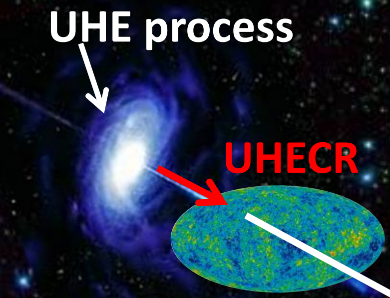
First results from two deep Askaryan Radio Array stations

08/05/2016

Thomas Meures

Neutrinos from the GZK mechanism

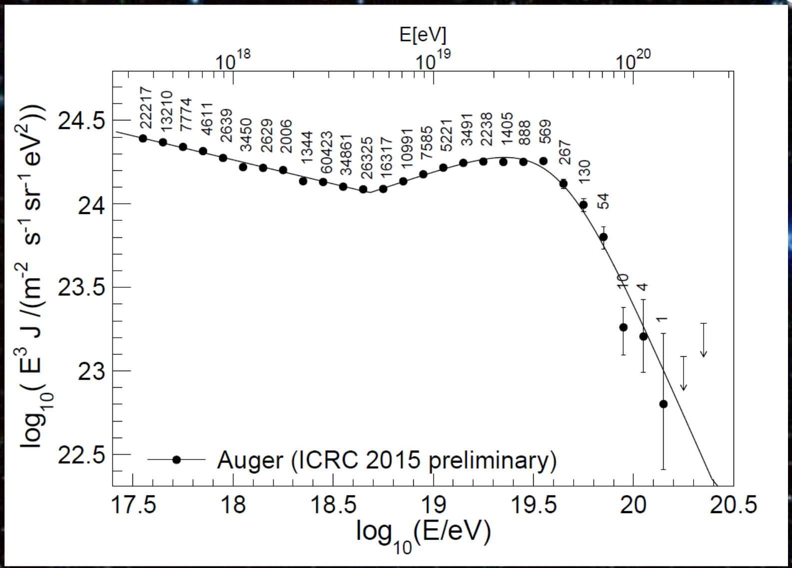


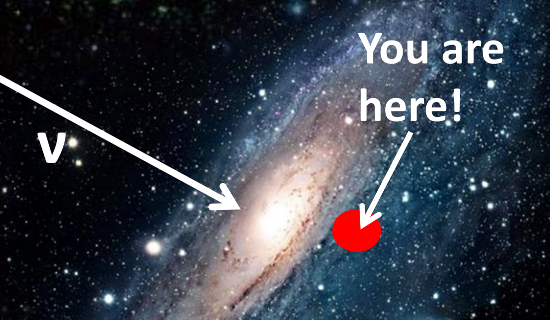
GZK effect:
Cosmic ray interaction with CMB
→ Resonant at ~10^19.5eV
→ Cosmic rays don't reach us
→ Neutrinos are produced

Neutrinos carry exclusive information about UHECRs:

- Composition
- Source distribution
- Energy spectrum

The measured Cosmic ray flux





Strong evidence for GZK-neutrinos
But: Expect <1 ν / km^3 / yr

UHE Neutrino detection via the Askaryan effect

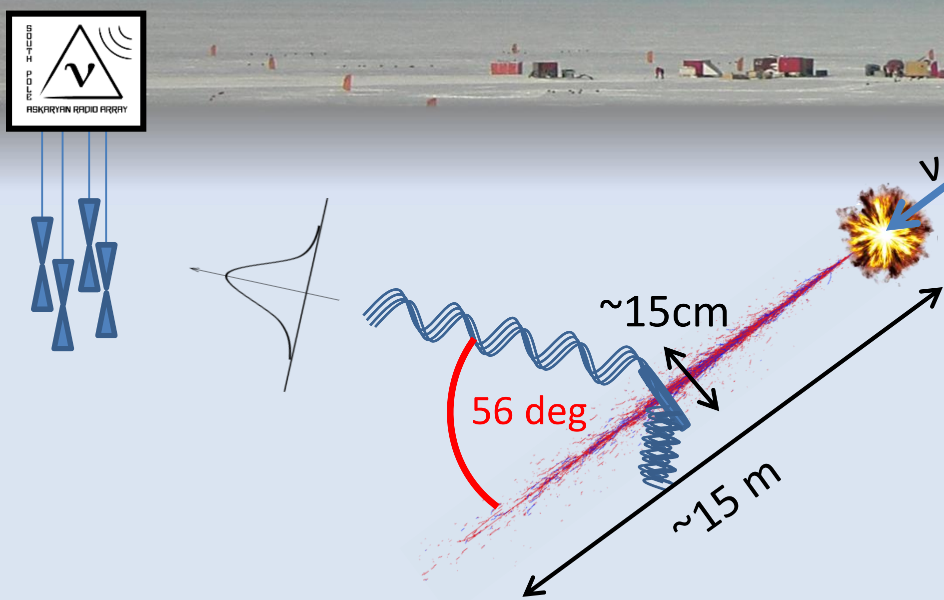
The Askaryan effect:

An excess negative charge (~20%) built up in neutrino induced cascades through:

- **Compton scattering**
- **Other ionizing effects**

→ Moving current, emits electromagnetic radiation

→ Coherent for radio wavelength



The advantages of radio waves:

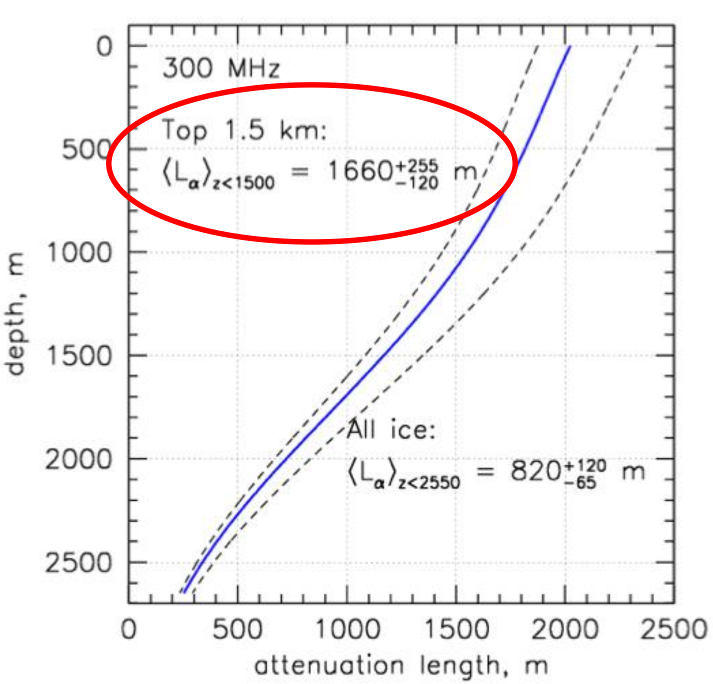
- visible within ~1 km in ice

→ Observe big detector volume with few sensors

→ **Very cost efficient**

→ **Effect has been verified in beam tests:** arXiv:hep-ex/0611008

Detector site

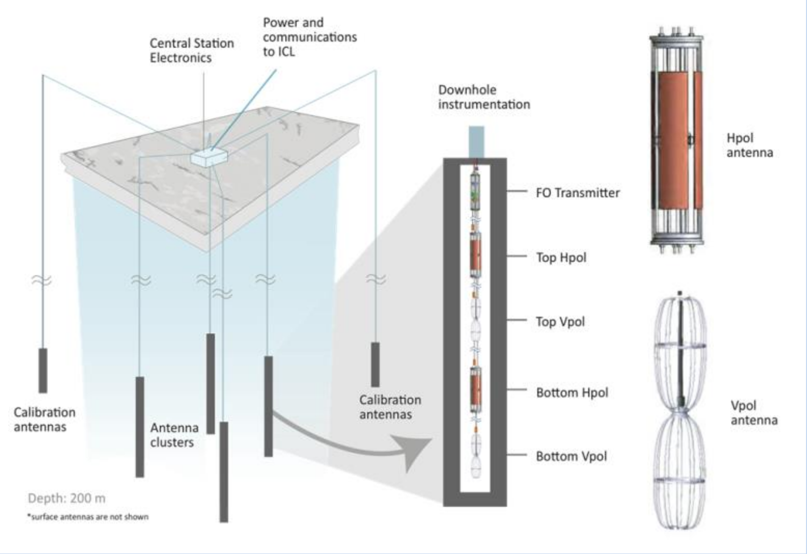


South Pole:

- Ice thickness: 3 km, area: O(1000km^2)
- Radio-quiet zone
- Cold ice → good for attenuation length
- Available science infrastructure

The Askaryan Radio Array (ARA)

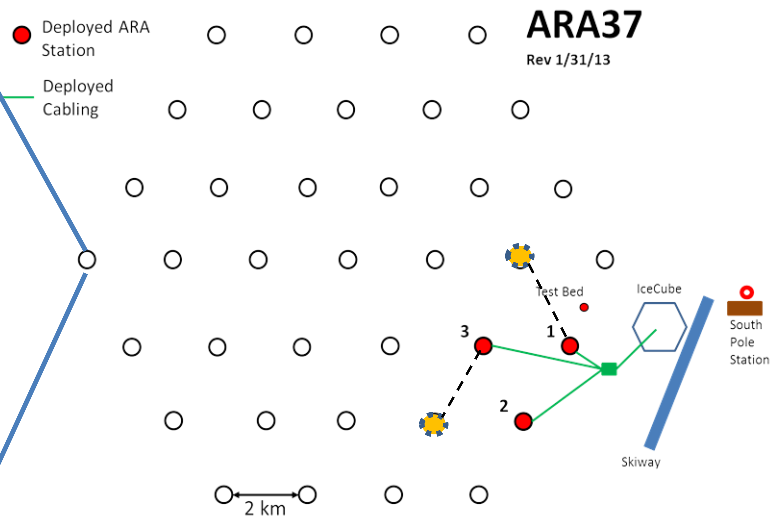
- 37 antenna stations planned (7-8M$)
- spaced by 2 km
  → **Maximizing effective volume by avoiding overlap**
- 180m Depth to avoid **ray bending effects**



