Acoustic detection of neutrinos

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Astrophysical neutrinos

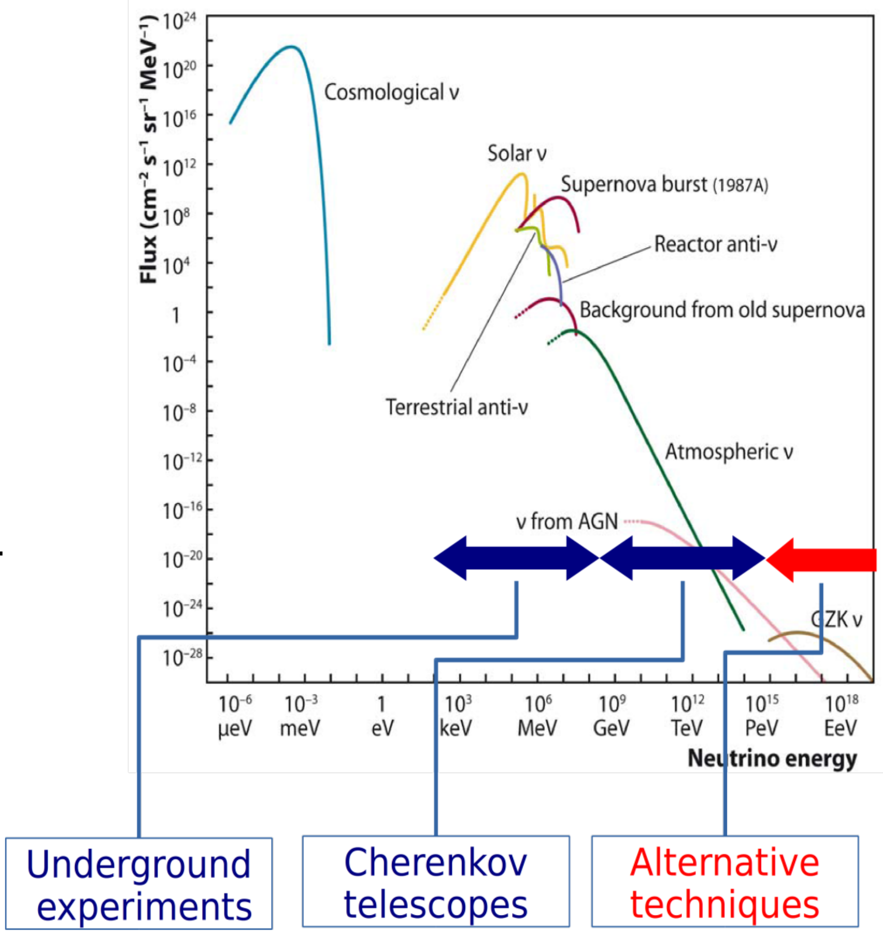
- Neutrino energies range from the μeV to EeV
- Each energy scale has its own detection technique
- Cosmogenic neutrinos related to the GZK cut-off energy: Greisen, Zatsepin and Kuzmin (1966): Universe is not transparent for high energy protons and ions.
- Mean free path for protons is ~50 Mpc.

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^o$$
$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

… with subsequent decay to *neutrinos*

- Neutrinos with energy above 10^{21} eV is absorbed at the Z-resonance by the relic neutrinos

$$\nu + \nu_{\text{C}\nu\text{B}} \rightarrow Z^o \rightarrow X$$
$$E_\nu^{\text{res}} = \frac{m_Z^2}{2m_\nu} \approx 4 \cdot 10^{21} \left(\frac{\text{eV}}{m_\nu}\right)$$



Astrophysical neutrinos (cont.)

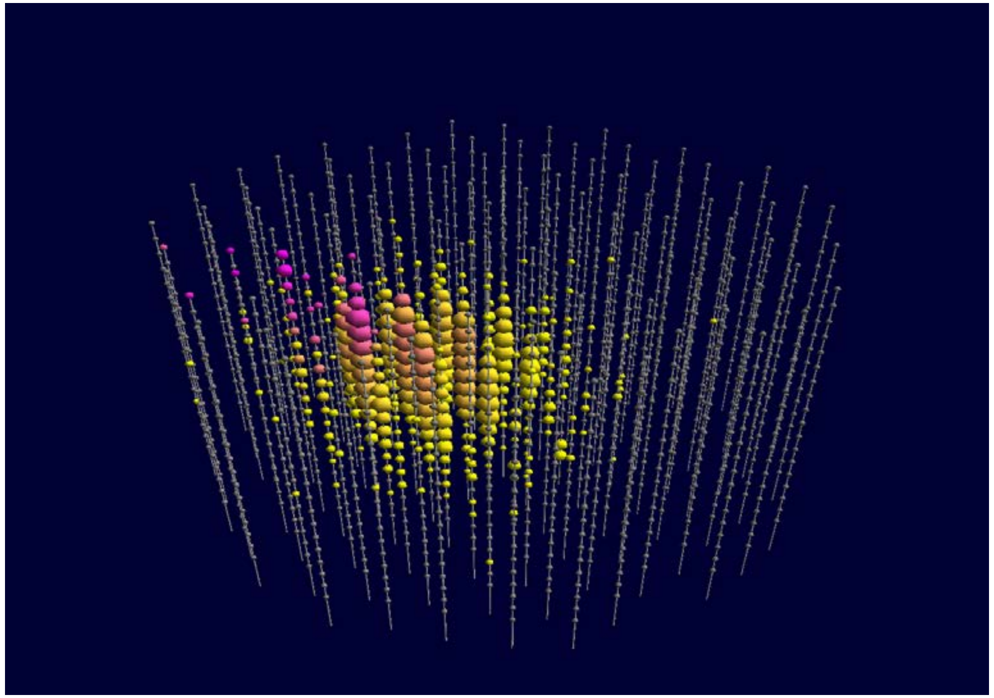
- Measurements of the most energetic neutrinos would:
  - Probe sources at large distances >50 Mpc, as neutrinos point back to their sources
  - Provide crucial information on CR propagation (GZK limit)
  - Allow to study particle physics at extreme energies E> 10^{18} eV, probe new physics
- But how do we detect neutrinos with energies above 1 EeV?
- Three methods to detect the UHE neutrino showers in air or water:
  - Optical, using the Cherenkov signal
  - Detecting the coherent radio signal
  - Acoustically – Why?

Detection of UHE neutrinos

A matter of scale:

Flux of UHE ν 's is of the order of 100 km^{-2} $year^{-1}$ requiring detectors of tens – hundreds of km^3 , clearly not-feasible in terms of traditional Cerenkov detectors.

