ANTARES and Beyond: Neutrino Telescopy in the Mediterranean

Physics with ν Telescopes

ANTARES: Design and Status

Towards the KM3NeT Detector

Acoustic Detection

Summary

MPI Colloquium
Munich,
16. December 2003

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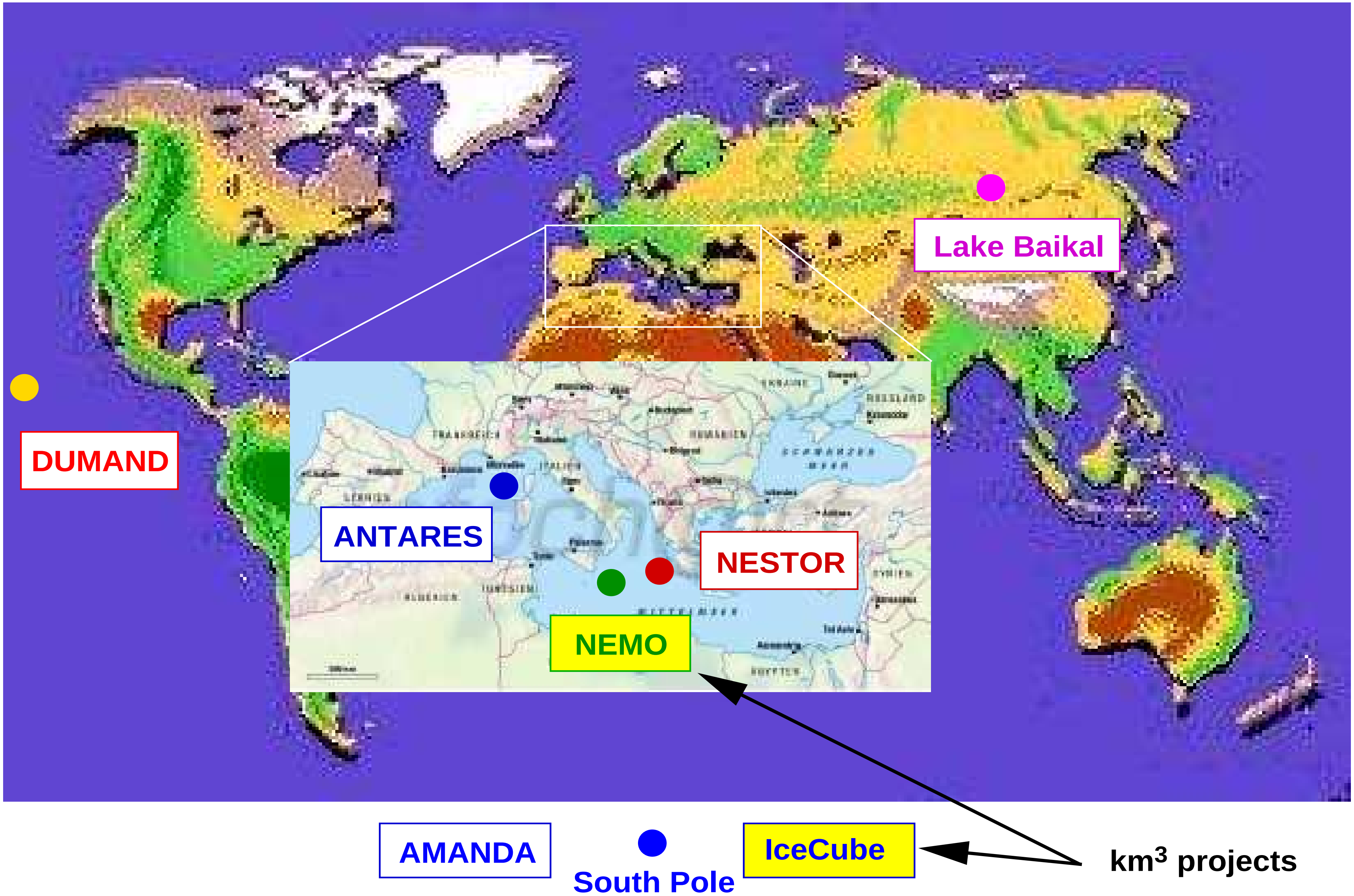
Created with LaTeX on Linux

The Neutrino Telescope World Map

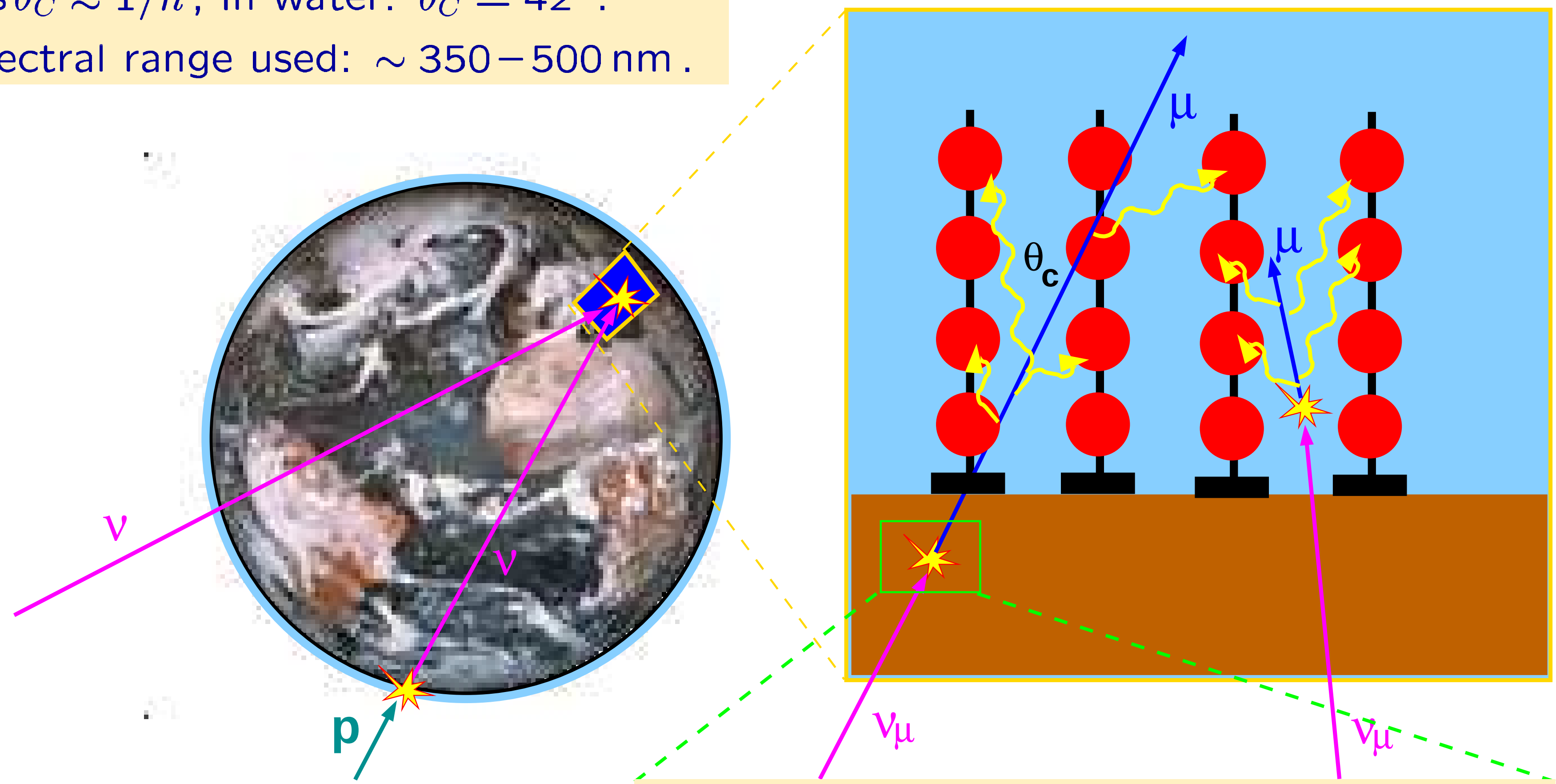


MPI Colloquium, Munich, 16.12.2003

The principle of neutrino telescopes

Čerenkov light:

- $\cos\theta_C \approx 1/n$; in water: $\theta_C = 42^\circ$.
- Spectral range used: $\sim 350-500\,\text{nm}$.



Role of the Earth:

- Screening against all all known particles except ν's.
- atmosphere = target for production of secondary ν's (atmospheric ν's).

Neutrino reactions:

- Reaction mechanism studied in detail at accelerators (in particular HERA).
- Extrapolation to highest energies $\gtrsim 100$ TeV uncertain.
- Key reaction: $\nu_\mu N \to \mu X$ (ν_μ CC).

Particle and Astrophysics with Neutrino Telescopes

Low-energy limit:

- short muon range;
- only few photo sensors give signal;
- in sea water: ^{40}K background prohibitive.

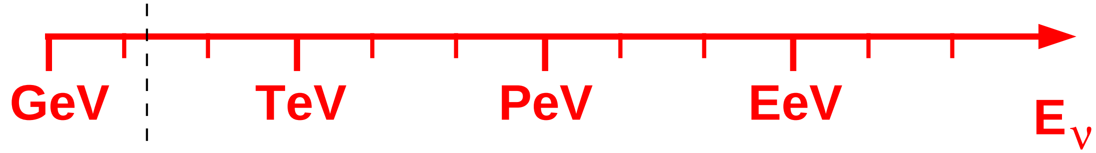
Intrinsic limit, can only be overcome with specialized, very densely instrumented detector.

Neutrino Oscillations:
Direction, Energy, Flavor

Dark matter search (WIMPs):
Direction, Energy

Cosmic point sources:
Direction, (Energy)

Diffuse cosmic neutrino flux:
(Direction), Energy



High-energy limit:

- fluxes decrease as $E^{-2} \ldots E^{-3}$;
- large detection volume needed.

Ultimate volume (at least) one cubic kilometer.

... and also:
GZK−neutrinos
Z bursts
magnetic monopoles
topological defects
top−down scenarios
supernova detection
...

Neutrino Fluxes and Event Numbers

Observed event numbers for diffuse fluxes:

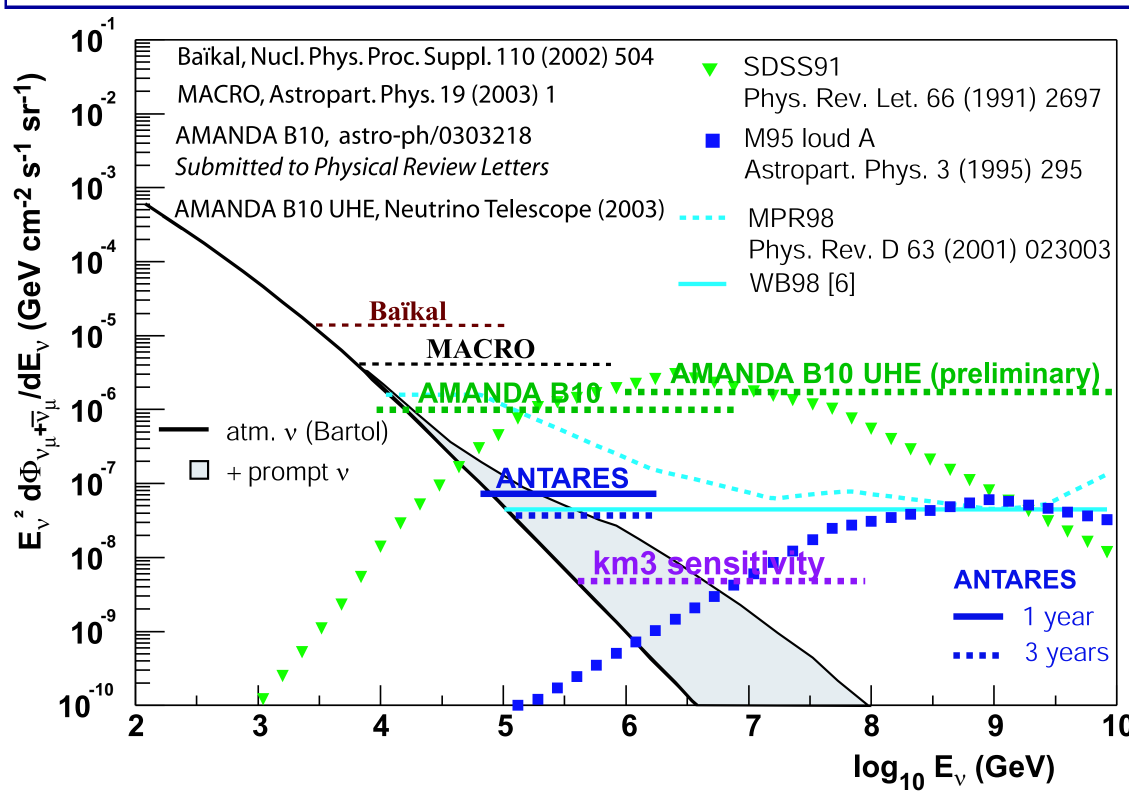
$$\frac{\mathrm{d}N_{\mathrm{evt}}}{\mathrm{d}E_\nu\,\mathrm{d}t} = \int_\Omega \underbrace{\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu\,\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}\Omega}} \cdot \underbrace{\sigma(\nu_\mu N \to \mu X)} \cdot (\rho\,\underbrace{V_{\mathrm{eff}}}) \cdot T\,\mathrm{d}\Omega + \underbrace{\frac{\mathrm{d}N_{\mathrm{evt}}(\nu_e,\nu_\tau)}{\mathrm{d}E_\nu\,\mathrm{d}t} + \frac{\mathrm{d}N_{\mathrm{evt}}(\mathrm{NC})}{\mathrm{d}E_\nu\,\mathrm{d}t}}$$

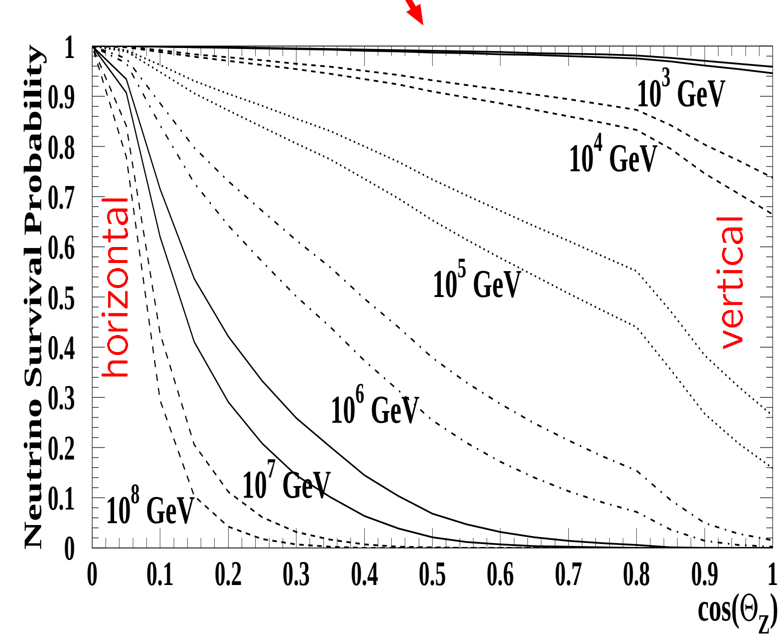
Incoming cosmic flux $\Phi \propto E_\nu^{-2}$ (?)

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

eff. volume, increases with range(μ). But: bad E_ν measurement

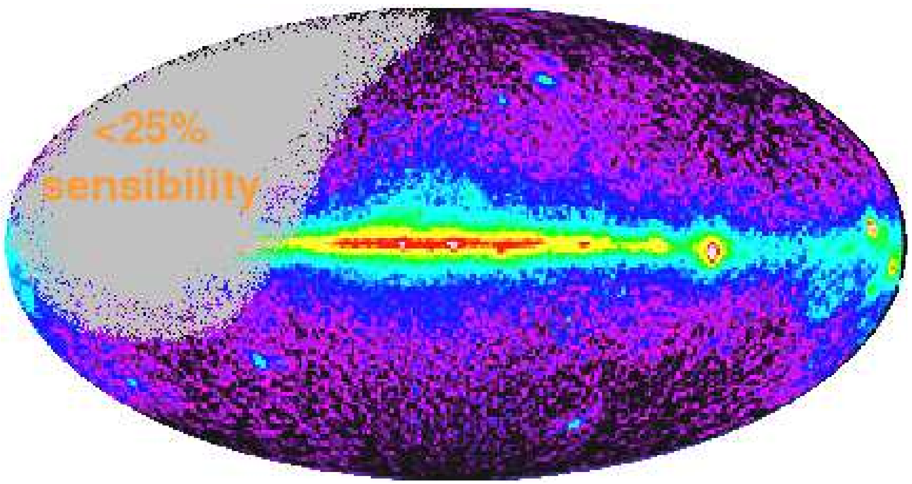
contributions from other neutrino flavors and NC reactions

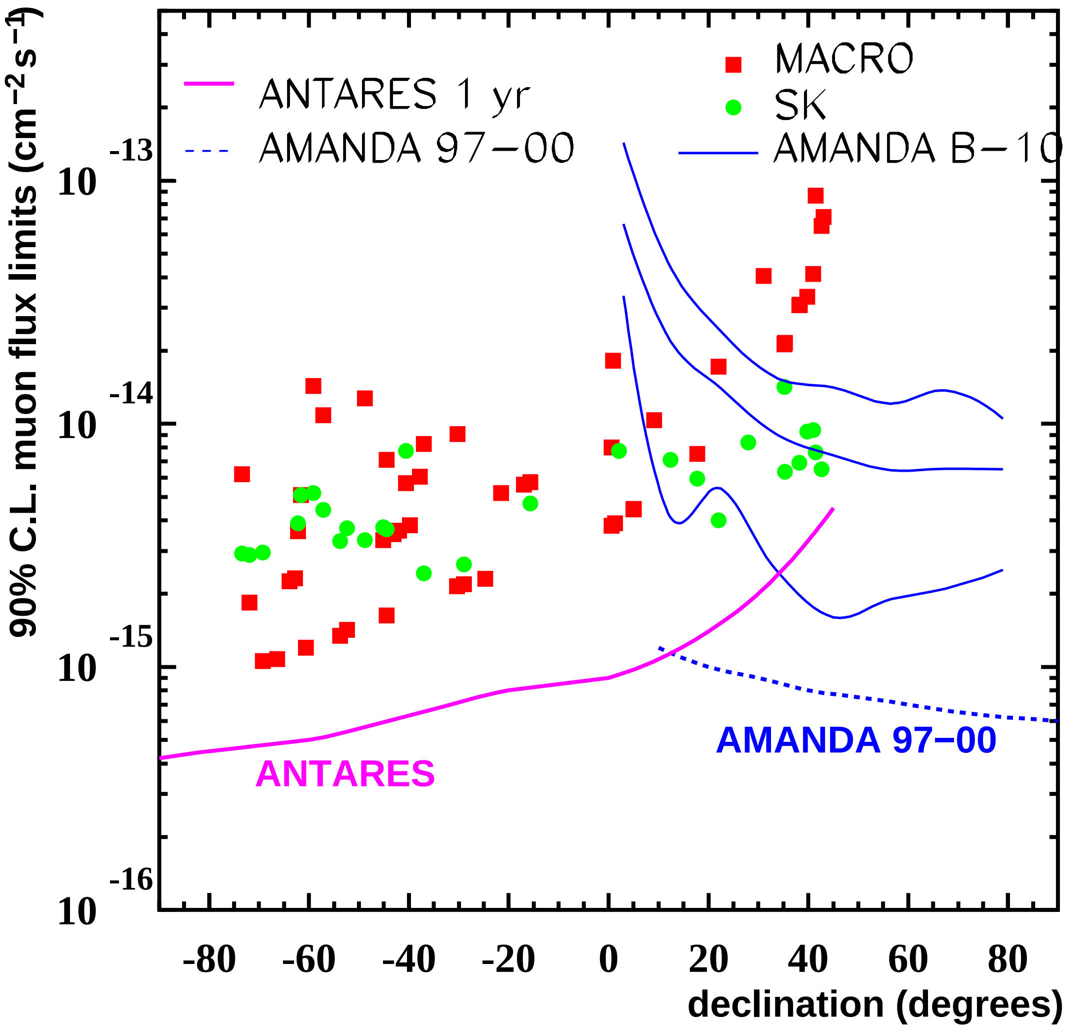




Neutrinos from Astrophysical Point Sources

- **Sky coverage:**
  Complementary to AMANDA/ IceCube,
  Galactic Center seen $\sim 70\%$ of the time.
- **High sensitivity**
  due to good angular resolution ($0.2 - 0.3^\circ$ at high ν energy);
  energies $\gtrsim \mathcal{O}(100\,\mathrm{GeV})$.
- **Expectation after 1 year:**
  Improve existing limits for Southern hemisphere or discover something!





