Fiber optic hydrophones for acoustic neutrino detection

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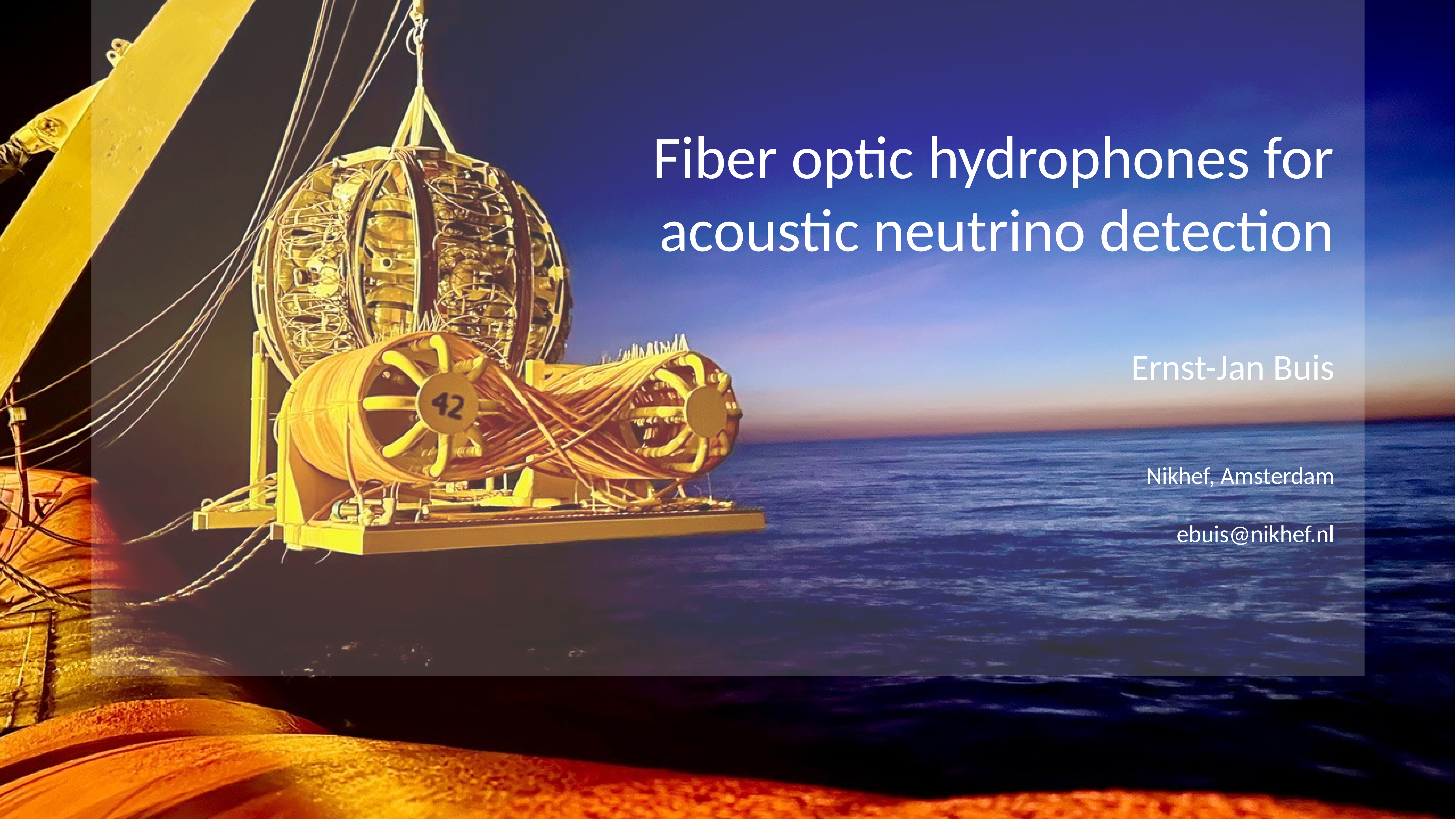
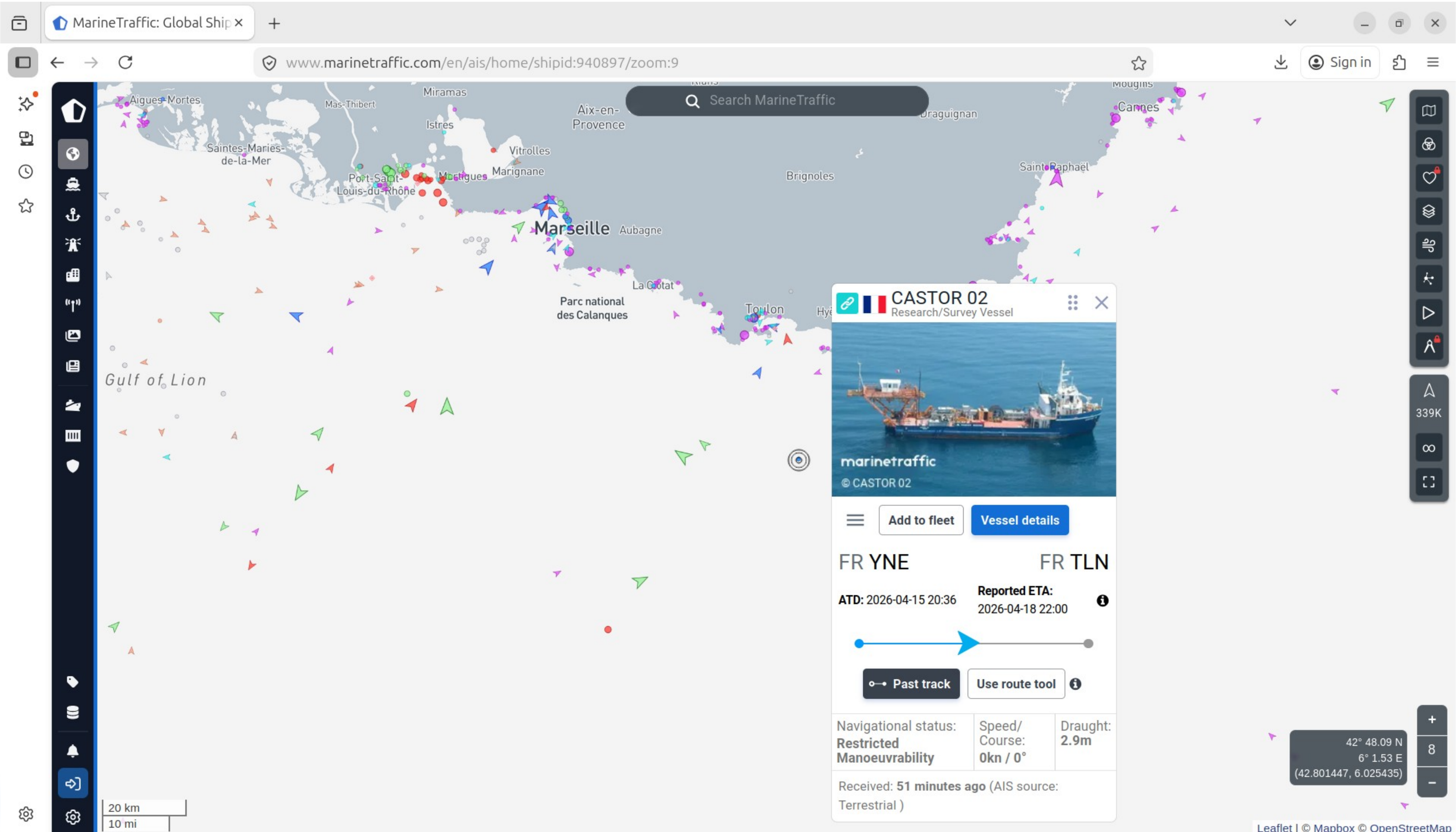
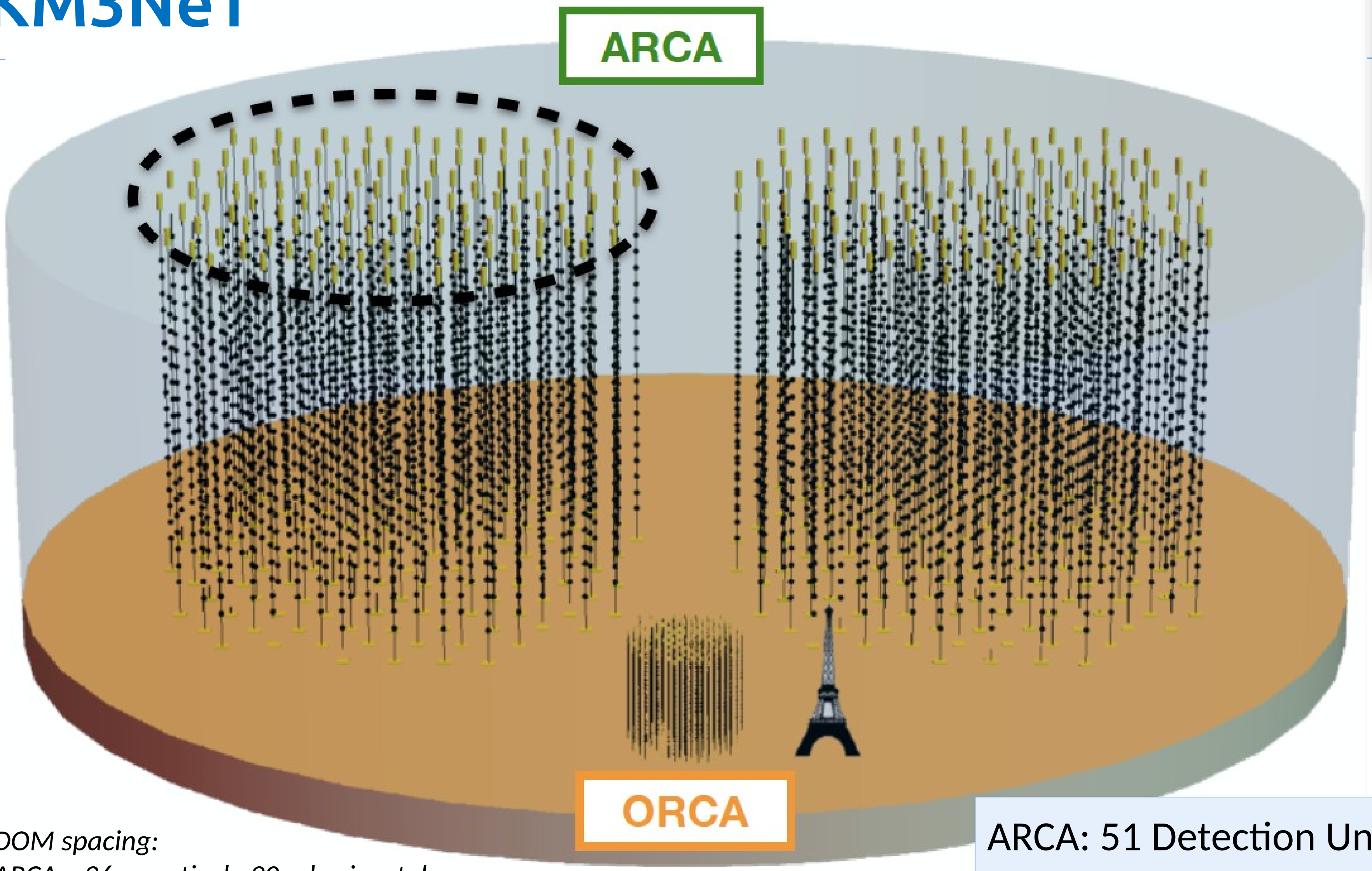



42


MarineTraffic: Global Ship
www.marinetraffic.com/en/ais/home/shipid:940897/zoom:9
Sign in
Search MarineTraffic
Aigues-Mortes
Miramas
Mas-Thibert
Istres
Aix-en-Provence
Draguignan
Cannes
Saintes-Maries-de-la-Mer
Vitrolles
Port-Saint-Louis-du-Rhône
Martigues
Marignane
Brignoles
Saint-Raphaël
Marseille
Aubagne
La Ciotat
Parc national des Calanques
Toulon
Gulf of Lion
CASTOR 02
Research/Survey Vessel
marinetraffic
© CASTOR 02
Add to fleet
Vessel details
FR YNE
FR TLN
ATD: 2026-04-15 20:36
Reported ETA: 2026-04-18 22:00
Past track
Use route tool
Navigational status: Restricted Manoeuvrability
Speed/ Course: 0kn / 0°
Draught: 2.9m
Received: 51 minutes ago (AIS source: Terrestrial)
339K
42° 48.09 N
6° 1.53 E
(42.801447, 6.025435)
8
20 km
10 mi
Leaflet | © Mapbox © OpenStreetMap

KM3NeT

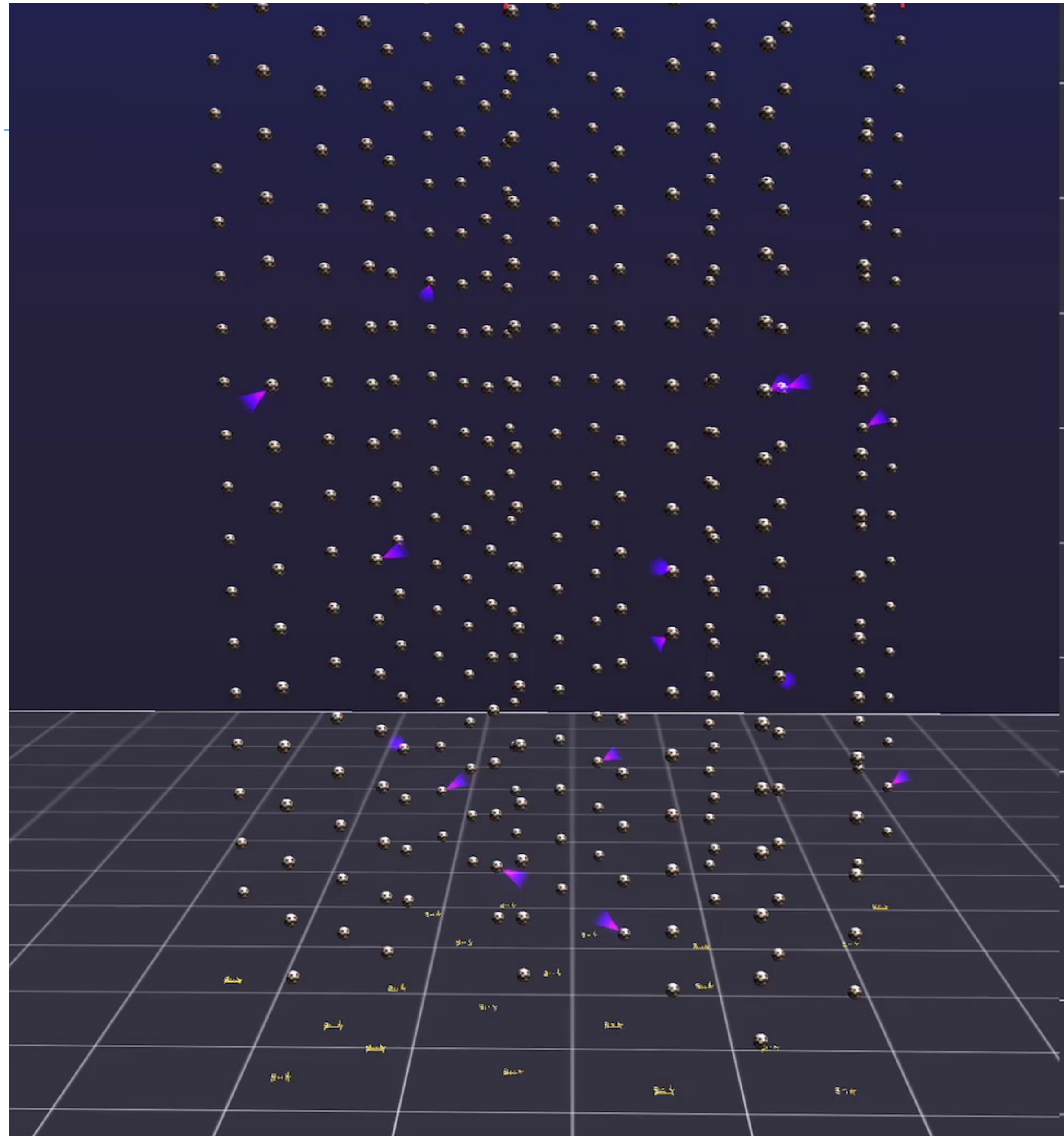


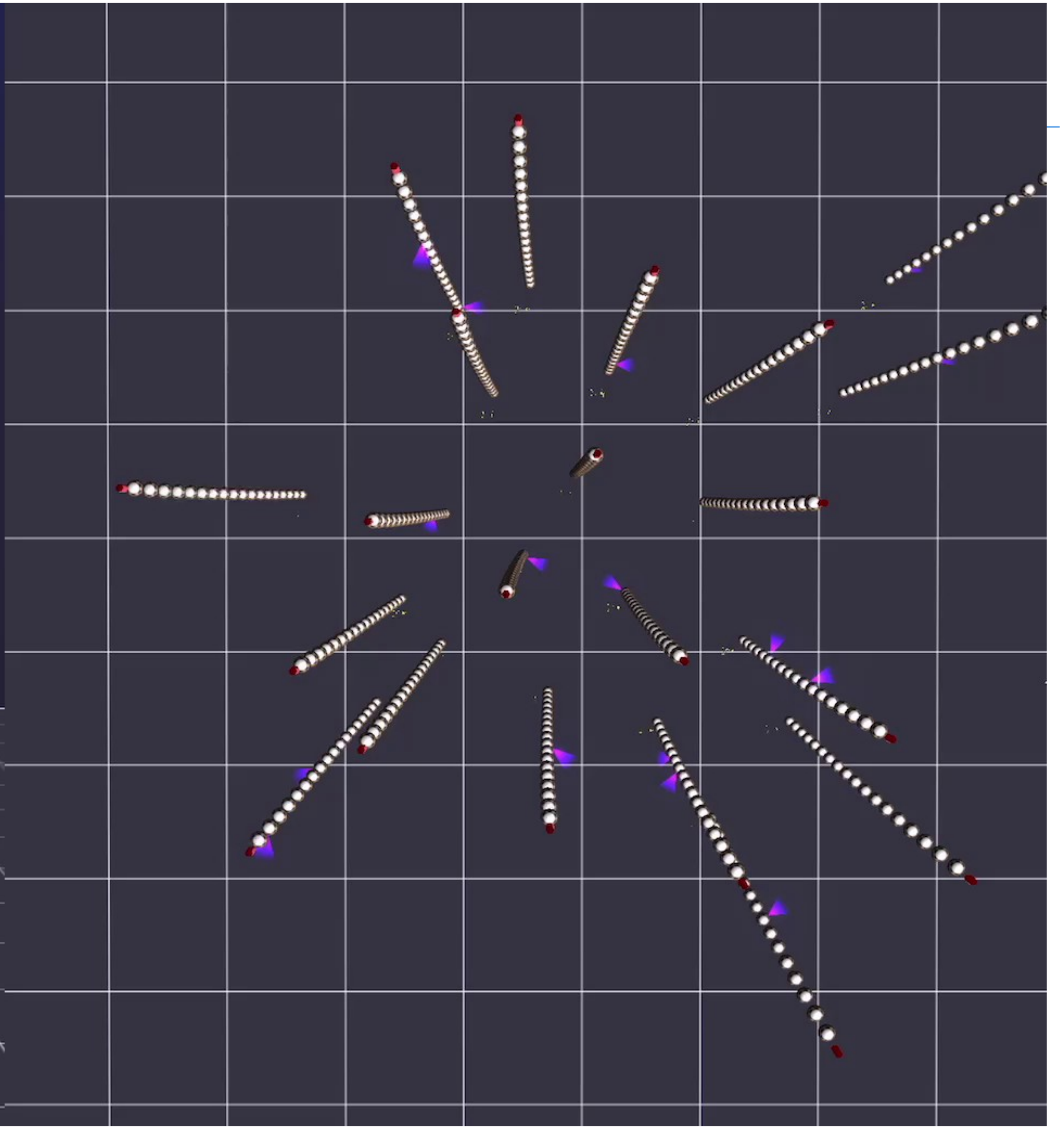
DOM spacing:
ARCA 36m vertical, 90m horizontal
ORCA 9m vertical, 20m horizontal

ARCA: 51 Detection Units deployed; 230 planned
ORCA: 33 Detection Units deployed; 100 planned

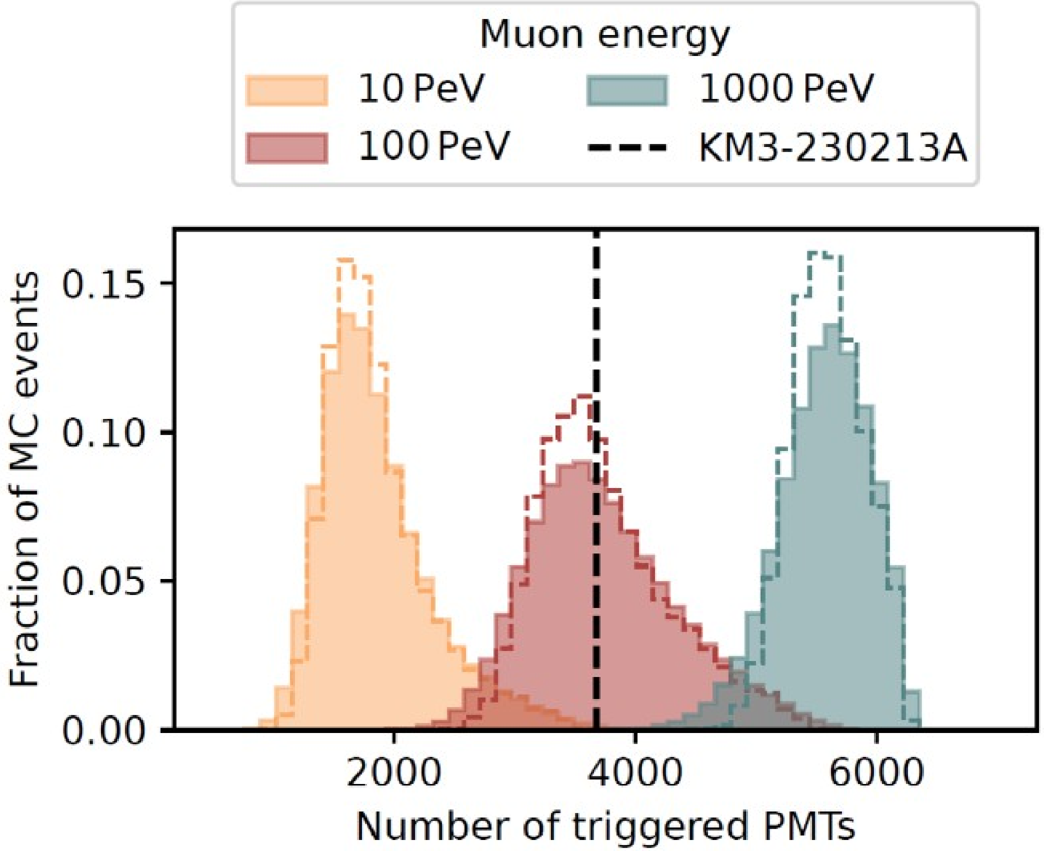
February 13 2023, 01:16:47 UTC

KM3-230213A





Energy measurement



Energy is measured from the amount of light:

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

$90\%\ CL: 35\ PeV - 380\ PeV$

(10 000 times the energy of the LHC)

The neutrino energy is higher:

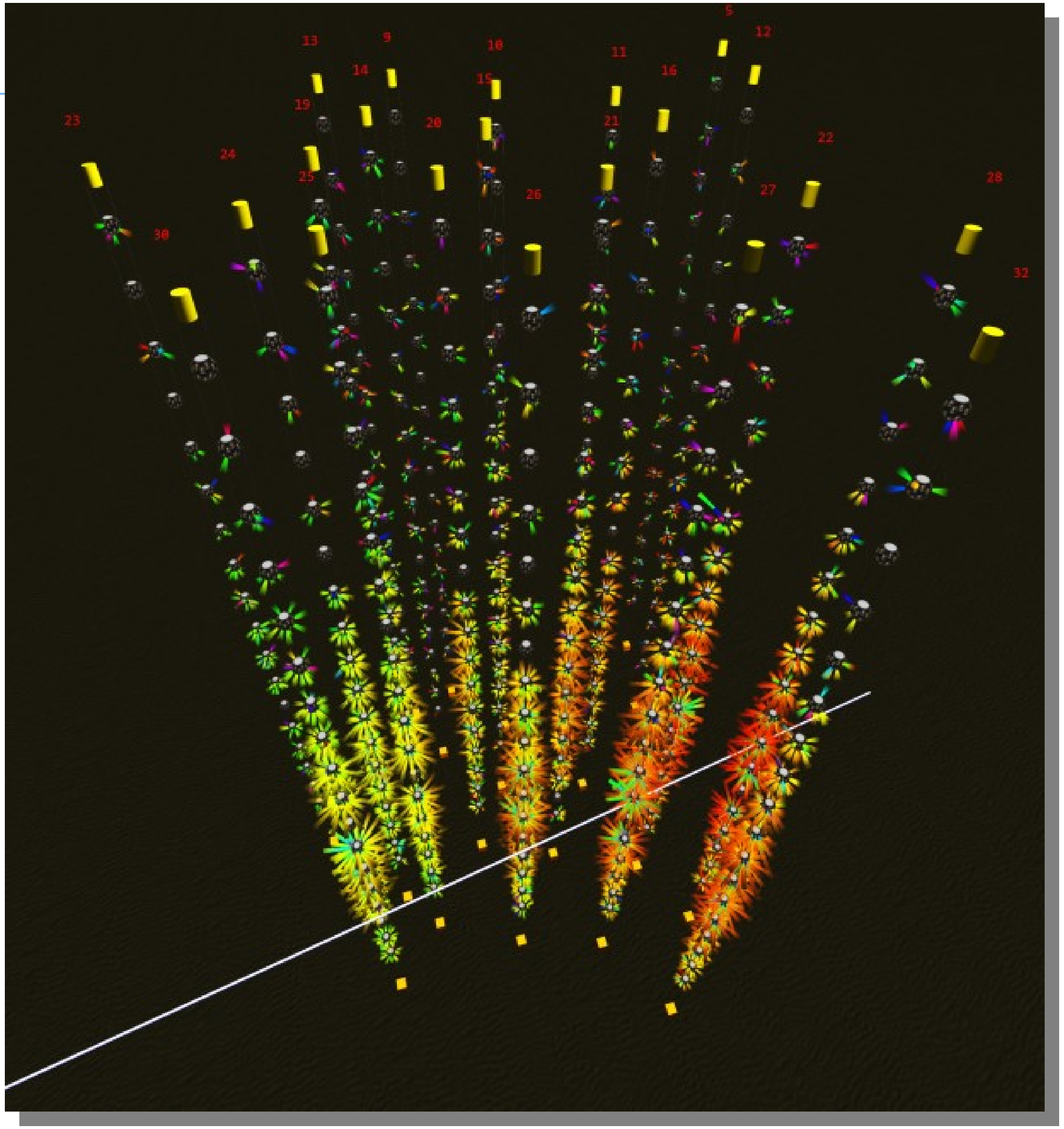
$$E_\nu = 220^{+570}_{-100}\ PeV$$

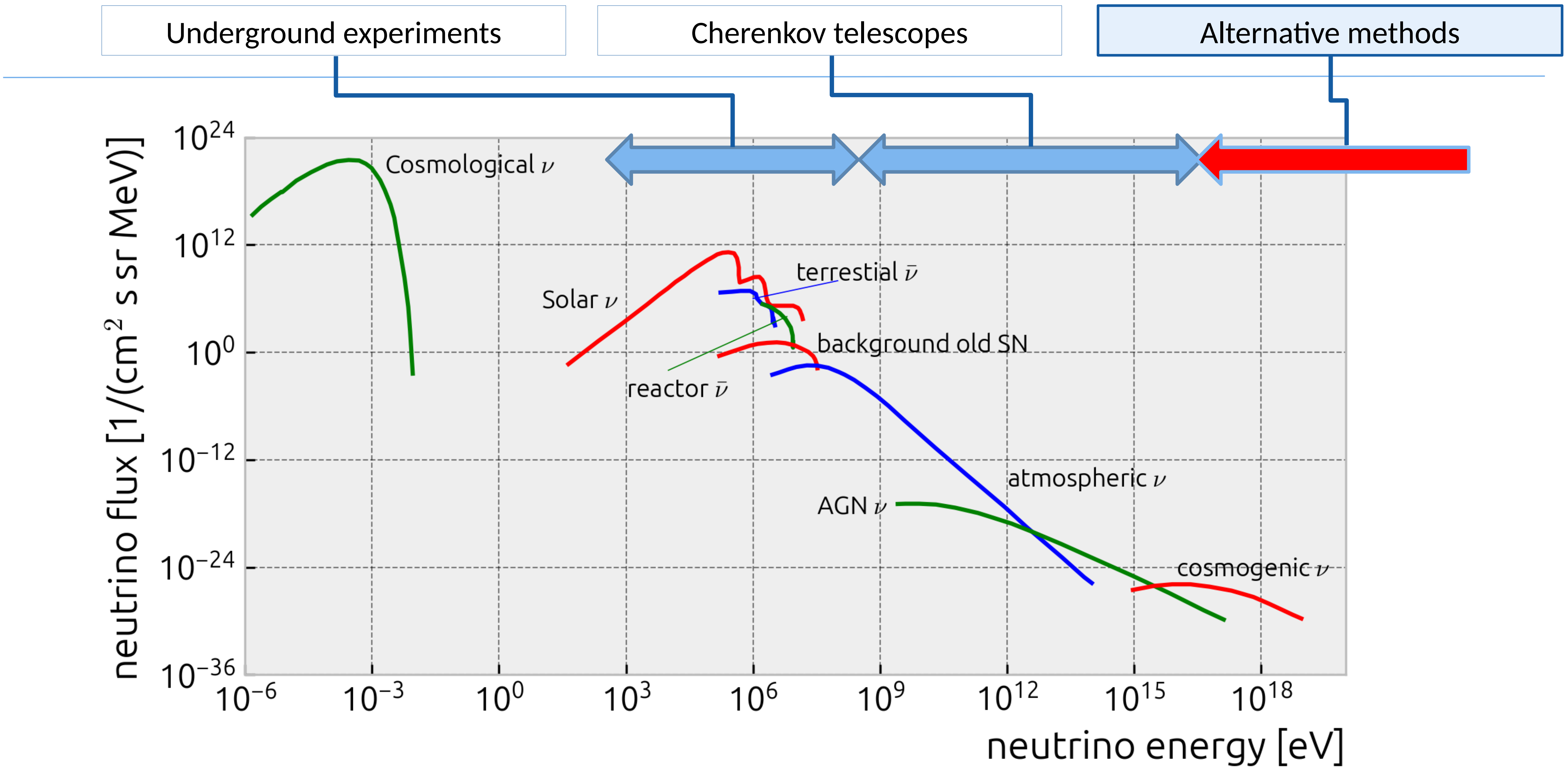
$90\%\ CL: 72 PeV - 1.5 EeV$

(assuming an E^{-2} source spectrum)

A 120 PeV muon!

- 120 PeV = 0.02 J
- Lorentz boost factor $\gamma \approx 10^9$
- lifetime of the muon is 2.2 µs,
  but 42 minutes in our reference frame!

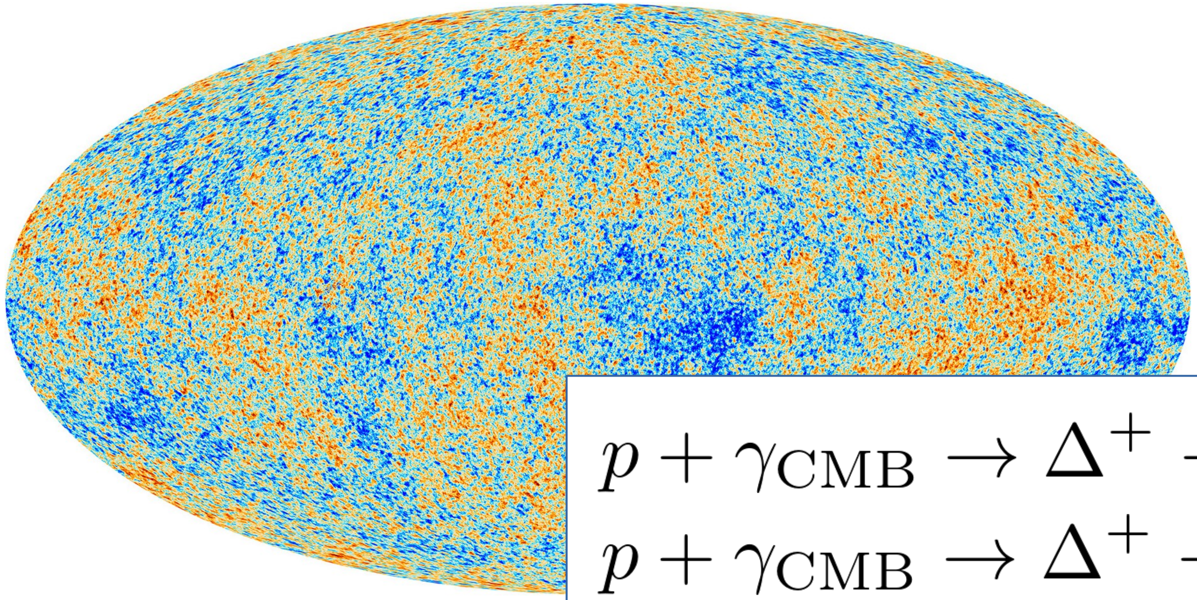


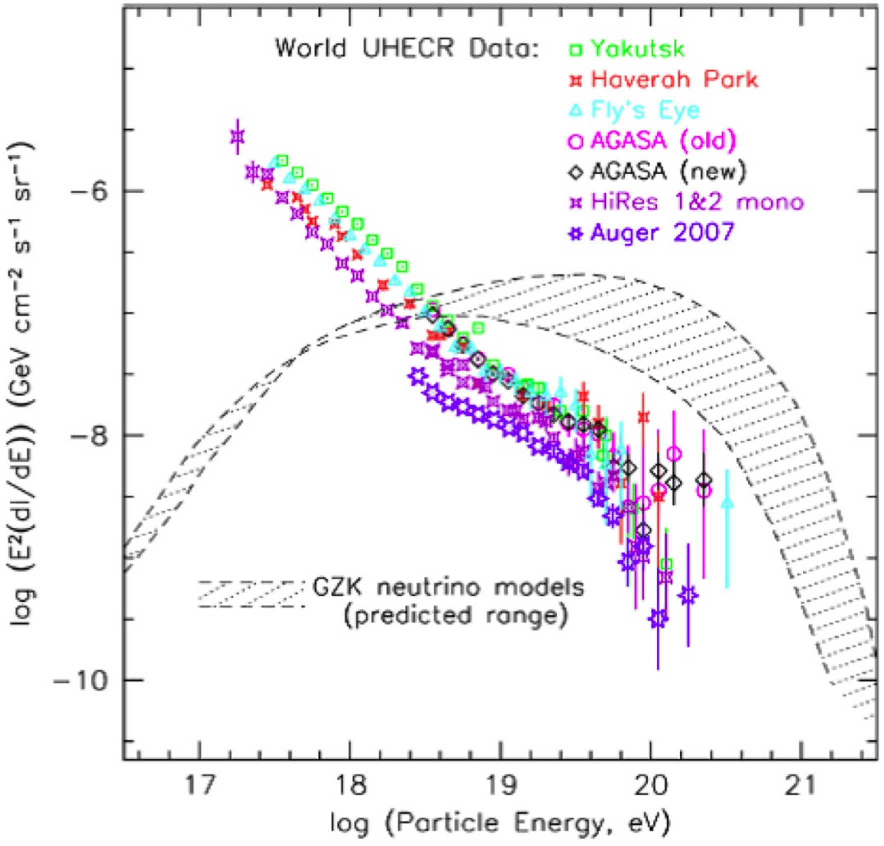


Underground experiments
Cherenkov telescopes
Alternative methods
neutrino flux [1/(cm^2 s sr MeV)]
10^{24}
10^{12}
10^{0}
10^{-12}
10^{-24}
10^{-36}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
neutrino energy [eV]
Cosmological ν
Solar ν
terrestial $\bar{\nu}$
background old SN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

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



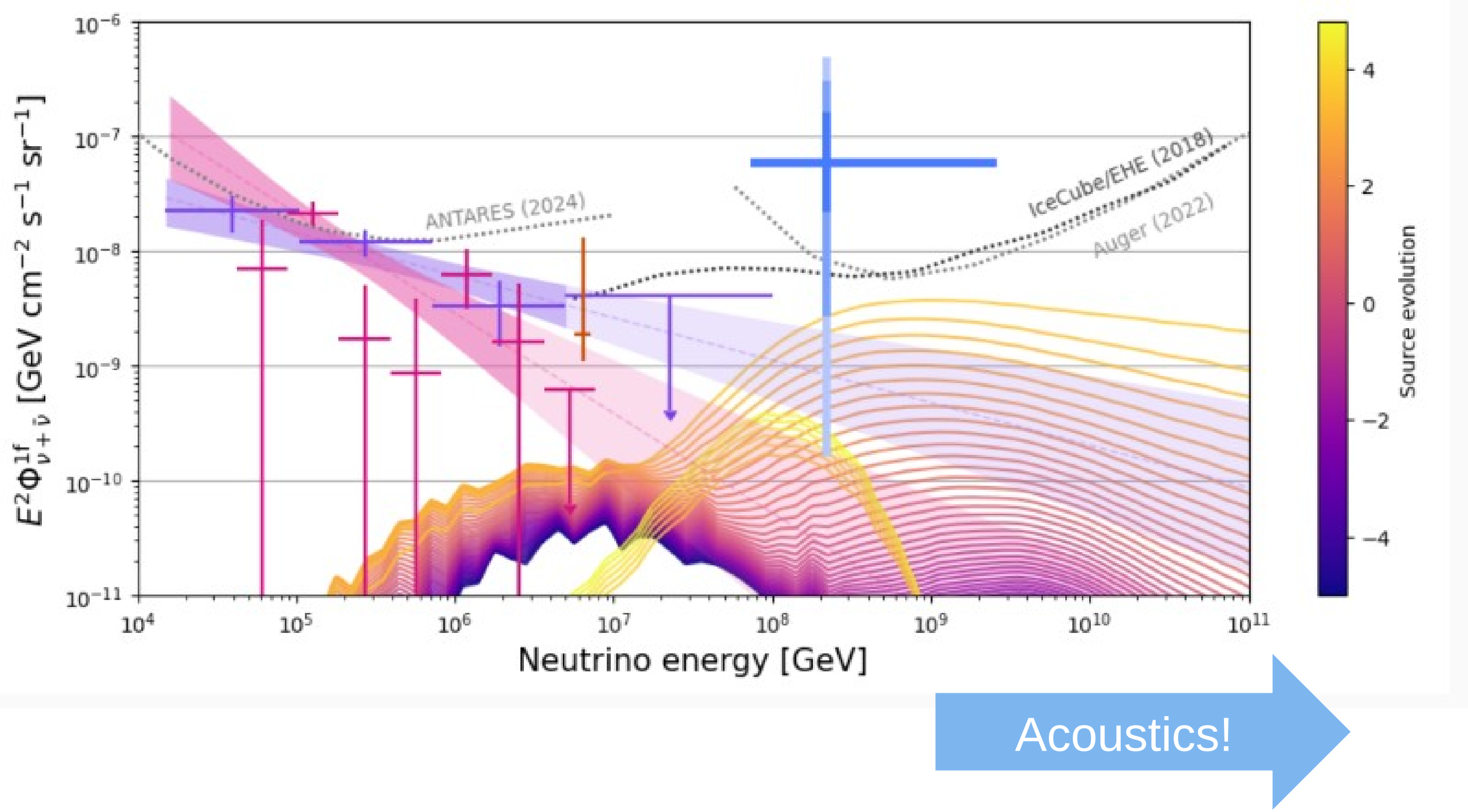


$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{o}$$
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

… with subsequent decay to *neutrinos*

A cosmic origin

Adriani et al, 2025



- Flux predictions, depends on
  - cosmic rays composition (protons, ions)
  - source evolution
  - cosmic ray cut-off energy
  - cosmic ray spectral spectral index

- 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

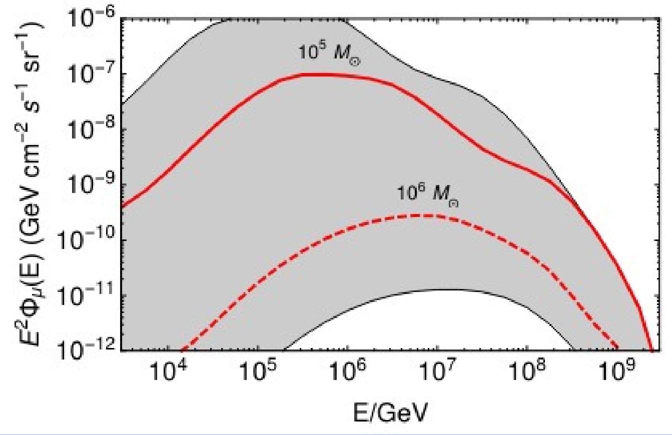
- Astrophysical sources, origin of UHECR:
  - GZK neutrinos
  - AGNs, Blazars
  - Tidal Disuption Events (TDE)
  - Magnetars

- Exotics:
  - Superheavy dark matter

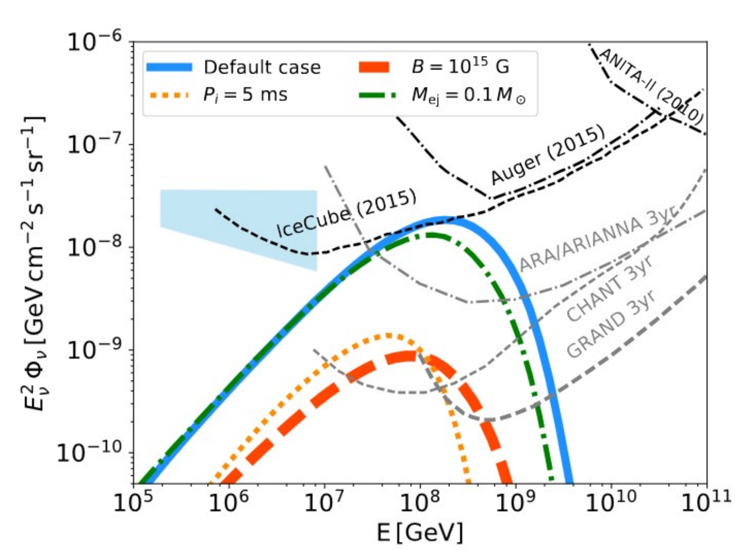
- Particle physics at energy scale presently unreachable
  - Cross section measurement

- Cosmic neutrino background
- Serendipity
  - Is there a fundamental end to the CR spectrum?

