Acoustic Detection of Neutrinos: Review and Future Potential

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PHYSICS

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ICHEP 2014, Valencia, July 05, 2014

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Outline

ⓘ Snapshot, not: exhaustive or unbiased ⓘ

- Introduction: Why Acoustic Neutrino Detection and How Does It Work?
- Acoustic Neutrino Detection Test Setups
- Acoustic Neutrino Detection: Status and Results
- The Future: KM3NeT
- Summary and Outlook

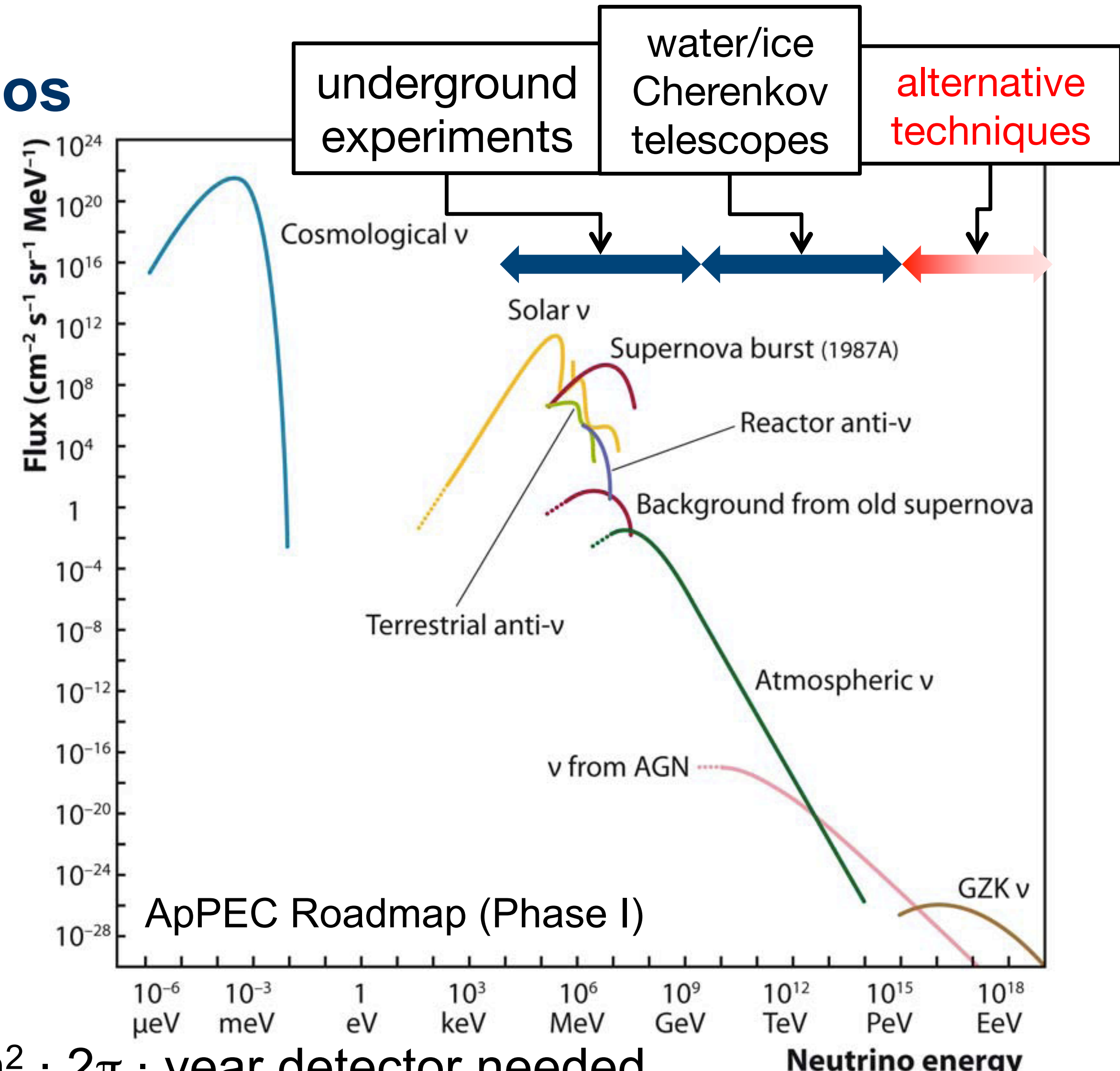
Introduction: Why Acoustic Neutrino Detection and How Does It Work?

Cosmogenic neutrinos

"GZK neutrinos"

produced in interactions of CRs at highest energies with CMB photons

$$p + p(\gamma) \rightarrow \pi + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_e + \nu_\mu$$



for GZK ν: >100km² · 2π · year detector needed

Thermo-acoustic model (Askariyan 1979)

energy deposition ⇒ local heating (μK) ⇒ expansion ⇒ pressure signal

Wave equation for pressure *p* for the deposition of an energy density ε :

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

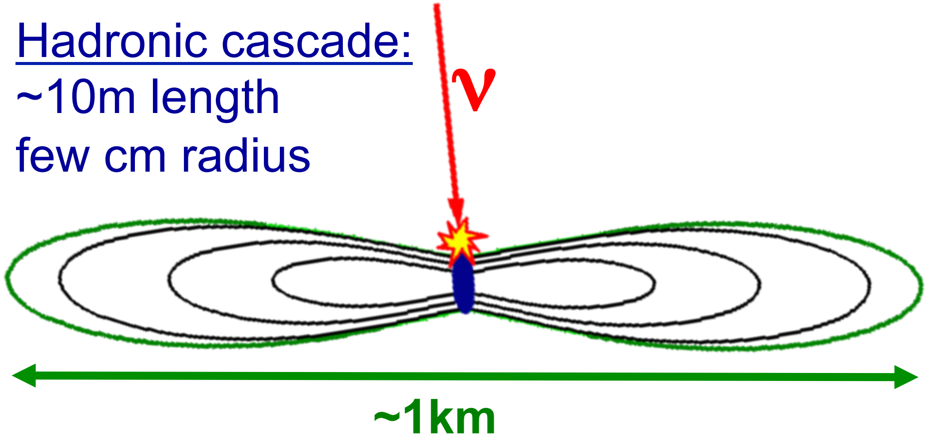
α = volume expansion coefficient

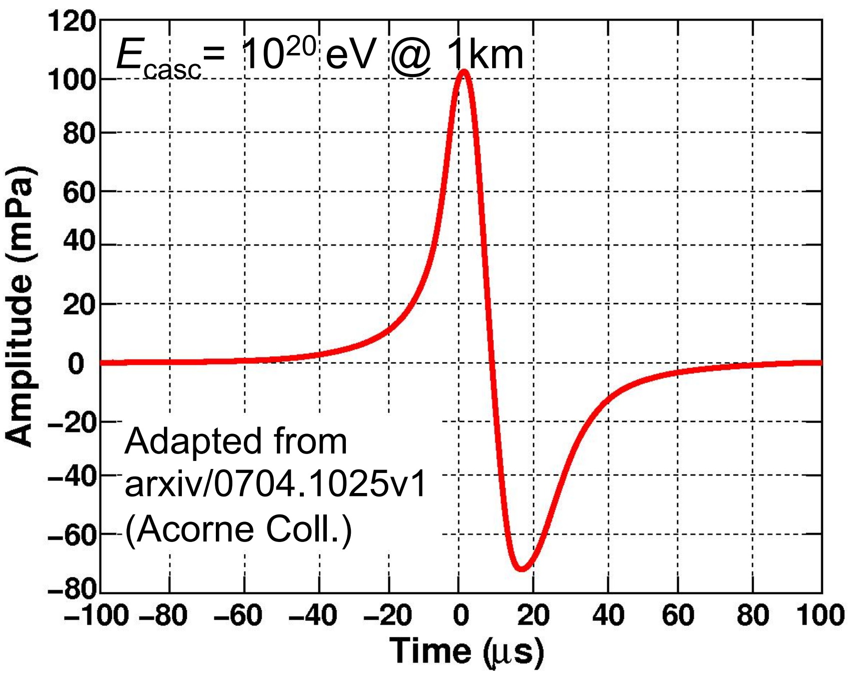
C_P = specific heat capacity (at constant pressure)

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

Confirmed in laboratory measurements

Acoustic detection of neutrinos

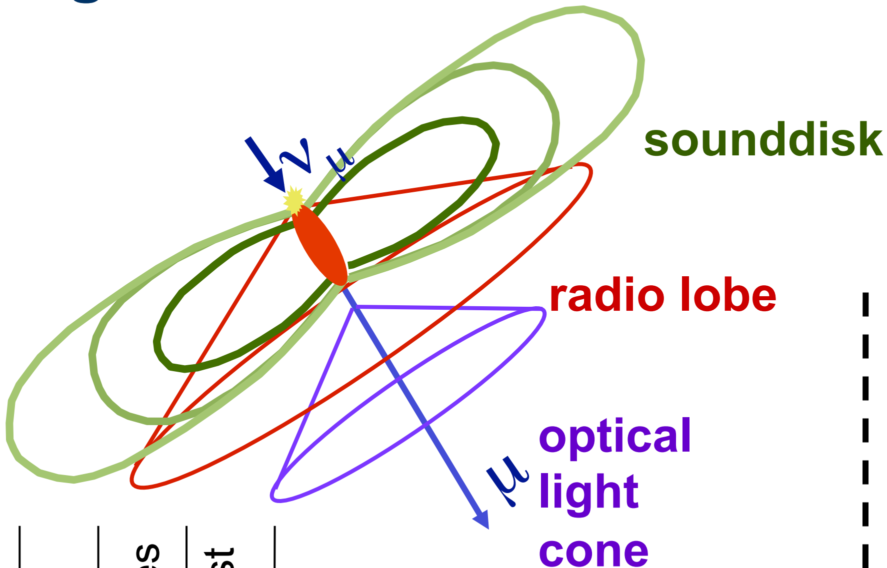




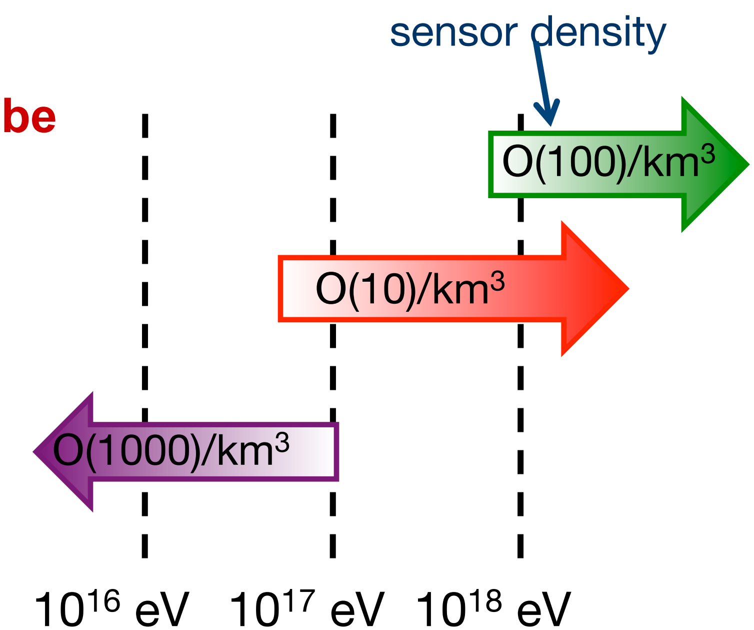
Pressure field:
Characteristic “pancake” pattern
Long attenuation length (~5 km @ 10 kHz)
Allows for neutrino detection at $E \gtrsim 10^{18}$eV

$$P(r = 200\,\mathrm{m}) \approx 10 \times \frac{E_{casc}}{1\,\mathrm{EeV}}\,\mathrm{mPa}$$

