Simulation chain and signal classification for acoustic neutrino detection in sea water

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Overview

- aim: compare sensitivities of different detector configurations
- use Mediterranean Sea as an example
  (based on measurements from/around AMADEUS)
- adaptable software approach (modular SeaTray software, based on IceTray)

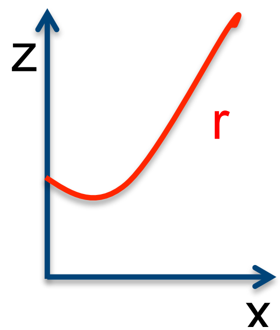
Content:

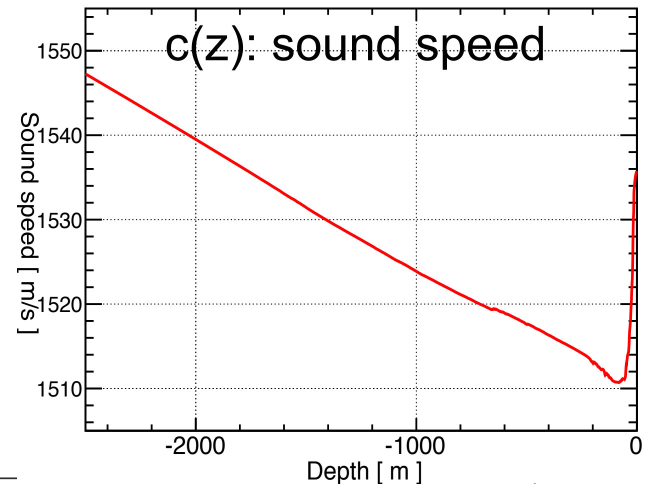
- Effects of refraction on the simulation
- Simulation using parameterizations
- Full simulation chain
- Signal classification

Influence of curved sound paths on simulations

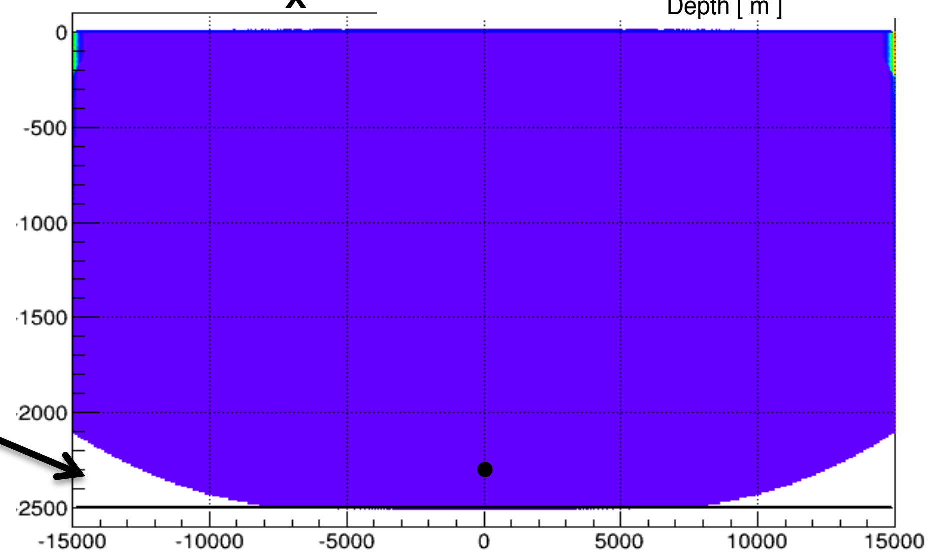
- Sound path is bent towards lower speed (upwards for the deep sea)
- Path r determined by:

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

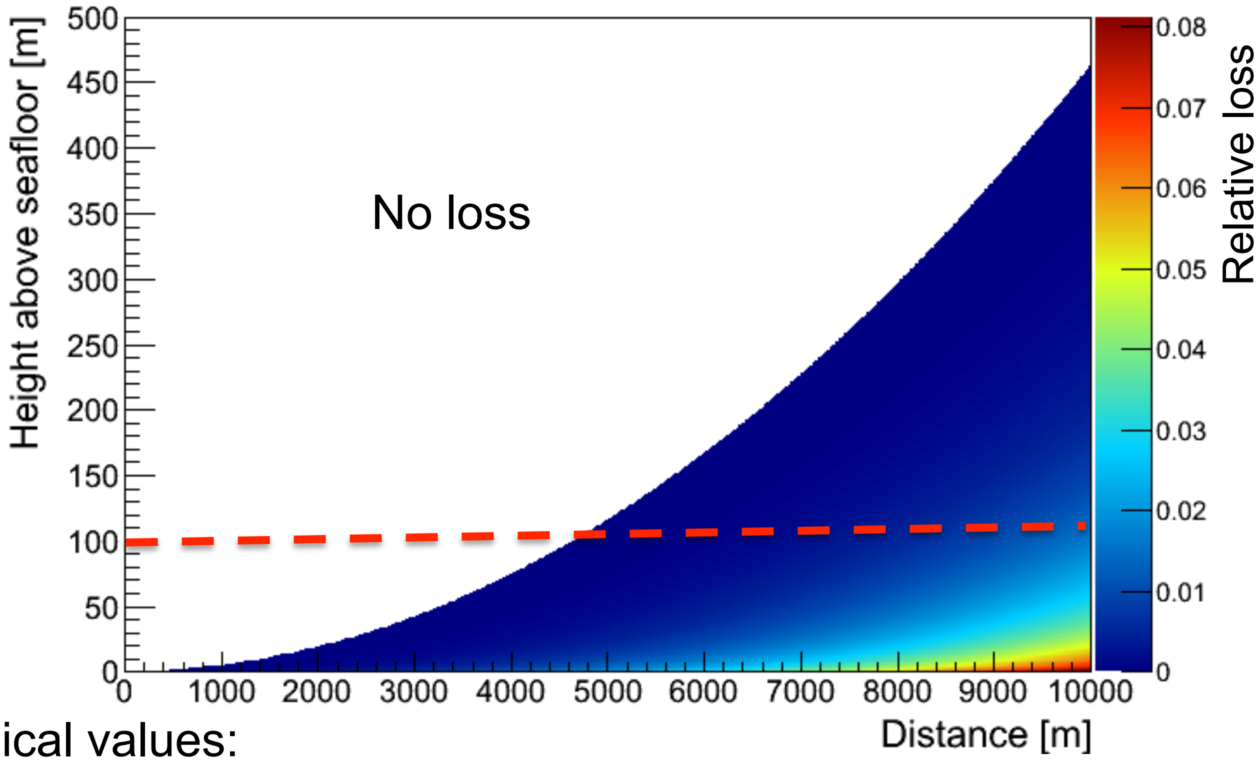




- Requires ray tracing: 100.000 times slower than with straight paths
- Refraction leads to a blind space for hydrophones



Loss of effective volume



Typical values:

- Hydrophone mounted > 100 m above seafloor

➡ No significant impact on the effective volume derived from simulations
Use straight propagation to save time

Approaches towards simulation

Simulation consists of several modules in a framework (SeaTray)

➡ Modules are easy to replace/reuse

Full simulation:

- Generate waveform & noise sample
- Full DAQ/Trigger simulation
- Deriving flux limits, developing analysis methods etc.

