The radio detection method for high energy neutrinos

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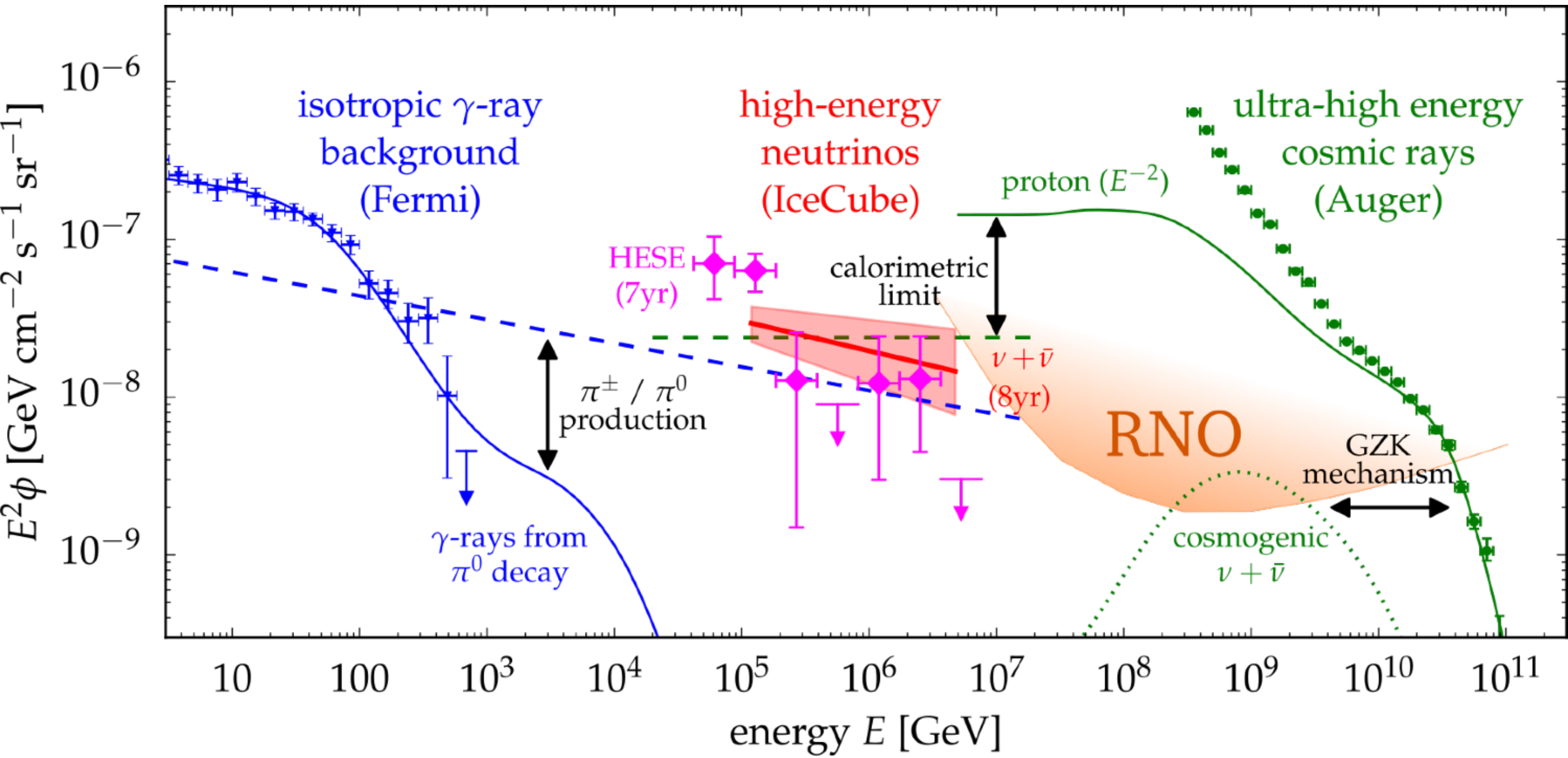
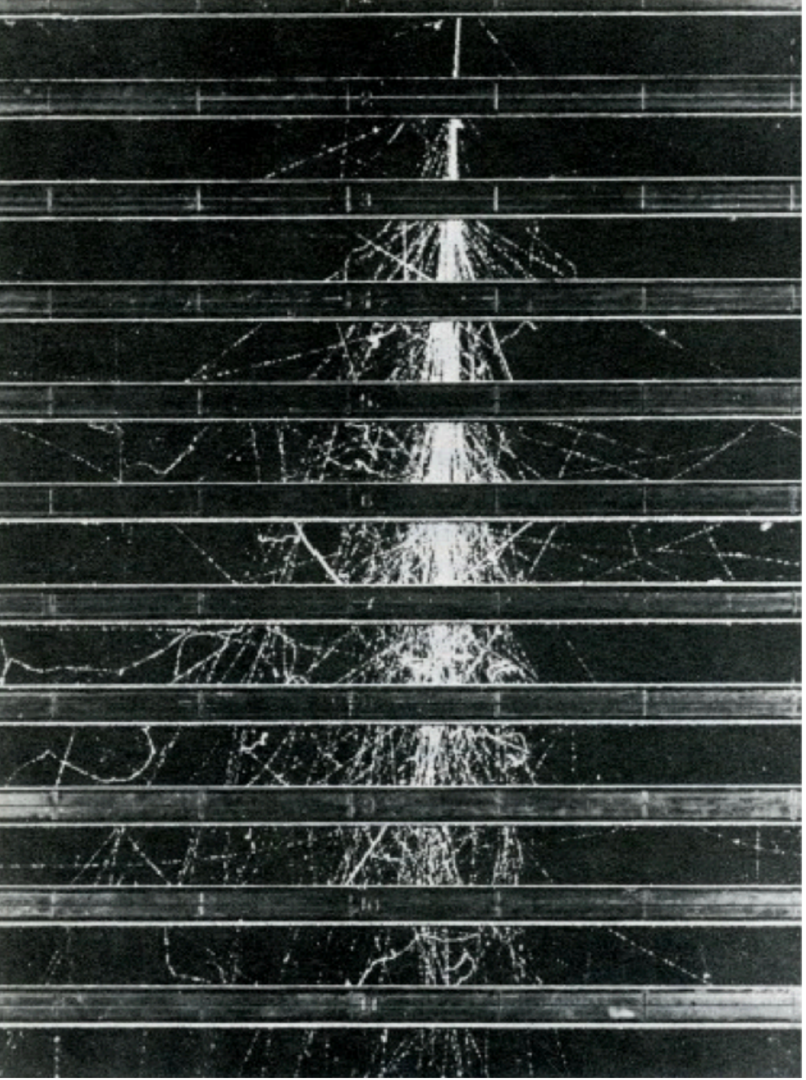
SOUTH POLE ASKARYAN RADIO ARRAY

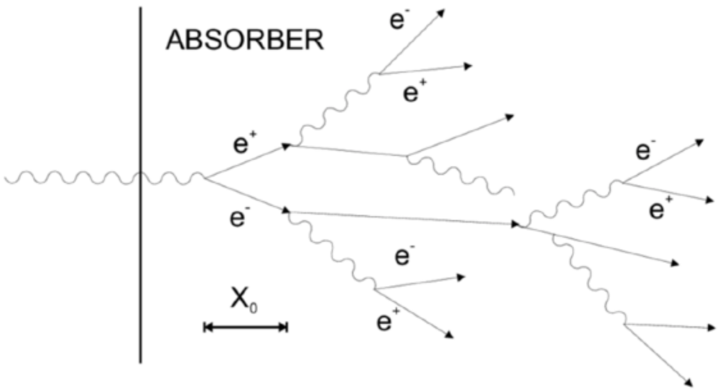


isotropic γ-ray
background
(Fermi)
high-energy
neutrinos
(IceCube)
ultra-high energy
cosmic rays
(Auger)
proton (E^{-2})
HESE
(7yr)
calorimetric
limit
$\nu + \bar{\nu}$
(8yr)
RNO
GZK
mechanism
$\pi^{\pm}$ / π^{0}
production
γ-rays from
π^{0} decay
cosmogenic
$\nu + \bar{\nu}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
energy E [GeV]

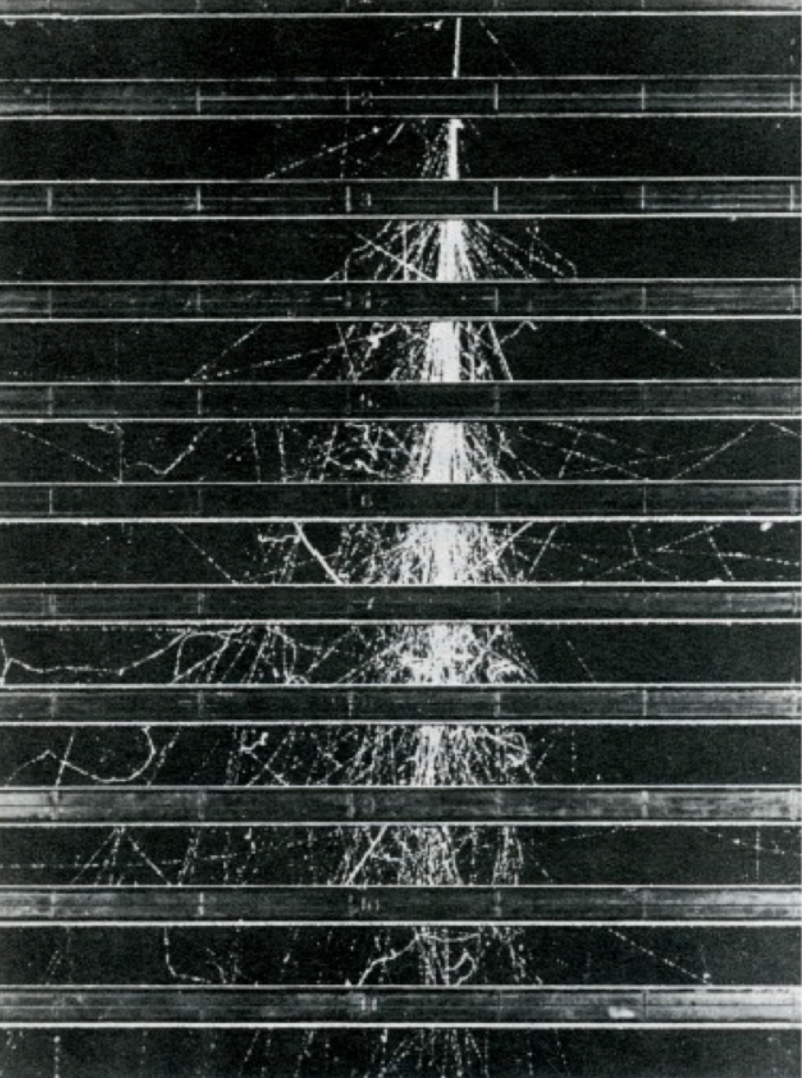


Development of an cosmic ray induced shower in a dens medium.

Length of shower (X_max) ~ Log(E),   ~5 m
Width: ~0.1 m



MIT Cosmic rays group, 1933.



http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/325.html

Atomic and nuclear properties of materials:

Water (ice) (H_2O)

Quantity	Value	Units	Value	Units
<Z/A>	0.55509			
Density	0.918	g cm^{-3}		
Minimum ionization	1.996	MeV g^{-1}cm^2	1.832	MeV cm^{-1}
Nuclear collision length	58.5	g cm^{-2}	63.73	cm
Nuclear interaction length	83.3	g cm^{-2}	90.77	cm
Pion collision length	86.0	g cm^{-2}	93.68	cm
Pion interaction length	115.2	g cm^{-2}	125.5	cm
Radiation length	36.08	g cm^{-2}	39.31	cm
Critical energy	78.99	MeV (for e^-)	76.90	MeV (for e^+)
Molière radius	9.69	g cm^{-2}	10.55	cm
Plasma energy $\hbar\omega_p$	20.57	eV		
Muon critical energy	1035.	GeV		
Melting point	273.1	K	0.000E+00	C
Boiling point @ 1 atm	373.1	K	99.96	C
Index of refraction (@ STP, Na D)	1.31			

Composition:

Elem	Z	Atomic frac*	Mass frac*
H	1	2.00	0.111894
O	8	1.00	0.888106

* calculated from mass fraction data.

Explanation of some entries

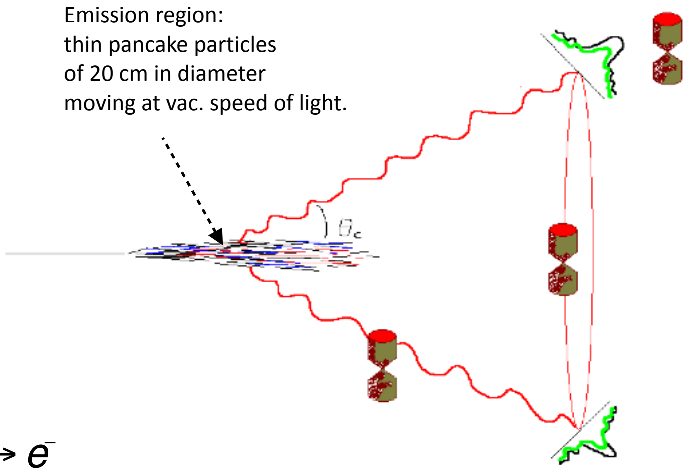
For muons, $dE/dx = a(E) + b(E)\,E$. Tables of $b(E)$: PS PDF TEXT

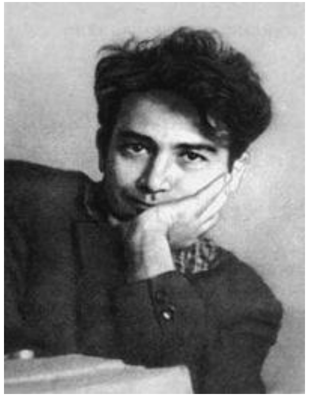
Table of muon dE/dx and Range: PS PDF TEXT

Note: Index of refraction of liquid water is 1.333

The Askaryan effect - the idea

High energy showers produce radio waves in dense dielectric Media.
Why?





Gurgen Askaryan

2 pieces of the effect:

- Showers in matter will have ~15% charge asymmetry due to
  Compton Scattering: $\gamma + e^-_{H_2O} \rightarrow e^-$
  Positron annihilation: $e^+ + e^-_{H_2O} \rightarrow \gamma$

- Small shower size: E-fields add coherently!

