International School on Nuclear Physics, 27th Course:
Neutrinos in Cosmology, in Astro, Particle and Nuclear Physics
Erice, Sicily, September 2005

Neutrino Telescopy in the Mediterranean Sea

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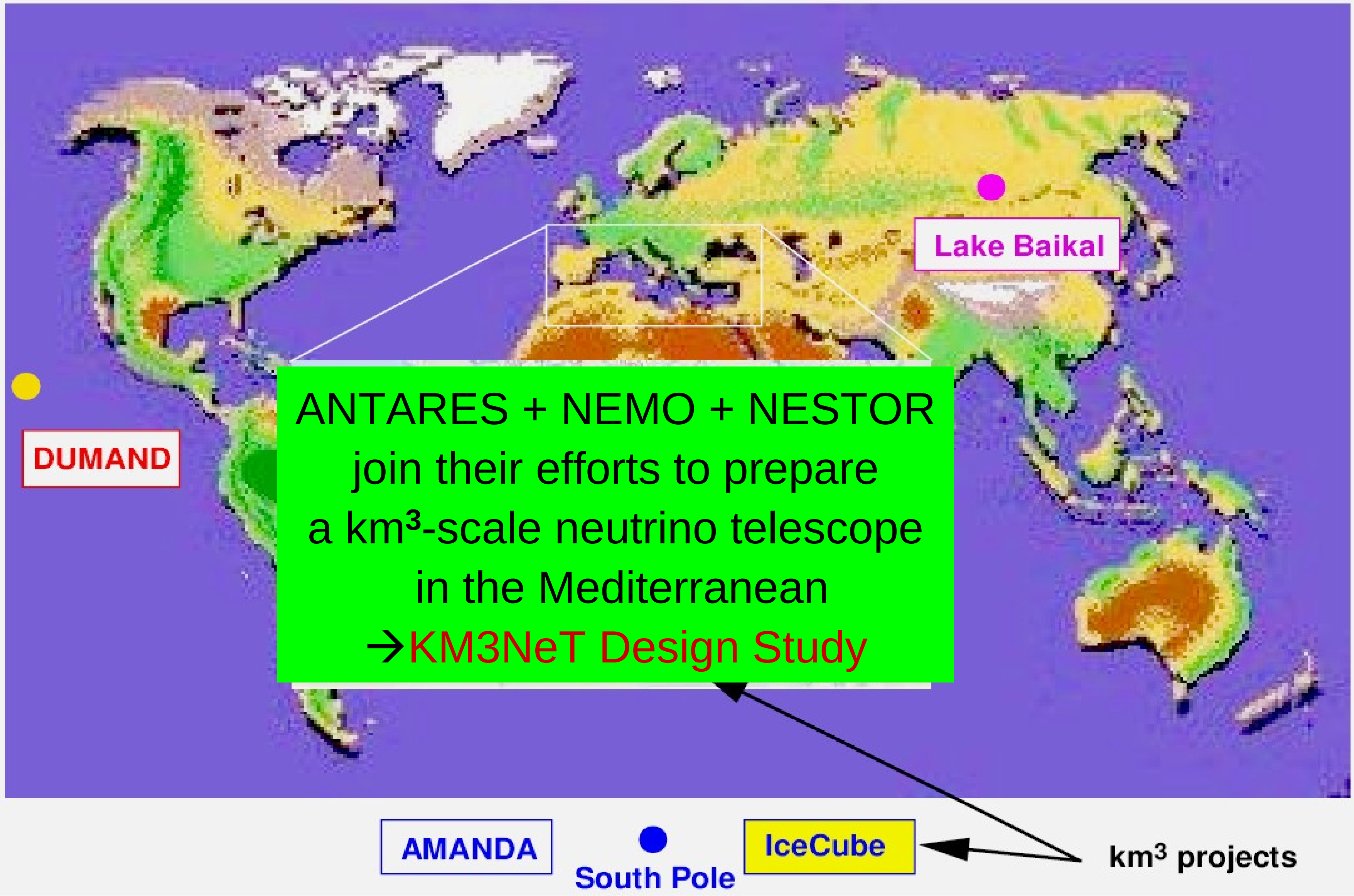
23.09.2005

- Physics with Neutrino Telescopes
- Current Projects
- Aiming at a km^3 Detector in the Mediterranean Sea
- Conclusions and Outlook

Why Neutrino Telescopes?

- Neutrinos traverse space without deflection or attenuation
  - they point back to their sources;
  - they allow for a view into dense environments;
  - they allow us 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



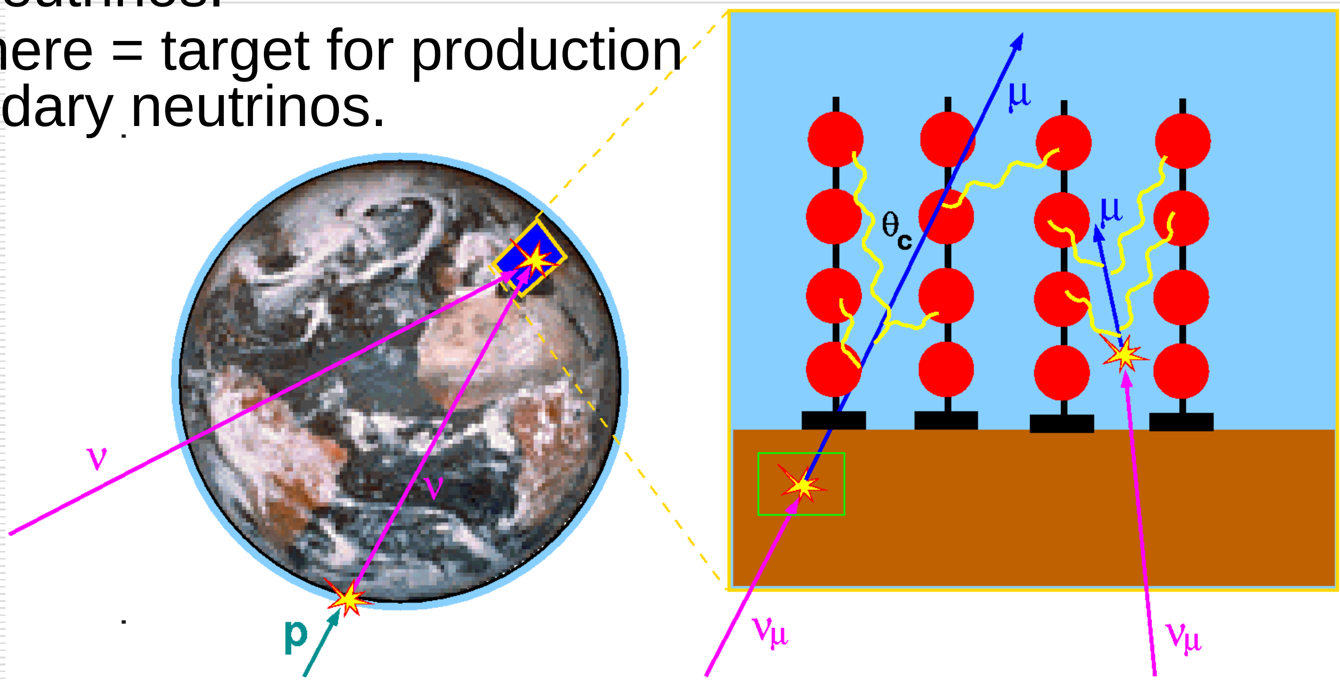
The Principle of Neutrino Telescopes

<u>Role of the Earth:</u>

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

<u>Čerenkov light:</u>

- In water: $\theta_C \approx 43°$
- Spectral range used: ~ 350-500nm.

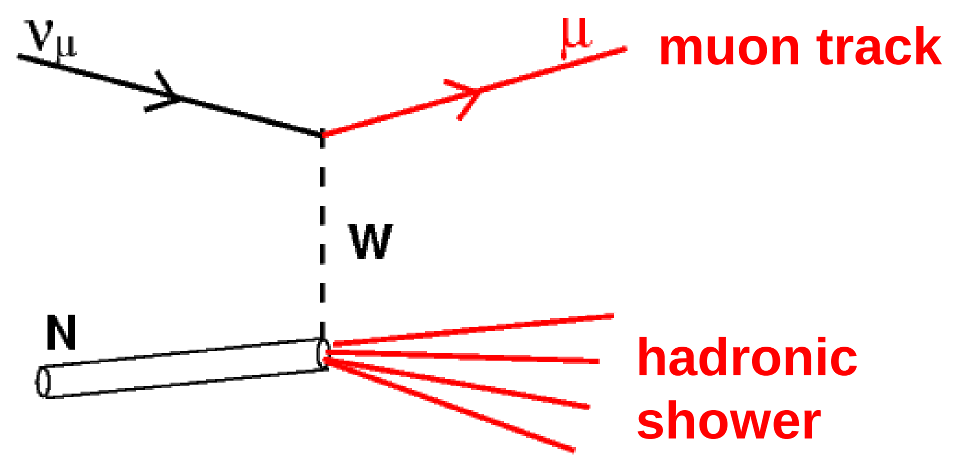


<u>Neutrino reactions (key reaction is $\nu_\mu N \rightarrow \mu X$):</u>

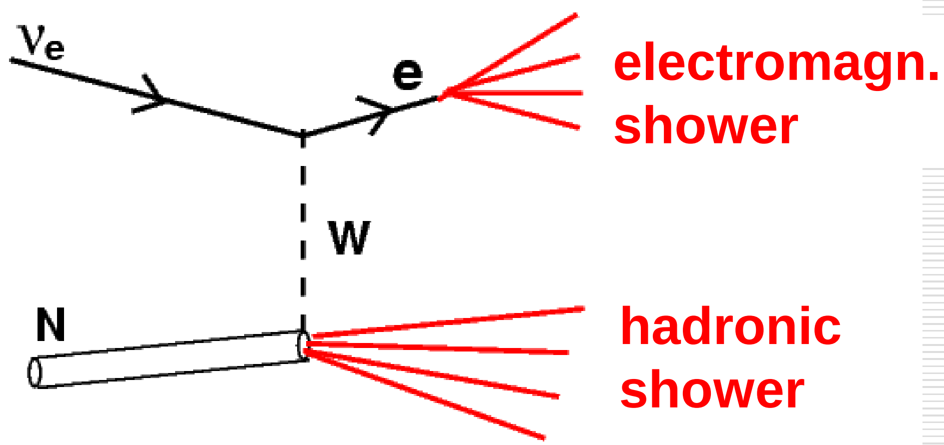
- Cross sections and reaction mechanisms known from accelerator experiments (in particular HERA).
- Extrapolation to highest energies (> 100 TeV) uncertain.

