Cosmogenic Neutrinos

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Neutrinos Beyond IceCube
April 24th, 2014

THE OHIO STATE UNIVERSITY

CCAPP

NSF

BSF
United States – Israel
Binational Science Foundation

NASA

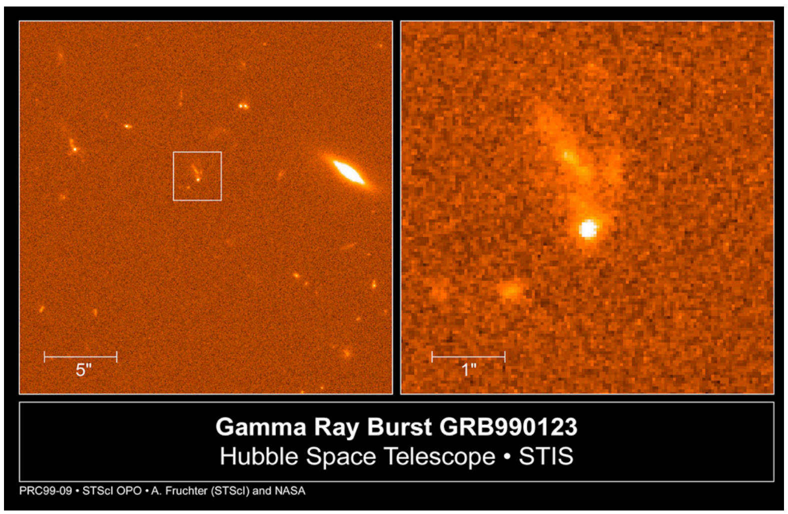
Outline

- 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?



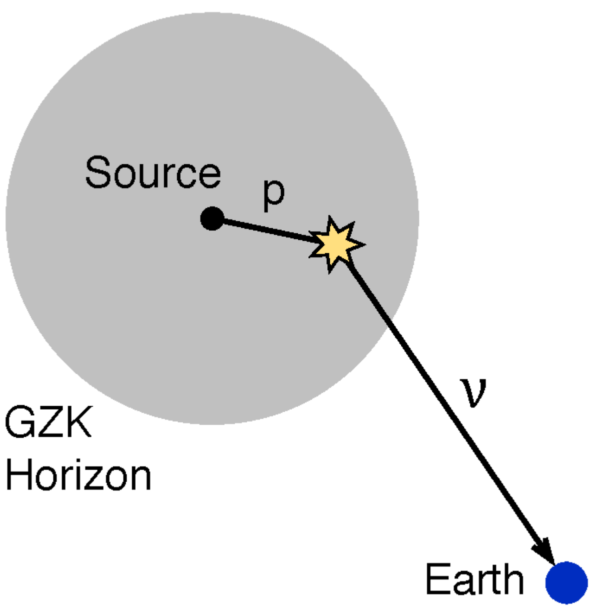
Credit: NASA/Swift/NOAO/Michael Koss (Univ. of Maryland) and Richard Mushotzky

- ~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 ~50 Mpc:



(not to scale)

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

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

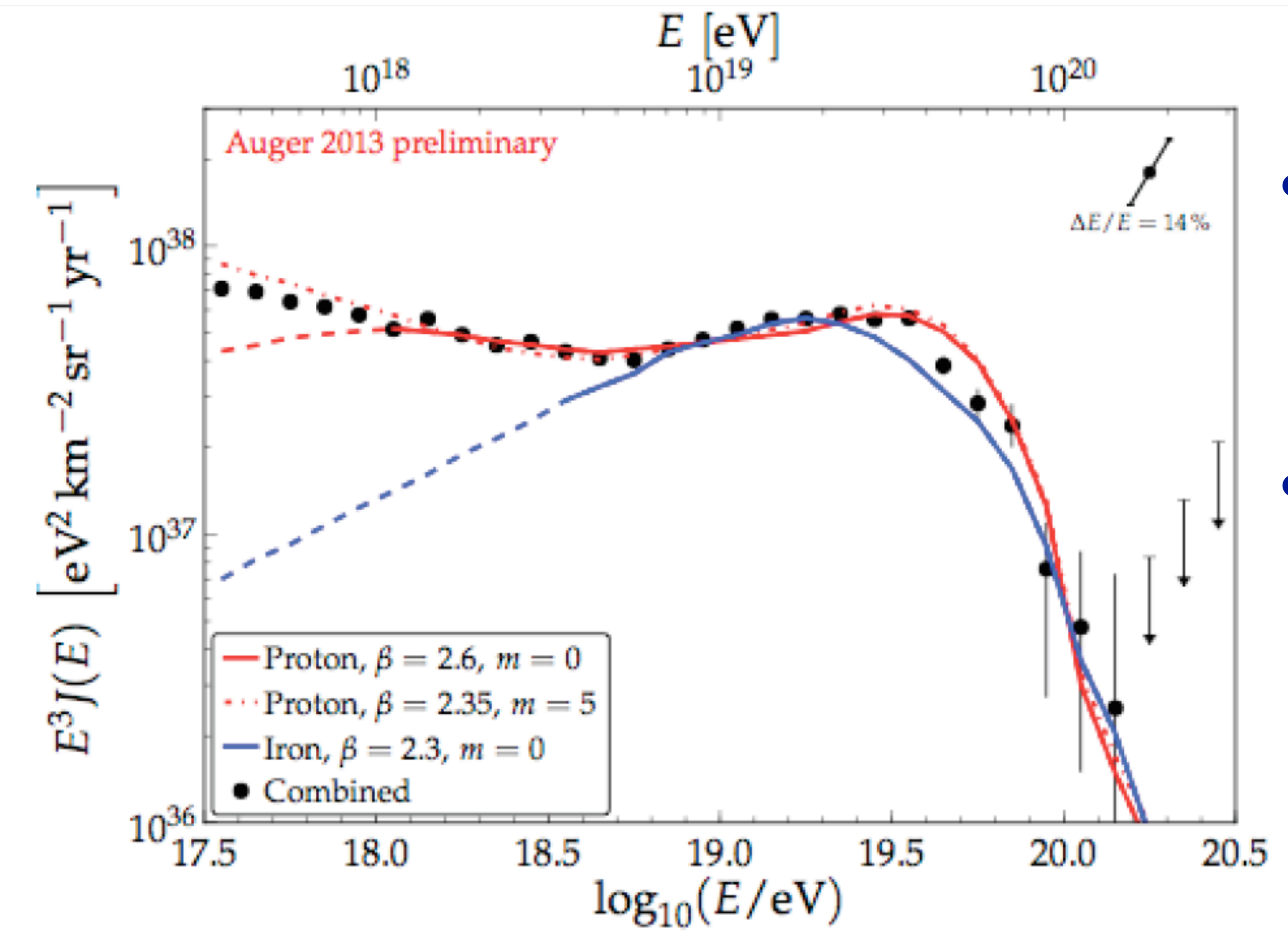
$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^{-} + \overline{\nu}_{\mathbf{e}}$$

$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

$$\mu^{+} \rightarrow \mathbf{e}^{+} \overline{\nu}_{\mu} \nu_{\mathbf{e}}$$

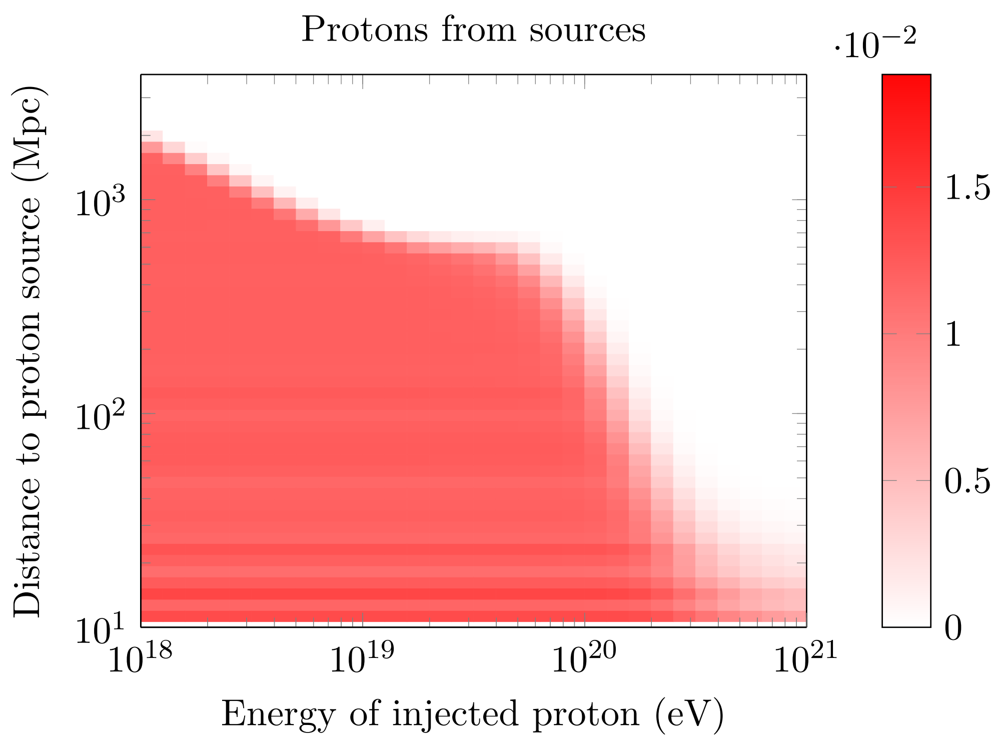
- Other resonances too, they all sit on continuum of $p + \gamma \rightarrow n\ \pi^{+}$

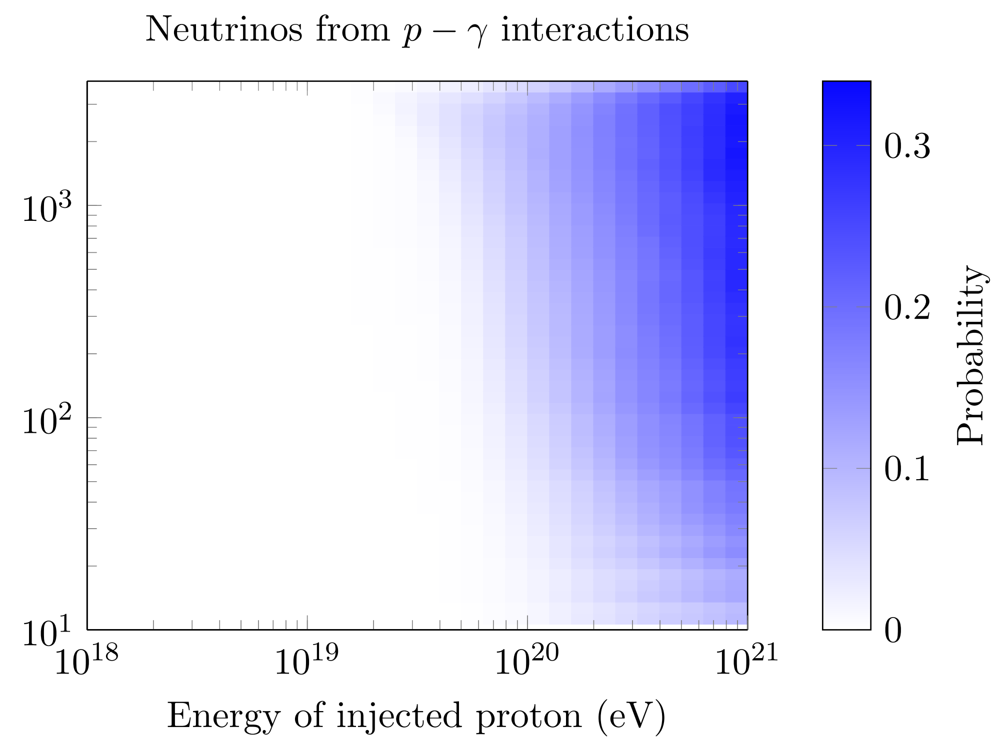
Evidence points to a GZK cutoff...



