

*Physics Seminar, Zeuthen, 22.12.2004*

# Neutrino Telescopy in the Mediterranean – ANTARES, KM3NeT and Acoustics

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**Univ. Erlangen**



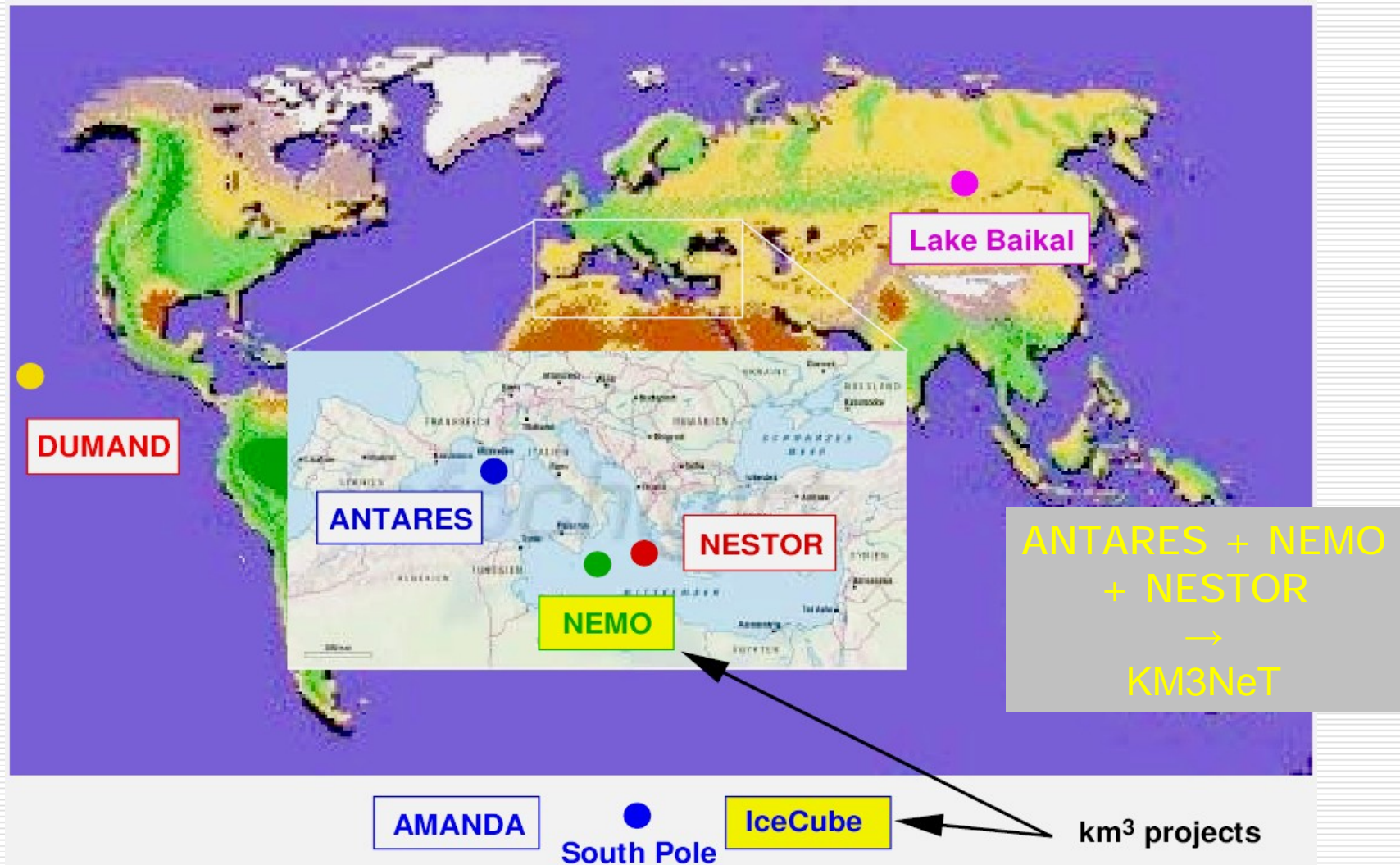
- Physics with  $\nu$  telescopes
- ANTARES: Design and status
- The KM3NeT Design Study: towards a  $\text{km}^3$ -scale detector
- Acoustic detection
- Summary

# Why Neutrino Telescopes?

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- Neutrinos traverse space without deflection or attenuation
  - they point back to their sources;
  - they allow a view into dense environments;
  - they allow to investigate the universe over cosmological distances.
- Neutrinos are produced in high-energy hadronic processes  
→ distinction between electron and proton acceleration.
- Neutrinos could be produced in Dark Matter annihilation.
- Neutrino detection requires huge target masses  
→ use naturally abundant materials (water, ice).

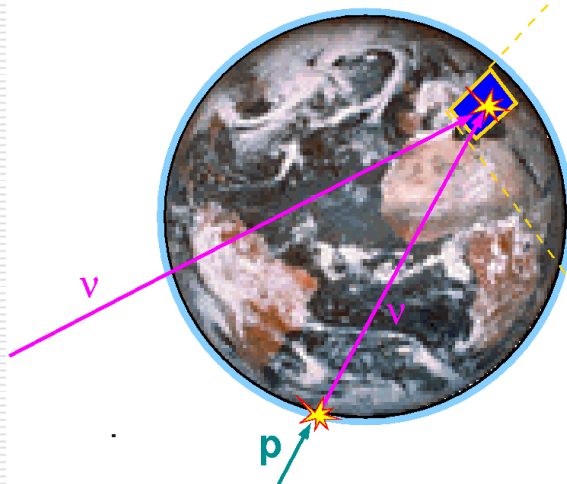
# The Neutrino Telescope World Map



# The Principle of Neutrino Telescopes

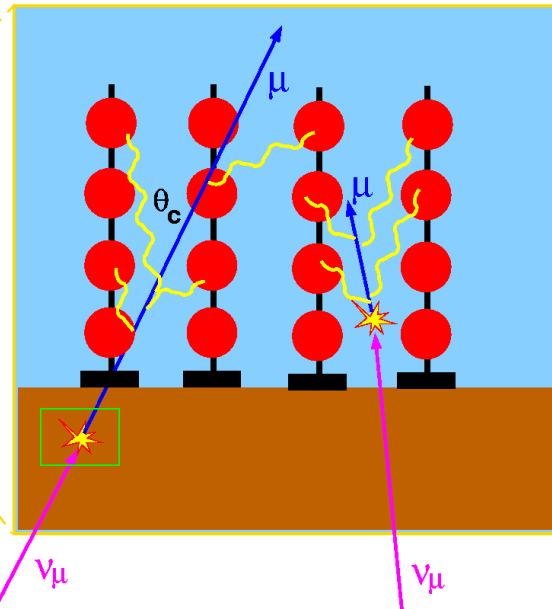
## Role of the Earth:

- Screening against all particles except neutrinos.
- Atmosphere = target for production of secondary neutrinos.



## Čerenkov light:

- In water:  $\theta_c \approx 43^\circ$
- Spectral range used:  $\sim 350\text{-}500\text{nm}$ .

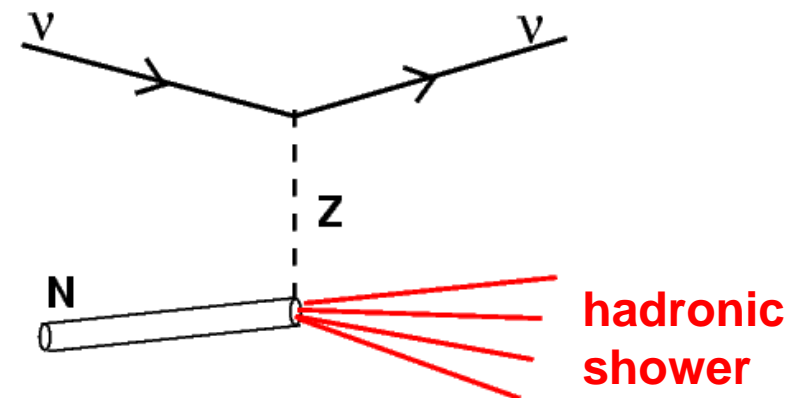
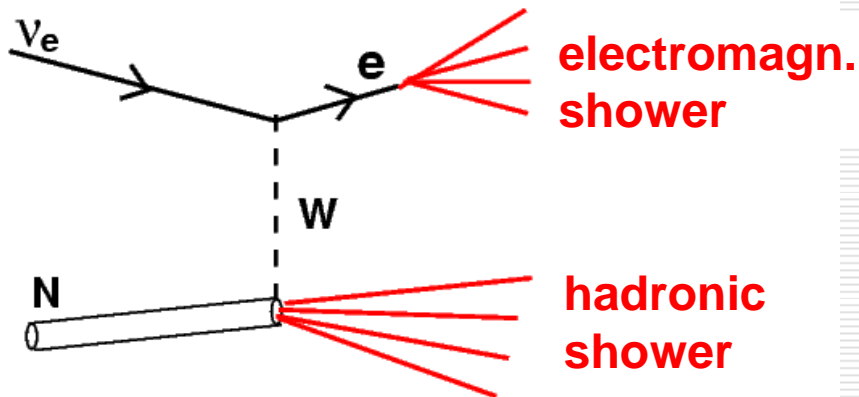
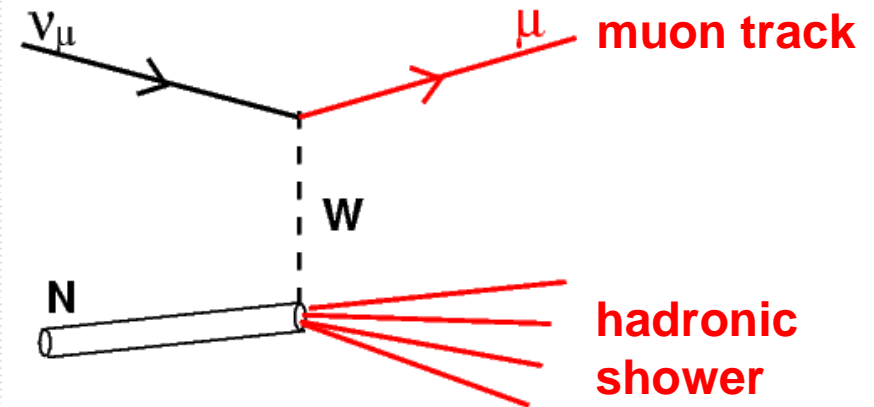


## Neutrino reactions (key reaction is $\nu_\mu N \rightarrow \mu X$ ):

- Cross sections and reaction mechanisms known from accelerator experiments (in particular HERA).
- Extrapolation to highest energies ( $> 100\text{ TeV}$ ) uncertain.

# Neutrino Interaction Signatures

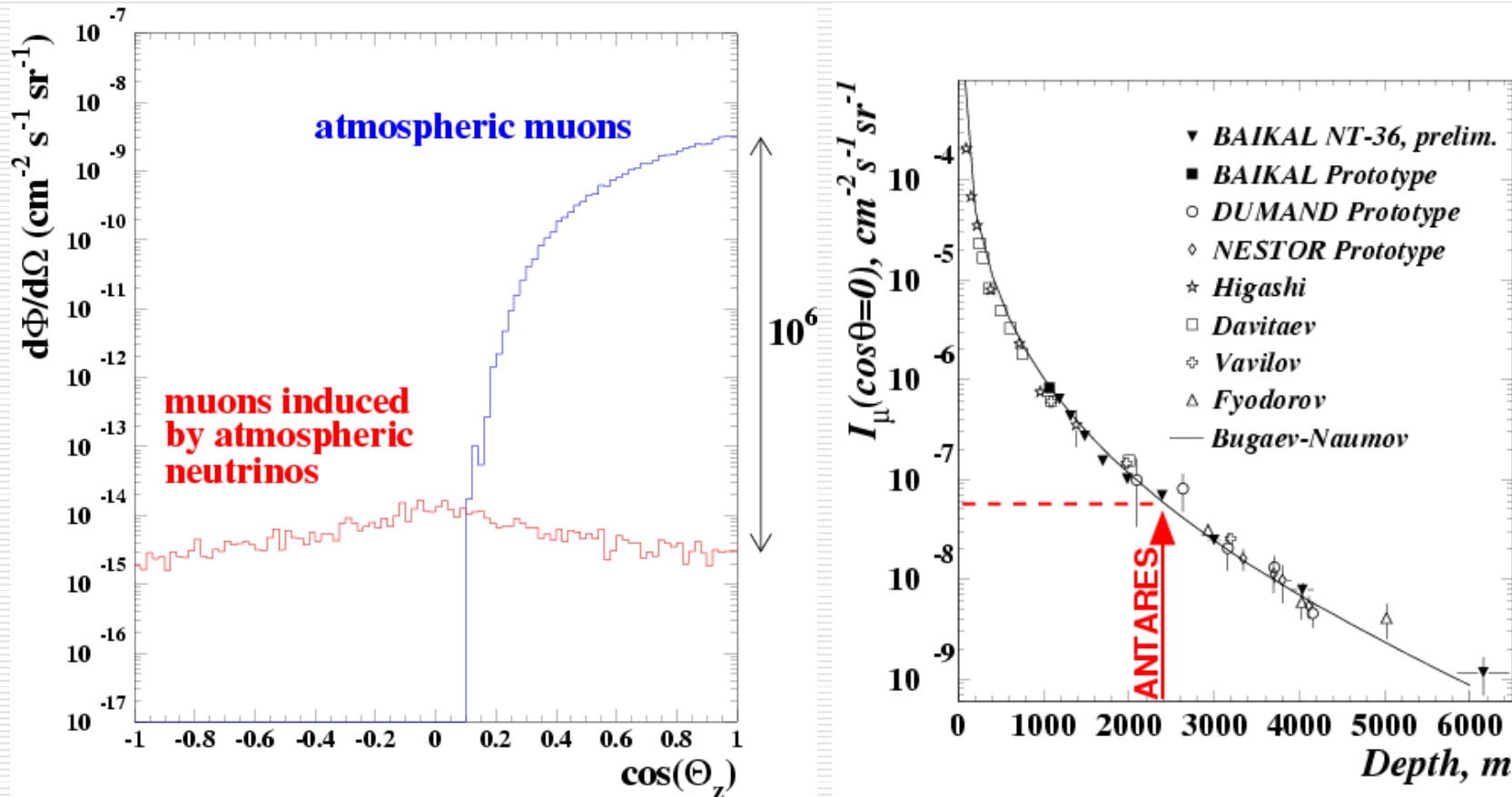
- Neutrinos mainly from  $\pi$ - $\mu$ -e decays, roughly  $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ ;
- Arrival at Earth after oscillations:  $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ ;
- Key signature: muon tracks from  $\nu_\mu$  charged current reactions (few 100m to several km long);
- Elm./hadronic showers: “point sources” of Čerenkov light.