Neutrino Interaction Signatures

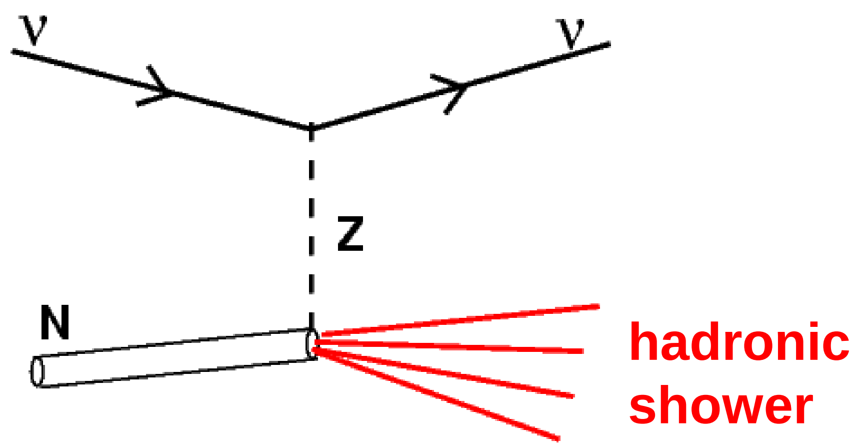
- Neutrinos mainly from π-μ-e decays, roughly $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$;
- Arrival at Earth after oscillations: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$;
- Key signature: muon tracks **from ν_μ charged current reactions** (few 100m to several km long);
- Electromagnetic/hadronic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



precise angular reconstruction of neutrino direction (<0.3° @ E>10TeV), energy resolution ~ factor 2 above 1 TeV



good energy resolution, angle more difficult



angular and energy resolution difficult

Particle and Astrophysics with ν Telescopes

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

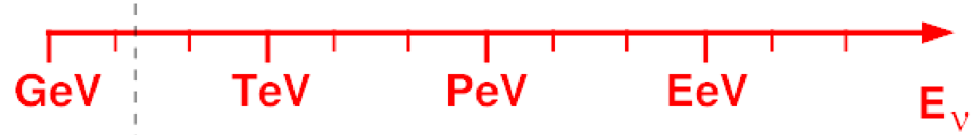
Intrinsic limit, can only be overcome with specialized, very densely instrumented detector.

Neutrino Oscillations:
Direction, Energy, Flavor

Dark matter search (WIMPs):
Direction, Energy

Cosmic point sources:
Direction, (Energy)

Diffuse cosmic neutrino flux:
(Direction), Energy

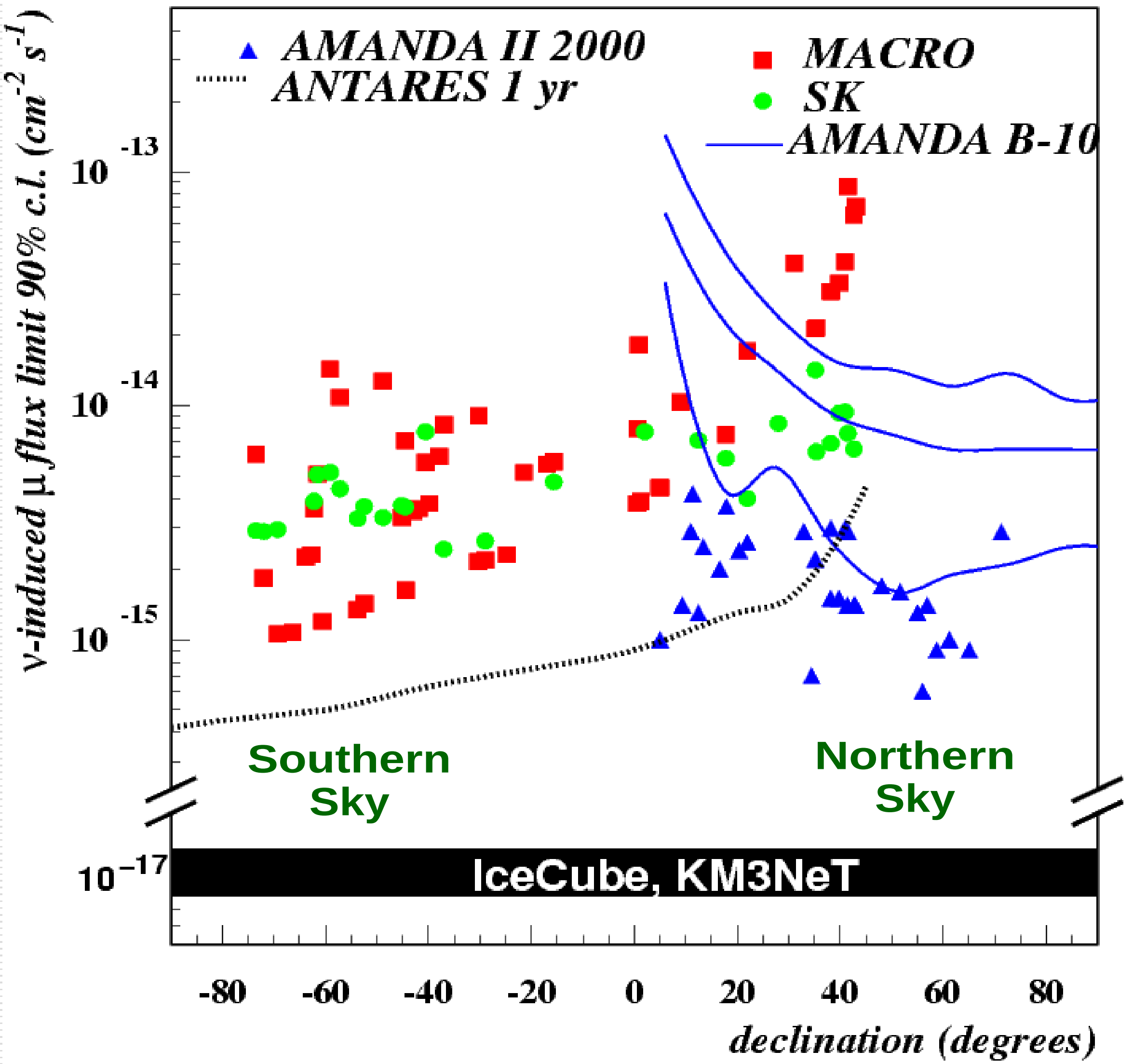


High-energy limit:
- fluxes decrease as $E^{-2} \dots E^{-3}$;
- large detection volume needed.

Ultimate volume (at least) one cubic kilometer.

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

Neutrinos from Astrophysical Point Sources

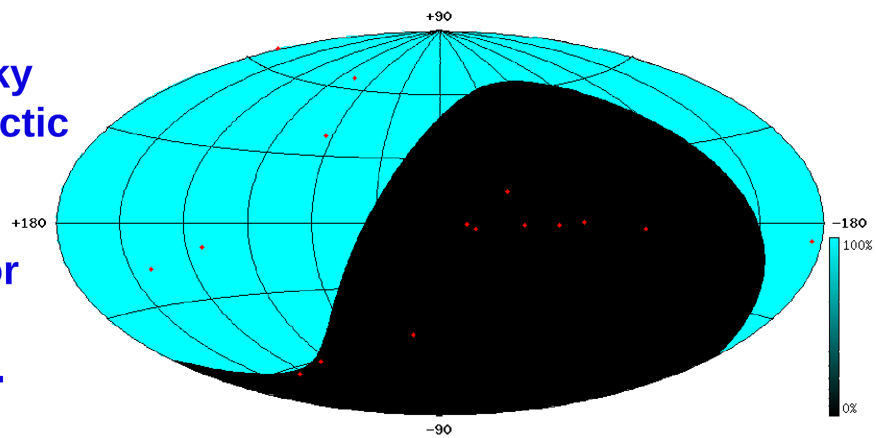


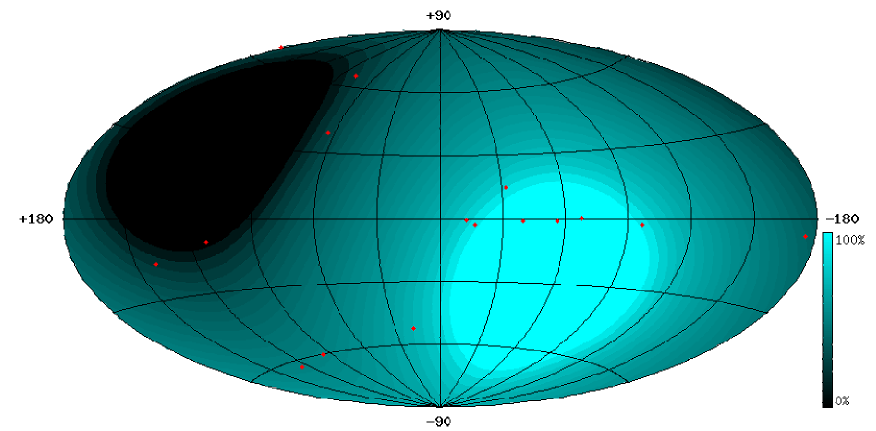
- Association of neutrinos to specific astrophysical objects.
- Energy spectrum, time structure, multi-messenger observations provide insight into physical processes inside source.
- Searches profit from very good angular resolution of water Čerenkov telescopes.
- km³ detectors needed to exploit full potential of neutrino astronomy.