- 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

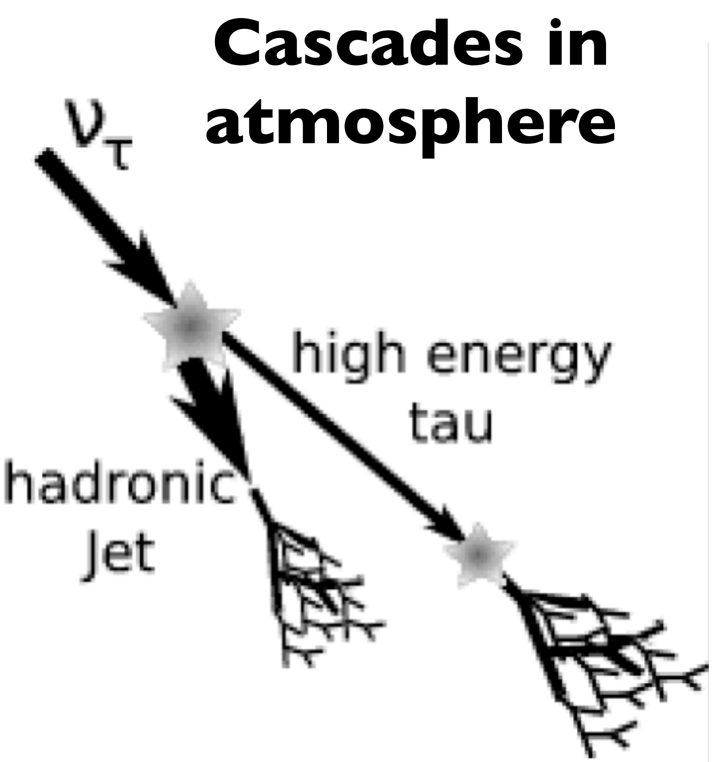
Neutrinos that reach earth with >$10^{17.5}$ eV

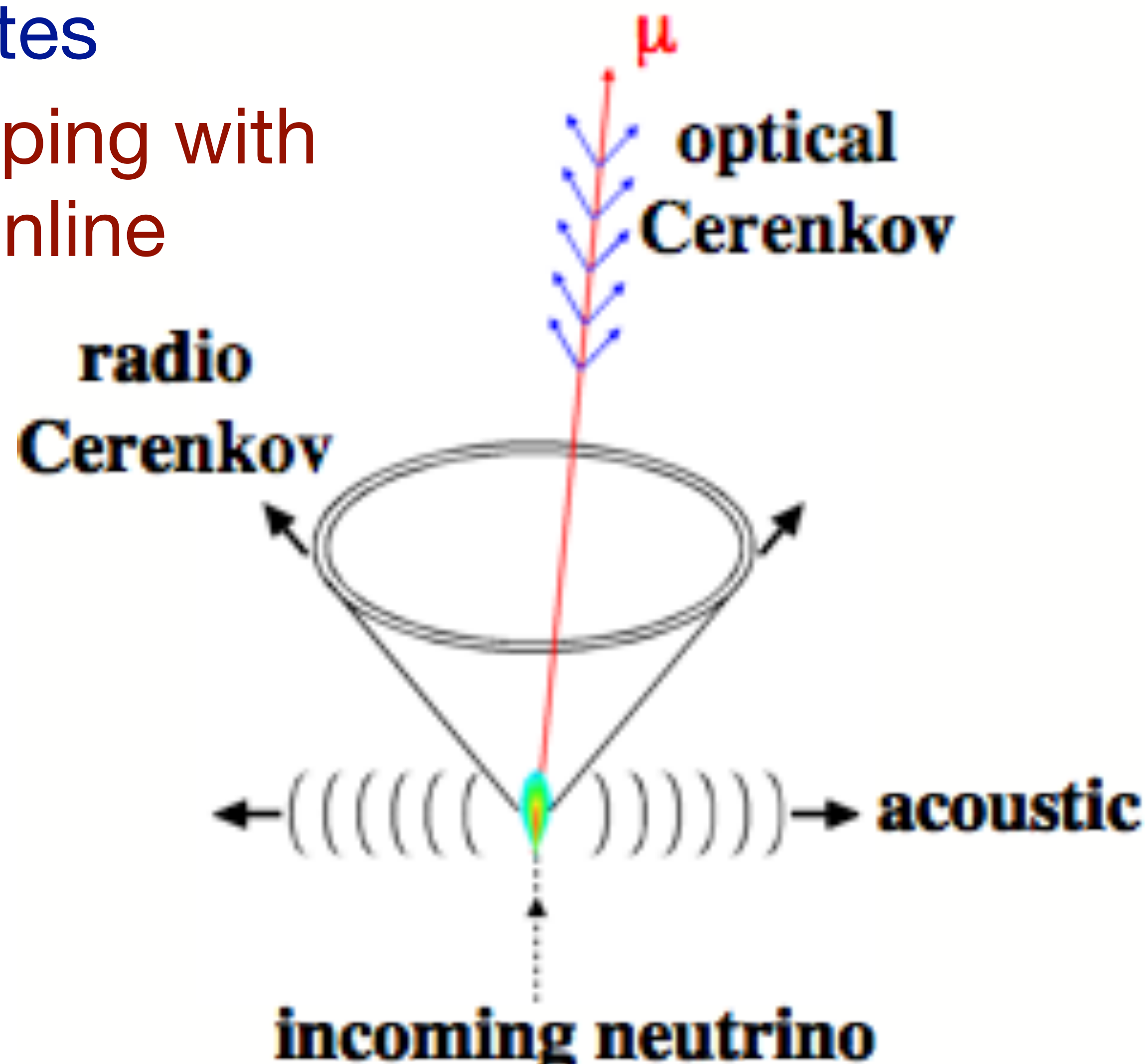
Using CRPropa program, generated protons from sources with flat spectrum, flat redshift dependence to 4 Gpc, propagate through GZK interactions

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





Need to go beyond km^3-scale

$\lesssim$ 10 neutrinos from GZK / km^2 / year

10^{18} eV: νN interaction length ≈ 300 km

→ 0.03 neutrinos / km^3 / year

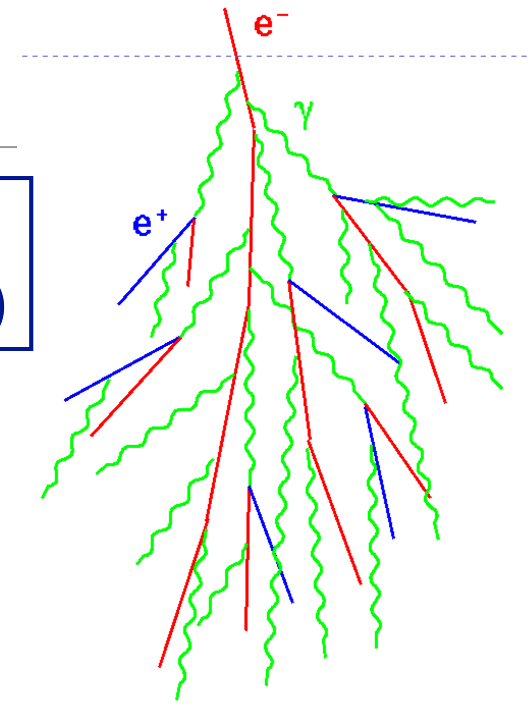
At most, we see 1/2 the sky

→ 10^{-2} neutrinos / km^3 / year

To be assured sensitivity to "guaranteed" GZK-induced neutrino flux, we need ≫10^2 km^3 detection volume!

Radio Cerenkov Technique (Askaryan Effect)

Idea by Gurgen Askaryan (1962)



- Coherent Cerenkov signal from net "current," instead of from individual tracks
- ~20% charge asymmetry develops (mainly Compton scattering)
- Excess moving with v > c/n in matter

  → Cherenkov Radiation dP ∝ v dv
- If $\lambda >> R_{Moliere}$ → Coherent Emission $P \sim N^2 \sim E^2$

  $\lambda > R_{Moliere}$ → Radio/Microwave Emission

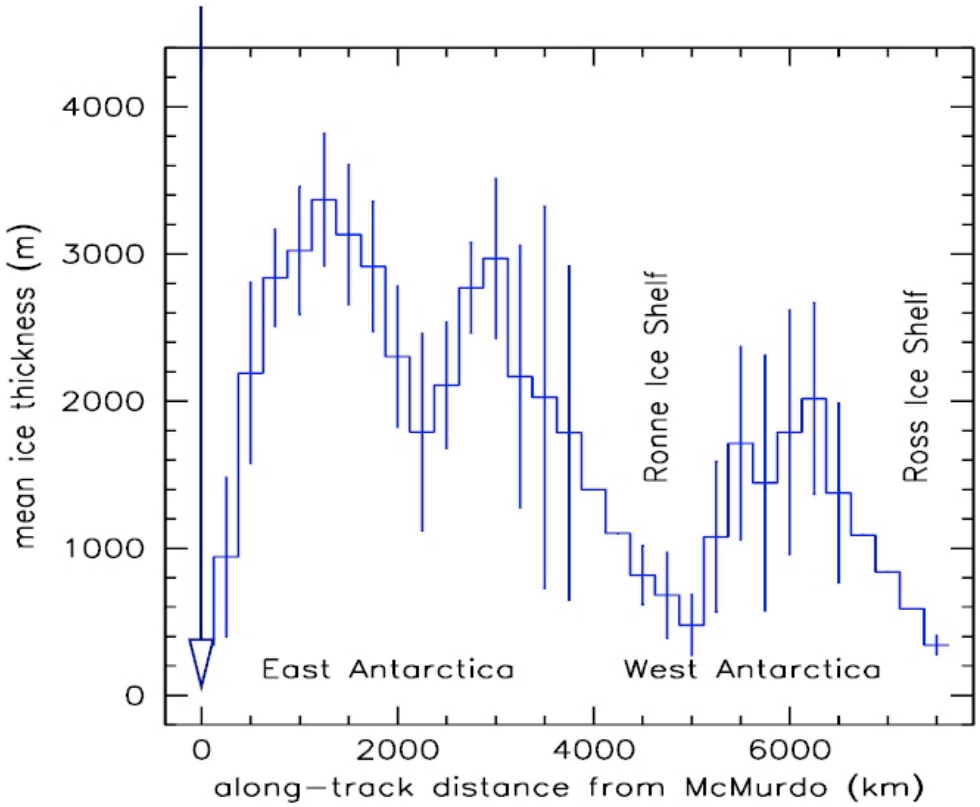
$R_{Moliere} \approx$ 10 cm, L ~ meters → Radio!

This effect has been confirmed experimentally in sand, salt, ice:

PRL 86, 2802 (2002)
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)
PRL 99, 171101 (2007)

Antarctic Ice

Ice thicknesses



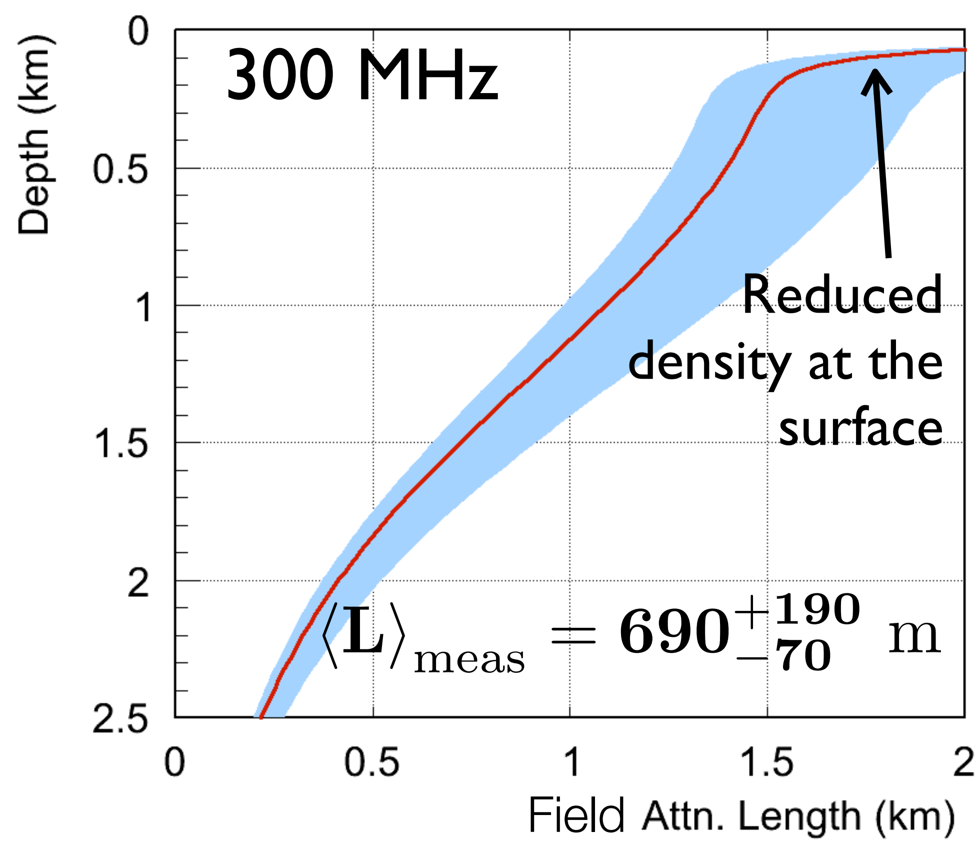
[P. Gorham]

2 km depths are typical across the continent

Radio Attenuation Lengths

0.2 km < depth <1.5 km:

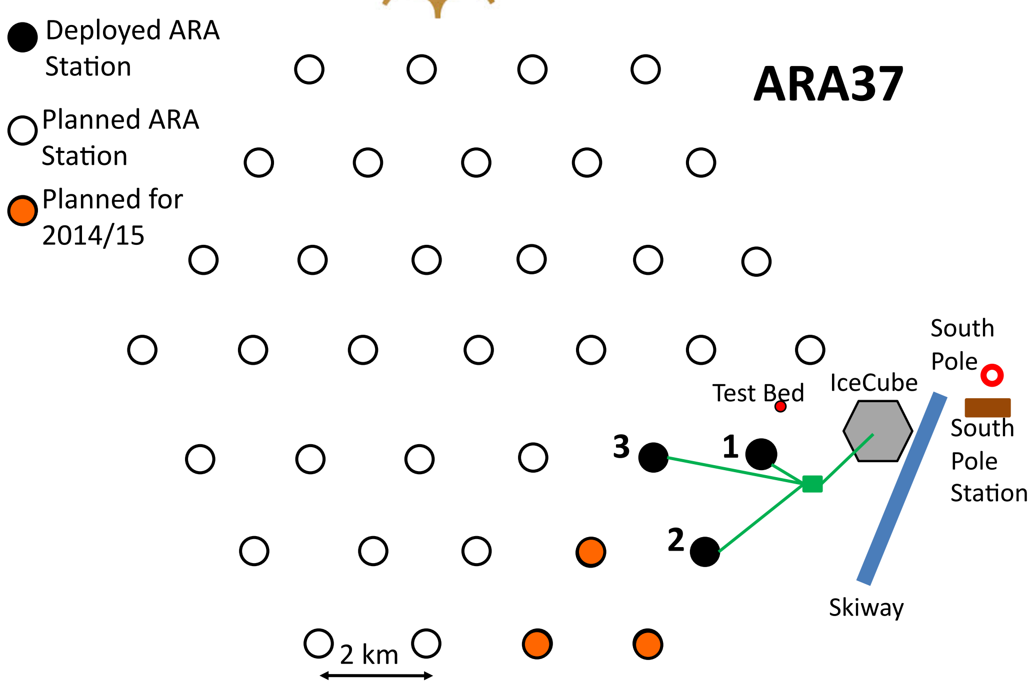
$$\langle \mathbf{L} \rangle_{\text{shallow}} = \mathbf{1200}^{+\mathbf{350}}_{-\mathbf{100}}\ \text{m}$$

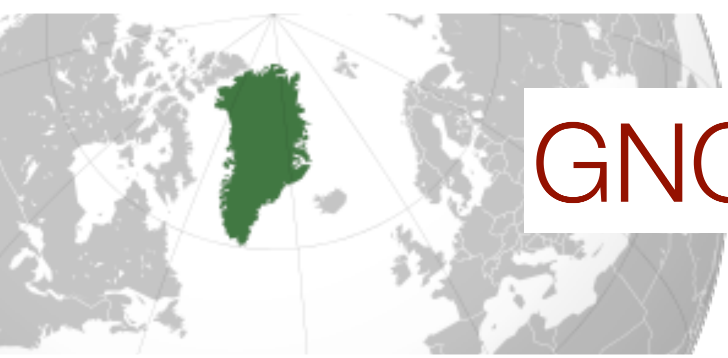


ARA and other *in situ* experiments

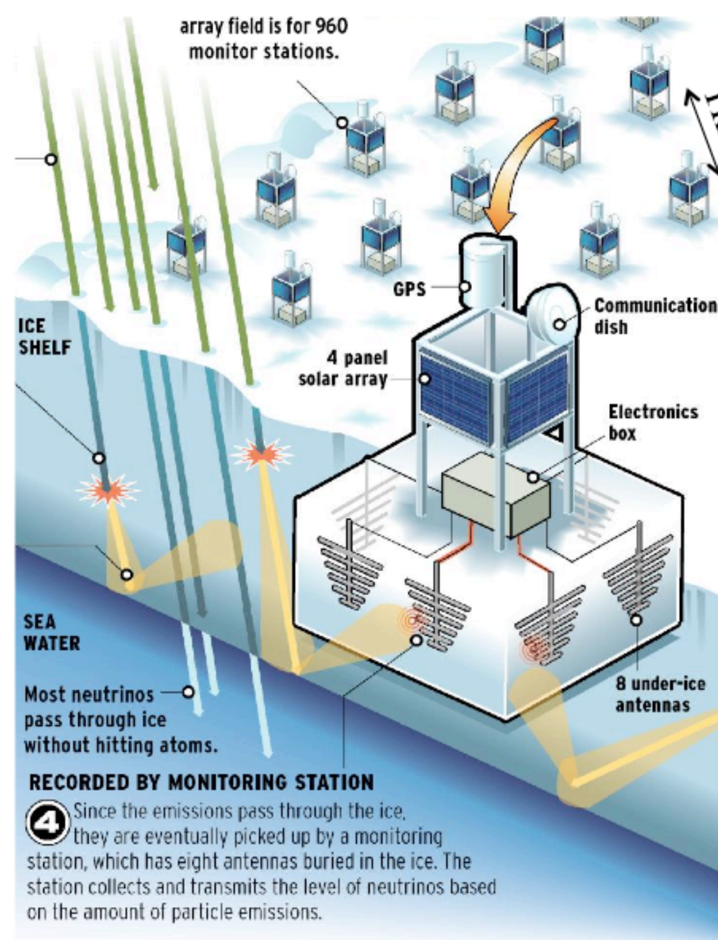
Radio Cerenkov *in situ*

ARA





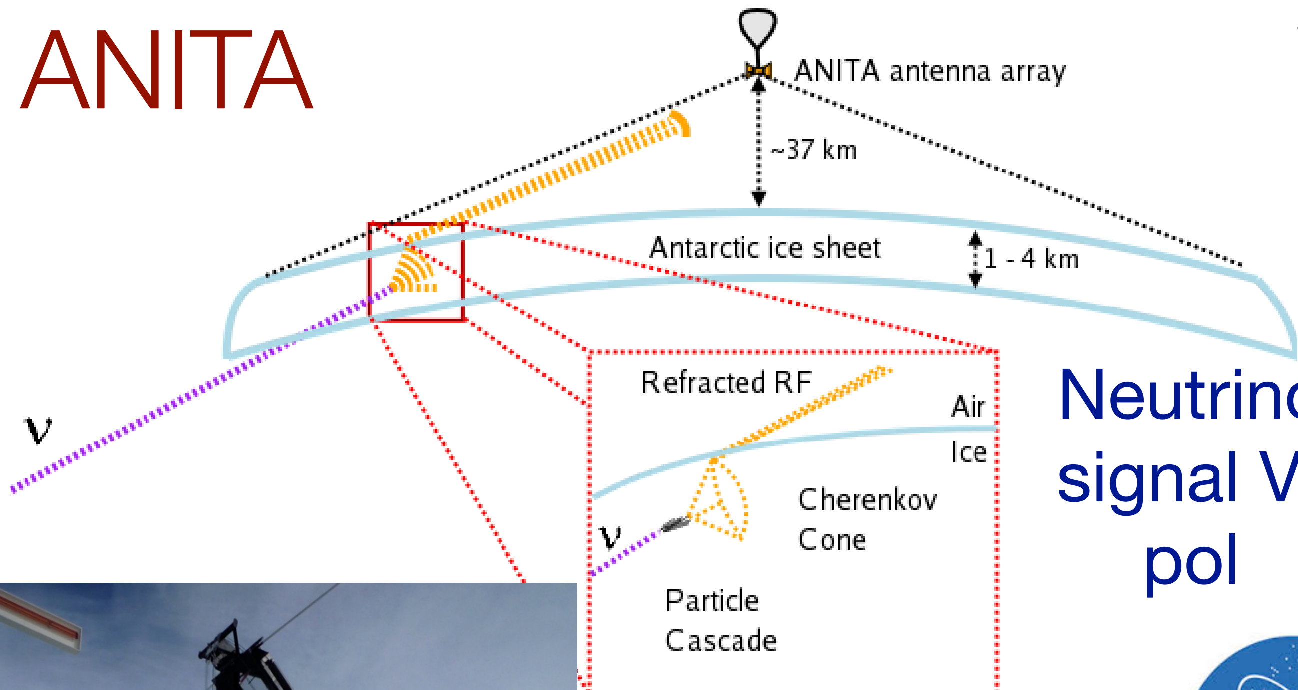
ARIANNA



From OC Register 2012

Radio Cerenkov Balloon Experiments

ANITA

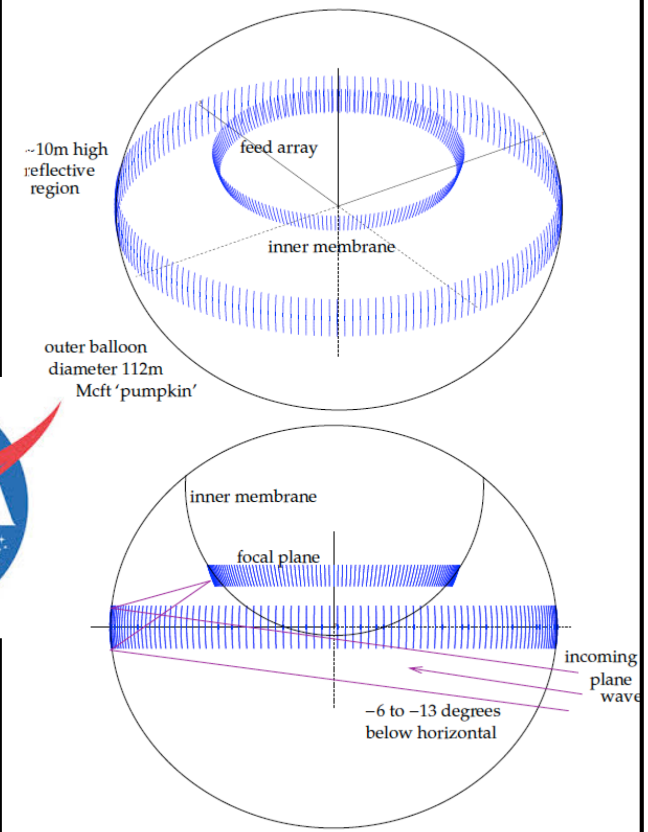


Neutrino signal V-pol

Long duration balloon program operated by NASA

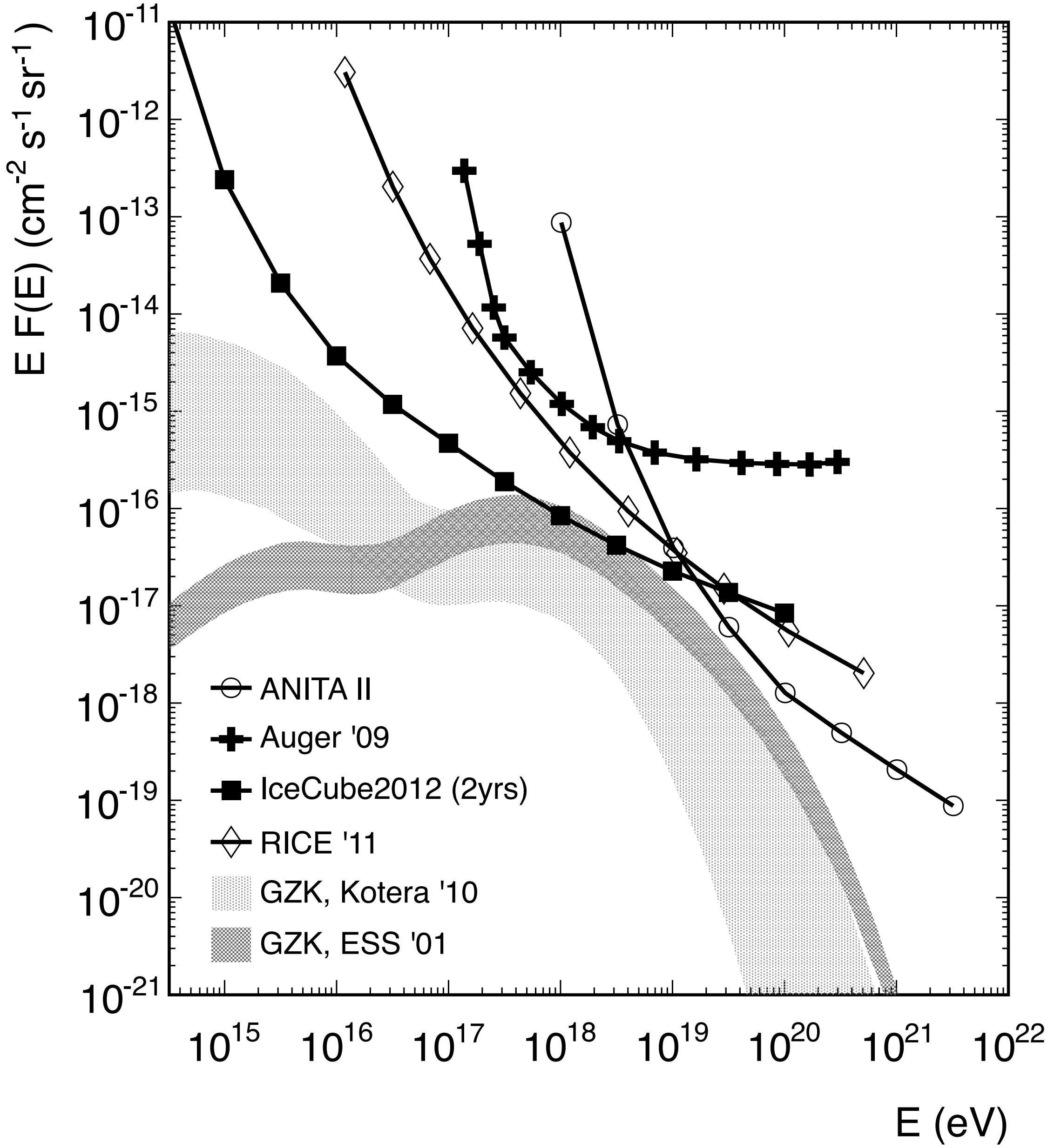
ANITA 1: 2006-2007
ANITA 2: 2008-2009
ANITA 3: 2014-2015

