History of acoustic neutrino detection

Robert Lahmann
ARENA 2018, Catania, June 12, 2018

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

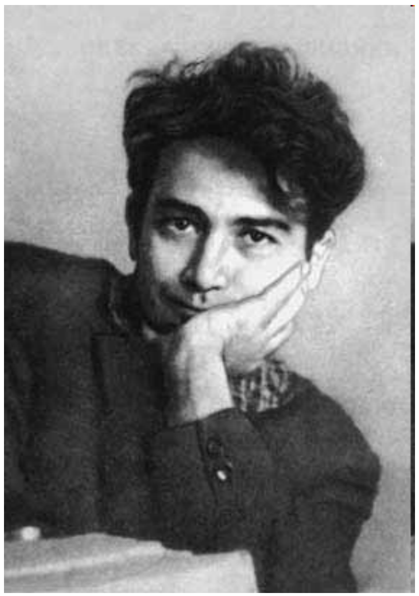
Outline

- A historic introduction to acoustic neutrino detection
- Acoustic test setups
- Status and results
- Challenges for the future

(Apologies for any omissions, mistakes, biases…)

A historic introduction to acoustic neutrino detection

The acoustic Askariyan effect



HYDRODYNAMIC RADIATION FROM THE TRACKS OF IONIZING PARTICLES IN STABLE LIQUIDS

G. A. Askaryan

When ionizing particles pass through liquids the molecules of the medium are entrained by singly-charged ion aggregates which are pushed apart; in addition, small micro-explosions, due to localized heating, occur close to the tracks of the particles. These processes can lead to the formation of localized cavities and nuclei or "seeds" at which the transition to the vapor or gas phase is possible. (The development of these nuclei into bubbles of visible dimensions, which takes place if the liquid is sufficiently unstable, is used in new devices for studying ionizing radiation — so-called "vapor" and "gas" bubble chambers [1-3].)

G.A. Askariyan, *Hydrodynamic Radiation From the Tracks of Ionizing Particles in Stable Liquids*, Sov. J. At. En. 3 (1957) 921, Russian original: *At. Energ.* **3**, 152 (1957).

1957: Use hydrodynamic radiation to detect particles
(detection of neutrino published in *Science* on 20 July 1956)

The thermo-acoustic effect

Thermo-acoustic effect: (Askariyan 1979)
energy deposition ⇨ local heating (~μK) ⇨ expansion ⇨ pressure signal

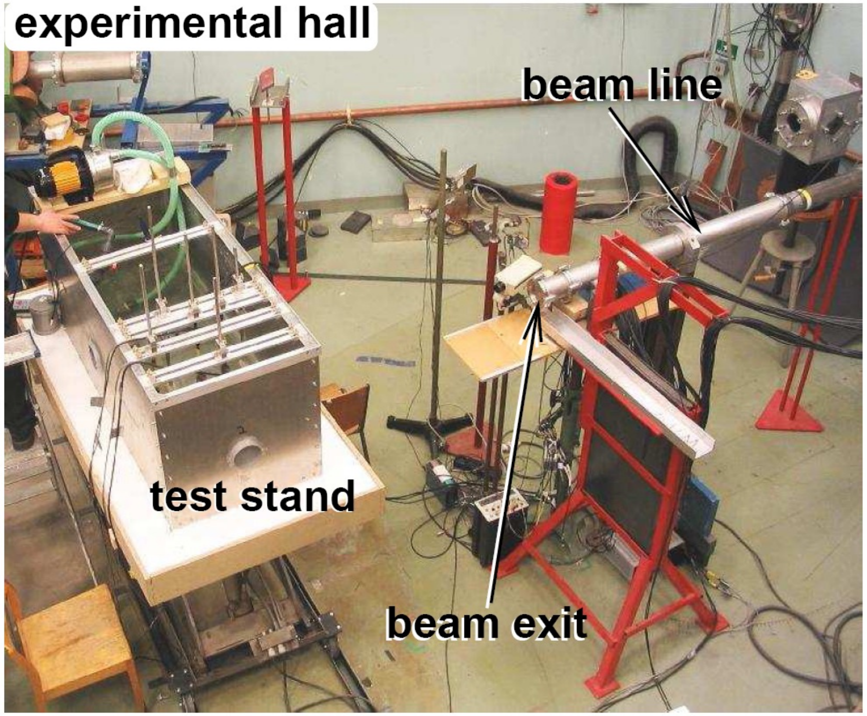
Confirmed in laboratory experiments (see next slide)

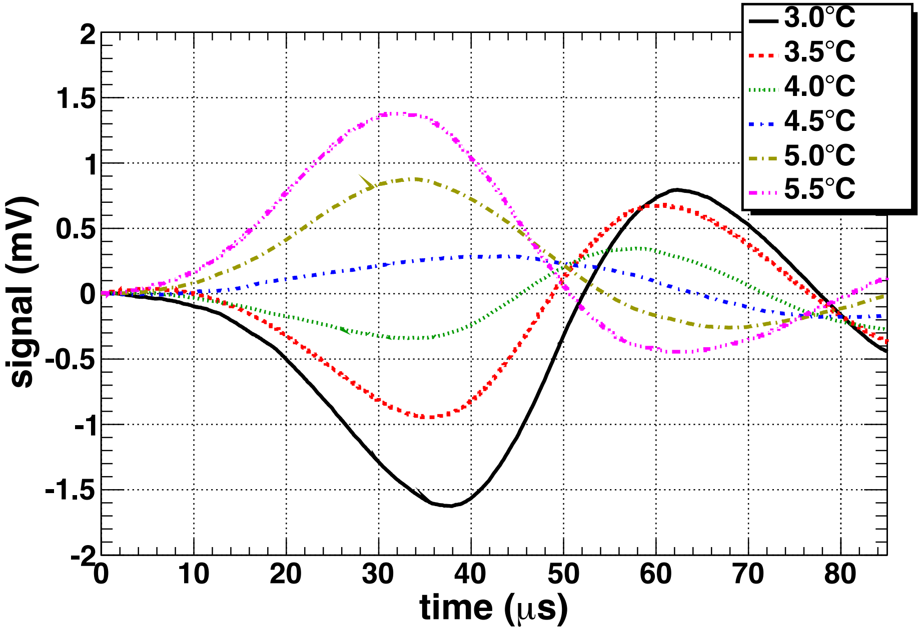
From R. Nahnhauer, ARENA 2010;

First ideas presented at the 1976 DUMAND workshop independently by T. Bowen and B.A. Dolgoshein,
Proceedings not accessible (to me) but see:

G. A. Askaryan and B.Dolgoshein, JETP Lett. 25 (1977) 213
T.Bowen, Proc. 15th ICRC, Plovdiv, 1977, V6, p. 277

Measurements of thermoacoustic effect





More details:
https://arxiv.org/abs/1501.01494
(neither first nor only measurement – see also references in that publication)

Acoustic ideas for DUMAND

strongly connected to the early DUMAND project:

DEEP UNDERWATER MUON AND NEUTRINO DETECTOR

1973: Cosmic Ray Conference in Denver → DUMAND steering committee
1975: First DUMAND workshop, (Washington), start of the project
1976: DUMAND Workshop (Honolulu), Thermo-acoustic model, acoustic detector
1977: DUMAND acoustic workshop (La Jolla)
1978: several DUMAND workhops
1979: DUMAND workshop (Khabarovsk+Baikal)
1980: several DUMAND symposia and workshops

} **experimental test of Thermo-acoustic model explanation of signal shape and origin study of background conditions in the ocean**

until 1980 close collaboration of scientists from US and Russia, particularly in acoustic technology development
after Soviet occupation of Afghanistan most links lost

A. Roberts(1992): Russian participation in DUMAND was strong at this time, and continued strong until it was abruptly cut off by the Reagan administration.[2] Even after their connection with DUMAND had

[2]The severing of the Russian link was done with elegance and taste. We were told, confidentially, that while we were perfectly free to choose our collaborators as we liked, if perchance they included Russians it would be found that no funding was available for us.

From R. Nahnhauer, ARENA 2010

Acoustic signals of neutrino interactions in water

Thermo-acoustic effect: (Askariyan 1979)
energy deposition ⇨ local heating (~µK) ⇨ expansion ⇨ pressure signal

Wave equation for the pressure p for deposition of an energy density ε :

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

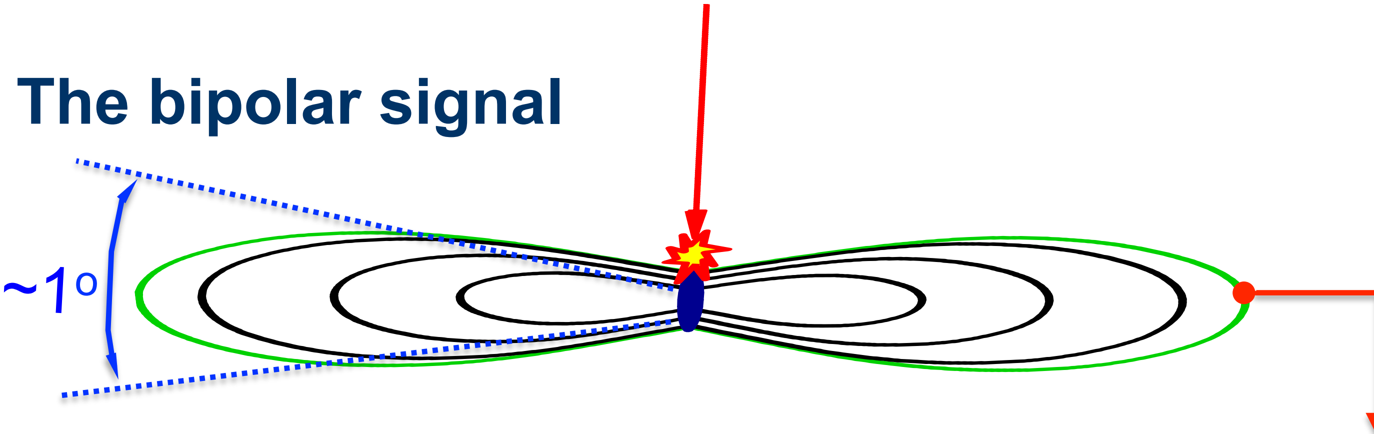
α = Volume expansion coefficient

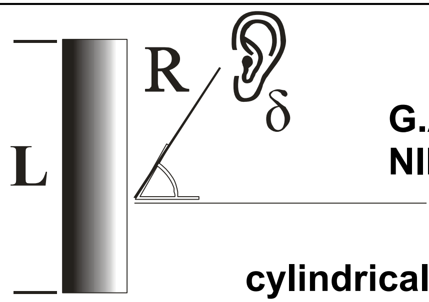
C_P = specific heat capacity (at constant pressure)

c = speed of sound in water (ca. 1500 m/s)

