Towards a Cubic Kilometer Neutrino Telescope in the Mediterranean

High Energy Neutrino Astronomy
HENA
Workshop
Paris, 16/17 June 2003

Physics Motivation

ν Telescopes in Sea Water

Current Activities and Plans

km^3 Detector: Objectives and R&D

Conclusions

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Particle and Astrophysics with Neutrino Telescopes

Low-energy limit:

- short muon range;
- only few photo sensors give signal;
- ^{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

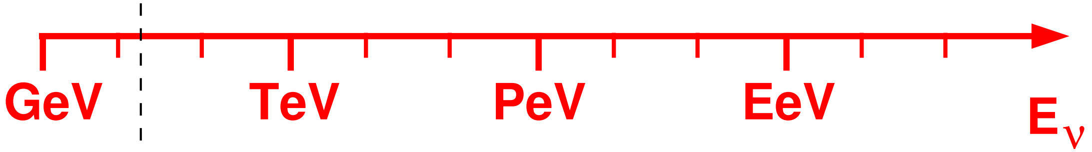
Cosmic point sources:
Direction, (Energy)

Diffuse cosmic neutrino flux:
(Direction), Energy

High-energy limit:

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

Required volume (at least) one cubic kilometer.



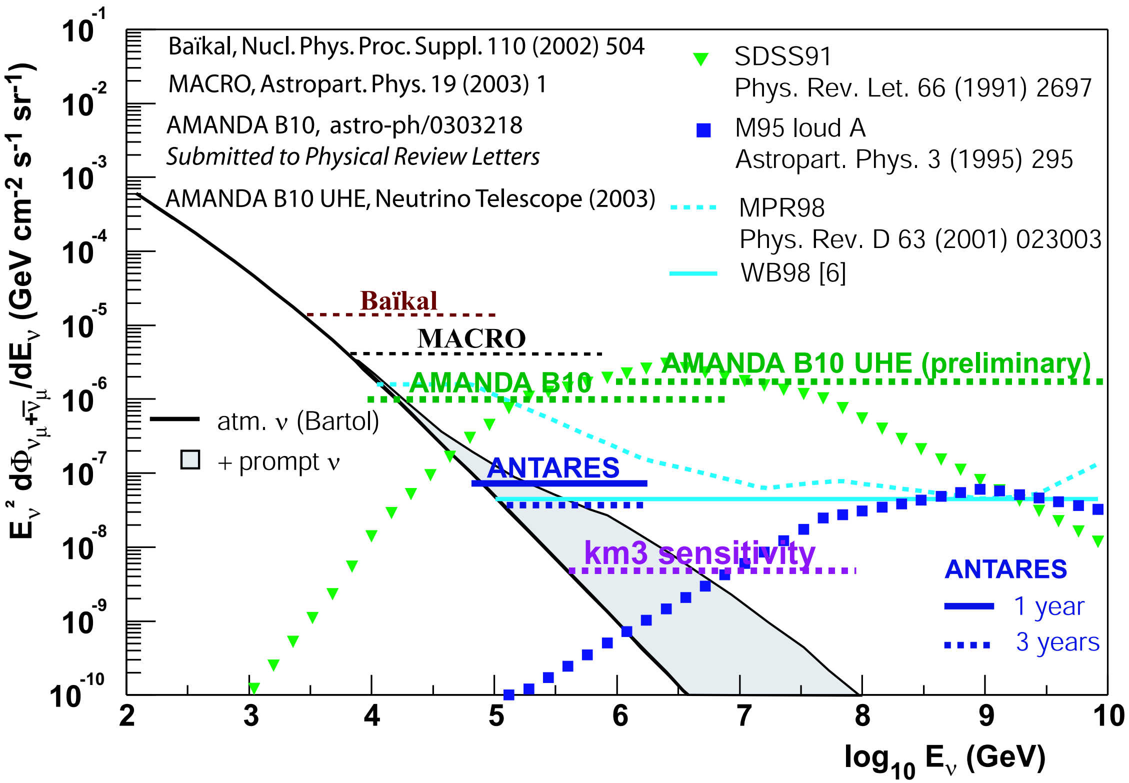
... and also:
GZK–neutrinos
Z bursts
magnetic monopoles
topological defects
top–down scenarios
supernova detection
...

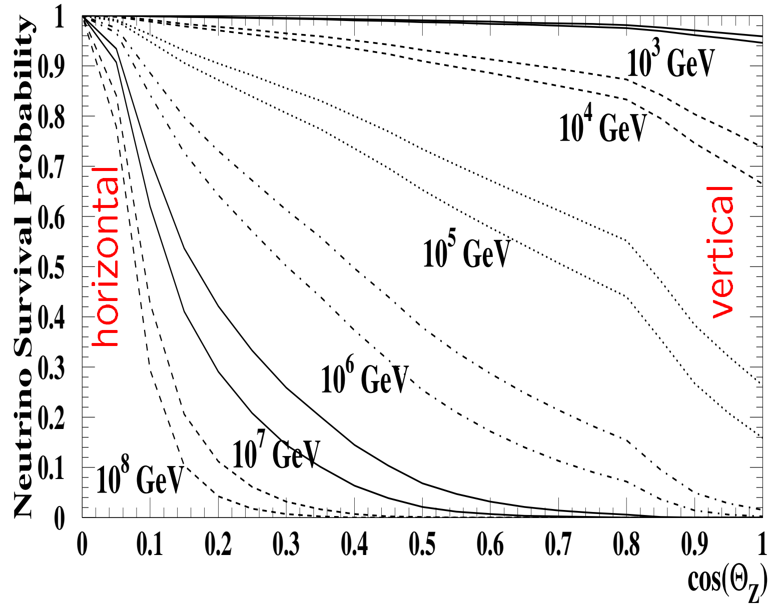
Neutrino Fluxes and Event Numbers

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





A Northern-Hemisphere km^3 ν Telescope

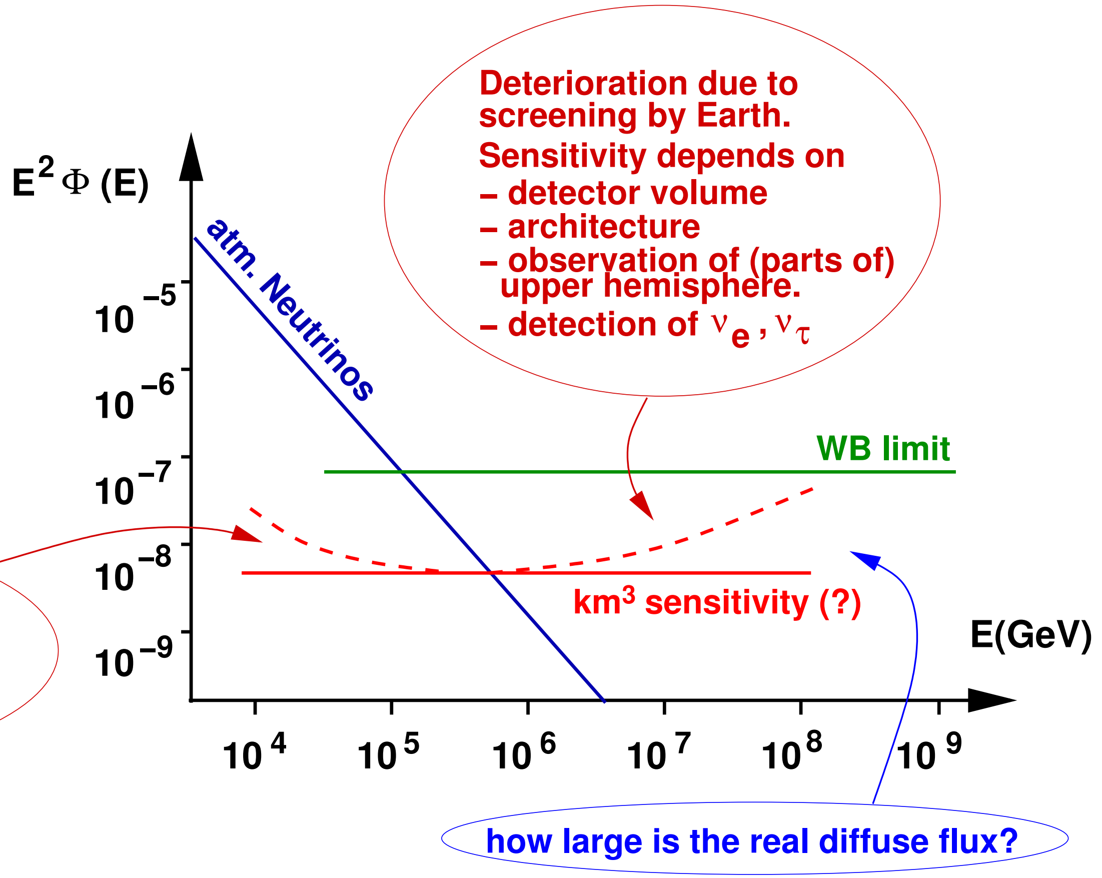
The physics case:

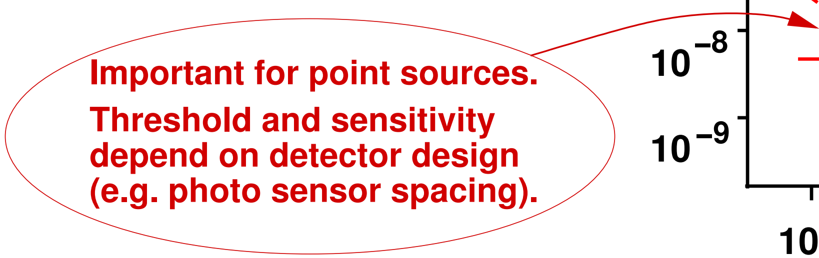
- Complement sky coverage of IceCube.
- Observe galactic center.
- Increased point source sensitivity.

The requirements:

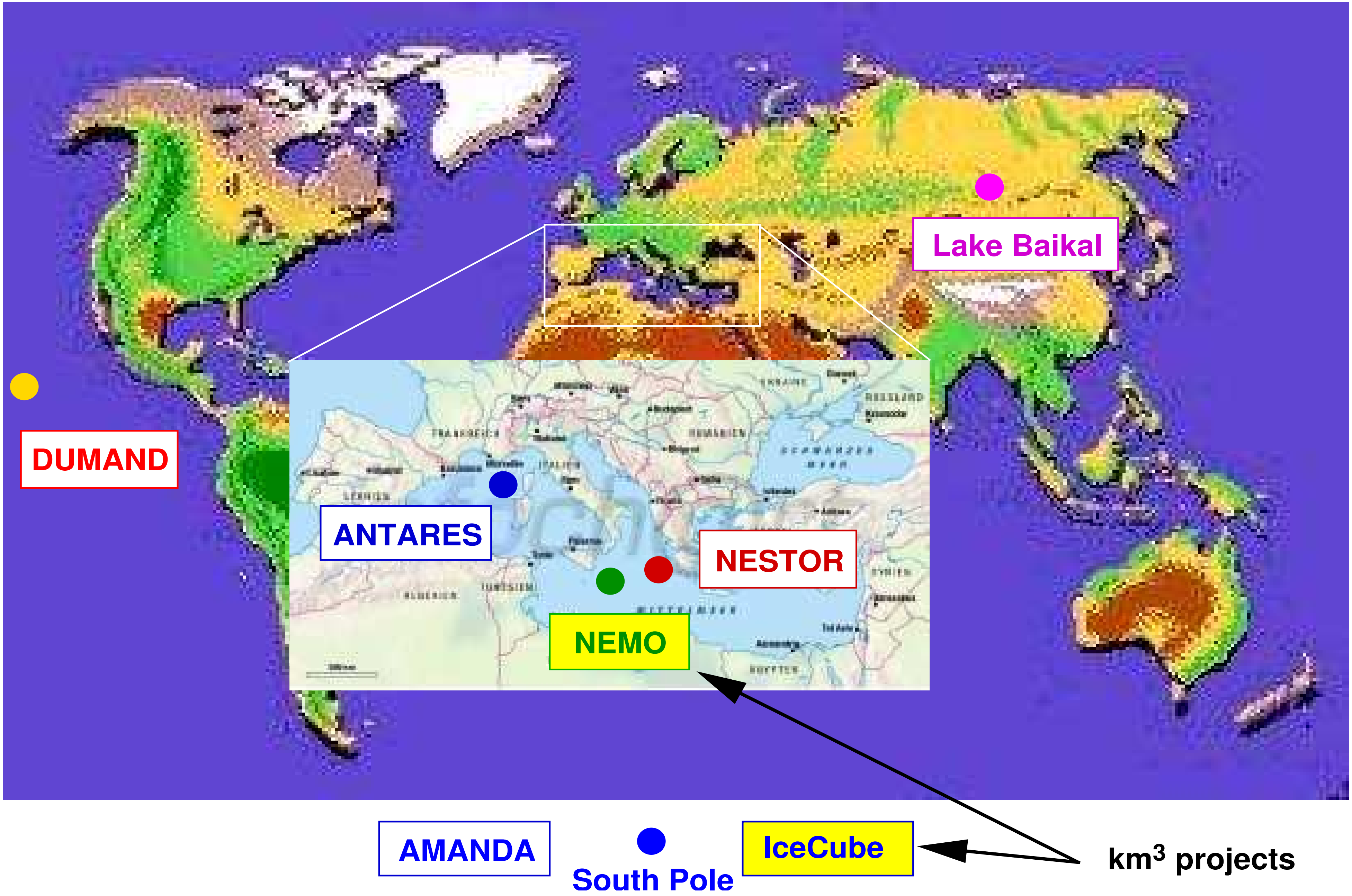
- Sufficient volume to measure cosmic neutrino fluxes: 1 km^3 or 10 km^3? Extendable!
- Sensitivity to ν_e, ν_τ and to ν from upper hemisphere.
- R&D and construction within 8–10 years.

Some links between physics requirements and design considerations:





The Neutrino Telescope World Map



Past, Presence and Future of ν Telescopes

Sweet water

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

Salt water

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

Ice

- AMANDA:
  data taking.
- IceCube:
  km^3 project, in preparation.
- – suitable ice only in Antarctica.

The Mediterranean Sea offers optimal conditions . . .