Neutrino signatures in different media



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



adapted from: R. Nahnhauer, ARENA Conf. 2010

Acoustic Neutrino Detection Test Setups

Acoustic detection test setups

First generation acoustic test setups follow two “philosophies”:

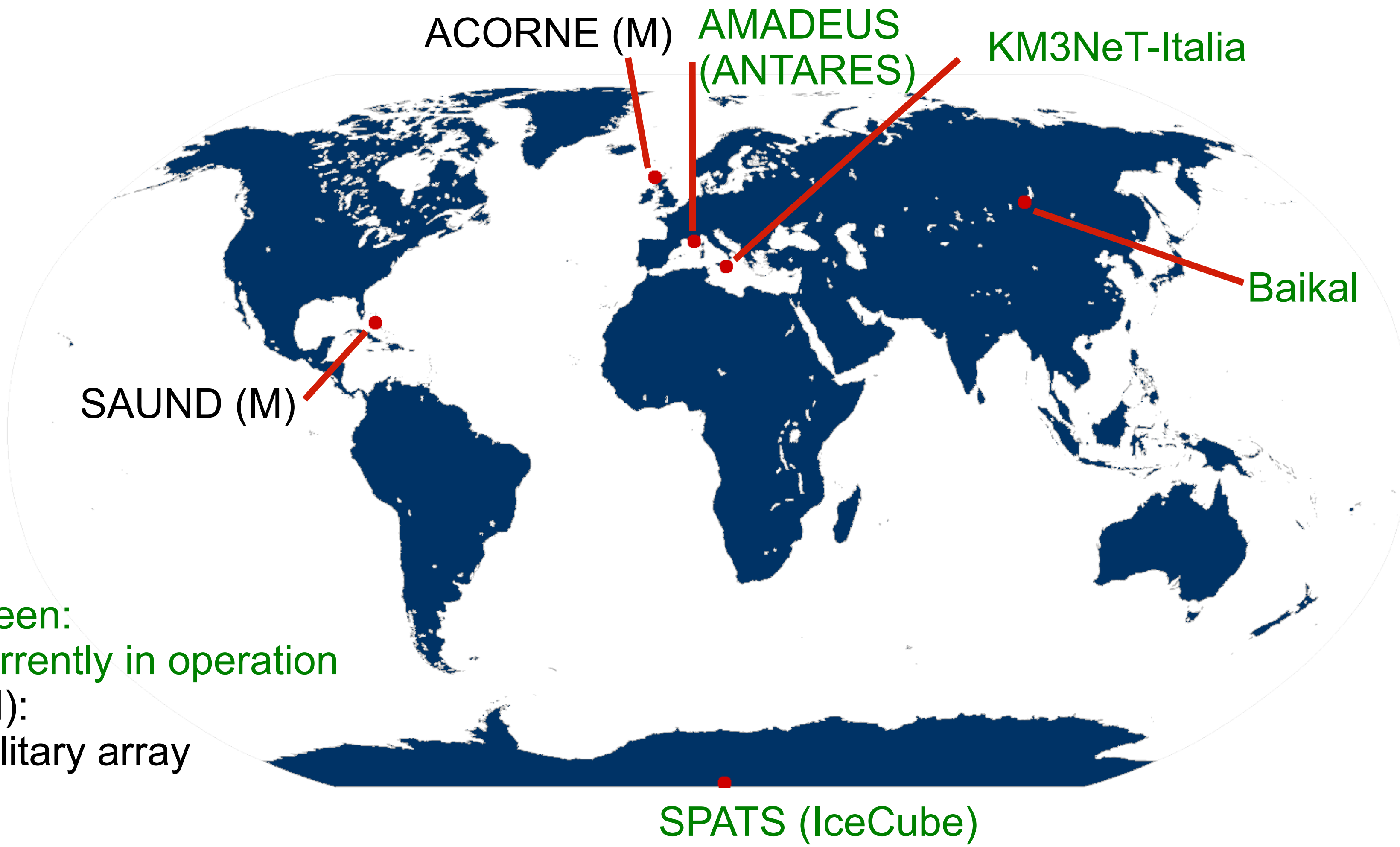
- “We can get access to an acoustic array; why not use it for some tests for acoustic particle detection?”
- “We have a neutrino telescope infrastructure; why not install some acoustic sensors to test acoustic particle detection?”

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

Array size:

O(10) sensors, used for feasibility studies (background), developing techniques/algorithms

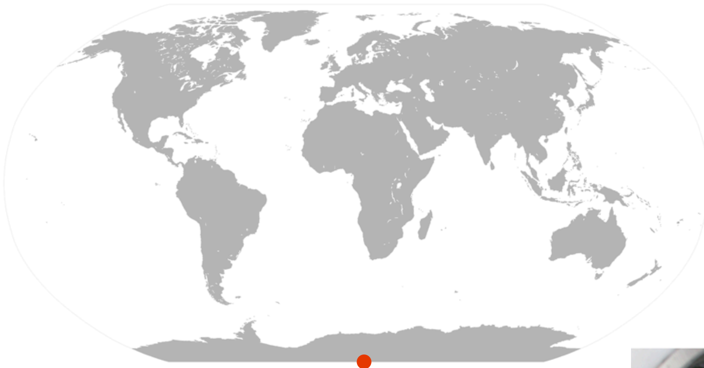
Test Setups in ice and water

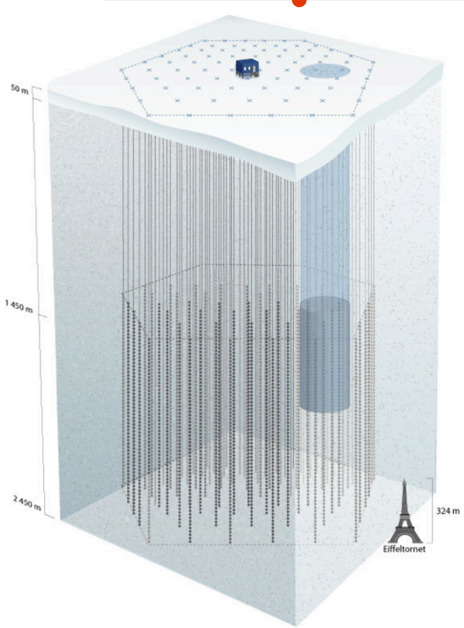


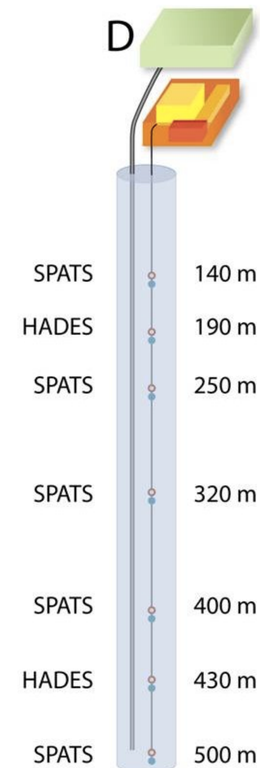
green:
currently in operation
(M):
military array

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

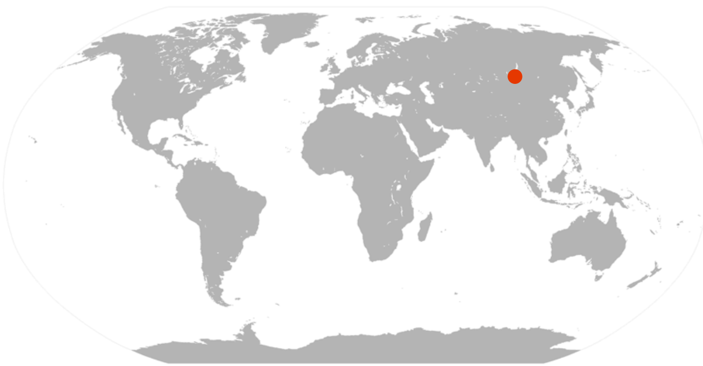


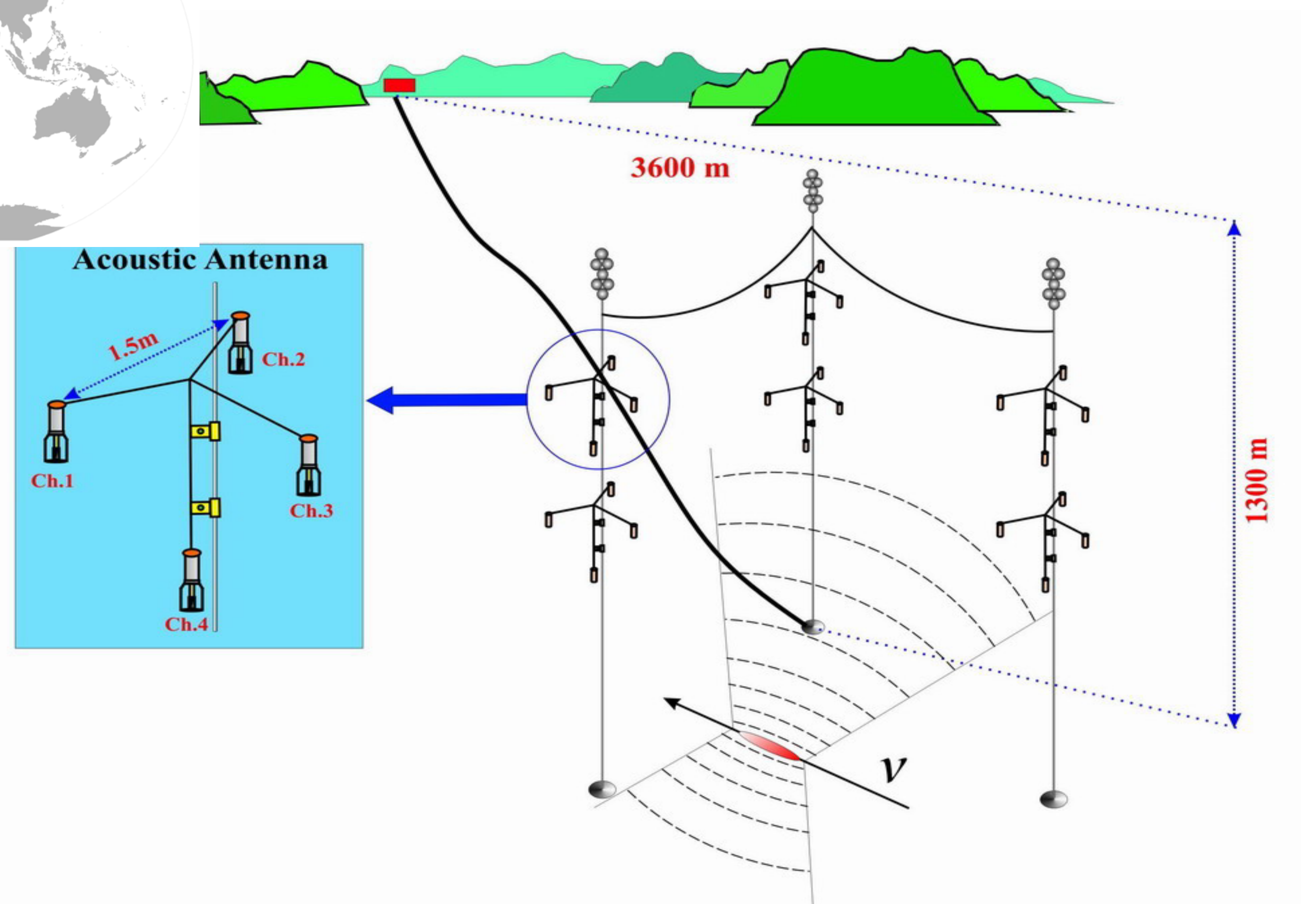




Lake Baikal

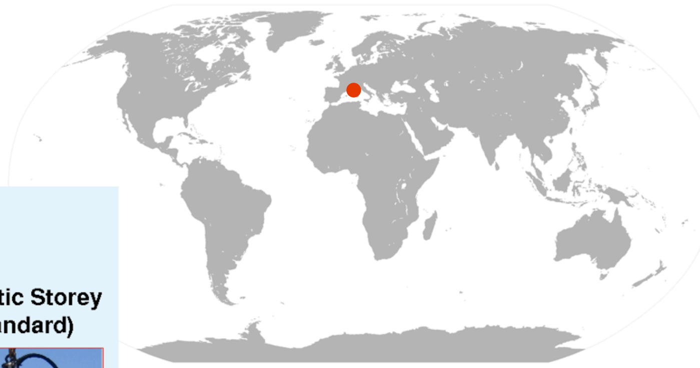
- Planned: 6 tetrahedral antennae with 4 hydrophones each in >500m depth
- Currently one antenna installed

