Data Analysis Techniques From

ACoRνE

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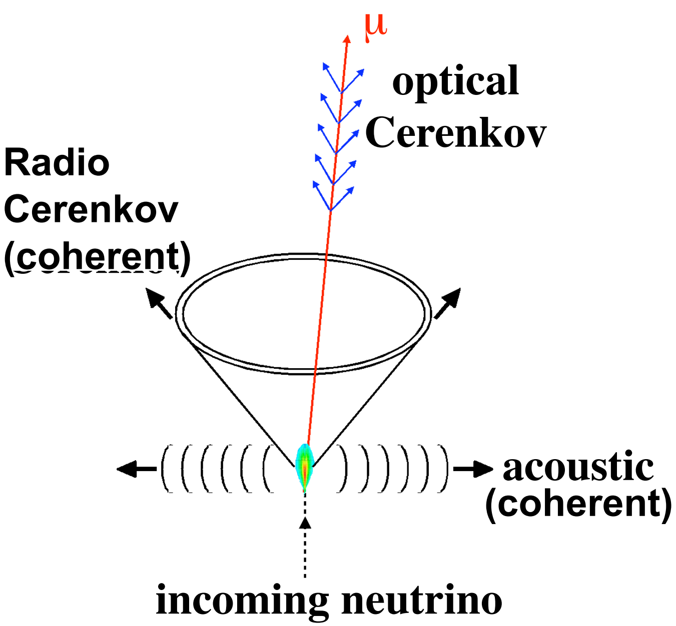
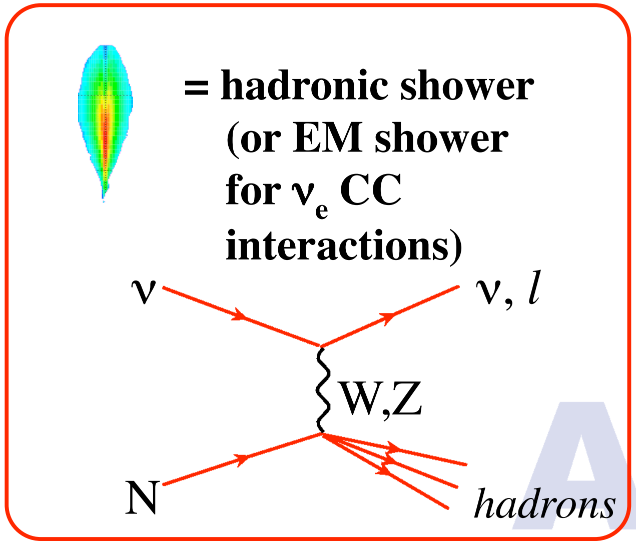
Why Acoustic Neutrinos?

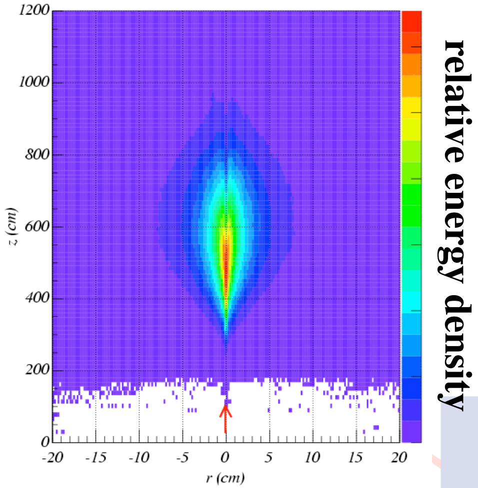
- 4 ways of detecting UHE neutrinos - Optical, radio, air showers, and acoustic.
- At energies > 1 x 10^{18} eV, the magic number is 1 particle per square km per year (in dense material), so for even just a few particles many km^3 arrays are needed.
- Limits Optical and air showers, leaving acoustic and radio as two complementary techniques.

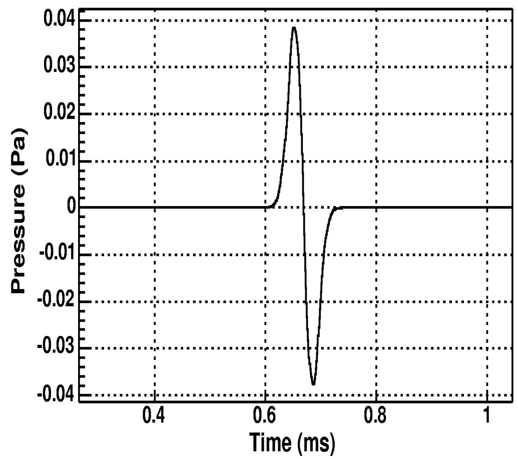


	Attenuation Length		
	water	ice	salt
EM optical (Cerenkov)	~ 50 m	~ 100 m	? (large)
EM radio (0.1-1.0 GHz)	~ 0	~ few km	~ 1 km
Acoustic (10 kHz)	~ 10 km	? (large)	? (large)

