Neutrino Detection, Position Calibration and Marine Science with Acoustic Arrays in the Deep Sea

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Robert Lahmann

VLVnT 2011, Erlangen, 14-Oct-2011

Friedrich-Alexander-Universität Erlangen-Nürnberg

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Outline

- Introduction: Neutrinos and Sound
- Use of Sound in the Sea and the AMADEUS acoustic system
- Ambient Background and Transient Sources
- The Future: Simulations and KM3NeT

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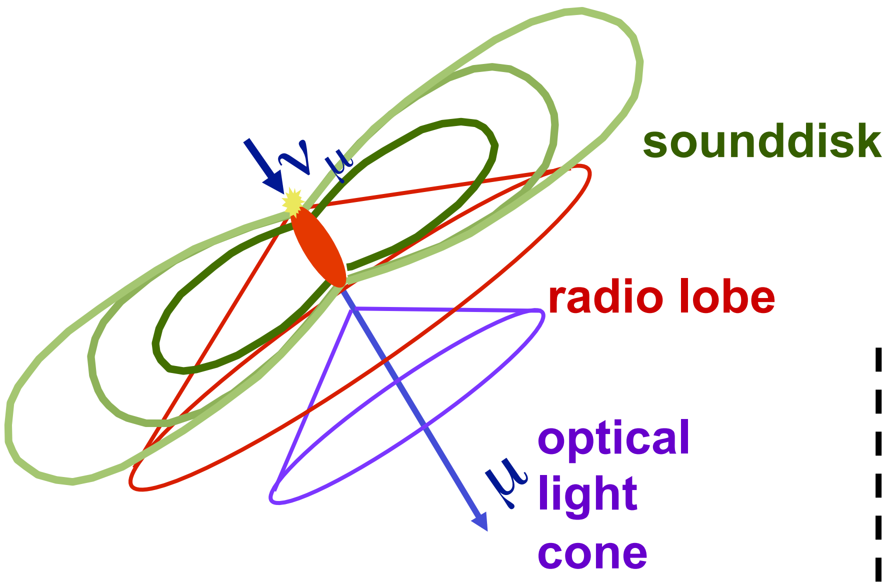
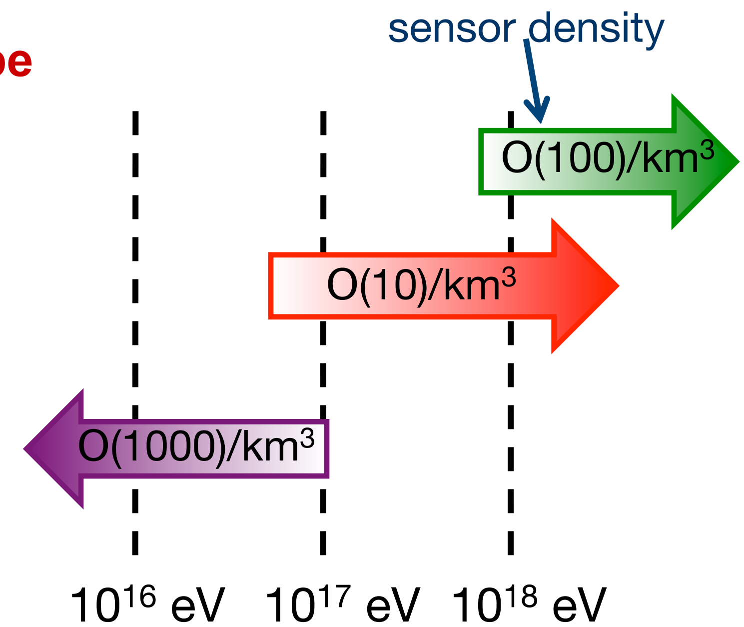
Neutrino Signatures in Different Media





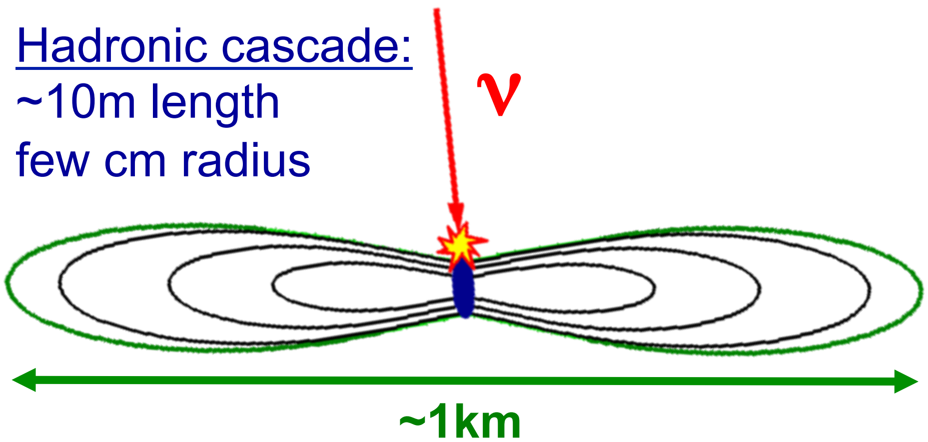
adapted from: R. Nahnhauer, ARENA Conf. 2010

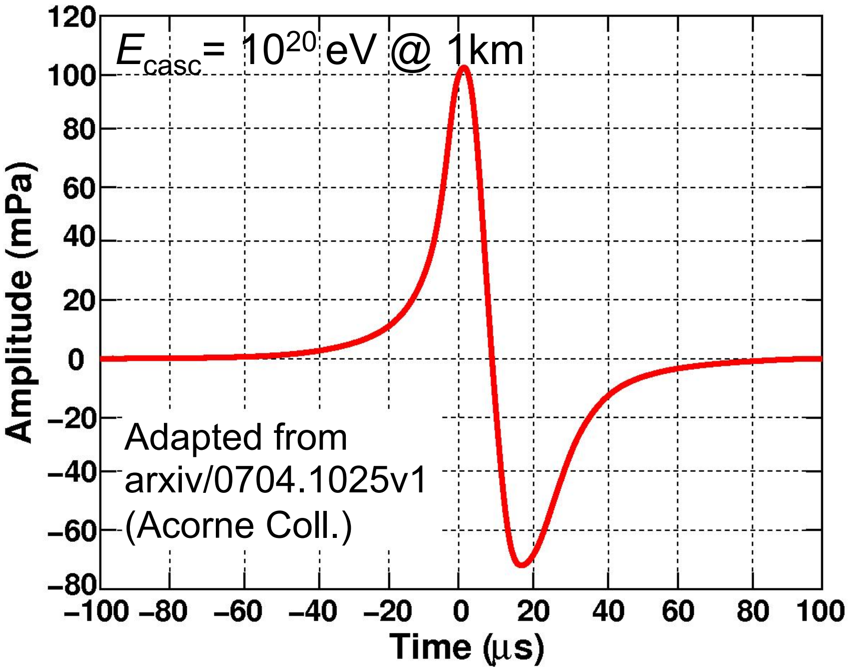
	Ice	Water	Salt domes	Permafrost
light	✓	✓		
radio	✓		✓	✓
sound	✓	✓	✓	✓

Acoustic Detection of Neutrinos

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

Hadronic cascade:
~10m length
few cm radius





Pressure field:
Characteristic "pancake" pattern
Long attenuation length (~5 km @ 10 kHz)
Allows for neutrino detection at $E \gtrsim 10^{18}$eV

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

Acoustic Detection Test Set-Ups

First generation acoustic test set-ups 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?"

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Acoustic Detection Set-Ups

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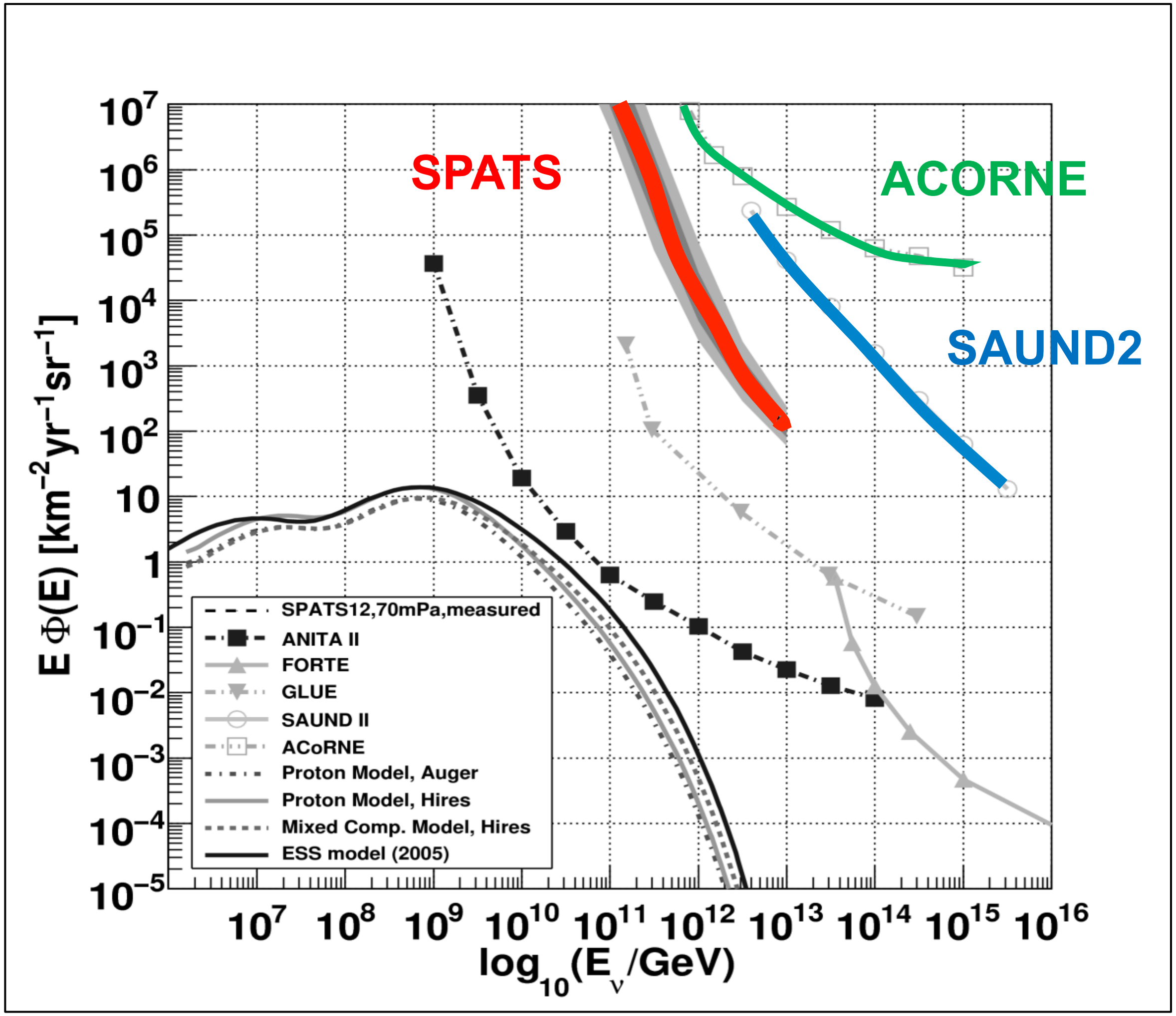
Overview Acoustic Detection Set-Ups

Experiment	Location	Medium	Sensor Channels	Host Experiment
SPATS	South Pole	Ice	80	IceCube
Lake Baikal	Lake Baikal	Fresh Water	4	Baikal Neutrino Telescope
OvDE	Mediterranean Sea (Sicily)	Sea Water	4	NEMO
AMADEUS	Mediterranean Sea (Toulon)	Sea Water	36	ANTARES
ACoRNE	North Sea (Scotland)	Sea Water	8	Rona military array
SAUND	Tongue of the Ocean (Bahamas)	Sea Water	7/49(*)	AUTEC military array

(*) The number of hydrophones was increased from 7 in SAUND I to 49 in SAUND II

Limits on UHE Neutrino Flux



R. Abbasi et al.,arXiv:astro-ph/1103.1216

The Lesson so Far

Existing Acoustic Setups:

- Proof of principle
- Limits not competitive

➔What is the potential of a “real” acoustic neutrino detector and what does it have to look like?

