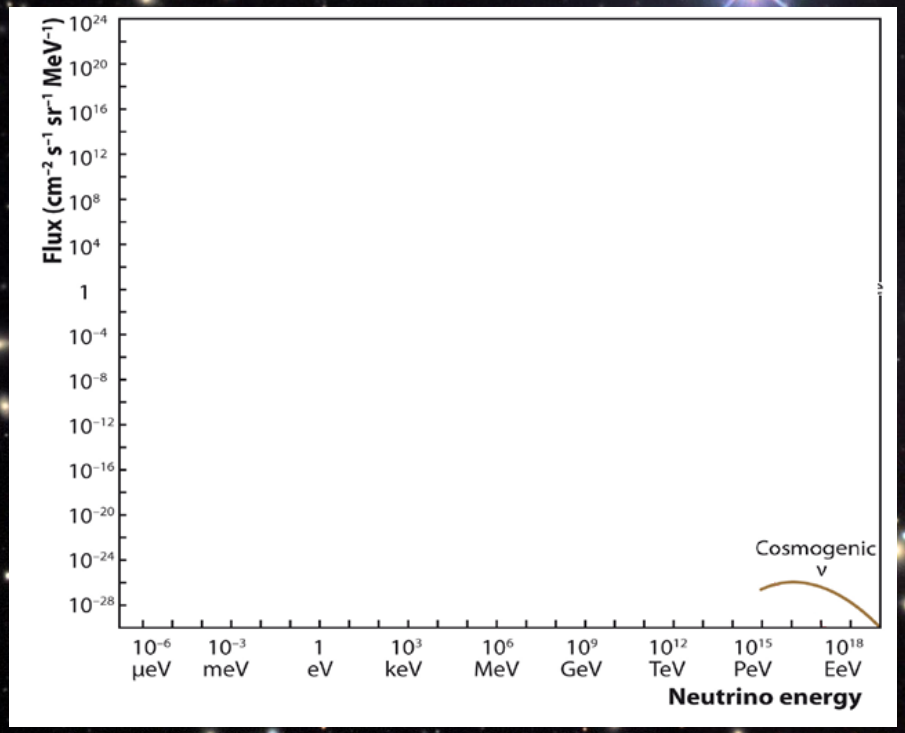
First analysis results from the Askaryan Radio Array

09/17/2015

Thomas Meures

What is our research goal?



The Askaryan Radio Array (ARA) is a detector for ultra-high energy neutrinos

- **Why is it interesting to look for them?**
- **How can we do it?**

What is our research goal?

trying to understand processes of extremely high energy in the far universe, as in…

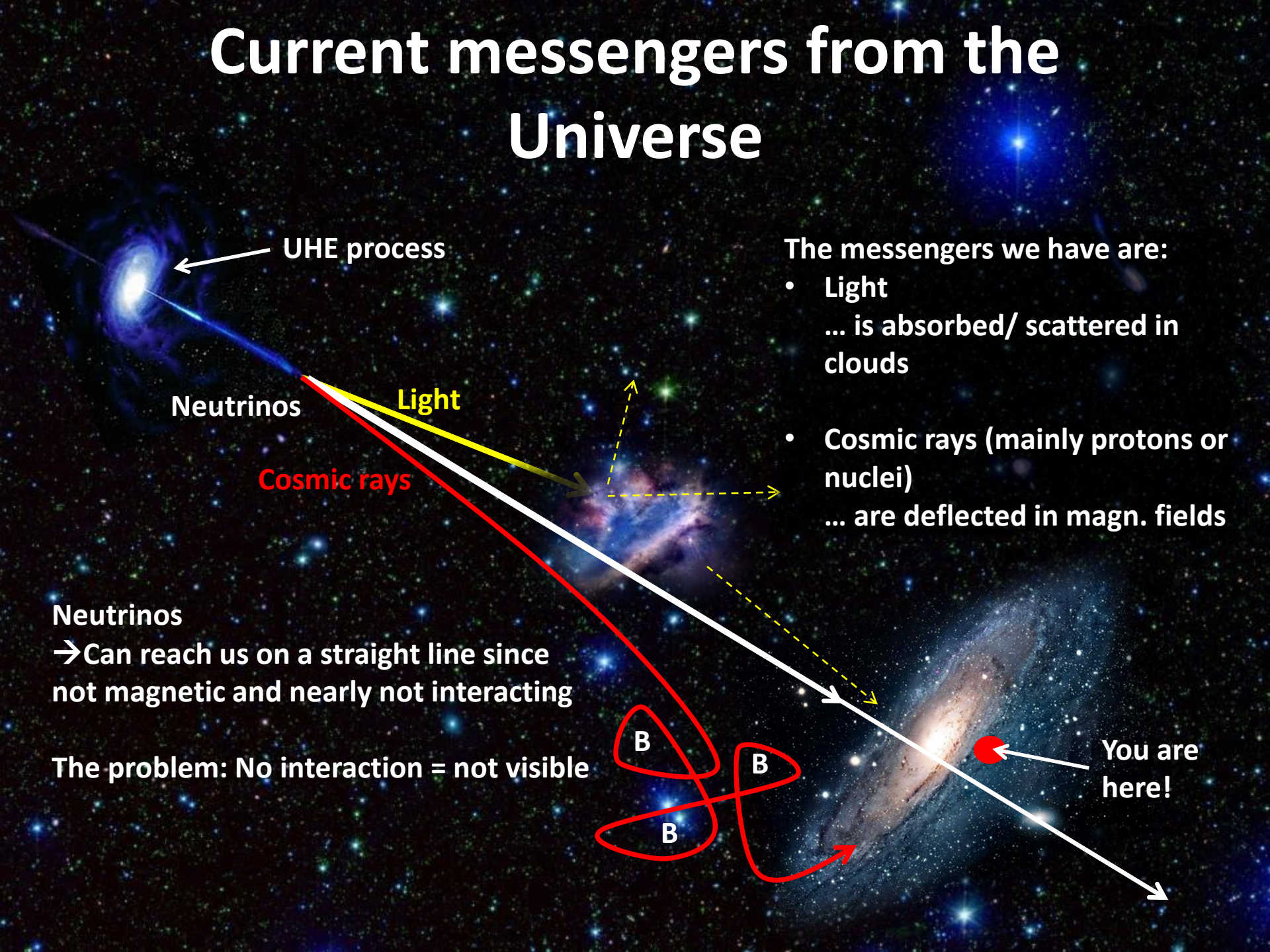
- Active Galactic Nuclei ?
- Gamma-Ray Bursts ?
- … ?

because…

- We can not produce these processes on earth

- They can tell us about …
  - The structure of the Universe
  - The development of the Universe
  - New physics?

Current messengers from the Universe



The messengers we have are:

- Light
  … is absorbed/ scattered in clouds
- Cosmic rays (mainly protons or nuclei)
  … are deflected in magn. fields

Neutrinos
→Can reach us on a straight line since not magnetic and nearly not interacting

The problem: No interaction = not visible

Neutrinos from ultra-high energy processes

UHE process

UHECR

Neutrinos are produced in interaction of Ultra-High Energy Cosmic rays (UHECR) and the cosmic microwave background (CMB)

The GZK mechanism

A resonant interaction between UHECR and the CMB:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

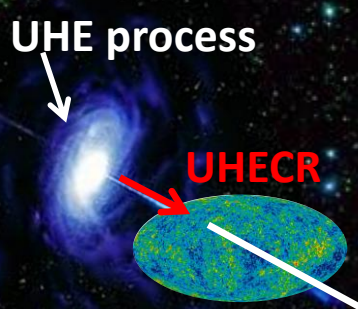
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutrino ν

You are here!

Interaction probability peaks at cosmic ray energy around $E_{CR} \approx 10^{19.5} eV$!

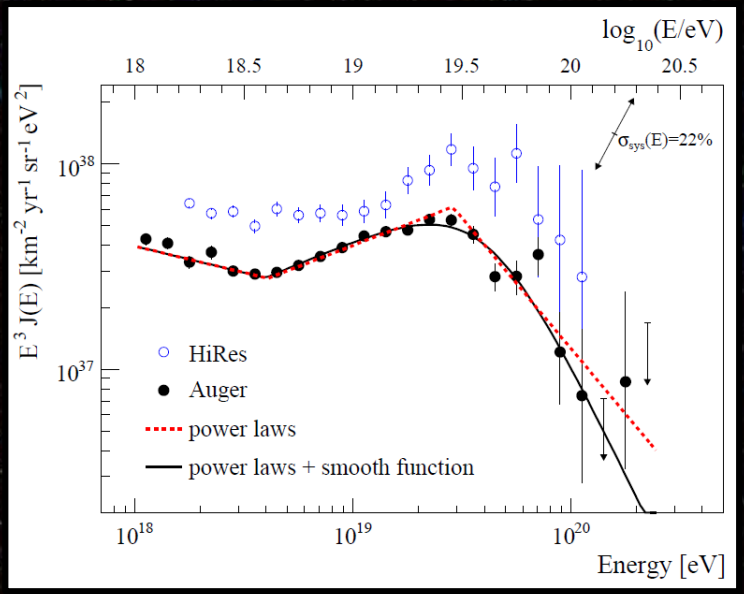
The consequences of the GZK mechanism

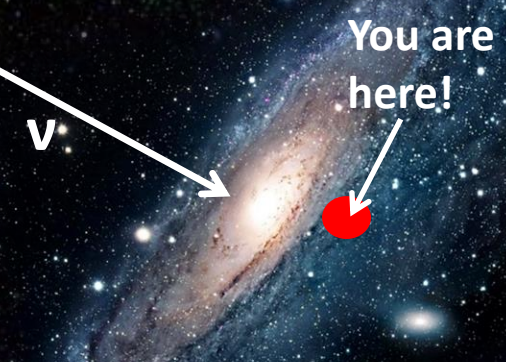


CMB is everywhere → UHECR **will** lose their energy in the GZK mechanism, if energy above threshold.
→ UHECRs never reach us
→Neutrino flux is one of the few possibilities to investigate UHECRs

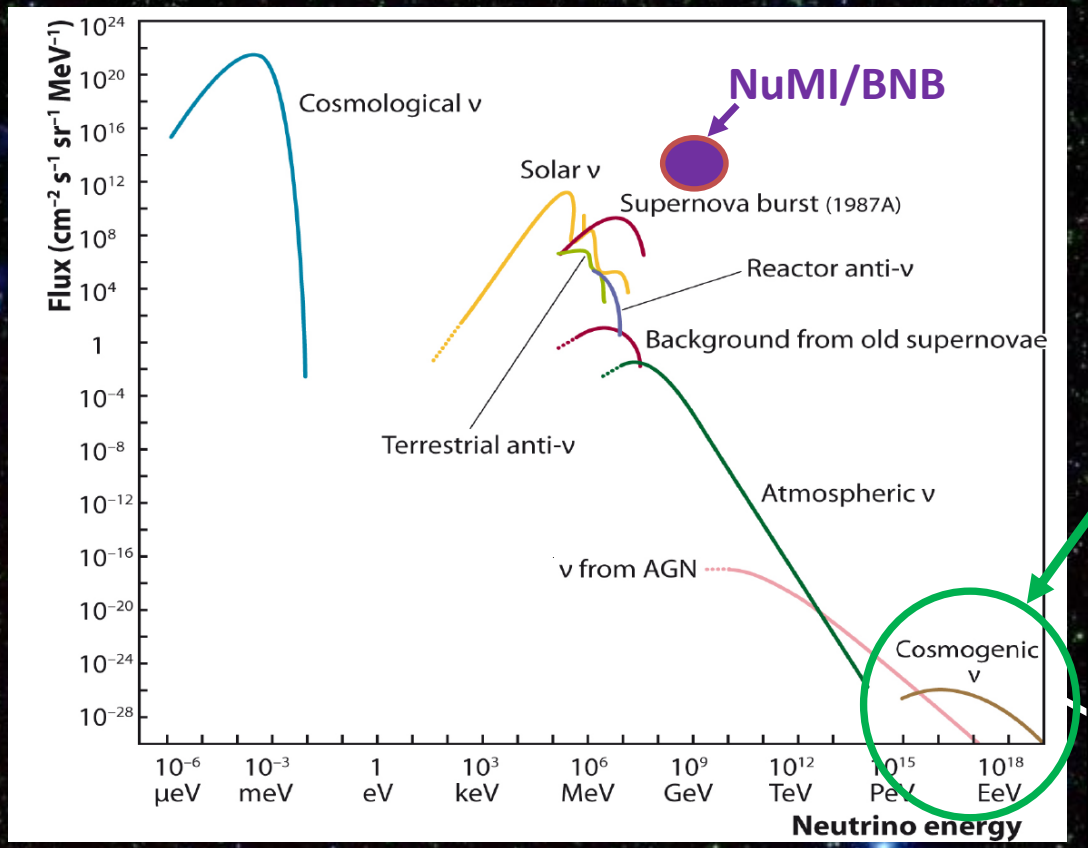
Neutrinos carry exclusive information about UHECRs

