Radio Detection of the Highest Energy Neutrinos

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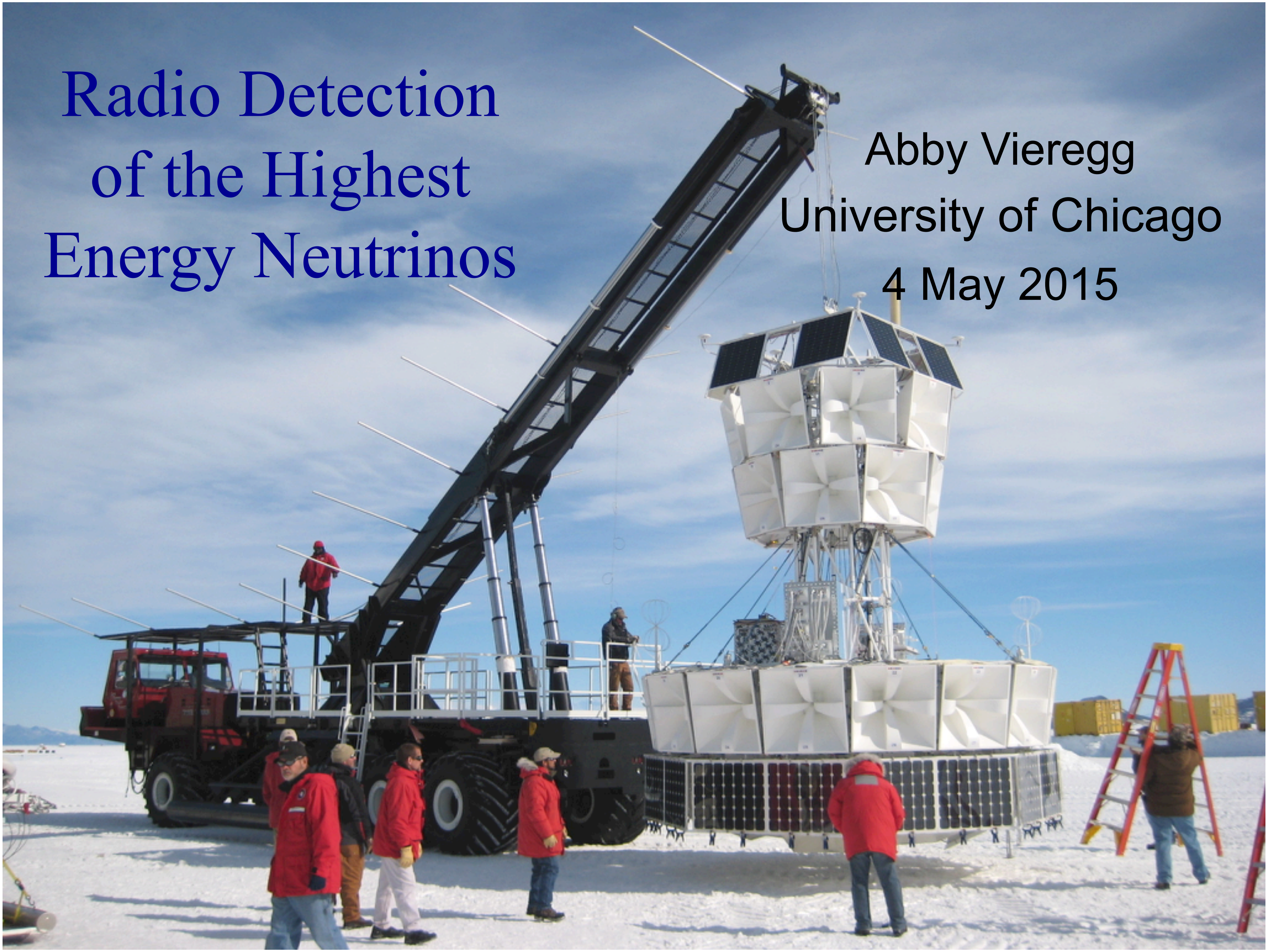
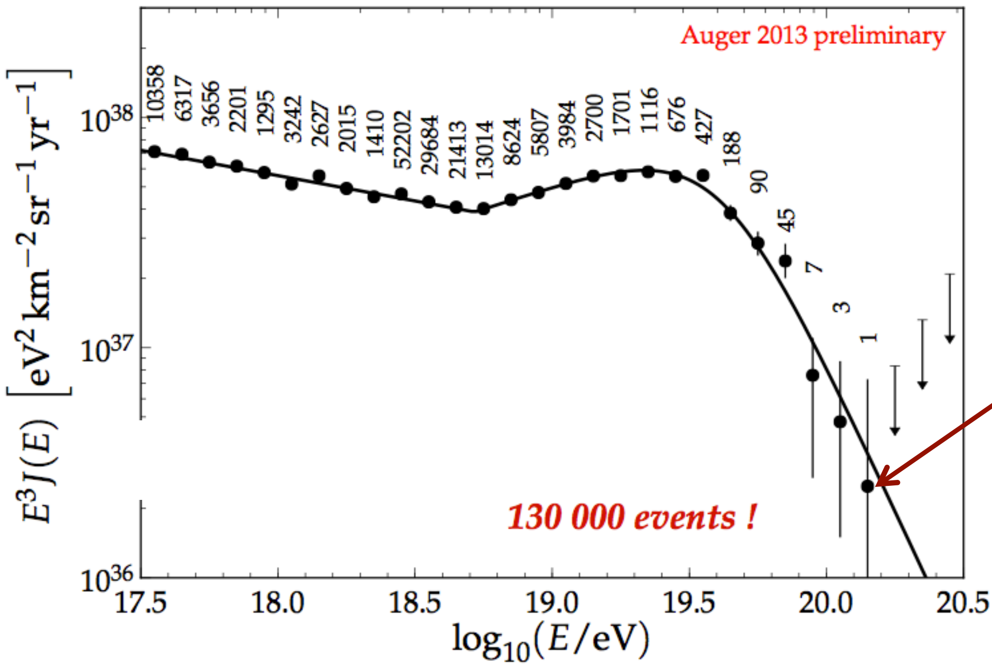
University of Chicago
4 May 2015



Neutrinos: The Ideal UHE Messenger

UHE Cosmic Ray Flux



- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei suffer curvature induced by B fields
- But: we know there are sources up to 10^{20} eV!!

UHE Neutrino Detectors:

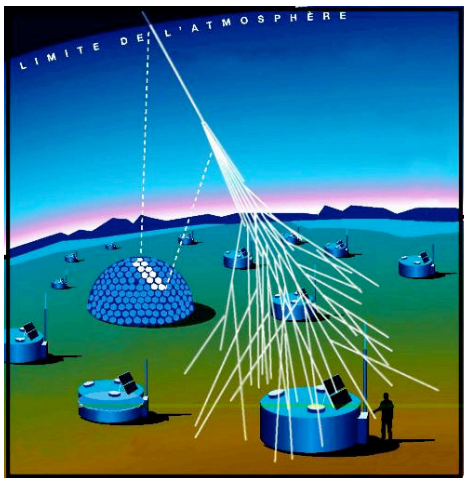
- Highest energy observation of extragalactic sources
- Very distant sources
- Deep into opaque sources

Neutrino Production: The GZK Process

GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

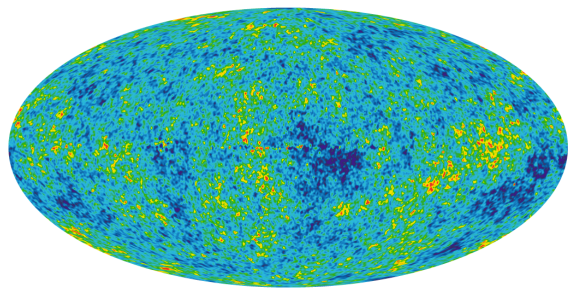
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$\rightarrow \mu^{+} + \boxed{\nu_{\mu}}$$
$$\rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}}$$

cosmic rays



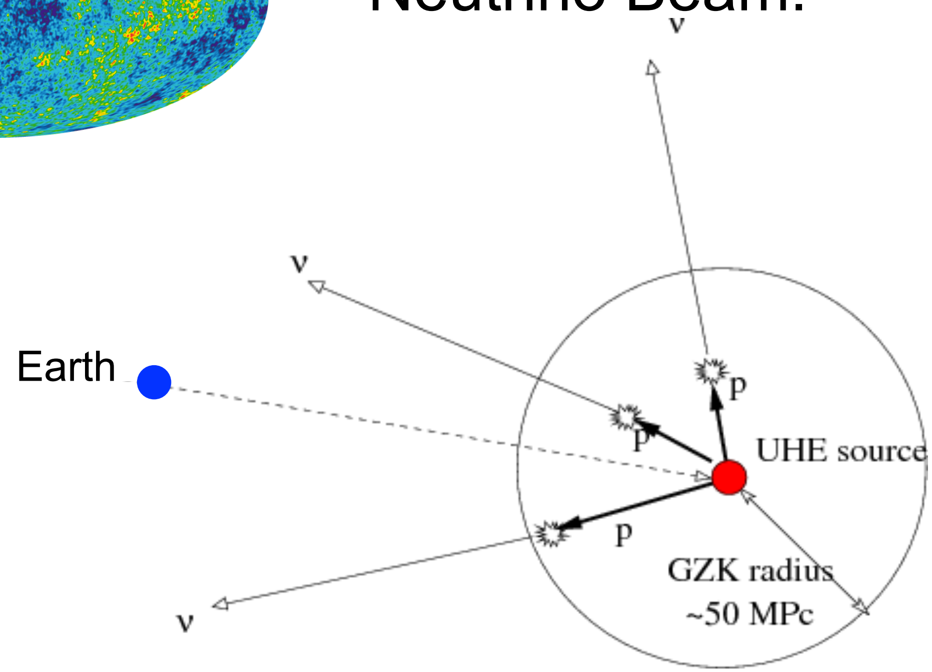
+

CMB



= Neutrino Beam!

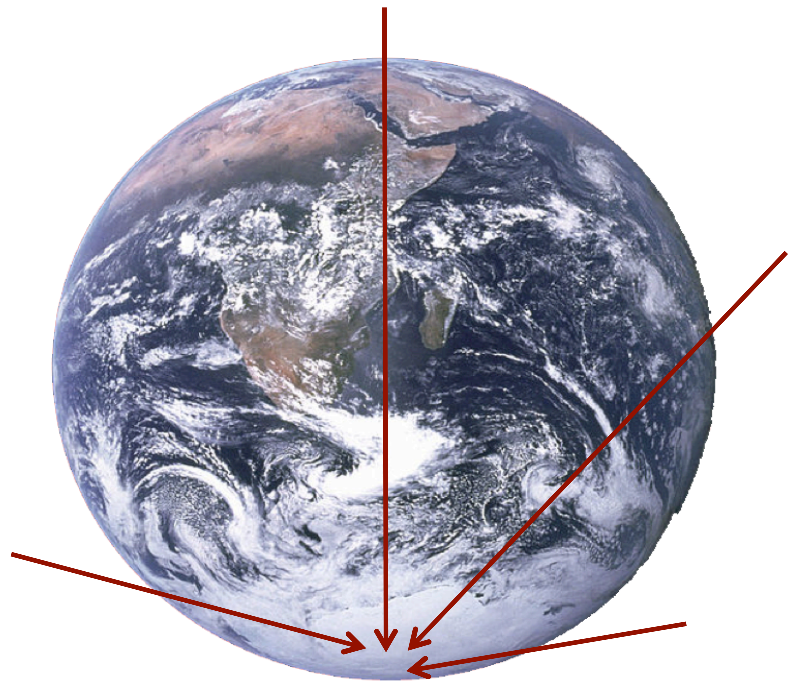
- Discover the origin of high energy cosmic rays
- Uniquely constrain cosmic evolution of UHECR sources
- Constrain UHECR composition and maximum UHECR energy



A Particle Physics Case

Probe weak interactions at energies not achievable on earth

- E_{CM} is ~200 TeV (LHC "only" 14 TeV)
  - Measure neutrino-nucleon cross section in a new regime
    - L_{int} ~ 300 km: use Earth-shielding as cross-section analyzer (count events with different path lengths through the earth)
    - Probe exotic models