Acoustic detection could be the solution ⟹ if building large scale detectors is feasible (finance, technology, sustainability)



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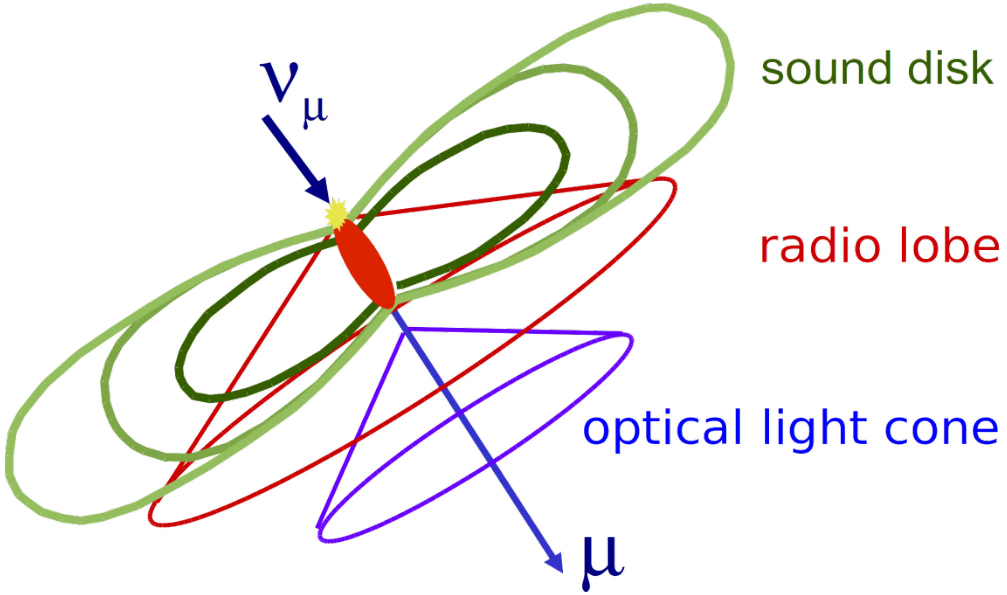
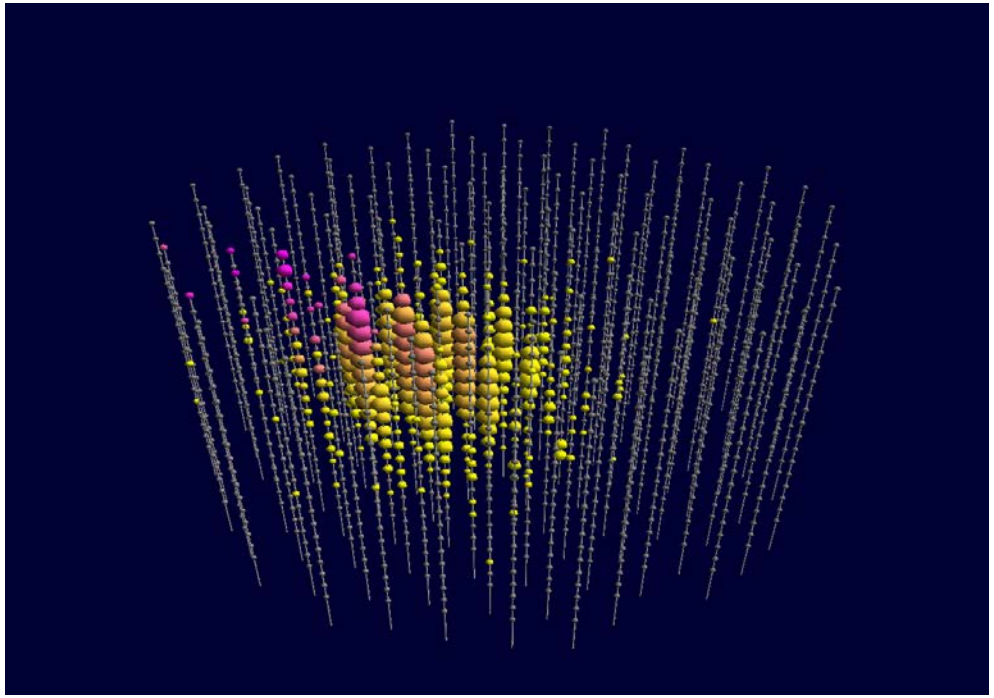


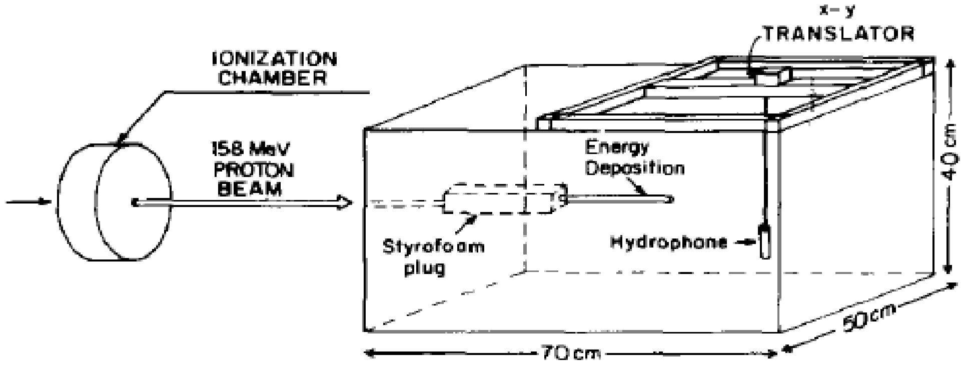


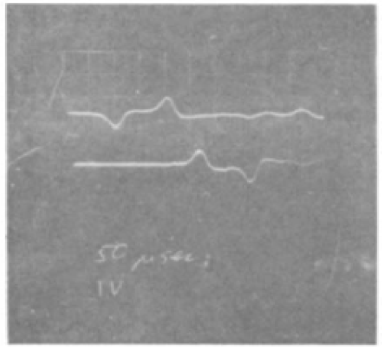
Detection of UHE neutrinos

- Rapid expansion of medium after energy deposition and subsequent heating.
- Expansion leads to a pressure wave in water.
- First idea by Askaryan (1957)
- *Wave equation* p is given by energy deposition ε.

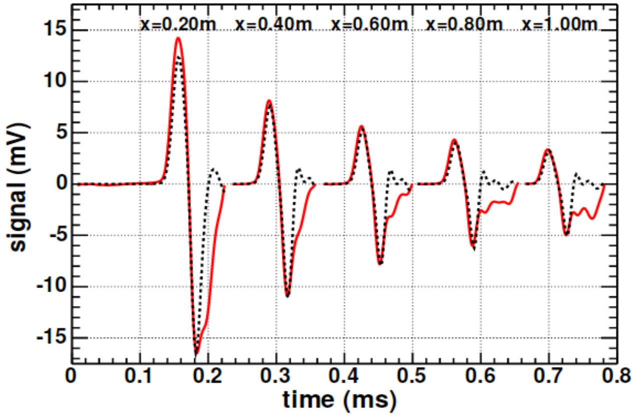
$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{C_p}\frac{\partial^2 \varepsilon}{\partial t^2}$$

- Acoustic signal of particle beams already studied and measured in the 60s and 70s by Askaryan, Beron, Hofstadter, Learned, Sulak and others.
- Measurements using proton and electron beams and piezo hydrophones at Brookhaven, Stanford and Khar'kov
- Later work at Desy, Sheffield, Erlangen, and others.