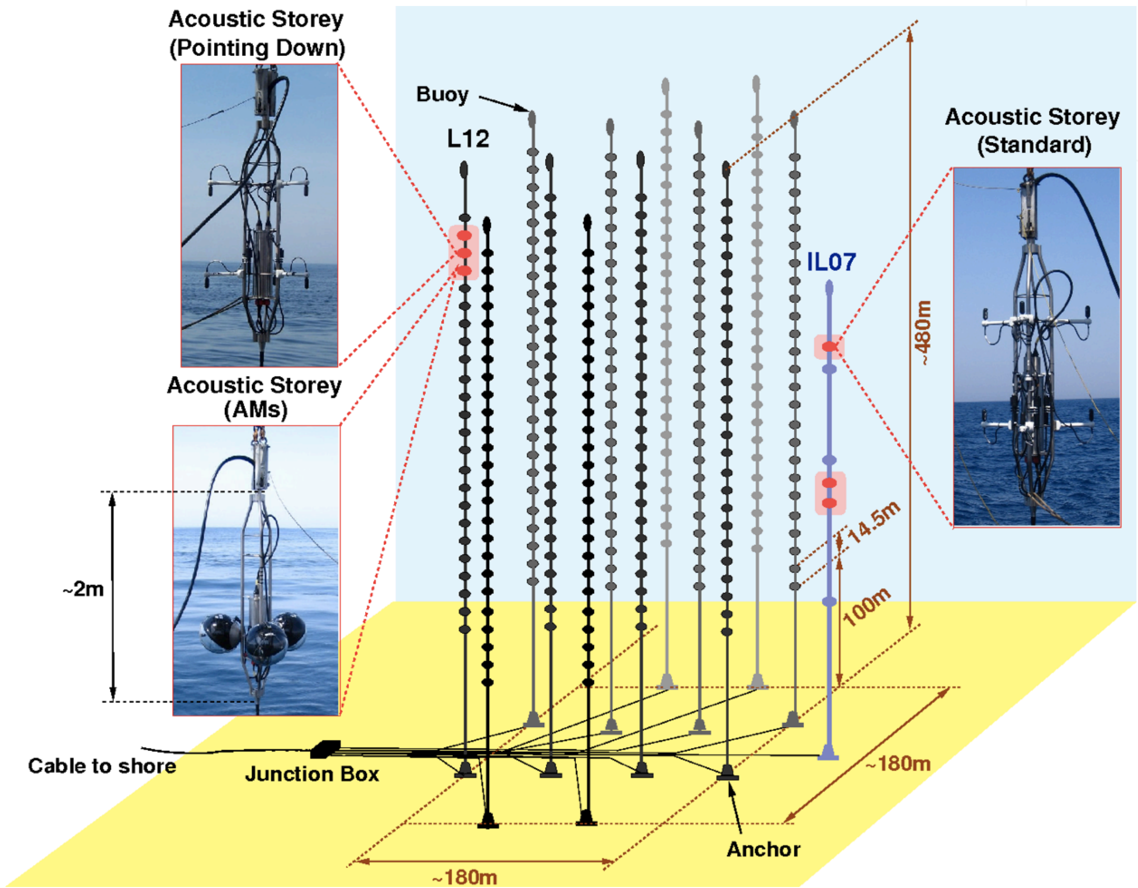




N. Budnev, ARENA 2014, Annapolis

AMADEUS – ANTARES





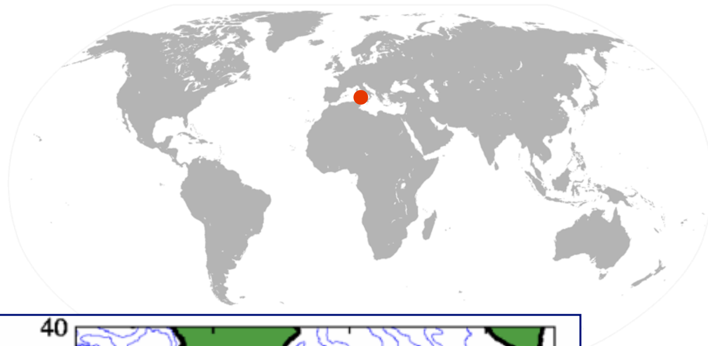
Operation started 2007

36 acoustic sensors on 6 stories

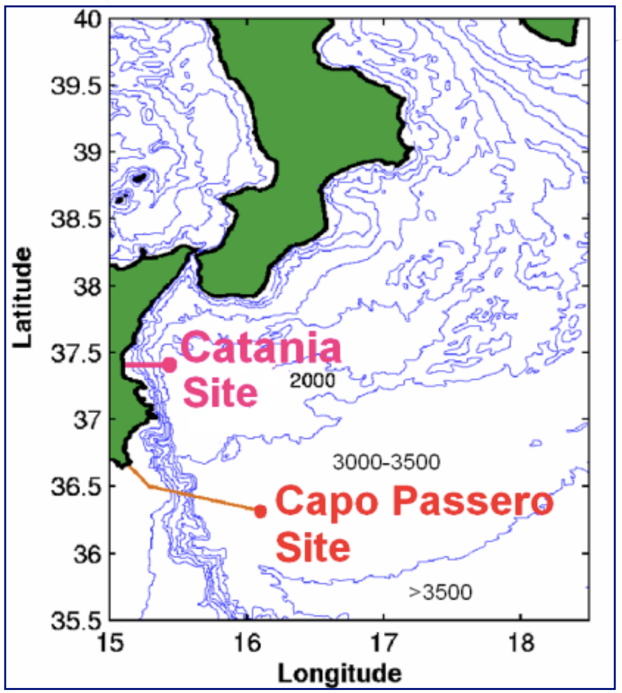
Local clusters for direction reconstruction

Depth 2300 – 2100 m

KM3NeT-Italia

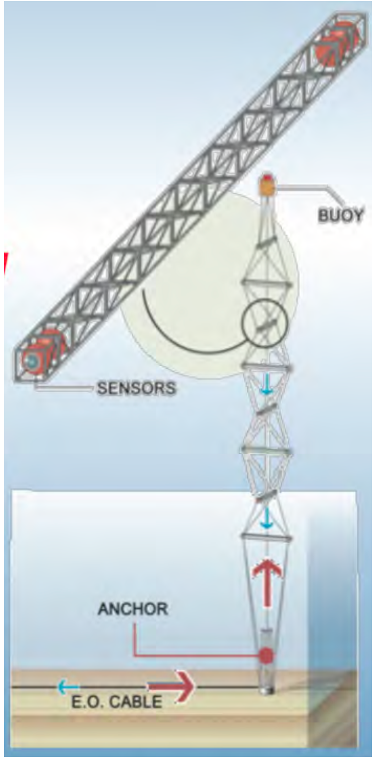


- Test Site at 2000 m depth, 25 km offshore Catania
- Operation of test setup OnDE (4 hydrophones) from 2005 -2006



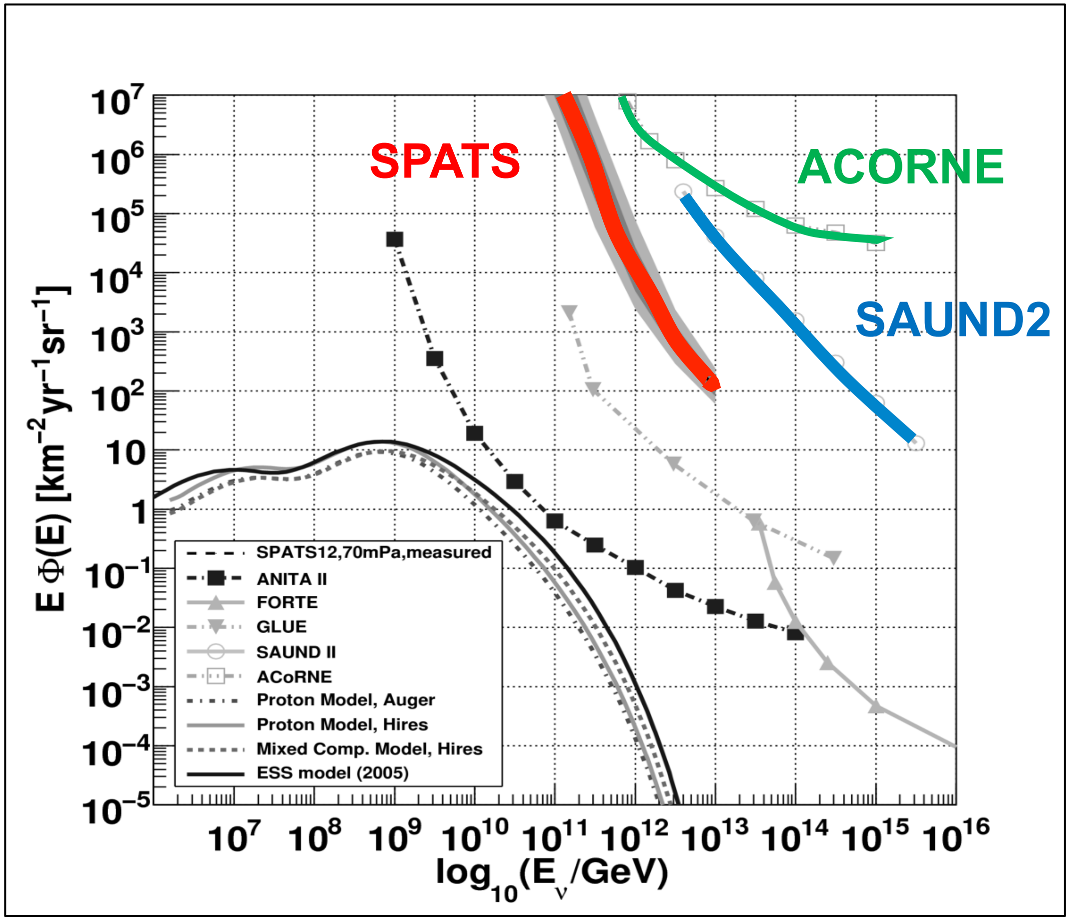
New structures deployed in context of KM3NeT-Italia:
8 “towers”
24 “strings”

