Fiber optic hydrophones for acoustic neutrino detection

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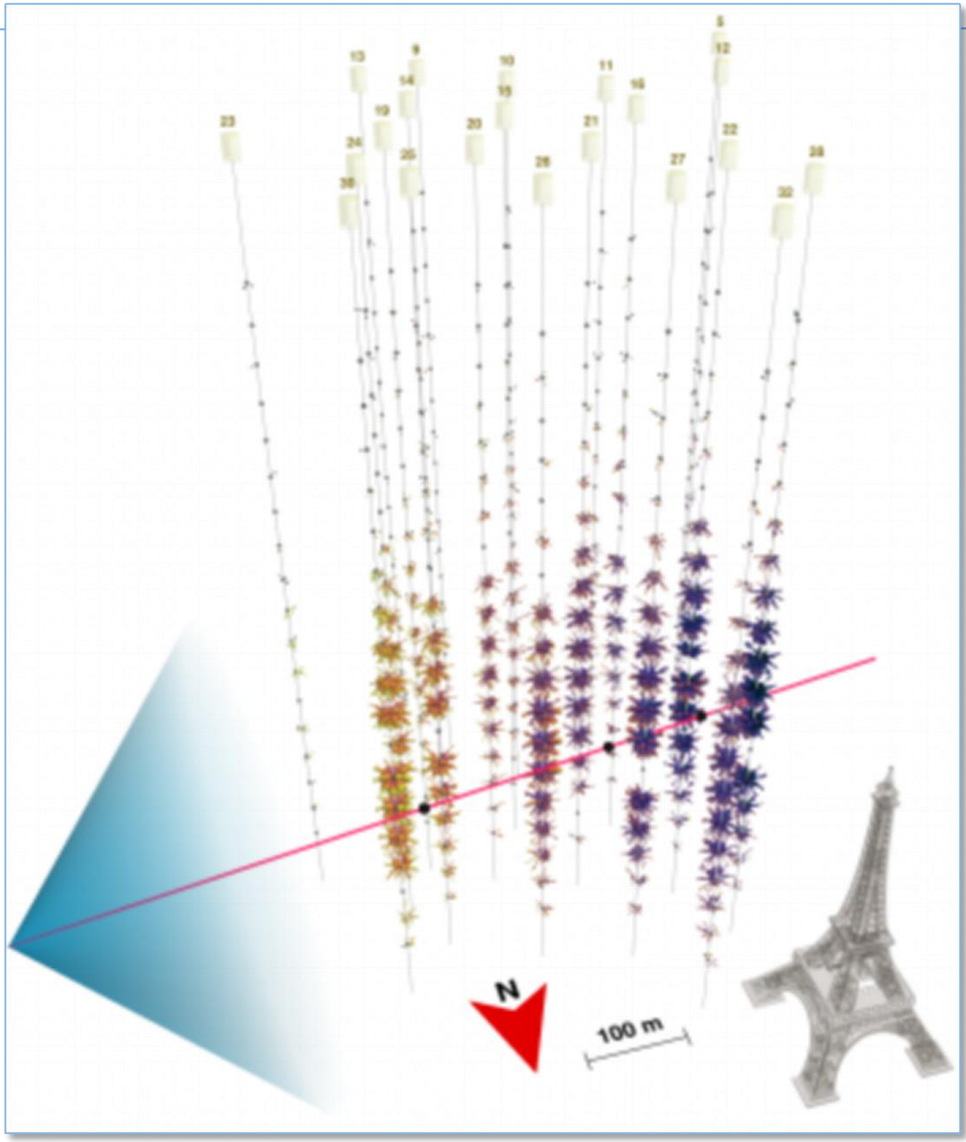
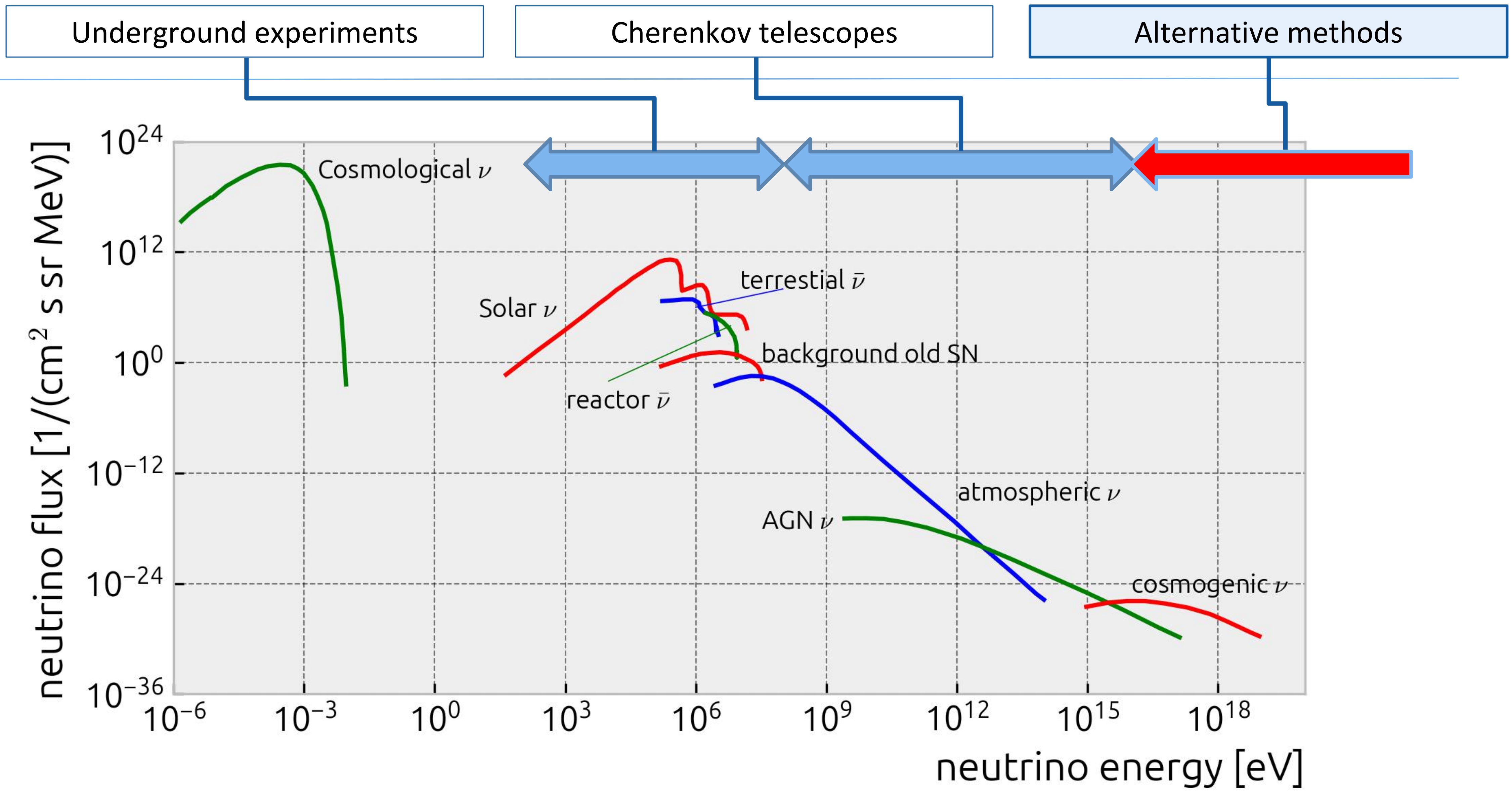
KM3-230213A

$$E_\mu = 120^{+110}_{-60} \text{ PeV}$$

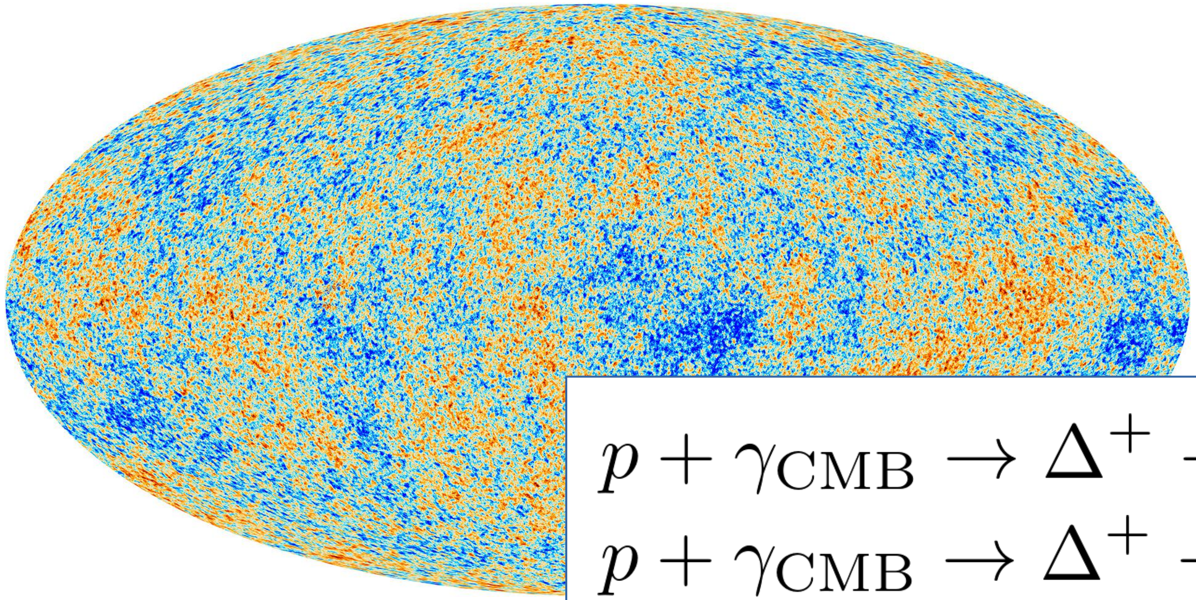
$$E_\nu = 220^{+570}_{-110} \text{ PeV}$$

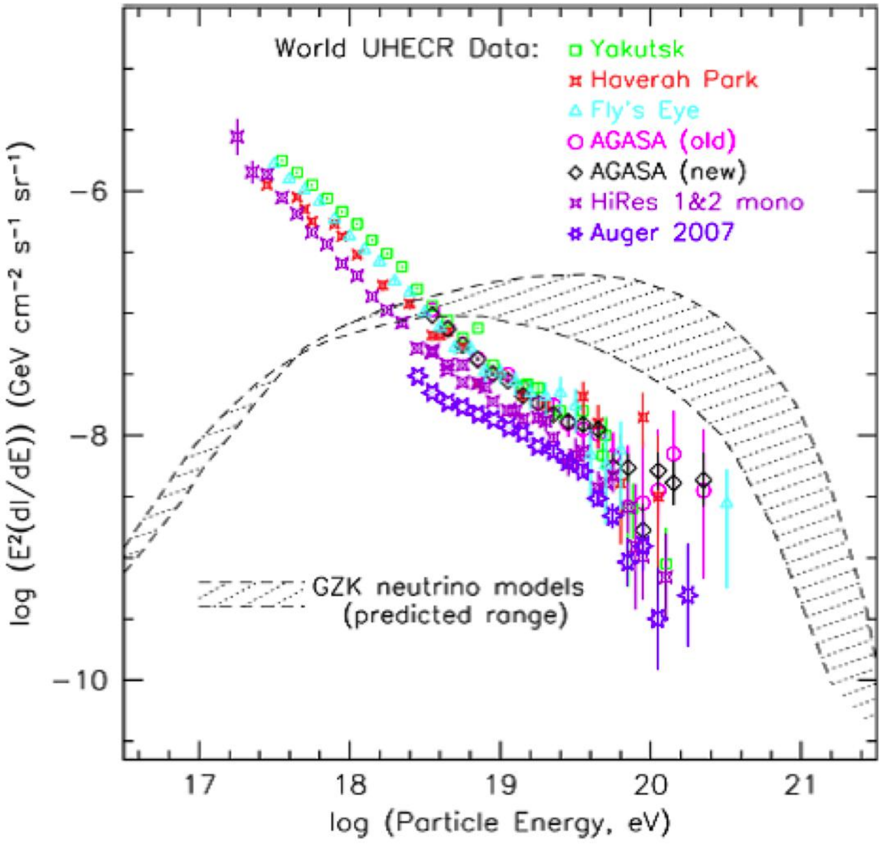



Underground experiments
Cherenkov telescopes
Alternative methods
Cosmological ν
Solar ν
terrestial $\bar{\nu}$
background old SN
reactor $\bar{\nu}$
atmospheric ν
AGN ν
cosmogenic ν
neutrino flux [1/(cm^2 s sr MeV)]
neutrino energy [eV]
10^{24}
10^{12}
10^{0}
10^{-12}
10^{-24}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}

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



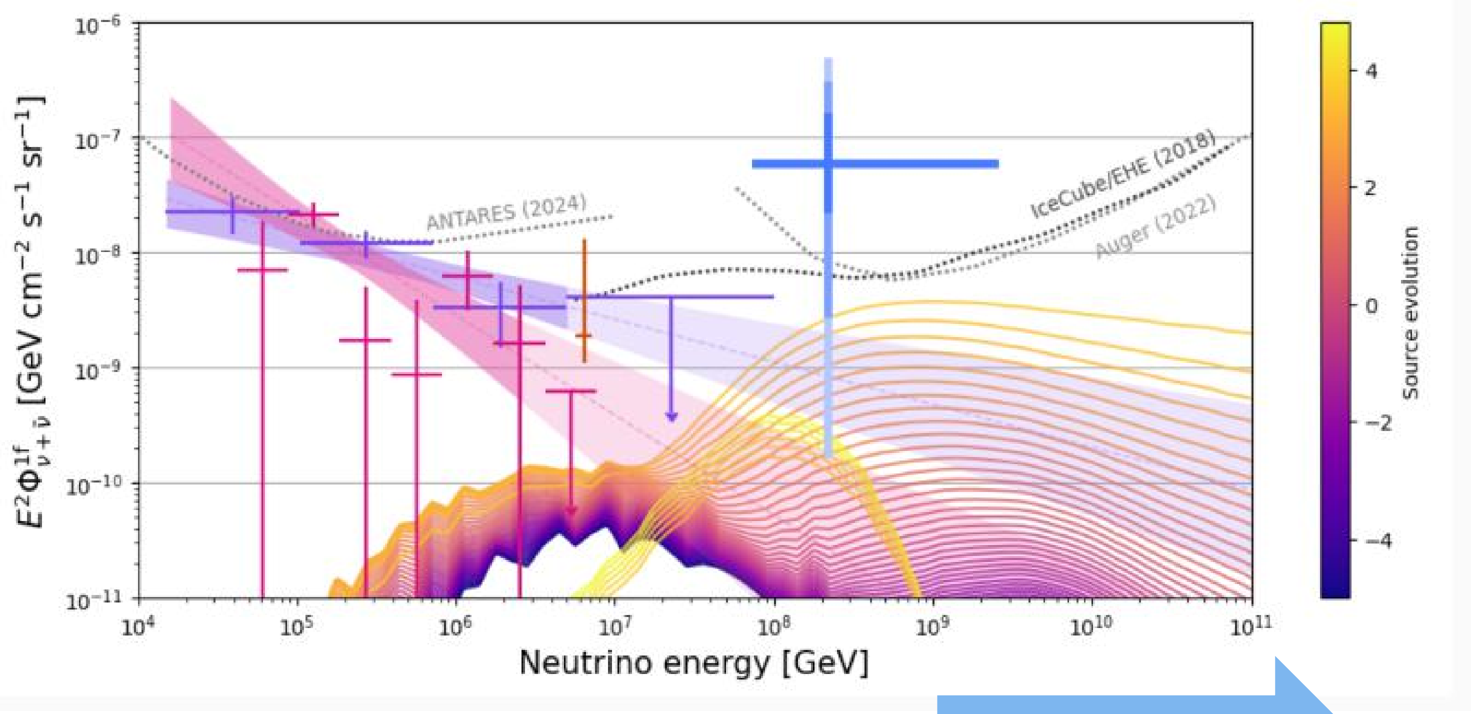


$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{o}$$
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

… with subsequent decay to *neutrinos*

A cosmic origin

Adriani et al, 2025



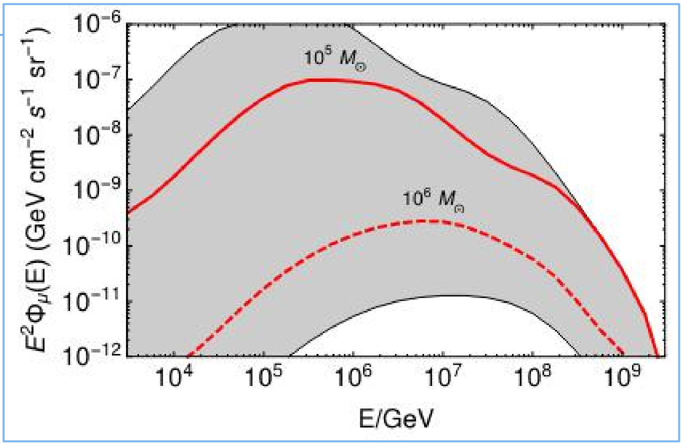
Acoustics!

- Flux predictions, depends on the composition of the cosmic rays (Protons, ions)
- VHE event shows a preference for proton dominated cosmic flux
- (Flux prediction differs with more than 3 orders of magnitude)

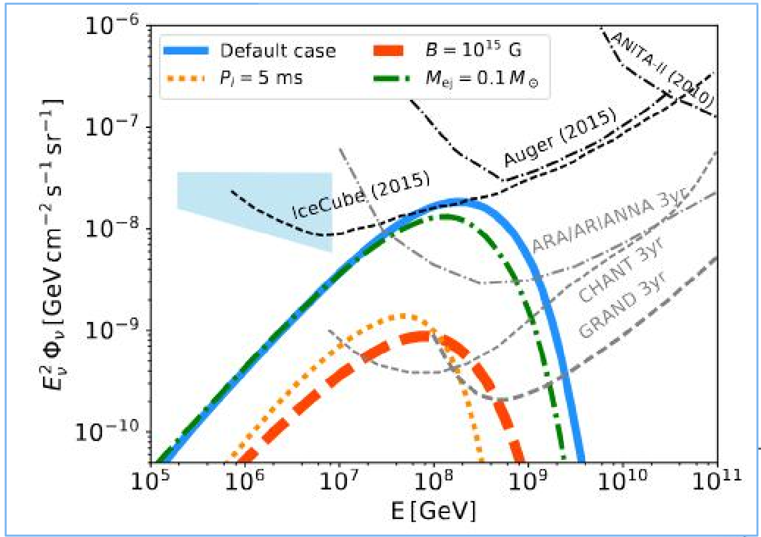
Scientific objectives of an acoustic telescope

- Astrophysical sources, origin of UHECR:
  - GZK neutrinos
  - AGNs, Blazars
  - Tidal Disuption Events (TDE)
  - Magnetars
- Exotics:
  - Superheavy dark matter
- Particle physics at energy scale presently unreachable
  - Cross section measurement
- Cosmic neutrino background
- Serendipity
  - Is there a fundamental end to the CR spectrum?

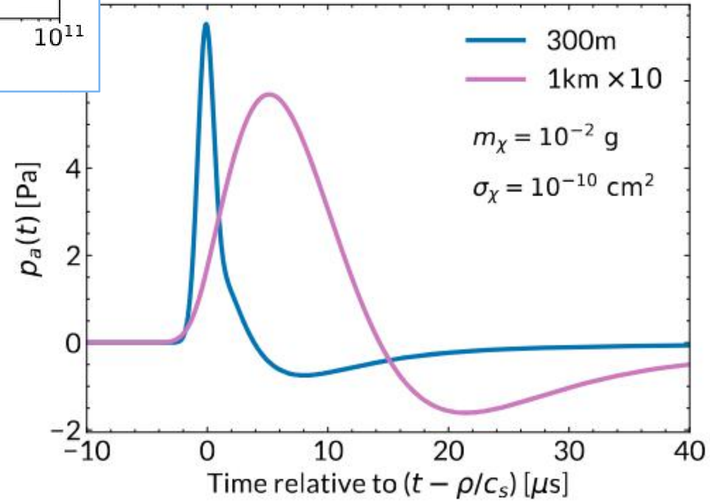
Lunardini, Winter 2017



Fang, Metzger 2017

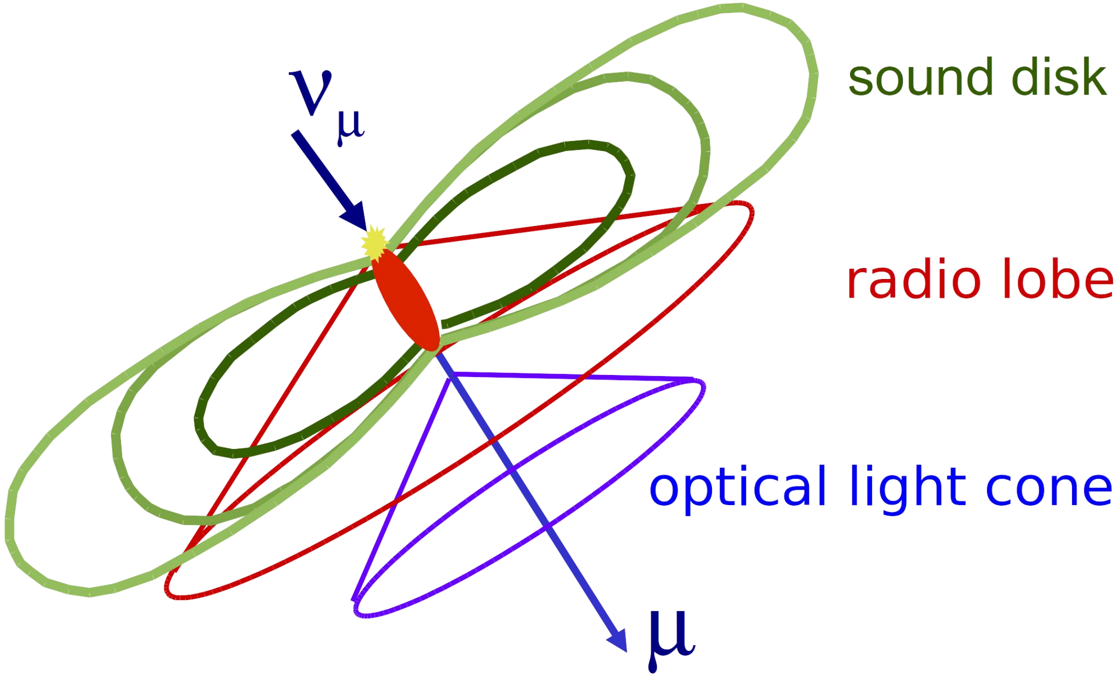


Cleaver et al, 2025



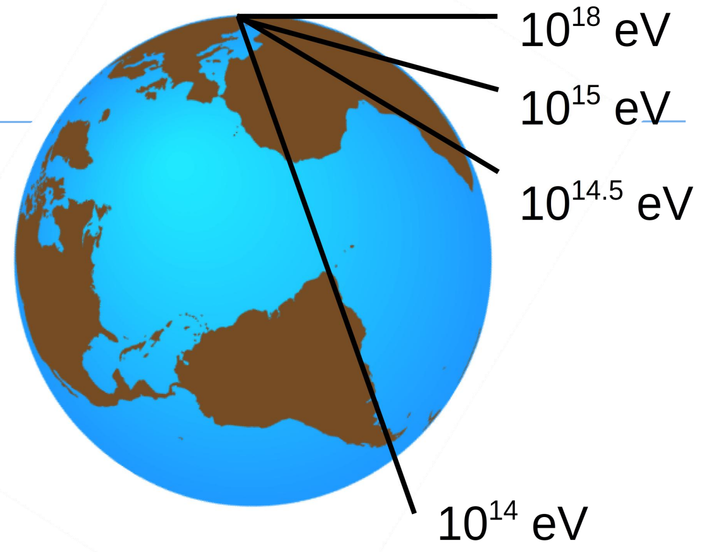
Detection of high energy neutrinos

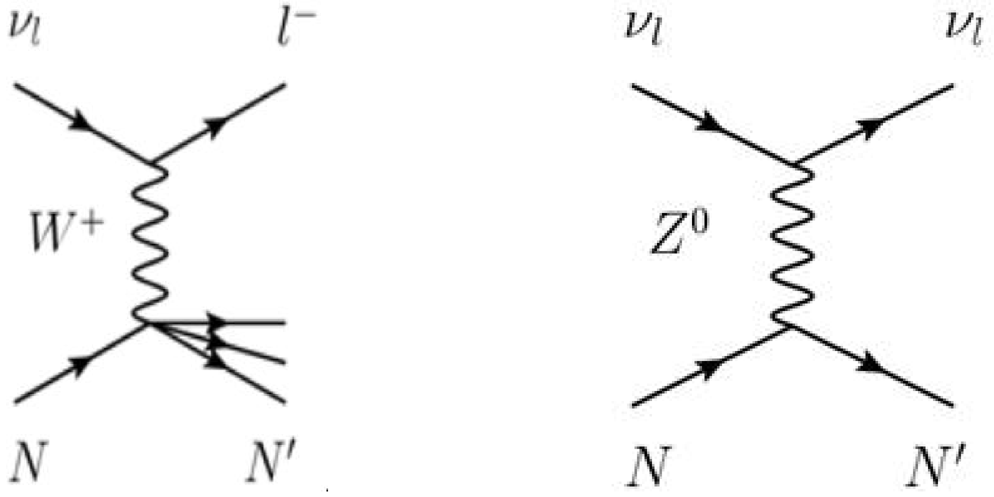
- Three methods of observing neutrinos in large scale telescopes
  - Optical, Cherenkov radiation
  - Coherent radio emission
  - *Acoustic signals*



Neutrino interactions in water

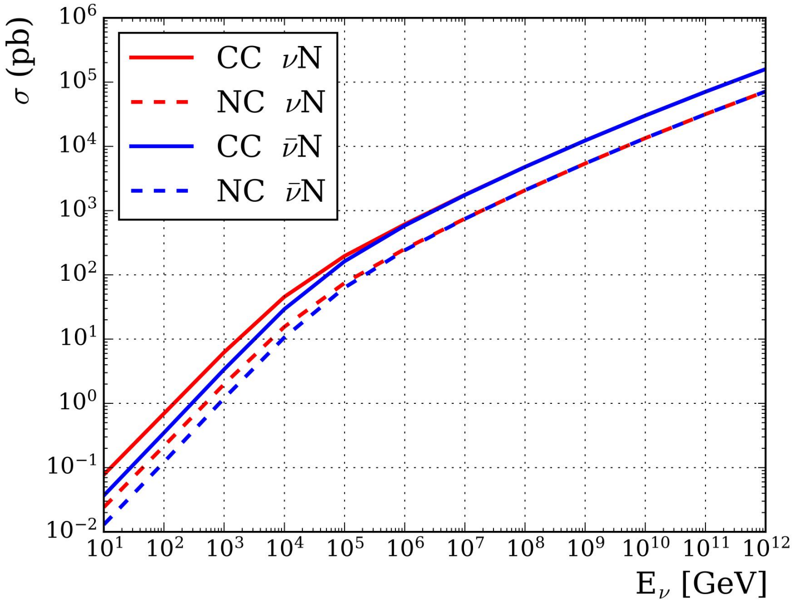
- Both neutral and charge current interactions.
- Assume tau and muon escape unobserved.
- Cross section increases with energy
  - Expect UHE neutrinos skimming or from zenith.





