Physikalisches Kolloquium, Universität Bayreuth

Neutrino Astronomy in the Deep Sea

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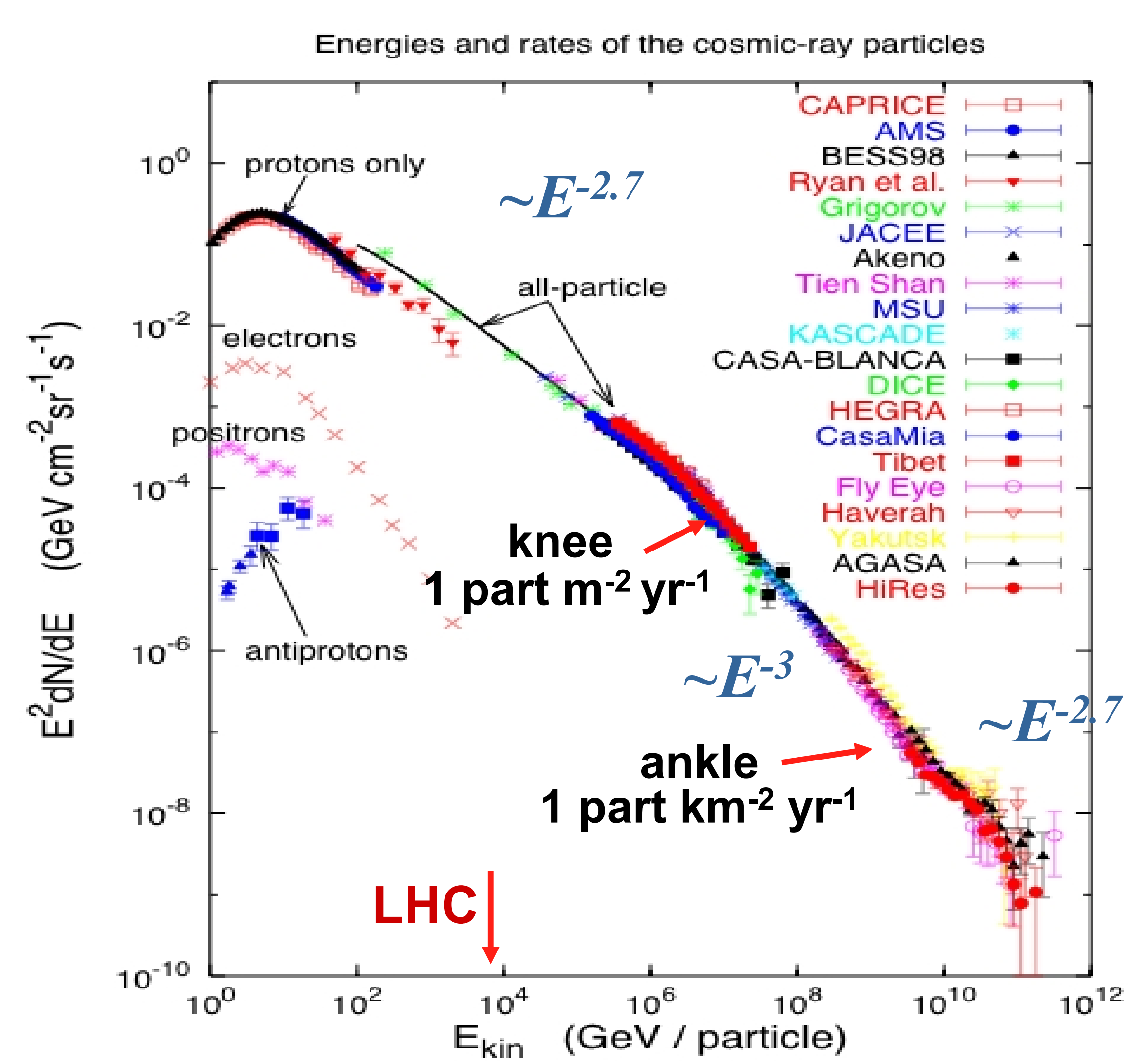
21.11.2006

- Introduction
- ANTARES and Other Current Projects
- Aiming at a km^3 Detector in the Mediterranean Sea: The KM3NeT Design Study
- Conclusions and Outlook

The Mysterious Cosmic Rays



- Particles impinging on Earth from outer space carry energies up to
  10^{21} eV
  (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

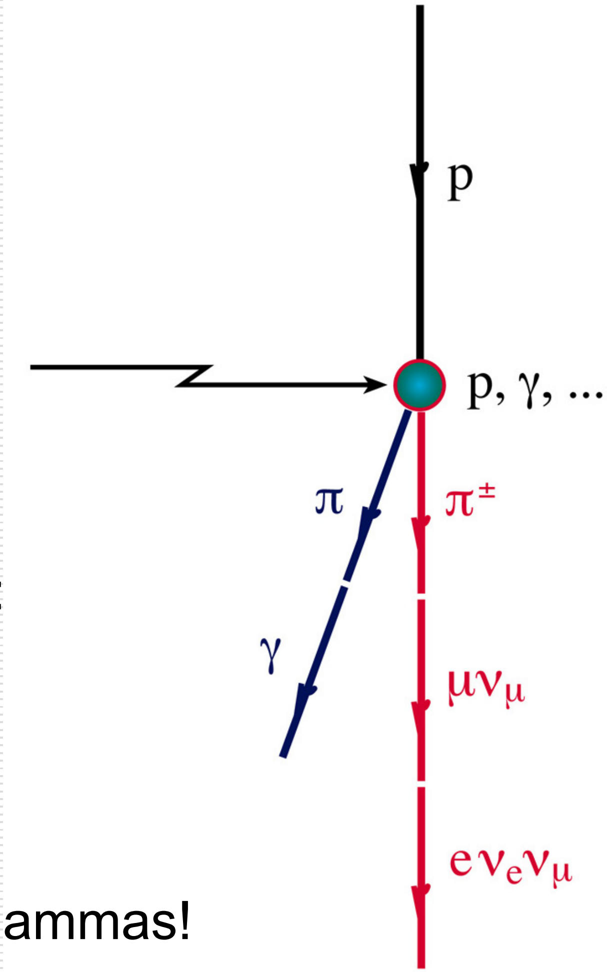
$$\downarrow$$

Cosmic rays

$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

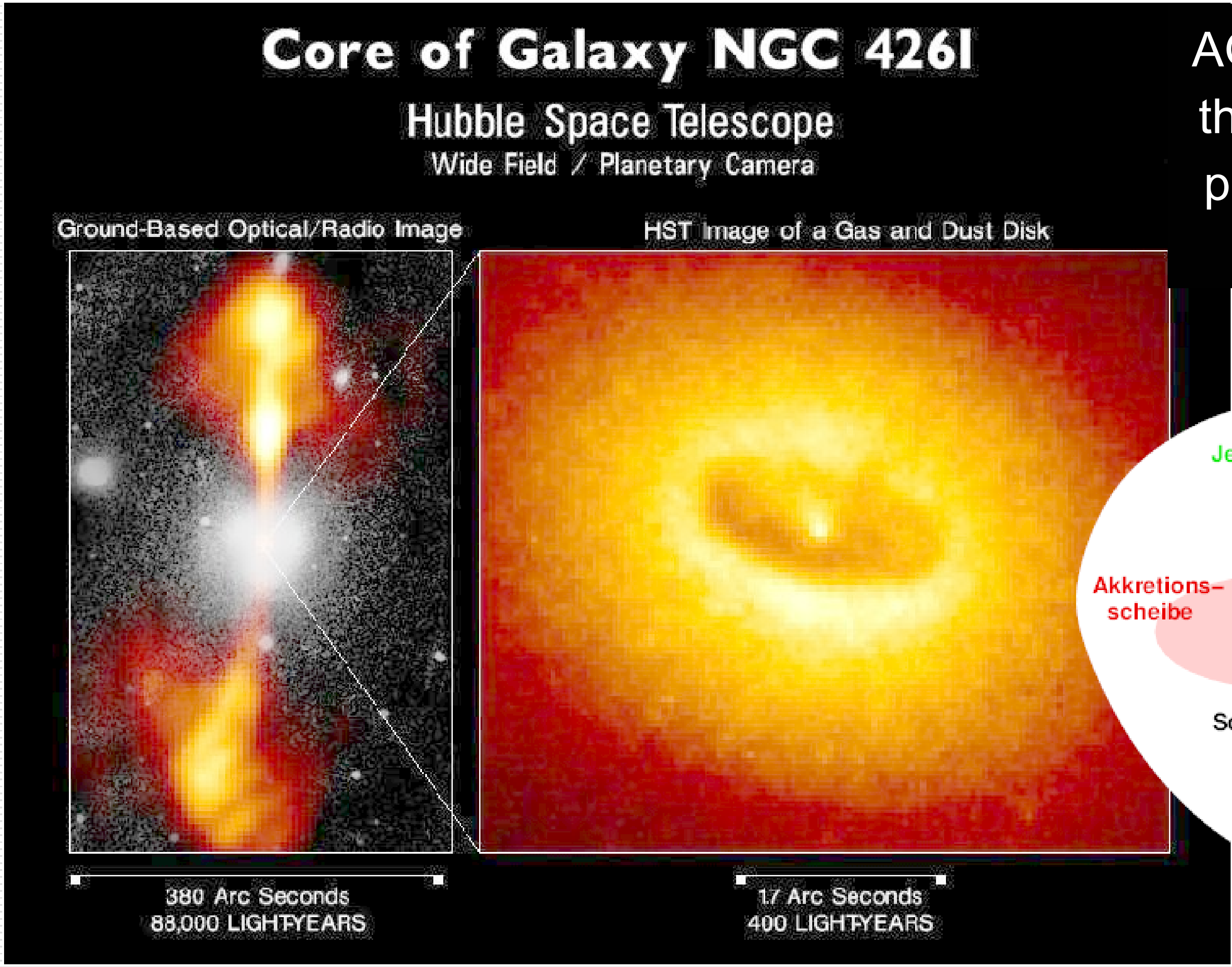
- Simultaneously, gamma production takes place:

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

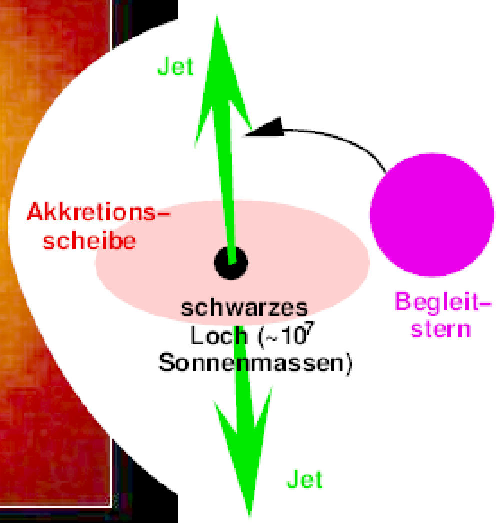


- Cosmic ray acceleration yields neutrinos and gammas!

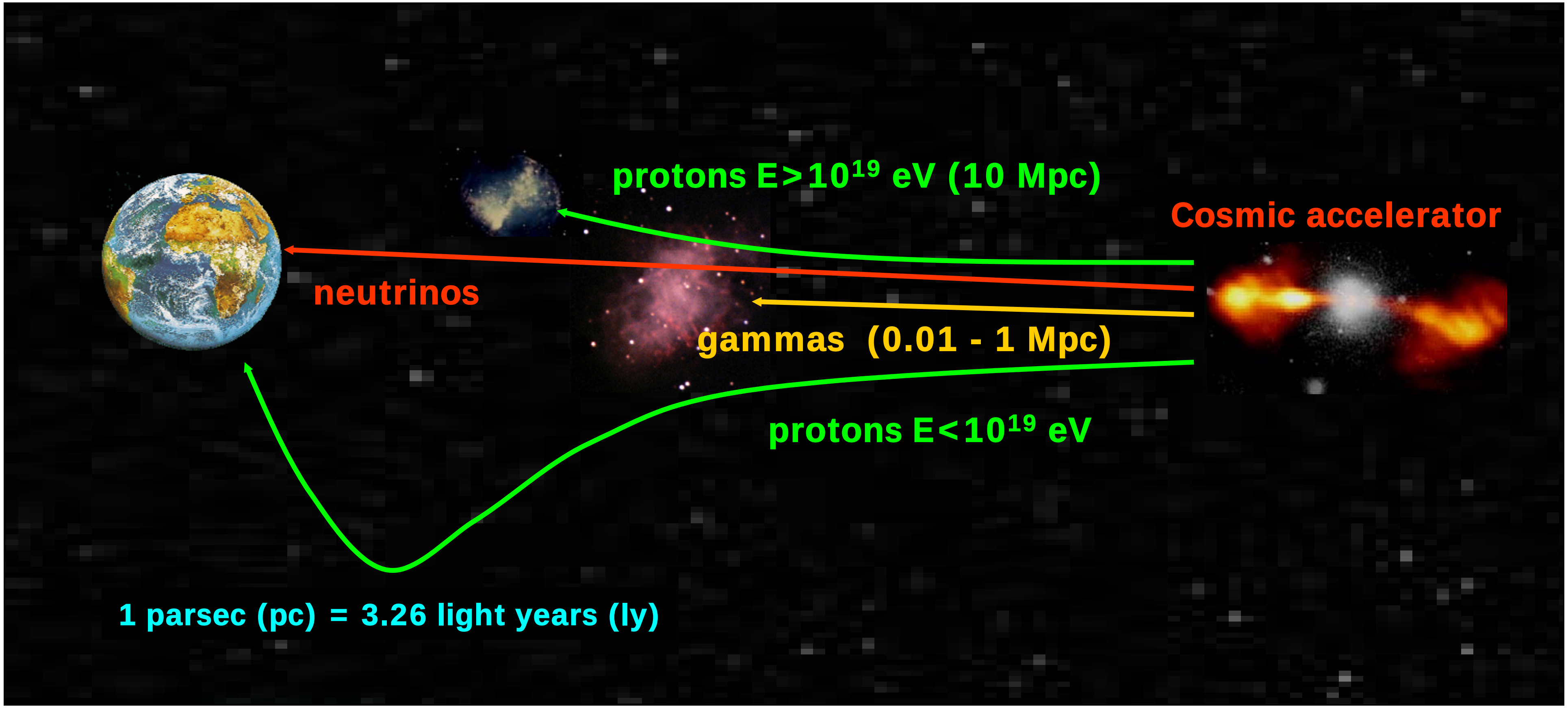
Candidate accelerators: Active Galactic Nuclei



AGNs are amongst the most energetic phenomena in the universe.



Particle propagation in the Universe



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

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).

Astro- and Particle Physics with ν Telescopes

Neutrino Oscillations:
Direction, Energy, Flavor

Dark matter search (WIMPs):
Direction, Energy

Astrophysical point sources:
Direction, (Energy), Time

Diffuse cosmic neutrino flux:
(Direction), Energy

Low-energy limit:
- short muon range
- small number of photons detected
- background light from K40 decays

High-energy limit:
- neutrino flux decreases like E^{-n} ($n \approx 2$)
- large detection volume needed.

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

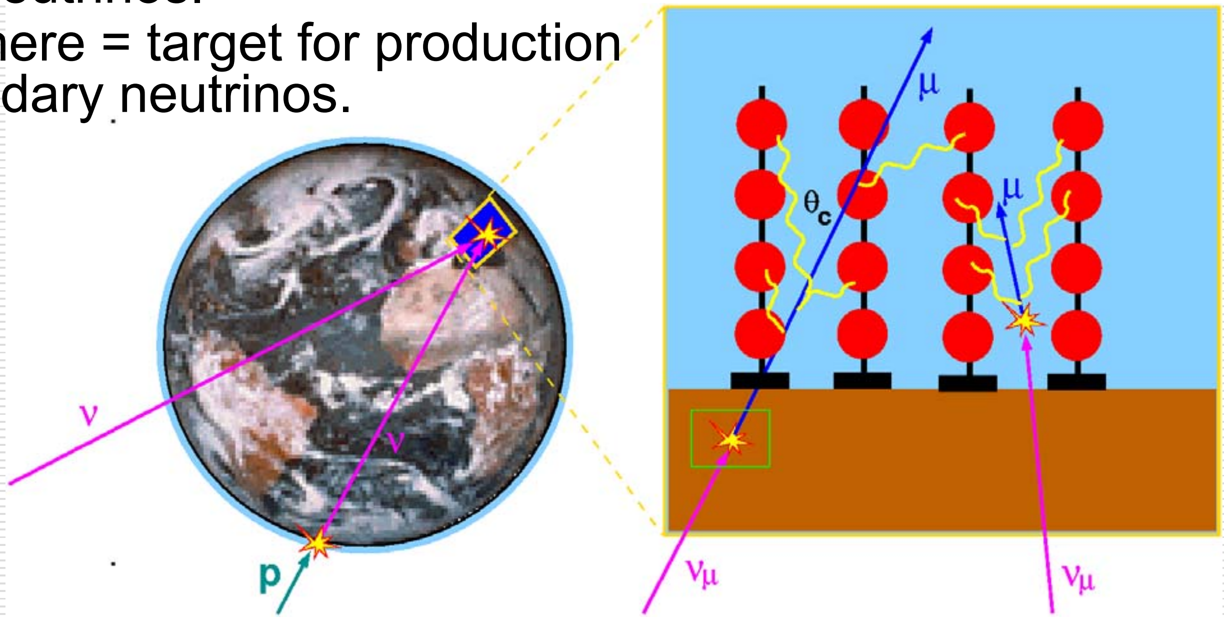
The Principle of Neutrino Telescopes

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.