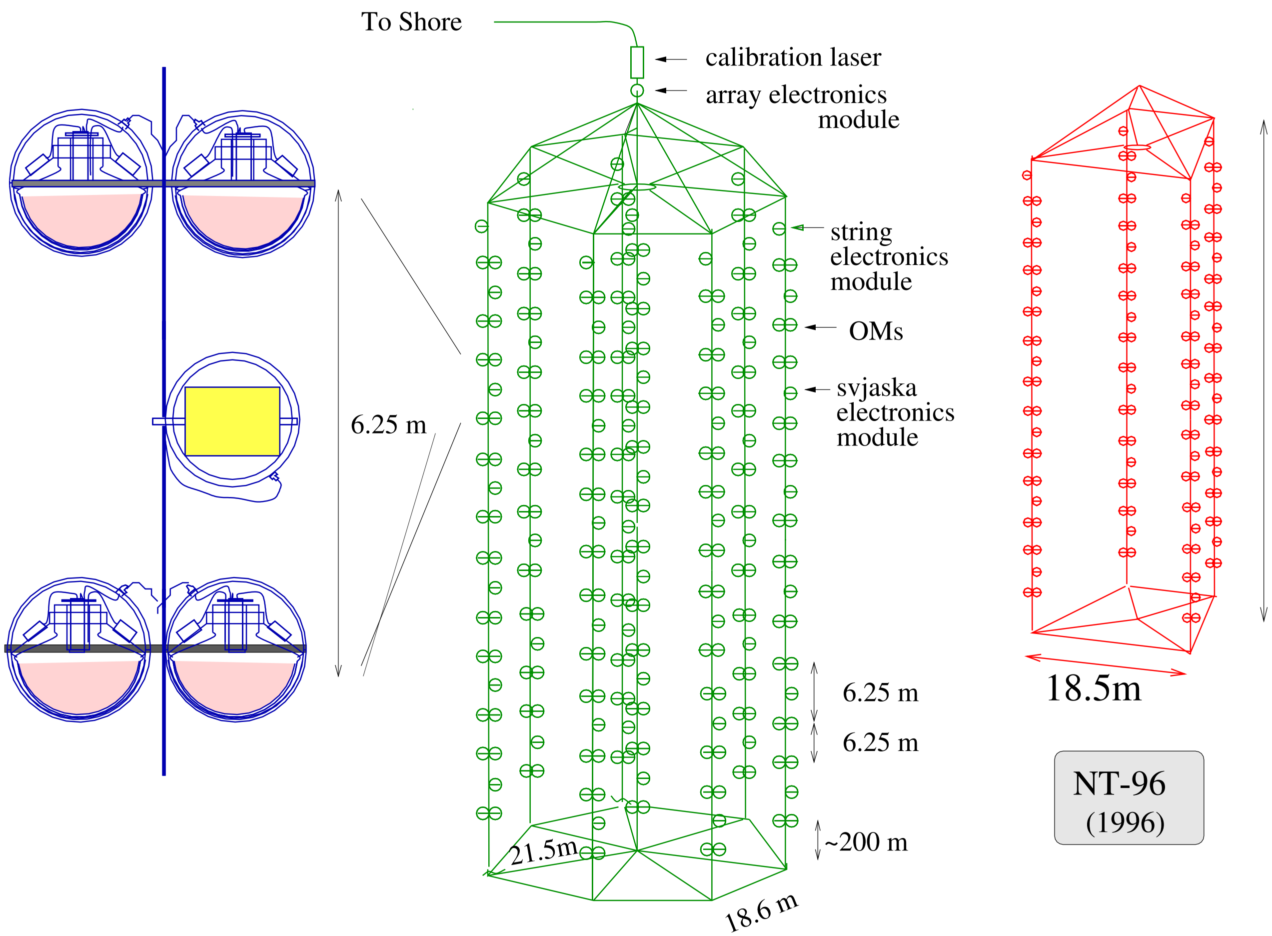
- due to its **properties** (water quality, depth, temperature, . . .);
- due to the existing **infrastructure**;
- since the world **expertise** for sea water νT's is concentrated in the European countries;
- since it is a perfect stage for a large **European science project**.

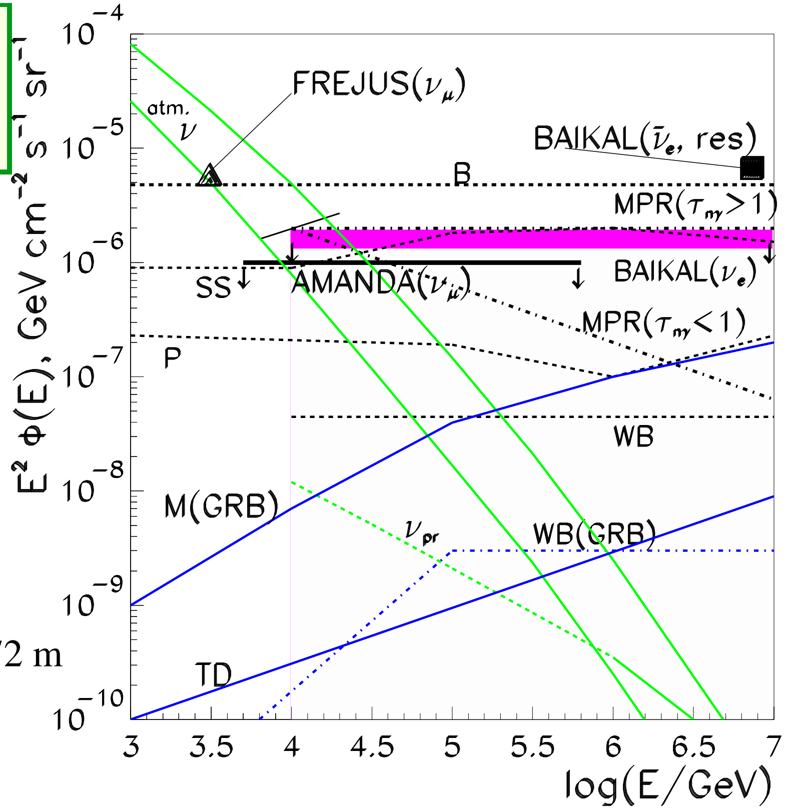
Common European effort needed to realize a future km^3 ν telescope in the Mediterranean Sea.