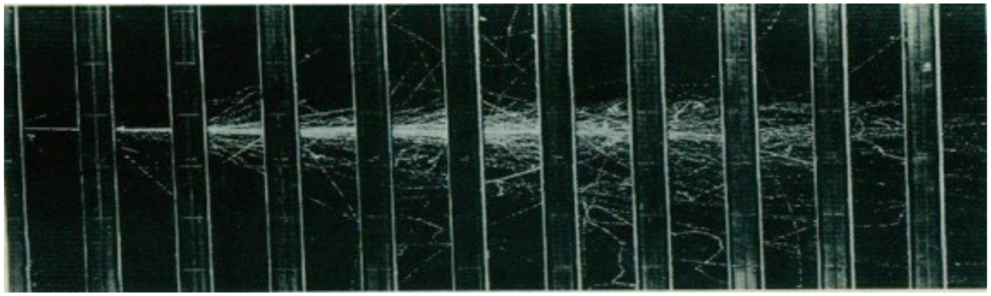
- With flavor tagging (perhaps unrealistic)
  - Neutrino oscillations
  - Neutrino decay

Radio Detection Principle: the Askaryan Effect

Bright, broadband radio emission: the Askaryan Effect

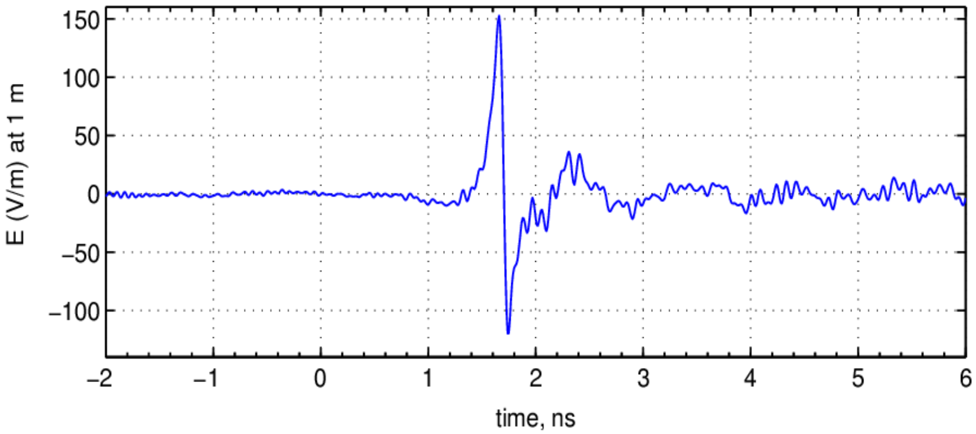
- EM shower in dielectric (ice) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if λ > Moliere radius

e^+, e^-, γ ⟶



Typical Dimensions:
L ~ 10 m
$R_{moliere}$ ~ 10 cm

Askaryan Effect Observed at SLAC



ANITA Coll., PRL (2007)

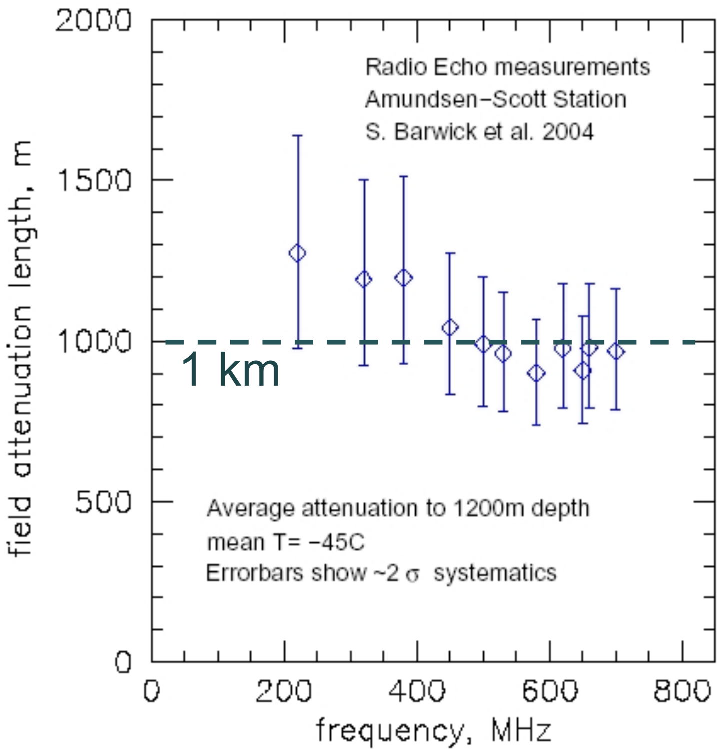
Other detection techniques:

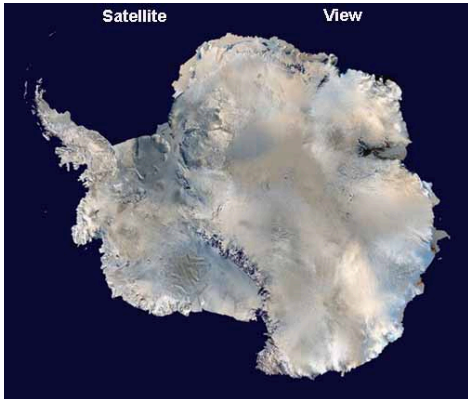
- Optical Cherenkov emission
- Acoustic signal

UHE Neutrino Radio Detector Requirements

- ~1-10 GZK neutrinos/km^2/year
- L_{int} ~ 300 km
  → ~ 0.01 neutrinos/km^3/year
- Need a huge (>> 100 km^3), radio-transparent detector
- 3 media: salt, sand, and ice
- Long radio attenuation lengths in south pole ice
  - 1 km for RF (vs. ~100 m for optical signals used by IceCube)

→ Ice is good for radio detection of UHE neutrinos!



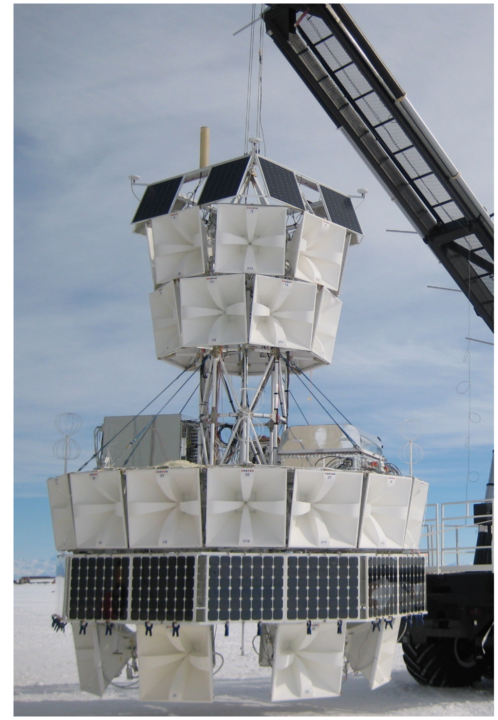


ANITA-I & ANITA-II: Best Limit > 10^{19} eV

NASA Long Duration Balloon, launched from Antarctica

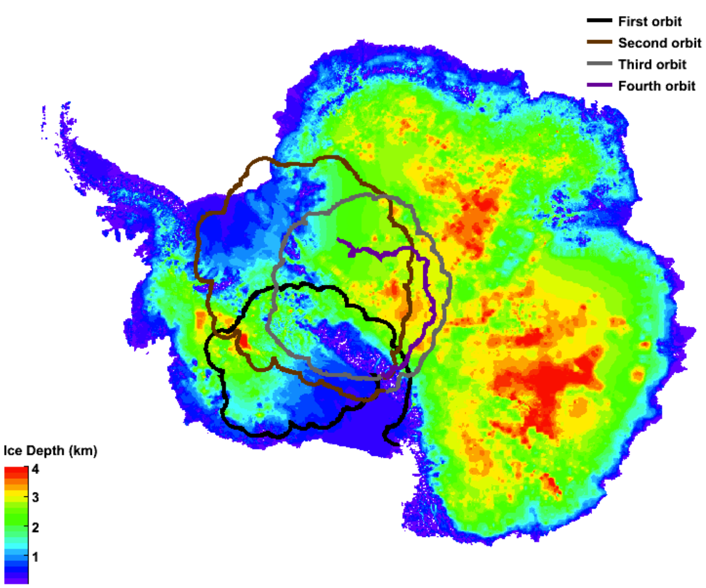
ANITA-I: 35 day flight 2006-07

ANITA-I: 30 day flight 2008-09



Instrument Overview:

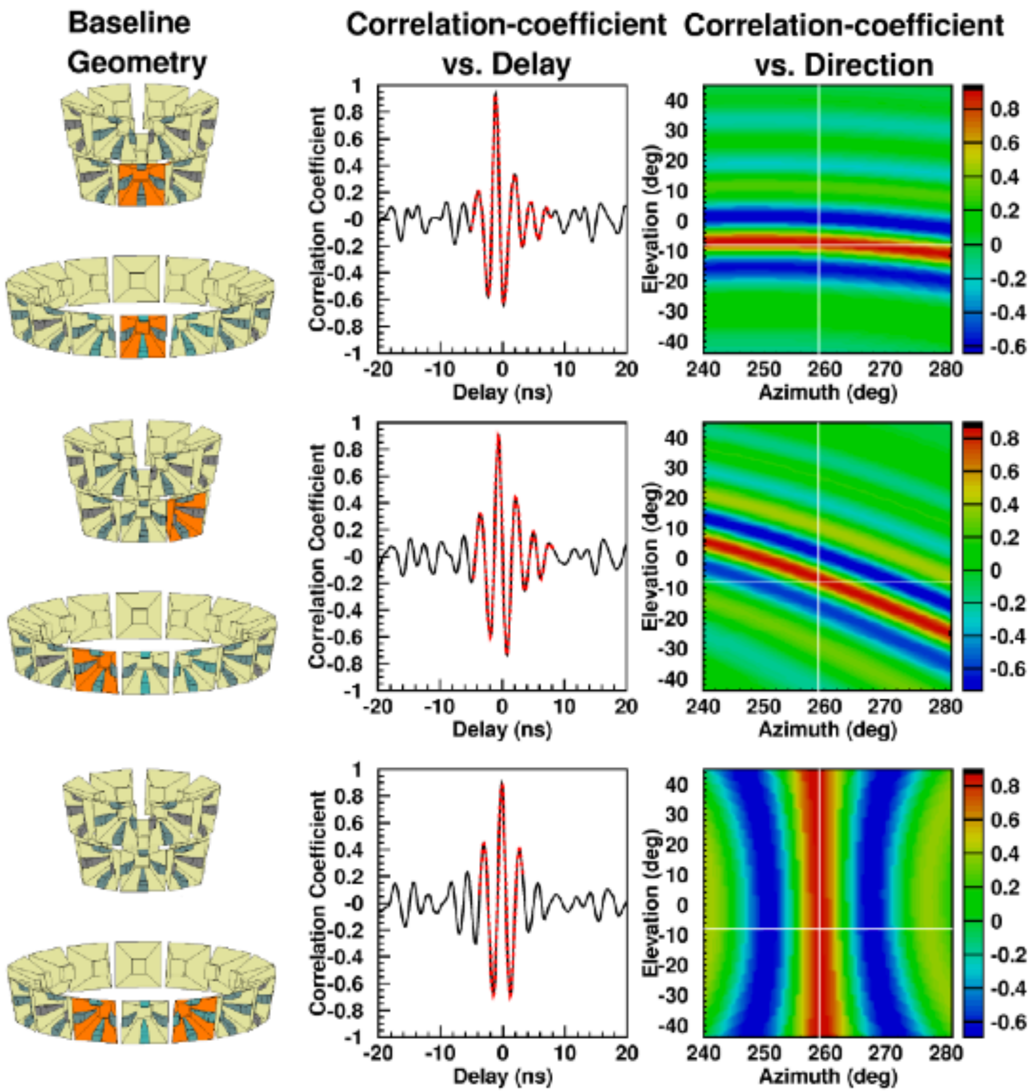
- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas (interferometry)
- In-flight calibration from ground
- Threshold limited by thermal noise