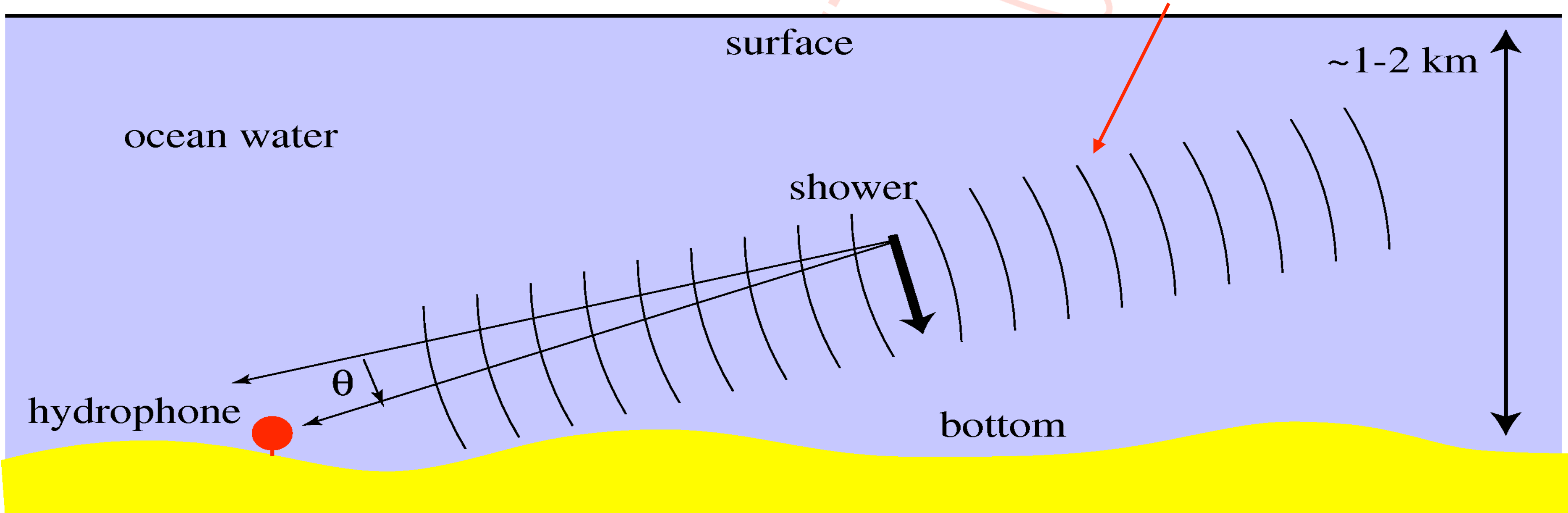
Detection of Acoustic Neutrinos





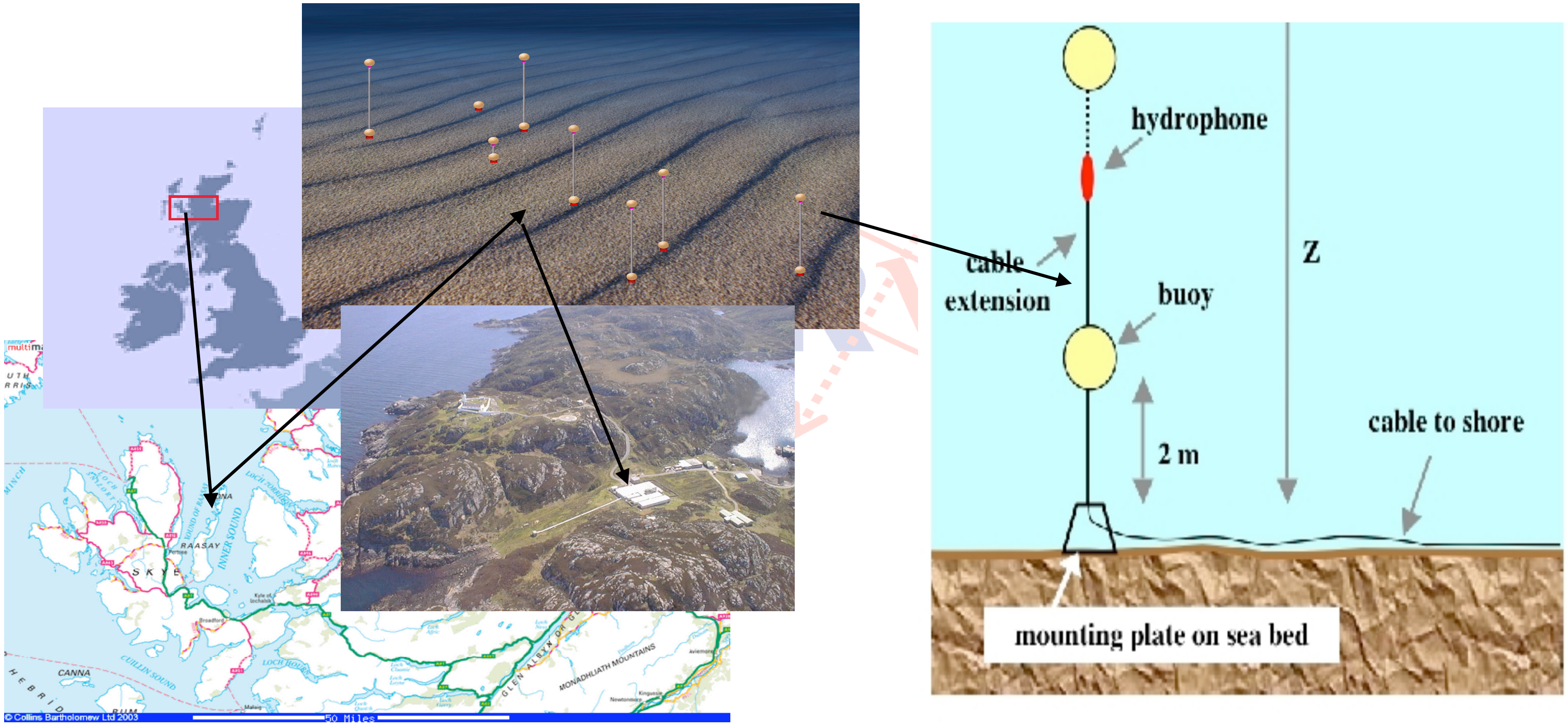


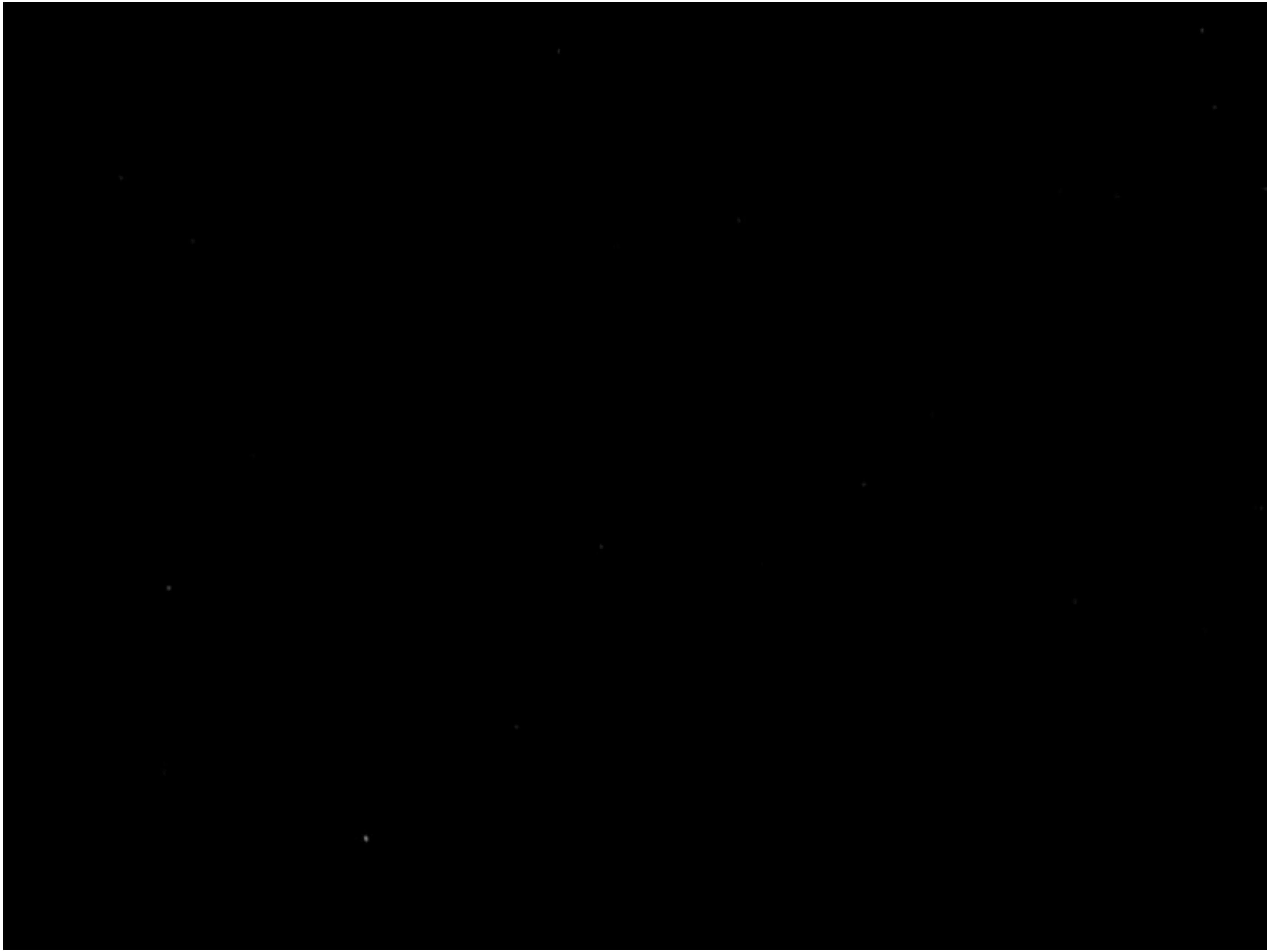
"pancake" propagates ⊥ to shower direction



The Rona Array

- Off the Isle of Skye we have an 8 detector array
- We have been taking since December 2005





Data Reduction

ACoRNE has been taking data since December 2005

Data written to tape every night ↓

Unfiltered data stored in ADC counts @ 140 kHz

10 seconds of data passed to reduction code ↓

5 most energetic pulses stored

10 seconds of differentiated data passed to reduction code ↓

5 most neutrino-like pulses stored

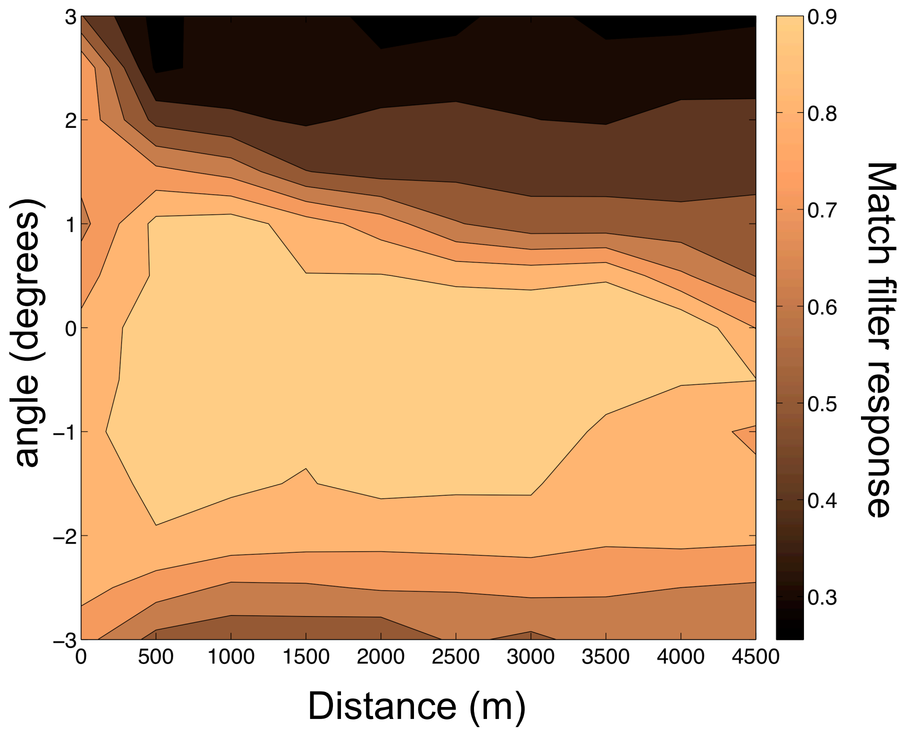
5 most energetic pulses stored

↓

Unique pulses kept, with priority given to neutrino-like pulses

Match Filtering

- If the signal that is being searched for is known, or thought to be known, a match filter is the optimal filter to use.
- For our data reduction, a set of 9 matched filters were developed covering 0→5000 m and -3→3 degrees.
- The filters were developed using a specifically designed ultra high energy neutrino shower parameterisation (Bevan et. al. 2007).



The match filter response for a 10^{11} GeV pulse

Co-incidence

Data reduction output

Data split into 2 second segment

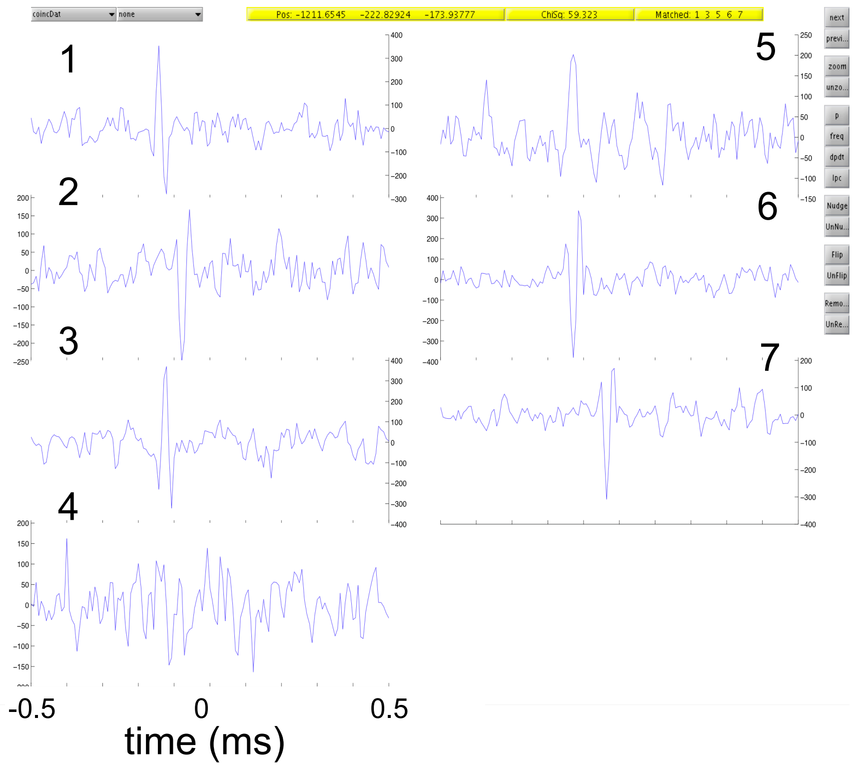
Every possible co-incidence of every pulse considered

Causality check performed

If fail, all possible co-incident events below are considered, i.e. if an 8 fold fails, all possible 7 fold co-incidences are tested

All co-incident events stored

Example Event



Notice – Hydrophone 4 does not appear to match the others, and the pulses do not appear to align.

