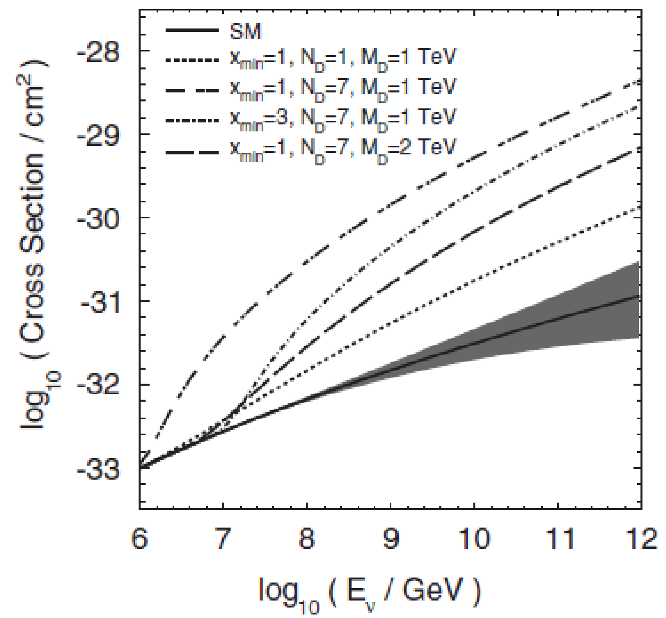
Extra Dimensions and the Neutrino-Nucleon Cross-Section at High Energies

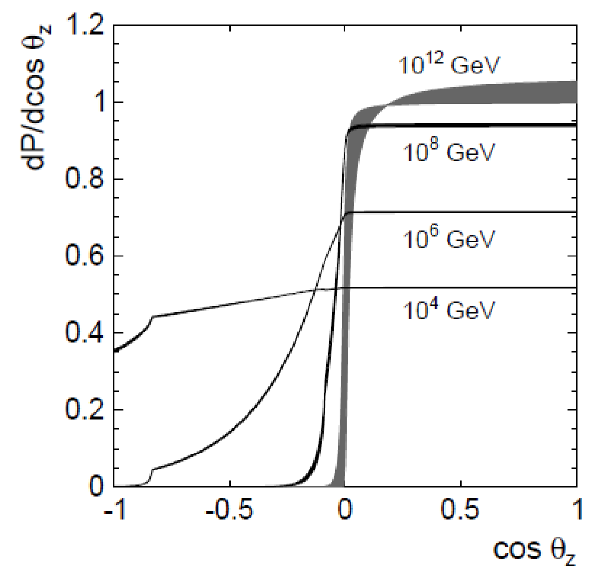
Spencer Klein, ***LBNL & UC Berkeley***

- **Extra dimensions & the Neutrino Cross-section**
- **Atmospheric & 'GZK' and neutrinos as a beam**
- **Measuring the $\sigma_{\nu N}$ via absorption in the Earth**
- **Prospects with ARA, ARIANNA and IceCube**
- **Conclusions**

Extra dimensions & $\sigma_{\nu N}$

- Many theories predict that the universe has more than 3+1 dimensions.
  - The extra dimensions are rolled up (compactified), with a distance scale below current range of observation
- At an energy ~ ħ/length scale, $\sigma_{\nu N}$ rises precipitously
  - Details depend on number of extra dimensions, model, etc.
- To measure, need a ν beam, adjustable absorber, and detector.
  - Atmospheric neutrinos
  - 'GKZ' neutrinos
  - Once they are observed, extra-terrestrial neutrinos may also be usable

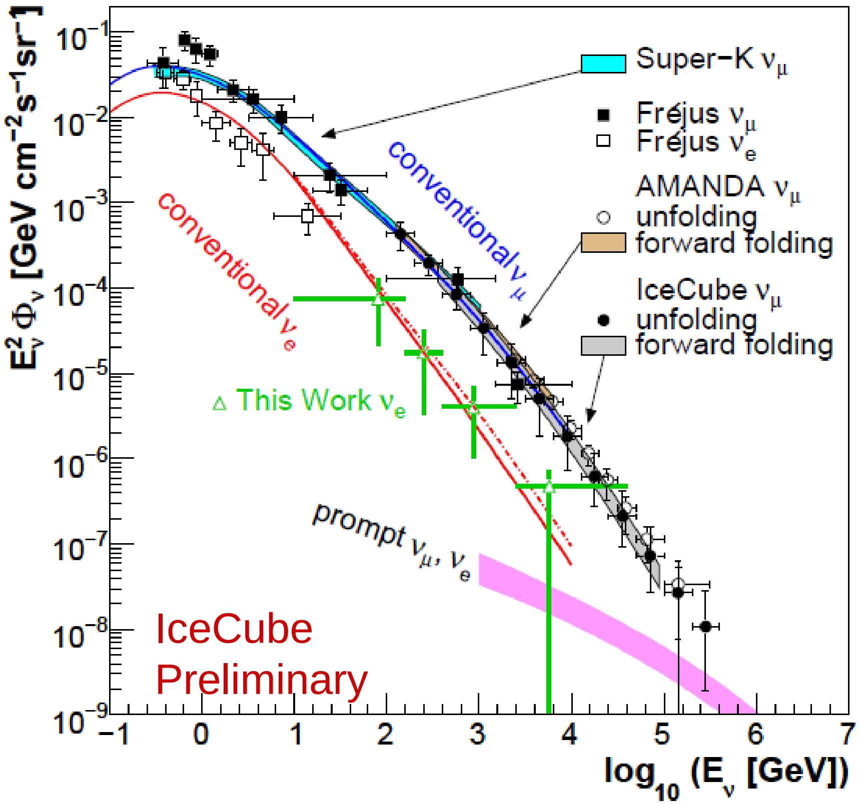




A. Connolly, R. S. Thorne and David Waters, PRD 83, 113009 (2011)

Atmospheric Neutrinos

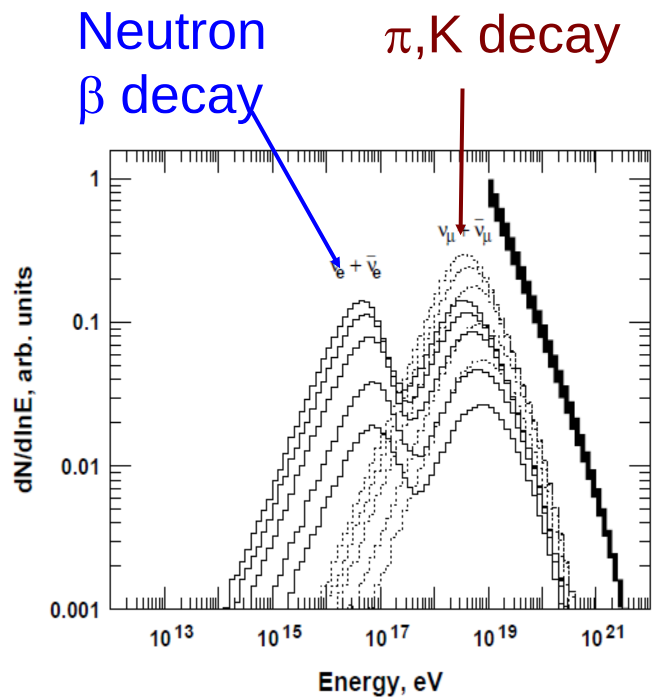
- From cosmic-ray air showers
- From decays of π,K,η, charmed particles
  - π/K produce mostly ν_μ
  - Charm produces ν_μ:ν_e ~ 1:1
- Fluxes are poorly known
  - π/K known to 20%
  - Charm not yet observed; pQCD calculations are factor of 2
    - Diffractive production also possible/expected
- Any $\sigma_{\nu N}$ analysis must determine its own beam flux
- Angular distributions are much better known