- Associate neutrino flux to specific **astrophysical objects**;
- Study **physics processes** inside source;
- Relate to **“events”** by time correlation.

Indirect Dark Matter detection

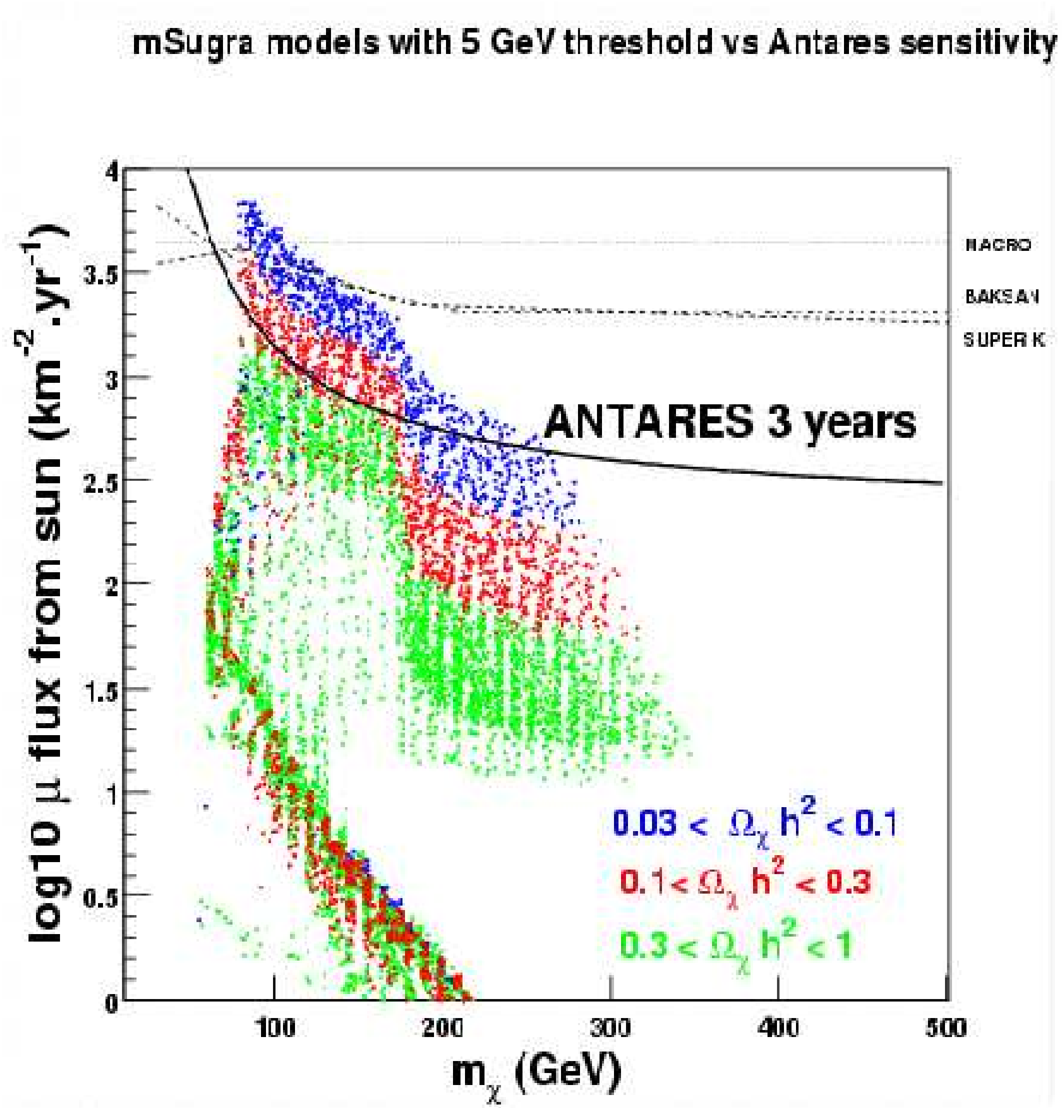
Indirect WIMP detection

- **Gravitational trapping:**
  WIMPs may be trapped in the gravitational field of Earth, Sun or Galactic Center.
- **Candidate particle:**
  SUSY Neutralino (χ).
- **WIMP annihilation**

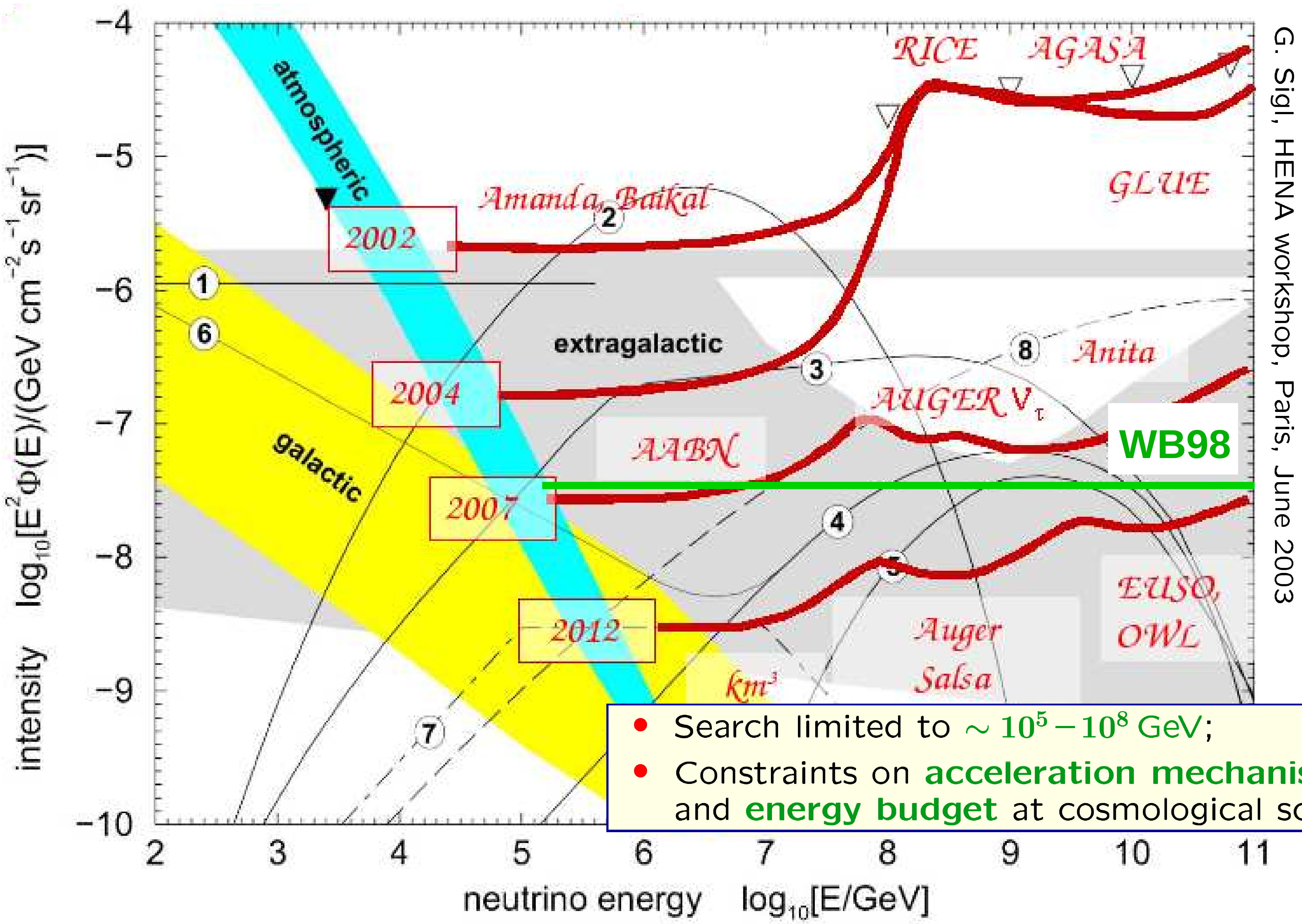
  $$\chi + \chi \rightarrow \text{hadrons} \rightarrow \nu + X$$
  $$\chi + \chi \rightarrow Z^0 Z^0 \rightarrow \nu\bar{\nu} + X$$

  ν energy spectrum depends on neutralino mass and on annihilation products
  → estimated sensitivity extremely model-dependent.
- **The ANTARES sensitivity**
  covers part of the SUSY parameter phase space.
  High sensitivity for low Ω_χ (high annihilation cross section).

Neutralinos from the sun



The diffuse cosmogenic neutrino flux

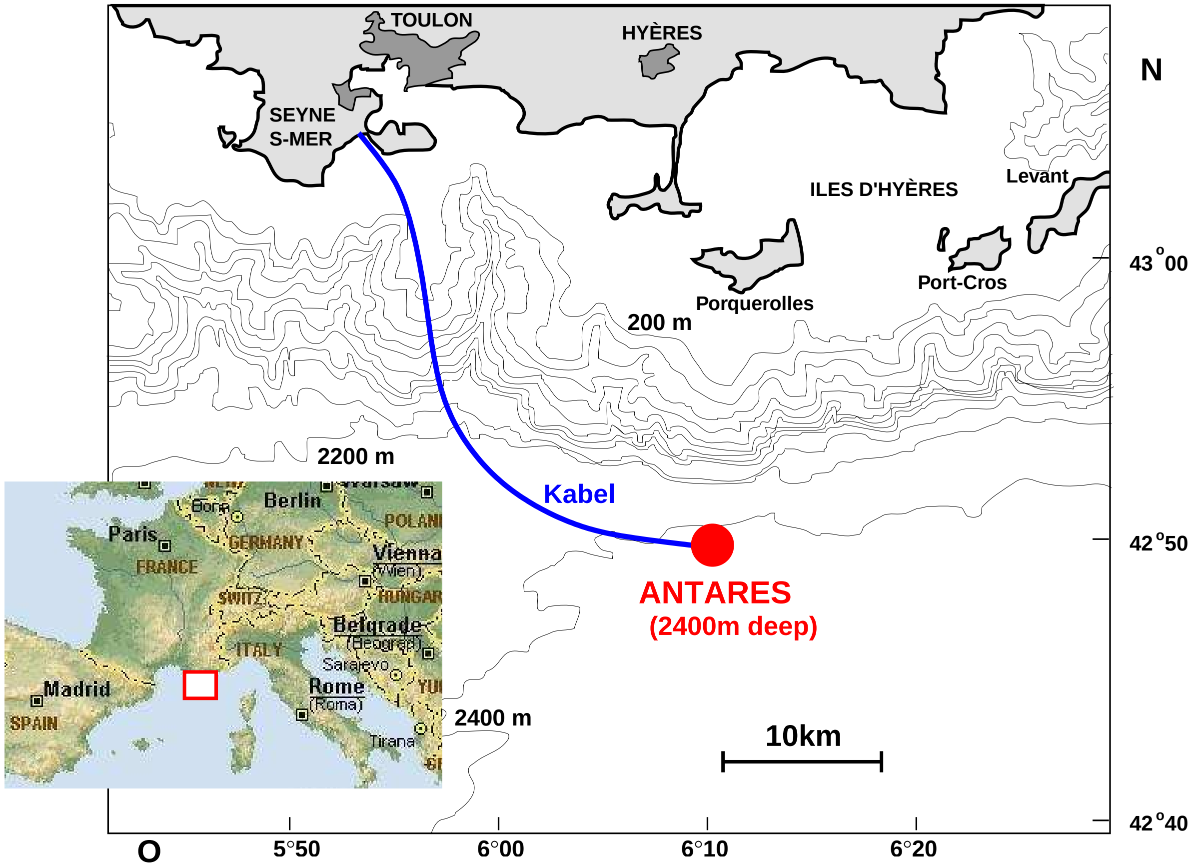


- Search limited to $\sim 10^5 - 10^8$ GeV;
- Constraints on **acceleration mechanism** and **energy budget** at cosmological scales.

The ANTARES Project

The ANTARES Collaboration

- European Collaboration:
  France, Germany, Italy, NL, Spain, Russia, UK.
- Particle physics, astronomy and
  sea science institutes.



The mission

Design, construct and operate a neutrino telescope in the Mediterranean Sea.

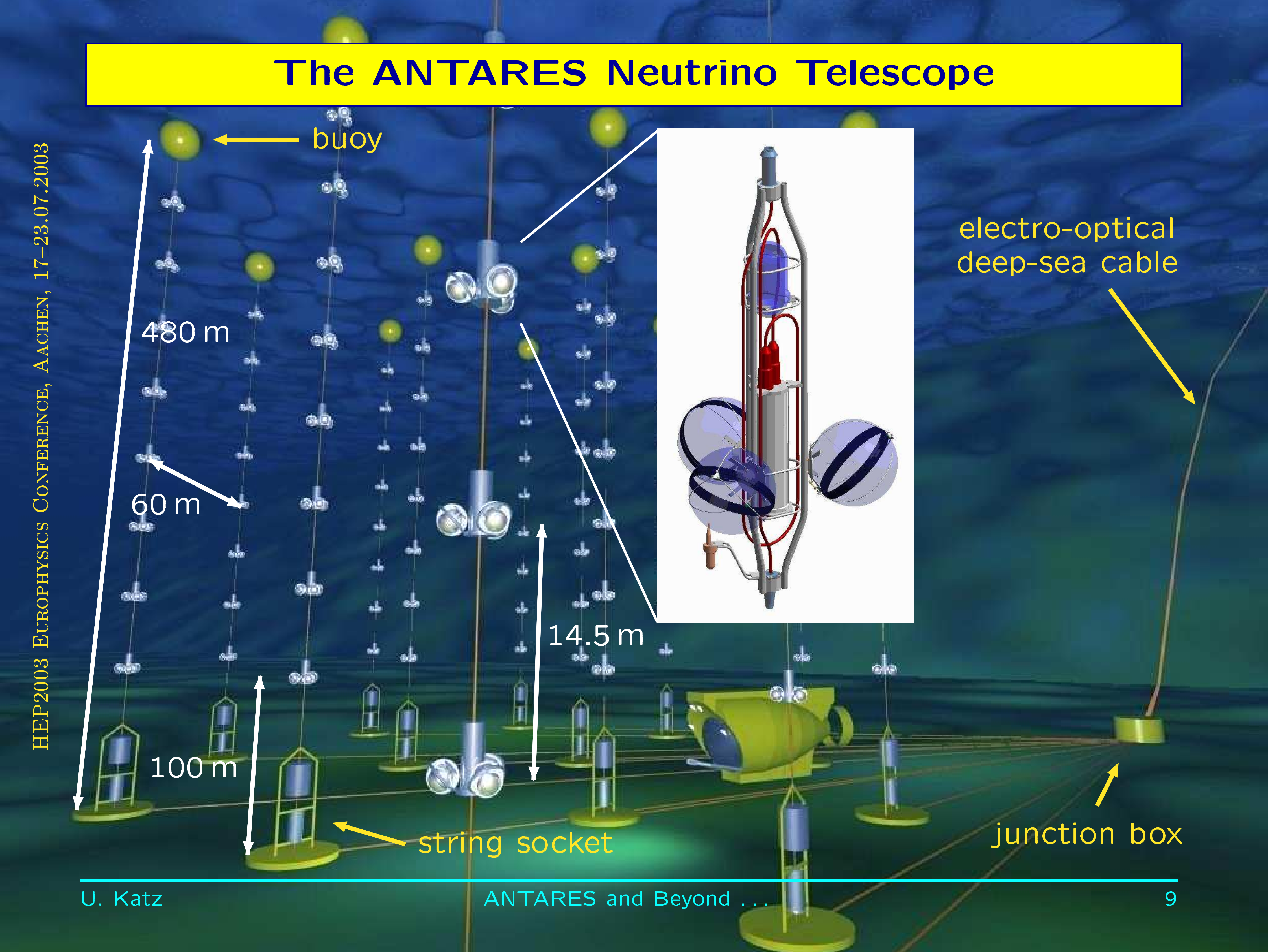
The objectives

- Physics:
  Detect neutrinos,
  astrophysical sources,
  WIMP annihilation,
  neutrino oscillations,
  ...
- Technology:
  Prove feasibility and long-term stability of a deep-sea neutrino telescope.