(F. Simeone,
2013 Erice School
on cetacean echolocation
and outer space neutrinos)



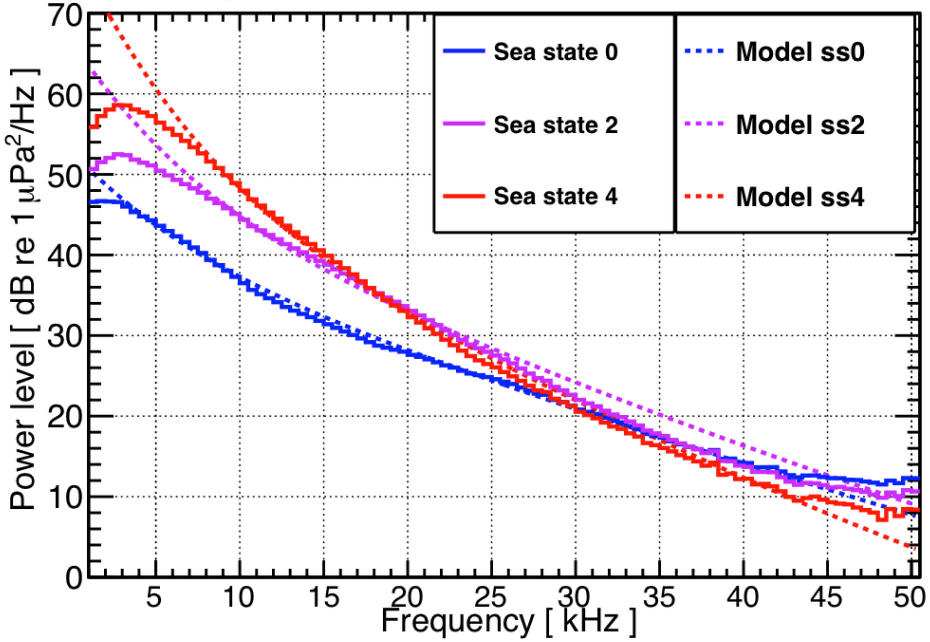
Acoustic Neutrino Detection: Status and Results

Limits on UHE neutrino flux

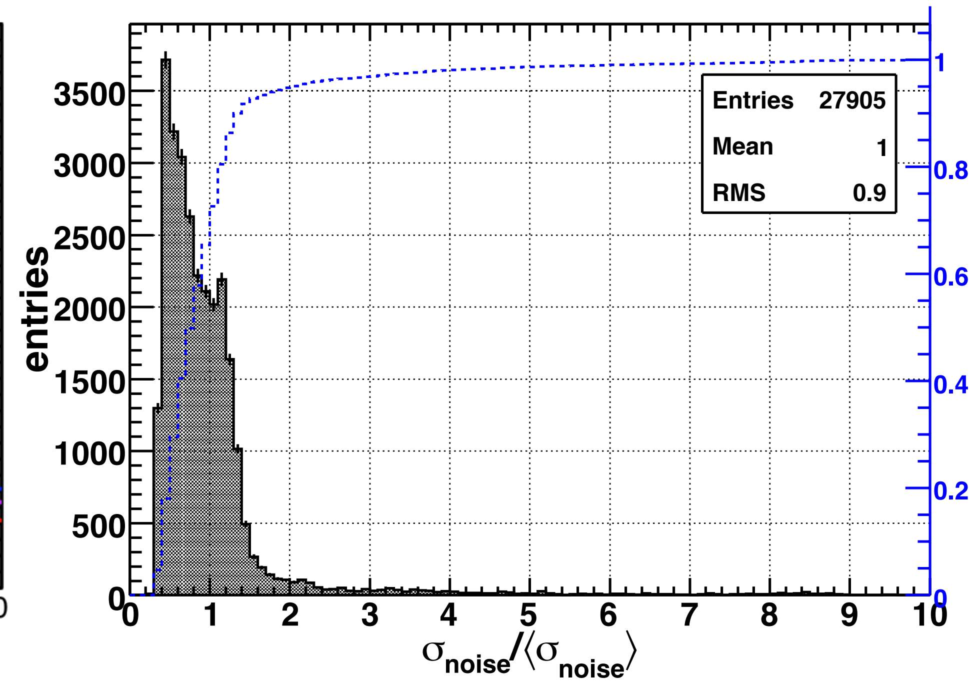


R. Abbasi et al.,arXiv:astro-ph/1103.1216; adapred from R. Nahnhauer, Ricap 2011

Noise measurements for AMADEUS site



D. Kießling, MSc Thesis (2013)



1 entry = noise level (f = 10 – 50kHz) of 10s of continuous data recorded every hour with one hydrophone (2008 – 2010 data) (R. Lahmann, ICRC 2011)

Background conditions in Mediterranean Sea well measured
⇒Input for Monte Carlo simulations

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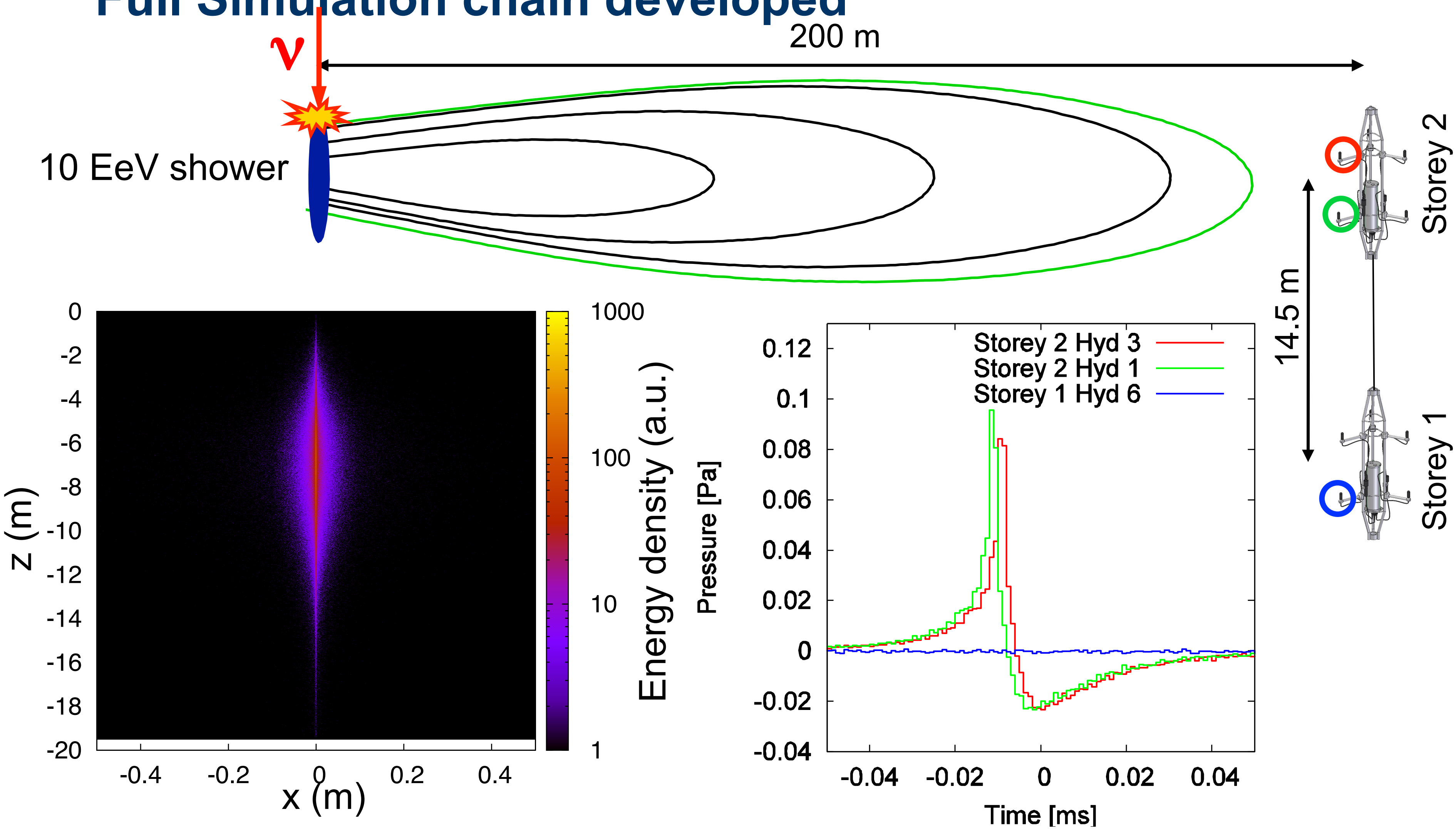
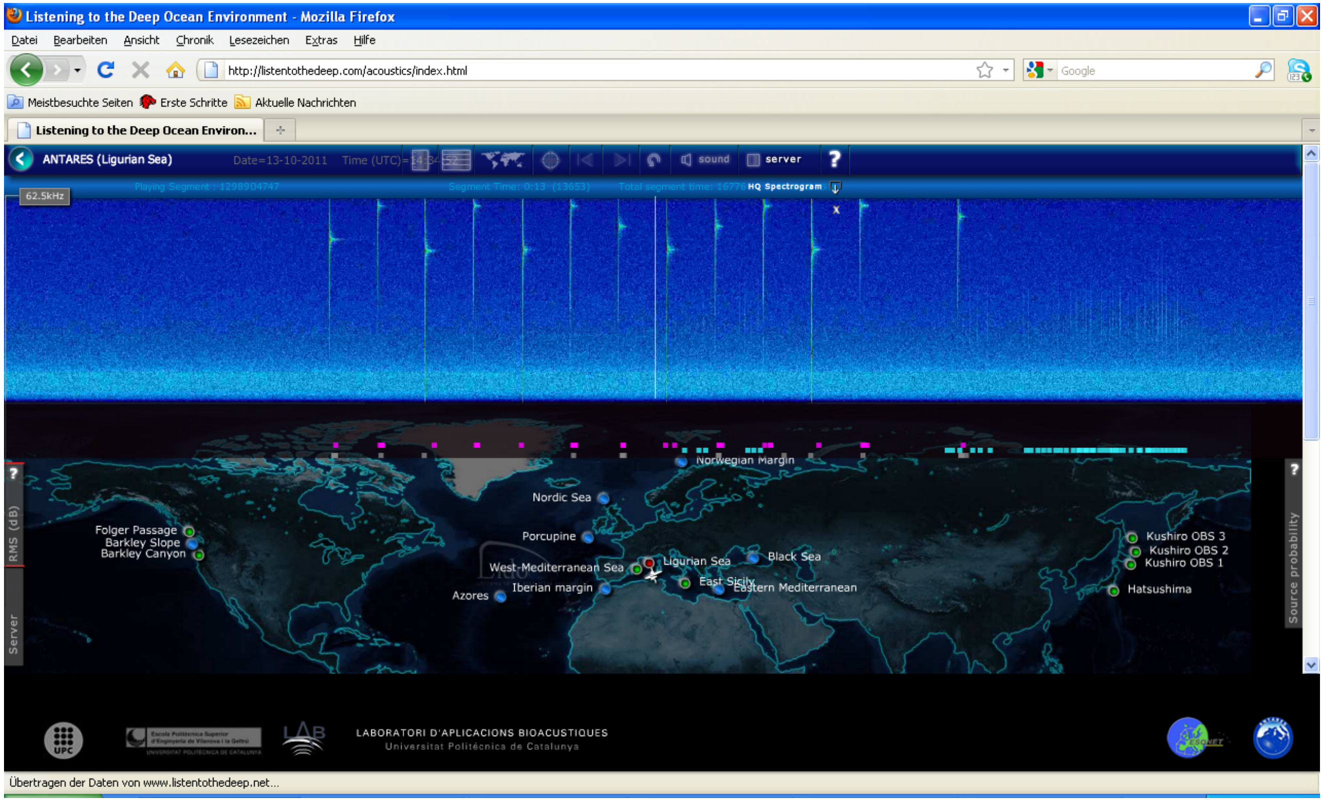
Full Simulation chain developed



MC according arXiv:0903.0949v2 to (Acorne Coll.)