Removing Noise, Nudging and Flipping

Co-incident event (may contain random noise)

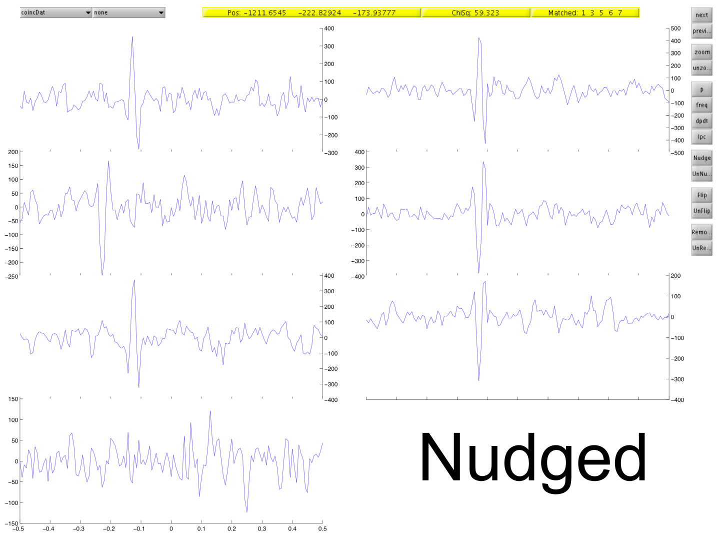
Cross correlate all pulses in the event

Using the cross correlation, find pulses that match, remove others (noise) and align.

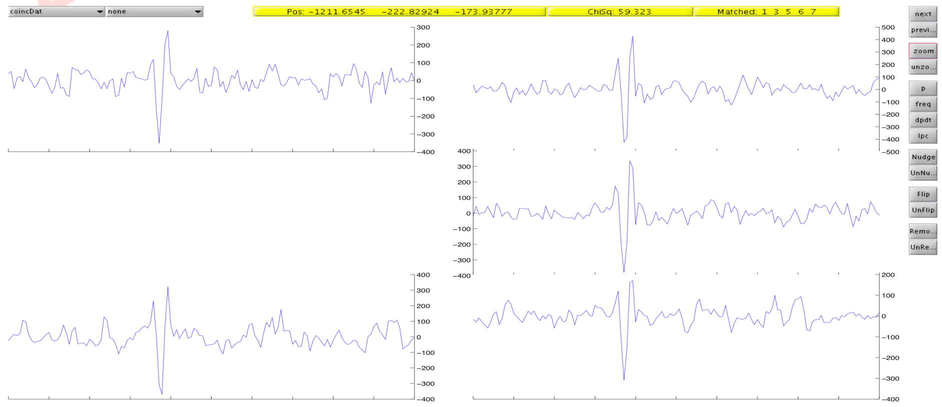
Find inverted pulses and flip

Store Event

Aside - Pulses need nudging due to the match filter slightly mis-triggering, but why some pulses are inverted is yet to be fully understood



Nudged

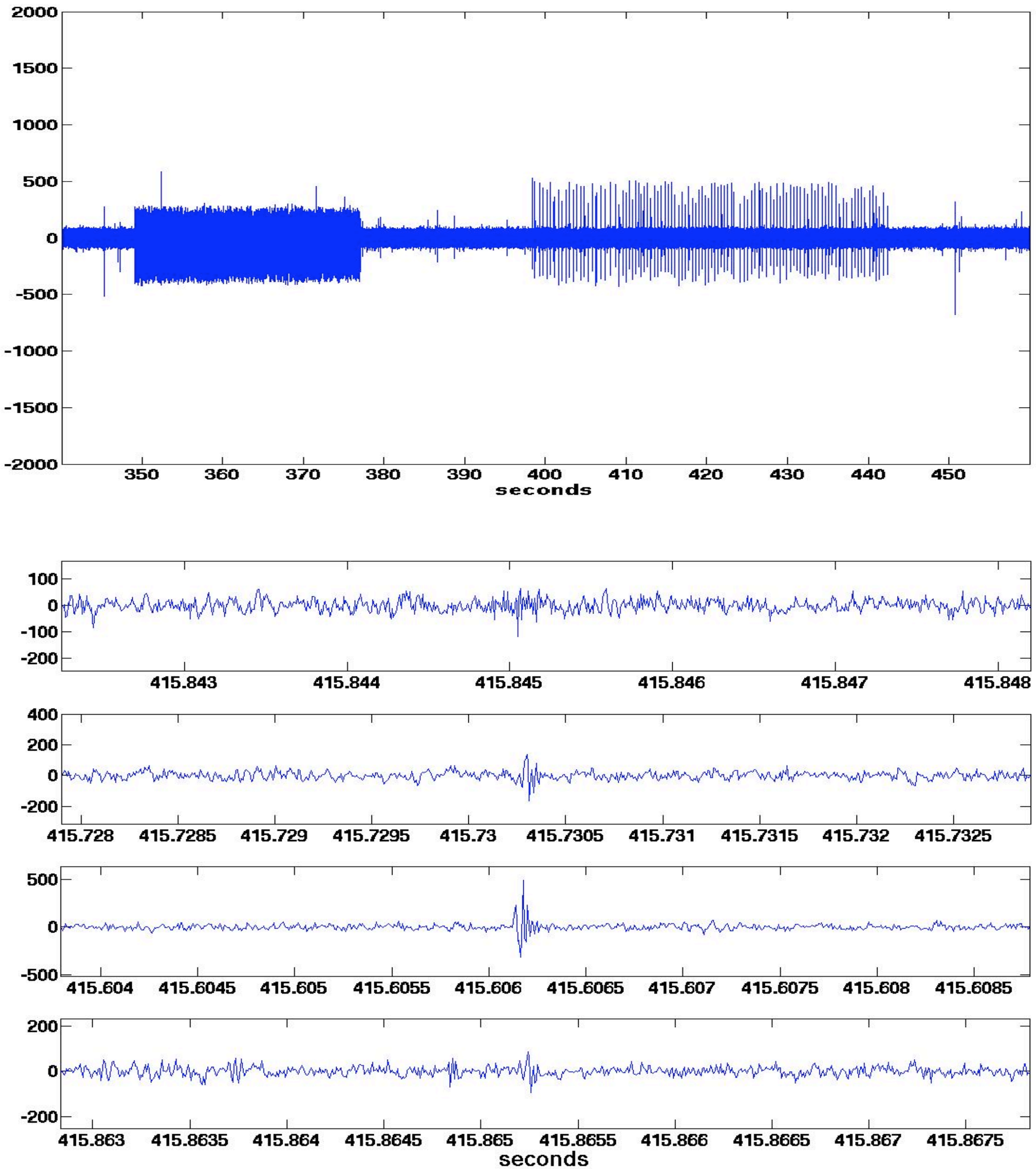


Final event

Rona Field Trip

- In August 2007, we went to Rona and placed (after a few stomach churning days!) a selection of pulses (including predicted neutrino like pulses) above the detector array.
- The data was collected from our DAQ and run through the analysis code to see if we could successfully pick out the pulses, and reconstruct the boat position.

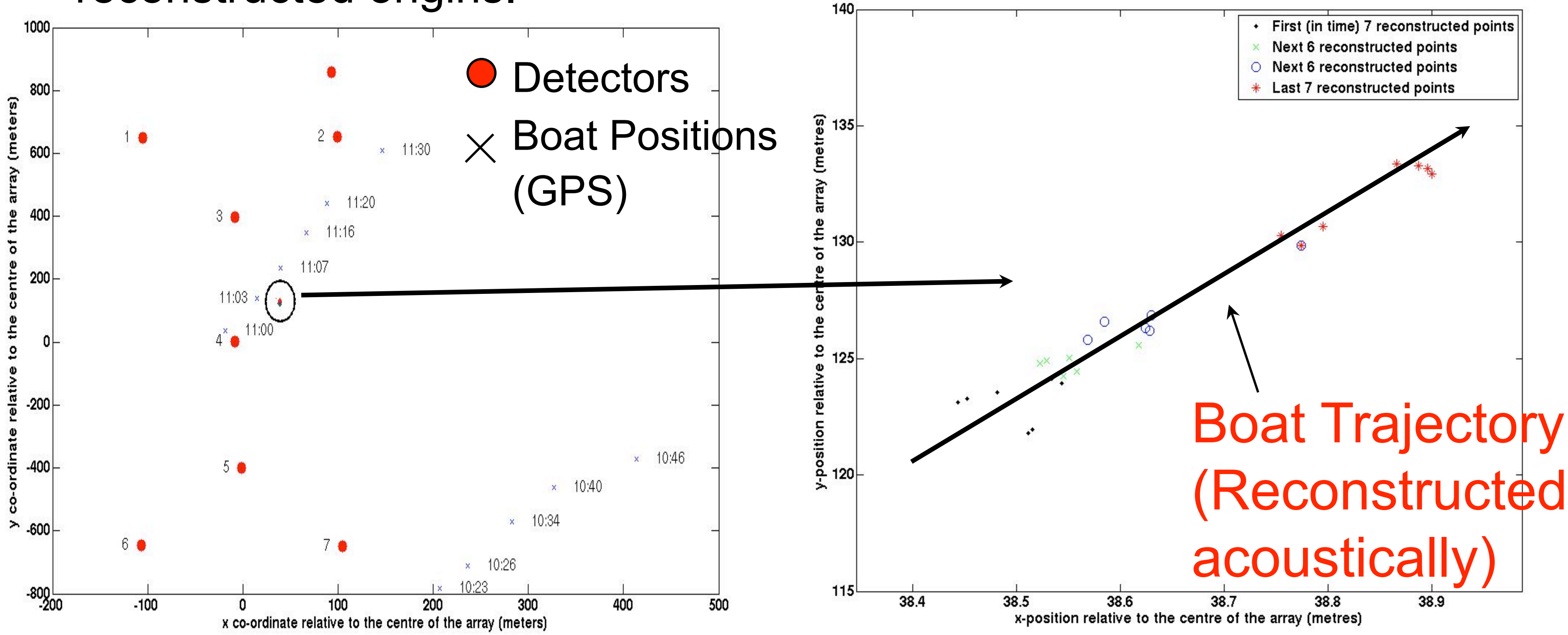
Picking Out the Pulses



- The top plot shows raw data where 2 periods of pulse injection can be seen
- The bottom plot shows a close up of one of these pulses on the 4 nearest detectors
- Reconstructed 25% of events