But first: Acoustic neutrino detection isn’t the first application of sound in water …

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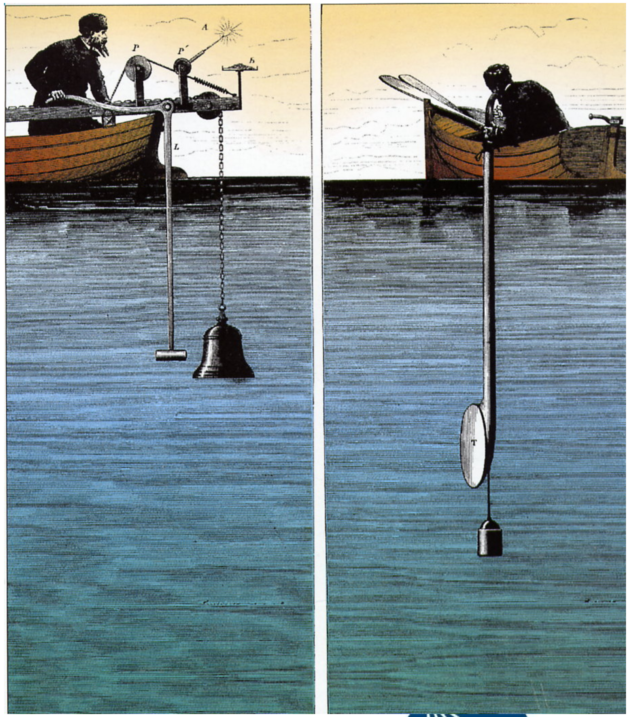
Sound in Water

"Of all the forms of radiation known, sound travels through the sea the best"

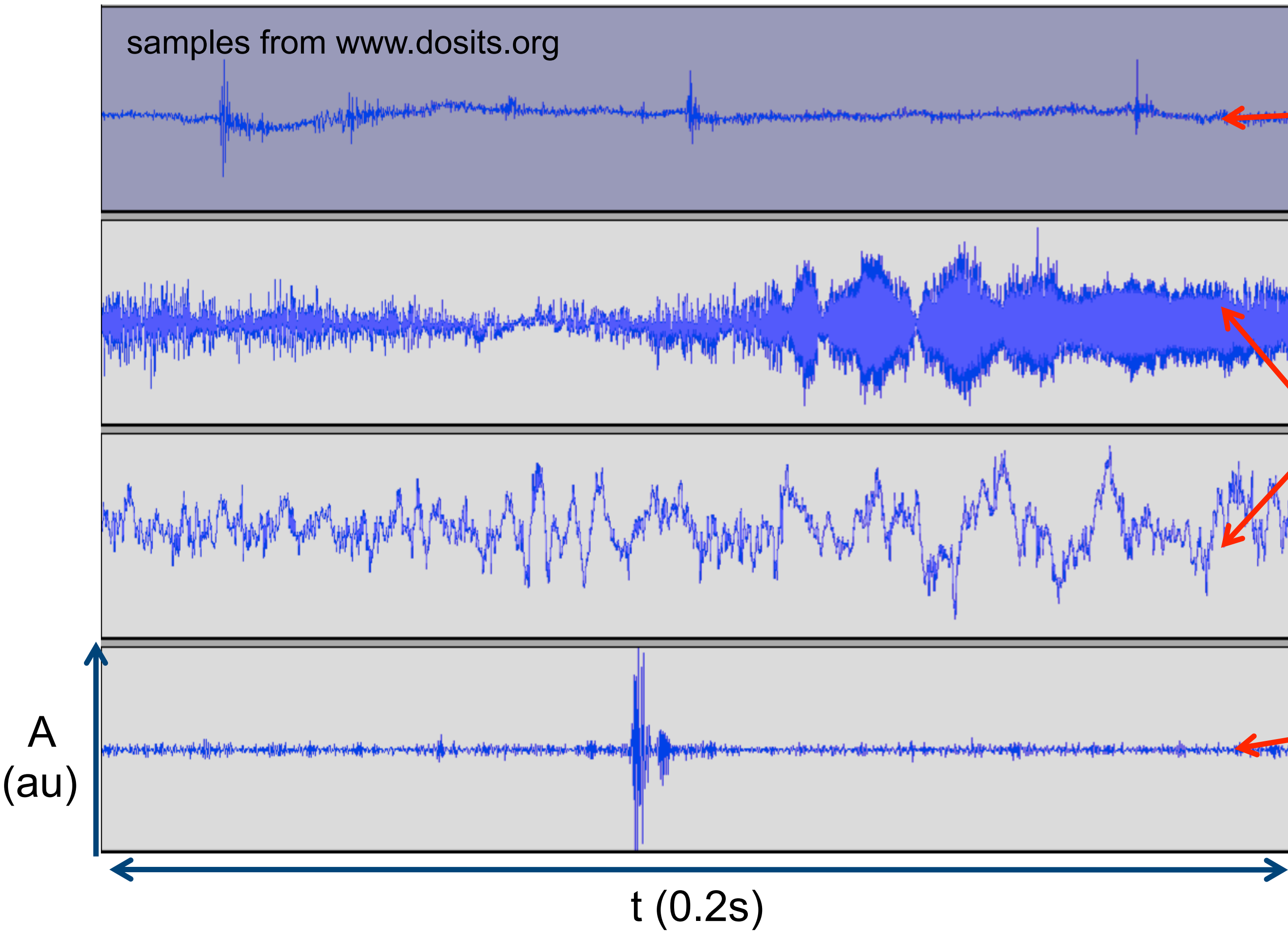
(R. Urick, Principles of Underwater Sound, 3rd edition, 1967)

Used by marine animals and humans for communication and positioning

Speed of sound investigated (at least) since 1826 (from title page of "Physics Today", Oct. 2004, experiment in Lake Geneva)

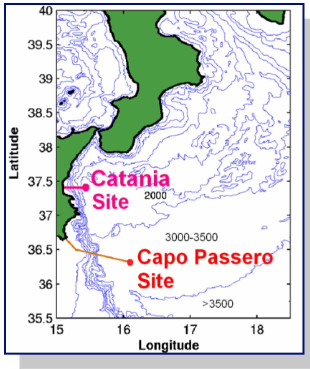


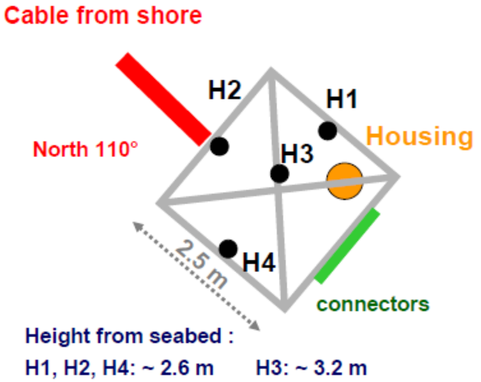
The Deep Sea is Loud!



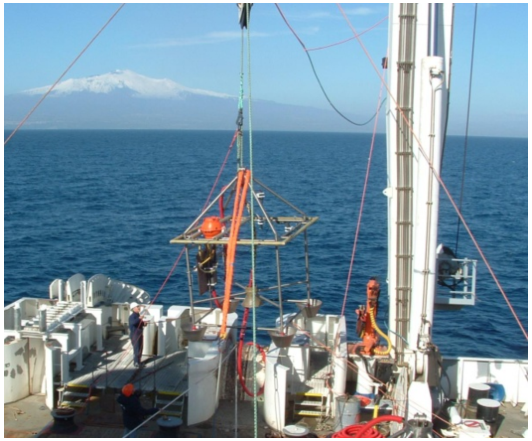
Interdisciplinary Cooperation

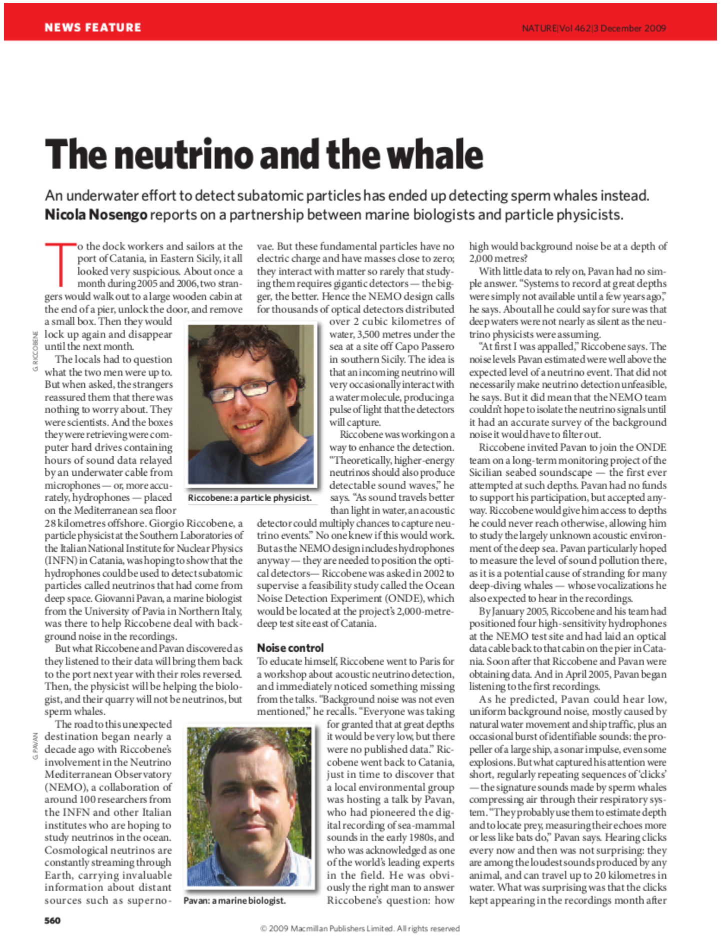
OnDE I (Jan. 2005 –Nov. 2006)
(Ocean Noise Experiment)





In collaboration with Uni-Pavia CIBRA





NEWS FEATURE — NATURE|Vol 462|3 December 2009

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.

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.

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.

G. RICCOBENE

Riccobene: a particle physicist.

G. PAVAN

Pavan: a marine biologist.

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

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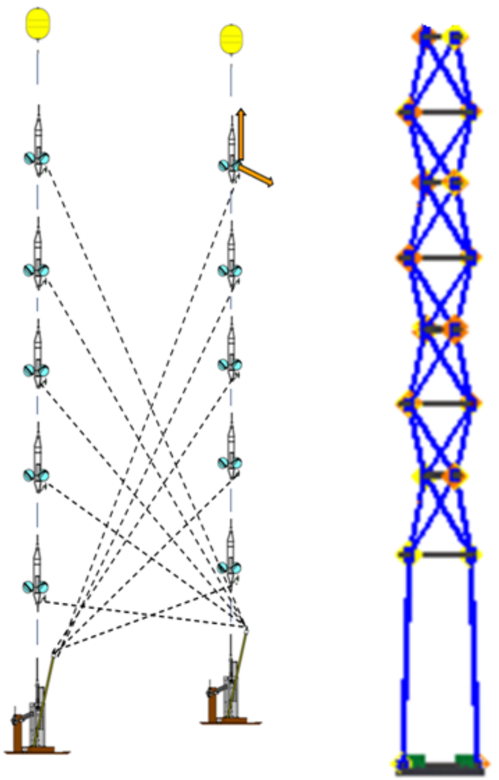
Nature New Feature, Vol. 463, p. 560 (2009)

