Physikalisches Kolloquium, ISKP Bonn

Acoustic Neutrino Detection – Status and Perspectives

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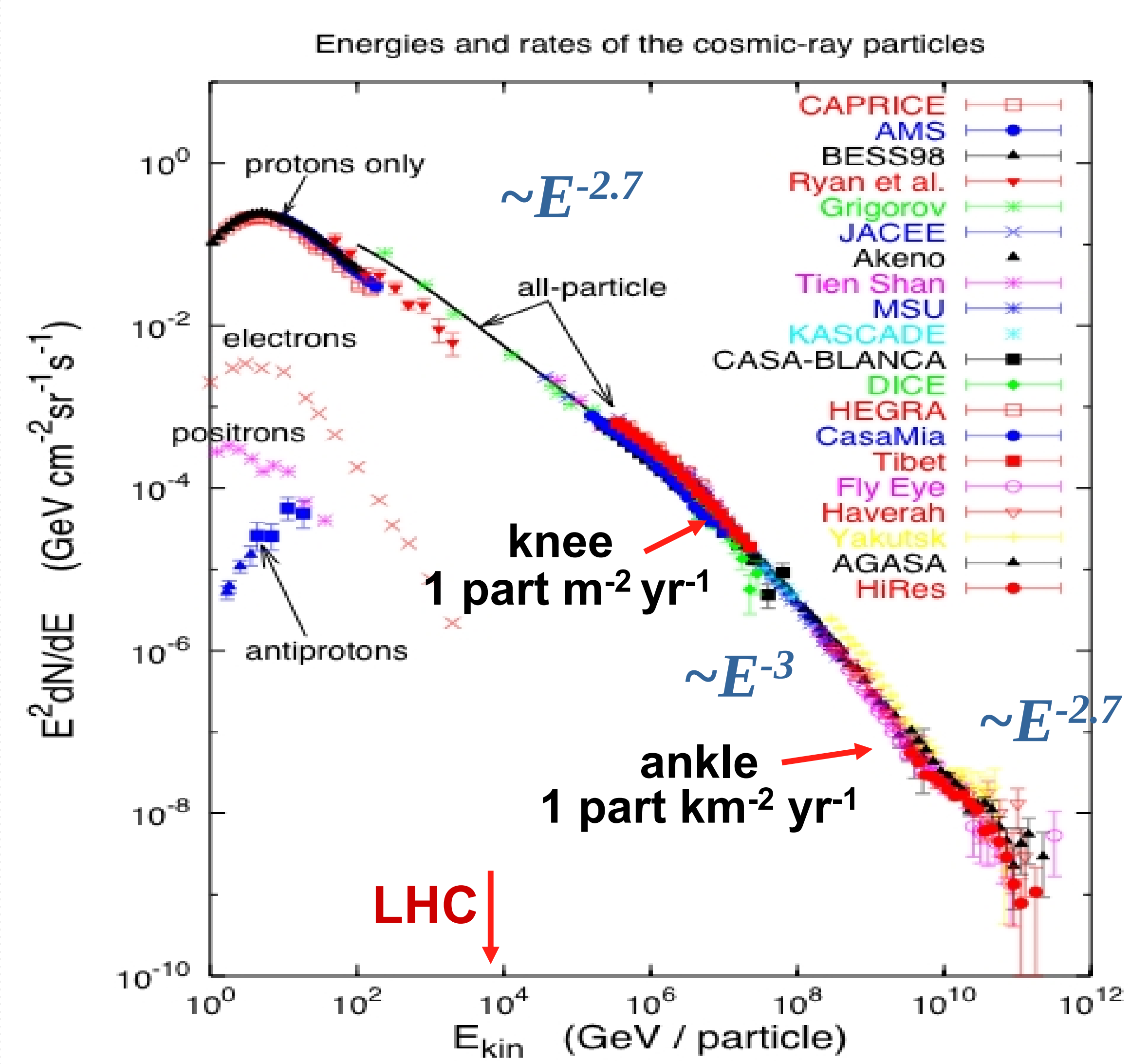
30.11.2006

- Introduction
- Current experimental activities
- Acoustic R&D in Erlangen and ANTARES
- Conclusions and Outlook

The Mysterious Cosmic Rays



- Particles impinging on Earth from outer space carry energies up to 10^{21} eV (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

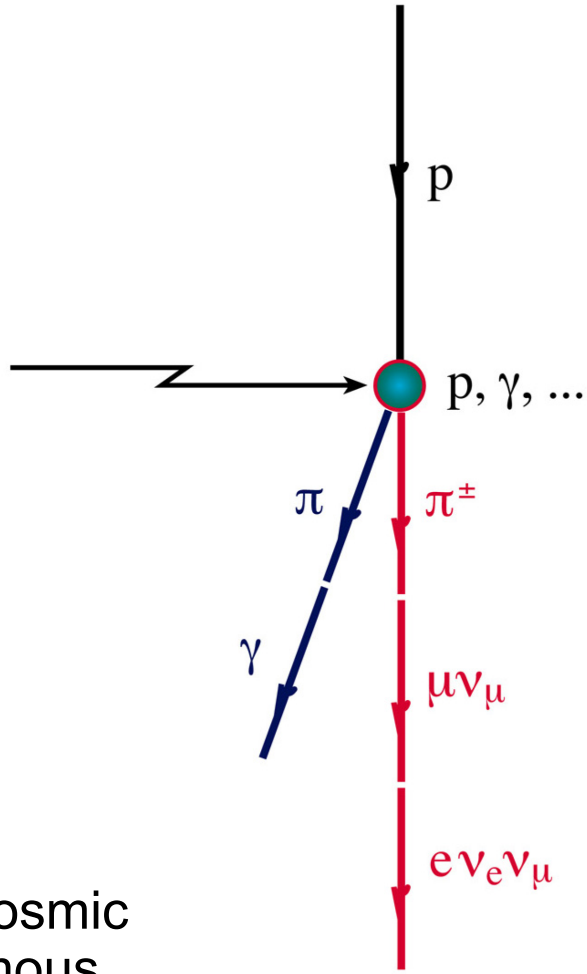
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Cosmic rays

- Simultaneously, gamma production takes place:

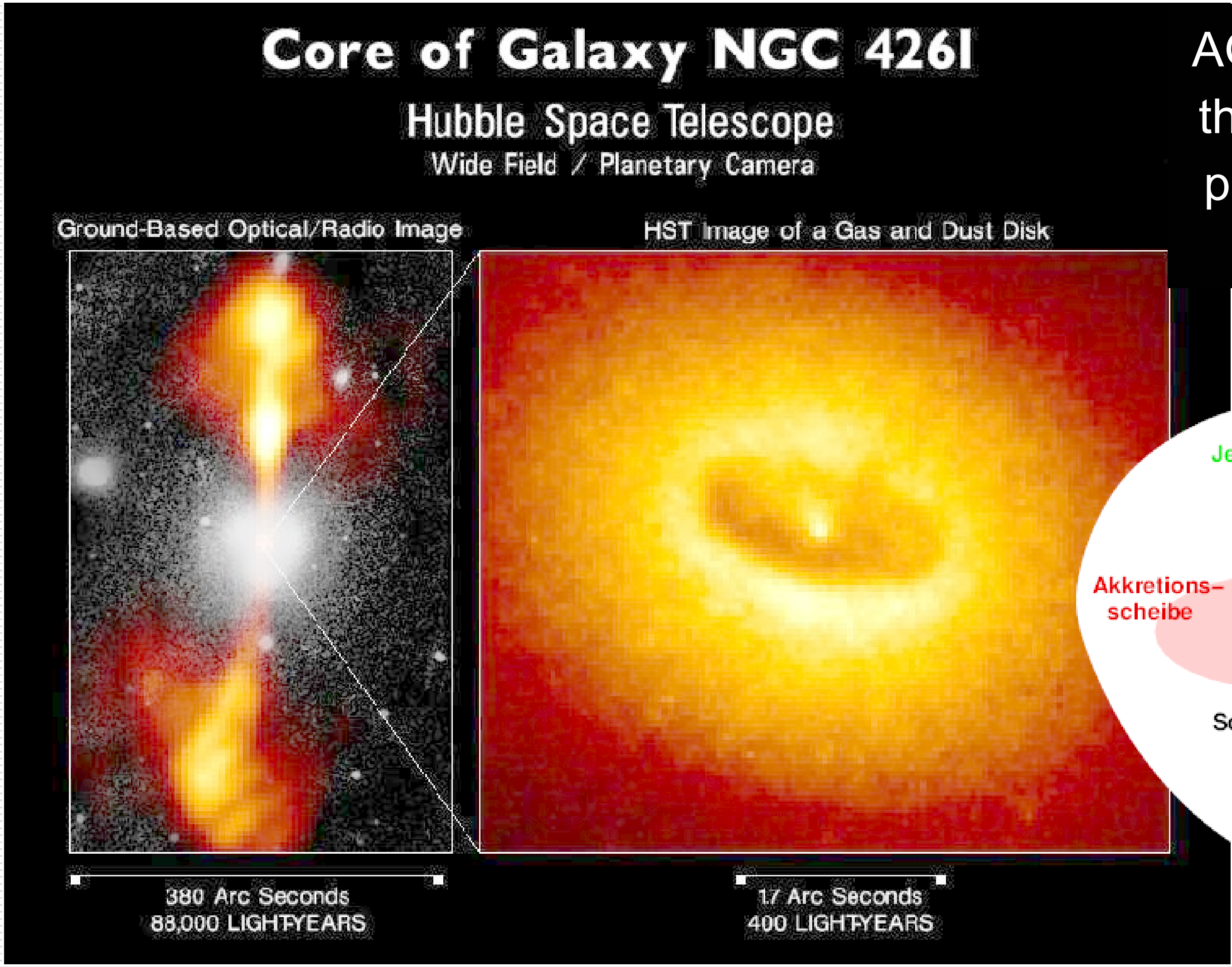
$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

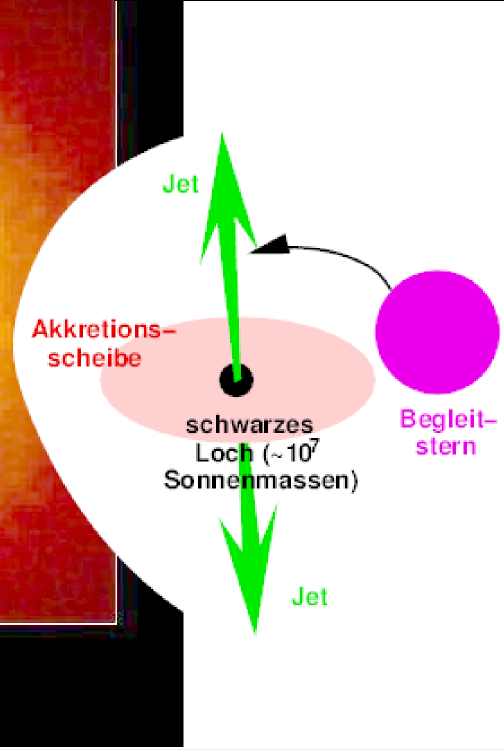
- Neutrinos and gammas are the messengers of cosmic ray acceleration … but only neutrinos are unanimous



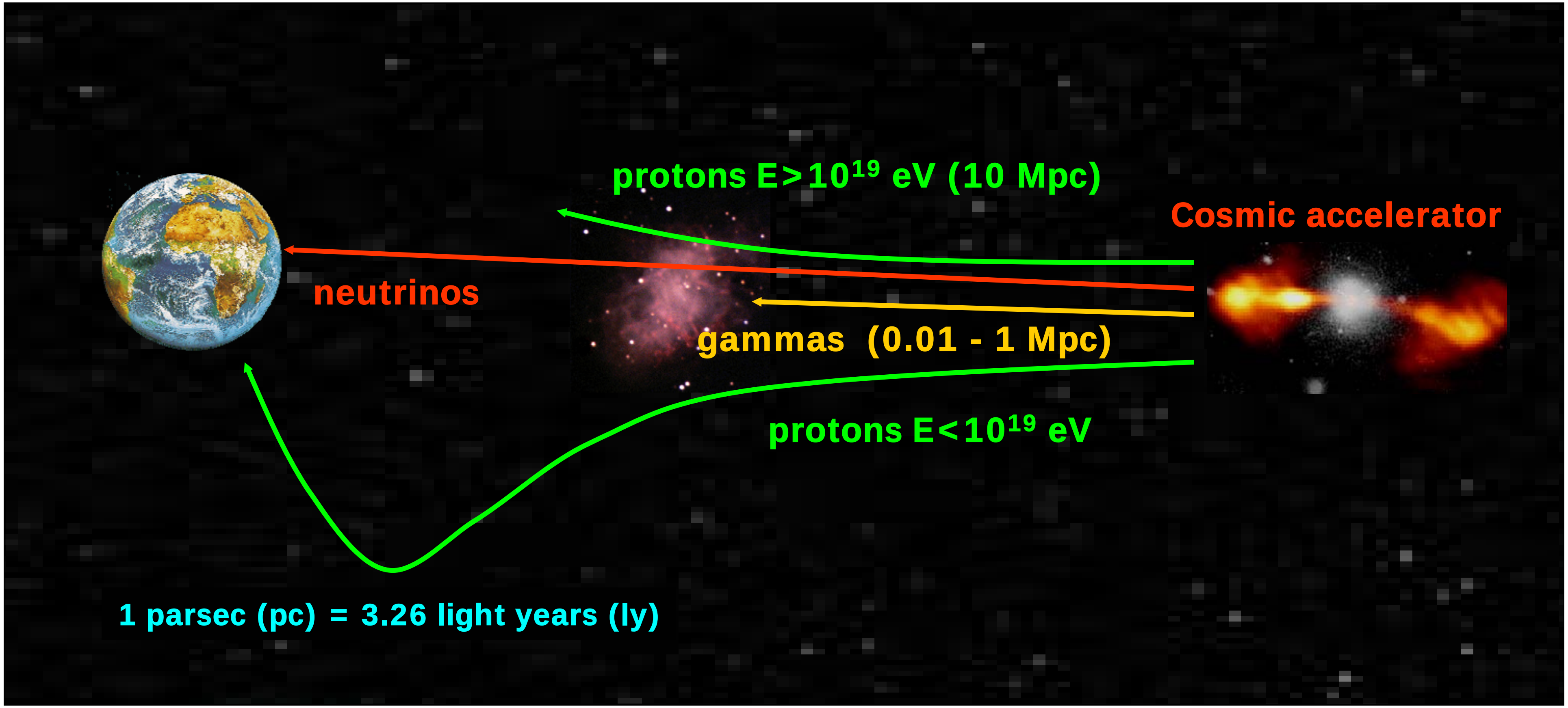
Candidate accelerators: Active Galactic Nuclei

AGNs are amongst the most energetic phenomena in the universe.





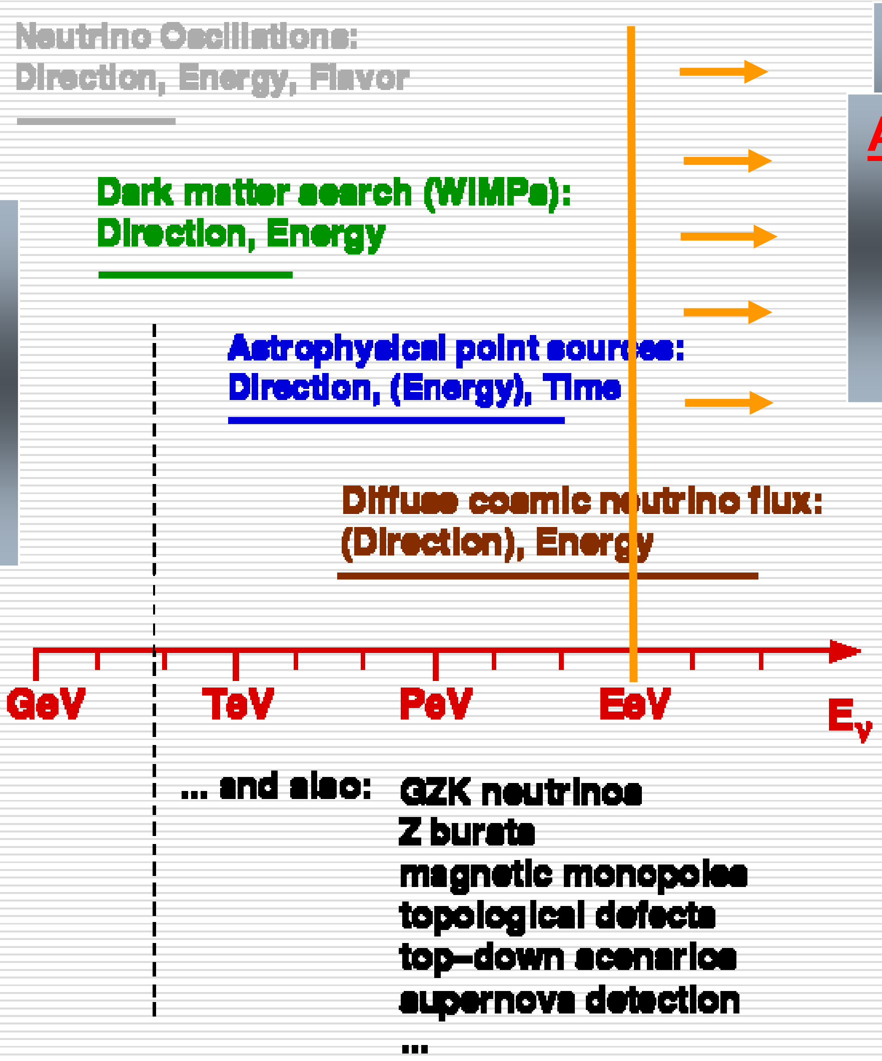
Particle propagation in the Universe



Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

Astro- and Particle Physics with ν Telescopes

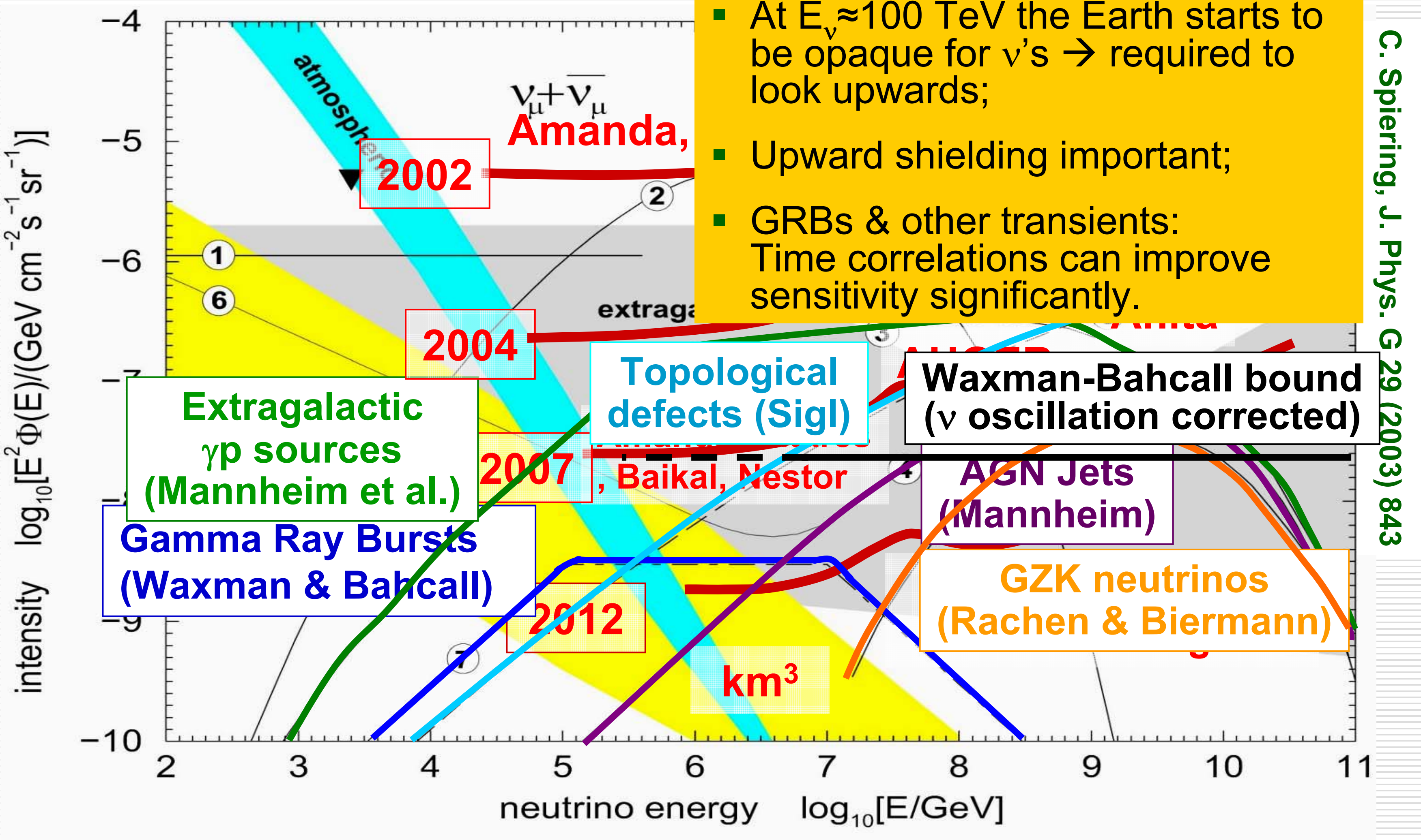
Low-energy limit:
- short muon range
- small number of photons detected
- background light from K40 decays