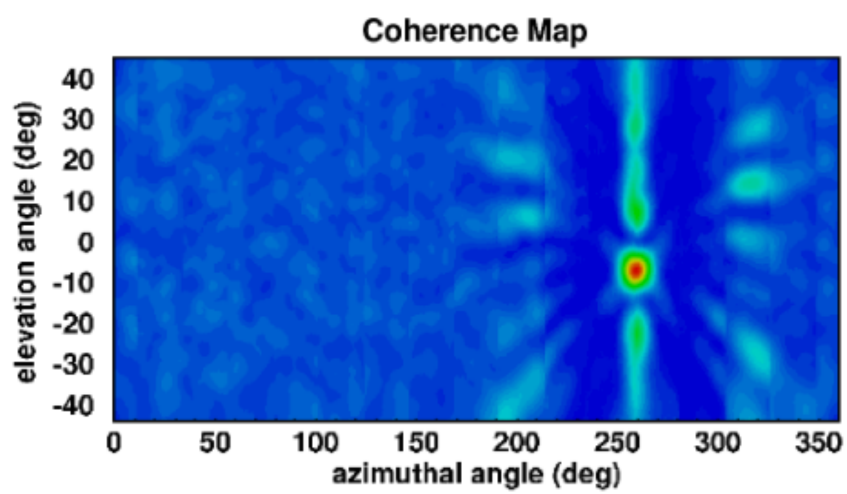
UHE Neutrino Search Results:

	ANITA-I	ANITA-II
Neutrino Candidate Events	1	1
Expected Background	1.1	0.97 +/- 0.42

The Interferometric Analysis Technique



- Use timing delays between antennas to determine direction
- Developed for ANITA, used by ARA

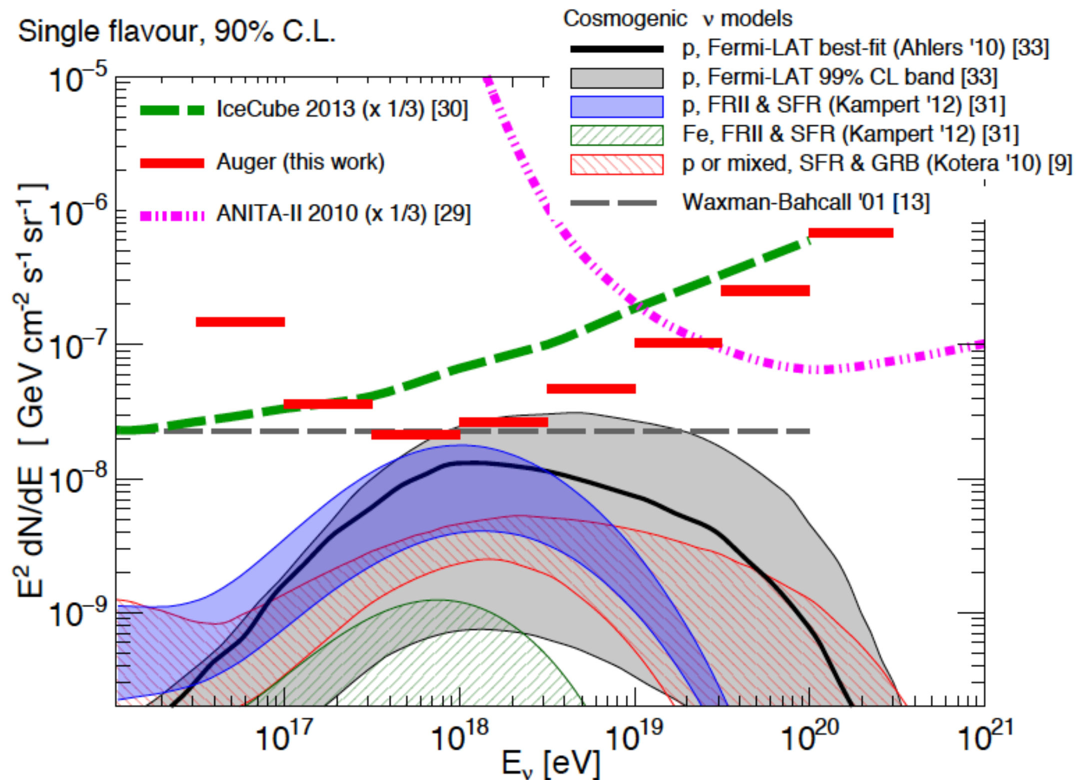


ANITA Coll: arXiv:1304.5663

Models & Current Constraints

Best current limits:

- >10^{19} eV: Radio Detection (ANITA)
- <10^{19} eV: Optical Detection (IceCube) and Air Showers (Auger)

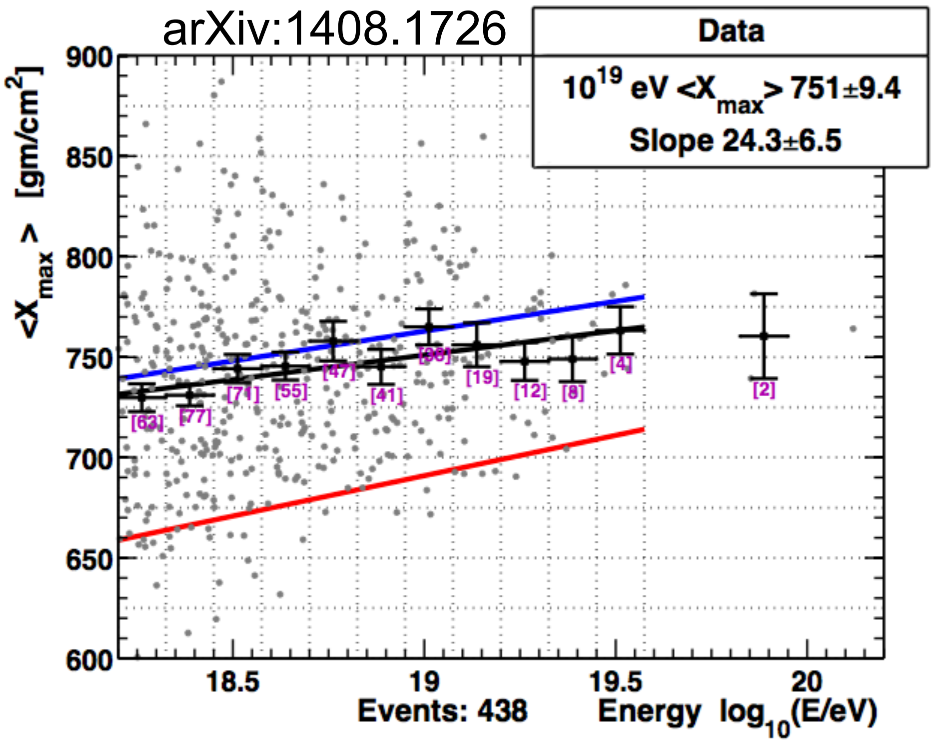


Auger Coll., arXiv:1504.05397

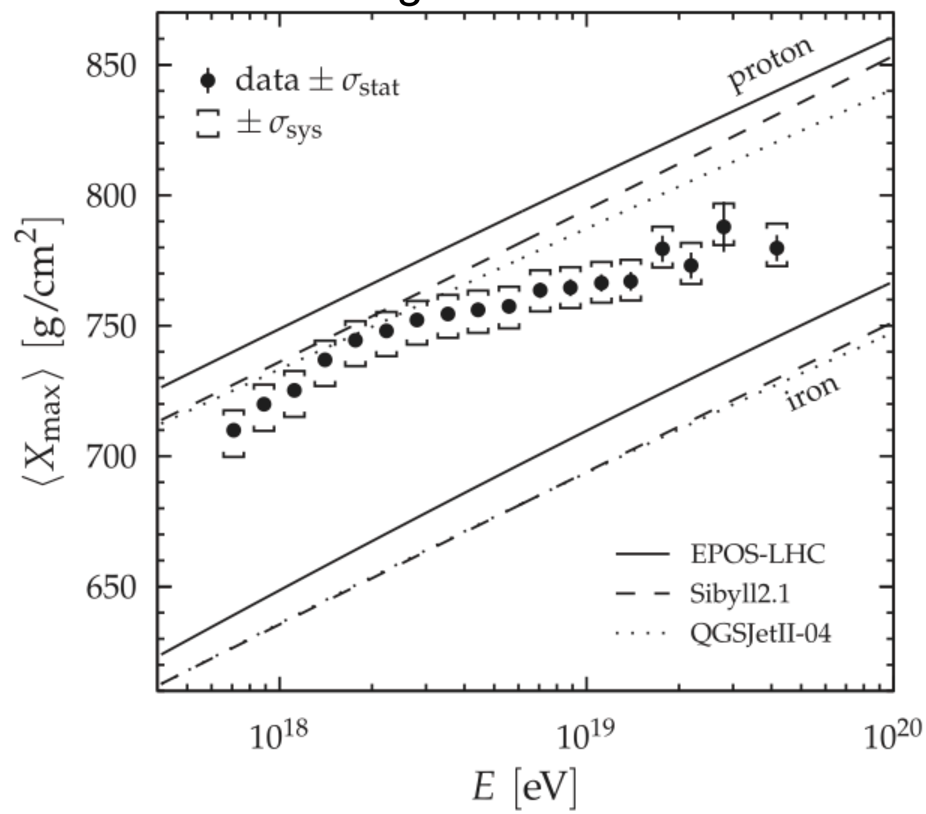
- Starting to constrain some models (source evolution and cosmic ray composition)
- How do we get a factor of ~100 to dig into the interesting region and make a real UHE neutrino observatory?
- Why bother? Not a fishing expedition! There is a floor on the flux predictions.

Recent Results: UHE Cosmic Rays Are Not All Iron

Telescope Array
arXiv:1408.1726



Auger: PRD 2015

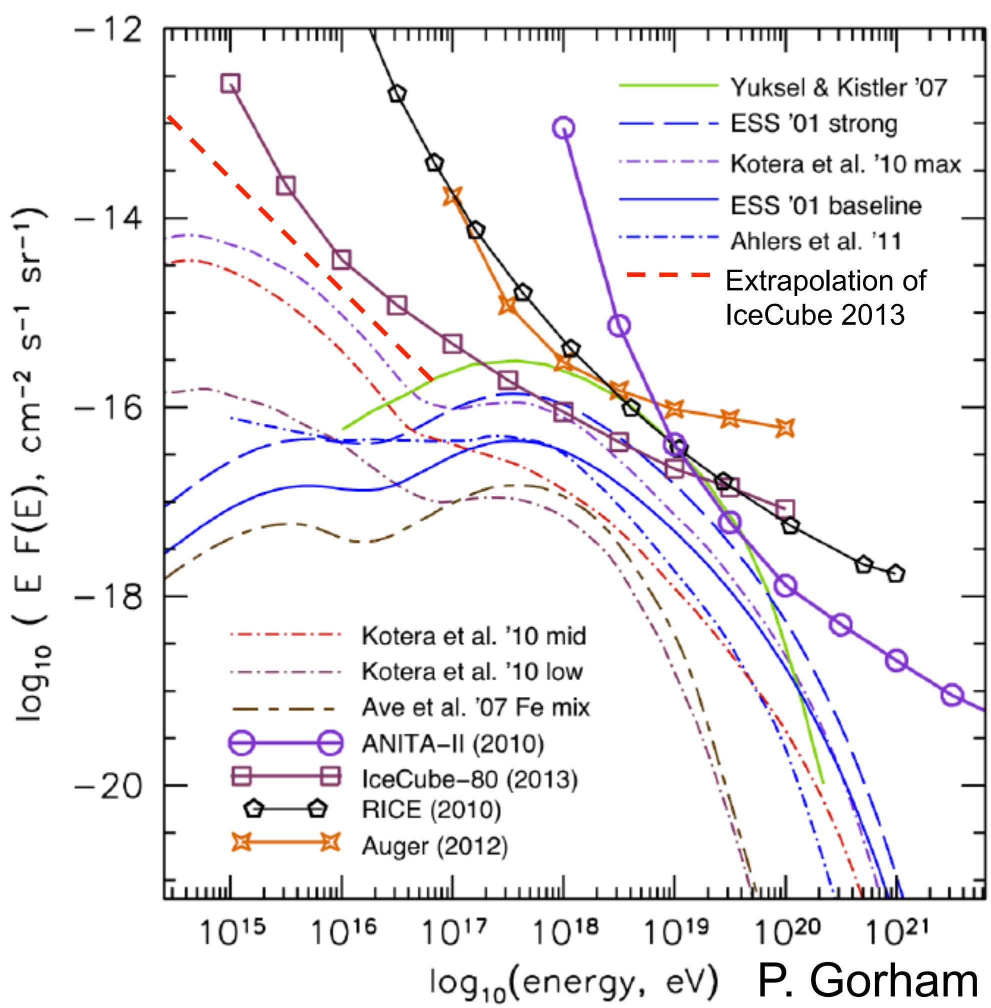


- Auger + Telescope Array now both indicate mostly proton composition
- Brings floor of GZK neutrino predictions up

What Kind of Detector Is Interesting to Build Next?