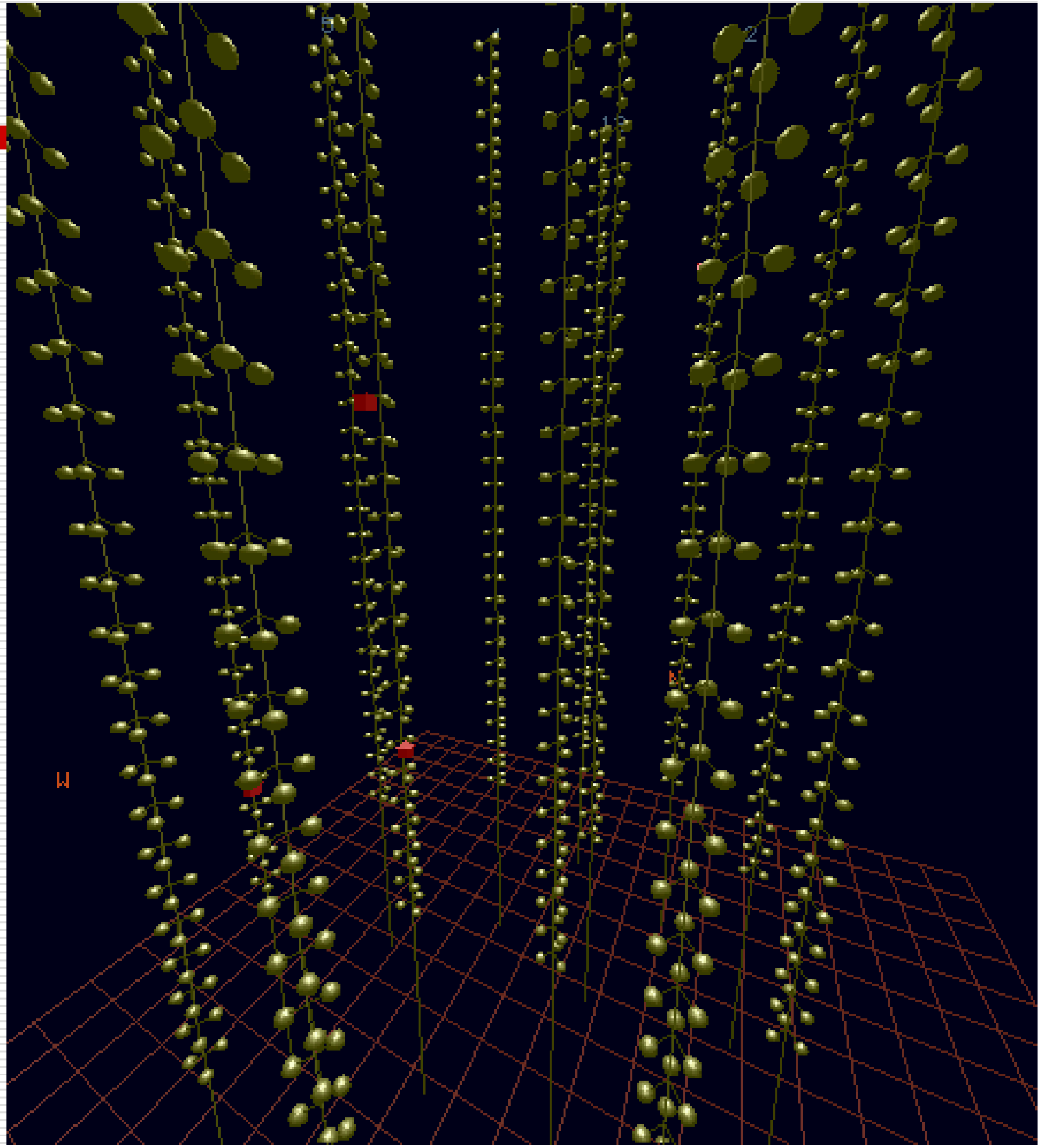


Angular resolution in water:

- Better than ~0.3° for neutrino energy above ~10 TeV, 0.1° at 100 TeV
- Dominated by angle(ν,μ) below ~10 TeV (~0.6° at 1 TeV)

μ Reconstruction

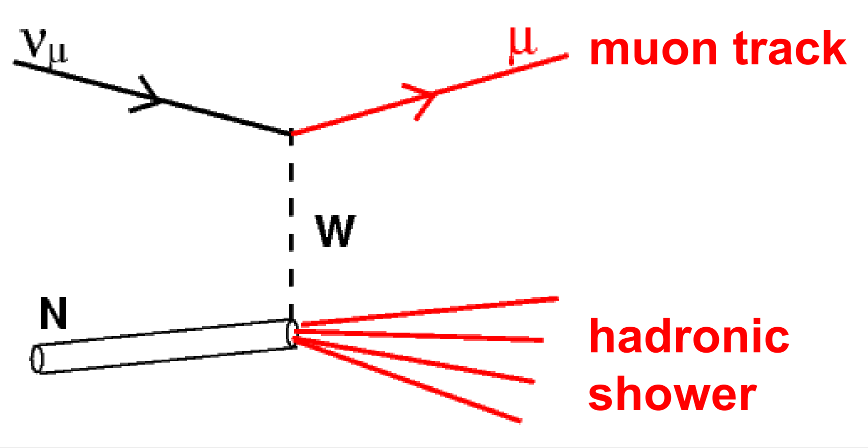
- The Cherenkov light is registered by the photomultipliers with nanosecond precision.
- From time and position of the hits the direction of the muon can be reconstructed to ~0.1°.
- Minimum requirement: 5 hits … in reality rather 10 hits.
- Position calibration to ~10cm required (acoustic methods).

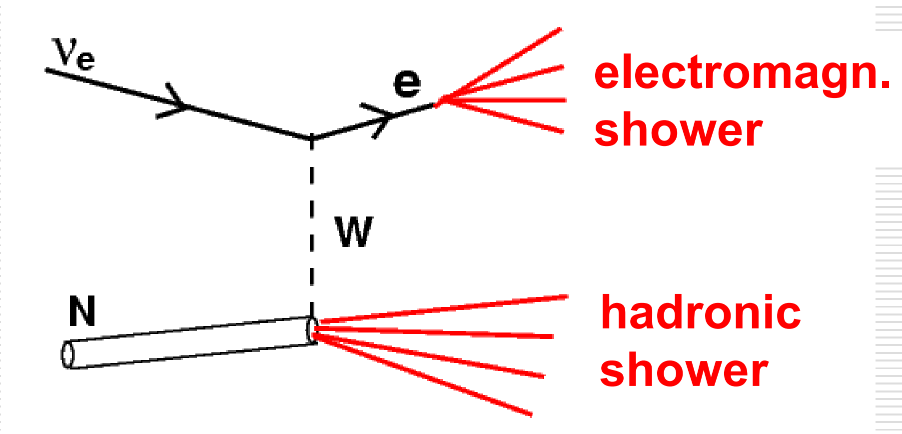


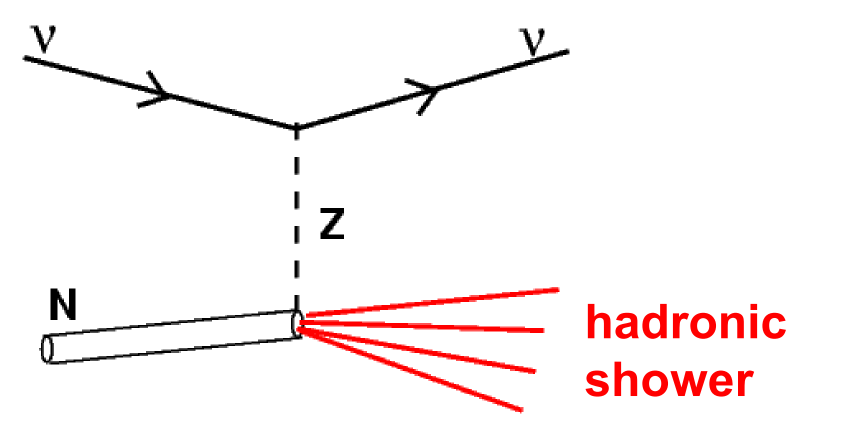
1.2 TeV muon traversing the detector.

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 Cherenkov light.



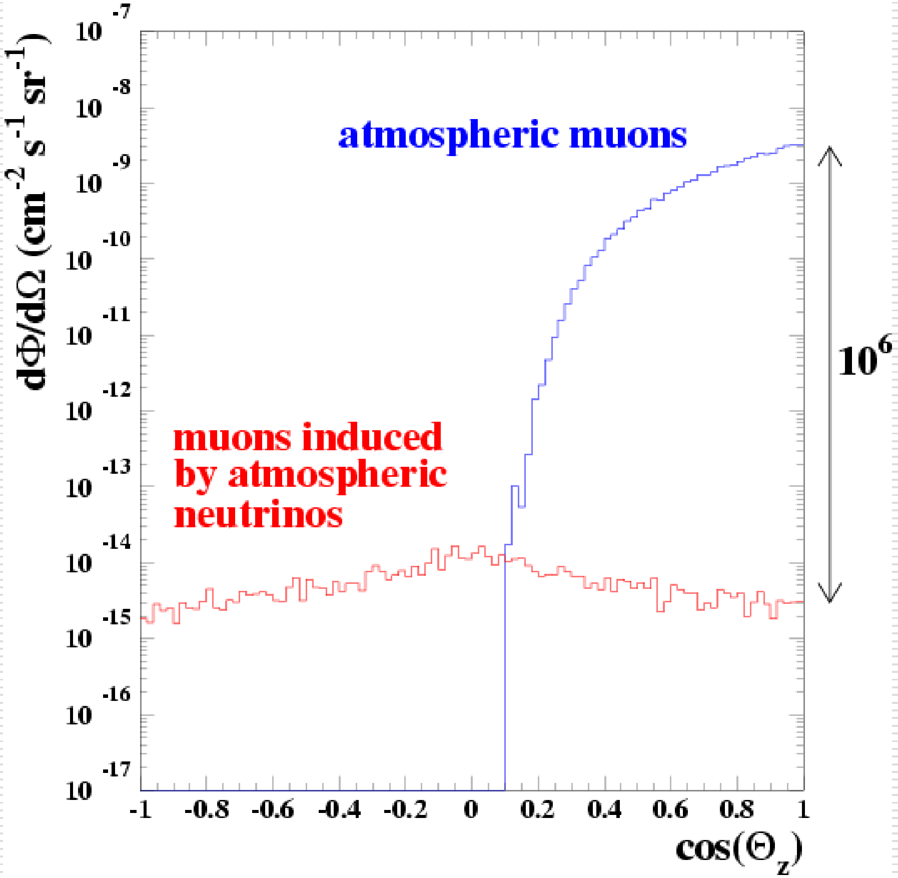


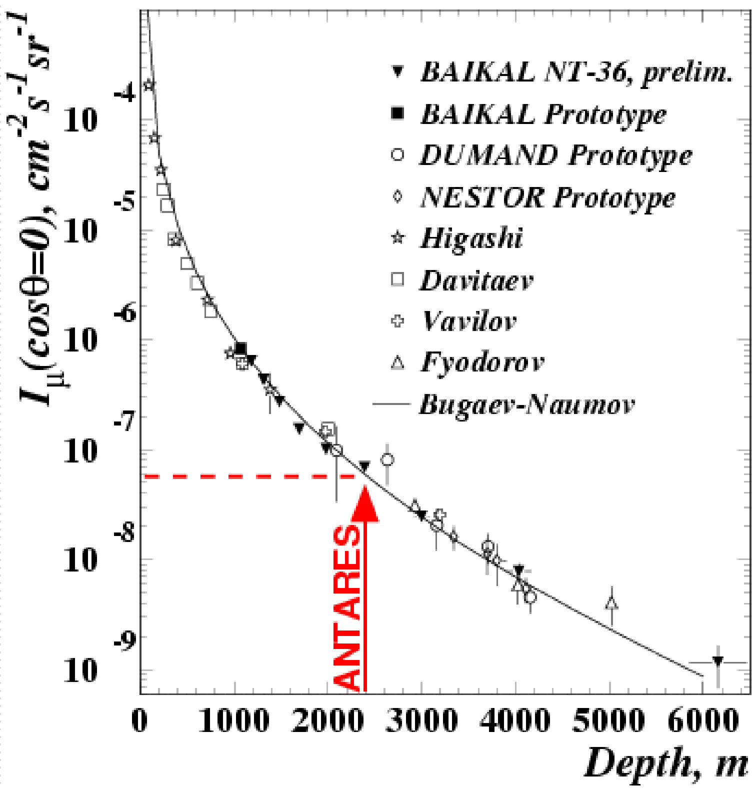


Muons: The Background from Above

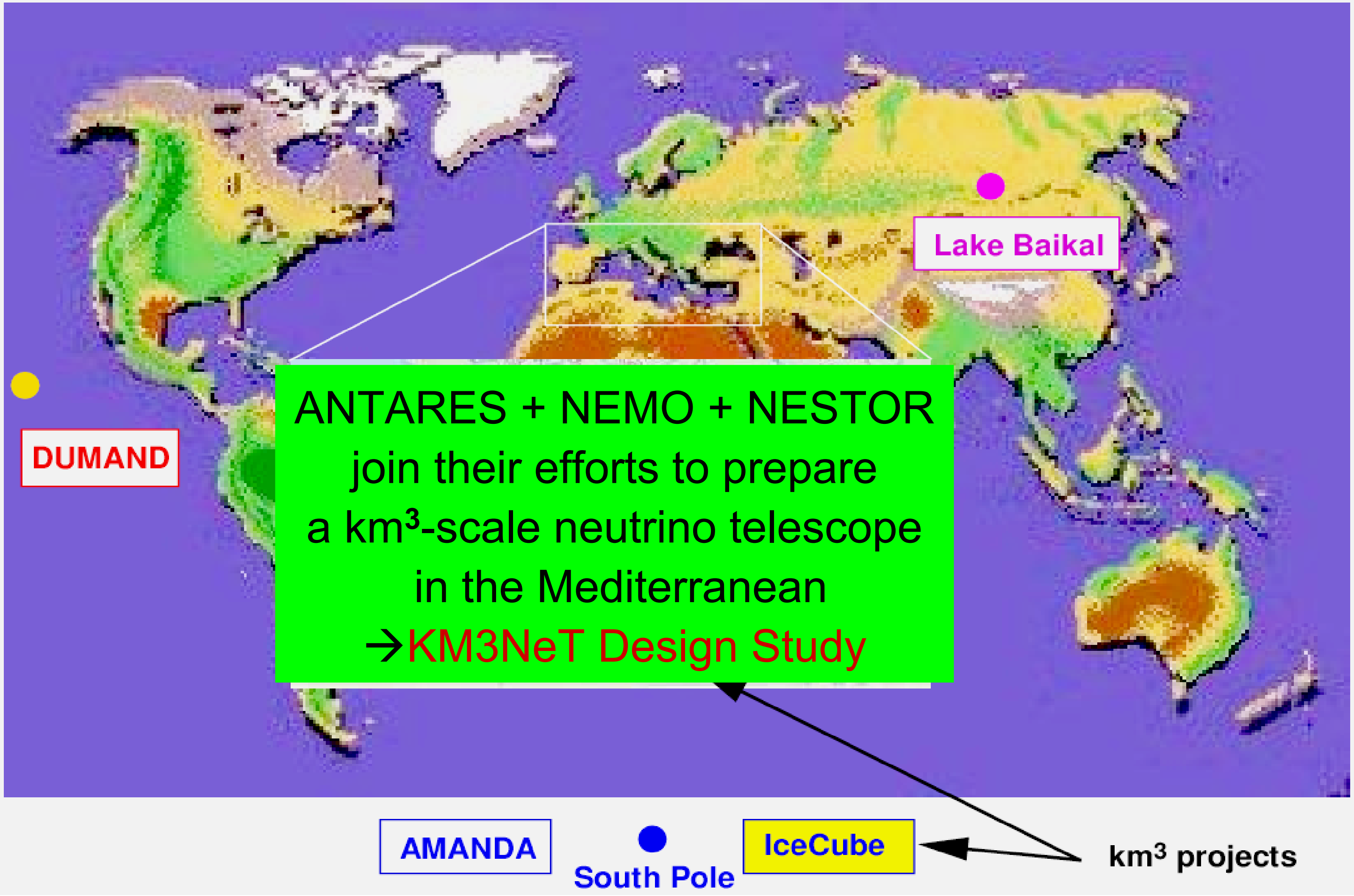
Muons can penetrate several km of water if E_μ > 1TeV;