High-energy limit:

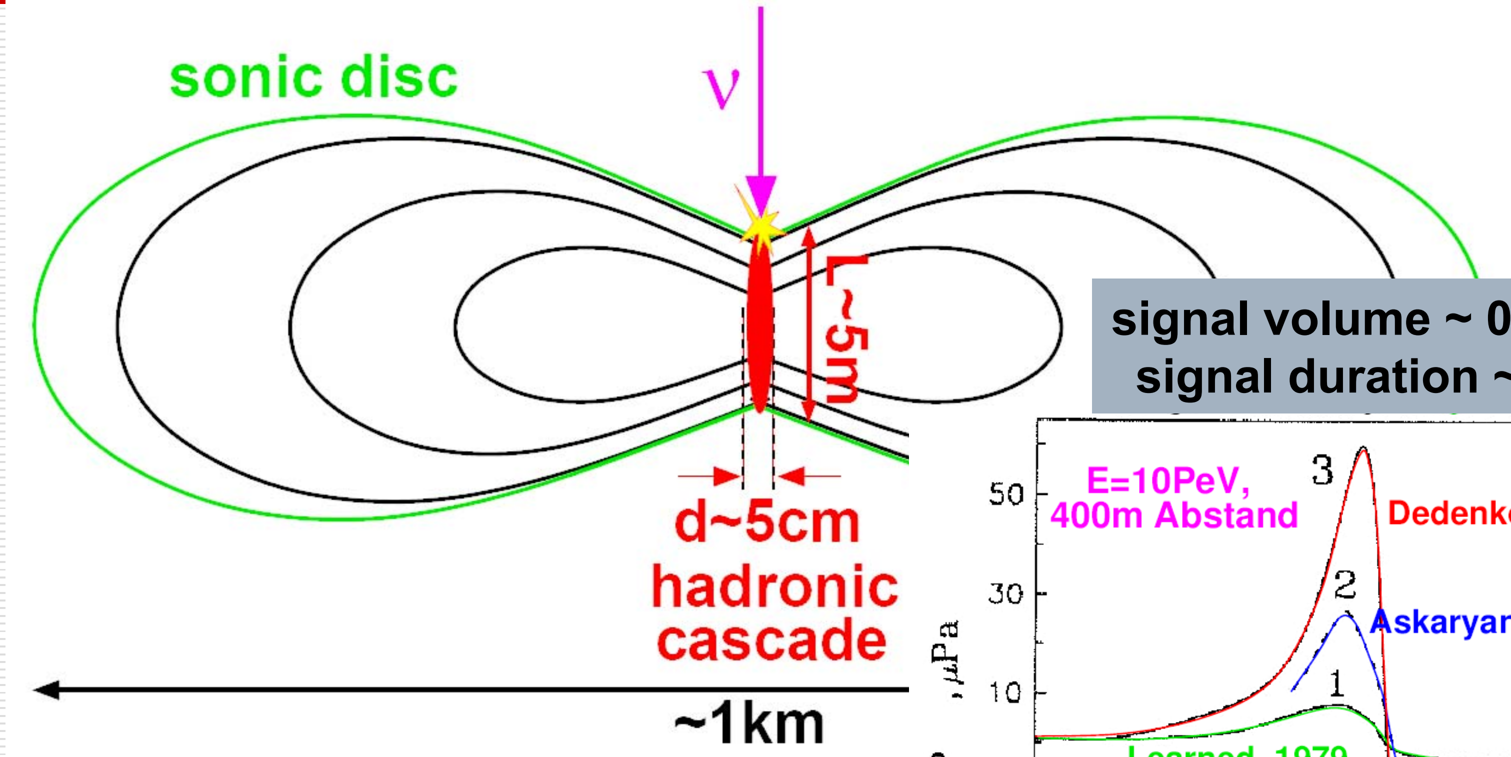
Acoustic detection:
might be a viable option to study neutrino fluxes at $E > 10^{18}$ eV

Diffuse ν Flux: Models, Limits and Sensitivities

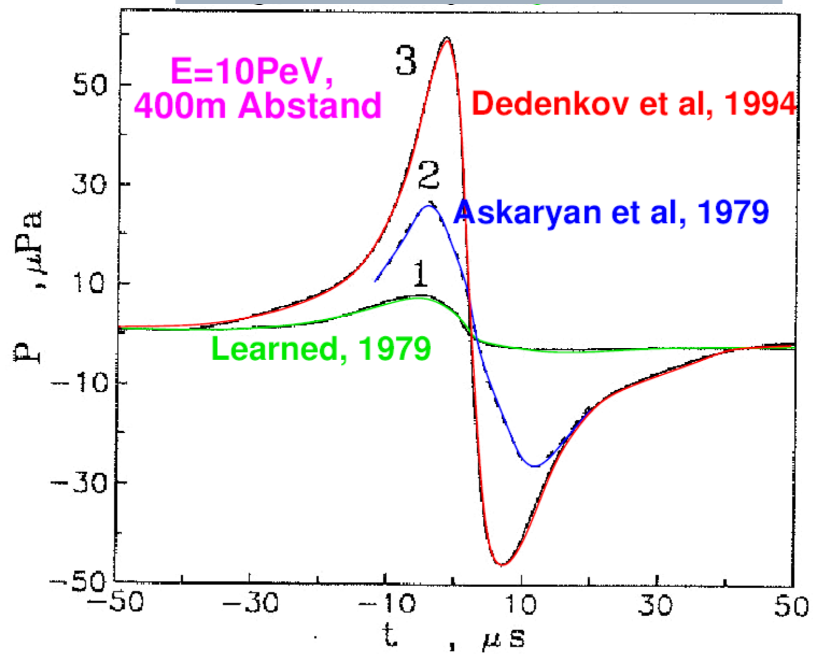


- At $E_\nu \approx 100$ TeV the Earth starts to be opaque for ν's → required to look upwards;
- Upward shielding important;
- GRBs & other transients: Time correlations can improve sensitivity significantly.

Sound from a neutrino reaction



signal volume ~ 0.01 km³
signal duration ~ 50 μs



Energy deposition in shower (core)
→ heating of water (~nK)
→ expansion (if T > 4°C)
→ acoustic pulse.

The thermo-acoustic model

- Particle reaction in medium (water, ice, ...) causes energy deposition by electromagnetic/hadronic showers.
- Energy deposition is fast compared to (shower size)/c_s and dissipative processes → instantaneous heating
- Thermal expansion and subsequent rarefaction causes bipolar pressure wave with pressure

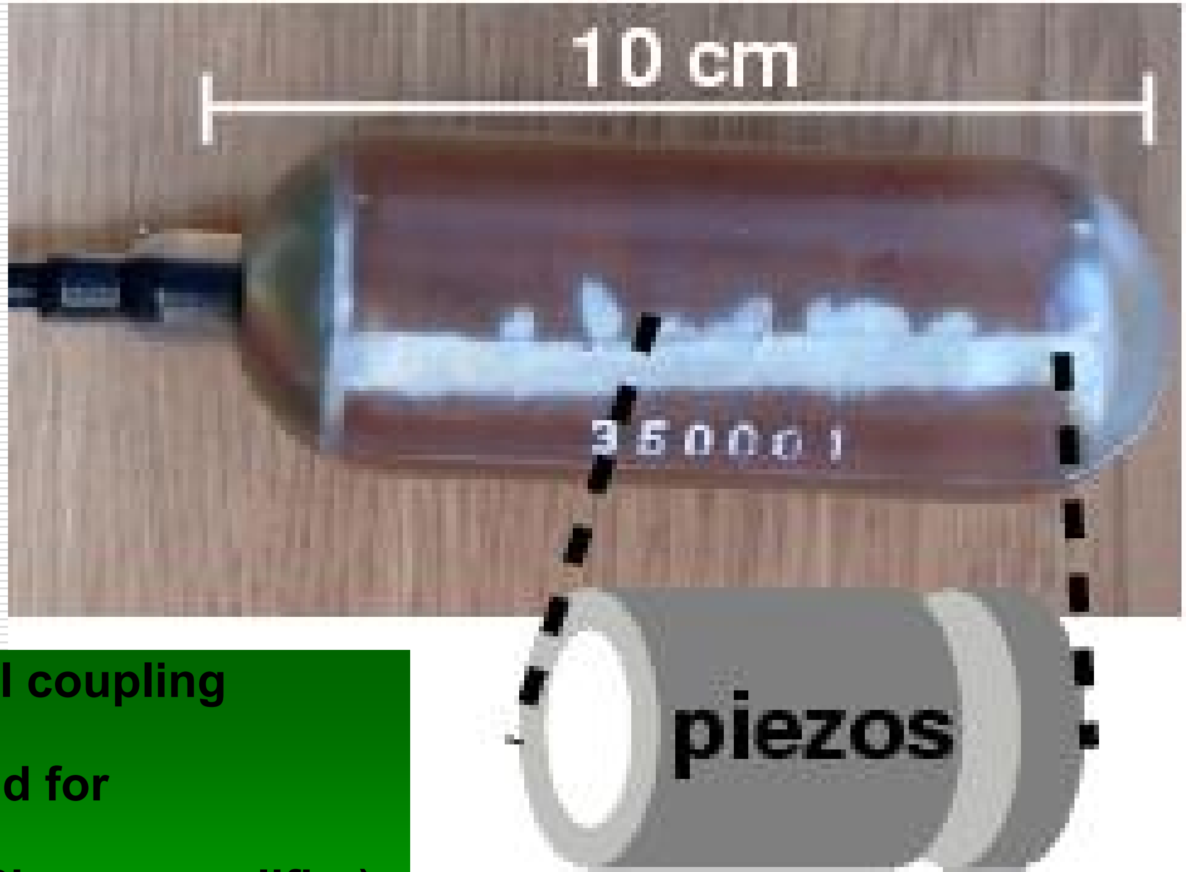
$$P \sim (\alpha/C_p) \times (c_s/L_c)^2 \times E$$

α	= (1/V)(dV/dT)
	= thermal expansion coefficient of medium
C_p	= heat capacity of medium
c_s	= sound velocity in medium
L_c	= transverse shower size
c_s/L_c	= characteristic signal frequency
E	= shower energy

Piezo-Based Acoustic Sensors

Piezo elements

Commercial hydrophones (for water):



- **Principle: electro-mechanical coupling in Piezo materials;**
- **Can be used for receiving and for transmitting signals**
- **Custom-designed sensors (Piezo + amplifier): cheap and sensitive**

Experimental Activities in Different Media

Sea water

- ☺ Homogeneous;
- ☺ Rather well-understood environment;
- ☹ Substantial acoustic background;
- ☹ Signal amplitude expected to be smaller than in ice or salt.

Current activities:

- SAUND (Caribbean Sea)
- ACORνE/RONA (Scotland)
- Mediterranean Sea:
  - NEMO/OνDE
  - ANTARES: Erlangen, …
- Kamchatka, Lake Baikal, …

Antarctic Ice

- ☺ Low acoustic background (?);
- ☺ Signal amplitude expected to be larger than in water;
- ☹ Inhomogeneous;
- ☹ Not well studied.

Current activities:

- IceCube/SPATS

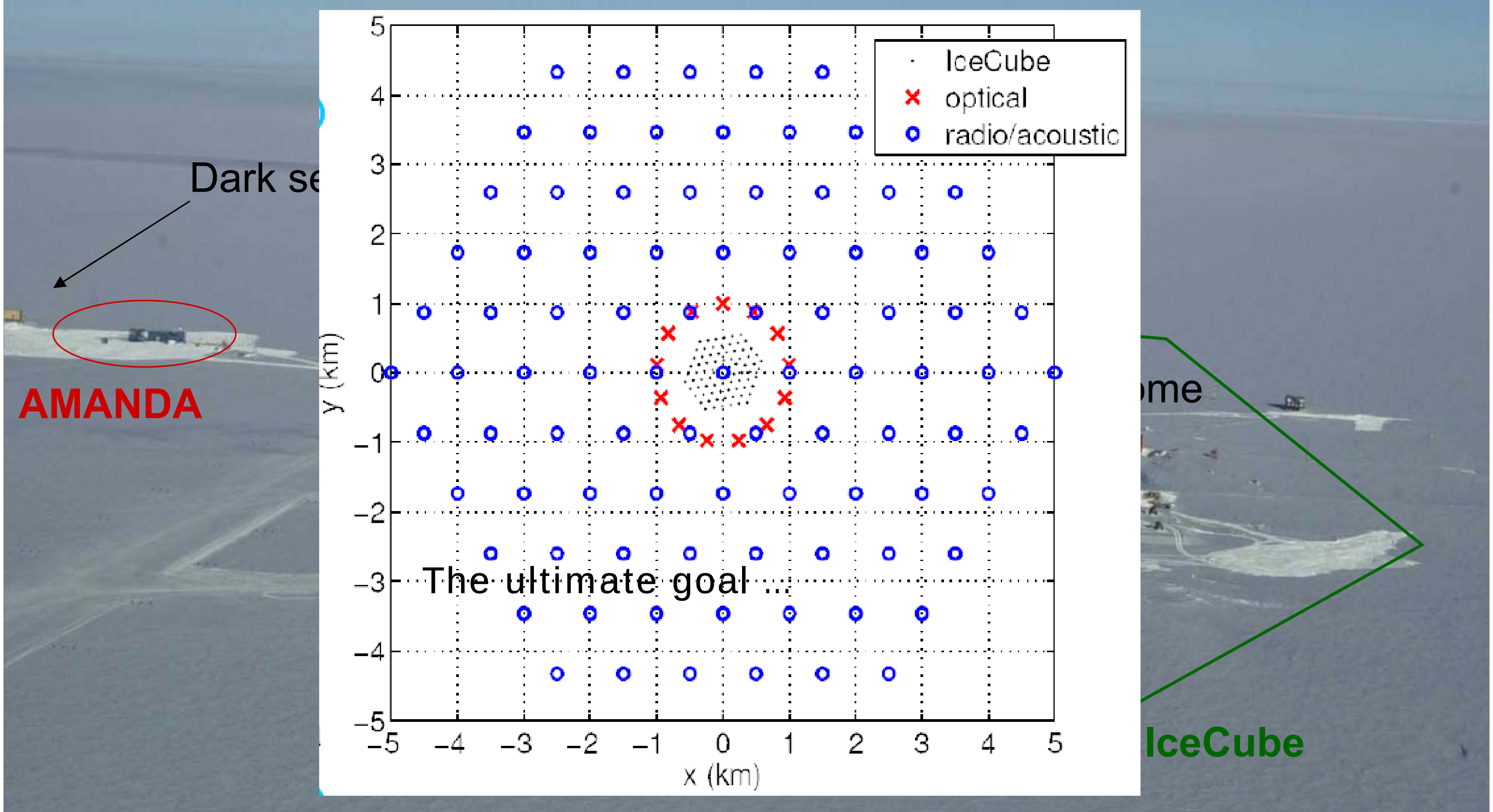
Salt domes

- ☺ "Easily" accessible;
- ☹ Not well (not at all?) studied.

