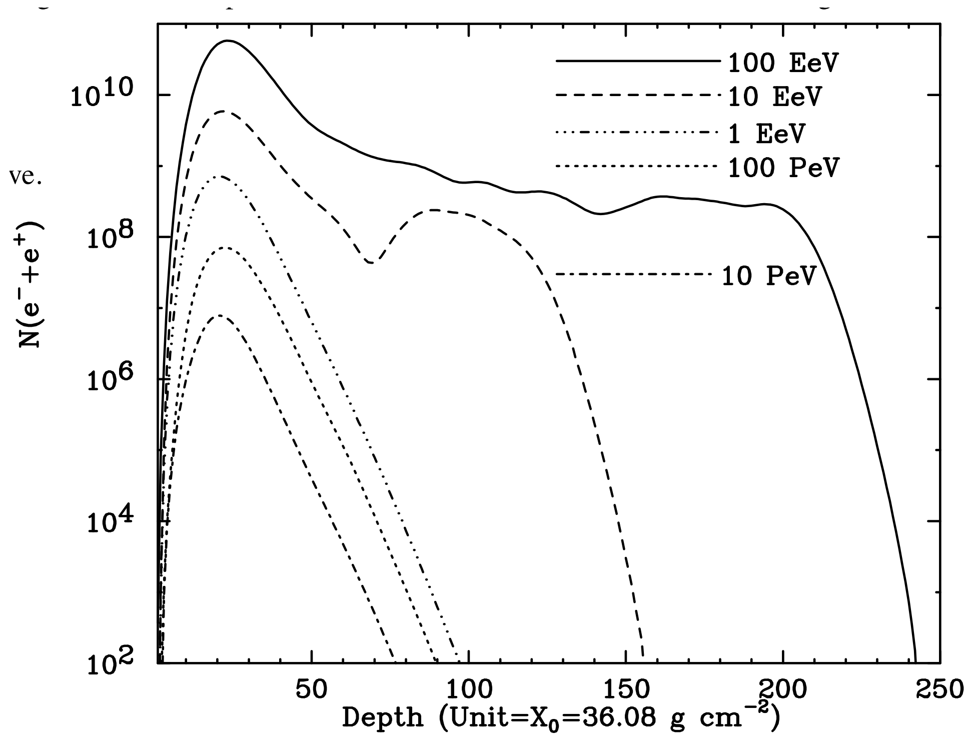






LPM effect

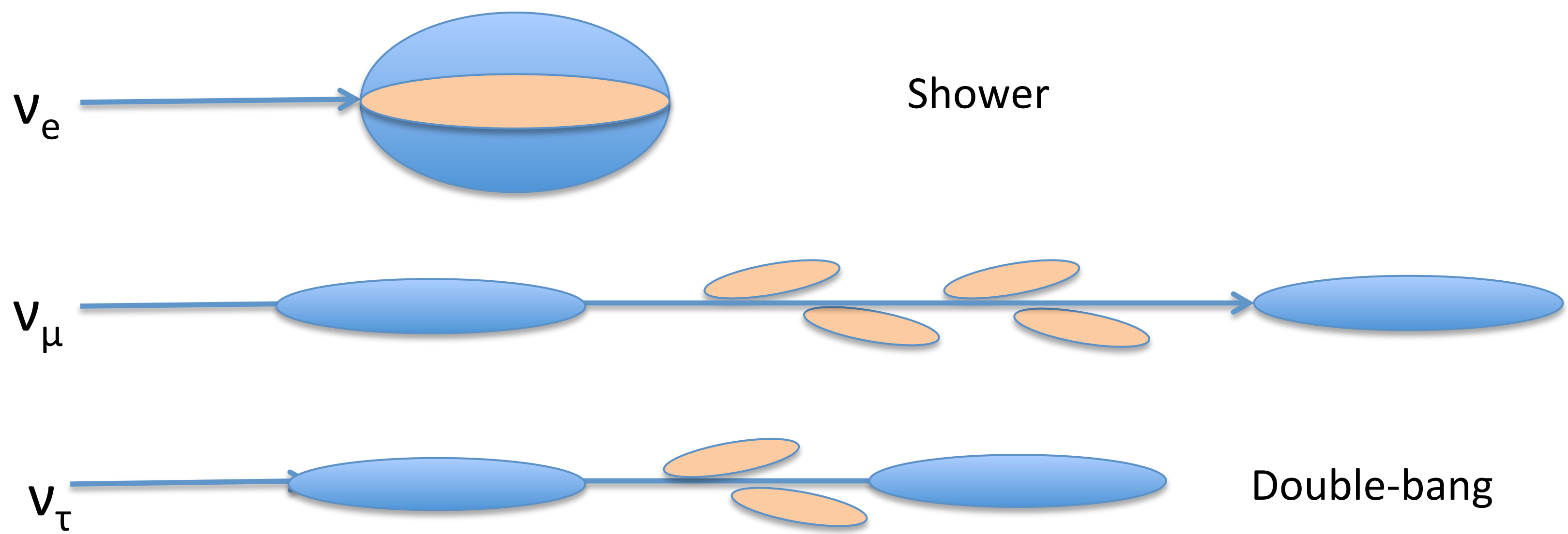
- At sufficiently high energies, interaction length increases dramatically
- Hadronic showers
  - For $E_\nu > 1$ EeV, LPM effect becomes important
- Electromagnetic showers
  - $E_{LPM,E\text{-}M} = 2.4$ PeV
  - EeV neutrinos will show lengthening of shower profiles
- Shower profile → charge excess profile → radio signal
- Developing models for including LPM effect in radio pulse profile