Exavolt Antenna (EVA)



UHE neutrino flux - current constraints

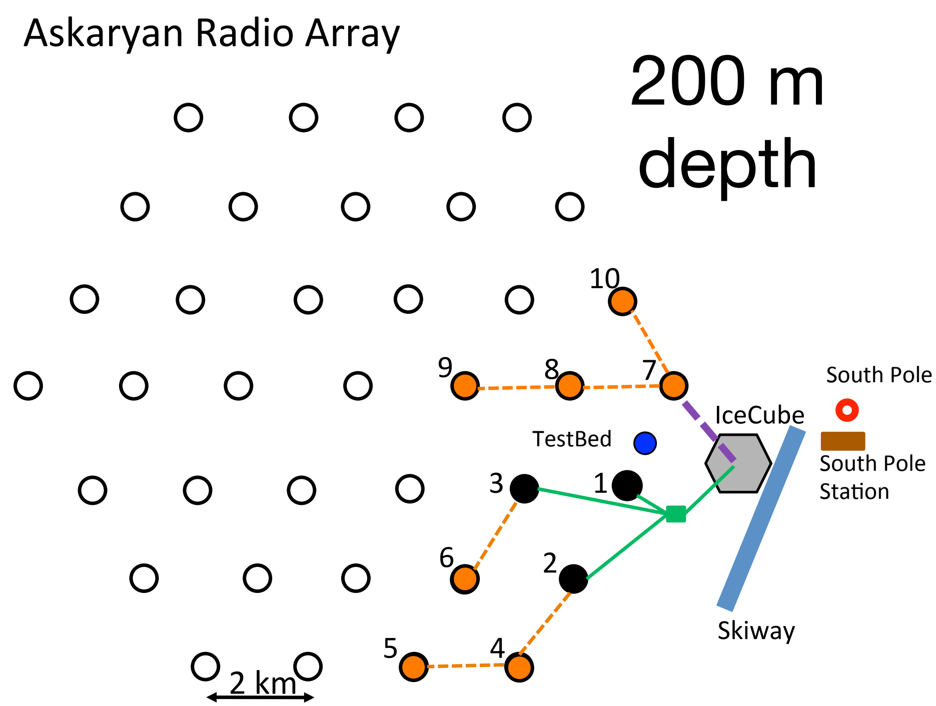
- IceCube: Best constraints $E_\nu \lesssim 10^{19}$ eV
  - Cutting into most optimistic data-inspired models
  - Radio *in situ* arrays will overtake IceCube for $E_\nu > 10^{17.5\text{-}18}$ eV
- ANITA: Best constraints for $E_\nu \gtrsim 10^{19}$ eV
  - EVA: higher gain, lower threshold



Askaryan Radio Array (ARA)

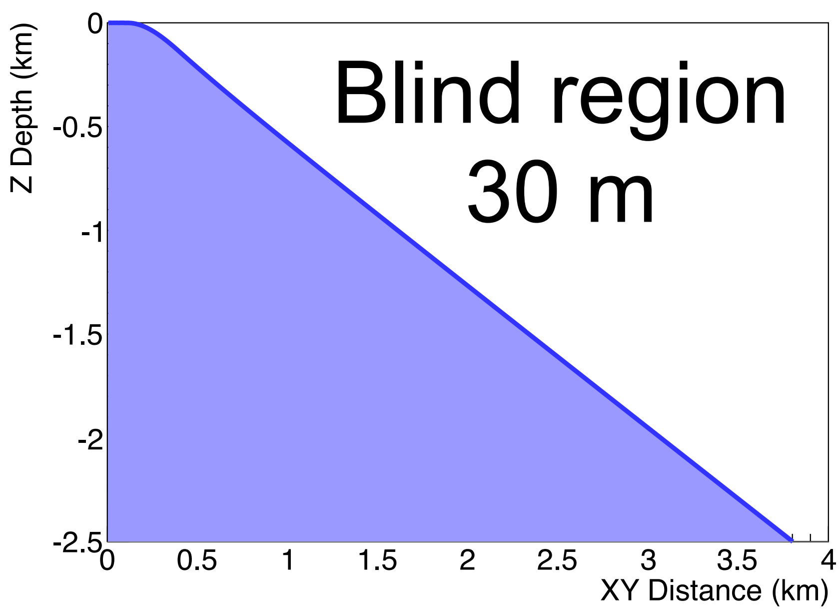
Ohio State University and CCAPP, University of Wisconsin, University of Maryland and IceCube Research Center, University of Kansas and Instrumentation Design Laboratory, University of Bonn, National Taiwan University, University College London, Universite Libre de Bruxelles, Univ. of Wuppertal, Chiba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

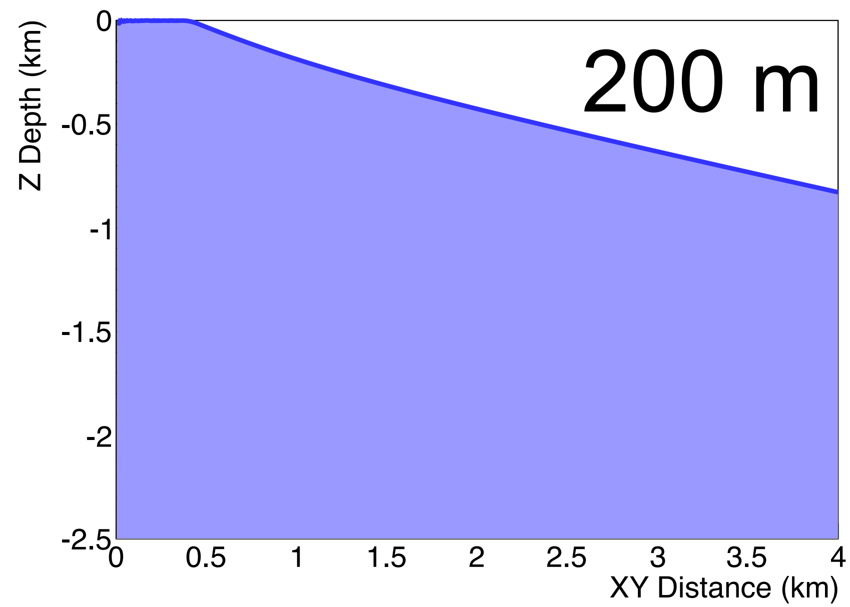
- Radio array at the South Pole
- Testbed station, Stations A1-A3 deployed
- Phase1: 37 stations ~100 km^2
  - Establish flux, first astronomy/ particle physics
- Phase 2: ~1000 km^2
  - High statistics astronomy/ particle physics exploitation



NSF has funded Testbed+3 Stations (ARA3). Pending approval for ARA10 (had proposed to deploy in 2014-2015 and 2015-2016)

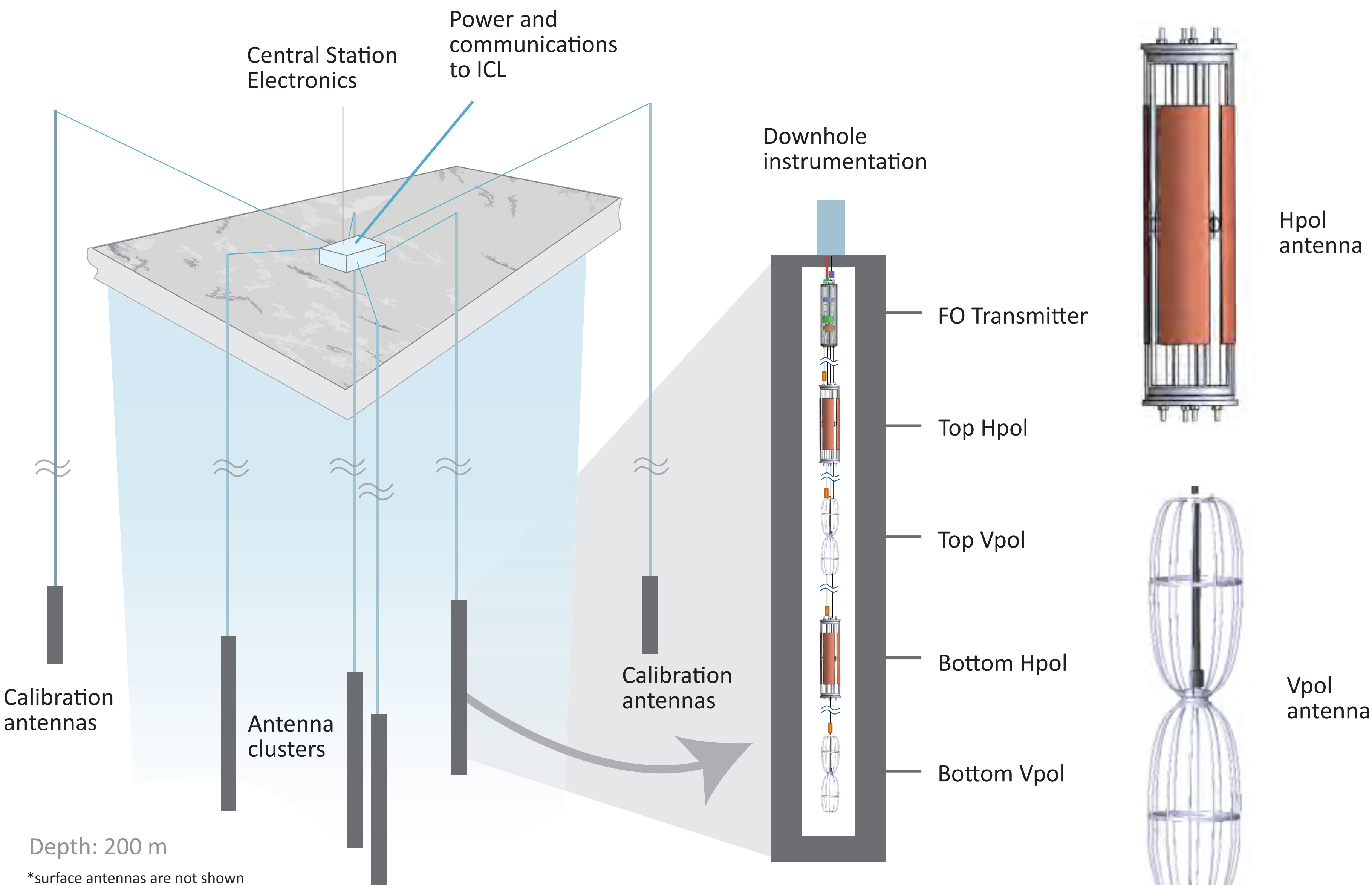
Surface vs. Depth



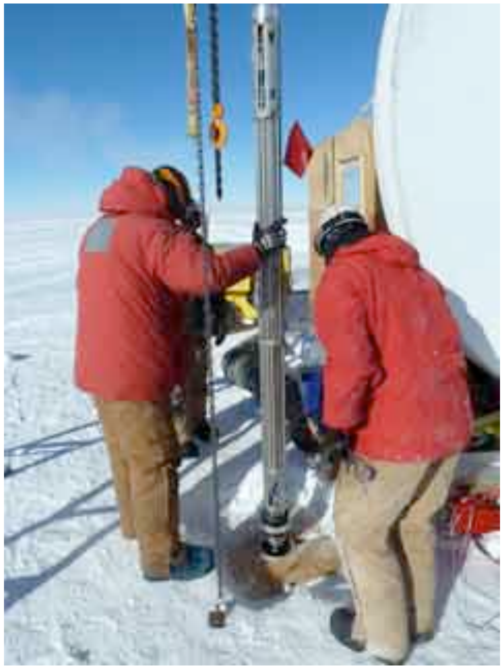


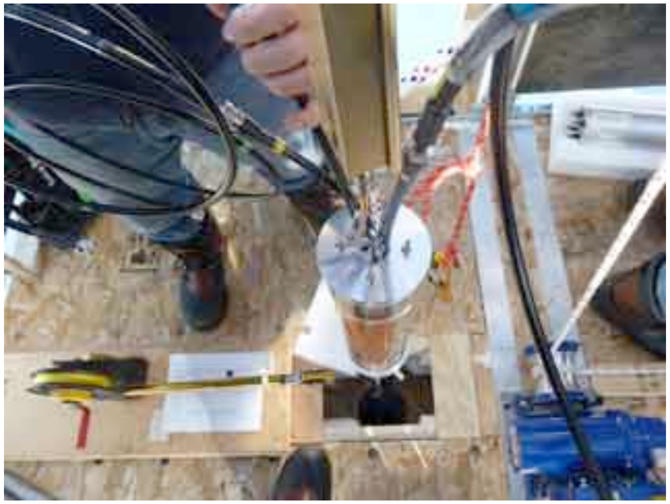
- For station at 30 m depth, visible neutrinos suffer more absorption in earth
  → At 10^{18} eV, we find $[A\Omega]_{eff}$ (200 m) = 3 × $[A\Omega]_{eff}$ (30 m)
  - 10^{19} eV: Factor of 4
- Remember ARIANNA looks for reflections too