Fruitful cooperation with marine science

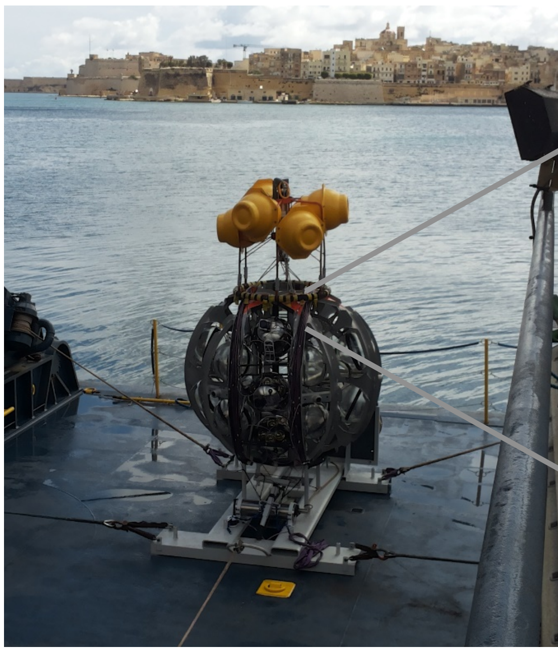
Life data from AMADEUS setup at http://listentothedeep.org/
(Maintained by University of Barcelona)



The Future: KM3NeT

KM3NeT string design

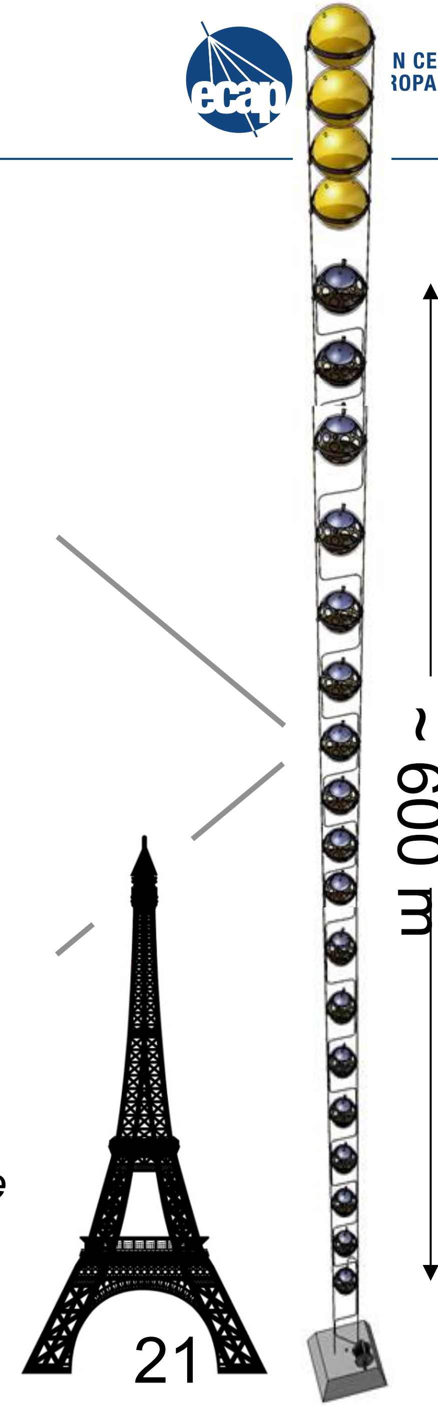
Launcher vehicle



– *rapid deployment*
– *autonomous unfurling*
– *recoverable*

Optical module

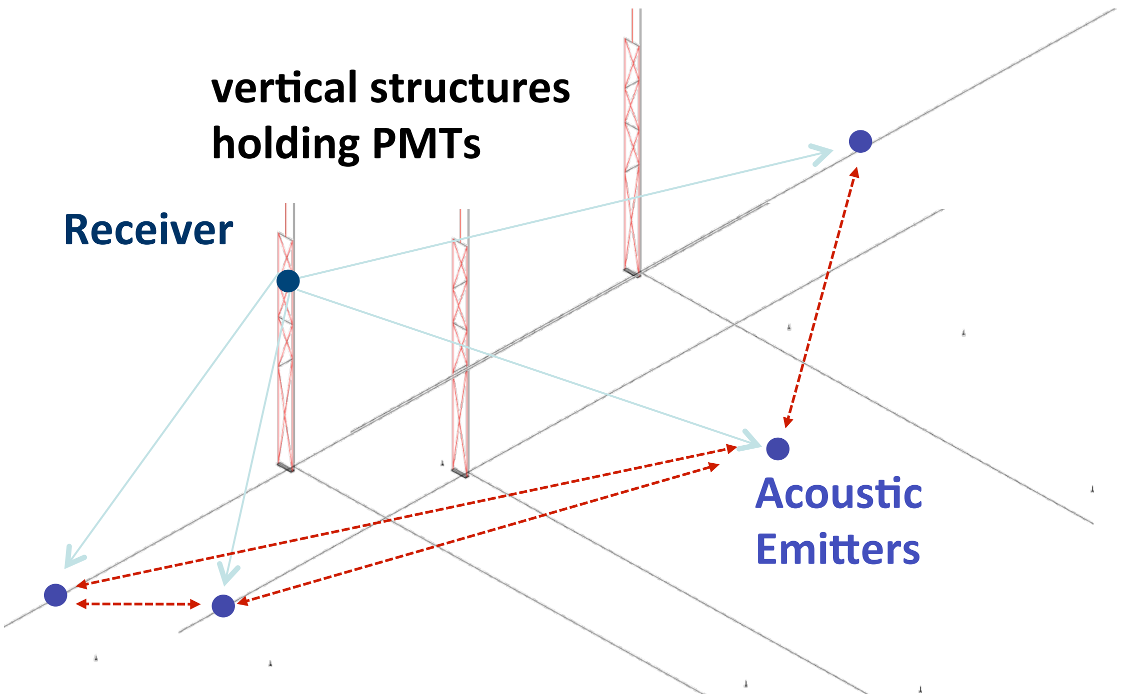
– *31 x 3” PMTs*
– *low-power HV*
– *LED & piezo inside*
– *FPGA readout*
– *White Rabbit*
– *DWDM*



M. de Jong, Neutrino 2014, Boston

Positioning in deep sea Cherenkov neutrino telescopes

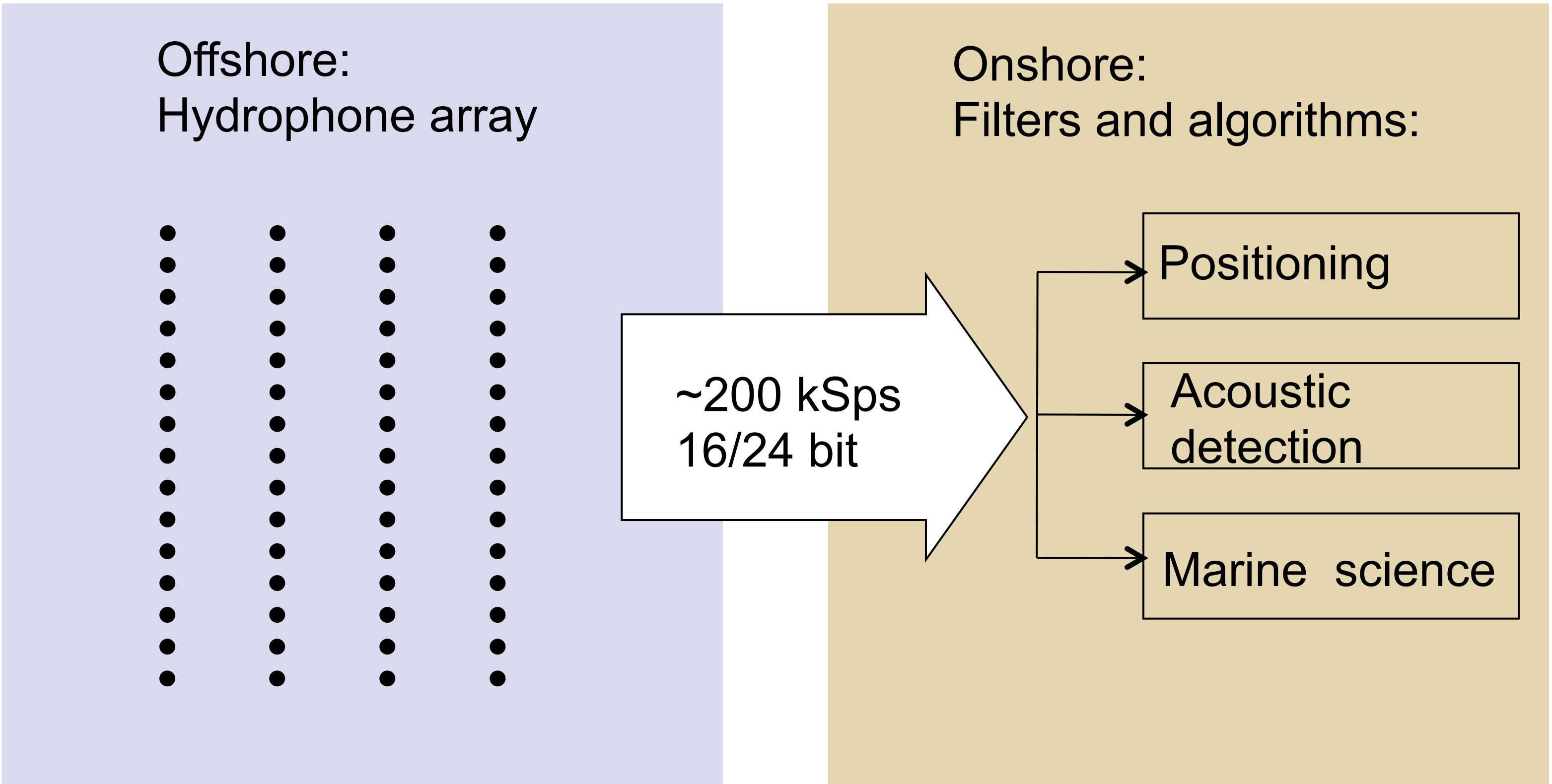
Movement of Optical Modules with deep sea currents needs to be monitored



Deep Sea Neutrino Telescopes always contain acoustic sensors for position calibration