➡ Requires a lot of CPU time (> 10s/event)

Using parameterizations:

- Very fast (1 ms/event), providing an estimate of the detector performance

Simulation with parameterizations

Particle Generator

↓

Parameterization of the pressure amplitude, attenuation and ambient noise

↓

Coincidence Trigger

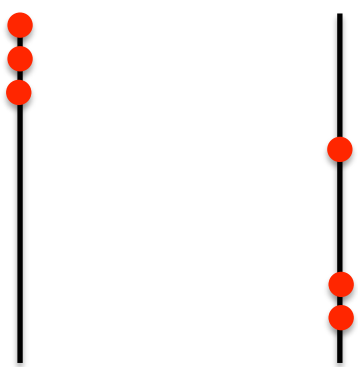
➡ Allows quick assessment of a detector layout (~day)

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

Comparing different detector setups

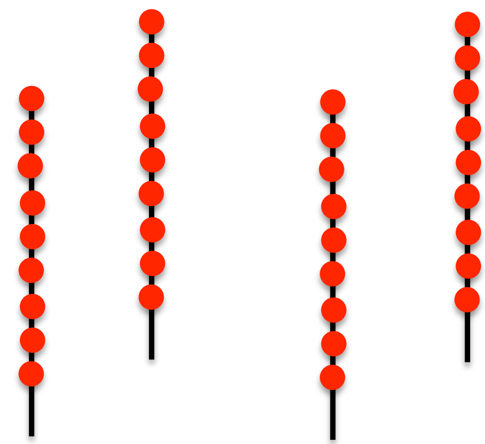
AMADEUS

- 2 lines, 230m apart
- 3 floors/line, 14.5 – 100m
    - 6 hydrophones/floor



KM3NeT Phase 1

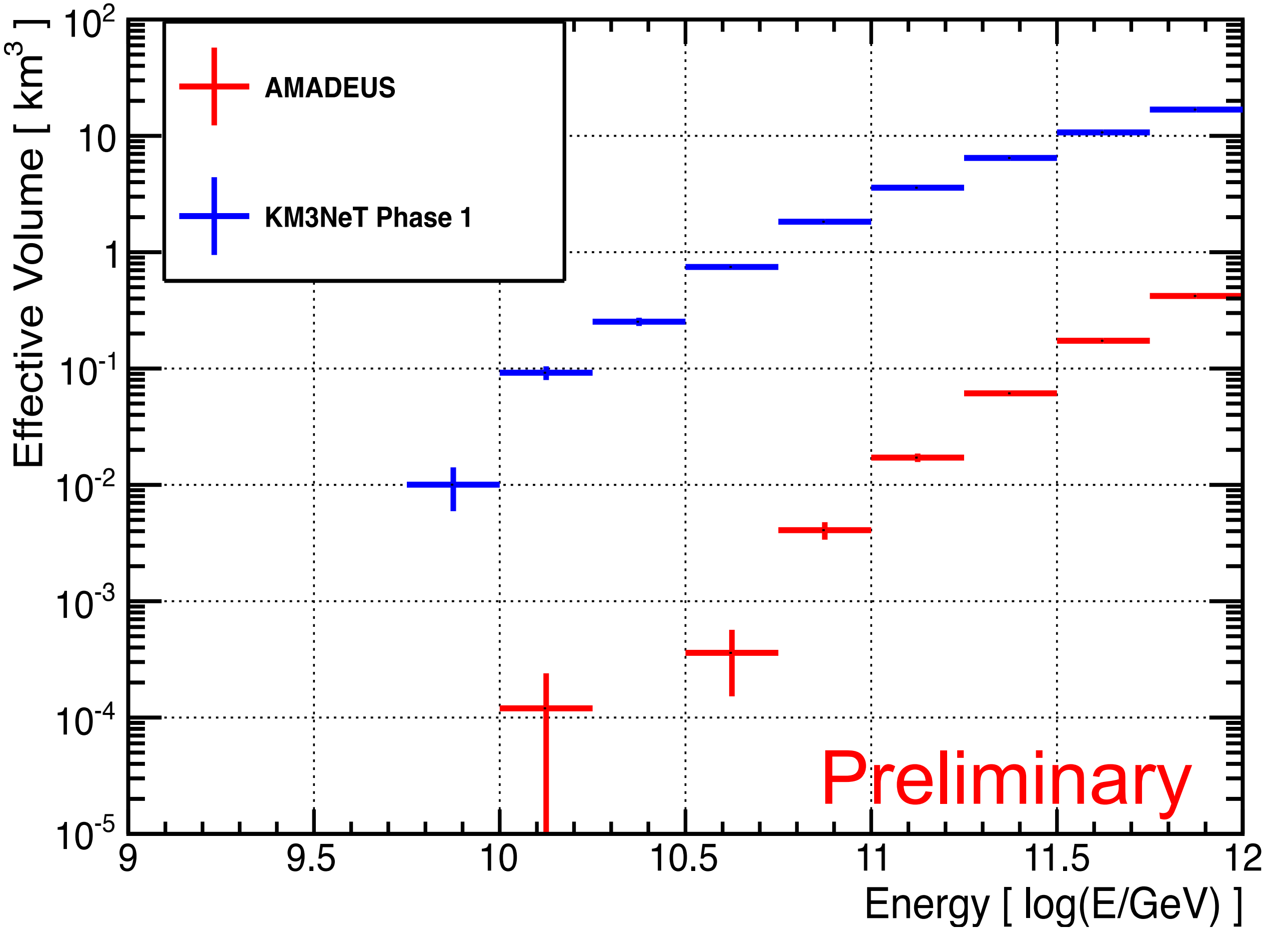
- 24 lines, 100m apart
- 18 optical modules/line, 36m
    - 1 acoustic sensor/module



Comparing apples and oranges:

- 2D setup vs. 3D setup
- Different number of sensors per cluster

Effective volume for acoustic detection



Amplitude @200m:

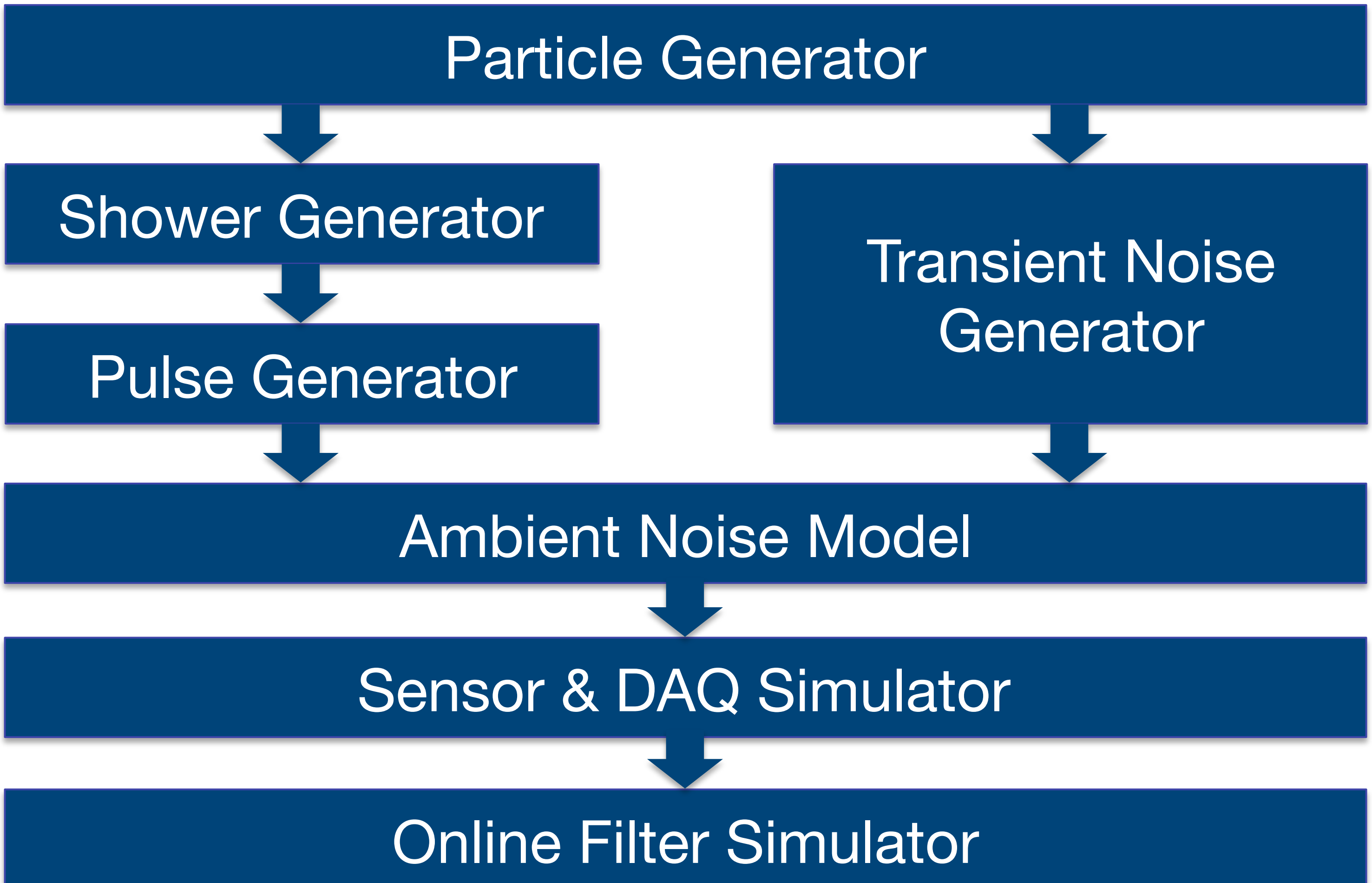
$$100 \frac{mPa}{EeV} \times E_{Shower}$$