Solution (analytical/numerical) with assumption of an instantaneous energy deposition

The bipolar signal

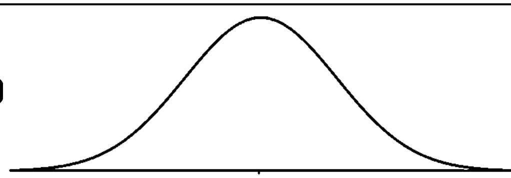




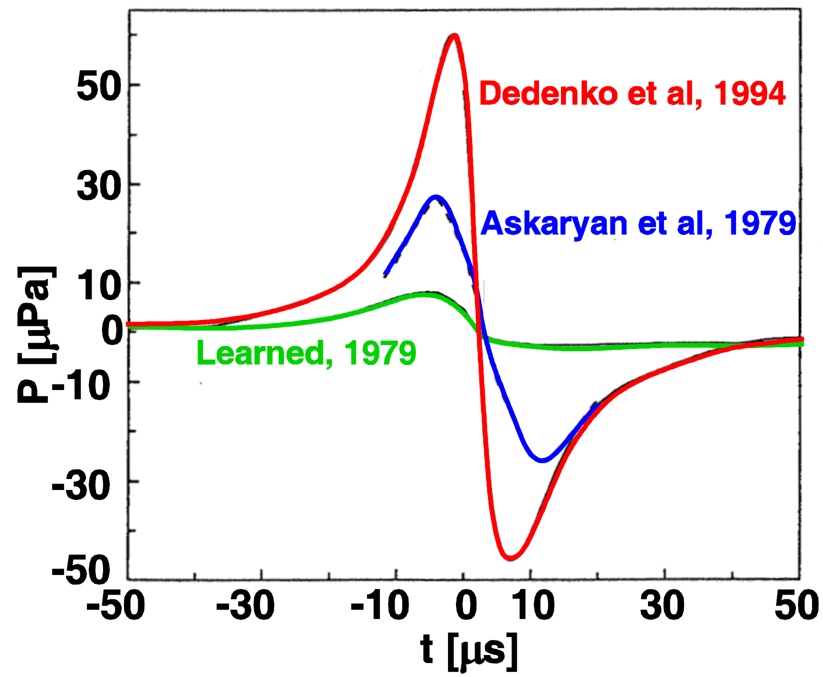
G.A. Askaryan et al.
NIM 164(1979) 267

cylindrical energy distribution

J. Learned,
Phys.Rew. D 19
(1979) 3293



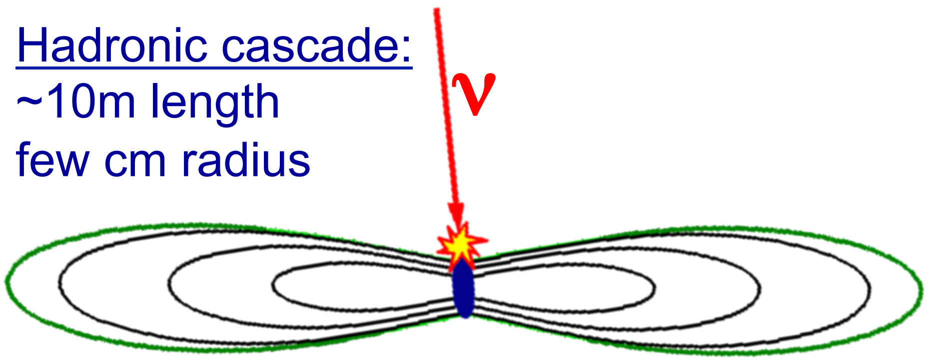
Gaussian width of lateral energy distr.



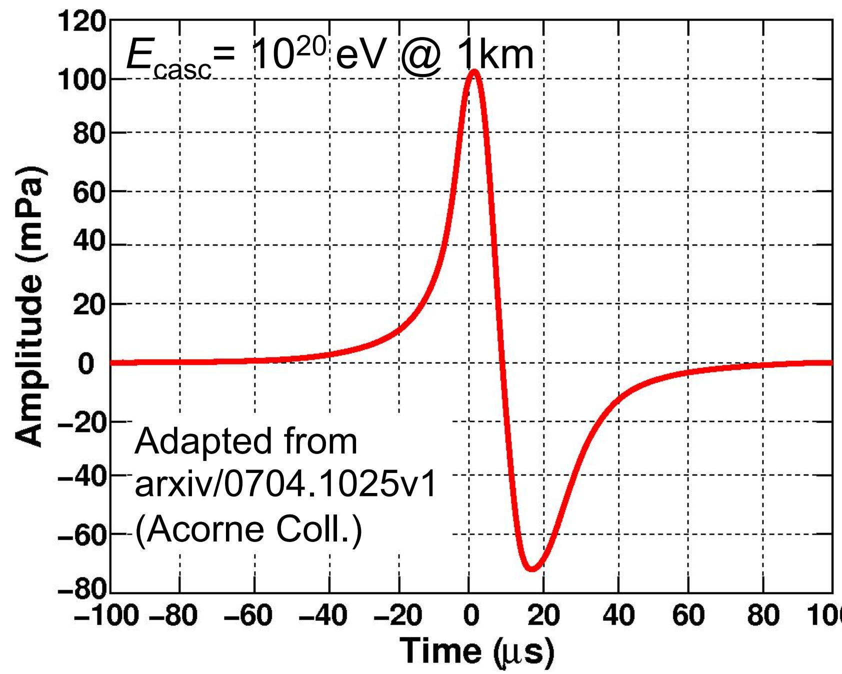
A.V. Butkevich et al., Phys. Part. Nuc., 29 (3), 266, 1998

Simulations of acoustic signals in water and ice

Hadronic cascade:
~10m length
few cm radius

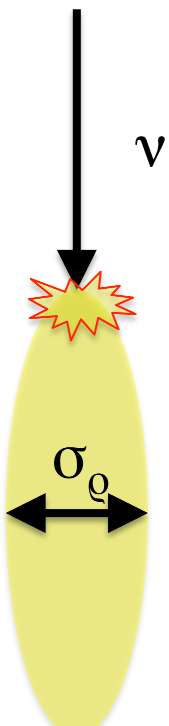


Pressure field:
Characteristic "pancake" pattern



$$P(r = 200\,\mathrm{m}) \approx 10 \times \frac{E_{casc}}{1\,\mathrm{EeV}}\,\mathrm{mPa}$$

The bipolar pulse

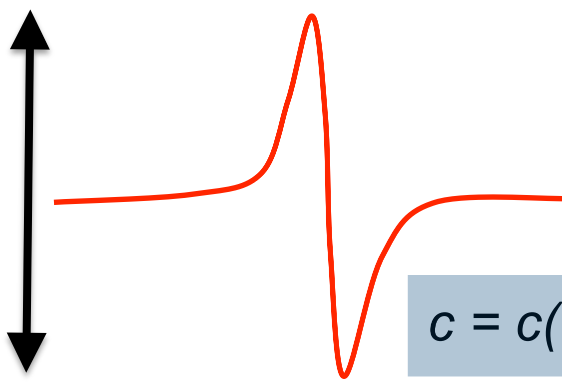


$$E_0 = \int \varepsilon \, dV$$

Analytical calculation of a signal in the far field for a Gaussian energy density

$$p_{max} \propto \gamma_G \frac{E_0}{\sigma_\rho^2}$$

$2p_{max}$



$$\gamma_G = \frac{c^2 \alpha}{C_P}$$

c = c(temp, pressure, salinity)

α	= Volume expansion coefficient
C_P	= specific heat capacity (at constant pressure)
c	= speed of sound in water (ca. 1500 m/s)

