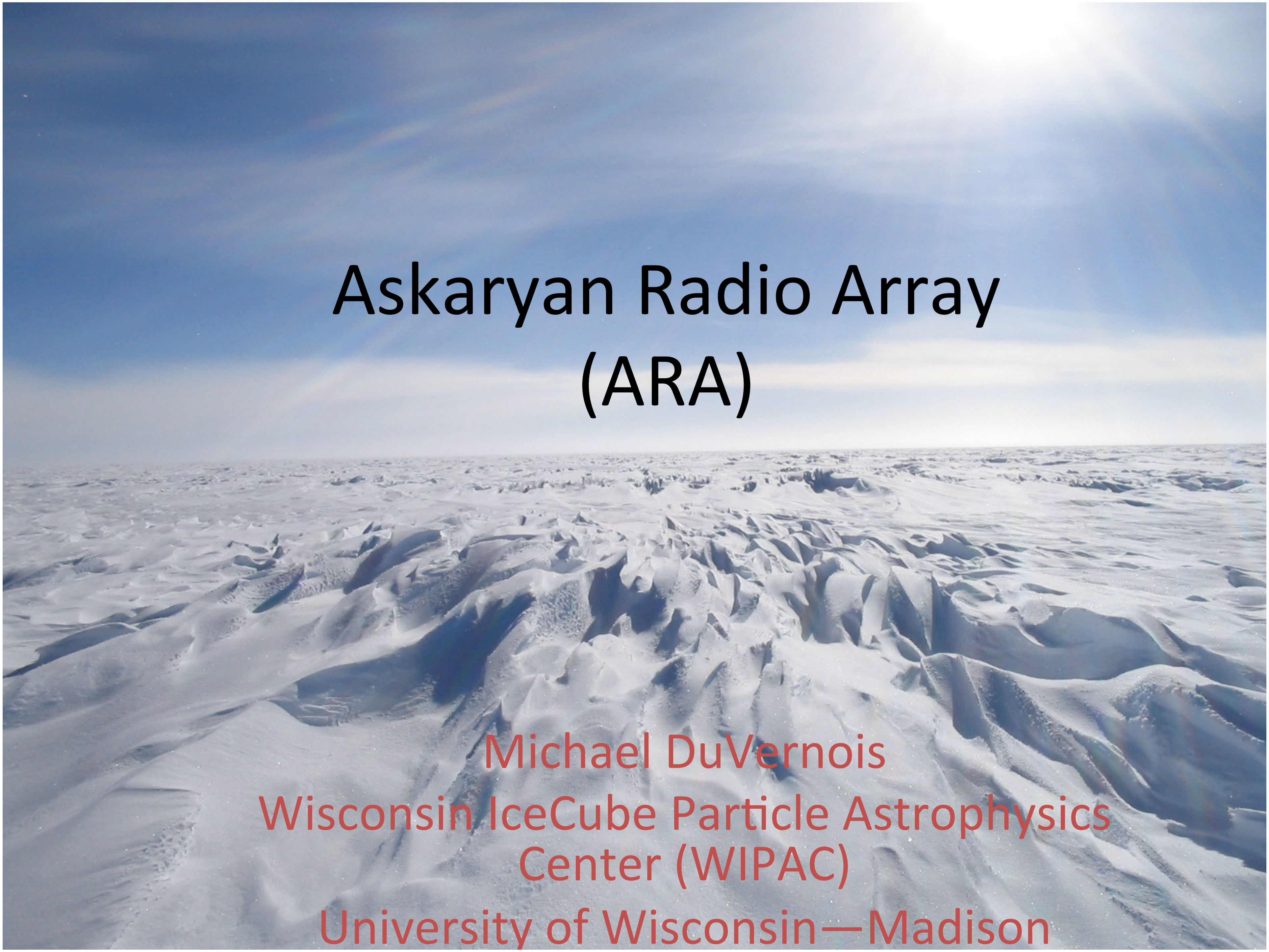


Askaryan Radio Array
(ARA)

Michael DuVernois
Wisconsin IceCube Particle Astrophysics Center (WIPAC)
University of Wisconsin—Madison

PHYSICS

Cosmic Rays and Neutrino Sources

Cosmic rays exist at highest energies:

The puzzle

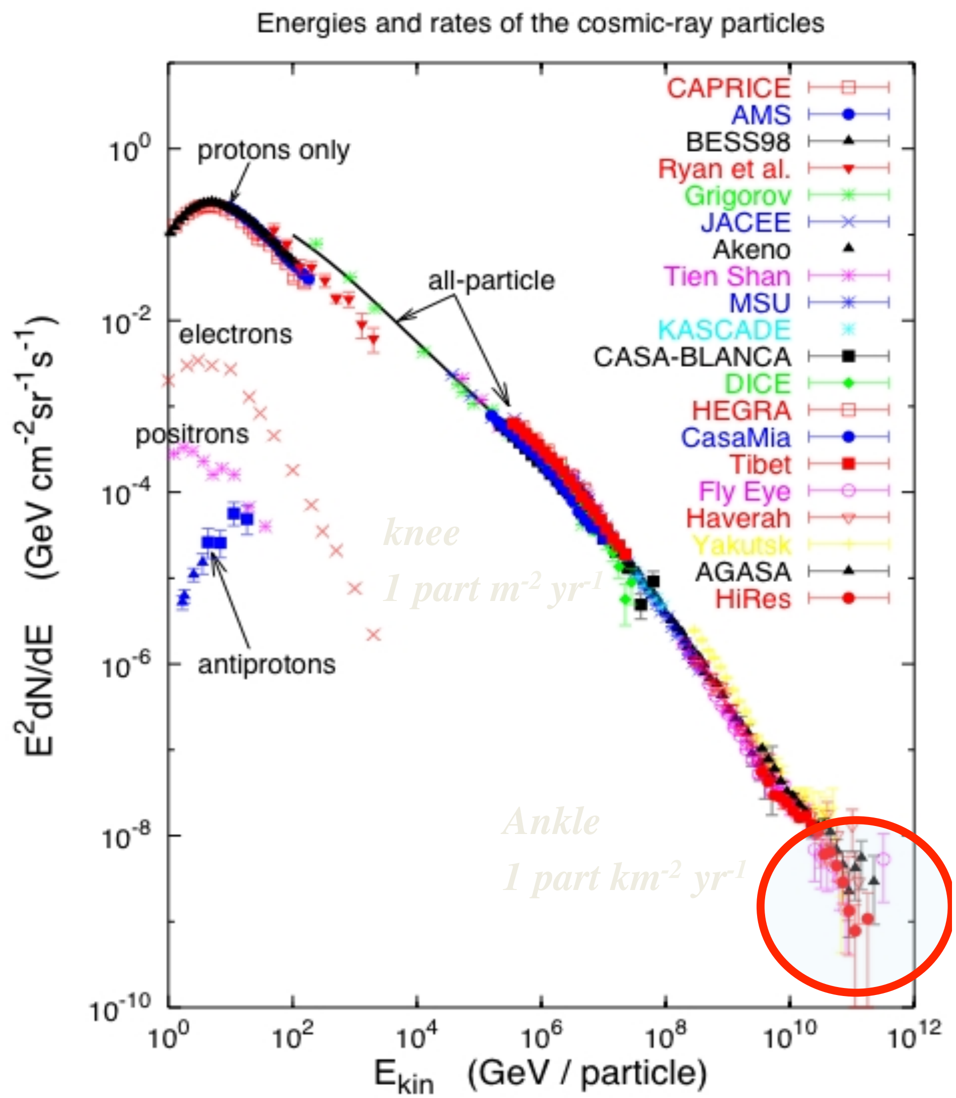
No nearby (<50Mpc) sources observed.
More distant sources are not observable in cosmic rays due to collisions with microwave background.

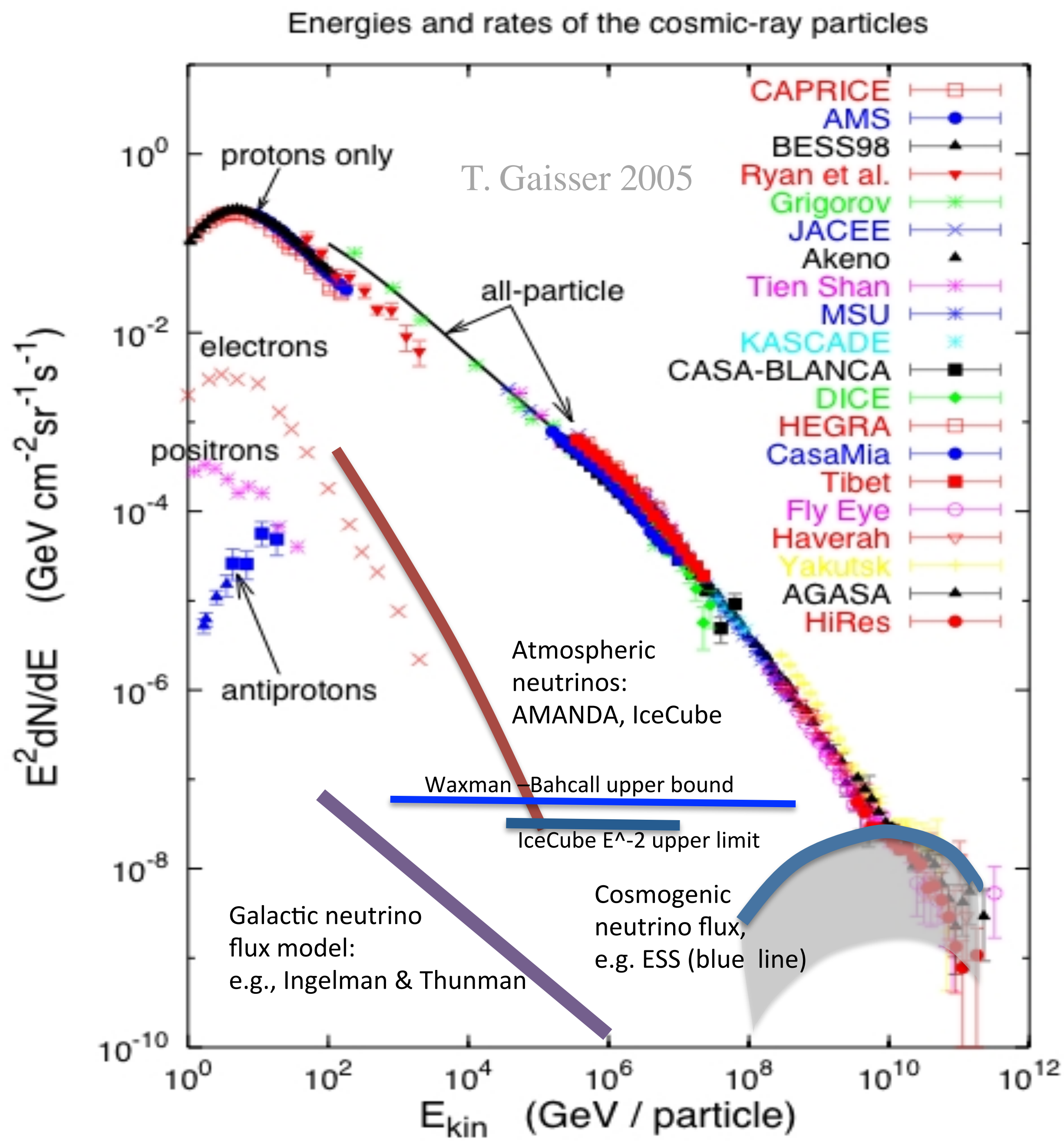
Neutrinos above $10^{17\text{-}19}$ eV, GZK or cosmogenic neutrinos are at some level guaranteed.

However, fluxes will be small, requires very large detectors

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

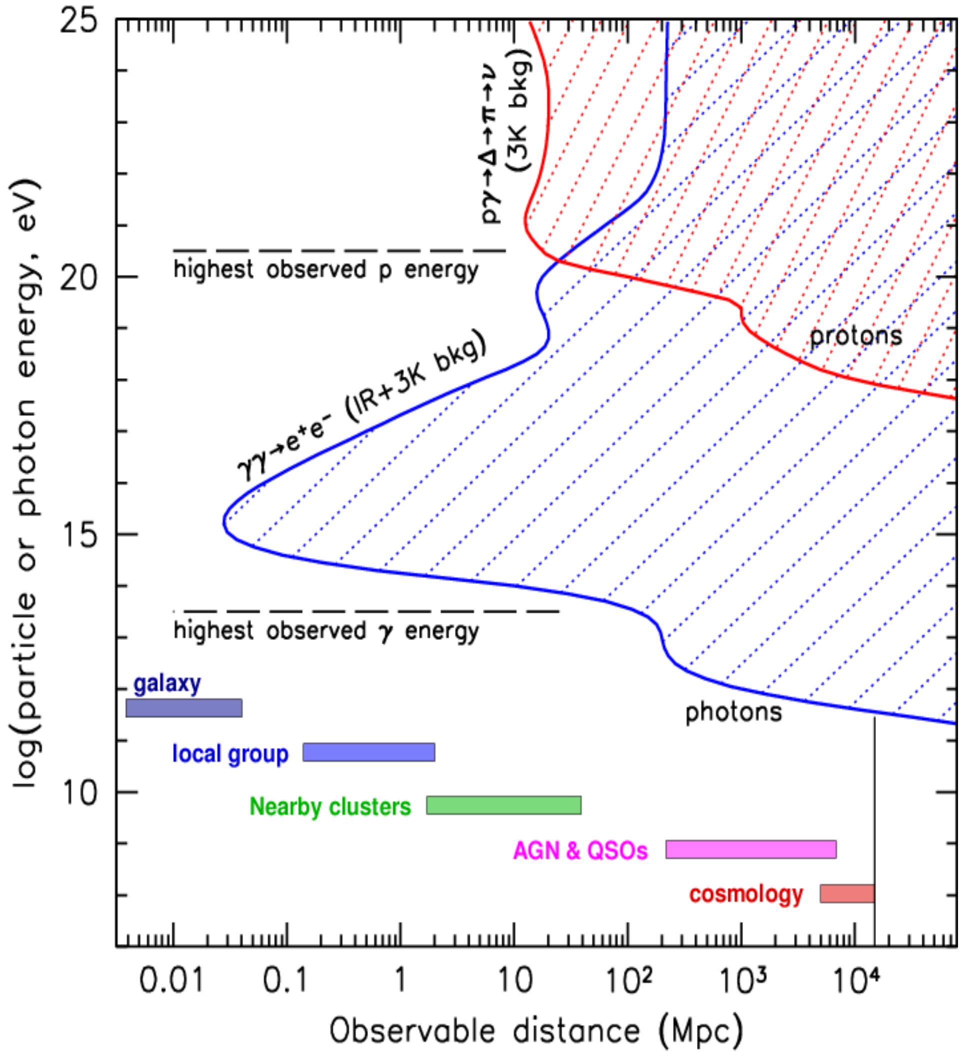
Gaisser 2005





Energies and rates of the cosmic-ray particles
T. Gaisser 2005
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
Atmospheric
neutrinos:
AMANDA, IceCube
Waxman –Bahcall upper bound
IceCube E^-2 upper limit
Galactic neutrino
flux model:
e.g., Ingelman & Thunman
Cosmogenic
neutrino flux,
e.g. ESS (blue line)
E^2dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
E_{kin} (GeV / particle)