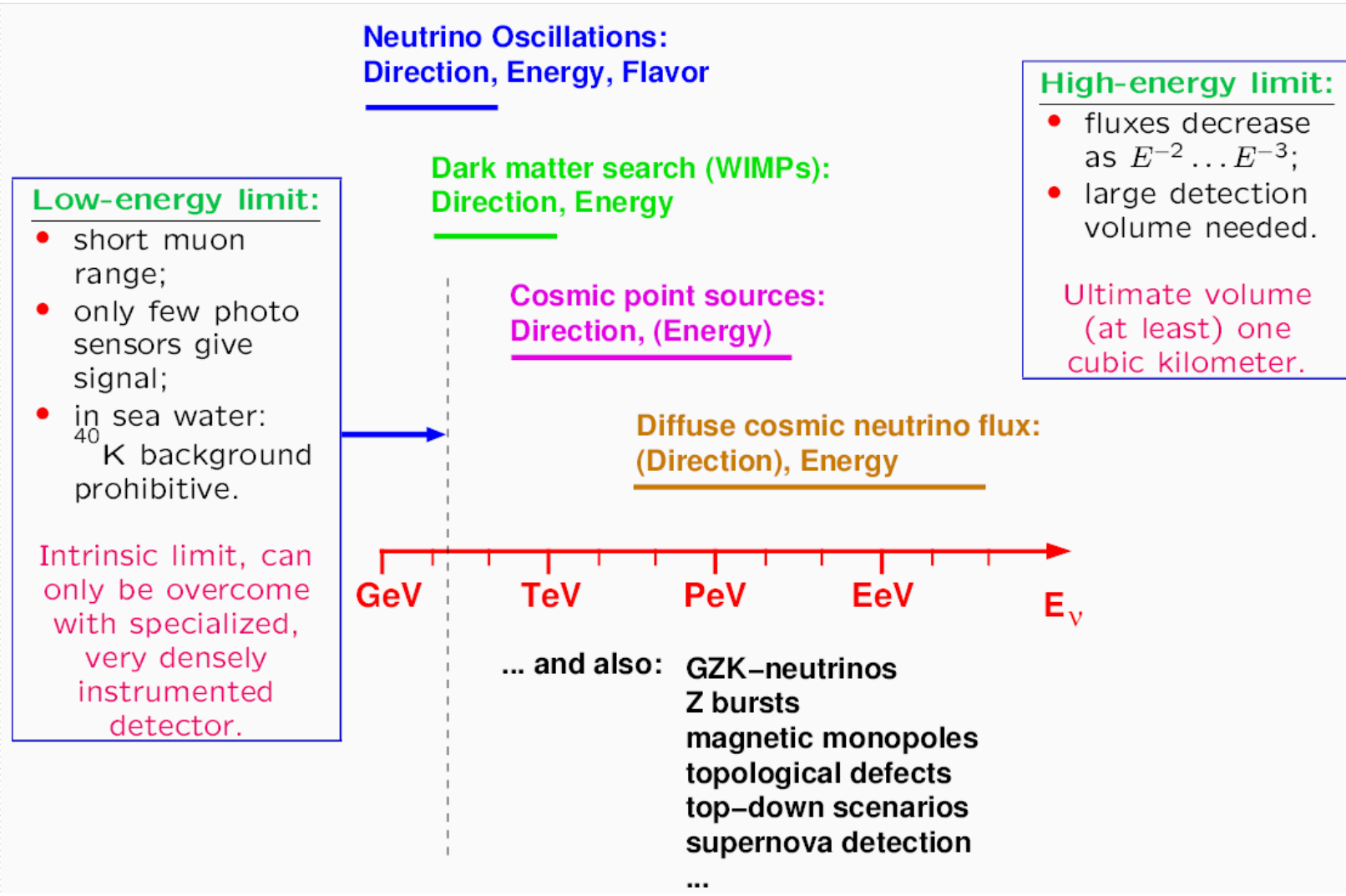
# Muons: The Background from Above

Muons can penetrate several km of water if  $E_\mu > 1\text{TeV}$ ;

Identification of cosmic  $\nu$ 's from above: needs showers or very high energies.



# Particle and Astrophysics with $\nu$ Telescopes





# Neutrino Fluxes and Event Numbers

## Observed event numbers for diffuse fluxes:

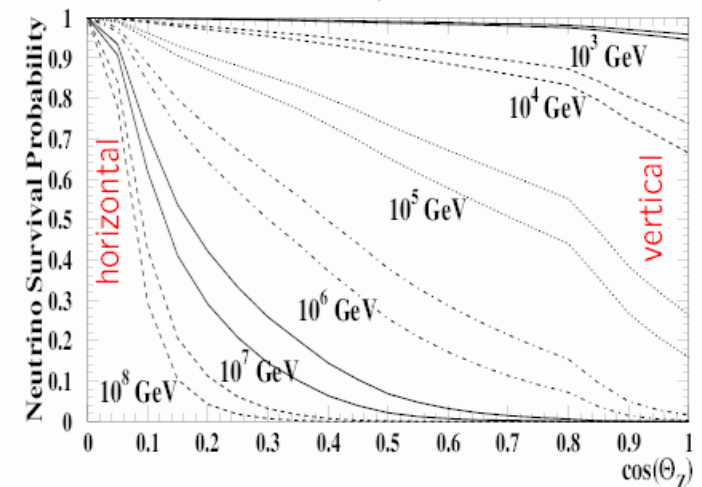
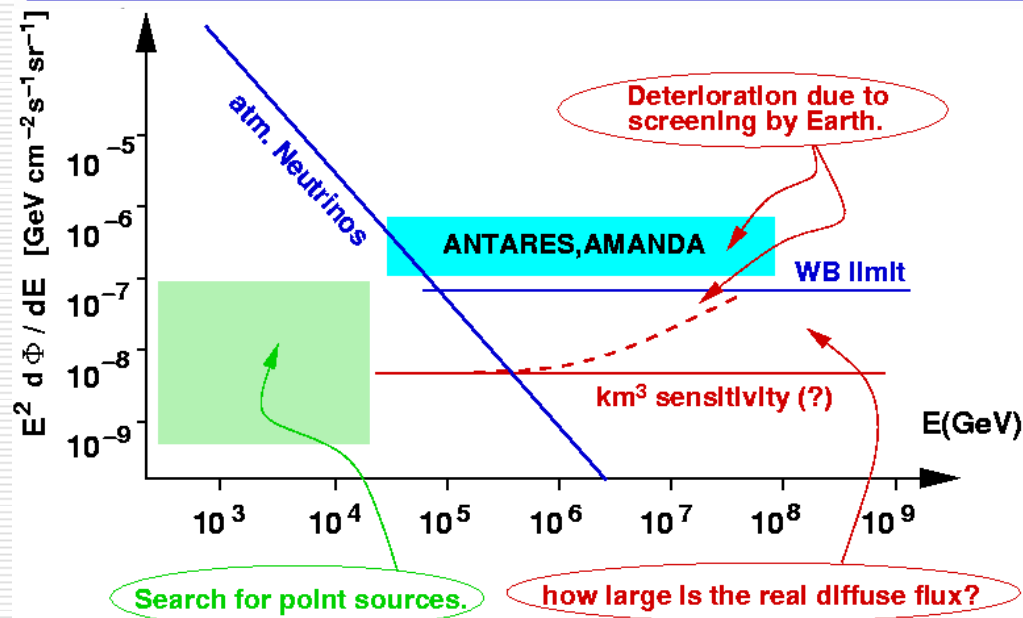
$$\frac{dN_{\text{evt}}}{dE_\nu dt} = \int_{\Omega} \underbrace{\frac{dN_\nu}{dE_\nu dt dA d\Omega}}_{\text{Incoming cosmic flux}} \cdot \underbrace{\sigma(\nu_\mu N \rightarrow \mu X)}_{\nu_\mu \text{ CC cross section}} \cdot \underbrace{(\rho V_{\text{eff}})}_{\text{eff. volume}} \cdot \underbrace{T}_{\text{contributions from other neutrino flavors and NC reactions}} d\Omega + \frac{dN_{\text{evt}}(\nu_e, \nu_\tau)}{dE_\nu dt} + \frac{dN_{\text{evt}}(\text{NC})}{dE_\nu dt}$$

Incoming  
cosmic flux  
 $\Phi \propto E_\nu^{-2}$  (?)

$\nu_\mu$  CC cross  
section  $\sigma \propto E_\nu$   
(weaker rise at  
 $E \gtrsim 10$  TeV)

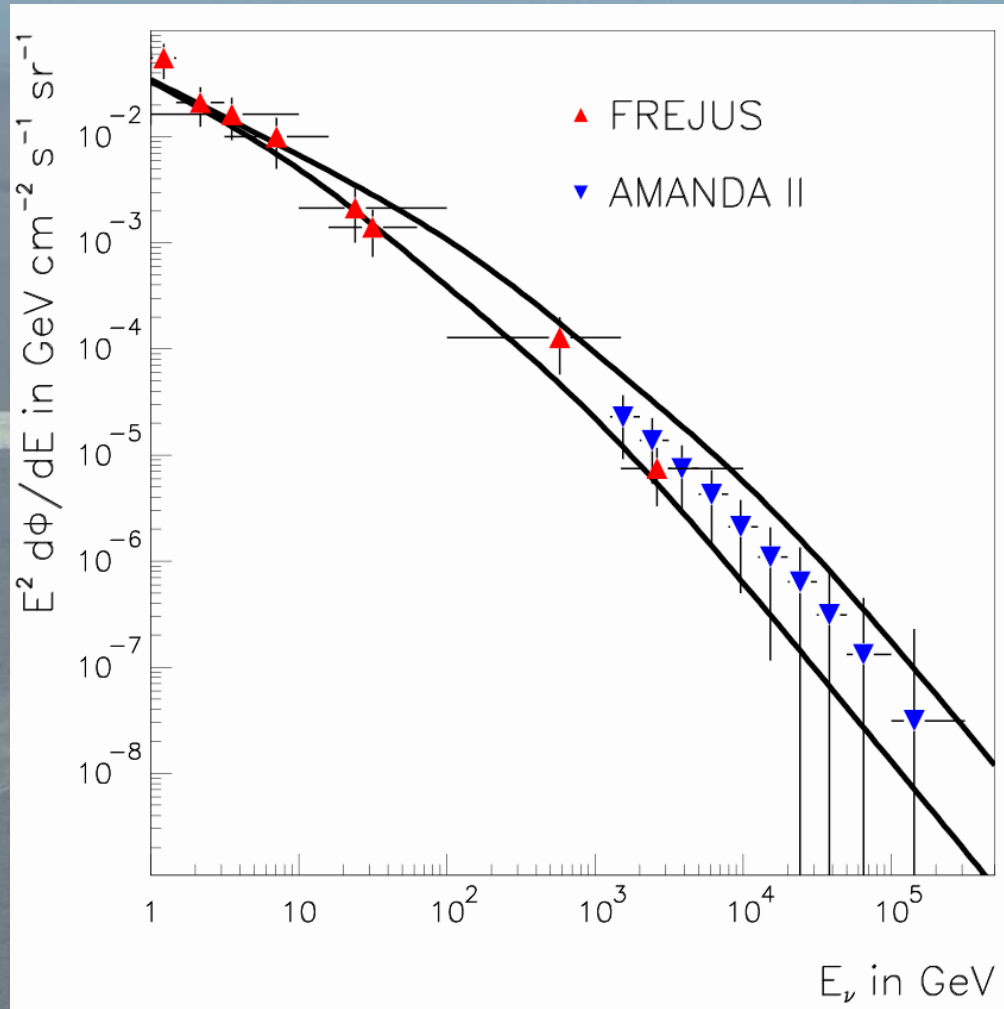
eff. volume,  
increases with  
range( $\mu$ ).  
But: bad  $E_\nu$   
measurement

