Acoustic particle detection

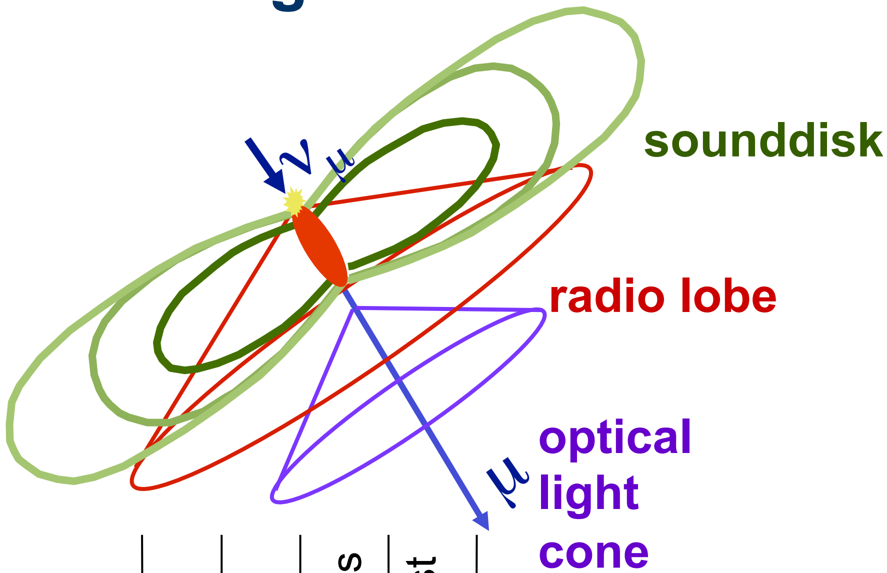
Robert Lahmann
HAP Workshop: The Non-Thermal Universe
Erlangen, 21-Sept-2016

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

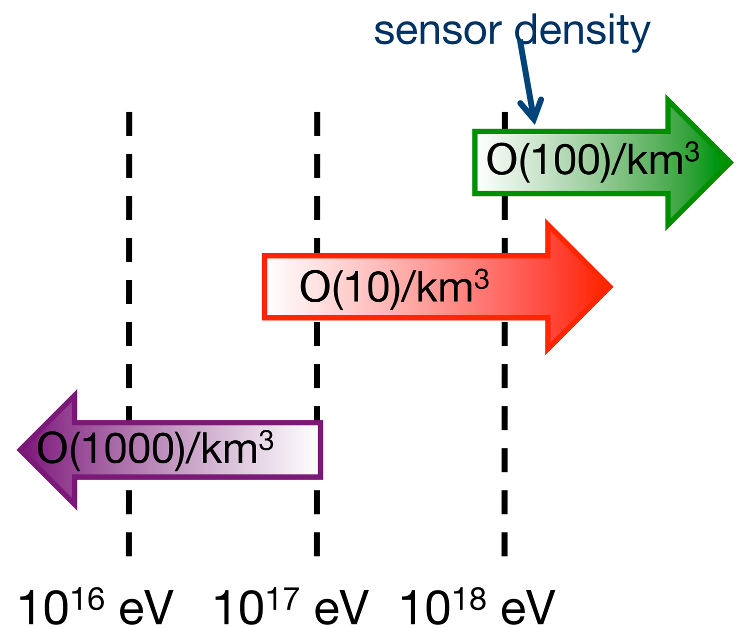
Outline

- Introduction: acoustic neutrino detection
- The “first generation” of acoustic neutrino test setups
- Lessons learned and future activities
- Conclusions

Neutrino signatures in different media



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



adapted from: R. Nahnhauer, ARENA Conf. 2010

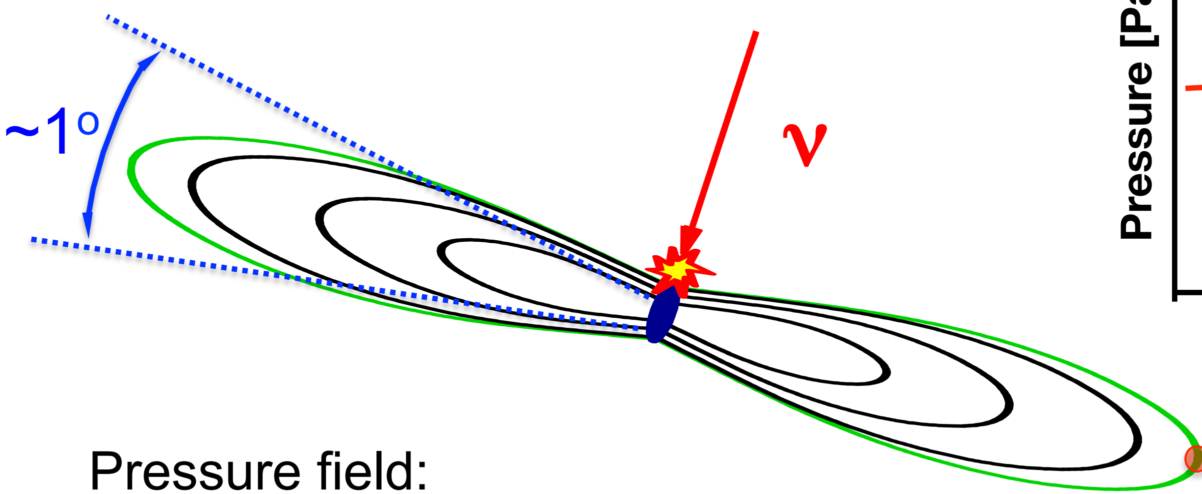
Advatages of acoustic detection:

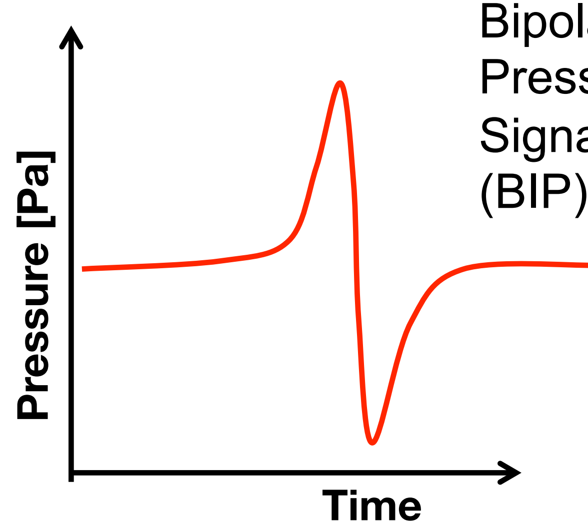
- long attenuation length
- simple, robust technology
- multi purpose applications

Acoustic signals of neutrino interactions

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

<u>Hadronic cascade:</u>
~10m length, few cm radius



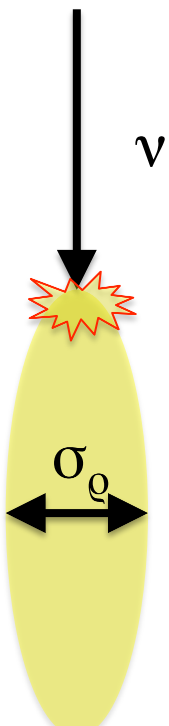


Bipolar
Pressure
Signal
(BIP)

<u>Pressure field:</u>
Characteristic "pancake" pattern

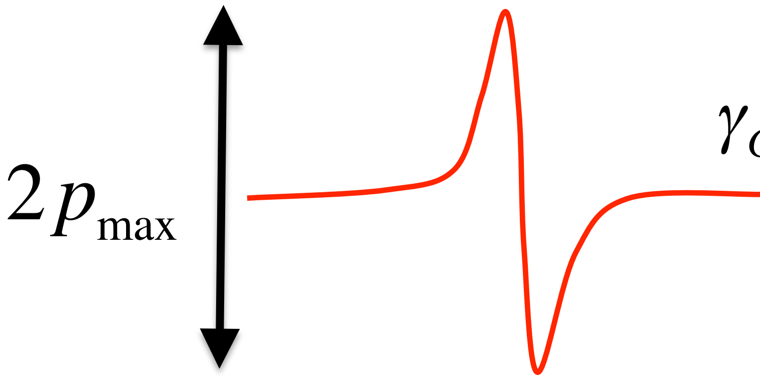
f_{max} = O(10kHz)

The bipolar pulse



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

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



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

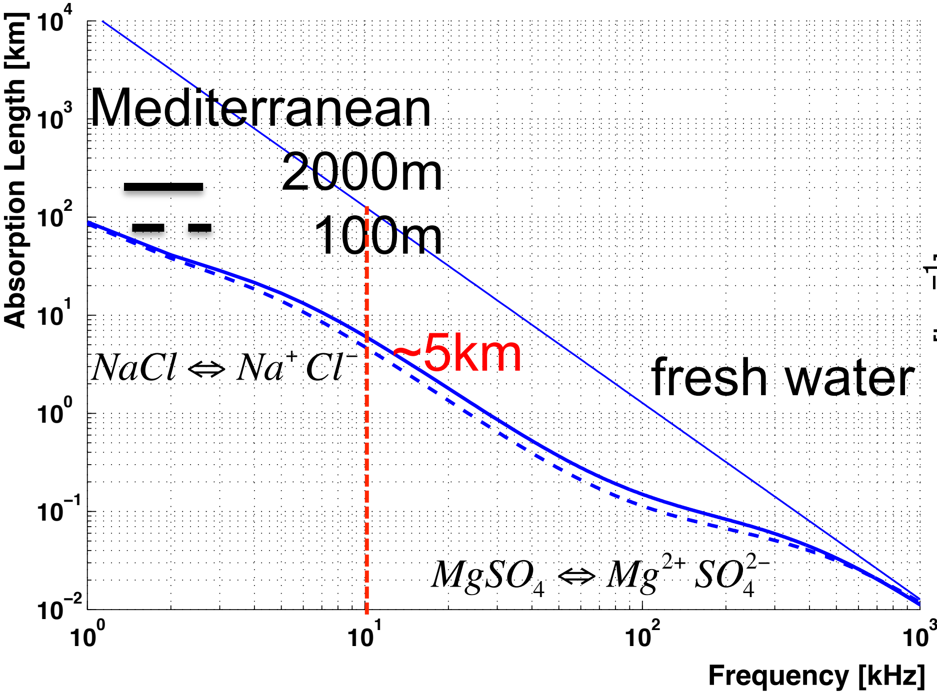
- ~1.12 cold ice
- ~0.15 Med.
- ~0.015 Baikal

$$E_0 = \int \varepsilon \, dV$$ (ε : energy density)

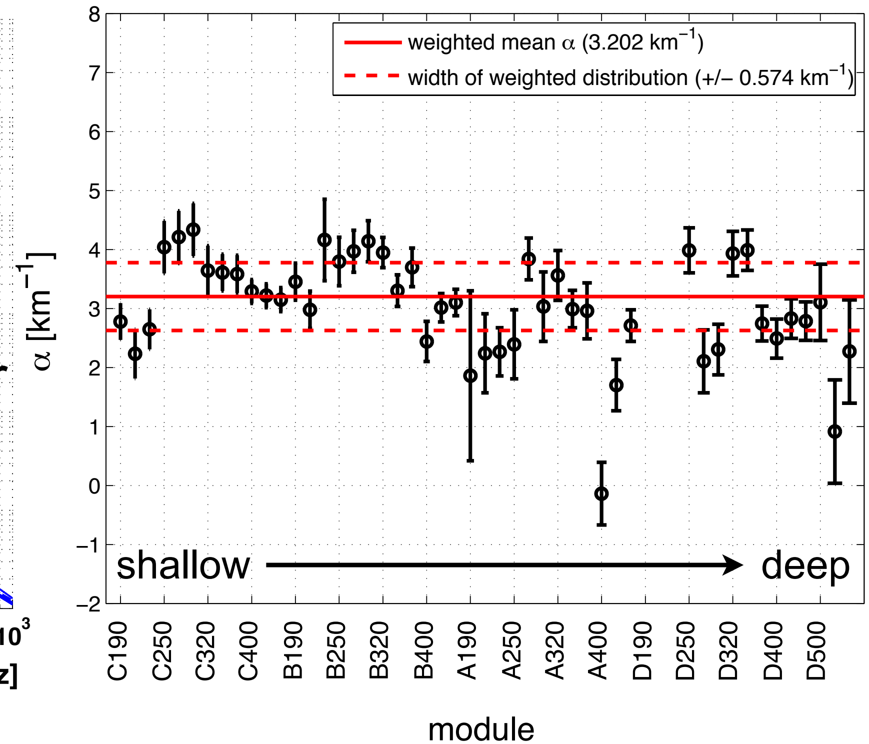
- α = Volume expansion coefficient
- C_P = specific heat capacity (at constant pressure)
- c = speed of sound (ca. 1500 m/s in water)

Attenuation length

water



IceCube site (SPATS)



(from: T. Karg, ARENA2012)

$$\lambda = 312^{+68}_{-47}\,m$$

shorter than expected, but no show stopper

Acoustic detection test setups

“First generation” acoustic test setups for feasibility studies (background), developing techniques/algorithms