Current activities:

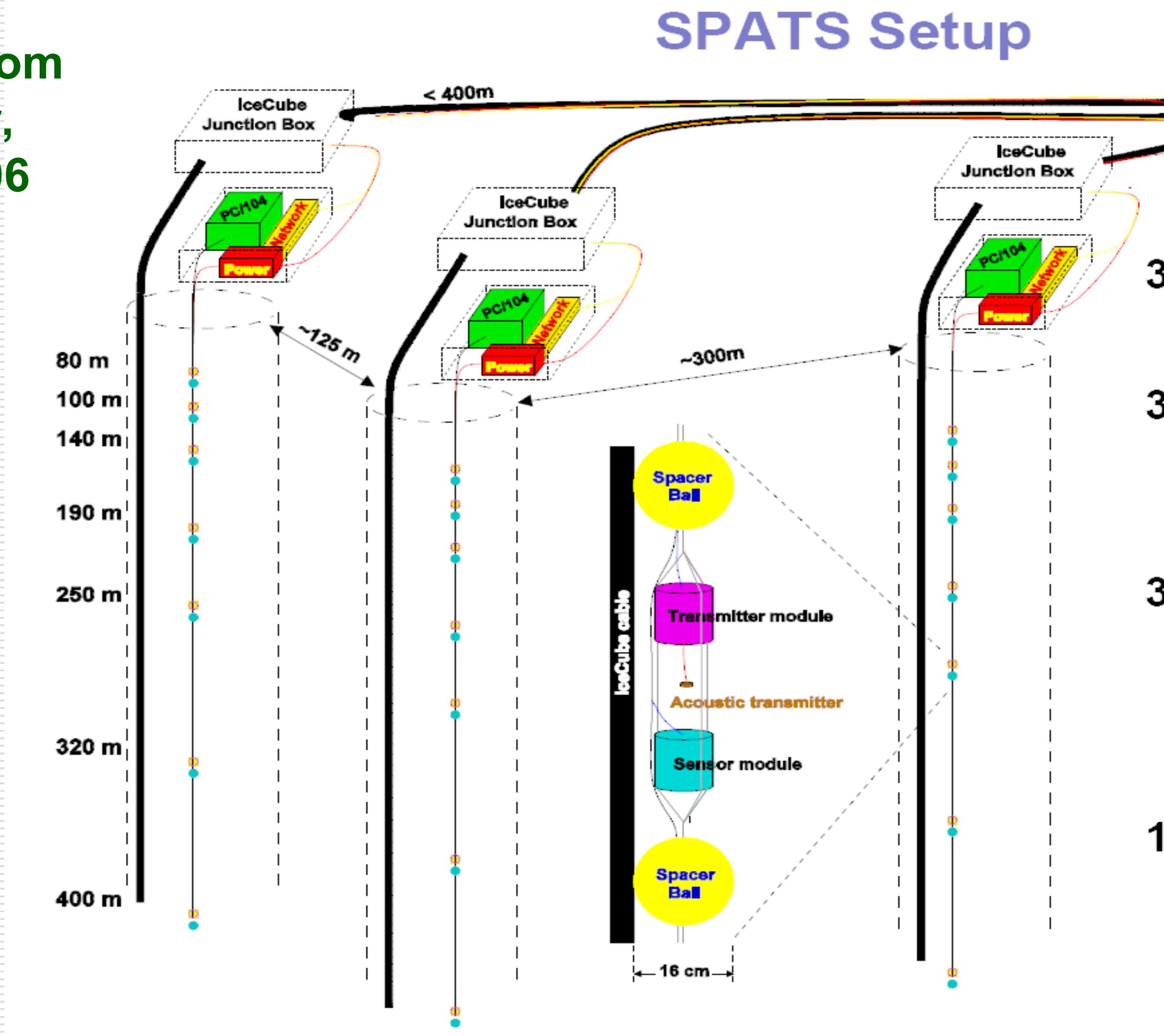
- R&D and site exploration

Acoustic Plans in the IceCube Framework



SPATS = South Pole Acoustic Test Setup

Taken from S. Böser, ARENA06



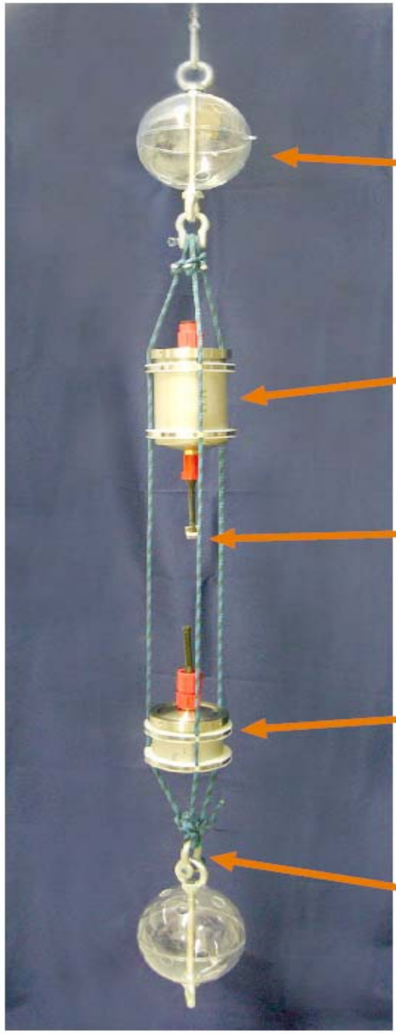
3 IceCube holes
- down to 400m

3x7 acoustic stages
- sensors
- transmitters

3x1 Acoustic Box
- PC/104 CPU
- Power supply
- DSL network

1 Master-PC
- Power supply
- DSL network
- GPS Time code

SPATS Acoustic Stages



Taken from S. Böser, ARENA06

Acoustic stages

Spacer balls
- ensure distance to walls and IC cable
- large holes to flood with water

Transmitter module
- HV pulse generation (1kV @ 10µs)
- temperature / pressure sensors

Transmitter
- ring-shaped piezoceramics
  - ➔ generates acoustic wave

Sensor module
- three channels
  - ➔ directional sensitivity
  - ➔ noise rejection

Solid junctions
- shackles, ropes, etc. specified for ≥ 22kN

SPATS Acoustic Sensors

Taken from S. Böser, ARENA06

Sensor module

Piezo ceramics

- individually calibrated

Three-stage amplifier board

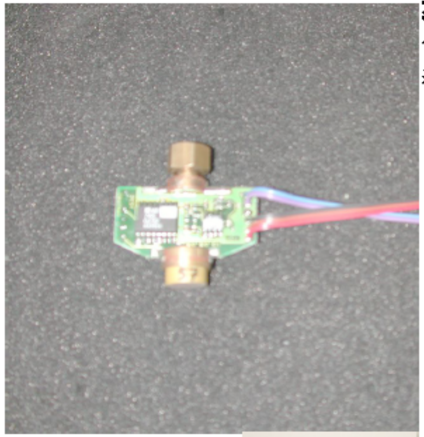
- low noise
- differential output

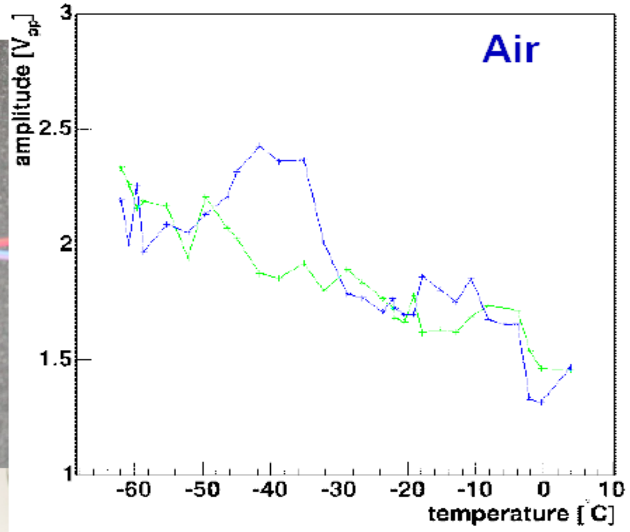
Mechanical contact

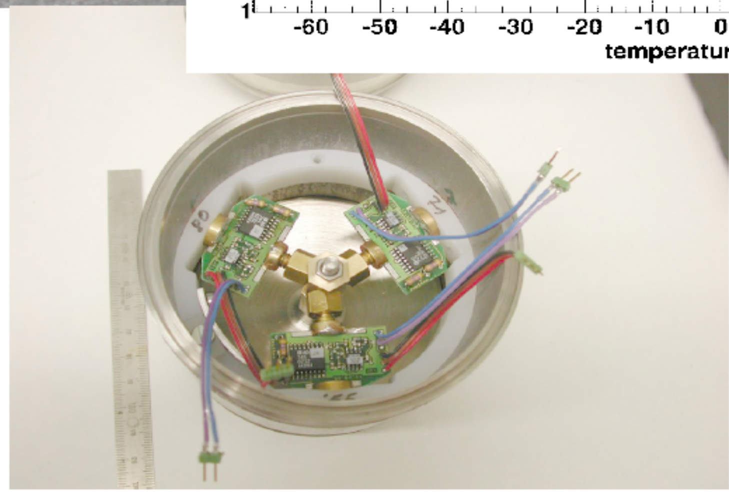
- Preload screw
  ➔ signals get larger
  - at low temperature
  - at higher pressure

Sensor module

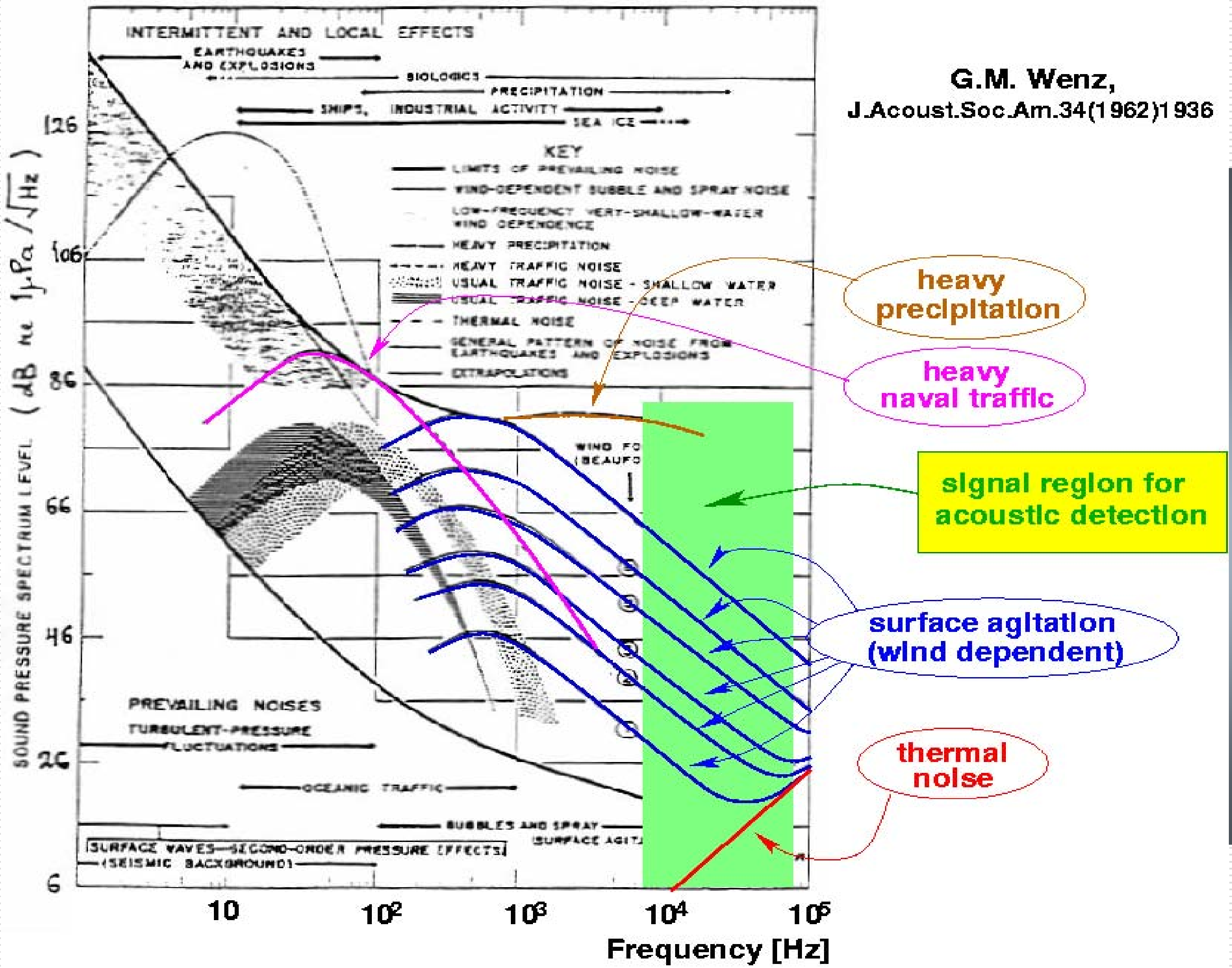
- three channels
- voltage conversion board
  36-13VDC ➔ ±5VDC







The Signal and the Noise in the Sea



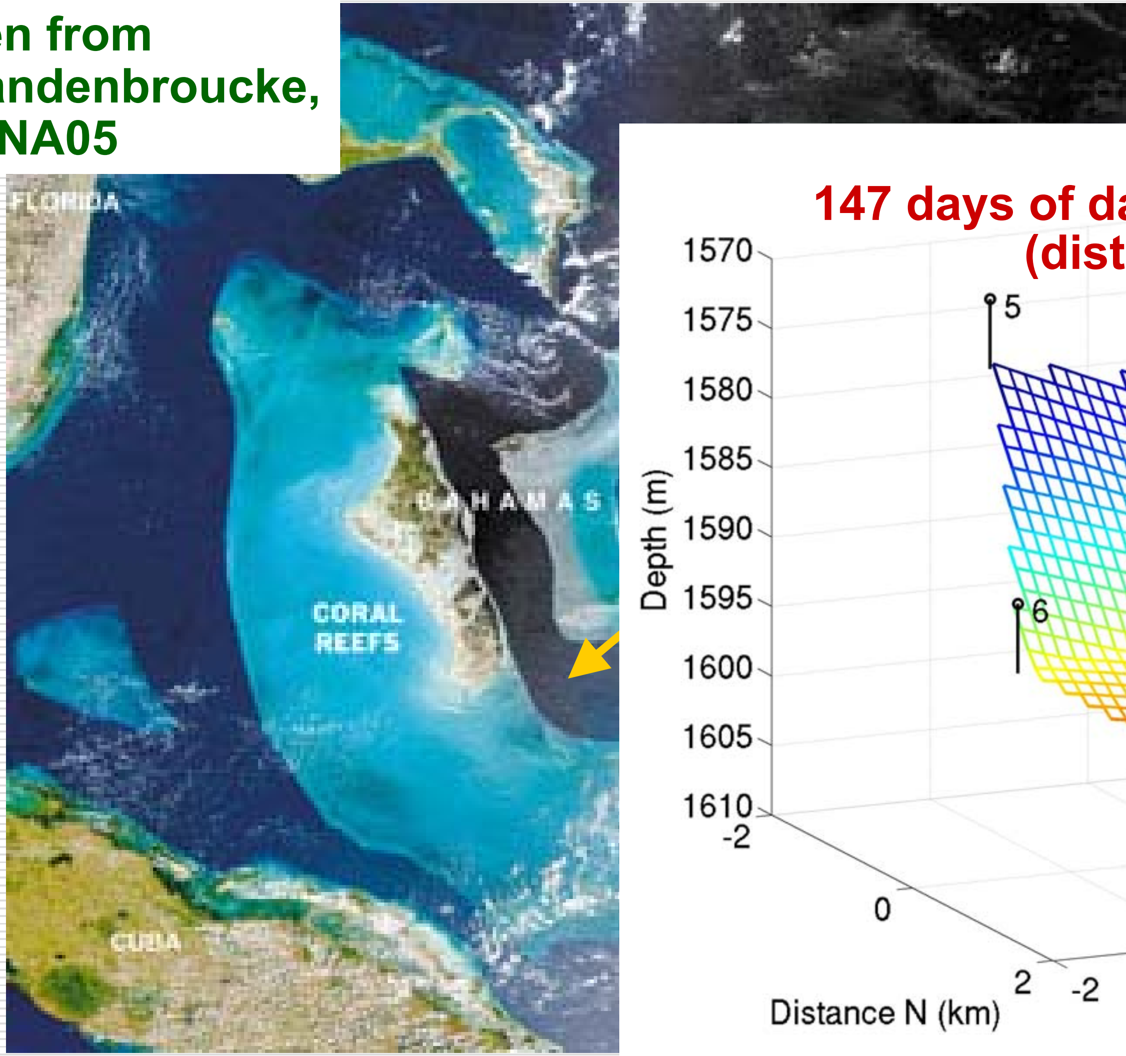
<u>Rough and optimistic estimate:</u>

signal ≈ noise at O(0.1-1 mPa)

(shower with 10-100 PeV @ 400m)

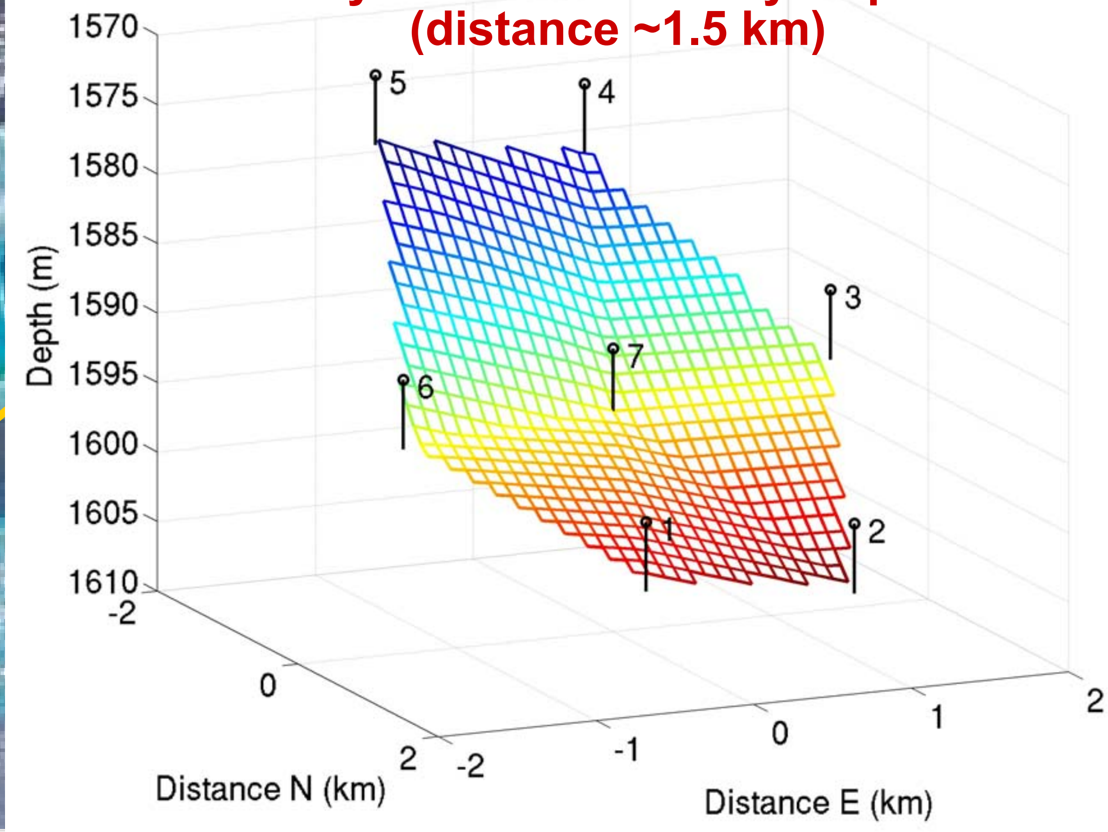
SAUND-I: Using a Military Array

Taken from J. Vandenbroucke, ARENA05



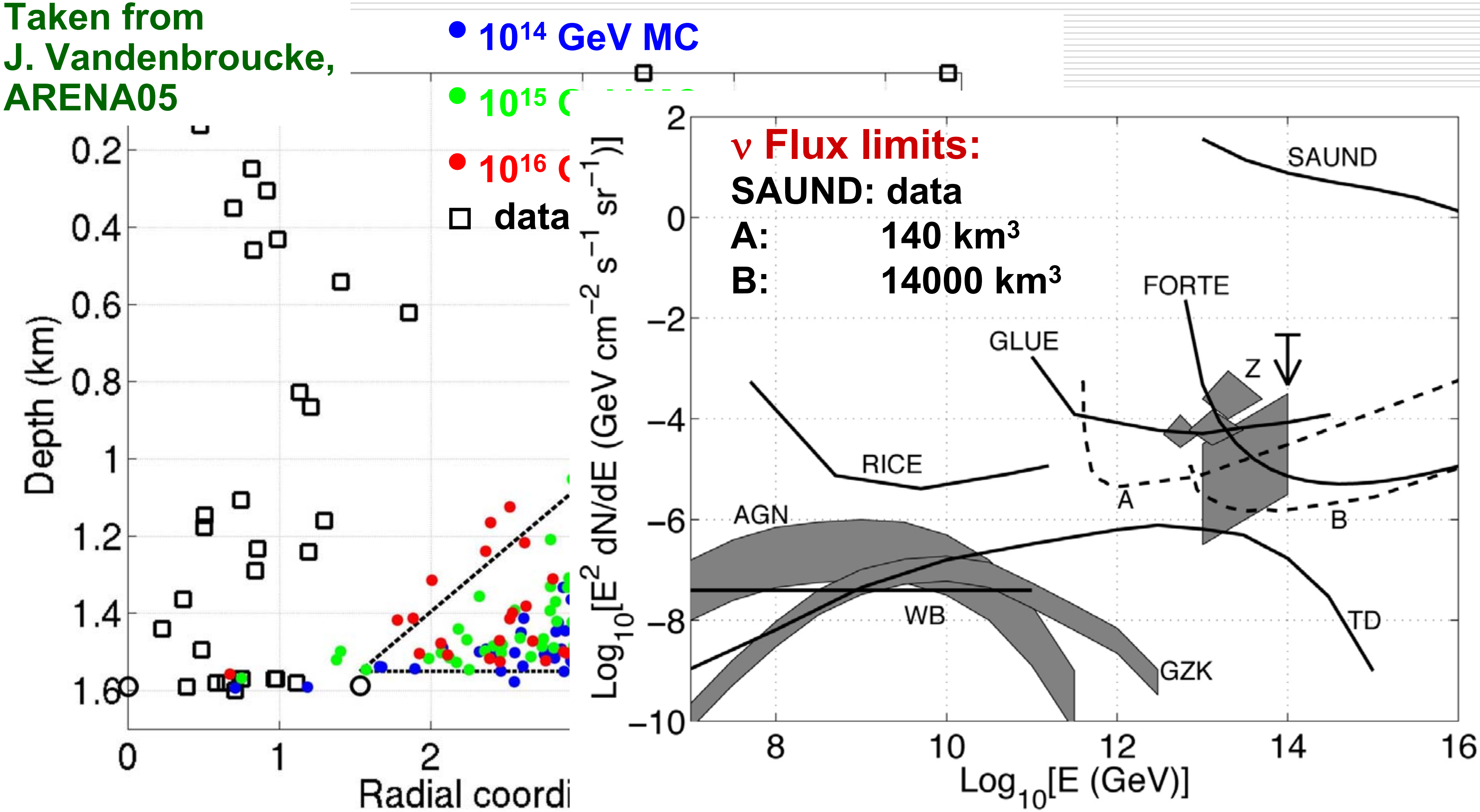
The „Tongue of the Ocean“

147 days of data with 7 hydrophones (distance ~1.5 km)