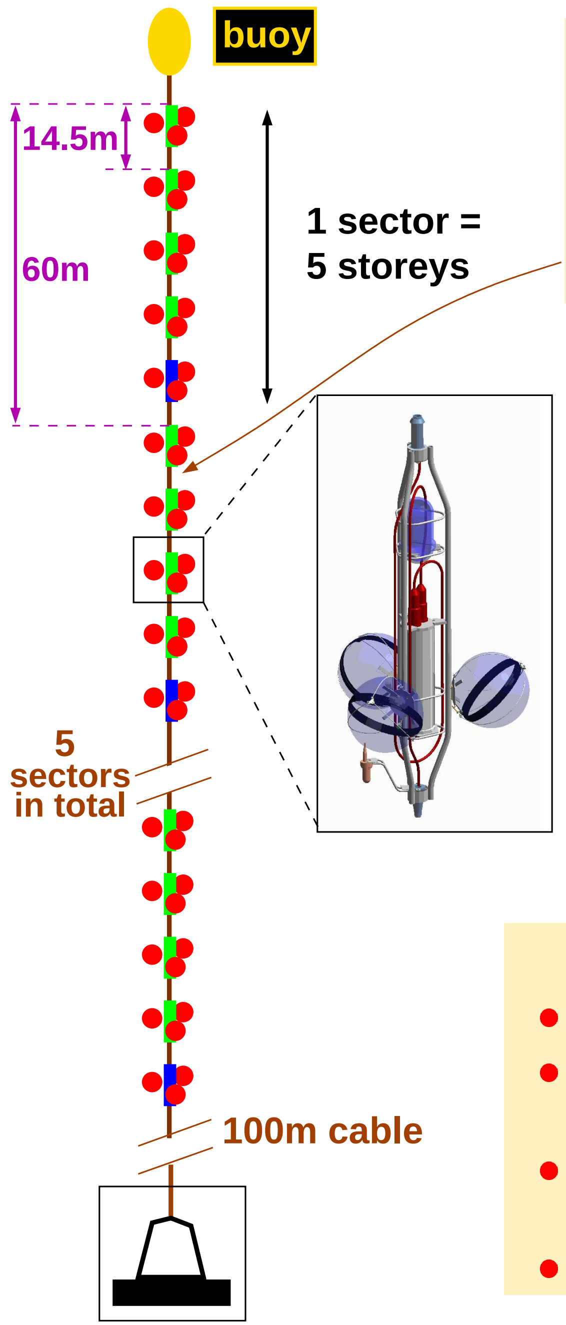
The challenge

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

The ANTARES Neutrino Telescope



Detector strings



Electro-optical-mechanical cable (EMC):

- Lines for data transfer, voltage supplies, . . . ;
- "Mechanical backbone".

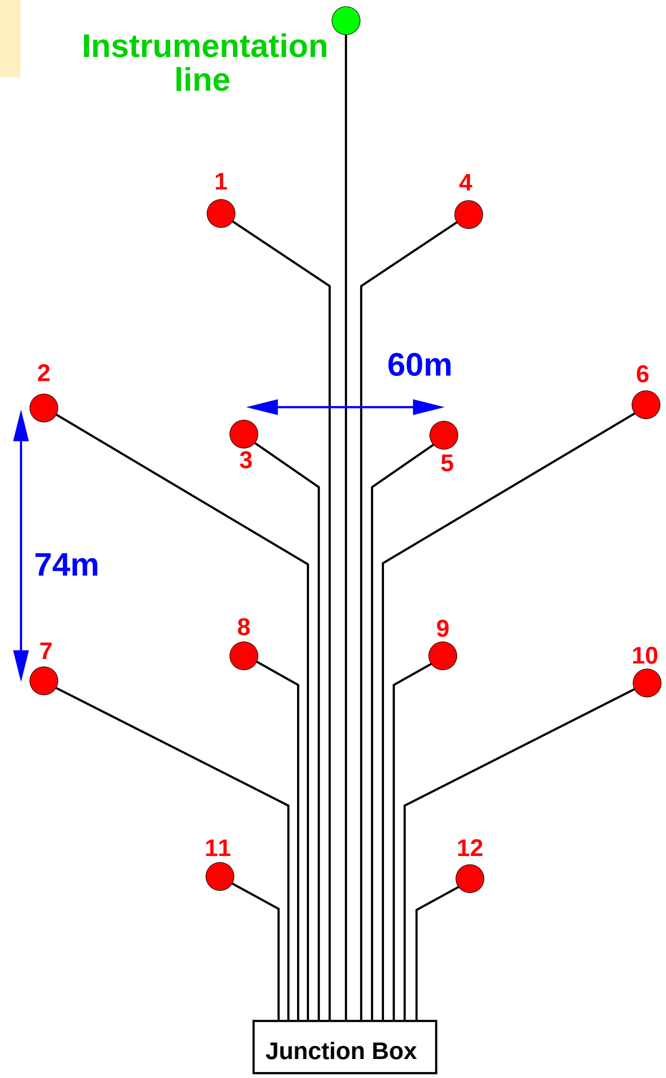
Per storey:

- 3 optical modules (OMs);
- Read-out electronics (signal digitization, data transfer, slow control, . . .);
- Calibration instruments (compass, tiltmeter, optical beacons, acoustic transponders).

On the sea floor:

- Electronics;
- Measurement devices for sound velocity and pressure;
- Release mechanism for string (acoustically activated);
- Connection to Junction Box.

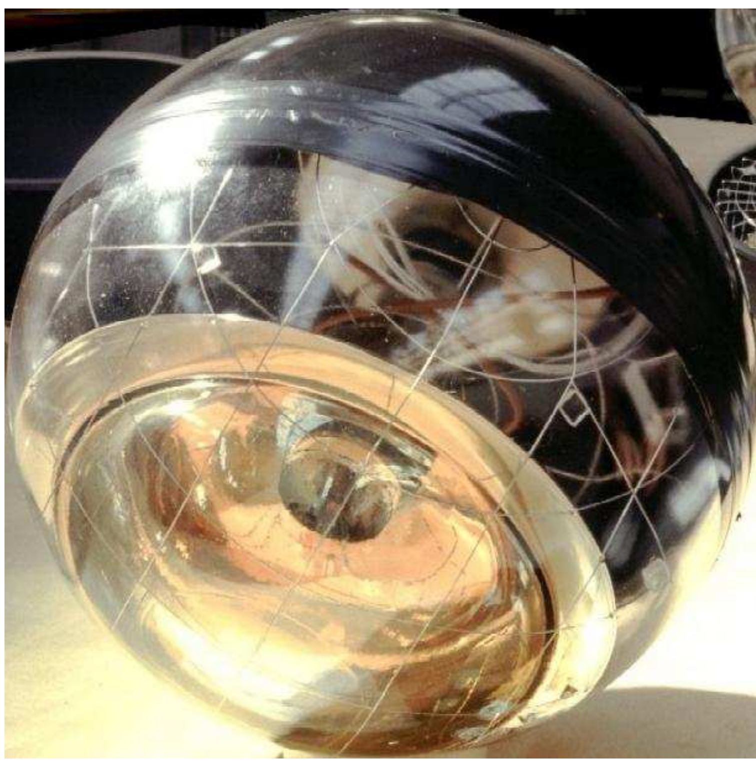
ANTARES detector lay−out:



Optical Modules

- **Photo multiplier tubes:**
  Hamamatsu 10″ ($550\,\mathrm{cm}^2$ cathode area);
  transfer time spread (TTS) $\sim 2.7\,\mathrm{ns}$;
  quantum efficiency $> 20\%$ @ $1760\,\mathrm{V}$
  for $330\,\mathrm{nm} \lesssim \lambda \lesssim 460\,\mathrm{nm}$.
- **Glass spheres:**
  outer diameter $43\,\mathrm{cm}$;
  qualified for $600\,\mathrm{bar}$;
  light transmission $\gtrsim 95\%$.

43 cm



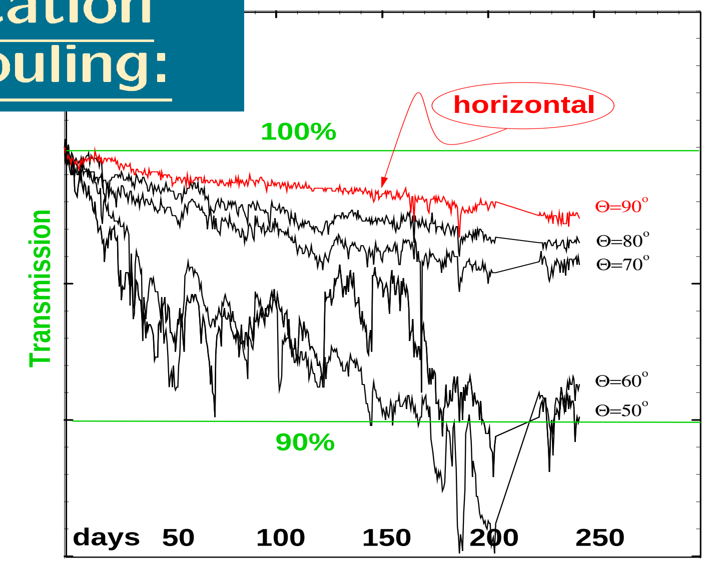
Environmental conditions

Control measurements

Continuous survey of:

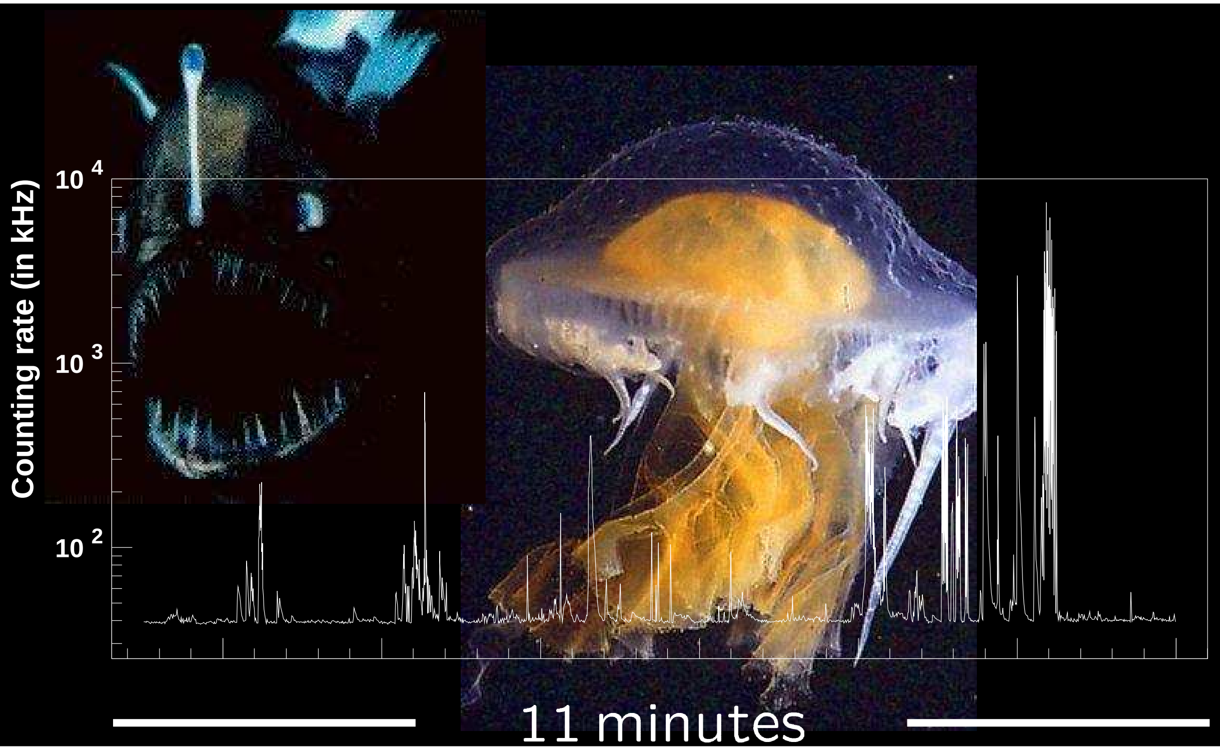
- light absorption;
- current velocity;
- velocity of sound;
- salinity;
- temperature and pressure.

Sedimentation and bio-fouling:



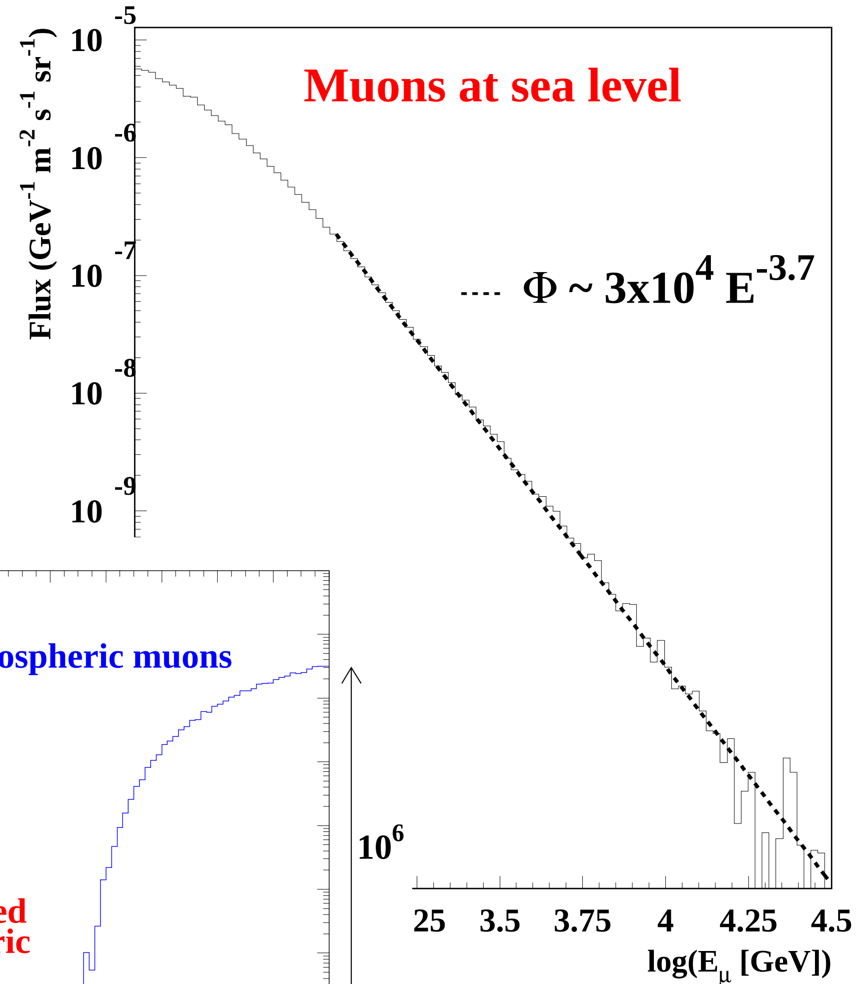
Optical background:

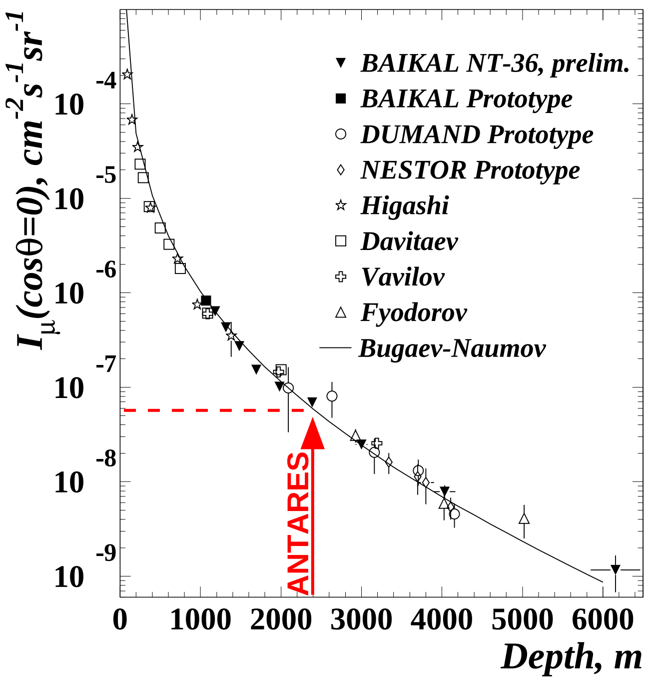
- Continuous rate from ^{40}K decays and noise: $\sim 70\,$kHz/PM
- Short-term (?) MHz-rates caused by bioluminescence (bacteria, jellyfish, shrimp, fish, . . .)
  $\rightarrow$ dead-time/PM $\sim 5\%$.

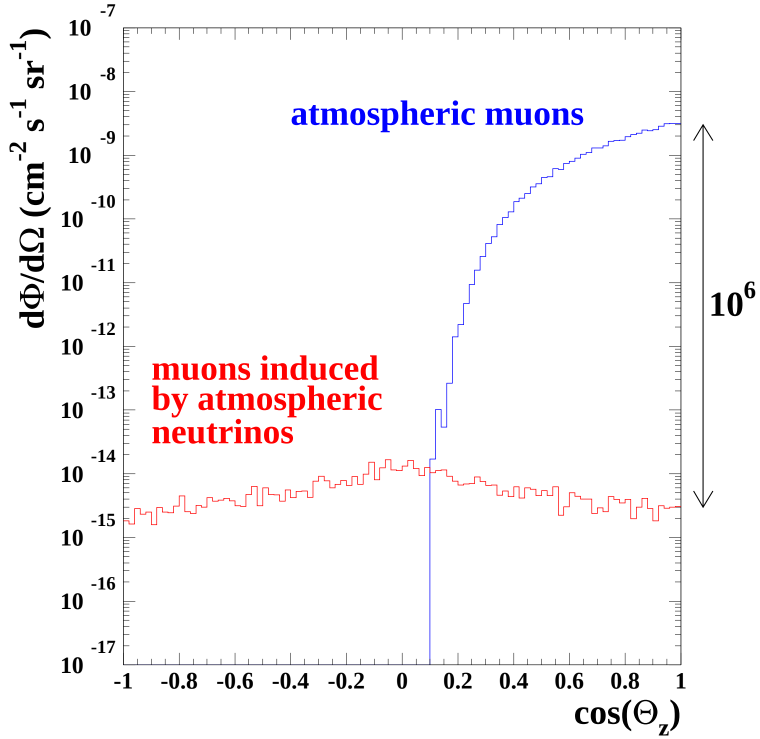


The background from above

- Dominant background:
  Muons from atmospheric showers.
- Can penetrate to 2 km water depth if their energy exceeds ~ 1 TeV.
- Neutrino telescopes need the Earth as screen, except
  - if the vertex of the ν reaction is detected (hadronic shower);
  - possibly at highest energies.