One station:

- **Measurement system:**
  - 4 holes, 20 m spacing
  - Deployed at depth of 180 m
  - 16 antennas, 150 MHz – 850 MHz
    (8 horizontally polarized., 8 vertically pol.)
- **Calibration system:** 4 pulsing antennas

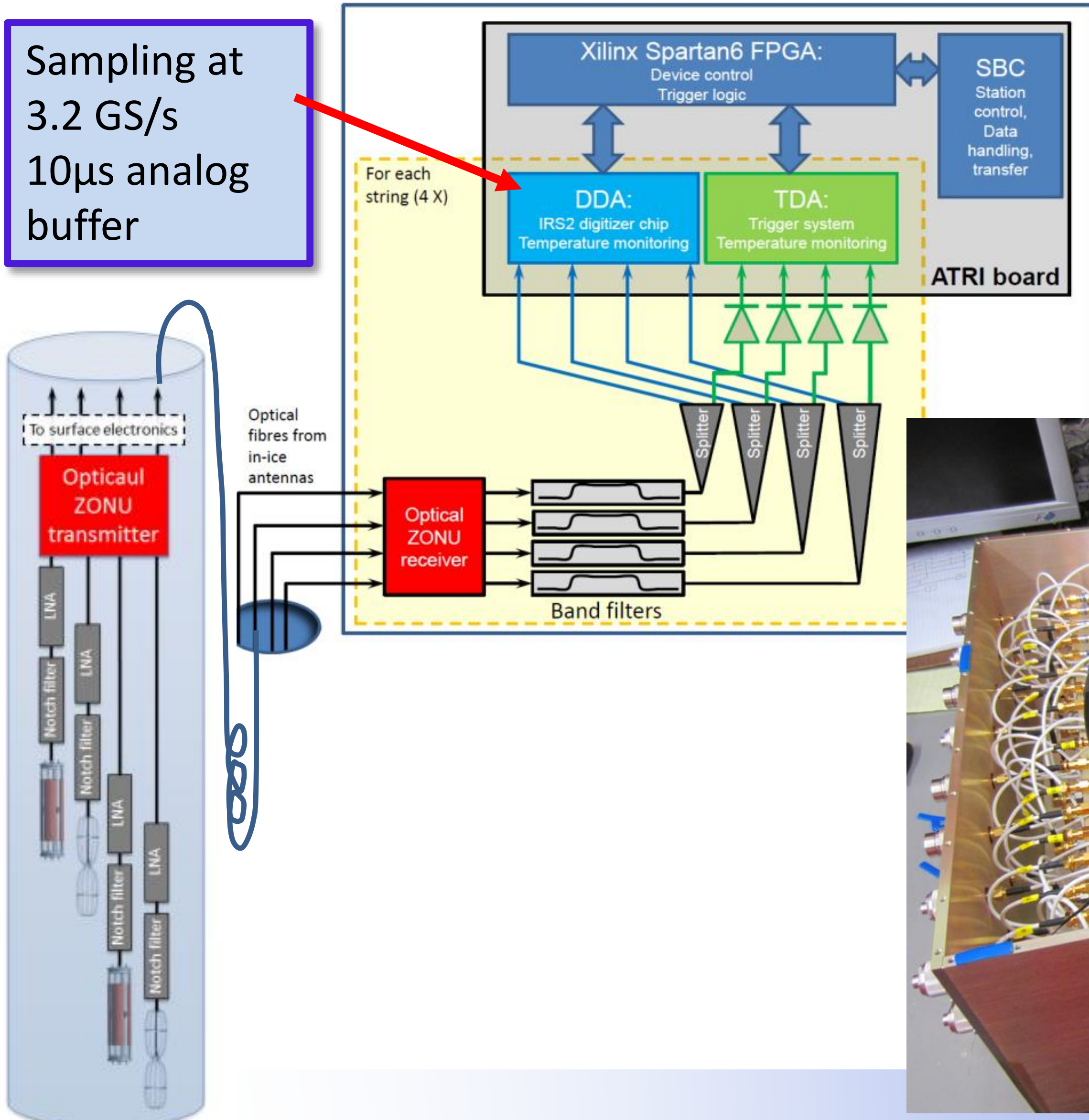
Each station is an autonomous detector!



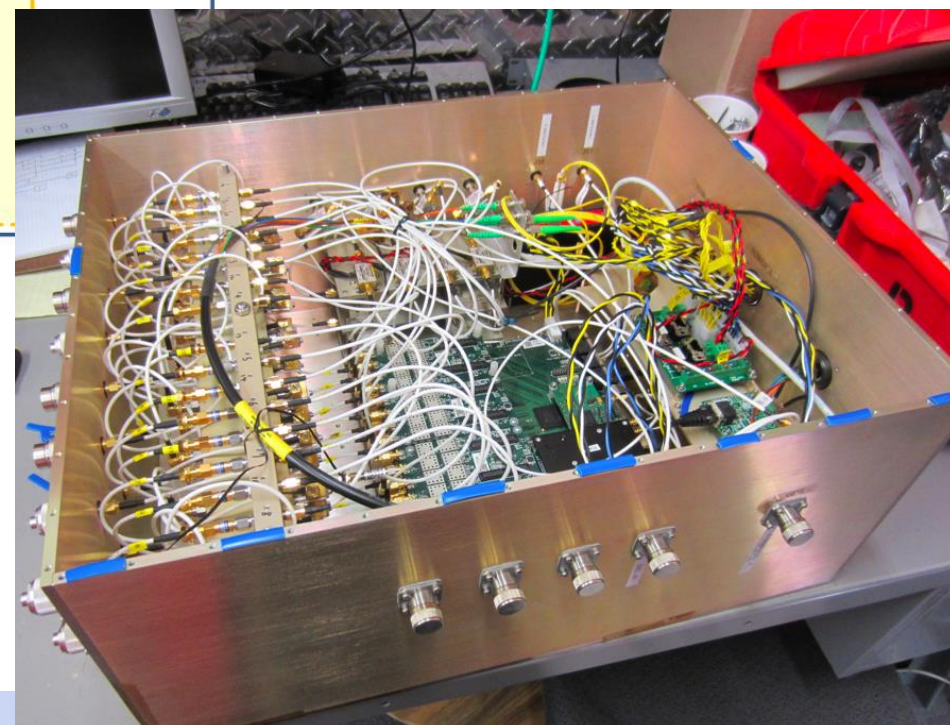
- Prototype station: Testbed, first results: arXiv:1404.5285
- 3 deep stations deployed and operating at the current date
- 2 additional stations funded for 17/18 deployment