Neutrinos as messengers



Study of the highest energy processes and particles throughout the universe requires PeV-ZeV neutrino detectors

To "**guarantee"**EeV neutrino detection, **design for the GZK neutrino flux**

Existence of extragalactic neutrinos inferred from CR spectrum, up to 10^{20} eV, and similarly, Galactic up to 10^{18} eV

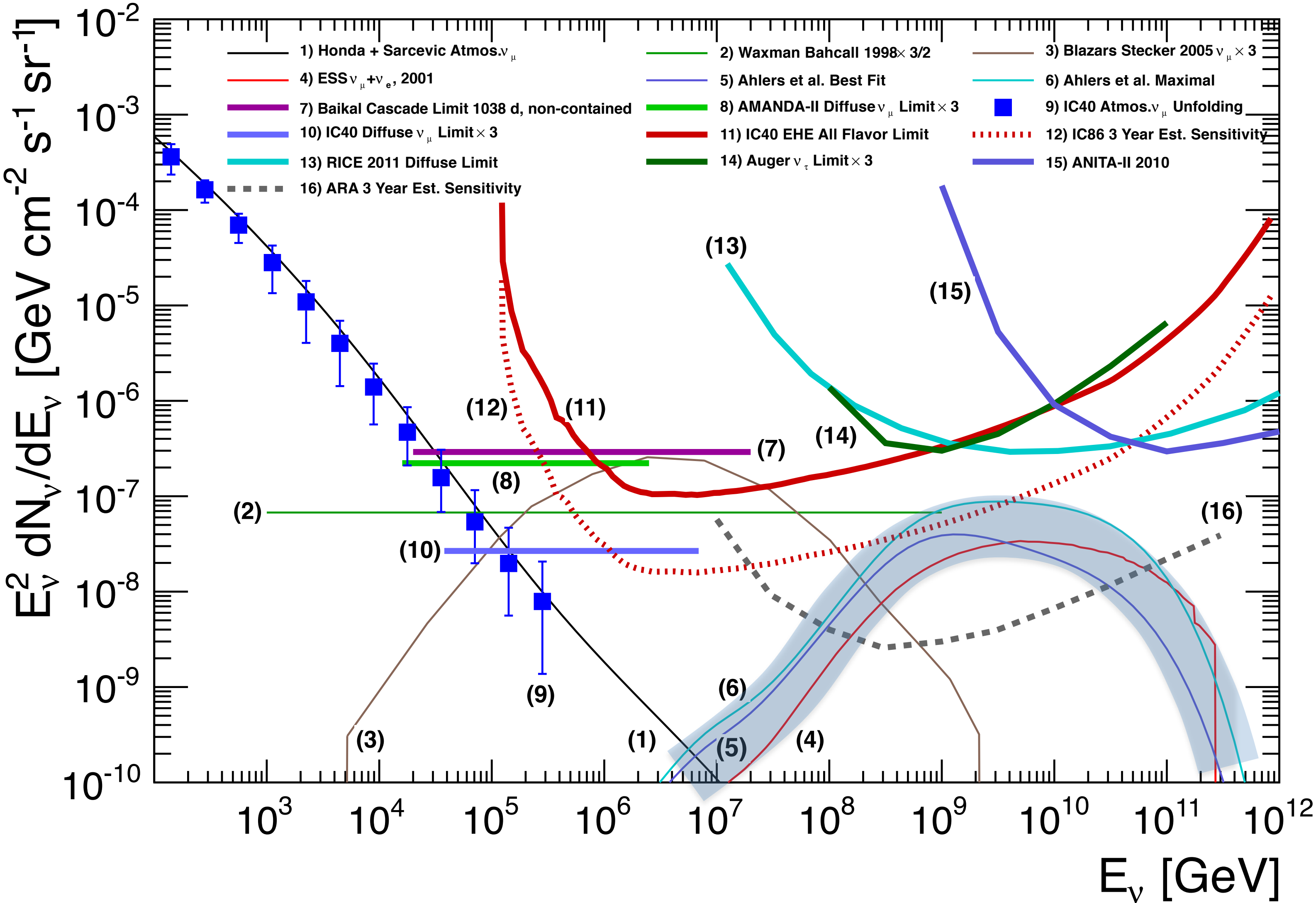
Need gigaton (km^3) mass (volume) for TeV to PeV detection, and teraton at 10^{19} eV

Neutrino detection associated with EM sources will ID the UHECR sources

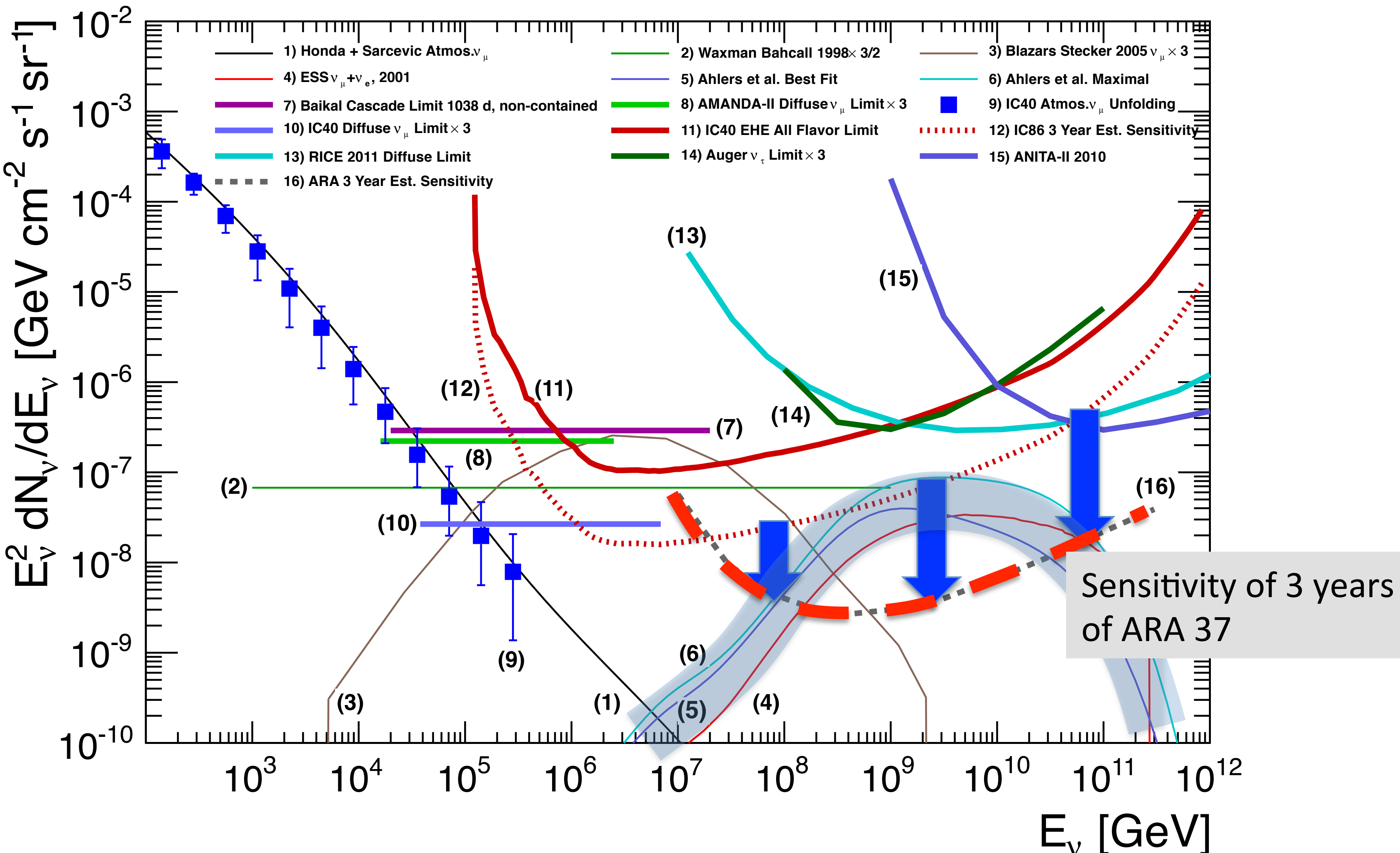
"EM Hidden" sources may exist, visible only in neutrinos.

Neutrino eyes see farther (z>1), and deeper (into compact objects), than gamma-photons, and straighter than UHECRs,with no absorption at (almost) any energy

The cosmic energy frontier, 10^7 to 10^{11} GeV
Cosmogenic or *GZK* neutrinos

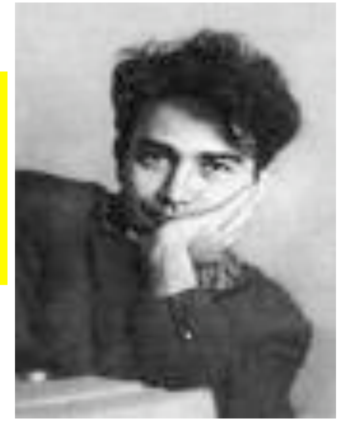


The cosmic energy frontier, 10^7 to 10^{11} GeV
Cosmogenic or *GZK* neutrinos

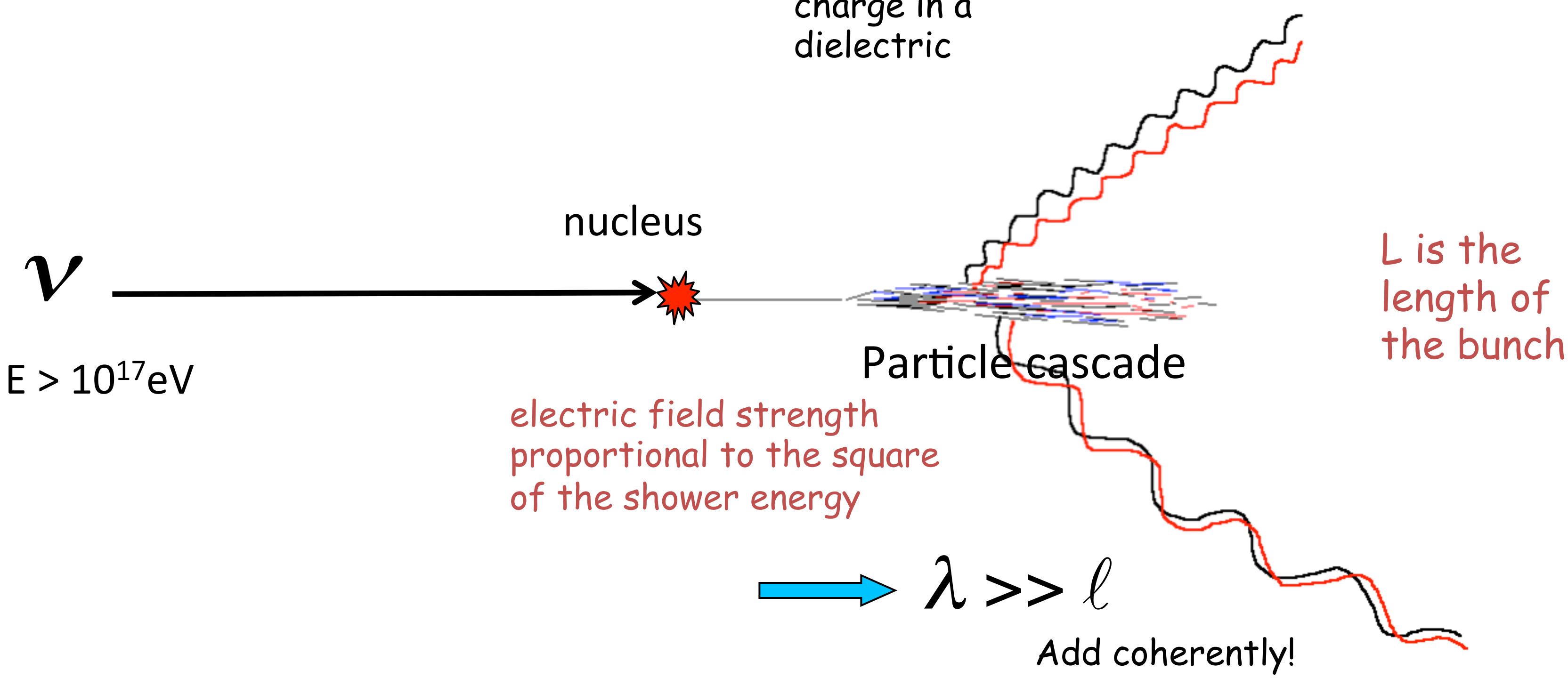


ASKARYAN EFFECT

Detection mechanism proposed by G. Askaryan (1962):
Measure the coherent RF signal generated by neutrino interaction in dielectric media (such as ice)



charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric → wavelengths shorter than the bunch length suffer from destructive interference



Askaryan Effect

In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

Compton scattering: $\gamma + e^-_{(at\ rest)} \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-_{(at\ rest)} \rightarrow \gamma + \gamma$

In dense material $R_{Moliere}$~ 10cm.

$\lambda << R_{Moliere}$ (optical case), <u>random phases</u> $\Rightarrow$ **$P \propto N$**

$\lambda >> R_{Moliere}$ (microwaves), <u>coherent</u> $\Rightarrow$ **$P \propto N^2$**

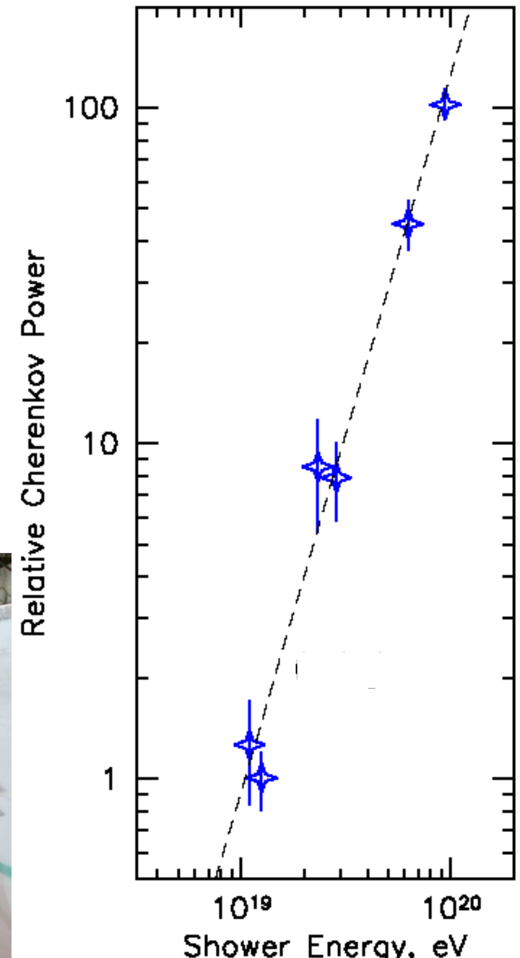
$$\frac{dP_{CR}}{d\nu} \propto \nu d\nu$$

Validation at SLAC

"Little Antarctica"

ANITA I beamtest at SLAC (June06): proof of Askaryan effect in ice

- Coherent (Power ~ E^2)
- Linearly Polarized



Natural target material?

