9. Neutrino Astronomy

Corso "**Astrofisica delle particelle**"

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Università di Bologna. A.a. 2011/12

Outlook

- Why Neutrino Astronomy?
- Astrophysical Sources of ν_μ
- A Numerical example. A Galactic source of neutrinos: neutron star with accretion disk
- Event rate in a underground detector
- Upper Bounds on Neutrino Diffuse Fluxes
- Neutrino telescopes
- ICECUBE, ANTARES, NEMO
- The KM3 project in the Mediterranean sea

See: hep-ph 0906.2634

High-Energy Astrophysics with Neutrino Telescopes

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Abstract

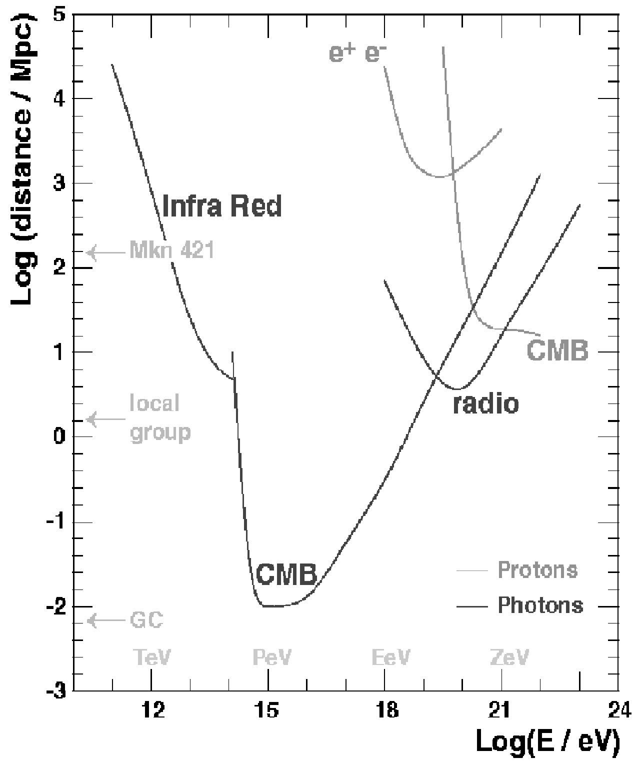
Neutrino astrophysics offers new perspectives on Universe investigation: high energy neutrinos, produced by the most energetic phenomena in our Galaxy and in the Universe, carry complementary (if not exclusive) information about the Cosmos with respect to photons.

While the small interaction cross section of neutrinos allows them to come from the core of astrophysical objects, it is also a draw-back, as their detection requires a large target mass. This is why it is convenient to place neutrino telescopes in natural locations, like deep underwater or under-ice sites. In order to supply for such extremely hostile environmental conditions, new frontiers technologies are under development.

The aim of this work is to review the motivations for high energy neutrino astrophysics, the physics and the technologies used in underwater/ice Cherenkov experiments, with a special focus on the project of the construction of a km^3 scale detector in the Mediterranean Sea.

9.1 Why Neutrino Astronomy?

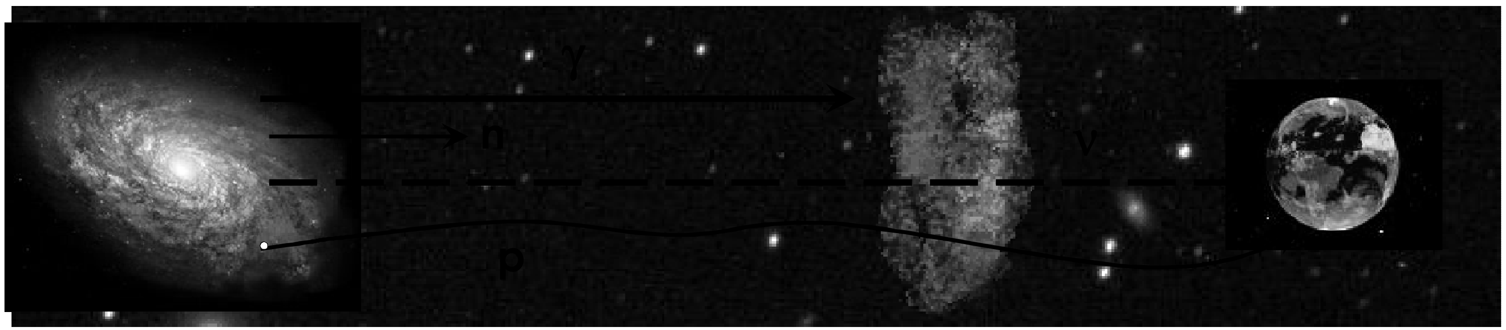
Photon and proton mean free range path



- Neutrino Astronomy is a quite recent and very promising experimental field.

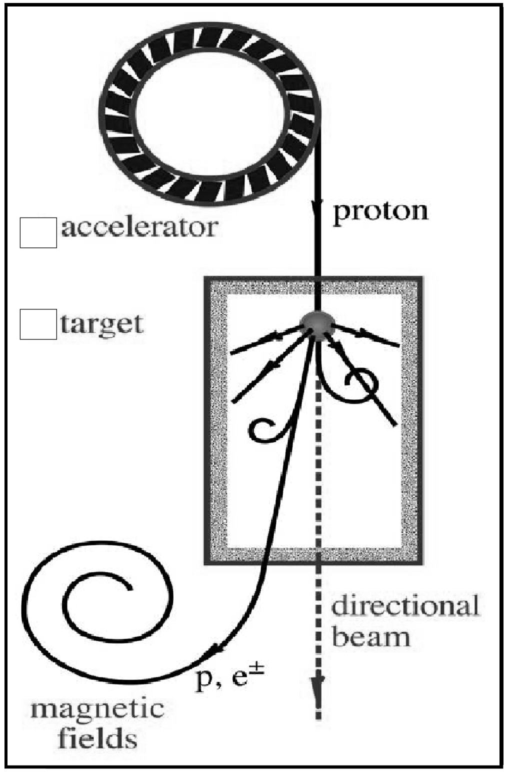
- Advantages:
  - Photons: interact with CMB and matter (r~10 kpc @100 TeV)
  - Protons: interact with CMB (r~10 Mpc @10^{11} GeV) and undergo magnetic fields ($\Delta\theta > 1^{o}$, $E < 5 \cdot 10^{10}$ GeV)
  - Neutrons: are not stable (r~10 kpc @10^{9} GeV)

- Drawback: large detectors (~GTon) are



Production Mechanisms

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



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

Cosmic rays

$$\downarrow$$

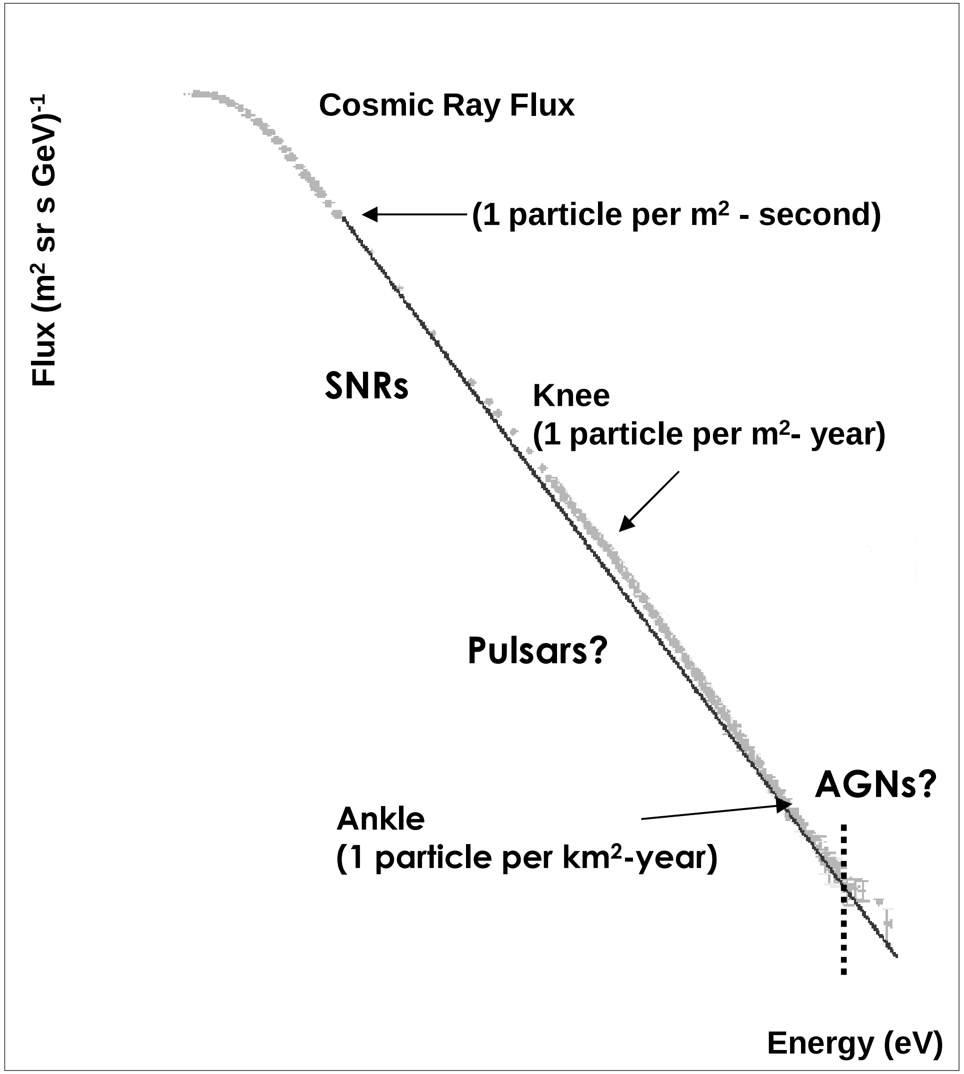
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

•In these scenarios, high energy photons would also be produced:

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

Gamma ray astronomy

Cosmic Rays ←→ Neutrinos



- Cosmic rays follow a broken power-law:

$$\frac{dN}{dE} \propto E^{-\gamma} \quad \begin{cases} \gamma = 2.7 \\ \gamma = 3.0 \\ \gamma = 2.7 \end{cases}$$

--> the knee

--> the ankle

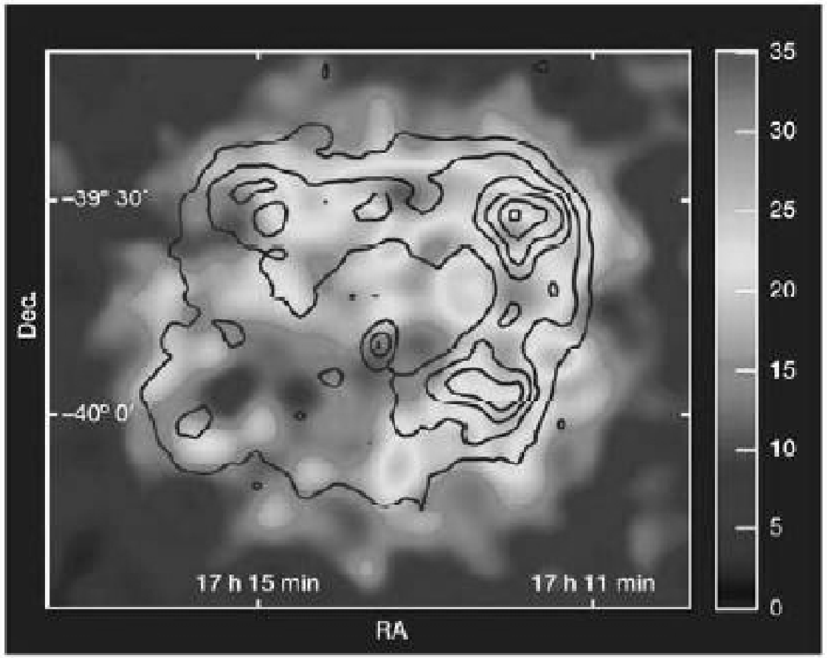
- Beyond 6×10^{19} eV, the flux should vanish due to the interaction of protons with the CMB (GZK limit)

- High energy neutrinos could give information about the origin of cosmic rays.

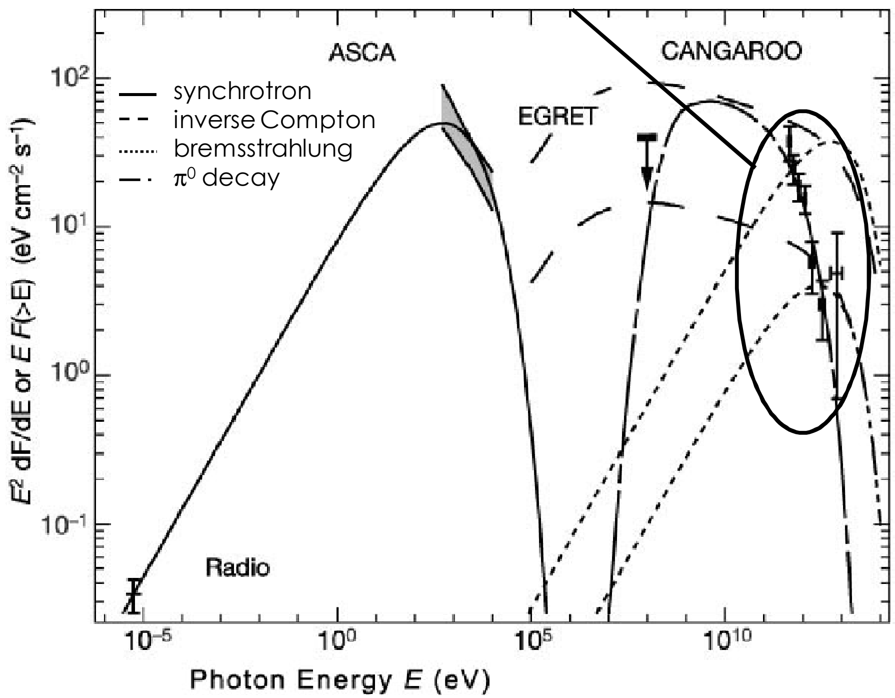
High Energy Photons (see cap. 6)

- The observation of TeV photons can be explained by
  -leptonic processes (inverse Compton, bremsstrahlung) or
  -the decay of neutral pions produced in hadronic interactions (→neutrino).

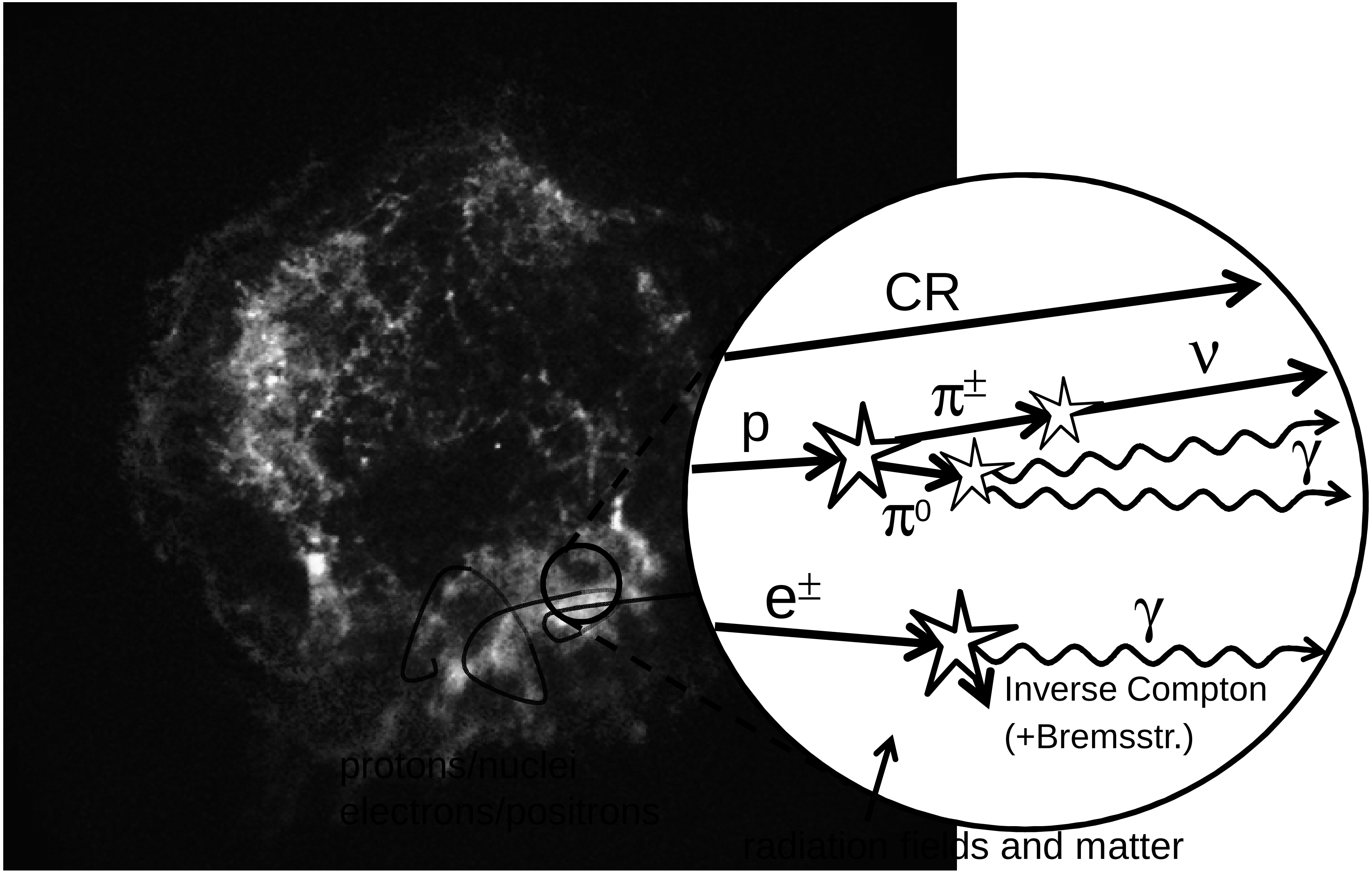
TeV gamma-ray image of RX J1713.7-3946 (H.E.S.S.). The superimposed contours show the X-ray surface brightness as seen by ASCA in the 1-3 keV range.



SNR RX 1713.7-3946 emission better explained by π^0 decay (still controversial)

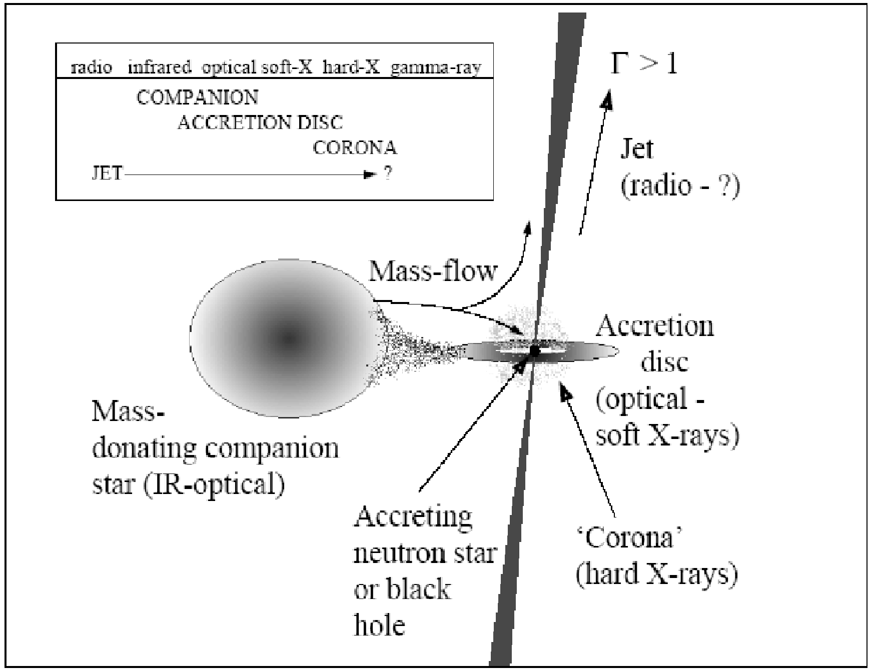


γ and ν in cosmic accelerators



9.2 Astrophysical Sources

- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars



- Micro-quasars: a compact object (BH or NS) towards which a companion star is accreting matter.
- Neutrino beams could be produced in the Micro-Qquasar jets.
- Several neutrinos per year could be detected by 1 km3 detector.

Astrophysical Sources

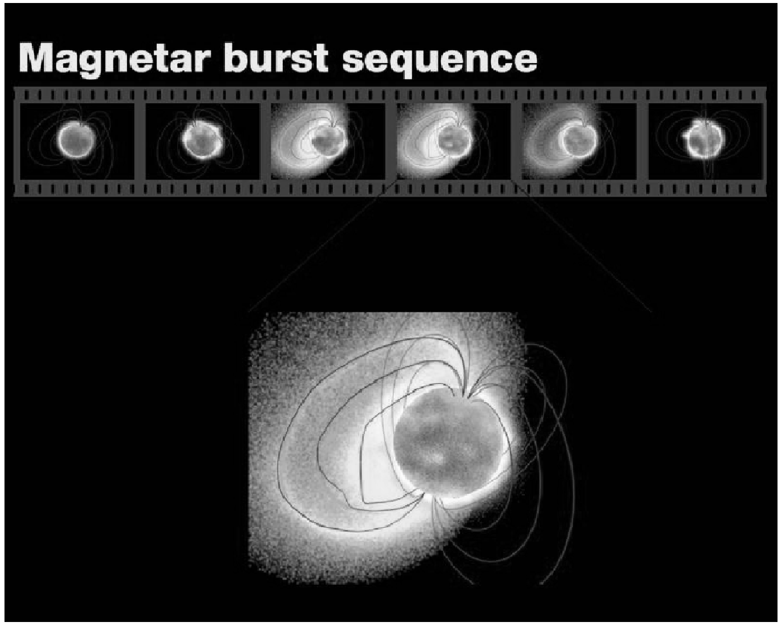
- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants

Several scenarios (optimistic?):

- Plerions (center-filled SNRs): 1-14 ev/km$^3\cdot$ y.
- Shell-type SNRs: 40-140 ev/km$^3\cdot$ y.
- SNRs with energetic pulsars: ~100 ev/km$^3\cdot$ y.

Astrophysical Sources

- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - …



- Isolated neutron stars with surface dipole magnetic fields $\sim 10^{15}$ G, much larger than ordinary pulsars.
- Seismic activity in the surface could induce particle acceleration in the magnetosphere.
- Event rate: $\sim 1\ (0.1/\Delta\Omega)$ ev/km$^3 \cdot$ y.

