Antarctic Neutrino Detection Experiments Utilizing The Askaryan Effect In-Ice, Which Begin And End With The Letter “A” And Have Either 2 or 3 Syllables (but definitely not more than 3)

- ANITA (balloon)
- ARA (South Pole)
ANITA/ARA science

• Primary mission: “GZK neutrinos” caused by photo-production of UHECR on CMB: $\gamma N \rightarrow \Delta \rightarrow \pi X \rightarrow \nu X$
  - 2013 Observation by IceCube of first UHE non-atmospheric neutrinos (~PeV)!
  - Sub-GZK, but perhaps there is a high-energy tail that extends into ANITA sensitive energy range?

• Detection scheme: Coherent RF emitted by shower from $\nu N \rightarrow lN' + $shower in-ice collisions.

• Cylindrical shower has dimensions ~10 meters in length; ~20 cm in diameter; Cherenkov radiation coherent down to lambda~20 cm
  - Strategy pioneered by RICE experiment (1996-2012)
  - Signal verified in two SLAC testbeam experiments
ANITA/ARA concept

- Balloon at ~37 km altitude
- Cascade produces UHF-microwave EMP
- Antarctic ice sheet
- Earth
- 0.1-100 EeV neutrinos
- Refracted RF
- Ice
- Cascade
- 56° Cherenkov cone
- 1-3 km
- ~700 km to horizon
- Observed area: ~1.5 M square km

Figure 2: Schematic of the ARA Testbed station.
ANITA/ARA +/-

+ Advantages of the ANITA strategy relative to in-ice:
  - Huge, RF-transparent target volume
  - Triggering near thermal floor in RF quiet environment
  - In-air receivers allow pre-flight calibration
    • Sub-degree resolution in both $\theta$ and $\phi$
    • Better polarization separation for in-air (or on-surface, a la' ARIANNA)

• Disadvantages:
  - Poor depth perception (i.e., cannot tell if an event originated on the surface or sub-surface)
    • But have several handles on neutrino events, nonetheless!
  - Typical distance-to-interaction point is $\sim100$ km
    • Neutrino must be energetic enough to produce detectable pulse!
    • Threshold $\sim 10,000$ PeV (10 EeV)
  - 35 day livetime
ANITA Flight History

• 2004: ANITA-Lite flies 2-chs. Piggyback on TIGER
  – Full verification of DAQ, backgrounds!
• 12/06–1/07: ANITA-1 = First full mission
• 12/08-1/09: ANITA-2 = ANITA-1 + lots of 10-30% improvements to give overall doubling sensitivity!
• 12/14: ANITA-3 = ANITA-2 + significant changes to DAQ, triggering, hardware – targets UHECR detection & extends low-frequency reach
• 12/16: ANITA-4=final ANITA flight; ~ANITA-3
Published Science Results

- Best limits on neutrino flux for $E > 10^{19}$ eV +
  - Radioglaciology: First direct (i.e., time-domain) measurement of crystalline ice Ih birefringence
  - UL on fluxes of ultra-relativistic monopoles
  - GRB neutrinos
  - Lorentz invariance
  - Surface roughness probed by measuring surface albedo @ $\lambda \sim 1$ m
  - Unexpectedly, demonstration of ANITA as a charged UHECR detector via radio emissions!
    - 20 Hpol-dominant events via “geomagnetic + Askaryan” radiation
    - Unique to ANITA – triggering at frequencies >200 MHz
Radio Air Shower Energy Measurements

- Two effects:
  - $\mathbf{v} \times \mathbf{B}_{\text{earth}}$ (uniform polarization, $\mathbf{E}$ transverse to $\mathbf{B}_{\text{earth}}$)
  - Askaryan in-air: radial $\mathbf{E}$
    - (i.e., transverse at all points to Circular Cherenkov ring)
Radio Cherenkov ring (θ_c ~1 degree!)
ANITA-2 → ANITA-3

- Improve sensitivity to RF from UHECR EAS
  - Restore Hpol triggers that were dropped in ANITA2 before we realized ANITA was a UHECR detector!
  - Real time, event-by-event interferometry using 3-bit waveforms lowers trigger threshold to ~2.5 SNR
    - Demonstrated performance @ 300 Hz
  - Add cylindrical Hpol Rx with sensitivity down to 80 MHz to bridge low → high frequency understanding of radio emissions from air showers
    - UNIQUE feature of ANITA-continuous coverage over “coherent” → “partially coherent” radio-frequency regime
Hpol low-frequency antenna hangs under gondola

3 m x 5 m!
f>60 MHz
ANITA-3 UHECR

• Expect to see ~10 UHECR per day via radio emissions
  – Threshold ~1 EeV
  – mean observed energy ~30 EeV
  – Modest improvement w/ ANITA-4
• Excellent UHE aperture!
  – May observe GZK cutoff!
Improving UHECR energy estimate

AUGER/TA: redundant energy measurements!!