ARA station


Central Station
Electronics
Power and
communications
to ICL
Downhole
instrumentation
Hpol
antenna
FO Transmitter
Top Hpol
Top Vpol
Bottom Hpol
Bottom Vpol
Vpol
antenna
Calibration
antennas
Antenna
clusters
Calibration
antennas
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

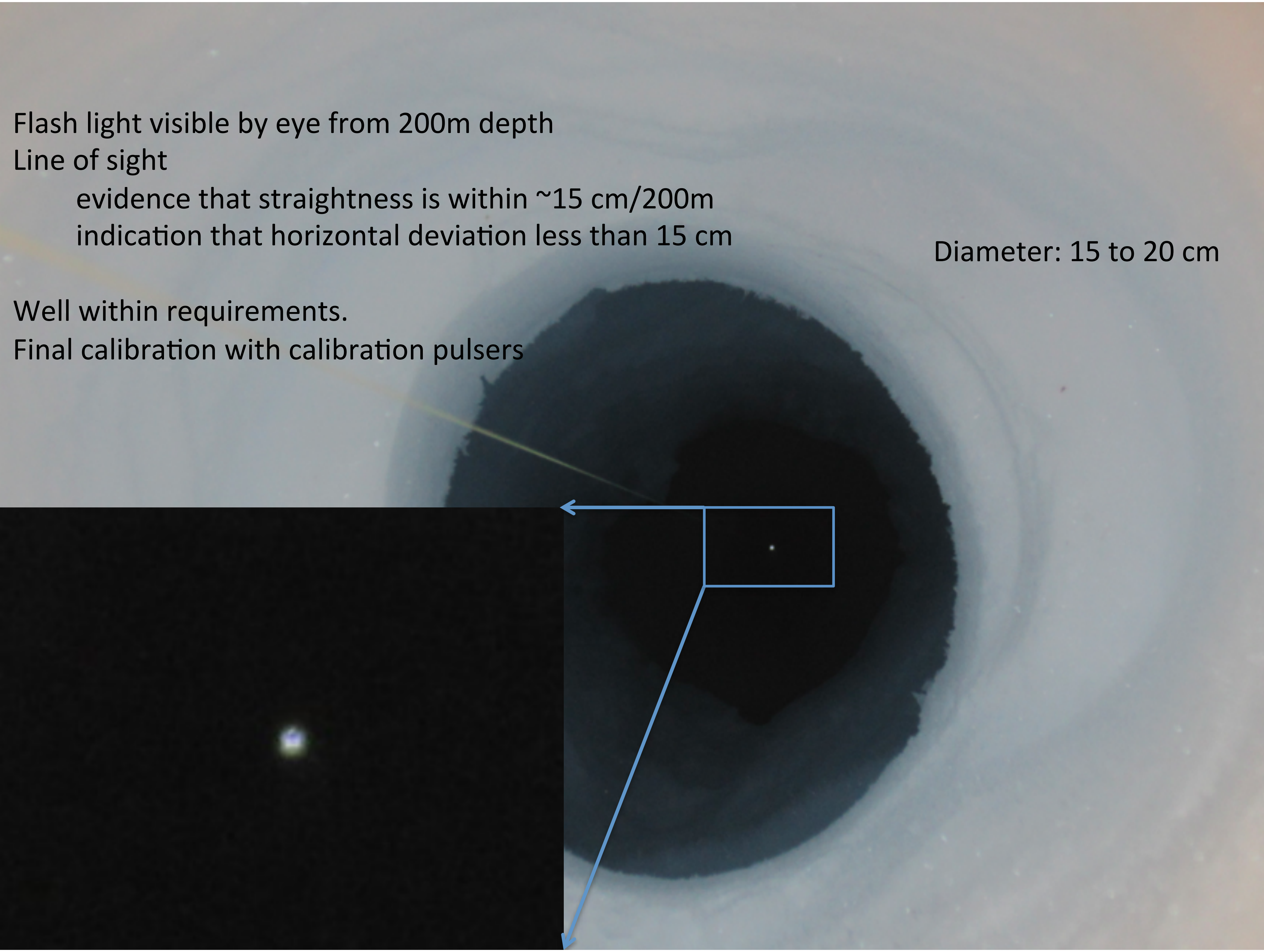
Line of sight

- 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

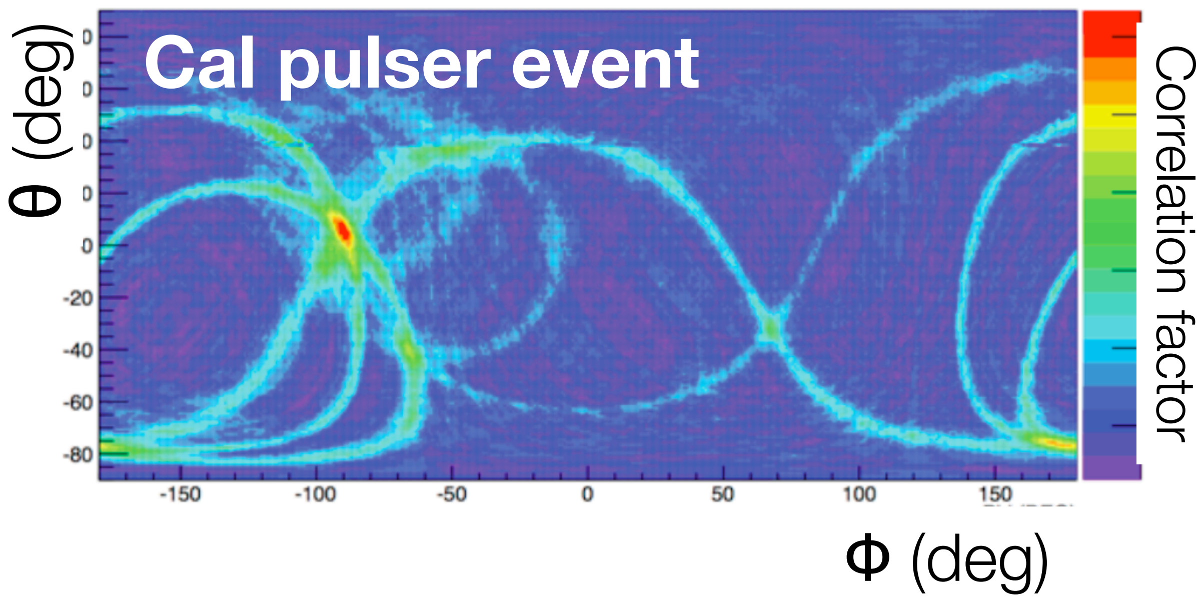


First ARA physics result! From ARA Testbed

arXiv:1404.5285

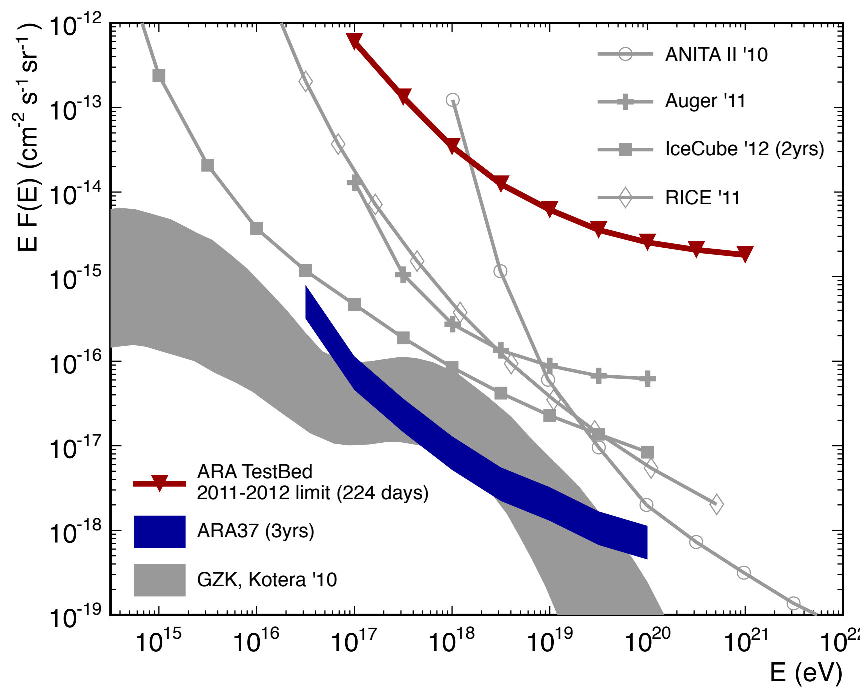
Interferometric Map: Guided by data and simulation

- Require quality reconstruction using mapped correlations



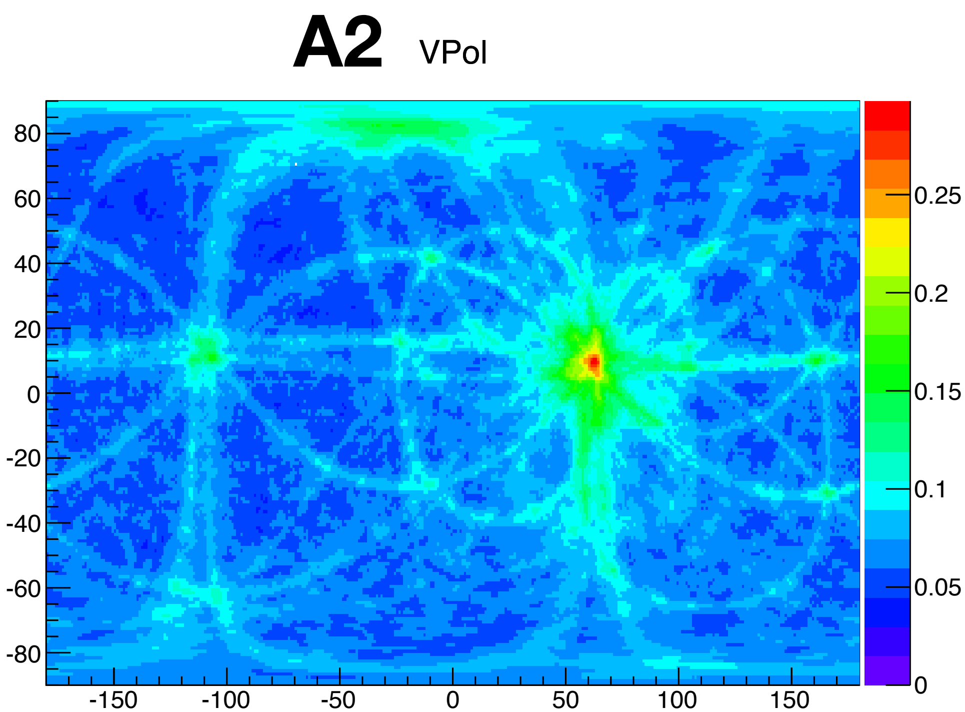
All analyses blind to 90% of data set

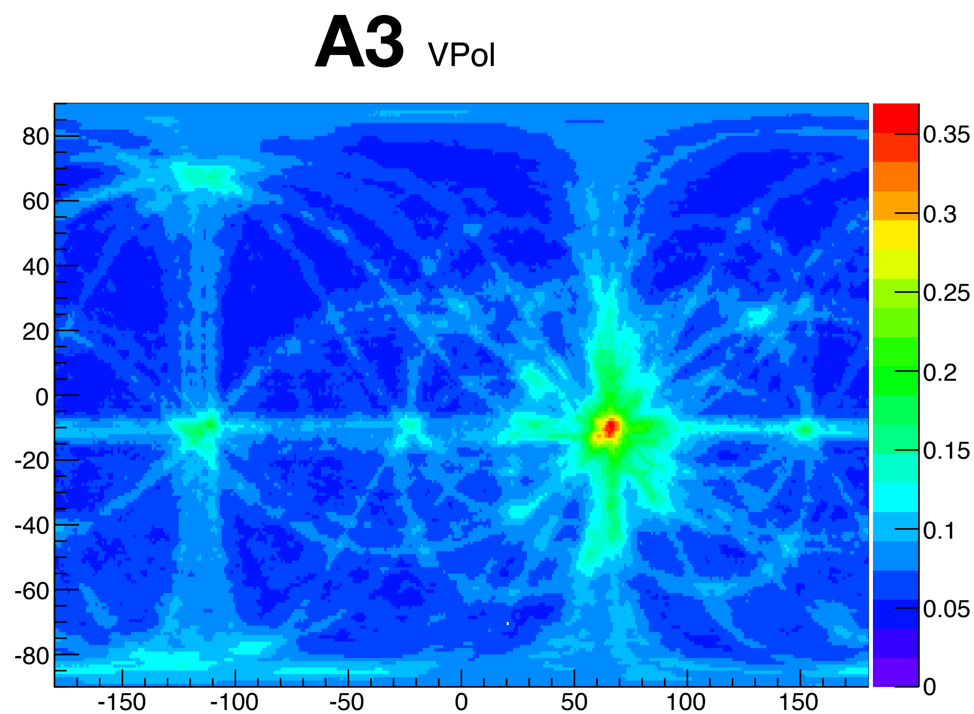
- Constrain neutrino flux based on 224 days livetime in 2011-2012
- 2 other analyses: Coherently Summed Wave, Template-based