Astrophysical Sources

- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
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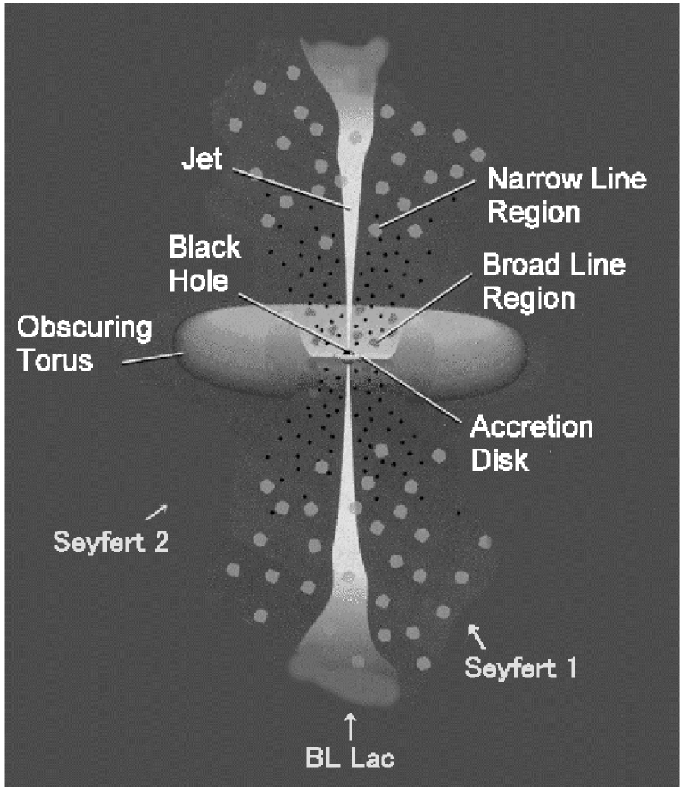
  - …

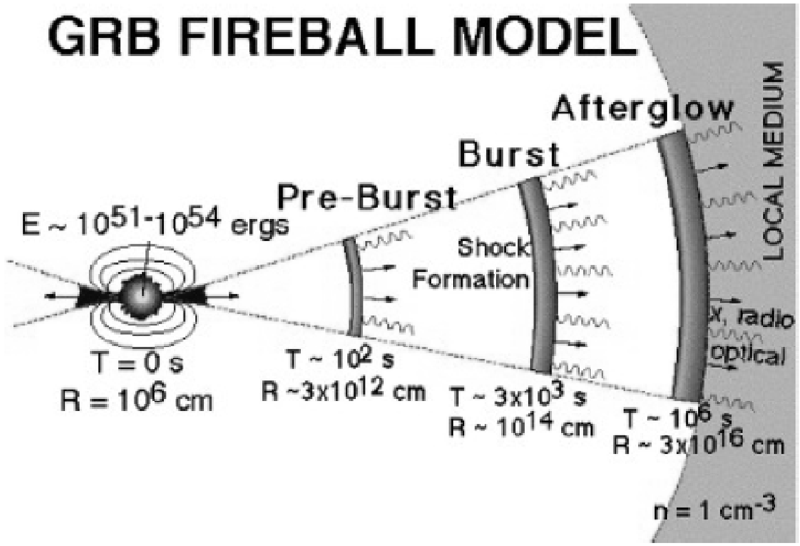


- **Extra-galactic sources**: most powerful sources in the Universe
  - AGNs

- Active Galactic Nuclei includes Seyferts, quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.
- Detectable neutrino rates (~1-10 ev/year/km^3) could be produced.

Astrophysical Sources

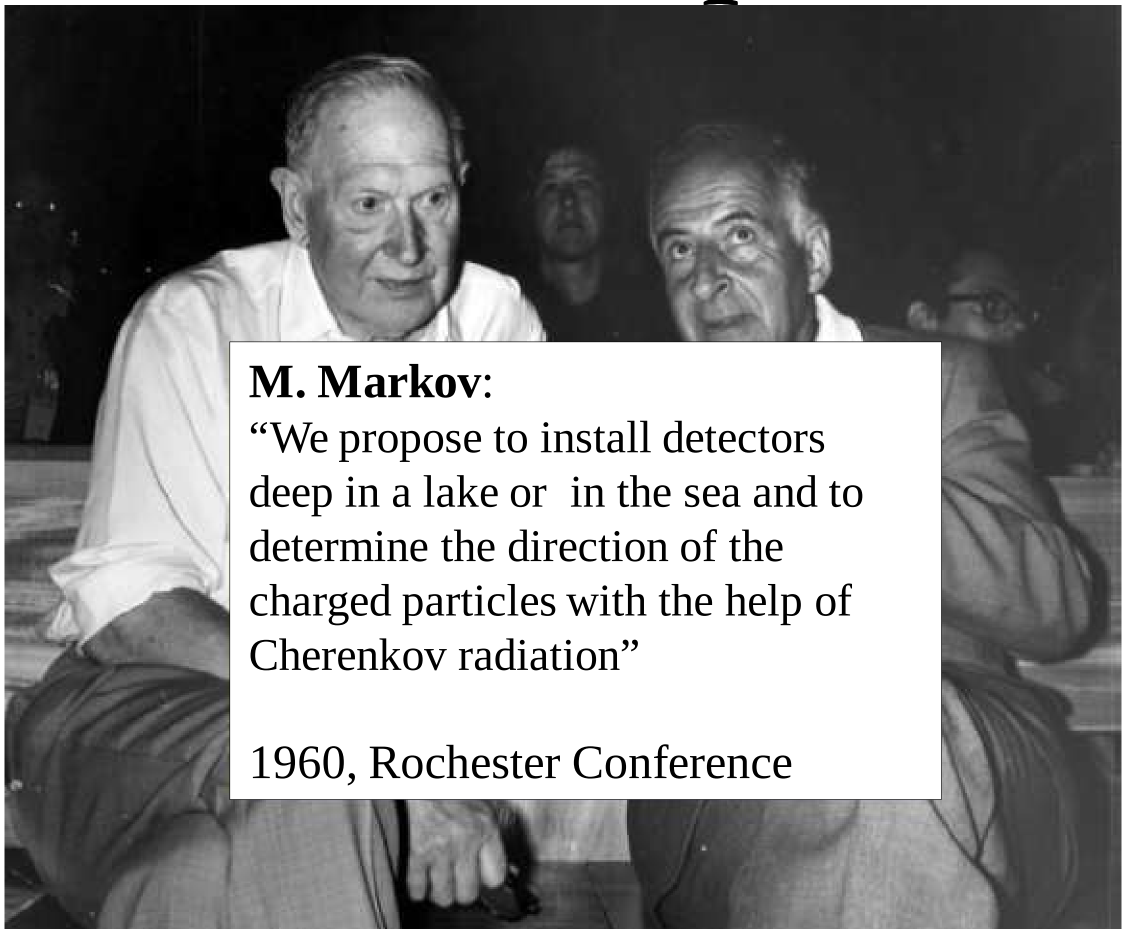
- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - …



- **Extra-galactic sources**: most powerful sources in the Universe
  - AGNs
  - GRBs

- GRBs are brief explosions of γ rays (often + X-ray, optical and radio).
- In the fireball model, matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star.
- Time correlation enhances the neutrino detection efficiency.

9.3 Recipes for a Neutrino Telescope

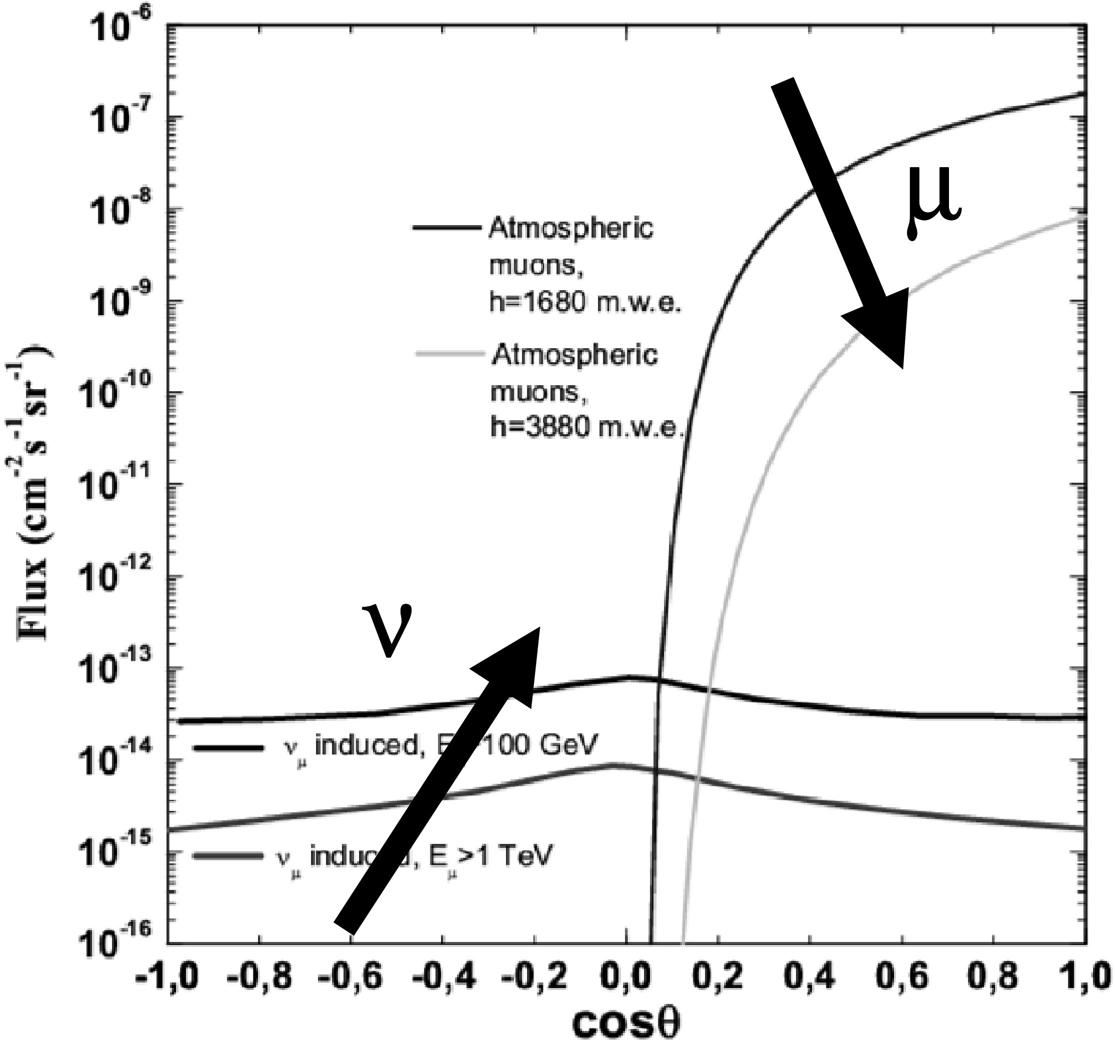


M. Markov:
“We propose to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation”

1960, Rochester Conference

Deep in a transparent medium

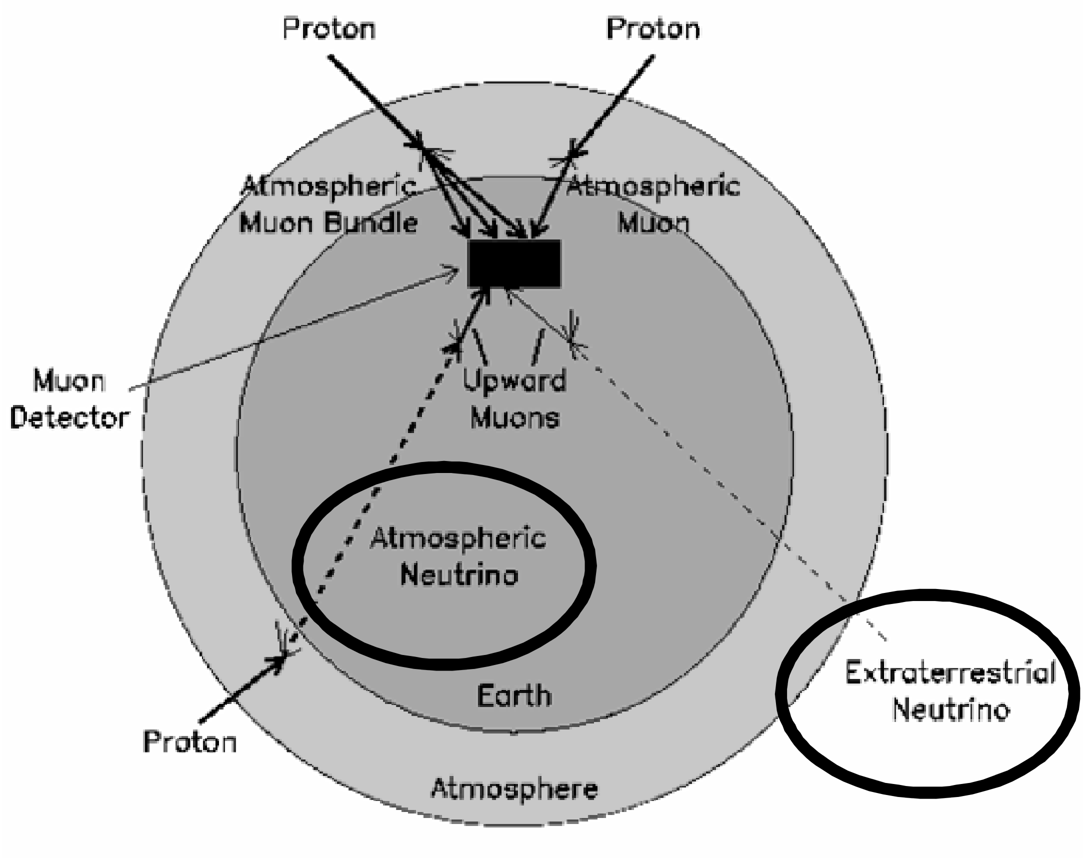
- **Water or Ice**:
  - large (and inexpensive) target for ν interaction
  - transparent radiators for Cherenkov light;
  - large deep: protection against the cosmic-ray muon background



νT: a detector looking to the bottom

• Atmospheric muons dominate by many order of magnitude the neutrino-induced muons.

• Only upward-going particles are candidate for extraterrestrial ν .



Atmospheric neutrinos represent the irreducible background for NT

Upward-going muons (or horizontal muons) ARE neutrino-induced!

Atmospheric muon flux

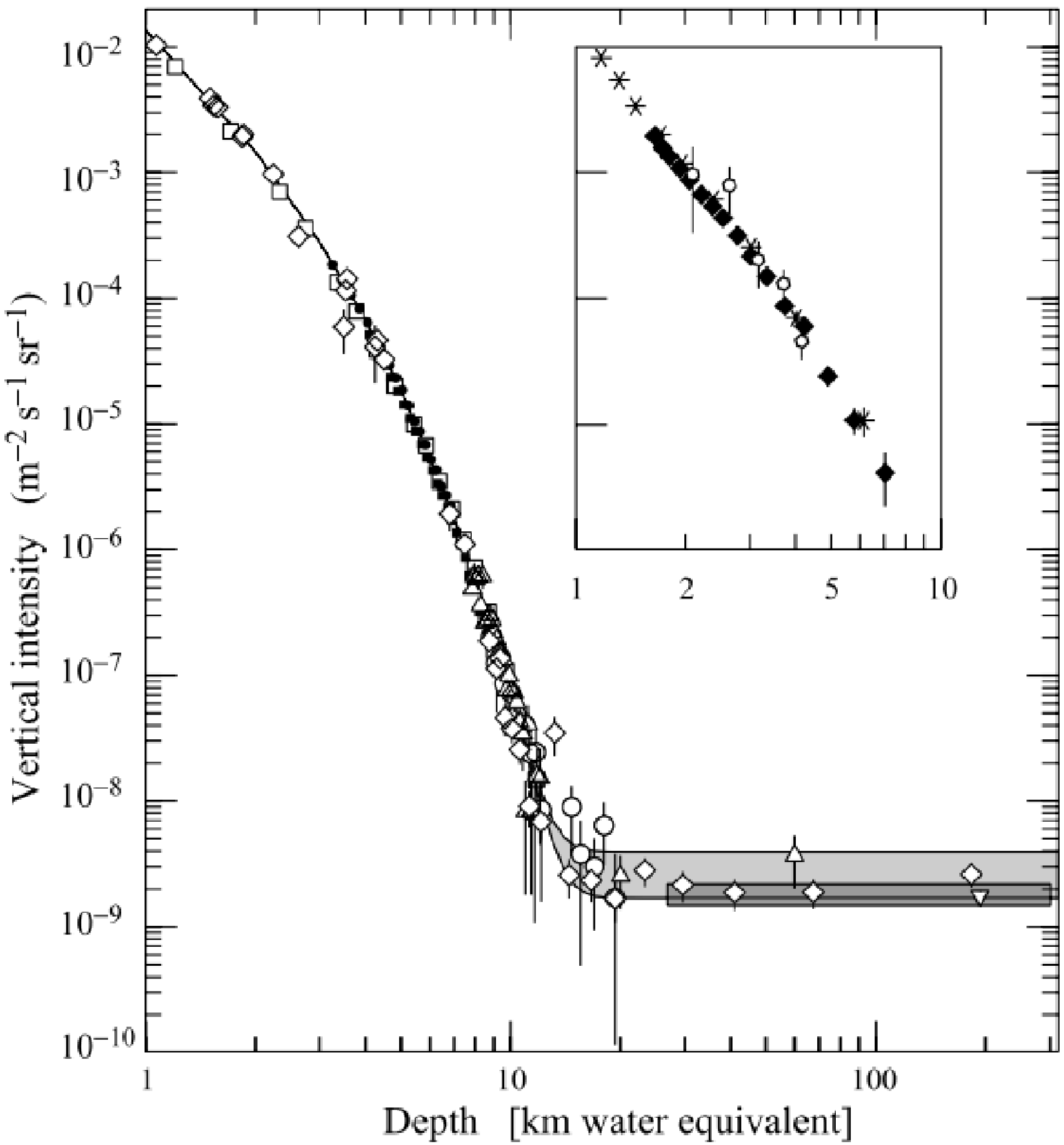
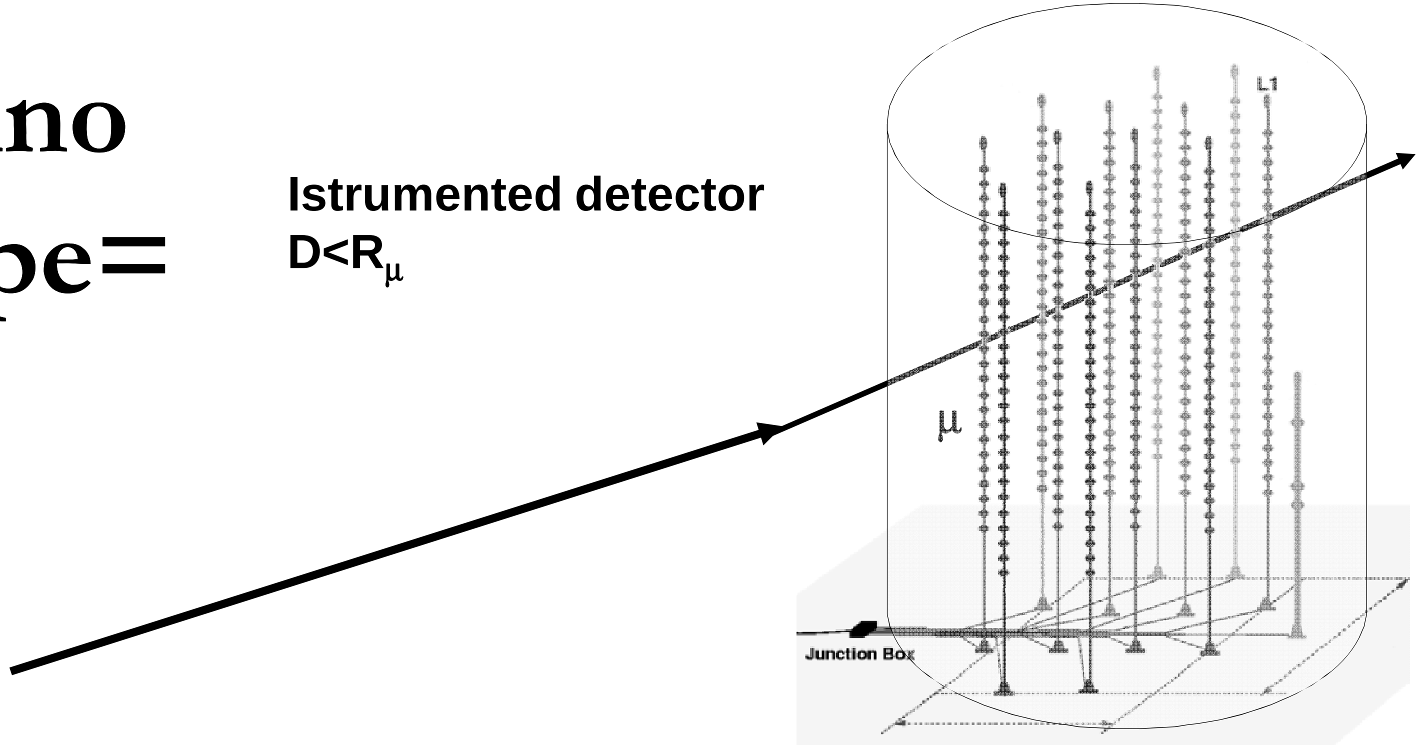


Figure 9: *Vertical muon intensity vs. depth (1 km.w.e.= 10^5 gcm^{-2} of standard rock). Fig. from [30]. The experimental data are from: the compilations of Crouch ◇ [61], Baksan [62], LVD ○ [63], MACRO ● [64], Frejus [65], and SNO △ [66]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.*

Muons cannot cross more than ≈ 15 km.w.e.

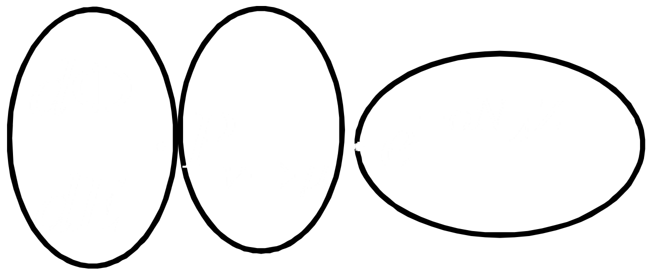
Neutrino telescope=

Istrumented detector
$D<R_{\mu}$



A- Source neutrino energy spectrum

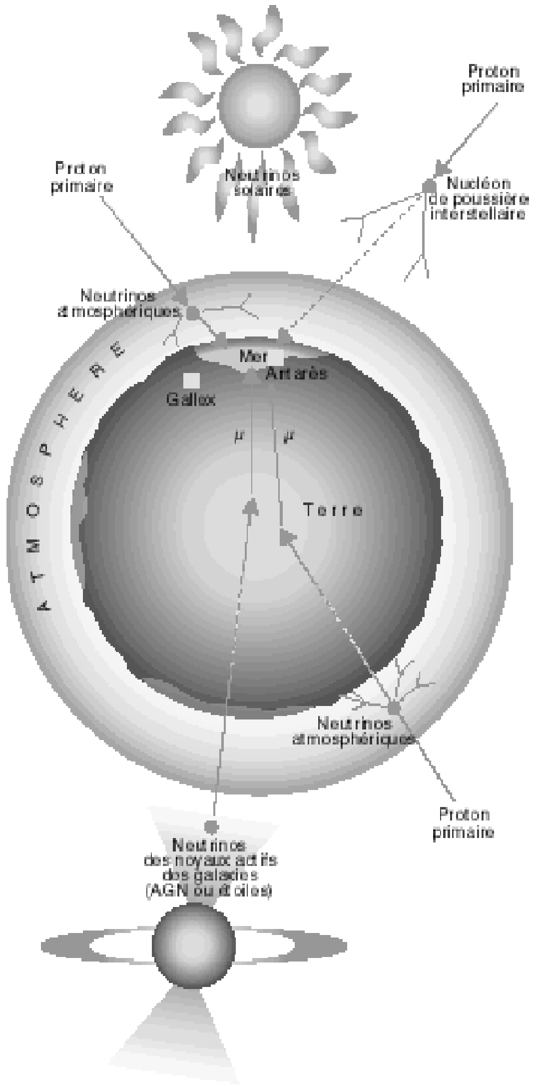
Event number / (area × time)



B- ν-induced muon detection probability

C- Earth absorption probability for ν

A) Example of a Galactic source of neutrinos.