The measured Cosmic ray flux



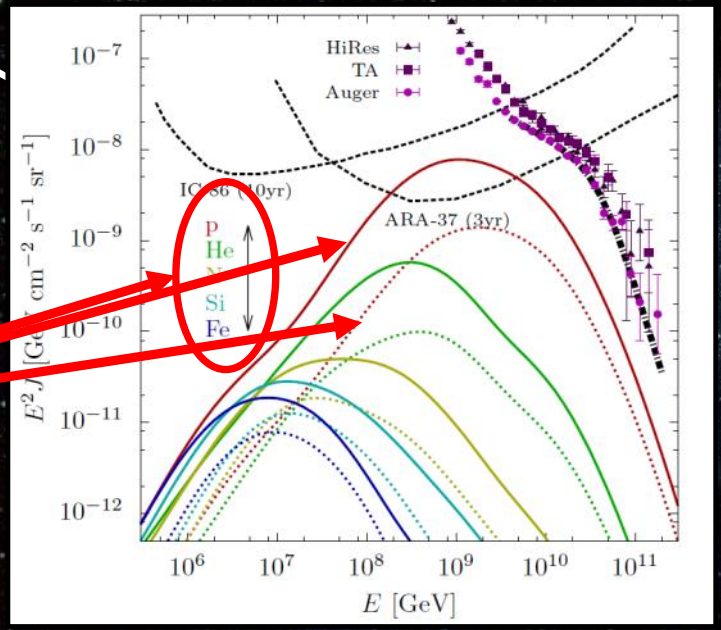


The expected neutrino flux



Cosmogenic:
< 1 interaction/gton/year
Need a giant detector

The predicted neutrino flux



- **CR composition**
- **Source distribution**
- **Energy spectrum**

How can we "see" ultra-high energy neutrinos?

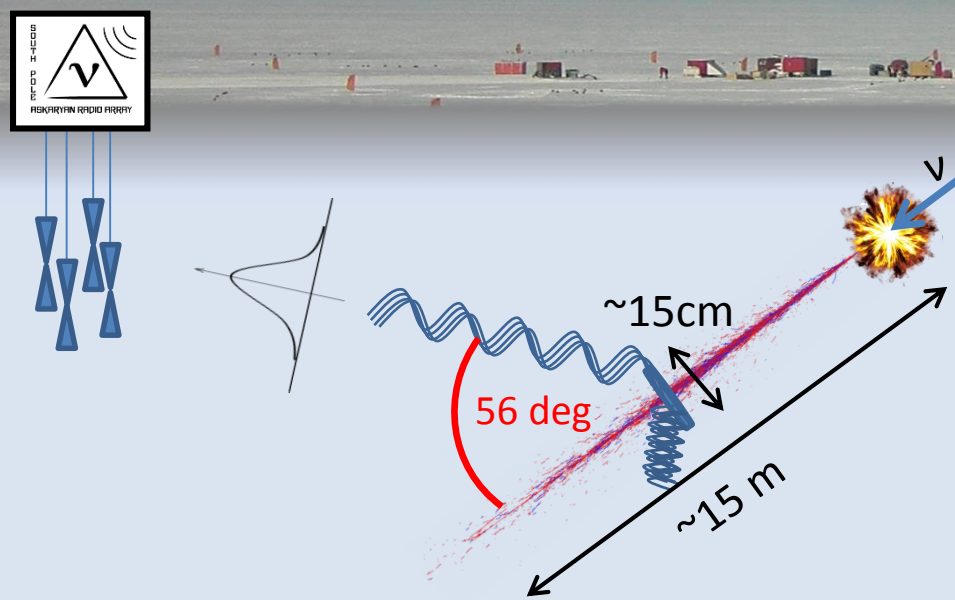
Via the Askaryan effect:

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



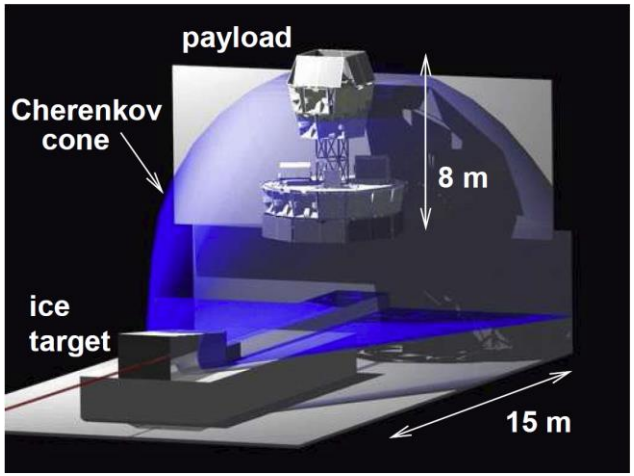
The advantages of radio waves:

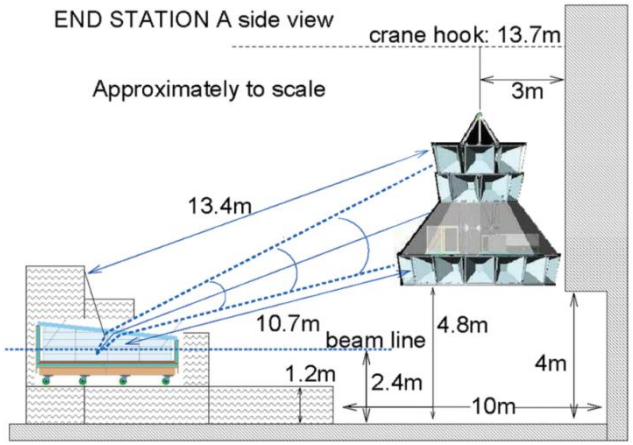
- visible within ~1 km in ice

→ Observe big detector volume with few sensors

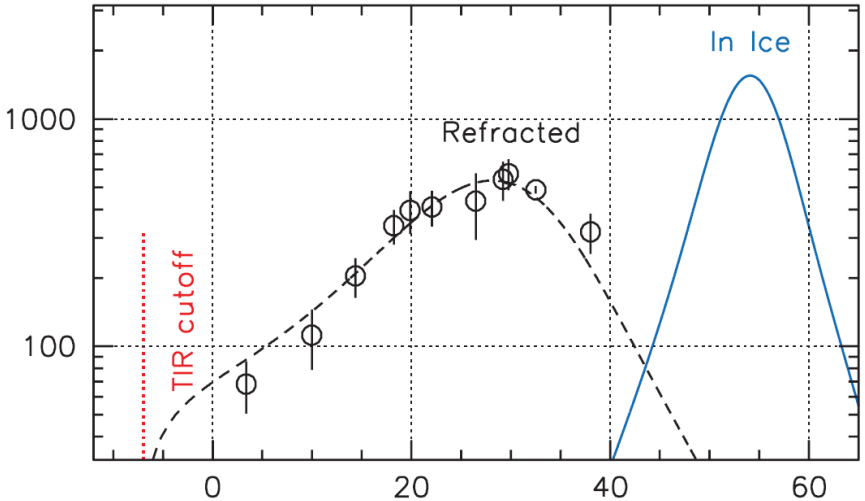
→ **Very cost efficient**

The askaryan effect





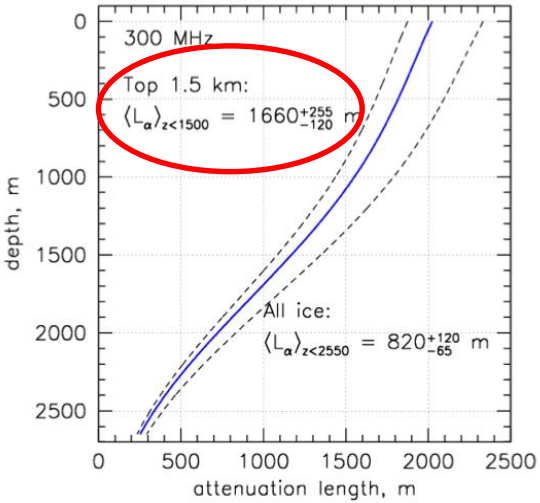
- **Predicted in 1962, 1965 by G. Askaryan**
- **Verified at SLAC beam in sand (2001), salt(2005), ice (2007)**
- **Electron beam emulates the EM cascade**



Where can we build such a big detector?

We need to see what nature supplies as radio transparent media: **Ice and salt**

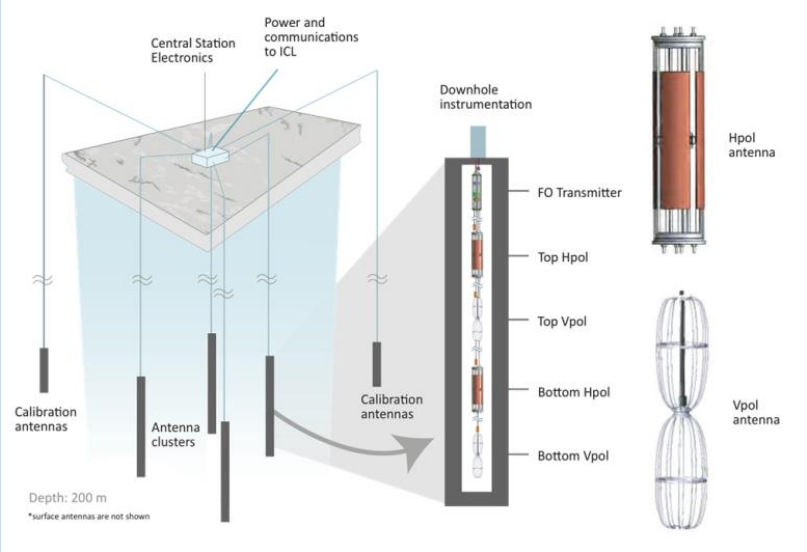
- Salt mines
- Ice: Biggest volumes in **Greenland and Antarctica →basically unlimited**



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)

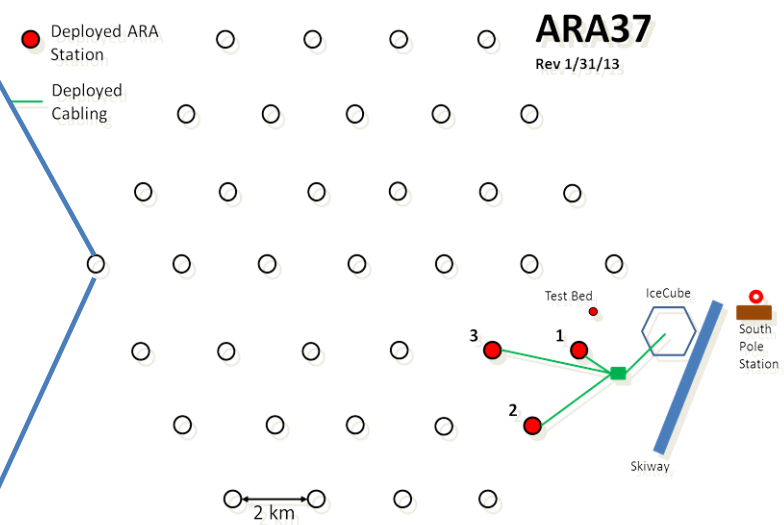


One station:

- **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!