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



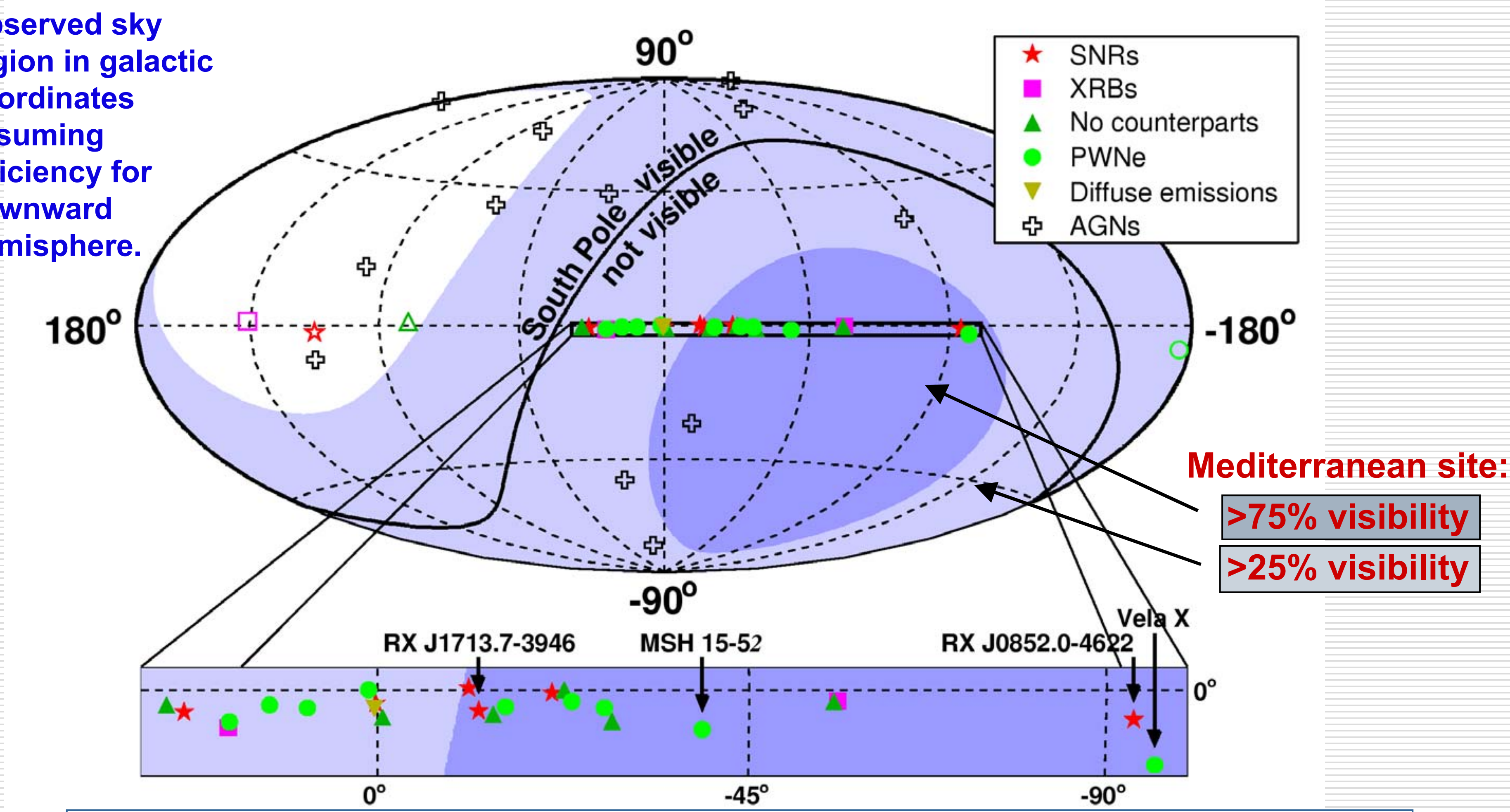


The Neutrino Telescope World Map



Sky Coverage of Neutrino Telescopes

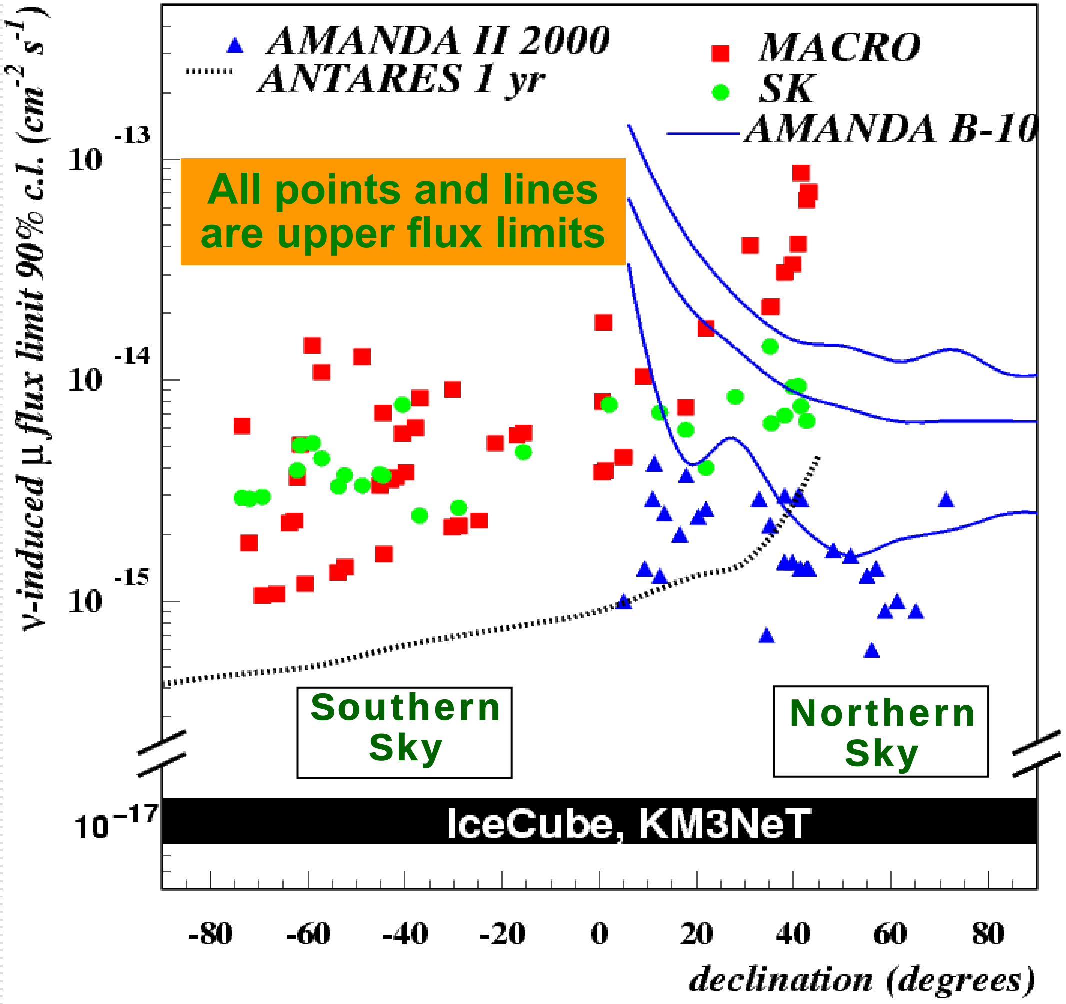
Observed sky region in galactic coordinates assuming efficiency for downward hemisphere.



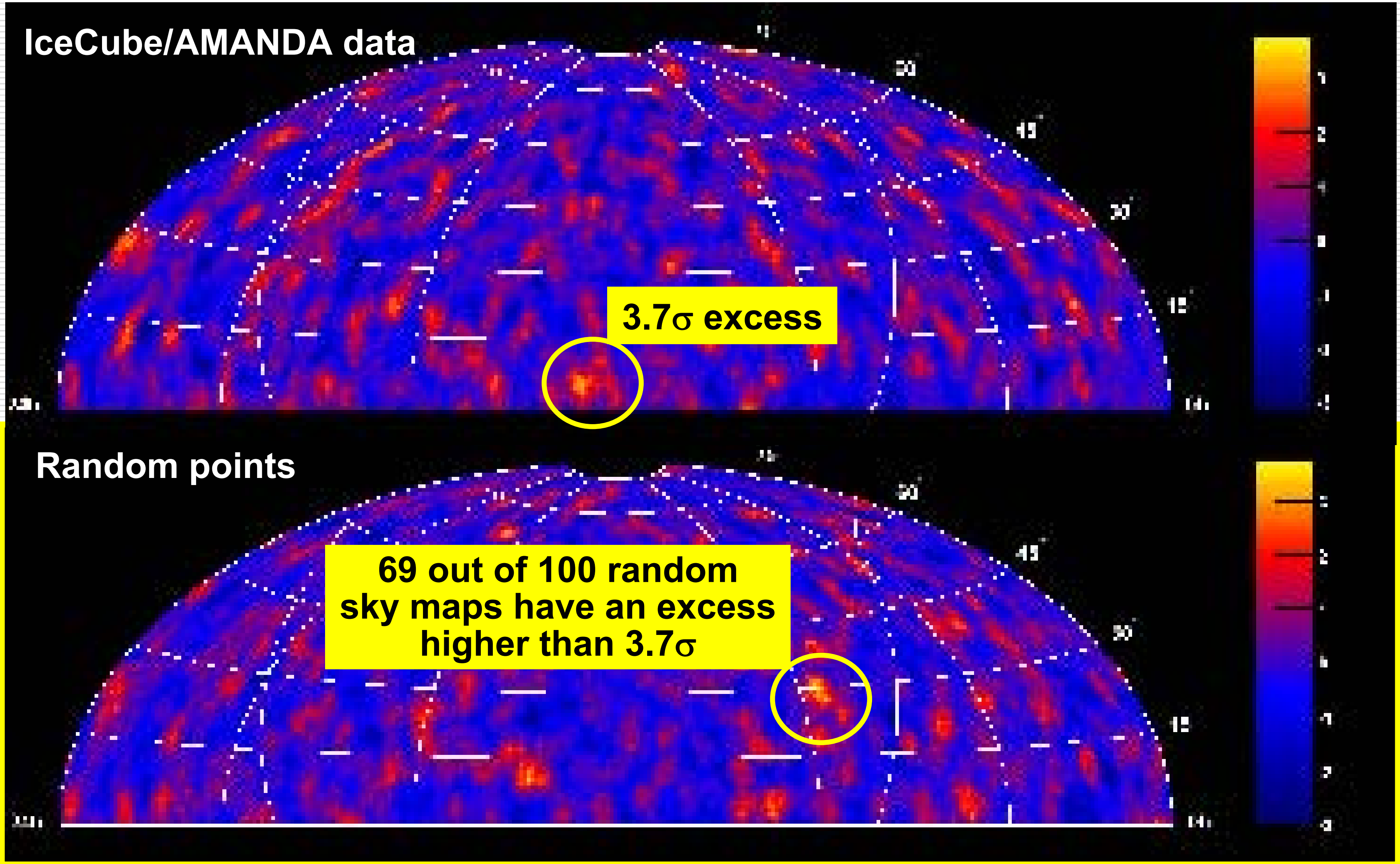
→ We need ν telescopes in both hemispheres to see the whole sky

Neutrinos from Astrophysical Point Sources

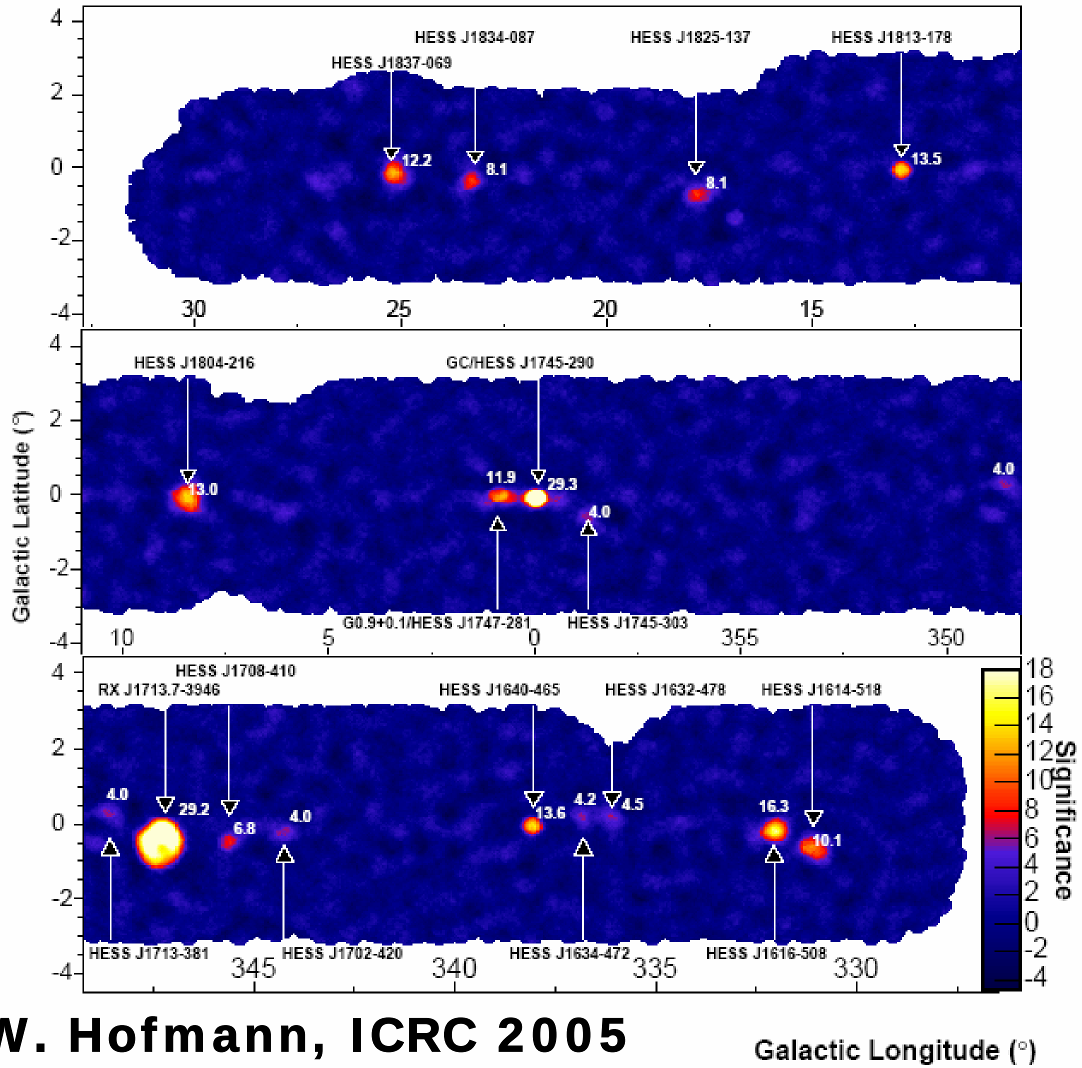
- Association of neutrinos to specific astrophysical objects.
- Energy spectrum, time structure, multi-messenger observations provide insight into physical processes inside source.
- Measurements profit from very good angular resolution of water Čerenkov telescopes.
- km³ detectors needed to exploit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



Does AMANDA/IceCube see Point Sources?



High-energy γ sources in the Galactic Disk

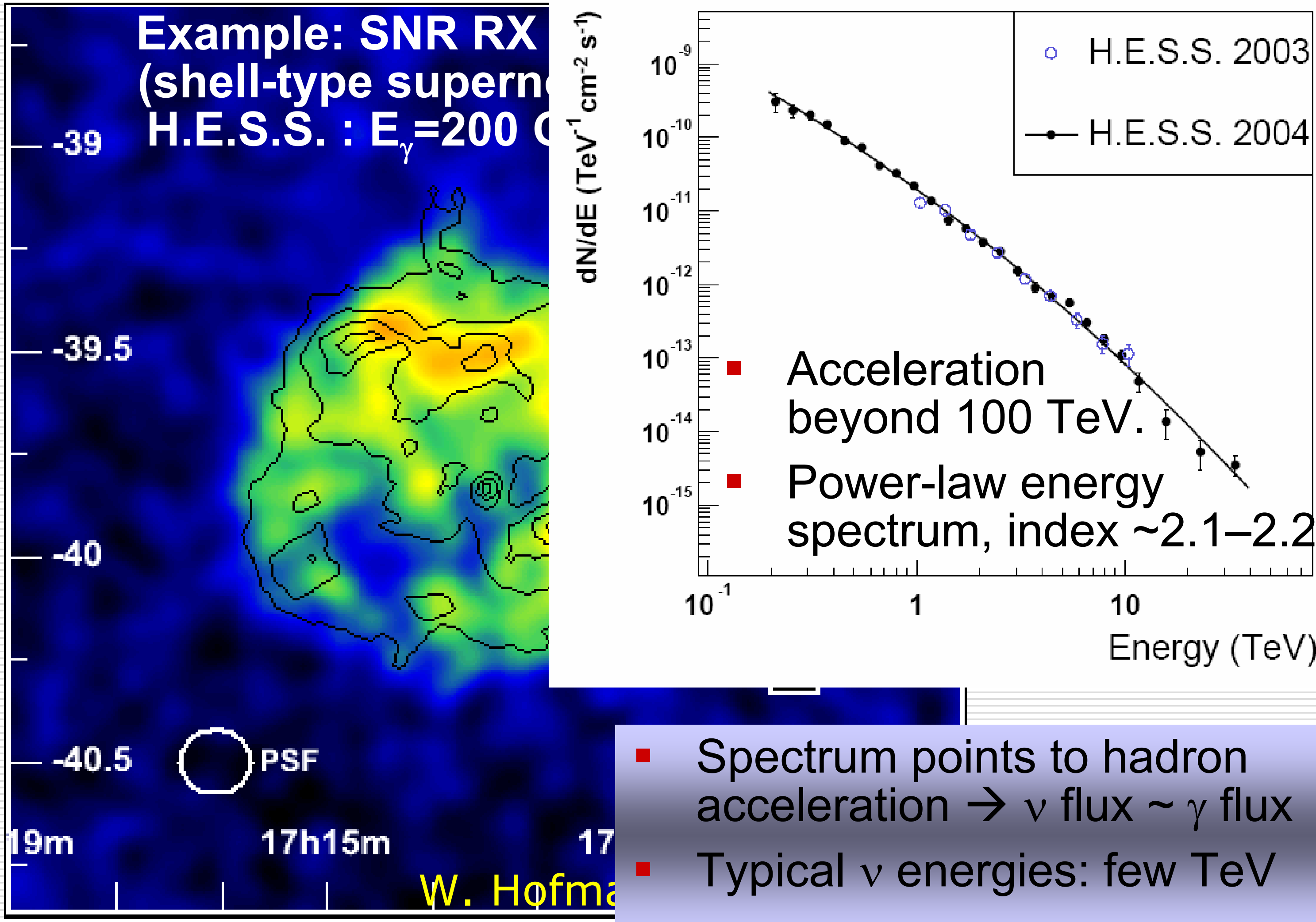


W. Hofmann, ICRC 2005

Update June 2006:

- 6 γ sources could be/are associated with SNR, e.g. RX J1713.7-3946;
- 9 are pulsar wind nebulae, typically displaced from the pulsar;
- 2 binary systems (1 H.E.S.S. / 1 MAGIC);
- 6 have no known counterparts.

Neutrinos from Supernova Remnants



- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index ~2.1–2.2.

