33. International Meeting on Fundamental Physics, Benasque, 2005

Neutrino Telescopy Today and Tomorrow – Towards km³-Scale Detectors

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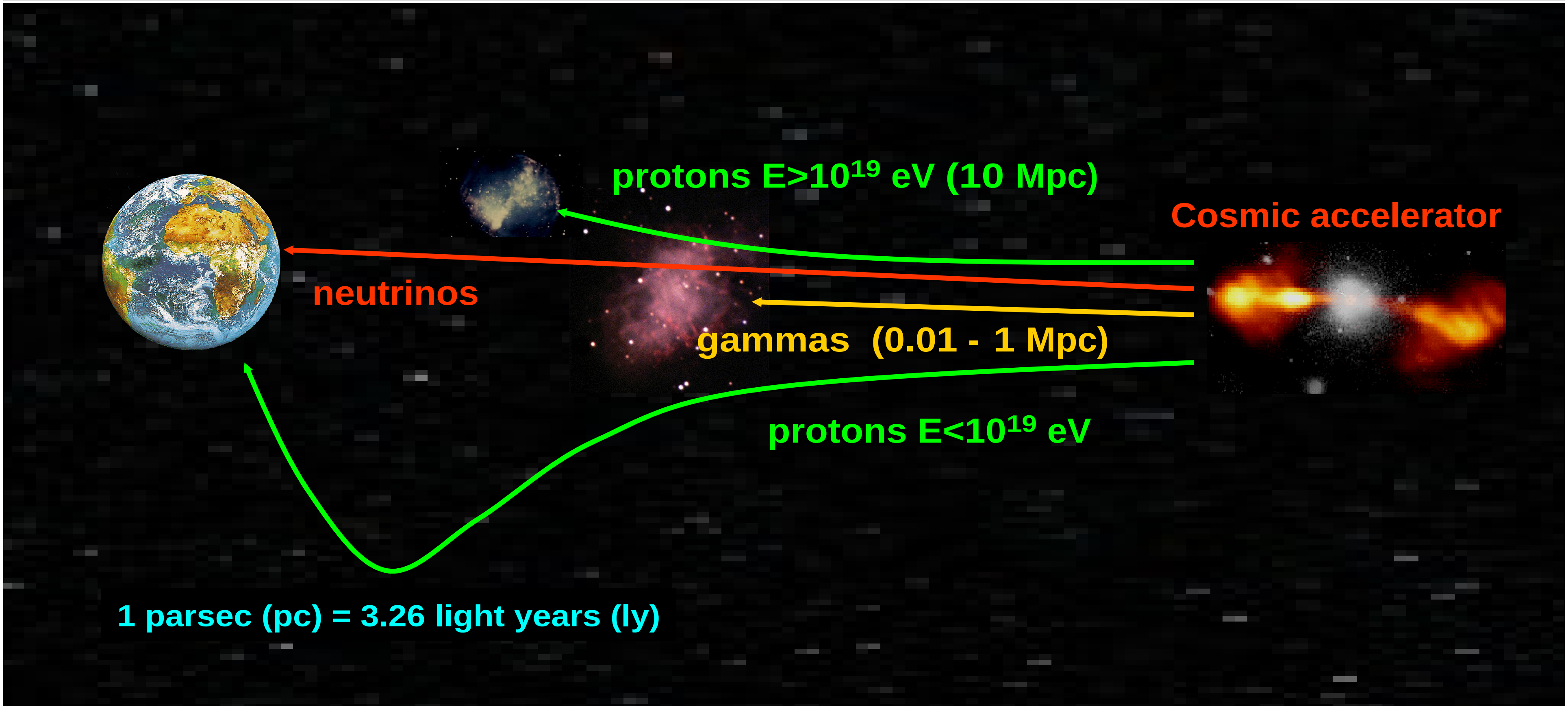
10.03.2005

- Introduction
- Current Projects
- Aiming at a km³ Detector in the Mediterranean Sea
- The KM3NeT Design Study
- 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
  $\rightarrow$ distinction between electron and proton acceleration.
- Neutrinos could be produced in Dark Matter annihilation.
- Neutrino detection requires huge target masses
  $\rightarrow$ use naturally abundant materials (water, ice).

Particle propagation in the Universe



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

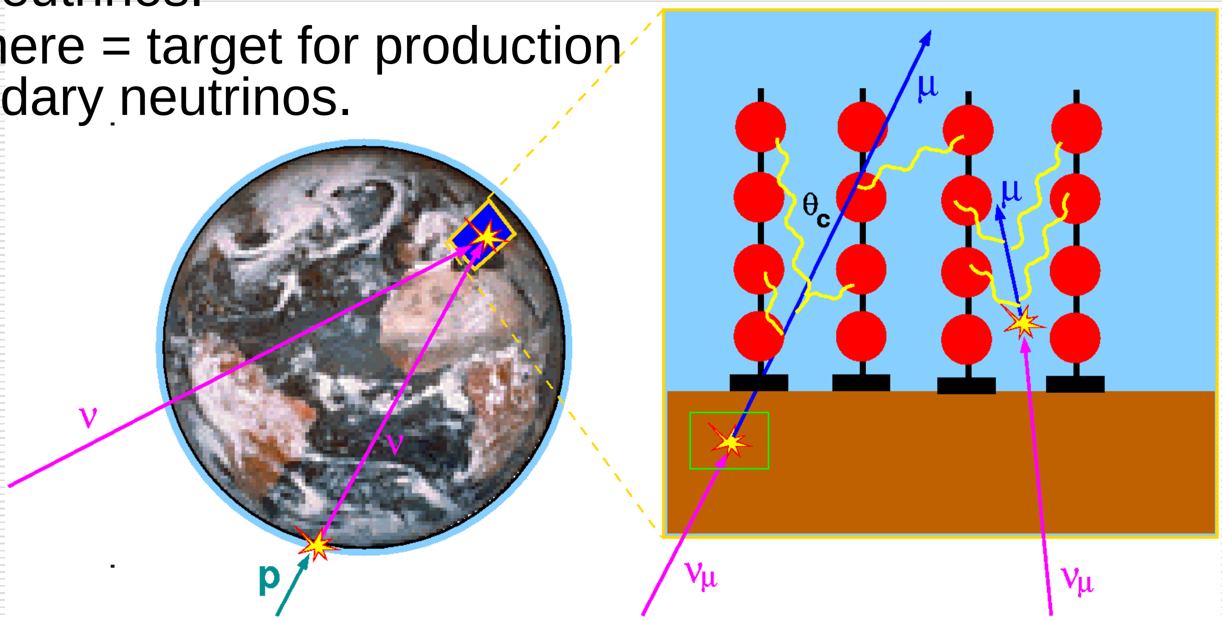
The Principle of Neutrino Telescopes

Role of the Earth:

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

Čerenkov light:

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

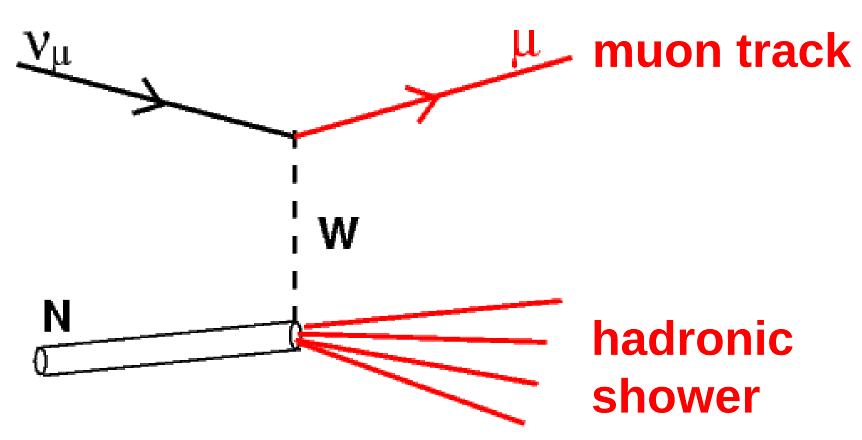


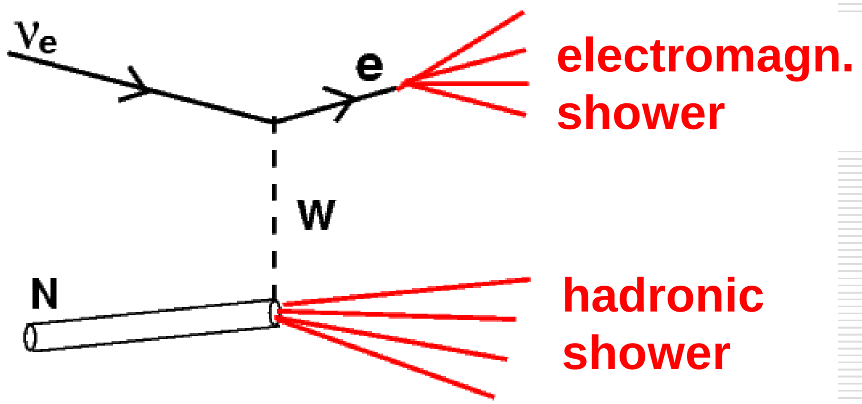
Neutrino reactions (key reaction is $\nu_\mu N \rightarrow \mu X$):

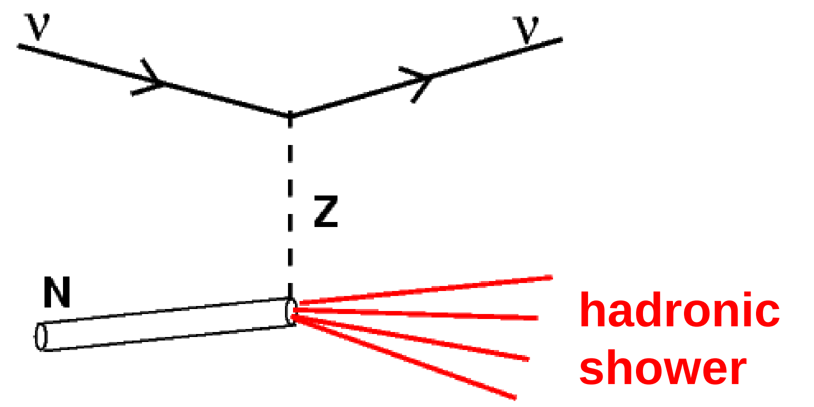
- Cross sections and reaction mechanisms known from accelerator experiments (in particular HERA).
- Extrapolation to highest energies (> 100 TeV) uncertain.

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.



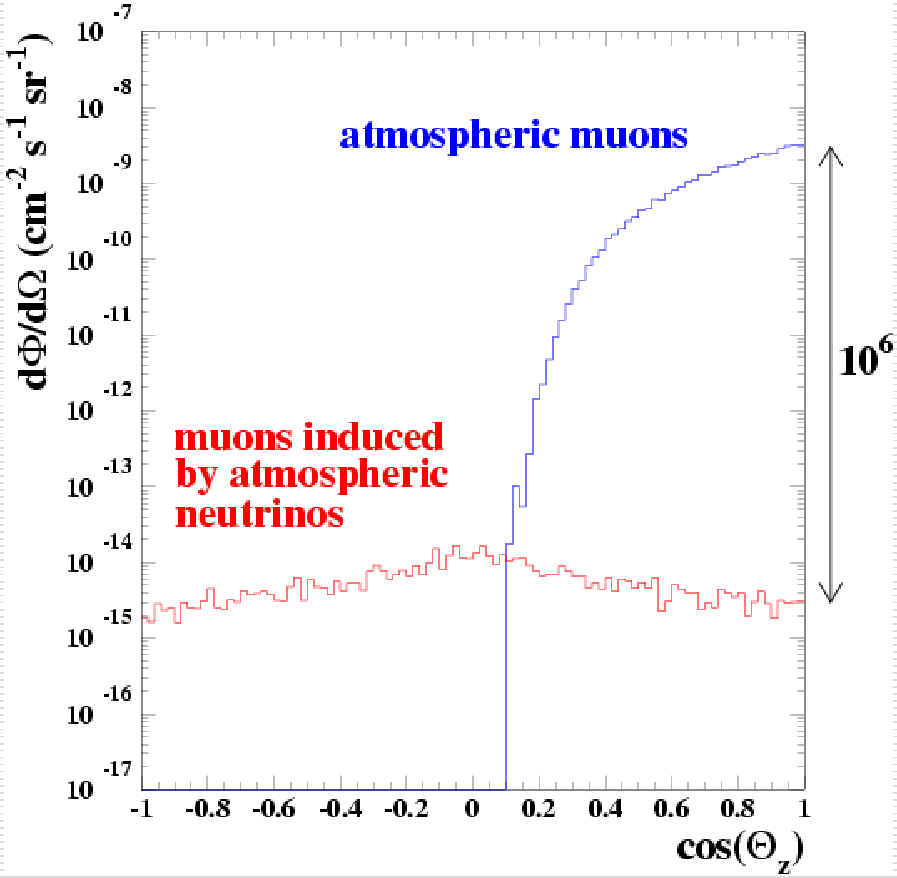


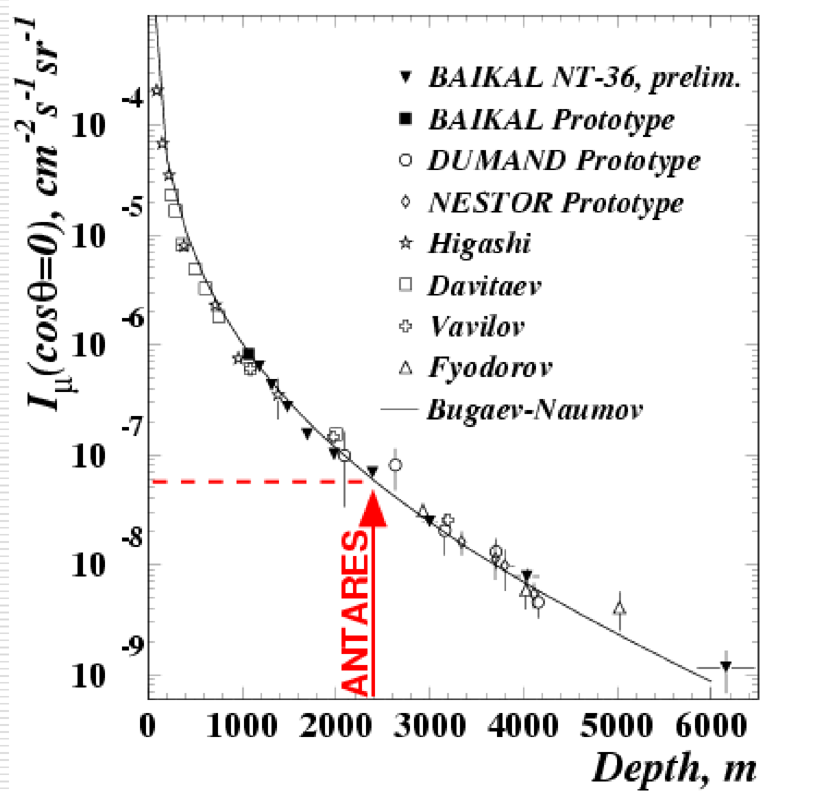


Muons: The Background from Above

Muons can penetrate several km of water if E_μ > 1TeV;

Identification of cosmic ν's from above: needs showers or very high energies.