TeV γ-rays and neutrinos can be produced from **hadronic processes**:

$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{o} + p$

$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$

Neutral mesons decay in **<u>photons</u>**:

$\pi^{o} \rightarrow \gamma\gamma$

charged mesons decay in **<u>neutrinos</u>**:

$\pi^{+} \rightarrow \nu_{\mu} + \mu+$

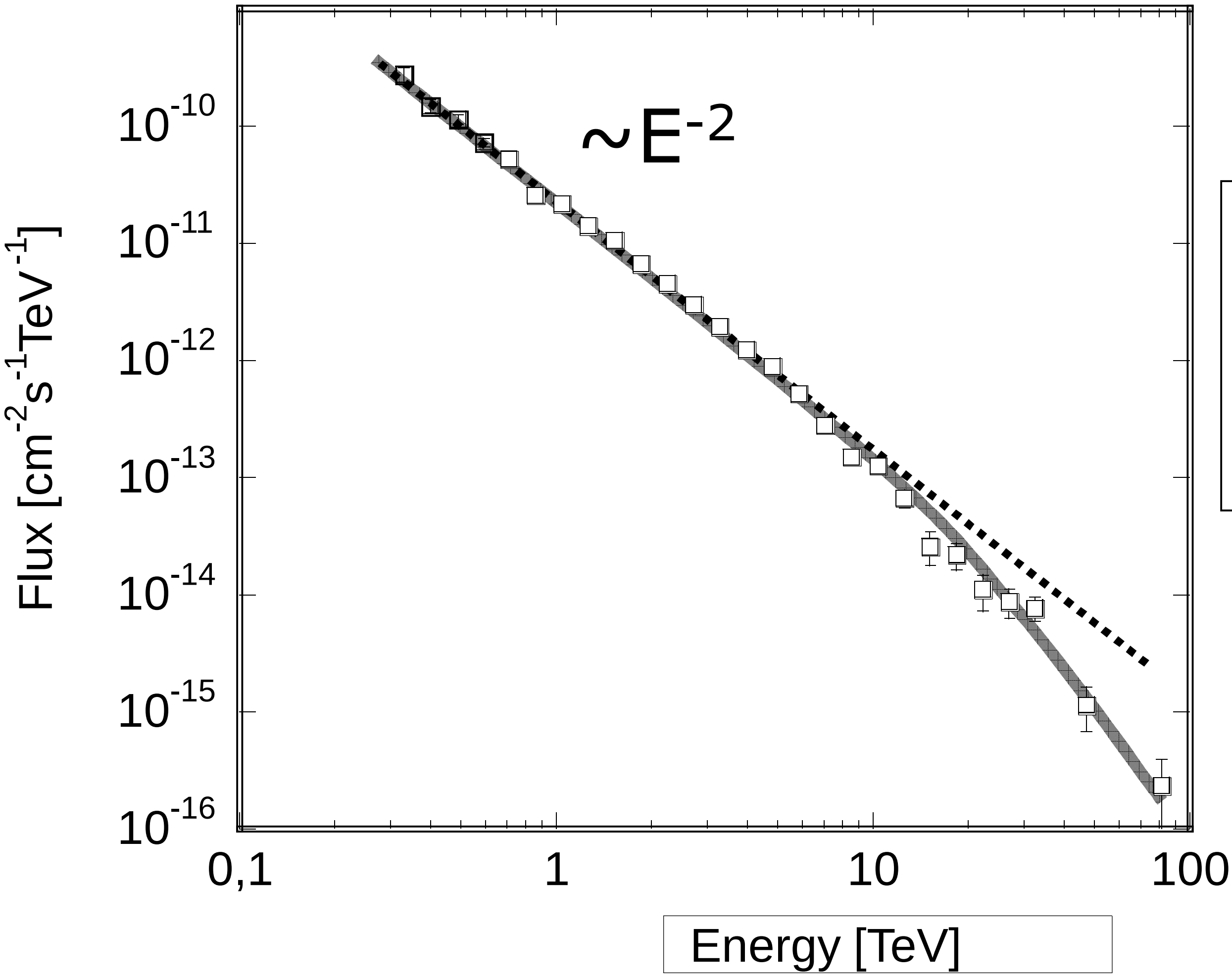
$\mu^{+} \rightarrow \nu_{\mu} + \nu_{e} + e^{+}$

$\pi^{-} \rightarrow \nu_{\mu} + \mu^{-}$

$\mu^{-} \rightarrow \nu_{\mu} + \nu_{e} + e^{-}$

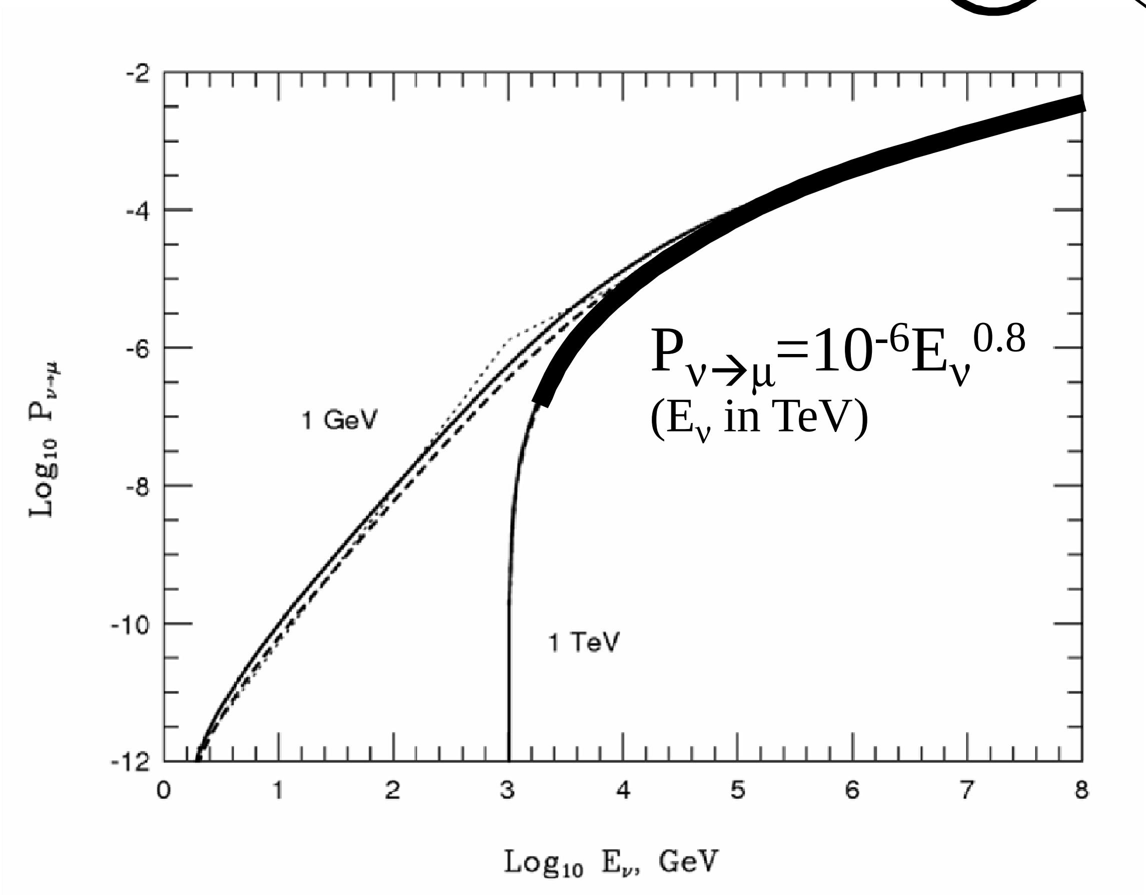
$\#\nu = \#\gamma$

A source candidate: RX J1713.7-3946



RX J1713.7-3946 seen by HESS (gamma rays)

B) μ production probability

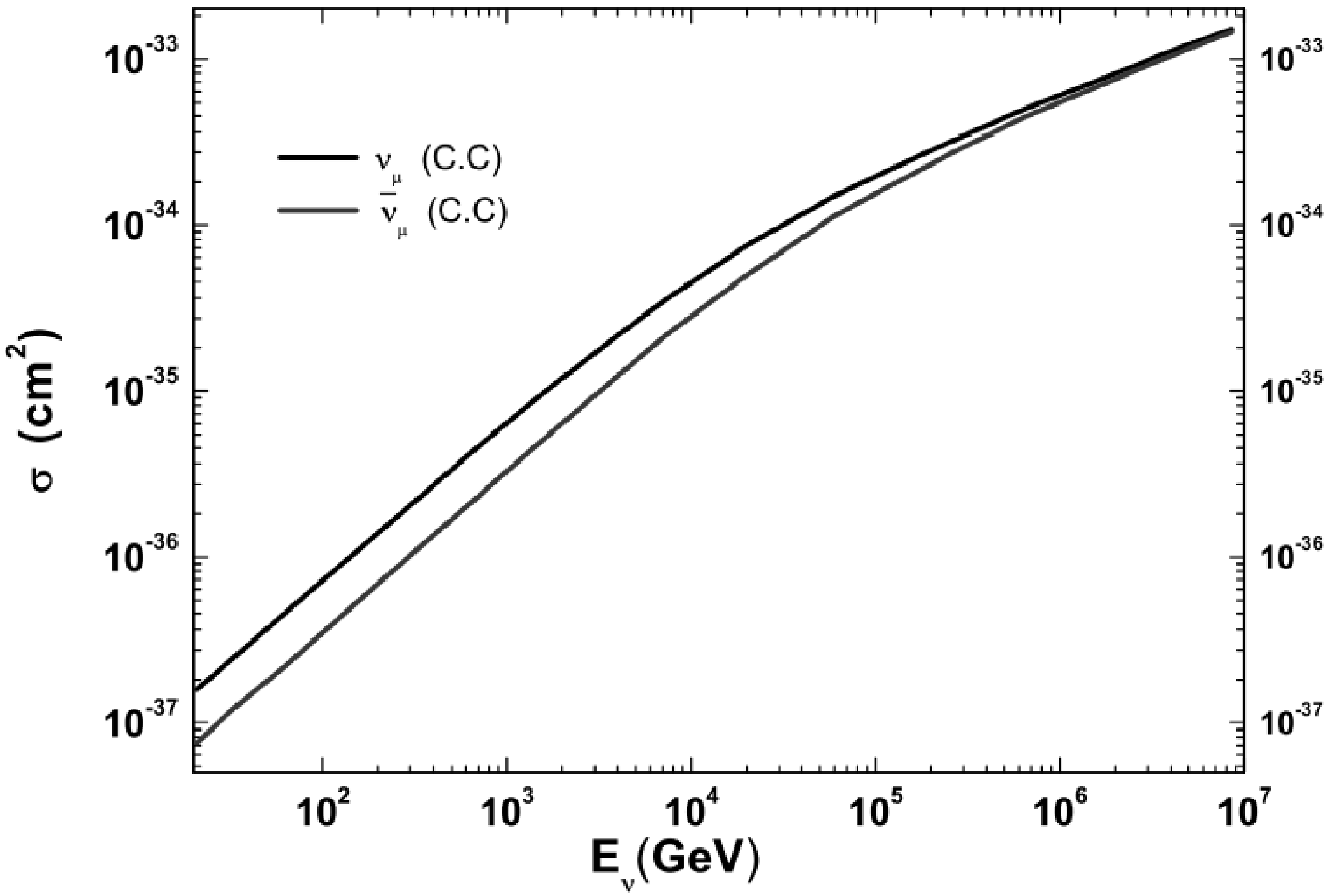


$\sim E_\mu$ Neutrino cross section

Muon range

$\sim E_\mu$, E_μ <0.5 TeV

Neutrino cross section



Problem: estimate the energy of the neutrino for which the Earth is not anymore transparent

Muon Range

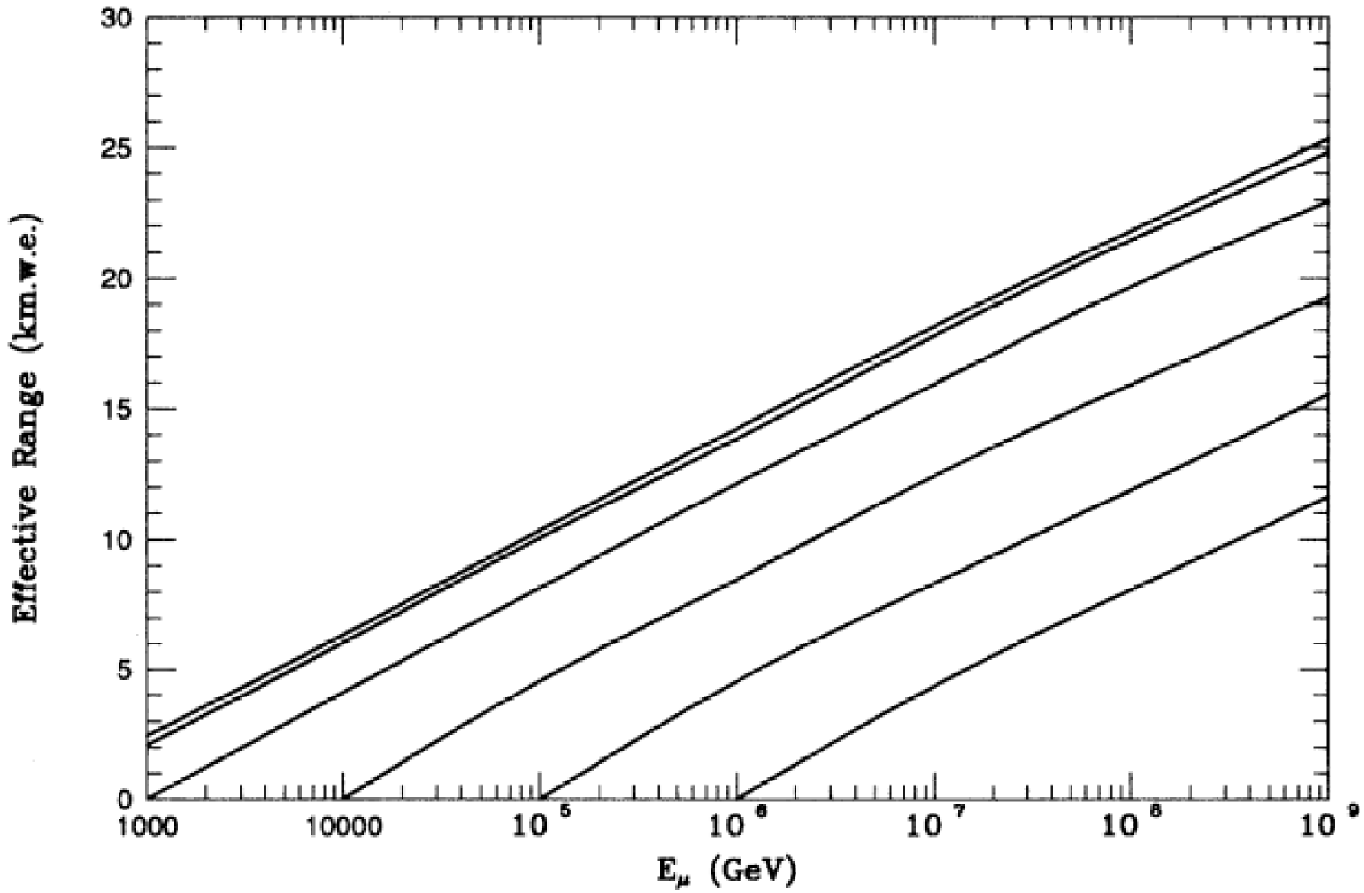
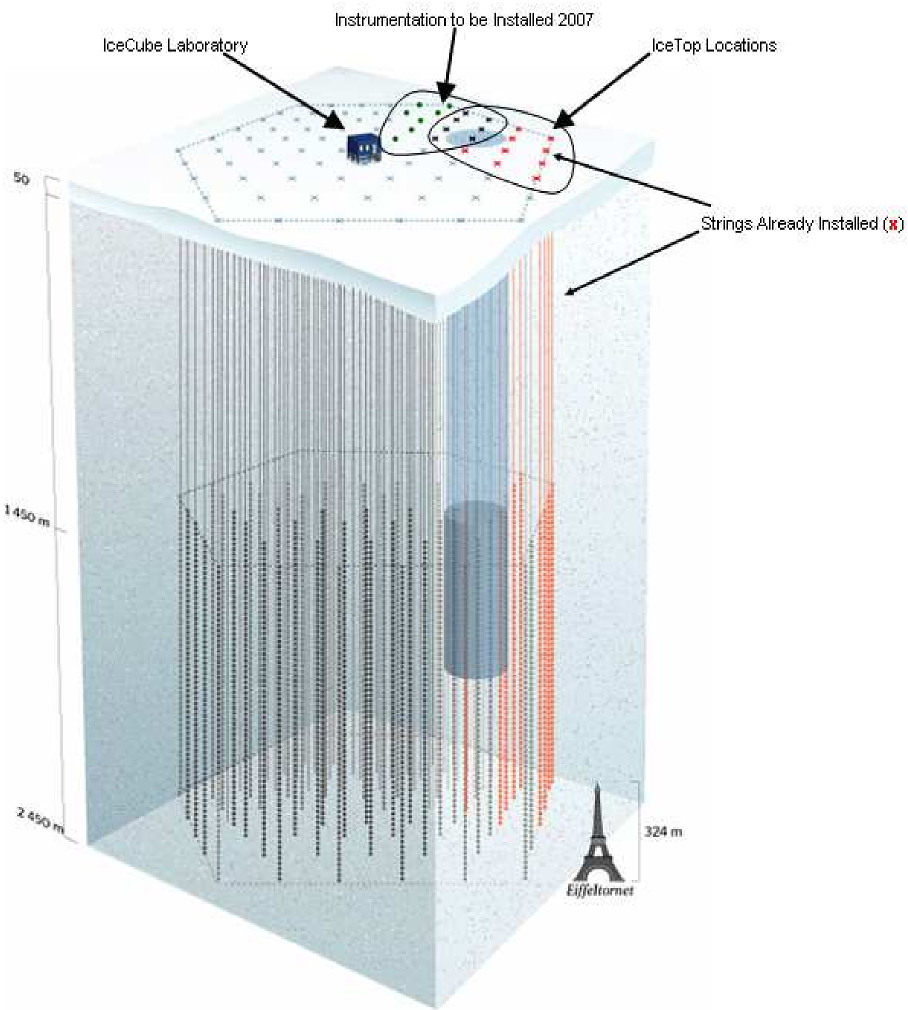
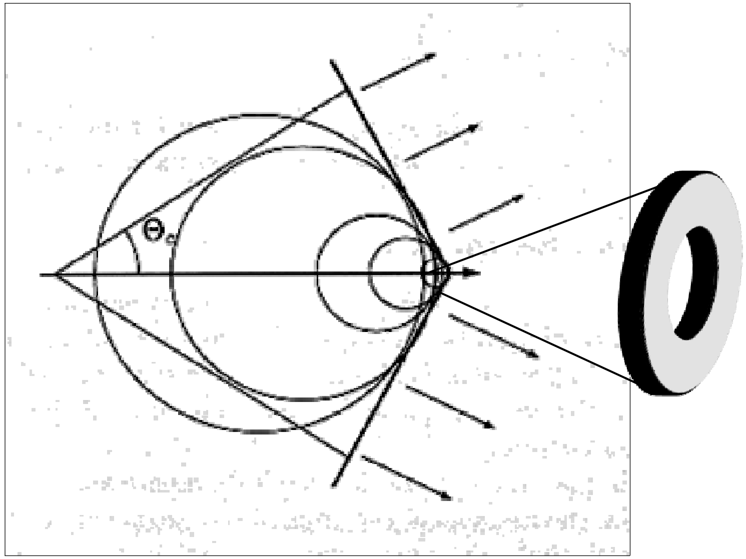


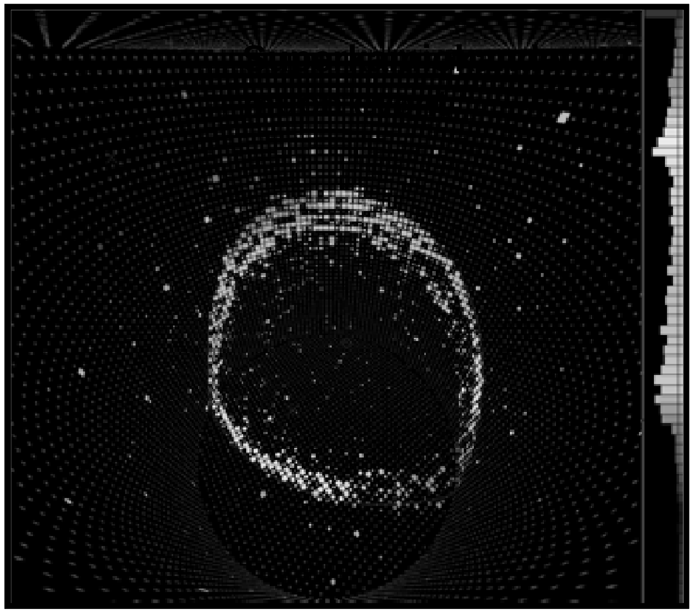
Figure 12: *Effective muon range as a function of the initial energy* E_o. *Curves correspond (from top to bottom) to different threshold energies* E_{thr} *of the muon arriving at the detector.* $E_{thr} = 1, 10^2, 10^3, 10^4, 10^5, 10^6$ *GeV. From [69].*

→ Detector size



Cherenkov light emission





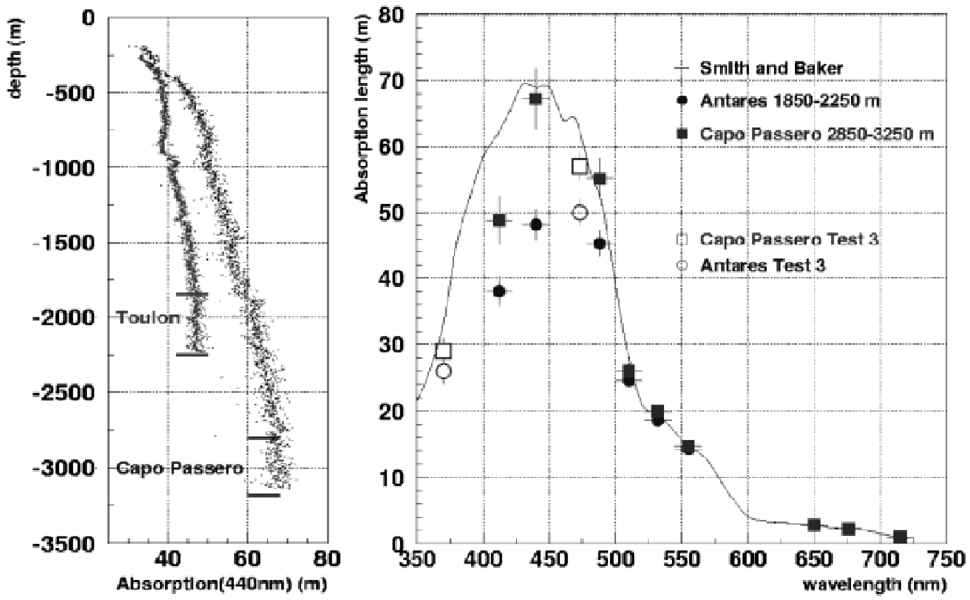
- Cherenkov light emitted by reletivistic particles in a trasparent medium, with : $\beta n(\lambda) > 1$
- Dominant photon emission in the blue-UV band (see cap. 7).
- In the range in which water/ice are most transparent:

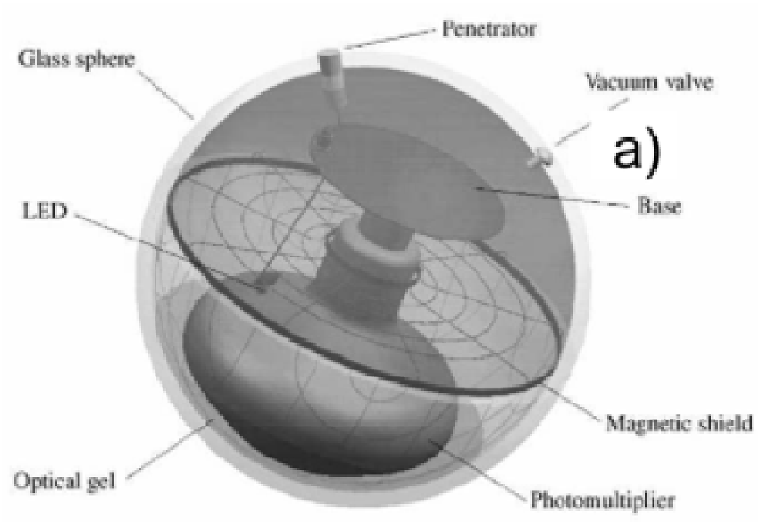
$$\frac{dN}{dx} = \frac{2\pi\alpha}{c} \int_{\beta n>1} \left[1 - \frac{1}{\beta^2 - n(\lambda)^2}\right] \frac{1}{\lambda^2}$$

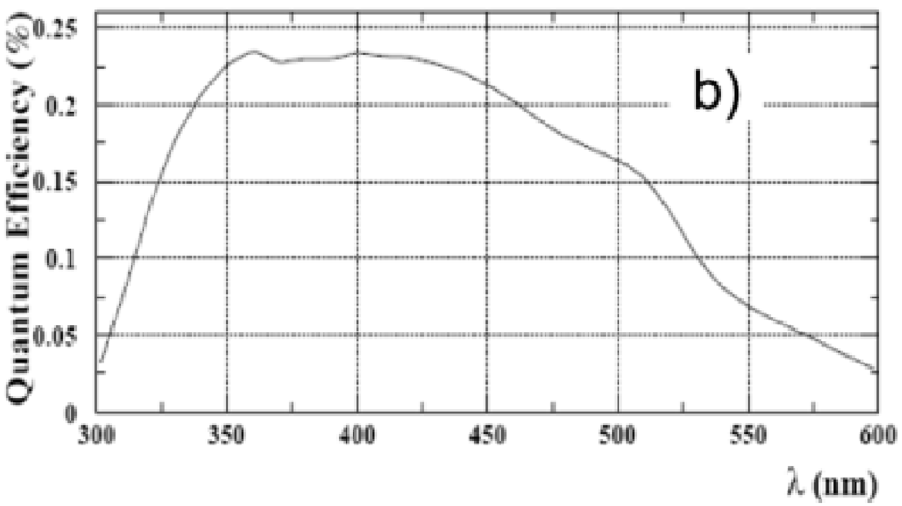
$$\left.\frac{dN}{dx}\right|_{300nm}^{700nm} \approx 300 \frac{photons}{cm}$$

Water properties/optical module

Water absorption length measured in the Toulon (blue) and Capo Passero (red). Left: La(λ) with λ = 440 nm as function of the depth. Right: various measurement of the absorption length in the two sites as function of the wavelength, compared to the behaviour of pure seawater (solid line).







How many light sensors → € ?

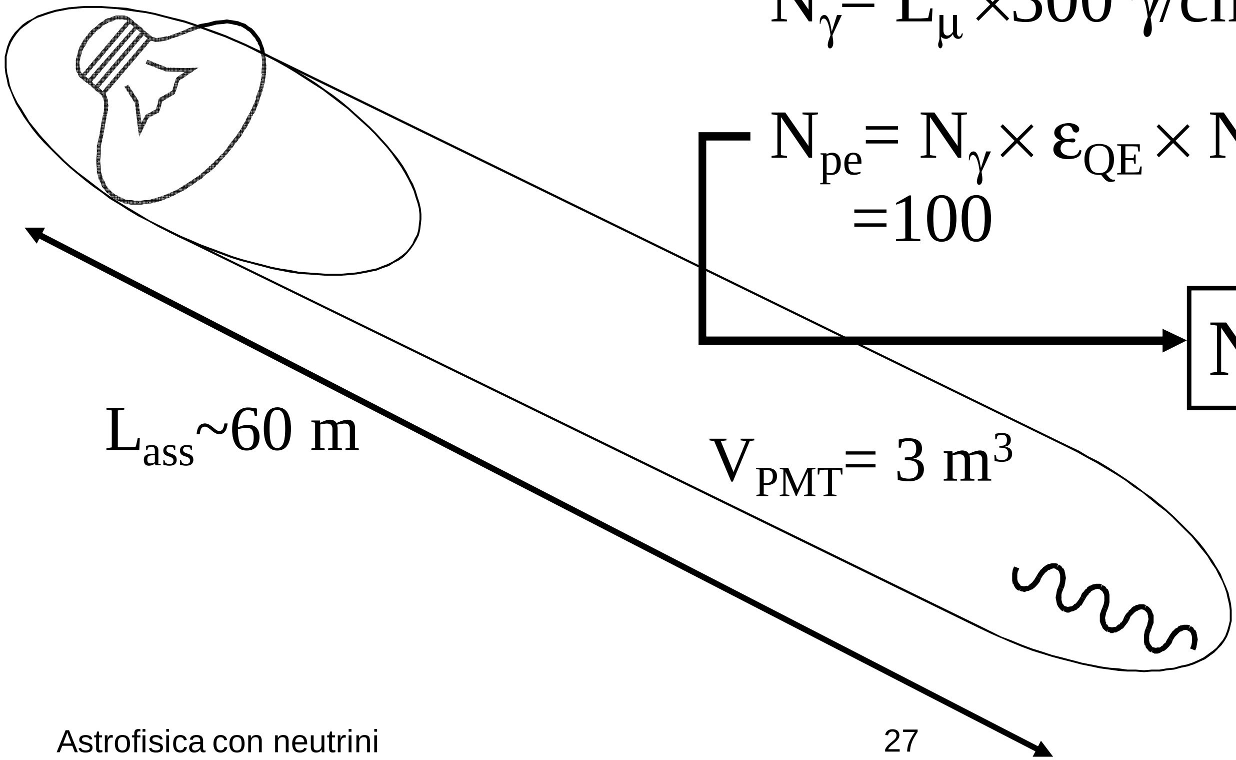
Problem: Let assume a muon track of L_μ=1 km. How many PMTs N_{PMT} are needed in 1 km^3 detector volume in order to detect ~100 photoelectrons N_{pe} ?

10” PMT =0.05 m^2

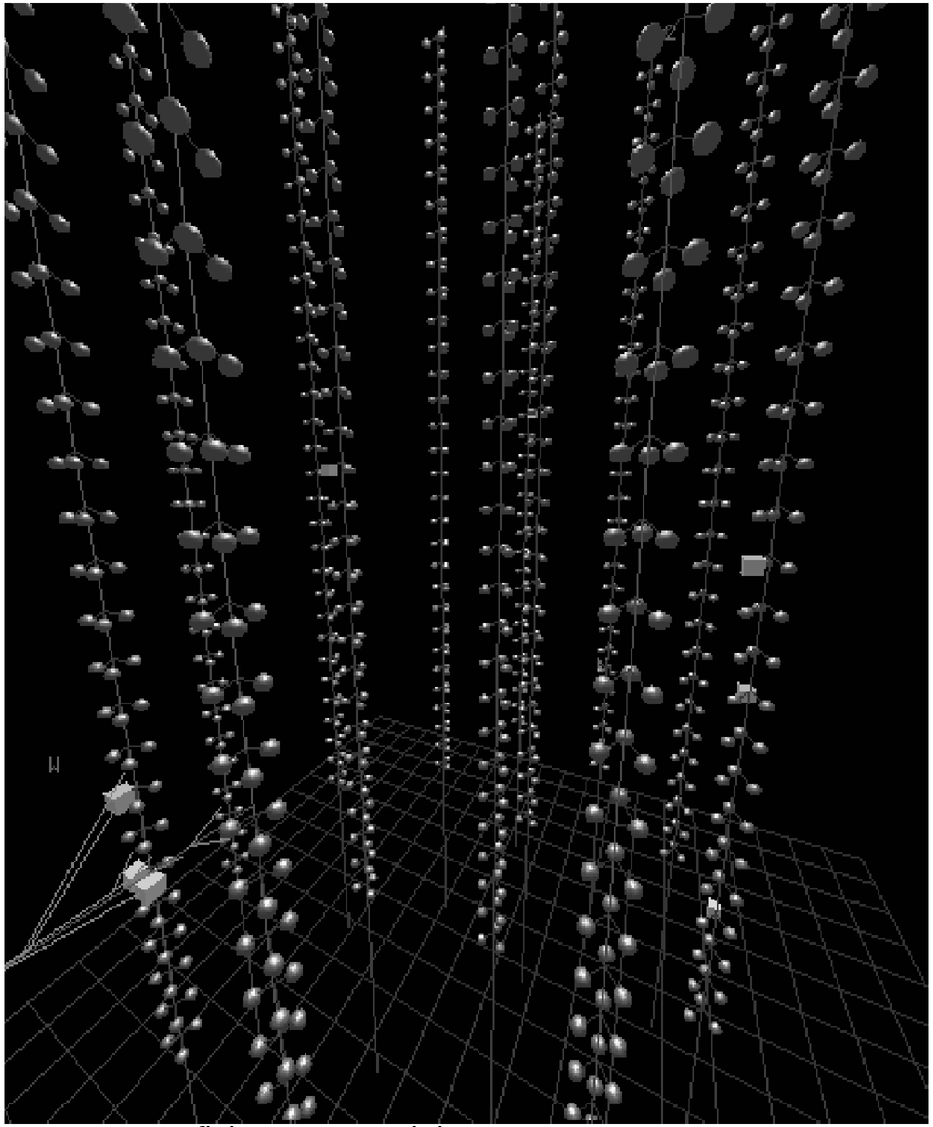
$N_\gamma = L_\mu \times 300\ \gamma/cm = 3x10^7\ \gamma$

$N_{pe} = N_\gamma \times \varepsilon_{QE} \times N_{PMT} \times (V_{PMT}/1\ km^3) = 100$

→ N_{PMT}=5000



Track reconstruction



• Cherenkov photons emitted by a μ crossing the detector are correlated in space and time

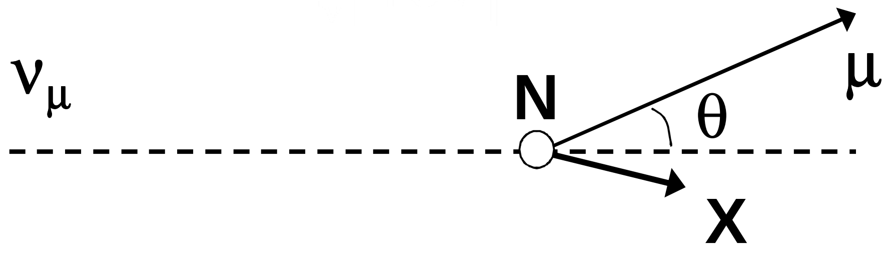
• μ can be reconstructed looking for time-space correlation between fired PMTs (hits).

Detecting ν

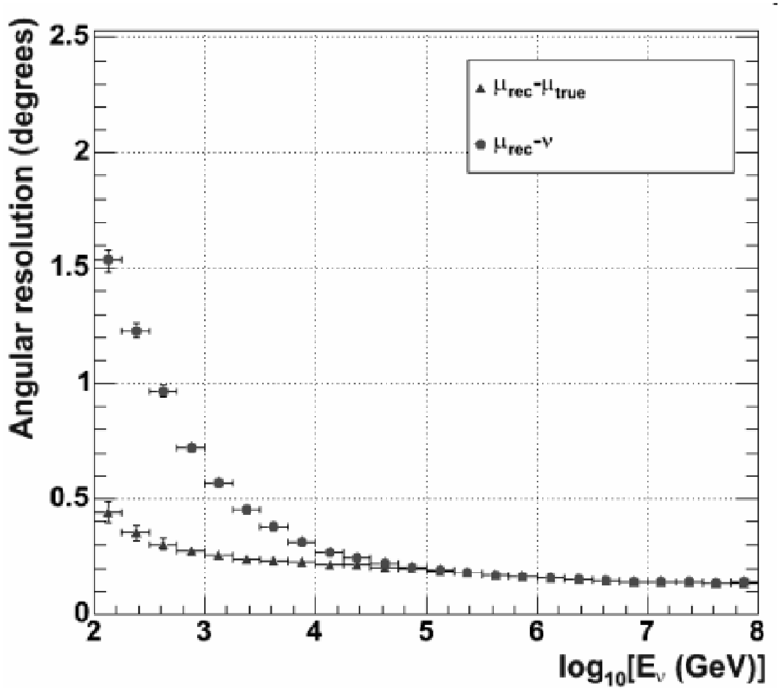
• Neutrino detection through CC interaction with production of a charged lepton

• Neutrino astronomy requires the reconstruction of the neutrino ***direction*** and an estimate of the ***energy***

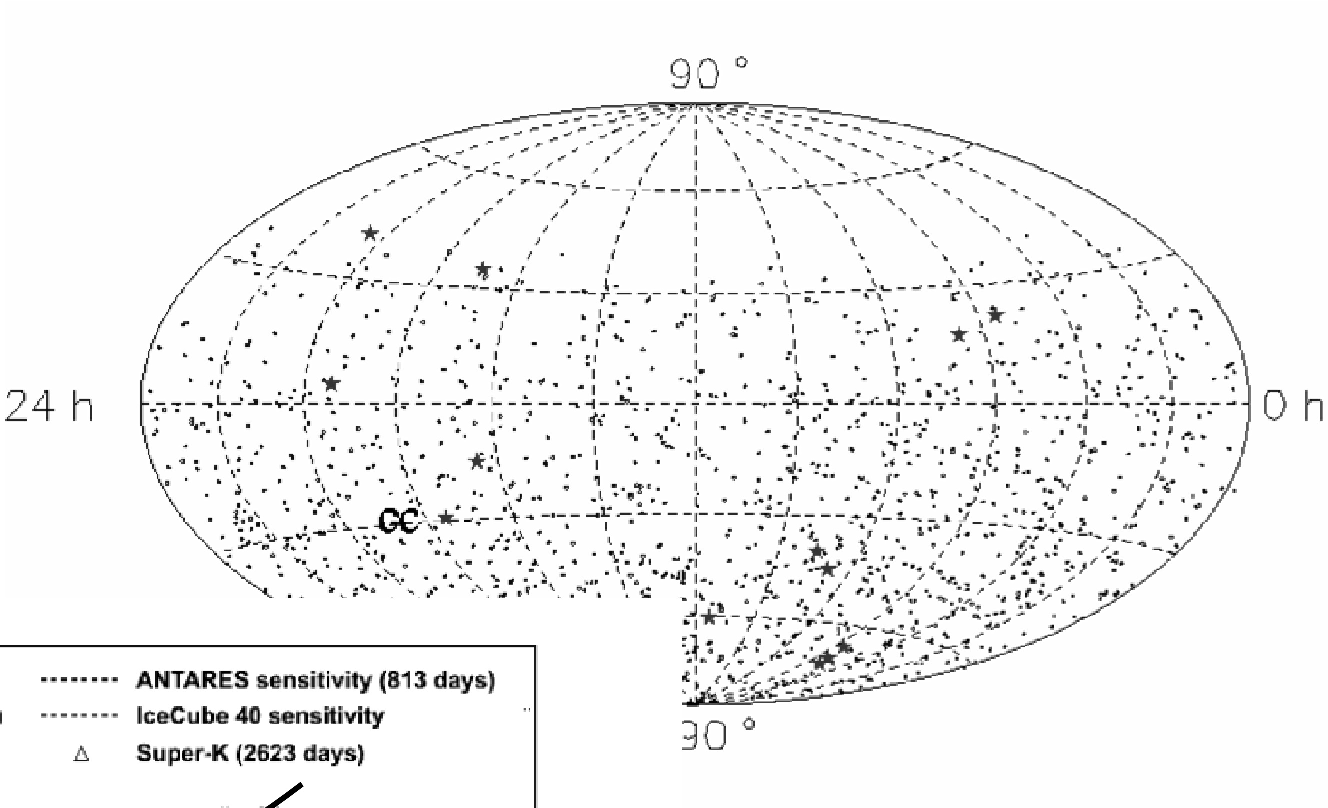
For Eν >TeV, μ e ν are almost collinear.
In water:

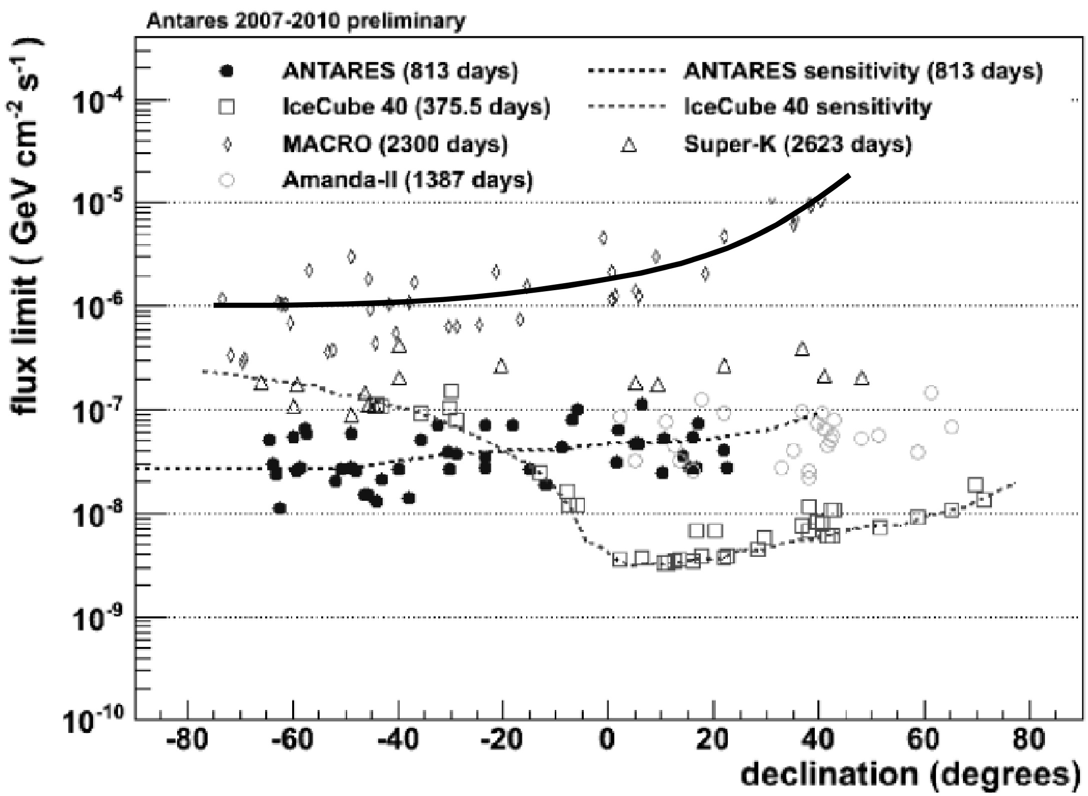


μ reconstruction allows the measurement of the ν direction



MACRO (A=1000 m^2, T=5 y) results: no evidence!





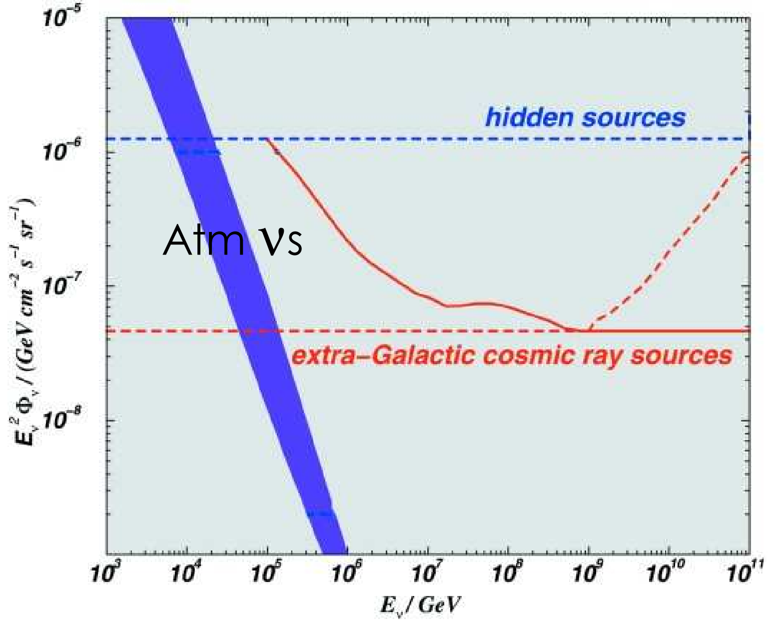
Larger area experiments needed!