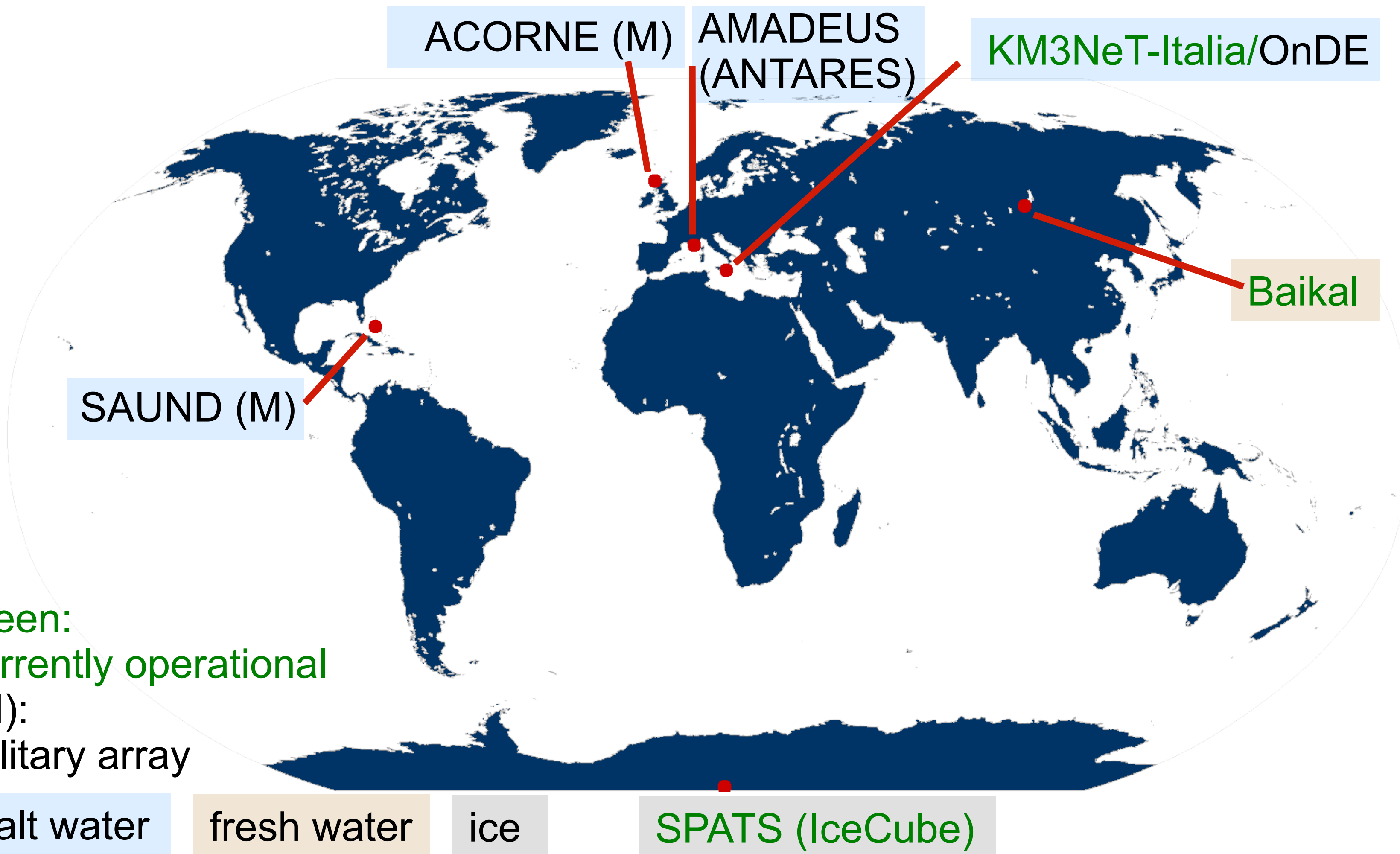
Two approaches:

- Use of existing (military) arrays
- piggybacking on neutrino telescope infrastructure

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

Array size:
O(10) sensors

Test setups in ice and water

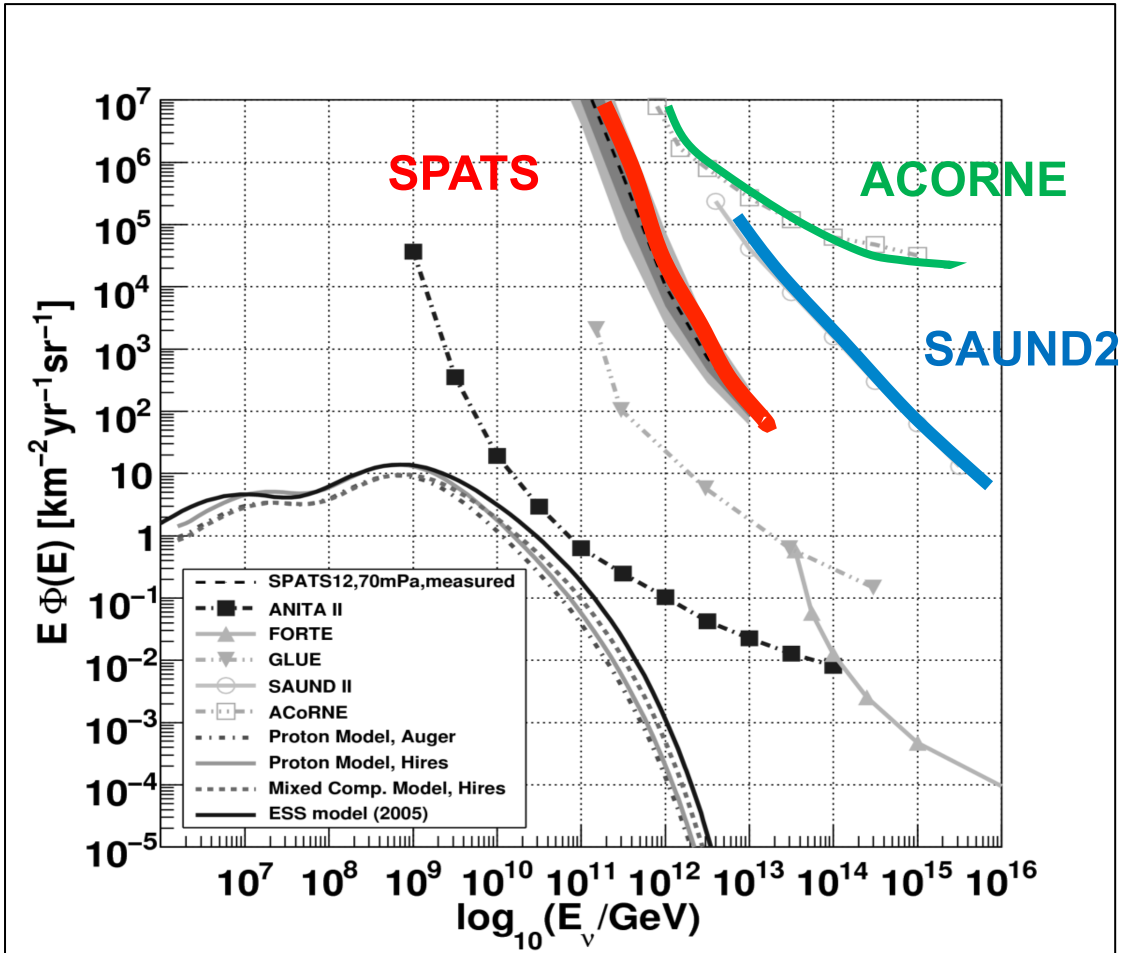


green: currently operational
(M): military array

salt water | fresh water | ice

Limits on UHE neutrino flux

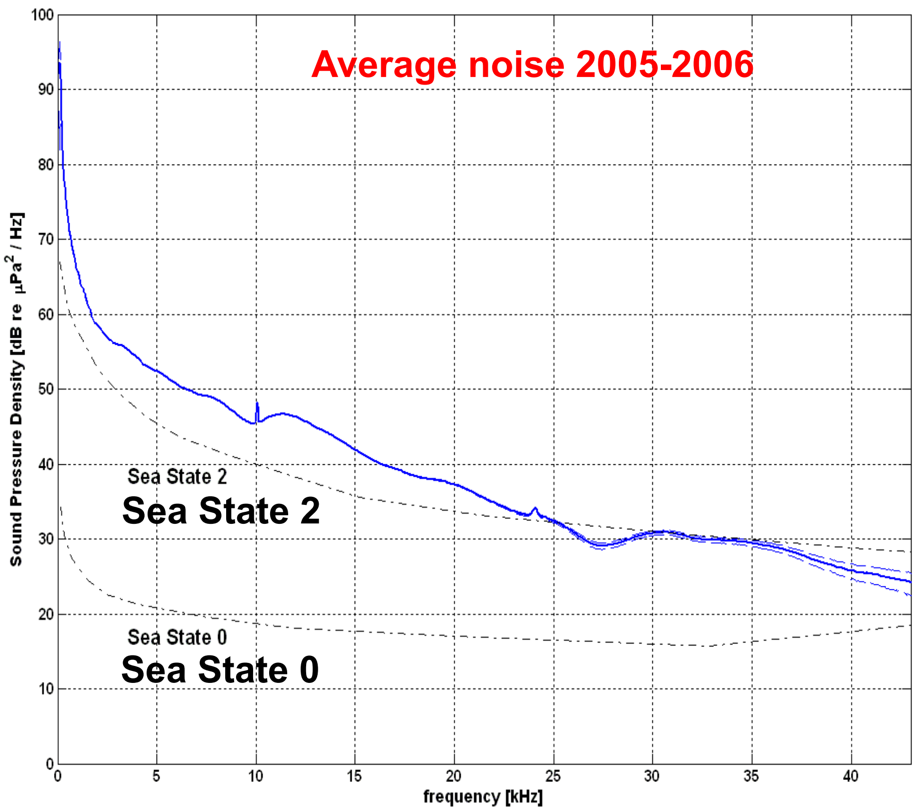
SPATS, ARENA 2012

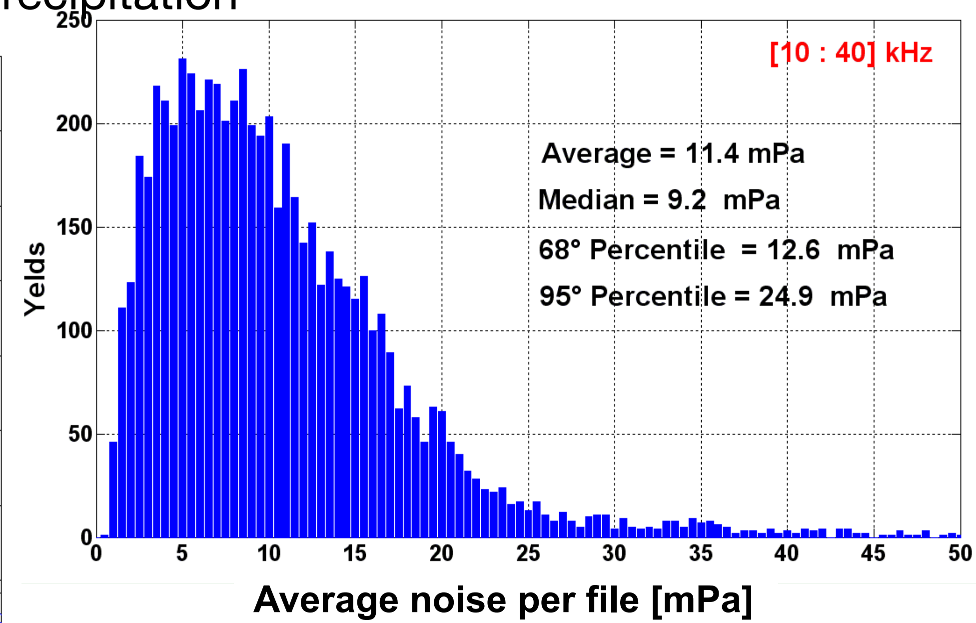


R. Abbasi et al.,arXiv:astro-ph/1103.1216

OnDE ambient noise (ARENA 2008)

Main source: Surface agitation and precipitation





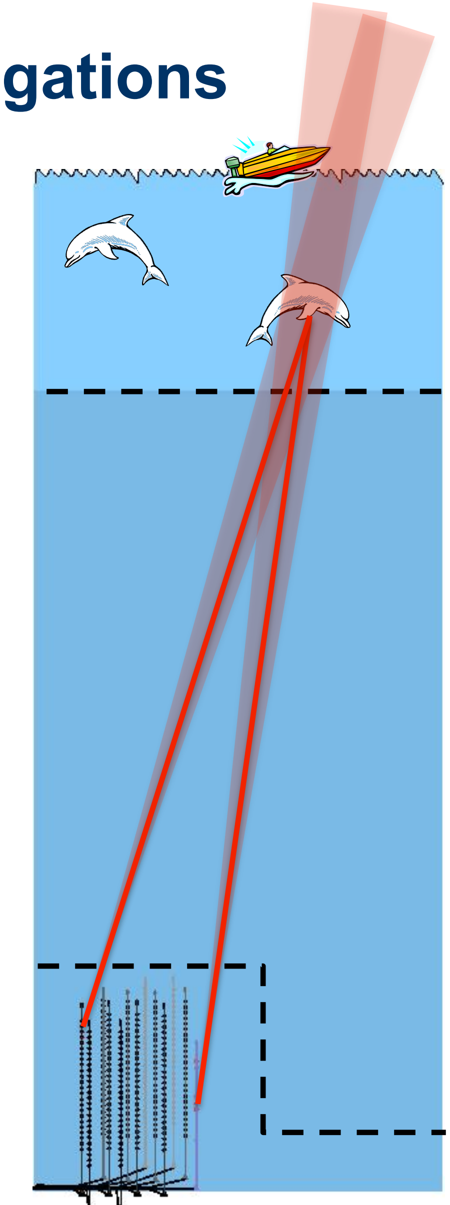
astro/ph 0804.2913

$$A_p(f_1, f_2) = \left[\int_{f_1}^{f_2} PSD\cdot(f)df\right]^{\frac{1}{2}}$$

The average noise in the [20:43] kHz band is $5.4 \pm 2.2_{stat} \pm 0.3_{syst}$ mPa

