DESY *Dienstagsseminar*, Hamburg, 21.12.2004

Neutrino Telescopy in the Mediterranean – ANTARES, KM3NeT and Acoustics

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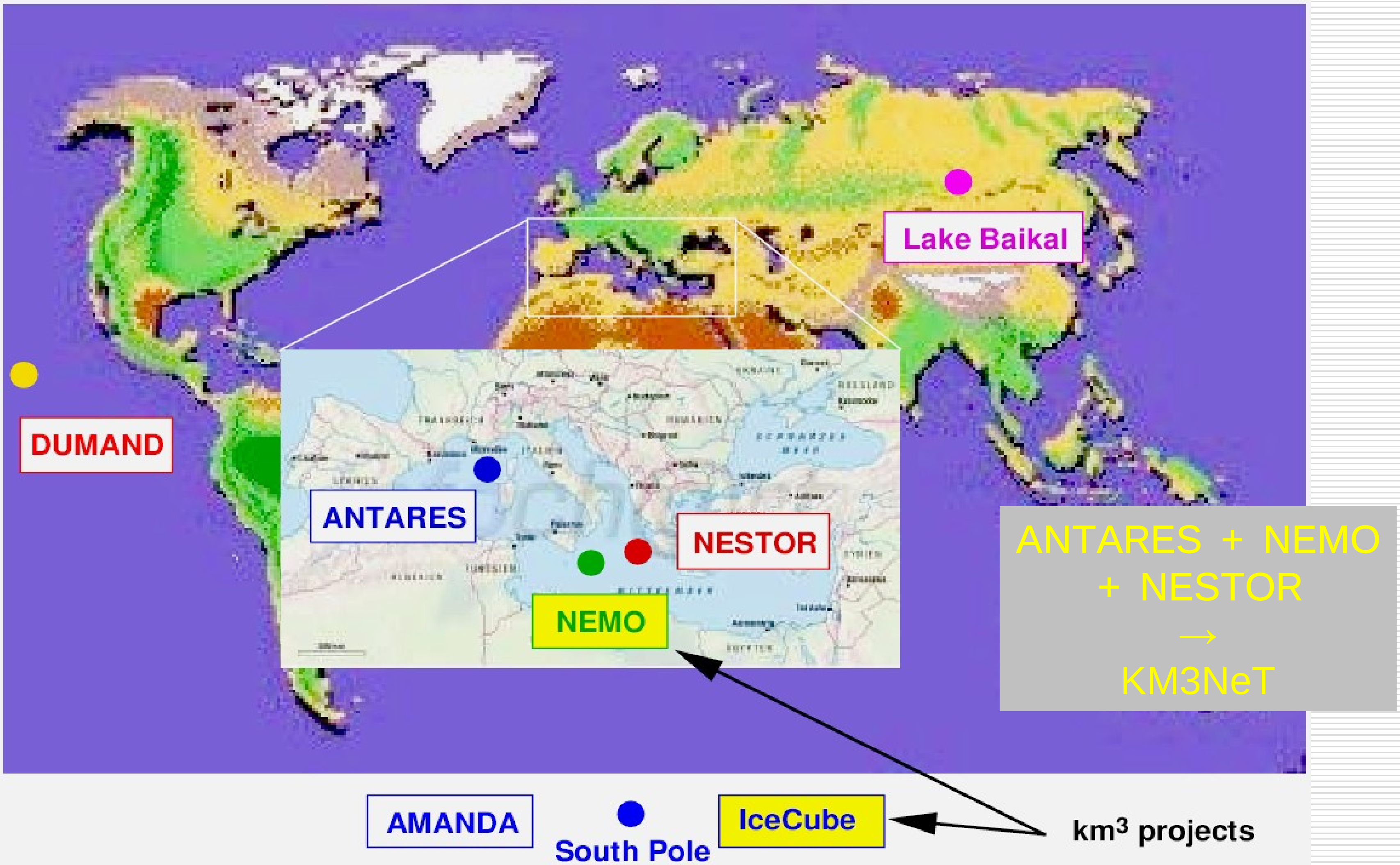
- Physics with ν telescopes
- ANTARES: Design and status
- The KM3NeT Design Study: towards a km^3-scale detector
- Acoustic detection
- Summary

Why Neutrino Telescopes?

- 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
  $\rightarrow$ 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).

The Neutrino Telescope World Map



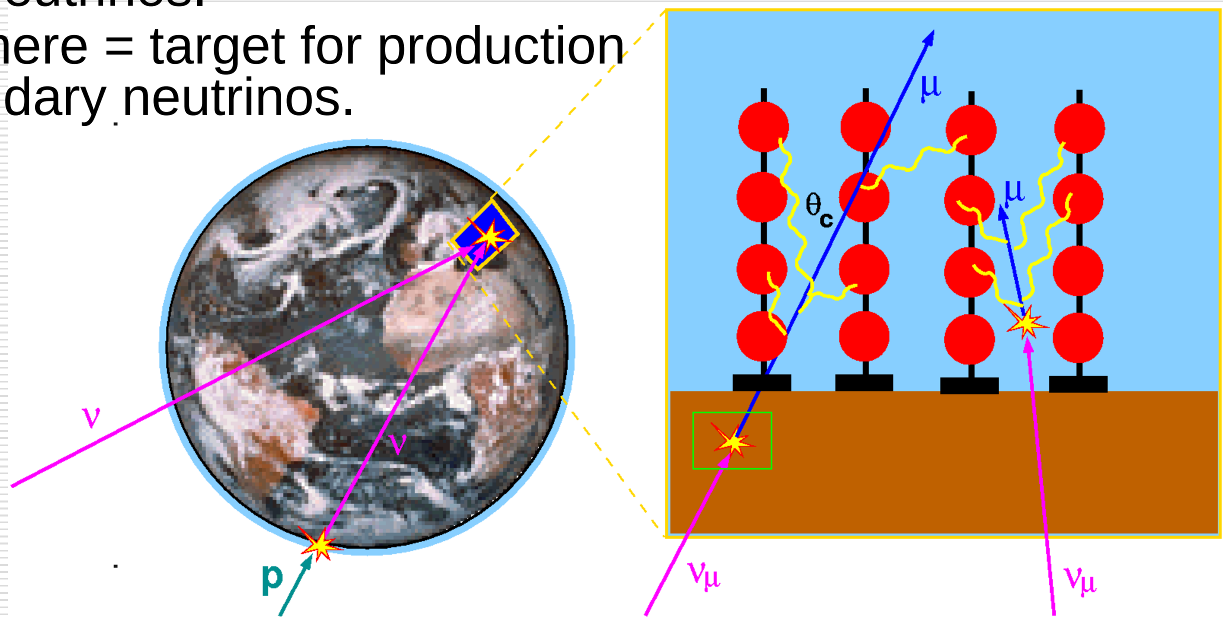
The Principle of Neutrino Telescopes

Role of the Earth:

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

Čerenkov light:

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

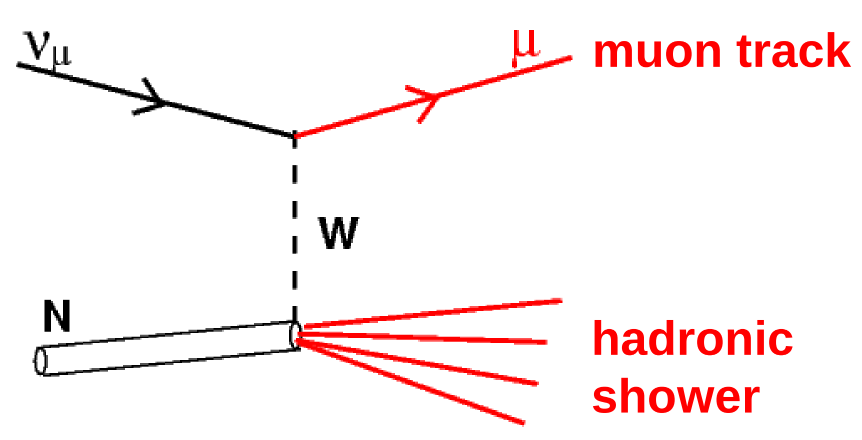


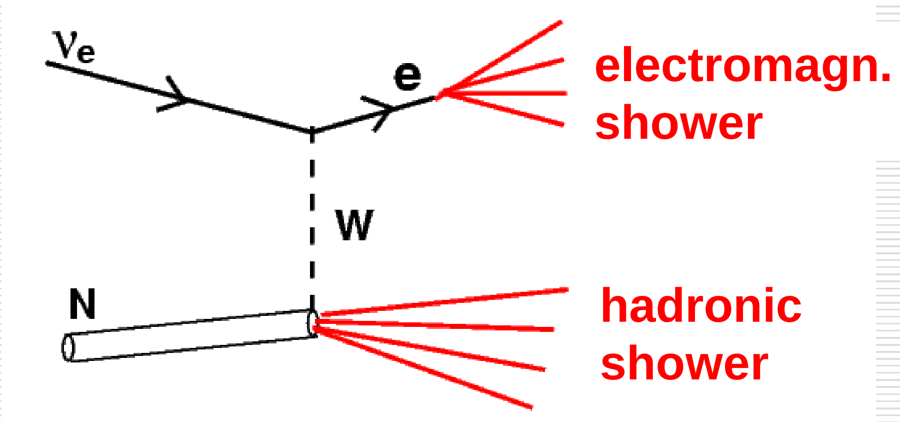
Neutrino reactions (key reaction is $\nu_\mu N \rightarrow \mu X$):

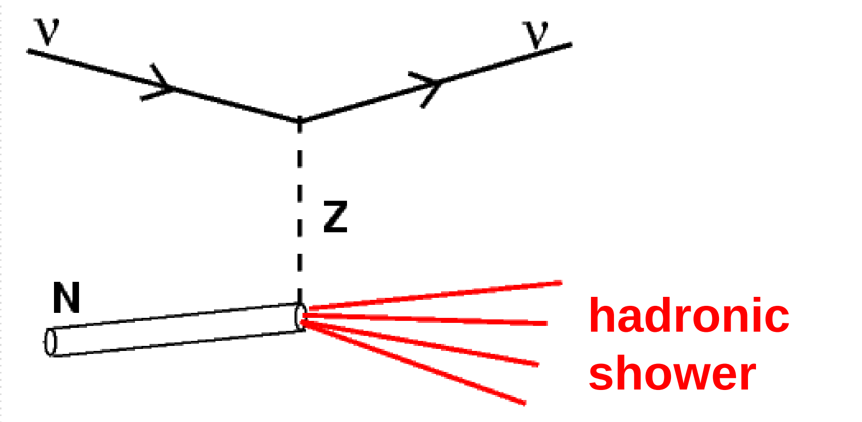
- Cross sections and reaction mechanisms known from accelerator experiments (in particular HERA).
- Extrapolation to highest energies (> 100 TeV) uncertain.

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:
  $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$;
- Key signature: muon tracks
  from ν_μ charged current reactions
  (few 100m to several km long);
- Elm./hadronic showers:
  "point sources" of Čerenkov light.



