Experimente zur Akustischen Neutrinodetektion

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- Rekonstruktion von Richtung und Ort akustischer Quellen
- The Road Ahead

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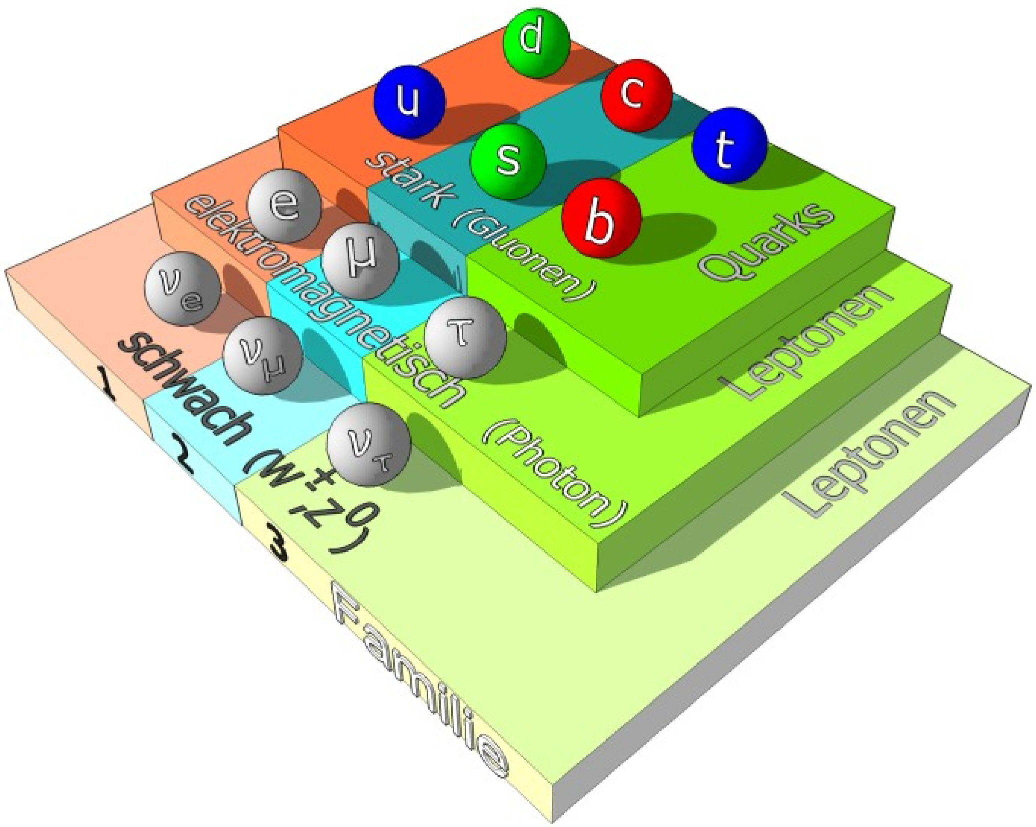
PHYSICS

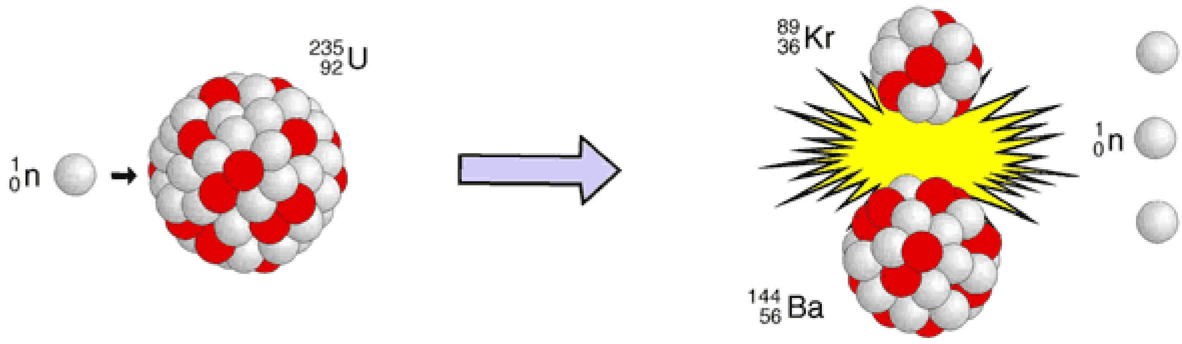
Neutrinos: Quellen und Nachweismethoden

Neutrinos im Standardmodell



Neutrinos: - Nur schwache Wechselwirkung
- ungeladen
- fast masselos

Reaktorneutrinos



$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{89}_{36}Kr + {}^{144}_{56}Ba + 3\,{}^{1}_{0}n + 210\ \text{MeV}$$

$$^{89}_{36}\mathrm{Kr} \rightarrow {}^{89}_{37}\mathrm{Rb} + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e \qquad \mathrm{E} = 4.990\,\mathrm{MeV} \qquad t_{1/2} = 3.15\,\mathrm{min}$$

$$^{144}_{56}\mathrm{Ba} \rightarrow {}^{144}_{57}\mathrm{La} + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e \qquad \mathrm{E} = 3.120\,\mathrm{MeV} \qquad t_{1/2} = 11.5\,\mathrm{s}$$

Pro U-235 Zerfall durchschnittlich 6.1 (Anti-) Elektron-Neutrinos

KKW mit 1MW thermischer Leistung: $10^{17}\ \nu/\mathrm{s}$

Erster Nachweis von Neutrinos

Reines und Cowan 1956 (Nobelpreis Reines 1995)

Target: 400 Liter Wasser / Cadmiumchlorid-Lösung

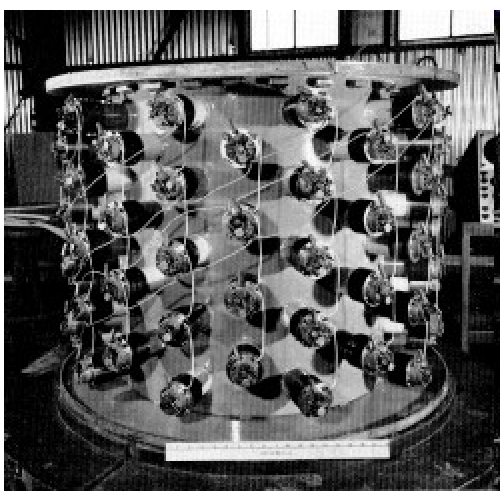
Reaktion des Anti-Neutrinos:

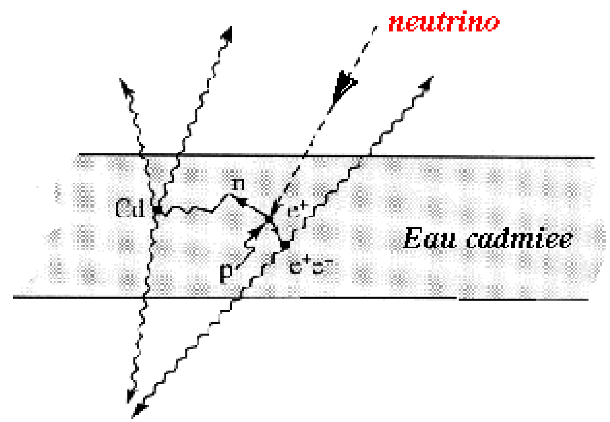
$$\bar{\nu}_e + p^+ \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

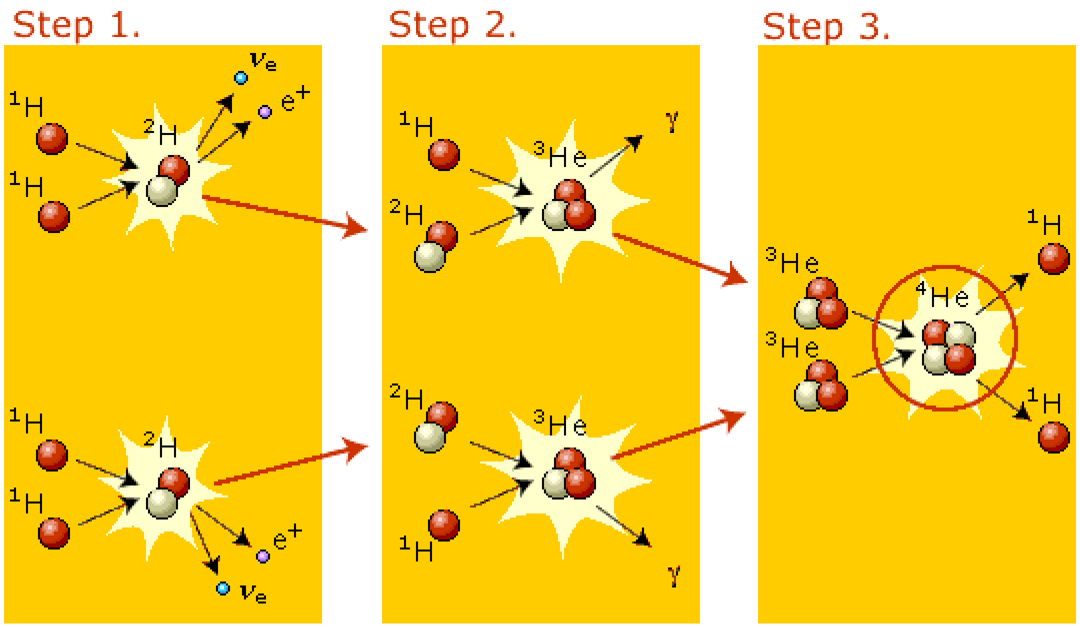
$$n + Cd \rightarrow X + \gamma + \gamma$$

Nachweis über Zeitverzögerung der Photonemission (15 µs)





Solare Neutrinos



pp-Reaktion: $4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2\,{}^0_1\mathrm{e}^+ + 2\nu_e + 2\gamma$ $\quad E_\nu \leq 0.420\,\mathrm{MeV}$

Alle Reaktionen: $\quad E_\nu < 20\,\mathrm{MeV}$

Nachweis solarer Neutrinos

- Niedrige Energien: Radiochemischer Nachweis von Elektron-Neutrinos (z.B. solare Neutrinos)
- z.B. Gallex und Sage Experimente:
  $\nu_e + {}^{71}\mathrm{Ga} \longrightarrow {}^{71}\mathrm{Ge} + e^-$
- Problem: Grosse Mengen an GaCl (teuer) unter Tage (technisch schwierig) benötigt

Neutrions von SN Explosionen (I)

- Sterne mit M> 8 M_o explodieren an ihrem Lebensende als Supernova
- 99% der freiwerdenden Gravitationsenergie wird von Neutrinos getragen

- ν_e werden im “neutronization process” (10 ms) erzeugt:

$$e^- + p \rightarrow n + \nu_e$$

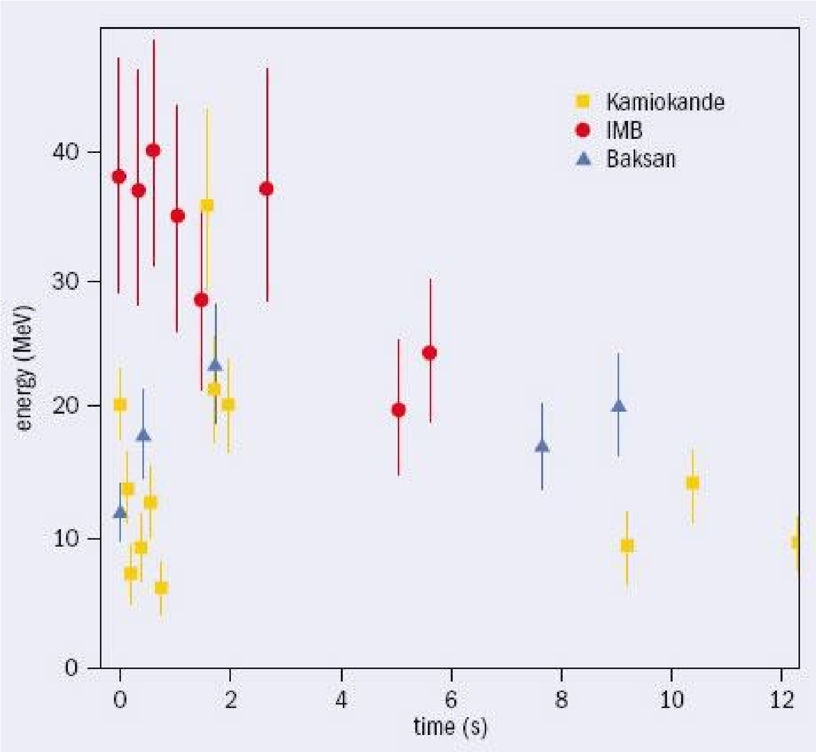
- Neutrinos aller flavors (ν_e, ν_μ, ν_τ) werden in der

  “thermalization phase” (~10s) erzeugt:

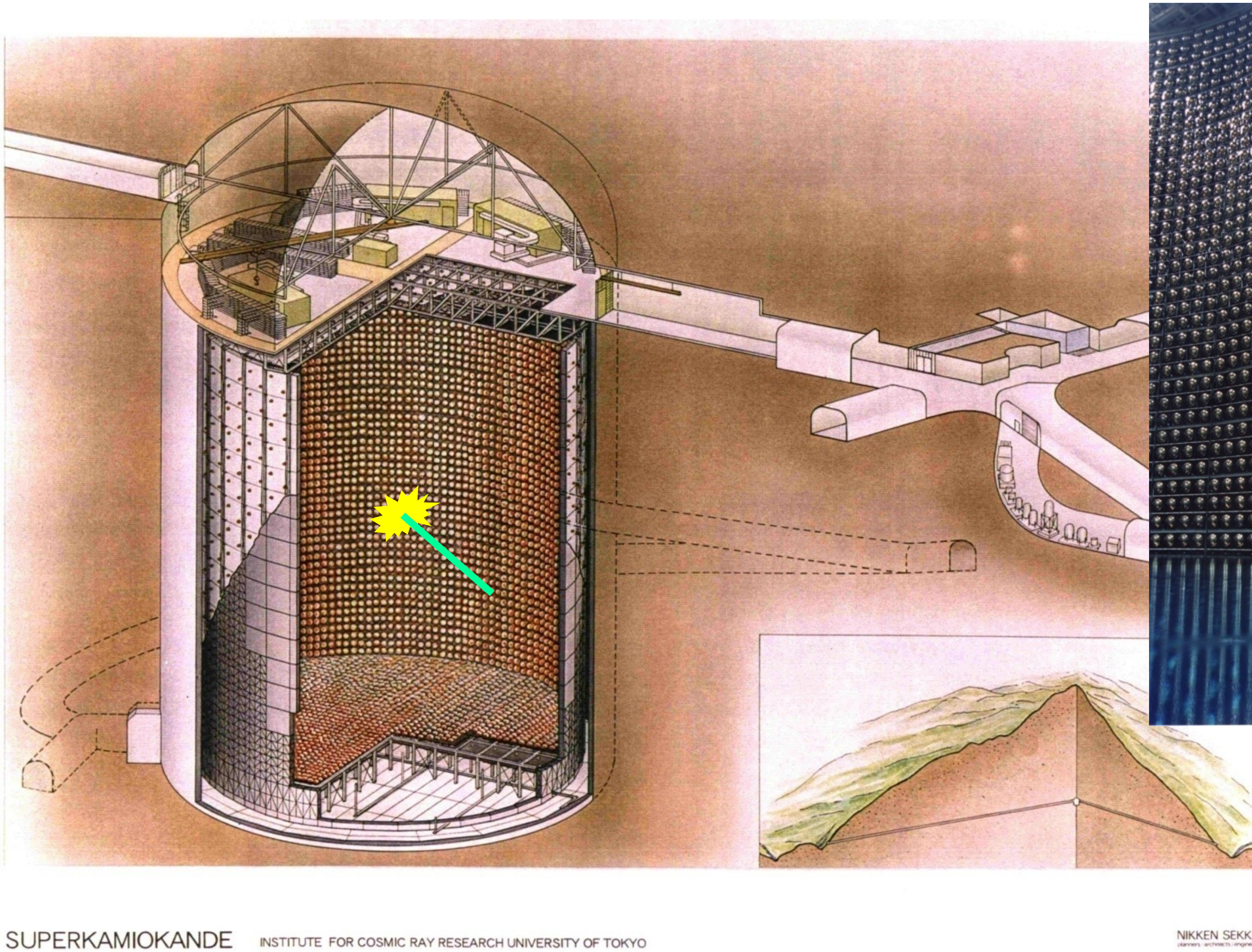
$$e^- + e^+ \rightarrow \nu + \nu$$

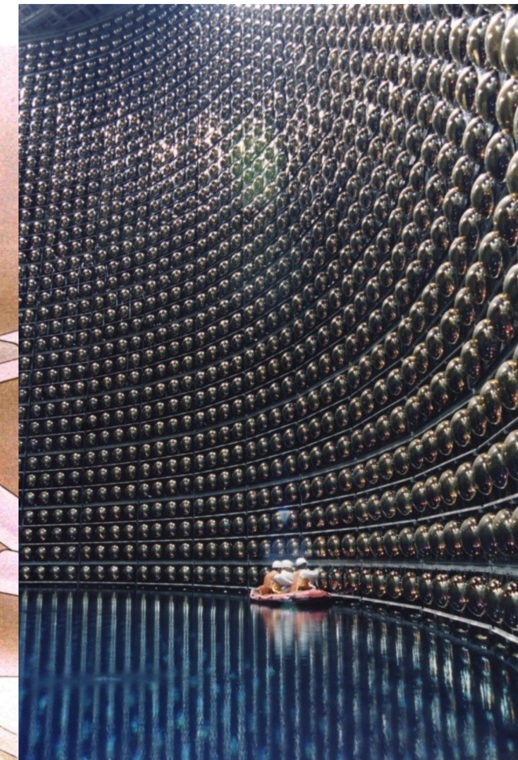
Neutrions von SN Explosionen (II)

Neutrinos der SN 1987A (52 kpc) am 23. Februar 1987 von den Kamiokande, IMB and Baksan Experimenten detektiert

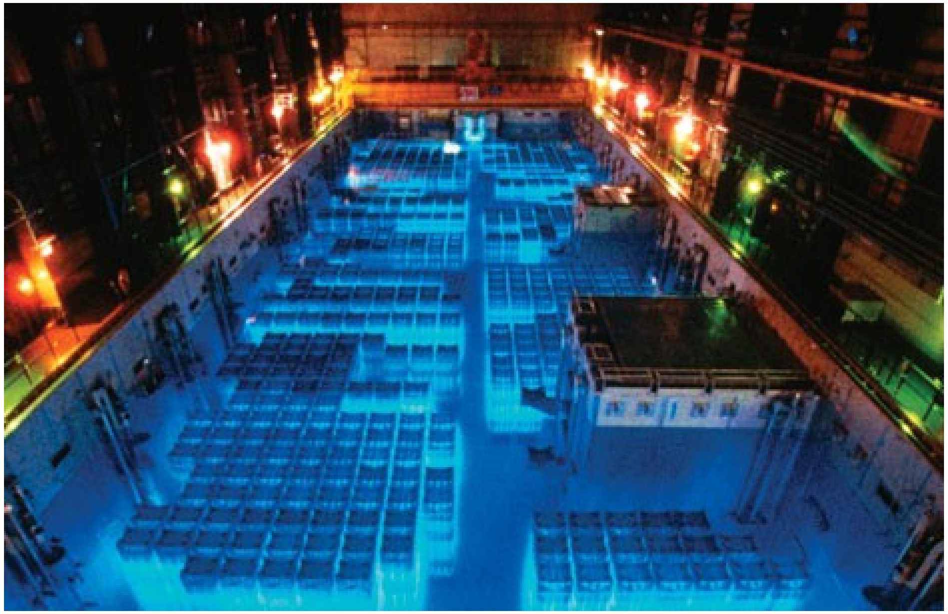


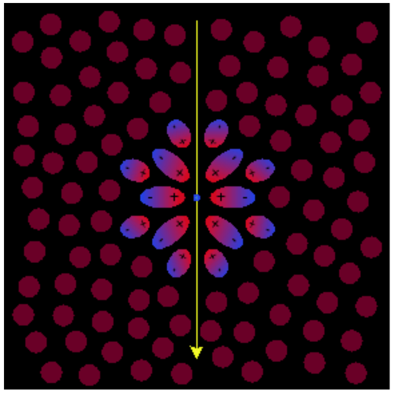
Funktionsweise (Super-) Kamiokande



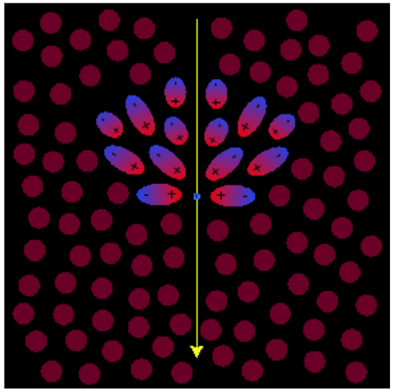


Nachweis mit Cherenkov-Strahlung

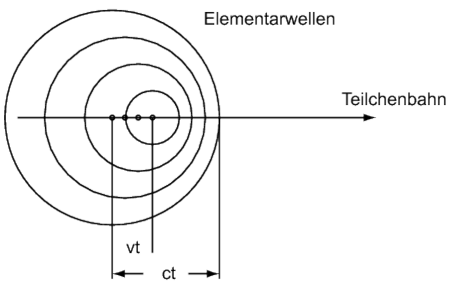




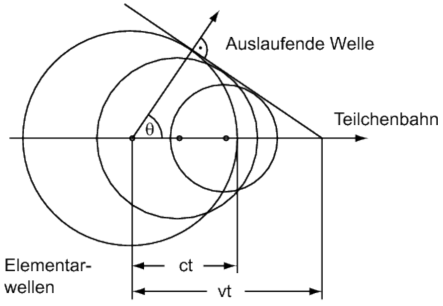
(a) v < c



(b) v > c

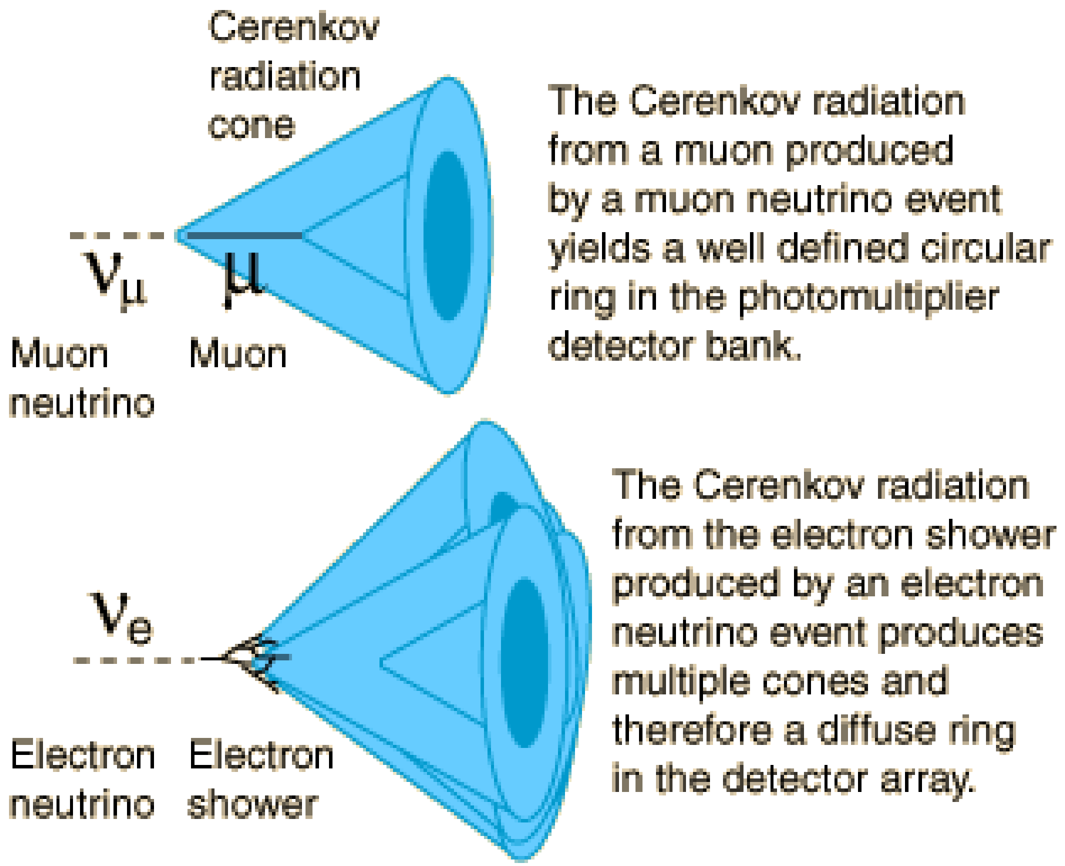


(c) $v < c$



(d) $v > c$

Neutrinoflavor-Bestimmung bei SuperK

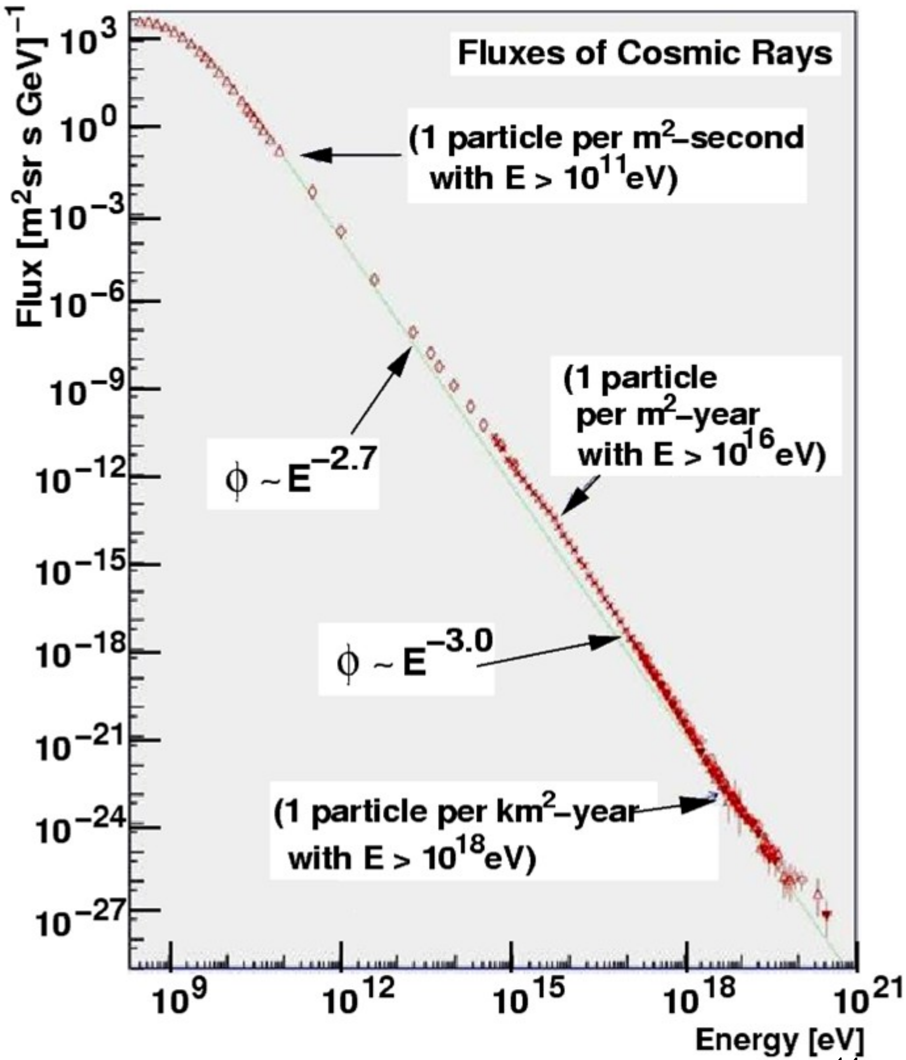


Atmosphärische Neutrinos

Erzeugt durch Beschuss der Erdatmosphäre mit Kosmischer Strahlung

Kosmische Strahlung:

- Besteht aus Protonen und Kernen
- Spektrum über ~12 Größenordnungen vermessen



Erzeugung Atmospharischer Neutrinos

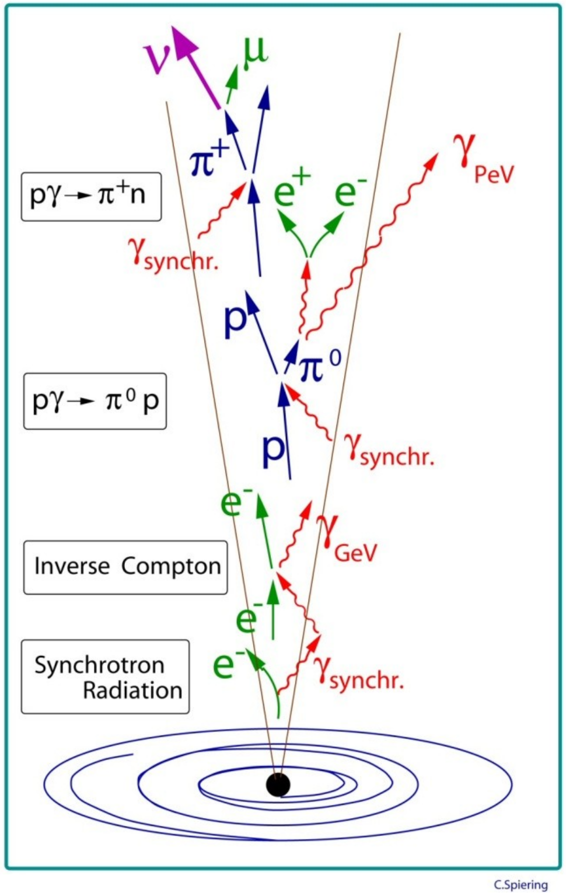
Spektrum wird von AMANDA/IceCube seit langem gemessen

Neutrinoastronomie

Erzeugung kosmischer Neutrinos (I)

1) Entstehung am Ort der Beschleunigung von Hadronen

Particle Generation in AGN Jets



Erzeugung kosmischer Neutrinos (II)

2) Produktion durch Reaktion kosmischer Strahlung (Hadronen) auf dem Weg zur Erde

Reaktion beschleunigter Protonen mit interstellaren Medium, 3K Mikrowellen-Hintergrundstrahlung (CMB) oder Synchrotronstrahlung

$$p + p(\gamma) \rightarrow \boldsymbol{\pi} + X$$
$$\hookrightarrow \boldsymbol{\mu} + \boldsymbol{\nu}_\mu$$
$$\hookrightarrow e + \boldsymbol{\nu}_e + \boldsymbol{\nu}_\mu$$

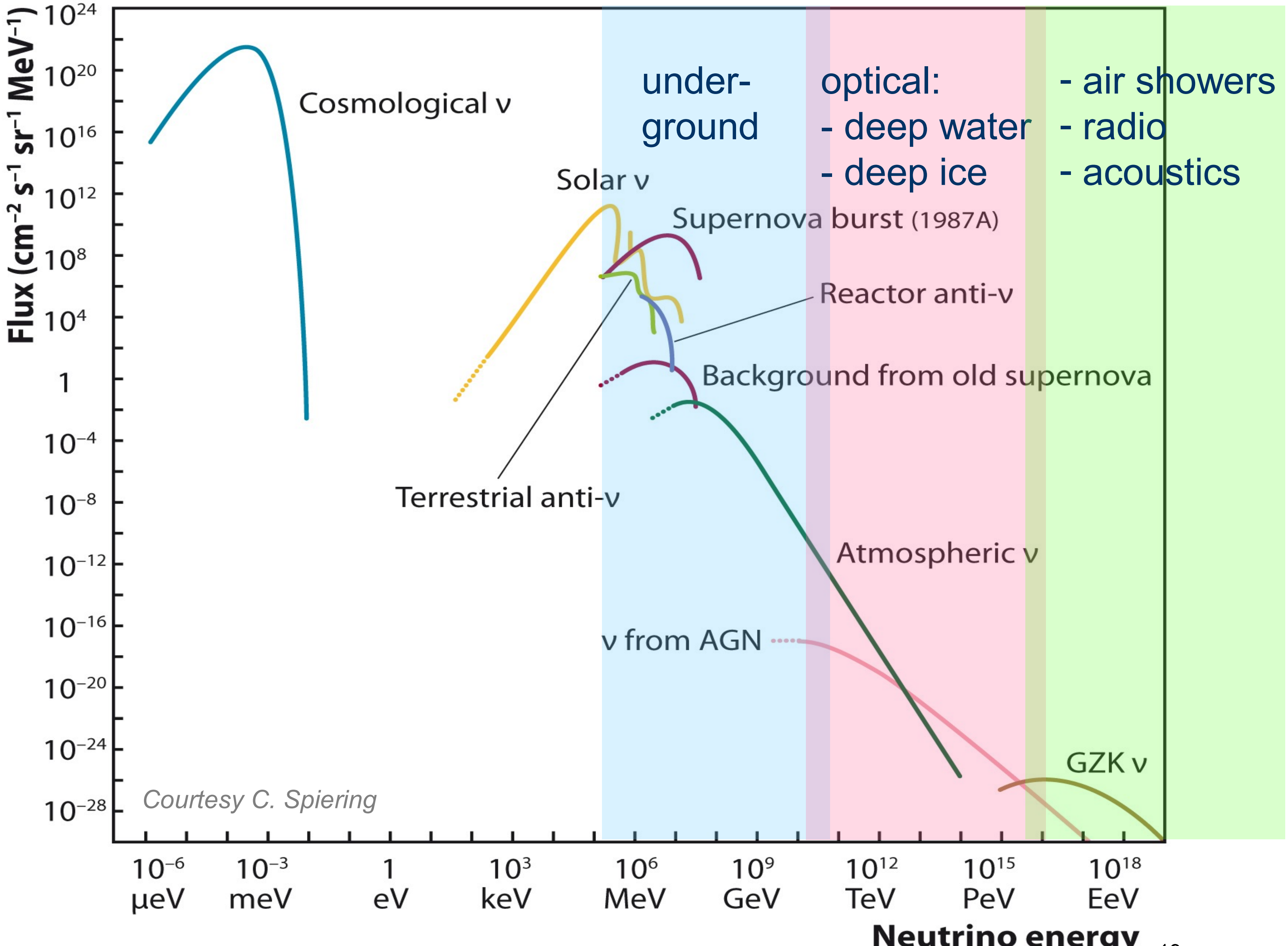
Neutrino-Oszillation führt zu $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

Die Reaktion $p + \gamma_{CMB} \rightarrow \boldsymbol{\pi}^+ + n$ hat eine Schwelle von $E_p \gtrsim 4 \times 10^{19}$ eV

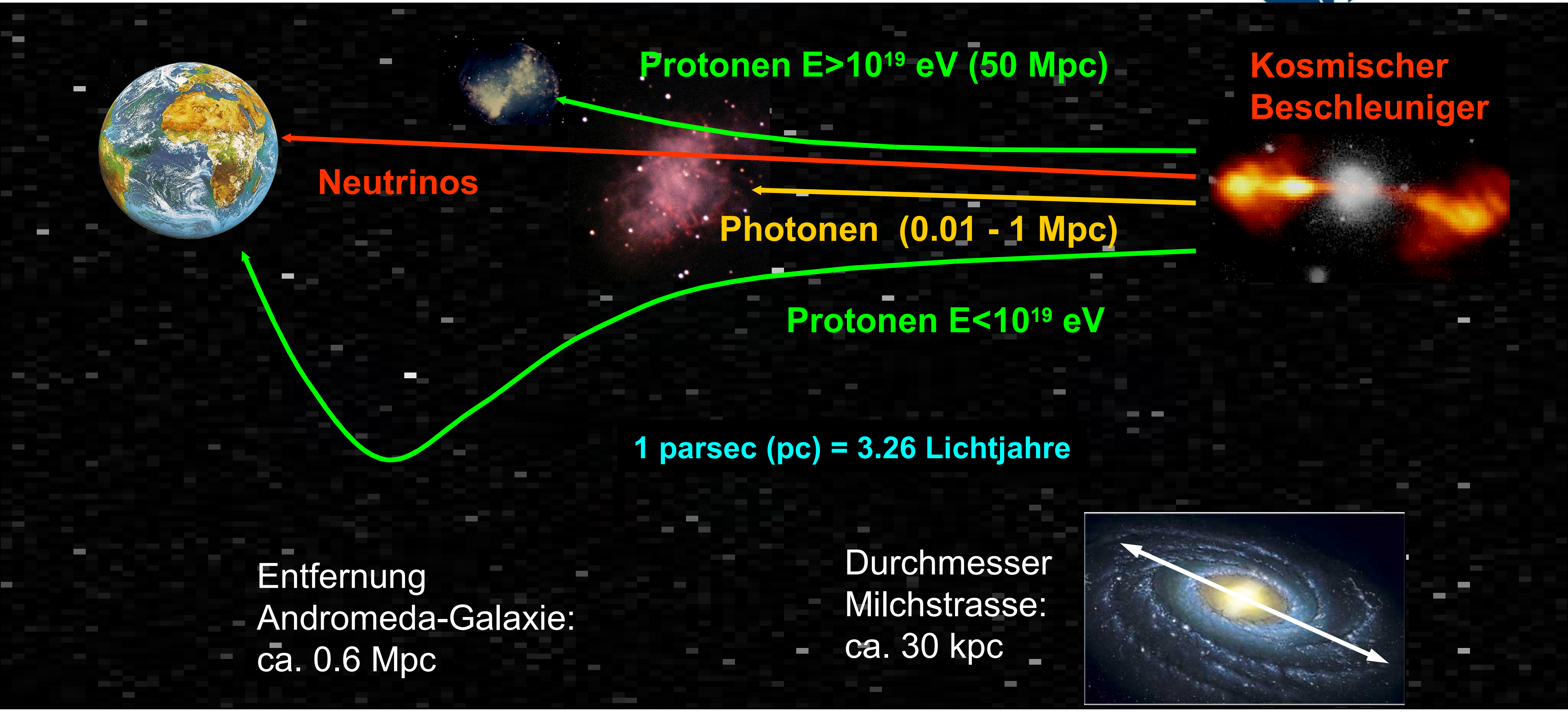
GZK-Cutoff: (Greisen, Zatsepin, Kuzmin)

- begrenzt die Reichweite hochenergetischer Protonen auf ca. 50 Mpc
- Von weiter entfernten Quellen sagt das Modell einen Neutrinofluss voraus

Neutrino Flüsse: Übersicht



Elementarteilchen: Ihr Weg durch das Universum



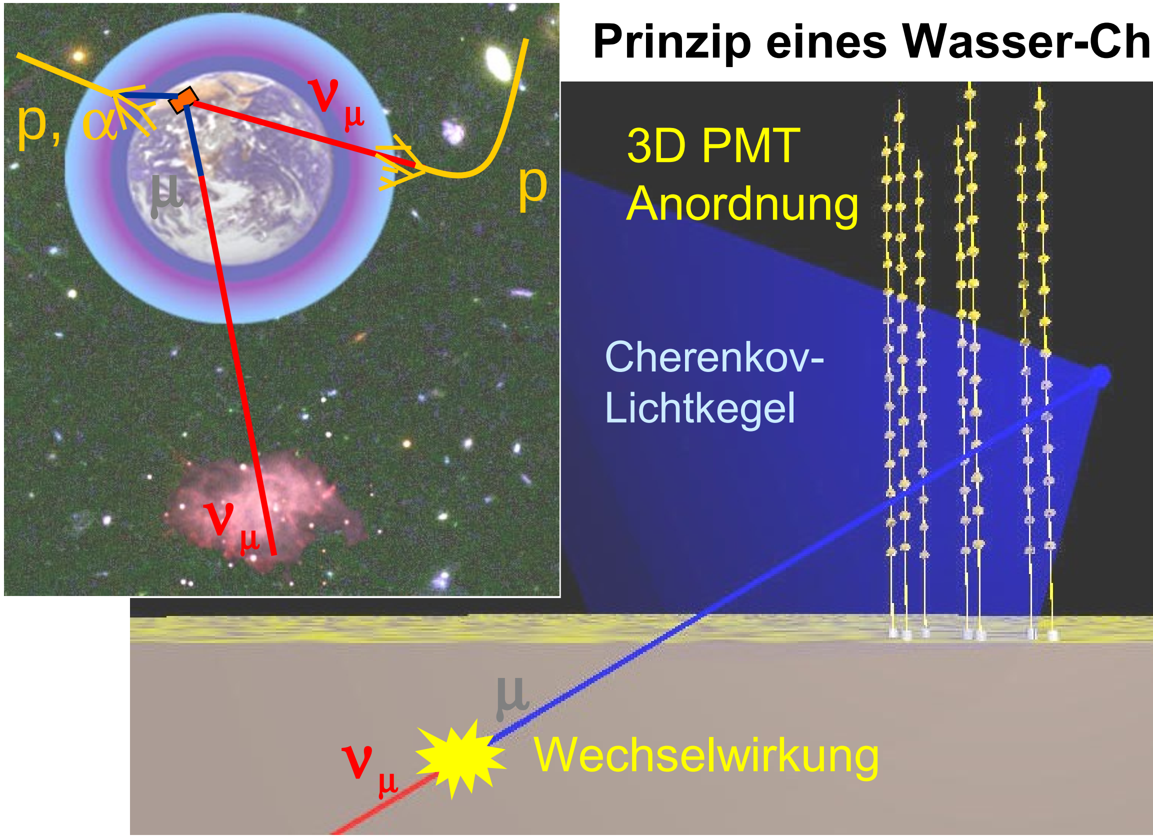
Photonen: Absorption durch Strahlung oder Staub;
Protonen/Atomkerne: Ablenkung durch magn. Felder, Reaktionen mit Photonen (CMB)
Neutrinos: Nur schwache Wechselwirkung, also fast ungehinderte Propagation

Neutrinoastronomie: Ein paar Fakten

- Extrem kleine Flüsse machen sehr große Detektoren notwendig
- Noch kein hochenergetisches kosmisches Neutrino nachgewiesen
- Indizien für Existenz: Gemessenes Spektrum kosmischer Strahlung
- Indiz für GZK-cutoff von Auger

Optische Neutrino-Detektion

Prinzip eines Wasser-Cherenkov Neutrino-Teleskops



<u>Optische Detektion:</u>
Optimiert für Myon-Neutrinos

Abschwächlänge bestimmt
Abstände der Photomulitplier

$\lambda_{abschw.}$ ~ 60 m @ 470 nm (blau)

Obere Energieschwelle bestimmt durch Detektorvolumen
⇒ Begrenzung durch technische/finanzielle Aspekte
⇒ Alternative bei ultra-hohen Energien: Akustik !

Kosmische Strahlung – die höchsten Energien

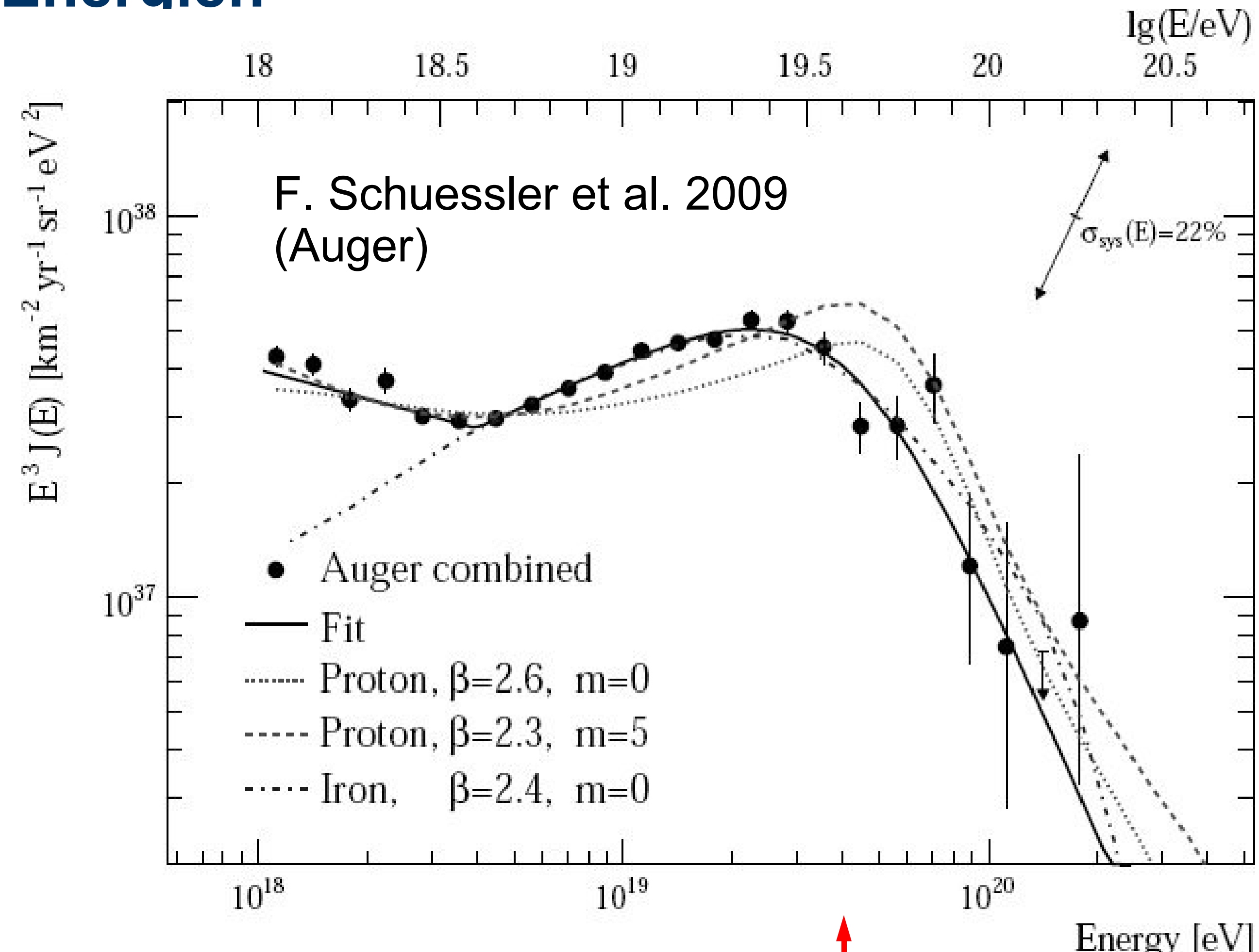


Photo-Pion Produktion

Schwelle: $E_p > 4 \times 10^{19}$ eV

Akustische Neutrinodetektion

Akustische Detektion von Neutrinos

Thermoakustisches Modell nach Askariyan

Energiedeposition ⇨ lokale Erwärmung (nK) ⇨Ausdehnung ⇨Drucksignal

Wellengleichung für den Druck p bei Deposition einer Energiedichte ε :

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

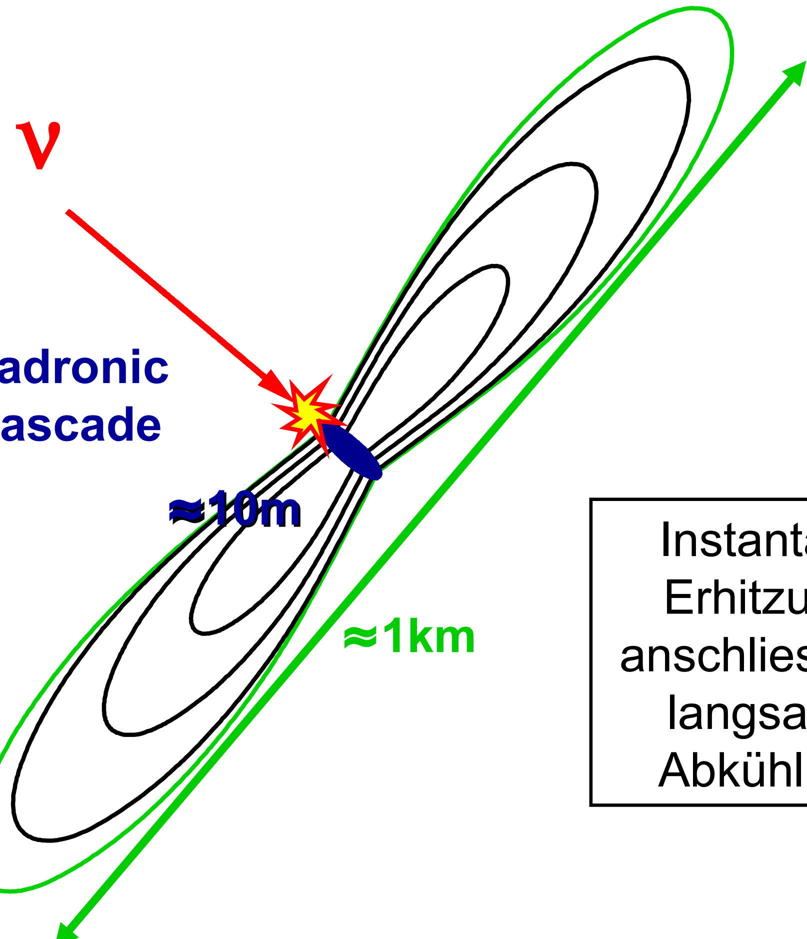
α = Volumenexpansionskoeffizient

C_P = spezifische Wärmekapazität (bei konstantem Druck)