- Science goals for high energy neutrino observatories:

1) Measure the highest energy particles in the universe
2) Get to the floor of pessimistic GZK UHE flux predictions (requires x100 sensitivity)
3) Measure the high energy region (cutoff?) of the astrophysical neutrino flux measured by IceCube
   - Getting down to PeV energies with radio techniques would be new and very exciting



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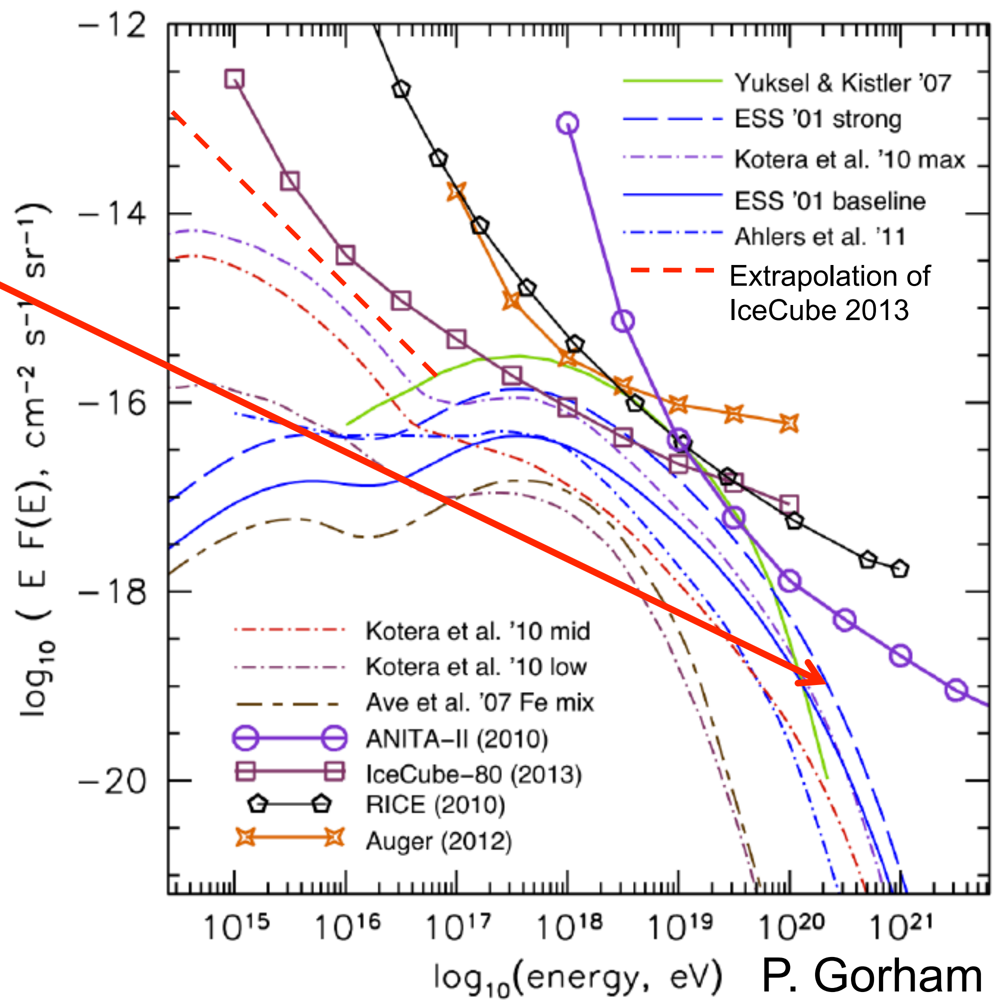

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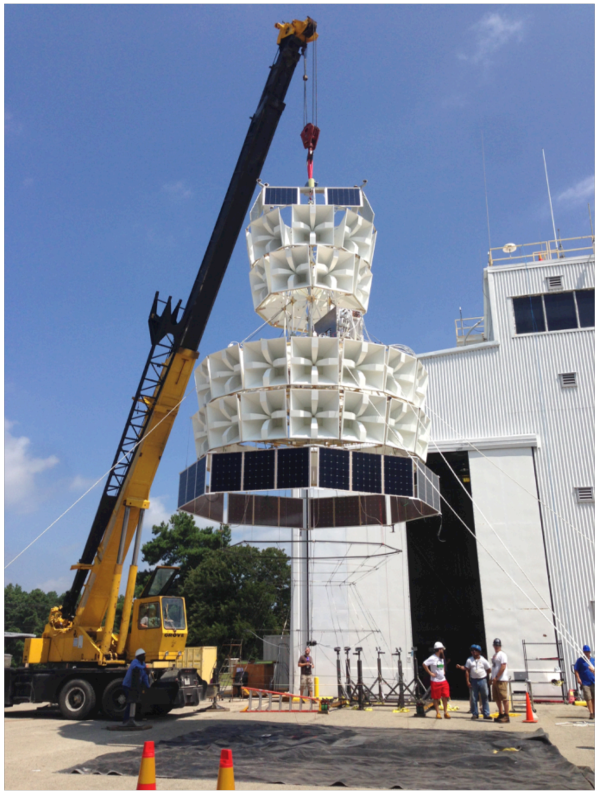
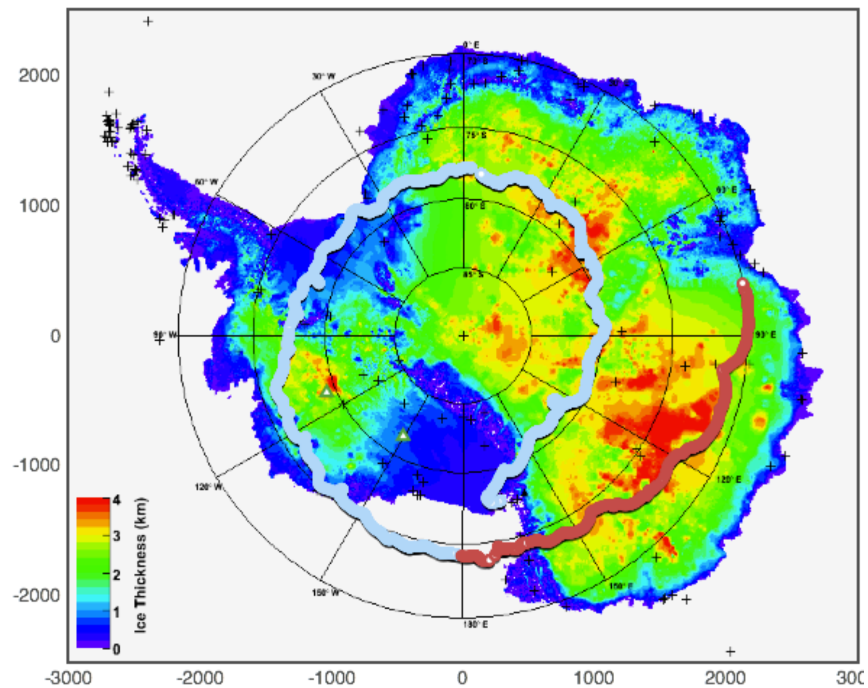
ANITA-III: December 2014

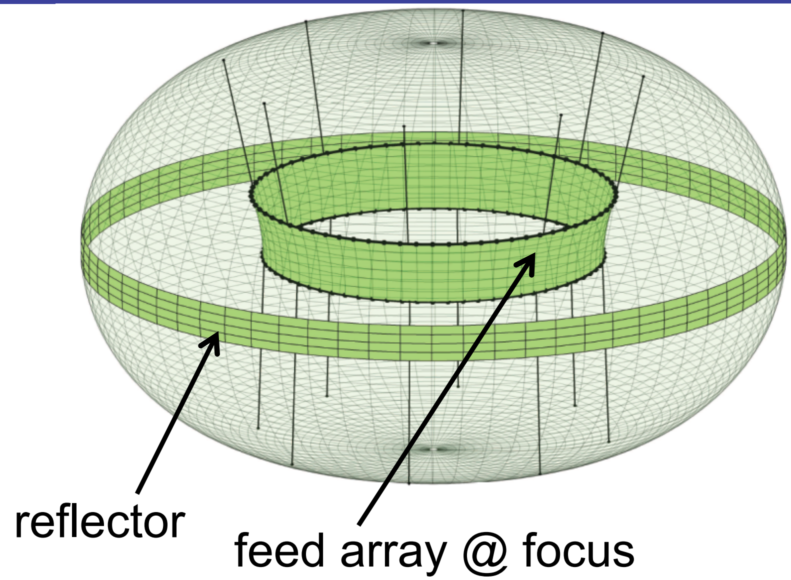




- Full payload integration July 2014
- Launched December 2014, 22 Day flight
  - Improve to ~200 UHECR events
  - Factor of ~a few more sensitivity for neutrinos
- Data drives and expensive components recovered by Aussies
  - drives are in quarantine in Australia, after a long boat ride from Antarctica

EVA: ExaVolt Antenna

- Idea: Turn an entire NASA super pressure balloon into the antenna
- Currently: 3 year NASA grant for developing 1/5 scale engineering test, full RF + float test
- Full Balloon: best sensitivity at highest energies

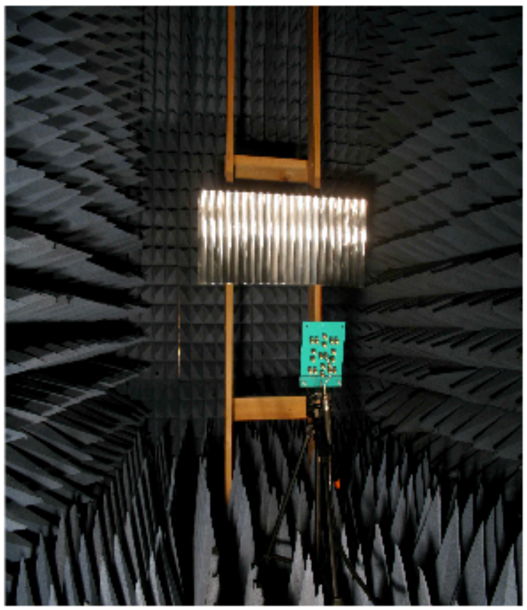


Gorham et al. (2011)

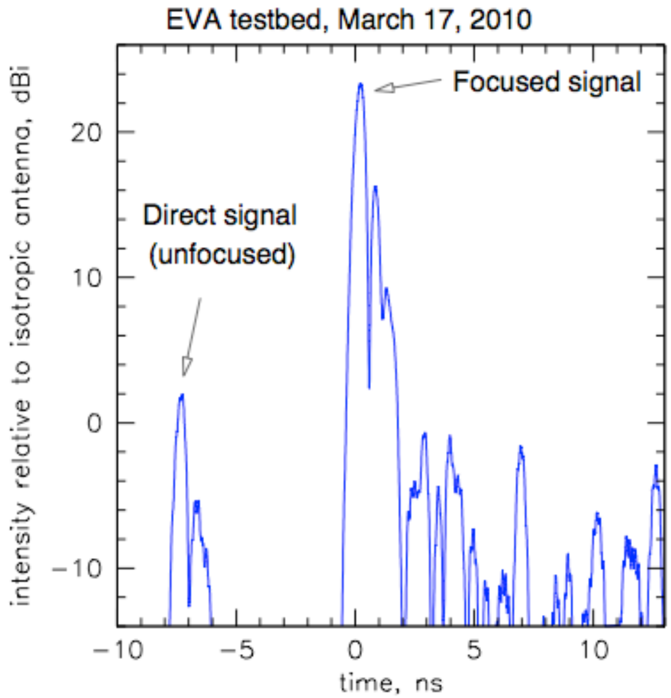
→ Feed design: dual-polarization, broadband, sinuous antennas on inner membrane

EVA Scale Model Test Results

- Microwave scale model testbed
  - Measured directivity ~22dB
- Scale prototype test: Fall 2014