- 37 antenna stations planned
- 3 stations deployed at the current date (two currently operating)



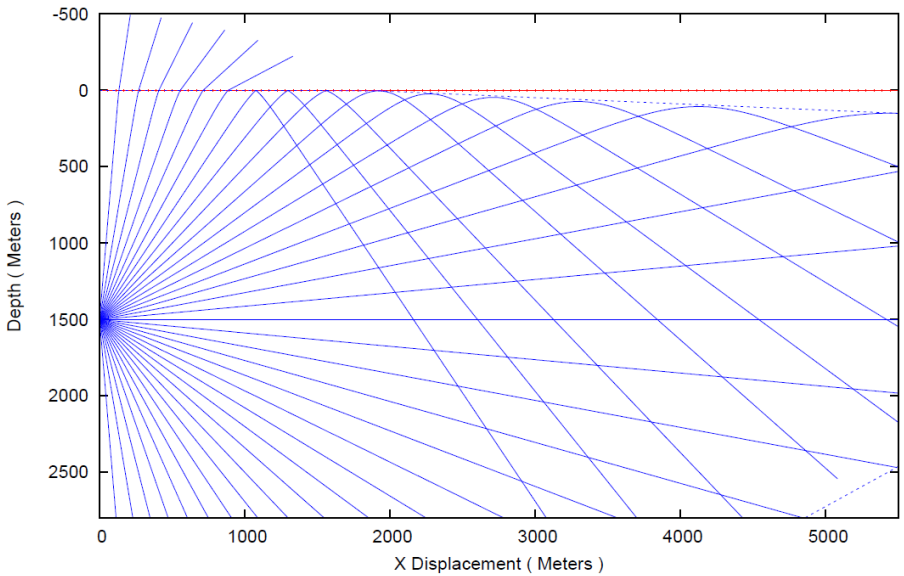
- Stations spaced by 2 km
  → **Maximizing effective volume by avoiding overlap**

Ray-tracing

Changing index of refraction in top 200 m

→ Makes reconstruction difficult

→ Produces shadowed areas

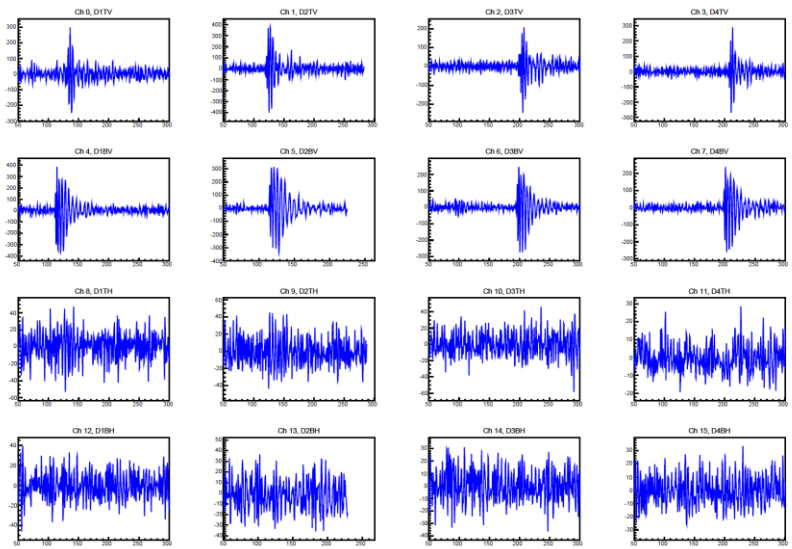


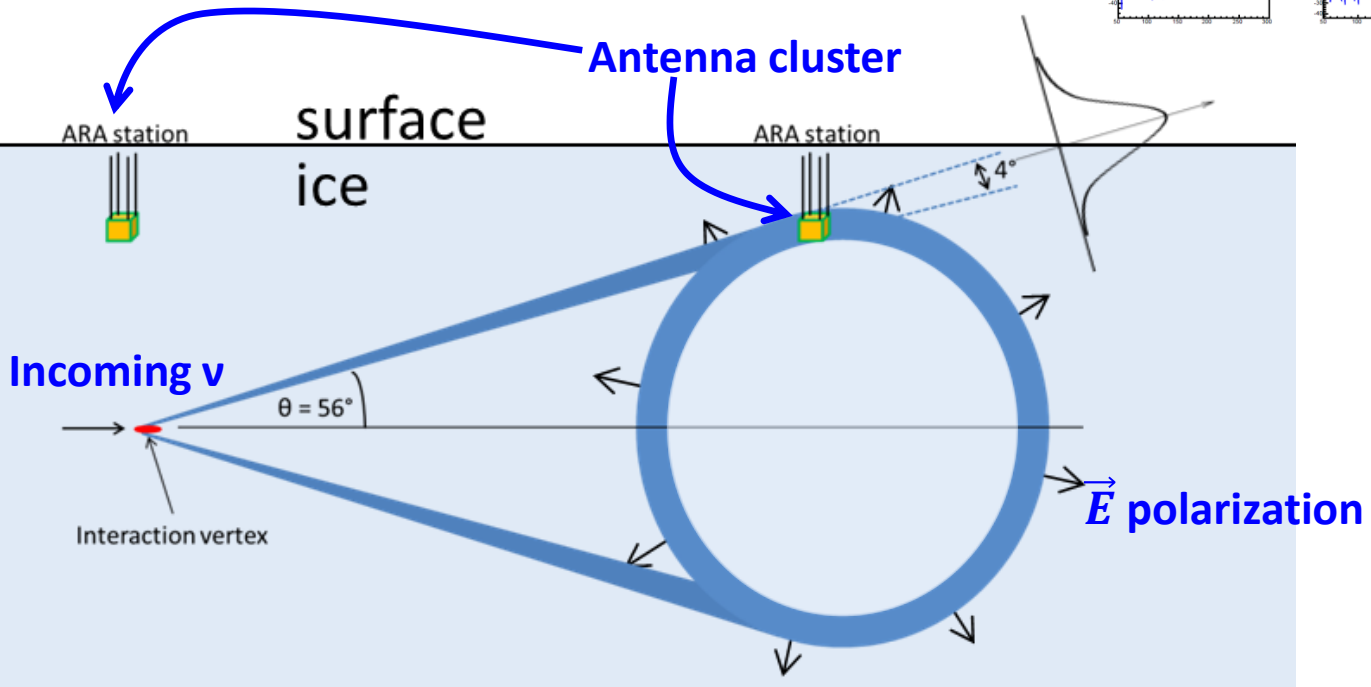
What if …

we found a neutrino

For incoming angle and Energy we need:

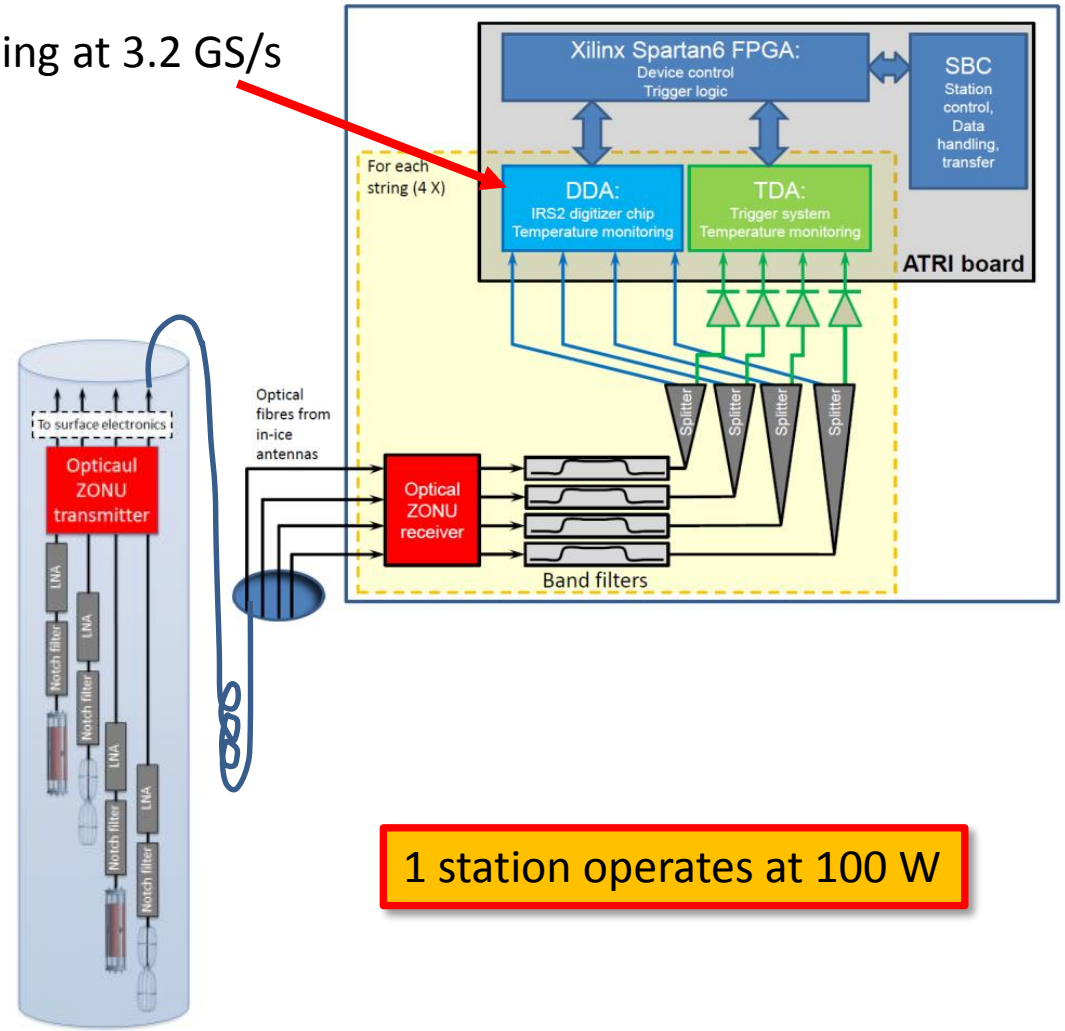
- Angular reconstruction
- Polarization
- Amplitude
- Distance reconstruction





The detector Hardware and DAQ

Digitizing at 3.2 GS/s



Why did we wait so long to do this?