SAUND-1: A First Neutrino Flux Limit

Taken from
J. Vandenbroucke,
ARENA05



RONA Hydrophone Array / ACoRνE

- Currently 8 wide-band hydrophones available (read out @ 140kHz);
- Collected 2.8TByte of unfiltered data
- ACoRνE: Acoustic Cosmic Ray Neutrino Experiment
  - Data analysis
  - Simulation
  - Reconstruction
  - Sensitivity predictions

NEMO (Phase 1): Current Status

Shore station

- Test site at 2000 m depth operational.
- Funding ok.
- Completion expected by 2006.

Geoseismic station SN-1 (INGV)

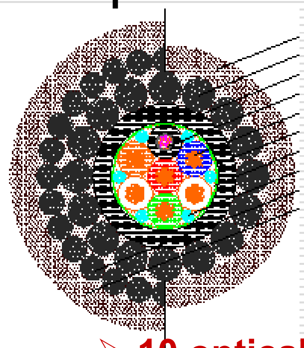
5 km e.o. cable

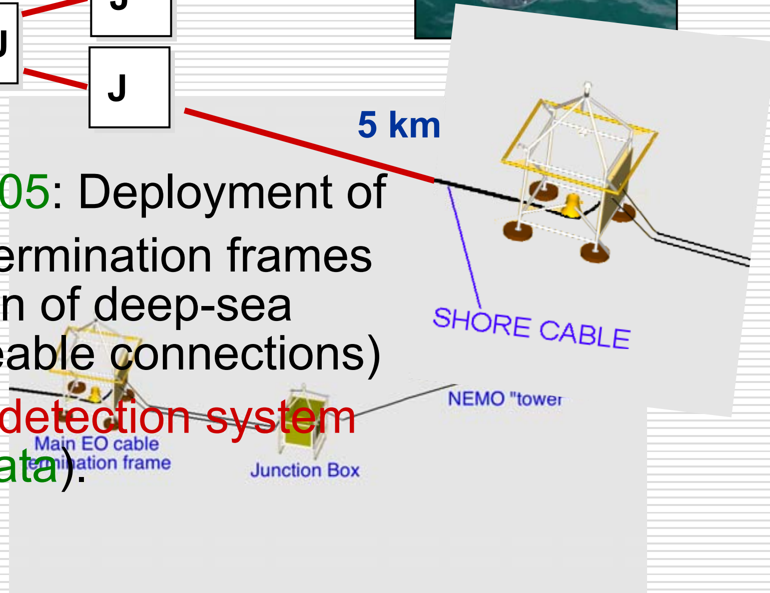
21 km e.o. Cable with single steel shield

J — BU — J — J

2.5 km e.o. Cable with double steel shield

5 km





January 2005: Deployment of

- 2 cable termination frames (validation of deep-sea wet-mateable connections)
- acoustic detection system (taking data).

- **10 optical fibres standard ITU- T G-652**
- **6 electrical conductors Φ 4 mm^2**

The OνDE Setup

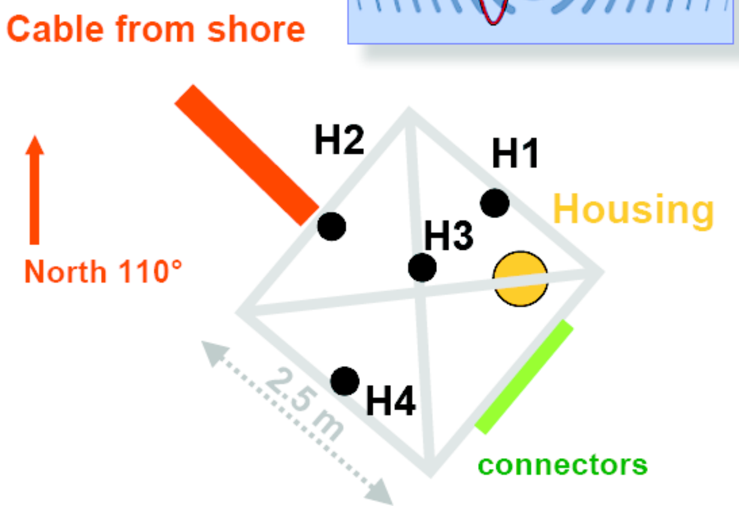
Installed on NEMO TSS (Test Site South) frame.

Equipped with 4 hydrophones, acoustic signal digitization (24bit@96 kHz) at 2000m depth.

On-line monitoring and data recording on shore.

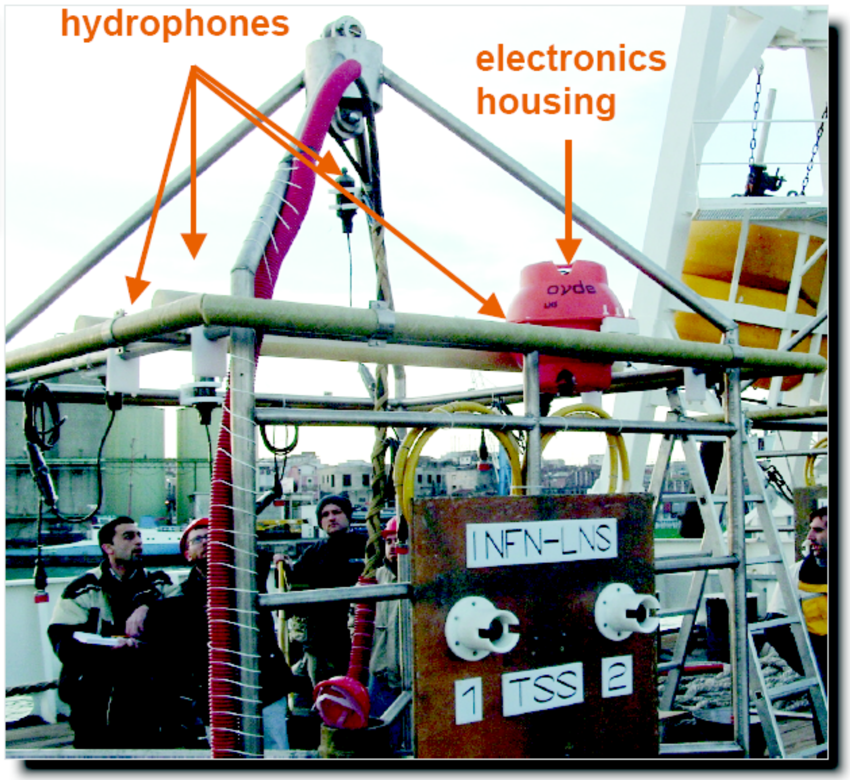
Continuous data taking since Jan 23, 2005.

Taken from G. Riccobene, ARENA06

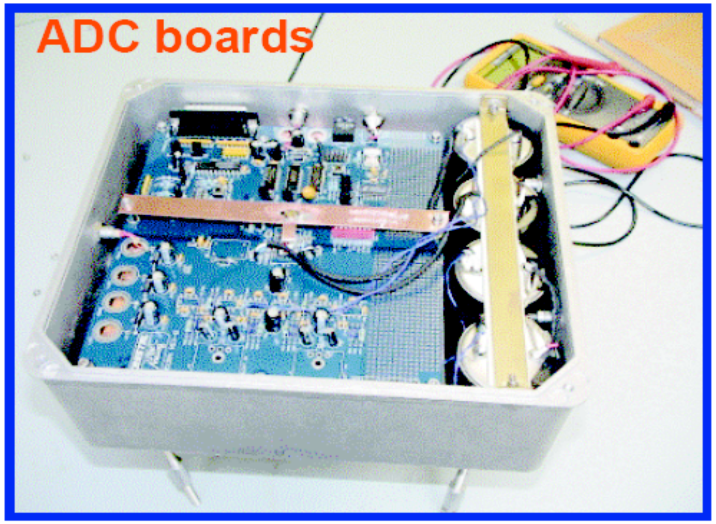


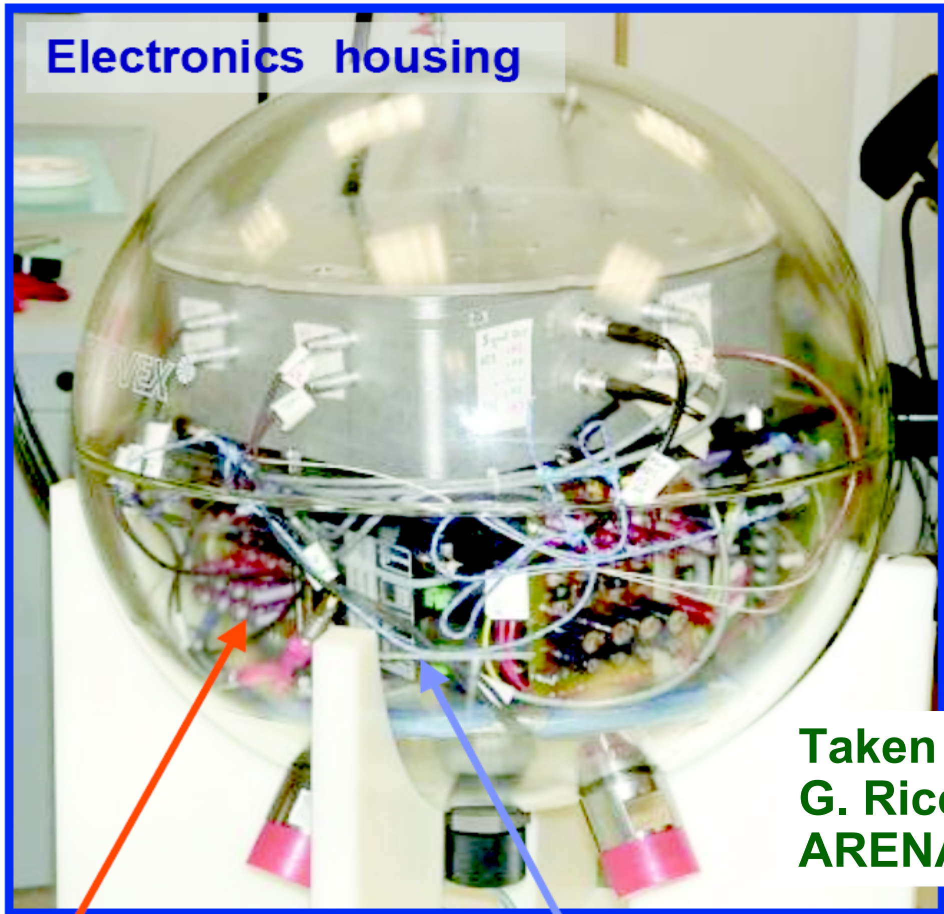
Height from seabed :

H1, H2, H4: ~ 2.6 m H3: ~ 3.2 m



OνDE Hydrophones and Electronics





Power:
transformers and
regulators

Electro/Optical
Modem

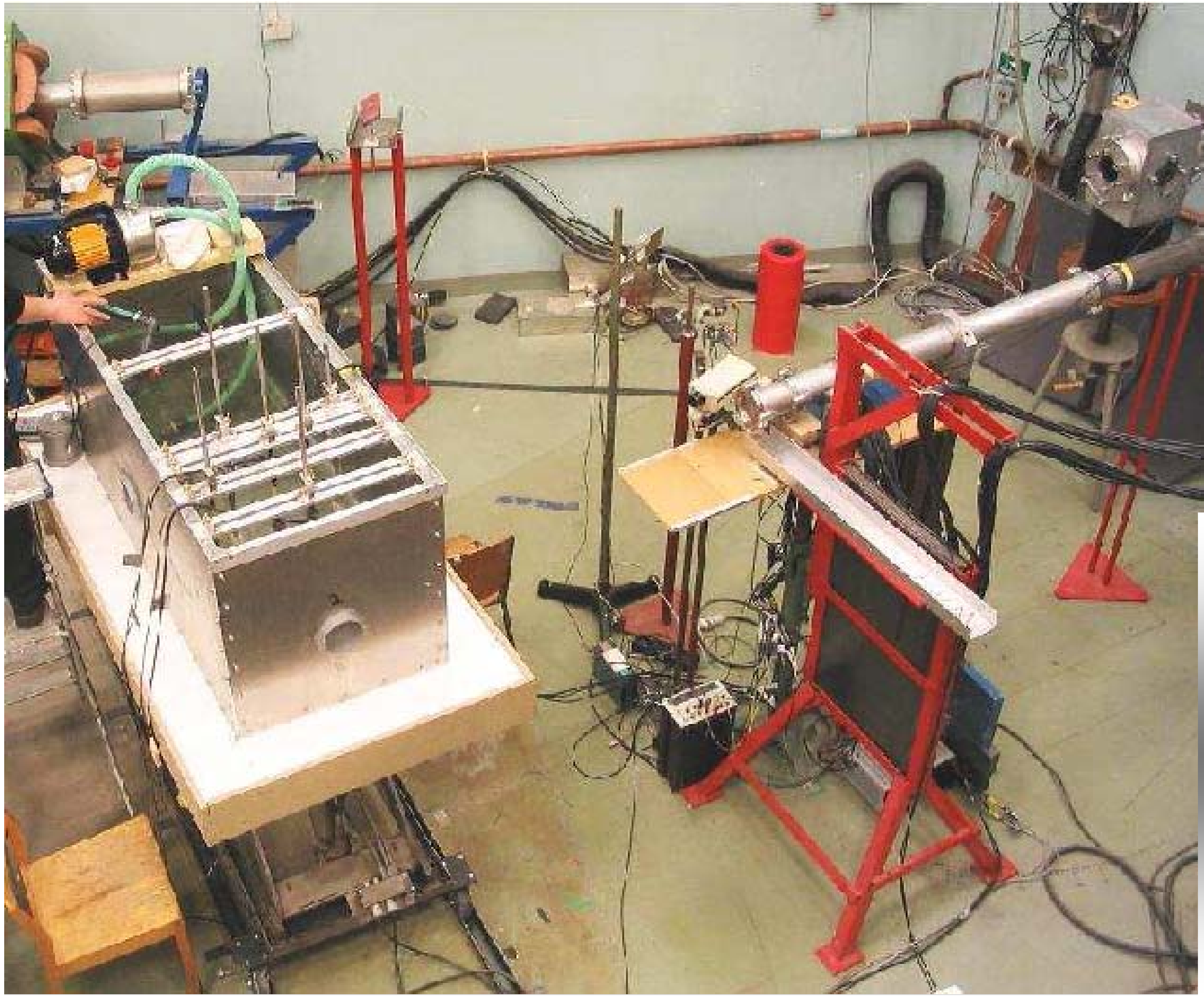
Taken from G. Riccobene, ARENA06

Acoustic Activities in Erlangen

Since 2002:

- Tests of the thermo-acoustic model;
- Studies of Piezo-based acoustic sensors;
- Design/production of deep-sea hydrophones;
- First in-situ measurement at the ANTARES site;
- Preparation of the integration of acoustic sensors into the ANTARES detector;
- Simulation and sensitivity studies.

A Beam Test with Protons ...