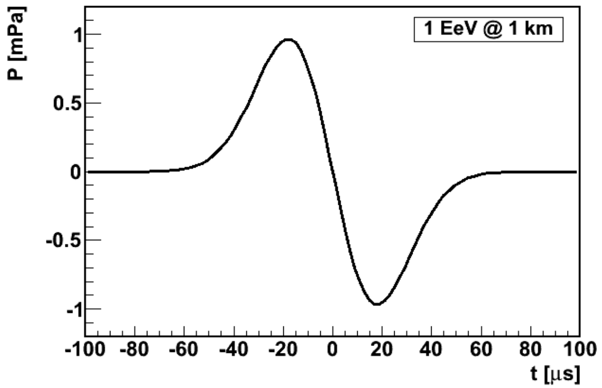
Sulak et al 1979

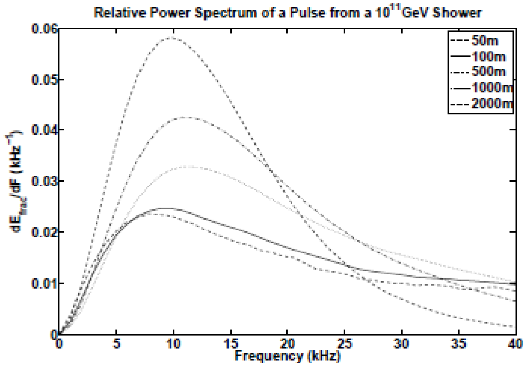


Lahmann et al 2015

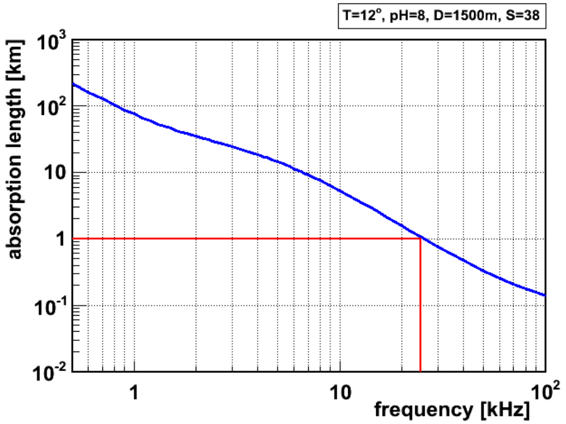
Acoustic signal of neutrinos

- Bipolar pulse, several mPa amplitude
- Frequency spectrum peaks at 5-10 kHz.
- Spectrum depends on the position of the hydrophones wrt to the source (both distance and angle).
- Absorption length of sea water @ 5 kHz is ~ 10km, @ 25 kHz is ~1 km.
  - *Large detection volumes possible*
- Sea state noise: omnipresent noise due to the rain, wind and waves at the surface.

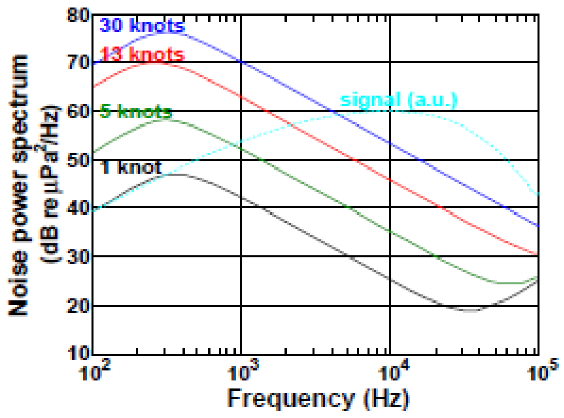




Bevan et al 2007

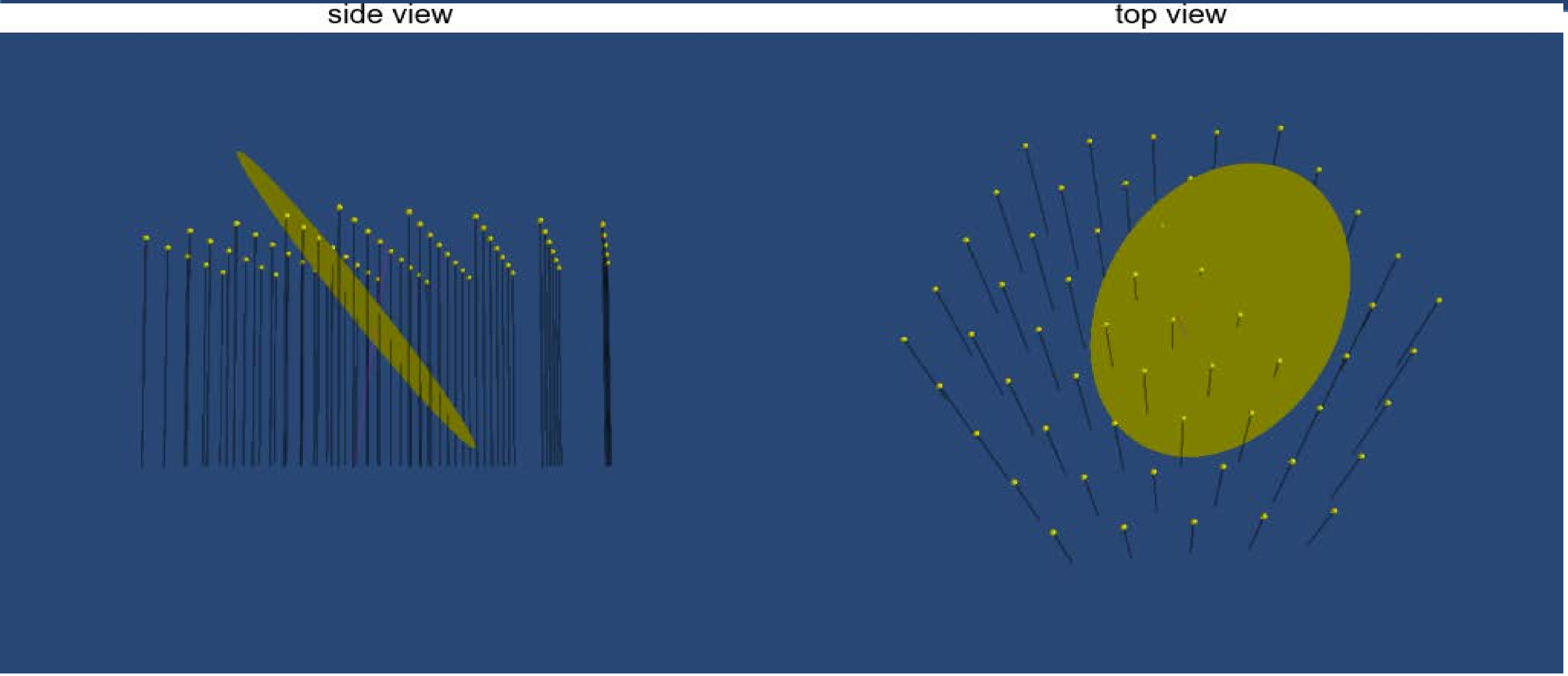


Ainslie & McColm 1998



Lehtinen et al 2001

Event topology



- Sensitivity:
  Detect *mPa pulses* in the range of 5-30 kHz.
  Sensitive to 'Deep-sea state zero'.
- Simple and robust, easy to deploy.
- Price per sensor should be low as many hydrophones (>1000) are required in a telescope.

