How to Search for Neutrinos and Find Cetaceans with Acoustic Arrays in the Mediterranean Sea

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Scripps Institution, La Jolla, April 18, 2019

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Outline

- Neutrinos and Fundamental Forces
- Deep Sea Neutrino Telescopes
- Acoustic Neutrino Detection
- KM3NeT and Fiber based Hydrophones

… and some sidetracking

Neutrinos and Fundamental Forces

Energy Units

- Electron volt (eV)
  Kinetic energy of an electron after being accelerated in an electric field of 1V:
  $1\text{eV} = 1.6 \times 10^{-19}\,\text{As} \bullet 1\text{V} = 1.6 \times 10^{-19}\,\text{J}$

- Kinetic energy of a tennis ball (m=57g) with 120 km/h speed:

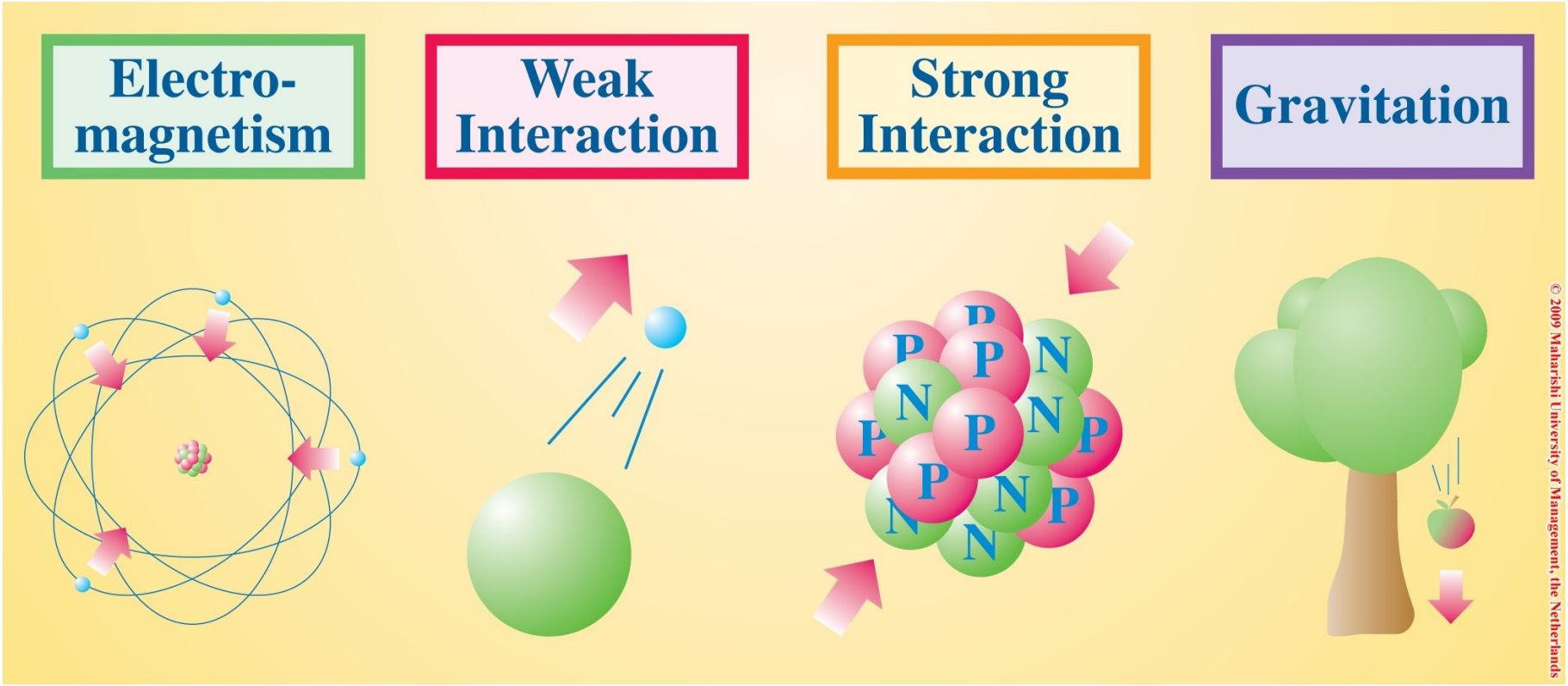
$$E = \tfrac{1}{2} m v^2 = 32\text{J} = 2 \times 10^{20}\,\text{eV}$$

- Can express masses according to $E=mc^2$:

Proton mass: $m_p = 938\ \text{MeV}$

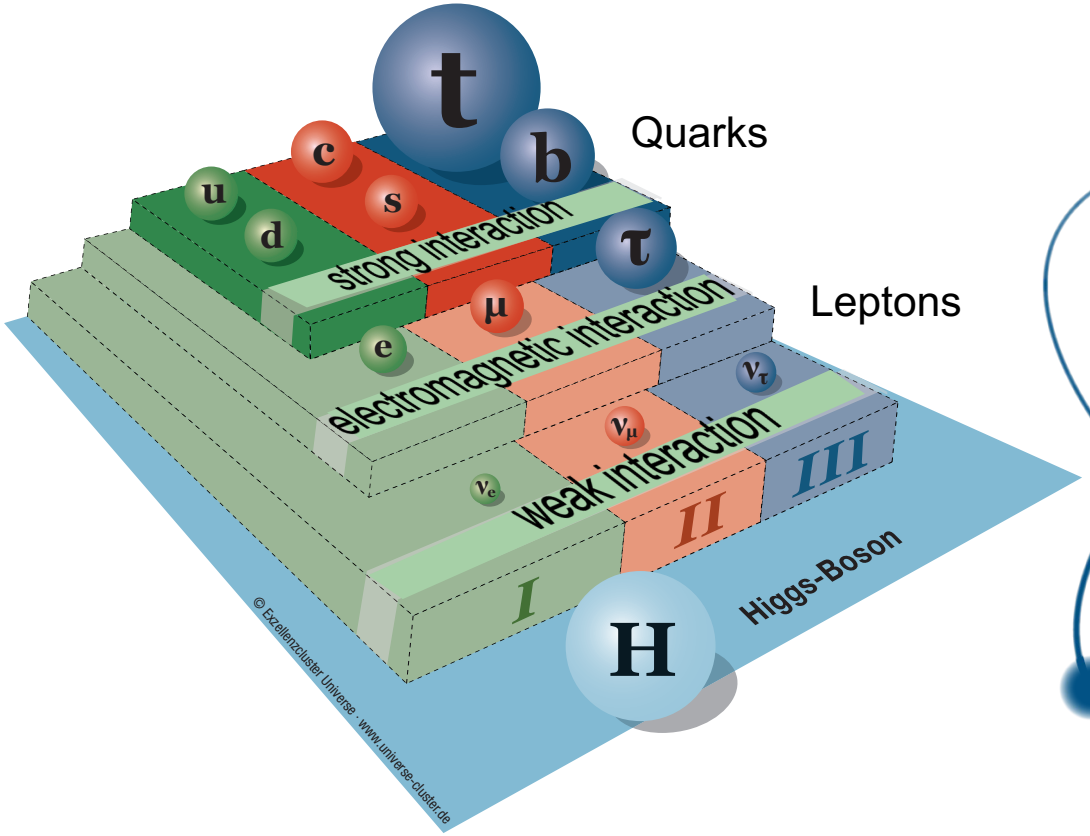
Neutrino mass: $m_\nu < 2\ \text{eV}$

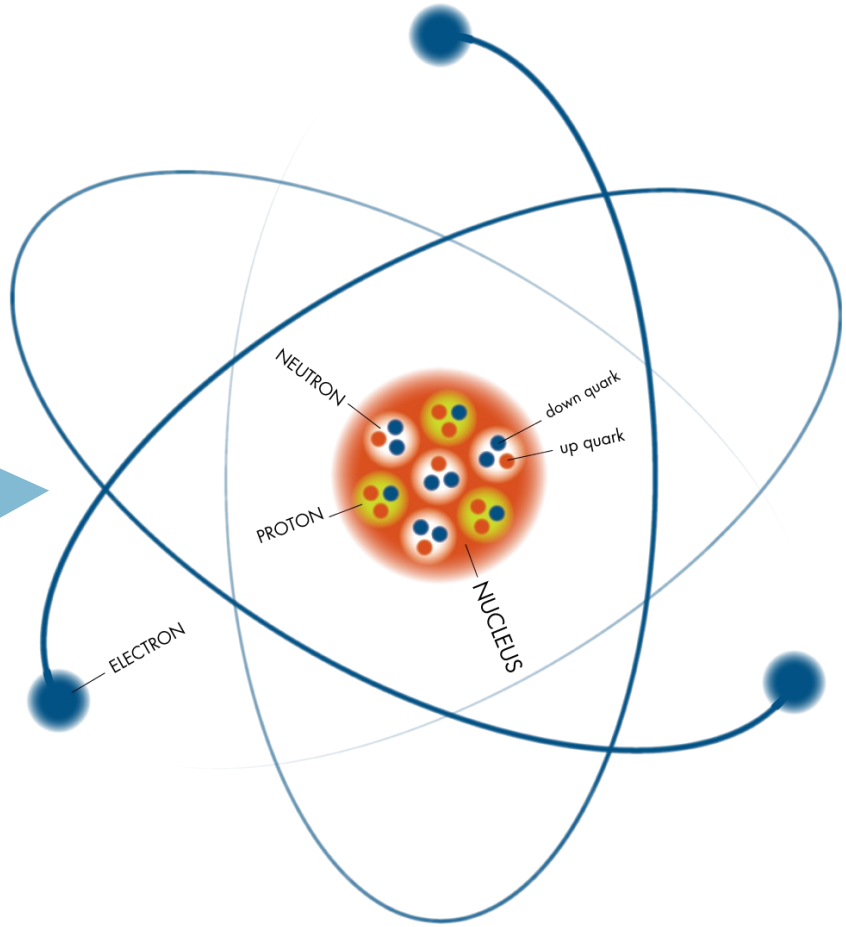
The Four Fundamental Forces of Nature



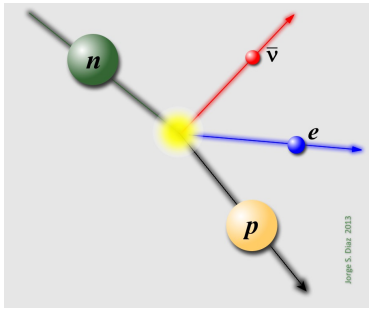
https://physicswithsampurkis.wordpress.com/2014/01/10/the-four-fundamental-forces/

Forces and Particles



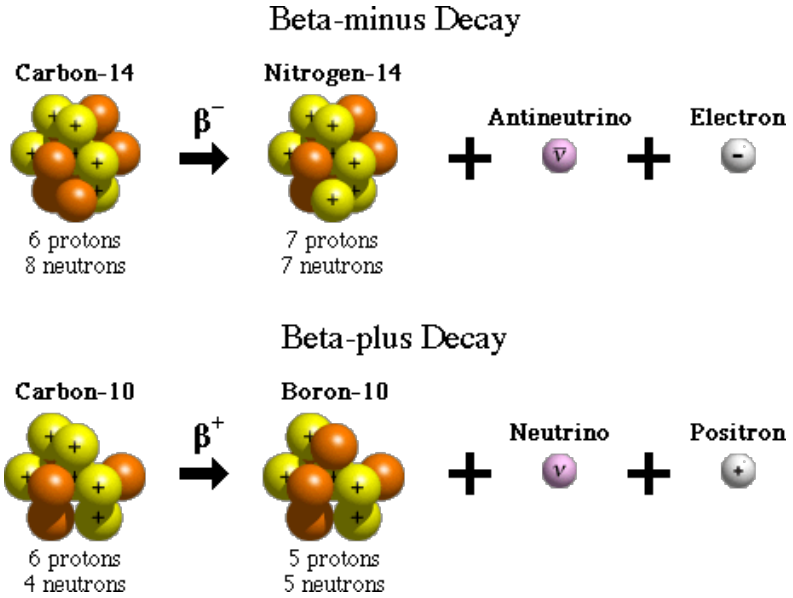


Neutrinos from Beta Decay



life time of free neutron: t ≈ 15min

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



muon decay:

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

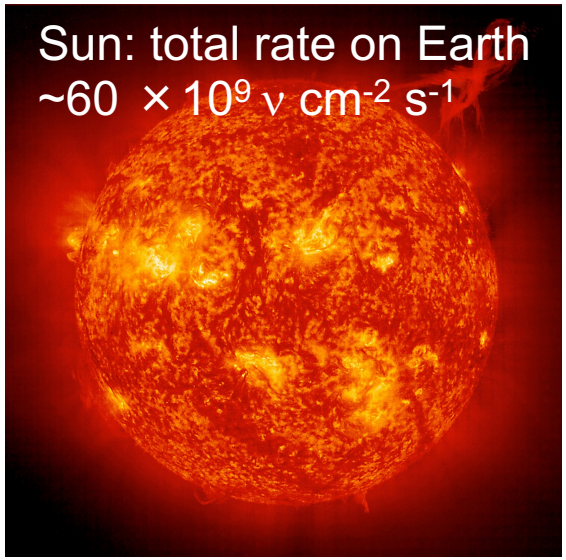
muon life time : t ≈ 2×10^{-6}s

Detection through inverse β-decay:

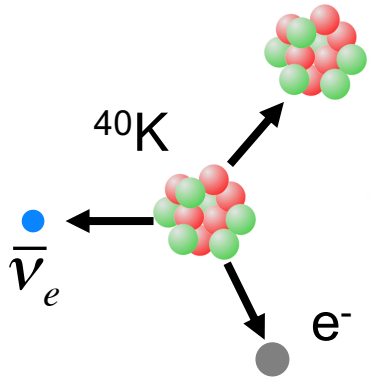
$$\nu_e + n \rightarrow p + e$$

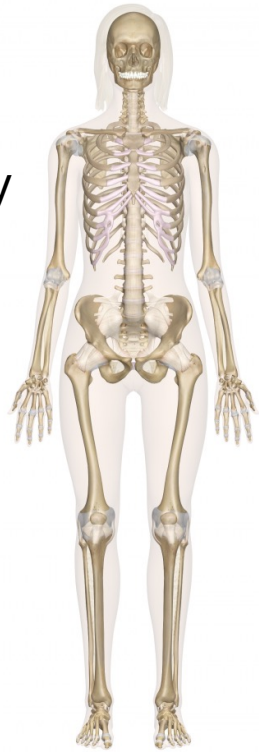
Sources of Neutrinos

Nuclear power plant with 1MW thermal power: 10^{17} ν/s



Human body:
~5000 ν/s
through K-40 decay





Neutrinos in Astroparticle Physics

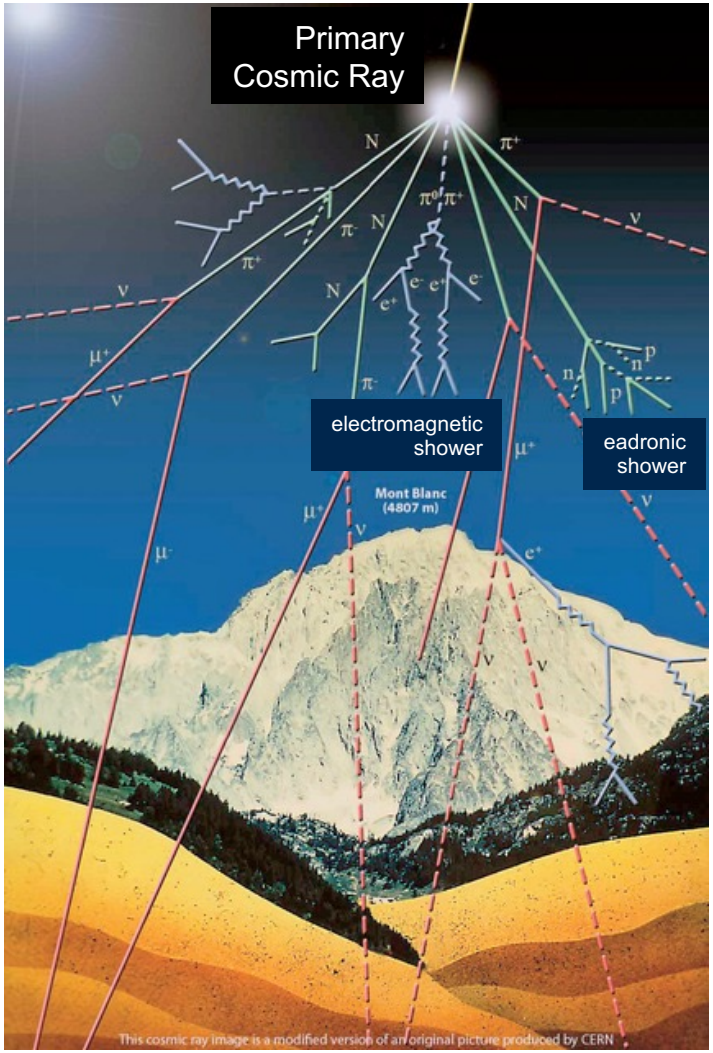
Cosmic Rays and Astroparticle Physics

The Earth is constantly bombarded with ‘Cosmic Rays’:
protons, nuclei, (electrons)