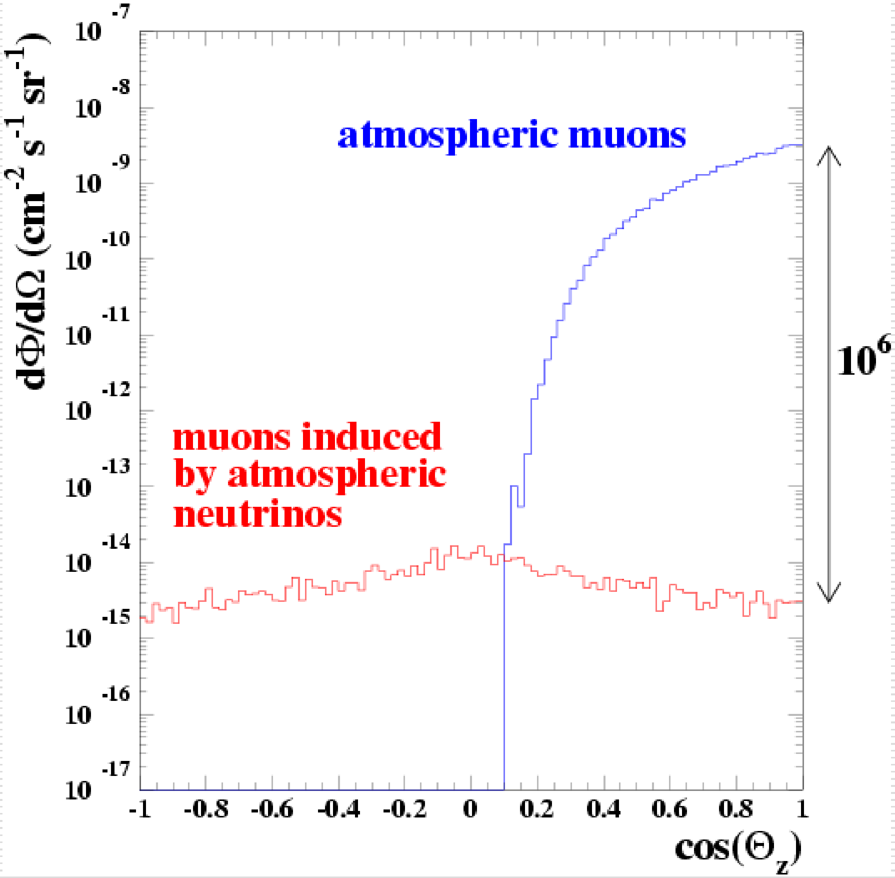


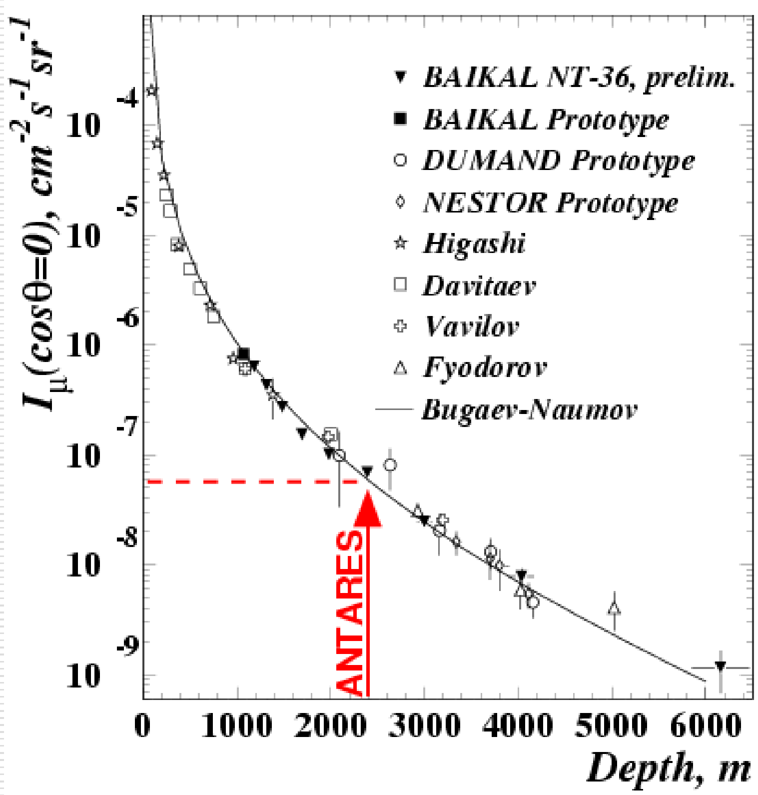


Muons: The Background from Above

Muons can penetrate several km of water if E_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

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.

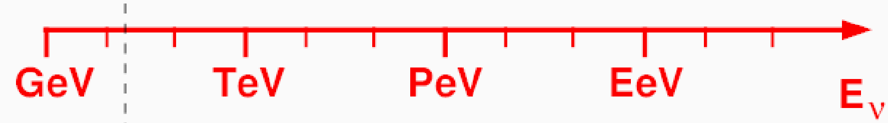
Dark matter search (WIMPs):
Direction, Energy

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.



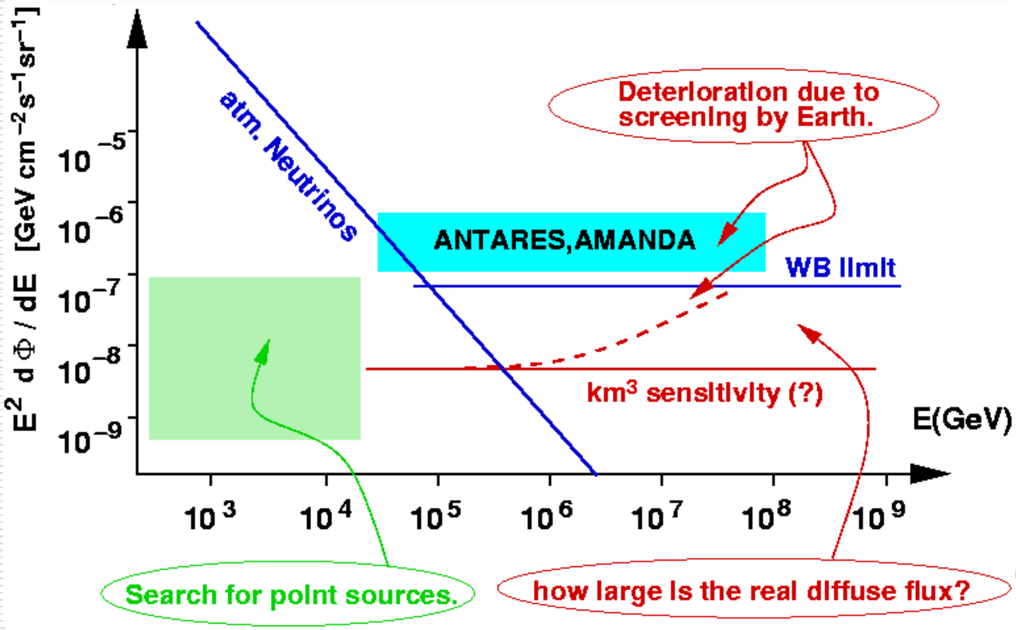
... and also:
GZK–neutrinos
Z bursts
magnetic monopoles
topological defects
top–down scenarios
supernova detection
...

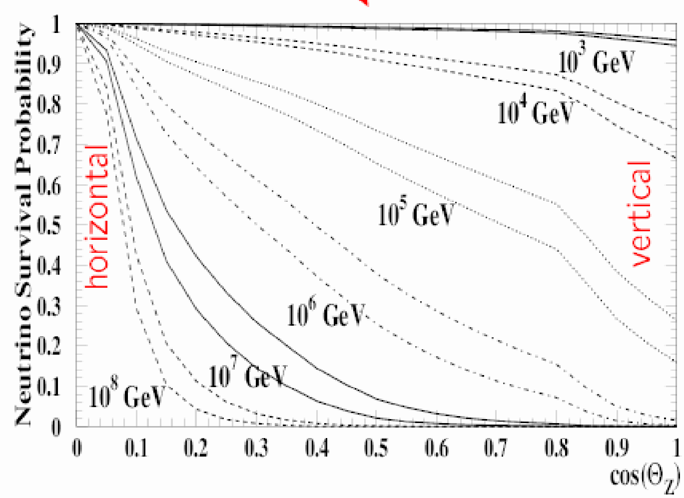
Neutrino Fluxes and Event Numbers

Observed event numbers for diffuse fluxes:

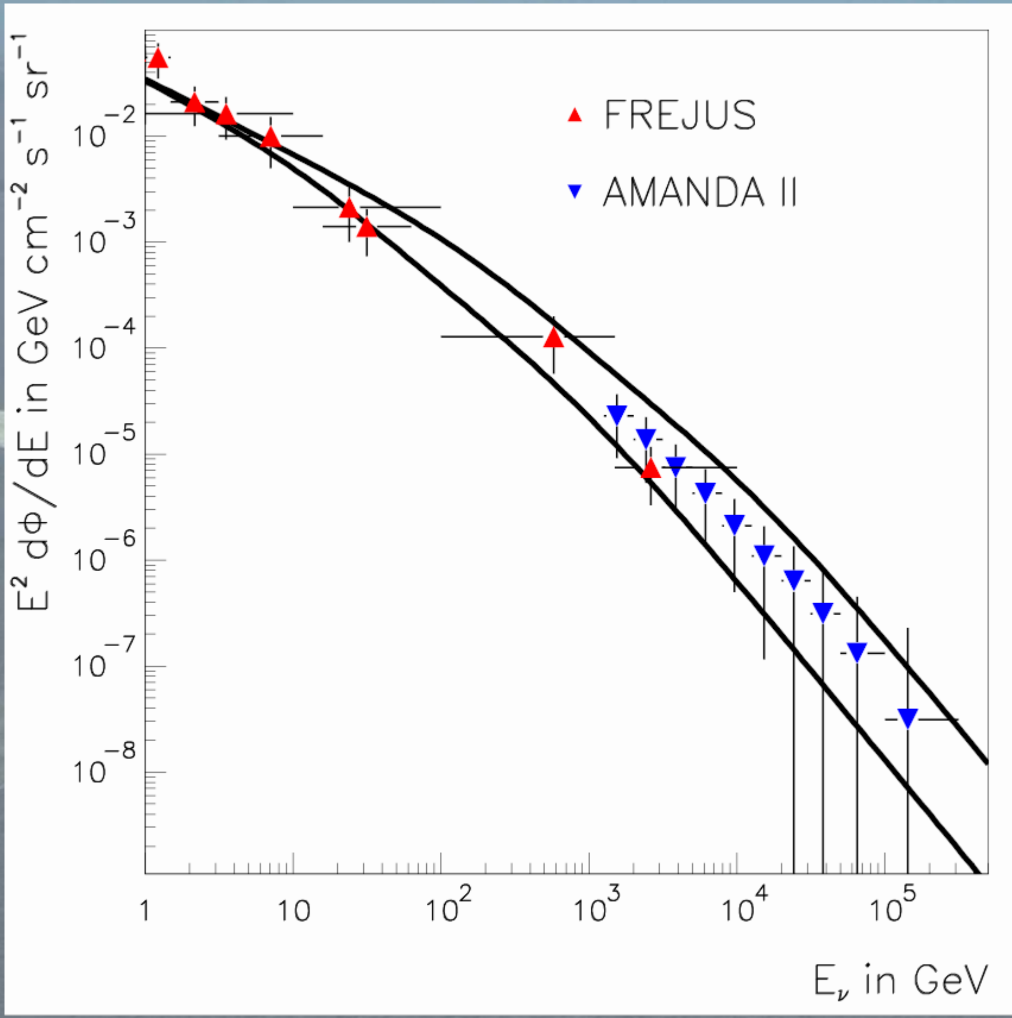
$$\frac{\mathrm{d}N_{\mathrm{evt}}}{\mathrm{d}E_\nu\,\mathrm{d}t} = \int_\Omega \underbrace{\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu\,\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}\Omega}} \cdot \underbrace{\sigma(\nu_\mu N \to \mu X)} \cdot (\rho\,\underbrace{V_{\mathrm{eff}}}) \cdot T\,\mathrm{d}\Omega + \underbrace{\frac{\mathrm{d}N_{\mathrm{evt}}(\nu_e,\nu_\tau)}{\mathr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

