Outline

• Ultra-high energy (UHE) neutrinos: What will we learn from them?

• Radio is necessary for a long-term UHE neutrino program

• ARA and other *in situ* experiments

• Science implications of current and future constraints
Ultra-high energy neutrinos: What will we learn from them?
Motivations for ultra-high energy (UHE) neutrinos (>10^{17} eV)

• Sources of UHE cosmic rays should also produce UHE neutrinos through photo-hadronic interactions
  - Gamma Ray Bursts?
  - Active Galactic Nuclei?
  
  - ~Once per/day, brightest object in sky
  
  • Cosmic
  
  • Black hole at center of a galaxy accreting mass
Motivations for ultra-high energy (UHE) neutrinos (>10^{17} eV)

- **Greisen-Zatsepin-Kuzmin (GZK):** Ultra-high energy (UHE) cosmic rays >10^{19.5} eV slowed by cosmic microwave background (CMB) photons within \sim 50 \text{ Mpc}:

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^* \rightarrow n + \pi^+ \]

\[ n \rightarrow p + e^- + (\bar{\nu}_e) \]

\[ \pi^+ \rightarrow \mu^+ (\nu_\mu) \]

\[ \mu^+ \rightarrow e^+ (\nu_\mu \bar{\nu}_e) \]

\(\nu\)'s from GZK process first pointed out by Berezinsky and Zatsepin (1969)

- Other resonances too, they all sit on continuum of \[ p + \gamma \rightarrow n \pi^+ \]
Evidence points to a GZK cutoff...

- Cosmic ray data points to cutoff at GZK threshold
- If this is indeed due to GZK process, UHE neutrinos have to be there!
Protons and neutrinos are complementary probes of UHE sources

Protons that keep at least half their energy

Neutrinos that reach earth with $>10^{17.5}$ eV

Using CRPropa program, generated protons from sources with flat spectrum, flat redshift dependence to 4 Gpc, propagate through GZK interactions
Radio: needed for a long-term UHE neutrino program
Detection Techniques

- $< 10^{19}$ eV: optical dominates current constraints
- $> 10^{19}$ eV: radio dominates
  - Radio thresholds dropping with experiments coming online

Cascades in atmosphere
Need to go beyond km$^3$-scale

\[ \approx 10 \text{ neutrinos from GZK / km}^2 / \text{year} \]

$10^{18}$ eV: $\nu N$ interaction length $\approx 300$ km

$\rightarrow 0.03$ neutrinos / km$^3$ / year

At most, we see 1/2 the sky

$\rightarrow 10^{-2}$ neutrinos / km$^3$ / year

To be assured sensitivity to “guaranteed” GZK-induced neutrino flux, we need $\gg 10^2$ km$^3$ detection volume!
Radio Cerenkov Technique (Askaryan Effect)

- Coherent Cerenkov signal from net “current,” instead of from individual tracks
- \( \sim 20\% \) charge asymmetry develops (mainly Compton scattering)
- Excess moving with \( v > c/n \) in matter
  \[ \rightarrow \text{Cherenkov Radiation} \quad dP \propto v \, dv \]
- If \( \lambda >> R_{\text{Moliere}} \rightarrow \text{Coherent Emission} \)
  \[ P \sim N^2 \sim E^2 \]
- \( \lambda > R_{\text{Moliere}} \rightarrow \text{Radio/Microwave Emission} \)

\( R_{\text{Moliere}} \approx 10 \text{ cm}, \quad L \sim \text{meters} \rightarrow \text{Radio!} \)

This effect has been confirmed experimentally in sand, salt, ice:
- PRL 86, 2802 (2002)
- PRD 72, 023002 (2005)
- PRD 74, 043002 (2006)

Idea by Gurgen Askaryan (1962)
Antarctic Ice

Ice thicknesses

Radio Attenuation Lengths

0.2 km < depth < 1.5 km:

$$\langle L \rangle_{\text{shallow}} = 1200^{+350}_{-100} \text{ m}$$

$$\langle L \rangle_{\text{meas}} = 690^{+190}_{-70} \text{ m}$$

2 km depths are typical across the continent
ARA and other *in situ* experiments
Radio Cerenkov in situ

ARA

- Deployed ARA Station
- Planned ARA Station
- Planned for 2014/15

ARA37

ARIANNA

Array field is for 960 monitor stations.

ICE SHELF

- Most neutrinos pass through ice without hitting atoms.

SEA WATER

- Recorded by monitoring station

Since the emissions pass through the ice, they are eventually picked up by a monitoring station, which has eight antennas buried in the ice. The station collects and transmits the level of neutrinos based on the amount of particle emissions.

From OC Register 2012
Radio Cerenkov Balloon Experiments

ANITA

Long duration balloon program operated by NASA

ANITA 1: 2006-2007
ANITA 2: 2008-2009

Exavolt Antenna (EVA)
UHE neutrino flux - current constraints

- IceCube: Best constraints $E_\nu \lesssim 10^{19}$ eV
  - Cutting into most optimistic data-inspired models
  - Radio *in situ* arrays will overtake IceCube for $E_\nu > 10^{17.5-18}$ eV
- ANITA: Best constraints for $E_\nu \approx 10^{19}$ eV
  - EVA: higher gain, lower threshold
Askaryan Radio Array (ARA)

Ohio State University and CCAPP, University of Wisconsin, University of Maryland and IceCube Research Center, University of Kansas and Instrumentation Design Laboratory, University of Bonn, National Taiwan University, University College London, Universite Libre de Bruxelles, Univ. of Wuppertal, Chiba Univ., Univ. of Delaware