The detector Hardware and DAQ

Sampling at 3.2 GS/s
10µs analog buffer



1 station operates at 100 W power consumption
More info in: arXiv:1105.2854

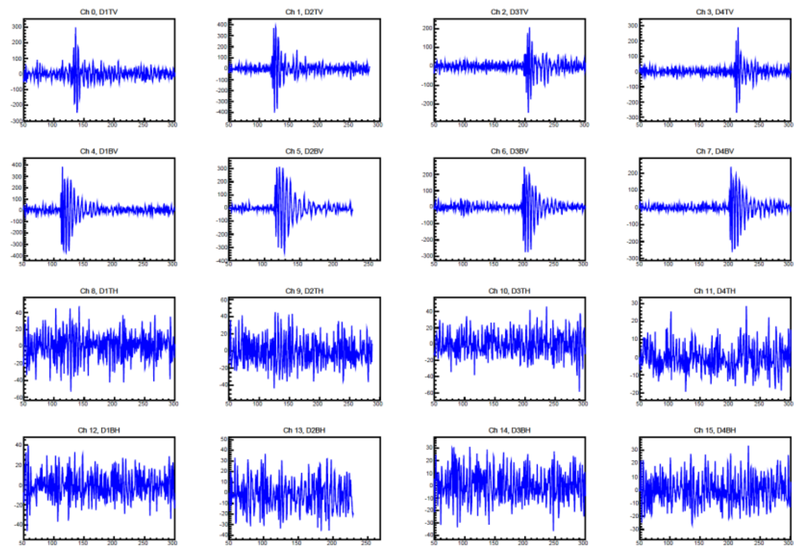


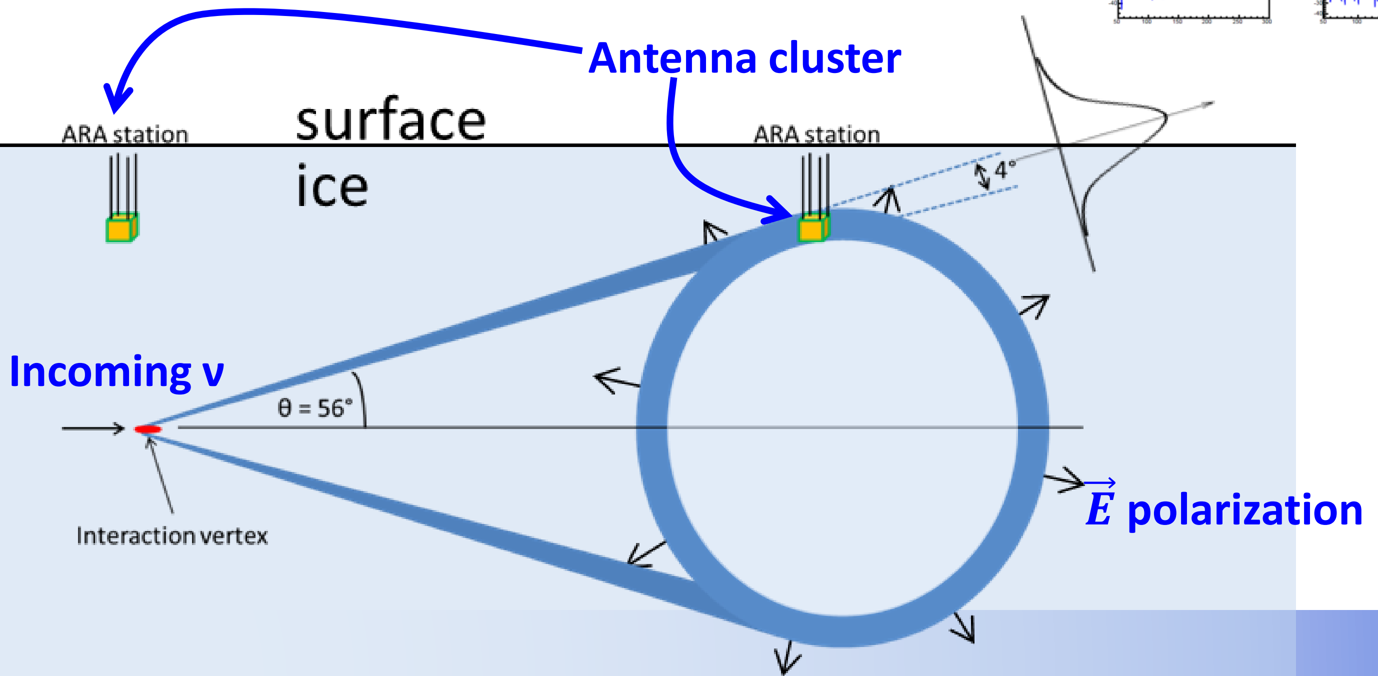
What if …

we found a neutrino

For incoming angle and Energy we need:

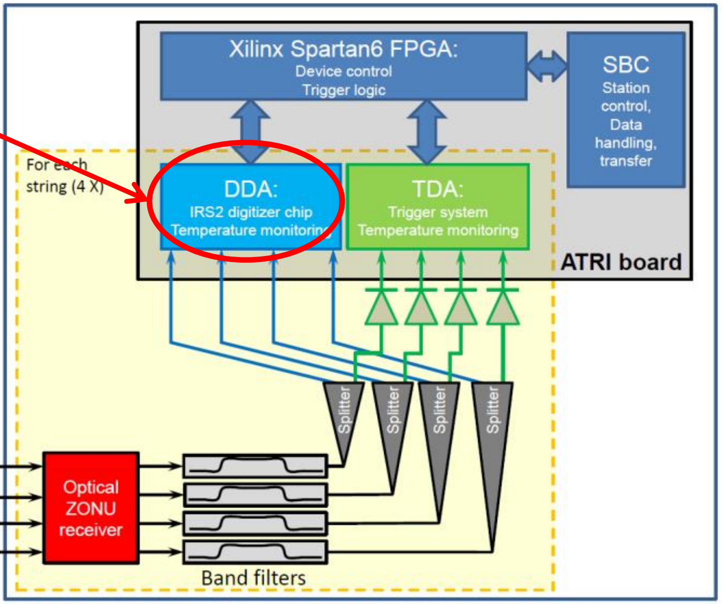
- **Angular reconstruction**
- Distance reconstruction
- Amplitude
- Polarization



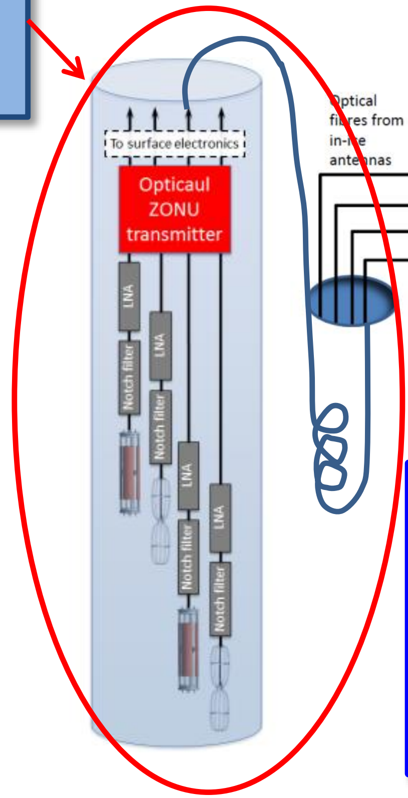


Calibration needed

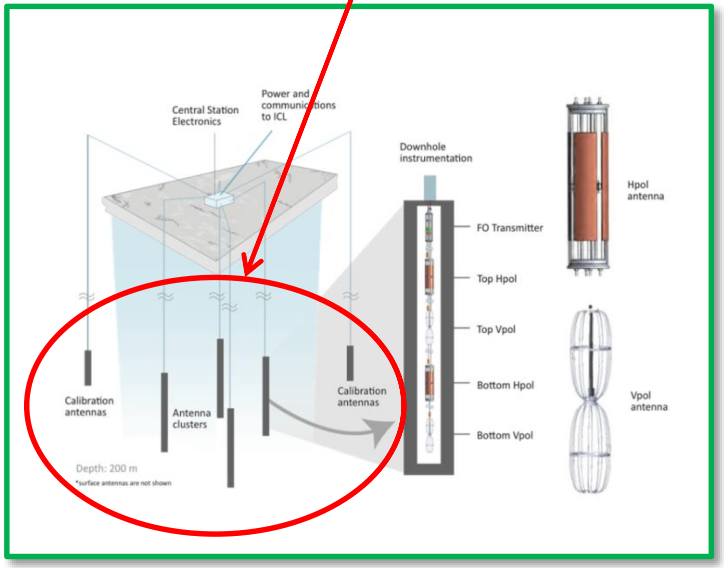
Digitizer chip: IRS2
For waveform timing, amplitude
Achieved 100 ps timing precision



Signal chain:
Frequency response, directional gain, signal to noise ratio

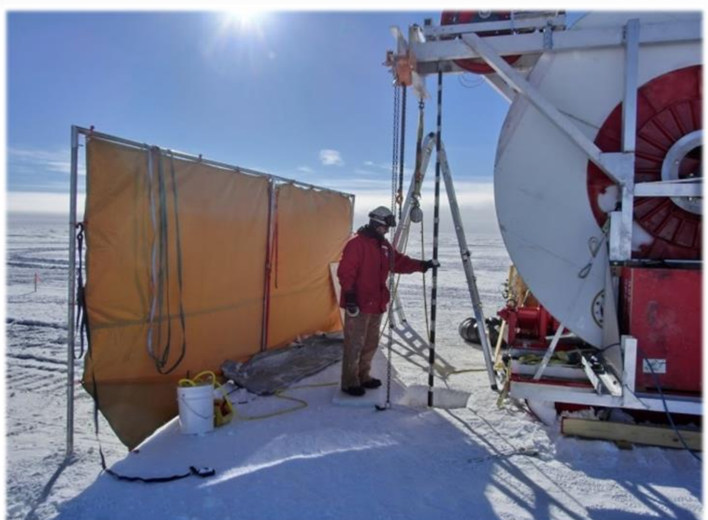


Station geometry on cm level



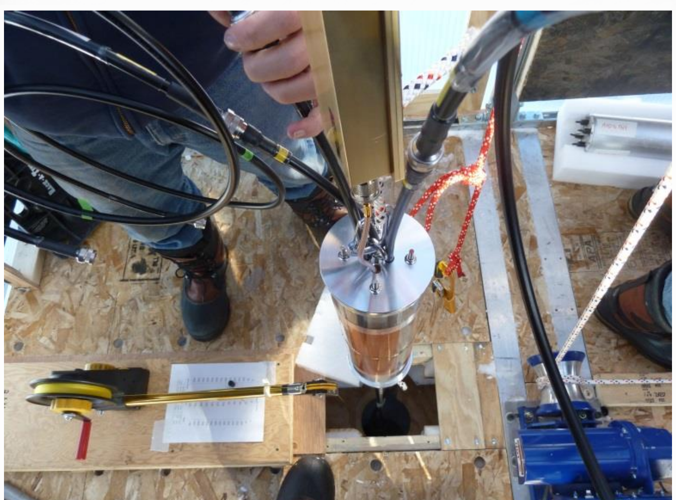
Current status good enough for…
Angular reconstruction - Yes
Polarization – Sort of
Distance reconstruction - No
Energy reco - No