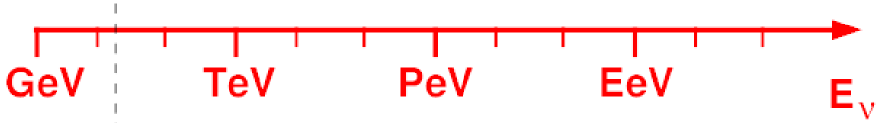
Particle and Astrophysics with ν Telescopes

Neutrino Oscillations:
Direction, Energy, Flavor

Dark matter search (WIMPs):
Direction, Energy

Cosmic point sources:
Direction, (Energy)

Diffuse cosmic neutrino flux:
(Direction), Energy



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.

High-energy limit:

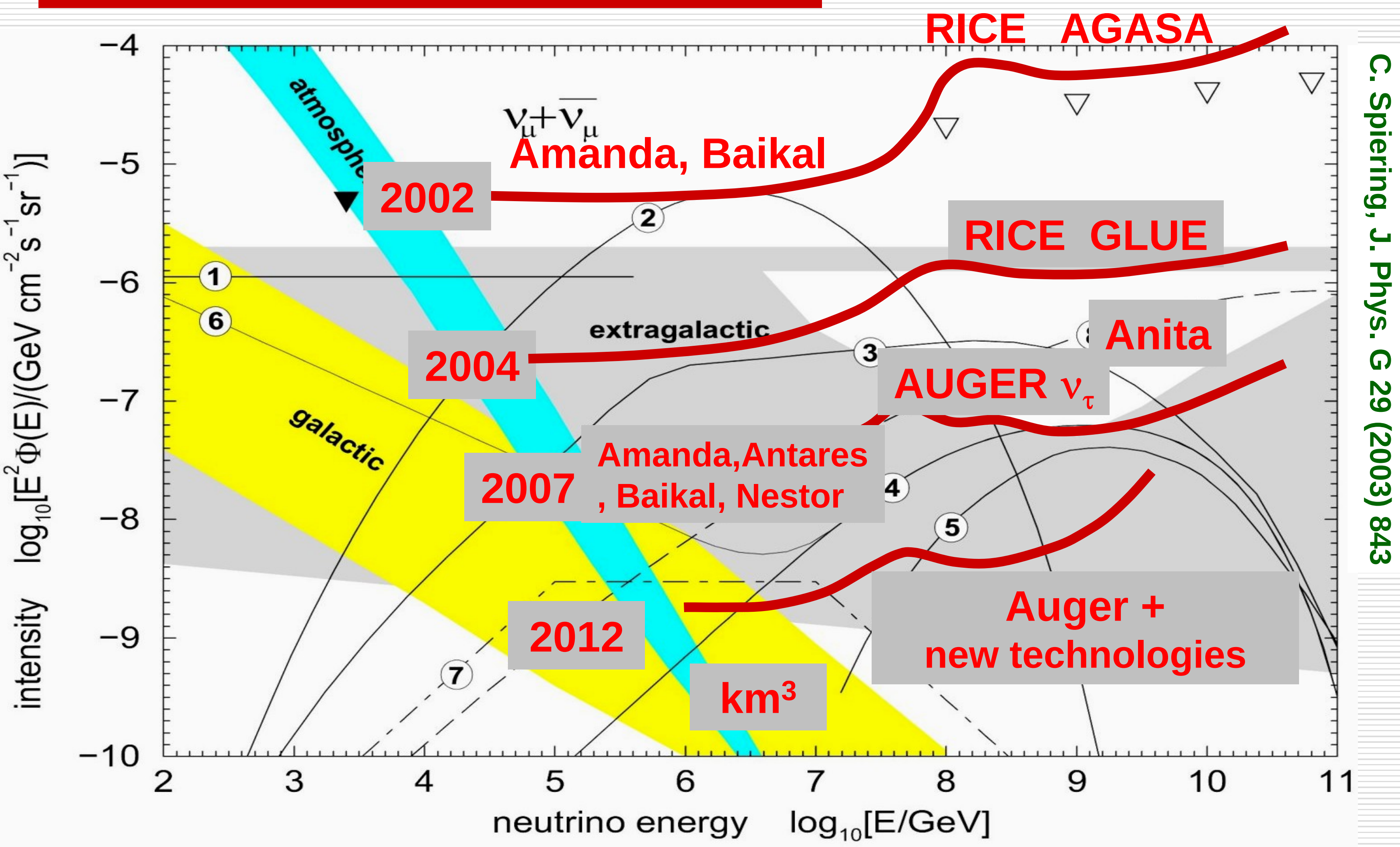
- fluxes decrease as $E^{-2} \ldots E^{-3}$;
- large detection volume needed.

Ultimate volume (at least) one cubic kilometer.

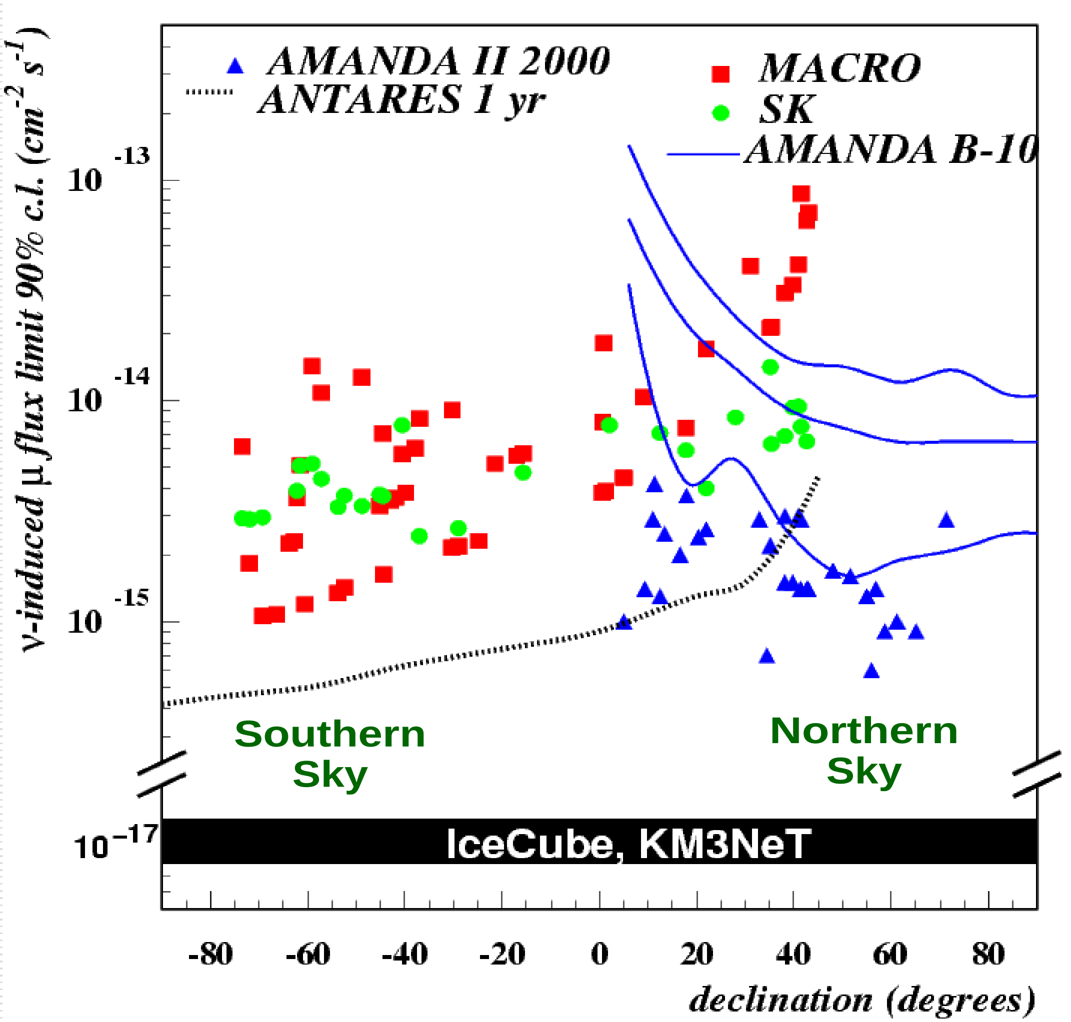
... and also:

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

Diffuse ν Flux: Limits and Sensitivities



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.

