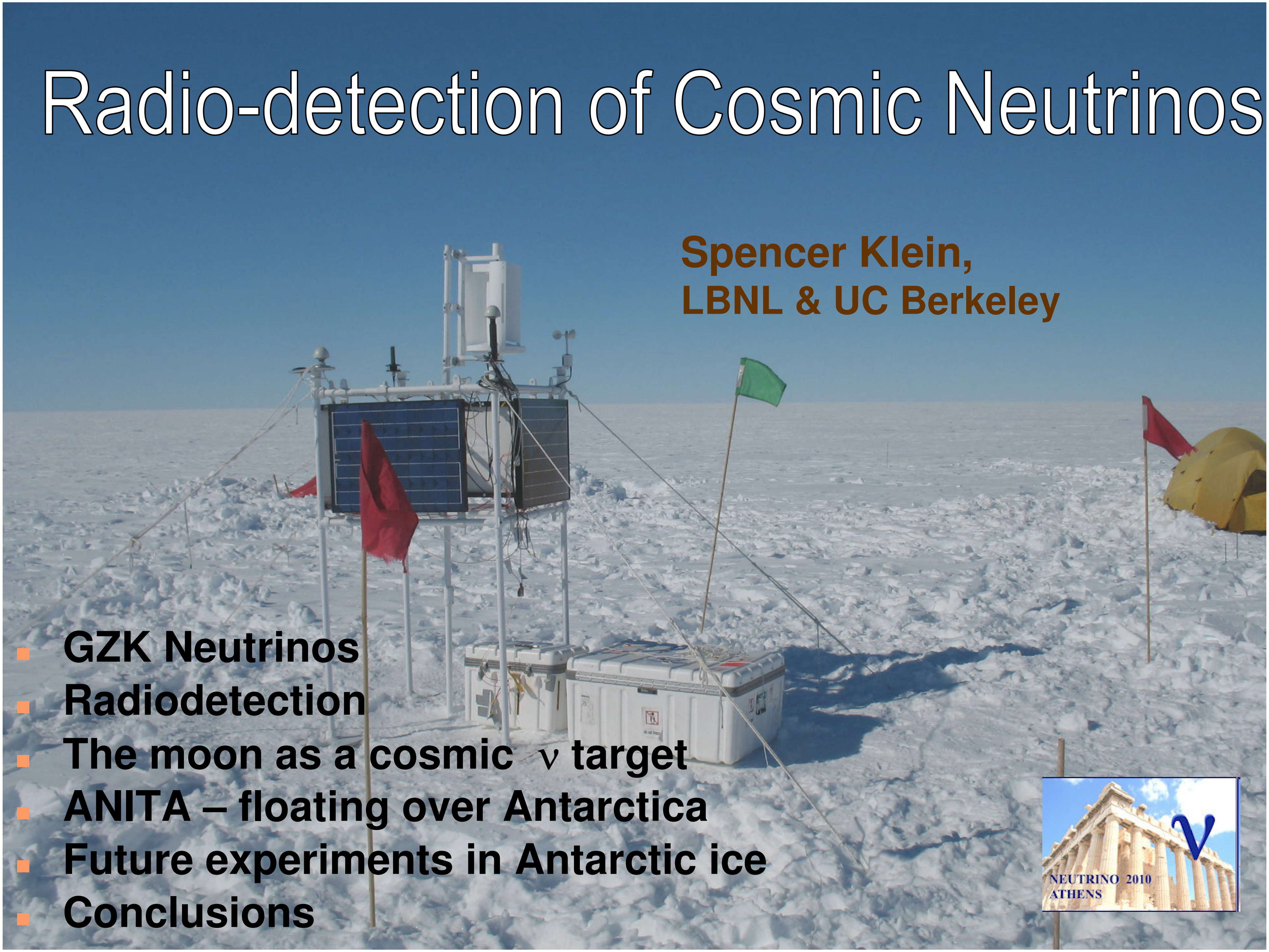
Radio-detection of Cosmic Neutrinos

Spencer Klein,
LBNL & UC Berkeley

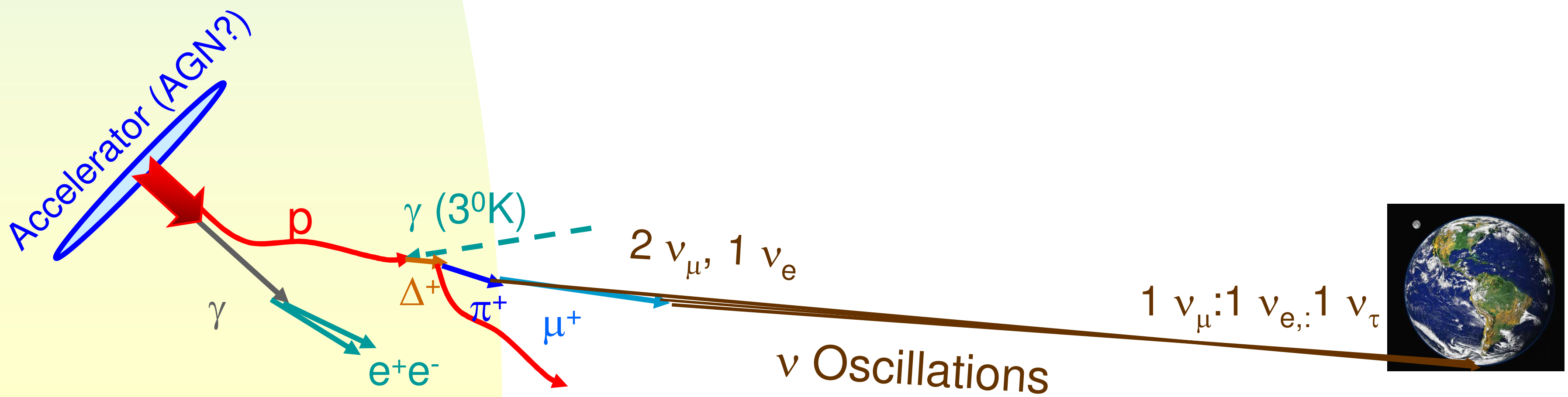


- **GZK Neutrinos**
- **Radiodetection**
- **The moon as a cosmic ν target**
- **ANITA – floating over Antarctica**
- **Future experiments in Antarctic ice**
- **Conclusions**