9.5 Upper Bounds on Neutrino Diffuse Fluxes

- Upper bounds from UHE cosmic rays and γ diffuse flux can be established.
- The first limit comes from the isotropic gamma ray background:

$$\Phi_\nu \leq \Phi_\gamma(\text{MeV-GeV})\ O_\gamma$$

$$E^2\ d\Phi/dE < 10^{-6}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



- Concerning cosmic rays, it can be established the following relationship:

$$\Phi_\nu \leq \Phi_{CR}(E_{CR}=f^{-1}E_\nu)\ K\ O_n\ P$$

Waxman-Bahcall

- Source transparent to HE neutrons (E_n~10^{19} eV)
- Spectral shape up to GZK cut-off is $dN/dE \propto E^{-2}$

$$E^2\ d\Phi/dE < 4.5\times10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

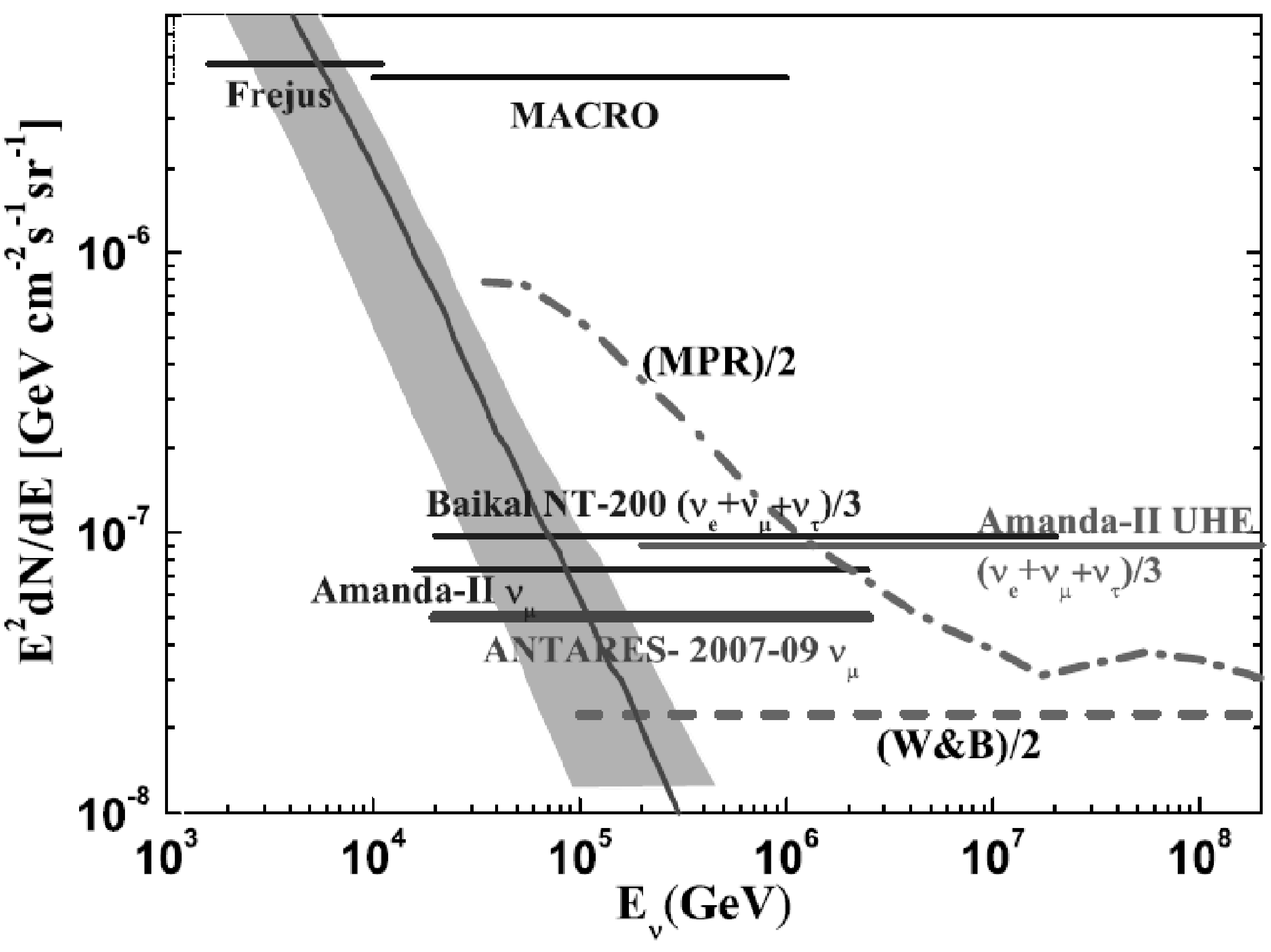
Mannheim-Protheroe-Rachen

- There is no assumption about the opacity and the spectral indexes of the sources.

$$E^2\ d\Phi/dE < 2\times10^{-6} - 4.5\times10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

Oscillations reduce these limits in a factor two: 1:2:0 $\rightarrow$ 1:1:1

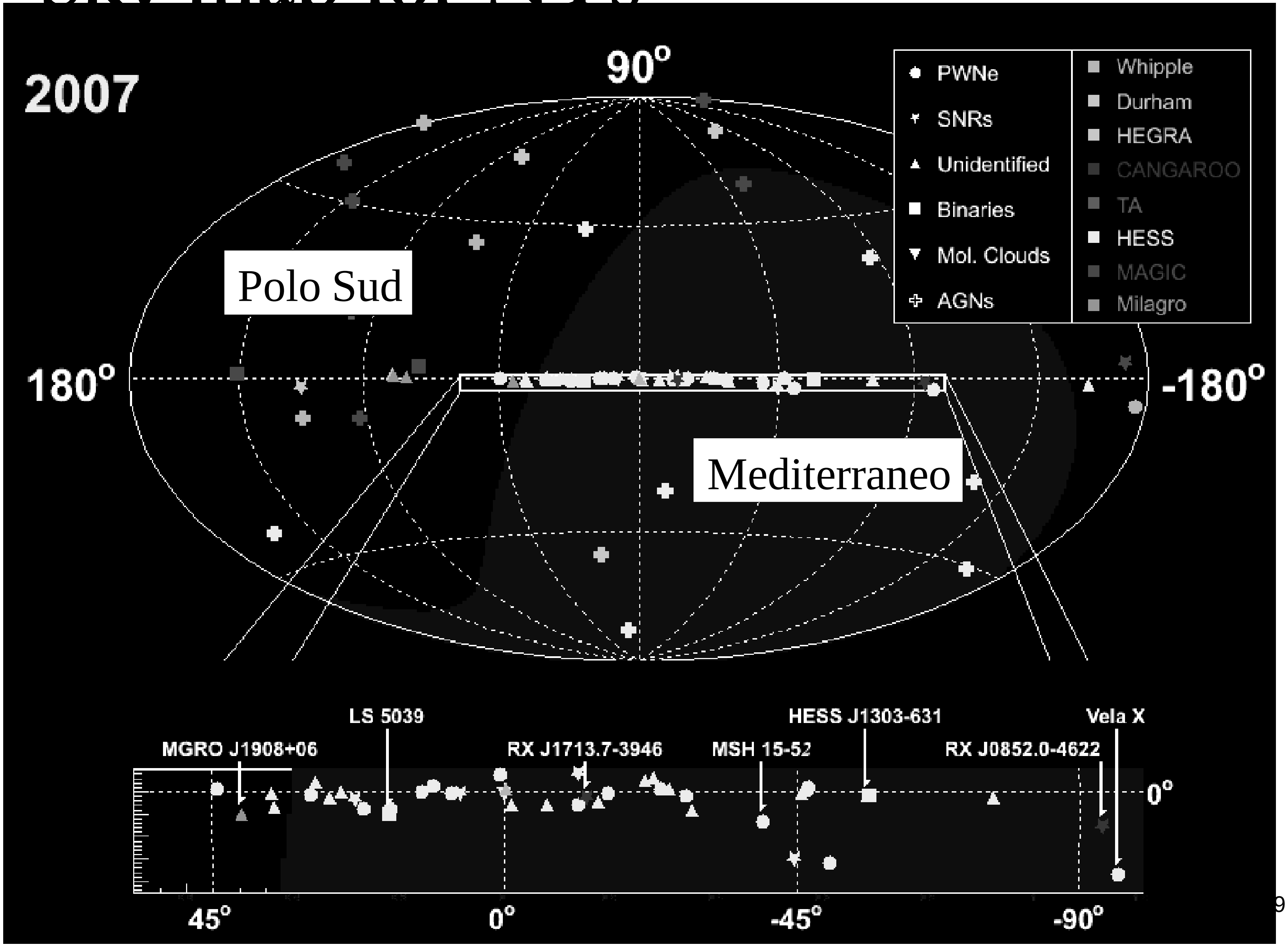
Search for a diffuse flux



9.6 The neutrino telescope projects

- **IceCube (South Pole)**
- **Km3 (Mediterranean Sea)**
  - **ANTARES** (subproject)
  - **NEMO** (subproject)

Sky map for NTs

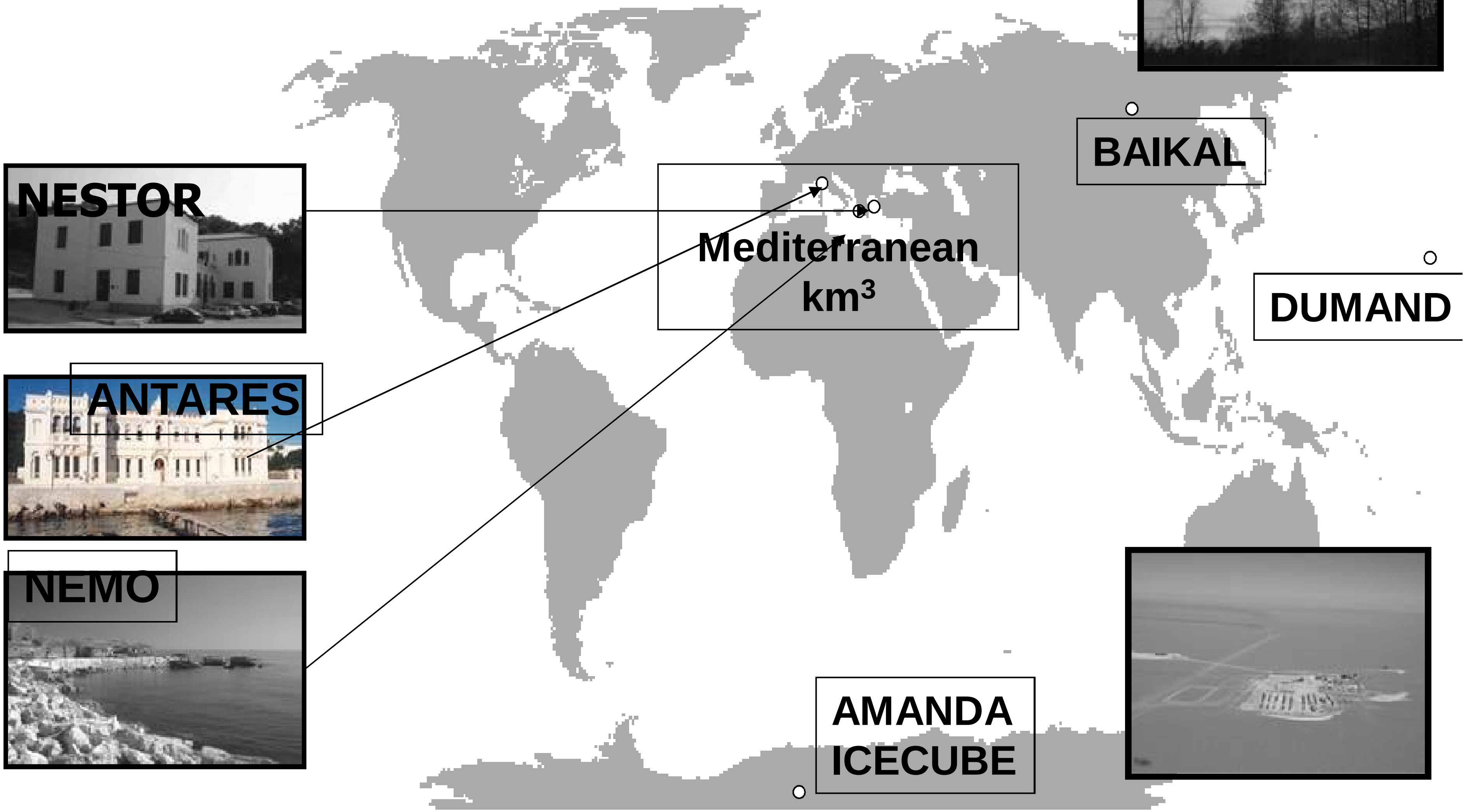


Neutrino-induced muons form cosmic sources in a km^3 detector

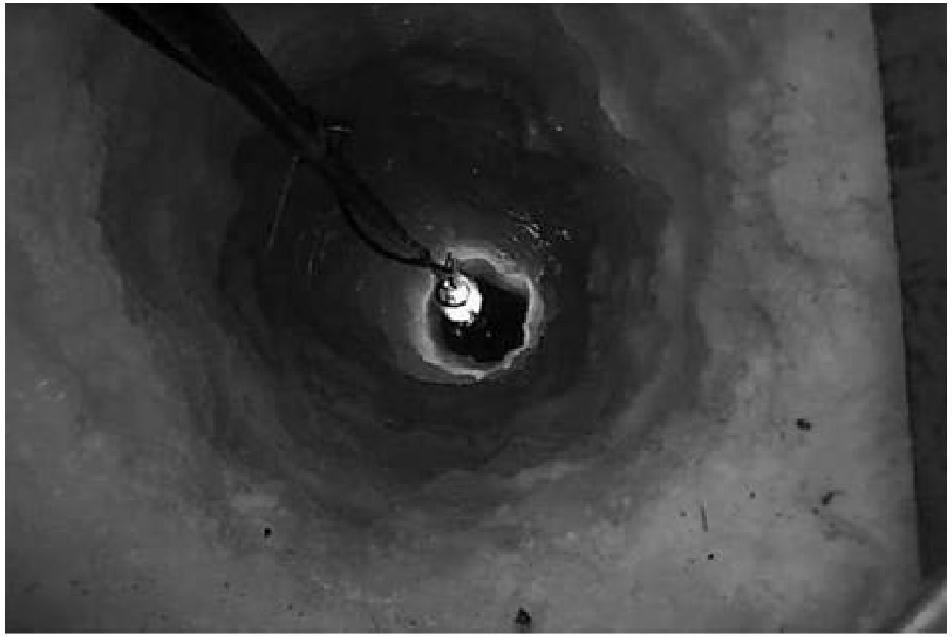
Diffuse Flux	
"UHE" (GZK):	few / year ?
Diffuse, from GRB: (Waxman)	20 / year
Diffuse, from AGN (thin): (Mannheim)	few / year
" " (thick):	>100 / year

Point sources	
GRB (030329): (Waxman)	1÷10 / burst
AGN (3C279): (Dermer)	few / year
galactic SNR (Crab-like): (Protheroe)	few / year ?
Galactic Microquasars :(Distefano)	1 ÷ 100 / year

Neutrino telescopes

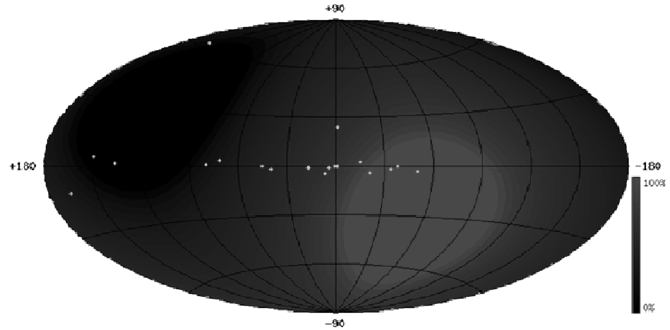


Difference between ice…

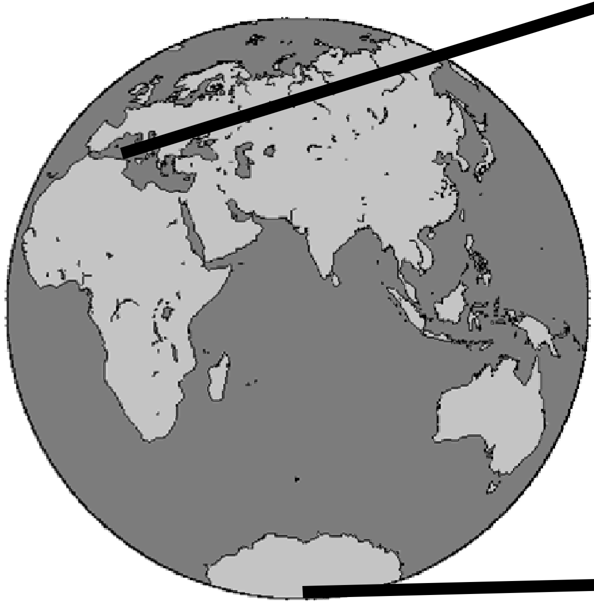


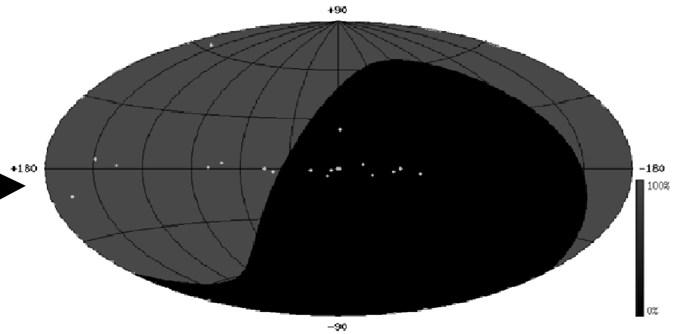
… and Mediterranean water

i) Sky View



Mediterranean Sea
43º North
2/3 of time: Galactic Centre





0.5 π sr instantaneous common view
1.5 π sr common view per day

AMANDA/IceCube
South Pole

ii) Logistics

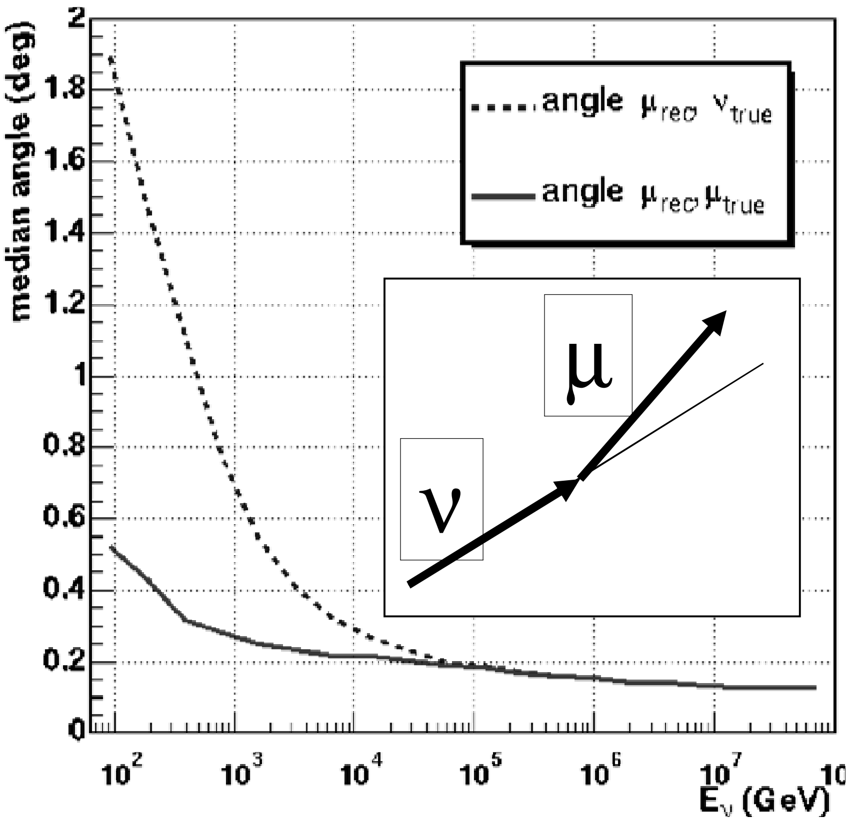
iii) Medium optical properties

Il mezzo **assorbe** e **diffonde** i fotoni. Ciò diminuisce il volume sensibile e la precisione nella ricostruzione

• Ghiaccio: maggiore lunghezza di **assorbimento** → miglior V_{PMT}

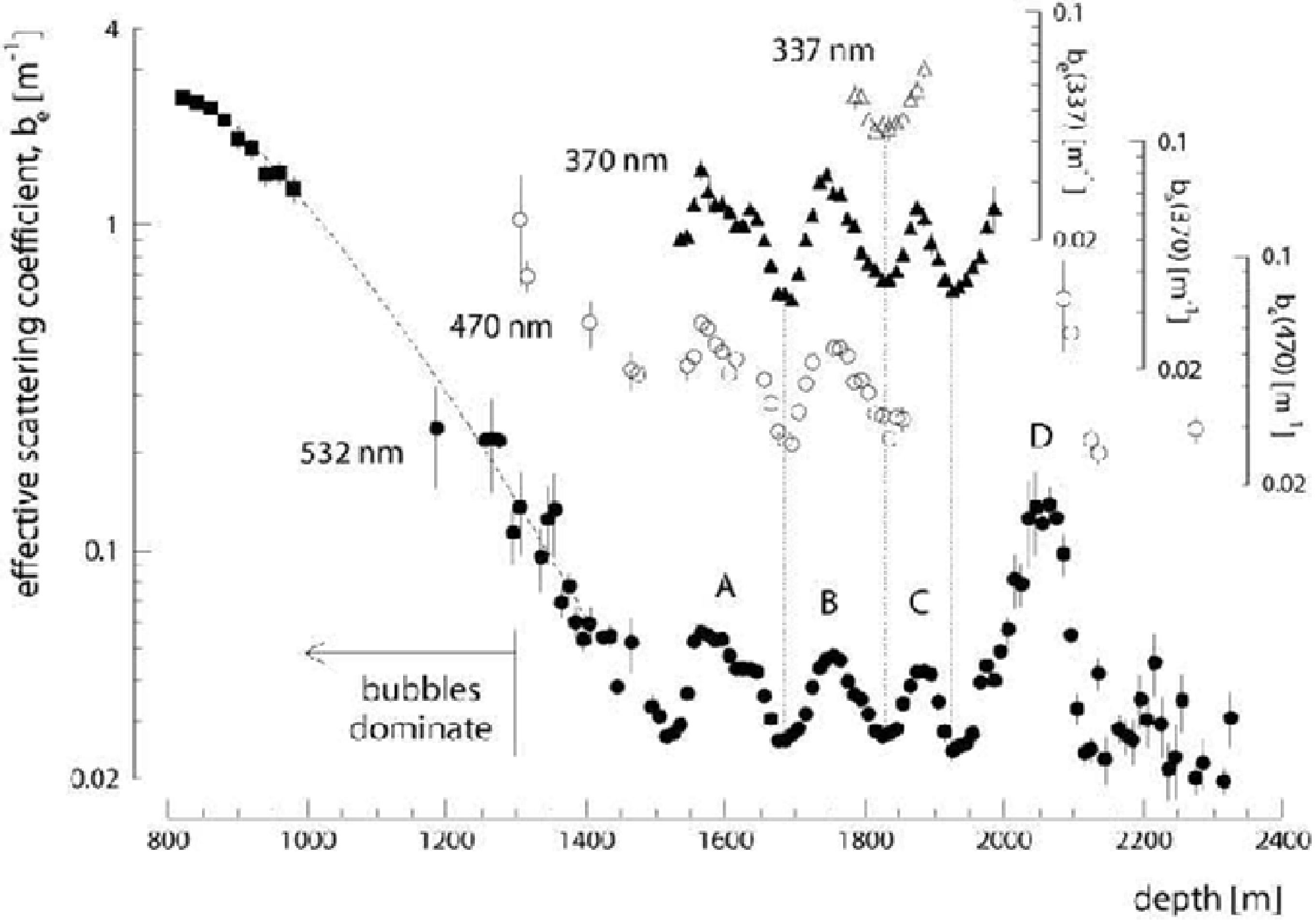
• Acqua: minore lunghezza di **diffusione** → migliore ricostruzione