AMADEUS transient background investigations

- Sources: Very diverse;
  Shipping traffic, marine mammals, …
  ⇨ Mostly originating from near surface
- Suppression:
  - signal classification
  - Project reconstructed signals to surface, perform clustering



Lessons learned and future experiments

Mediterranean (➔ KM3NeT):

- Ambient noise low and stable;
  reduction of SNR for signal detection crucial
- Transient background:
  High level of (mainly dolphins);
  Recognition of “acoustic pancake” crucial

Lake Baikal (➔ GVD):

- Good background conditions, easy deployment, but low signal amplitude due to low temperature in lake

Ice (➔ IceCube-Gen2 ?):

- Attenuation length shorter than expected, but no show stopper;
  combination optical/radio/acoustic provides unique potential

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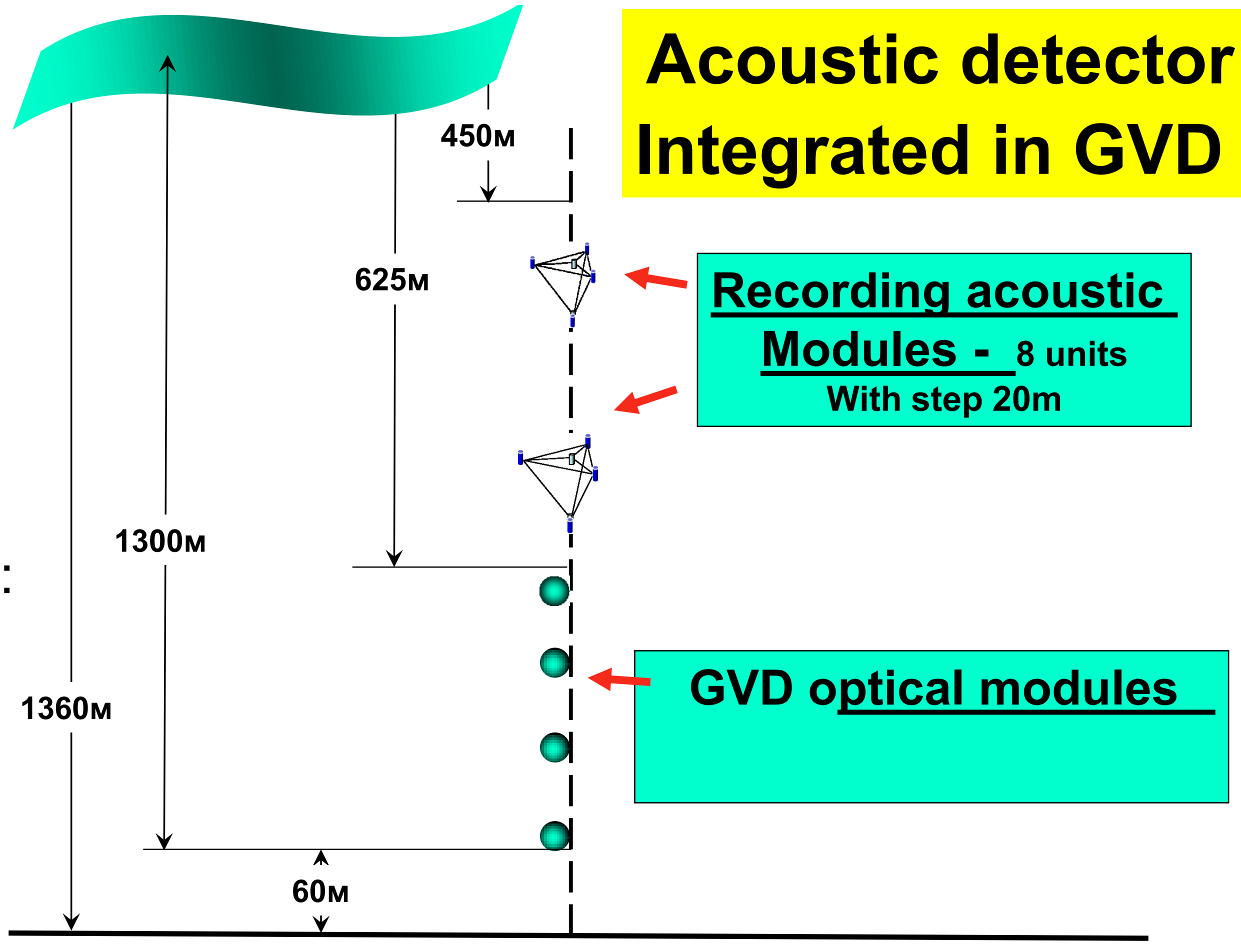
Lake Baikal

GVD:
Gigaton Volume Detector;
Planned for 2020

Main problem for acoustic detection: low temperature



(from: N.Budnev, ARENA2016)

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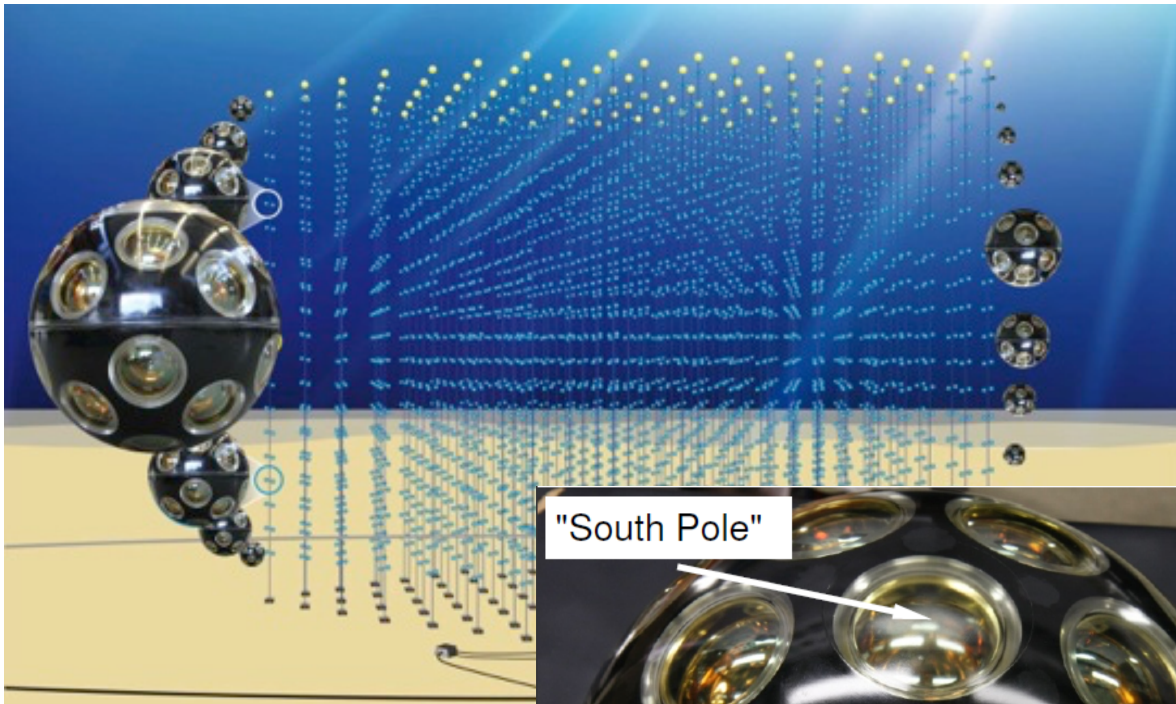
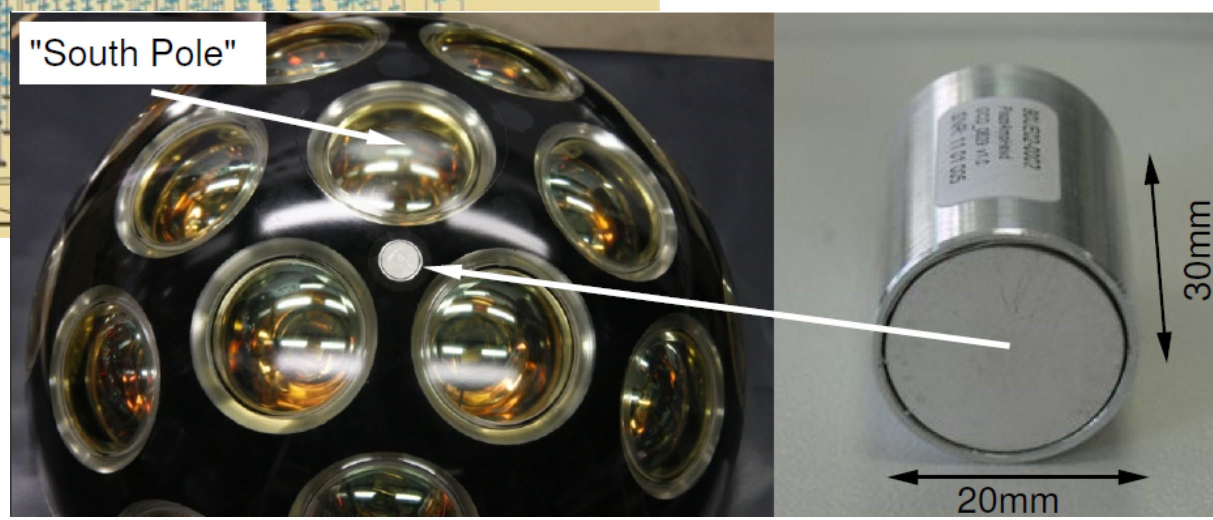
KM3NeT design

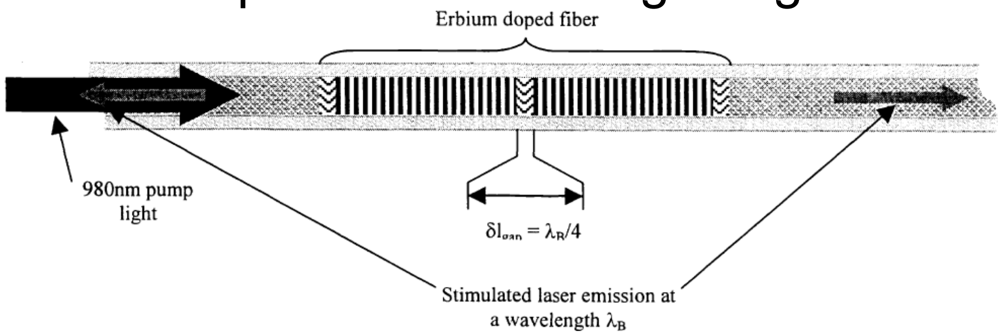


piezo sensor integrated into OM



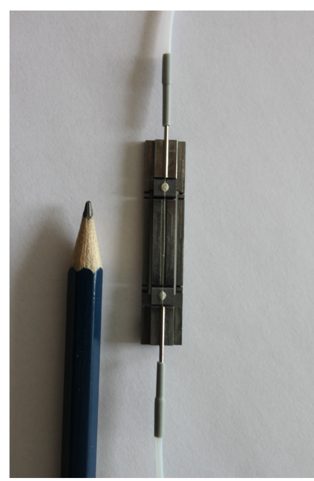
Potential fiber hydrophone system for KM3NeT

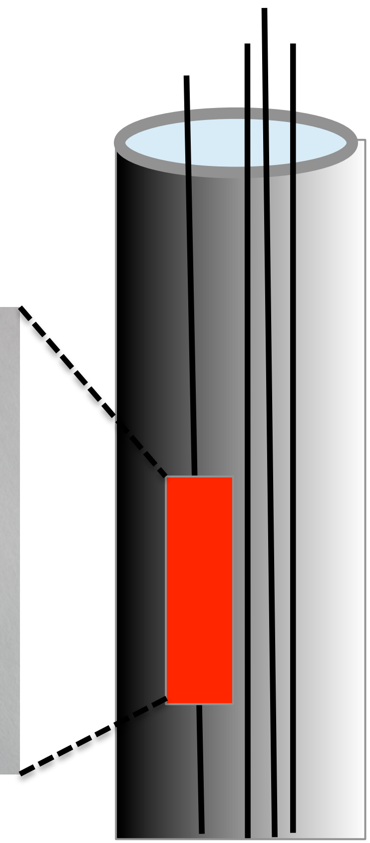
- Erbium doped fibers with a grating



- Sensor
  - Convert pressure pulse to a mechanical deformation of the fiber: <u>strain</u>
- Interrogator
  - on-shore system