Noise: 15 mPa

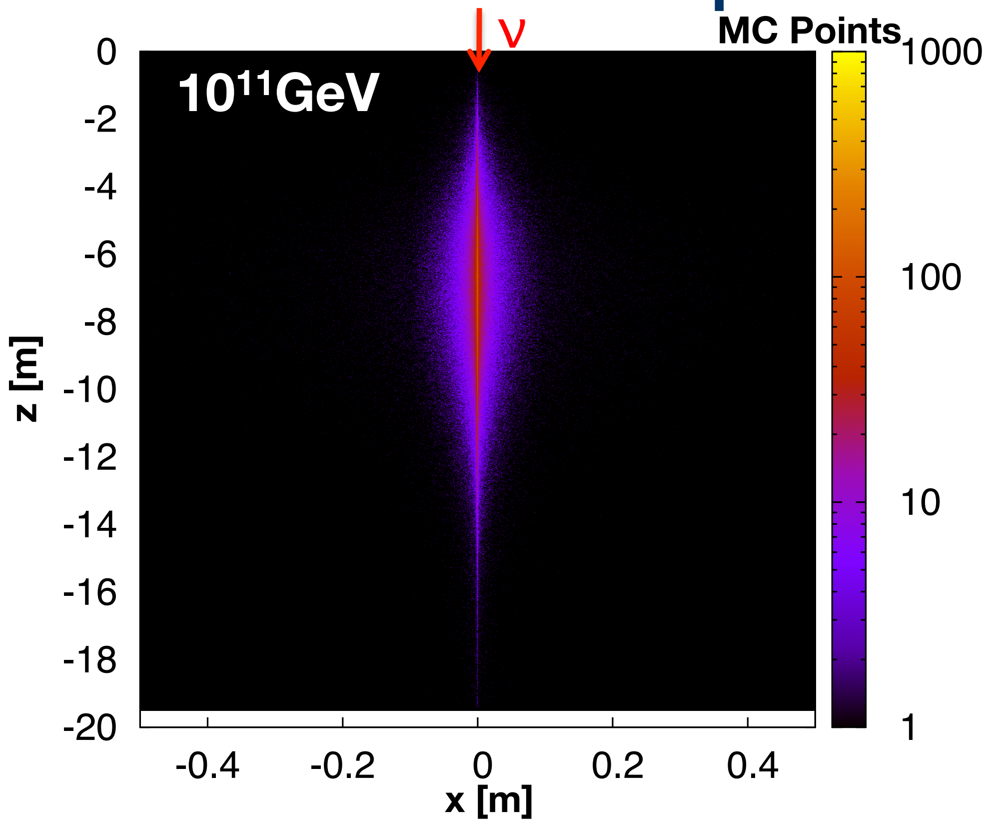
Min. SNR: >2

Min. #Sensors: 6

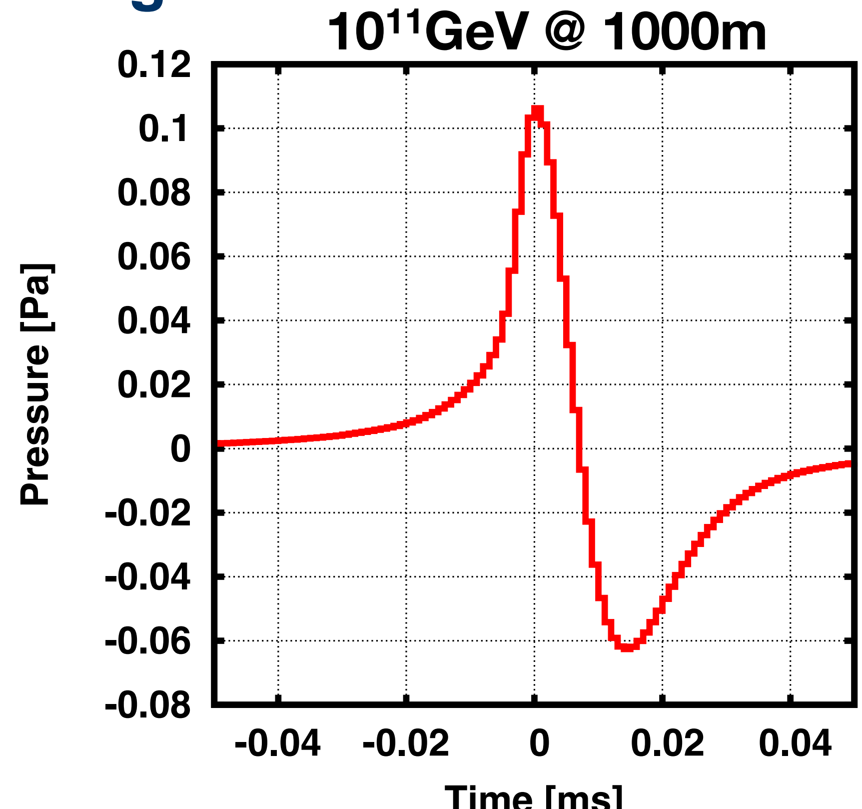
Simulation chain modules



Shower & Pressure pulse modeling

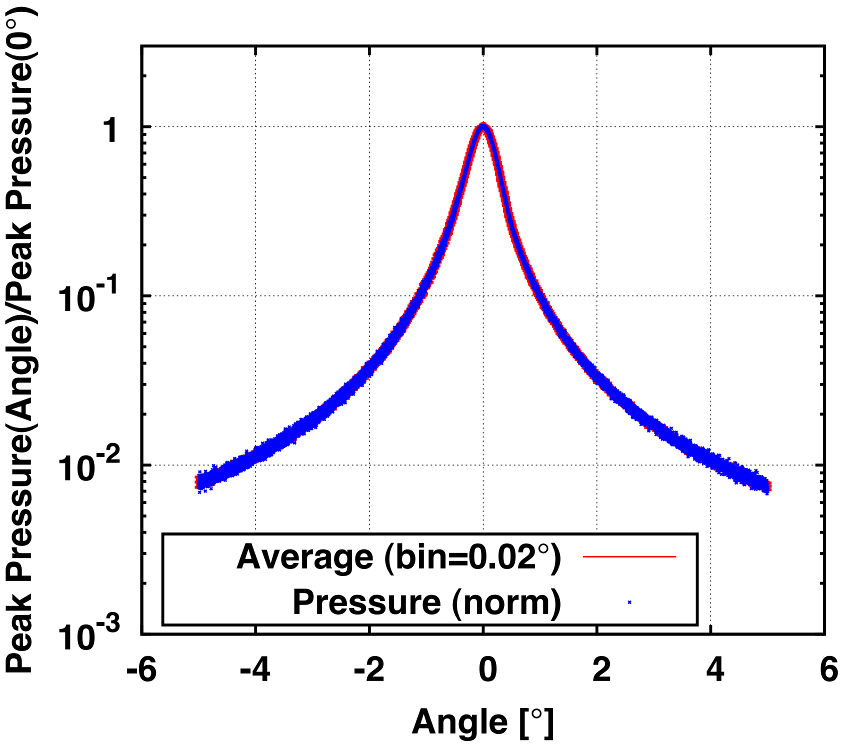


Points produced with density proportional to the deposited energy density (Acorne Coll., arXiv:0903.0949v2)