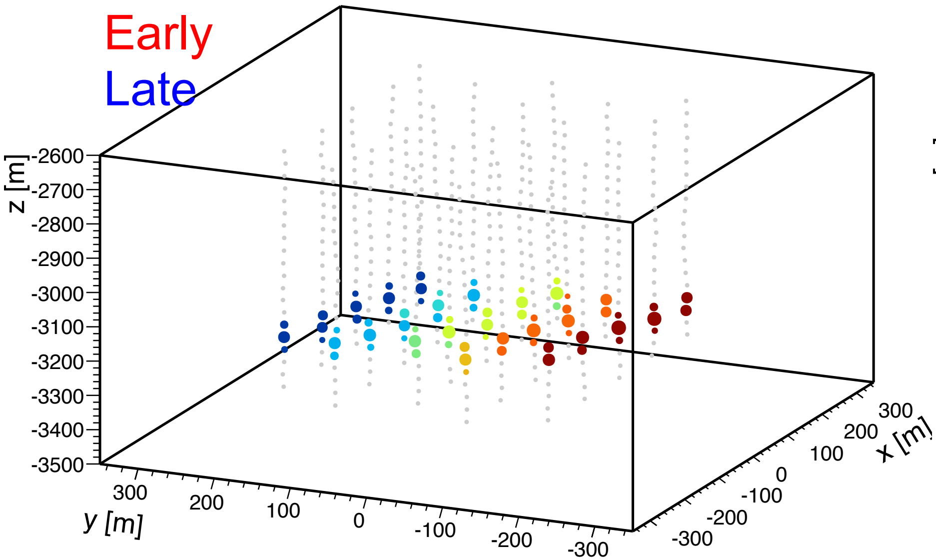
Principle of future deep sea acoustic test arrays

The obvious thing to do: All data to shore

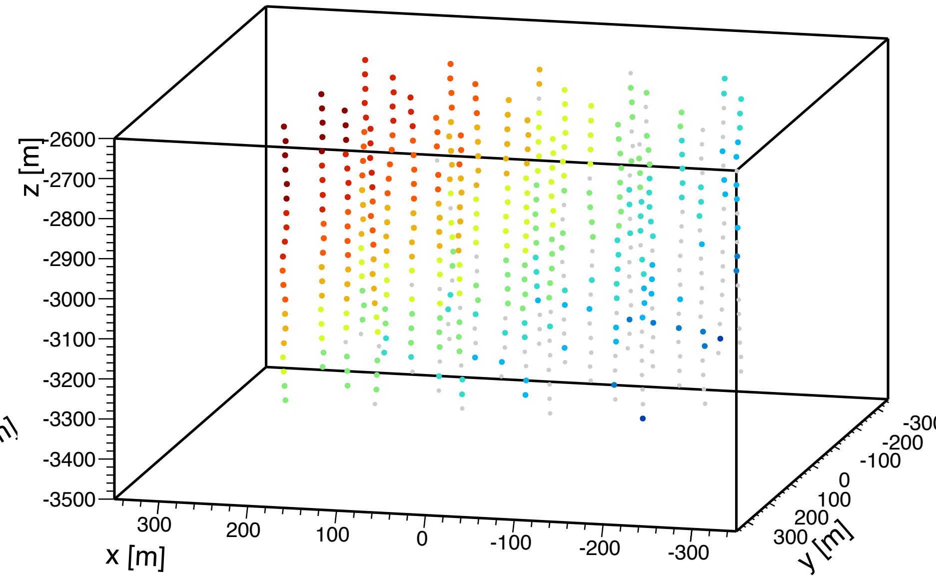


Simulated events

Neutrino @ 1.8 km, E=10^{21}eV, Θ=16°

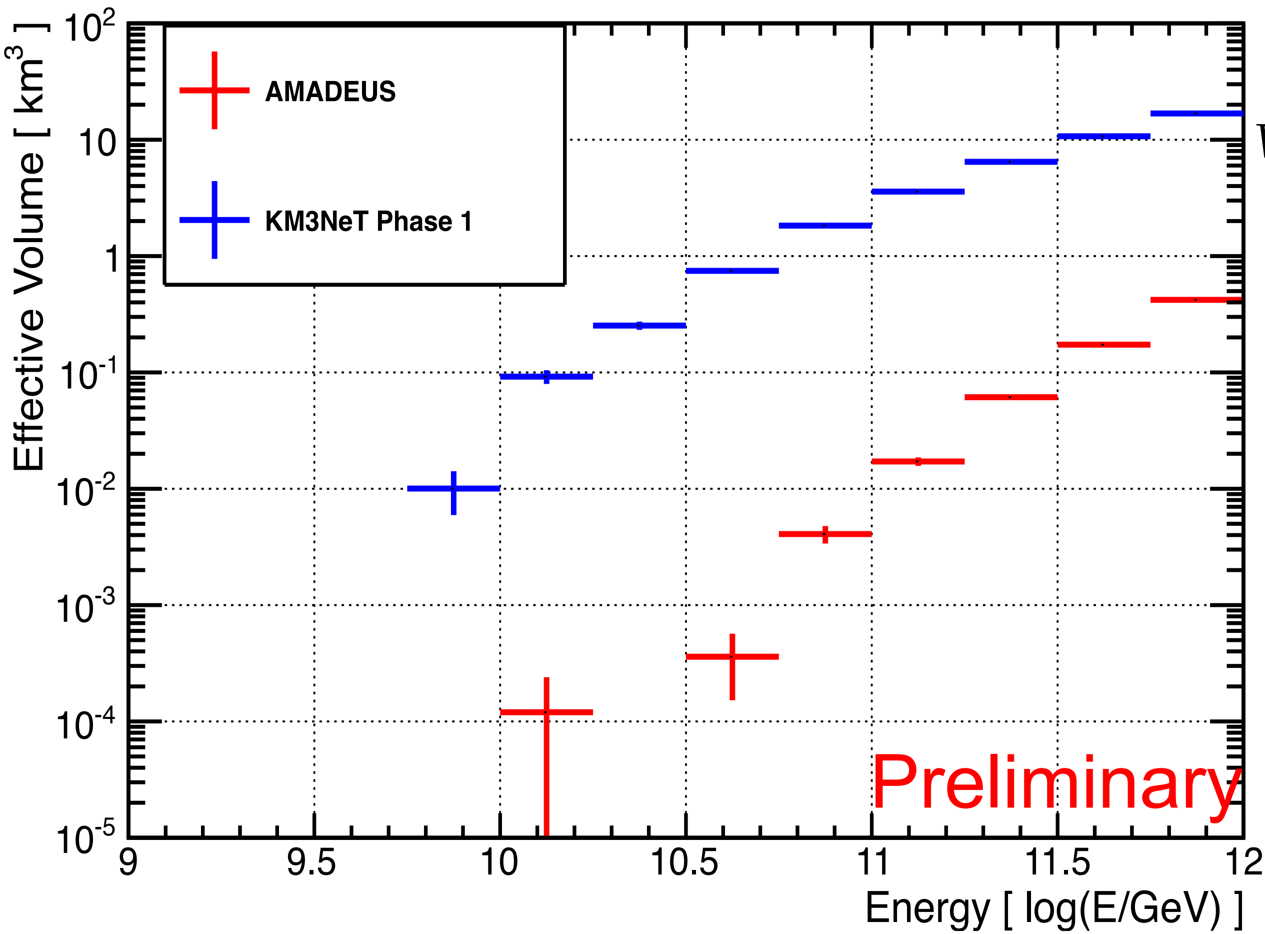


Spherical background (e.g. ship)



- Neutrinos (Energy 10^{19} – 10^{21} eV)
- Signals from the positioning system
- Spherical sources
- Random coincidences

Effective volume for acoustic detection



$$V_{\mathrm{eff}} = \frac{\sum p(\mathrm{E}, \mathbf{x}, \mathbf{e}_p)\delta_{\mathrm{sel}}}{N_{\mathrm{gen}}} V_{\mathrm{gen}}$$

Noise: 15 mPa
Min. SNR: >2
Min. #Sensors: 6

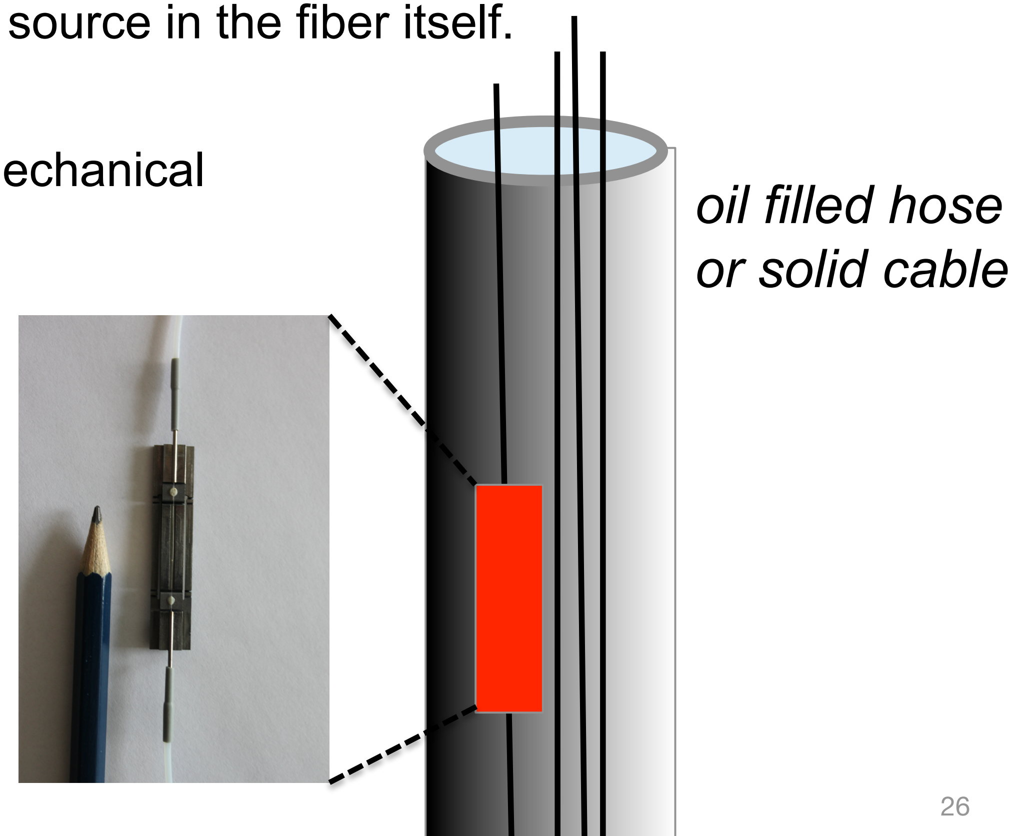
Fiber hydrophone system

- Erbium doped fibers with a grating
  - Pump laser λ=980 nm, Erbium induced emission light λ=~1550 nm.
  - Fibers are locally doped with Erbium in a gratingstructure. This results in an extremely <u>coherent light</u> source in the fiber itself.
- Sensor