TNO (Dutch organization for applied scientific research) joined KM3NeT to pursue this technique





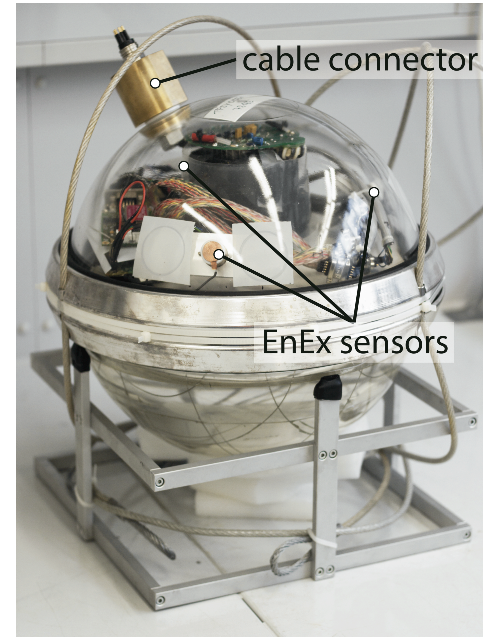
oil filled hose or solid cable

Acoustic Sensors for IceCube-Gen2

- IceCube-Gen2 is a planned extension of IceCube Neutrino Observatory
- Increased detector volume (~ 10 km^3) in the Antarctic ice
  - Increased spacing between detector modules (~ 240 m – 300 m)
  - → Optical geometry calibration (accuracy < 1m) is expected to deteriorate

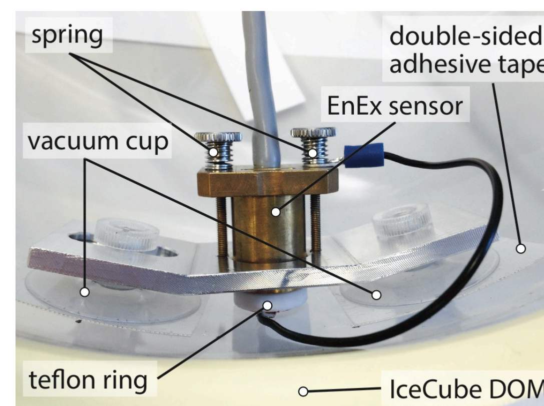
→ Use acoustic signals, due to larger extinction length (~ 300m [SPATS]) for geometry calibration

- Develop acoustic positioning concept for IceCube-Gen2
- Use sensors for acoustic neutrino detection



Up to now: (master's thesis S. Wickmann)

- Modified existing acoustic sensor from the EnEx project
  - Two channels: Channel 1 for positioning, channel 2 for neutrino detection
  - Substantially reduced power consumption
- Integrated modified sensor into an IceCube DOM
- Tested the acoustic positioning concept in water



[SPATS] : R. Abbasi, et al., Astropart. Phys. 34, 382–393 (2011).

Conclusions

- "First generation" acoustic arrays have been used to investigate neutrino detection methods and provide input for simulations
- Extension of investigations possible with KM3NeT, GVD and IceCube-Gen2

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Thank you for your attention!

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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 :

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

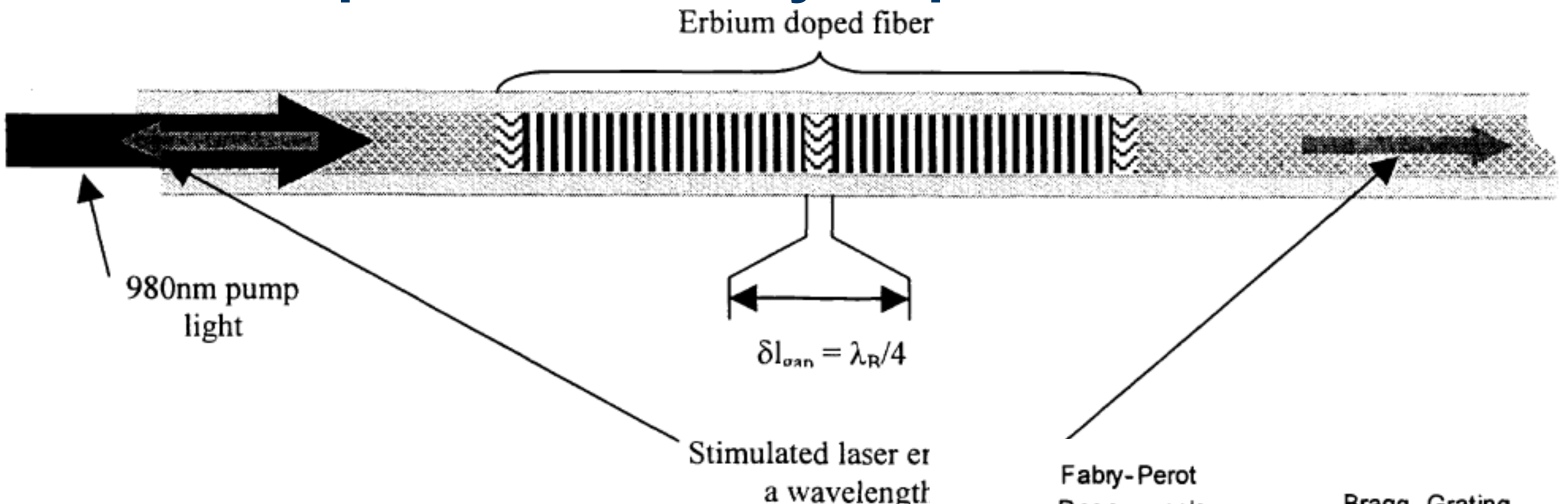
α = Volume expansion coefficient

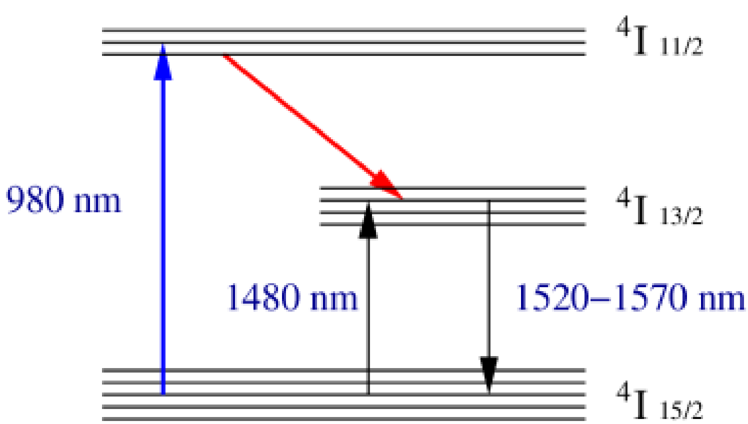
C_P = specific heat capacity (at constant pressure)

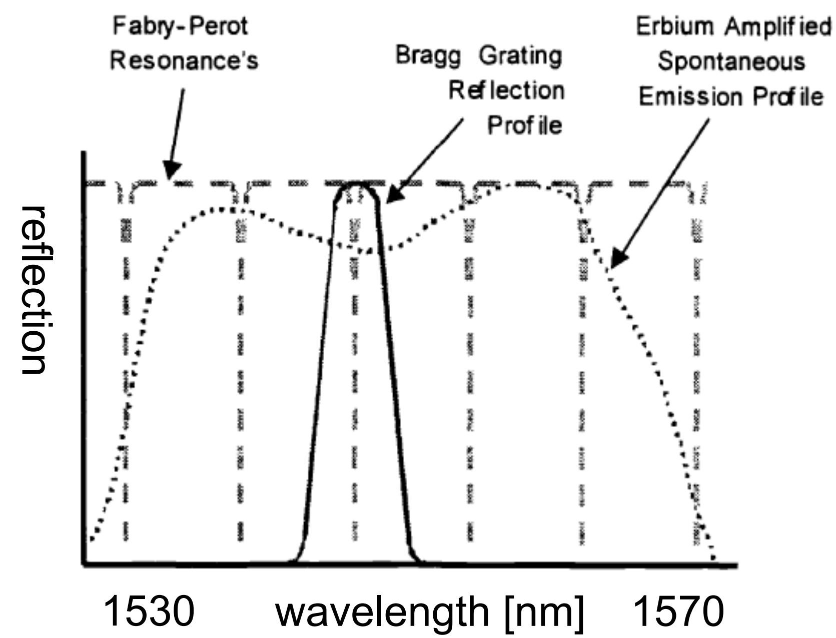
c = speed of sound in water (ca. 1500 m/s)

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

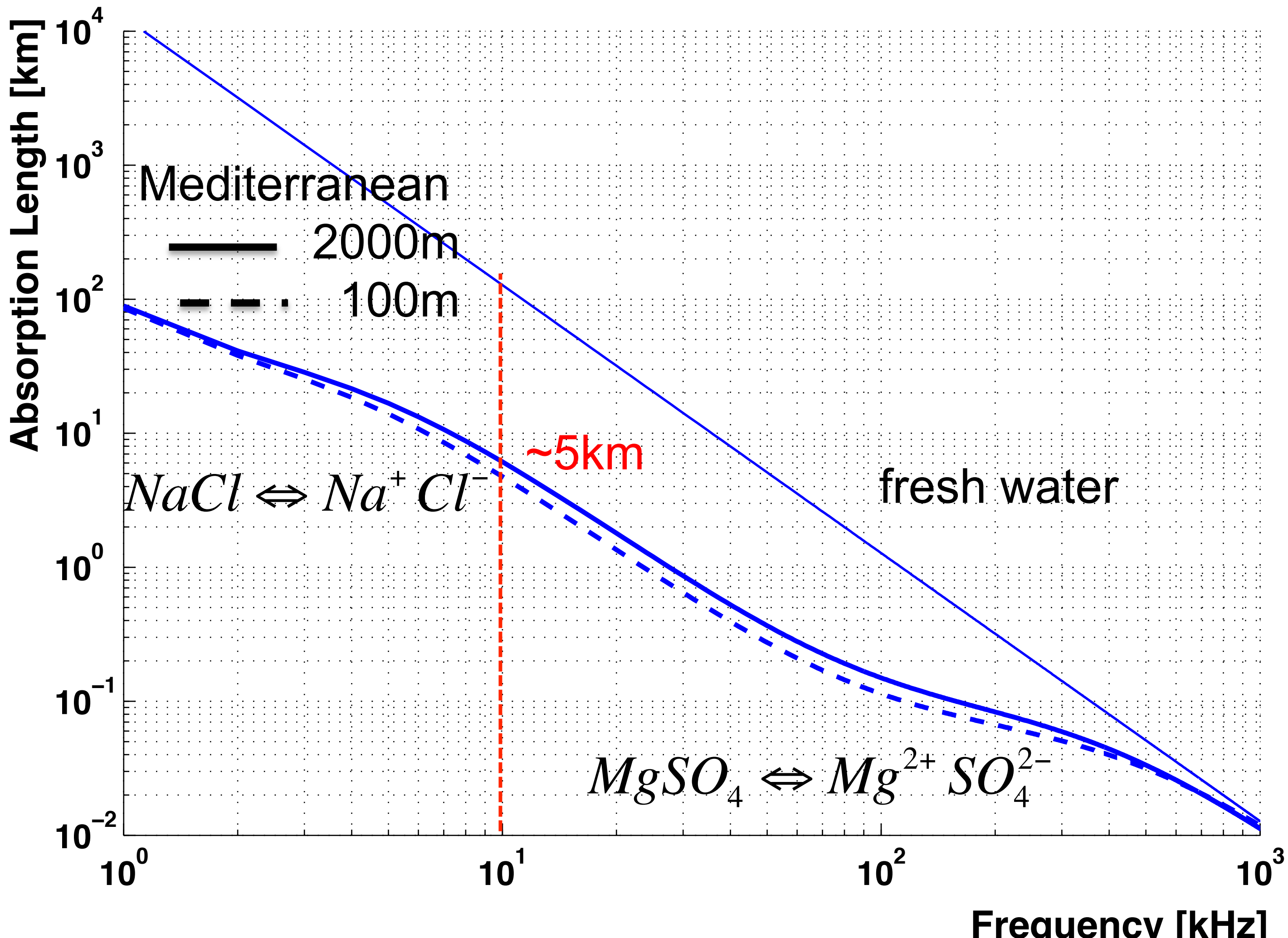
Erbium doped fibers as hydrophones for KM3NeT?