- Spectrum points to hadron acceleration → ν flux ~ γ flux
- Typical ν energies: few TeV

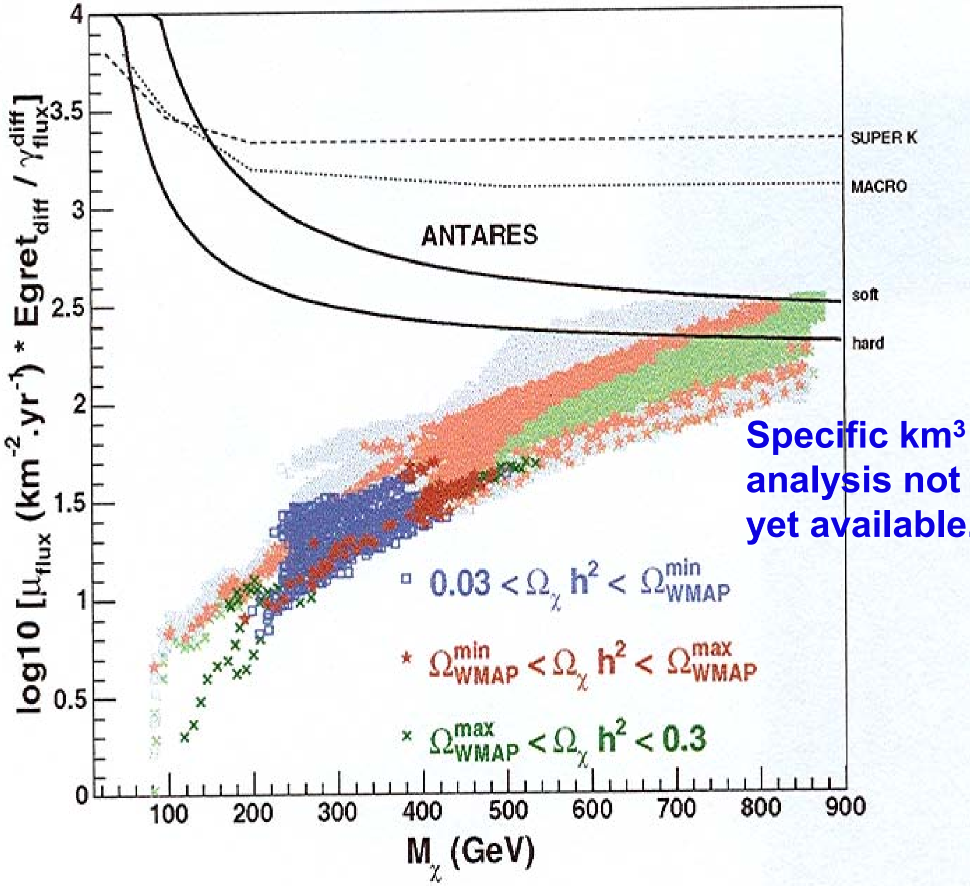
Indirect Search for Dark Matter

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

$$\chi\chi \to \nu + X$$

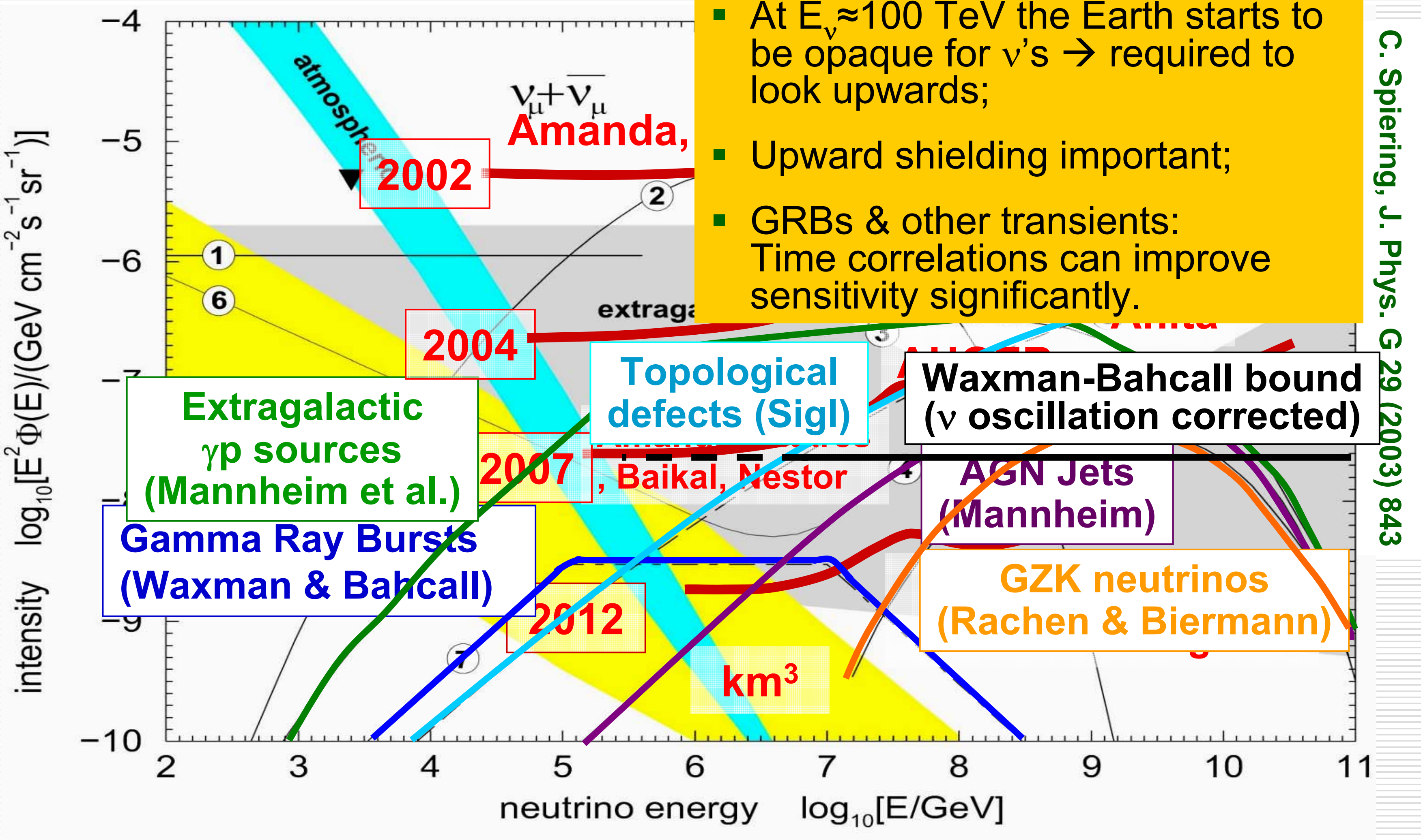
- Detection requires low energy threshold (O(100GeV) or less).
- Flux from Galactic Center may be enhanced due to supermassive Black Hole [see e.g. P. Gondolo and J. Silk, PRL 83(1999)1719].
- But: model uncertainties on ν flux are orders of magnitude!

Neutrino flux from the Galactic Center (from G. Bertone et al., astro-ph/0403322)



Specific km³ analysis not yet available.

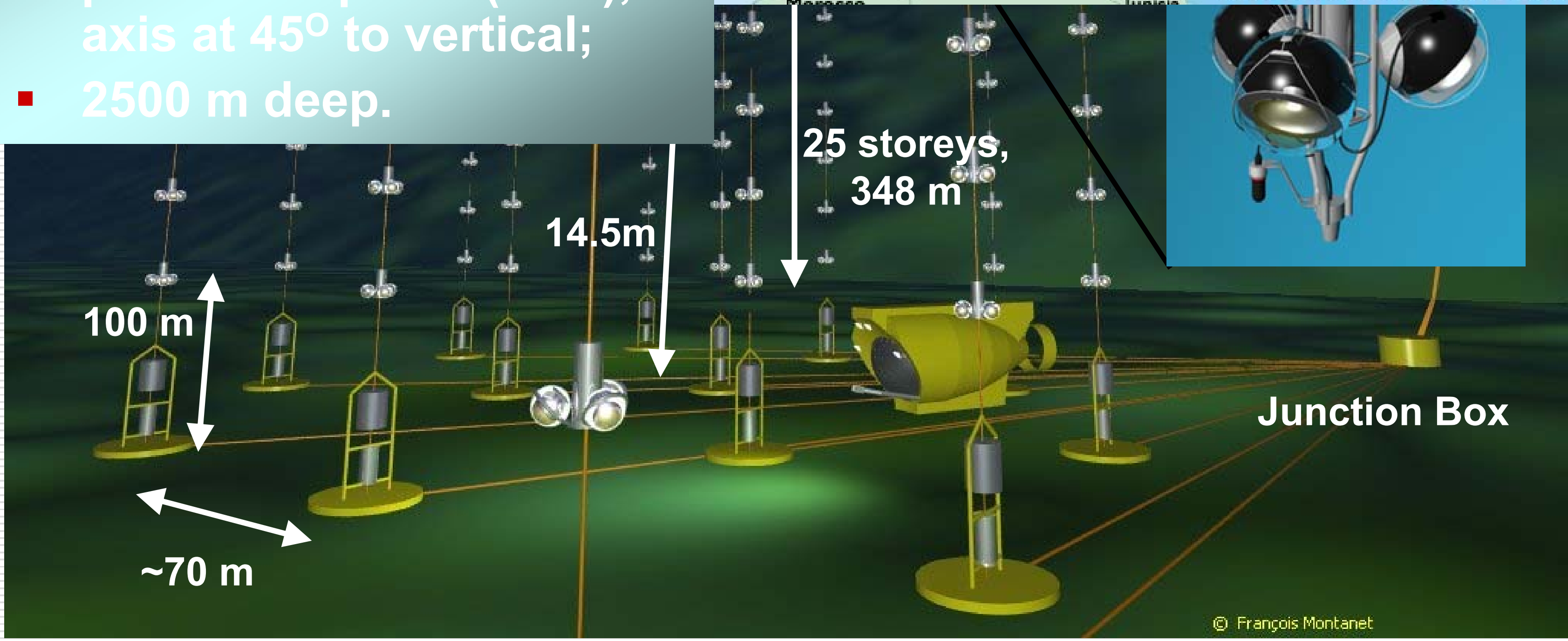
Diffuse ν Flux: Models, Limits and Sensitivities



- At $E_\nu \approx 100$ TeV the Earth starts to be opaque for ν's → required to look upwards;
- Upward shielding important;
- GRBs & other transients: Time correlations can improve sensitivity significantly.

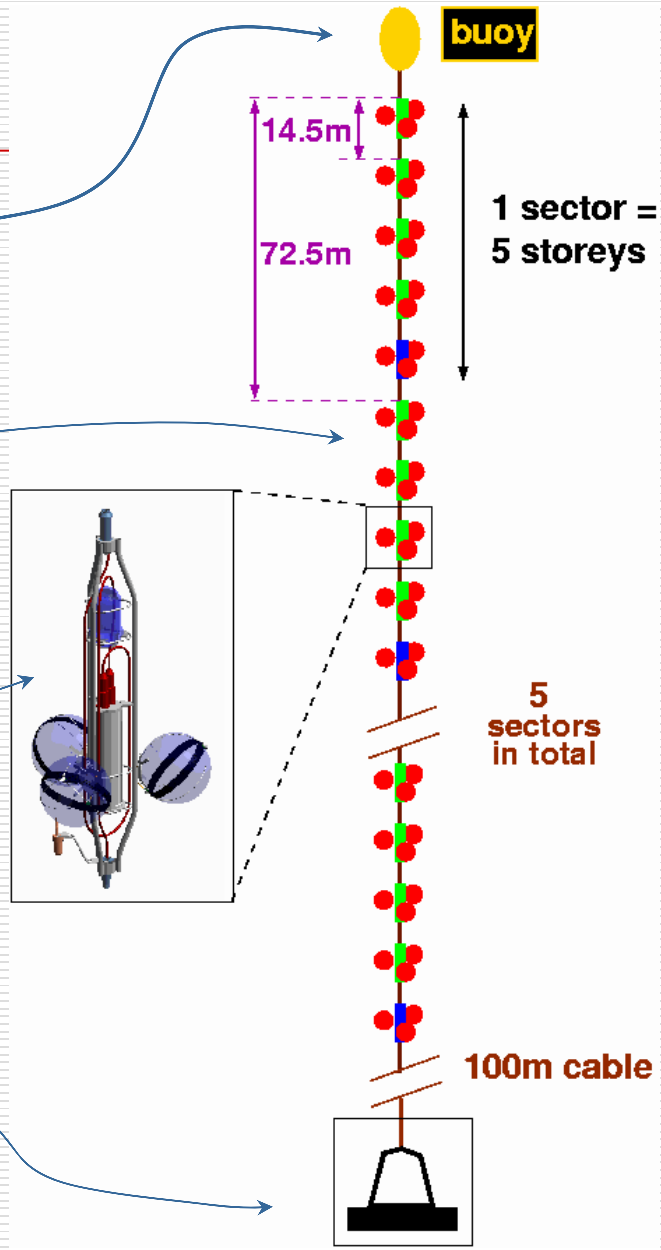
ANTARES: Detector Design

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



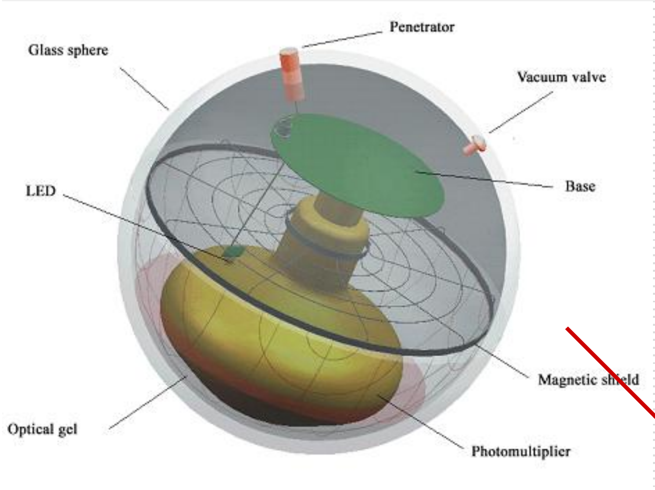
ANTARES: Detector Strings

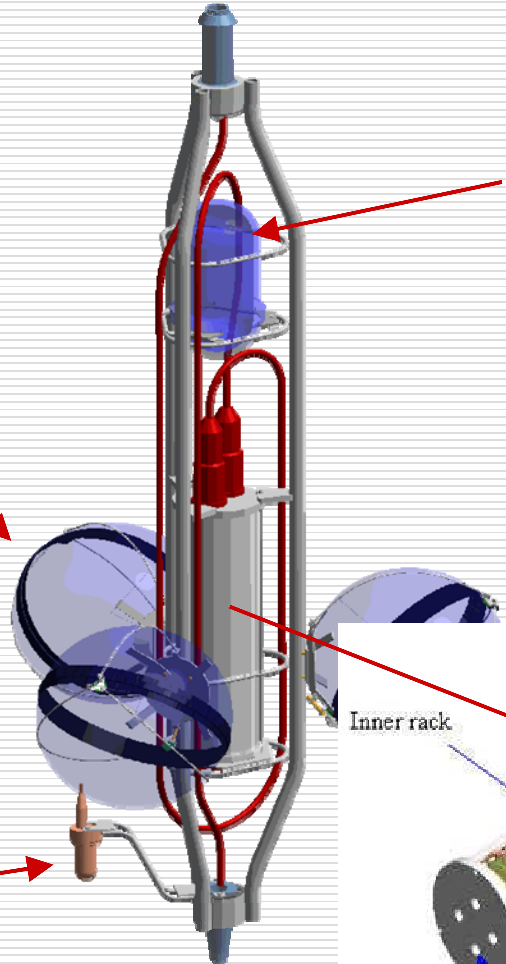
- Buoy:
  - buoyancy ~6400 N;
  - keeps string vertical to better than 20m displacement at top.
- Electro-optical-mechanical cable:
  - metal wires for power supply etc.;
  - optical fibers for data;
  - mechanical backbone of string.
- Storeys:
  - 3 optical modules per storey;
  - titanium cylinder for electronics;
  - calibration devices (light, acoustics).
- Anchor:
  - deadweight to keep string at bottom;
  - release mechanism operated by acoustic signal from surface.



ANTARES: Components of a Storey

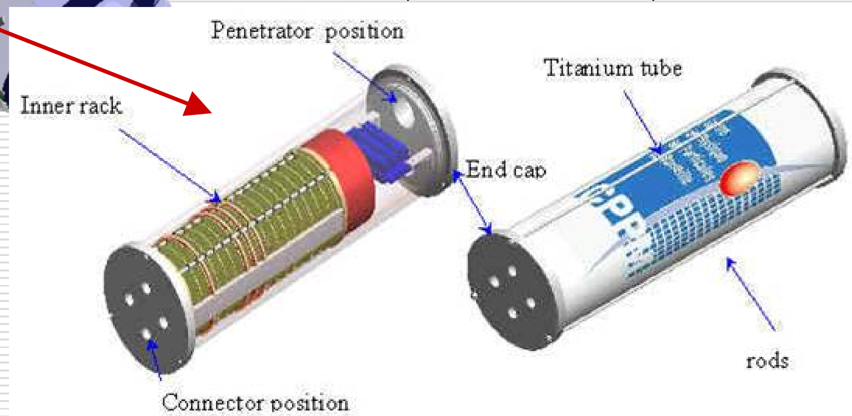
Optical Module





LED Beacon
for time calibration purposes

Titanium cylinder
housing electronics for readout, calibration, …



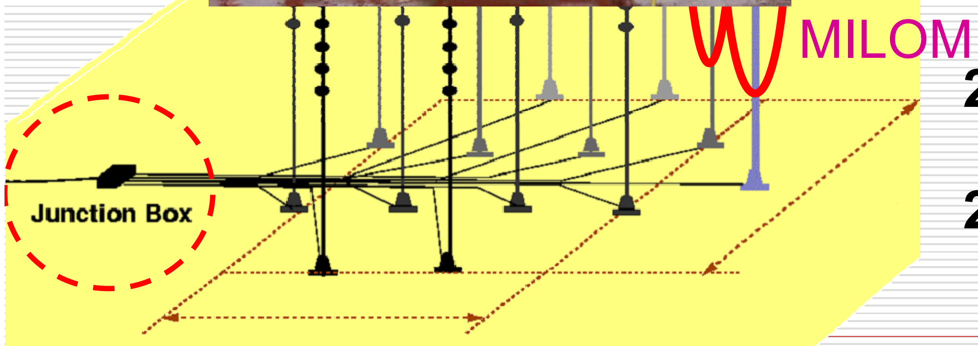
Hydrophone (RX)
for positioning

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 Construction Milestones



2001 – 2003:

- Main Electro-optical cable in 2001
- Junction Box in 2002
- Prototype Sector Line (PSL) &
  Mini Instrumentation Line (MIL) in 2003

2005 – Now:

- Mini Instrumentation Line with OMs (MILOM) running since 12 April 2005
- Line 1 running since 2 March 2006, first complete detector line
- Line 2 running since 21 Sept. 2006