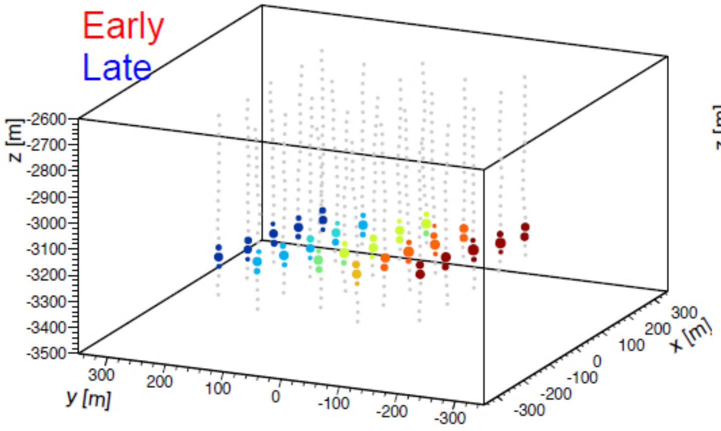
> 100 strings, > 1000 hydrophones, > 100 km^3

Event topology

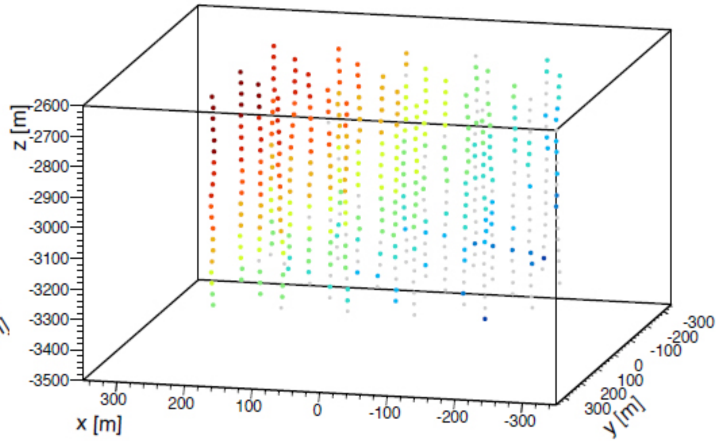
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Simulated events

Neutrino @ 1.8 km, $E=10^{21}$eV, $\Theta=16°$



Spherical background (e.g. ship)



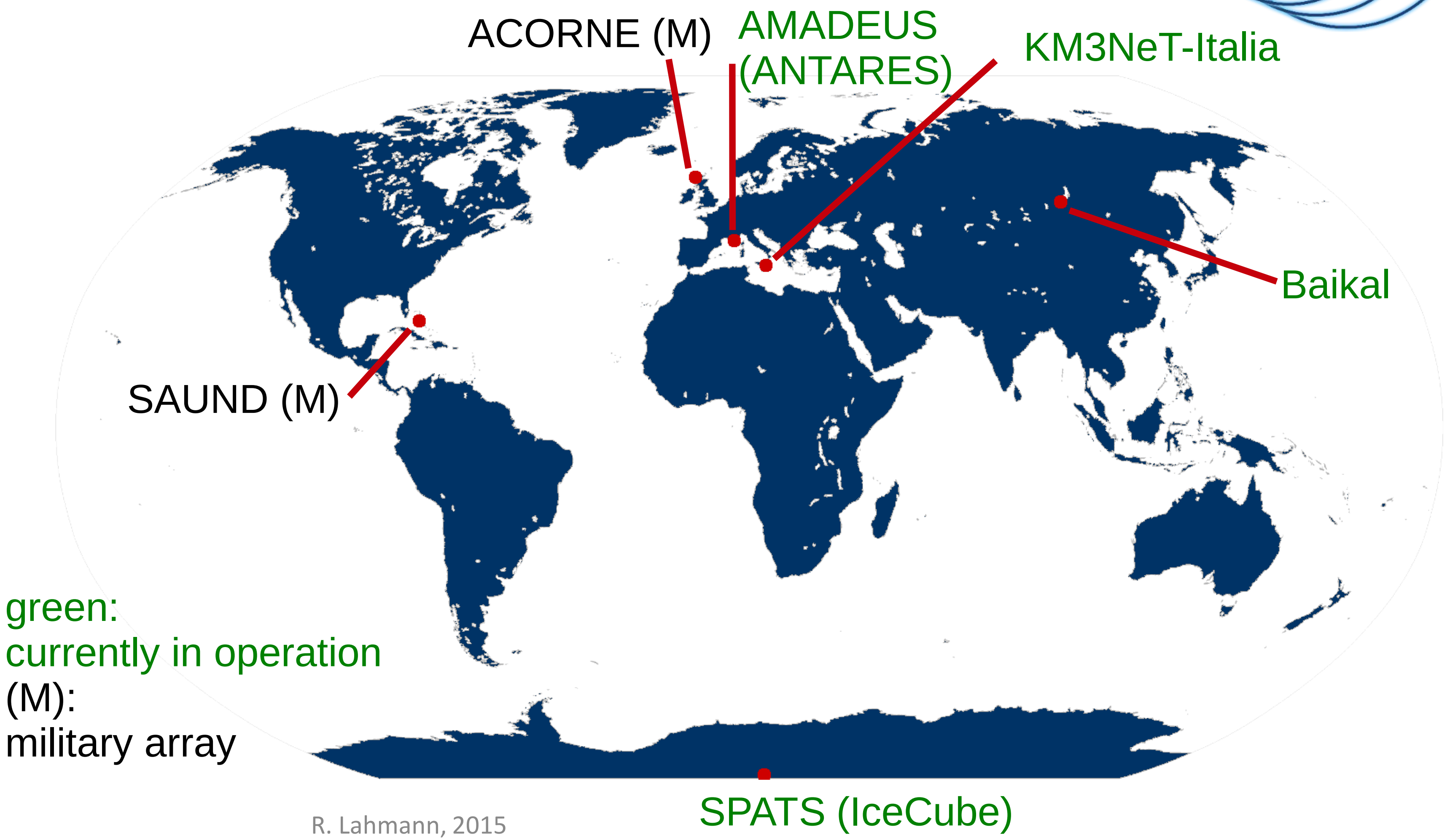
- Neutrinos (Energy $10^{19} – 10^{21}$ eV)
- Signals from the positioning system
- Spherical sources
- Random coincidences

First attempts

First generation acoustic test setups were either

- Feasibility studies using existing acoustic detection arrays, or
- Feasibility studies installing acoustic detector in existing neutrino infrastructure.

Technology used includes piezo - hydrophones (water) and glaciophones (ice)
Typically O(10) sensors, used for feasibility studies, developing techniques/algorithms