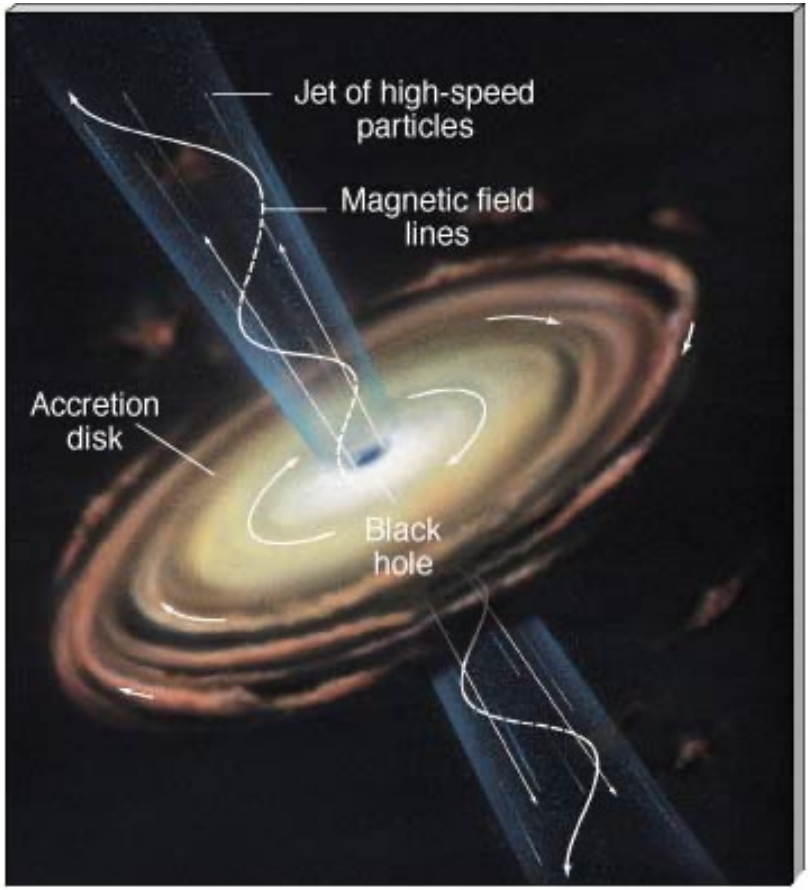
Highest energy of a particle measured so far ~3×10^{20} eV 

How and where in the Universe are particles accelerated to such energies?

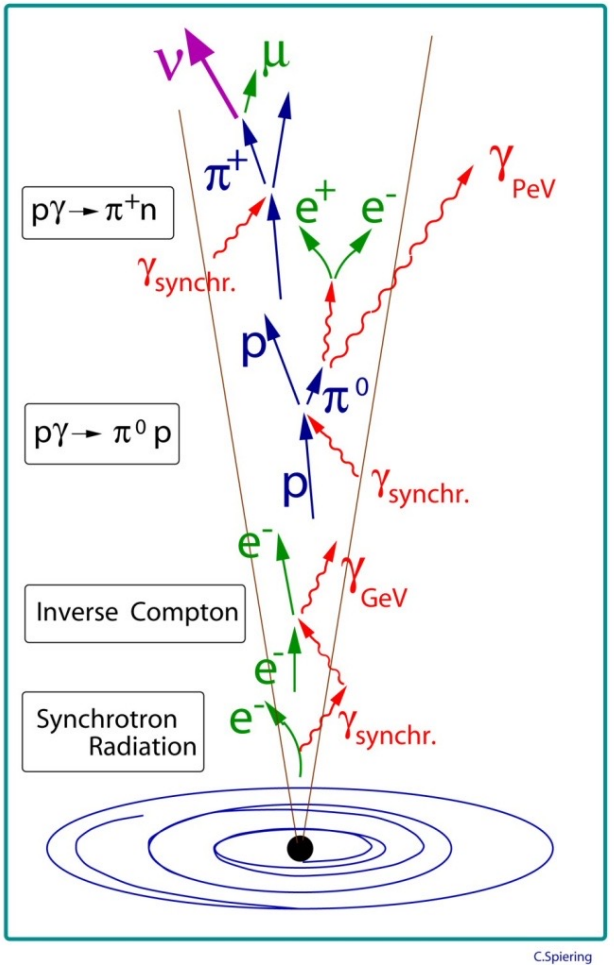
Astroparticle Physics:
Uses particles of cosmic origin detected on Earth to search for cosmic accelerators



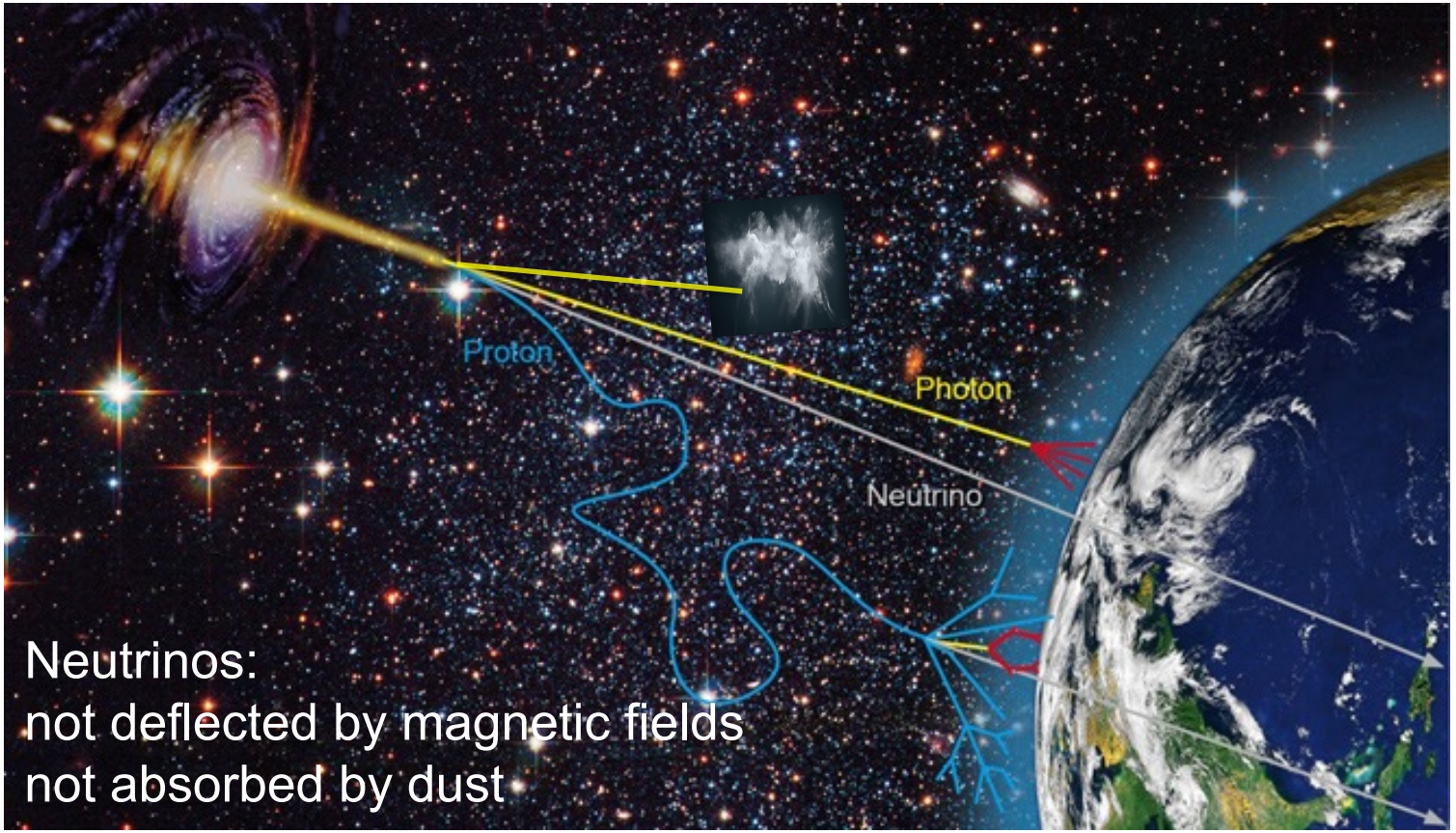
Active Galactic Nuclei (AGNs)



Particle Generation in AGN Jets



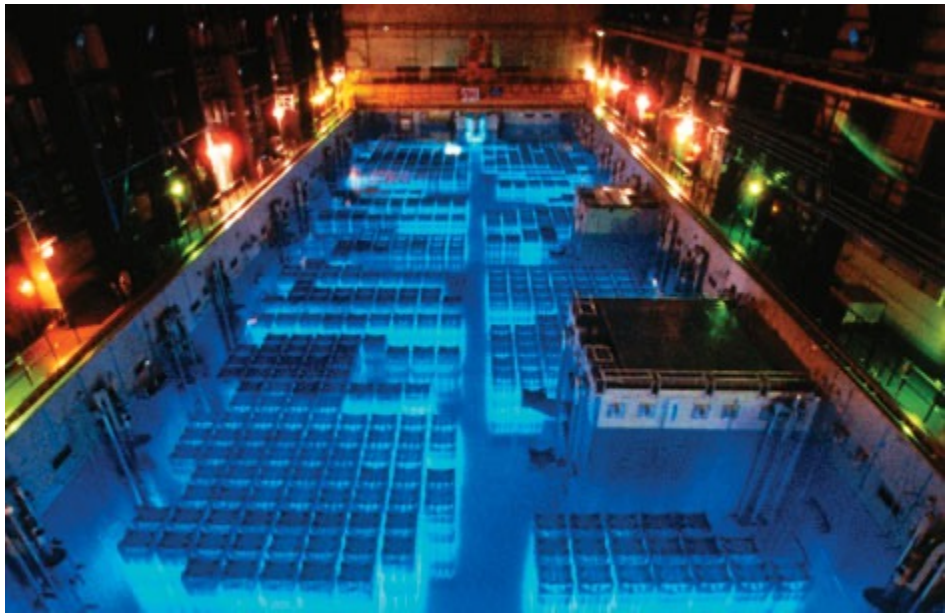
Messenger Particles of Astroparticle Physics