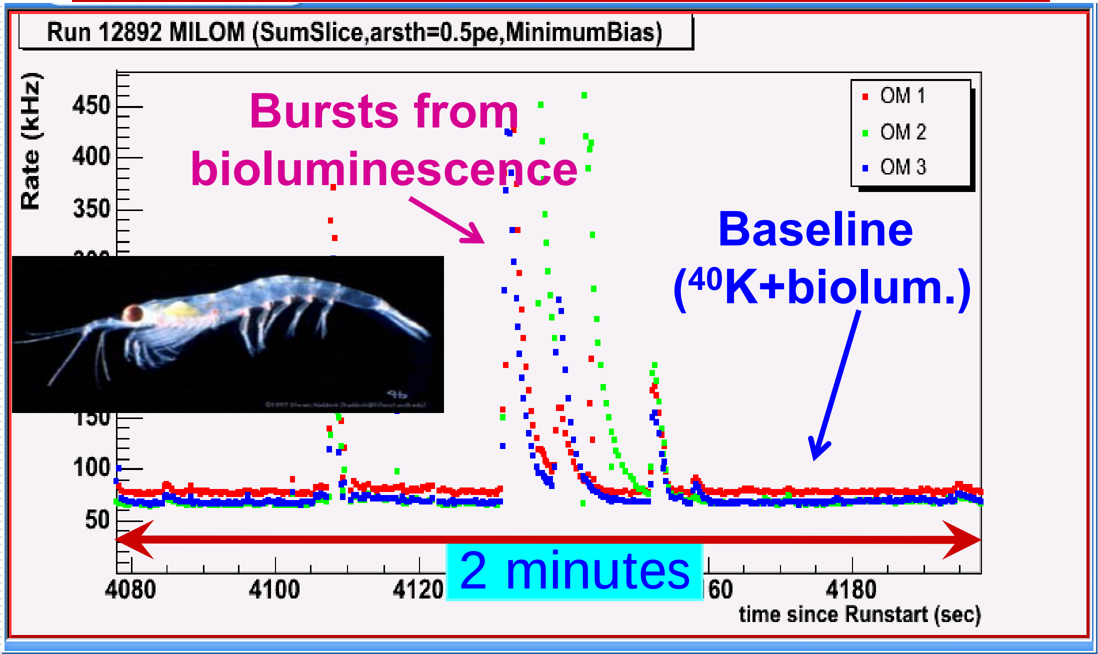
2006 – 2007:

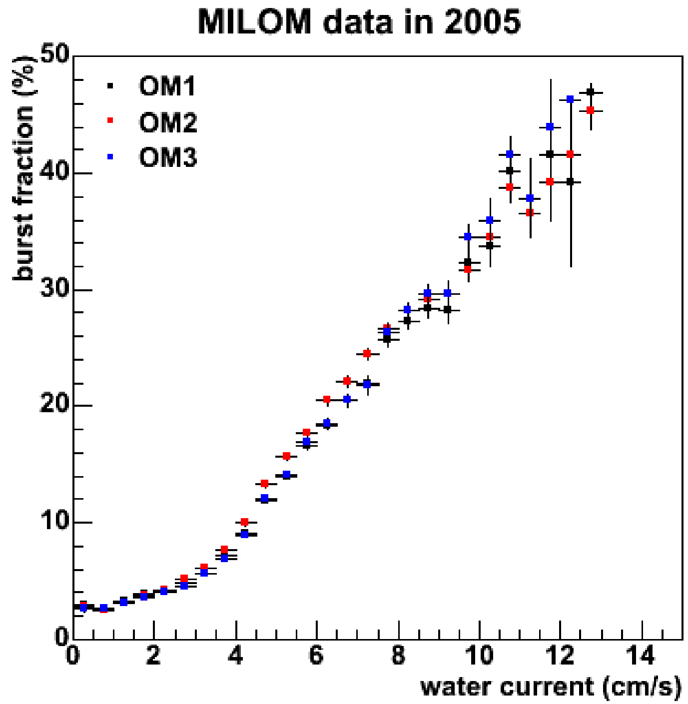
- Installation of ren

2007+:

- **Physics with ful**

ANTARES: Data from 2500m Depth (MILOM)

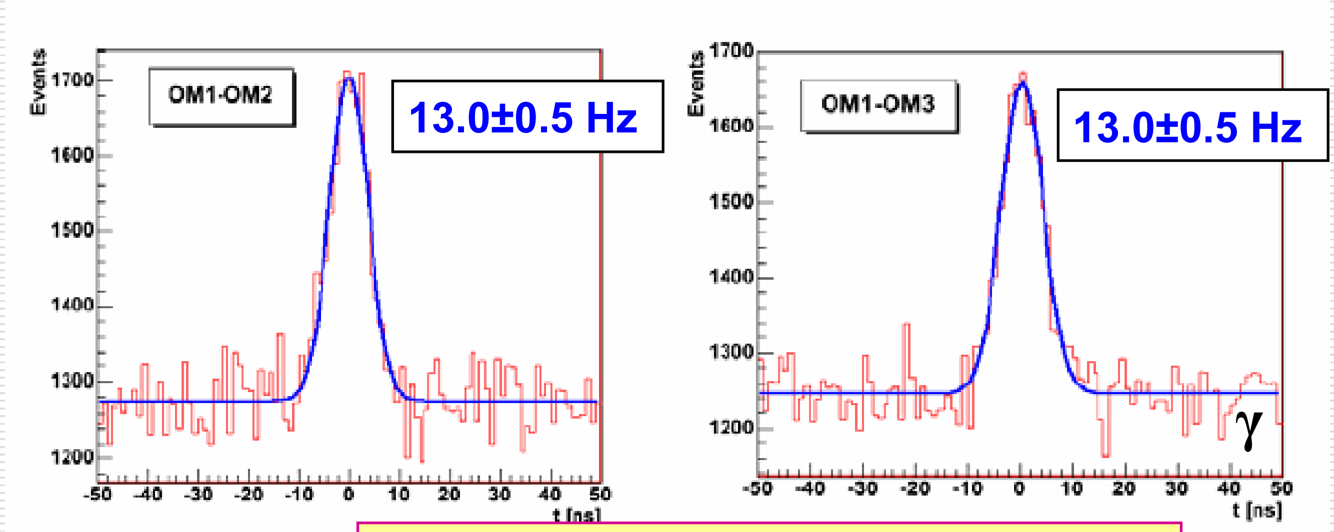




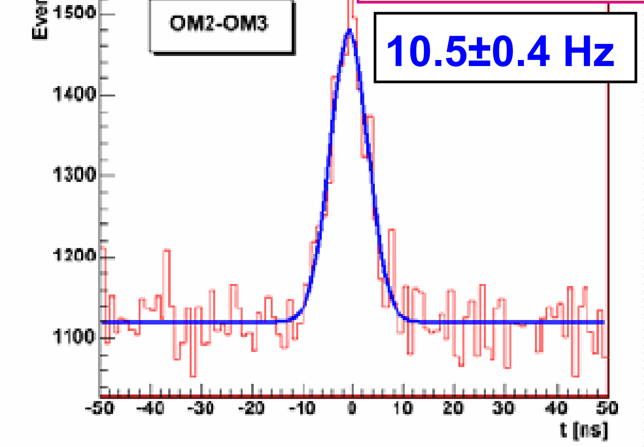
- Background light:
  - bioluminescence (bacteria, macroscopic organisms)
  - decays of ^{40}K (~30 kHz for 10'' photomultiplier)
- Correlation with water current
  - Light bursts by macroscopic organisms – induced by pressure variation in turbulent flow around optical modules ?!

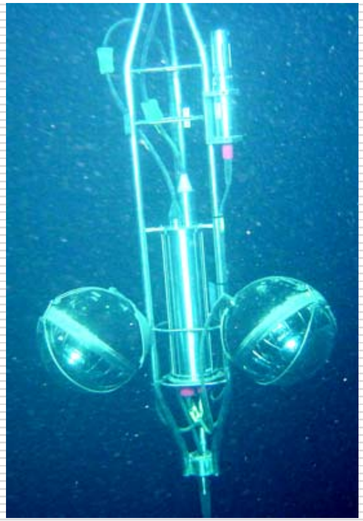
Burst-fraction:
fraction of time when rate > baseline + 20%

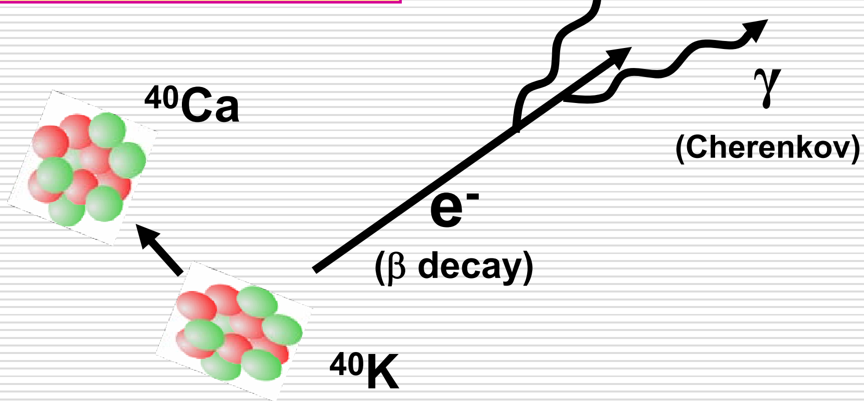
ANTARES: Coincidence rates from ^{40}K decays



Simulation: 12 Hz ± 4 Hz (sys)



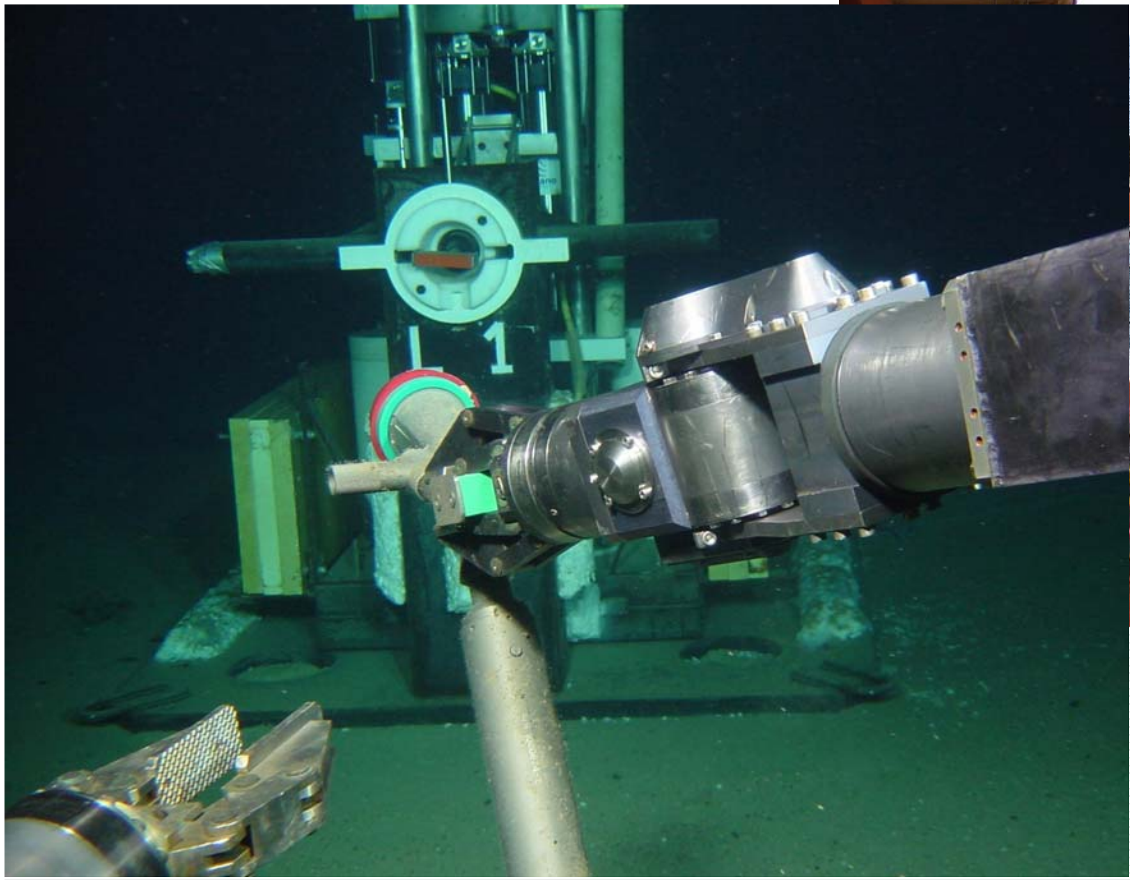


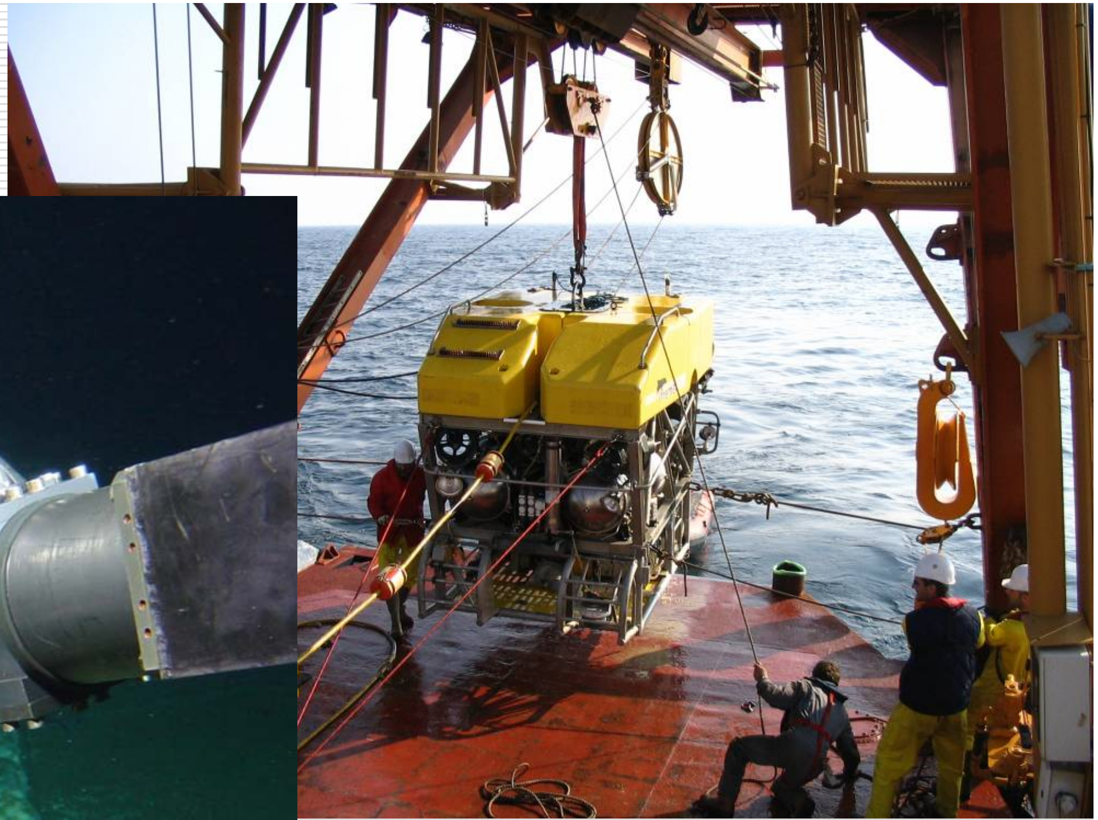


ANTARES: First Detector line installed …

14. Feb. 2006

… and connected by ROV Victor!