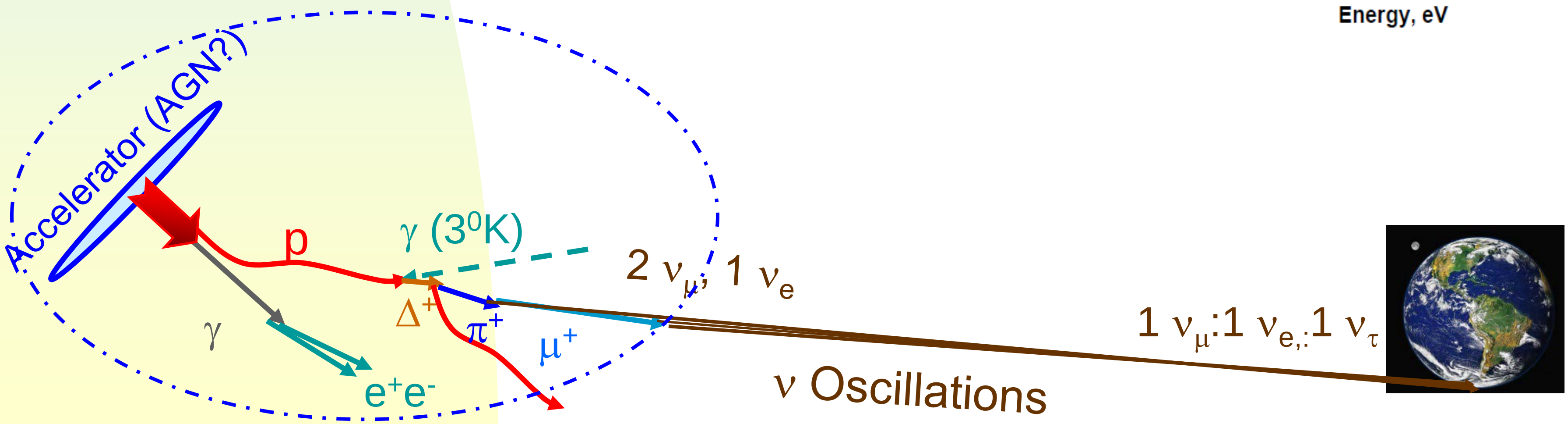


IceCube Collaboration: arXiv:1212.4760

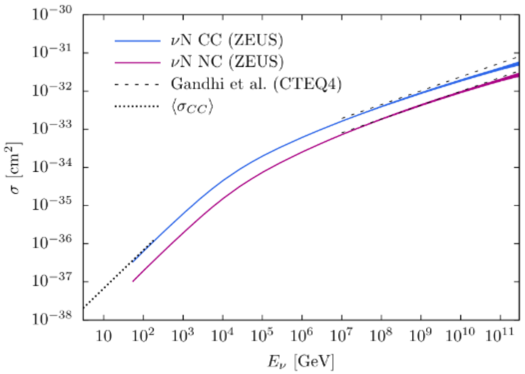
Greisen-Zatsepin-Kuzmin neutrinos

- At energies above $4*10^{19}$eV, protons interact with the 3^0K microwave background radiation
  - $p + \gamma_{3°K} \to \Delta^+ \to n\pi^+,\ \pi^+ \to \nu\mu,\ \mu \to e\nu\nu$
  - 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

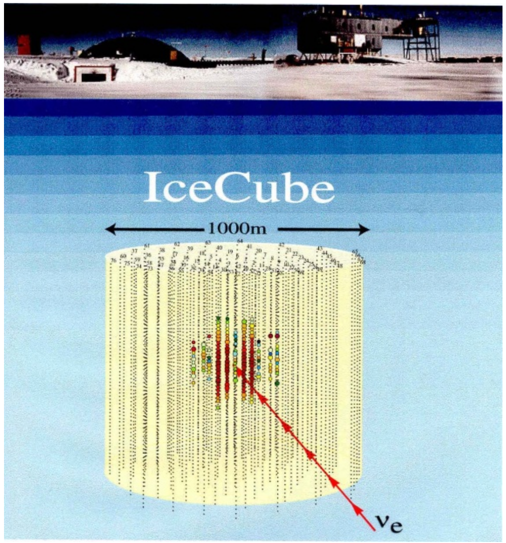




Detecting GZK neutrinos

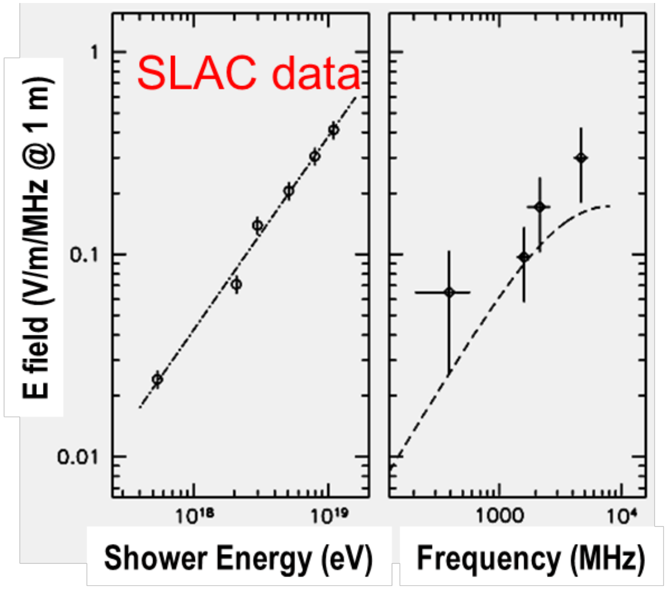


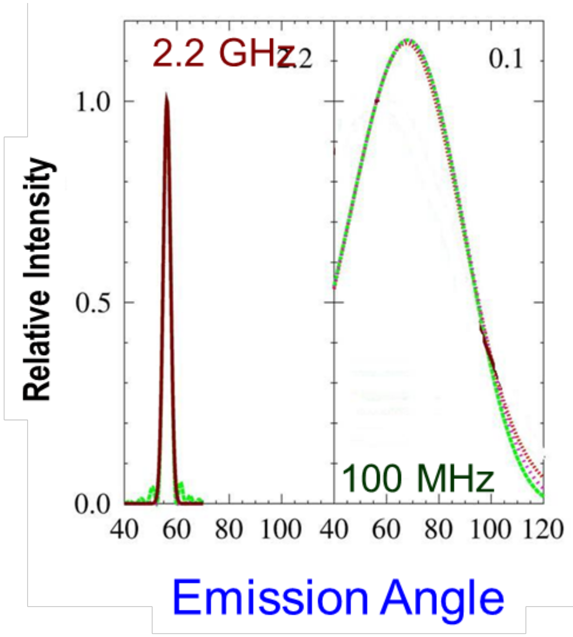
- Cross-sections rise with energy
  - Standard model $\sigma \sim 10^{-33}$ to 10^{-32} cm^2
  - Uncertainty due to low-x (10^{-3} to 10^{-7}) parton distributions
- ν are absorbed by the Earth
  - Observe horizontal or downgoing events
- Most sensitive to ν_e, which deposit all of their energy in showers
  - EM shower from electron (~0.8E_ν)
    - LPM effect lengthens shower
  - Struck nucleon takes 20% of energy, producing a hadronic shower
- >100 km^3 needed to see 100 events in 3-5 years
- Optical Cherenkov detectors are too small (~1 km^3)
  - A new technique is needed.