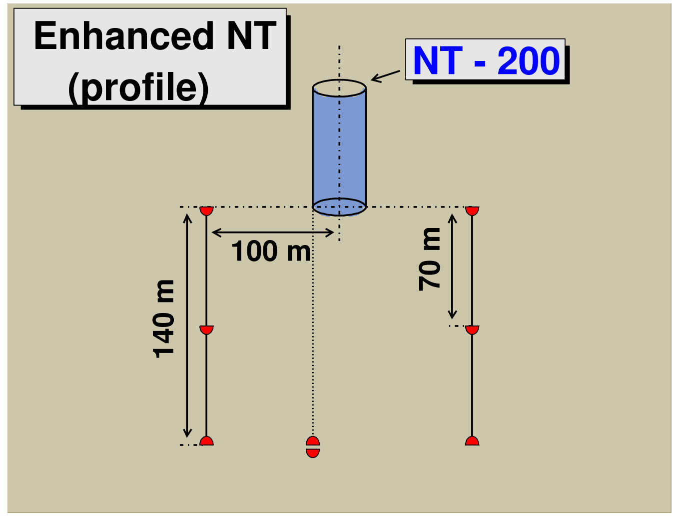
The Neutrino Telescope in Lake Baikal

- 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

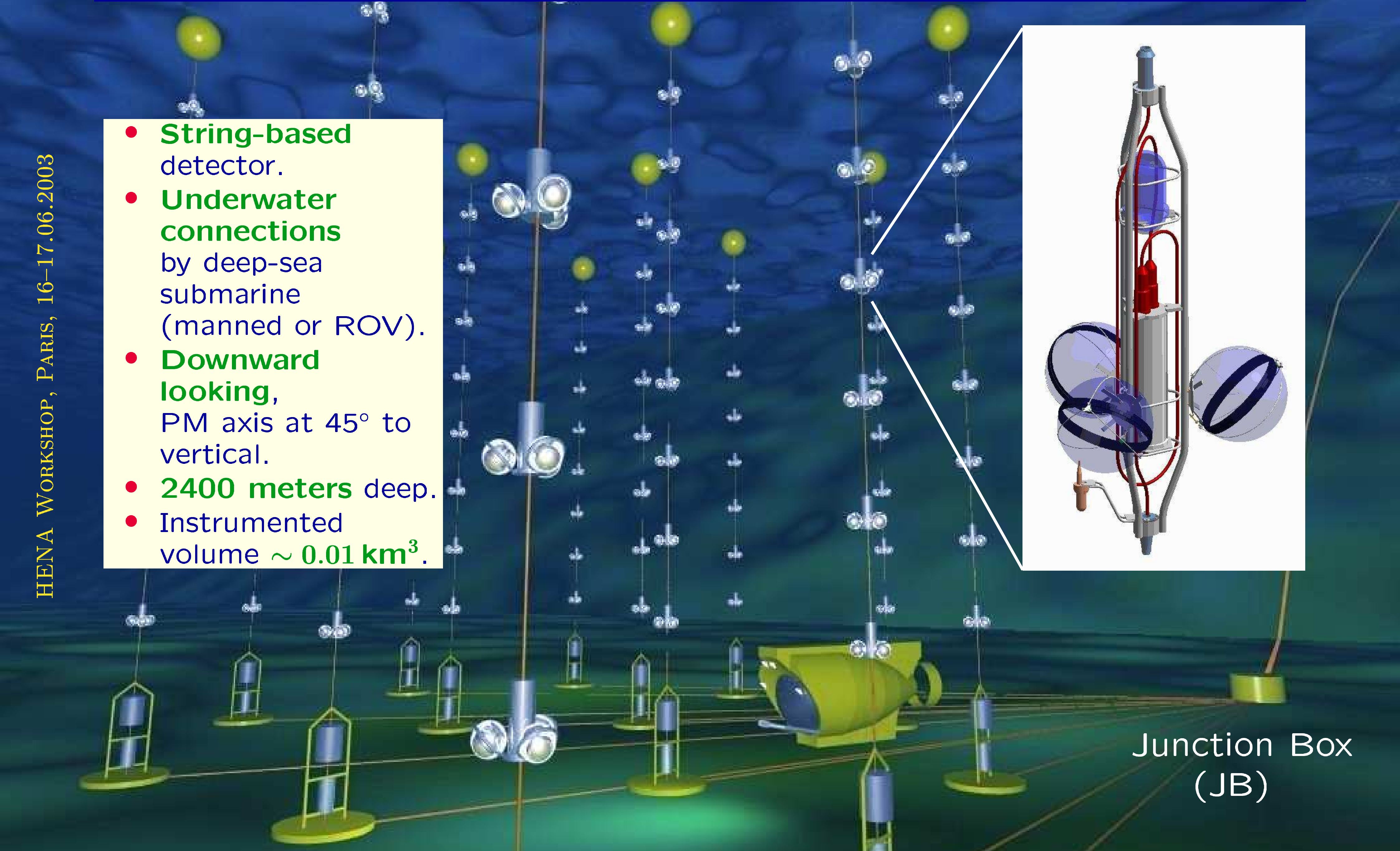






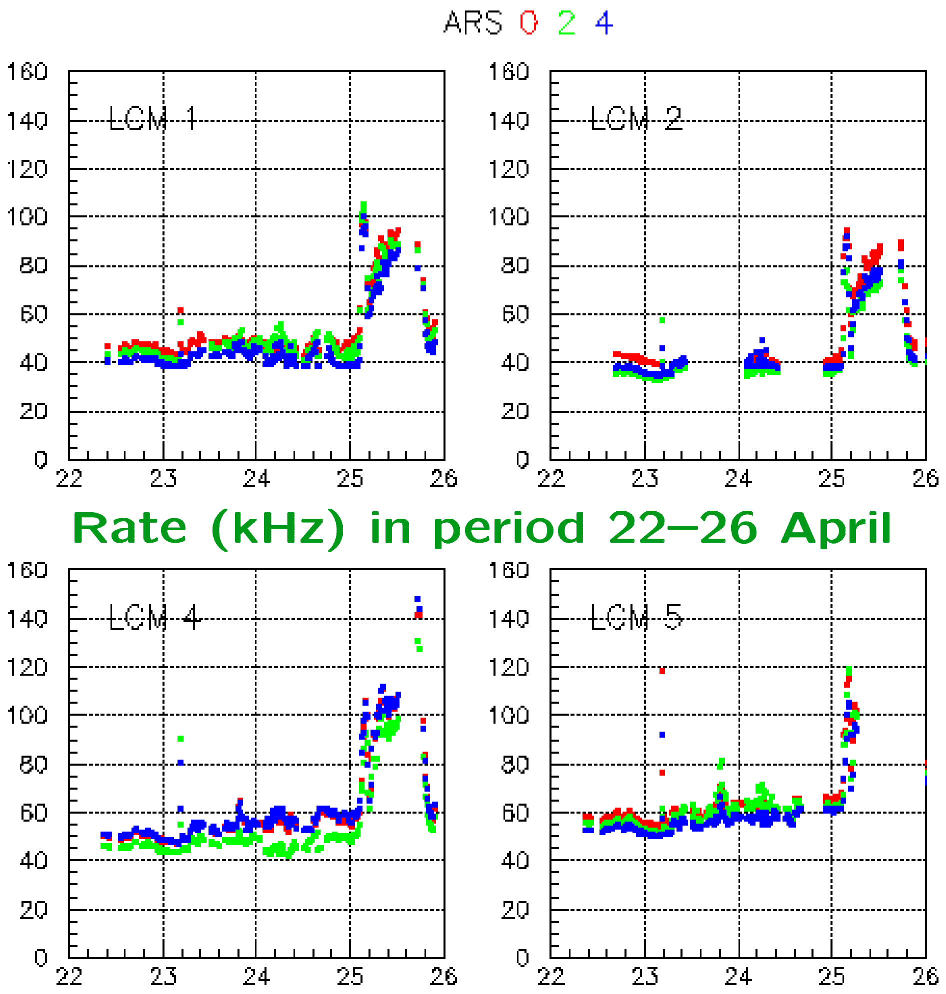
ANTARES

- **String-based** detector.
- **Underwater connections** by deep-sea submarine (manned or ROV).
- **Downward looking,** PM axis at 45° to vertical.
- **2400 meters** deep.
- Instrumented volume $\sim 0.01\,\mathbf{km}^3$.



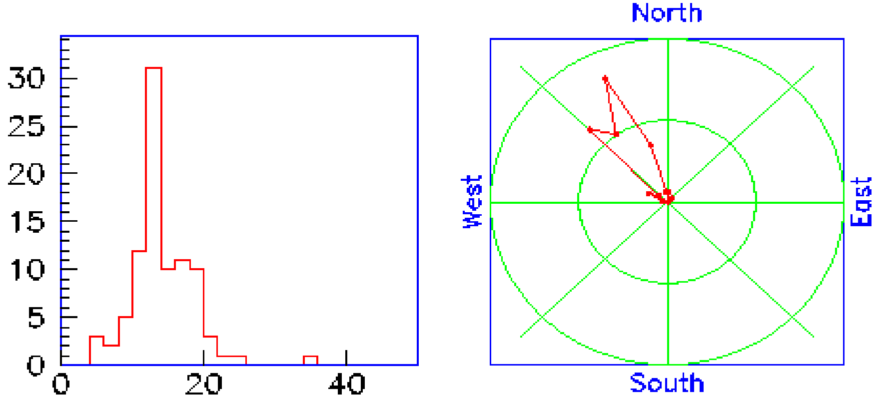
First Data from ANTARES Prototype Installation

- Prototype string PSL (5 storeys) and mini instrumentation line (MIL) deployed.
- Connected to JB on 16/17 March.
- PSL still taking data.
- MIL operational until 11 April.