ARA construction: Drilling



ARA Construction: Deployment and commissioning

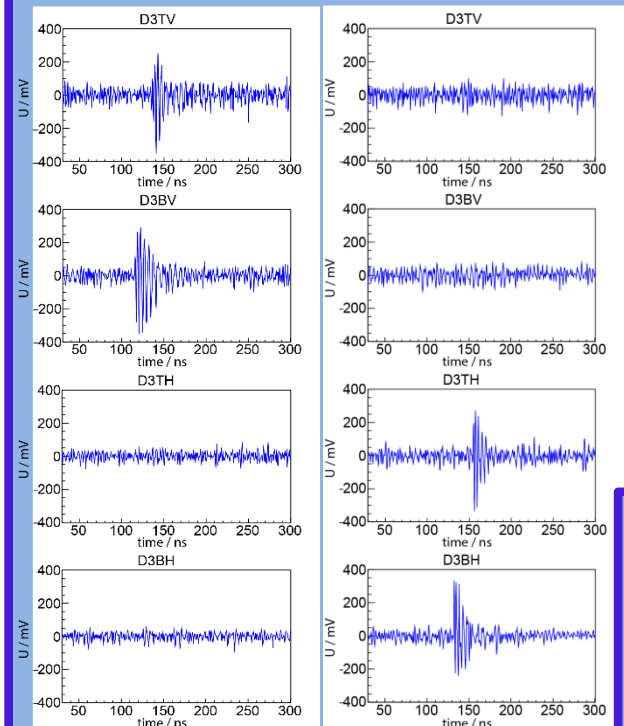
Deployment



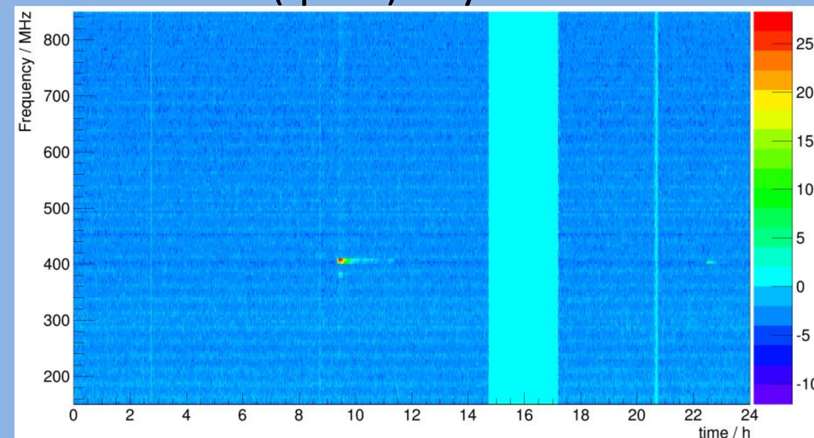
Commissioning

The detector performance

A calibration signal on ARA03

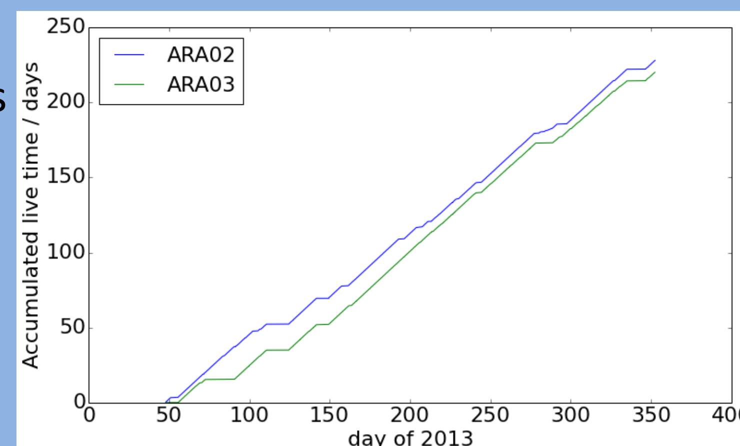


Winter (quiet) day in ARA03



Accumulated ~224 days of live time in 10 months

31 of 32 channels performing well



2013 Data analysis: The challenge

We need to exclude all thermal noise (10TB of data)

Simple filter: Check consistency of antenna hits with plane wave

What we roughly see within 10 months in 2 stations:

Trigger at ~5HZ → 300 000 000 events

• Neutrinos (Ahlers2010)	0.2
• Thermal noise	299.998 M
• Impulsive radio background	2000

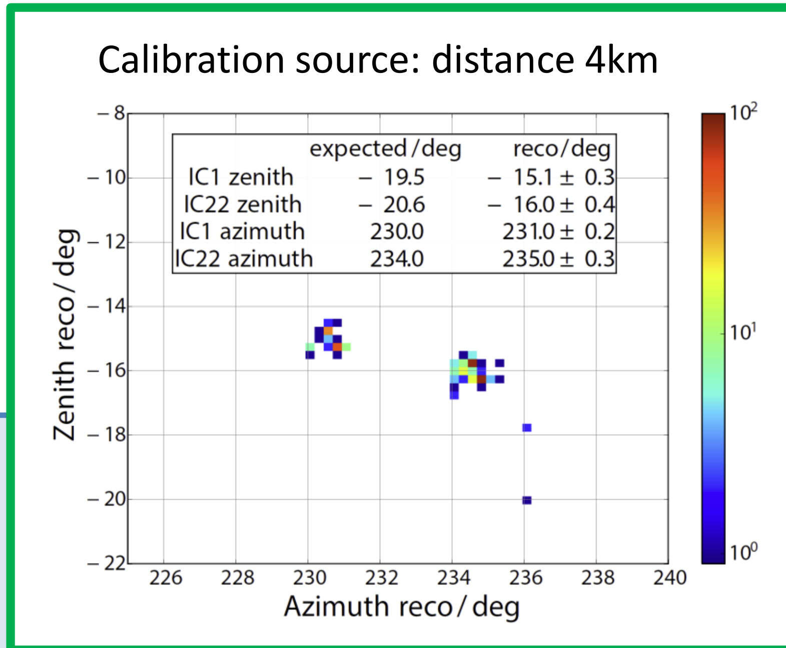
Look like neutrino events, but …

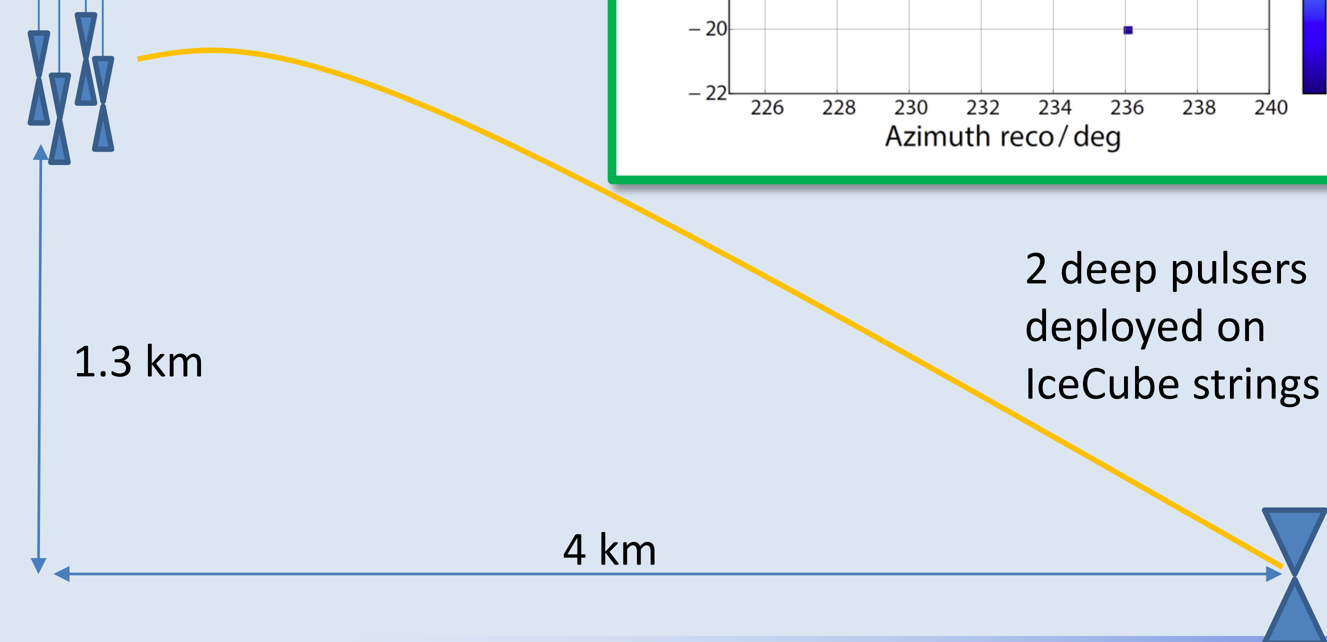
- Only neutrinos can penetrate the ice deeply and produce a point-like radio source

→ reconstruct the vertex location

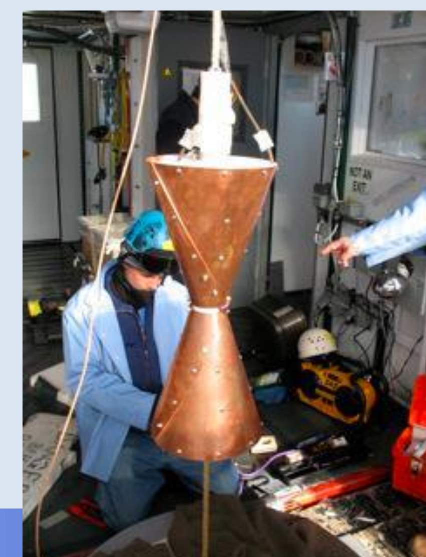
→ reject all background by angular cuts: Calibration pulsers, human activity, etc…

