Radio Detection of the Highest Energy Neutrinos

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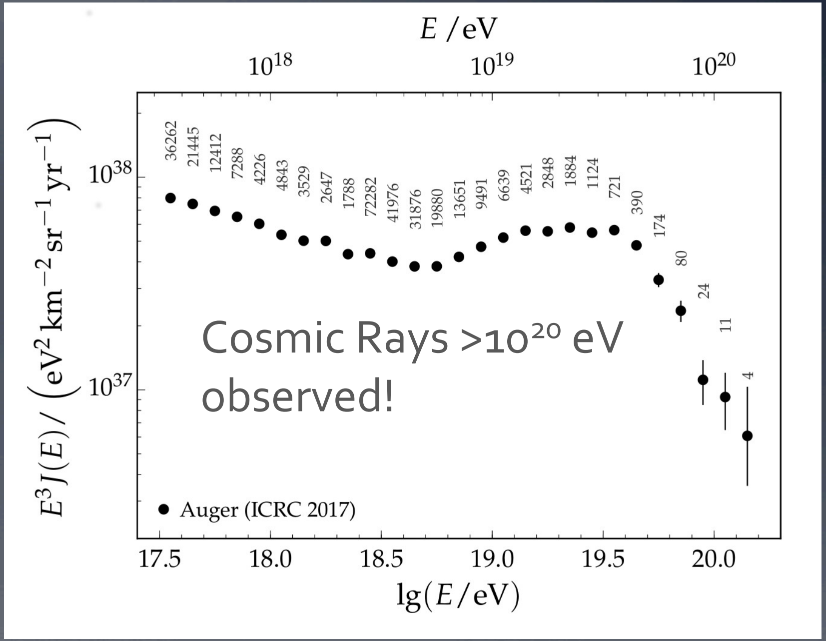
University of Chicago

TeVPA, August 2017

Neutrinos: The Ideal UHE Messenger

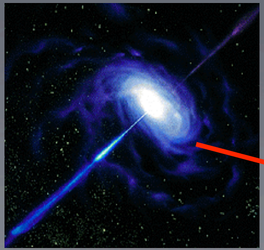
Possible Messenger Particles:

- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei deflect in magnetic fields
- Neutrons decay
- Neutrinos: point back to sources, travel unimpeded through universe



UHE Neutrino Detectors:

- Open a unique window into the universe
  - Highest energy observation of extragalactic sources
  - Very distant sources
  - Deep into opaque sources
- How the high energy universe evolves?



Neutrino Production: The GZK Process

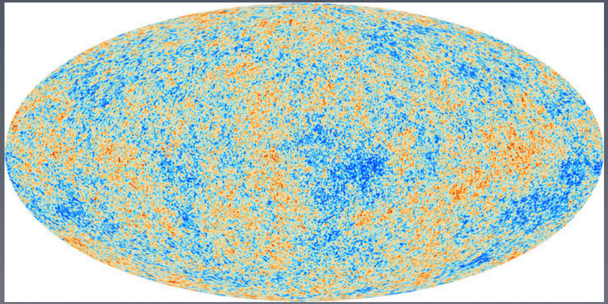
GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

$$
\begin{aligned}
p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} & \\
& \rightarrow \mu^{+} + \boxed{\nu_{\mu}} \\
& \quad \rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}}
\end{aligned}
$$

Cosmic Rays

+

CMB



= Neutrino Beam!

Discover the origin of high energy cosmic rays and neutrinos?

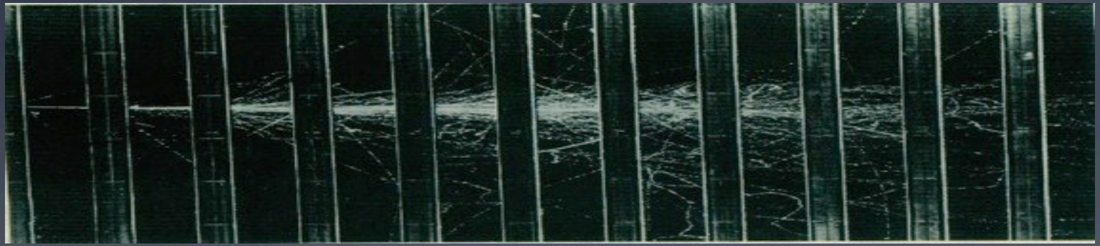
What is the high energy cutoff of our universe?

What is(are) the acceleration mechanism(s)?

Detection Principle: The Askaryan Effect

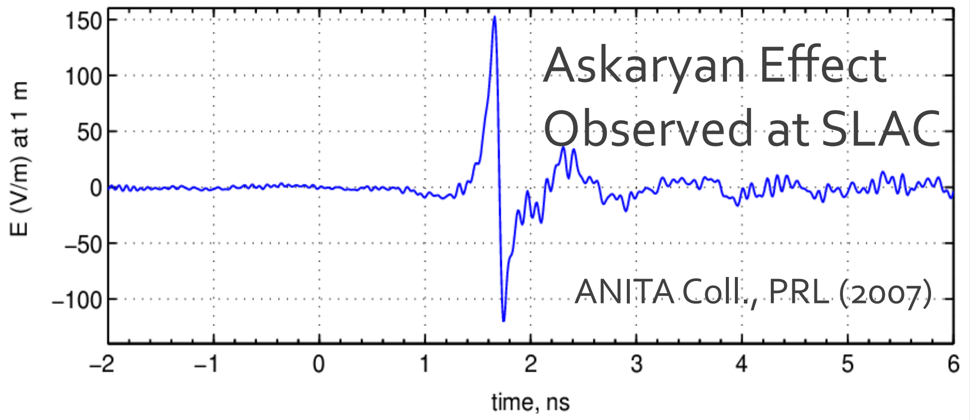
- EM shower in dielectric (ice) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if λ > Moliere radius

e^+, e^-, γ →



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

→ Radio Emission is stronger than optical for UHE showers



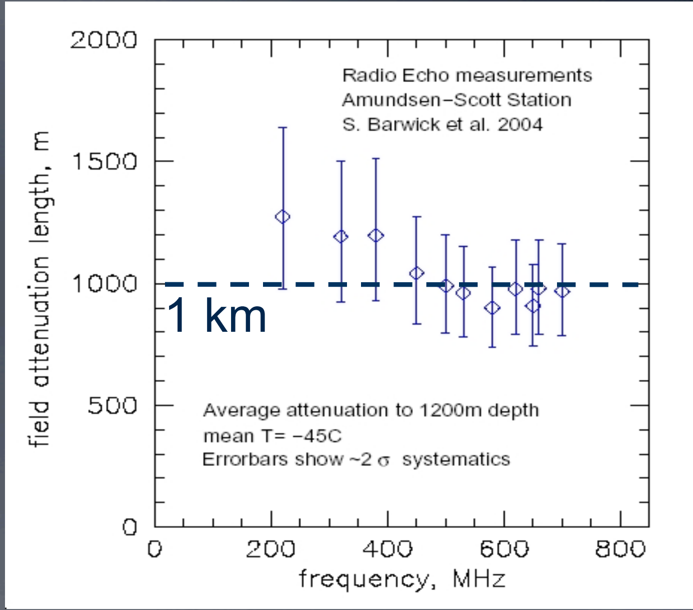
Askaryan Effect Observed at SLAC

ANITA Coll., PRL (2007)