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

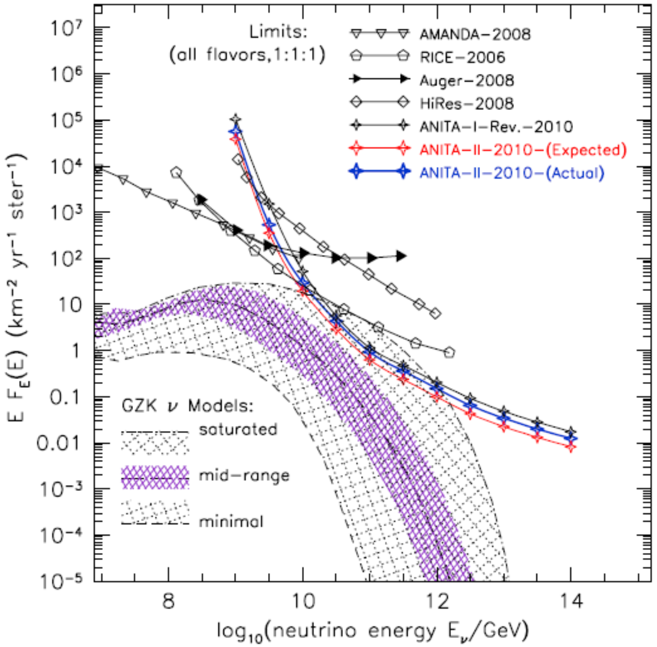




SLAC data:D. Saltzberg *et al.*, PRL **86**, 2802 (2001)
Angles: O. Scholten et al. J.Phys.Conf.Ser. **81**, 012004 (2007)

Radiodetection experiments

- Radio-telescope searches for ν interactions in the moon
  - Thresholds >> 10^{20} eV; no signal seen
- ANITA balloon experiment circled Antarctica twice
  - 1 event over a background of 1
  - Threshold ~ few 10^{19} eV
    - Soft onset
  - 1 more flight planned



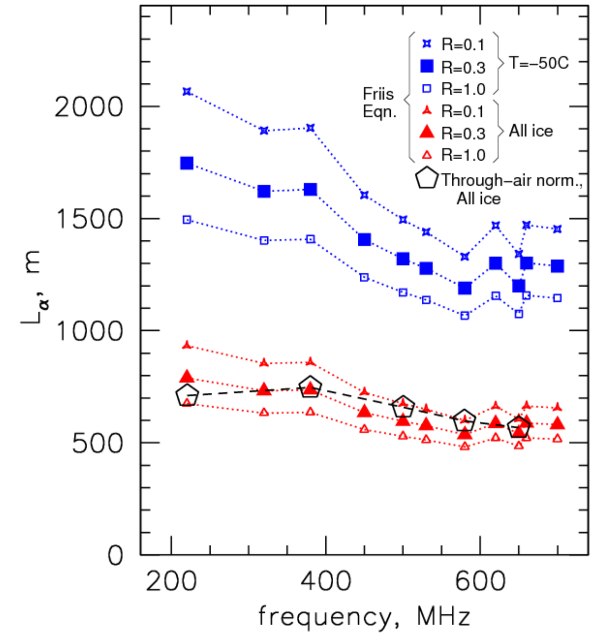
A. Vieregg, yesterday;
ANITA Collaboration: PRD85, 049901 (2012); PRD82, 022004 (2010)

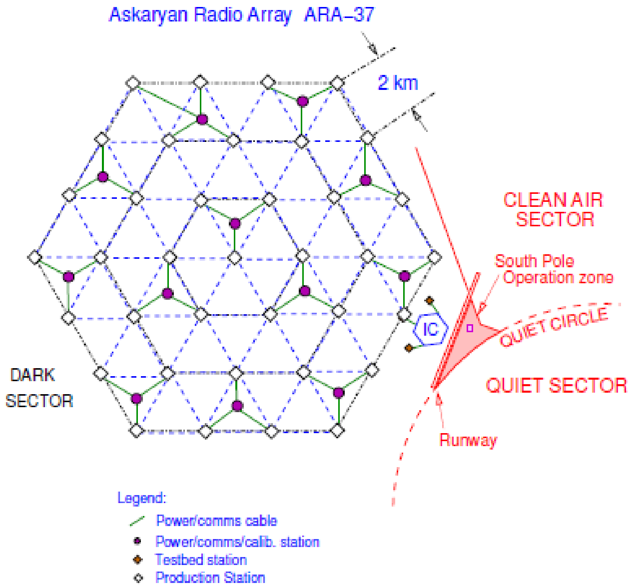
Antarctic In-Ice Detectors

- In-ice detector have thresholds ~ $10^{17\text{-}18}$ eV
  - Sensitive to most of GZK spectrum
- Pioneered by RICE experiment
  - Instrumented some AMANDA holes with radio detectors
- Two funded proposals funded for prototype installations
  - Sensitivity scales with $$$
  - ARA at the South Pole
  - ARIANNA on the Ross Ice Shelf
- Planned Target Volume >"100 km^3"
  - 100 GZK ν in 3-5 years
- Logistics is tough in Antarctica

ARA at the South Pole

- Clusters of radio antennas in 200 m deep holes
  - ◆ On a ~1-1.5 m triangular grid
  - ◆ Radio Attenuation length 500-1500 m
    - Frequency & temperature dependent
- ARA-37 proposal submitted