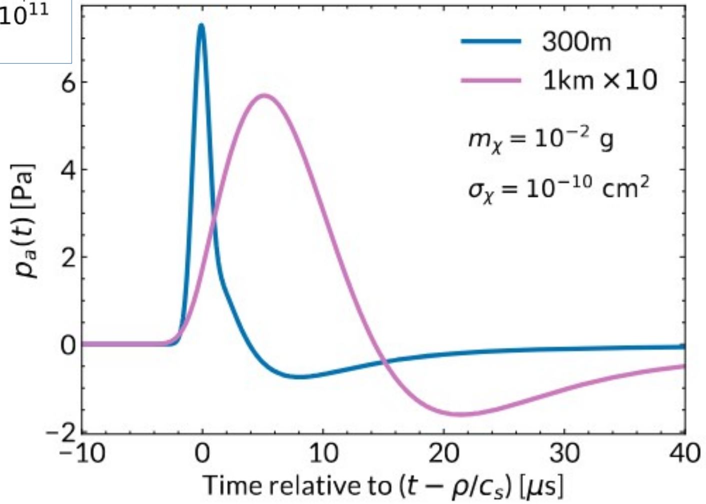
Lunardini, Winter 2017



Fang, Metzger 2017

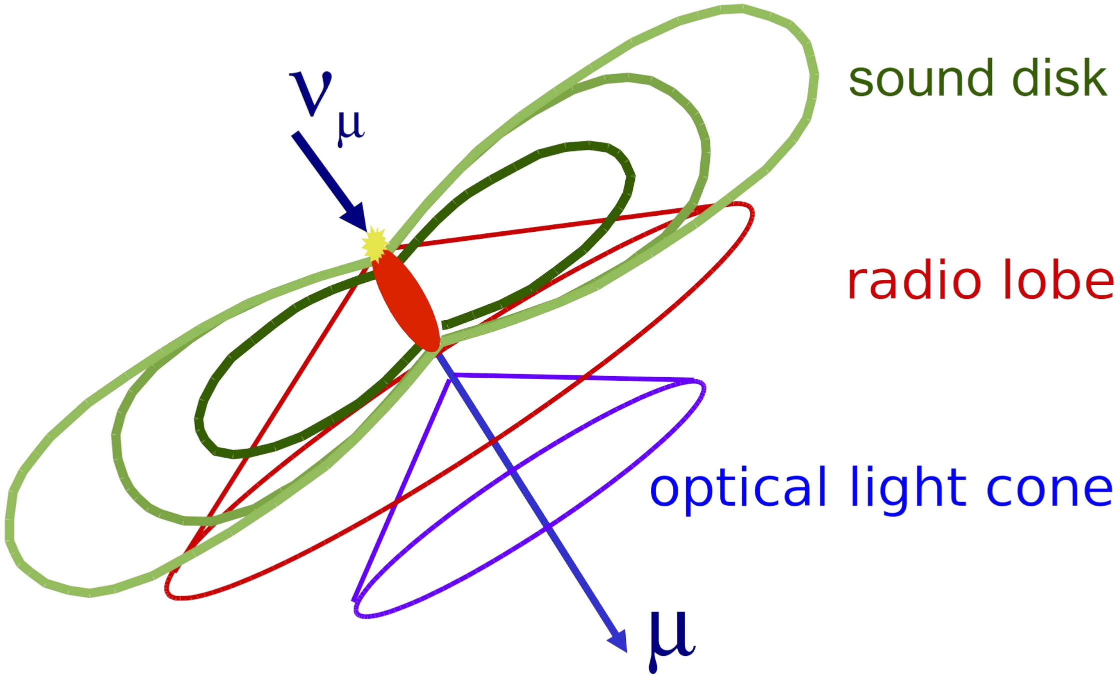


Cleaver et al, 2025

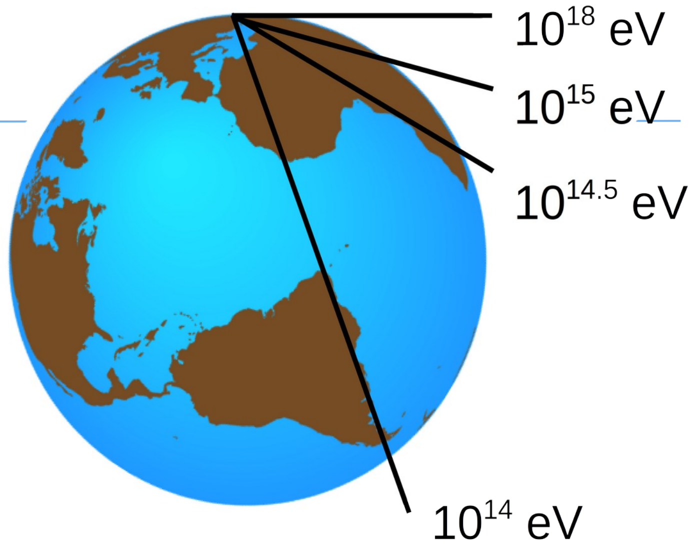


Detection of high energy neutrinos

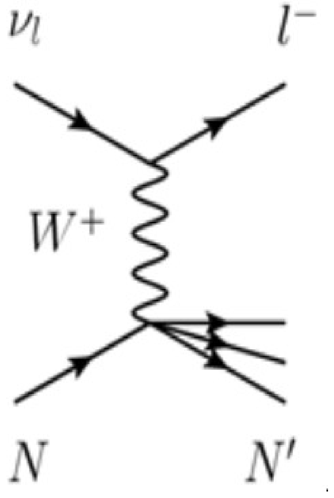
- Three methods of observing neutrinos in large scale telescopes
  - Optical, Cherenkov radiation
  - Coherent radio emission
  - *Acoustic signals*



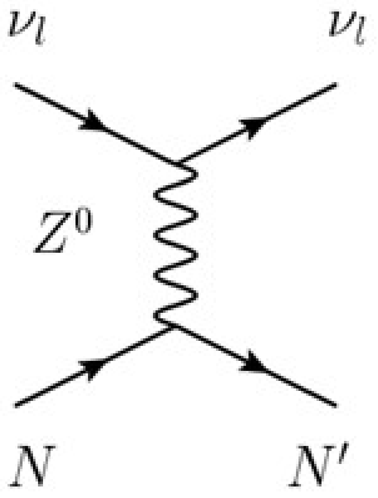
Neutrino interactions in water



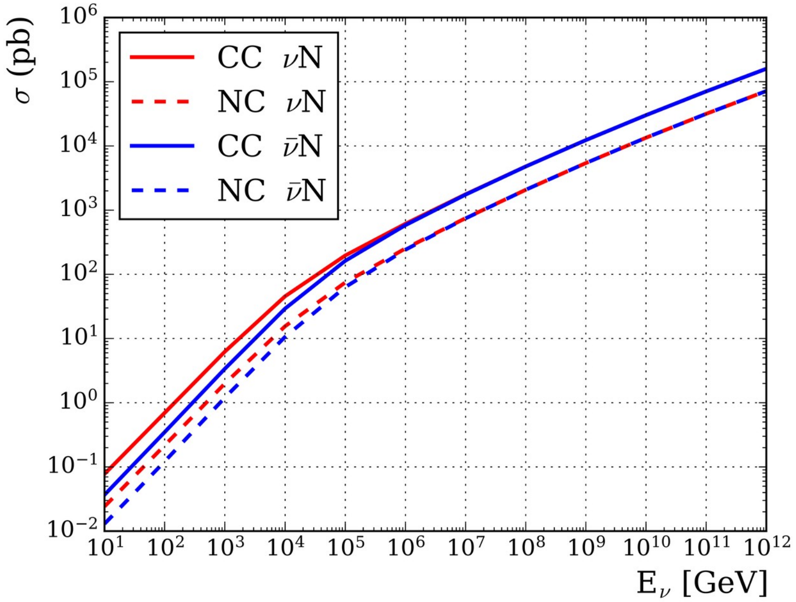
- Both neutral and charge current interactions.
- Assume tau and muon escape unobserved.
- Cross section increases with energy
  - Expect UHE neutrinos skimming or from zenith.



CC

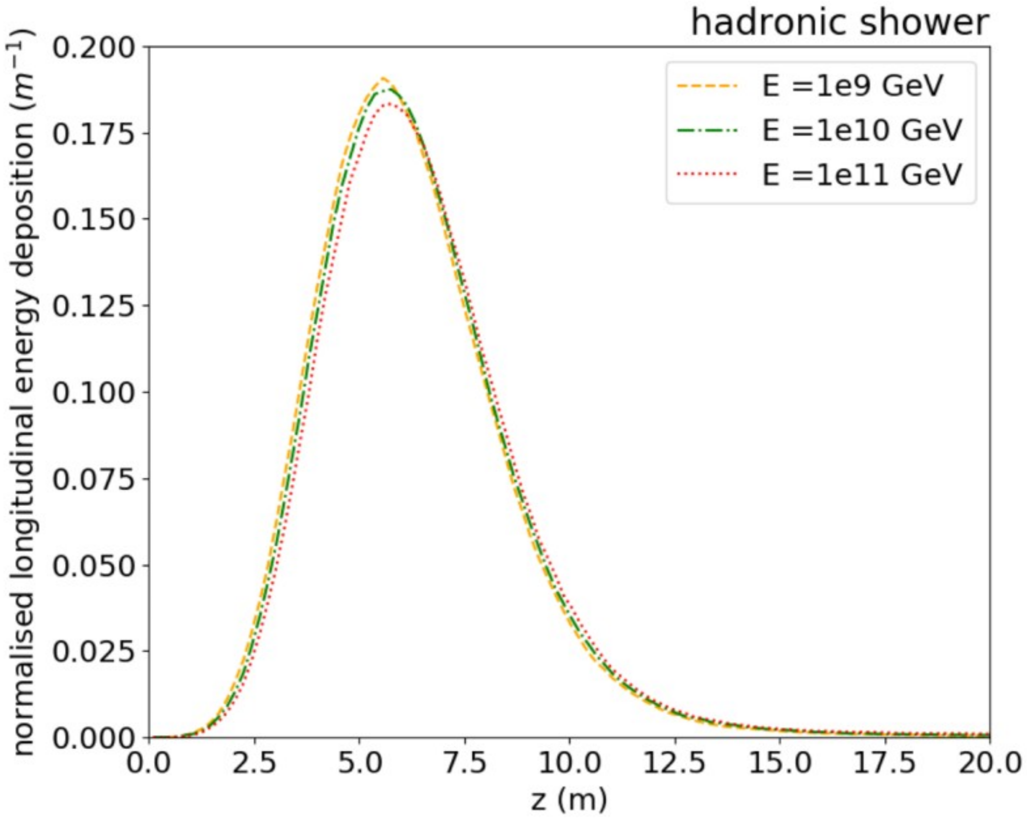


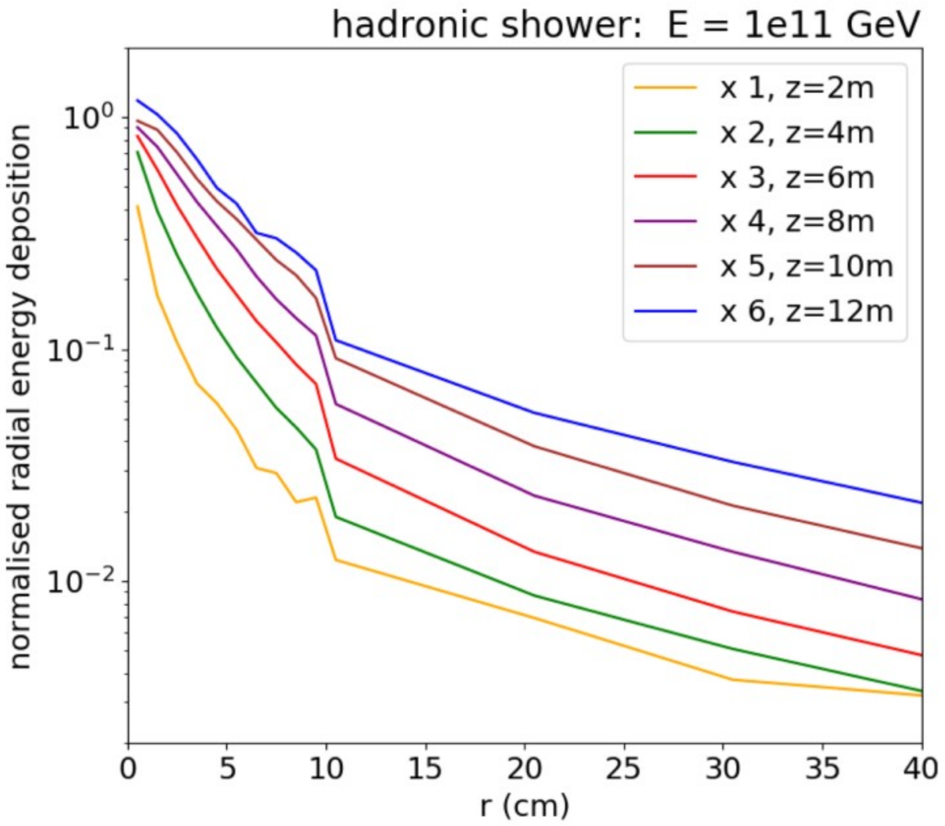
NC



Particle showers in water

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





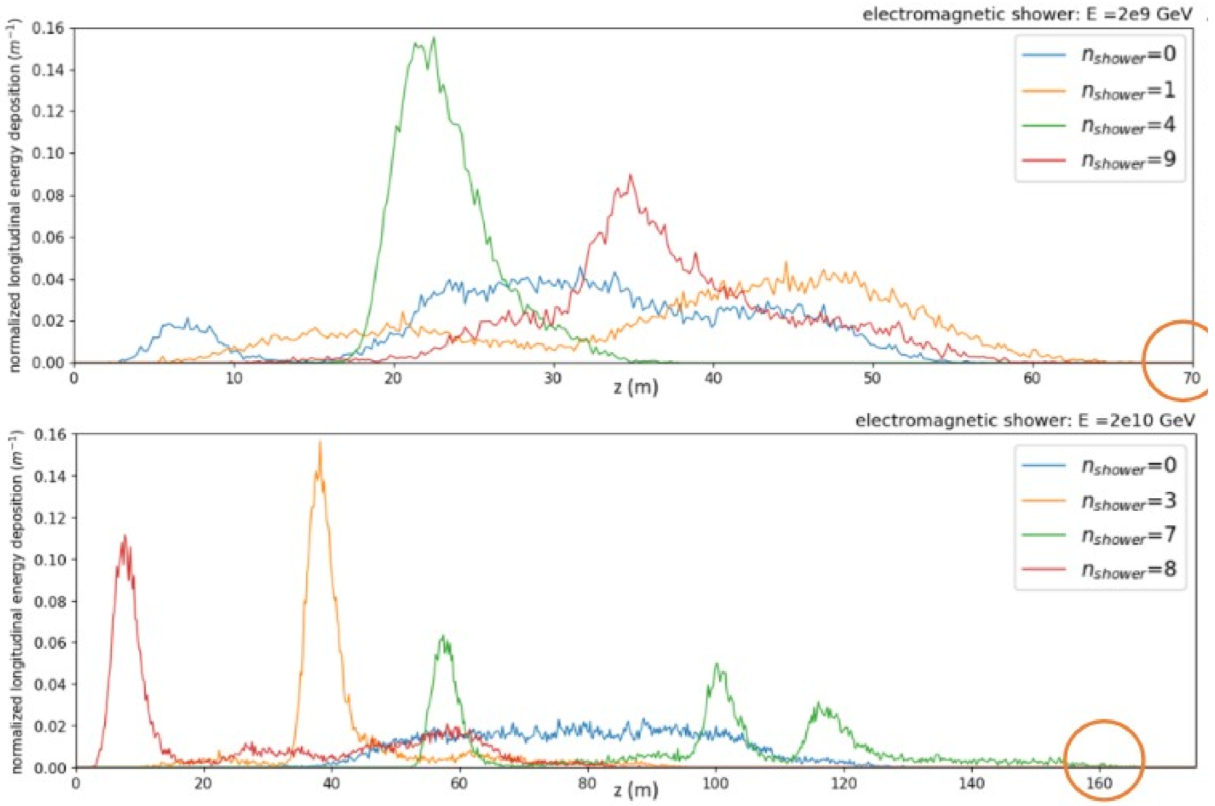
Particle showers in water at the highest energies

- 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*.

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

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

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

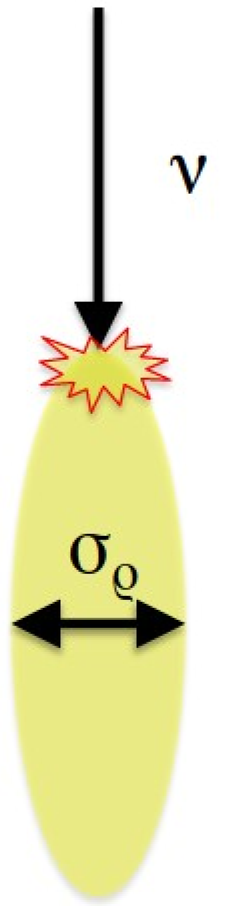
Grüneisen parameter

Water properties:

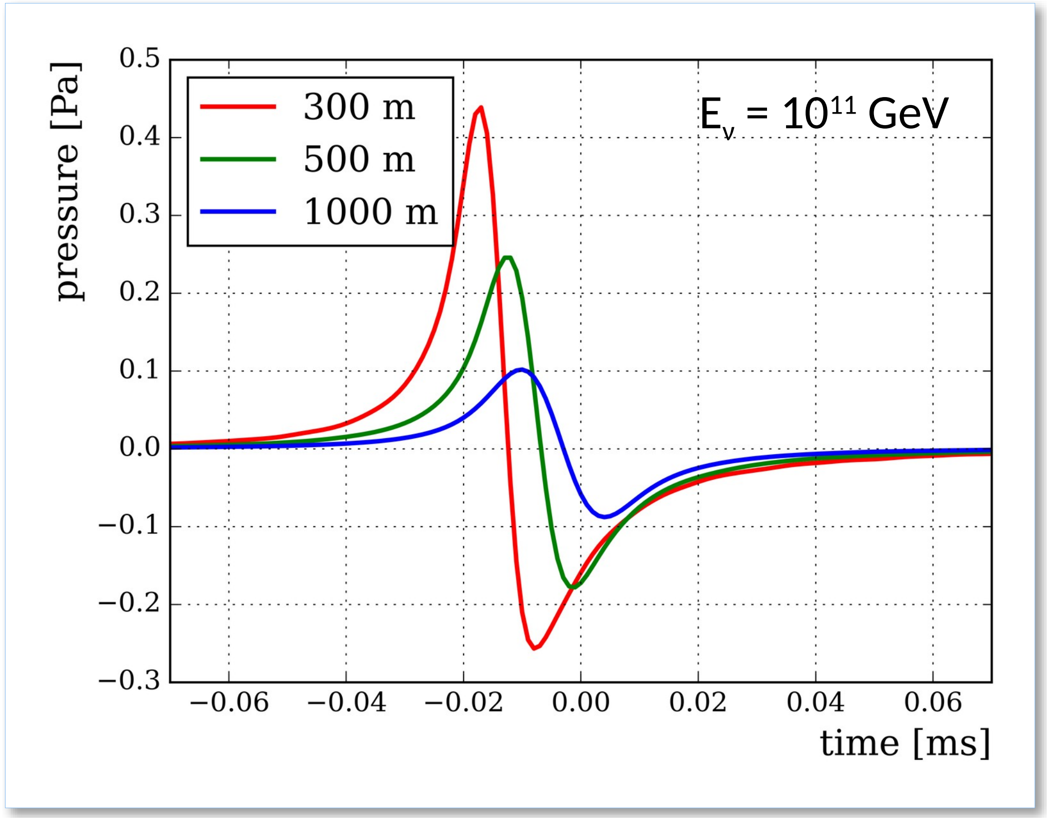
c = speed of sound

C_p = expansion coefficient

α = heat capacity



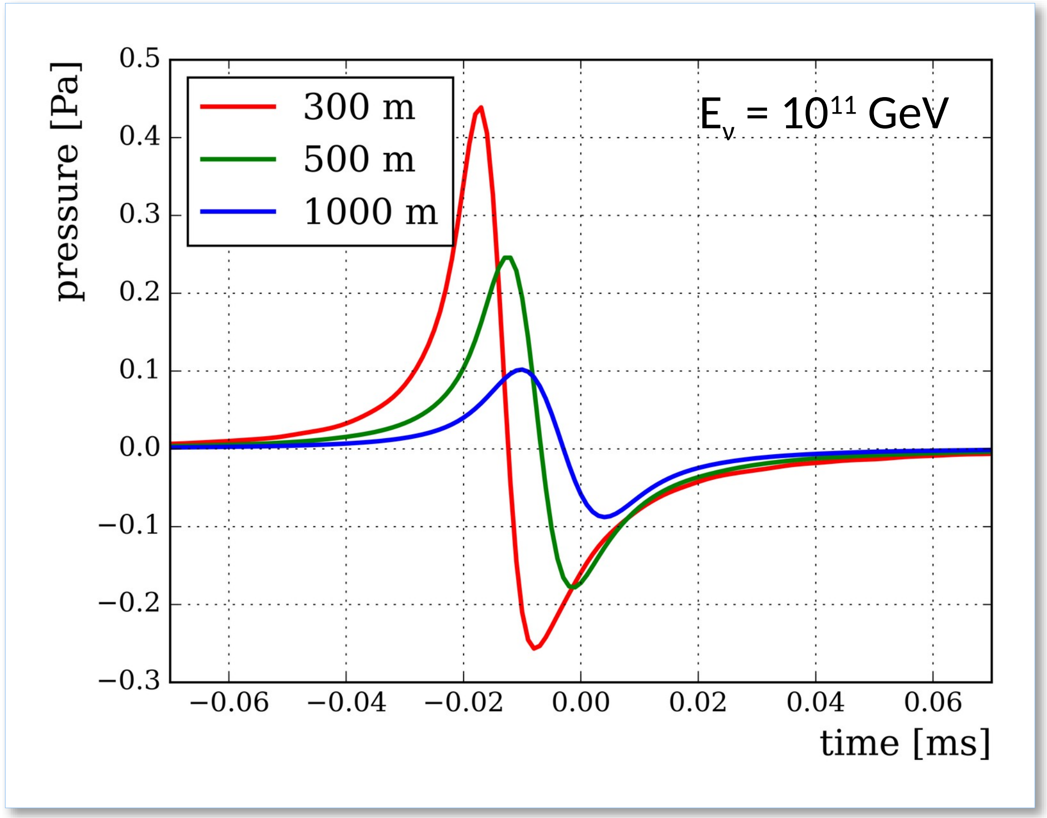
Acoustic neutrino signals

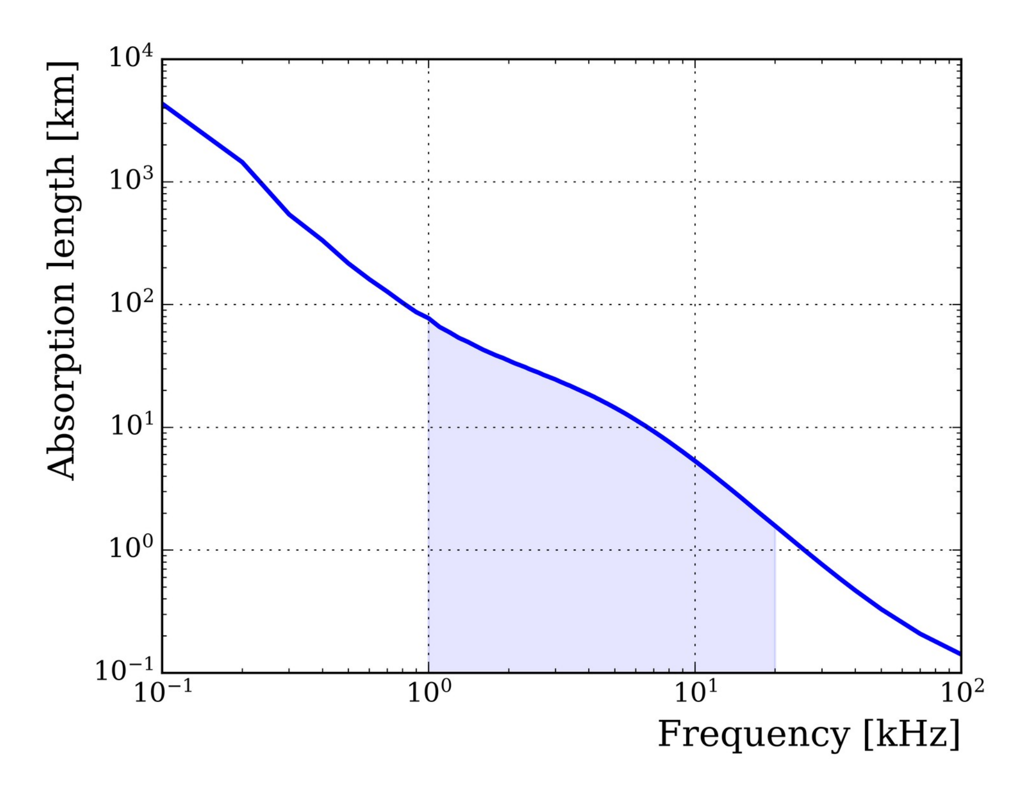


- Pulse asymmetry
- Broad spectrum that peaks at 5-12 kHz.
- Near field effects
- Complex waveforms in case of LPM effect