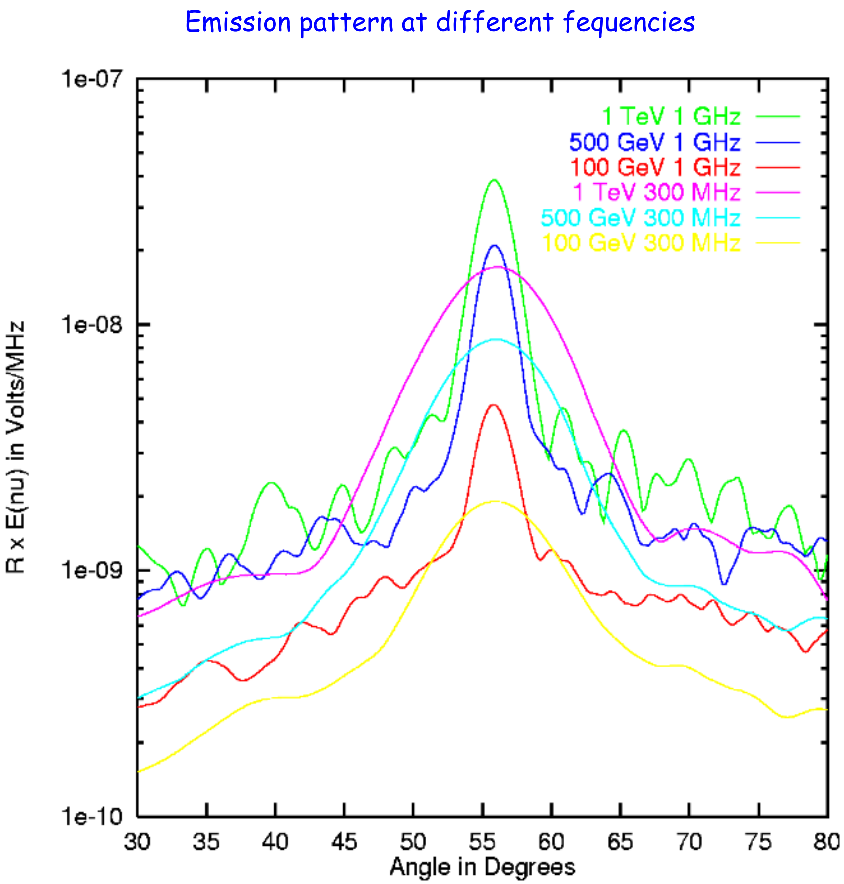
$$\lambda >> R_{moliere} \rightarrow P \propto N^2_{particles}$$

Ice: R~10 cm, ν_{peak}~1 GHz

(Power ~ sqr(El. Field), in that direction)

Angular distribution for different frequencies

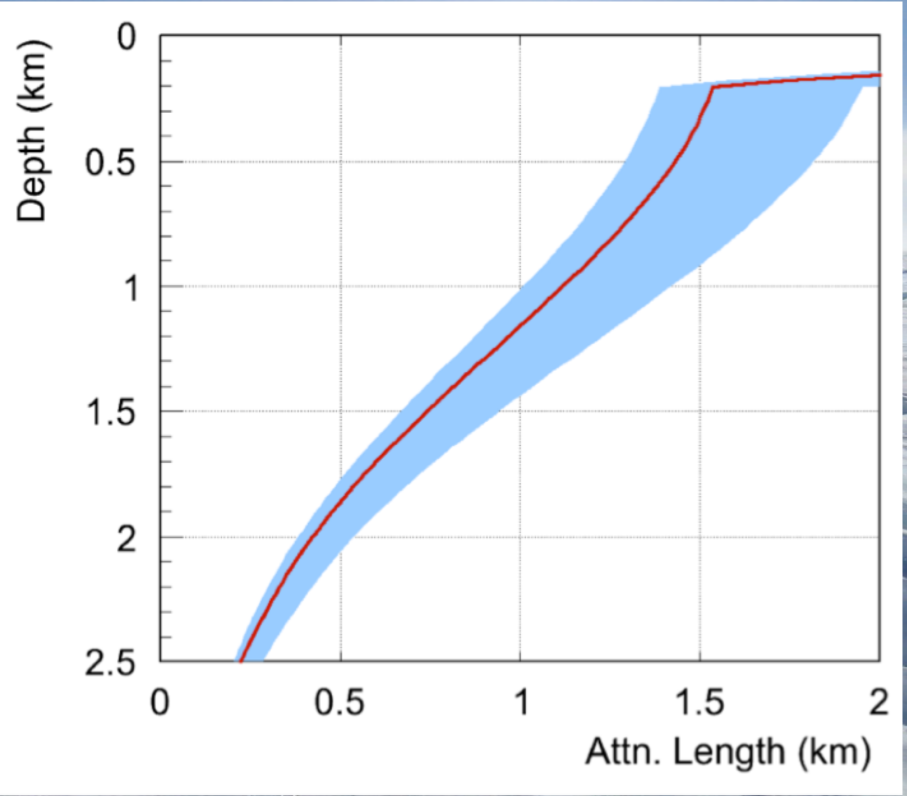
Emission up to
+- 5° off the
Cherenkov angle



see eg.: J. Alvarez-Muniz et al., Astrop. Phys. 35 (2012) 287-299 and references therein

South Pole glacial ice: cold and RF transparent

- Thickness: 2800m
- Temperature: -55°C at top, -40°C at 1500m
- Attenuation length at 300MHz (0-1500m): ~ 1.5km
- Low noise



Ground penetrating radar (350MHz) image of Antarctic ice sheet

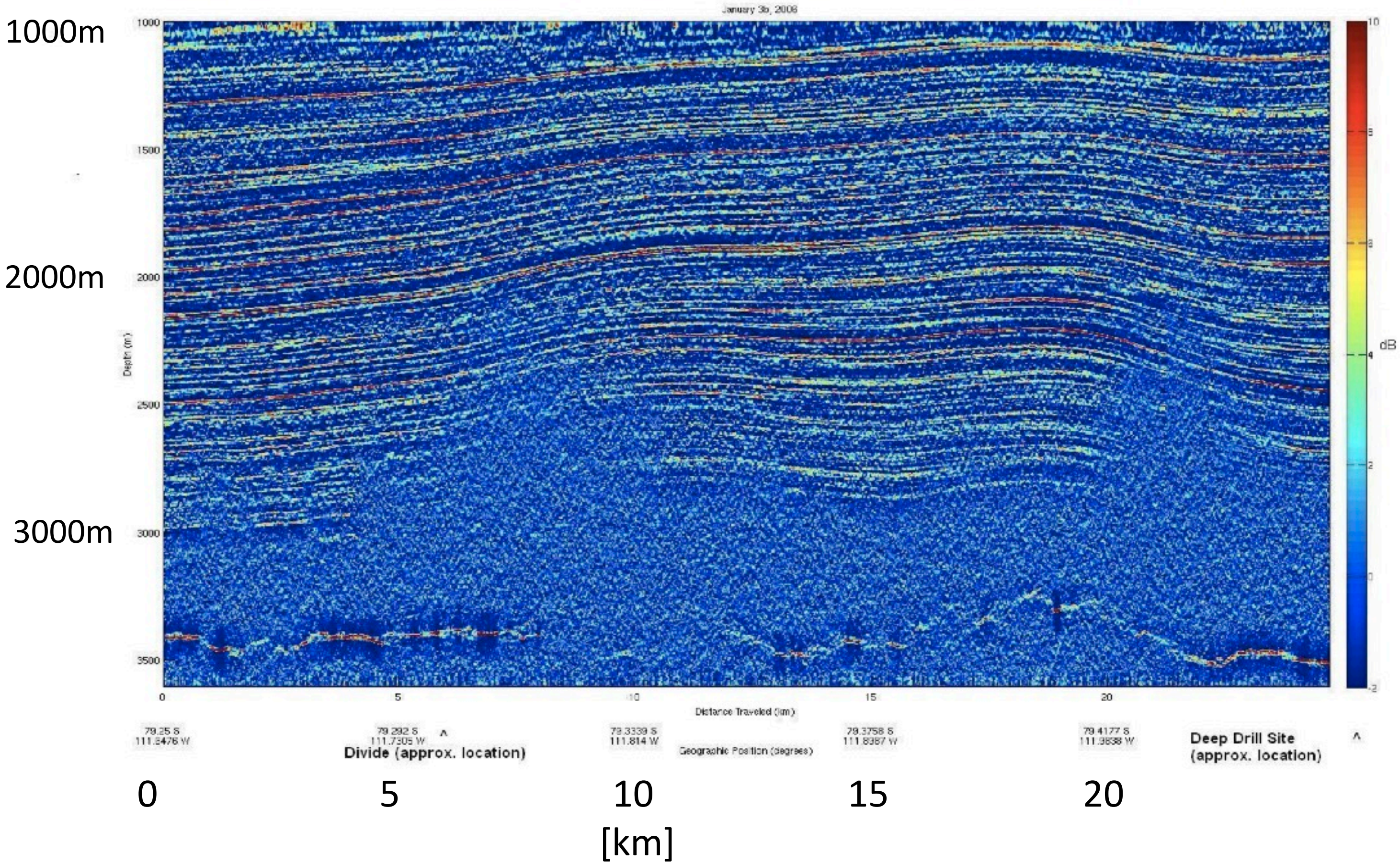
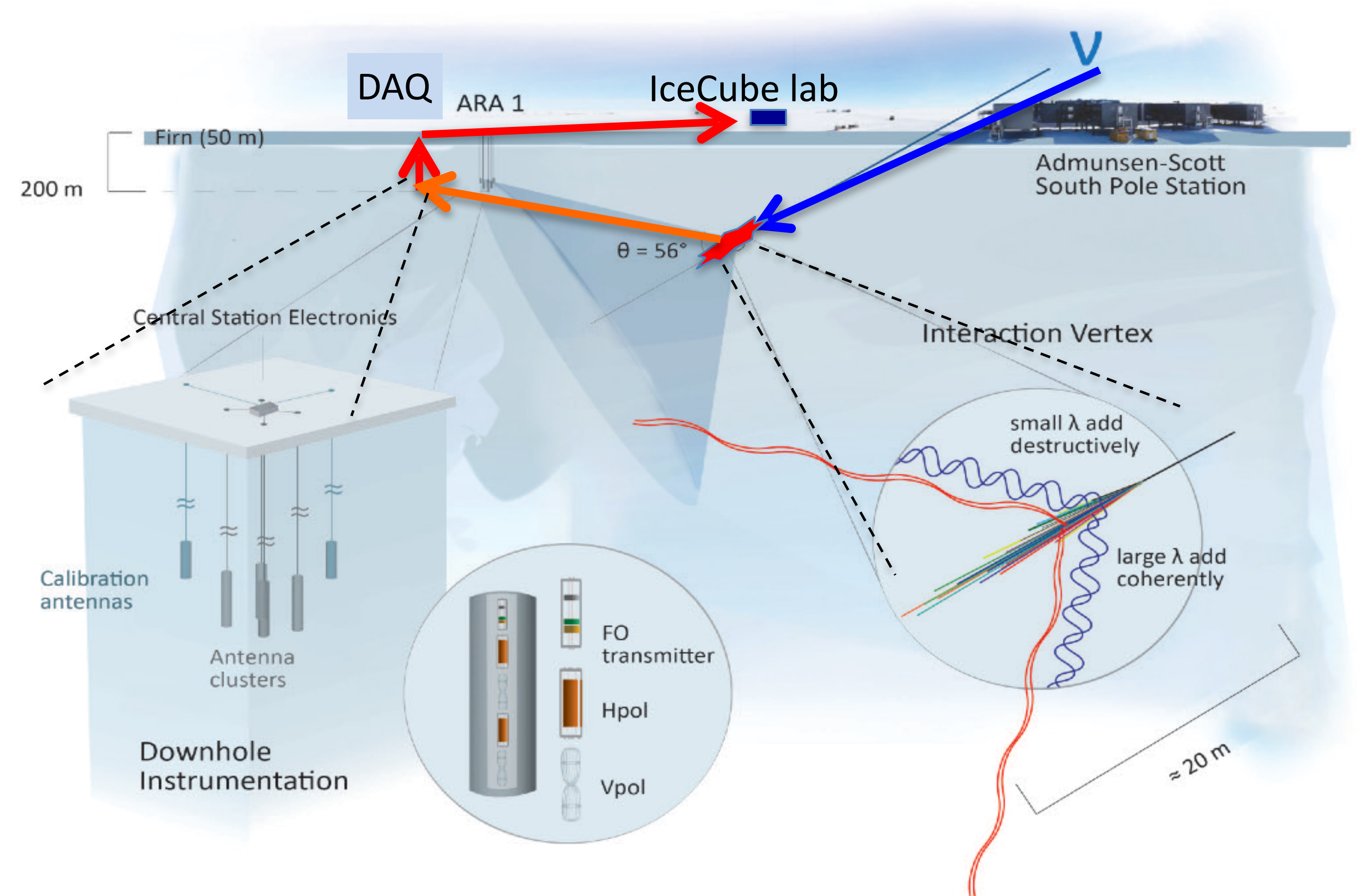


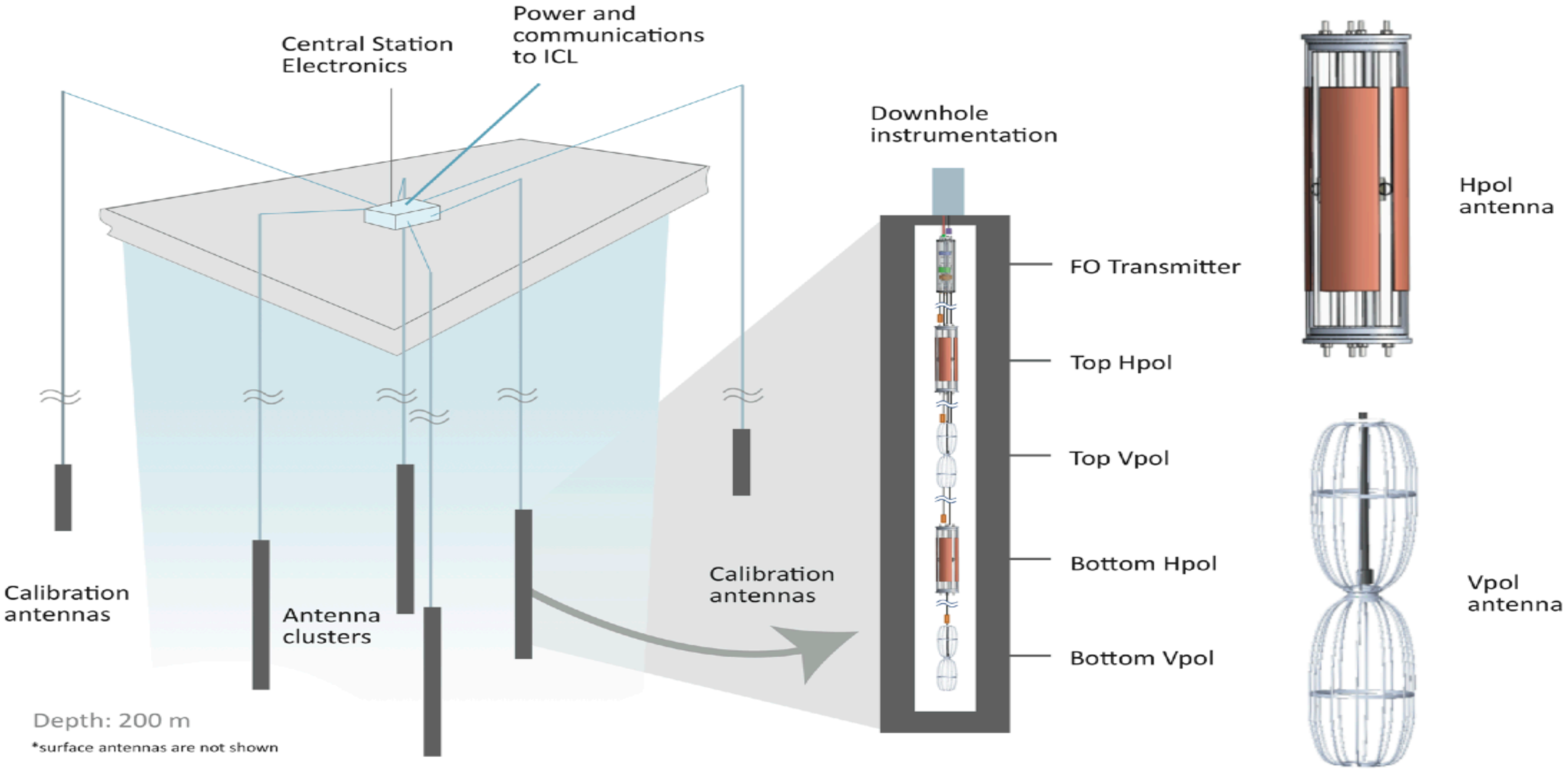
Figure:
WAIS GPR map at 150MHz
~4km deep, 25km wide