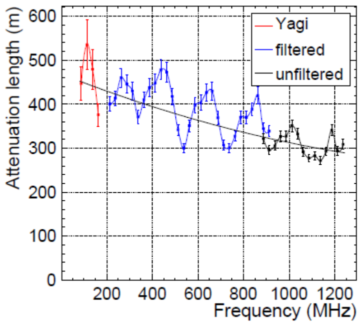


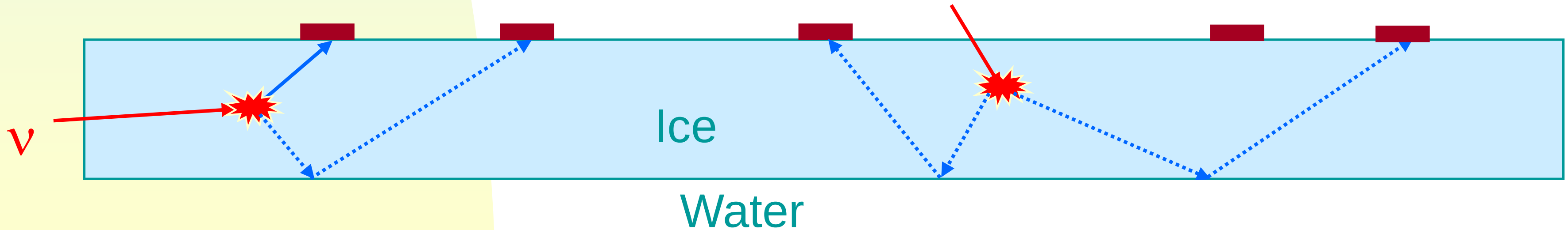


ARA Collaboration: Astropart Phys. **35**, 457 (2012)

ARIANNA in Moore's Bay

- 570 m of ice floating atop seawater
  - The smooth ice-water interface reflects radio waves like a mirror
- Reflection increases collection area
  - Larger solid angle
    - Sensitive to downward-going neutrinos
- Surface stations avoid drilling costs
  - Refraction in the firn limits near-surface sensitivity
  - Warmer ice, so attenuation length is 300-500 m
- Detector array of ~900 Stations, each with 8 antennas

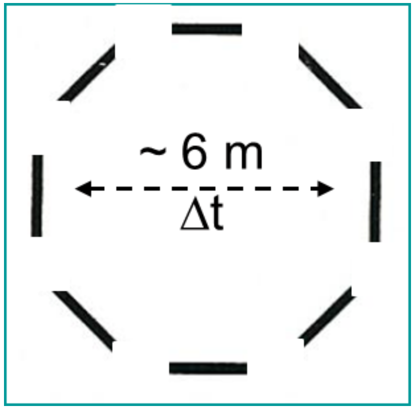




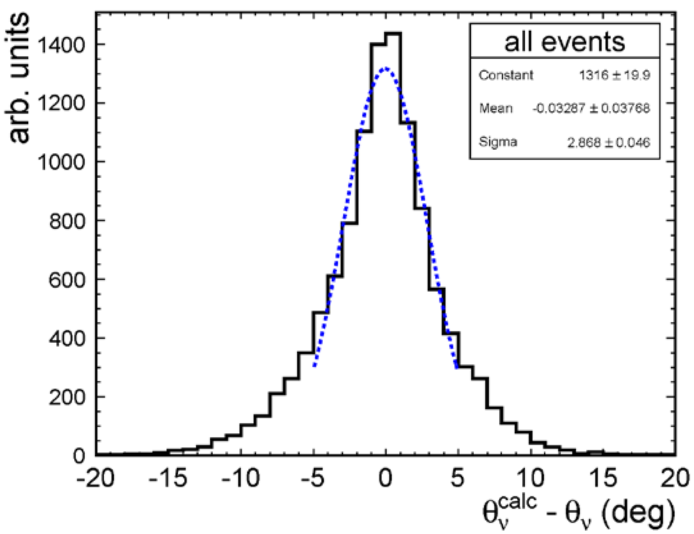
S. Barwick, tomorrow; SK ft. ARIANNA Collaboration: arXiv:1207.3846

Angular Resolution

- Both ARA and ARIANNA should have angular resolutions of a few degrees
- A single ARIANNA station can determine the neutrino direction, modulo a 4-fold ambiguity
- Time delays between different antenna give direction vector D to interaction
- Measured frequency spectrum gives angle between D and the shower Cherenkov cone
- Radio waves are polarized pointing toward shower
  - Perpendicular antennas measure polarization, giving angle between D and neutrino direction



Antenna arrangement (looking down)

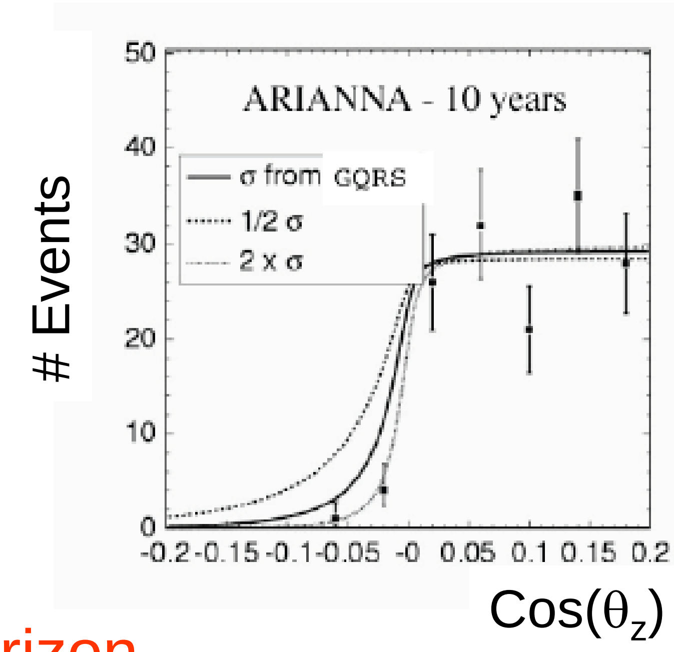


Zenith Angle Resolution

K. Dookayka ft. ARIANNA Collaboration, presented at the 32nd ICRC

Measuring $\sigma_{\nu N}$

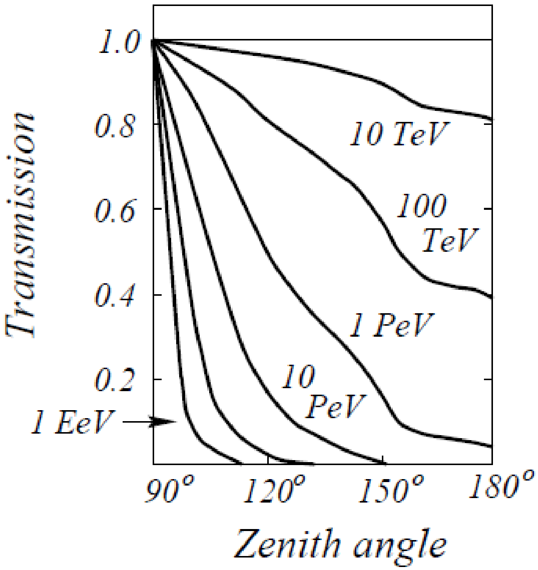
- Measure the neutrino flux as a function of energy and zenith angle
  - Absorption increases with zenith angle
- Self-normalizing
- At >10^{17}eV, the Earth is opaque to neutrinos, so all of the action is at the horizon
- Proposed detectors can measure $\sigma_{\nu N}$ at ~ 10^{18} eV to a factor of ~ 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