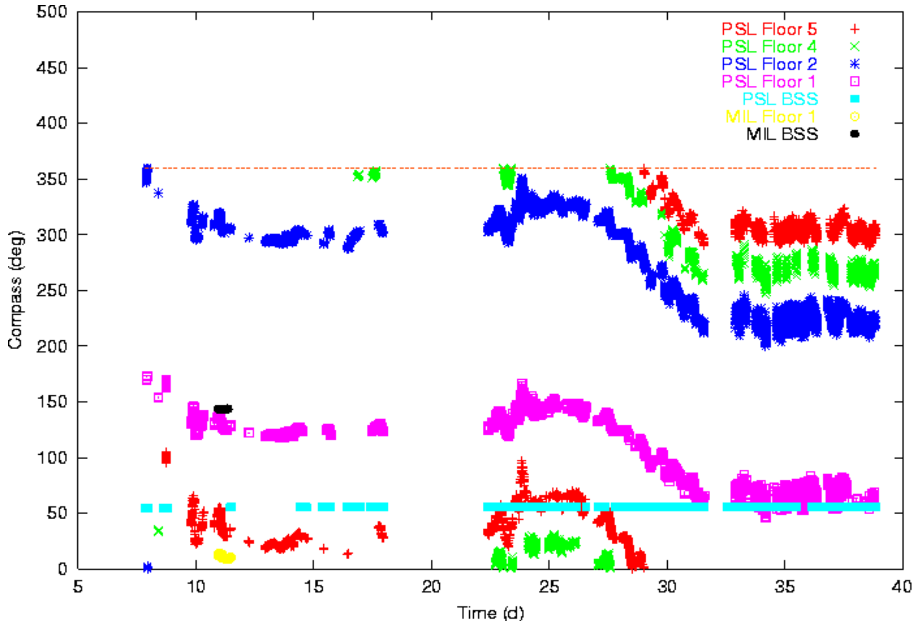


Rate (kHz) in period 22–26 April

Sea currents (mm/s) over 30 min:

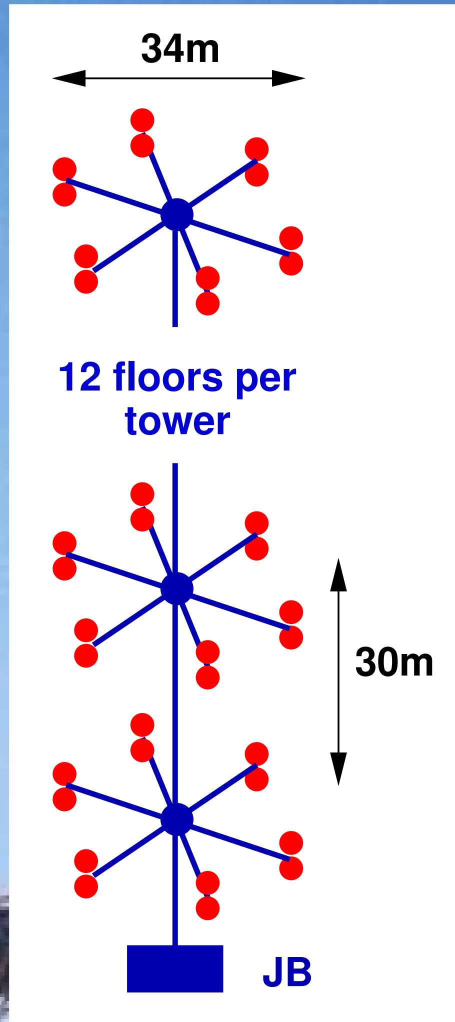


Compass headings over 30 days:



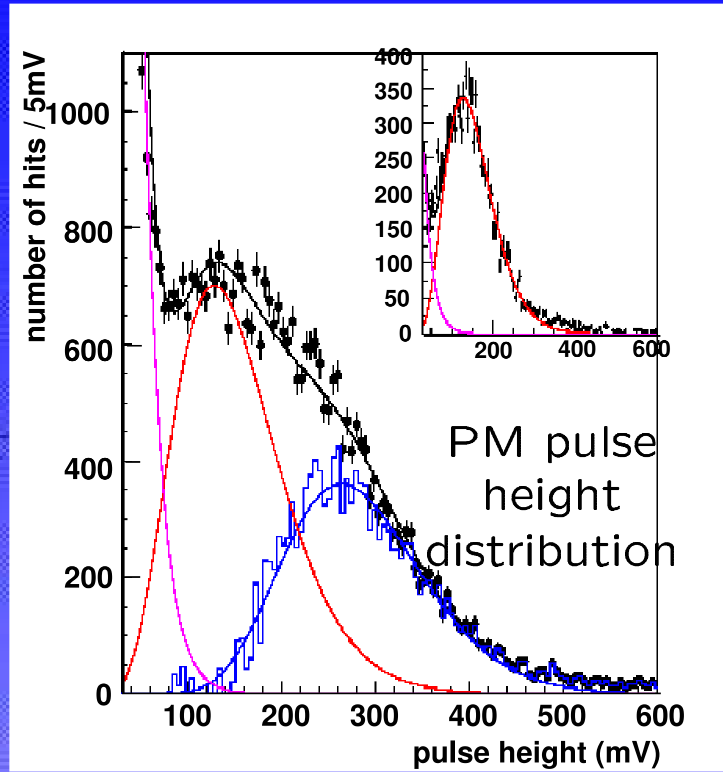
NESTOR

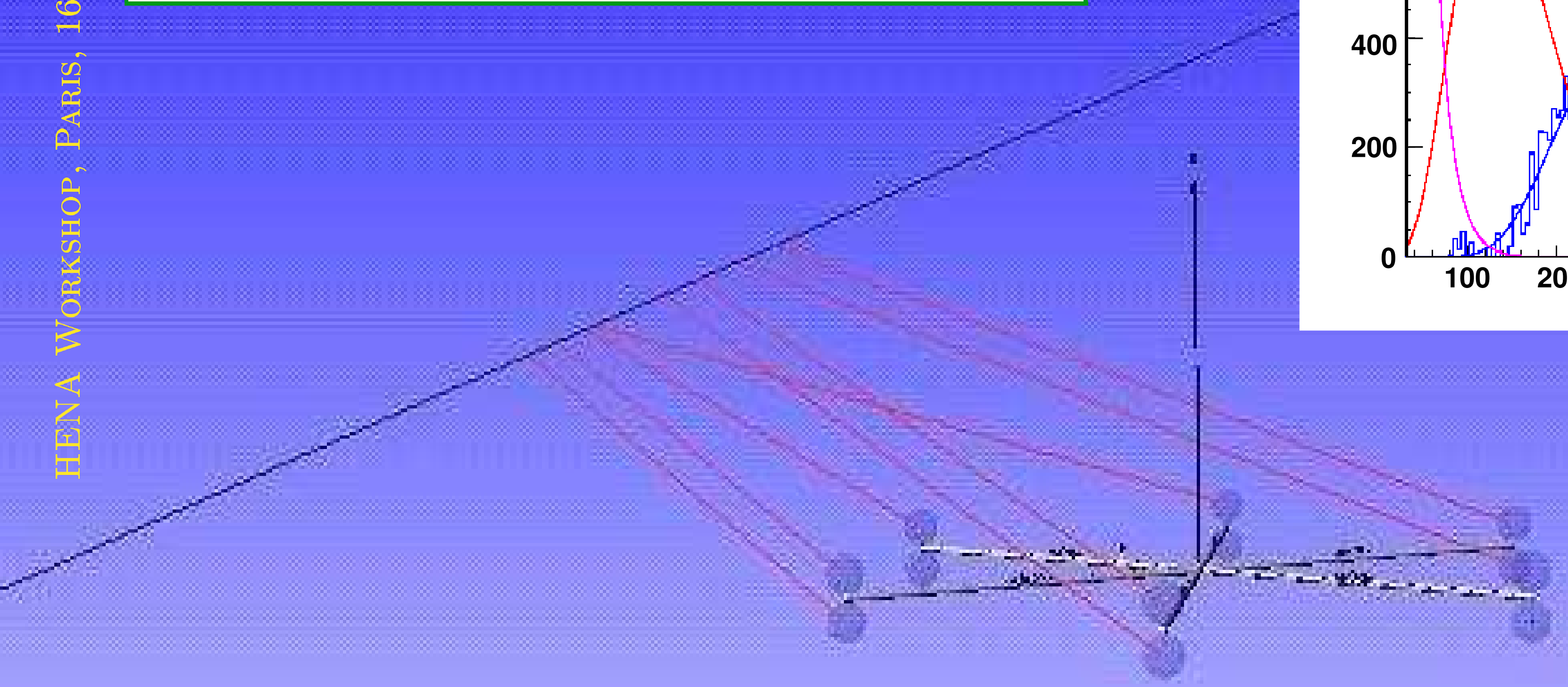
- **Tower-based** detector (titanium structures).
- **Dry connections** (recover – connect – deploy).
- **Up- and downward looking PMs.**
- **3800 meters** deep (5200 m available at Pylos site).
- Instrumented volume: $\sim 0.0003\,\mathrm{km}^3$ **per tower**.