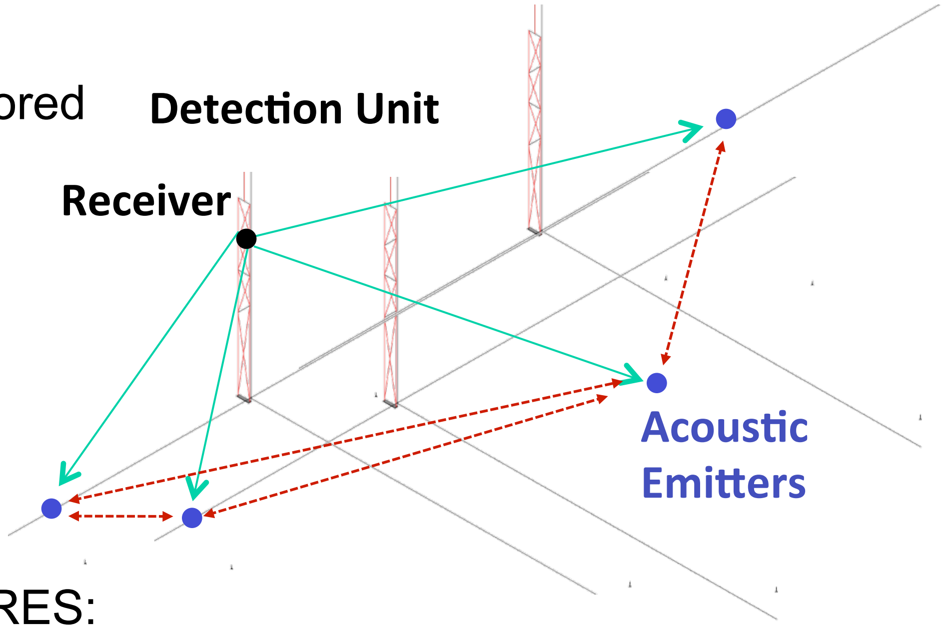
Positioning in Deep Sea Cherenkov Neutrino Telescopes

Movement of Optical Modules with deep sea currents needs to be monitored



ANTARES

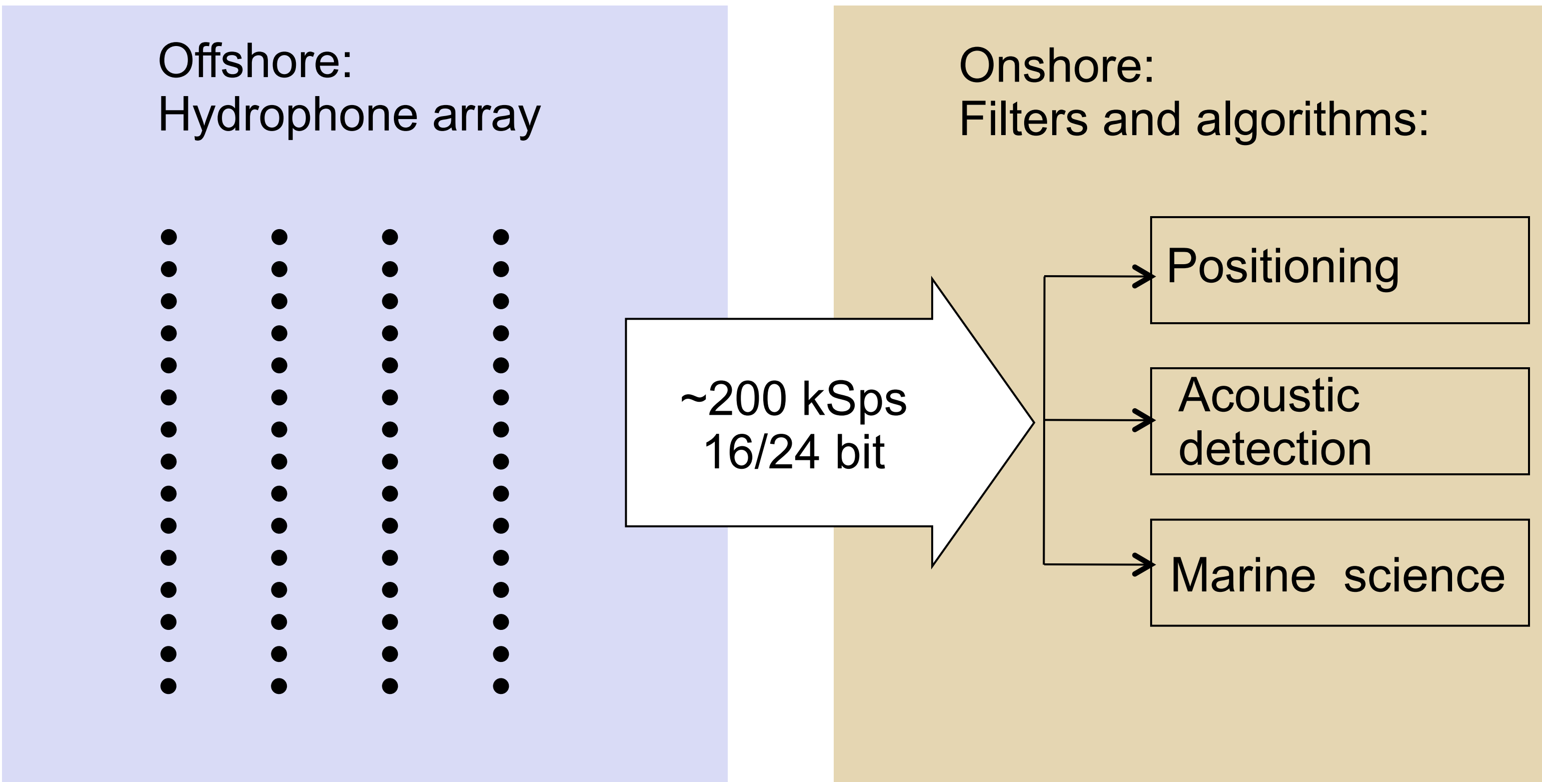
NEMO II / KM3NeT PPM



ANTARES:
Commercial system calculates time delay measurements offshore
Disadvantage:
- Raw signals not recorded, debugging difficult
- Potential of hydrophones not fully used

Principle of Future Deep Sea Acoustic Test Arrays

The obvious thing to do: All data to shore

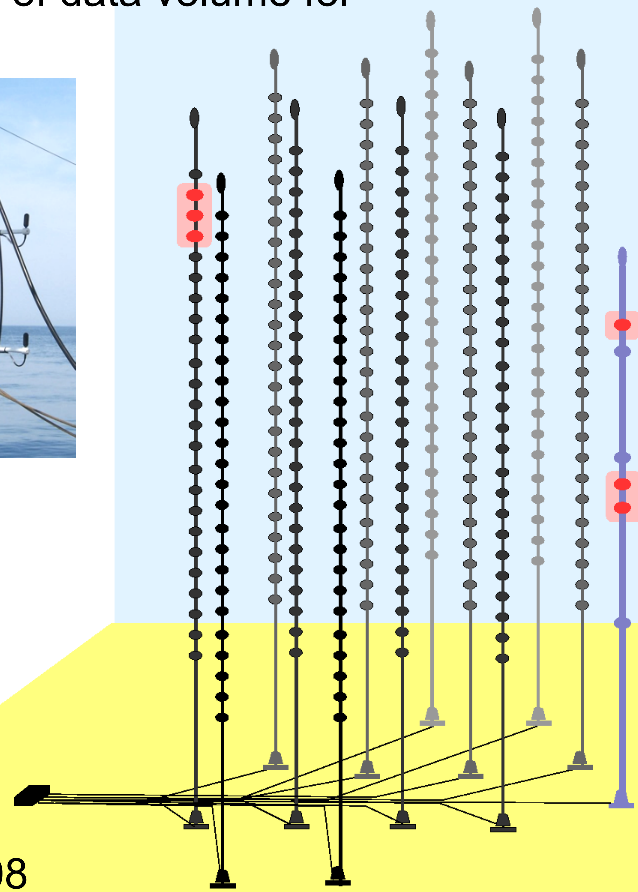


The AMADEUS System of the ANTARES detector

- 34/36 sensors operational
- Continuous data taking with >90% uptime
- Online filter selects ~1% of data volume for storage

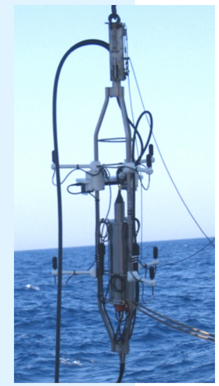
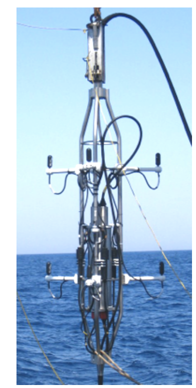
<u>Hydrophones:</u>
Typical sensitivity:
-145 dB re 1V/μPa
<u>Digitization:</u>
16bit @ 250kHz
<u>Recorded Frequency:</u>
2 ~ 100 kHz



<u>Line 12:</u>
Operation
started
30-May-2008

<u>Instrumentation Line:</u>
Operation
started
5-Dec-2007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Goals of AMADEUS

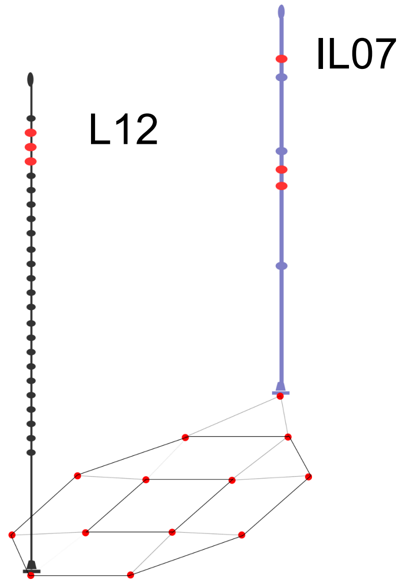
Main objective: feasibility study for a potential future large-scale acoustic neutrino detector

Main science case: Cosmogenic neutrinos

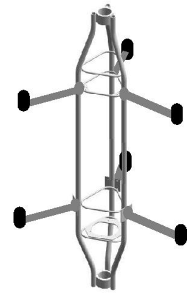
Main tasks:

- Long term hardware tests
- Determine energy threshold for neutrino detection
- Investigate background conditions
- Devise high efficiency, high purity neutrino detection algorithms

Position Reconstruction with Hydrophones

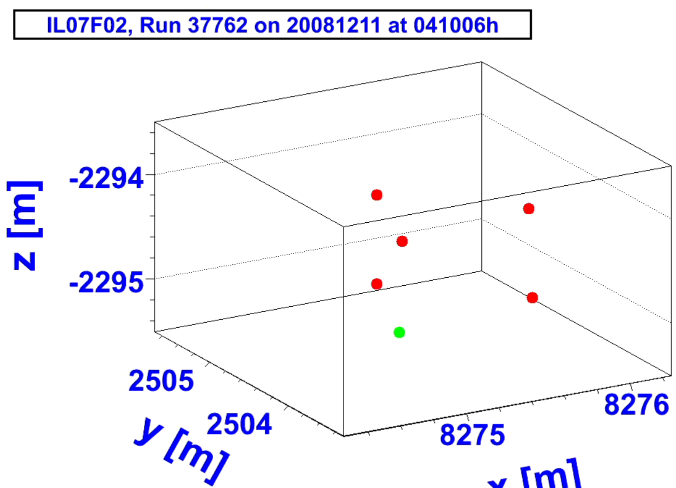


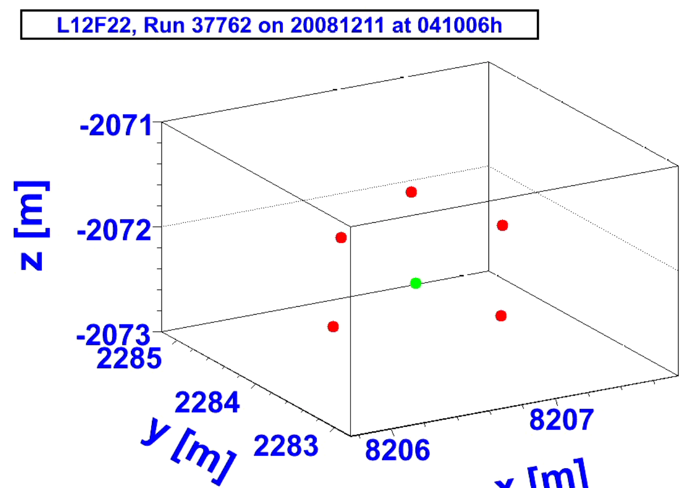
Receive signals from emitters on anchors of the 13 lines



Reconstruct position of each hydrophone individually using

$$\left|\vec{r}_{\text{reception}} - \vec{r}_{\text{emission}}\right| = c_s \times \left(\mathrm{t}_{\text{reception}} - \mathrm{t}_{\text{emission}}\right)$$