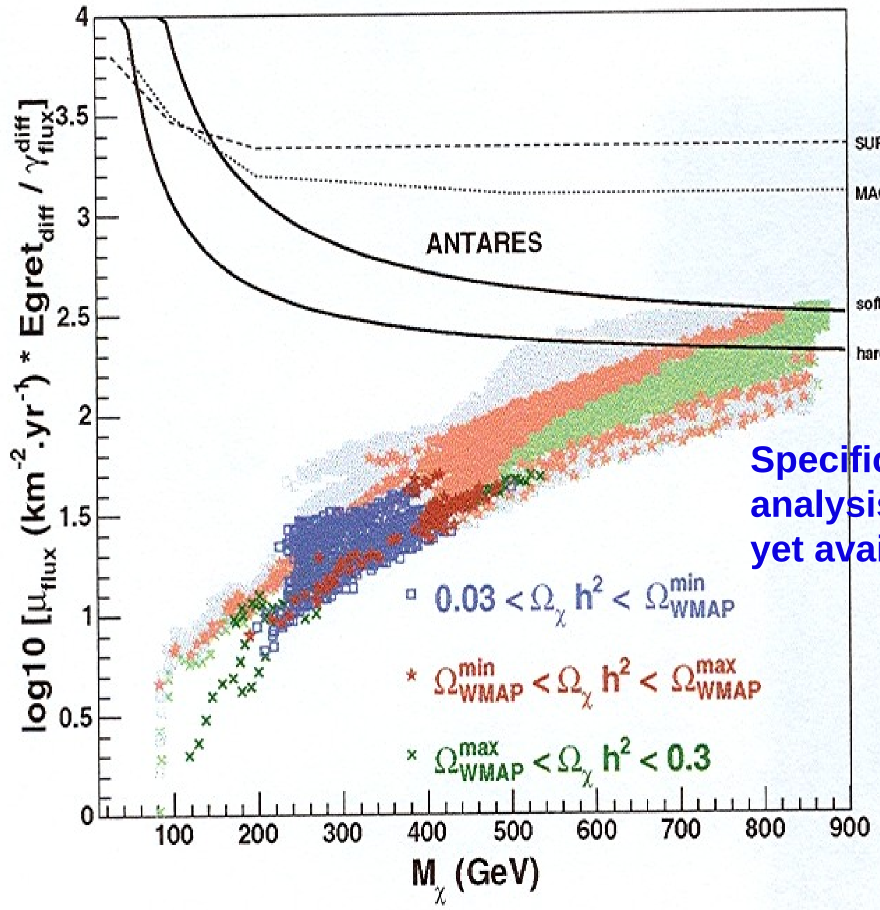
Indirect Search for Dark Matter

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

$$\chi\chi \rightarrow \nu + X$$

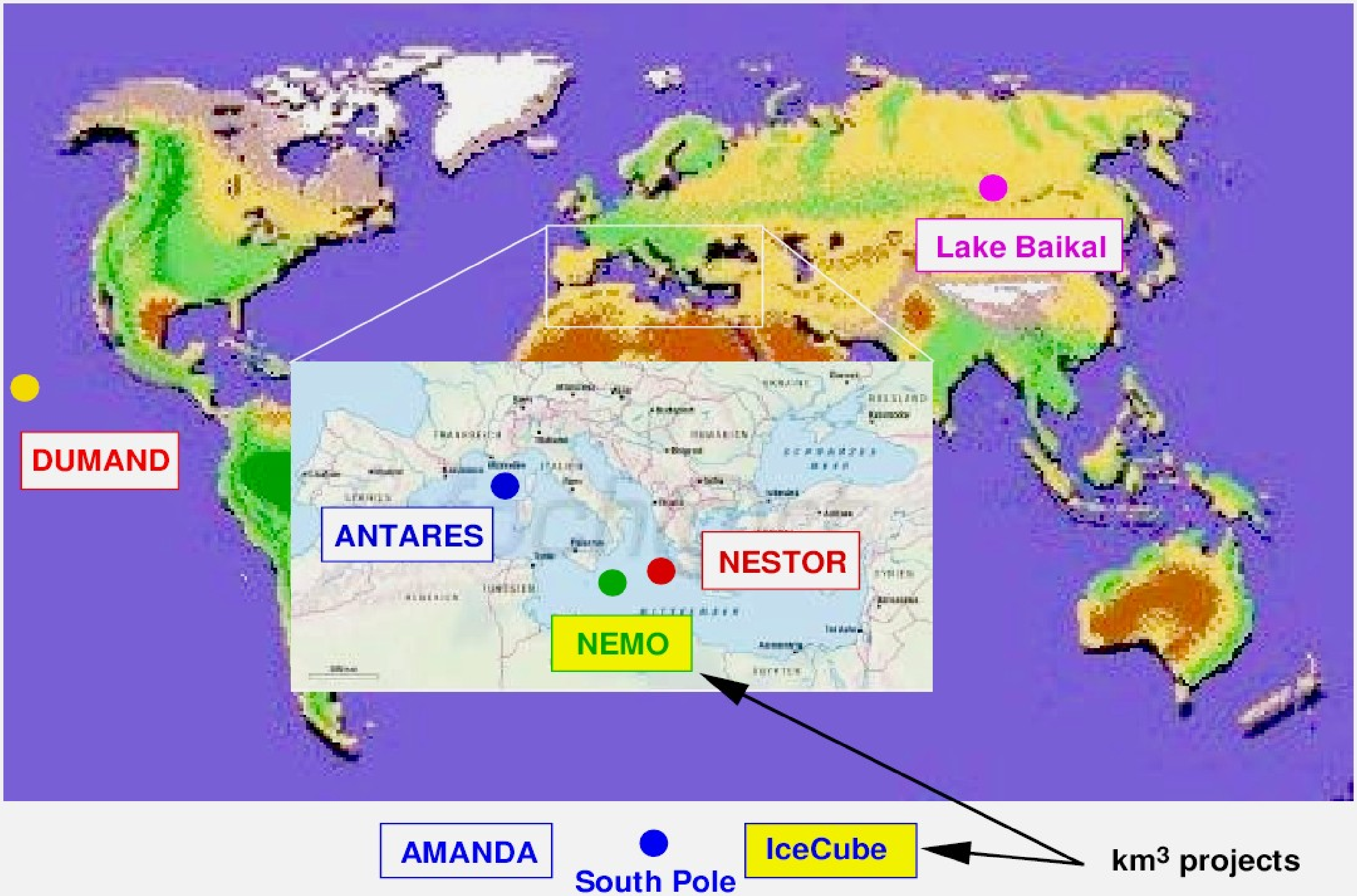
- Detection requires low energy threshold (O(100GeV) or less).
- Flux from Galactic Center may be enhanced if a Black Hole is present → exciting prospects [see e.g. P. Gondolo and J. Silk, PRL 83(1999)1719].
- But: model uncertainties are orders of magnitude!

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

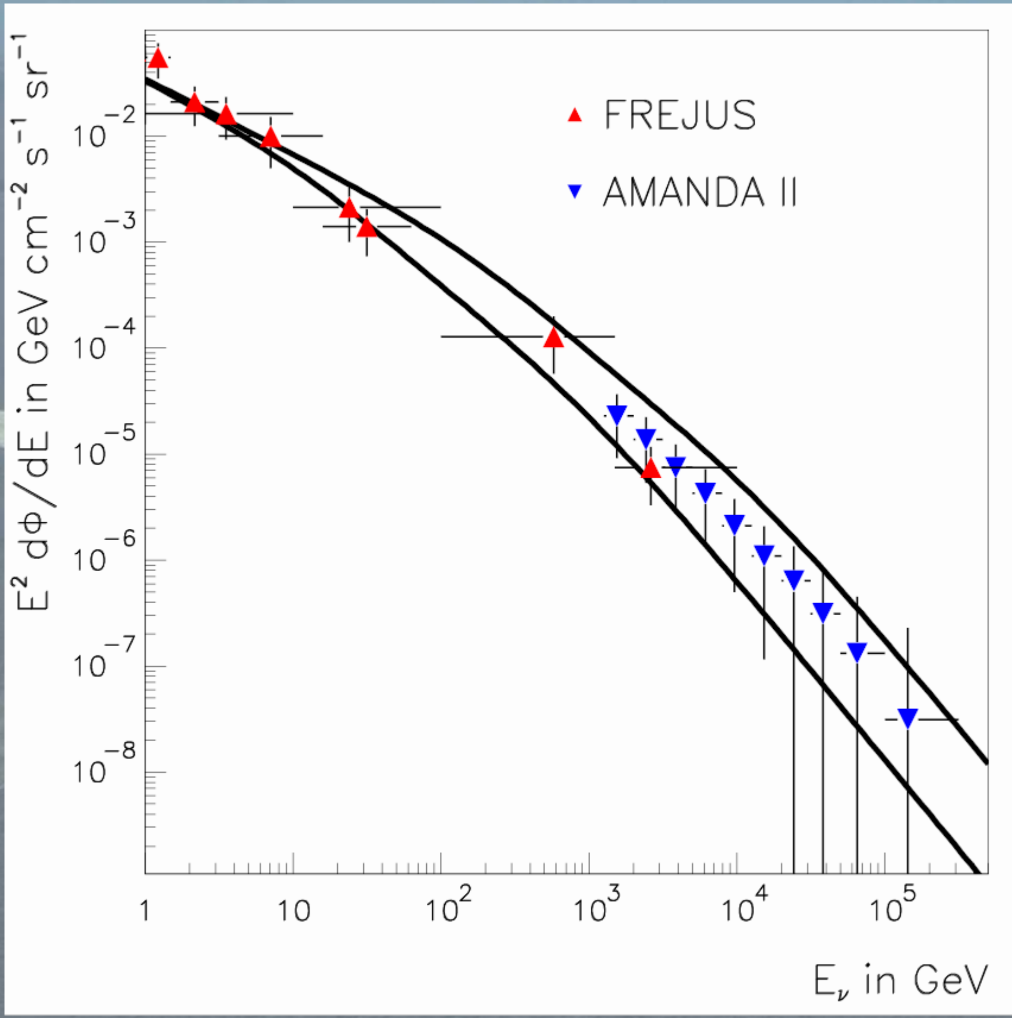


Specific km³ analysis not yet available.

The Neutrino Telescope World Map



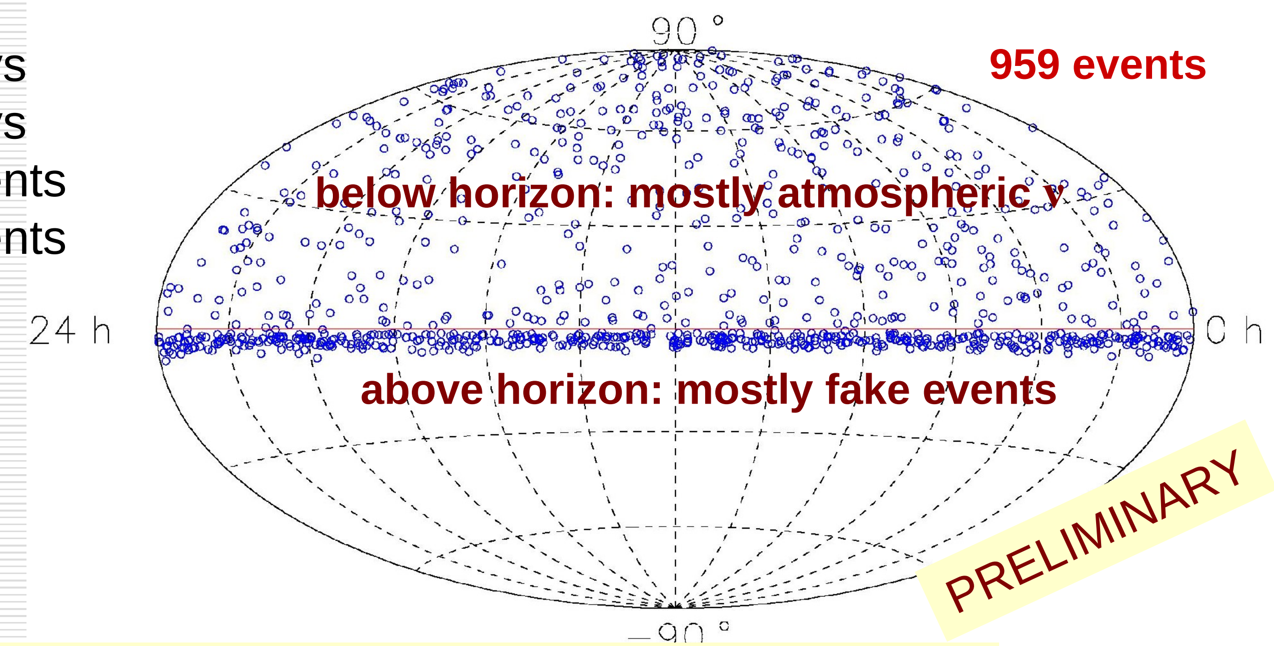
AMANDA: Pioneer Data



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

AMANDA: Search for ν point sources

Live time	
2000:	197 days
2001:	194 days
2000+2001:	959 events
below horizon:	465 events



Consistent with atmospheric ν:

No evidence for point sources

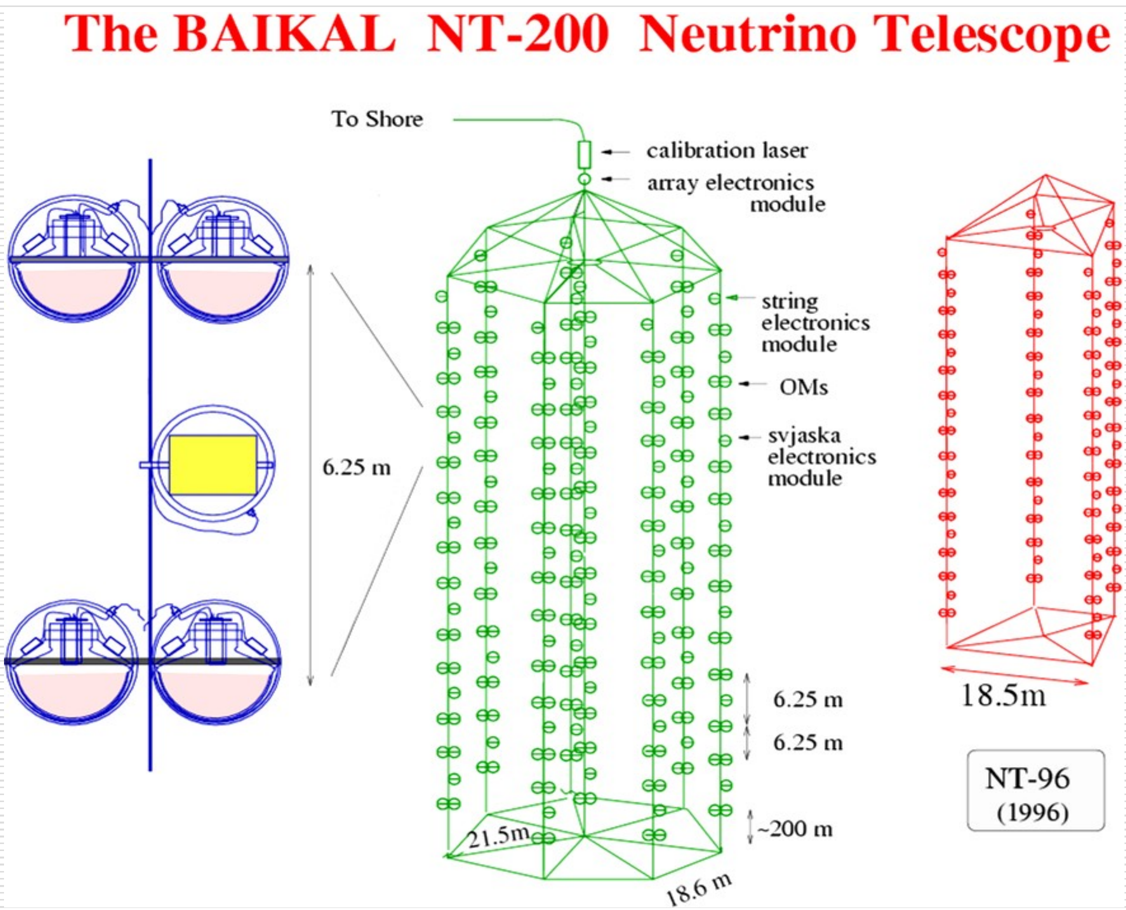
based on first 2 years of AMANDA-II data

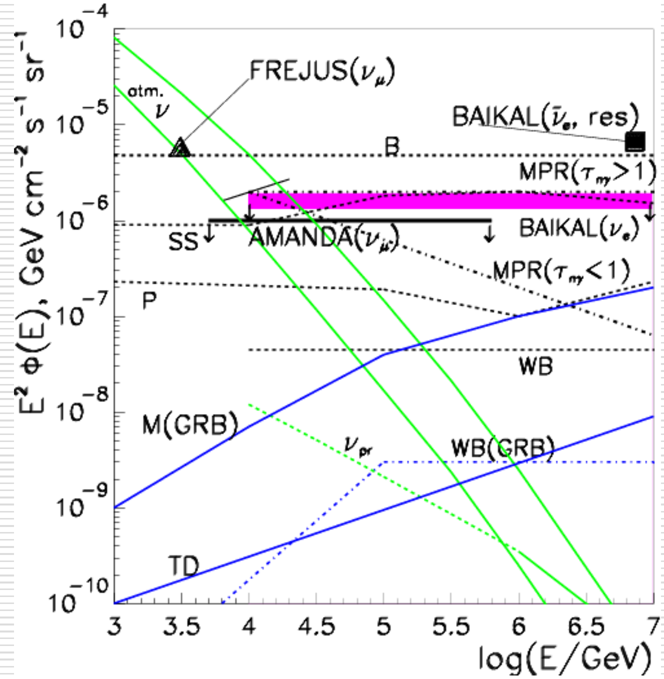
... but new data provide much higher statistics:

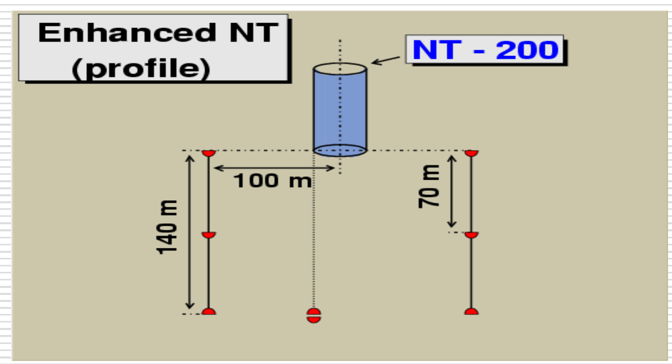
>3000 events, highest point source significance 3.5σ (Crab!)