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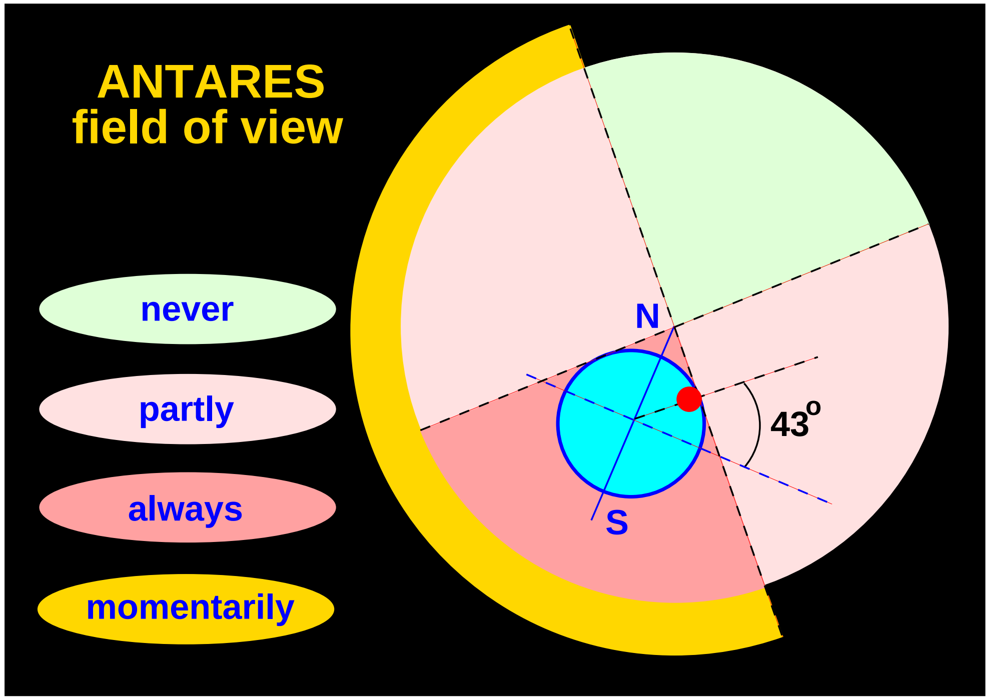
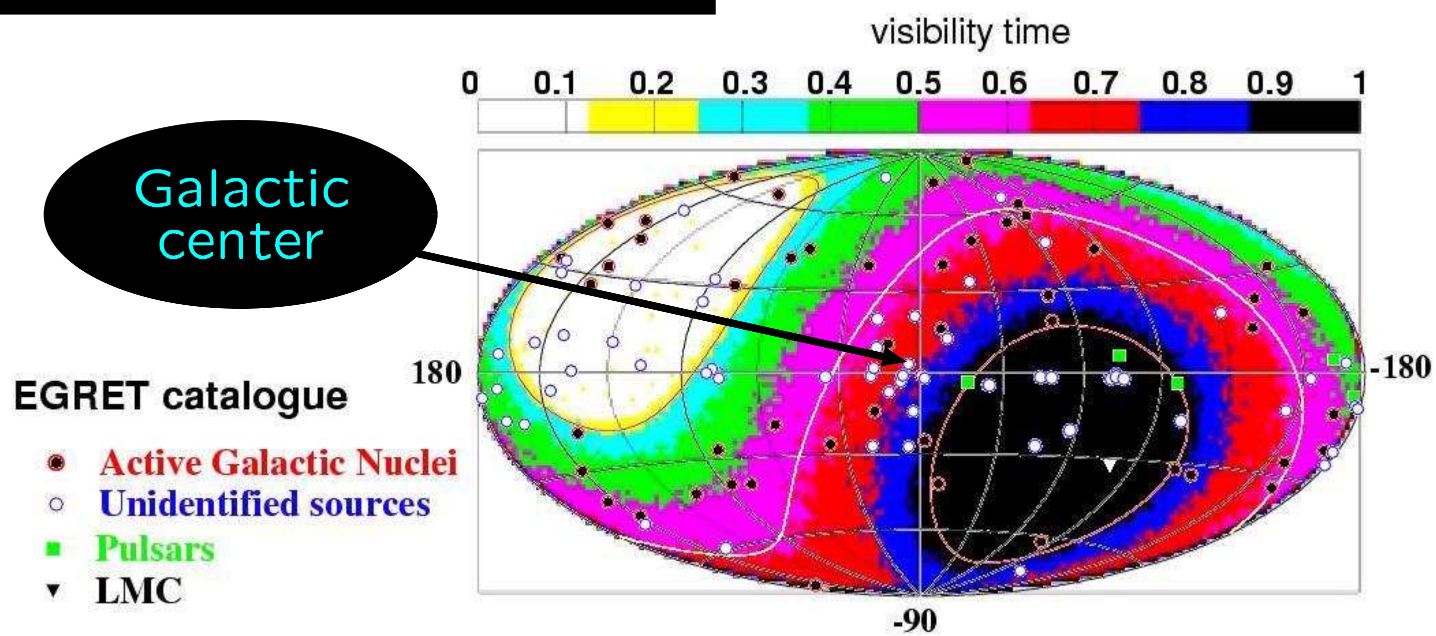
The ANTARES field of view



- 3.5π field of view, of these 0.5π 24h/day.
- Complementary to AMANDA/IceCube, 1.5π overlap.
- Galactic center and many potential point sources are accessible.
- $E_\nu \gtrsim 100\,\text{TeV}\ldots 10\,\text{PeV}$: Earth is opaque for neutrinos
  $\Rightarrow$ restricted field of view (only horizontal ν's).



Reconstruction of direction and energy

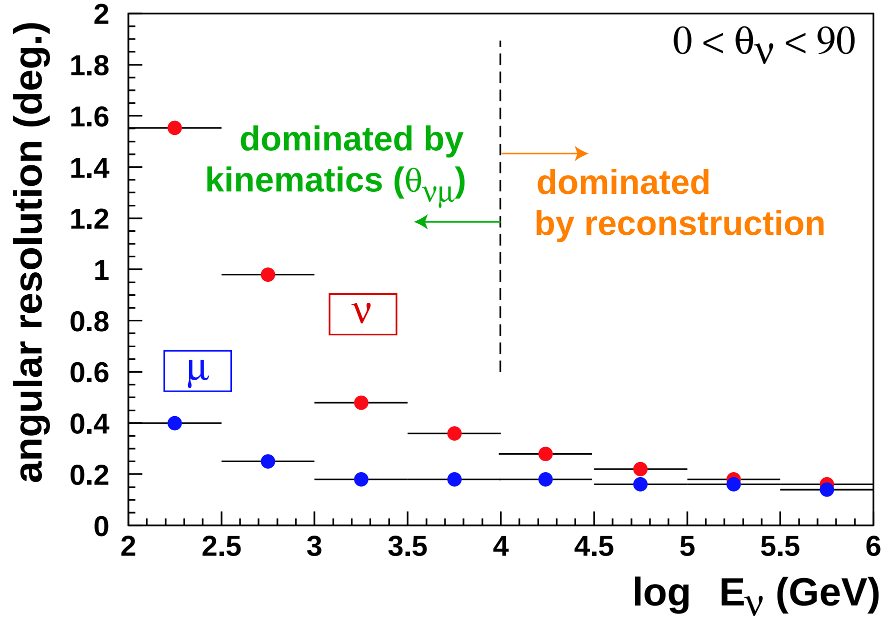
Angular resolution

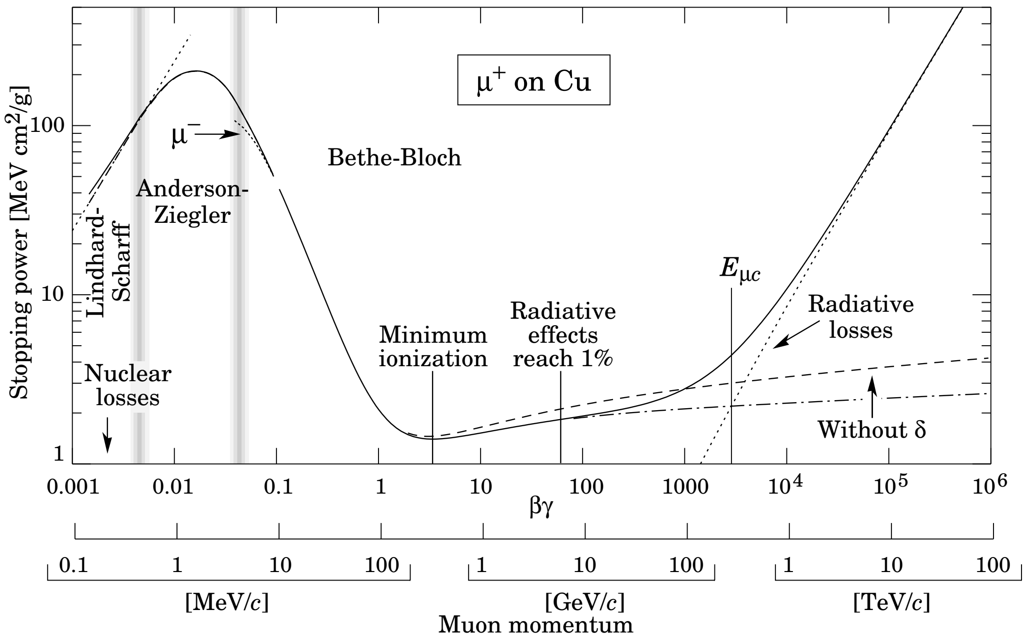
- Average angle $\theta_{\nu\mu}$ depends on E_ν:

$$\langle\theta_{\nu\mu}\rangle \approx 0.7^\circ / E_\nu[\text{TeV}]$$

- Uncertainty of muon angle:
  - detector calibration (position, time);
  - multiple scattering.
- Search for point sources: $S/B \propto 1/\Delta\theta^2$

  $\Rightarrow$ large advantage of ANTARES over ice experiments ($\Delta\theta_{\text{IceCube}} \sim 1^\circ$).





Energy determination

- $E_\mu \lesssim 200$ GeV: μ range.
- $E_\mu \gtrsim 1$ TeV (cosmic sources): dE/dx (signal amplitude).
- Resolution: factor of 2−2.5 in E_μ for $E_\mu \gtrsim 1$ TeV.
- Neutrino energy E_ν:
  - $E_\nu > E_\mu$;
  - $\text{RMS}(E_\mu/E_\nu) < 1/\sqrt{12}$.

ANTARES: The preparatory phase

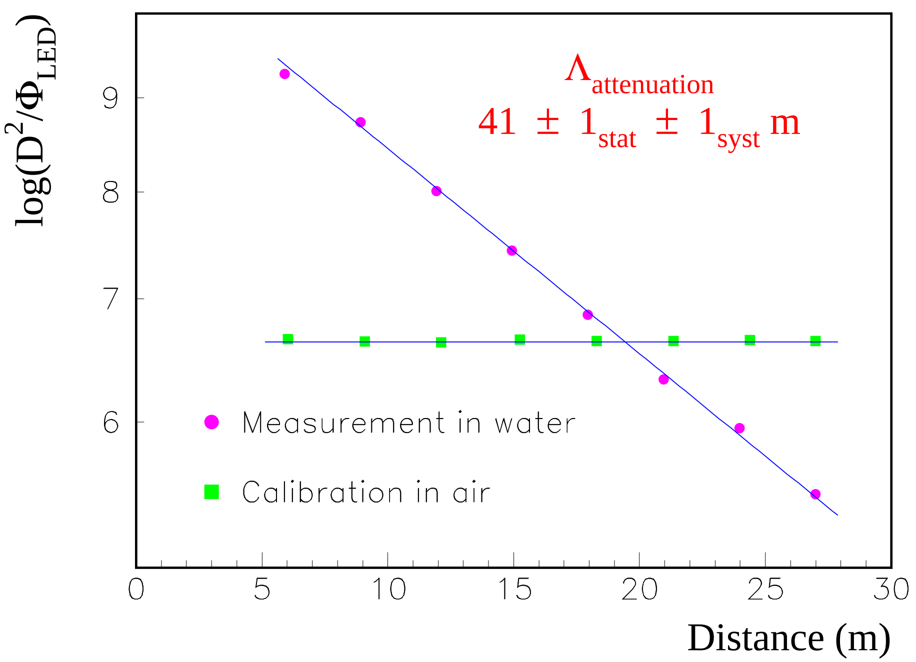
Environment assessment

- **Development of tools**
  for measuring environmental parameters.
- **Numerous measurement campaigns:**
  - optical parameters of water;
  - salinity, temperature,...;
  - current velocity and direction;
  - sedimentation and biofouling;
  - bioluminescence;
  - bathymetric profile.
- **Sea floor survey**
  with deep-sea submarine.

Prototype string

- **Design:**
  16 storeys à 2 PMs, 350 m long, equipped with full readout electronics and slow control devices.
- **Operation:**
  Several battery-operated immersions (1998/99), connected to shore (1999). Successful data taking.

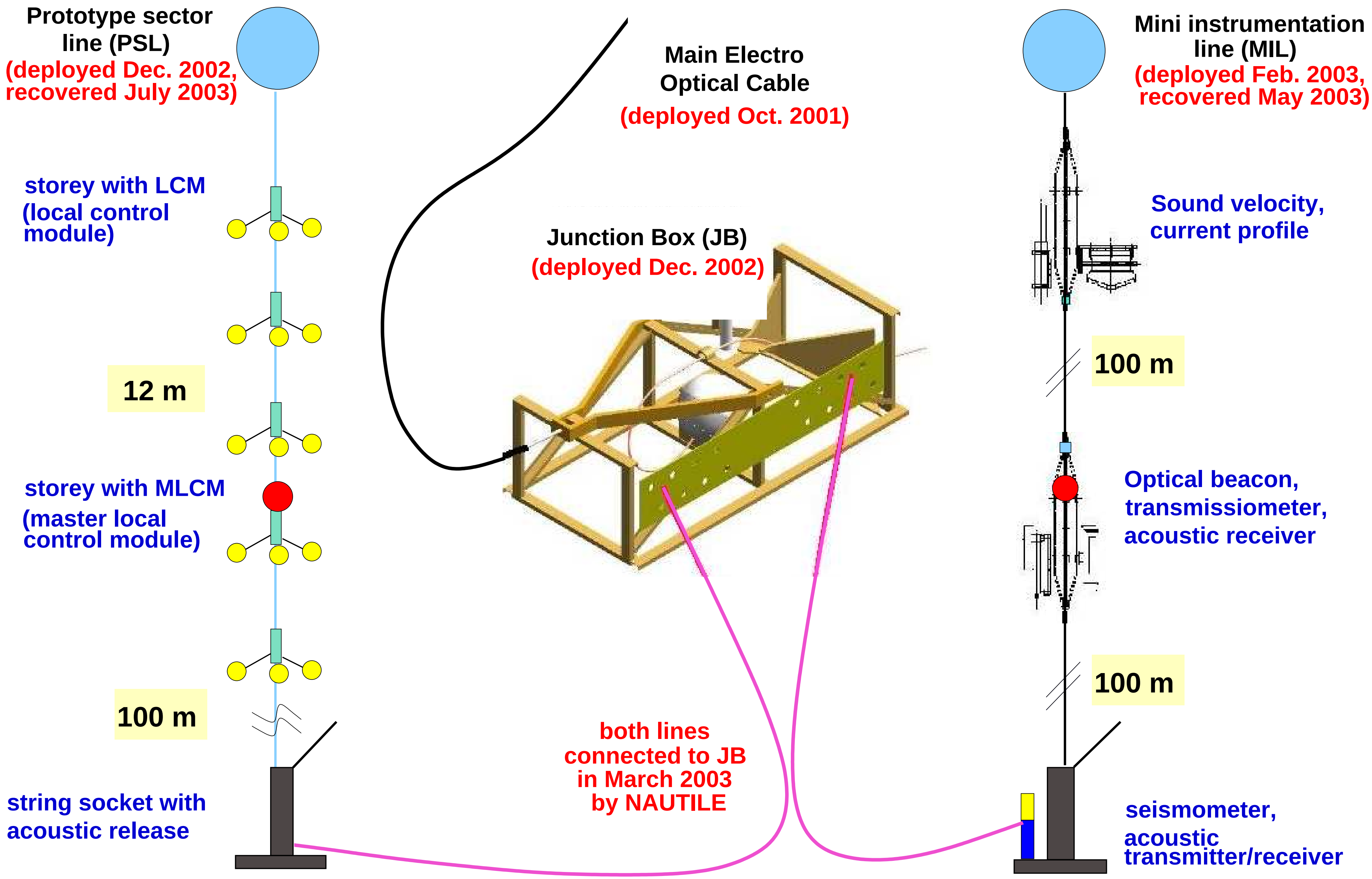
Determination of $\Lambda_{attenuation}$



D: Distance between LED and PMT

Φ_{LED}: LED luminosity to obtain a constant current on PMT

Detector status



Sea operations

Junction Box deployment

Preproduction line deployment

Underwater connection by NAUTILE

Positioning accuracy

- **Surface position**
  monitored and stabilized by differential GPS.
- **Underwater position**
  monitored by acoustic triangulation.
- **Accuracy on sea bed:**
  a few meters!