- 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



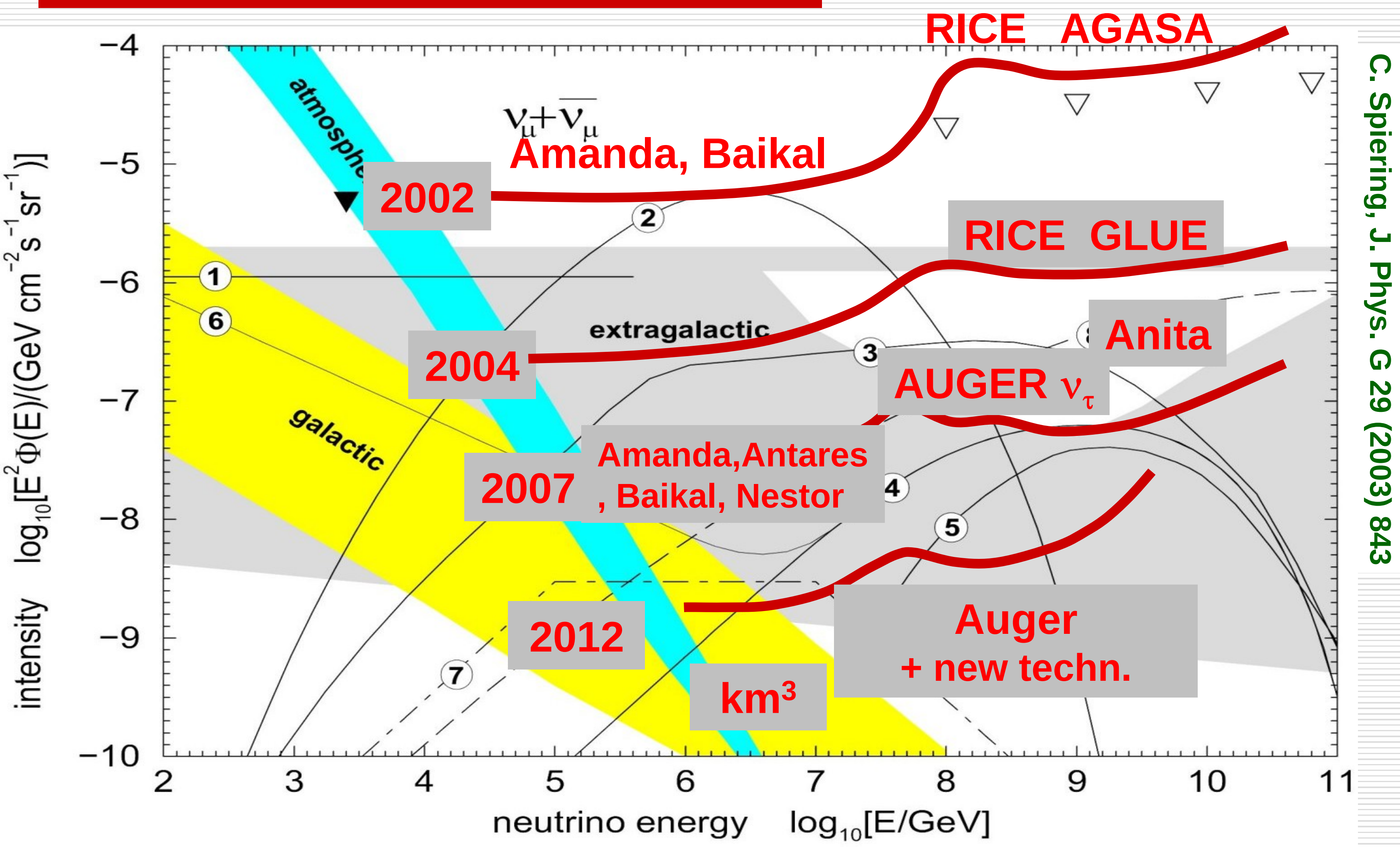


AMANDA/Baikal: Pioneer Data

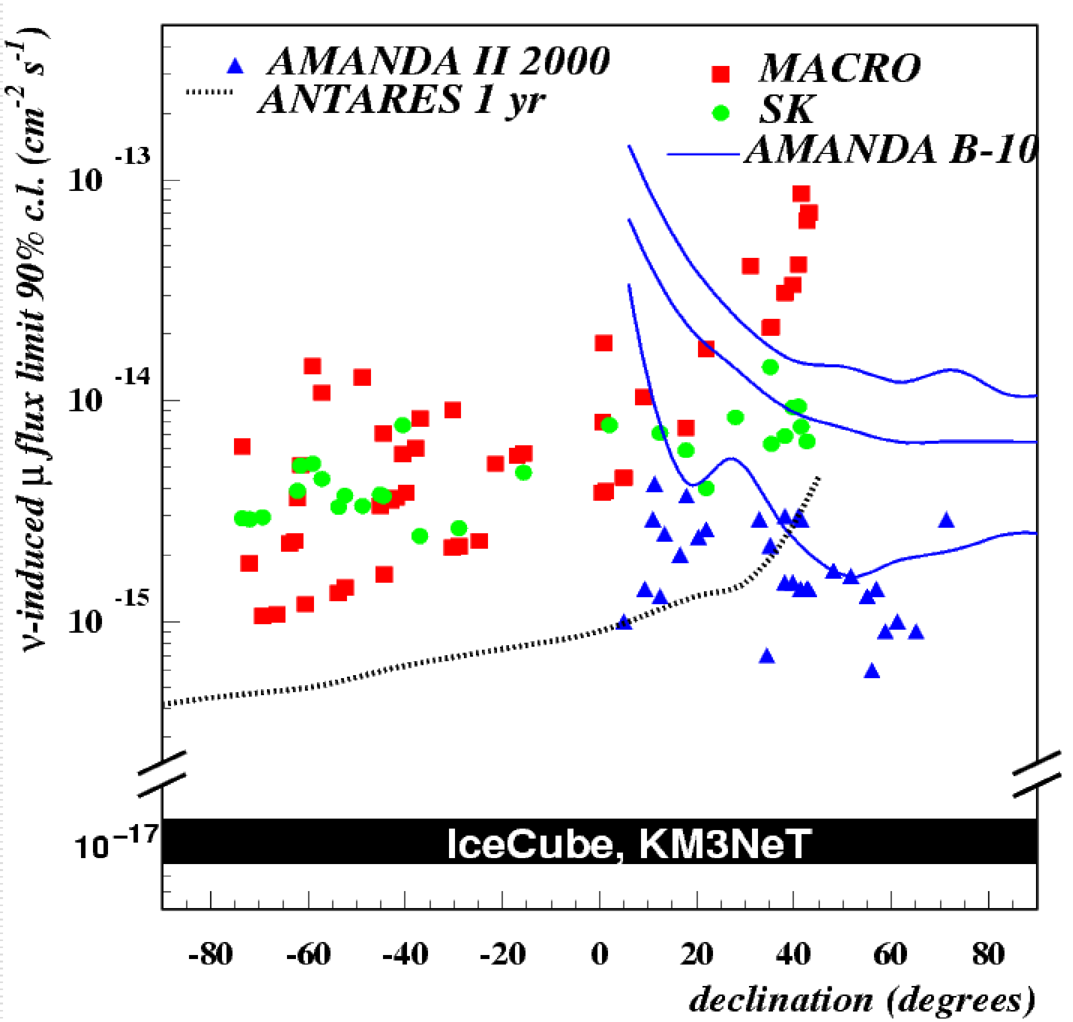


- Measurement of the neutrino flux by AMANDA-II;
- Nice agreement with FREJUS data at lower energies;
- Flux compatible with expectation for atmospheric ν's;

Diffuse ν Flux: Limits and Sensitivities



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;
- km³ detectors needed to exploit full potential of neutrino astronomy.

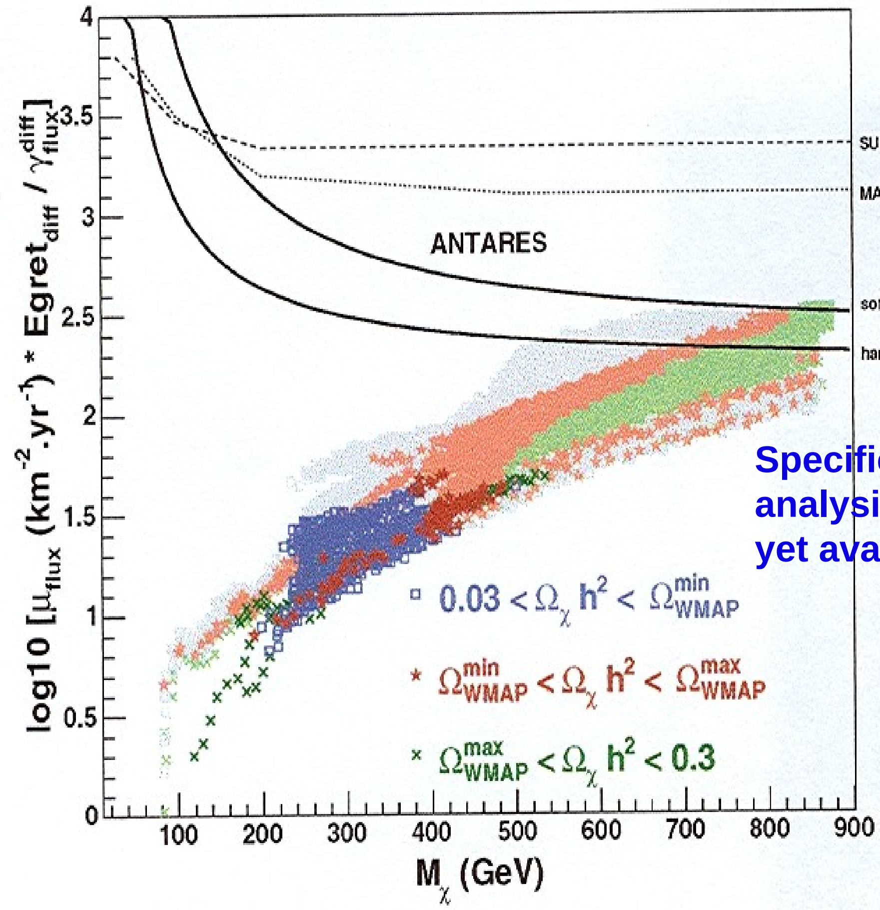
Indirect Search for Dark Matter

- 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!

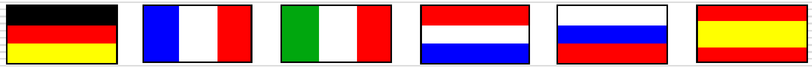
from G. Bertone et al., astro-ph/0403322



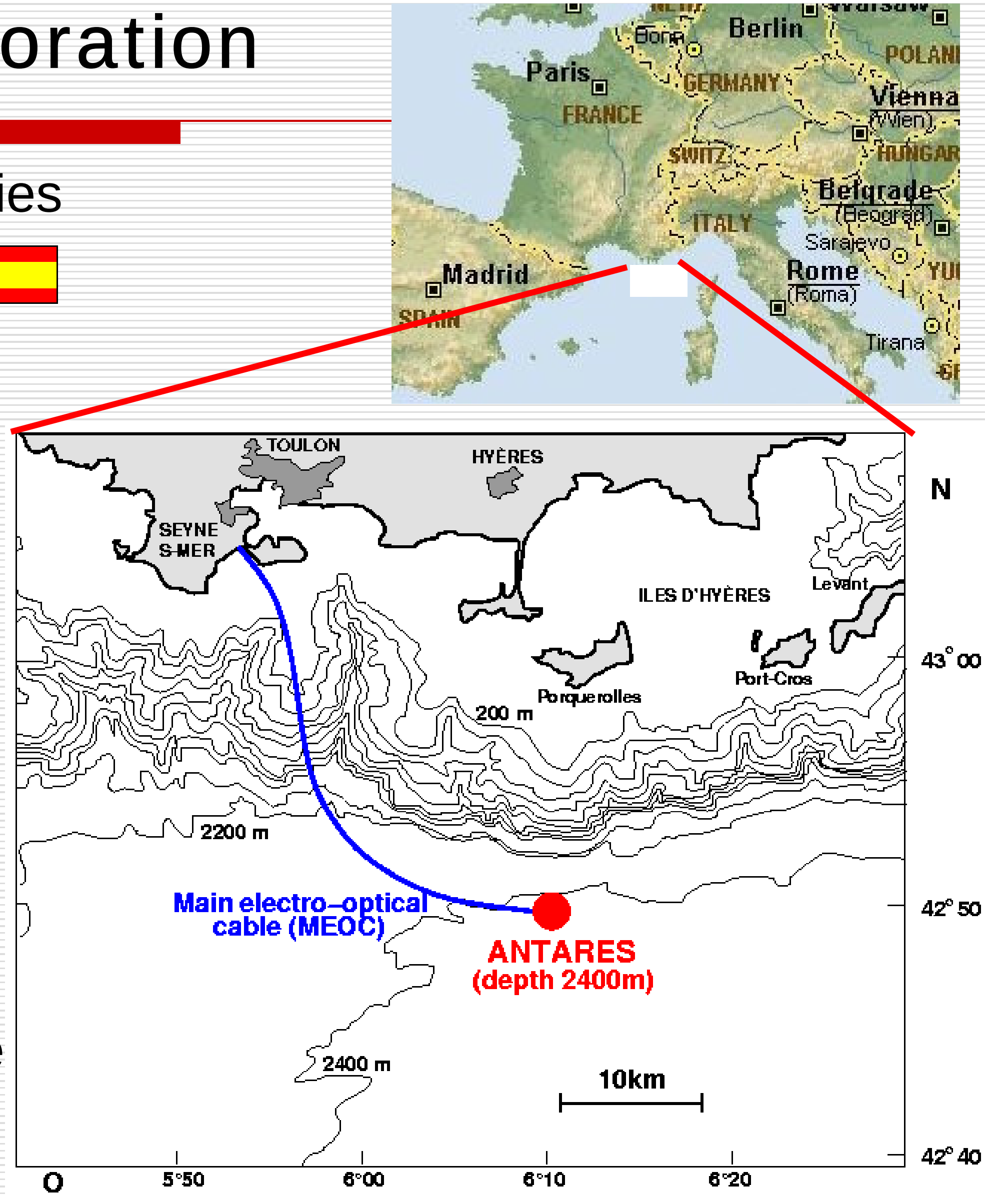
Specific km³ analysis not yet available.