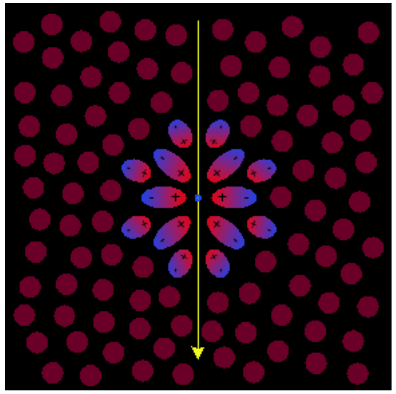


from http://www.ung.si/en/research/cac/projects/cta/

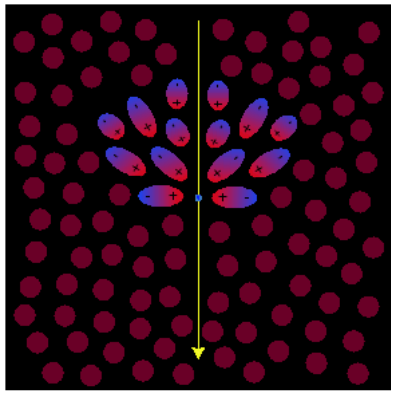
Deep Sea Neutrino Telescopes

Cherenkov Radiation

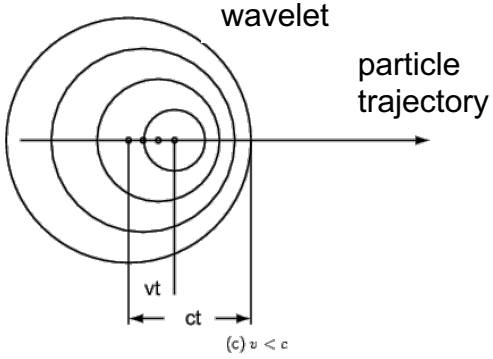


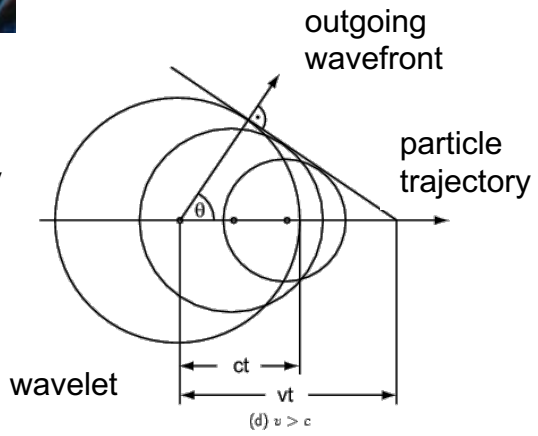


(a) $v < c$

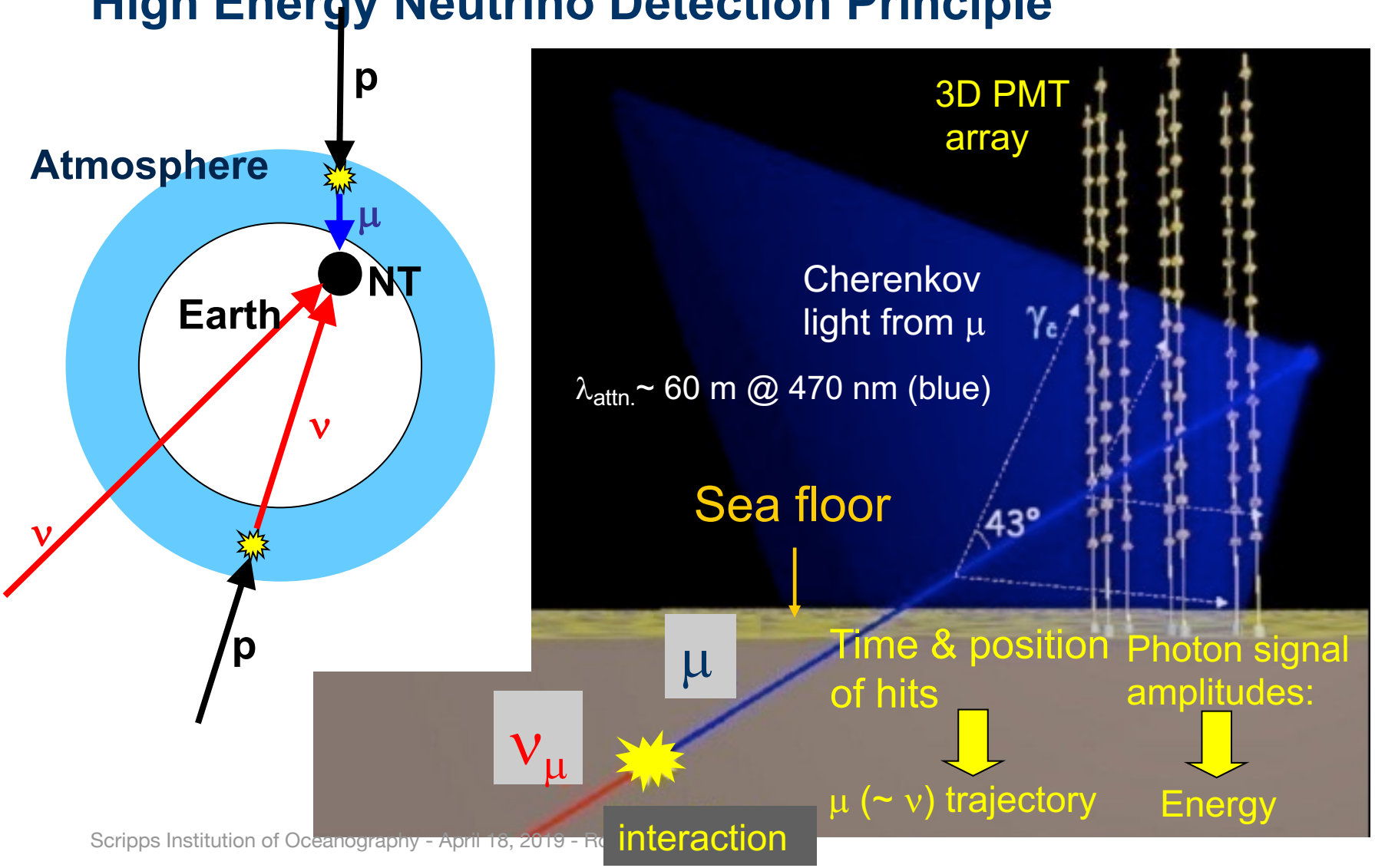


(b) $v > c$

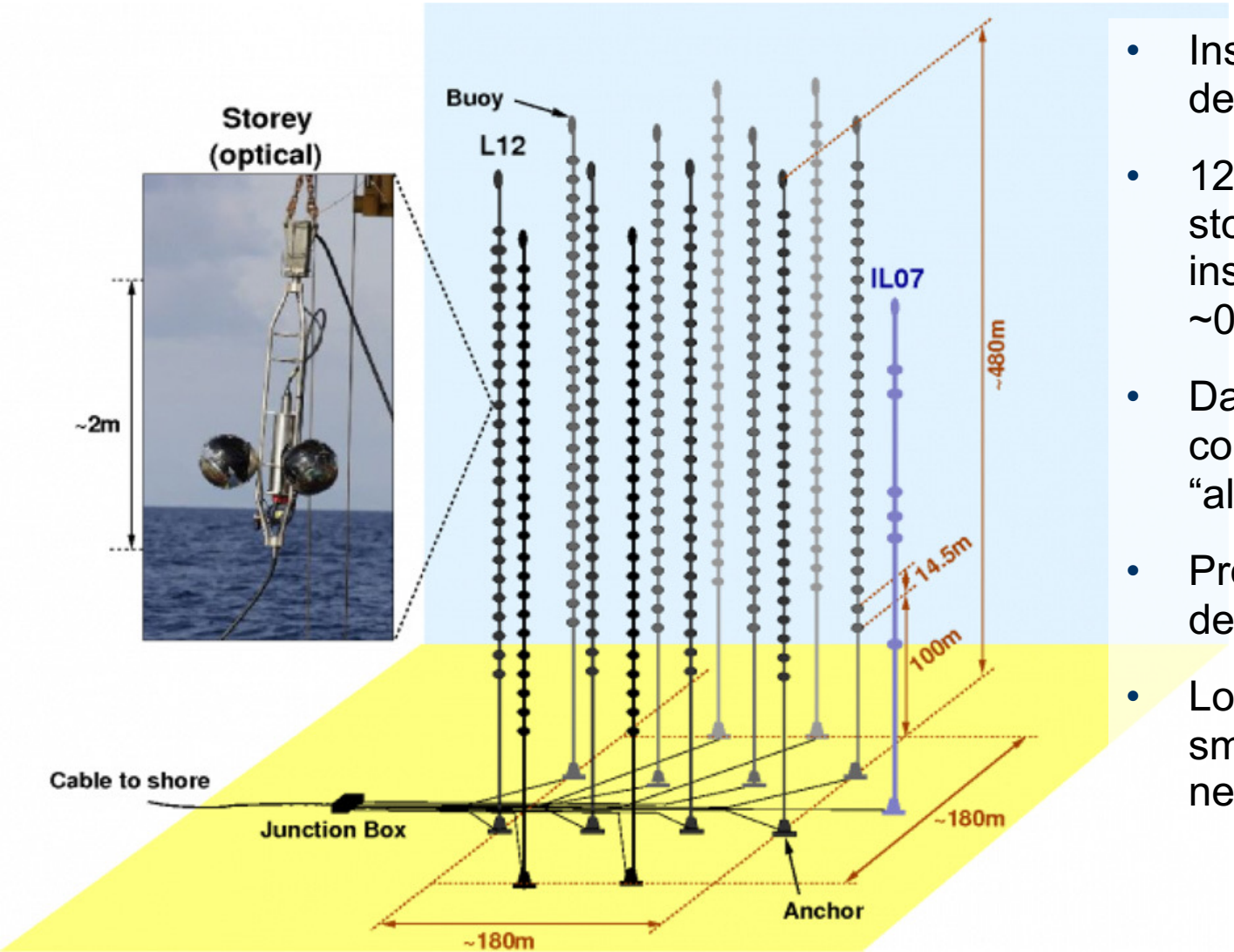




High Energy Neutrino Detection Principle



ANTARES: The first deep-sea ν telescope



- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume ~0.01km^3
- Data taking in full configuration since 2008 “all data to shore”
- Proof of principle of deep-sea ν telescope
- Lots of results – but (too) small for cosmic neutrinos

ANTARES movie

ANTARES Movie

The KM3NeT Neutrino Telescope

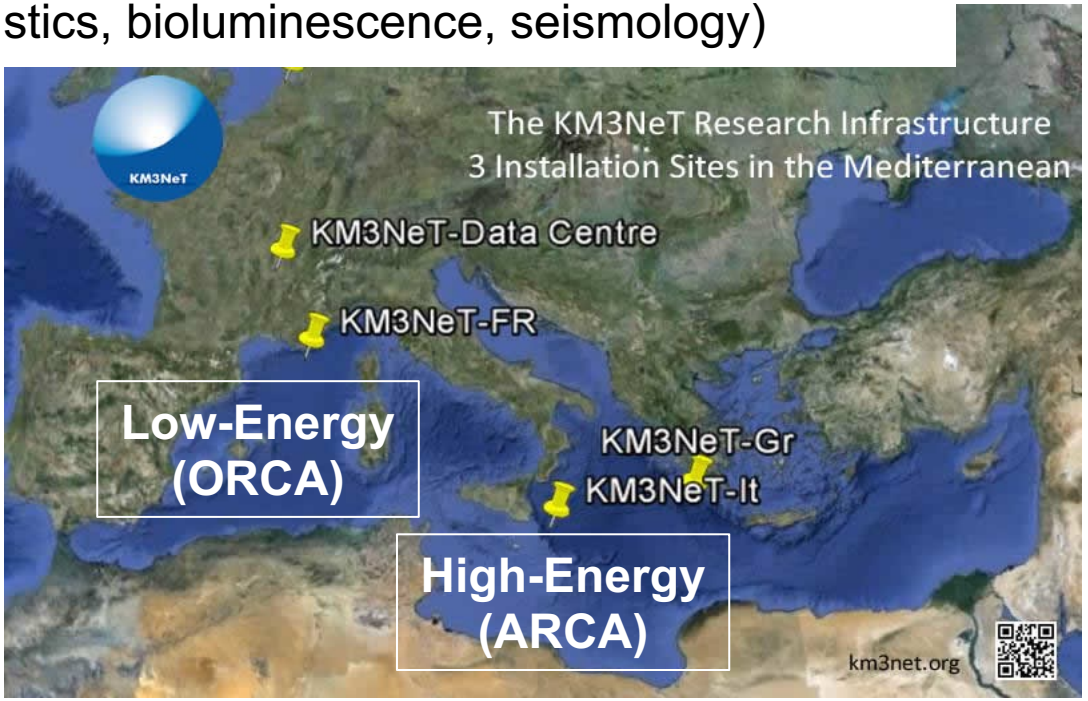
KM3NeT is currently under construction; 2 main physics topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)

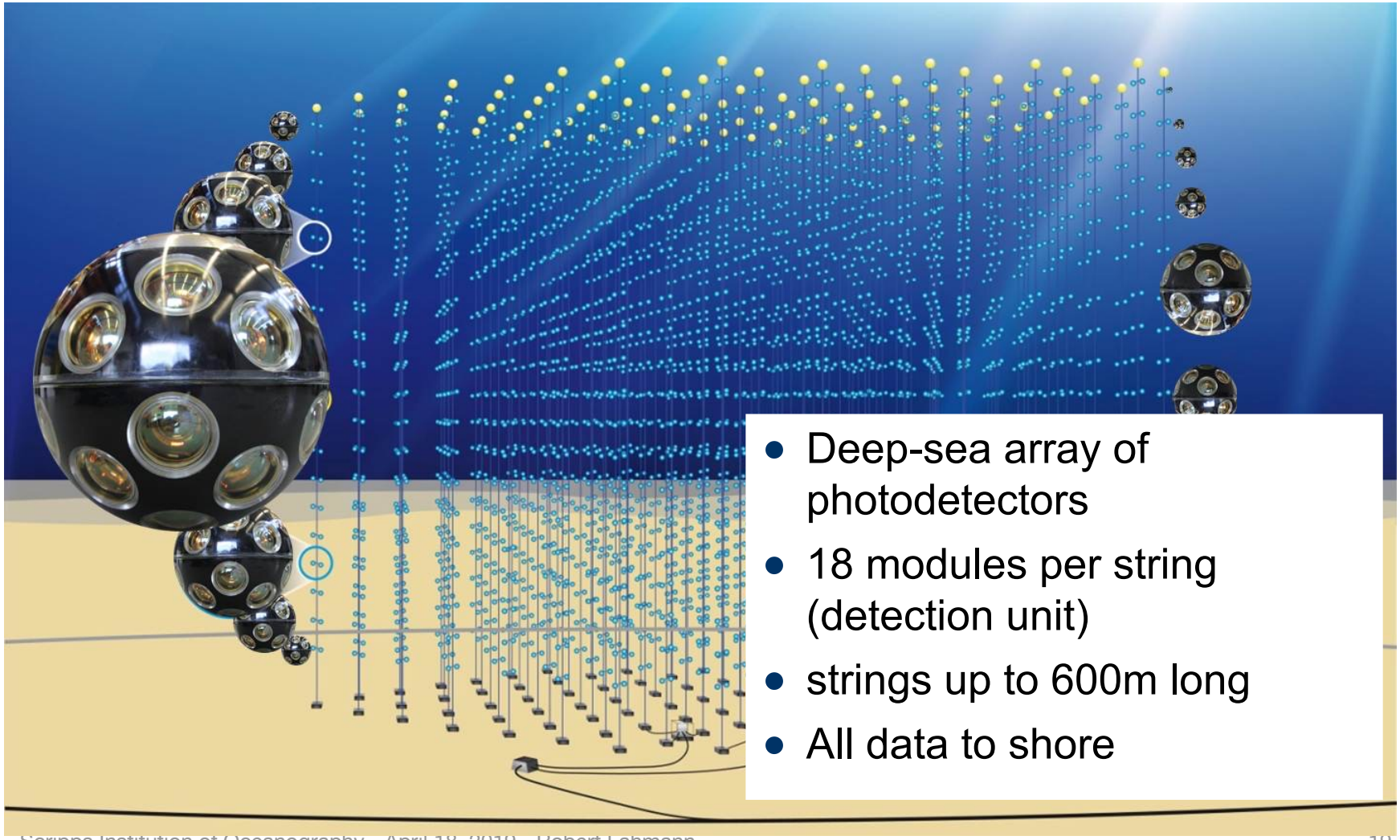
… and Deep Sea Observatory

(Oceanography, bioacoustics, bioluminescence, seismology)

- Single Collaboration
- Single Technology
- Single Management



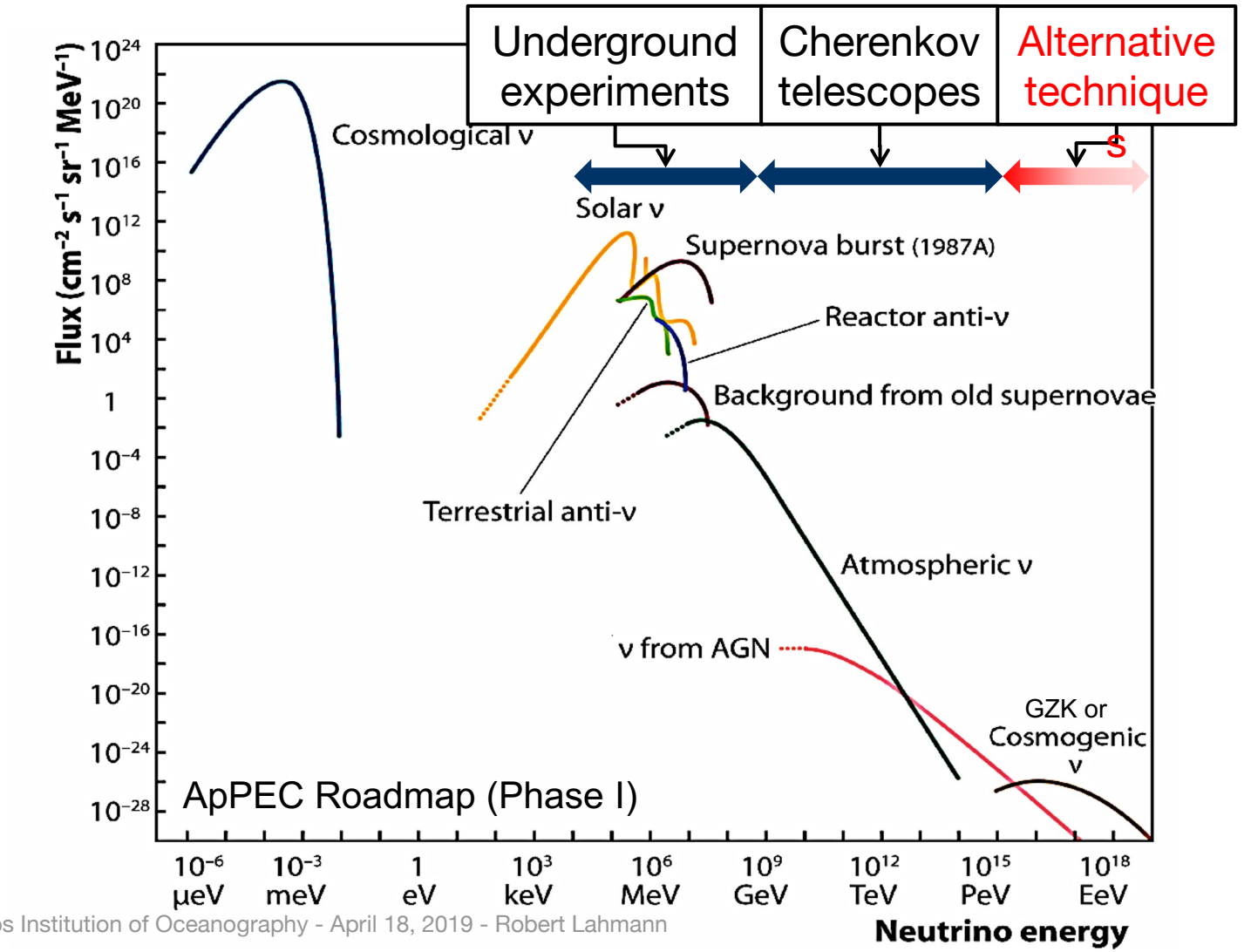
The KM3NeT Concept



- Deep-sea array of photodetectors
- 18 modules per string (detection unit)
- strings up to 600m long
- All data to shore