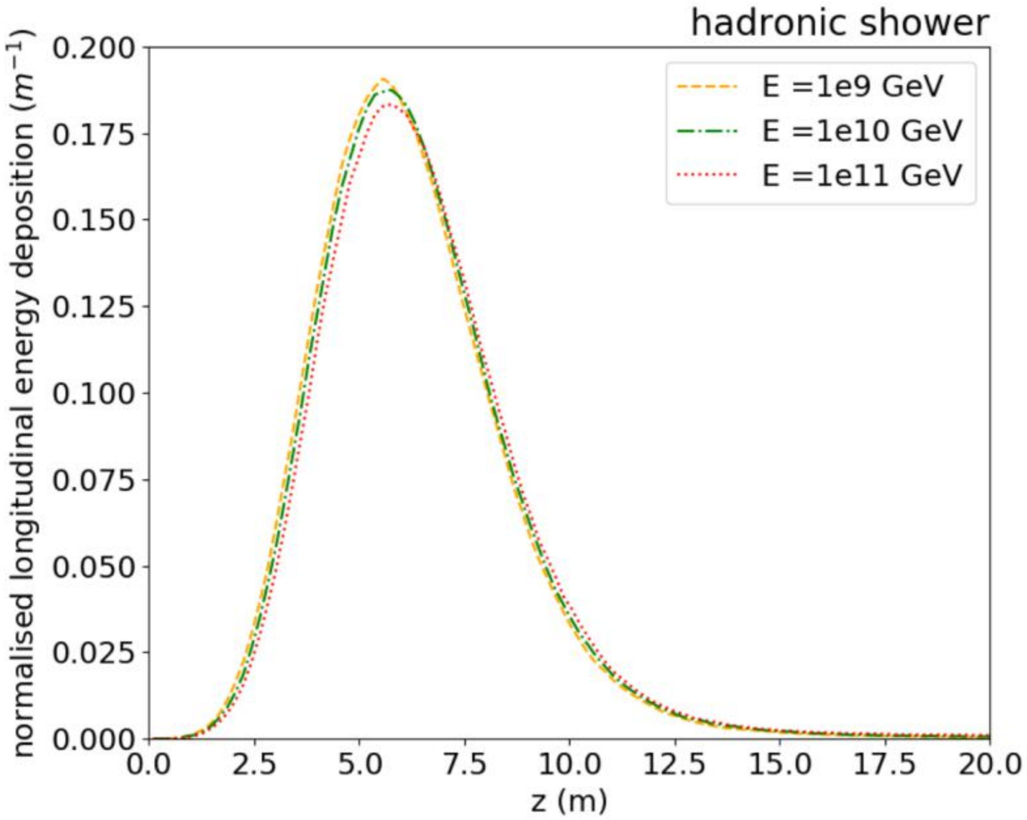
CC

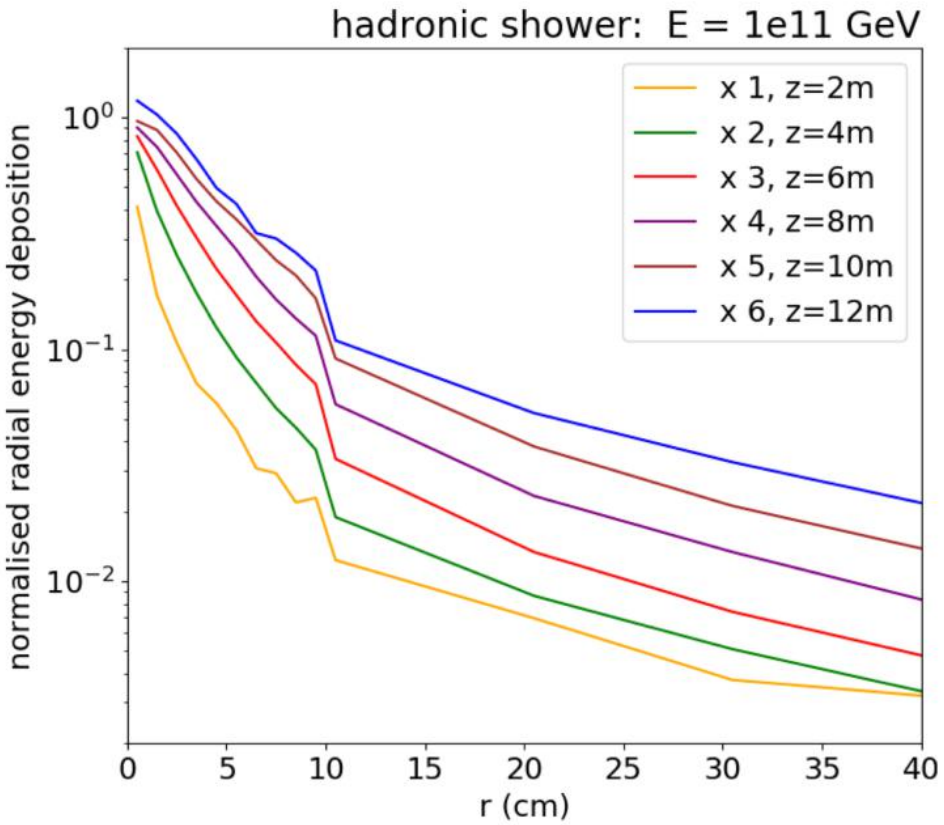
NC



Particle showers in water

- Particle showers include of hadronic and electromagnetic showers
- Both longitudinal and radial energy deposition





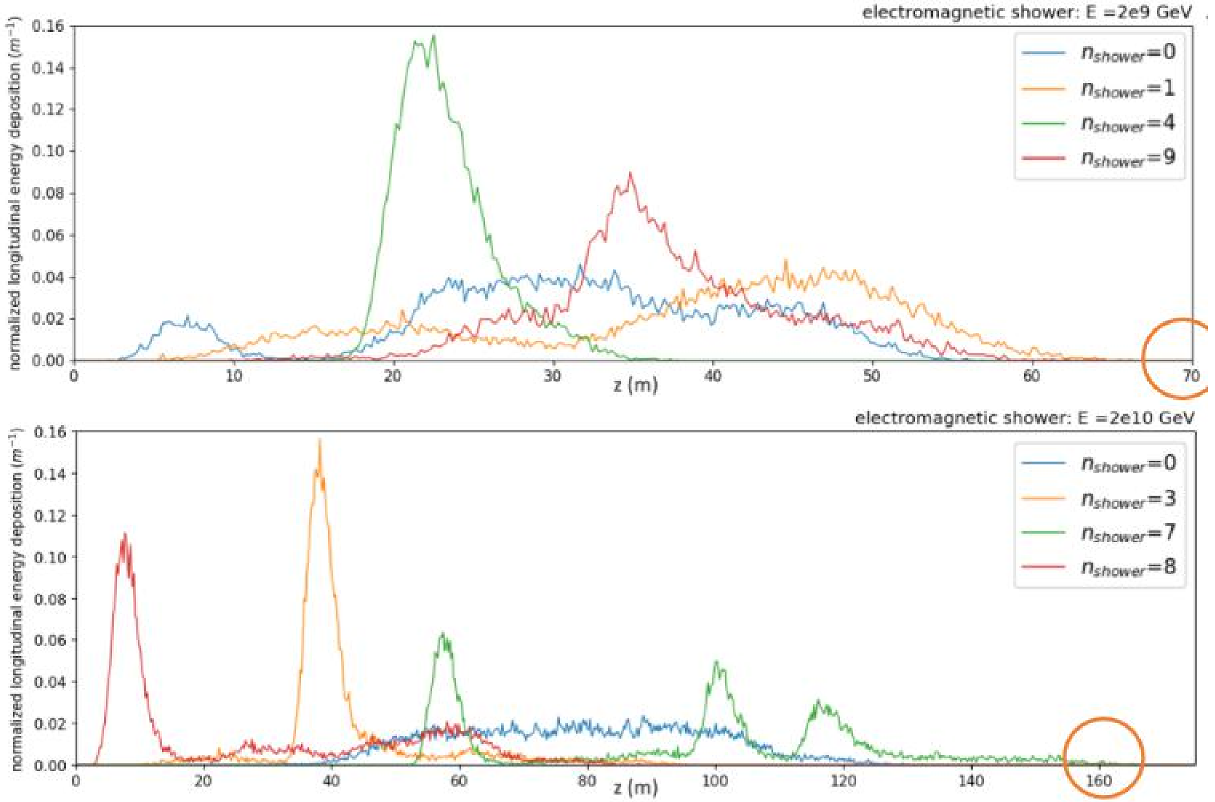
Particle showers in water at the highest energies

- At energies above the shower geometries are affected by the LPM effect
  - Reduce cross sections for EM processes in the shower

- Extended longitudinal energy distribution, subshowers

- Pronounced in EM showers

- Corsika simulations



C. Gatius, MSc thesis

Acoustic neutrino signals

- First idea by Askaryan (1957)
- Wave equation **p** is given by energy deposition *ε*.

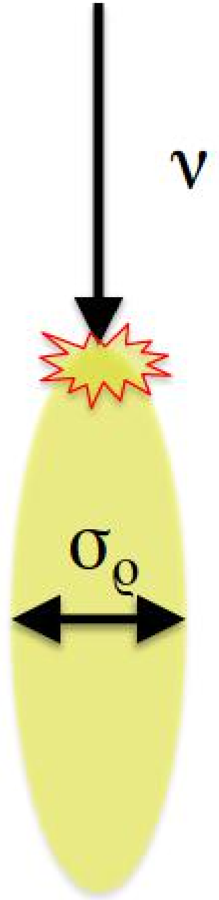
$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{C_p}\frac{\partial^2 \varepsilon}{\partial t^2}$$

Water properties:

c = speed of sound

C_p = expansion coefficient

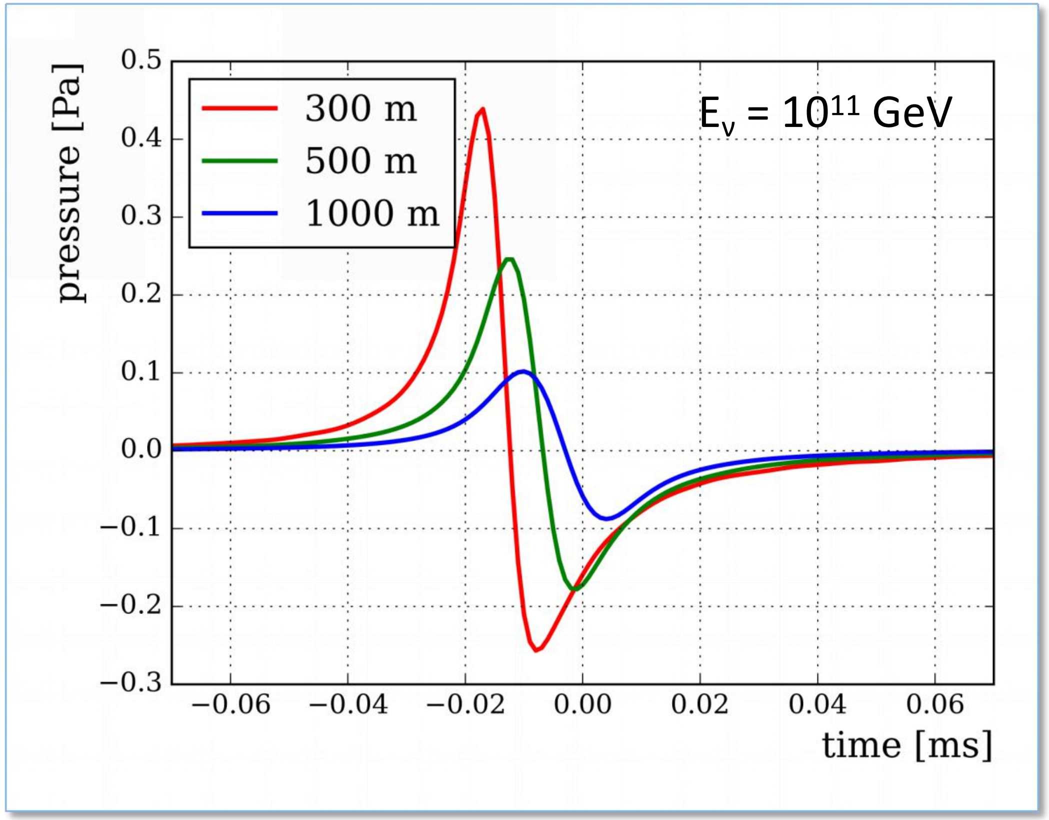
α = heat capacity



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

$$\gamma_G \equiv c_s^2 \alpha / c_p$$ Grüneisen parameter

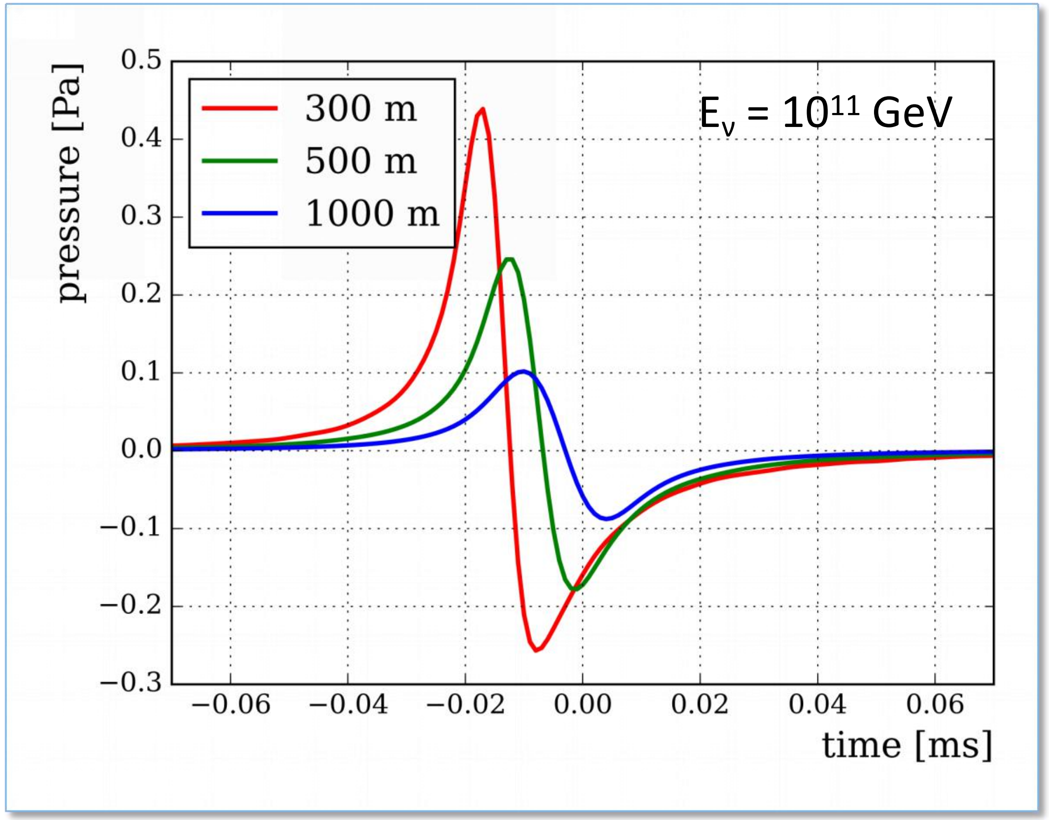
Acoustic neutrino signals

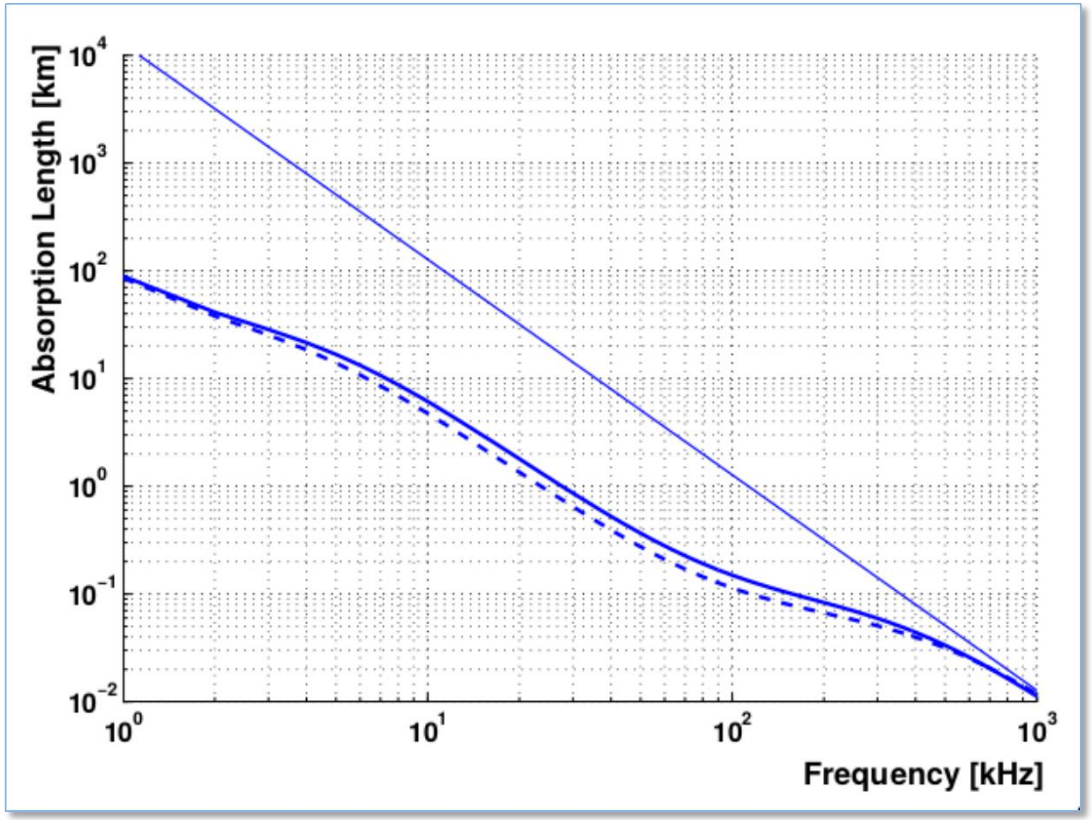


- Pulse asymmetry
- Broad spectrum that peaks at 5-12 kHz.
- Near field effects
- Complex waveforms in case of LPM effect

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

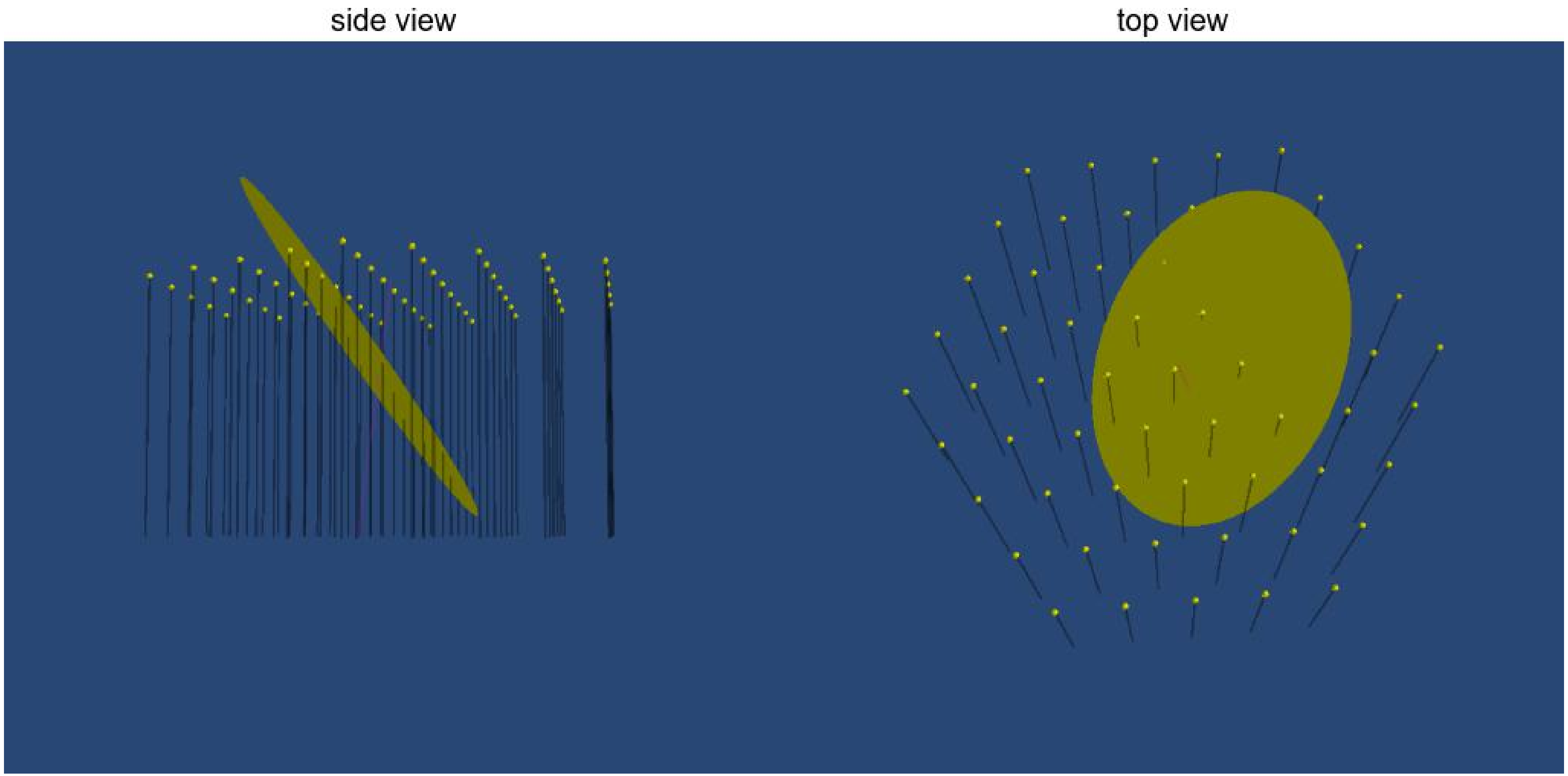
Acoustic neutrino signals





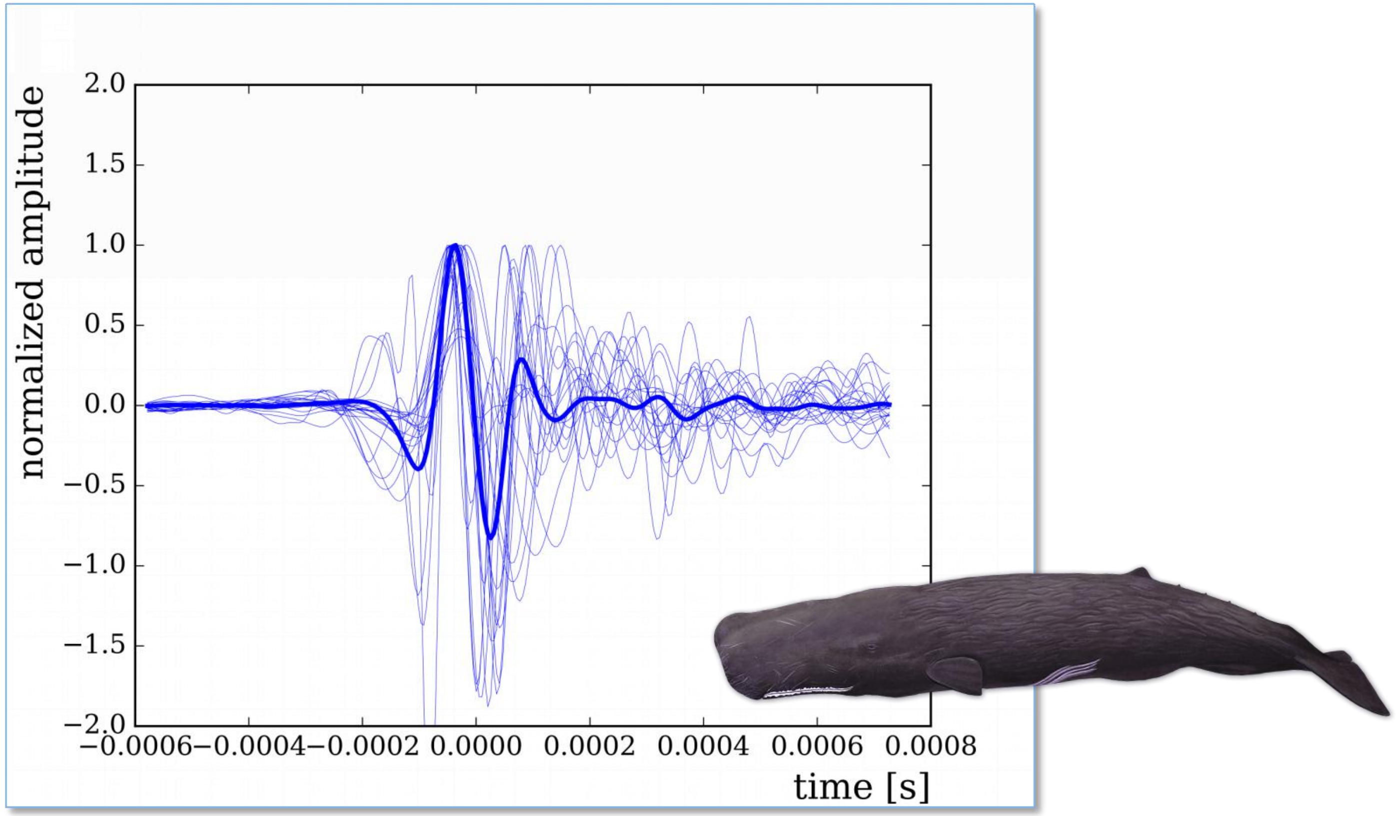
-> Detect **mPa** pulses in a static pressure environment of **MPa**

Event topology



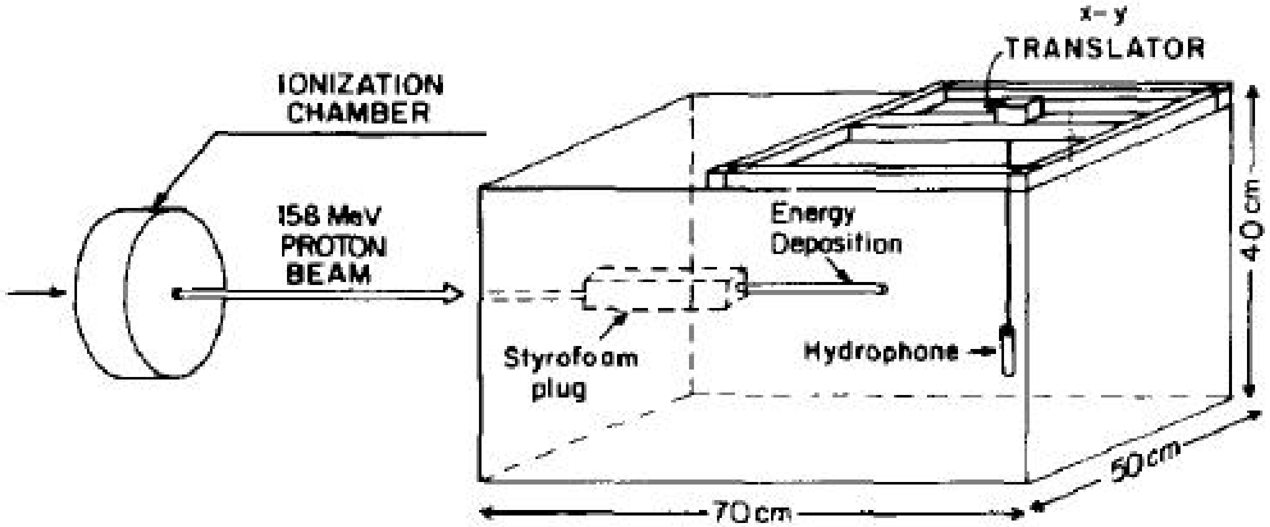
Expected noise sources

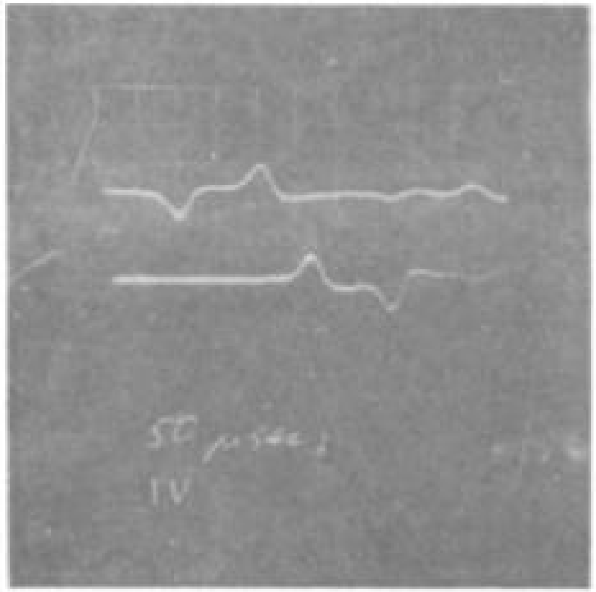
- Sea state noise:
  - Omnipresent, wide-band noise.
  - Related to weather conditions
- Marine biology
  - sound clicks from sperm whales
- Shipping noise
  - mostly low frequent and continous acoustic source