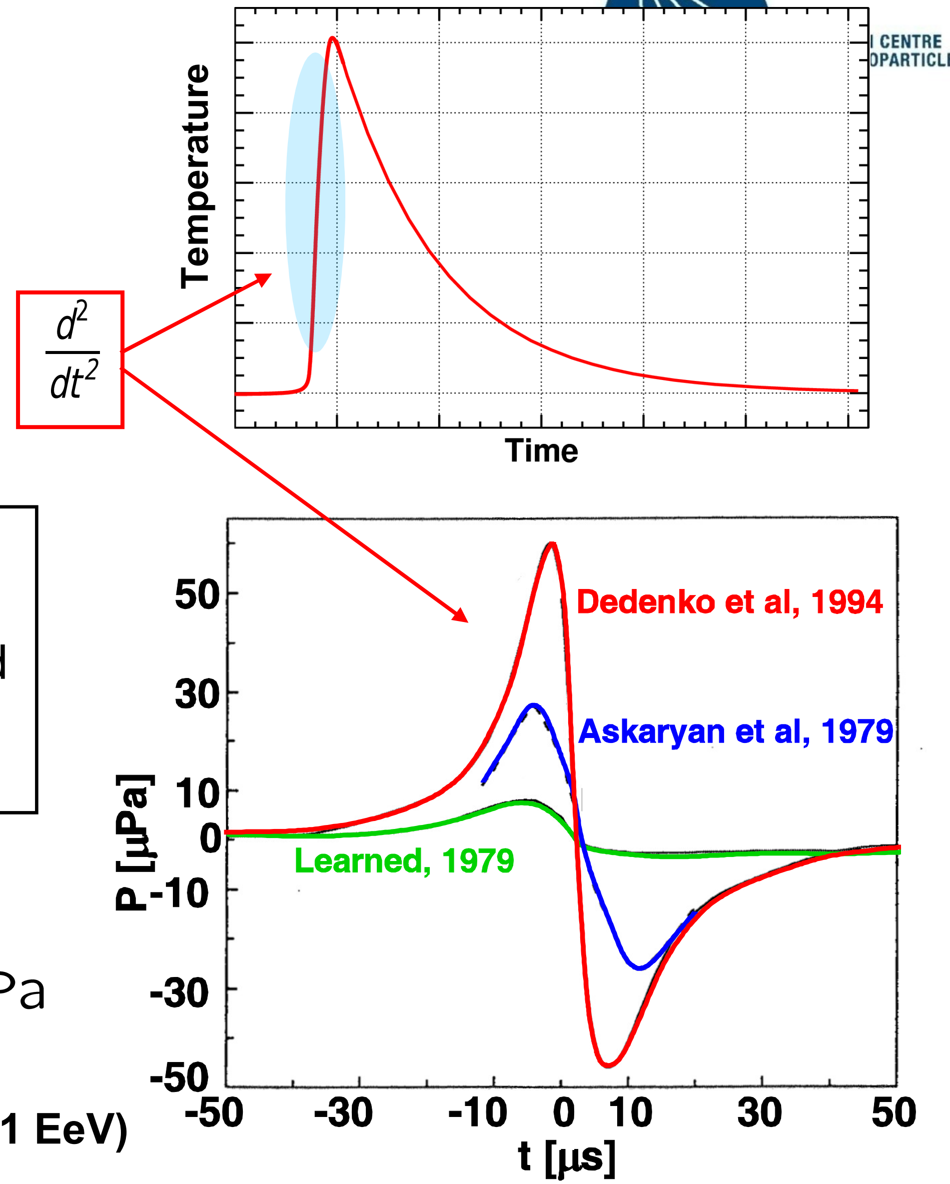
c = Schallgeschwindigkeit im Wasser (ca. 1500 m/s)

Lösung durch Kirchhoff-Integral und Annahme instantaner Energiedeposition

Akustische Signale von Neutrinos



Instantane Erhitzung, anschliessend langsame Abkühlung

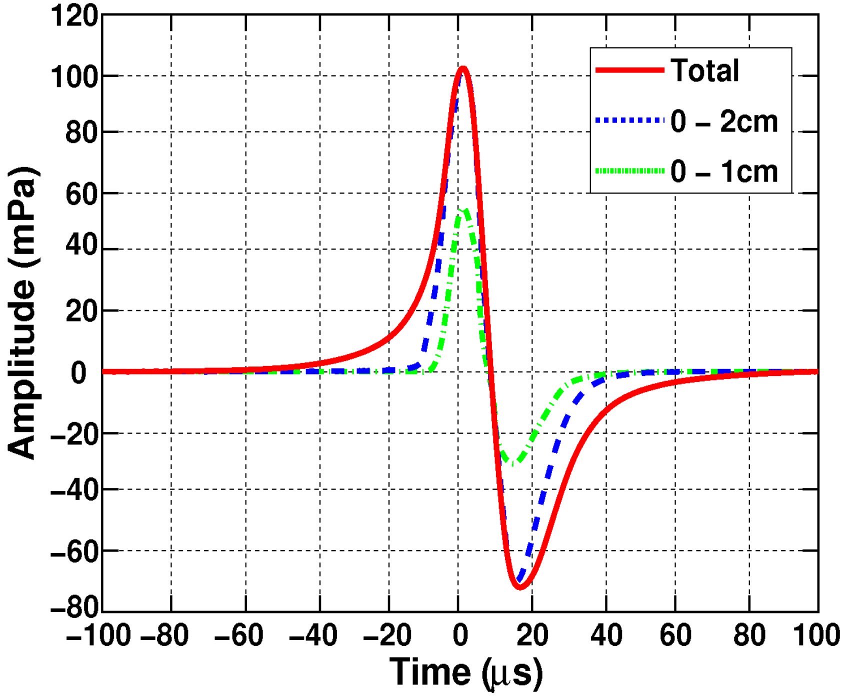


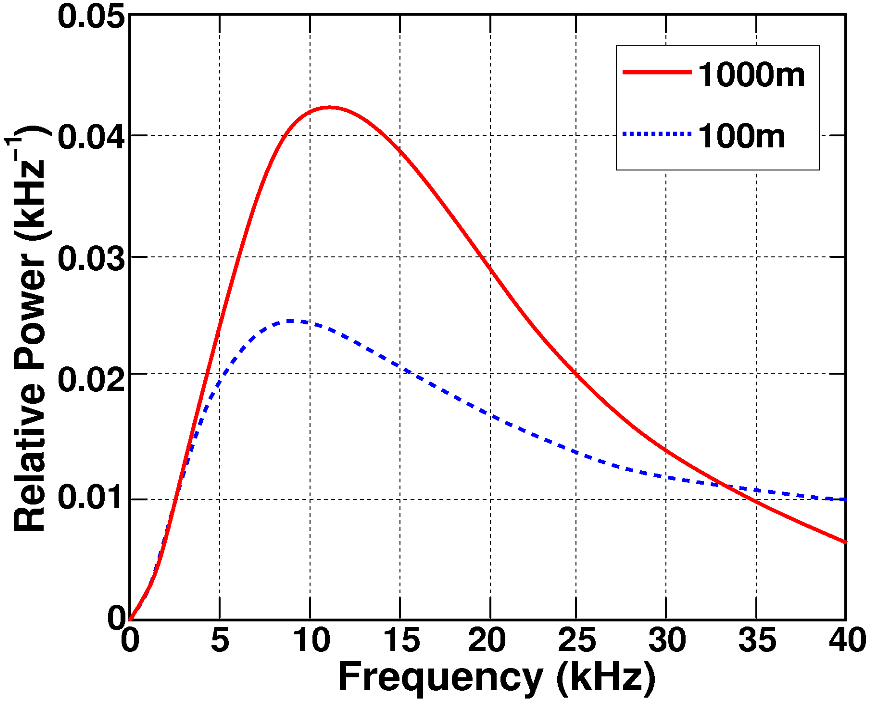
$$P(r = 200\,\mathrm{m}) \approx 10 \times \frac{E_{casc}}{1\,\mathrm{EeV}}\,\mathrm{mPa}$$

Erwartete Detektionsschwelle $E_\nu > 10^{18}$ eV (1 EeV)

A.V. Butkevich et al., Phys. Part. Nuc., 29 (3), 266, 1998

Pressure pulse of a neutrino induced cascade





S.Beavon et al.
ArXiv: 0704.1025

S.Beavon et al.
ArXiv: 0704.1025

Energy: 10^{20} eV
Distance: 1000 m

Das akustische Signal

Signaleigenschaften:

- Bipolarer Puls
- Charakteristische Frequenz: ~10kHz
- Amplitude: ~10 mPa (E = 1EeV, d=200m)
- Charakteristische “Scheibe” der Druckausbreitung
- Drucksignal: $p \propto E \cdot \alpha(T)$

  Expansionskoeffizient α ist 0 bei T = 4^0C

  (Mittelmeer: T ≈ 14^0C)

Schallpropagation im Wasser

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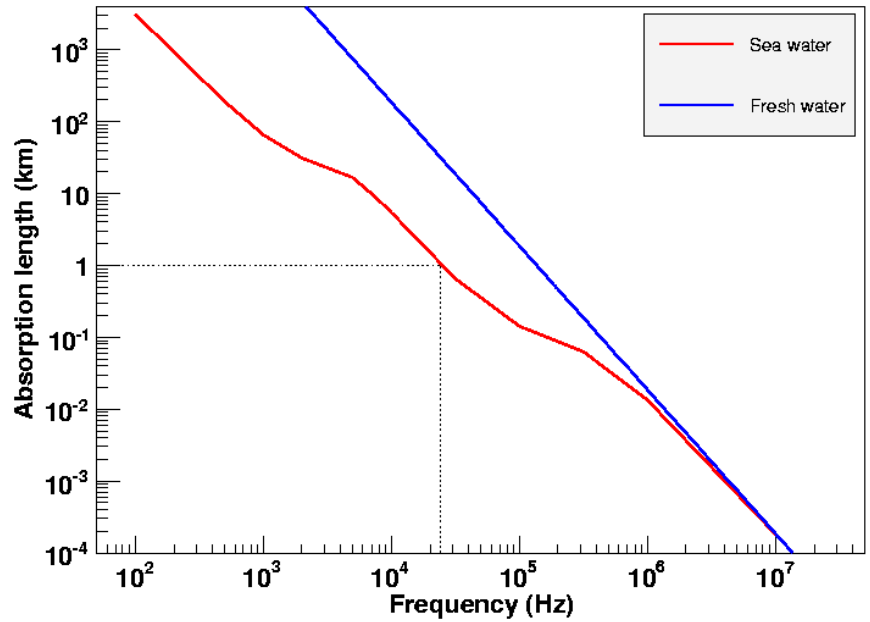
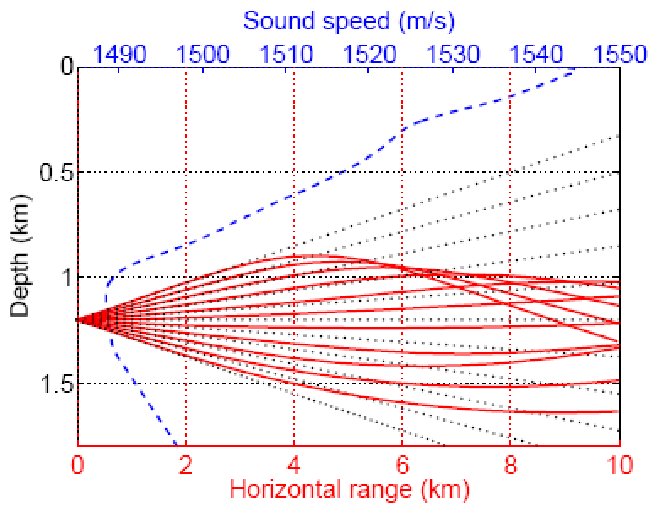
Abschwächlänge bei 20kHz
in Meerwasser: ca. 1km!

Simulationen müssen frequenzabhängige Signalabschwächung berücksichtigen.

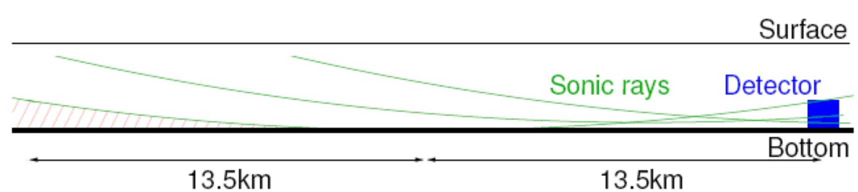


J. Vandenbroucke et al., astro-ph/0406105



(SAUND)

Vertikales Schallgeschwindigkeits-Profil führt zu Beugungseffekten

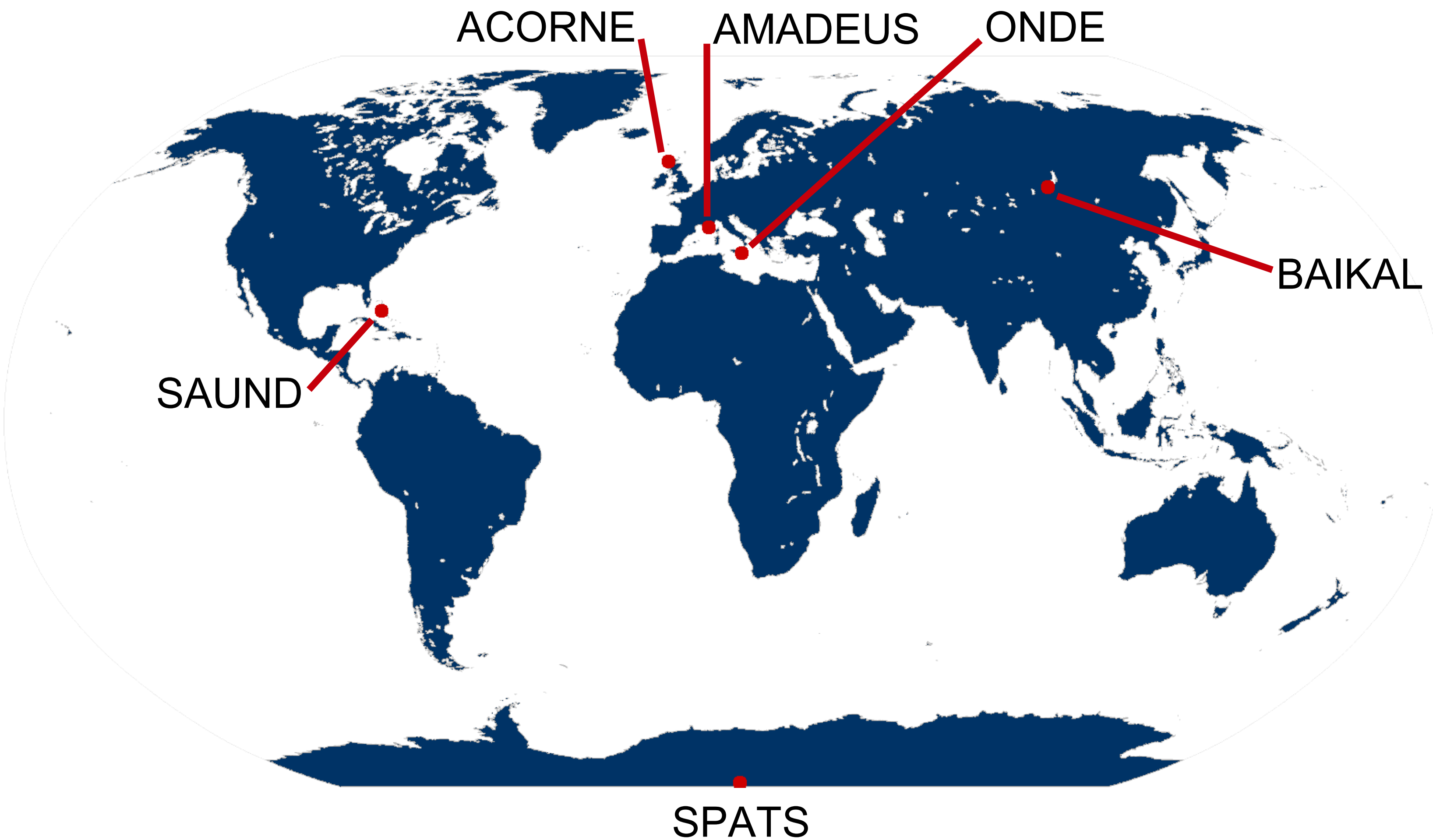


Vorteile der Akustischen Detektion

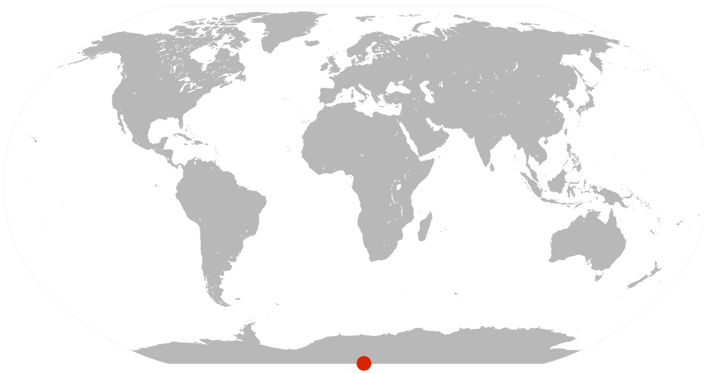
- Große Abschwächlängen für Drucksignale im Wasser
- gleiche Sensitivität für alle Neutrino-Sorten durch Messung von Schauern (Cherenkov optimiert für Muon-Neutrinos)
- Für E ~ 300 TeV: $\lambda_\nu = 2r_{Erde}$
  Erde wird undurchlässig für Neutrinos, Teleskope müssen „nach oben" sehen: Keine (hochenergetische) Schauererzeugung durch geladene Teilchen aus der Atmosphäre
- Technisch unkomliziert: Keine Hochspannung, niedrige Signalfrequenzen
- Hybriddetektor (optisch+akustisch) möglich

Experimente zur akustischen Neutrinodetektion

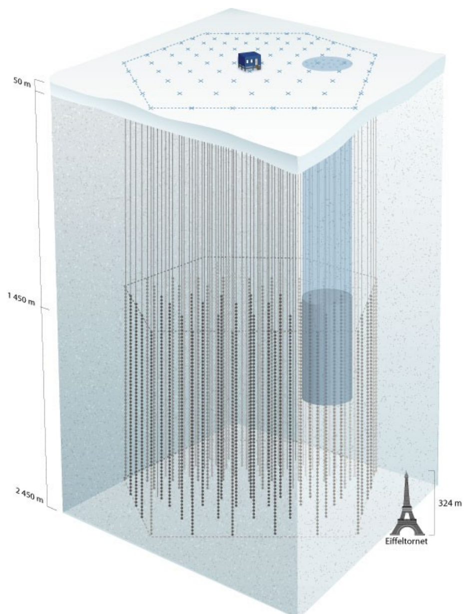
Experimente in Eis and Wasser

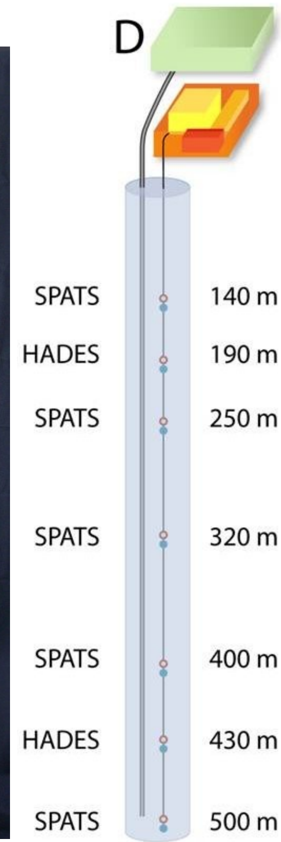


SPATS

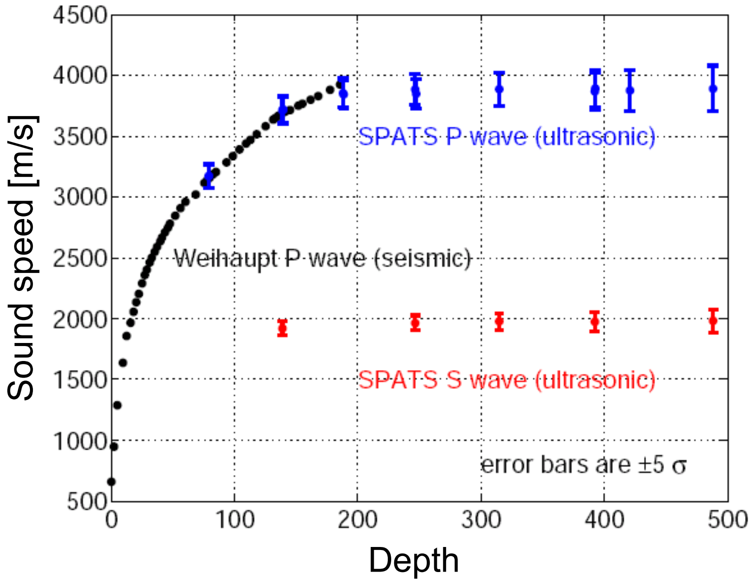


- Ice as detector medium
- 4 Strings with 7 “stages” each
- A stage consists of a transmitter module and a receiver module





SPATS – speed of sound in ice

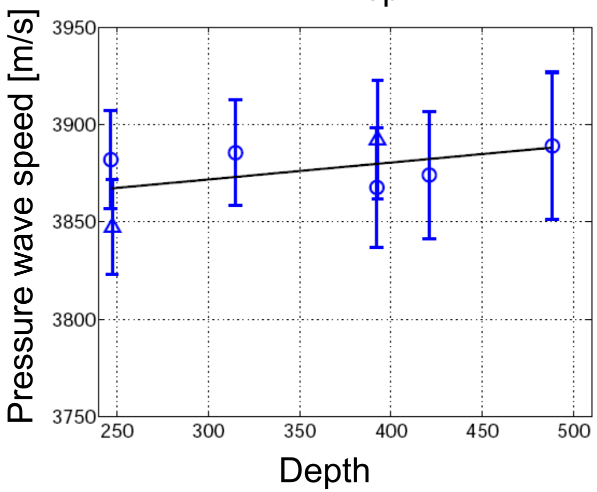


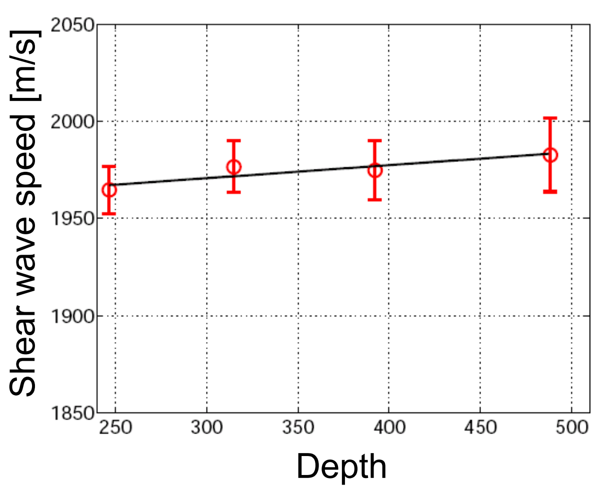
Sound velocity measurements of Pressure and shear waves

Agreement with previous measurements

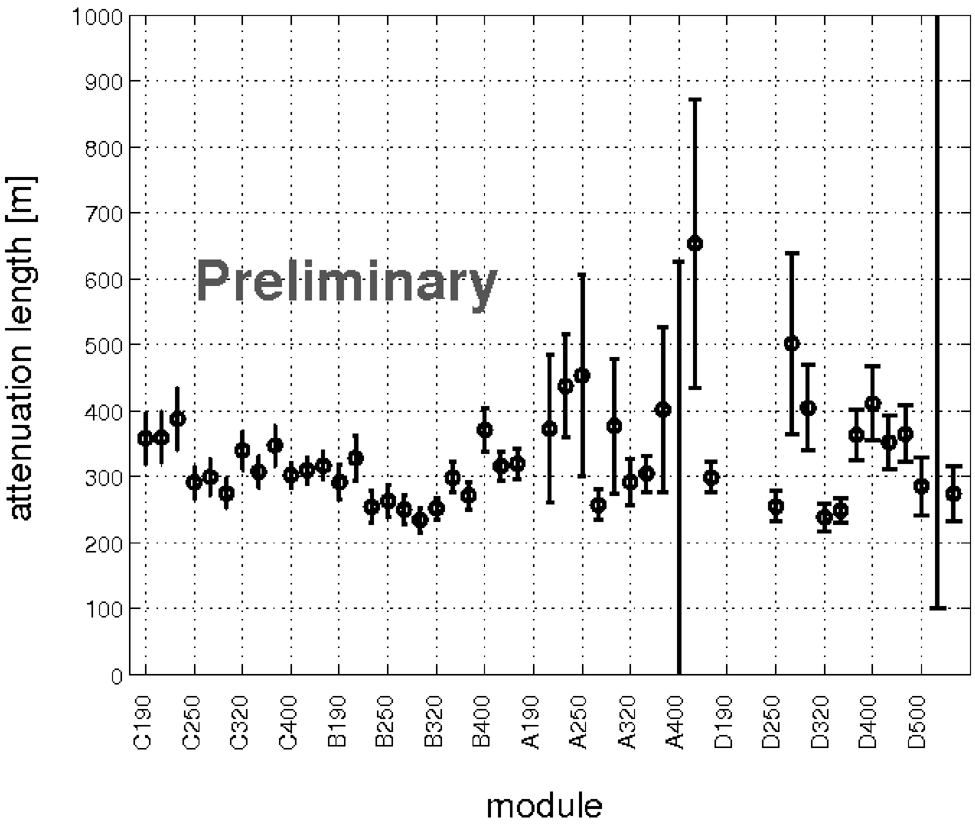
New results for greater depths

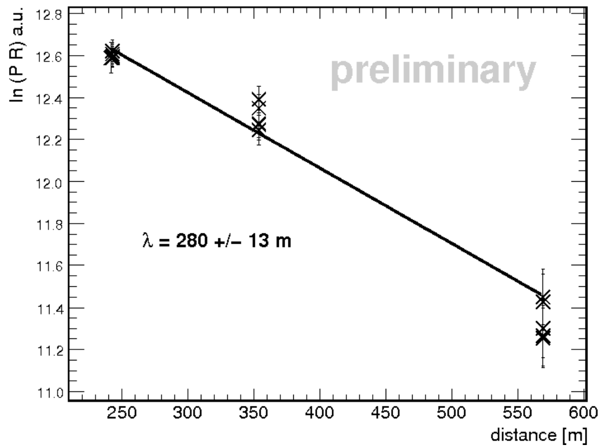
R. Abbasi et al. 2009





SPATS – attenuation length in ice

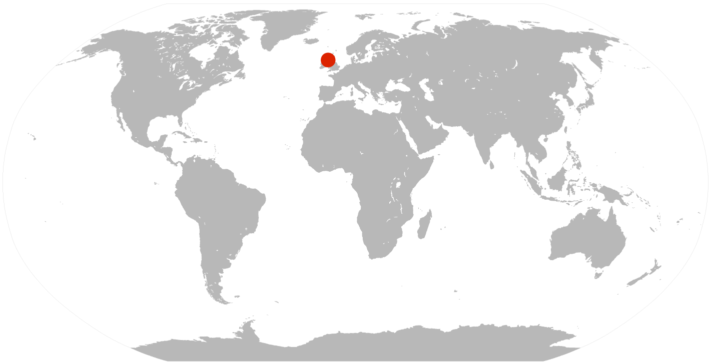




F. Descamps et al. 2009

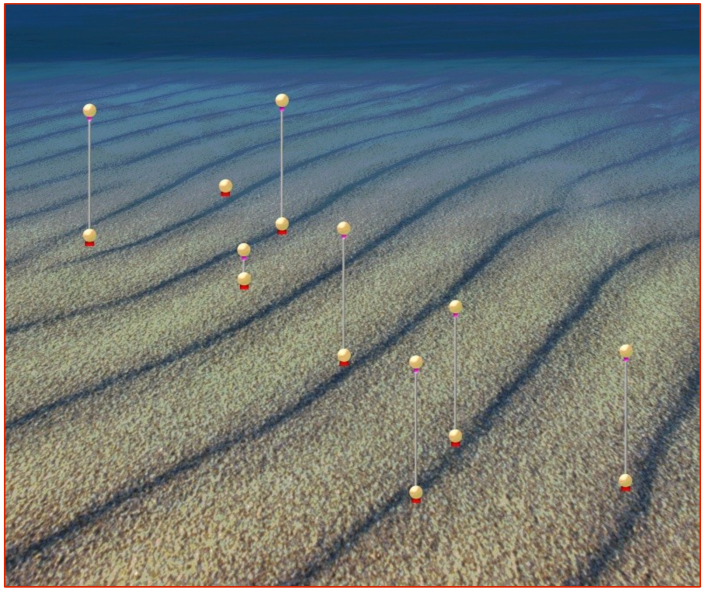
Attenuation length about 300 meters in ice
→ too small for large scale acoustic detector