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

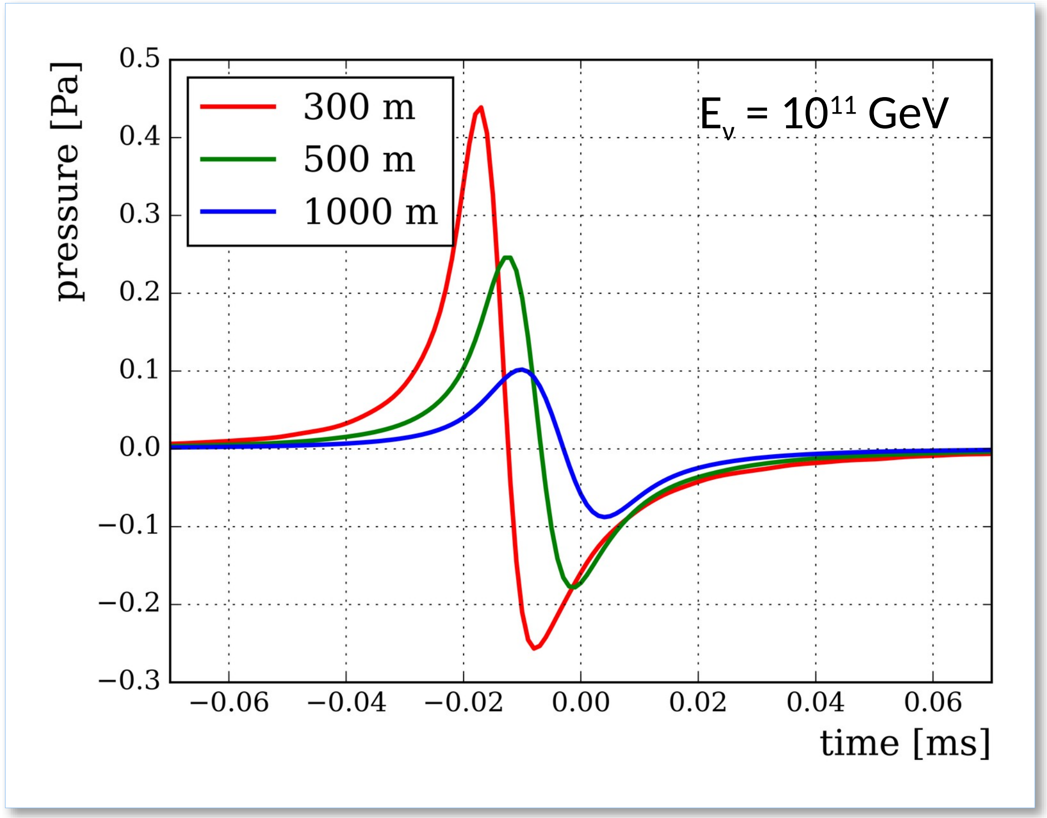
Acoustic neutrino signals

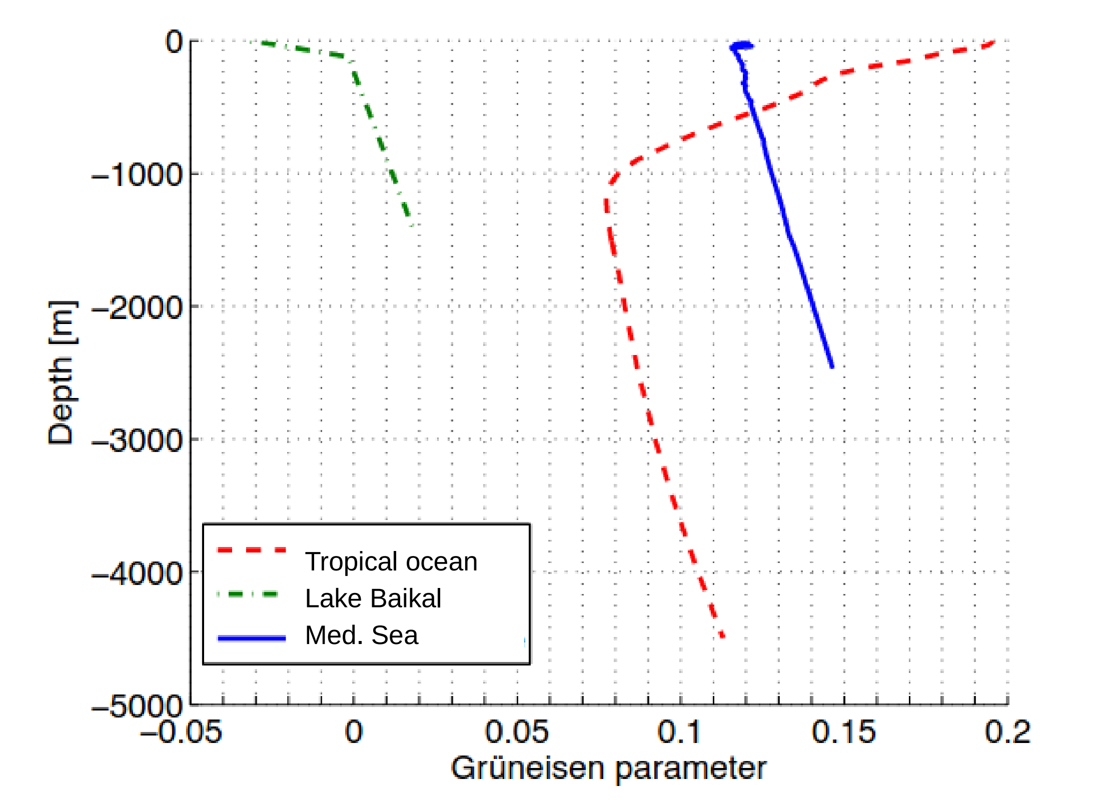




-> Detect **mPa** pulses in a static pressure environment of **MPa**

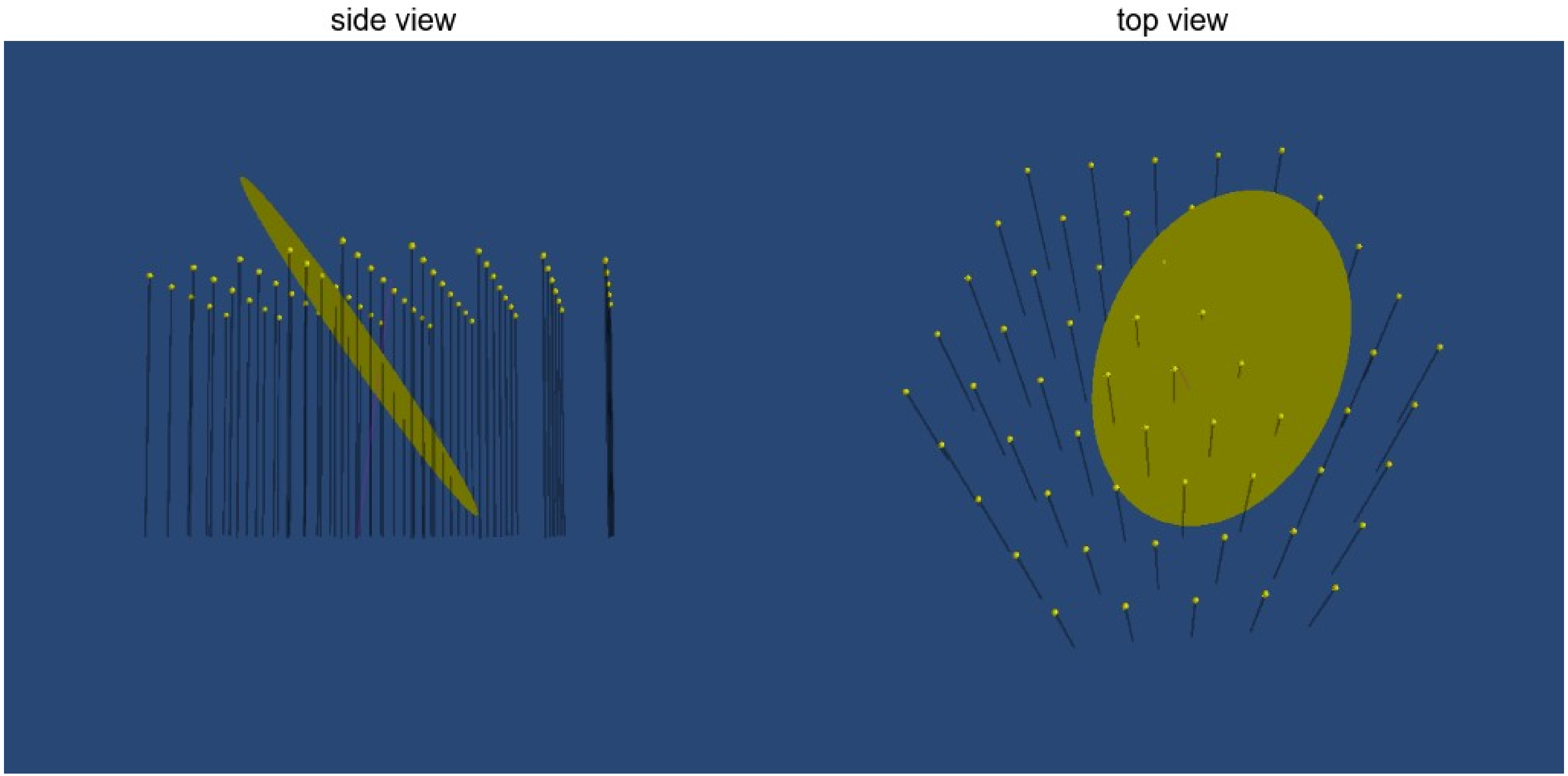
Acoustic neutrino signals





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

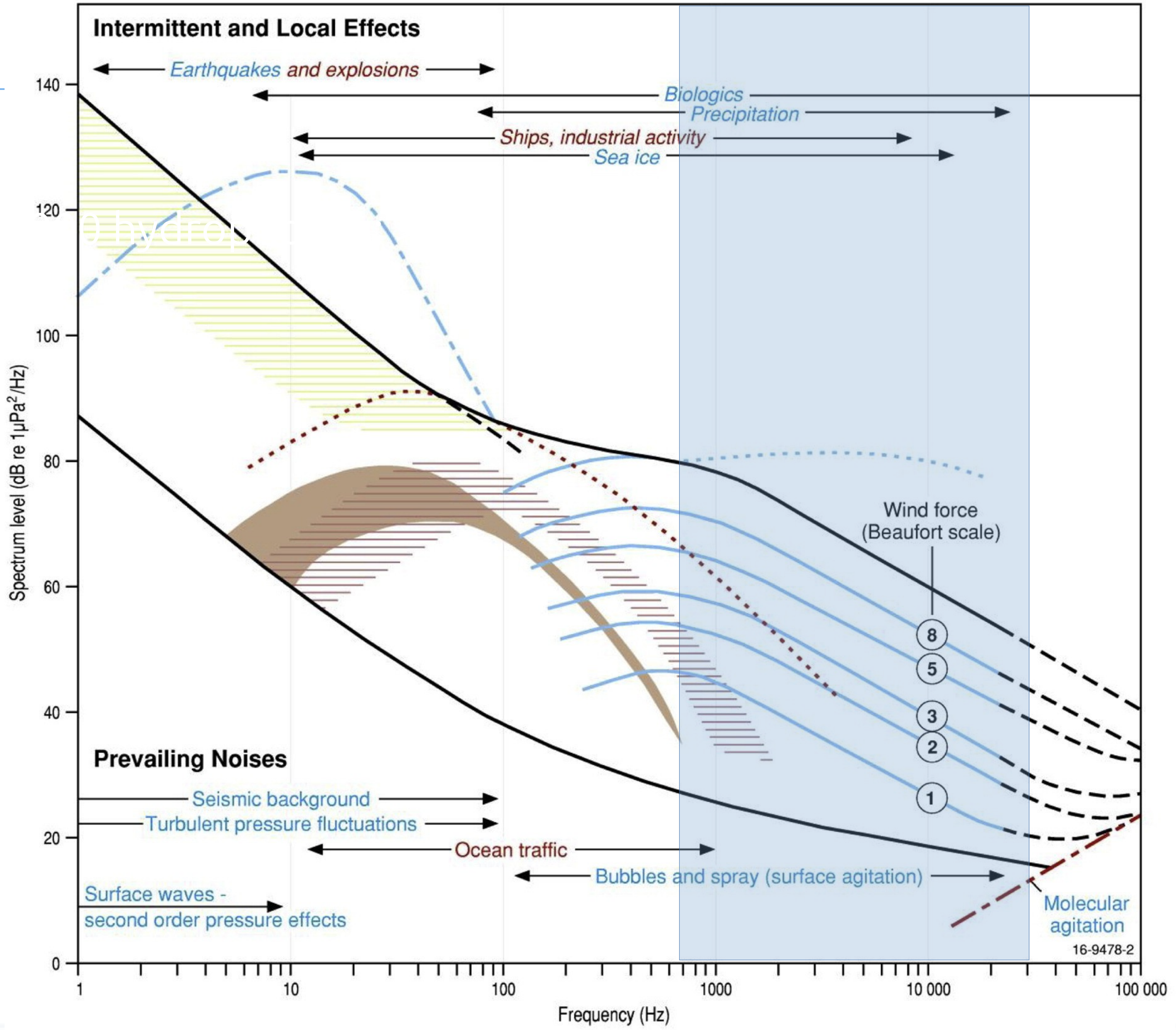
Event topology



Expected noise sources

- Sea state noise:
  - Omnipresent, wide-band noise.
  - Related to weather conditions

- Shipping noise
  - mostly low frequent and continuous acoustic source

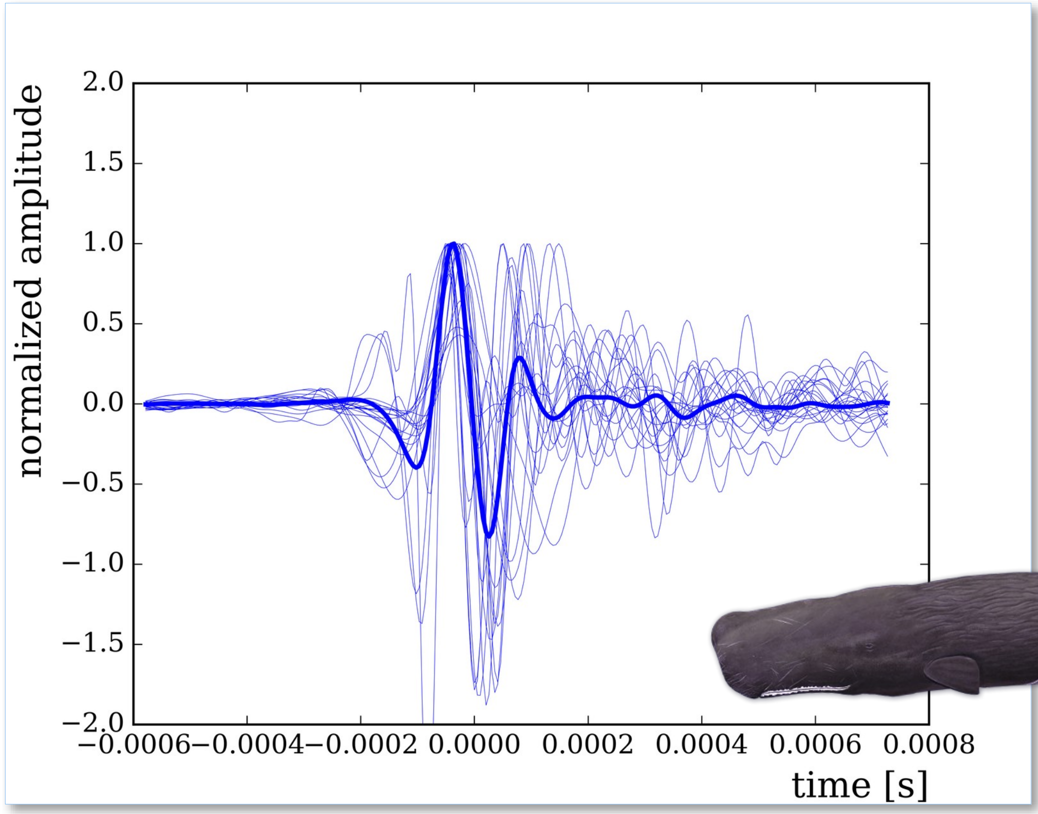


Expected noise sources

- Sea state noise:
  - Omnipresent, wide-band noise.
  - Related to weather conditions

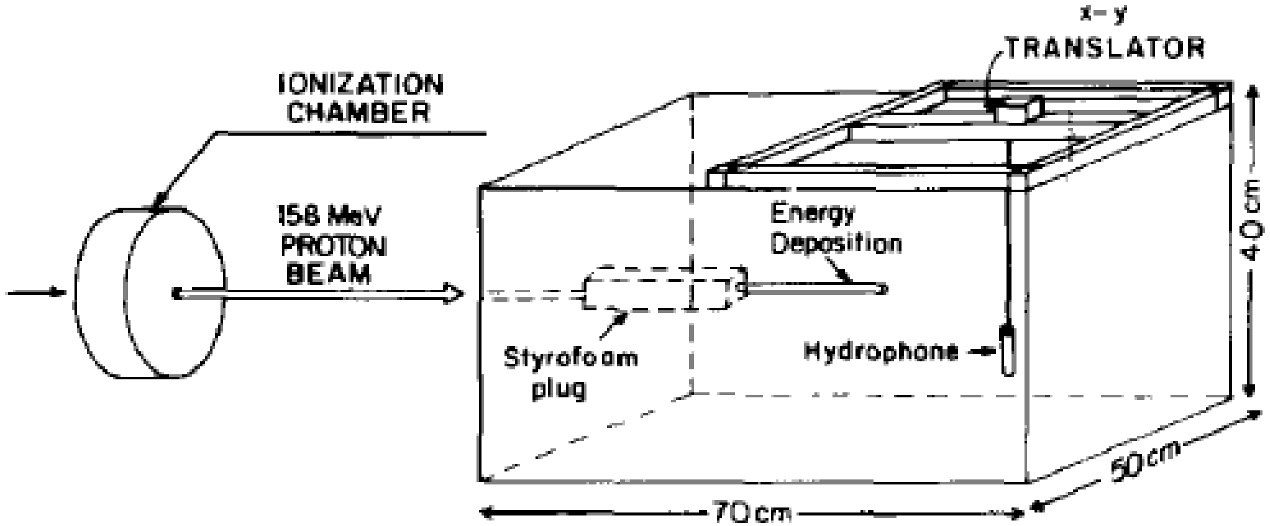
- Shipping noise
  - mostly low frequent and continuous acoustic source

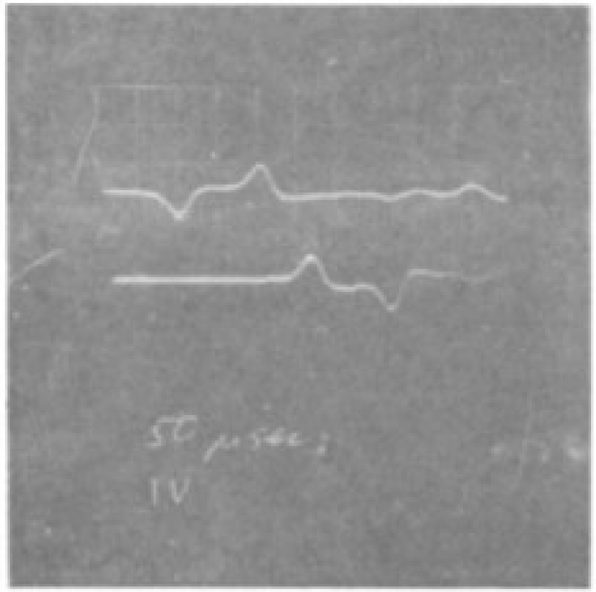
- Marine biology
  - sound clicks from sperm whales



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

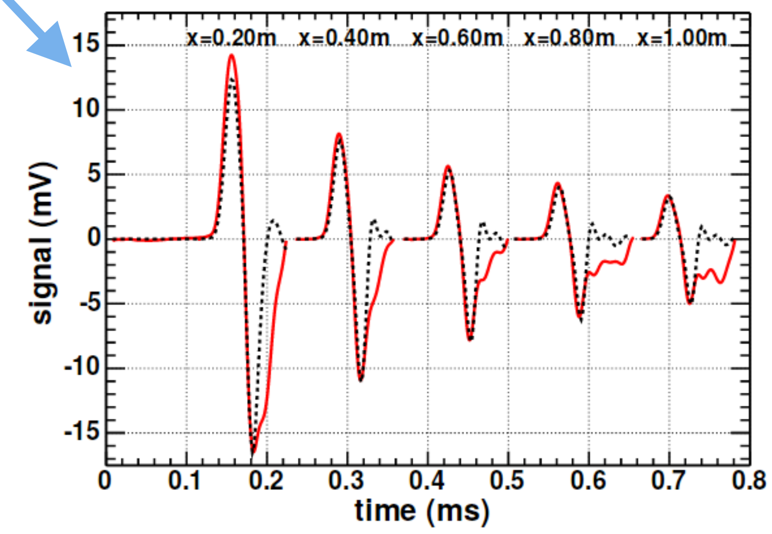
Acoustic detection of particles

- 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.

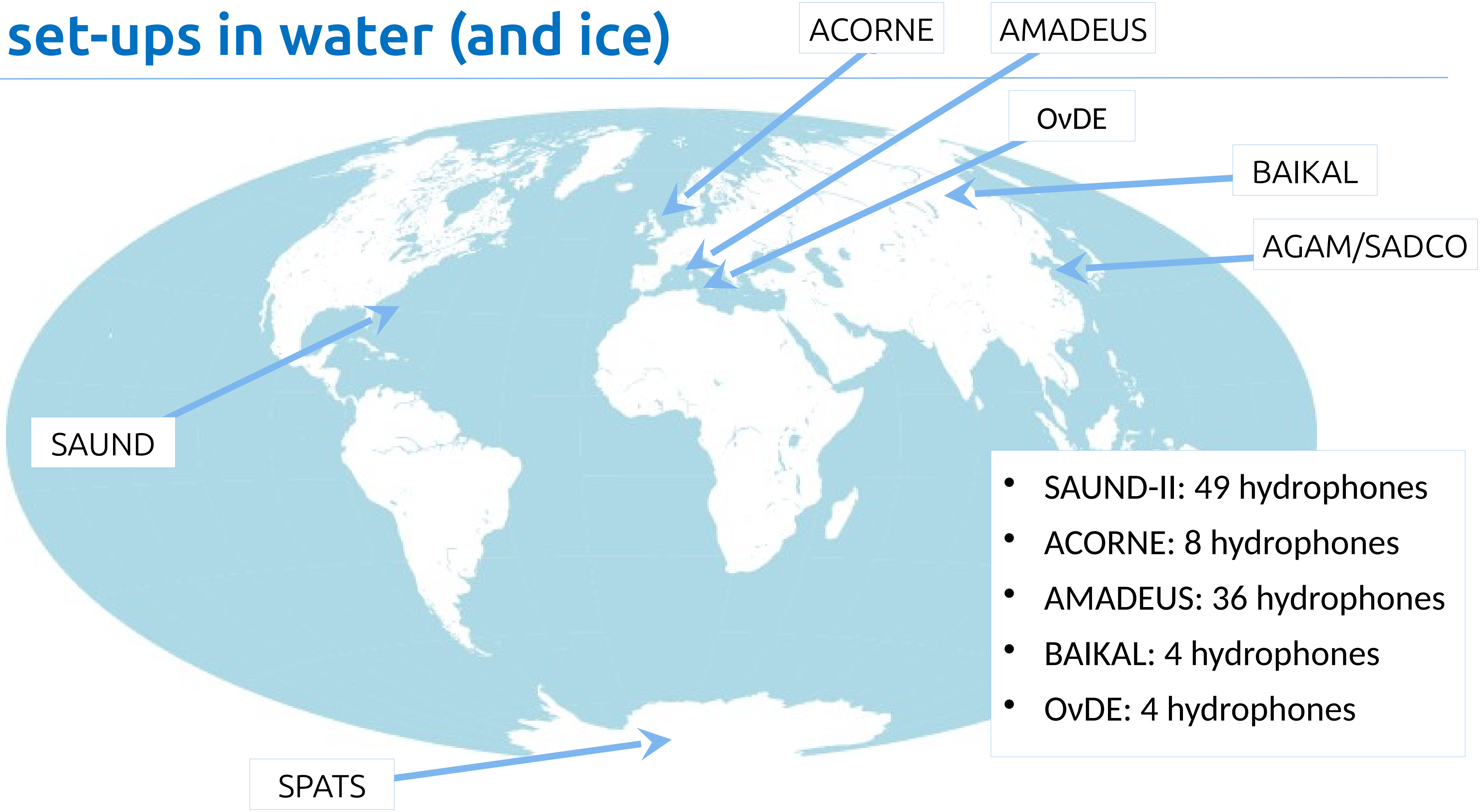
Detailed investigations at particle accelerators:

- variation of hydrophone position
- variation of water temperature



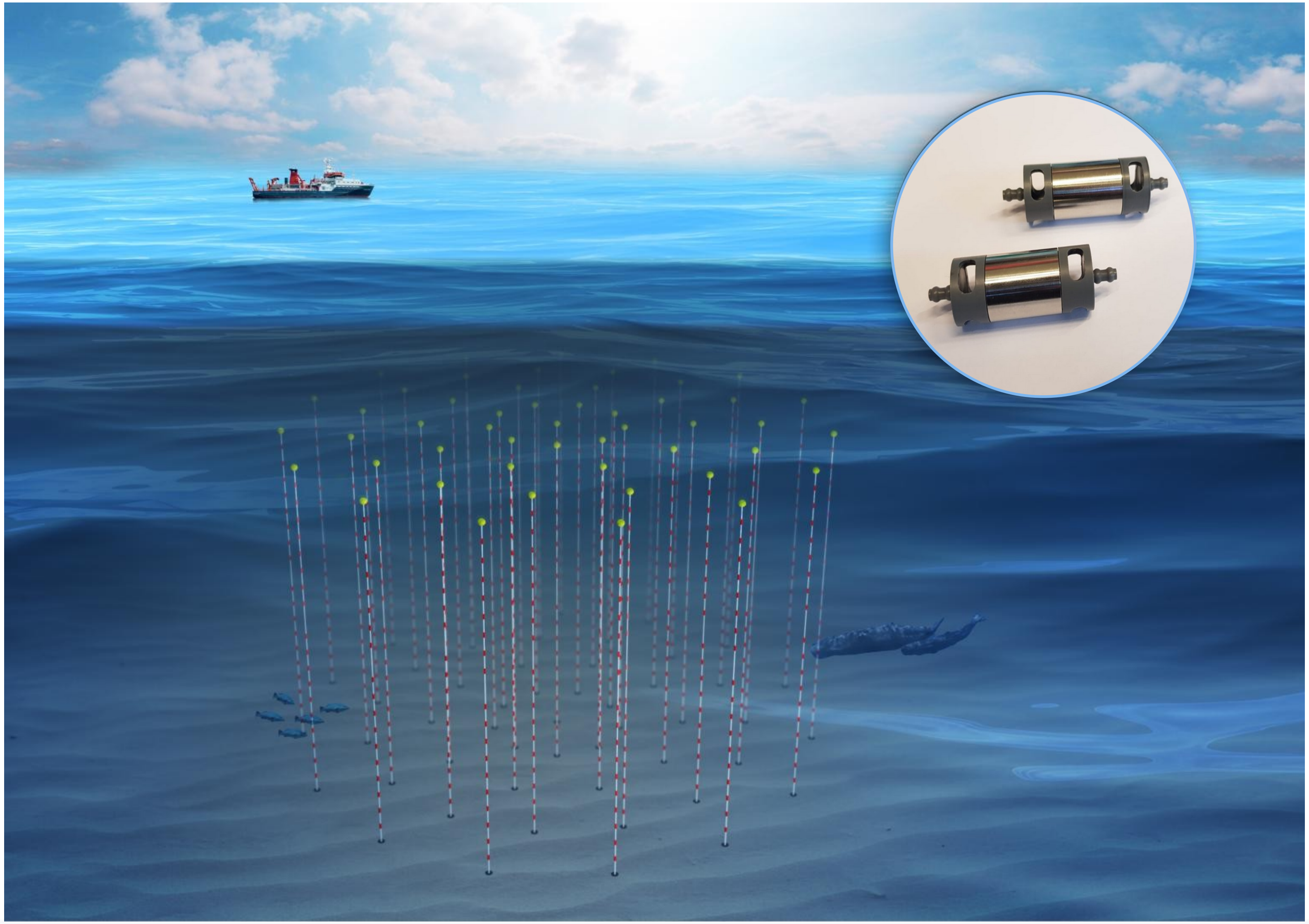
Lahmann et al 2015

Test set-ups in water (and ice)

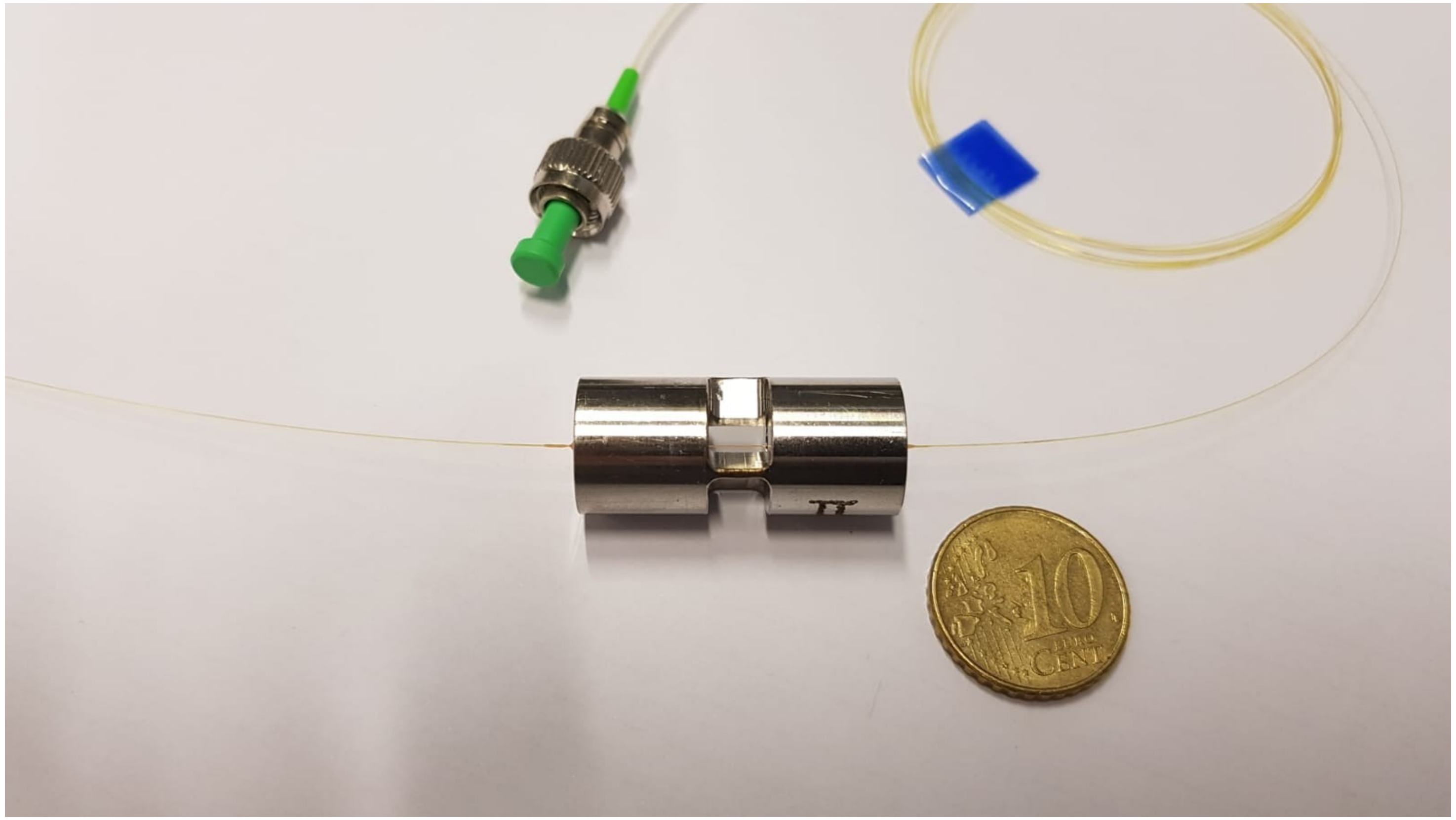


- SAUND-II: 49 hydrophones
- ACORNE: 8 hydrophones
- AMADEUS: 36 hydrophones
- BAIKAL: 4 hydrophones
- OvDE: 4 hydrophones

Future telescope concept

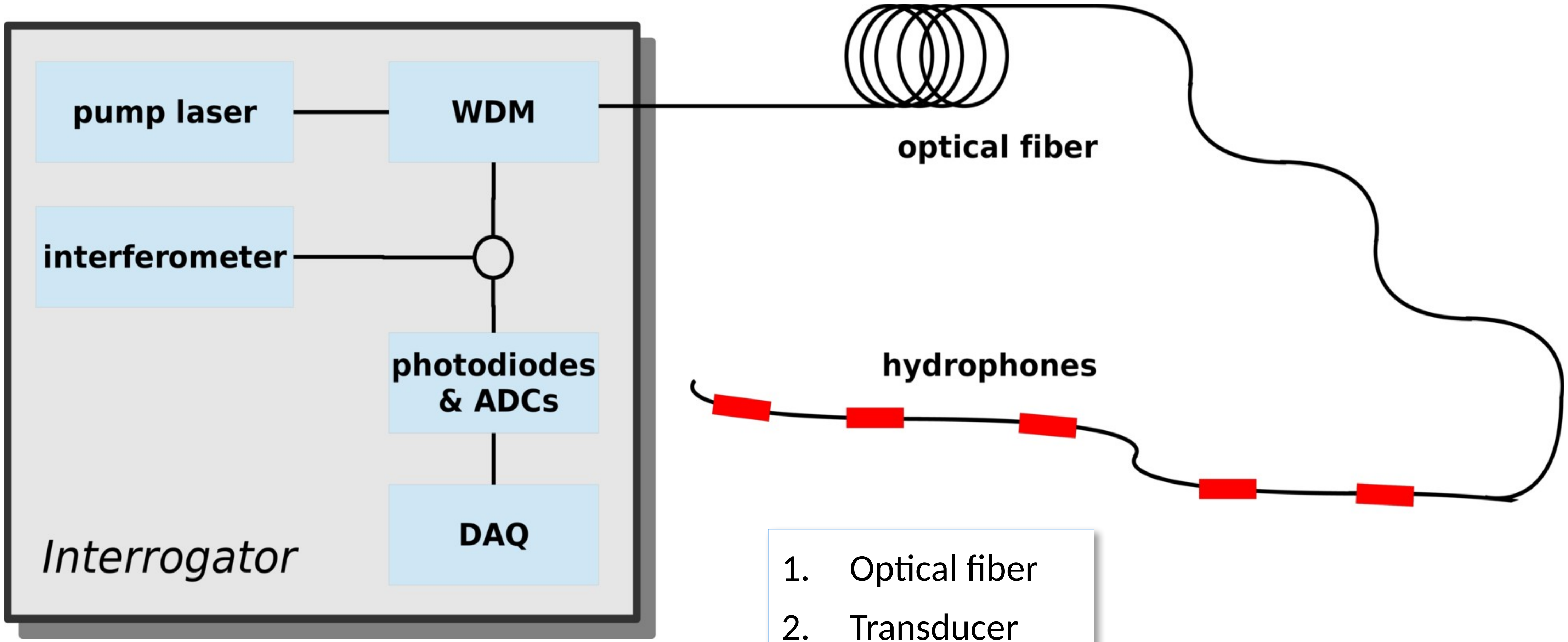


Future telescope concept ... based on fiber hydrophones



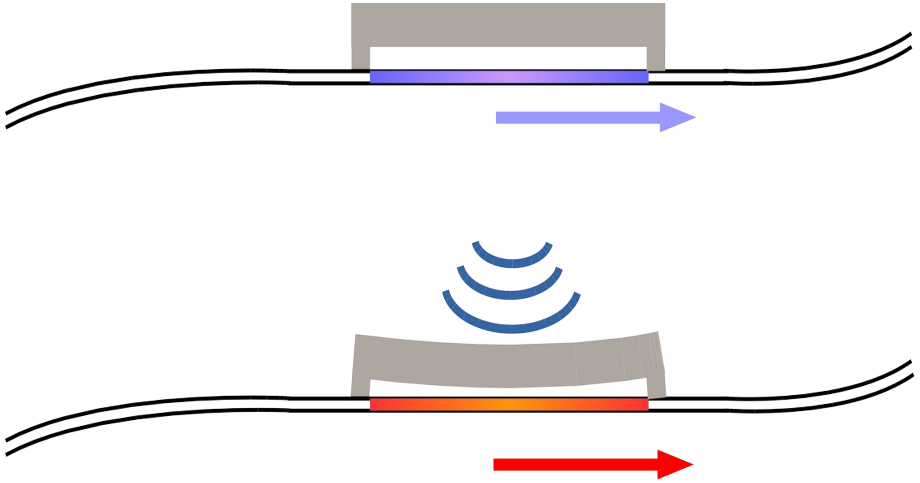
How to detect mPa pulses?

Future telescope concept … based on fiber hydrophones

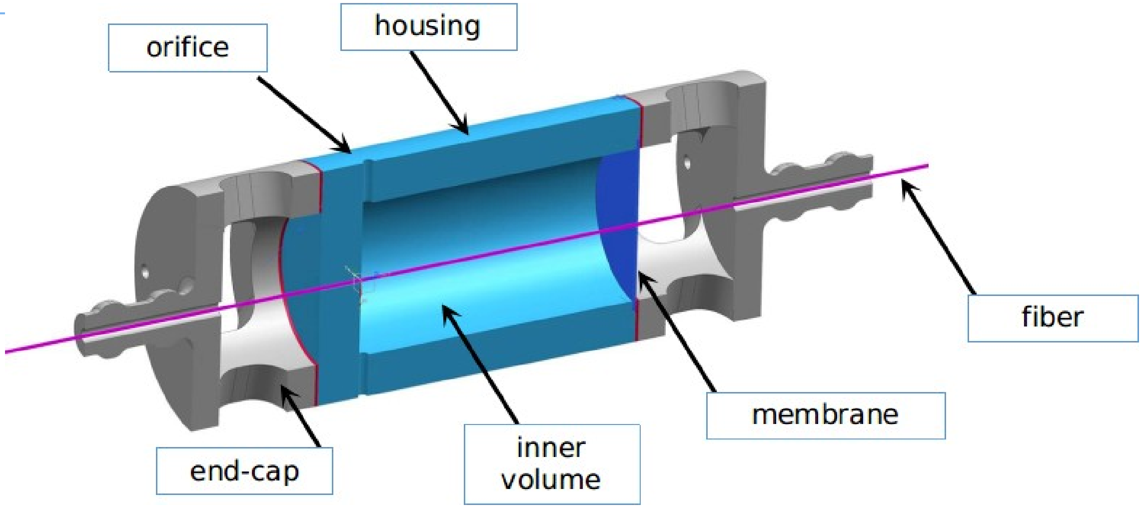


1. Optical fiber
2. Transducer
3. Interrogator

Fiber optic hydrophone concept



Transducer convert pressure into a wavelength shift.