Gorham et al. (2011)



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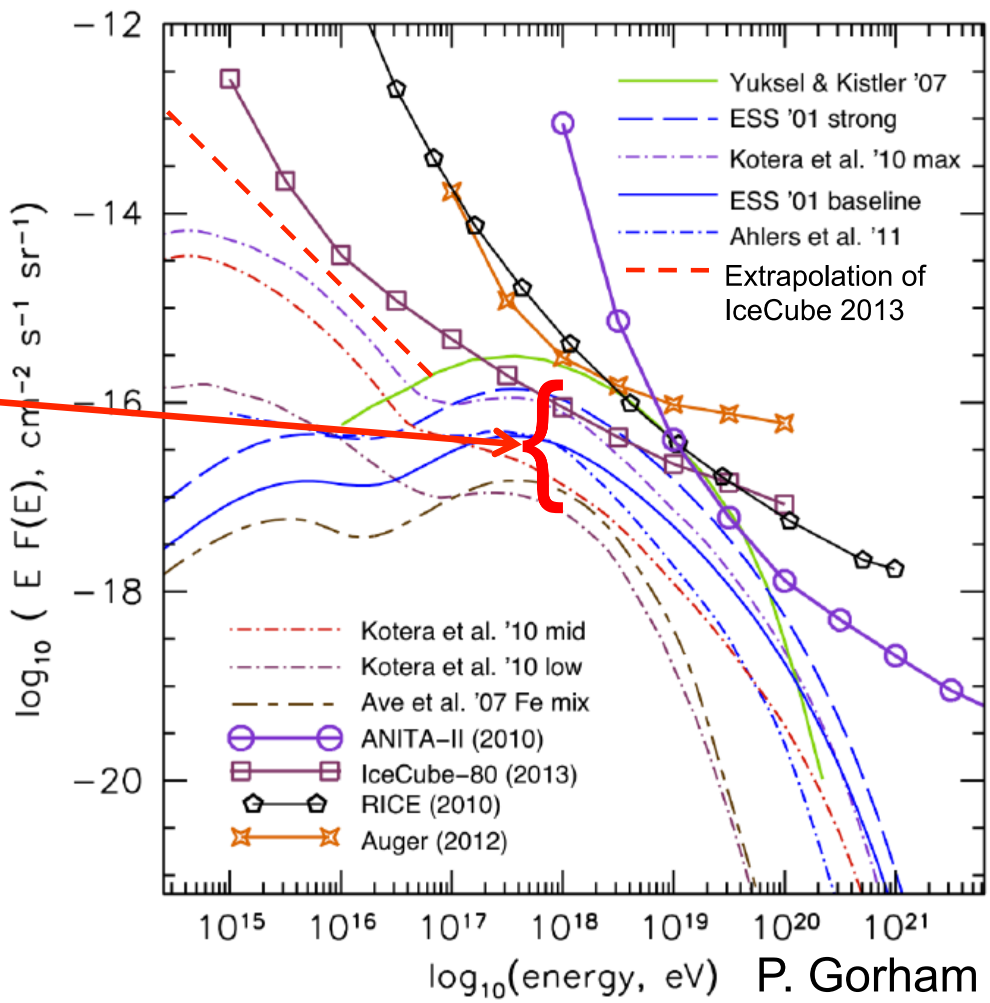

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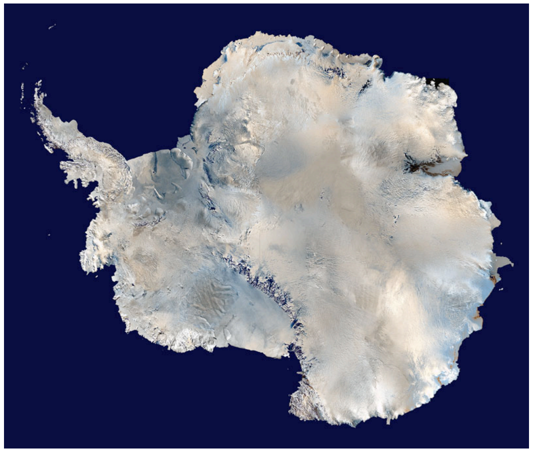
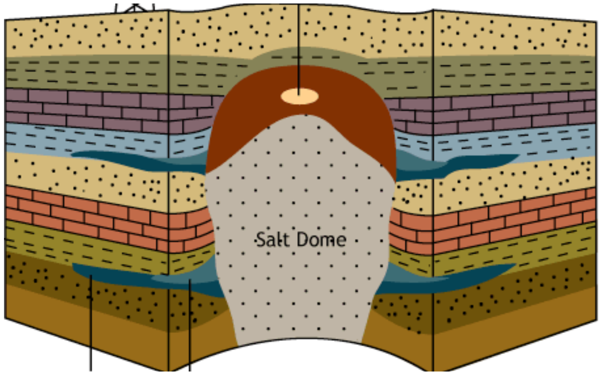
Discovering GZK Neutrinos with Radio: Go to the Ground



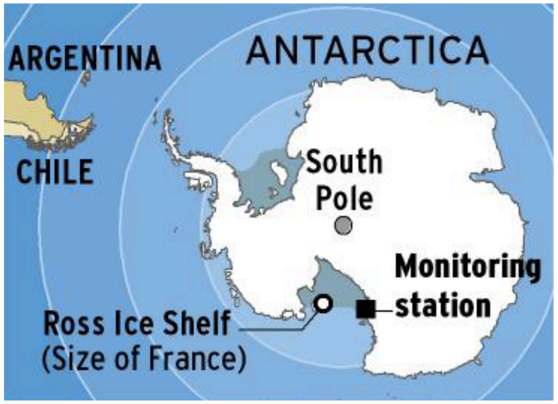
Why go to the ground?

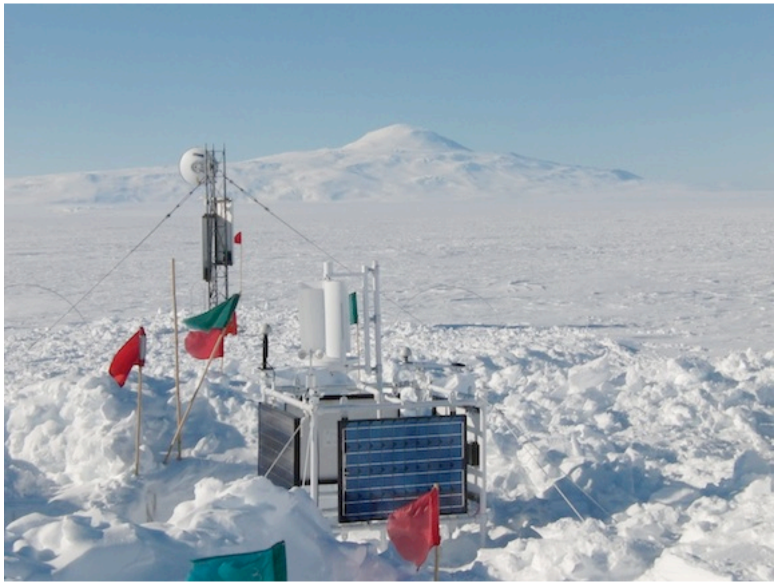
- Much more livetime
- Understandable man-made background
- Lower energy threshold
- Use more antennas than on a balloon
- But: smaller instrumented volume

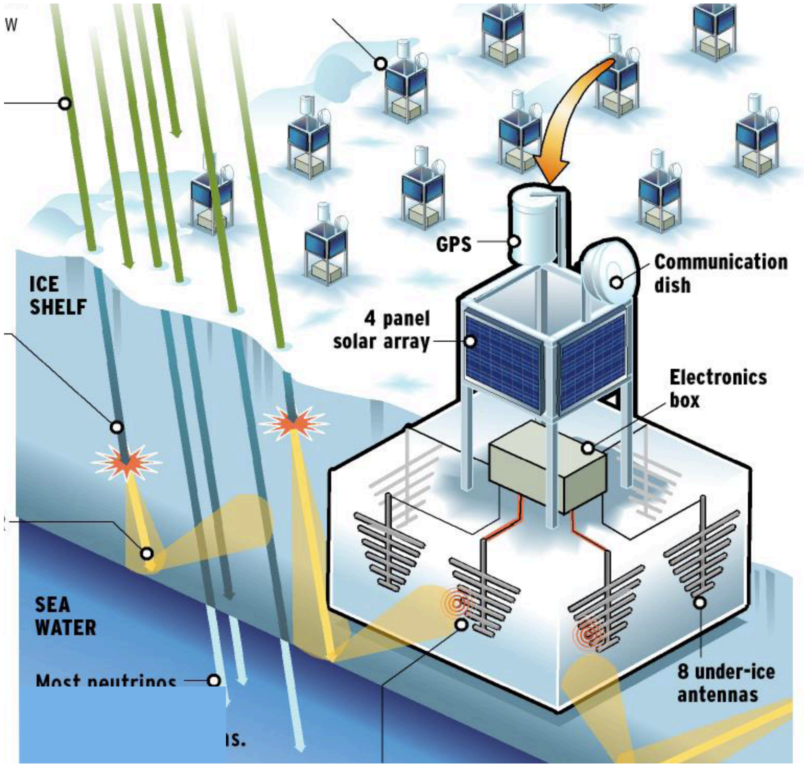


ARIANNA

- Idea: Ground-based array of antennas on the surface of the Ross Ice Shelf
- Currently: 3 stations operating well, 4 more installed in December 2014
- Plan: proposal submitted for full array (1000 detectors)
- Solar Power: stations have operated through 58% of the year on solar power alone

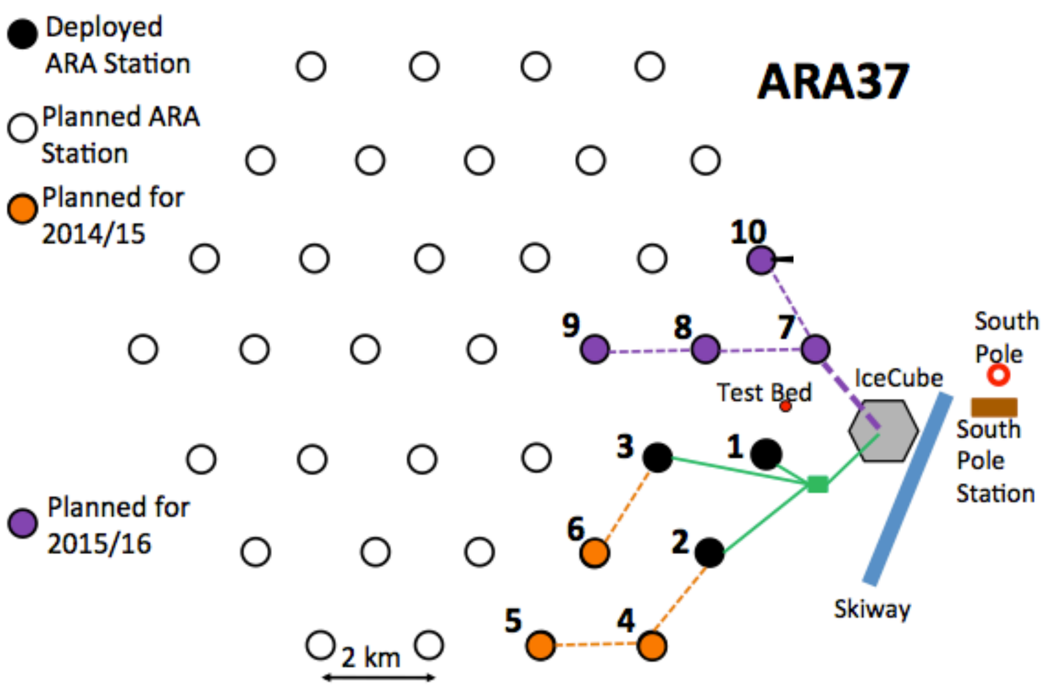






ARIANNA Coll. See arXiv:1410.7369

ARA: Askaryan Radio Array



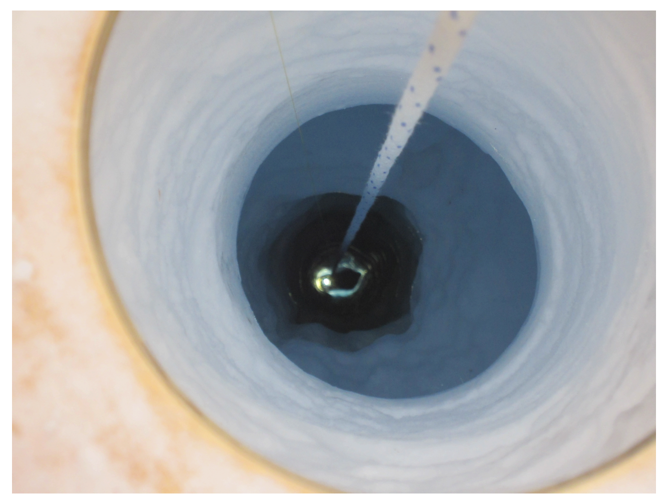
Idea: 37-station array of antennas buried 200m below the surface at the South Pole