- Technology wasn't ready

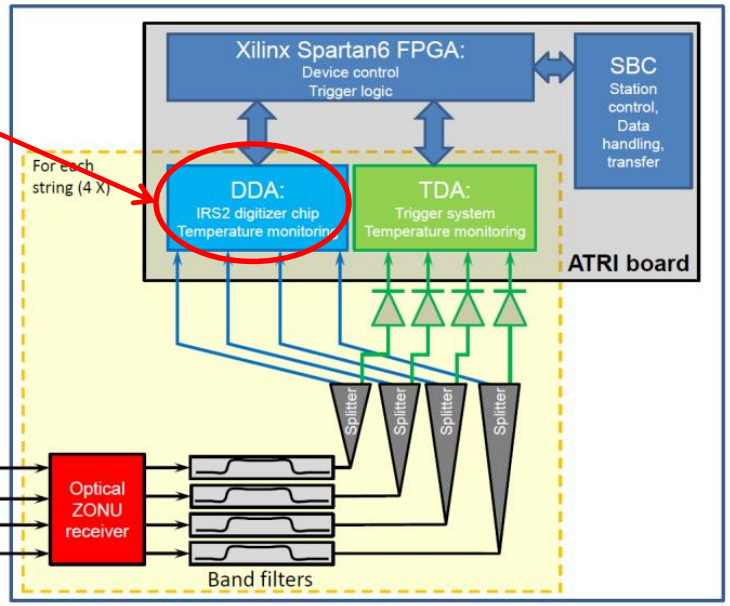
Need:

- extremely high sampling speed for many channels
- Extremely compact devices
- Extremely low power consumption

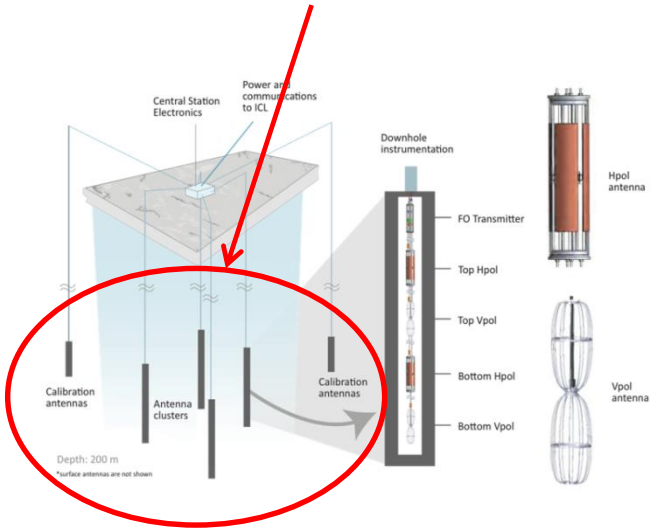
1 station operates at 100 W

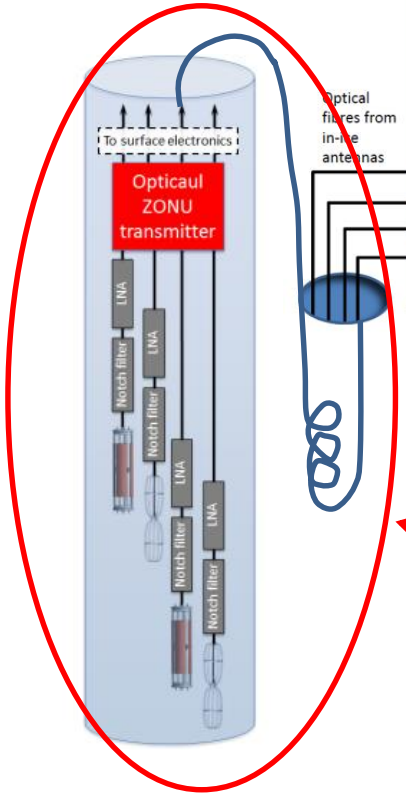
Calibration efforts

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



Station geometry on cm level, cable delays
For vertex reconstruction

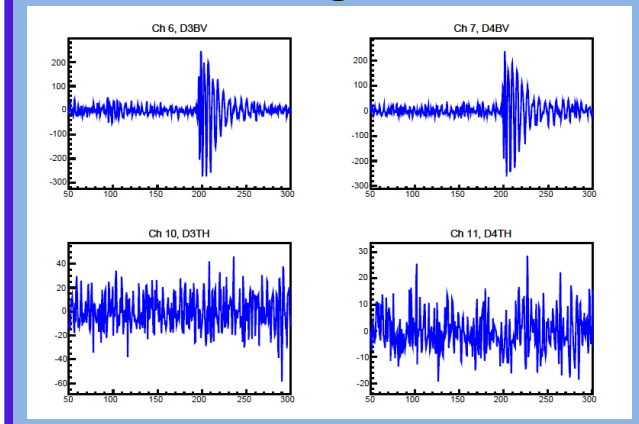




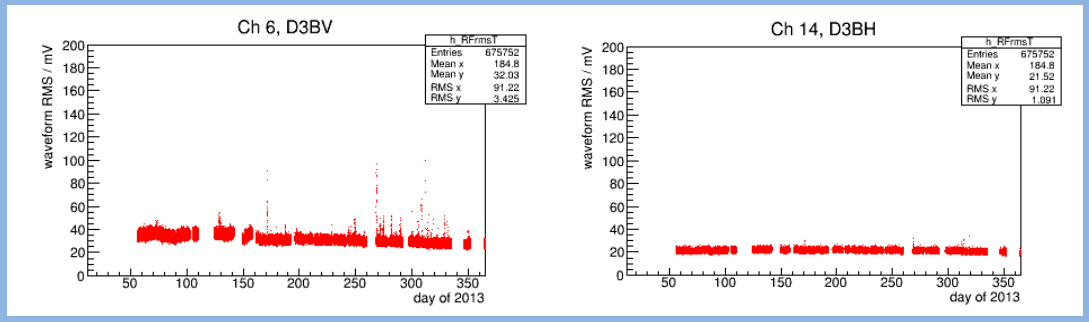
Signal chain:
Frequency response, amplitude, signal to noise ratio

The detector performance

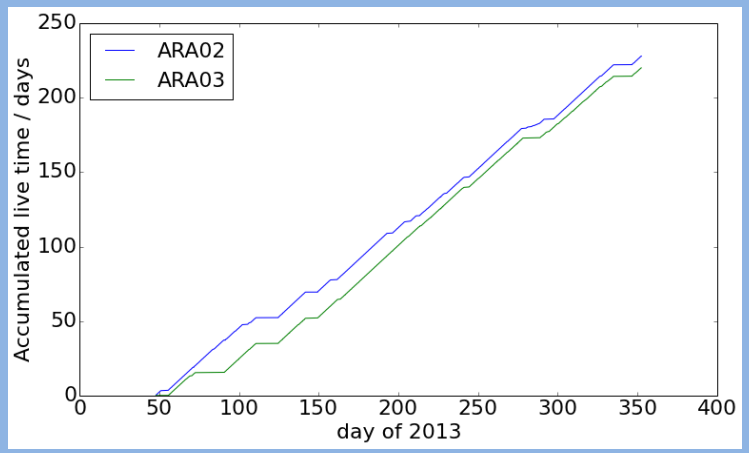
A calibration signal on ARA03



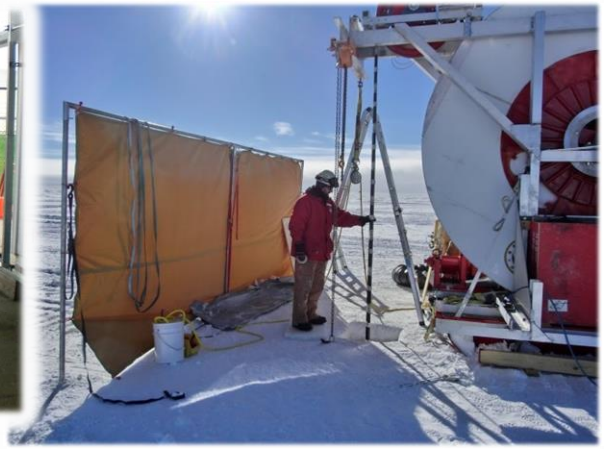
Noise RMS in 2013 (ARA02):



- Accumulated ~220 days of live time in 10 months
- 31 of 32 channels performing well

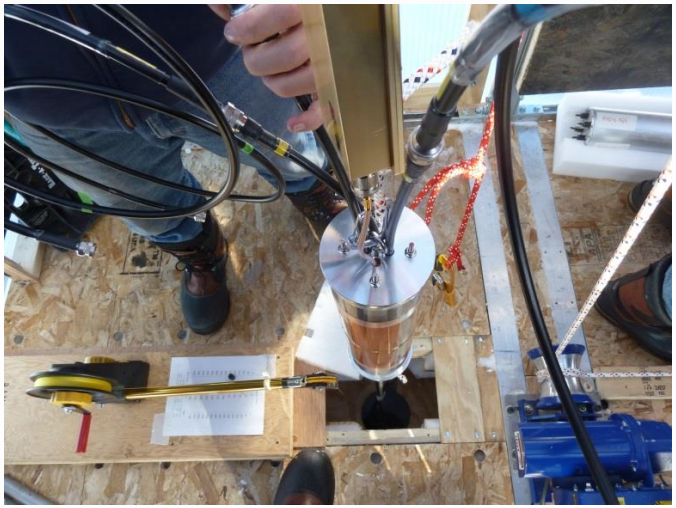


ARA construction: Drilling



ARA Construction: Deployment and commissioning

Deployment



Commissioning

Data analysis: The challenge

What we roughly see within 10 months in 2 station:

150 000 000 events

- Neutrinos (Ahlers2010) 0.2
- Thermal noise 149.999 M
- Impulsive radio background 1000

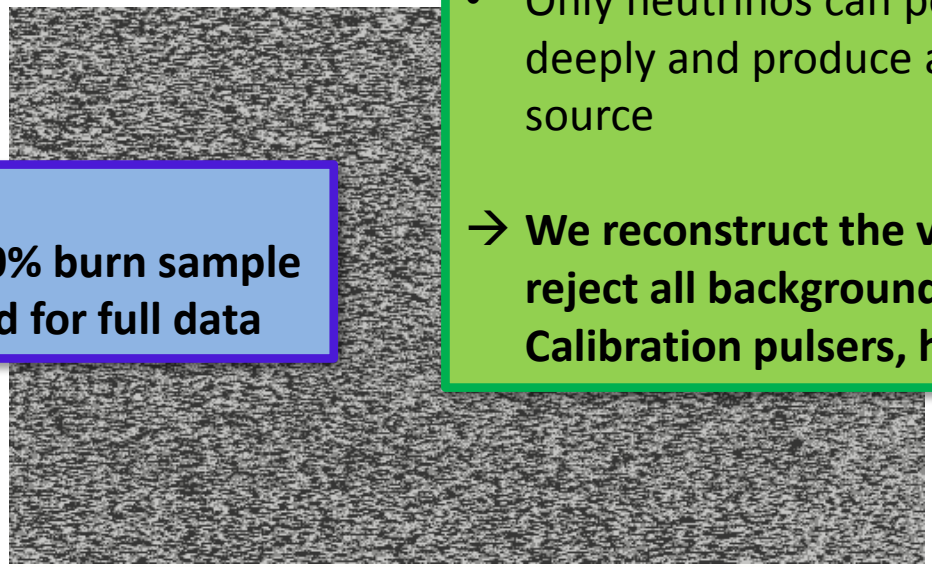
We need to exclude all thermal noise (10TB of data):

Time sequence filter

Look like neutrino events, but …

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

→ **We reconstruct the vertex location and reject all background by angular cuts: Calibration pulsers, human activity, etc…**



We do a blind analysis:
Develop all this on a 10% burn sample
Extrapolate background for full data

Thermal noise filtering

Time sequence algorithm:

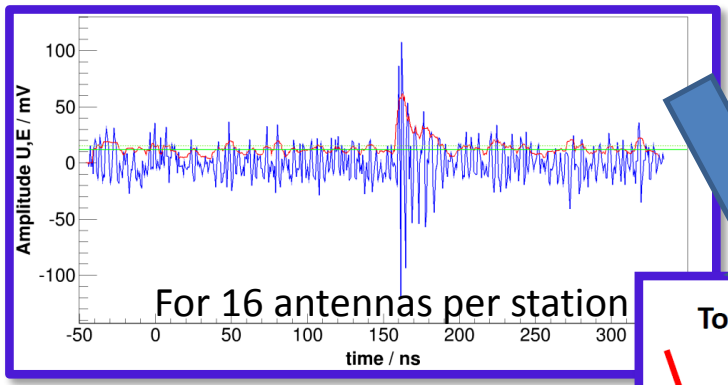
- Boosted hit count

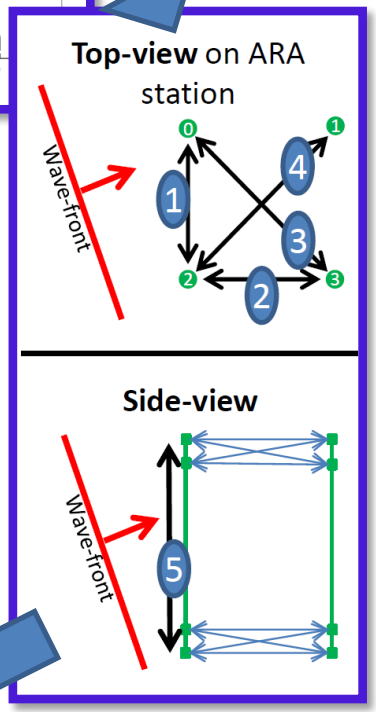
1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave

→***quality parameter***

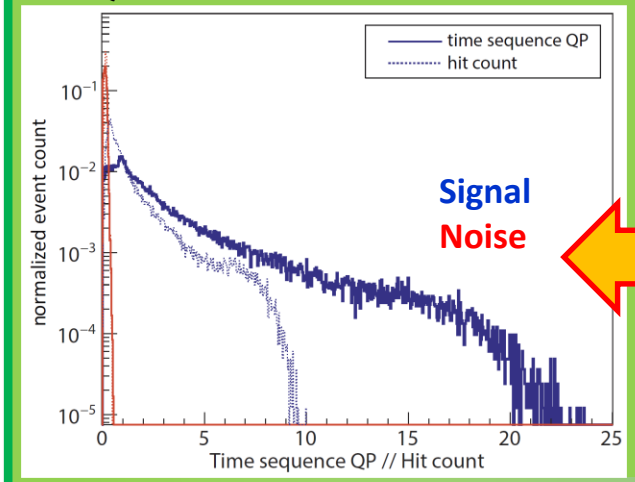
$QP \approxeq$ ***(similarity to wavefront)*** $\star$ ***(hit count)***

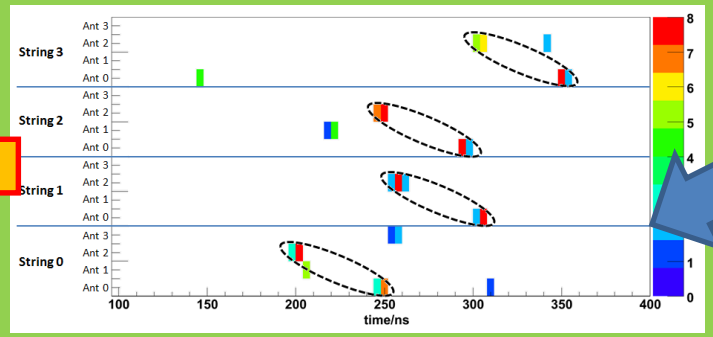
Keeps 92% of neutrinos between 1E18eV and 1E19eV at 99.9% noise rejection!





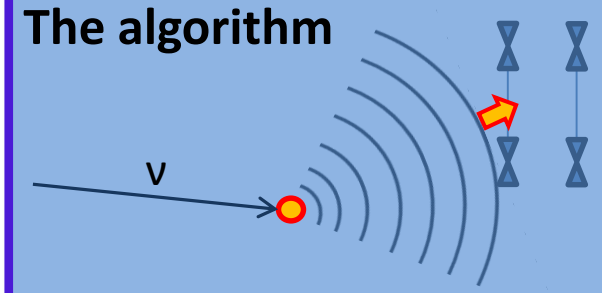
QP for simulated neutrinos



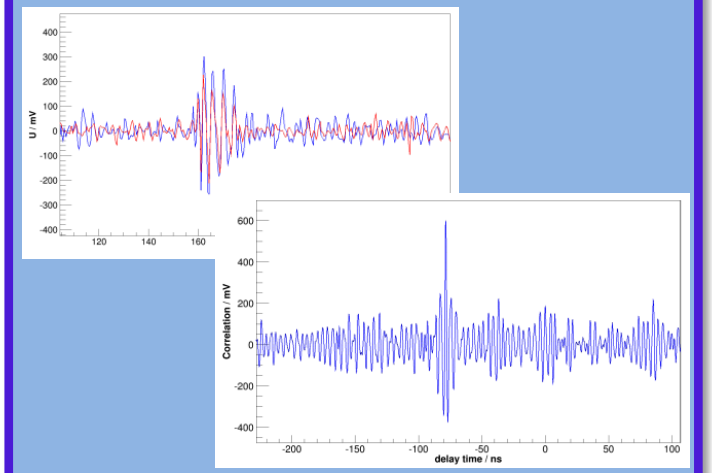


Vertex reconstruction

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

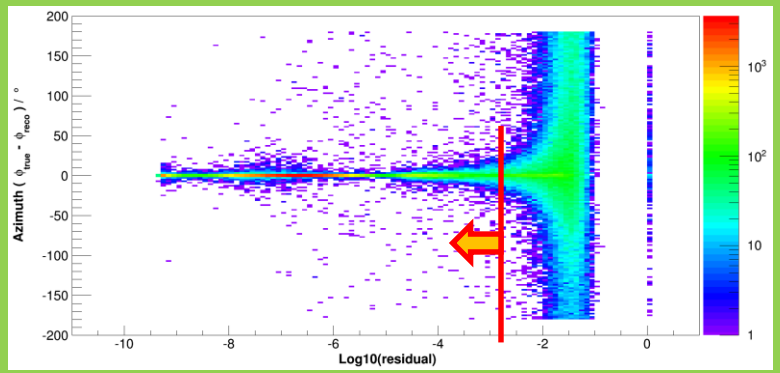
Main quality criterion is residual:

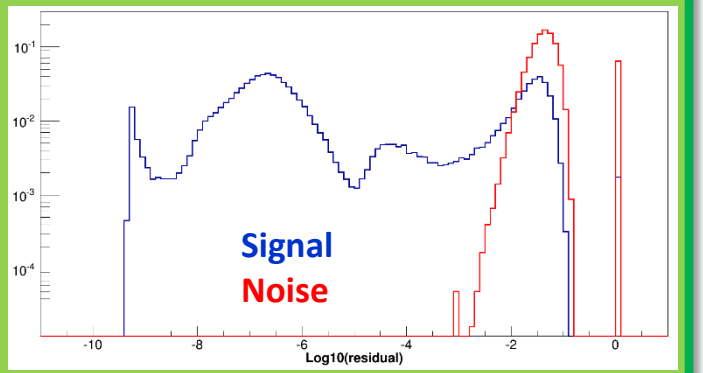
$$\mathrm{res} = \left\| \frac{\boldsymbol{b}}{|\boldsymbol{b}|} - \frac{\boldsymbol{A} \cdot \boldsymbol{v}}{|\boldsymbol{A} \cdot \boldsymbol{v}|} \right\|^2 \cdot \frac{\mathbf{1}}{\boldsymbol{N_{ch}}}$$

