Future Prospects of UHE neutrino detection with Electromagnetic Fields

Dr. Jordan Hanson[1]

[1]Department of Physics and Astronomy
University of Kansas, Lawrence, KS, USA

VHEPA 2014

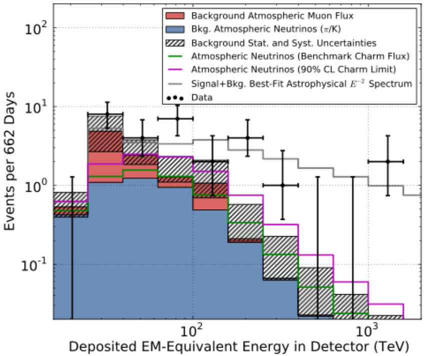
Outline

1. Introduction and Physical Arguments
2. Experimental Mechanisms
3. Experimental Approaches in the Future
4. Summary and Conclusions

Introduction and Physical Arguments

- Why are UHE neutrinos from the cosmos interesting?
- Origin of cosmic rays from weakly interacting particles - 100 YEAR PROBLEM.
- Confirmation of Standard Model decay modes at extraordinary energies
- Physics beyond standard model affects neutrino event rates, cross-section, and flavor physics
- Example of a proposed experiment **using** UHE neutrinos

- IceCube measured neutrino spectrum up to 1 PeV: index $dN/dE \propto E^{-2.2\pm0.4}$.
- Raises several interesting questions...
- Gap in energy, favoring spectral cutoff?
- Uncertainty in spectral index, and confirmations of WB bound

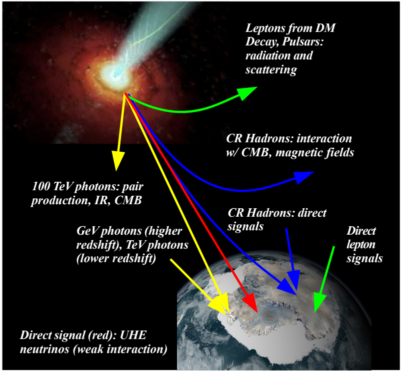


- Can we project this spectrum to next generation detectors, or GZK scale?
- Can remain consistent with the data and vary index within errors, project upwards in energy.

Model and Reference	Model Class	Predicted N_ν	MRF $(2.3/N_\nu)$
ESS Fig. 4 $(\nu_e + \nu_\mu)$ [9]	No source evo.	30.8	0.0746
Kotera (2010) Fig. 1 [5]	SFR1, Pure Proton	37.1	0.0621
ESS Fig. 9 [9]	Strong evo.	104.9	0.0219
Kalashev Fig. 2 [8]	High E_{max}, $z \leq 2$	96.1	0.0239
Barger Fig. 2 [6]	Strong evo.	114.9	0.0200
Yuksel, Kistler (2007) [7]	SFR evo.	45.4	0.0506
Yuksel, Kistler (2007) [7]	QSO evo.	55.5	0.0414
Yuksel, Kistler (2007) [7]	GRB evo.	156.1	0.0147
Ave et al. (2005) [2]	Pure Fe comp.	11.3	0.204
Todor Stanev [10]	Fe, CMB+IRB	2.40	0.956
Kotera Fig. 7 upper [5]	Mixed comp.	21.7	0.106
Kotera Fig. 7 lower [5]	Pure Fe	7.50	0.307
Fermi-LAT [3]	$E_{cross} = 10^{17.5}$ eV	15.5	0.148
Fermi-LAT [3]	$E_{cross} = 10^{18.0}$ eV	21.1	0.109
Fermi-LAT [3]	$E_{cross} = 10^{18.5}$ eV	32.9	0.0699
Fermi-LAT [3]	$E_{cross} = 10^{19.0}$ eV	42.8	0.0.0537
WB (1999) [1]	No source evo.	22.4	0.103
WB (1999) [1]	QSO evo.	67.1	0.0343
Olinto review (2011) [4]	Fe, $E_{max} = 100$ EeV	0.14	16
Olinto review (2011)	Mixed, $E_{max} = 10$ EeV	0.068	33
Olinto review (2011)	Proton, $E_{max} = 3$ ZeV	101.3	0.0227
Olinto review (2011)	Various protonic, SFR	37.1	0.0621
IceCube Meas. (2013, ≤ 1 PeV) [11]	E^2 diffuse fit.	57.7	0.040
IceCube Meas x 2 (2013, ≤ 1 PeV) [11]	E^2 diffuse fit.	115.5	0.020
IceCube Meas. (2013, ≤ 1 PeV) [11]	$E^{-2.2}$ diffuse fit.	0.830	2.77

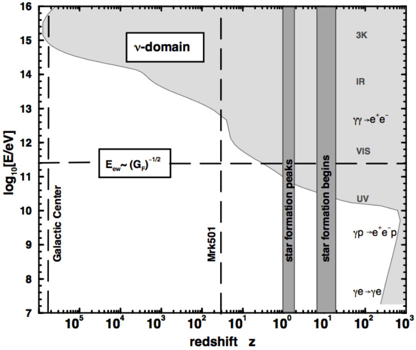
Table 2: Tabulation of the full ARIANNA sensitivity against various models for the astrophysical neutrino flux. Note that the final lines include the recent IceCube reported results [11].

