Radio detection of UHE cosmic neutrinos

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Topics

• Background
  – UHE cosmic particles & large detectors
  – Radio emission from showers

• ANITA

• ARA & ARIANNA

• Lunar observations

• Related topics (not discussed)
  – Auger, Acoustic, UHE cosmic rays
Cosmic Rays

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
1. Acceleration predictions depend on scenario – could be “no ν’s”.
2. “GZK” neutrinos are guaranteed – a guide for experiment design.
4. Constraints from EGRET & UHECR
5. $E_\nu \sim 0.05 E_p$
Cosmogenic (GZK) neutrinos

(Kotera, Allard, Olinto)

Note.
- Must also fit UHECR
Detection

\[ A = N A_1 \]

- Large Area
- Detect showers
- Particles near field small
- Radio * Acoustic
- Radiation optical

* Better Technique

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio emission from showers

From Jamie Alvarez-Muniz @ OSU workshop (2/12)
Also see Tim Huege for status of geo-magnetic

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Experiment confirms theory (Jamie Alvarez-Muniz)

Experiments at SLAC: sand, salt & ice

Bunches of \( \sim \text{GeV} \) bremsstrahlung photons dumped in sand & salt & ice: \( E_0 \sim 6 \times 10^{17} - 10^{19} \) eV.

- Askaryan effect seen !!!
- Linearly polarized signal
- Power in radio waves goes as \( E_0^2 \)
- Bipolar pulses in time-domain
- Agreement with theoretical expectations

Frequency spectrum

Angular distribution of electric field

More attempts: K. Belov, A. Romero-Wolf @ this meeting

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ANITA

- ANITA Overview

- Neutrino detection
  - event generation
  - event simulation
  - ANITA detector
  - analysis
  - results

- Cos-Ray detection

- Other

- ANITA 3, EVA
Overview

Shamelessly borrowed from P. Garham

ANITA will seek the origin of the highest energy particles in the universe, by turning the continent of Antarctica into an enormous **Neutrino Telescope**

Cold ice: Most radio transparent Solid known

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Neutrino interactions

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Cherenkov and Total Internal Reflection

\[ \Theta_c = \Theta_{TIR} \]
Fig. 19: A false-color map of sky exposure quantified by total neutrino aperture (here given for $E_{\nu} = 10^{20}$ eV) as a function of right-ascension and declination for the ANITA-I flight.
ANITA flight(s)

- 3 orbits (6 weeks)
- Ice depth 0-4 km
- Bases

Also: ANITA-LITE

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Event Simulation

• Askaryan mechanism
  – Signal Characteristics

• Determine list of sources

• For each source
  – Determine launch angle via ray tracing
  – Propagation effects
  – Emission spectrum
  – Spectrum at detector

• Sum spectra from sources
Event → source list

- NC events
  - Hadronic shower + possible 2\textsuperscript{nd} interaction

- CC events
  - $\nu_e$ em + hadronic shower
  - $\nu_\tau$, $\nu_\mu$ hadronic shower + brem/photoneuclear → secondary showers
  - $\nu_\tau$ decay

- Model fluctuations
  - multiple sub-showers

- Multiple paths
  - reflection from bottom

- Exotica
  - Monopoles: quasi-continuous photonuclear
Event Geometry

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio emission

- Frequency domain – linear response
  - ice attenuation
  - velocity of propagation
  - antenna, amps, filters (time domain for discriminators)

- Spectrum from Alvarez-Muniz, Zas, & Friends

- Could be improved.
Propagation (See discussion of ice properties)

- Ray tracing (part of geometry)
- Attenuation
  - 3-zone model, with temperature/depth vertical profiles
- Refraction (de-focusing)
- Scattering: reflection/transmission
- Birefringence (not included)
- Dispersion (not included)
Cerenkov Beam

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ANITA detector

- Airframe and payload infrastructure

- Analog front end
  - Antennas
  - Low Noise Amps, filter, splitter
  - Cables/connectors/boxes

- Trigger
  - multistage, narrow dt: reduce accidentals

- Digitizer
  - Low power switched capacitor array

- Efficient data handling
ANITA Payload

- Weight
- Rigidity
- Form-factor
- Power
- Thermal
- Remote

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Front end: antennas

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
RF subsystems (ANITA-I)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ANITA-II RF system

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
# Triggers

<table>
<thead>
<tr>
<th></th>
<th>LΦ</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>V</td>
<td>3+ full</td>
<td>2/3 + full</td>
<td>( \hat{\mathcal{C}} ) prefers ( V )-pol</td>
<td></td>
</tr>
</tbody>
</table>

But bad for \( \cos \)-ray

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Radio detection of cosmic neutrinos, NOW-12 (Seckel)
**Digitizing electronics (Anita-I)**