ARA deep stations: analyses underway

- First cal pulser reconstructions



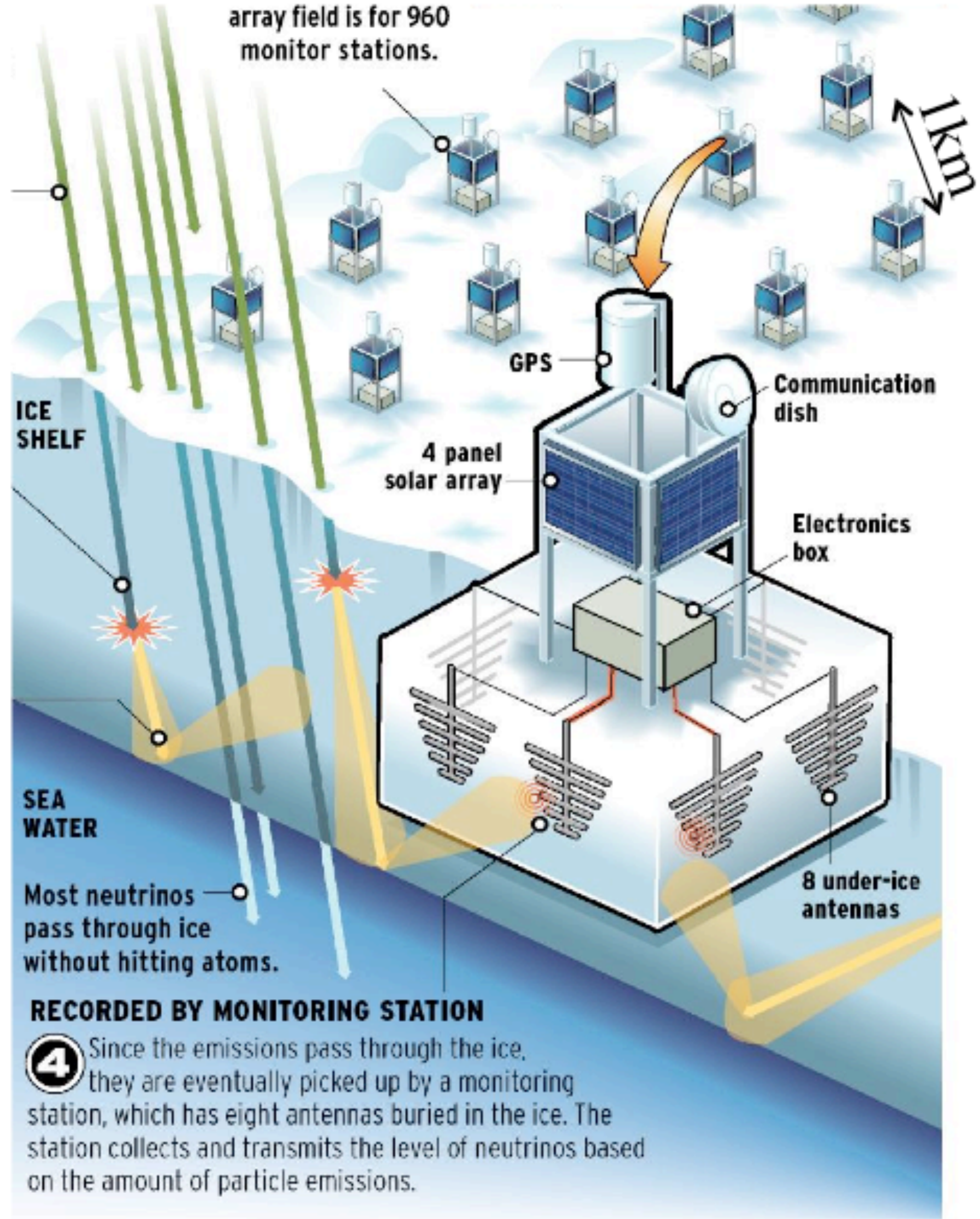


- Deep stations show consistent ~95% livetime

ARIANNA

- Radio array on Ross Ice Shelf http://arianna.ps.uci.edu
- Completed 7 station array in Dec. 2013
- Propose 960 station array

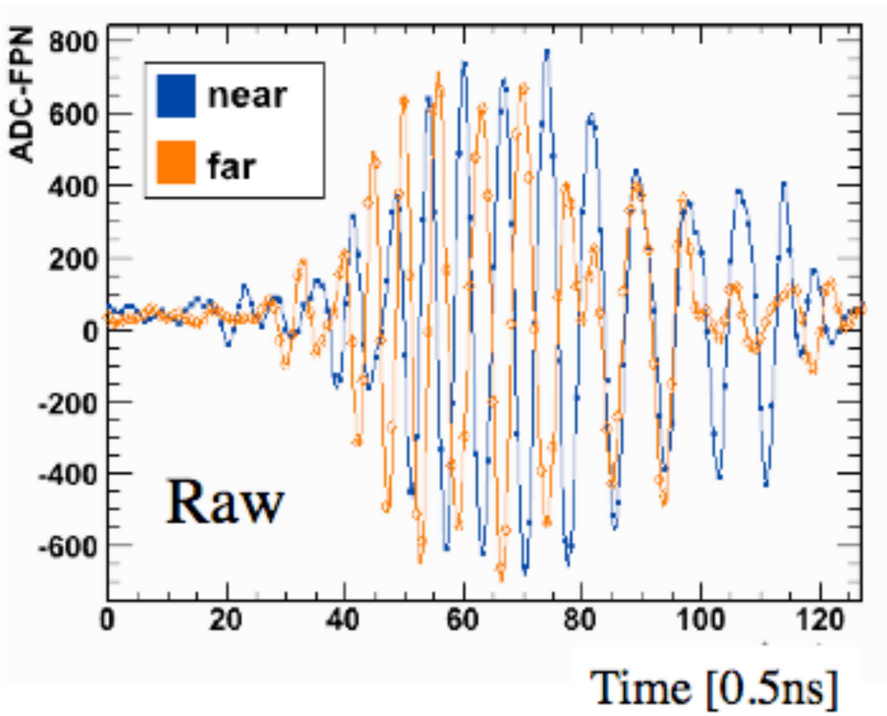
US
Sweden
New Zealand

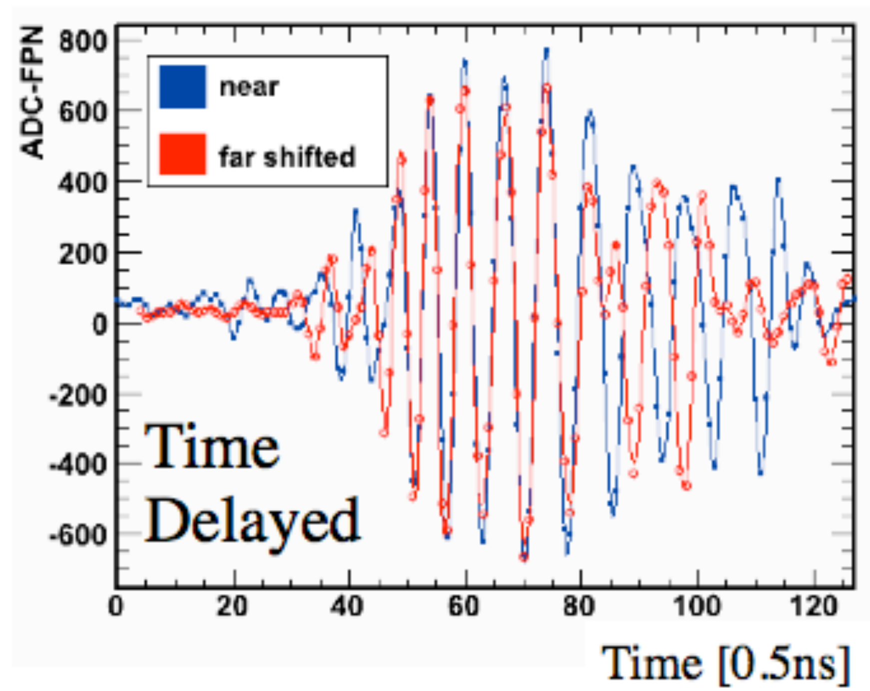


From OC Register 2012

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

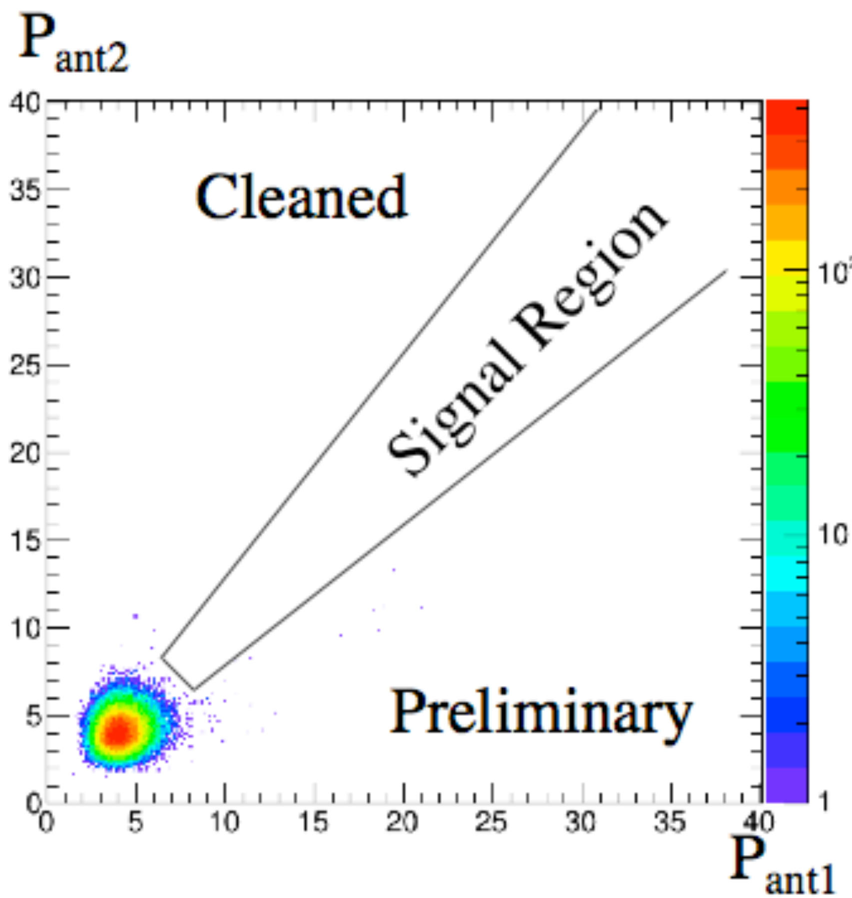
Data Analysis: HRA Station 3

(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



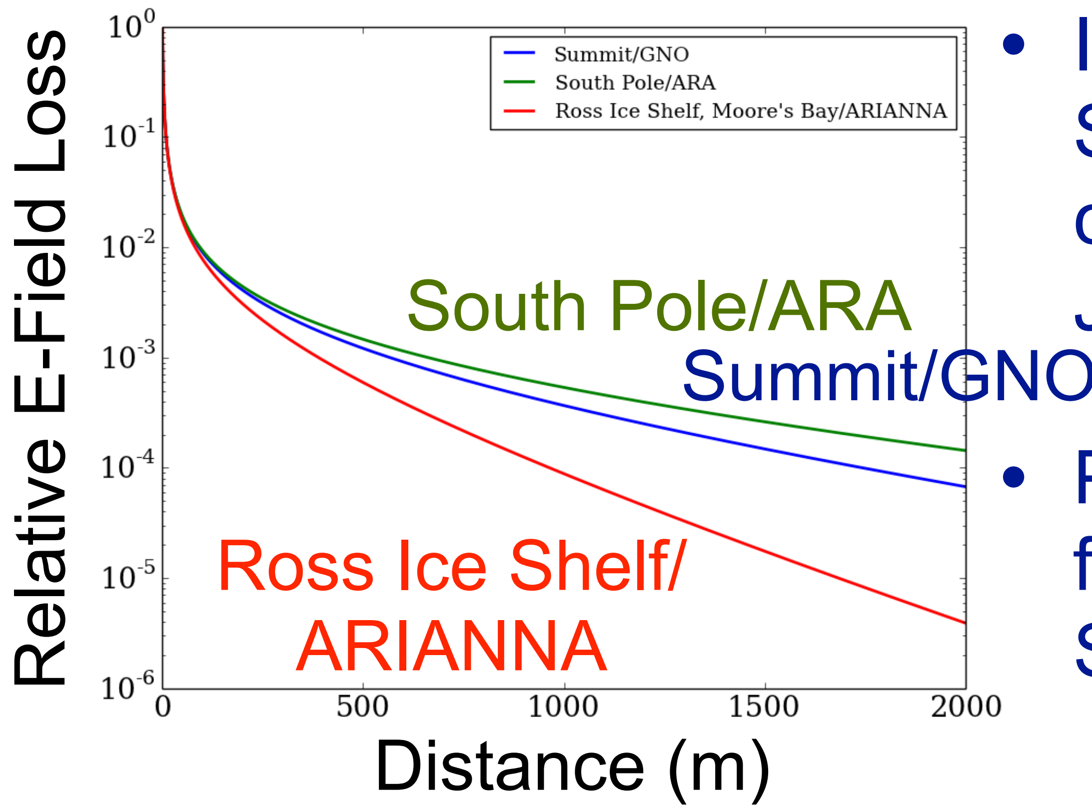
Complete rejection of BG without timing or event reconstruction