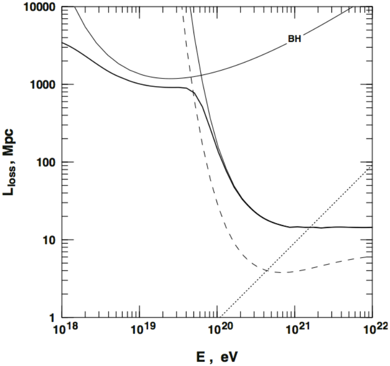
Why are UHE neutrinos from the cosmos interesting?



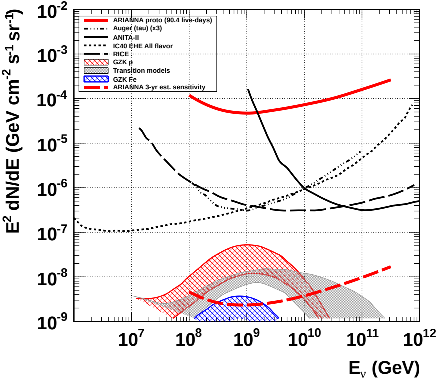
- CR: Lower enery (galactic) hadrons must diffuse to Earth. Rigidity considerations. Z=[1:56].
- EAS from 10^{17}-$10^{19.5}$eV hadrons, deflected by 1-10 degrees. GZK effect above.
- GeV photons interact directly, predominantly galactic sources (fewer extra-galactic).
- $>$ 100 TeV photons absorbed in IR, CMB, pair-production.
- Leptons (electrons, positrons) radiate, diffuse and scatter. Only diffuse signal is measured.
- Neutrinos interact weakly with Earth, direct from CR decay/source.

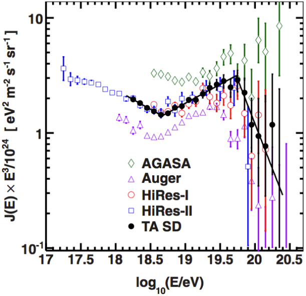
Why are UHE neutrinos from the cosmos interesting?





Confirmation of particle physics decay modes at extraordinary energies



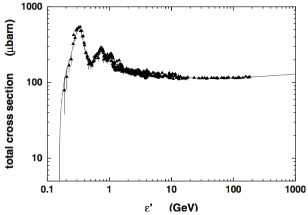


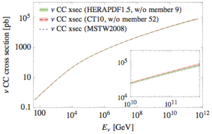
$$p^+ + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

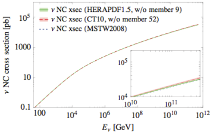
$$\pi^+ \rightarrow e^+ + \bar{\nu_\mu} + \nu_\mu + \nu_e$$

$$n \rightarrow p^+ + e^- + \bar{\nu_e}$$

Confirmation of SM decay modes at extraordinary energies





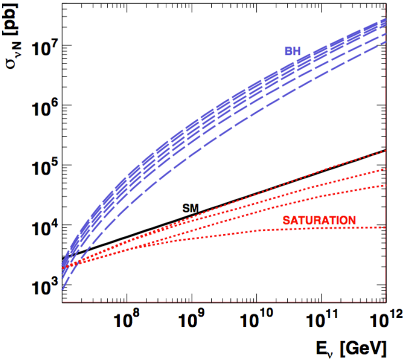


- The $\Delta^+(1232)$ interaction is infered from lab measurements.
- Can we really treat the GZK interaction like lab measurements with Lorentz boost?
- What are the deep-inelastic scattering cross-sections for CC and NC interactions well above the weak-scale?