Acoustic Neutrino Detection

Neutrino fluxes: Motivation for Acoustic Detection



Acoustic signals of neutrino interactions in water I

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

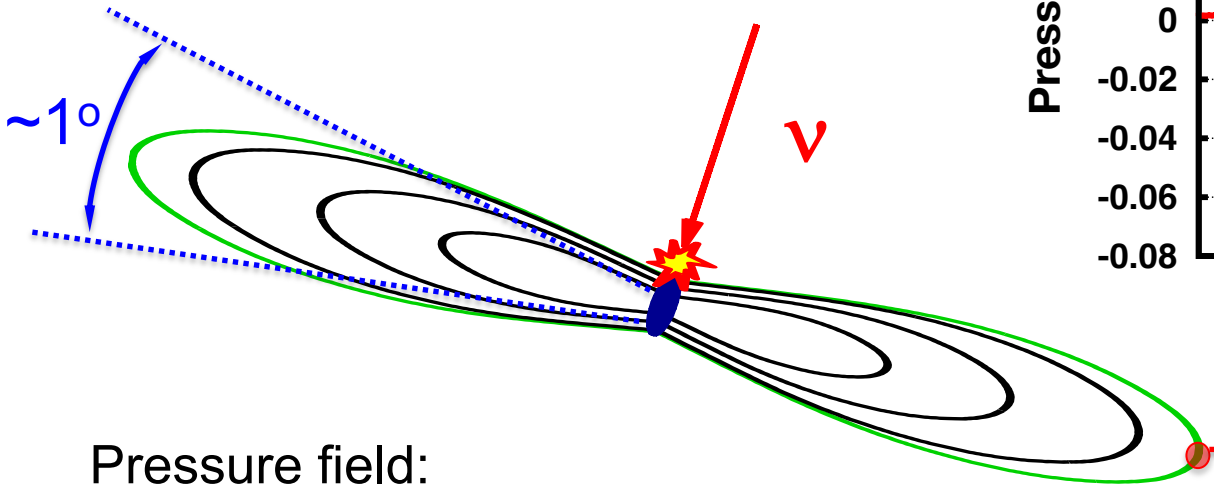
C_P = specific heat capacity (at constant pressure)

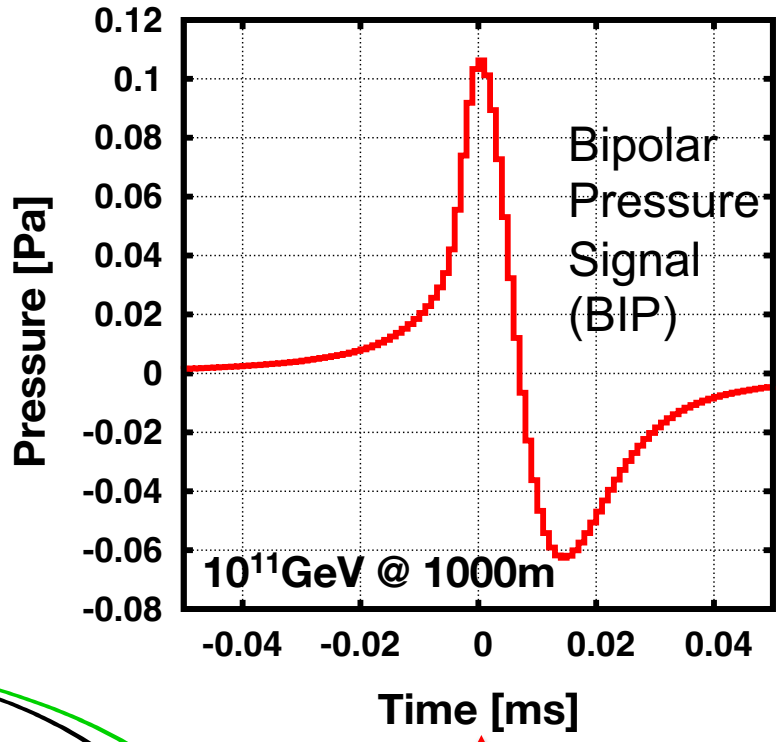
c = speed of sound in water (ca. 1500 m/s)

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

Acoustic signals of neutrino interactions in water II

Particle cascade:
~10m length, few cm radius

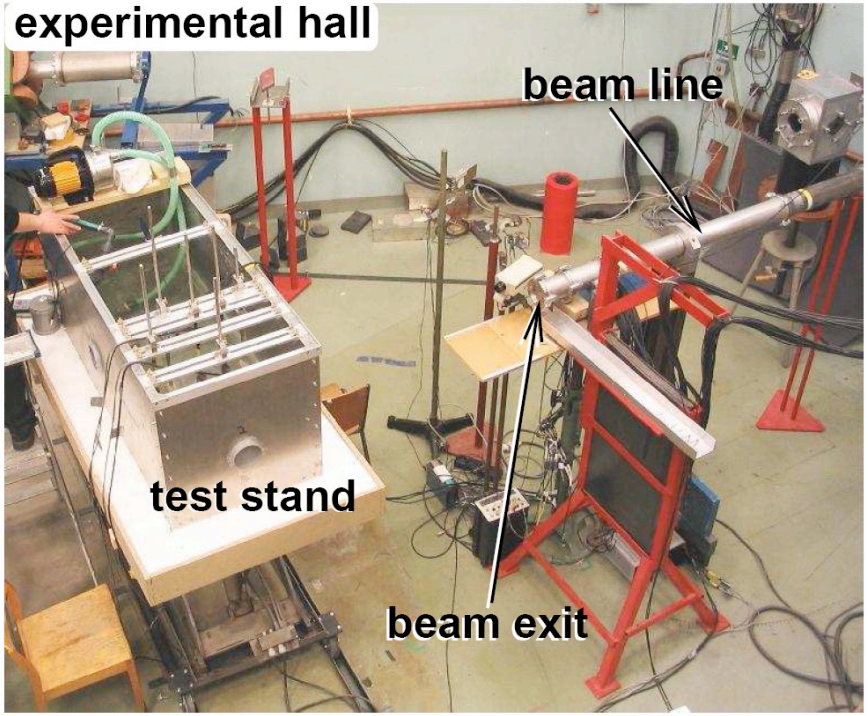


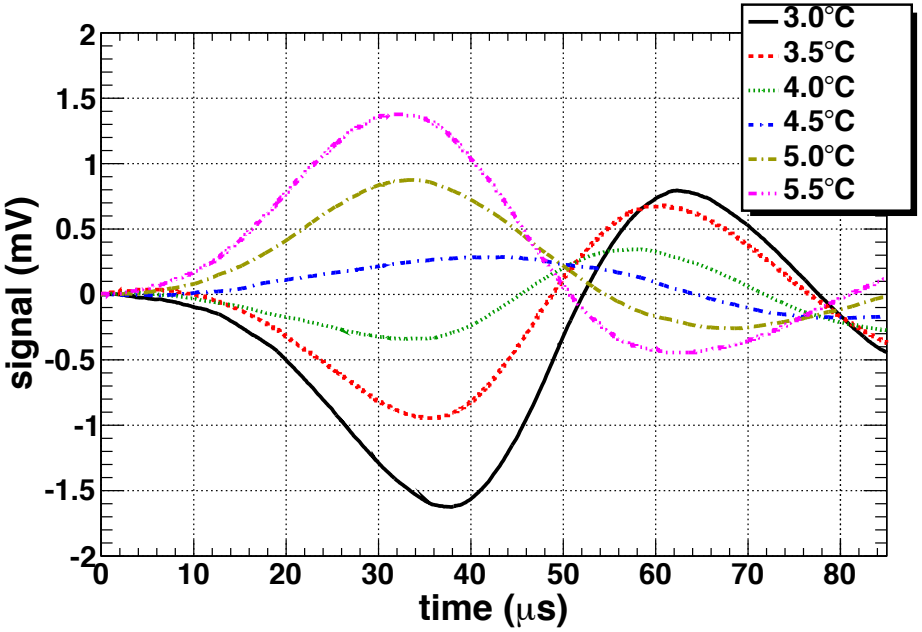


Pressure field:
Characteristic “pancake” pattern
Long attenuation length (~5 km @ 10 kHz)

Measurements of thermoacoustic effect

Proton beam into water tank:





More details:
https://arxiv.org/abs/1501.01494

Historical Interlude: The DUMAND Project

- In 1973, the steering committee for the **Deep Underwater Muon And Neutrino Detector (DUMAND)** was formed
- Planned to be installed off-shore of Hawaii
- Originally, both optical and acoustic detection were considered
- In 1995, further efforts on DUMAND were cancelled by the DOE
- In 1977 a DUMAND acoustic workshop was held at La Jolla…

DUMAND – Deep Underwater Muon and Neutrino Detection

Steering Committee, 1977
F. Reines, Chairman
H. Blood
H. Bradner
D. Cline
W. V. Jones
J. Learned
A. Roberts
D. Schramm
L. Sulak
G. Wilkins

PROCEEDINGS

of the

LA JOLLA WORKSHOP on ACOUSTIC DETECTION OF NEUTRINOS

25-29 July 1977

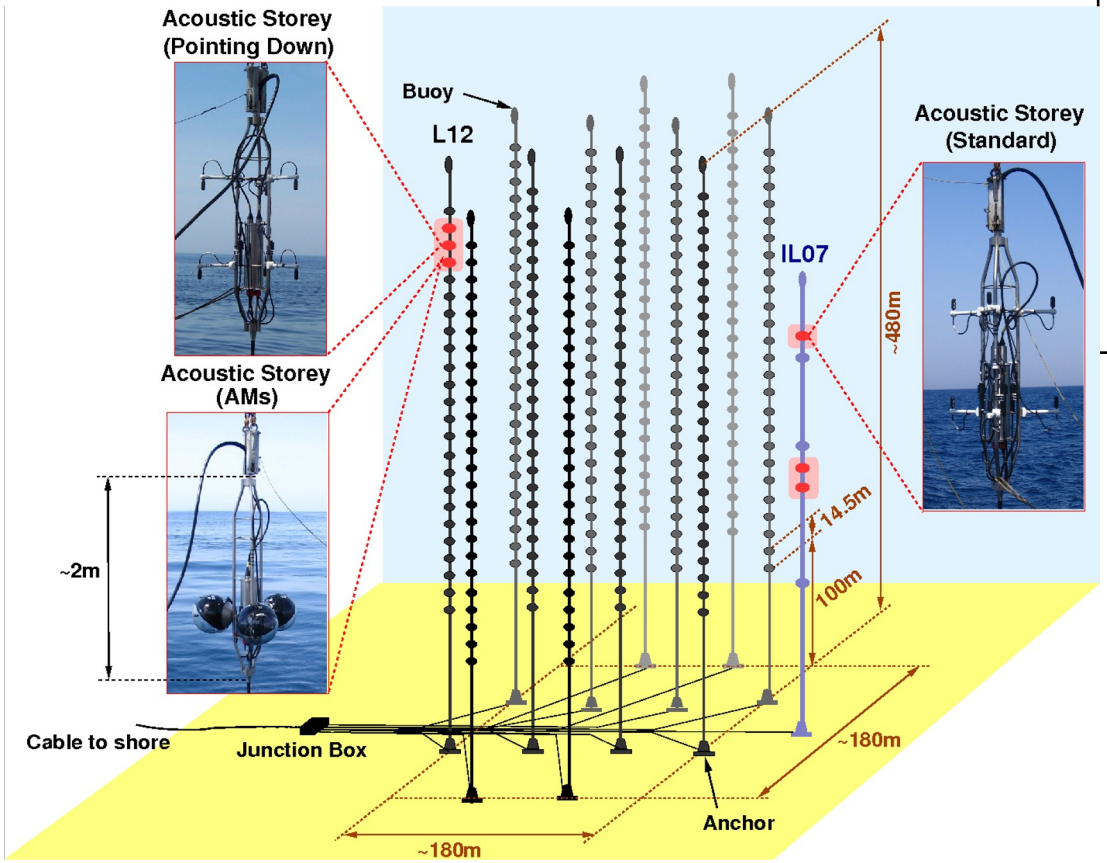
Institute of Geophysics and Planetary Physics

Scripps Institution of Oceanography

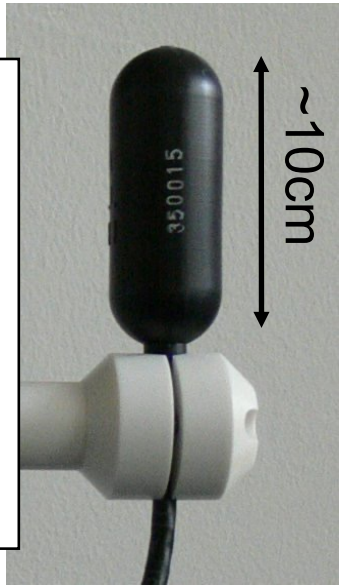
University of California, San Diego

Hugh Bradner, Editor

AMADEUS – ANTARES



Hydrophone:
Piezo sensor
with pre-amplifier
and band pass filter
in PU
coating
(Typical sensitivity
-145 dB re. 1V/μPa)