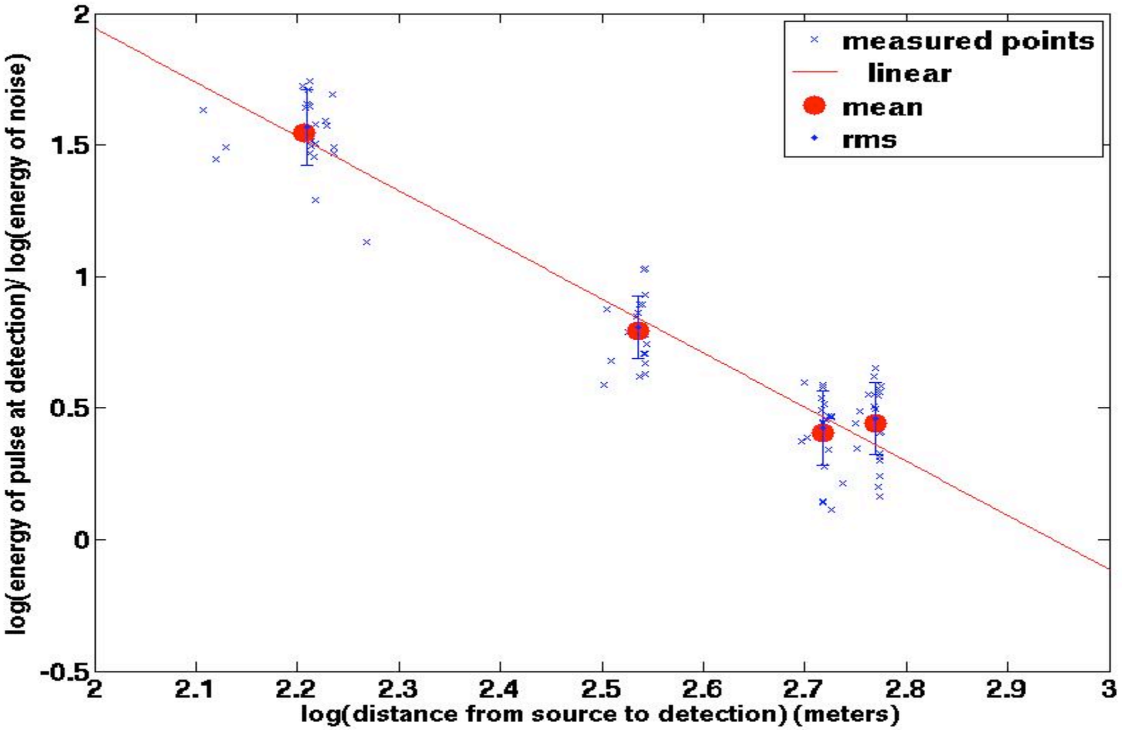
Boat Reconstruction

- Using the known detector positions and the time of arrival of the pulse on each hydrophone, each detected pulses' origin (if detected on > 4 detected) could be calculated.
- The boat, and drift, was successfully reconstructed
- Plots show the detector positions, the boat positions, and the reconstructed origins.



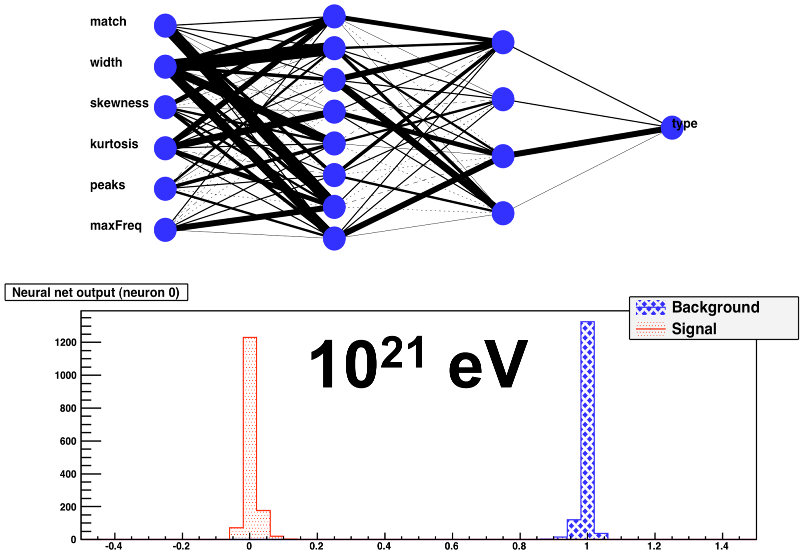
Energy Dissipation

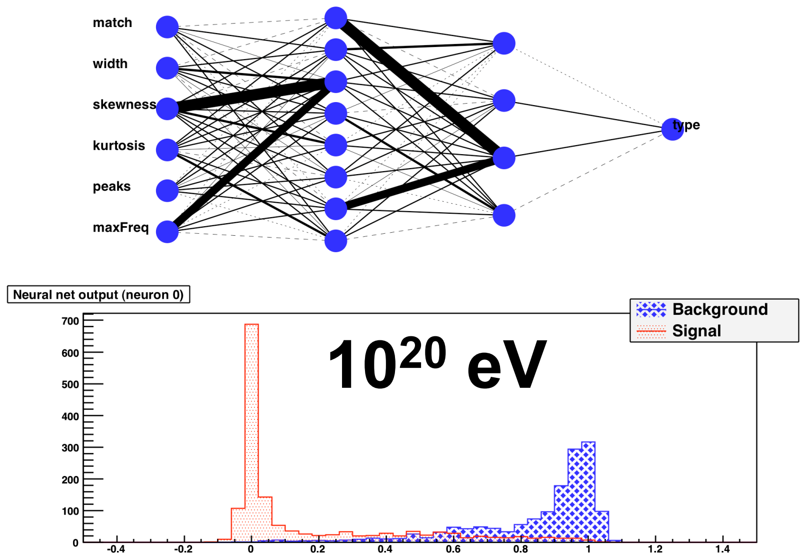
- Another test was to see if the energy of the reconstructed pulses fell as $1/r^2$.
- Again, this proved successful with the slope of the line being -2.1 ± 0.23.



Further Analysis

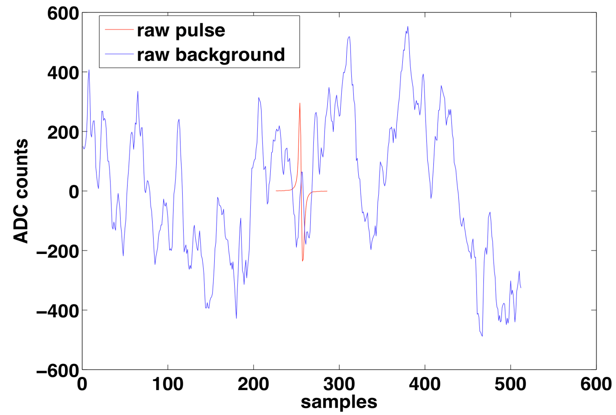
- The Rona field trip proved a successful test of the analysis code. Using this analysis structure the Rona data was reduced. The code, however, still does not discriminate against non-neutrino like events. To further reduce the data each event was further scrutinised.
- This test was in the form of a neural network. Each pulse was tested separately, and was classified by peak frequency, width around the peak frequency that contains 69 % of the data, kurtosis, skewness, peakyness, and match filter output (others classifiers were tried).

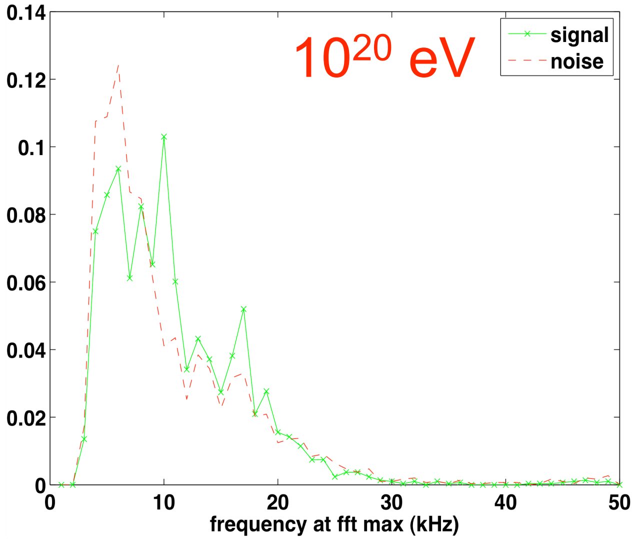


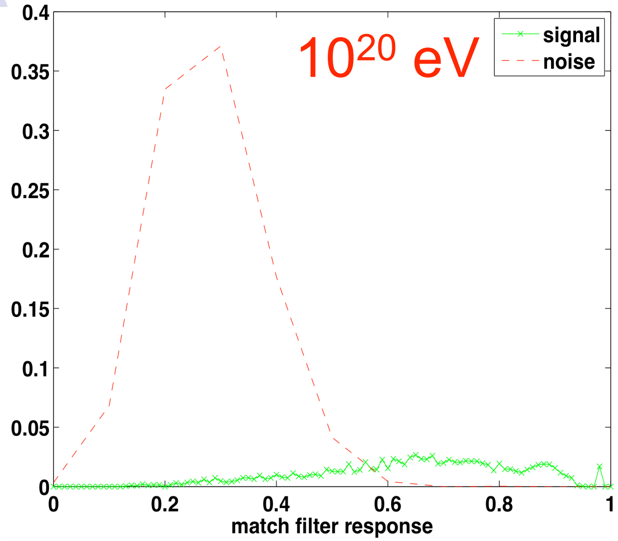


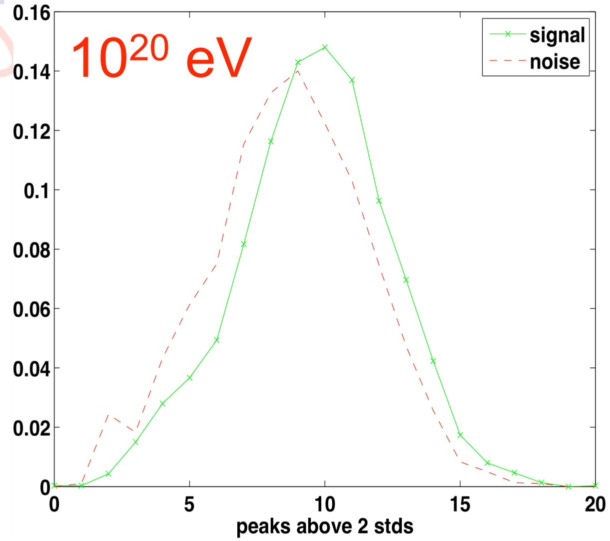
Peak Frequency, Width, and Matched Filter Out

A 1×10^{20} eV pulse superimposed on a random sample of noise from the Rona data.