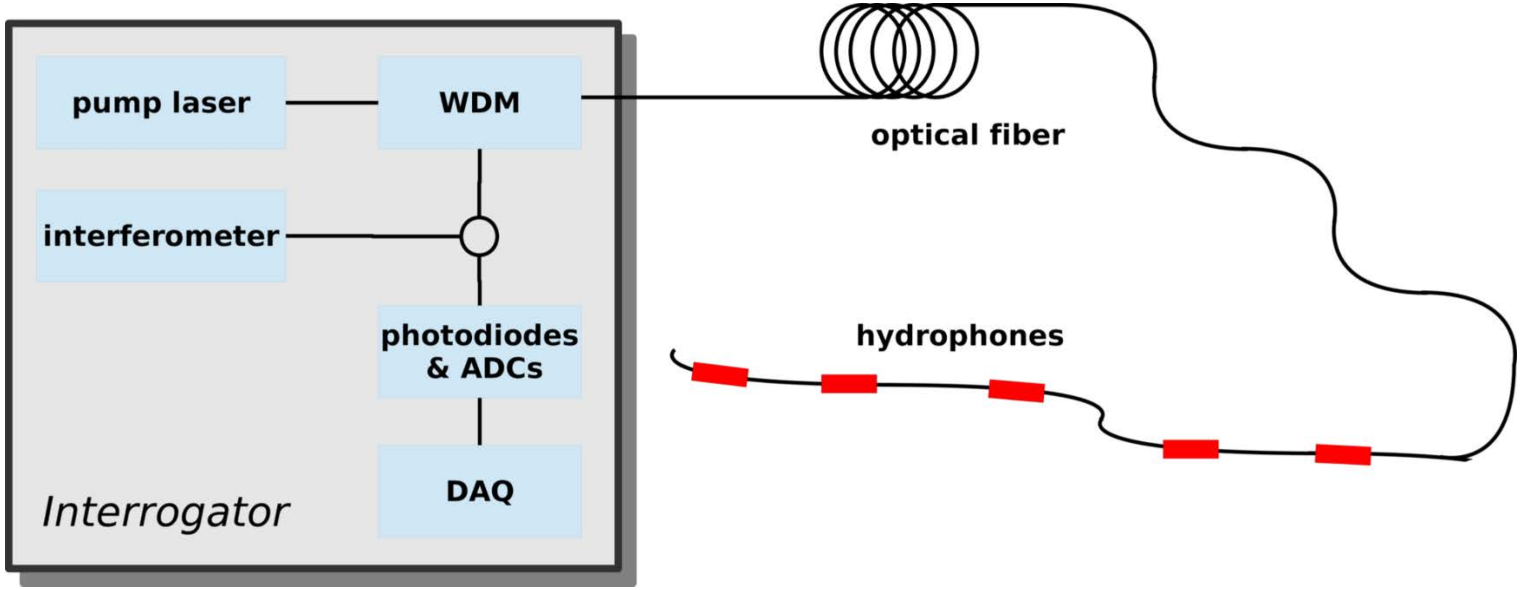
R. Lahmann, 2015

Measurement principle

Actively pursued by TNO, with contributions from Erlangen, plus others.

NCSR “Demokritos” is starting to get into this.

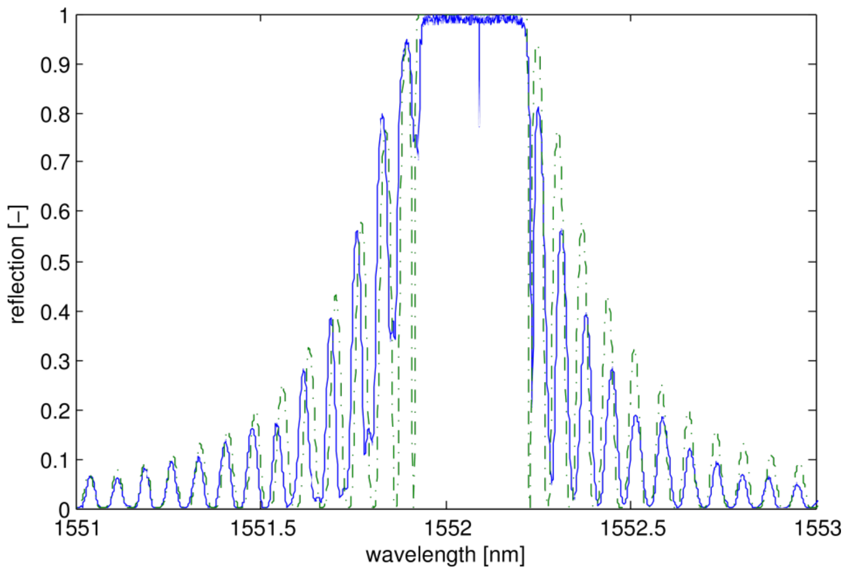
Three main components:
1) hydrophone sensor
2) optical fiber
3) interrogator

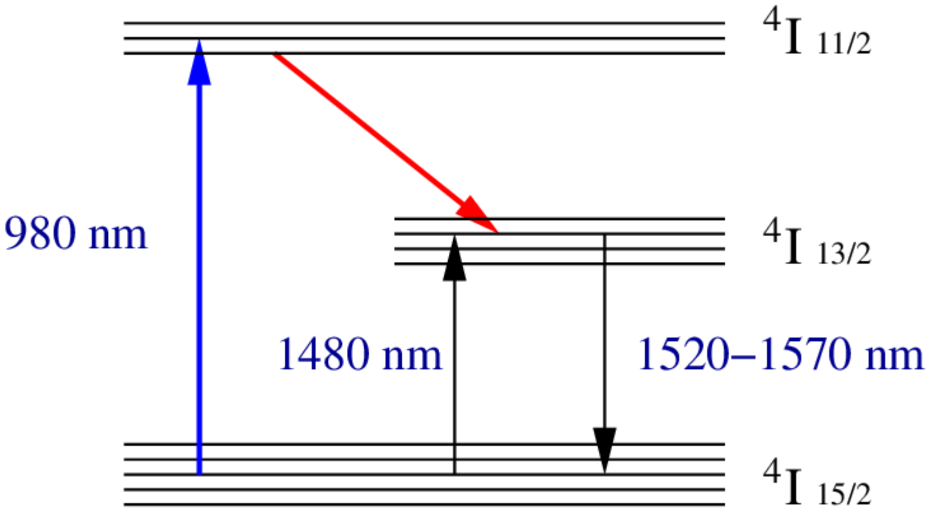


By EJ Buis

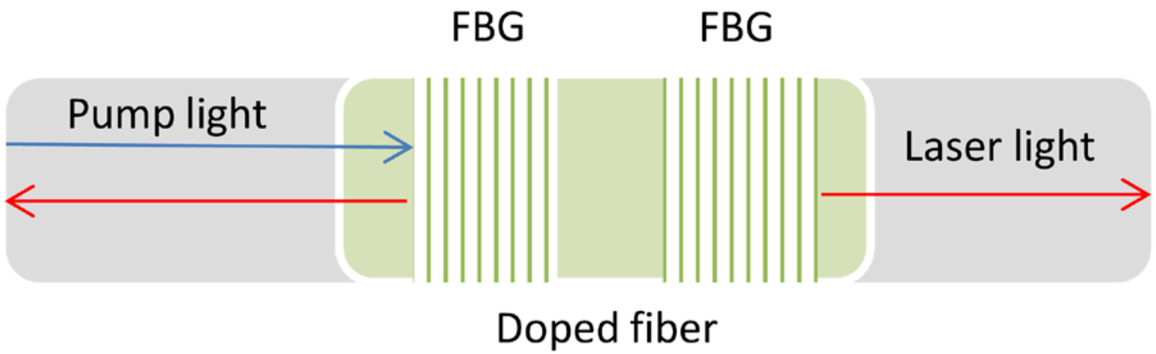
Fiber lasers

- Optical fiber includes fiber lasers based on *erbium doped fibers*
- Grating structure applied to create a laser