Operation from
Dec. 2007 to Nov. 2015

36 acoustic sensors on
6 stories

Local clusters for
direction reconstruction

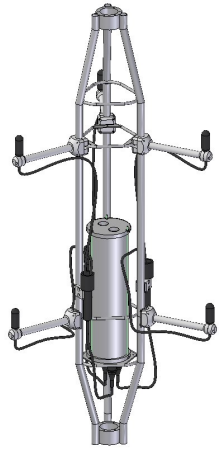
Depth 2300 – 2100 m

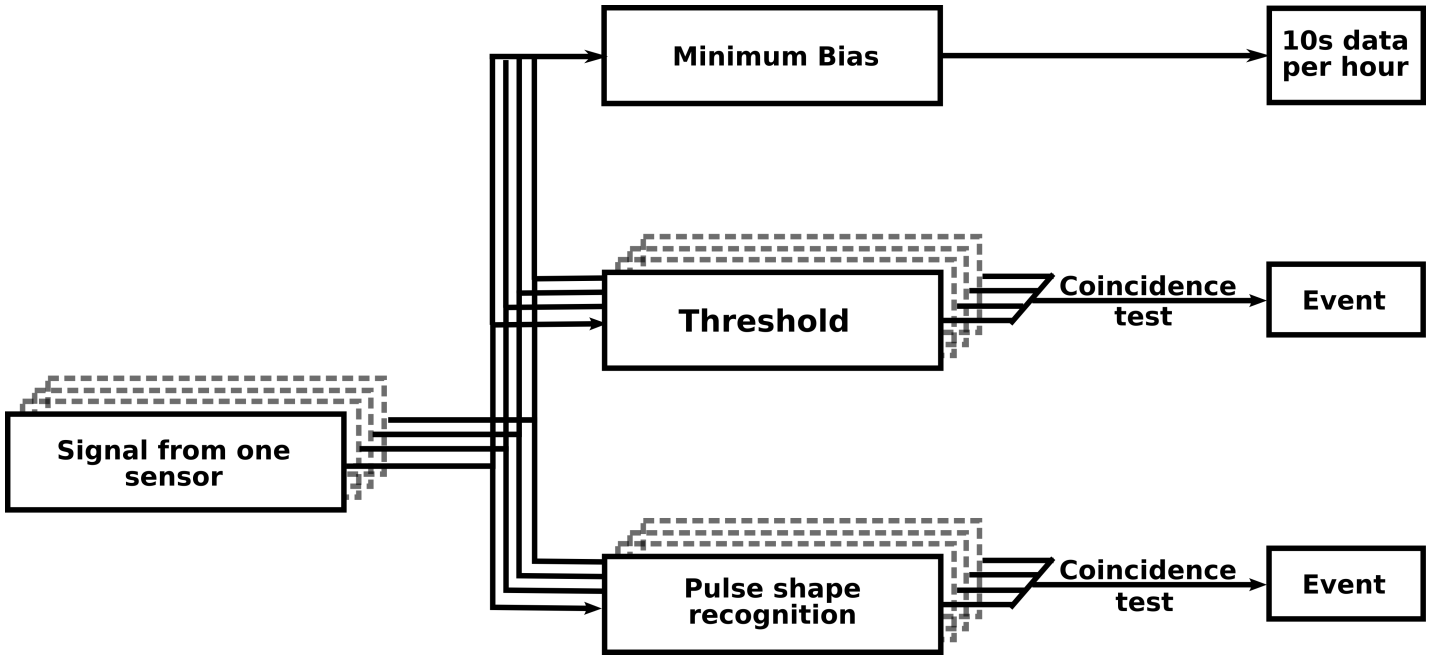
Movie IL07

IL07 Movie

The Onshore Filter System

Task: Reduce incoming data rate of ~1.5 TByte/day to ~15 GByte/day



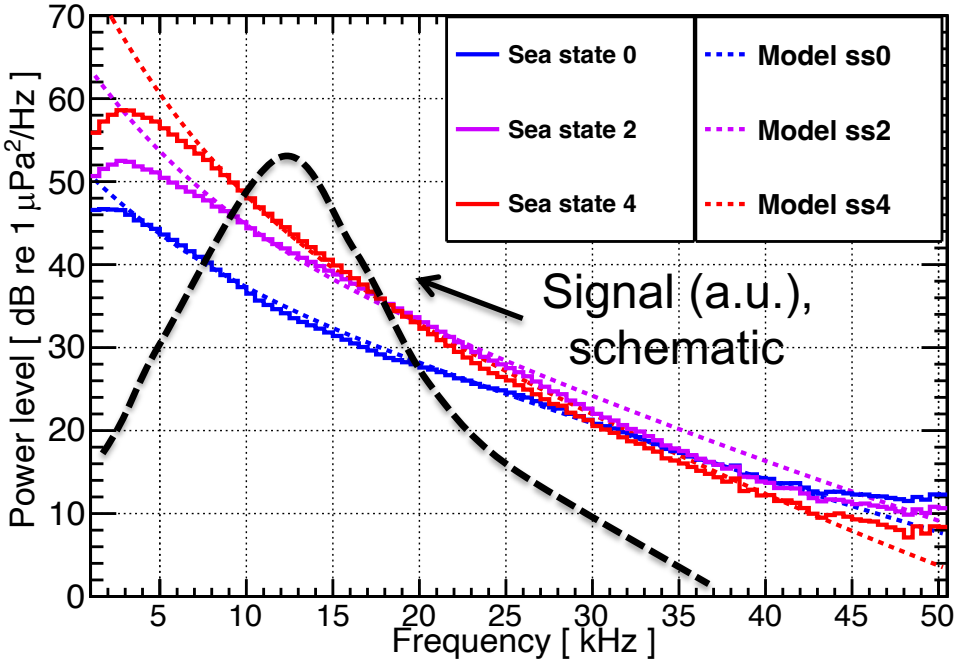


System very flexible

Local clusters (storeys) advantageous for fast (on-line) processing

Background for Acoustic Detection in the Sea

Ambient noise

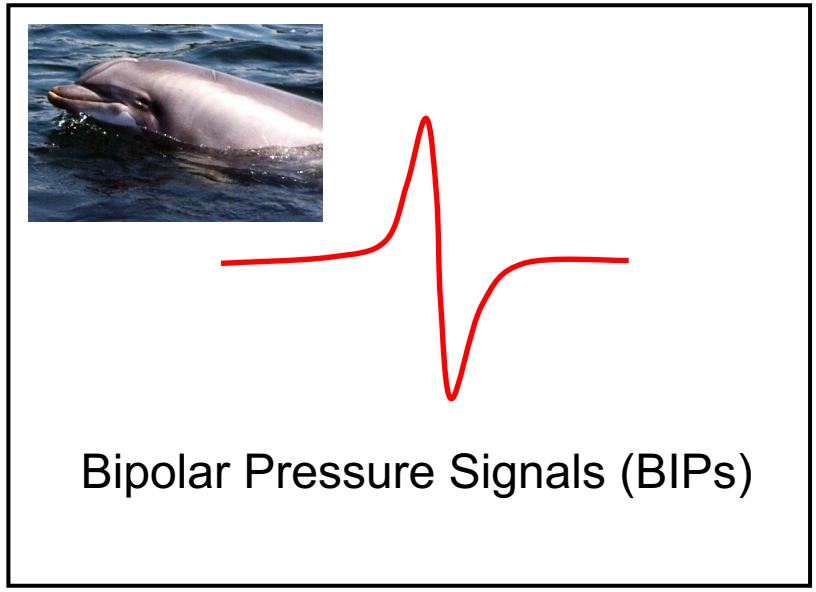


⇨**Determines intrinsic energy threshold**

Depends on “sea state”

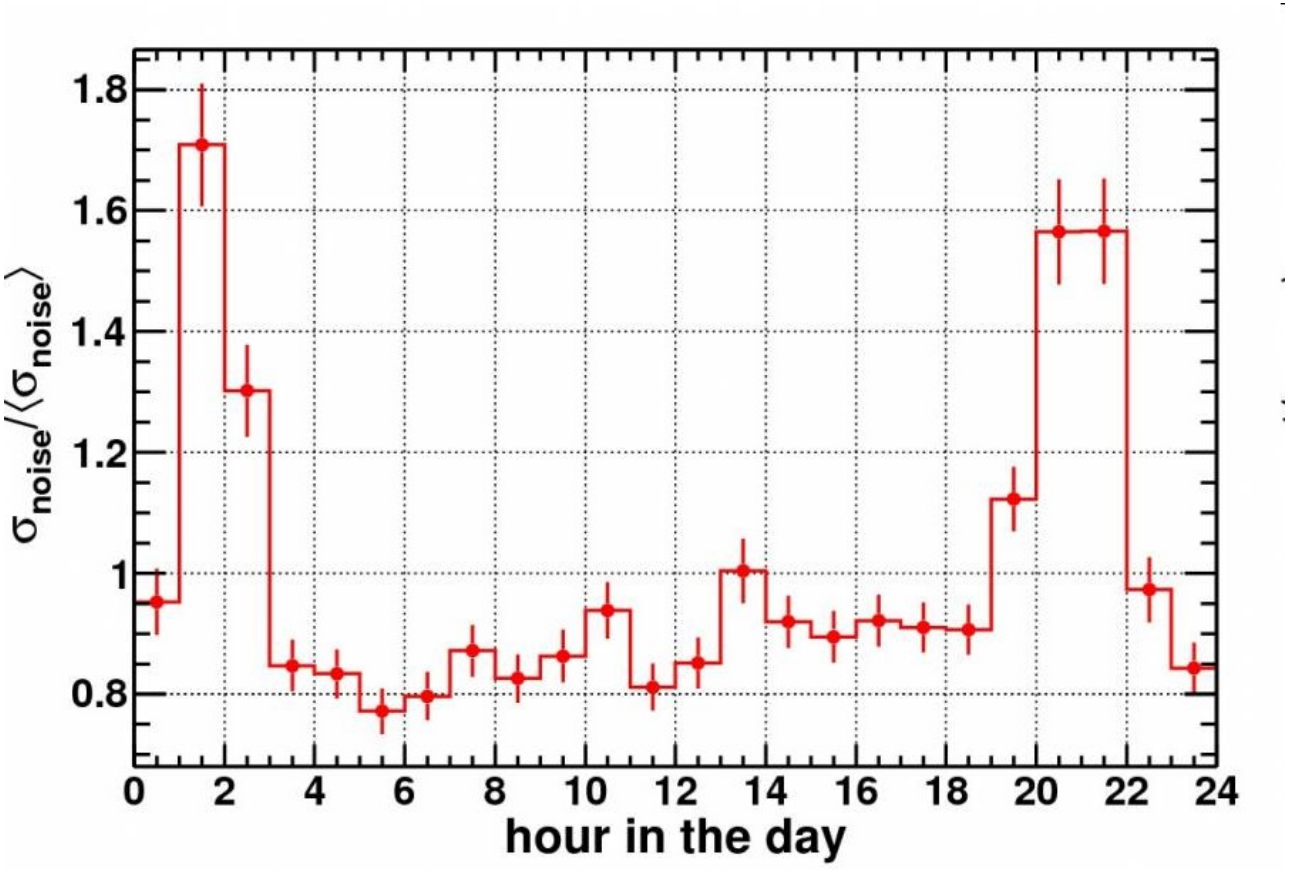
(surface agitation and precipitation)

Transient background



⇨**Determines fake neutrino rate**

Ambient Noise – Daily Variations

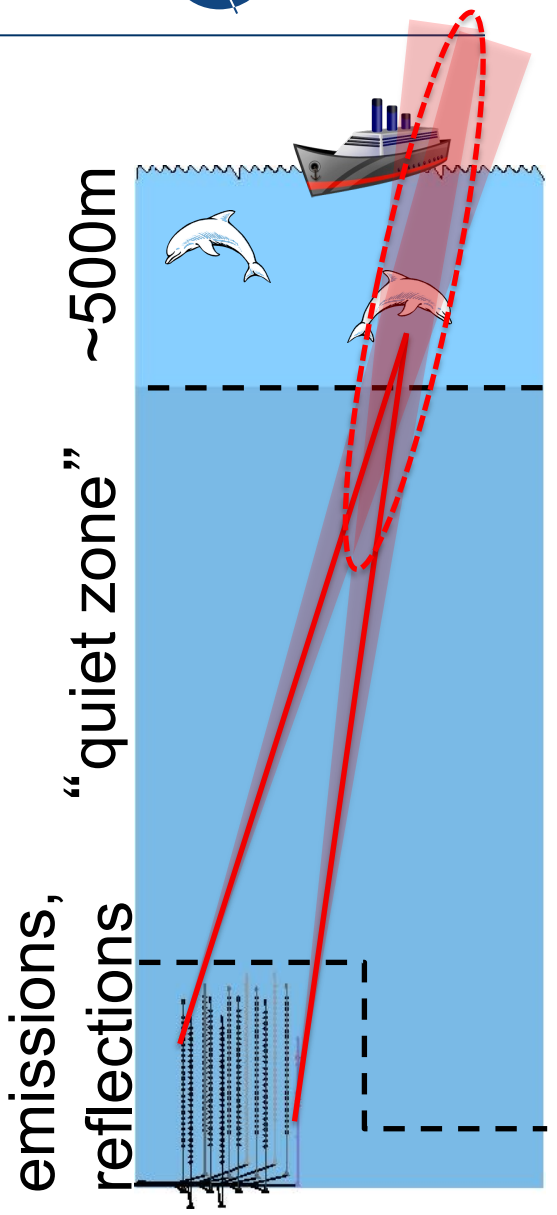


Strong variations over the day; correlated with ferry schedules

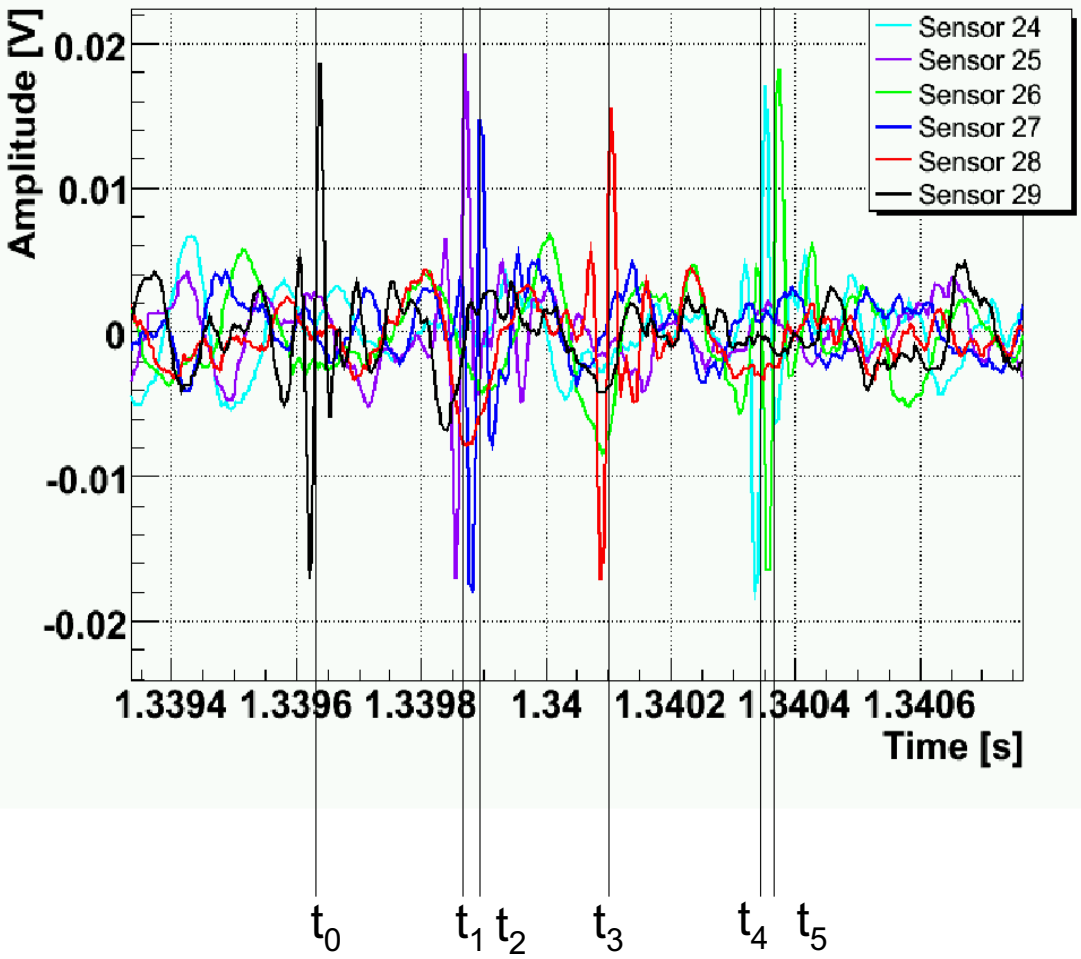
$\langle\sigma_{noise}\rangle$ is about 10 mPa (10-50 kHz) and 95% of the time below $2\langle\sigma_{noise}\rangle$

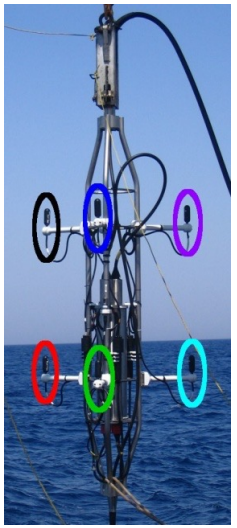
Transient Background

- Mostly originating from near surface
- Sources very diverse:
  Shipping traffic, marine mammals, …
  ⇨ perform signal classification
- Analysis:
  - Define “neutrino-like events” based on machine learning algorithms
  - Identify directions from individual storeys
  - Identify source position from multiple directions
  - Remove events from moving sources