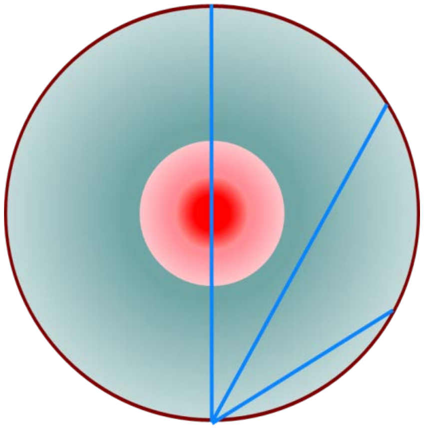
Plot by Amy Connolly

Current Studies

- IceCube can measure $\sigma_{\nu N}$ in the TeV energy range
  - Atmospheric neutrino flux drops rapidly with energy
  - Absorption rises rapidly with energy
- Sweet spot is 30-70 TeV
  - 100 times the energy of accelerator measurements
- Use ν_μ which have a much larger flux
  - ~1^0 angular resolution
  - ~ factor of 2 ν energy resolution
- Analysis is in progress



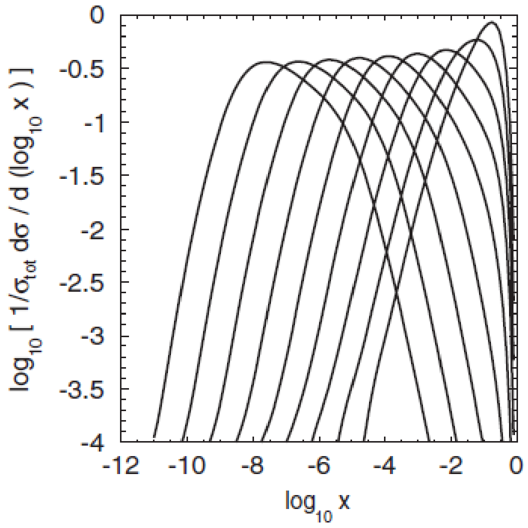
IceCube Collaboration, Preliminary Design Document



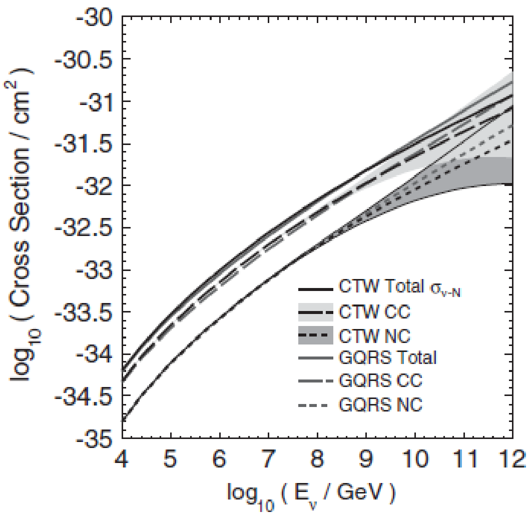
S. Miarecki, presented at 2011 Intl. Neutrino Summer School

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 target
For $E_\nu = 10^4 \ldots 10^{12}$ GeV



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

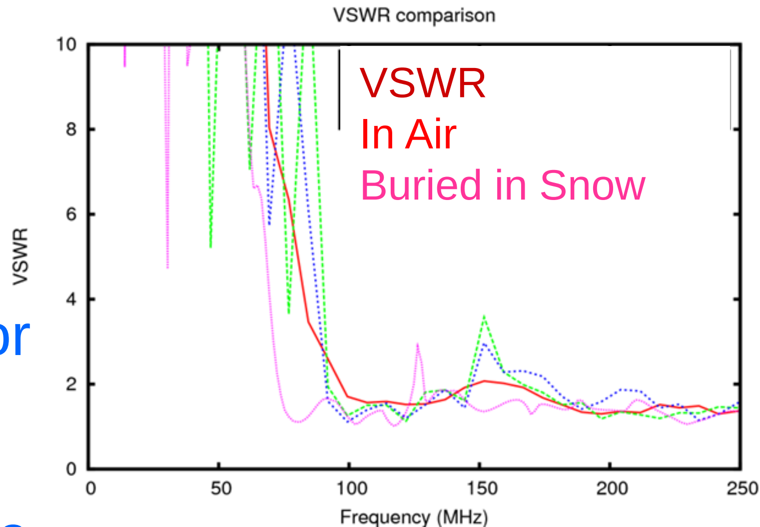
Conclusions

- If there are extra ‘rolled-up’ dimensions, than $\sigma_{\nu N}$ rises precipitously at a center-of-mass energy ~ hbar over that scale.
- By observing neutrino absorption in the Earth, we can determine $\sigma_{\nu N}$ in a flux independent manner.
- Unless ultra-high energy cosmic-rays are heavy ions, GZK neutrinos provide a useful beam for this measurement.
- Future experiments like ARA and/or ARIANNA will be able to measure $\sigma_{\nu N}$ to a factor of ~2.
  - Good enough to rule out extra dimensions
- A proof-of-principle measurement is underway in IceCube. It will be sensitive at energies around 50 TeV.

Backup Slides

Signal Detection Hardware

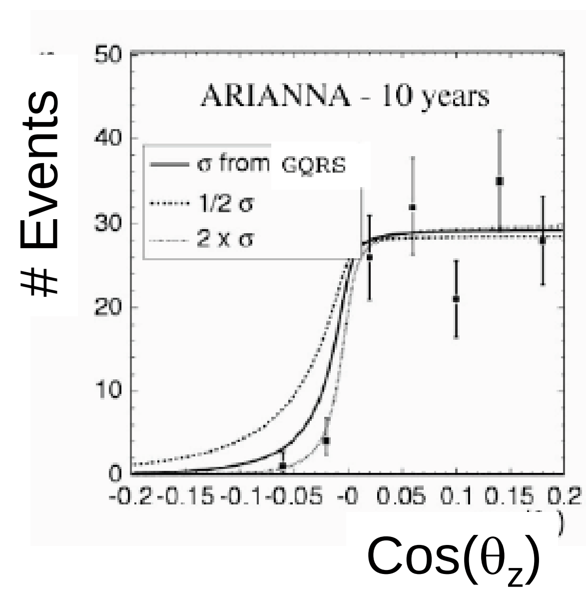
- Log Periodic Dipole Antenna
  - Good directionality & polarization sensitivity
  - 105-1300 MHz in air
    - In ice, index of refraction n> 1
    - Wavelength $\Lambda = c/nf$ is shorter
  - Antenna impedance is altered, shifted to slightly lower frequencies
- Low noise pre-amp & switch capacitor array 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

The ARIANNA proposal

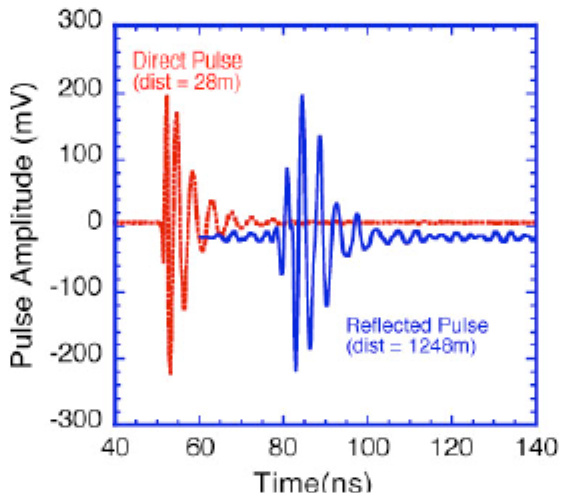
- Each station is autonomous
  - Local trigger & intelligence
  - Spacing is a tradeoff between maximum volume/cost vs. seeing events with multiple stations
- Stations with 8 antennas
  - Antennas are in shallow trenches
  - Autonomous data acquisition
- Site is 110 km from McMurdo station, shielded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