Ref: WAIS 2006 CReSIS Radar Data Summary

Detection of ultrahigh-energy neutrinos in ARA



ARA Station

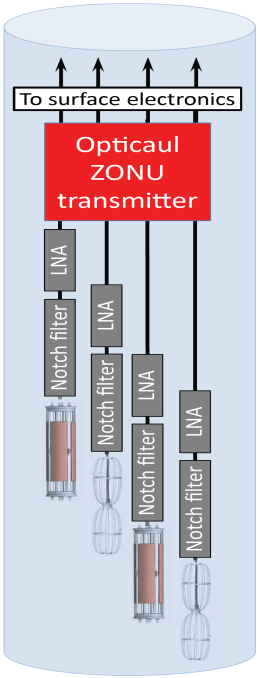

Power and
communications
to ICL
Central Station
Electronics
Downhole
instrumentation
Hpol
antenna
FO Transmitter
Top Hpol
Top Vpol
Bottom Hpol
Bottom Vpol
Vpol
antenna
Calibration
antennas
Antenna
clusters
Calibration
antennas
Depth: 200 m
*surface antennas are not shown

ARA DAQ

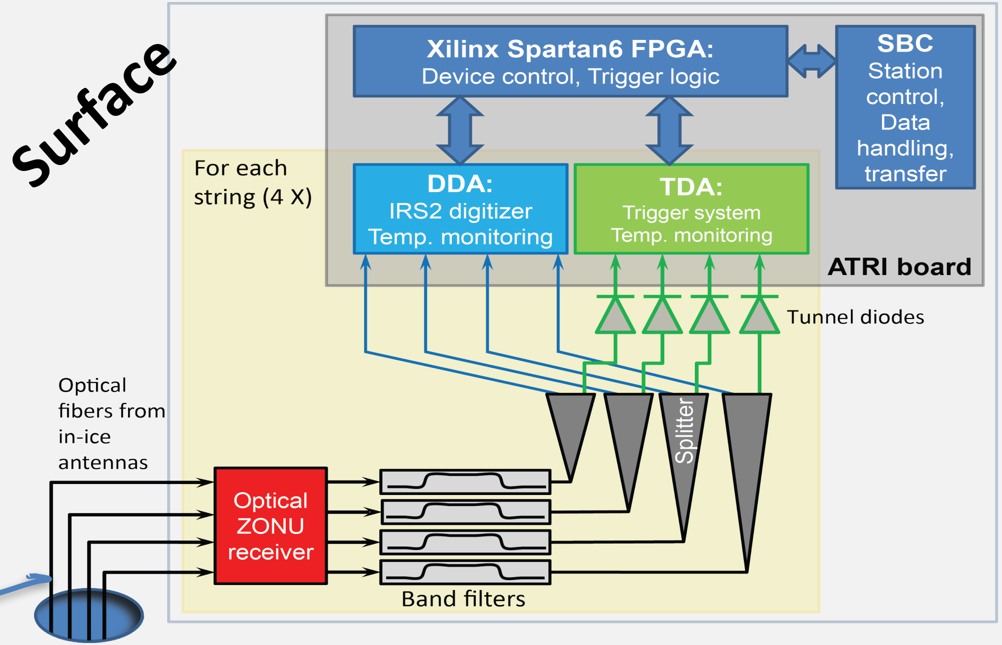
In-ice:

- Notch filter at 450 MHz (anthropogenic noise)
- Low noise amplifiers
- Optical RF analog over fiber (Zonu)

1 detector string: 4 antennas



X 4



Band filters: 150-850 MHz

IRS2 digitizing chip: sampling up to 4 GHz, 10 μs buffer

Trigger on 3 out of 8 antennas in 170 ns

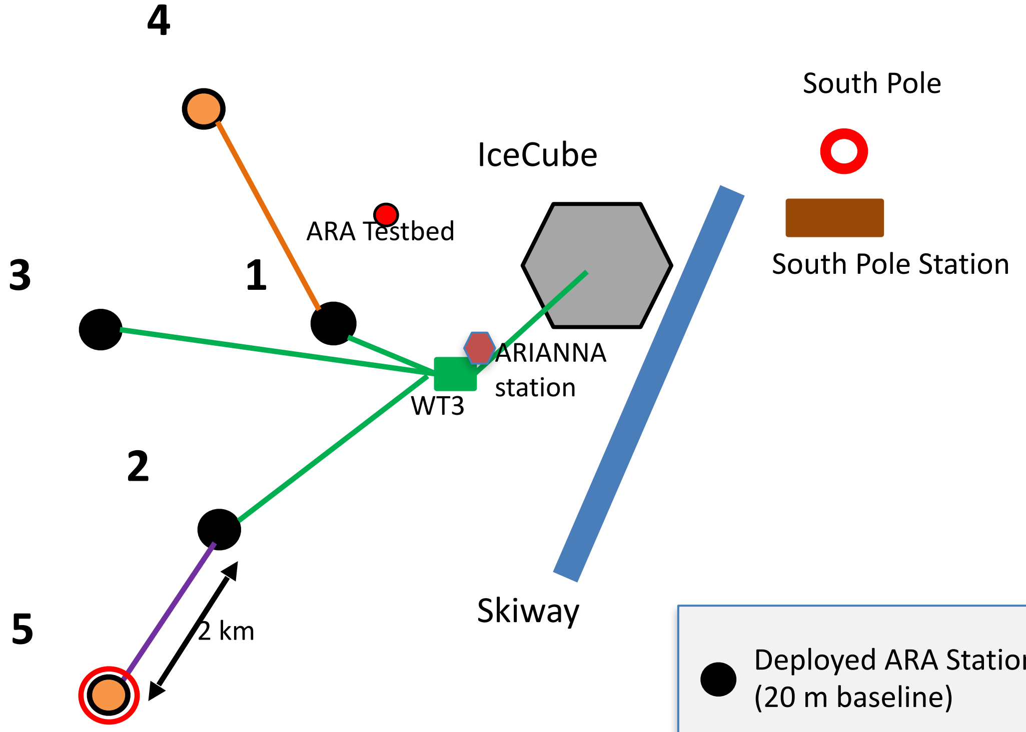
Trigger rates:

- ~ 5 Hz RF events
- 1 Hz Calibration pulser
- 0.5 Hz Forced software trigger

Askaryan Radio Array: 2017/18 upgrade

1. Major maintenance on stations 1, 2 and 3.
2. Repaired power system

   (now just passive cables to IceCube lab)
3. Deployed 2 new stations (40m baseline up from 20m)
4. Deployed Phased Array in ARA station 5. Integrated in trigger and readout.



Testbed: 2010/11
ARA 1: 2011/12
ARA 2-3:2012/13
ARA 4-5: 2017/18

- Deployed ARA Station (20 m baseline)
- Instrumentation deployed in 17/18 season (40 m baseline)
- Includes interferometric trigger string: “phased array”.

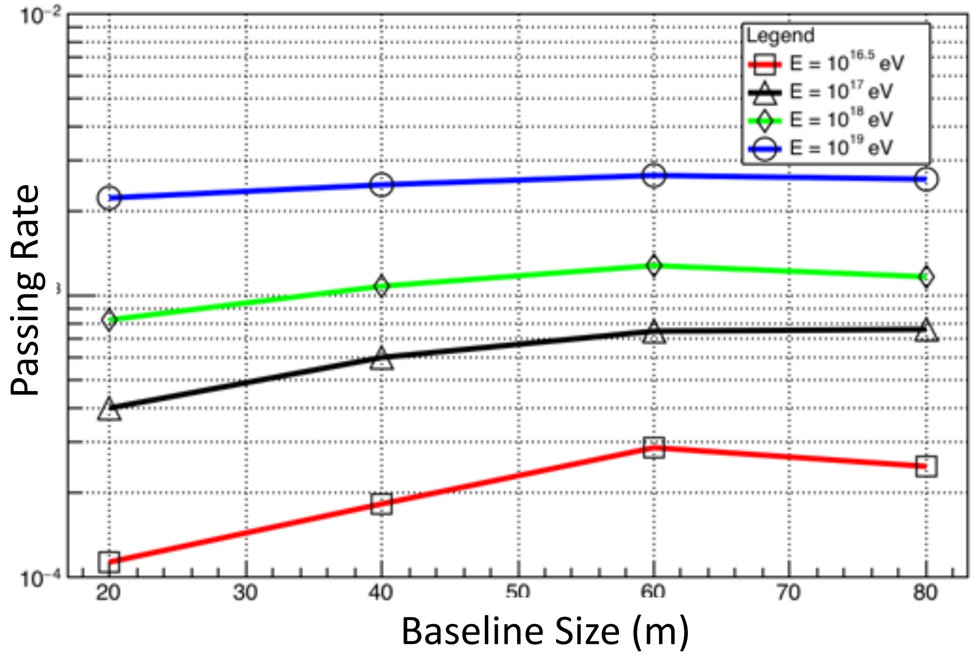
Installation of ARA

Geometry Optimization: *Better performance for larger geometry.*

$$\text{Passing Rate} = \frac{reconstructed\ events(nchan \geq 4)}{Total\ Simulated\ Events}$$

Selection ~ "analysis level"

nchan>=4



Energy 10^{18} eV

Size	Passing Rate	Azimuthal Resolution
20 m	8.14×10^{-4}	0.14°
40 m	1.082×10^{-3}	0.10°

- Passing Rate and angular resolution increases as we increase the baseline size

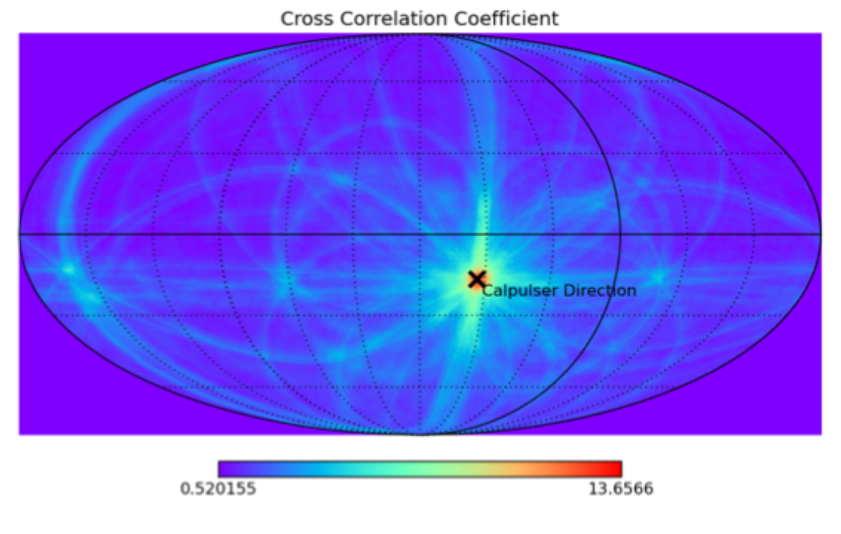
Calibration

There is no physics background like in water/ice Cherenkov neutrino detectors:

No muons, no atmospheric neutrinos!

Only thermal noise and man made backgrounds.