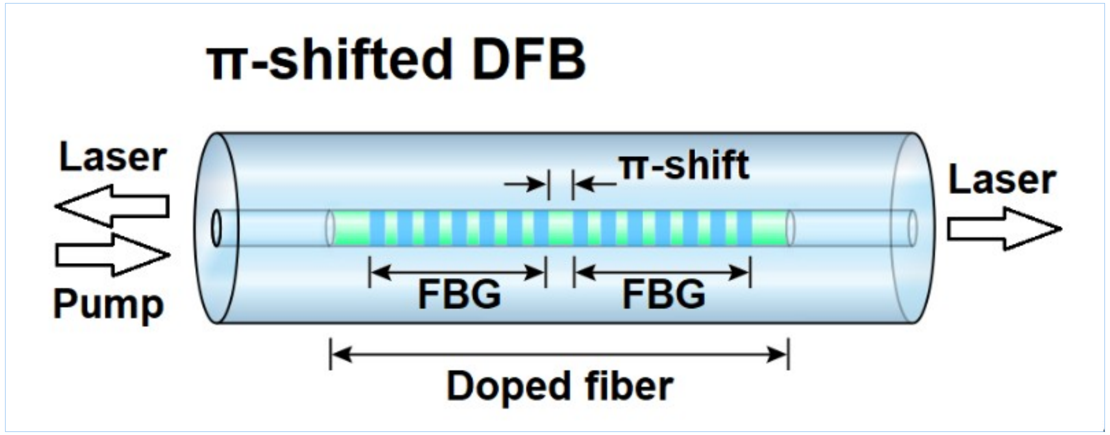
EJB et al., Astropart.Phys. 170 (2025) 103109 (arXiv:2501.12999)

Fiber laser

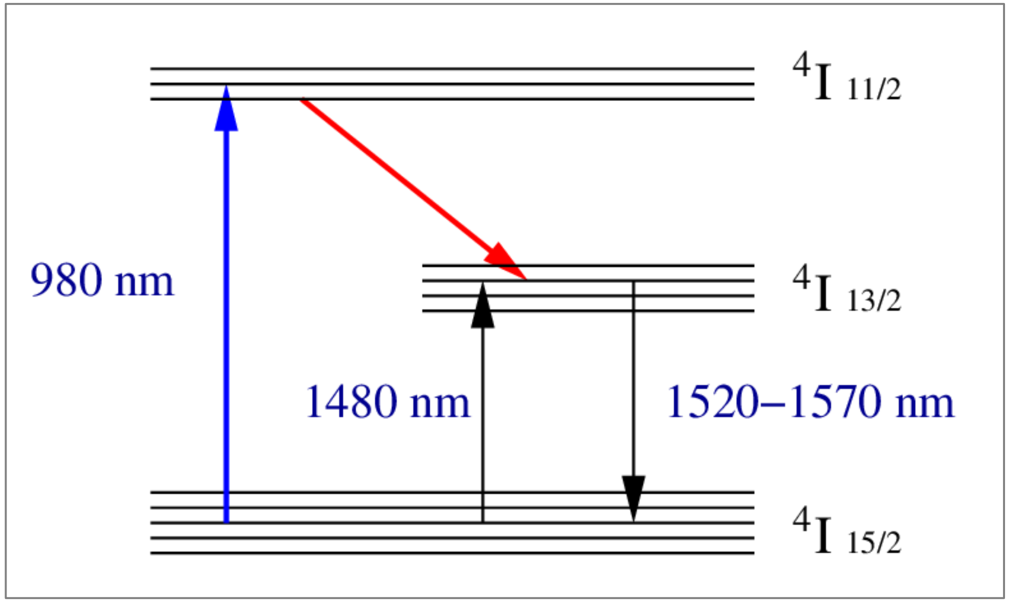
- Optical fiber includes fiber lasers
- Optical lasers are based on

erbium doped fibers

- Grating structure applied to create a laser



Er levels



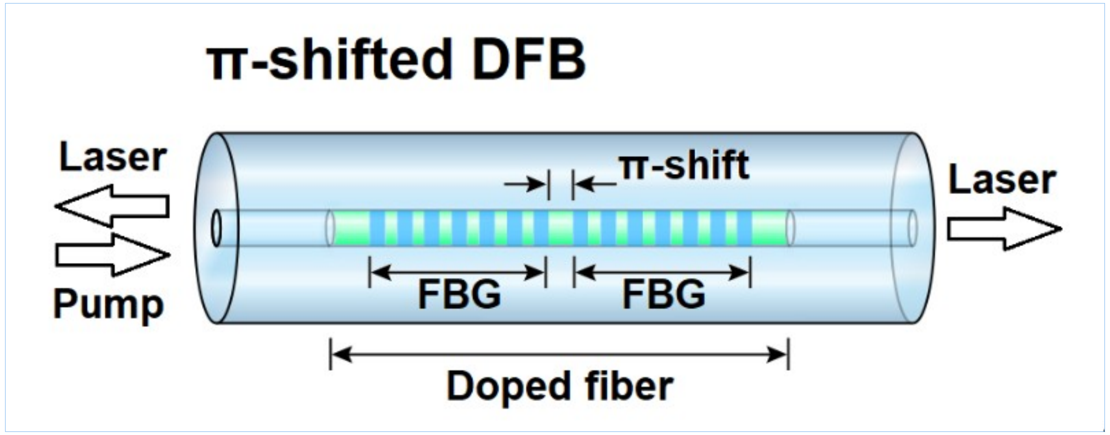
Pumping @ 980 or 1480 nm,
Laser source at 1520-1570 nm

Fiber laser

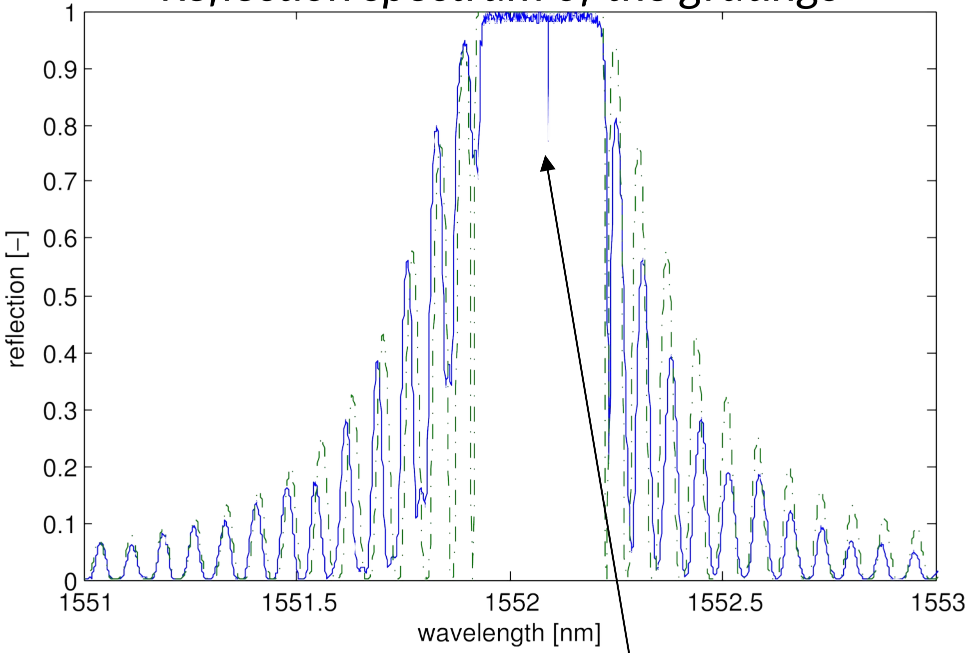
- Optical fiber includes fiber lasers
- Optical lasers are based on

  erbium doped fibers

- Grating structure applied to create a laser



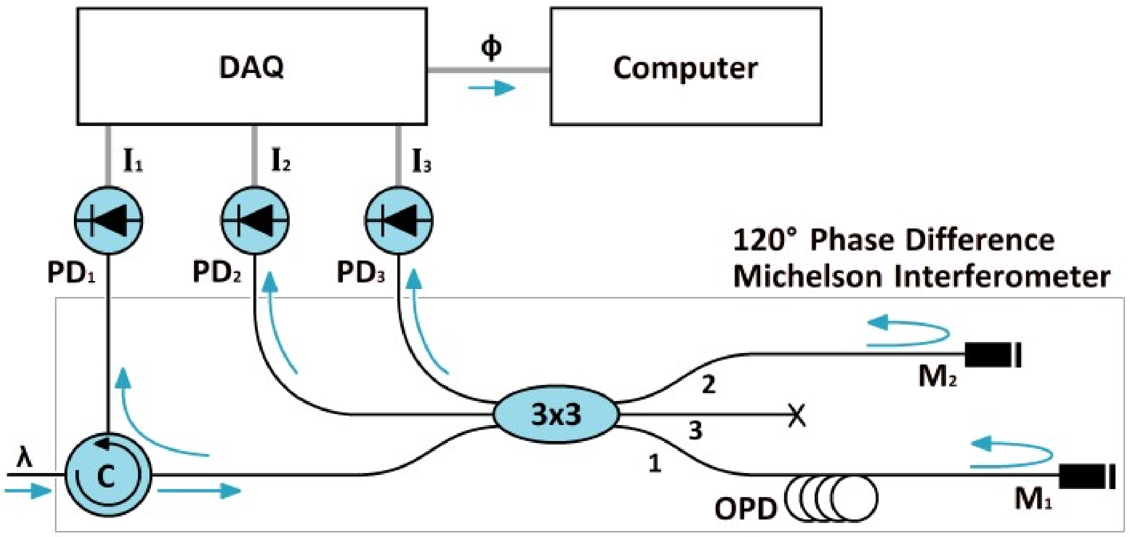
Reflection spectrum of the gratings



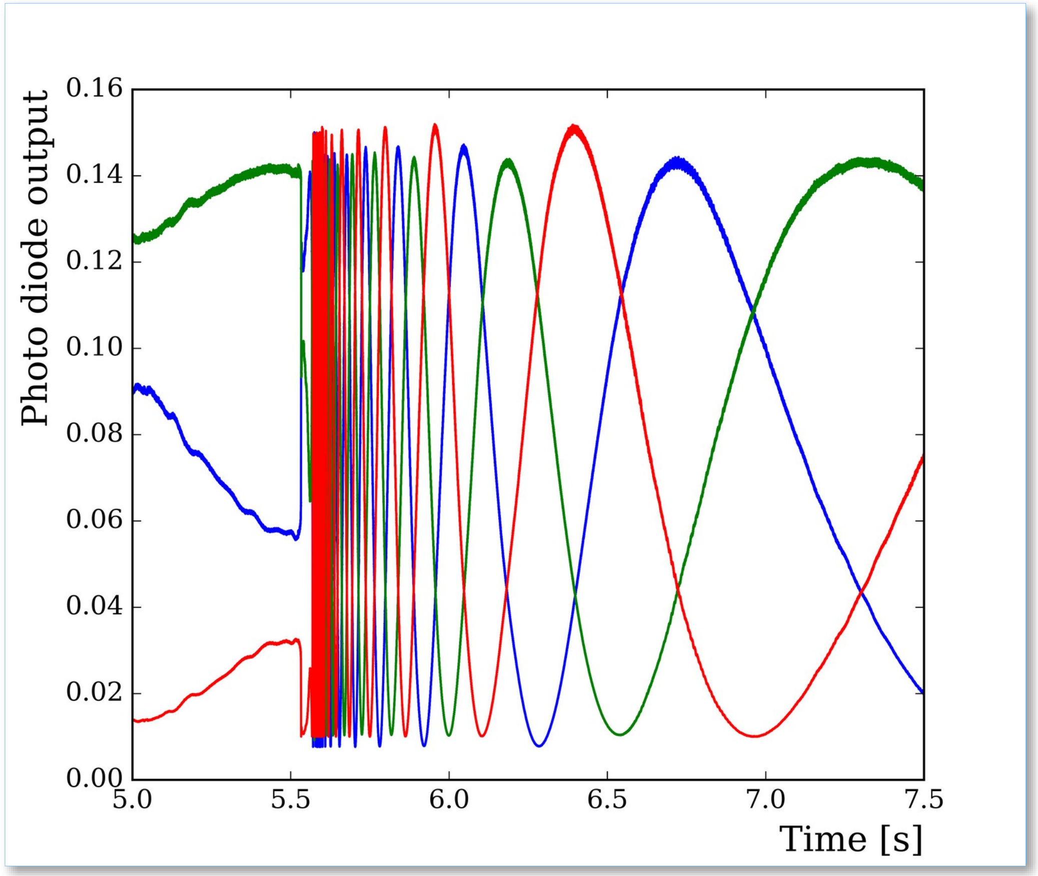
Coherent light source
(~1 fm linewidth)

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

Data acquisition



3 x 3 arm Michelson interferometer

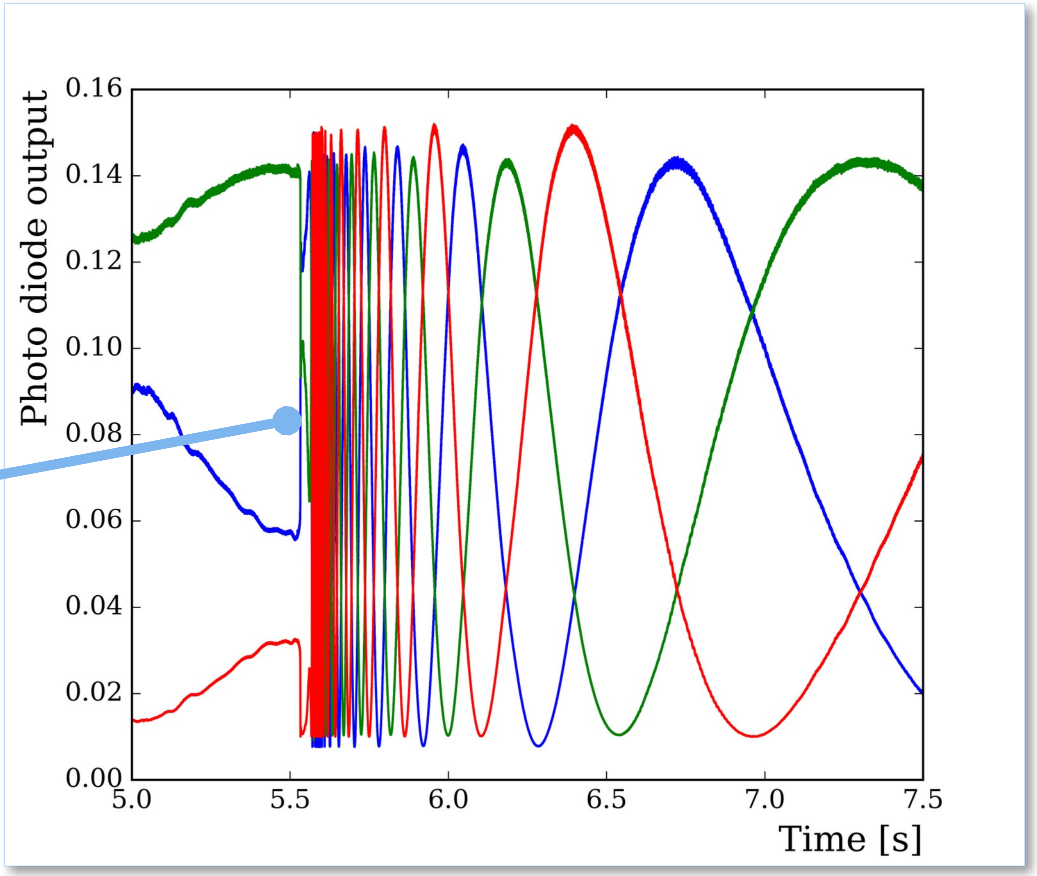


Data acquisition

3x3 arm Michelson interferometer:

- introduce a shift of 120° in each arm
- keep optical path difference (OPD) fixed

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



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

Measured wavelength shift

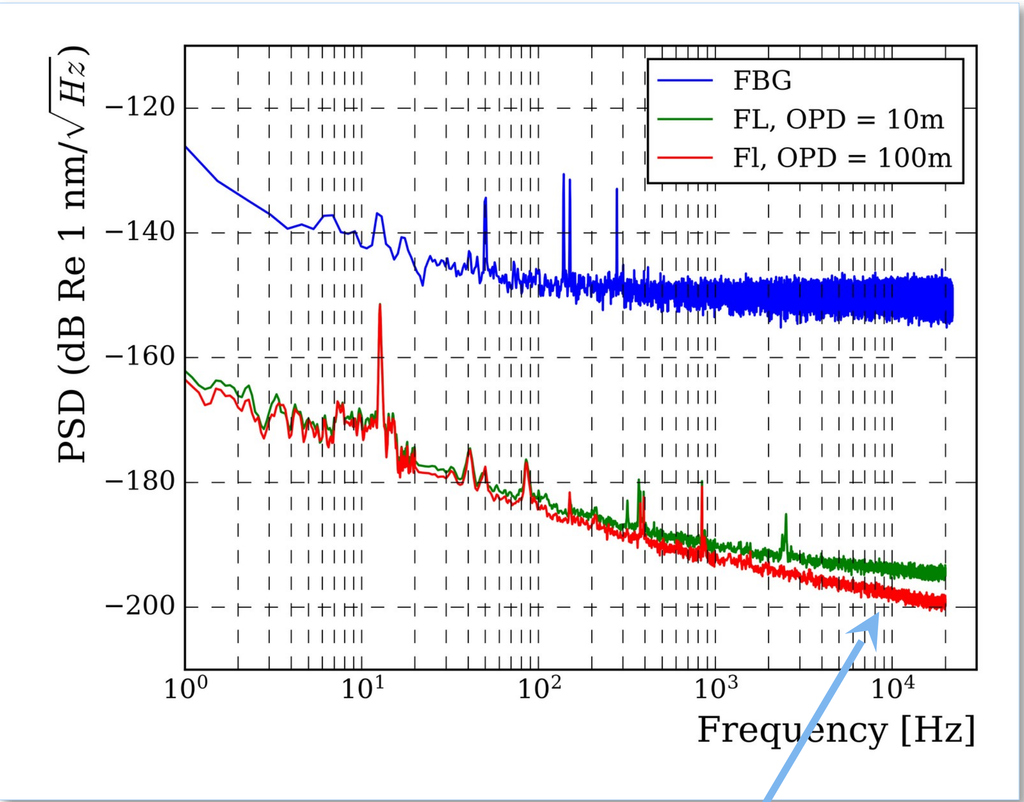
Data acquisition

3x3 arm Michelson interferometer:

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

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

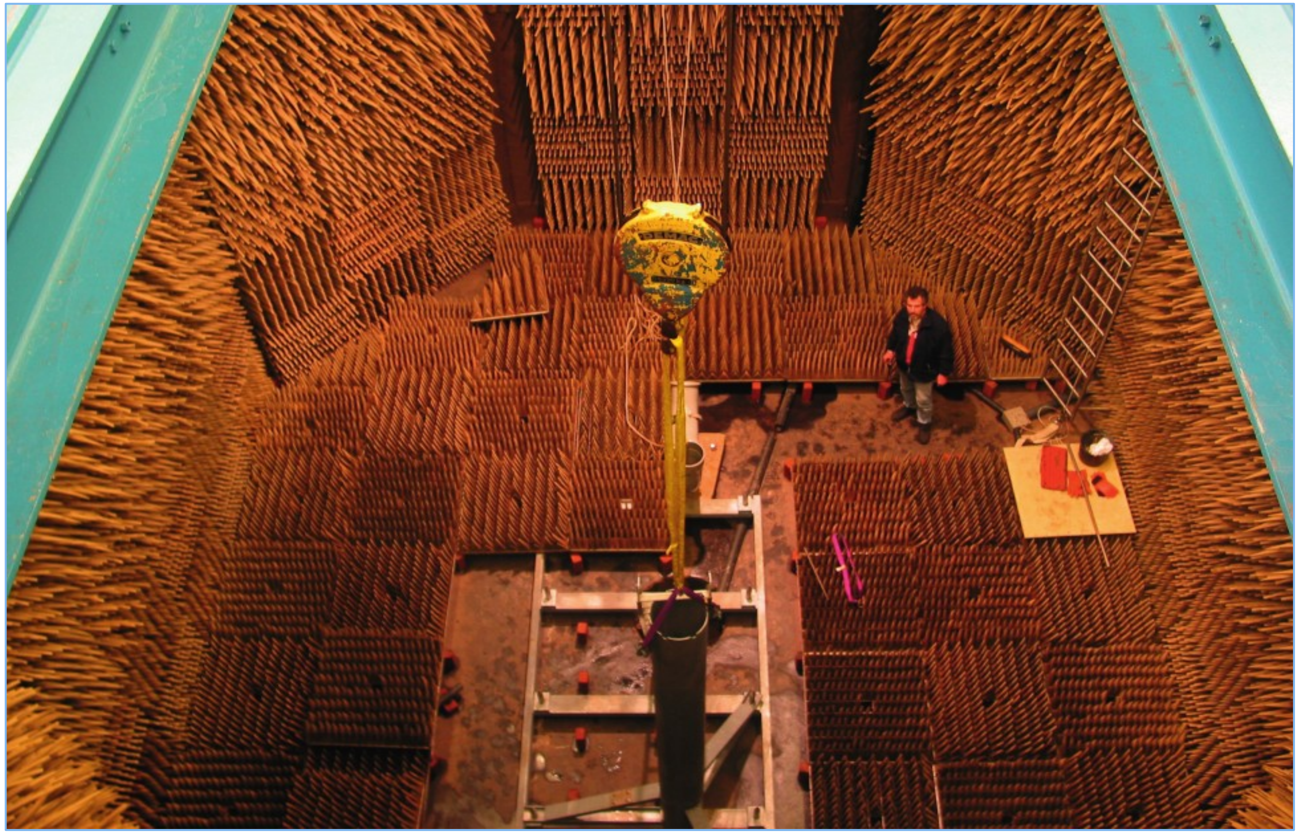
$$\mathrm{OPD} = \frac{\Delta\lambda}{2\pi}\arctan\left(\frac{\sqrt{3}(I_+ - I_-)}{2I_s - I_+ - I_-}\right)$$



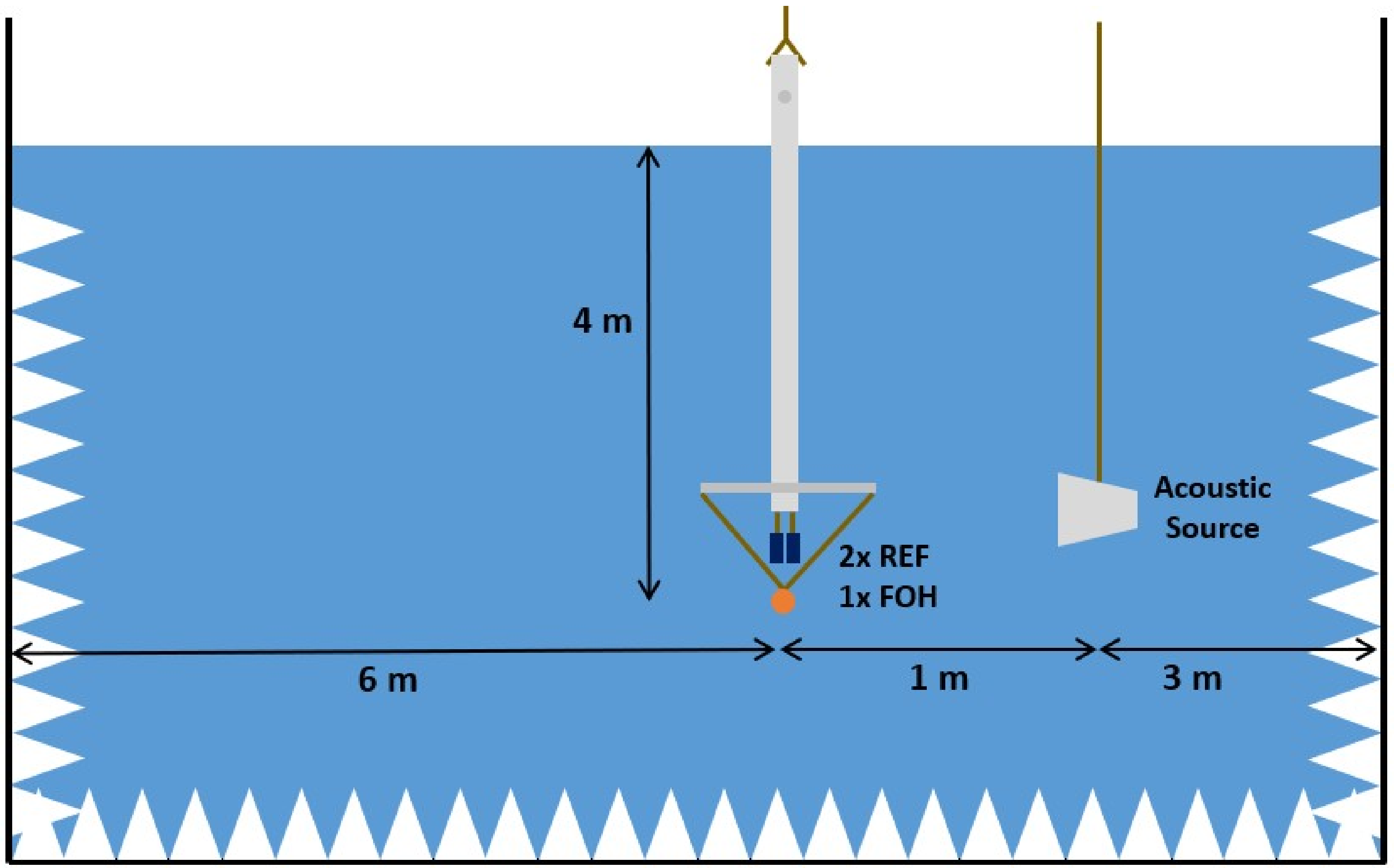
Interferometer sensitivity to **10^{-19} m/√Hz**

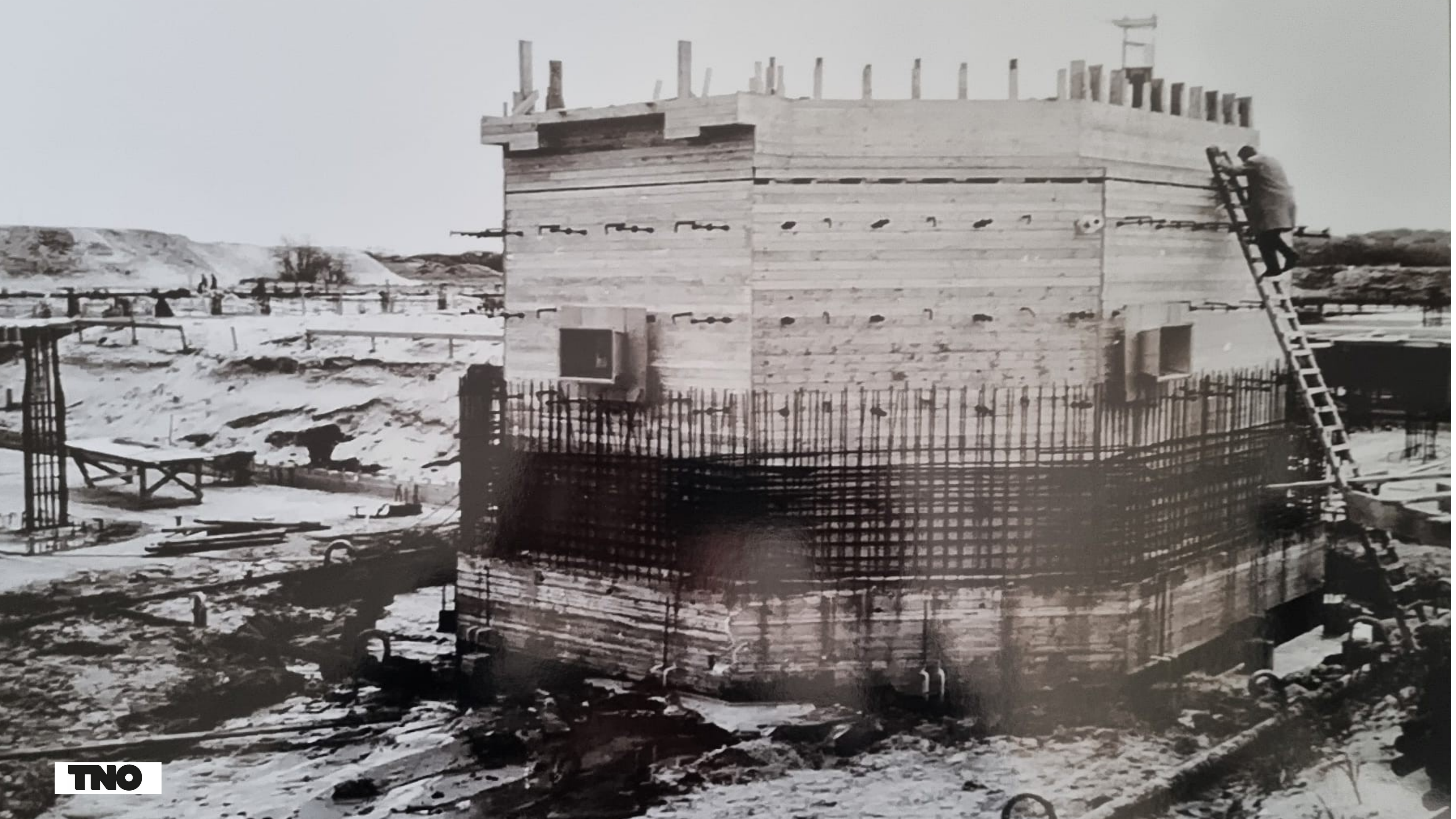
Experimental setup in an anechoic basin

- Anechoic basin at TNO the Hague
- 8 x 10 x 8 m^3



Experimental setup in an anechoic basin

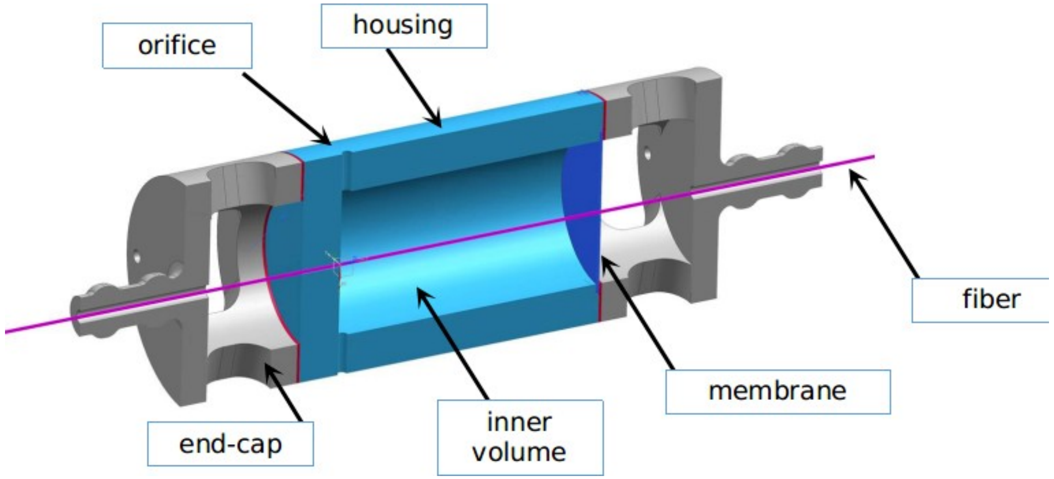


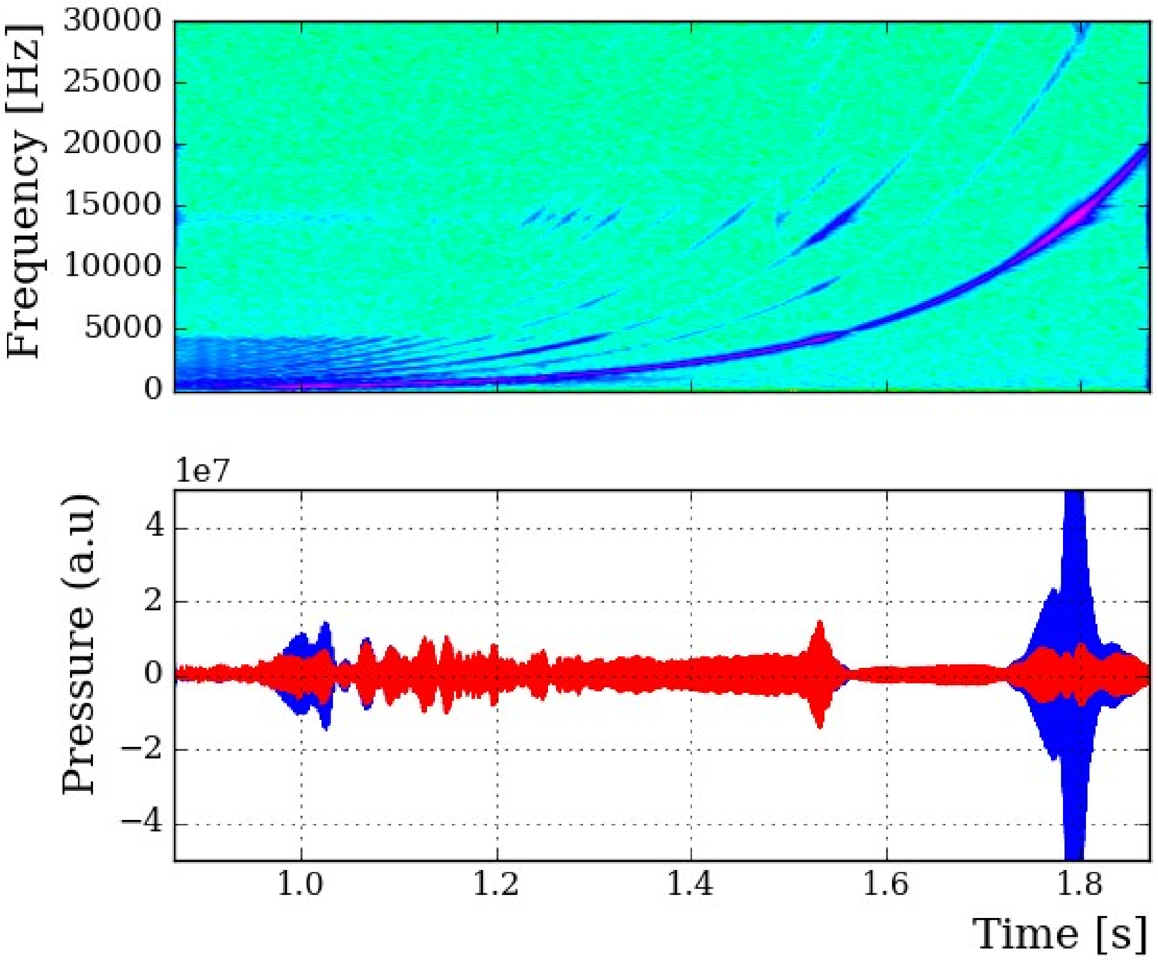

TNO

Instrument response

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

- Two types:
  - single membrane
  - double membrane





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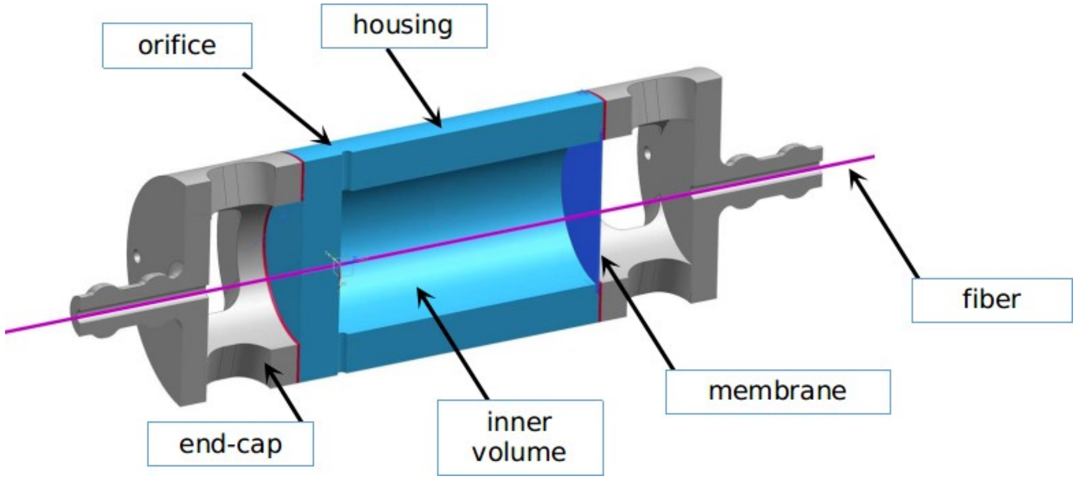
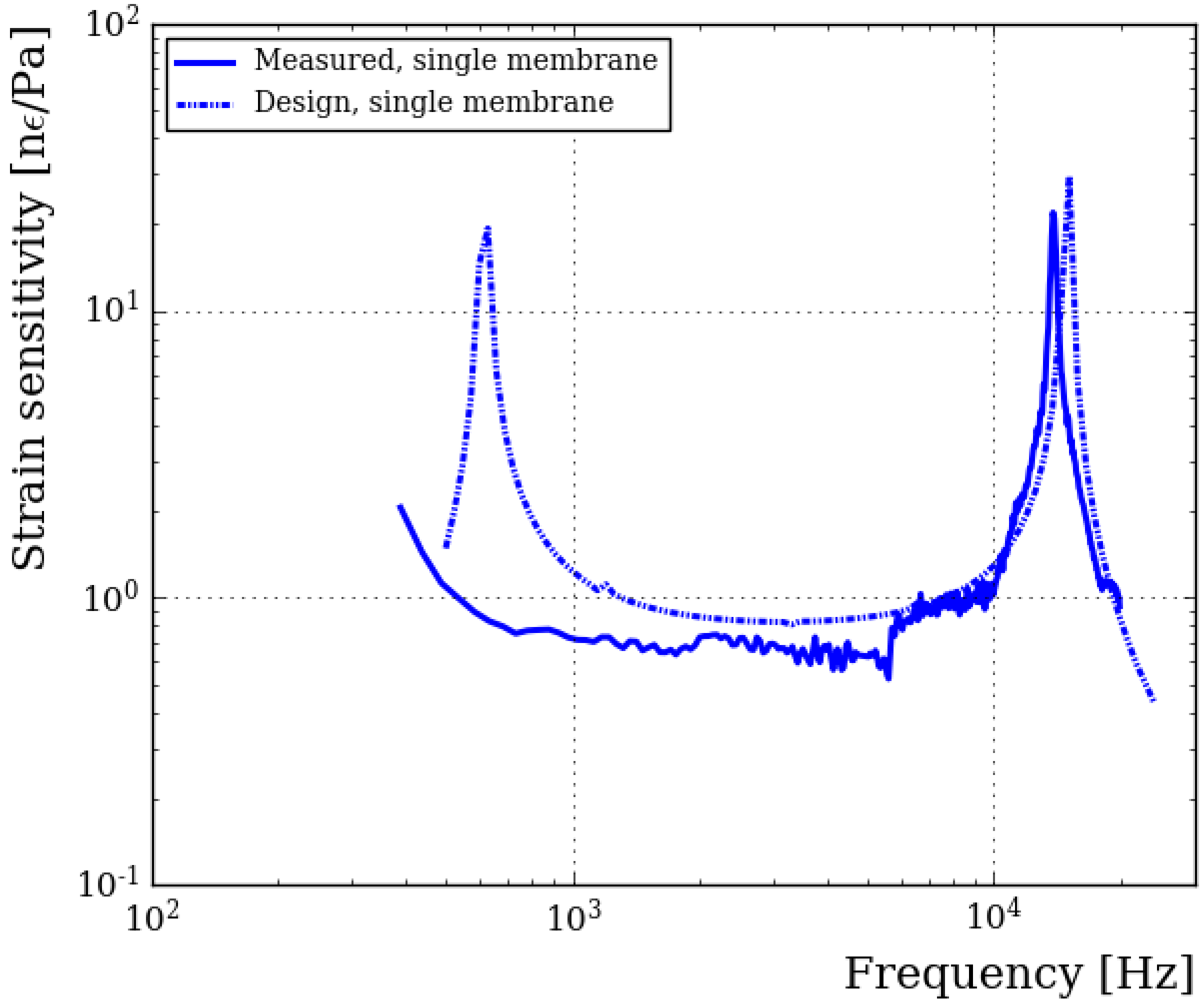
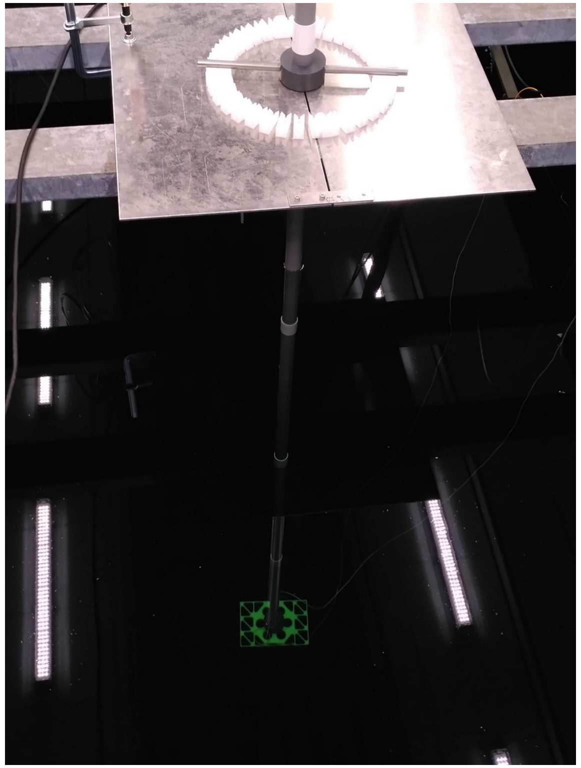
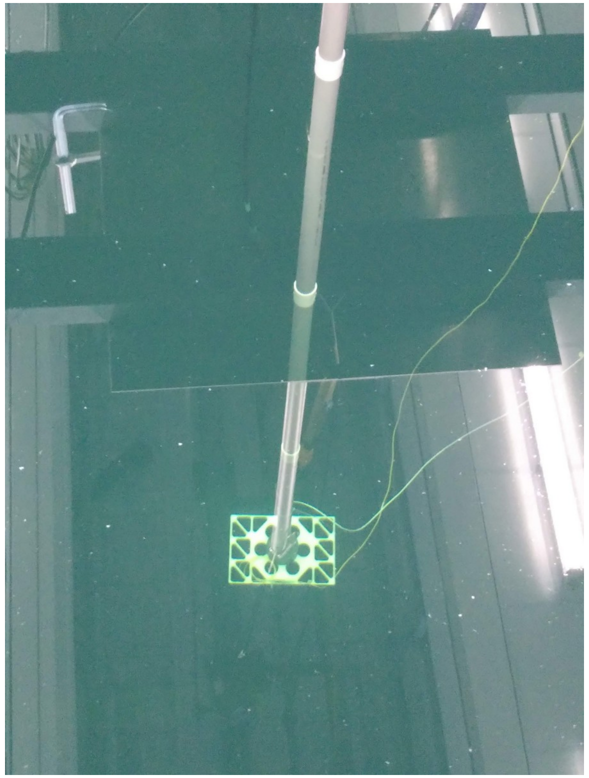
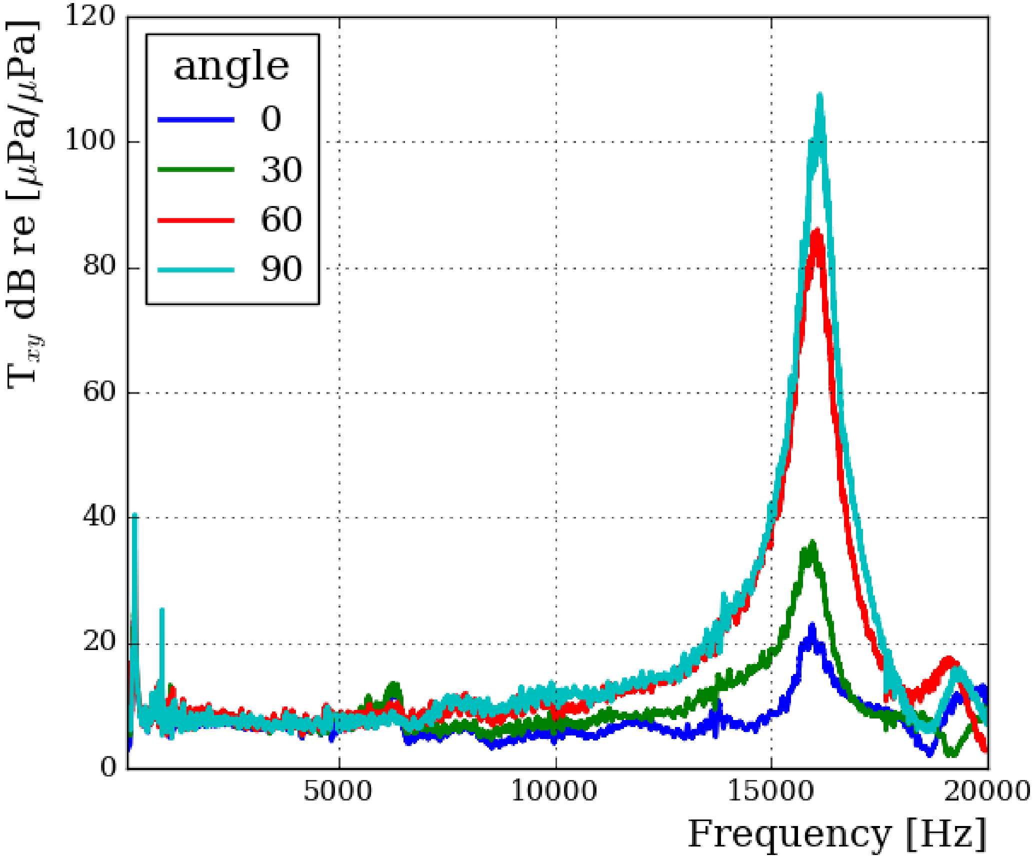