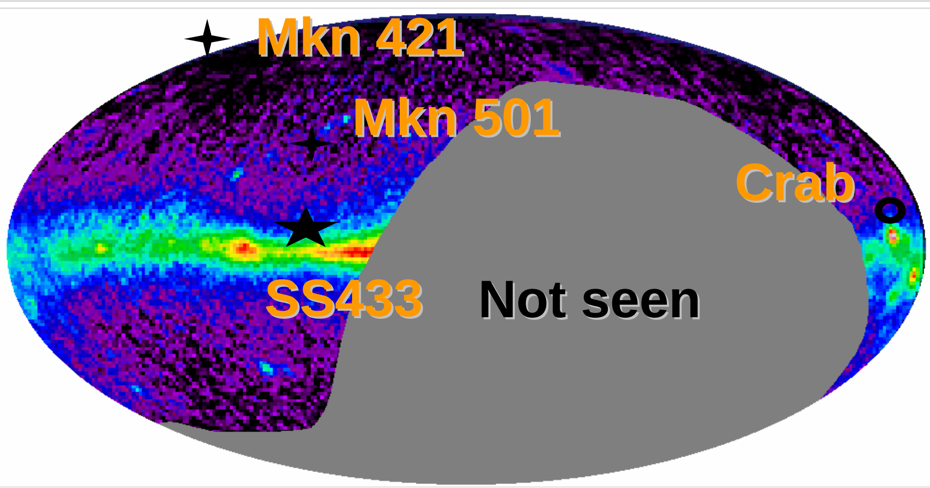
Sky Coverage of Neutrino Telescopes

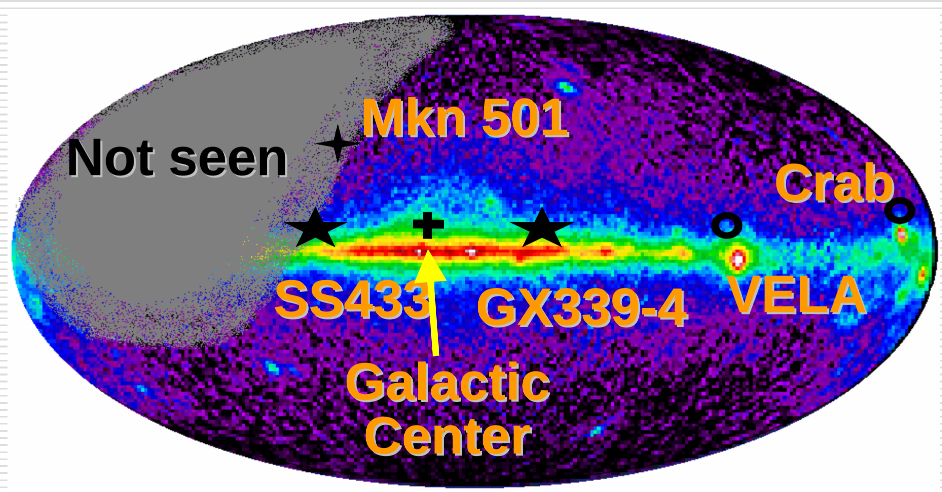
South Pole	Mediterranean

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



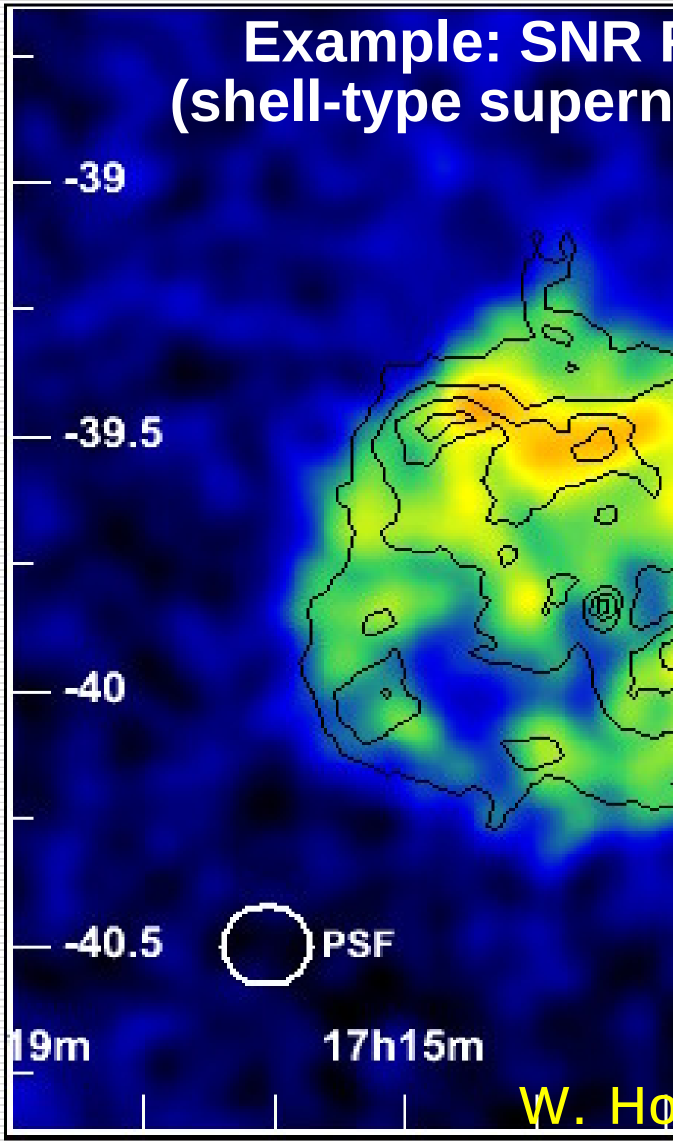




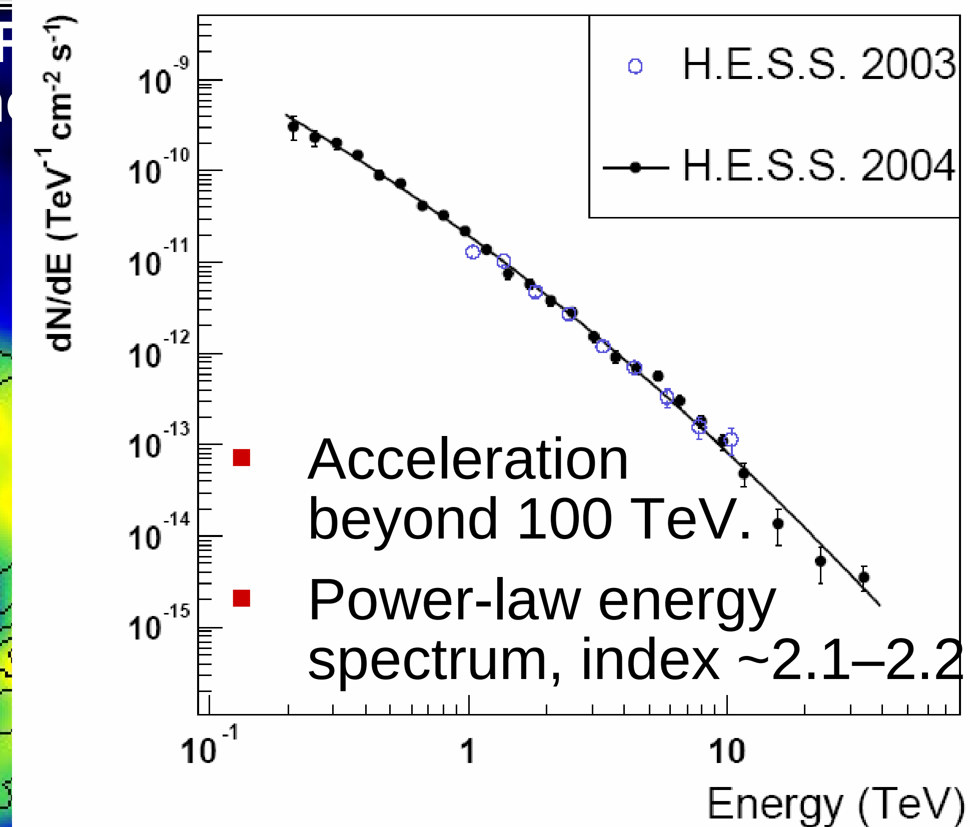


→ We need ν telescopes in both hemispheres to see the whole sky

Neutrinos from H.E.S.S. sources?



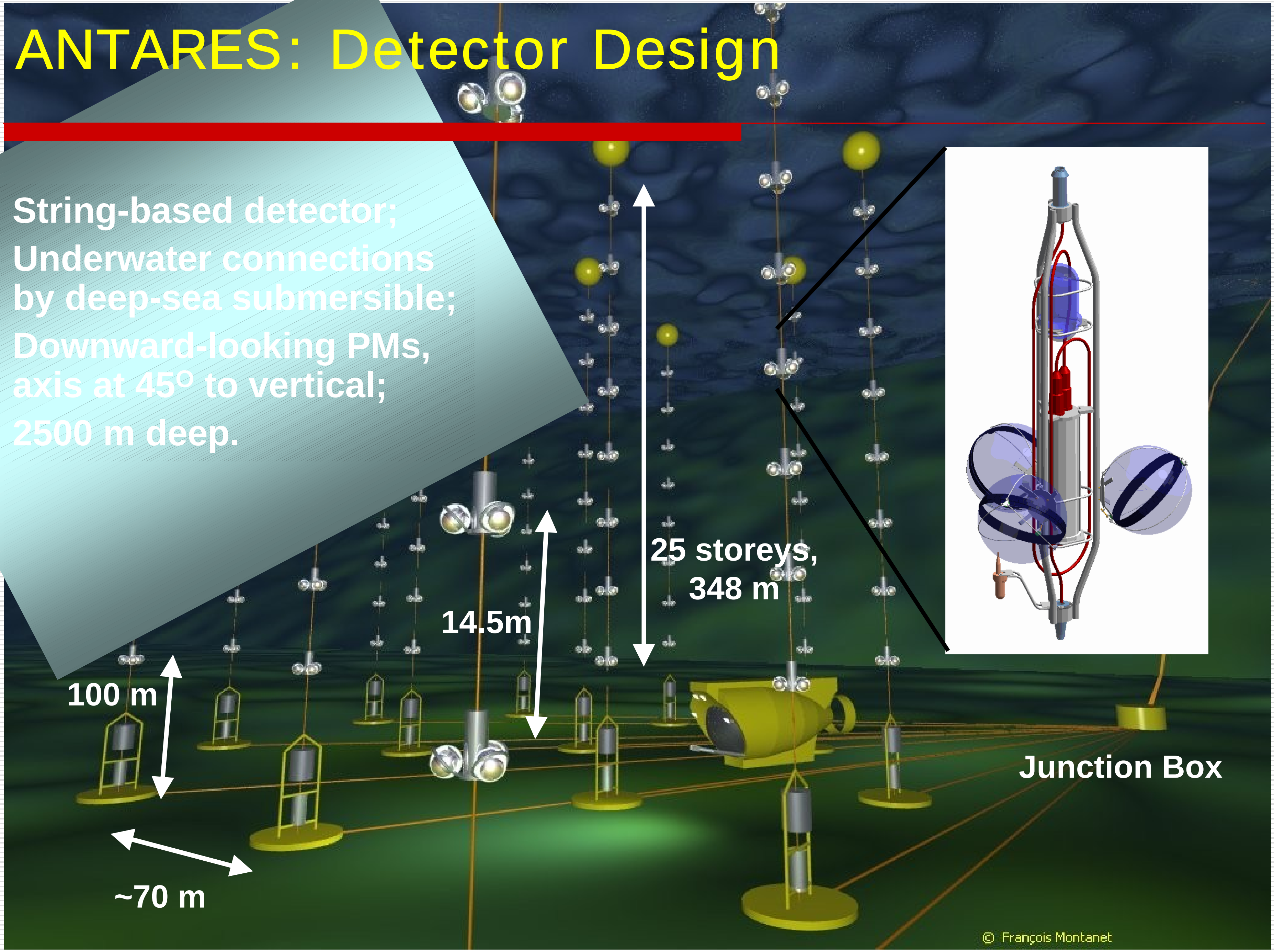
W. Hofmann, ICRC 2005



- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index ~2.1–2.2.
- Spectrum points to hadron acceleration
- → Neutrino flux ~ γ flux
- Detectable in current & future neutrino telescopes?!