Currently: 3 stations + testbed deployed and working

Plan: Proposal pending for next stage of deployment (10 stations)

V Pol Antennas

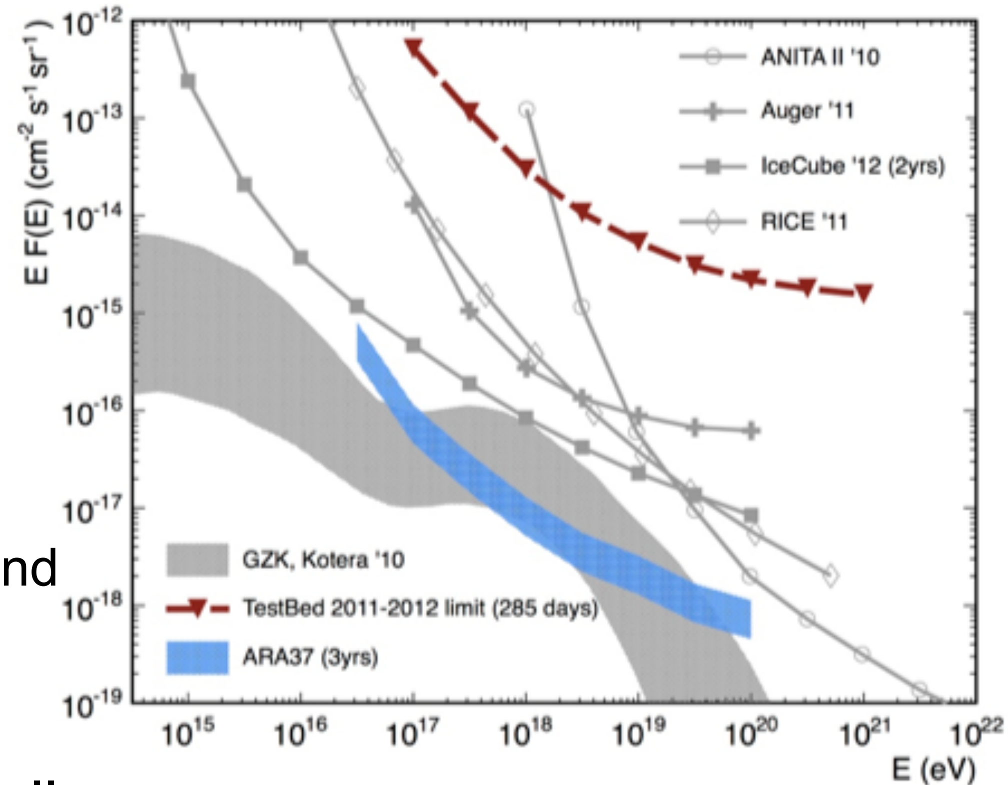
H Pol Antennas



ARA Collaboration. Astropart. Phys. (2012)

ARA Testbed Data Analysis

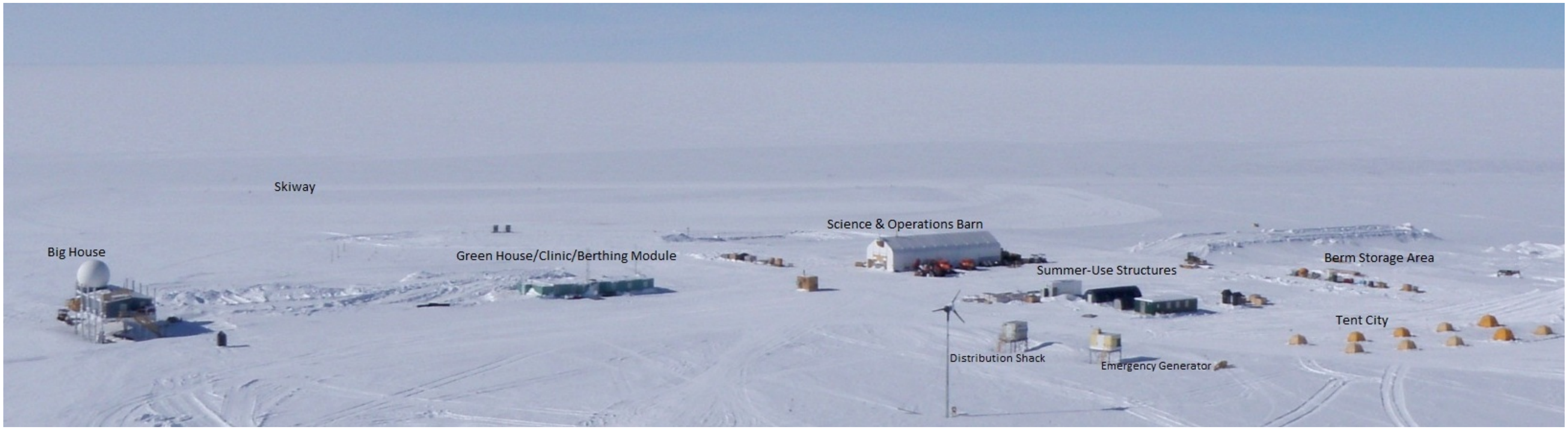
- 2011 and 2012 testbed station data
- Three independent blind analyses, look at 10% sample
- Cut-based analysis:
  - Reconstruction cuts
    → reject thermal noise background
  - Impulsiveness cuts
    → reject continuous wave background
  - Directionality cuts
    → reject man-made background
- Future: much more volume instrumented, trigger and analysis improvements for full 37-station array
- See Aongus Murchada talk



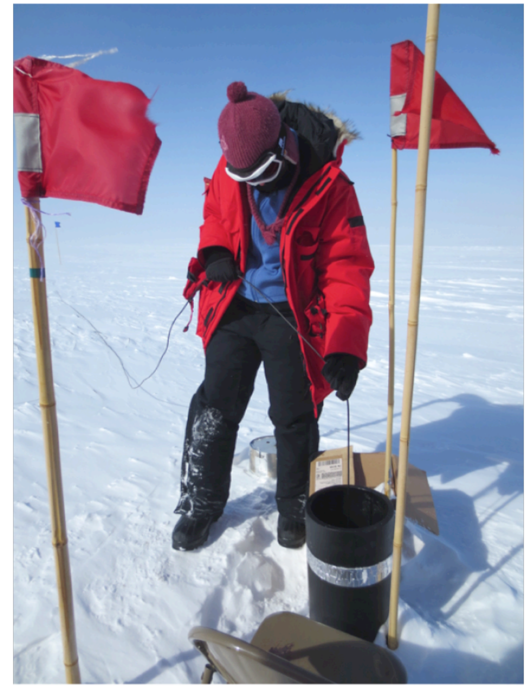
ARA Collaboration: arXiv:1404.5285

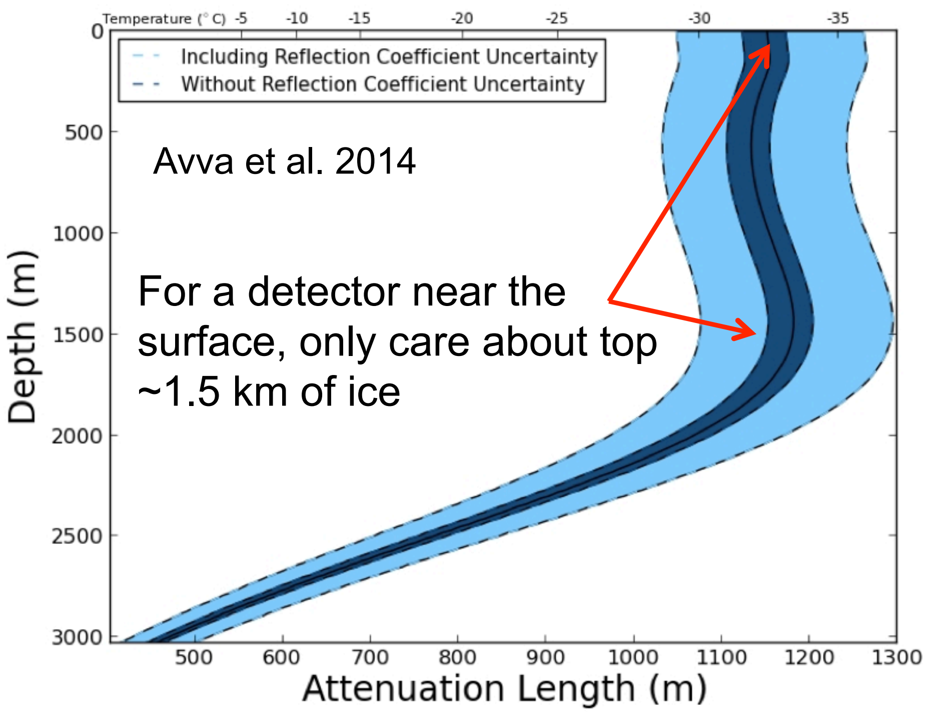
Alternative Site: Summit Station Greenland

- Most ice volume of any reasonable site
  - 3 km thick ice at Summit Station, water layer at bottom (reflections add to effective volume)
- Sunlight 10 months/year → solar power
- Relatively quick to get to (direct flight from New York)
- Sees Northern Sky
- Year-round, NSF-Operated
- Access: C-130 flights, annual overland traverse, long summer season
- Plans for a new station called “Isi,” construction begins 2015



Summit Station Site Characterization June 2013





- Measured the attenuation length of the ice at 100-1000 MHz
- Measured firn properties (100m depth vs. 200m at South Pole)
- ~1 km attenuation length at 300 MHz, slightly less than South Pole

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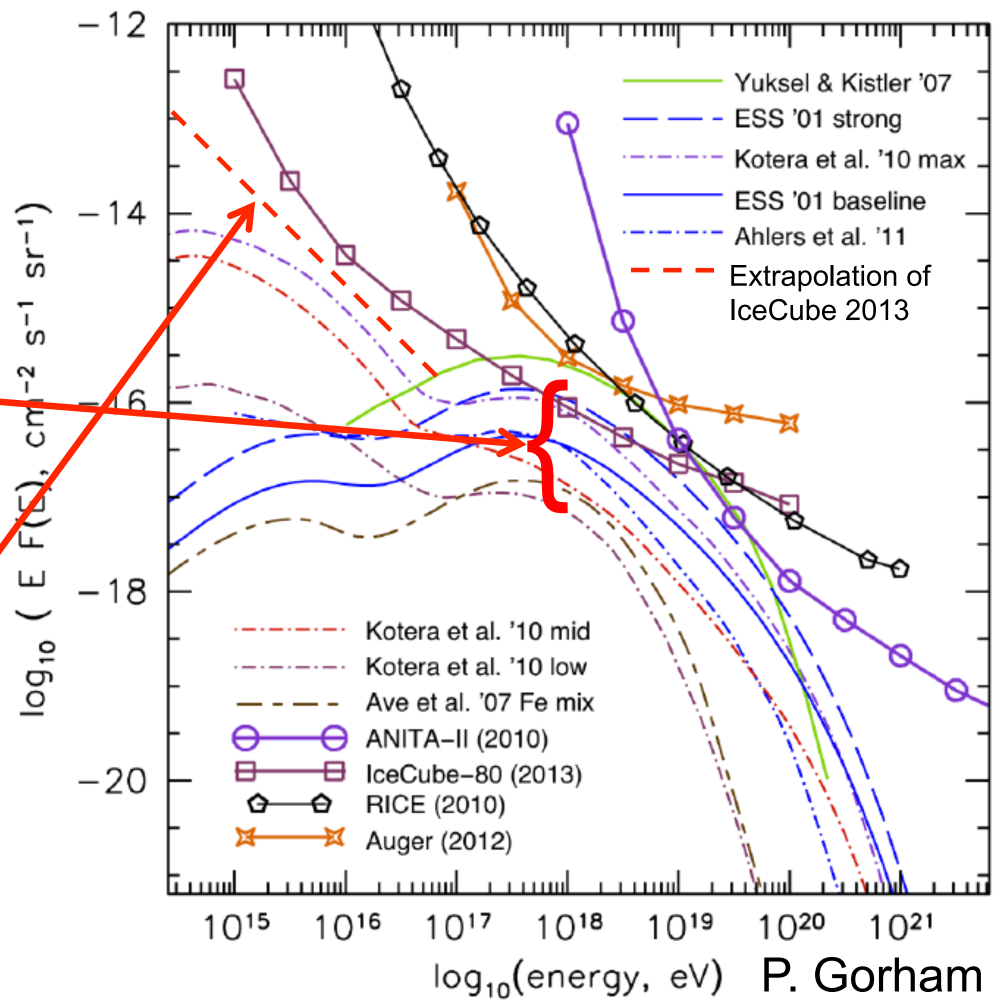

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How Do You Push Down to 1 PeV with Radio?