Instrument response: directionality







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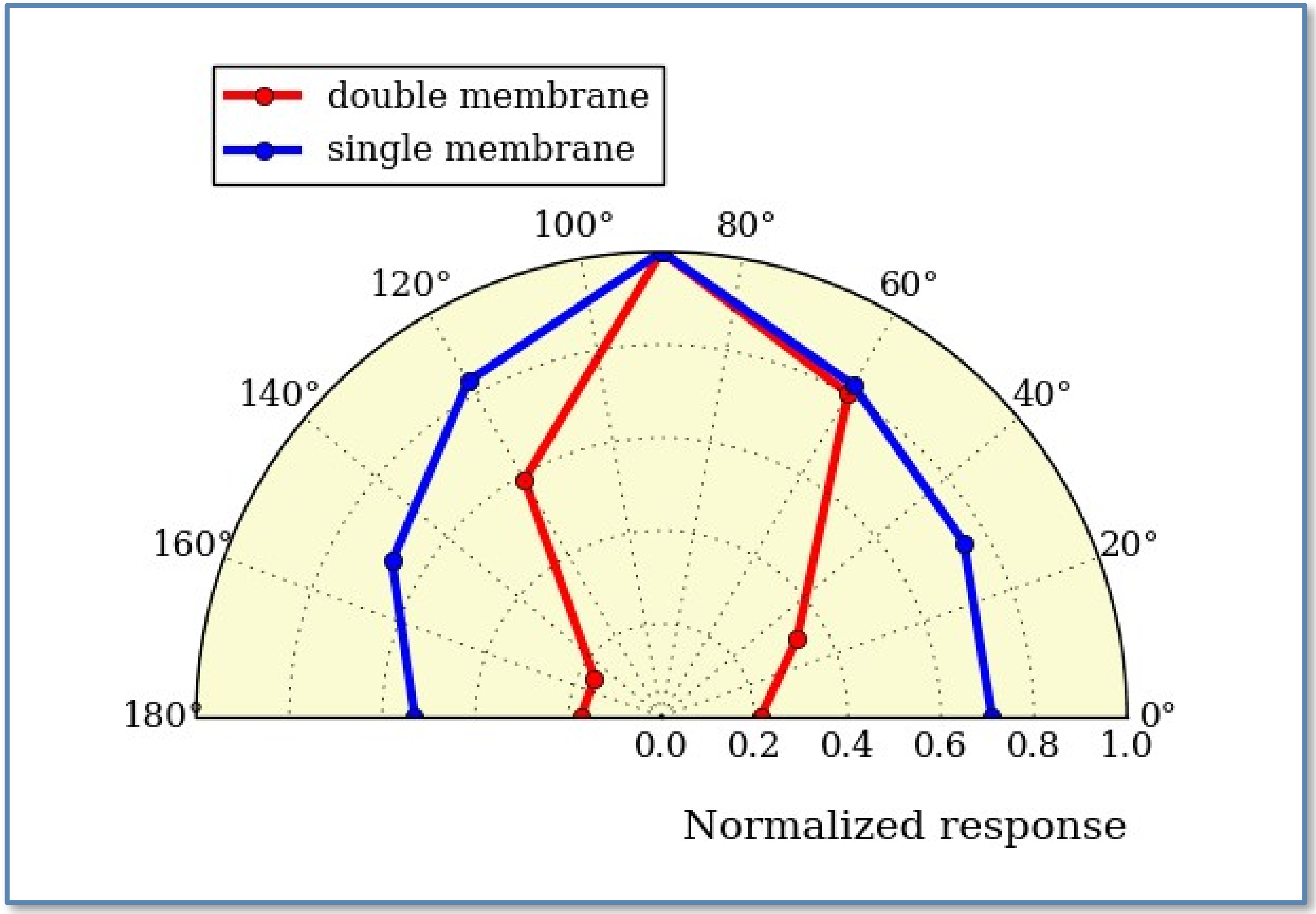
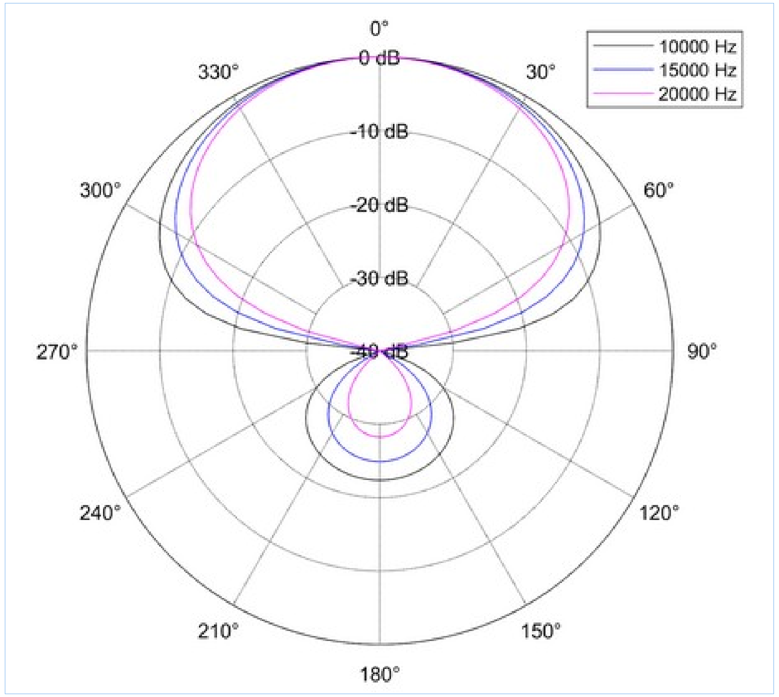
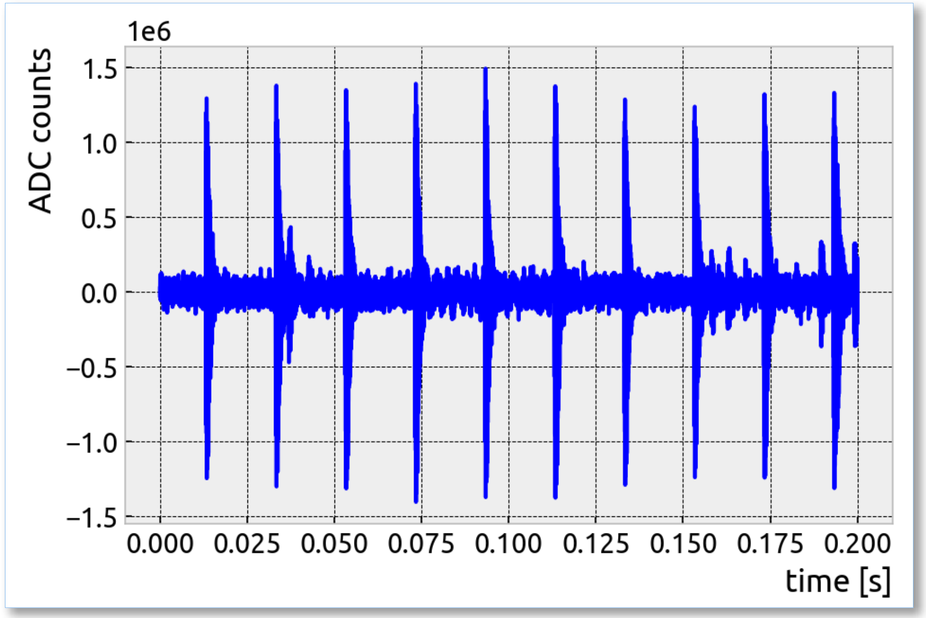


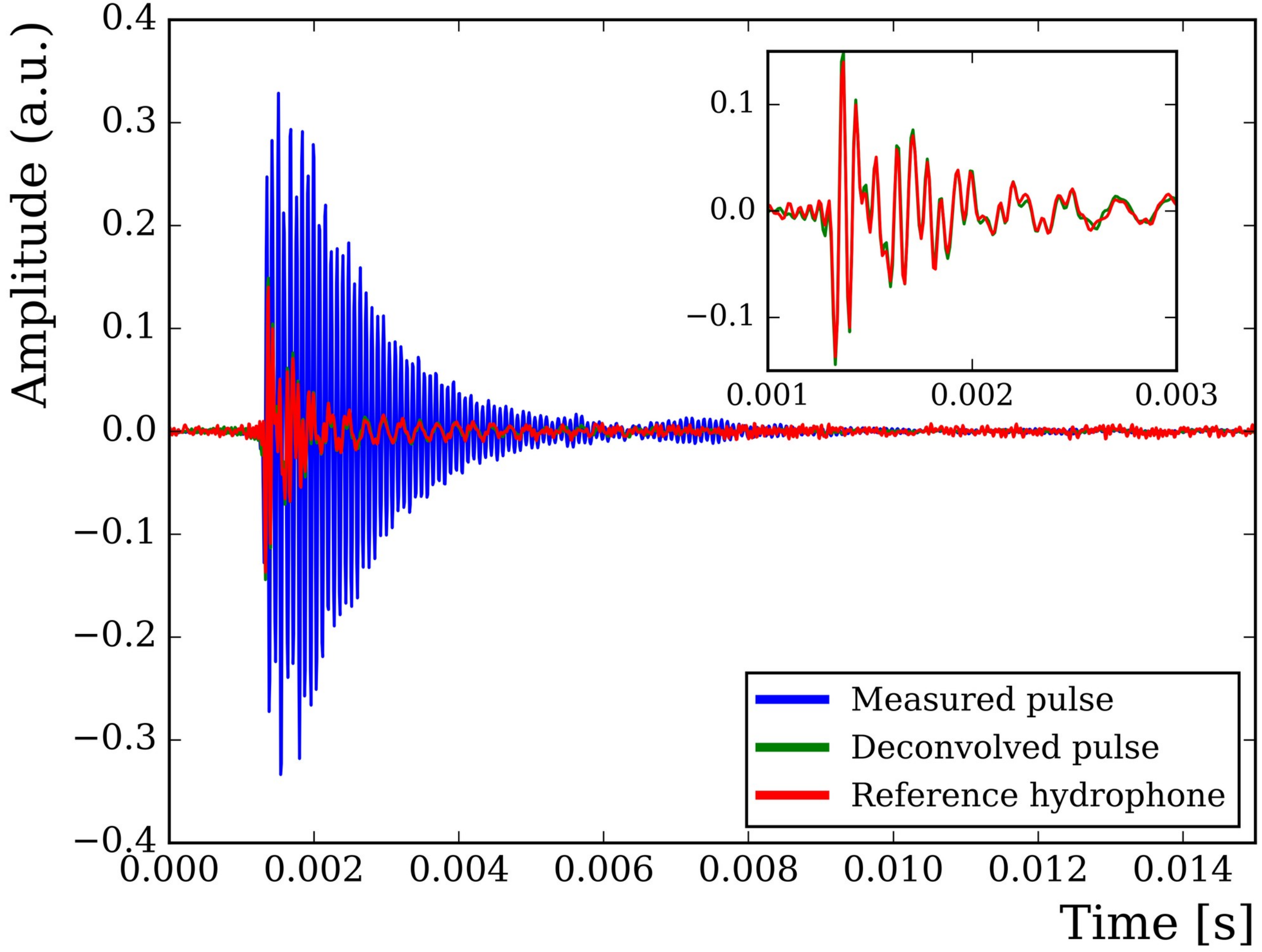


Theoretical deep-sea noise vertical angle distribution

Example pulses

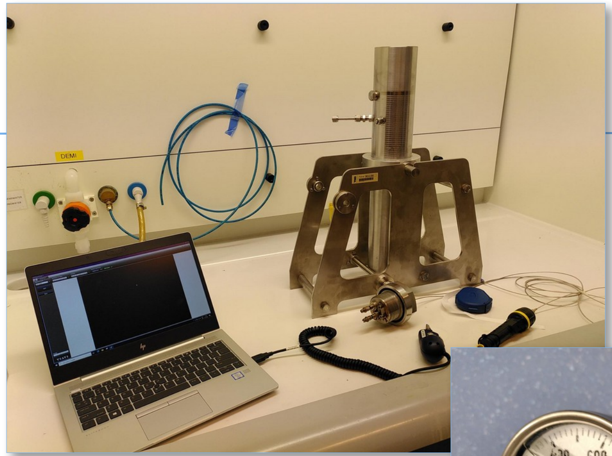
Ringtones of neutrinos

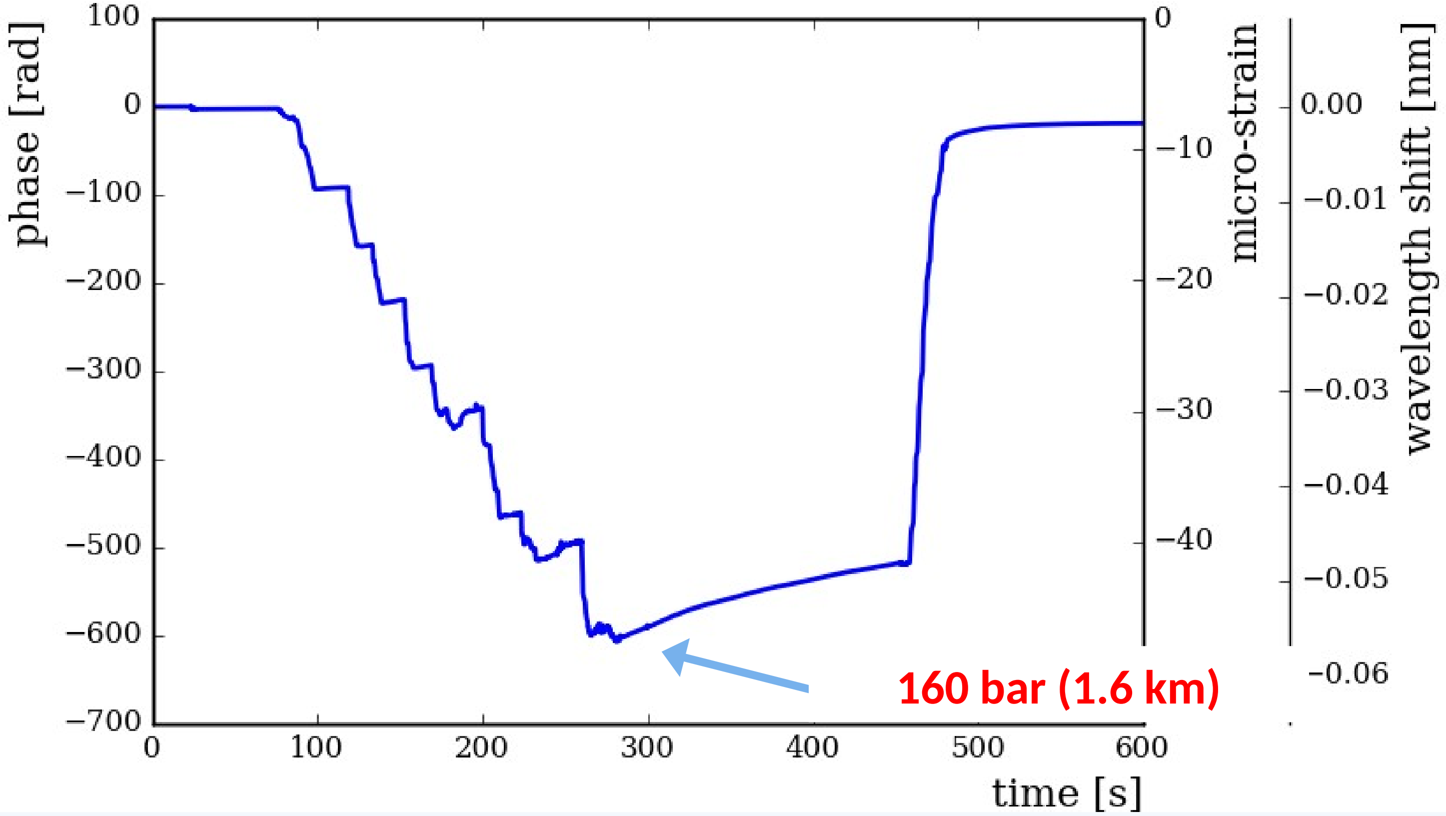




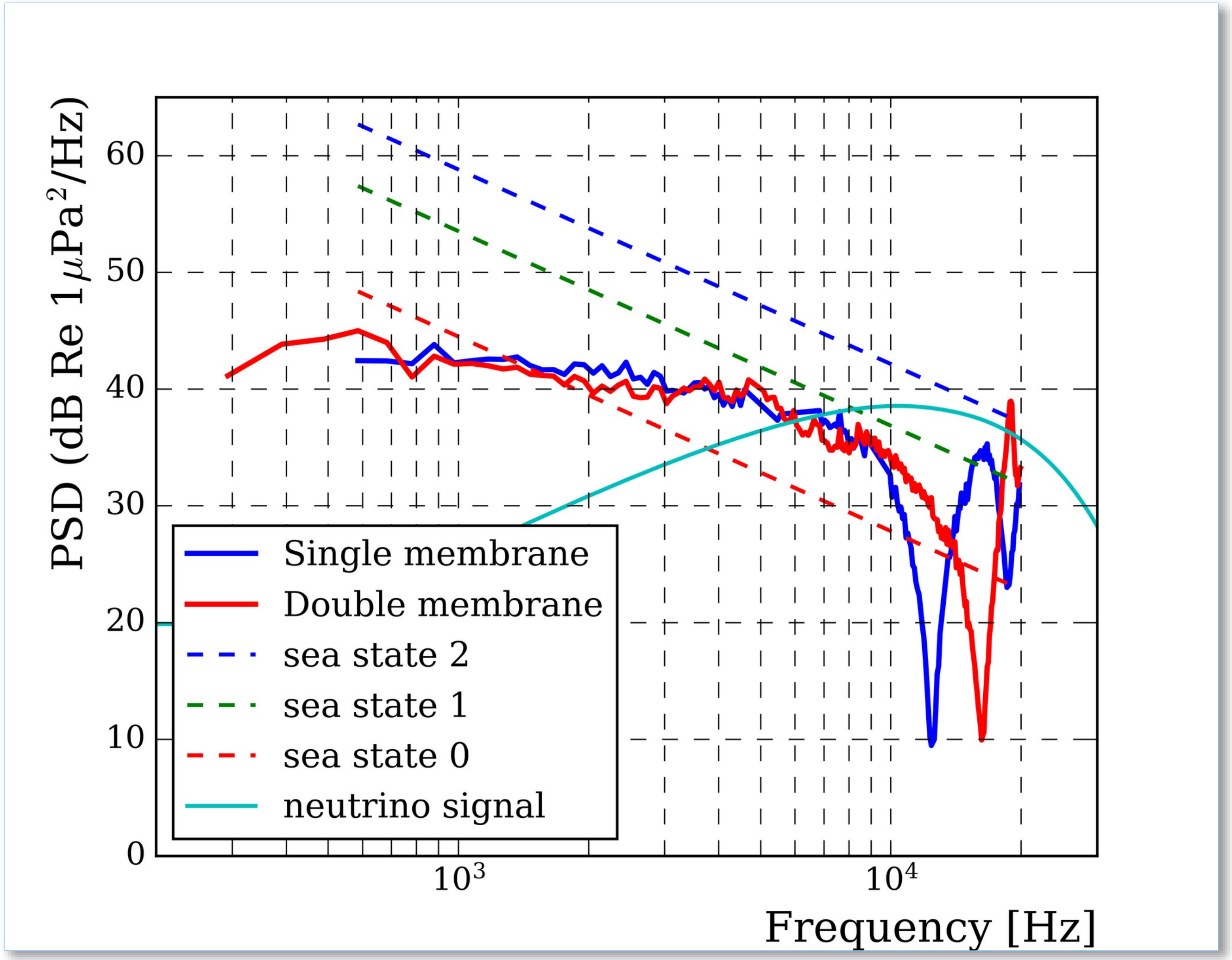
Pressure qualification

- 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 output

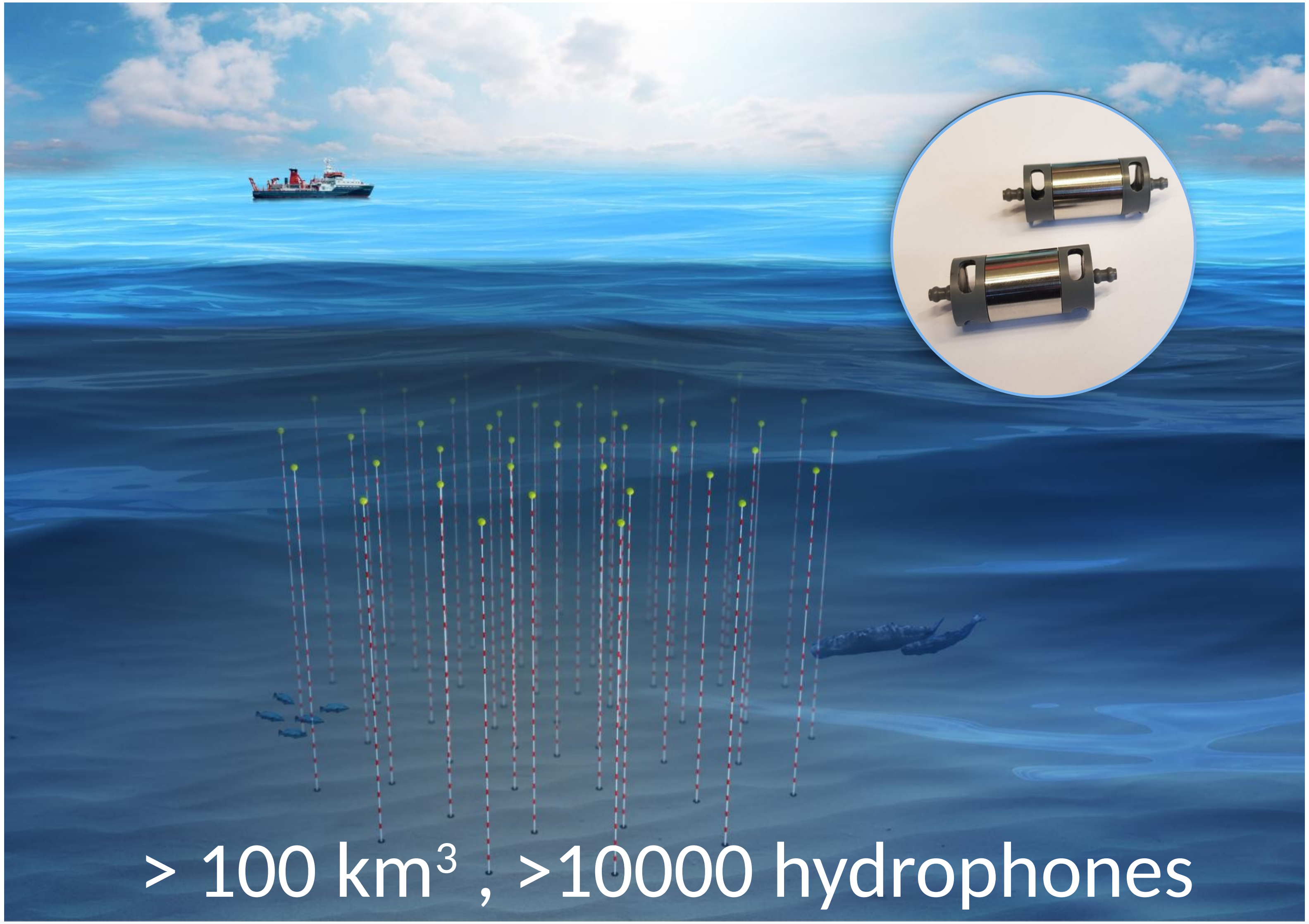




Hydrophone sensitivity



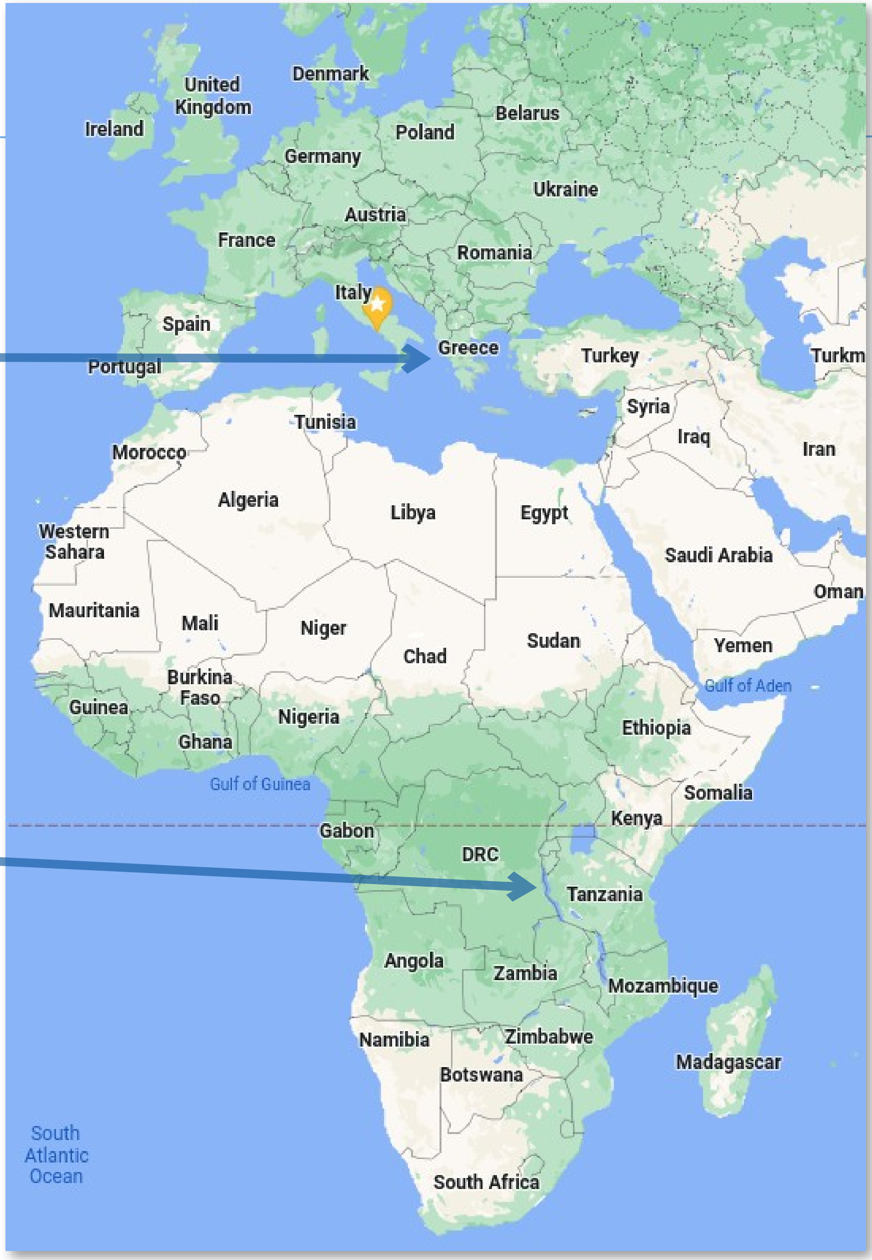
Future telescope concept



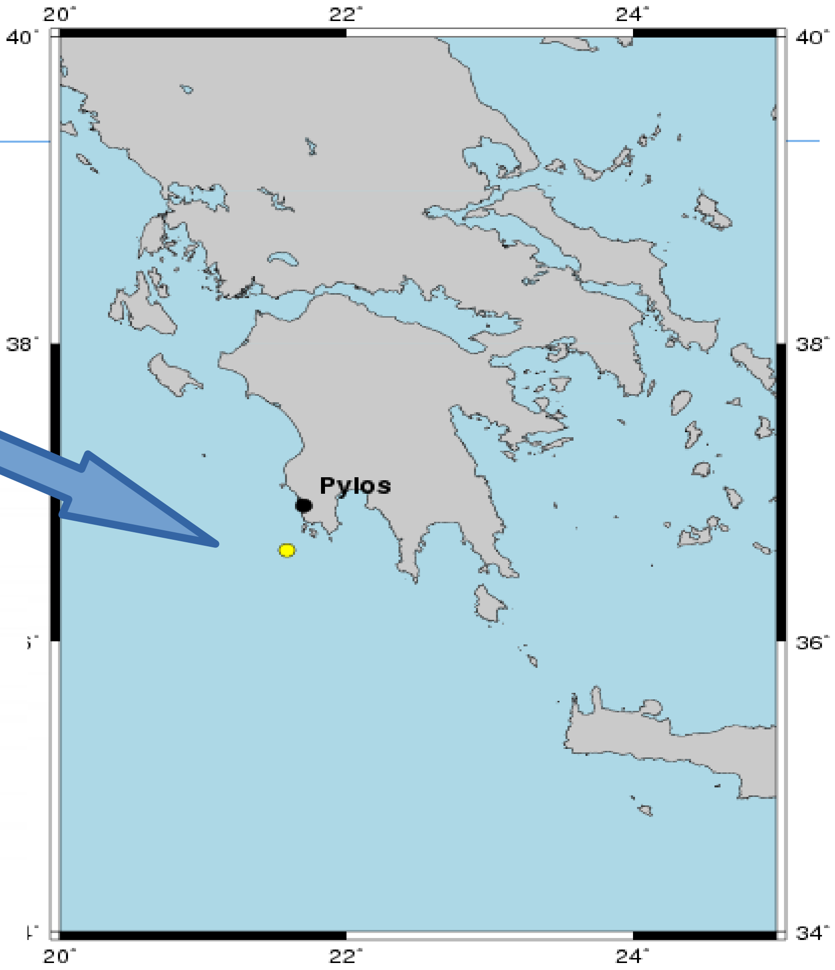
Sites

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

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

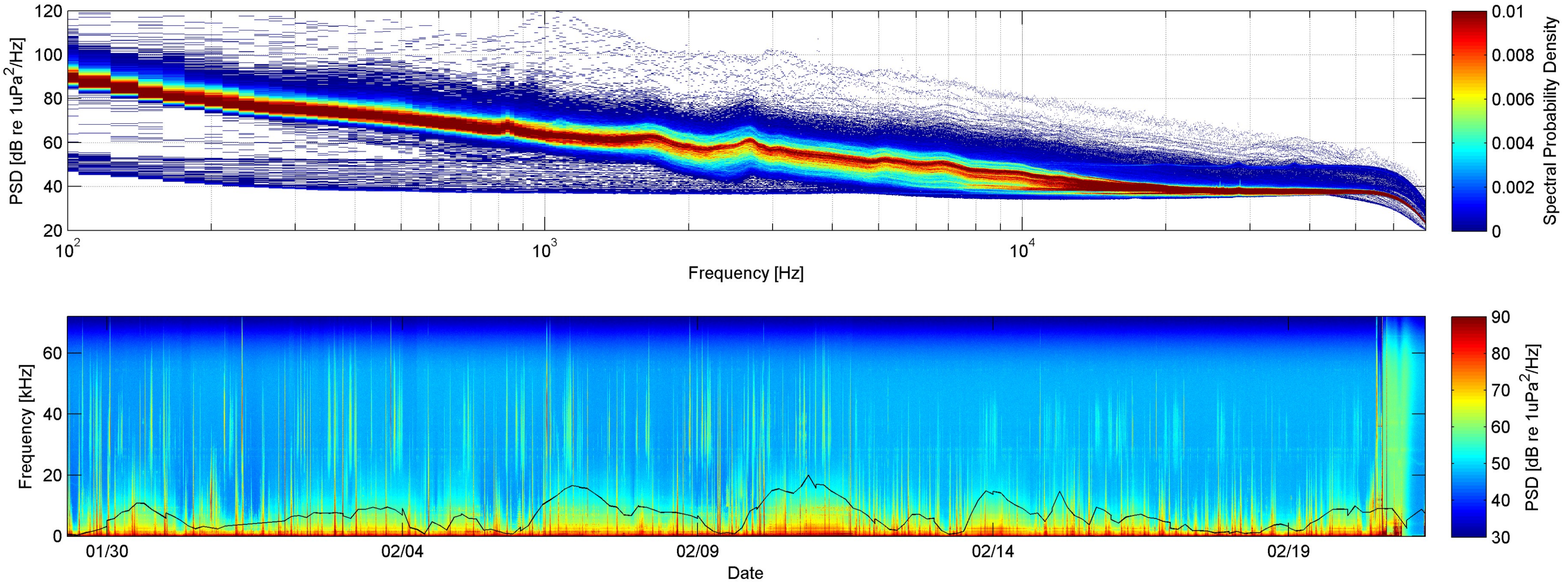


Pilot measurements Pylos site



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

Pilot measurements Pylos site



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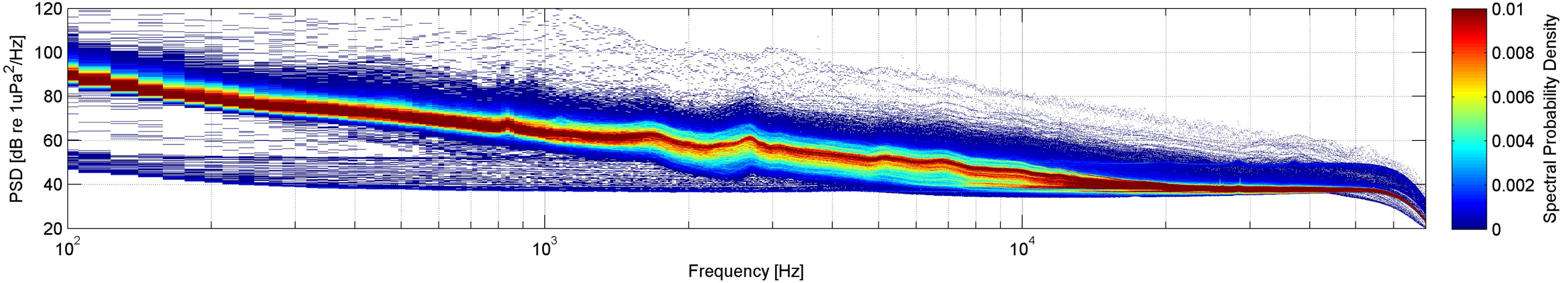
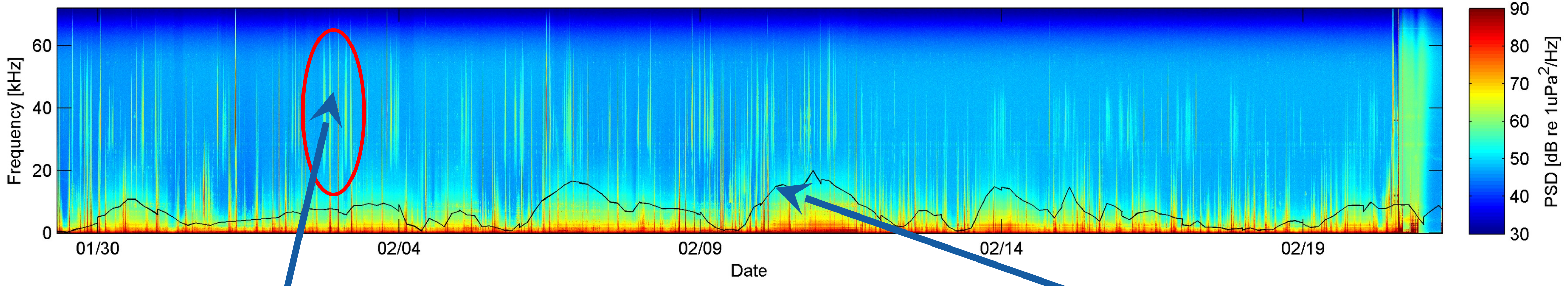


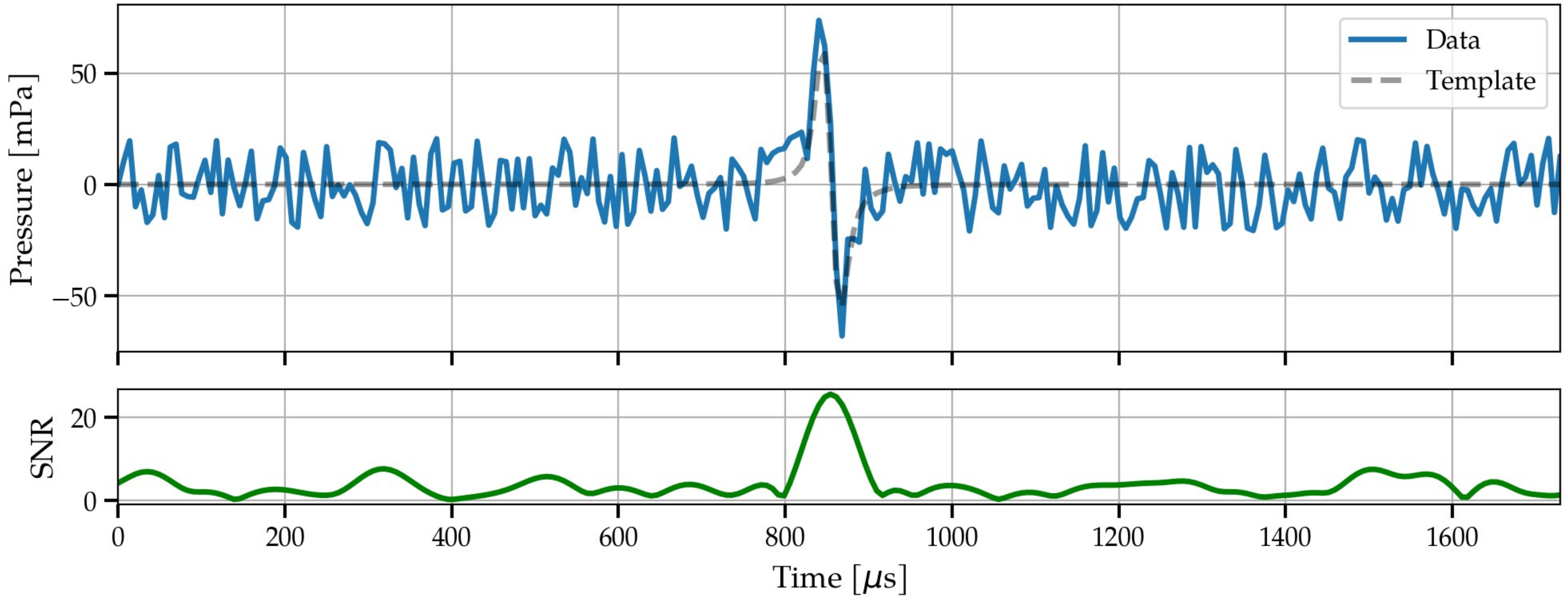


Bottlenose dolphins!