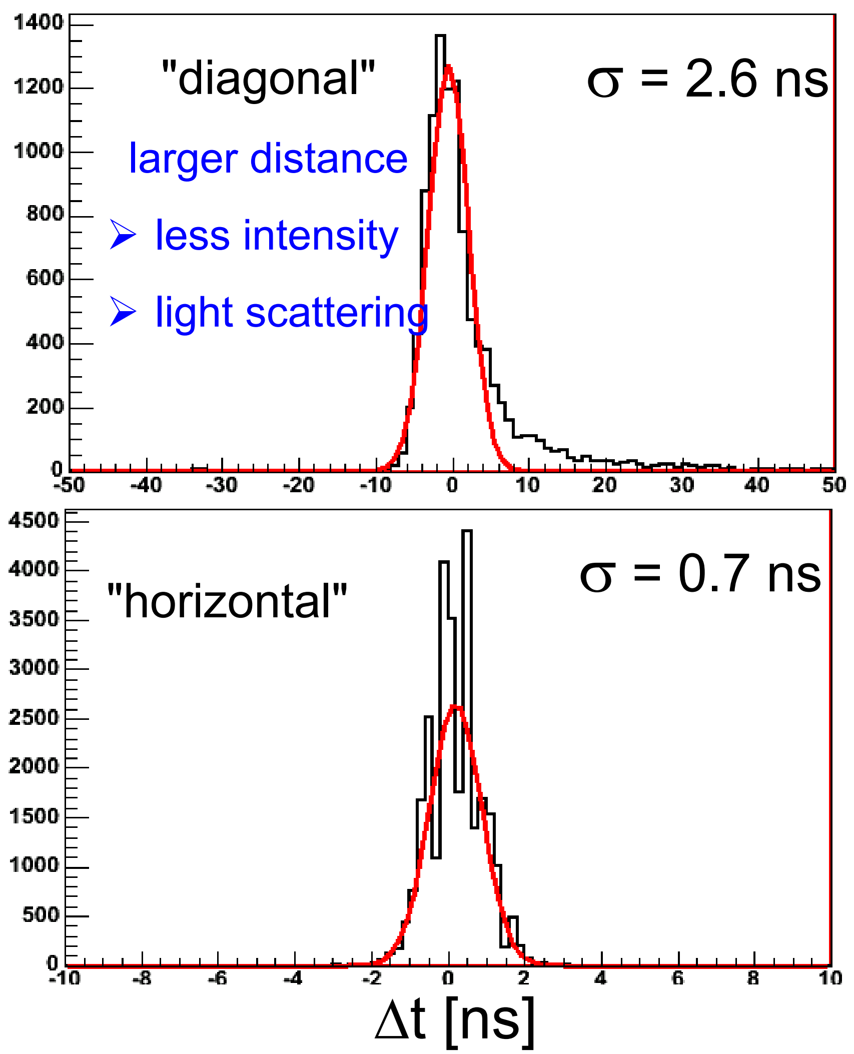


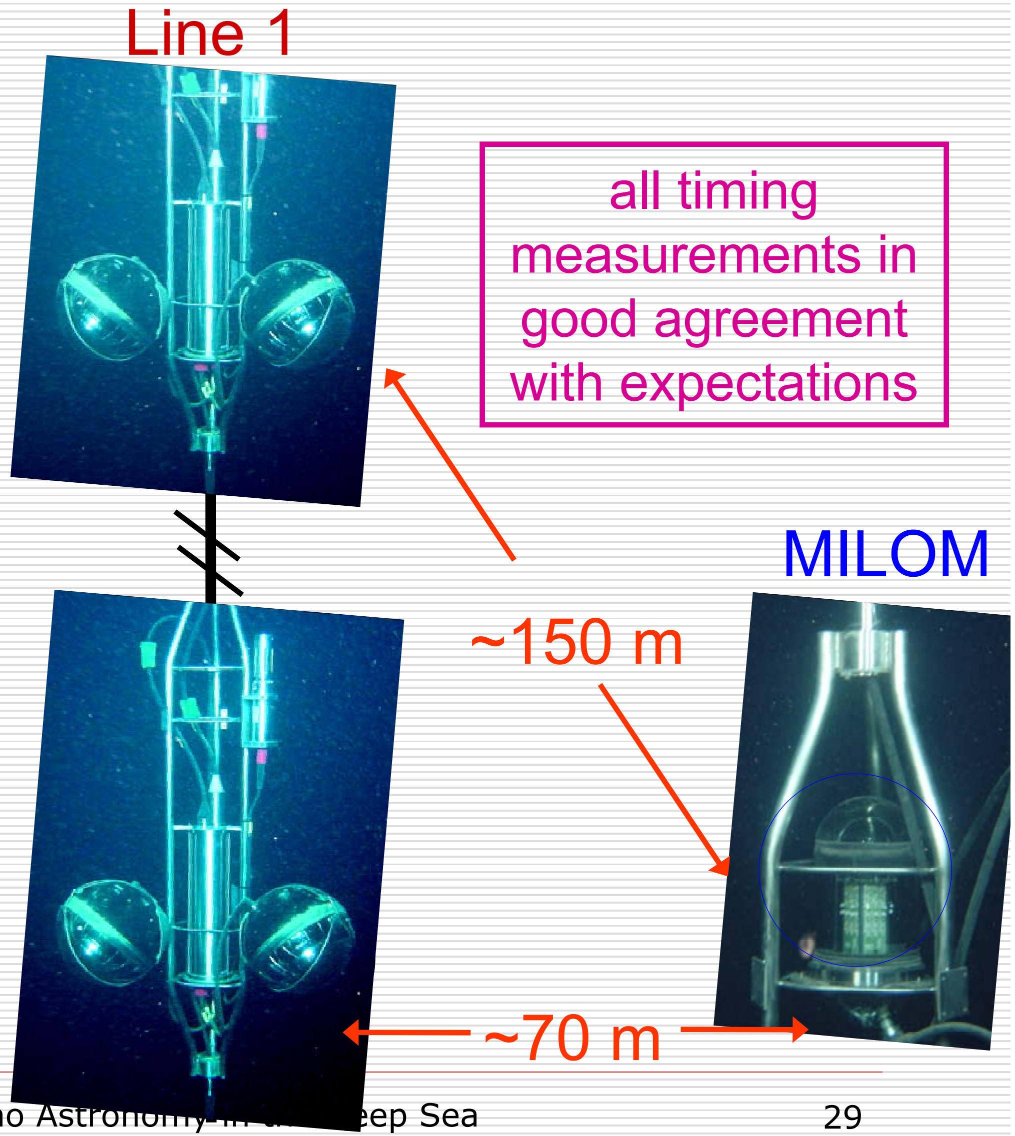


2. March 2006

(ROV = Remotely operated submersible)

ANTARES: Time Calibration with LED Beacons

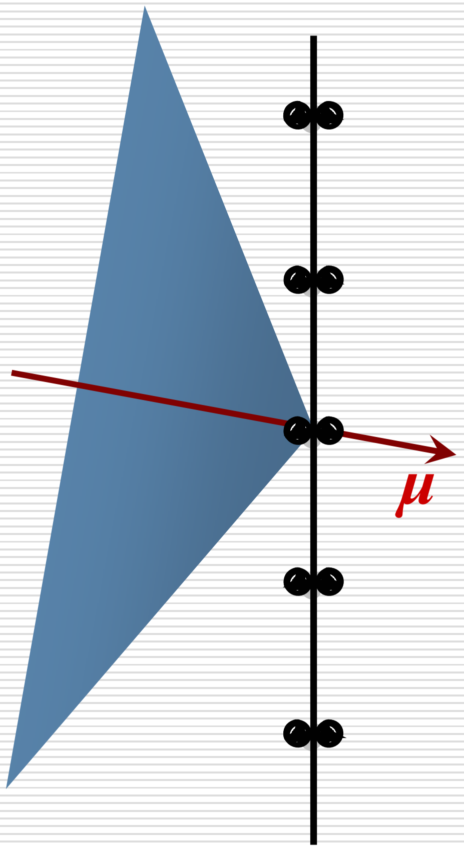


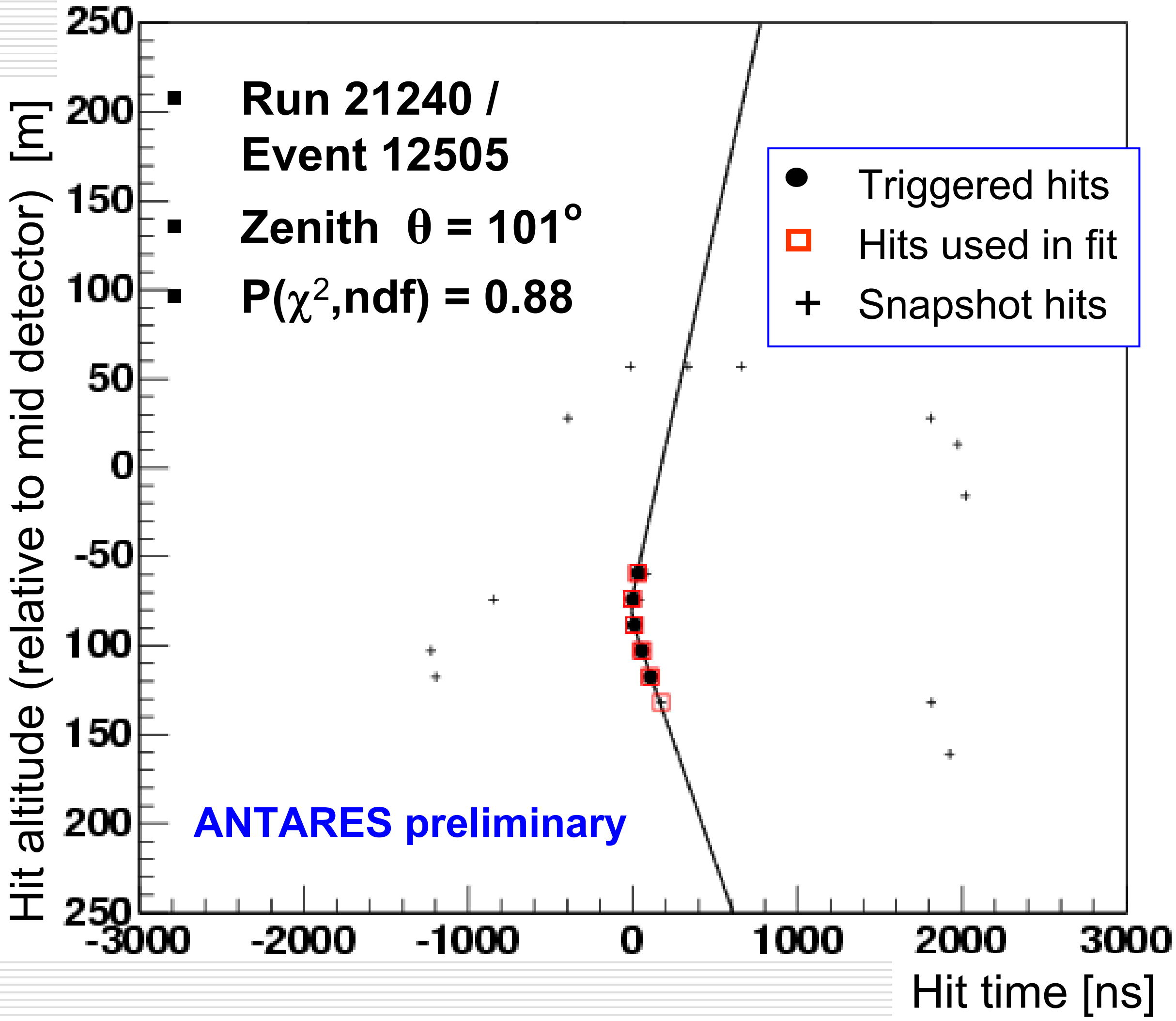


all timing measurements in good agreement with expectations

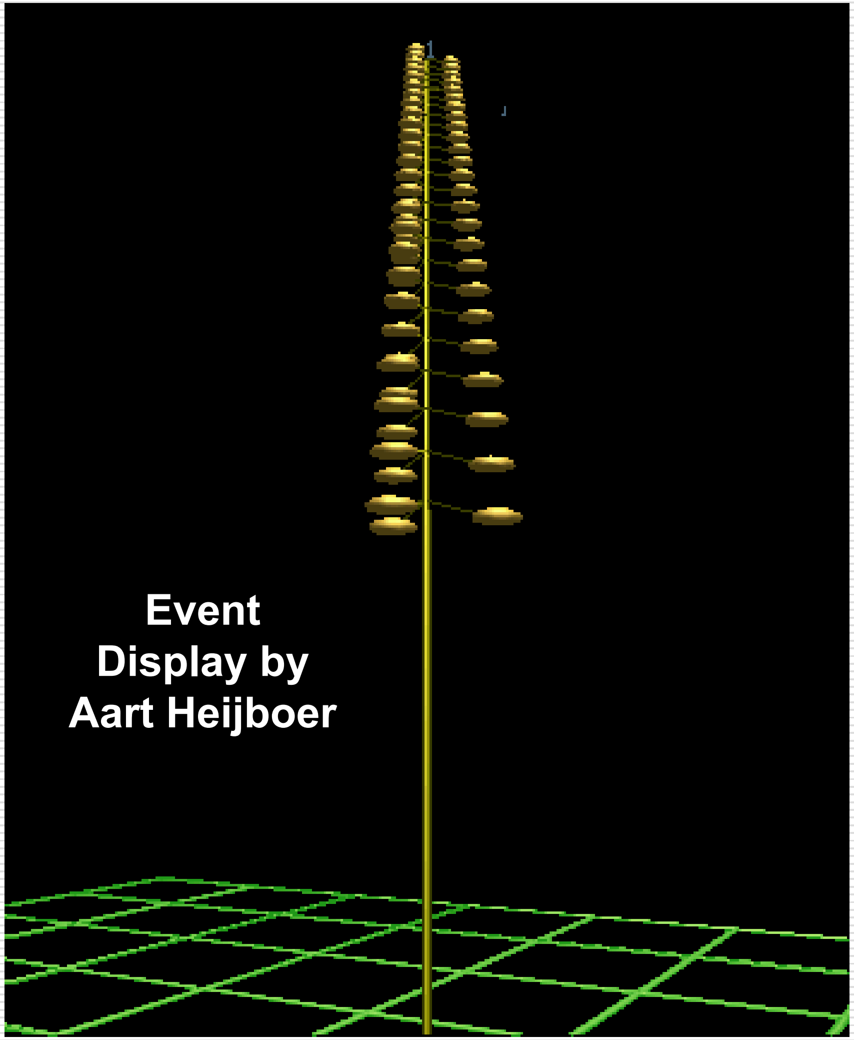
ANTARES: First Atmospheric Muons

χ^2 minimisation to find zenith angle of track

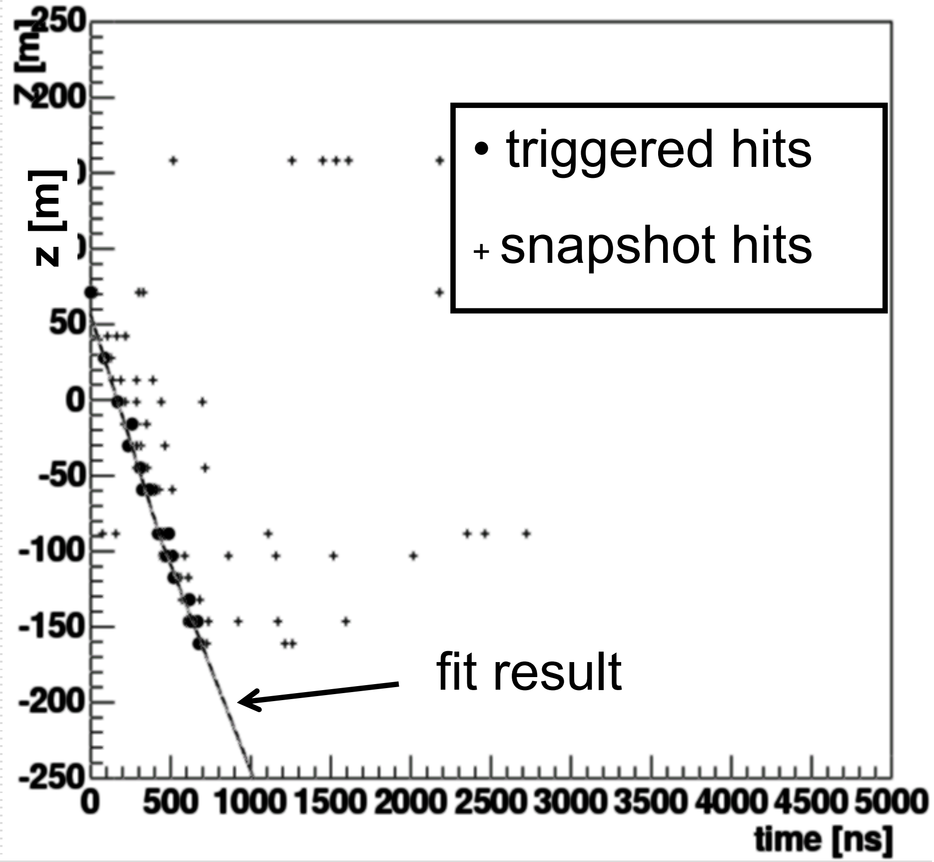




ANTARES: The first muon with Line 1



Recorded on March 4th:
2 days after Line 1 connection

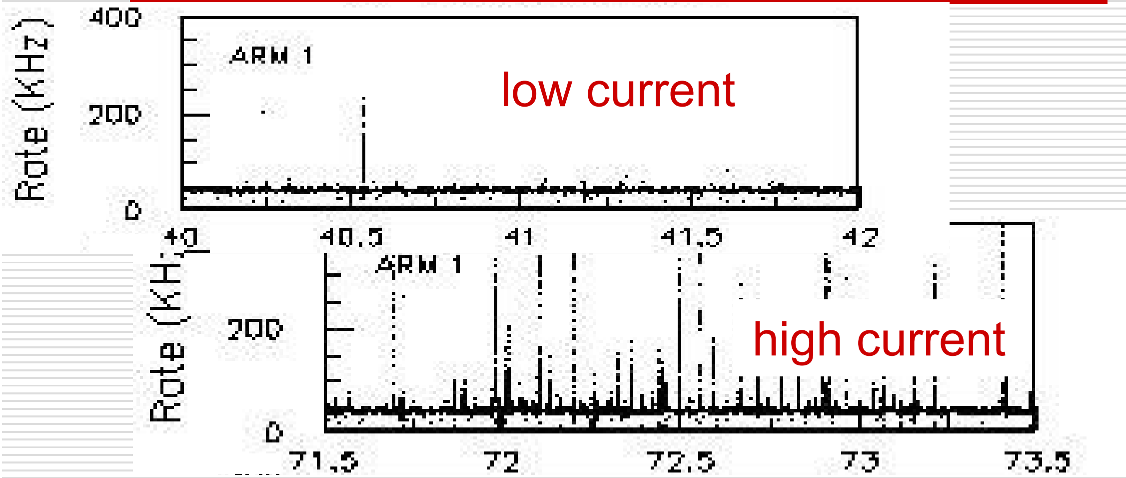


NESTOR: Rigid Structures Forming Towers

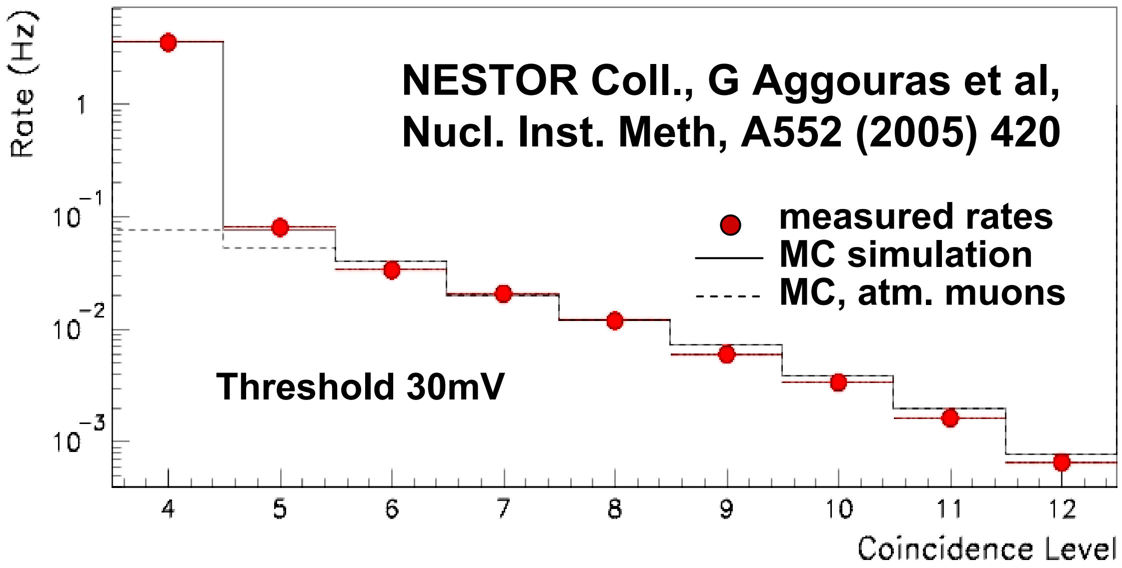
- Tower based detector (titanium structures).
- Dry connections (recover − connect − redeploy).
- Up- and downward looking PMs (15’’).
- 4000 m deep.
- Test floor (reduced size) deployed & operated in 2003.
- Deployment of 4 floors planned in 2007