Lake Baikal: A Sweet-Water ν Telescope

- Pioneers in under-water technology for ν telescopes.
- Many excellent physics results.
- Further upgrades planned, but km³ hardy reachable.

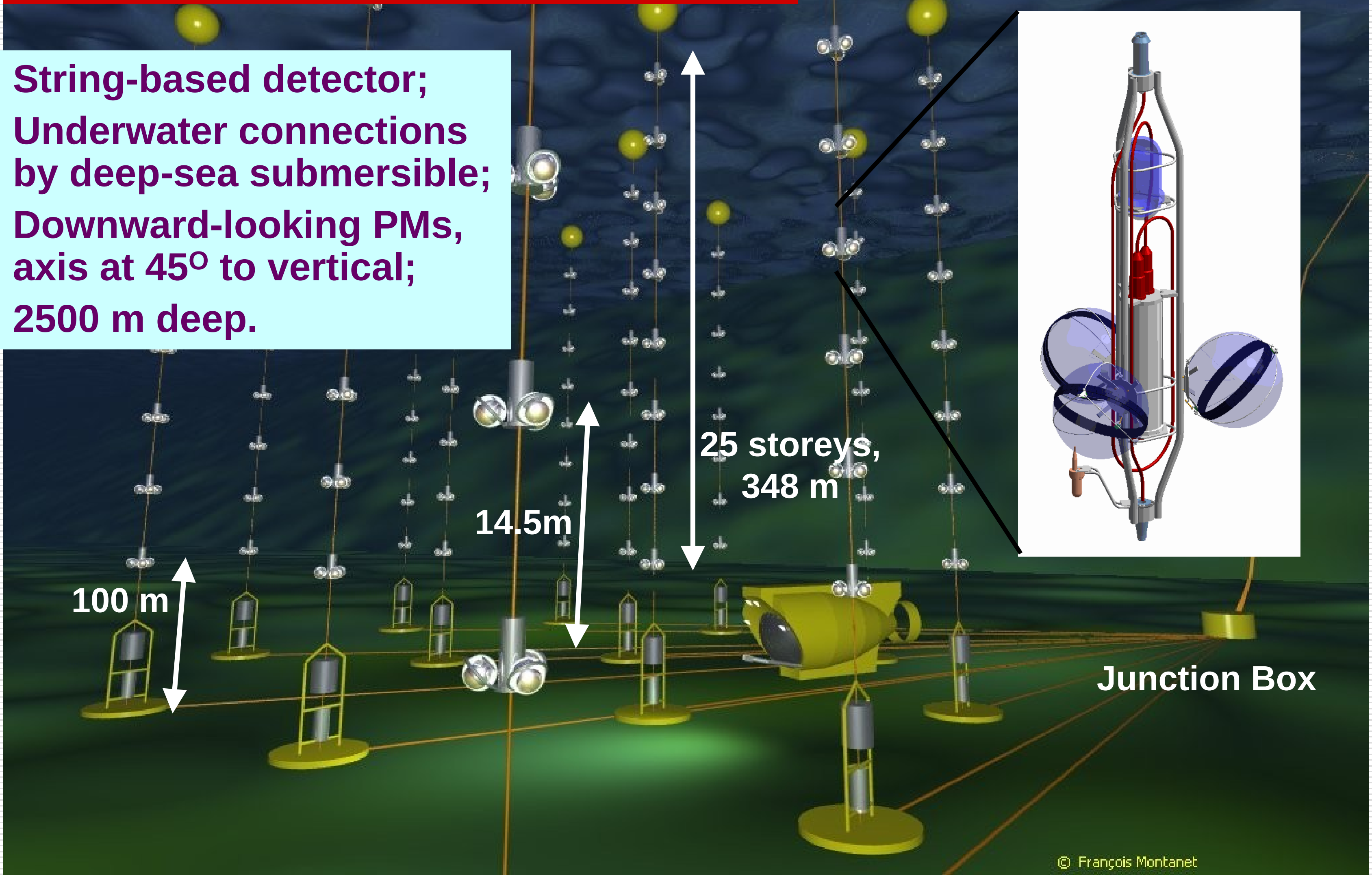






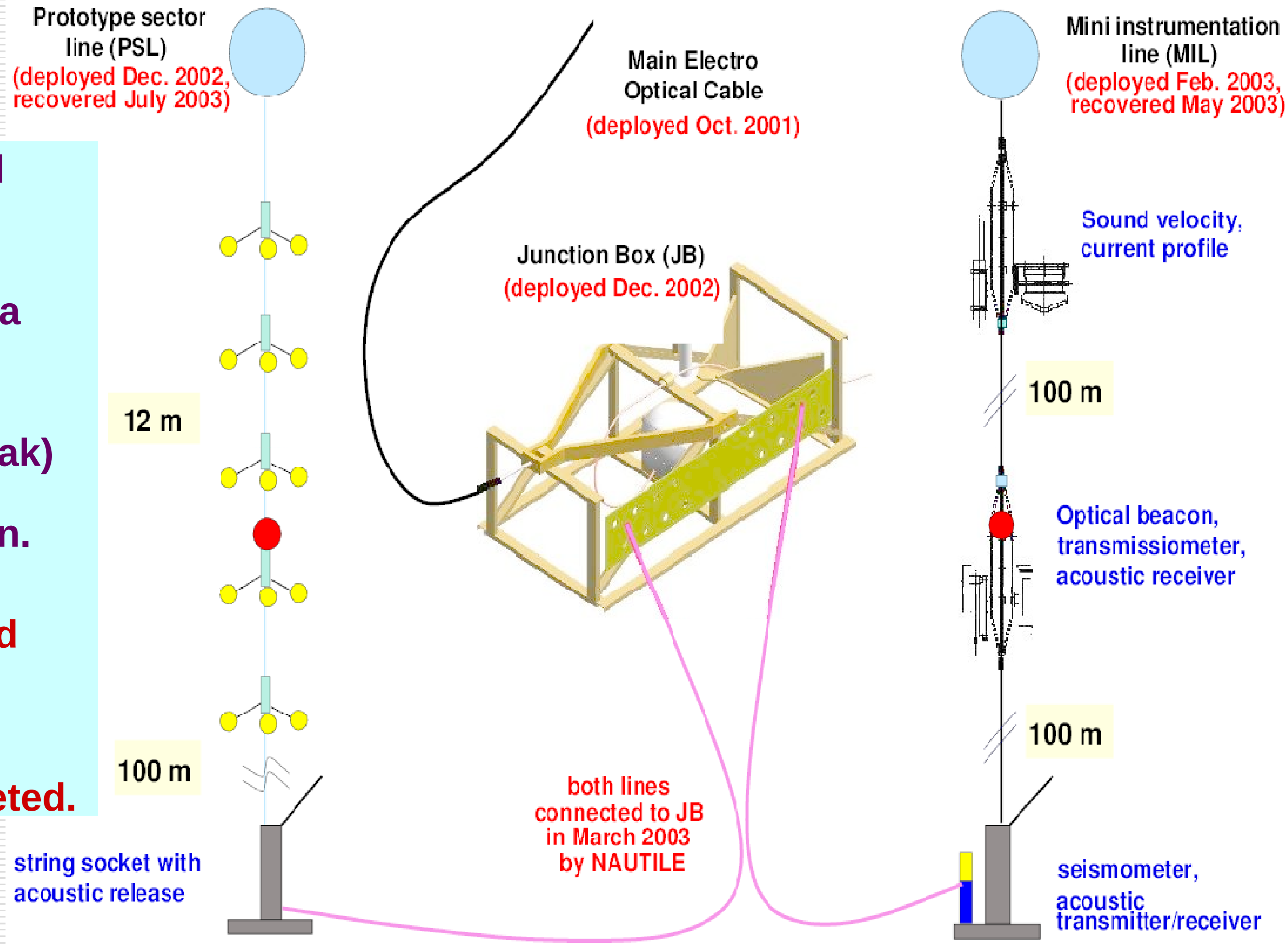
ANTARES: Detector Design

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



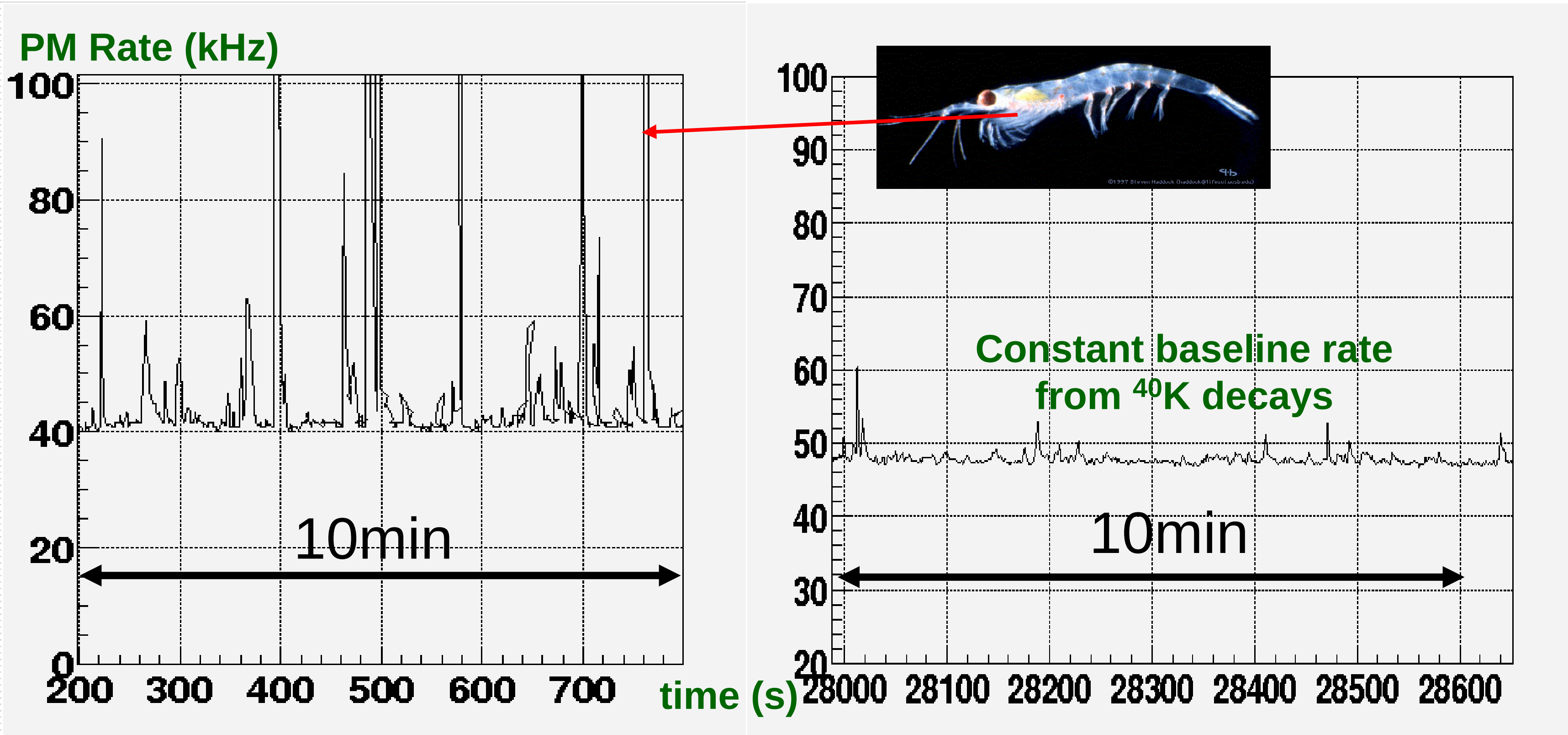
ANTARES: Status and Way to Completion

- **2003: Deployment and operation of two prototype lines.**
- **Several months of data taking.**
- **Technical problems (broken fiber, water leak)**
  → no precise timing,
  no μ reconstruction.
- **Early 2005: 2 upgraded prototype lines;**
- **Mid-2005: Line 1;**
- **2007: Detector completed.**