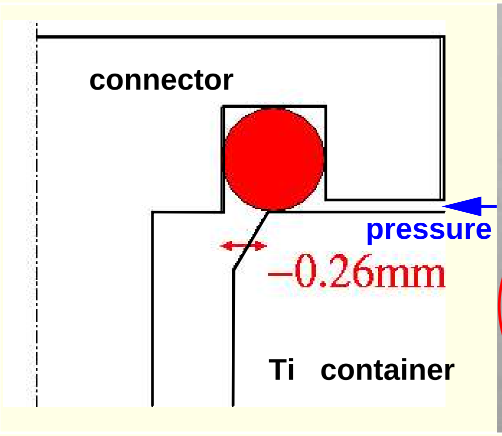
2 Problems and Their Diagnose

The clock fiber failure

- **The symptom:**
  The clock signal did not arrive at the readout modules (both lines!)
- **The consequences:**
  → no data with ns time resolution;
  → no measurement of signal charges;
  → no acoustic positioning.
  However, we still were able to
  → measure PM rates;
  → control HV settings, thresholds;
  → take slow control data (compasses, tiltmeters etc.).
- **The diagnose:**
  One plastic tube around the optical fiber for the clock signal collapsed.
  ⇒ Plastic material changed by manufacturer without notification.
  ⇒ Even worse: material not qualified for high-pressure applications!
- **The remedy:**
  Final cable design modified (use steel tubes now).

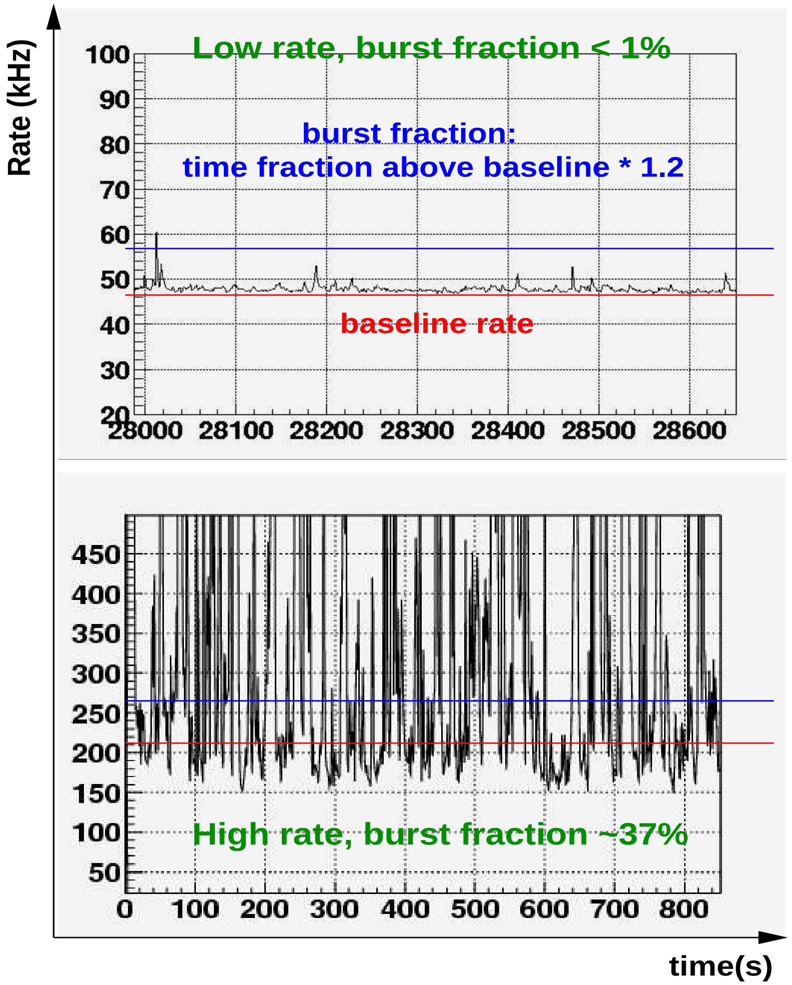
A water leak

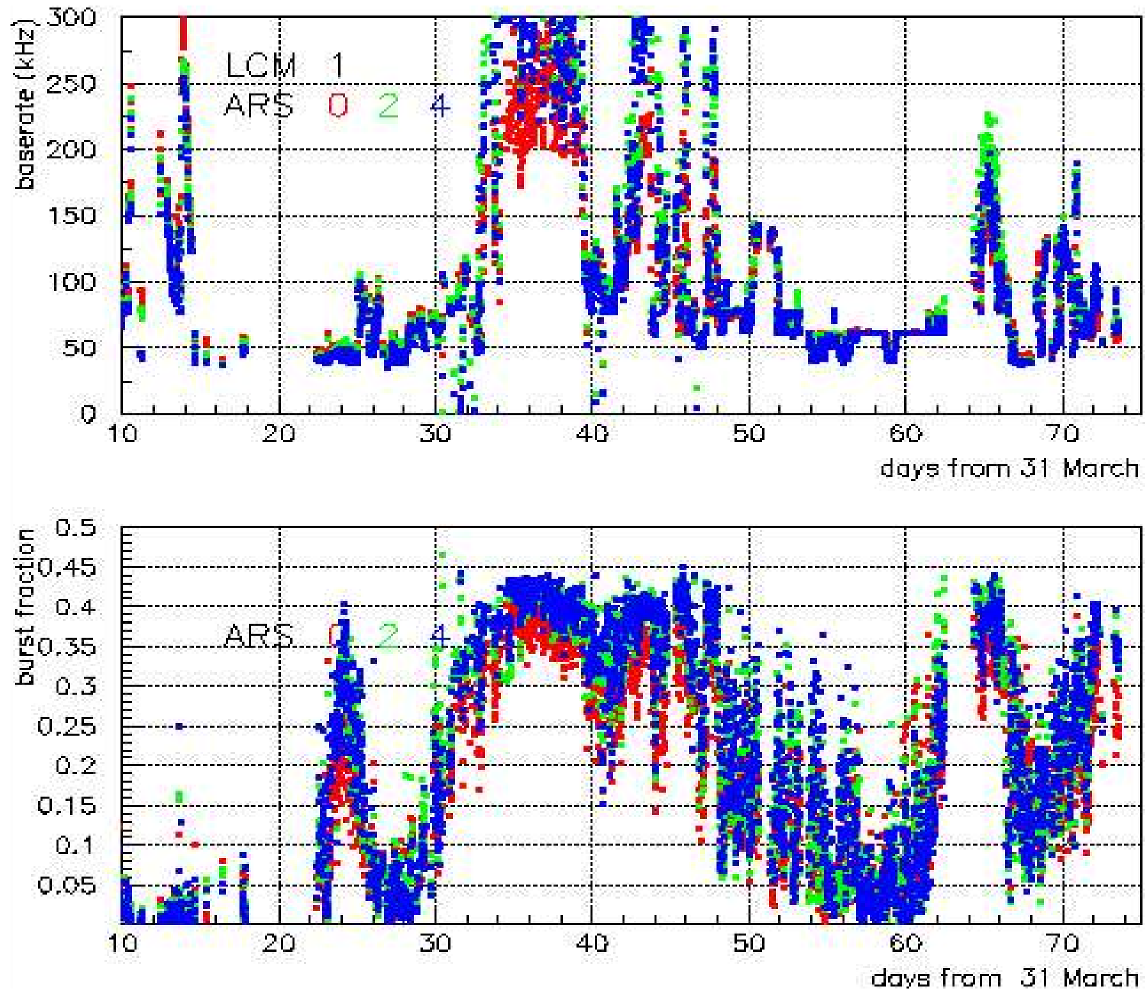
- **The symptom:**
  The mini instrumentation line stopped to work on April 11.
- **The consequence:**
  Immediate recovery of the line.
- **The diagnose:**
  An o-ring secured connector had developed a leak.
  Specifications of hole diameter and tolerances by manufacturer were wrong.
  No problems seen in pressure tests!



- **The remedy:** different connectors.

Rate measurements and bioluminescence



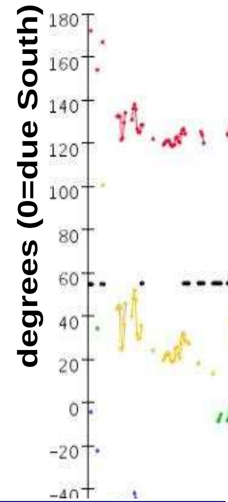
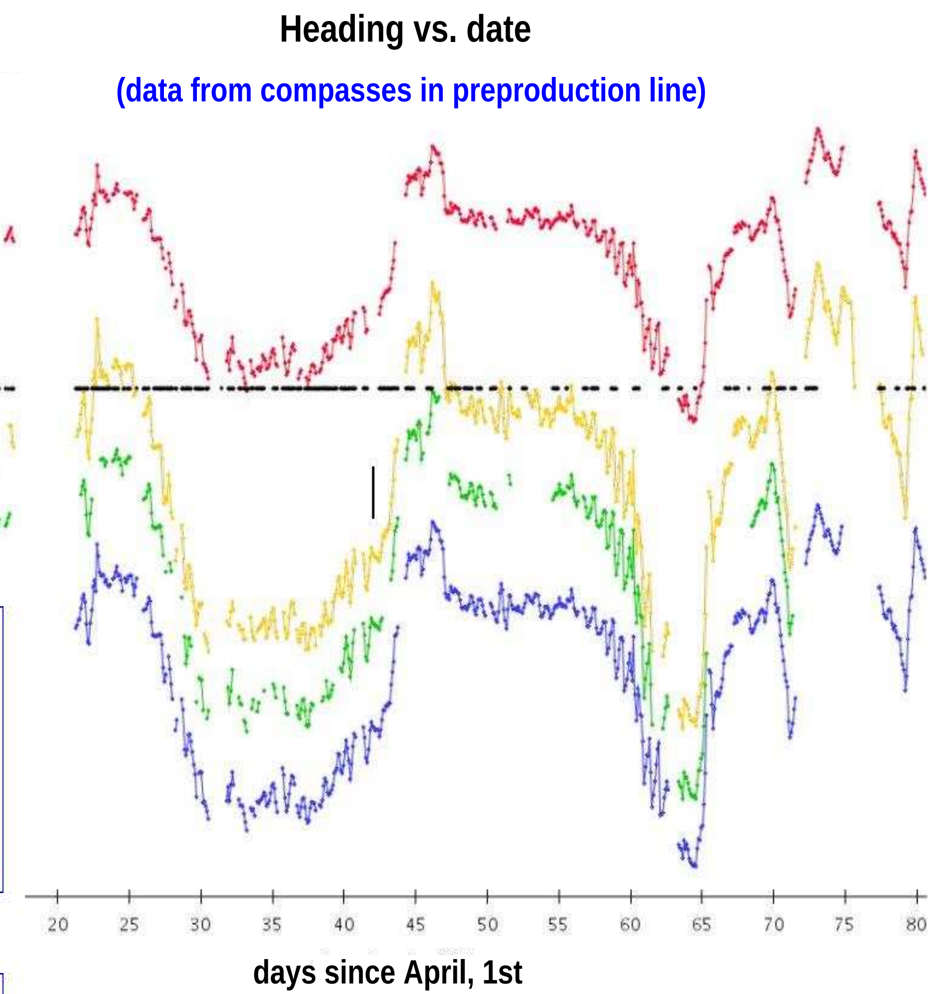


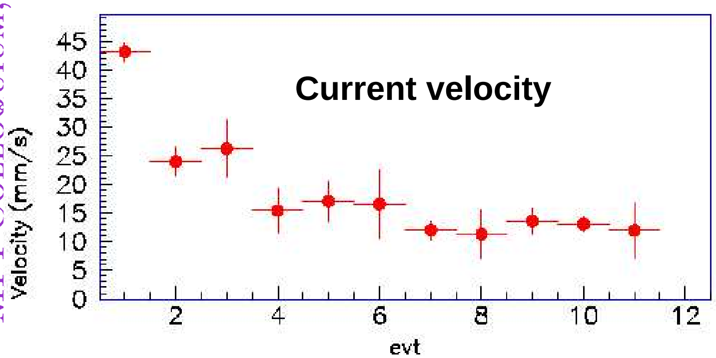
Observations:

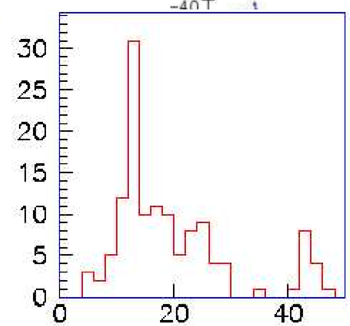
- Strong variability of rates: bursts and slow changes.
- "Base line rate" (BR) and "burst fraction" (BF).
- Some correlation between BR and BF, but low-low, high-low, low-high, high-high all appear.
- Mostly bioluminescence (^{40}K: $\sim 50\,$kHz/PM).

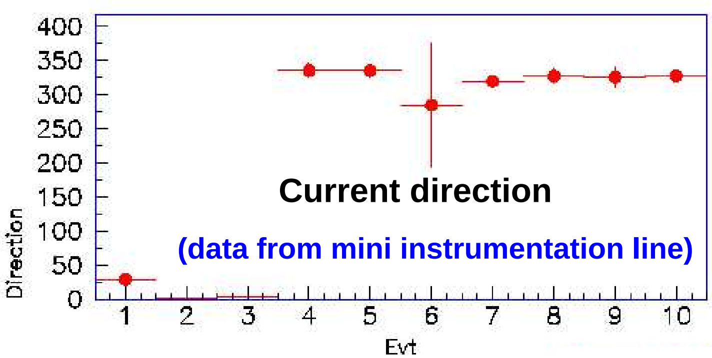
Currents and line movement

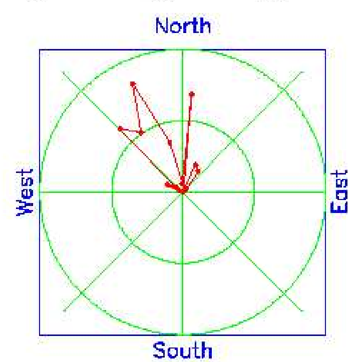
- The storeys move "as a rigid body". Correlation with current!?
- Current measurement operational.
- Short-term movements correlated with PM rates (bioluminescence?).









The detailed understanding of environmental conditions is vital and achievable.

Summary: ANTARES

- ANTARES: A first-generation water Čerenkov neutrino telescope in the Mediterranean
- First installation steps successfully completed, prototype detector modules deployed and operated.
- Mass production starting after minor design modifications, detector expected ready by early 2007
- Discovery potential for cosmogenic neutrinos and dark matter
- Feasibility proof for neutrino telescope in sea water.

A northern-hemisphere km^3 ν telescope

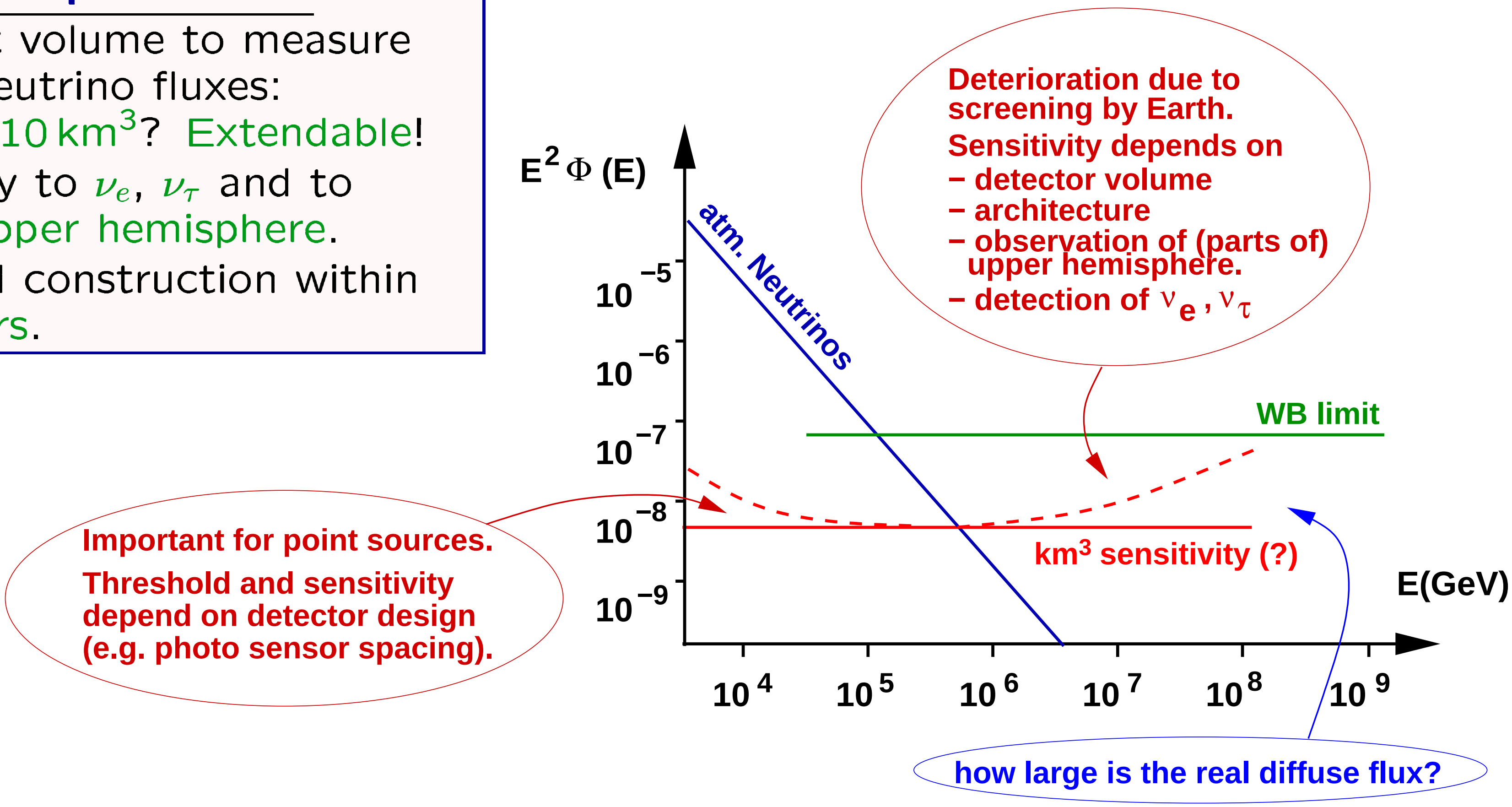
The physics case:

- Complement sky coverage of IceCube.
- Observe galactic center.
- Increased point source sensitivity.

The requirements:

- Sufficient volume to measure cosmic neutrino fluxes: 1 km^3 or 10 km^3? Extendable!
- Sensitivity to ν_e, ν_τ and to ν from upper hemisphere.
- R&D and construction within 8–10 years.

Some links between physics requirements and design considerations:



Past and present ν telescopes

Fresh water

- + no potassium;
  + surface ice: access, calibration;
  – water transparency, bioluminescence;
  – depth $\lesssim 1400\,\mathrm{m}$.
- Lake Baikal
  demonstrated feasibility of water Čerenkov ν telescope.