The ANTARES Collaboration

- 20 Institutes, 6 European countries

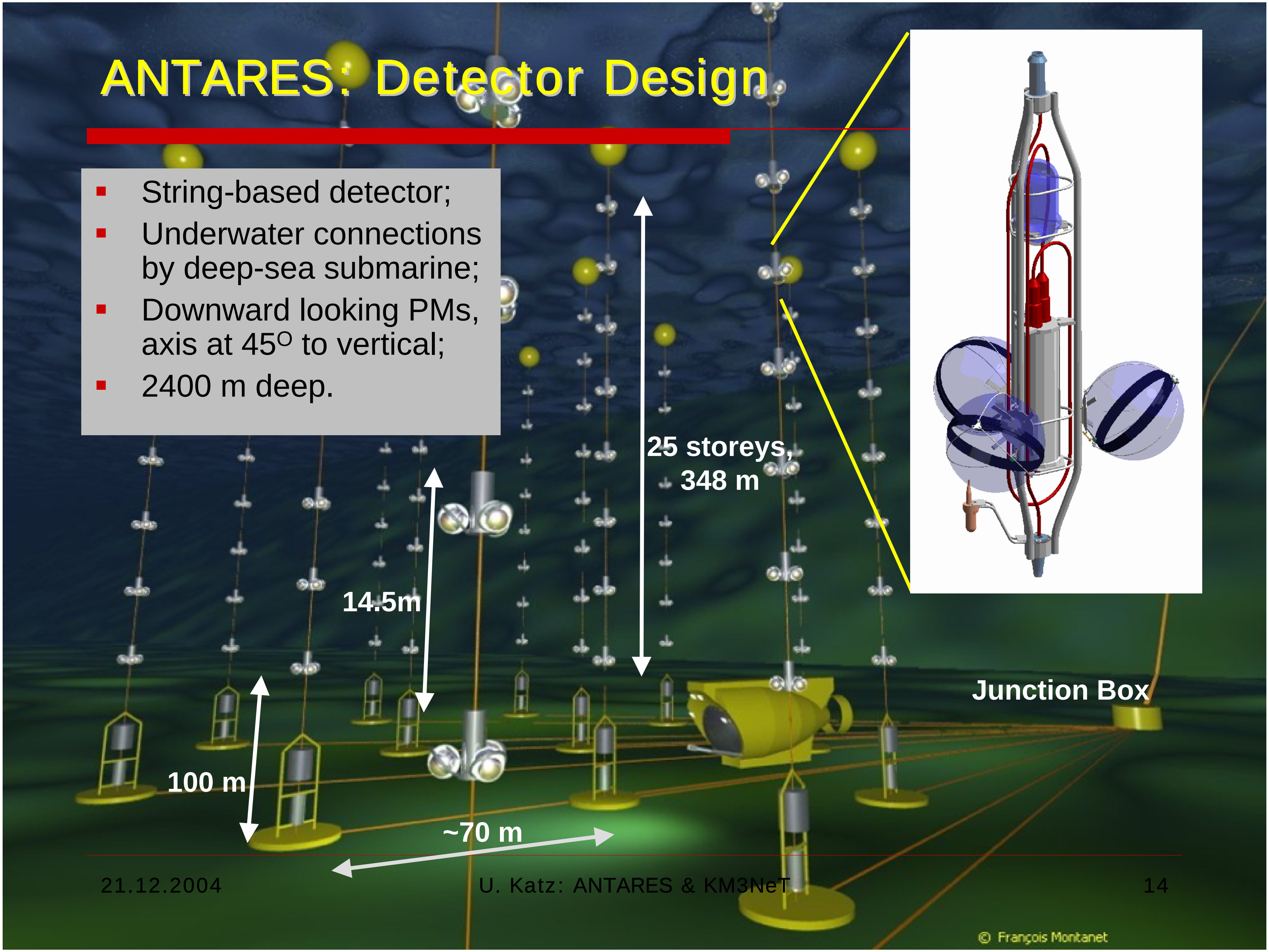


- Institutes:
  Particle physics,
  astronomy/astrophysics,
  sea science & technology;
- The mission:
  Design, construct and
  operate a ν telescope in
  the Mediterranean Sea;
- The challenge:
  Build a high-tech particle
  detector in the hostile,
  poorly known and uncontrollable
  deep-sea environment.



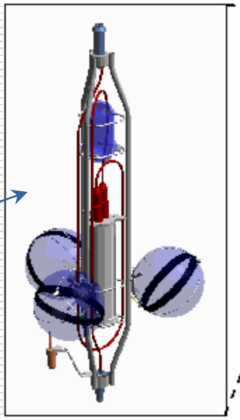
ANTARES: Detector Design

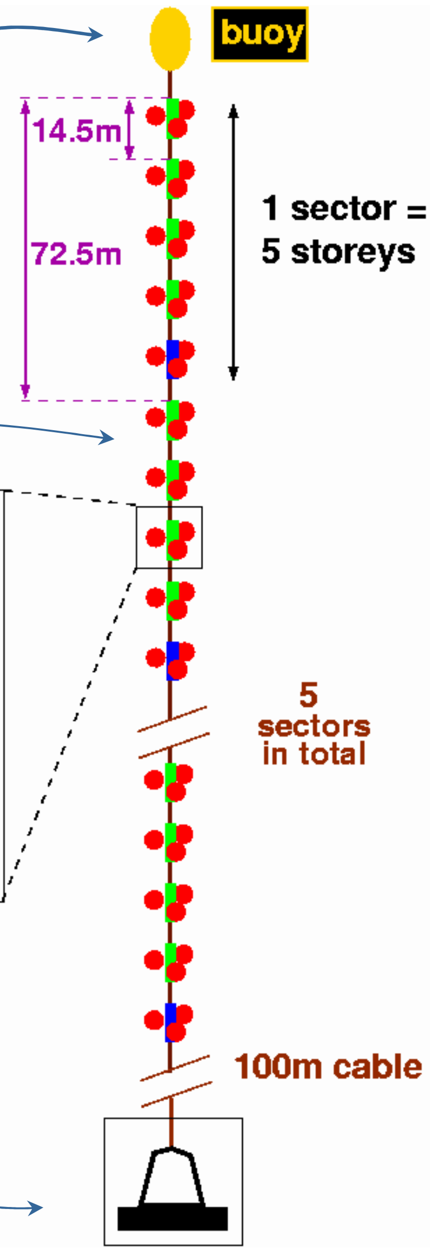
- String-based detector;
- Underwater connections by deep-sea submarine;
- Downward looking PMs, axis at 45^{O} to vertical;
- 2400 m deep.



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.





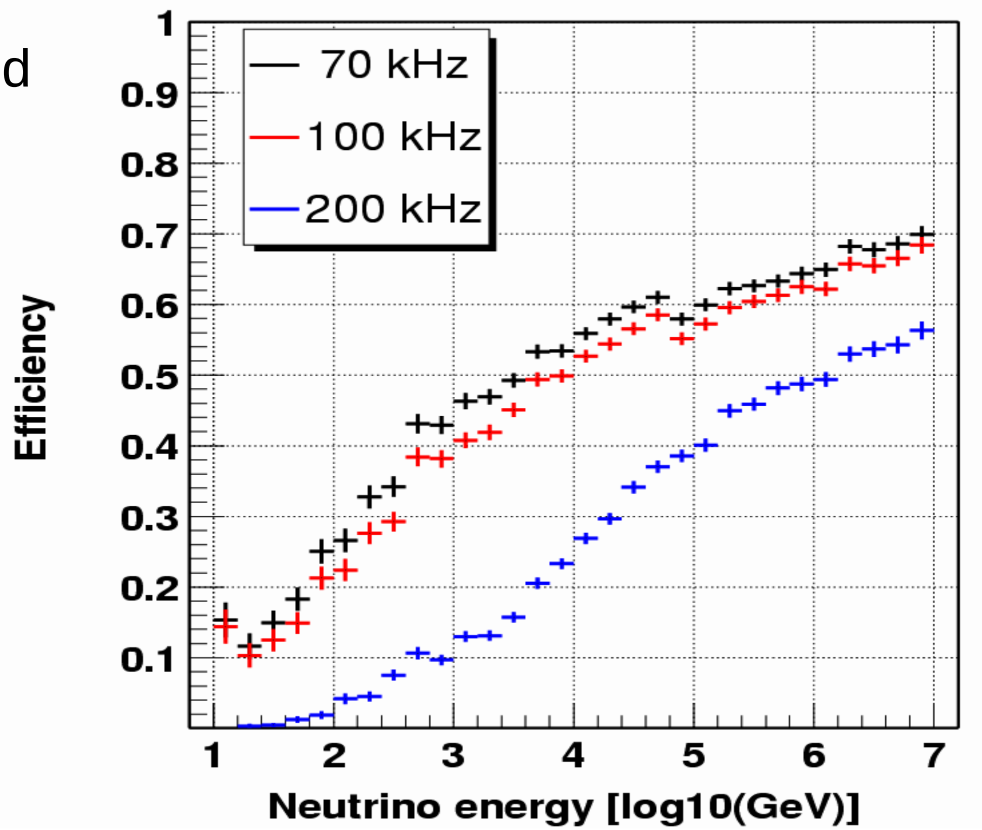
ANTARES: Optical Modules

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

43 cm

ANTARES: DAQ and Online Filter

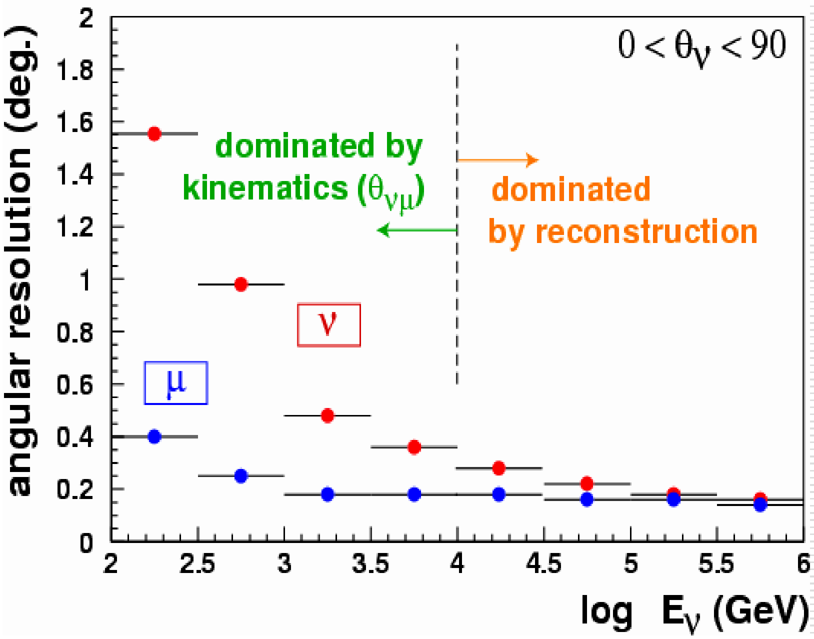
- Data acquisition:
  - digitization *in situ* (Analog Ring Sampler, ARS);
  - single photon electron (SPE) and wave form modes;
  - all-data-to-shore concept: all hits above low threshold (~0.3 SPE) sent to shore;
  - no hardware trigger;
- Online filter:
  - raw data rate ~1GB/s reduced to ~1MB/s by online filter (PC farm);
  - criteria:
    → local coincidences,
    → signal amplitudes,
    → causality.