Tells us how well reconstructed position fits time differences

Reconstruction results

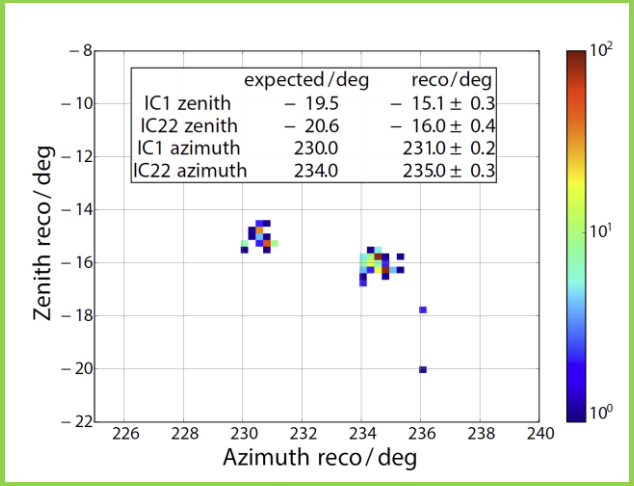
Reconstruction error vs residual



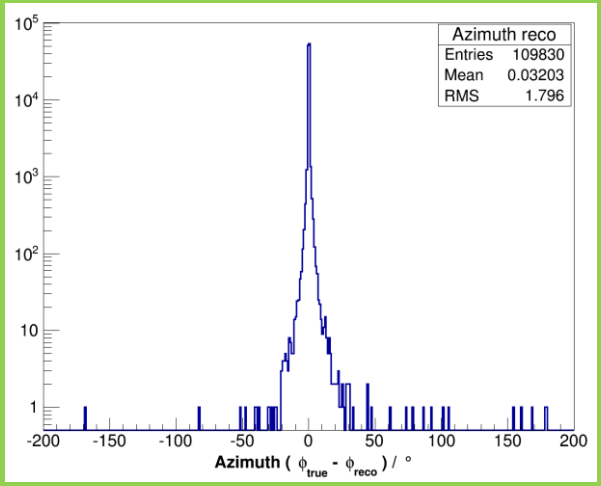


Other quality criteria further clean out bad reconstructions

Calibration source: distance 4km



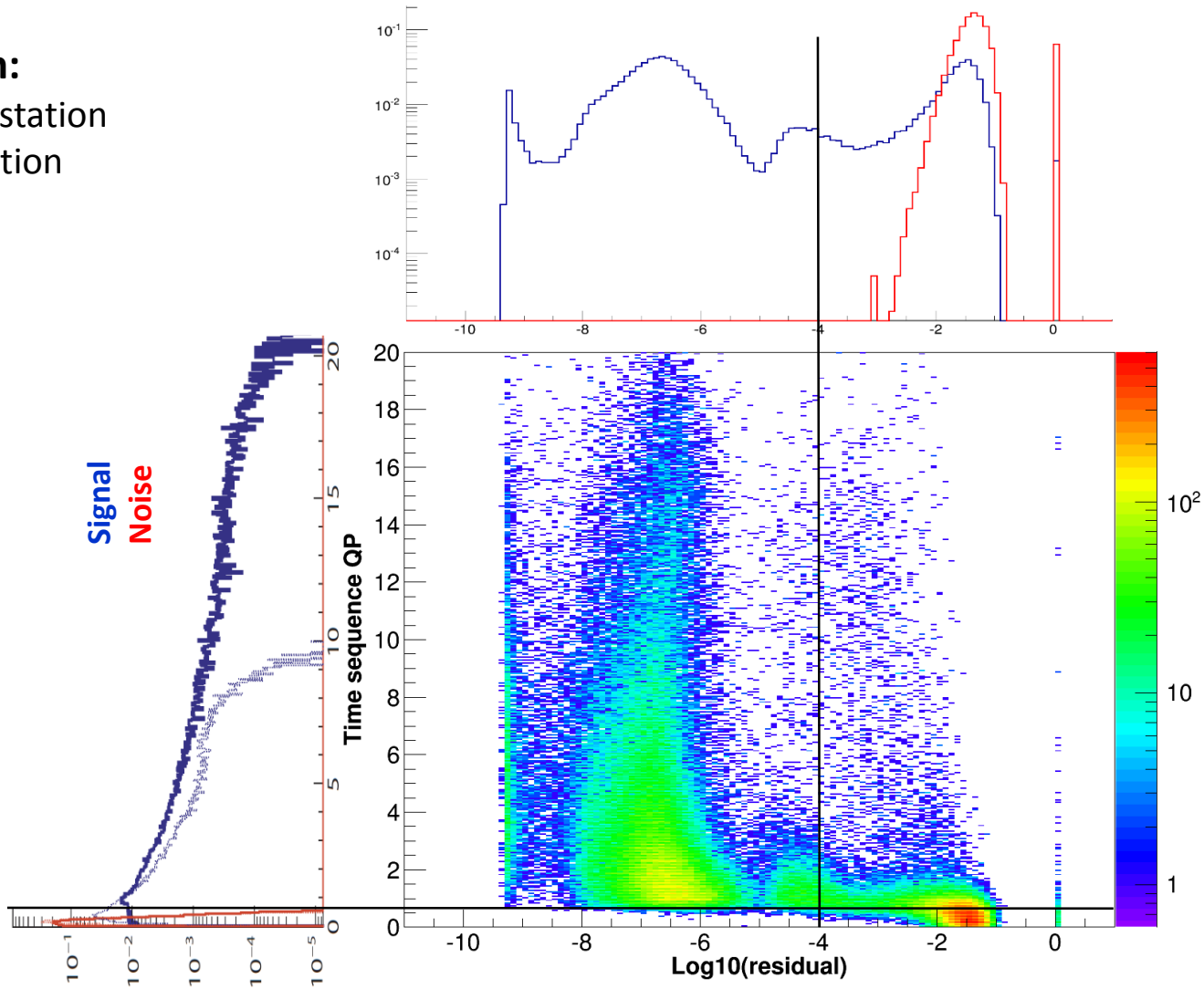
Azimuth reco of simulated neutrinos



Analysis parameters on simulated neutrinos

Simulate neutrinos with:

- Random vertex around station
- Random incoming direction
- Energy between
  10^16eV – 10^21eV



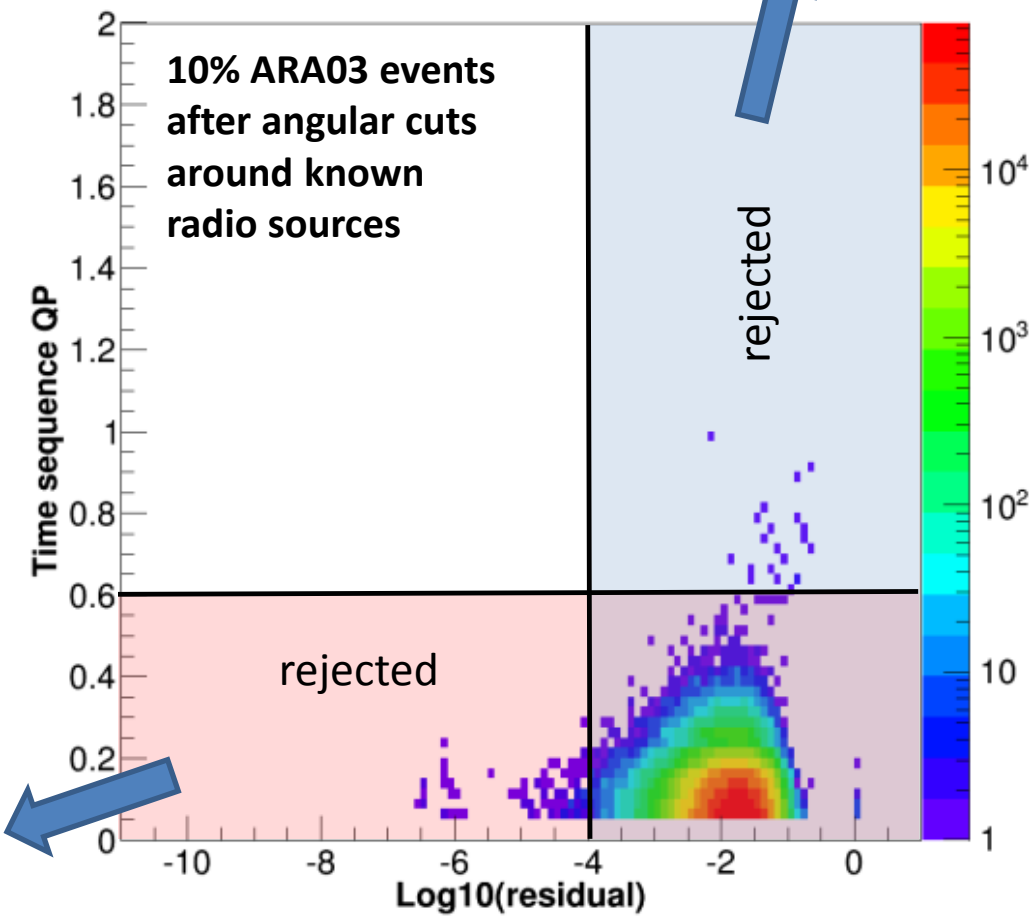
Neutrino identification = Background rejection

Reminder: Within 10 months…

- Neutrinos 0.2
- Impulsive background 1000
- Thermal noise 150 M

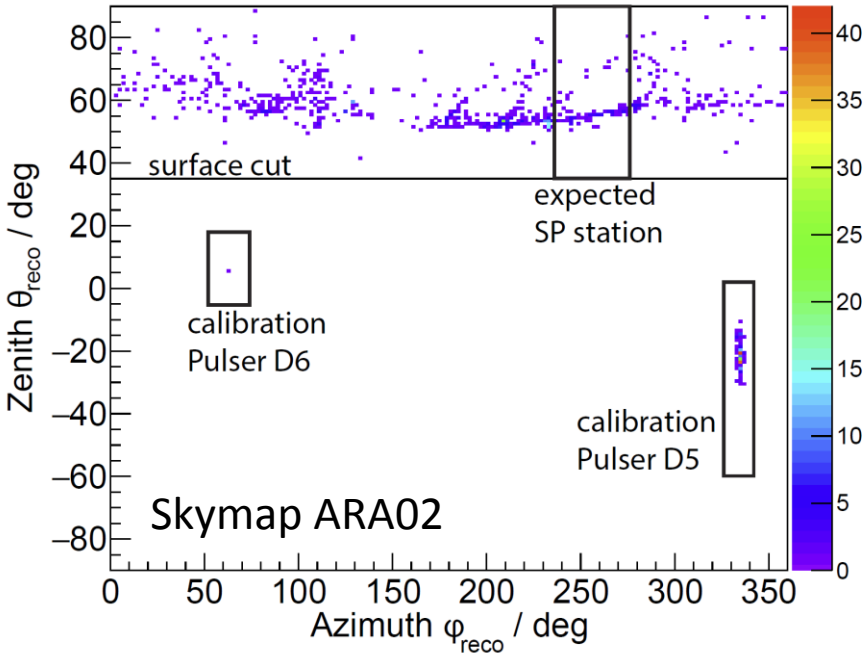
- Thermal noise events:
  Cut QP<0.6
- Impulsive events, miss-reconstructed:
  Cut res>1E-4

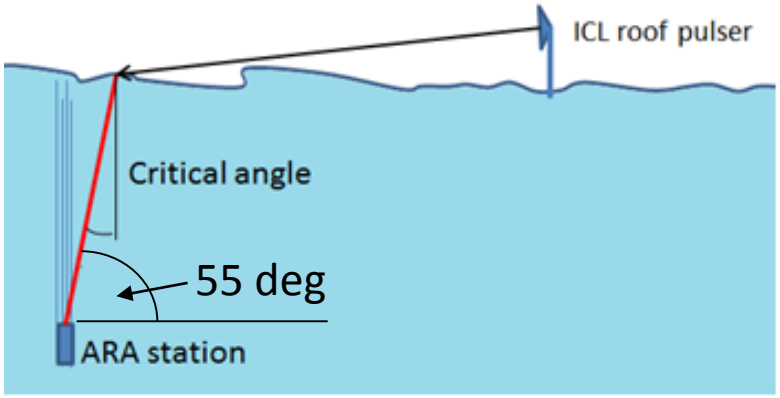
Impulsive events, miss-reconstructed

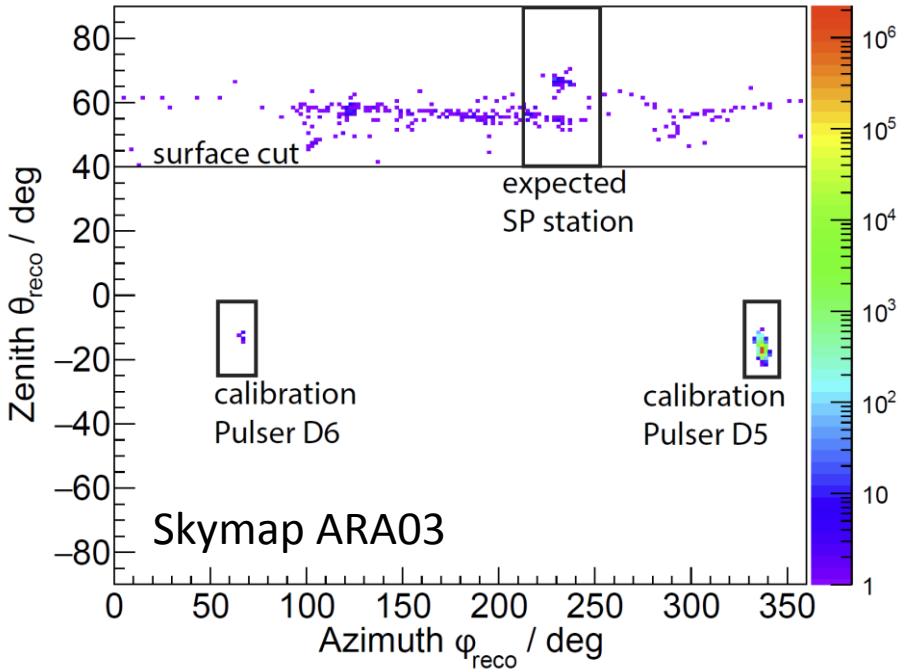


Thermal noise events

Results

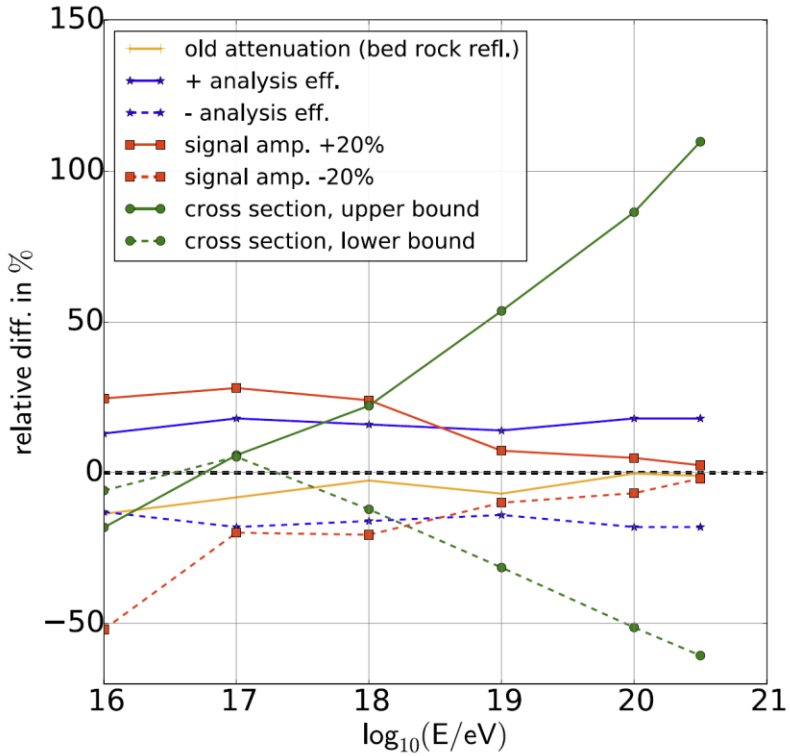

surface cut
expected
SP station
calibration
Pulser D6
calibration
Pulser D5
Skymap ARA02
Zenith θ_{reco} / deg
Azimuth φ_{reco} / deg