- Lunar regolith (20m attenuation length)
  Parkes Telescope; GLUE; WSRT; …
- Ice (100-1500m attenuation lengths)
  Forte (satellensaltedite); ANITA (balloon); ARA
- Salt (100-500m attenuation lengths)
  SalSA (proposed,)
- Air is too thin
- Water is RF lossy, natural, outdoor, sand (as opposed to pure silica) is also lossy

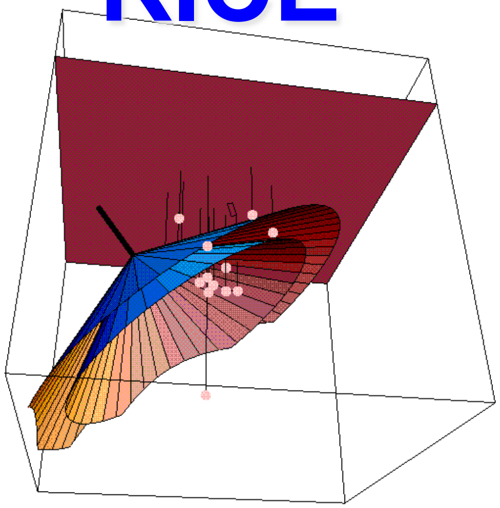
INSTRUMENTATION

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA) heritage:
Existing and previous instruments using radio in Polar ice

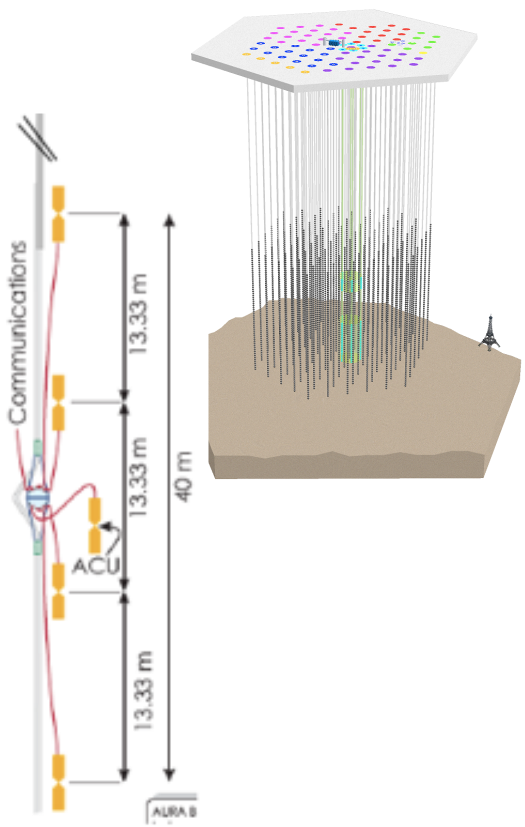
Members of all three efforts are currently involved with ARA

RICE



- array of single dipole antennas deployed between 100 and 300m near the Pole
- much of the instrumentation was deployed in AMANDA holes
- Pioneered technique in the ice

Special radio detectors and pulsers in IceCube



ANITA

- balloon payload of horn antennas
- surveys the ice cap from high altitude for RF refracted out of the ice
- → high fidelity data acquisition system >Gs/sec waveform capture

ARA- Collaboration

- ARA is an international Collaboration
  - 14 institutions
  - ~50 authors

Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole

P. Allison,[1] J. Auffenberg,[2] R. Bard,[3] J. J. Beatty,[1] D. Z. Besson,[4] S. Böser,[5] C. Chen,[6] P. Chen,[6] A. Connolly,[1] J. Davies,[7] M. DuVernois,[2] B. Fox,[8] P. W. Gorham,[8] E. W. Grashorn,[1] K. Hanson,[9] J. Haugen,[2] K. Helbing,[10] B. Hill,[8] K. D. Hoffman,[3] M. Huang,[6] M. H. A. Huang,[6] A. Ishihara,[11] A. Karle,[12] D. Kennedy,[4] H. Landsman,[2] A. Laundrie,[2] T. C. Liu,[6] L. Macchiarulo,[8] K. Mase,[11] T. Meures,[9] R. Meyhandan,[8] C. Miki,[8] R. Morse,[8] M. Newcomb,[2] R. J. Nichol,[7] K. Ratzlaff,[13] M. Richman,[3] L. Ritter,[8] B. Rotter,[8] P. Sandstrom,[2] D. Seckel,[14] J. Touart,[3] G. S. Varner,[8] M. -Z. Wang,[6] C. Weaver,[12] A. Wendorff,[4] S. Yoshida,[11] and R. Young[13]

(ARA Collaboration)

[1]*Dept. of Physics, Ohio State Univ., Columbus, OH 43210, USA.*
[2]*IceCube Research Center, Univ. of Wisconsin- Madison WI 53703.*
[3]*Dept. of Physics, Univ. of Maryland, College Park, MD, USA.*
[4]*Dept. of Physics and Astronomy, Univ. of Kansas, Lawrence, KS 66045, USA.*
[5]*Dept. of Physics, Univ. of Bonn, Bonn, Germany.*
sics, Grad. Inst. of Astrophys.,& Leung Center for Cosmology and Particle Astrophysics, National Taiwan Univ., Taipei, Taiwan.
[7]*Dept. of Physics and Astronomy, Univ. College London, London, United Kingdom.*
[8]*Dept. of Physics and Astronomy, Univ. of Hawaii, Manoa, HI 96822, USA.*
[9]*Dept. of Physics, Univ. Libre de Bruxelles, Belgium.*
[10]*Dept. of Physics, Univ. of Wuppertal, Wuppertal, Germany.*
[11]*Dept. of Physics, Chiba university, Tokyo, Japan.*
[12]*Dept. of Physics, Univ. of Wisconsin Madison, Madison, WI, USA.*
[13]*Instrumentation Design Laboratory, Univ. of Kansas, Lawrence, KS 66045, USA.*
[14]*Dept. of Physics, Univ. of Delaware, Newark, DE 19716.*

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

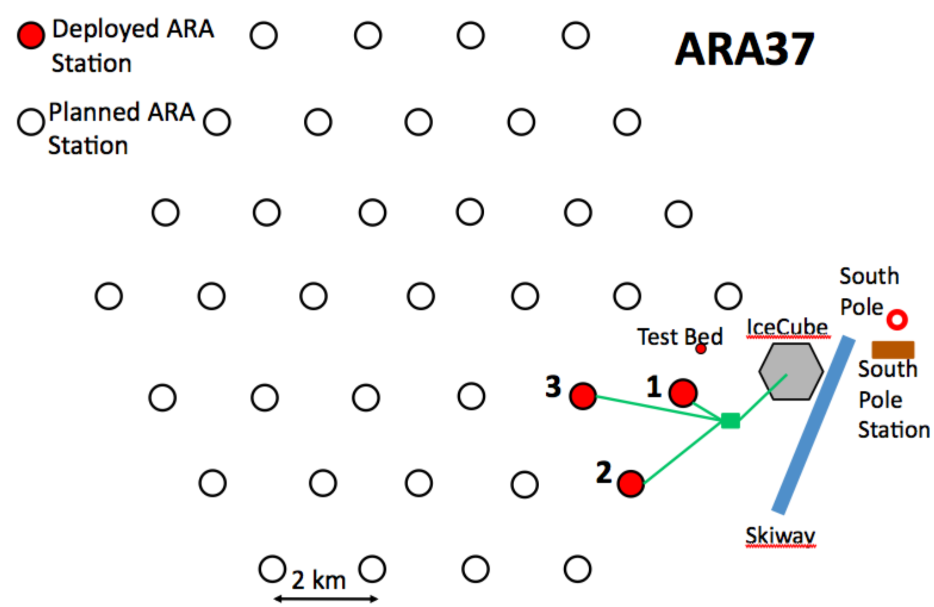
Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

Scientific Goal:

- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole



Areal coverage: ~150km^2

ARA station geometry

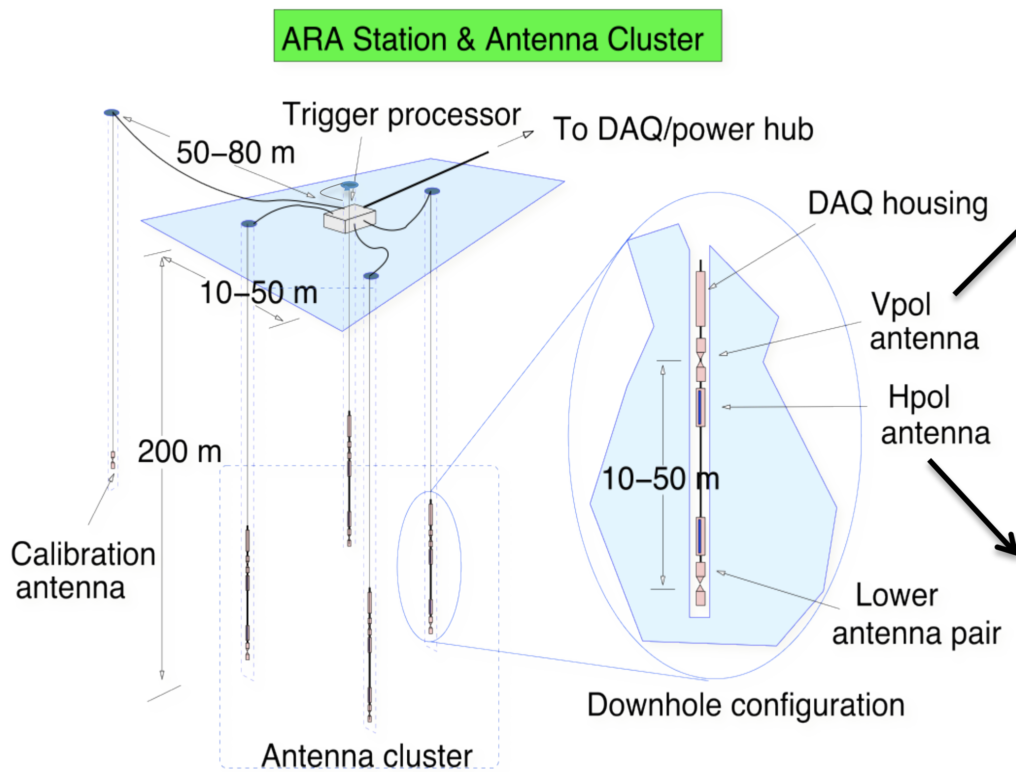
Design goals and choices:

- Every station is a fully functioning detector.

→ Lower energy threshold: nearby events (300m) can be reconstructed.

Background rejection:

→ Embedded strings: Allow good vertex resolution and high vertical resolution for background rejection

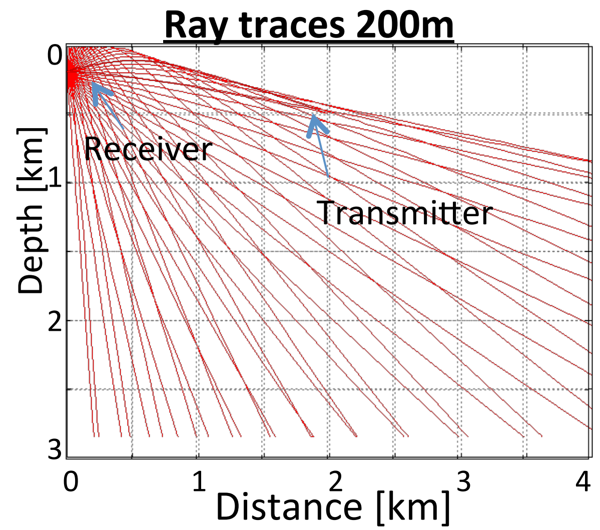


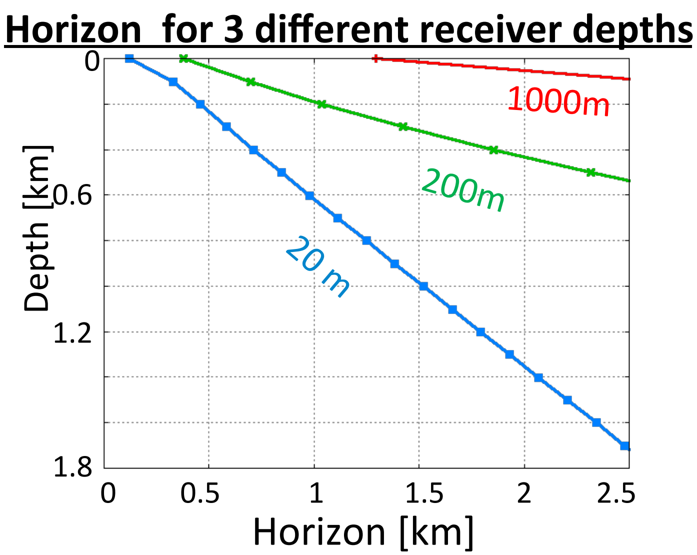
Why strings?