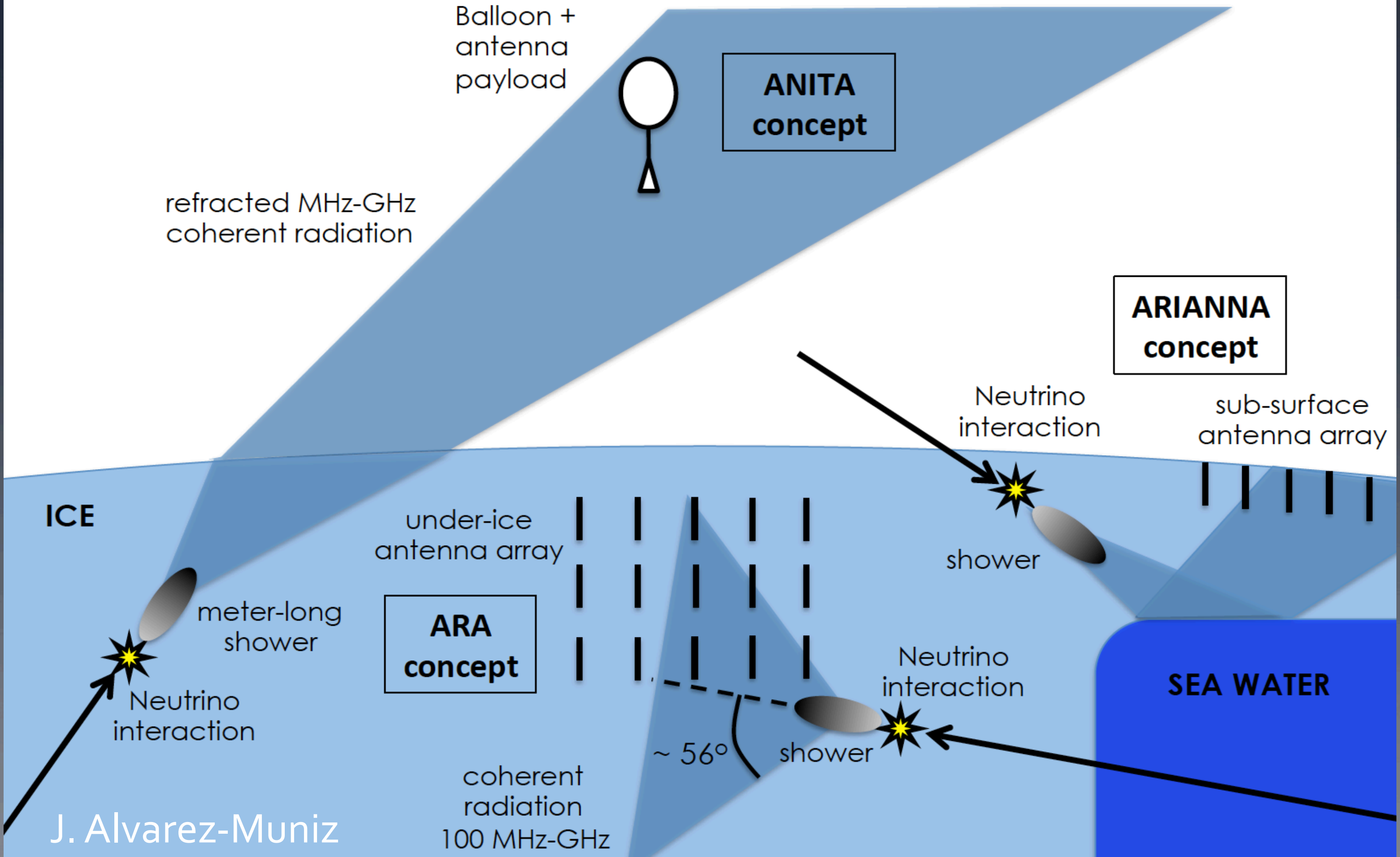
UHE Neutrino Detector Requirements

- 1 GZK neutrinos/km^2/year
- L_{int} ~ 300 km
  → 0.003 neutrinos/km^3/year
- Need a huge (> 1000 km^3), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF (vs. ~100 m for optical signals used by IceCube)

→ Ice is good for radio detection of UHE neutrinos!



The Concept: Radio Detection in Dense Media



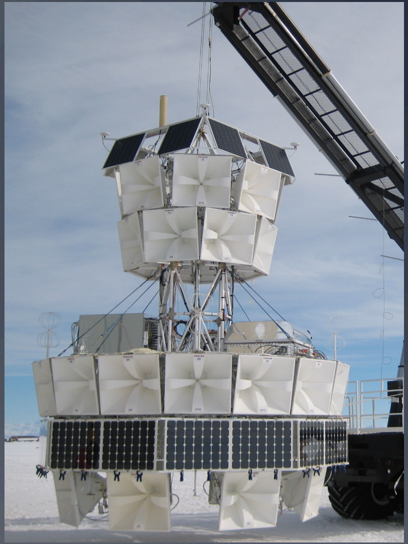
J. Alvarez-Muniz

ANITA-1 & ANITA-2: Best Limit > $10^{19.5}$ eV

NASA Long Duration Balloon, launched from Antarctica

ANITA-I: 35 day flight 2006-07

ANITA-II: 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:

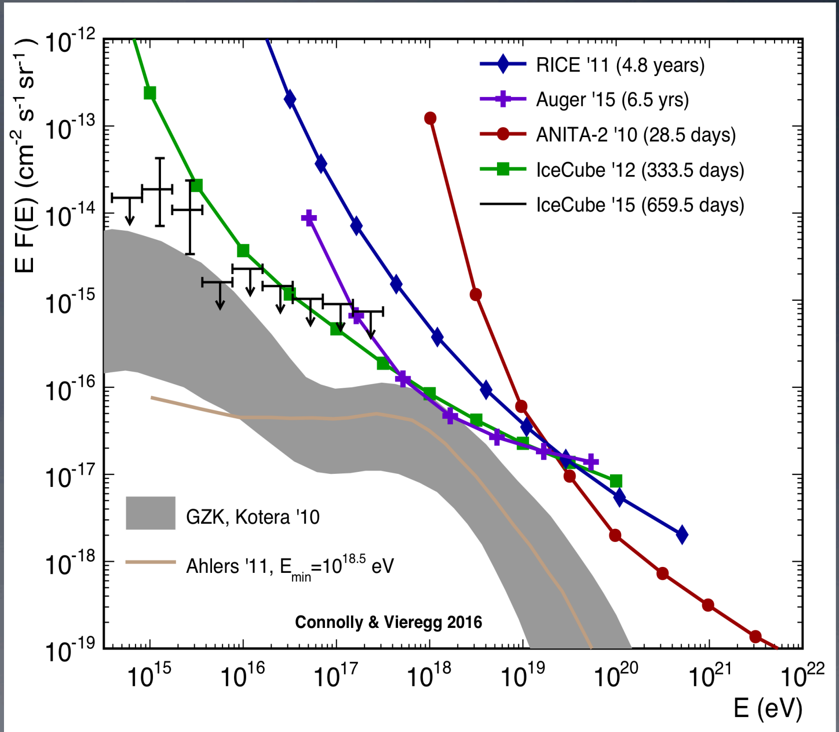
	ANITA-I	ANITA-II
Neutrino Candidate Events	1	1
Expected Background	1.1	0.97 +/- 0.42

Models & Current Constraints

<u>Best current limits:</u>

$>10^{19.5}$ eV: Radio Detection (ANITA)

$<10^{19.5}$ eV: Optical Detection (IceCube) and Indirect Detection (Auger)

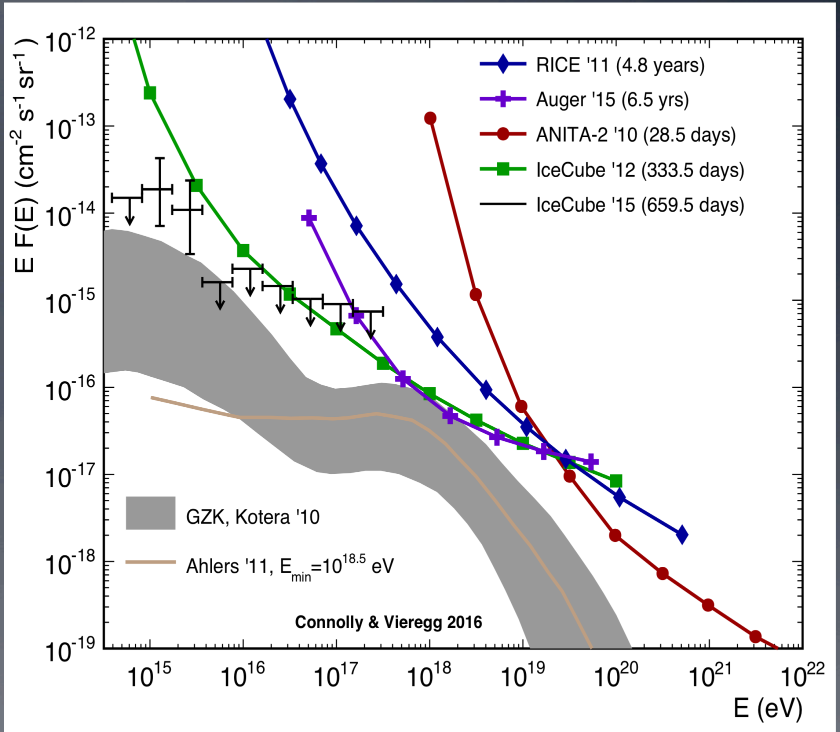


- Constraining models (source evolution and cosmic ray composition)
- How do we get a factor of ~100 to dig into the interesting region and make a real UHE neutrino observatory?
- Why bother? Not a fishing expedition! There is a floor on the flux predictions.

What Kind of Detector Is Interesting to Build?