Physics beyond standard model affects neutrino event rates, cross-section, and flavor physics

- Several ways to change UHE neutrino cross section w/ BSM phyisics
- Microscopic black holes/Extra dimensions (increase)
- Lorentz-invariance violations (change mean energy)

$$\sigma_{BH} \approx E_\nu^{1/2} \left(\frac{1}{M_D^2}\right)^{\frac{n+2}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{3+n}{2})}{(2+n) M_{BH}}\right)^{\frac{2}{n+1}}$$



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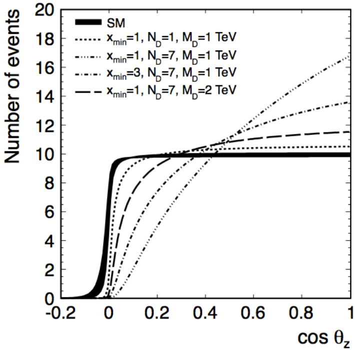
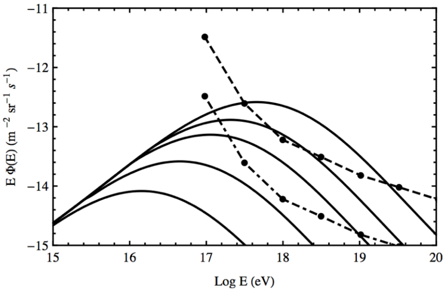


Physics beyond standard model affects neutrino event rates, cross-section, and flavor physics

- Several ways to change UHE neutrino cross section w/ BSM phyisics
- Microscopic black holes/Extra dimensions (increase)
- Lorentz-invariance violations (change mean energy)
- Additionally, space-time foam dispersion

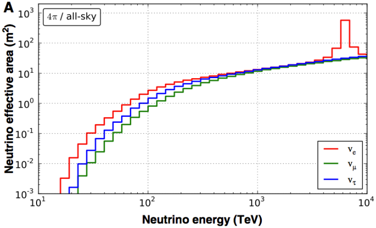


Physics beyond standard model affects neutrino event rates, cross-section, and flavor physics

- Neutrino flavor oscillations average to democratic distribution...to first order. Flavor ratio after cosmic oscillations:

$$(1-2\Delta):(1+\Delta+\bar{\Delta}):(1+\Delta-\bar{\Delta})$$
$$\Delta \approx O(\sin(\epsilon)) + O(\sin(\theta_{13}))$$
$$\bar{\Delta} \approx O(\sin^2(\epsilon)) + O(\sin^2(\theta_{13})) + O(\sin(\epsilon)\sin(\theta_{13}))$$

$$R_\mu = \frac{\phi_{\nu\mu}}{\phi_{\nu e} + \phi_{\nu\tau}} \approx \frac{1}{2} + \frac{3}{4}(\Delta + \bar{\Delta})$$



$$R_{GR} = \frac{\phi_{\bar{\nu} e}}{\phi_{\nu\mu} + \phi_{\bar{\nu}\mu}}$$

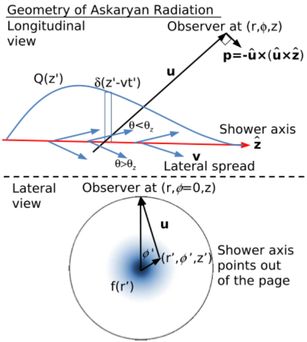
R_{GR} is also proportional to Δ and $\bar{\Delta}$. We need more IceCube events and more data at higher energies.

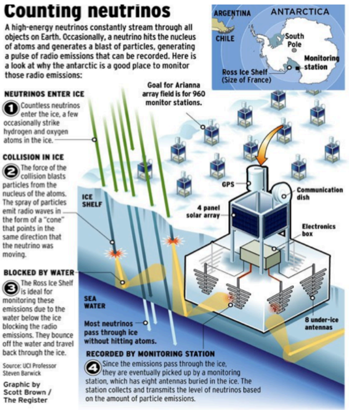
Experimental Mechanisms

- Electromagnetic fields from the Askaryan Effect in Ice
- Similar efforts involving moon
- Electromagnetic shower from tau-decay in atmosphere (detailed discussion: G. W-S. Hou and J. Alvarez-Muniz)
- Cerenkov photons forming tracks/showers in ice.

Askaryan Effect

Charge excess in hadronic and electromagnetic components radiates GHz (RF) pulse in dielectric medium.