ANTARES: Detector Design

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMs, axis at 45° to vertical;
- 2500 m deep.



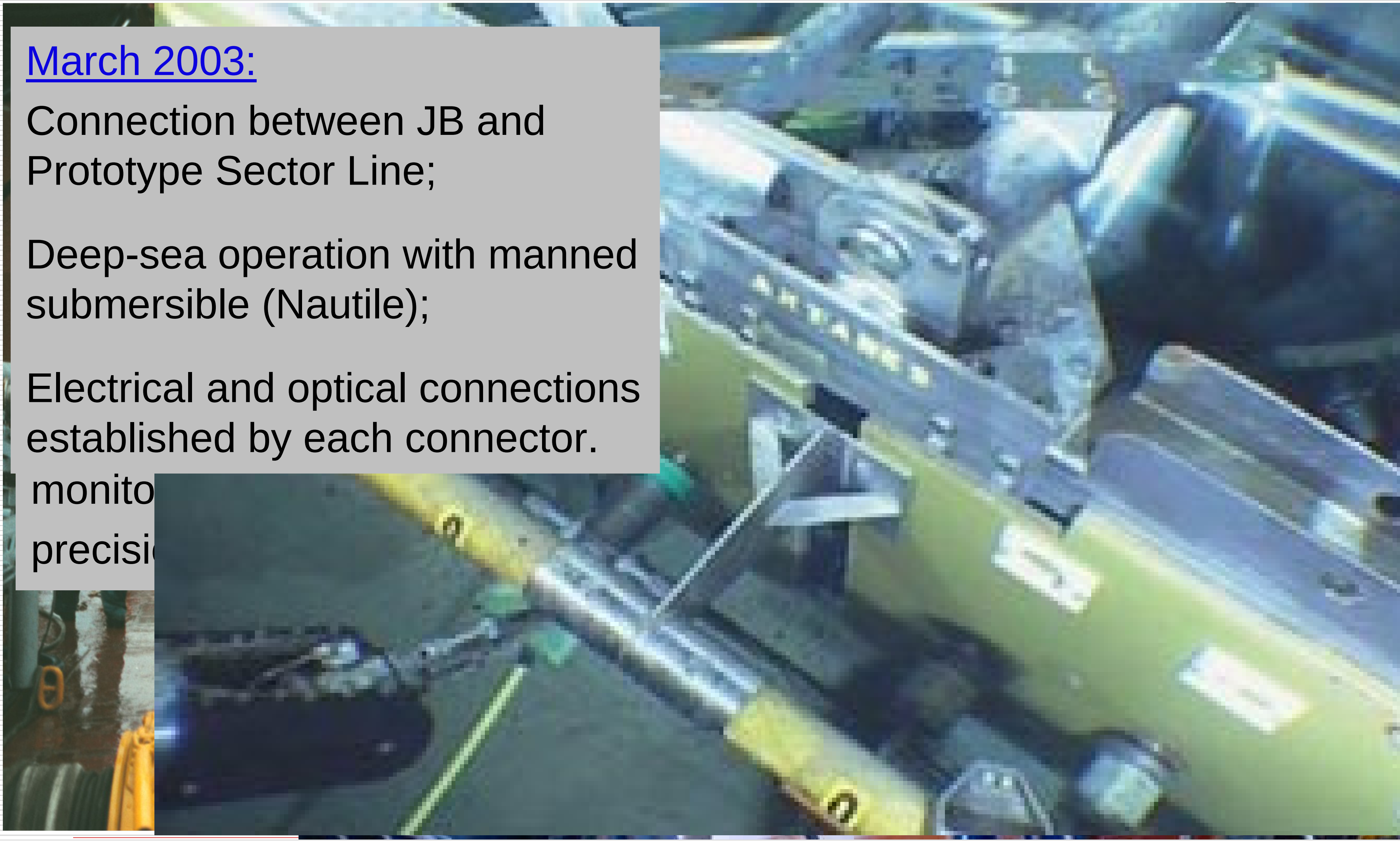
ANTARES: Optical Modules

- Photomultipliers:
  - transfer time spread ~2.7ns (FWHM);
  - quantum efficiency >20% for 330 nm < λ < 460nm;
- Glass spheres:
  - qualified for 600 bar;

43 cm

Hamamatsu 10´´ PM

ANTARES: Sea Operations



March 2003:

Connection between JB and Prototype Sector Line;

Deep-sea operation with manned submersible (Nautile);

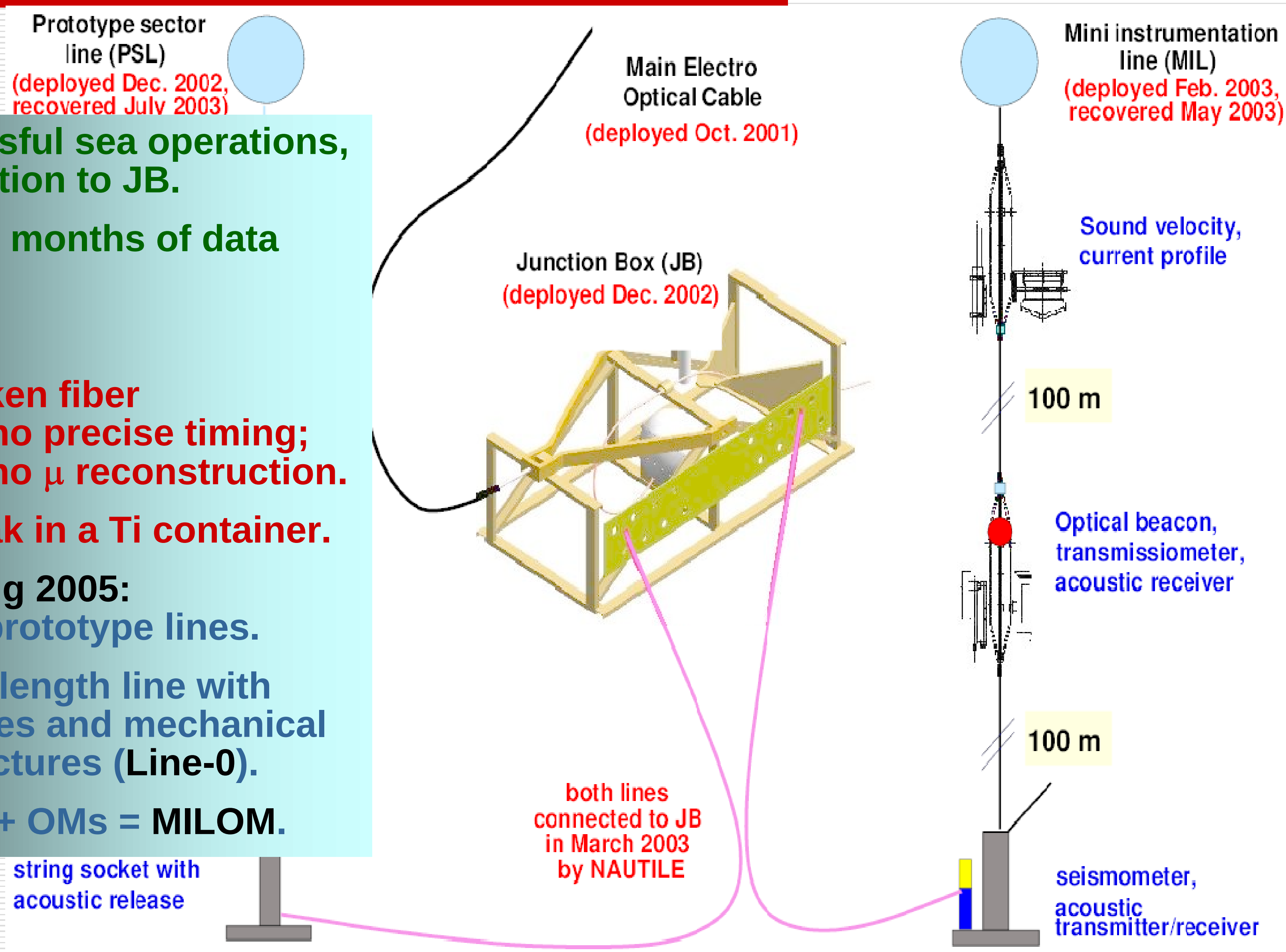
Electrical and optical connections established by each connector.