Acoustic detection of particles

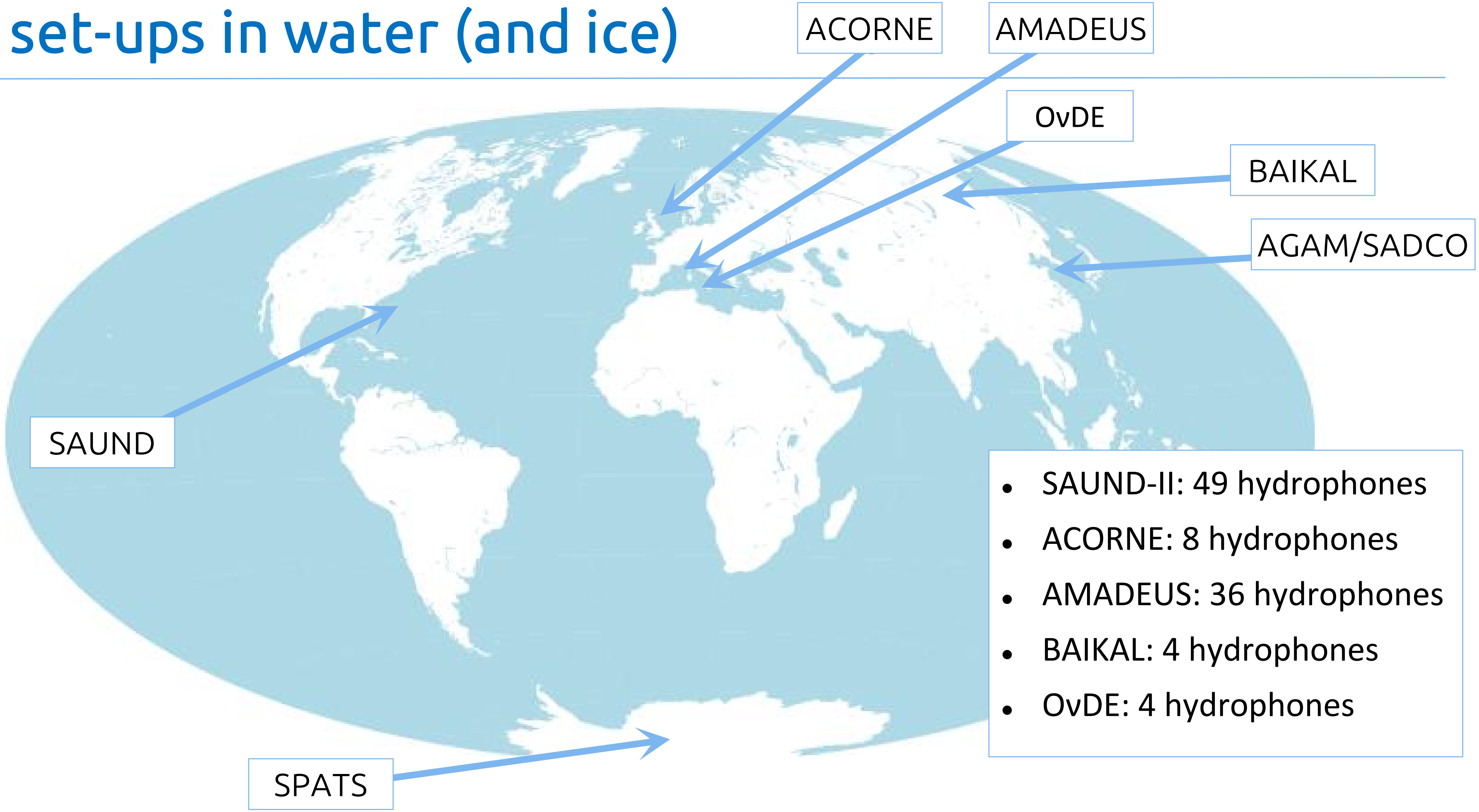
- Acoustic signal of particle beams already studied and measured in the 60s and 70s.
- Measurements using proton and electron beams at Brookhaven, Stanford, Khar'kov
  - Askaryan, Beron, Hofstadter, Learned, Sulak and others.





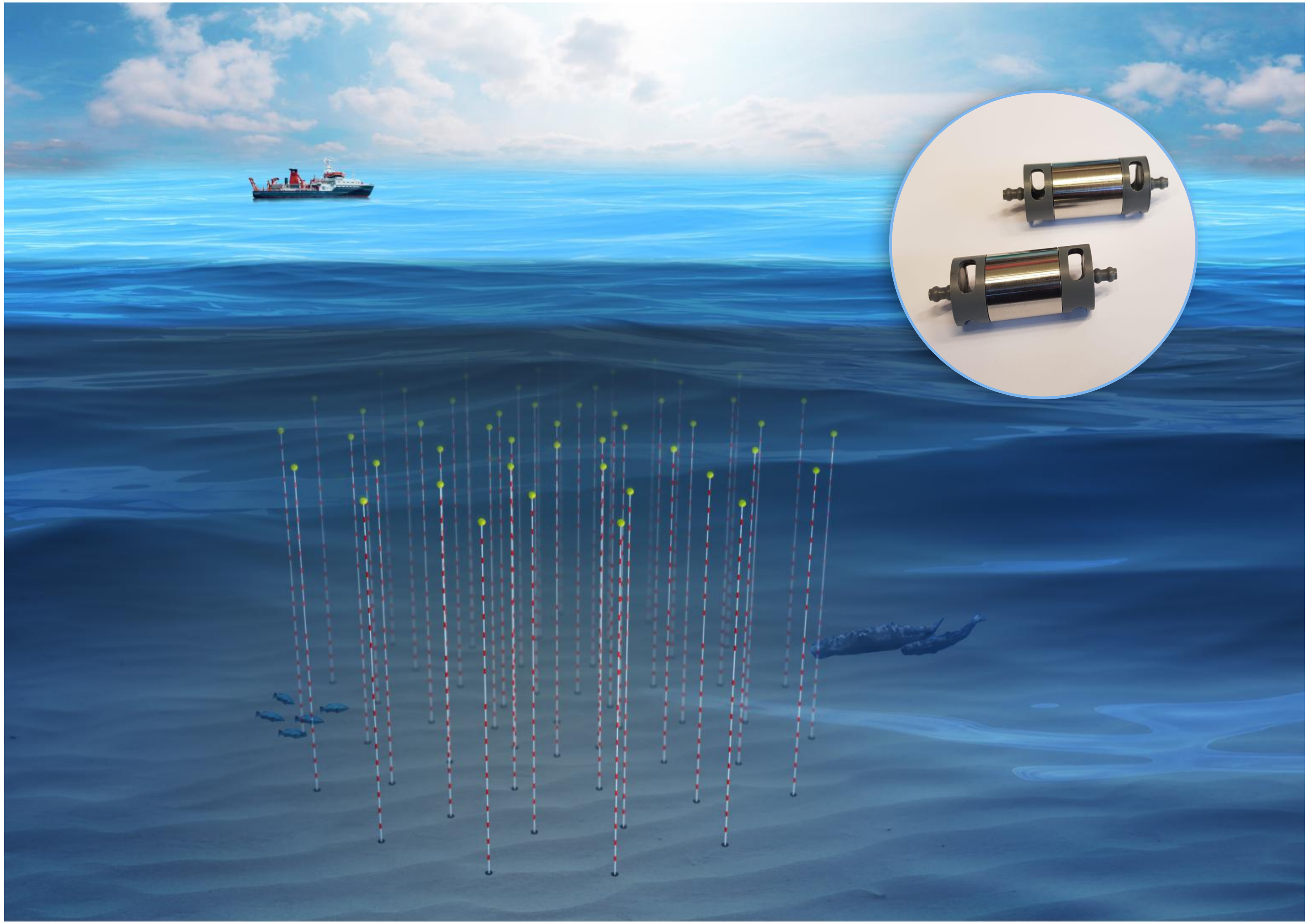
Sulak et al 1979

Test set-ups in water (and ice)

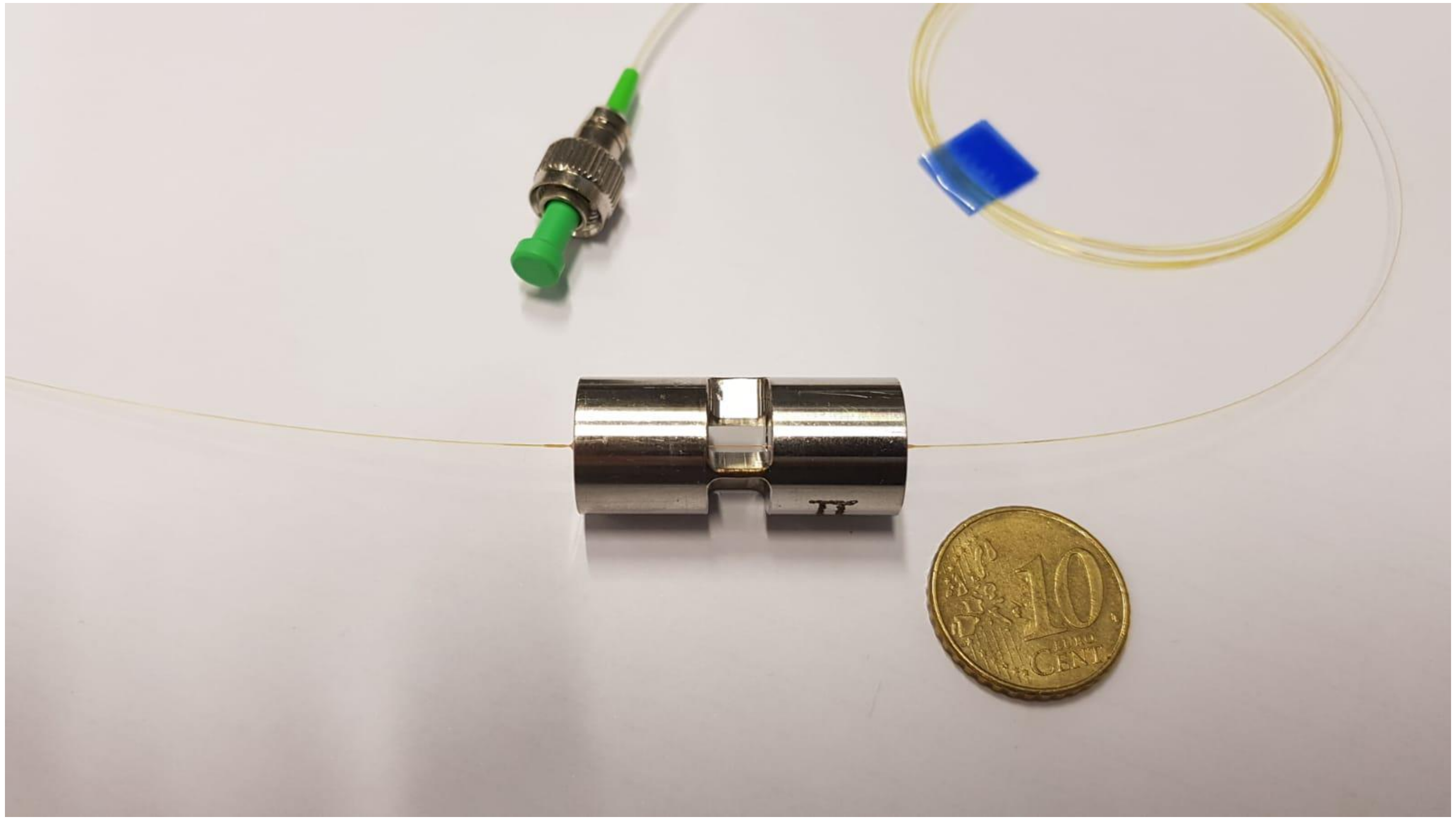


- SAUND-II: 49 hydrophones
- ACORNE: 8 hydrophones
- AMADEUS: 36 hydrophones
- BAIKAL: 4 hydrophones
- OvDE: 4 hydrophones

Future telescope concept

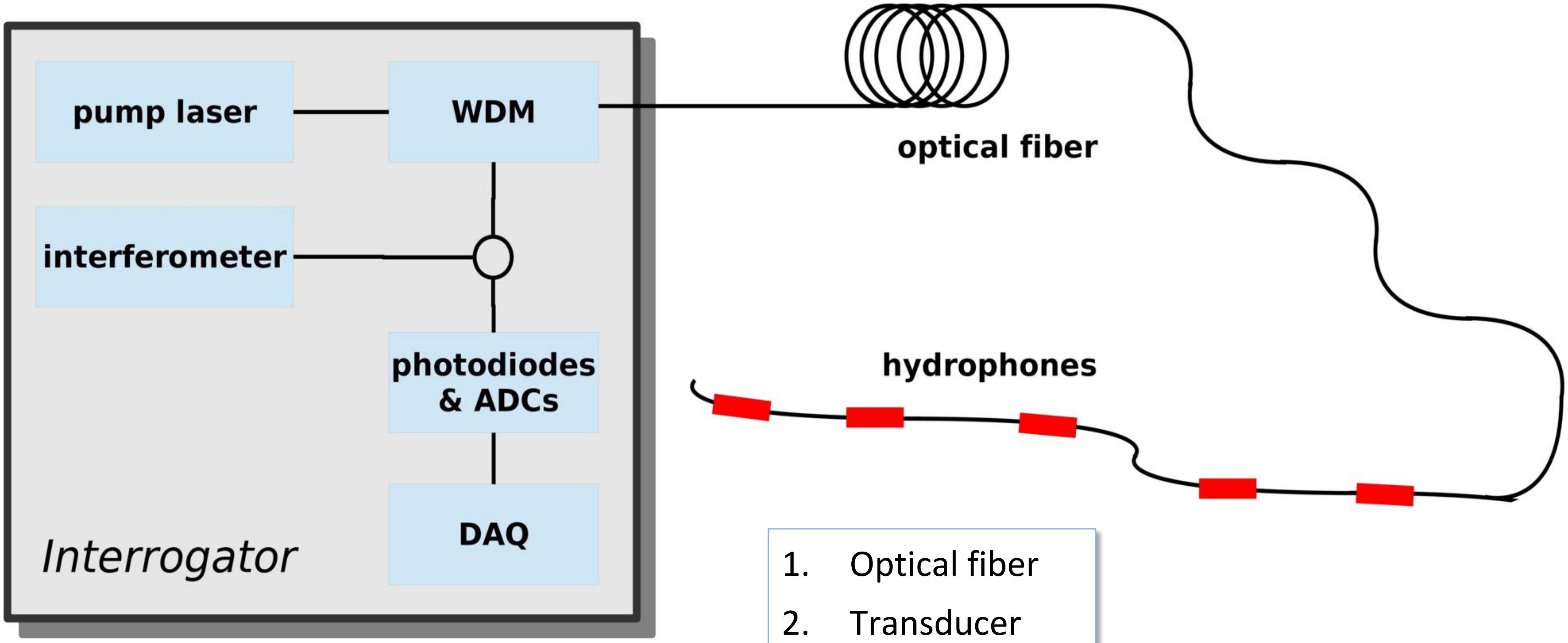


Future telescope concept … based on fiber hydrophones



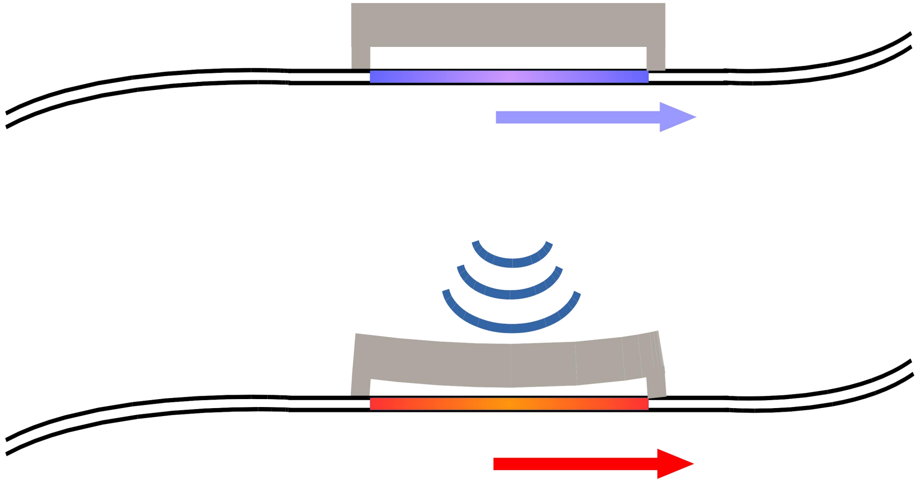
How to detect mPa pulses?

Future telescope concept … based on fiber hydrophones

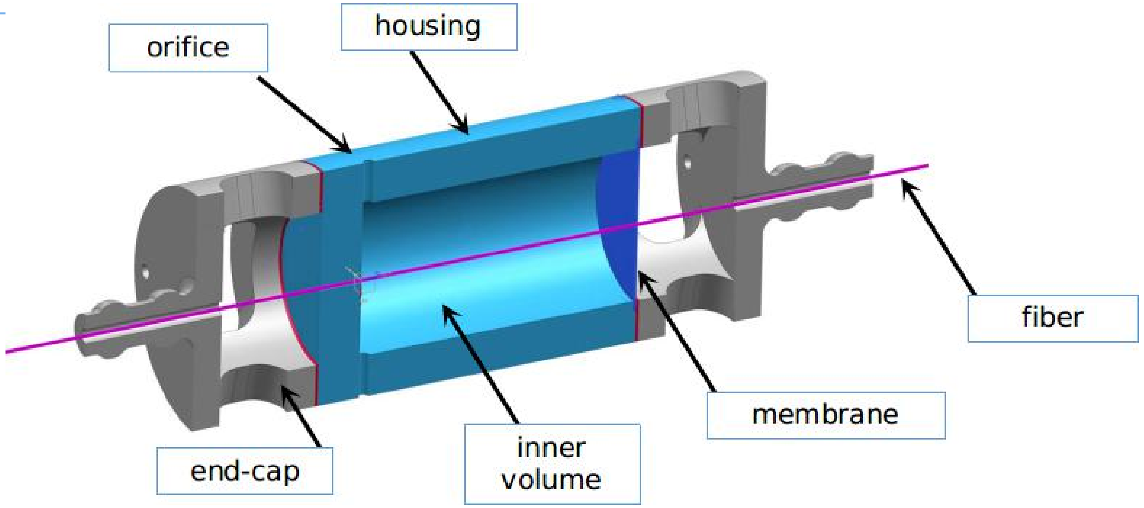


1. Optical fiber
2. Transducer
3. Interrogator

Fiber optic hydrophone concept

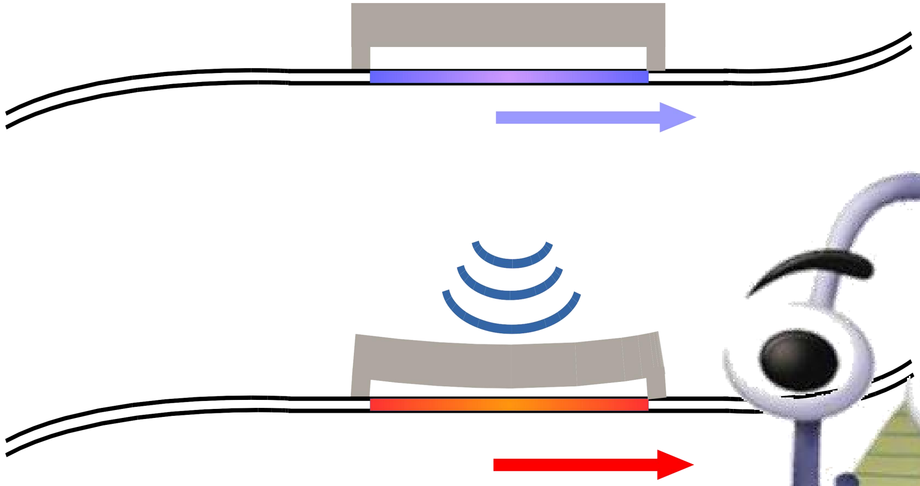


Transducer convert pressure into a wavelength shift.

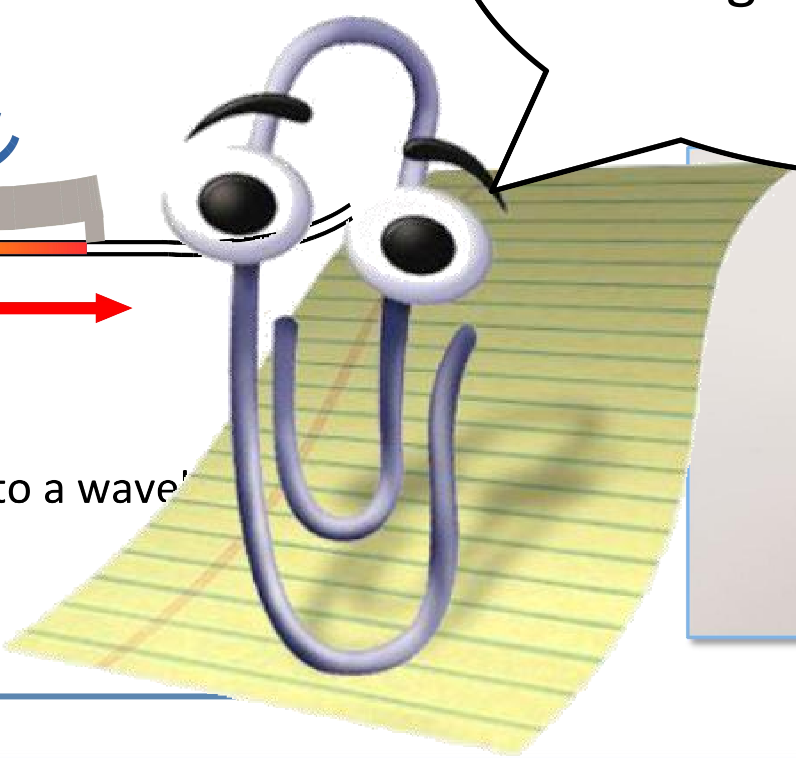


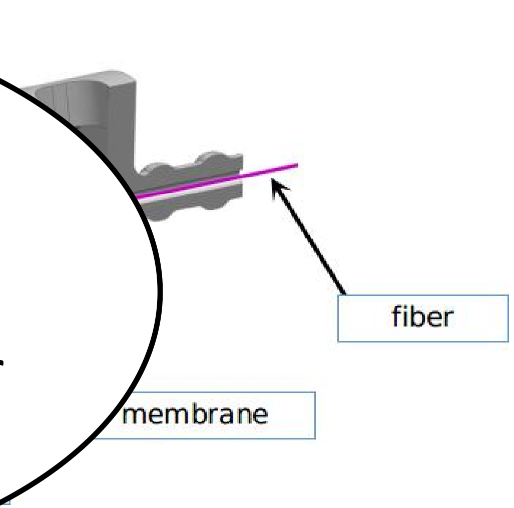
EJB et al., Astropart.Phys. 170 (2025) 103109 (arXiv:2501.12999)

Fiber optic hydrophone concept



Transducer convert pressure into a wave





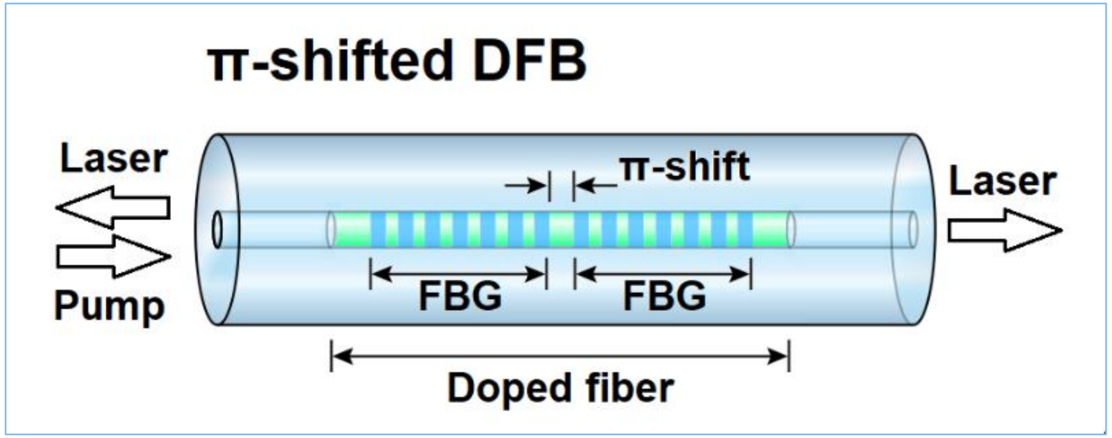
EJB et al., Astropart.Phys. 170 (2025) 103109 (arXiv:2501.12999)

Fiber laser

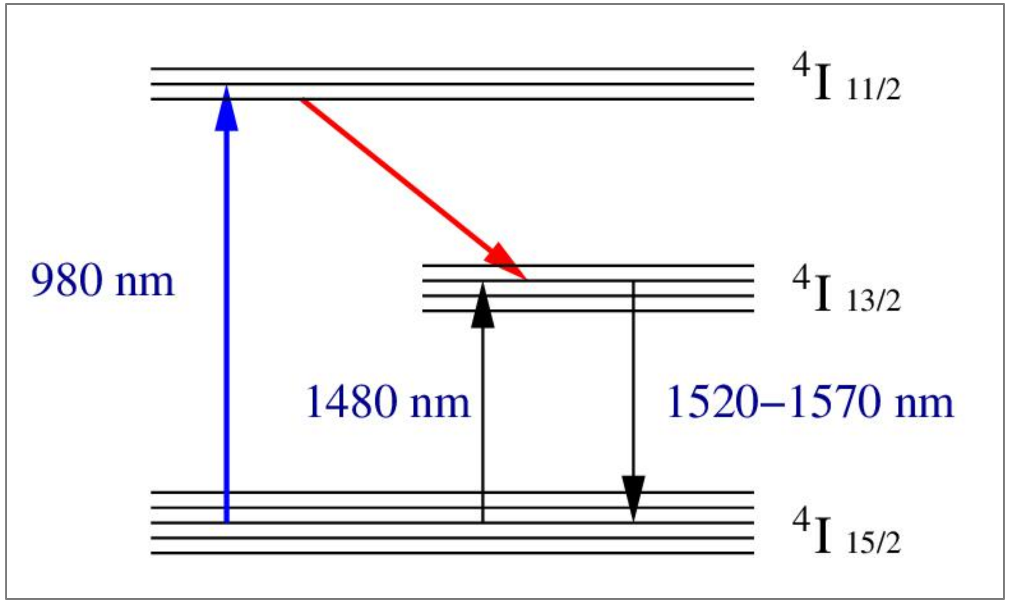
- Optical fiber includes fiber lasers
- Optical lasers are based on