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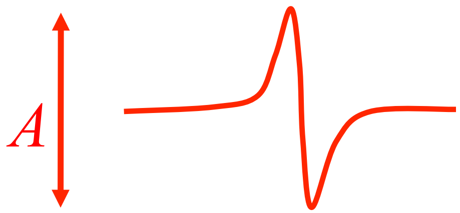
Background for Acoustic Detection in the Sea

Bipolar (BIP) events

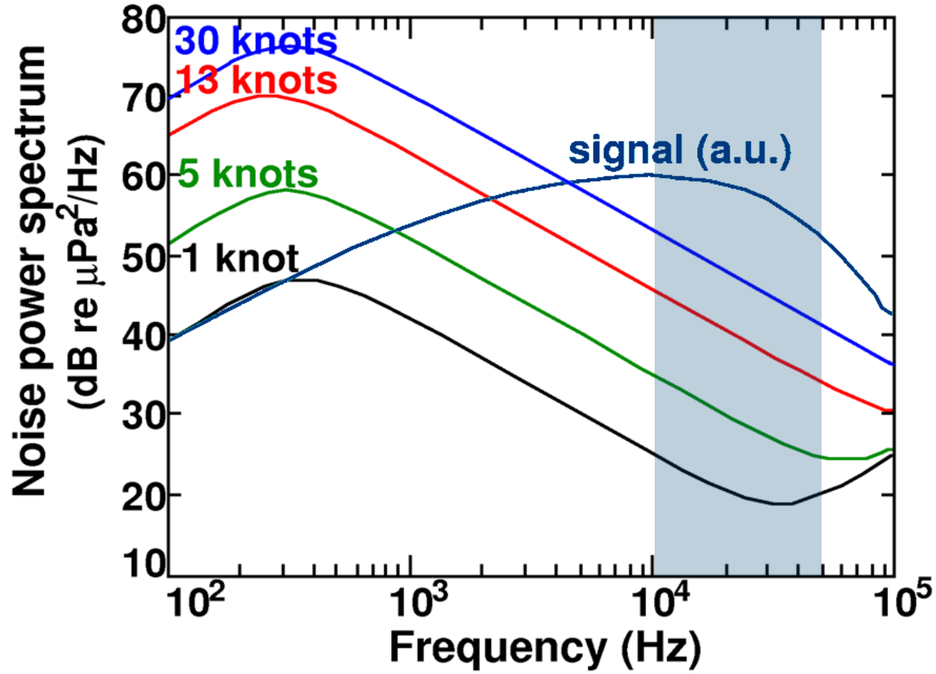


Bipolar Pressure Signals (BIPs)

Have to measure rate of BIP events: $\frac{d^3N}{dA\,dV\,dt}$

⇨**Determines fake neutrino rate**

Ambient noise



N.G. Lehtinen et al., arXiv:astro-ph/0104033

⇨**Determines intrinsic energy threshold**

Depends on “sea state” (surface agitation)

cf. Wenz, J. Acoust.Soc. Am. 34 (1962) 1936

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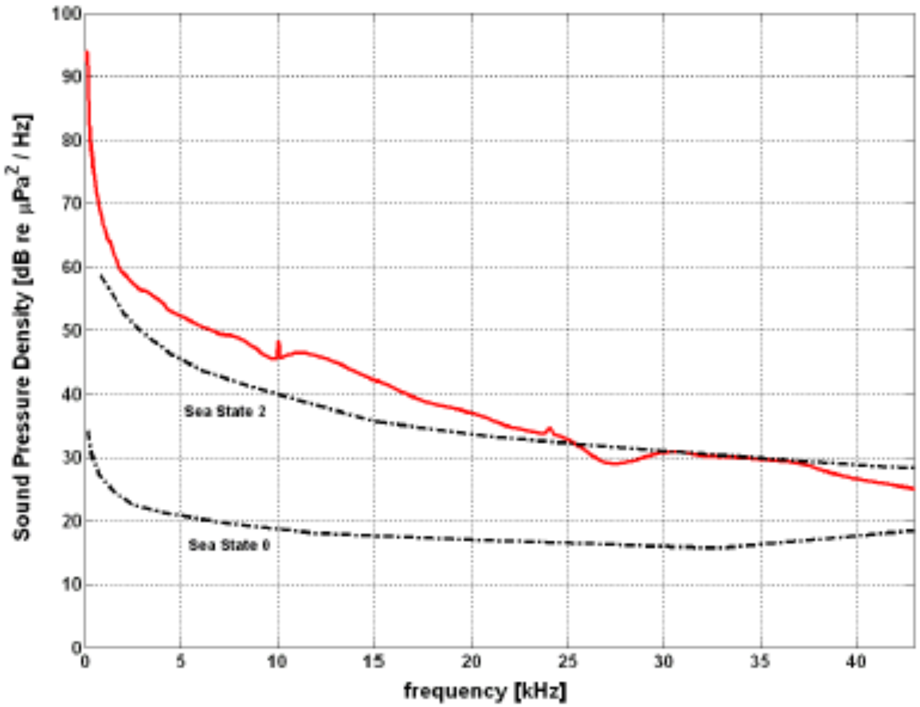
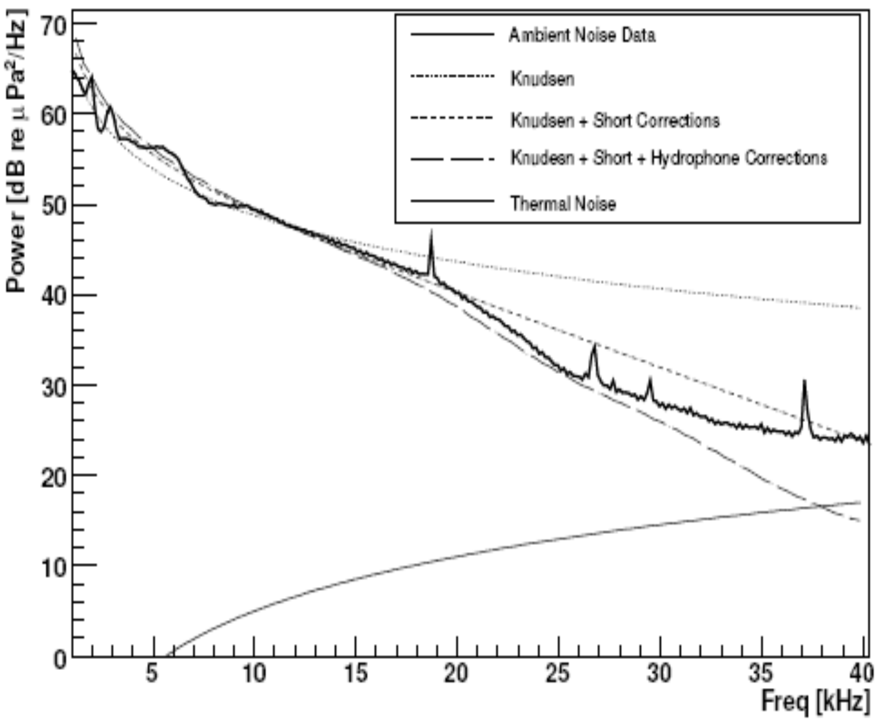
Ambient Noise: DeepSea



G. Riccobene, NIMA 604 (2009) 149

OnDE (Sicily)

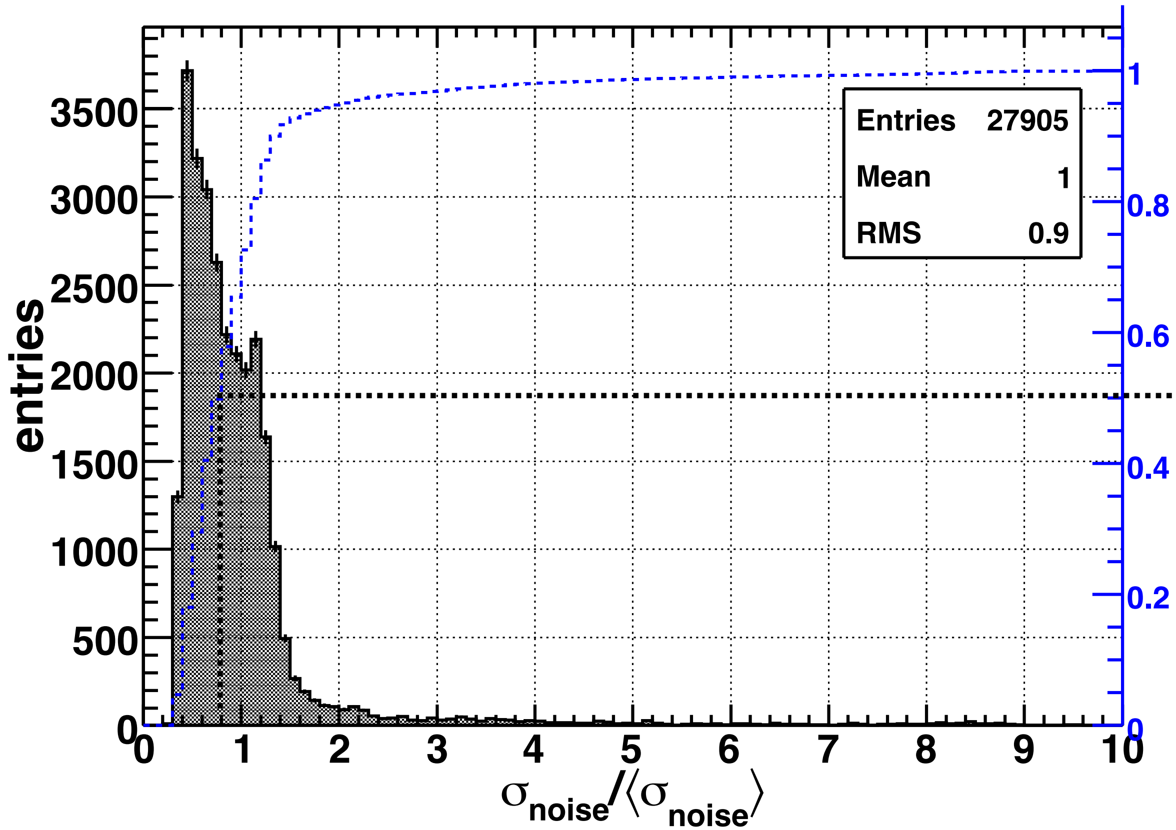


N. Kurahashi, G. Gratta.Phys. Rev. D 78 (2008)

SAUND (Bahamas)

Distribution of Ambient Noise Level (AMADEUS)

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



Median:

$0.8\langle\sigma_{noise}\rangle$

≈ 8 mPa

For sensor sensitivity of -145^{+2}_{-2} dB re 1V/µPa (lab calibration), the mean noise level is 10^{+3}_{-2} mPa

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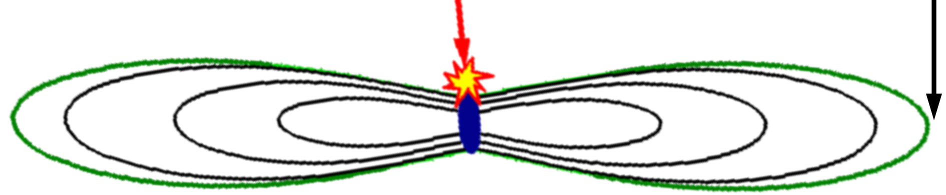
Ambient Noise Conclusion

Evaluate for f = 10 to 50 kHz (best S/N)

Assume detection threshold for bipolar signals with S/N = 2
@200m along shower axis



- Median:
  P_{thd} = 16 mPa ⇨ E_{thd} ≈ 1~2 EeV
- 95% of time ambient noise is below $2\langle\sigma_{noise}\rangle$ (~20 mPa)
  P_{thd} = 40 mPa ⇨ E_{thd} ≈ 4 EeV

⇨ Good conditions for neutrino detection
(stable threshold, level as expected)