monito

precisi

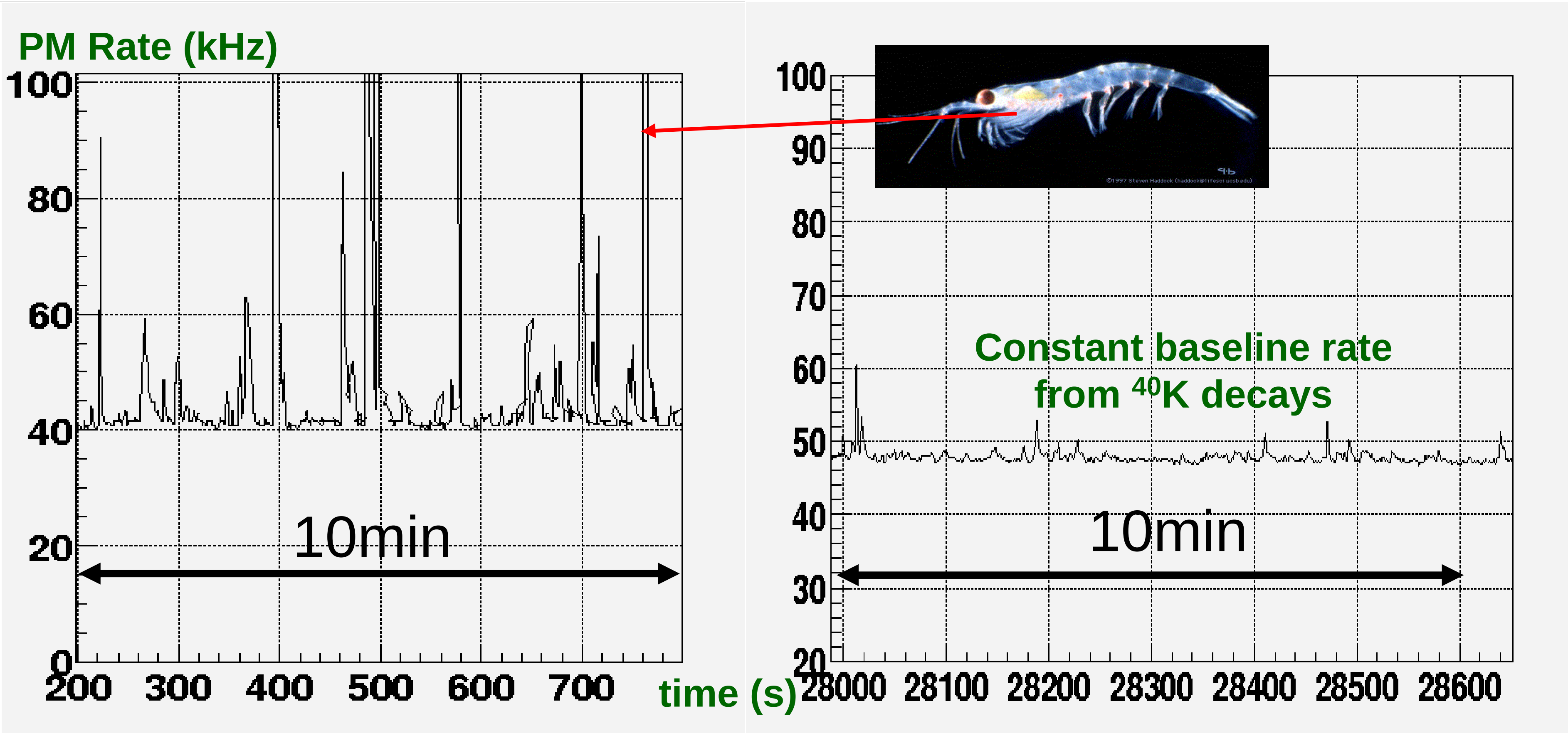
ANTARES: Status 2003 and Next Steps

- **Successful sea operations, connection to JB.**
- **Several months of data taking.**
- **But:**
  - **Broken fiber**
    → no precise timing;
    → no μ reconstruction.
  - **1 leak in a Ti container.**
- **➔Spring 2005:**
  2 new prototype lines.
  - **Full-length line with cables and mechanical structures (Line-0).**
  - **MIL + OMs = MILOM.**



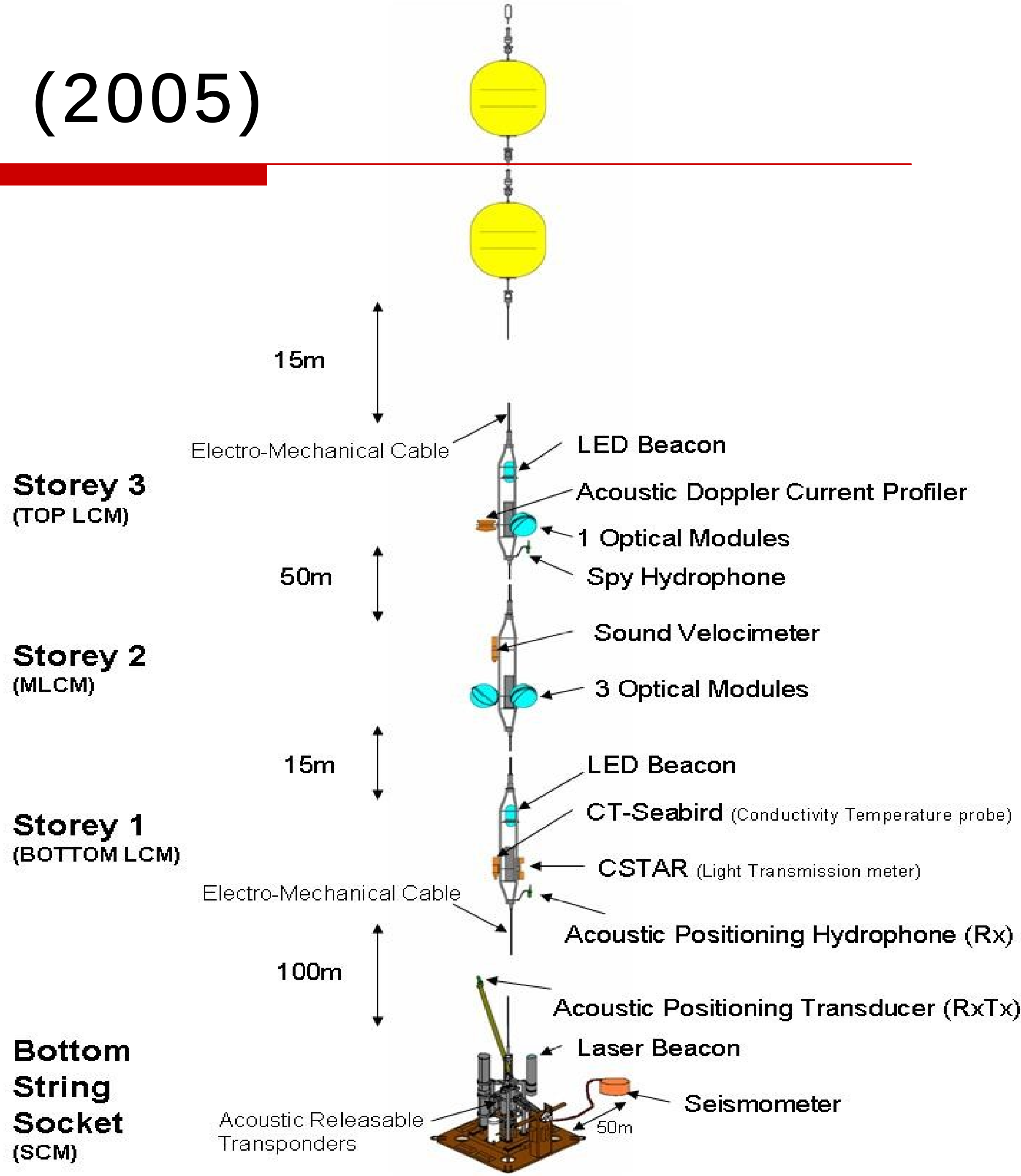
ANTARES: First Deep-Sea Data

- Rate measurements: Strong fluctuation of bioluminescence background observed



ANTARES: MILOM (2005)

- Successful operation over several months
- Major progress:
  - **Validation of final electronics cards and OMs;**
  - **Validation of time calibration ($\Delta t < 1$ ns);**
  - **Validation of acoustic positioning;**
  - **Measurements and long-term monitoring of environmental parameters;**
  - **Tests and improvements of data acquisition.**



ANTARES: Line-0 (2005)

- Objectives:
  - test of mechanical structure of a full line (23 storeys);
  - test of cables and connection interfaces.
- Equipped with water leak sensors and sensors for attenuation measurements.
- Recovered in May 2005:
  - no water leaks in electronic containers;
  - optical transmission losses → interface problem between cable and electronics cylinder.
- Solution currently tested, detector installation planned to proceed according to schedule →Detector complete ~ 2006/07.

NESTOR: Rigid Structures Forming Towers

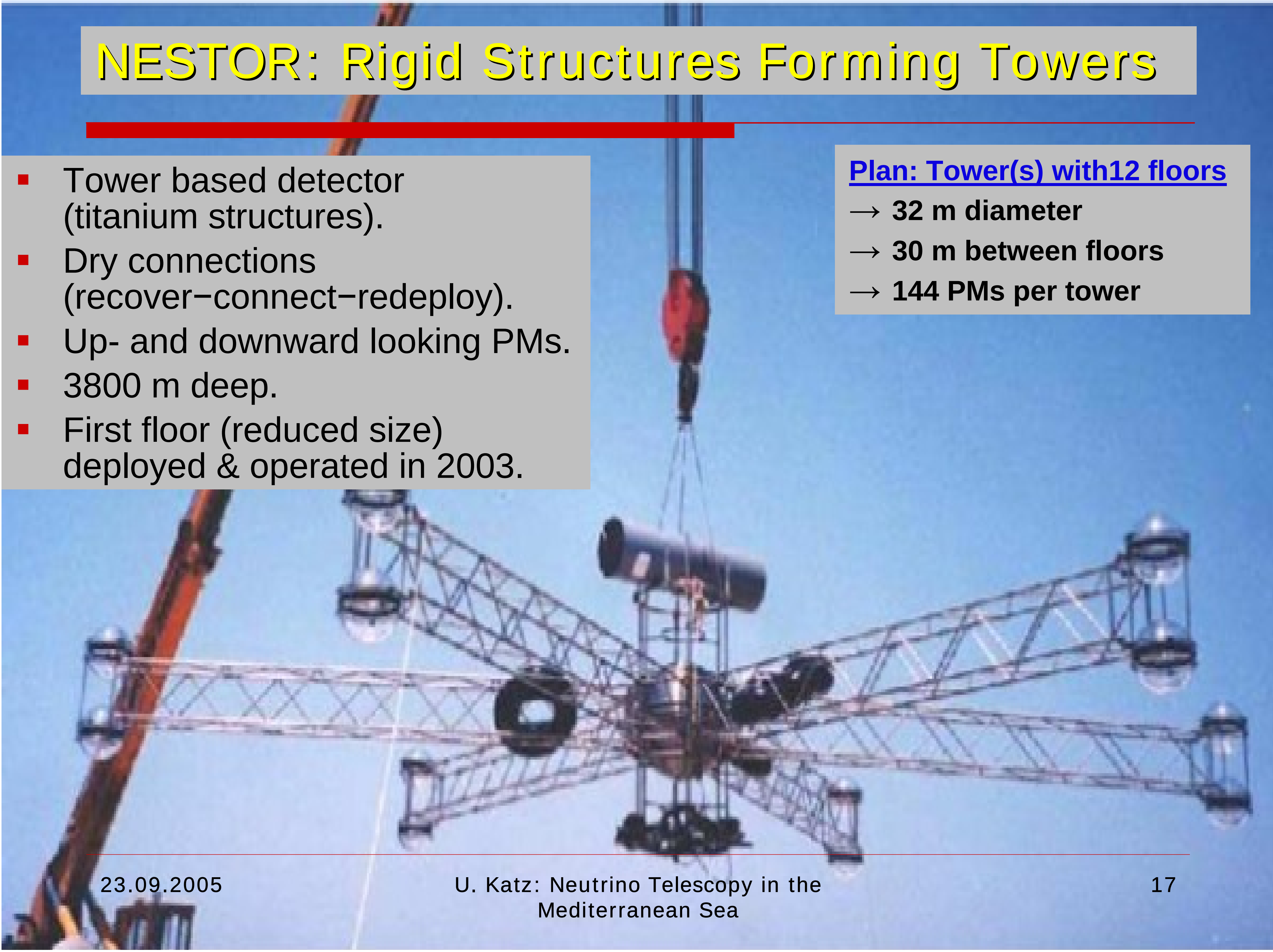
- Tower based detector (titanium structures).
- Dry connections (recover−connect−redeploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