Plan: Tower(s) with12 floors
→ **32 m diameter**
→ **30 m between floors**
→ **144 PMs per tower**

NESTOR: Data from the Deep Sea

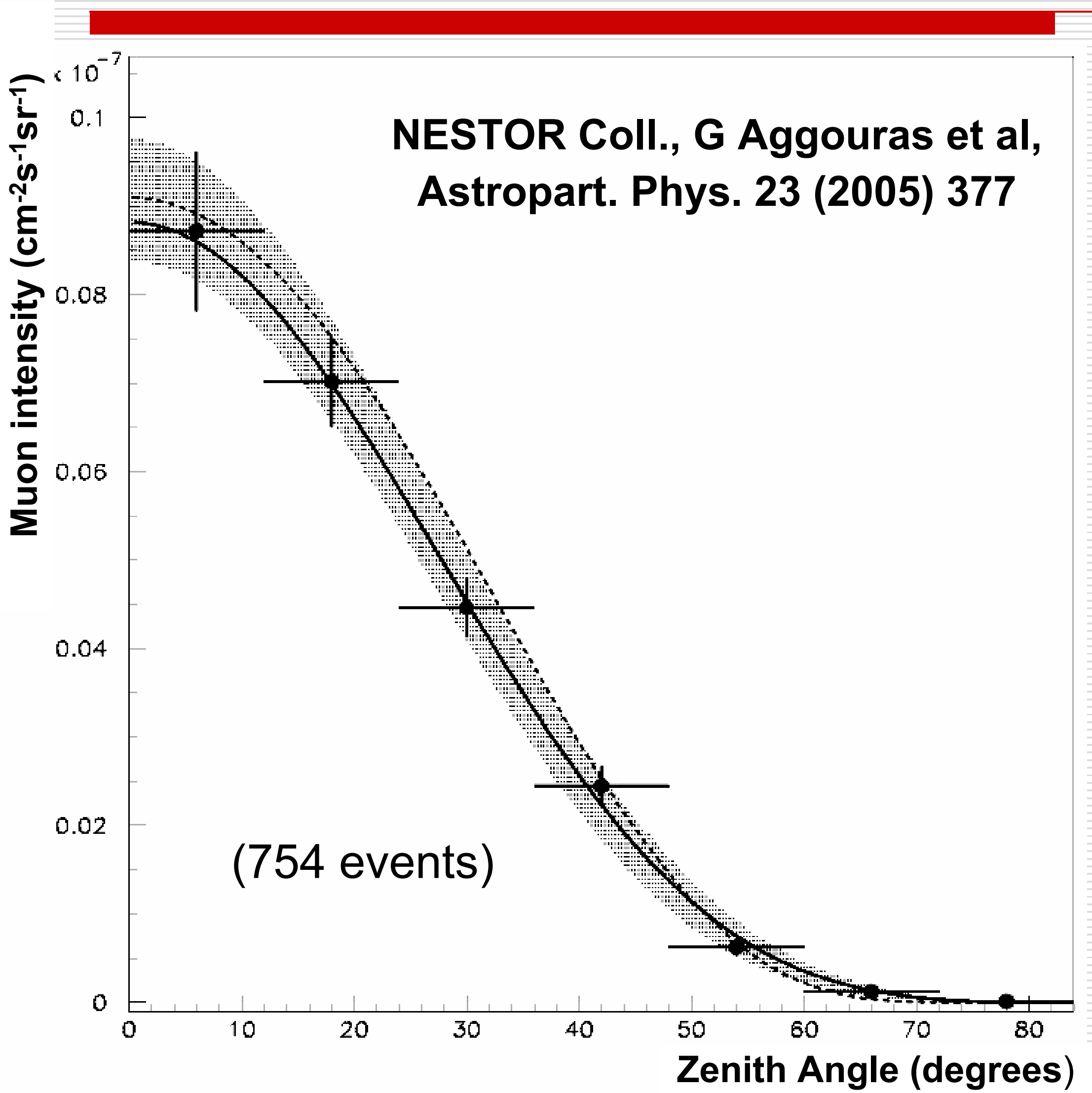


- Background baseline rate of 45-50 kHz per PM
- Bioluminescence bursts correlated with water current, on average 1.1% of the time.



- Trigger rates agree with simulation including background light.
- For 5-fold and higher coincidences, the trigger rate is dominated by atmospheric muons.

NESTOR: Measurement of the Muon Flux



Atmospheric muon flux determination and parameterisation by

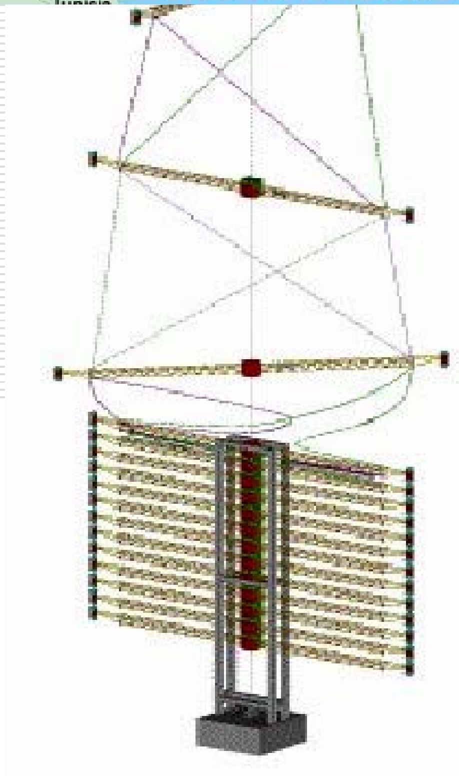
$$\frac{dN}{d\Omega \cdot dt \cdot ds} = I_0 \cdot \cos^{\alpha}\theta$$

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

Results agree nicely with previous measurements and with simulations.

The NEMO Project

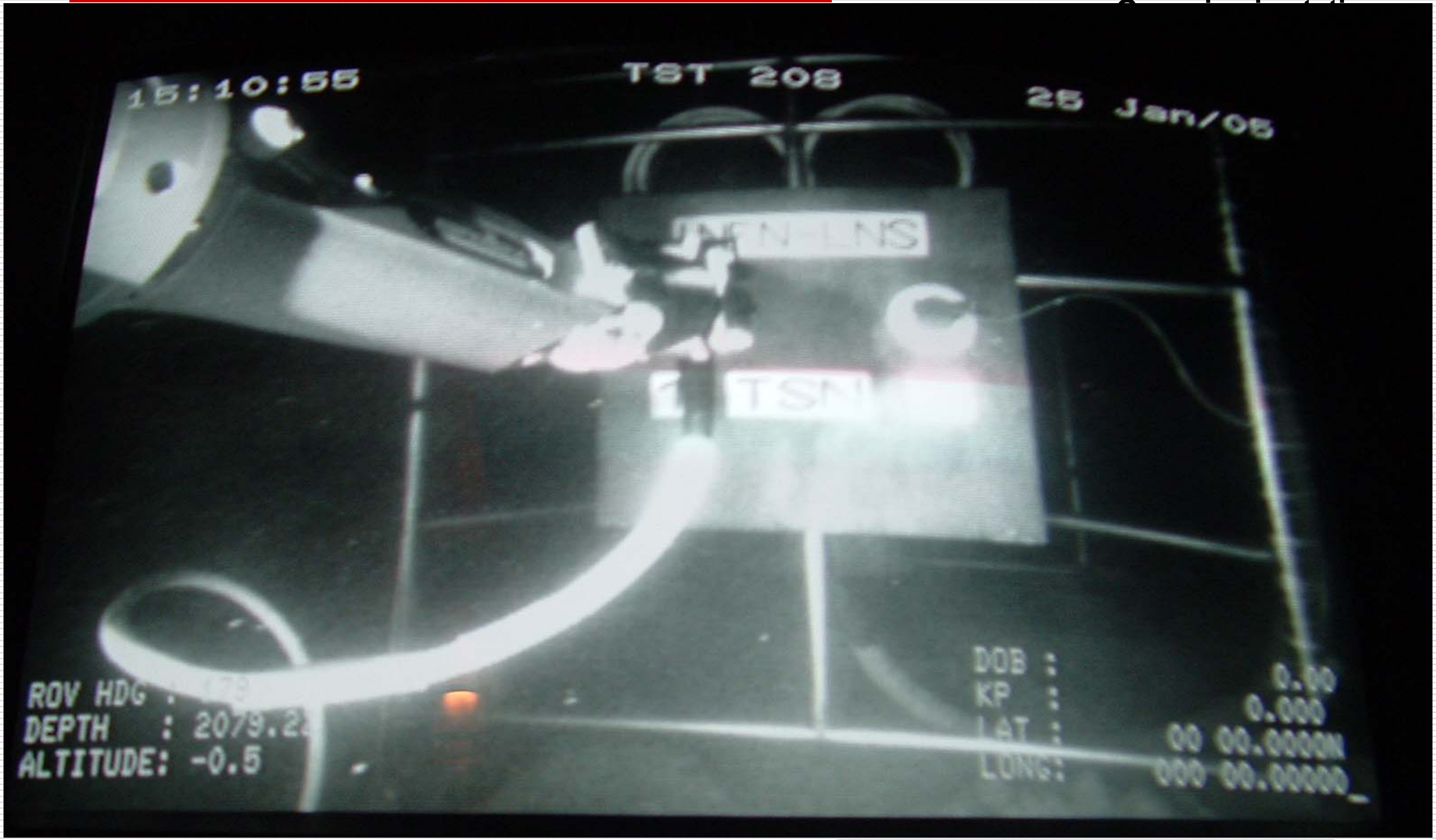
- Extensive site exploration (Capo Passero near Catania, depth 3500 m);
- R&D towards km³: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.



Example: Flexible tower

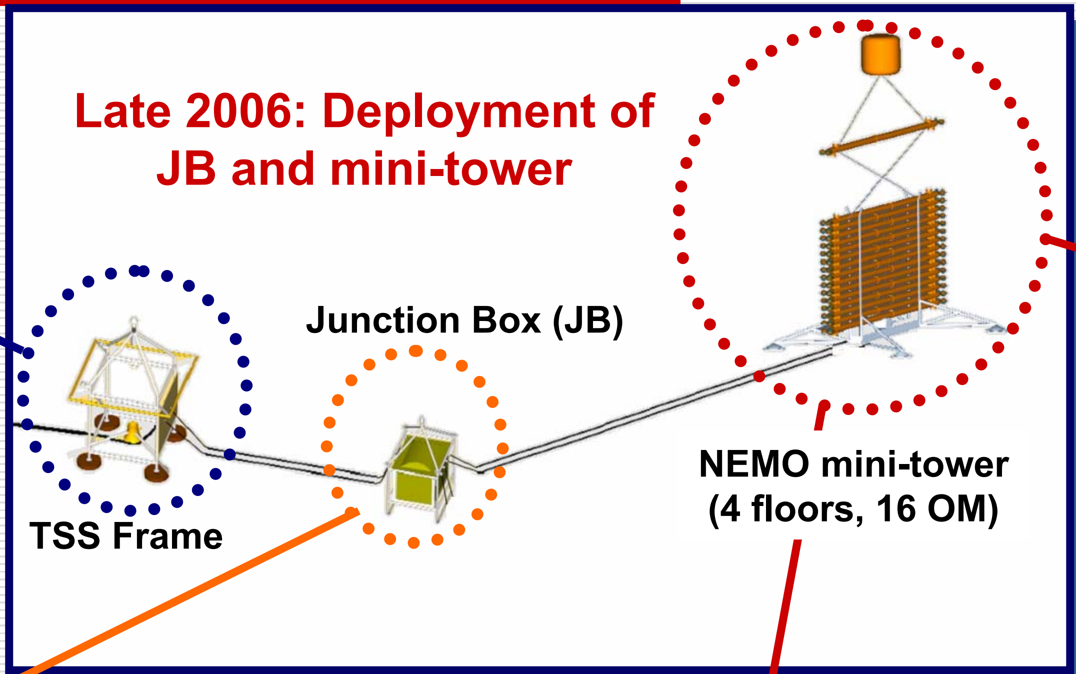
- 16 arms per tower, 20 m arm length, arms 40 m apart;
- 64 PMs per tower;
- Underwater connections;
- Up- and downward-looking PMs.

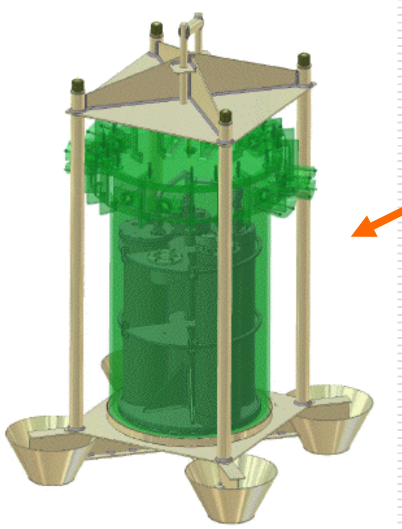
NEMO Phase I: Current Status

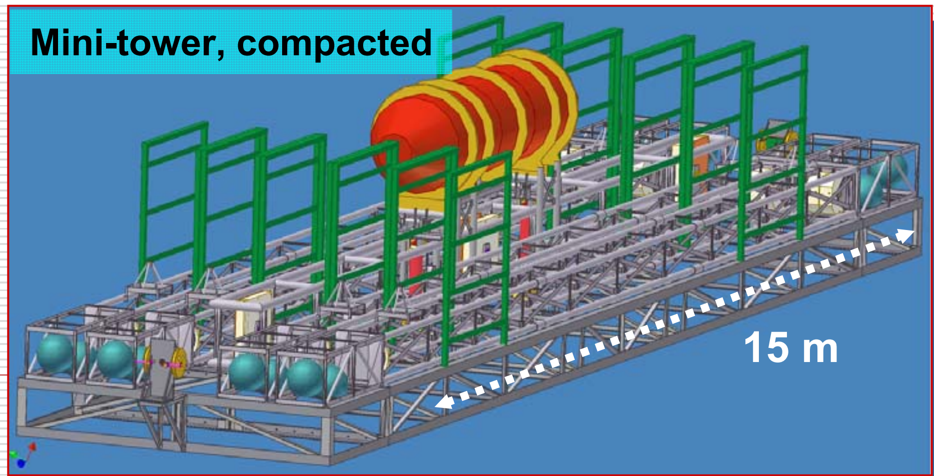


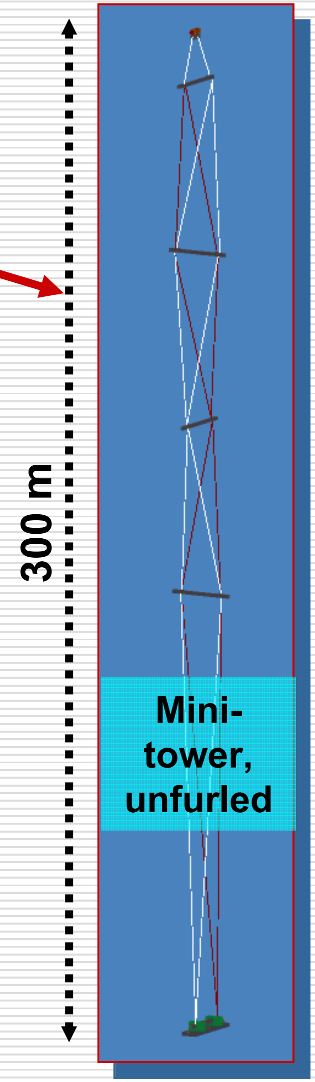
NEMO Phase-1: Next Steps

Deployed January 2005







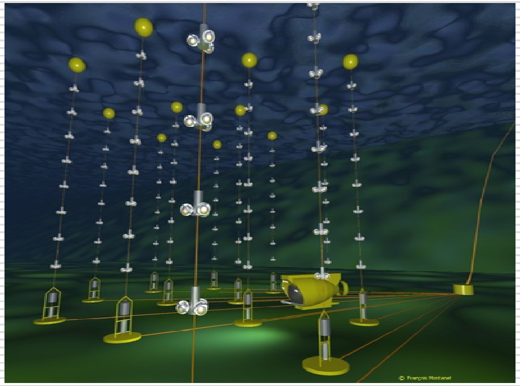


Aiming at a km³-Detector in the Mediterranean

HENAP Report to PaNAGIC, July 2002:

- "The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ..."
- "... a km³-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 km³-scale, the construction of which is considered technically feasible."

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



scale up

dilute

new design

Existing telescopes "times 30" ?

- Too expensive
- Too complicated
  (production, maintenance)
- Not scalable
  (readout bandwidth, power, ...)

R&D needed:

- Cost-effective solutions
  to reduce price/volume by factor ~2
- 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

KM3NeT Design Study (FP6): The last years

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 marine science/technology institutes (Jan. 2004).
- Proposal submitted to EU 04.03.2004.
- Confirmation that Design Study will be funded (Sept. 2004).
- KM3NeT on ESFRI list of Opportunities, March 2005.
- 2nd VLVνT Workshop, Catania, 08-11.11.2005.
- ESFRI presentation, Brussels, Nov. 2005.
- Design Study contract signed, Jan. 2006 (9 M€ from EU, ~20 M€ overall).
- Start of Design Study project, 01.02.2006.
- Kick-off meeting, Erlangen, April 2006.

And: Essential progress of ANTARES, NEMO and NESTOR in this period!