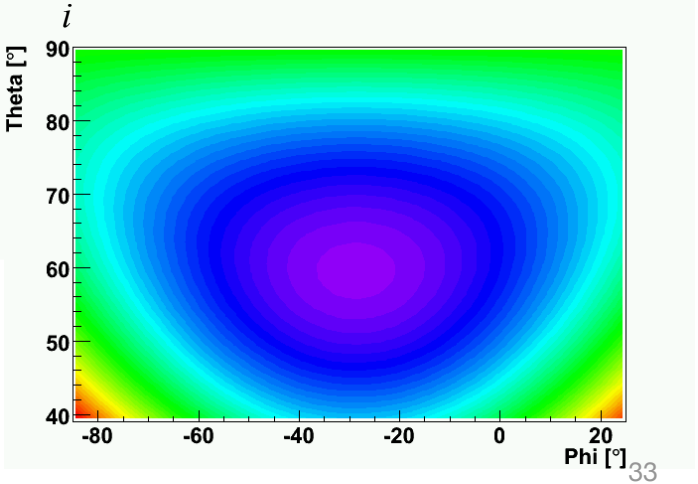


Source Direction Reconstruction





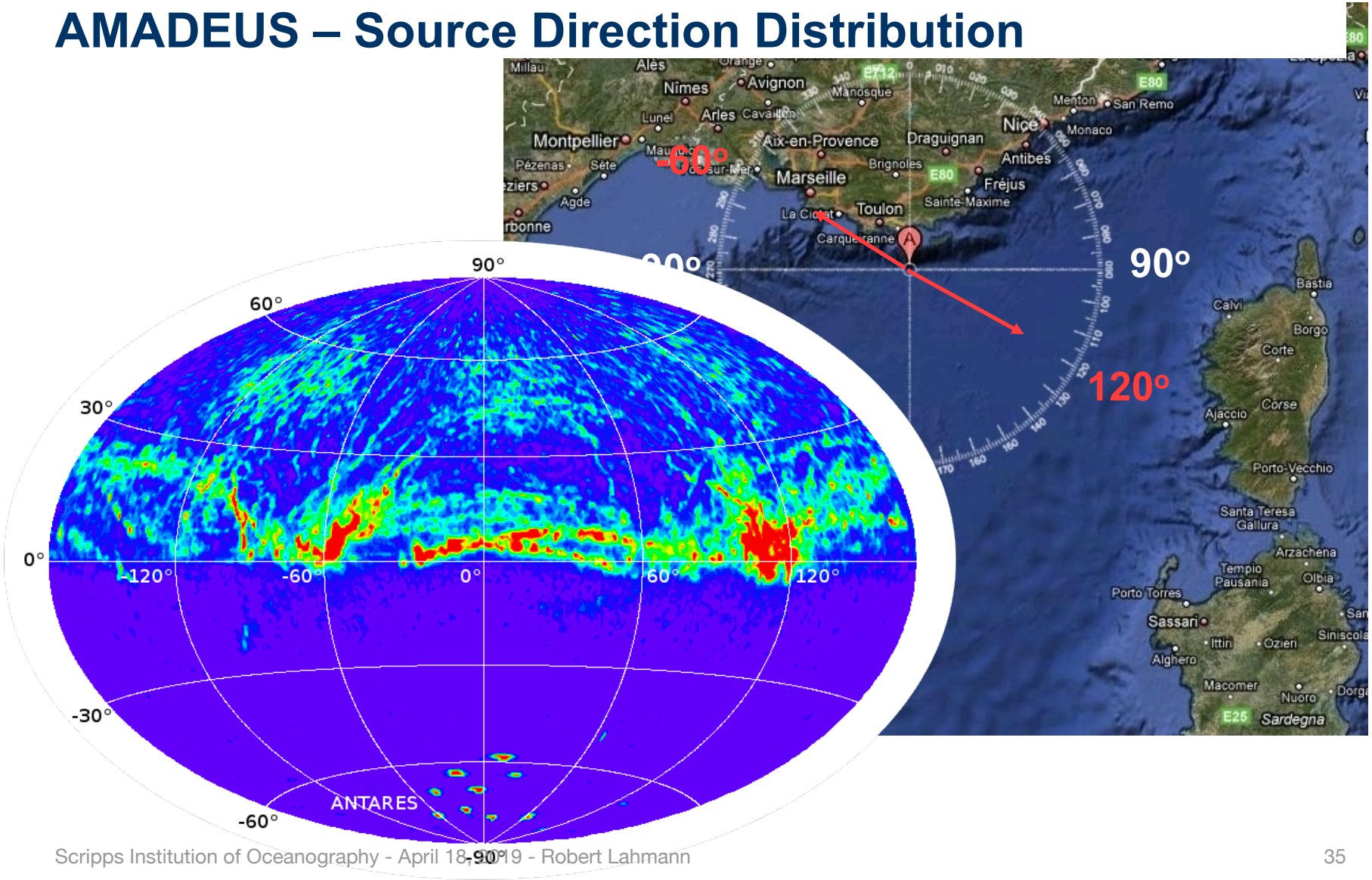
$$\sum_i \left(t_{i_{measured}} - t_{i_{expected}}(\vartheta,\varphi) \right)^2$$



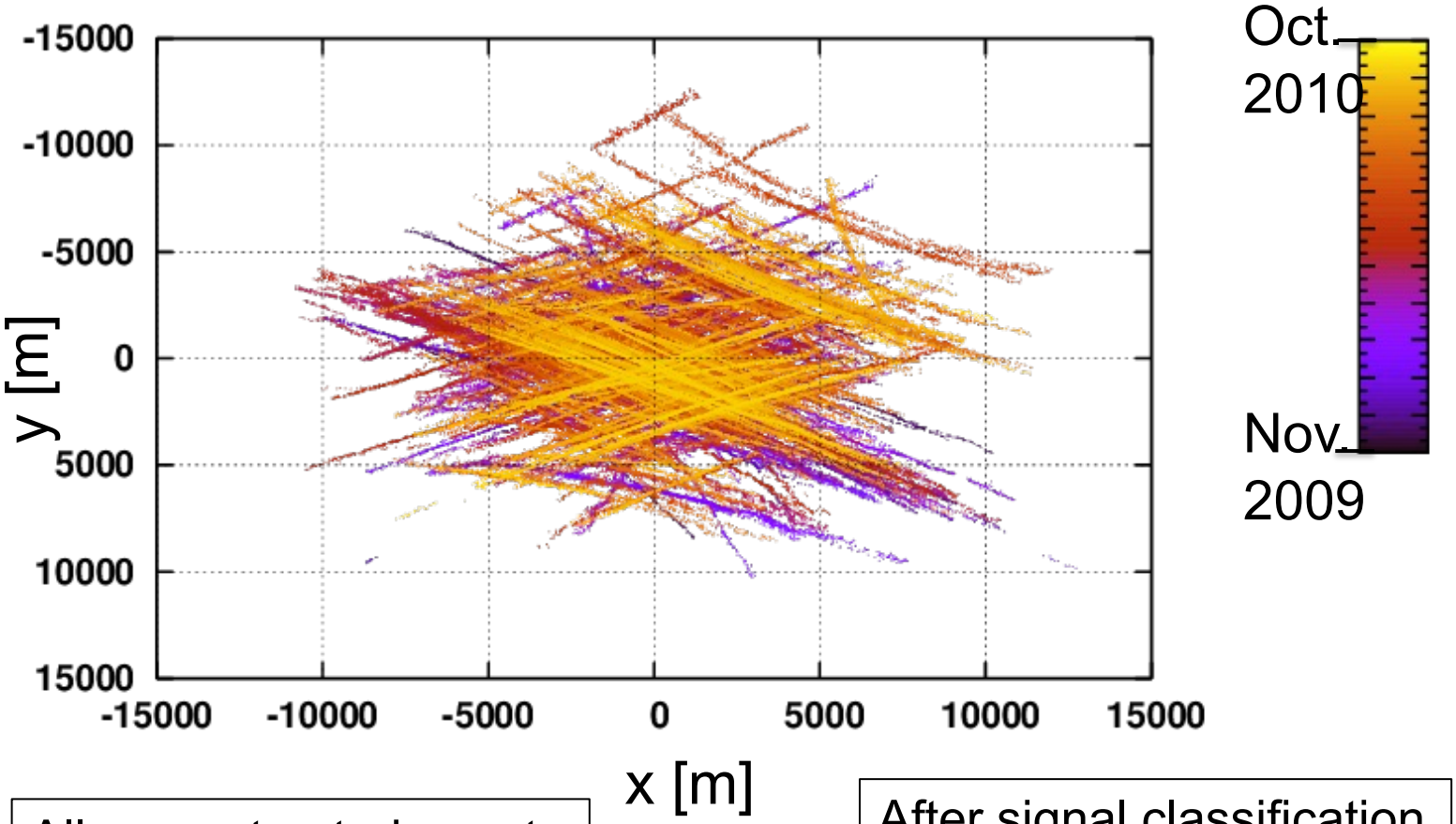
Track Movie

Track movie

AMADEUS – Source Direction Distribution



Cluster Analysis of Moving Sound Emitting Objects



All reconstructed events
ave. rate: 0.3 Hz

$\Rightarrow$

After signal classification
and cluster analysis
ave. rate: 0.002 Hz

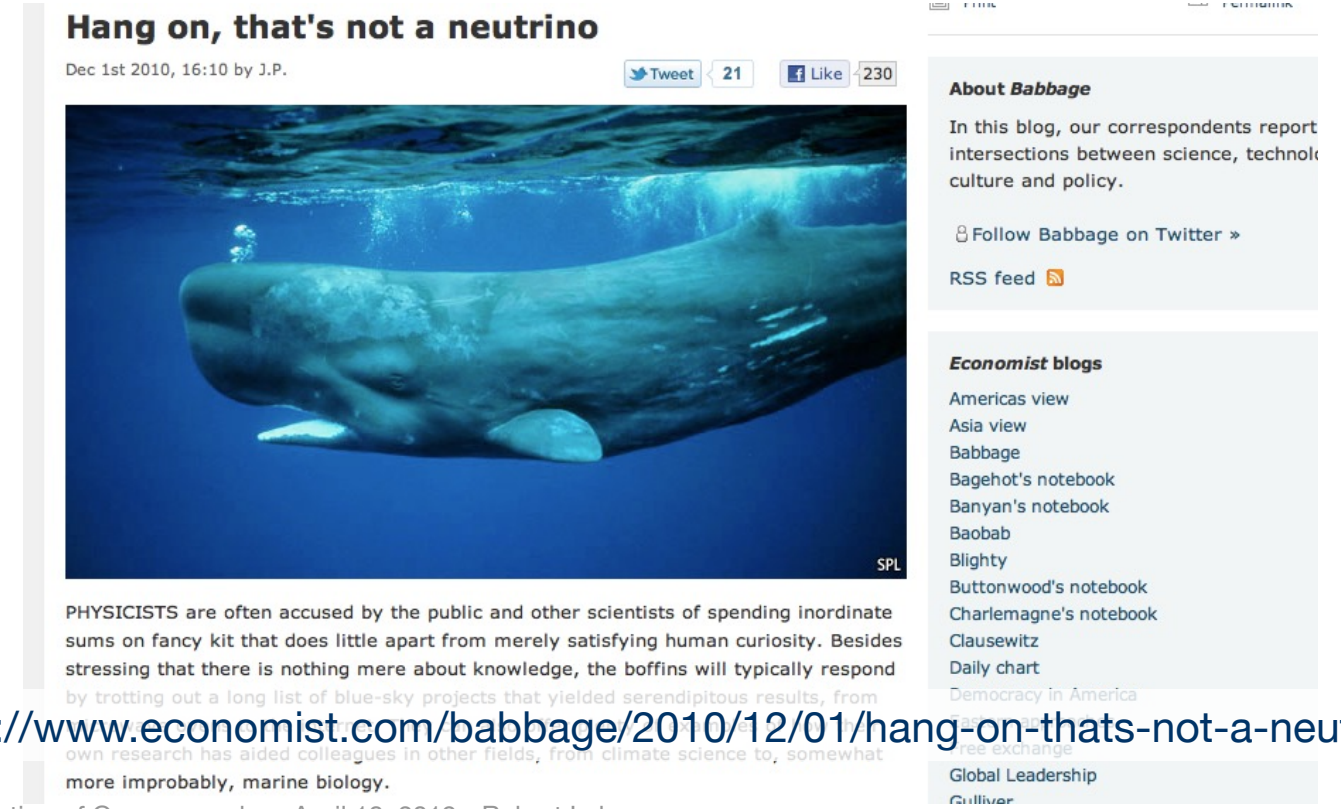
AMADEUS: Lessons Learned

- Ambient noise:
  Background low and stable, reduction of SNR for neutrino detection crucial
- Transient background:
  High level of background (mainly dolphins);
  High level of reduction already achieved with AMADEUS, recognition of “acoustic pancake” crucial

Marine Science with AMADEUS

Marine Science with AMADEUS

- (Formerly) life data from AMADEUS: http://listentothedeep.org/
- Press releases in 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 stressing that there is nothing mere about knowledge, the boffins will typically respond by trotting out a long list of blue-sky projects that yielded serendipitous results, from

own research has aided colleagues in other fields, from climate science to, somewhat more improbably, marine biology.

About *Babbage*

In this blog, our correspondents report intersections between science, technol culture and policy.