Media for acoustic detection

- Water
- Ice
- Salt domes
- Permafrost

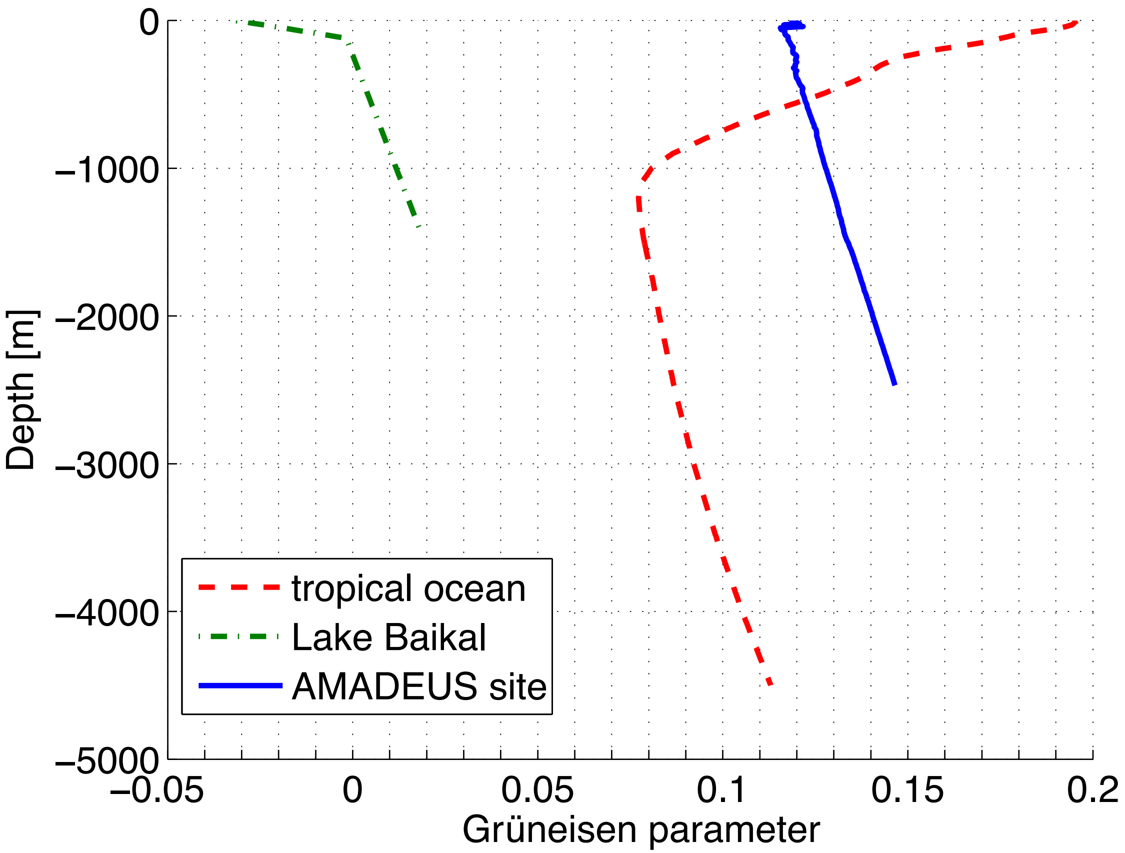
G. Manthei, J. Eisenblätter, and T. Spies, *Experience on acoustic wave propagation in rock salt in the frequency range 1–100 kHz and conclusions with respect to the feasibility of a rock salt dome as neutrino detector*, in: Proceedings of the 1st International Workshop on Acoustic and Radio EeV Neutrino detection Activities (ARENA 2005), Zeuthen, Germany, May 17–19, Int. J. Mod. Phys. A21S1, World Scientific, 2006, p. 30, ISBN 981-256-755-0.

P.B. Price, *Attenuation of acoustic waves in glacial ice and salt domes*, J. of Geophys. Res 111 (2006) B02201, arXiv:astro-ph/0506648v1.

R. Nahnhauer, A.A. Rostovtsev, and D. Tosi, *Permafrost – An Alternative Target Material for Ultra High Energy Neutrino Detection?*, Nucl. Inst. and Meth. A 587 (2008) 29, arXiv:0707.3757v1 [astro-ph].

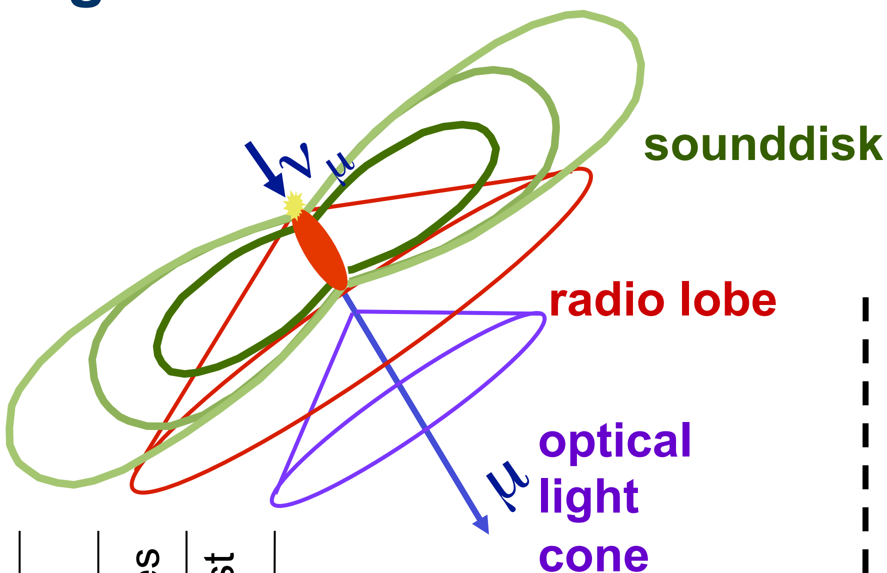
No activity in salt/permafrost known to me;

Grüneisen parameter

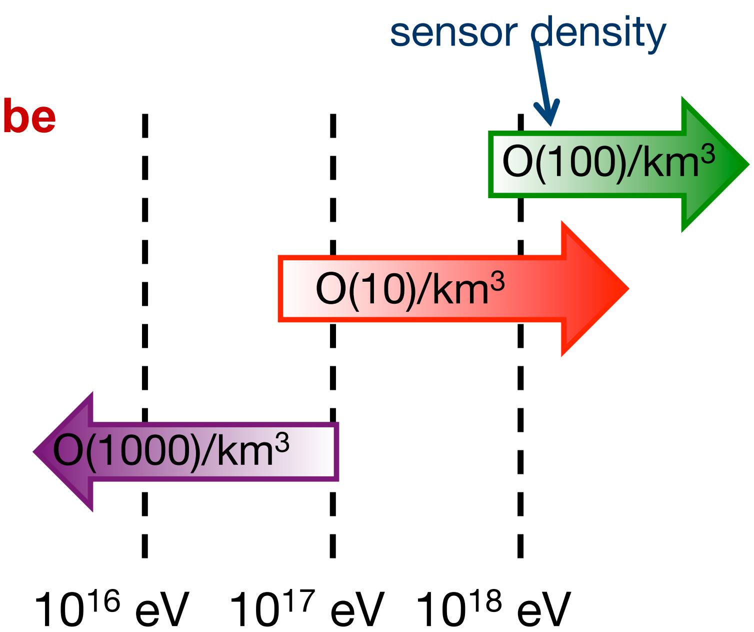


Ice: (-51°C): 1.12; NaCl (30°C): 2.87 (G. Gratta ICATPP Como, 2007)

Neutrino signatures in different media



	Ice	Water	Salt domes	Permafrost
light	✓	✓		
radio	✓		✓	✓
sound	✓	✓	✓	✓



adapted from: R. Nahnhauer, ARENA Conf. 2010

“Modern history” of acoustic detection

year	name	location	participants	ac. talks
2000	RADHEP	Los Angeles	50	1
2003	Acoustic mini-ws.	Stanford	20	16
2005	ARENA2005	Zeuthen	90	26
2006	ARENA2006	Newcastle	50	13
2008	ARENA2008	Rom	80	22
2010	ARENA2010	Nantes	80	12
2012	ARENA2012	Erlangen	70	10
2014	ARENA2014	Annapolis	60	5
2016	ARENA2016	Groningen	55	10
2018	ARENA2018	Catania	60	10

Acoustic Neutrino Detection Test Setups

Acoustic detection test setups

First generation acoustic test setups follow two “philosophies”:

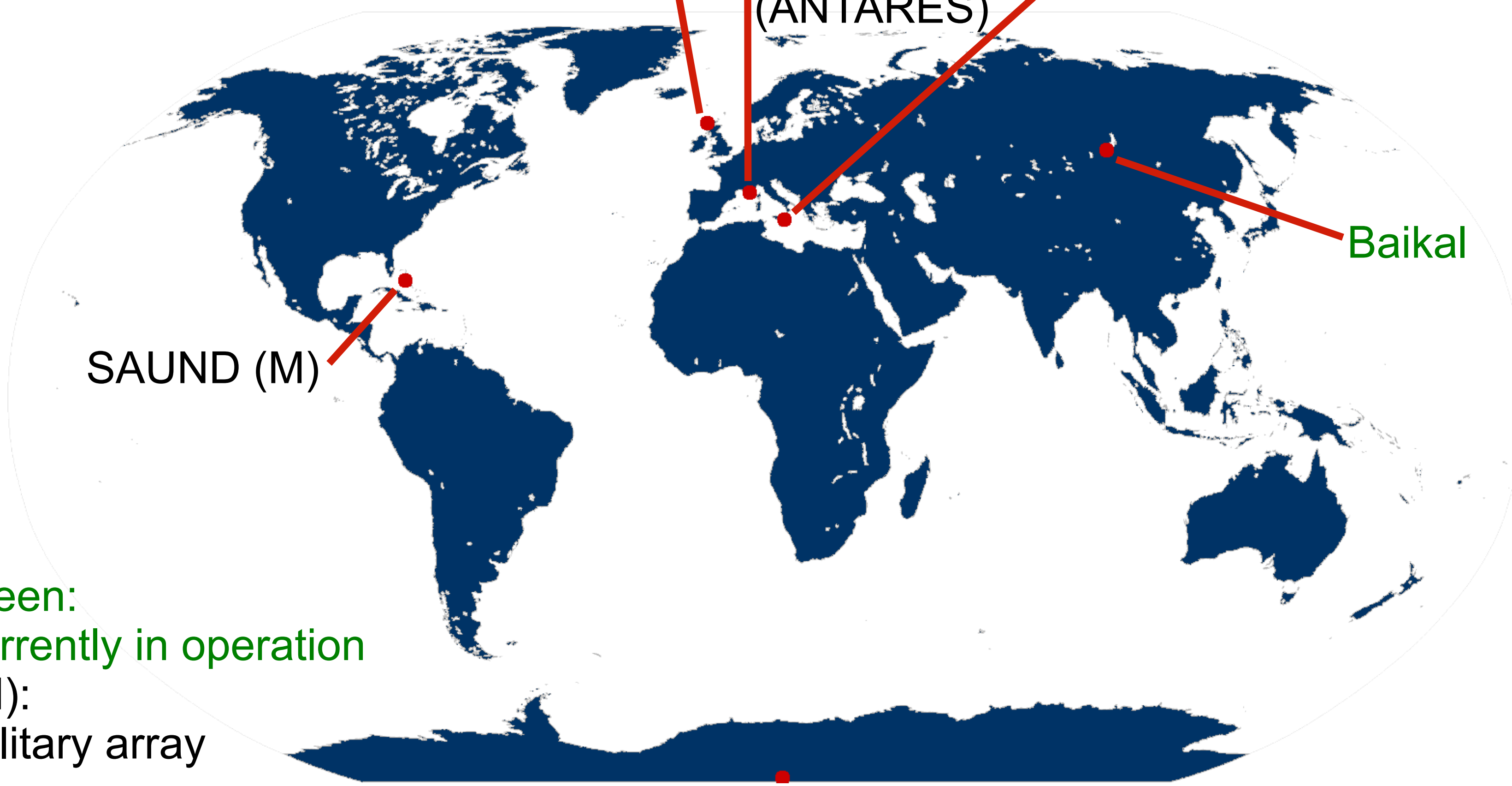
- “We can get access to an acoustic array; why not use it for some tests for acoustic particle detection?”
- “We have a neutrino telescope infrastructure; why not install some acoustic sensors to test acoustic particle detection?”