NEUTRINO 2010
ATHENS

Probing the EHE Cosmos

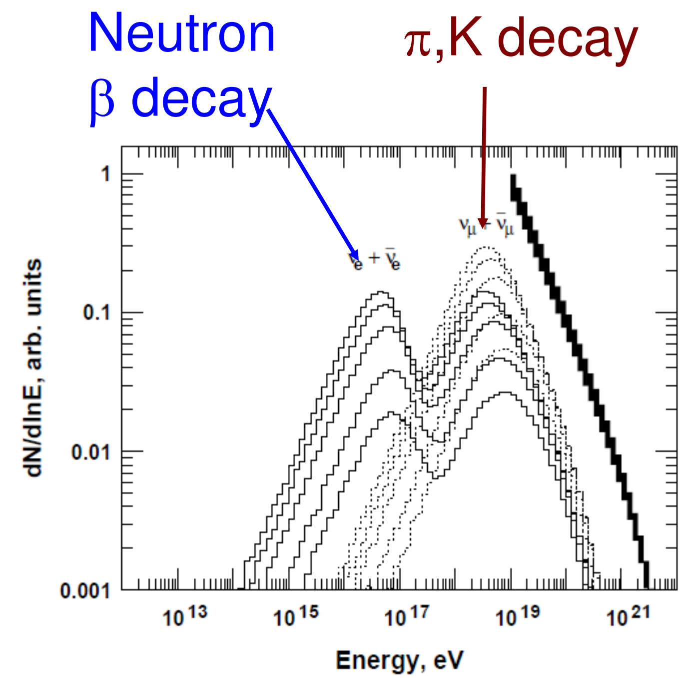
- At energies above 4×10^{19} eV energies, only ν have a cosmic (> 100 Mpc) range.
  - Other particles interact with the 3K cosmic microwave background radiation
    - γ pair produce & heavier nuclei photodissociate
- Protons are excited to Δ^+
  - Greisen-Zatsepin-Kuzmin (GZK) interactions
- ν from in-flight p → Δ^+ excitation are ‘GZK neutrinos’
  - “Guaranteed’ ν signal’
- Protons & nuclei bend in interstellar magnetic fields



GZK Neutrinos

- Flux depends on cosmic-ray spectrum & composition
- ν energy spectrum probes cosmic evolution out to redshift ~ 3-5
  - As redshift increases, the cosmic microwave photons are more energetic
    - Protons interact at lower energies.
- ν spectrum peaks just below 10^{19} eV (ν_e,ν_μ) with a 2nd peak at 10^{16} eV (ν_e)
  - All experiments focus on higher energy peak
- ν from π,K decay have ν_e:ν_μ:ν_τ = 1:2:0
  - Oscillations alter this to a nearly 1:1:1 ratio

Engel, Stanev, Seckel, PRD 64, 093010 (2001)



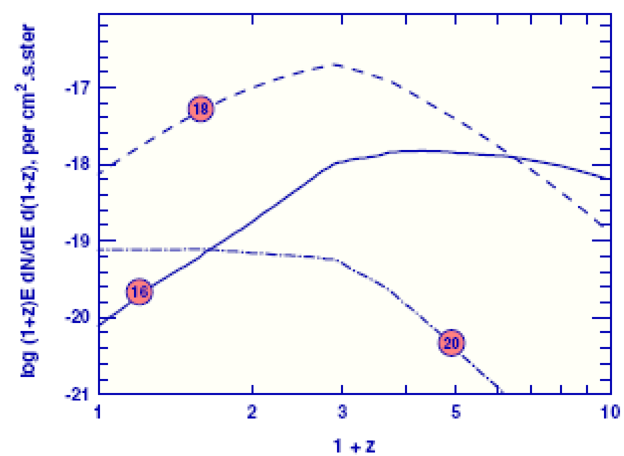
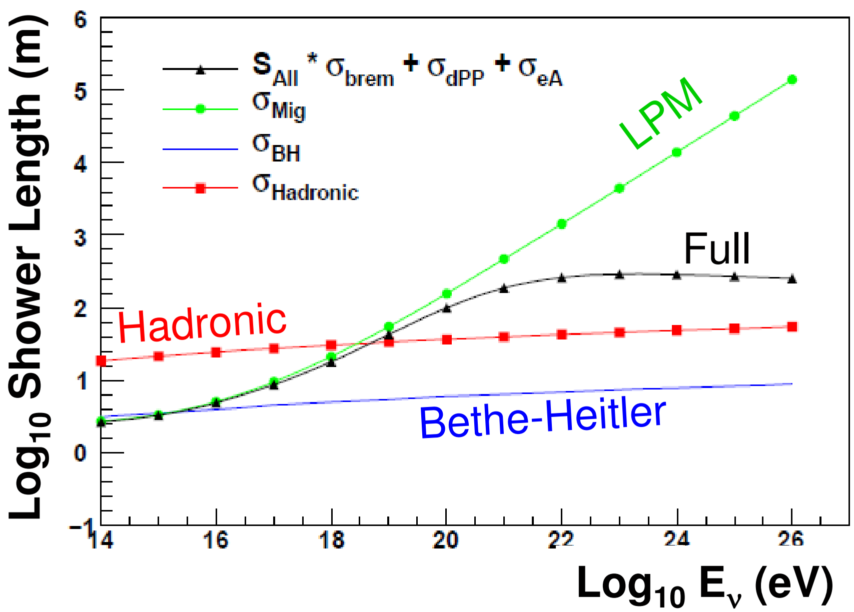


Figure 4. Contribution of different redshifts to the cosmogenic neutrino flux at 10^{16}, 10^{18}, and 10^{20} eV.

Neutrino Interactions

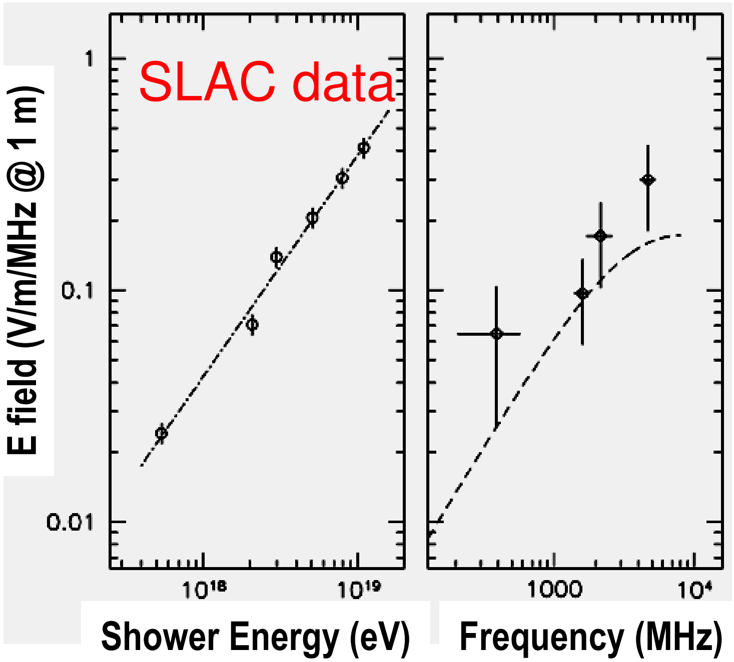
- Cross-section is large enough so that ν are absorbed in earth
  - ν are either horizontal or down-going
  - Measure $\sigma_{\nu N}$ from zenith angle distribution
    - Sensitive to low-x parton distributions & some new physics
- Radio signals come from EM and hadronic showers
- 20% of neutrino energy goes into a hadronic shower
- 80% of ν_e energy produces an electromagnetic shower
  - EM showers are elongated by LPM effect, altering radio emission
    - 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