- Science goals for high energy neutrino observatories:

1) Measure the highest energy particles in the universe
2) Reach more pessimistic GZK UHE flux predictions (requires x100 sensitivity)
3) Measure the astrophysical neutrino flux measured by IceCube to higher energies



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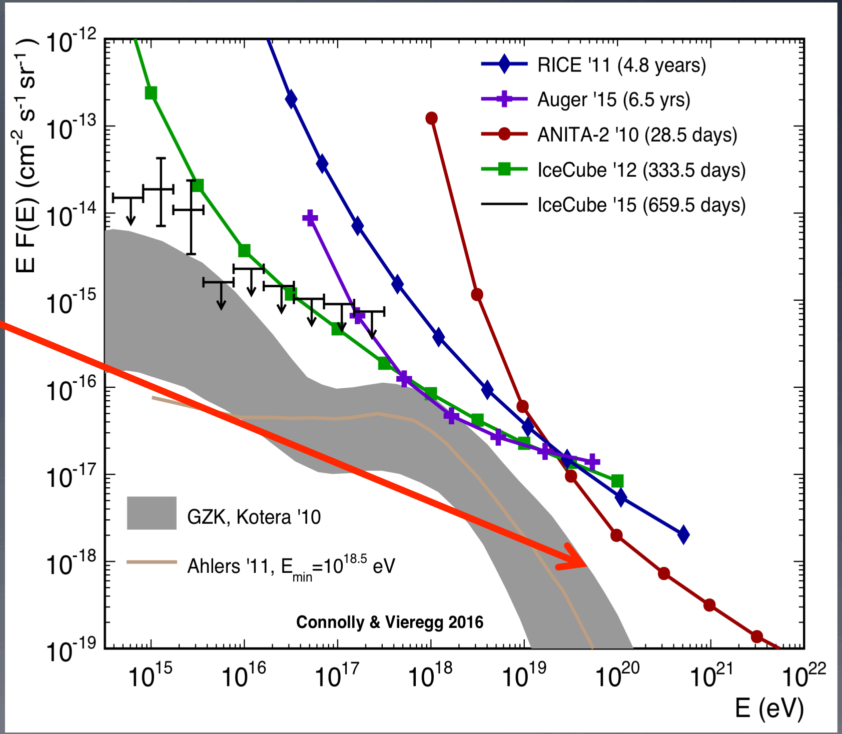
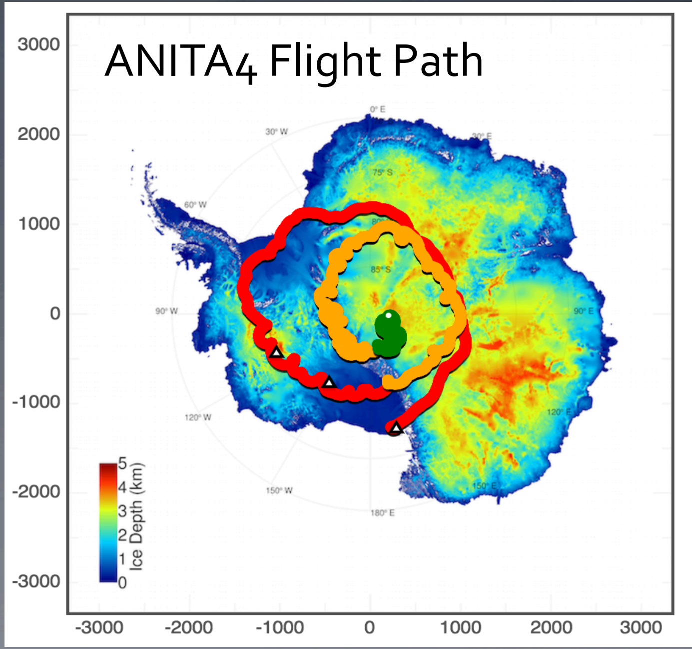


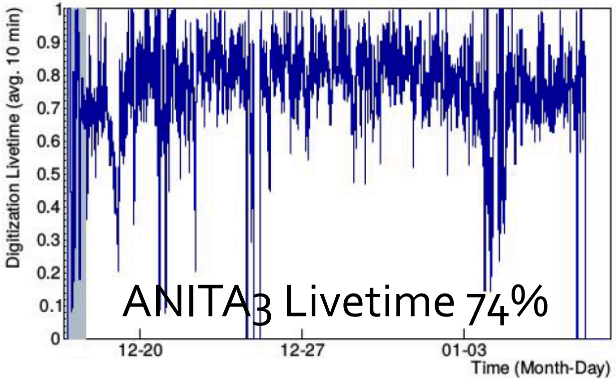
ANITA-3 and ANITA-4

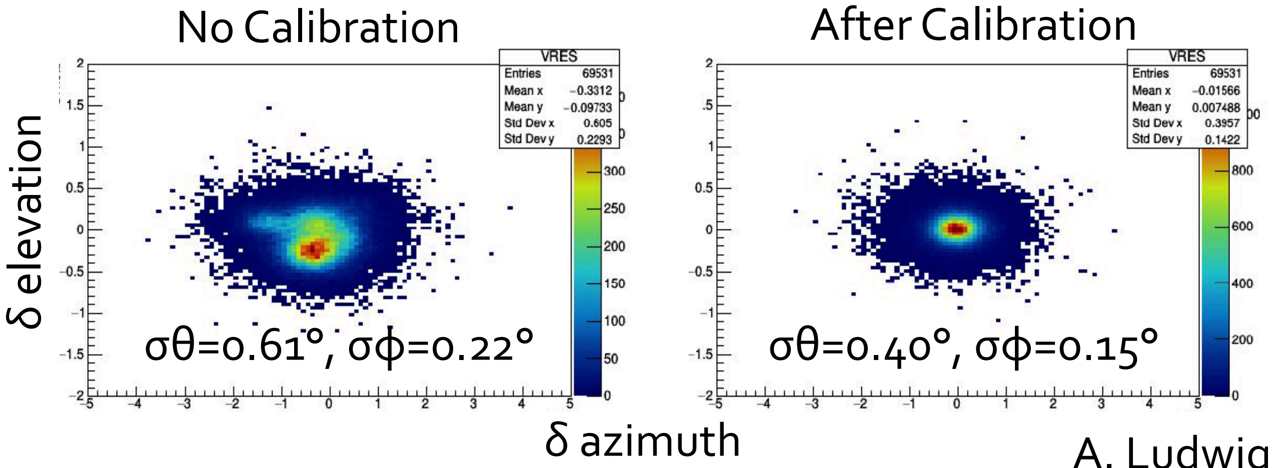
- ANITA3: Flight in 2014
  - Analysis nearing unblinding (see C. Deaconu talk)
- ANITA4: Flight in 2016
  - New programmable notch filter
  - Data drives recovered, analysis underway
- Projected world-leading sensitivity @ $>10^{19.5}$ eV
- Expect 100's of cosmic rays > 10^{18} eV and a factor of a few sensitivity to neutrinos
- Best sensitivity to transients!



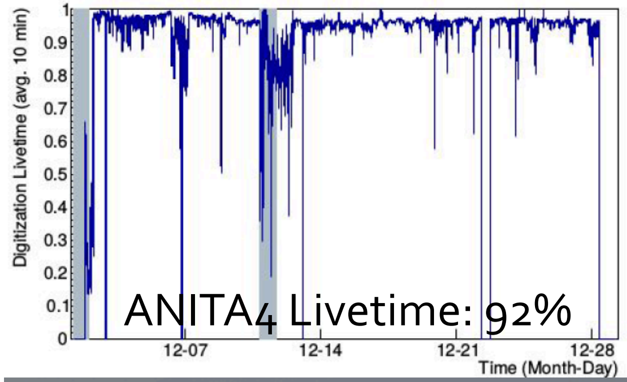
Improvements for ANITA-4

- Programmable notch filters led to significantly increased sensitivity (see O. Banerjee talk)
- Achieved pointing resolution for ANITA4, using calibration pulses: best ever for ANITA (see A. Ludwig talk)