Technology:
Hydrophones (in water) and glaciophones (in ice) using piezo ceramics

Array size:

O(10) sensors, used for feasibility studies (background), developing techniques/algorithms

Test Setups in ice and water

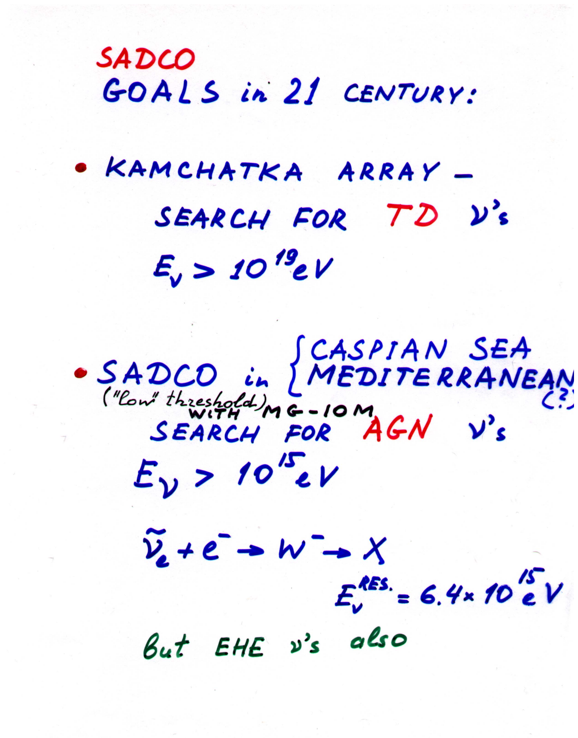


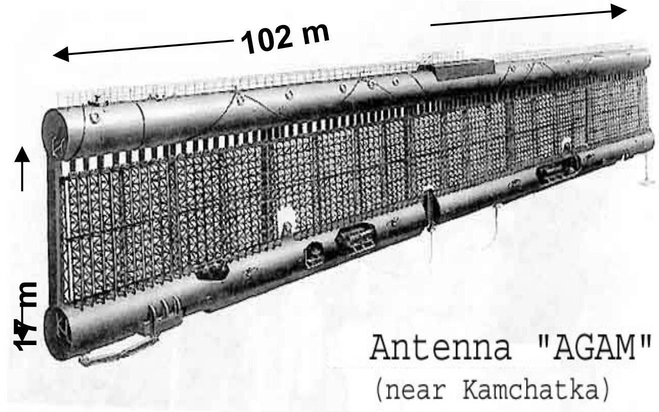
green:
currently in operation
(M):
military array

Military: AGAM - MP10 - SADCO

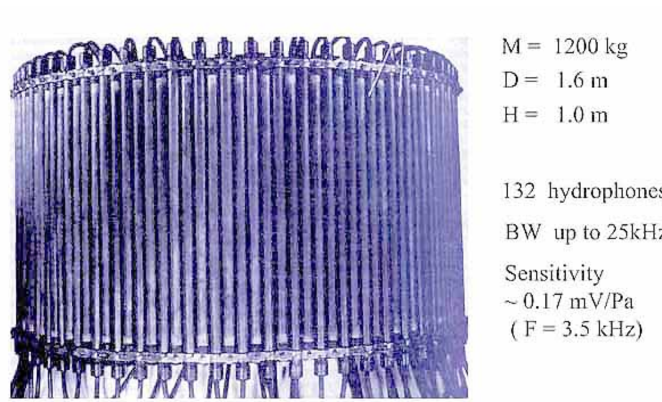
Adapted from R. Nahnhauer, ARENA 2010

From a talk of I. Zelesnykh given by J. Learned at Stanford-2003





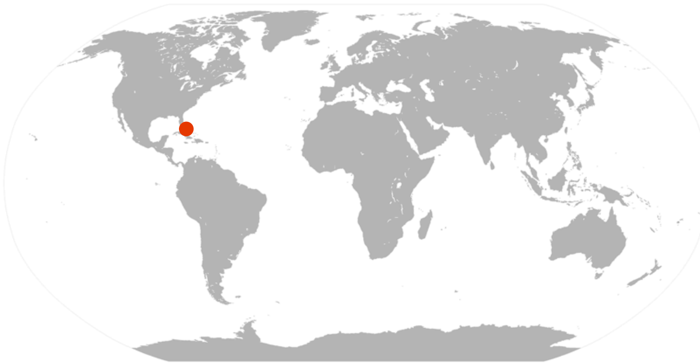
2400 hydrophones
f < 2 kHz
V_{eff} > 100 km^3 for
E_ν > 10^{20} eV

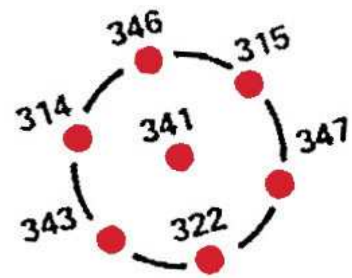


Portable Submarine Antenna MG-10M as a basic module of the deep-water Neutrino Telescope Test from oil platforms in Caspian Sea

See also arXiv: astro-ph/9705189v1: Present status of project not known (to me)

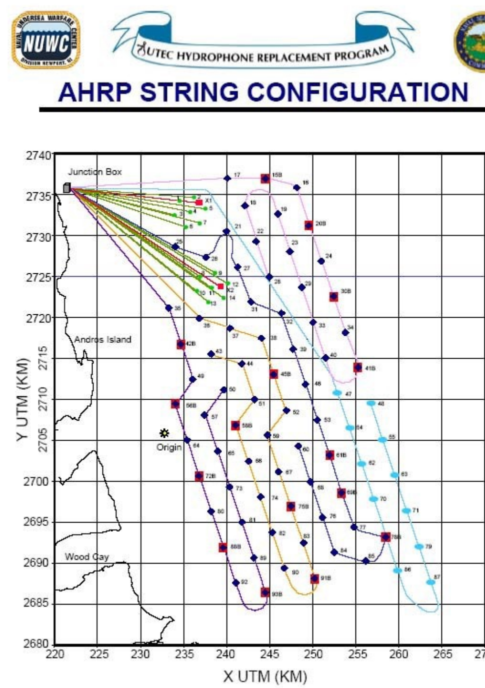
Military array: AUTEC - SAUND





SAUND I:
7 hydrophones
at 1600 m depth,
1.5 km spacing

Study of Acoustic
Ultrahigh-energy Neutrino Detection

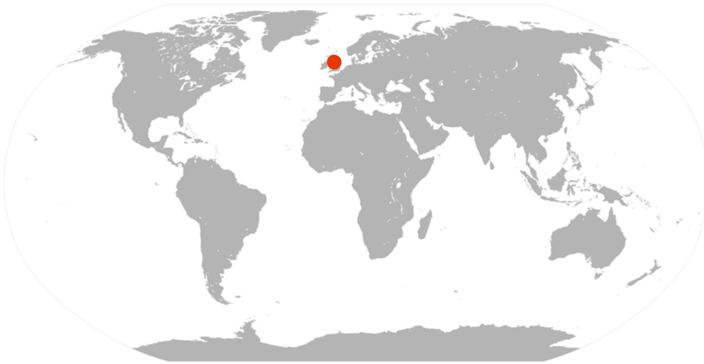


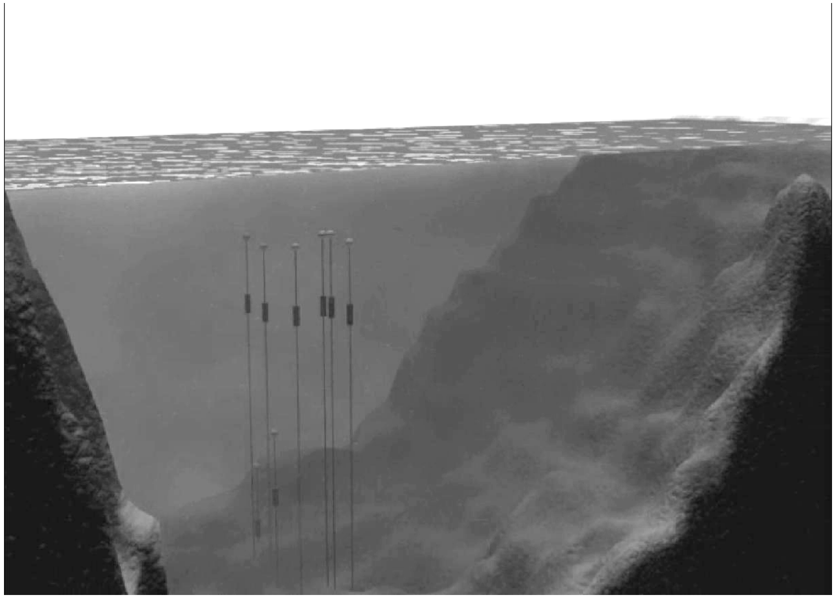
SAUND II:
49 hydrophones
20 km x 50 km area
Spacing of 3 to 5 km