Sound absorption length in water



Acoustic signals of neutrino interactions in water I

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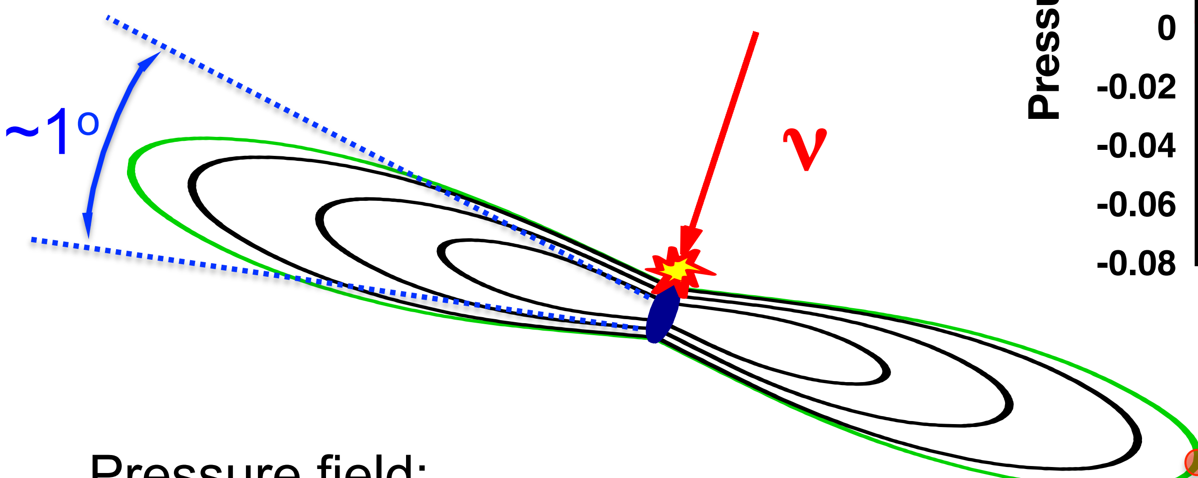
C_P = specific heat capacity (at constant pressure)

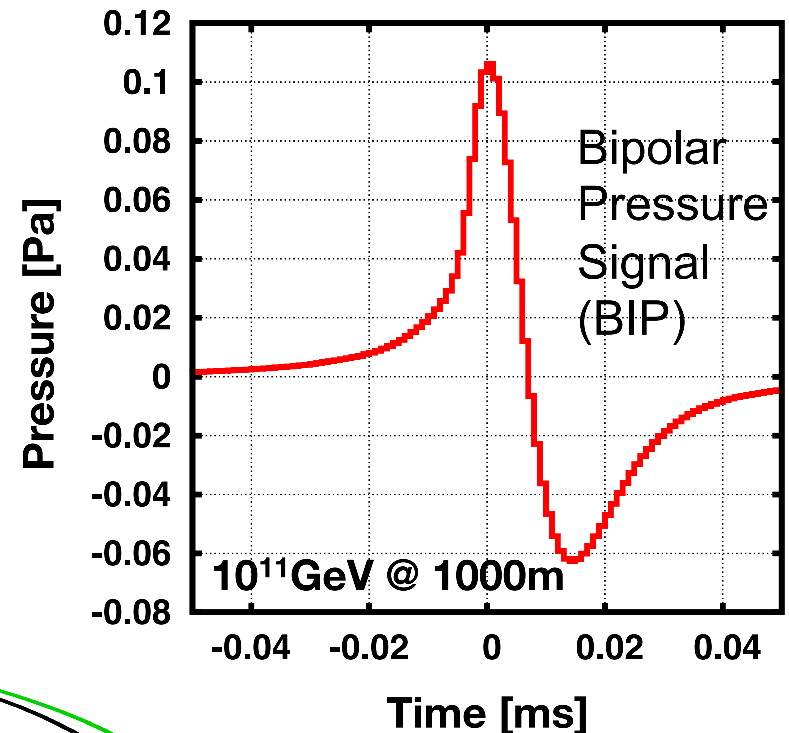
c = speed of sound in water (ca. 1500 m/s)

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

Acoustic signals of neutrino interactions in water II

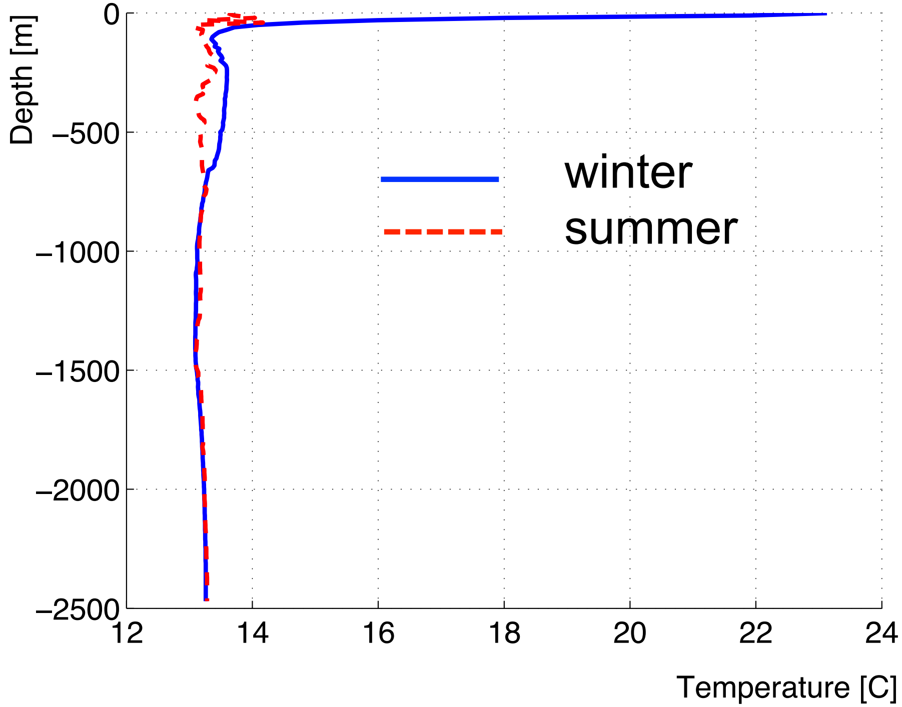
Hadronic cascade:
~10m length, few cm radius
(simulations by ACoRNE Coll.)



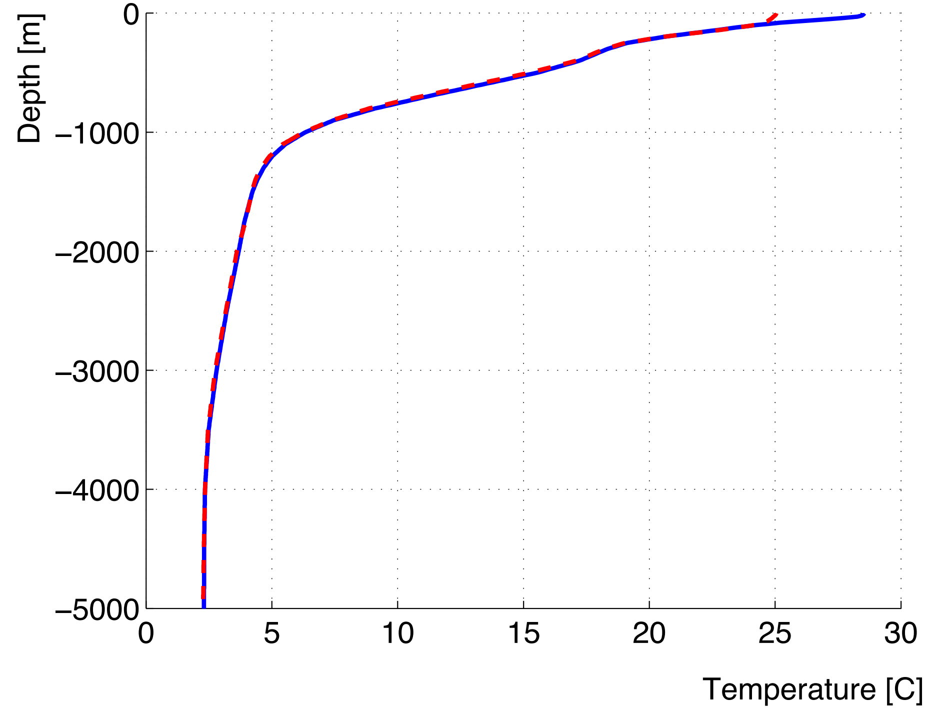


Pressure field:
Characteristic "pancake" pattern
Long attenuation length (~5 km @ 10 kHz)