A. Ludwig



O. Banerjee

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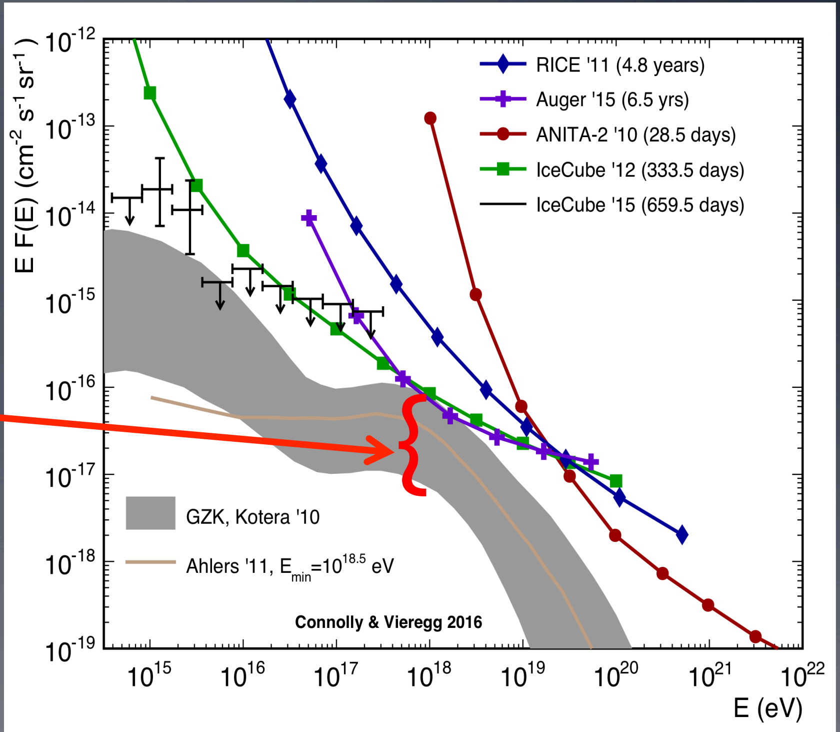
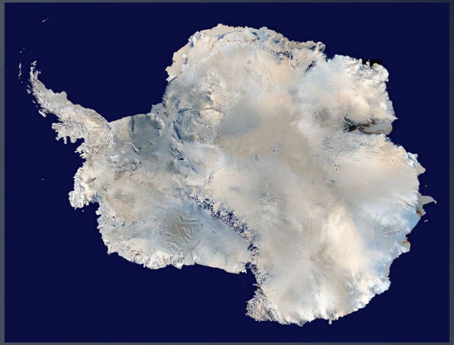
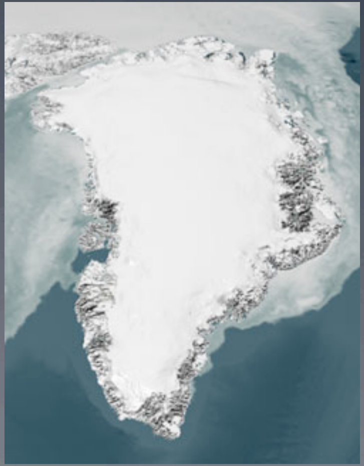


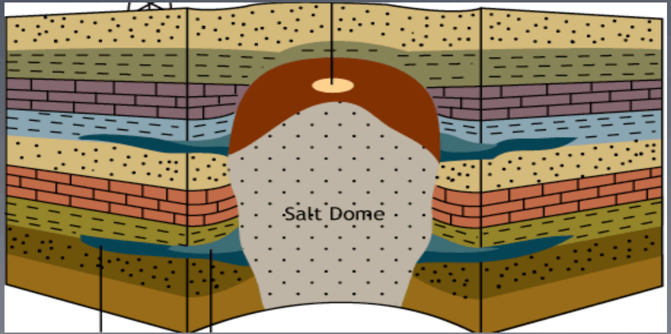
Discovering UHE Neutrinos with Radio: Go to the Ground

- More livetime
  - 300 days/year vs. 30 days/3 years
- Understandable man-made background
- Lower energy threshold
- Use more antennas than on a balloon
- But: smaller instrumented volume

