New sensors for acoustic neutrino detection

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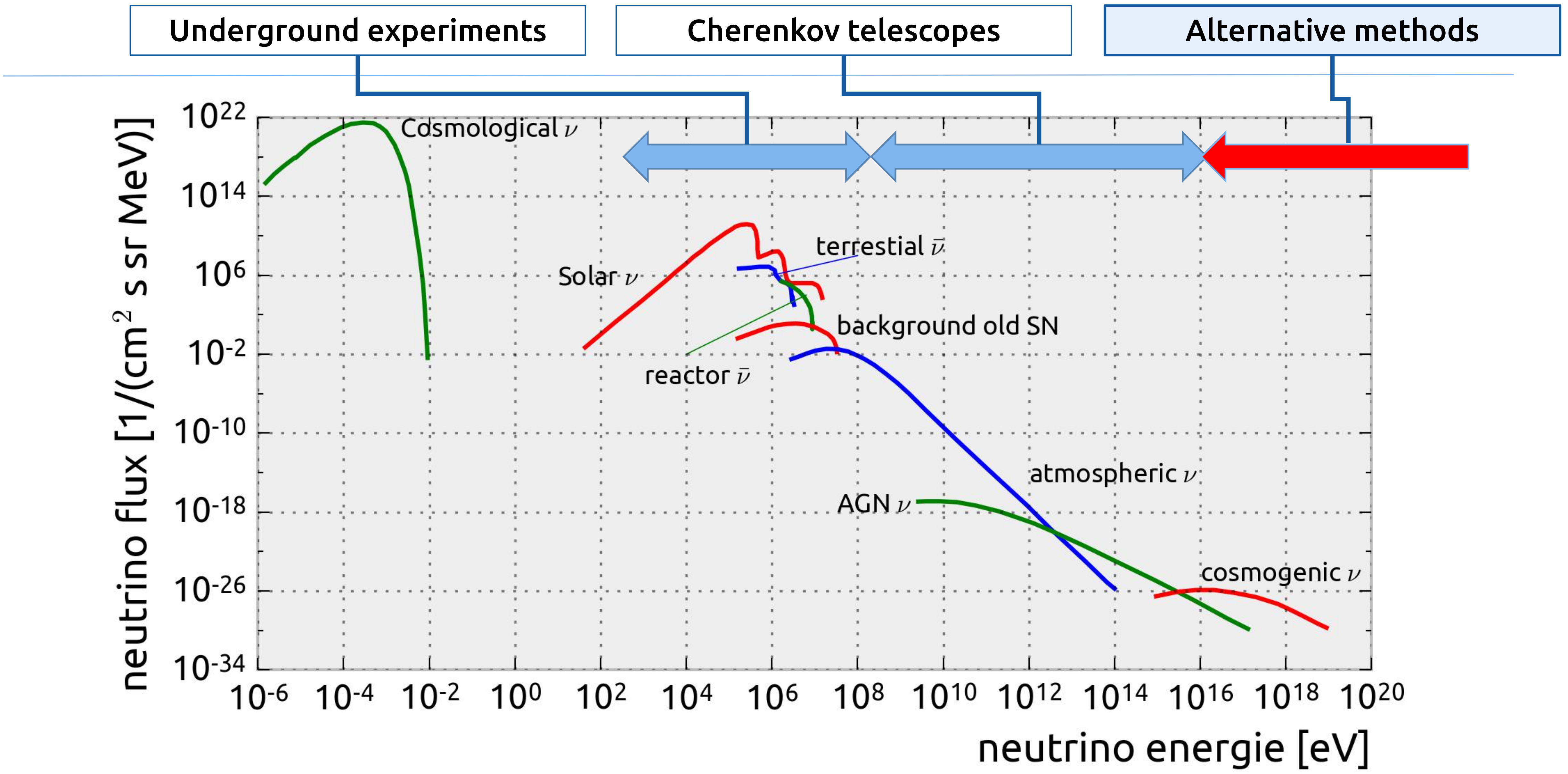
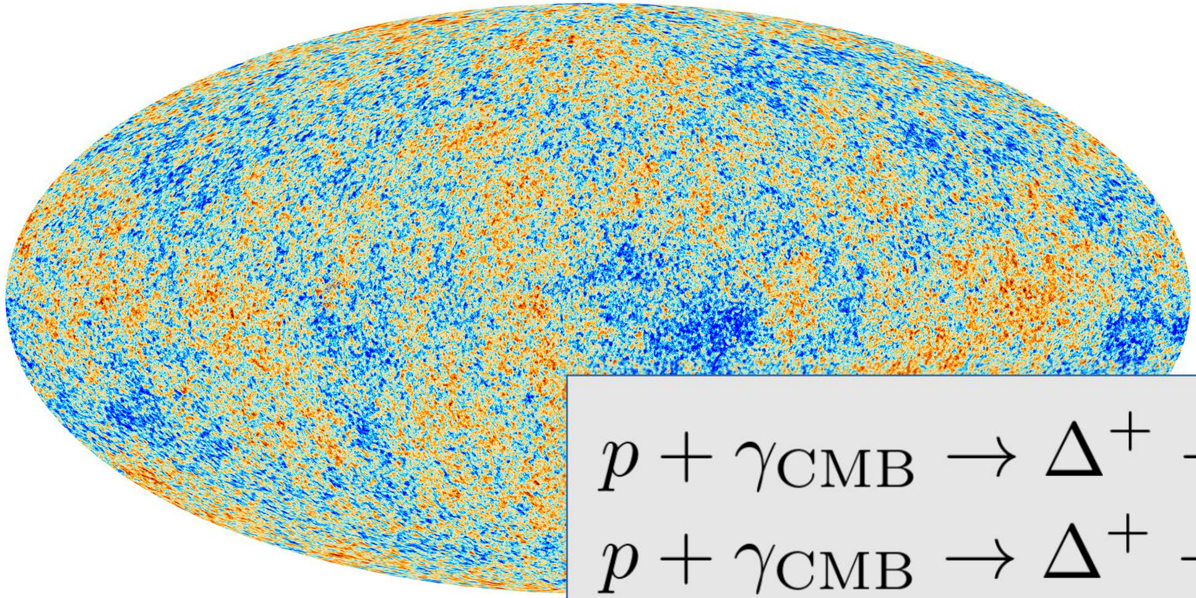
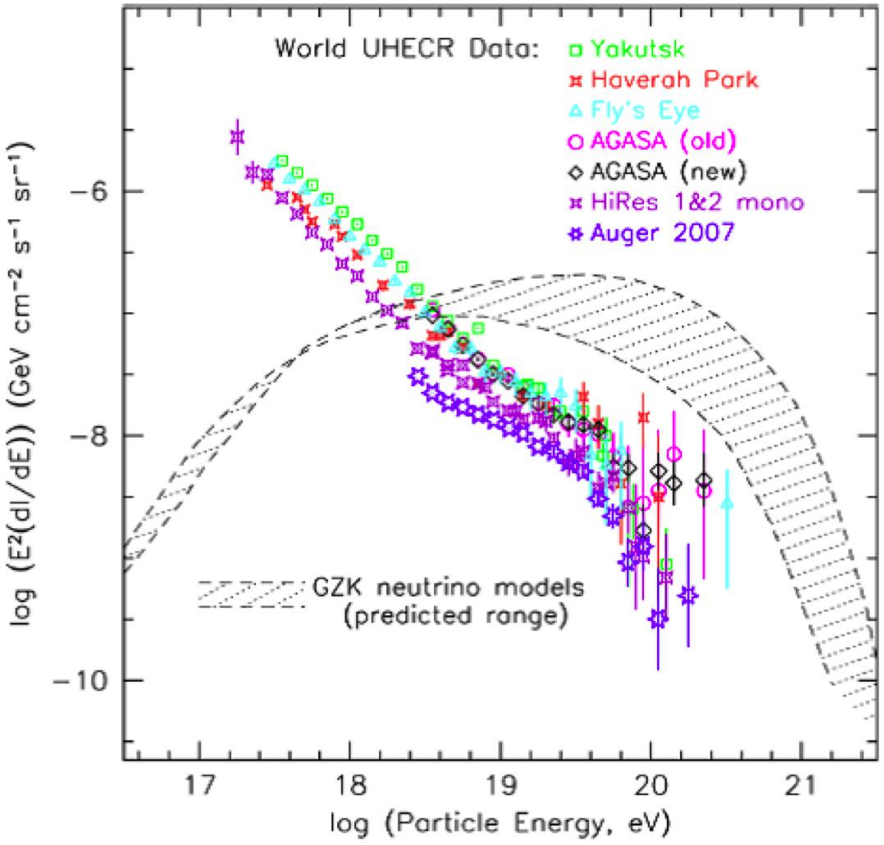

Underground experiments
Cherenkov telescopes
Alternative methods
Cosmological ν
terrestial ν̄
Solar ν
background old SN
reactor ν̄
atmospheric ν
AGN ν
cosmogenic ν
neutrino flux [1/(cm² s sr MeV)]
neutrino energie [eV]

The GZK cut-off

- Greisen, Zatsepin and Kuzmin (1966): Universe is not transparent for high energy protons and ions.
- Berezinsky and Zatsepin: first prediction of associated neutrino flux





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

... with subsequent decay to *neutrinos*

Acoustic neutrino signals

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

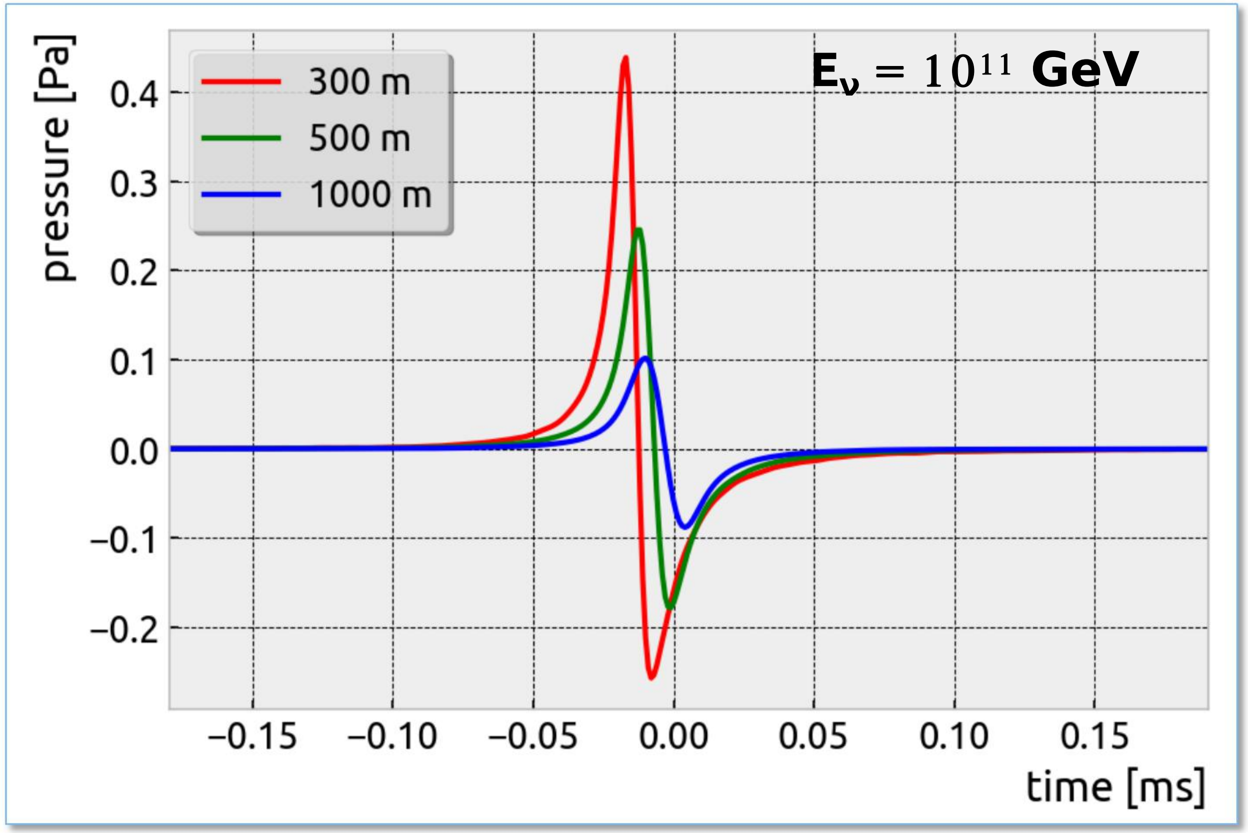
$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{C_p}\frac{\partial^2 \varepsilon}{\partial t^2}$$