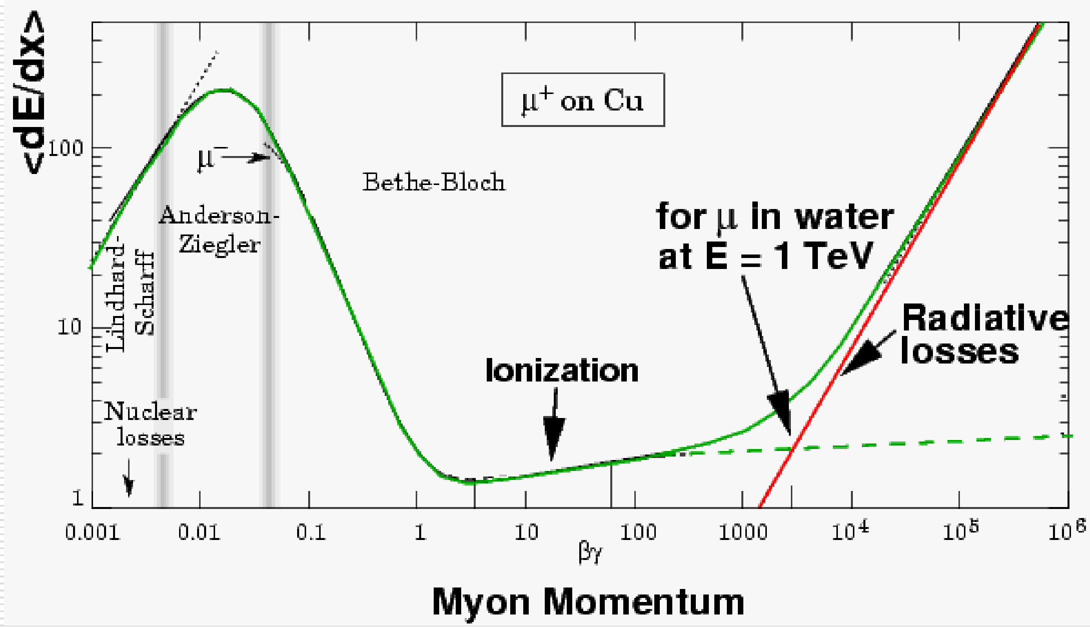


ANTARES: Expected Performance (μ Events)

Angular resolution:
- E_ν < 10 TeV: dominated by angle(ν,μ);
- E_ν > 10 TeV: dominated by reconstruction accuracy;

Energy reconstruction:
- E_μ < 1 TeV: muon range;
- E_μ > 1 TeV: Čerenkov light yield from radiative losses (small elm. showers);



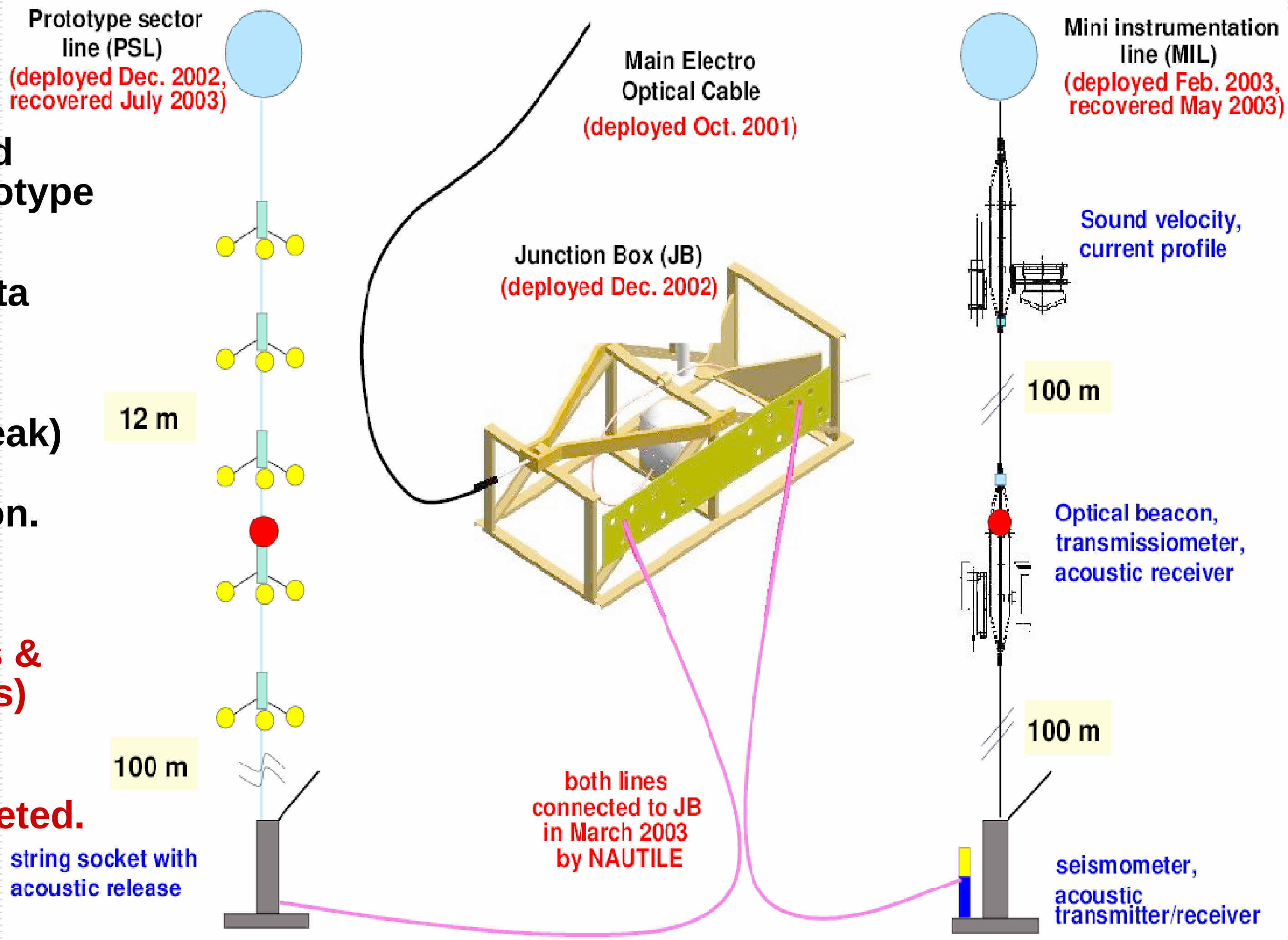


$$\Delta\theta \approx 0.2^o - 0.3^o (E_\nu > 10\text{TeV})$$

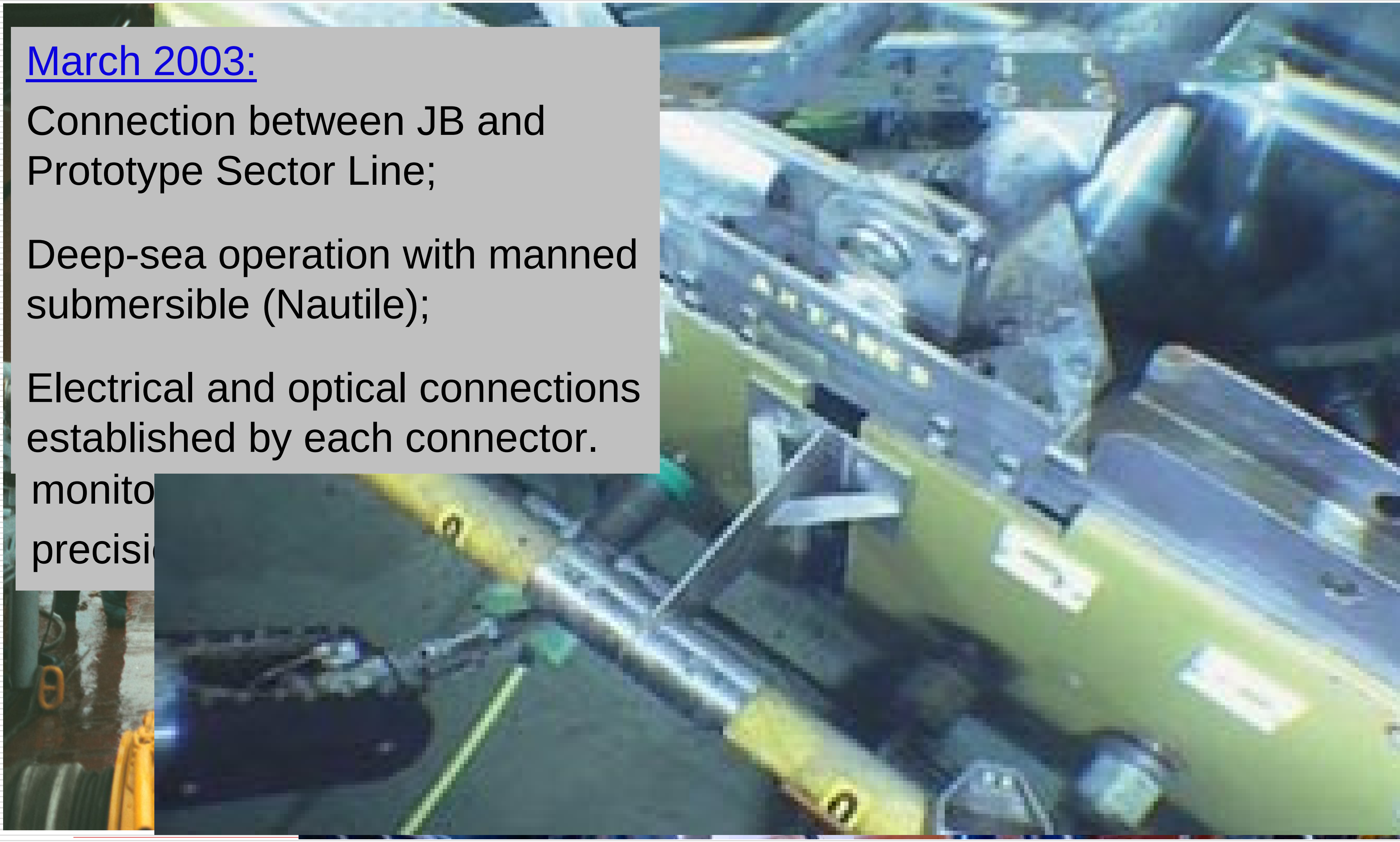
$$\Delta(\log E_\mu) \approx 0.3 (E_\mu > 1\text{TeV})$$

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 μ reconstruction.
- **Early 2005: upgraded prototype line (cables & mechanical structures)**
- **Spring 2005: Line 1;**
- **2007: Detector completed.**



ANTARES: Sea Operations



March 2003:

Connection between JB and Prototype Sector Line;

Deep-sea operation with manned submersible (Nautile);

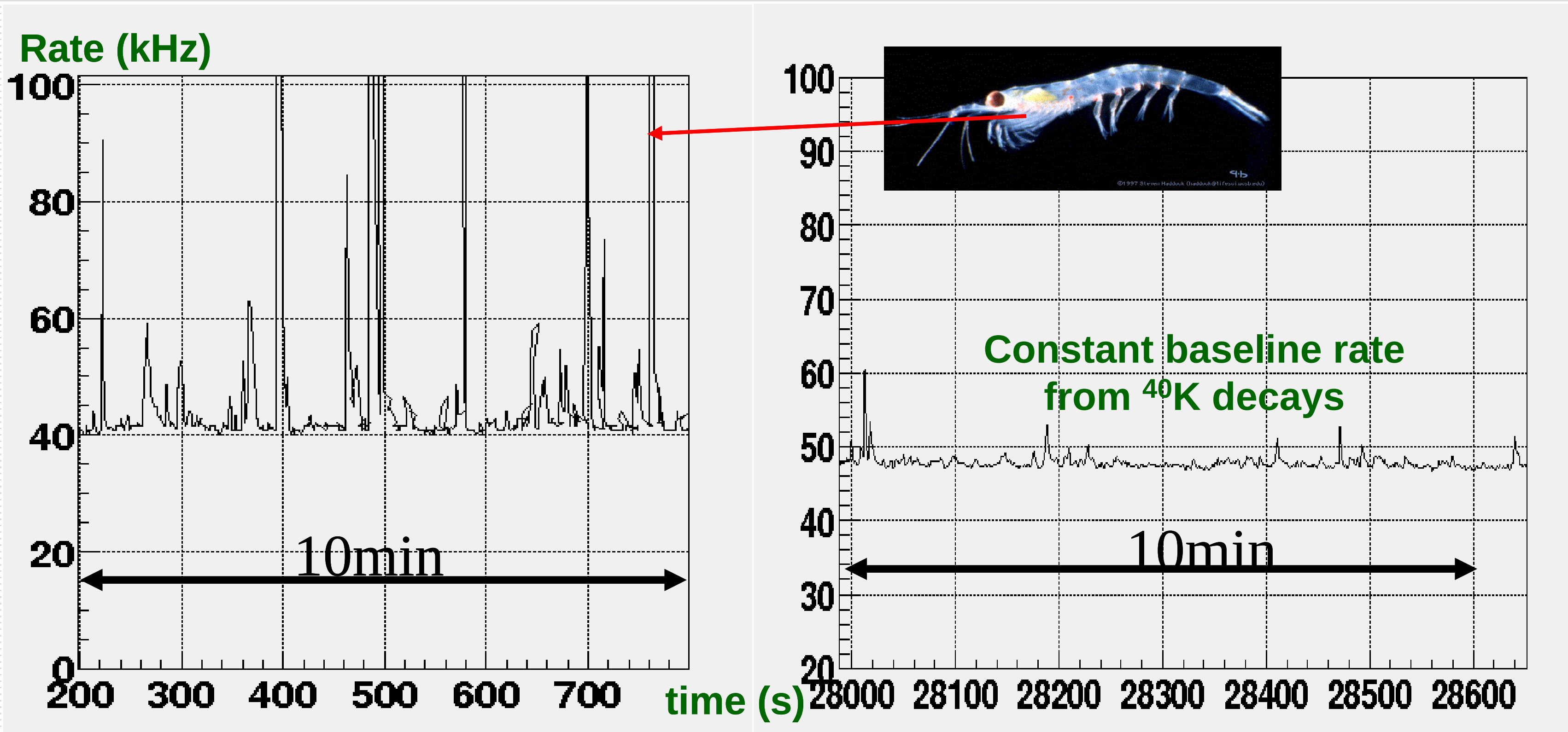
Electrical and optical connections established by each connector.