contributions  
from other  
neutrino flavors  
and NC  
reactions



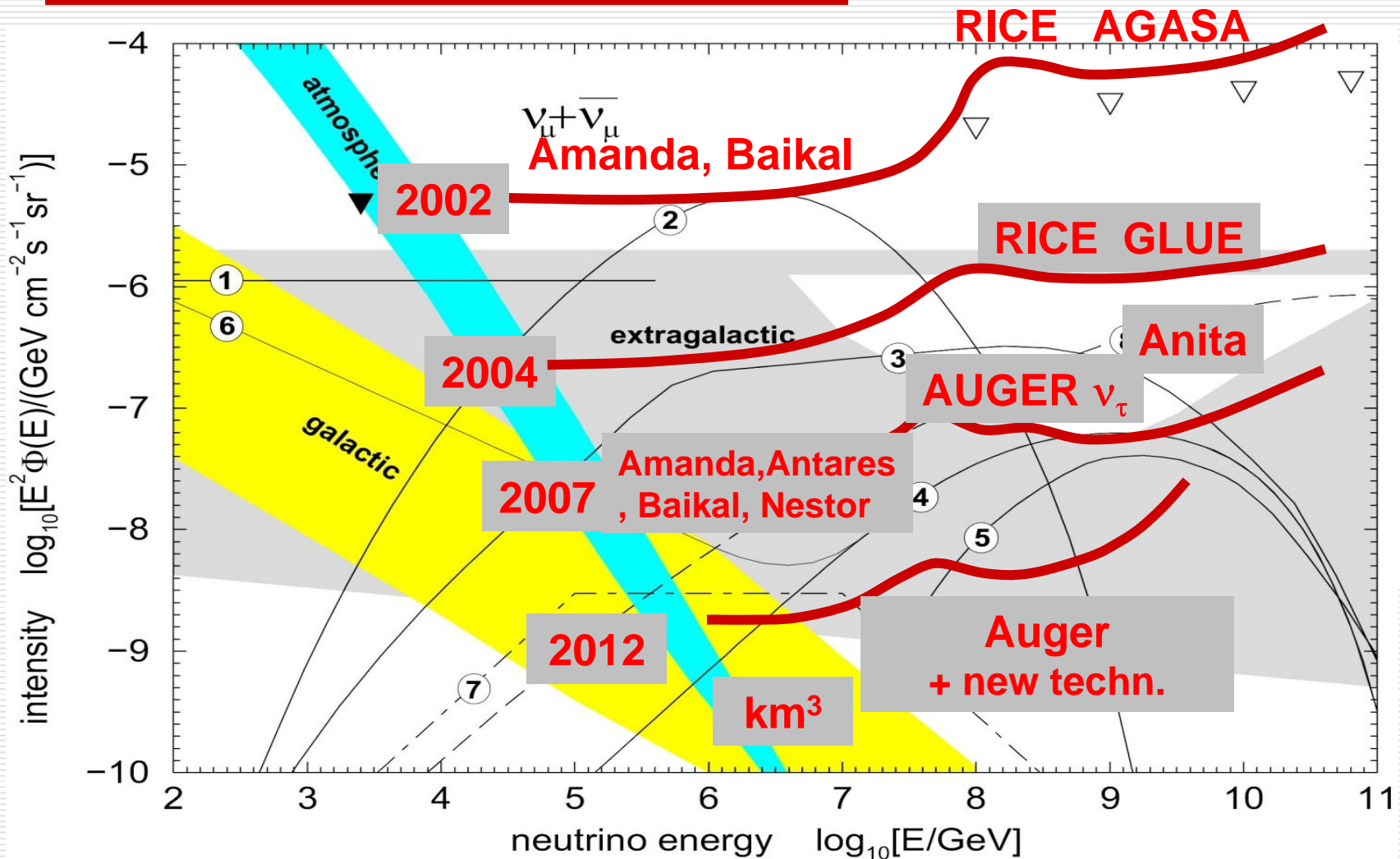


# AMANDA/Baikal: Pioneer Data



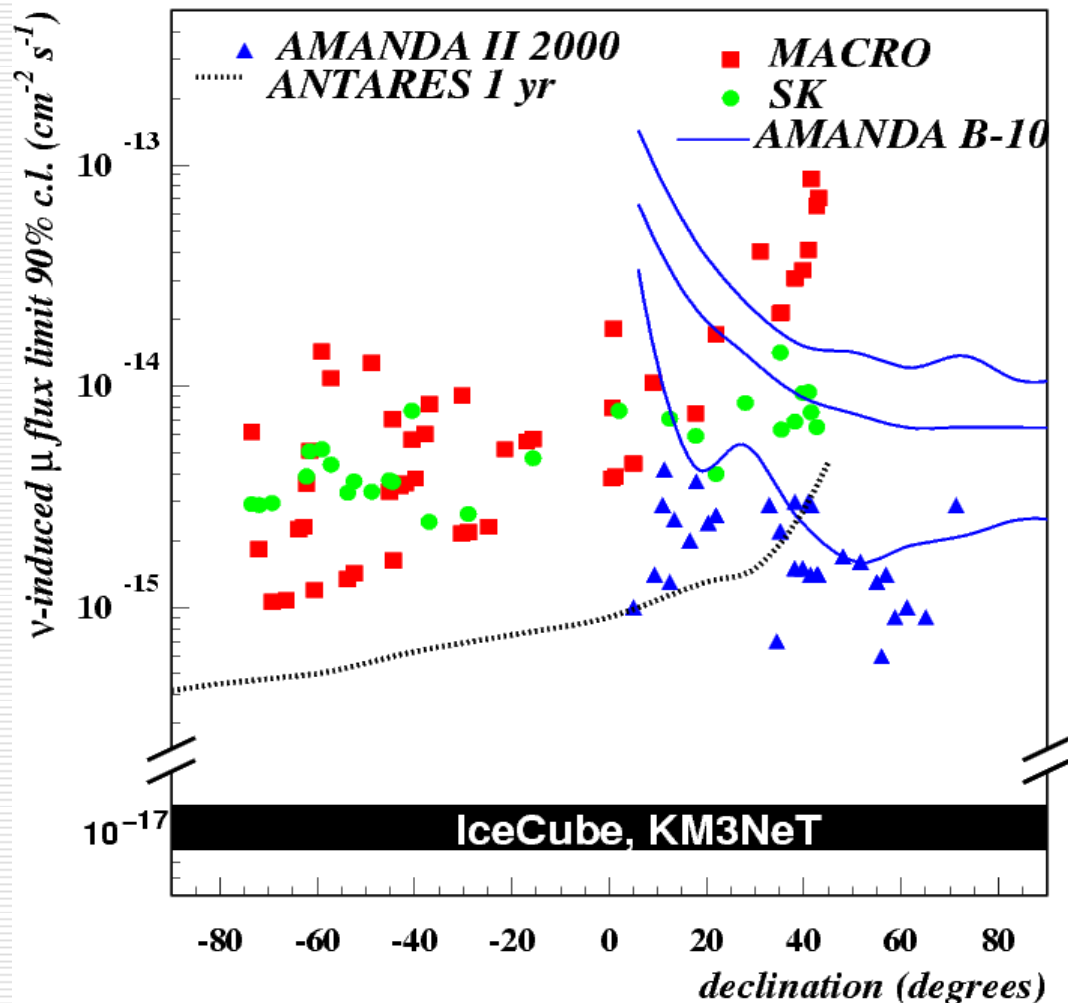
- Measurement of the neutrino flux by AMANDA-II;
- Nice agreement with FREJUS data at lower energies;
- Flux compatible with expectation for atmospheric  $\nu$ 's;

# Diffuse $\nu$ Flux: Limits and Sensitivities



C. Spiering, J. Phys. G 29 (2003) 843

# Neutrinos from Astrophysical Point Sources



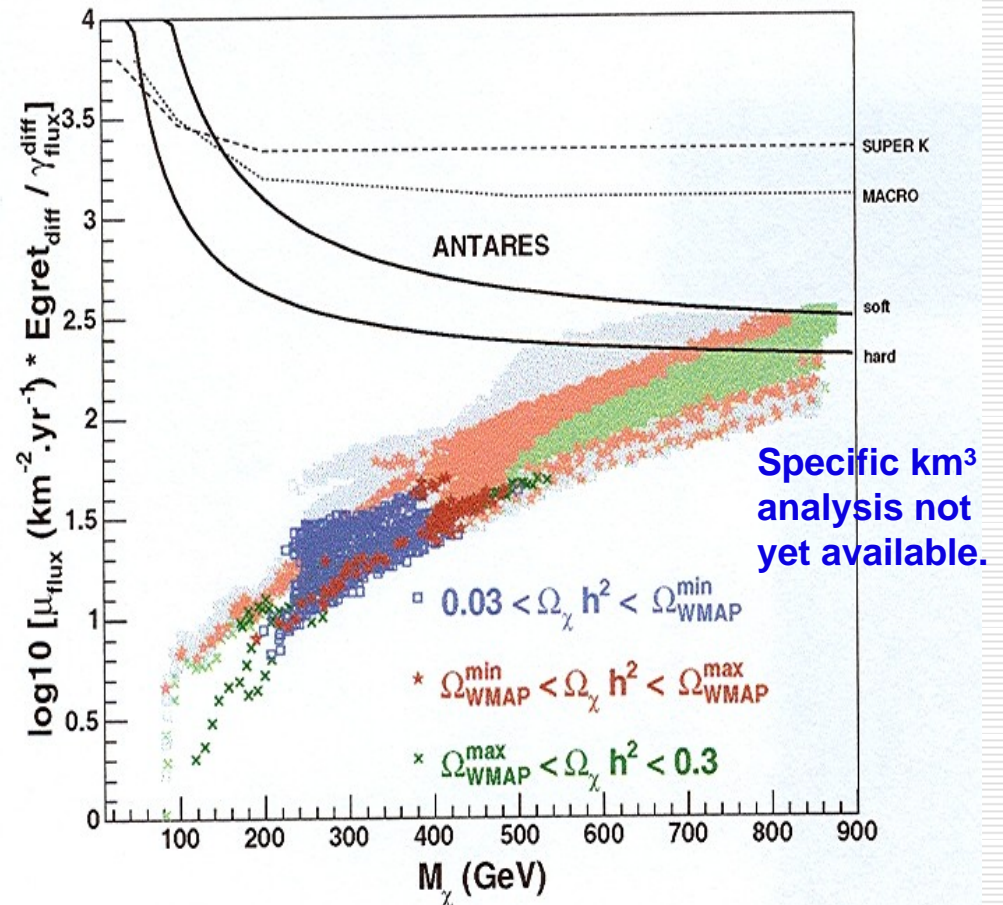
- So far no sources of high-energy neutrinos discovered;
- Current projects reach sensitivity to explore some model predictions;
- Sky coverage complementary between ANTARES and AMANDA/ IceCube;
- km<sup>3</sup> detectors needed to exploit full potential of neutrino astronomy.

# Indirect Search for Dark Matter

- WIMPs can be gravitationally trapped in Earth, Sun or Galactic Center;
- Neutrino production by  

$$XX \rightarrow \nu + X$$
- Detection requires low energy threshold (O(100GeV) or less).
- Flux from Galactic Center may be enhanced if a Black Hole is present → exciting prospects [see e.g. P. Gondolo and J. Silk, PRL 83(1999)1719].
- But: model uncertainties are orders of magnitude!

from G. Bertone et al., astro-ph/0403322





# The ANTARES Collaboration

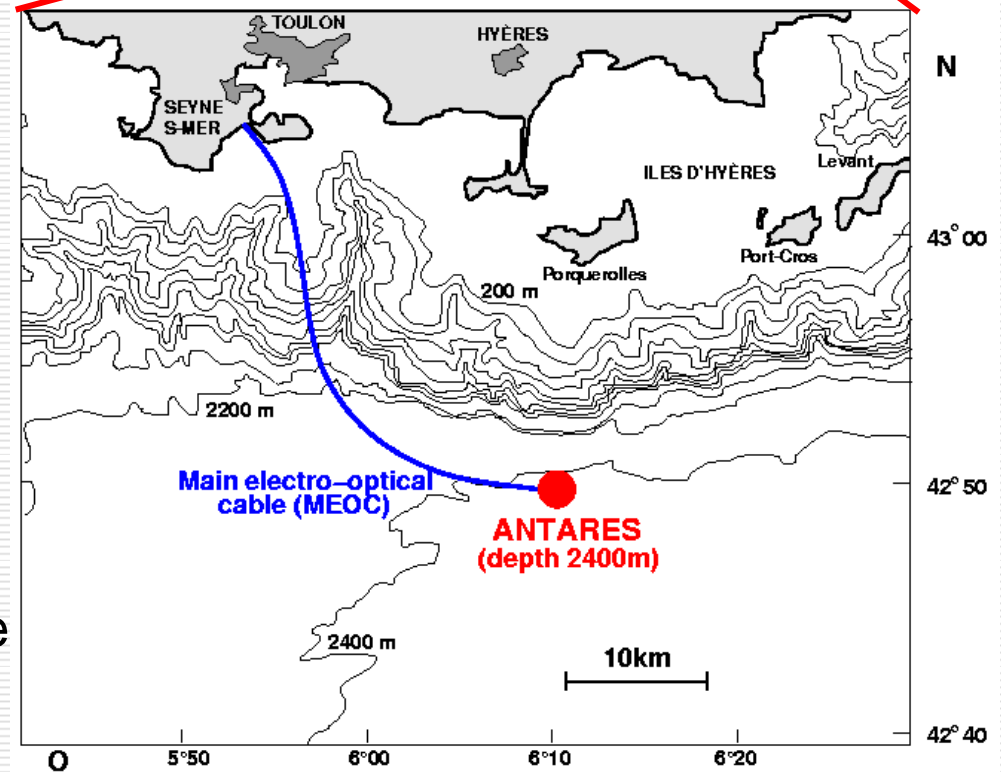
- 20 Institutes, 6 European countries



- Institutes:  
Particle physics,  
astronomy/astrophysics,  
sea science & technology;