Plan: Tower(s) with12 floors

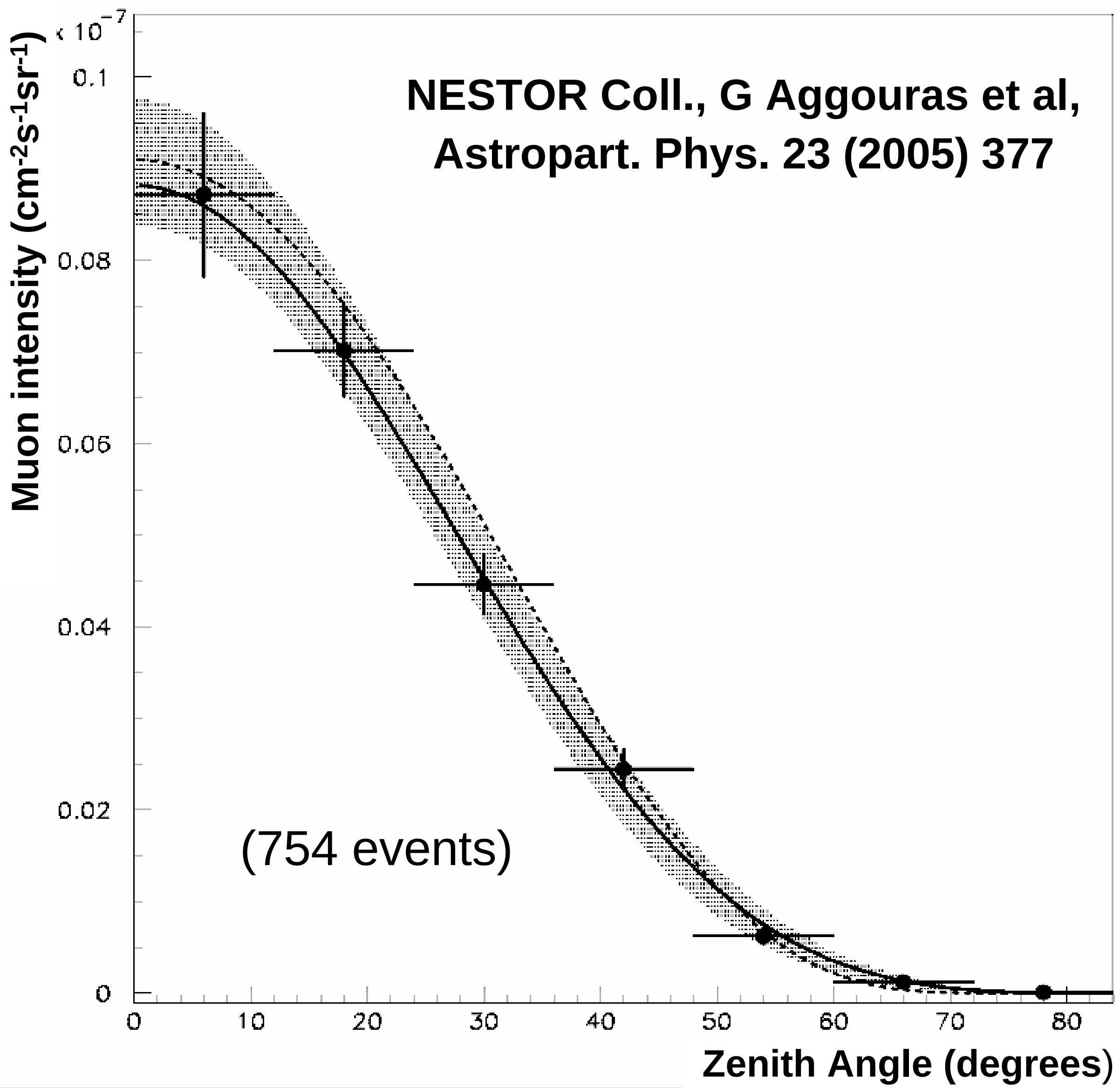
→ 32 m diameter

→ 30 m between floors

→ 144 PMs per tower



NESTOR: Measurement of the Muon Flux



Atmospheric muon flux determination and parameterisation by

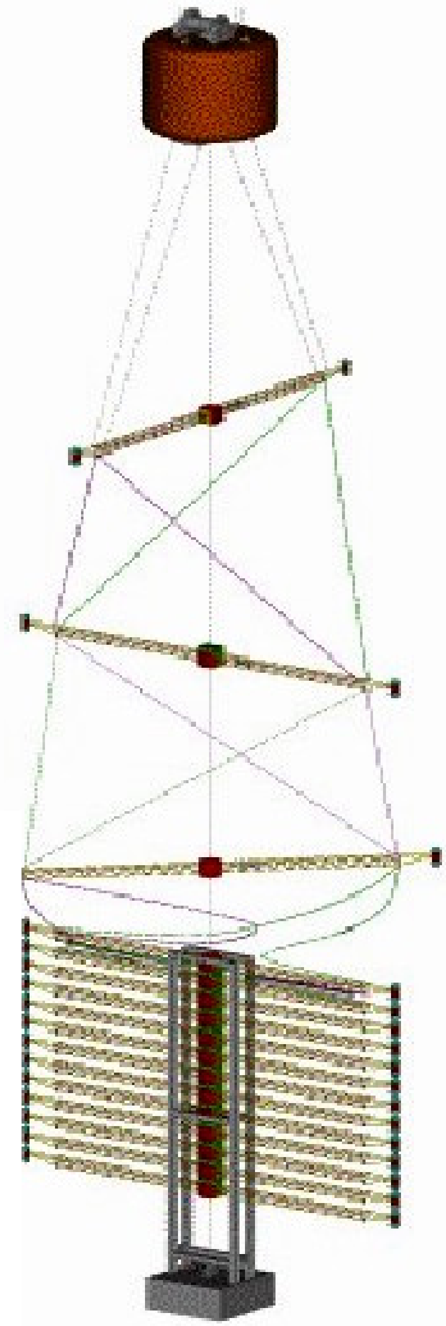
$$\frac{dN}{d\Omega \cdot dt \cdot ds} = I_0 \cdot \cos^{\alpha}\theta$$

α = 4.7 ± 0.5(stat.) ± 0.2(syst.)
I_0 = 9.0 ± 0.7(stat.) ± 0.4(syst.)
$\times 10^{-9}$ cm^{-2} s^{-1} sr^{-1}

Results agree nicely with previous measurements and with simulations.