Salt water

- + optical water properties;
  + sufficient depth (→ site choice);
  – potassium, bioluminescence;
  – chemically aggressive;
  – no "surface".
- DUMAND:
  pioneering work, stopped 1995.
- ANTARES, NESTOR:
  first data from prototype installations.
- NEMO:
  R&D towards a km^3 ν telescope.

Ice

- AMANDA:
  data taking.
- IceCube:
  km^3 project, in preparation.

The Mediterranean Sea offers optimal conditions . . .

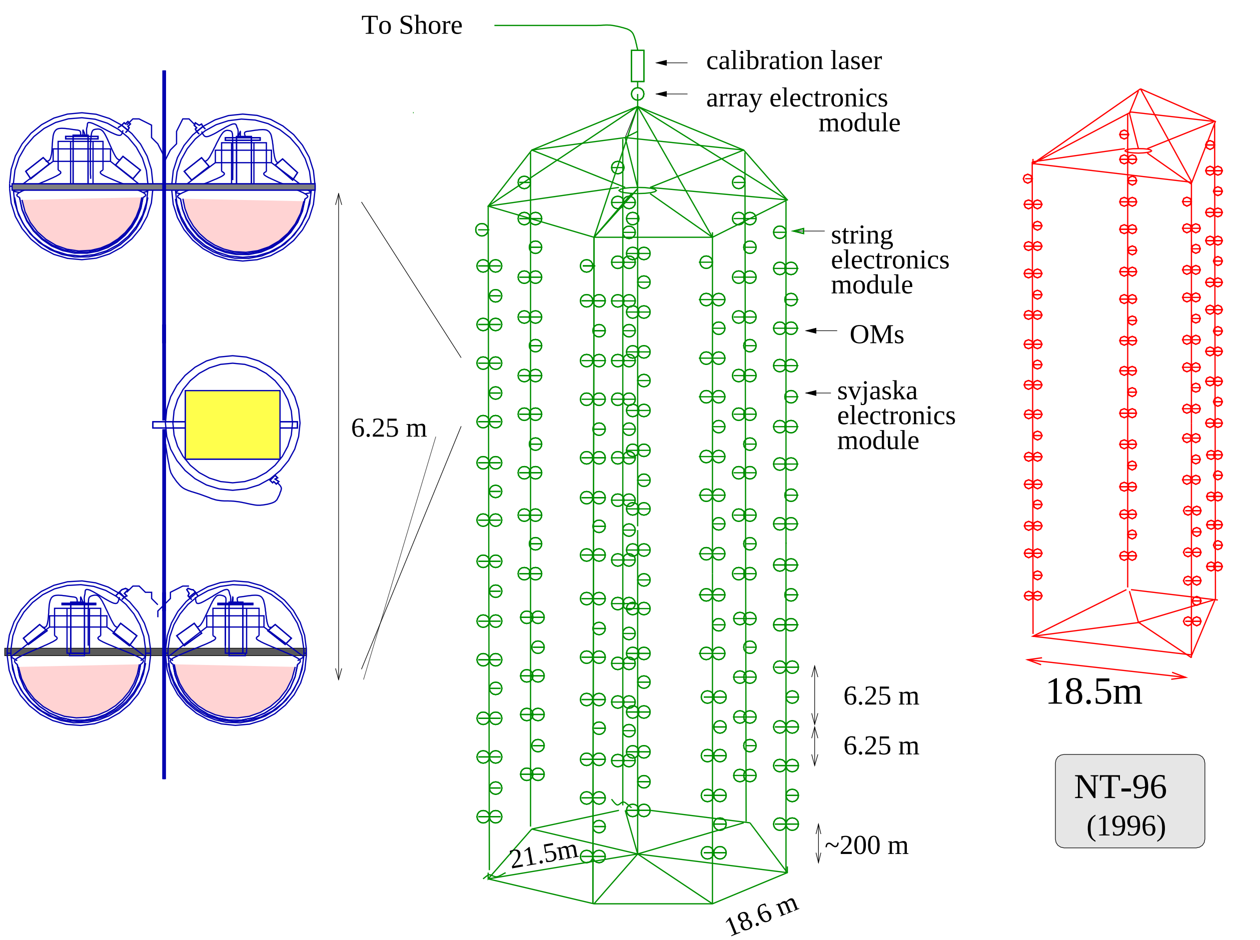
- due to its **properties** (water quality, depth, temperature, . . .);
- due to the existing **infrastructure**;
- since the world **expertise** for sea water νT's is concentrated in the European countries;
- since it is a perfect stage for a large **European science project**.

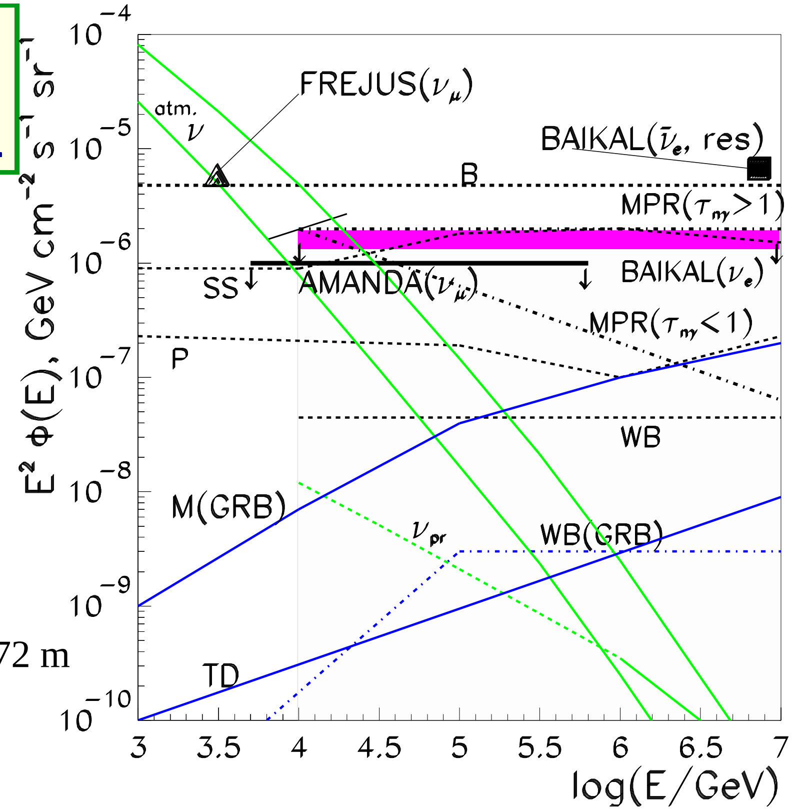
Common European effort needed to realize a future km^3 ν telescope in the Mediterranean Sea.

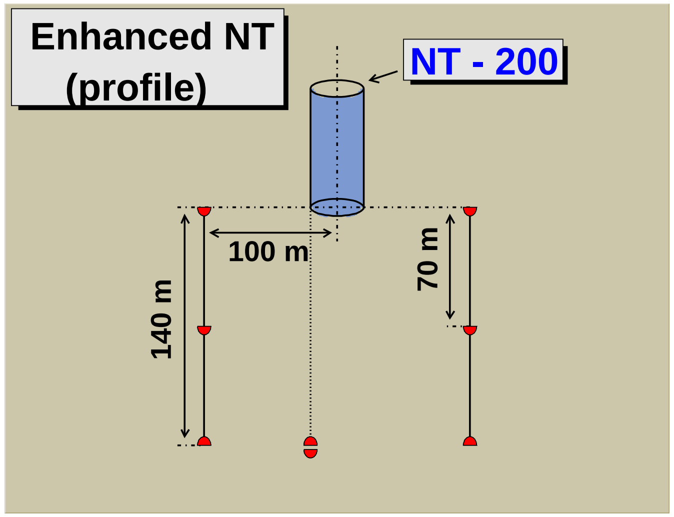
The Neutrino Telescope in Lake Baikal

- Pioneers in under-water technology for ν telescopes.
- Atmospheric ν's observed, limits on diffuse ν fluxes.
- Further extension planned, but km^3 hardly reachable.

The BAIKAL NT-200 Neutrino Telescope

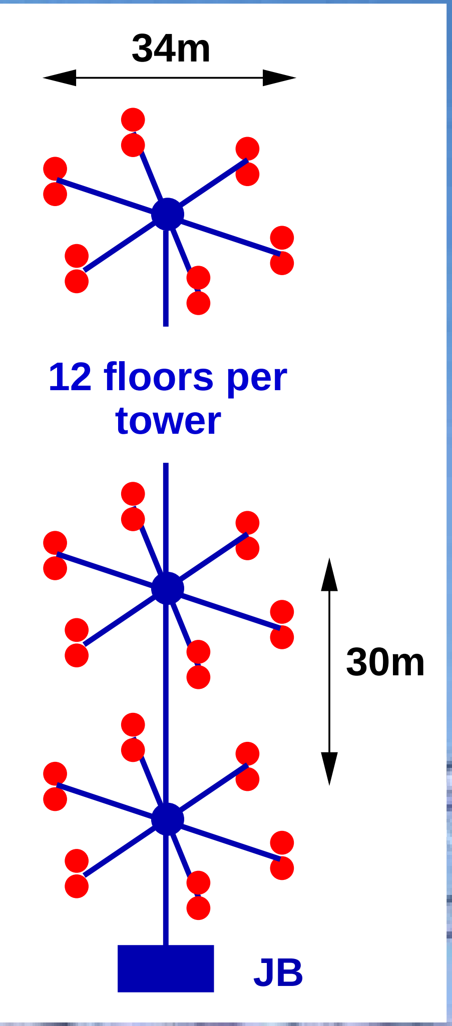






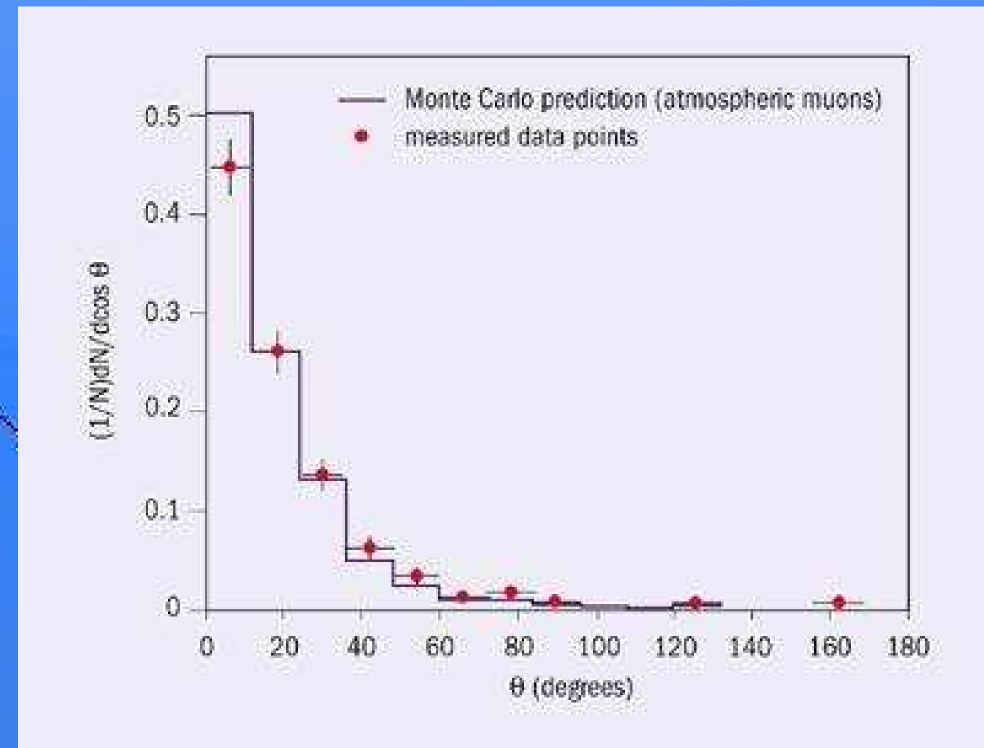
NESTOR

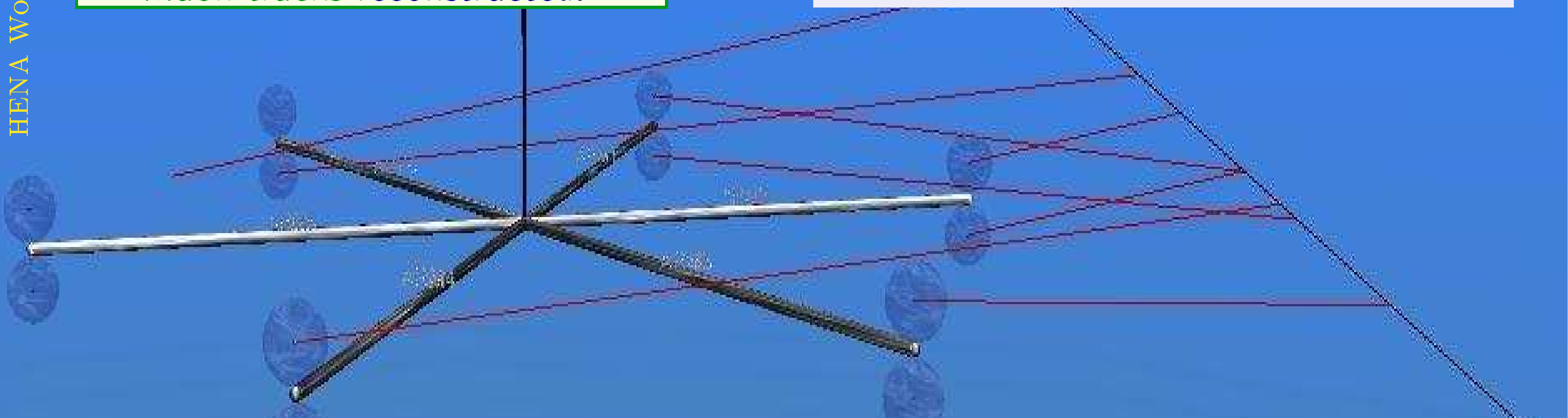
- **Tower-based** detector (titanium structures).
- **Dry connections** (recover – connect – deploy).
- **Up- and downward looking PMs.**
- **4000 meters** deep (5200 m available at Pylos site).
- Instrumented volume: $\sim 0.0003\,\text{km}^3$ **per tower**.



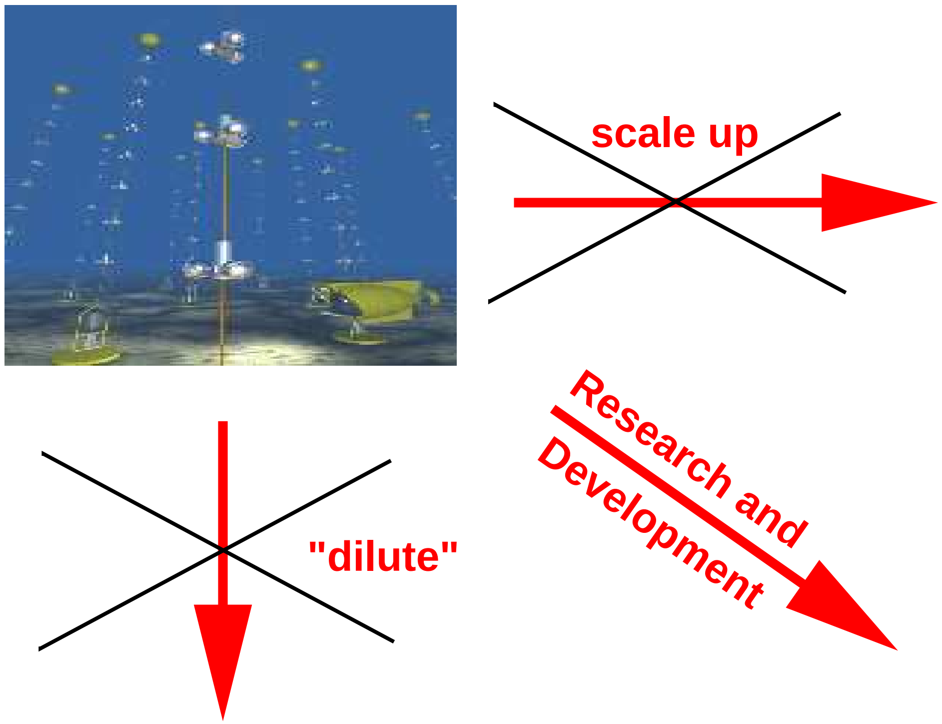
First Data from NESTOR Prototype Floor

- January 2002:
  Deployment of LAERTIS
  at 4200 meters depth,
  successful taking
  of environmental data.
- March 2003:
  Deployment of first
  prototye floor (reduced size).
- PM signals read out,
  wave forms available,
  5 million event triggers taken,
  background rates as expected.
- Muon tracks reconstructed.





How to Increase ν Telescopes to a km^3?



Existing νT'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, ...

km3 volume with ~same number of PMs as in existing νT's ?

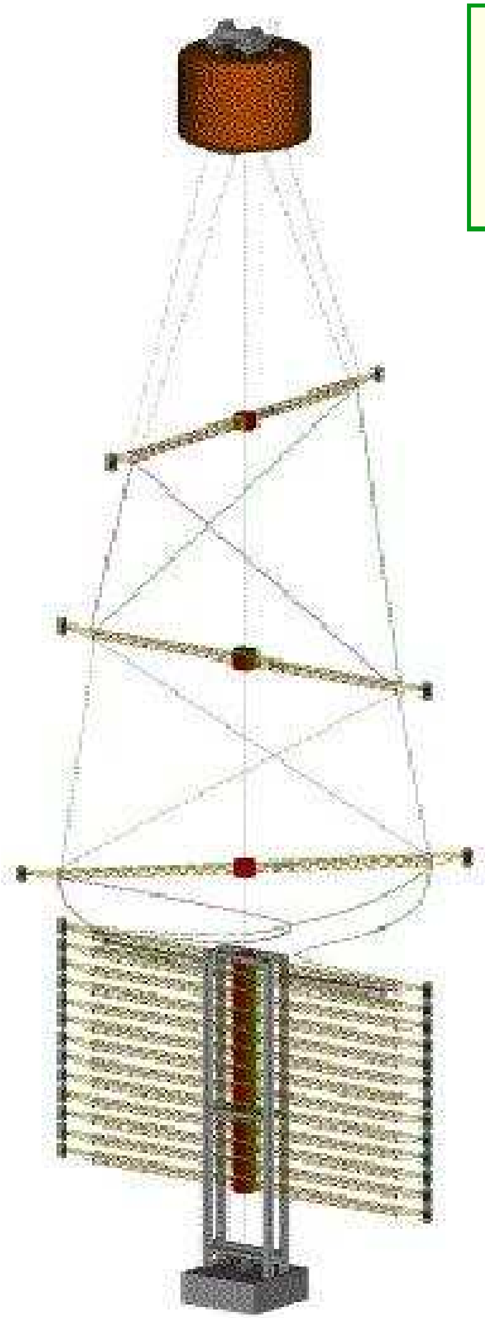
- **PM distance:**
  determined by light attenuation in water (+PM properties).
- **Efficiency loss:**
  Effective volume $\ll 1\,\text{km}^3$ except maybe at highest E_ν.