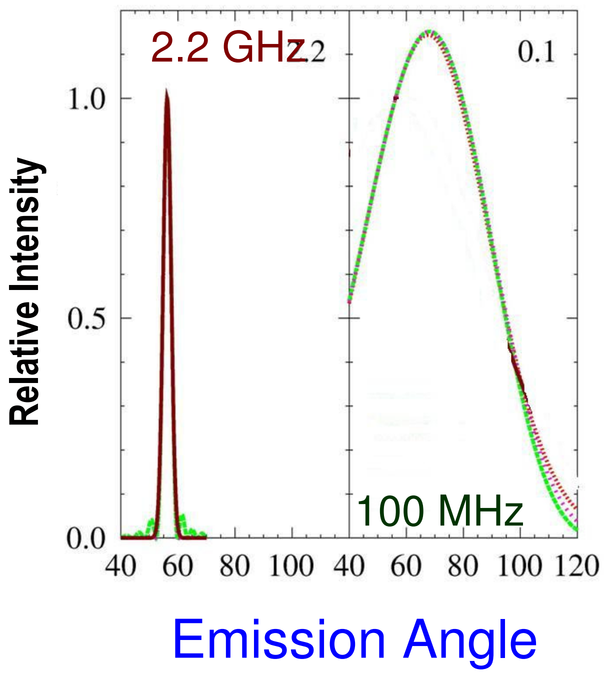


L. Gerhardt & SK, 2010

Radio Emission from Showers

- Showers contain ~ 20% more e^- than e^+
  - Compton scattering of atomic e^- in target
  - Positron annihilation on atomic e^-
- For wavelengths > transverse size of the shower, the net charge emits Cherenkov radiation coherently.
  - Radio energy ~ E_ν^2
  - Maximum frequency ~ few GHz
    - Medium dependent
  - Radiation at Cherenkov angle
    - Angular distribution broadens at lower frequencies.
- Studies with 25 GeV e^- beams at SLAC incident on salt, sand and ice targets
  - Confirmed theoretical calculations



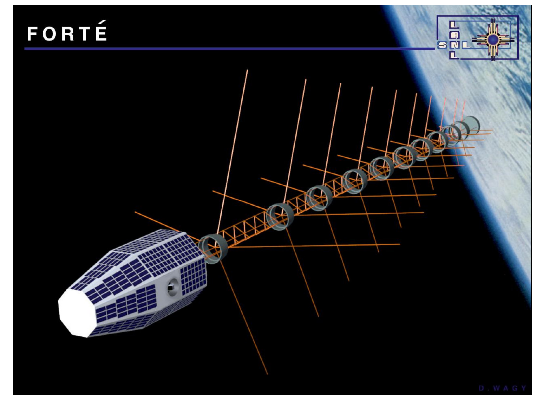


SLAC data:D. Saltzberg *et al.*, PRL **86**, 2802 (2001)
Angles: O. Scholten et al. J.Phys.Conf.Ser. **81**, 012004 (2007)

Zooming in on Neutrinos

- Radio waves from the moon
  - 240,000 km range increases threshold to >>10^{20} eV
    - Above most of GZK energy spectrum

- FORTE satellite: radio pulses from Greenland

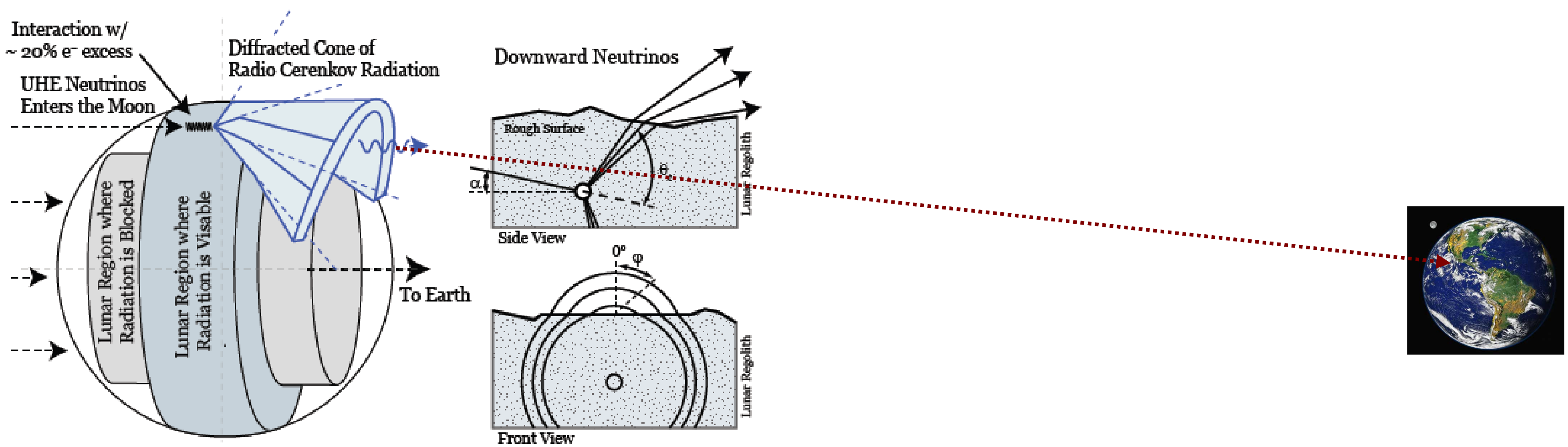


- ANITA Balloon Experiment circled Antarctica
  - Looking down, for ν interactions in ice
    - Up to 650 km from detector
  - Closer than the moon; threshold $10^{18.5}$-10^{19} eV
    - Upper portion of GZK peak

- Antennas Embedded in Antarctic ice
  - Pioneered by RICE experiment
  - Detectors can reach 10^{17} eV threshold,
    - Most of the GZK spectrum
  - ARA and ARIANNA experiments at prototype stage

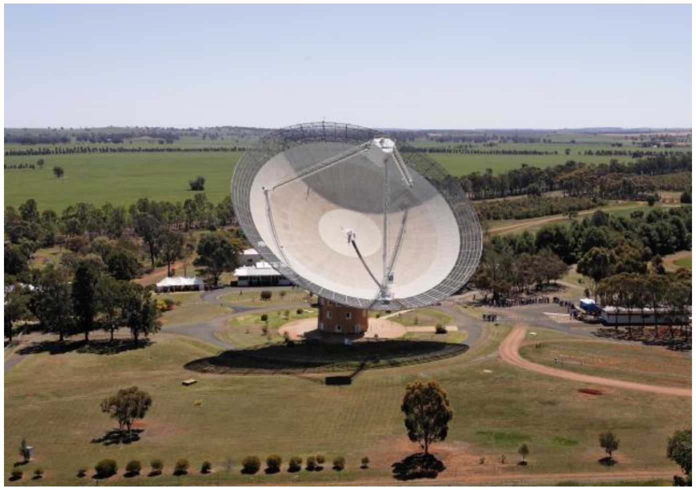
Lunar Signals

- Sensitive volume depends on frequency
  - Radio absorption length ~ 9 m/f(GHz) sets maximum 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