The NEMO Project

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

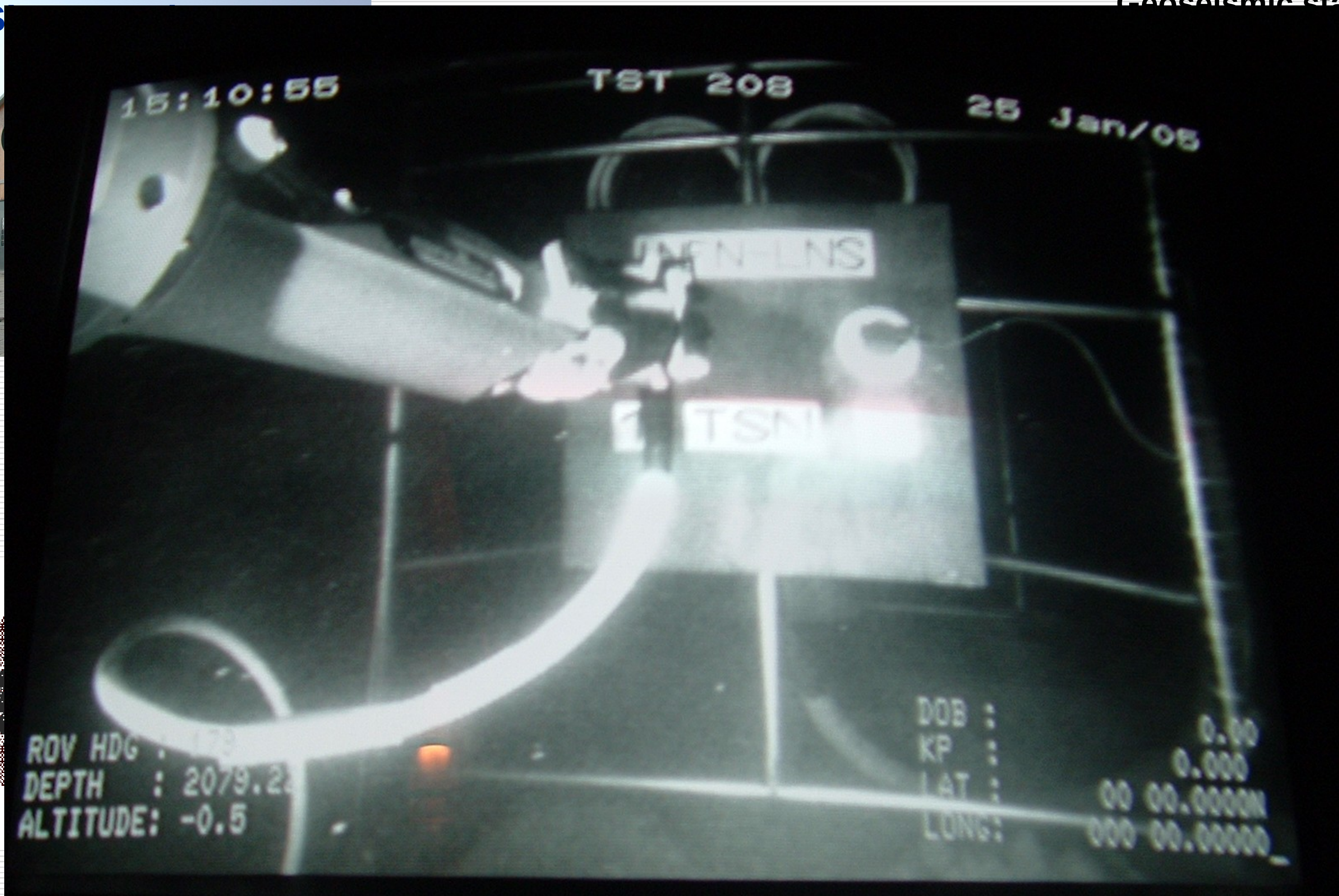


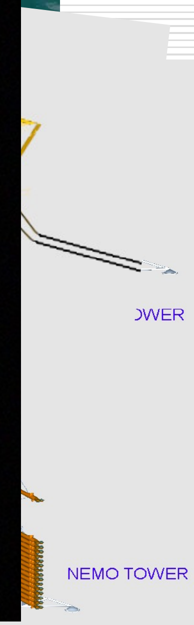
Example: Flexible tower

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

NEMO Phase I

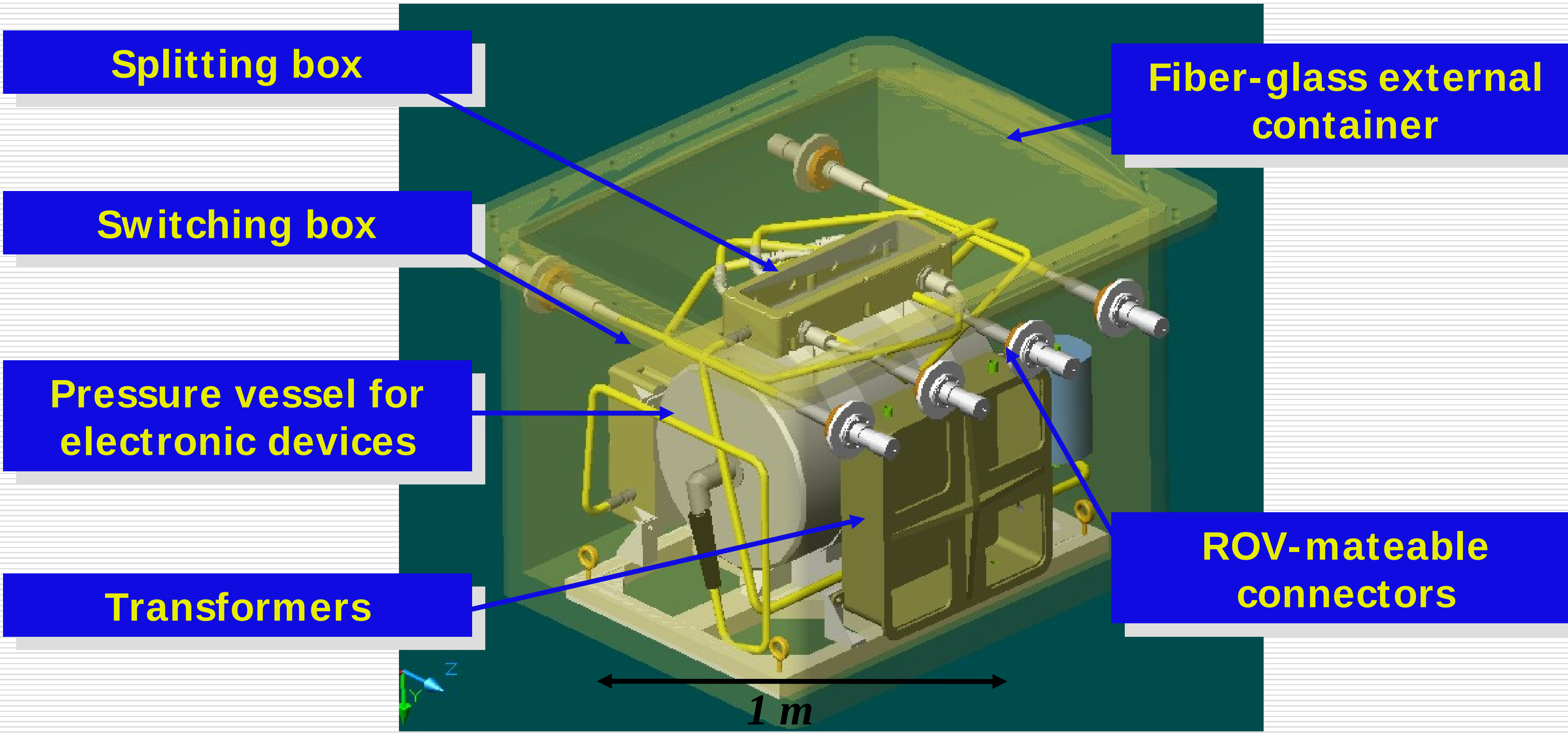
Geoseismic station





NEMO: Junction Box R&D

Aim: Decouple the problems of pressure and corrosion resistance.



Current Projects: Summary

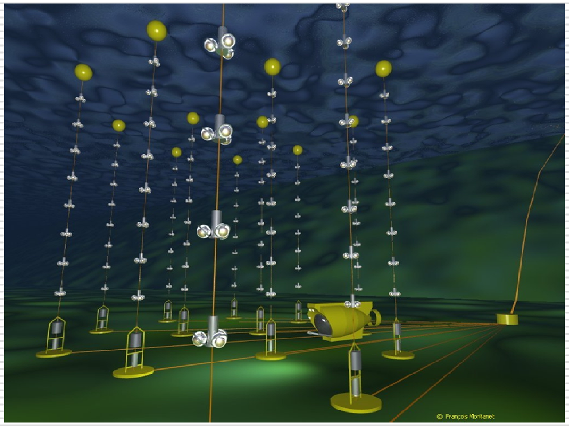
- ANTARES + NESTOR: first installation steps successfully completed, prototype detector modules deployed and operated; ANTARES construction in preparation, detector expected to be complete by 2007;
- Discovery potential for cosmic neutrinos and Dark Matter;
- NEMO: Ongoing R&D work for next-generation km^3-scale detector.

Aiming at a km^3-Detector in the Mediterranean

HENAP Report to PaNAGIC, July 2002:

- “The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ...“
- “... a km^3-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^3-scale, the construction of which is considered technically feasible.”

How to Design a km^3 Deep-Sea ν Telescope



scale up

dilute

new design

<u>Existing telescopes " times 100" ?</u>

- Too expensive
- Too complicated: production, deployment takes forever, maintenance impossible
- Not scalable (readout bandwidth, power, ...)

<u>R&D needed:</u>

- Cost-effective solutions to reduce price/volume by factor 2-5
- Stability goal: maintenance-free detector
- Fast installation time for construction & deployment less than detector life time
- Improved components

<u>Large volume with same number of PMs?</u>

- PM distance: given by absorption length in water (~60 m) and PM properties
- Efficiency loss for larger spacing

The KM3NeT Design Study History (EU FP6)

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

- Initial initiative Sept 2002.
- VLVνT Workshop, Amsterdam, Oct 2003.
- ApPEC review, Nov 2003.
- Inclusion of sea science/technology institutes (Jan 2004).
- Proposal submission 04.03.2004.
- Evaluation report received June 2004 (overall mark: 88%).
- Confirmation that Design Study will be funded (Sept. 2004).
- Invitation to negotiations with EU Commission (July 2005).
- Submission of "negotiation documents" 30.09.2005
- 2nd VLVνT Workshop, Catania, 08-11 Nov. 2005
- 9 M€ funding from EU expected from 01.02.2006 ...

KM3NeT Design Study Participants

- Cyprus: Univ. Cyprus
- France: CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IreS Strasbourg, APC Paris-7 (?)), Univ. Mulhouse (?), IFREMER
- Germany: Univ. Erlangen, Univ. Kiel
- Greece: HCMR, Hellenic Open Univ., NCSR Democritos, NOA/Nestor, Univ. Athens
- Italy: CNR/ISMAR, INFN (Univs. Bari, Bologna, Catania, Genova, Napoli, Pisa, Roma-1, LNS Catania, LNF Frascati), INGV, Tecnomare SpA
- Netherlands: NIKHEF/FOM (incl. Univ. Amsterdam, Univ. Utrecht, KVI Groningen)
- Spain: IFIC/CSIC Valencia, Univ. Valencia, UP Valencia
- UK: Univ. Aberdeen, Univ. Leeds, Univ. Liverpool, Univ. Sheffield

Particle/Astroparticle institutes (17) – Sea science/technology institutes (7) – Coordinator