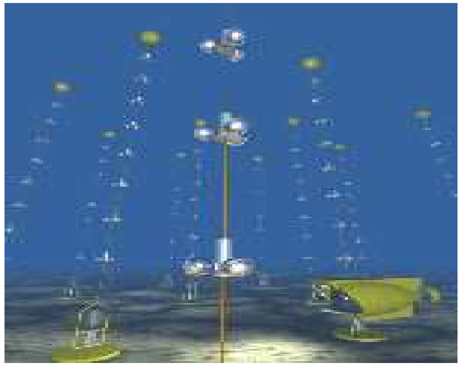
First Data from NESTOR Prototype Floor

- 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, background rates as expected.
- Muon tracks reconstructed.





How to Increase ν Telescopes to a km^3?



scale up

"dilute"

Research and Development

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 ?

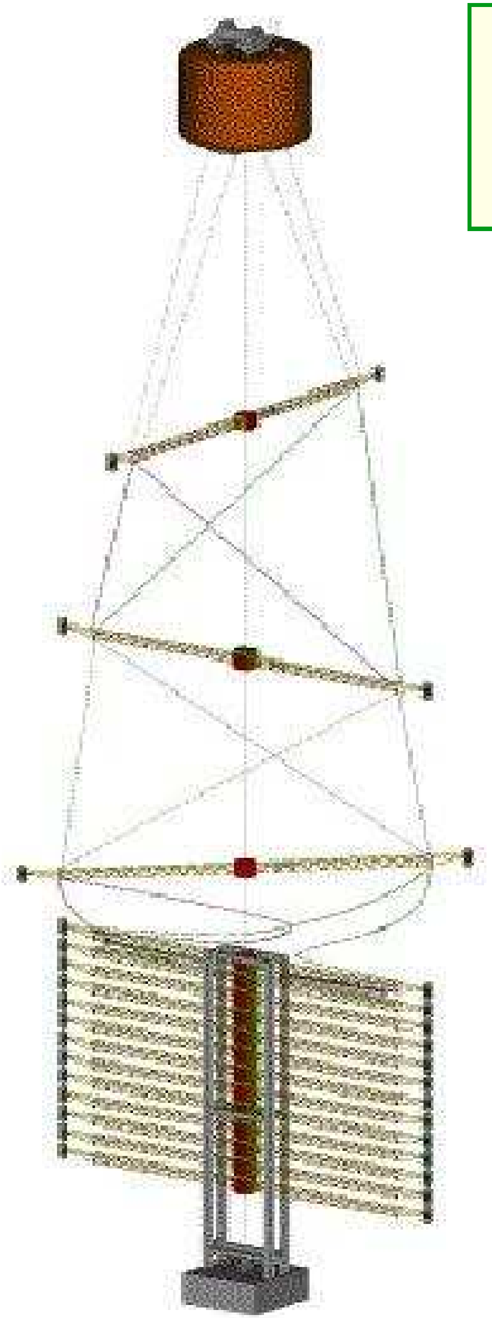
- **PM distance:**
  determined by light attenuation in water (+PM properties).
- **Efficiency loss:**
  Effective volume $\ll 1\,\mathrm{km}^3$ except maybe at highest E_ν.

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).



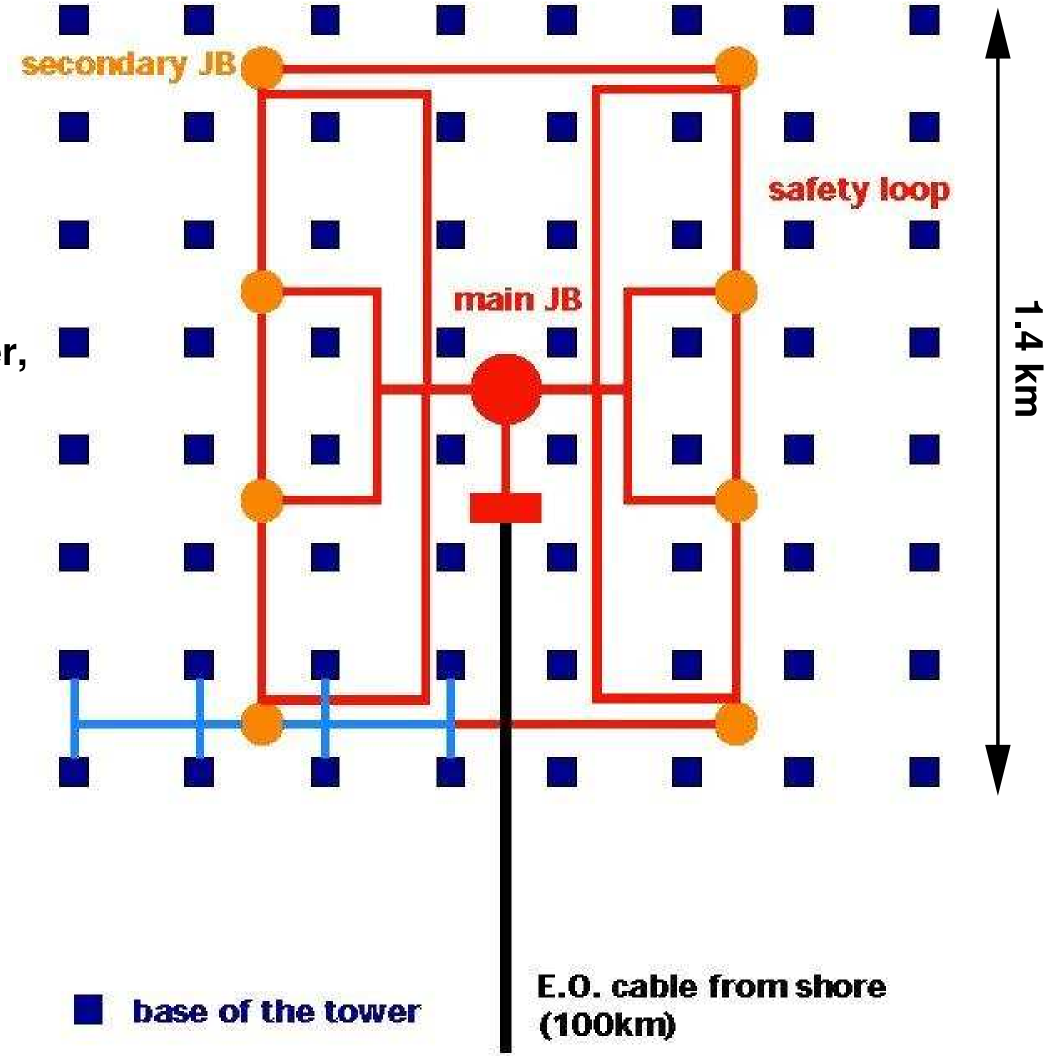
64 towers,
16 arms each,
20m arm length,
arms 40m apart.