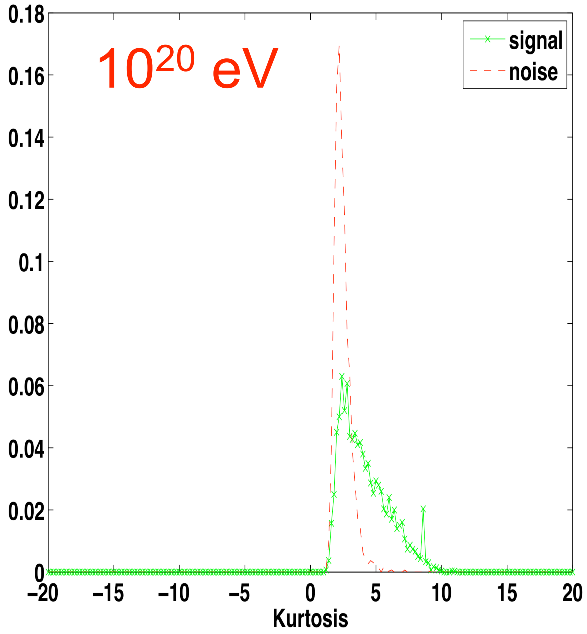


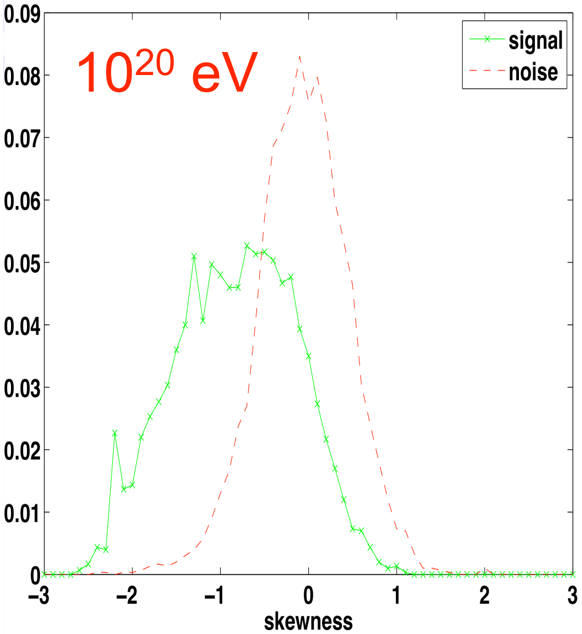
Kurtosis and Skewness

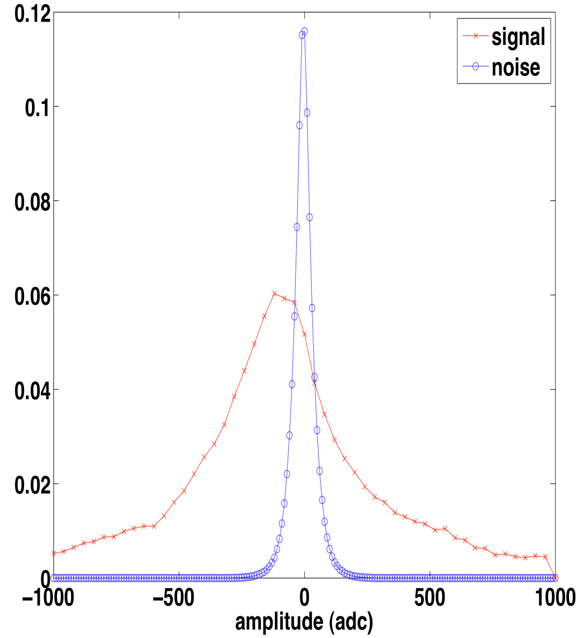
$$\text{kurtosis} = \frac{E((x-\mu)^4)}{\sigma^4} \quad \text{skewness} = \frac{E((x-\mu)^3)}{\sigma^3}$$

μ is mean of pulse, σ the standard deviation, and E is the expectation value.

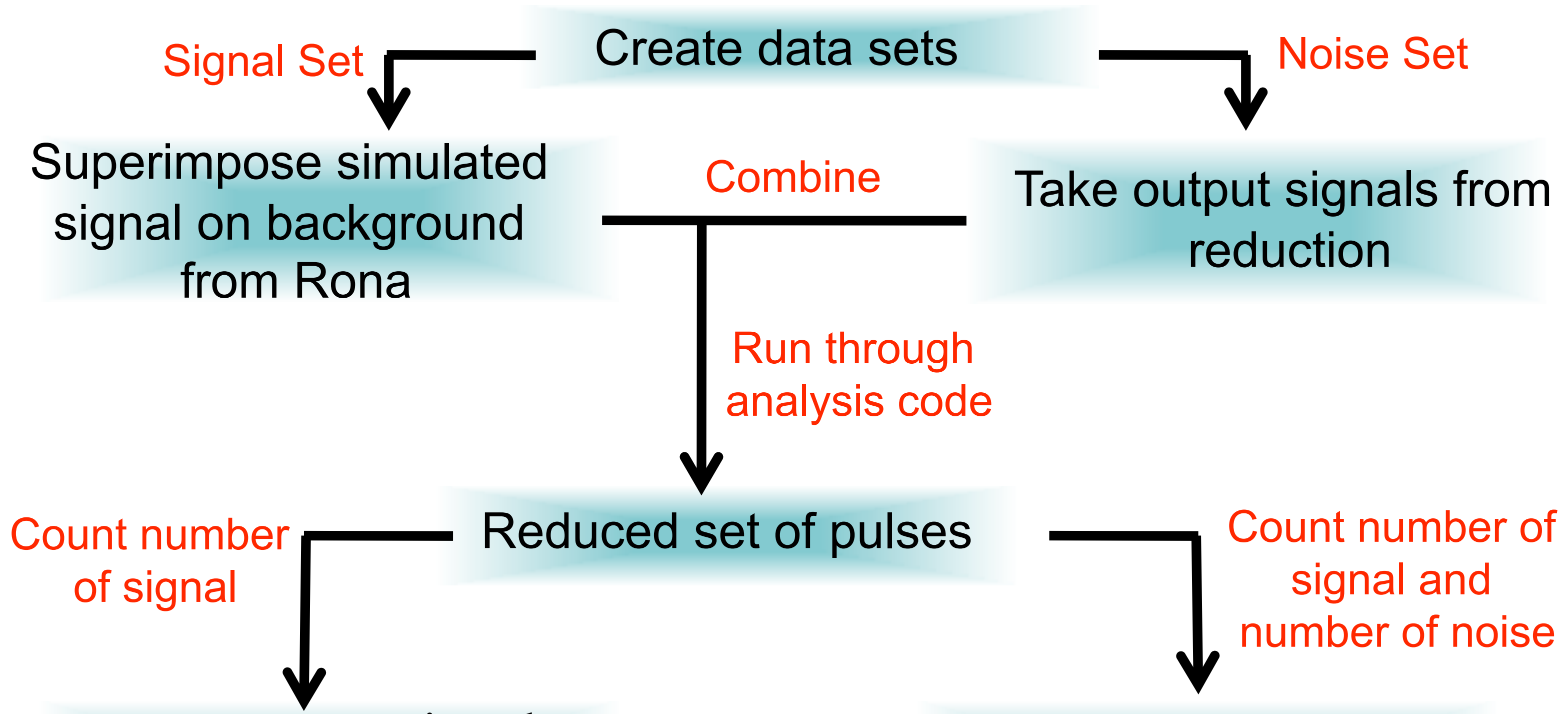
What does this actually mean in terms of the shape of the pulse?







Purity and Efficiency



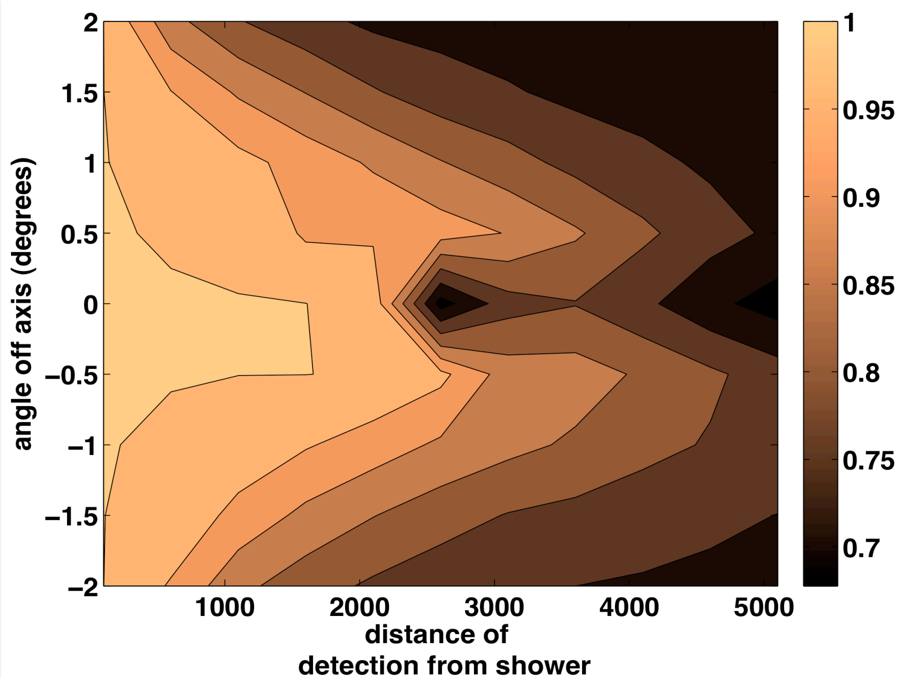
$$\text{efficiency} = \frac{\text{signal}}{\text{total signal}}$$