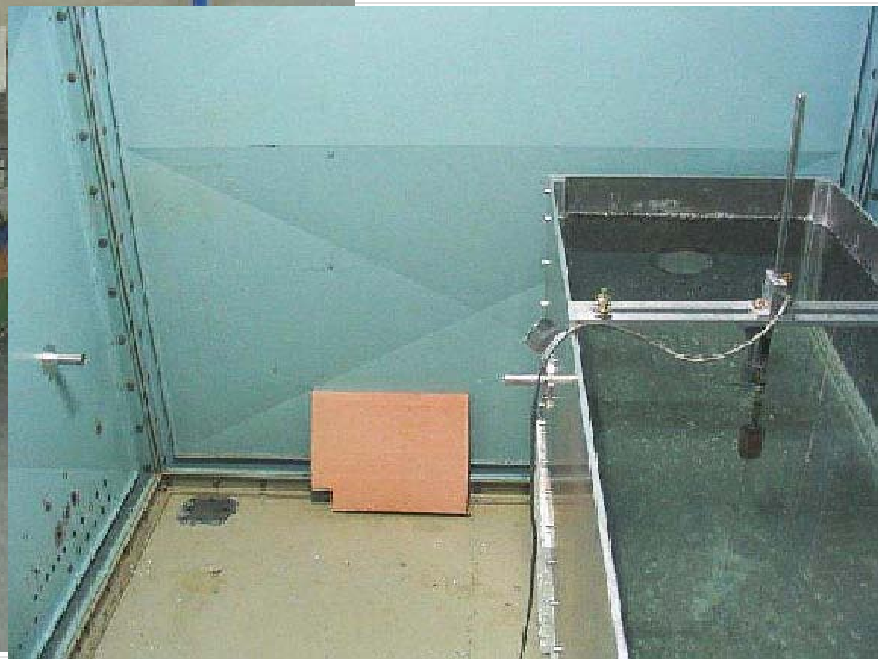


Commercial hydrophone, frequency range 2 – 150 kHz

- Feb. 2004 at Theodor Svedberg Laboratory, Uppsala;
- 177 MeV protons, pulse duration 30ms, energy 10 – 400 PeV;
- Penetration depth in water: 22cm;

... and a Beam Test with an Infrared Laser

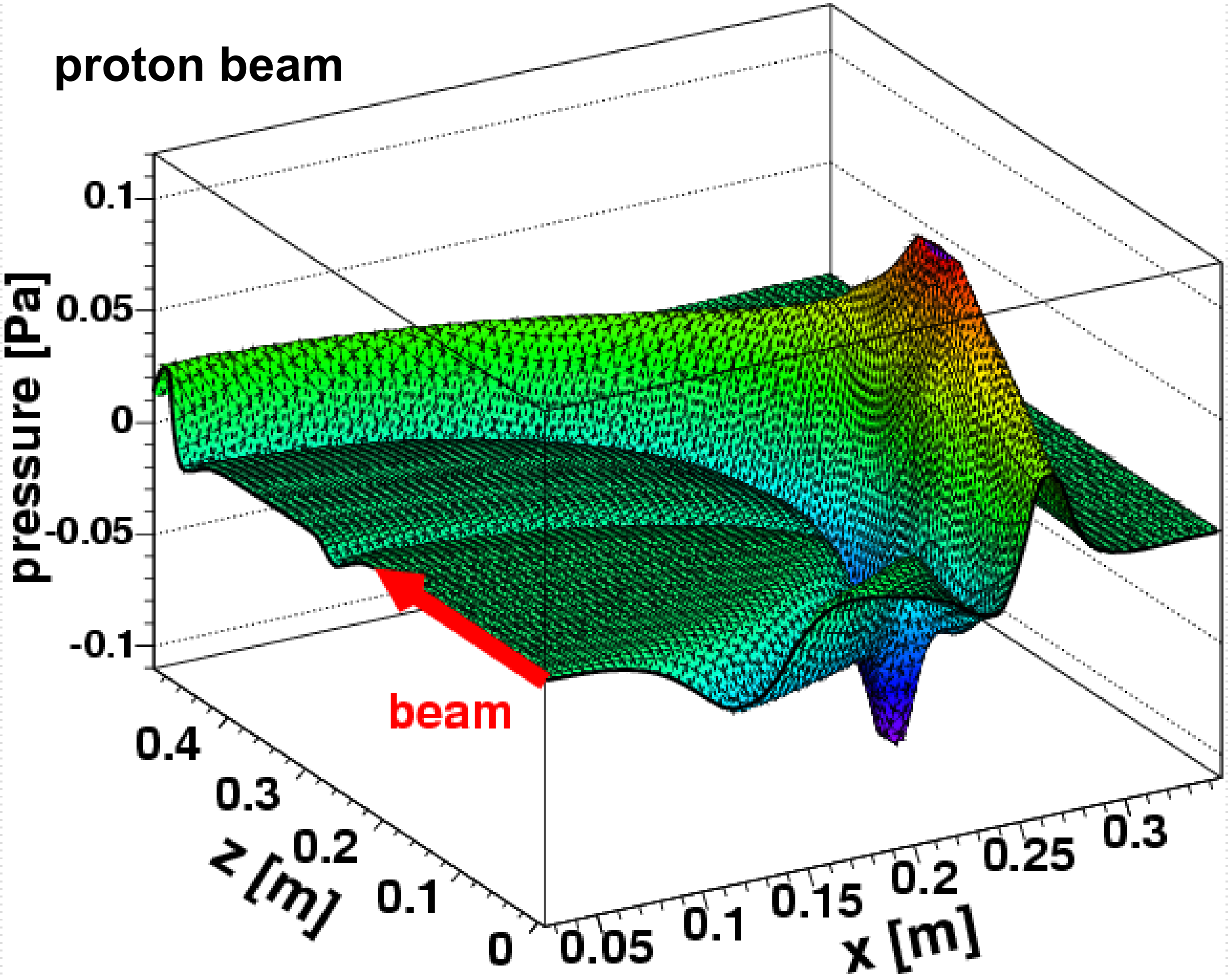
- Nd:YAG-Laser, λ=1064 nm;
- Absorption length 6 cm;
- Pulse duration 10 ns.



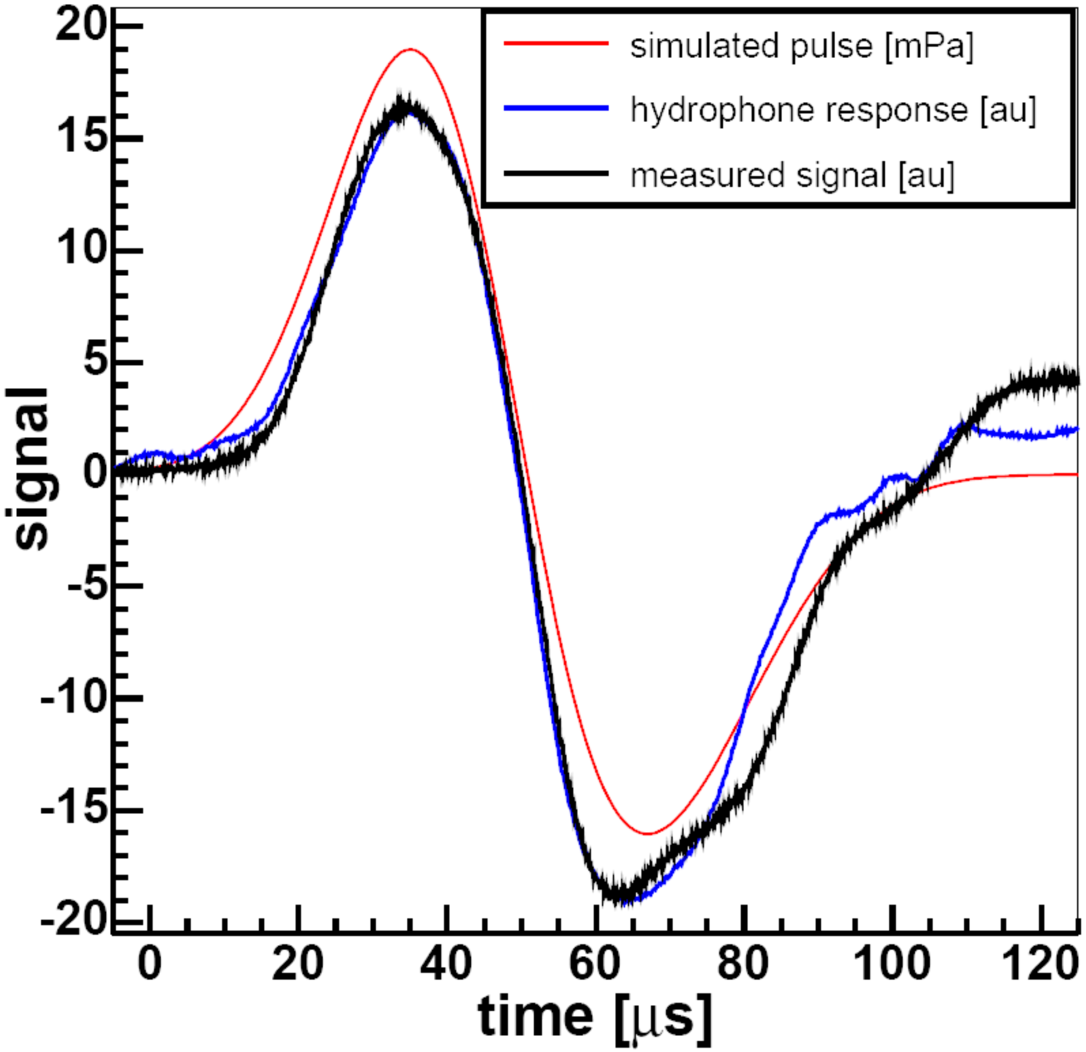
Simulation of expected results

Procedure:

- Geometry of energy deposition (GEANT, laser beam parameters);
- Assume instantaneous energy deposit and corresponding water expansion;
- Calculate sonic field by numeric solution of wave equation.

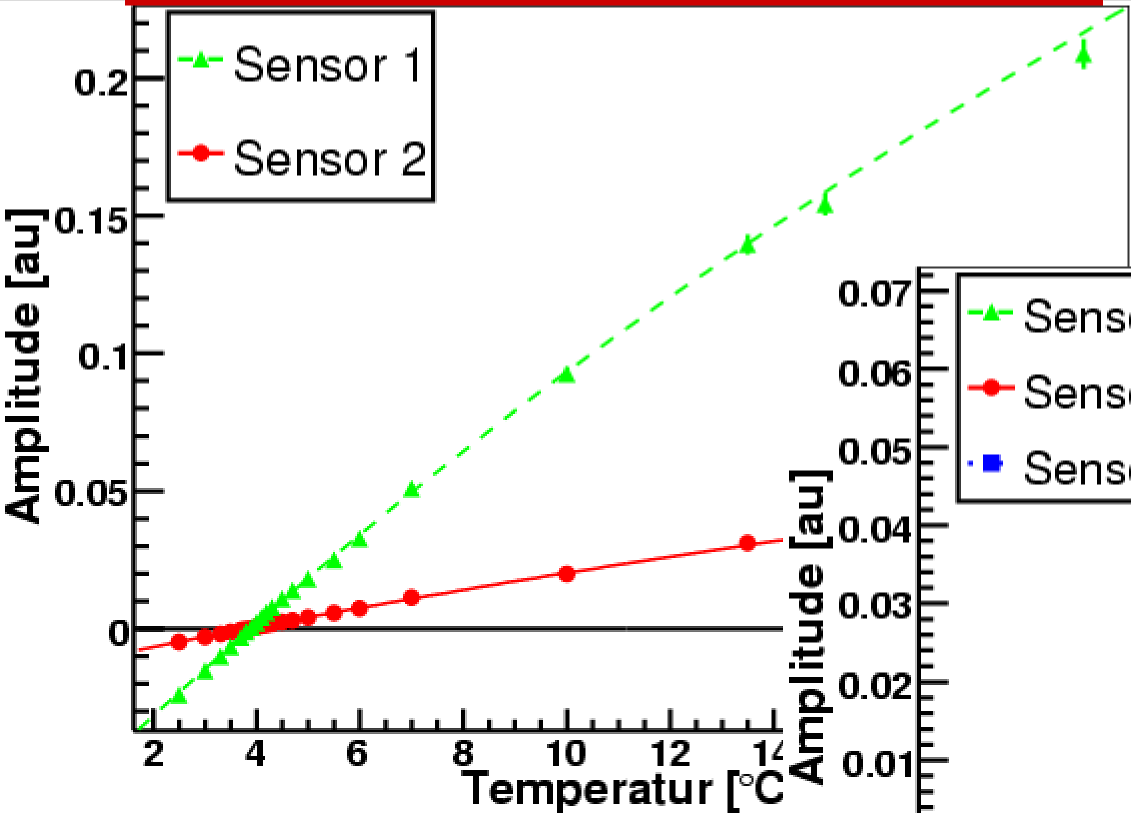


Comparison of data and simulation

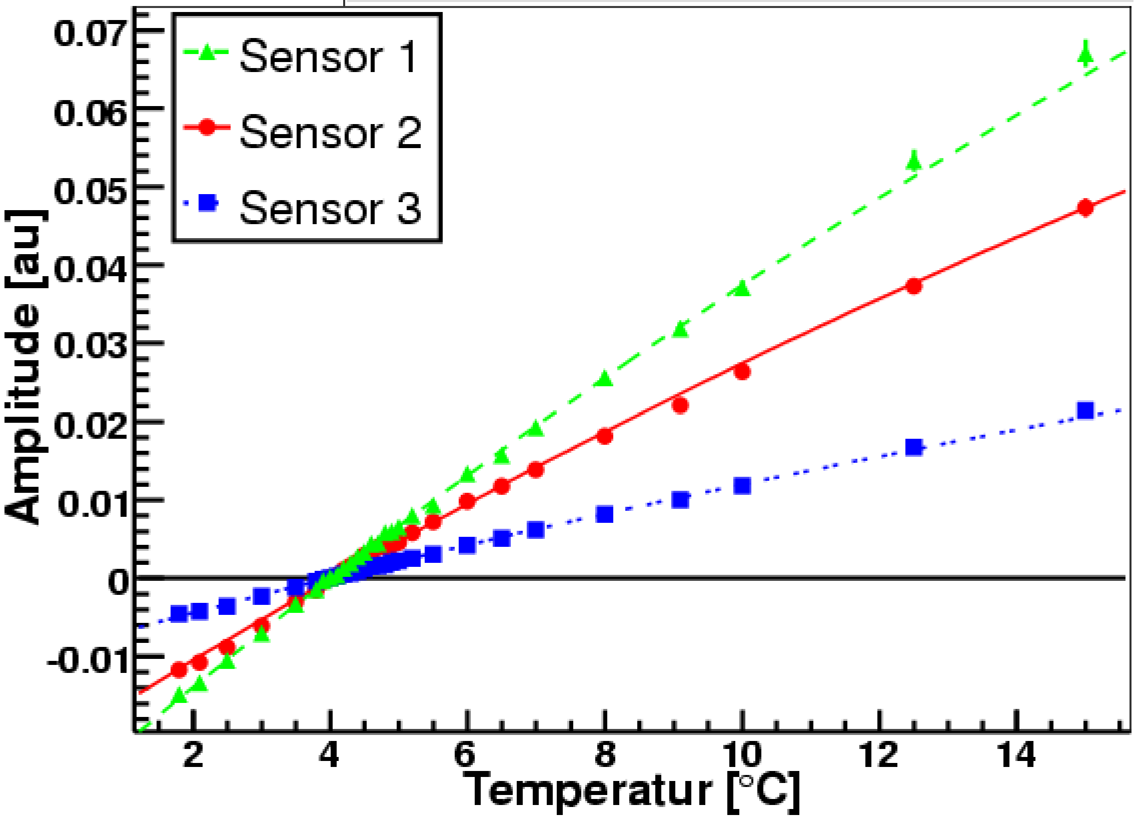


- Problem: Measured pulse is affected by frequency-dependent response of hydrophone.
- Studied by generating the predicted pulse with Piezo transducer and measure it with the hydrophone.
- Result: Very good agreement (normalization fitted to data).
- Absolute calibration understood to few-%-level.

Is the Signal Really Acoustic?



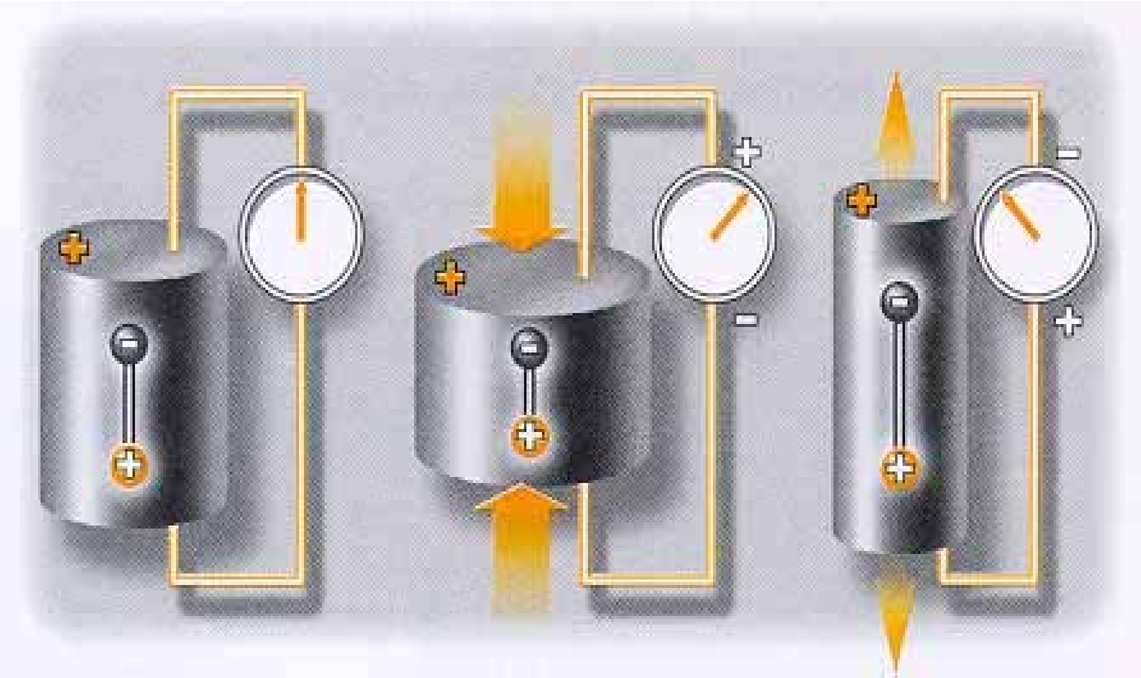
- The crucial test: The temperature dependence
- Exactly as expected!