monito

precisi

ANTARES: First Deep-Sea Data

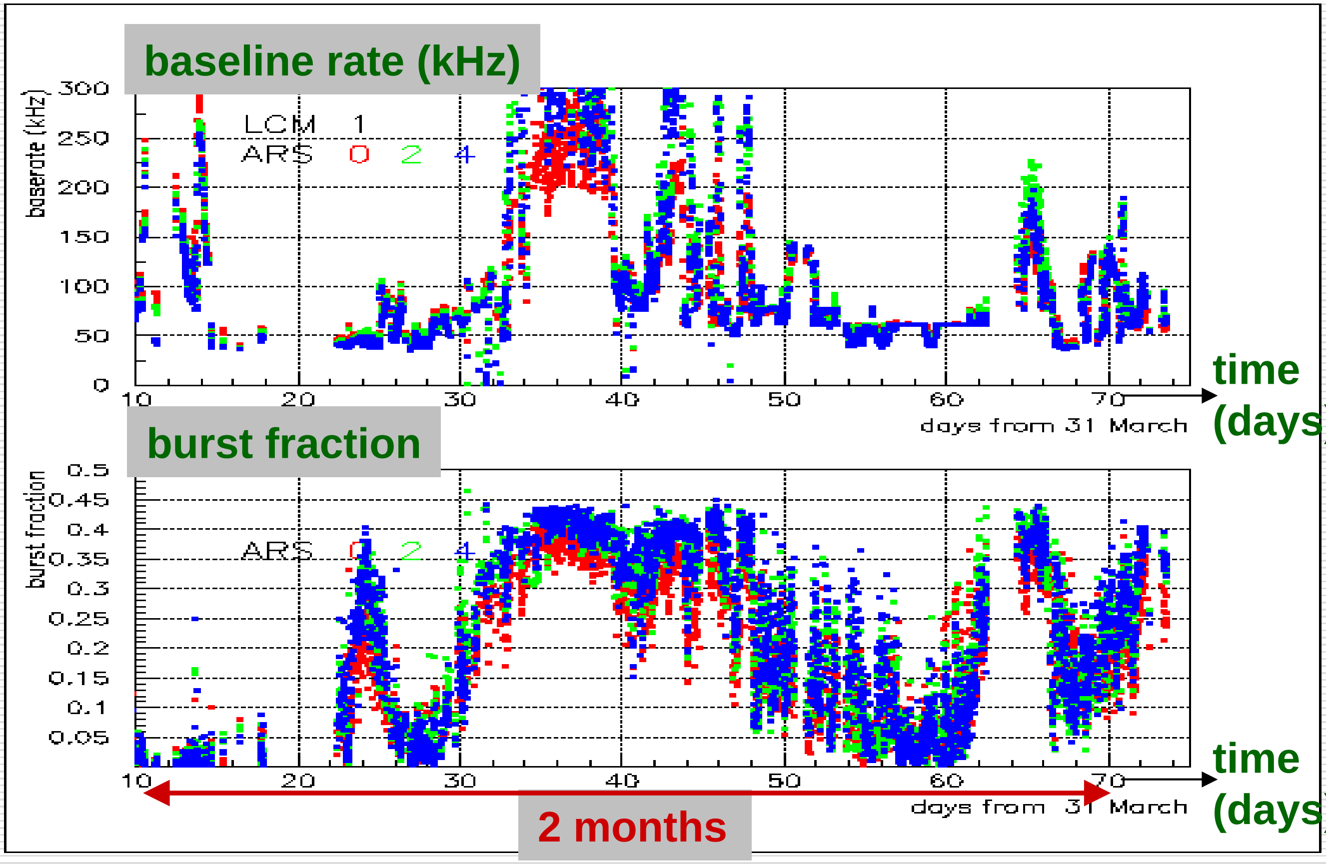
Rate measurements: Strong fluctuation of bioluminescence background observed



ANTARES: Long-term Measurements

baseline rate = 15-minute average

burst fraction = time fraction above 1.2 x 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

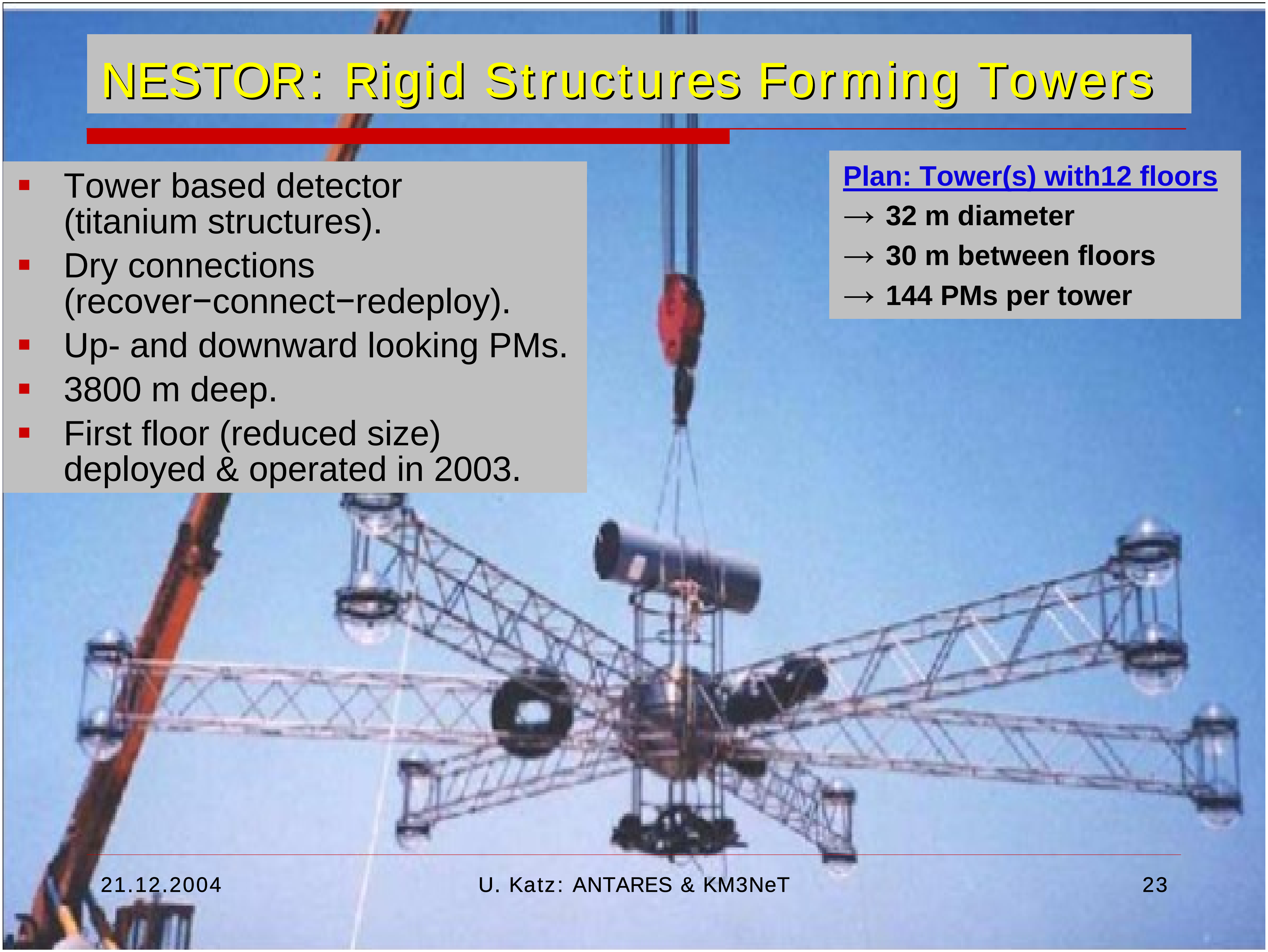
- Tower based detector (titanium structures).
- Dry connections (recover−connect−redeploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