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 decide to cooperate in preparing a future km^3 νT in the Mediterranean Sea

Design Study:

- Instrument of the EU FP6 programme to fund preparation of laboratory installations for multi-disciplinary, multi-national access.
- Application by ~ March 2004.

success → **proceed, TDR in 2007**

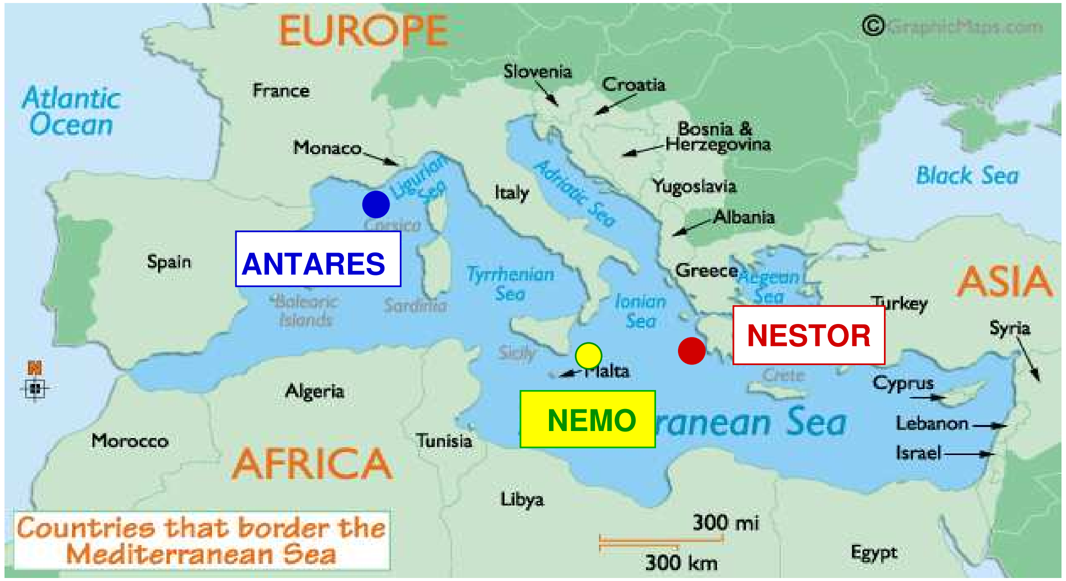
rejected → **proceed with national funding ?!**

Work Packages:

- Site characteristics;
- KM3 architecture;
- Material considerations, deployment strategies and technologies;
- Power distribution, cables & connectors;
- Photo sensors;
- Electronics;
- Data transmission;
- Readout;
- Calibration methods;
- Beyond km^3;
- Software tools;
- Physics.

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:**
  - Arguments reviewed by ApPEC.
  - Further input provided by running of prototypes.
  - ApPEC Recommendation expected by 2003/2004.
  - 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.