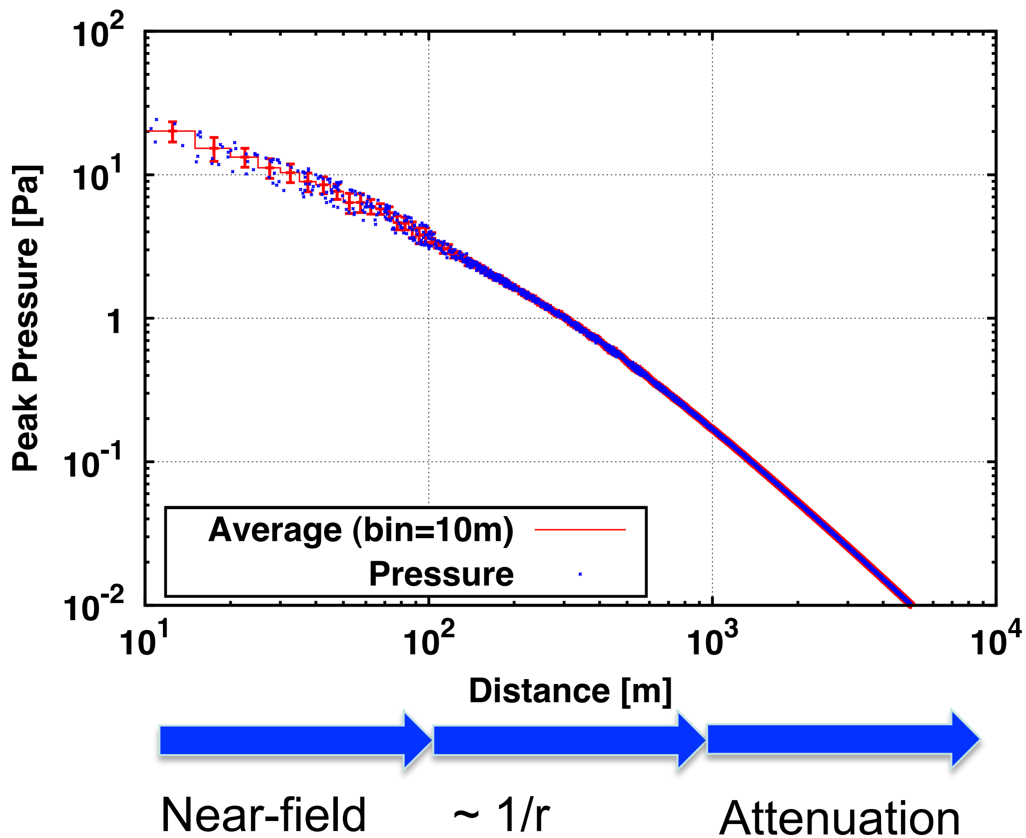


Calculated pressure pulse at the sensor including attenuation

Pressure Pulse – Amplitude dependence

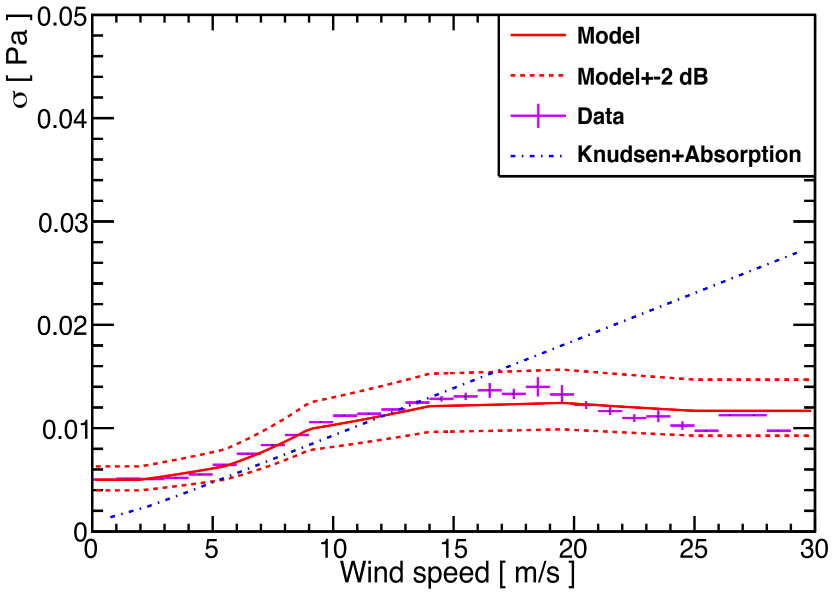


Peaked emission perpendicular to shower axis ➔ "Pancake"
Opening angle FWHM ≈0.6°

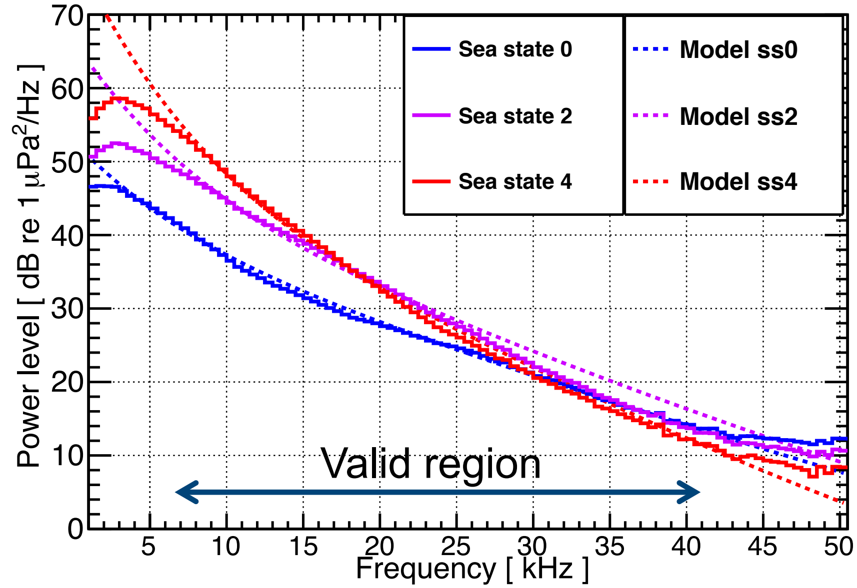


Ambient noise

Noise level 10 – 50 kHz



Model developed from AMADEUS data



- Ambient noise from 5 years of AMADEUS data
- Determines energy threshold

DAQ & Sensor simulation

Directional system response of the sensors &
Inherent noise of the sensors

System response of the ADC board &
Inherent noise of the ADC board

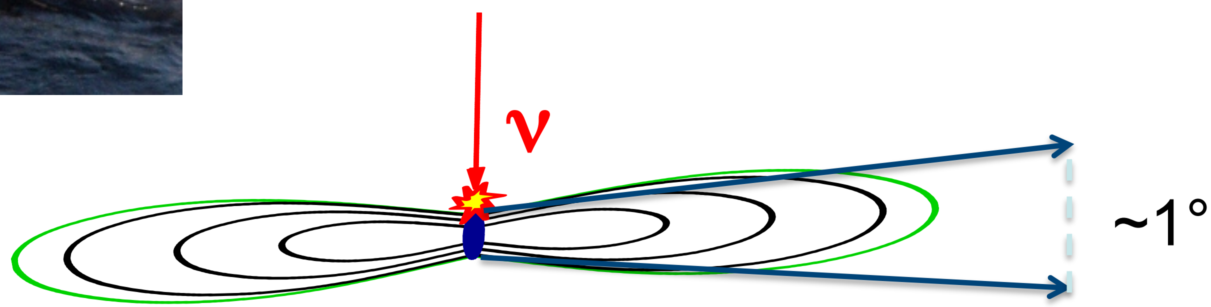
Filter simulation

According to online filter used in AMADEUS
Matched filter + coincidence test

→ Has to be adapted for different setups

Signal classification needed

- High rate of transient background with bipolar pulses, from e.g. whales and dolphins
- Additional background suppression is necessary