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

Lower frequency Experiments



- NuMoon @ Westerbork 64 m dish
  - 113-175 MHz
  - No events in 47 hours of observation
- Low frequency array for radio astronomy (LOFAR)
  - 36 stations in Northwest Europe
    - 120-240 MHz 48 antennas/station
    - 10-80 MHz 96 antennas/station
- Square Kilometer Array
  - Proposed radio telescope array with 1 km^2 collecting area
    - In South Africa or Australia

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

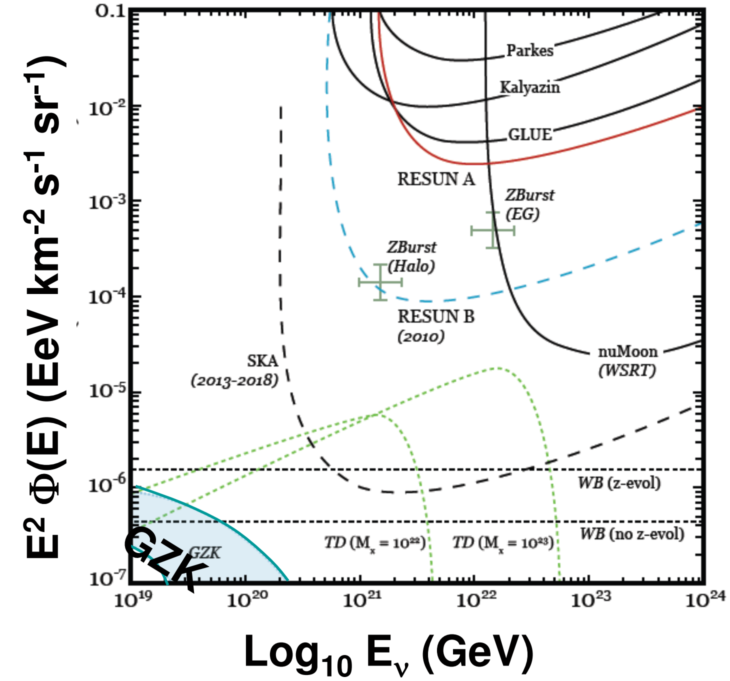
Higher Frequency Experiments

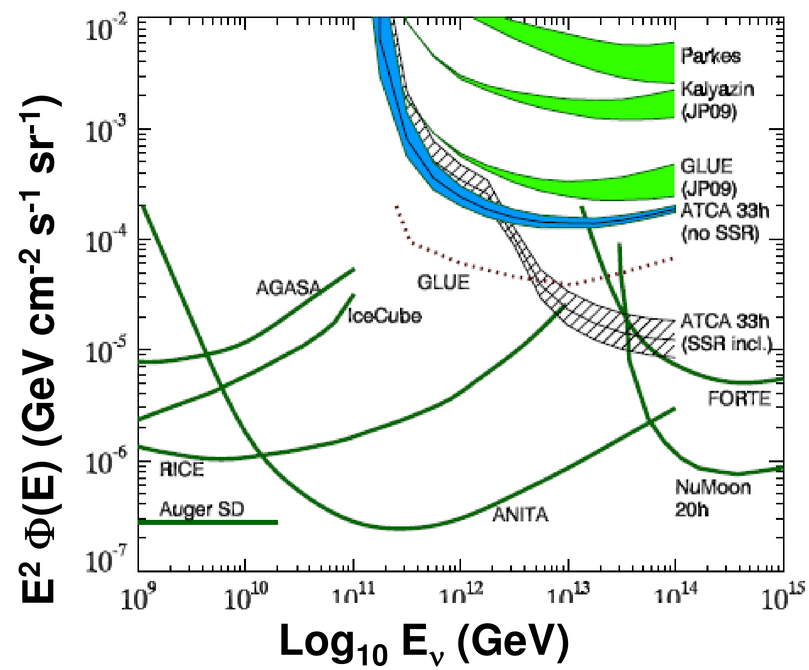
- Lunaska @ Australia Telescope Compact Array
  - 6 nights of data with 6 22 m dishes
    - Beam size matches the moon
  - 600 MHz bandwidth (1.2-1.8 GHz)
    - De-dispersion filter needed
- Resun
  - 45 hours of data with 4 25-m VLA (very large array) dishes
  - 1.45 GHz
  - 50 MHz bandwidth
  - Resun-B is planned

Lunaska - C. W. James *et al.*, PRD 81, 042003 (2010)
Resun – T. R. Jaeger *et al.*, arXiv:0910.5959

Lunar results

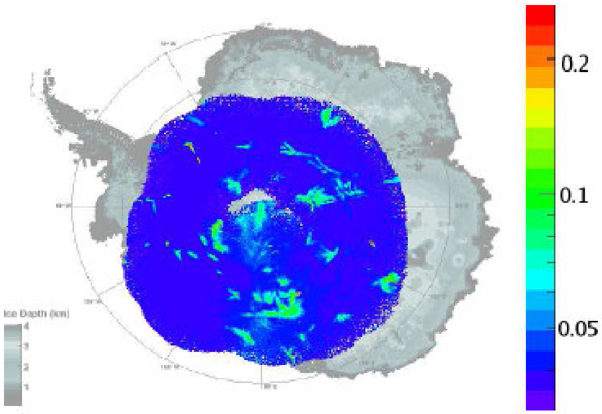
- Thresholds >> 10^{20} eV
  - Small fraction of GZK spectrum
  - Probes exotic models, like topological defects
- Multi-dish apparatus reach lower thresholds
- Lower frequency experiments (NuMoon) have higher thresholds, but a larger effective volume, giving them lower limits
- Lunaska (ATCA) presented two limits for different models of lunar surface roughness

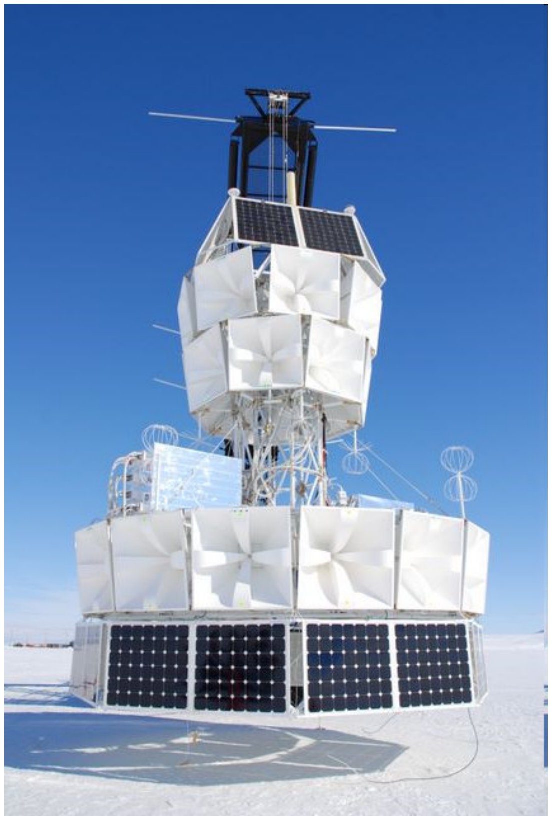




ANITA Balloon

- Two flights
  - 35 day flight in 2006/7
  - 31 day flight in 2008
  - Altitude ~ 35 km
- 40 (32) horn antenna search for radio pulses out to the horizon (~ 650 km)
  - Separate channels for vertical and horizontal polarization
  - 26.7 M trigger on broadband pulses
    - Mostly thermal noise
- Calibrations from buried transmitters buried measure signal propagation through ice, firn and snow-air interface.