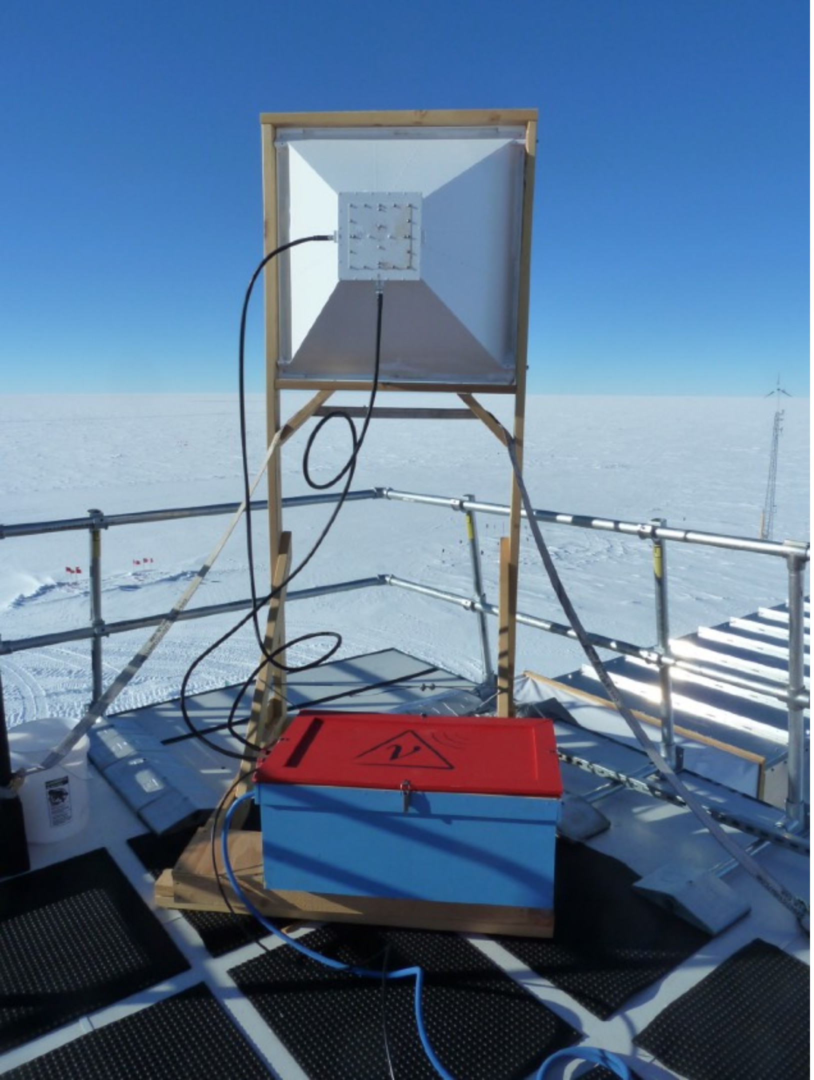
Local calibration pulser



→ ARA uses various radio pulsers:

- Local pulser antennas, embedded with detector
- Deep pulser (1500m) deployed with IceCube
- Pulser on IceCube lab building
- Portable pulsers from the surface

Calibration

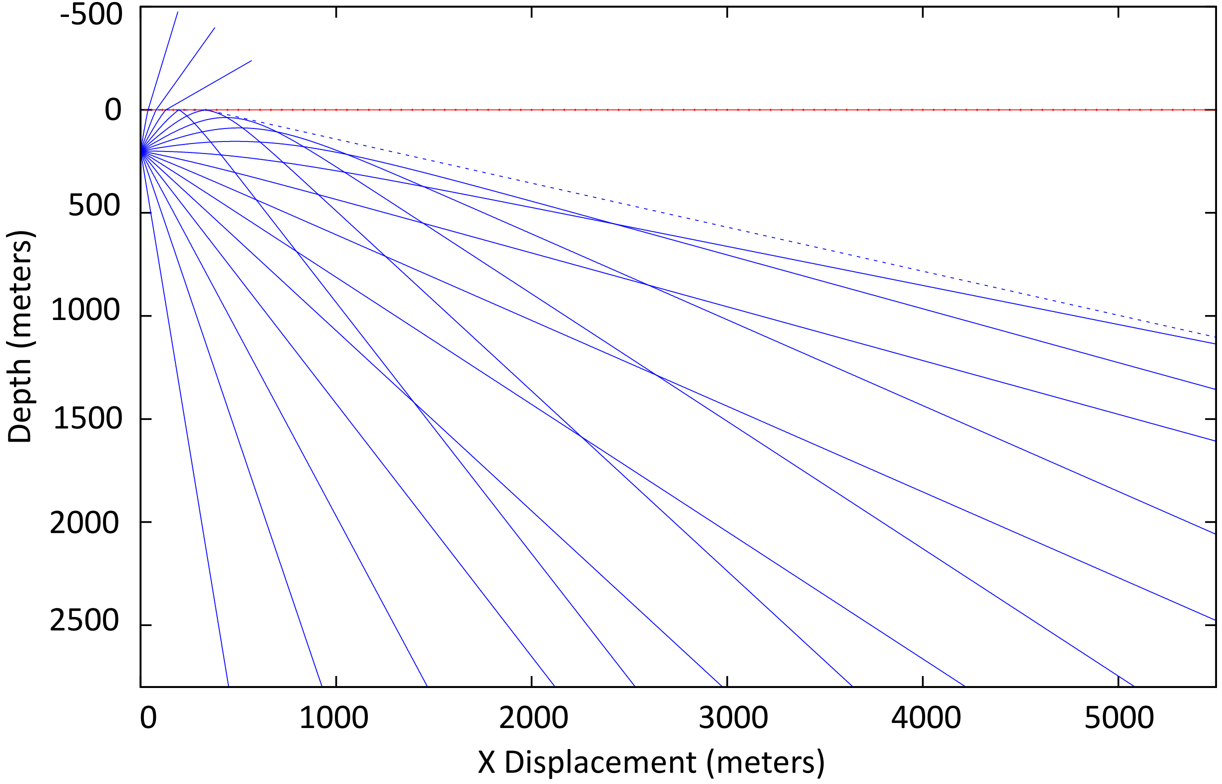


Pulser on rooftop of
the IceCube Lab.

Distance: 4 km

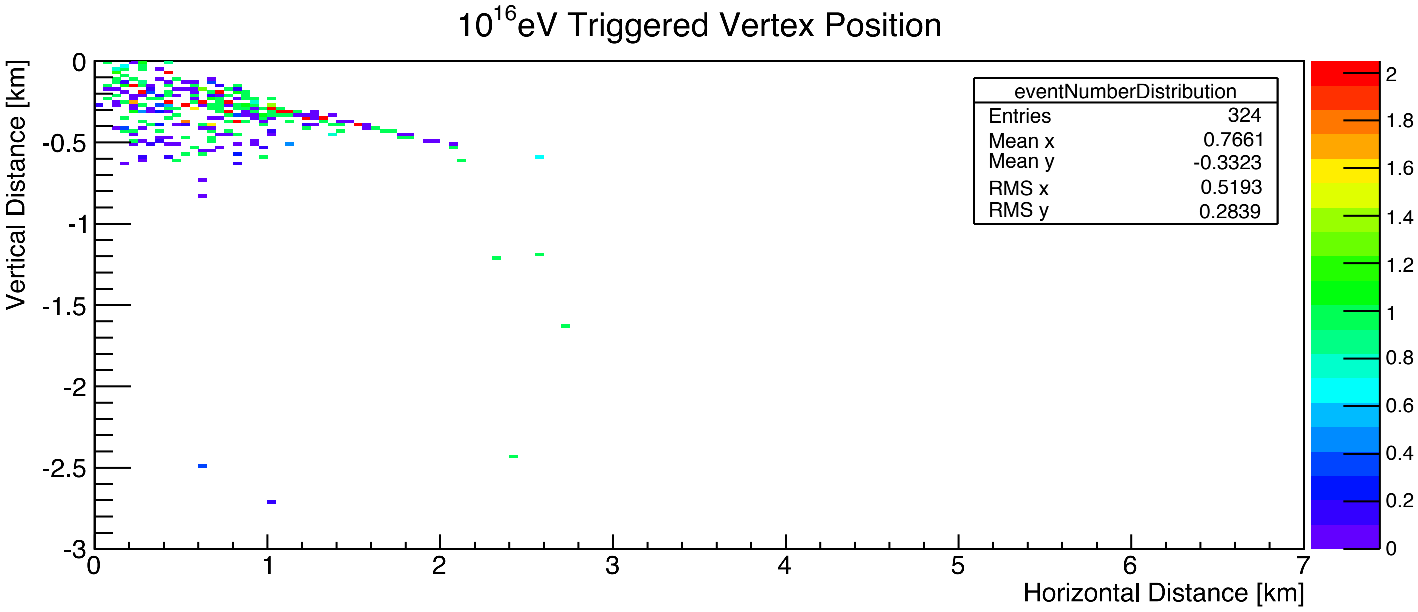
Propagation of radio signals in the ice

ray traces from200m



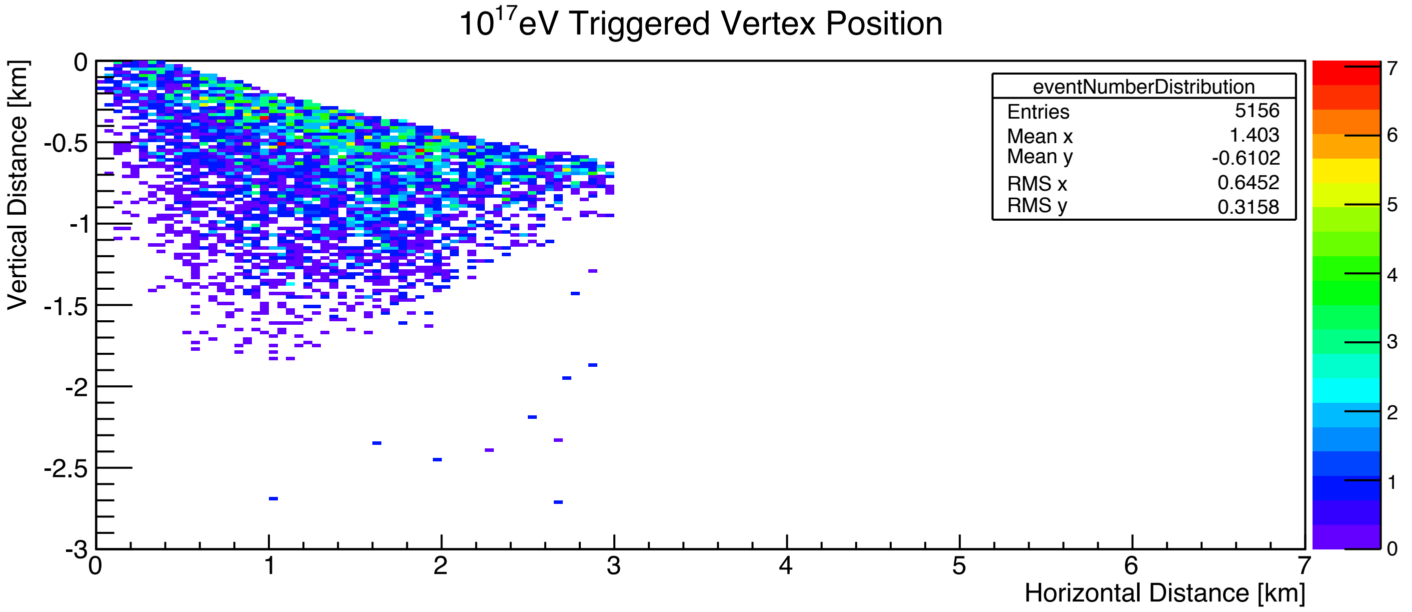
Visibility of neutrinos with one station.

Simulated events triggering
ARA station at 200m



Depth and effective volume at South Pole.

Simulated neutrino events triggering
ARA station at 200m



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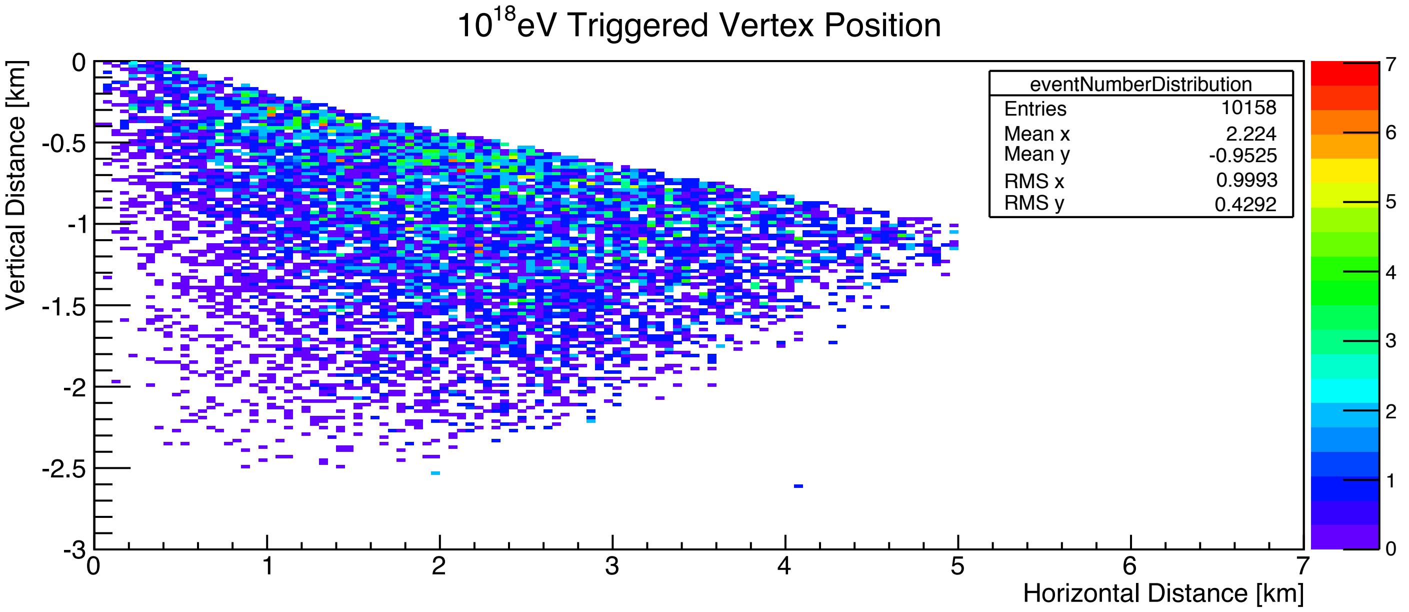