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. Event 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 $N_{min.}$

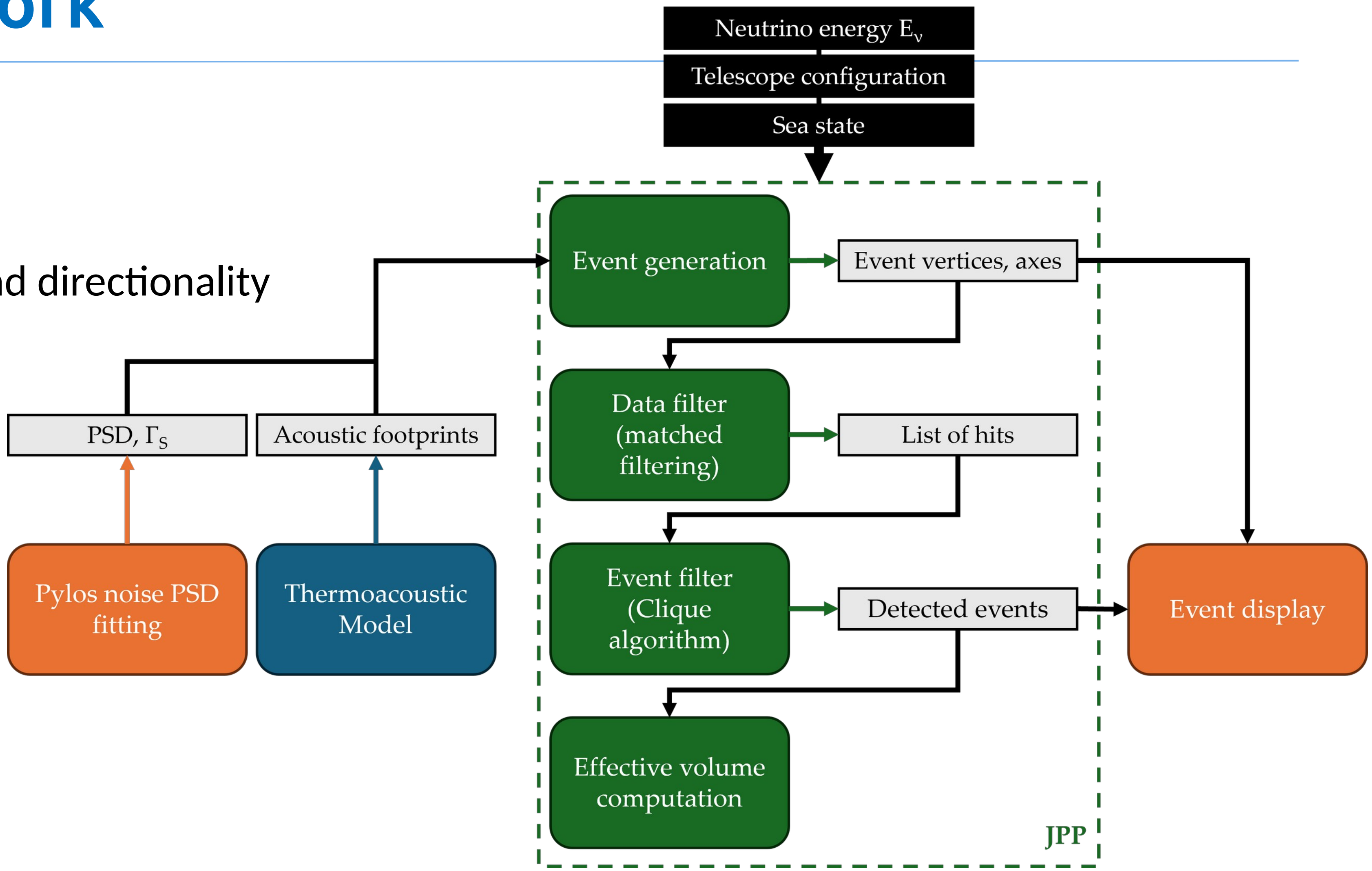
$$(T_2 - T_1) \leq \frac{|\vec{r_2} - \vec{r_1}|}{c}$$

Simulation framework

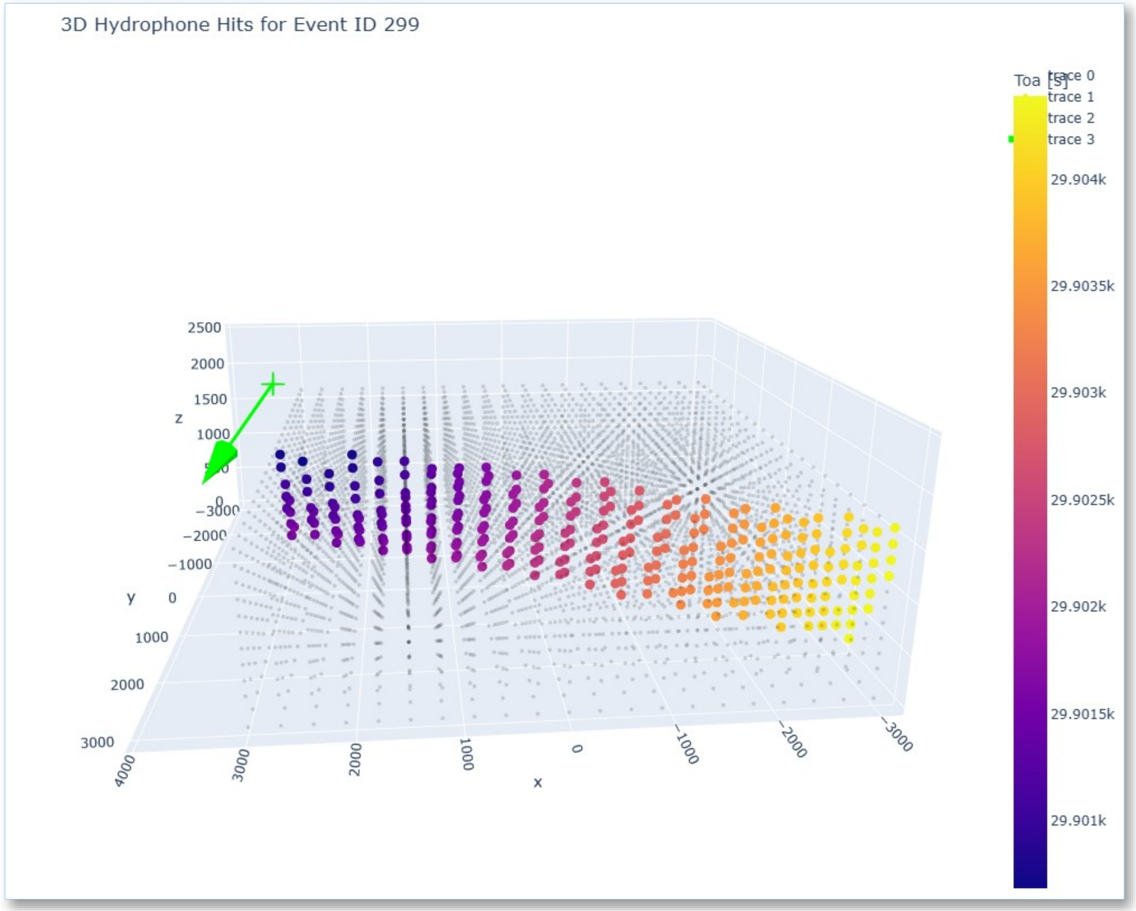
- <u>Included:</u>
- Simulated pulses
- Measured data
- Measured transfer functions and directionality

- Hit selection (matched filter)
- Event selection (Clique)

- <u>Next:</u>
- Hydrophone optimization
- Geometry optimization
- Clique rules optimization



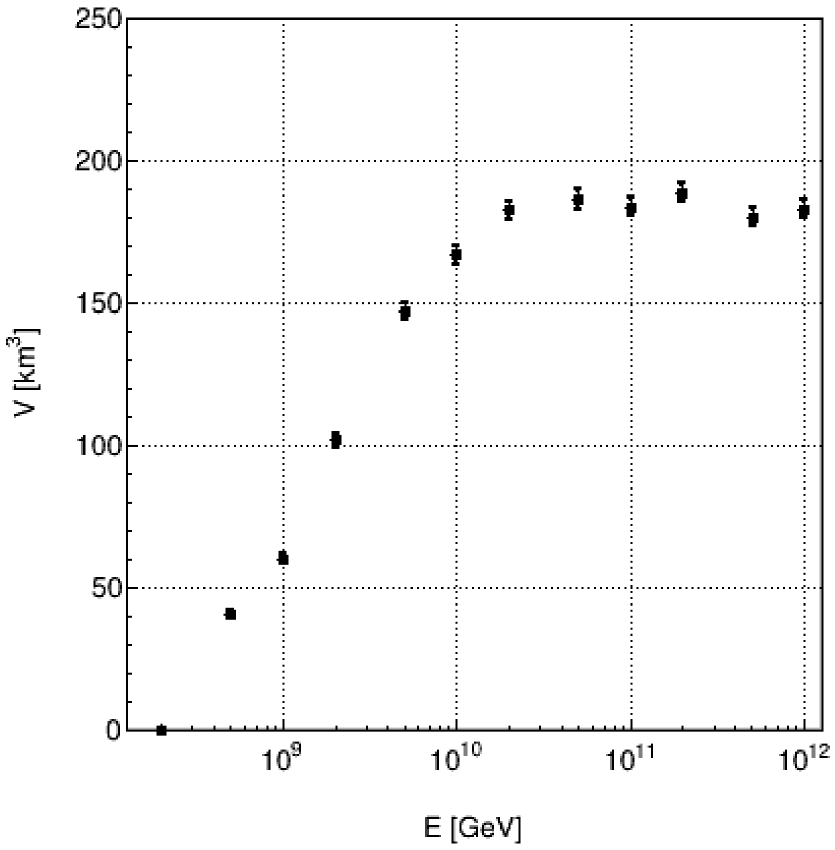
Telescope concept



Telescope parameters

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

Telescope concept



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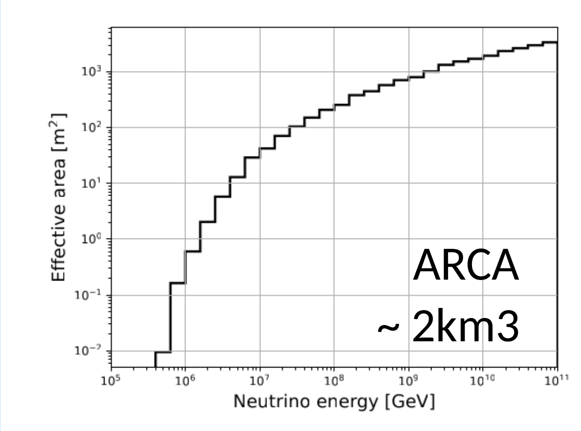
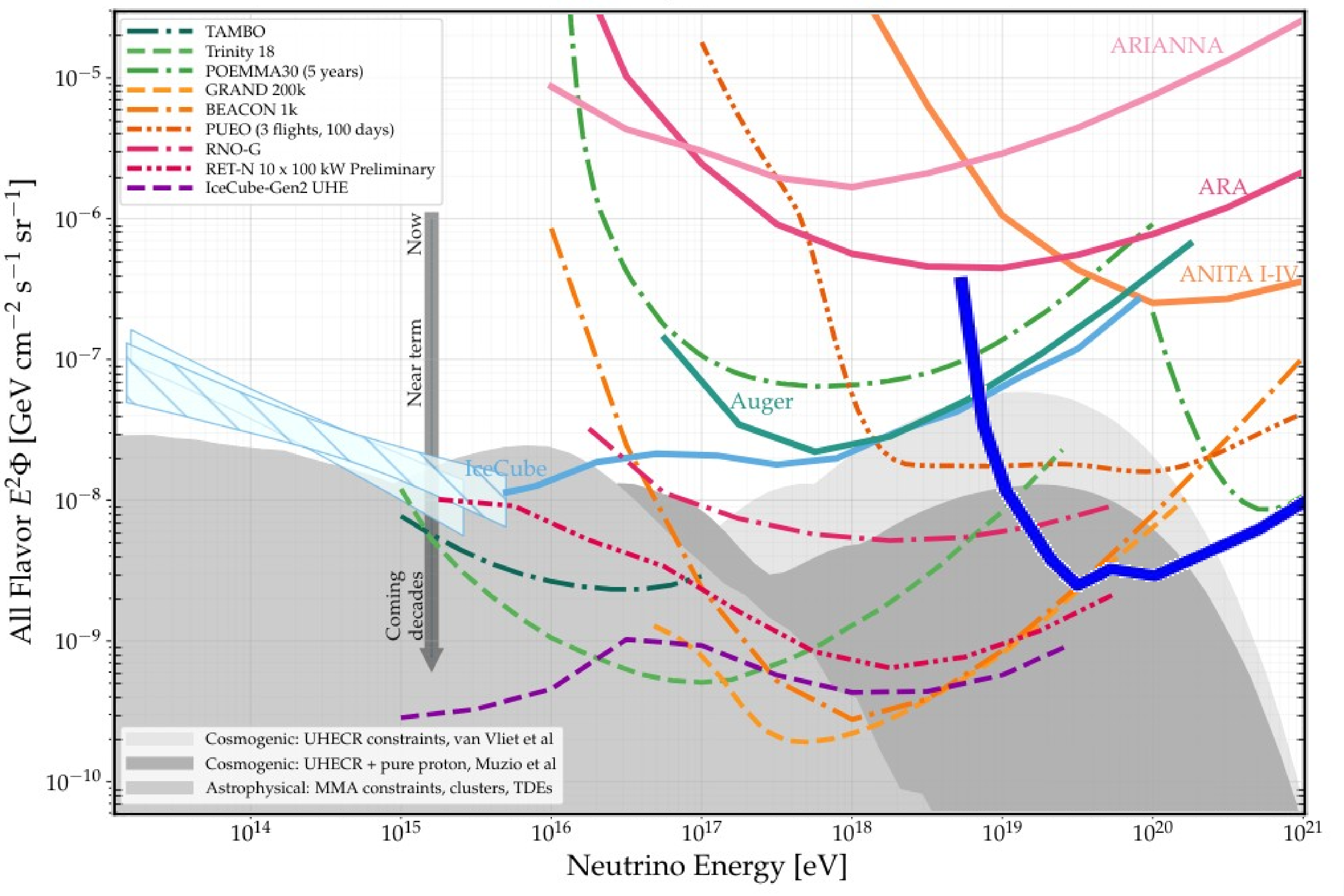


Differential sensitivity

Snowmass whitepaper, arXiv2203.08096



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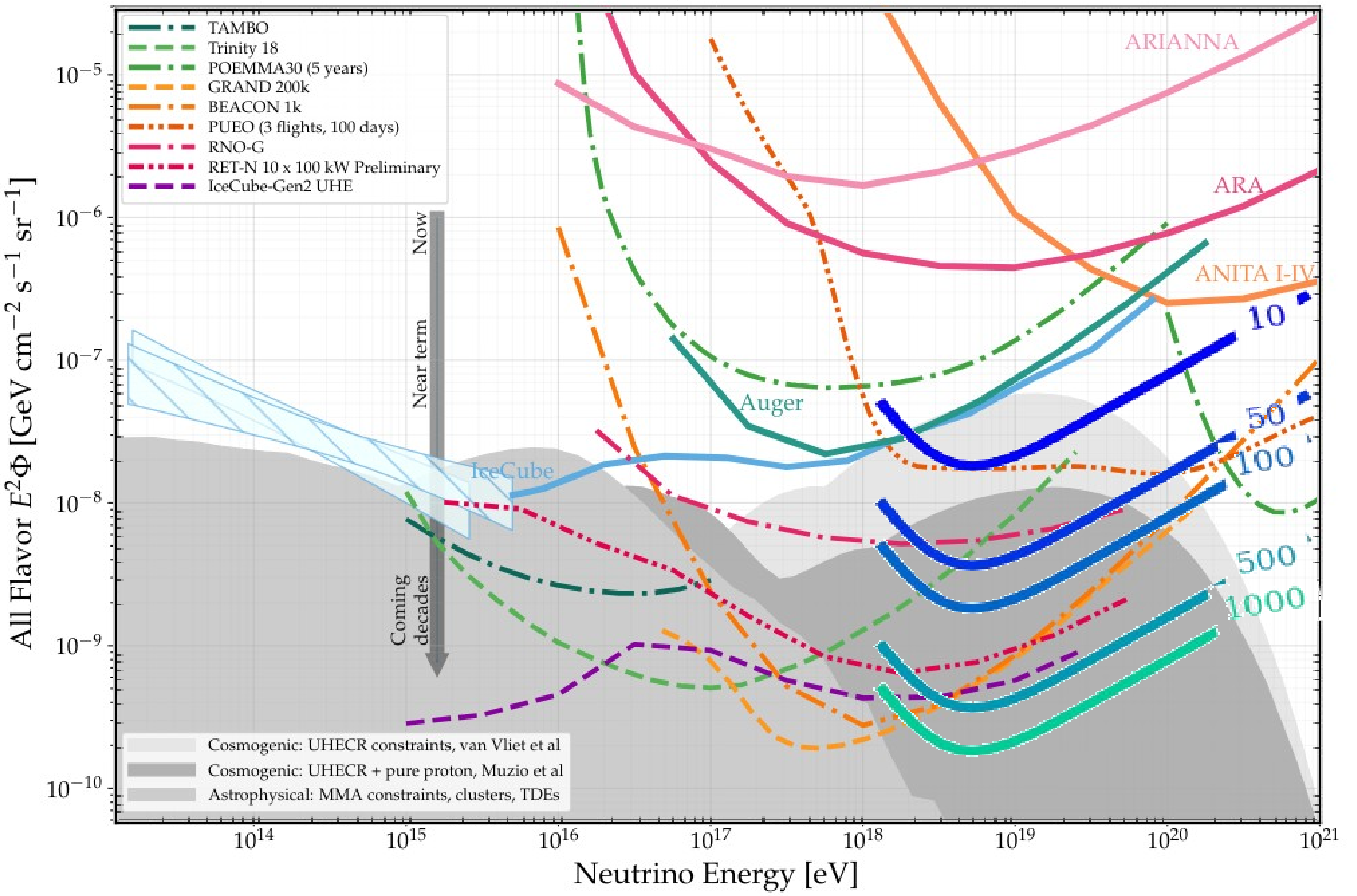
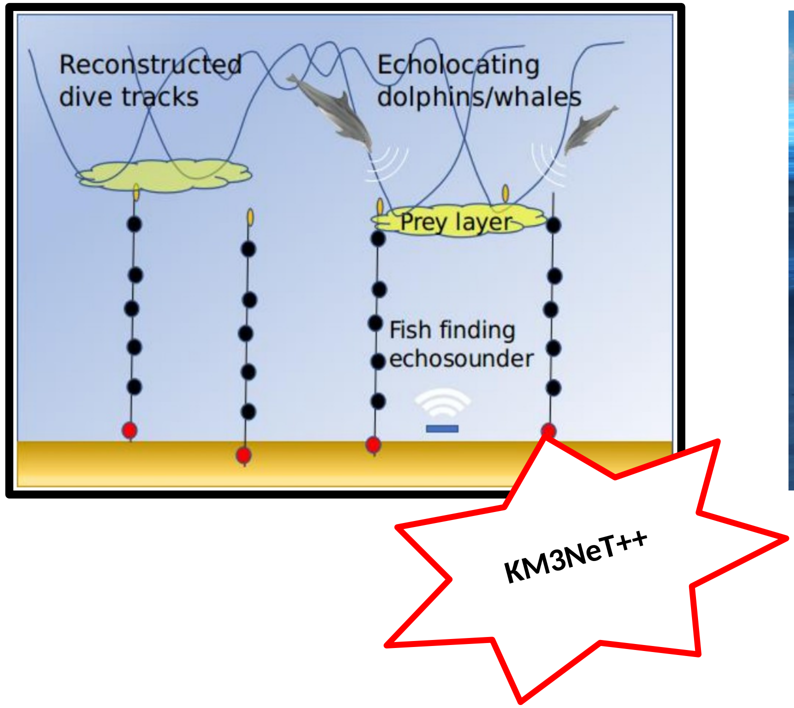
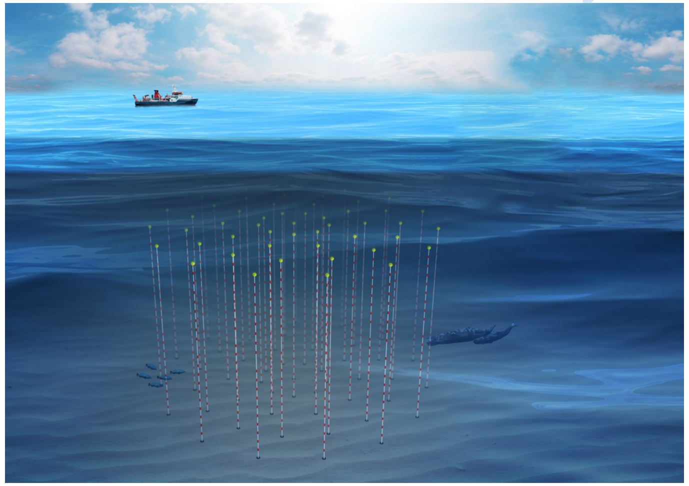


10 km3, 10yr

1000 km3, 10yr

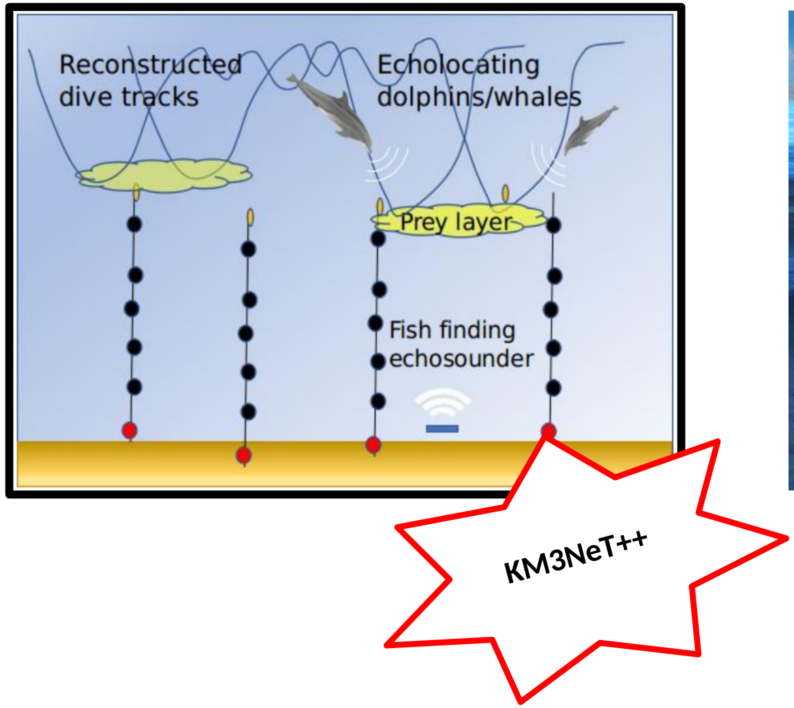
1: Lab measurements 2: Pathfinder 3: Acoustic telescope

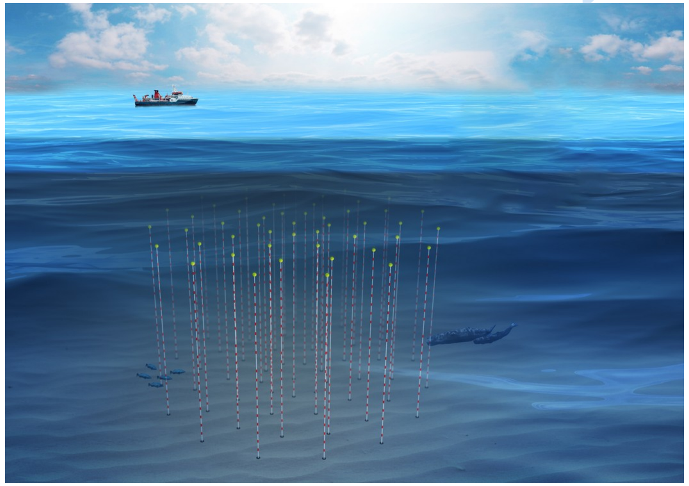




Towards a telescope in 3 steps

1: Lab measurements 2: Pathfinder 3: Acoustic telescope





Pathfinder concept:

- Four hydrophone lines connected to the ORCA
- Collaboration with NIOZ, marine ecology and oceanography
- Collaboration with industry, (re)design to manufacturing
- https://doi.org/10.61686/YABMN82191

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 guaranteed source; Did we see a glimpse?

- 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

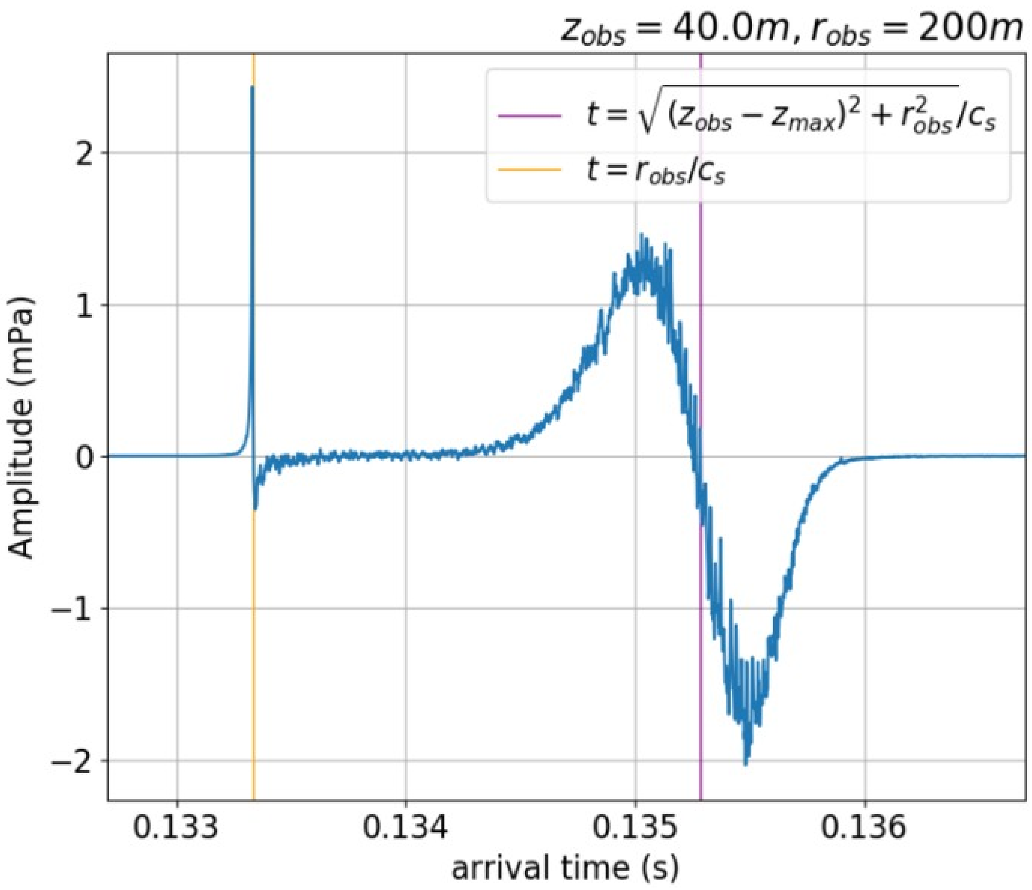
- Benefit from heritage from KM3NeT!
  - New working group established within the collaboration

- Multidisciplinarity: oceanography, marine ecology, marine conservation

- Synergies:
  - KM3NeT: understanding the environment, data-analysis
  - PAO, RNO-G, GRAND: scientific objectives, signal processing
  - LV, LISA: multi-messenger, signal processing
  - ET, R&D: fiber optic sensing network

Back-up

Near field effects

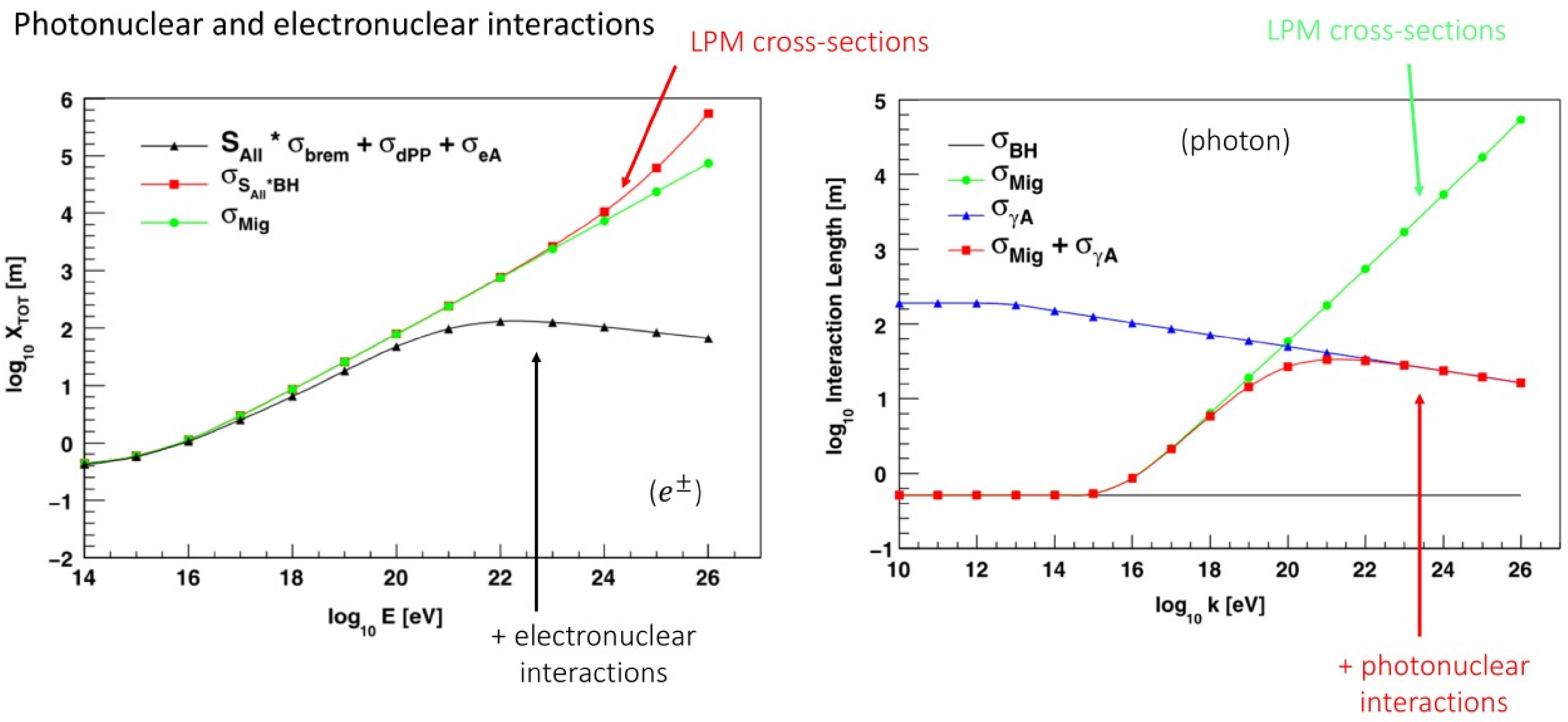


C. Gatius, E.J. Buis (2022)

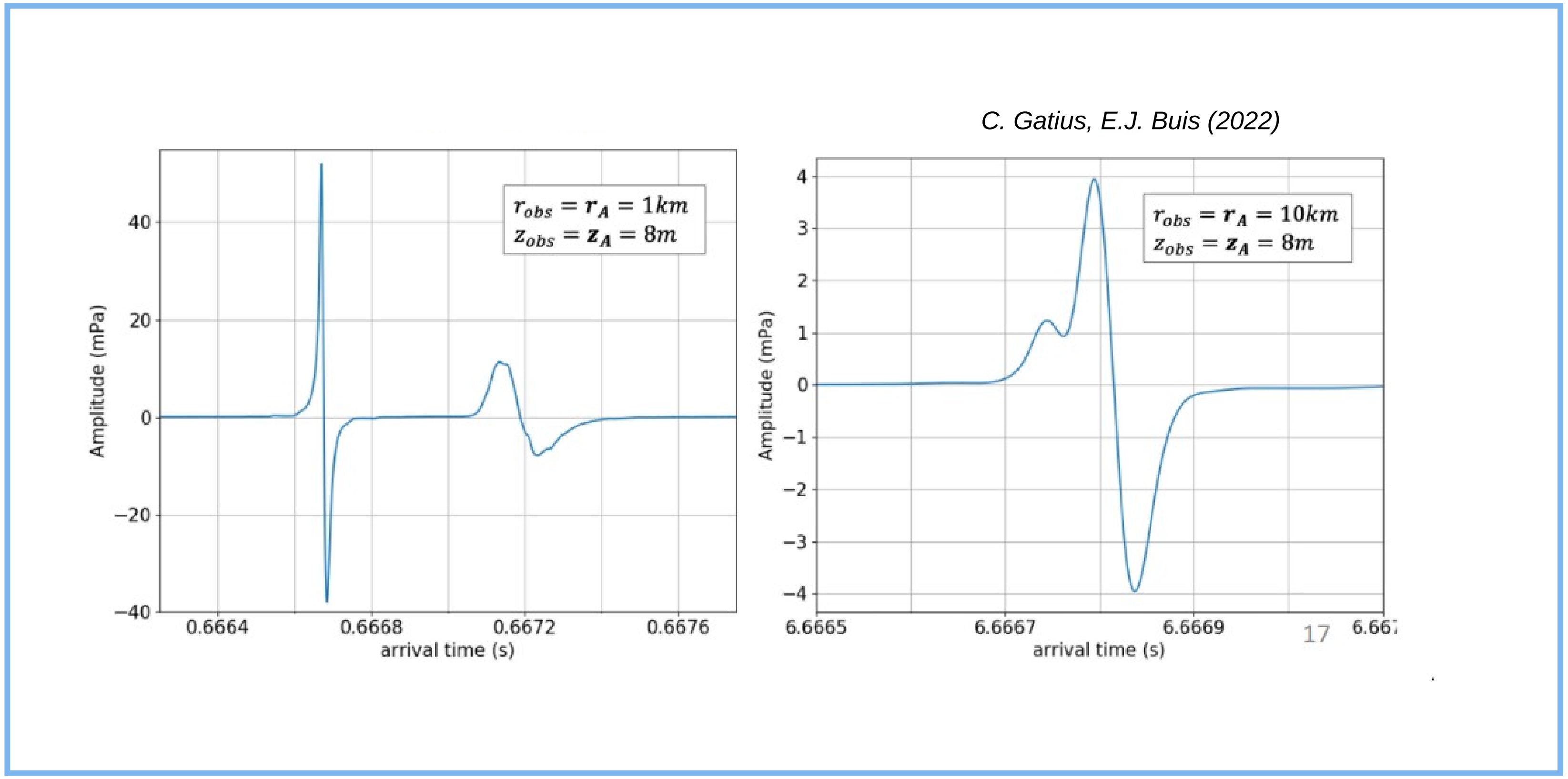
- Near field effect: two distinct pulses.