- Radio array at the South Pole
- Testbed station,
  Stations A1-A3 deployed
- Phase 1: 37 stations ~100 km$^2$
  - Establish flux, first astronomy/particle physics
- Phase 2: ~1000 km$^2$
  - High statistics astronomy/particle physics exploitation

NSF has funded Testbed+3 Stations (ARA3). Pending approval for ARA10 (had proposed to deploy in 2014-2015 and 2015-2016)
• For station at 30 m depth, visible neutrinos suffer more absorption in earth
  \[ \text{At } 10^{18} \text{ eV, we find } [A\Omega]_{\text{eff}} (200 \text{ m}) = 3 \times [A\Omega]_{\text{eff}} (30 \text{ m}) \]
  \[ -10^{19} \text{ eV: Factor of 4} \]
• Remember ARIANNA looks for reflections too
ARA station

Depth: 200 m
*surface antennas are not shown
ARA On-Ice Activities 2012-2013

- Stations A2 and A3 drilled to 200 m depth
- Last A3 hole completed on 31 December 2012
Flash light visible by eye from 200m depth
Line of sight
  evidence that straightness is within ~15 cm/200m
  indication that horizontal deviation less than 15 cm
  Well within requirements.
  Final calibration with calibration pulsers

Diameter: 15 to 20 cm
First ARA physics result! From ARA Testbed
arXiv:1404.5285

Interferometric Map: Guided by data and simulation

- Require quality reconstruction using mapped correlations
- Constrain neutrino flux based on 224 days livetime in 2011-2012
- 2 other analyses: Coherently Summed Wave, Template-based
ARA deep stations: analyses underway

- First cal pulser reconstructions

- Deep stations show consistent ~95% livetime
ARIANNA

- Radio array on Ross Ice Shelf
  [http://arianna.ps.uci.edu](http://arianna.ps.uci.edu)

- Completed 7 station array in Dec. 2013

- Propose 960 station array

US

Sweden

New Zealand
Bounce Tests
Pulser->Seavey TRX->Station

Notes: Time delays are determined from all 4 antennas, compatible with plane wave

Shown by S. Barwick at ICRC
Data Analysis: HRA Station 3  
(Dec 15, 2012 - Mar 15, 2013)

552473 events collected in 2/4 majority logic at 5 sigma thresholds on each channel

Remove event if
(1) Too much power below highpass
(2) Unusual peaks in power spectrum
(3) No waveforms consistent with time domain expectation
(4) Inconsistent power in parallel antenna

Complete rejection of BG without timing or event reconstruction

Shown by S. Barwick at ICRC
Greenland Neutrino Observatory (GNO) (Univ. of Chicago, UCLA, Univ. of Hawaii)

- Summit Station being considered - 3 km thick ice, water layer at bottom (reflections add to sensitivity)
- Sees Northern sky, sunlight 10 months/year solar power
- Year-round, NSF-Operated

Ice at Summit Station characterized June 2013

Plan to deploy first module Spring 2015

Distance (m)

Relative E-Field Loss

South Pole/ARA
Summit/GNO
Ross Ice Shelf, Moore’s Bay/ARIANNA

Ross Ice Shelf/ARIANNA
Science implications
Which type of models has IceCube excluded?

- Excluded models have strong source evolutions
- Example:
  - FR-II (AGN) redshift evolution
    \[ \alpha = 2.3, \text{ dip,} \]
    \[ E_{\text{max}} = 10^{20.5} \text{ eV} \]
  - Kotera et al. (2010)
*in situ* arrays will constrain the redshift evolution of UHE sources

- In ~7 station-years, ARA can distinguish between Star Formation Rate and AGN evolutions

From Connolly, Horiuchi & Griffith, in preparation.

From A. Connolly, S. Horiuchi (UC Irvine) & N. Griffith (OSU), in preparation.
Neutrinos from the sources too!

Cosmogenic spectra from Connolly, Horiuchi & Griffith, in preparation.
• Radio technique is what is needed for long-term UHE neutrino program
• ARA10 will already exceed IceCube’s sensitivity especially at highest energies
• IceCube:
  - ~$250M, 250 authors
• ARA10:
  - ~$5M, 30 authors

• If UHECR’s are heavy, radio will be necessary
Exotic Physics: Lorentz Invariance Violation (LIV)

\[ \nu \rightarrow \nu' \ e^+ \ e^- \] (Coleman and Glashow)
Neutrino loses \( \sim 3/4 \) of its energy

Attenuation vs. redshift

Observed neutrino spectra

Different energies, same \( \alpha_{\nu} = 8 \times 10^{-26} \)

Exotic physics with UHE neutrinos

- $\nu$’s produce interactions at higher center-of-mass energies than LHC
  - $E_\nu=10^{18}$ eV: $\sqrt{s}=45$ TeV!
- Sensitive to enhanced cross-sections - extra-dimensions?
- Compare power consumption!
  - LHC: 10% of Geneva
  - ARA37: ~one Christmas tree

Connolly et al., 2011

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Legend:
- SM
- $x_{\min}=1$, $N_D=1$, $M_D=1$ TeV
- $x_{\min}=1$, $N_D=7$, $M_D=1$ TeV
- $x_{\min}=3$, $N_D=7$, $M_D=1$ TeV
- $x_{\min}=1$, $N_D=7$, $M_D=2$ TeV
Summary

• Radio technique brings the necessary scalability to carry out a long term astrophysics and particle physics program with UHE neutrinos

• Current UHE limits constraining cosmogenic models with strong redshift evolutions
  - *in situ* arrays will constrain evolution of sources early
  - Capability of reaching even heavy CR scenarios

• Don’t dismiss exotic scenarios - UHE cosmic neutrinos are unique in that no other particles at these energies will have traveled so far to get here