ACORNE

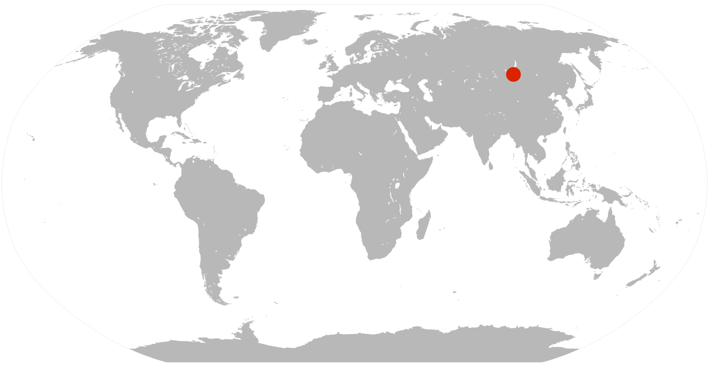


Rona hydrophone array,
a submarine ranging array in North-West Scotland used by the ACORNE experiment

7 hydrophones read out continuously

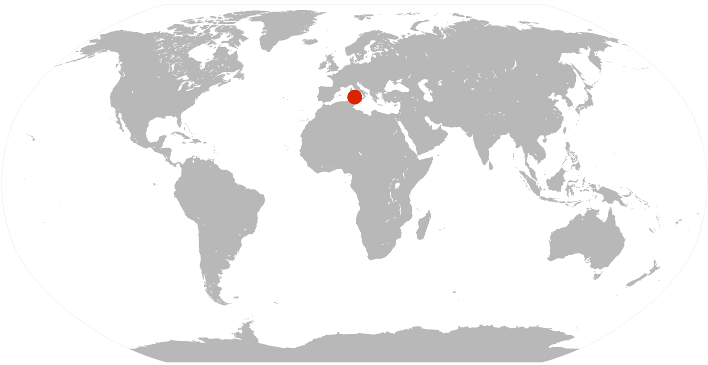


Lake Baikal

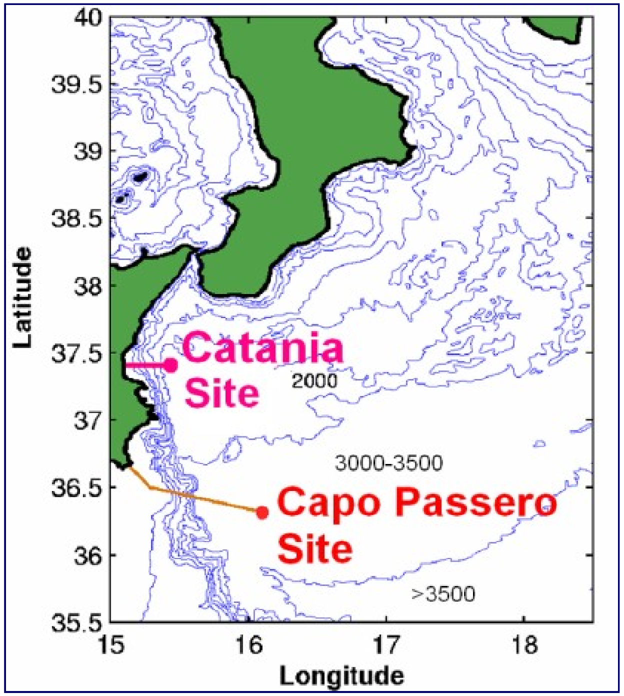


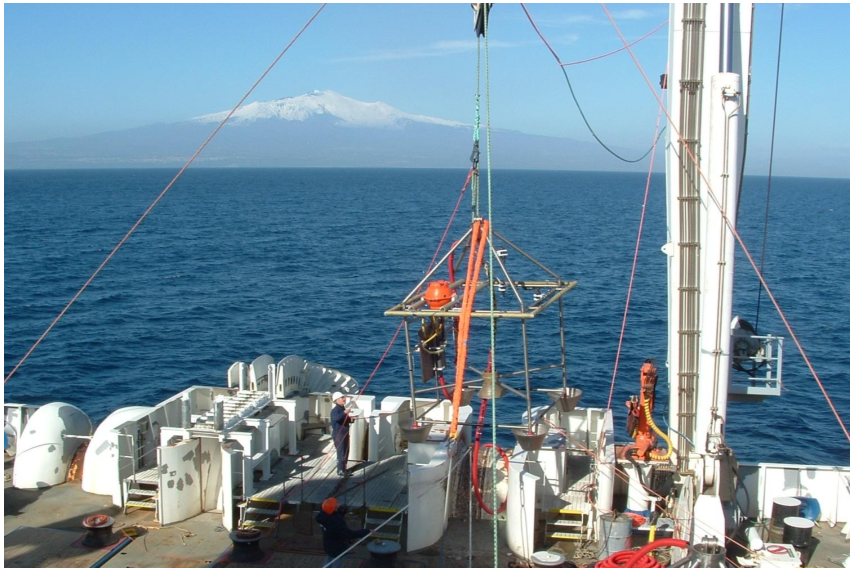
Tetrahedral antenna
4 hydrophones
150 meter depth

ONDE

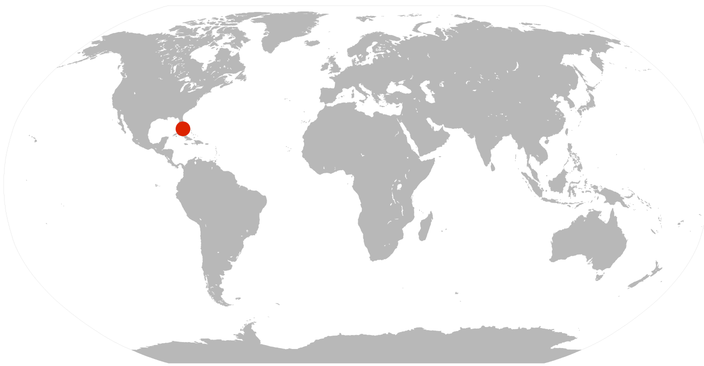


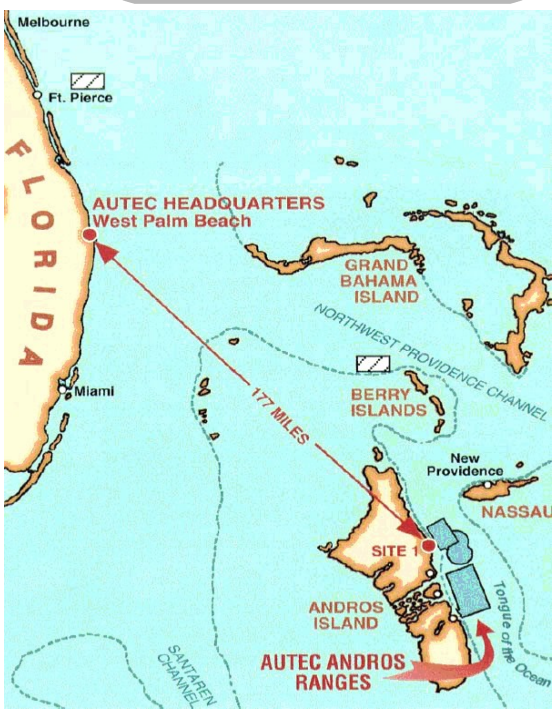
Test Site at 2000 m depth,
25 km offshore Catania.
Operation from 2005 -2006
Recovered in 2008
4 hydrophones

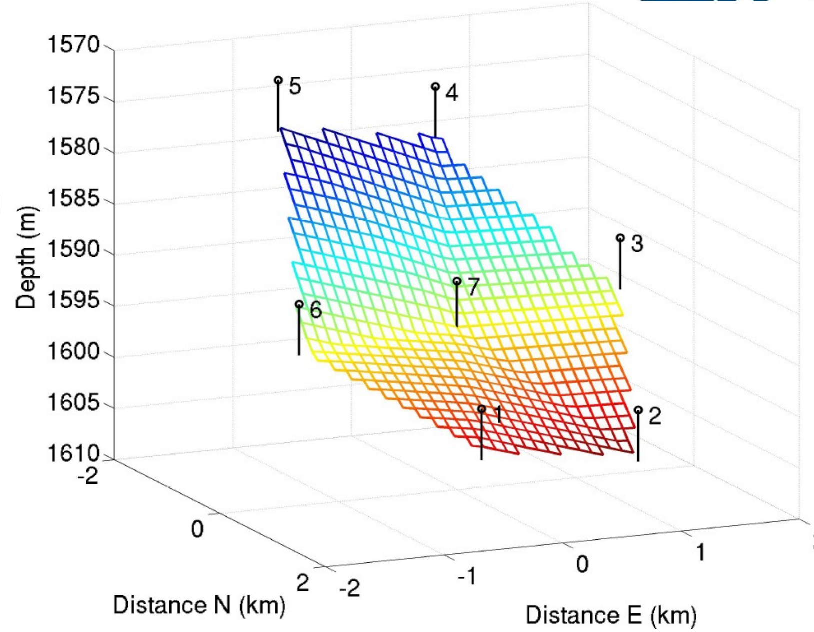




SAUND



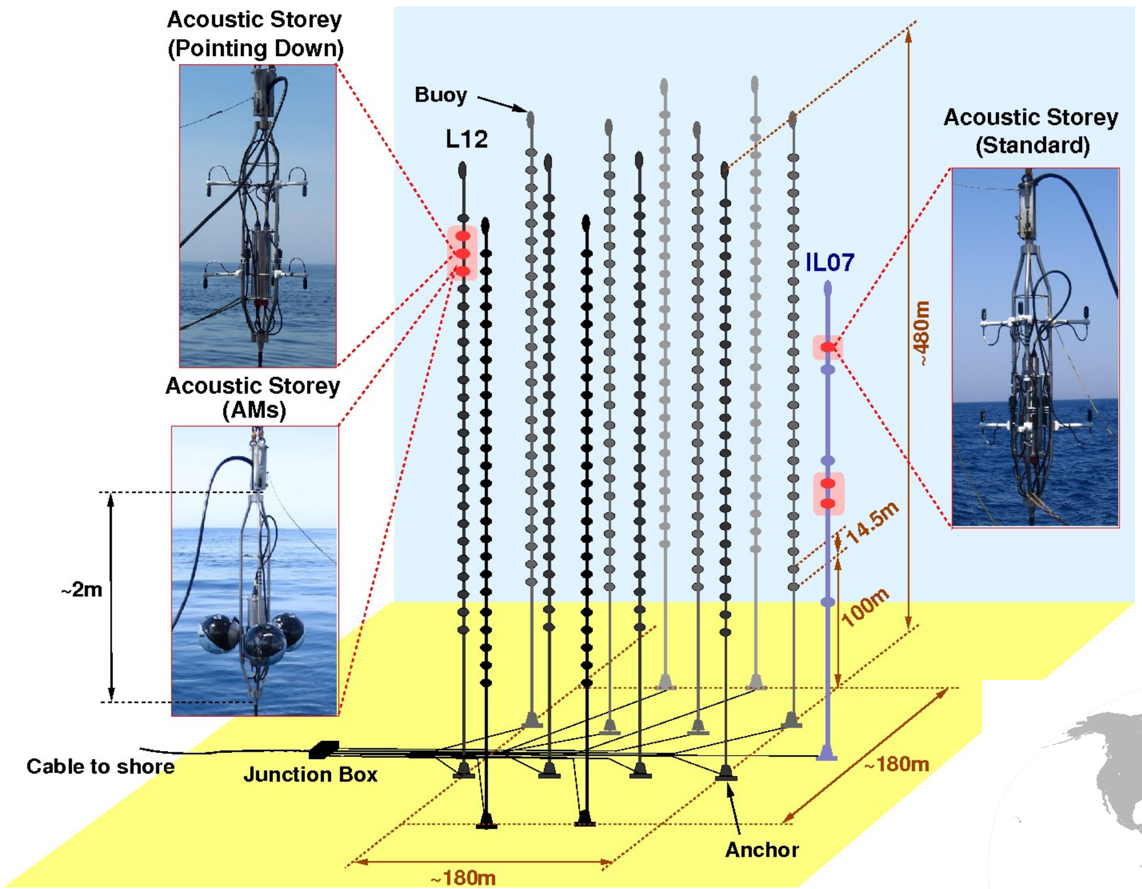




SAUND:
7 hydrophones at 1600 m depth
1.5 km spacing

SAUND II:
49 hydrophones
20 km x 50 km area
Spacing of 3 to 5 km

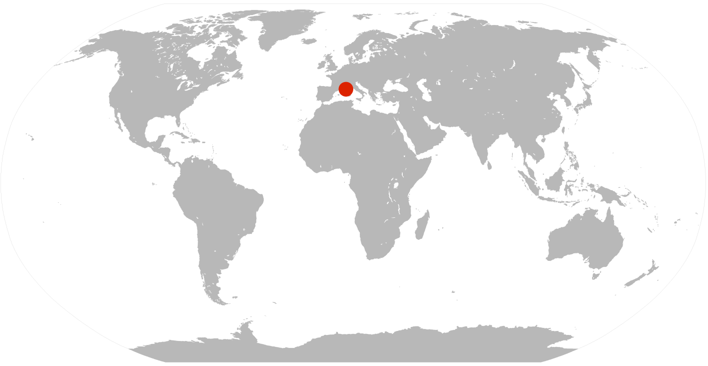
AMADEUS in ANTARES



36 acoustic sensors on 6 stories

Local clusters for direction reconstruction

Depth 2300 – 2100 m



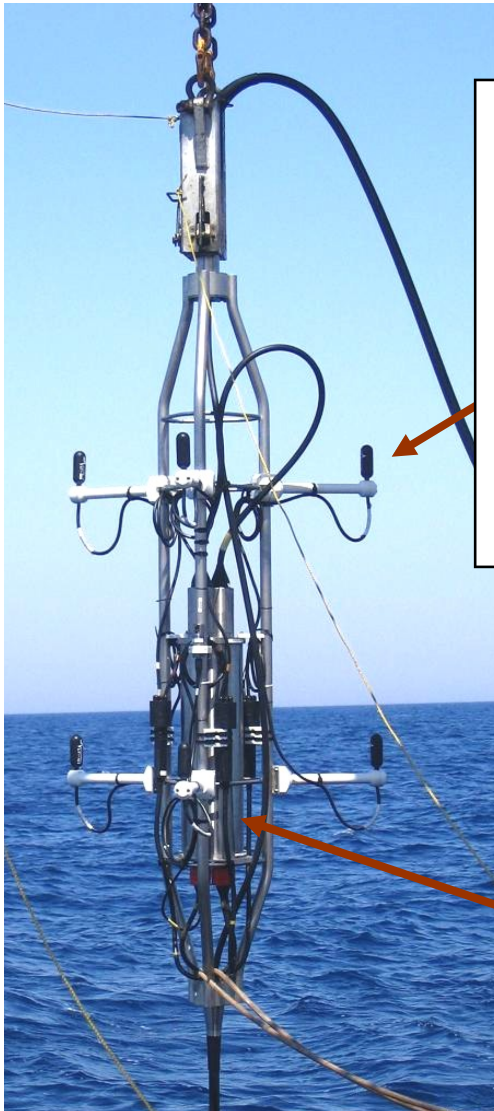
Timeline

- IL07 connected Dec. 2007
- L12 connected May 2008
- Main Cable Interruption June – Sept 2008
- L12 Failure Dec 2008
- L12 recovered and redeployed July 2008

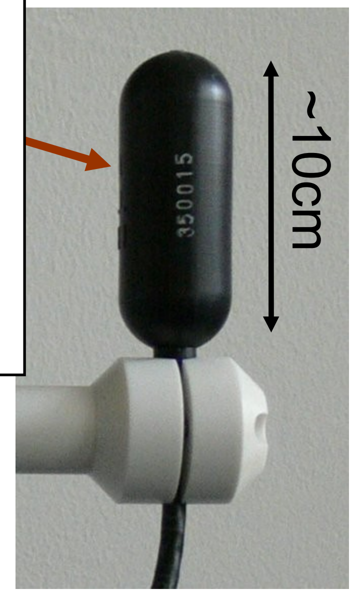
Data from 2-line AMADEUS System Sept – Dec 2008

Setup of Acoustic Storey with Hydrophones

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS



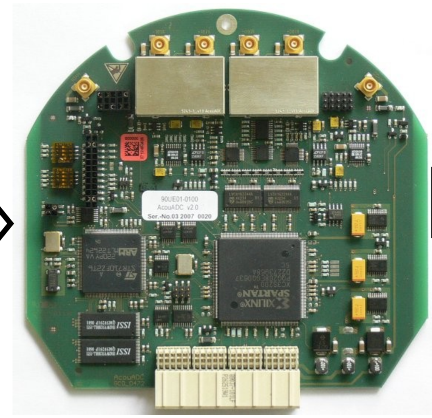
Hydrophone:
Piezo sensor
with pre-amplifier
and band pass filter
in PU
coating
(Typical sensitivity
-145 dB re. 1V/μPa)

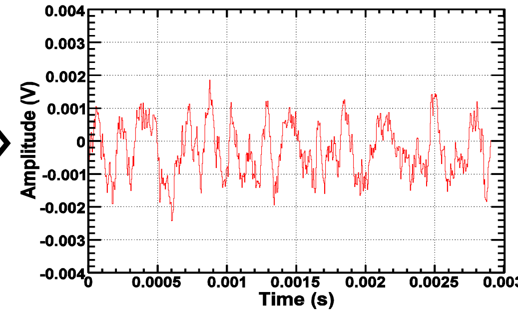


Titanium cylinder
with electronics

3 custom designed
Acoustic ADC boards

AMADEUS Signalkette





Hydrophone
(piezo+preamp)

Filter (analog+digital),
amplifier

The Onshore Filter System

Task:
Reduce incoming data rate of ~1.5 TByte/day to ~15 GByte/day

System extremely flexible, all components scalable

Allows for coincidence triggers on several hydrophones

Local clusters (storeys) big advantage for fast (on-line) processing

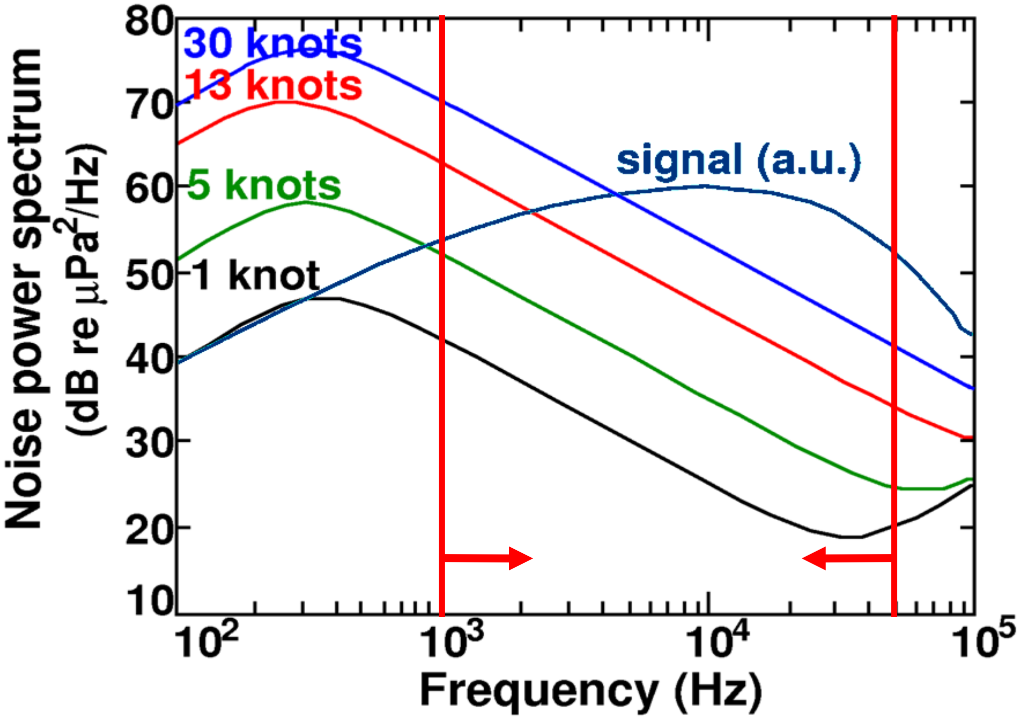
Acoustic servers:
4 servers in total, 2 for filtering: 2 Dualcore, 3 GHz
2 Quadcore, 3 GHz