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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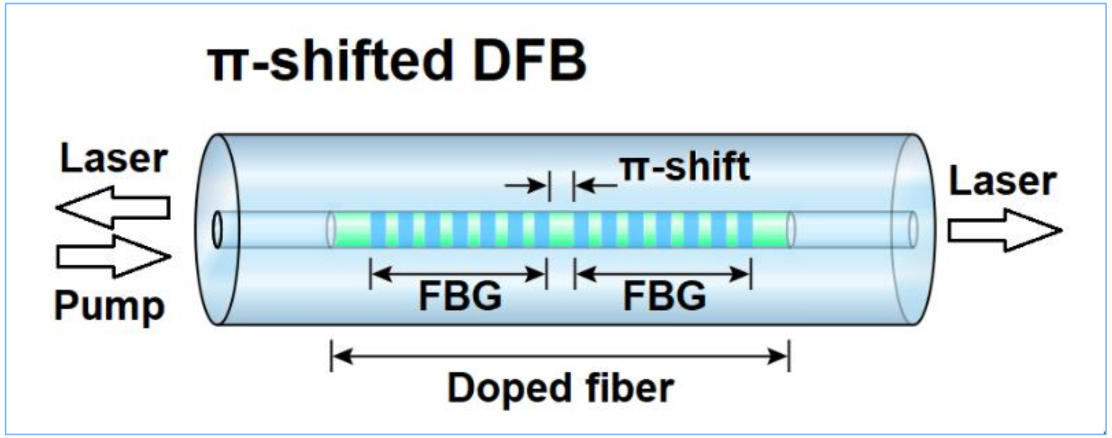
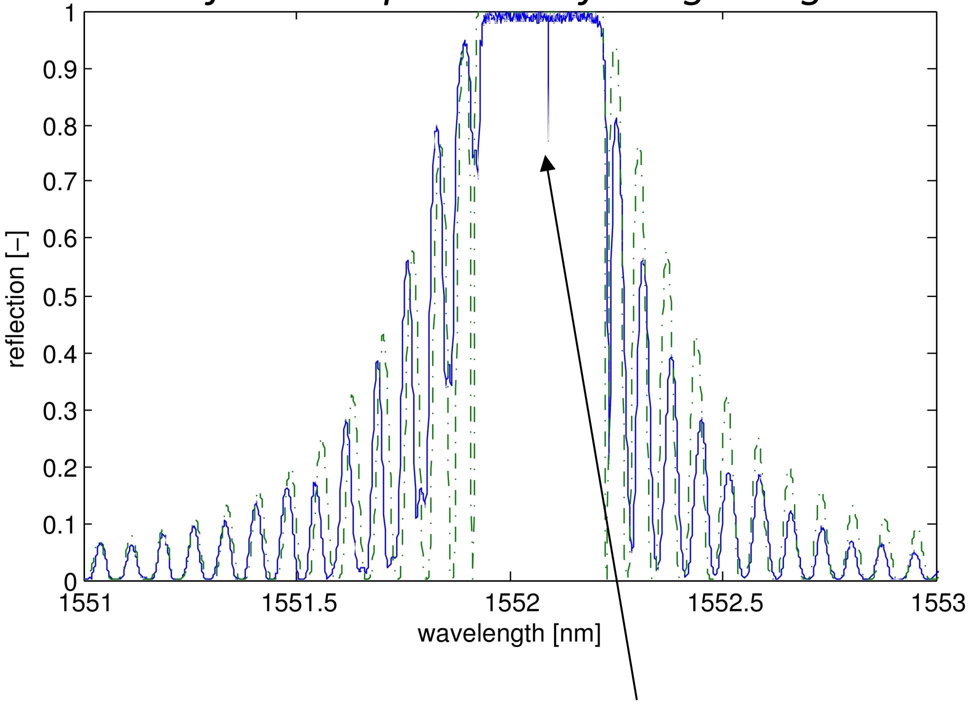
- Optical lasers are based on

  erbium doped fibers

- Grating structure applied to create a laser



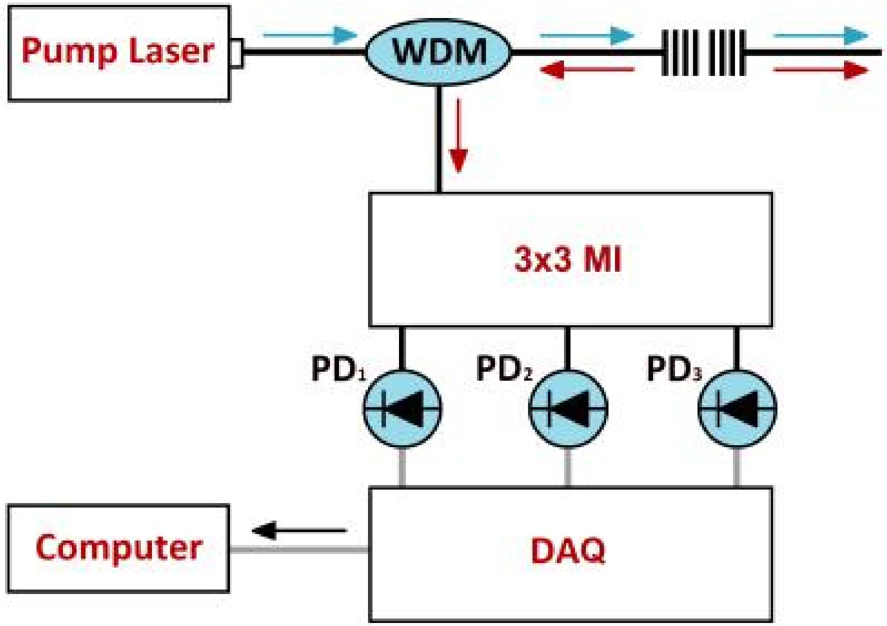
Reflection spectrum of the gratings

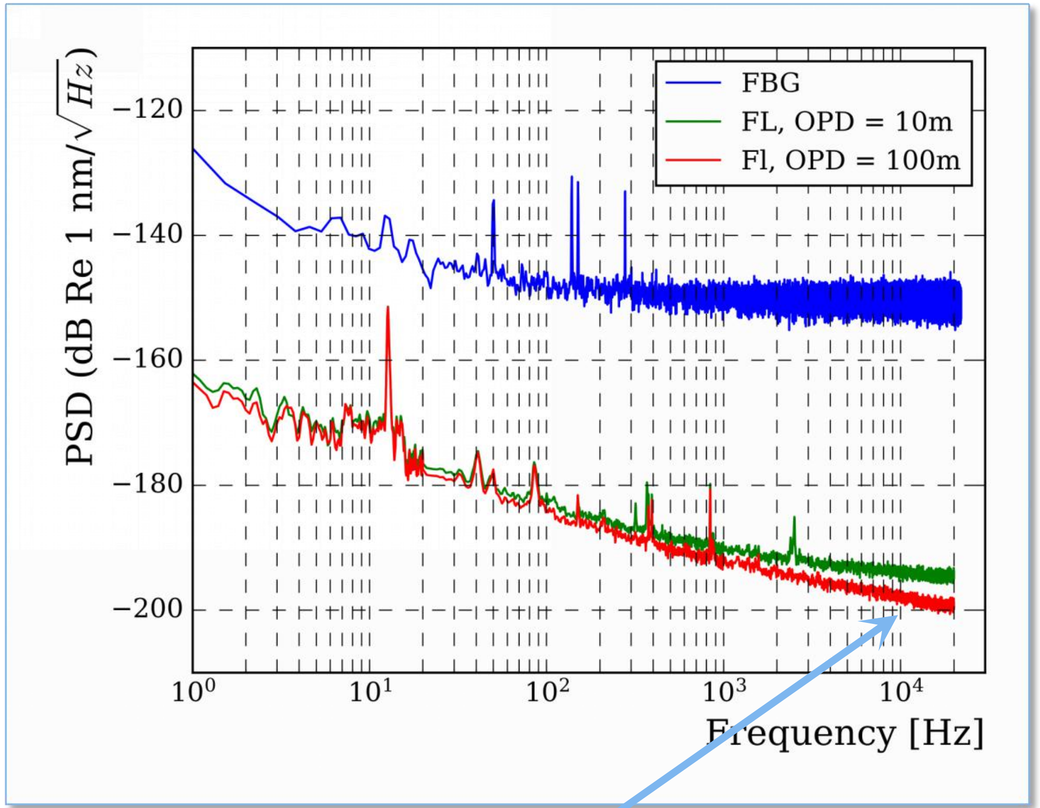


Coherent light source
(~1 fm linewidth)

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

Data acquisition



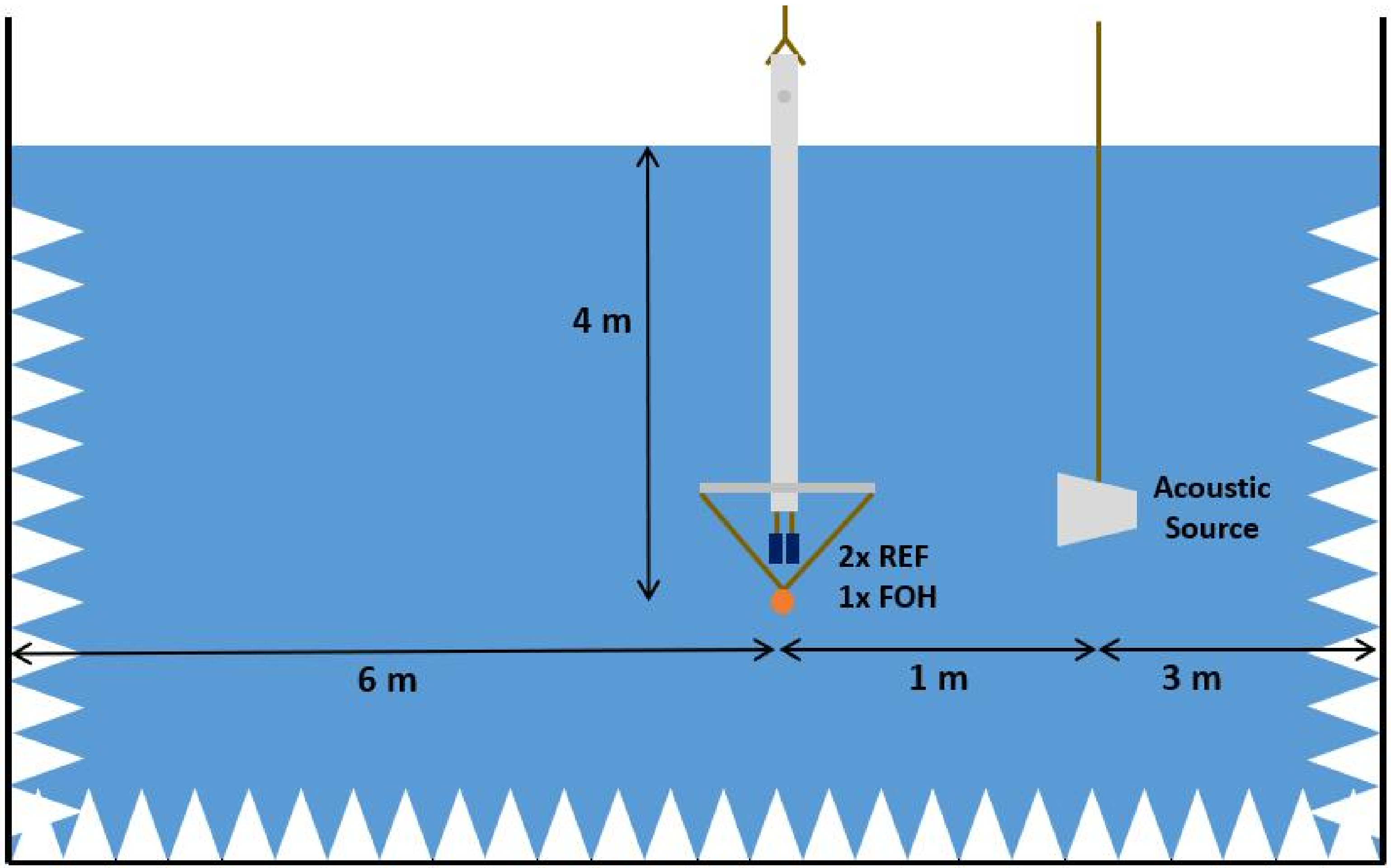


Interferometer sensitivity to **10^{-19} m/√Hz**

Experimental setup in an anechoic basin

- Anechoic basin at TNO the Hague
- $8 \times 10 \times 8\ m^3$

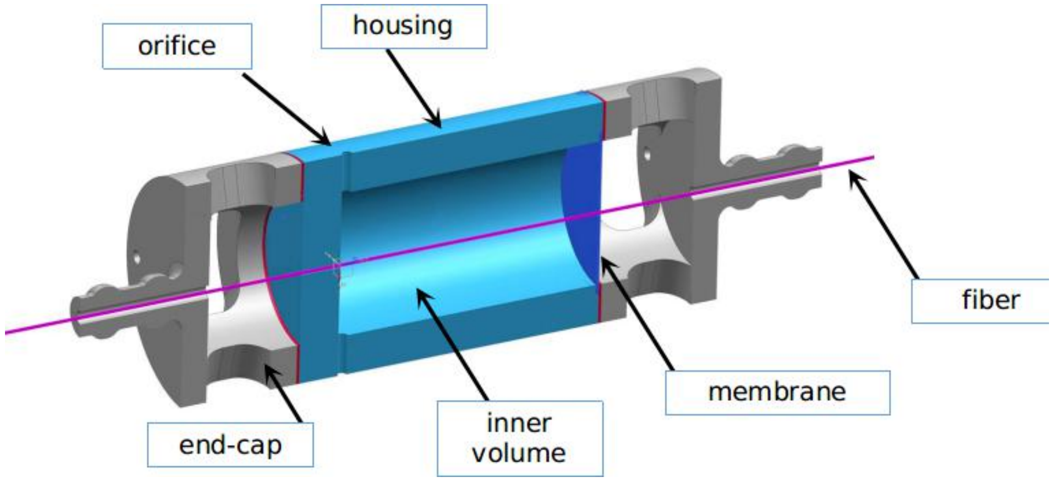
Experimental setup in an anechoic basin

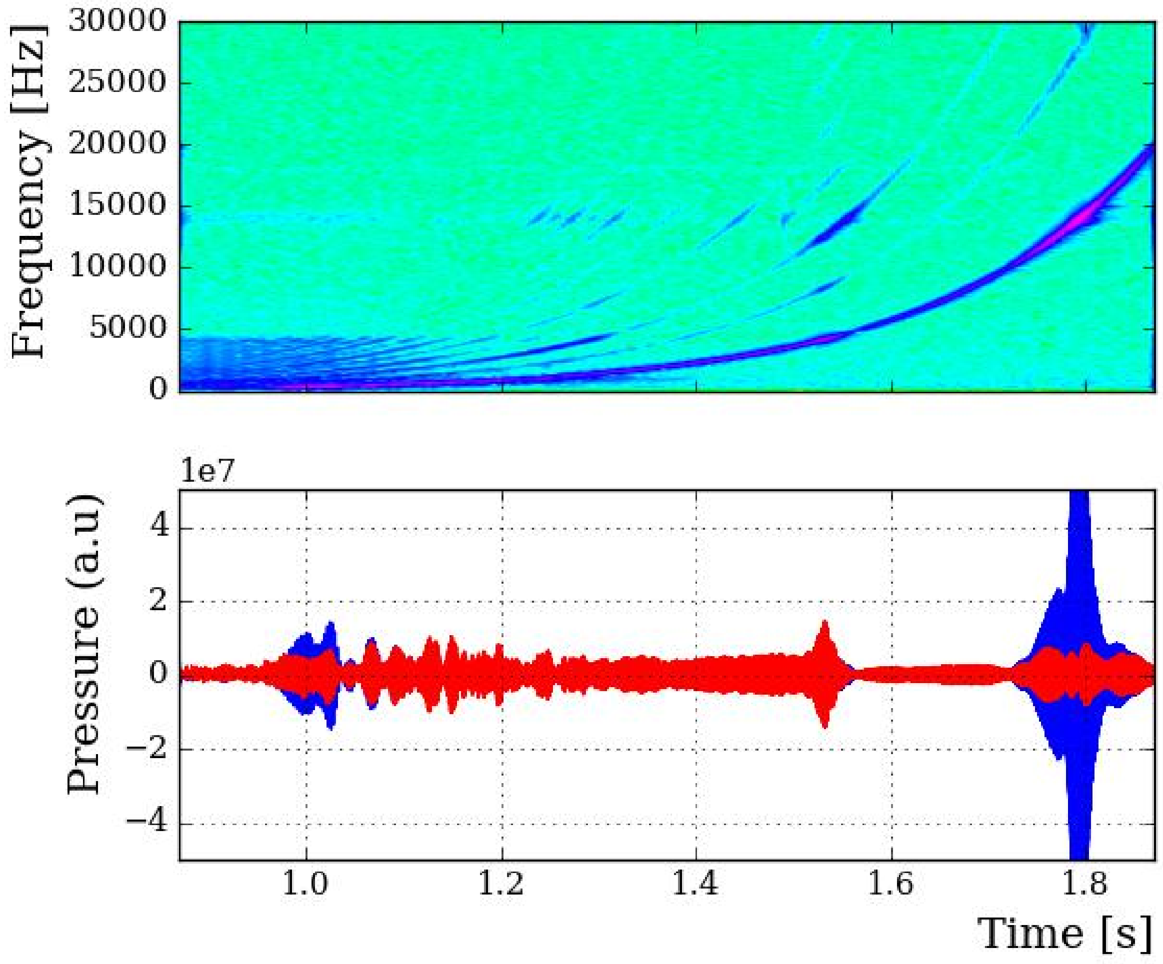


Instrument response

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

- Two types:
  - single membrane
  - double membrane





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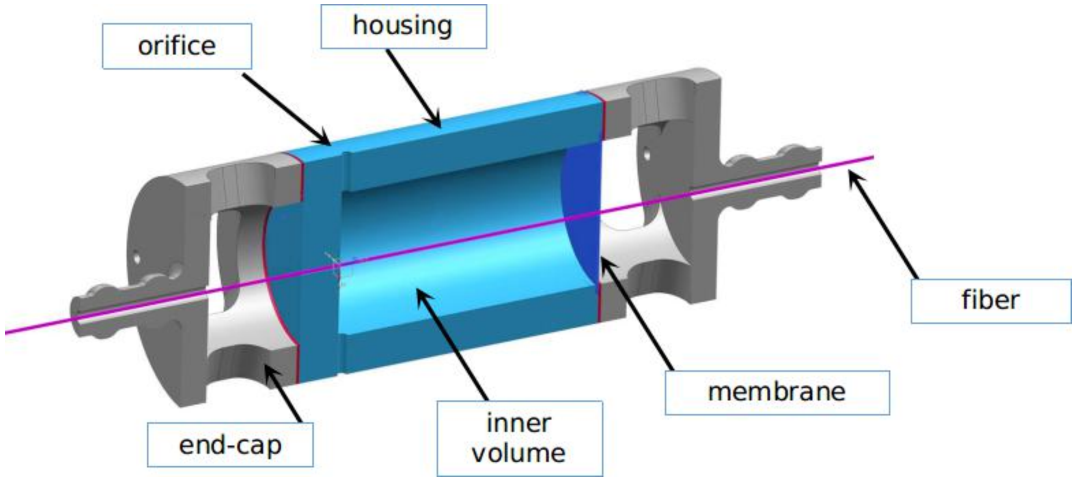
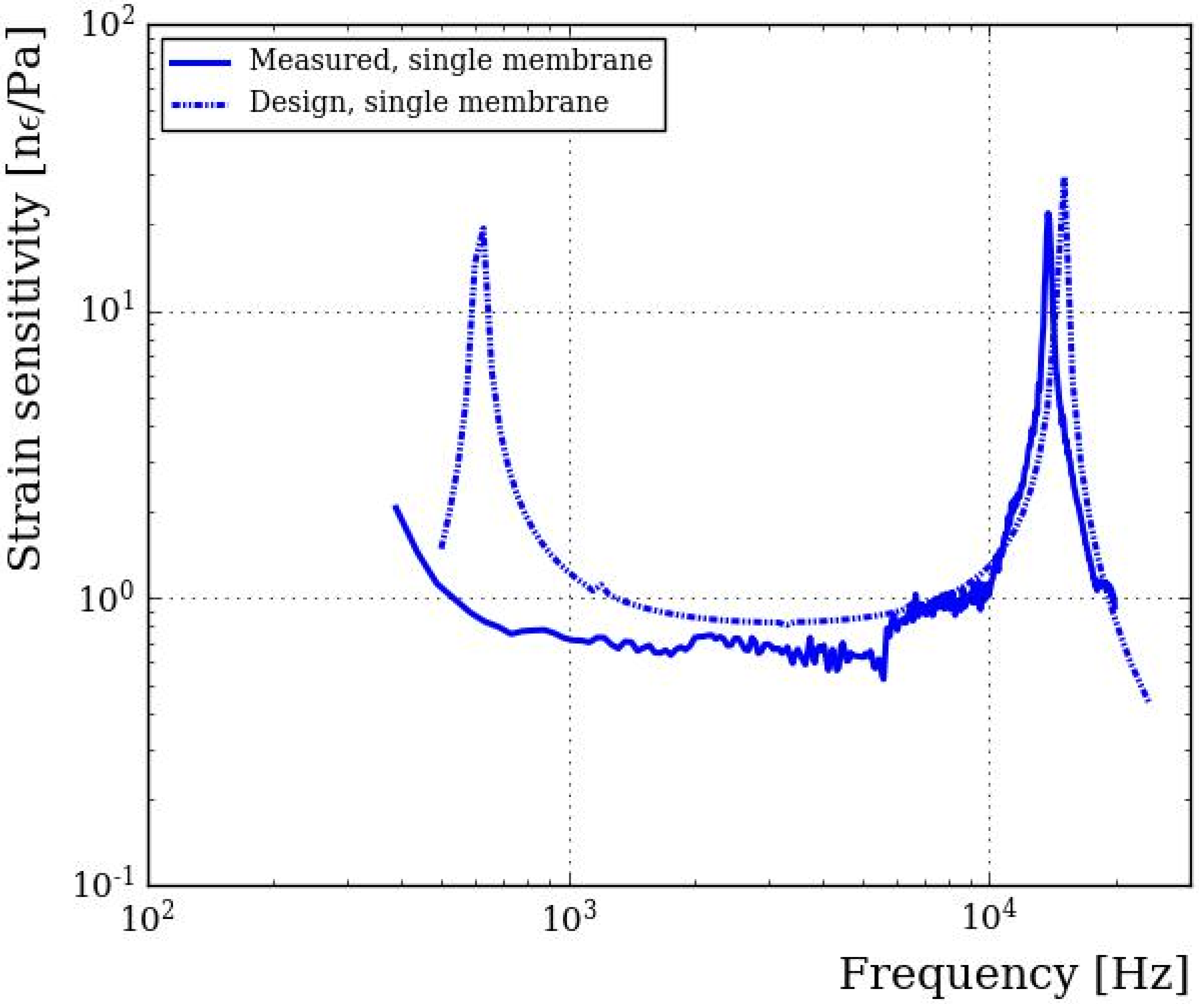
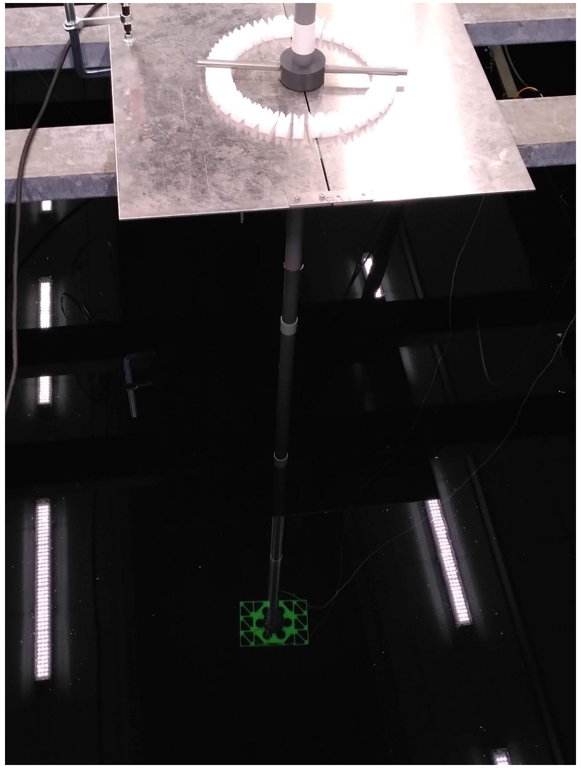
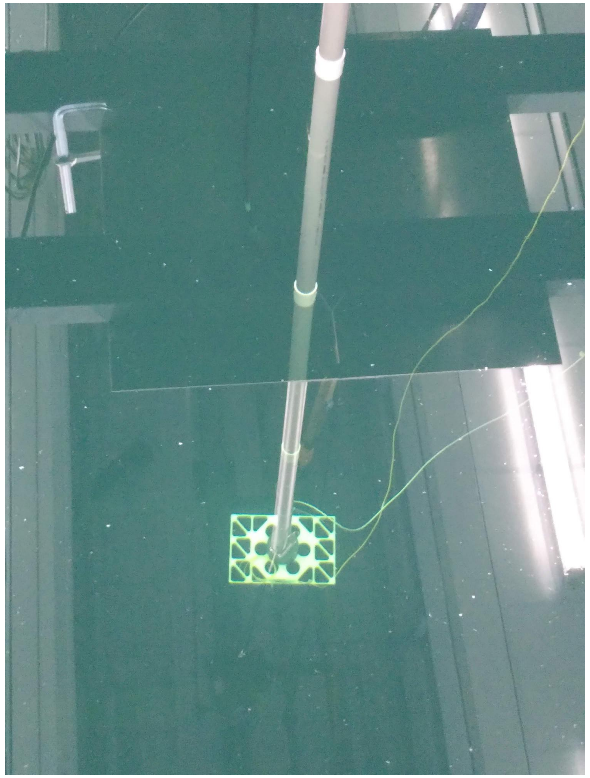
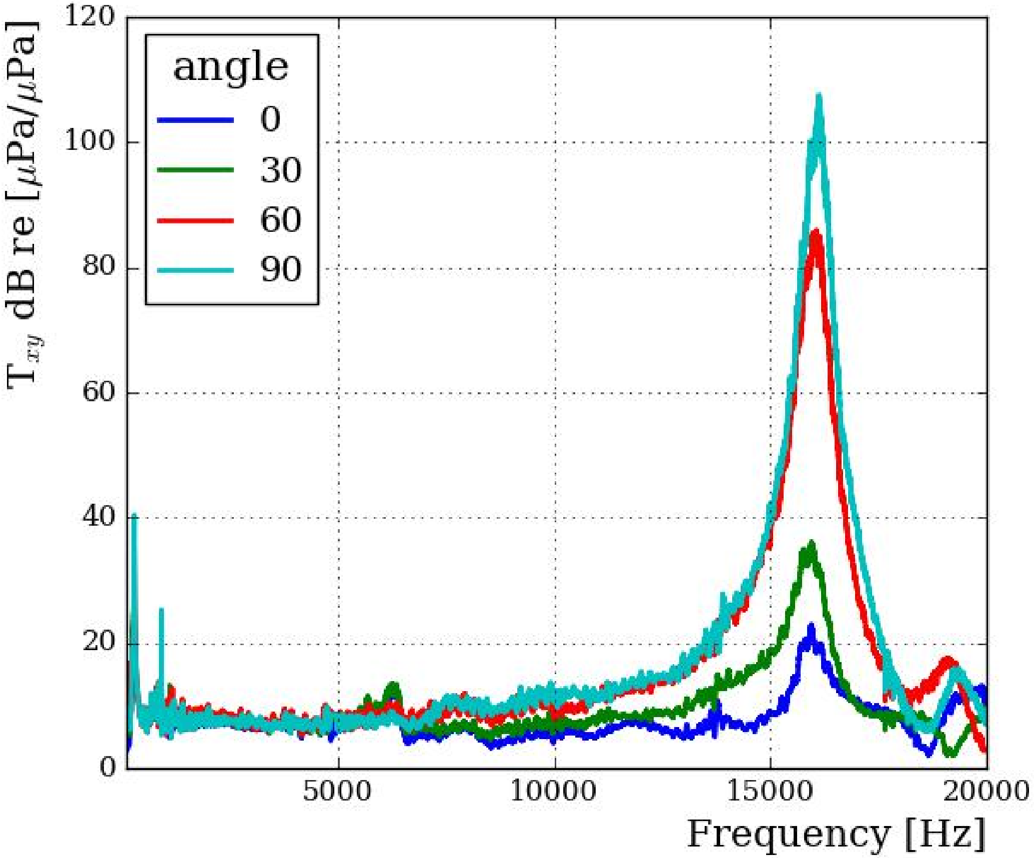