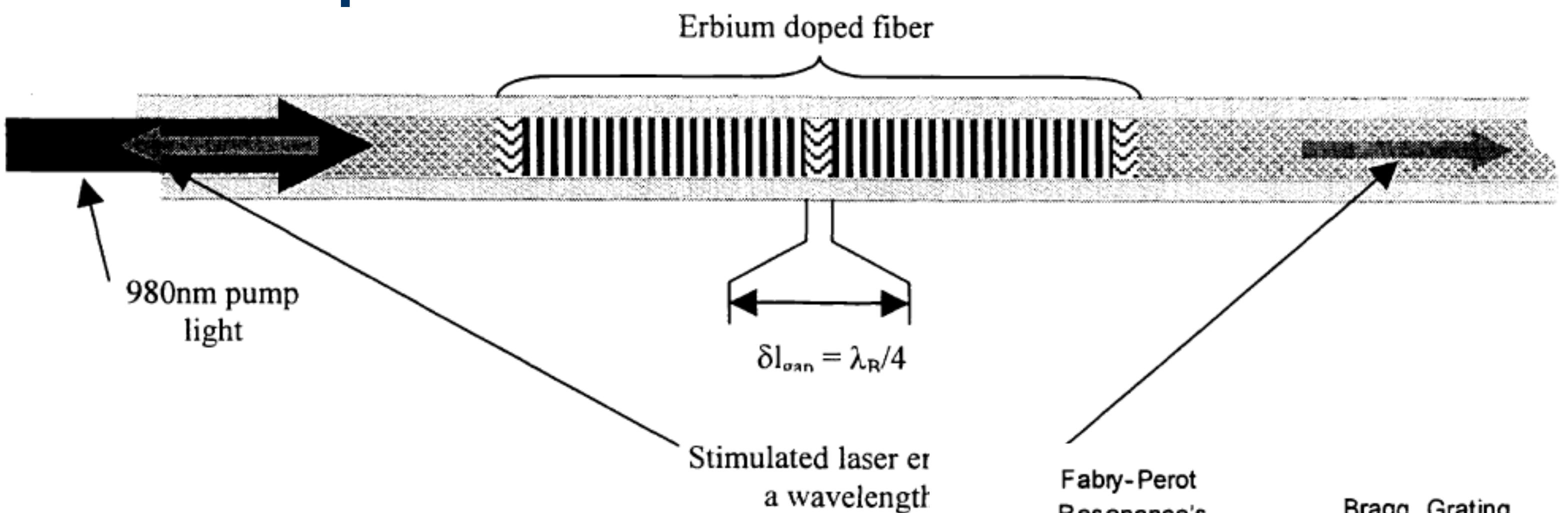
  Convert pressure pulse to a mechanical deformation of the fiber: <u>strain</u>
- Interrogator

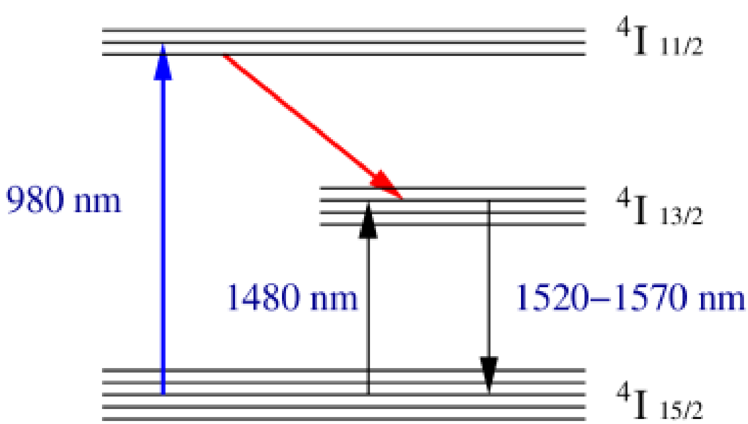
  on-shore system

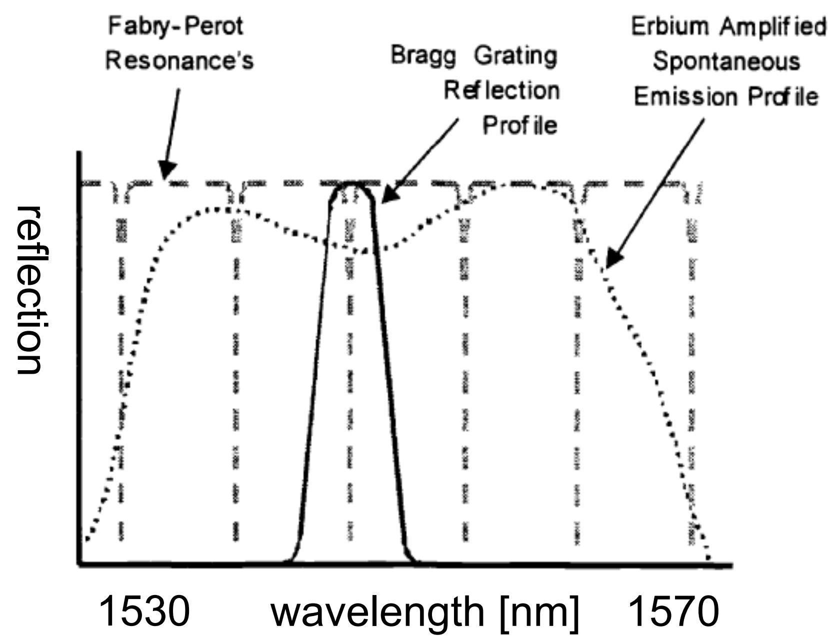
TNO (Netherlands organization for applied scientific research) joined KM3NeT to pursue this technique



Erbium doped fibers







Conclusions and Outlook

- Acoustic neutrino detection is a promising technique for the detection of neutrinos at ultra-high energies
- A number of first generation acoustic neutrino detection test setups have proven the feasibility of the technique and measured background conditions
- KM3NeT provides an excellent framework for a second generation acoustic detection test setup “for free”
- New concepts (fiber based hydrophones) may eventually lead to a “real” acoustic neutrino detector

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Thank you for your attention

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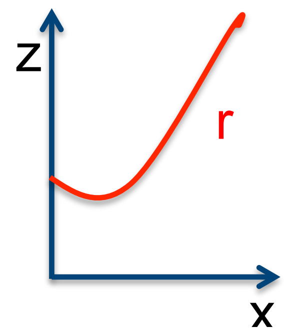
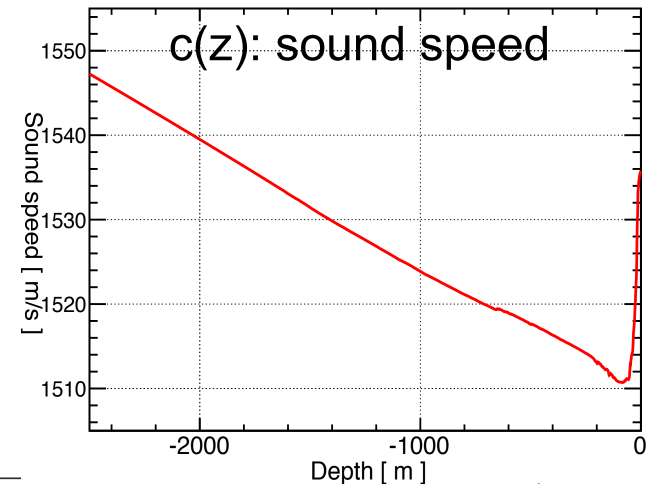
Backup slides

Influence of curved sound paths on simulations

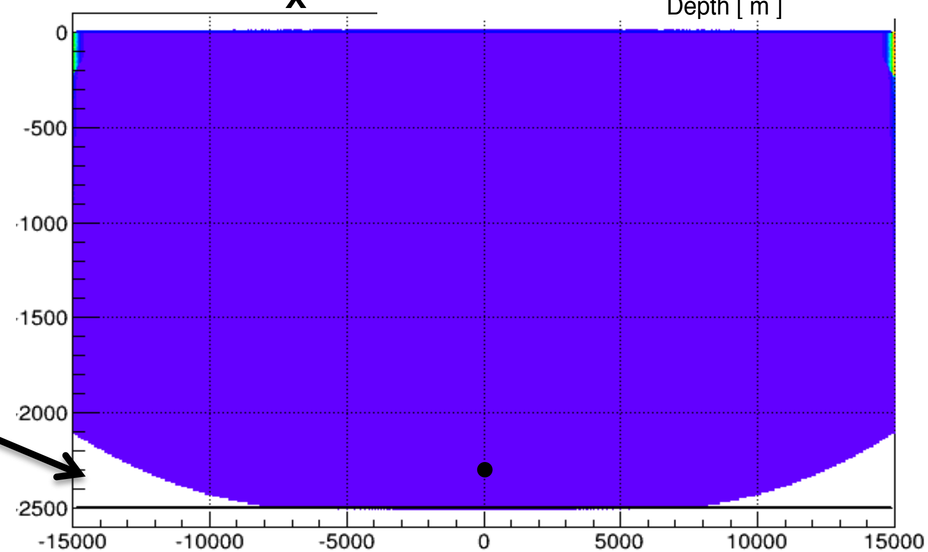
- Sound path is bent towards lower speed (upwards for the deep sea)
- Path r determined by:

$$\frac{\partial^2 r}{\partial x^2} = -\left(1+\left(\frac{\partial r}{\partial x}\right)^2\right)\cdot\frac{\partial c}{c\cdot\partial z}$$

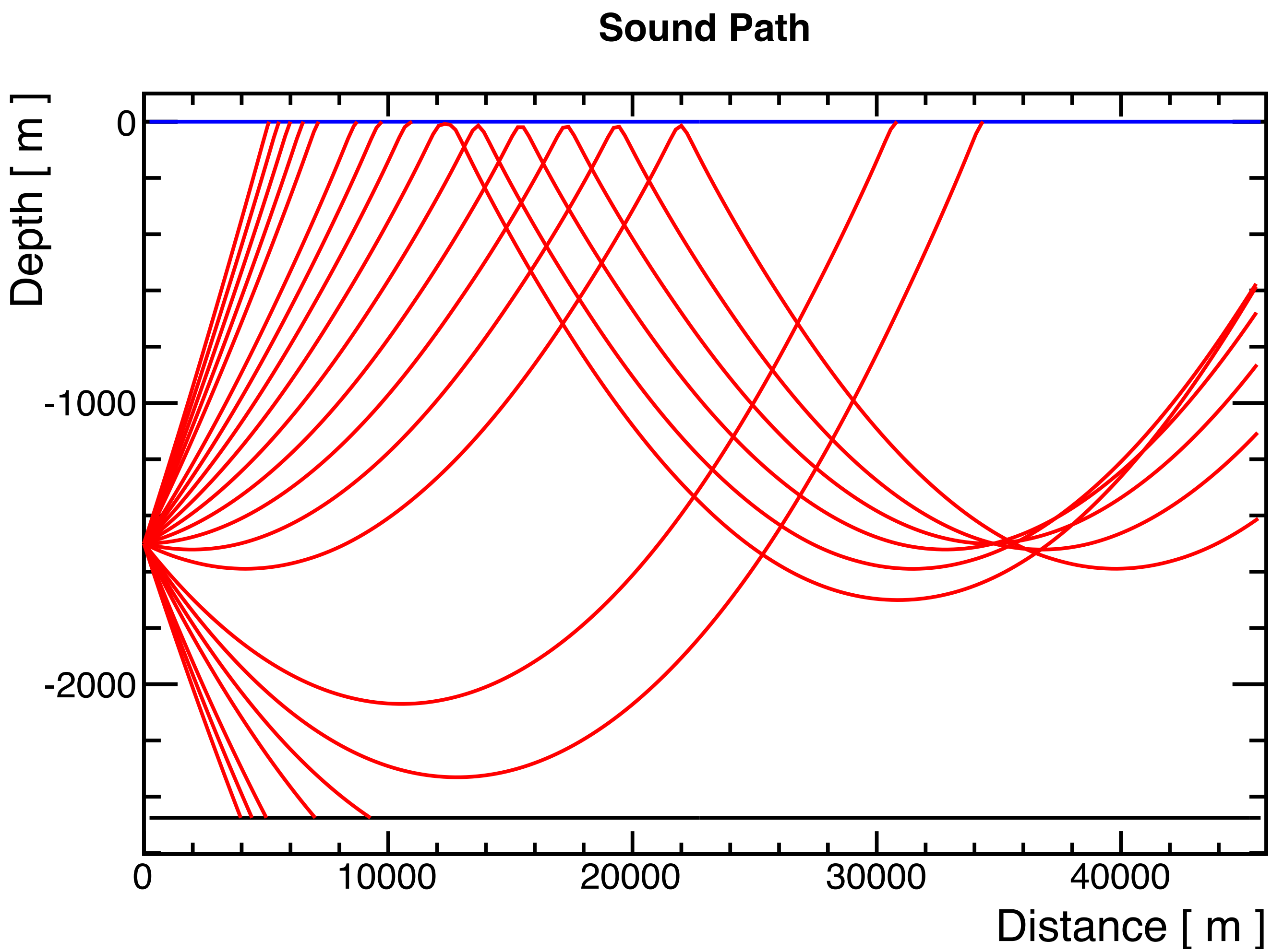




- Requires ray tracing: 100.000 times slower than with straight paths
- Refraction leads to a blind space for hydrophones