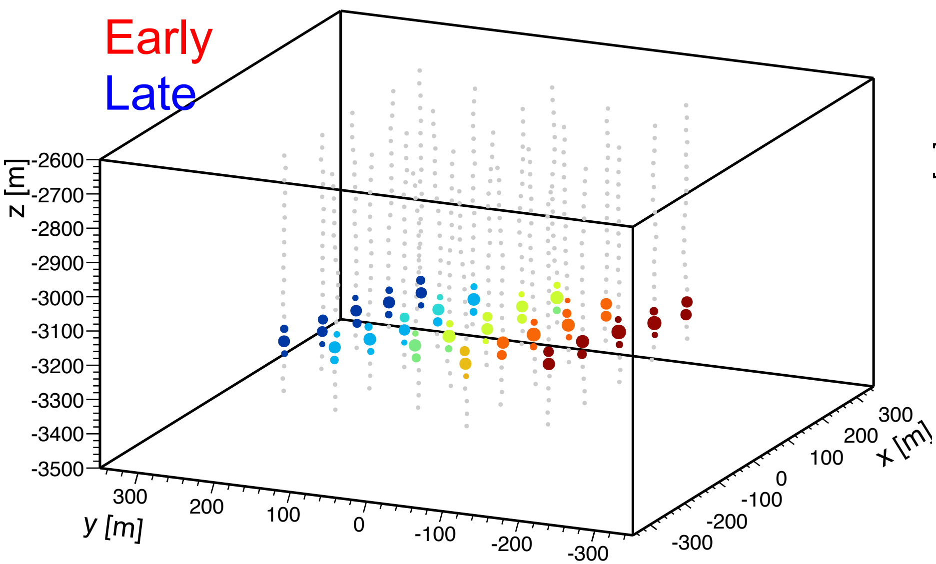
- Acoustic signal from neutrinos is emitted in a *O*(20 m) thick plane
- Most background is emitted as spherical waves

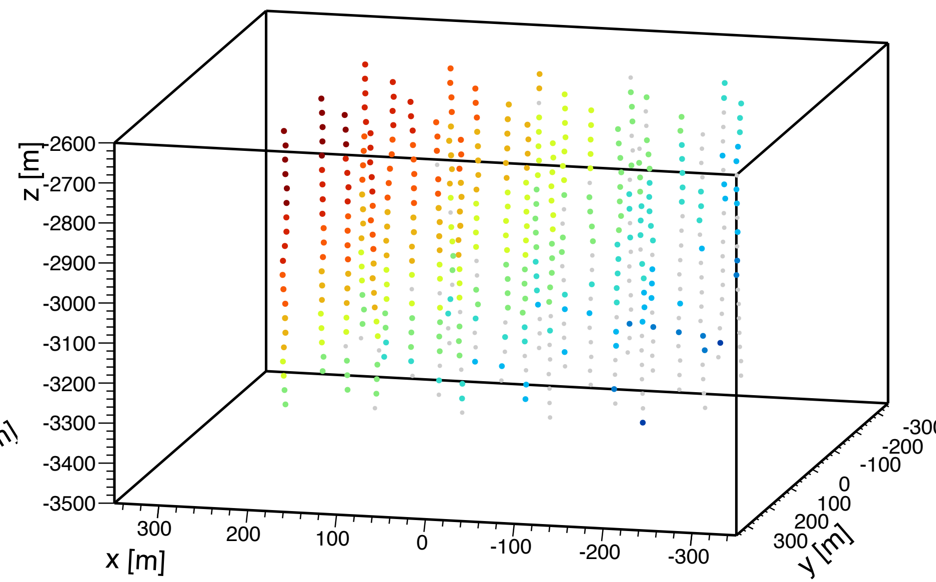
➡ Use the sound propagation geometry as classification for the signals in a large volume acoustic detector

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

Distinctive features of signals

- Generate characteristic features from the signature for classification
- Features should be independent of the detector geometry
- Good candidates are:
  - Number of hits
  - Center of gravity of the event
  - Principal components
  - PCA also yields a pancake-reconstruction:
    - RMS of the distance from the triggered hydrophones to the plane
    - Agreement of the reconstructed vertex with the pancake plane
  - …

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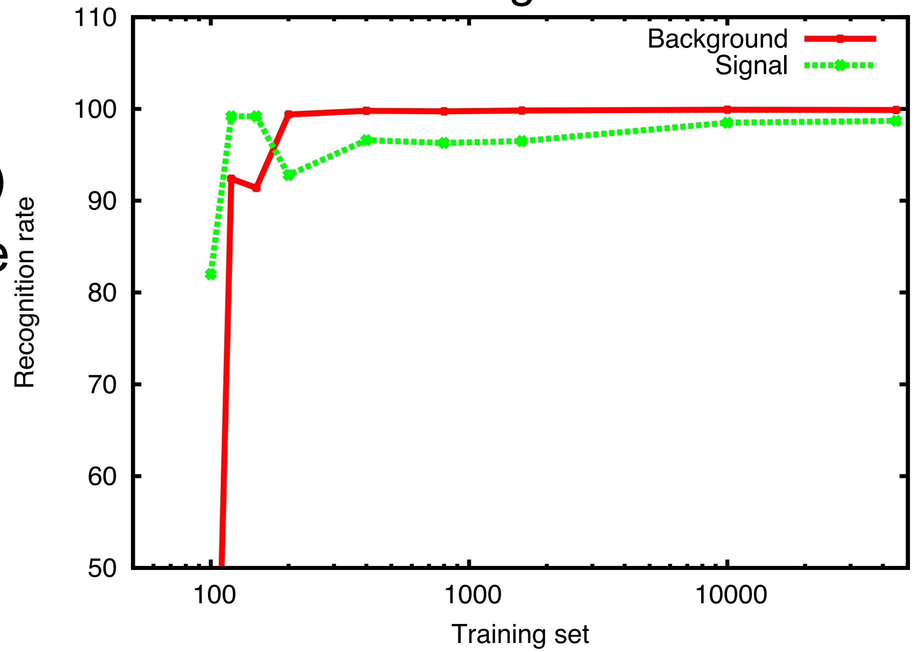
Classification with boosted trees

- Use these features for a multivariate analysis
- Boosted Trees show the best performance: Recognition rate of 99%
- Tested with different detector geometries:
  - 8 lines, 14 floors
  - 24 lines, 18 floors (KM3NeT Ph1)
- Classification works with the same features and learned models for similar setups!
- Outlook: Checking the stability of the classification with reduced signal quality

Learning curve:



Summary and Outlook

- Fully operational simulation chain available
- Refraction of sound paths has negligible effect on sensitivity in simulations
- DAQ Simulation will be adapted to KM3NeT
- Signal classification is working, but has to be tested with overlapping events

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Thank you for your attention!