ANTARES: First Deep-Sea Data

- Rate measurements: Strong fluctuation of bioluminescence background observed



NESTOR: Rigid Structures Forming Towers

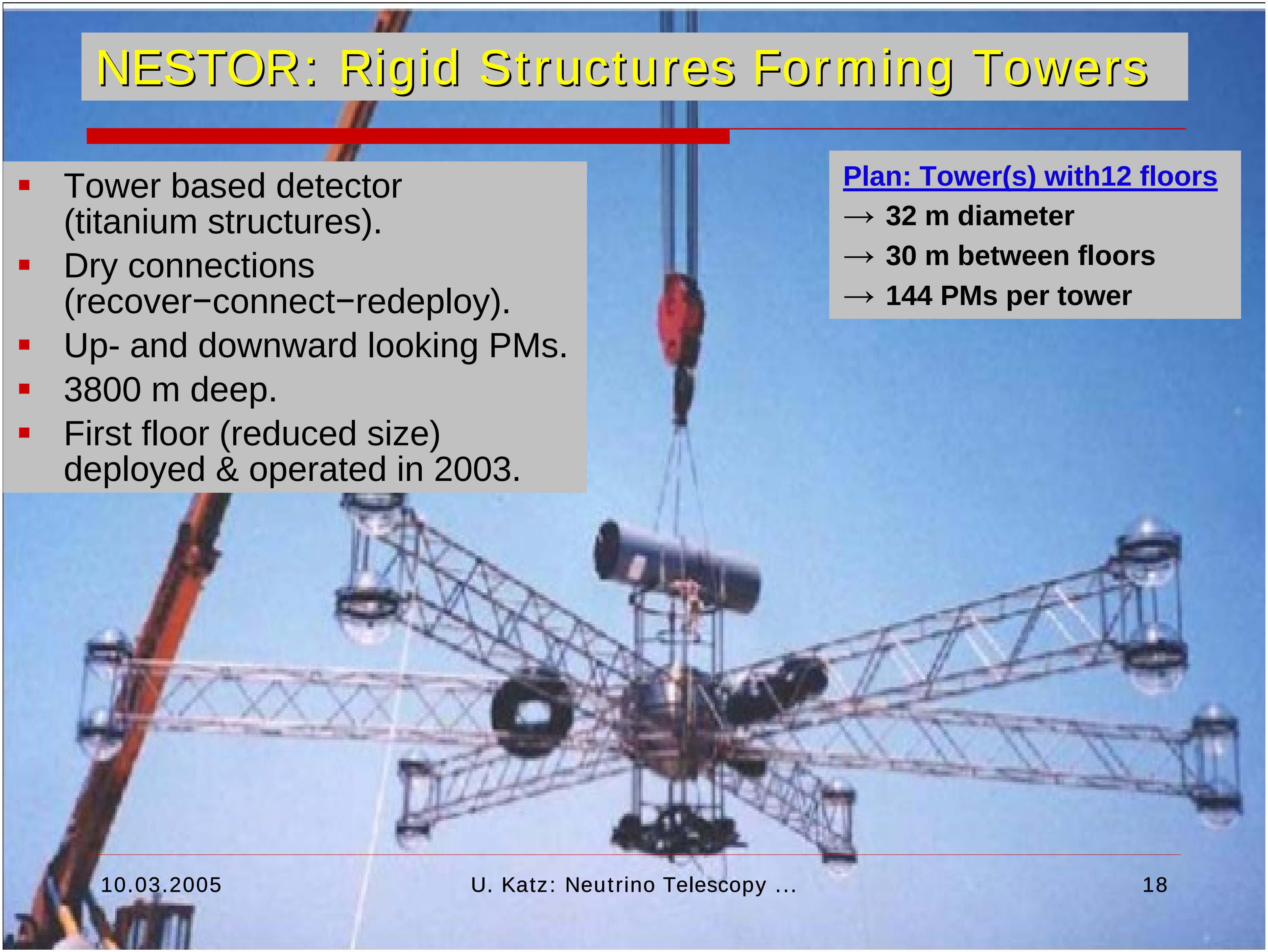
- Tower based detector (titanium structures).
- Dry connections (recover−connect−redeploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

Plan: Tower(s) with12 floors

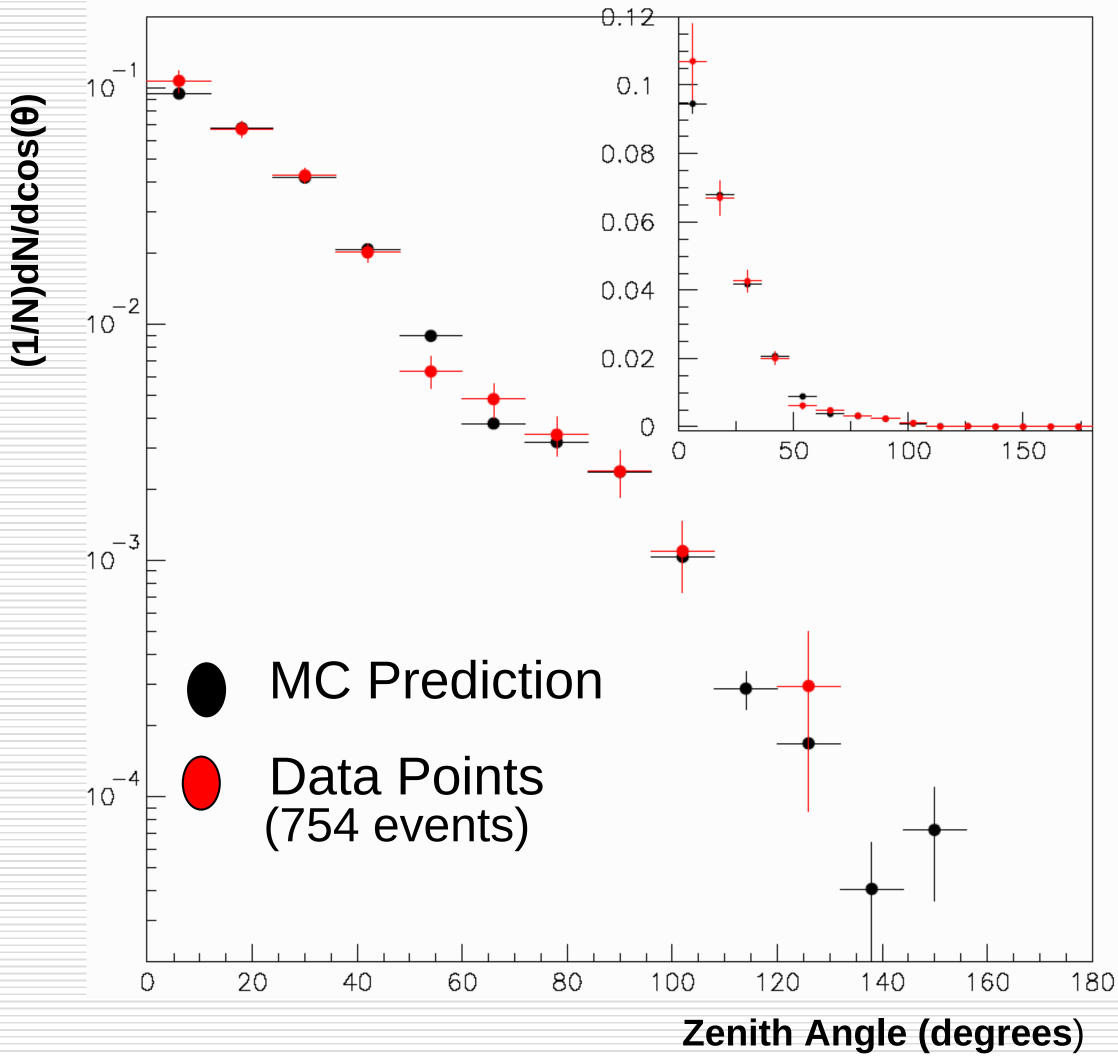
→ **32 m diameter**

→ **30 m between floors**

→ **144 PMs per tower**



NESTOR: Measurement of the Muon Flux



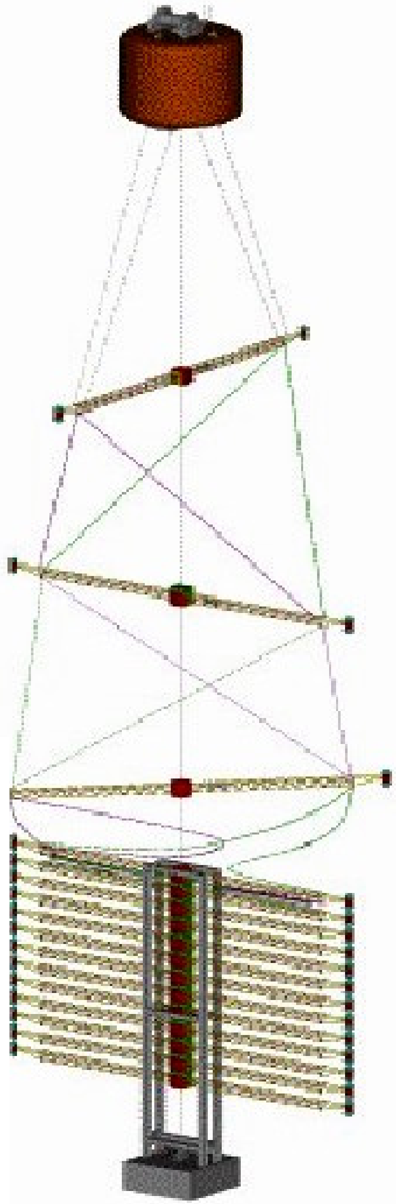
Atmospheric muon flux determination by reweighting MC simulation to observed raw zenith distribution using

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

Results agree nicely with previous measurements and with simulations.

The NEMO Project

- Extensive site exploration (Capo Passero near Catania, depth 3340 m);
- R&D towards km³: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

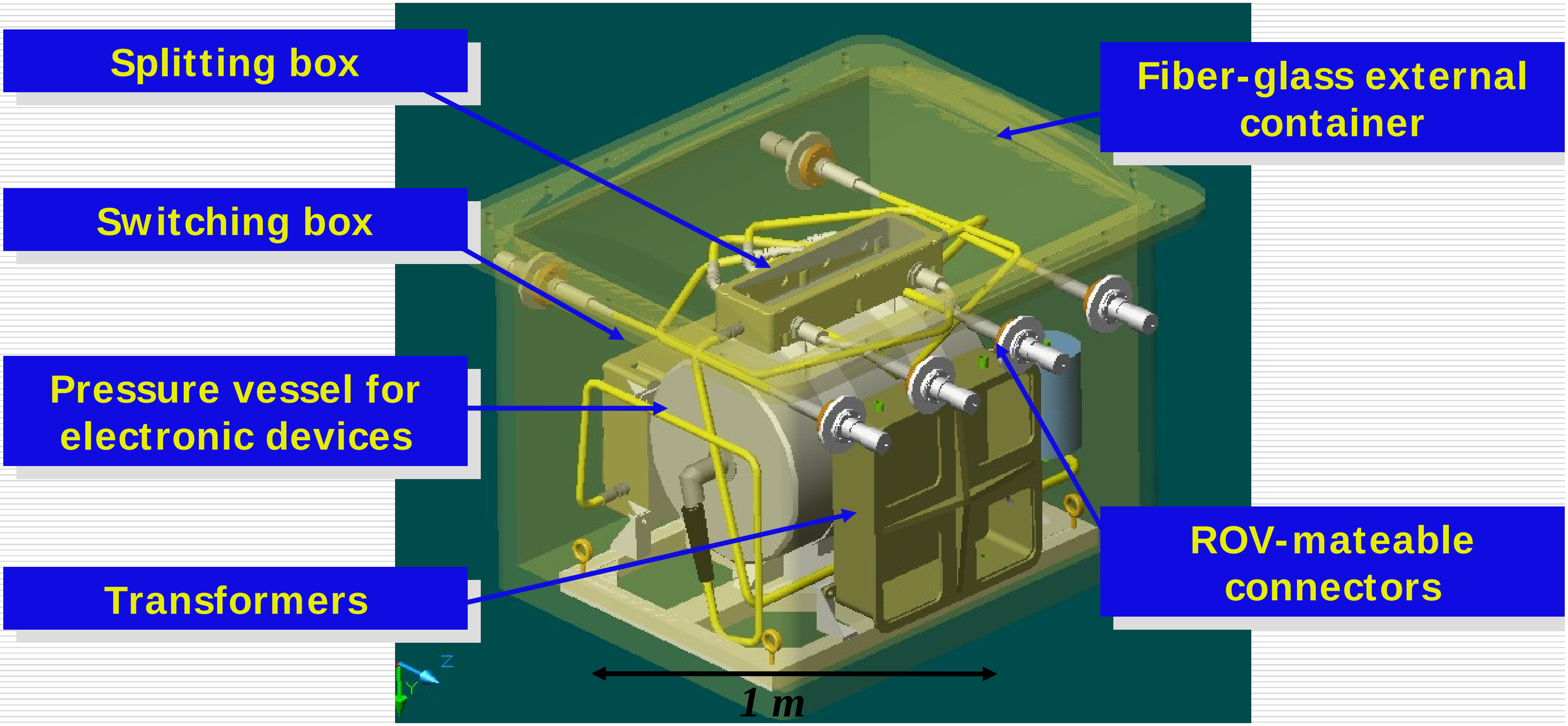


Example: Flexible tower

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

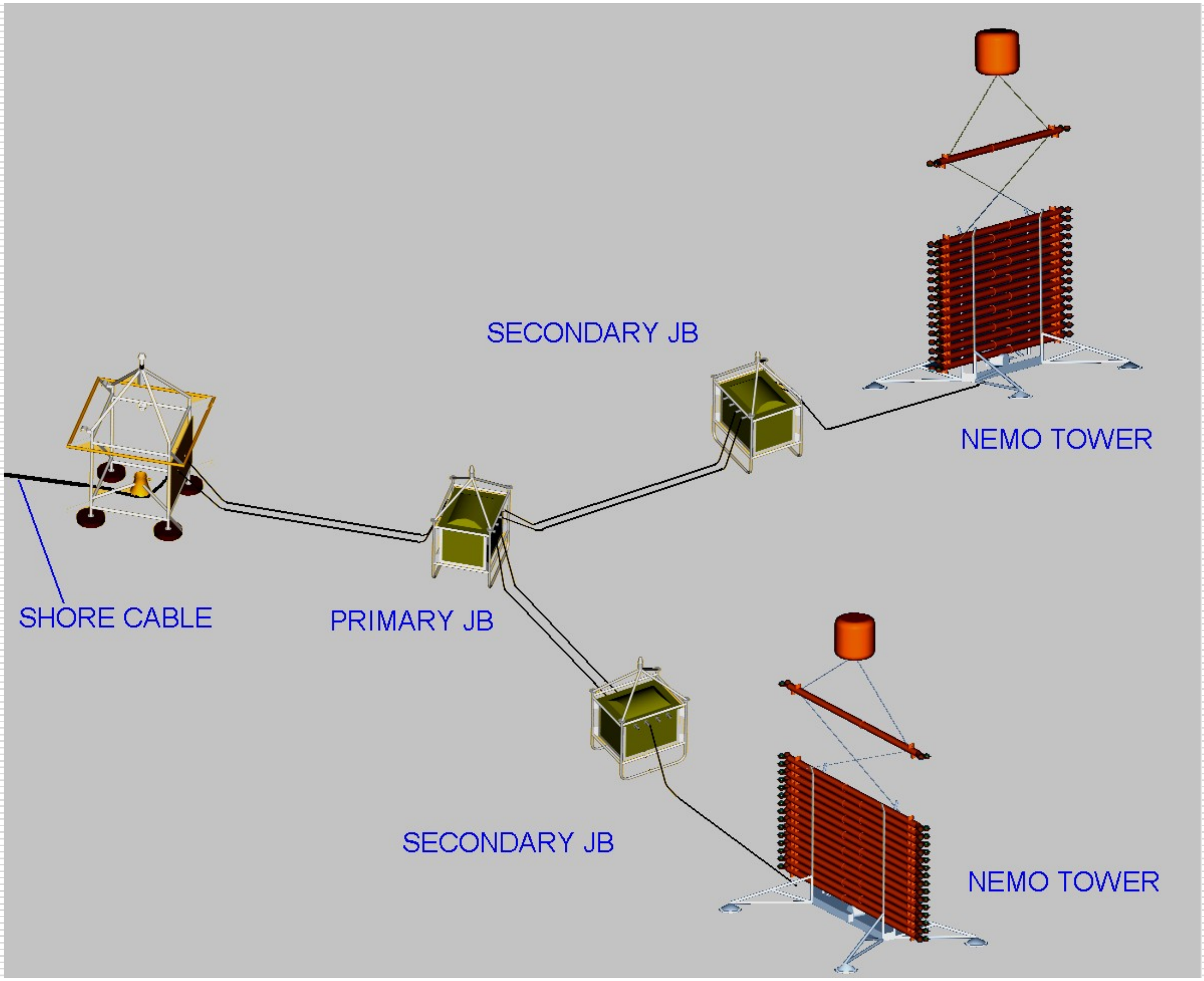
NEMO: Junction Box R&D

Aim: Decouple the problems of pressure and corrosion resistance.