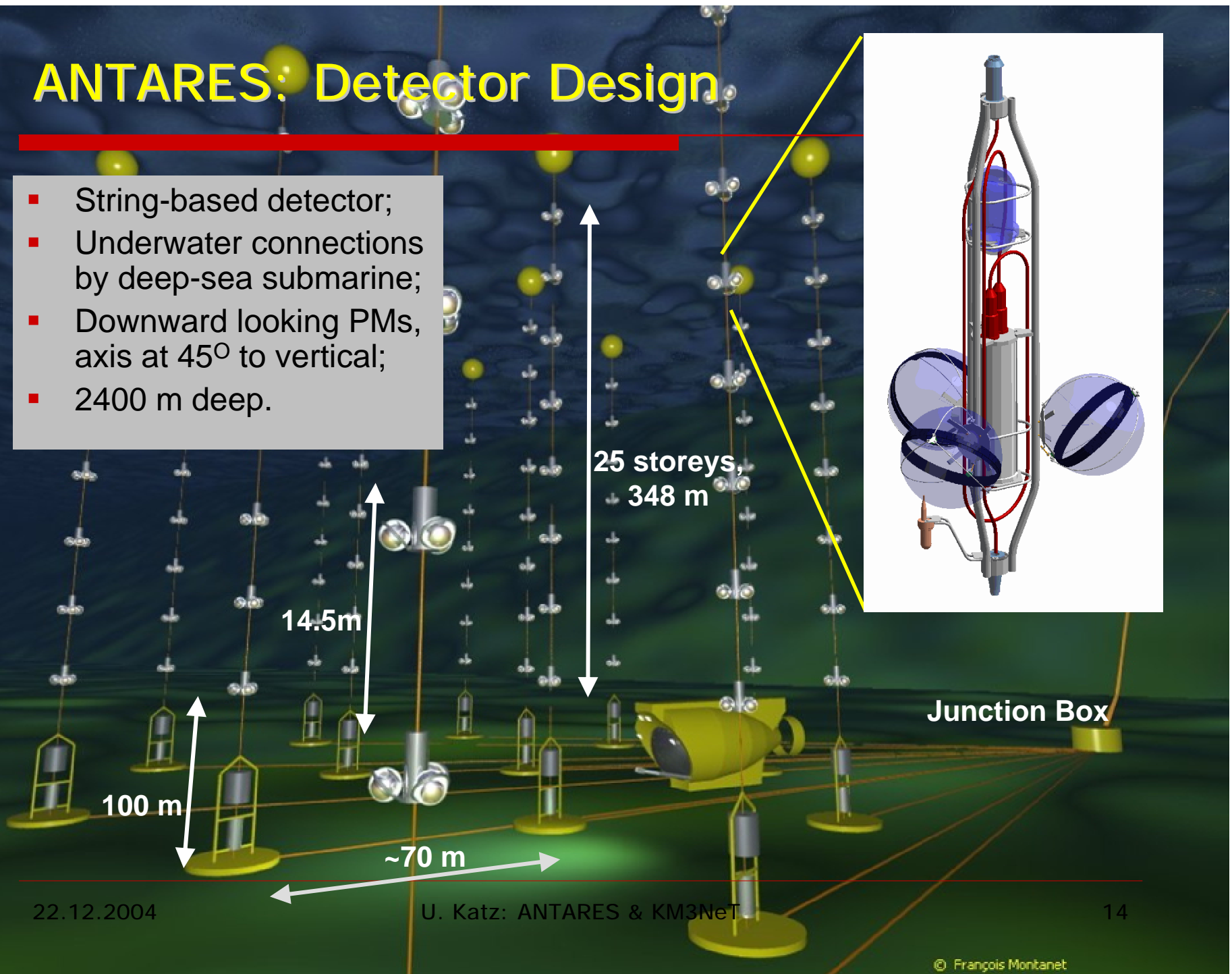
- The mission:  
Design, construct and  
operate a  $\nu$  telescope in  
the Mediterranean Sea;

- The challenge:  
Build a high-tech particle  
detector in the hostile,  
poorly known and uncontrollable  
deep-sea environment.



# ANTARES: Detector Design

- String-based detector;
- Underwater connections by deep-sea submarine;
- Downward looking PMs, axis at  $45^\circ$  to vertical;
- 2400 m deep.



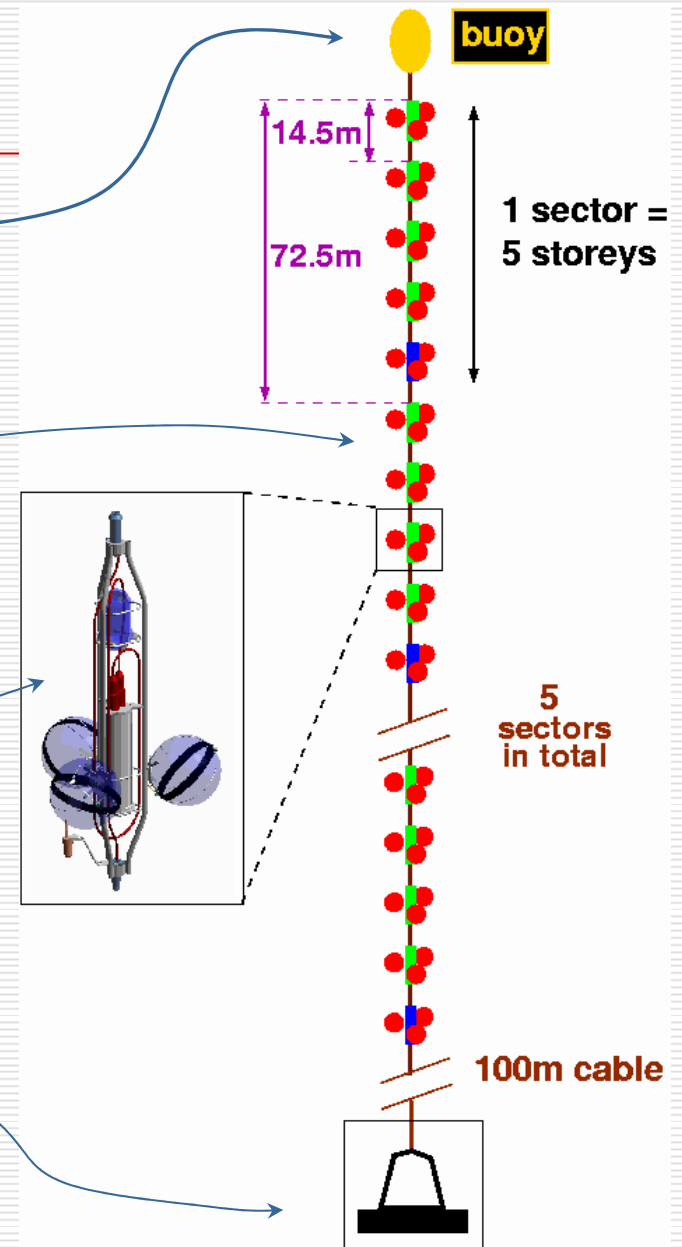
22.12.2004

U. Katz: ANTARES & KM3NeT

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# ANTARES: Detector Strings

- Buoy:
  - buoyancy ~6400 N;
  - keeps string vertical to better than 20m displacement at top.
- Electro-optical-mechanical cable:
  - metal wires for power supply etc.;
  - optical fibers for data;
  - mechanical backbone of string.
- Storeys:
  - 3 optical modules per storey;
  - titanium cylinder for electronics;
  - calibration devices (light, acoustics).
- Anchor:
  - deadweight to keep string at bottom;
  - release mechanism operated by acoustic signal from surface.





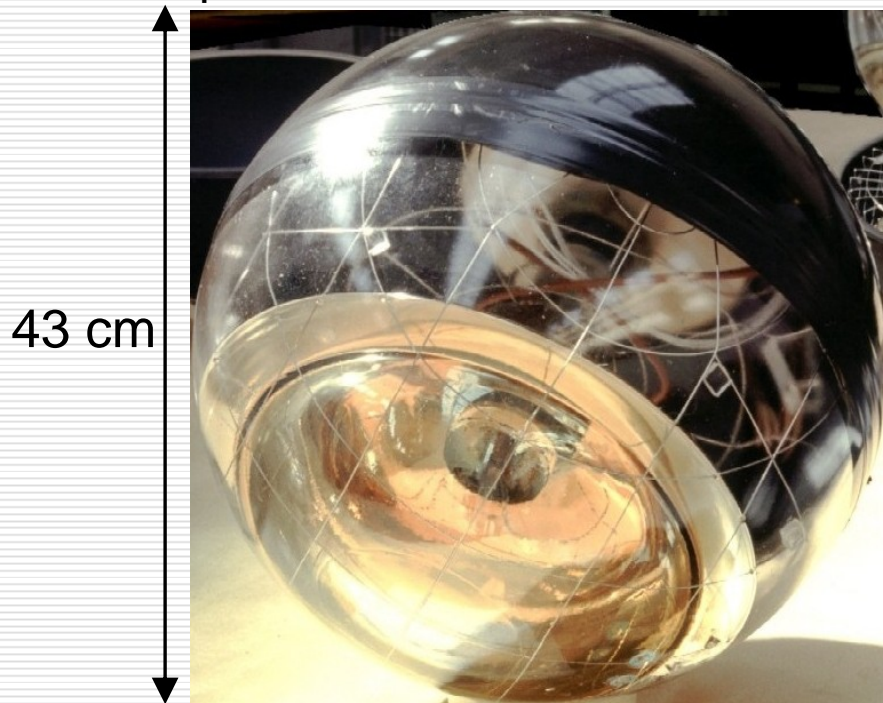
# ANTARES: Optical Modules

## ■ Photomultipliers:

- transfer time spread  $\sim 2.7\text{ns}$  (FWHM);
- quantum efficiency  $>20\%$  for  $330\text{ nm} < \lambda < 460\text{nm}$ ;

## ■ Glass spheres:

- qualified for 600 bar;



Hamamatsu 10'' PM



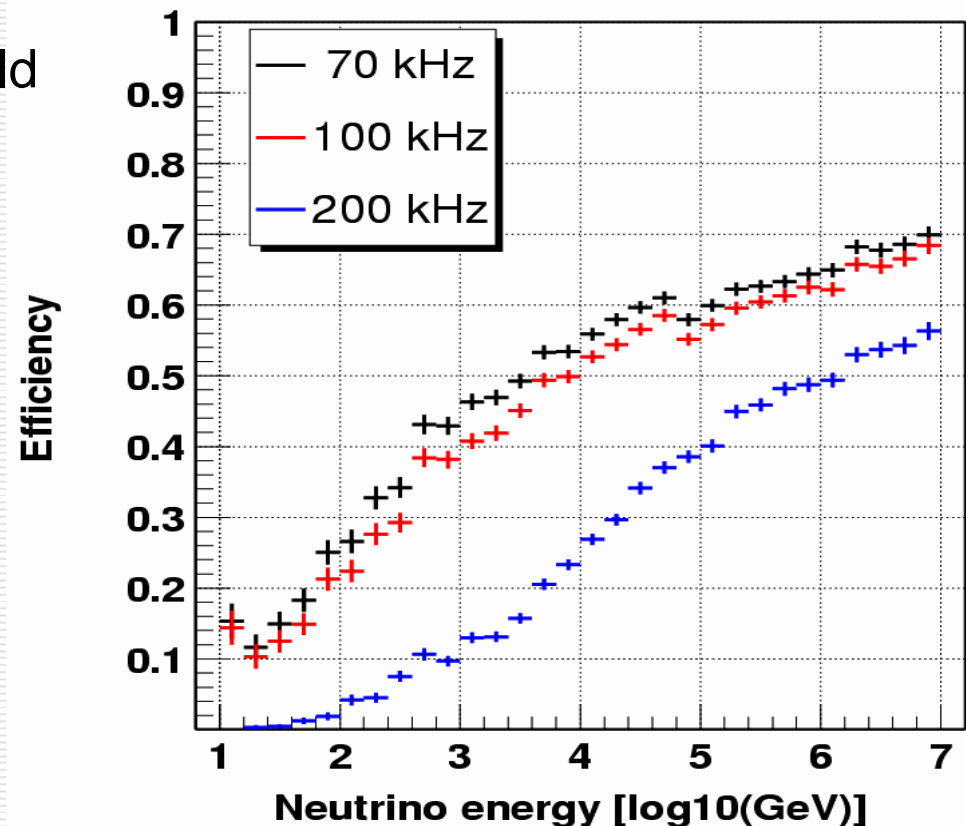
# ANTARES: DAQ and Online Filter

## ■ Data acquisition:

- digitization *in situ* (Analog Ring Sampler, ARS);
- **single photon electron (SPE)** and **wave form** modes;
- **all-data-to-shore** concept:  
all hits above low threshold  
( $\sim 0.3$  SPE) sent to shore;
- no hardware trigger;