Film

Akustischer Untergrund in der Tiefsee

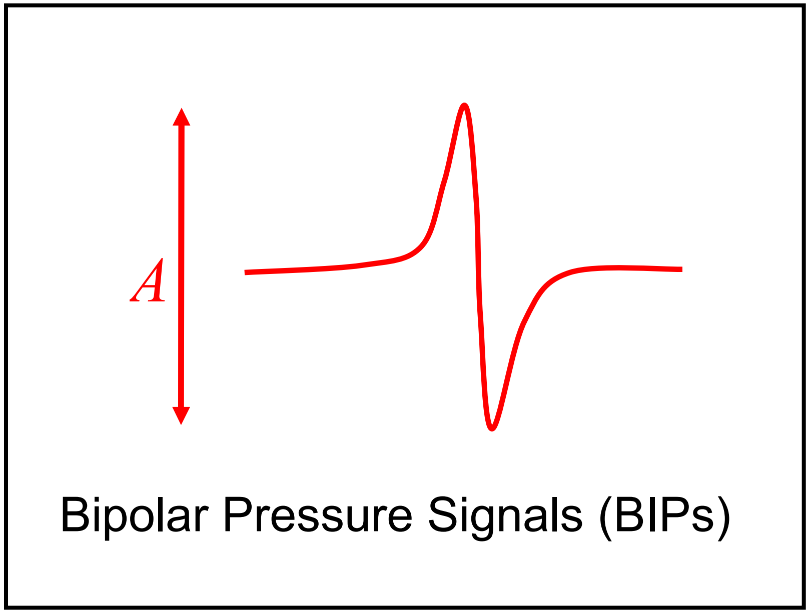
Akustischer Untergrund in der Tiefsee

Statistisches Rauschen



N.G. Lehtinen et al., astro-ph/0104033

Neutrino-ähnliche Signale

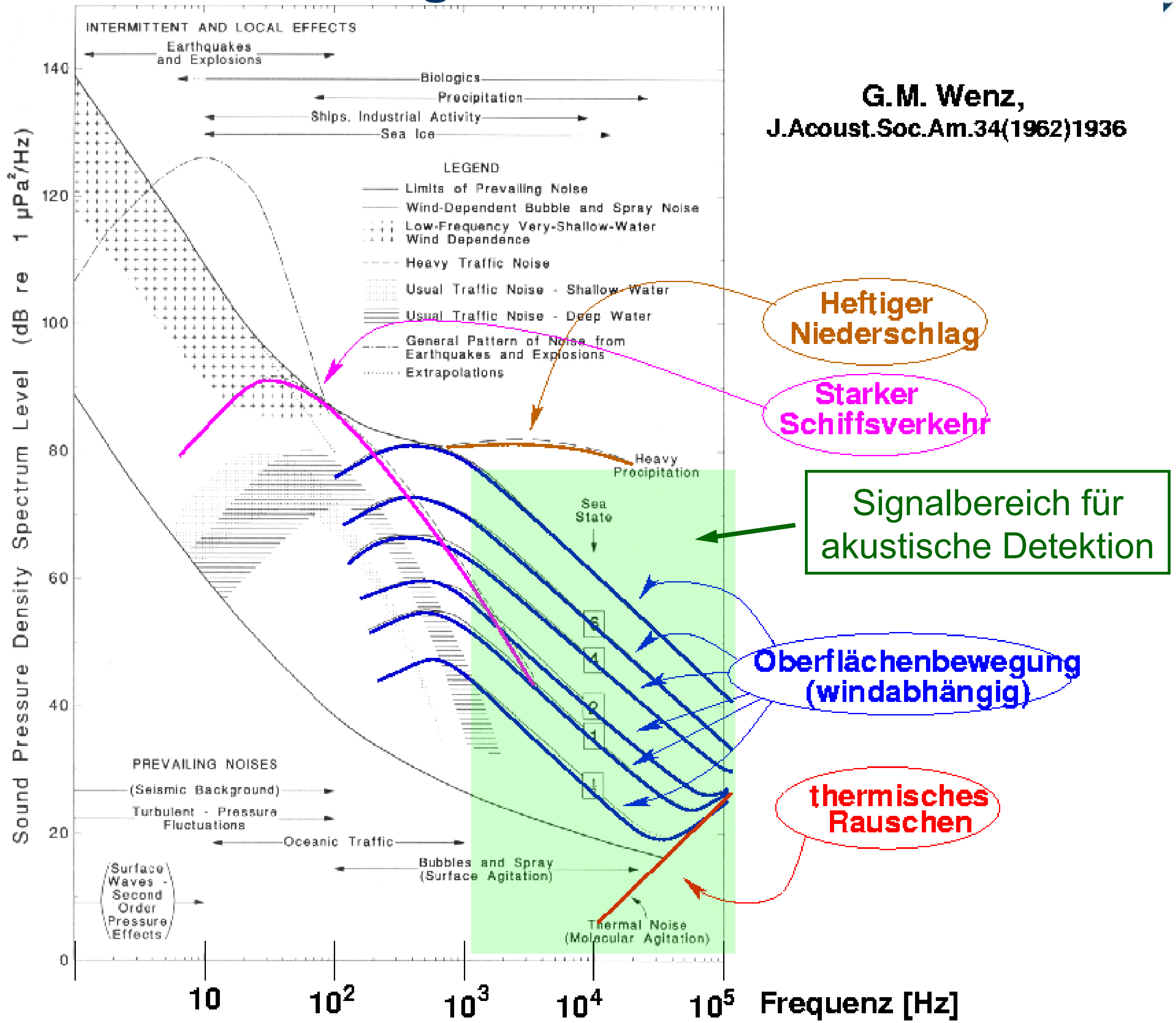


- Ein Hydrophon im Prinzip ausreichend
- Hydrophon-Synchronisierung nicht wichtig

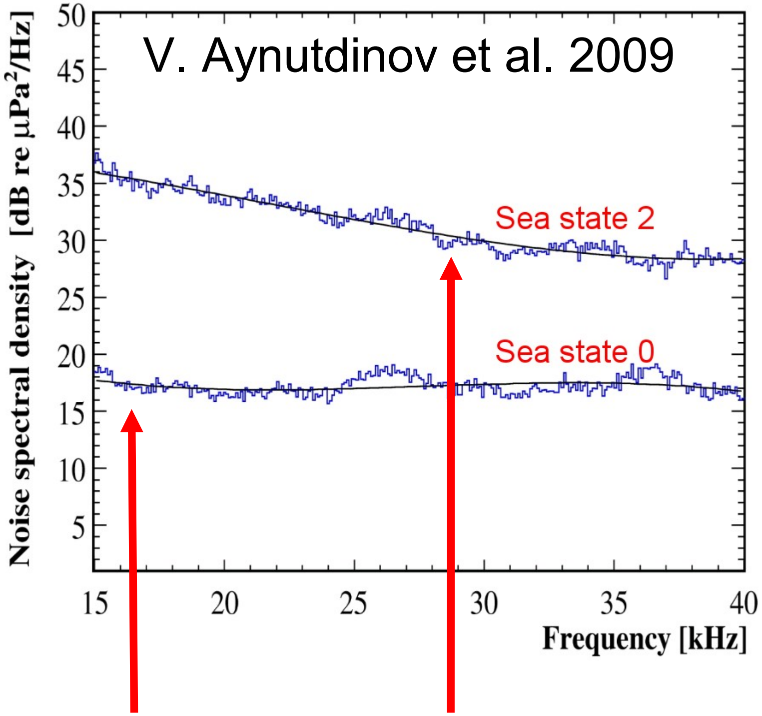
- Hydrophon-Array notwendig
- Hydrophon-Synchronisierung wichtig

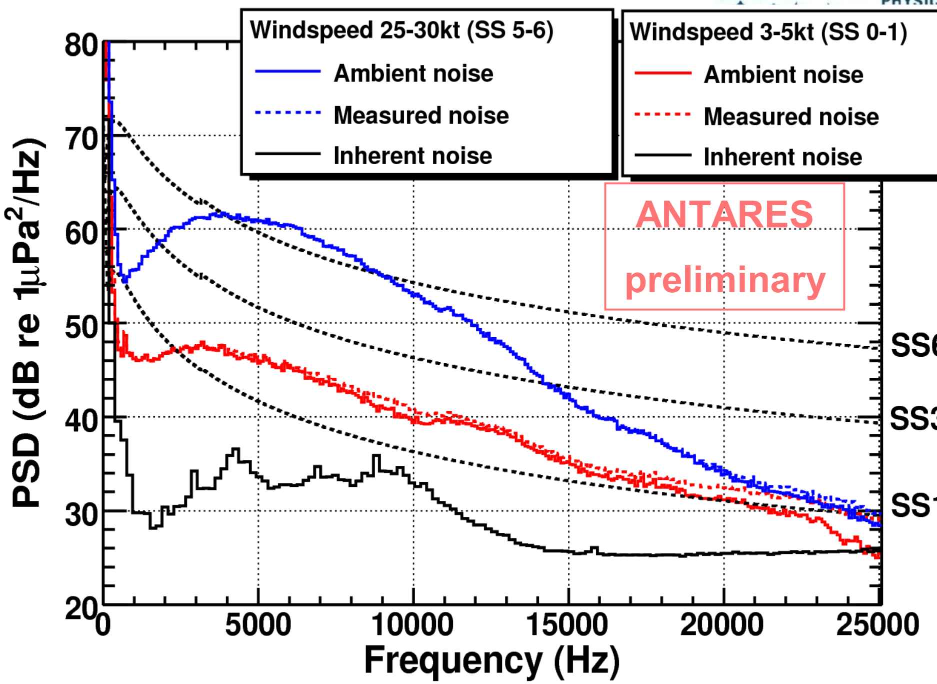
Akustischer Untergrund in der Tiefsee

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Wind-Abhangigkeit des Rauschens



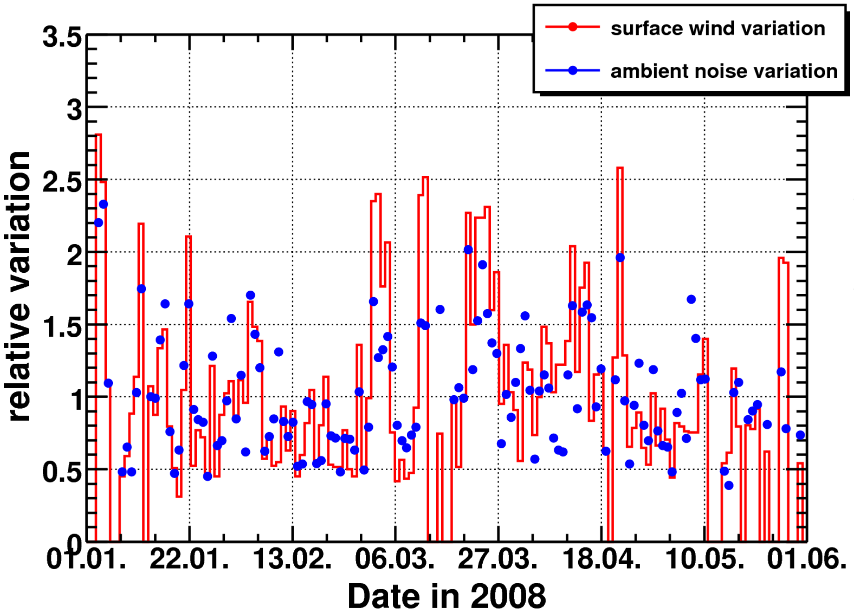


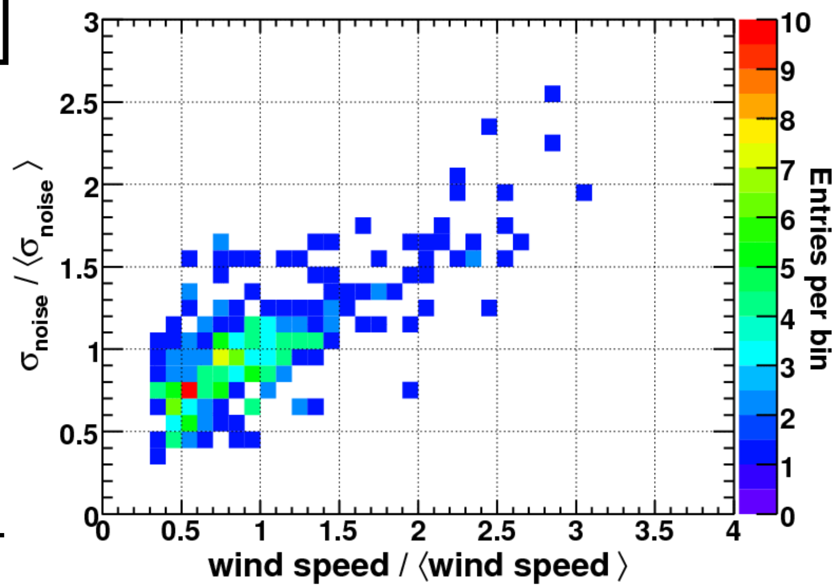
Varying noise conditions in dependence of the sea state are seen by all experiments in water

AMADEUS: Wetterdaten von 5 Stationen

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Correlation with Weather Conditions





Noise correlation measured by the AMADEUS detector
Weather conditions measured at Hyères airport, about 30km north of ANTARES site

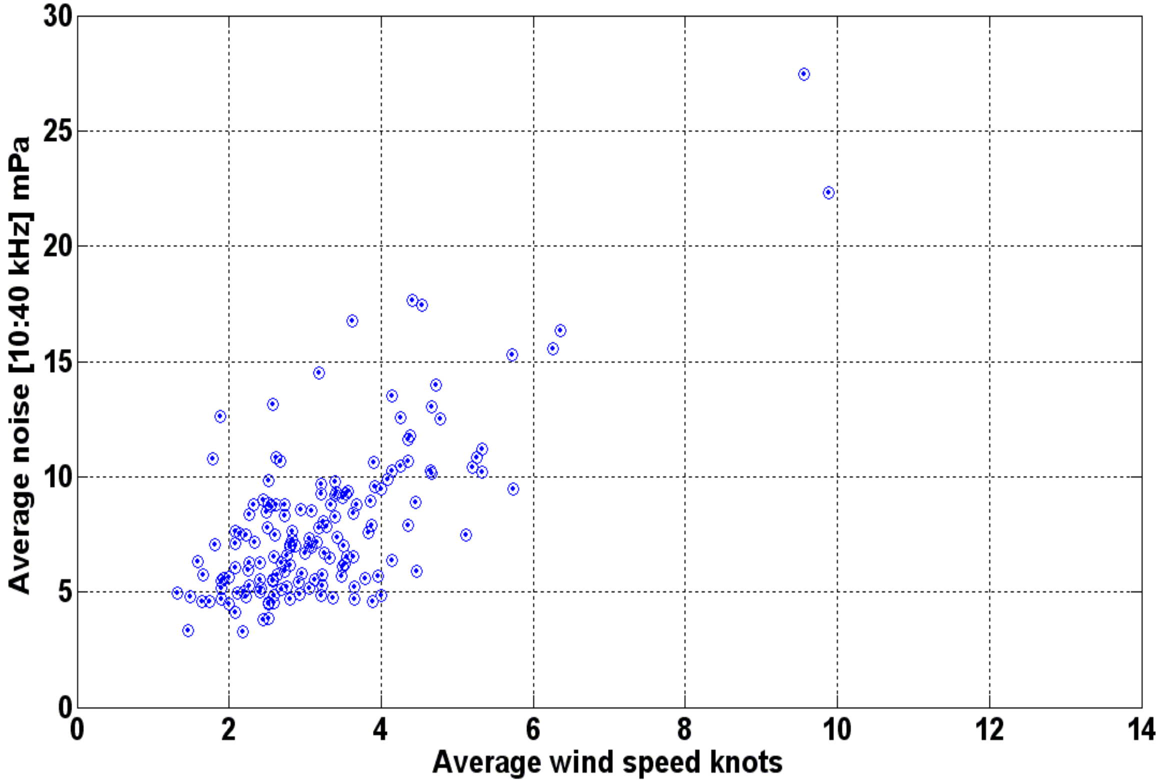
Correlation coefficient ~ 80%

Deep-sea noise dominated by sea surface agitation

Hydrophone noise integrated from 1 to 50 kHz

Correlation with Weather Conditions

Similar behavior seen by the ONDE detector
Wind speed measured 20 km away 155 days (2005, daily average)

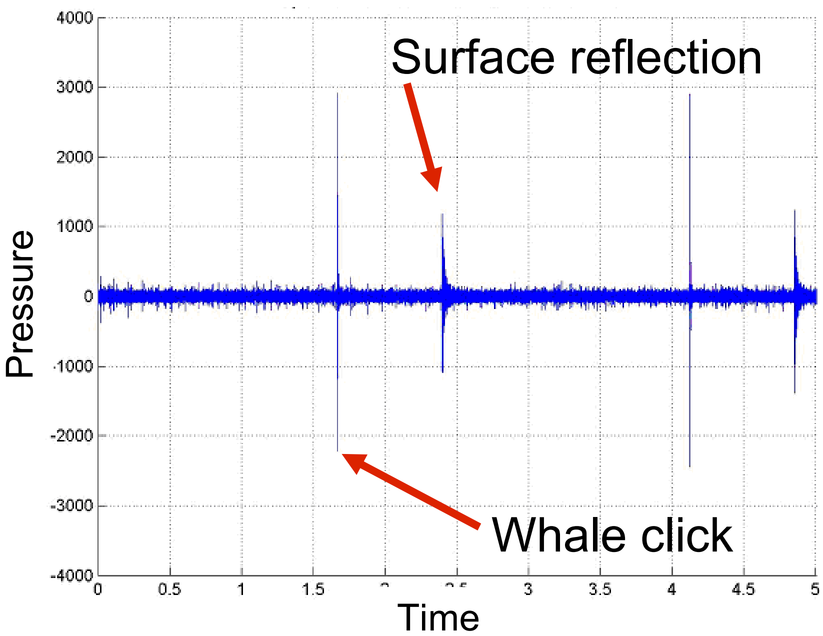


ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Rekonstruktion von Richtung und Ort akustischer Quellen

ONDE – sea mammal tracking

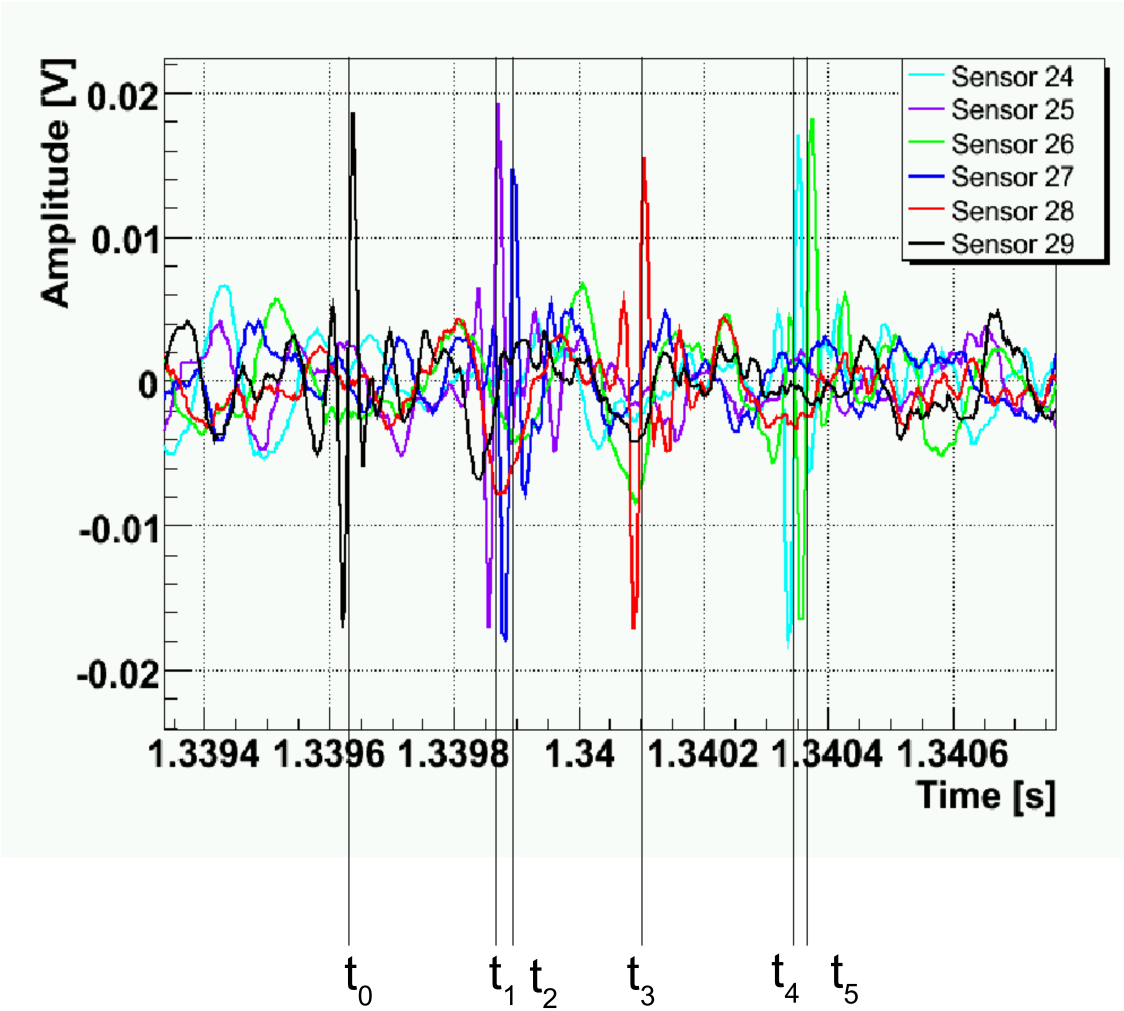
Detection range > 40 km
Tracking of sperm whales
Monitor
- Presence
- Routes

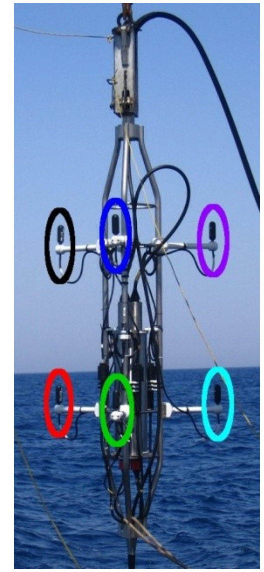


Direction reconstruction using time delays between hydrophones

Depth reconstruction using reflection on surface

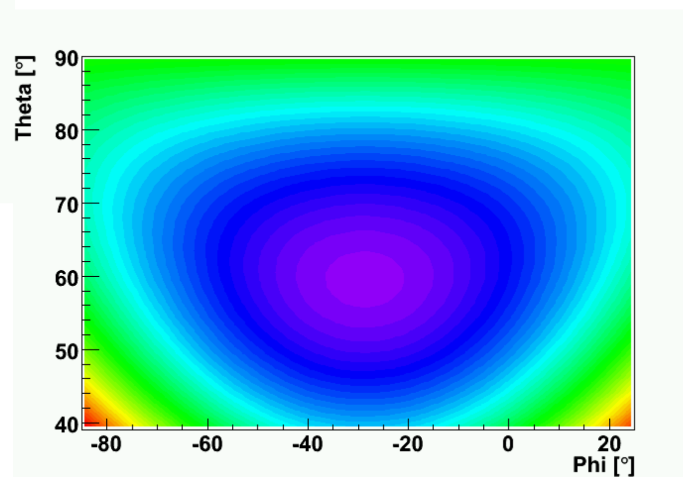
Richtungsrekonstruktion



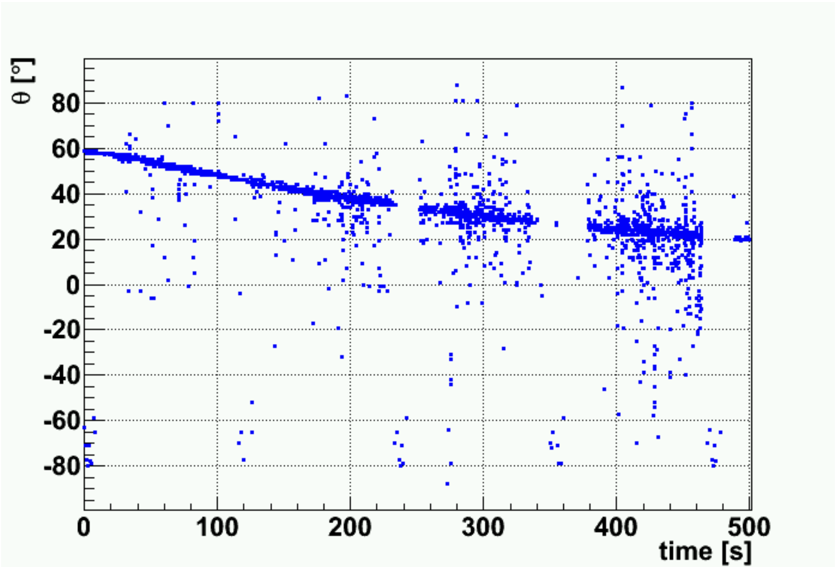


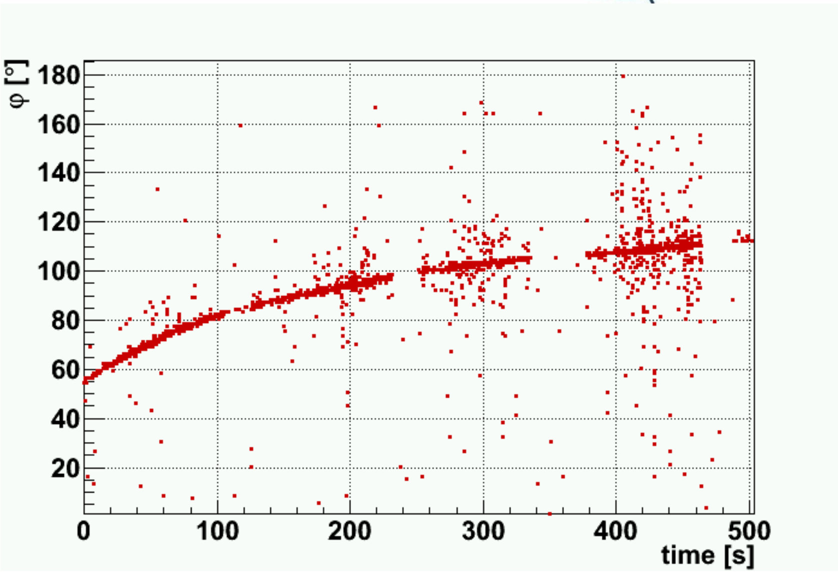
minimize

$$\sum_i \left(t_{i_{measured}} - t_{i_{\exp ected}}(\vartheta,\varphi)\right)^2$$