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.
- **. . .**

The NEMO project

- Extensive site exploration (Capo Passero, depth 3340 m).
- R&D towards km^3: architecture, mechanical structures, readout, electronics, cables, . . .
- Measurements at Catania test site planned (depth 2000 m).



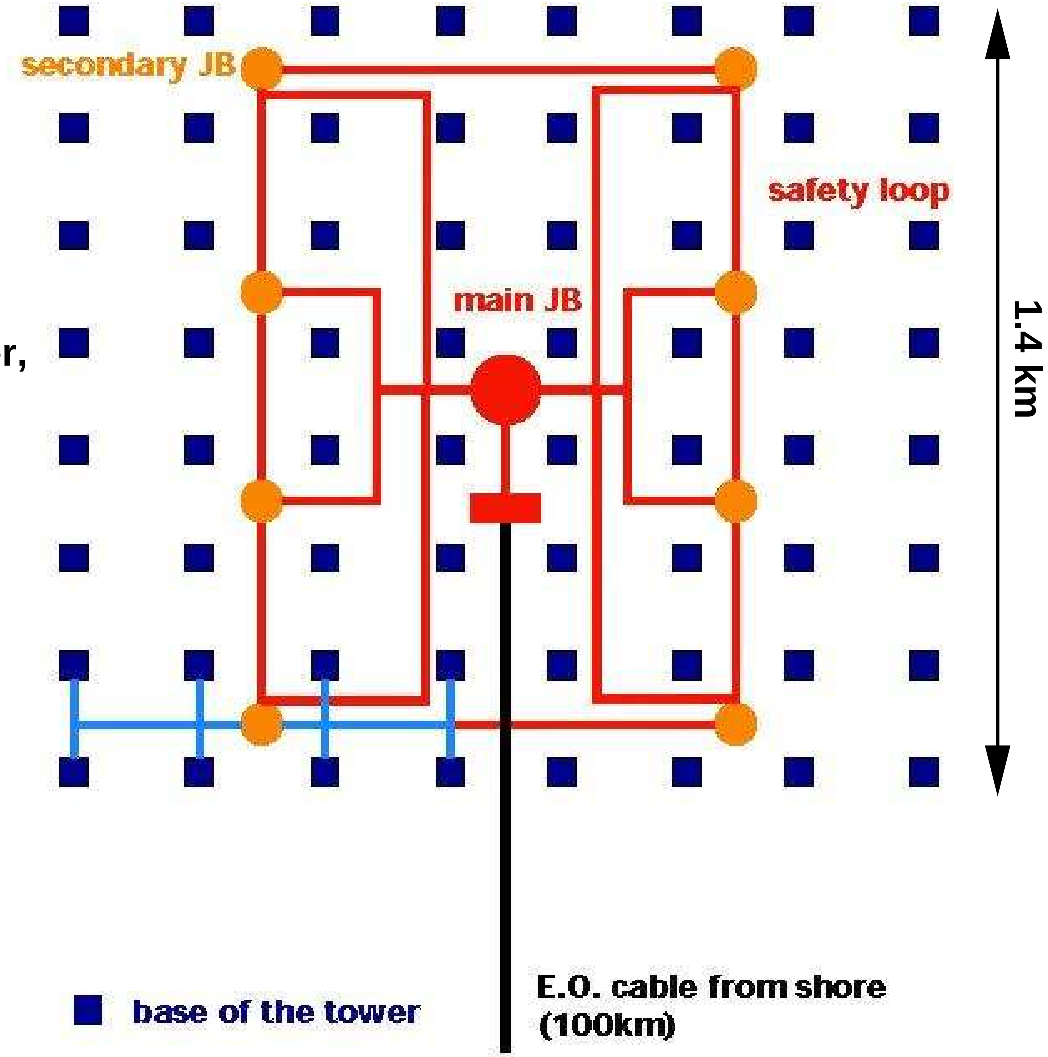
64 towers,
16 arms each,
20m arm length,
arms 40m apart.

64 PMs per tower,
4096 altogether.

Underwater
connections.

Up– and down–
looking PMs.

Instrumented
volume:
1.2 km^3



A Common European Effort

End of 2002:

ANTARES, NEMO and NESTOR decided to cooperate in preparing a future km^3 νT in the Mediterranean Sea

KM3NeT Design Study:

- Instrument of the EU FP6 programme to fund preparatory work and feasibilty studies for research infrastructure.
- Proposal in preparation, application by 4. March 2004.

success → **proceed, TDR in 2007**

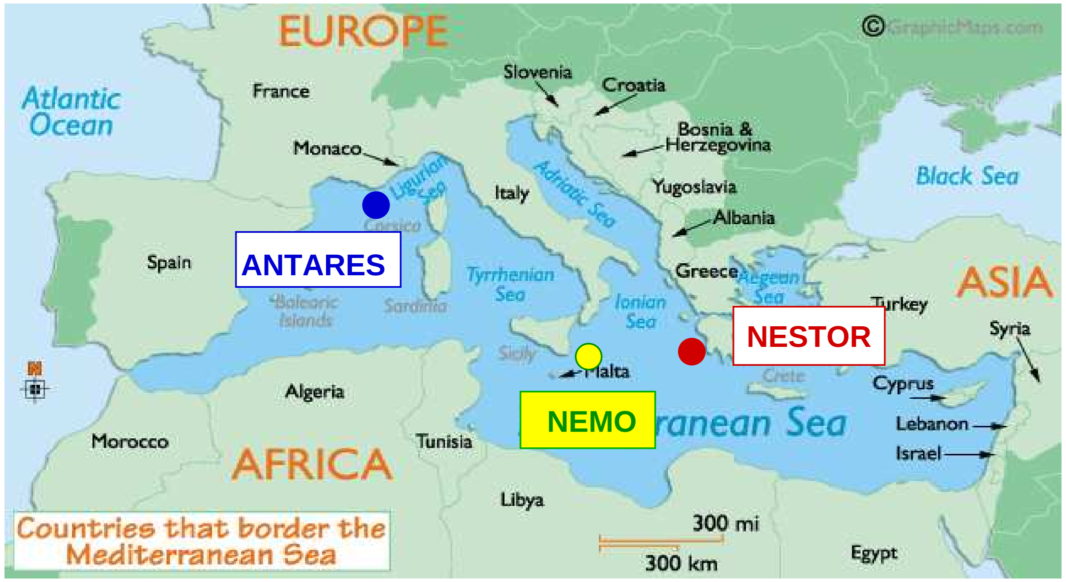
rejected → **proceed with national funding ?!**

Work Packages:

- Design Study Management
- Scientific assessment
  simulation, design optimization, . . .
- Cooperation with industry
  to develop commercial products
- Information technology
  read-out, data transport, on-line processing
- Infrastructure & support
  site, deployment & recovery, shore station, maintenance
- Quality assurance
- Resource exploration
  funding, legal aspects, management
- Associated sciences
  interfaces for usage by biologists, oceanographers, geologists, environmental scientists, . . .

Site Characterization and Selection

3 suitable sites explored in detail:



Measurements and assessments:

- Optical properties of water (absorption, scattering);
- Current velocity and direction;
- Bathymetric surveys;
- Bioluminescent activity;
- Biofouling;
- Sedimentation;
- Geological stability;
- ...

Site selection:

- **Delicate decision**
  Strong national interests and political arguments involved.
- **Major scientific criteria:**
  → water quality;
  → depth;
  → geological environment;
  → distance to shore;
  → infrastructure.
- **Decision path:**
  - Further input provided by running of prototypes.
  - Arguments reviewed by ApPEC.
  - Not clear who decides ...
- **Meanwhile:**
  continue to organize common effort and start up activities.

The Architecture

Some questions:

- **Strings or rigid towers or flexible towers or ...?**
  Determines mechanical stability, significant impact on overall cost, ...
- **Wet or dry connections?**
  Cost and long-term availability of deep-sea submarines?
  Effort for underwater connections depends on detector depth.
- **Distance of photo sensors?**
  Depends on water transparency and on active area and efficiency of photo sensors.
  Note: Factor 2 in average distance gives factor 8 in detector size with same number of sensors.
- **Homogeneous detector or dense core?**
  E_ν dependence of effective volume.

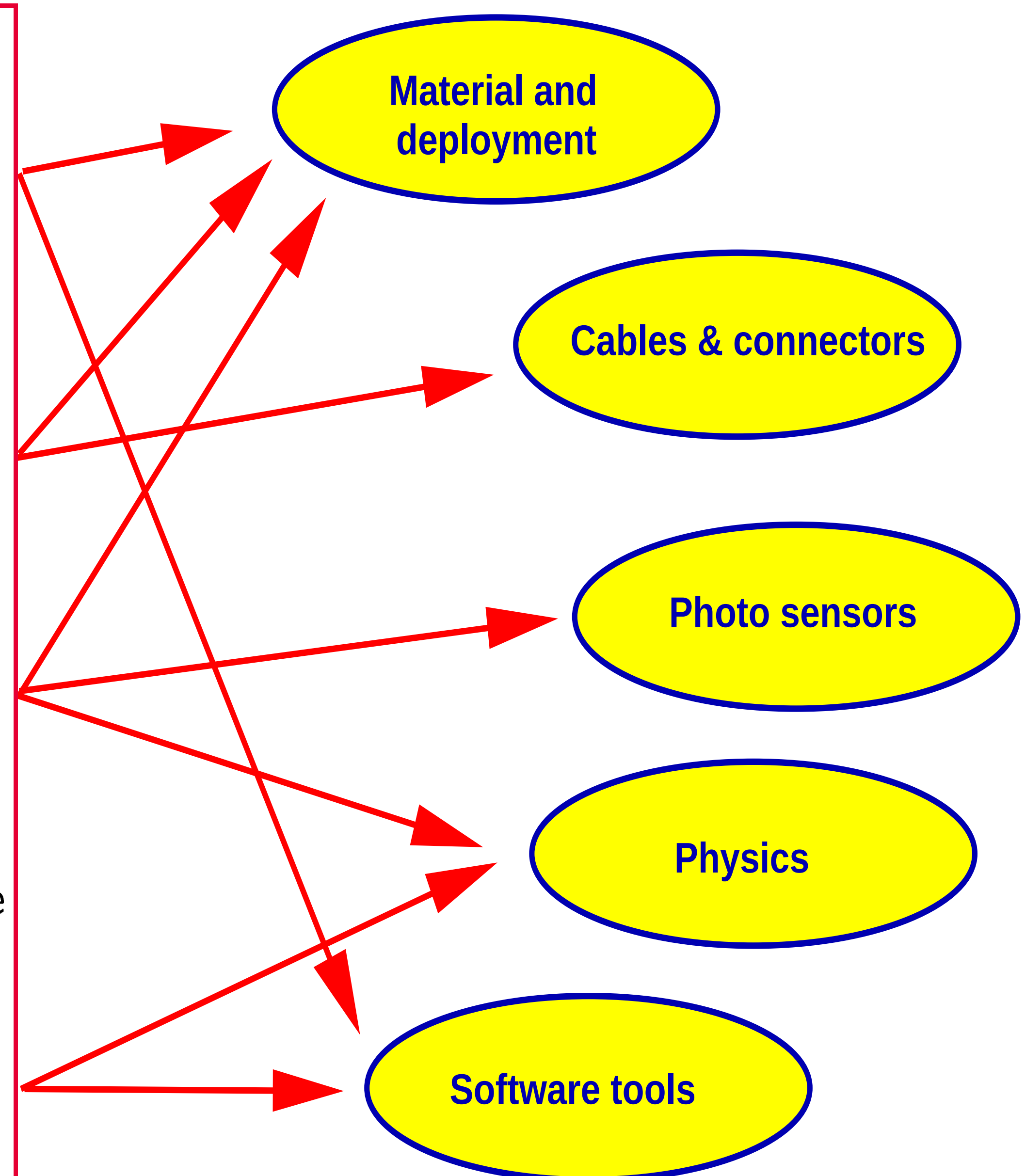


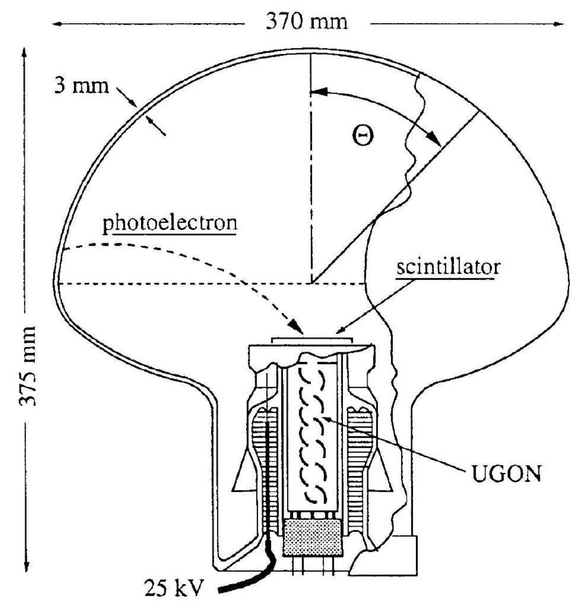
Photo Sensors

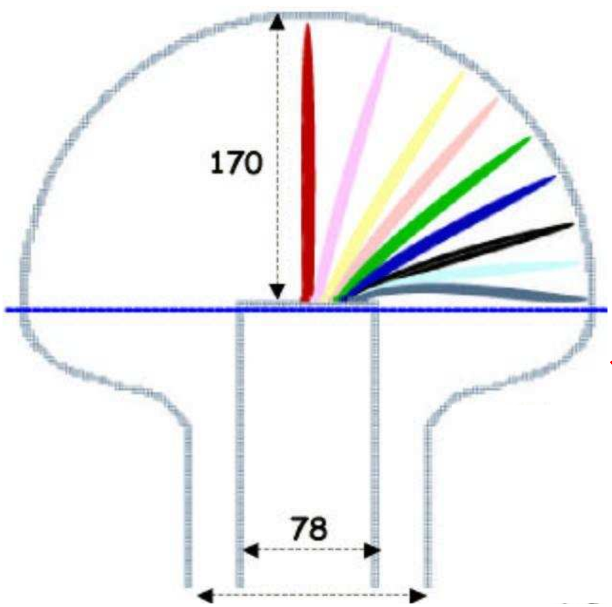
Development goals:

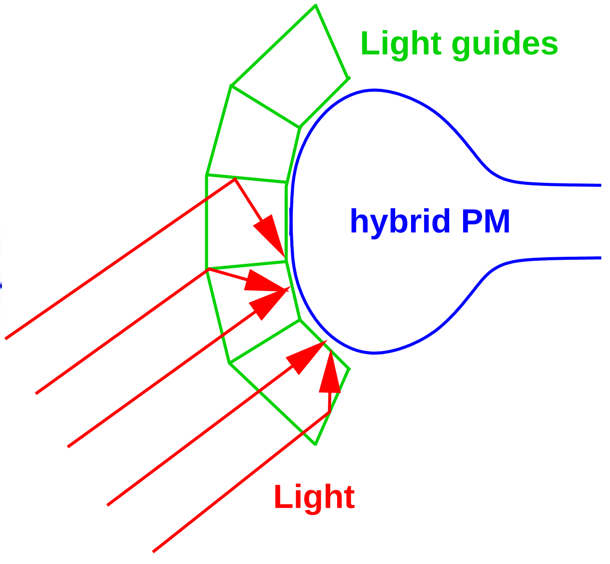
- Increase area and efficiency.
- Retain or improve time resolution.
- Obtain directional sensitivity.
- Reduce costs.
- Ensure long-term stability in deep-sea environment.

Approaches:

- Hybrid photomultipliers (see below).
- Hybrid photo diodes (HPDs).
- Avalanche photo diodes (APDs).
- Photocathode improvements (spectral quantum efficiency).
- Gas electron multiplication (GEM) ?







The Baikal HPM:

Hybrid PM + scintillator photo sensor.
Large sensitive area with low-diameter PMs.

Developments at INFN Genova:

- Optimize geometry:
  - transfer-time spread improved to $\mathcal{O}(1\,\mathrm{ns})$;
  - correlation of γ and e impact positions.
- Use light guides to determine light direction.

Readout and Data Acquisition

Problems:

- **Enormous data stream to shore:**
  ANTARES $\times$ 100: $\mathcal{O}$(750 GByte/s).

- **Large Power consumption**
  of the off-shore electronic components poses problems to power distribution and to cooling.
  (ANTARES power $\times$ 100: $\mathcal{O}$(3 MWatt))

- **Operation stability:**
  Is rate of failures that stop the system proportional to the number of components?
  Is system operatable?

- **Maintenance:**
  How many deep-sea operations per year are needed to keep 90%, 80%, ... of the functionality?

Ideas:

- **Fast optical data transmission:**
  Profit from developments in industry.
  DWDM technology:
  one color per photo sensor?

- **Realize readout with passive/optical elements:**
  – reduces power consumption;
  – avoids failures;
  – "maintenance-free".

- **Trigger and filter on shore:**
  May be installed later to use latest technology.
  Allows for modifications to match the needs of data taking.

Material Considerations

Material must . . .