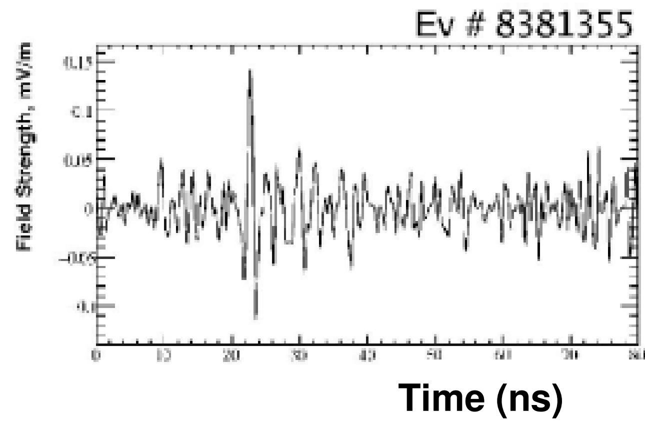




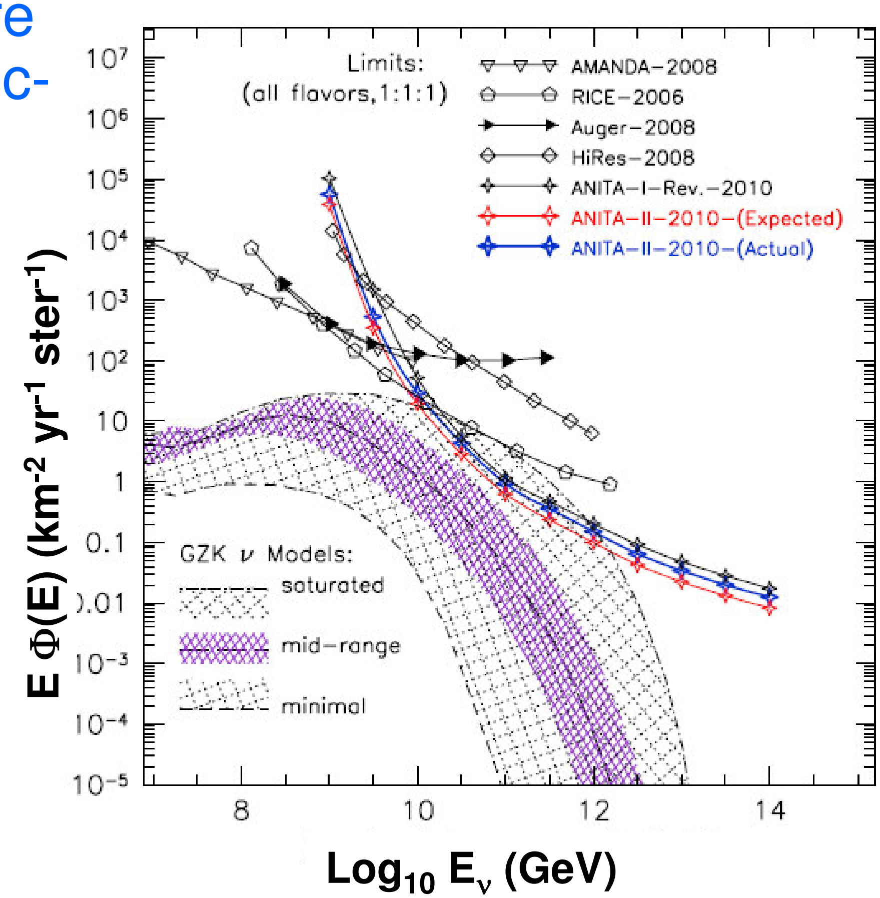
ANITA Results

- Cuts remove thermal, payload & anthropogenic noise, and misreconstructions
- 5 events remain
  - ◆ 3 horizontally polarized events are likely reflected signals from cosmic-ray air showers
- 2 vertically polarized events are consistent with signal
  - ◆ Expected background 1 ± 0.4
- Upper limit constrains 'interesting' GZK models
- ANITA-3 flight requested w/ more antennas and better trigger

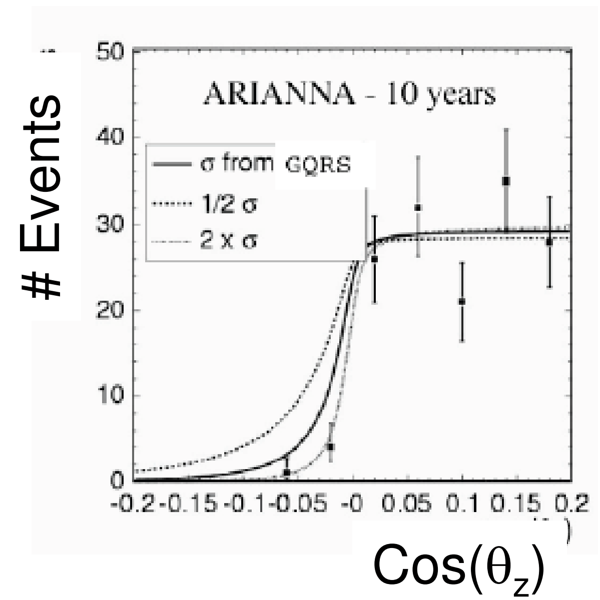
Posters by Abigail Vieregg and Eric Grashorn