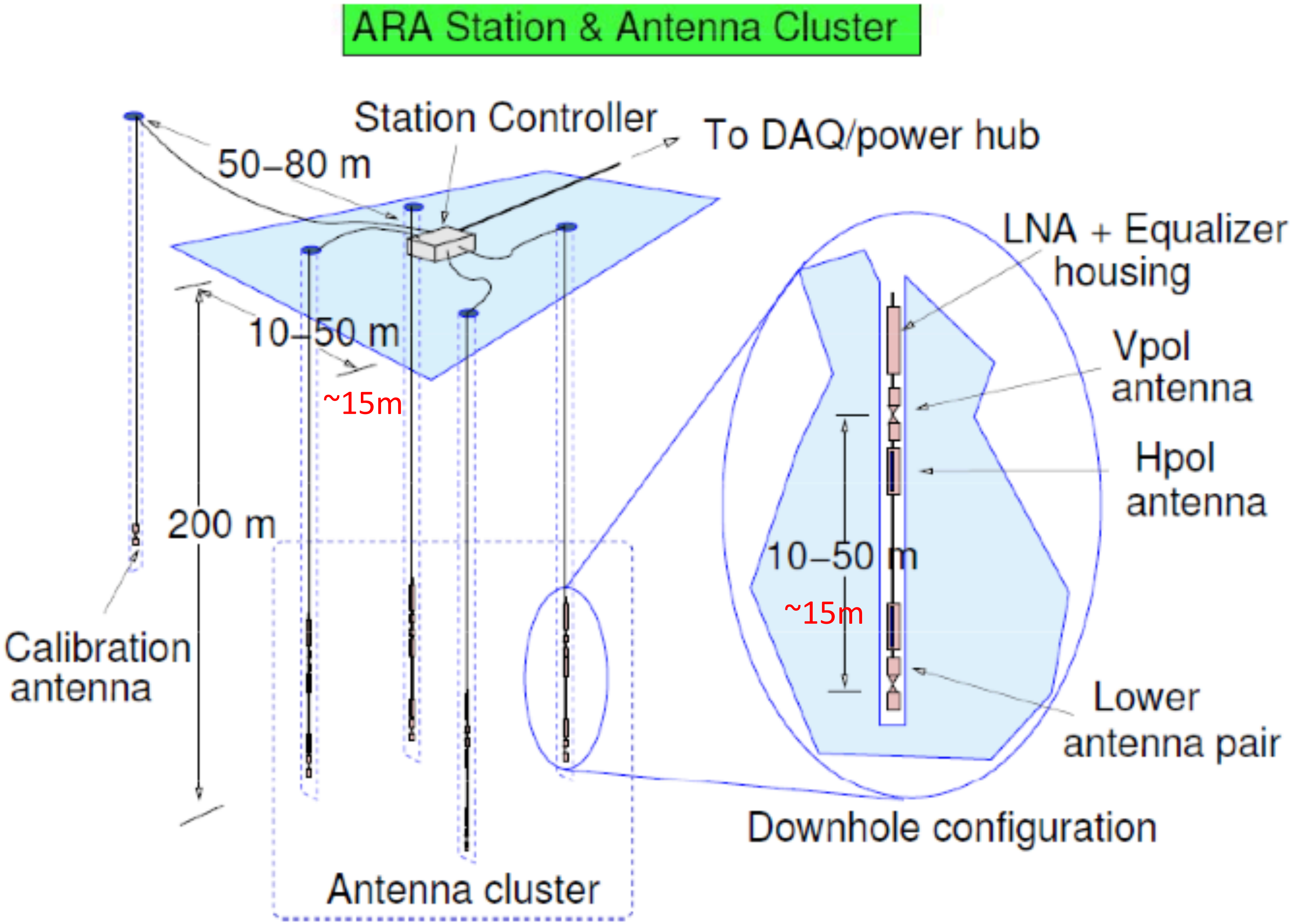
(rather than surface antennas)

- Acceptance: x2
  - Embedded detectors have larger acceptance due to shadowing caused by gradual change of index of refraction in the upper 200m of ice.
  - Gain at 200m depth compared to surface: > x2 event rate

- Background rejection:
  - Transient backgrounds, man made and natural come from surface!
  - Neutrino events generate vertex in the ice and the signal can be uniquely separated by basic event reconstruction.



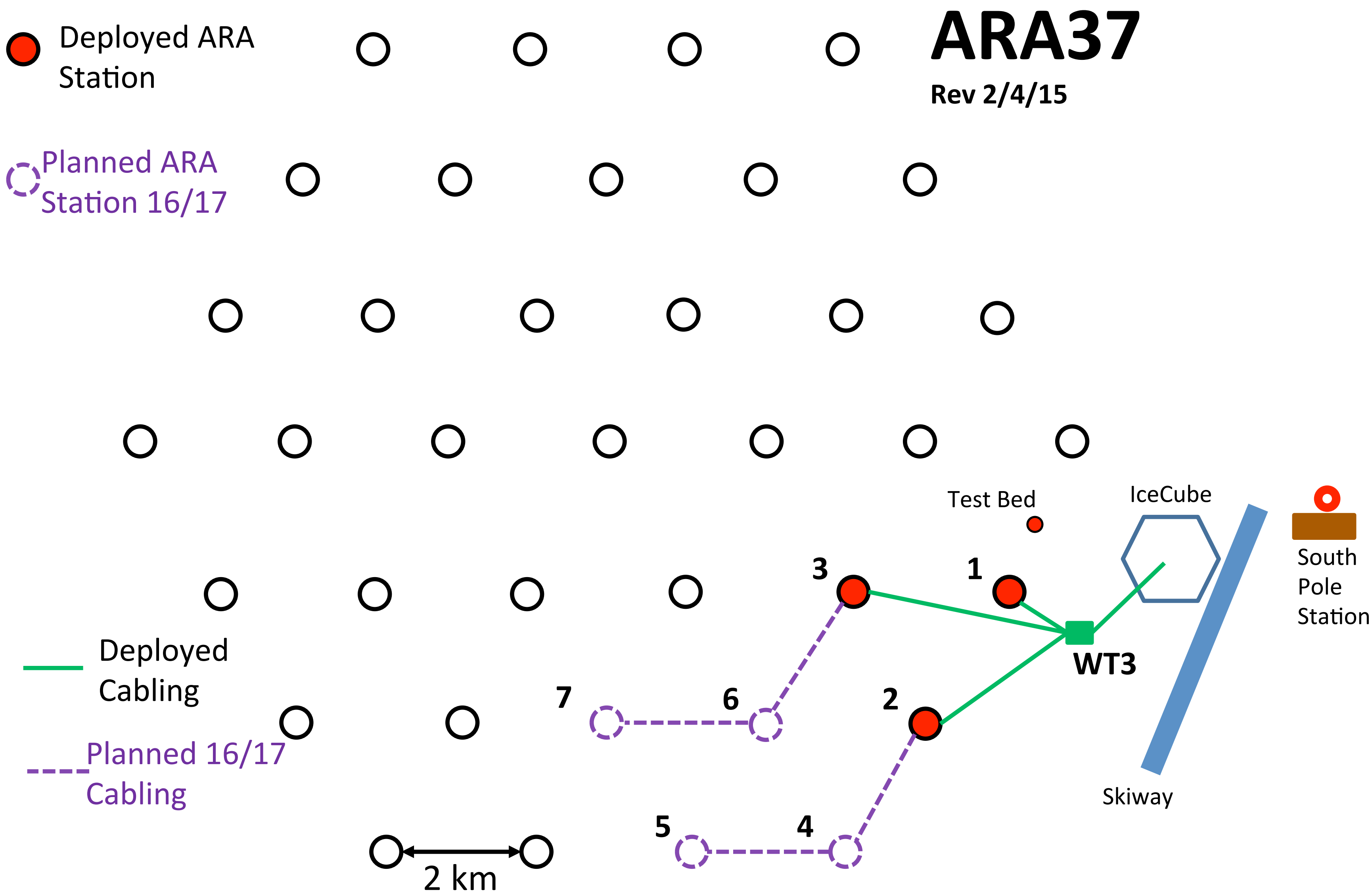



ARA Station & Antenna Cluster
Station Controller
To DAQ/power hub
50–80 m
10–50 m
~15m
200 m
Calibration antenna
Antenna cluster
LNA + Equalizer housing
Vpol antenna
Hpol antenna
10–50 m
~15m
Lower antenna pair
Downhole configuration

Signal Chain

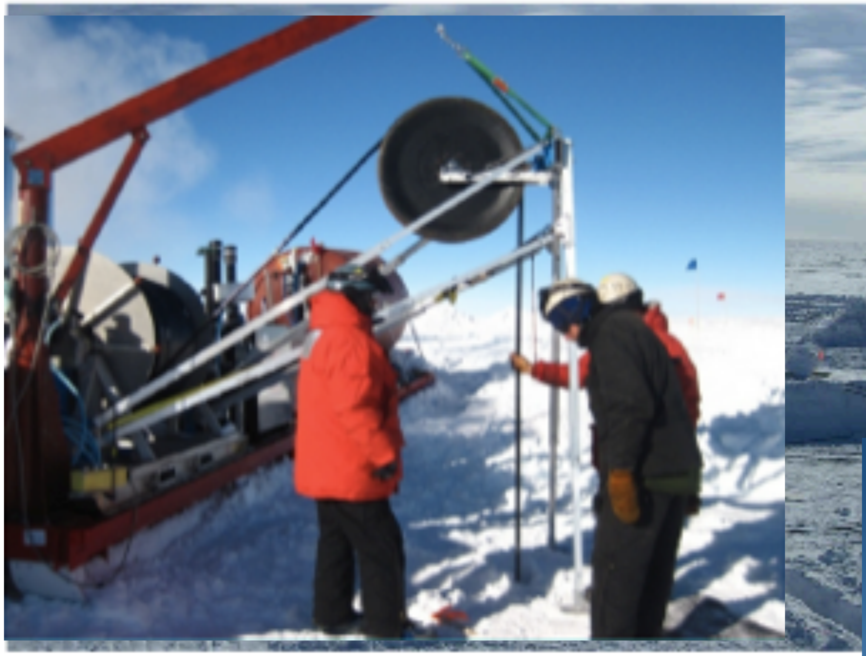
- Physics: Neutrino interacts in the ice, charged particles generate shower, Askaryan radio pulse
- Antennas: Radio pulse wave-front arrives, superimposed on thermal (background) noise
- LNA: Amplify the delicate signal with minimum additional noise, close to the antenna
- RFoF (transmitter & receiver): Transmit signal to the surface without cable distortions, and then return optical to electrical signal
- Trigger: Diode detectors ("square law") followed by combinatorial logic (e.g., 5/16 or in the future something more complex)
- Readout: Analog capacitor storage, triggered readout, digitization, transfer to station computer, fiber to IceCube Lab building, hard drive storage, & satellite to North

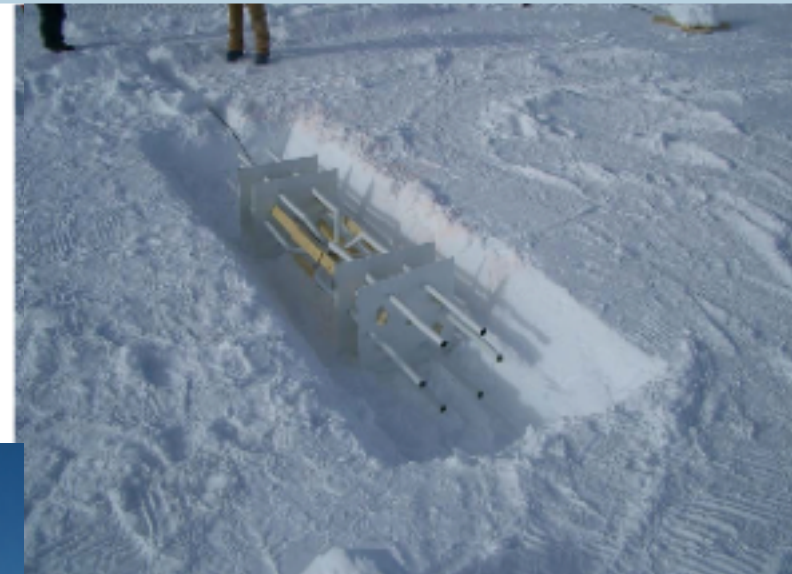
RECENT WORK

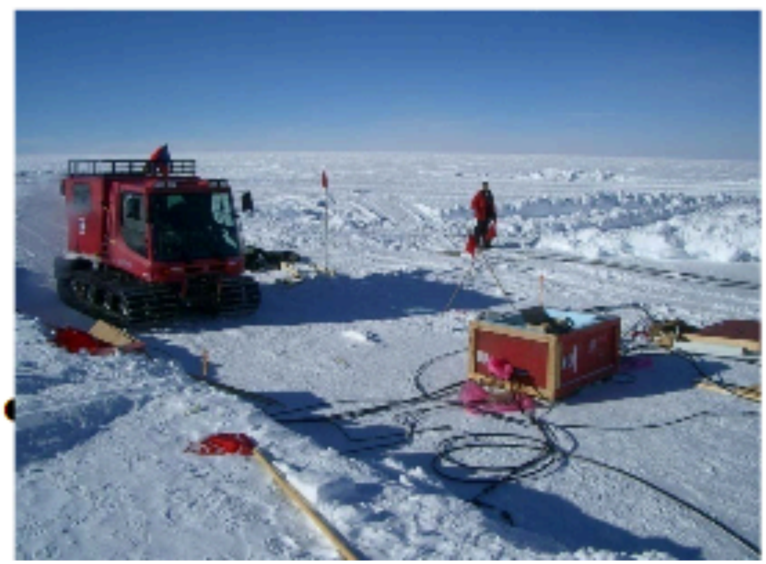


ARA37
Rev 2/4/15
Deployed ARA Station
Planned ARA Station 16/17
Test Bed
IceCube
South Pole Station
3
1
2
6
7
4
5
WT3
Skiway
Deployed Cabling
Planned 16/17 Cabling
2 km

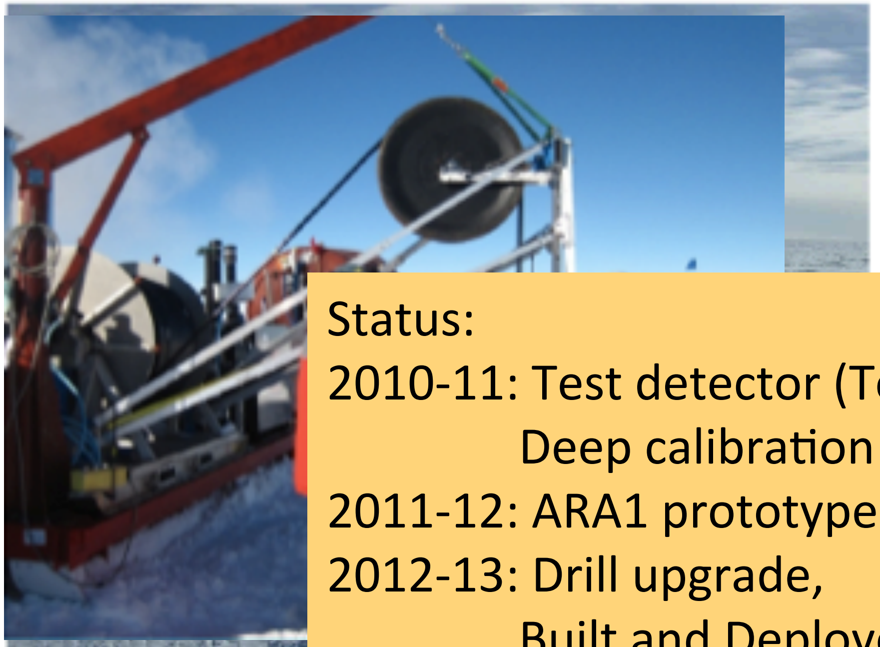
ARA field activities on the ice







ARA field activities on the ice



Status:

2010-11: Test detector (TestBed, shallow) deployed

Deep calibration pulsers deployed with IceCube

2011-12: ARA1 prototype deployed: ~70m due to drill limitations

2012-13: Drill upgrade,

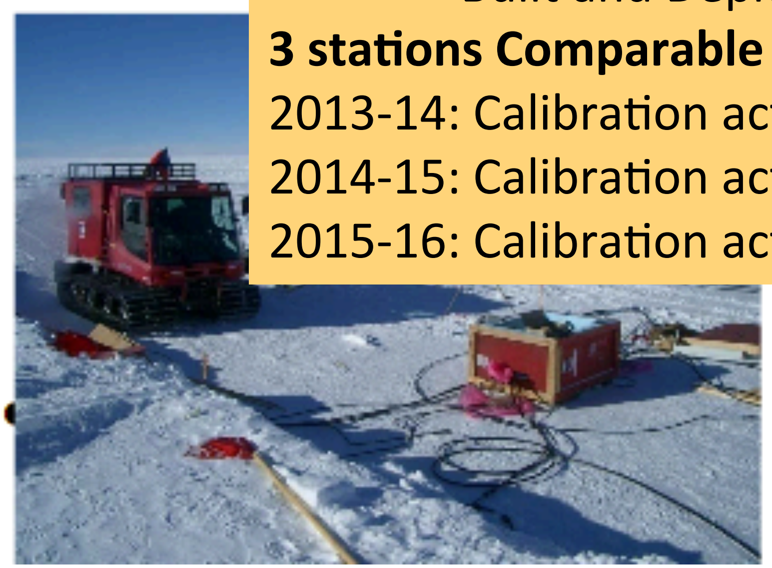
Built and Deployed two more stations, now at 200m depth