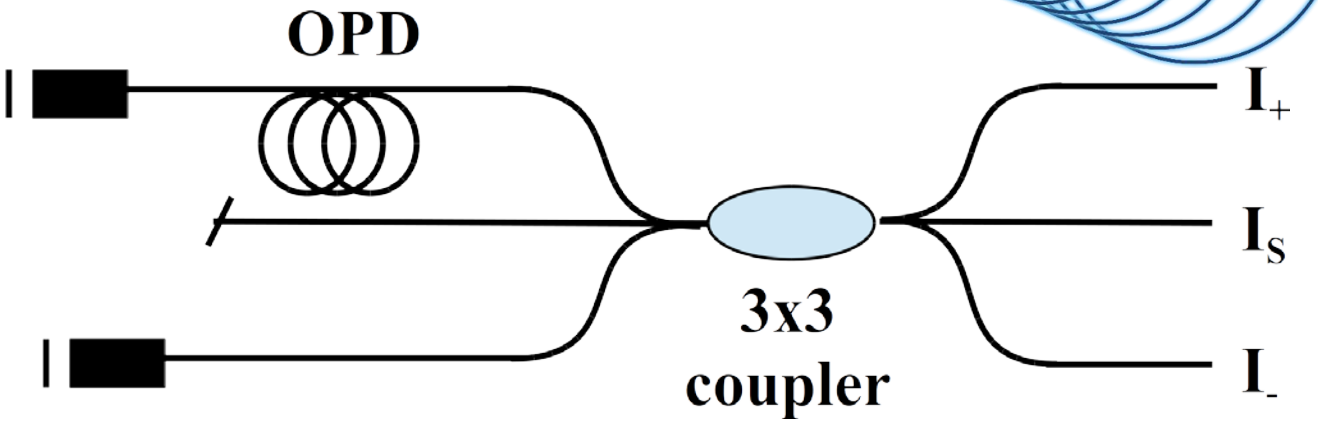


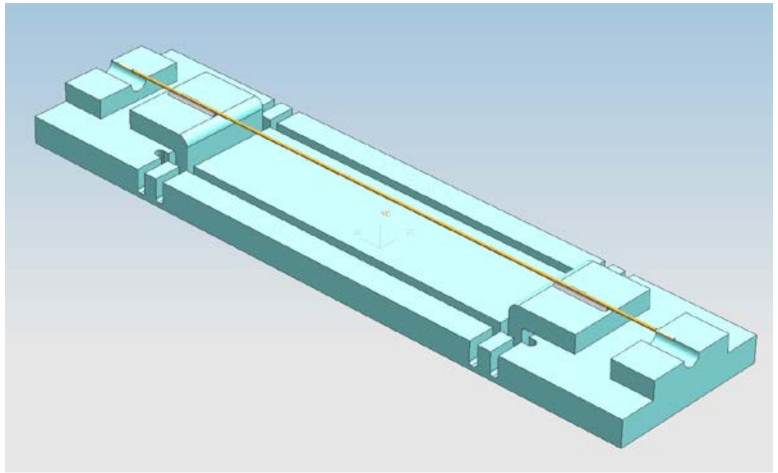
Pumping @ 980 or 1480 nm,
Laser source at 1520-1570 nm



Sensor - interrogator

- Sensor is a mechanical transducer that converts pressure in strain in the fiber
- Size is related to the acoustic wavelength





- 3x3 interferometer: *coupler* with fixed phase difference in output branches.

Current status

Work done so far indicates that sensor + fiber laser exhibits good linearity, and noise levels are low, able to measure signals at the mPa level.

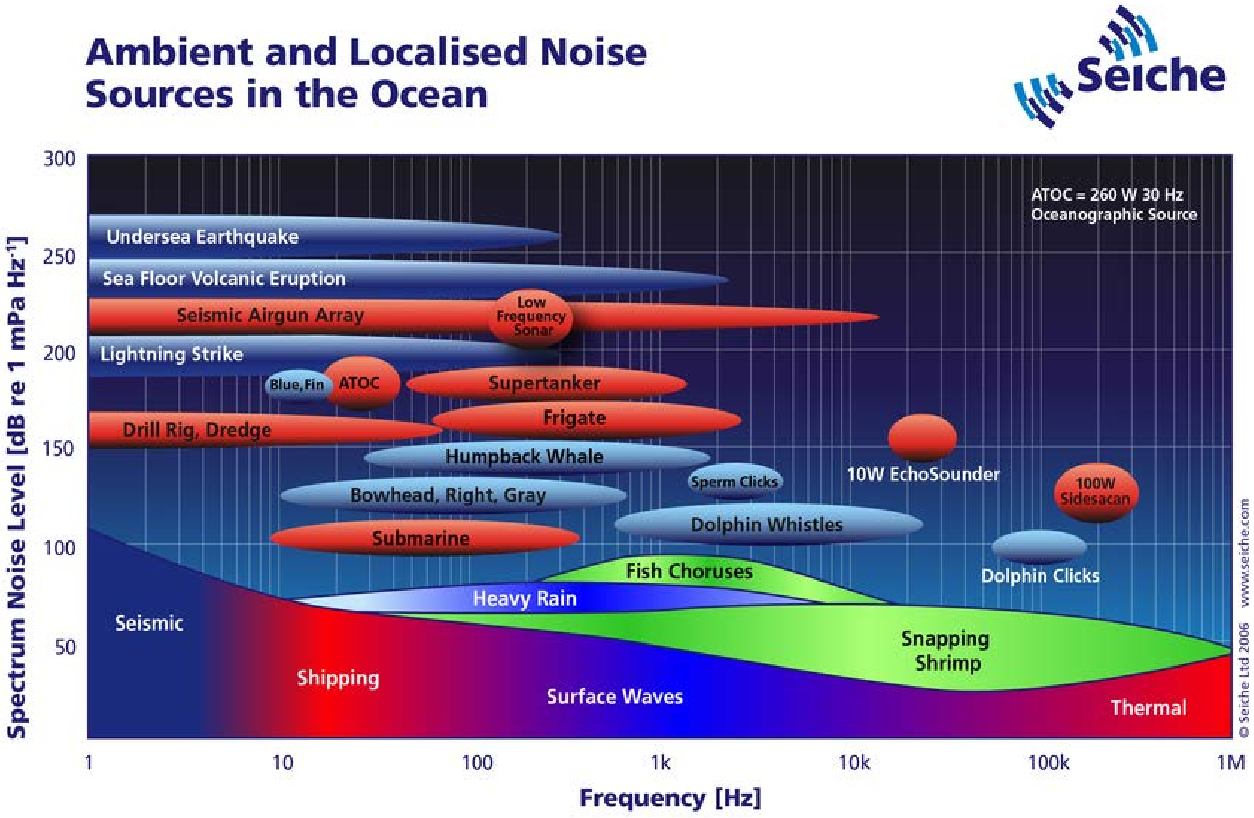
Work to be done in sensor optimization,
pressure compensation mechanism
fiber laser design, fiber diameter
multiplexing

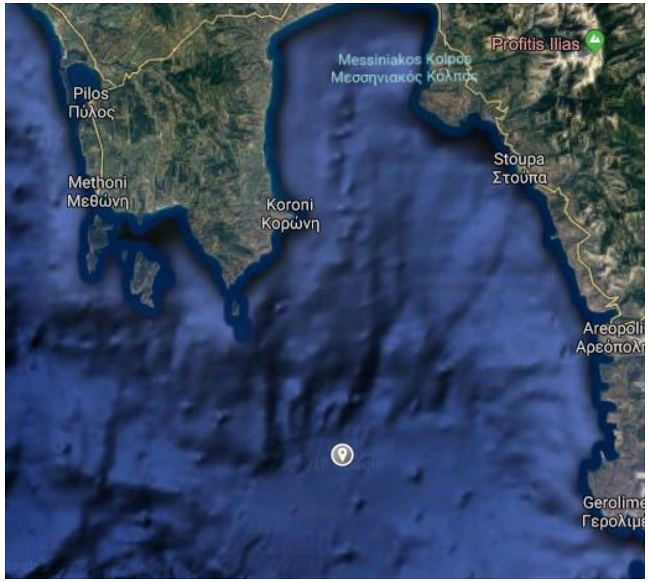
Advantages of the system
Proper sensitvity: *mPa pulses, sea state 0 sensitivity*
Cost-effective: *design for mass scale production*
Passive system (remote pumping and interrogation); easy deployment.