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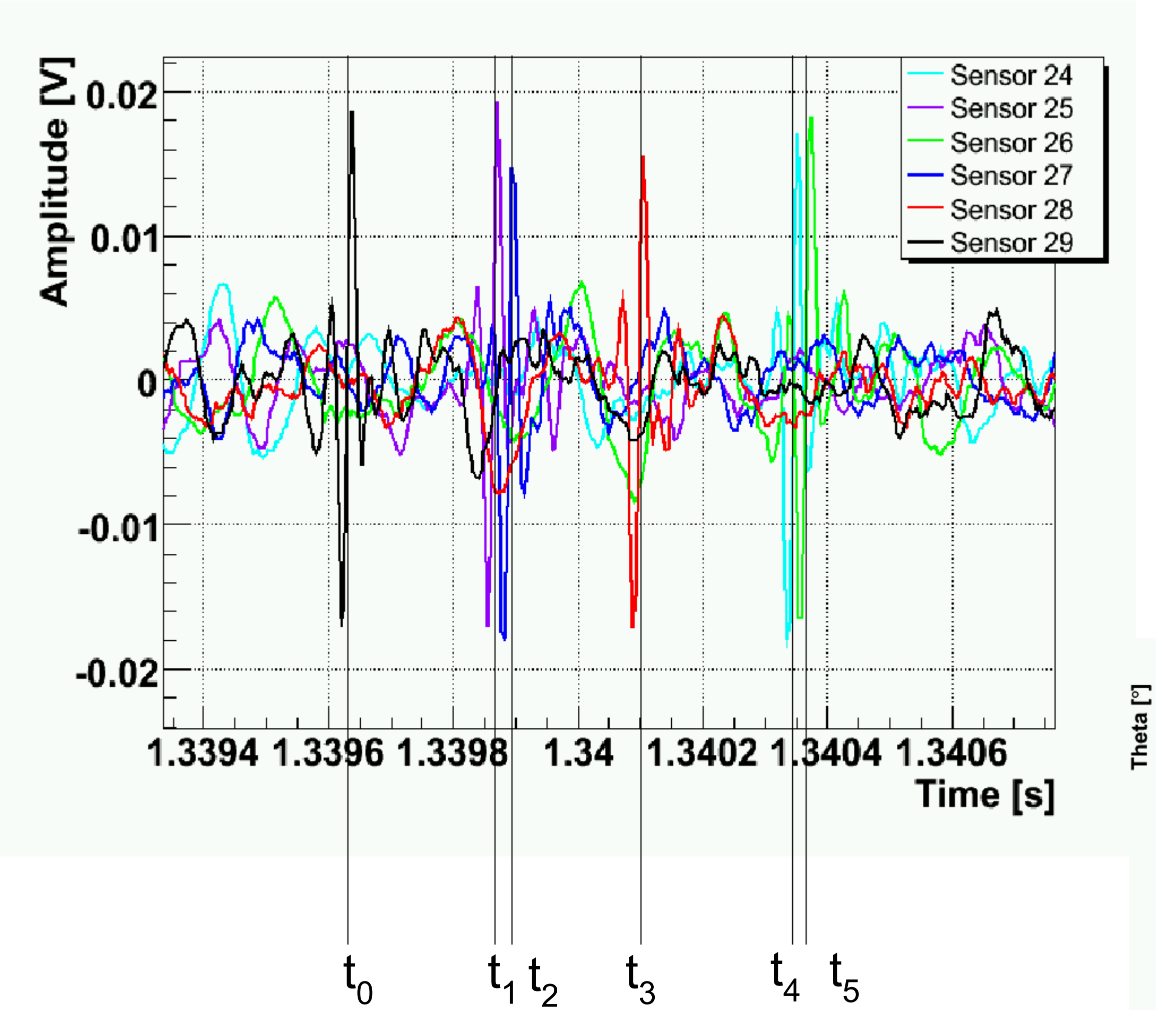
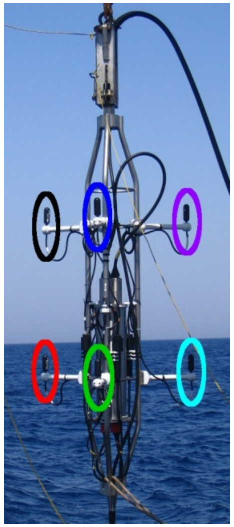
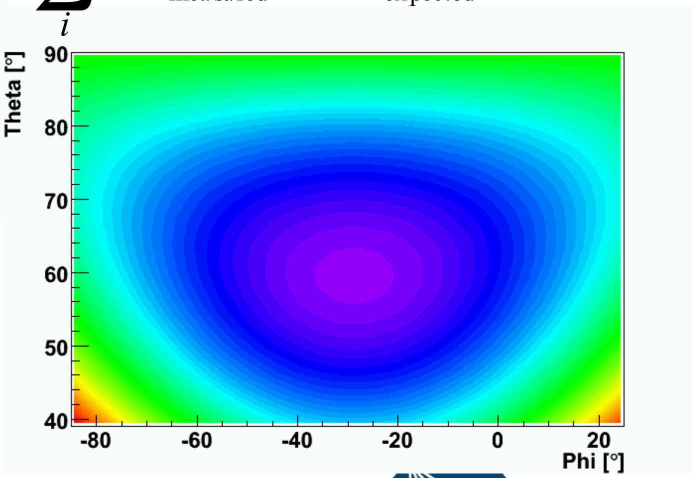
Source Direction Reconstruction





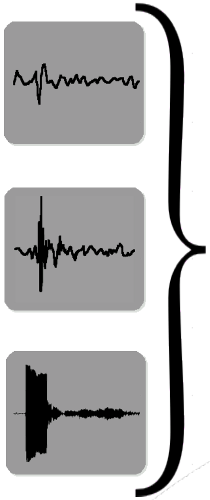
minimize

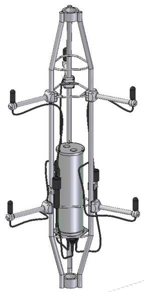
$$\sum_i \left(t_{i_{\text{measured}}} - t_{i_{\text{expected}}}(\vartheta, \varphi) \right)^2$$

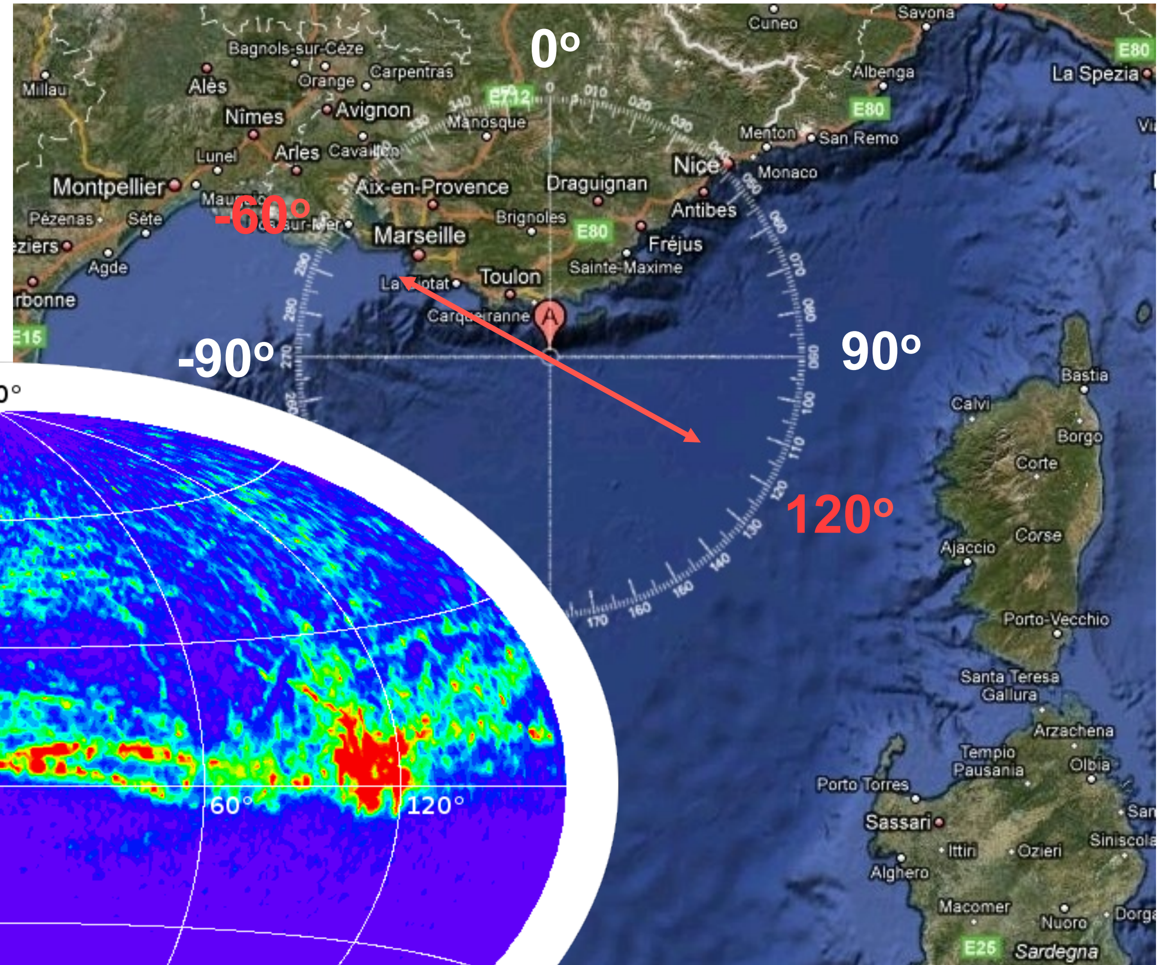


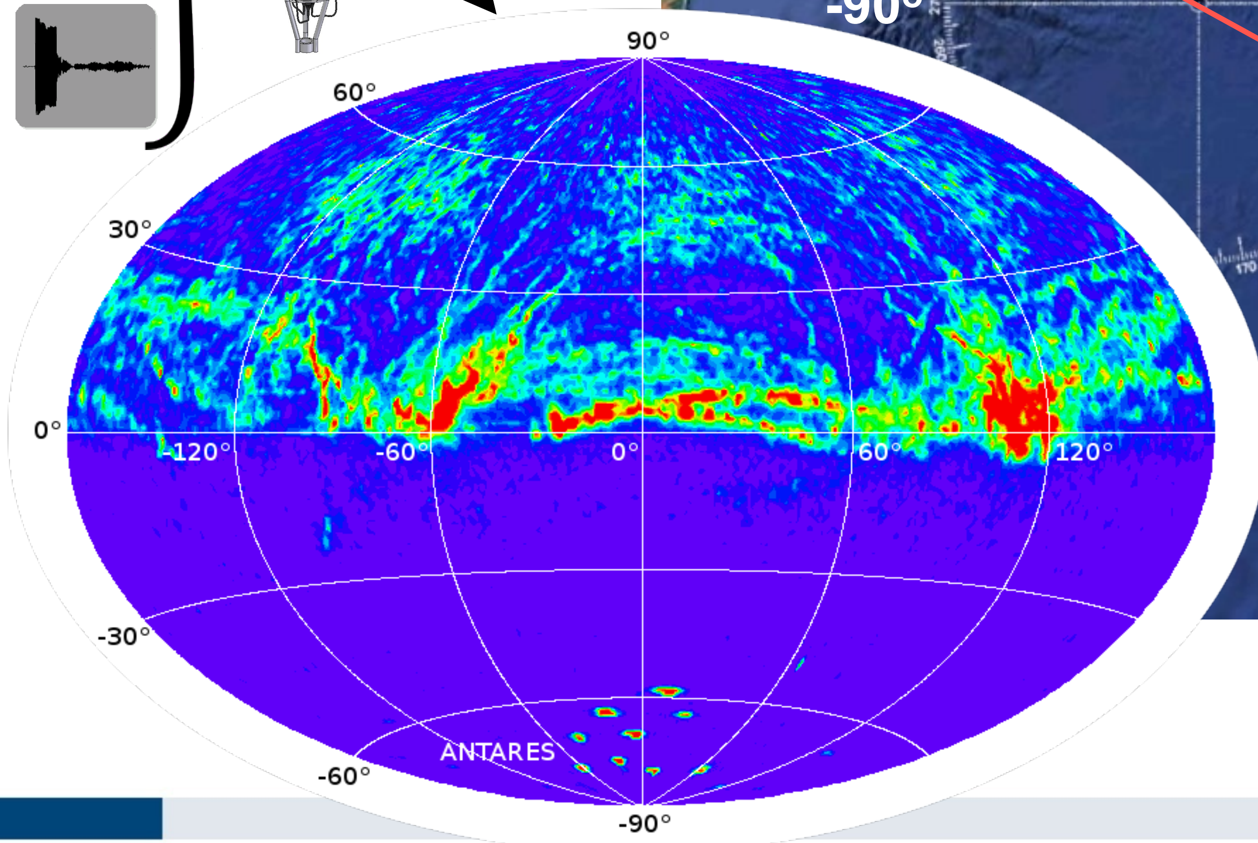
Error: ~3° in φ,   < 1° in ϑ

AMADEUS - Source Direction Distribution









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Marine Science with AMADEUS

- Life data from AMADEUS web page: http://listentothedeep.org/ (Maintained by University of Barcelona)
- Press releases Dec. 2010, picked up by several media:

Hang on, that's not a neutrino

Dec 1st 2010, 16:10 by J.P.