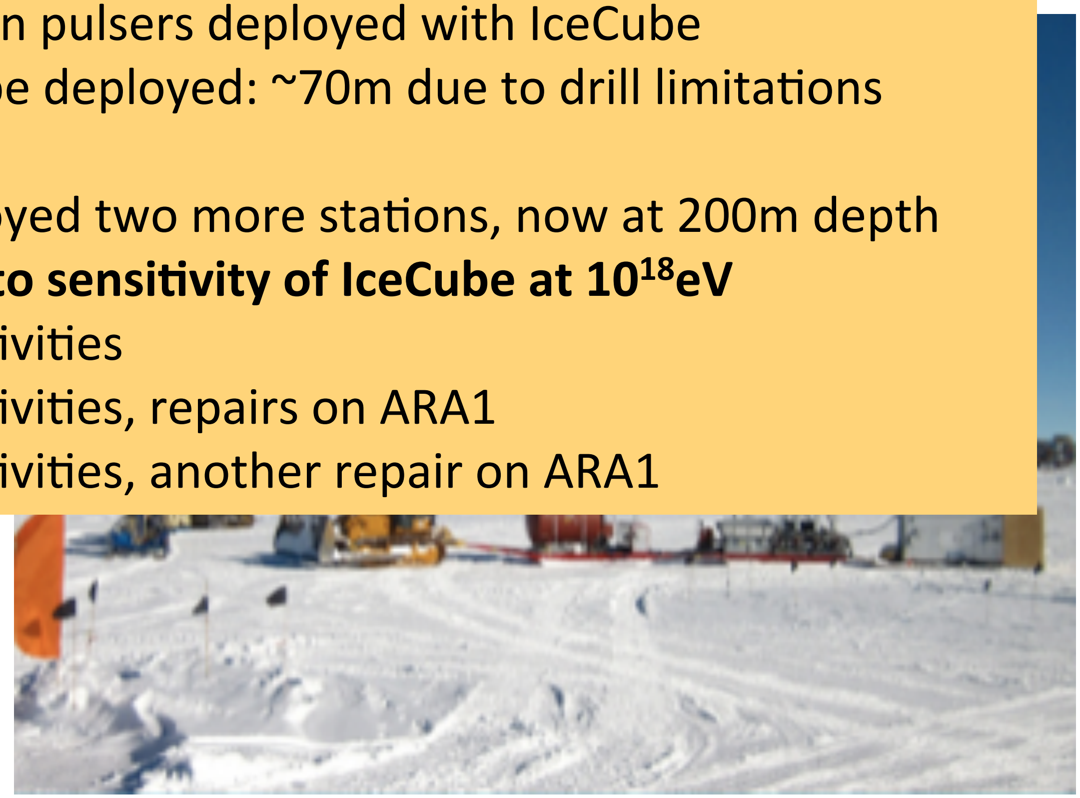
3 stations Comparable to sensitivity of IceCube at 10^{18}eV

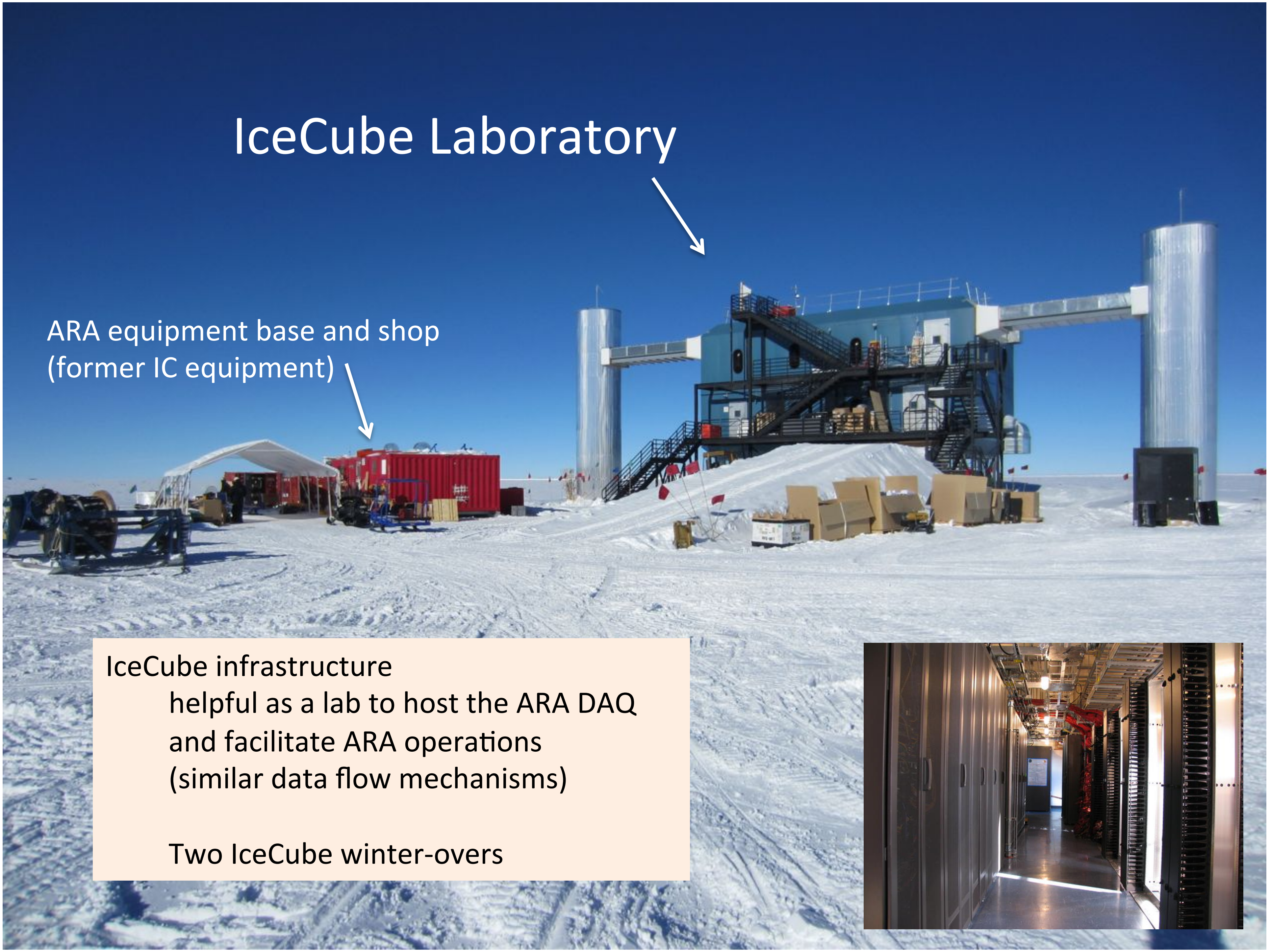
2013-14: Calibration activities

2014-15: Calibration activities, repairs on ARA1

2015-16: Calibration activities, another repair on ARA1







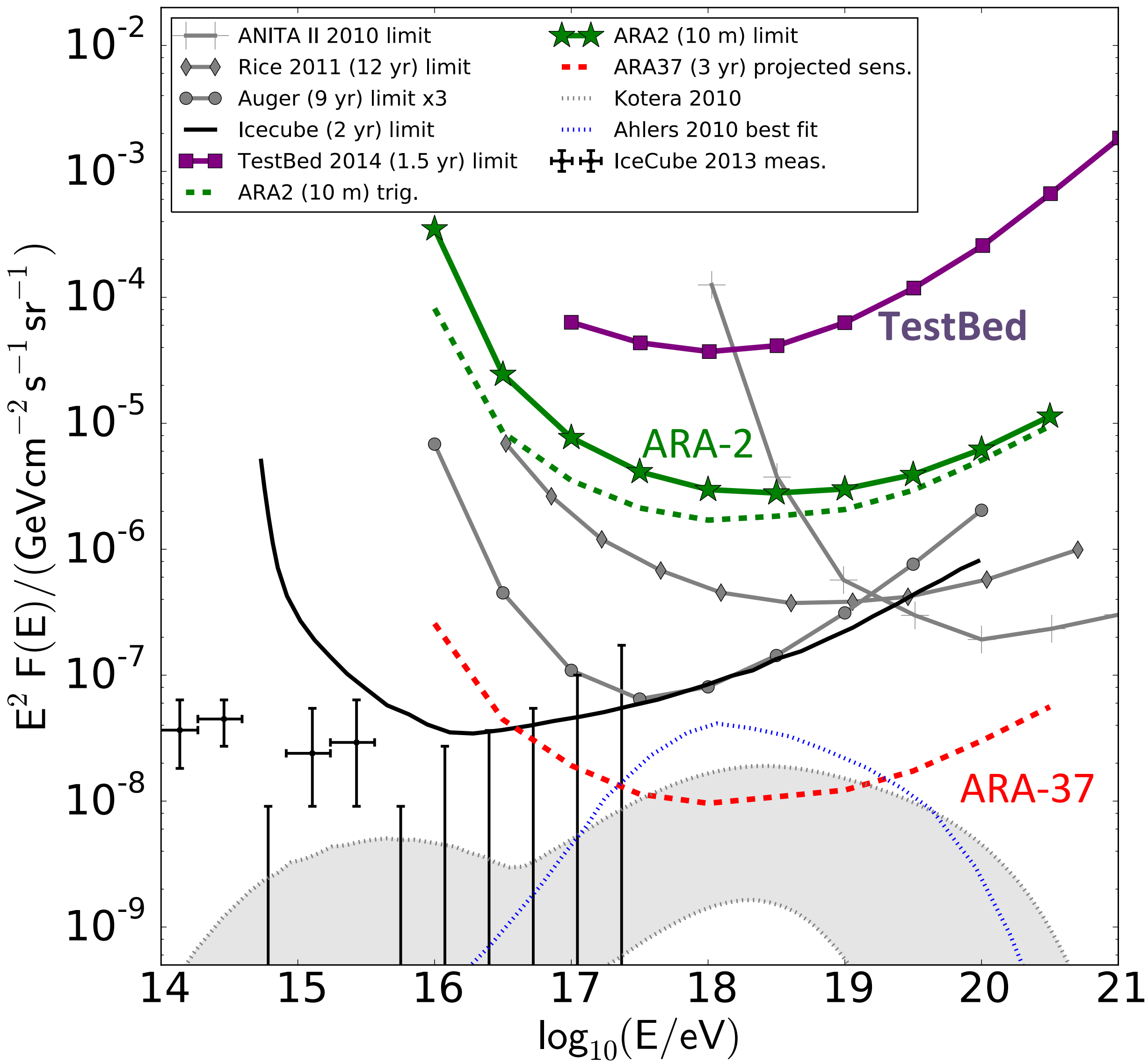
IceCube infrastructure

helpful as a lab to host the ARA DAQ and facilitate ARA operations (similar data flow mechanisms)

Two IceCube winter-overs

First results & summary

- Demonstration of analysis chain
- Good sensitivity above 10^{17} eV
- Relatively low energy threshold
- Many improvements possible to hardware, processing



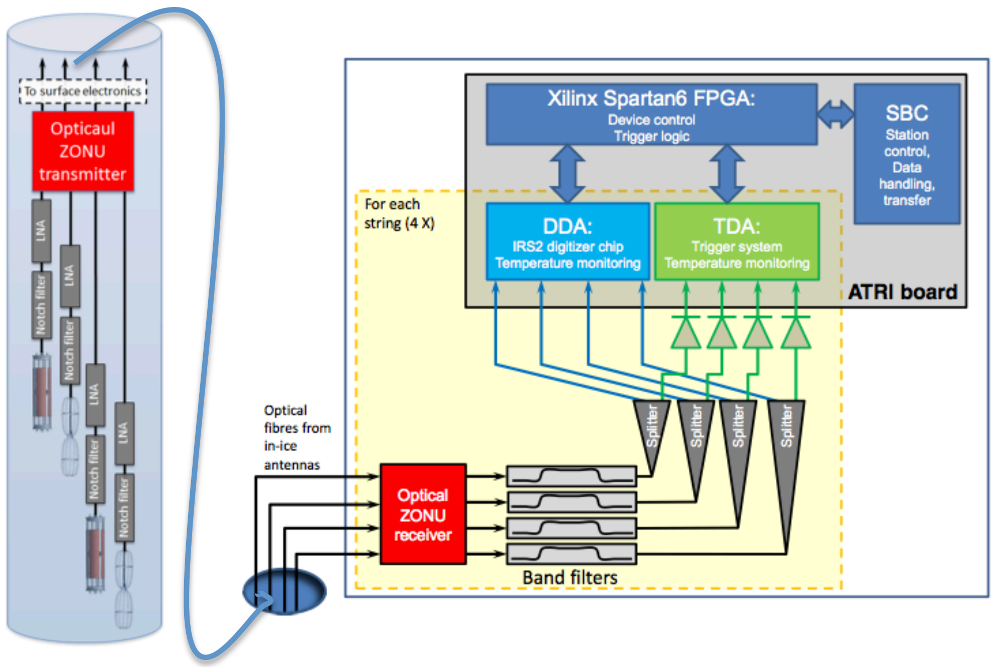
The Future…

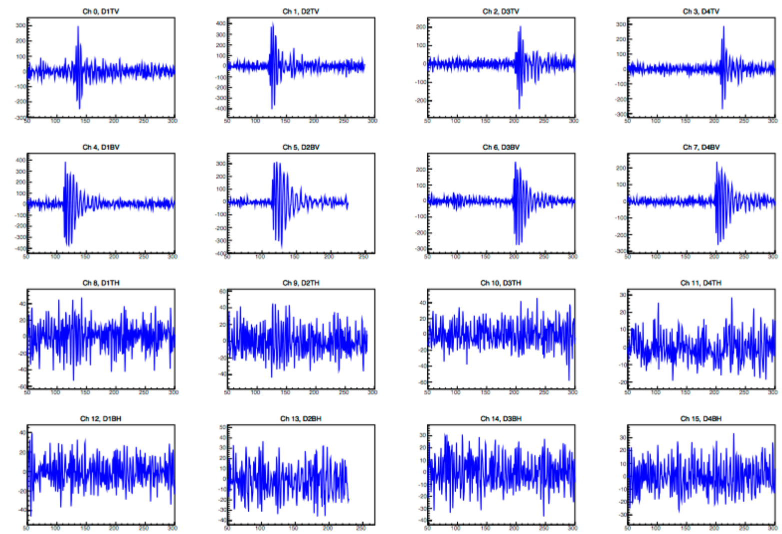
- NSF funding has been slow/difficult
- Three similar, competing projects (ARA, ARIANNA, GNO)
- Looking ahead for a four year deployment push to complete the ARA-37 design
  - Electronics updates
  - Better trigger algorithms
  - Data reduction at on-line & off-line
- Farther out, even larger detector in concert with the rest of Generation 2 IceCube