Temperature profile

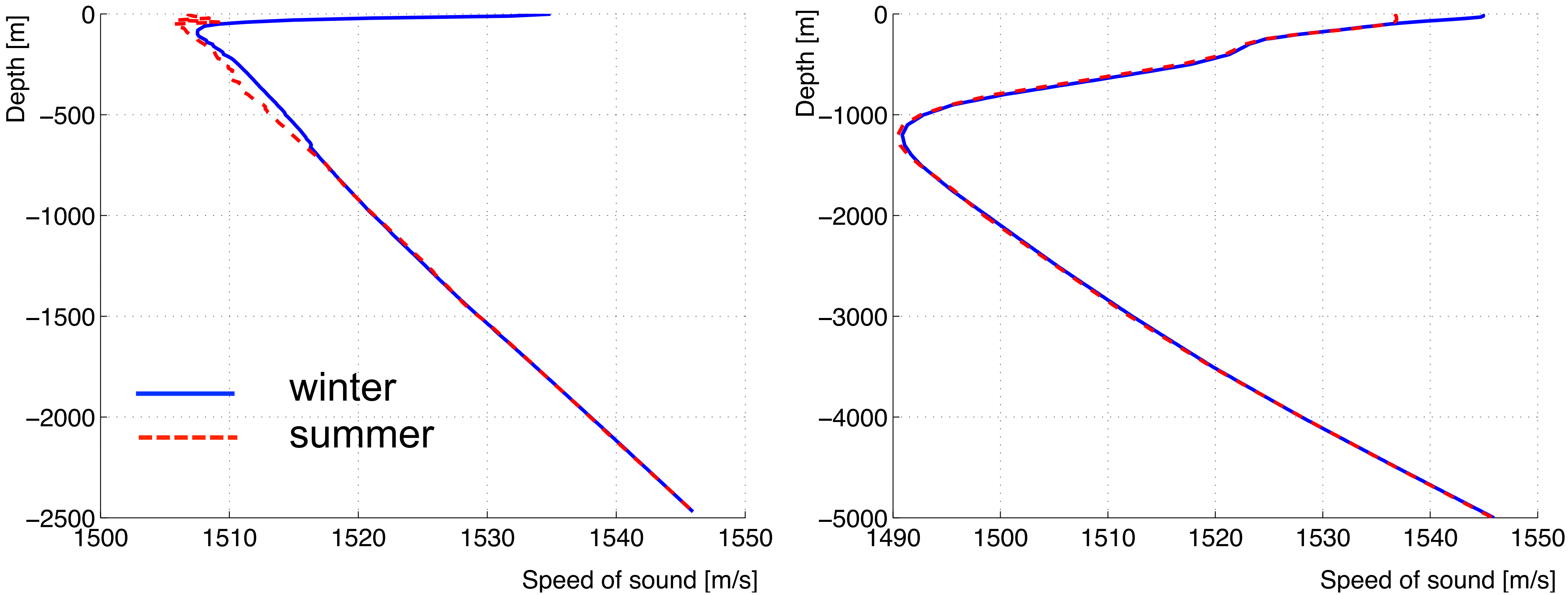


Mediterranean Sea



Tropical Ocean
24°30'N and 72°30'W

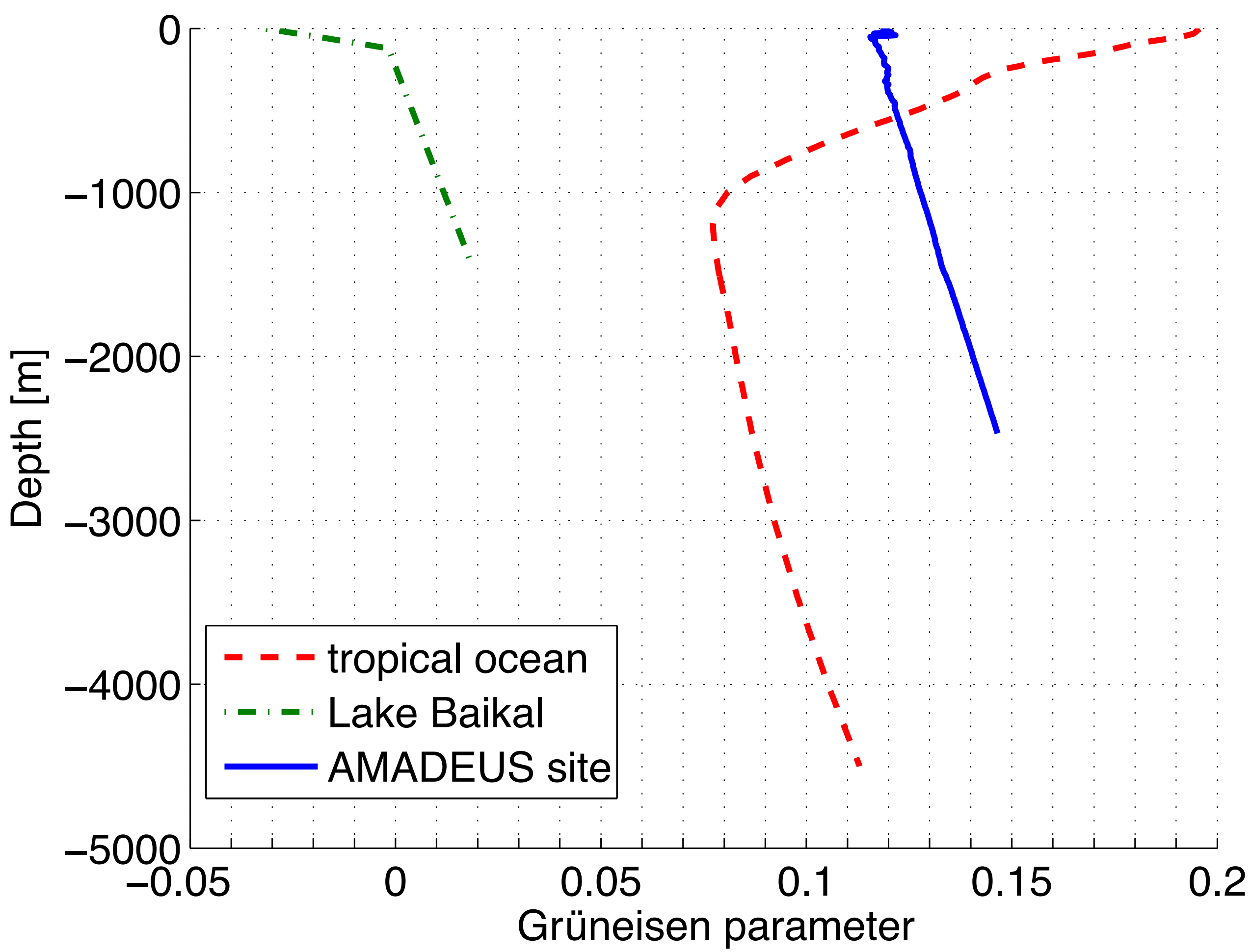
Speed of sound vs. depth



Mediterranean Sea

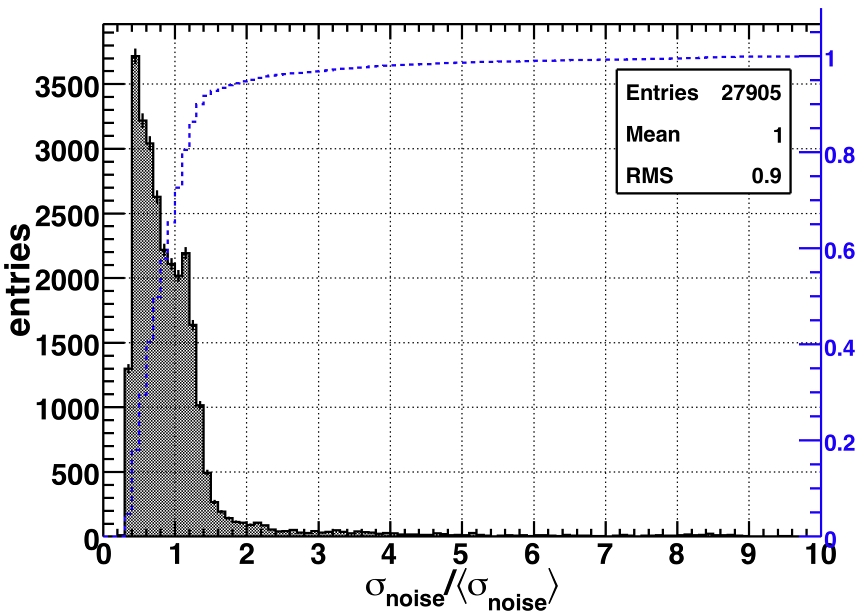
Tropical Ocean
24°30'N and 72°30'W

Grüneisen parameter



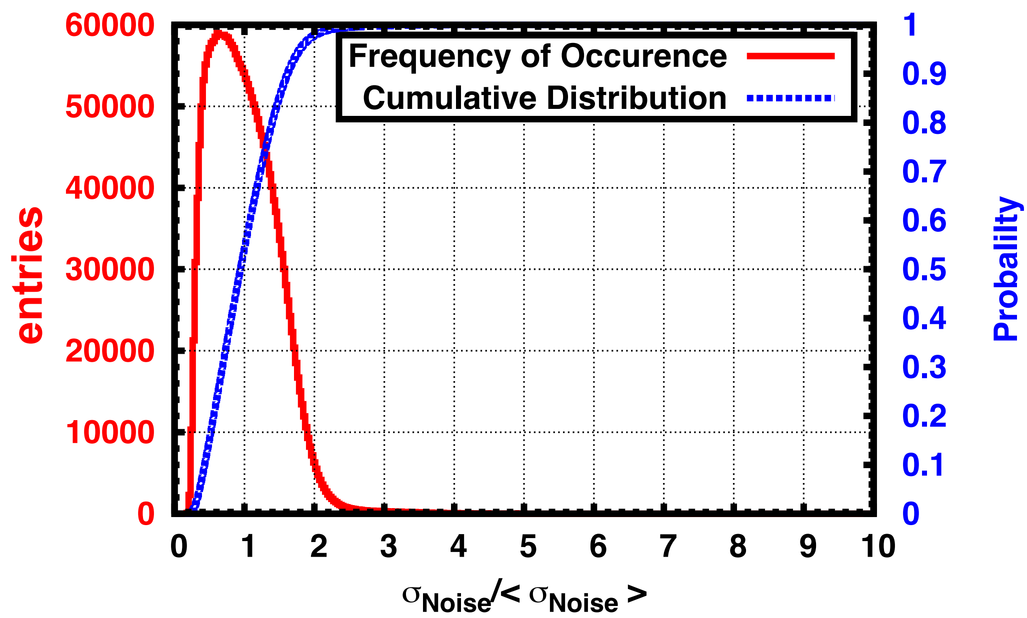
AMADEUS ambient noise

Measurement



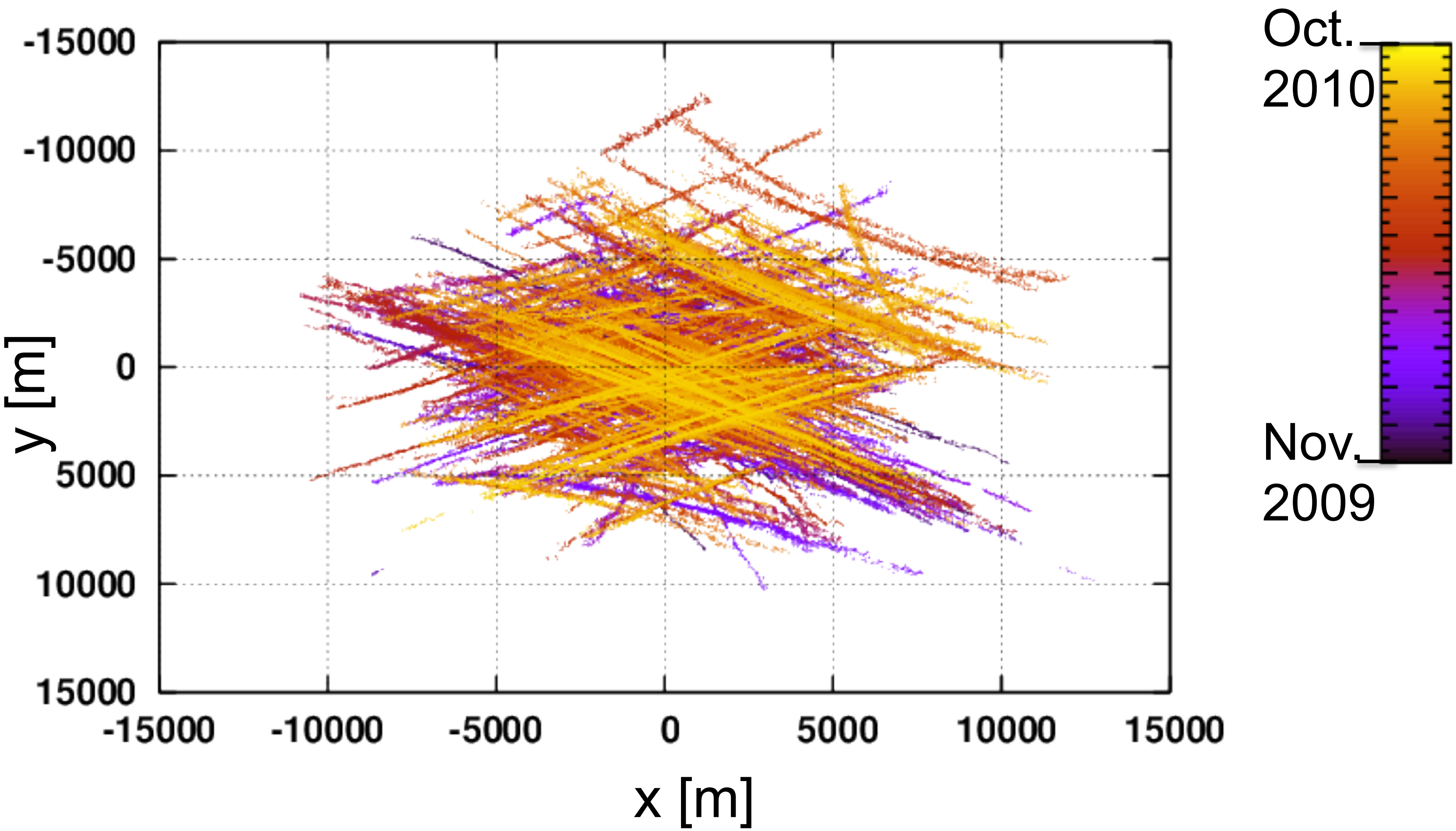
Data of 2008-2010

Simulation

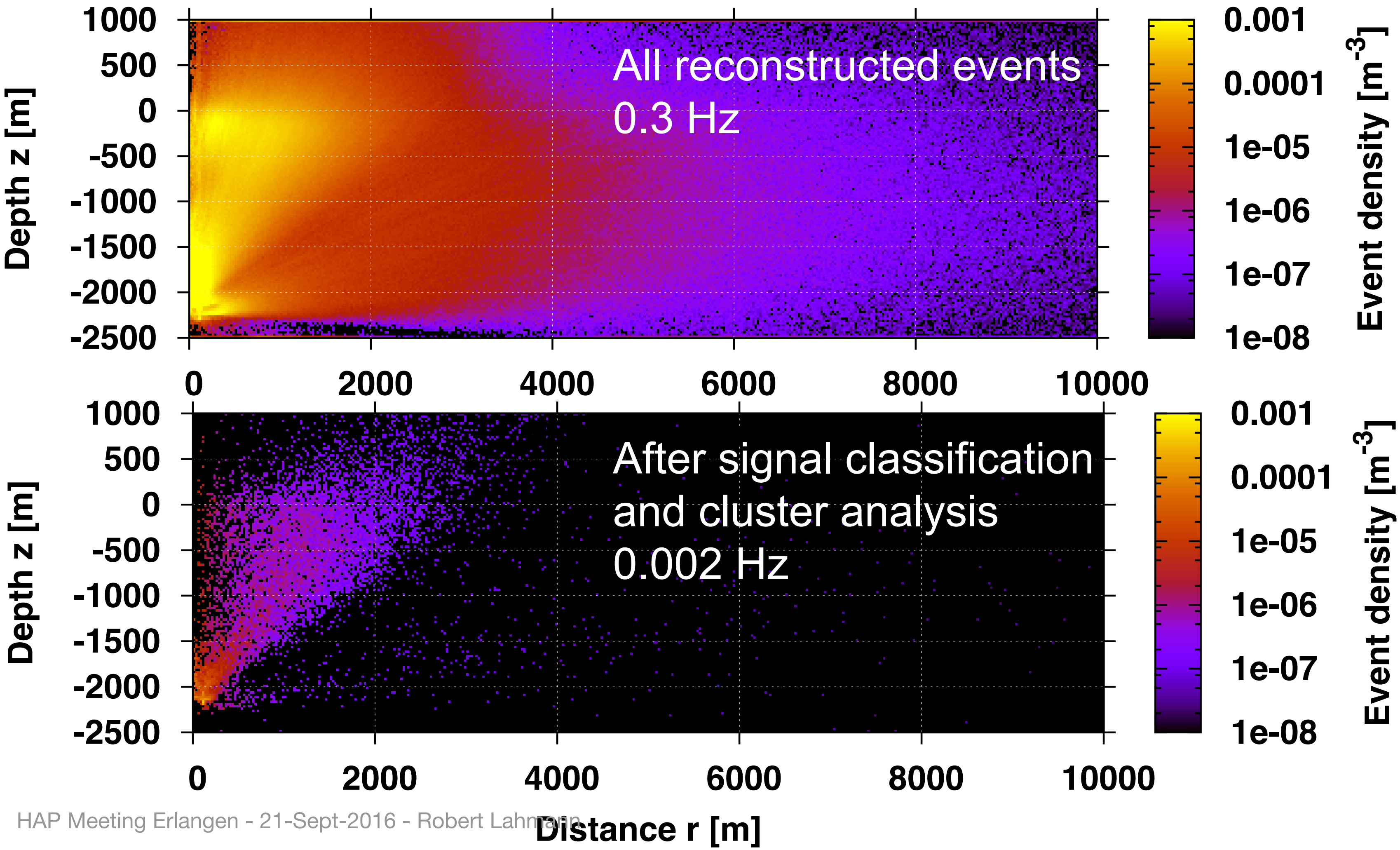


<σ_{noise}> is about 10 mPa (10-50 kHz) and 95% of the time below 2<σ_{noise}>

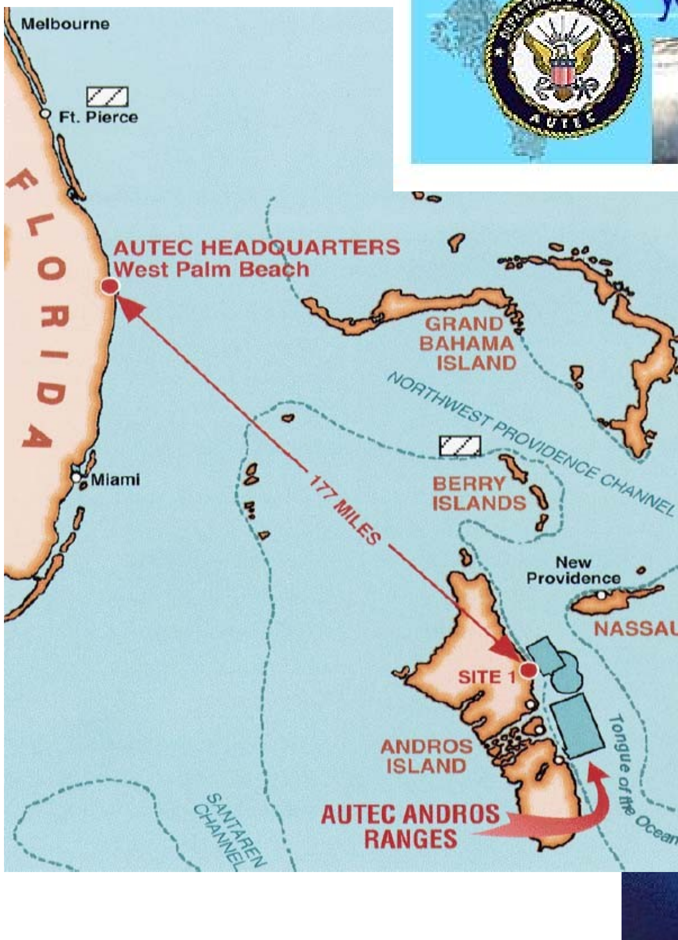