Instrument response: directionality







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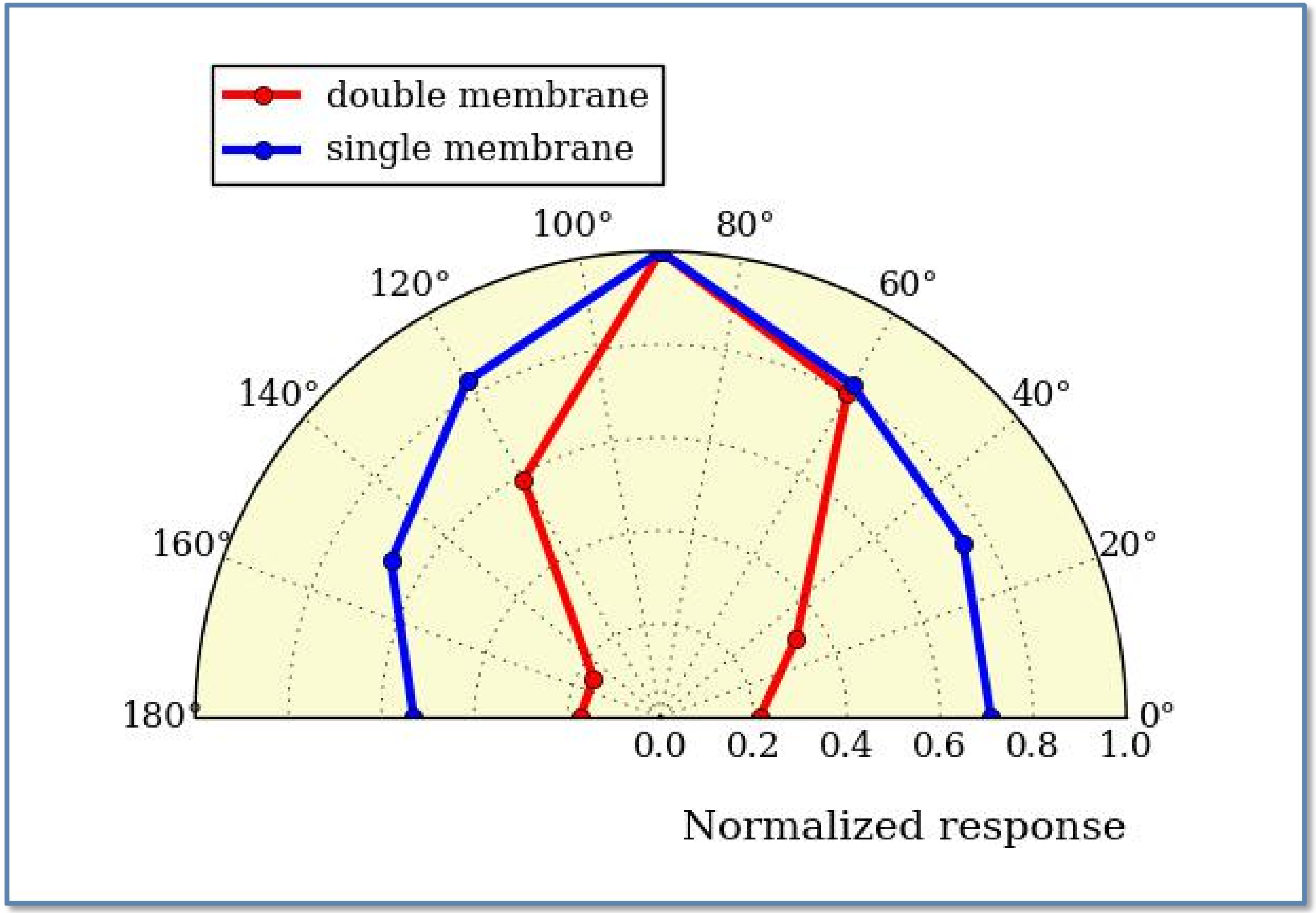
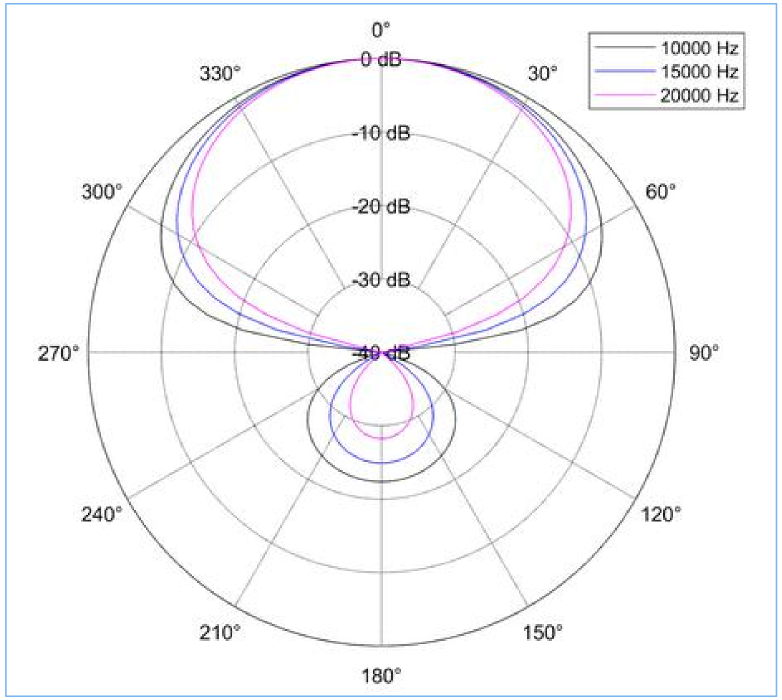
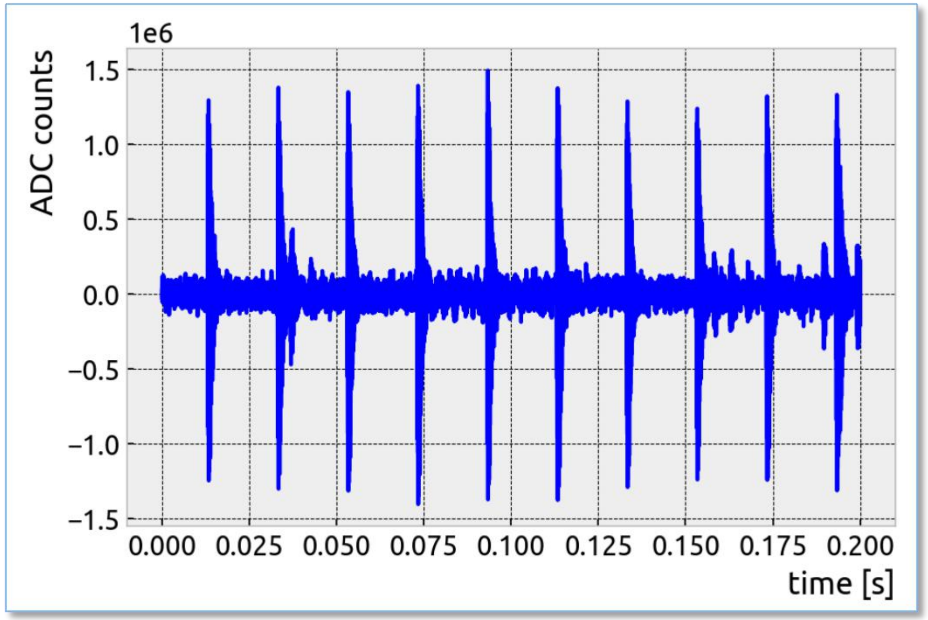


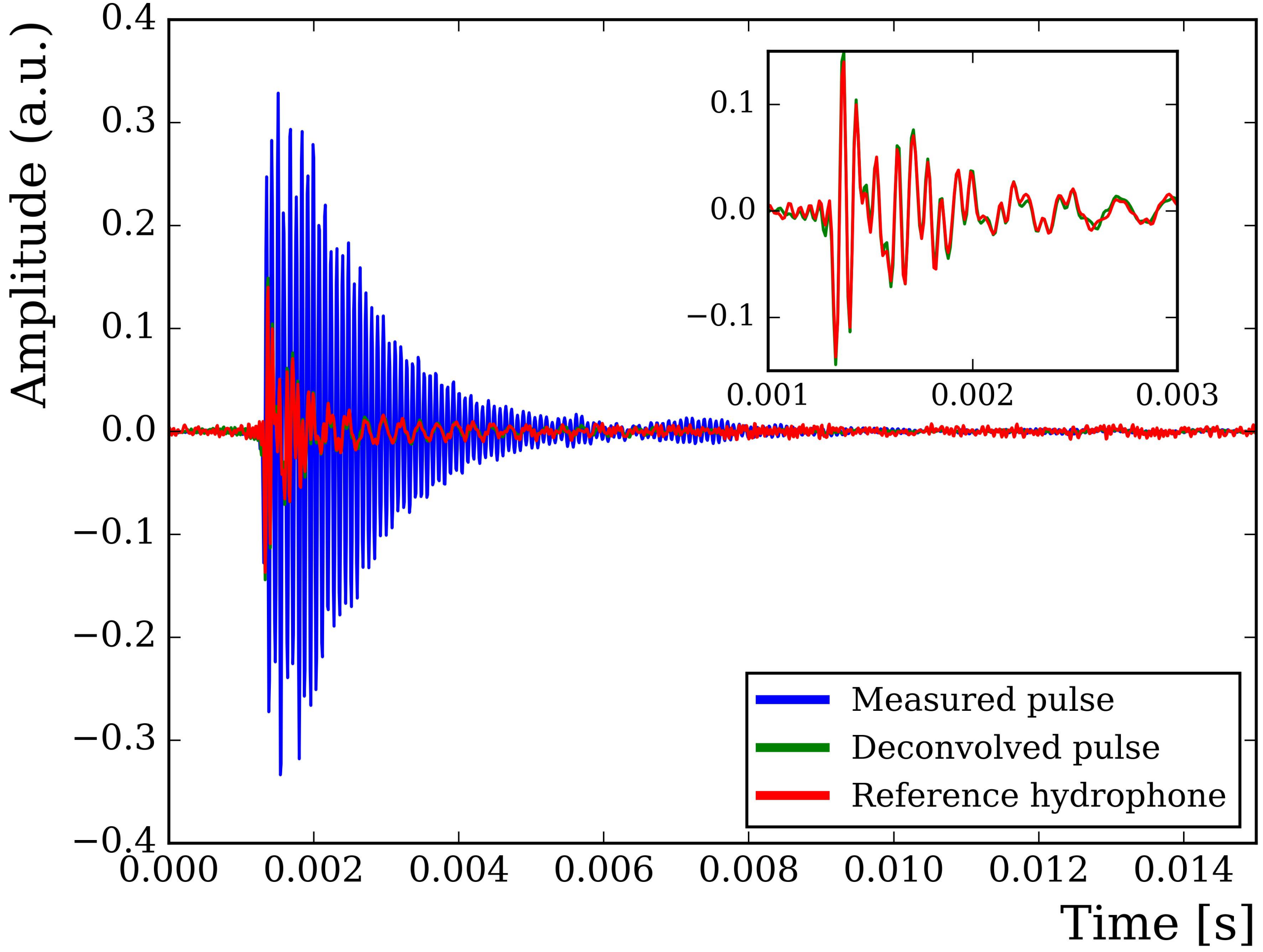


Theoretical deep-sea noise vertical angle distribution

Example pulses

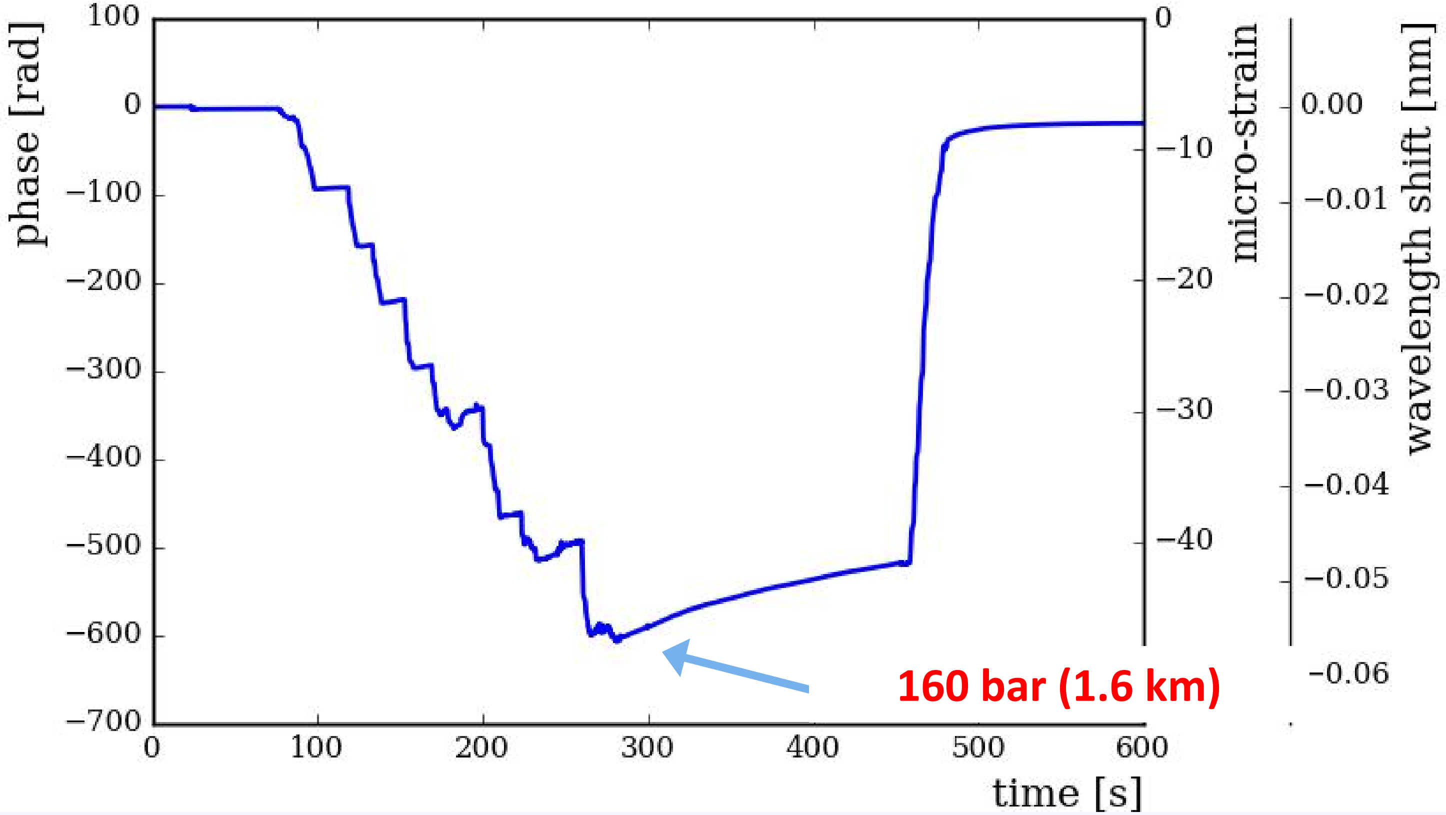
Ringtones of neutrinos

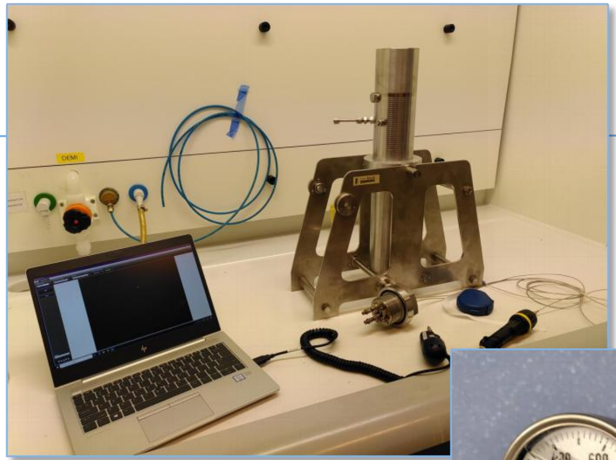




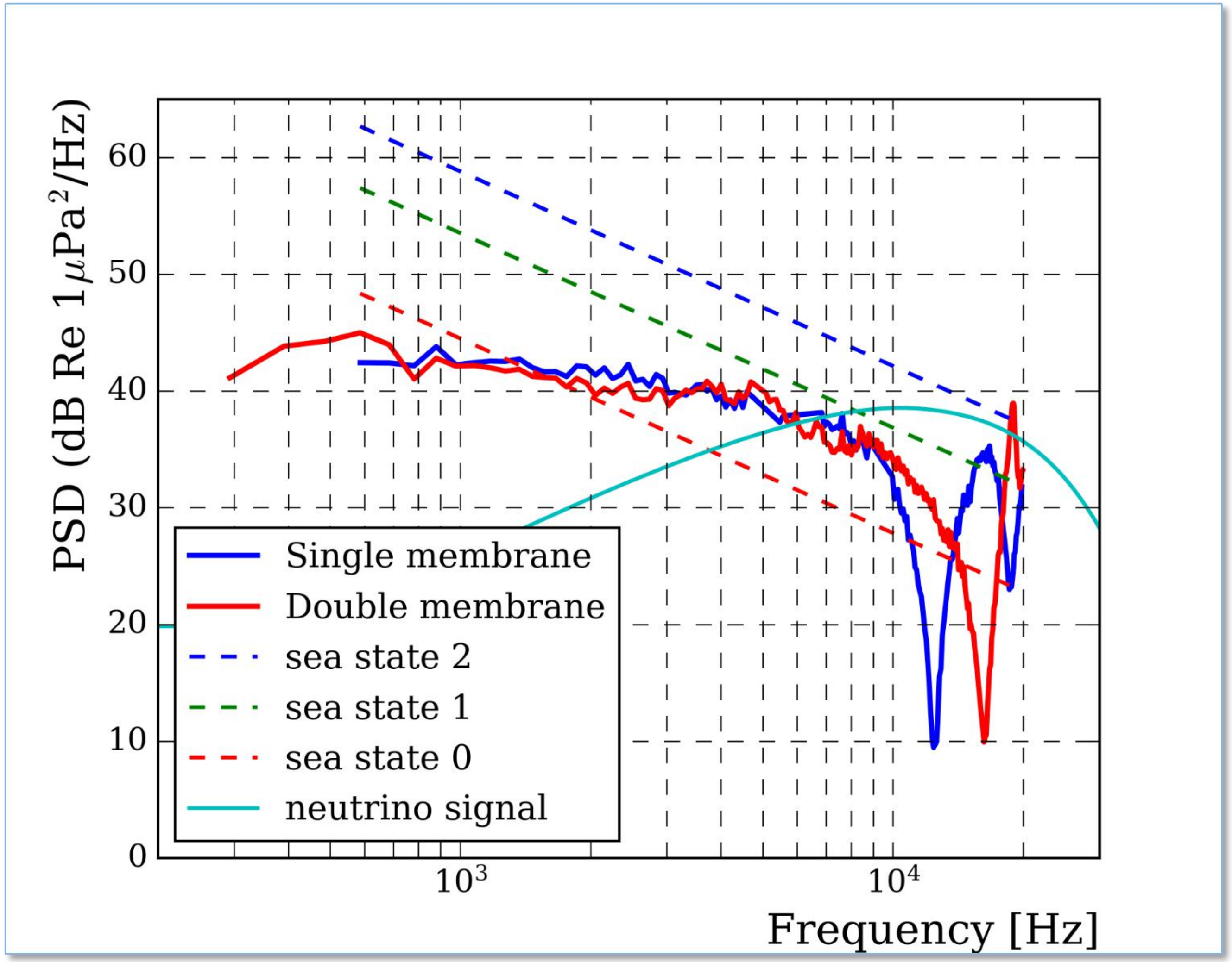
Pressure qualification

- Apply pressure in steps of ~20 bars; Max pressure **160 bar** (1.6 km)
- No impact on the transfer function measure before and after
- No loss in light outplut

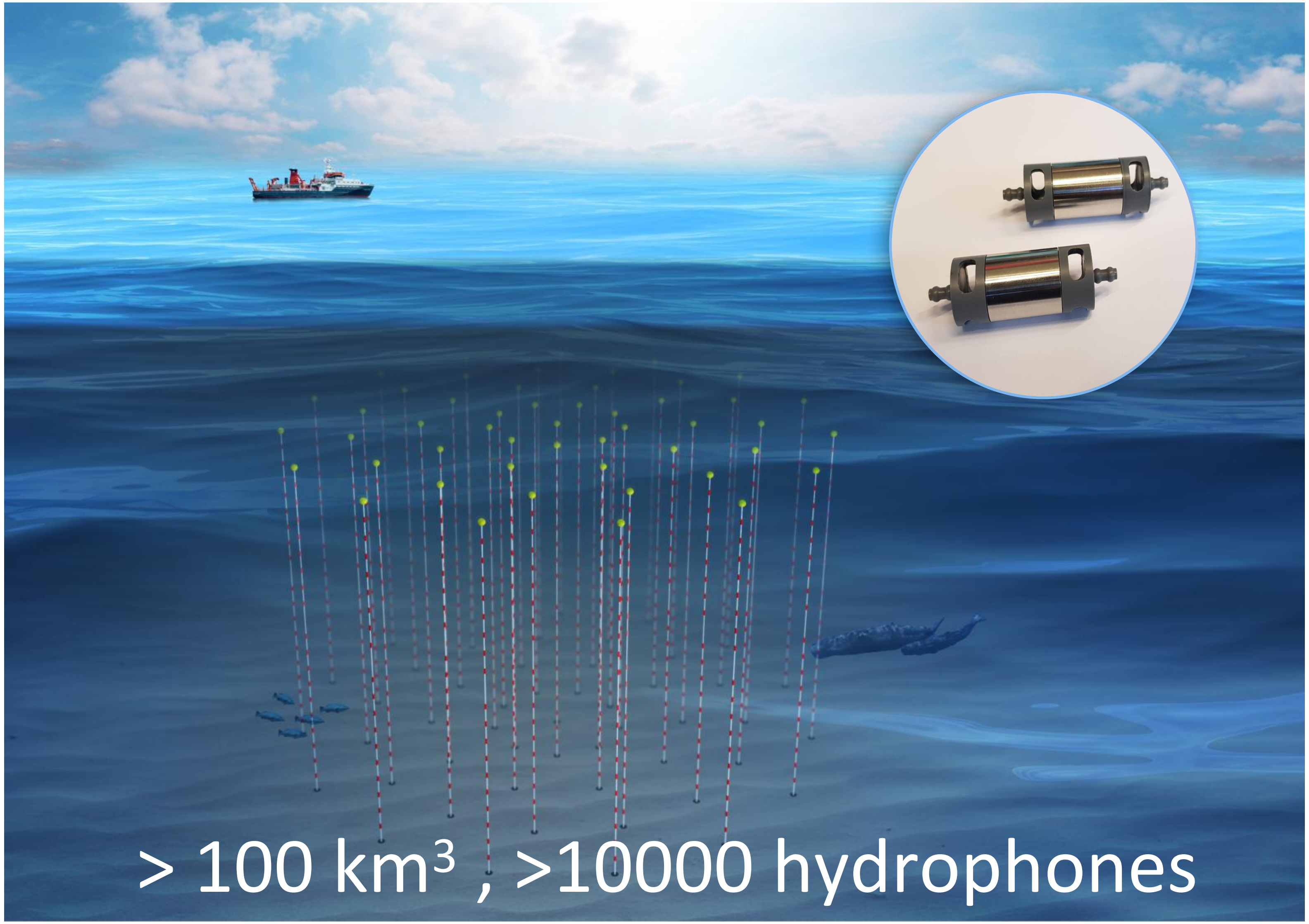




Hydrophone sensitivity



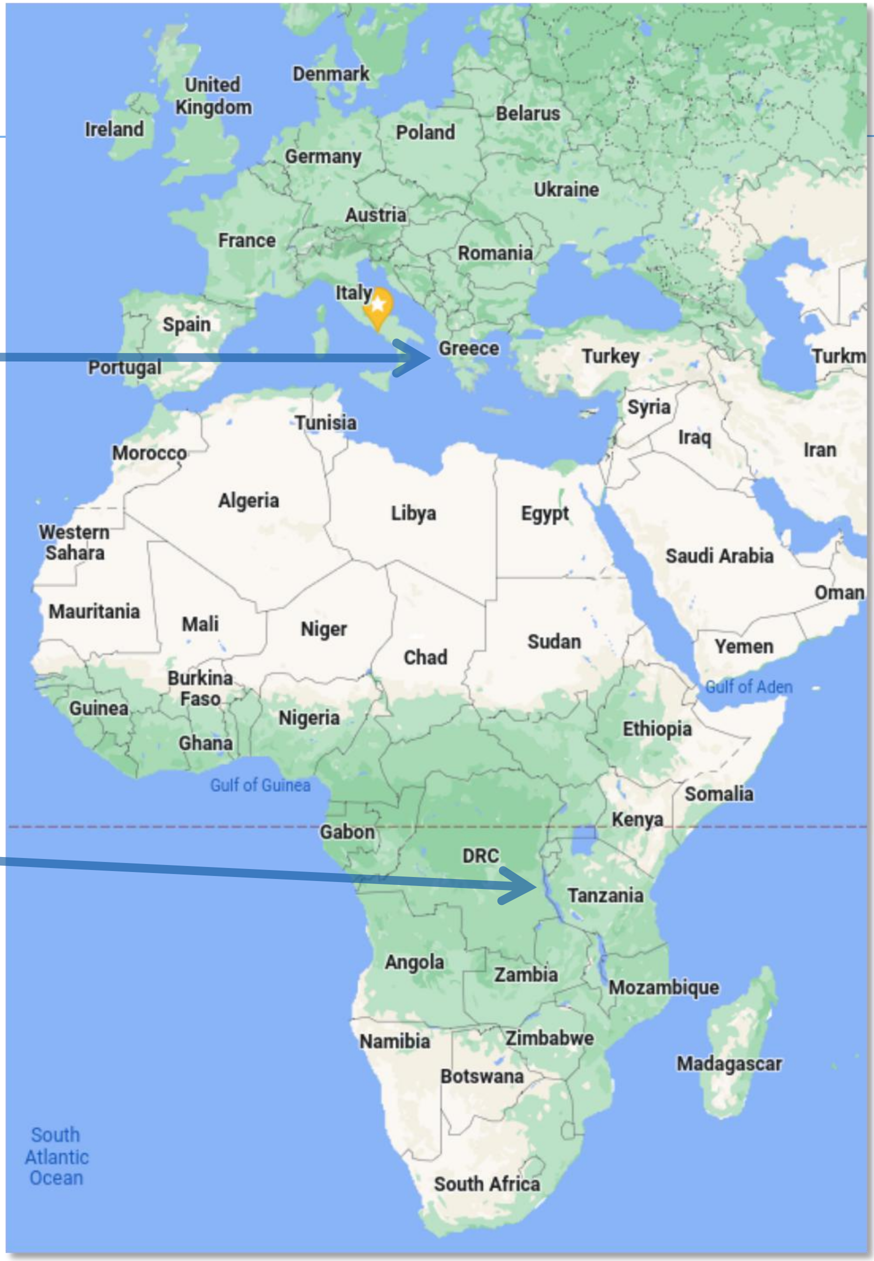
Future telescope concept



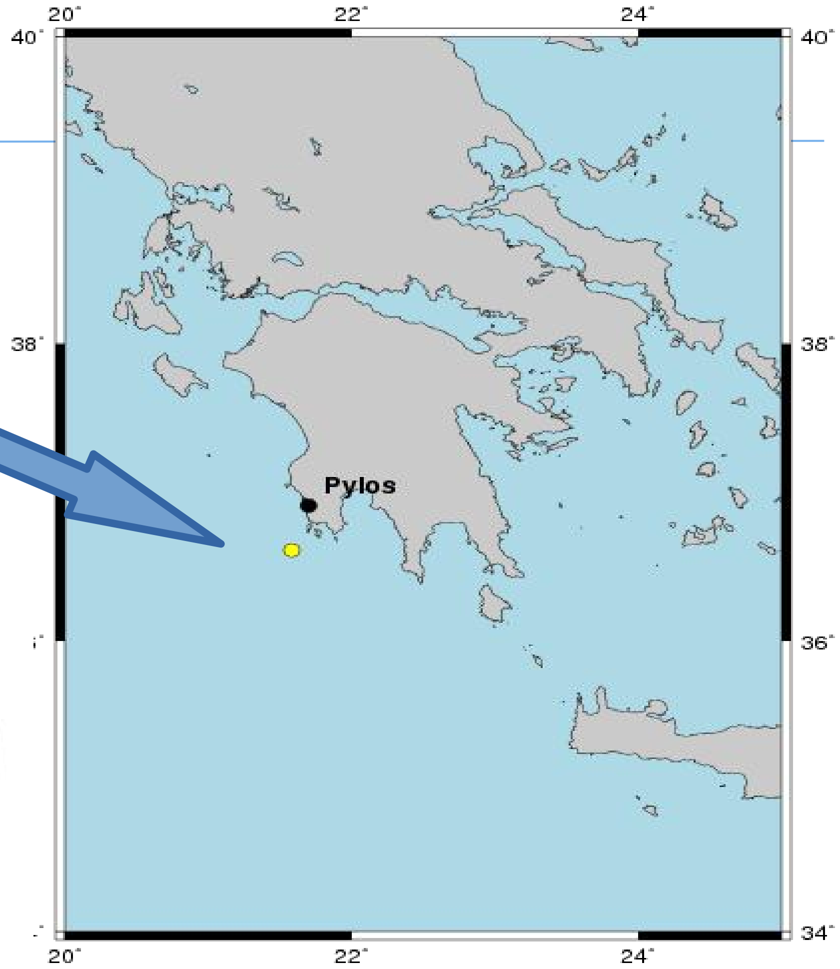
Sites

- Mediterranean Sea, Greece
  - + Depth: > 2 km
  - + accesible
  - + Relatively warm
  - – Noise: shipping, toothed whales