Waveform from a ν candidate event



Antarctic In-Ice Detectors



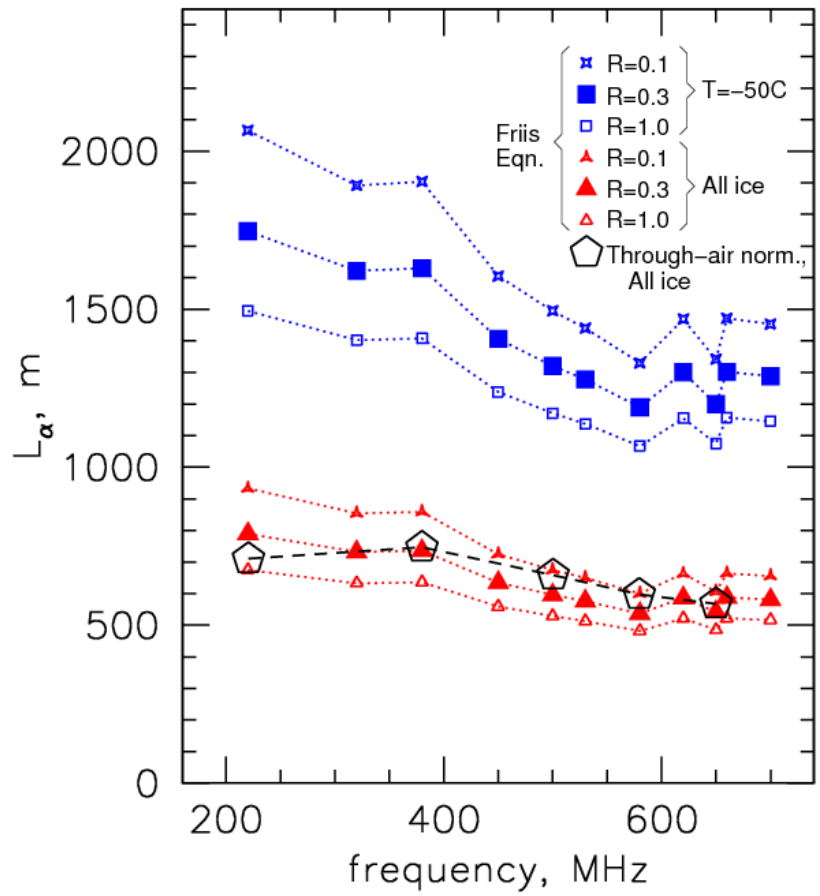
Plot by Amy Connolly

- Sensitive to most of GZK spectrum
  - Key to probe cosmic evolution
  - Thresholds ~ $10^{17\text{-}18}$ eV
- Planned Target Volume 100 km^3
  - 100 GZK ν in 3-5 years
    - Measure $\sigma_{\nu N}$
- Two funded proposals funded for prototype installations
  - Sensitivity scales with $$$
    - -- > No plots showing effective area…
  - ARA at the South Pole
  - ARIANNA on the Ross Ice Shelf
- Logistics in Antarctica can be tough
  - Winter power…

Askaryan Radio Array (ARA)

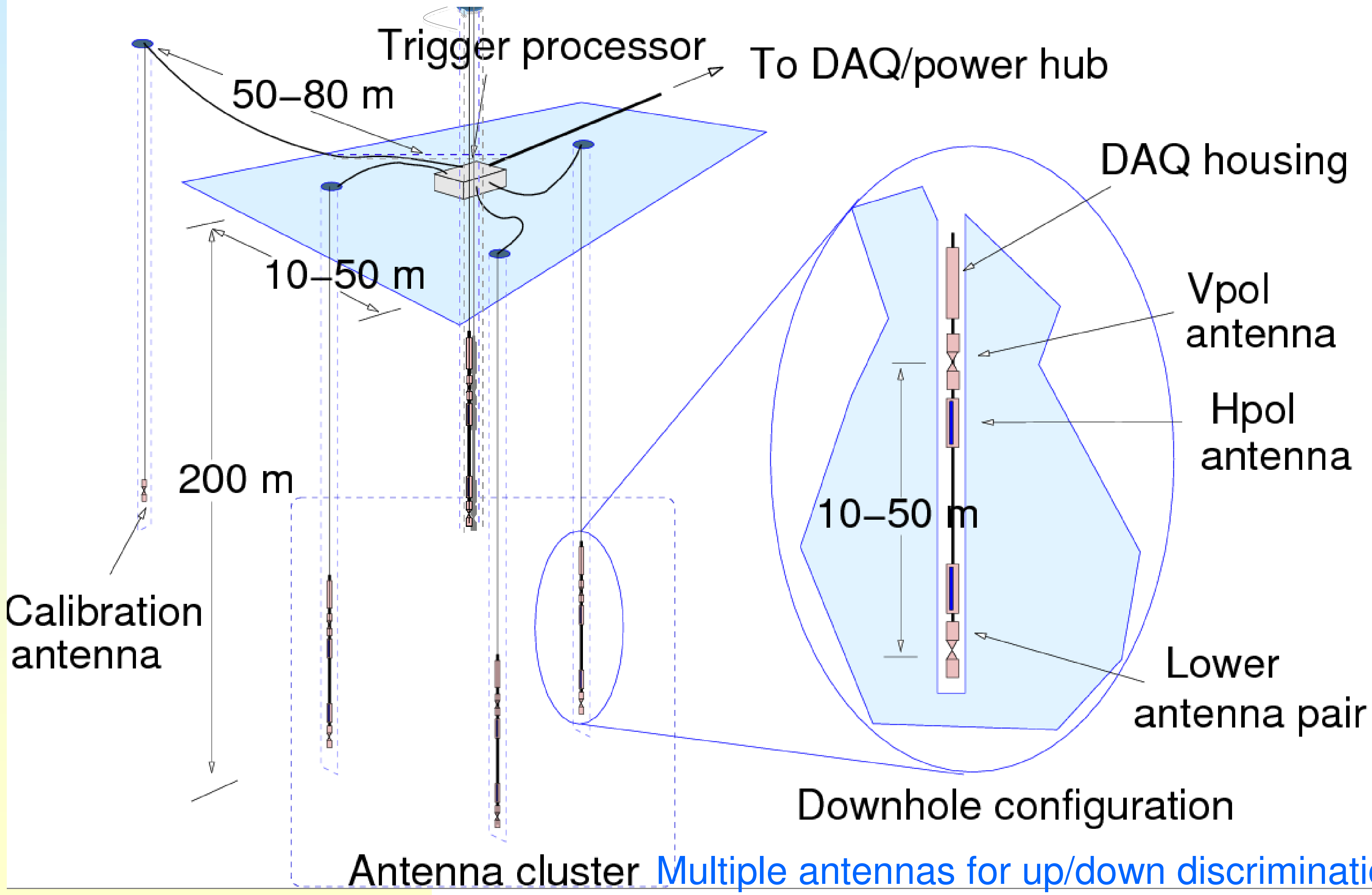
- Radio antenna clusters in 200 m deep holes at the South Pole
  - Clusters on 1-1.5 km triangular grid
- Series of prototypes deployed in IceCube holes
- Attenuation length > 500 m
  - Measurement sensitive to reflection coefficient of ice-rock interface
- Electronics under discussion
  - Possible variation: more, but simpler channels, with time-over-threshold electronics
- Hole drilling and power options being studied

Poster by Kara Hoffman



ARA stations and antenna clusters

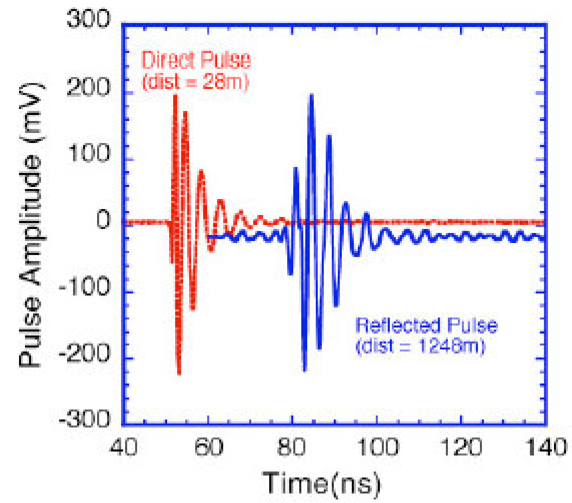
4 receiver strings + 1 buried calibration transmitter/cluster
Prototype Development in progress