Also measured:

- sound velocity
- geometrical dependence
- energy dependence …

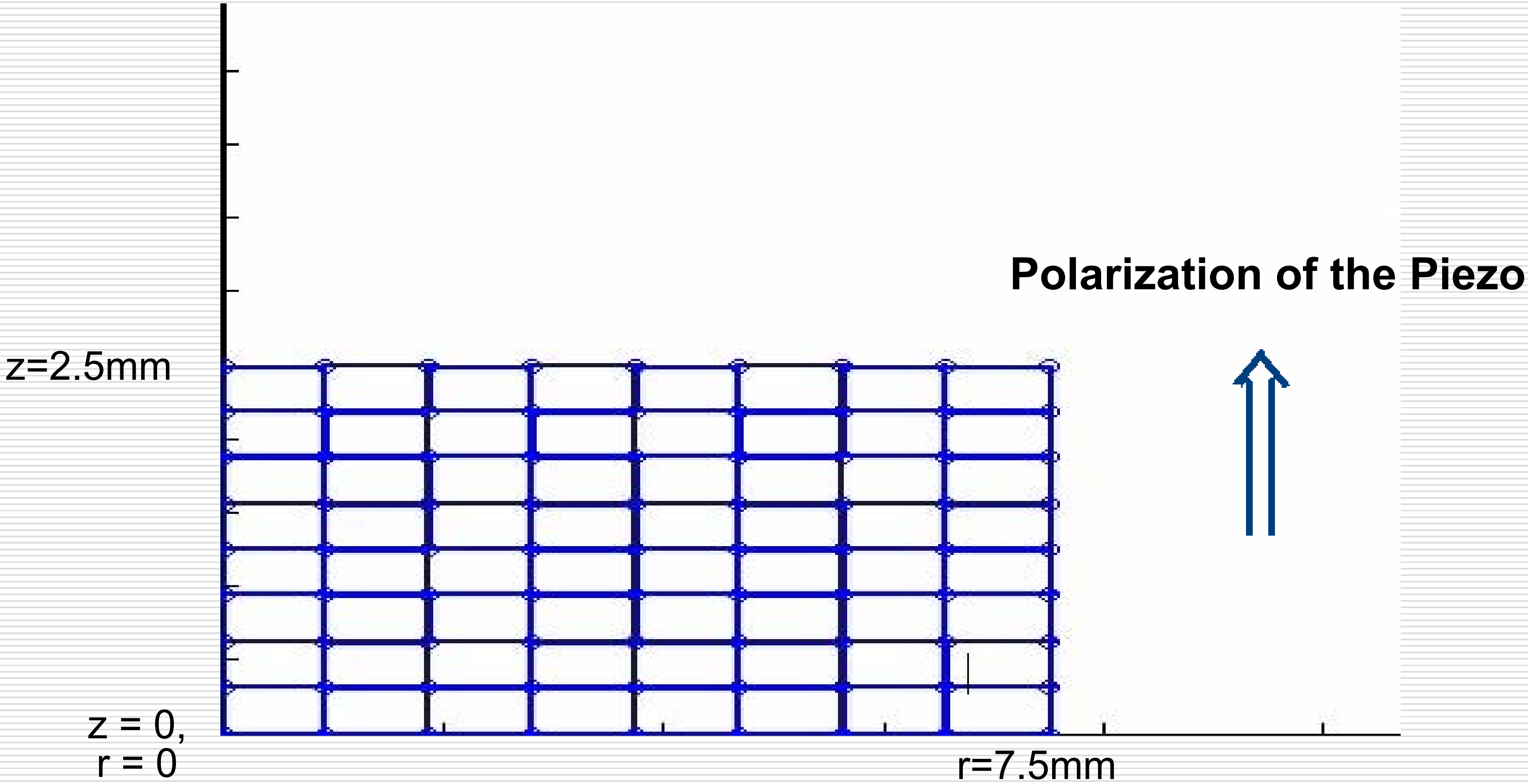
Going into Details of Piezo Elements



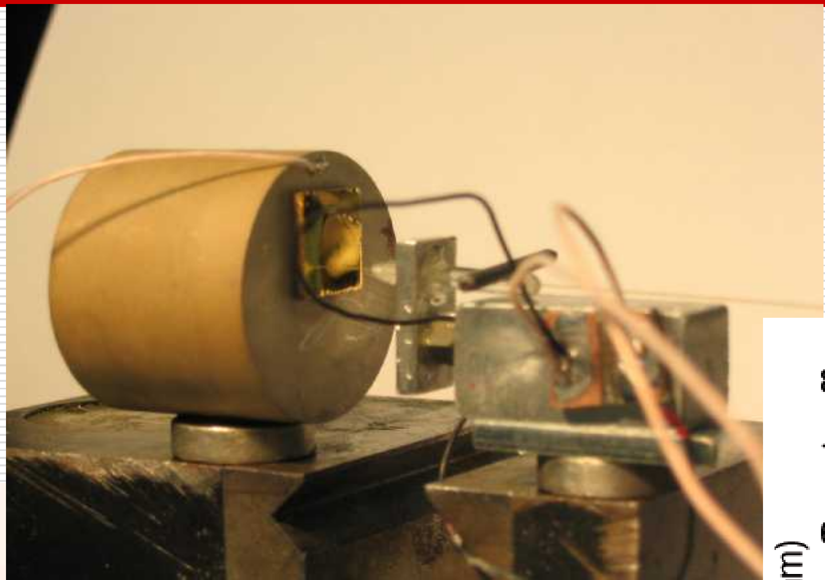
- **Equation of motion of Piezo element is complicated (coupled partial differential equations (PDE) of an anisotropic material):**
  - **Hooks law + electrical coupling**
  - **Gauss law + mechanical coupling**
- **Finite Element Method chosen to solve these PDE.**

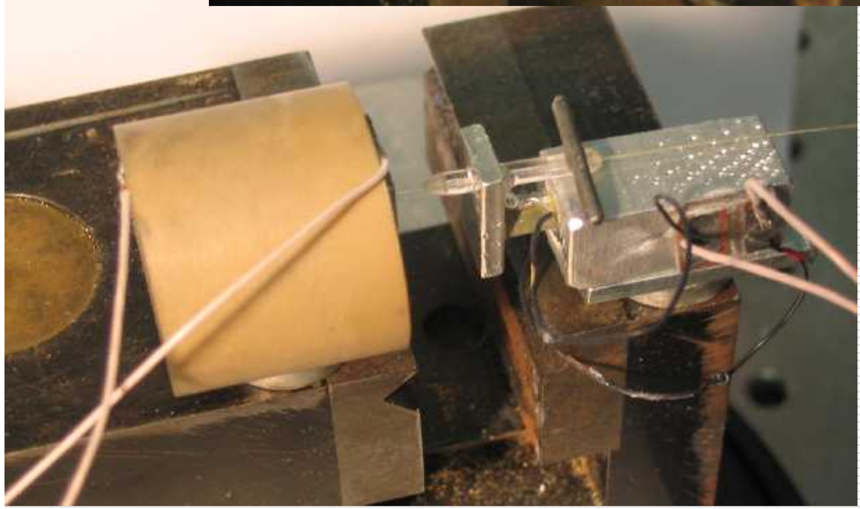
How a Piezo Element Moves

20 kHz sine voltage applied to Piezo disc with r=7.5mm, d=5mm

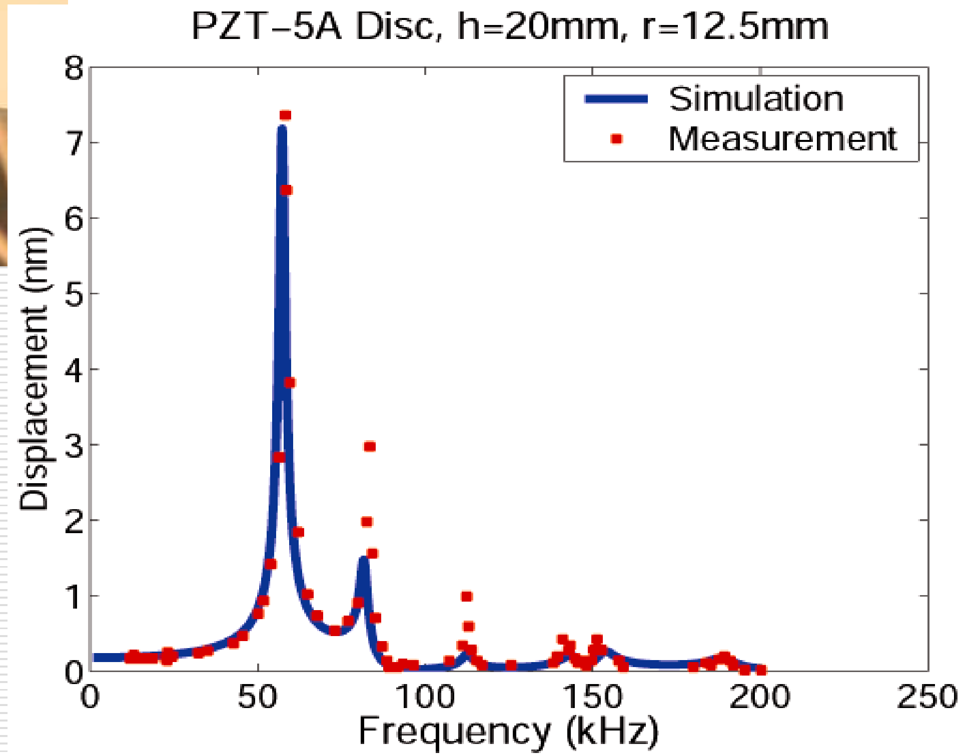


Checking with Measurements



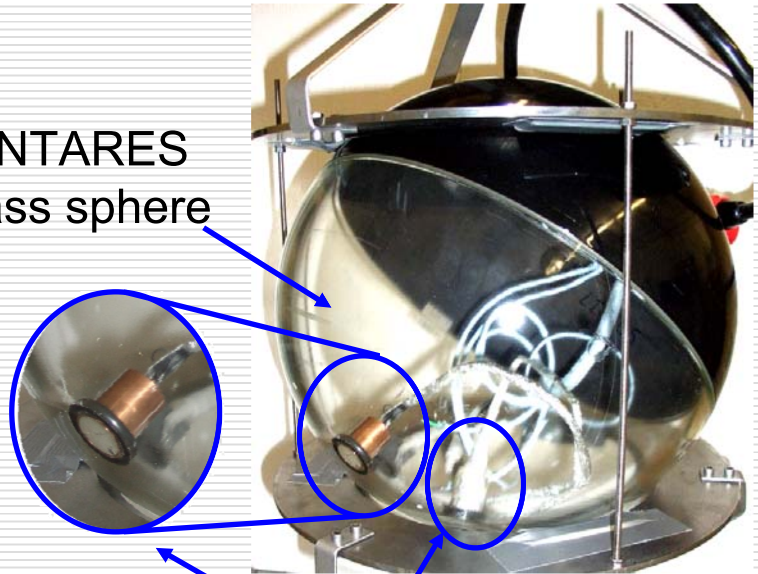


Direct measurement of oscillation amplitude with Fabry-Perot interferometer as function of frequency



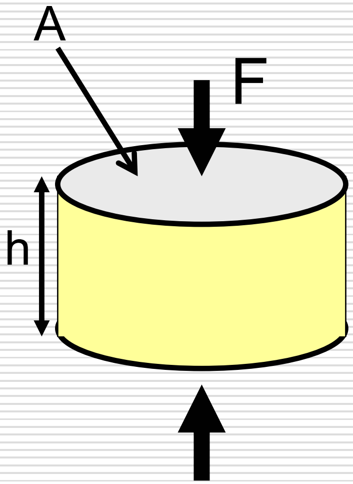
Aim: Acoustic Sensors

- Basic Design of Sensors for the ANTARES acoustics
  - Sensor = Piezo element (disc and/or tube) + pre-amplifier
  - either encapsulated in polyurethane → "hydrophone"
  - or coupled to ANTARES glass sphere → "acoustic module“ (AM)

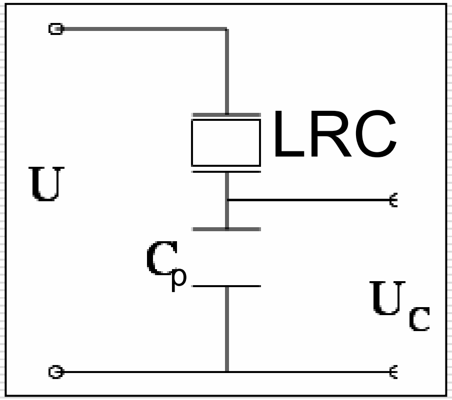


Electro-Mechanical Equivalent Circuit

- Analogy between enforced mechanical and electrical oscillation
- ⇒ mechanical properties of Piezo can be expressed by equivalent electrical properties:



force F	$U=F/\alpha$	voltage U
elongation x	$Q=\alpha\cdot x$	charge Q
stiffness S	$C=\alpha^2/S$	capacity C
damping W	$R=W/\alpha^2$	resistance R
inertia m	$L=m/\alpha^2$	inductance L



(C_p = electrical capacity between electrodes)

α = electromechanical coupling constant (depends on material)

$$F_{ext} = m\ddot{x} + W\dot{x} + Sx$$

$$\longleftrightarrow$$

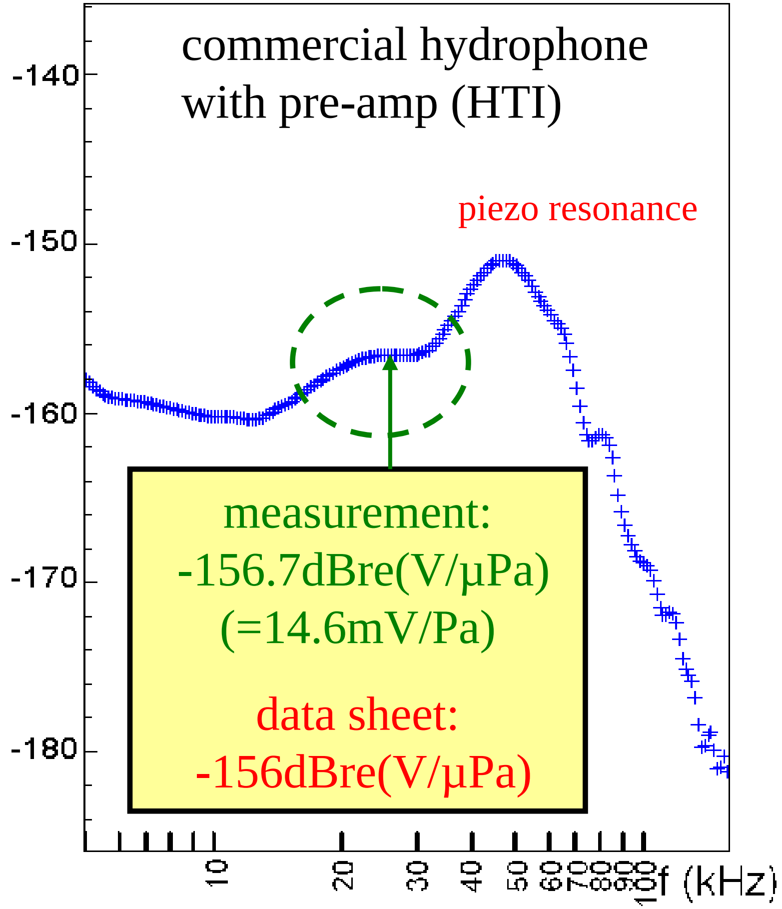
$$U_{ext} = L\ddot{Q} + R\dot{Q} + \tfrac{1}{C} Q$$

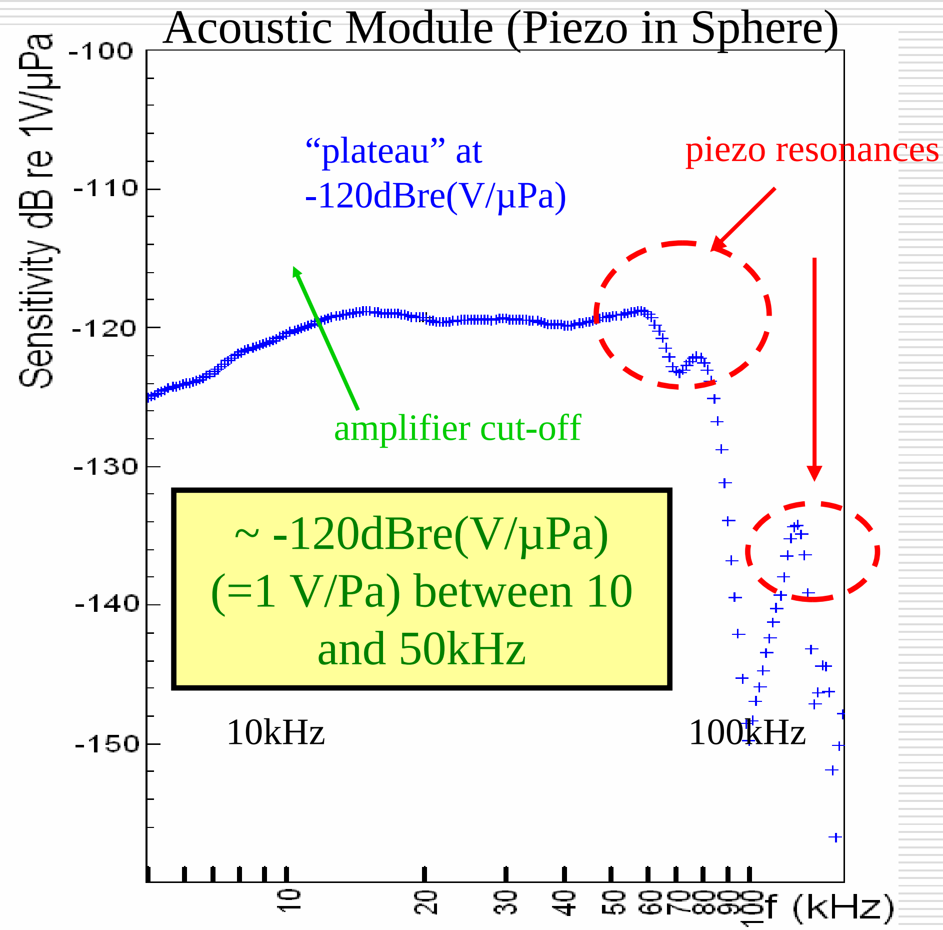
knowledge of equivalent circuit ⇒ simple model of Piezo