- Lake Tanganyika:
  - + Maximum depth 1425 m, mean depth 700 m
  - + Warm, fresh water
  - + No cetaceans
  - – Noise relatively unexplored

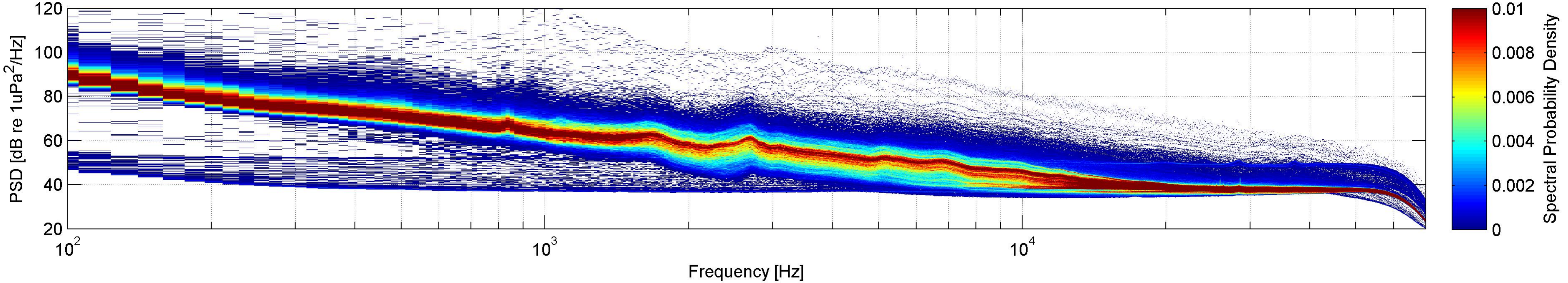


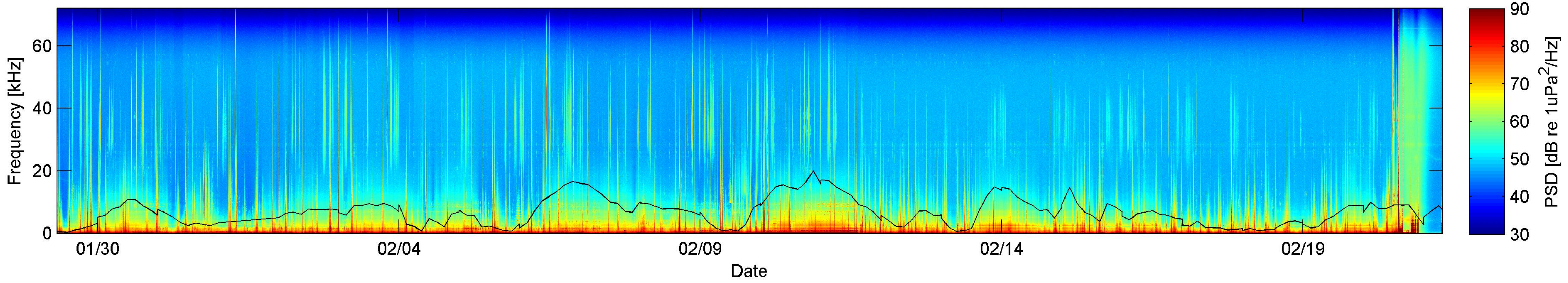
Pilot measurements Pylos site



Loggerhead DSG-ST ocean acoustic data logger at a depth of 850 and 1350 m

Pilot measurements Pylos site





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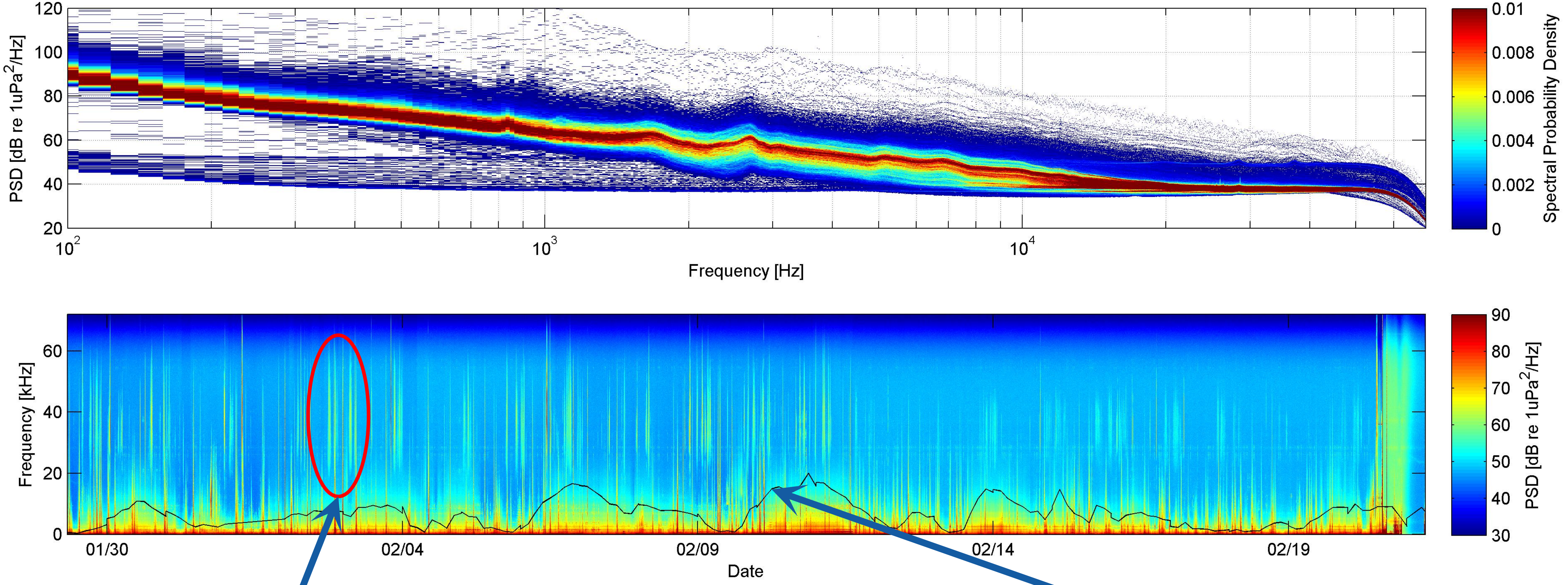


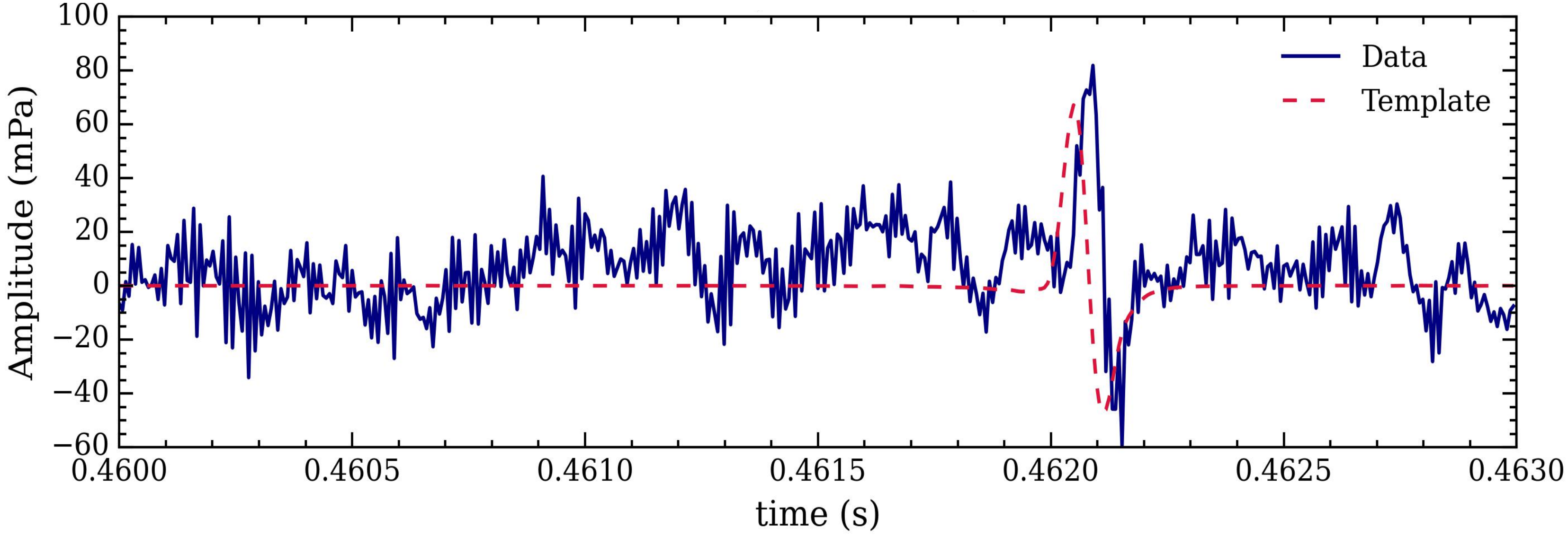
Bottlenose dolphins!

Strong correlation of wind speed with sea state noise

Event selection: 2-step process

1. Filter hits on basis of single waveforms, use e.g. matched filtering

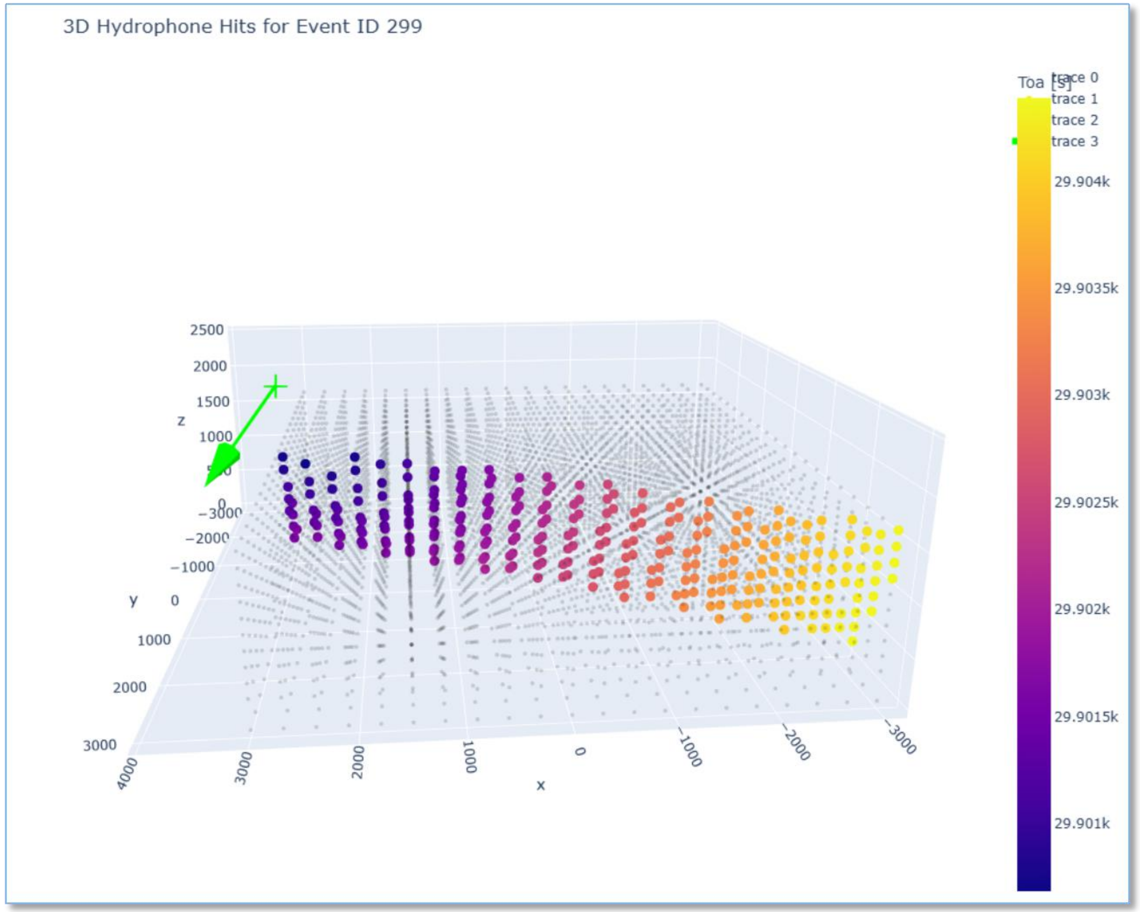
   (Noise extracted from Pylos data, LIGO sw for analysis)



2. Data filter: Select event using ***clique*** algorithm (subspace clustering) to suppress the noise hits:

   Find a set of pair-wise causally related hits with a minimum size $N_{min.}$

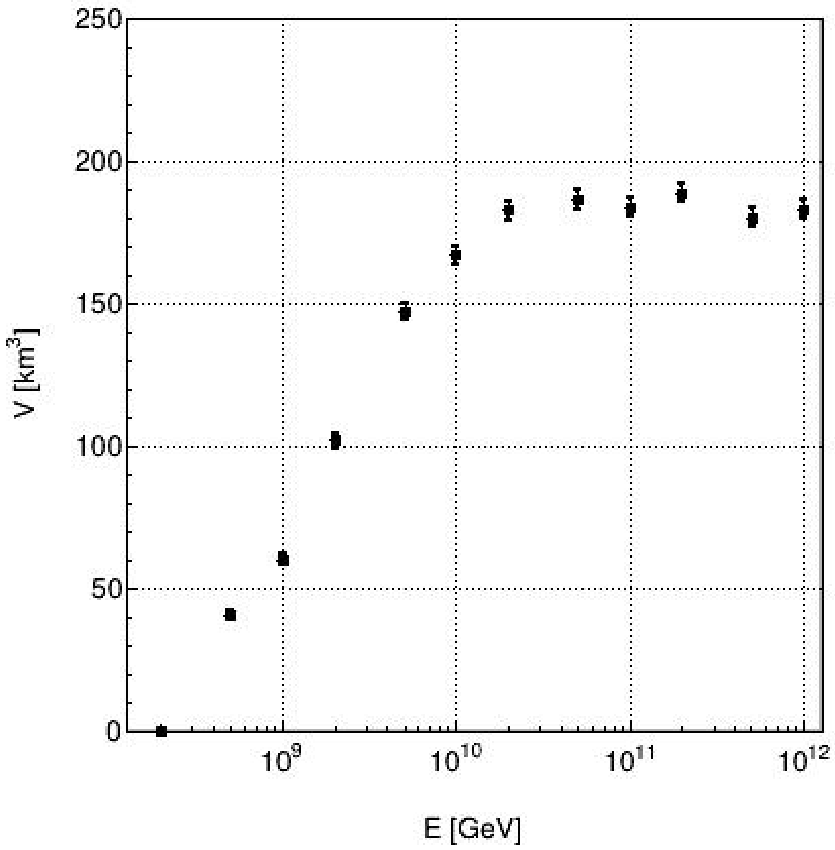
Telescope concept



Telescope parameters

- detector size D = 10 km
- number of hydrophones N ~ 10000

Telescope concept



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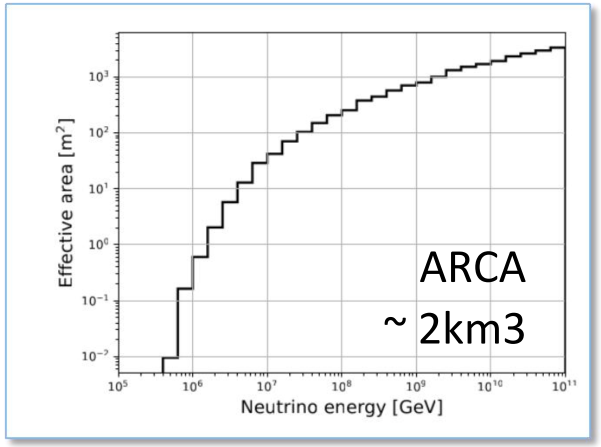
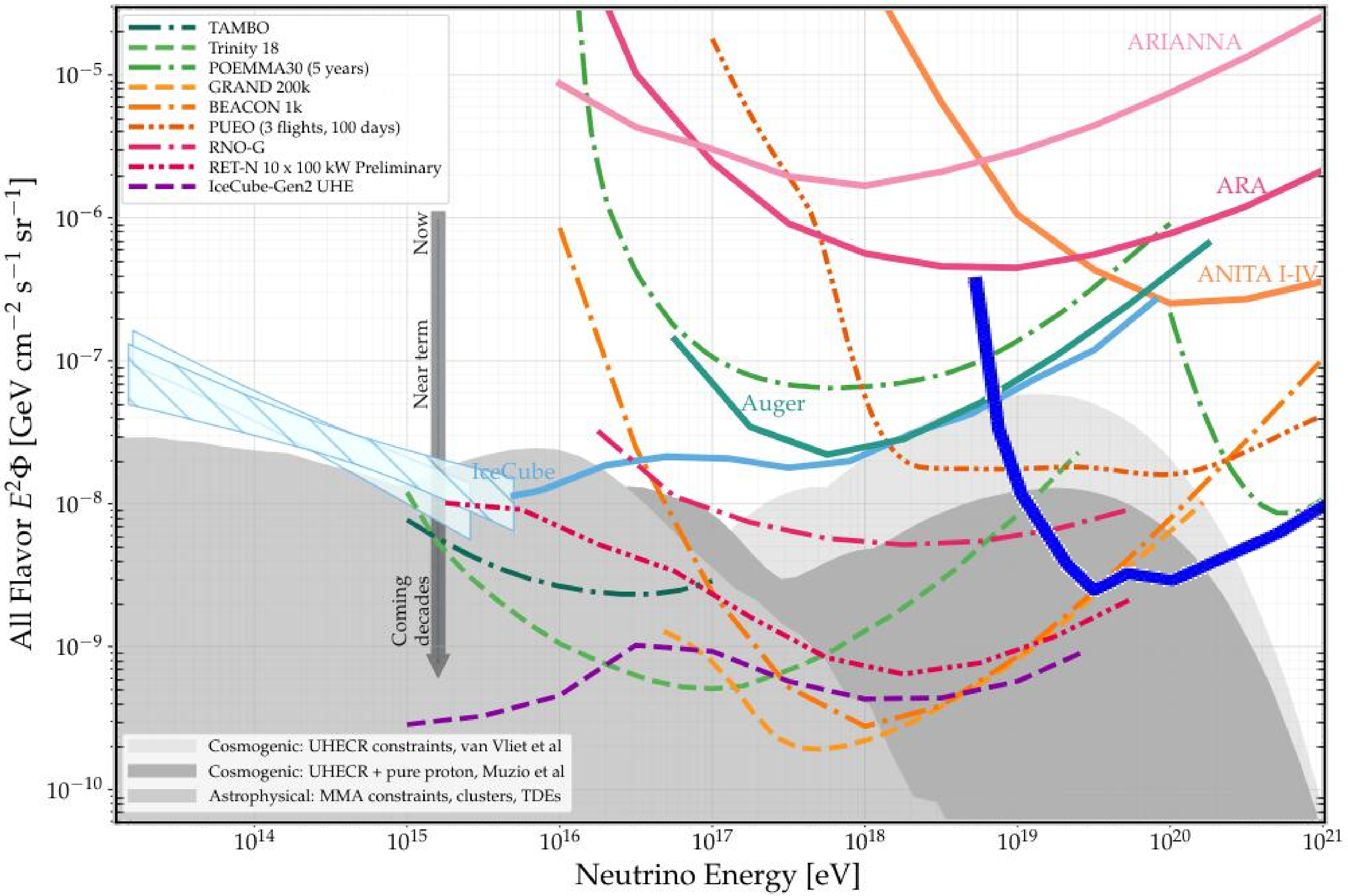


Differential sensitivity

Snowmass whitepaper, arXiv2203.08096



Differential sensitivity

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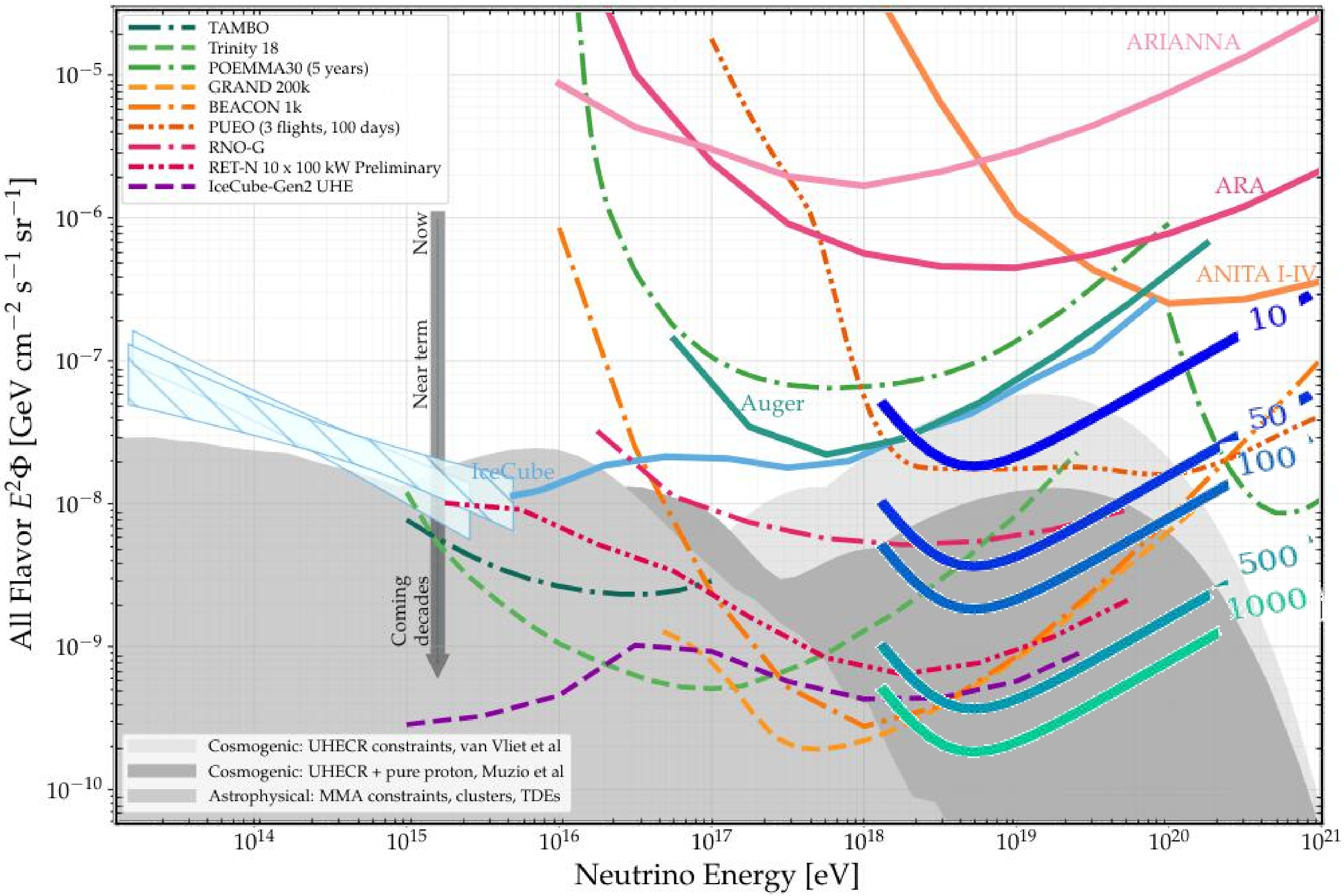


10 km3, 10yr

1000 km3, 10yr

Conclusions

- Neutrinos are the messengers to probe the CR spectrum beyond the GZK cut-off, i.e beyond 10^9 GeV.
  - Neutrinos from the induced at the GZK cut-off are a garantueed source; Did we see a glimse yet?