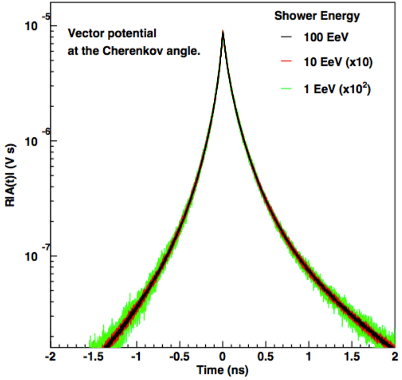


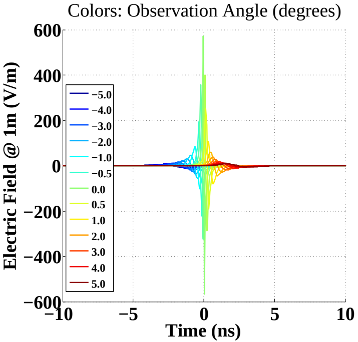


Article in the OC Register:
Pat Brennan and Scott Brown, Dec 9th,2011

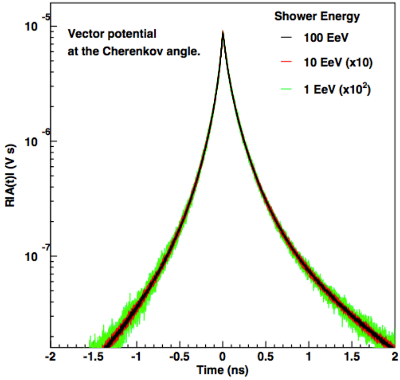
Askaryan Effect

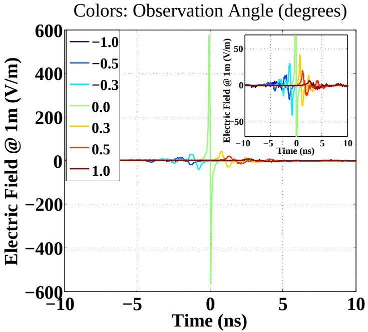
Vector potential: 0.3° degrees off-cone.





Askaryan Effect w/ LPM effect

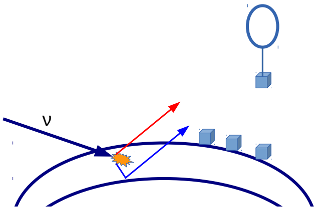


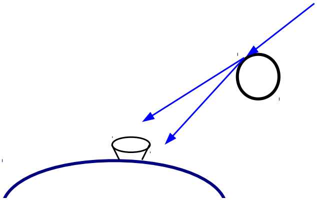


Askaryan Effect Detection

- Balloon detectors - wide field of view, long distances (high thresholds)
- Surface detectors - low threshold (require many)

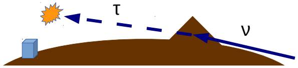
- Radio reception from Lunar regolith - very long distances (high threshold)





Earth-skimming tau Detection

- Tau flavor neutrino converts to charged tau lepton via CC
- Tau lepton decays in atmosphere producing electromagnetic shower
- Cerenkov photons, Askaryan...lower energy means less power
- Tau regeneration



Experimental Approaches in the Future

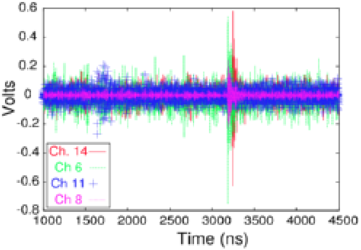
- ANITA - Balloon class Askaryan
- ARIANNA - Surface array Askaryan
- EVA - Balloon class Askaran
- The Moon - Ground based radio telescopes
- Ashra-NTA - G.W-S. Hou
- Auger - J. Alvarez-Muniz
- PRIDE - **Using** neutrinos as a measurement tool.

Precursor: RICE (Radio Ice Cerenkov Experiment)

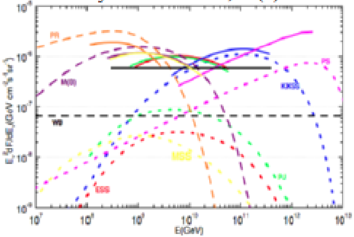
RF can travel km in ice.

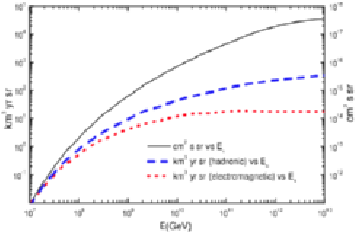
RICE
ANITA
ARIANNA
ARA
EVA

Radio Ice Cerenkov Experiment – Array of Dipole antennas at the South Pole

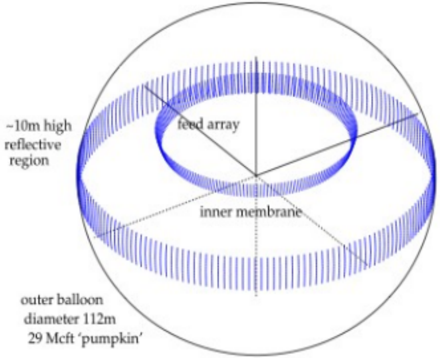


Kravchenko, I., et al. (2006). RICE limits on the diffuse ultrahigh energy neutrino flux. Physical Review D, 73(8).