$$\text{purity} = \frac{\text{signal}}{\text{signal} + \text{noise}}$$

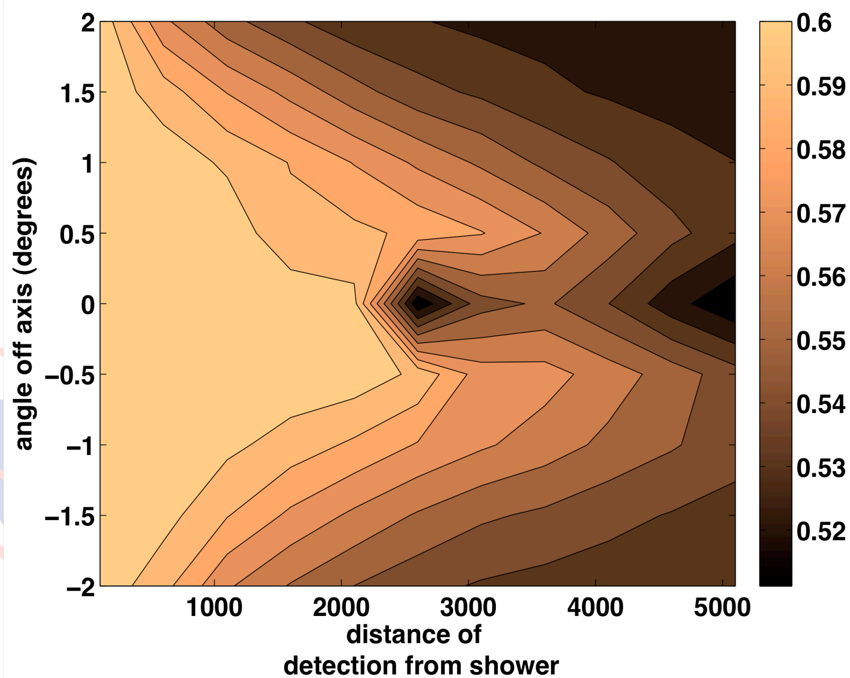
Purity and Efficiency - 2

For a superimposed 10^{20} eV pulse

Efficiency



Purity



Rona Monte Carlo

Generate a random point with a random direction in a fiducial volume

↓ Calculate distance and angle off axis from point to all hydrophones

↓ Calculate distance neutrino would have travelled through the Earth

Use pulse parameterisation to calculate maximum amplitude

↓ Attenuate pulse with distance travelled to the hydrophones and calculate off axis reduction

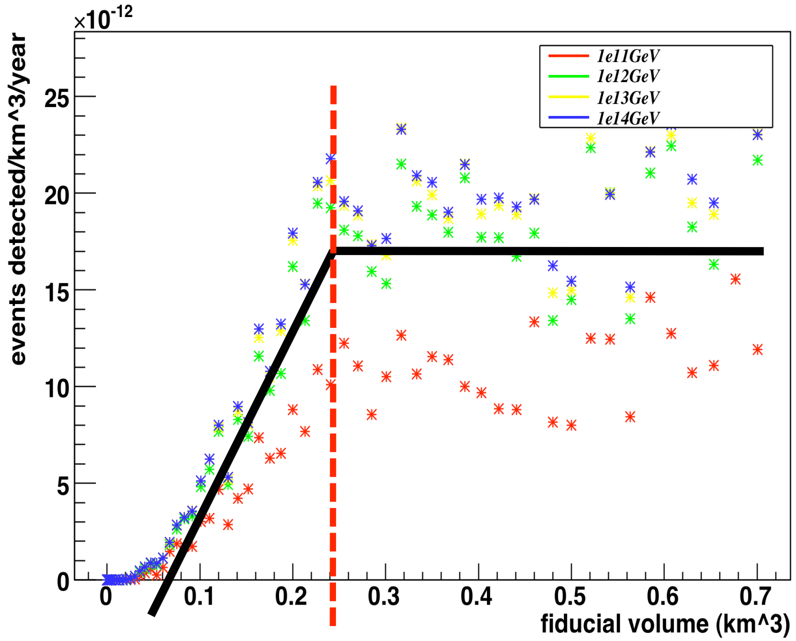
↓ Add a weight as a function of distance travelled through the Earth

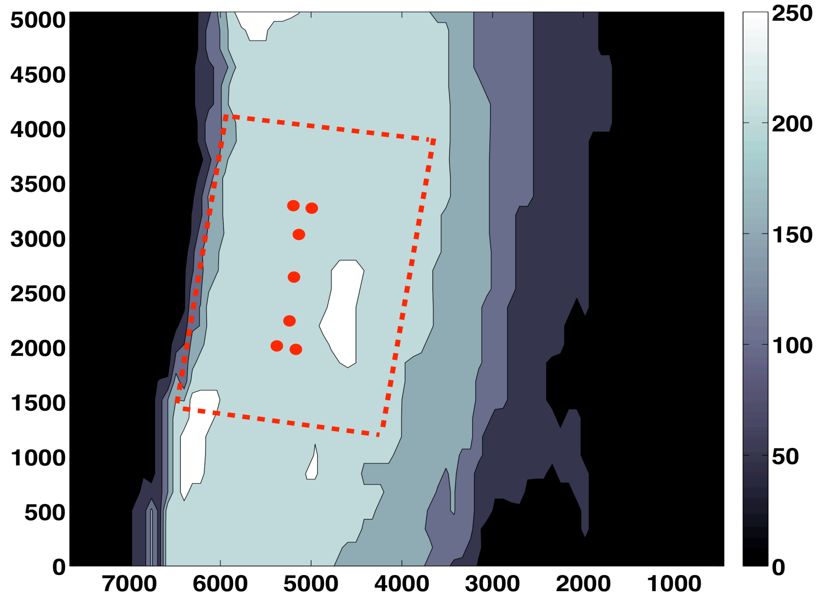
Make a threshold cut at each hydrophone

↓ Require a 4-fold co-incidence

Record event

Fiducial Volume



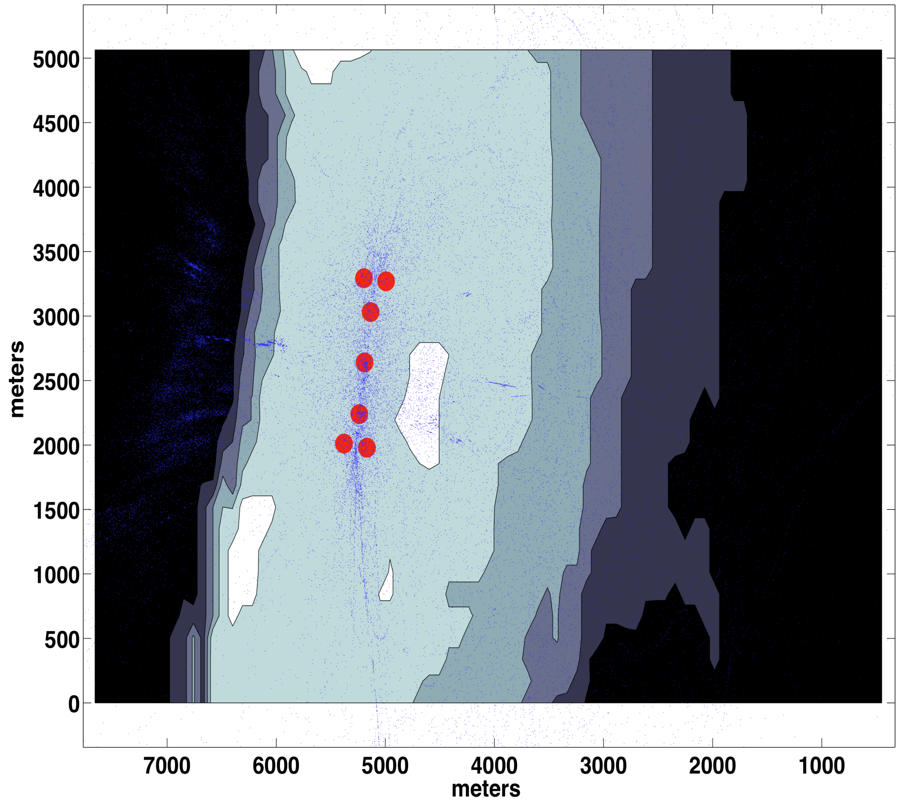


Using the Monte Carlo described previously, the fiducial volume that the events are generated in is grown. The volume at which the number of events detected per km^3 stops increasing with volume is considered the optimal fiducial volume.