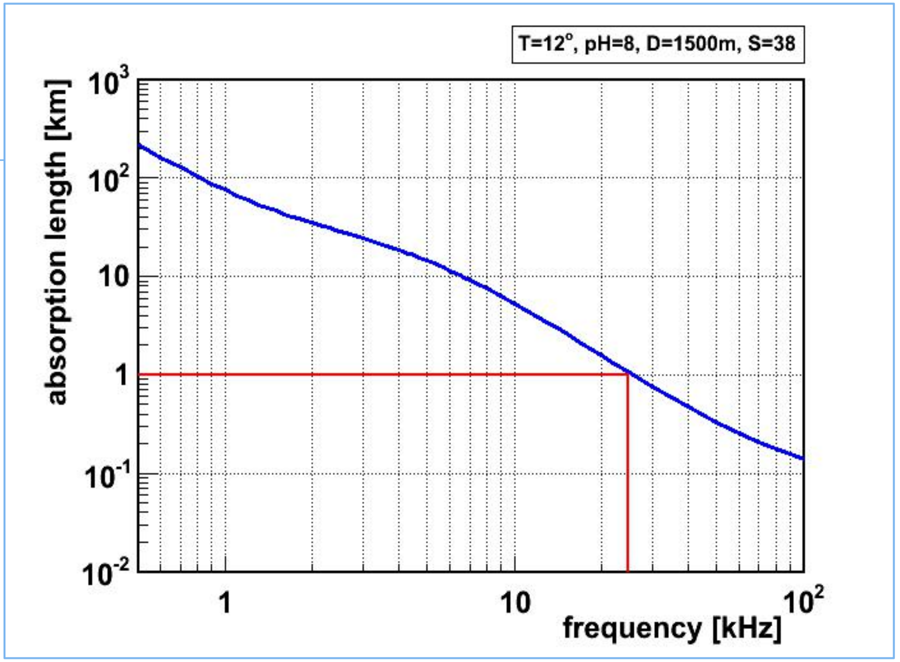
c = Speed of sound

C_p= expansion coefficient

α = heat capacity

Acoustic neutrino signals





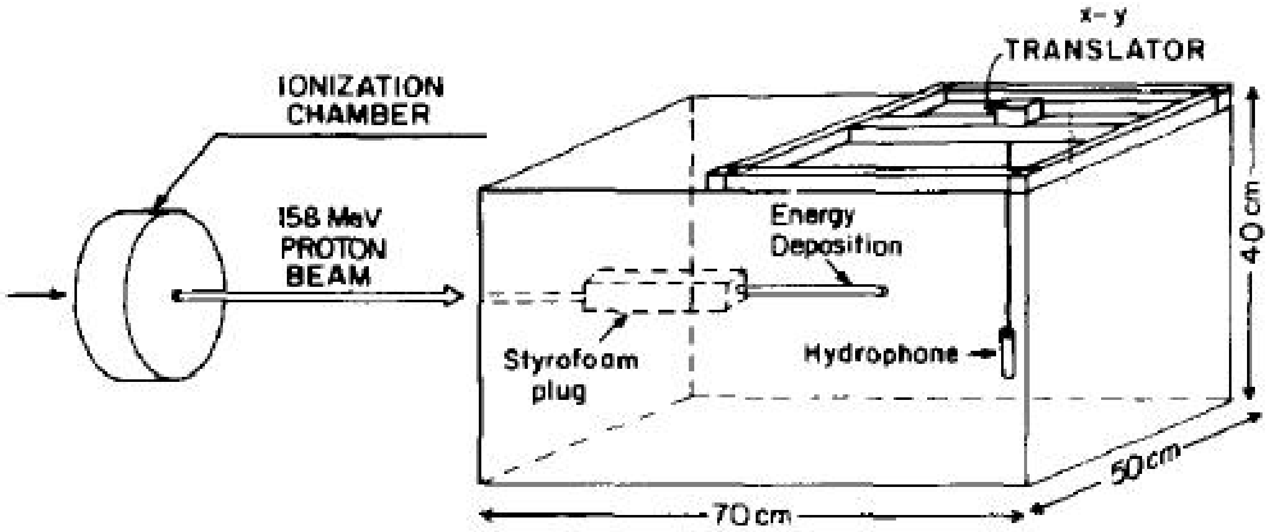
- Broad spectrum that peaks at 5-12 kHz.
- Near field effects
- Pulse asymmetry

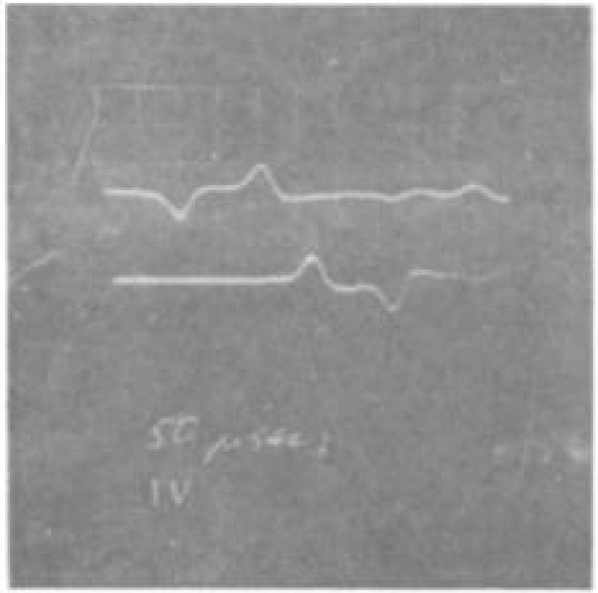
-> Detect mPa pulses in a static pressure environment of MPa!

Acoustic detection of particles

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

- Later work at Desy, Sheffield, Erlangen, and others.





Sulak et al 1979

Acoustic detection of particles

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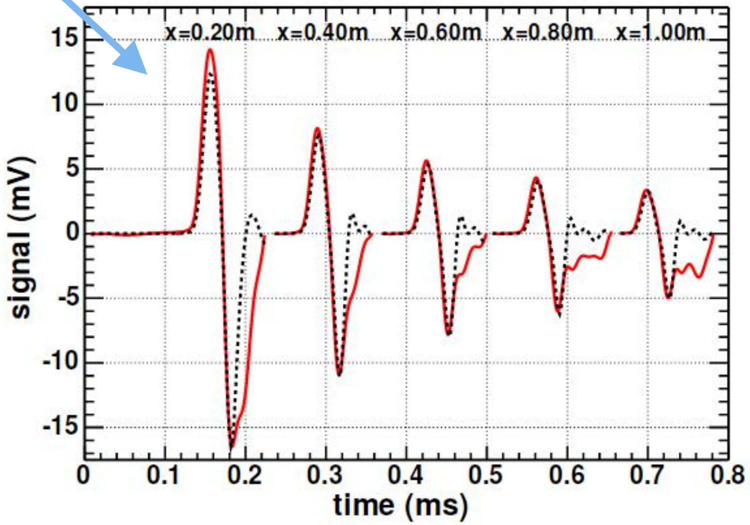
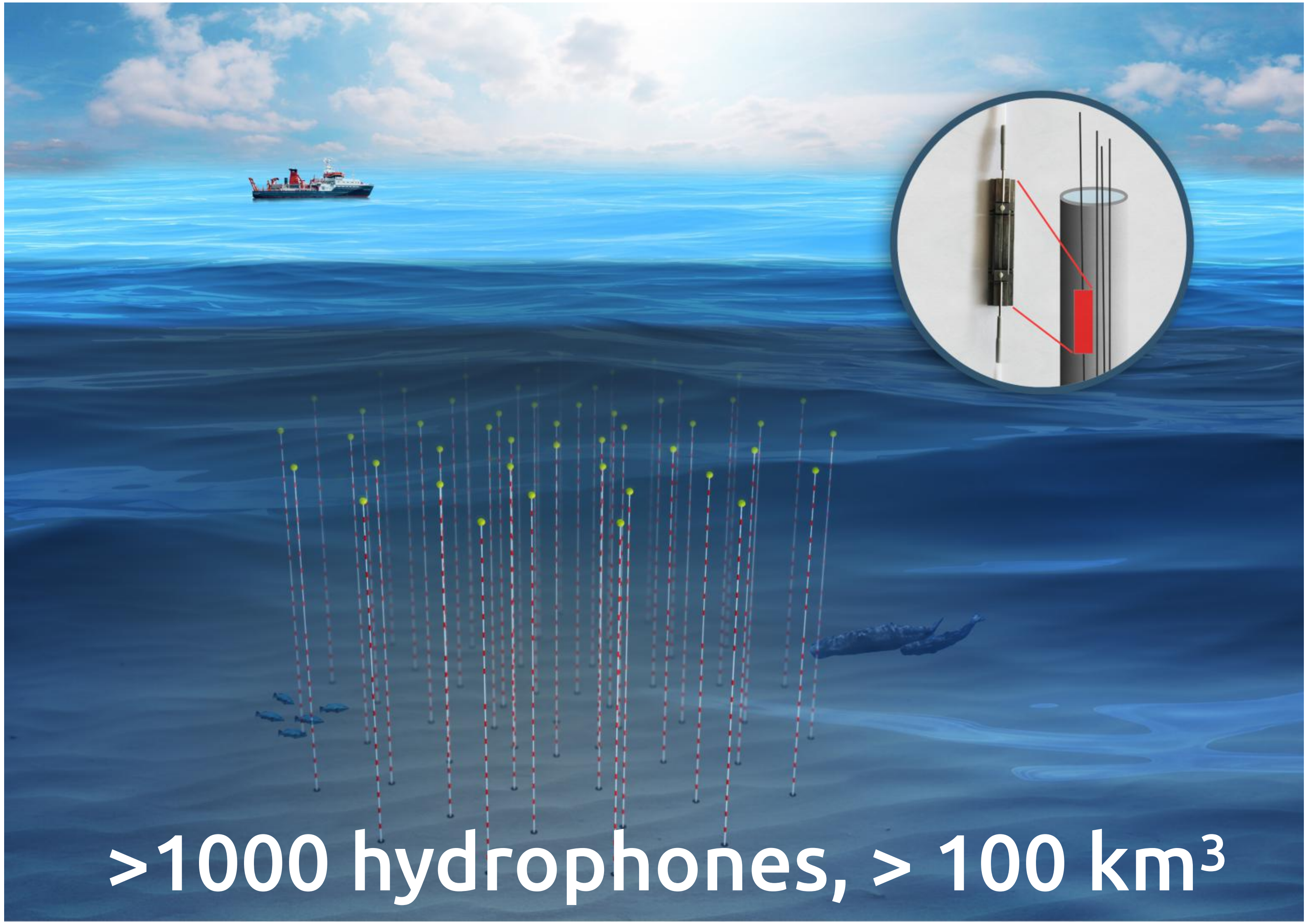
Detailed investigations at particle accelerators:

- variation of hydrophone position
- variation of water temperature

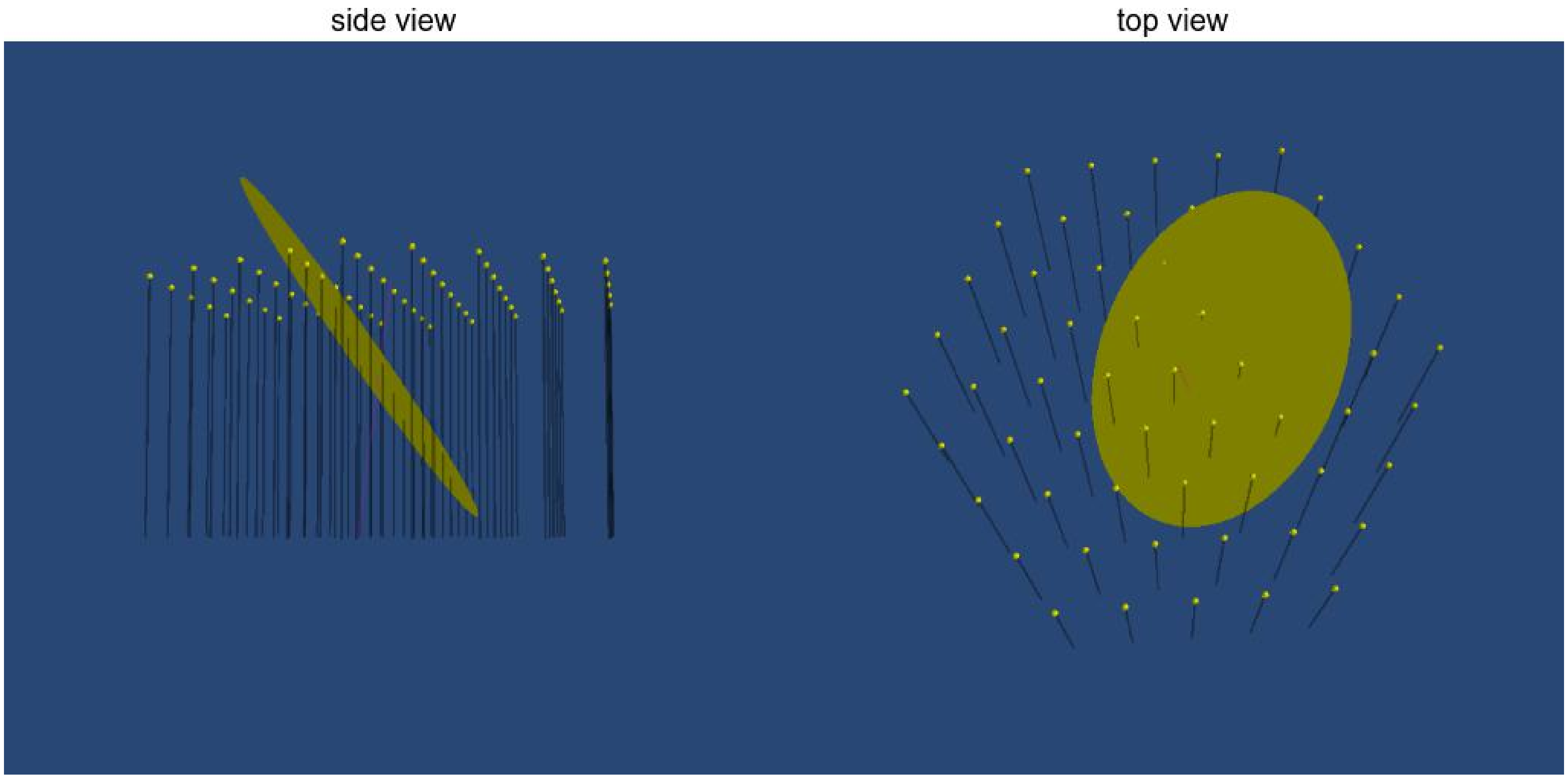


Lahmann et al 2015

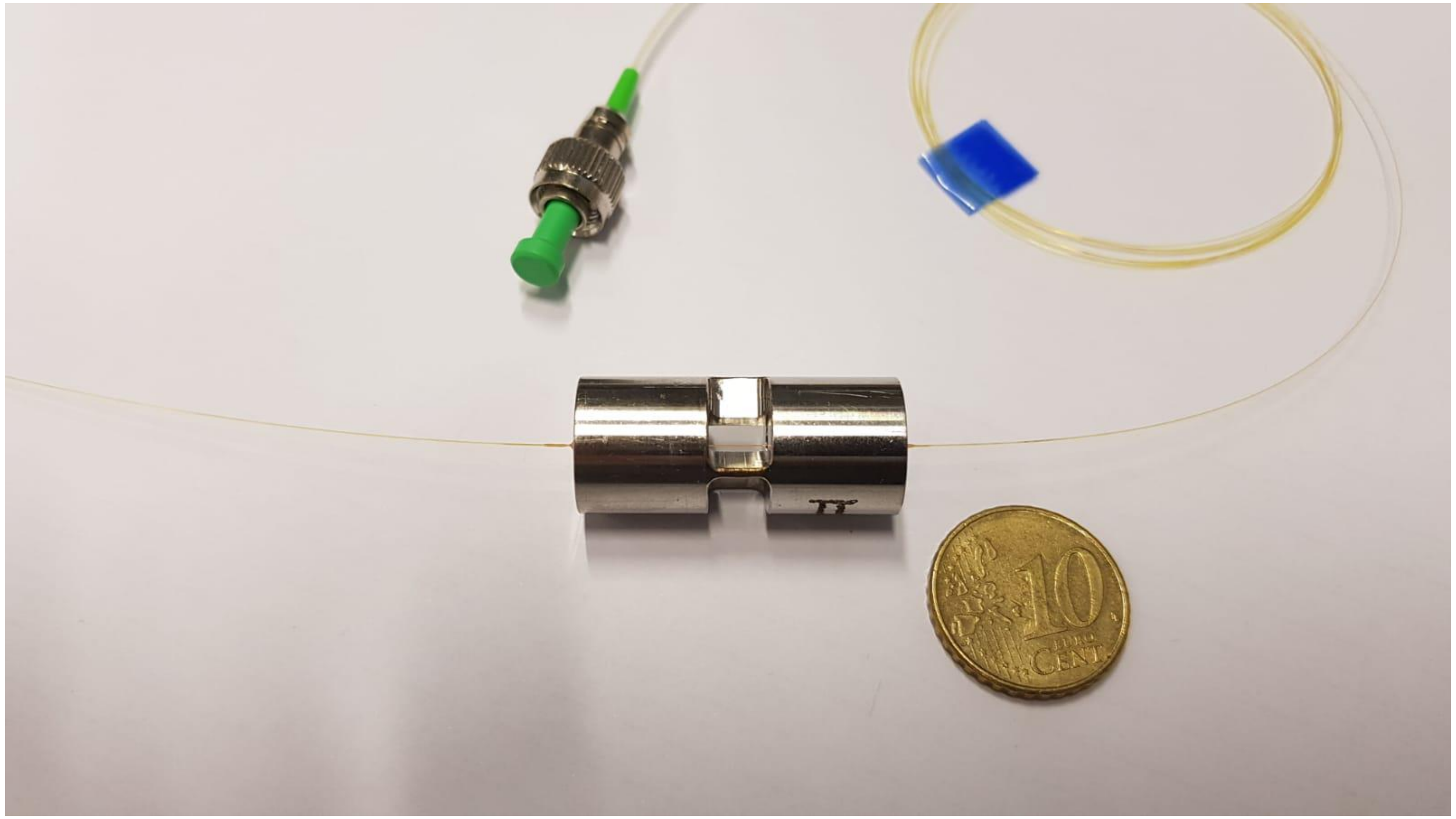
Future telescope concept



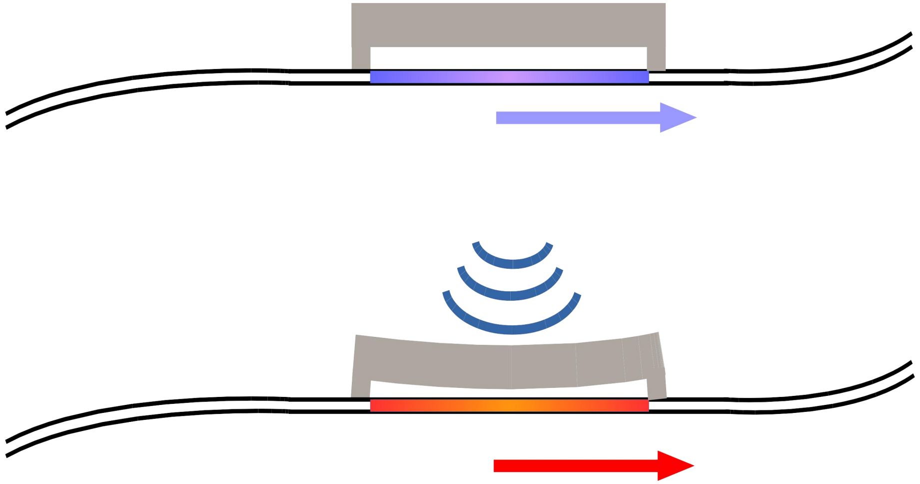
Event topology



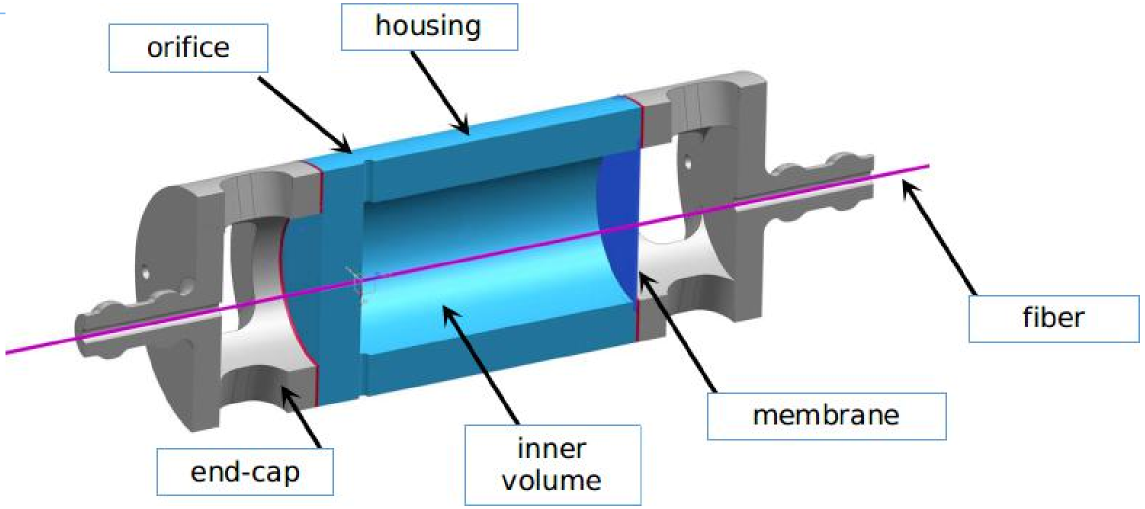
Future telescope concept … based on fiber hydrophones



Fiber optic hydrophone



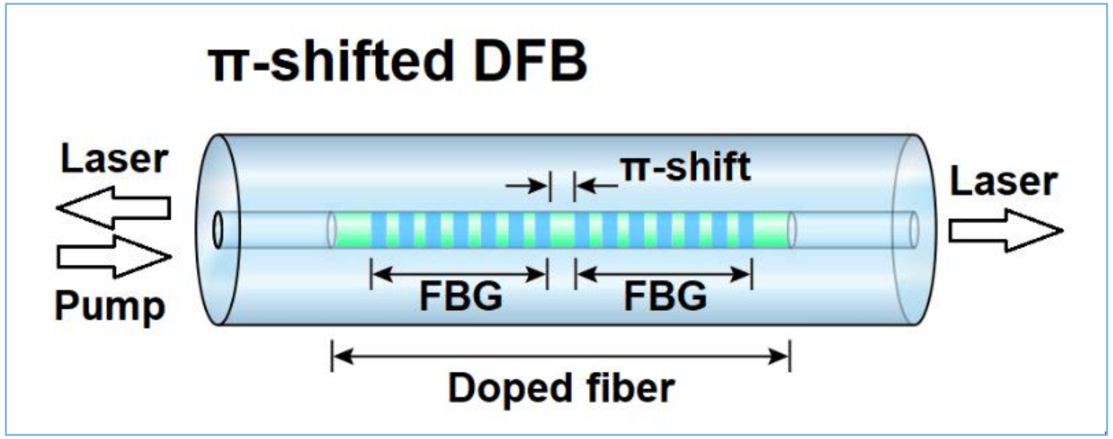
Transducer convert pressure into a wavelength shift.



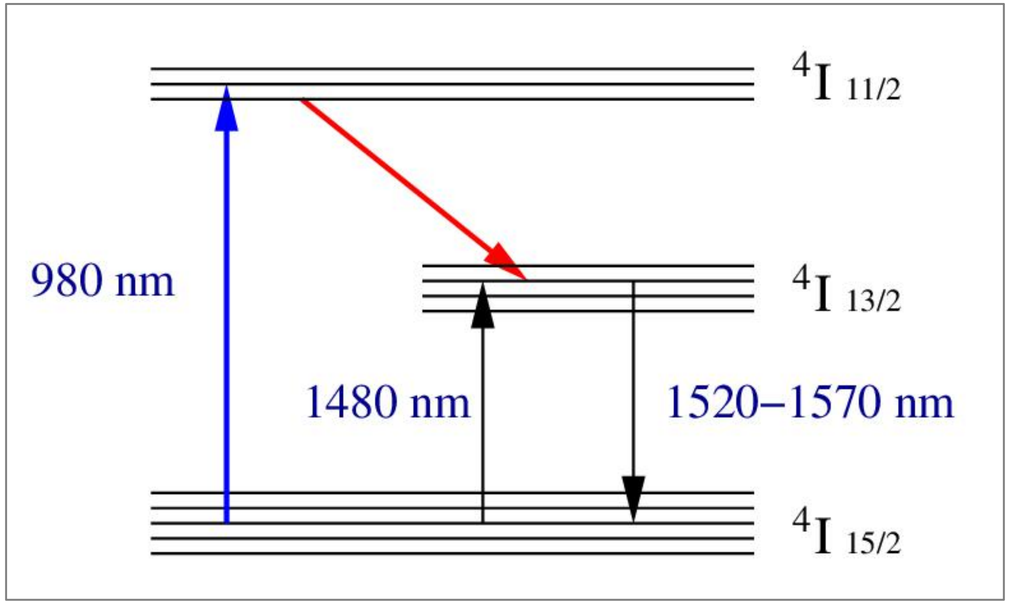
Fiber laser

- Optical fiber includes fiber lasers
- Optical lasers are based on

  erbium doped fibers
- Grating structure applied to create a laser



Er levels



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

Fiber laser

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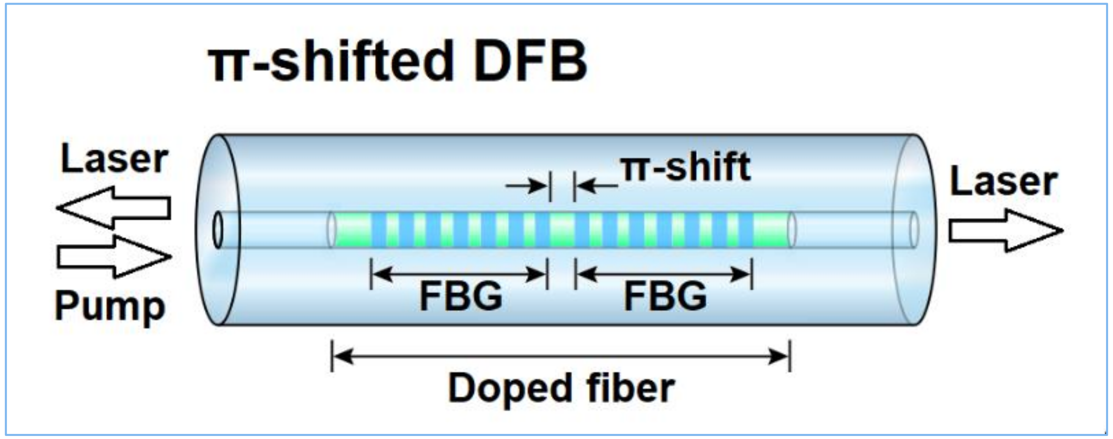
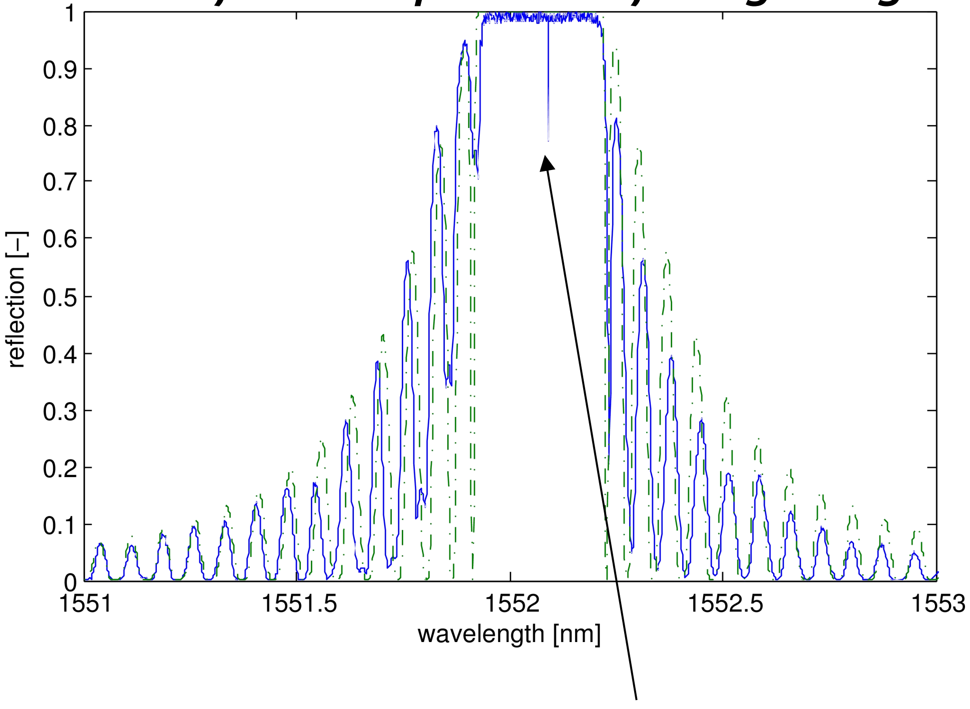