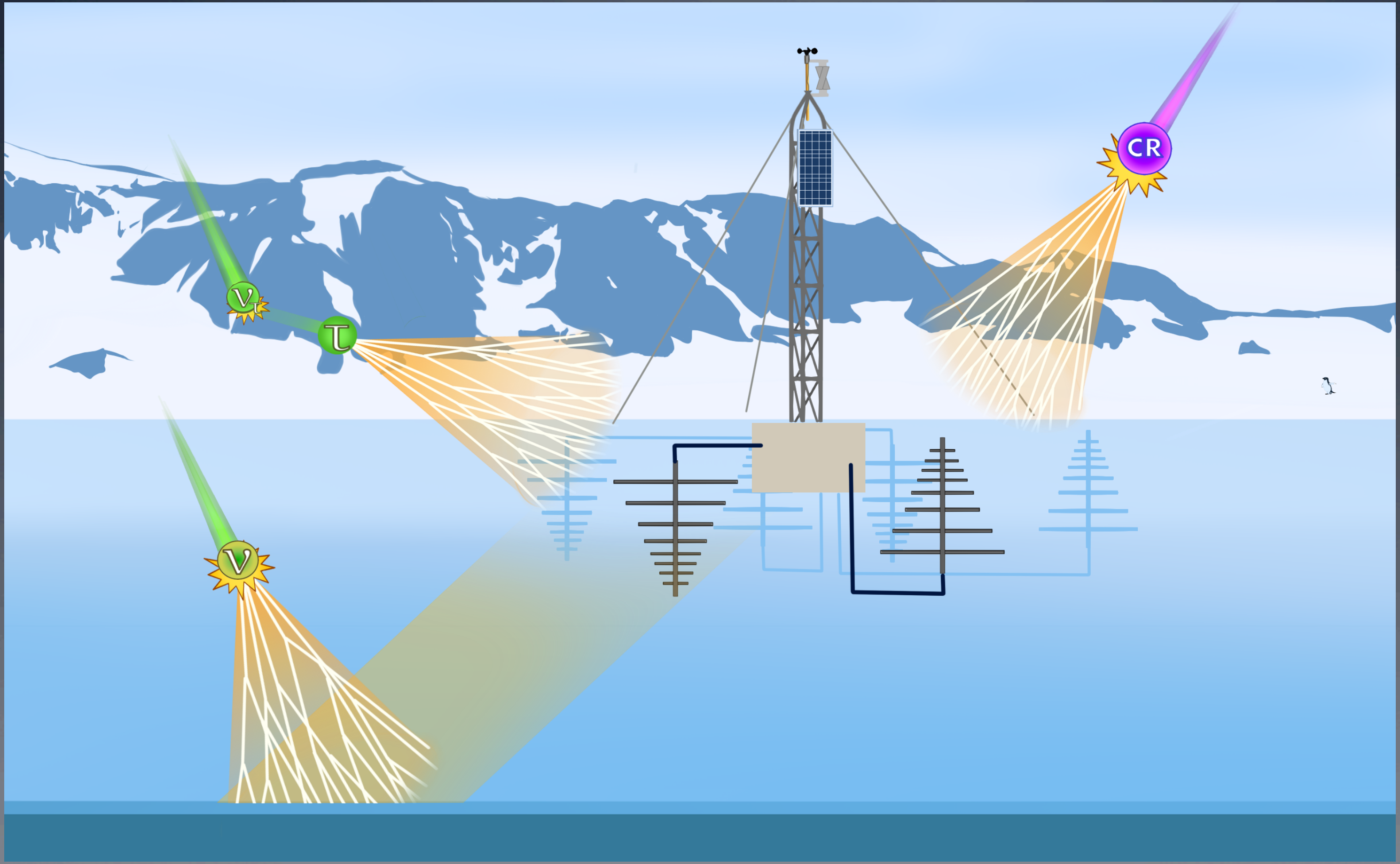


ARA, ARIANNA



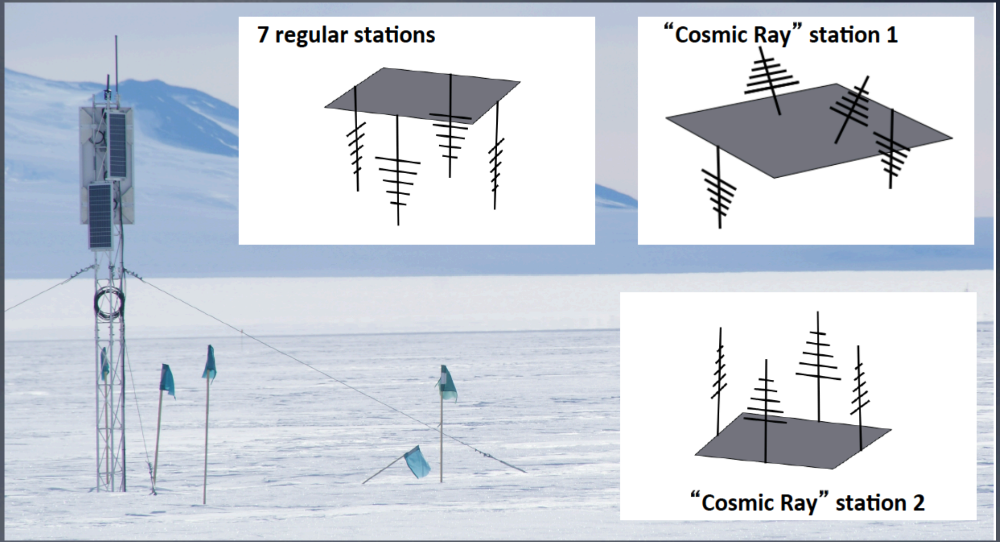


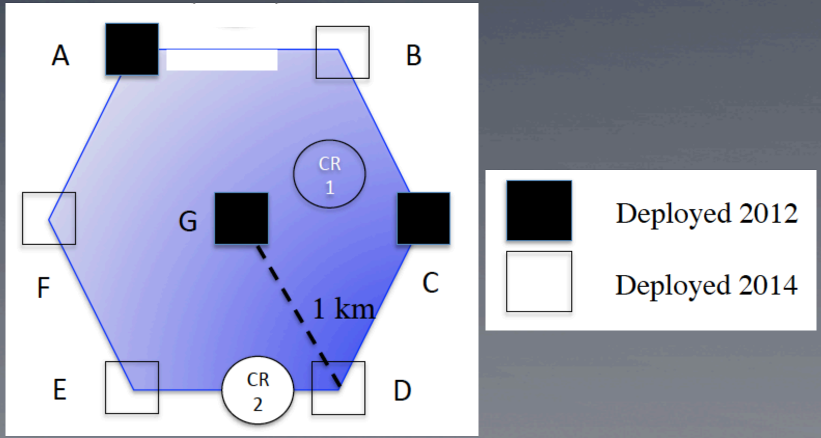
The ARIANNA Concept

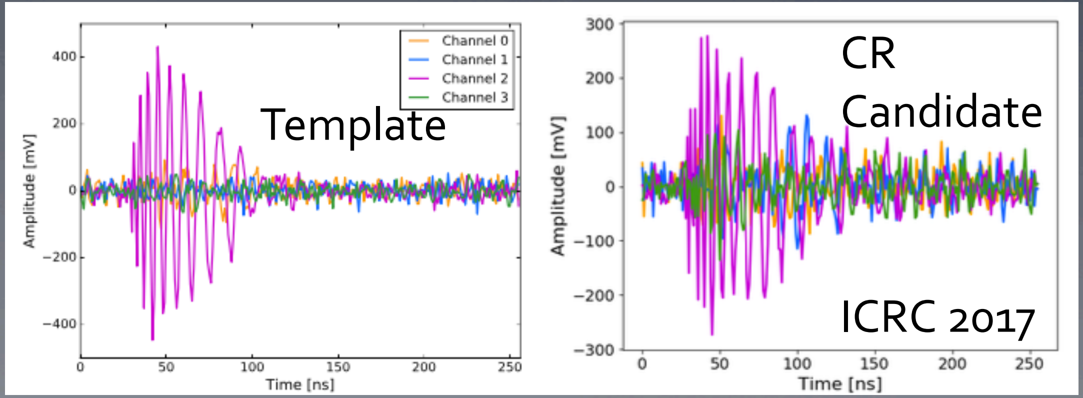


ARIANNA

- On the Ross Ice Shelf, Antarctica
- Hexagonal Radio Array deployed and working (7 stations)
- Found cosmic ray candidates with template search
- See C. Persichilli talk