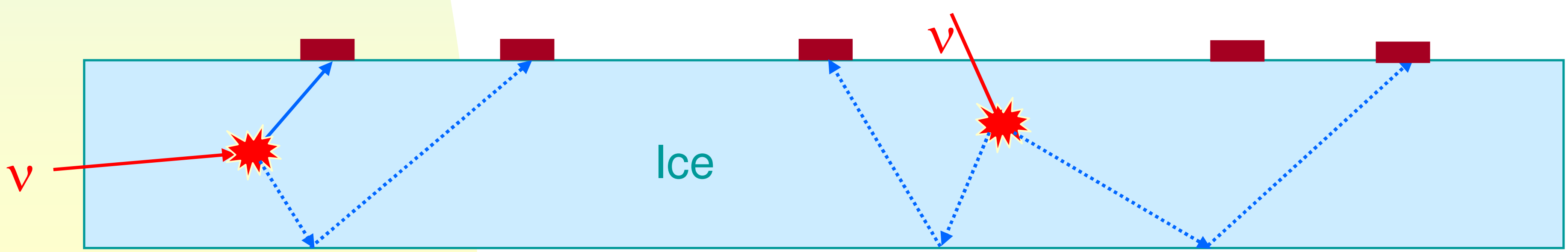
Multiple antennas for up/down discrimination

ARIANNA concept

- In Moore's Bay on the Ross Ice Shelf
  - ~ 570 m of ice floating on seawater
    - The smooth ice-water interface reflects radio waves like a mirror
  - 110 km from McMurdo station
- Sensitive to downward-going neutrinos
  - Larger solid angle
- Reflection increases collection area
- Stations with 4-8 dipole antennas in shallow trenches
  - 4-8 m antenna separation gives directional info
  - Orientations measure pulse polarization



Signal reflection from interface

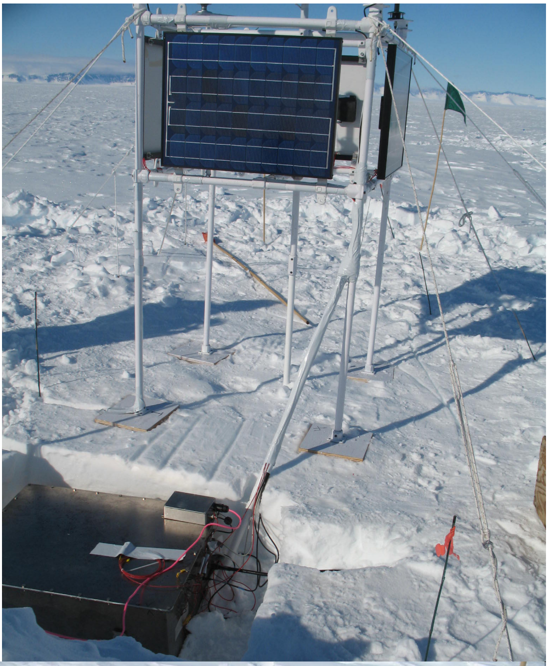


Dotted lines show reflected signal

S. Barwick, NIM A602, 279 (2009).

ARIANNA in the Field

- Site characteristics studied in 2007 & 2009
  - Ice thickness 572 ± 6 m
  - Radio attenuation length ~ 500 m
    - Ice-water interface attenuation < 3 db
- 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
- Design of a 7-station array is mostly funded and in progress



L. Gerhardt *et al.*, arXiv:1005.5193;
D. Saltzburg et al., submitted to Astropart. Phys.

ARIANNA in the Field

- Site characteristics studied in 2007 & 2009
  - Ice thickness 572 ± 6 m
  - Radio attenuation length ~ 500 m
    - Ice-water interface attenuation < 3 db
- Prototype with 4 antennas, 2 GS/s waveform digitizer readouts, wind and solar power, Iridium modem
  - Deployed in Dec. 2009 for 1 year
  - Log-periodic dipole antennas
    - ~ 50 MHz to 1 GHz
  - Triggered on >=2/4 antennas
    - After temporary internet connection was removed, triggers were thermal noise
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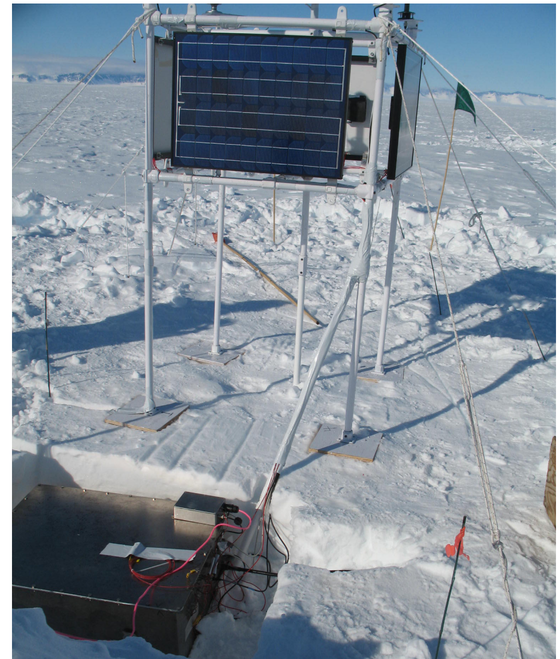


ARA and ARIANNA

Factor	ARA	ARIANNA
Radio Atten.Length	500-2000 m ?	300-500 m
Acceptance	Horizontal	Horizontal + Downgoing
Logistics	Drilling, South Pole - 2800 m elevation	Green Field Site

Conclusions

- Neutrino interactions at energies above 10^{17} eV produce substantial coherent radio Cherenkov emission.
  - The radio energy increases as the square of the neutrino energy.
  - These signals have been studied in beam tests at SLAC.
- Many experiments have searched for radio emission from cosmic neutrino interactions.
  - Radio-telescope arrays have searched for signals of n interactions in the moon, with a threshold $E > 10^{20}$ eV.
  - The ANITA balloon experiment has set limits that constrain current predictions on the GZK neutrino flux.
  - The proposed ARIANNA and ARA radio detectors will emplace radio antennas on the Ross Ice Shelf and at the South Pole respectively.
    - Sensitive to the entire GZK ν energy range
      - Can probe cosmic evolution of high-energy sources.
    - They will also measure $\sigma_{\nu N}$ at EHE energies