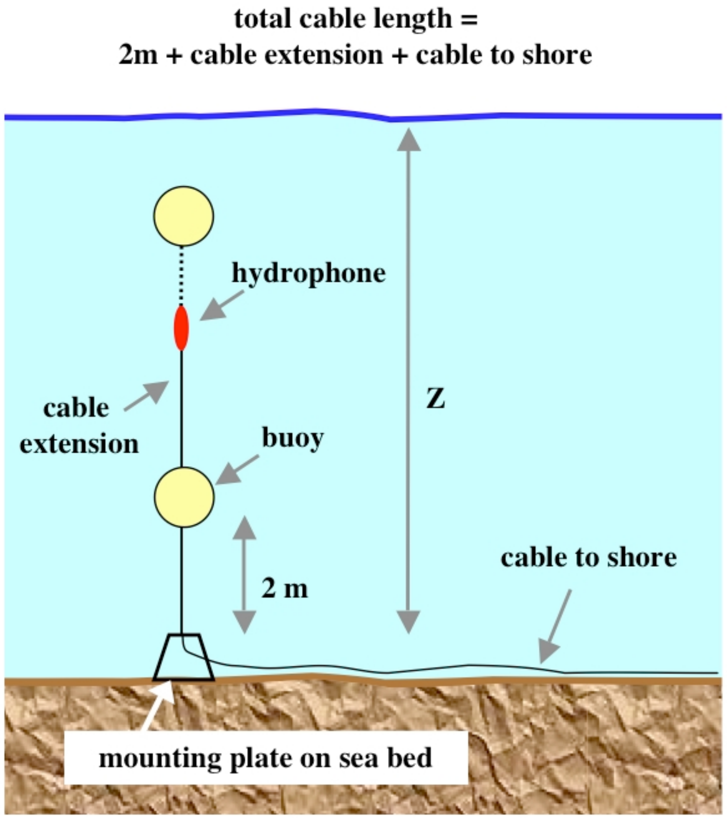
Data taking:
65 $*10^6$ events
in 195 days

Military array: RONA - ACoRNE

- 8 hydrophones in North-West Scotland

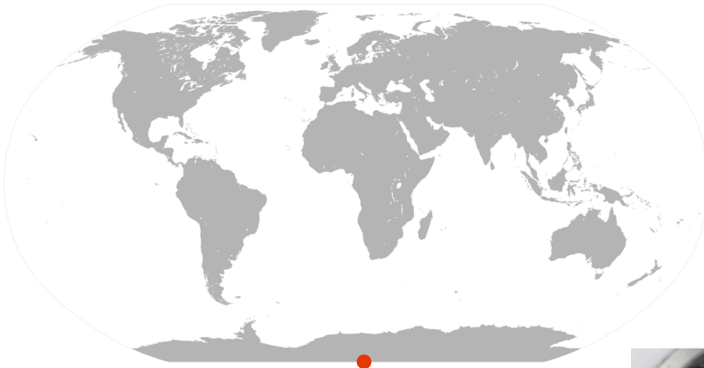


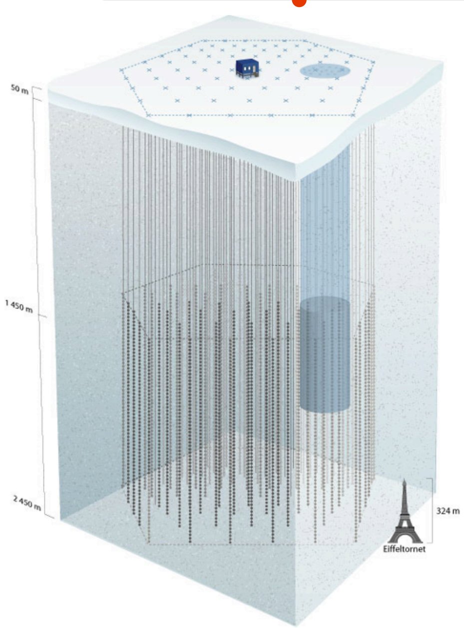


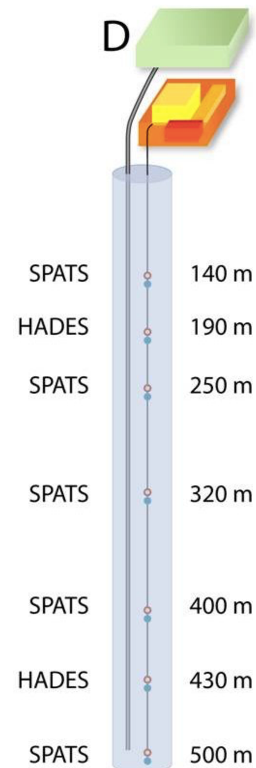


SPATS – IceCube

- Ice as detector medium
- 4 strings with 7 “stages” each
- A stage consists of a transmitter module and a receiver module (attenuation length measurements)
- Taking data since 2006, currently no further developments planned







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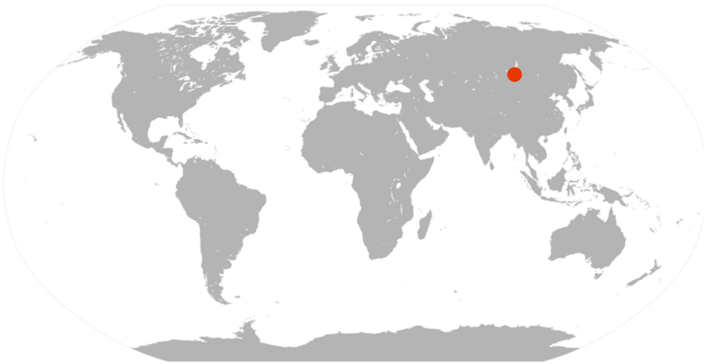
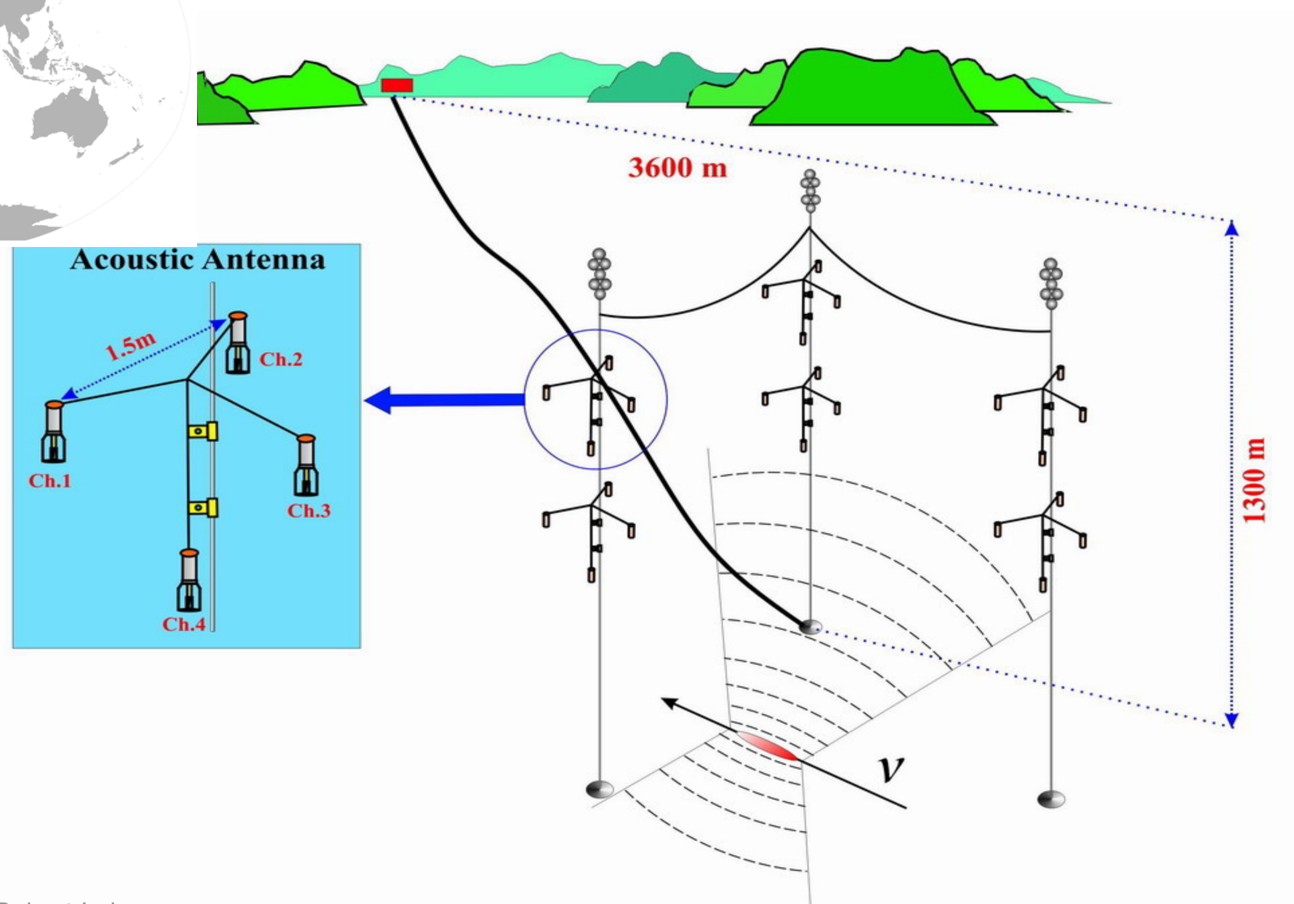
Lake Baikal