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

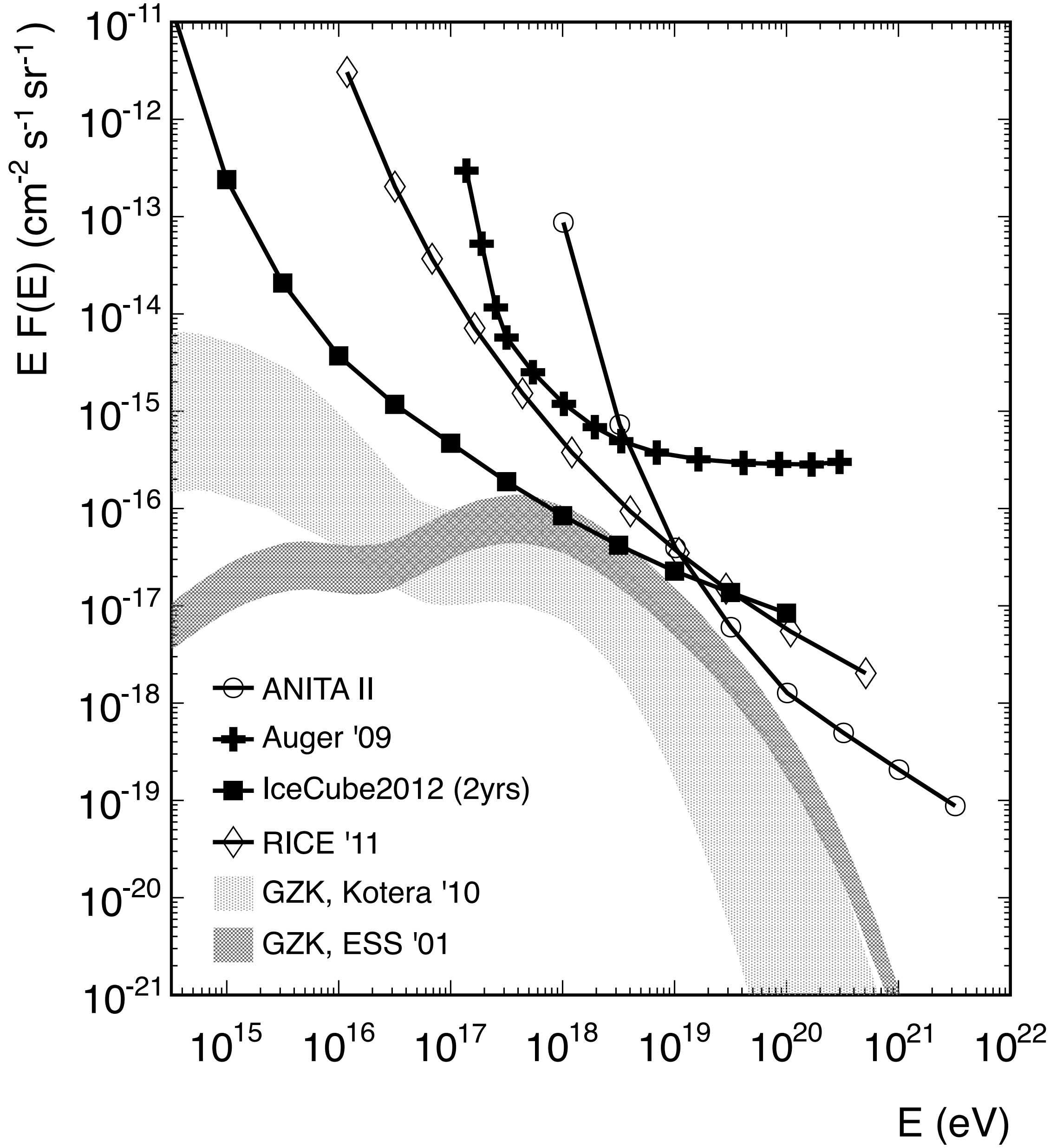


- Ice at Summit Station characterized June 2013
- Plan to deploy first module Spring 2015

Science implications

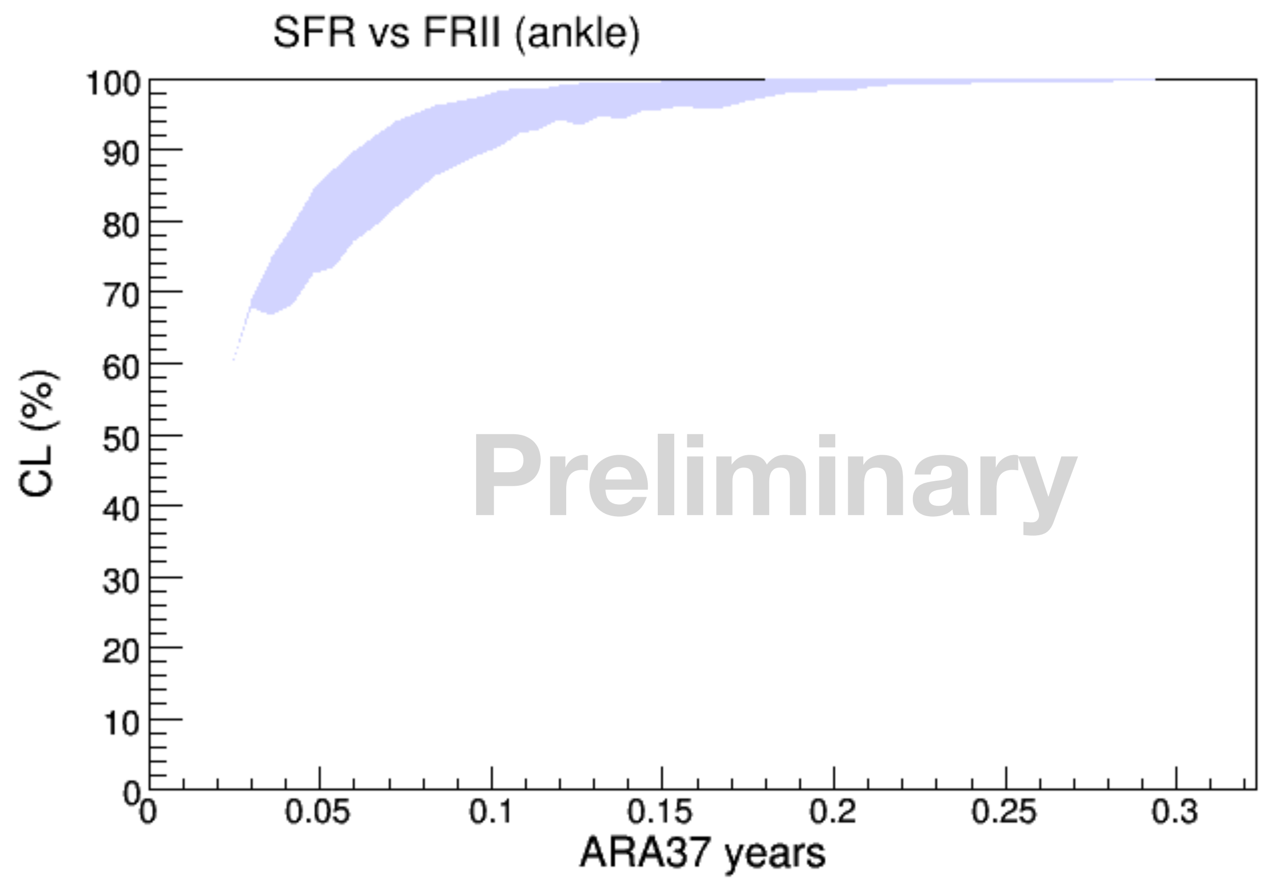
Which type of models has IceCube excluded?

- Excluded models have strong source evolutions
- Example:
  - FR-II (AGN) redshift evolution
    α=2.3, dip,
    $E_{max}=10^{20.5}$ eV
    Kotera *et al.* (2010)



in situ arrays will constrain the redshift evolution of UHE sources

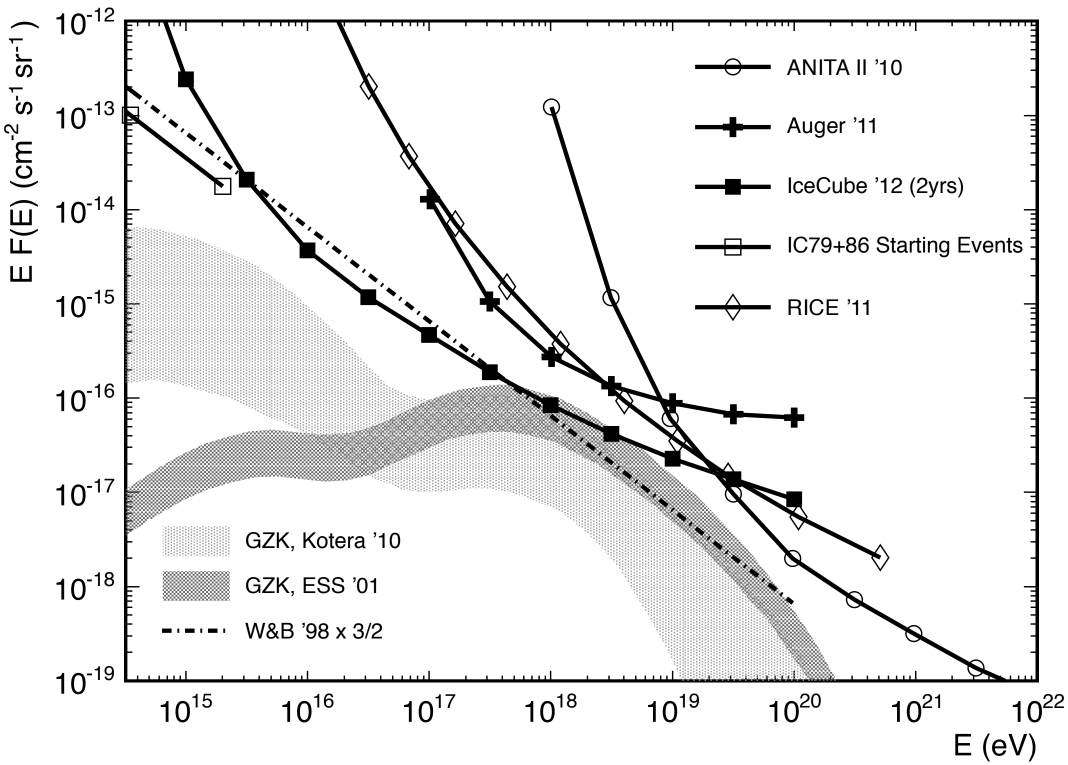
- In ~7 station-years, ARA can distinguish between Star Formation Rate and AGN evolutions

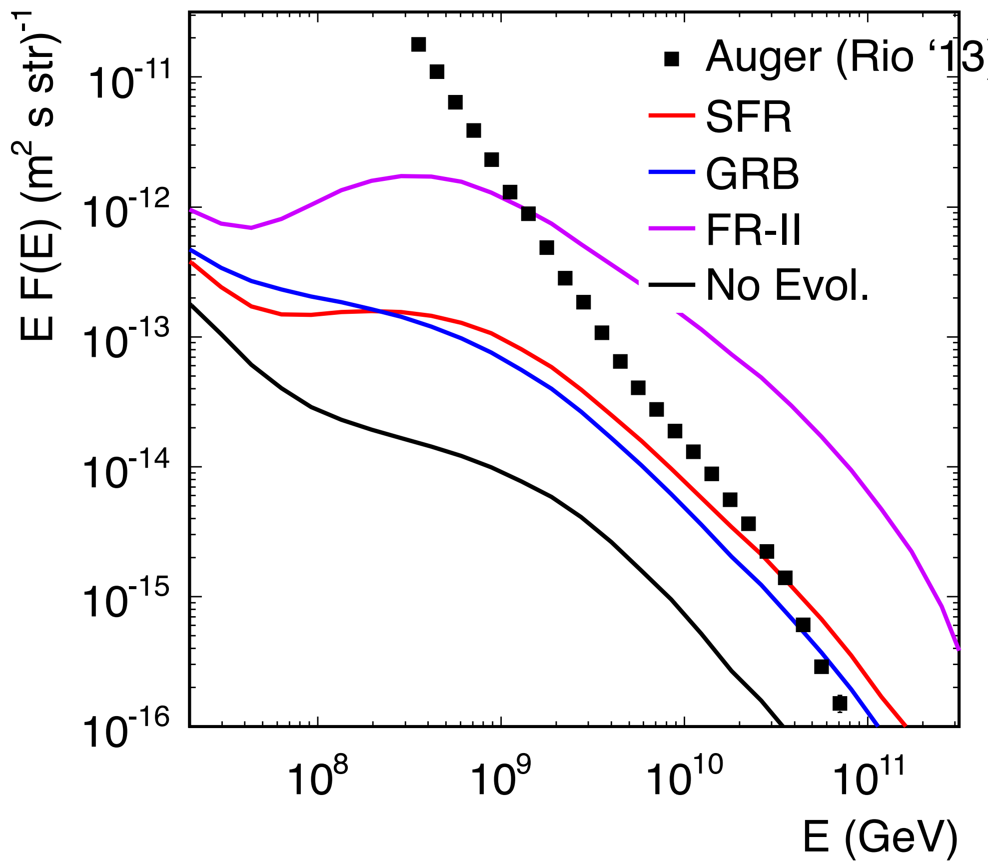


From Connolly, Horiuchi & Griffith, in preparation.