Tweet 21 Like 230

SPL

PHYSICISTS are often accused by the public and other scientists of spending inordinate sums on fancy kit that does little apart from merely satisfying human curiosity. Besides

microwave ovens to the internet. They can also offer plenty of examples of how their own research has aided colleagues in other fields, from climate science to, somewhat more improbably, marine biology.

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e.g. http://www.economist.com/blogs/babbage/2010/12/astroparticle_physics

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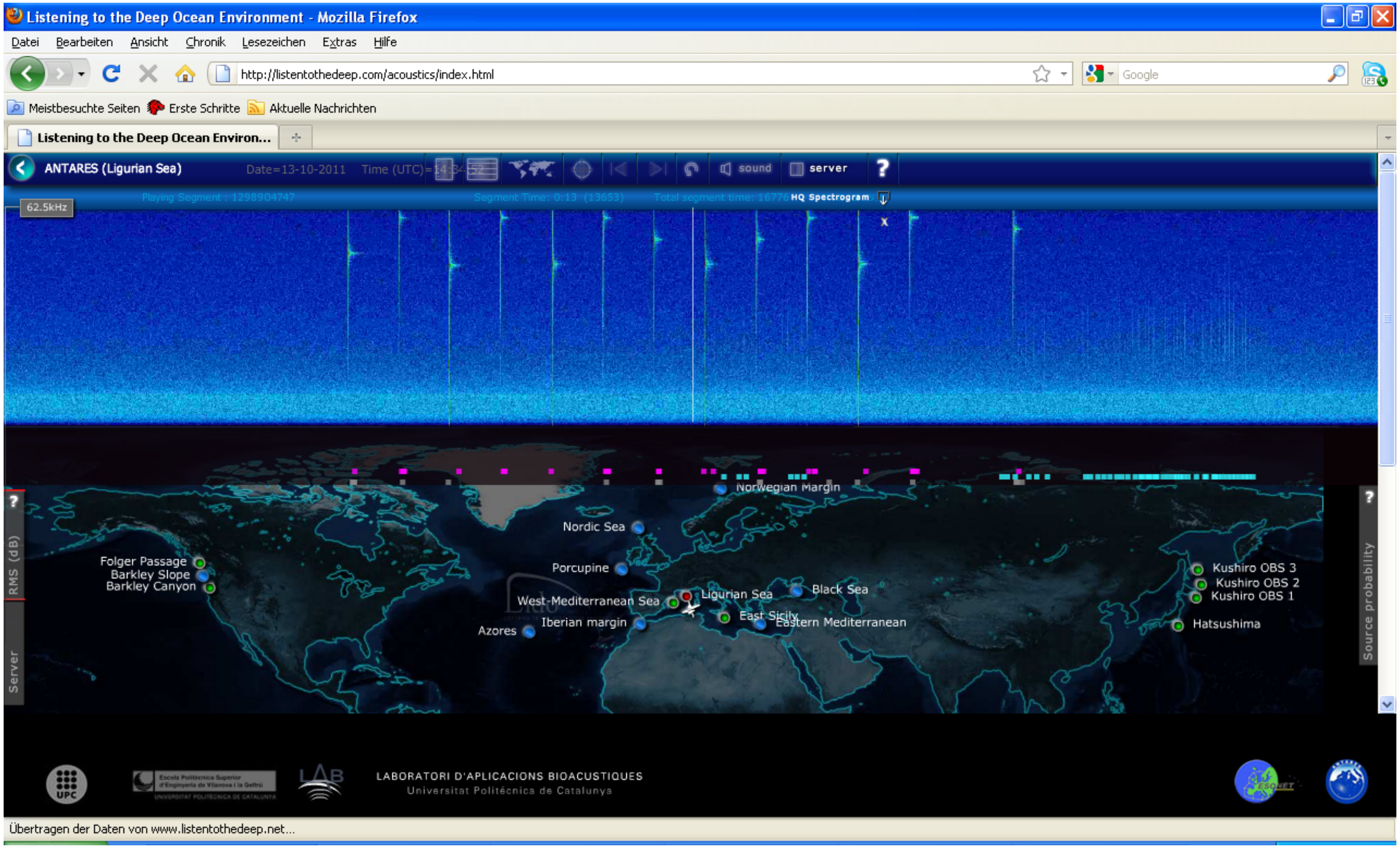
Life Data from AMADEUS



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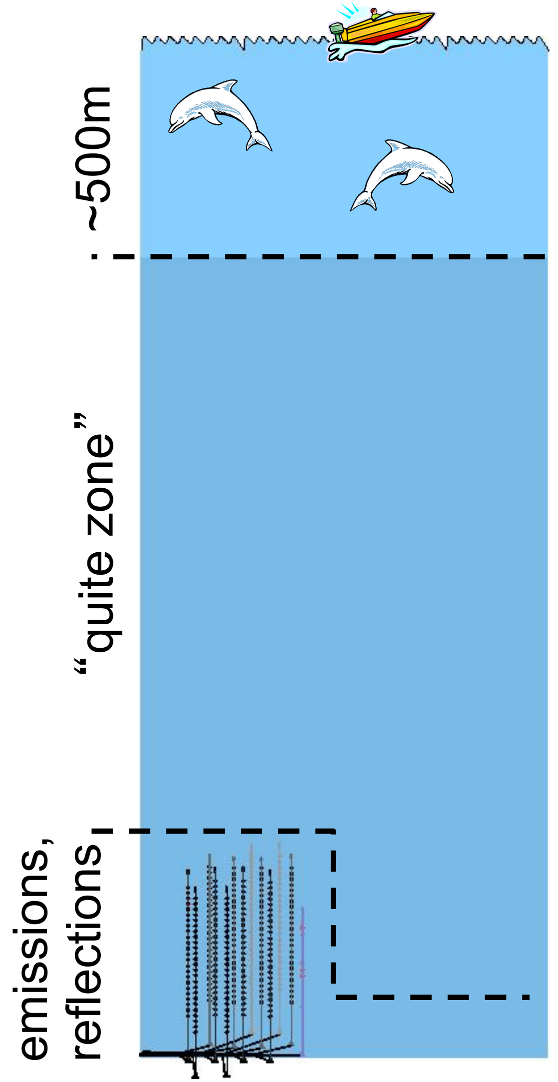
Transient Background Conclusions

- Exclude region near surface
- Very diverse transient background, signal classification crucial
- Cut on pattern of pressure field (“pancake”)



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The Neutrino Detection Rate

Energy threshold:
Depends on detection method

Effective volume:
Depends on detection method

Number of detected events

$$N = 2\pi T \int dE \Phi(E) \frac{V_{eff}(E)}{\lambda(E)}$$

Flux: Depends on process of neutrino production

Mean Free Path: Depends on neutrino **cross section**

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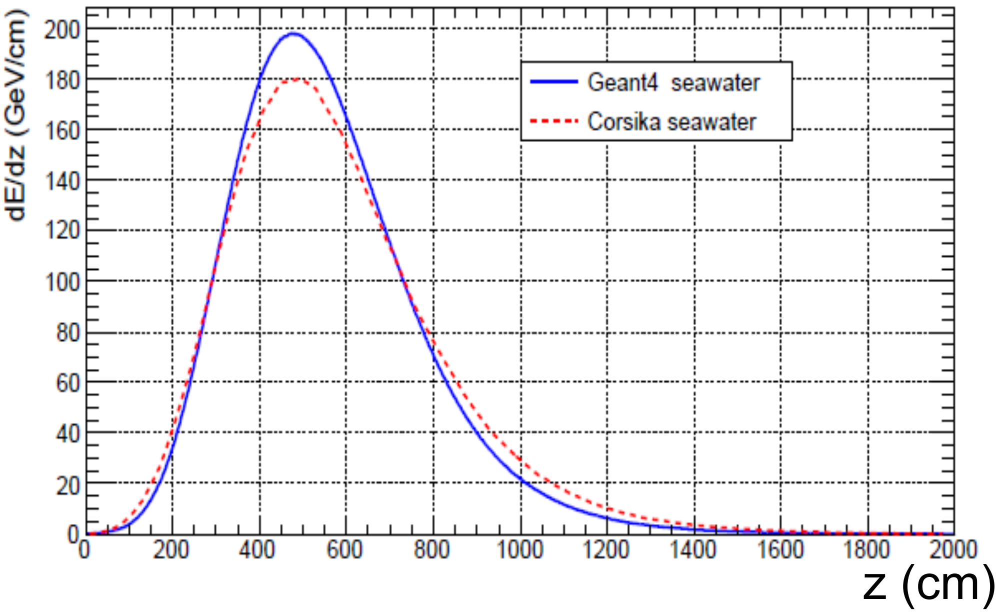
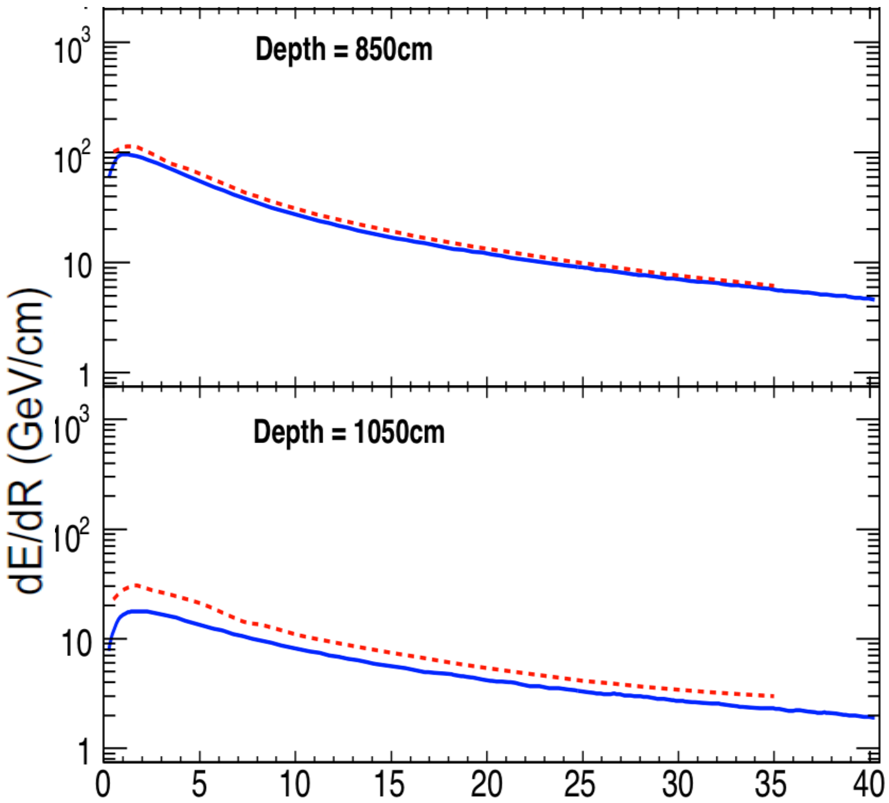
Energy Deposition by UHE Hadronic Showers





longitudinal and lateral hadronic shower profile from CORSIKA (adapted for seawater)