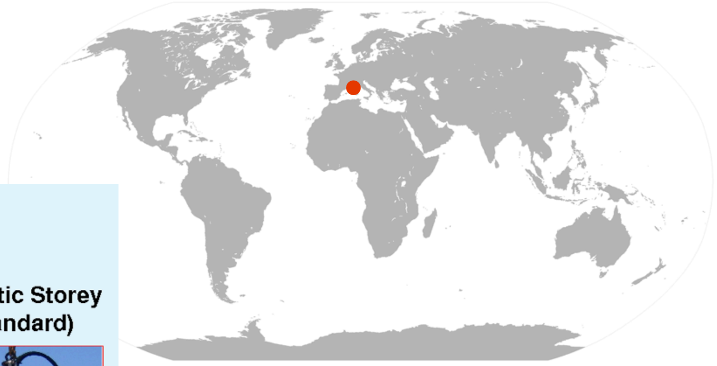
- Planned: 6 tetrahedral antennae with 4 hydrophones each in >500m depth
- Currently one antenna installed

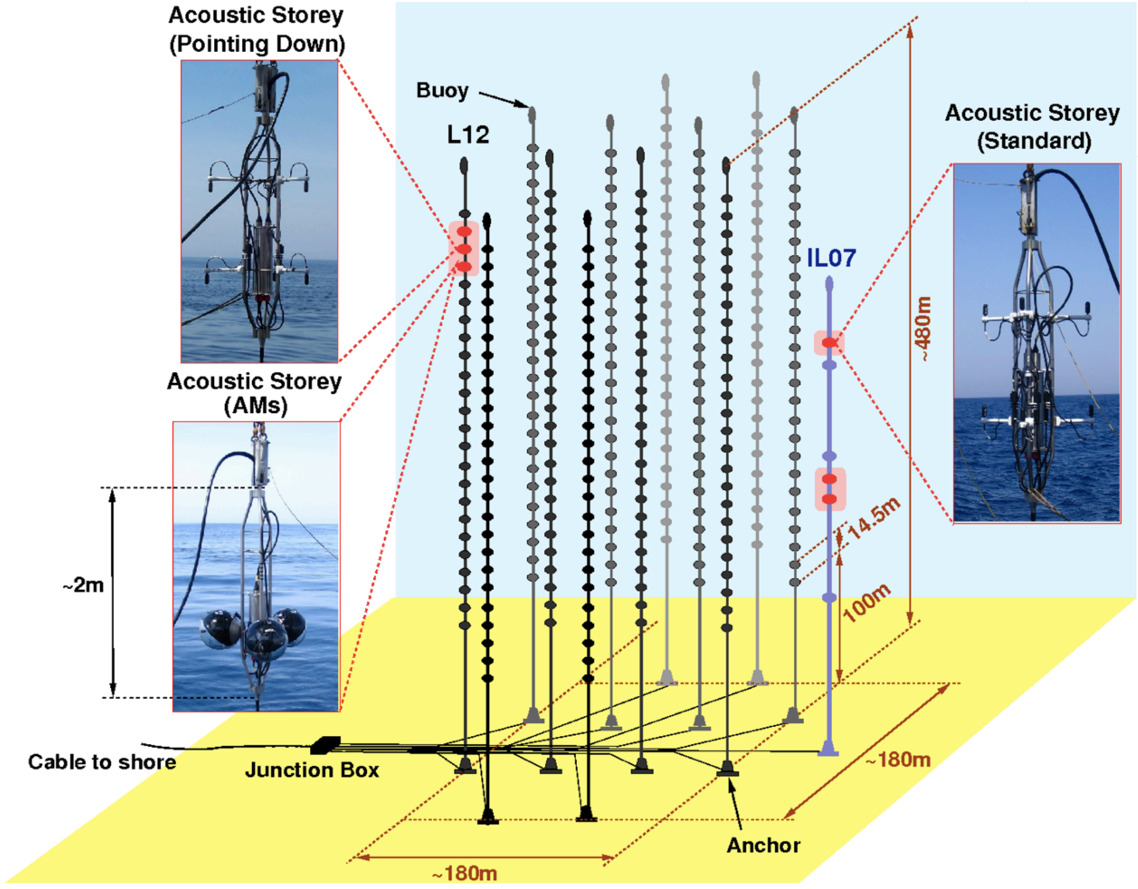




N. Budnev, ARENA 2014, Annapolis

AMADEUS – ANTARES





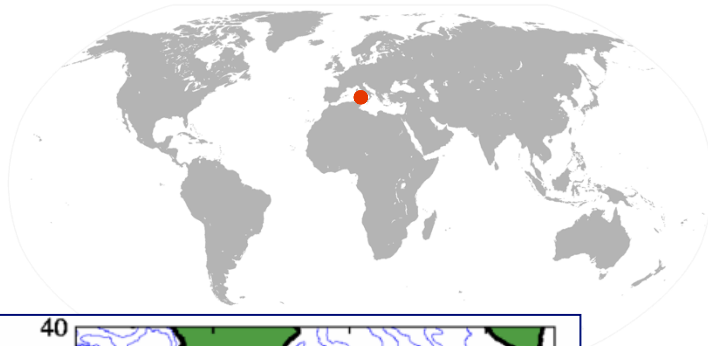
Operation from 2007 to 2015

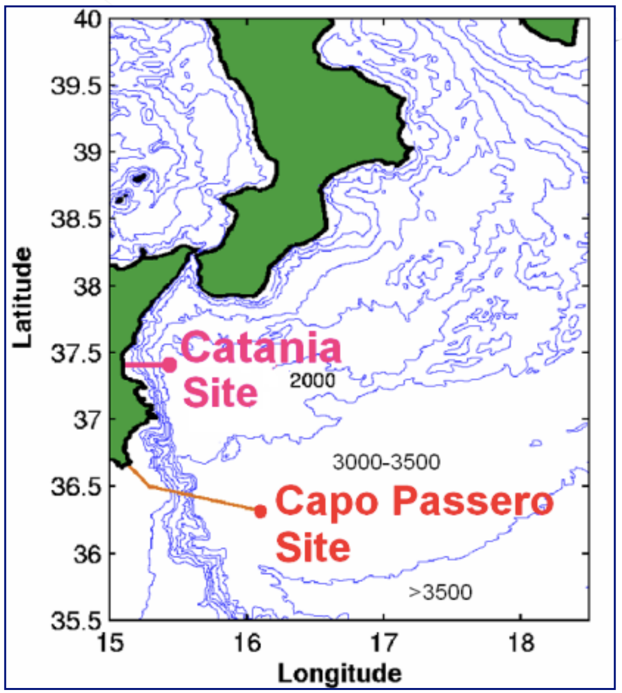
36 acoustic sensors on 6 stories

Local clusters for direction reconstruction

Depth 2300 – 2100 m

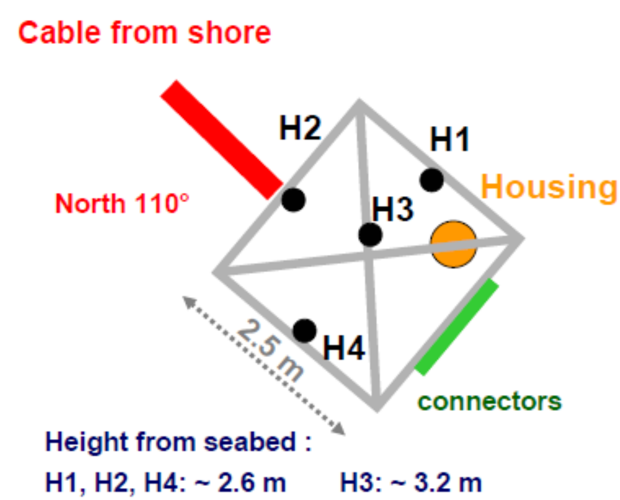
KM3NeT-Italia/OnDE





OnDE I (Jan. 2005 –Nov. 2006)
(Ocean Noise Experiment)