Reconstruction performance

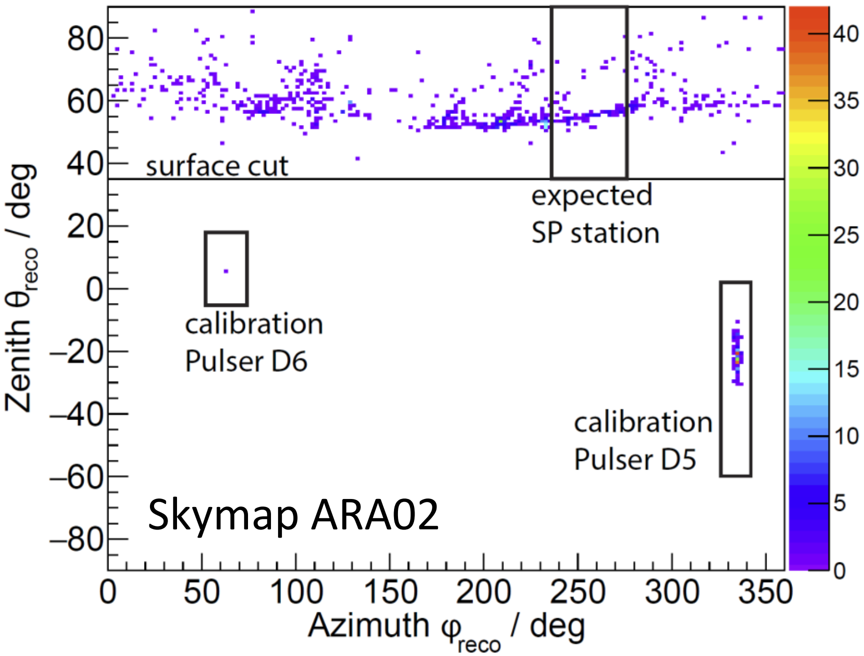




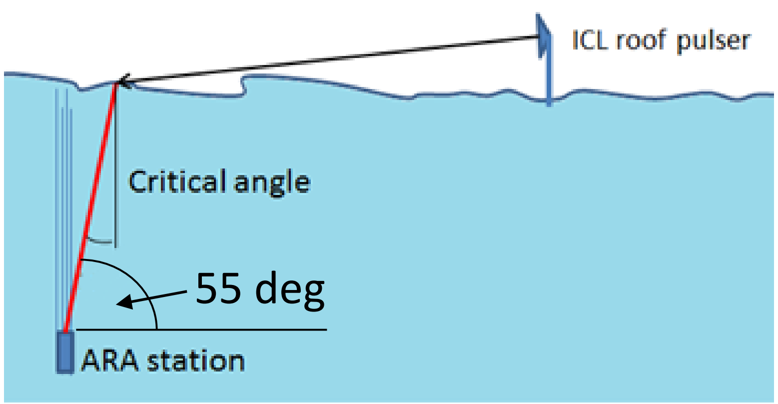
2 deep pulsers deployed on IceCube strings

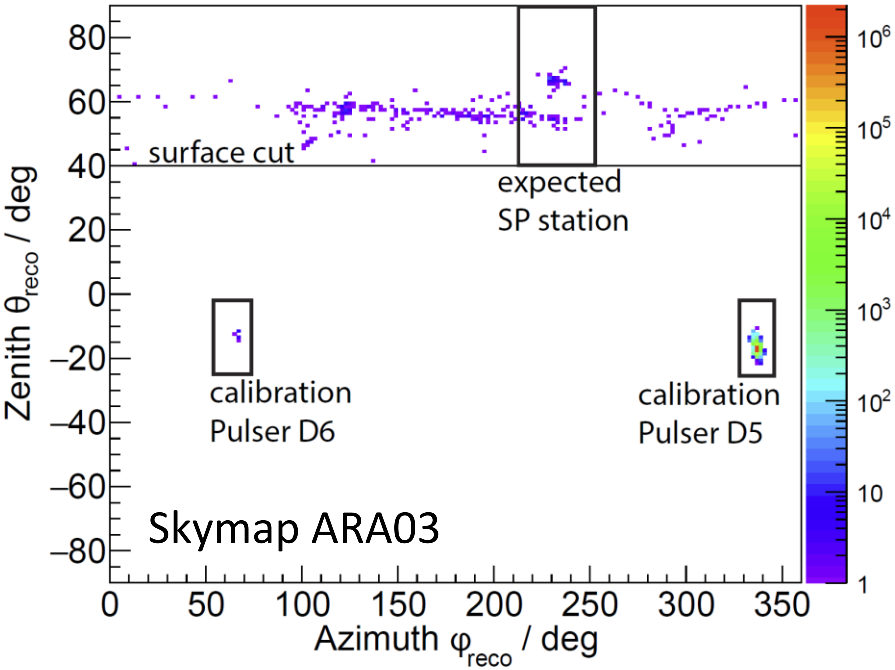


Results



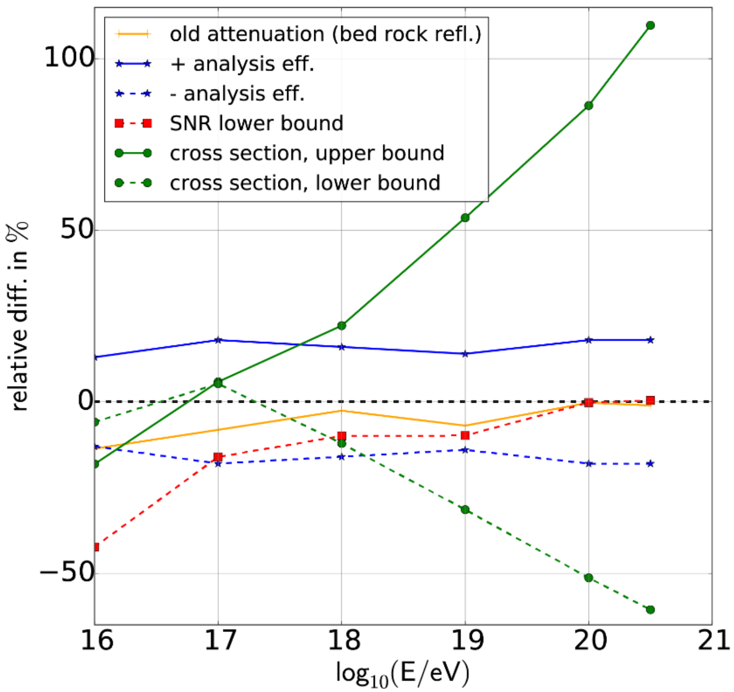
No event in signal region!





Systematic errors

Relative error on the final effective area



Dominant errors are:

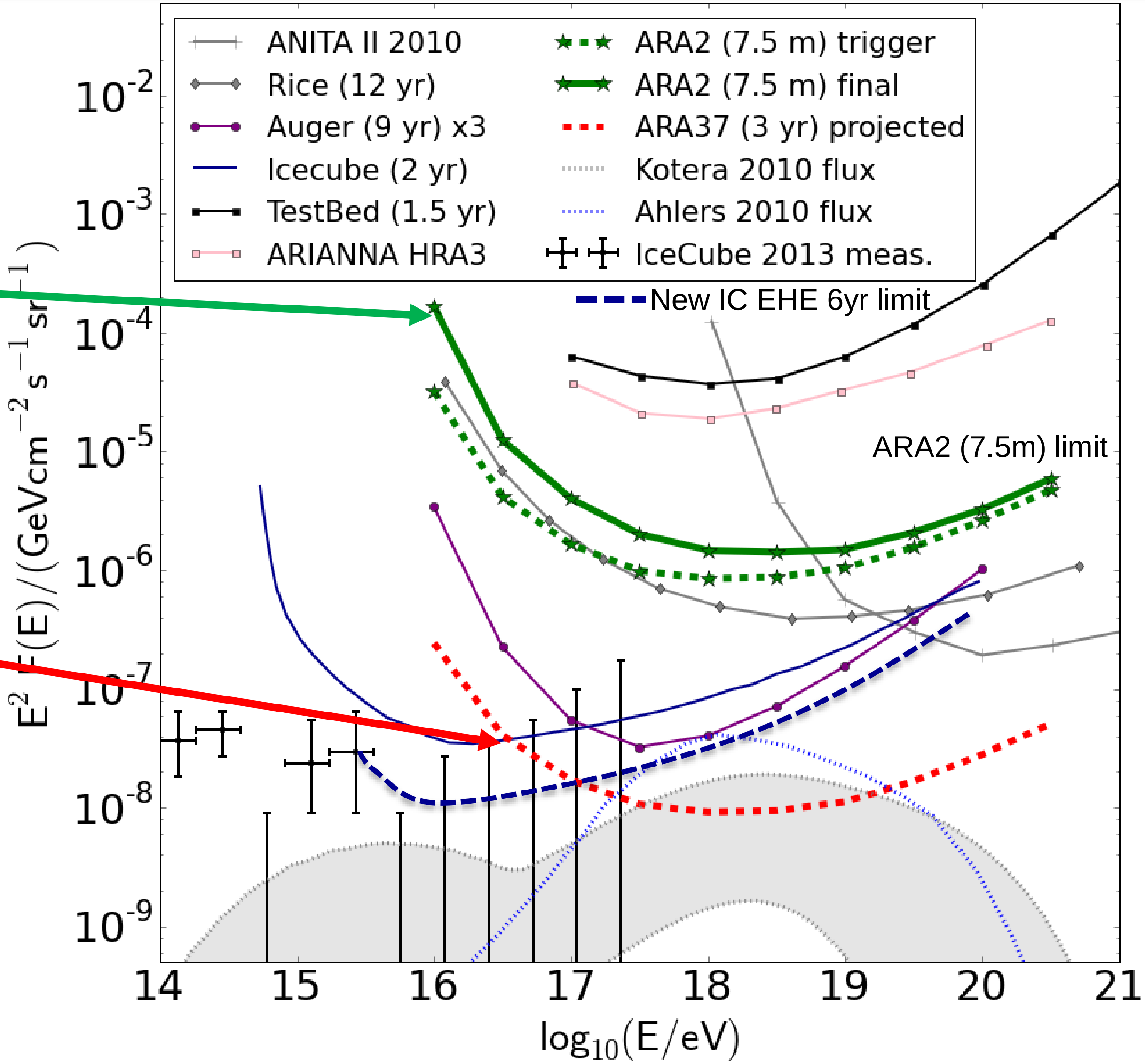
- Interaction cross section uncertainties: never measured at these energies
- Signal amplitude:
  Calibration of the signal chain still relatively coarse
  → **This can be improved significantly**