## ■ Online filter:

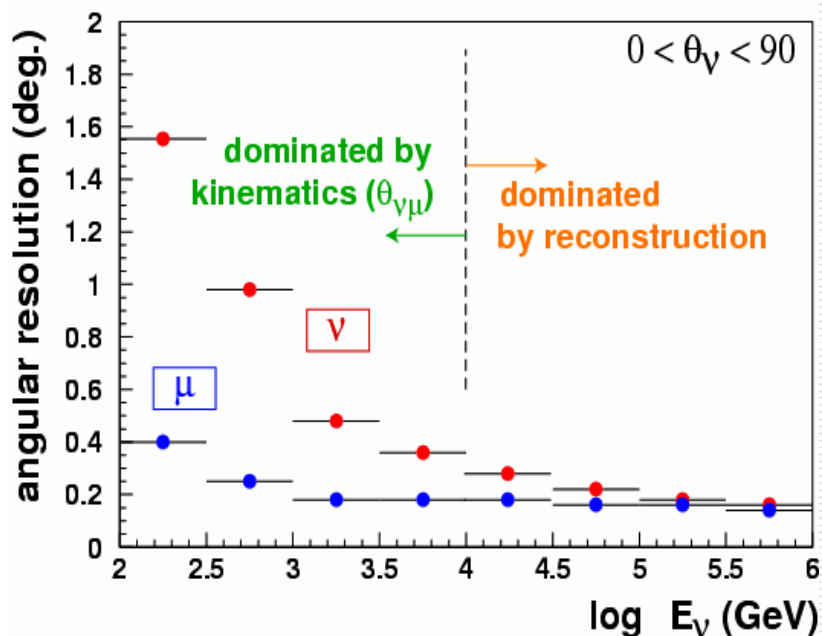
- raw data rate  $\sim 1$  GB/s  
reduced to  $\sim 1$  MB/s by  
online filter (PC farm);
- criteria:
  - local coincidences,
  - signal amplitudes,
  - causality.



# ANTARES: Expected Performance ( $\mu$ Events)

## Angular resolution:

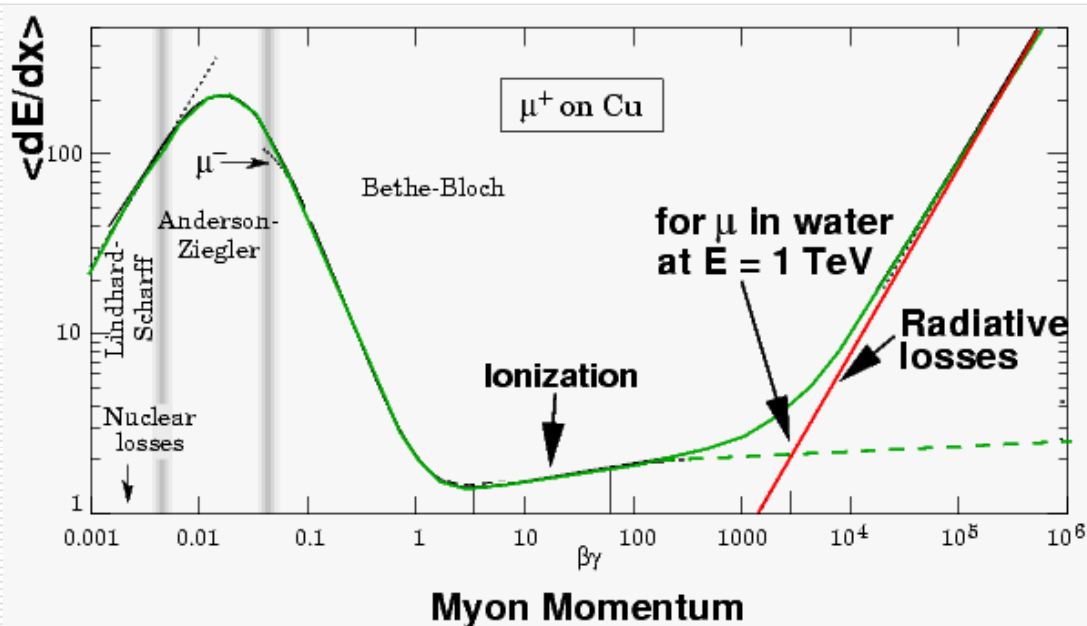
- $E_\nu < 10$  TeV: dominated by angle( $\nu, \mu$ );
- $E_\nu > 10$  TeV: dominated by reconstruction accuracy;



$$\Delta\theta \approx 0.2^\circ - 0.3^\circ (E_\nu > 10 \text{ TeV})$$

## Energy reconstruction:

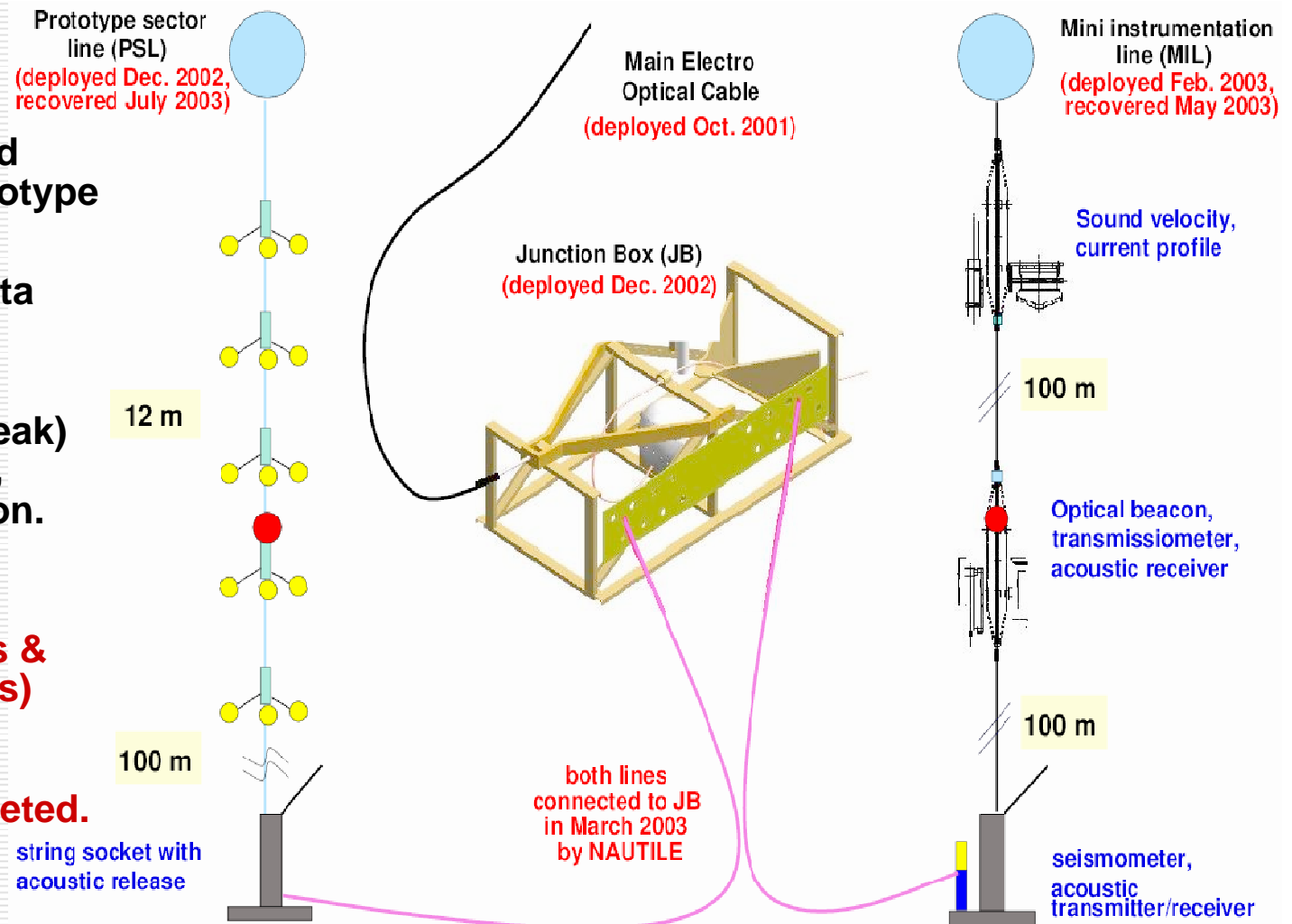
- $E_\mu < 1$  TeV: muon range;
- $E_\mu > 1$  TeV: Čerenkov light yield from radiative losses (small elm. showers);



$$\Delta(\log E_\mu) \approx 0.3 (E_\mu > 1 \text{ TeV})$$

# ANTARES: Status and Way to Completion

- **2003: Deployment and operation of two prototype lines.**
- **Several months of data taking.**
- **Technical problems (broken fiber, water leak)**  
→ no precise timing, no  $\mu$  reconstruction.
- **Early 2005: upgraded prototype line (cables & mechanical structures)**
- **Spring 2005: Line 1;**
- **2007: Detector completed.**



# ANTARES: Sea Operations

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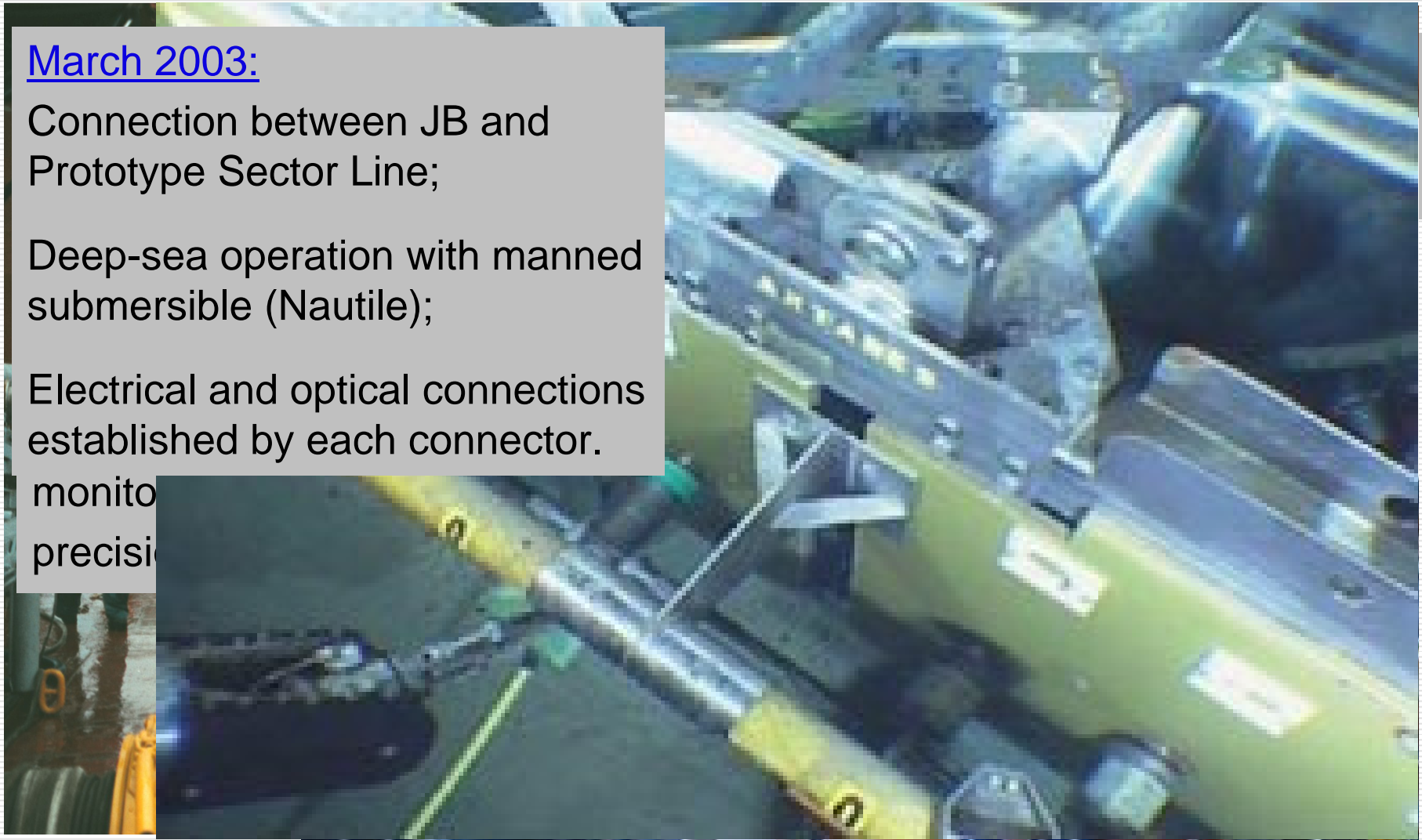
March 2003:

Connection between JB and  
Prototype Sector Line;

Deep-sea operation with manned  
submersible (Nautil);