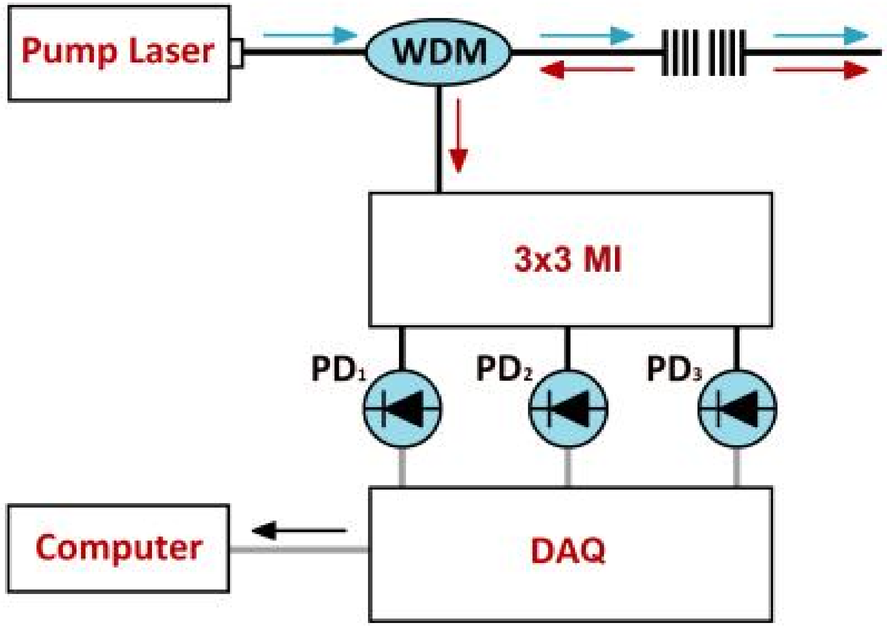
Reflection spectrum of the gratings



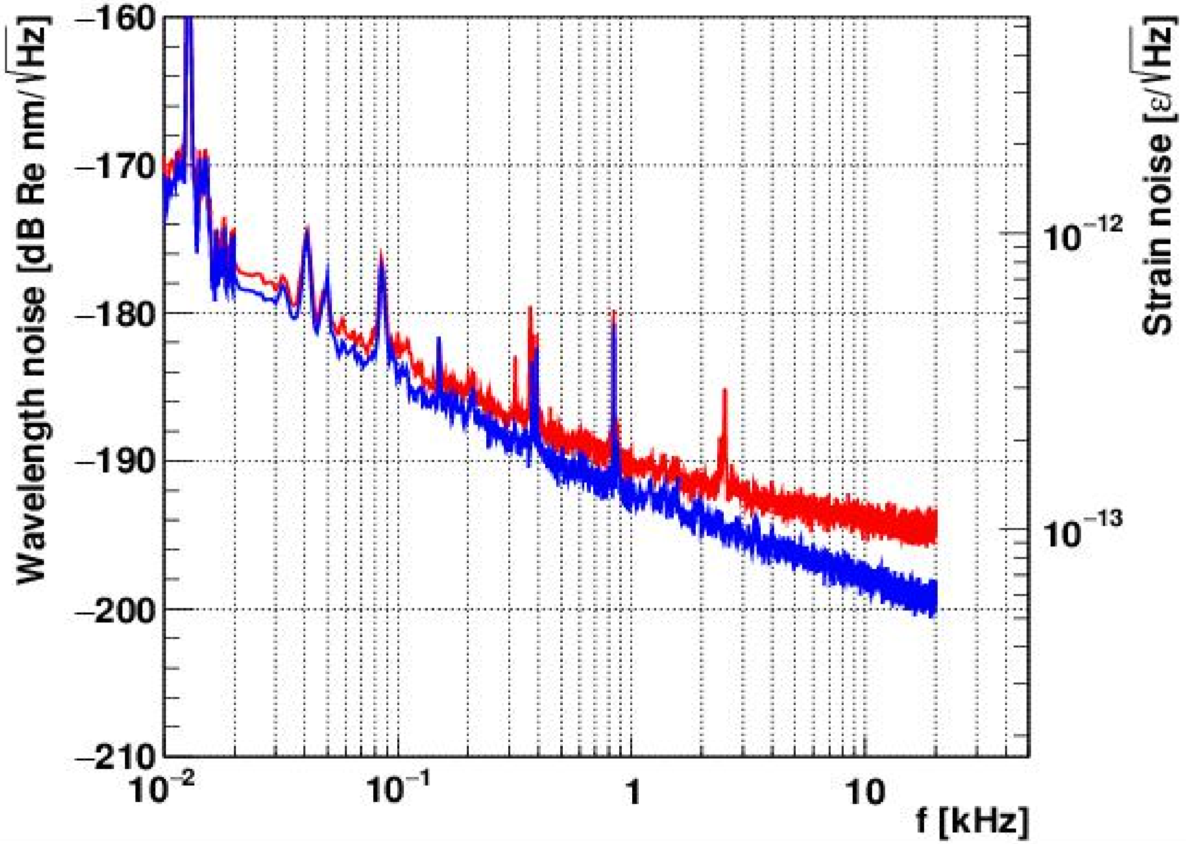
Coherent light source

Need small cavity (to match the transducer). Now as small as *14mm*. Development with Exail.