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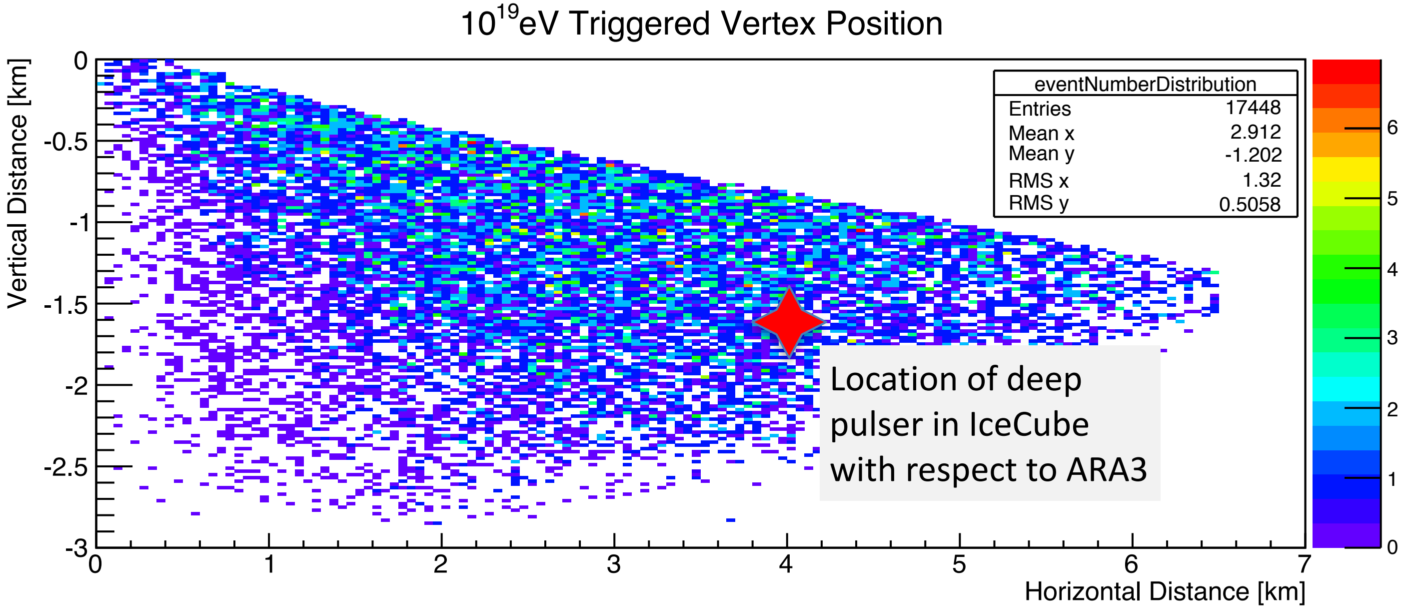
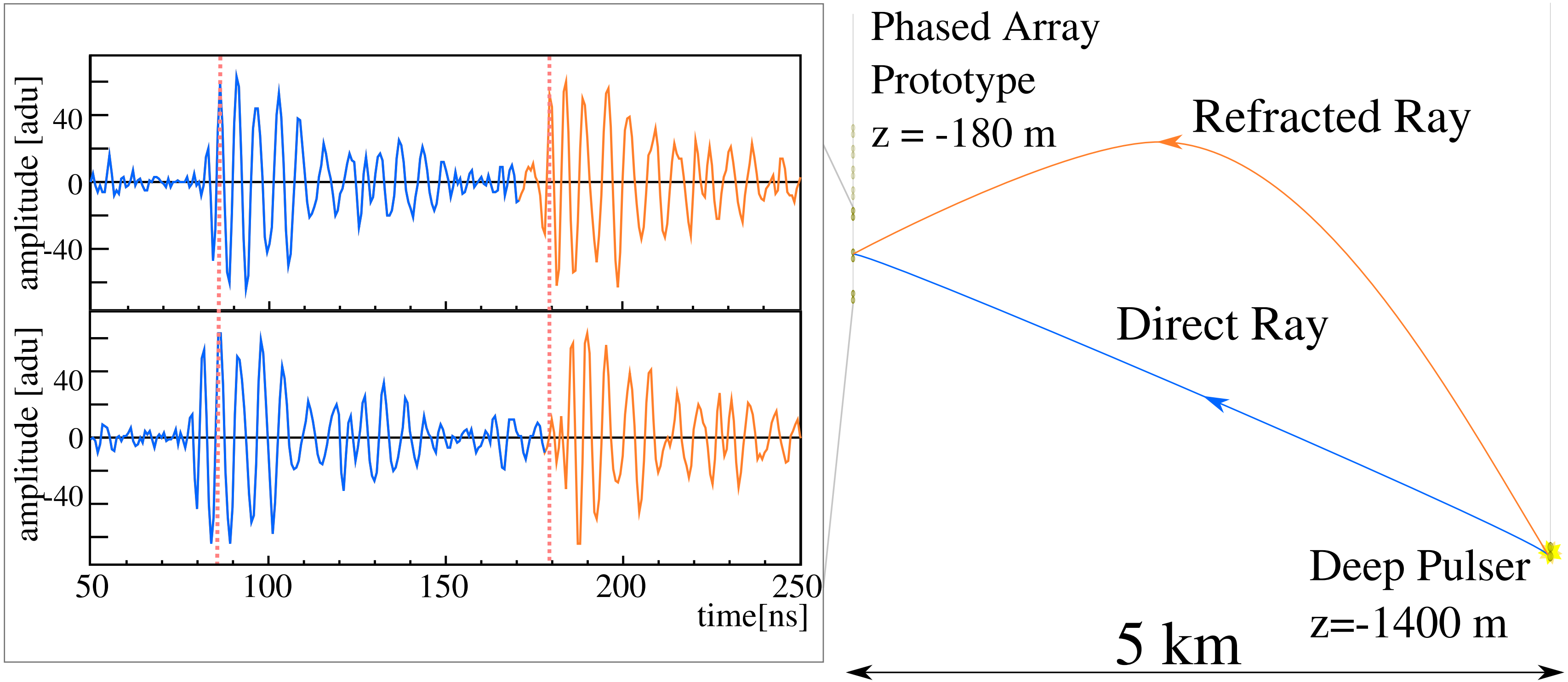




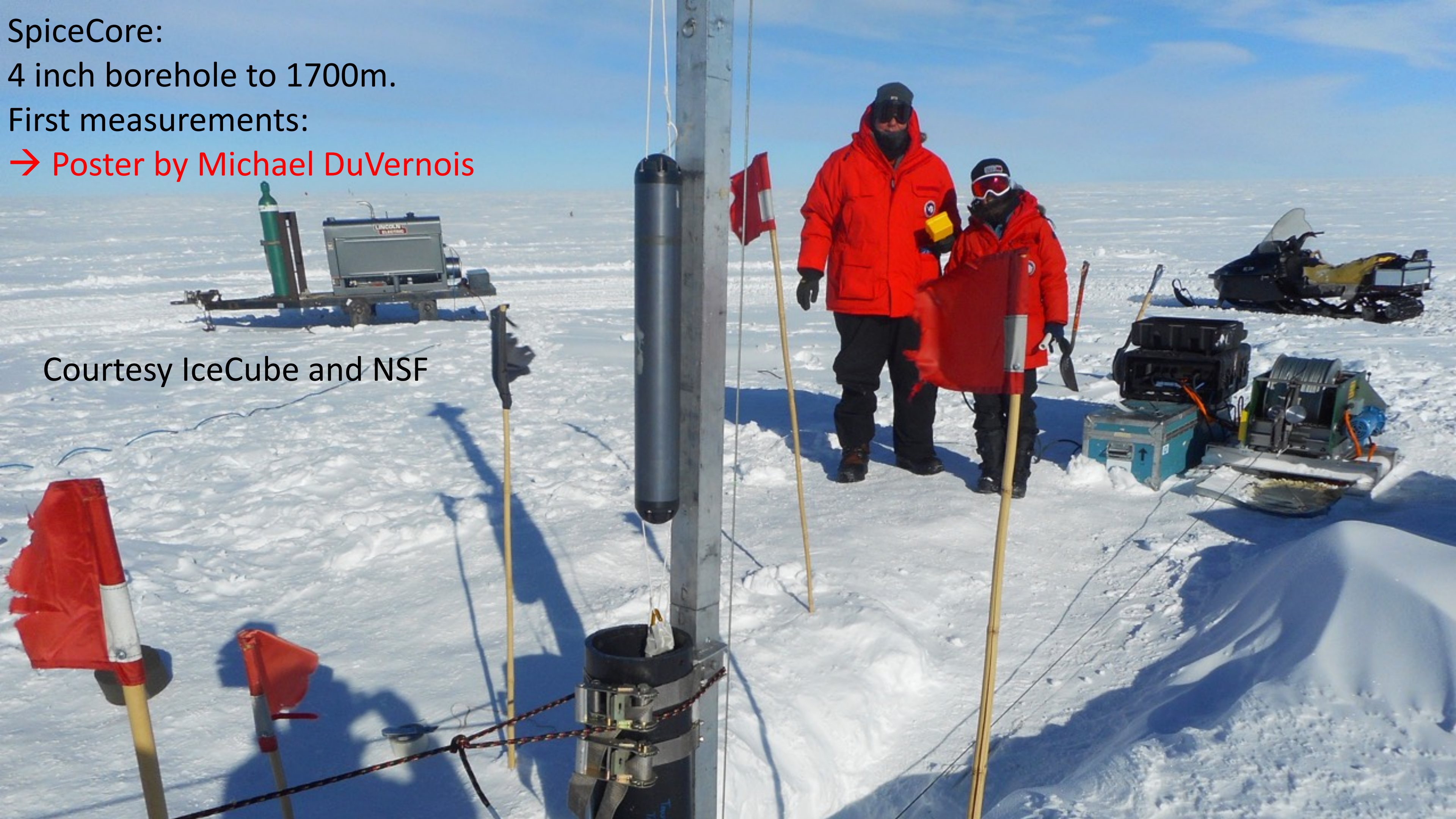
amplitude [adu]
40
0
-40
amplitude [adu]
40
0
-40
50
100
150
200
250
time[ns]
Phased Array
Prototype
z = -180 m
Refracted Ray
Direct Ray
Deep Pulser
z=-1400 m
5 km

SpiceCore:

4 inch borehole to 1700m.

First measurements:

→ Poster by Michael DuVernois



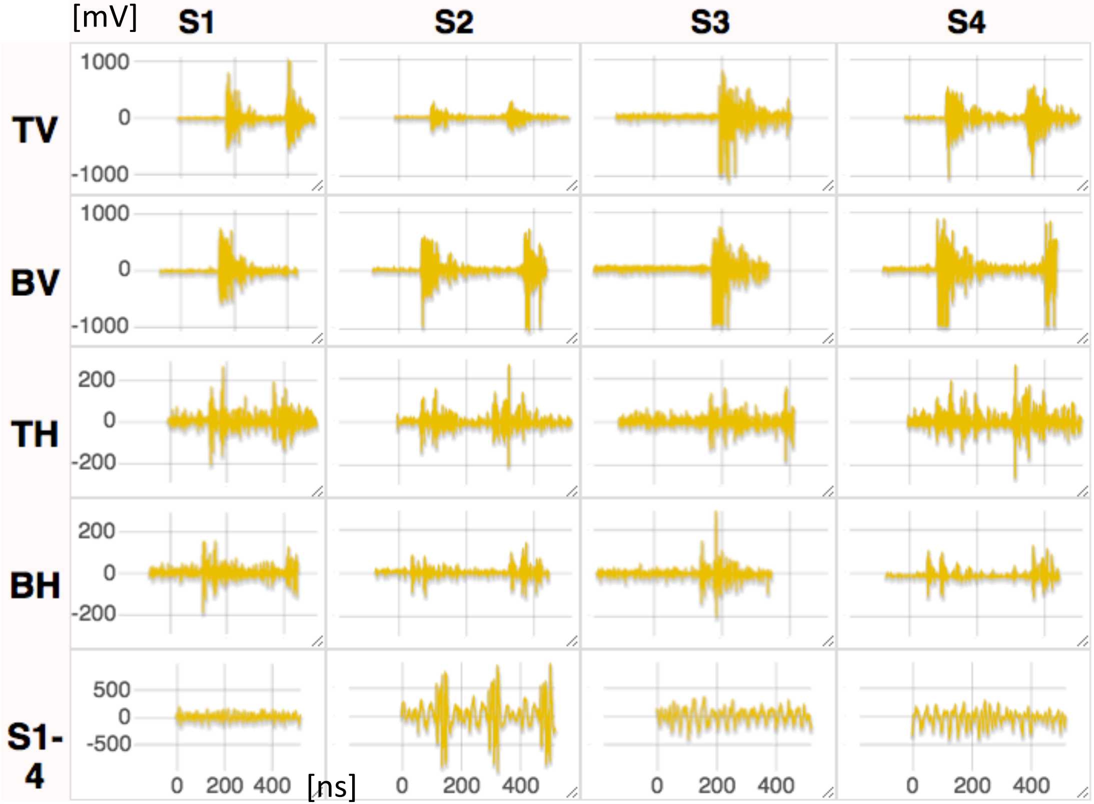
Courtesy IceCube and NSF

Deep Pulser data

Pulser at 1500m depth, 4km distance as observed with ARA stations.

Double pulses observed as expected (in hindsight):
Will allow precise reconstruction of vertex distance, thus energy.

A2 run8573 ev537

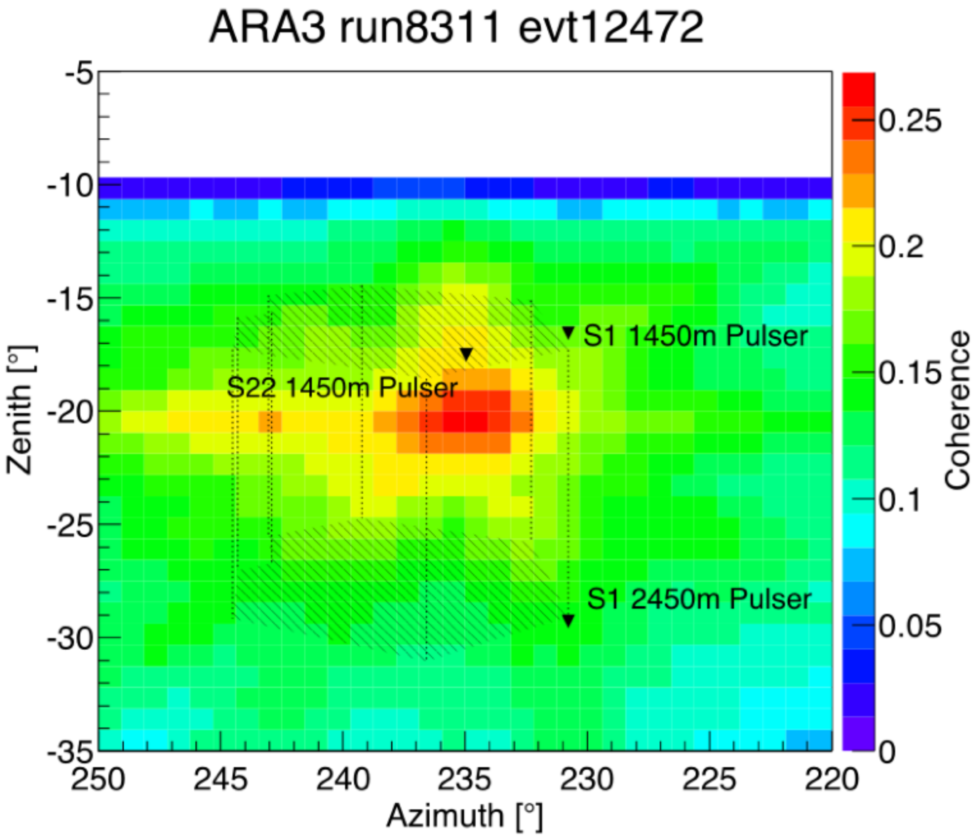


Deep pulser Vpol mode

- Double pulse – 1^{st} & 2^{nd} ray
- Birefringence
- Polarization mixing

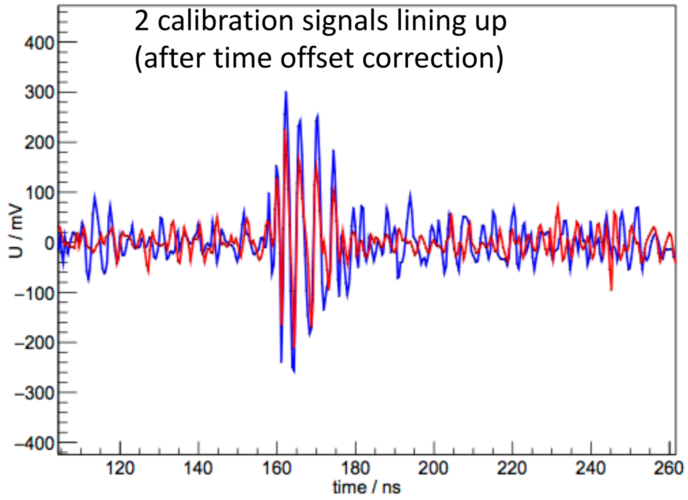
Reconstruction of pulser signal at 4 km distance

Deep pulser event
Reconstruction using
interferometric analysis.