From A. Connolly, S. Horiuchi (UC Irvine) & N. Griffith (OSU) , in preparation.

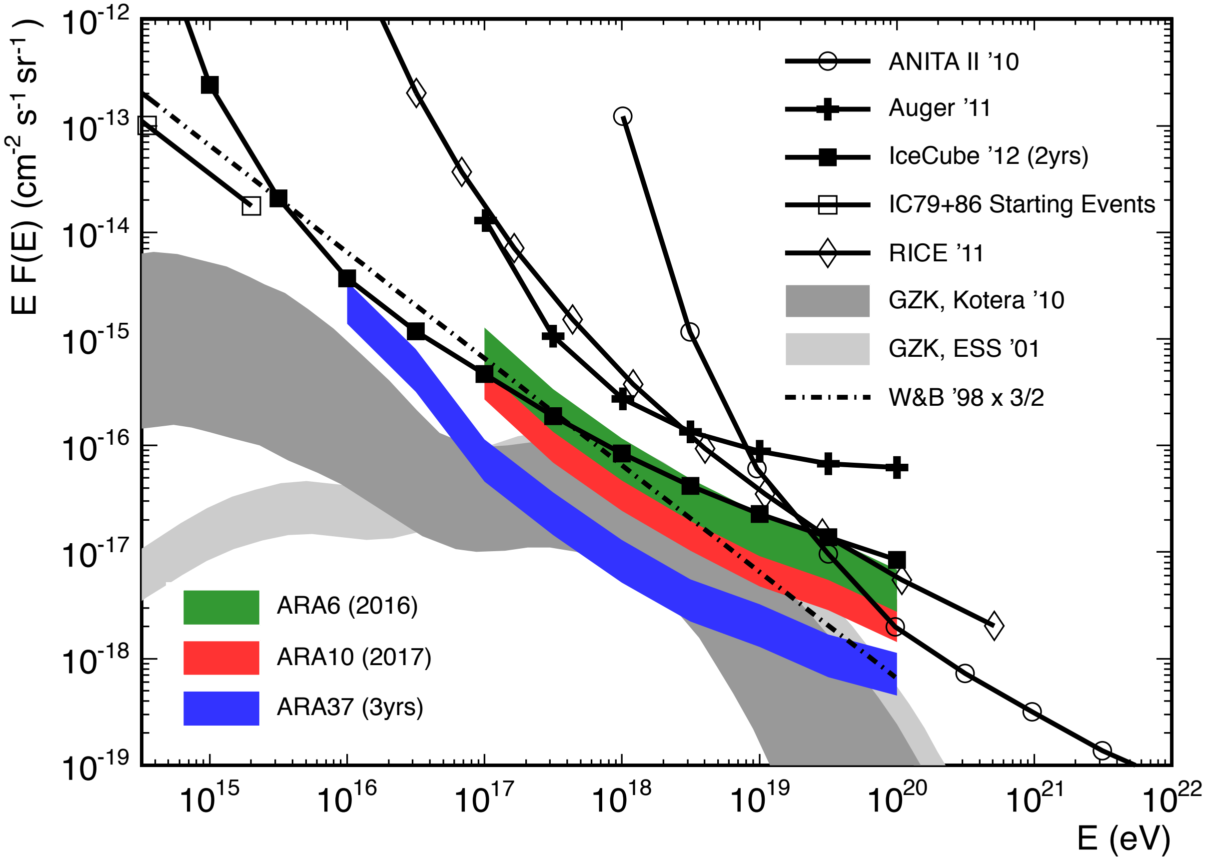
Neutrinos from the sources too!





Cosmogenic spectra from Connolly, Horiuchi & Griffith, in preparation.

Future



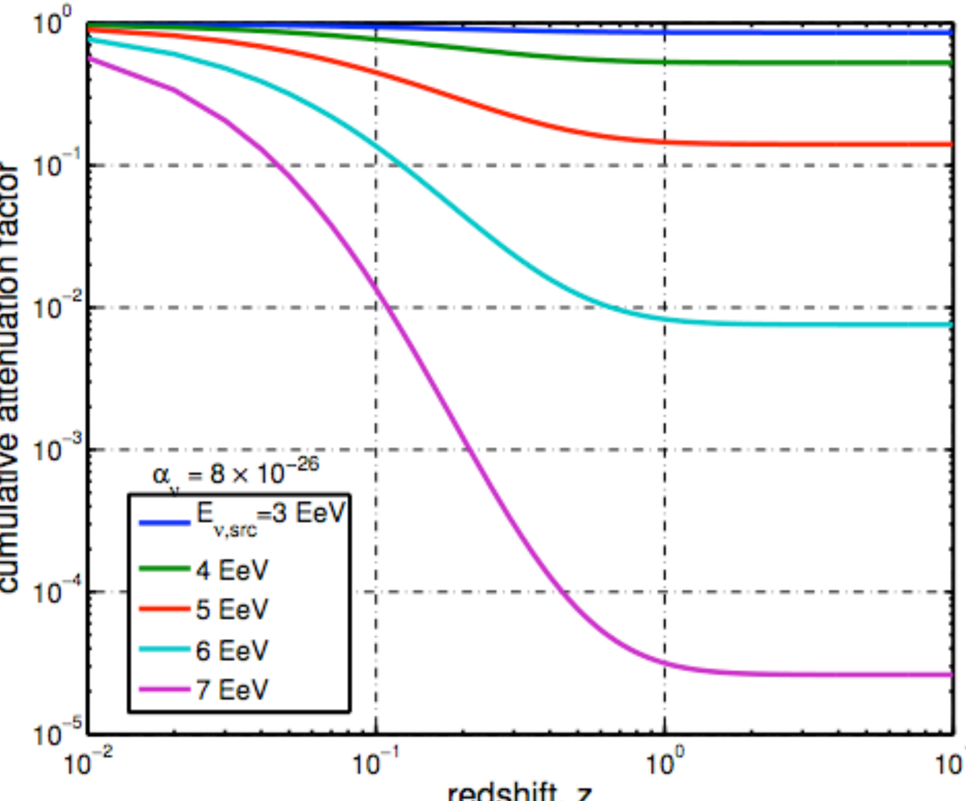
- If UHECR's are heavy, radio will be necessary

- 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

Exotic Physics: Lorentz Invariance Violation (LIV)

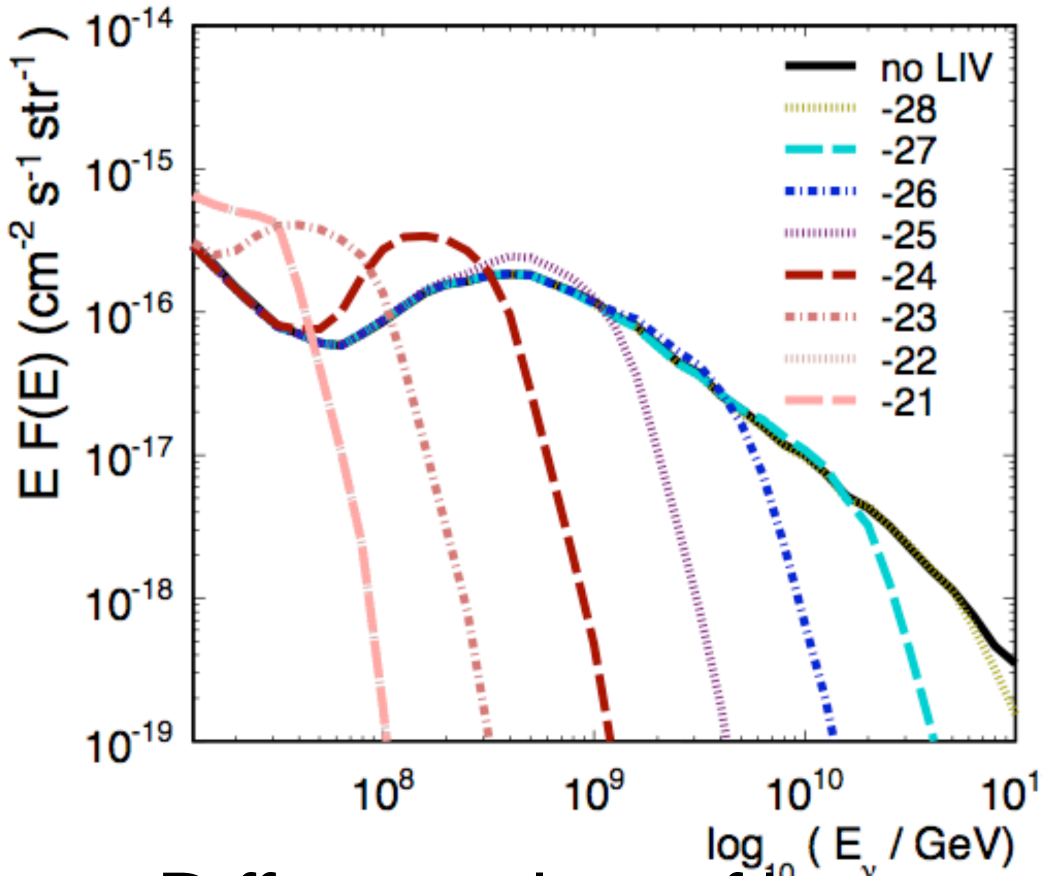
$\nu \rightarrow \nu'\ e^+\ e^-$ (Coleman and Glashow)
Neutrino loses ~3/4 of its energy

Attenuation vs. redshift



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

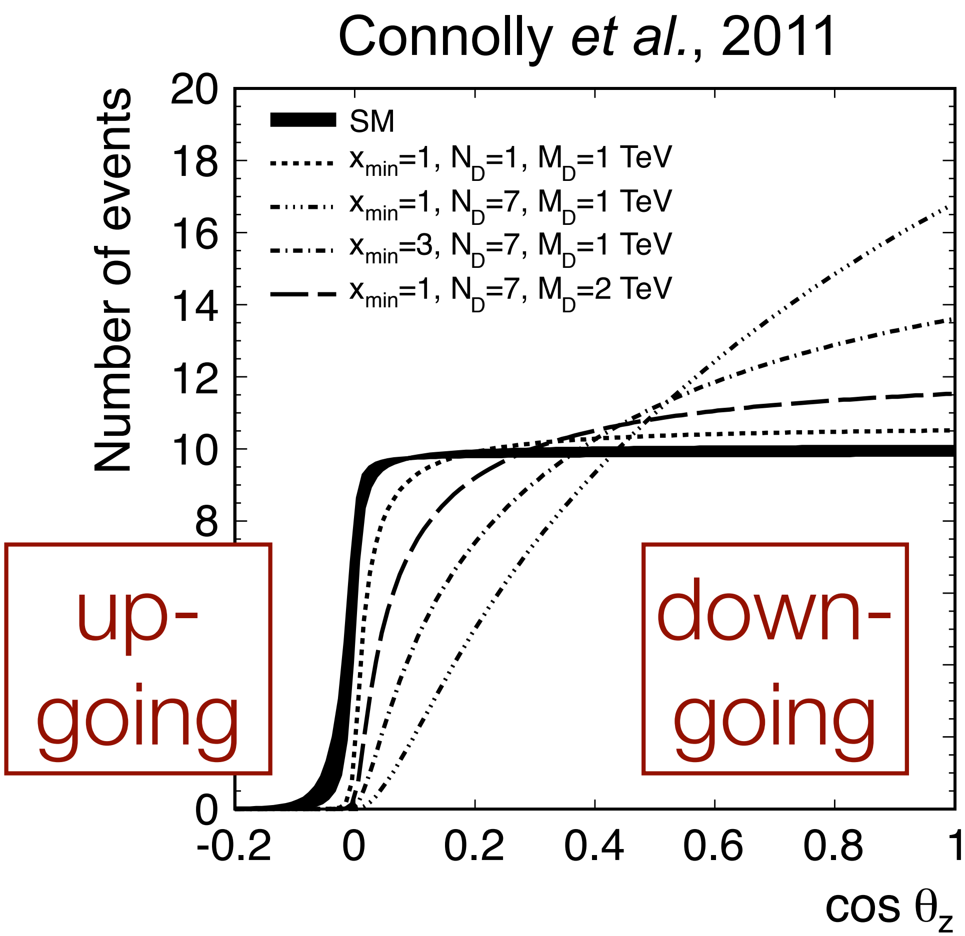
Observed neutrino spectra



Different values of $\log_{10} \alpha_\nu$

P.W. Gorham, A. Connolly et al., Phys.Rev. D86 (2012) 103006

Exotic physics with UHE neutrinos



- ν'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

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