Cluster analysis of moving sound emitting objects

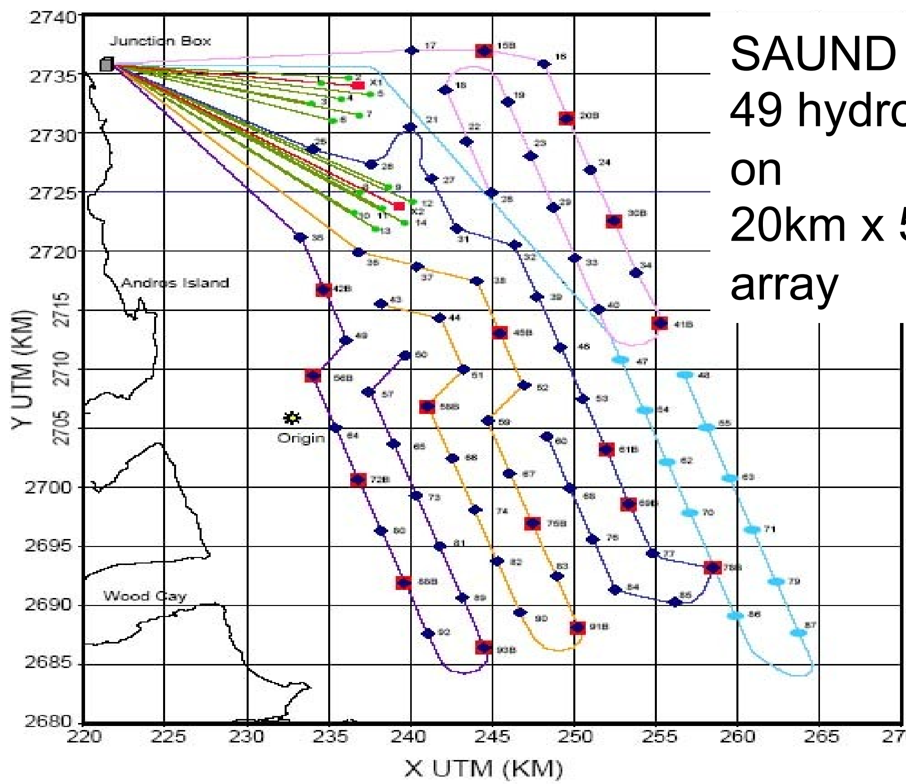


Spatial distribution of transient background



SAUND and AUTEC

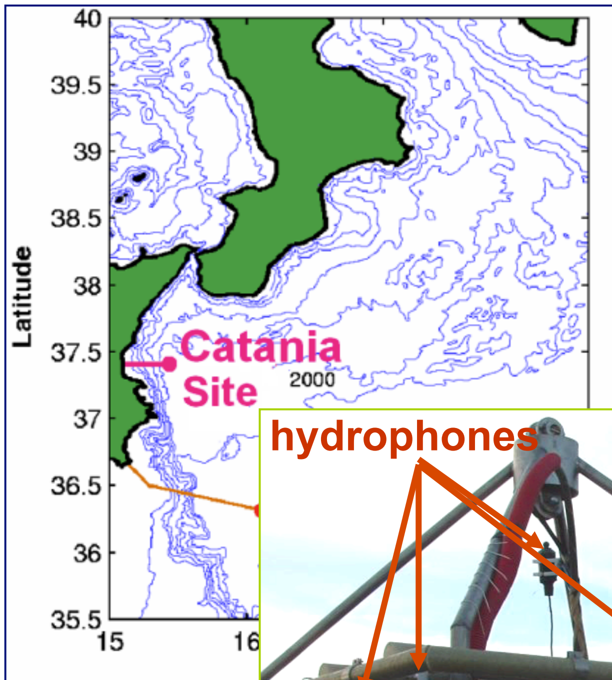


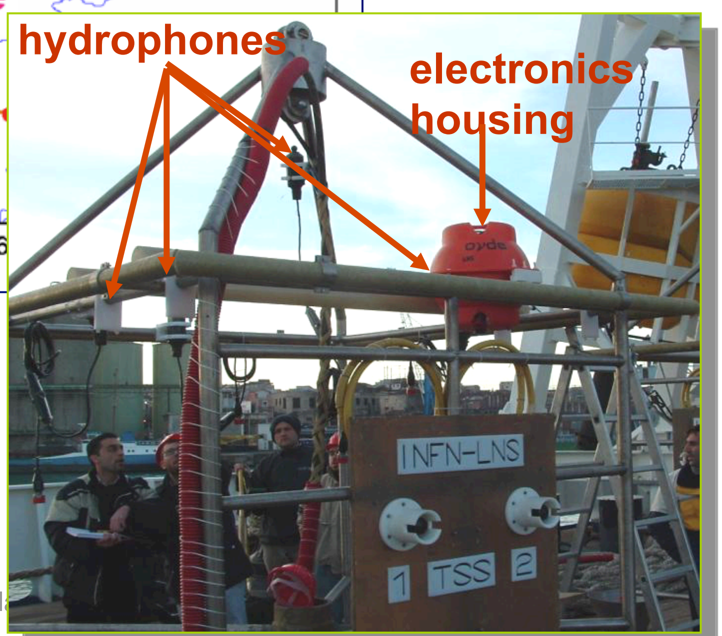


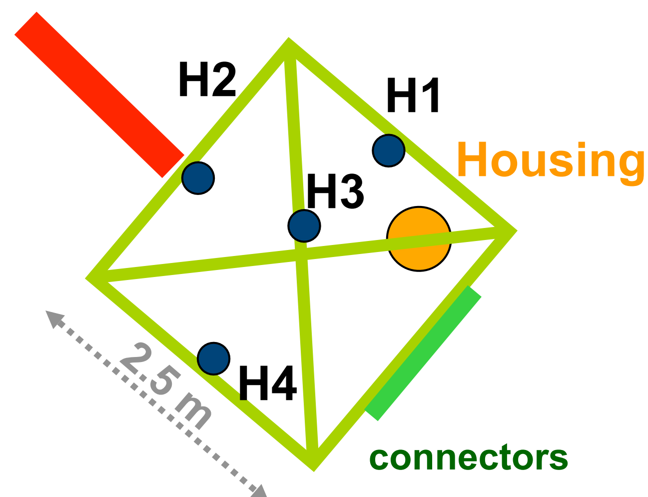
SAUND II :
49 hydrophones
on
20km x 50km
array

OnDE and KM3NeT-Italia

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







Height from seabed :

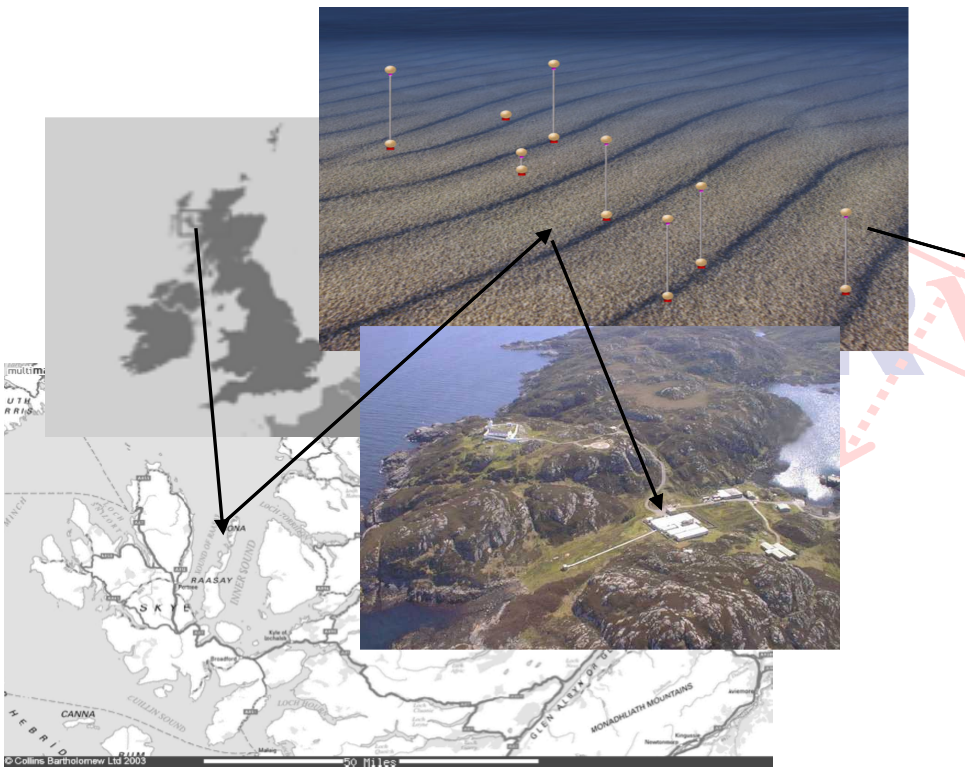
H1, H2, H4: ~ 2.6 m H3: ~ 3.2 m

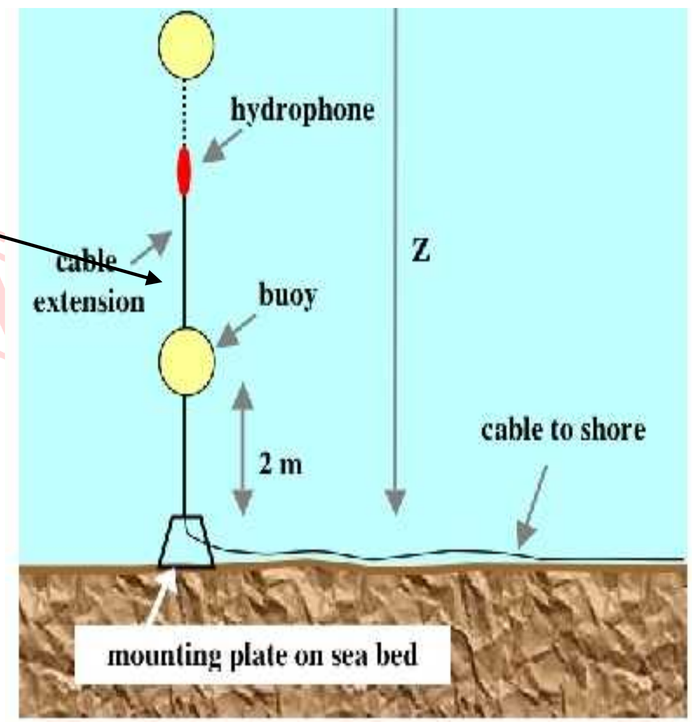
KM3Net-Italia activities covered by F. Simeone

The Rona Array (ACoRNE Collaboration)