S. Bevan et al., Astropart.Phys.28 (2007)

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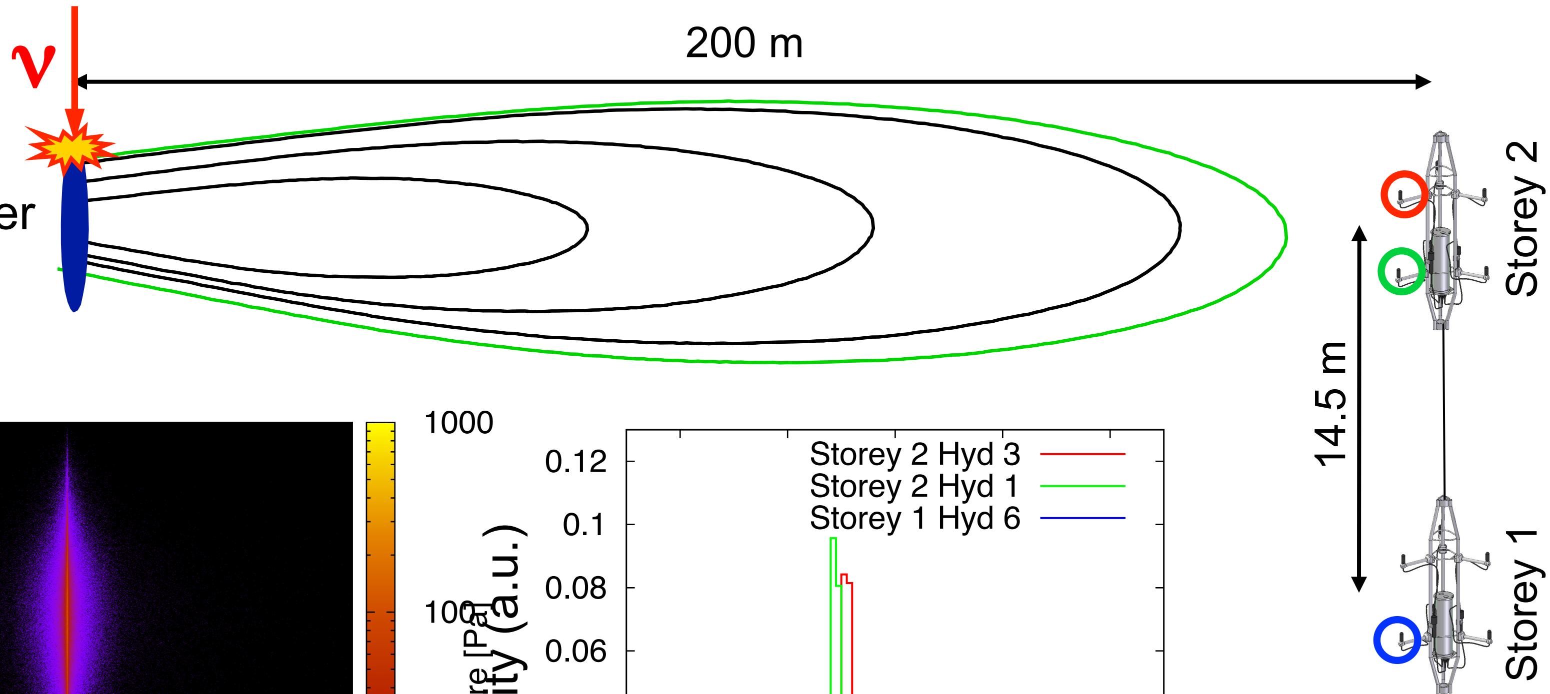
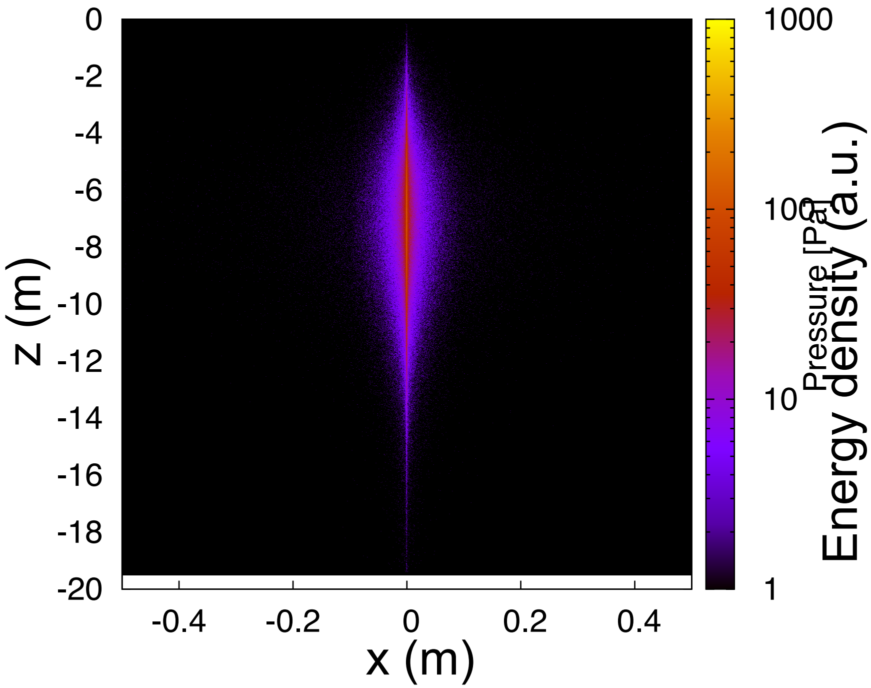
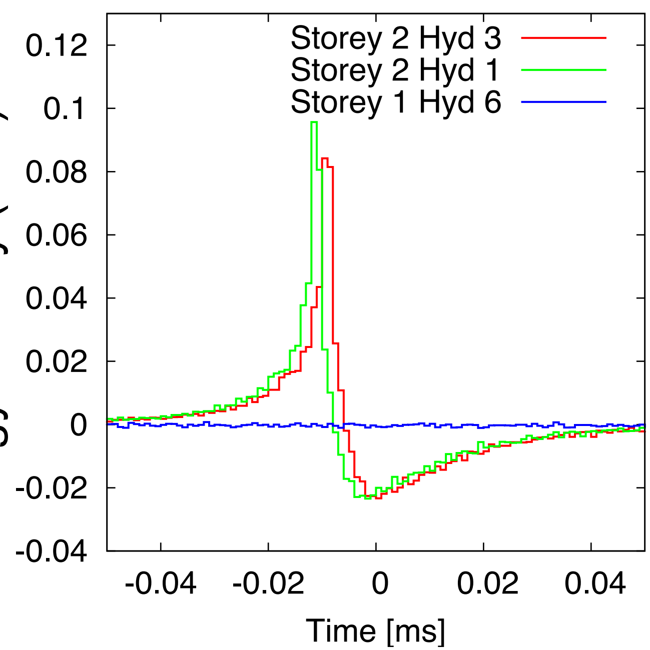
Simulation of Neutrino-Induced Acoustic Pulses







MC according to arxiv/0704.1025v1 (Acorne Coll.)

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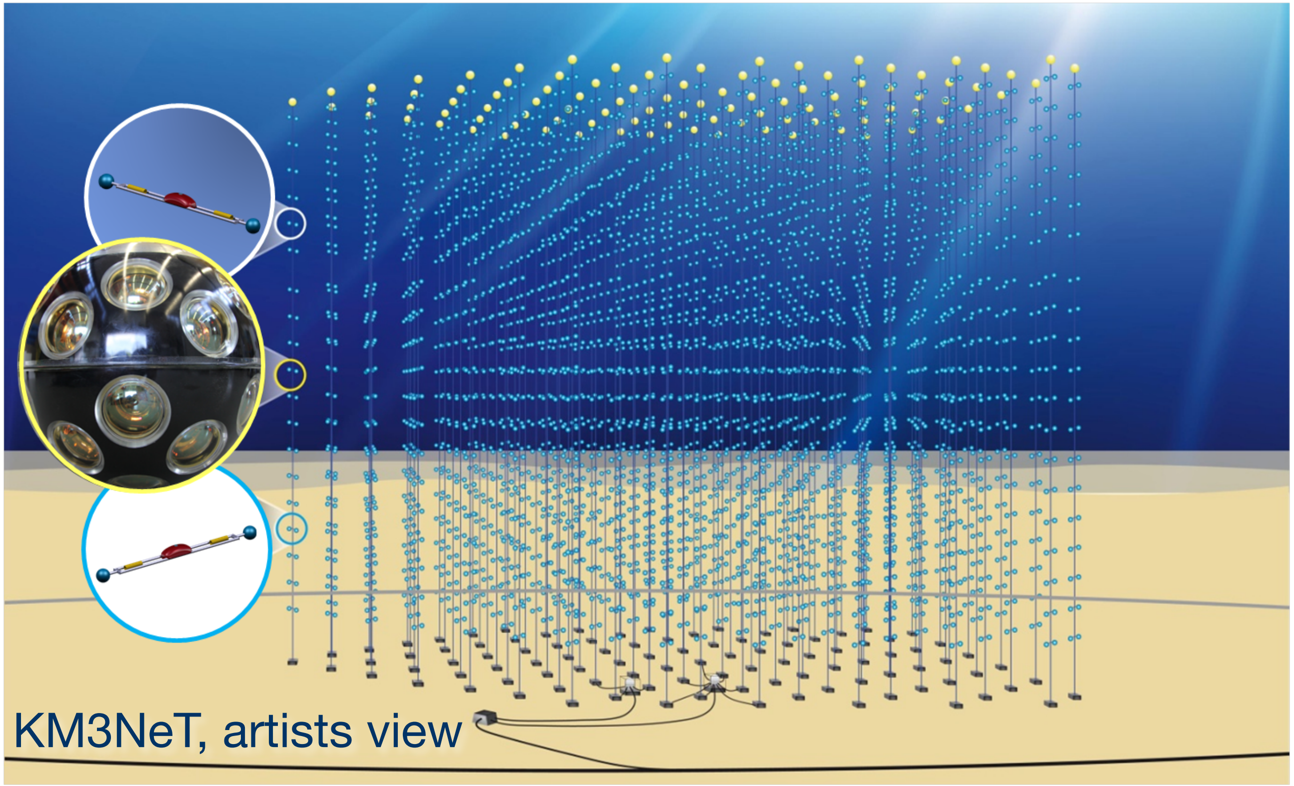
Hybrid Detection in KM3NeT



- “all data to shore”-principle adopted
- already: one software framework

⇒ intermediate step for acoustic detection
Cooperation of European players

Conclusions and Outlook

- Acoustic detection is a promising approach for the detection of UHE neutrinos
- Ambient background in the Mediterranean Sea: Stable, level as expected
- Transient background in the Mediterranean Sea: Methods for suppression developed; work in progress;
  Interesting for marine science
- Monte Carlo simulations and algorithms for neutrino selection under development
- KM3NeT: Combined system for acoustic positioning and neutrino detection planned; intermediate step for acoustic detection of UHE neutrinos

Funded by:
Bundesministerium
für Bildung
und Forschung

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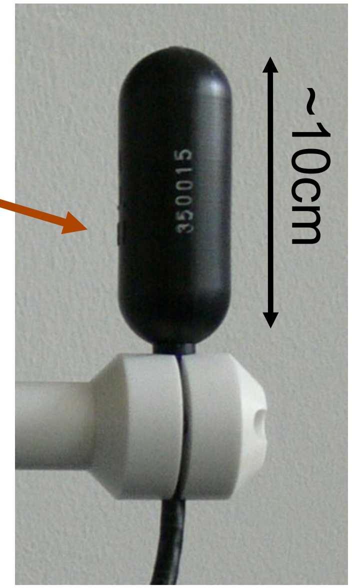
Backup transparencies