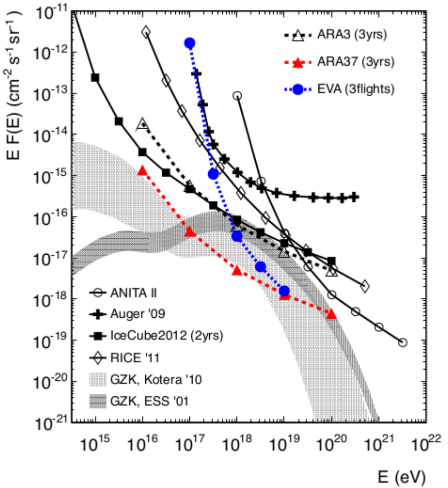


ANITA and EVA

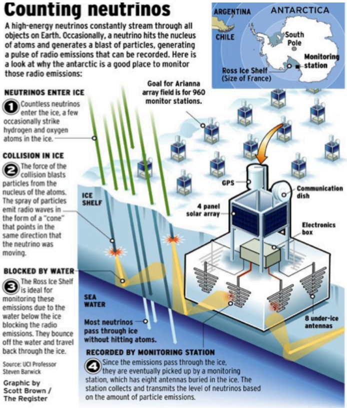


Balloon Exeriments - ANITA and EVA

- Higher end of the spectrum can be constrained by current ANITA data
- EVA: longer flight duration, larger collection area, and consistent altitude improve sensitivity
- ANITA: observed radio geomagnetic cosmic ray pulses. Current work at SLAC to reproduce this effect in controlled magnetic field, and compare to CoREAS from Corsika.
- http://www.symmetrymagazine.org/ 2014/cosmic-rays-on-demand



ARIANNA - Antarctic Ross Ice Shelf Antenna Neutrino Array



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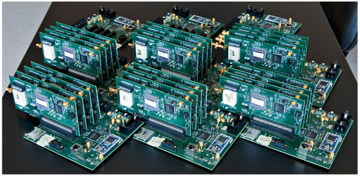
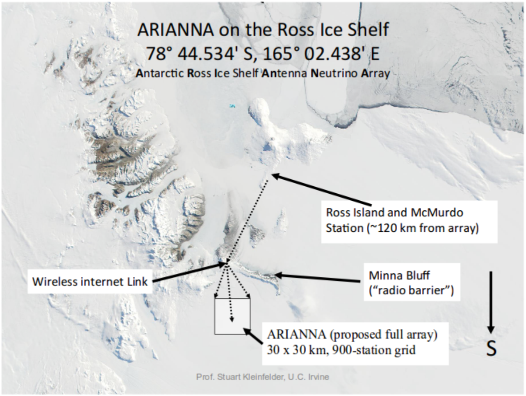
- Attenuation lengths ≈ 500 m, high relfection
- Far from backgrounds, close logistics
- PhD Dissertation, Jordan Hanson (2013 UCI)
- PhD Dissertation, Joulien Tatar (2014 UCI)
- "Design and Performance of the Autonomous Data Acquisition System for the ARIANNA High Energy Neutrino Detector." S. Kleinfelder for ARIANNA collab. IEEE Transactions on Nuclear Science, v.60 (2), 2013
- "A Radio Detector Array for Cosmic Neutrinos on the Ross Ice Shelf" S.R. Klein for ARIANNA collab. IEEE Transactions on Nuclear Science, v.60 (2), 2013

ARIANNA is Under Construction and Taking Data

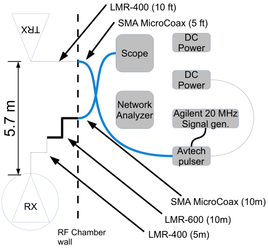
2012 ARIANNA Station Production

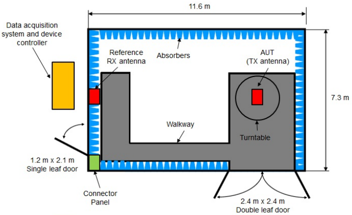




What does the UHE neutrino signal look like?

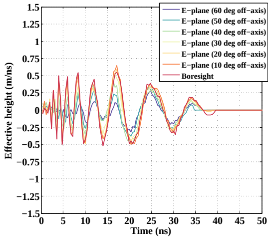
- Response of logarithmic-dipole array antennas
- Response of amplifier, filters etc.
- Measured properties of Ross ice shelf
- Combine with knowledge of pure signal to search data
- Correlate against thermal background
- Look for paper next month on arXiv.org

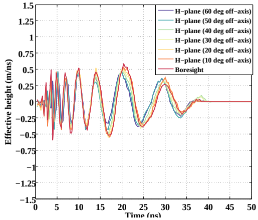




Results for ARIANNA signal antennas

- Can derive response knowing r, V_{src}, and V_L
- r: distance between antennas
- V_{src}: input pulse
- V_L: observed voltage on oscilloscope
- $V_L(t) = \frac{Z_0}{2\pi r c Z_L} h_{rx} \circ h_{rx} \circ \dot{V}_{src}(t)$