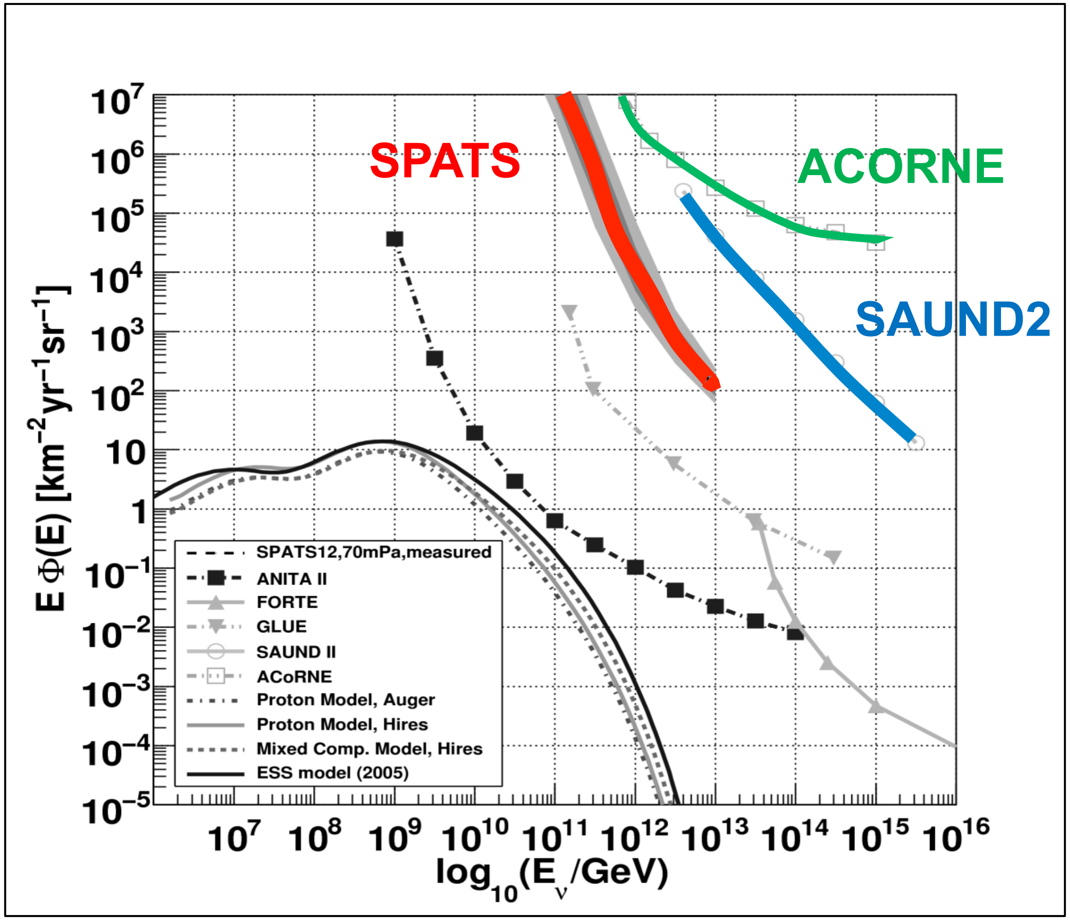
- Test Site at 2000 m depth, 25 km offshore Catania
- Operation of test setup OnDE (4 hydrophones) from 2005 -2006



In collaboration with Uni-Pavia CIBRA

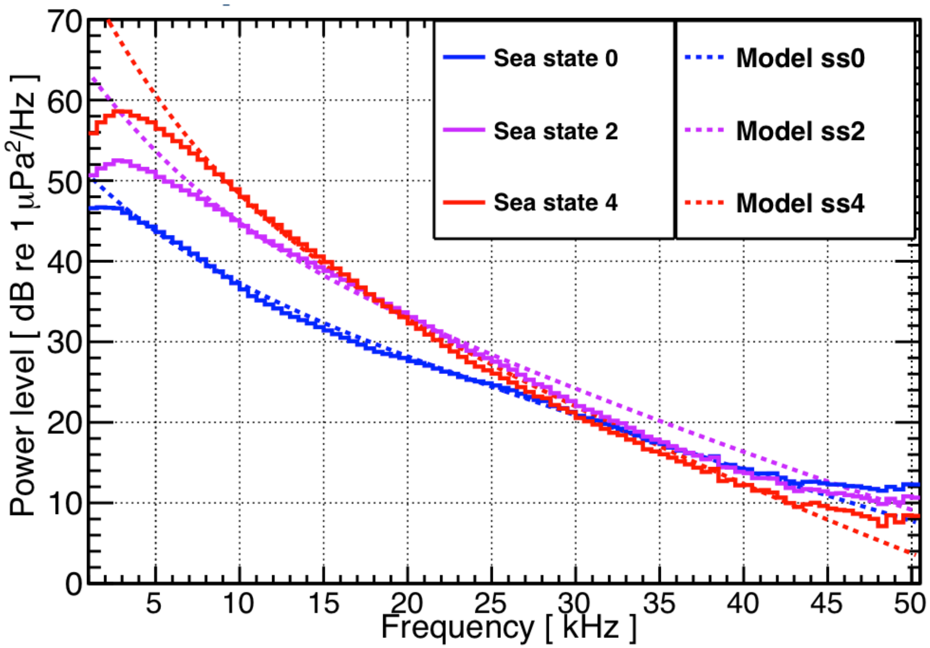
Acoustic Neutrino Detection: Status and Results

Limits on UHE neutrino flux

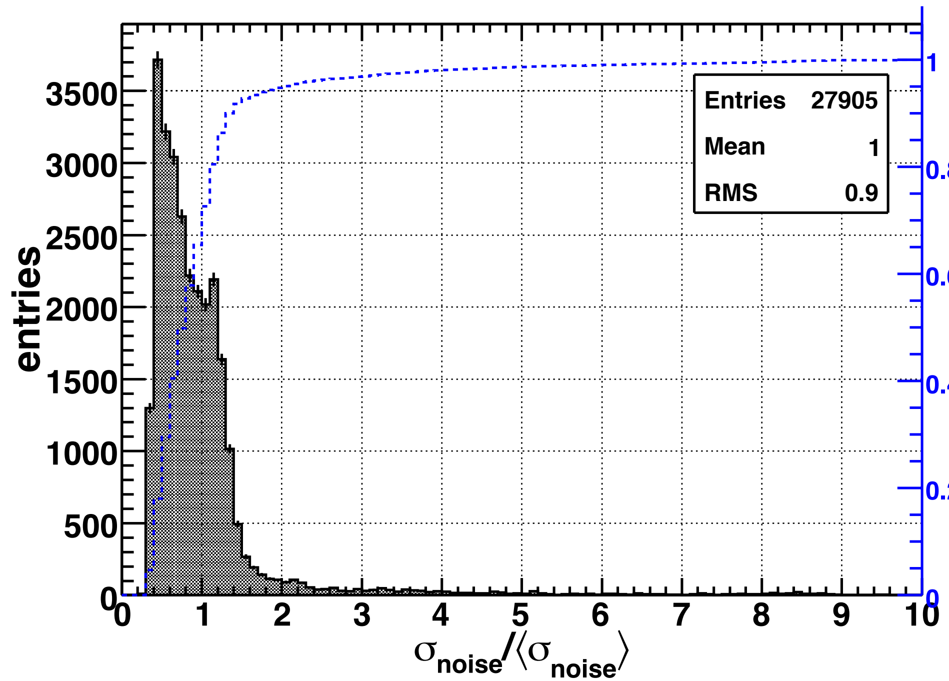


R. Abbasi et al.,arXiv:astro-ph/1103.1216; adapred from R. Nahnhauer, Ricap 2011

Noise measurements for AMADEUS site



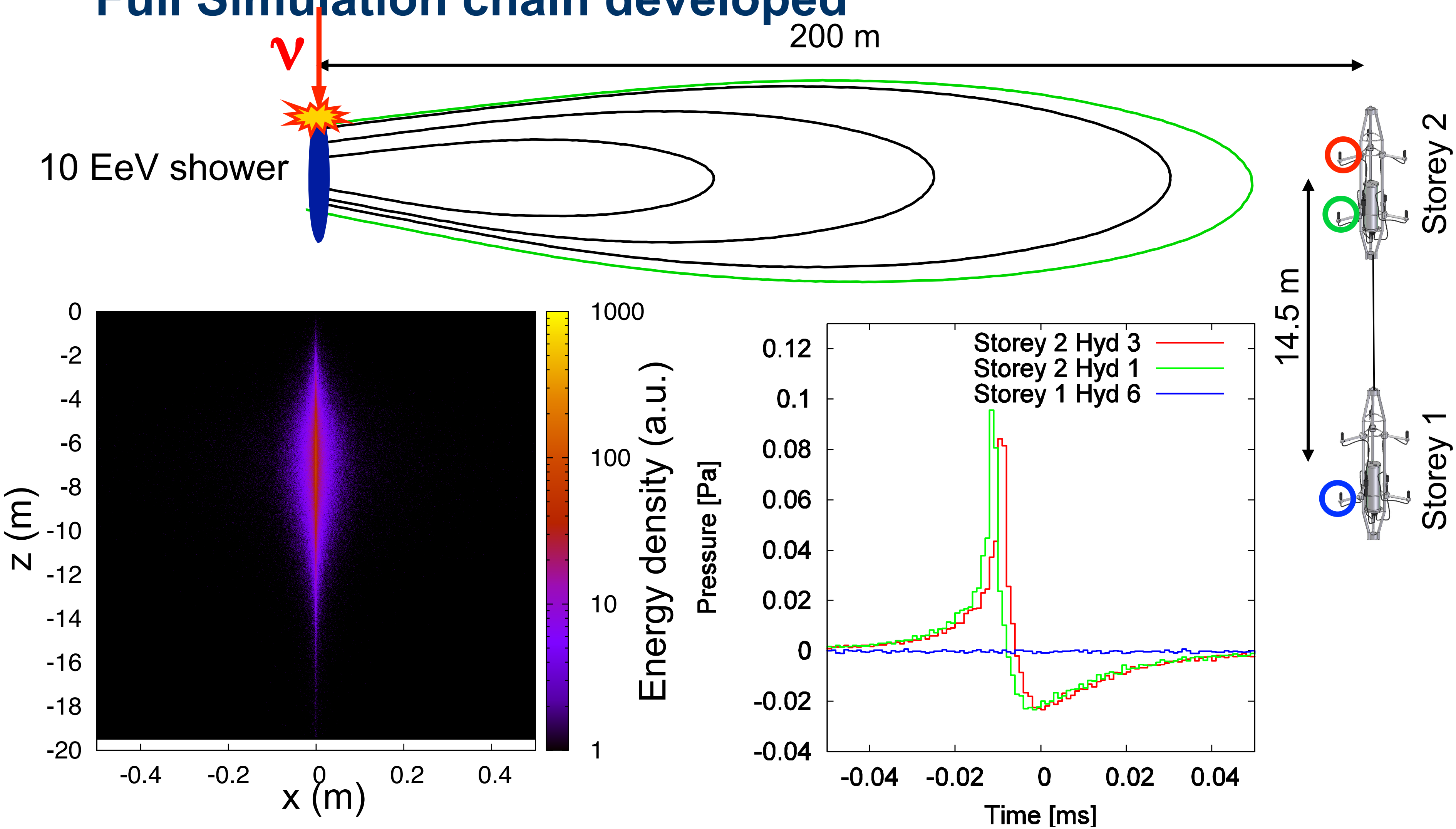
D. Kießling, MSc Thesis (2013)



1 entry = noise level (f = 10 – 50kHz) of 10s of continuous data recorded every hour with one hydrophone (2008 – 2010 data) (R. Lahmann, ICRC 2011)

Background conditions in Mediterranean Sea well measured
⇒Input for Monte Carlo simulations

Full Simulation chain developed



MC according arXiv:0903.0949v2 to (Acorne Coll.)