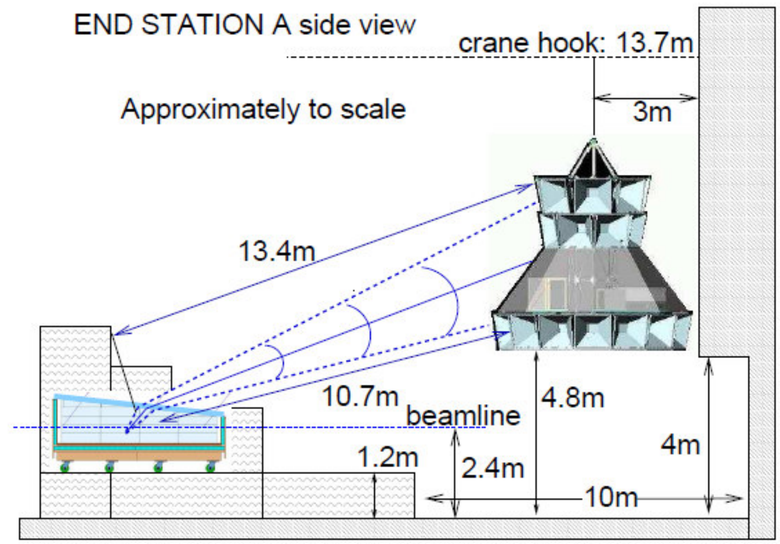
UHE Neutrino Posters

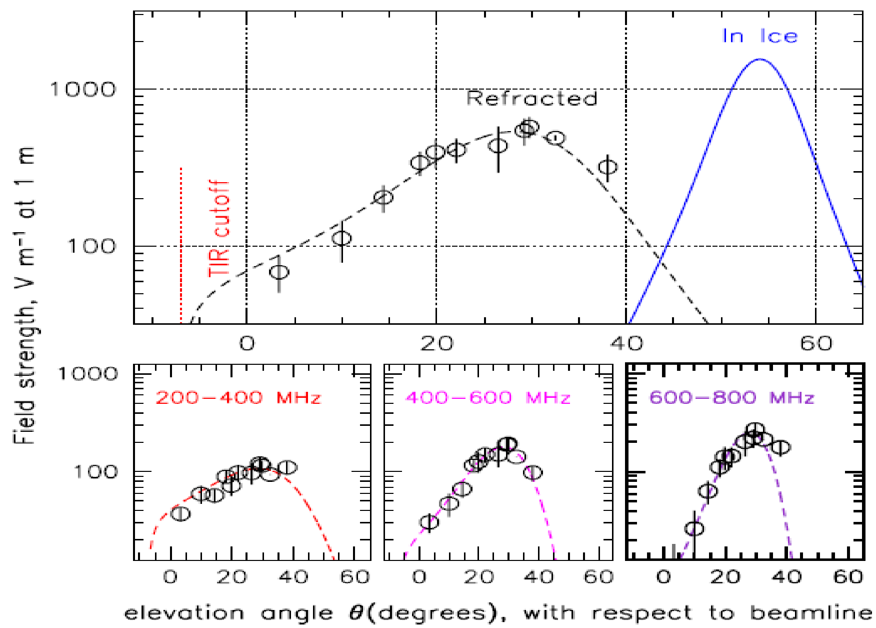
- Recent Results and Future Prospects of the South Pole Acoustic Test Setup
  - Rolf Nahnhauer
- UHE neutrino detection with the surface detector of the Pierre Auger Observatory
  - Jose Luis Navarro
- New Results from the ANITA Search for Ultra-High Energy Neutrinos
  - Abigail Vieregg
- ANITA and the Highest Energy Cosmic Rays
  - Eric Grashorn
- The Askaryan Radio Array
  - Kara Hoffman
- The GEM-EUSO Mission to Explore the Extreme Universe
  - Gustavo Medina Tanco
- A small Air Shower Particle Detector Array dedicated to UHE neutrinos
  - Didier Lebrun

Backup Slides

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

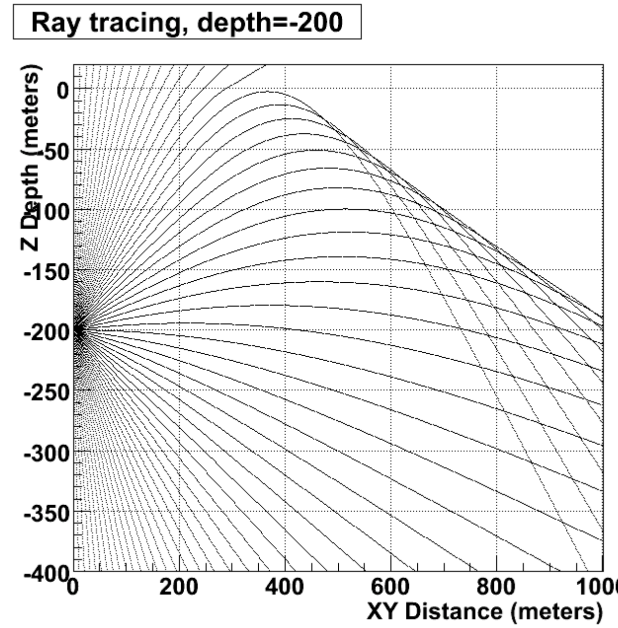




ANITA Collab., 2007

Ray Tracing in Antarctic Ice

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



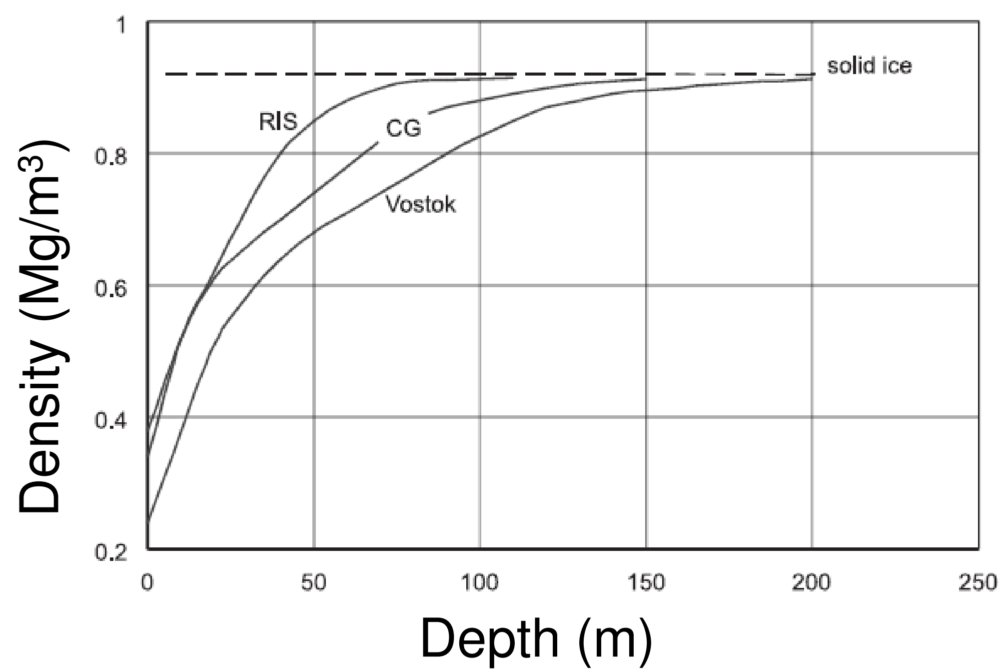


Figure 2. Firn density versus depth at three polar locations: the Ross Ice Shelf (RIS) and Vostok Station in Antarctica and Central Greenland (CG).