BACKUP SLIDES

ARA DAQ

- In-ice:
  - Notch filter at 450 MHz (anthropogenic noise)
  - Low noise amplifiers
  - Optical Zonu RF over fiber
- Surface:
  - 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





Vpol calibration pulser event in ARA03

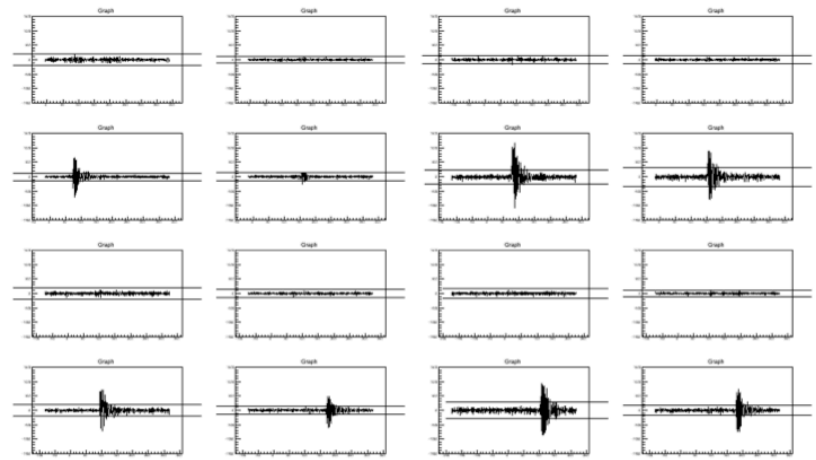
- Trigger rates:
  - ~ 5 Hz RF events
  - 1 Hz Calibration pulser
  - 0.5 Hz Forced software trigger

K. Mase @ ICRC: Calibration of the ARA front end, 1/8, 1136

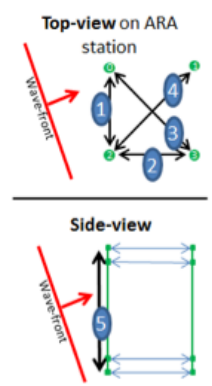
From the South to the North

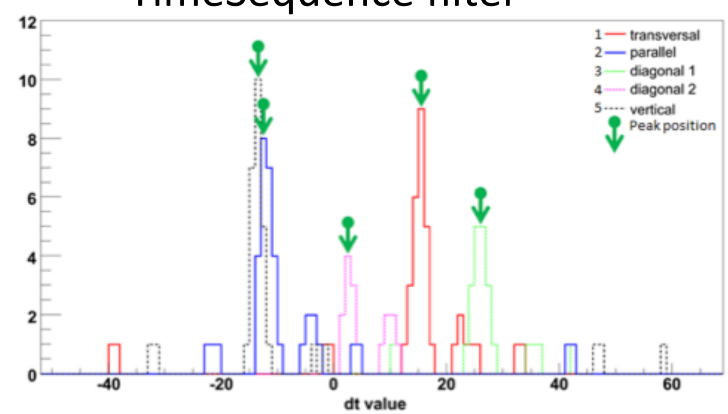
- Filtering at Pole to reduce data volume
- ~80 GB/day/station -> 250 MB over satellite
- Remainder is picked up by hand once a year
- Currently 3 filters:
  - Nchannel filter: calculate threshold from recorded waveforms, allow events that exceed threshold
  - TimeSequence: calculate compatibility of hit timing with plane wave
  - Minbias: random selection of 1 event per 200

Nchannel filter



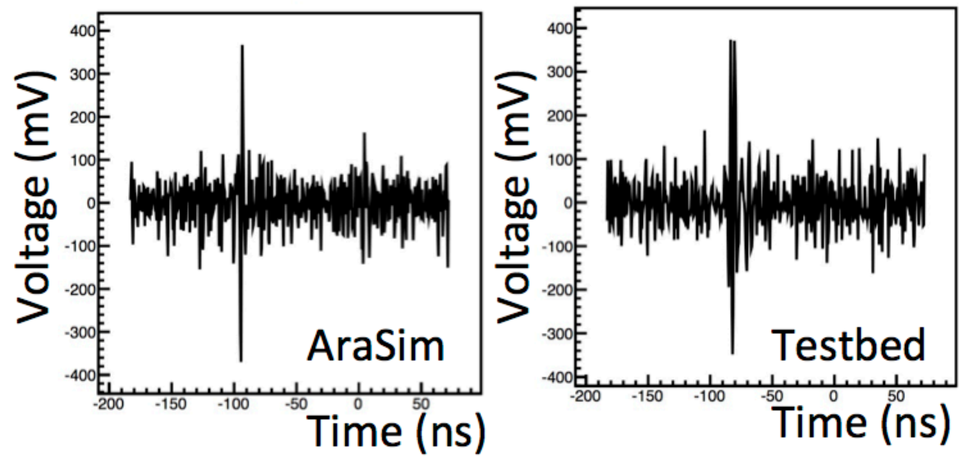
TimeSequence filter

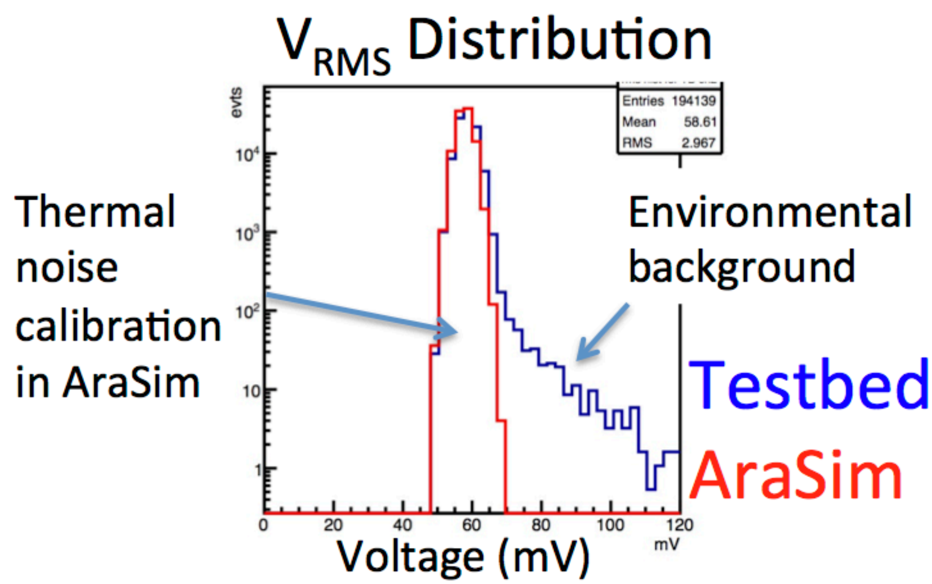




Simulation: AraSim

- Official collaboration Monte Carlo simulation package for assessing sensitivity and general use
- Simulated events written in data format for direct comparison
- Simulates full trigger and signal chain for neutrino events detected by ARA stations
- Takes into account:
  - Index of refraction model
  - Calibrated noise simulation
  - Antenna and electronics responses
  - Trigger model





First Analyses: ARA 2/3

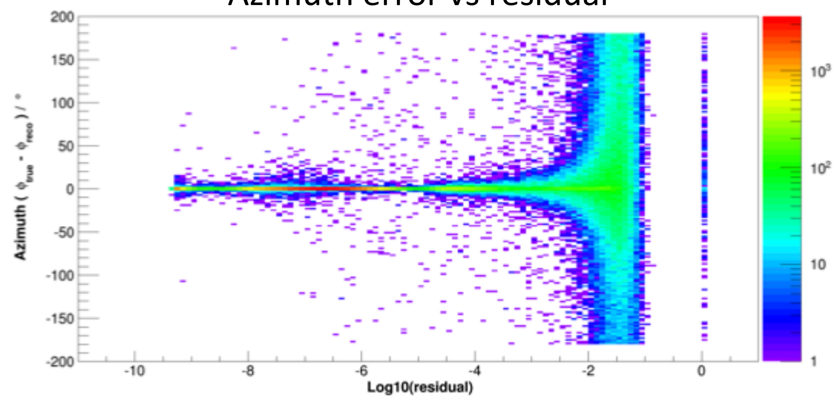
- Matrix based event reconstruction (Bancroft's Method)
  - System of equations based on arrival time differences from correlation
  - Causality for 1 antenna:
    $c^2\left(t_v - t_i\right)^2 = \left(x_v - x_i\right)^2 + \left(y_v - y_i\right)^2 + \left(z_v - z_i\right)^2$
  - Difference for 2 antennas:

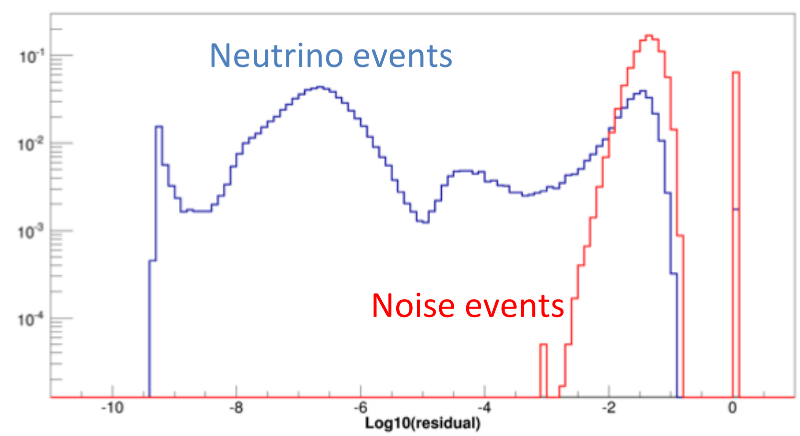
$$x_v \cdot 2dx_{ij} + y_v \cdot 2dy_{ij} + z_v \cdot 2dz_{ij} - t_v \cdot 2c^2 dt_{ij} = r_i^2 - r_j^2 - c^2\left(dt_{i,ref}^2 - dt_{j,ref}^2\right)$$

  - Write as vectors: A*v = b, v = (x_v,y_v, z_v, t_v)
  - Linear algebra: scan over t_v, minimize residual