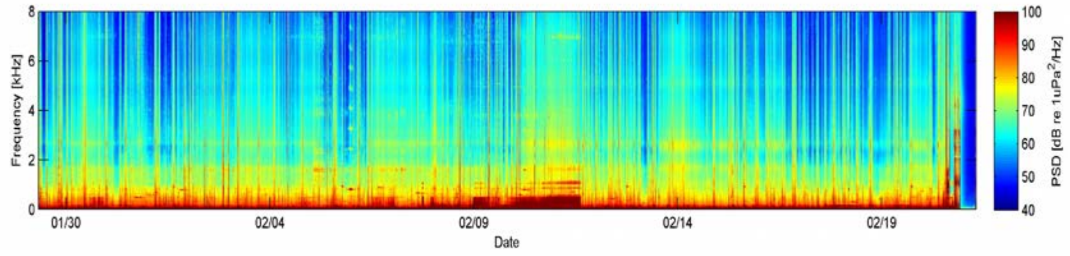
Work is on-going, with the next major step being to build and test a full prototype line equipped with fiber laser hydrophones in the sea within the next 2 - 3 years

Ongoing activities

Ambient noise characterization: Site chosen carefully after having understood very well the ambient acoustic load







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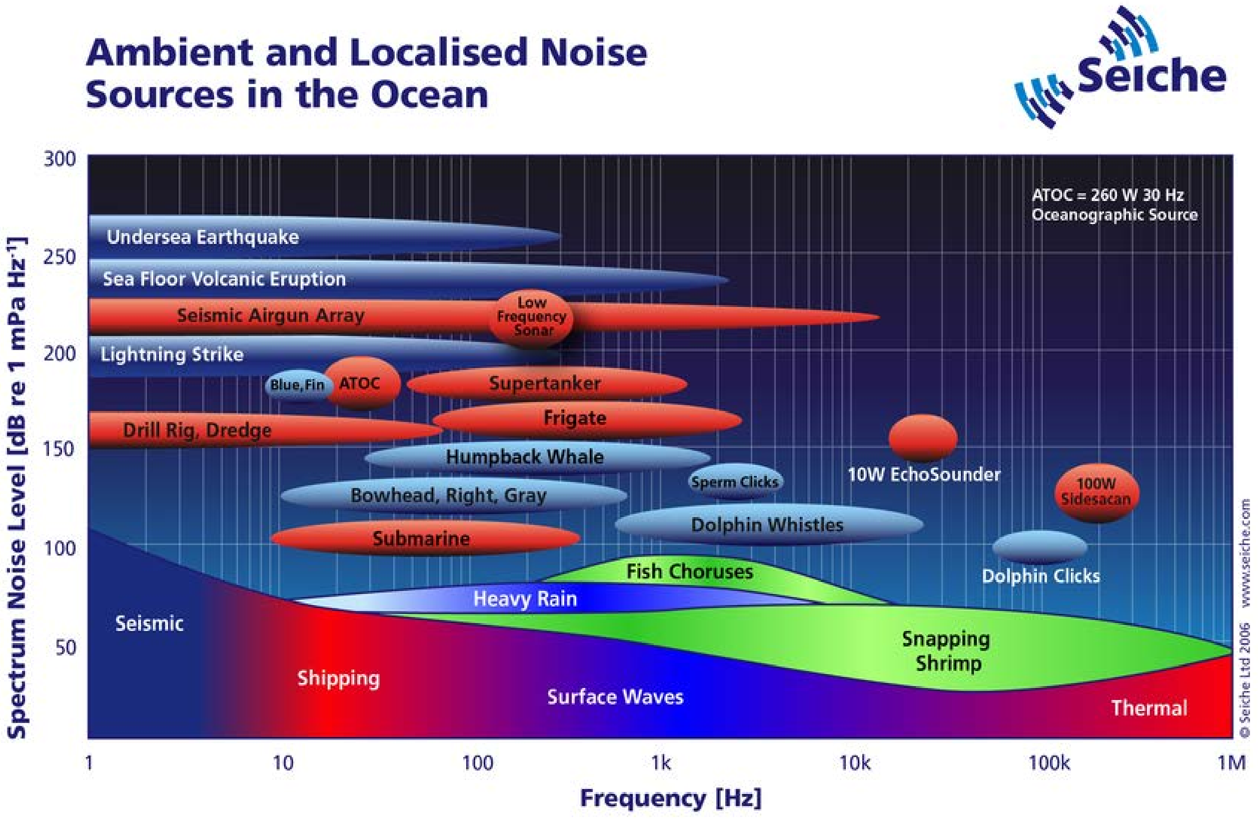
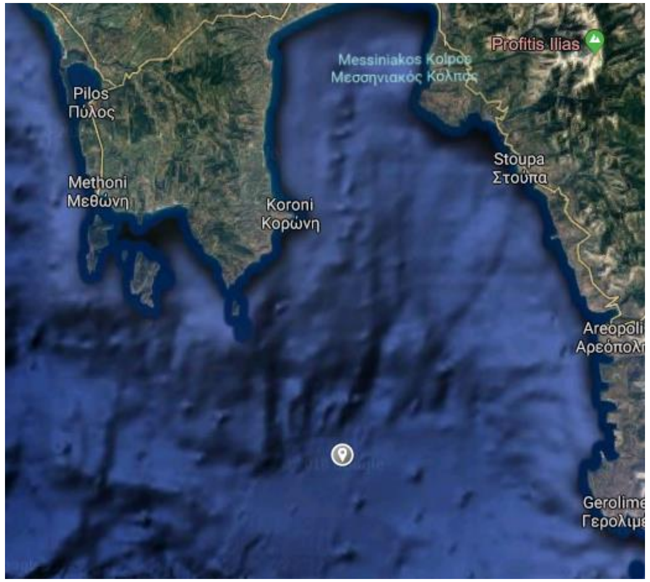
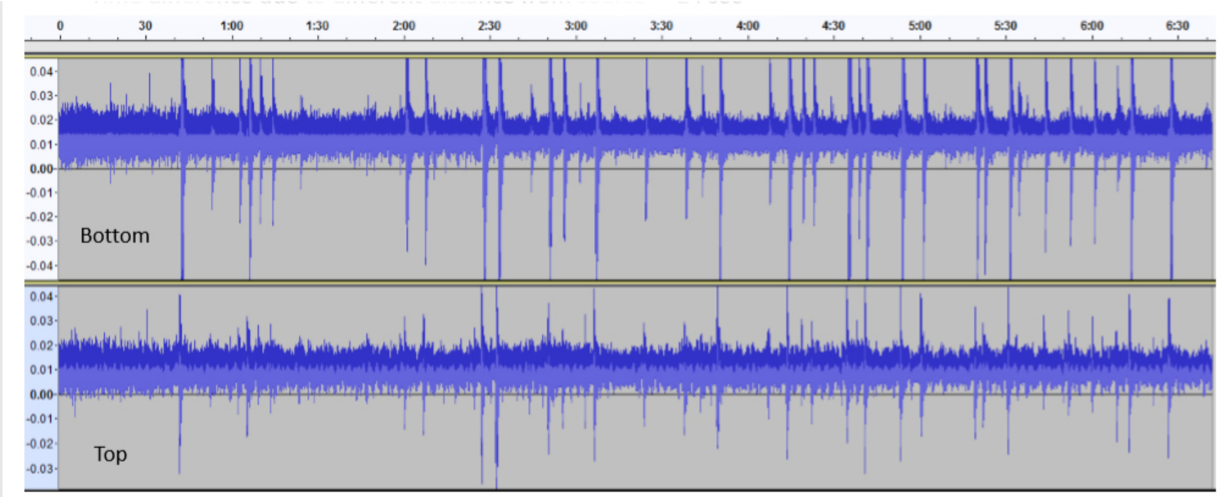
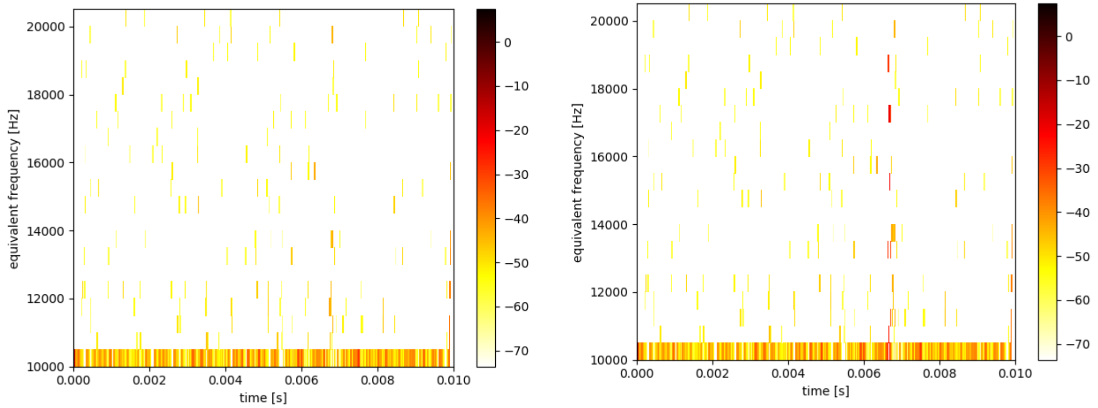