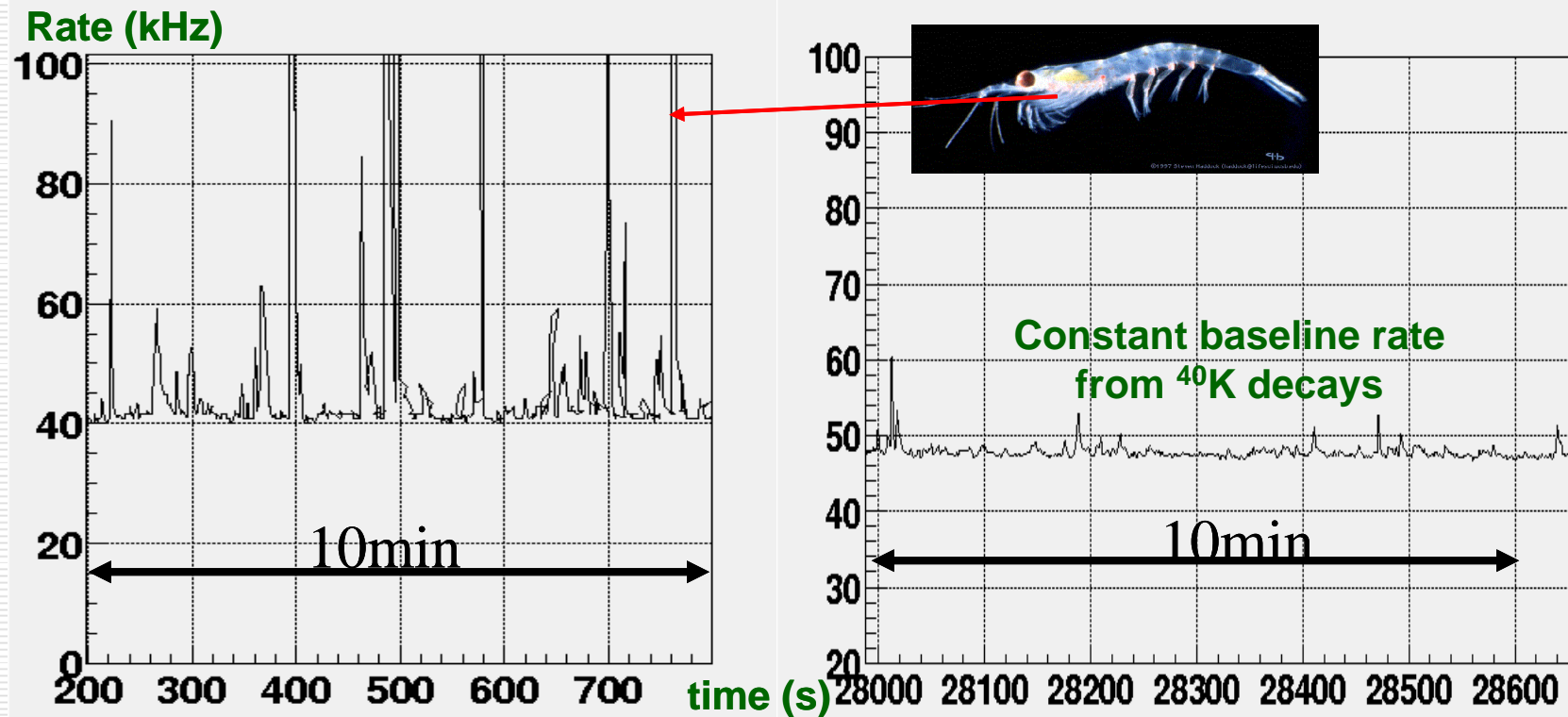
Electrical and optical connections  
established by each connector.

monito  
precisi



# ANTARES: First Deep-Sea Data

Rate measurements: Strong fluctuation of bioluminescence background observed

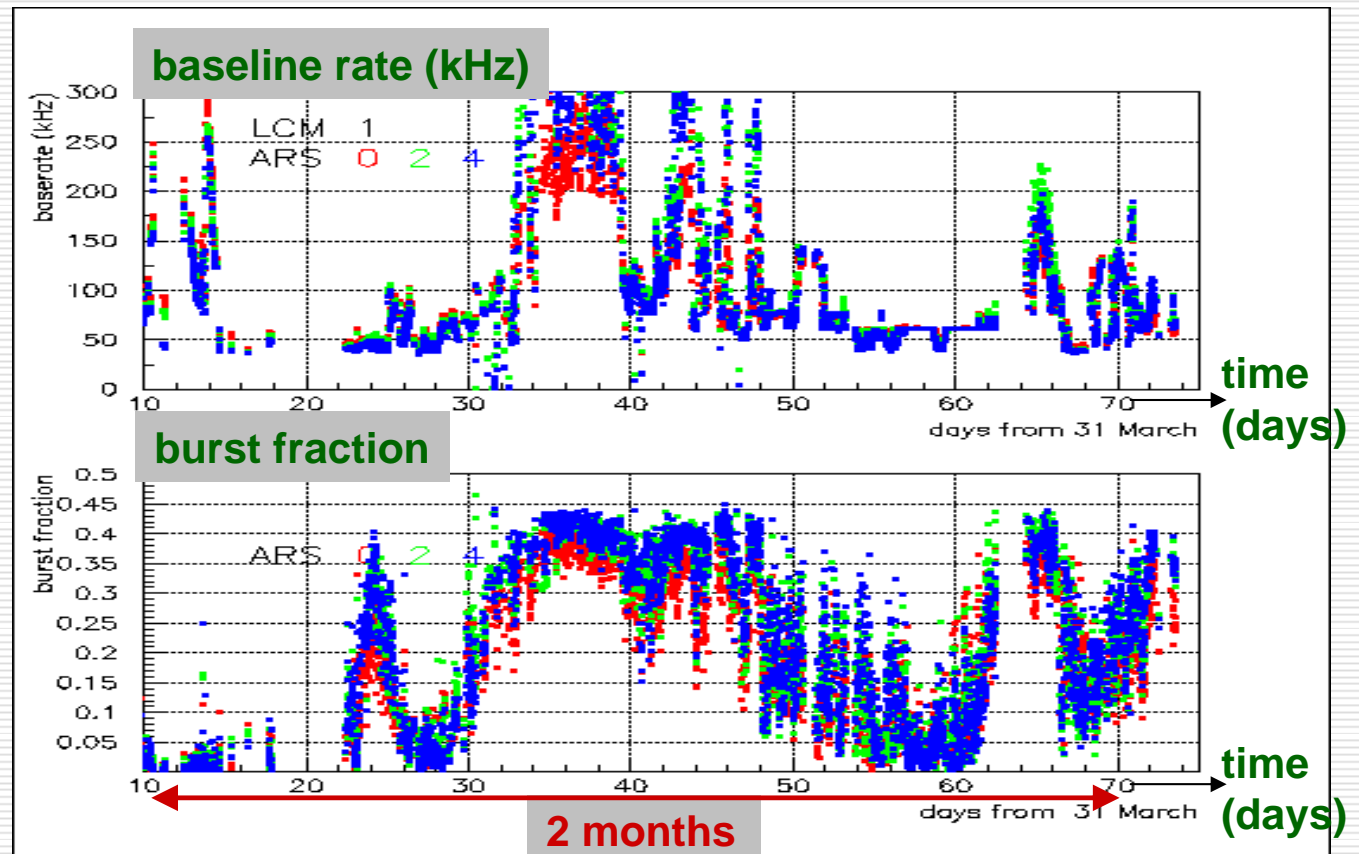




# ANTARES: Long-term Measurements

baseline rate =  
15-minute average

burst fraction =  
time fraction above  
 $1.2 \times$  baseline rate



- Also measured: current velocity and direction, line heading and shape, temperatures, humidities, ...
- Important input for preparation & optimization of ANTARES operation.



# NESTOR: Rigid Structures Forming Towers

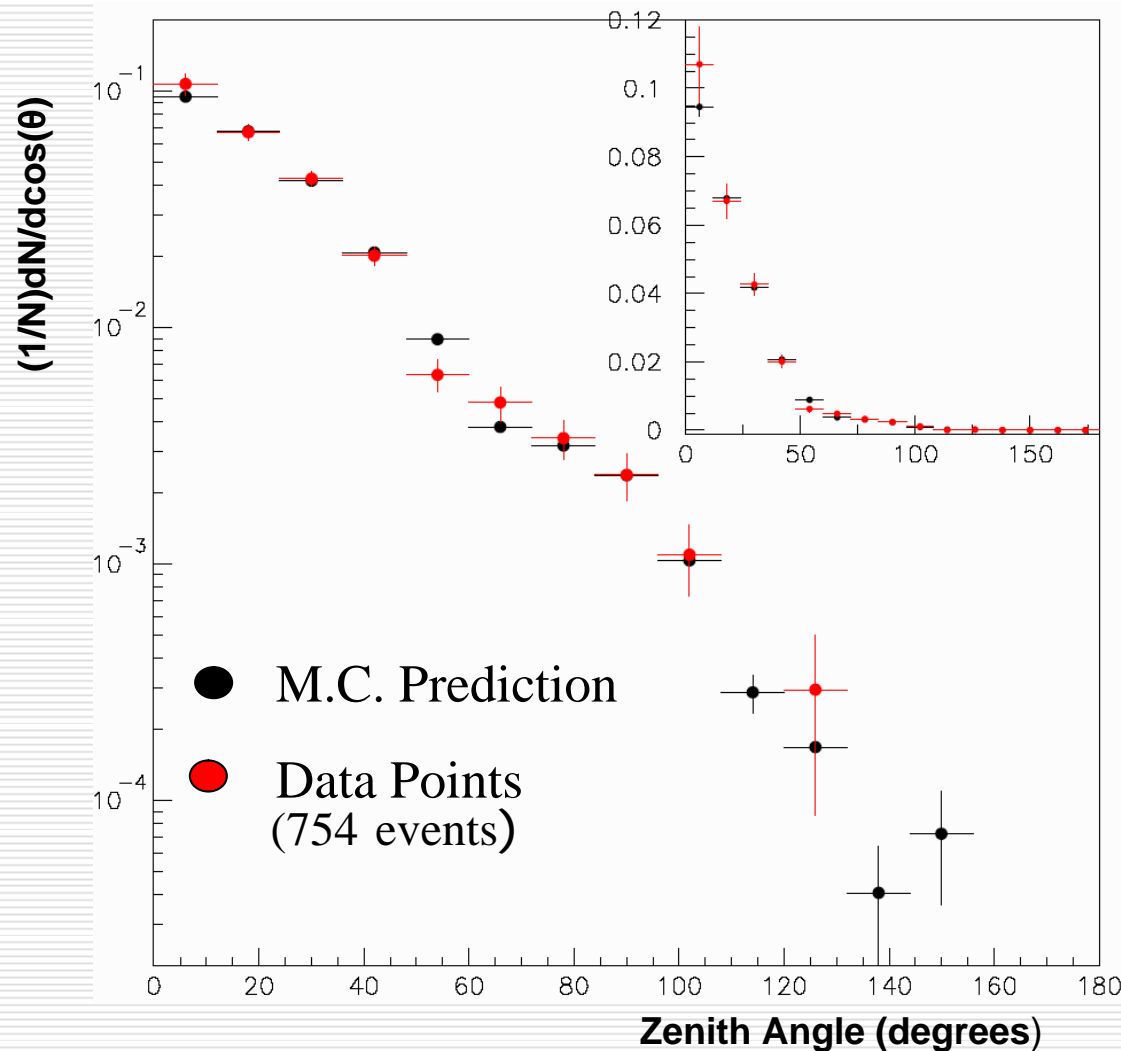
- Tower based detector (titanium structures).
- Dry connections (recover-connect-redeploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

## Plan: Tower(s) with 12 floors

- 32 m diameter
- 30 m between floors
- 144 PMs per tower



# NESTOR: Measurement of the Muon Flux



Atmospheric muon flux  
determination by  
reweighting MC simulation  
to observed raw zenith  
distribution using

$$\frac{dN}{d\Omega \cdot dt \cdot ds} = I_0 \cdot \cos^\alpha \theta$$

Results agree nicely  
with previous measurements  
and with simulations.