Reconstruction

Based on time differences of signals of antenna pairs.

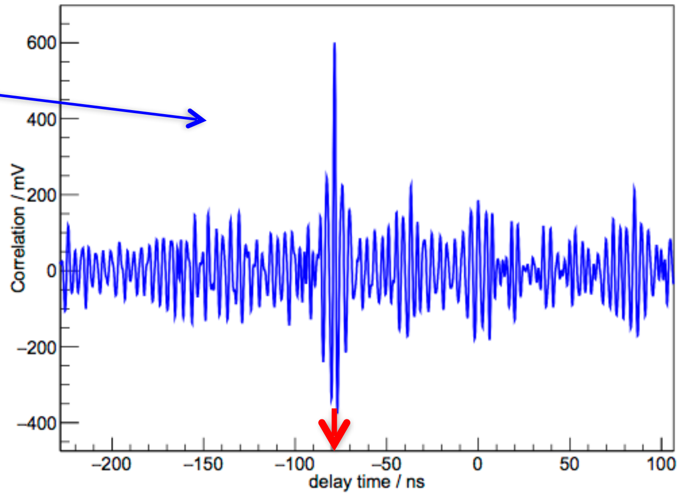


How to measure a time difference?

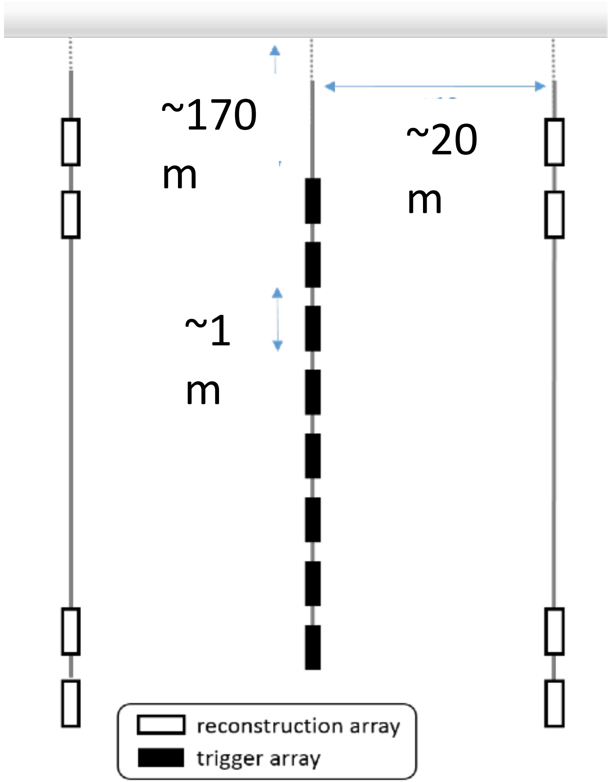
Shift in time such that they maximize the correlation function.

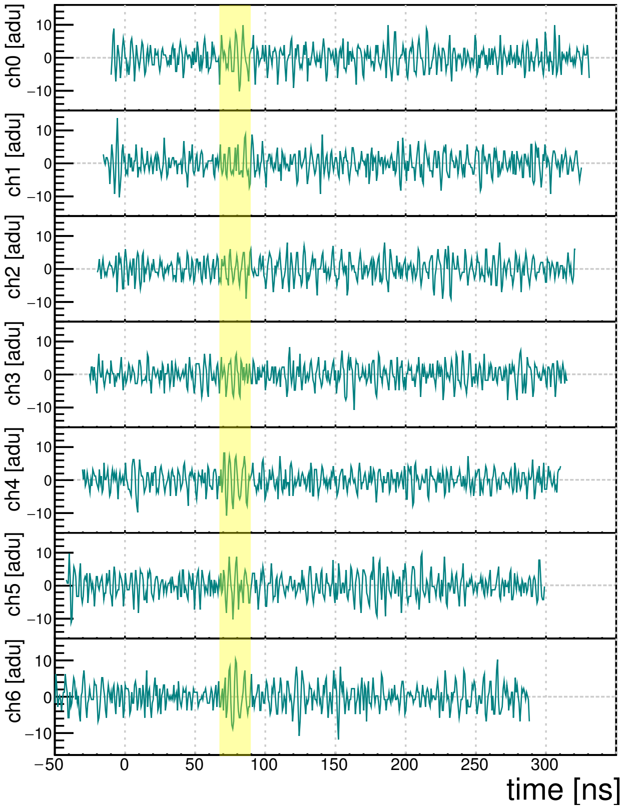
Typical resolution: 100psec

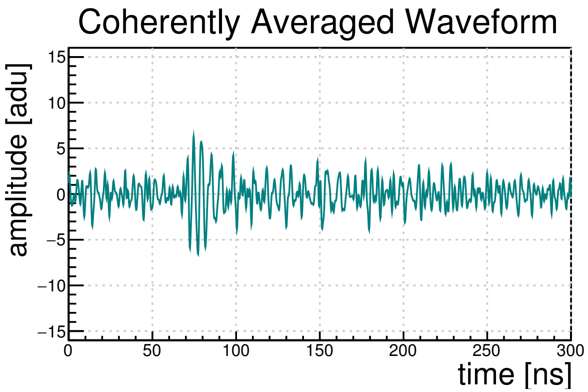
Do this for all time differences and compare minimize



Lowering trigger threshold with Phased Array of Antennas







Can improve signal to noise by almost sqrt(number of antennas).

4 years of 2 ARA stations.

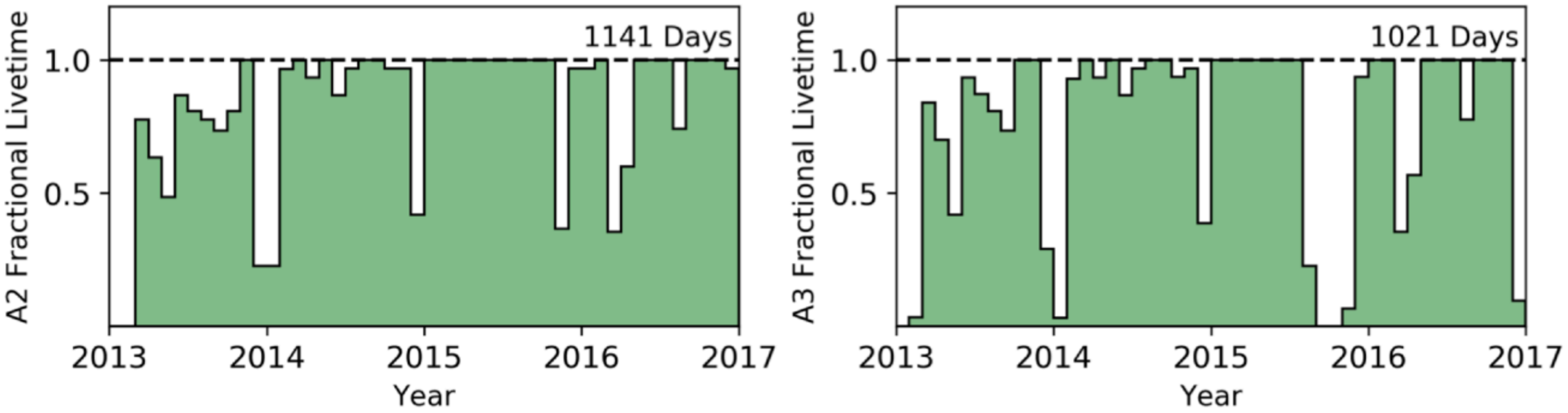


Fig. 2. Fractional livetimes for A2 (left) and A3 (right) from deployment in 2013 through the end of the analysis period in 2016. From the 4 years of deployment, roughly 3 years are analyzable due to intermittent downtimes.

Effective volume of an ARA station.

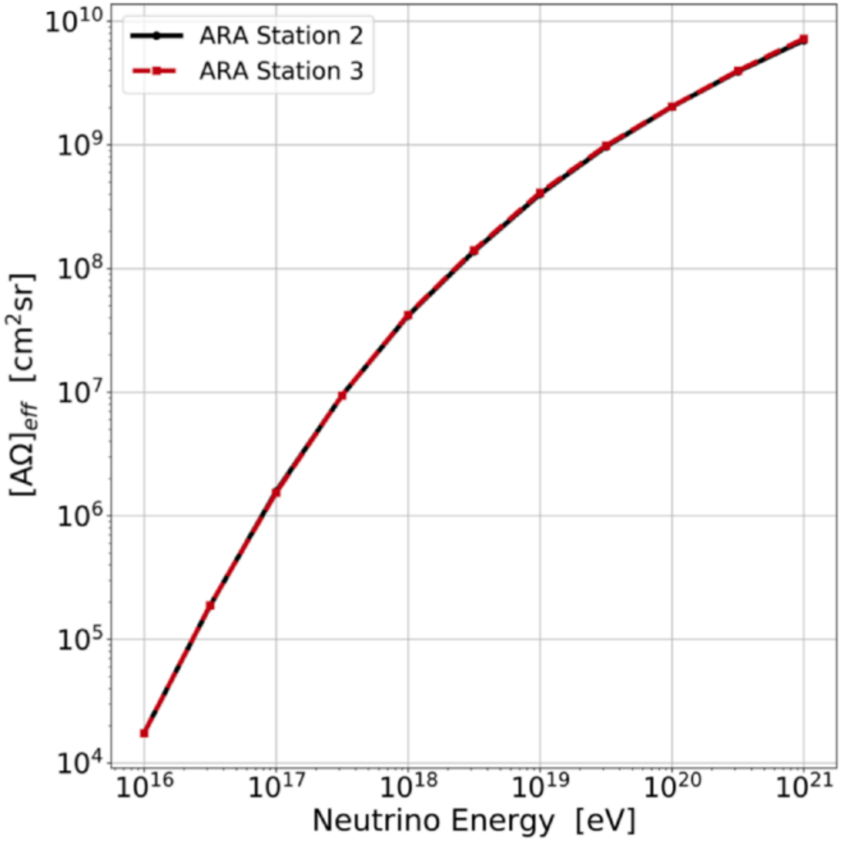


Fig. 3. The simulated trigger-level effective area-steradian ($[A\Omega]_{eff}$) for ARA stations A2 and A3, averaged across configurations.

Data (left) and signal simulation (right)

Cut variables:

C_sky: a cross correlation parameter

SNR:
Signal to Noise Ratio

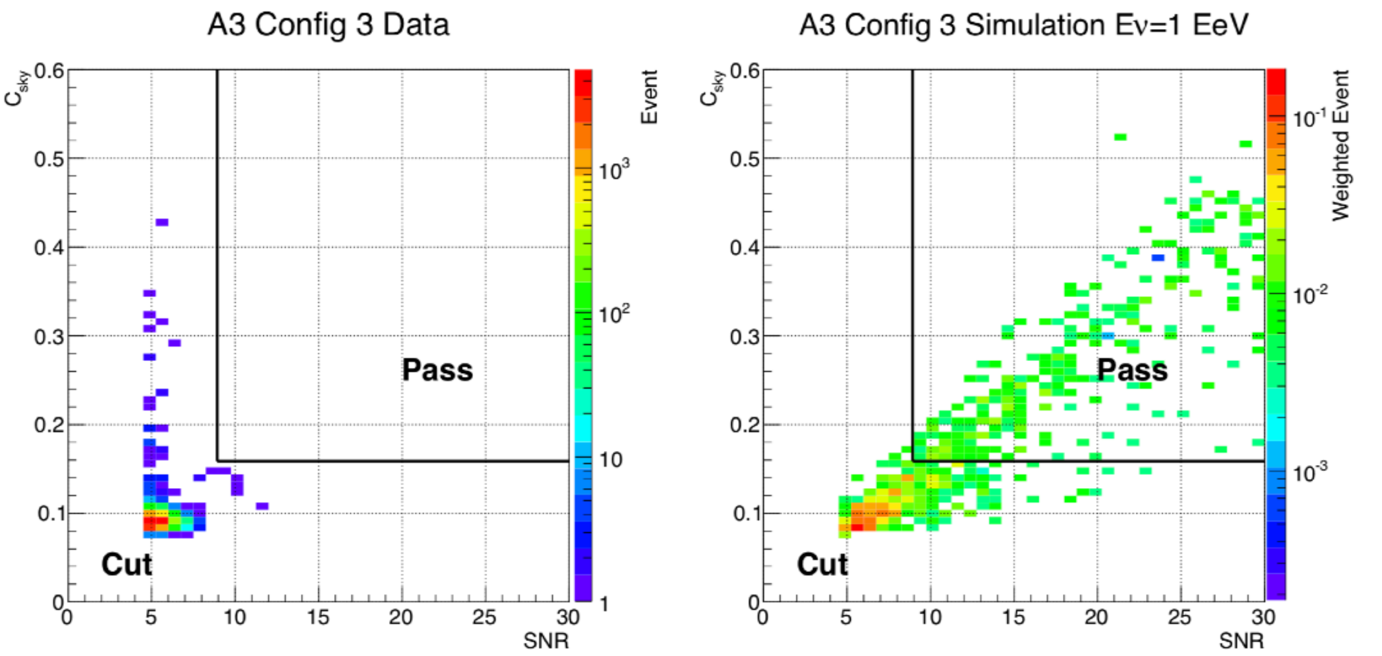
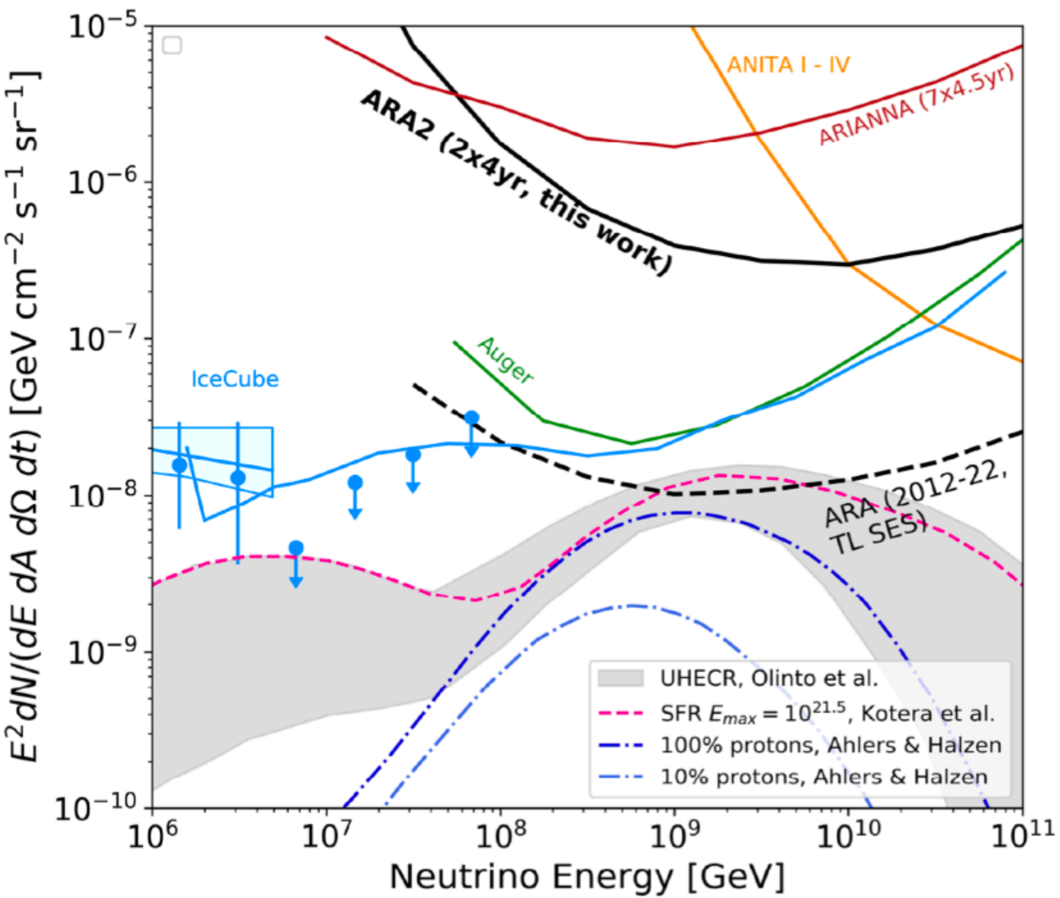