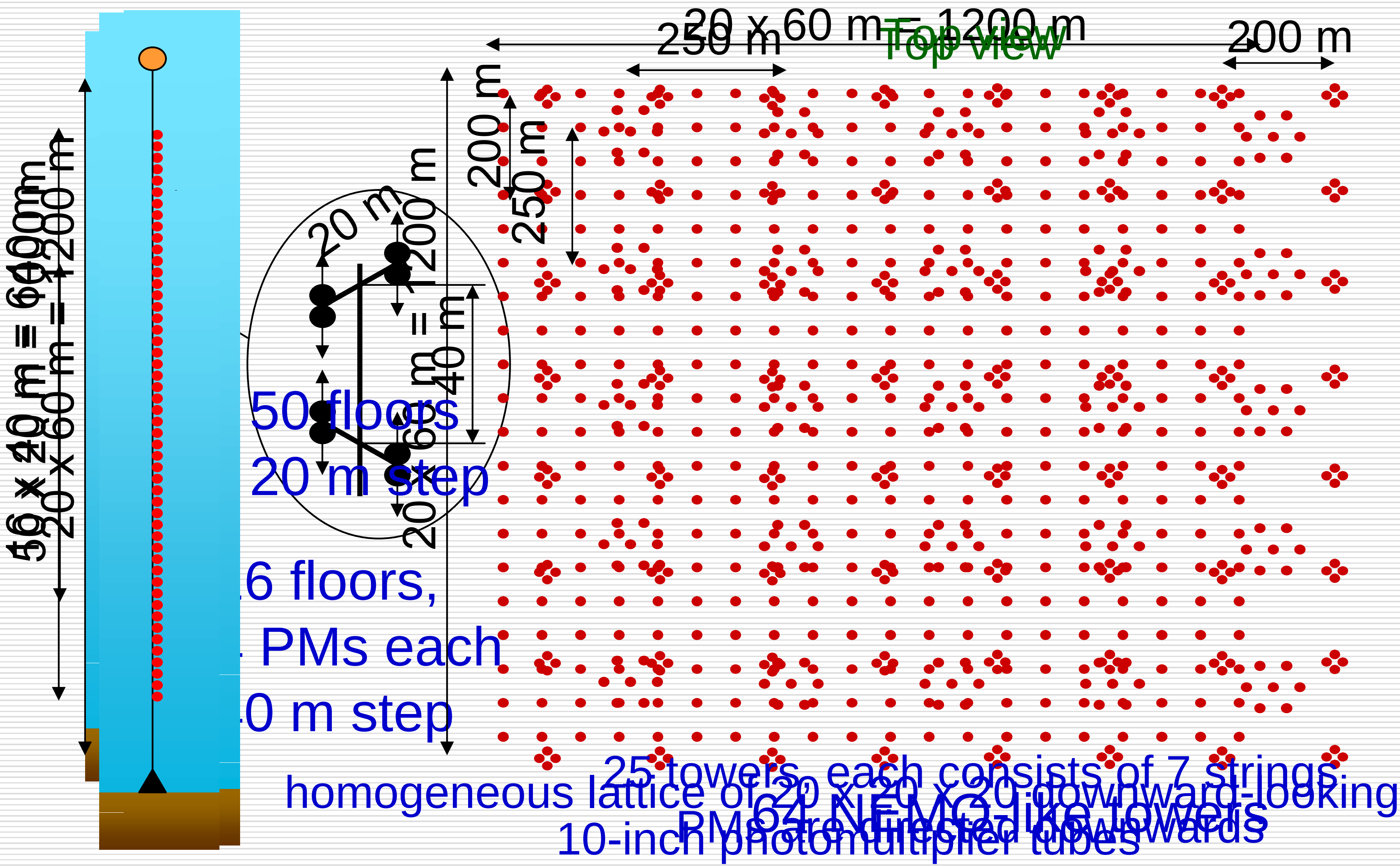
Some Key Questions

All these questions are highly interconnected !

- 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?
  (separate 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: Dependence on site choice

Detector Architecture

(D. Zaborov at VLVνT)



Sea Operations

- Rigid towers or flexible strings?
- Connection in air (no ROVs) or wet mateable connectors?
- Deployment from platform or boat?

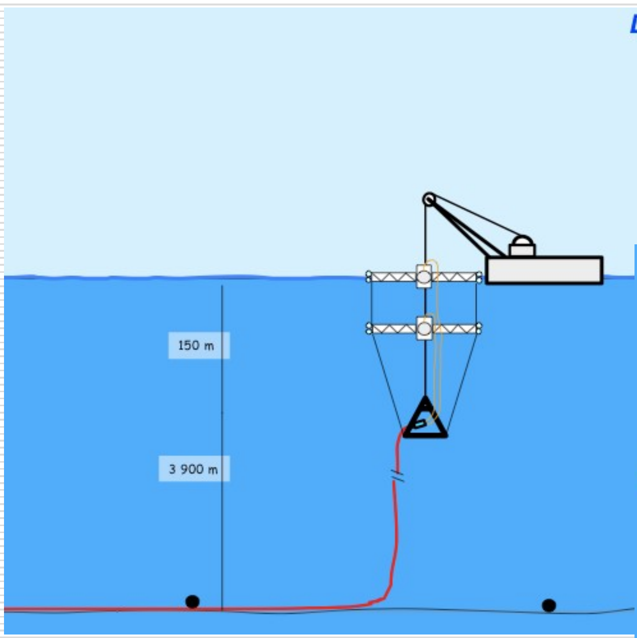
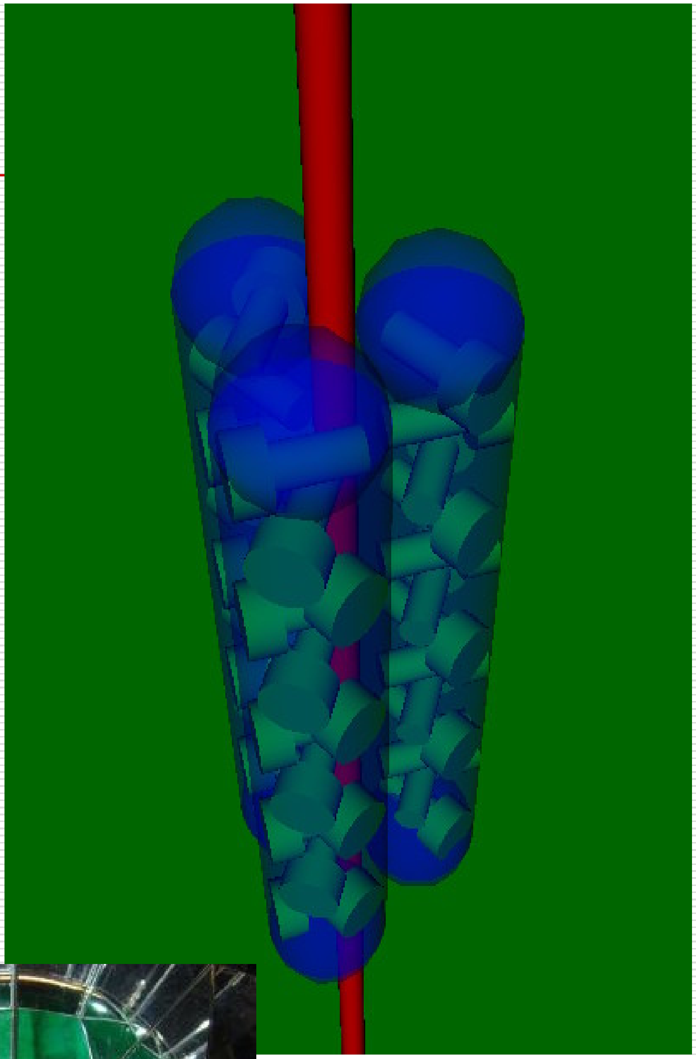
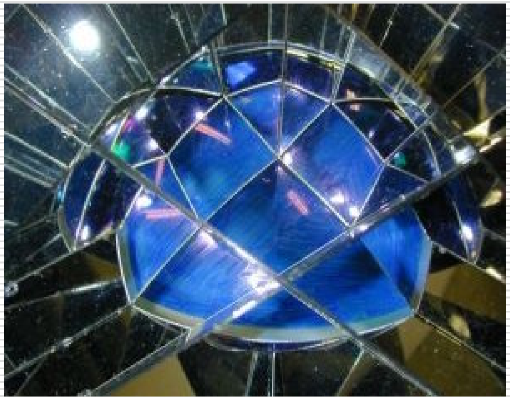
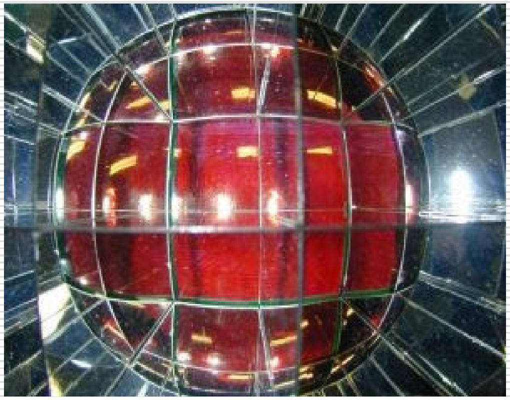


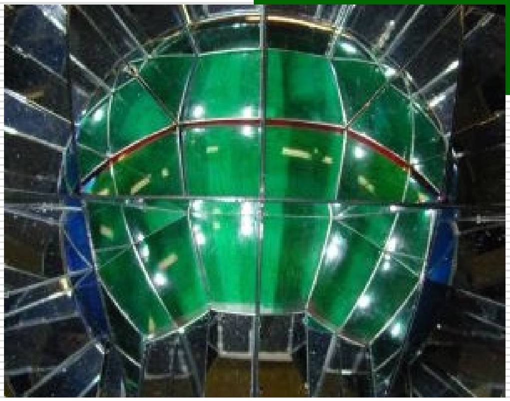
Photo Detection: Options



- Large photocathode area with arrays of small PMs packed into pressure housings - low cost!
- Determination of photon direction, e.g. via multi-anodic PMs plus a matrix of Winston cones.
- But: phase space for developments from scratch is too tight.







KM3NeT: Time Schedule

Time scale given by "community lifetime" and competition with ice detector

- Experience from current first generation water neutrino 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):

01.02.2006	Start of Design Study
Mid-2007	Conceptual Design Report
End of 2008	Technical Design Report
2009-2013	Construction
2010-20XX	Operation

Conclusions and Outlook

- Compelling scientific arguments for complementing IceCube with a km^3-scale detector in the Northern Hemisphere.
- The Mediterranean-Sea neutrino telescope groups NESTOR, ANTARES and NEMO comprise the leading expertise in this field. They have united their efforts to prepare together the future, km^3-scale deep-sea detector.
- An EU-funded Design Study (KM3NeT) will provide substantial resources for an intense 3-year R&D phase; expected to start by beginning of 2006.
- Major objective: Technical Design Report by end of 2008.