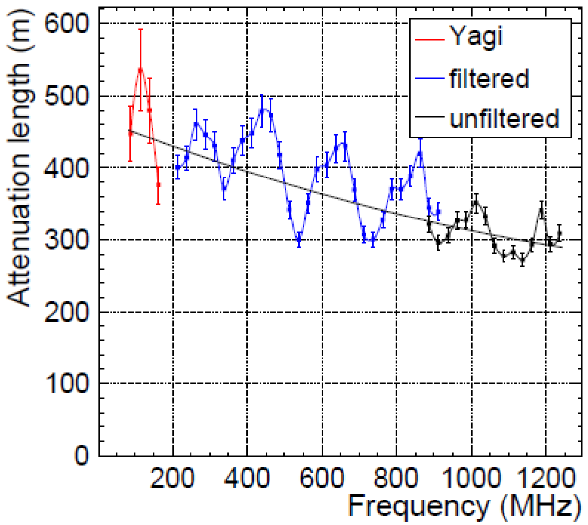
Plot by Amy Connolly

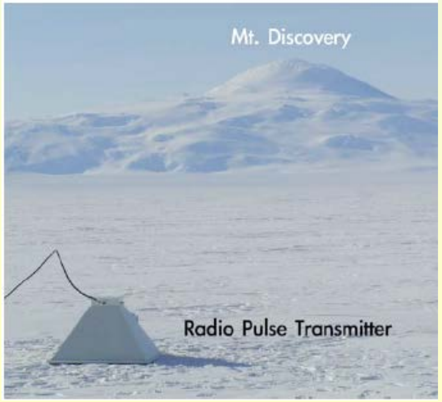
Field studies - ice properties

- Measure reflected signals from ice-water interface
  - Horn antennas
  - Ice thickness 572 ± 6 m
- Signal loss at interface and in-transit
- Absorption length 300-500 m
  - With conservative assumption – full reflection at interface
    - Ice-water interface attenuation < 3 db
  - Systematic uncertainty 15-55 m
- 183 MHz oscillations not well understoo



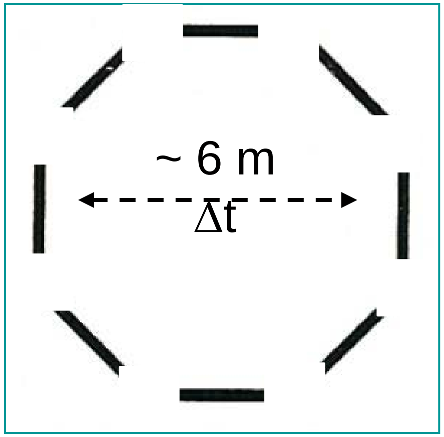
Signal reflection from interface



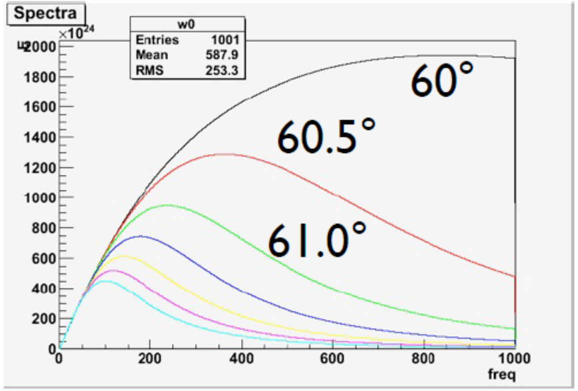


T. Barrella, S. Barwick, D. Saltzberg, 2010

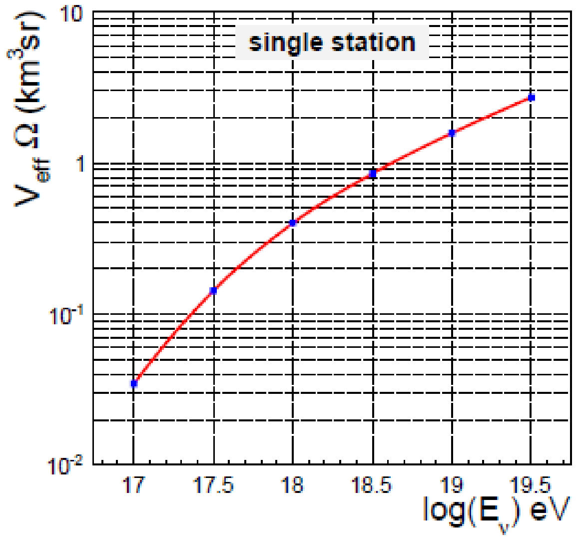
Directional determination



- 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)