ICL roof pulser
Critical angle
55 deg
ARA station


surface cut
expected
SP station
calibration
Pulser D6
calibration
Pulser D5
Skymap ARA03
Zenith θ_{reco} / deg
Azimuth φ_{reco} / deg

Systematic errors

Relative error on the final effective area



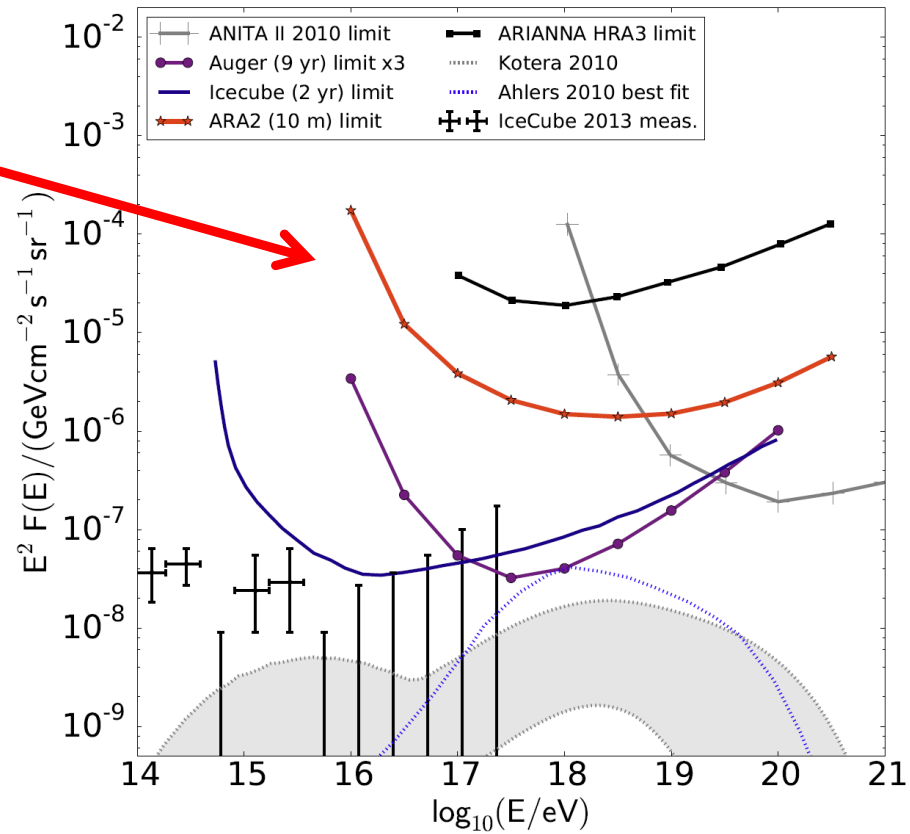
Dominant errors are:

- Interaction cross section uncertainties: has never been measured at such high energies
- Signal amplitude:
  Calibration of the signal chain is still relatively coarse.
  → **This can be improved significantly**

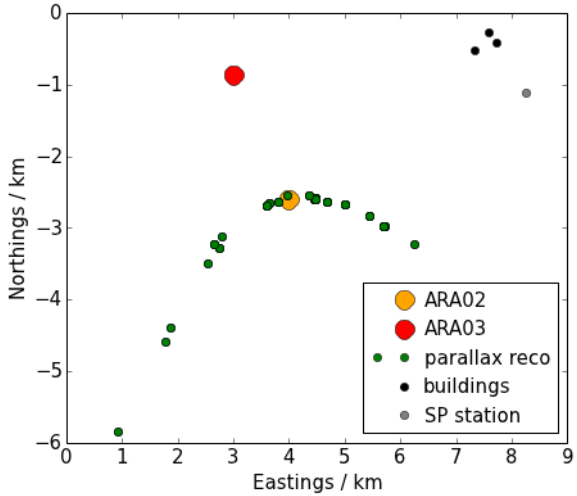
Results

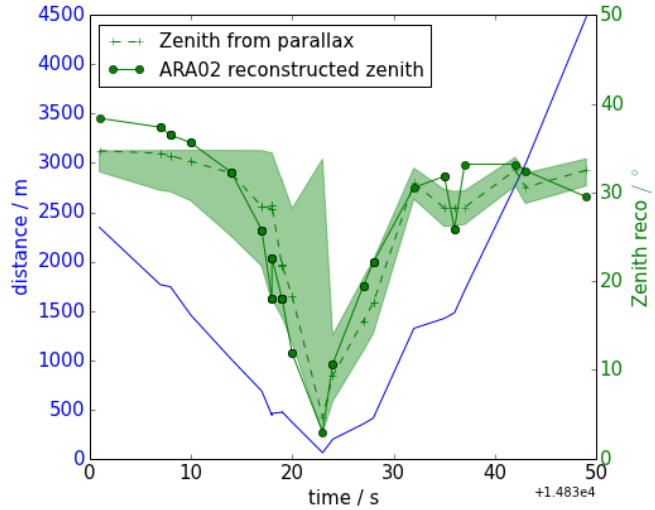
No neutrino candidate found
→matches expectation of 0.1 neutrinos from Ahlers2010 estimation after applying cuts.

We can place a limit



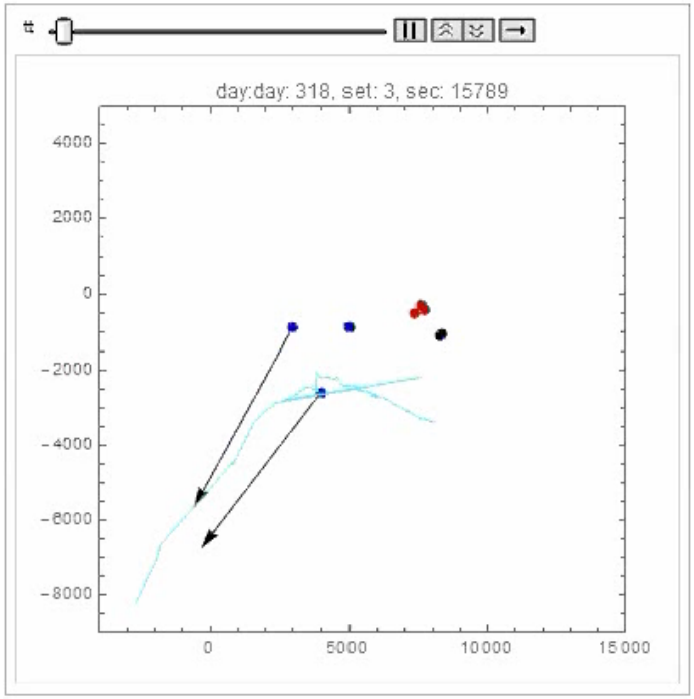
Lets look at the events which we have found





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!

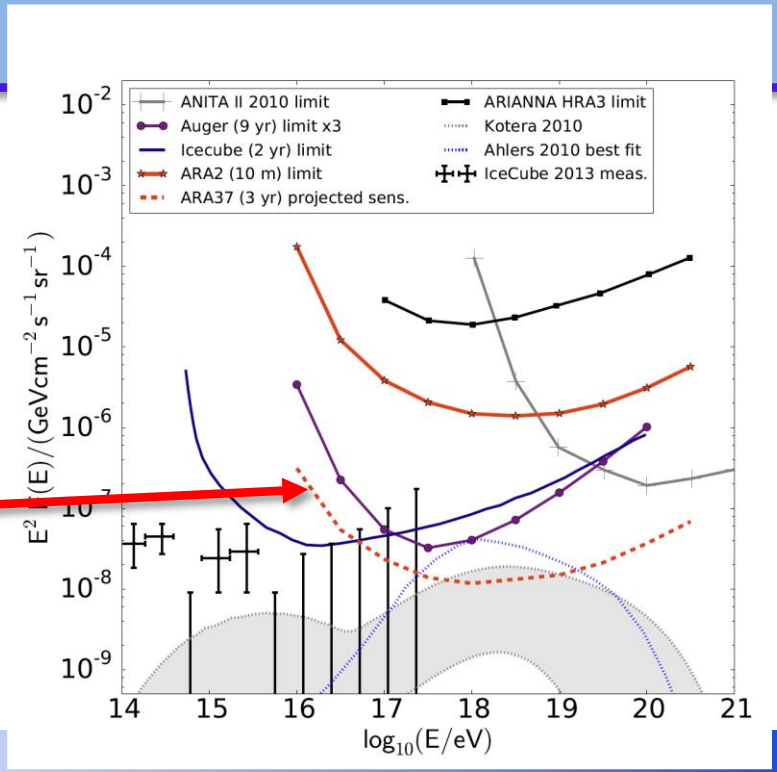
Summary & Conclusions

- Search for UHE neutrinos is interesting
- ARA is one of the pioneer neutrino detectors via radio waves
- initial ARA stations are deployed, calibrated and produce useful data
- Efficient analysis algorithms have been developed to reject thermal noise and to reconstruct radio signals
- A neutrino limit could be produced

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

ARA37 projected sensitivity

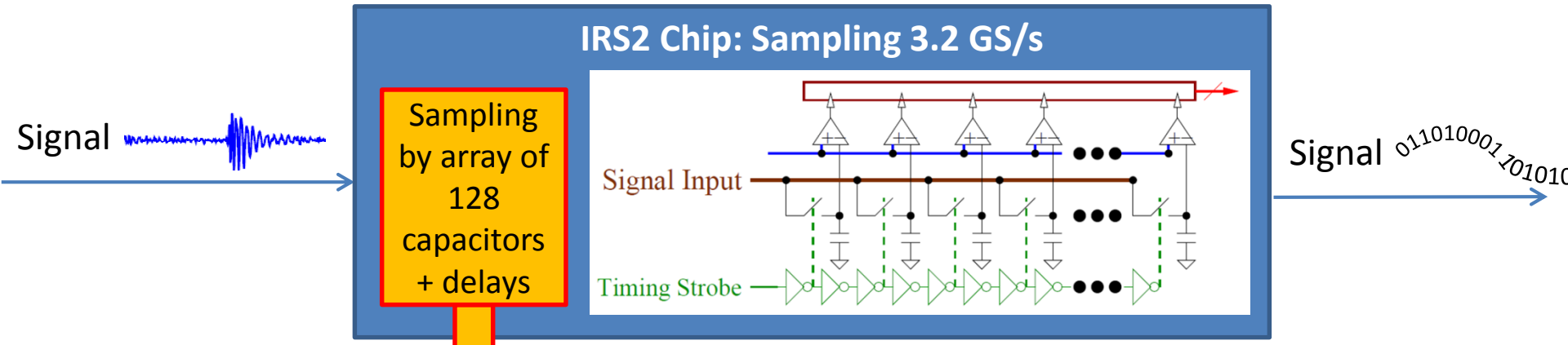
- Station operations have been improved significantly!