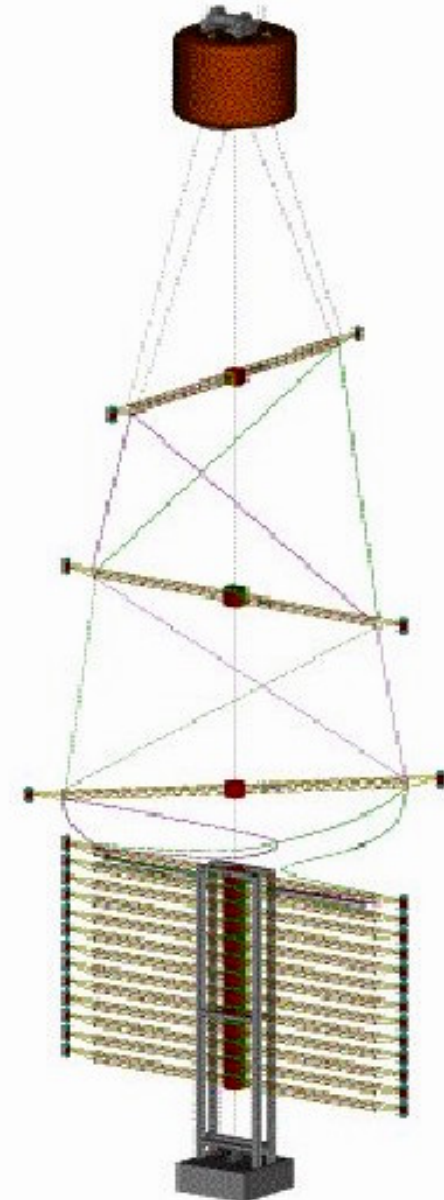
# The NEMO Project

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- Extensive site exploration (Capo Passero near Catania, depth 3340 m);
- R&D towards km<sup>3</sup>: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

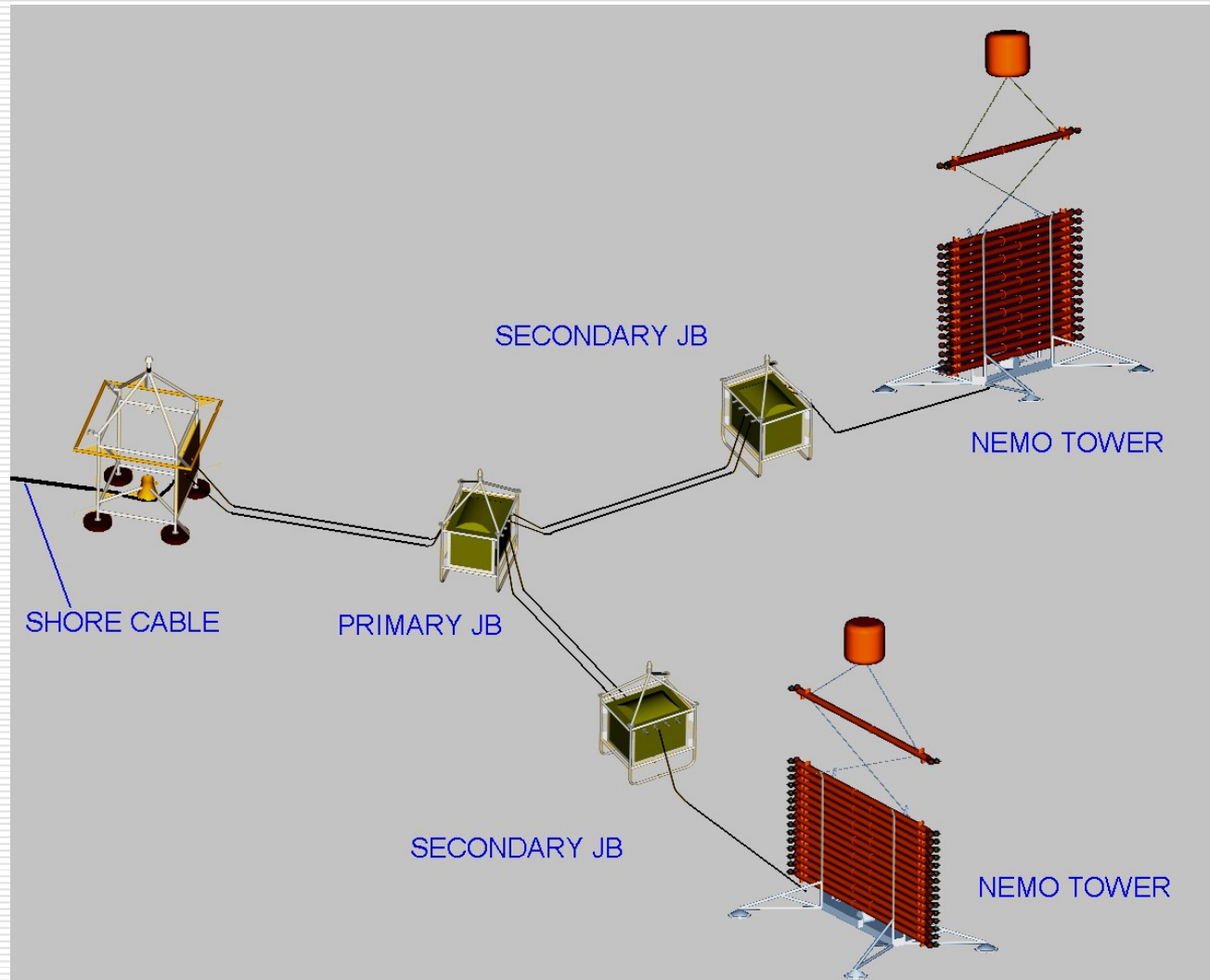
## Example: Flexible tower

- 16 arms per tower, 20 m arm length, arms 40 m apart;
- 64 PMs per tower;
- Underwater connections;
- Up- and down-looking PMs.



# NEMO: Phase-1 Test

- Test site at 2000 m depth identified.
- Test installation foreseen with all critical detector components.
- Funding ok.
- Completion expected by 2006.



# Current Projects: Summary

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- ANTARES + NESTOR: first installation steps successfully completed, prototype detector modules deployed and operated;
- ANTARES mass production in preparation, detector expected to be complete by 2007;
- Discovery potential for cosmic neutrinos and Dark Matter;
- Feasibility proof for neutrino telescopy in sea water;
- NEMO: Ongoing R&D work for next-generation km<sup>3</sup>-scale detector.

# Aiming at a Mediterranean km<sup>3</sup>-Detector

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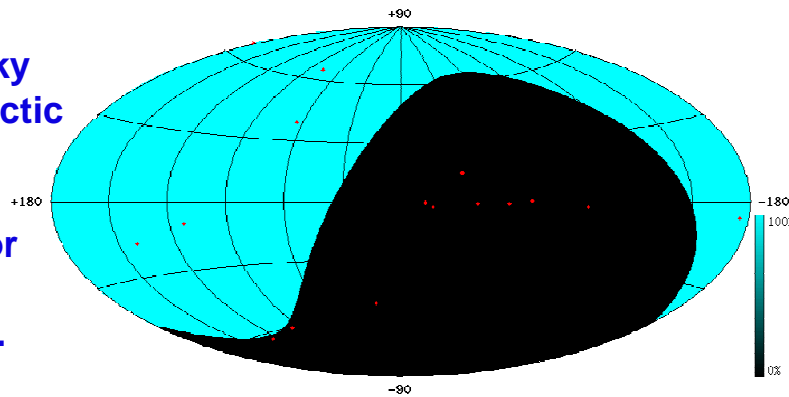
## **HENAP Report to PaNAGIC, July 2002:**

- “The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ...”
- “... a km<sup>3</sup>-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole.”
- “The detector should be of km<sup>3</sup>-scale, the construction of which is considered technically feasible.”

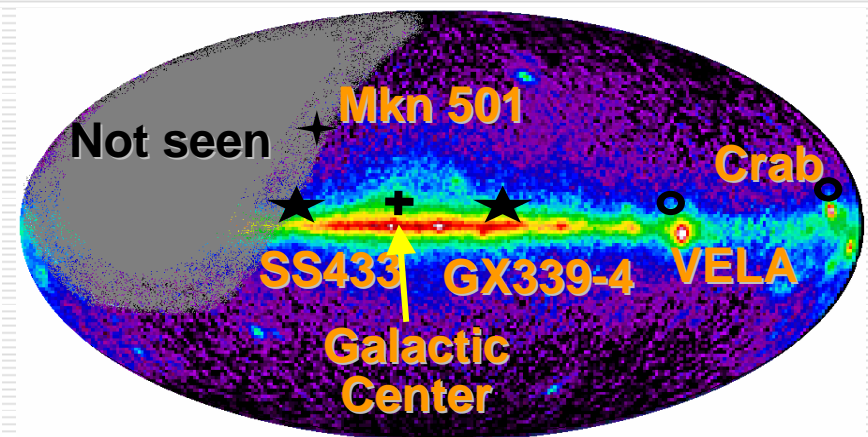
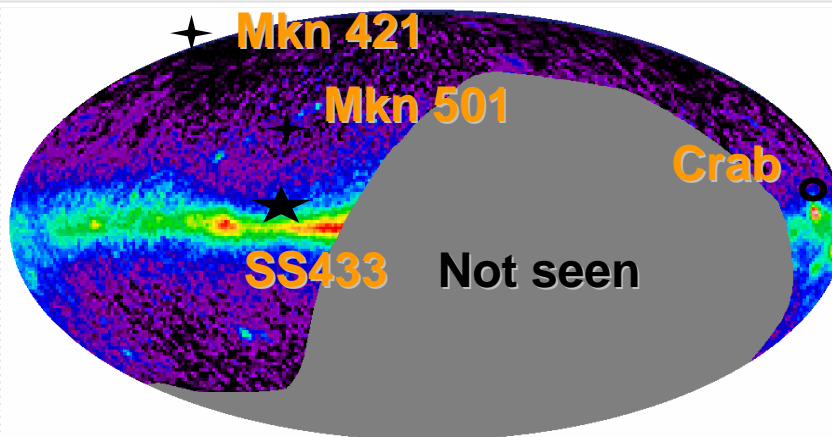
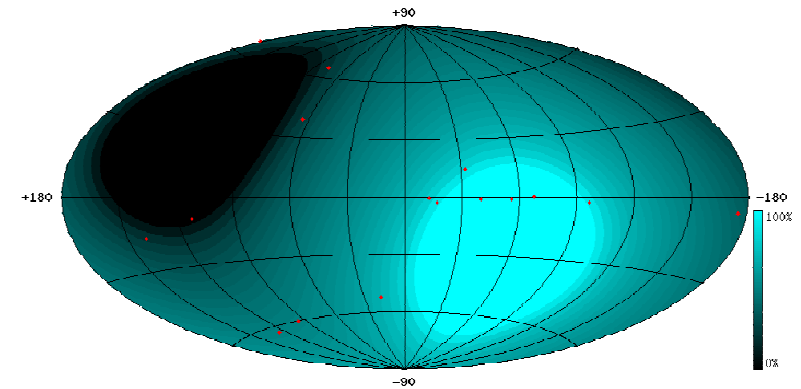
# Sky Coverage of Neutrino Telescopes

## South Pole

Region of sky seen in galactic coordinates assuming efficiency for downward hemisphere.



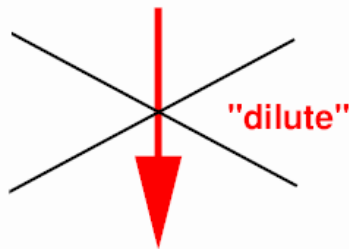
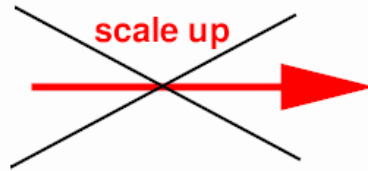
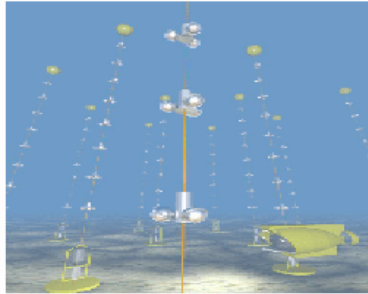
## Mediterranean



→ We need  $\nu$  telescopes in both hemispheres to see the whole sky



# How to Design a km<sup>3</sup> Deep-Sea $\nu$ Telescope



## Existing $\nu$ T's times 100–1000 ?

- **Too expensive:**  
ANTARES  $\times 100 = \mathcal{O}(2 \times 10^9)$  Euros.
- **Too complicated:**  
production/deployment take forever, maintenance impossible.
- **Not scalable:**  
e.g. readout bandwidth, online filter, power distribution, ....

## Research and Development needed:

- **Cost-effective solutions:**  
Reduce price/volume by factor  $\gtrsim 10$ .
- **Increased stability:**  
Goal: maintenance-free detector.
- **"Fast" installation:**  
Time for construction & deployment less than detector life time.
- **Photo sensors:**  
High quantum efficiency, large area, low noise, directional sensitivity.
- ...

## km<sup>3</sup> volume with $\sim$ same number of PMs as in existing $\nu$ T's ?

- **PM distance:**  
determined by light attenuation in water (+PM properties).
- **Efficiency loss:**  
Effective volume  $\ll 1 \text{ km}^3$  except maybe at highest  $E_\nu$ .

**A major  
R&D project  
is needed!**

# Some Key Questions

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- Which architecture to use?  
(strings vs. towers vs. new design)
- How to get the data to shore?  
(optical vs. electric, electronics off-shore or on-shore)
- How to calibrate the detector?  
(separation of calibration and detection units?)
- Design of photo-detection units?  
(large vs. several small PMs, directionality, ...)
- Deployment technology?  
(dry vs. wet by ROV/AUV vs. wet from surface)
- And finally: The site choice/recommendation!

# The KM3NeT Design Study (EU FP6)

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## Design Study for a Deep-Sea Facility in the Mediterranean for Neutrino Astronomy and Associated Sciences (KM3NeT)

- Initiative started **Sept. 2002** (ApPEC meeting, Paris).
- More than one year of intense discussions and coordination meetings between all European sea-water neutrino telescope projects.
- Inclusion of sea science&technology institutes (**Jan. 2004**).
- Proposal submitted **March 2004**, will **very likely be funded**.
- Participants: **35 institutes** from **8 European countries** (28 HEP/astrophysics, 7 sea science/technology; coordinator: Erlangen).