LPM effect

- Landau-Pomeranchuk-Migdal (LPM) effect
- Suppression of the high energy electromagnetic cross-sections (Bremsstrahlung and pair production) at high densities or energies.

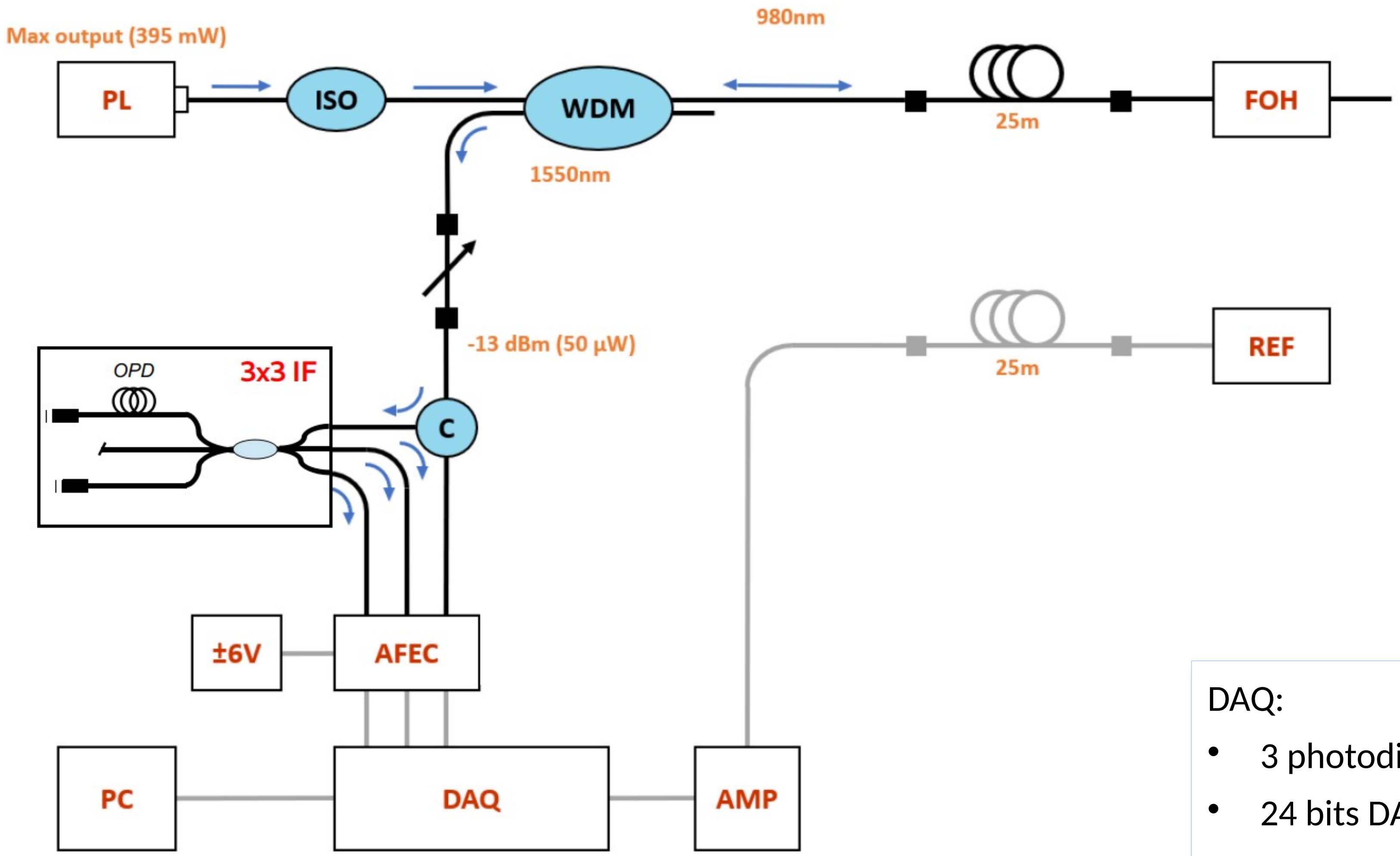


LPM effect



- Substructures in the shower → multiple acoustic pulses

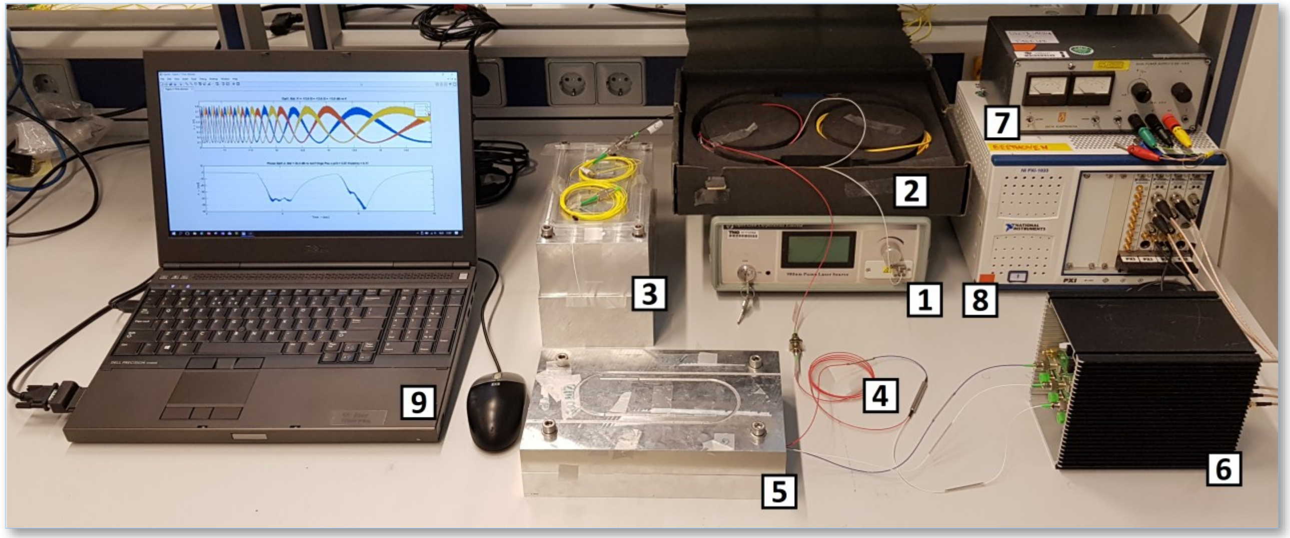
Data acquisition

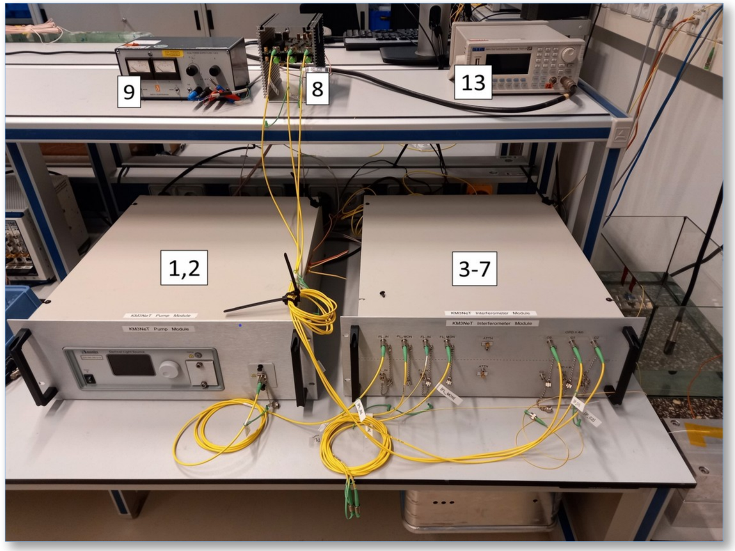


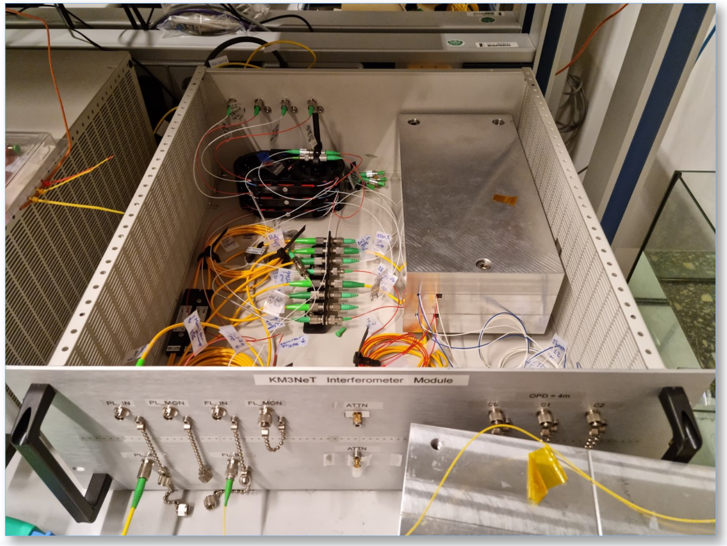
DAQ:

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

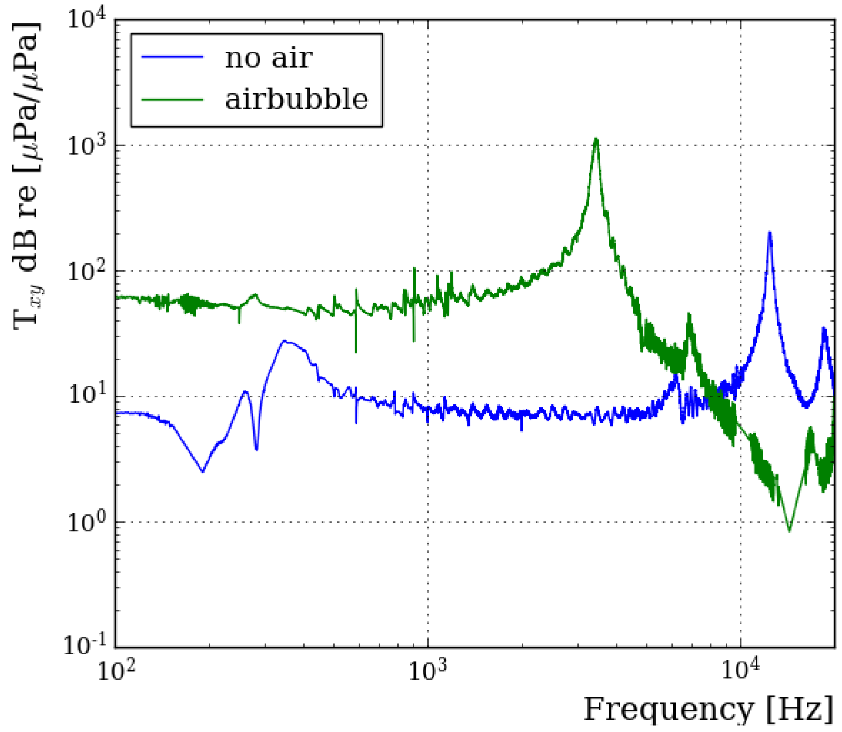
Interrogator



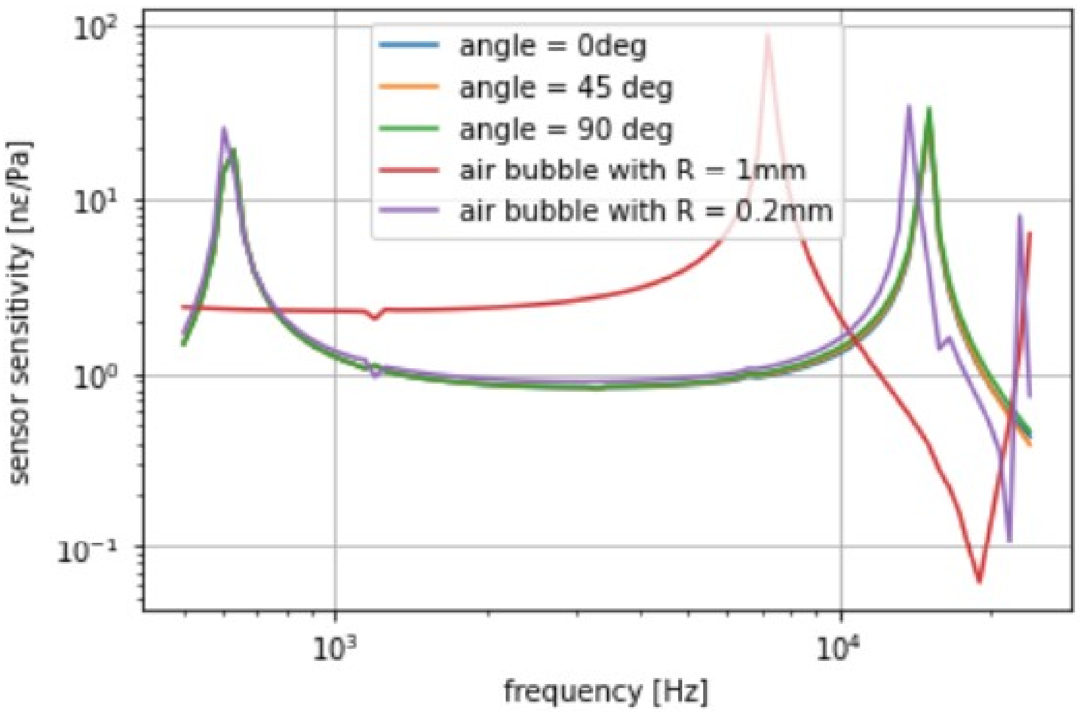




Instrument response: residual air



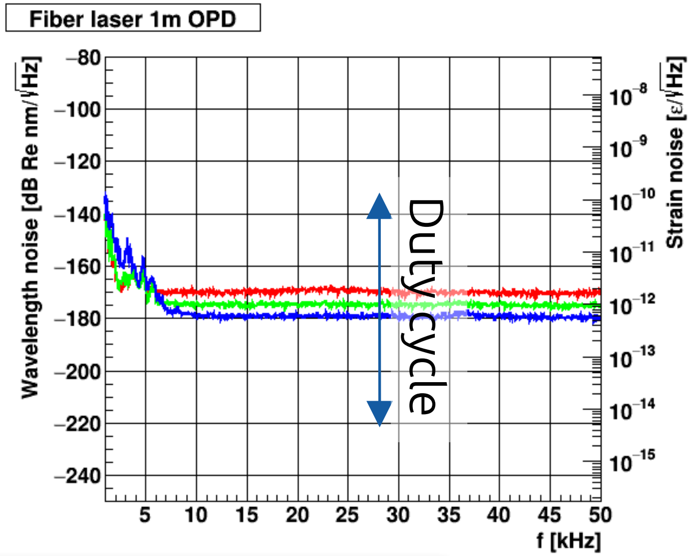
Comsol simulations

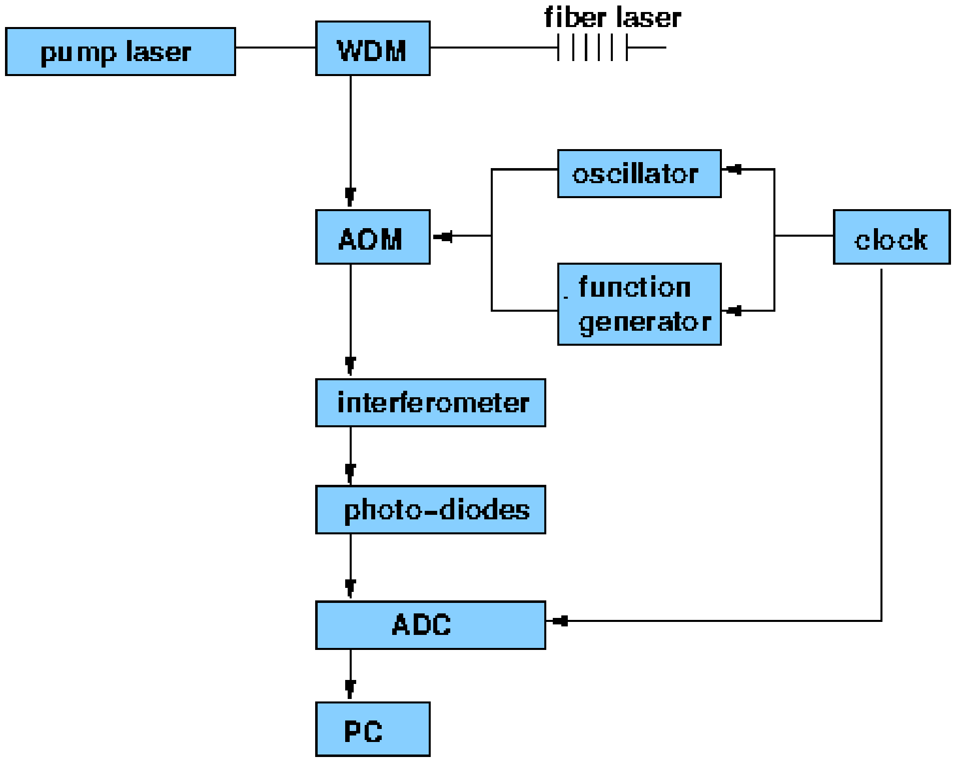


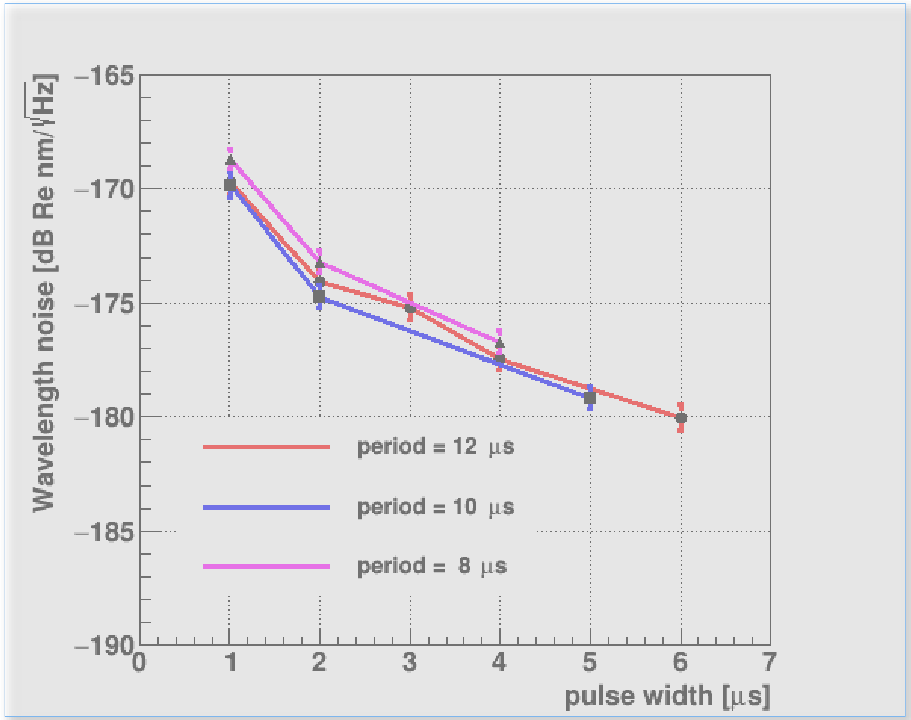
- Residual air in the transducer has a large impact on the transfer function!
(an air bubble of 1mm diameter has only 0.5% volume percentage)
- Established a procedure to fill the sensor

Time domain multiplexing (TDM)

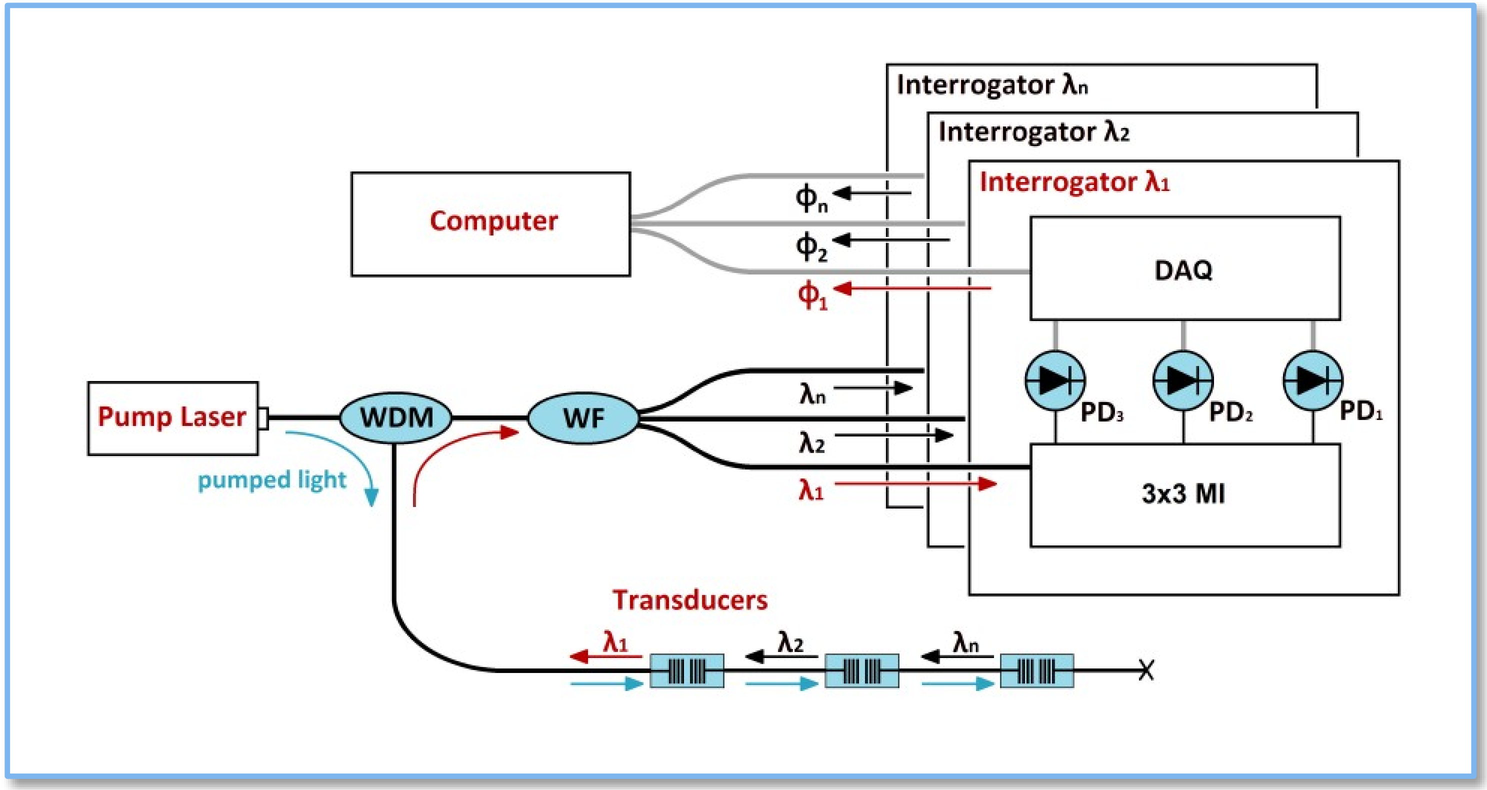
- Reduce the duty cycle when sampling the signal
- Insert an acoustic optical modulator in the DAQ system
- Noise floor increases with ~$^{10}\log(T/\Delta T)$

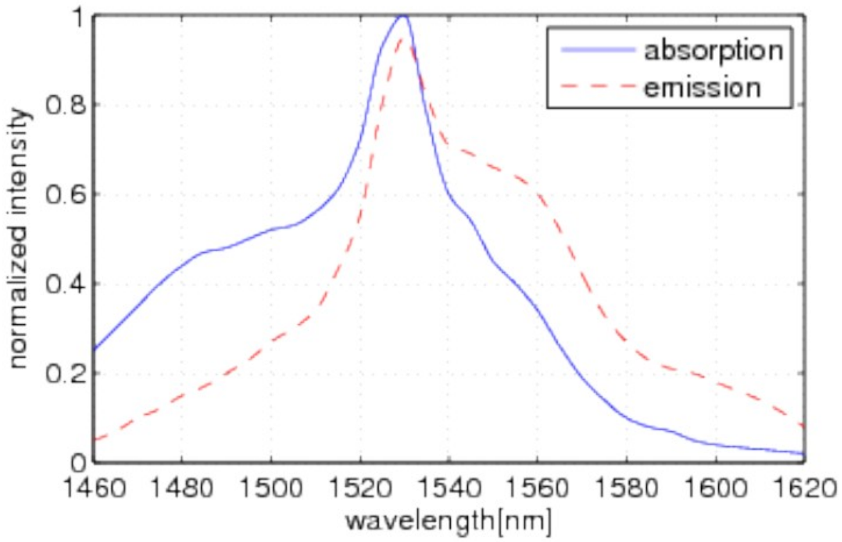


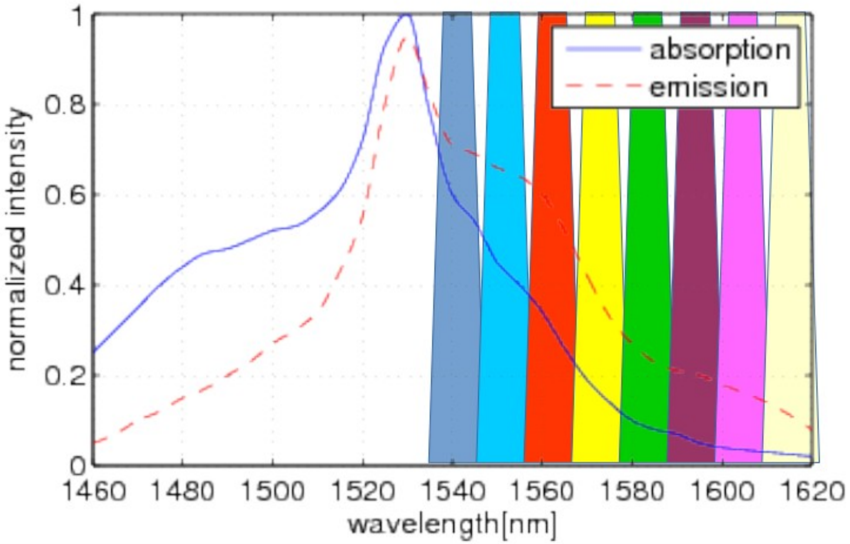




Wavelength domain multiplexing



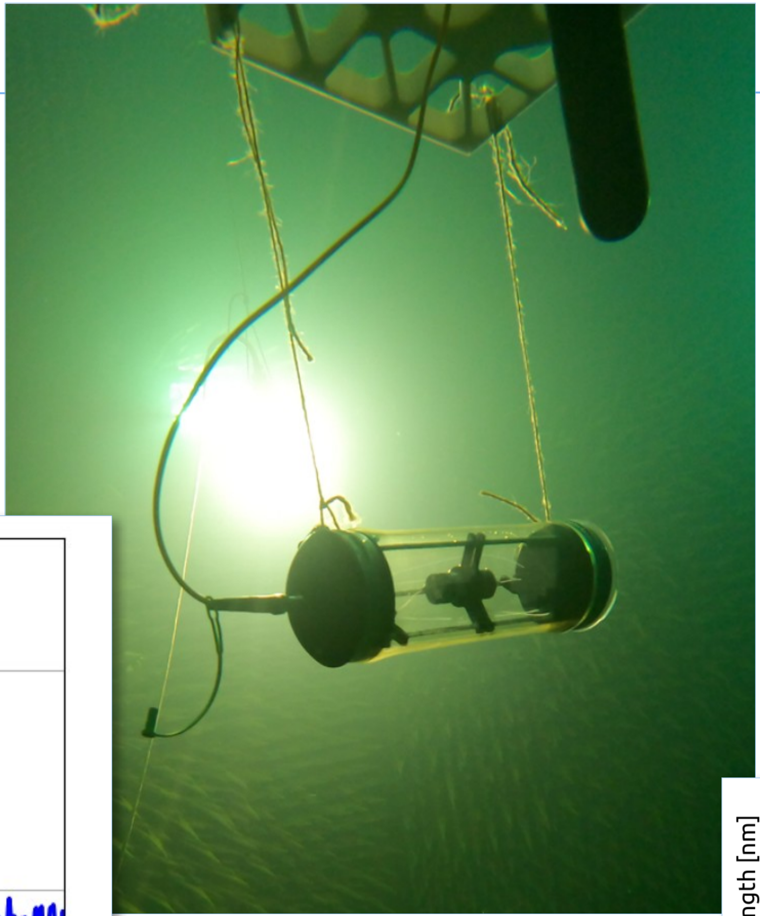


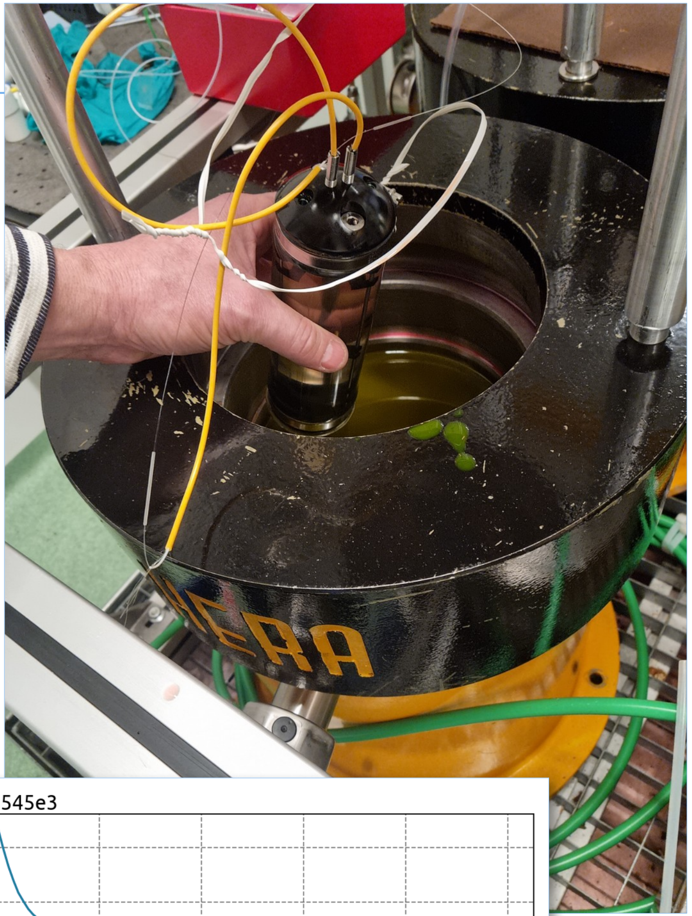


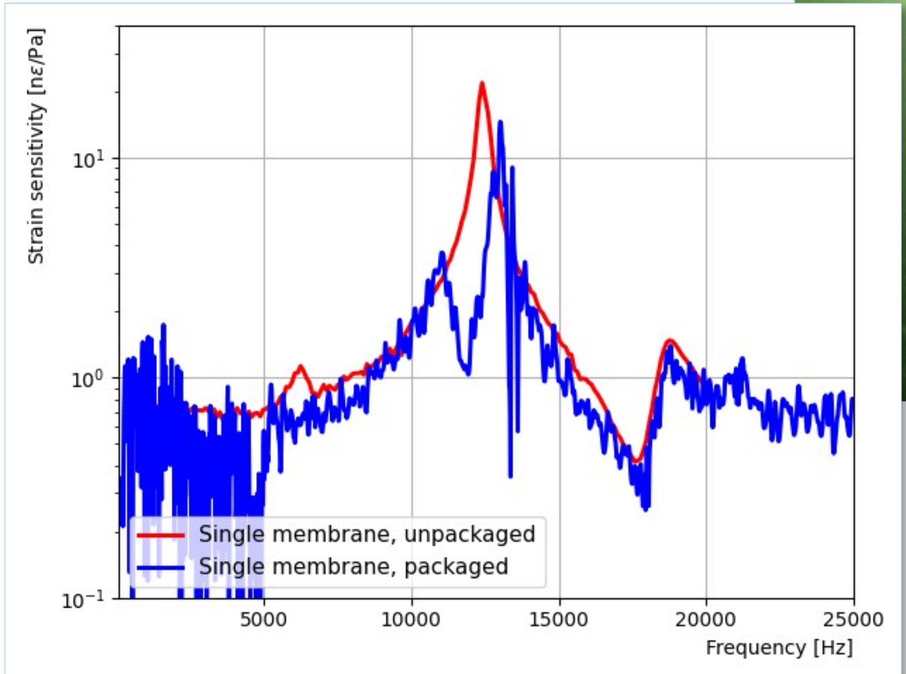
- Wavelength of each hydrophone can be tuned
- In practice, a finite number (~10) of laser lines fit the Erbium spectrum