J. Alvarez-Muniz and E. Zas, ICRC 1999, arXiv:astro-ph/9906347

Flavor determination

- ν_e produces prompt hadronic and electromagnetic showers
- ν_μ and ν_τ produce initial hadronic shower, stochastic losses, final hadronic shower, different lengths for produced μ and τ
- Each shower produces a radio Cherenkov signal
  - For ν_μ and ν_τ, multiple radio pulses with observable delays
- Analyses of ANITA data look for repeated triggers with short delays for magnetic monopoles too (Phys.Rev.D83:023513,2011)



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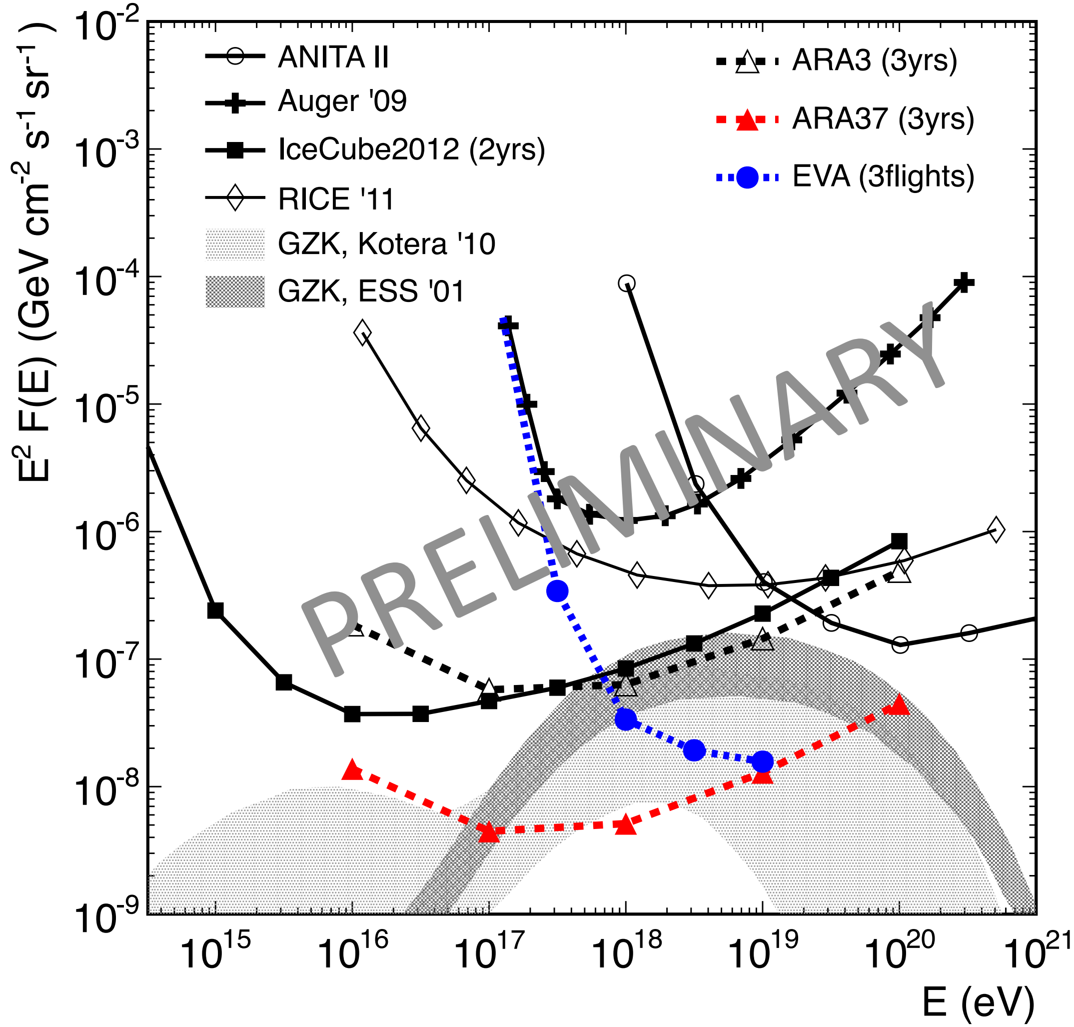
Experimental Sensitivity

- Trigger level sensitivity for ARA and EVA
- EVA's sensitivity extends to 10X lower energies than ANITA-II
- ARA3 - already built, taking data
  - Working on analysis
- ARA37 - planned



Conclusion

- The next generation of radio Cherenkov detectors is being built
  - Both balloon experiments and *in situ* arrays
- Will probe neutrino fluxes in EeV energy regime
- Analysis underway on preliminary ARA data
- Further modeling and simulation is necessary to fully interpret any neutrino signals observed from these detectors

Questions?