Plan: Tower(s) with12 floors

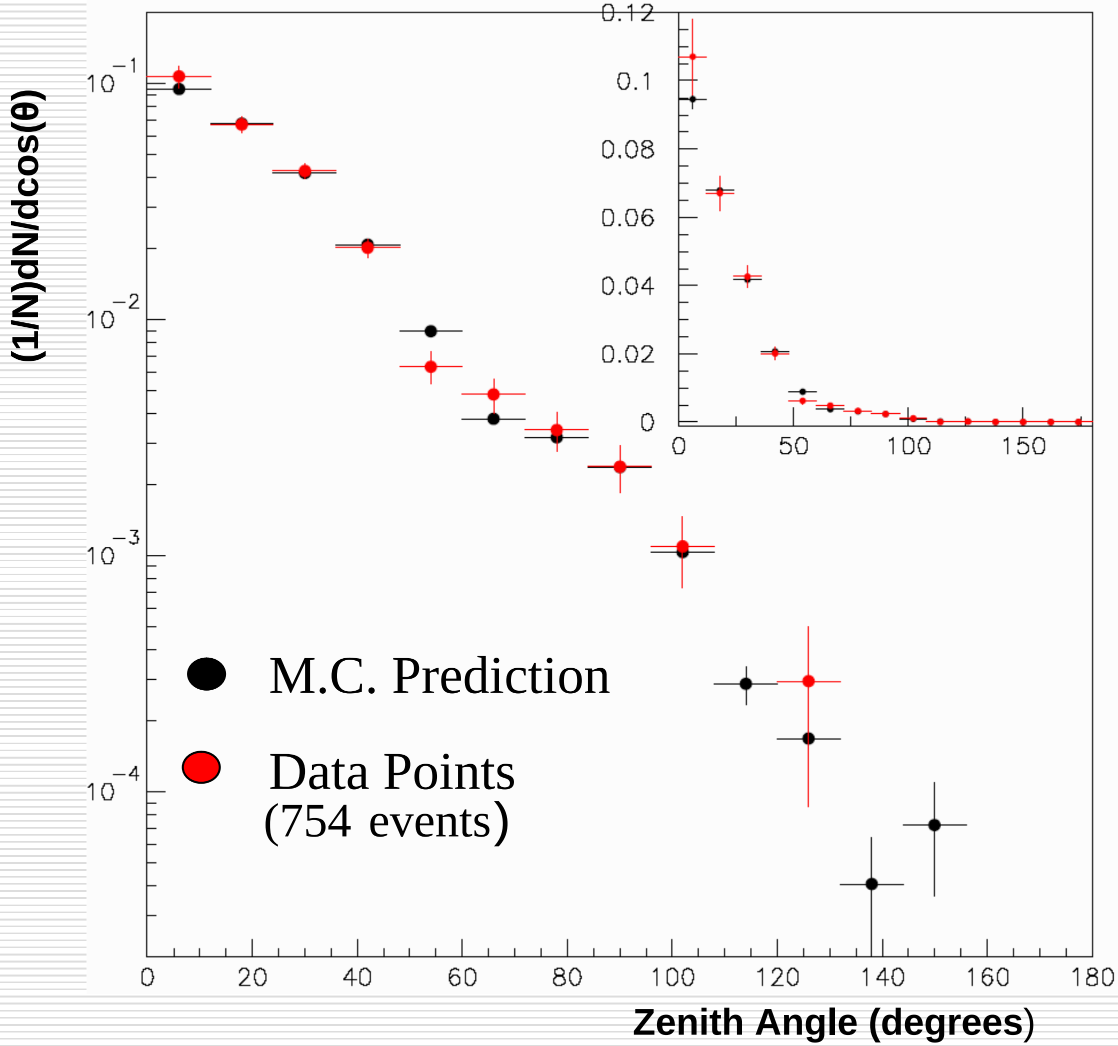
→ **32 m diameter**

→ **30 m between floors**

→ **144 PMs per tower**



NESTOR: Measurement of the Muon Flux



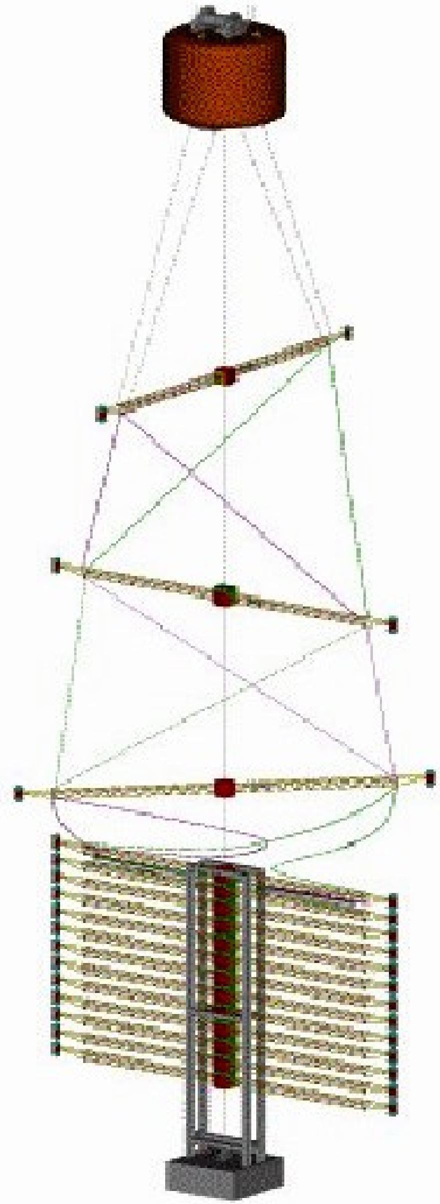
Atmospheric muon flux determination by reweighting MC simulation to observed raw zenith distribution using

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

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 km^3: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

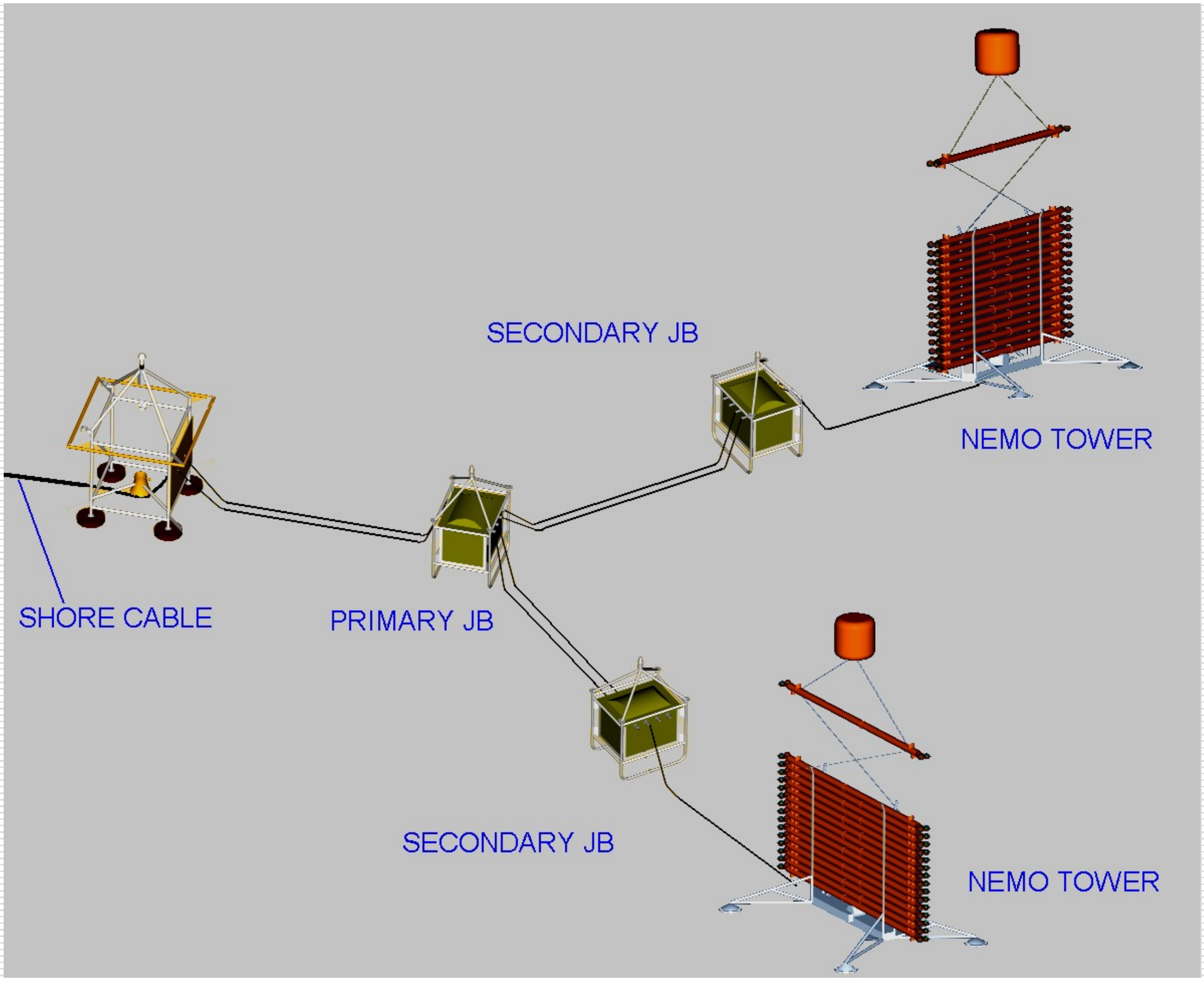


Example: Flexible tower

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

- 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^3-scale detector.

Aiming at a Mediterranean km^3-Detector

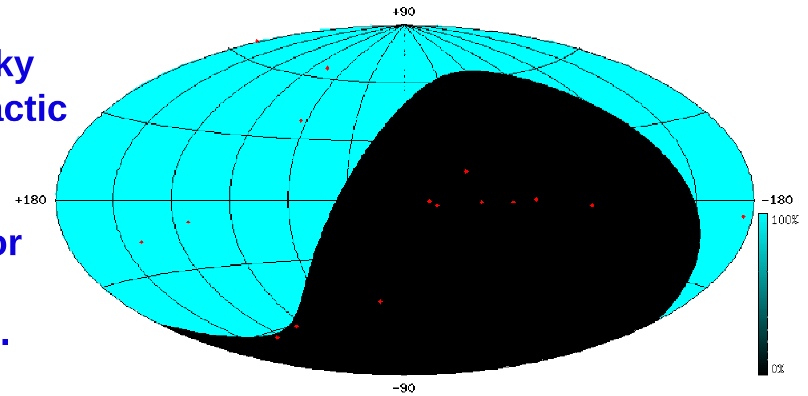
HENAP Report to PaNAGIC, July 2002:

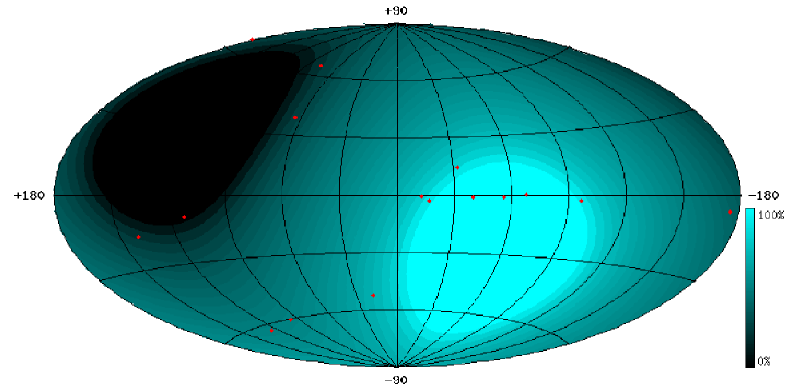
- “The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ...“
- “... a km^3-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole.”
- “The detector should be of km^3-scale, the construction of which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

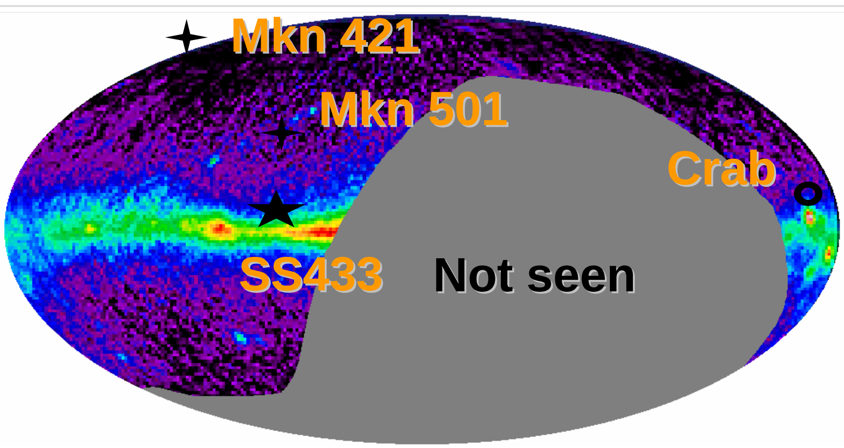
Sky Coverage of Neutrino Telescopes

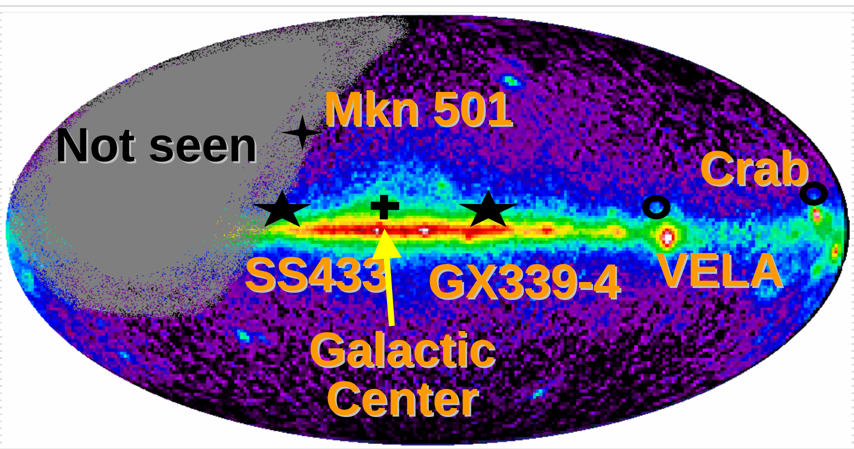
South Pole	Mediterranean

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



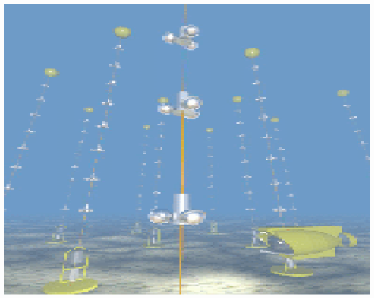


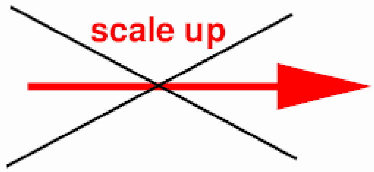




→ We need ν telescopes in both hemispheres to see the whole sky

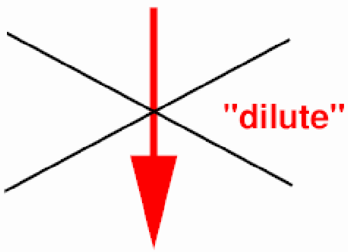
How to Design a km³ Deep-Sea ν Telescope





Existing 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.
- . . .