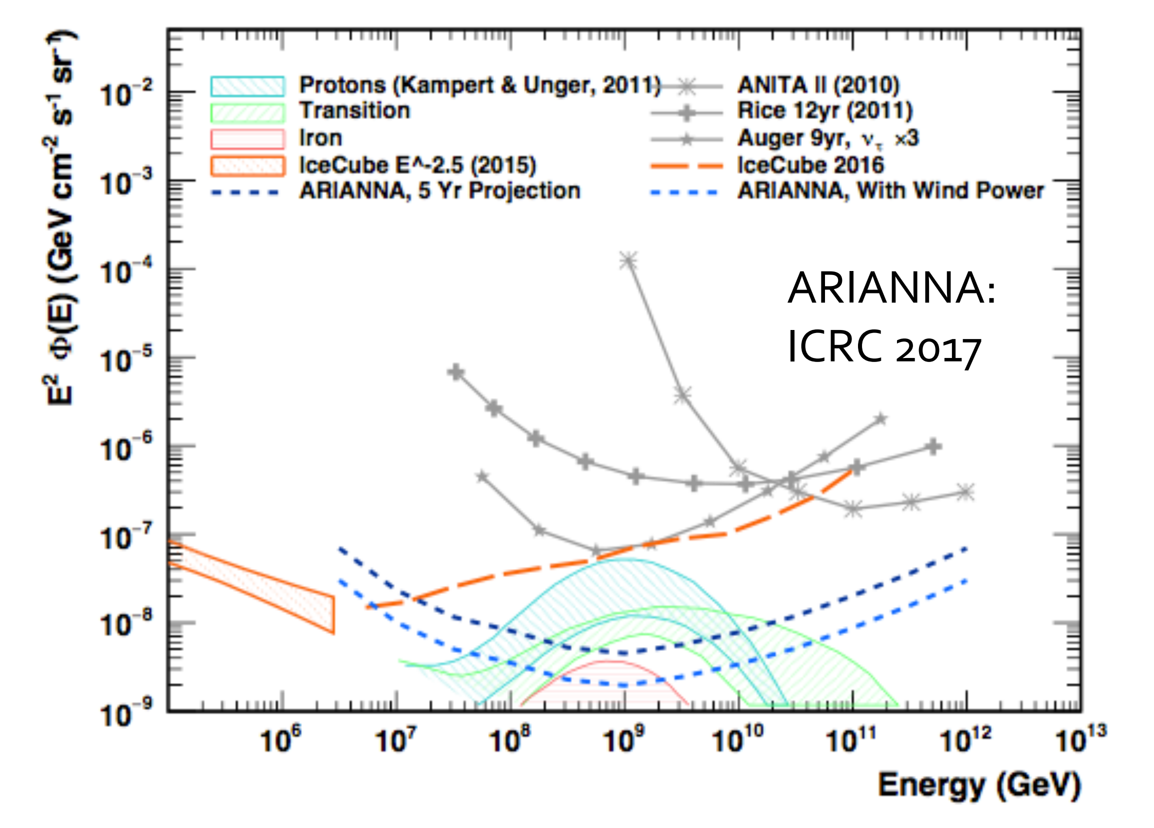




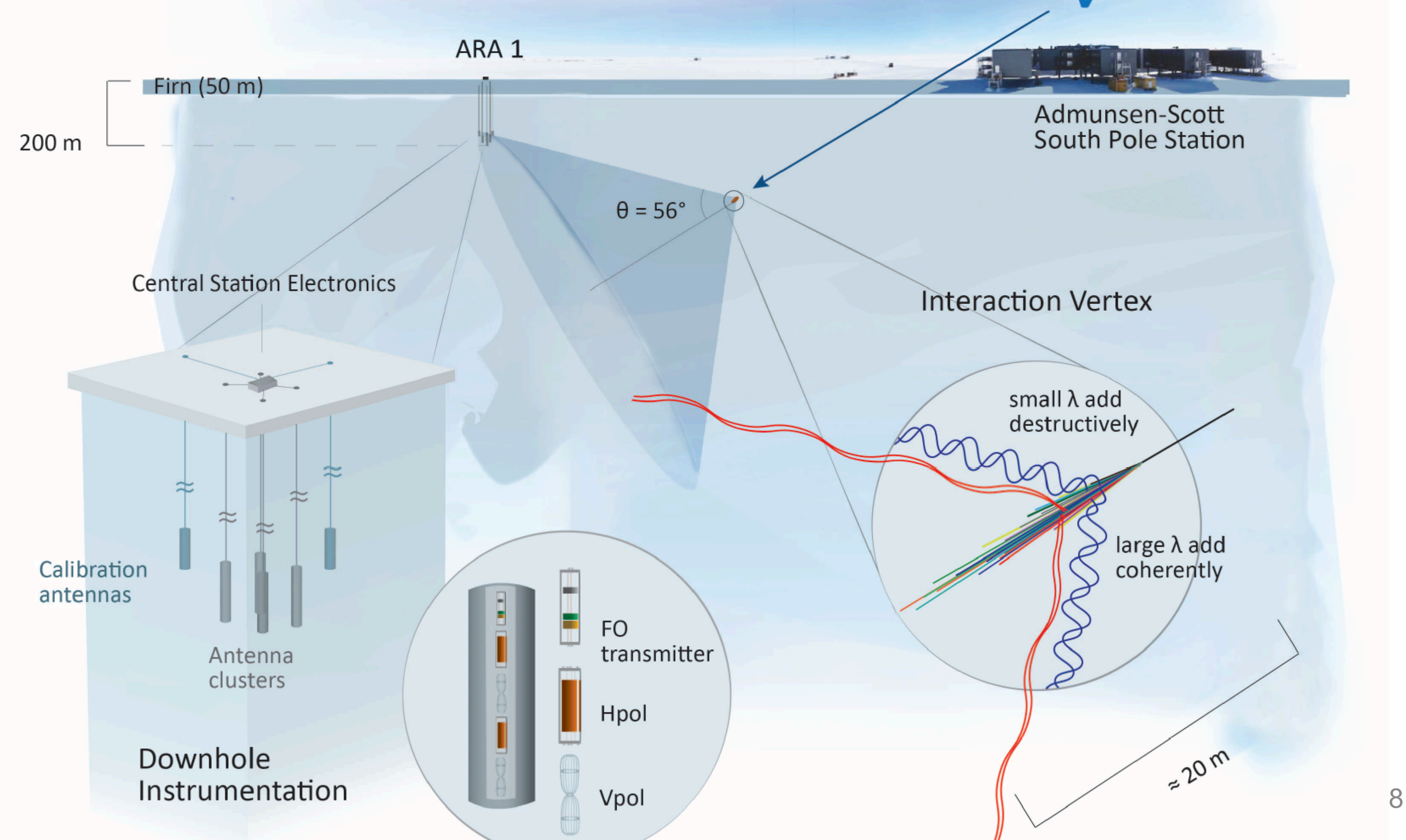


Projected ARIANNA Constraints

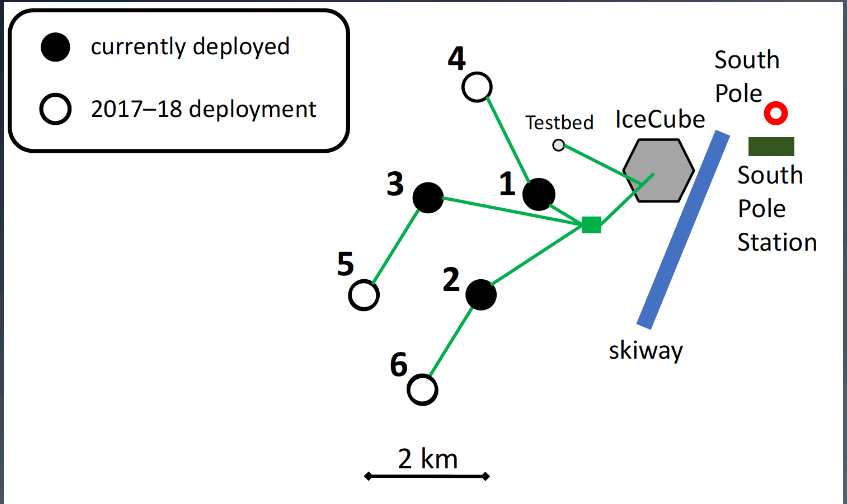
- Full array: 1296 stations
- Late 2017: deploying an ARIANNA-like station at South Pole
  - Coordination with ARA for power & calibration



Askaryan Radio Array (ARA)

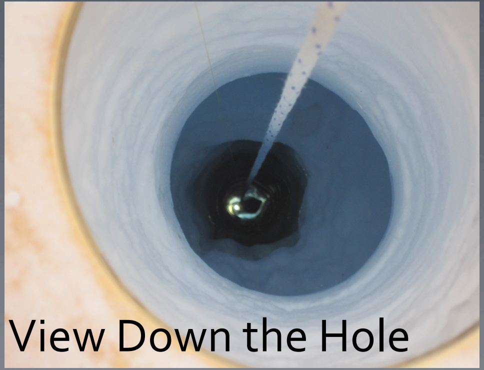


ARA: Askaryan Radio Array



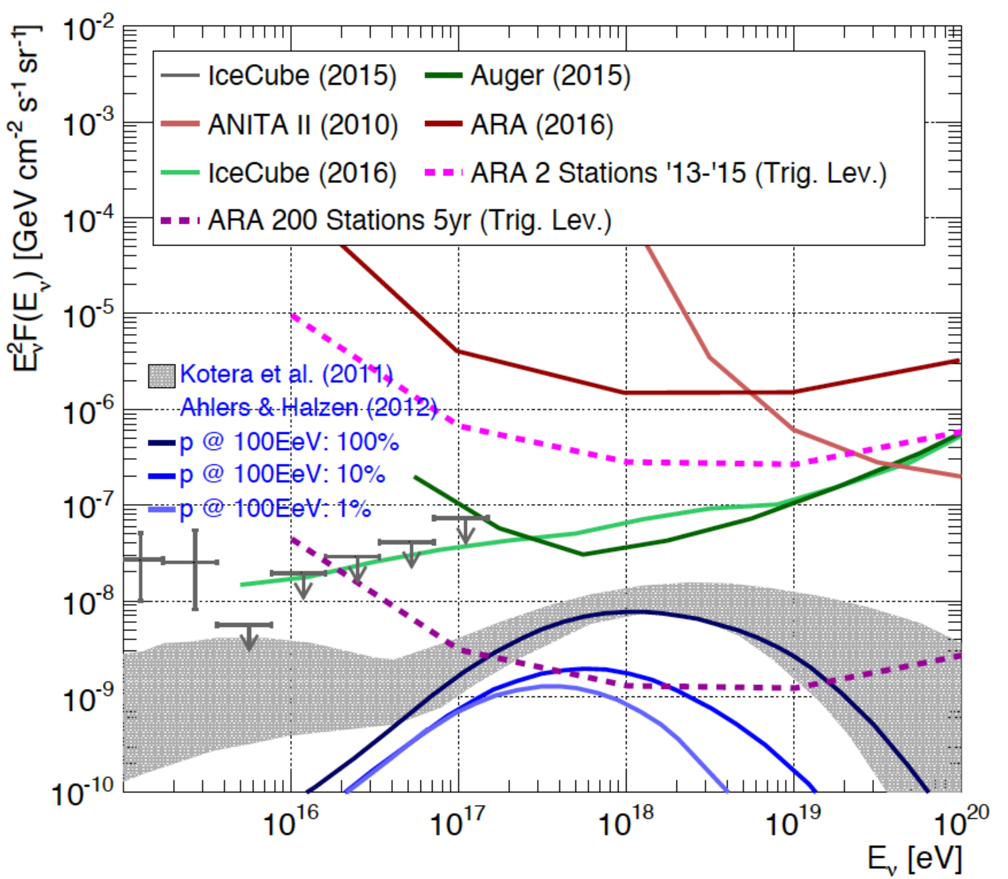
- Idea: 37-station array of antennas buried 200m below the surface at the South Pole
- Currently: 3 stations + testbed deployed
- Deploy 3 more stations in 2017/18

See B. Clark and C. Pfender talks



First Results and Projections from ARA

- Analysis of data from first two stations
  - Demonstration of end-to-end analysis tools
- Future: more volume instrumented, trigger and analysis improvements for full array



ARA Collaboration: ICRC2017

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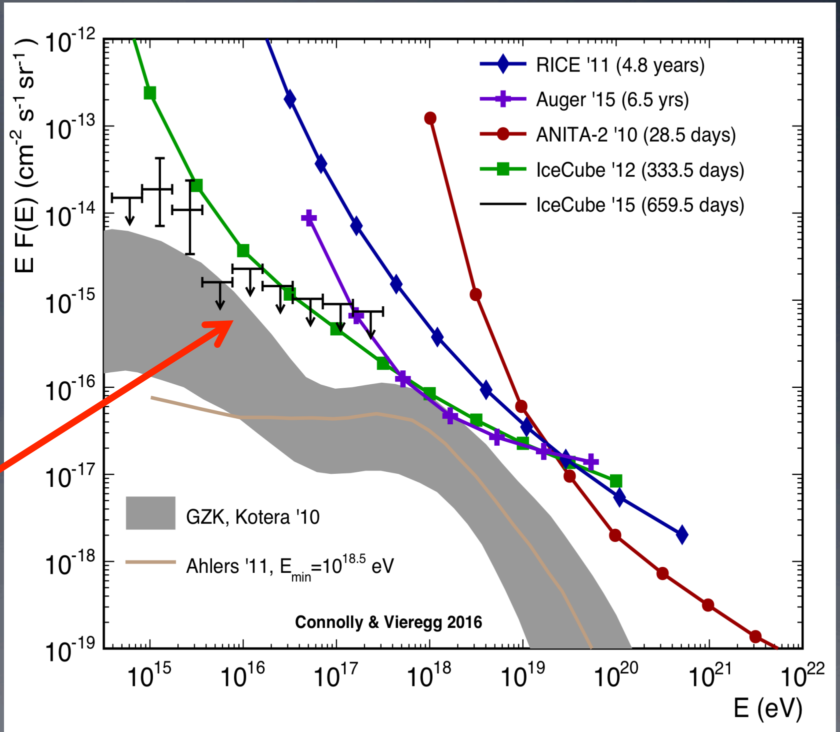


Can We Push the Threshold Down?