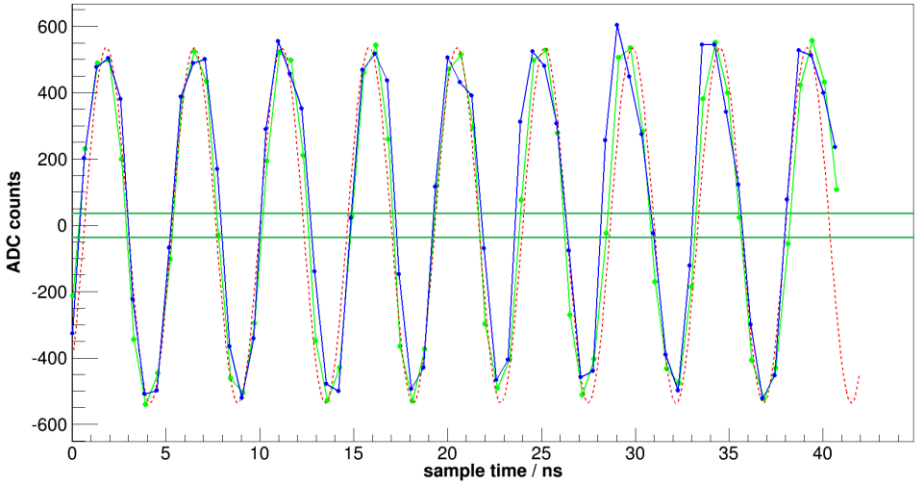
Thank You!

BACKUP

IRS2 calibration: timing



Use sine wave inputs for calibration

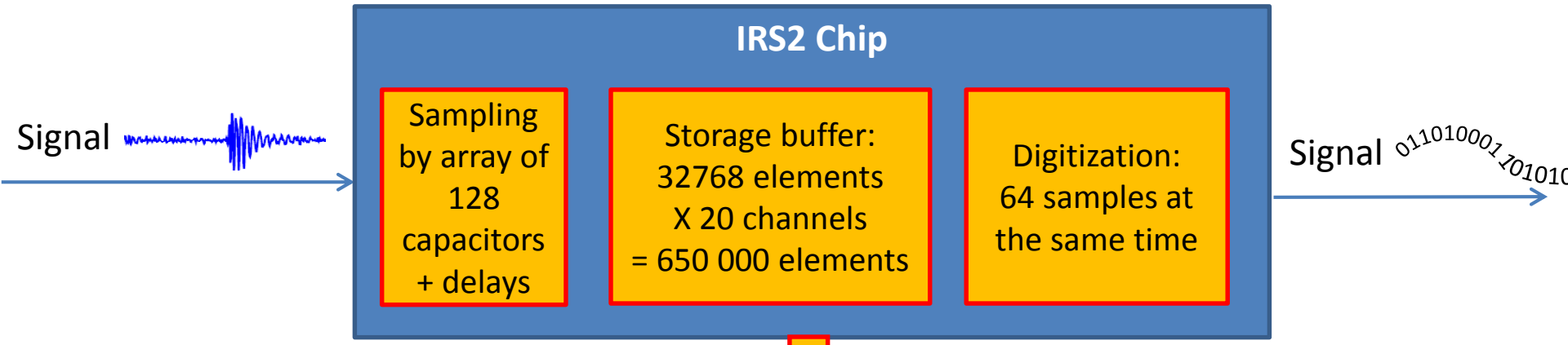


- Correct average speed through fit frequency
- Correct timing for individual samples at **+/- 30 ADC** counts

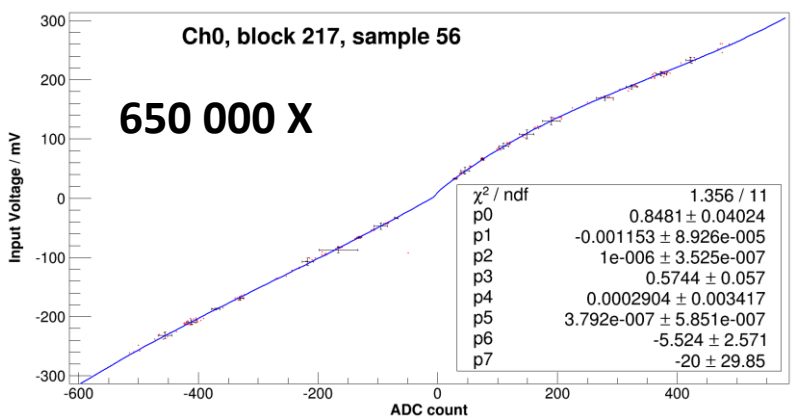
Multiple iterations

Multiple iterations

IRS2 calibration: voltage

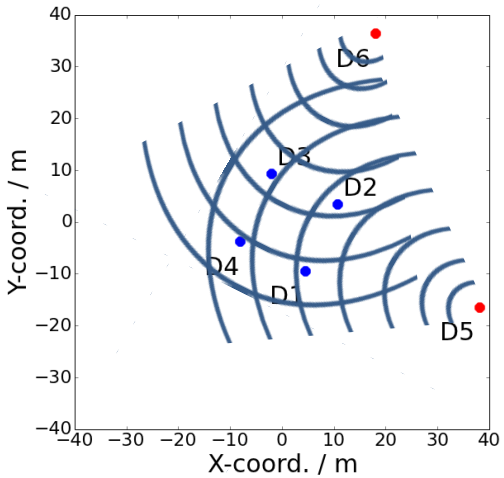


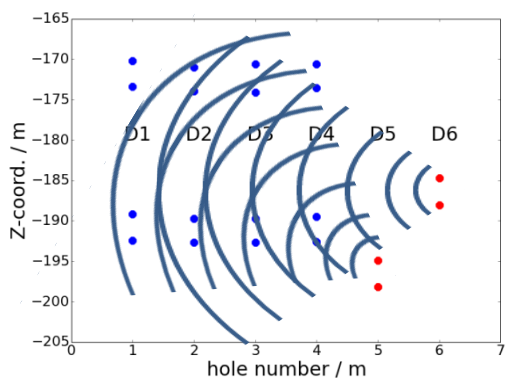
Use timing calibrated sine waves



- Fit waveform nominal input amplitude
- take calibration data for samples at peak values:
  Amplitude of fit, ADC counts
- Fit the resulting curve (multiple times with random seed)

Geometrical calibration





4 calibration sources per station (D5, D6)

→ 28 independent equations **from time differences dt**

Need initial assumptions:

- strings are perfectly vertical,
- internal structure and time delays are perfectly known
- Define reference string, fix rotation

→ **Reduces 80 unknowns to 17**

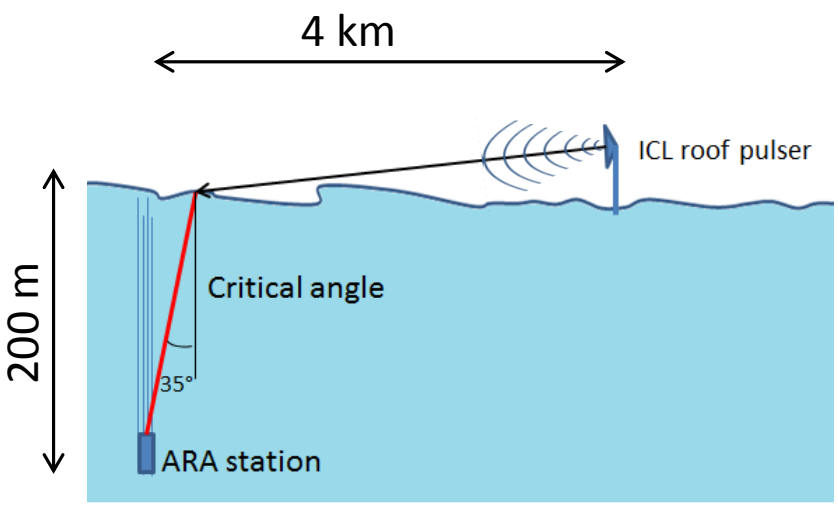
Fitting

- Minimize:

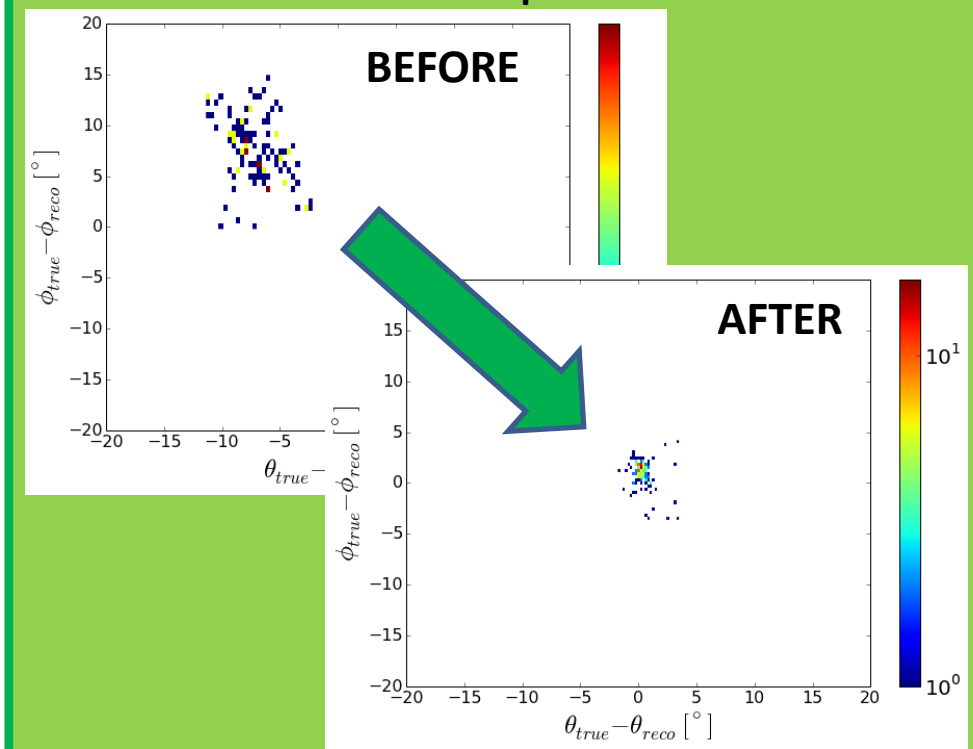
$$\chi^2 = \sum \left[c^2 (dt^2_{k,i,ref} - dt^2_{k,j,ref}) + x_k \cdot 2x_{ij} + y_k \cdot 2y_{ij} + z_k \cdot 2z_{ij} - t_{k,ref} \cdot 2c^2 dt_{k,i,j} - r_i^2 + r_j^2 \right]$$

k = calibration source
ref = reference antenna
i,j = measurement antennas

Calibration results



Cross check: ICL roof pulser reconstruction



Station	Parameter	RMS no cal.	RMS cal.
ARA02	Zenith θ	1.1°	0.6°
	Azimuth Φ	1.3°	0.8°
ARA03	Zenith θ	2.0°	0.6°
	Azimuth Φ	3.1°	1.2°

~1° RMS