- New detections methods are needed to probe a higher energy scale:
  - Should be preparing for a new telescope already now.

- Fiber optic sensors provides an enabler for an acoustic neutrino telescope;
  - First prototype seems promising, but further development is still needed.
  - A large number of hydrophones (>1000)
  - Requires industrial scale of manufacturing and integration (Design For Manufacturing)
  - Spin off opportunities are numerous. Launching customer?

Outlook

- Benefit from heritage from KM3NeT!
  - New working group established within the collaboration
- Multidisciplinarity: oceanography, marine ecology, marine conservation
- Synergies:
  - ARCA/ORCA: understanding the environment
  - PAO, Grand: scientific objectives, data analysis
  - LV: signal processing
  - ET, R&D: fiber optic sensing network

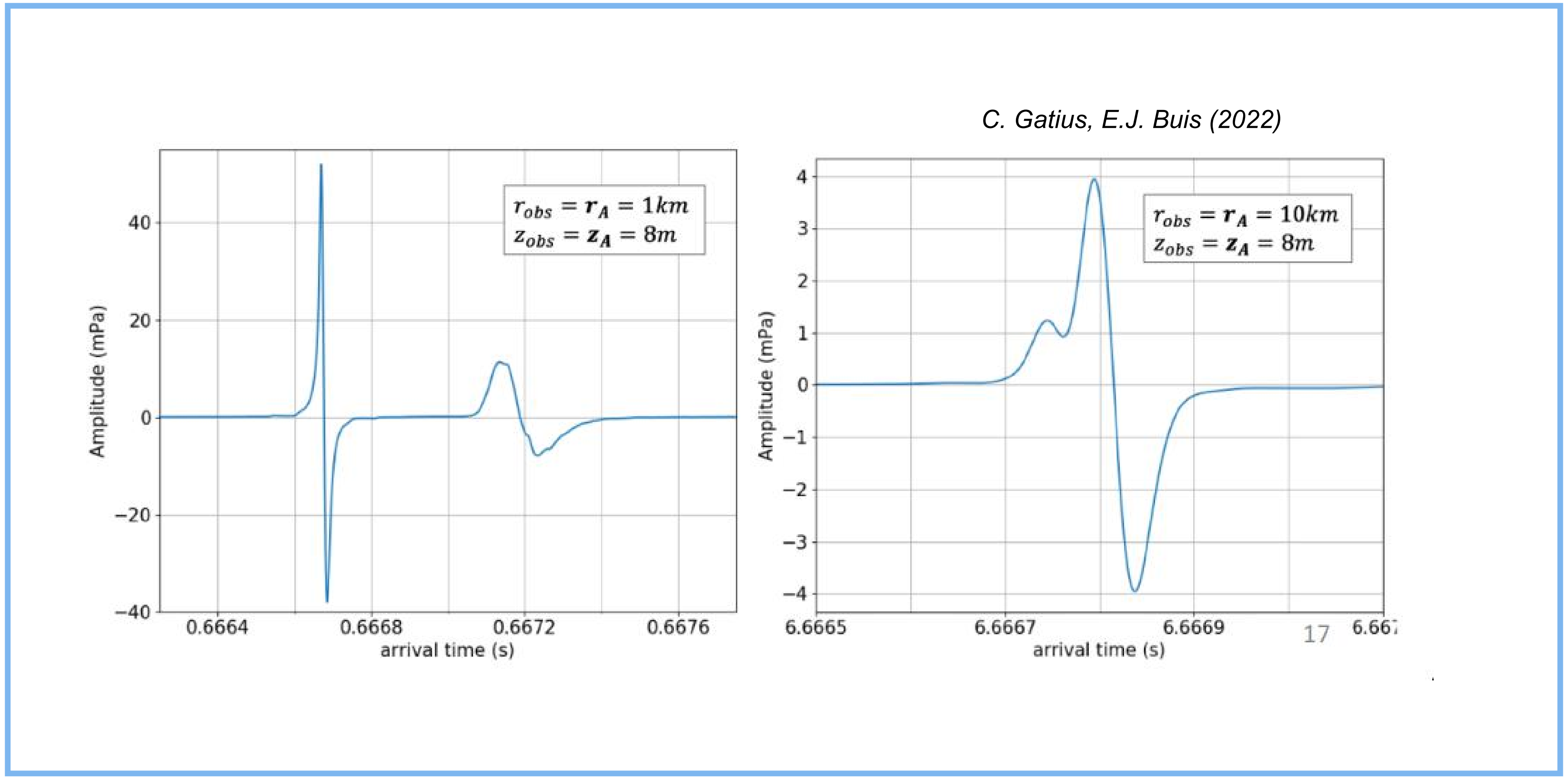
Back-up

How to reduce the detection threshold

- Operational energy range of a telescope. Energy range affected by:
  - LPM effect at the high energies
  - Low signal/small volume at energies < 10^{19} eV

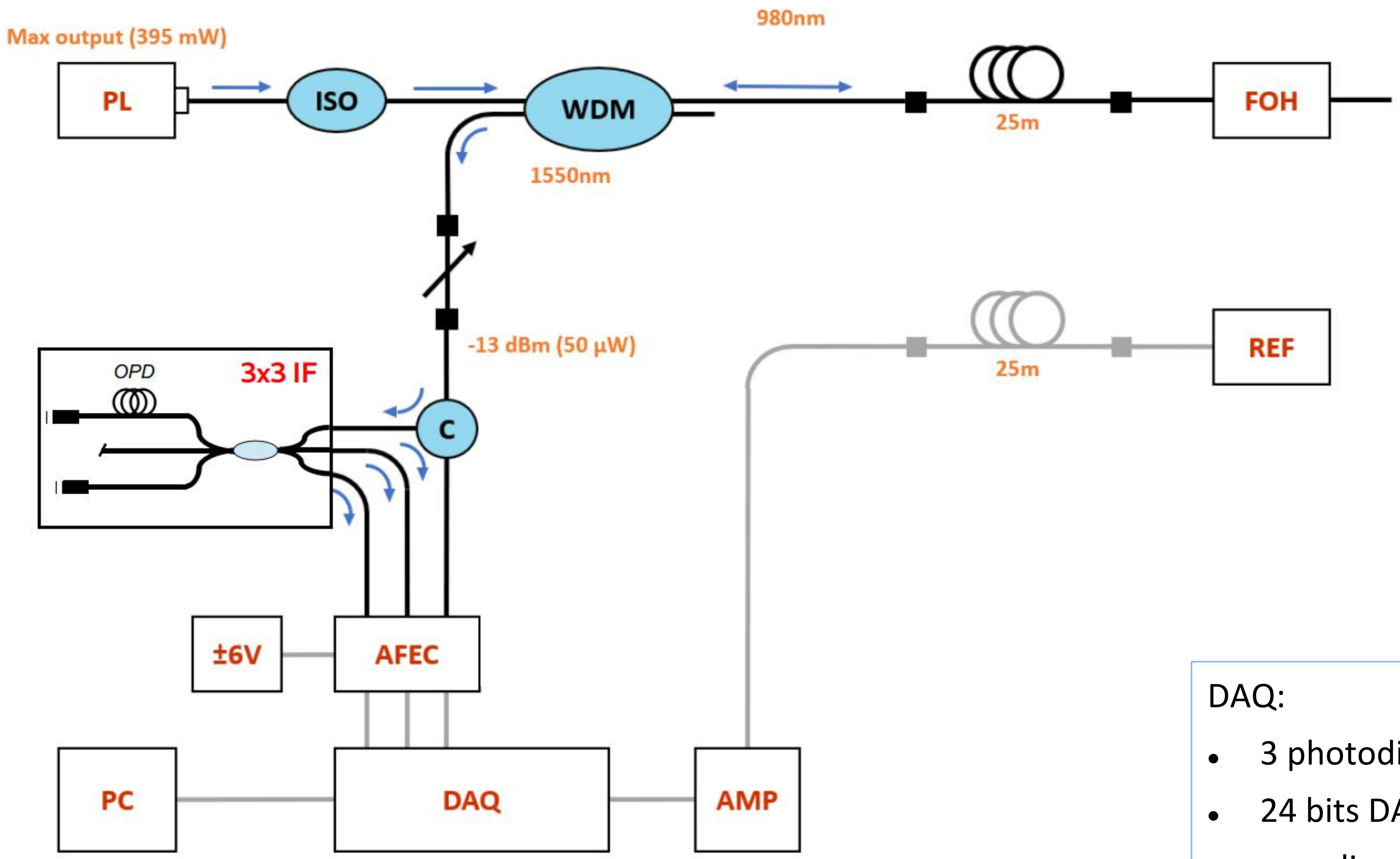
- How to lower the detection threshold by a factor 10?
  - **Larger volume (~1000km^3) /number of hydrophones (> 10000)**
  - **Reduce threshold of individual hydrophones**
  - Reduce threshold by increasing number of hydrophones in trigger.
  - Trigger studies, ML, stacking, etc

Near field effects



- Near field effect: two pulses. Sensitive to the longitudinal and transverse energy deposition

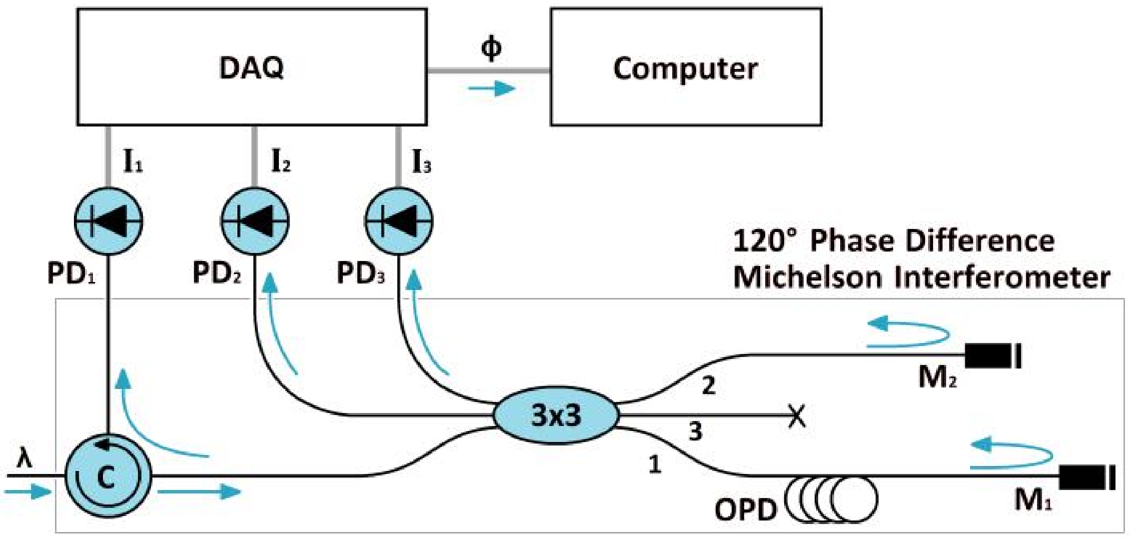
Data acquisition



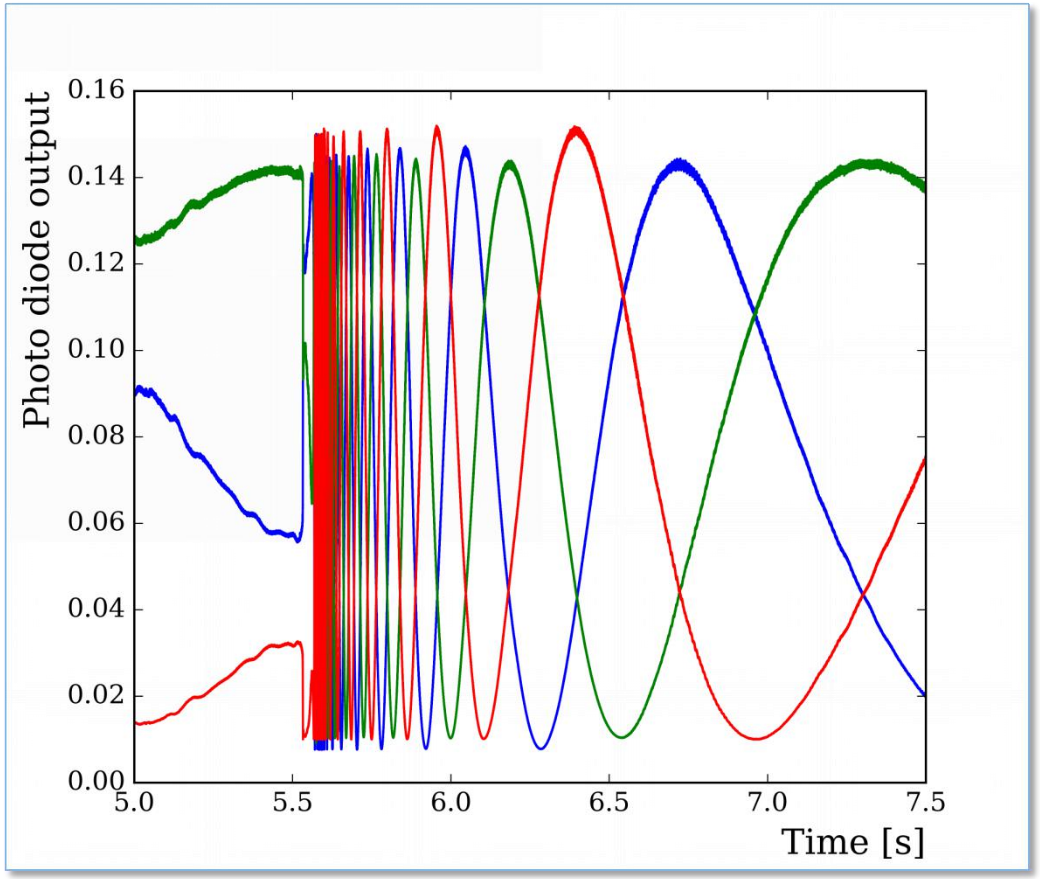
DAQ:

- 3 photodiodes,
- 24 bits DAC
- sampling rate 100 kHz

Data acquisition



3 x 3 arm Michelson interferometer

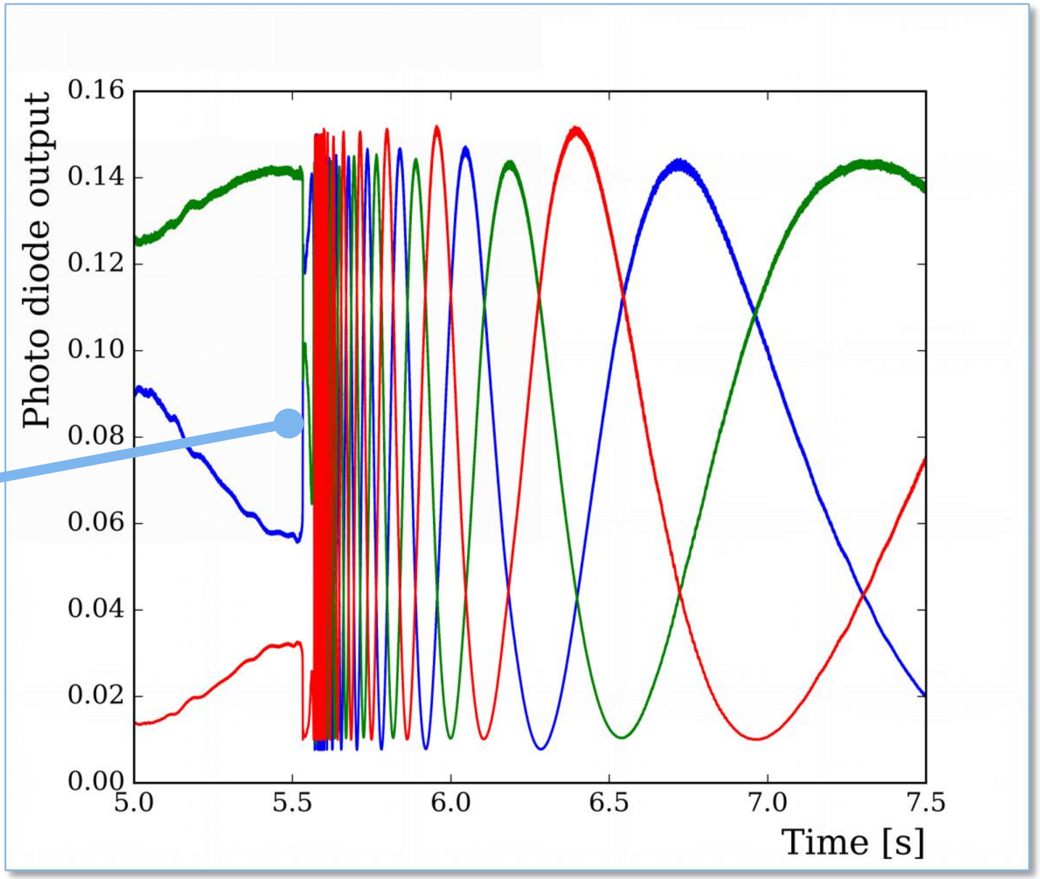


Data acquisition

3x3 arm Michelson interferometer:

- introduce a shift of 120^{o} in each arm
- keep optical path difference (OPD) fixed

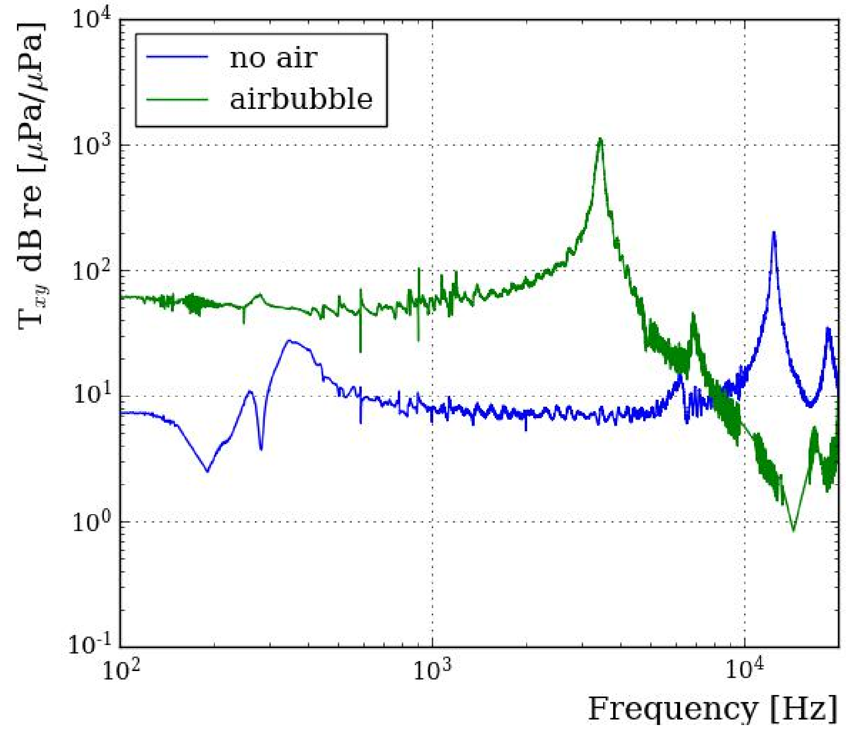
$$
\begin{aligned}
I_S &= I_0\left(1 + A\cos(\tfrac{2\pi}{\Delta\lambda}\mathrm{OPD})\right)\\
I_+ &= I_0\left(1 + A\cos(\tfrac{2\pi}{\Delta\lambda}\mathrm{OPD} + \tfrac{2\pi}{3})\right)\\
I_- &= I_0\left(1 + A\cos(\tfrac{2\pi}{\Delta\lambda}\mathrm{OPD} - \tfrac{2\pi}{3})\right)
\end{aligned}
$$



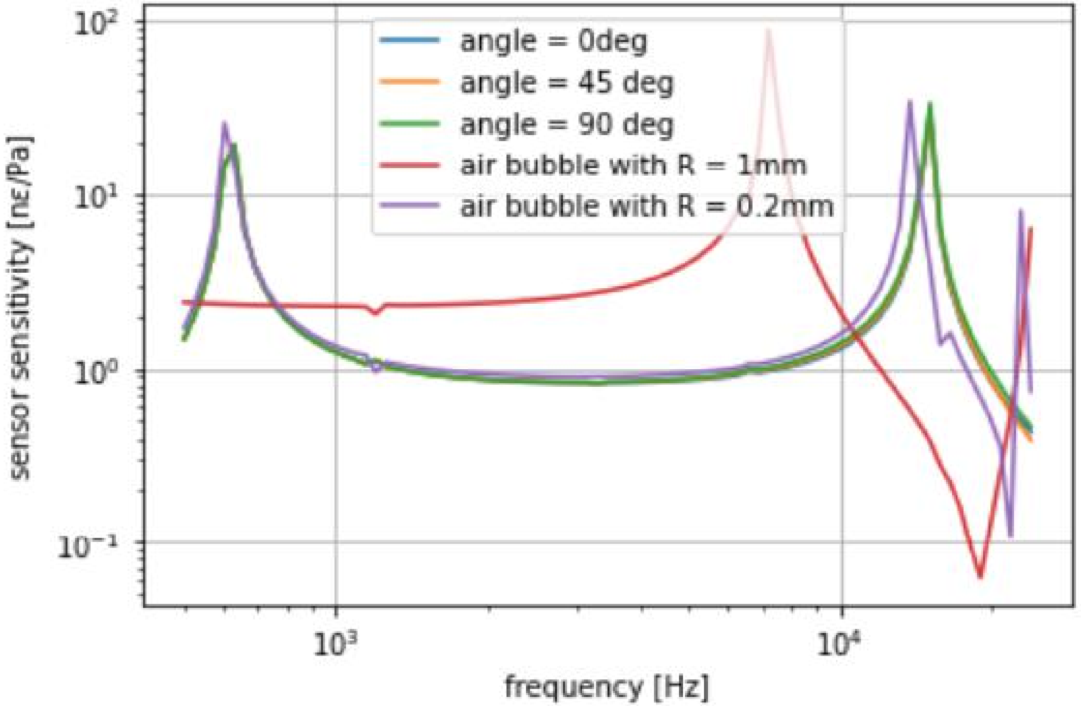
$$
\mathrm{OPD} = \frac{\Delta\lambda}{2\pi}\arctan\left(\frac{\sqrt{3}(I_+ - I_-)}{2I_s - I_+ - I_-}\right)
$$

measured wavelength shift

Instrument response: residual air



Comsol simulations

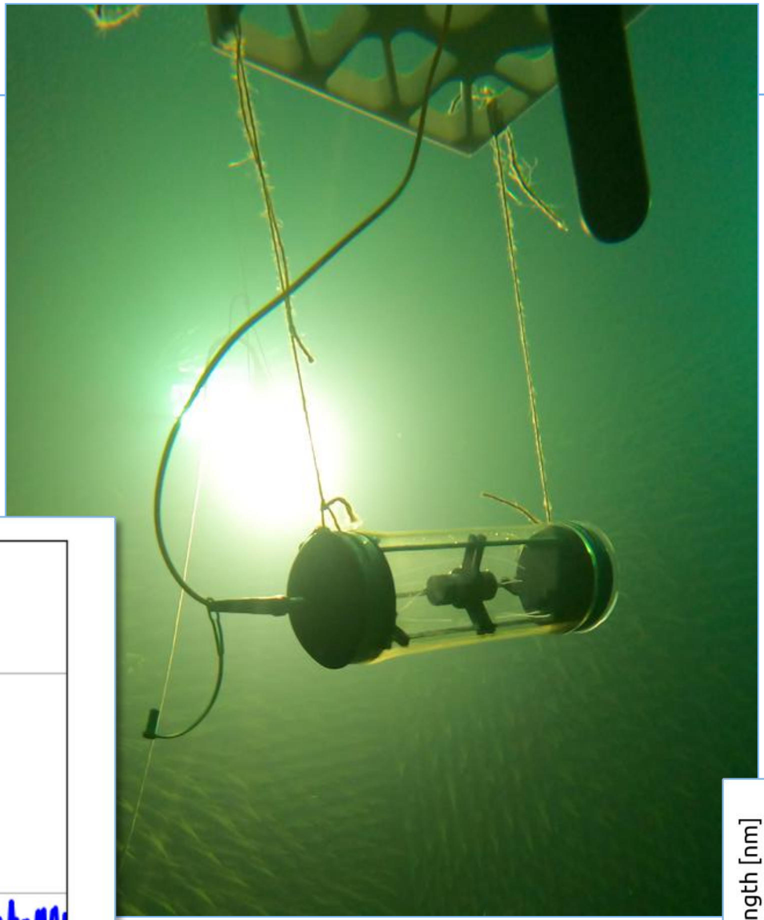


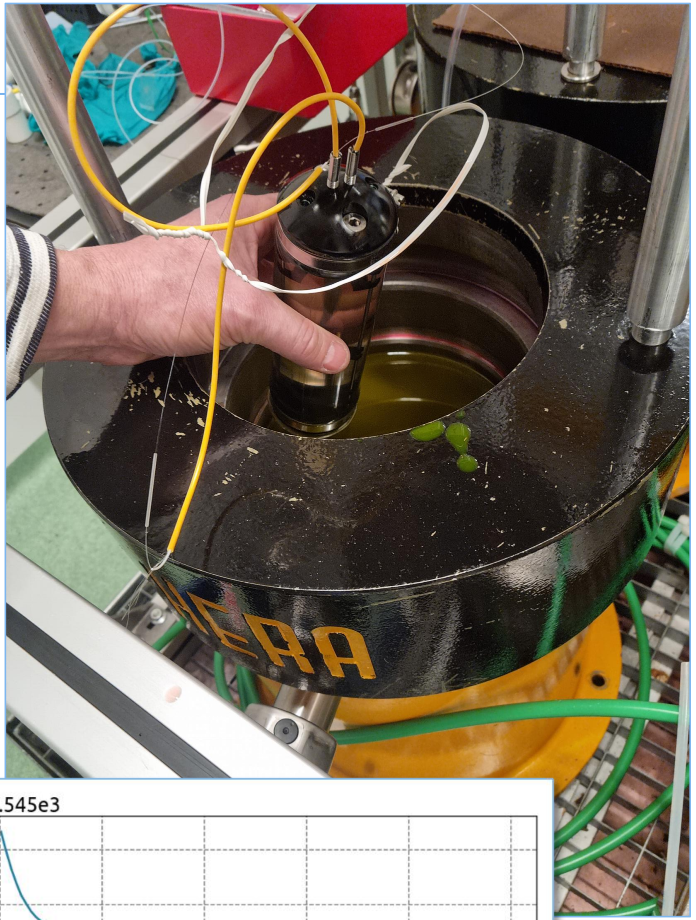
- Residual air in the transducer has a large impact on the transfer function!
  (an air bubble of 1mm diameter has only 0.5% volume percentage)