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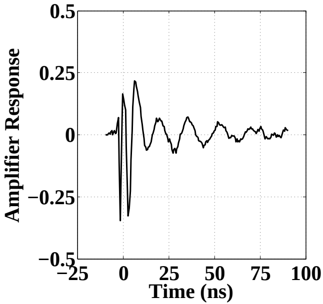
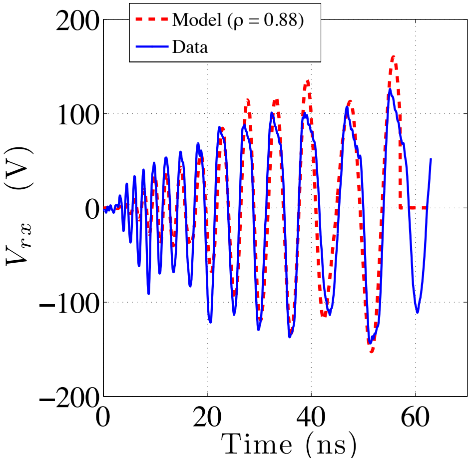
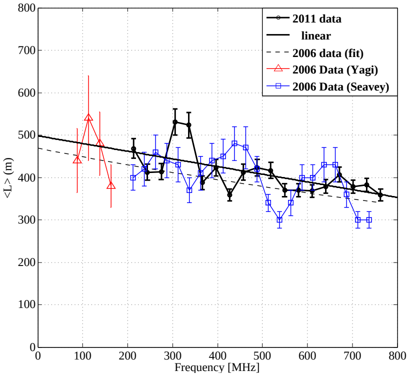


Results including Amplifier+Antennas (Pearson's $\rho = [-1, 1]$)

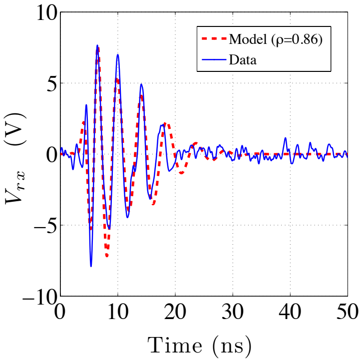


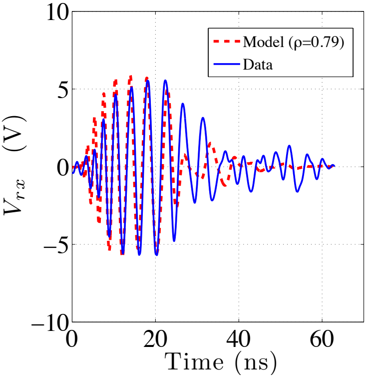
Results for Moore's Bay RF Attenuation Length

- Derive RF attenuation length from radio echos from ocean
- Known as radio-echo sounding
- About -16 dB/km
- Paper on arXiv.org in late April