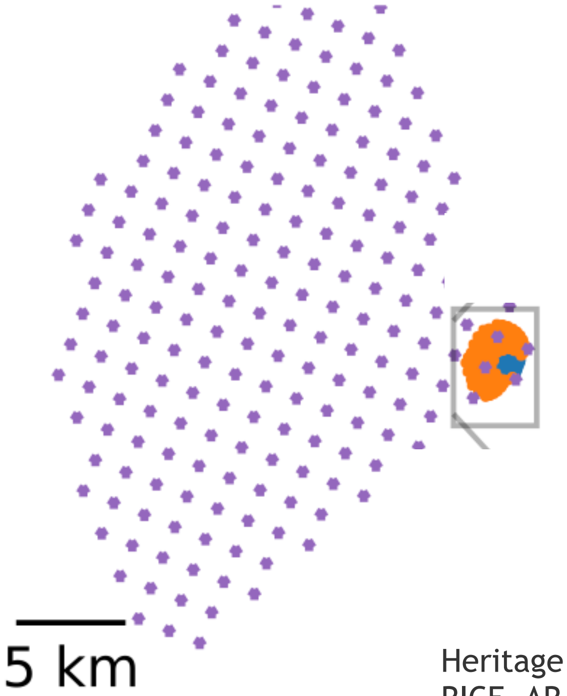
Fig. 4. An example of the bivariate cut plane, for which the final 2-D box cut is made for A3 configuration 3. (Left) The plane as observed in 10% "burn-sample" data, showing events clustering at low-correlation and low-SNR. (Right) The plane populated with simulated neutrinos at 10^{18} eV, showing events distributed throughout. Events at low-correlation and low-SNR are cut; events at higher values define the signal region, and pass the analysis.

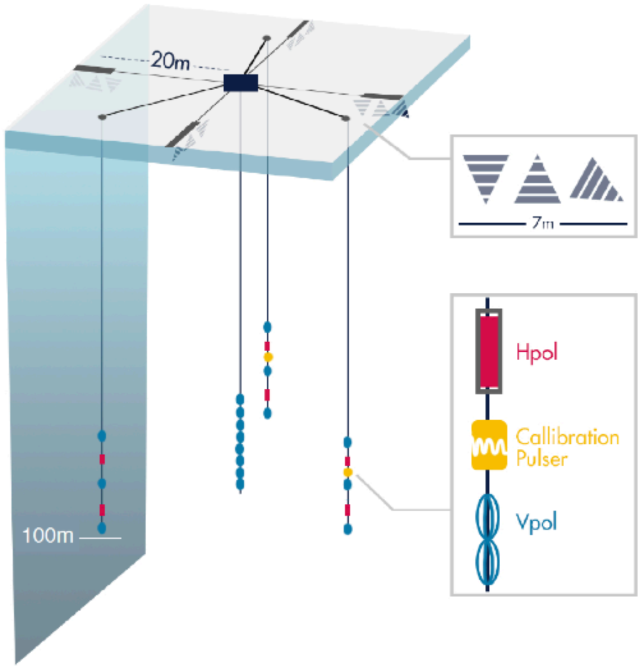
Recent result from ARA:
diffuse neutrino search based on 2 stations x 4 years of data.



Future vision - Gen2 radio array

200 stations
~500 km^2



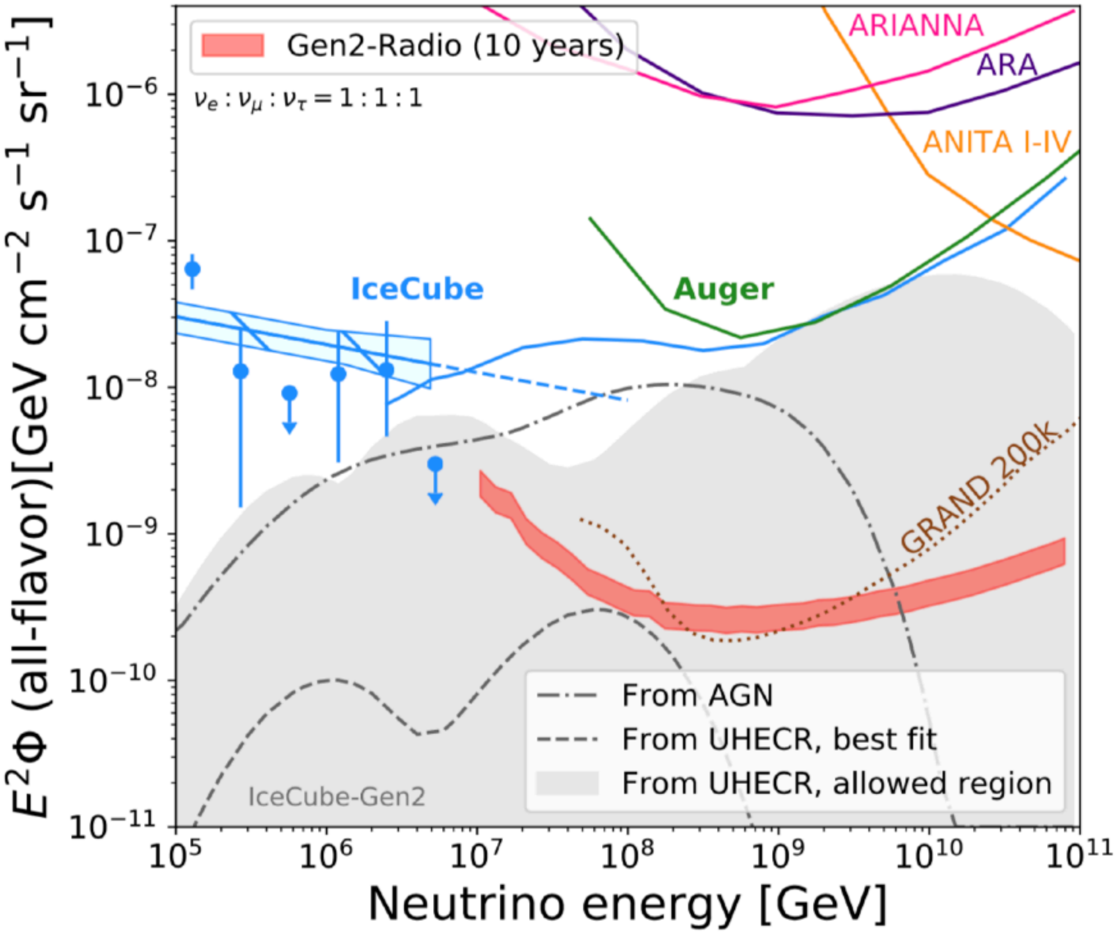


Heritage:
RICE, ARA, ARIANNA

RNO-G (Greenland) first deployment summer 2020

Future vision:

Sensitivity of a large radio component as part of a future array.



Summary

- 5 station ARA array at Pole is taking data, is producing results and has more science potential.
- Lots of progress in understanding of ice.
- Phased array addition important step to lowering threshold.
- Near future: RNO array in Greenland (not discussed today), further future: IceCube-Gen2 radio array.

- Radio technique is the most promising method to explore the neutrino sky at highest energies (1E16 to 1E19 eV).

IceCube-Gen2

The next Generation IceCube: from discovery to astronomy

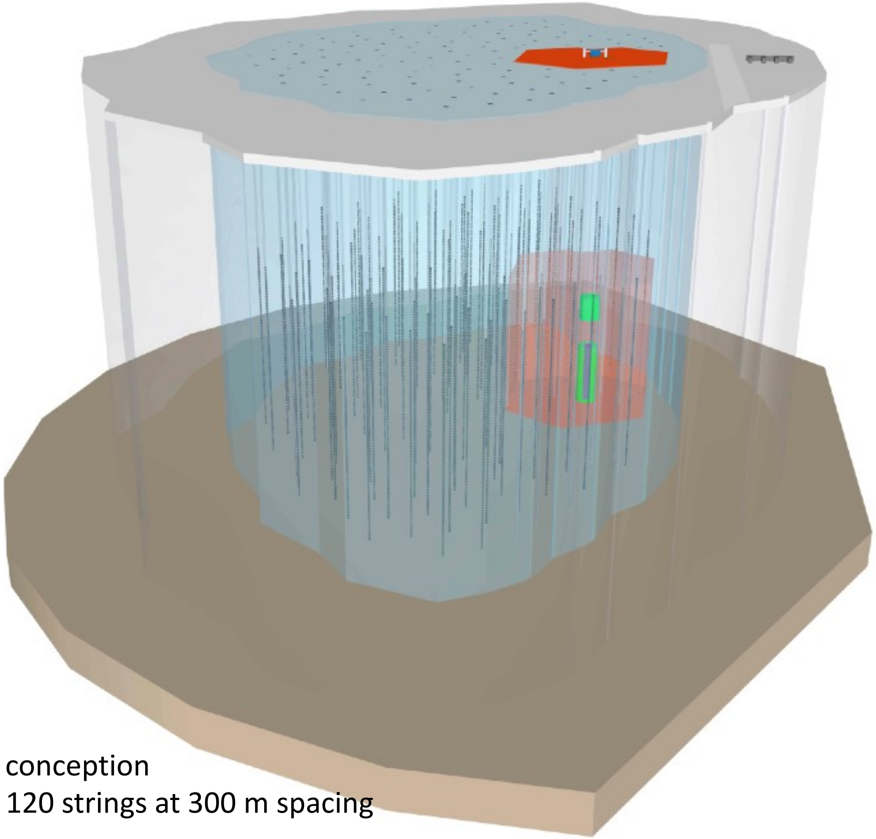
Multi-component observatory:
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector

Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase of contained event rate at high energies.