$$\left\| \frac{b}{|b|} - \frac{A*v}{|A*v|} \right\|^2$$

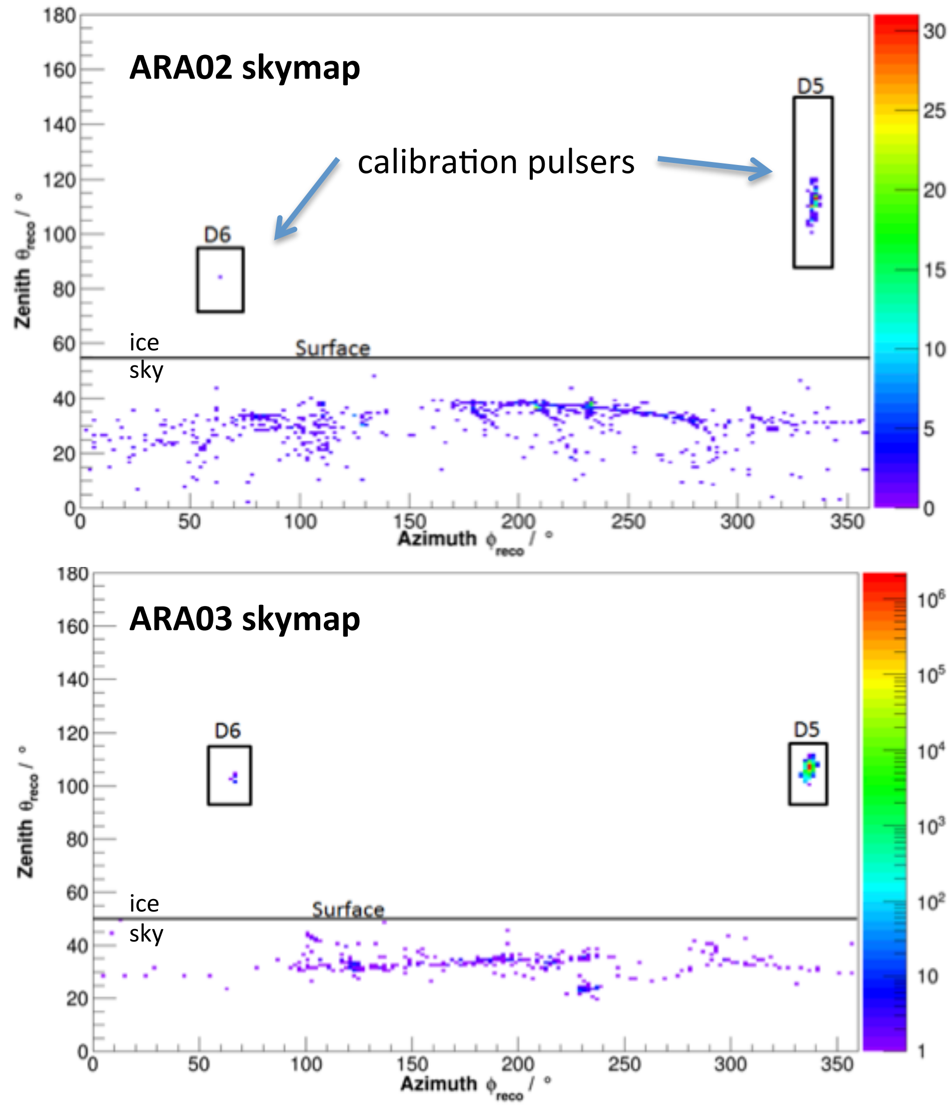
Azimuth error vs residual





First Analyses: ARA 2/3

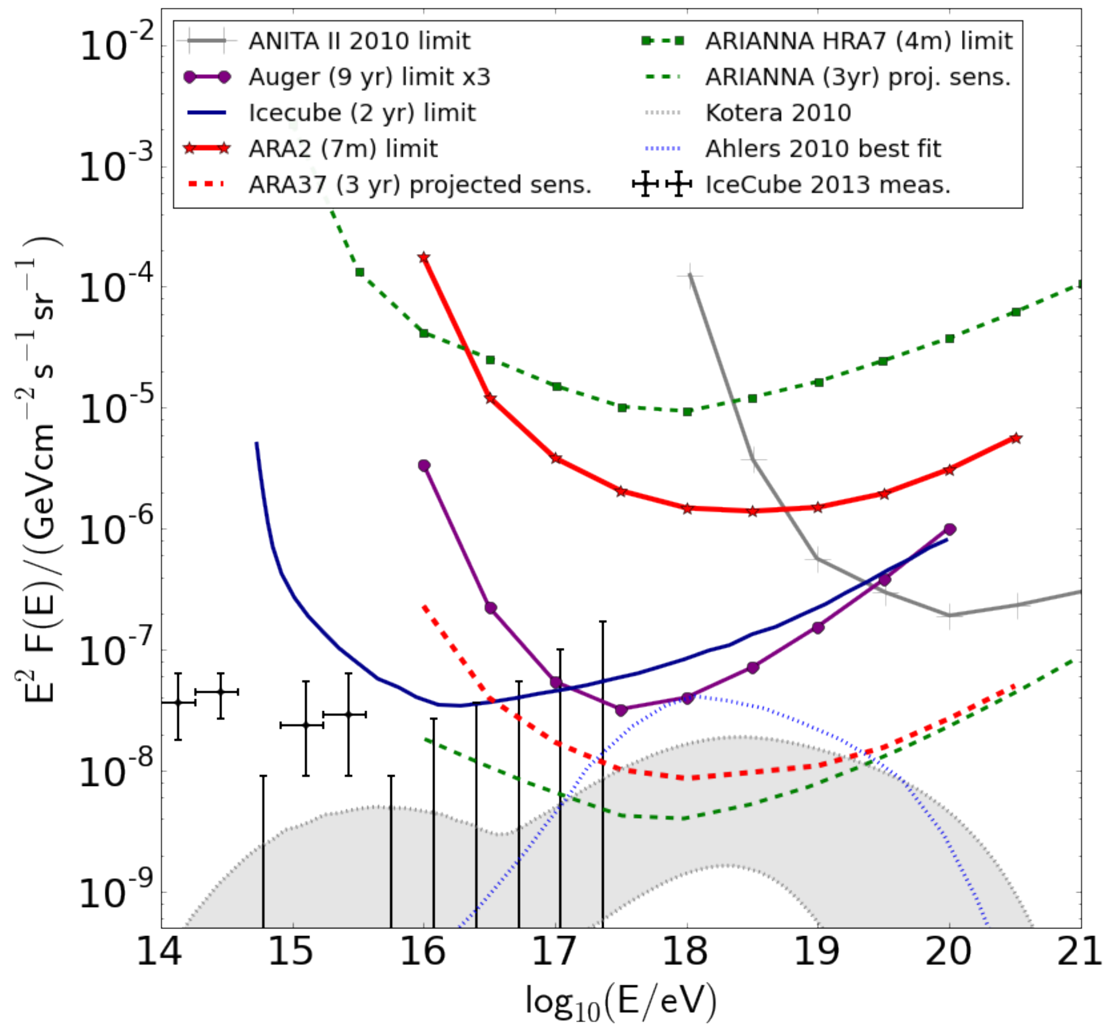
- 2 stations, 10 months of data (2013)
- Cut on:
  - Reconstruction quality (residual)
  - TimeSequence algorithm
- No neutrino candidates, set upper limit with systematic errors
- Expected (total):
  - 0.1 neutrinos,
  - 0.02 background
- Further information:
  - ICRC proceedings: 1115
  - **arXiv:1507.08991**



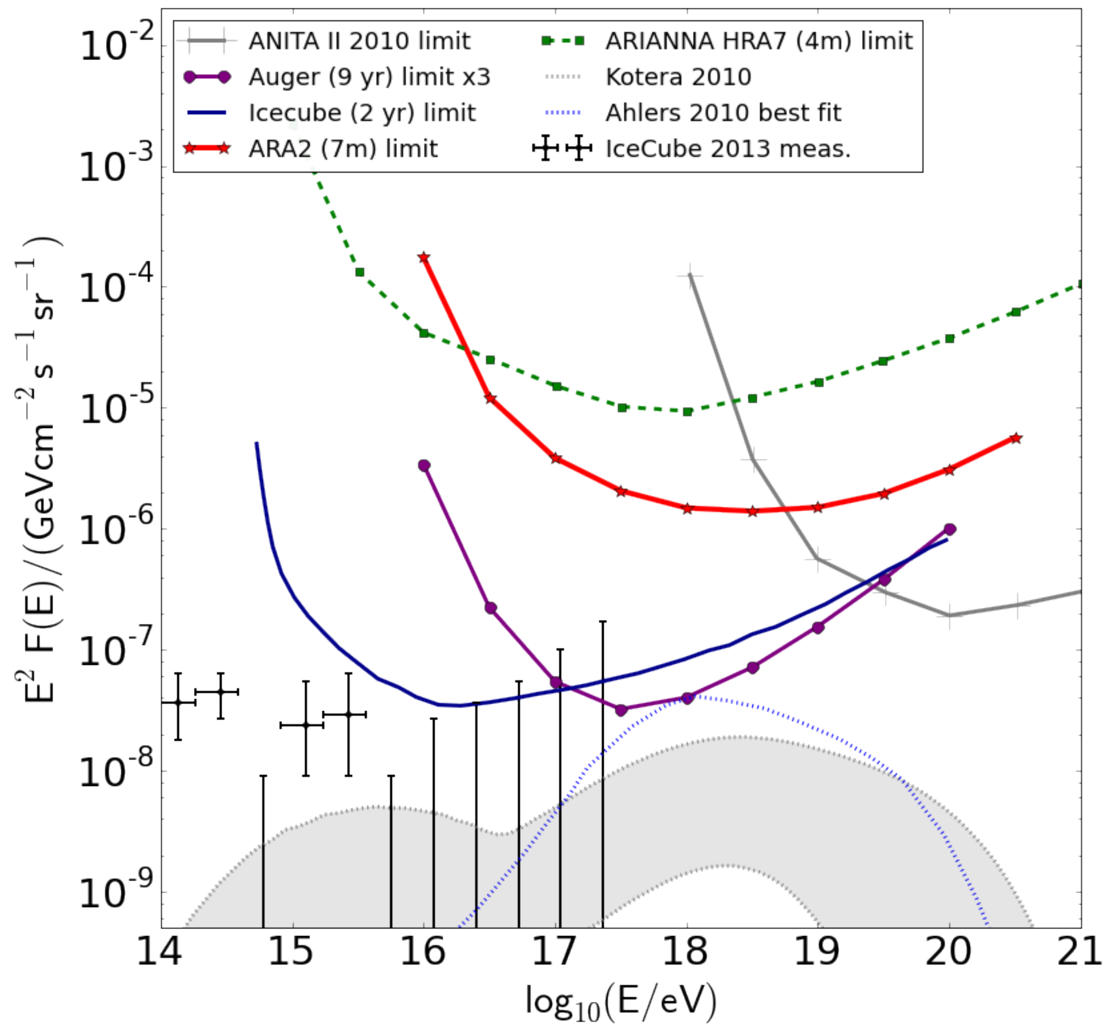
The final limit compared to ARIANNA limits and sensitivity

What is our sensitivity:

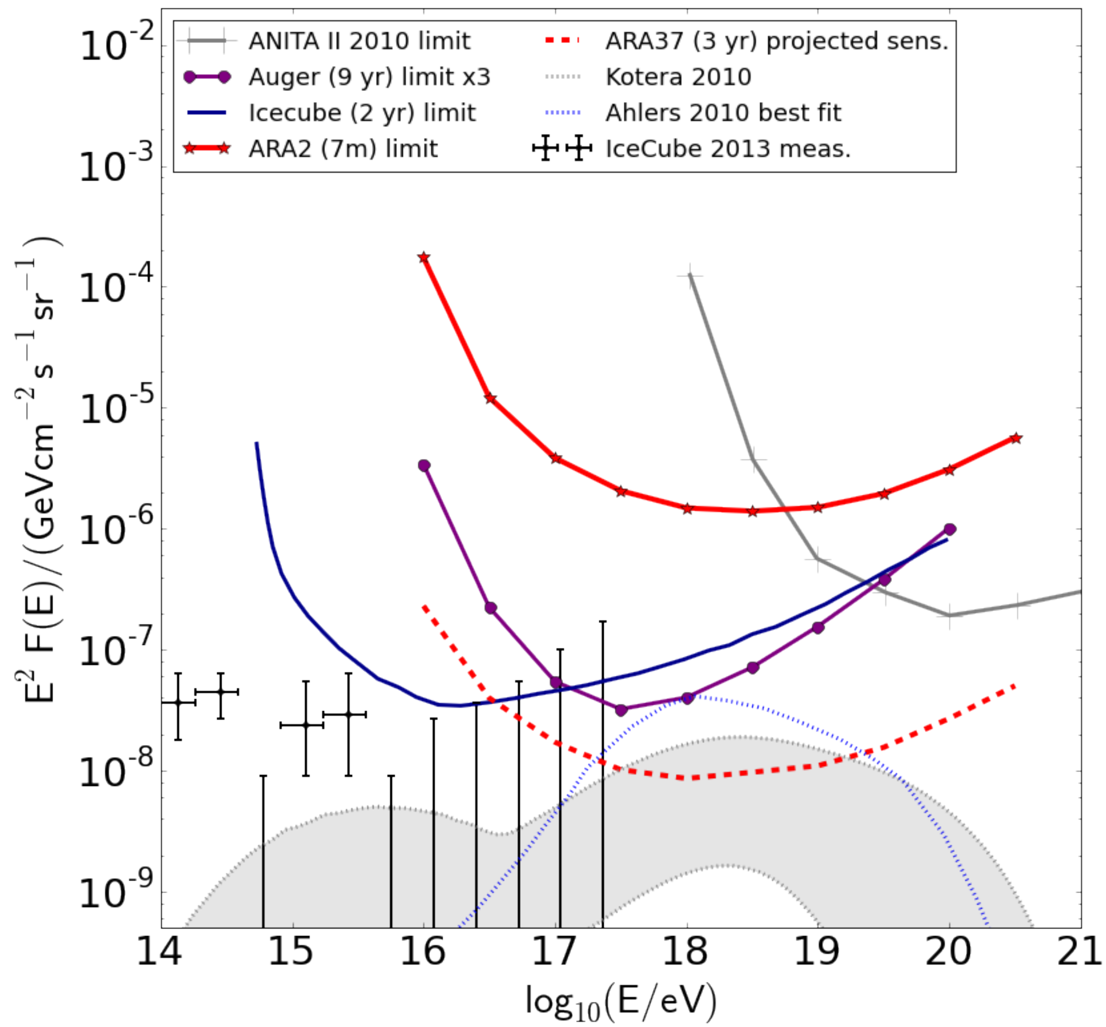
- Projected from the ARA2 trigger level of 2013: multiplied by (37/2) → for 37 stations 3.0*(365/224): 3 years of 100% lifetime as opposed to 224 days collected in 10 months. (actually 220 for A3 and 228 A2)
- Included loss from semi-optimized trigger settings <10%
- Loss due to coincidences is partly included: Coincidences between 2 stations
- **This is trigger level scaling!** Analysis efficiency is **NOT** accounted for



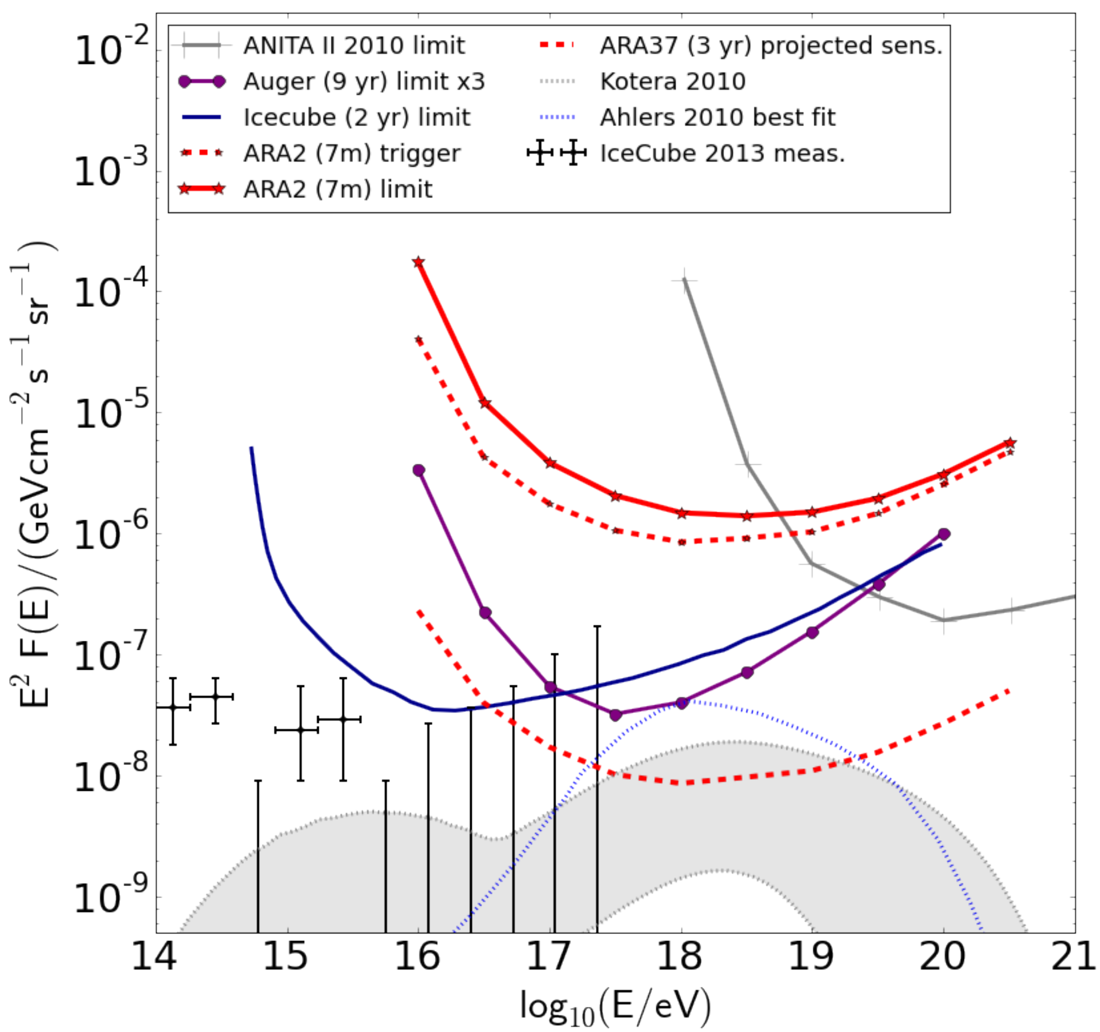
The final limit compared to ARIANNA limit