Motivation:

- Can you push threshold down to ~PeV, to measure IceCube's astrophysical neutrinos?

A Straightforward Goal:

- Achieve the highest signal to noise in the detector as possible to see small signals
  → Need an extremely high effective gain antenna

Solution: A Phased Array

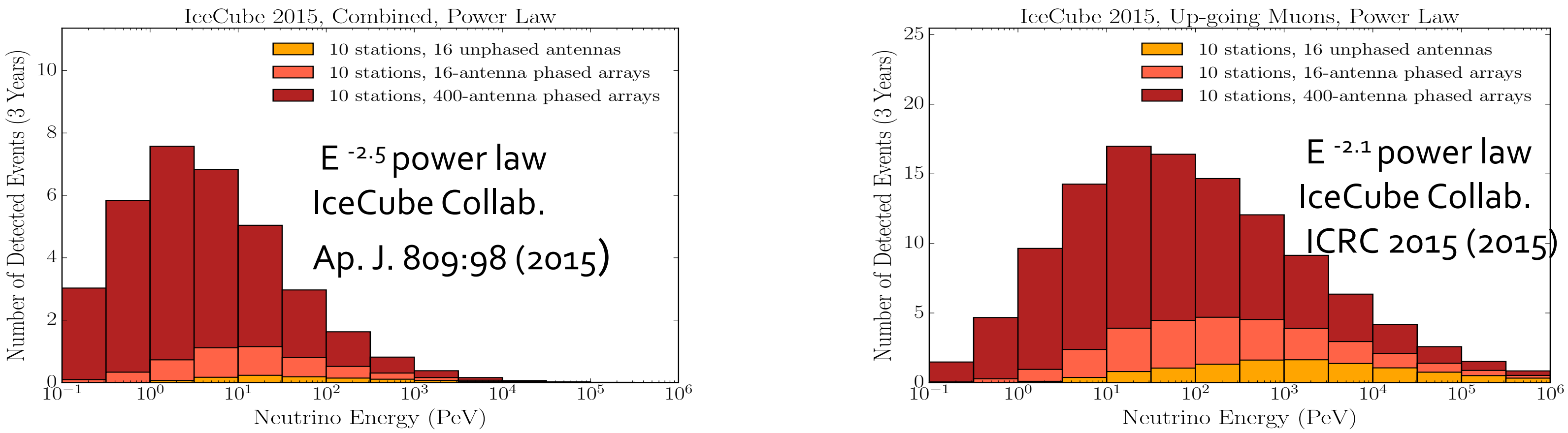
- Beamforming -- coherently sum signals from multiple antennas before triggering
- Signal is correlated between antennas and noise is uncorrelated: increase in SNR goes as sqrt(N)
- Create many beams at once to cover solid angle of interest
- We're already doing this in analysis, now do it in hardware

A. G. Vieregg et al. JCAP (2016)

A. Romero-Wolf et al. Astropart. Phys. 60 (2015)

(Optimistic) Improvement in Event Rate

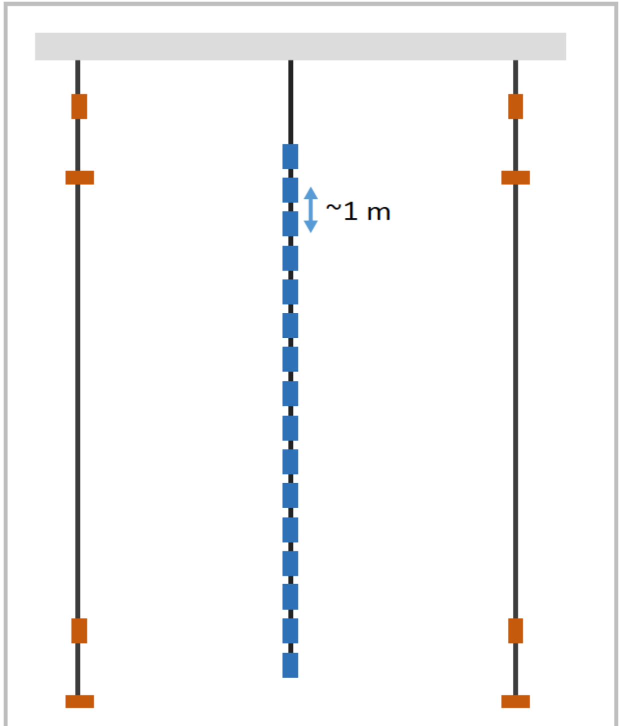
Event Rates: Monte Carlo simulation with ideal detector, 100m deep at Summit Station Greenland, 3 years, 10 stations



Station Configuration	Power Law ($E^{-2.5}$)	Power Law ($E^{-2.1}$)	Optimistic Cosmogenic	Pessimistic Cosmogenic
16-antenna	1.0	10.9	7.7	2.3
16-antenna, phased	5.3	33.0	19.6	6.0
400-antenna, phased	34.4	114.8	52.9	15.6

Plots from K. Bechtol

A Phased Array Trigger for ARA

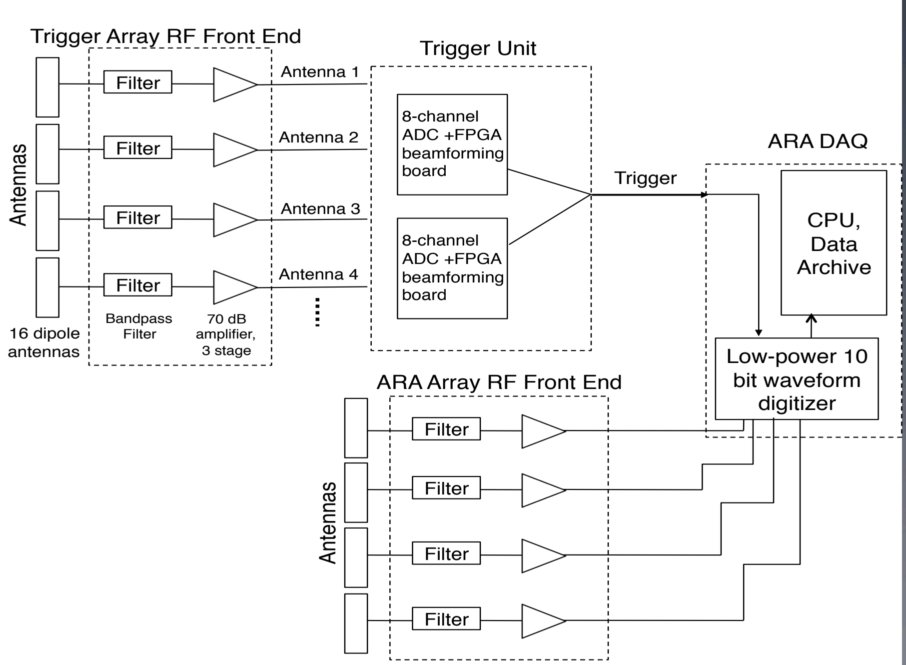


ARA station side-view (not to scale)

= Standard ARA pointing array (both pols)

= Phased array trigger (Vpol)

- Will be installed December 2017 at South Pole
- Custom 1.5 GSa/sec, 8-channel board
- Beamforming and power calculation done on FPGA
- Extends to larger channel count by daisy-chaining