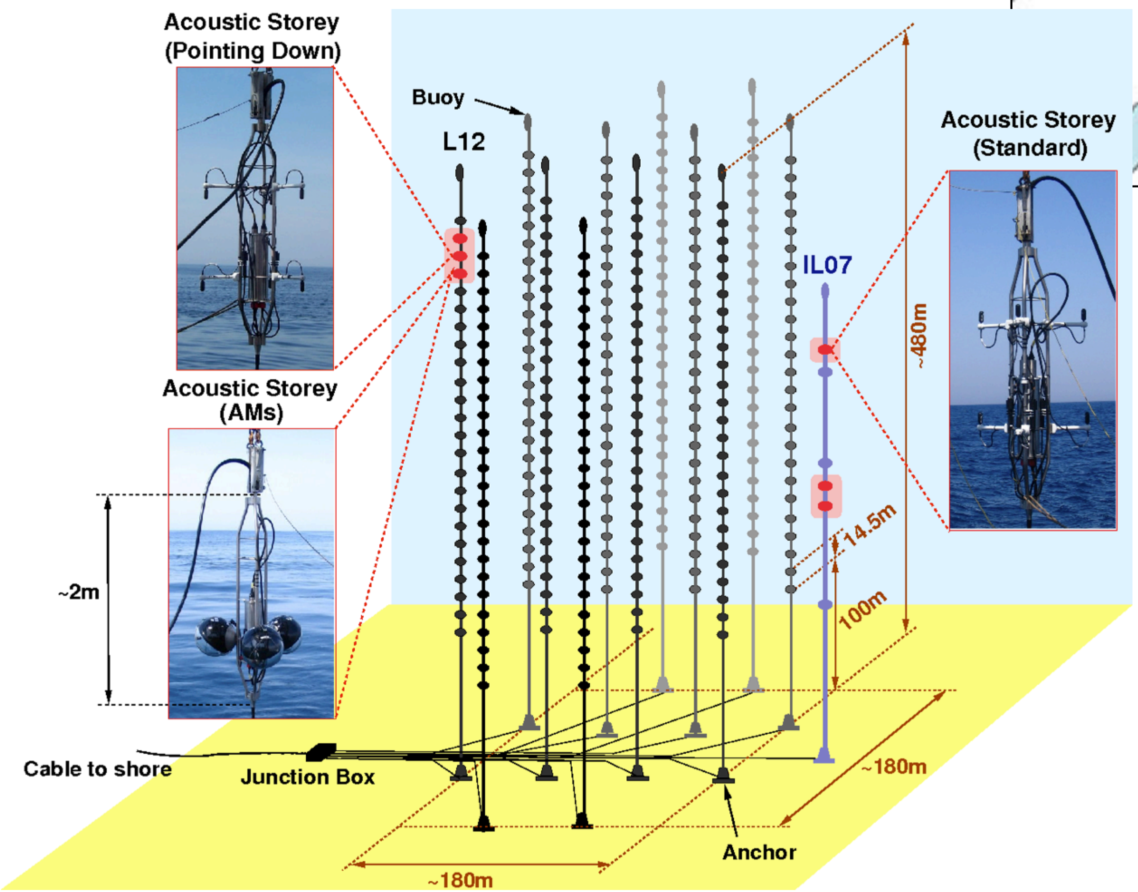
Off the Isle of Skye, 8 sensors

total cable length =
2m + cable extension + cable to shore





AMADEUS – ANTARES



Operational 2007-15

36 acoustic sensors on 6 stories

Local clusters for direction reconstruction

Depth 2300 – 2100 m

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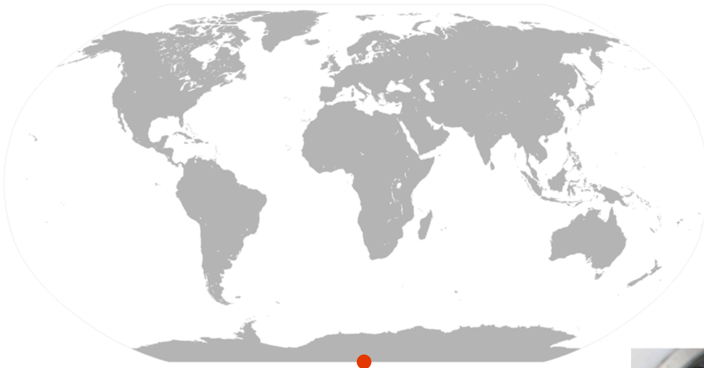
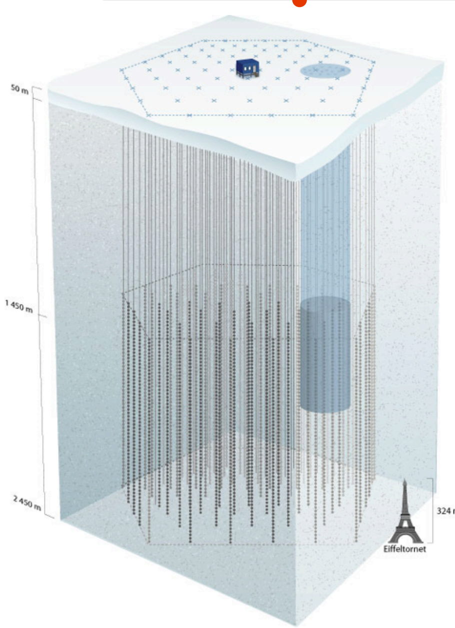
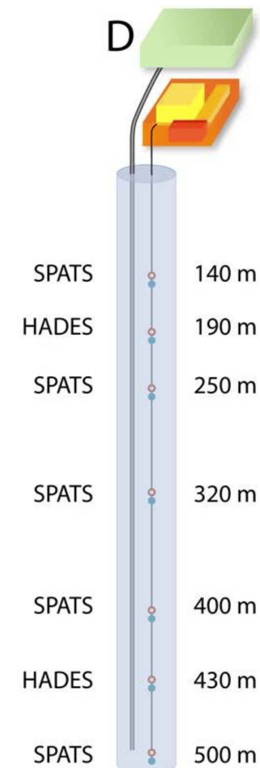
SPATS – IceCube

- 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

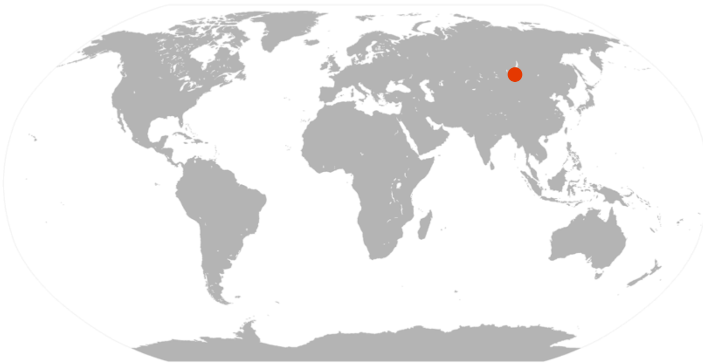


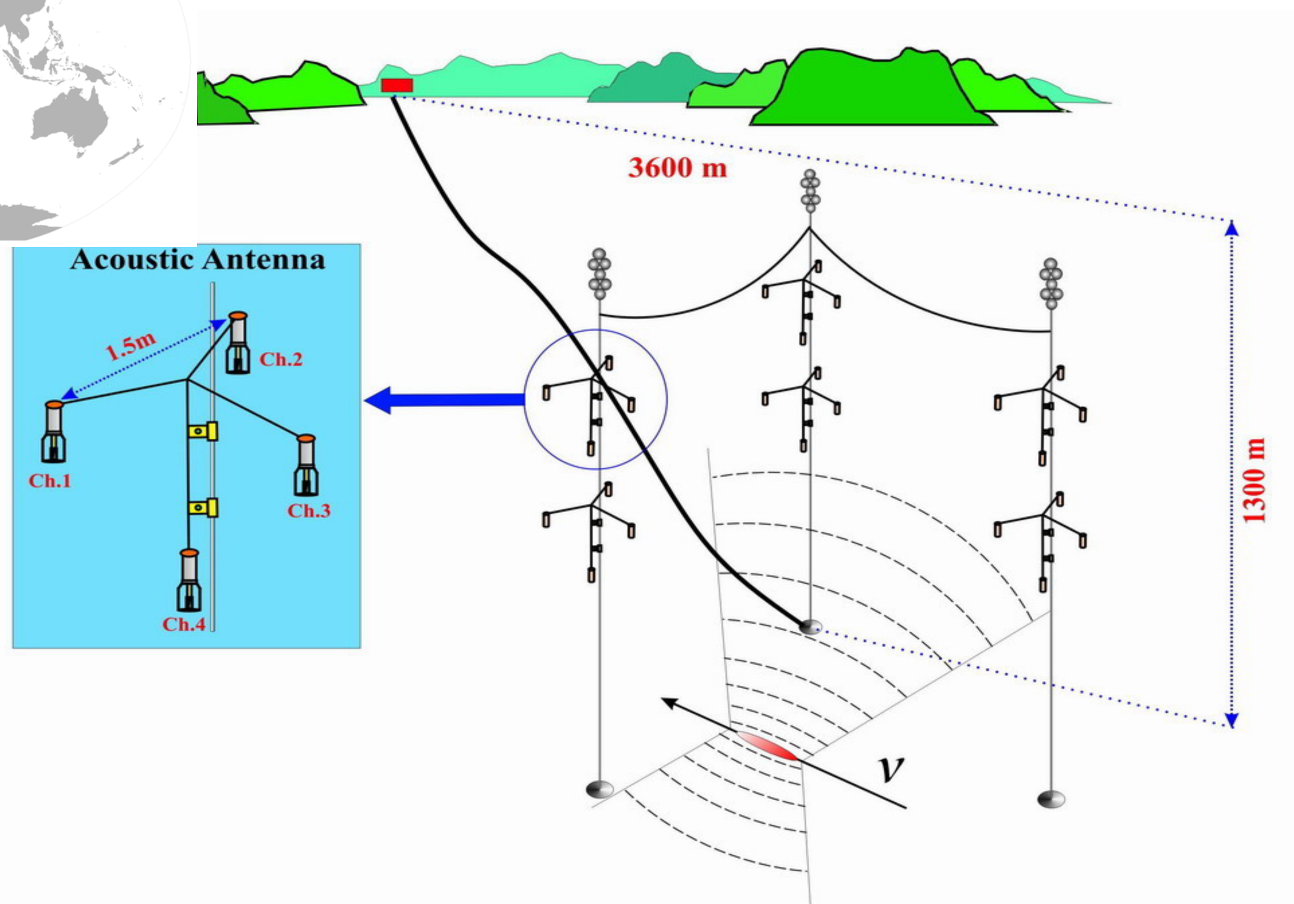




Lake Baikal

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

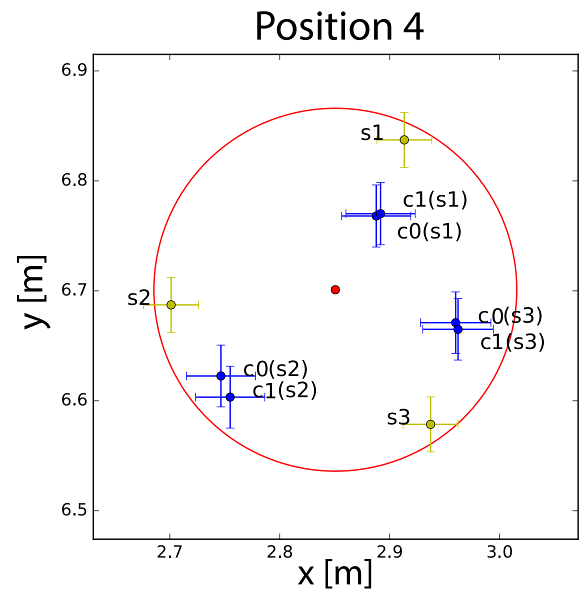




N. Budnev, ARENA 2014, Annapolis

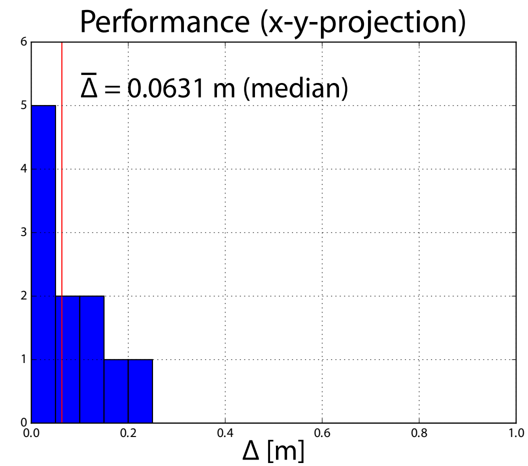
Acoustic Sensors for IceCube-Gen2

- Evaluation of the acoustic positioning concept in a swimming pool
  - 6 acoustic emitters
  - 1 Acoustic DOM (IceCube DOM with 3 acoustic sensors)
  - Acoustic positioning via trilateration
  - Compare reconstructed positions with reference
- Reconstructed positions are in good agreement with the reference positions (even without further corrections)
- Systematic errors are not yet fully understood
- Heading of the Acoustic DOM can be estimated
- Accuracy better than 7cm (x-y-plane) on average



Next steps:

- Integrate acoustic sensors into Icecube-Gen2 DOM
- Develop concept for acoustic emitters for IceCube-Gen2



S. Wickmann, master's thesis, RWTH Aachen University 2016

S. Wickmann et al., EPJ Web of Conferences, ARENA 2016 (in review)

Motivation for acoustic detection

Advatages of acoustic detection:

- long attenuation length
- simple, robust technology
- multi purpose applications