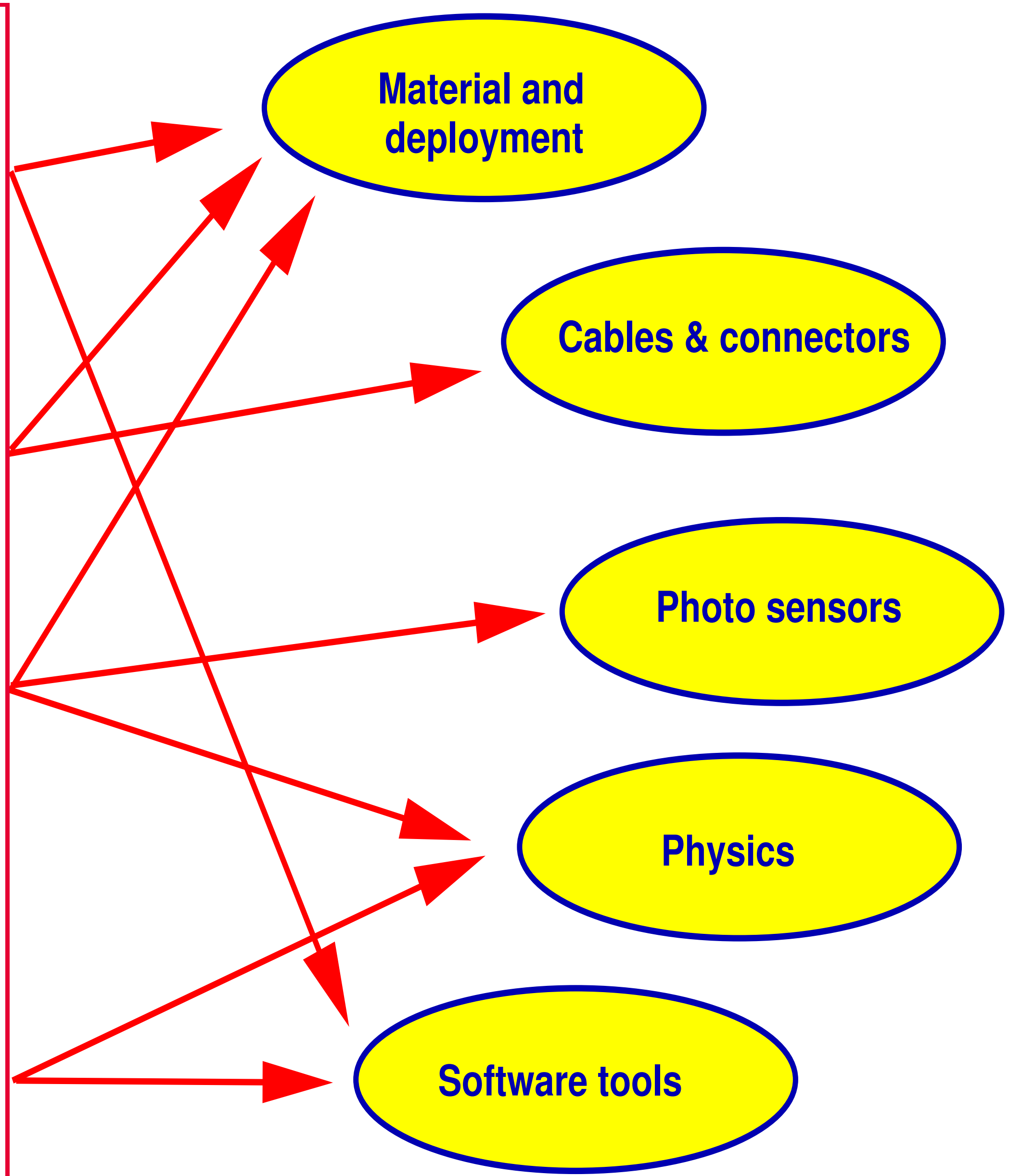


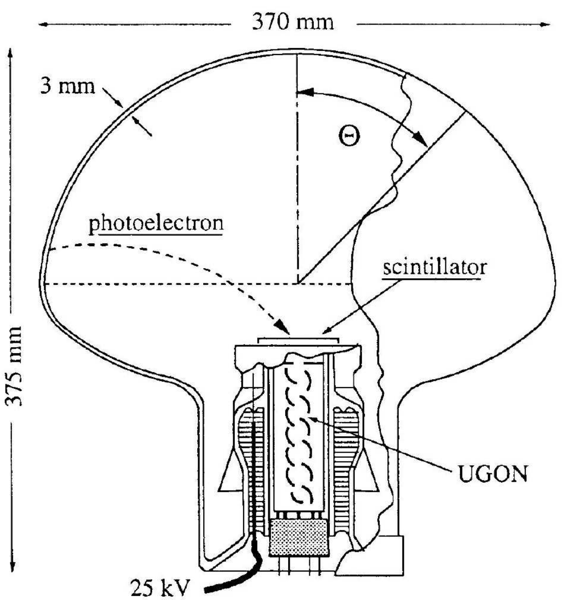
Photo Sensors

Development goals:

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

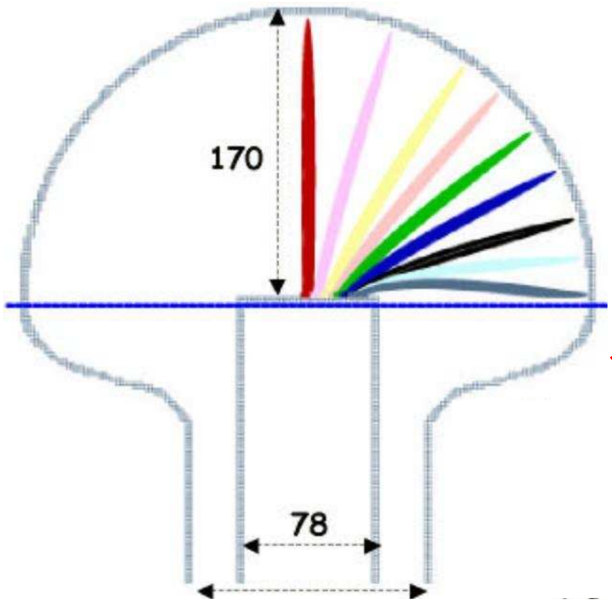
Approaches:

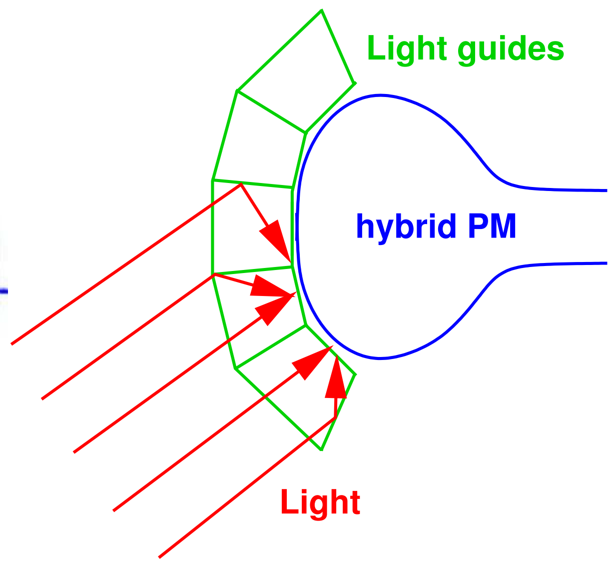
- Hybrid photomultipliers (see below).
- Hybrid photo diodes (HPDs).
- Avalanche photo diodes (APDs).
- Photocathode improvements (spectral quantum efficiency).
- Gas electron multiplication (GEM) ?



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 . . .

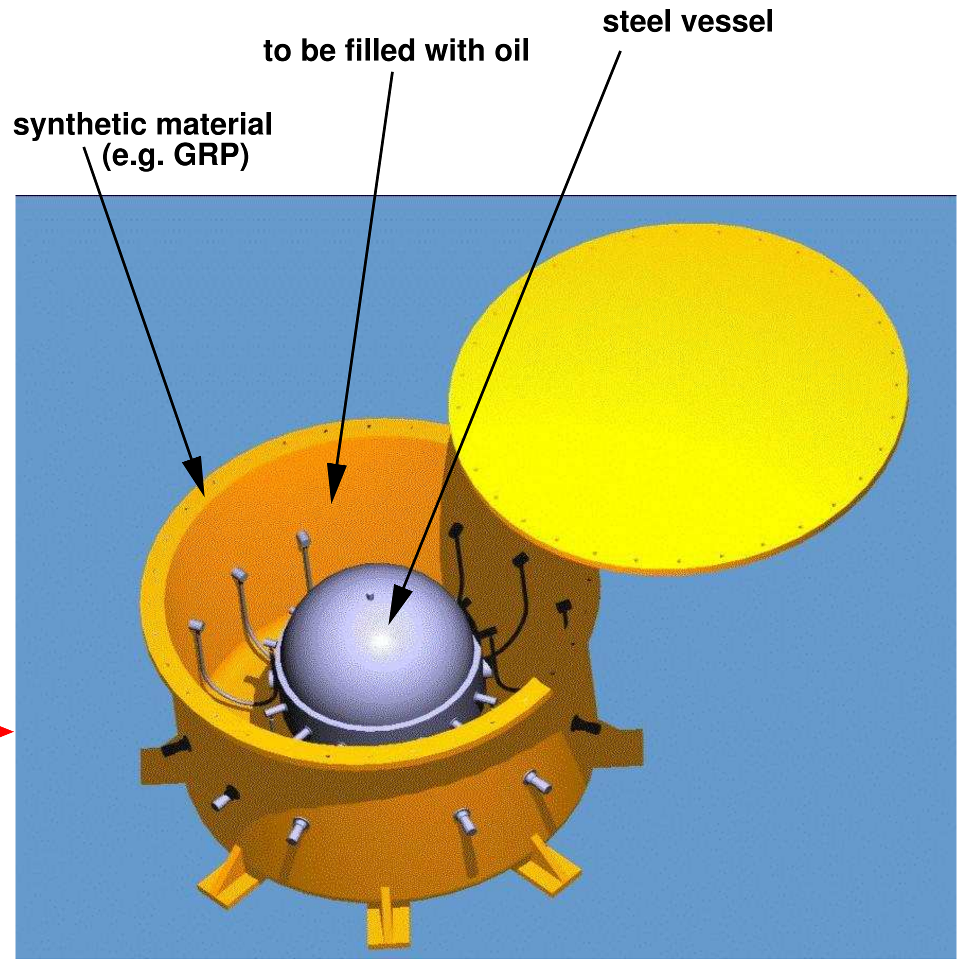
- **withstand high pressure**
  - steel;
  - titanium.
- **withstand corrosion**
  - titanium;
  - certain synthetics;
  - GRP (glass reinforced plastic).

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:



Conclusions

- A km^3-scale neutrino telescope in the Northern hemisphere has to complement IceCube to assess the physics potential of cosmic neutrinos.
- Natural choice: A deep-sea detector in the Mediterranean Sea.
- Successful operation of prototype installations by the ANTARES and NESTOR Collaborations demonstrates technical feasibility and provides valuable experience.
- Significant R&D efforts are necessary to develop cost-effective solutions with sufficient long-term stability.
- A common effort of the European groups to solve the major technical questions has begun in the framework of an EU FP6 Design Study proposal.
- Let's try our best to proceed and produce a Technical Design Report by 2007!