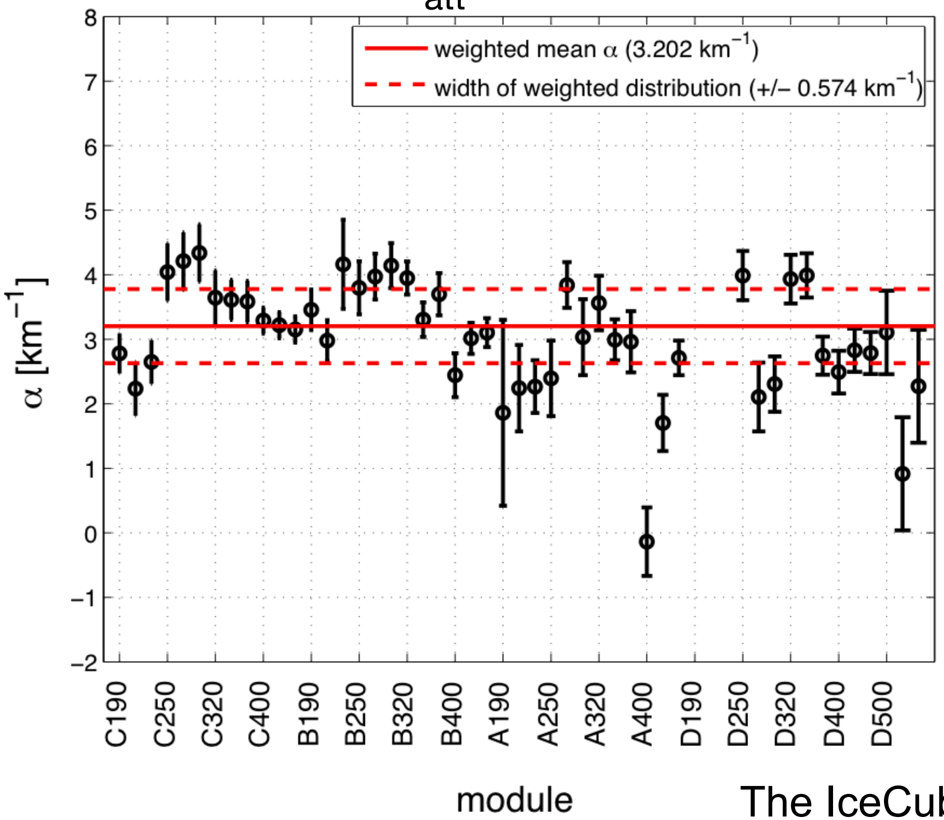
Sound path (long distance)

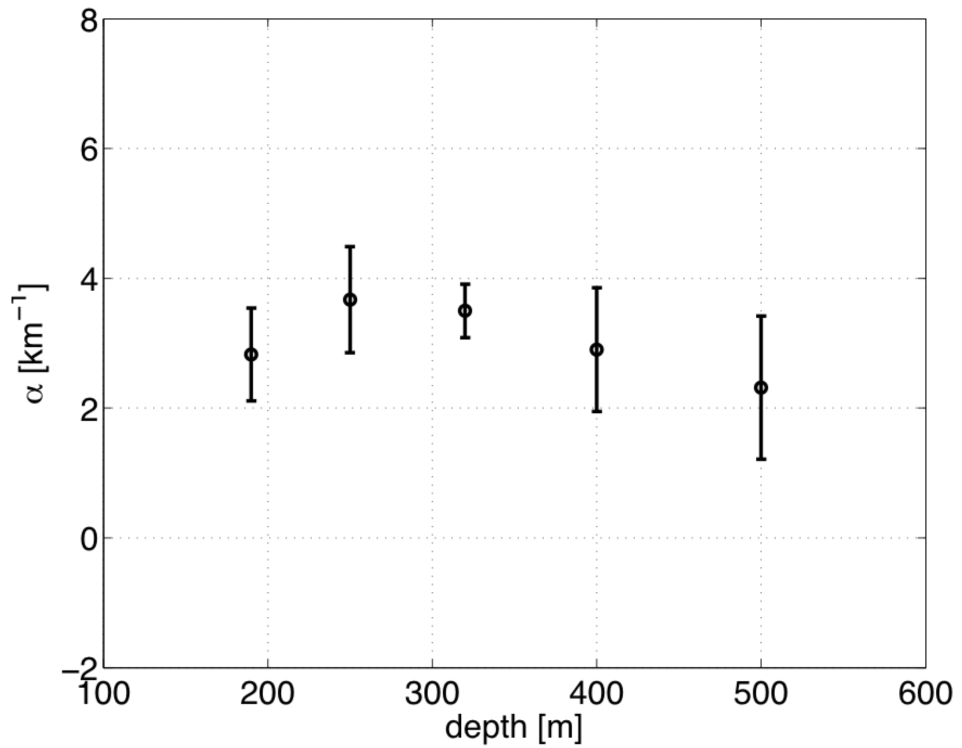


Attenuation in Ice

prediction from Rayleigh scattering and absorption on thermal phonons: λ_{abs} > 1km (5km)

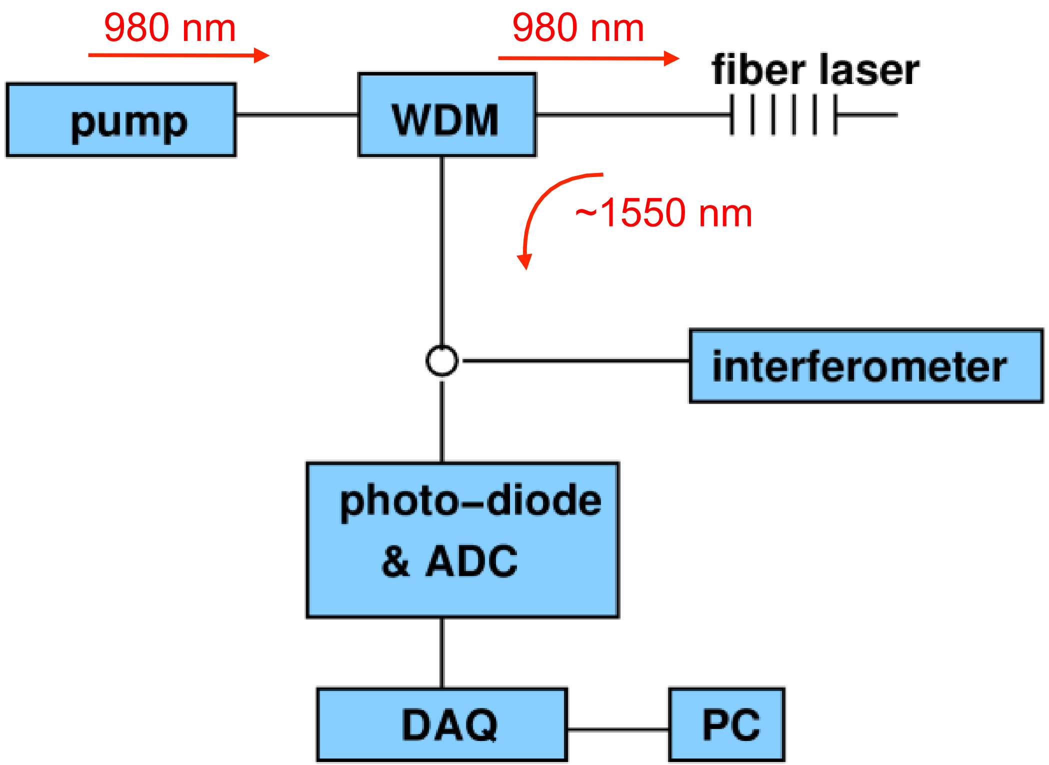
measured: $\lambda_{att} \approx$ 300m





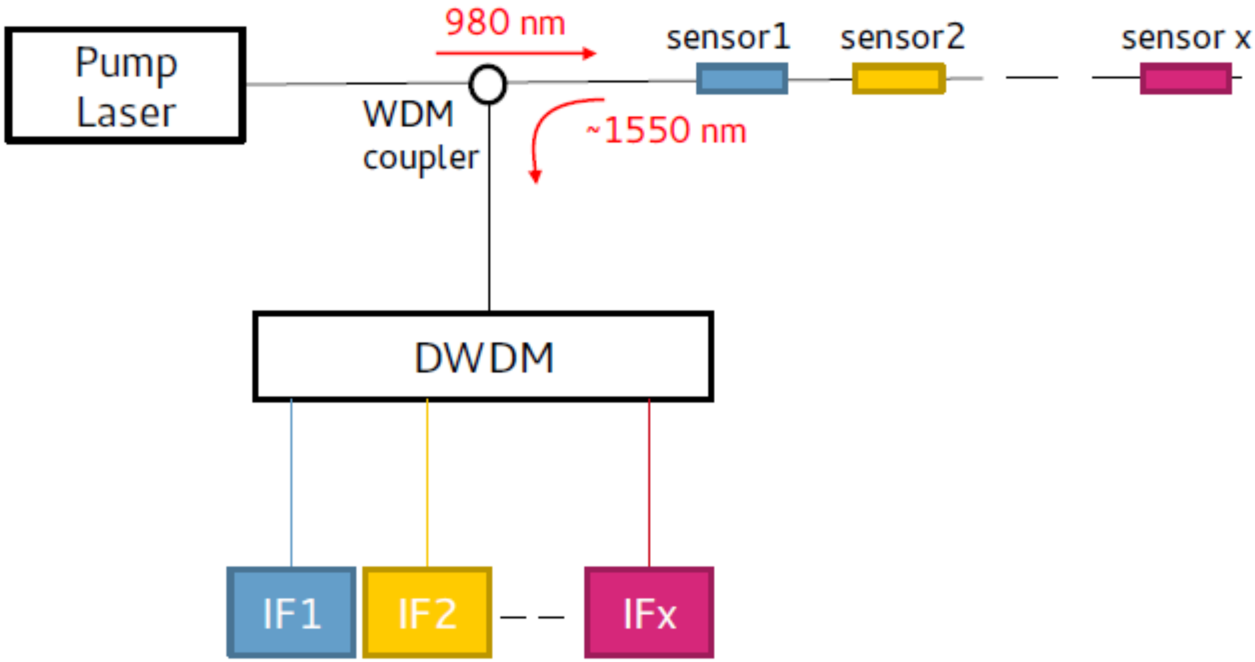
The IceCube Coll., Astropart.Phys. (2011)

Interrogation system



- A fiber is used to read out an interrogator.
- Pump laser power ~100 mW
- Received power ~10 μW

Interrogation system: multiplexing



- Include multiple sensors with each a specific grating structure
- Multiplexing with up to 10 sensors/fiber.