Figura: ANTARES MC

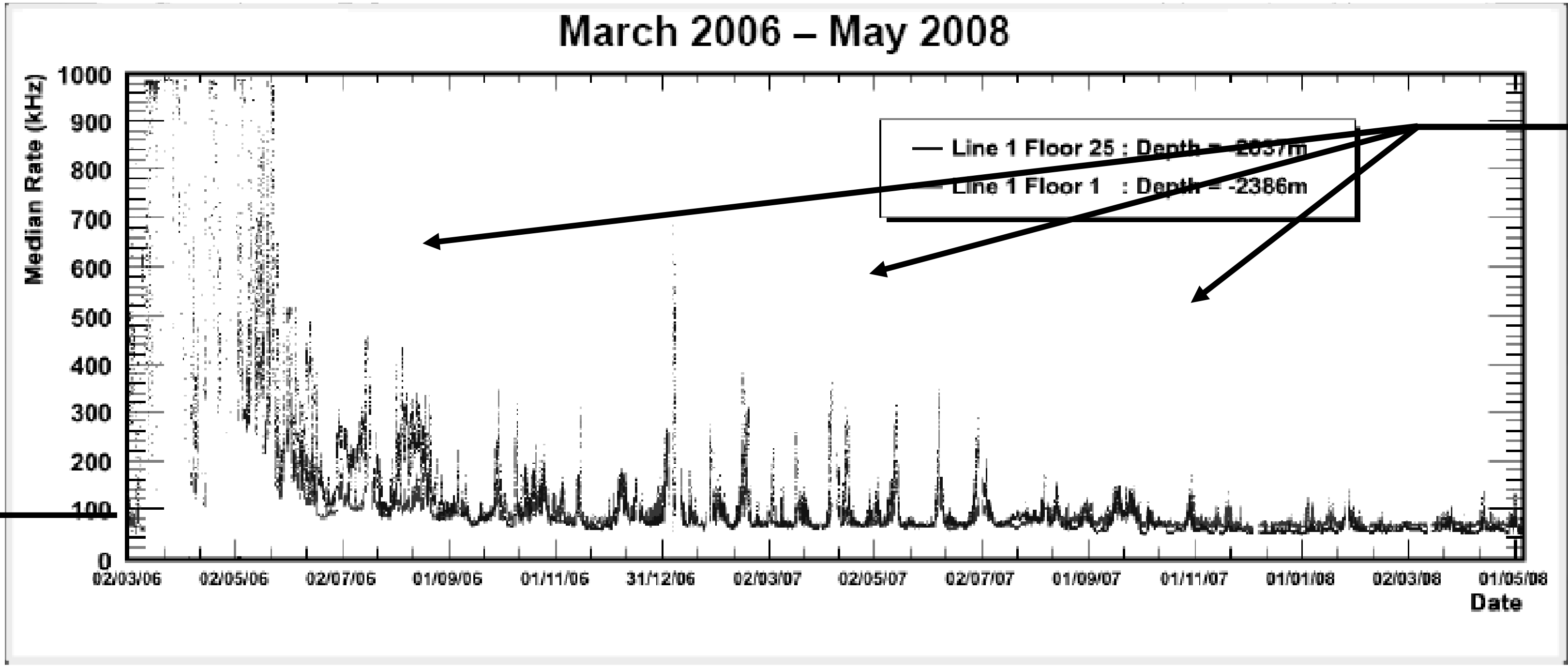


(…ghiaccio)

■ Coefficiente di diffusione ($1/L_{diff}$) per il ghiaccio. Occorre andare oltre 1400 m per evitare le bolle d'aria. Diversi picchi a diverse profondità dovuti a diversi tipi di polveri

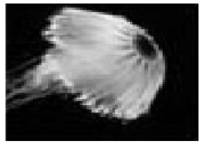


iv) Background (water)



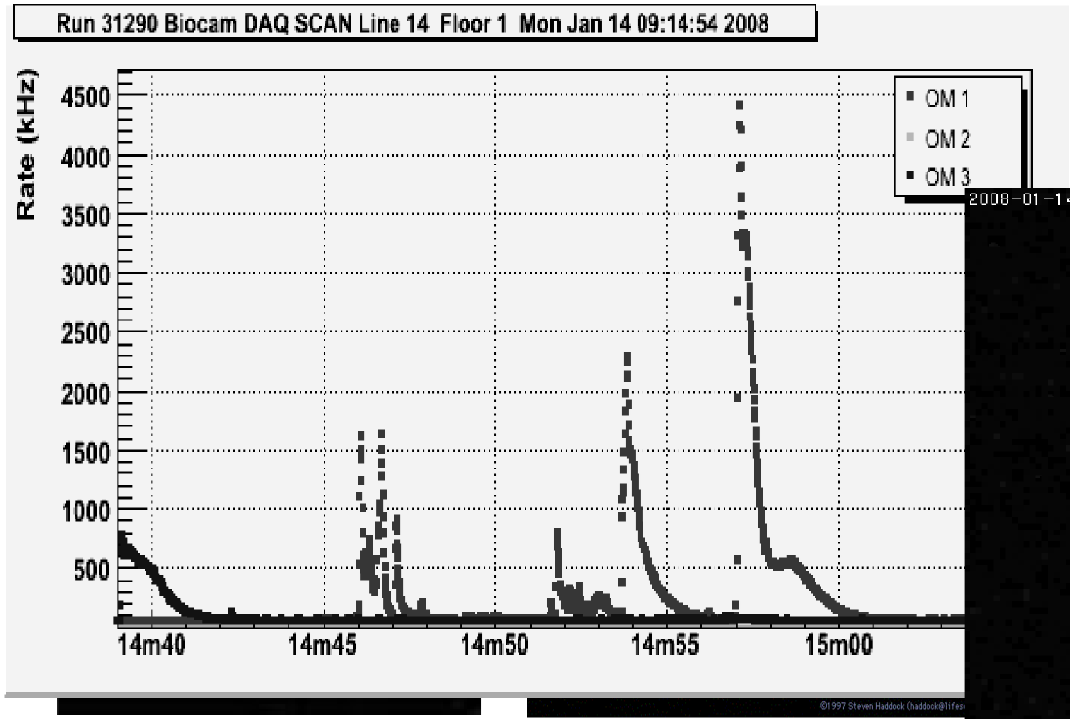
^{40}K **decays (rate ~50 kHz)**

Bioluminescence =
Bursts from macroorganismes
(strongly affected by current velocity)



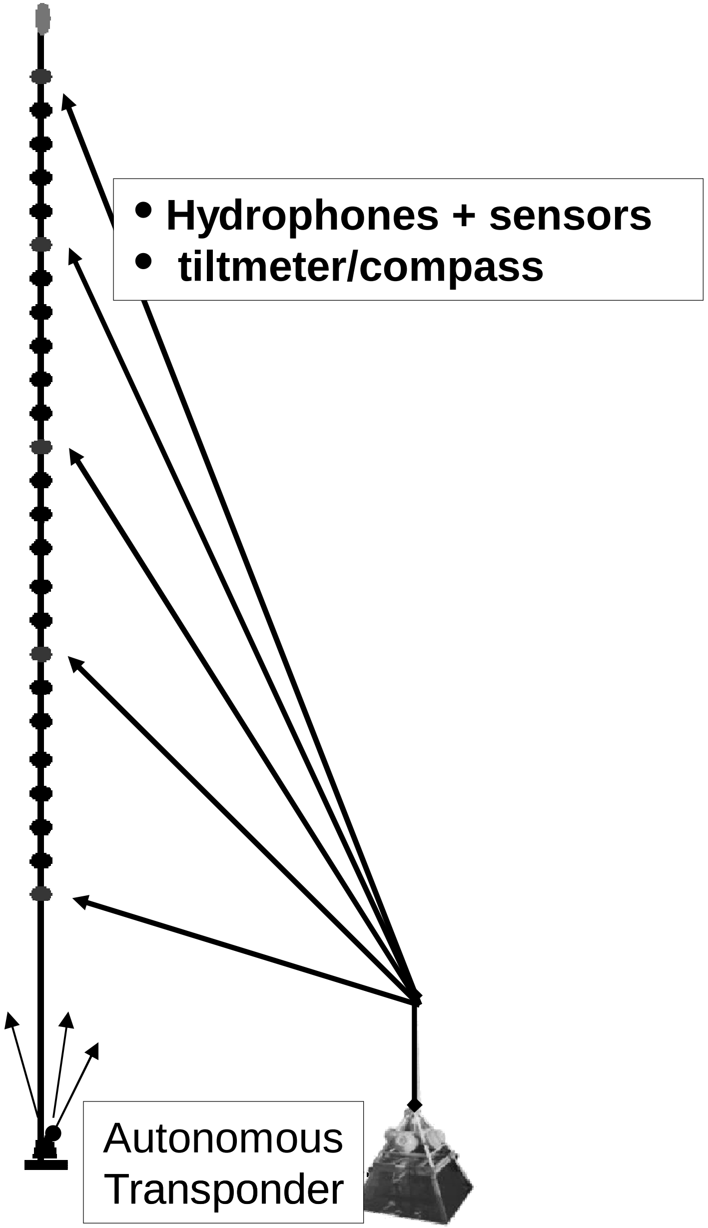
Life in the deep sea (ANTARES)

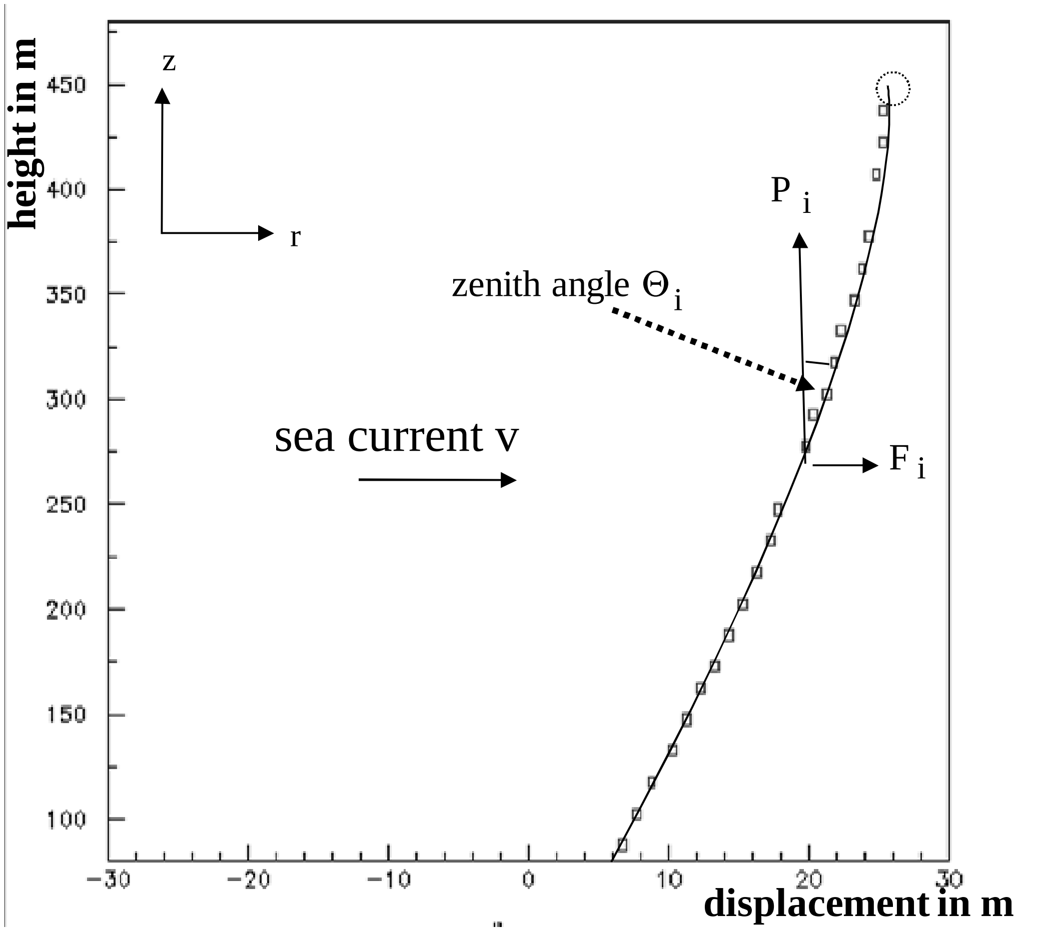
• Commercial IR Video Camera in “self triggering mode”



14-01-2008 floor1

v) OM positioning (water)

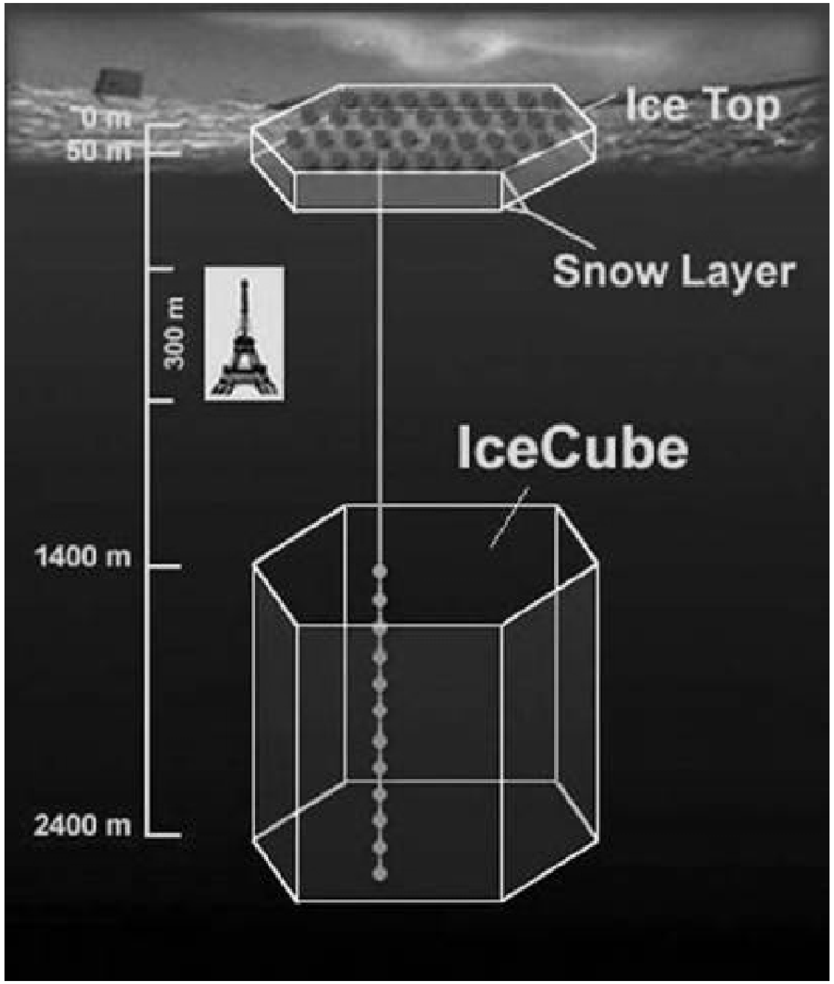




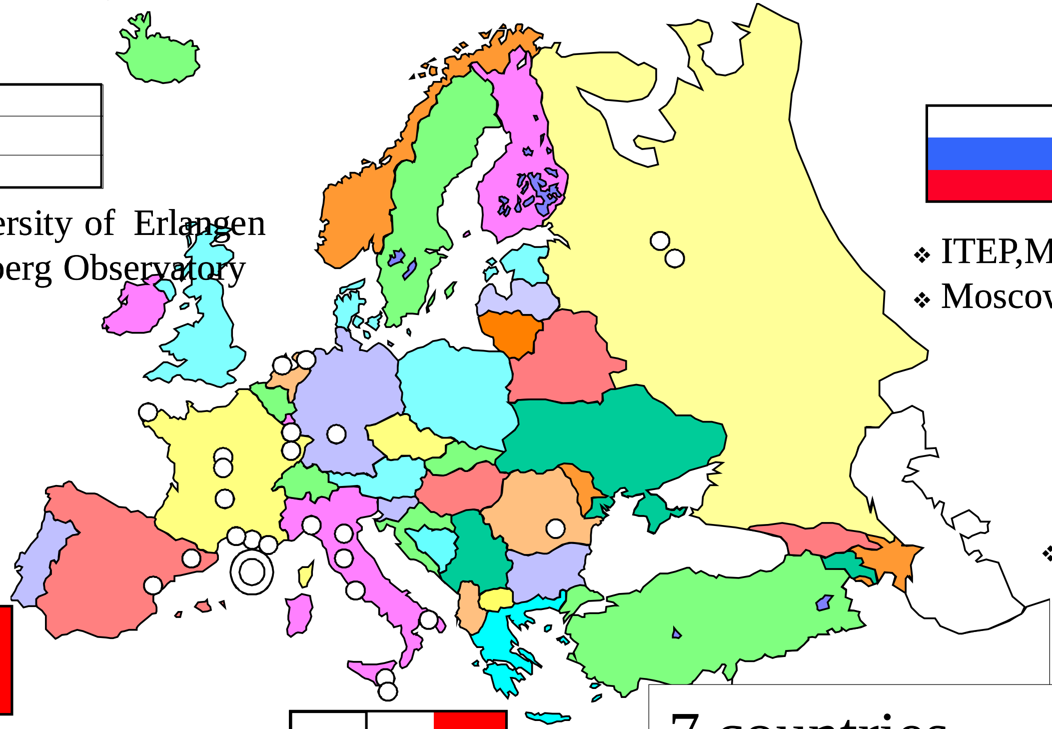
IceCube at the South Pole

- Rivelatore in fase di costruzione in Antartide:

- 80 stringhe (60 PMT/stringa)
- 4800 10" PMT (verso il basso)
- 125 m distanza tra stringhe
- 16 m distanza tra PMT sulla stringa
- Volume istrumentato: 1 km3
- **Completed (2012)**



The ANTARES Collaboration



- NIKHEF,
- Amsterdam
- Utrecht
- KVI Groningen
- NIOZ Texel

- University of Erlangen
  Bamberg Observatory

- ITEP,Moscow
- Moscow State Univ

- ISS, Bucarest

- IFIC, Valencia
- UPV, Valencia
- UPC, Barcelona

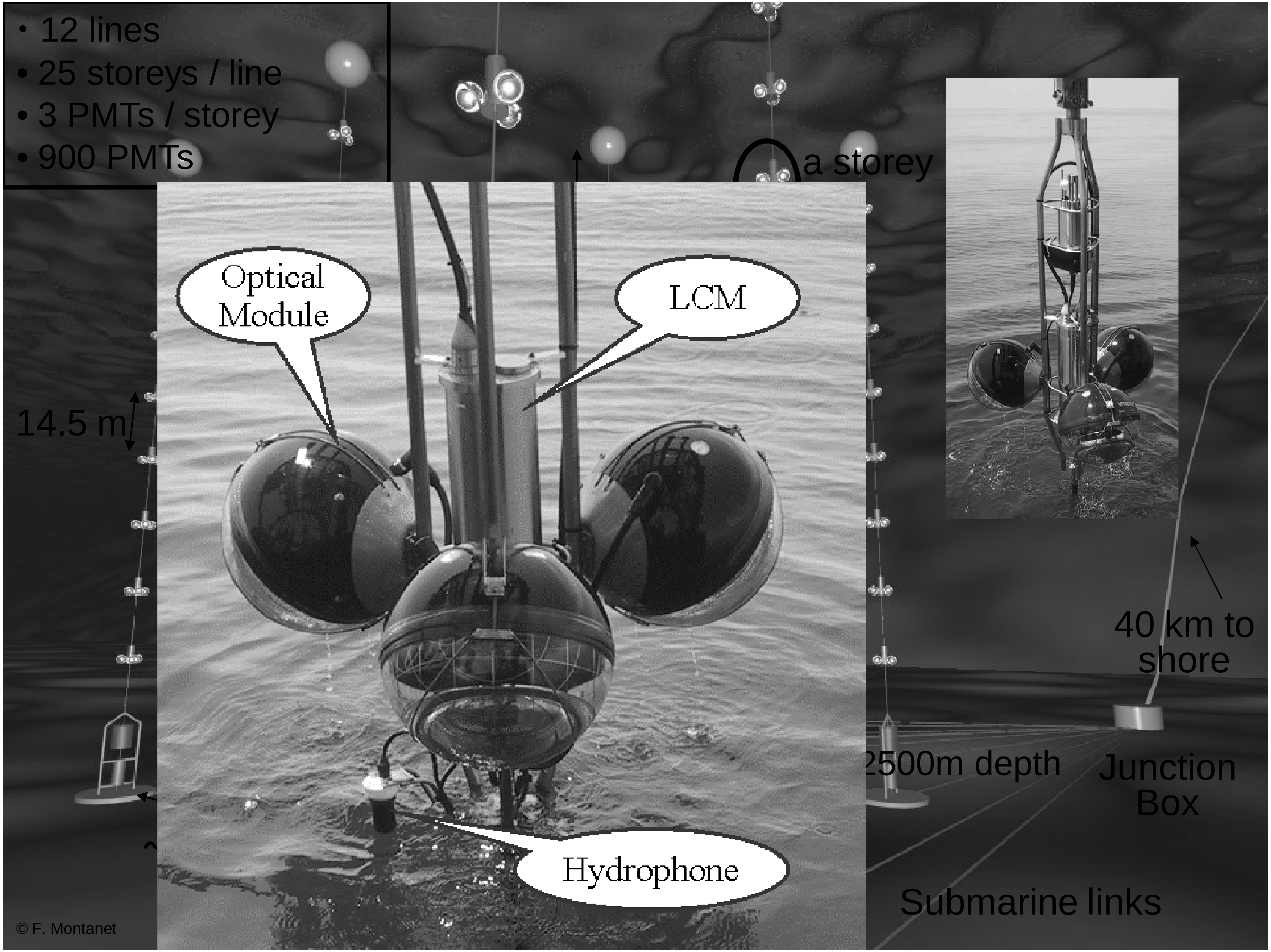
- CPPM, Marseille
- DSM/IRFU/CEA, Saclay
- APC, Paris
- LPC, Clermont-Ferrand
- IPHC (IReS), Strasbourg
- Univ. de H.-A., Mulhouse
- IFREMER, Toulon/Brest
- C.O.M. Marseille
- LAM, Marseille
- GeoAzur Villefranche

- University/INFN of Bari
- University/INFN of Bologna
- University/INFN of Catania
- LNS – Catania
- University/INFN of Pisa
- University/INFN of Rome
- University/INFN of Genova

7 countries
29 institutes
~150 scientists+engineers

The site


TOULON
HYÈRES
ILES D'HYÈRES
Levant
Porquerolles
Port-Cros
200 m
2200
TOULON A50
VERS TOULON
MARSEILLE A50
BAIE DE LA SEYNE
CENTRE VILLE
VERS
ST MANDRIER