Data acquisition

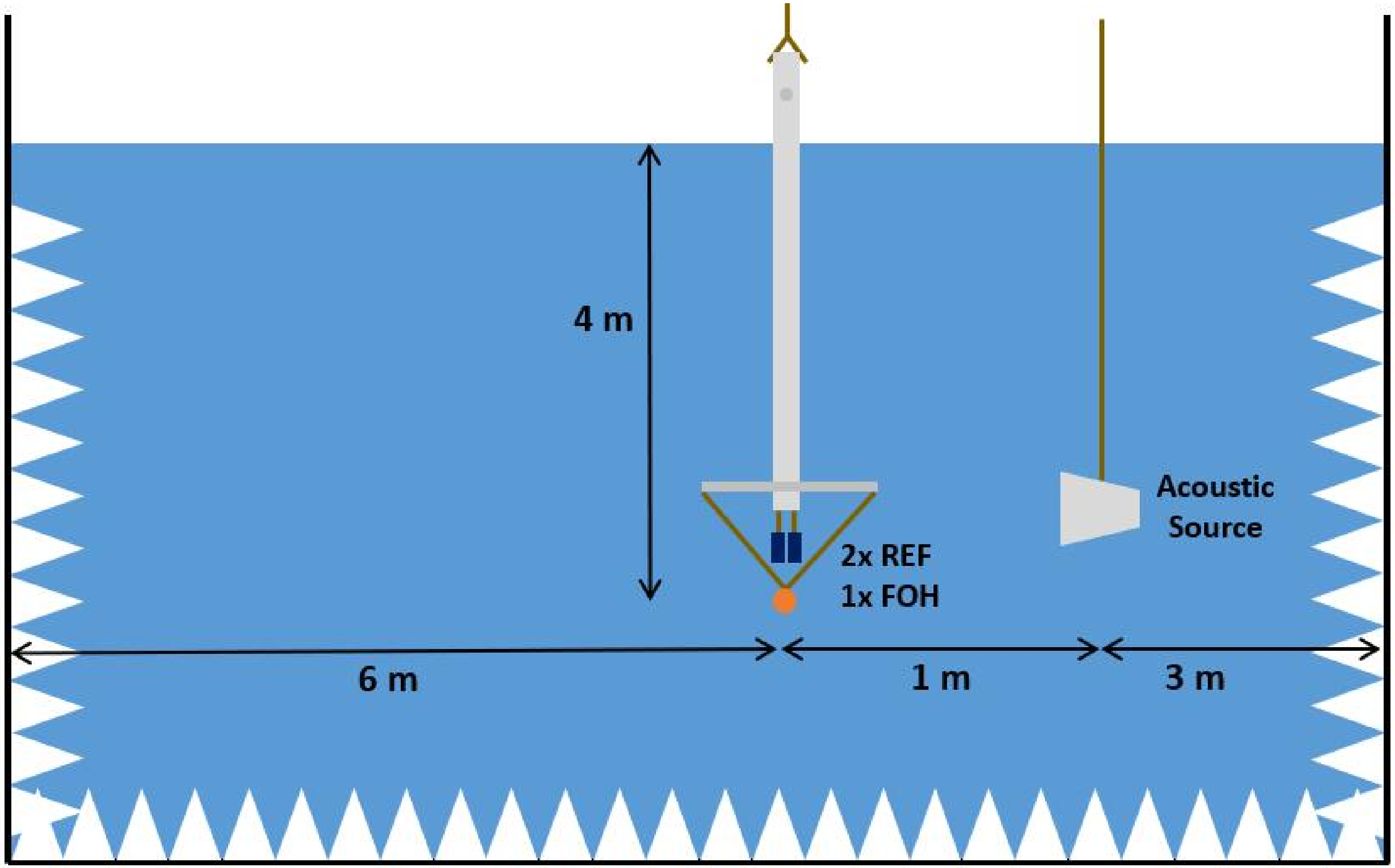


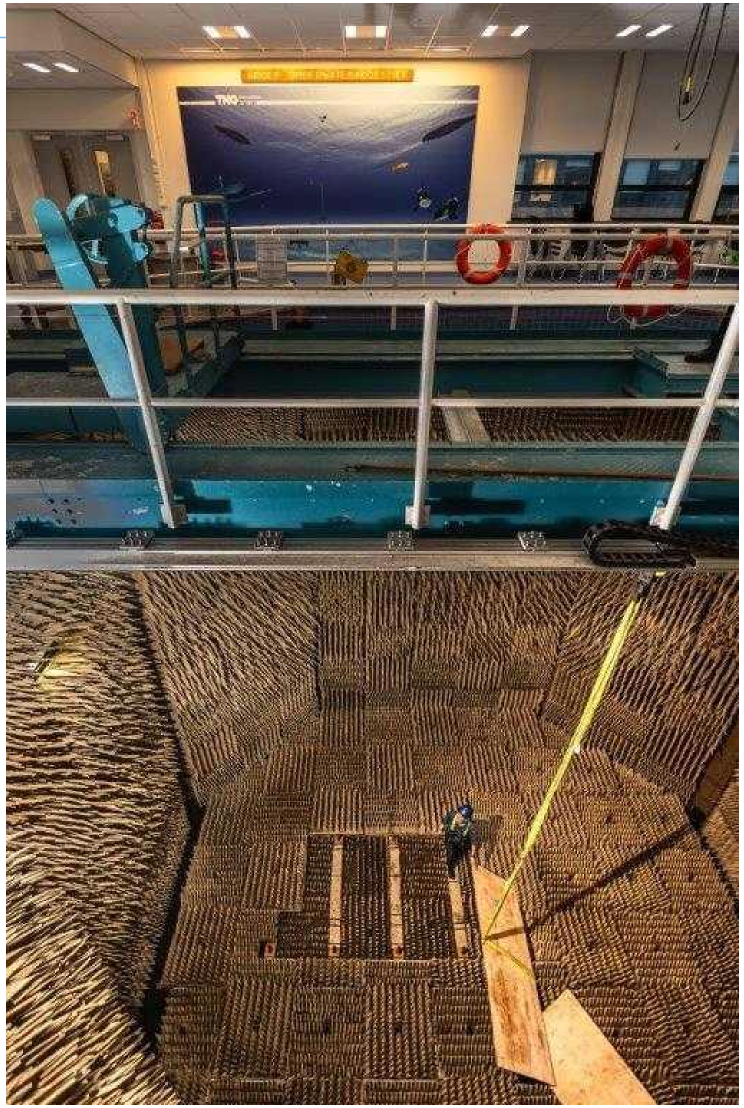
3x3 arm Michelson interferometer



Interferometer sensitivity to 10^{-19} m/√Hz

Experimental setup in an anechoic basin



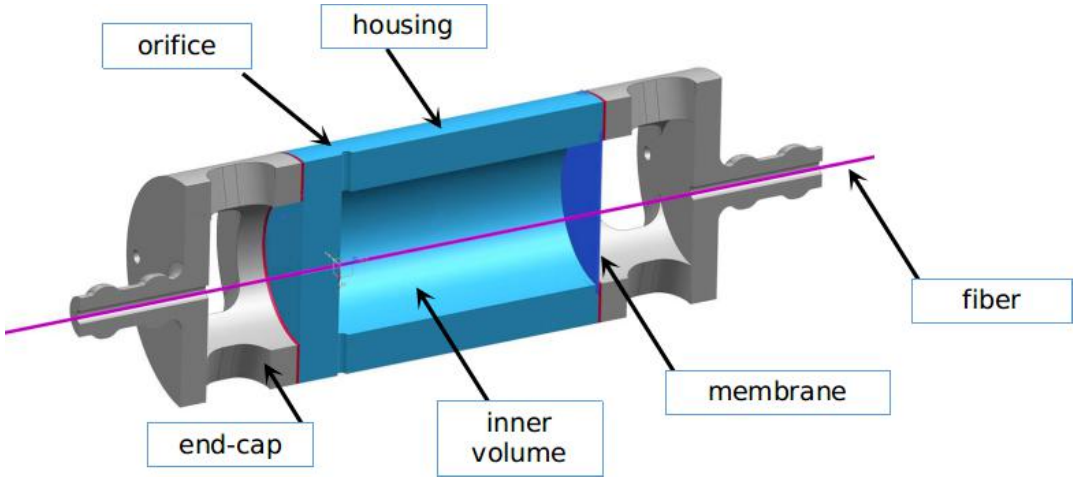


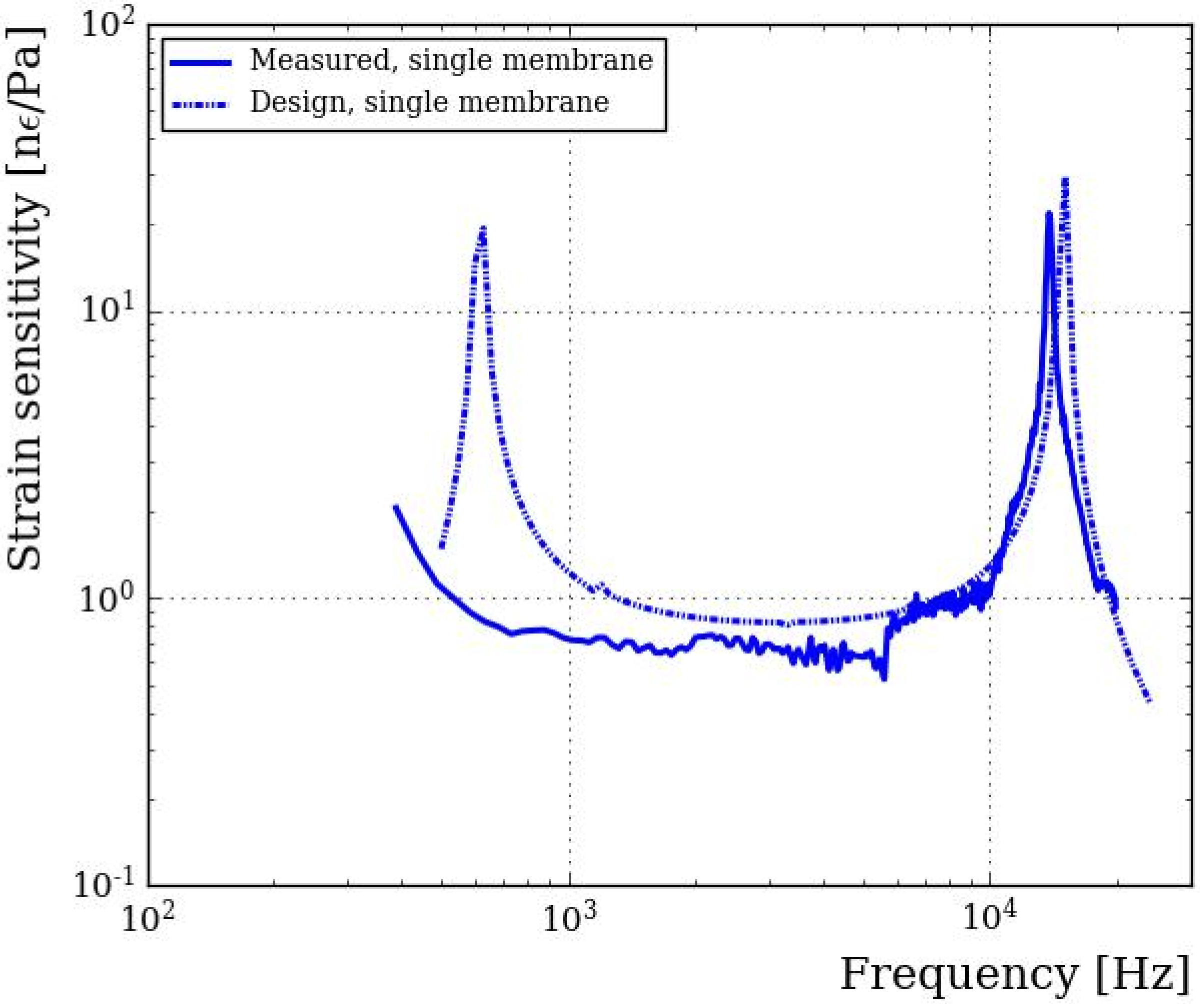
8 x 8 x 10 m^3

Instrument response

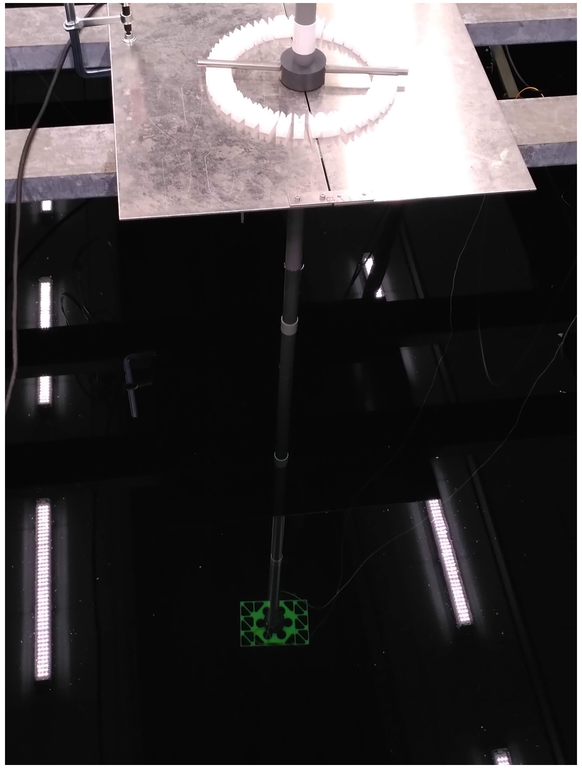
- Mechanical resonance peak ~15 kHz
- Helmholtz resonance peak at 600 Hz

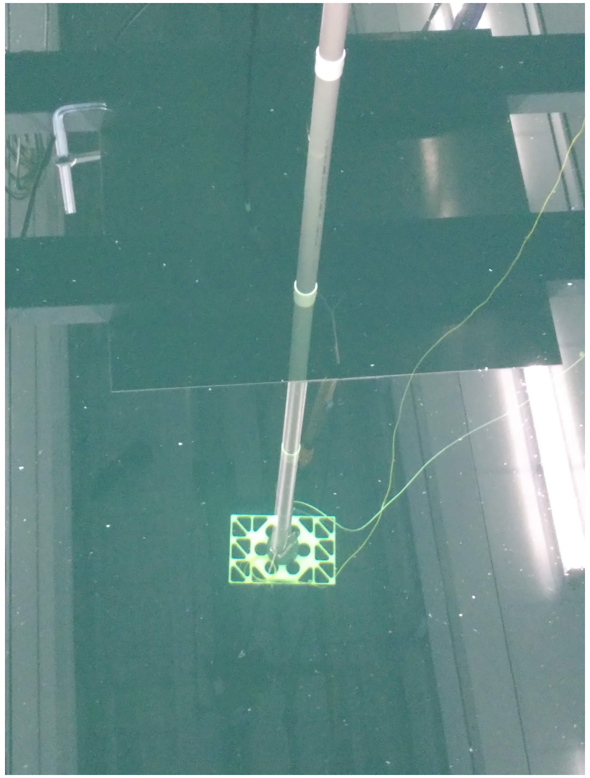
- Two types:
  - single membrane
  - double membrane

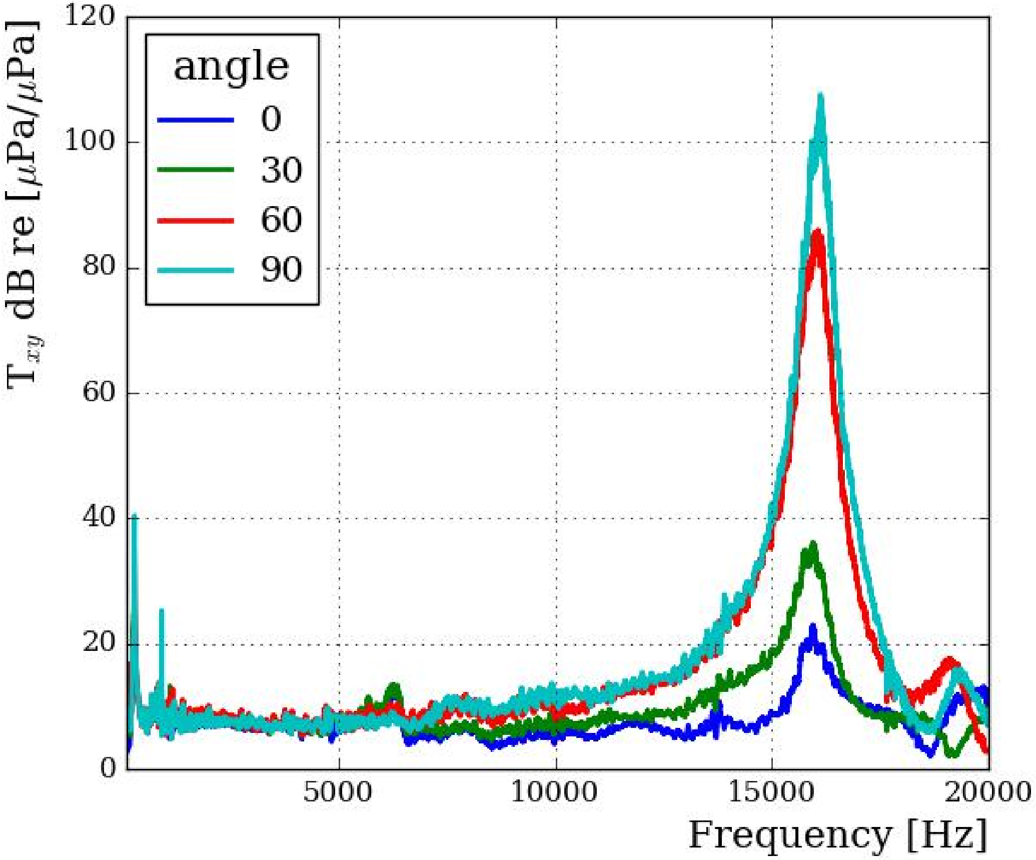




Instrument response: directionality







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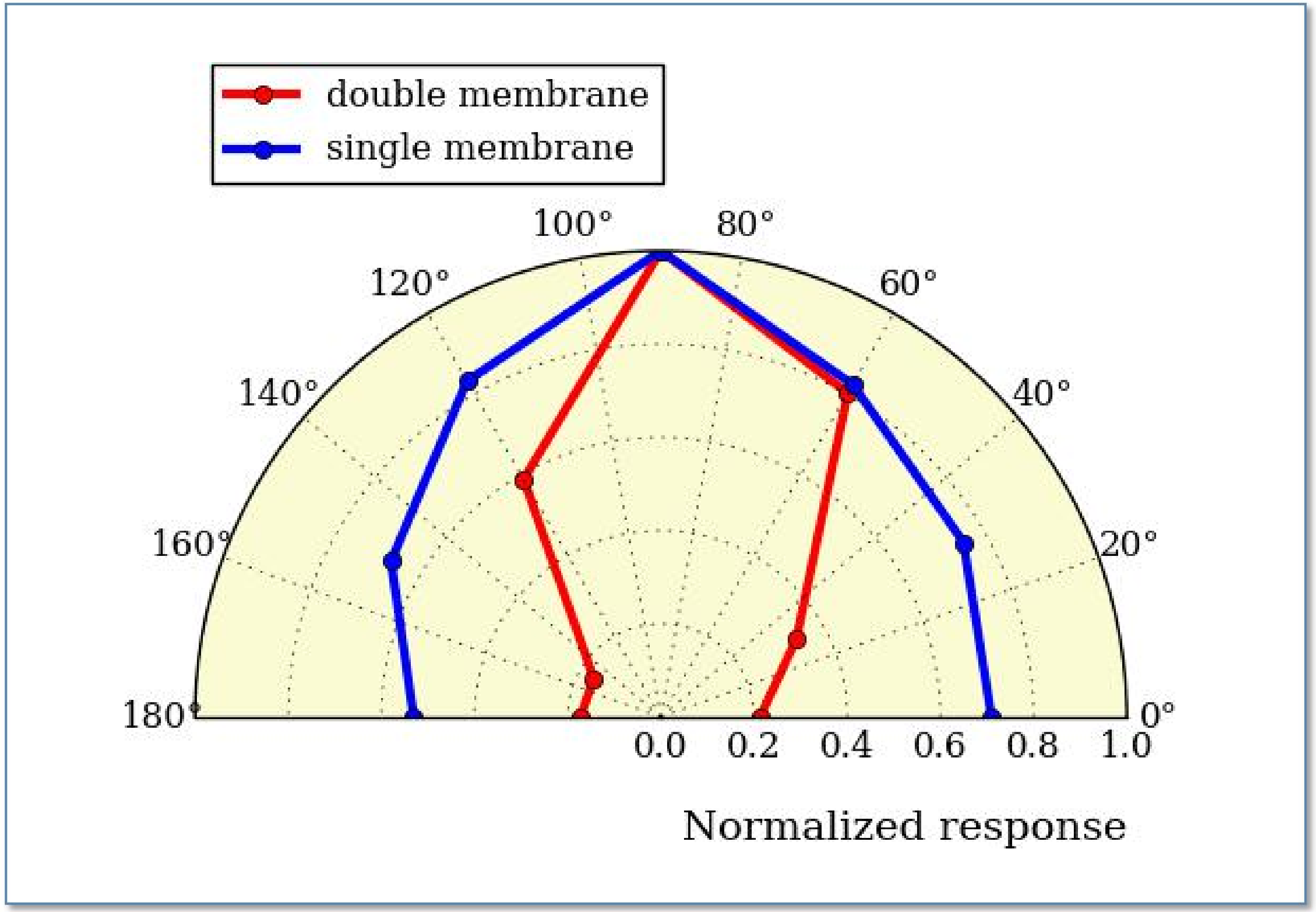
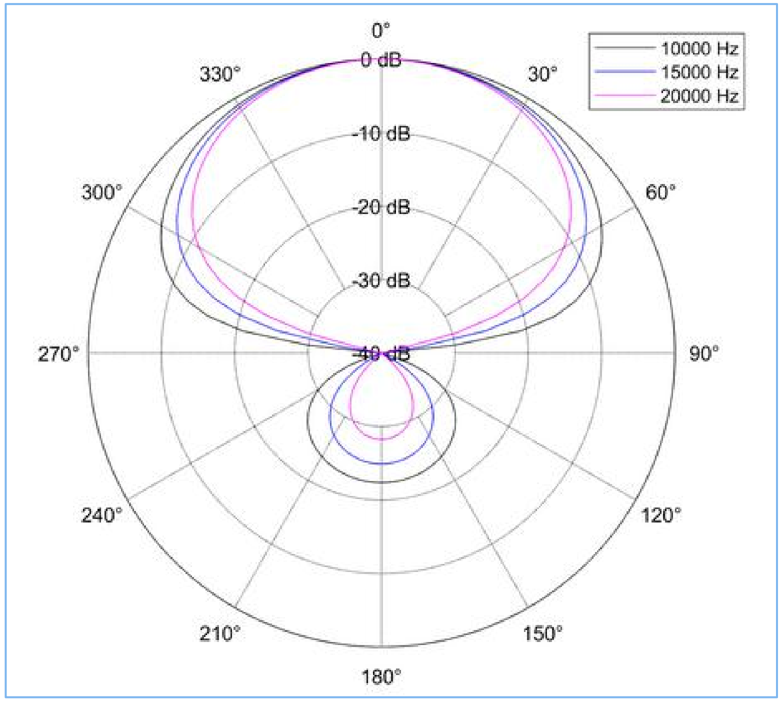
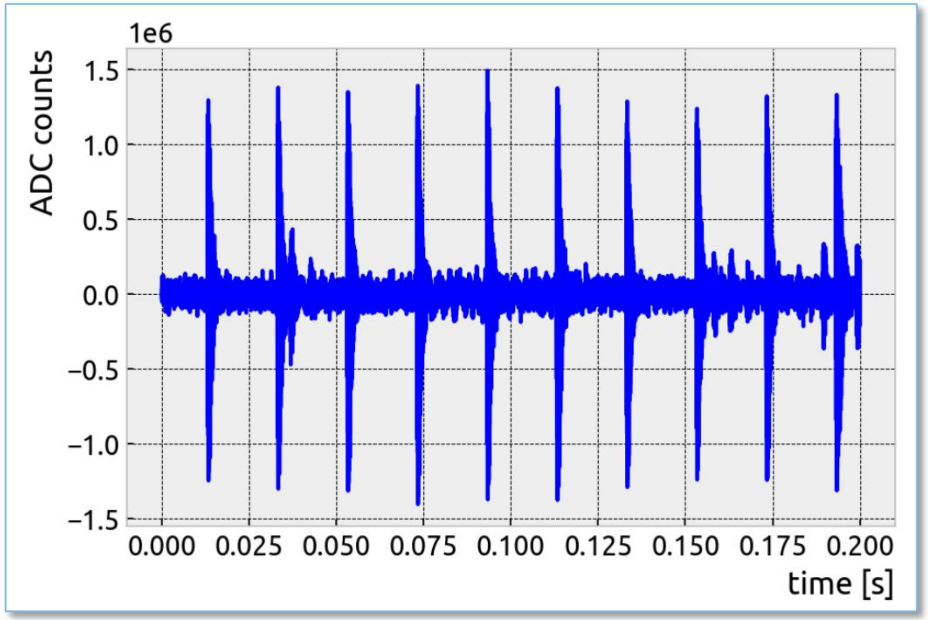