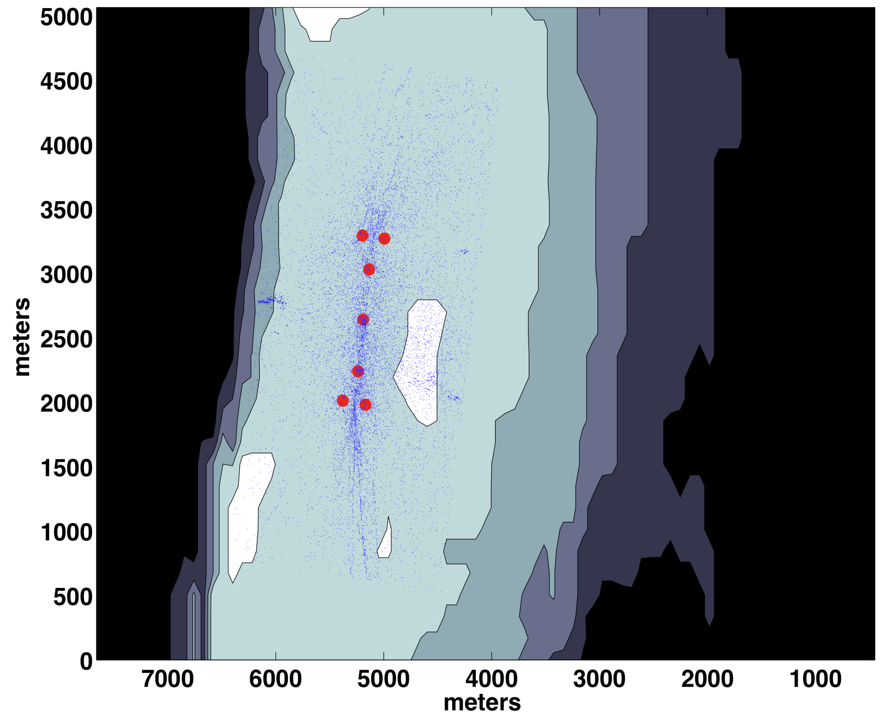
Result of Reduction - 1

2039.8 hours (85 days) to date

52187 Events passed the initial analysis

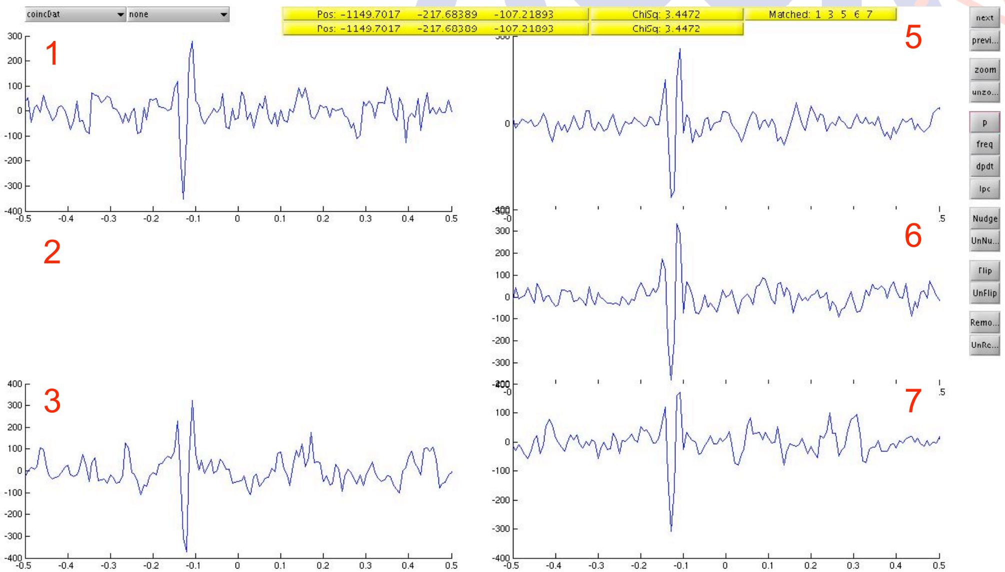


18078 passed the fiducial volume cut



Rona Reduction - 2

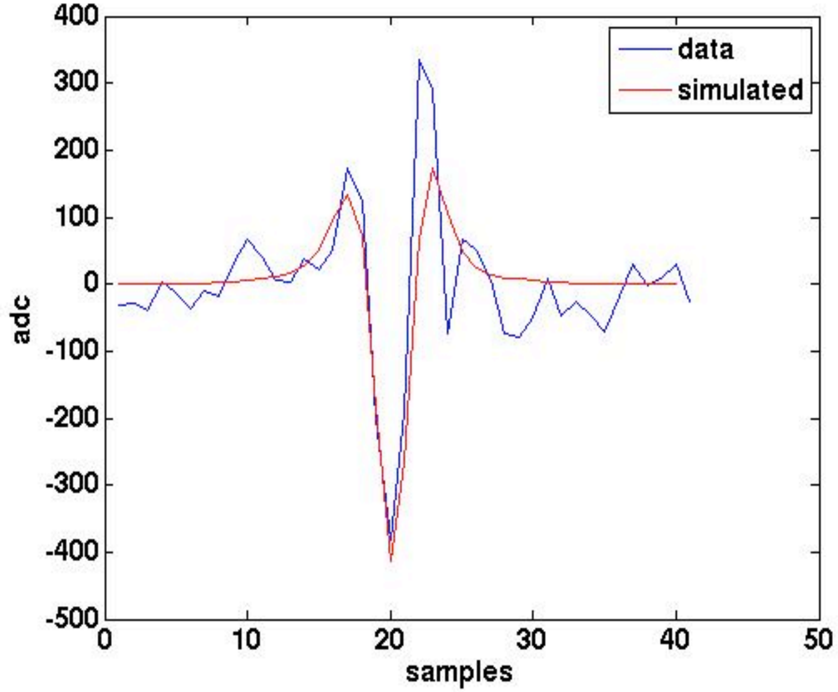
- A tighter cut on the neural network leaves 44 events.
- In scanning these events by hand, if any event exists, it is deeply buried in the noise. A further cut was made on the peak energy of the pulse which corresponds to an energy of 10^{11} GeV at 1 km. This reduced the background to 0.
- But, in performing sanity checks an interesting event appeared…….

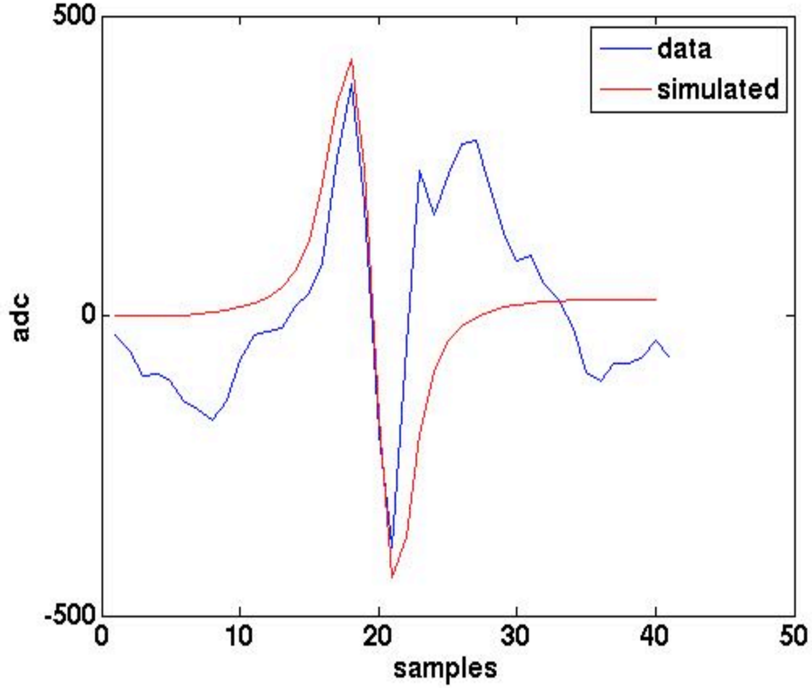


But it is outside the fiducial volume. The events reconstructs to (-1150,-227,-107), but the cut is at -1000 in x.

Rona Reduction - 3

This is the equivalent of a $10^{11.5}$ GeV neutrino at the source





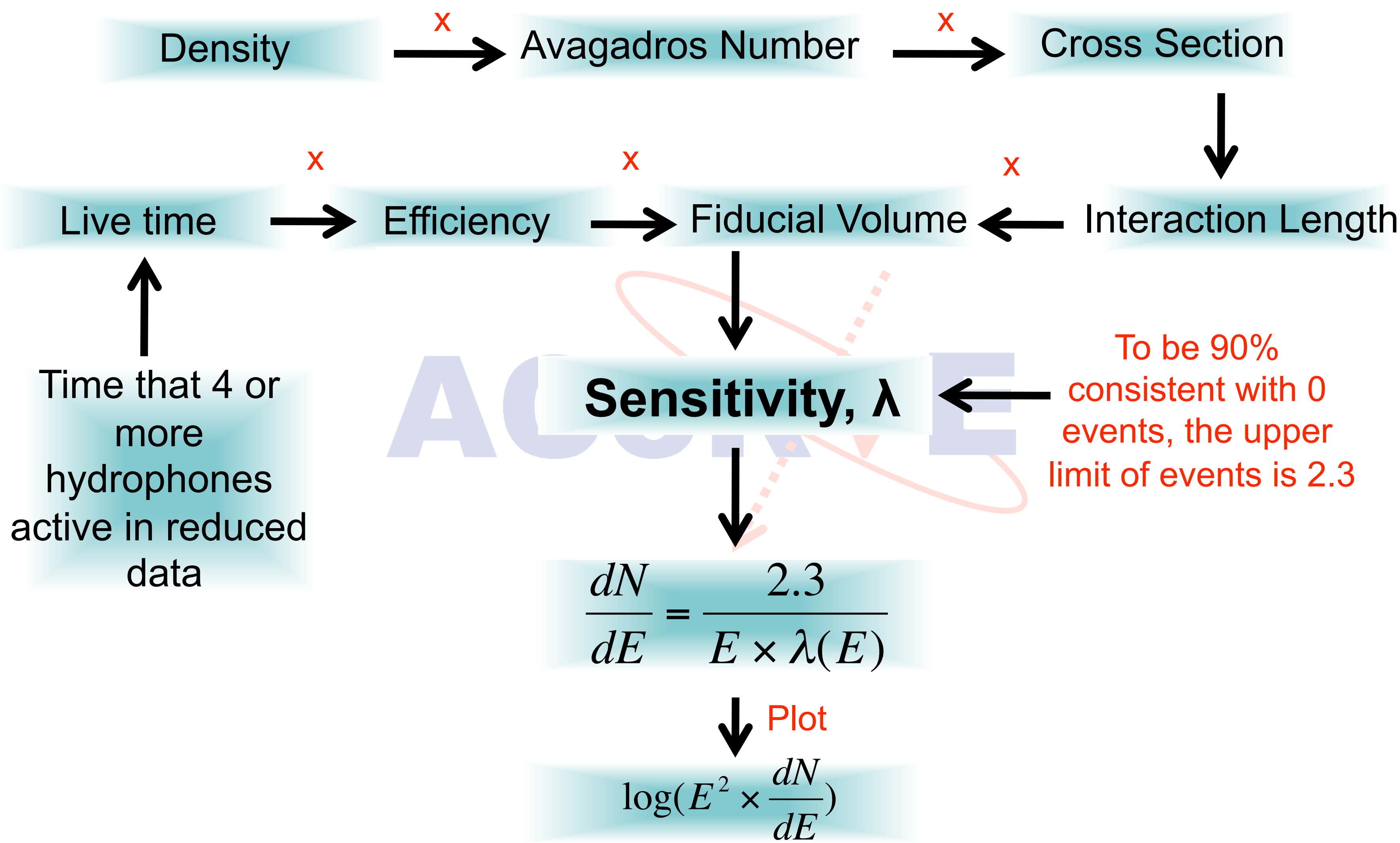
Efficiencies

Energy (GeV)	**Detection (%)**	**Analysis (%)**	**Combined (%)**
10^{11}	29	0	0
$10^{11.5}$	35	32	12
10^{12}	55	41	23
$10^{12.5}$	57	75	43
10^{13}	60	100	60