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Clausewitz
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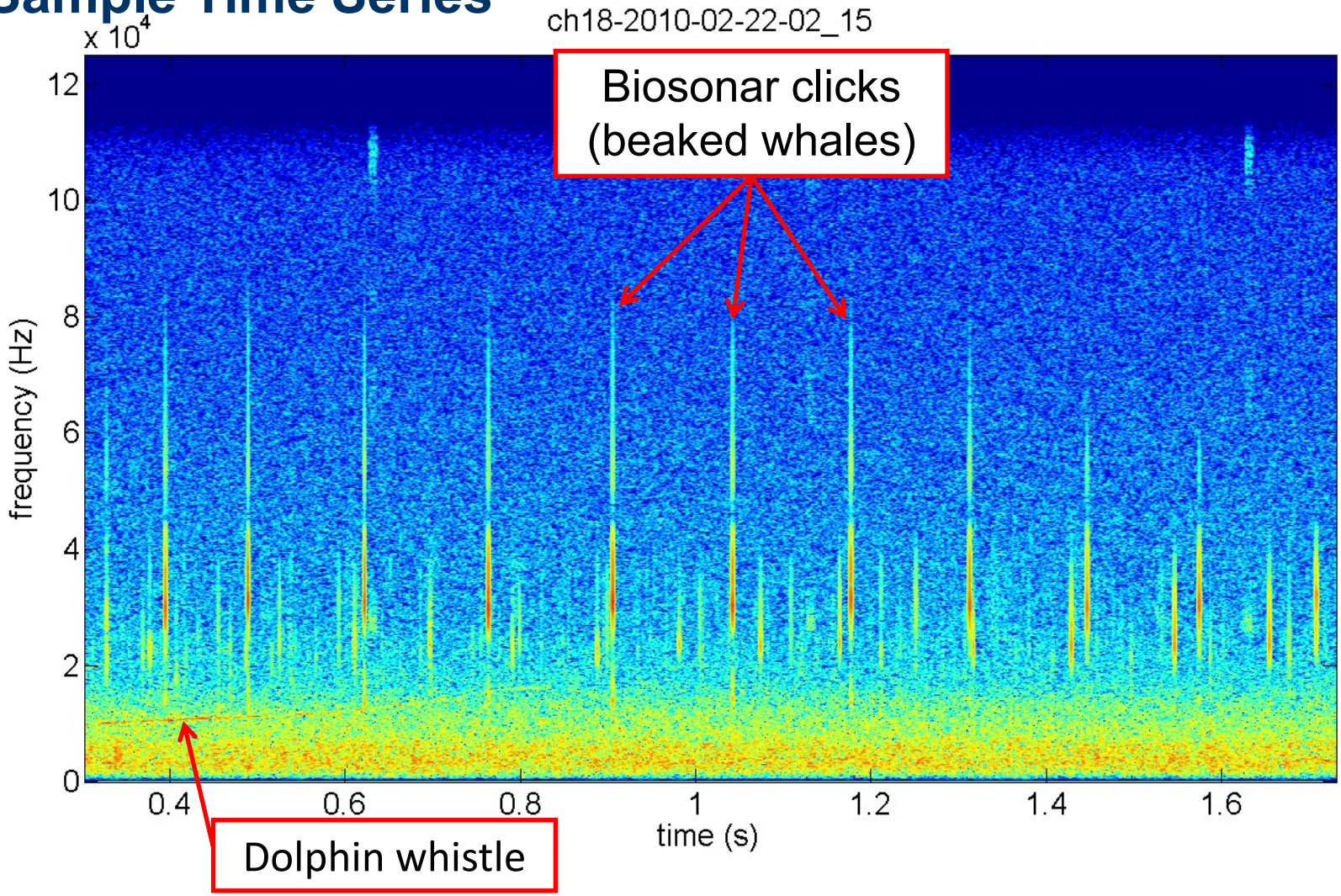
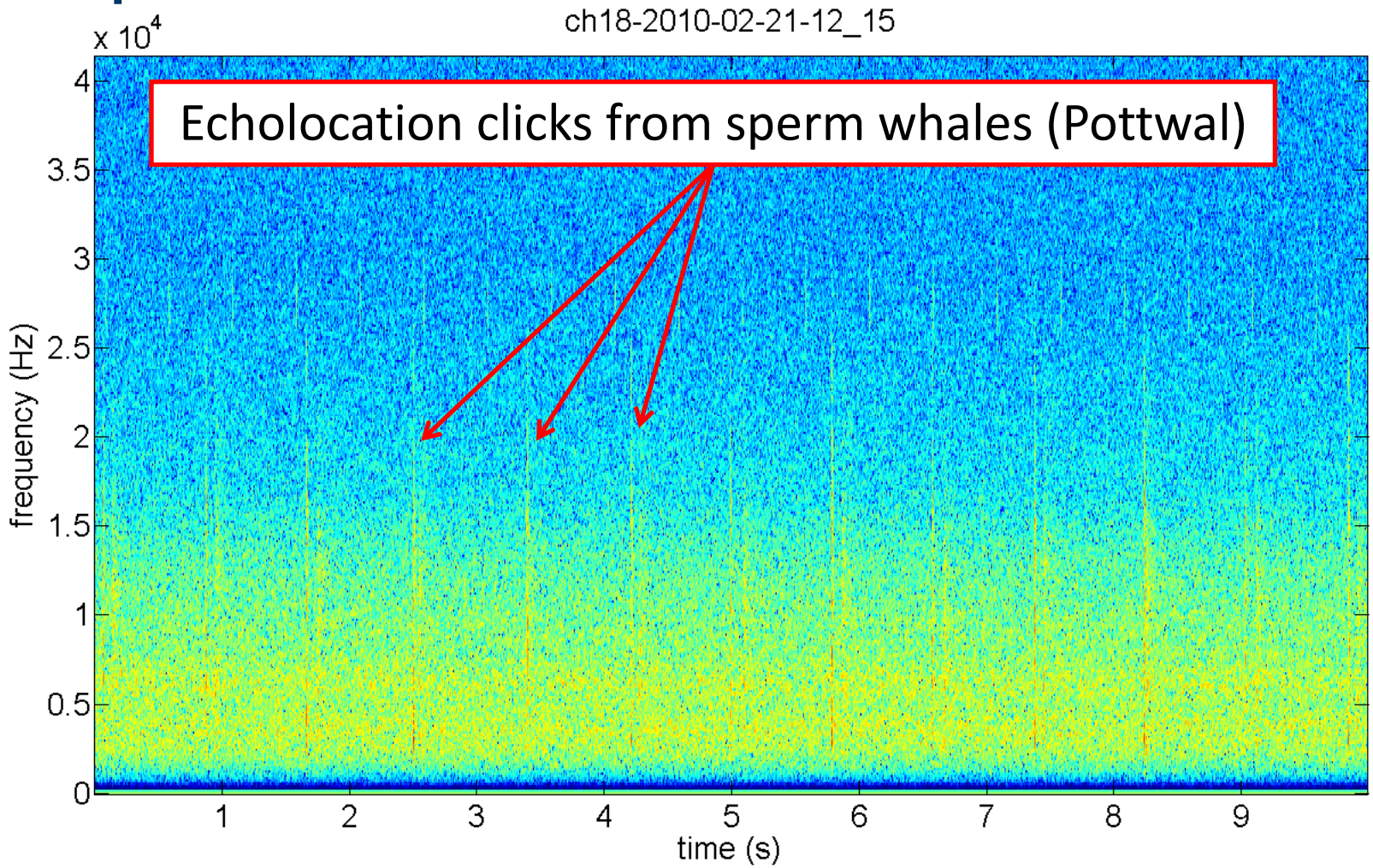
Democracy in America
Free exchange
Global Leadership
Gulliver

https://www.economist.com/babbage/2010/12/01/hang-on-thats-not-a-neutrino

Sample Time Series



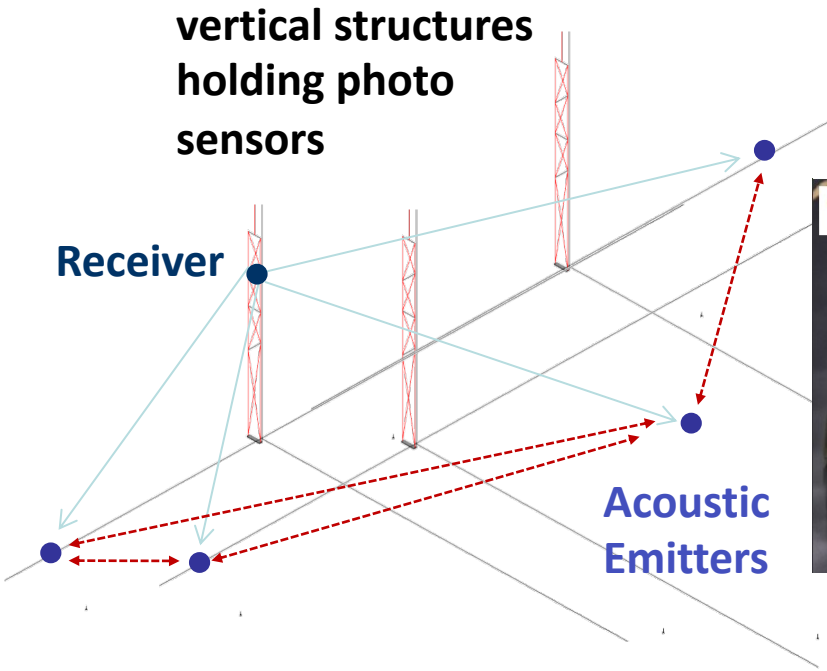
Sample Time Series



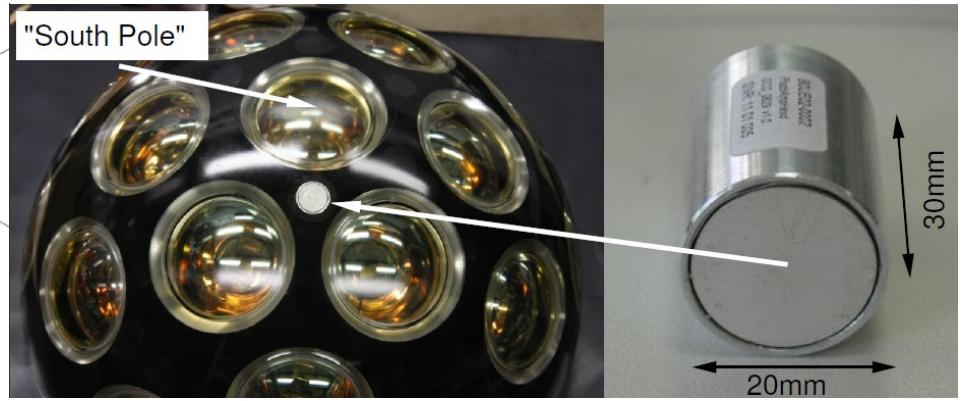
KM3NeT and Fiber Based Hydrophones

Positioning in Deep Sea Cherenkov Neutrino Telescopes

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

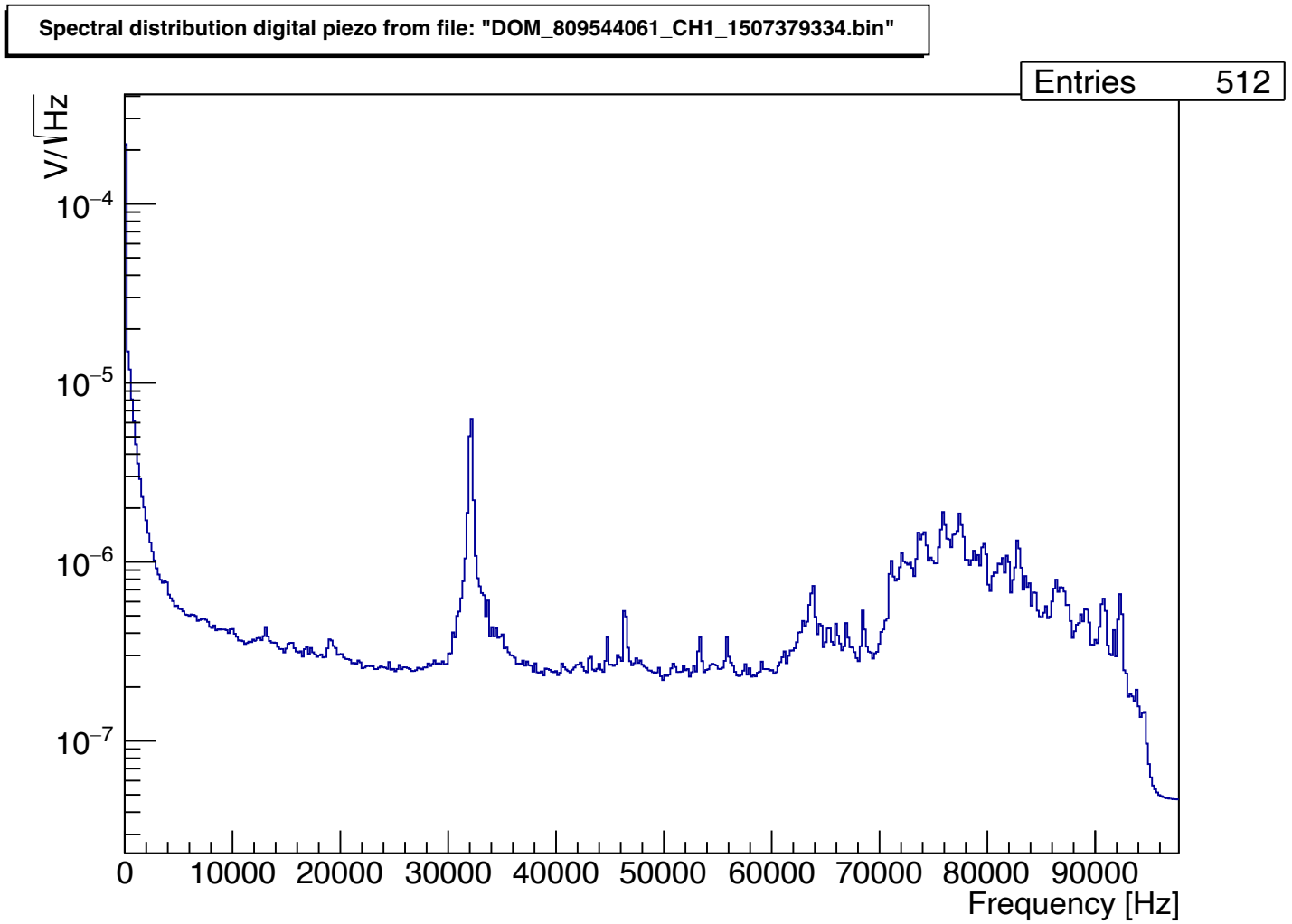


In KM3NeT:



piezo sensor integrated into OM

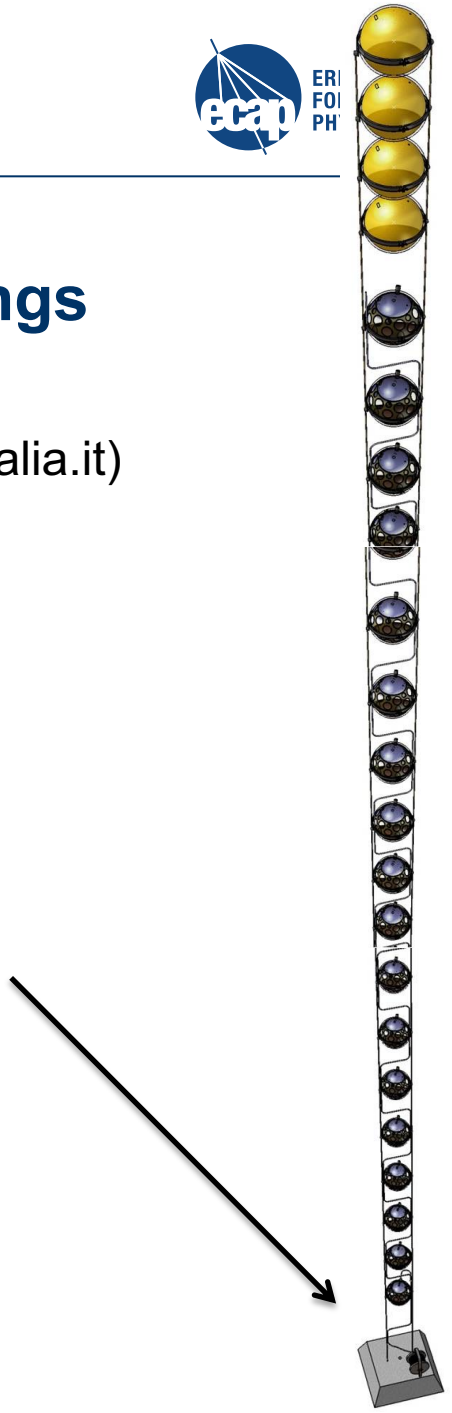
Power Spectral Density of Piezo Sensor



Hydrophones at Bases of KM3NeT Strings

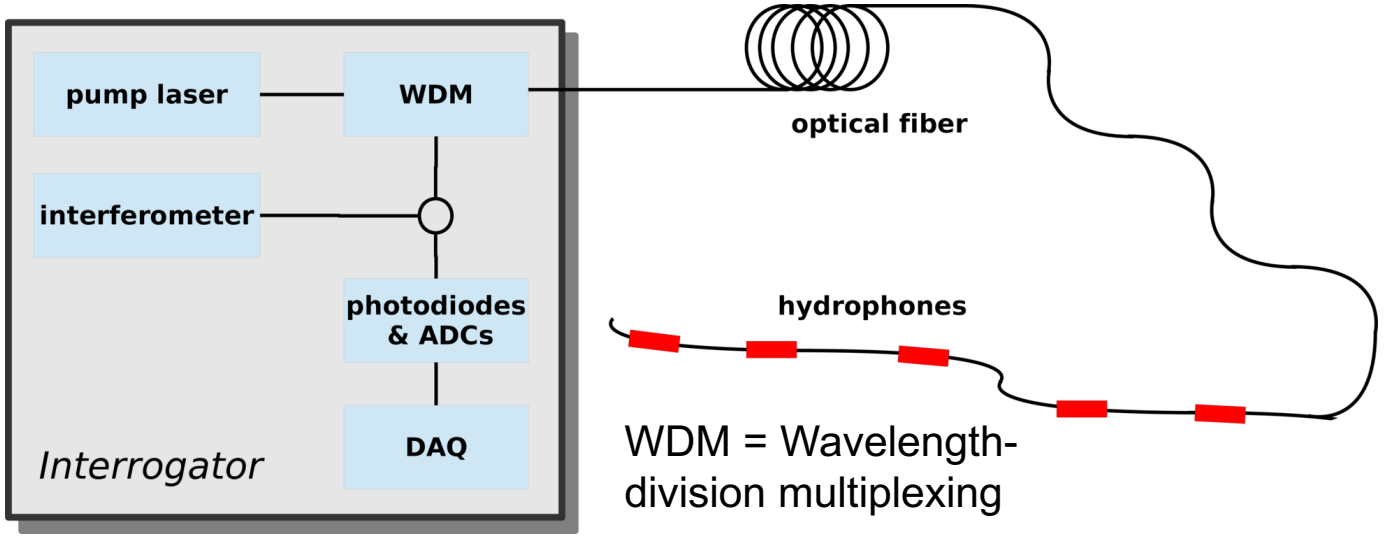
DG0330 manufactured by Colmar s.r.l. (http://www.colmaritalia.it)