Setup of Acoustic Storey with Hydrophones

Hydrophone:
Piezo sensor with pre-amplifier and band pass filter in PU coating

Typical sensitivity: -145 dB re 1V/μPa



Titanium cylinder with electronics

3 custom designed Acoustic ADC boards 16bit @ 250kHz

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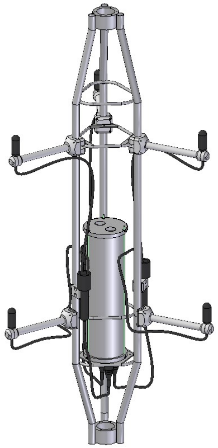
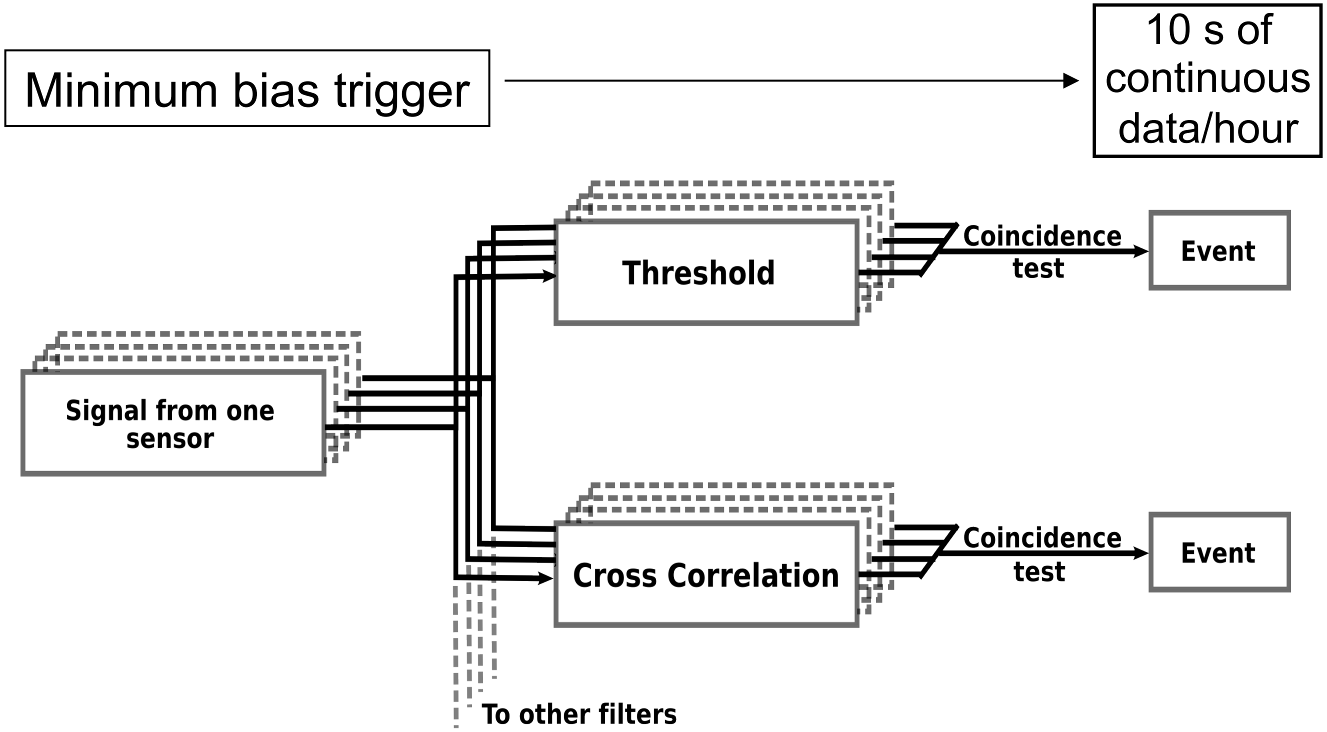
The Onshore Filter System

<u>Task:</u> Reduce incoming data rate of ~1.5 TByte/day to ~10 GByte/day





System extremely flexible, all components scalable

Local clusters (storeys) big advantage for fast (on-line) processing

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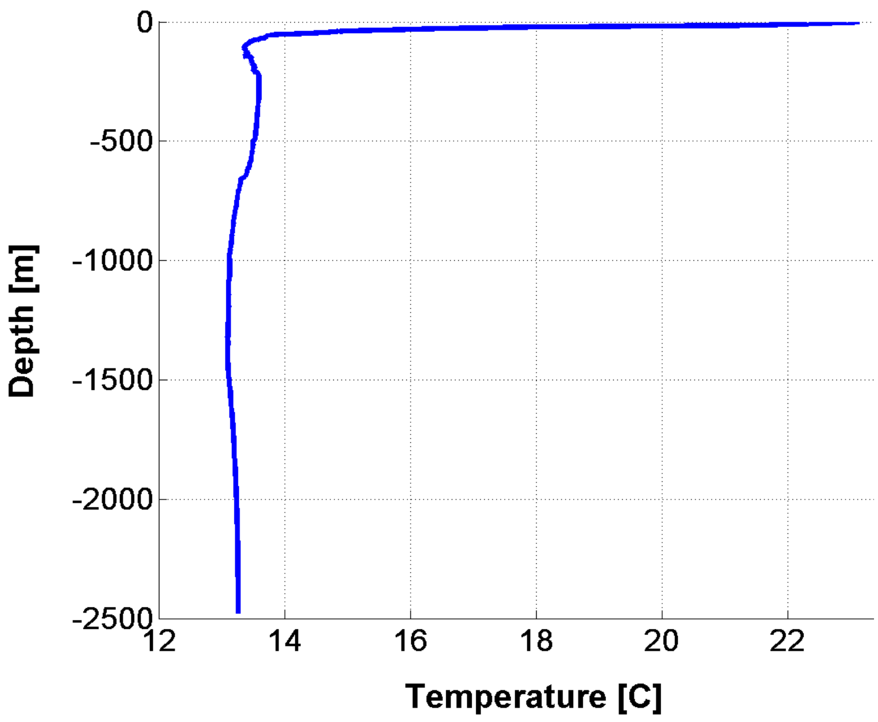
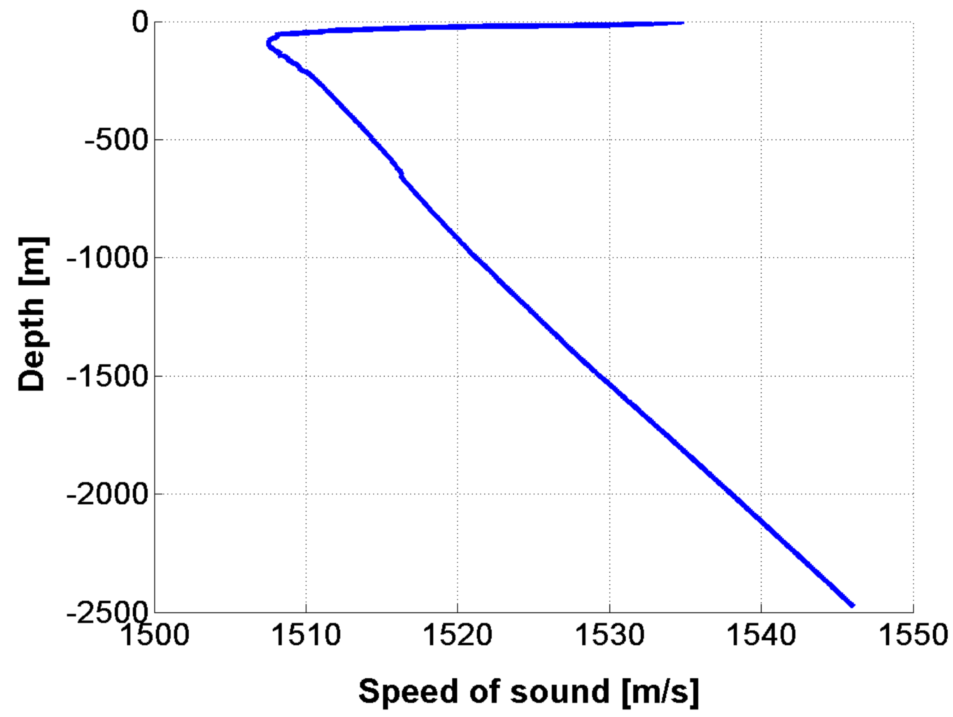
Properties of the Mediterranean Sea (ANTARES site)





Speed of sound depends on temperature, salinity, pressure (depth); temperature gradient only relevant up to ~100m below surface

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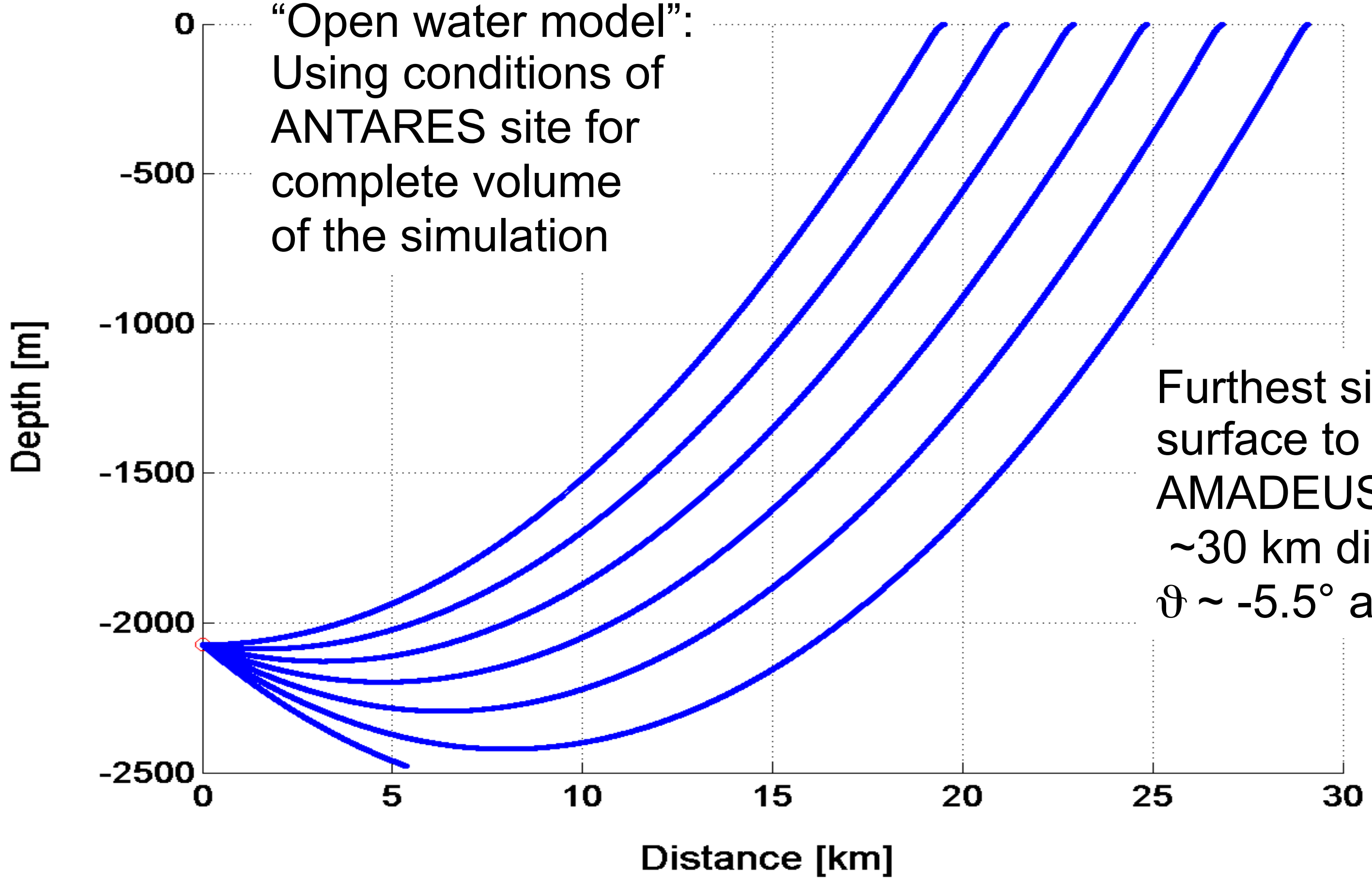
Refraction of Signals Reaching AMADEUS



"Open water model":
Using conditions of ANTARES site for complete volume of the simulation

Furthest signals from surface to reach AMADEUS:
~30 km distance,
ϑ ~ -5.5° arrival angle