NEMO: Phase-1 Test

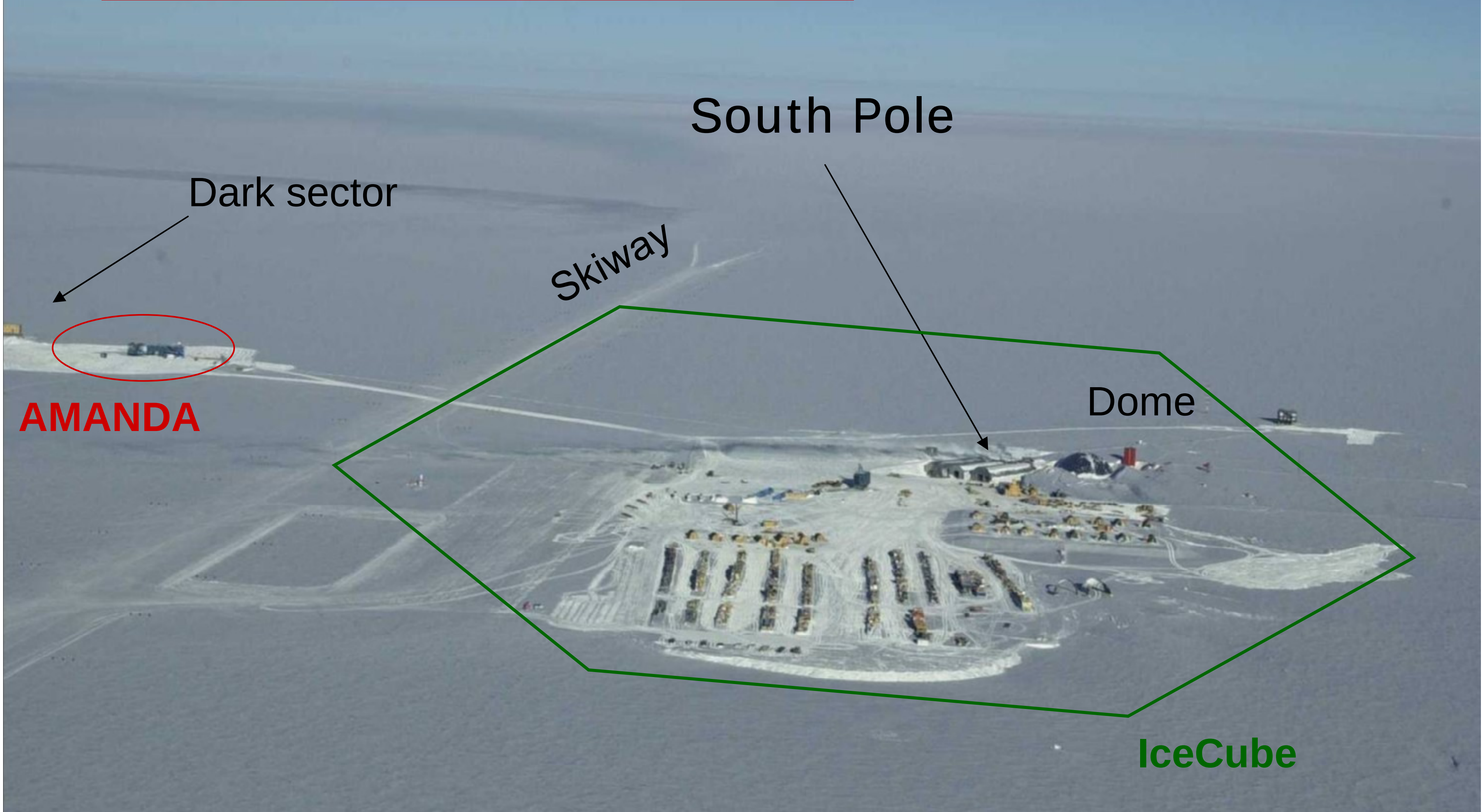
- Test site at 2000 m depth identified.
- Test installation foreseen with all critical detector components.
- Funding ok.
- Completion expected by 2006.



Current Projects: Summary

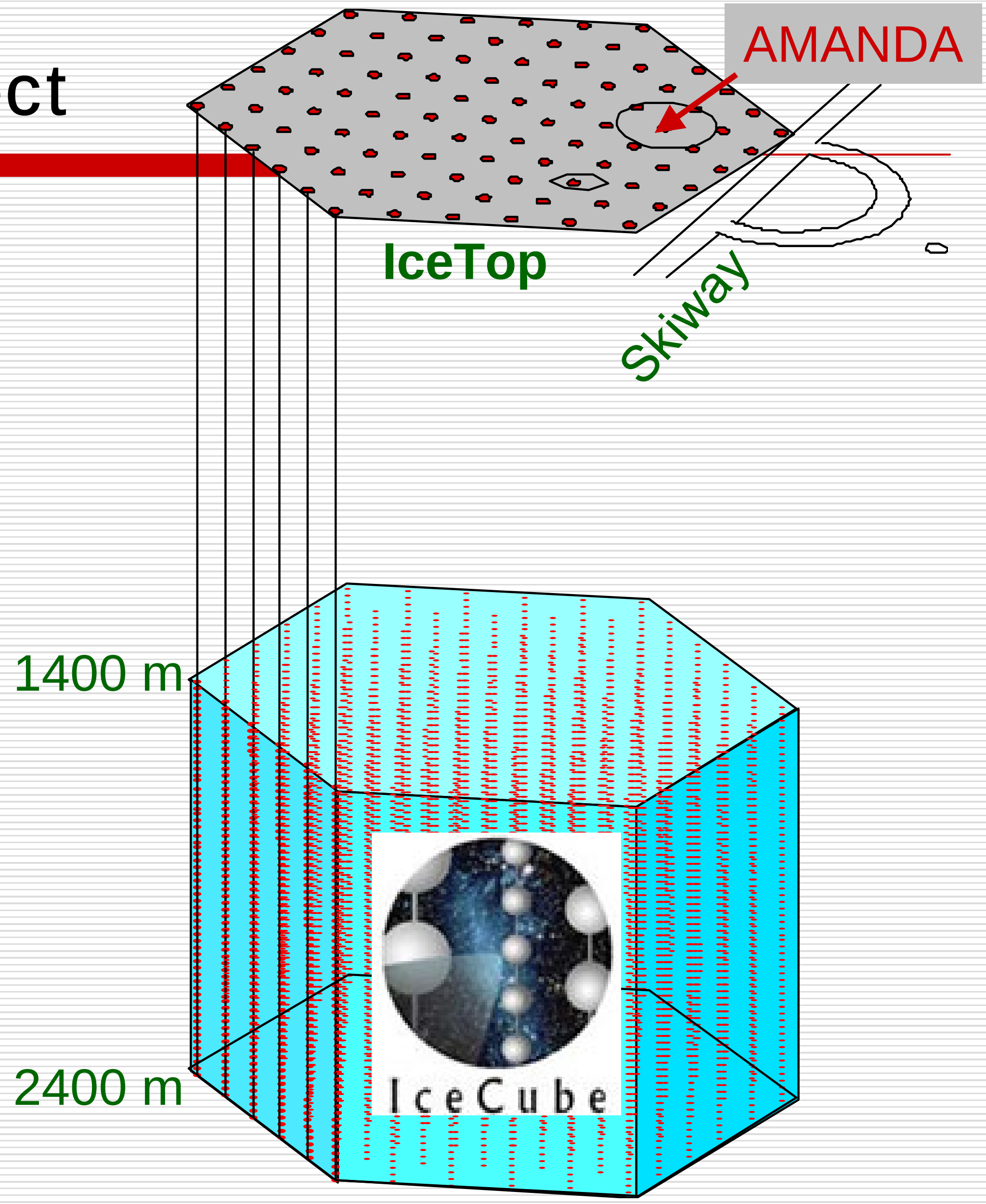
- AMANDA, Baikal: Taking data, feasibility proof of neutrino telescopy;
- ANTARES + NESTOR: first installation steps successfully completed, prototype detector modules deployed and operated; ANTARES construction in preparation, detector expected to be complete by 2007;
- Discovery potential for cosmic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

IceCube: a km^3 Detector in Antarctic Ice



The IceCube Project

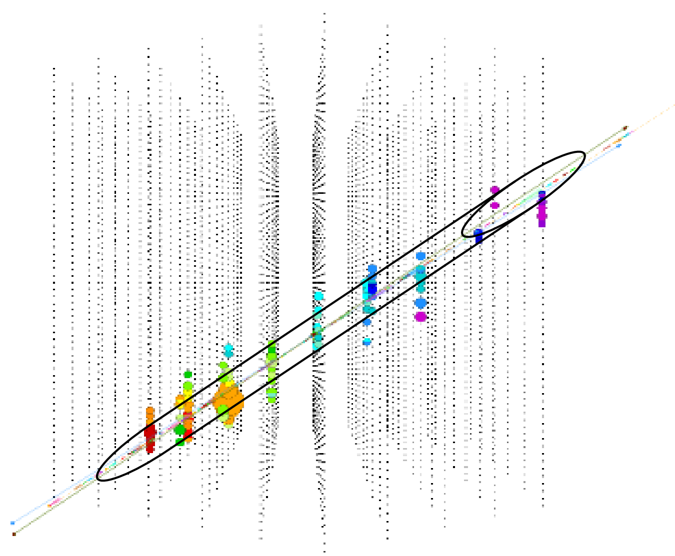
- **80 Strings;**
- **4800 PMTs;**
- **Instrumented volume: 1 km^3 (1 Gigaton)**
- **IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV**



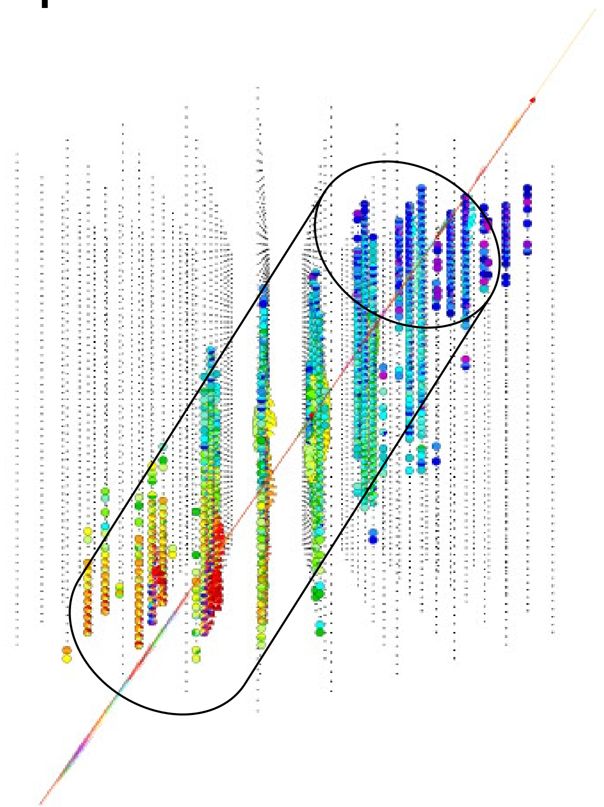
IceCube: How the events look like

The typical light cylinder around a muon is 20 m (100 GeV) to 600m (1 EeV) wide.