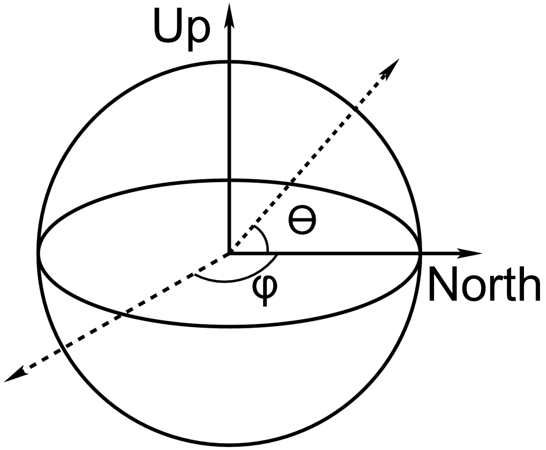


AMADEUS – source tracking



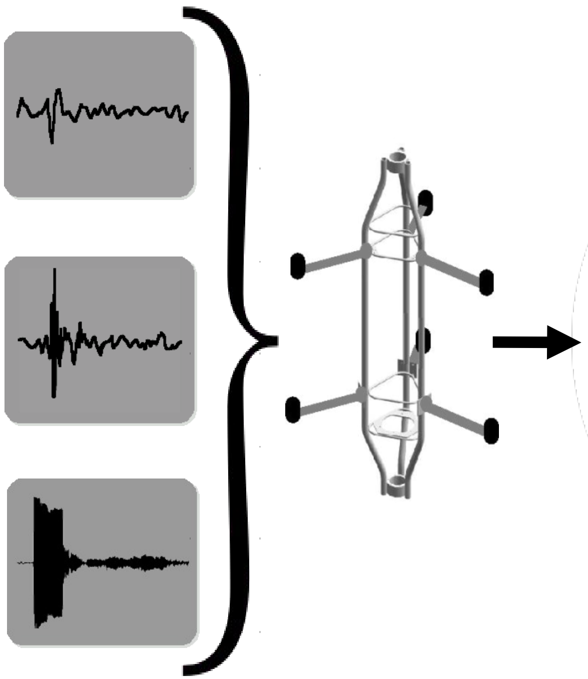


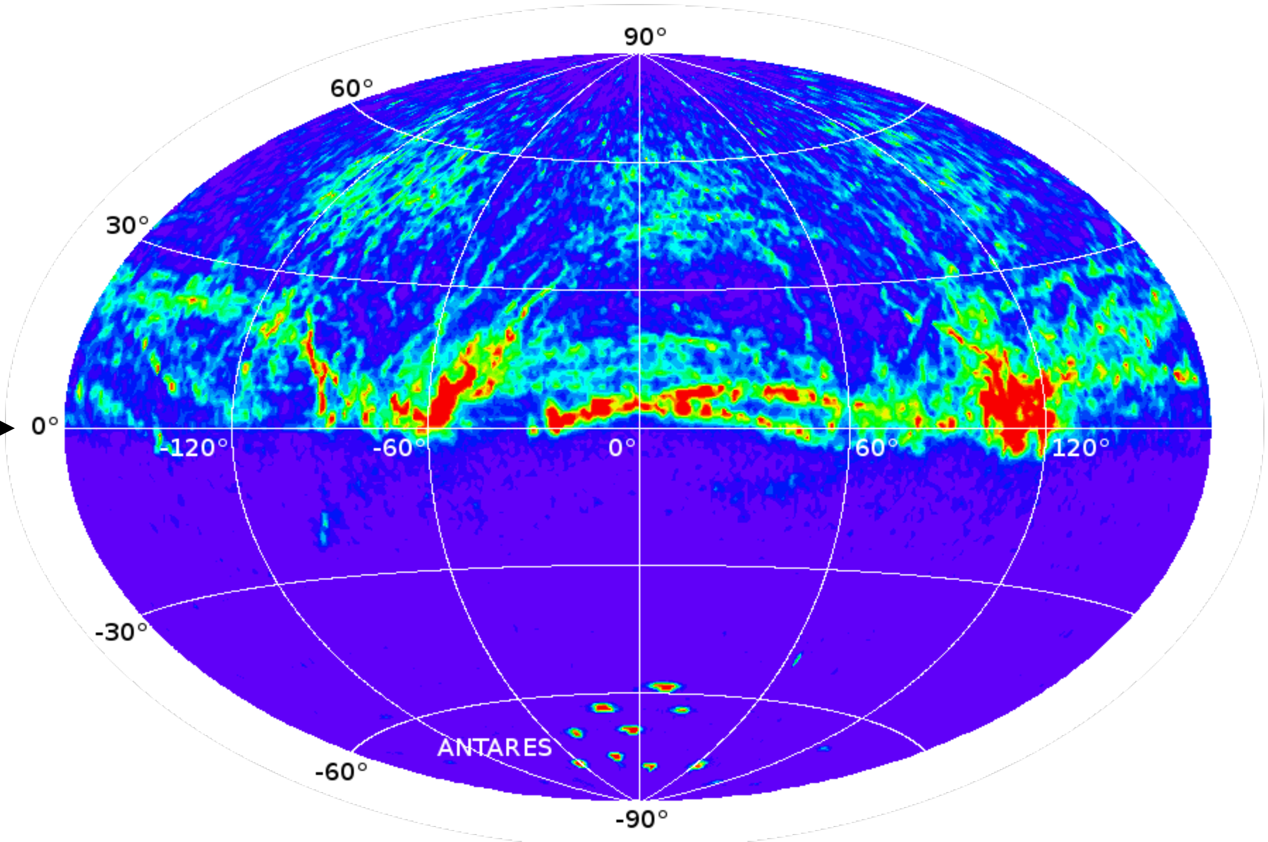
Sample of a moving emitter track interrupted by ANTARES positioning system



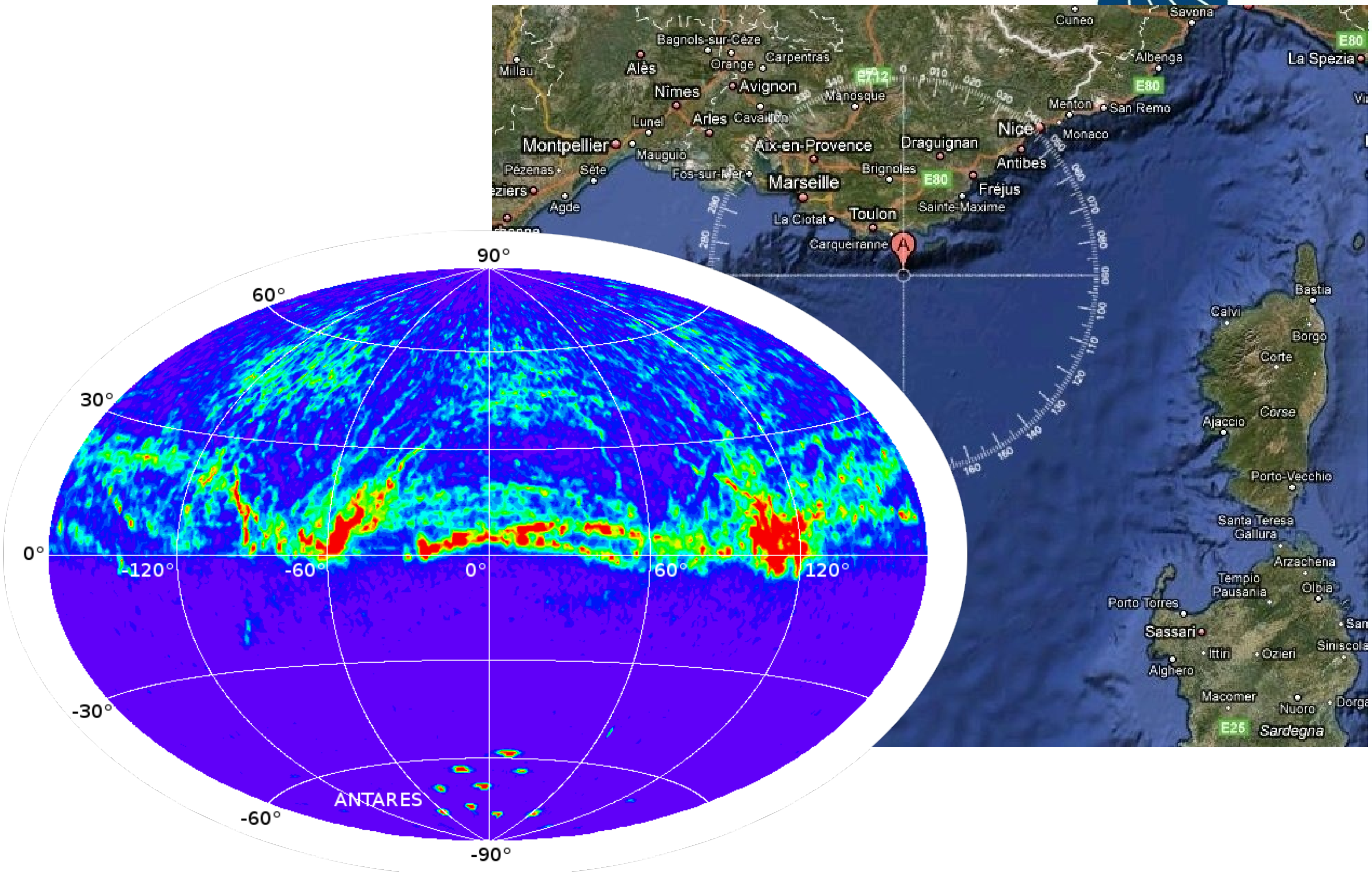
AMADEUS - Source direction distribution

Direction reconstruction for one story
All types of transient signals included, sea mammals, ships etc.
Origin points north to horizon

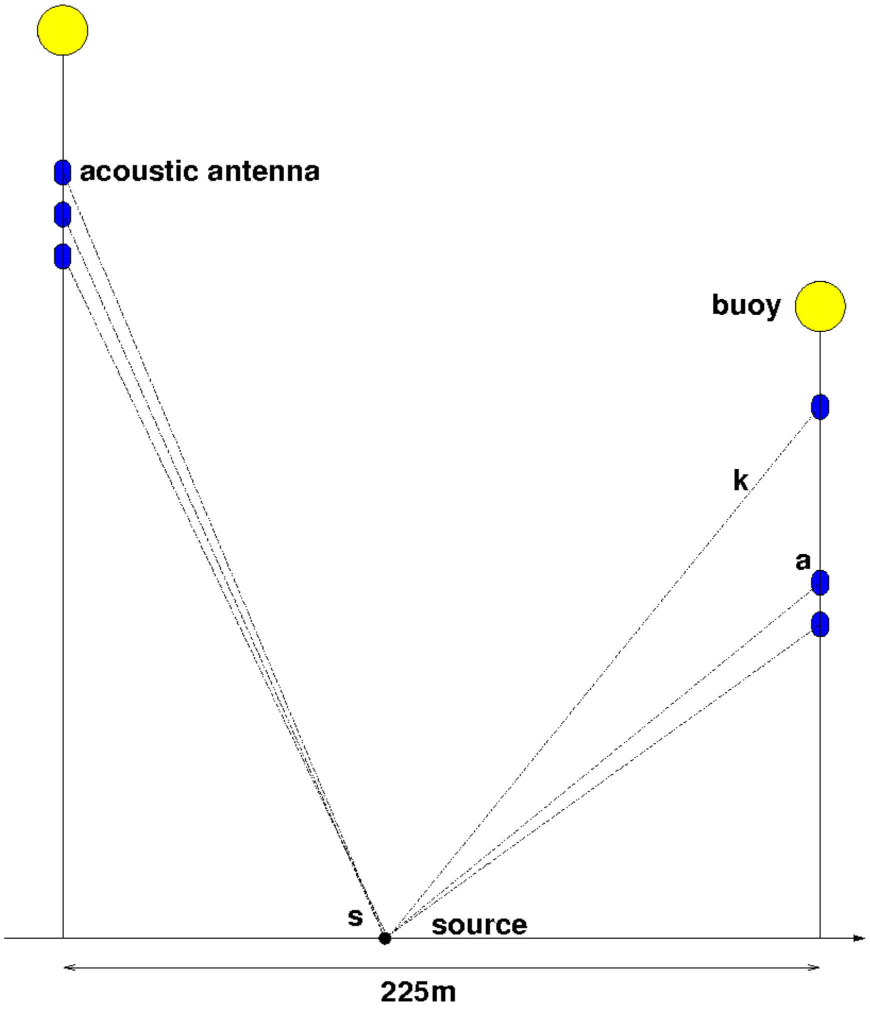




AMADEUS - Source direction distribution



Source reconstruction – from “ray tracing”



Minimisation of distance between recontructed “rays”

$$\frac{\partial}{\partial \vec{s}}\left(\sum^{N}\left(\vec{s}-(\vec{a}_i+n_i\cdot\vec{k}_i)\right)^2\right)=\vec{0}$$

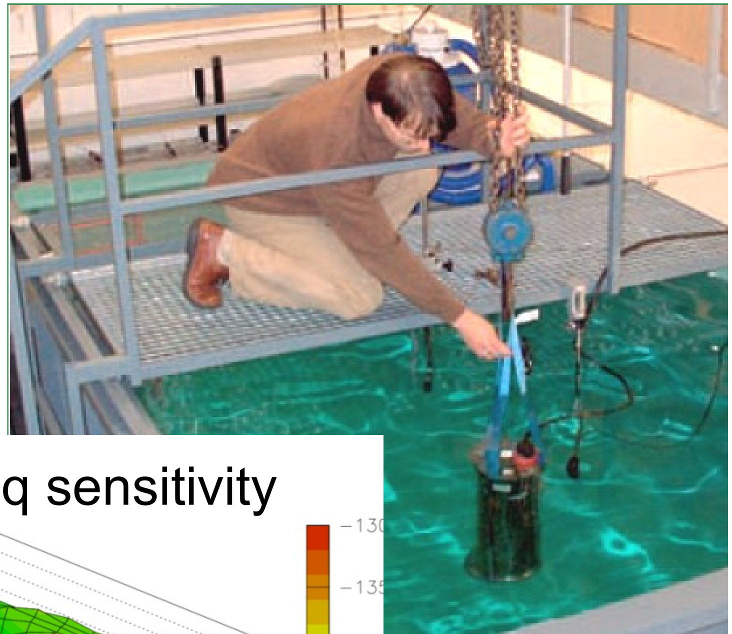
$\vec{s}=source$

$\vec{a}=story\ position$

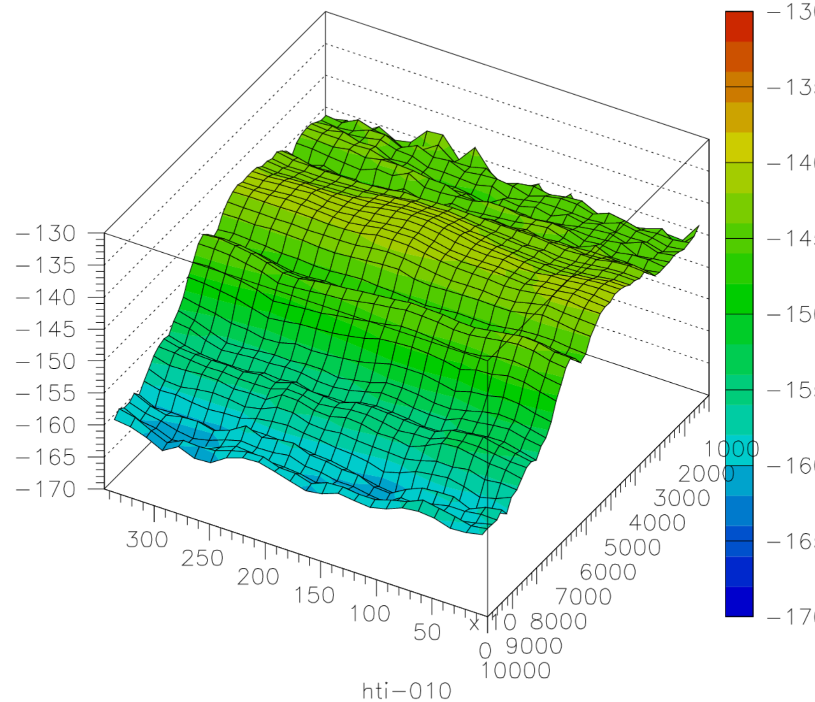
$\vec{k}=reconstructed\ direction$

AMADEUS: Das System Kalibrieren und Verstehen

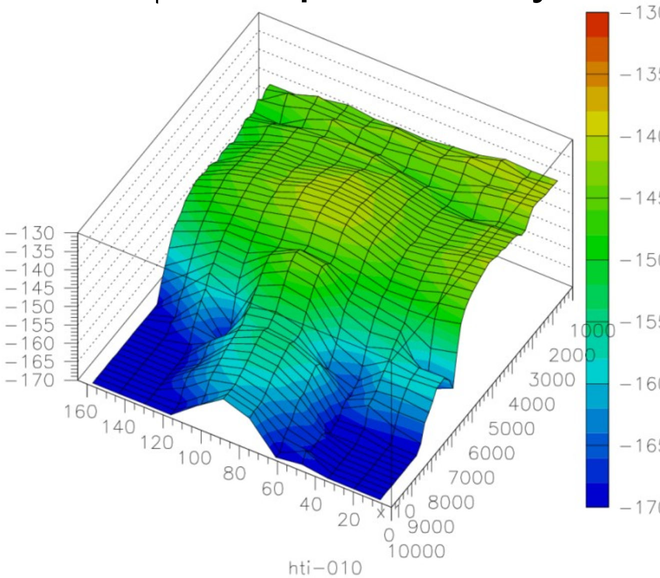
Directional Calibration of Hydrophones



φ - freq sensitivity



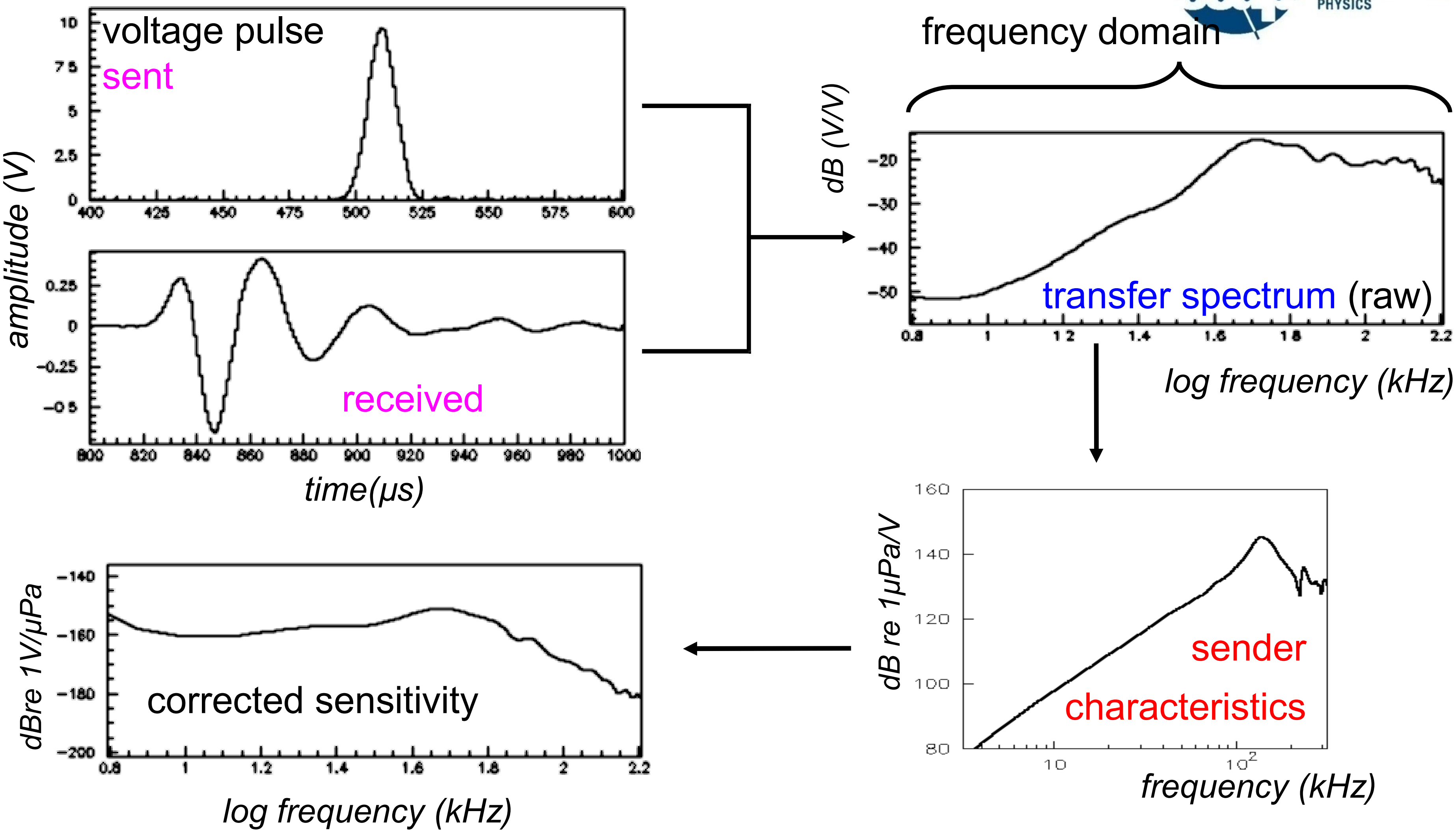
ϕ - freq sensitivity



Sensitivity measured with calibrated hydrophone, confirmed with reciprocity method

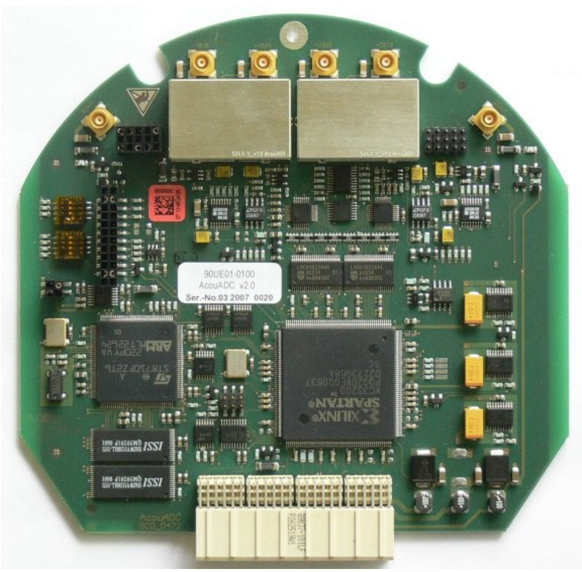
In-situ measurements planned

Hydrophone Sensitivity Measurement - Principles



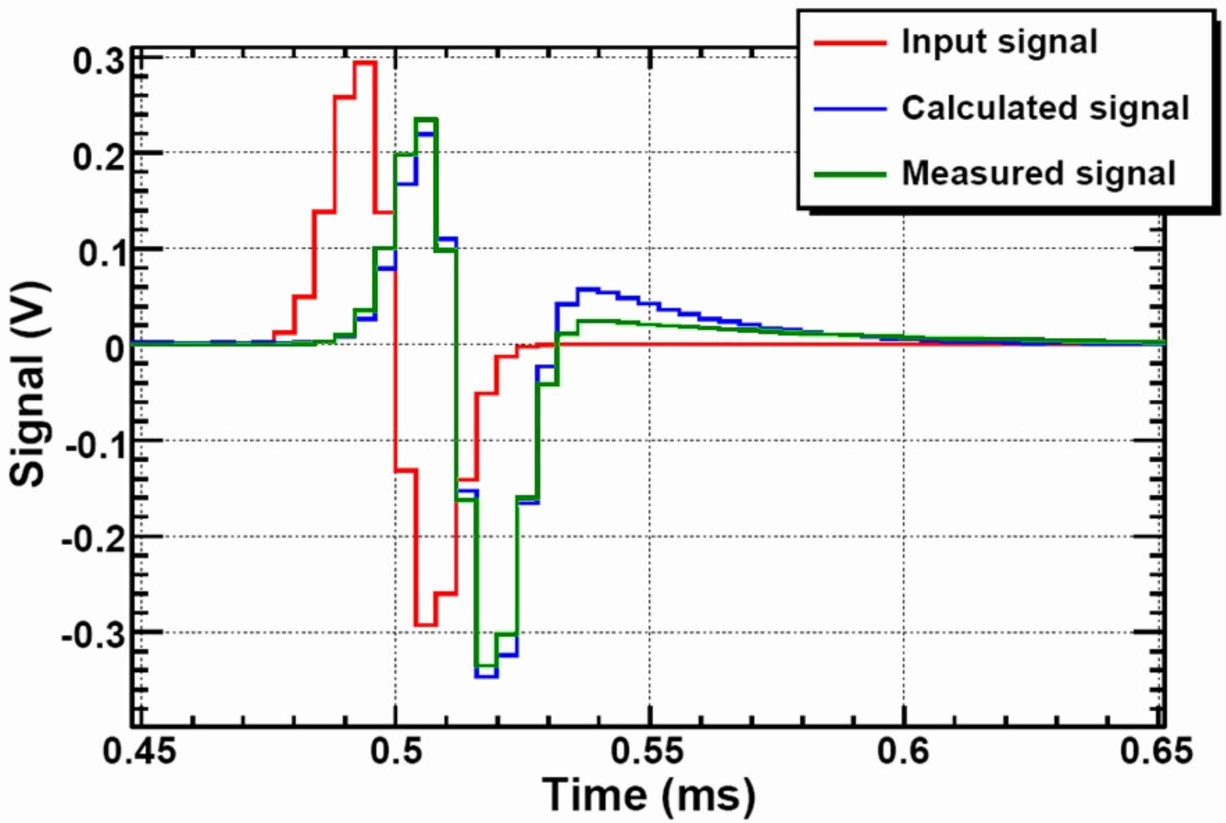
Characteristics of the Acoustic ADC boards