- ANITA – only handle via radio; strategy for reducing energy sys error:
  - lowering sensitivity into “well-modeled” f<200 MHz regime with dedicated Hpol cylinder antenna
  - Dedicated testbeam (T-510) just completed to quantify geomagnetic/Askaryan signals
  - More precise measurements of surface reflectivity/roughness over ANITA passband
Refining A1 UHECR energy-estimates

Procedure:
Model CoREAS/ZHSAires prescribes $\Delta \theta_c$ as
Knowing $\Delta \theta_c$, and measured signal amplitude => infer UHECR energy
Experimental set up

Up to a 1000 G vertical “geo” magnetic field created by 15 coils
Calibrating surface roughness via stereoscopic photos

FIG. 1: Antarctic topography along Vostok route (I)
FIG. 2: Antarctic topography along Vostok route (II)
FIG. 3: Antarctic topography along Vostok route (III)

1/14 Data taken by AARI, St. Petersburg – reconstruction of point-clouds in progress
Calibrating surface roughness via Solar albedo

Vpol, Direct Sun v. Reflection

Hpol, Direct Sun v. Reflection
Agreement with Fresnel Coefficients as $f(\text{incidence angle})$

Measured HPol Solar Reflectivity vs. Expectation ($n_{\text{ice surface}} = 1.35$)

Lines = Fresnel H- (top) & V-Pol (bottom)
More precise surface reflectivity probe

- 12/14: ANITA HiCal: Pathfinder class balloon, to be launched within hours of main ANITA-3 launch
  - Tx emits both direct + surface-reflected signal
- to fly within 200 km of ANITA for at least one hour
- Hardware:
  - “custom” transmitter that mimics EAS spectrum (ignition coil or piezo sparker [$10 @ Walmart) fed into a RICE-type dipole antenna
HiCal sparker at 5 mB
Simulated HiCal signal at $r=200$ km
Neutrino sensitivity

- ANITA-3+4: assume 50+50 days (x3 over ANITA-2)
- Factor of ~30% in trigger threshold, 20% in antenna area, better reconstruction & EMI control
- Net gain x3-5 in event rate
- Total improvement: ~1 order of magnitude

+ hundreds of UHECR!
EVA: The balloon is the antenna

Reflectors guide RF to Inner feed array

<table>
<thead>
<tr>
<th>BZ neutrino models</th>
<th>Events, ANITA-II, 28d</th>
<th>Events, EVA, 50d</th>
<th>ratio, EVA/ANITA</th>
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</thead>
<tbody>
<tr>
<td>Mixed UHECR composition [30]</td>
<td>0.05</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td>Minimal, no evolution [3, 32, 33]</td>
<td>0.3-0.9</td>
<td>9.2-38</td>
<td>~ 40</td>
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<tr>
<td>$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, Standard model [3]</td>
<td>0.7</td>
<td>29</td>
<td>41</td>
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<tr>
<td>Waxman-Bahcall $E^{-2}$ flux (minimal) [34]</td>
<td>0.49</td>
<td>6.5</td>
<td>13</td>
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<td>GRB UHECR-sources [46]</td>
<td>1.44</td>
<td>66</td>
<td>46</td>
</tr>
<tr>
<td>Strong source z-evolution [3, 31, 33]</td>
<td>2.2-5.3</td>
<td>40-60</td>
<td>11-18</td>
</tr>
<tr>
<td>Maximal, saturate all bounds [31, 33]</td>
<td>16-25</td>
<td>180-220</td>
<td>~ 10</td>
</tr>
</tbody>
</table>
2014 ARA neutrino detection efficiency (3 analyses)

Plateau efficiency ~40%; at high SNR, lose efficiency by, e.g., requiring that electronics are not saturated
ARA source reconstruction – 3 complementary techniques – resolution ~0.5° to neutrino interaction point
Coherently Summed Waveform and template-based analysis (latter: independent MC simulation!)
ARA result

The graph illustrates the energy spectrum of cosmic rays, showing data from various experiments including ANITA II '10, Auger '11, IceCube '12 (2yrs), and RICE '11. It also includes data from the ARA TestBed (2011-2012, 224 days) and ARA37 (3yr) experiments. The shaded regions represent the estimated range for GZK, Koteru '10.
ANITA-3 will fly in December, with major hardware improvements over ANITA-2; HiCal to follow.

In addition to enhanced neutrino sensitivity, effort to maximize UHECR sensitivity AND reduce systematic errors on UHECR energy estimate.

- Target 25% overall energy error

ANITA-4 has just been approved for 2016-17 flight.

ARA currently = testbed + 3 “deep” stations. ARA-2 & ARA-3 neutrino limit en route within the next couple of months.

But, future uncertain. No funding for two years, and no more deployment until 2015-16 (at the earliest).
Emission of radio signals from air showers

- Coherent at MHz frequency
- Two main emission mechanisms:

1. Geomagnetic emission
   Deflection of $e^-$ and $e^+$ in Earth's magnetic field
   $\rightarrow$ time dependent transverse current,
   linearly polarised $\vec{E} \propto \vec{v} \times \vec{B}$

2. Askaryan effect
   Time variation of net charge excess
   $\rightarrow$ linearly polarised,
   $\vec{E}$ radial oriented around shower axis

Same mechanism as in-ice,
But larger size=>coherence
@lower frequencies