# KM3NeT: Design Study Target Values

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**All the parameters  
need optimization !**

- **Detection principle:** water Čerenkov.
- **Detection volume:** 1 km<sup>3</sup>, expandable.
- **Angular resolution:** close to the intrinsic resolution ( $< 0.1^\circ$  for muons with  $E_\mu > 10$  TeV).
- **Energy reconstruction:** within a factor of 2 for  $\mu$  events.
- **Lower energy threshold:**  
a few 100 GeV for upward going neutrinos, possibility to go lower for  $\nu$  from point sources at known position.
- **Acceptance:**  
maximal angular acceptance for all  $\nu$  signals (including down-going neutrinos at VHE) and for all  $\nu$  flavors.
- **Duty cycle/operational lifetime:** close to 100% /  $\geq 10$  years.
- **Cost-effectiveness:**  $< 200$  M€ per km<sup>3</sup>.

# KM3NeT: Exploitation Model

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**Goal: facility exploited in multi-user and interdisciplinary environment.**

- Reconstructed data will be made available to the whole community;
- Observation of specific objects with increased sensitivity (dedicated adjustment of filter algorithms);
- Close relation to space-based observatories (alerts for GRBs, AGN flares etc.);
- Associated science communities participate in design, construction, maintenance and exploitation (biology, environmental sciences, geology/geophysics, oceanography);  
→ synergetic advantages from each other's expertise.

# KM3NeT: Time Schedule

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**Time scale given by "community lifetime" and  
time overlap with ice detector**

- Experience from current first generation water  $\nu$  telescopes is a solid basis for the design of the KM3NeT detector.
- Interest fades away if KM3NeT comes much later than IceCube (ready by 2010).

## Time schedule (optimistic):

01.01.2006	Start of Design Study
Mid-2007	Conceptual Design Report
End of 2008	Technical Design Report
2009-2013	Construction
2010-20XX	Operation

# KM3NeT: Summary

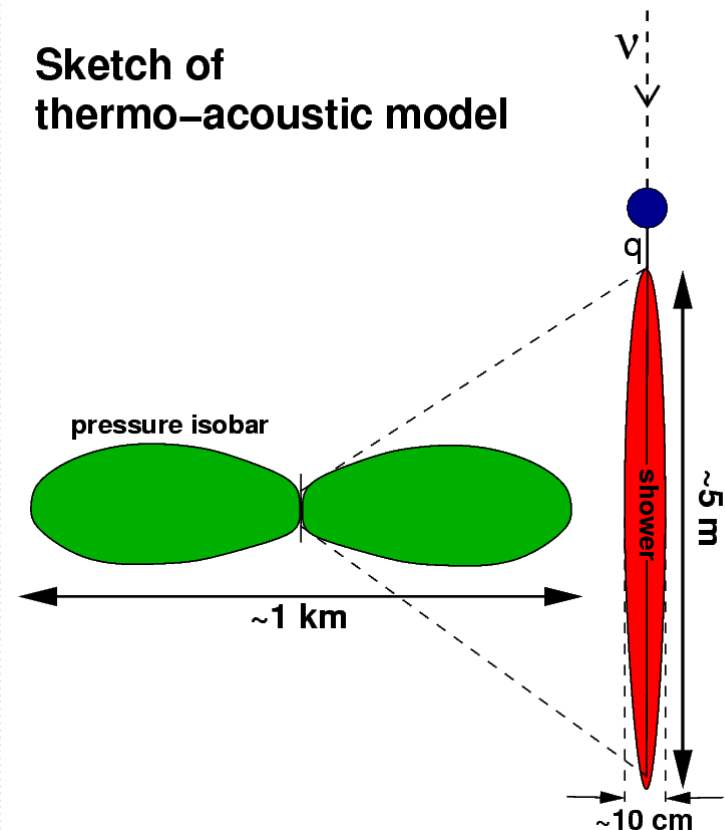
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- Strong physics motivation for km<sup>3</sup>-scale  $\nu$  telescope in Northern hemisphere;
- Mediterranean Sea offers optimal conditions;
- Large amount of R&D required (current detectors not scalable);
- Common European effort: KM3NeT Design Study;
- Goal: Technical Design Report by end of 2008.

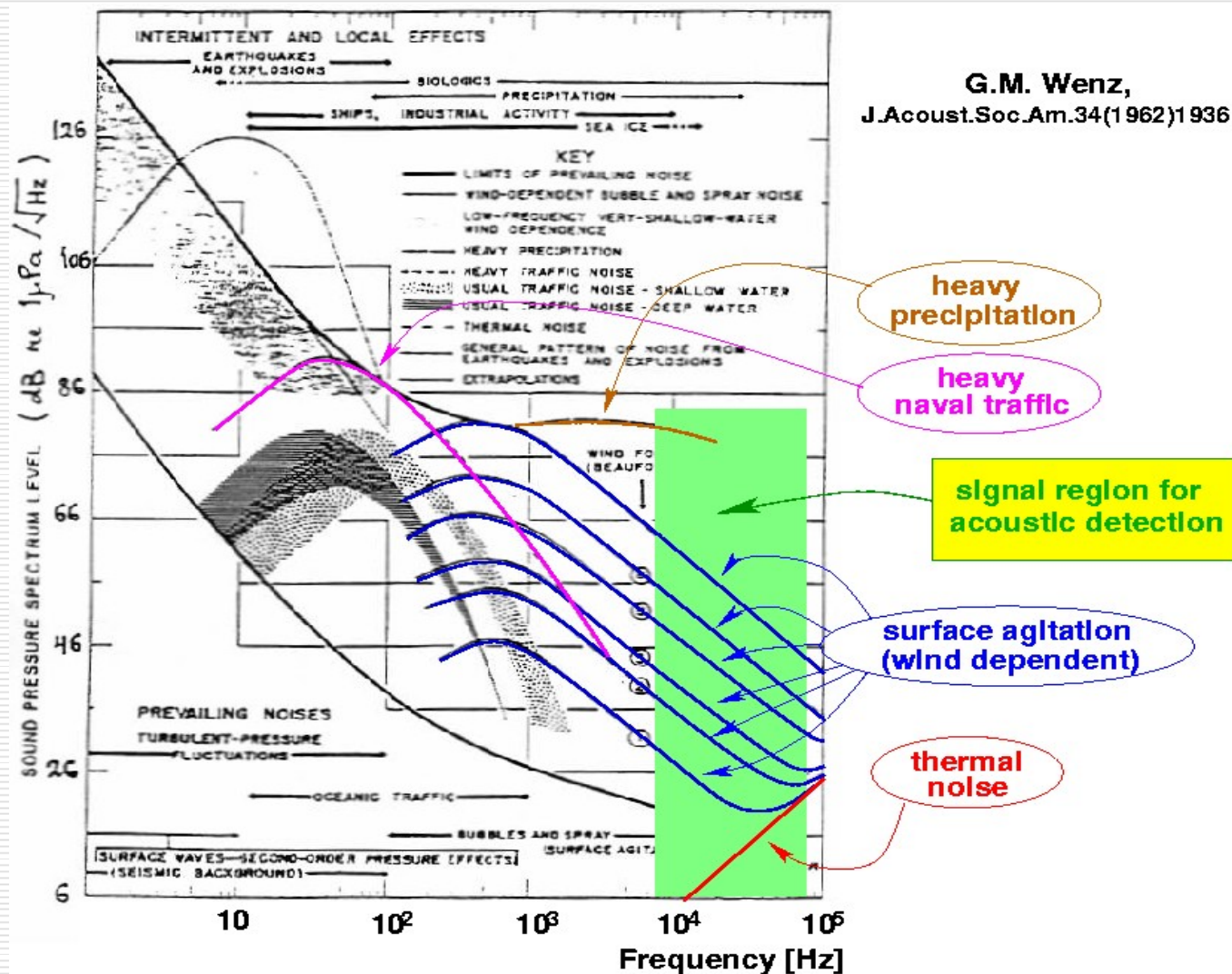


# Acoustic Detection of Neutrinos

- Principle: local heating of medium in region of high-energy shower causes pressure wave (**thermo-acoustic model**);
- Bipolar signal of  **$O(10\mu s)$**  duration; amplitude  **$\sim 10 \mu Pa \cdot E/PeV$**  at 400m distance (in water);
- Might allow for very large instrumented volumes (attenuation length  $O(1 \text{ km})$ );
- Currently rapidly growing interest in USA and Europe, studies for water, ice, salt;
- Option for  $\nu$  detection at energies above  **$10^{16} \dots 10^{17} \text{ eV}$** ?



# Background Conditions in the Deep Sea



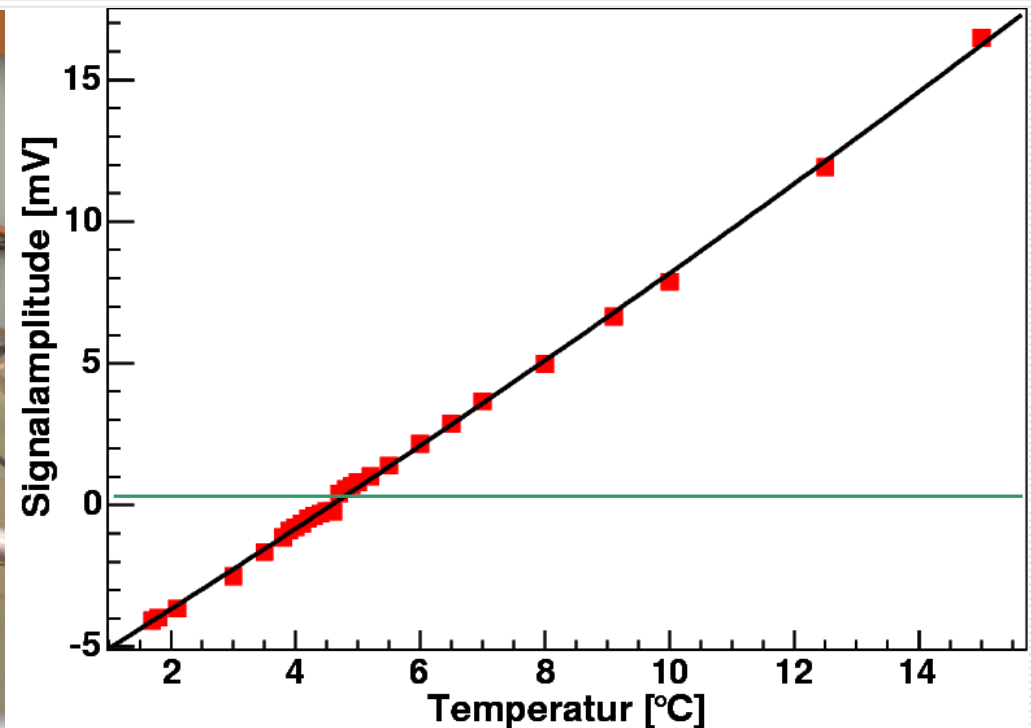
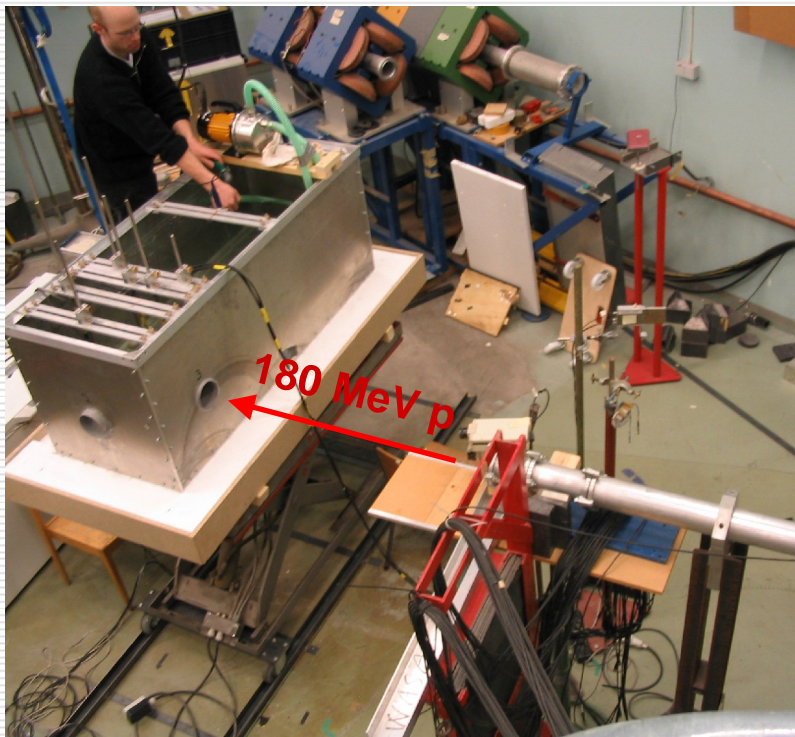
Rough and optimistic estimate:

**signal  $\approx$  noise  
at  $O(0.1-1 \text{ mPa})$**

**(shower with  
10-100 PeV  
@ 400m)**

# Acoustic Detection R&D Activities

- Ongoing work: sensor development, study/simulation of signal generation, test measurements (also *in situ*), ...
- Example: beam test measurements in Uppsala (cooperation Zeuthen/Erlangen): confirmation of expected T dependence.



# Acoustic Detection: Summary

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- Acoustic detection may be a promising future method for the investigation of cosmic neutrinos above  $\sim 10^{16}$  eV;
- R&D programs are pursued in various European and US groups;
- First results are encouraging;
- Major milestone for water detectors: foreseen long-term measurements in ANTARES.

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