3 Acoustic ADC boards (AcouADC boards) used per storey, each processing 2 sensors



- 16 bit digitisation (-2V to +2V)
- Bandwidth up to ~125 kHz
- Adjustable digitisation rate, max. 500 kSamples/s (Currently using downsampling 2: 250 kSamples/s transmitted to shore, i.e. 3MByte/s for 6 hydrophones)
- System extremely flexible due to use of FPGA off-shore (downsampling, adjustable gain 1 to 562, off-shore firmware updates possible)

Signal Response of AcouADC Board



Very good agreement between real and modelled system response

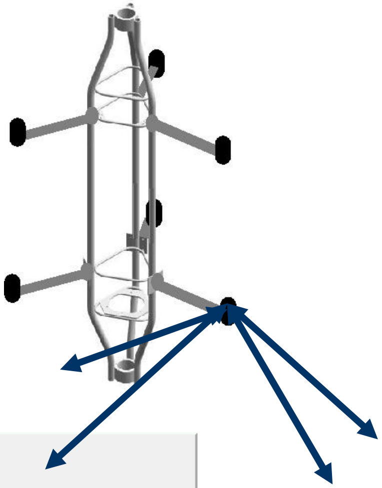
Method for Position Reconstruction

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

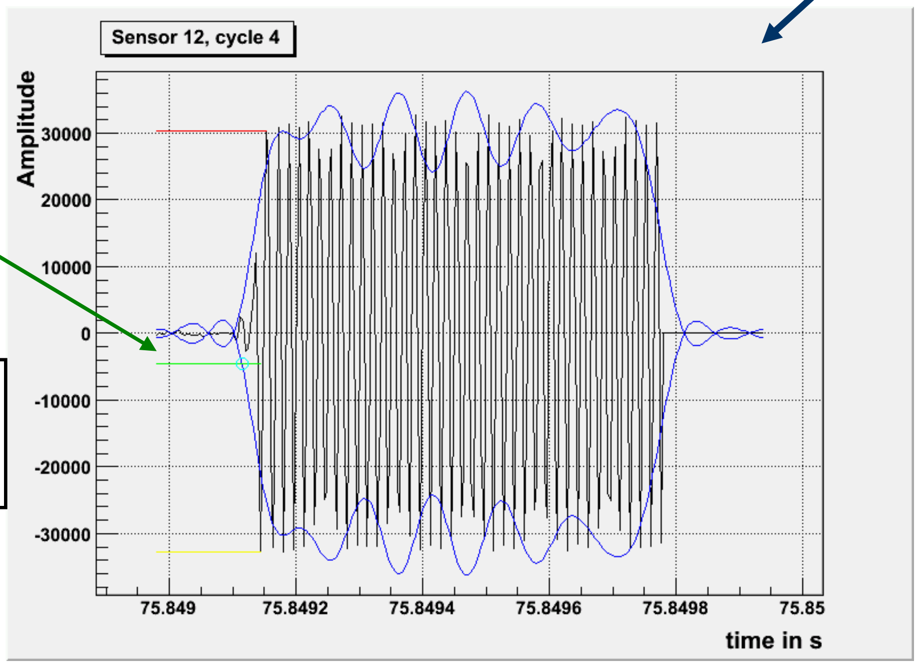
Main Method – using database info about emission time of pinger signals

- positioning of individual sensors
- use absolute time from > 3 pingers:

$| r_{reception} - r_{emission} | = c_s * (t_{reception} - t_{emission} - t_{offset})$

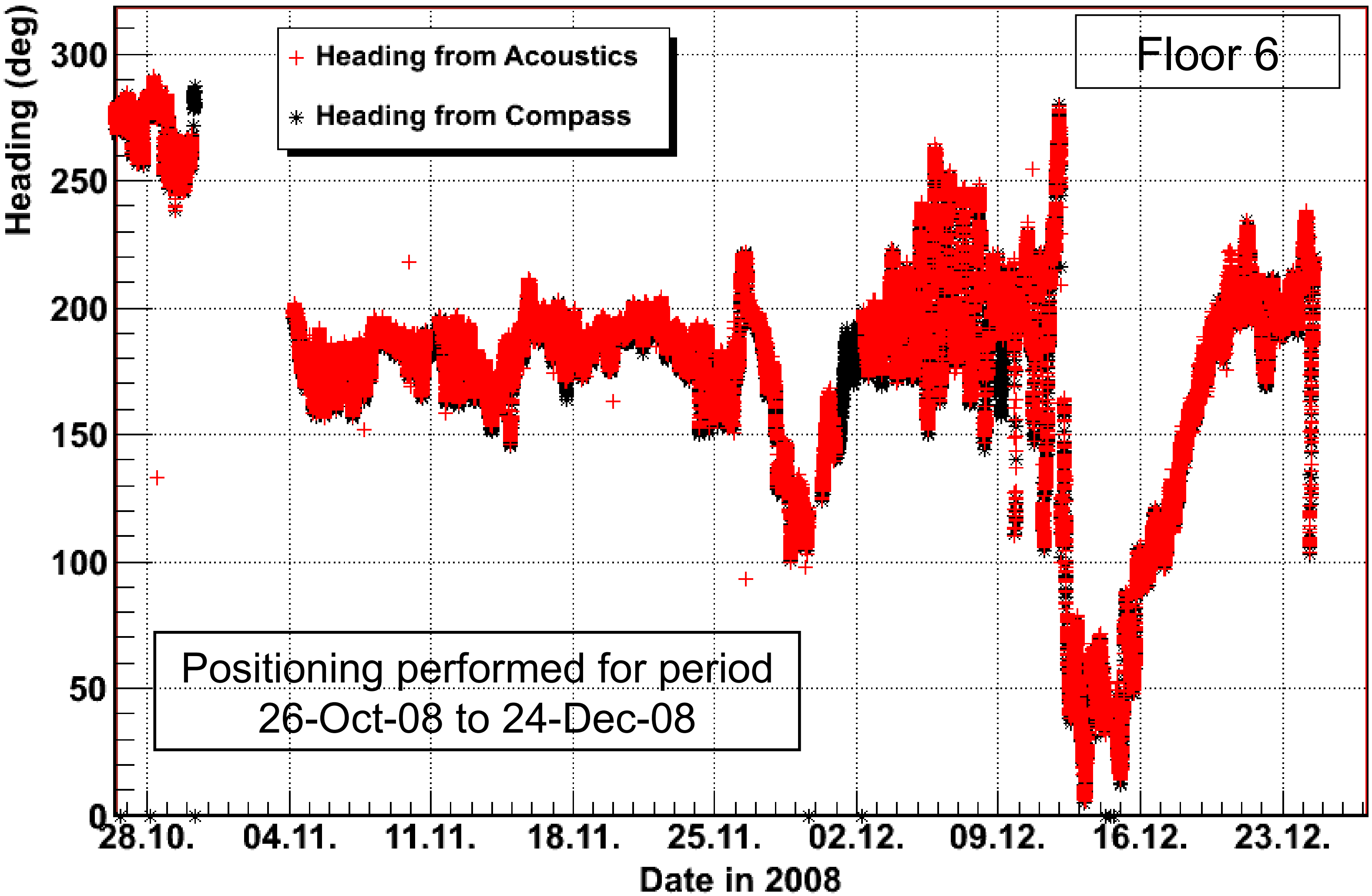


Threshold crossing defines $t_{reception}$

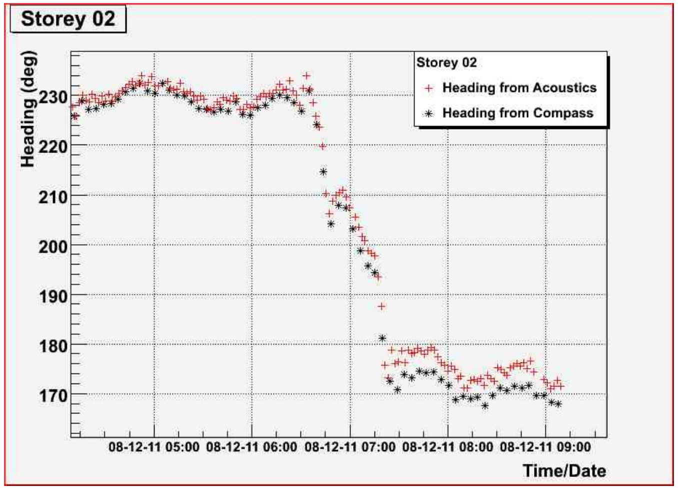


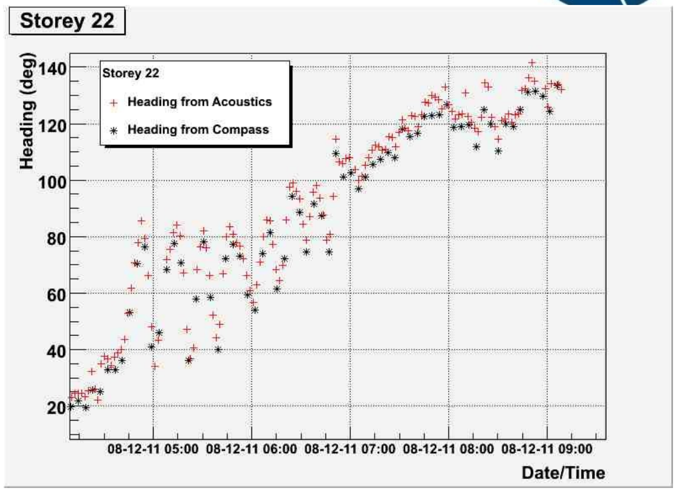
Get position/orientation by fitting storey geometry

Heading Reconstruction with AMADEUS

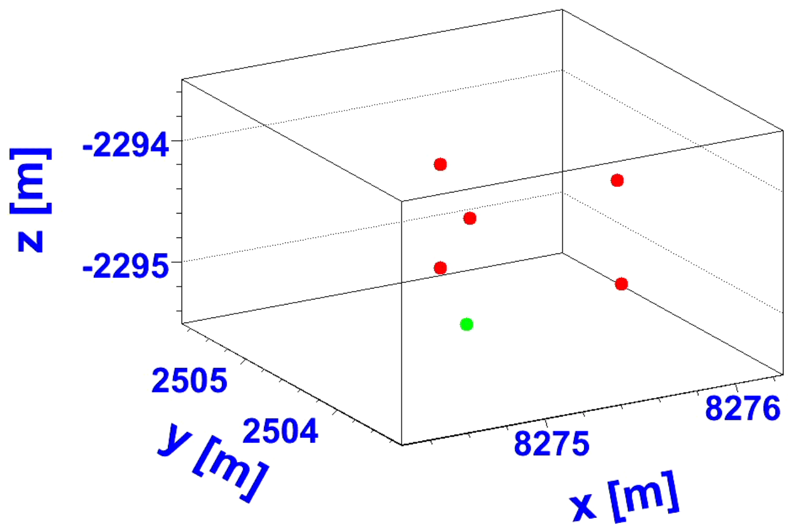


Position Reconstruction: Example

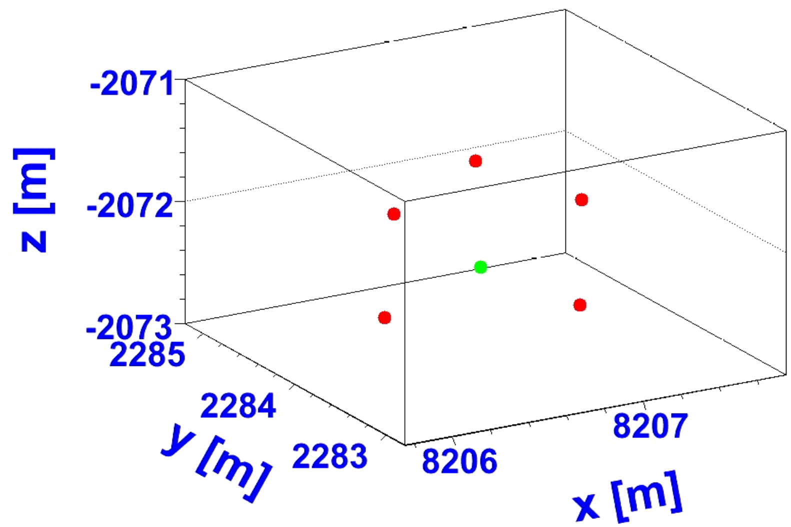


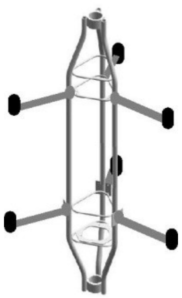


IL07F02, Run 37762 on 20081211 at 041006h



L12F22, Run 37762 on 20081211 at 041006h





ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

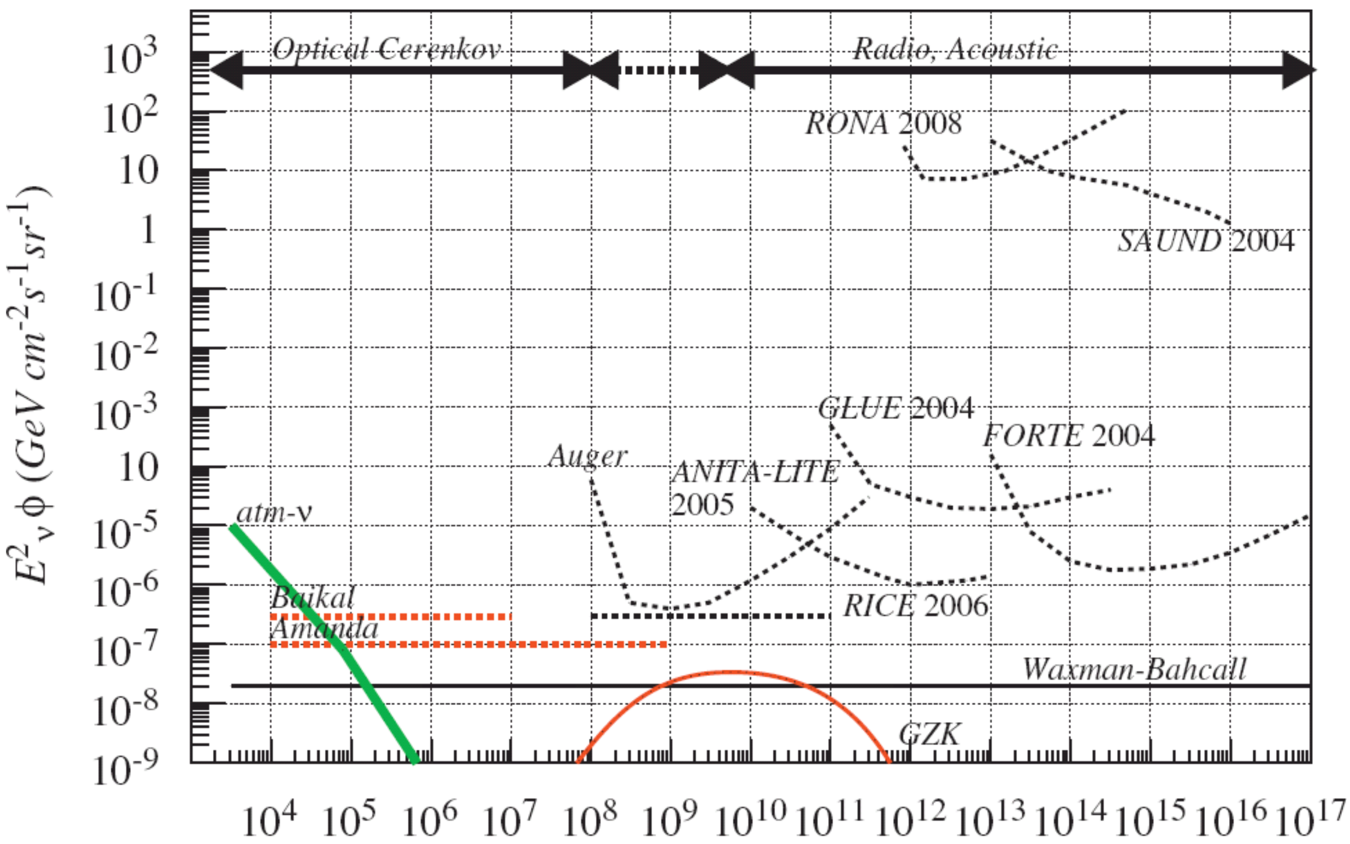
The Road Ahead

Wie bekommt man ein Flusslimit?

- Datennahme über einen möglichst langen Zeitraum; Berechnung der effektiven Messzeit
- Rekonstruktion von neutrinoähnlichen Signalen in einem definierten Volumen („fiducial volume“)
- Monte-Carlo-Simulationen:
  - Neutrino-Fluss
  - Wechselwirkungsquerschnitt
  - Schallerzeugung durch thermoakustisches Modell
  - Schallpropagation
  - Signalerzeugung im Detektor
- Keine Beobachtung: Flusslimit

ACORNE (RONA) / SAUND - Upper limit

Upper limits have been calculated for the RONA array and the SAUND detector



Bevan et al. 2009

Zukunft der akustischen Neutrinodetektion

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Nächste Chance für Akustik:
  KM3NeT (Wahrscheinlich Multipurpose akustisches System für Positionierung, Meeresforschung, Neutrinodetektion)
- Abschätzung der notwendigen Dimension (T. Karg, Doktorarbeit 2006):
  1500 km^3 mit 200 Sensorclustern/ km^3 notwendig

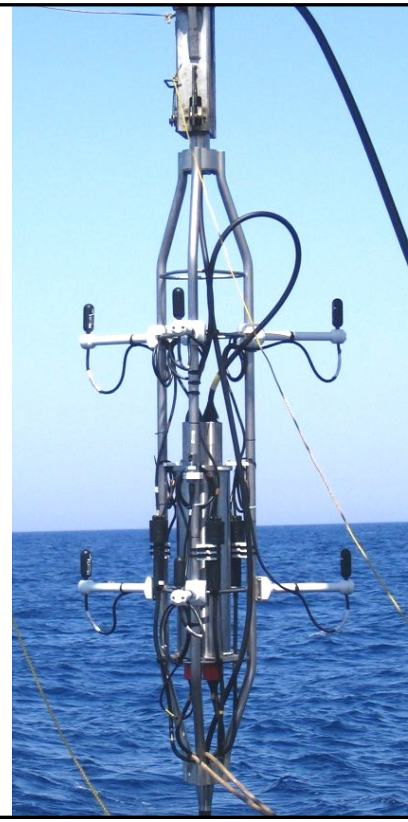
Zusammenfassung

Backups transparencies

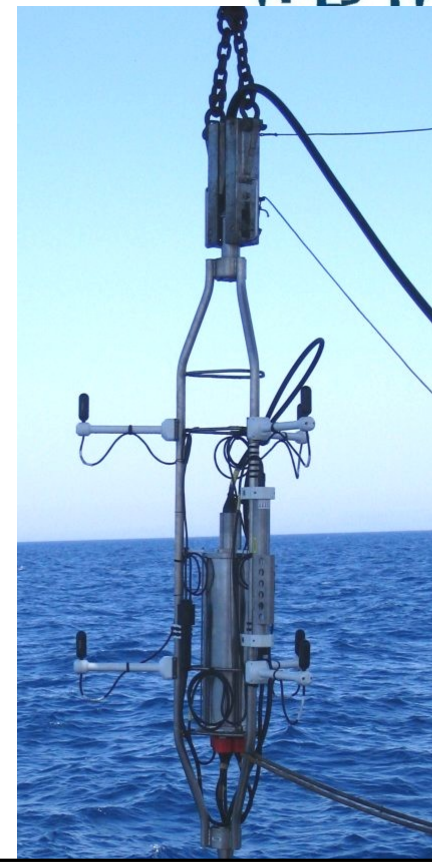
Acoustic Storeys on the IL07

Deployment July 2007

Storey 2
(6 commercial sensors)



Storey 3
(6 sensors produced at Erlangen)



Storey 6
(6 commercial sensors)

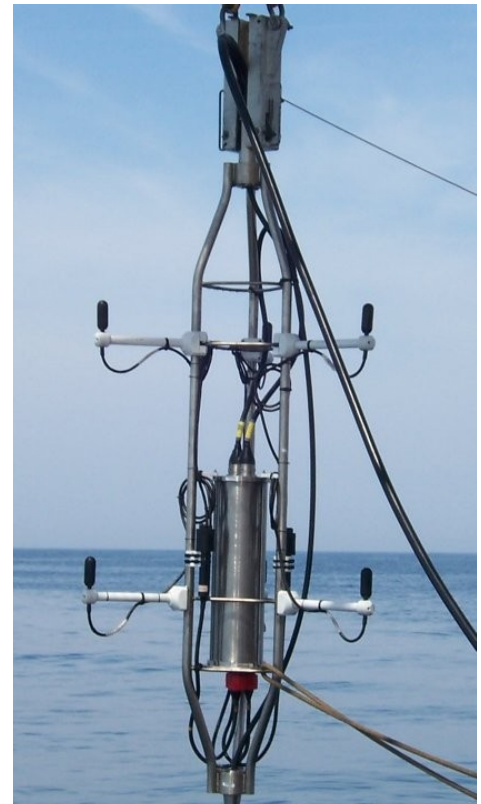
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Acoustic Storeys on Line 12

Deployment May 2008

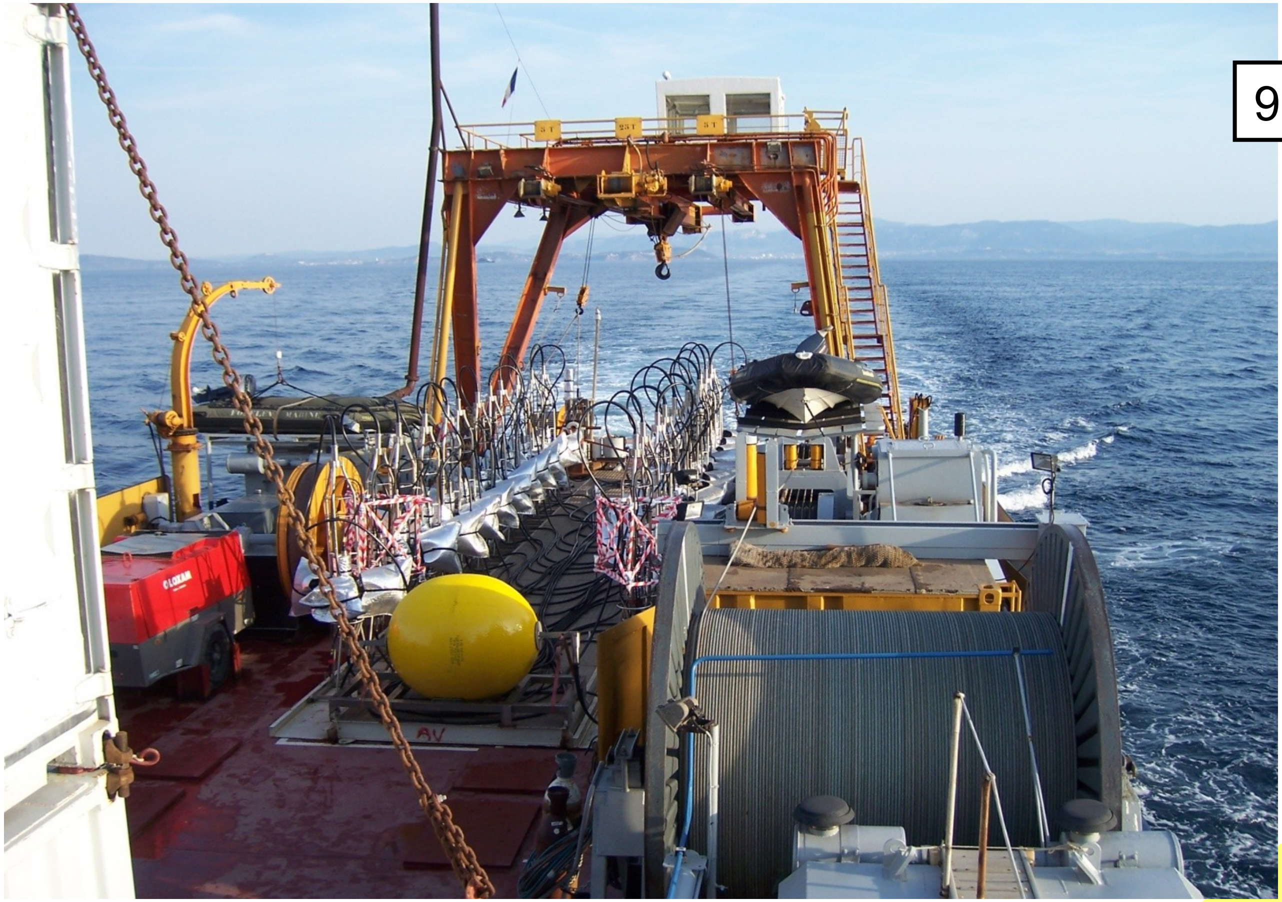
Storey 21
(3 “Acoustic Modules”, 6 sensors in total)