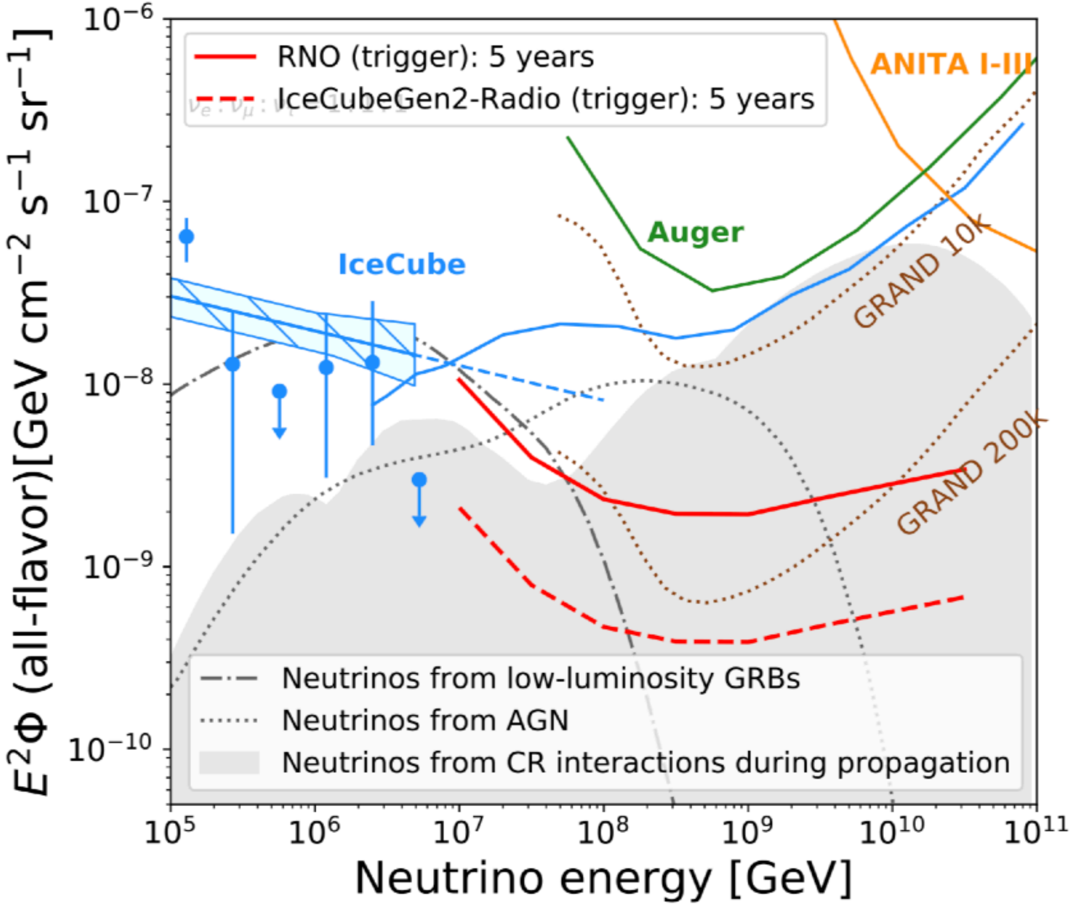
Cost: order $400M



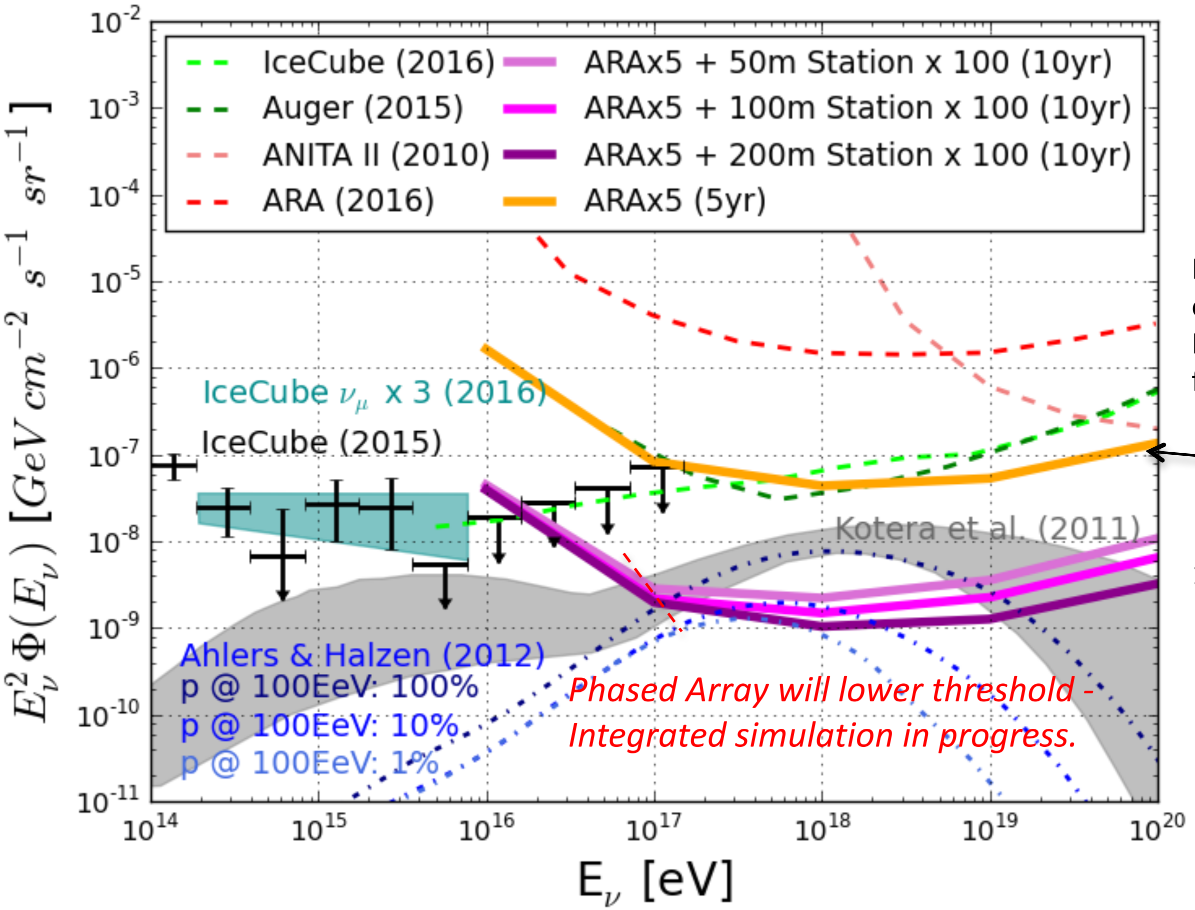
Artist conception
Here: 120 strings at 300 m spacing

Target sensitivity at high energies - beyond RNO

Radio component of IceCube-Gen2 sensitivity, scale, 5x RNO.



Sensitivity vs energy

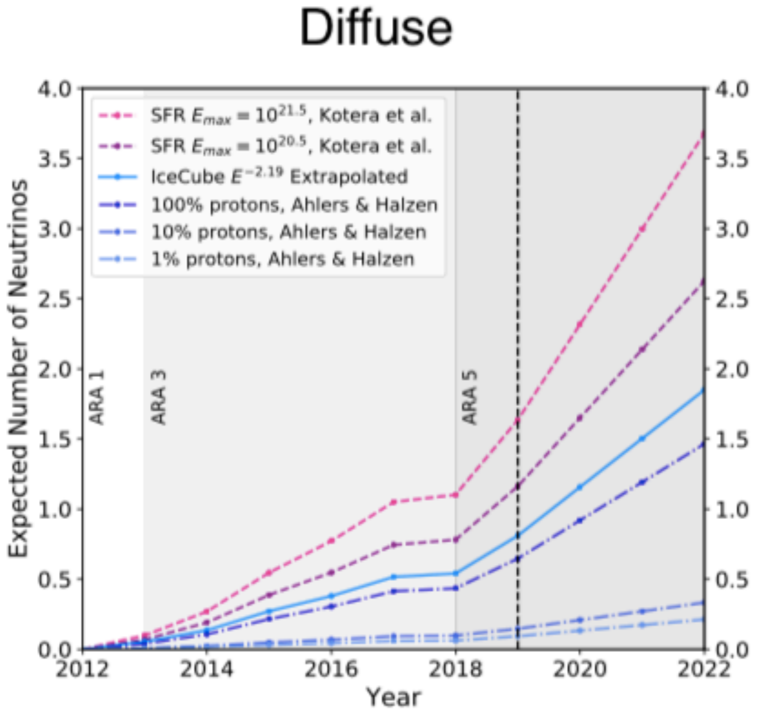


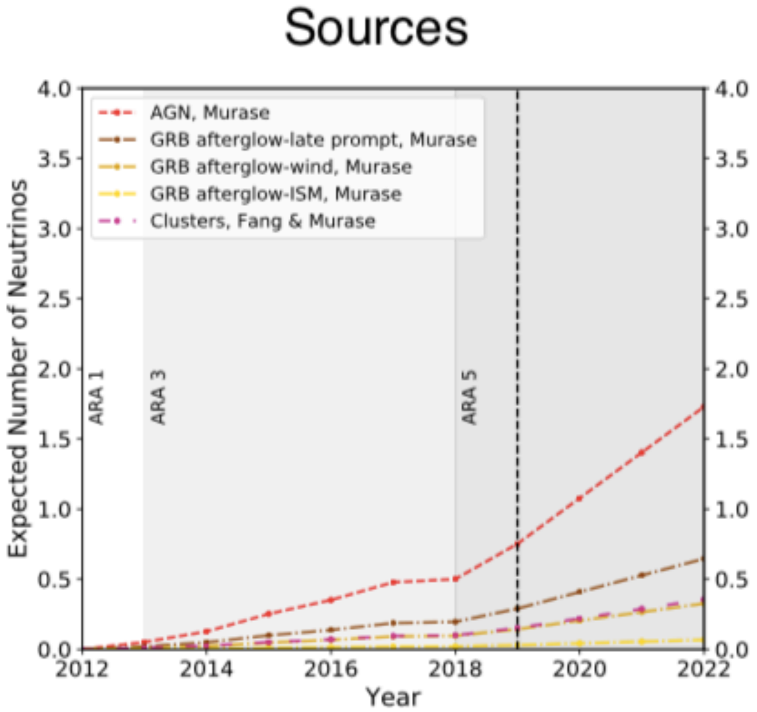
Published limit based on 8 months of data (arxiv:1507.08991)
Results on 3 stations 2 years this fall.

5 stations (5 yr), trigger level
Eg: IceCube 2016, E^-2.1:
2 events in 5 years

100 stations (10 yr), trigger level

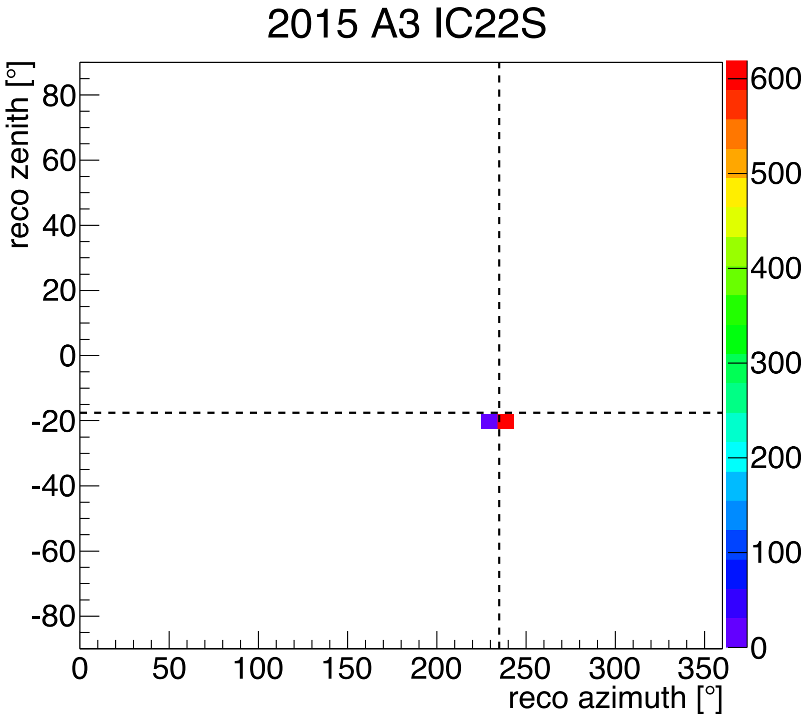
ARA 5 station array: expected neutrino event rates

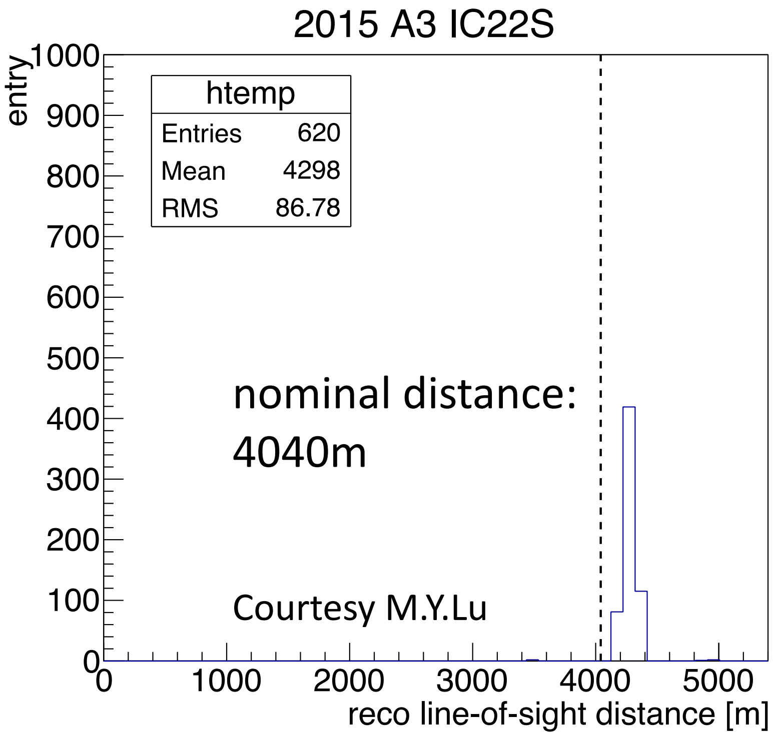




World's best neutrino telescope above 10^{17} eV by 2022

Vertex Reconstruction – Deep Pulser

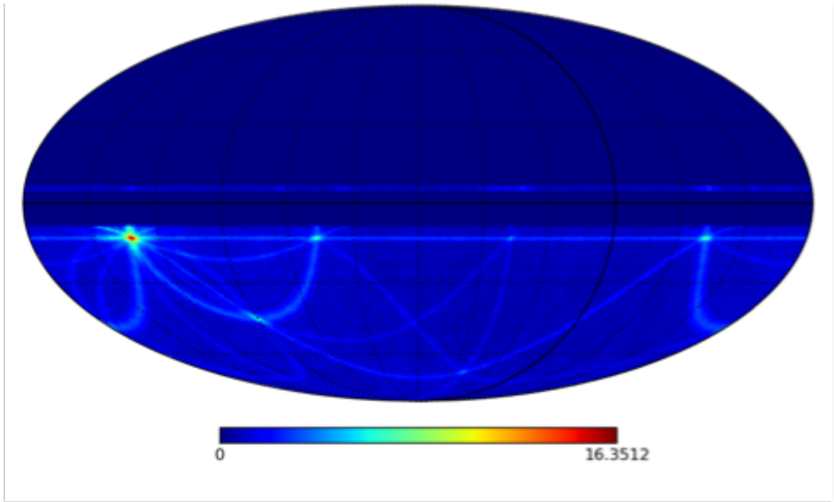


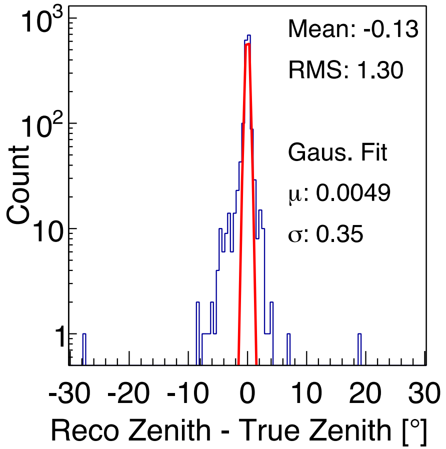


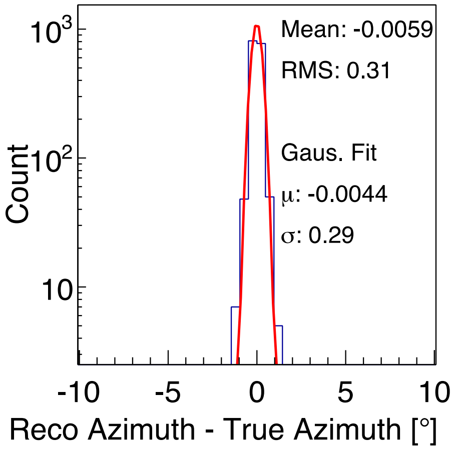
- Can reconstruct deep pulser position in 4 Km distance within 10%
- Confirms understanding dignalpropagation of the south pole ice

Vertex reconstruction - direction

- Simulated neutrino events at 10^{18}eV, neutrino vertices randomly scattered around an ARA station, up to 5km







True Vertex Distance: 2581m			
	True	Reco	Diff.
Zenith	102.74°	102.94°	0.2°
Azimuth	222.69°	222.89°	0.2°