ARA37 sensitivity

No neutrino candidate found (arXiv:1507.08991), →at expectation of 0.1 neutrinos from Ahlers2010 estimation after applying cuts.

ARA37 best neutrino sensitivity at 10^18eV

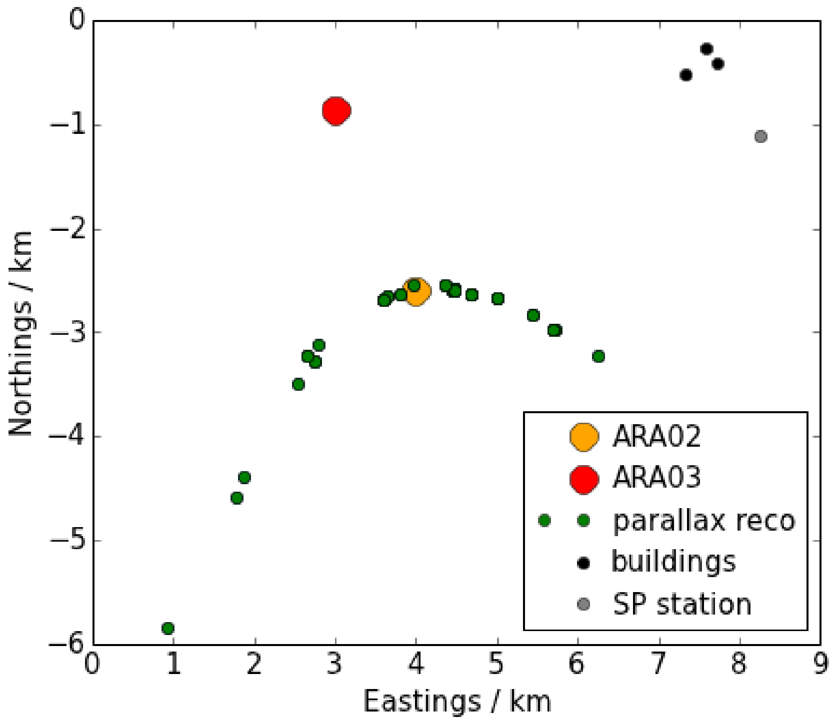
Need new ideas for the PeV range!

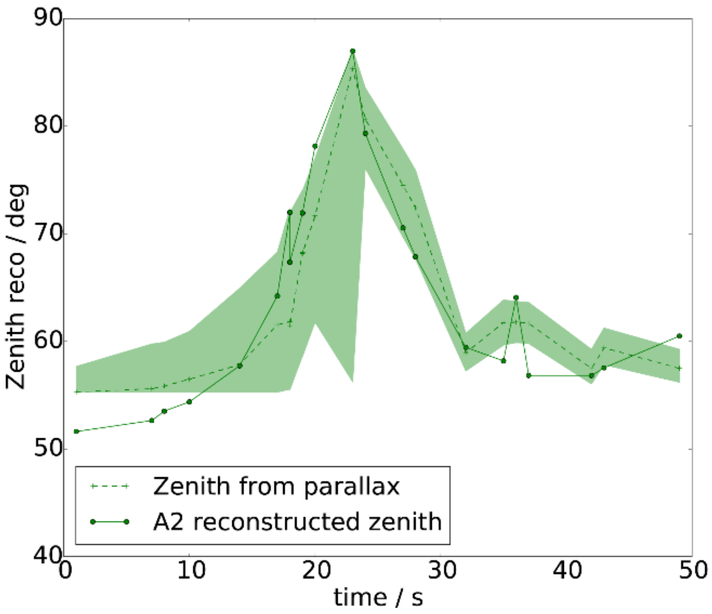


A look at the events which we have found

We can follow airplanes:

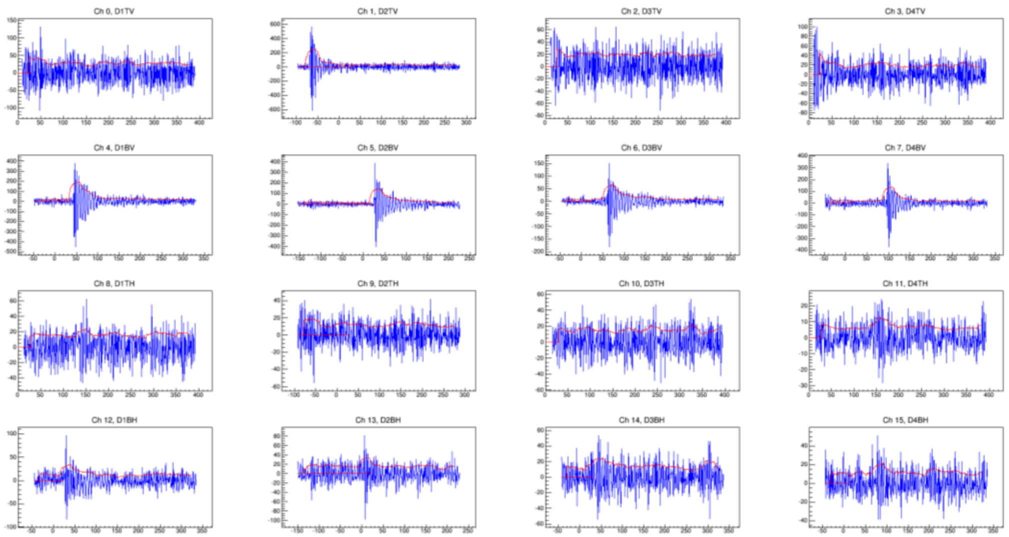
- Observed object is moving at a speed of 400 km/h at a height of roughly 500 m

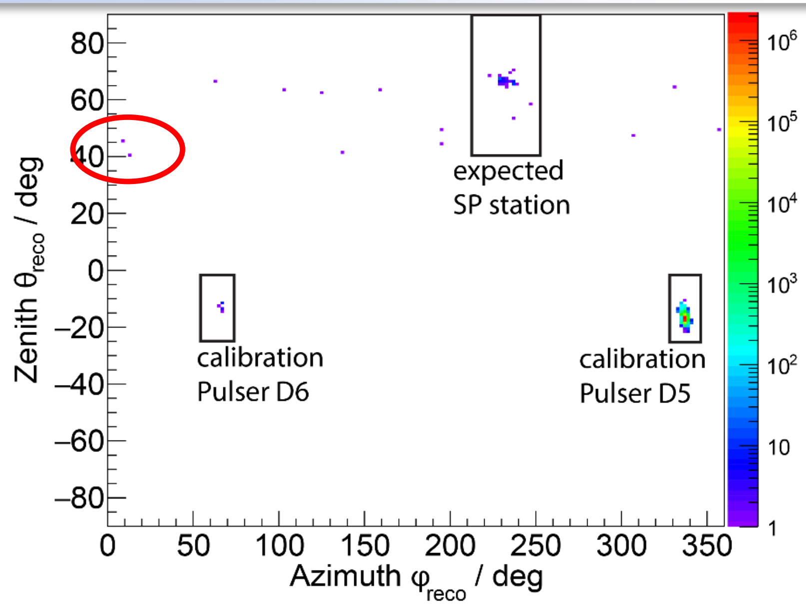




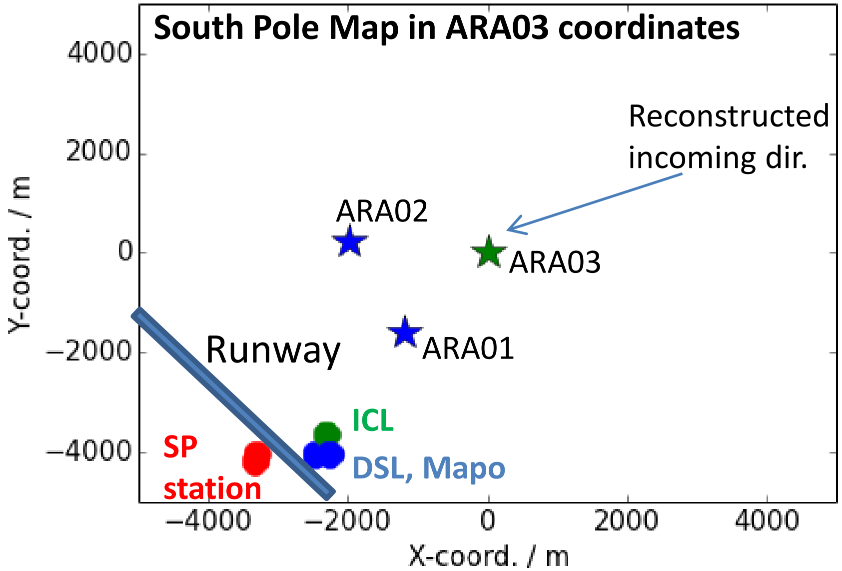
→ We can see radio events and reconstruct them properly!