Sensitivity – simulation studies

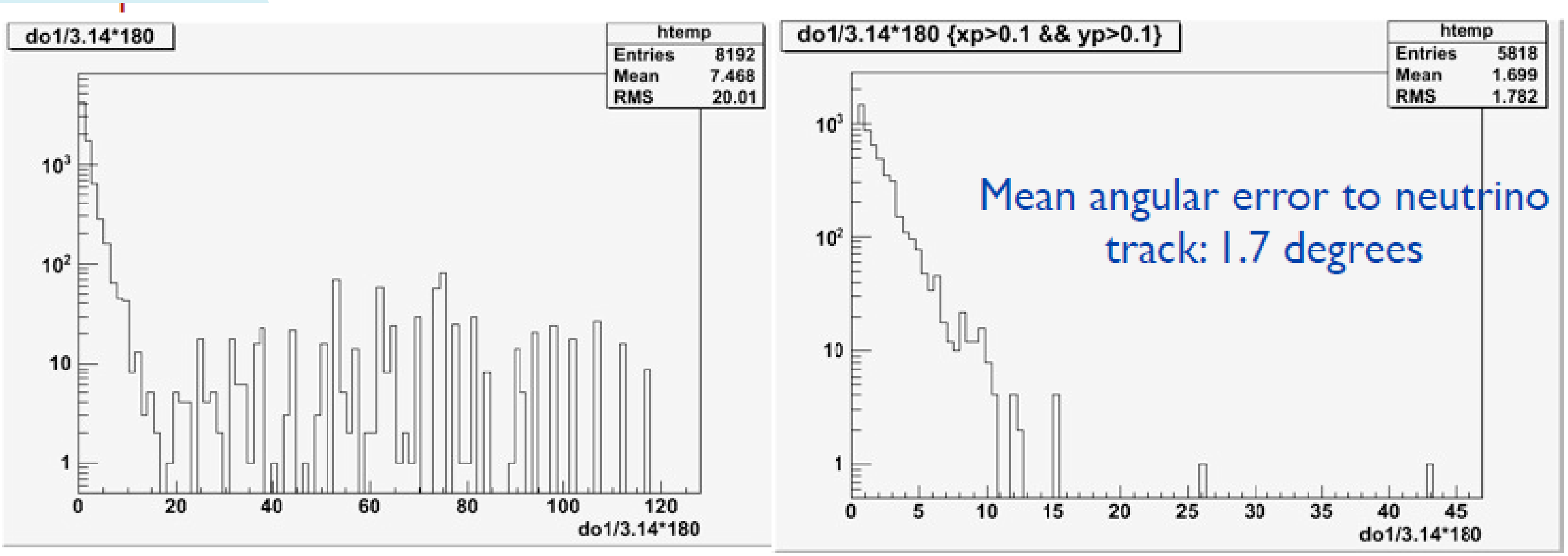


- ν_e, ν_τ NC + CC interactions
  - GZK (ESS) energy spectrum
  - 4 km by 4 km ‘throw’ area
    - Interaction in Antarctic ice
- Parameterized radio pulses
  - LPM effect narrows Cherenkov cone
- Radio absorption in ice depends on temperature
- 3 dB attenuation at ice-water interface
  - Polarization is preserved
- Firn layer density variation
- Antenna, electronics and trigger simulation

K. Dookayka, 2011 ICRC

Angular resolution

- Simple Monte Carlo
  - Parameterized RF signal, idealized propagation & electronics
  - No firn layer
  - No noise…