Fruitful cooperation with marine science

The neutrino and the whale

An underwater effort to detect subatomic particles has ended up detecting sperm whales instead. **Nicola Nosengo** reports on a partnership between marine biologists and particle physicists.

To the dock workers and sailors at the port of Catania, in Eastern Sicily, it all looked very suspicious. About once a month during 2005 and 2006, two strangers would walk out to a large wooden cabin at the end of a pier, unlock the door, and remove a small box. Then they would lock up again and disappear until the next month.

The locals had to question what the two men were up to. But when asked, the strangers reassured them that there was nothing to worry about. They were scientists. And the boxes they were retrieving were computer hard drives containing hours of sound data relayed by an underwater cable from microphones — or, more accurately, hydrophones — placed on the Mediterranean sea floor 28 kilometres offshore. Giorgio Riccobene, a particle physicist at the Southern Laboratories of the Italian National Institute for Nuclear Physics (INFN) in Catania, was hoping to show that the hydrophones could be used to detect subatomic particles called neutrinos that had come from deep space. Giovanni Pavan, a marine biologist from the University of Pavia in Northern Italy, was there to help Riccobene deal with background noise in the recordings.

G. RICCOBENE

Riccobene: a particle physicist.

But what Riccobene and Pavan discovered as they listened to their data will bring them back to the port next year with their roles reversed. Then, the physicist will be helping the biologist, and their quarry will not be neutrinos, but sperm whales.

The road to this unexpected destination began nearly a decade ago with Riccobene's involvement in the Neutrino Mediterranean Observatory (NEMO), a collaboration of around 100 researchers from the INFN and other Italian institutes who are hoping to study neutrinos in the ocean. Cosmological neutrinos are constantly streaming through Earth, carrying invaluable information about distant sources such as supernovae. But these fundamental particles have no electric charge and have masses close to zero; they interact with matter so rarely that studying them requires gigantic detectors — the bigger, the better. Hence the NEMO design calls for thousands of optical detectors distributed over 2 cubic kilometres of water, 3,500 metres under the sea at a site off Capo Passero in southern Sicily. The idea is that an incoming neutrino will very occasionally interact with a water molecule, producing a pulse of light that the detectors will capture.

G. PAVAN

Pavan: a marine biologist.

Riccobene was working on a way to enhance the detection. "Theoretically, higher-energy neutrinos should also produce detectable sound waves," he says. "As sound travels better than light in water, an acoustic detector could multiply chances to capture neutrino events." No one knew if this would work. But as the NEMO design includes hydrophones anyway — they are needed to position the optical detectors— Riccobene was asked in 2002 to supervise a feasibility study called the Ocean Noise Detection Experiment (ONDE), which would be located at the project's 2,000-metre-deep test site east of Catania.

Noise control

To educate himself, Riccobene went to Paris for a workshop about acoustic neutrino detection, and immediately noticed something missing from the talks. "Background noise was not even mentioned," he recalls. "Everyone was taking for granted that at great depths it would be very low, but there were no published data." Riccobene went back to Catania, just in time to discover that a local environmental group was hosting a talk by Pavan, who had pioneered the digital recording of sea-mammal sounds in the early 1980s, and who was acknowledged as one of the world's leading experts in the field. He was obviously the right man to answer Riccobene's question: how high would background noise be at a depth of 2,000 metres?

With little data to rely on, Pavan had no simple answer. "Systems to record at great depths were simply not available until a few years ago," he says. About all he could say for sure was that deep waters were not nearly as silent as the neutrino physicists were assuming.

"At first I was appalled," Riccobene says. The noise levels Pavan estimated were well above the expected level of a neutrino event. That did not necessarily make neutrino detection unfeasible, he says. But it did mean that the NEMO team couldn't hope to isolate the neutrino signals until it had an accurate survey of the background noise it would have to filter out.

Riccobene invited Pavan to join the ONDE team on a long-term monitoring project of the Sicilian seabed soundscape — the first ever attempted at such depths. Pavan had no funds to support his participation, but accepted anyway. Riccobene would give him access to depths he could never reach otherwise, allowing him to study the largely unknown acoustic environment of the deep sea. Pavan particularly hoped to measure the level of sound pollution there, as it is a potential cause of stranding for many deep-diving whales — whose vocalizations he also expected to hear in the recordings.

By January 2005, Riccobene and his team had positioned four high-sensitivity hydrophones at the NEMO test site and had laid an optical data cable back to that cabin on the pier in Catania. Soon after that Riccobene and Pavan were obtaining data. And in April 2005, Pavan began listening to the first recordings.

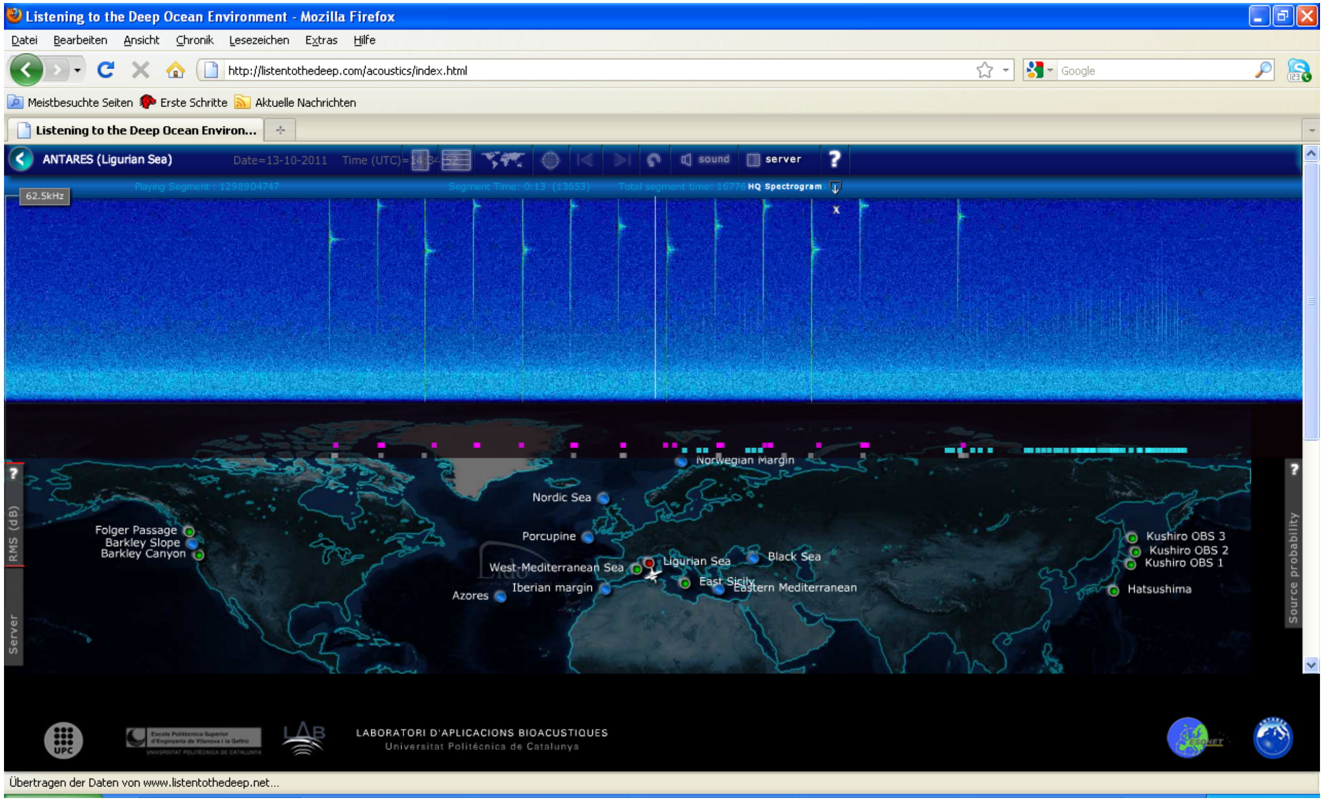
As he predicted, Pavan could hear low, uniform background noise, mostly caused by natural water movement and ship traffic, plus an occasional burst of identifiable sounds: the propeller of a large ship, a sonar impulse, even some explosions. But what captured his attention were short, regularly repeating sequences of 'clicks' — the signature sounds made by sperm whales compressing air through their respiratory system. "They probably use them to estimate depth and to locate prey, measuring their echoes more or less like bats do," Pavan says. Hearing clicks every now and then was not surprising: they are among the loudest sounds produced by any animal, and can travel up to 20 kilometres in water. What was surprising was that the clicks kept appearing in the recordings month after

560

Nature New Feature, Vol. 463, p. 560 (2009)

Fruitful cooperation with marine science

Data from AMADEUS setup at http://listentothedeep.org/
(Maintained by University of Barcelona)



Challenges for the future

- Monte Carlo simulations
- Reduce energy threshold
- Improve signal classification
- Revive hybrid detection

Thank you for your attention

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