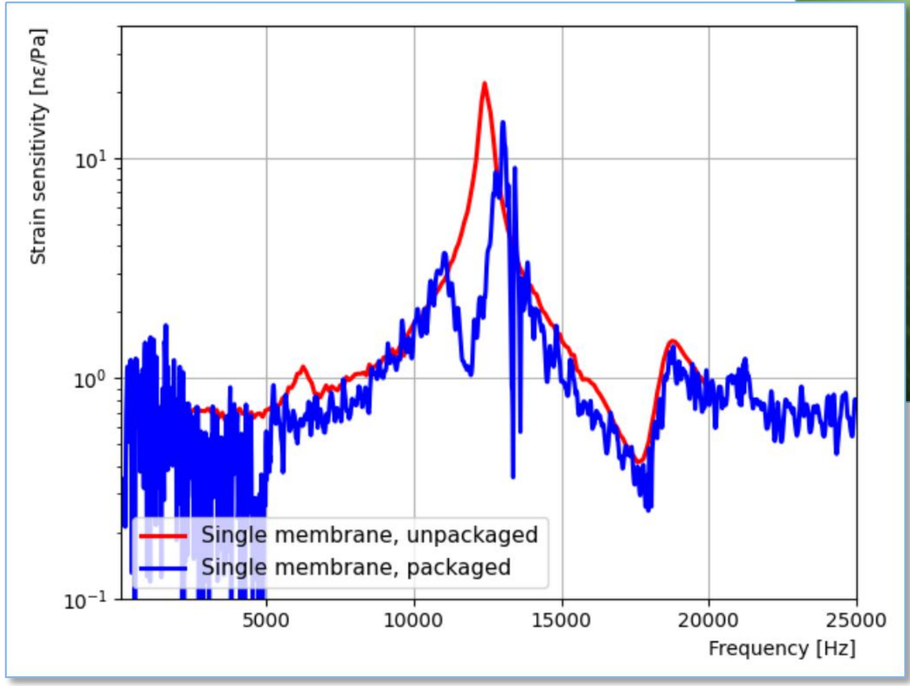
- Established a procedure to fill the sensor

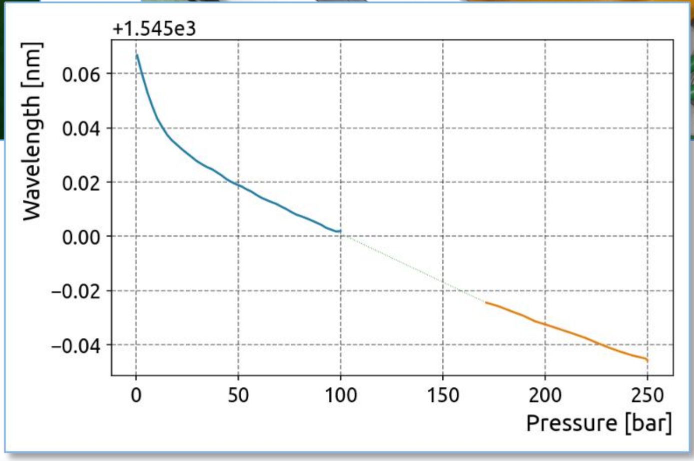
Pocket

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









Noise studies

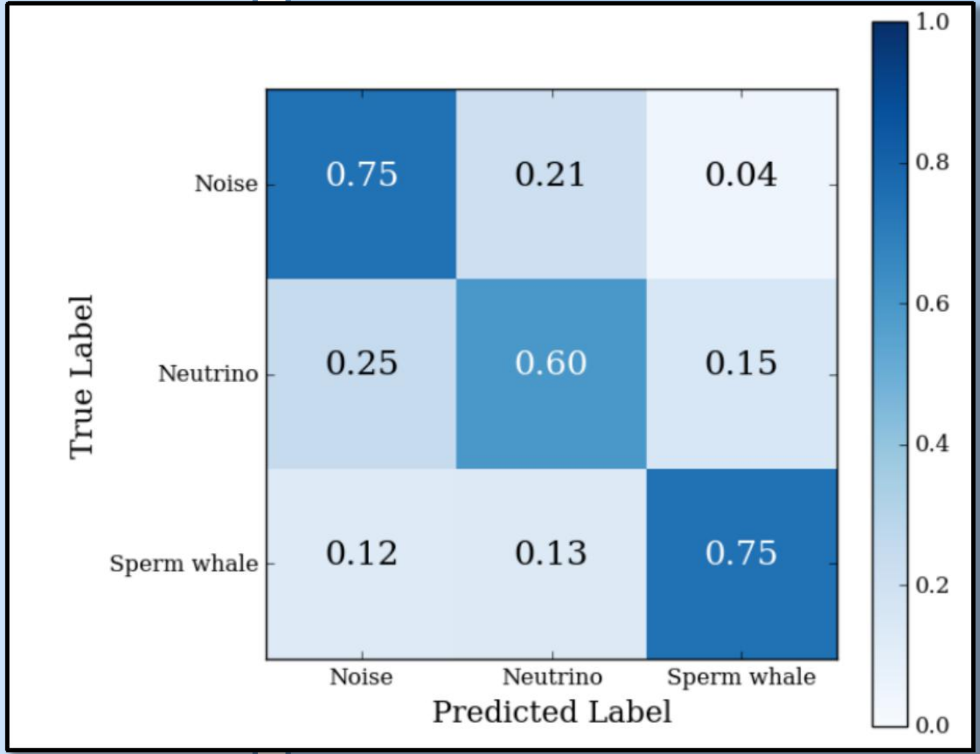
Neutrinos

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

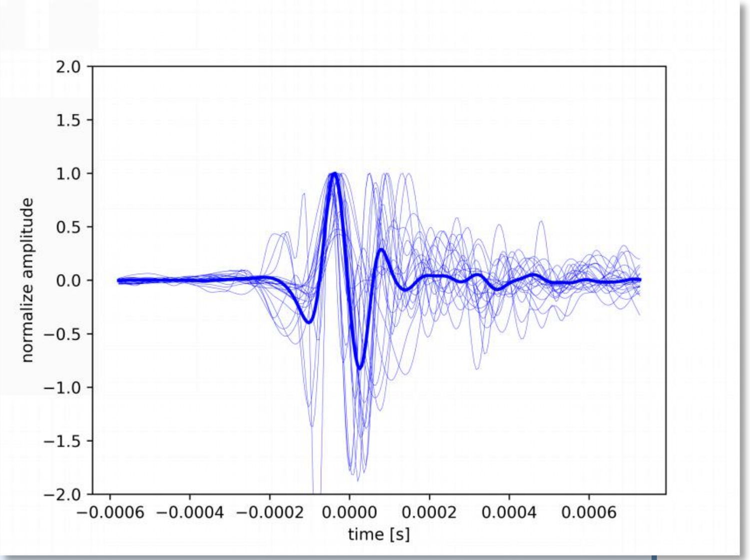
Noise:

- Random noise extracted from Mediterranean Sea

Confusion matrix



Liselotte Dijkema 2023

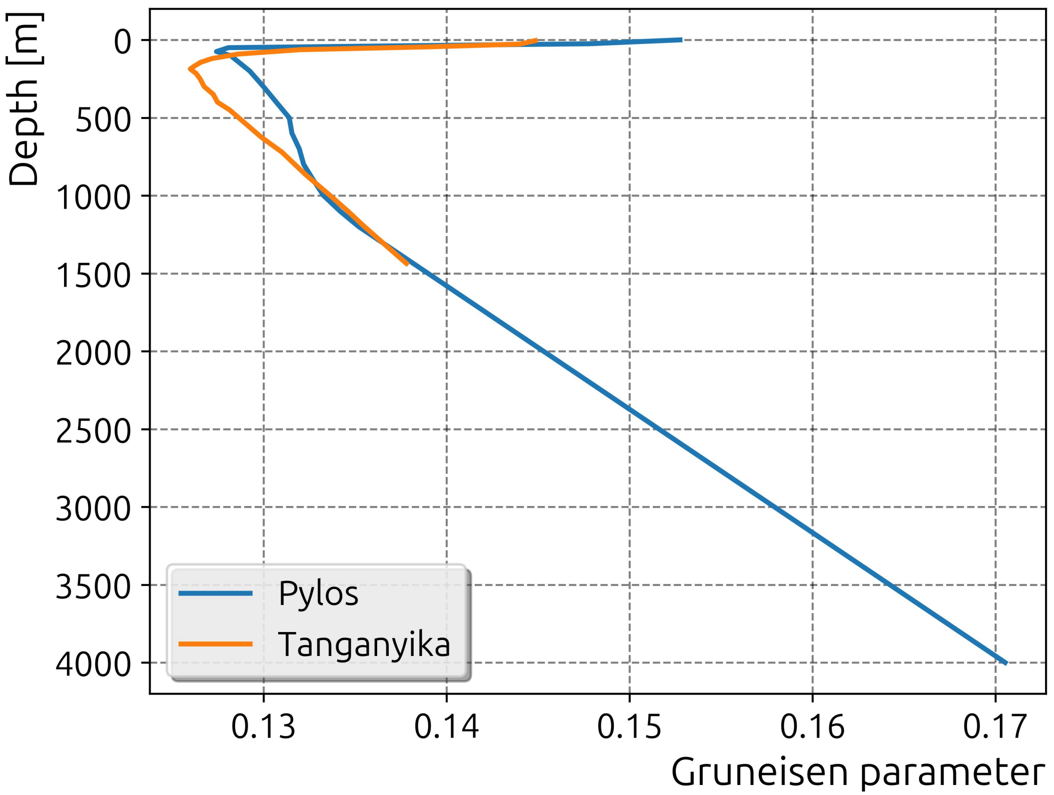


Sperm whale:

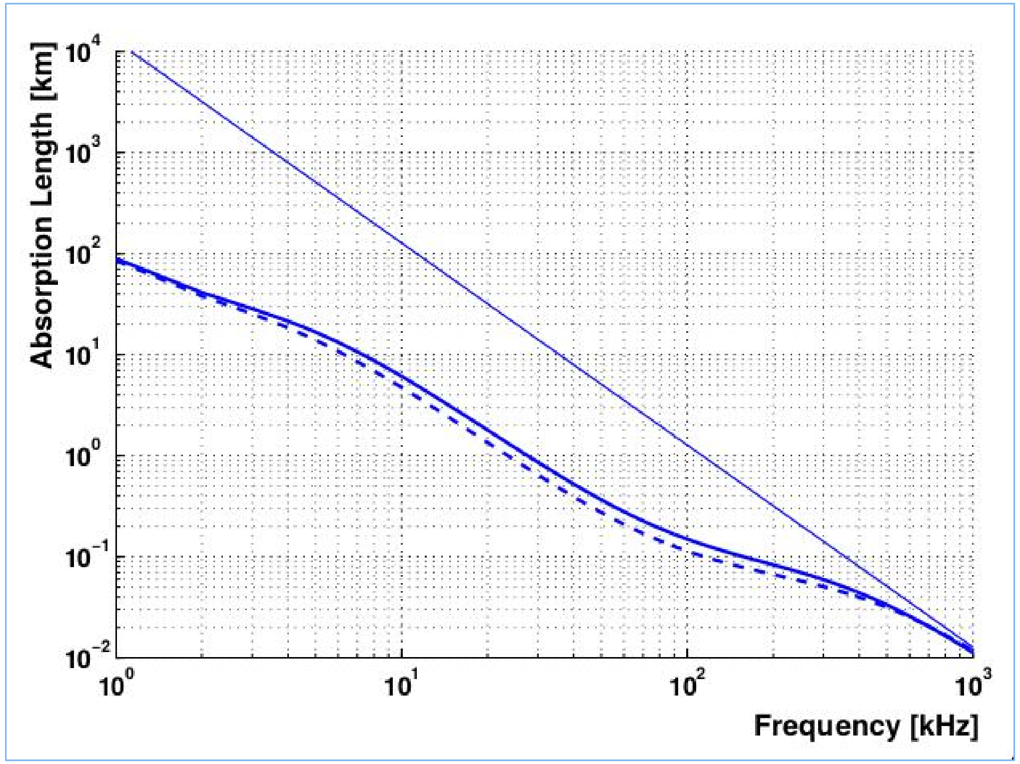
Train ML using a database of 10 000 recorded sperm whale clicks

Sites

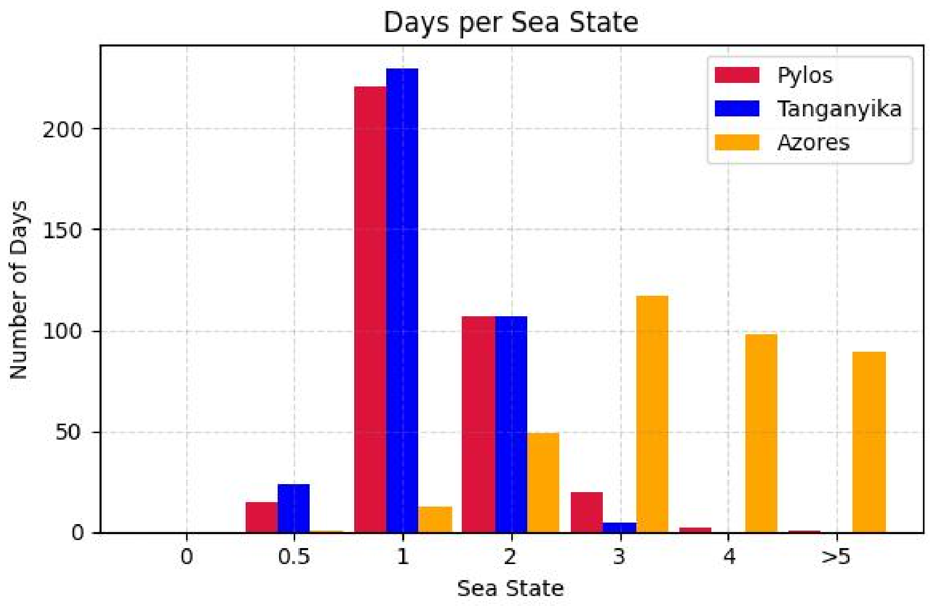
~ signal height

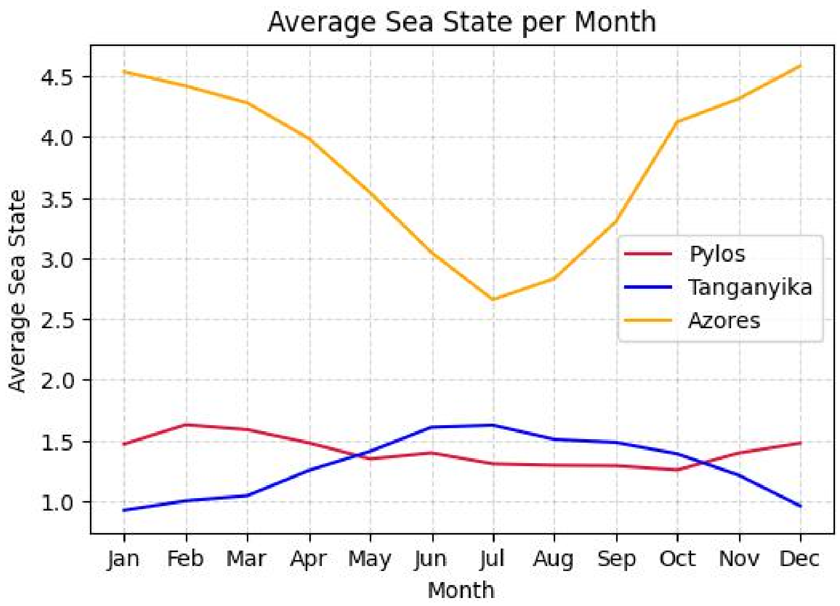


absorption



Sites

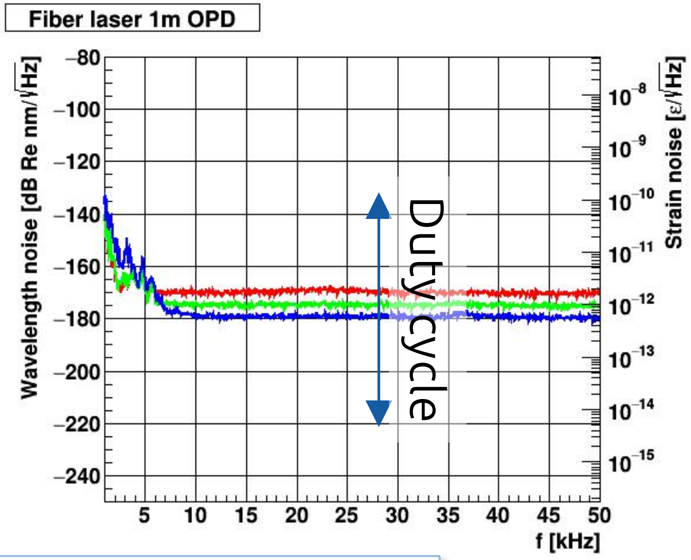


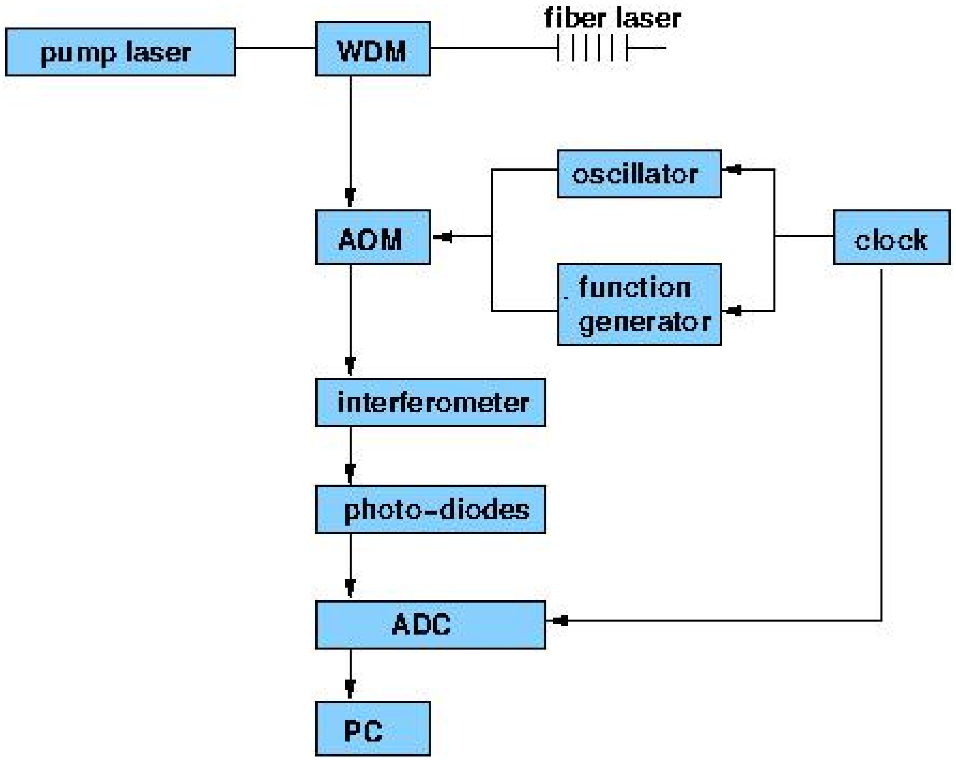


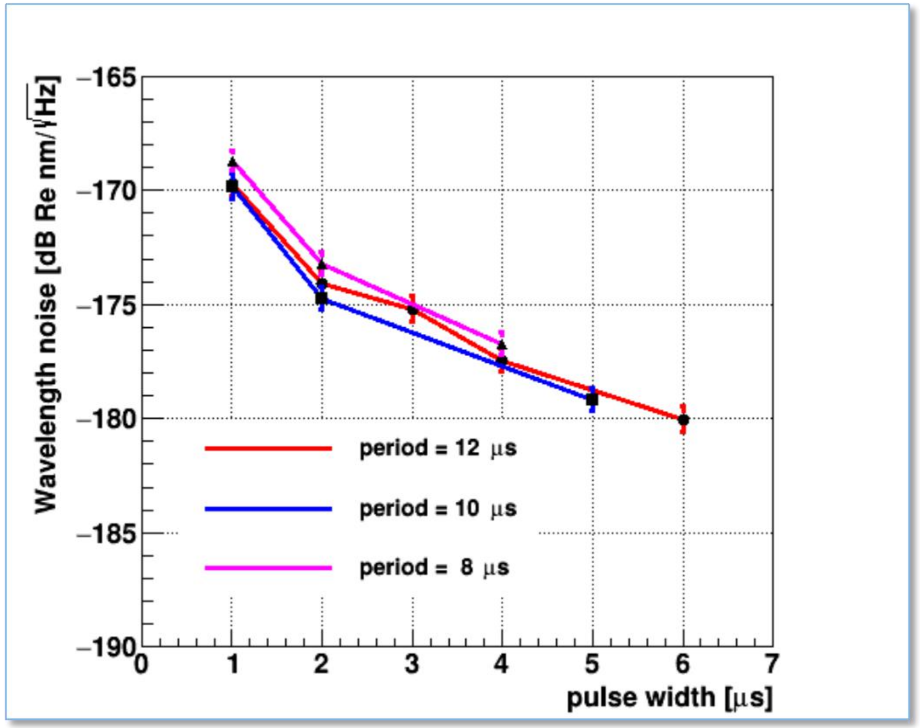
- Sea state noise: for both Pylos and Lake Tanganyika there are more than ~200 days/yr with SS1 or better
- Underwater noise and absorption yet to be verified

Time domain multiplexing (TDM)

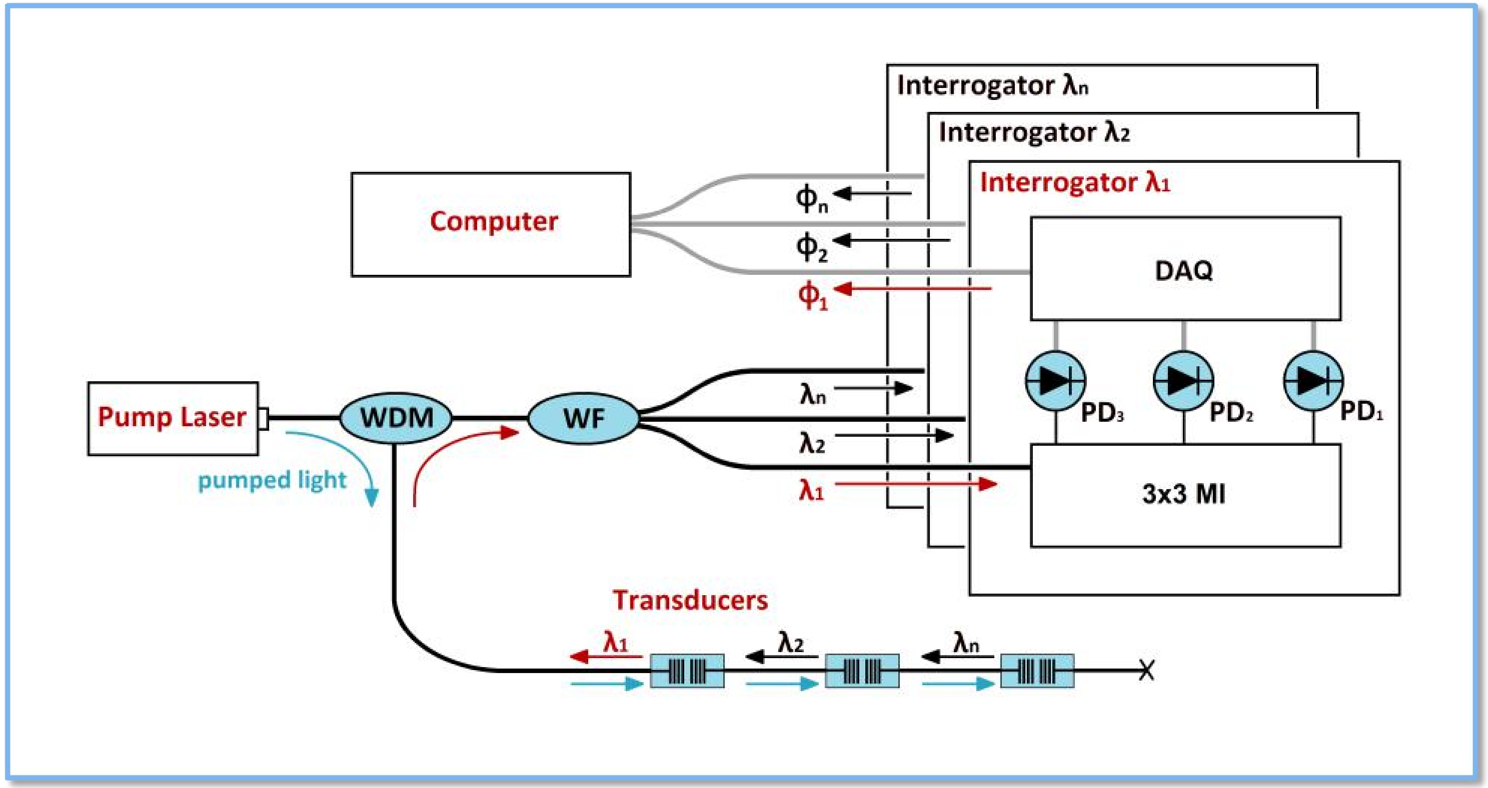
- Reduce the duty cycle when sampling the signal
- Insert an acoustic optical modulator in the DAQ system
- Noise floor increases with ~$^{10}\log(T/\Delta T)$

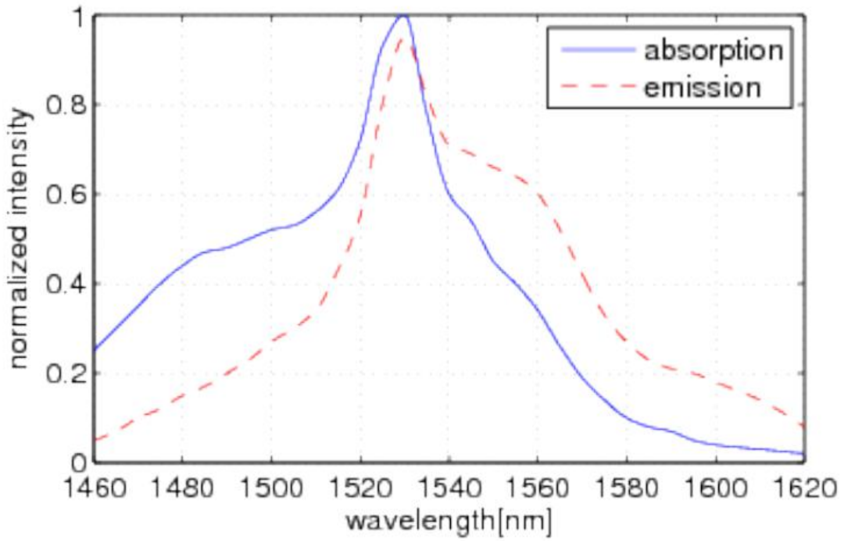


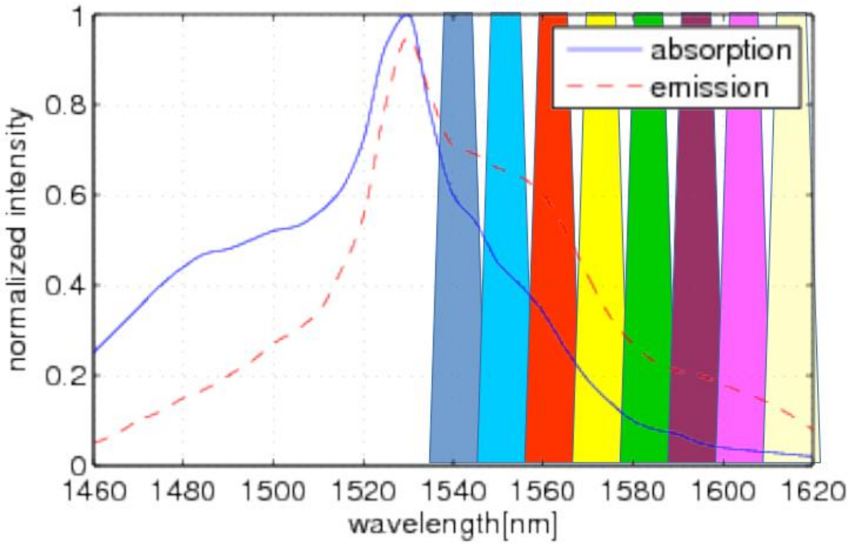




Wavelength domain multiplexing







- Wavelength of each hydrophone can be tuned
- In practice, a finite number (~10) of laser lines fit the Erbium spectrum

Interrogator