1) Be as close as you can be to events (so signals appear strong at the detector)

→ Directly embed antennas in ice

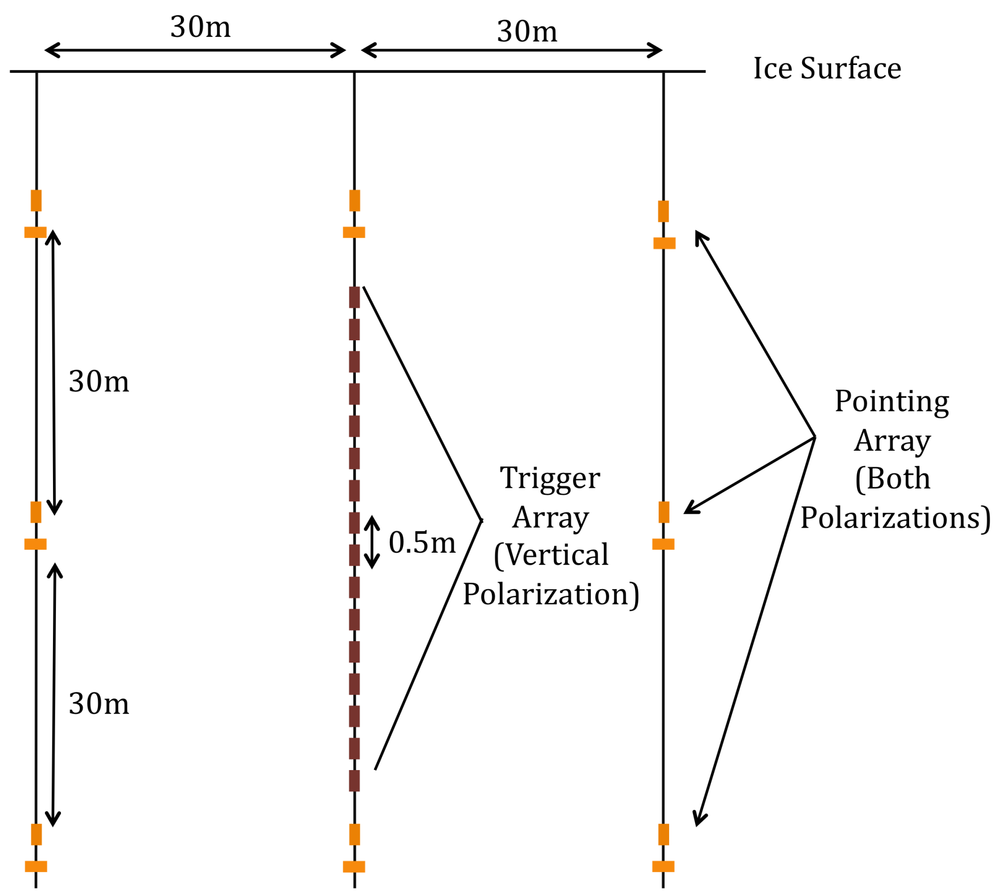
2) Need radio-clear ice to see far away (~1 km attenuation length)

3) Need to achieve the highest signal to noise in the detector as possible to see small signals

→ Need extremely high effective gain antenna

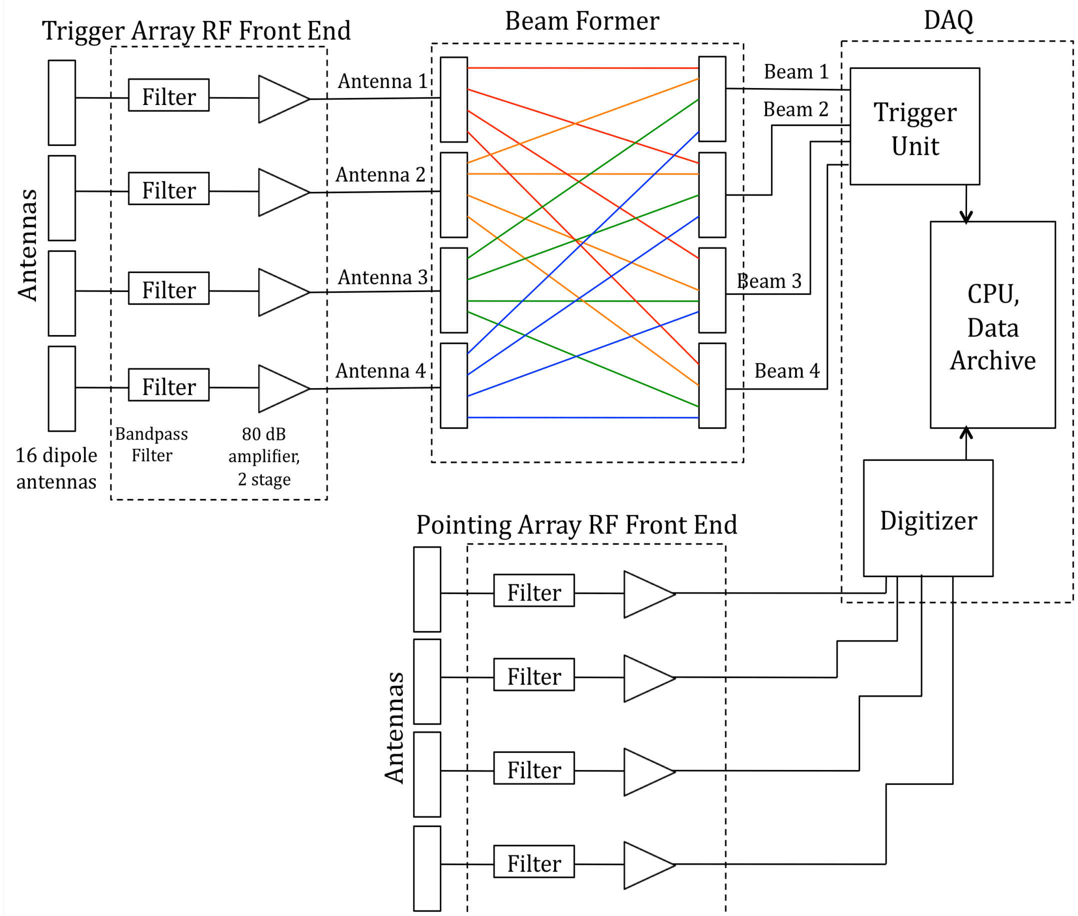
- Problem: high gain antennas don't fit down holes, and extremely high gain antennas are hard to make

- Answer: a phased array of low-gain antennas



A Phased Array for PeV and UHE Neutrinos

- Beamforming: for a given incident direction, calculate the system delay required between antennas to see the signal in-phase in all the antennas
- The signal is correlated between antennas and noise is uncorrelated: increase the SNR as sqrt(N)
- Create many beams at once to cover the solid angle of interest
- Analog or digital



Example: 16 Antenna Station

Back of the envelope calculation:

→ For 16 dipoles (2.15 dBi each), the effective gain per beam is 14.2 dBi.

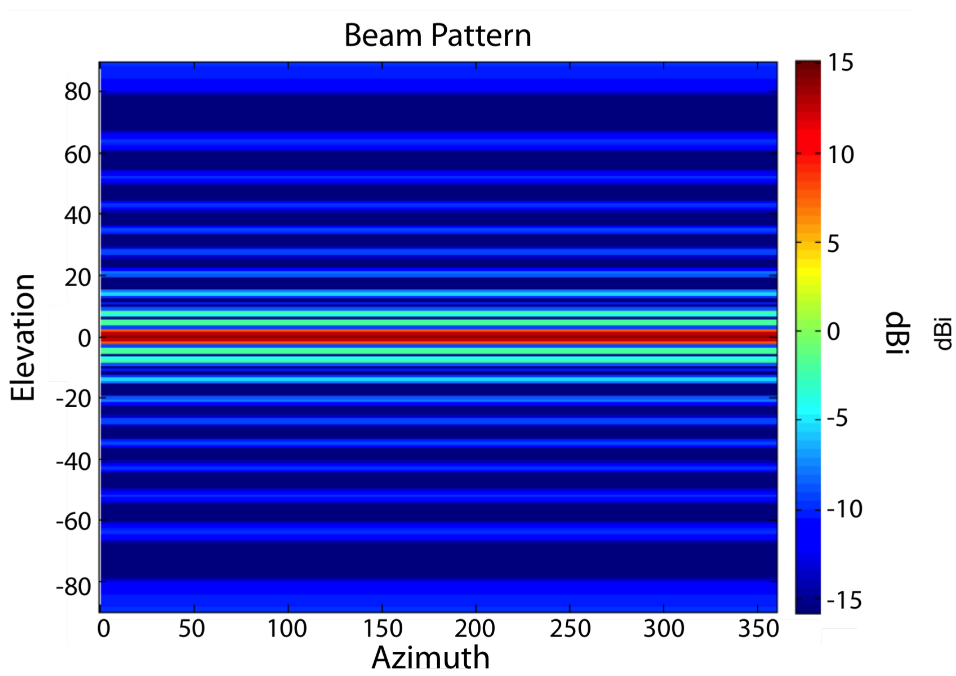
→ A factor of ~ 4 in electric field threshold

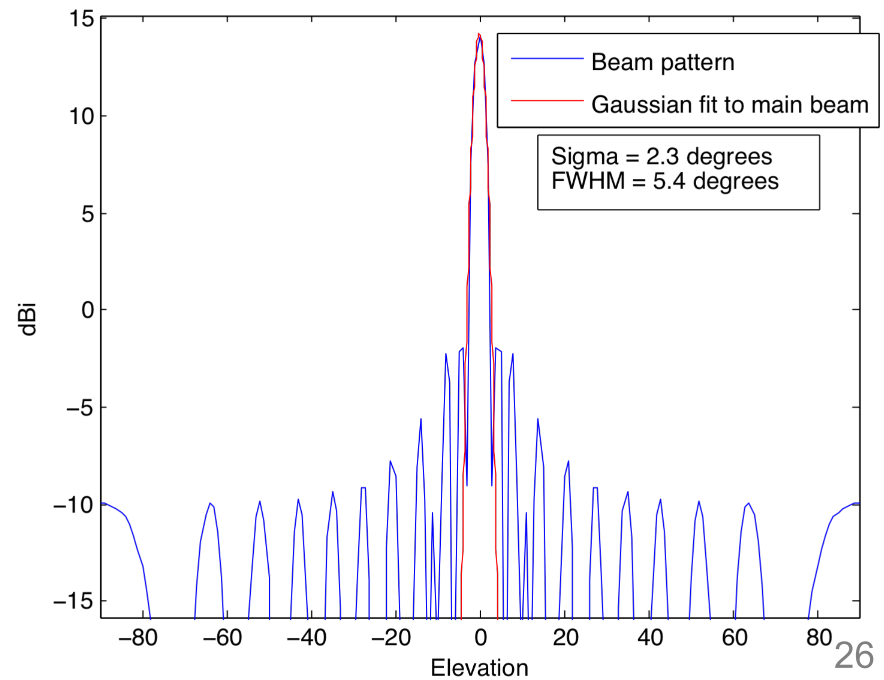
→ A falling neutrino spectrum means that is a large factor in neutrino event rate.