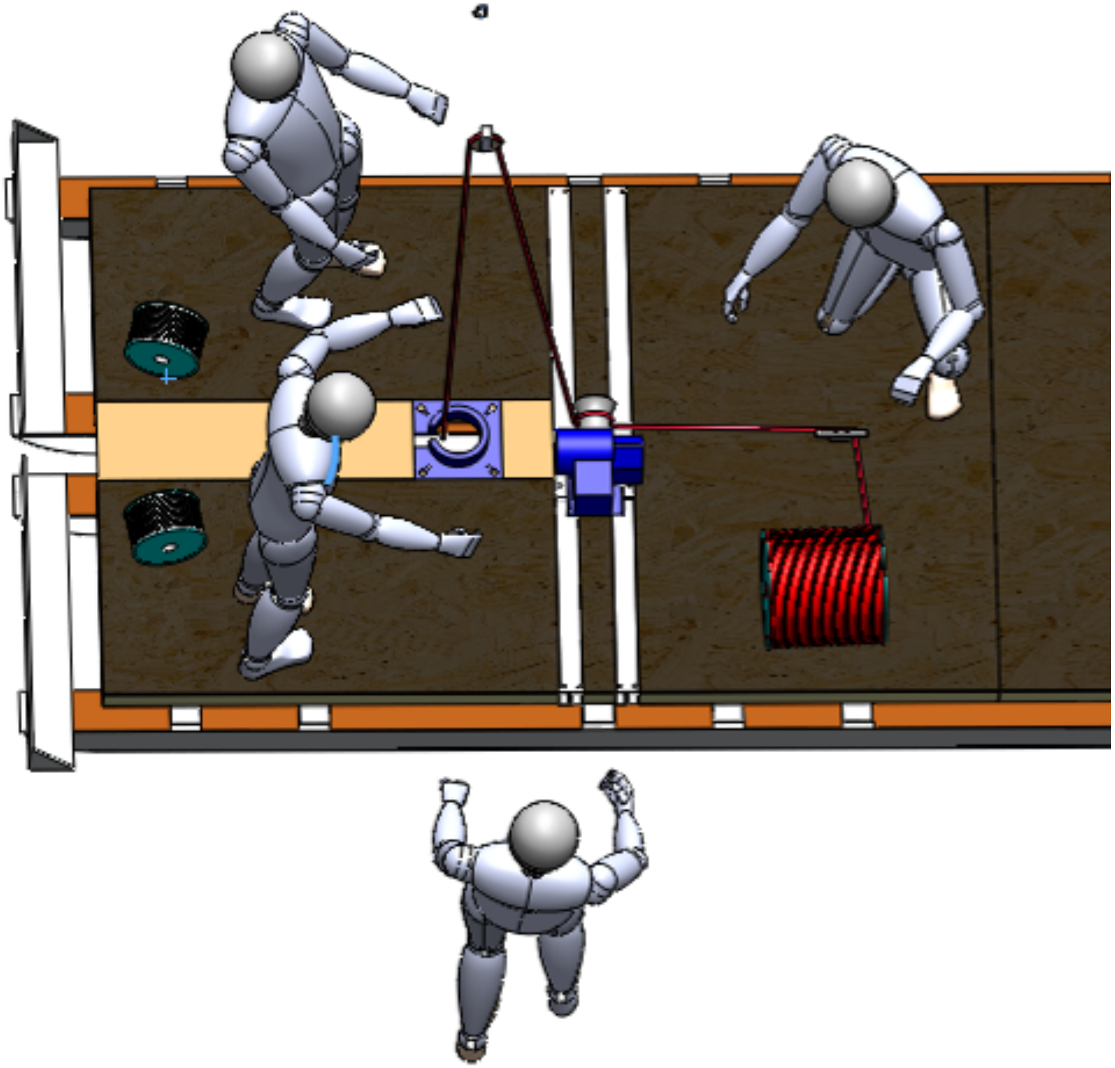
The final limit and sensitivity (ARA only)

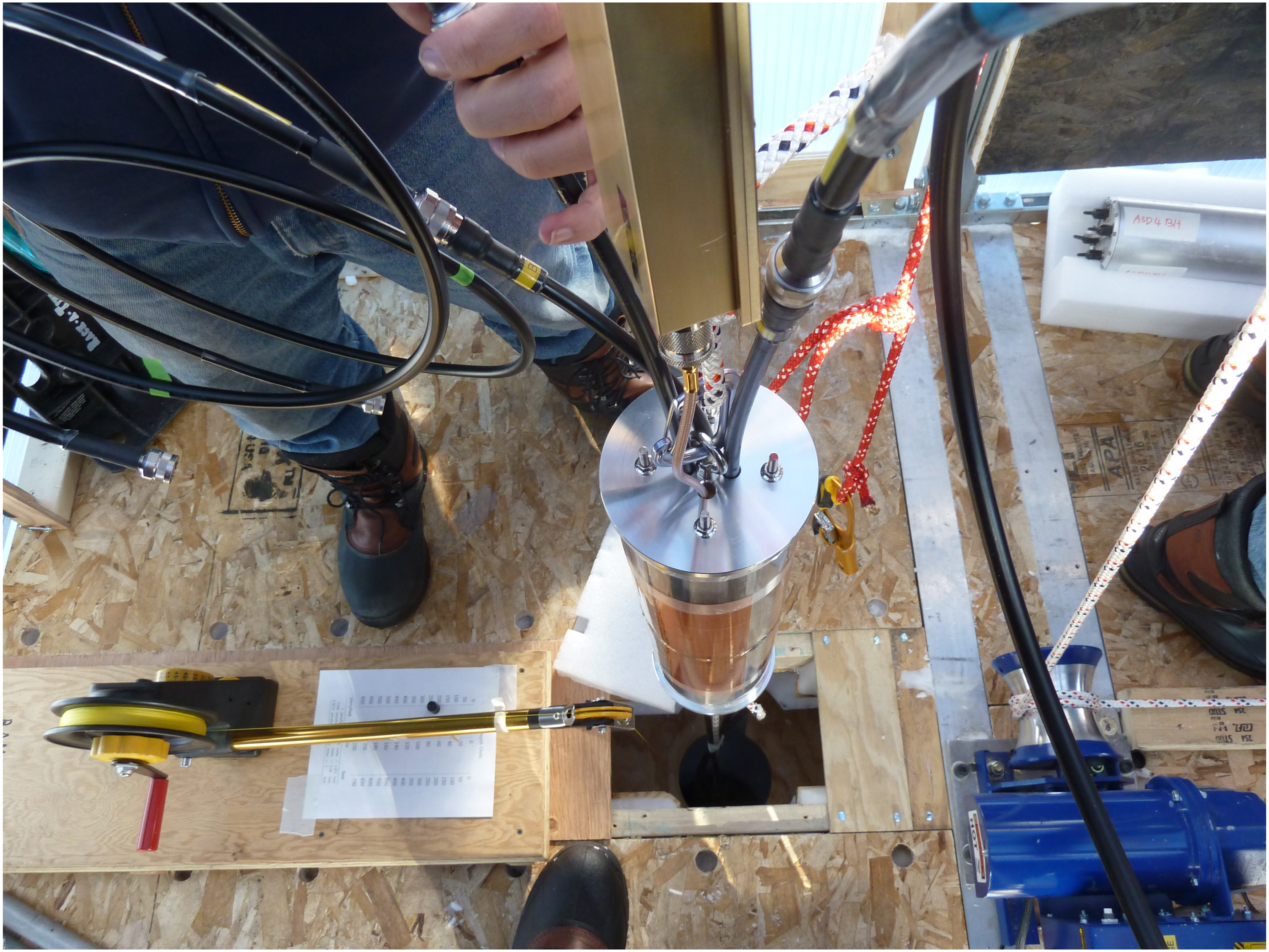


The final limit with the trigger level (ARA only)



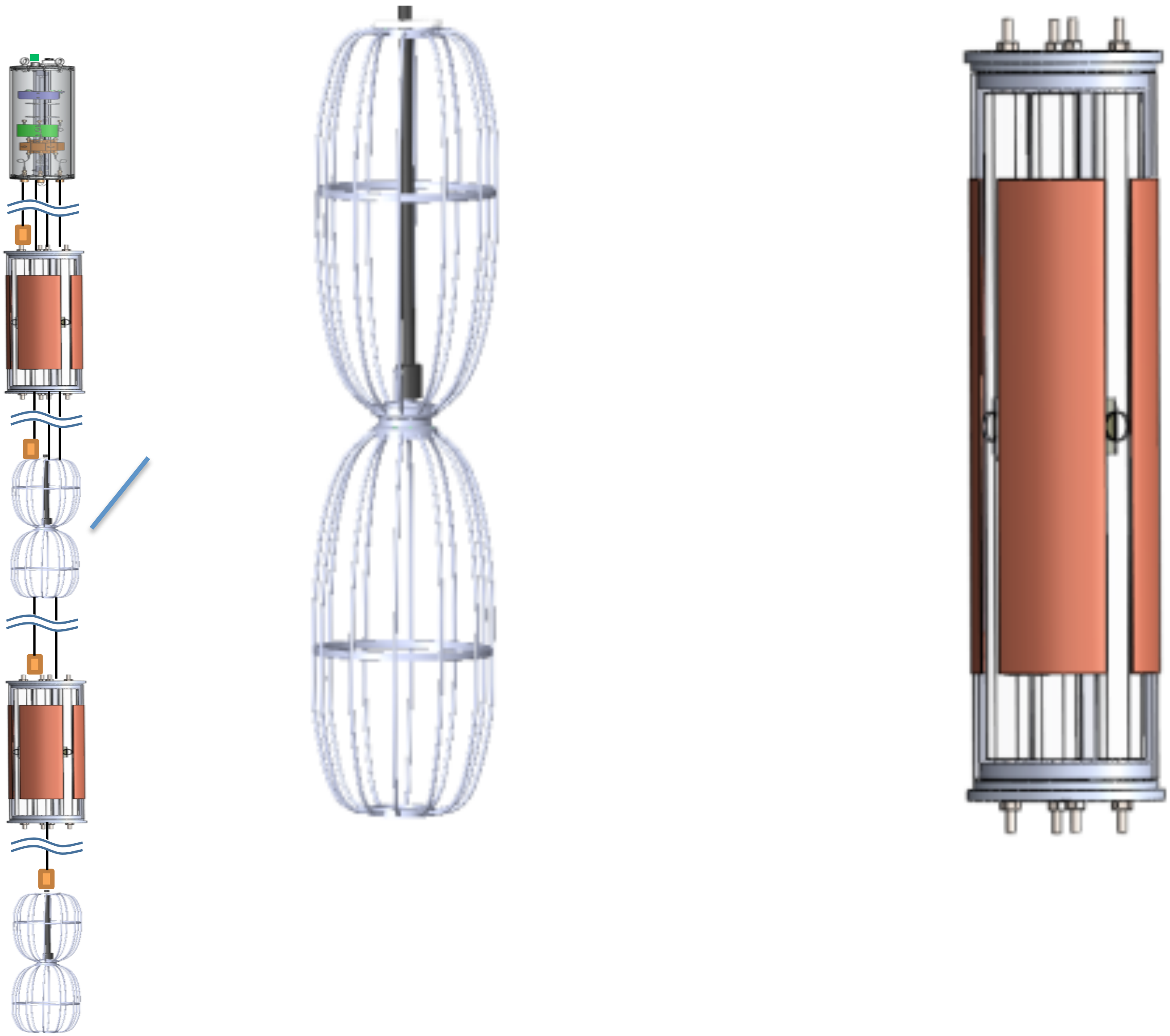
Deployment setup




A3D4 BH

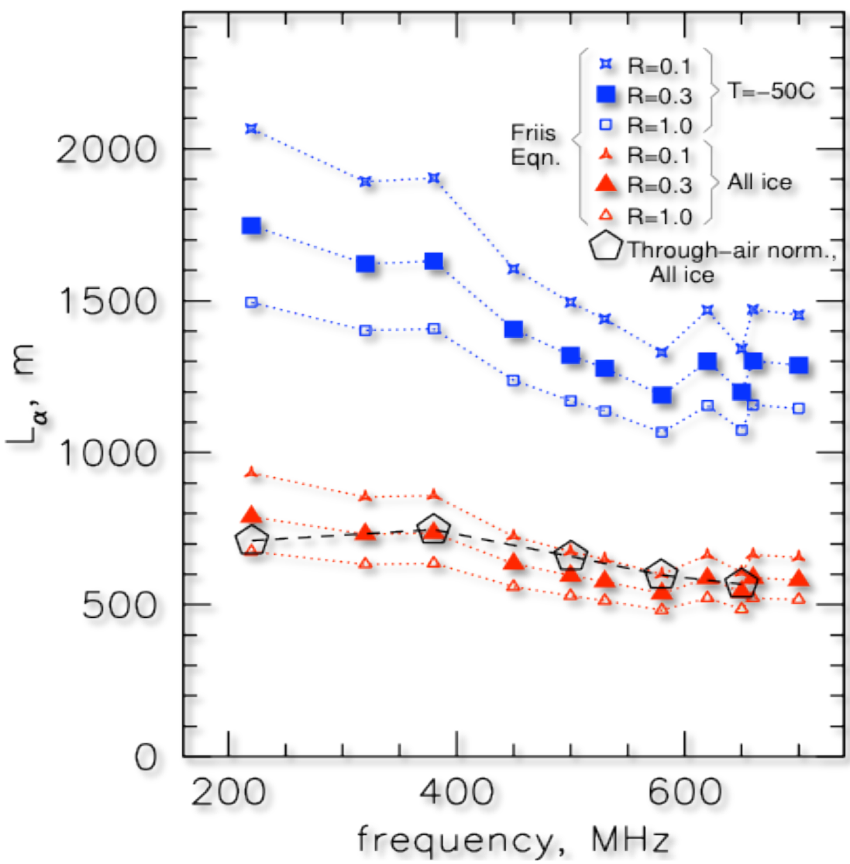
Cutting main trench

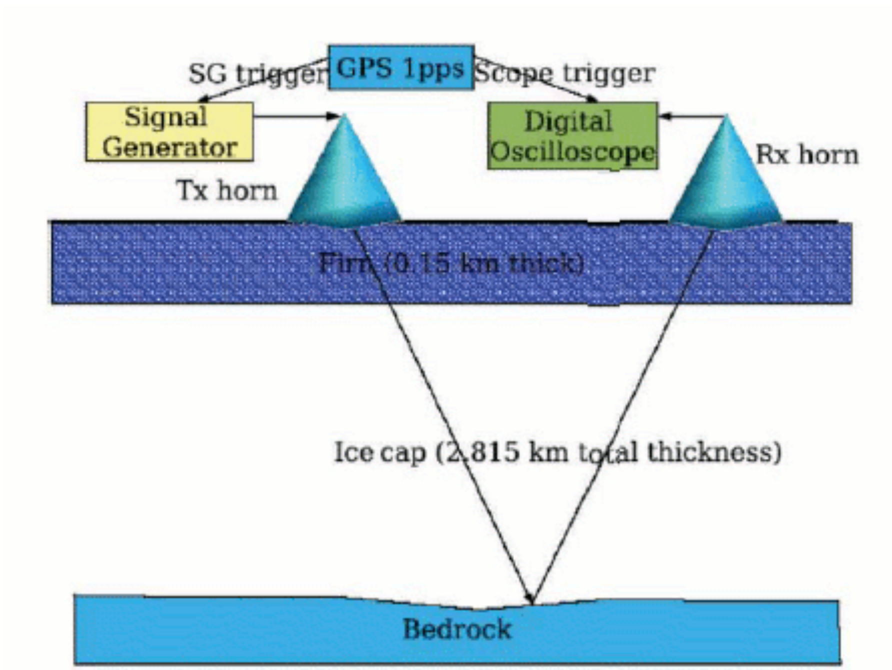
Hole qualifier



Ice Attenuation Length

- Most radio transparent material on Earth!
- Depends on ice temperature. Colder ice at the top.
- Reflection Studies (2004) (Down to bedrock, 200-700MHz): "normalize" average attenuation according to temperature profile.





Besson et al. *J.Glaciology*, 51,173,231,2005