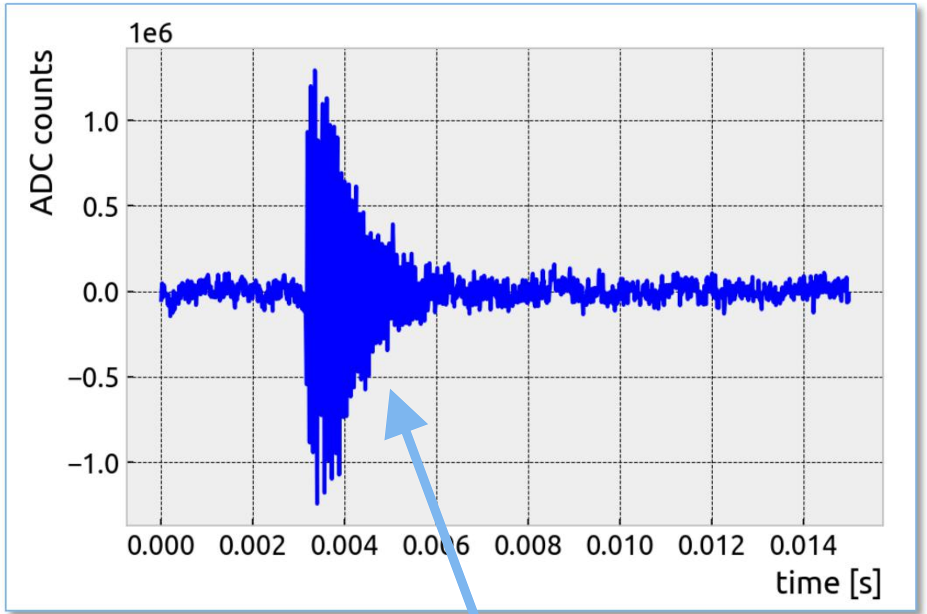


Theoretical deep-sea noise vertical angle distribution

Example pulses

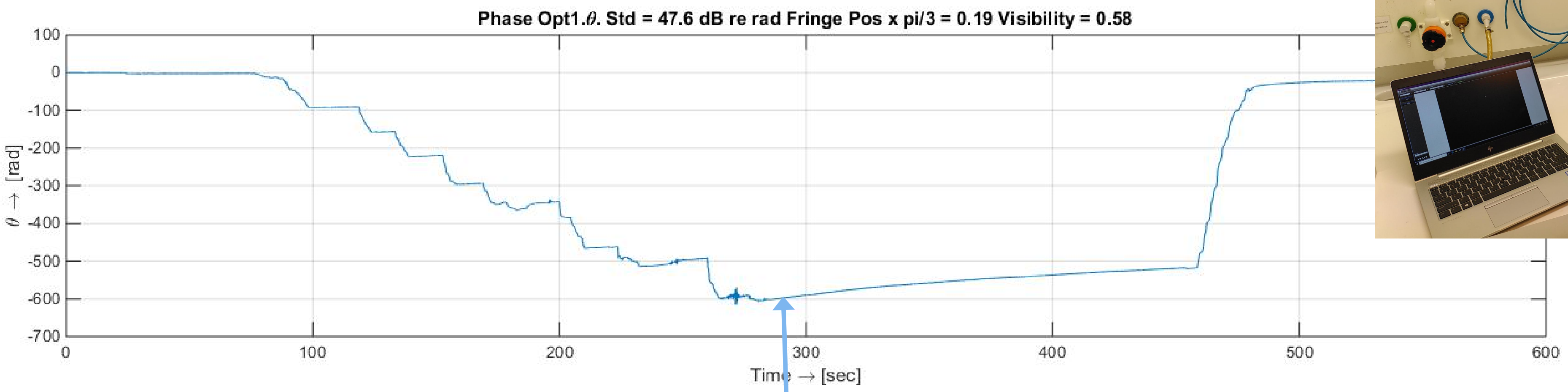
Ringtones of neutrinos

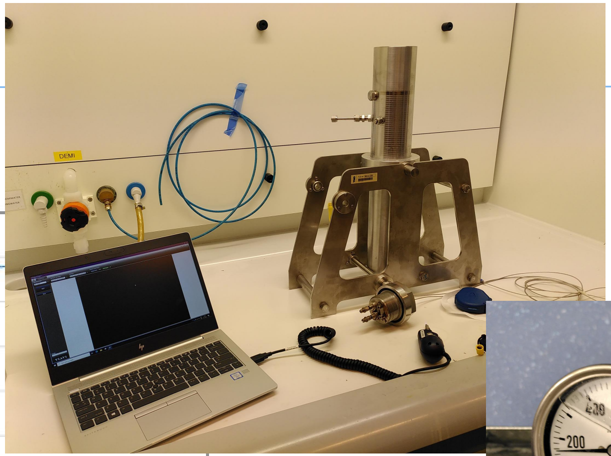


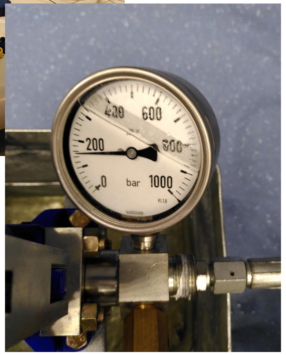


Ringing (mech. eigenfrequency)

Pressure qualification

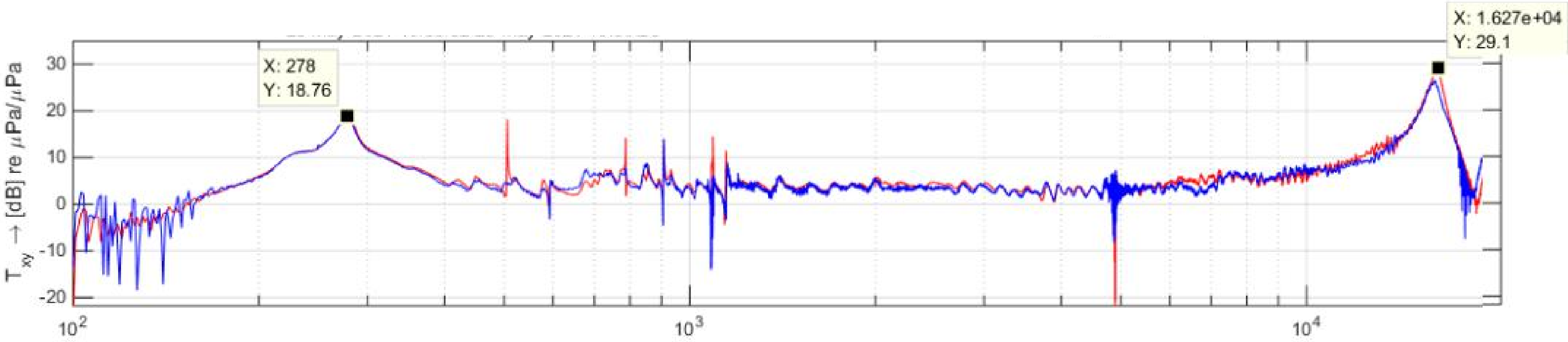






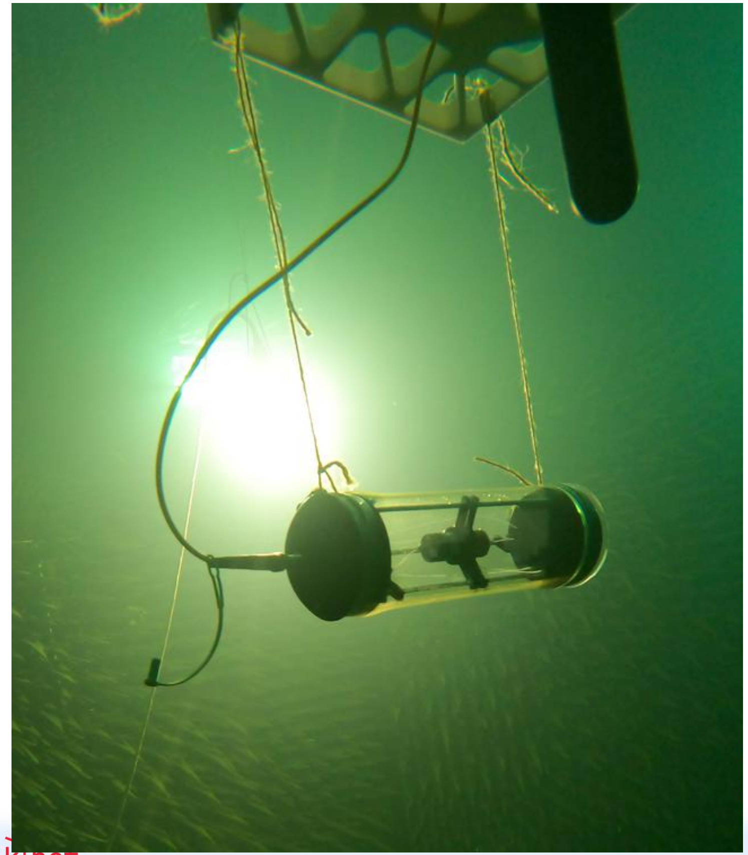
160 bar (1.6 km)

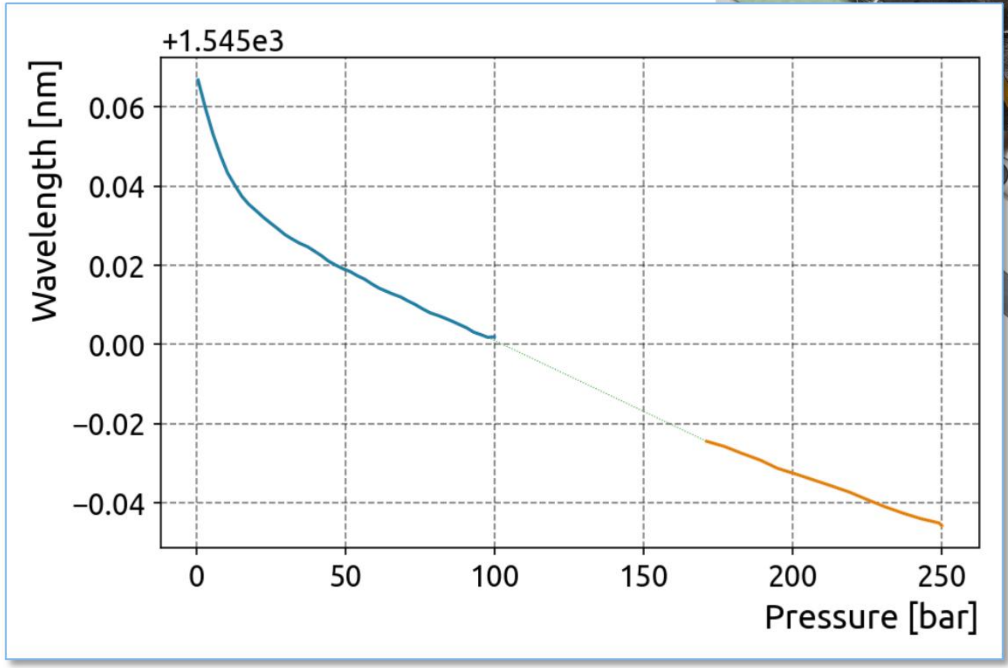
Apply pressure in steps of about 20 bars