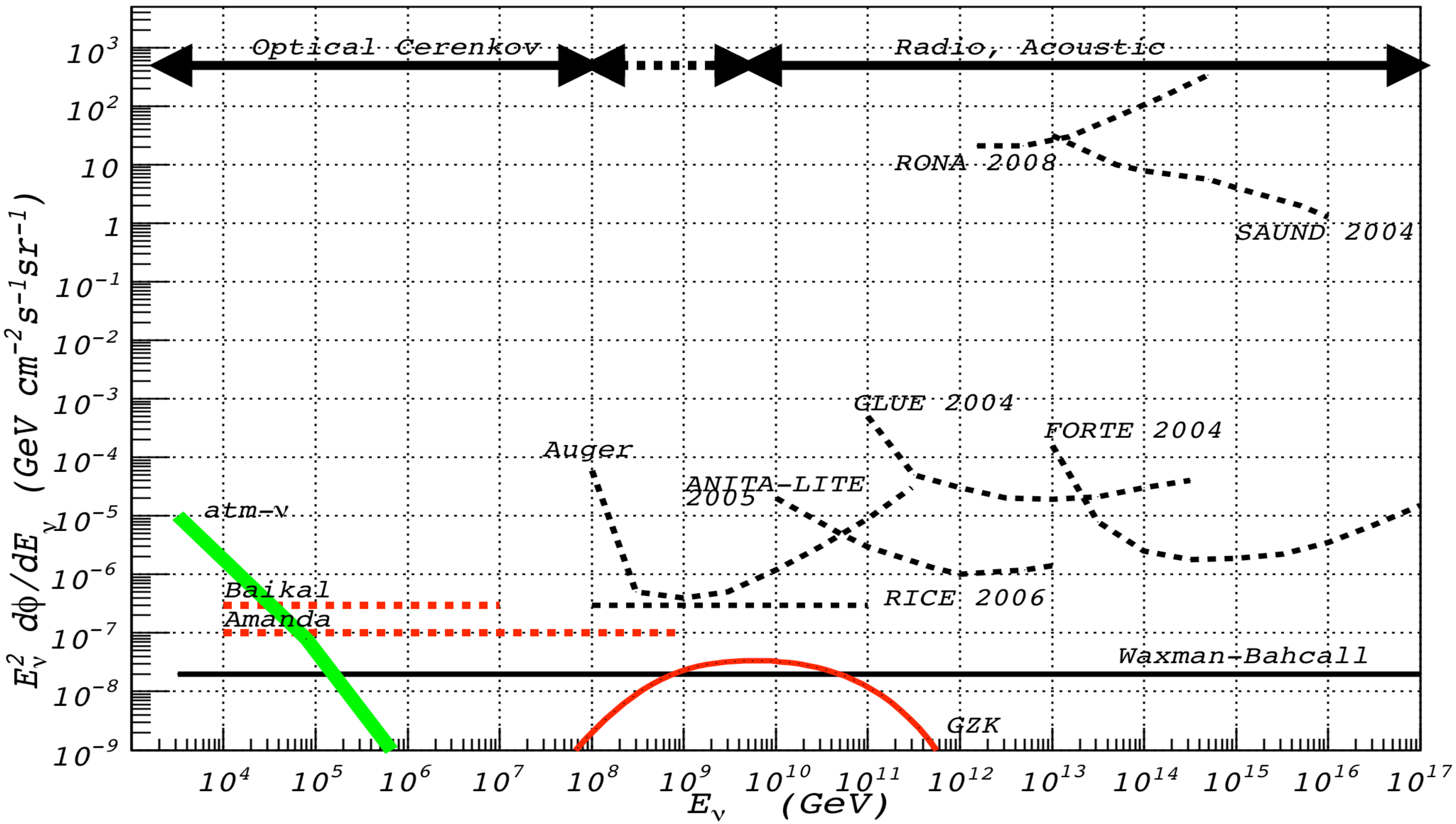
Detection – From Monte Carlo

Analysis – From using test pulses in analysis code

Rona Limit


Density
x
Avagadros Number
x
Cross Section
Interaction Length
x
Fiducial Volume
x
Efficiency
x
Live time
Time that 4 or more hydrophones active in reduced data
Sensitivity, λ
To be 90% consistent with 0 events, the upper limit of events is 2.3
$\frac{dN}{dE} = \frac{2.3}{E \times \lambda(E)}$
Plot
$\log(E^2 \times \frac{dN}{dE})$

Rona Limit



Optical Cerenkov
Radio, Acoustic
RONA 2008
SAUND 2004
GLUE 2004
FORTE 2004
Auger
ANITA-LITE 2005
atm-ν
Baikal
Amanda
RICE 2006
Waxman-Bahcall
GZK
$E_\nu^2\ d\phi/dE_\nu$ (GeV cm^{-2}s^{-1}sr^{-1})
E_ν (GeV)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17}

Conclusion

- Using a set of specifically designed match filters, co-incidence discrimination, and a neural network, 85 days of Rona data has successfully been reduced to 0 events.
- Using the efficiencies calculated from the Monte Carlo and data analysis a limit was set on the sensitivity of the Rona array to UHE neutrino flux.
- This limit is comparable with SAUND I, and shows that acoustic neutrino astronomy could be a complementary technique to radio at higher energies.

BACKUP

Motivation For UHE Astronomy

The motivation:

Is there new particle physics ?

- It is needed if we observe particles at energies > 5×10^{19} eV
- Is it the same new physics as the LHC - here we are at CME = 200 TeV ?
- Can be used to measure the neutrino nucleon cross section at to-date unreachable energies

If there is new physics :

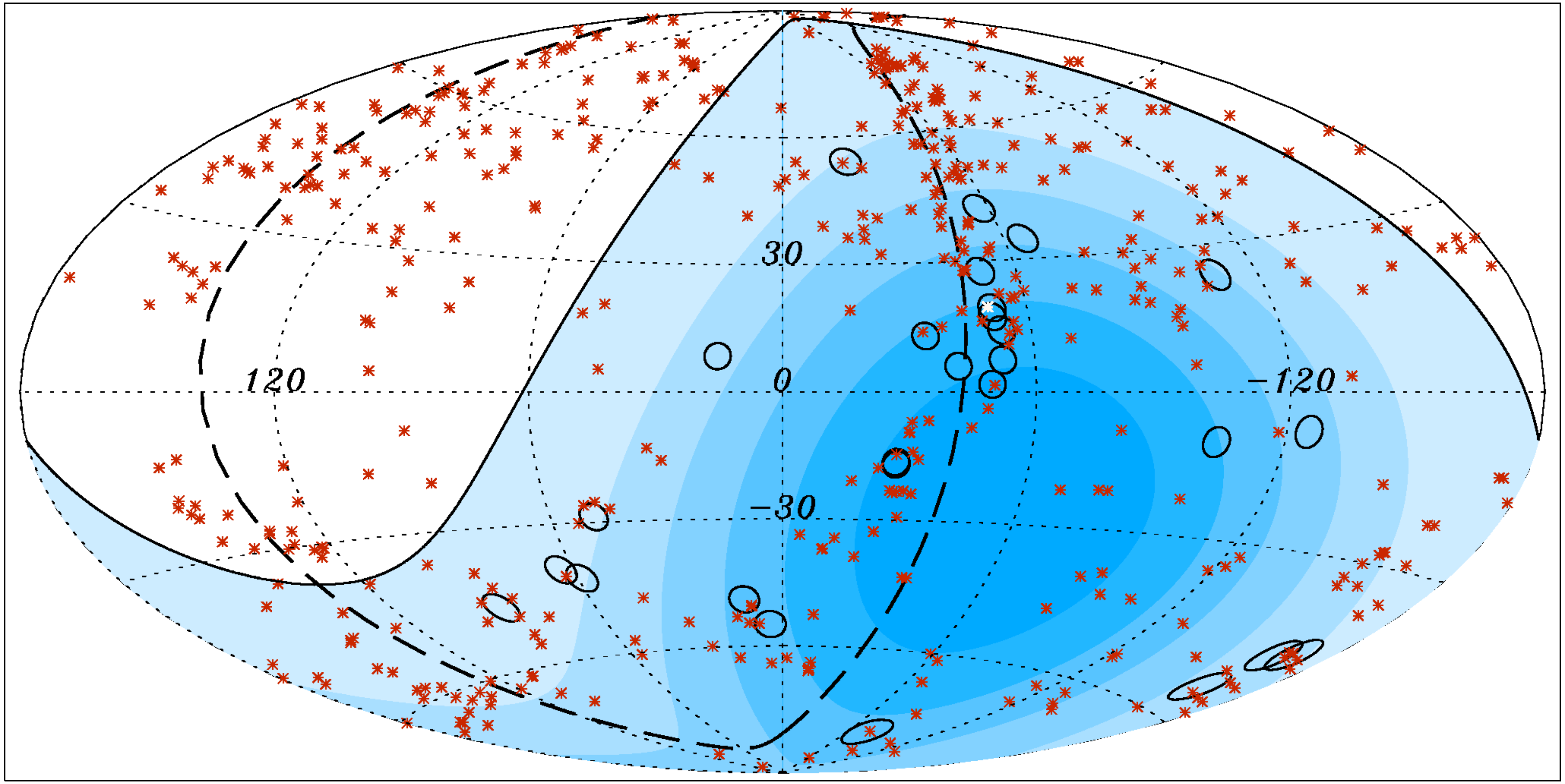
- Does it fit in a GUT model ?
- Can the same GUT model explain LHC data AND ultra-high energy ν ?

Is there new astro-physics ?

- The existence, in the first place, of UHE cosmic rays is a mystery
- What is the primary composition : protons or heavier nuclei ?
- Where do they come from and how are they accelerated ?

Motivation For UHE Astronomy

Pierre Auger sky map - 29 UHE particles detected



Why Neutrinos?

- Above 1x10^{14} eV photons interact with the cosmic microwave background.
- At higher energies, protons suffer due to a finite inelastic collision length of ~50Mpc with the CMB. Another major problem with using protons is they get deflected by galactic magnetic fields, making any pointing astronomy very hard.
- Neutrinos suffer no such problems….