Data reduction will be a big challenge

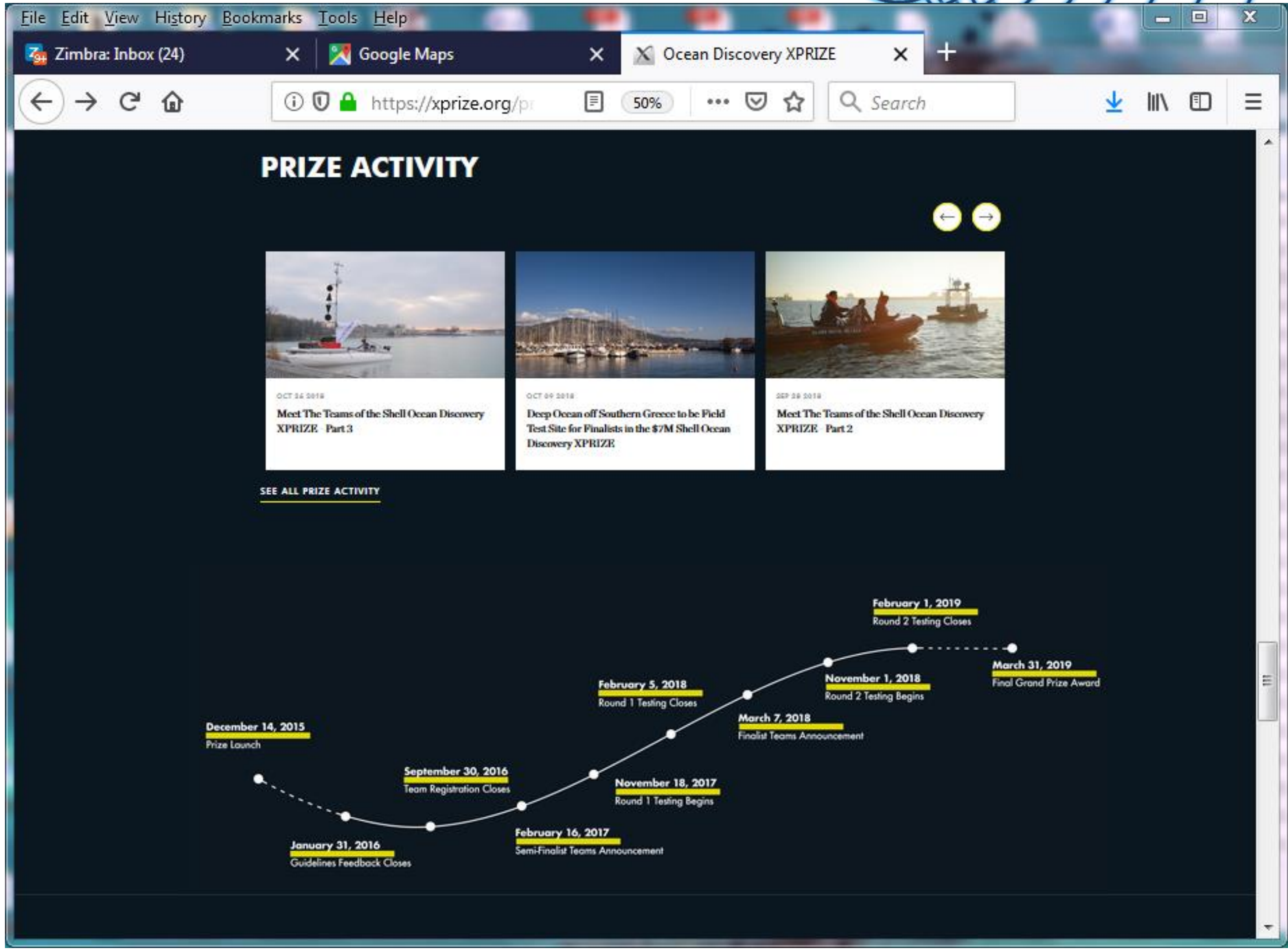
Data handling could well be a major issue in a full scale neutrino acoustic telescope. Data rates of the order of several hundreds of MB/sec can easily result in huge data sets requiring extremely large computing effort. Essentially a problem comparable to major HEP experiments. Long distance correlation effects will complicate computational paradigms.
Novel signal processing techniques and ML algorithms will be indispensable.



CWT decomposition of pure noise (left) and noise plus a 5% neutrino signal at t=0,0067

Latest developments

- Xprize.org – Final round of the Shell Ocean discovery competition is currently happening off the coast of SW Peloponnese.
- Mapping of the ocean floor down to 4.000m with an accuracy better than 5m over an area of 500Km^2 with autonomous systems over 24 hours.
- Detailed maps extremely important for sound propagation measurements and studies.



Outlook

• Acoustic neutrino detection is a promising technique for the detection of ultra-high energies neutrinos

• A number of first generation acoustic neutrino detection test setups have proven the feasibility of the technique and measured background conditions

• Novel technology choices and solutions may prove to be favorable for the establishment of a large scale acoustic neutrino detector in the not –so –distant future.

• KM3NeT could be the opportunity to establish such an infrastructure.