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>As-built Value &amp; Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td># of RF channels</td>
<td>80 = 32 top, 32 bottom, 8 monitor</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>2.6 GSa/s, greater than Nyquist</td>
</tr>
<tr>
<td>Sample resolution</td>
<td>$\geq 9$ bits = 3 bits noise + dynamic range</td>
</tr>
<tr>
<td>Samples in window</td>
<td>260 for a 100 ns window</td>
</tr>
<tr>
<td>Buffer depth</td>
<td>4 to allow rapid re-trigger</td>
</tr>
<tr>
<td>Power/channel</td>
<td>$&lt; 10$W including LNA &amp; triggering</td>
</tr>
<tr>
<td># of Trigger bands</td>
<td>4, with roughly equal power per band</td>
</tr>
<tr>
<td># of Trigger channels</td>
<td>8 per antenna (4 bands x 2 pols.)</td>
</tr>
<tr>
<td>Trigger threshold</td>
<td>$\leq 2.3\sigma$ above Gaussian thermal noise</td>
</tr>
<tr>
<td>Accidental trigger rate</td>
<td>$\leq 5$ Hz, gives ’heartbeat’ rate</td>
</tr>
<tr>
<td>Raw event size</td>
<td>$\sim 35$ kB, uncompressed waveform samples</td>
</tr>
</tbody>
</table>

- Key component: Switched Capacitor Array (SCA) by G. Varner.

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Operations

- **Campaign operations**
  - NH preparations
  - McMurdo
  - Flight
  - Recovery
  - Taylor Dome

- $C^3$
Analysis

• Timing Calibration

• Interferometry

• Backgrounds
  – Thermal (reconstruction amplitude)
  – Anthropogenic (clustering)

• I: 0 neutrino candidates
• II: 1 neutrino candidate

• Limits
Calibration (ground pulses from McMurdo, Taylor Dome)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Interferometry (correlations not feature extraction)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Backgrounds

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Clustering

<table>
<thead>
<tr>
<th>Cut requirement</th>
<th>Passed</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vpol</td>
<td></td>
</tr>
<tr>
<td>Hardware-Triggered Events</td>
<td>~ 26.7M</td>
<td></td>
</tr>
<tr>
<td>Quality Events</td>
<td>~ 21.2M</td>
<td>1.00</td>
</tr>
<tr>
<td>Reconstructed Events</td>
<td>320,722</td>
<td>0.96</td>
</tr>
<tr>
<td>Not Traverses and Aircraft</td>
<td>314,358</td>
<td>1.00</td>
</tr>
<tr>
<td>In Clusters &lt;100 Events</td>
<td>444</td>
<td></td>
</tr>
<tr>
<td>Isolated Singles</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Not Misreconstructions</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Not of Payload Origin</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total Efficiency</td>
<td></td>
<td>0.61</td>
</tr>
</tbody>
</table>

TABLE I: Event totals vs. analysis cuts and estimated signal efficiencies for ESS spectral shape [10].

Cluster Multiplicity | Number of Clusters |
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Camp</td>
<td>Not Camp</td>
</tr>
<tr>
<td>10-100</td>
<td>8</td>
</tr>
<tr>
<td>5-9</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Candidate events

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ANITA GZK flux limit

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Cosmic Ray Detection

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ANITA-I analysis

- Event selection
- Strong interference amplitude
- 16 events
  - 14 below horizon
  - 2 above
- Consistent waveforms w/reflection
- Correlated with B
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
MC and Energy Scale

- exposure
- reflection w/roughness
- freq-spectrum
- E-spectrum
- angular offset

\[ N \propto \sum \int_{E_T} \phi(E) \, dE = \frac{\Theta}{E_T} \quad \text{for } E^{-3} \]

\[ \Rightarrow \quad \text{if } \Theta \downarrow \text{ then } E \downarrow \]

- \( E(Y, \Theta) \) reasonable but extrapolated

- Issues w/ REAS 2

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Other – check the archives

- Magnetic Monopoles
  - Worlds best limits on relativistic “light” monopoles

- Neutrino cross-section
  - Constraint is actually on $\Phi*\sigma$
  - If flux is known – constraint on cross-section

- Lorentz invariance violation
  - Perhaps no neutrinos due to LIV?

- Anti-nuclear nuggets
  - Non-thermal emission from bow shock in air
ANITA-III

- Fly 2013/14
- Low resolution phased trigger (improve S/N)
- Dual triggers UHECR/UHEN
- More antennas

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ExaVolt Antenna (Gorham, etal - 1102.3883v2)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Ice Properties

- Index of refraction
  - polarization tensor
  - real
  - imaginary
  - two states: birefringence
  - dispersion
Ray tracing

\[ \sin \theta_e = \frac{\sin \theta}{n} \]

and use \( \theta_e \) for Fresnel

**NB: two solutions**

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Propagation: Attenuation

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
3D Temperature Model

Data for this model is provided by Dr. James Fastook, University of Maine, extracted from UMISM, the University of Maine Ice Sheet Model

Weighted Interpolation:

- Inverse square radial distance weights (200 km max)
- Inverse square ice thickness (200 m max diff)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)

Impurity vs depth (climate considerations)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Ice acts like lens. Can focus and increase E-field. Caustic at “shadow point” – point of stationary phase.