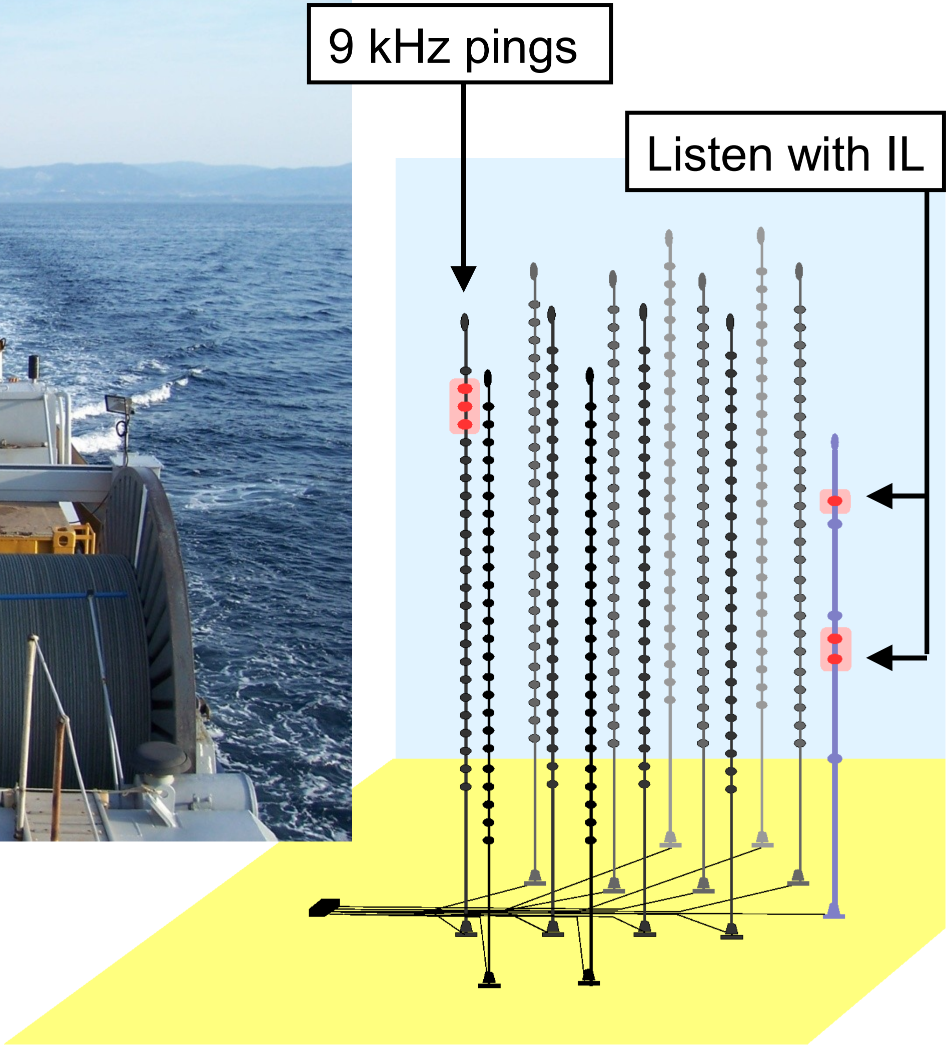
Storey 22
(6 commercial sensors)



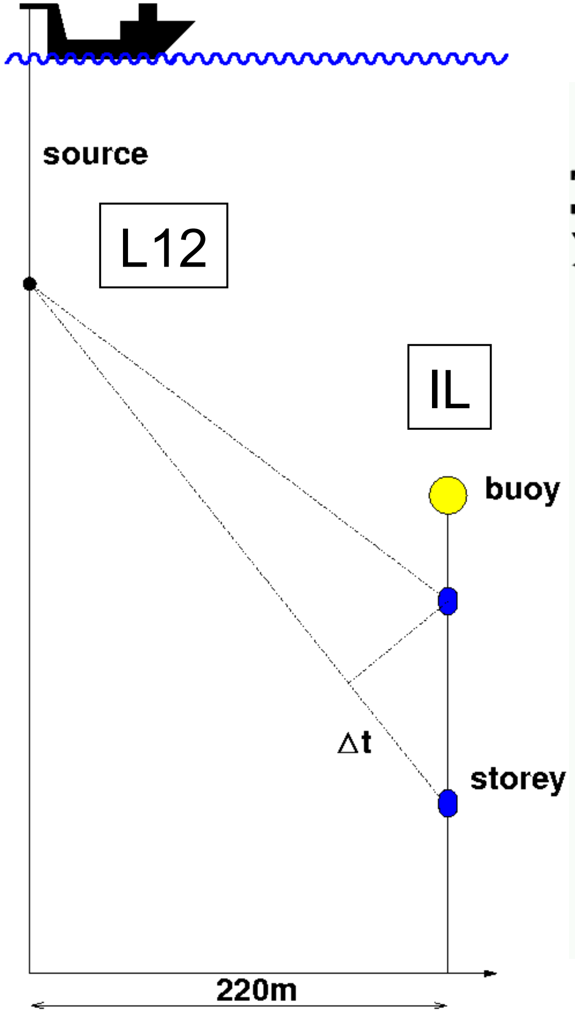
Storey 23
(6 sensors produced at Erlangen)

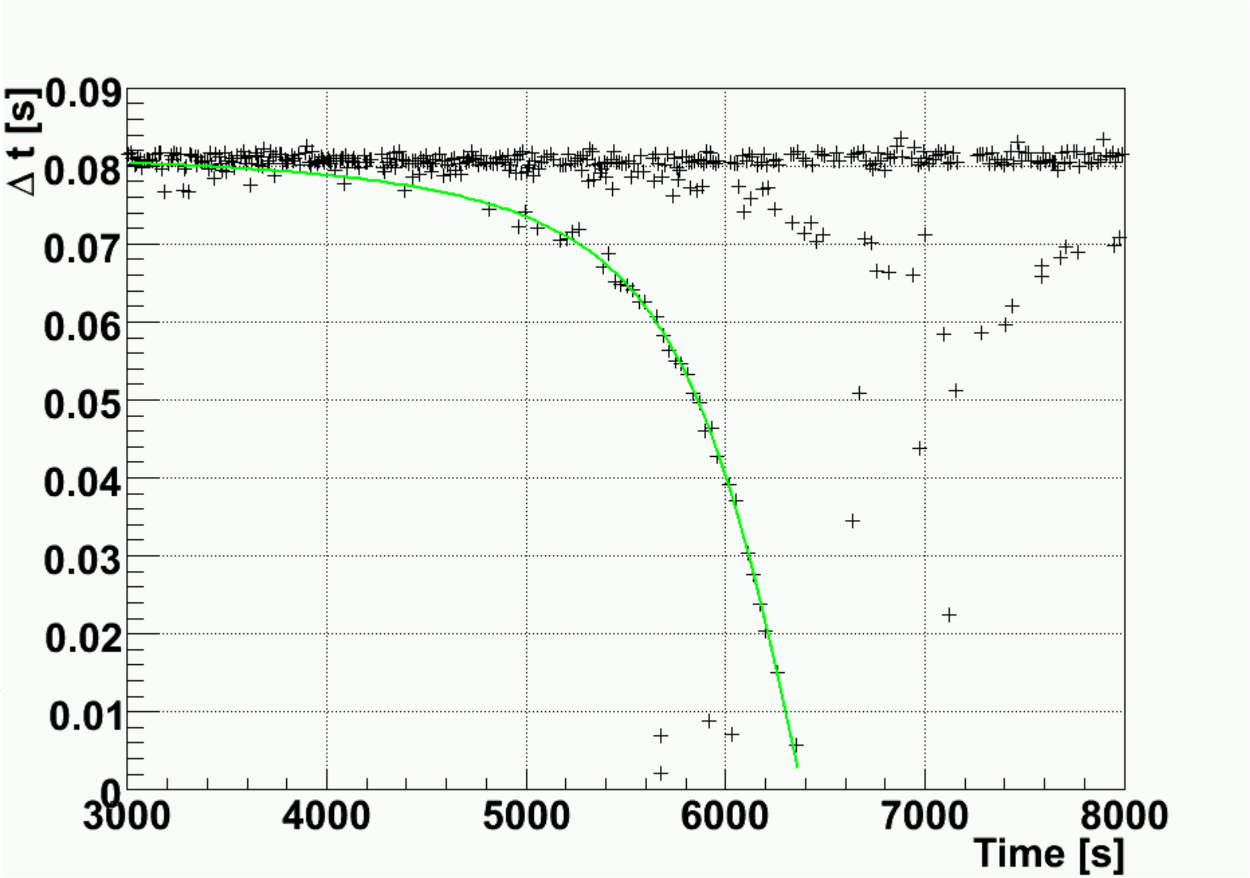
Deployment Line 12



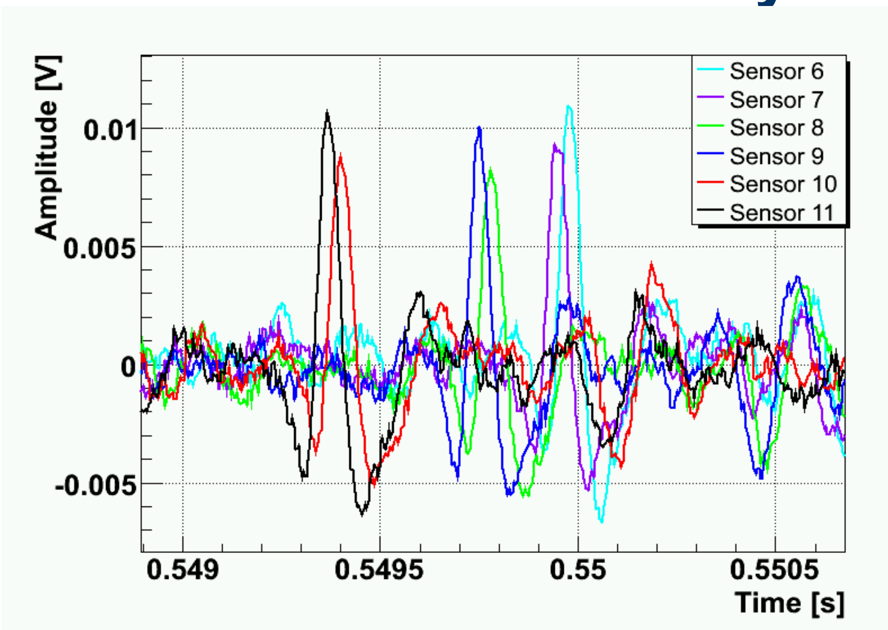


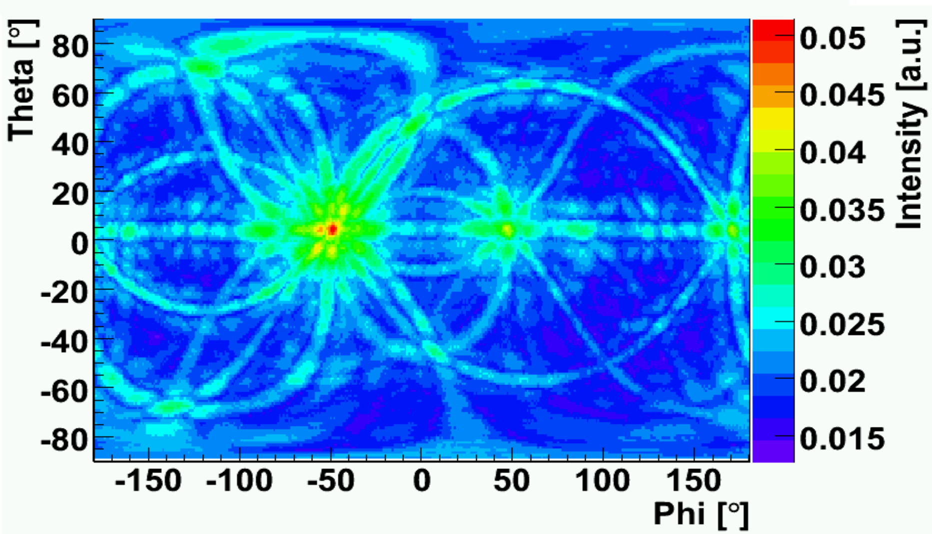
Deployment Line 12

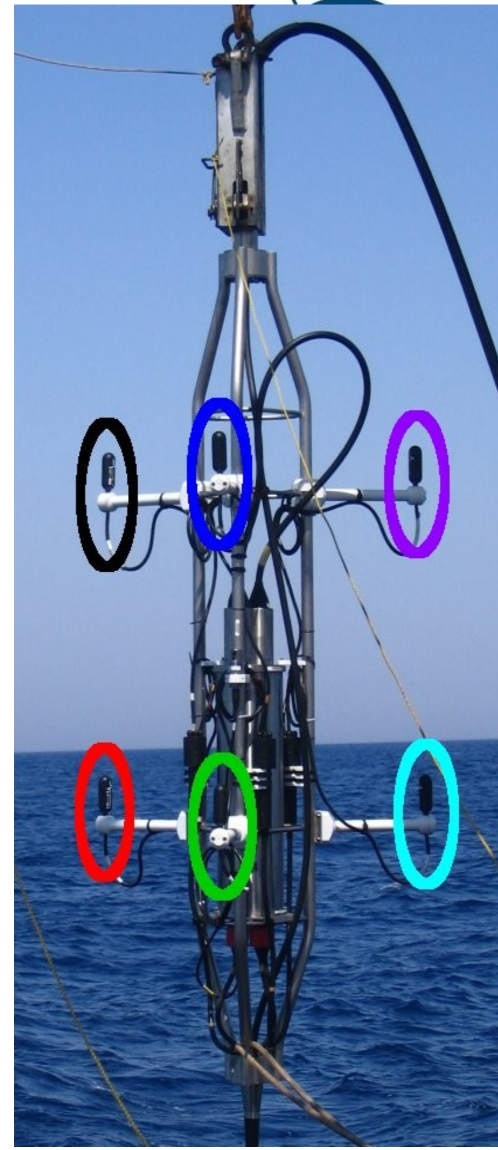




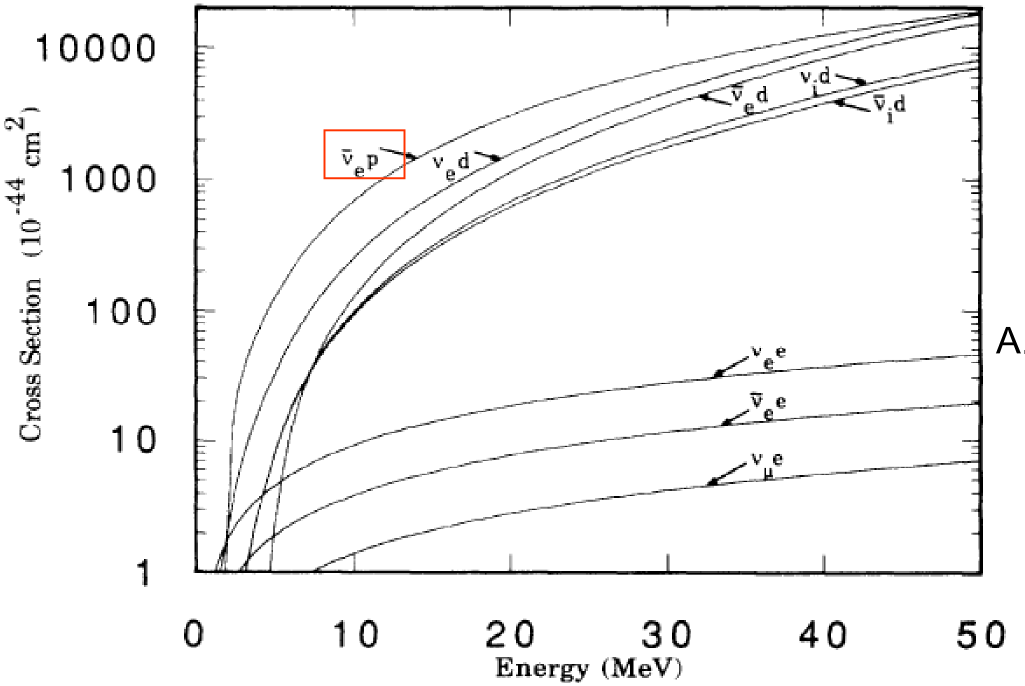
Directional sensitivity







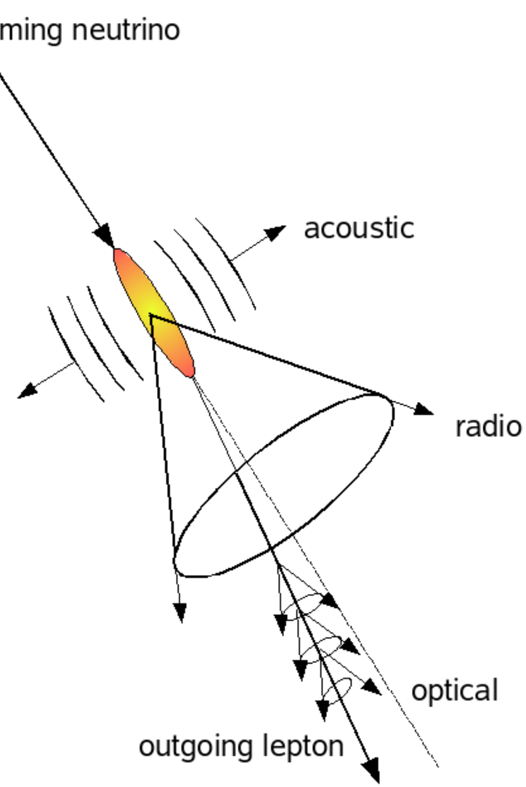
Neutrinowirkungsquerschnitte



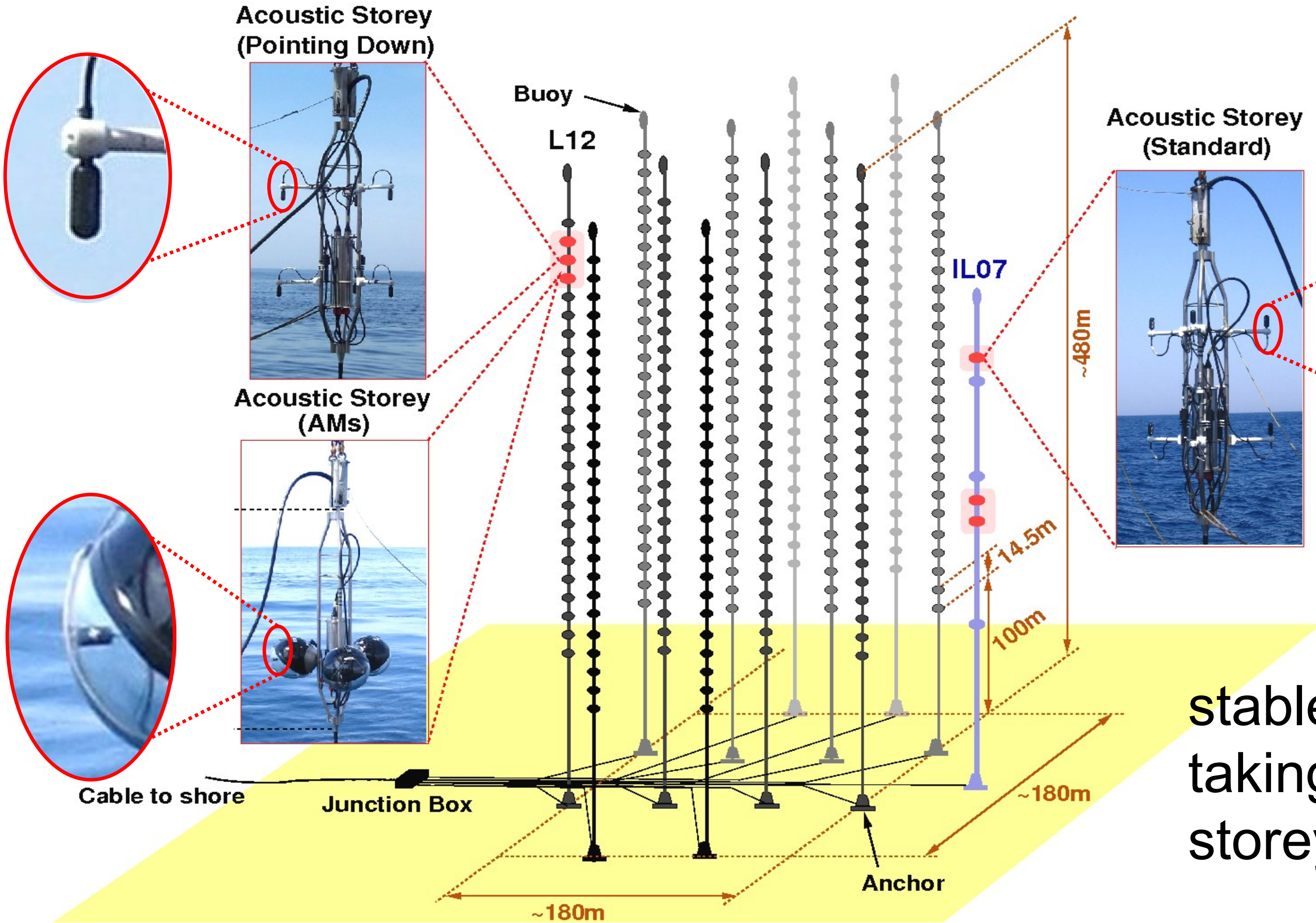
Highest cross section of ν-interaction is:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

A. Burrows, D.Klein, R. Gandhi PRD 45 (1992)3361

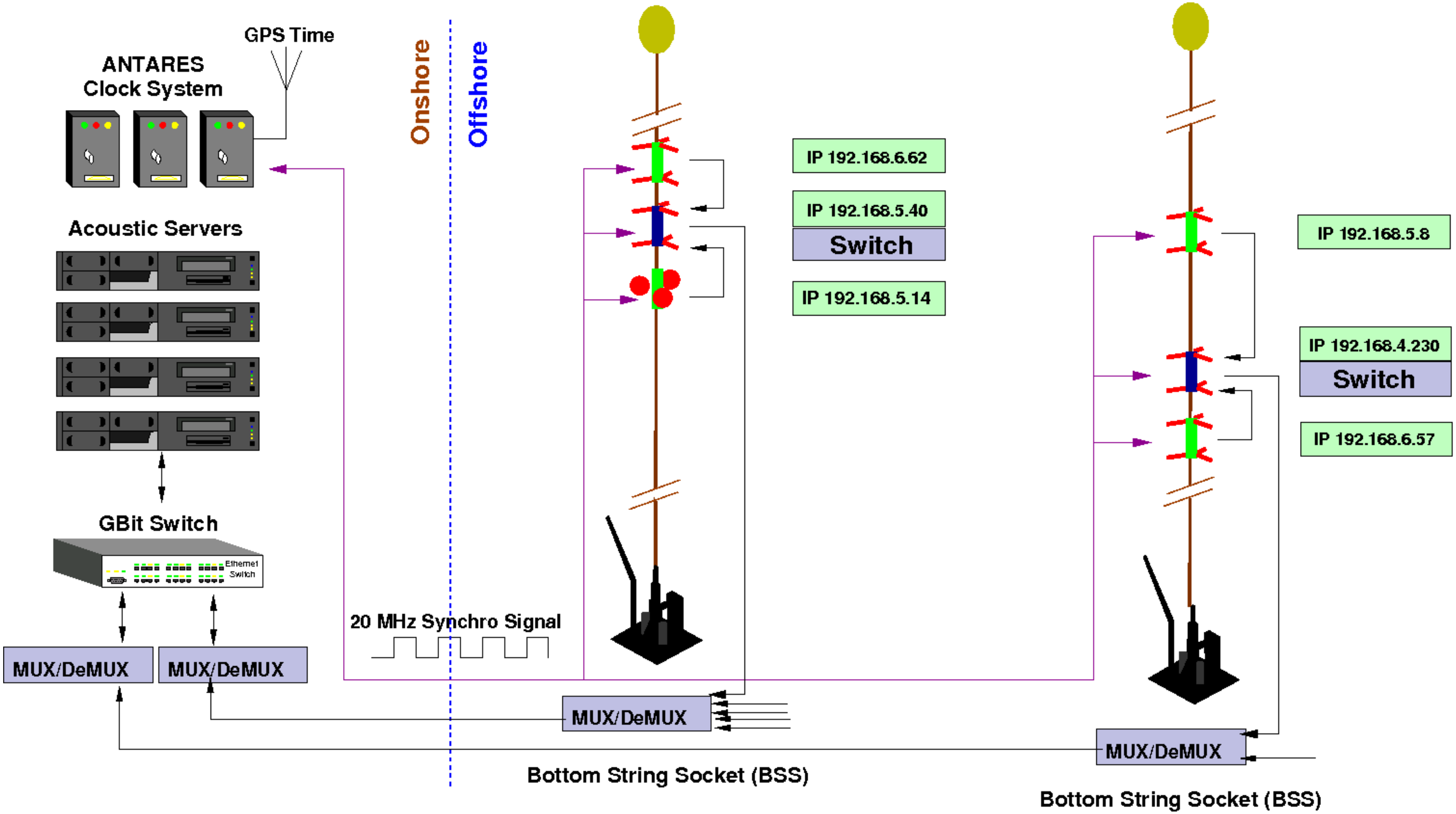

incoming neutrino
acoustic
radio
optical
outgoing lepton

The AMADEUS System



stable data-taking with 3 storeys on IL07

The Acoustic DAQ System



Nachweis kosmischer Neutrinos

- **Nachweis erfordert große Detektoren**
  □ Nutzung natürlich vorkommender Medien (Eis, Wasser)
- **Herkömmlicher Nachweis über Cherenkov-Strahlung von μ oder Schauerteilchen**