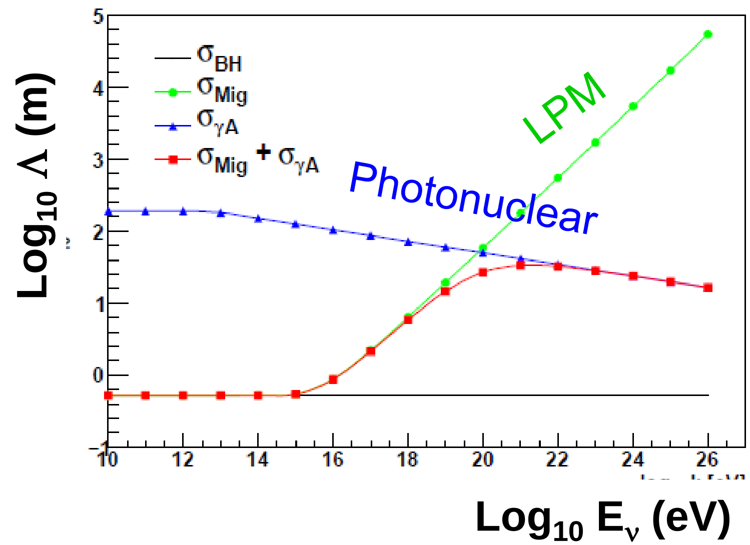


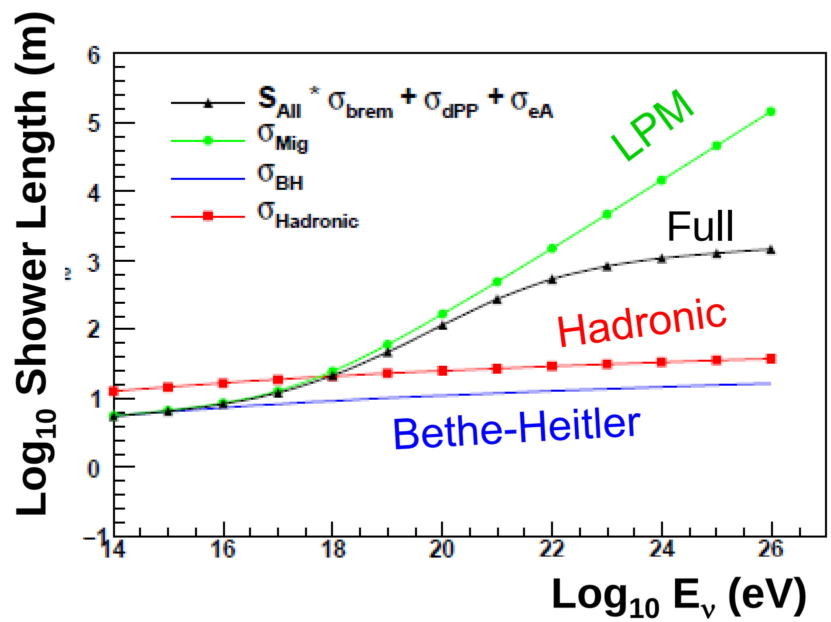
$\nu\ (\theta_l,\phi_l)$

Work by Stijn Buitink, LBNL. Similar work at UC Irvine

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

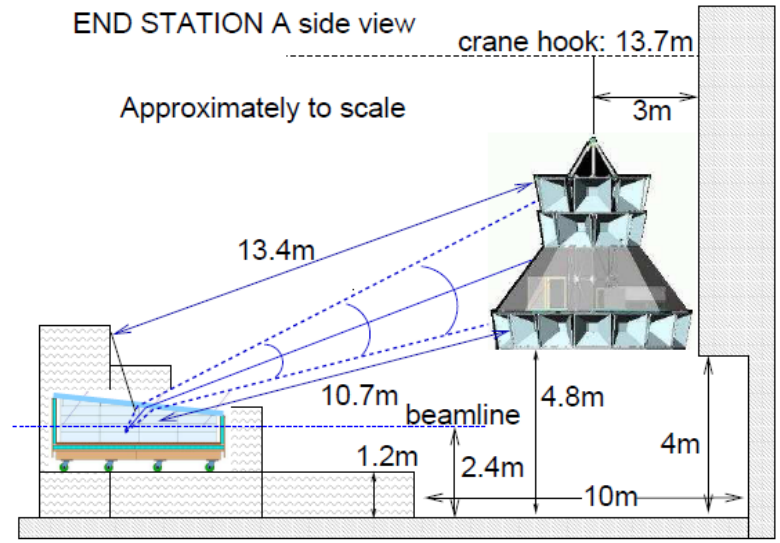


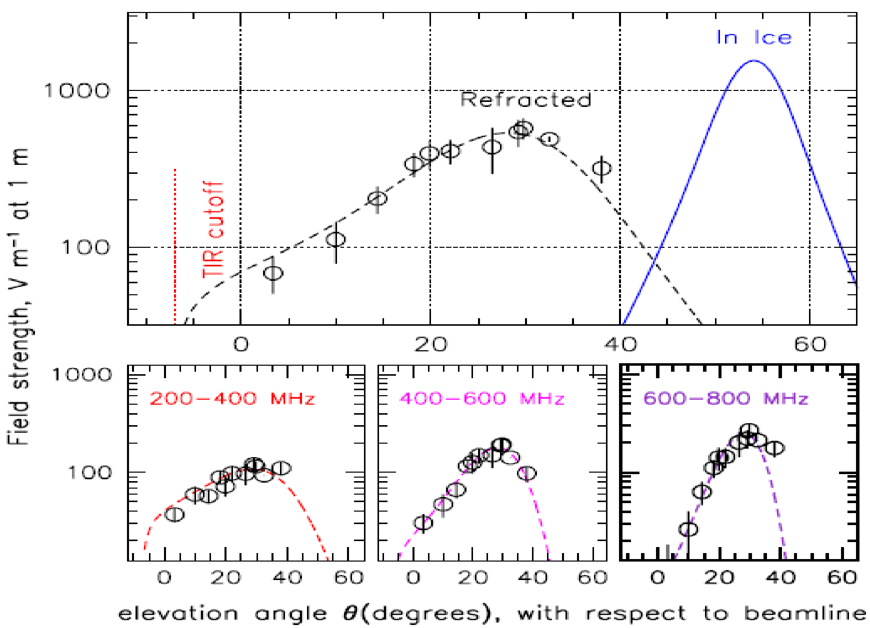


L. Gerhardt & SK, 2010

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

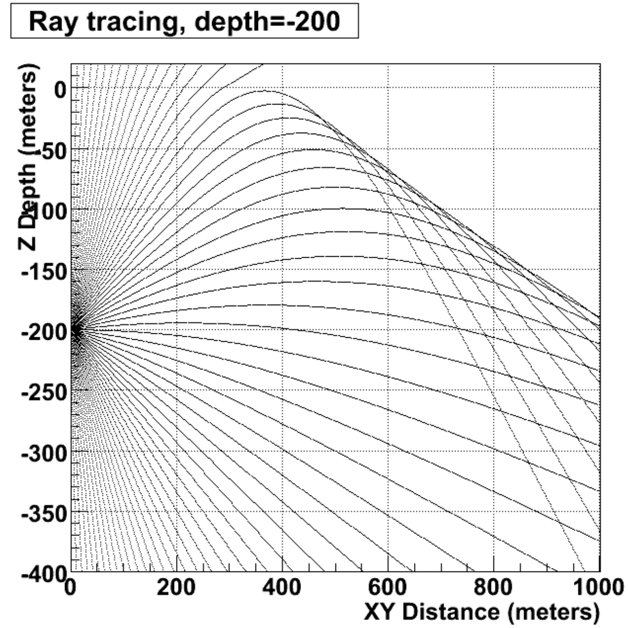




ANITA Collab., 2007

Surface Ice – “The Firn”

- The ice makes a slow transition from pure ice at 100 m depth, to snow at the surface
  - The “firn”
- Varying density
  - Varying index of refraction
  - Radio waves bend
    - So…ARA buries their antennas
- The Ross Ice Shelf has a smaller firn than the rest of Antarctica



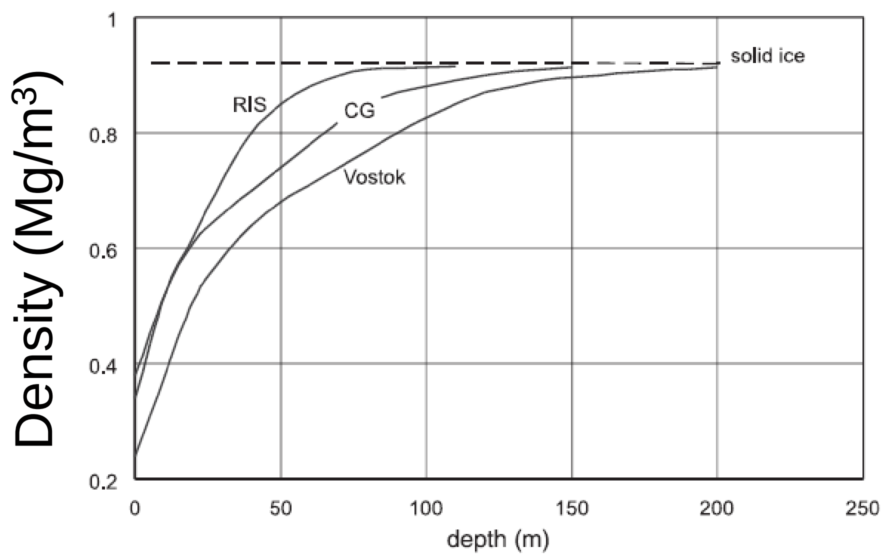


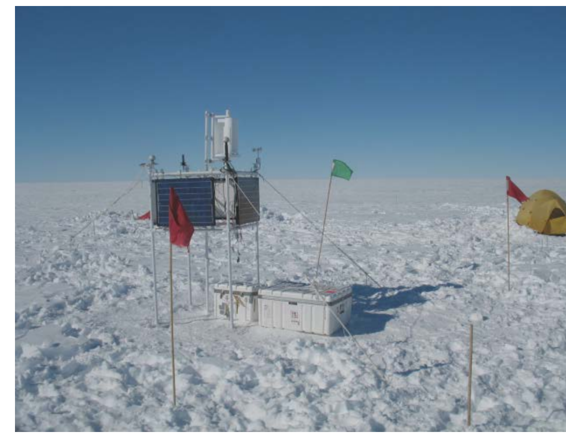
Figure 2. Firn density ions: the Ross Ice Shelf (RIS) and Vostok Station in Antarctica an

Depth (m)

Getting Started

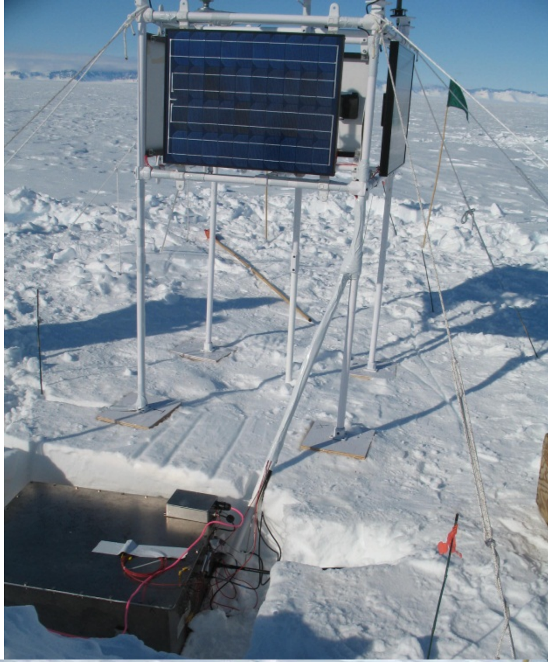
Logistics

- Currently helicopter access only
  - Twin Otter/C-130/road access possible
- No line-of-site to McMurdo station (or any other human habitation), so an intenet repeater on Mt. Discovery is needed
  - Will allow year-round high-bandwidth contact



Field Studies

- Site characteristics studied in 2007 -2012
  - Snow buildup ~ 80 cm/year
    - Argument for central power station
- 1st prototype deployed in Dec. 2009
  - 4 Log-periodic dipole antennas
    - ~ 50 MHz to 1 GHz
    - 2 GS/s waveform digitizer readouts
  - Triggered on >=2/4 antennas
    - After temporary internet connection was removed, triggers were thermal noise
  - Solar and wind power generators
    - It worked well until the sun set
  - Iridium Modem
- 2nd prototype deployed Nov., 2011



L. Gerhardt *et al.*, Nucl. Instrum. Meth. **A624**, 85 (2010)

Diagram showing Cherenkov emission