E_μ=10 TeV ≈ 90 hits

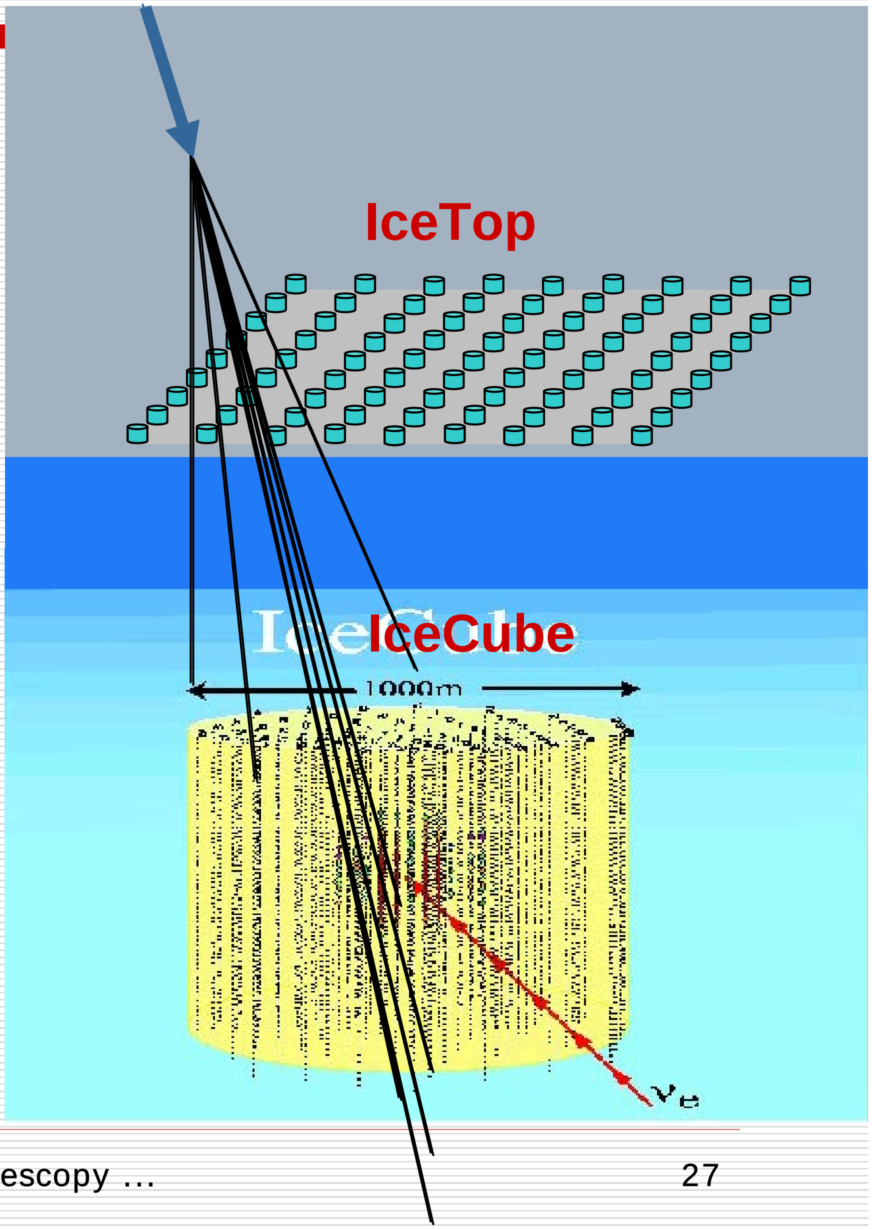


E_μ=6 PeV ≈ 1000 hits



IceTop/IceCube: Coincident events

- Energy range:
  - ~3 x 10^{14} – 10^{18} eV;
  - up to thousands of muons per event;
- Two functions:
  - veto and calibration;
  - cosmic-ray physics;
- Measure:
  - Shower size at surface;
  - High energy muon component in ice;
- Large solid angle:
  - One IceTop station per hole;
  - ~ 0.5 sr for cosmic-ray physics with "contained" trajectories;
  - Larger aperture as veto;



Aiming at a km^3-Detector in the Mediterranean

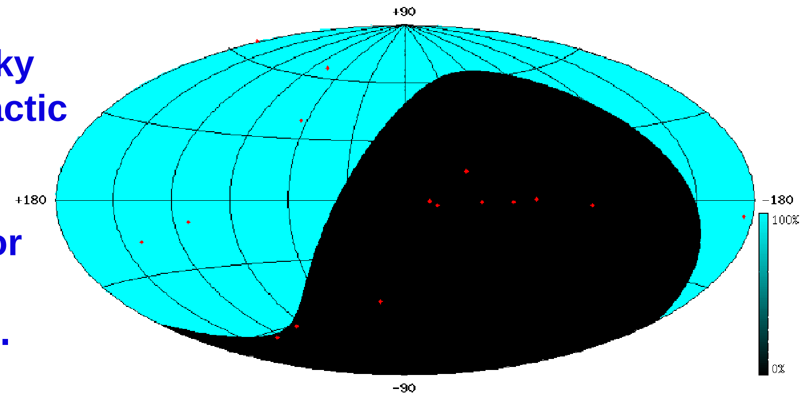
HENAP Report to PaNAGIC, July 2002:

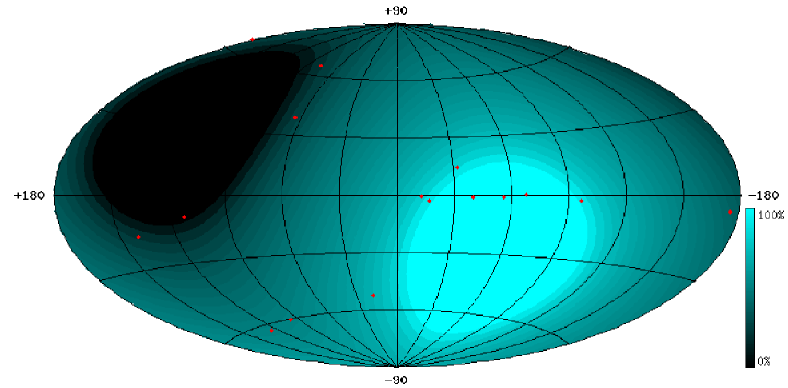
- “The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ...“
- “... a km^3-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole.”
- “The detector should be of km^3-scale, the construction of which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

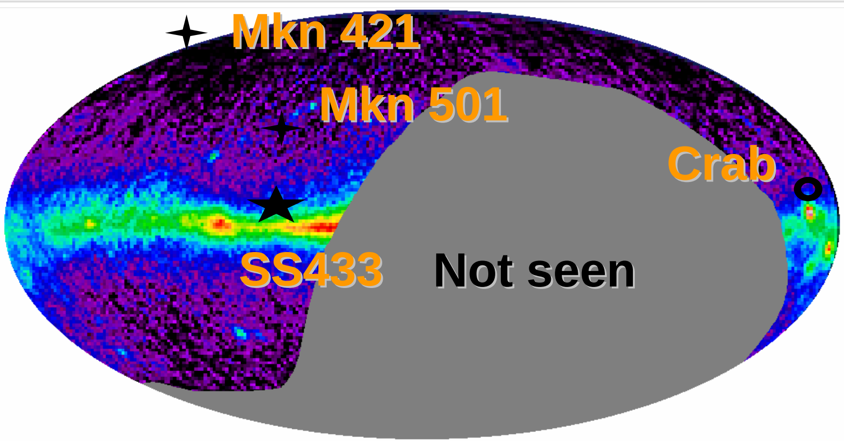
Sky Coverage of Neutrino Telescopes

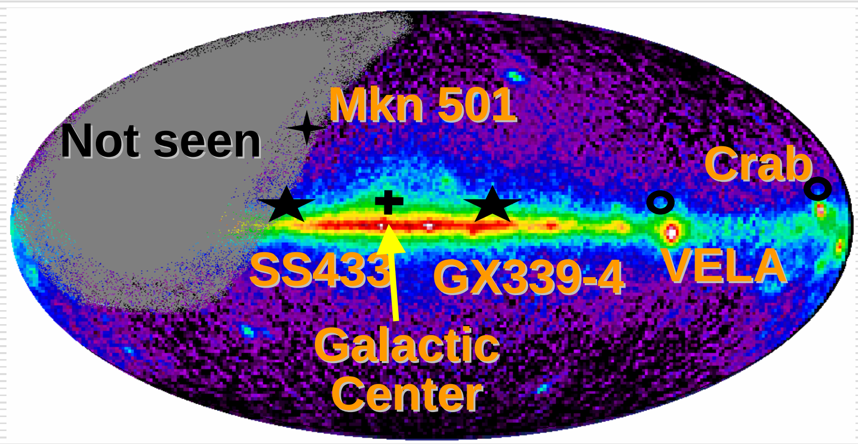
South Pole | **Mediterranean**

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



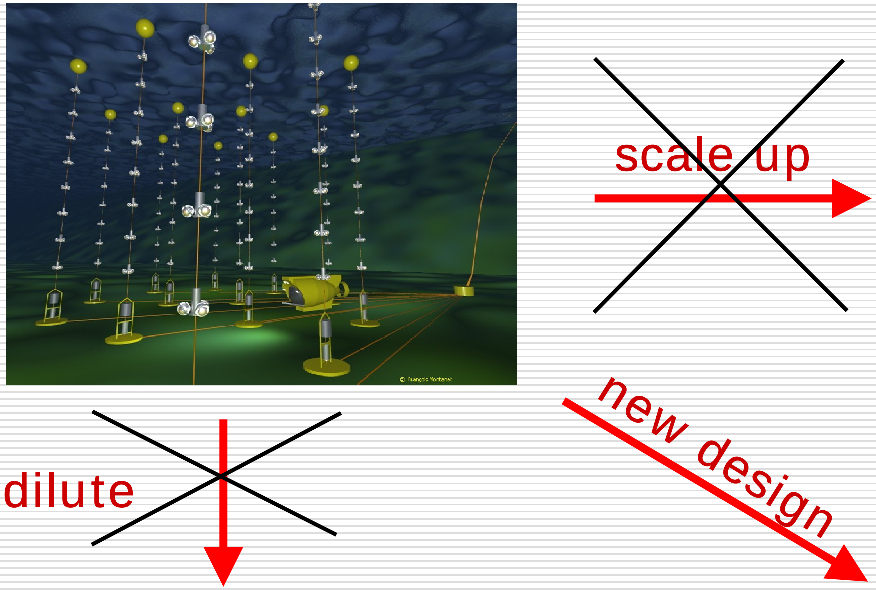






→ We need ν telescopes in both hemispheres to see the whole sky

How to Design a km³ Deep-Sea ν Telescope



Existing telescopes " times 100" ?

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

R&D needed:

- 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

Large volume with same number of PMs?

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

The KM3NeT Design Study (EU FP6)

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

- Initial initiative Sept 2002.
- Intense discussions and coordination meetings from beginning of 2003 on.
- 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%).
- Unofficial but reliable message (Sept. 2004):
  The KM3NeT Design Study will be funded !
- Currently waiting for EU budget allocation.

KM3NeT Design Study Participants

- Cyprus: Univ. Cyprus
- France: CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IreS Strasbourg), 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, Messina, Pisa, Roma-1, LNS Catania, LNF Frascati), INGV, Tecnomare SpA
- Netherlands: NIKHEF/FOM + Groningen?
- Spain: IFIC/CSIC Valencia, Univ. Valencia, UP Valencia
- UK: Univ. Aberdeen, Univ. Leeds, Univ. Liverpool, John Moores Univ. Liverpool, Univ. Sheffield

Particle/Astroparticle institutes – Sea science/technology institutes – Coordinator

Objectives and Scope of the Design Study

Establish path from current projects to KM3NeT:

- Critical review of current technical solutions;
- New developments, thorough tests;
- Comparative study of sites and recommendation on site choice (figure of merit: physics sensitivity / €);
- Assessment of quality control and assurance;
- Exploration of possible cooperation with industry;
- Investigation of funding and governance models.

Envisaged time scale of design, construction and operation poses stringent conditions.

Design Study Target Values

- Detection principle: water Čerenkov.
- Location in Europe: in the Mediterranean Sea.
- Detection view:
  maximal angular acceptance for all possible detectable neutrino signals including down-going neutrinos at VHE.
- Detection volume: 1 km^3, expandable.
- Angular resolution: close to the intrinsic resolution (< 0.1° for muons with $E_\mu > 10$ TeV).
- Lower energy threshold:
  a few 100 GeV for upward going neutrinos with the possibility to go lower for ν from known point sources.
- Energy reconstruction: within a factor of 2 for muon events.
- Reaction types: all neutrino flavors.
- Duty cycle: close to 100%.
- Operational lifetime: ≥ 10 years.
- Cost-effectiveness: < 200 M€ per km^3.

Most of these parameters need optimisation !