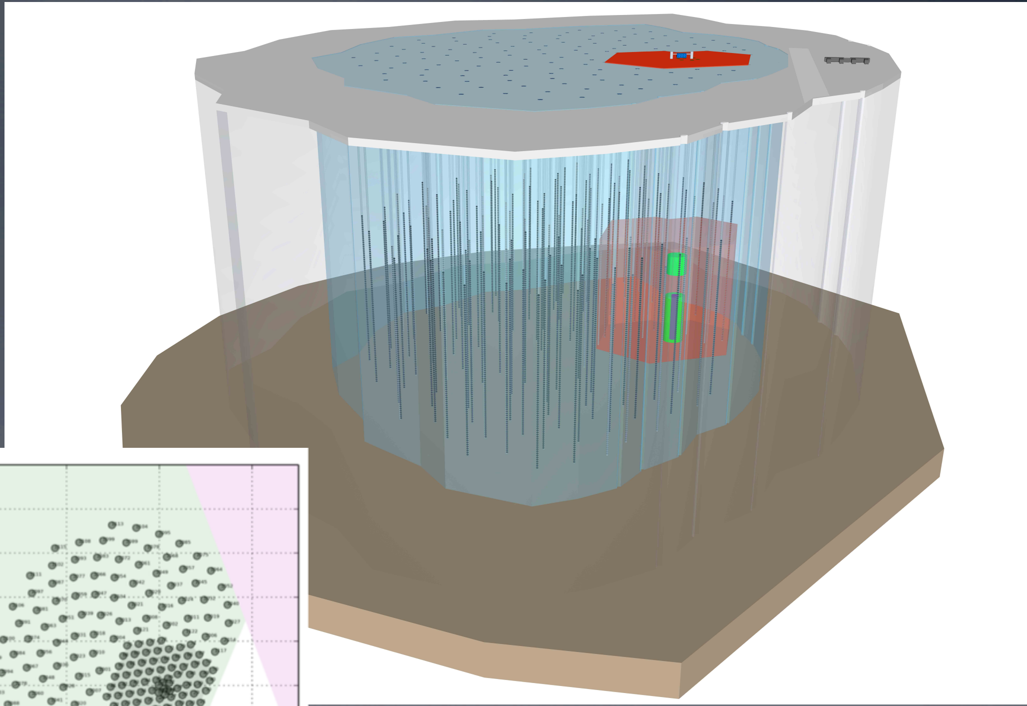


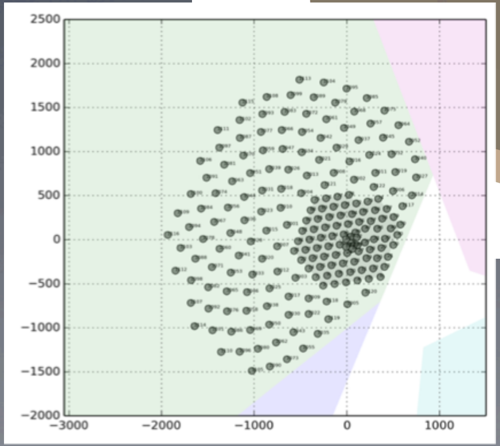
IceCube Gen-2: A Radio Component

Vision for a
Next Generation IceCube:

Focus on high energies allows factor of 2 larger string spacing (250m instead of 125m)

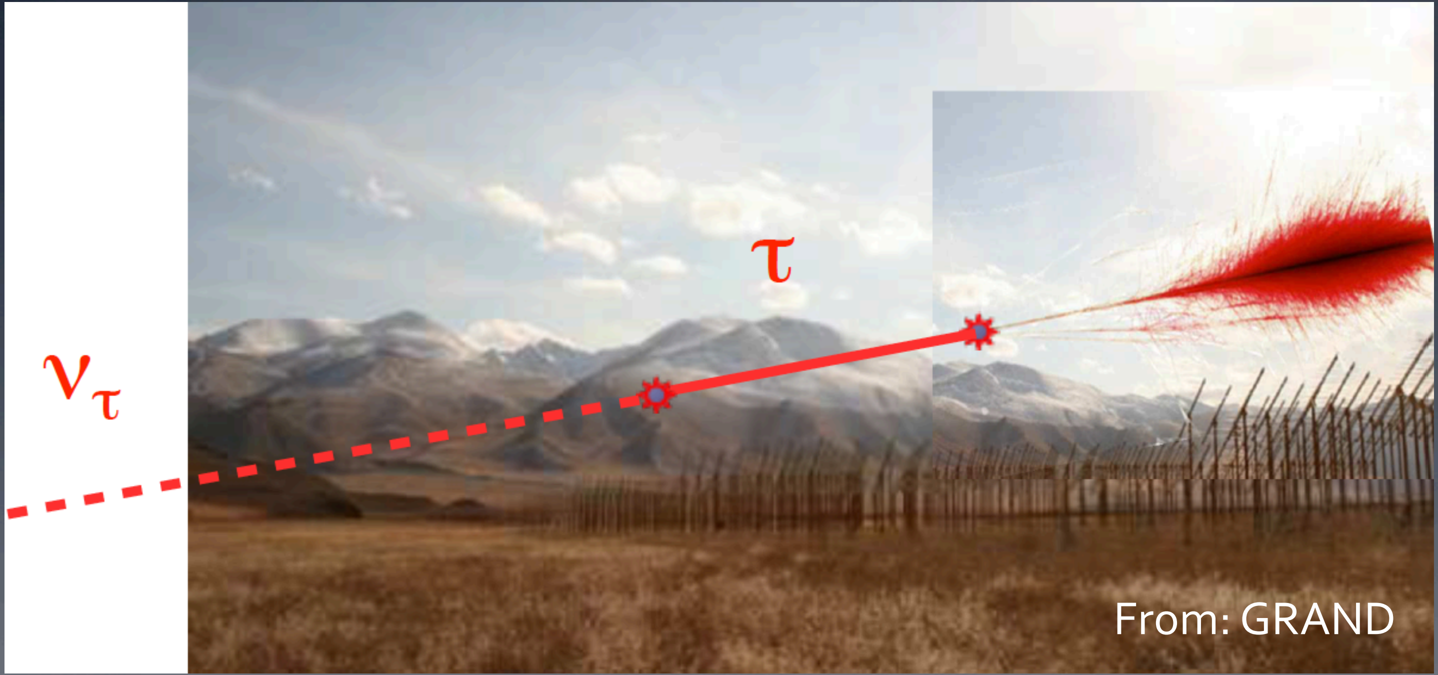
Possible significant radio component





arXiv:1412.5106

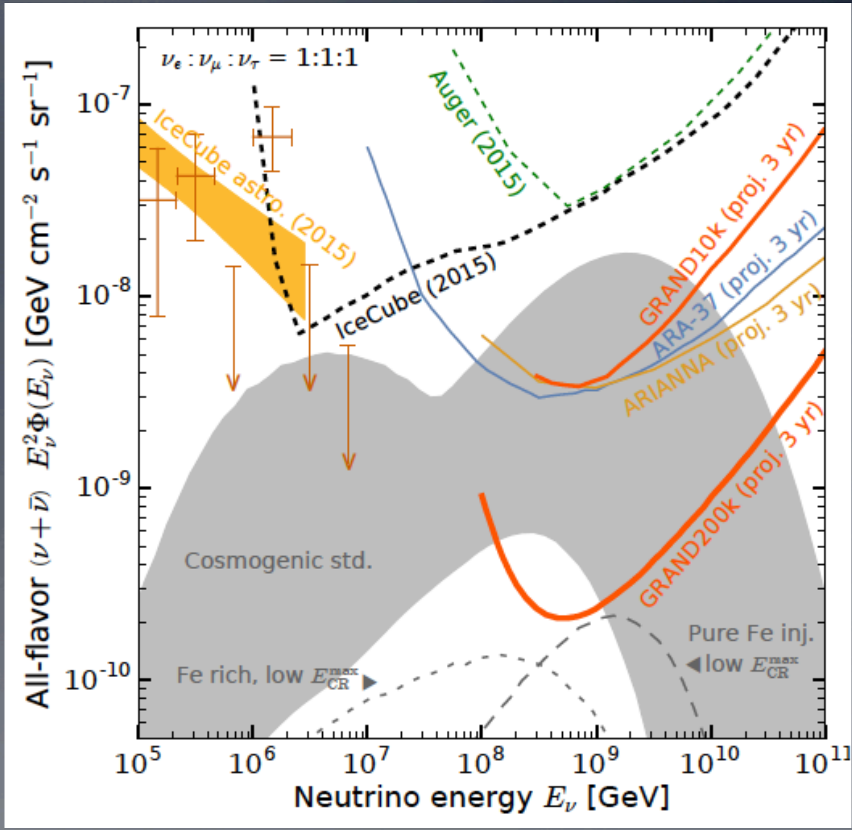
Radio Emission from Tau Neutrinos



- Observe from a mountain, surface, balloon (see S. Wissel talk)
- Possible with ARIANNA, ANITA, but doesn't require ice

GRAND

- An enormous array of antennas (200,000) in China
- Preliminary studies with TREND and GRANDProto (to be deployed in 2017) look very interesting
- See A. Ziles talk



Summary

- Observation of UHE neutrinos would open a new window onto the universe
- The radio technique can probe a new energy regime – from the highest energies down to (hopefully) PeV energies
- The tau neutrino channel is promising, and is accessible from a balloon, mountain, or surface configuration

Lunar Detection (e.g. LOFAR)

- Sensitive at highest energies, beyond GZK
- Analysis at LOFAR underway