Where did this come from?





Crude investigation:
Event occurred in August 2013
→ "NO" South Pole activity
Zenith reconstruction: 45 degree
→ suggests event generation at ice-air boundary
Possibly transition radiation from CR air showers: arXiv:1503.02808



Go further from here within ARA

Let's assume we are better in analyzing than in triggering!

Phased radio array trigger:

(see A. G. Vieregg et. al., arXiv:1504.08006)

- Use N antennas, combine signals with different phase shift
- **Can theoretically gain factor $\sqrt{N}$ in signal-to-noise ratio for triggering**

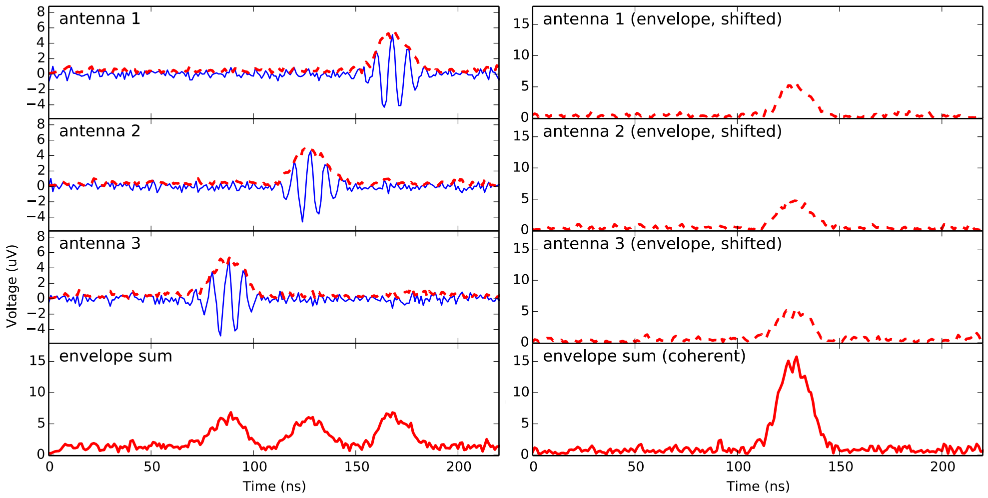
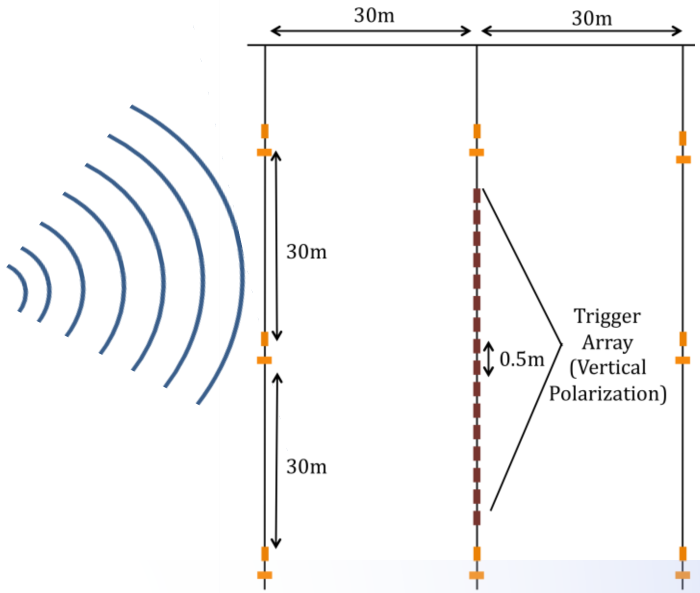


Figure J. Kelley



Phased radio array trigger:

- Technically challenging!
- Working towards deployment with ARA stations in 2017/18

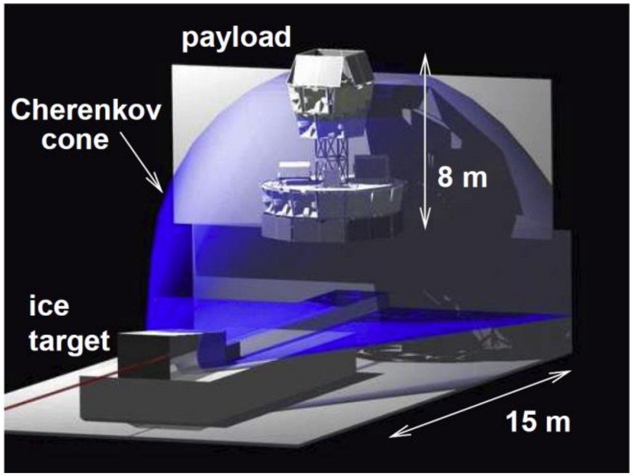
Summary & Conclusions

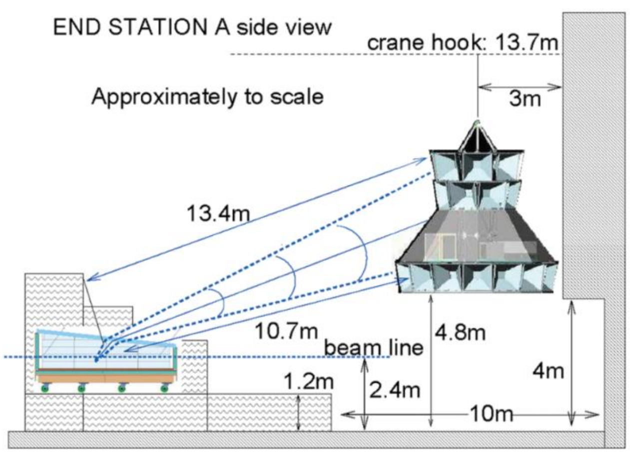
- Good science case for radio neutrino detection
- initial ARA stations are deployed, calibrated and produce useful data
- First analysis performed → neutrino limit
- Working on trigger improvement
- 2 more ARA stations will be deployed in 2017/18: Improves shown sensitivity by factor 2.5

ARA is an operating detector and when enlarged ready for a GZK neutrino detection

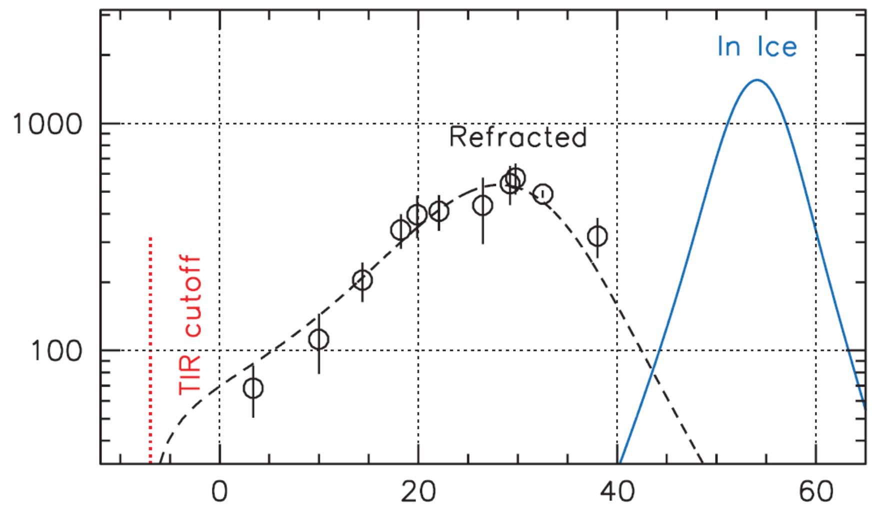
BACKUP

The askaryan effect





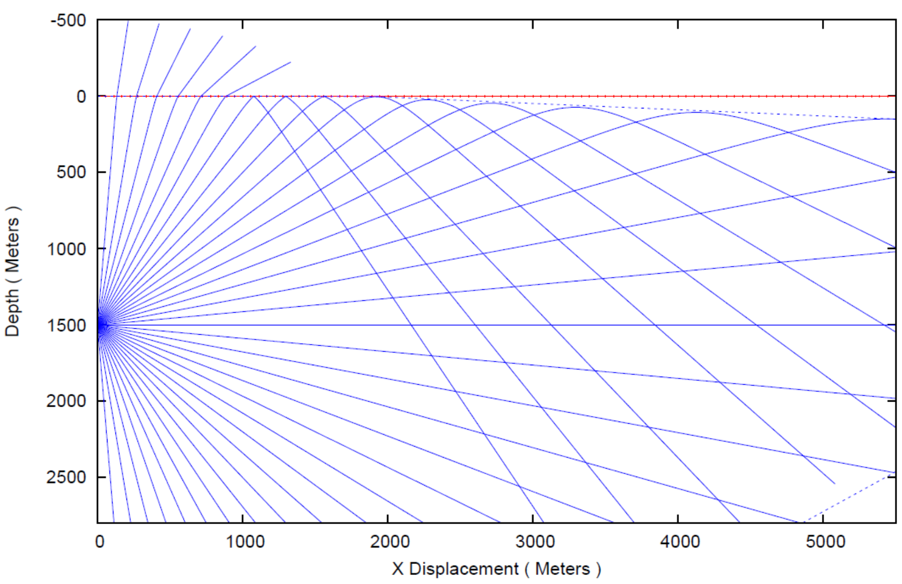
- Predicted in 1962, 1965 by G. Askaryan
- Verified at SLAC beam in sand (2001), salt(2005), ice (2007)
- Electron beam emulates the EM cascade