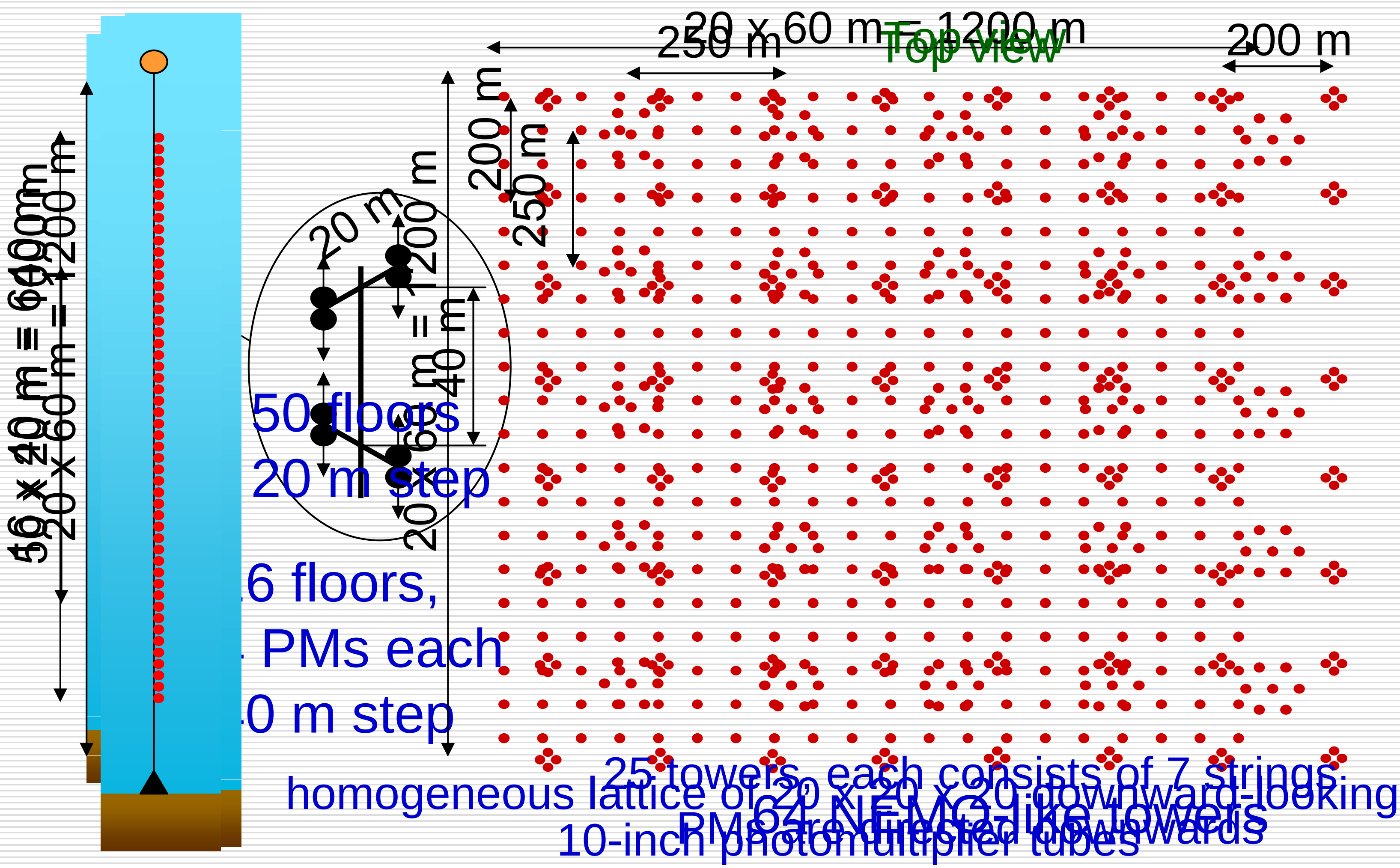
Some Key Questions

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: The site choice/recommendation!

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?

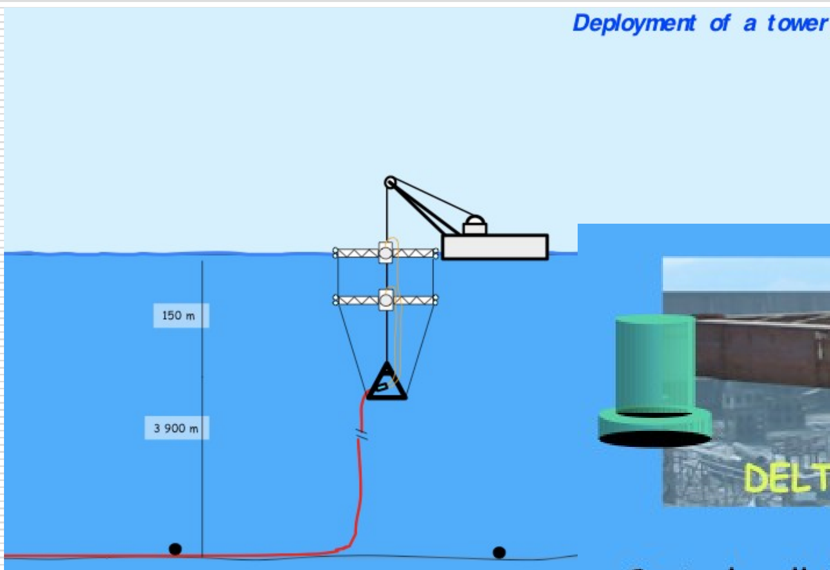
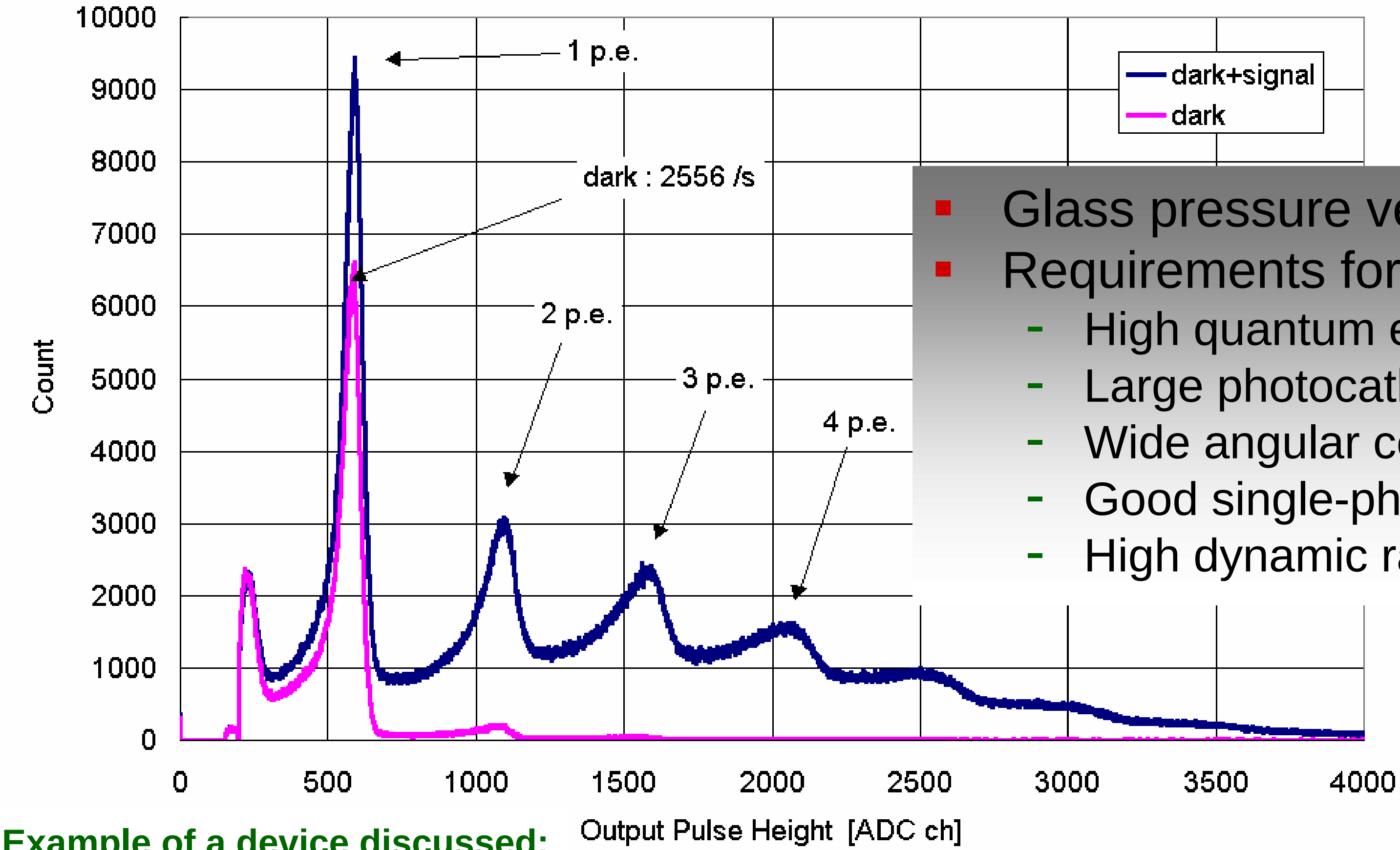


Photo Detection: Requirements

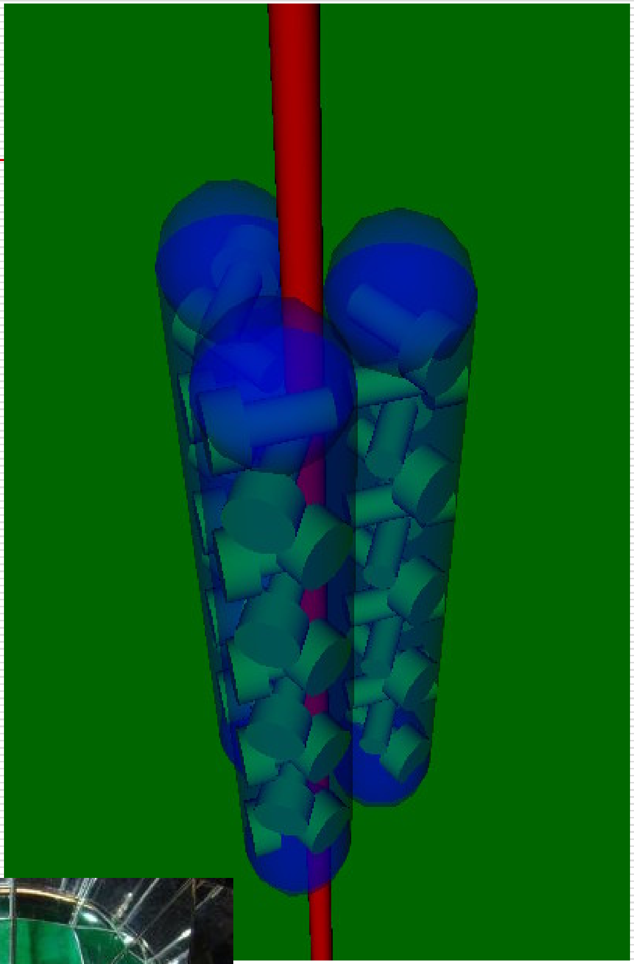


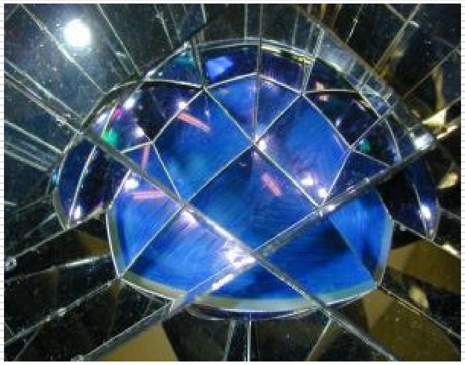
- Glass pressure vessel ≤ 17 inch
- Requirements for ν telescopes:
  - High quantum efficiency
  - Large photocathode areas
  - Wide angular coverage
  - Good single-photon resolution
  - High dynamic range

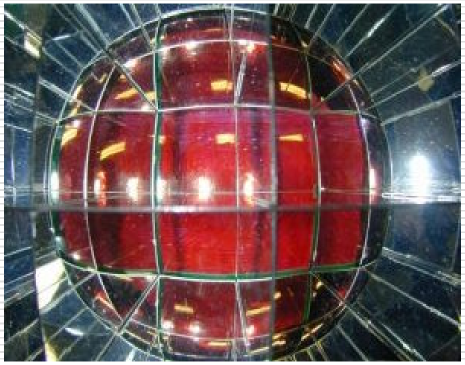
Example of a device discussed:
Hamamatsu HY0010 HPD
Excellent p.e. resolution

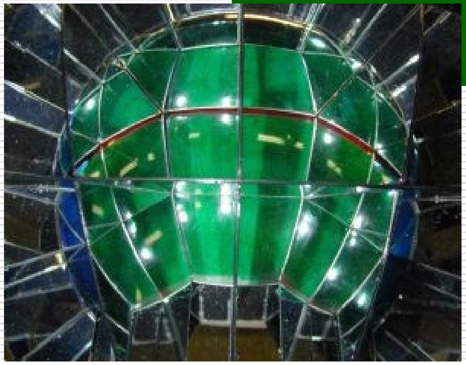
Photo Detection: Options

- 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.





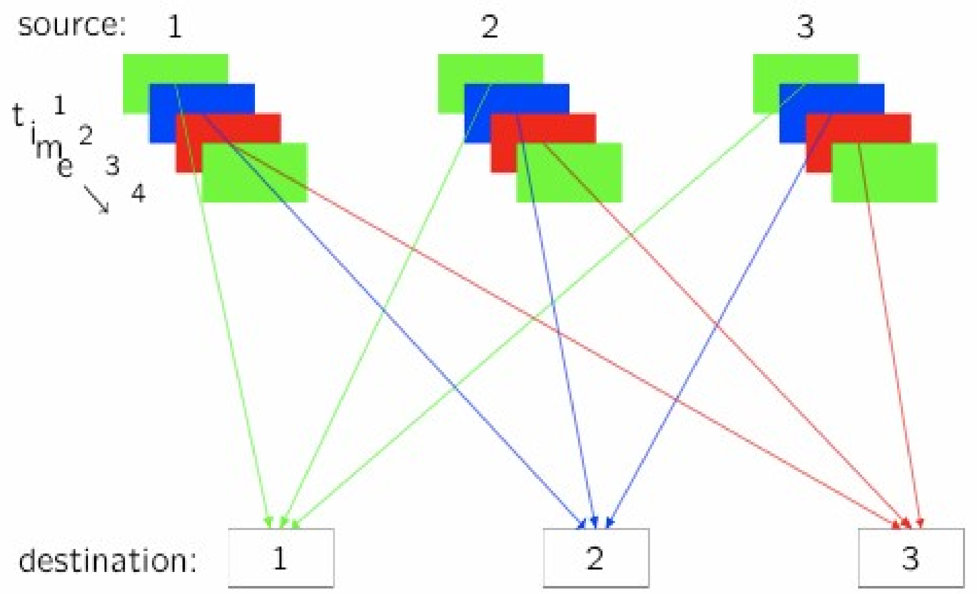




Readout and Data Transfer

- Data rate from a km^3 detector will be ~2.5-10 Gb/s
- Questions to be addressed:
  - Optimal data transfer to shore (many fibers + few colors, few fibers + many colors, etc.);
  - How much processing to be done at the optical module?
  - Analogue vs. digital OMs: differing approaches for front-end electronics
  - Data filtering
  - Distribution of (raw) data to data analysis centers

- **One possible data distribution concept;**
- **Application of current PP GRID technologies to some of these open questions?**



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):

01.01.2006	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.