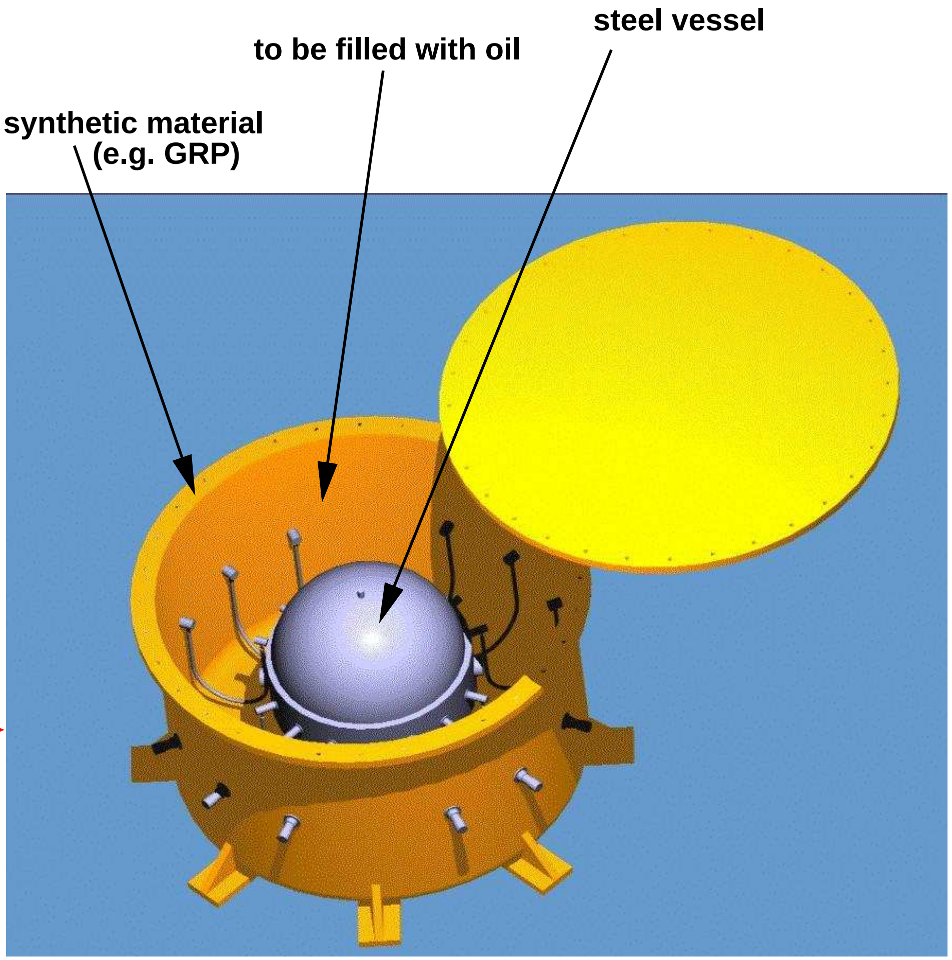
- **withstand high pressure**
  – steel;
  – titanium.
- **withstand corrosion**
  – titanium;
  – certain synthetics;
  – GRP (glass reinforced plastic).

Current installations almost exclusively use titanium (material and machining expensive).

Solutions:

- **Composite structures**
  Use separate material layers:
  outer layer against corrosion,
  inner layer against pressure.
  E.g. NEMO JB design.
- **Mechanical structures**
  (struttings, towers, etc.):
  Use of GRP seems possible.

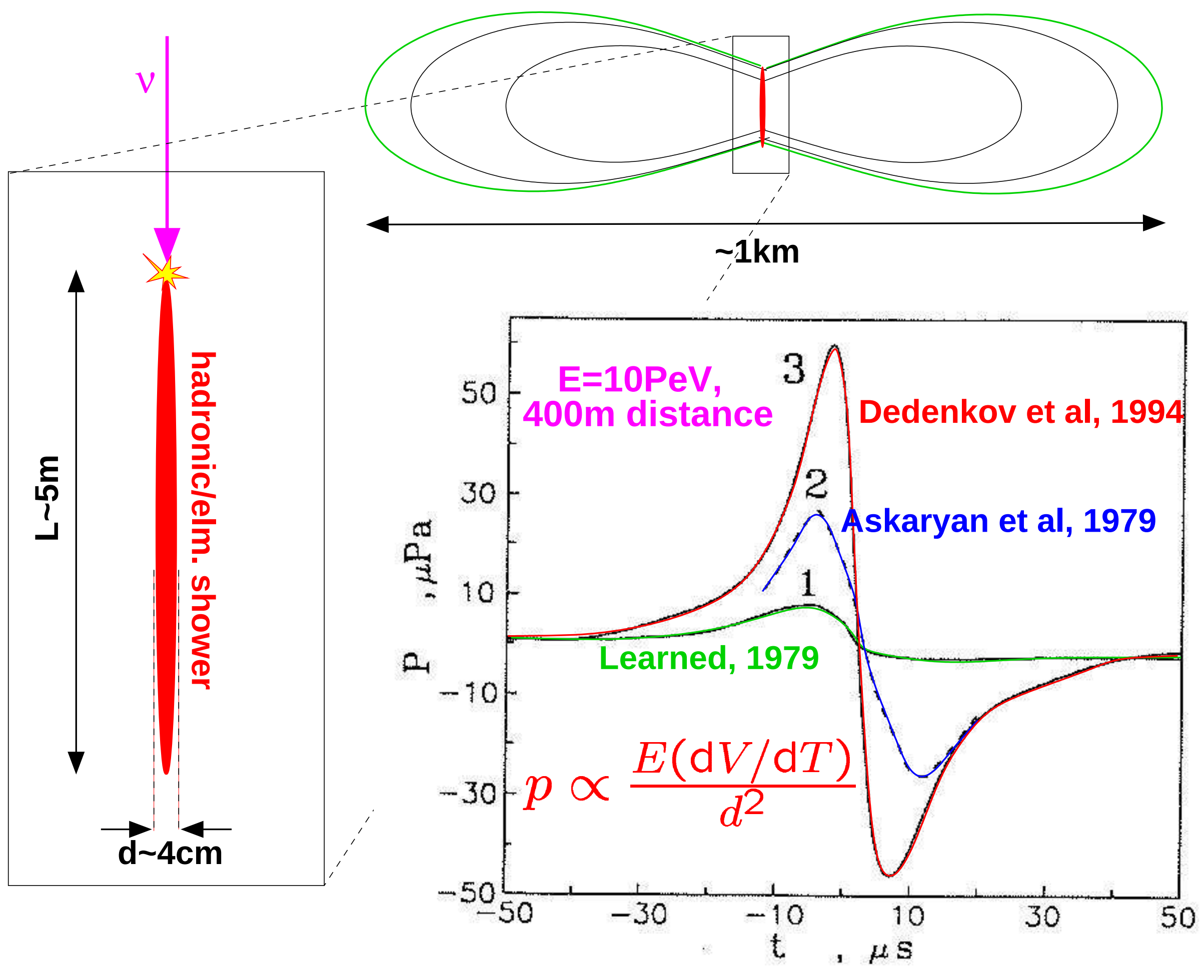
NEMO design for a composite−structure Junction Box:



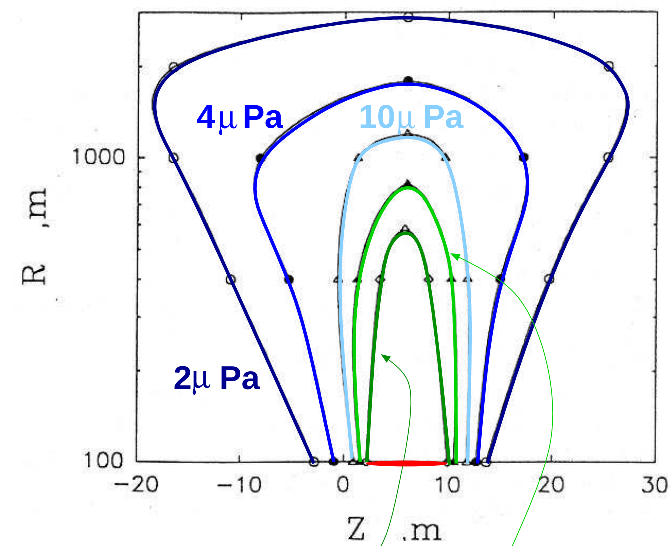
Summary: KM3NeT

- Strong physics motivation for km^3-scale neutrino telescope in Northern hemisphere
- Mediterranean offers optimal conditions
- Large amount of R&D required (current detectors not scalable)
- Common European effort initiated to obtain funding for prepatory phase
- Time scale set by IceCube project and "community life time" – go for it either now or never!

Acoustic detection: Can you hear neutrinos?



Shower with 10 PeV:



Temperature increase:

$$\Delta T = \frac{E}{c_{\mathrm{H_2O}} M_{\mathrm{H_2O}}} \approx 60\,\mathrm{nK}$$

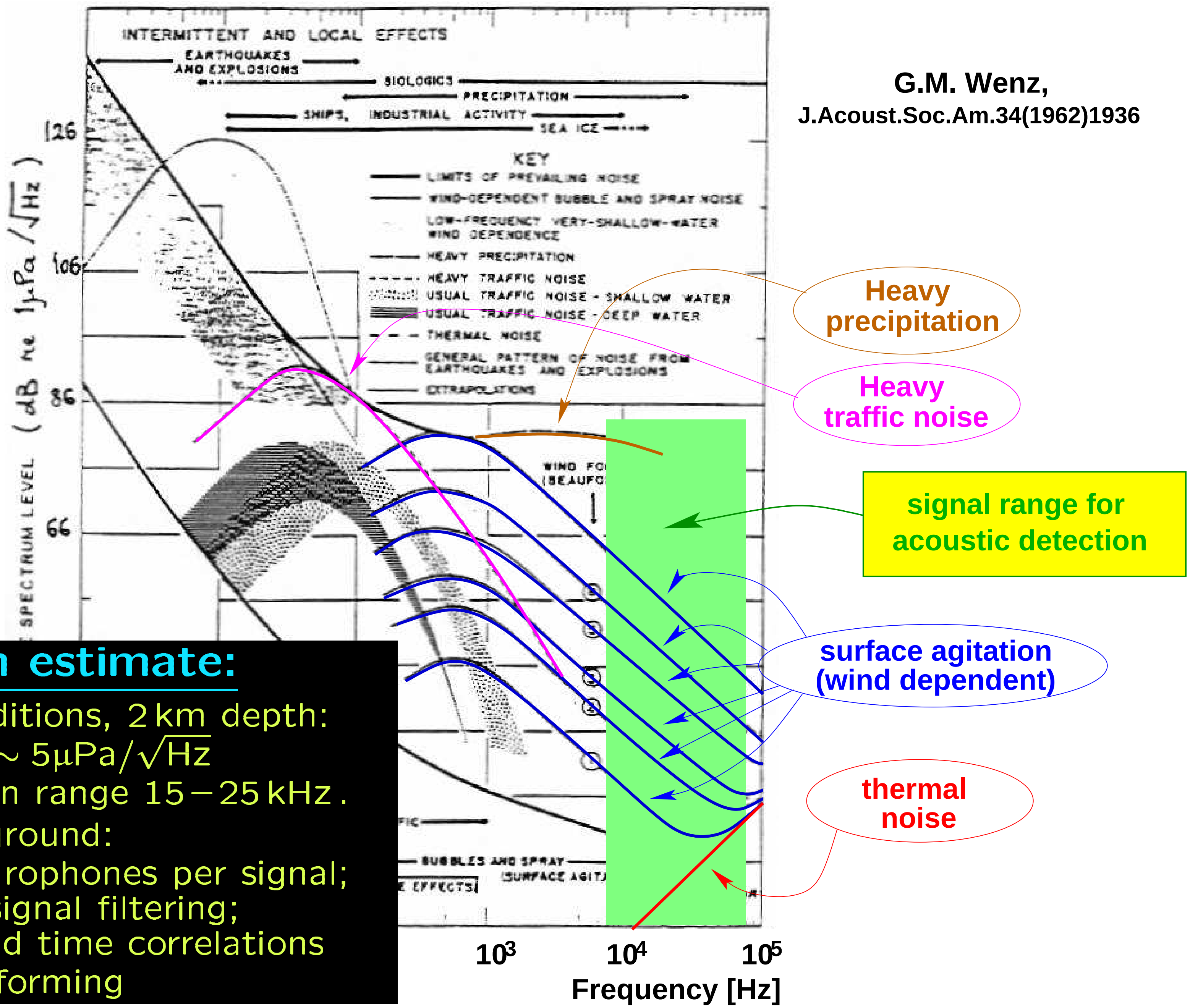
$$T_{\mathrm{Mediterranean}} \approx 14°\mathrm{C} > 4°\mathrm{C}$$
$$\Rightarrow \mathrm{d}V/\mathrm{d}T > 0$$

Motivation:

- Large range of sound in water → large-volume detectors.
- Detection of the hadronic/elm. shower → 4π acceptance.
- Sensitivity to all neutrino flavors.
- Complementary to radio Čerenkov method in ice (RICE experiment @ AMANDA).

Background conditions

G.M. Wenz,
J.Acoust.Soc.Am.34(1962)1936



Rough estimate:

- Optimal conditions, 2 km depth:
  Background $\sim 5\mu\text{Pa}/\sqrt{\text{Hz}}$
  $\Rightarrow \sim 500\mu\text{Pa}$ in range 15−25 kHz.
- Signal$\lesssim$background:
  - many hydrophones per signal;
  - efficient signal filtering;
  - spatial and time correlations
    → beam forming

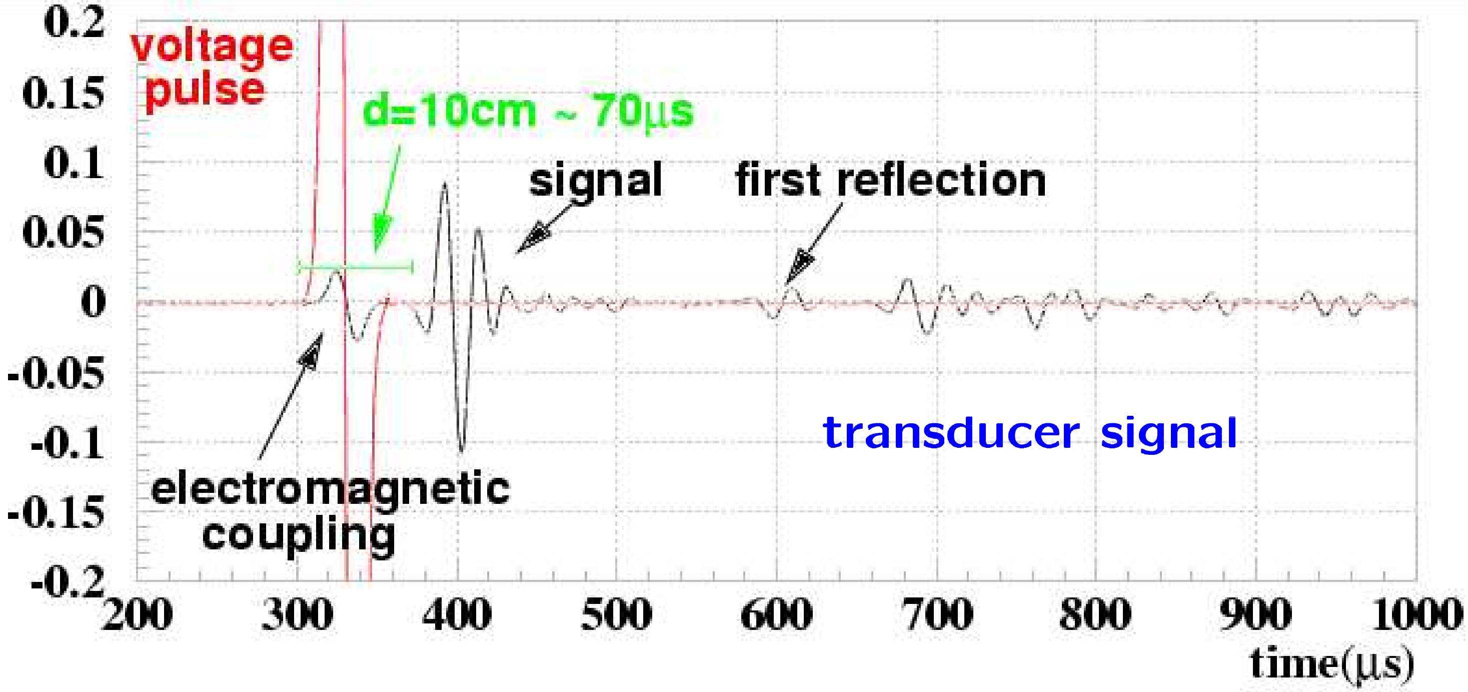
Acoustic R&D in Erlangen

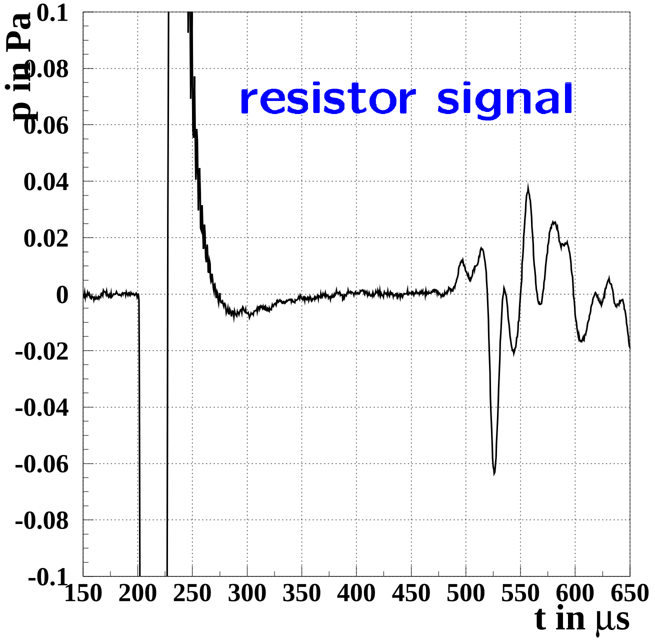
Activities:

(some in close collaboration with AMANDA/IceCube group at DESY-Zeuthen)

- Generation/acqusition of acoustic signals
- Characterization of commercial hydrophones (Piezo-based)
- Development of calibration sources
- Development of specialized hydrophones
- Development of simulation software
- Development of signal filters and triggers
- Beam tests at Uppsala (Feb. 2004)
- Equipment of 2 ANTARES strings with hydrophones (late 2005)

Some "acoustic pictures"





Summary: acoustics

- **Acoustic detection may be a promising future method for investigation of cosmic neutrinos above ~ 10 PeV**
- **Several acoustic R&D projects in Erlangen, in concert with world-wide activities**
- **First encouraging results**
- **Decisive milestone:
  long-term mesasurements
  in ANTARES environment**