Lab Equipment for Acoustic R&D Work

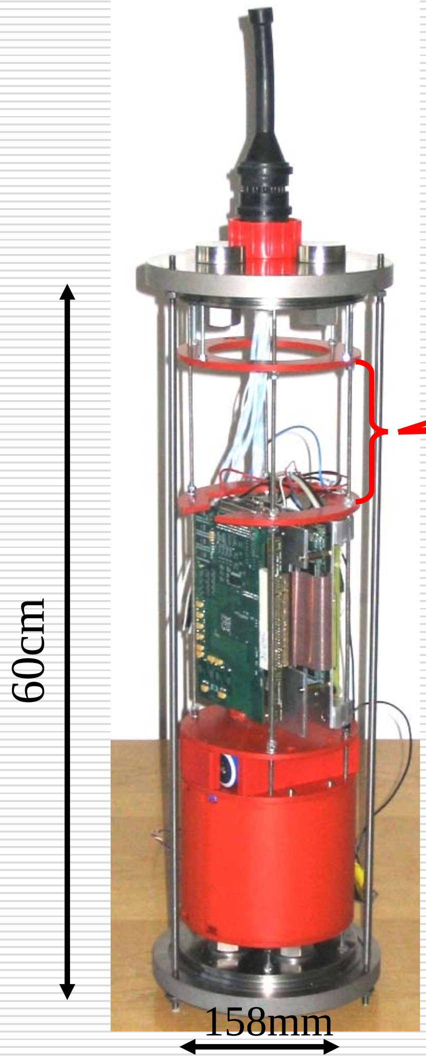
Piezo Calibration – Examples

Using exact prediction of acoustic pulses from Piezo transducers

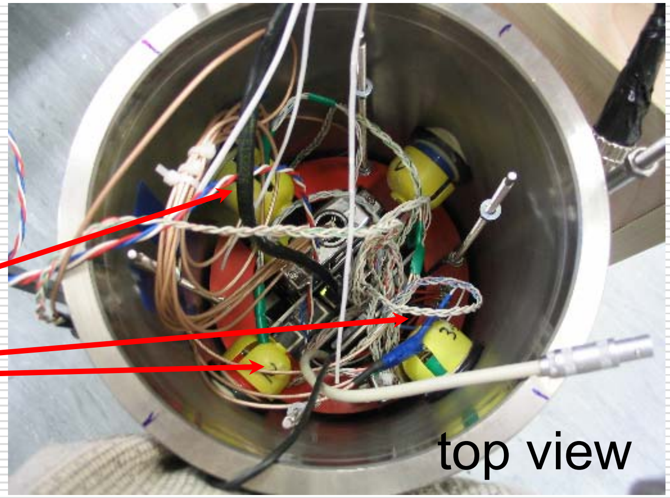




AMADEUS-0: 1st Acoustic Measurements in situ



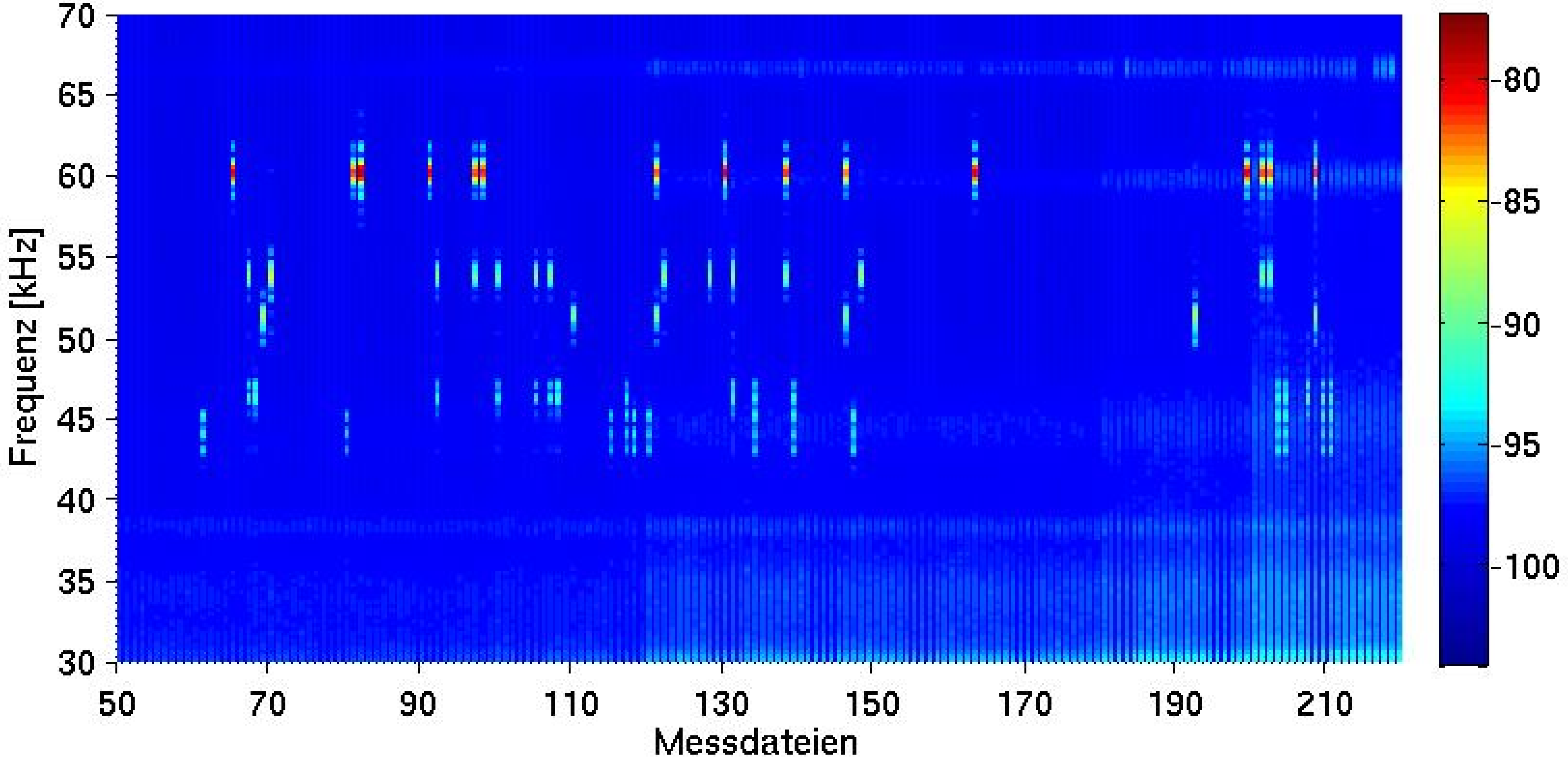
5 acoustic sensors



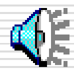
AMADEUS-0
=
Autonomous Module for Acoustic Detection Under the Sea

- Deployed with ANTARES test line (Line-0);
- Data taking March/May 2005, 12 GByte of data;
- Strategy: Write data to CF card (silent), if card full, stop data taking and dump to hard disk;
- Battery power sufficient for ~75 hours;
- Goals: Test sensors and DAQ chain, assess deep-sea acoustic background.

AMADEUS-0: A Spectrogram



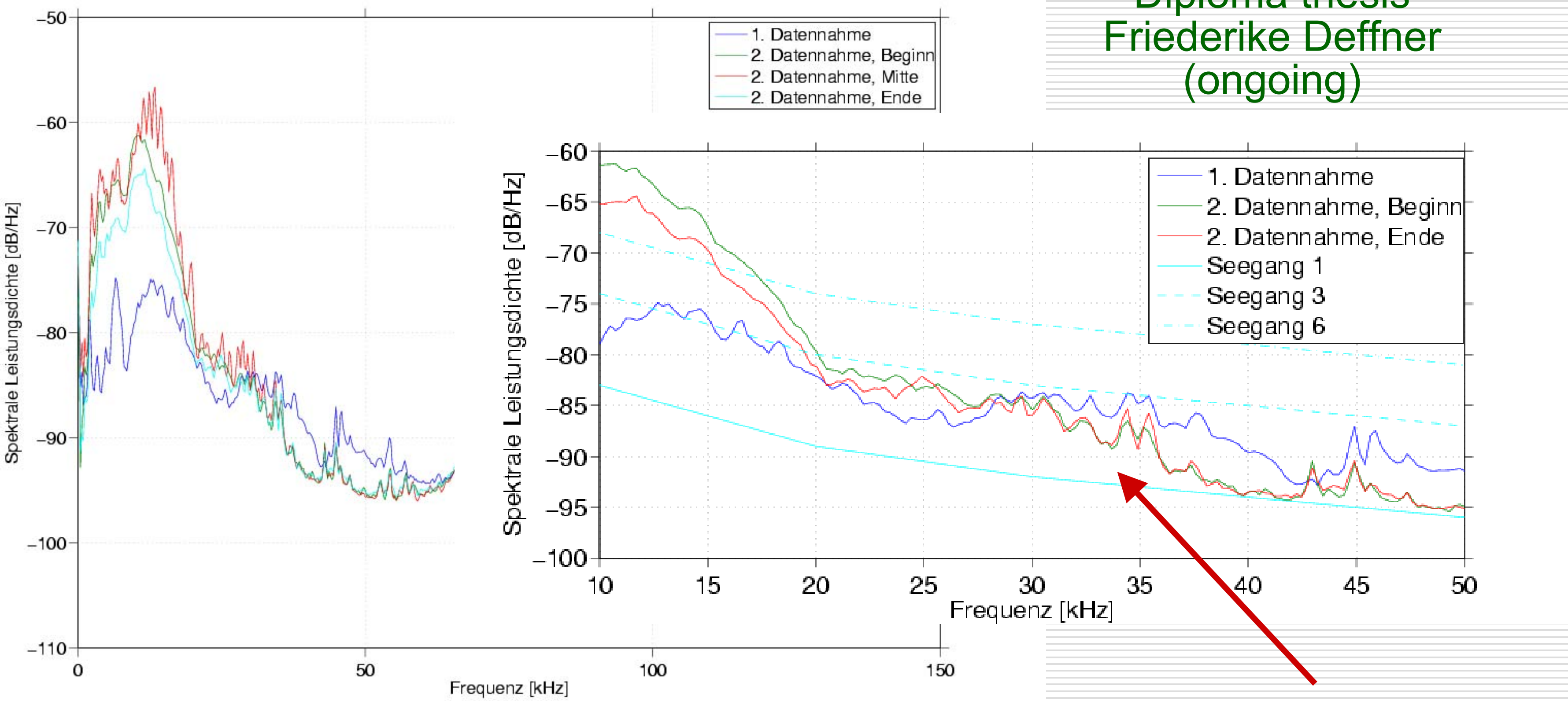
- Intensity spectrum vs. time
- “Pings” of various transducers clearly visible



stretched by factor 10

AMADEUS-0: Acoustic Power Spectrum

Diploma thesis
Friederike Deffner
(ongoing)



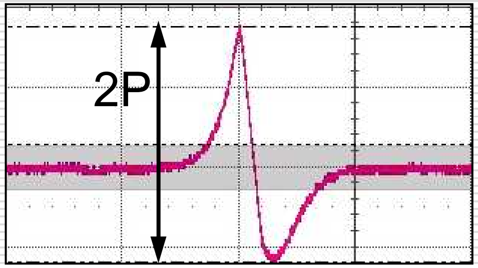
Spectrum above 20kHz to large part electronics noise

- **Intensity spectrum from Fourier analysis;**
- **Peak at ~75kHz: Eigenfrequency of Piezo; peaks at 90-120 kHz: electronics.**

Next Step: Correlated backgrounds

General background contributions:

- inherent noise of sensor/electronics
- thermal noise of water
- noise from sea surface, anthropogenic sources, etc.
- **point sources....**

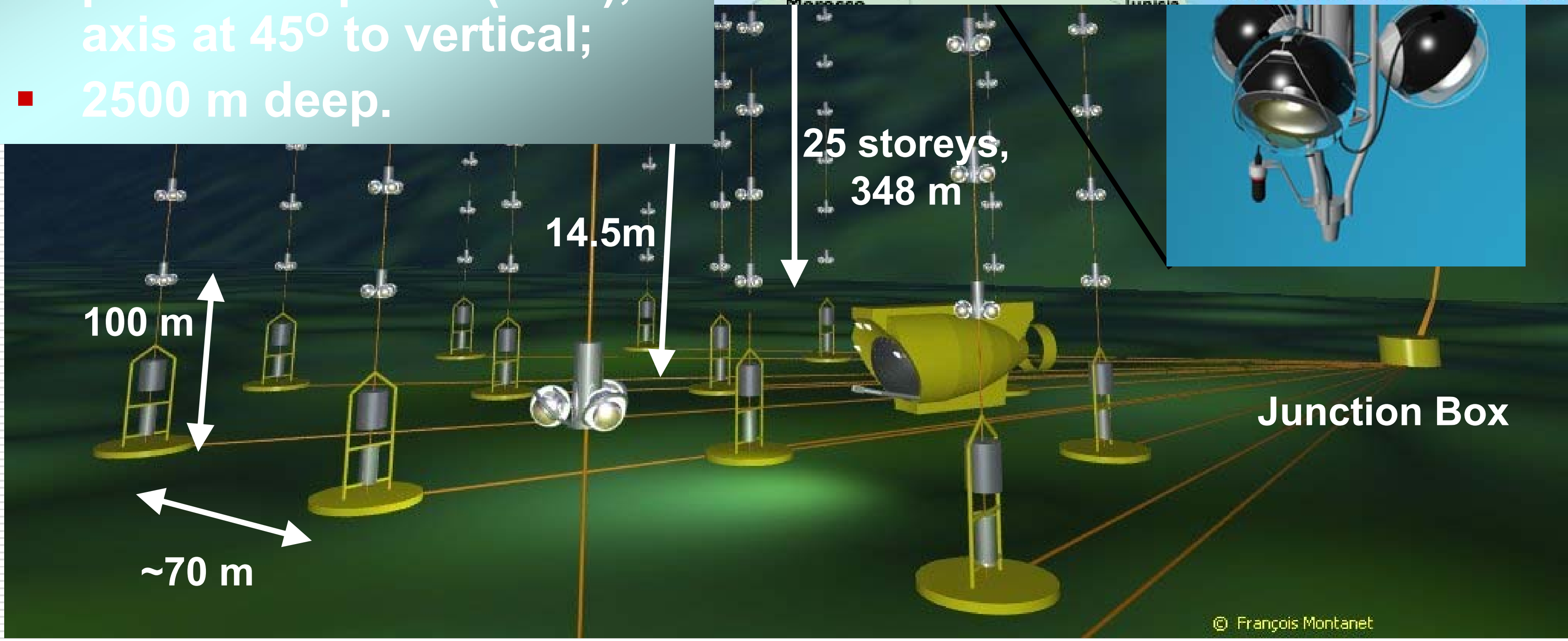


- From individual hydrophones: single bipolar pulse (BIP) rate
- Most important for a future acoustic detector: Point sources of bipolar signals!
- Can only be determined from measurements with several hydrophones - main objective: determine correlated BIP rate

$$\boxed{\frac{d^3N}{dPdVdt}}$$

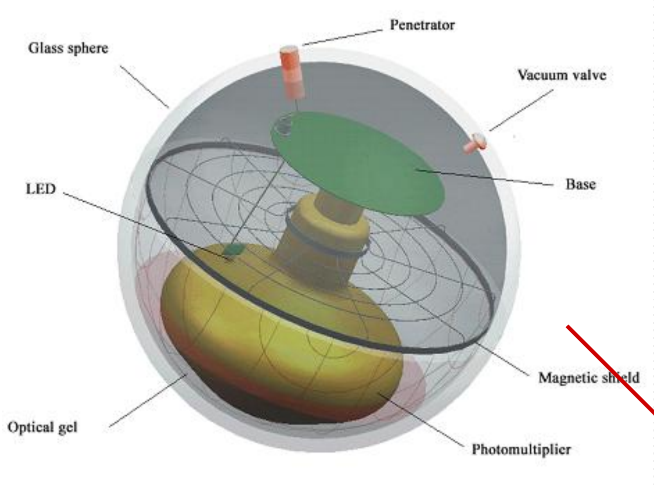
ANTARES: Detector Design

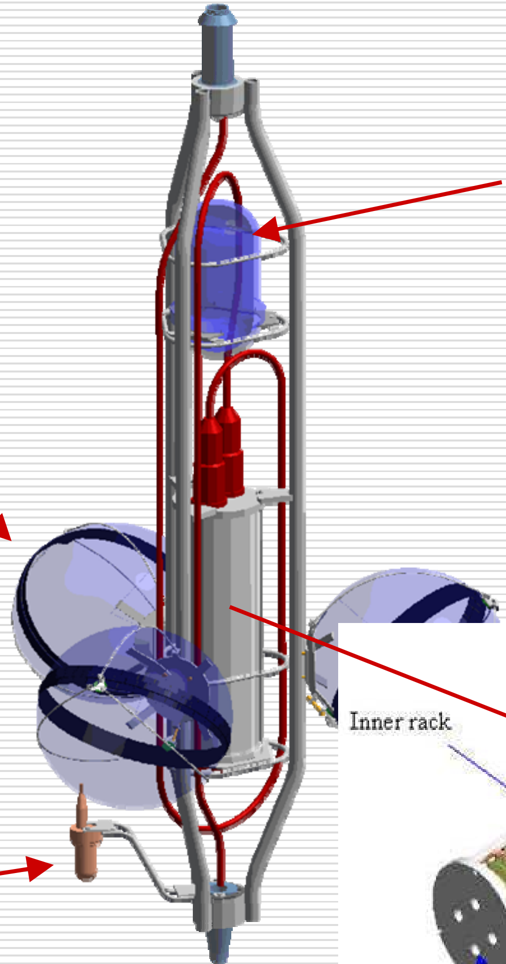
- **String-based detector;**
- **Underwater connections by deep-sea submersible;**
- **Downward-looking photomultipliers (PMs), axis at 45$^{\mathrm{o}}$ to vertical;**
- **2500 m deep.**



ANTARES: Components of a Storey

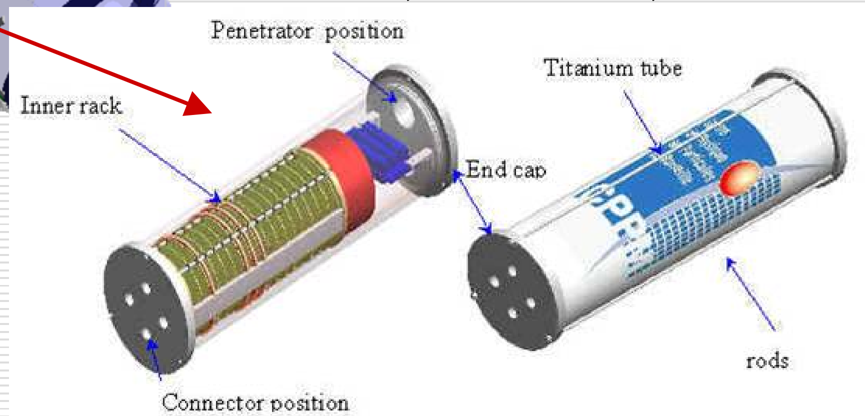
Optical Module





LED Beacon
for time
calibration
purposes

Titanium cylinder
housing electronics for
readout, calibration, …

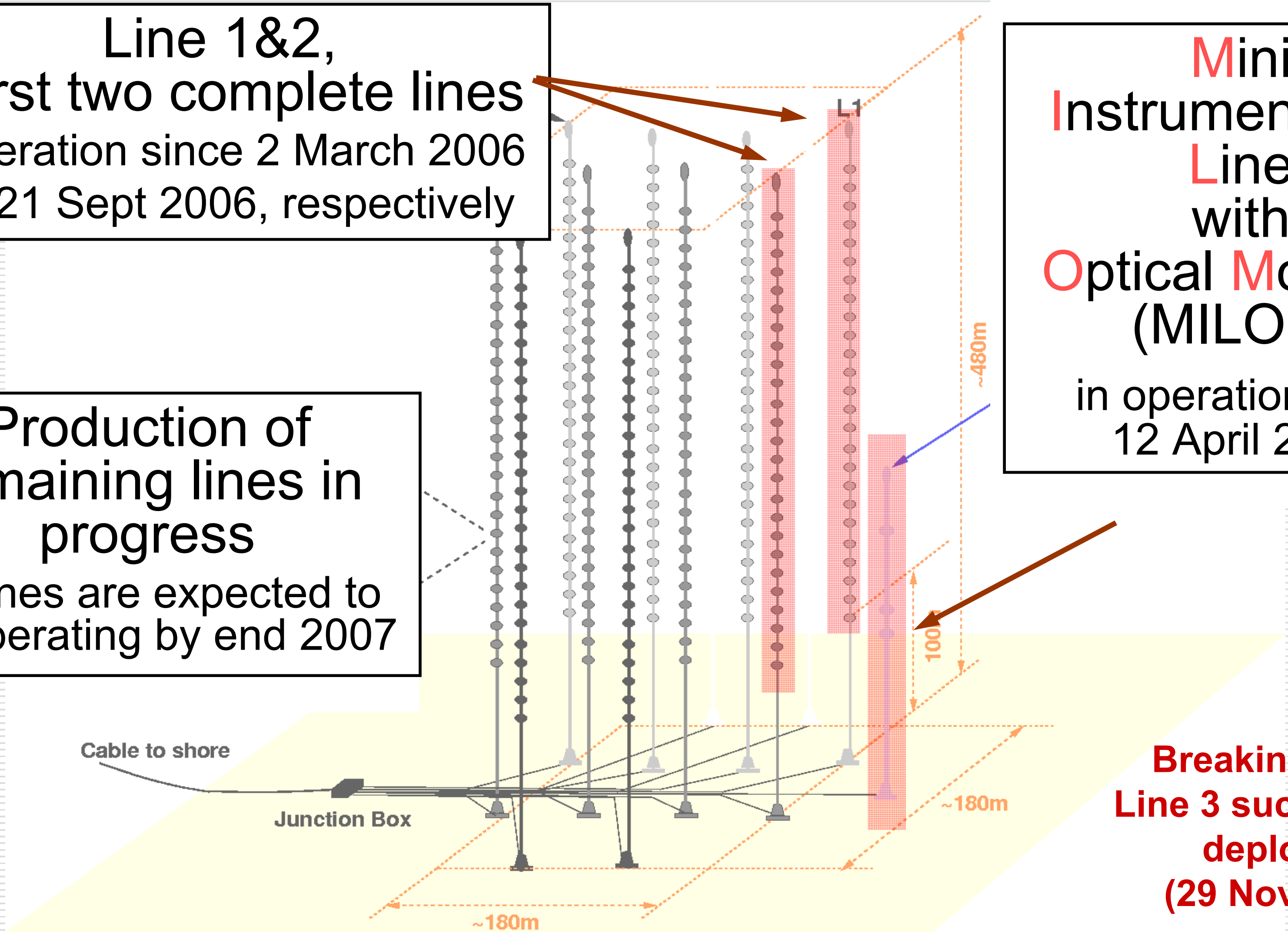


Hydrophone (RX)
for positioning

ANTARES: Current Status

Line 1&2,
first two complete lines
in operation since 2 March 2006
and 21 Sept 2006, respectively