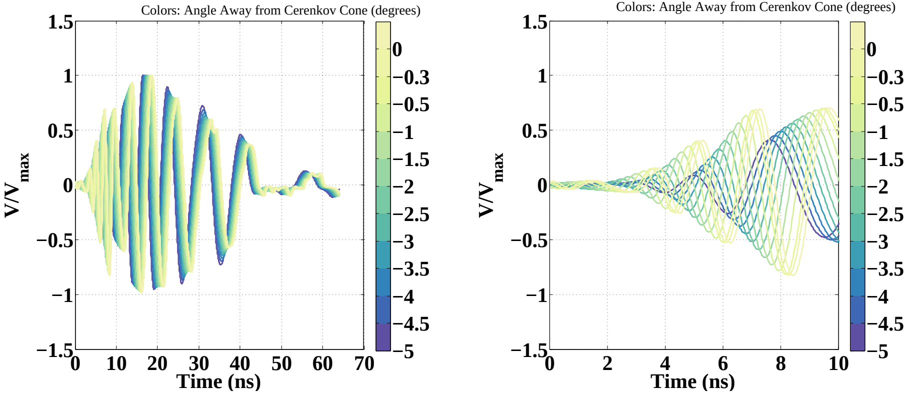


Results including Amplifier+Antennas+Ice Attenuation+Ice Depth

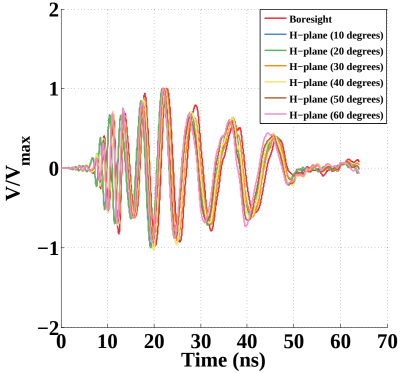


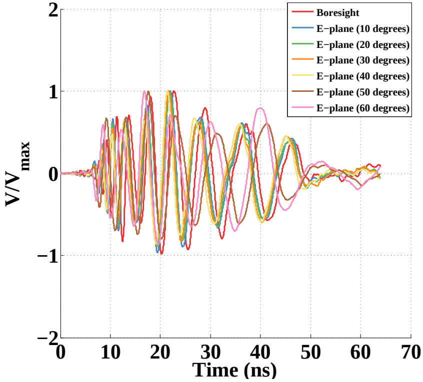


Including the Askaryan Signal as Input

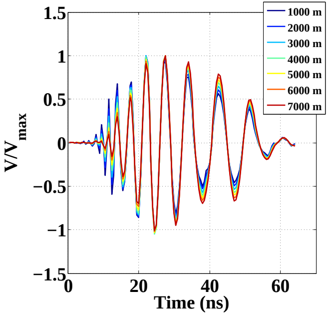


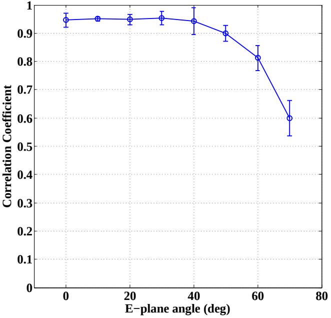
Including the Askaryan Signal as Input w/LPM effect (0.3° off-cone)





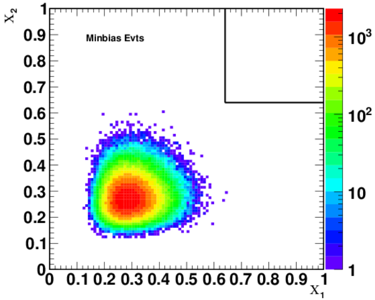
Two more effects: ice and template cross-correlation

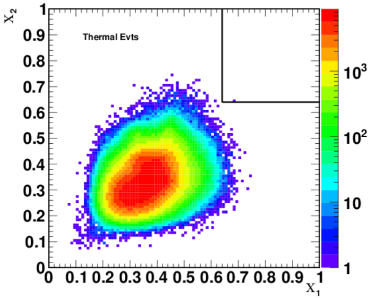




- The ice as giant attenuator (dielectric)
- Averaging over: ant. angle H-plane, Obs. angle, LPM/no-LPM, Ice

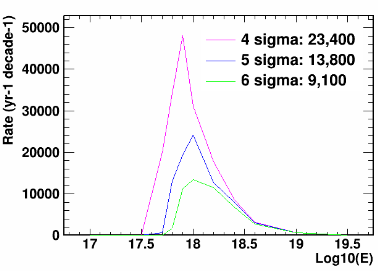
Usefullness of this approach: parallel antennas should have same signal

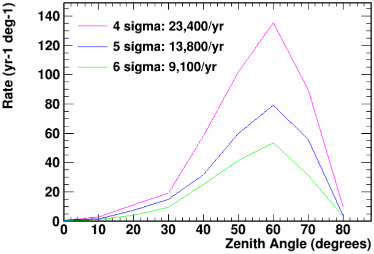




Usefullness of this approach: cosmic rays and CoREAS

Bottom line: about 1-10 UHE cosmic rays detectable per station per year in ARIANNA. Zenith dependence: consider size of radio footprint vs. increasing zenith angle. (These numbers may be adjusted for station parameters - stay tuned).

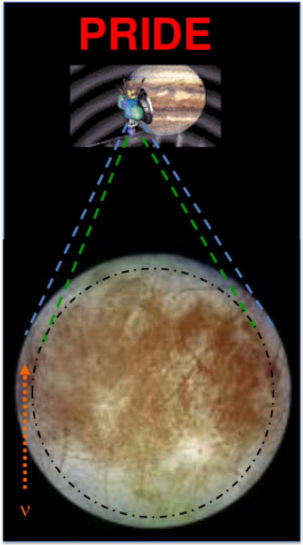




Experimental Approaches in the Future

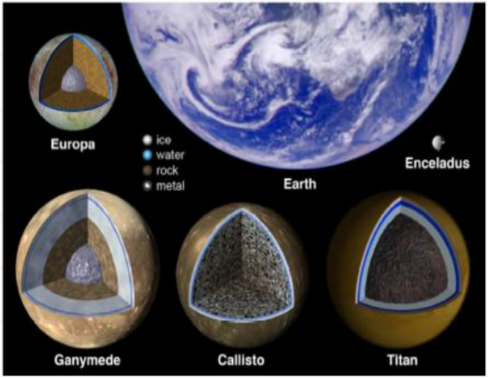
- ANITA - Balloon class Askaryan
- ARIANNA - Surface array Askaryan
- EVA - Balloon class Askaran
- The Moon - Ground based radio telescopes
- Ashra-NTA - G.W-S. Hou
- Auger - J. Alvarez-Muniz
- PRIDE - **Using** neutrinos as a measurement tool.