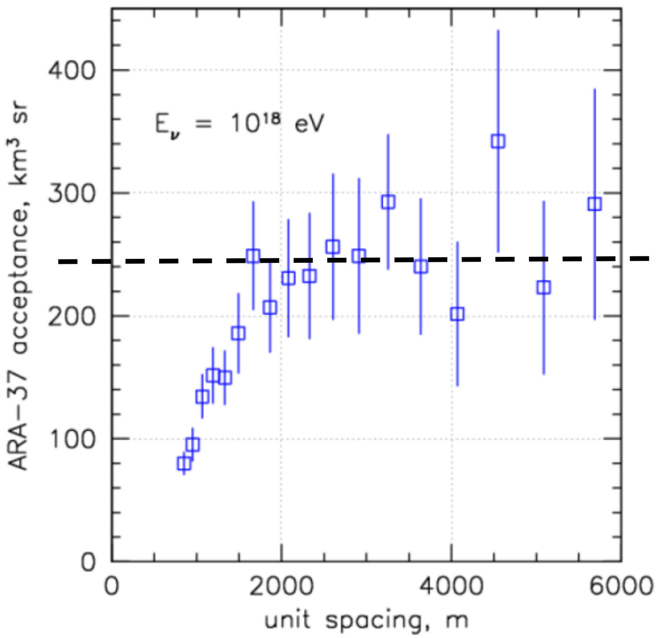
Find details here: arXiv:hep-ex/0611008

Motivation for detector geometry

Ray bending:
Changing index of refraction in top 200 m of the ice
→ Makes reconstruction difficult
→ Produces shadowed areas



2 km station spacing maximizes detector acceptance at 10^18eV



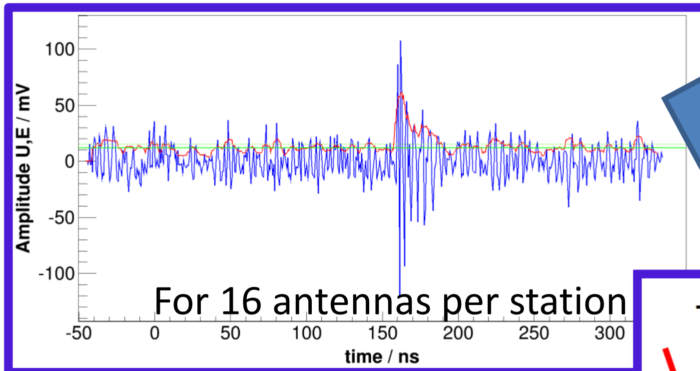
Thermal noise filtering

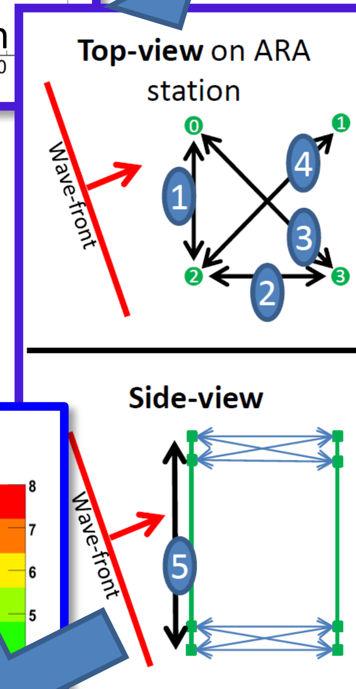
Time sequence algorithm:

1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave

→ ***quality parameter***

$QP \approx$ ***(similarity to plane wave–front) ⋆ (hit count)***

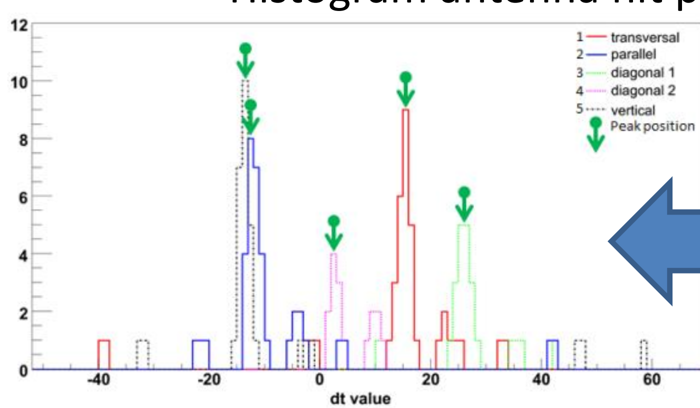


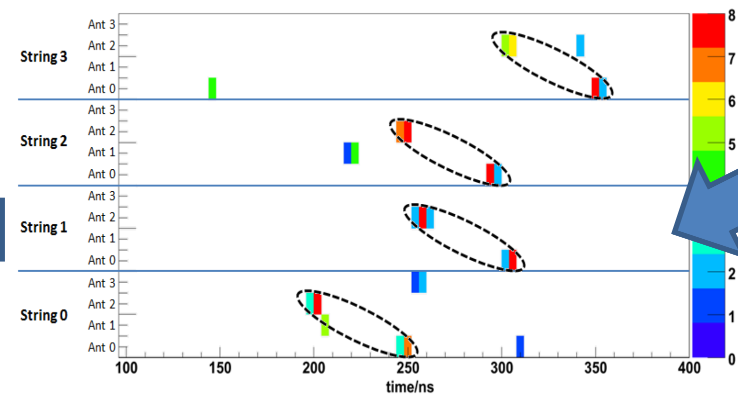


QP=∑peak height

Keeps 92% of neutrinos between 1E18eV and 1E19eV at 99.9% noise rejection!

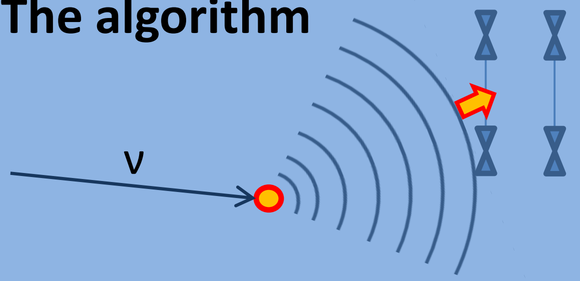
Histogram antenna hit pairs with same geom. relation



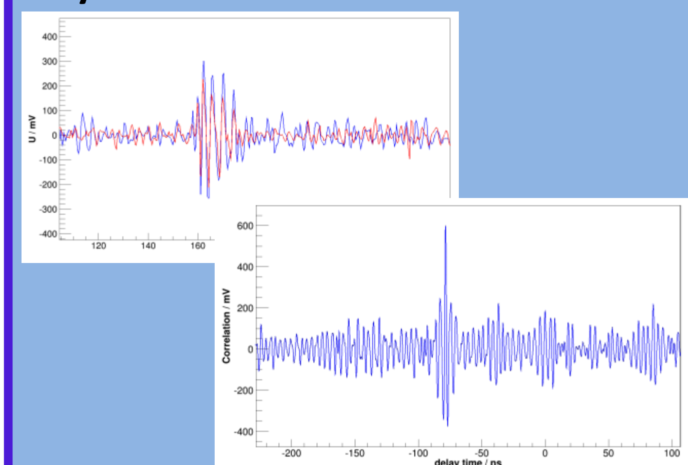


Vertex reconstruction

The algorithm



1. Determine time difference Δt by cross-correlation



2. Select good antenna pairs, based on correlation amplitude

3. Set up and solve system of linear equations

Signal arrival time from positions:

$$c^2(t_v - t_i)^2 = (x_v - x_i)^2 + (y_v - y_i)^2 + (z_v - z_i)^2$$

Use difference between antennas & reorder
→ **linear equation for vertex coordinates**

$$\boldsymbol{x_v} \cdot 2x_{ij} + \boldsymbol{y_v} \cdot 2y_{ij} + \boldsymbol{z_v} \cdot 2z_{ij} - \boldsymbol{t_{v,ref}} \cdot 2c^2 dt_{ij} = r_i^2 - r_j^2 - c^2(dt_{i,ref}^2 - dt_{j,ref}^2)$$

This can be represented by:

$$\mathbf{A}\vec{v} = \vec{b}$$

Solve with matrix decomposition tools

4. Apply quality criteria

Main quality criterion is residual:

$$\text{res} = \left\| \frac{\boldsymbol{b}}{|\boldsymbol{b}|} - \frac{\boldsymbol{A} \cdot \boldsymbol{v}}{|\boldsymbol{A} \cdot \boldsymbol{v}|} \right\|^2 \cdot \frac{1}{N_{ch}}$$

Tells us how well reconstructed position fits time differences