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Propagation: birefringence

- We don’t simulate this, but …
- \( \frac{dn}{n} \sim 10^{-3} \) is possible
- \( dt = 5 \) ns per km.
- Predict Hpol arrives first
Summary

• **Attenuation**
  – Temp & impurity model including in-grain and grain boundary
  – Temp and impurity model for Antarctic ice
  – Continent wide attenuation model (SP/Ross comparisons)
  – Most impurity data is “recent” – biased?
  – Could alter vertical profile. - would improve upper region.

• **Birefringence**
  – Crystal fabric likely anisotropic from 500-2000 m?
  – delta-n ~ few 10^-3
  – ~5 ns per km
  – observed ~50 ns over 6 km ?
  – for ARA possible that two polarizations displaced by ~10 ns.
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
The principal idea of ARA

1) Detection of Radio waves, emitted by neutrino induced cascades in ice
2) Achievement of $O(100\text{km}^3)$ detection volume using widely spaced antenna clusters, which detect “discrete” Cherenkov cones
3) Use timing + polarization information for neutrino reconstruction

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Array Layout

2010: Test bed
2011: ARA 1 (xx-CPU)
2012: ARA 2, 3

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Drill system

- Dry hole
- Ø6”, minimum
- 200m usable depth
- 2 holes/day (achievable with 2 shifts/day)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Antennas

Low freq: (>25 MHz) surface antennas

$H_{pol}$: Quad slot w/ferrite core

$V_{pol}$: Bird cage

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Antenna to central DAQ

- Band + notch filter, to limit the LNA input to “our” signal
- Low Noise Amplifier to enhance the signal for the data acquisition system
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Calibration pulser event from testbed

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Interpretation

amplitude analysis
\[ \Rightarrow \text{attenuation} \]

300 MHz
Top 1.5 km:
\[ \langle L_\alpha \rangle_{z<1500} = 1660^{+255}_{-120} \text{ m} \]

All ice:
\[ \langle L_\alpha \rangle_{z<2550} = 820^{+120}_{-55} \text{ m} \]

Timing of two pulses

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
ARA-37 sensitivity

300 km$^2$ sr
@ 10$^8$ - 10$^{15}$
Area 120 km$^2$
Depth 2

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Reconstruction

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Science expectations

<table>
<thead>
<tr>
<th>Model &amp; references</th>
<th>$N_v$:</th>
<th>ANITA-II, ANITA-I, ARA, (2008 flight) 3 years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline cosmogenic models:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protheroe &amp; Johnson 1996 [27]</td>
<td>0.6</td>
<td>59</td>
</tr>
<tr>
<td>Engel, Seckel, Staniewski 2001 [28]</td>
<td>0.33</td>
<td>47</td>
</tr>
<tr>
<td>Kotera, Allard, &amp; Olinto 2010 [29]</td>
<td>0.5</td>
<td>59</td>
</tr>
<tr>
<td><strong>Strong source evolution models:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engel, Seckel, Staniewski 2001 [28]</td>
<td>1.0</td>
<td>148</td>
</tr>
<tr>
<td>Kalashov et al. 2002 [30]</td>
<td>5.8</td>
<td>146</td>
</tr>
<tr>
<td>Barger, Huber, &amp; Marfatia 2006 [32]</td>
<td>3.5</td>
<td>154</td>
</tr>
<tr>
<td>Yuksel &amp; Kistler 2007 [33]</td>
<td>1.7</td>
<td>221</td>
</tr>
<tr>
<td><strong>Mixed-Iron-Composition:</strong></td>
<td></td>
<td></td>
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<tr>
<td>Ave et al. 2005 [34]</td>
<td>0.01</td>
<td>6.6</td>
</tr>
<tr>
<td>Staniewski 2008 [35]</td>
<td>0.0002</td>
<td>1.5</td>
</tr>
<tr>
<td>Kotera, Allard, &amp; Olinto 2010 [29] upper</td>
<td>0.08</td>
<td>11.3</td>
</tr>
<tr>
<td>Kotera, Allard, &amp; Olinto 2010 [29] lower</td>
<td>0.005</td>
<td>4.1</td>
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<tr>
<td><strong>Models constrained by Fermi cascade bound:</strong></td>
<td></td>
<td></td>
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<tr>
<td>Ahlers et al. 2010 [36]</td>
<td>0.09</td>
<td>20.7</td>
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<tr>
<td><strong>Waxman-Bahcall (WB) fluxes:</strong></td>
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<tr>
<td>WB 1999, evolved sources [37]</td>
<td>1.5</td>
<td>76</td>
</tr>
<tr>
<td>WB 1999, standard [37]</td>
<td>0.5</td>
<td>27</td>
</tr>
</tbody>
</table>