KM3NeT Design Study: Participants

- Cyprus: Univ. Cyprus
- France: CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IreS Strasbourg, APC Paris-7), Univ. Mulhouse/GRPHE, IFREMER
- Germany: Univ. Erlangen, Univ. Kiel
- Greece: HCMR, Hellenic Open Univ., NCSR Demokritos, NOA/Nestor, Univ. Athens
- Ireland: Dublin Institute of Advanced Studies (since 1.Nov.2006)
- 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 (29+1) – Sea science/technology institutes (7) – Coordinator

The KM3NeT Vision

- KM3NeT will be a multidisciplinary research infrastructure:
  - Data will be publicly available;
  - Implementation of specific online filter algorithms will yield particular sensitivity in predefined directions → non-KM3NeT members can apply for observation time;
  - Data will be buffered to respond to GRB alerts etc.
  - Deep-sea access for marine sciences.
- KM3NeT will be a pan-European project
  - 8+1 European countries involved in Design Study;
  - Substantial funding already now from national agencies.
- KM3NeT will be constructed in time to take data concurrently with IceCube.
- KM3NeT will be extendable.

Target price tag: 200 M€/km^3 or less

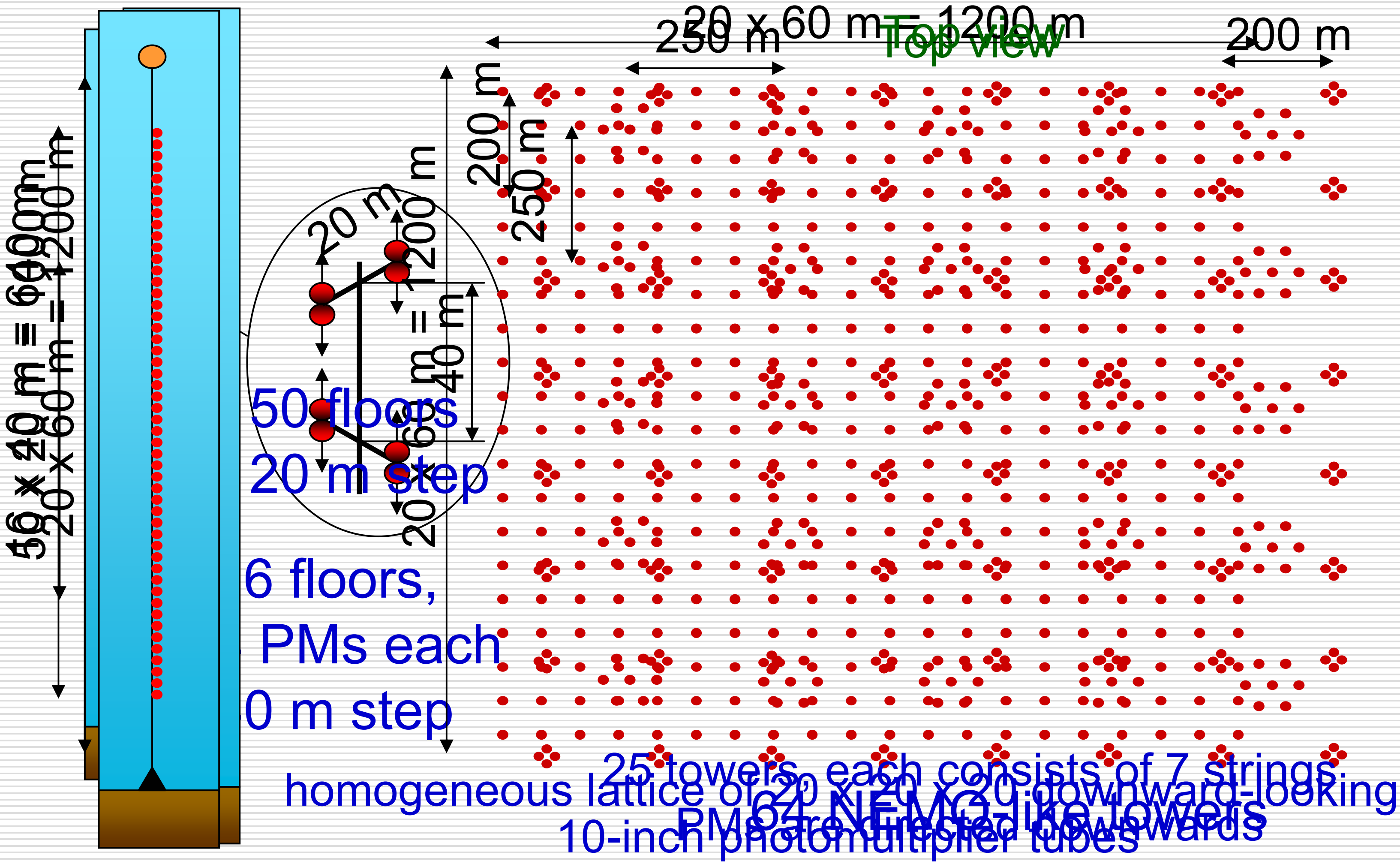
Some Key Questions

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 question

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?

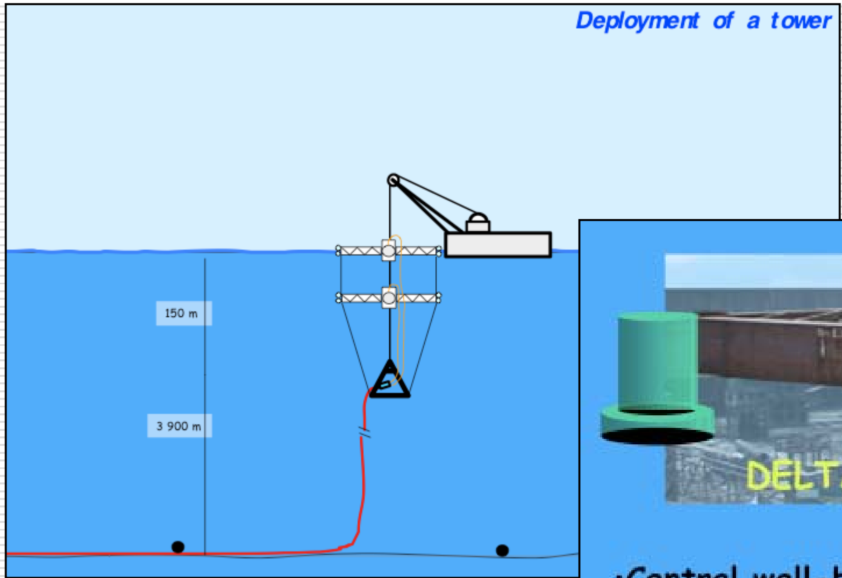
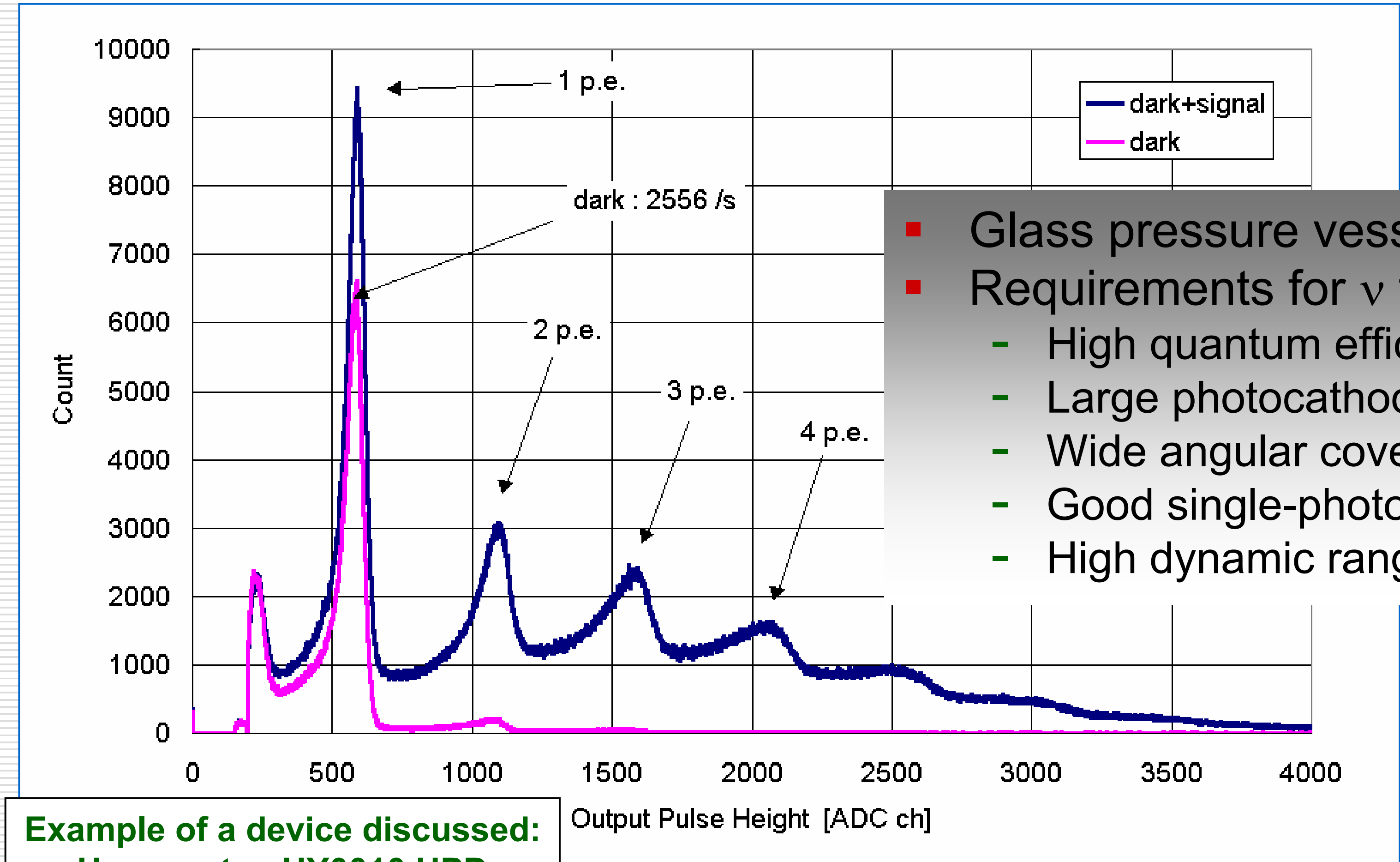


Photo Detection: Requirements

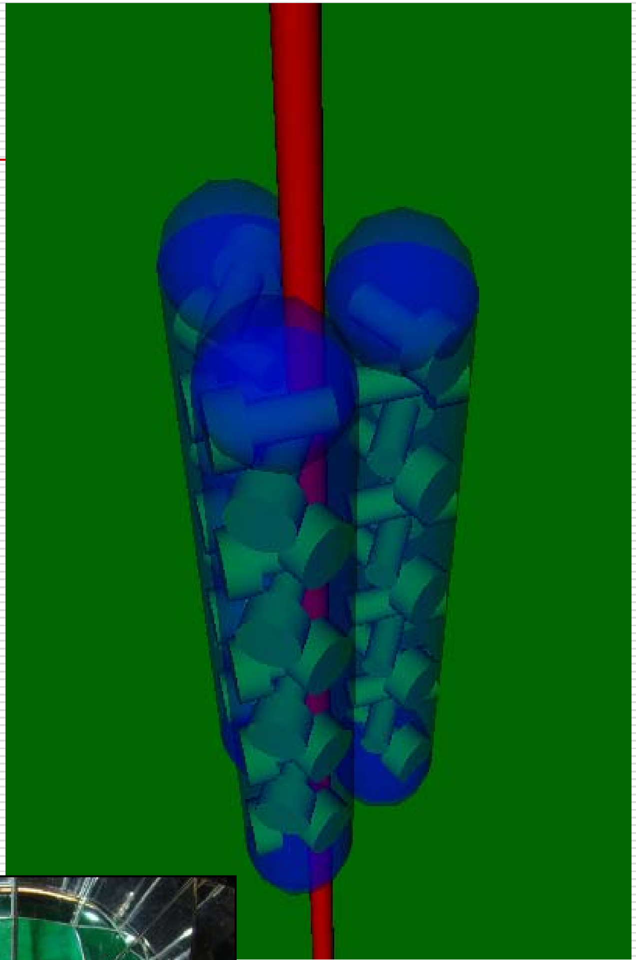


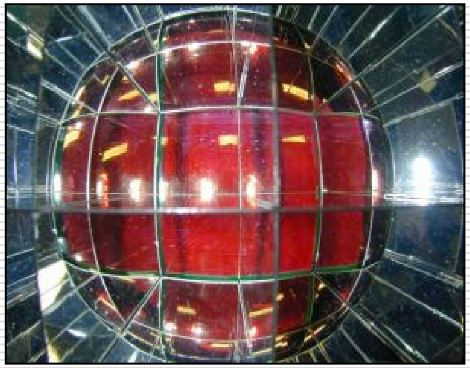
- Glass pressure vessel ≤ 17 inch
- Requirements for ν telescopes:
  - High quantum efficiency
  - Large photocathode areas
  - Wide angular coverage
  - Good single-photon resolution
  - High dynamic range

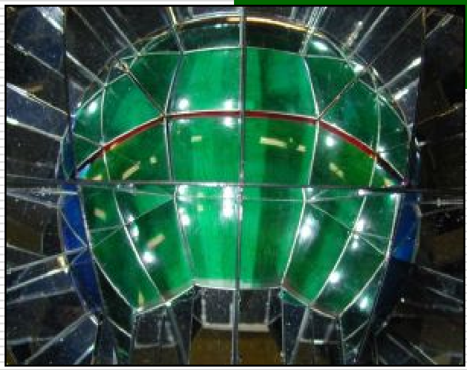
Example of a device discussed:
Hamamatsu HY0010 HPD
Excellent p.e. resolution

Photo Detection: Options

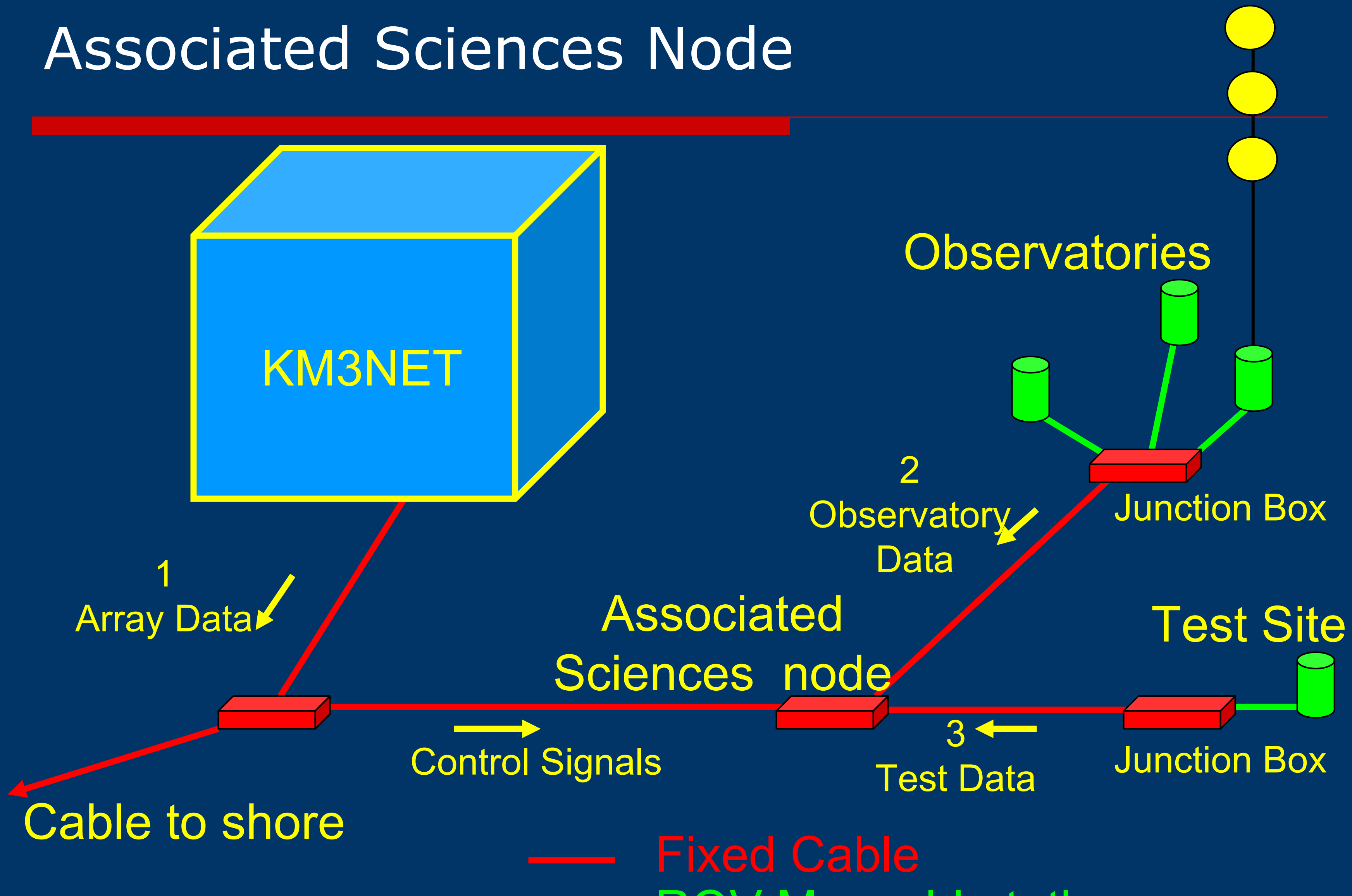
- Large photocathode area with arrays of small PMs packed into pressure housings - low cost!
- Determination of photon direction, e.g. via multi-anodic PMs plus a matrix of Winston cones.
- But: phase space for developments from scratch is too tight.







Associated Sciences Node



M. Priede, Sept. 2005

KM3NeT: Path to Completion

Time schedule (partly speculative & optimistic):

01.02.2006	Start of Design Study
Mid-2007	Conceptual Design Report
February 2009	Technical Design Report
2009-2010	Preparation Phase (possibly in FP7)
2010-2012	Construction
2011-20xx	Data taking

Call for Preparatory Studies will be restricted to ESFRI projects, expected January 2007

Conclusions and Outlook

- Compelling scientific arguments for neutrino astronomy and the construction of large neutrino telescopes.
- The Mediterranean-Sea neutrino telescope projects ANTARES, NESTOR and NEMO are under construction / taking data and promise exciting results.
- It is essential to complement IceCube with a km^3-scale detector in the Northern Hemisphere.
  - An EU-funded Design Study (KM3NeT) provides substantial resources for an intense 3-year R&D phase (2006-09).
  - Major objective: Technical Design Report by early 2009.