Production of
remaining lines in
progress
12 lines are expected to
be operating by end 2007



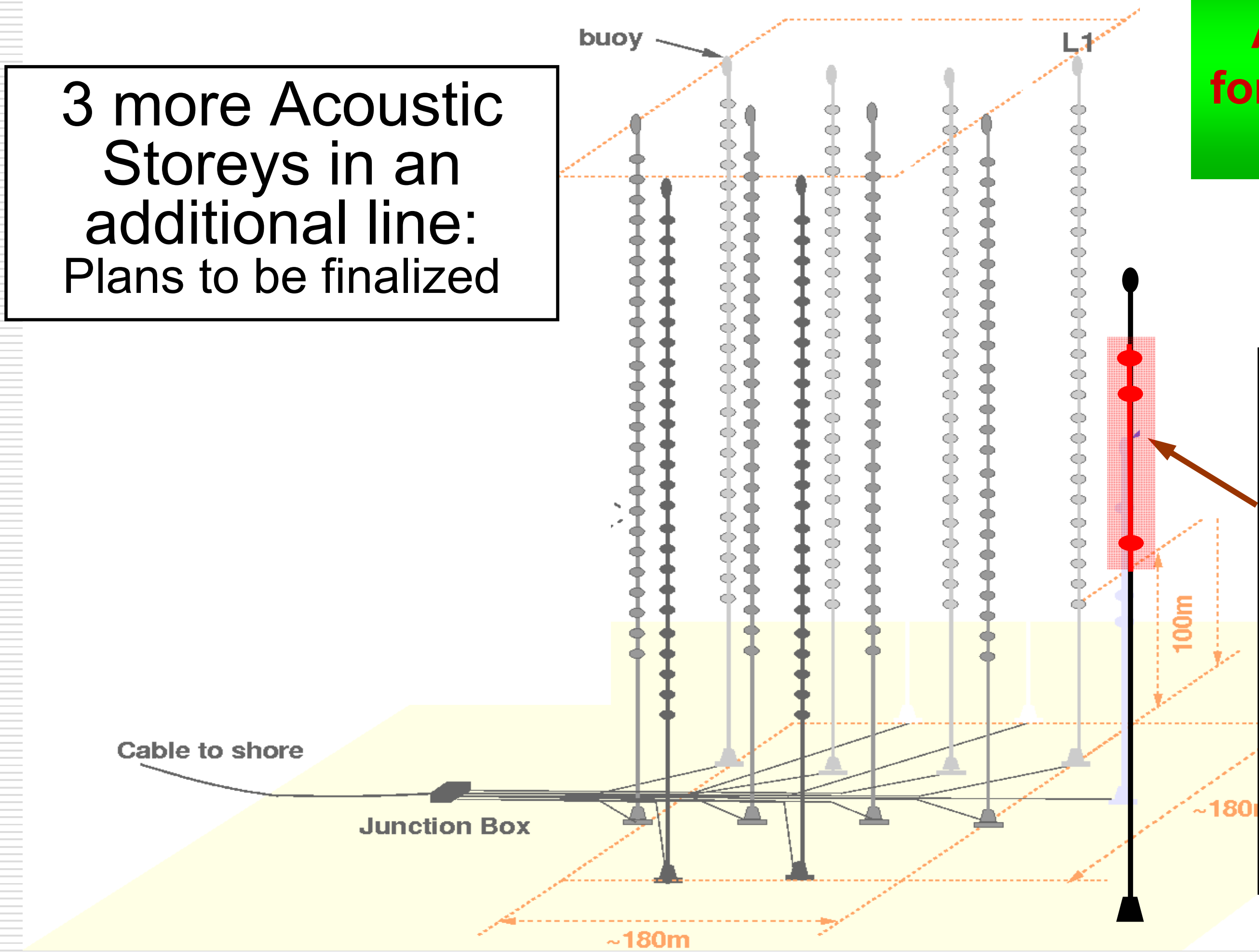
Mini
Instrumentation
Line
with
Optical Modules
(MILOM)
in operation since
12 April 2005

**Breaking news:
Line 3 successfully
deployed
(29 Nov. 2006)**

ANTARES: Setup with Acoustics (AMADEUS)

AMADEUS:
ANTARES Modules for Acoustic Detection Under the Sea

3 more Acoustic Storeys in an additional line:
Plans to be finalized



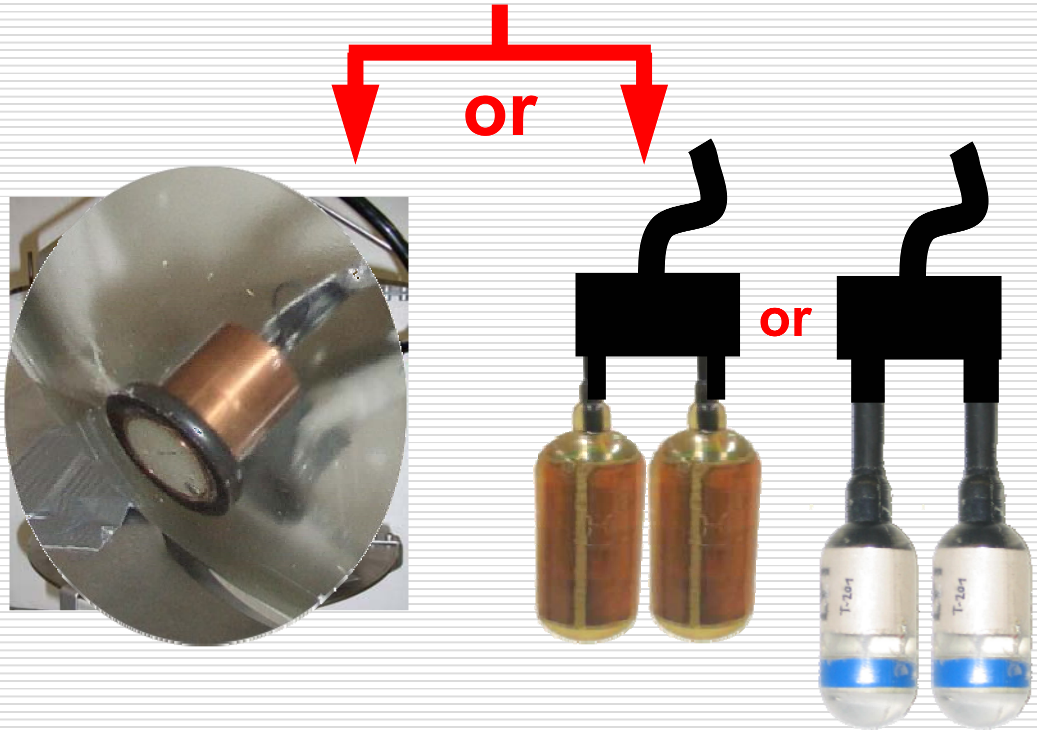
Instrumentation Line with 3 Acoustic storeys

Deployment foreseen first half 2007

Acoustic Sensors for AMADEUS

ANTARES optical module:

PMT (10") in glass sphere



acoustical module:

2 sensors (piezo with preamplifier) in one glass sphere

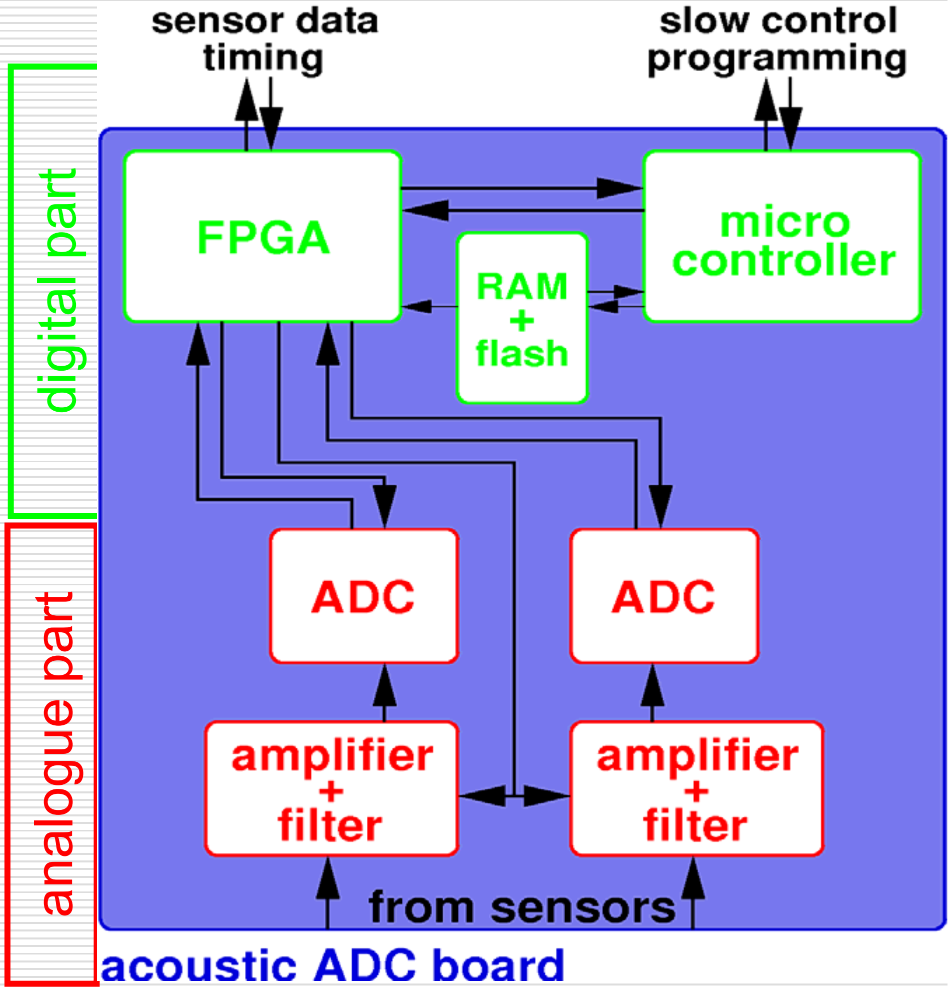
hydrophones:

2 separate sensors (commercial or custom) connected via fan-out

Acoustic ADC Board and More

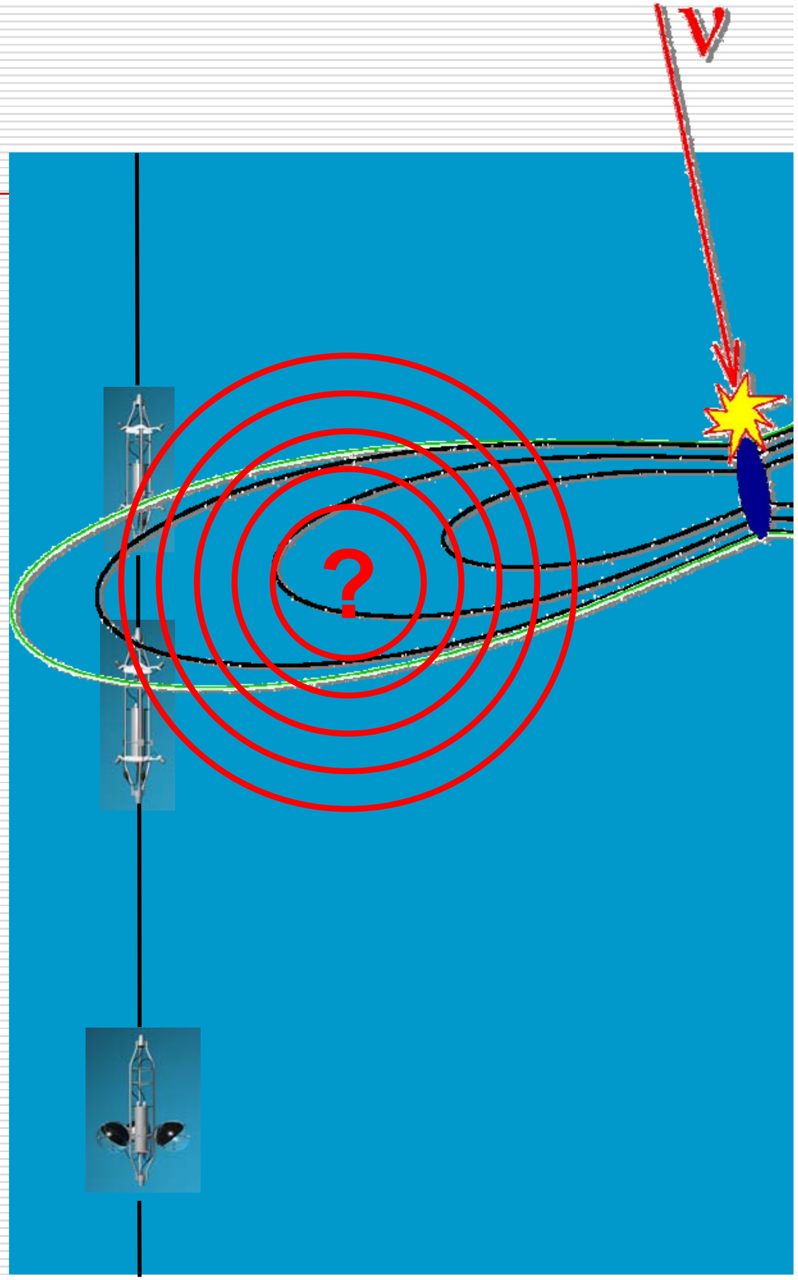
New components developed at Erlangen:

- **Acoustic sensors**
- **Acoustic ADC board**
  - all components tested
  - prototype board produced, currently tested
  - programming almost done
- **Online data filter in (PC farm)** (work started)

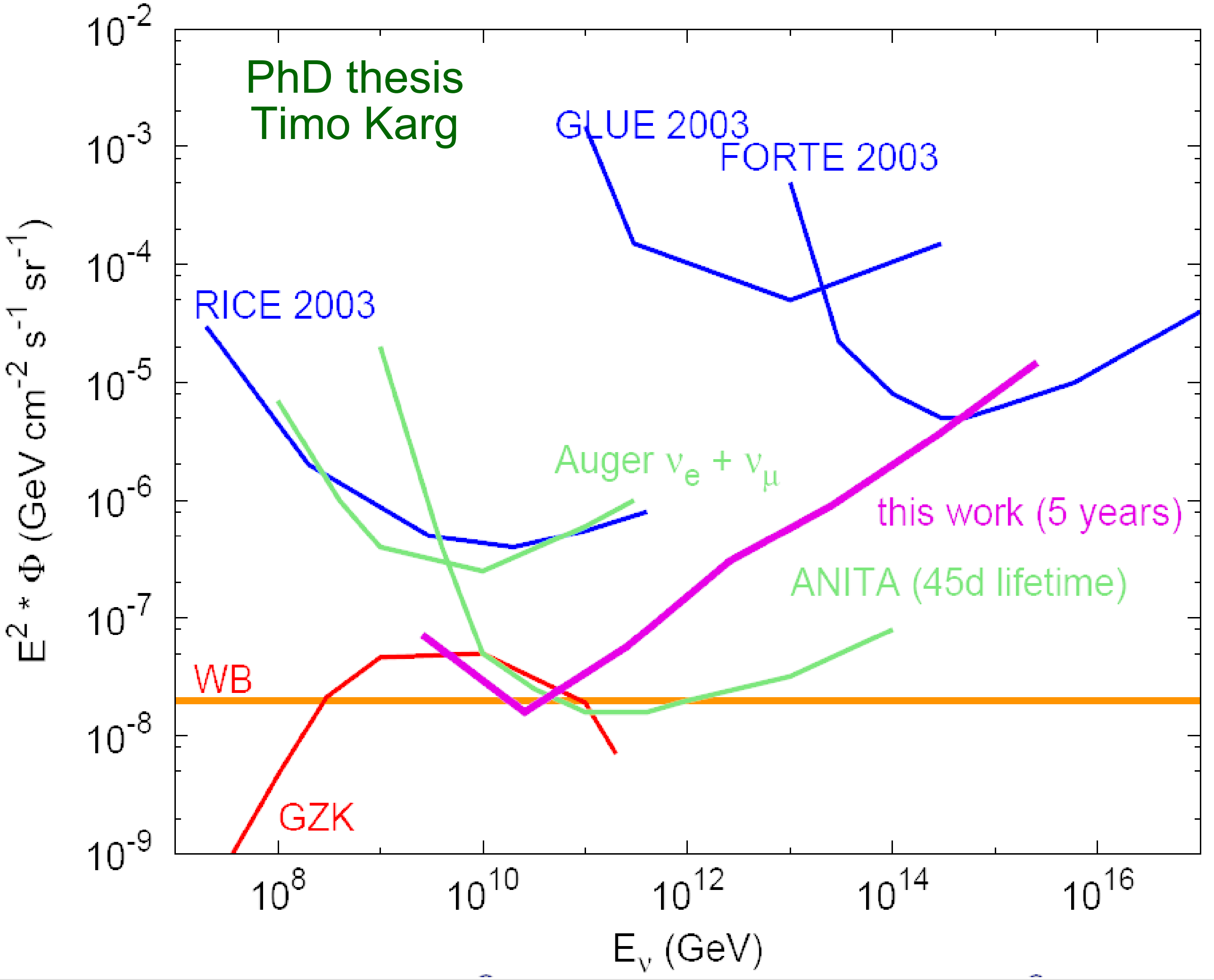


AMADEUS: Performance

- 3 (+3) storeys with 18 (36) sensors at 3 length scales (1m, 10m, 100m)
- dynamic range ¼ 3mPa – 10Pa (RMS)
- read-out sensors continuously and synchronously at ~ 200 kSPS
- data rate 10 (20) MBPS
- flexible design (sensors, gain, filter)



Sensitivity of a Future Acoustic Detector



- Full simulation chain, simplified reconstruction assumptions;
- Assumed:
  - 30 x 50 x 1 km^3 instrumented volume;
  - 200 sensor modules / km^3
  - threshold 5 mPa;
  - 3x10^5 channels @ 100 kHz

Conclusions and Outlook

- Acoustic detection of ultra-high energy neutrinos is a promising option; many experimental feasibility and R&D activities are under way.
- Various media are studied: Water, ice, salt, …
- Extensive R&D program in Erlangen directed towards deep-sea acoustic detection.
- First data available, extensive long-term studies in the context of the ANTARES experiment in preparation.
- Next steps to be taken when the results of these studies are available.