- spherical piezo-ceramic element
- read-out with a double gain option (+46 dB, +26 dB)



Optical fiber hydrophone technology

Measurement concept



Three main components:

1) hydrophone sensor

2) optical fiber

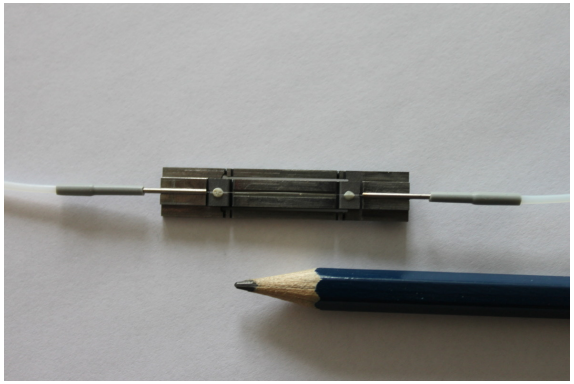
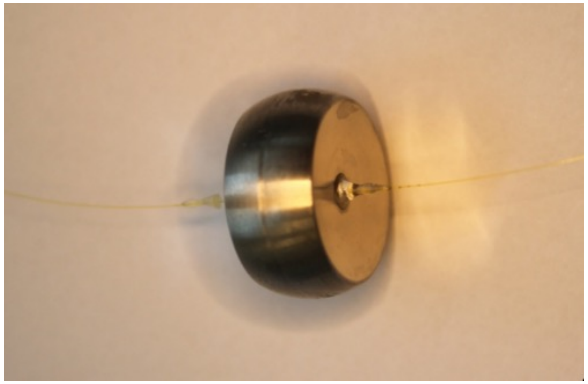
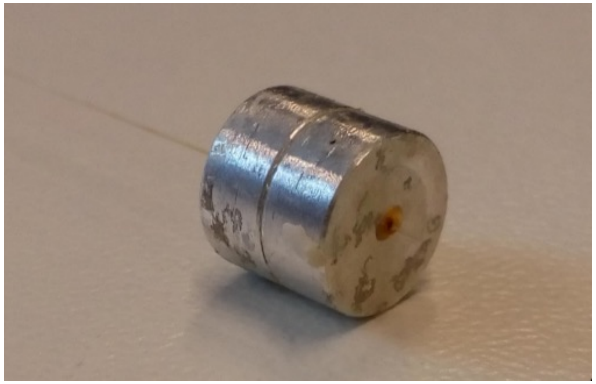
3) interrogator

Advantages over piezo-based hydrophones:

- passive
- no EM Interference

Sensor

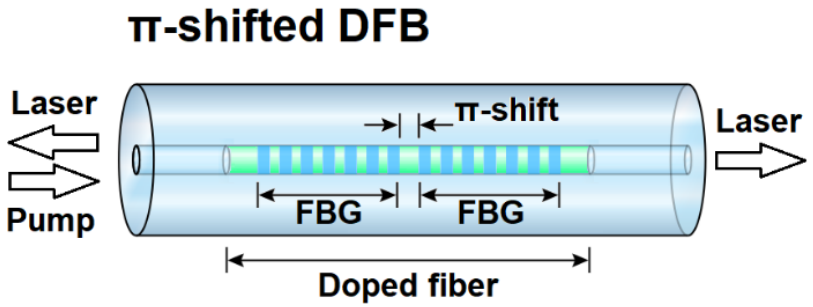
- Sensor is a *mechanical transducer* that converts pressure in strain in the fiber
- Design by FEM, use strain sensitivity requirement as input
- Material: Aluminum
- Size is related to the acoustic wavelength

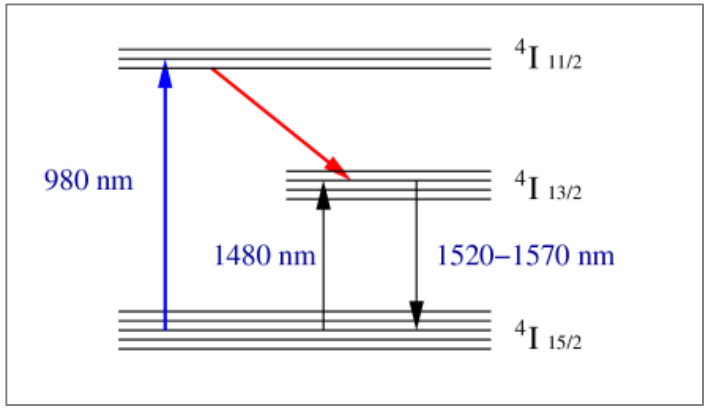
Transducers in various geometries

Fiber laser

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

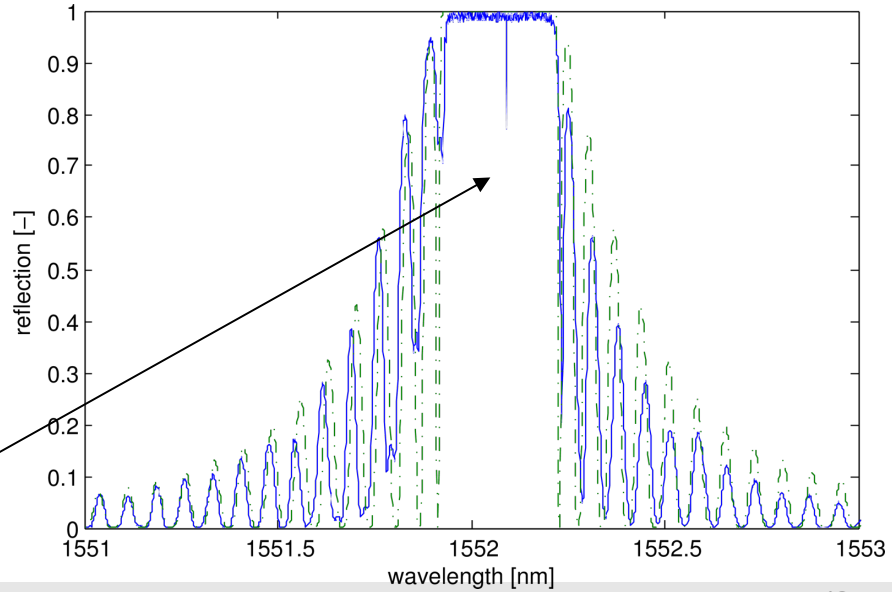


(DFB = distributed feedback laser)
(FBG = fiber Bragg grating)



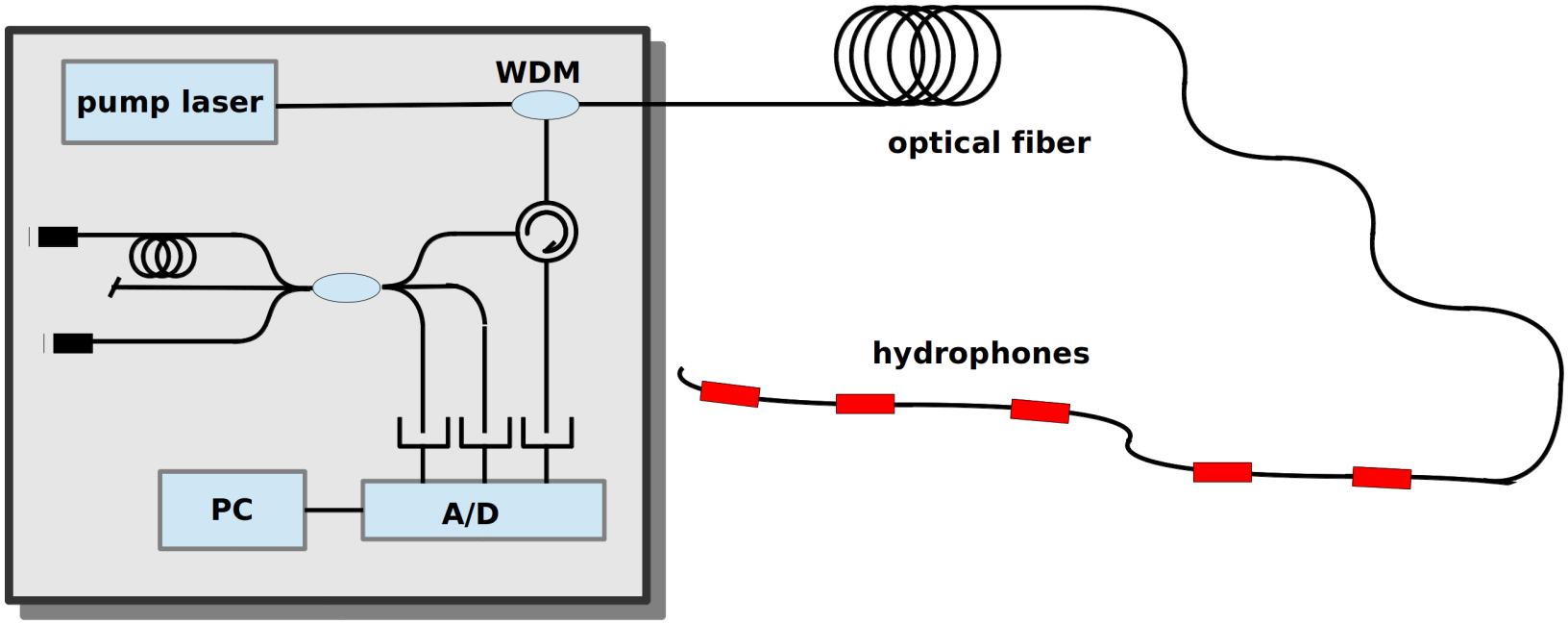
Er levels

Reflection spectrum of the gratings



Coherent light source:
line width ~ 5kHz.

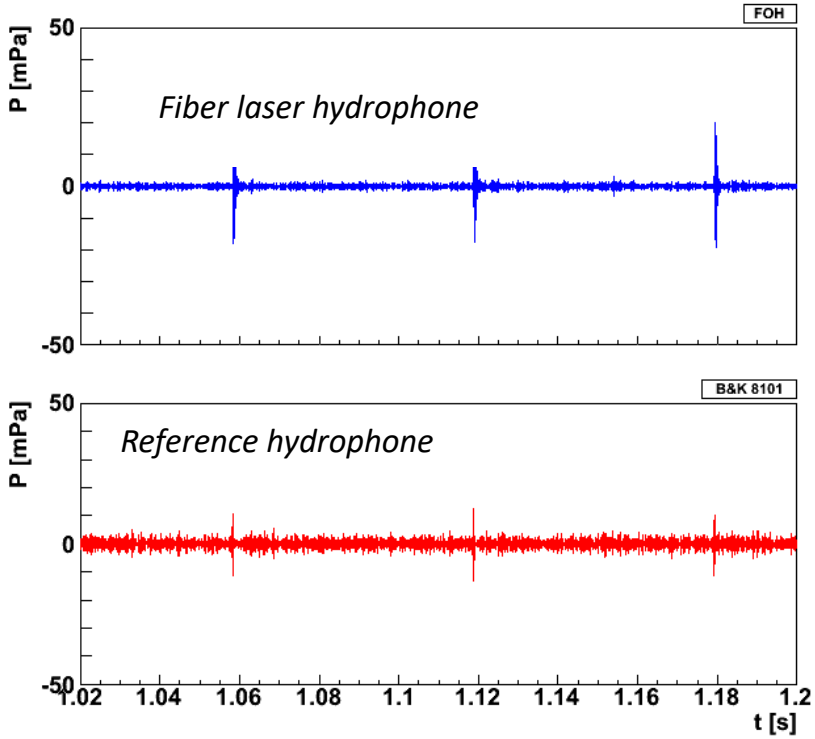
Interrogator

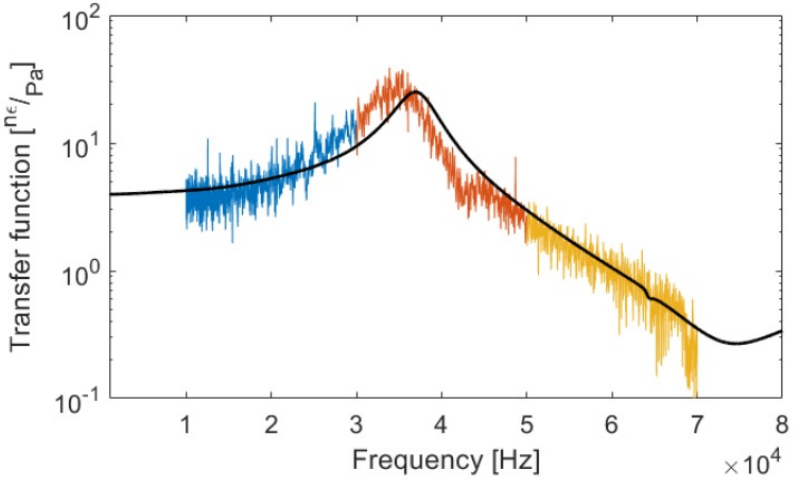


- **3x3 interferometer:** *coupler* with fixed phase difference in output branches.
- Standard commercial components

Characterization measurements

- Study of individual pulses.
- Compared fiber laser hydrophone with reference
- Results are just raw data, no signal processing applied.





Transfer function measurements versus design

Further Plans in KM3NeT

- Funding for one prototype string equipped with >3 hydrophones
- Working on a compact interrogator (i.e. an interferometer with 20m optical path difference, 3 photodiodes and 3 24-bits ADCs, all in one casing)
- Working on a new sensor for deployment to large depths

Summary

- Neutrinos are used as messenger particles in astroparticle physics to enhance our understanding of the Universe
- Acoustic signals in water (or ice) can be used to detect neutrinos at ultra high energies
- In the Mediterranean Sea, the ANTARES Neutrino Telescope has been taking data for more than 10 years and its acoustic neutrino detection test array AMADEUS operated from 2007 to 2015
- The KM3NeT Neutrino Telescope is under construction in the Mediterranean Sea
- It contain acoustic arrays (for position calibration) that can be used for marine science and acoustic neutrino detection
- Further options to expand KM3NeT

Bundesministerium für Bildung und Forschung

Thank you for your attention

Bundesministerium
für Bildung
und Forschung

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