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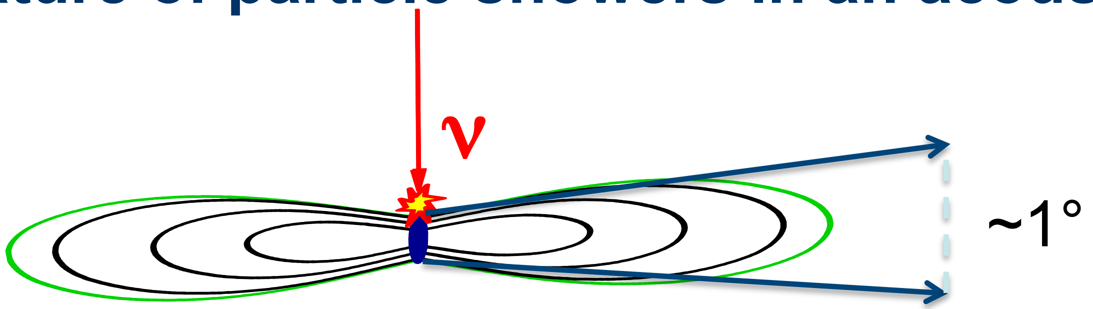
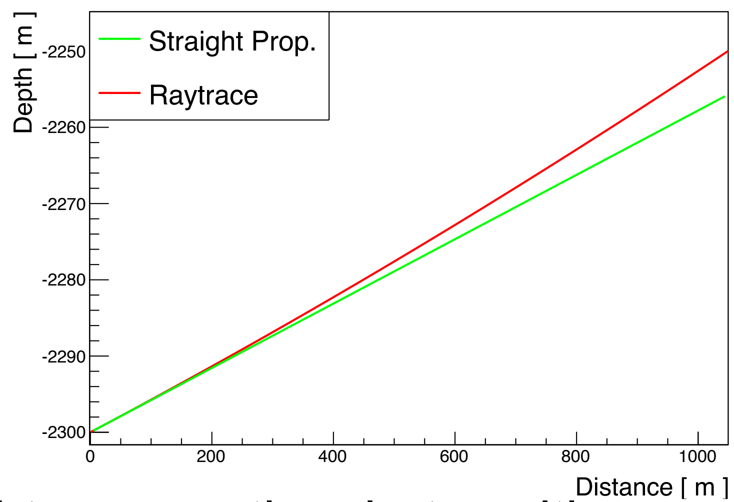
Backup

Signature of particle showers in an acoustic array



- Acoustic signal is basically emitted in a *O*(20 m) thick plane
  - Curved like a normal acoustic signal: ~10 m deflection after 1 km
- Typical detector setup:
  - ~100 m between lines
  - ~20 m between floors
- Signature of events is not affected by the curvature



→ Simulations can be done with straight propagation, but position reconstruction should include these effects for long distances

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Sound speed profile

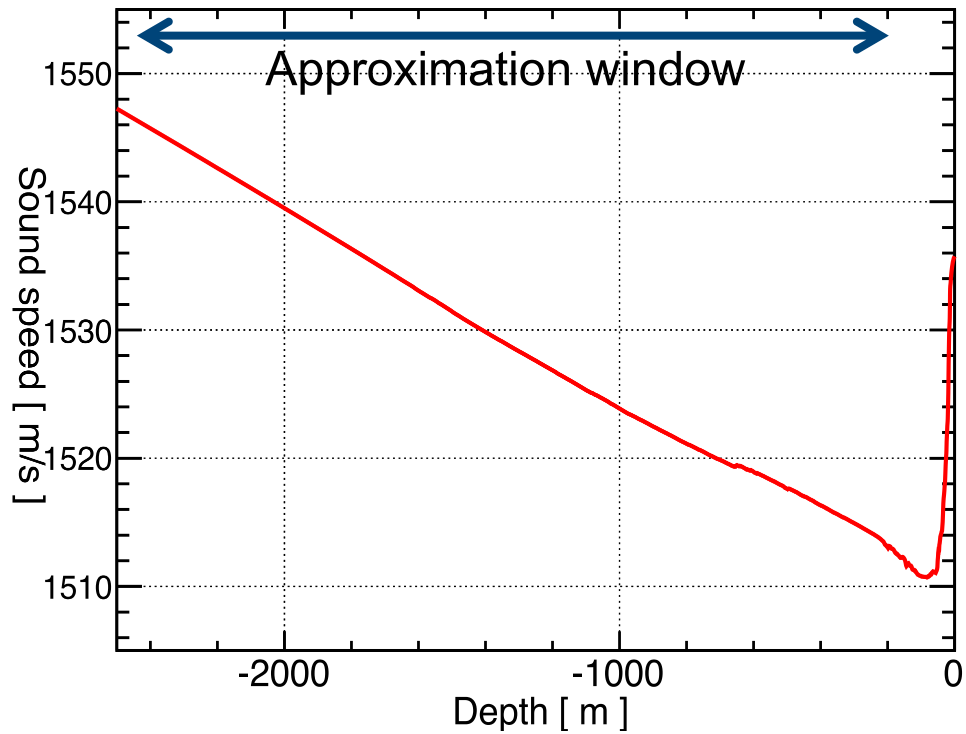
- Sound speed profile is nearly linear below 200 m
- Sound path mainly determined by:

$$\alpha = \frac{1}{c} \cdot \frac{\partial c}{\partial z}$$

- Approximation:

$$\alpha = const$$

Analytical solution possible



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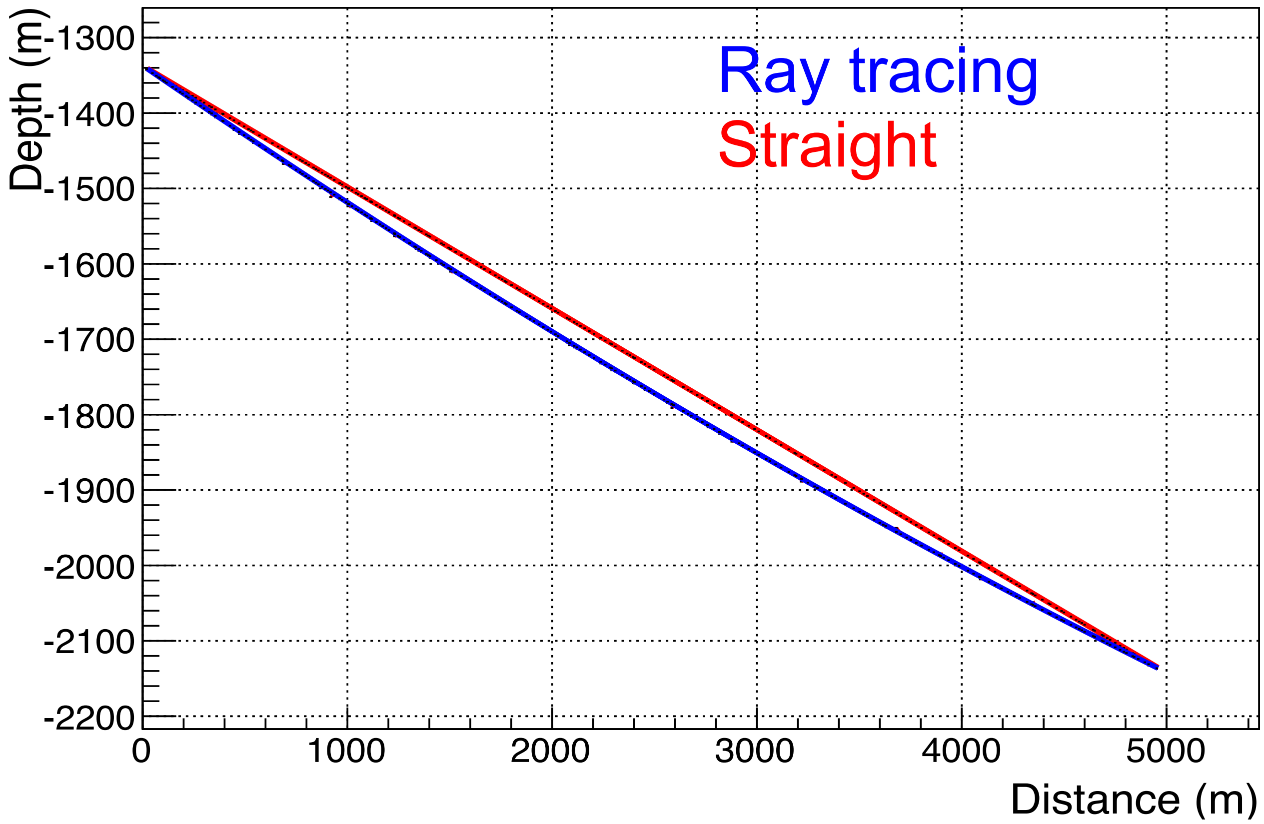
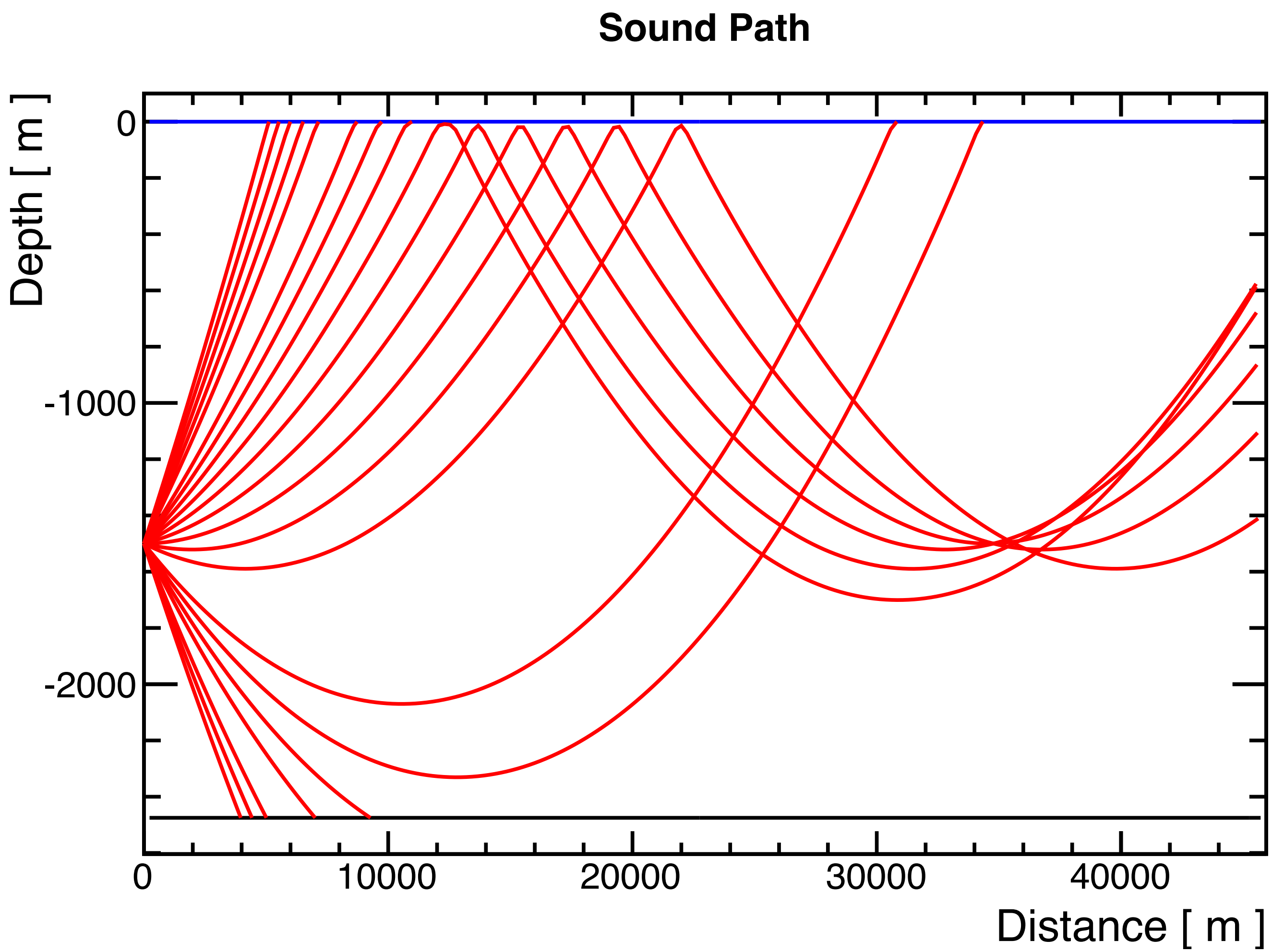
Sound path (short distance)



Sound path (long distance)



Acoustic Detection Principle

For neutrino energies $E_\nu > 10^{17}$ eV: alternative detection techniques necessary