PRIDE - Passive Radio Ice Depth Experiment



- The geophysical properties of moons of Jupiter and Saturn
- Use cosmic rays/neutrinos as a production mechanism for depth
- Event rate contains depth; depends on several factors
- Collaborators: Johns Hopkins: Tim Miller, Robert Schaefer, H. Brian Sequeira, G. Wesley Patterson
- KU: Dave Besson, Jordan Hanson (awaiting proposal)

PRIDE - Passive Radio Ice Depth Experiment



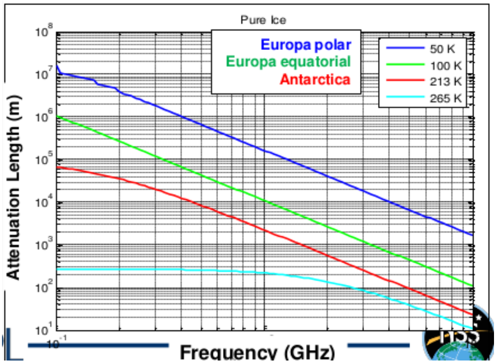
- Complete: Feasibility study (no idea-killing facts discovered about systems)
- Example: Europa ice is maybe few times 10 km thick (gravity), 1500 km radius, 100 K ice
- Keys: High SNR $(10 * (E/[10EeV])^2)$ comes from low thermal noise and long attenuation lengths
- Potential setback: heavily impure ice (shortens attenuation length)

Passive technique vs. Ice Penetrating Radar

Parameter	Ice Penetrating Radar	PRIDE
Dimensions (m)	$10 \times 3 \times 2$ array	$0.3 \times 0.3 \times 0.7$ (3-8 ant)
Mass (kg)	10	5-10 (horn array)
Power (W)	$10^2 - 10^4$ (peak)	10
Frequency (MHz)	5-50	200-2000
Passive/Active	Active	Passive

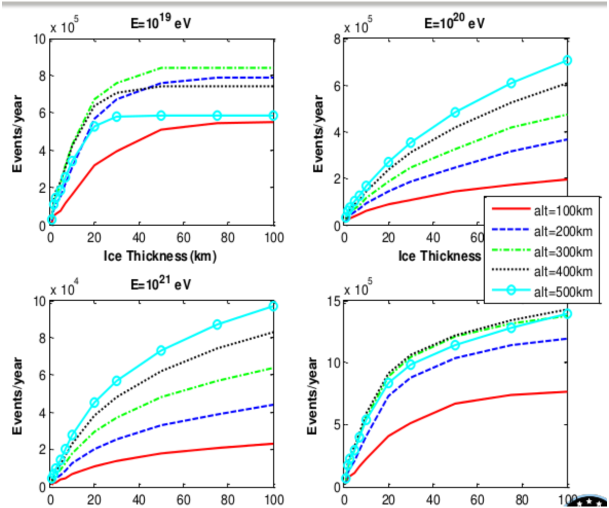
Notes: 1-100 MHz has been used in Antarctica in CReSIS at high power. See for example: https://www.cresis.ku.edu/.

PRIDE - Passive Radio Ice Depth Experiment



- One or two orders of magnitude longer attenuation lengths
- Simulation: 600MHz antennas with effective area $\approx 0.25\text{m}^2$, and background goes as kT/A_{ant}
- Satellite altitude: 100-500 km
- Require events to have SNR ≥ 5

PRIDE - Passive Radio Ice Depth Experiment



Next Steps

- More detailed simulation of neutrino interactions with crust, propagation
- More details on ice impurities
- Optimize multi-antenna detection, effective area
- Study thermal backgrounds from Jupiter, neutrino flux models
- Pin down neutrino flux! (Before satellite arrives)

- Candidate for low-power, GHz frequency transient recorder: ARIANNA
- ARIANNA consumes 10W (factor of 100-1000 smaller than ice penetrating radar
- Built-in trigger w/ pattern recognition

Summary and Conclusions

- The field of UHE neutrino astronomy is progressing forward
- IceCube has measured a signal which raises interesting questions.
- Several potential avenues for new experimental mechanism - Askaryan effect is one
- Electromagnetic field reconstruction separates thermal noise from neutrinos
- Far-future: listening for neutrinos to understand astrobiological environment
- Omnia cum omnibus junguter - "Everything is connected to everything else."

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