→ With more antennas, you push the threshold down farther.

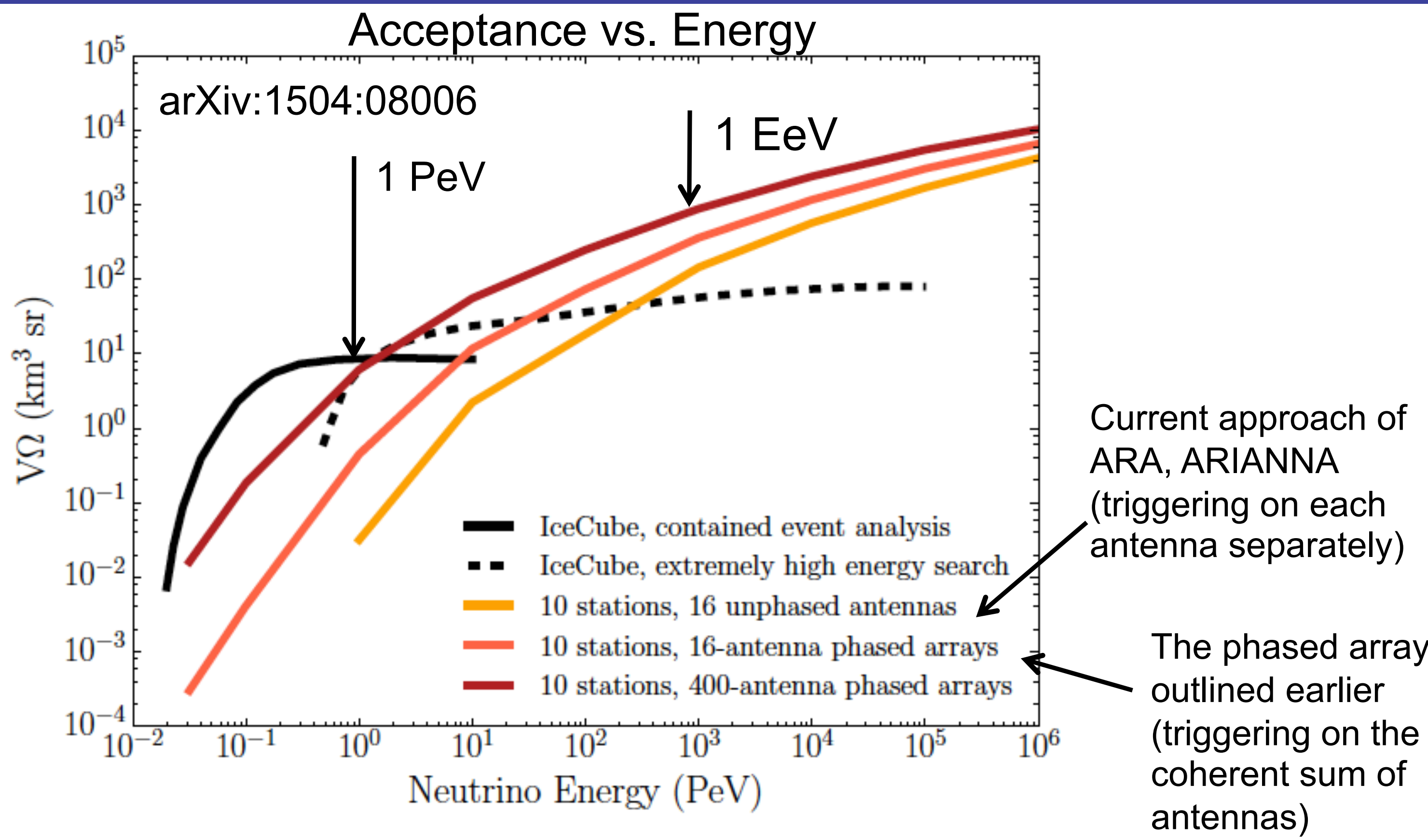
- 16 antennas in one hole and closely packed @ 200 MHz
- Only need ~10 beams to cover the solid angle of interest (horizon down to -50°)

→ **Greenland Neutrino Observatory**: deploying 8-antenna phased array prototype in June 2015 to Greenland





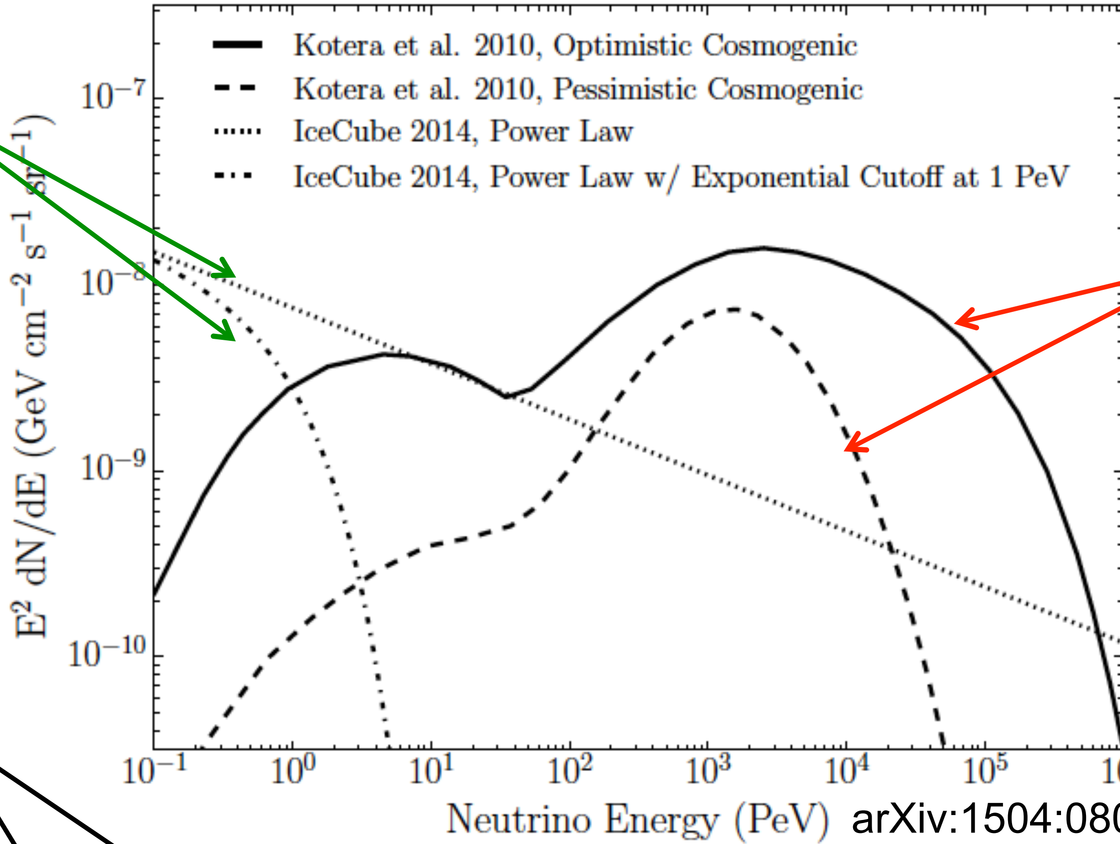
Acceptance Comparison for 10 Stations @ Summit



- Stations act independently and are far apart
- Increase is x10 at low energies and x3 at high energies simply from phasing (yellow → orange)
- Phasing 400 antennas provides good energy overlap with IceCube above 1PeV
- See Keith Bechtol's talk for details of simulations

3 Years of Observation, 10 Stations @ Summit

Astrophysical Models, based on Icecube data



arXiv:1504:08006

GZK Models (optimistic and pessimistic)

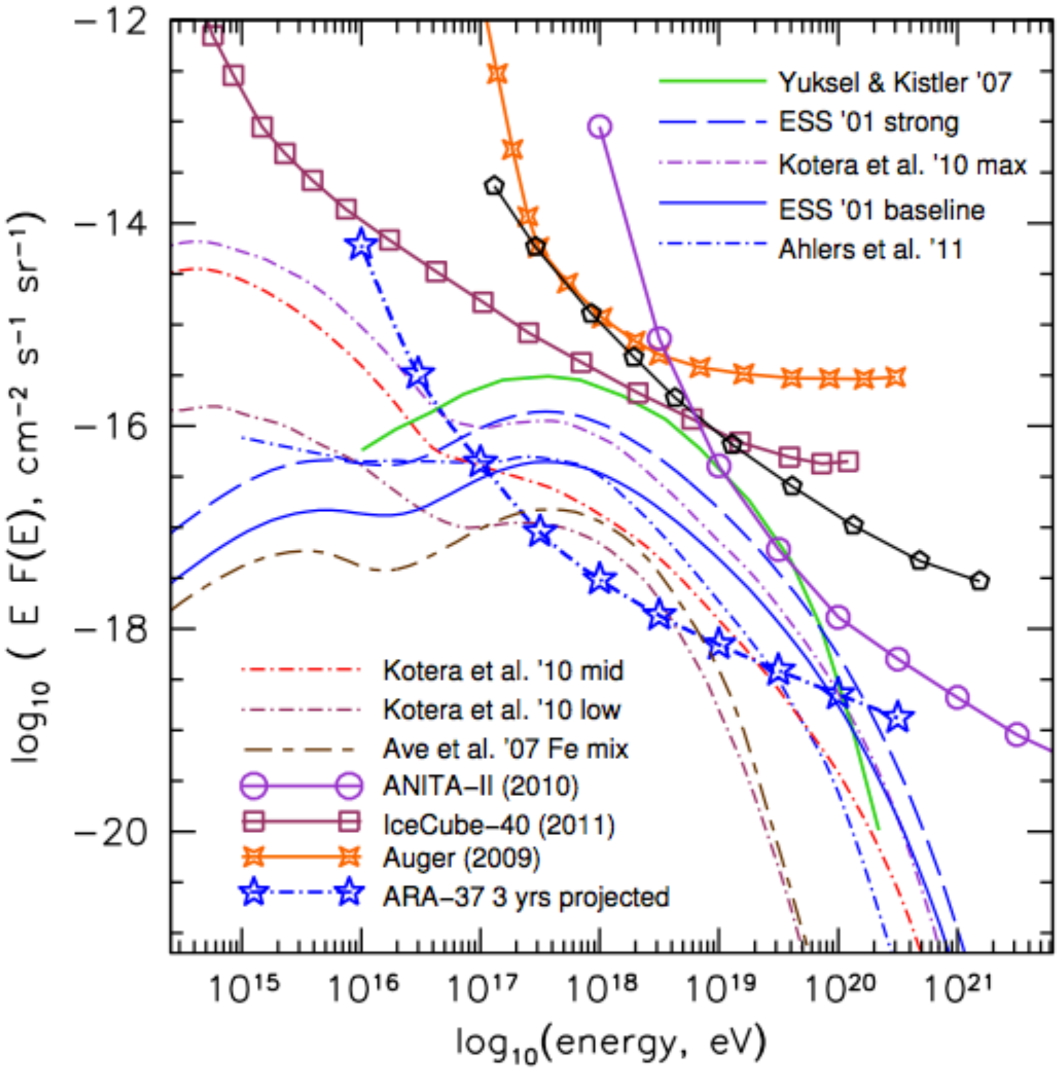
Just by phasing 16 antennas per station, can distinguish between spectrum with a cutoff or not

Station Configuration	Power Law	Power Law with Cutoff	Optimistic GZK	Pessimistic GZK
16-antenna, old method	0.9	0.0	7.7	2.3
16-antenna, phased	3.8	0.1	19.6	6.0
400-antenna, phased	18.4	2.2	52.9	15.6

Projected UHE Neutrino Sensitivity

What the sensitivity of a next-generation ground-based UHE neutrino detector looks like:

→ With tens of events per year, we'll have a real high-energy neutrino observatory for particle physics and astrophysics



ARA Coll. arXiv:1105.2854

Summary

- It is an exciting time in the search for UHE neutrinos!
- The radio technique has been proven, current results (ANITA) constrain models
- Large forward-looking efforts are in initial stages: ARA, ARIANNA, GNO, EVA, etc.
- The phased array radio technique will allow radio arrays to push the energy threshold down and achieve larger effective volume per station, providing meaningful overlap with IceCube and efficiently covering the UHE regime
- In 5 years, we hope to have a real UHE neutrino observatory running and to observe for many years