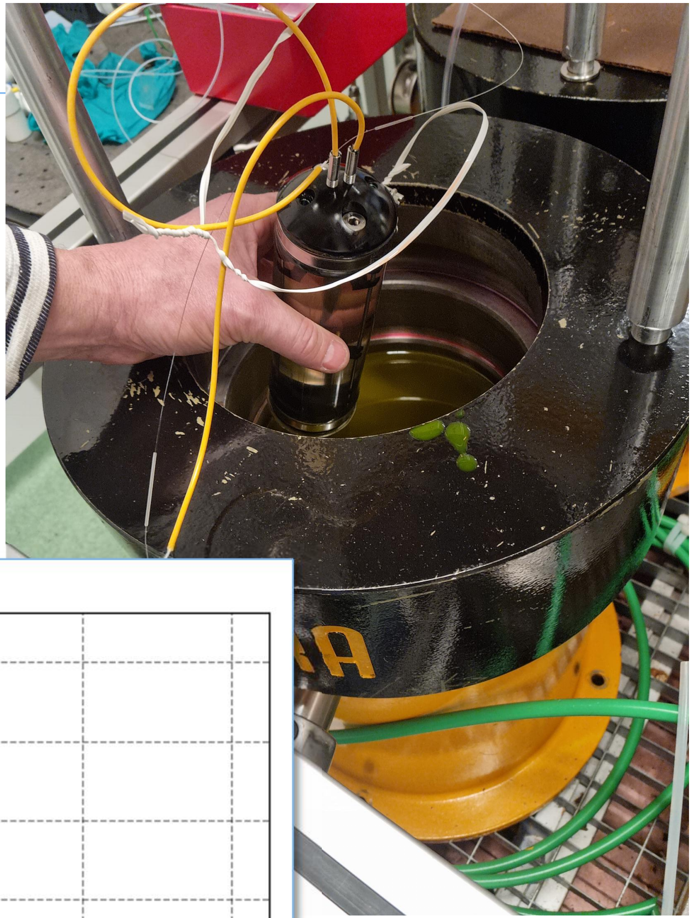


Pocket

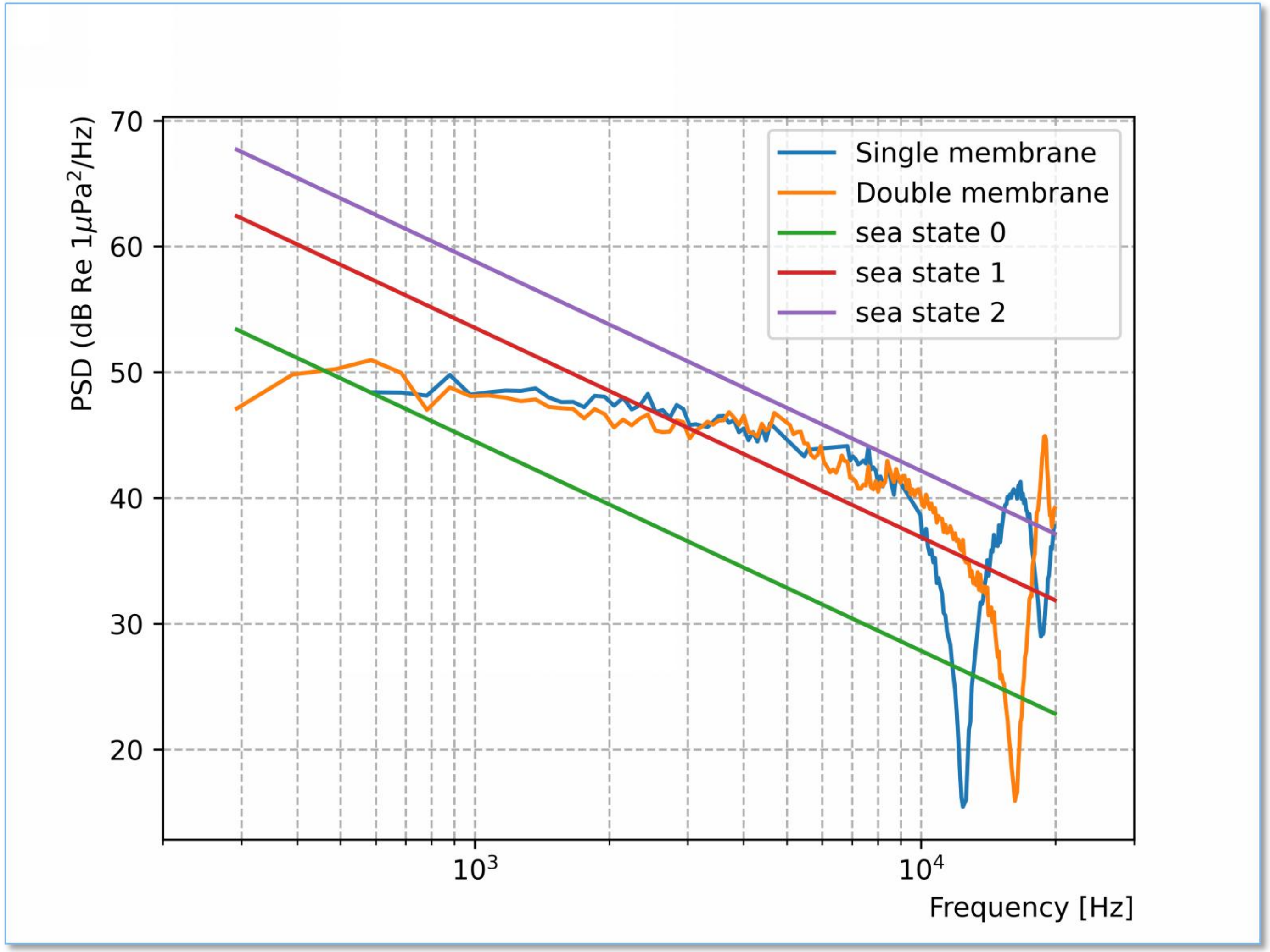
- Packaging is needed for safe deployment
- Pressure qualification up to 250 bar



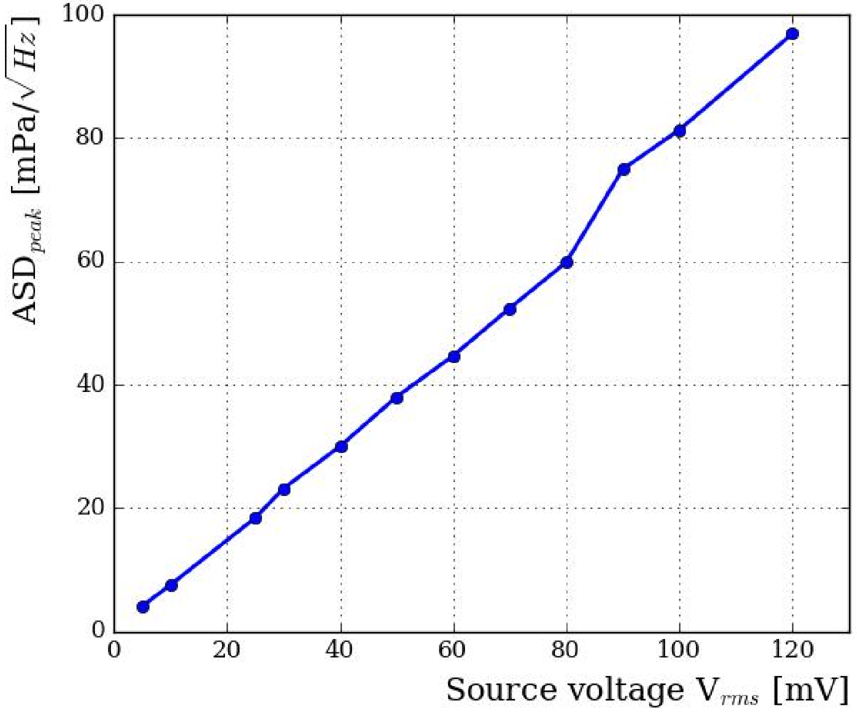




Hydrophone sensitivity

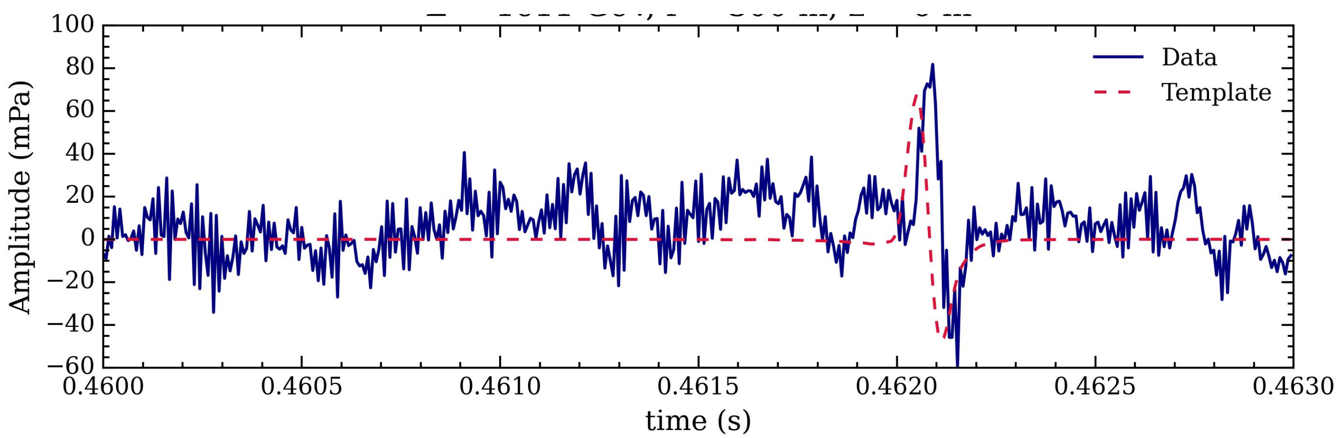


Linearity @ 5kHz



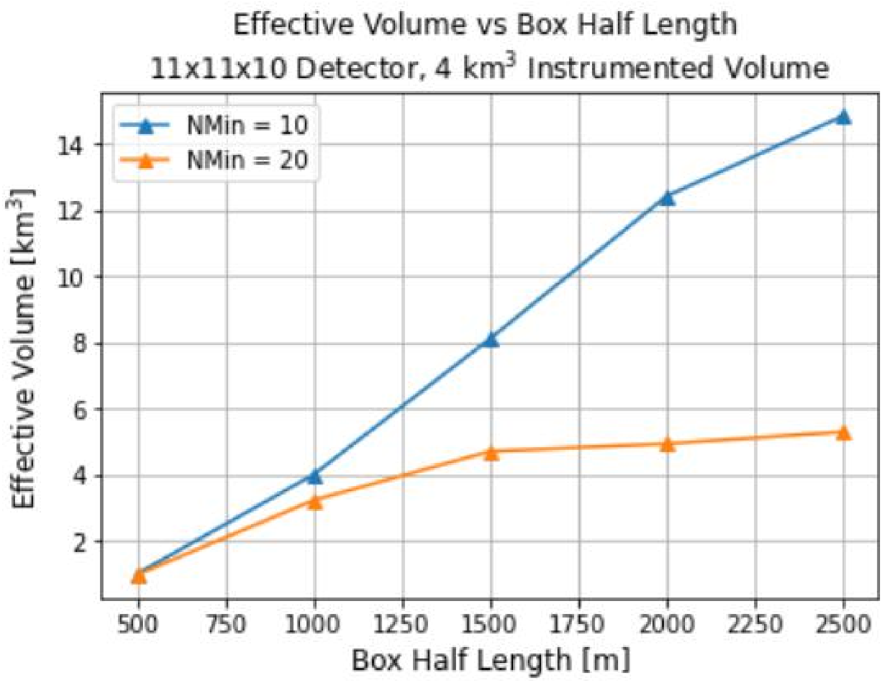
Event selection: 2-step process

1. Filter hits on basis of <u>single waveforms,</u> use e.g. matched filtering



Cecile van der Stappen

2. <u>Select event</u> using ***clique*** algorithm (subspace clustering) to suppress the noise hits:
   Find a set of pair-wise causally related hits with a minimum size $N_{min.}$



K.van Oers, M de Jong

Single waveform classification

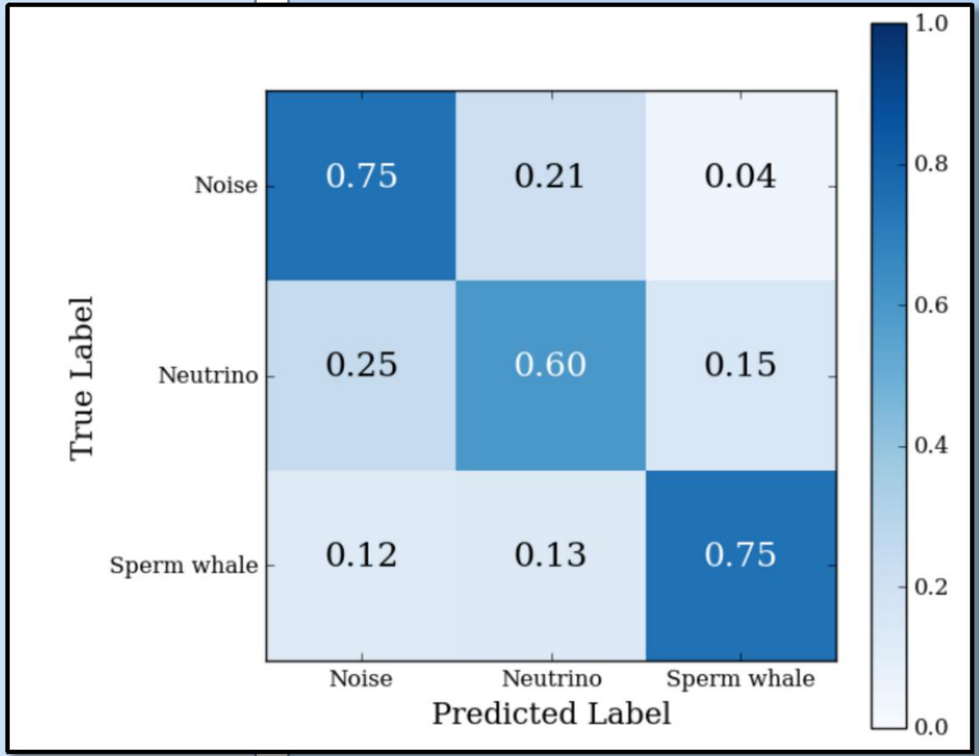
Neutrinos

- **Full simulation chain is in place: from neutrino interactions in water to acoustic neutrino pulses**

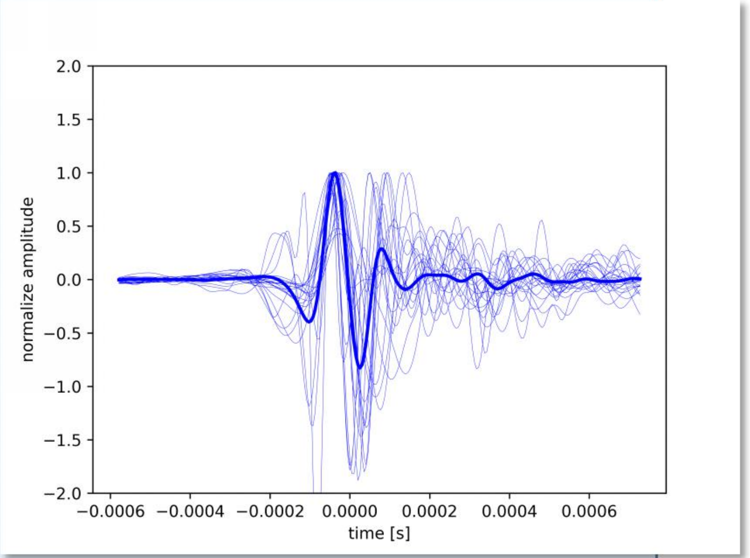
Noise:

- **Random noise extracted from Mediterrean Sea**

Confusion matrix



Liselotte Dijkema 2023



Sperm whale:
Train ML using a database of 10 000 recorded sperm whale clicks

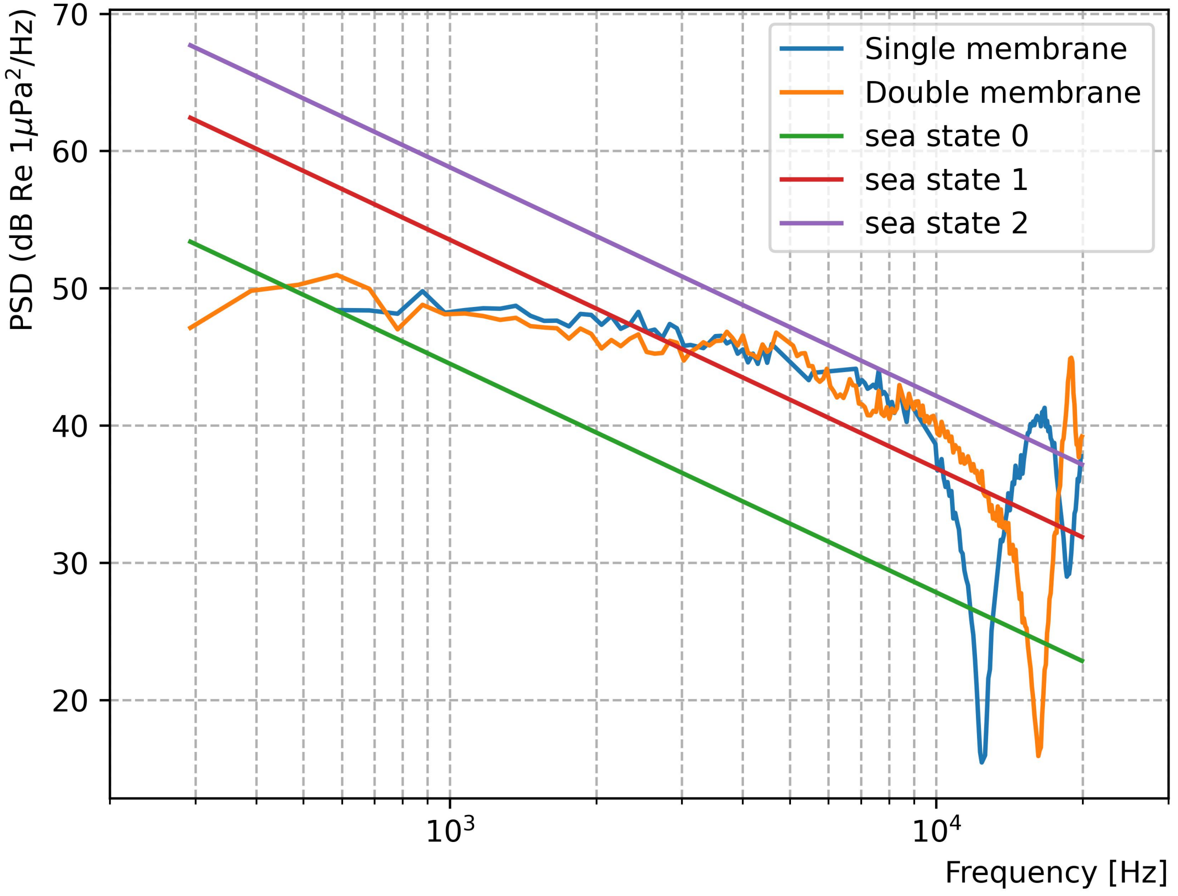
Conclusions

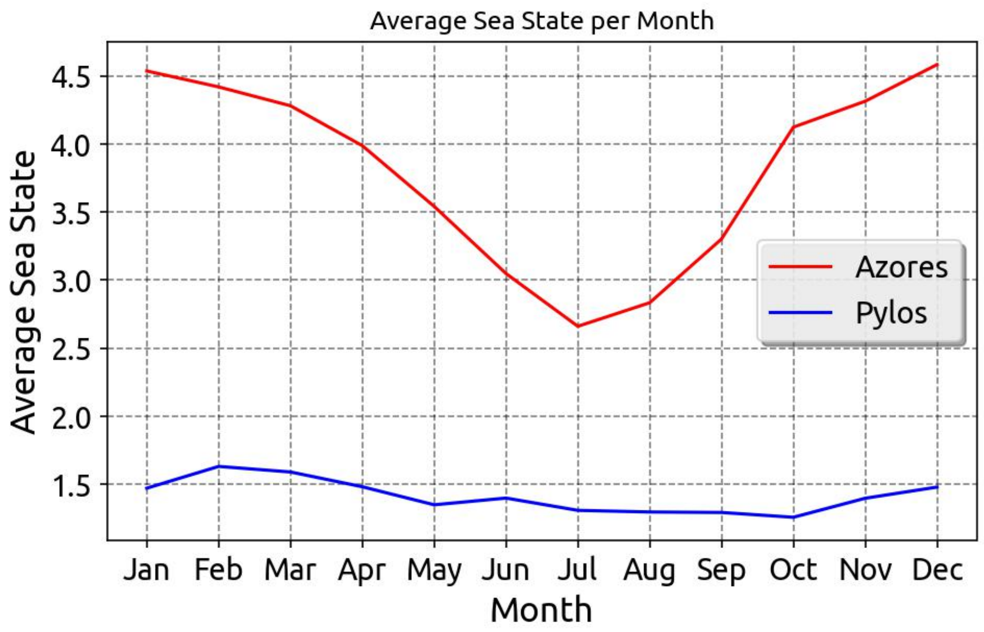
- Neutrinos are the messengers to probe the cosmic ray spectrum beyond the GZK cut-off, i.e beyond 10^{10} GeV.
  - Neutrinos from the induced at the GZK cut-off are a garantueed source;
- New detections methods are needed to probe this energy scale and acoustic detetction may be an means to establish a large volume telescope;
- Acoustic detection of neutrinos based on fiber optic sensors provides an enabler for a future acoustic neutrino telescope;
- Multidisciplinarity: oceanography, marine ecology, marine conservation;
- Benefit from heritage from KM3NeT (position calibration, underwater infrastructures, reconstruction).

Back-up

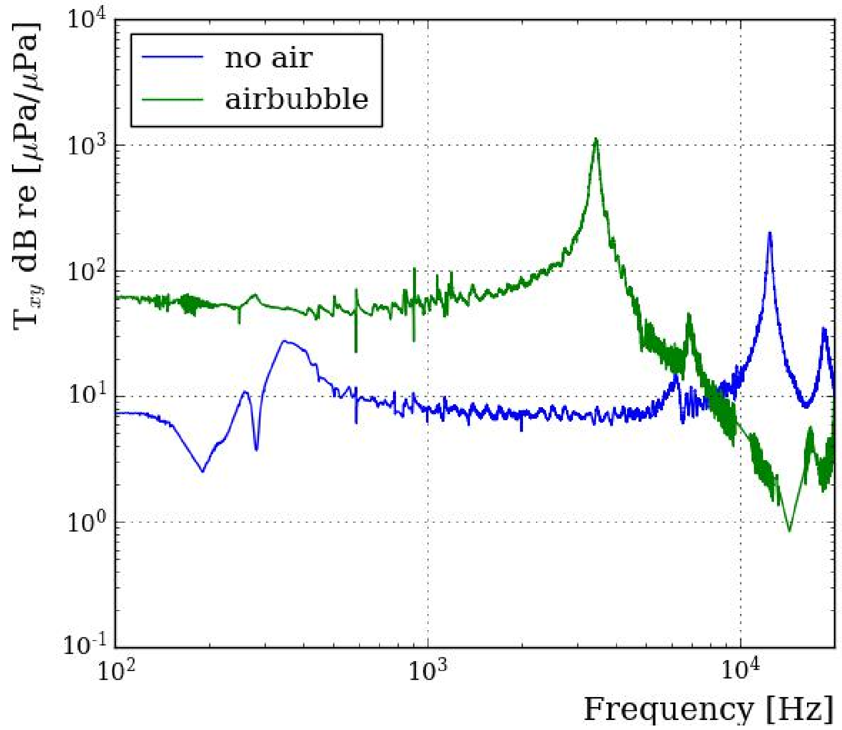
Hydrophone sensitivity

Compare sensitivity with 'seastate noise'

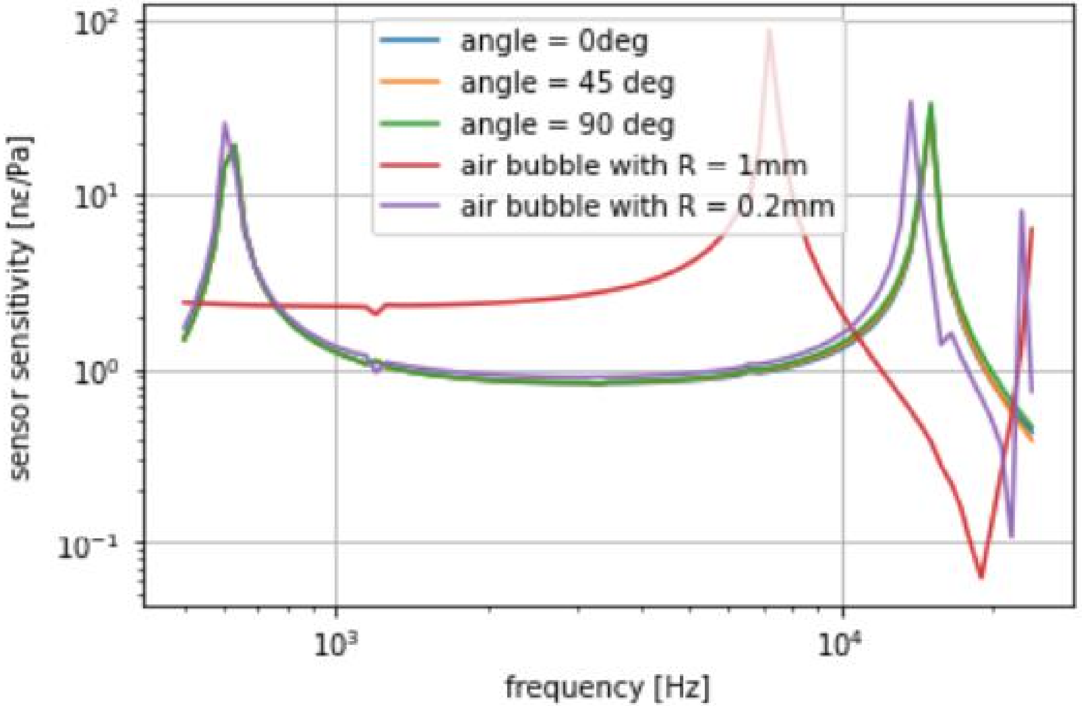




Instrument response: residual air



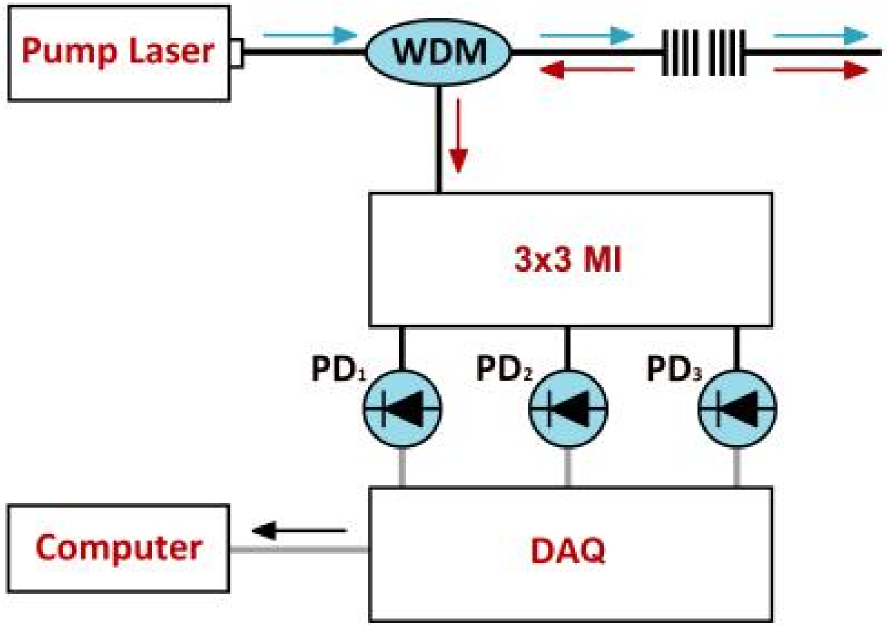
Comsol simulations



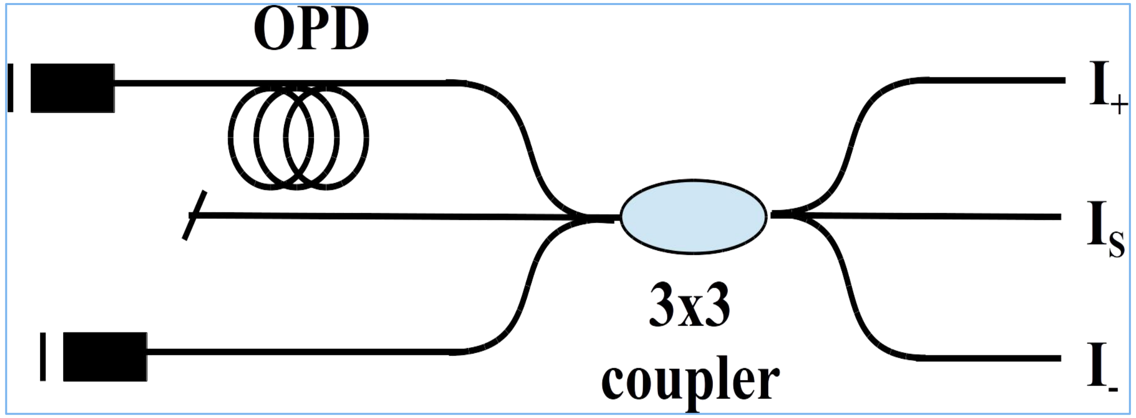
- **Residual air in the transducer has a large impact on the transfer function!**
  (an air bubble of 1mm diameter has only 0.5% volume percentage)

- **Established a procedure to fill the sensor**

Data acquisition



3x3 arm Michelson interferometer



$$I_S(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD)).$$

$$I_+(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD+\frac{2\pi}{3})).$$

$$I_-(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD-\frac{2\pi}{3})).$$

$$OPD = \frac{\lambda}{2\pi}\arctan\left(\sqrt{3}\frac{I_+ - I_-}{2I_s - I_+ - I_-}\right).$$