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
• Source: S. Barwick, (IAU 2012)

• [http://arianna.ps.uci.edu](http://arianna.ps.uci.edu)

• US, Sweden, New Zealand

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Ice properties

T. Barrella, et al., J. Glaciology, 2010

Amazing fidelity of reflected pulse from sea-water bottom -behaves as nearly flawless mirror

1-way attenuation length, averaged over depth and temperature

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Station design

ATWD based DAQ

Solar + wind

8 LPDA antennas
Hexagonal array

- **Nov 2011:**
  - Deploy 1 protostation w/new DAQ technologies
  - Establish wireless communication

- **Nov 2012:**
  - Deploy 3 stations for operation during sunlit months
  - Reduce power consumption to 10W
  - Deploy Wind/Solar system with LiFePO$_4$ battery technology
  - Establish communication/control with low power microcomputer

- **Nov 2013**
  - Deploy 4 stations to complete hex array
  - Focus on cost reduction and simplified deployment and commissioning
  - Investigate technologies for overwinter operation

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Technical Goals for 1000 km²

- Station costs: ~$10k US per station

- Fully “green” power system
  - Solar and wind only; no fossil fuels
  - Scalable to vary large areas

- Deployment at rate of 1 station/person/day

- 3 year construction for 960 stations
Sensitivity expectations

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Reconstruction

Energy Resolution

Angular resolution

$\sigma_E = 2.4$

$\sigma_\theta \approx 2.8^\circ$

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio telescope observations of moon

- Parkes
- GLUE (Goldstone)
- Kalyazin
- LUNASKA (Parkes/ACTA)
- nuMoon (WSRT)
- RESUN (EVLA)
- LOFAR
- SKA
Lunar concept (Jeager, Mutel, Gayley)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Overview of lunar cherenkov (JMG)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
frequency: aperture v threshold

\[ \Theta_c = \Theta_{TIR} \]

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, \( E \) [GeV] vs. \( E^2 \) [GeV^2 cm^2 s^{-1}] for different energies."
CR 100x $\nu$ – what to do

- separate $\nu$ from CR? (spatially, by features (e.g. $\gamma$-ray astronomy))
- proximity of surface suppresses CR signal
- up rate dominates?
- return to high-f?
- true for orbiter, too. (LORD)
- (JRS) fluxes already nu-optimistic
- some science still OK?
  - point sources
  - cross-sections

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Lunar technique

- promising for CR

- techniques going forward – see other talks
  - ATCA: coherent addition of signals from several ants
  - LOFAR: triggering(?)

- difficult for nu’s

- a lot of detail still to be done
  - see ANITA list of details
Satellites: Lunar satellites

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
FORTE (Lehtinen, et al.)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
PRIDE (Miller, et al.: Europa)

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Summary

- Cosmogenic neutrinos have something to say about UHECR origins
- Askaryan effect verified. Common understanding of Askaryan and geomagnetic
- Next generation of in-situ arrays ARA/ARIANNA 10’s of events/yr
- Lunar observations difficult for UHE neutrinos due to UHECR background
extra slides
Constant index of refraction

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Comparison – for discussion only (Dec 2009)
Neutrino detection

- Simulation
  - event generator
  - event simulation

- Detector

- Operations

- Analysis
  - calibration
  - backgrounds
  - reconstruction
Magnetic Monopoles

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Worlds best limit for (relativistic) monopoles
1. Acceleration predictions depend on scenario – could be “no ν’s”.
2. “GZK” neutrinos are guaranteed – a guide for experiment design.
4. Constraints from EGRET & UHECR
5. $E_\nu \sim 0.05 \ E_p$

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Scaling of Askaryan signals

- \( R \): Moliere radius
- \( L \): Width of shower max
  - Hadronic
  - EM: LPM effect

\[
\text{total track length} = \frac{E}{dE/dx} = S \times L
\]
Askaryan

Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Radio detection of cosmic neutrinos, NOW-12 (Seckel)
Go Remote: aperture $v$ threshold

\[ \Gamma \sim \int_{E_{\text{thr}}} E^{-\alpha} R^2 dE = E_{\text{thr}}^{-\alpha} R^2 \]

\[ \Gamma \sim R^{3-\alpha} \]

\[ \begin{cases} E^{-3} \quad \text{ok} \quad \text{Go Remote!} \\ E^{-2} \quad \text{wins} \end{cases} \]

Radio detection of cosmic neutrinos, NOW-12 (Seckel)