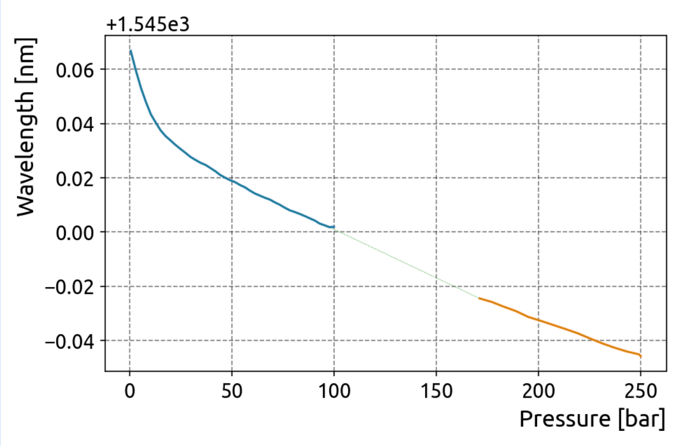
Pocket

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









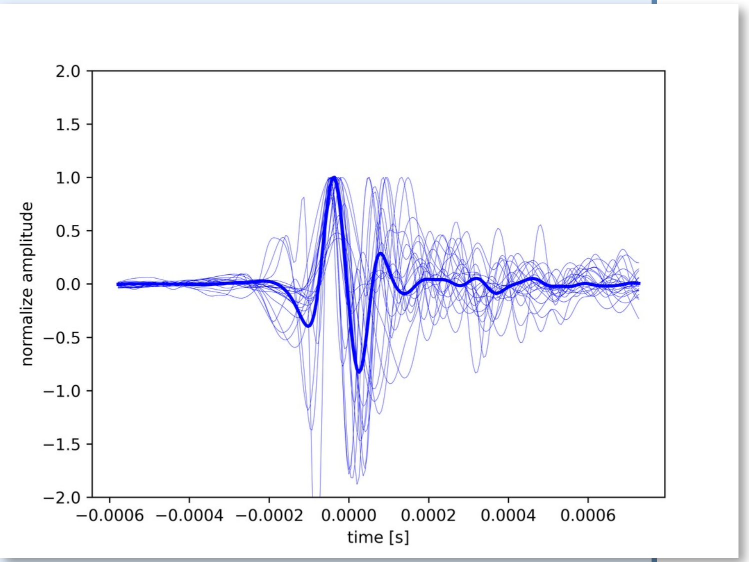
Noise studies

Neutrinos

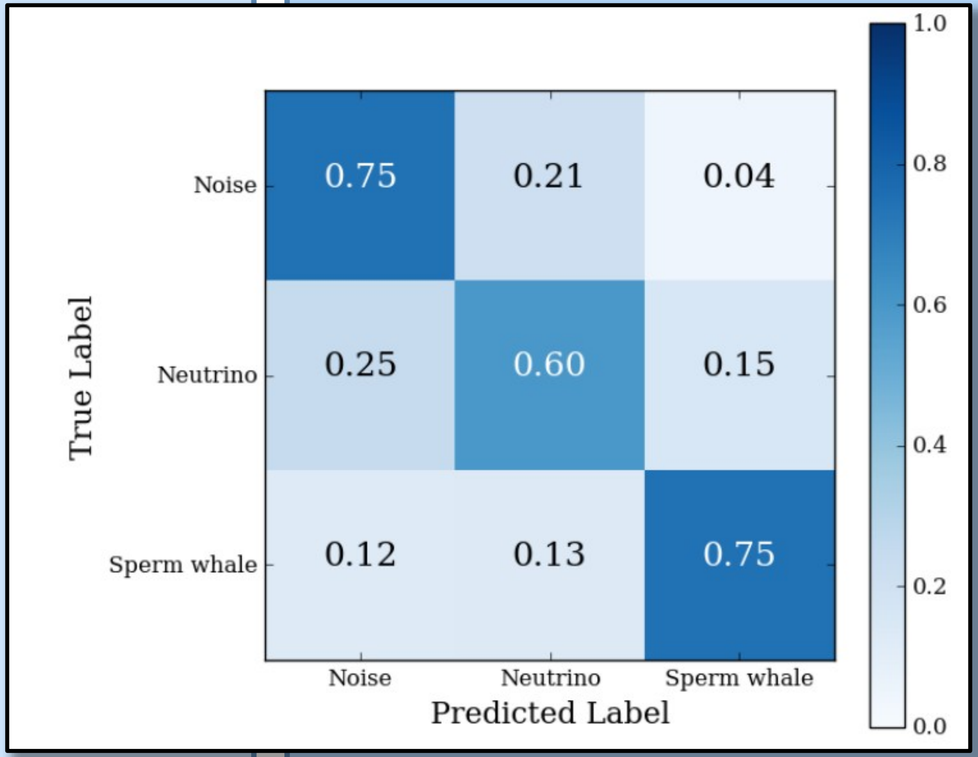
- Full simulation chain is in place: from neutrino interactions in water to acoustic neutrino pulses

Noise:

- Random noise extracted from Mediterranean Sea



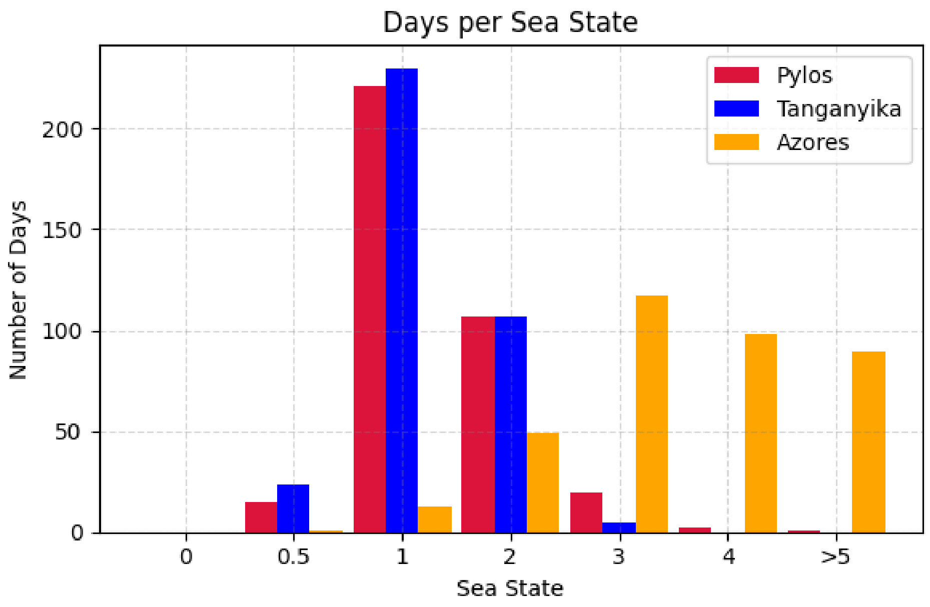
Confusion matrix

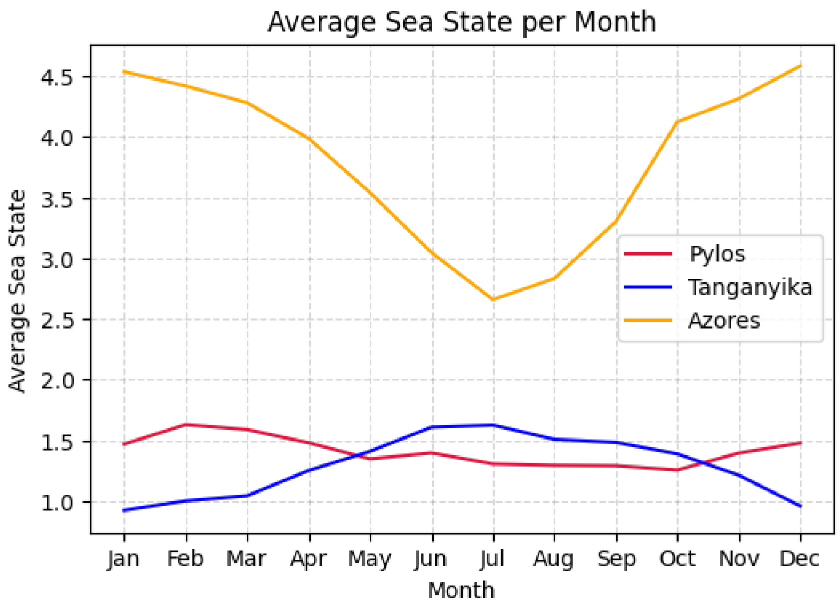


Liselotte Dijkema 2023

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

Sites



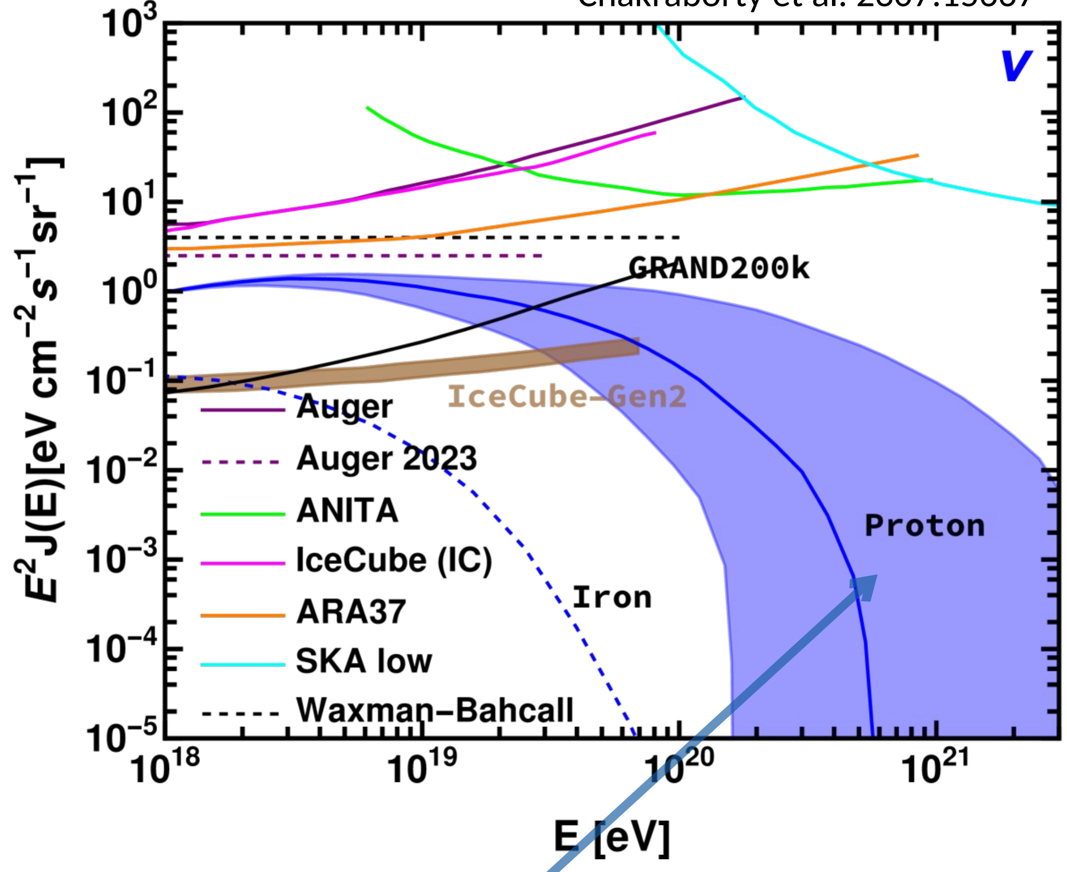


- Sea state noise: for both Pylos and Lake Tanganyika there are more than ~200 days/yr with SS1 or better
- Underwater noise and absorption yet to be verified

GZK

- Spread in flux:
  - CR composition
  - Cut-off energy
  - Spectral index of the CR spectrum near cut-off
  - Minimum (and maximum) distance to the CR source

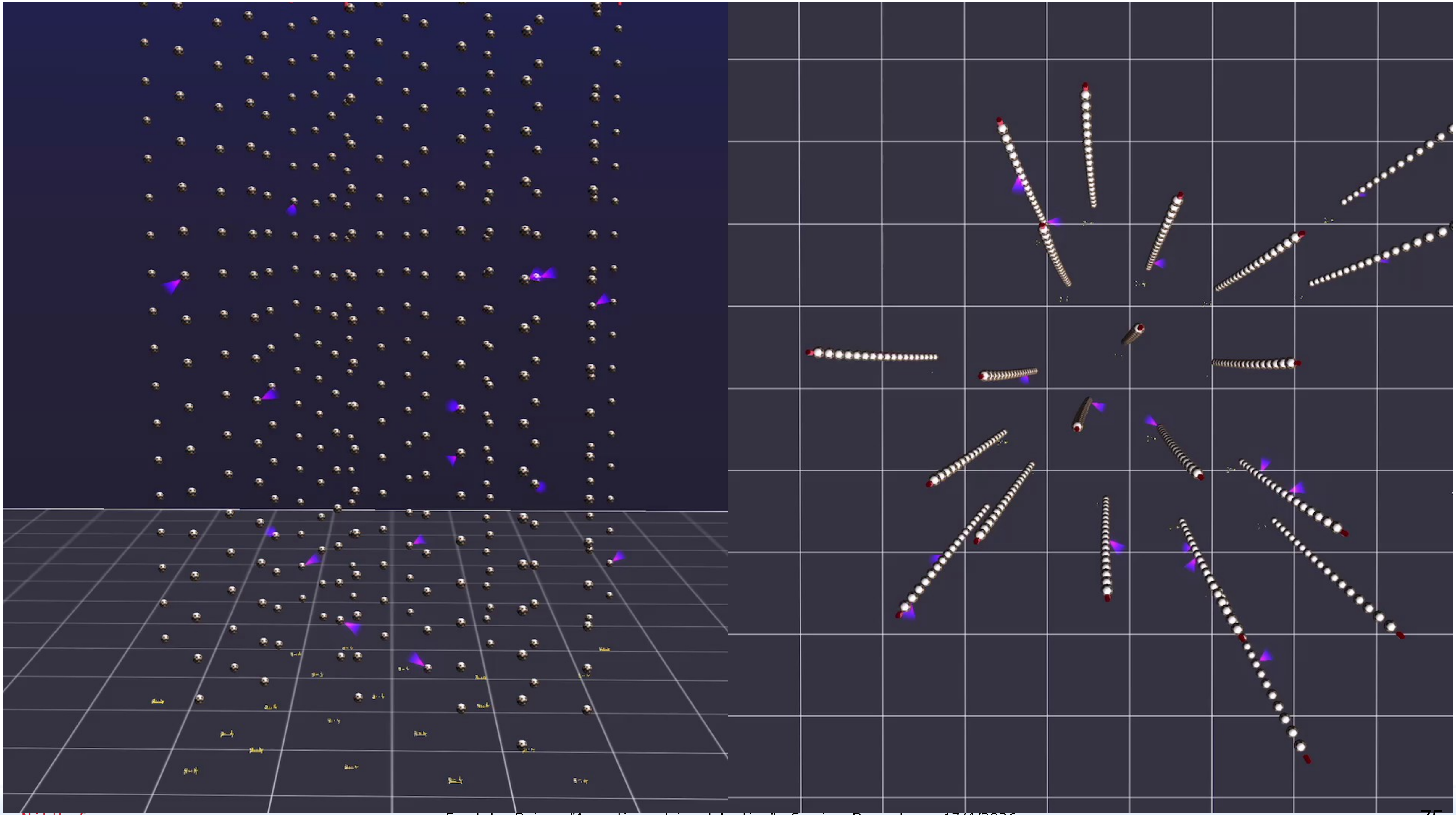
Chakraborty et al. 2307.15667

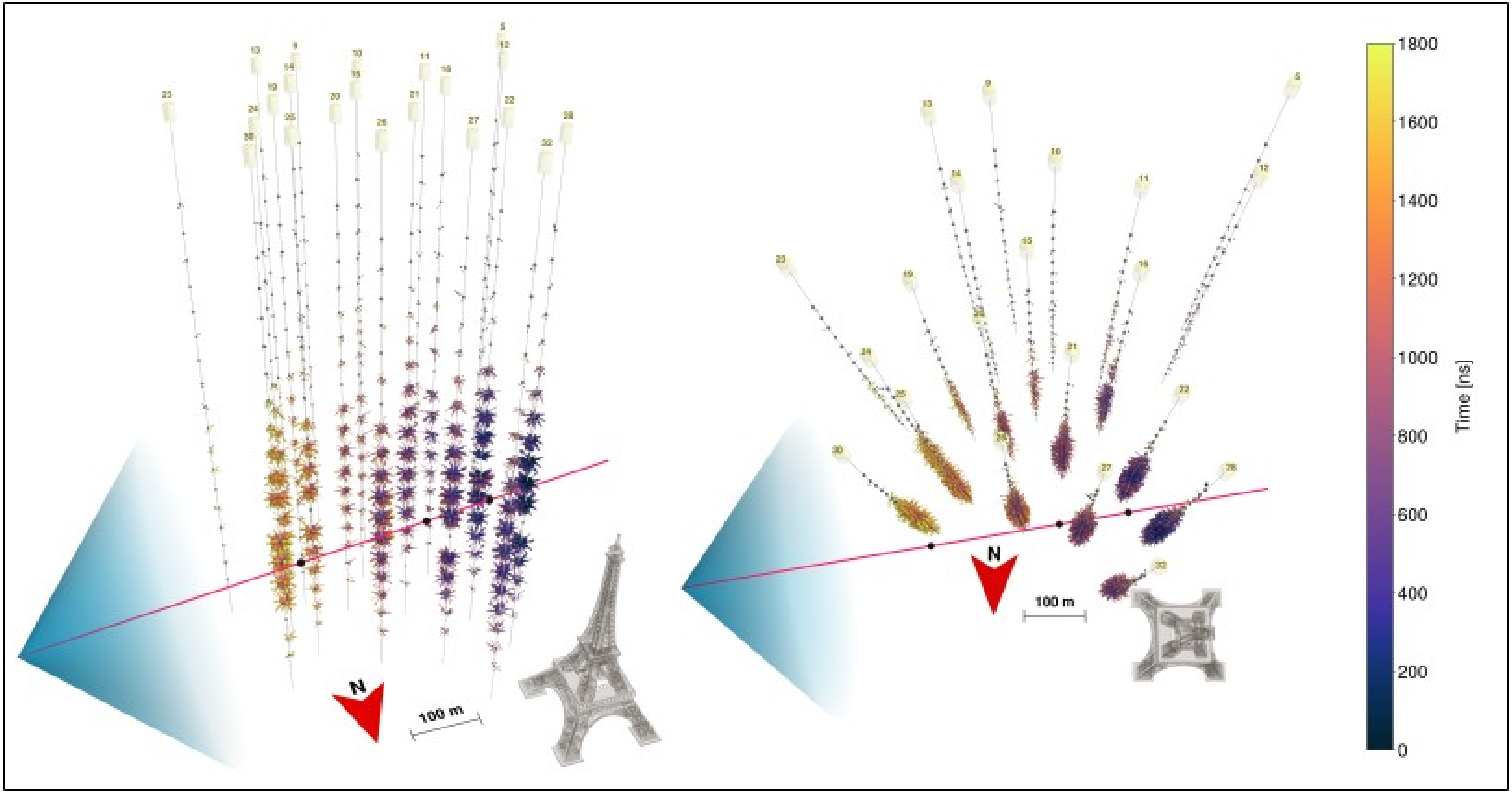


Most sensitive to E_{cut}, α and d_{min}

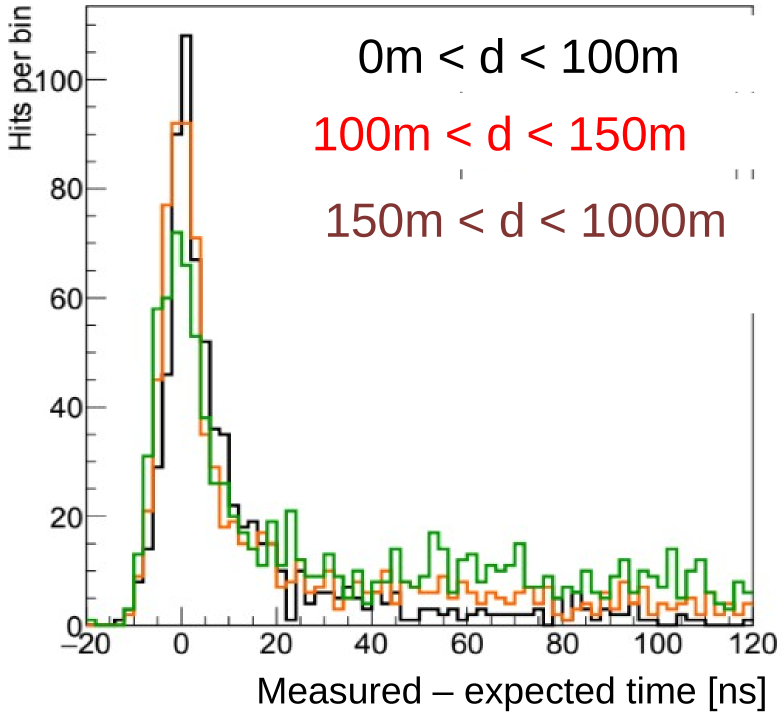
February 13 2023, 01:16:47 UTC

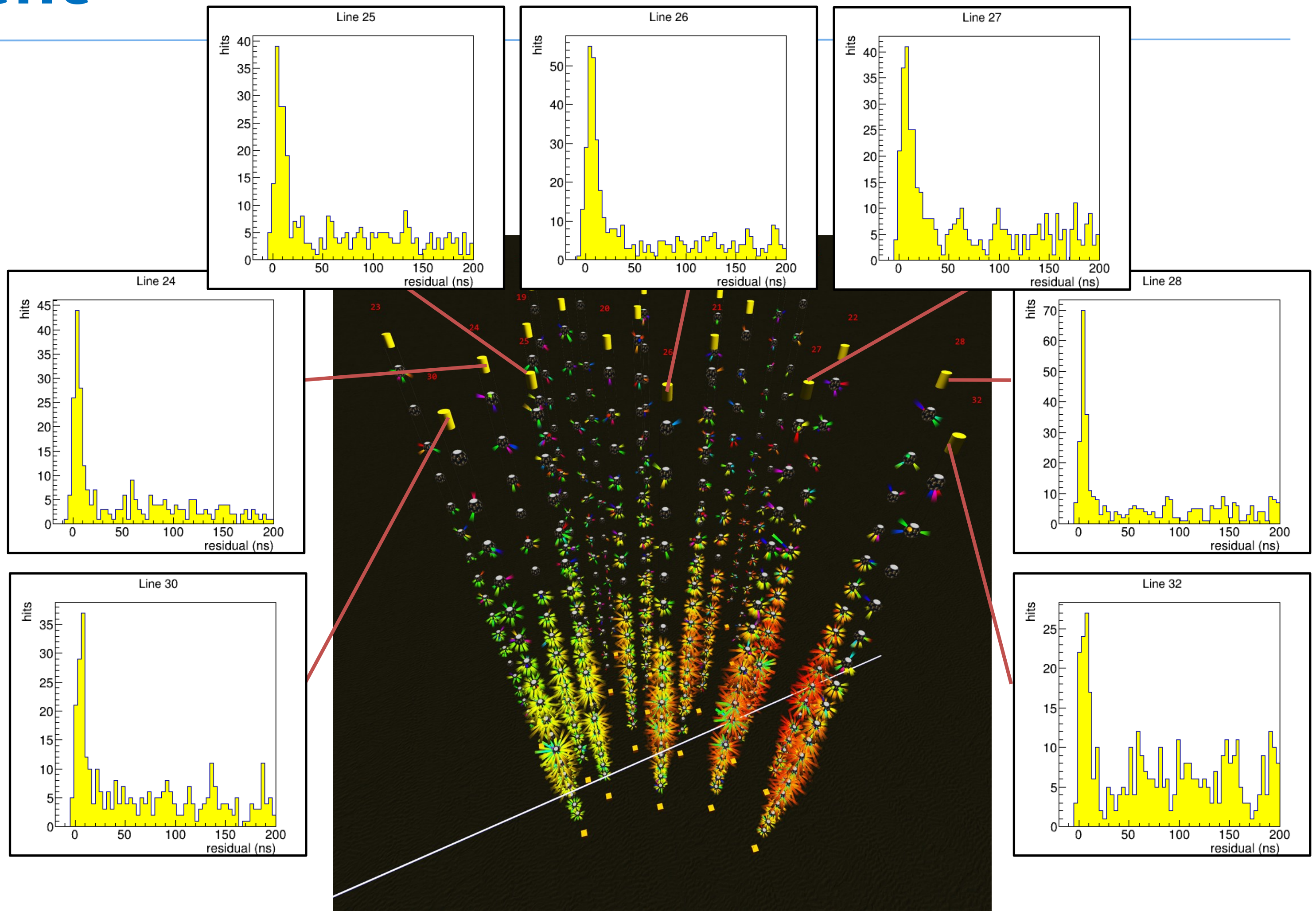
KM3-230213A




N
100 m
N
100 m
1800
1600
1400
1200
1000
800
600
400
200
0
Time [ns]

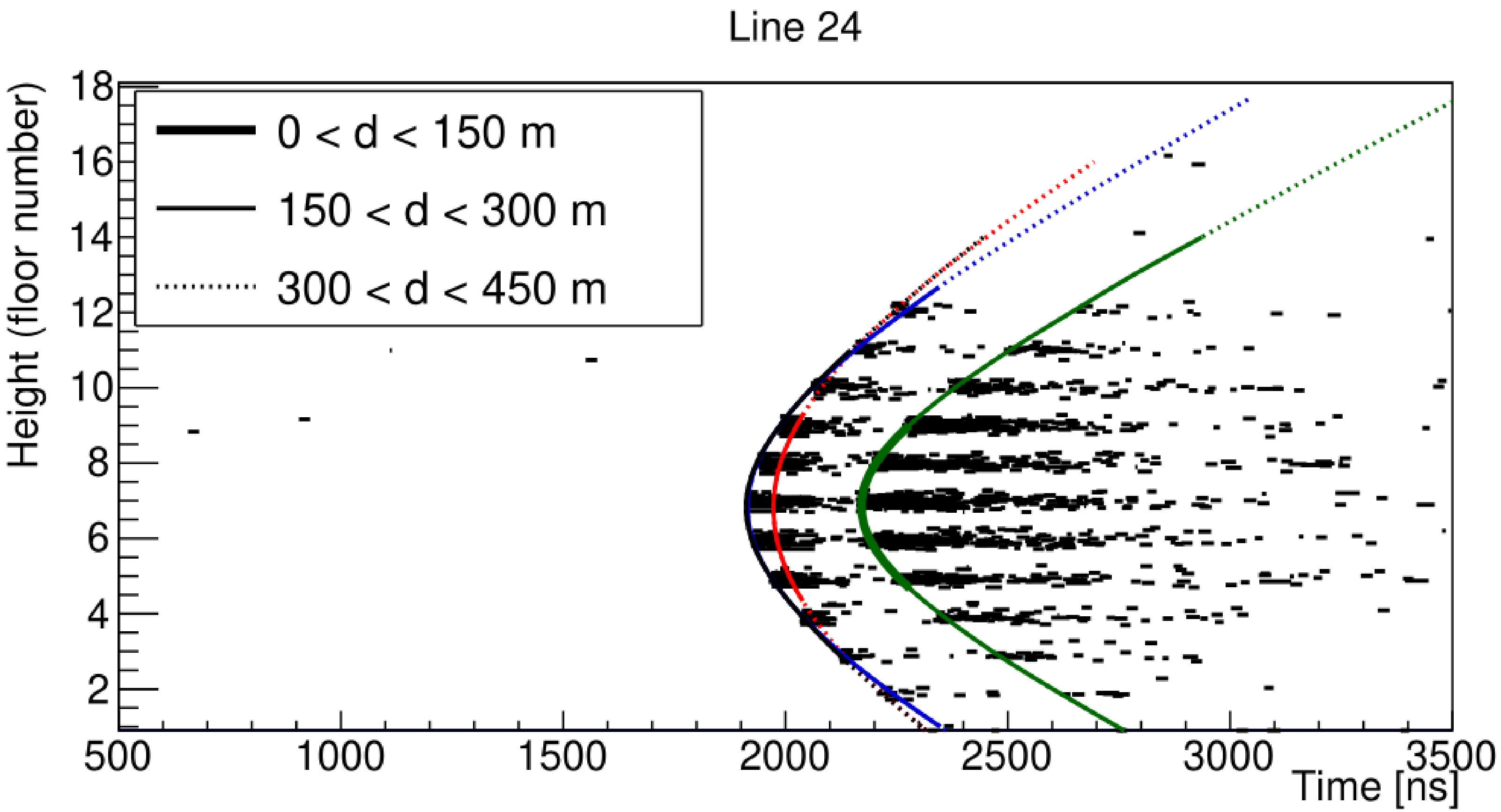
A very high energy event



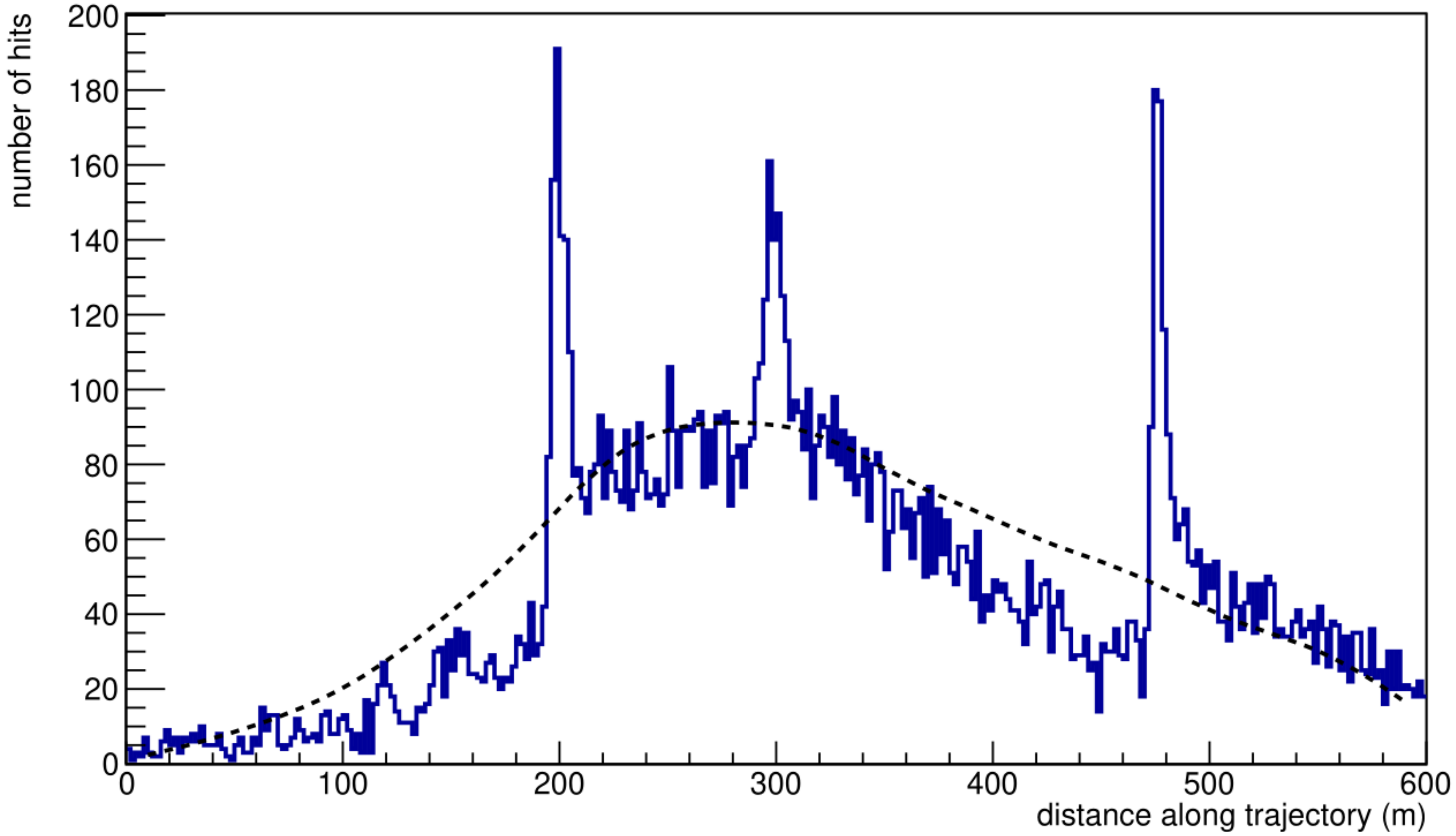


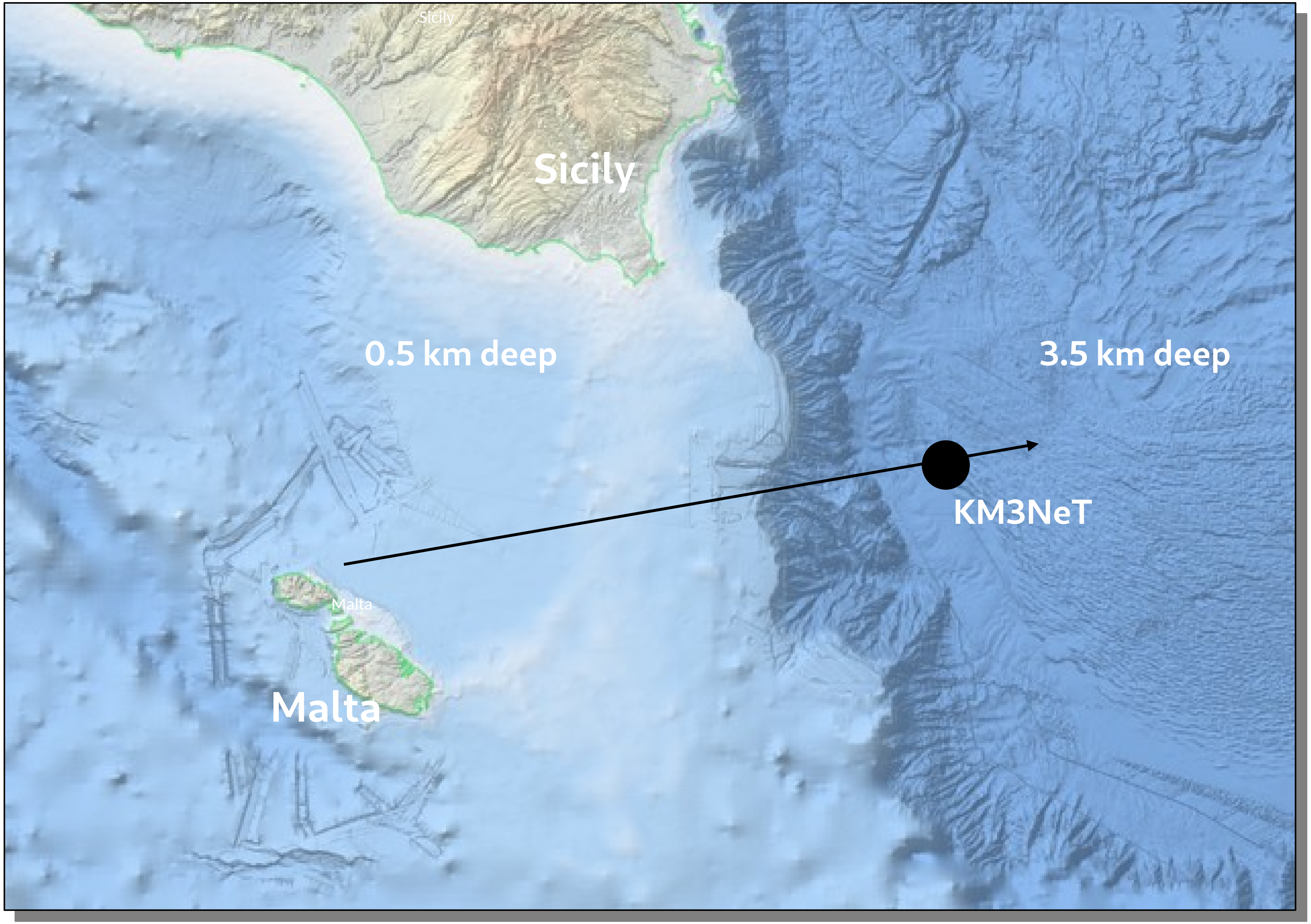
Light signals in excellent agreement with muon track hypothesis

A very high energy event



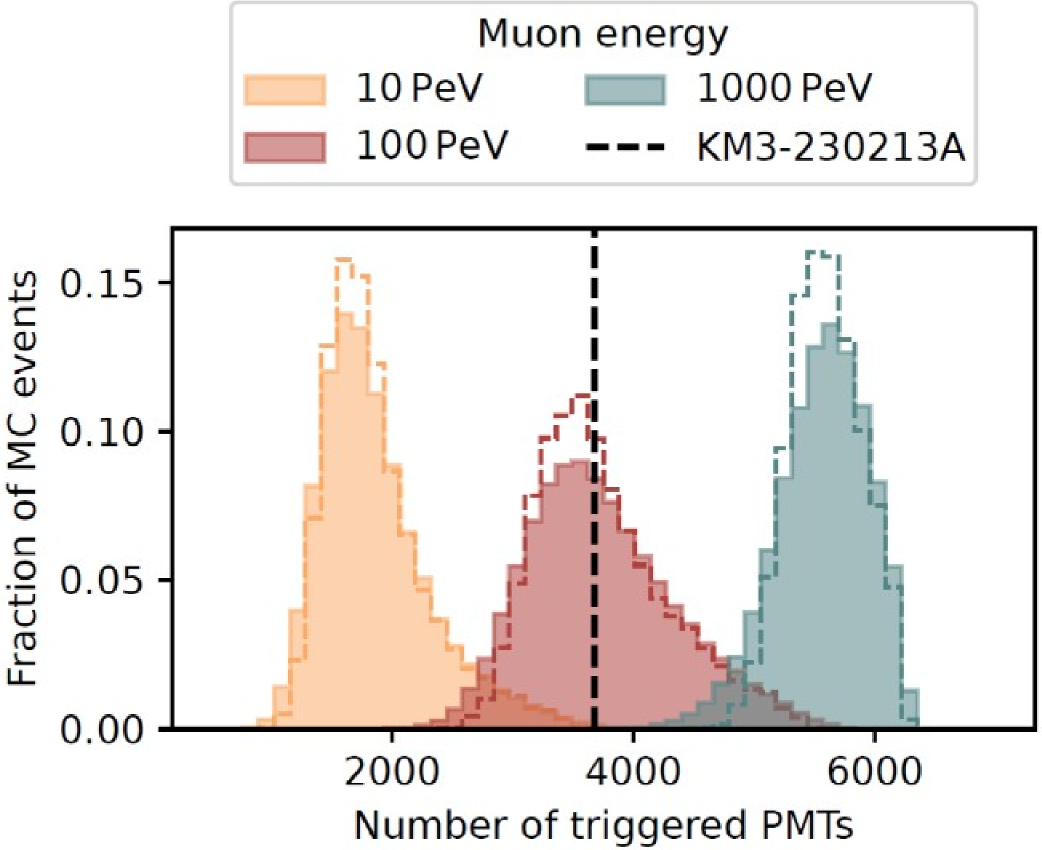
A very high energy event





KM3-230213A

Energy measurement



Energy is measured from the amount of light:

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

$90\%\ CL{:}\ 35\ PeV - 380\ PeV$

(10 000 times the energy of the LHC)

The neutrino energy is higher:

$$E_\nu = 220^{+570}_{-100}\, PeV$$

$90\%\ CL{:}\ 72 PeV - 1.5 EeV$

(assuming an E^{-2} source spectrum)

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