A major R&D project is needed!

Some Key Questions

- 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)

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

All the parameters need optimization !

- Detection principle: water Čerenkov.
- Detection volume: 1 km³, expandable.
- Angular resolution: close to the intrinsic resolution (< 0.1° for muons with E_μ > 10 TeV).
- Energy reconstruction: within a factor of 2 for μ events.
- Lower energy threshold:
  a few 100 GeV for upward going neutrinos, possibility to go lower for ν from point sources at known position.
- Acceptance:
  maximal angular acceptance for all ν signals (including down-going neutrinos at VHE) and for all ν flavors.
- Duty cycle/operational lifetime: close to 100% / ≥ 10 years.
- Cost-effectiveness: < 200 M€ per km³.

KM3NeT: Exploitation Model

<u>Goal:</u> **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

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

- Experience from current first generation water ν 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):

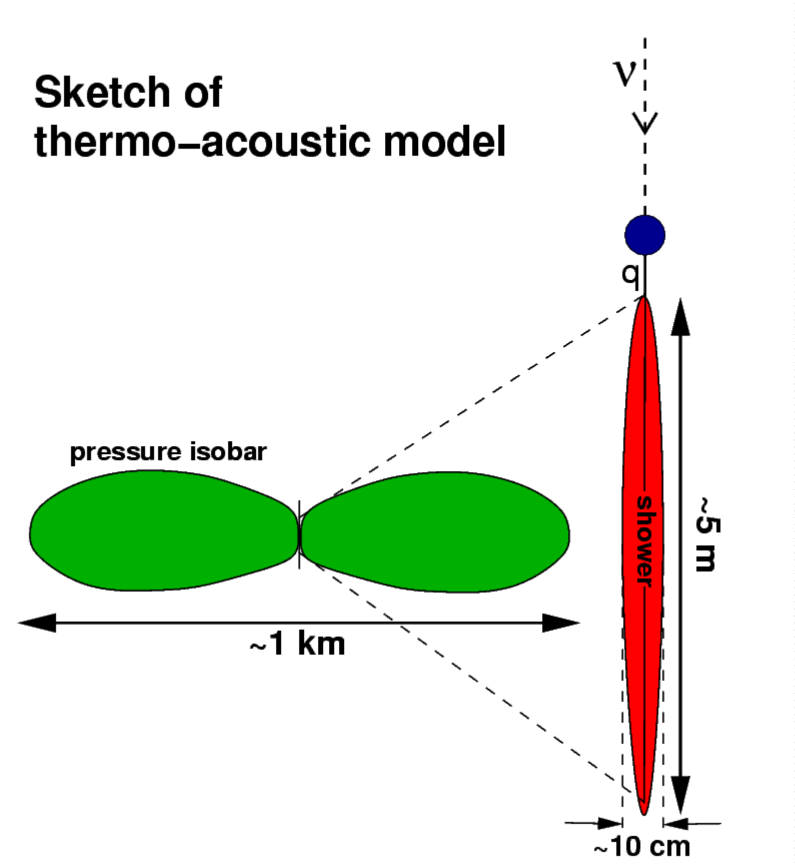
01.01.2006	Start of Design Study
Mid-2007	Conceptual Design Report
End of 2008	Technical Design Report
2009-2013	Construction
2010-20XX	Operation

KM3NeT: Summary

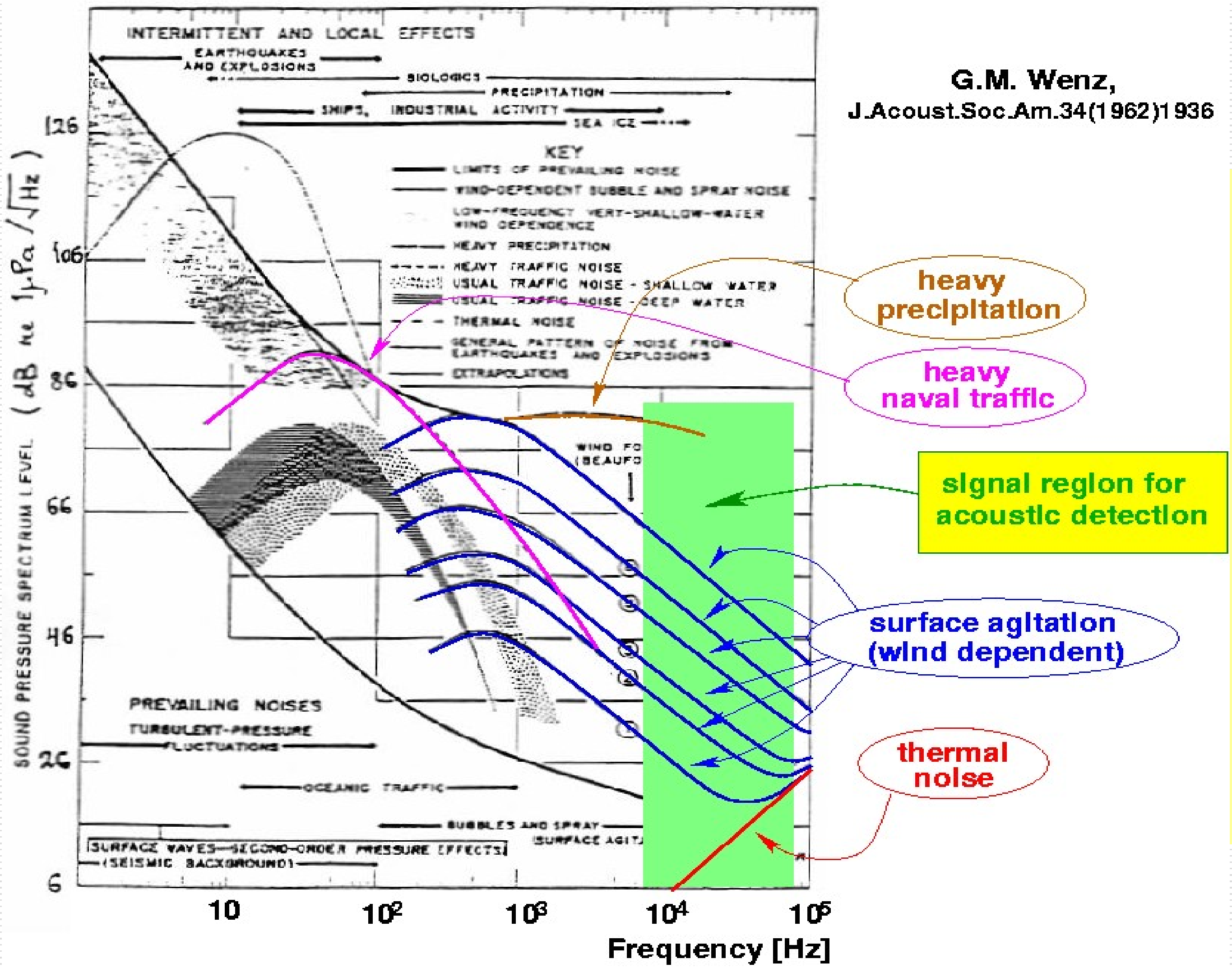
- Strong physics motivation for km^3-scale ν telescope in Northern hemisphere;
- Mediterranean Sea offers optimal conditions;
- Large amount of R&D required (current detectors not scalable);
- Common European effort: KM3NeT Design Study;
- Goal: Technical Design Report by end of 2008.

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(10μs) duration; amplitude ~10 μPa · E/PeV at 400m distance (in water);
- Might allow for very large instrumented volumes (attenuation length O(1 km));
- Currently rapidly growing interest in USA and Europe, studies for water, ice, salt;
- Option for ν detection at energies above $10^{16}...10^{17}$ eV?



Background Conditions in the Deep Sea



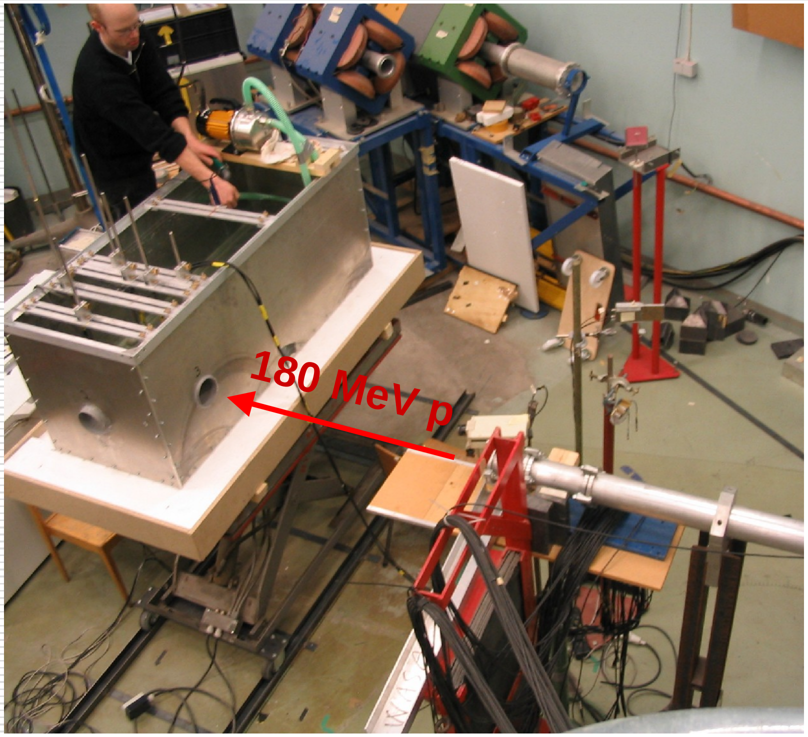
<u>Rough and optimistic estimate:</u>

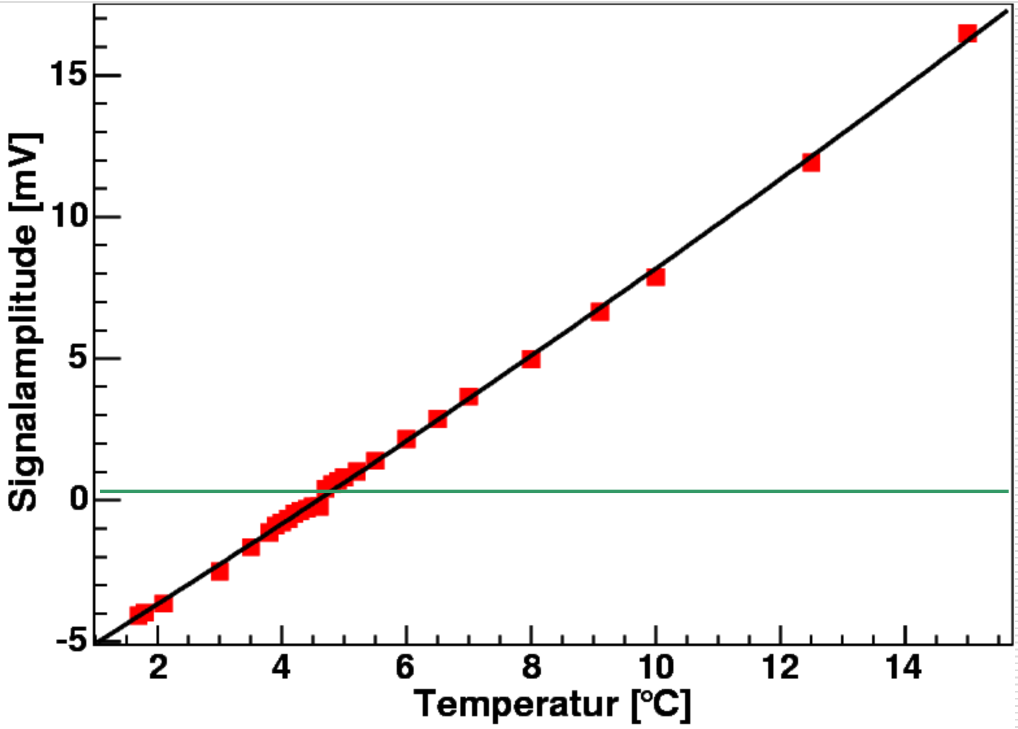
signal ≈ noise at O(0.1-1 mPa)

(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

- Acoustic detection may be a promising future method for the investigation of cosmic neutrinos above ~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.