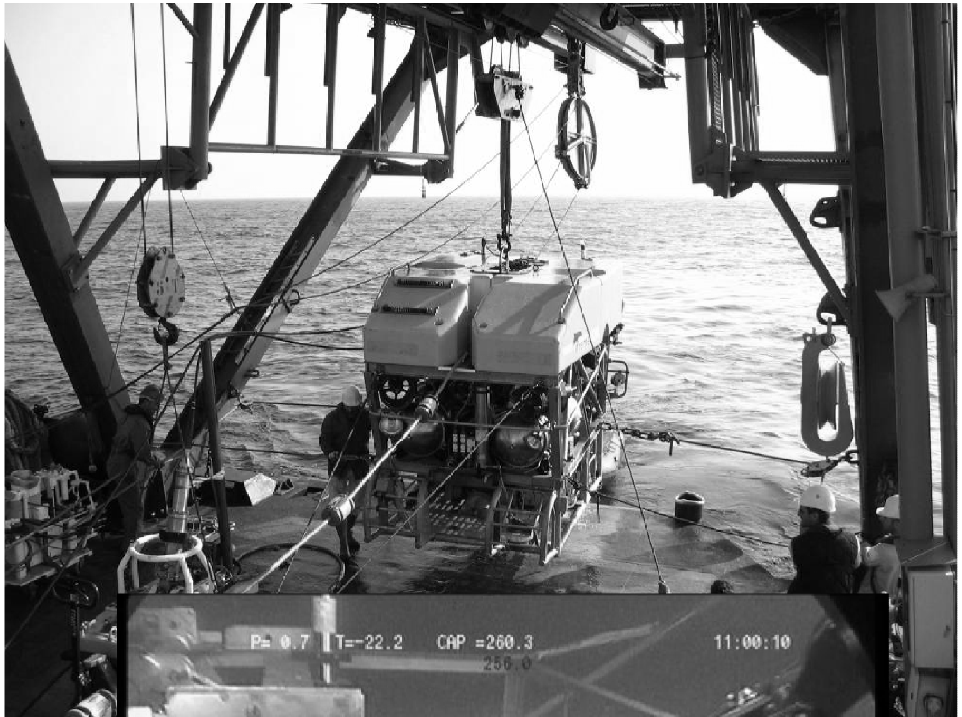


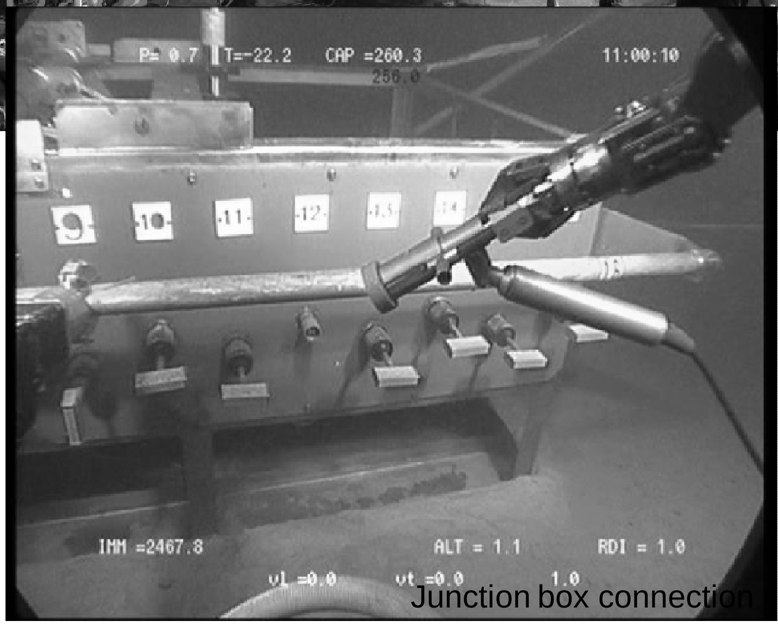
• 12 lines
• 25 storeys / line
• 3 PMTs / storey
• 900 PMTs
a storey
Optical Module
LCM
14.5 m
Hydrophone
40 km to shore
2500m depth
Junction Box
Submarine links
© F. Montanet

Deployment of a line

- ❖ DP boat « Castor 02 »
- ❖ Line positioning on sea bed within 1m
- ❖ 7 hours of operations

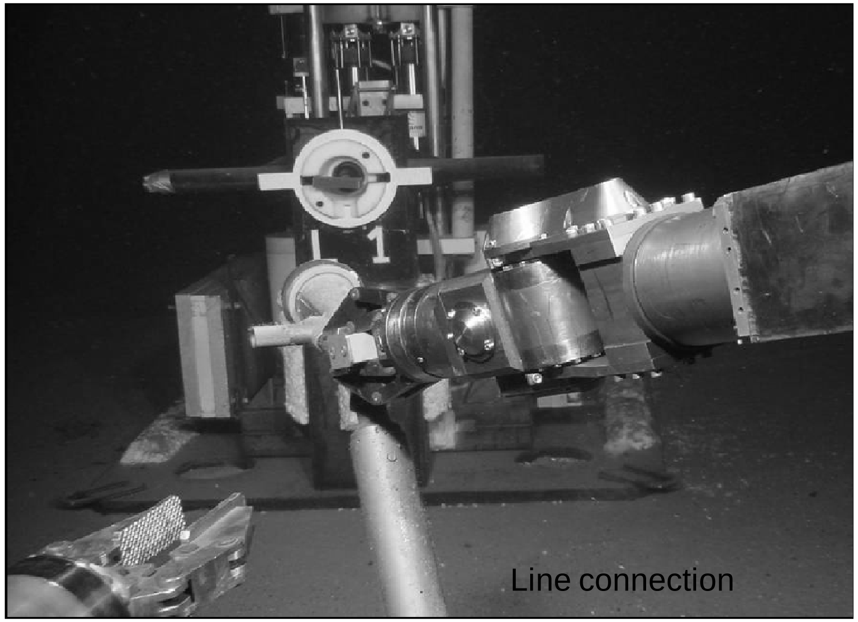
Line connection by ROV





Junction box connection

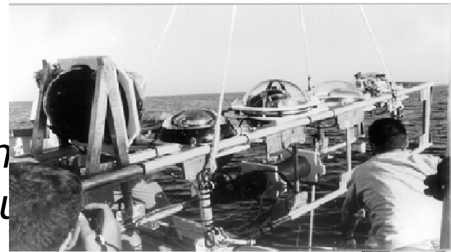
- ROV «VICTOR 6000» from IFREMER
- ODI link equipped with
wet mateable connector (4 optical, 2 electrical contacts)


Line connection

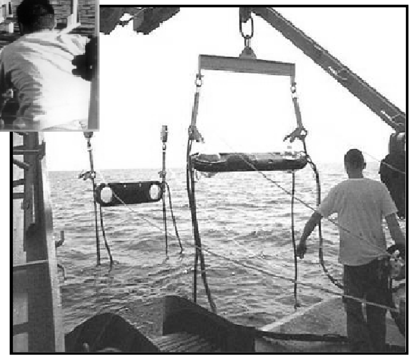
ANTARES milestones

- ❖ 1996: birth of Antares

Autonomous line



- ❖ 1996-2000: R&D
  - ➢ *Site measurements (optical background, foulin*
    absorption length, sea current,…)with autonomou
  - ➢ *Demonstrator line in 2000*



Demonstrator line

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

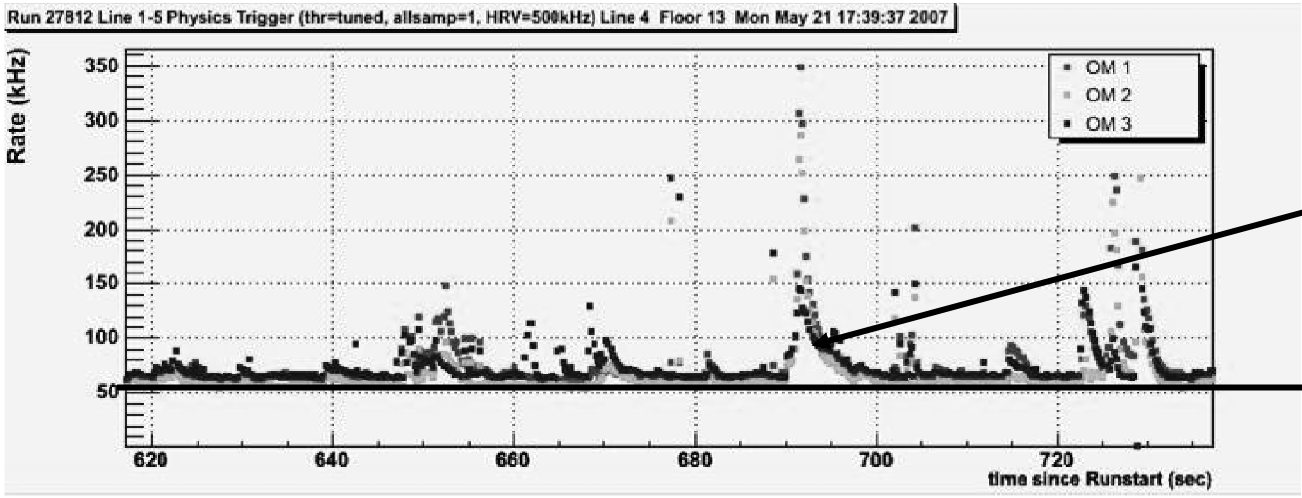
Cable installation

Junction Box

- ❖ 2004-2008: construction of the 12 lines detector

- ❖ 2007- 2013…: detector operation

Optical background



bursts

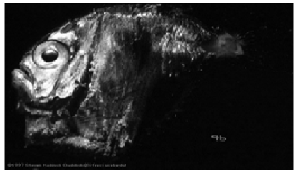
baseline

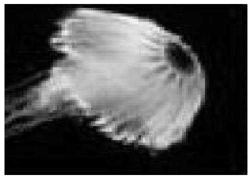
Baseline:

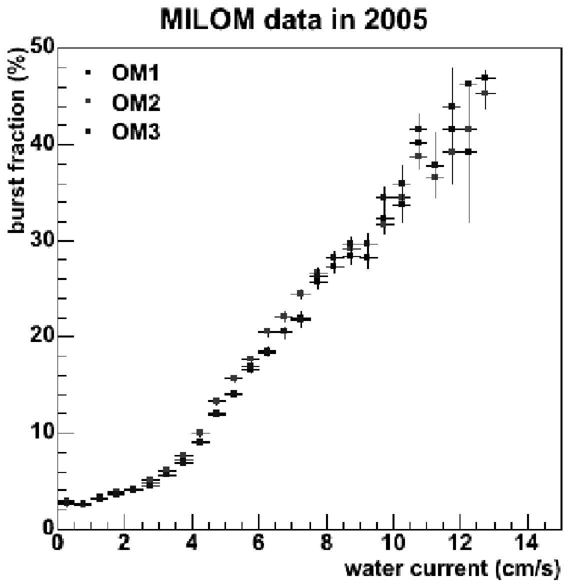
^{40}K decays + bacteria luminescence

Bioluminescence bursts:

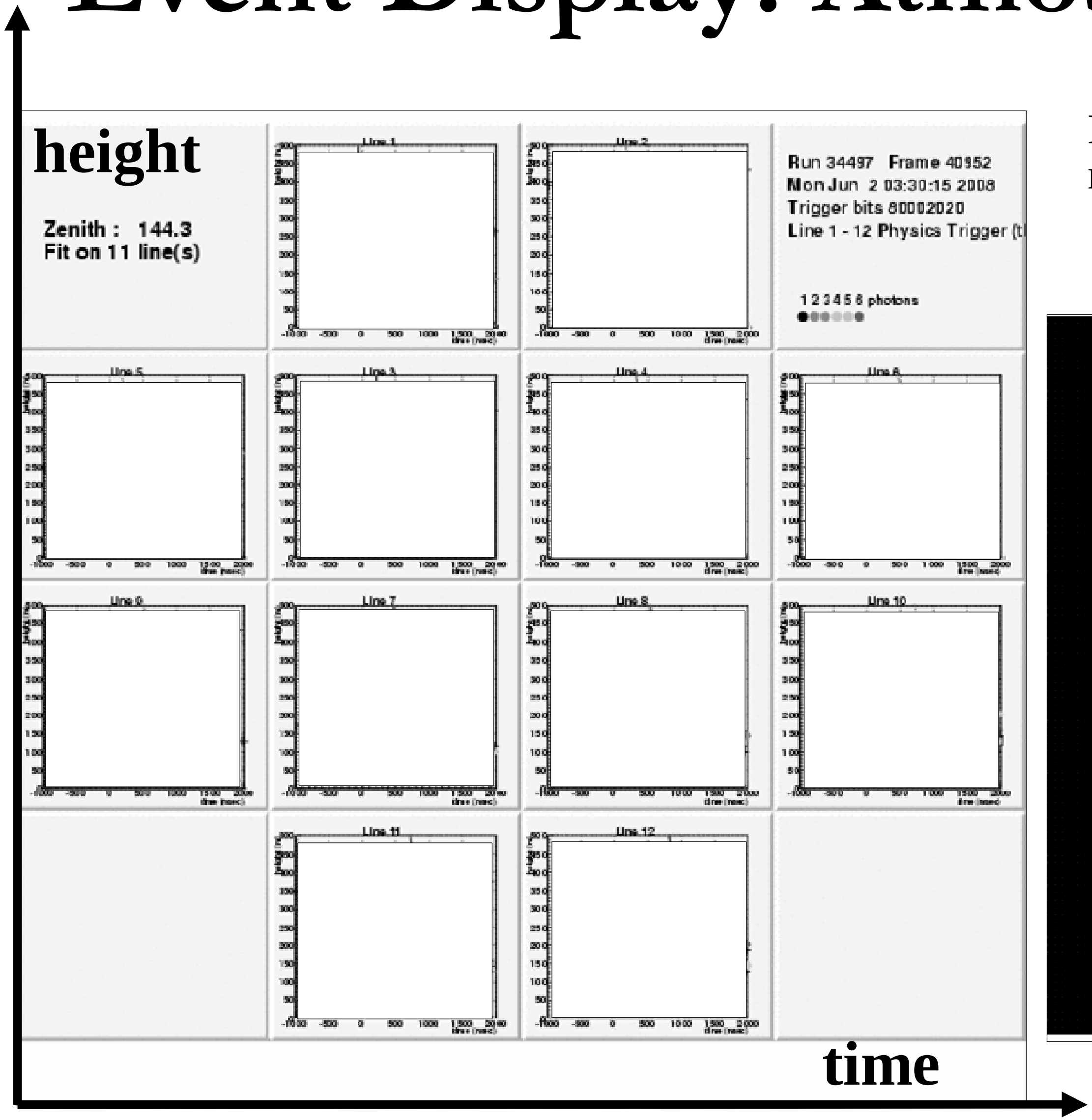
Animal species which emit light by flashes, spontaneous or stimulated around the detector.



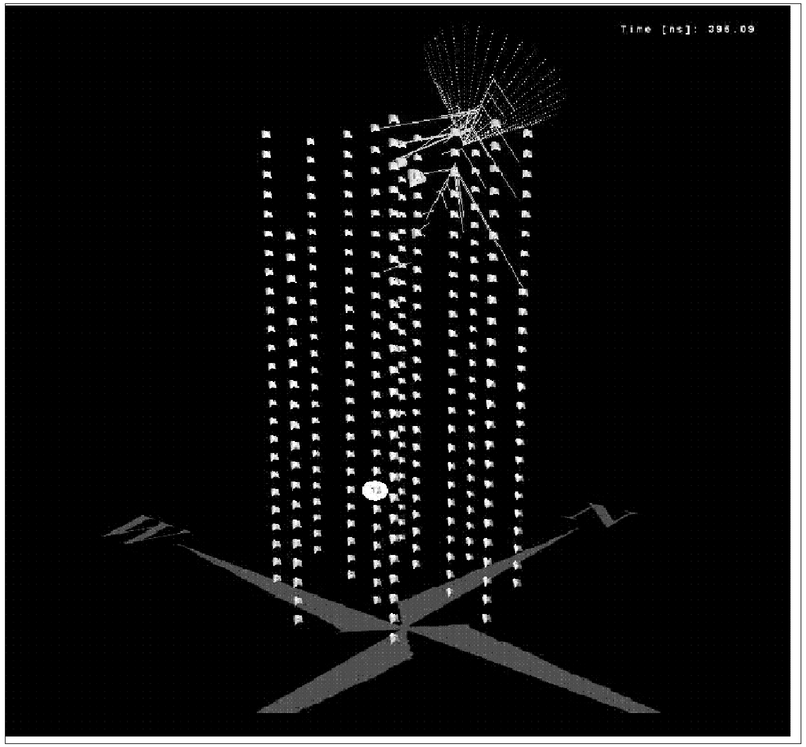




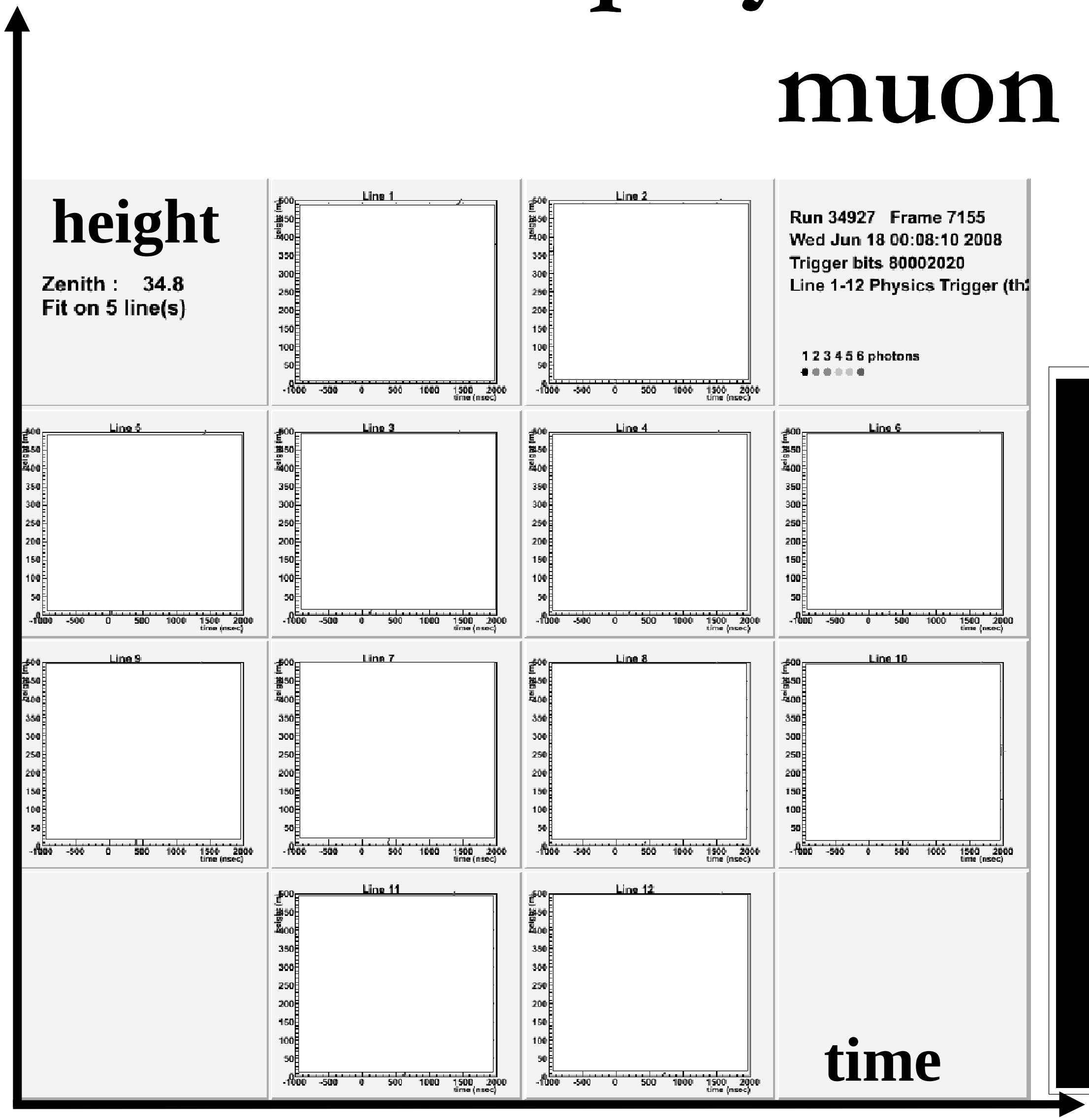
Event Display: Atmospheric Muons



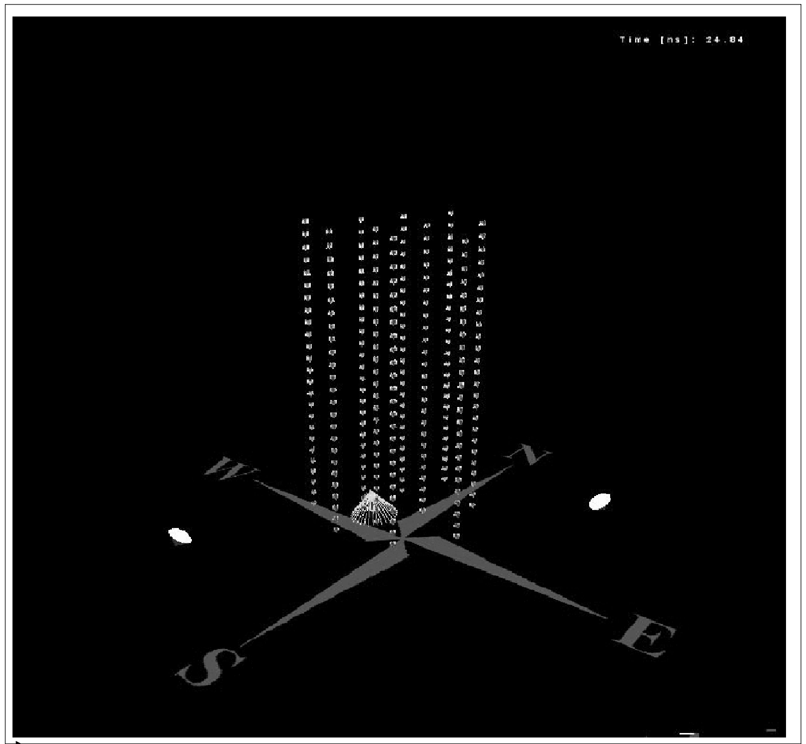
Example of a reconstructed down-going muon, detected in all 12 detector lines:



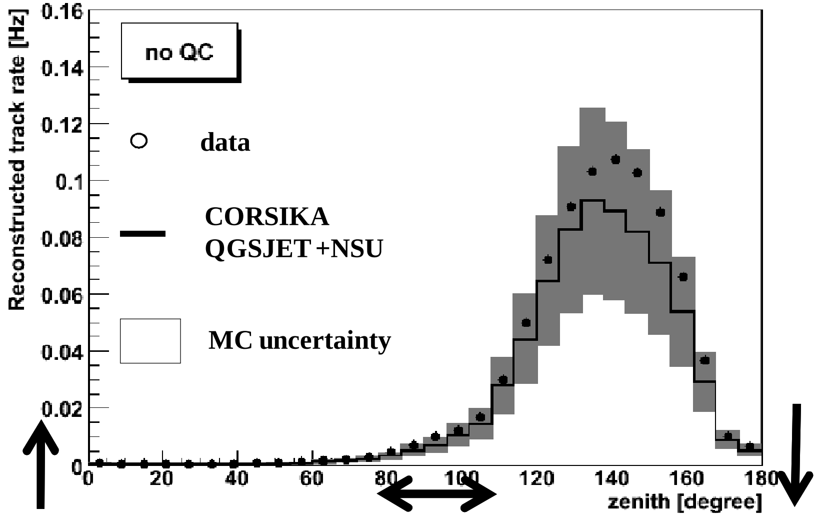
Event Display: Neutrino-induced muon

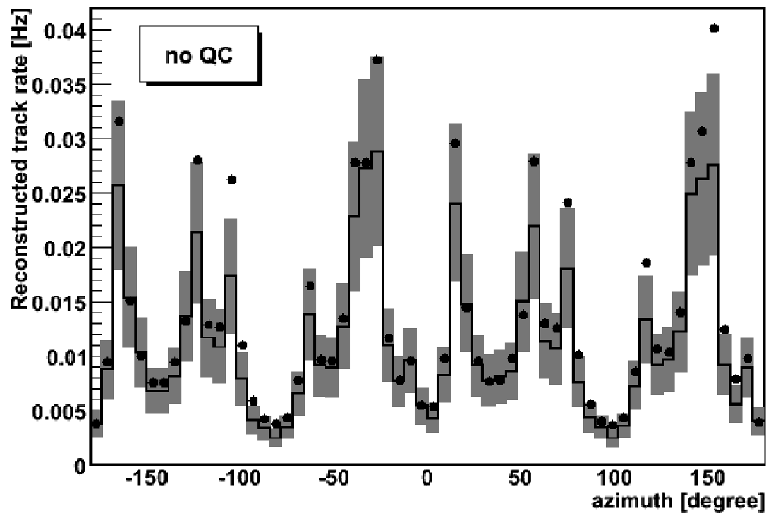


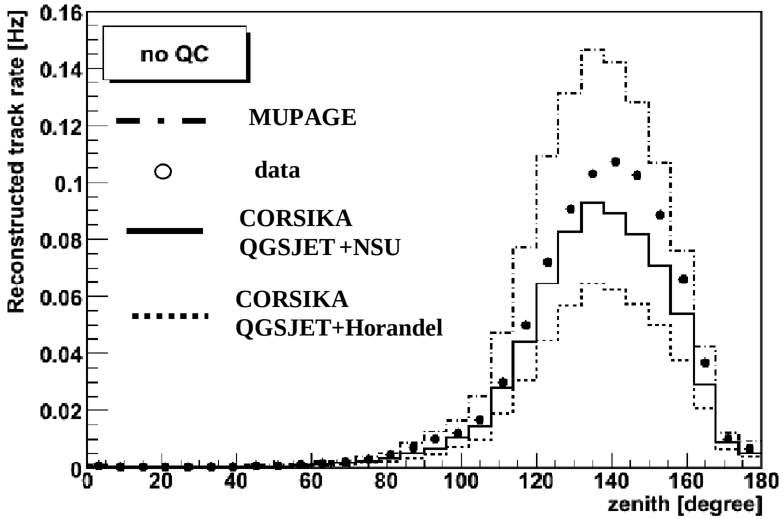
Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:



Downgoing Muons (5-lines)

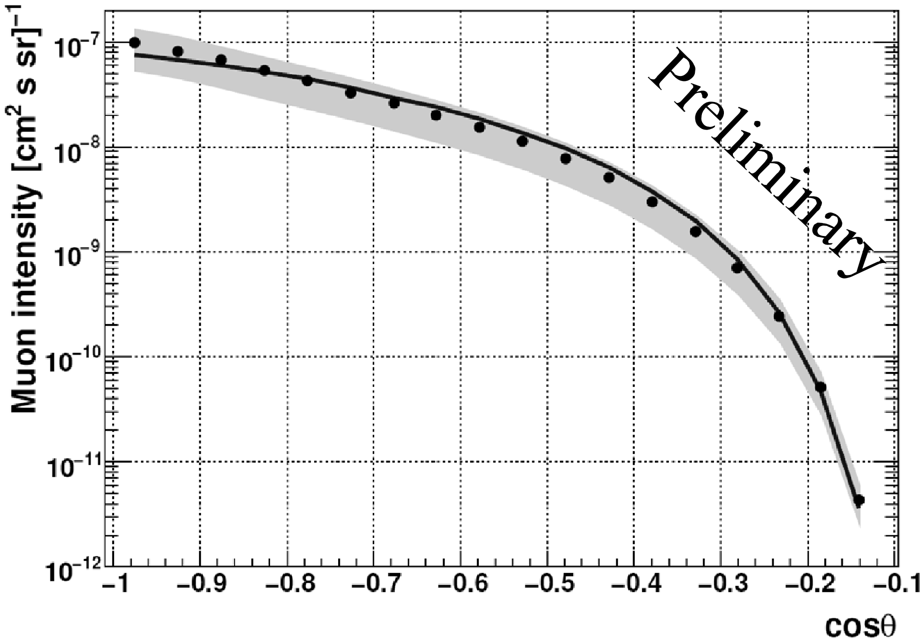


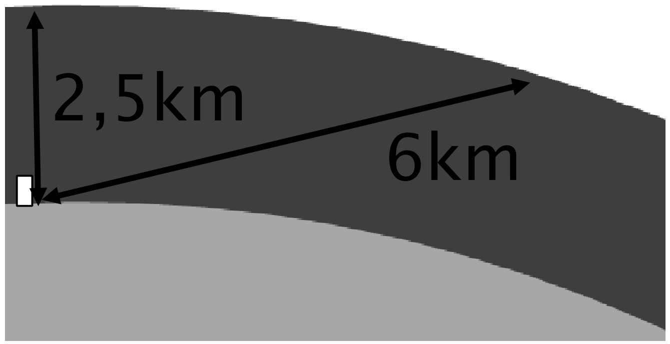


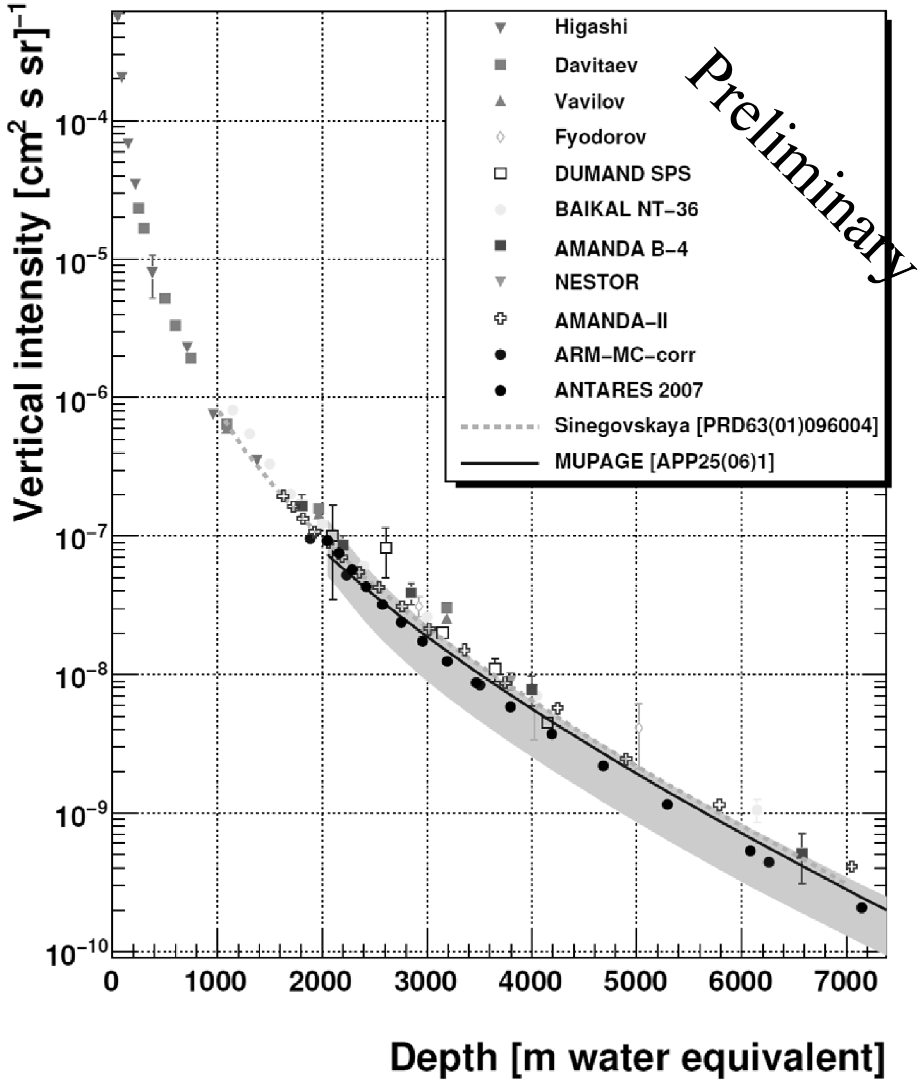


- Agreement within (substantial) theoretical + MC uncertainty
- Main experimental errors stem from OM efficiency and acceptance and optical water properties (λ_{abs} λ_{scatt})

5 lines (2007): Depth vs. Intensity



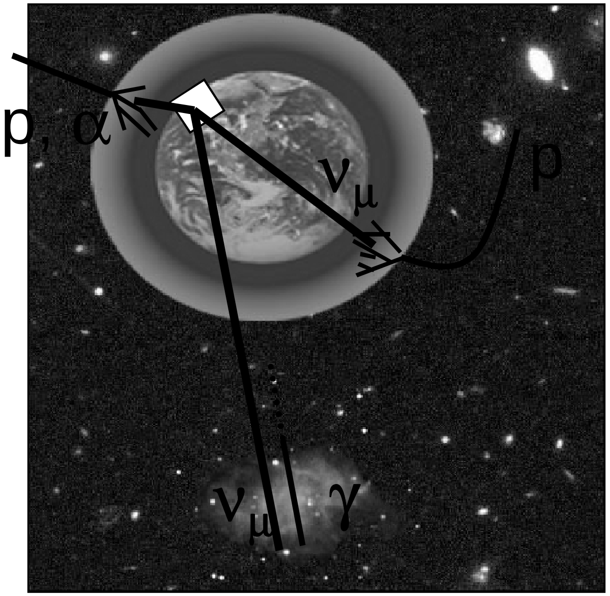


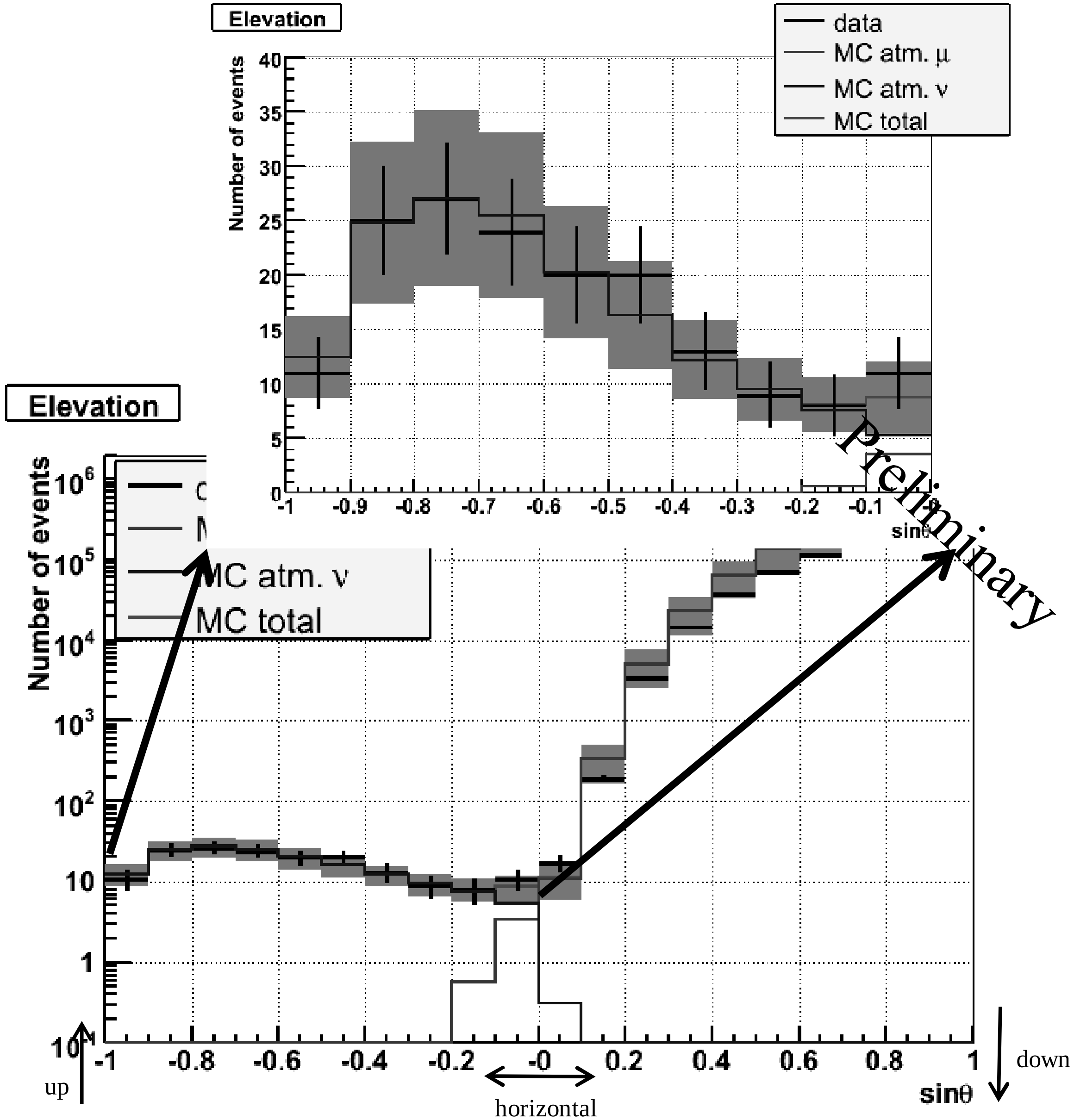


See talk: M. Bazzotti, 8/7/09, HE340

Work on reducing systematics is ongoing

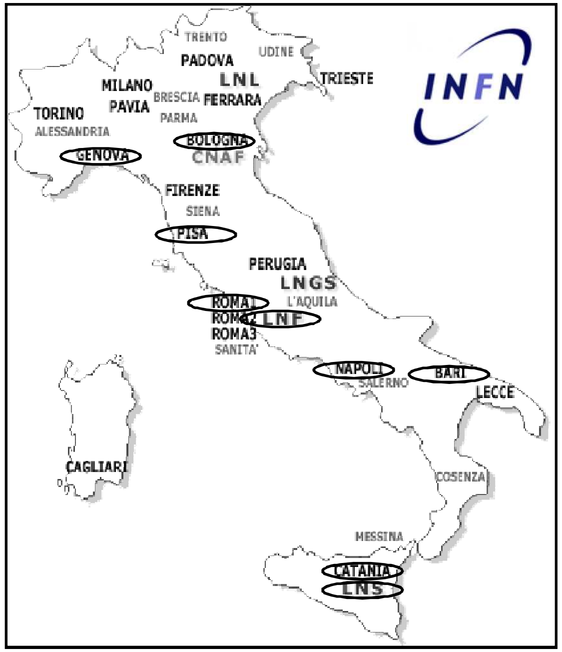
5 line data (2007): NEUTRINOS





168 active days
168 upward events
(multi-line fit)

The NEMO collaboration



INFN

Bari, Bologna, Catania, Genova, LNF, LNS, Napoli, Pisa, Roma

Università

Bari, Bologna, Catania, Genova, Napoli, Pisa, Roma *"La Sapienza"*

CNR

Istituto di Oceanografia Fisica, La Spezia
Istituto di Biologia del Mare, Venezia
Istituto Sperimentale Talassografico, Messina

Istituto Nazionale di Geofisica e Vulcanologia (INGV)

Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS)

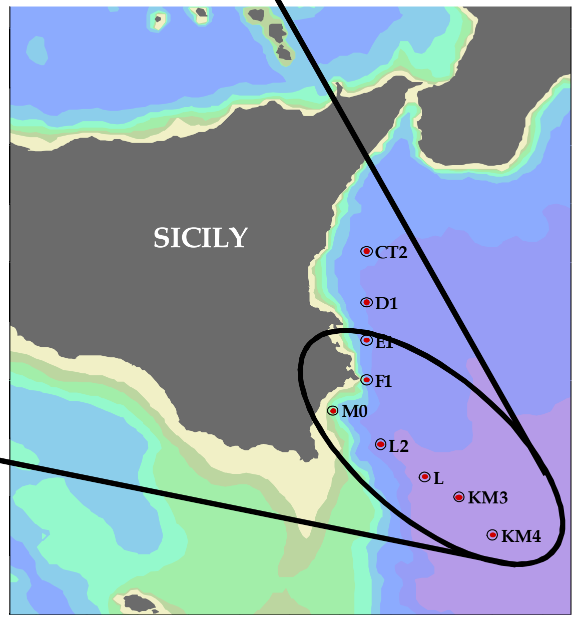
Istituto Superiore delle Comunicazioni e delle Tecnologie dell'Informazione (ISCTI)

More than 70 researchers from INFN and other italian institutes

The NEMO Site

	M0	L2	L	KM3	CP
5	2	2	0	0	0
25	3	2	2	0	0
50	2	2	0	0	0
75	3	0	0	0	0
100	0	4	0	0	0
200		0	0	0	2
300		0	2	0	0
400		0	2	0	0
500		0	2	2	0
600		6	0	0	0
700		0	2	2	2
800		0	3	0	2
900		4	2	12	8
1000		0	0	4	4
1100		0	4	4	0
1200		2	2	6	2
1300		0	0	4	2
1400		0	2	2	0
1500		0	2	0	2
2000		0	0	4	2
2500			0	0	0
3000			0	0	0
3300			0	0	0

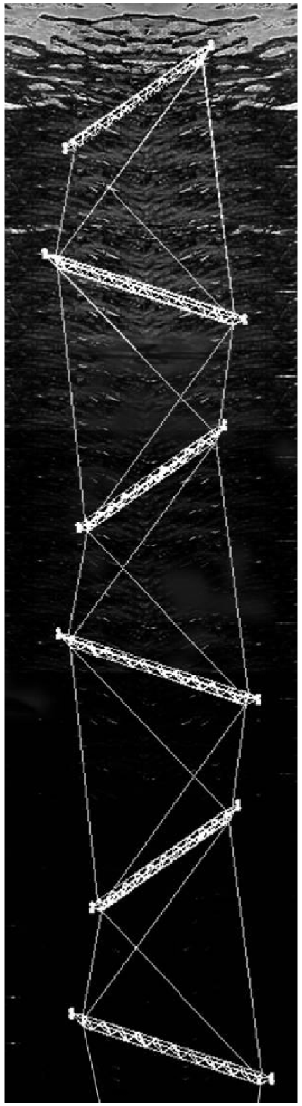
- Depths of 3500 m reached at 100 km from the shore
- Optimal water optical properties (La ≈ 70 m @ λ = 440 nm)
- Low optical backgroung from bioluminescence bacteria
- Stable water characteristics
- Low and stable deep sea water currents (3 cm/s avg., 10 cm/s peak)



- In a six years activity the NEMO collaboration has selected a deep sea site offshore Capo Passero (Sicily) with optimal oceanographycal and environmental properties

- The site has been proposed in january 2003 to ApPEC as a candidate for the km3 intallation

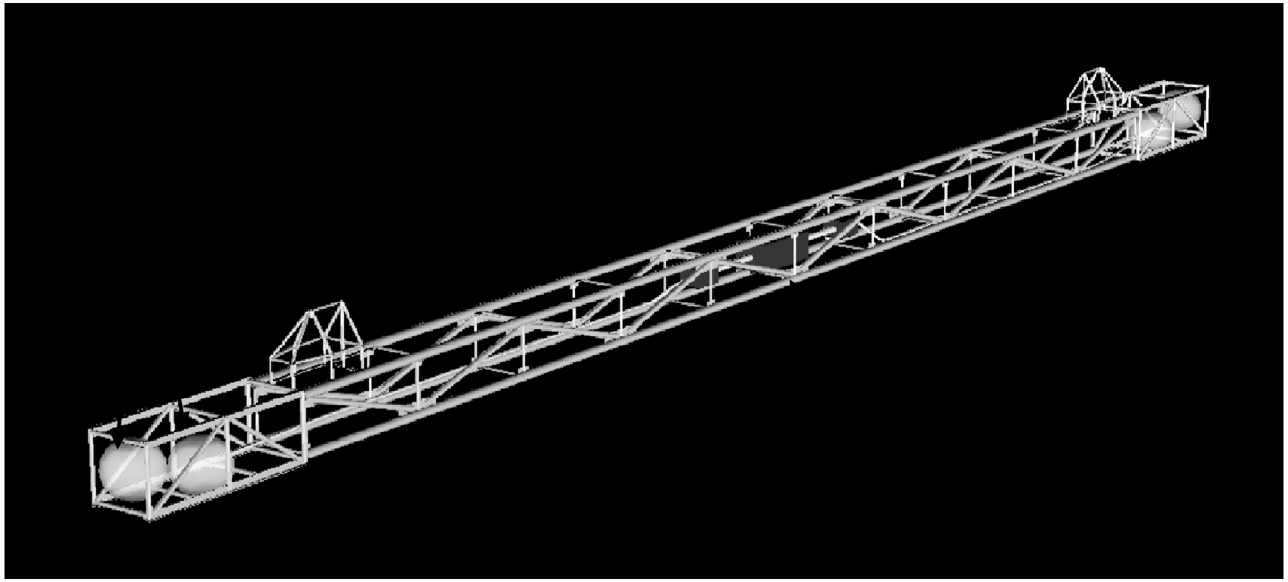
The NEMO "tower"



• Mechanical structures for the km^3 studied in order to optimize the detector performance

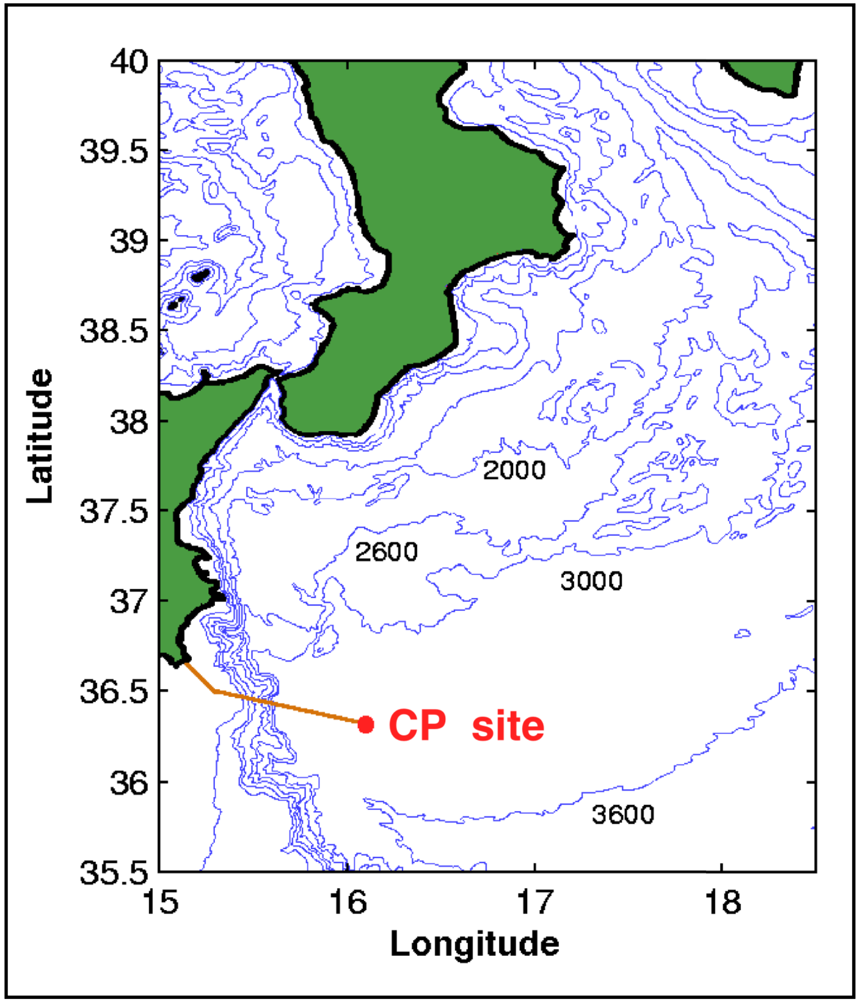
•Modular structure composed by a sequence of 15 m long storeys interconnected by tensioning cables. Full height 750 m.

•Power and data cables are kept separated from the tensioning ones



The NEMO Phase 2 project

A deep sea station on the Capo Passero site



OBJECTIVES

- Realization of an underwater infrastructure at 3500 m on the CP site
- Test of the detector structure installation procedures at 3500 m
- Installation of a 16 storey tower
- Long term monitoring of the site

INFRASTRUCTURE UNDER CONSTRUCTION

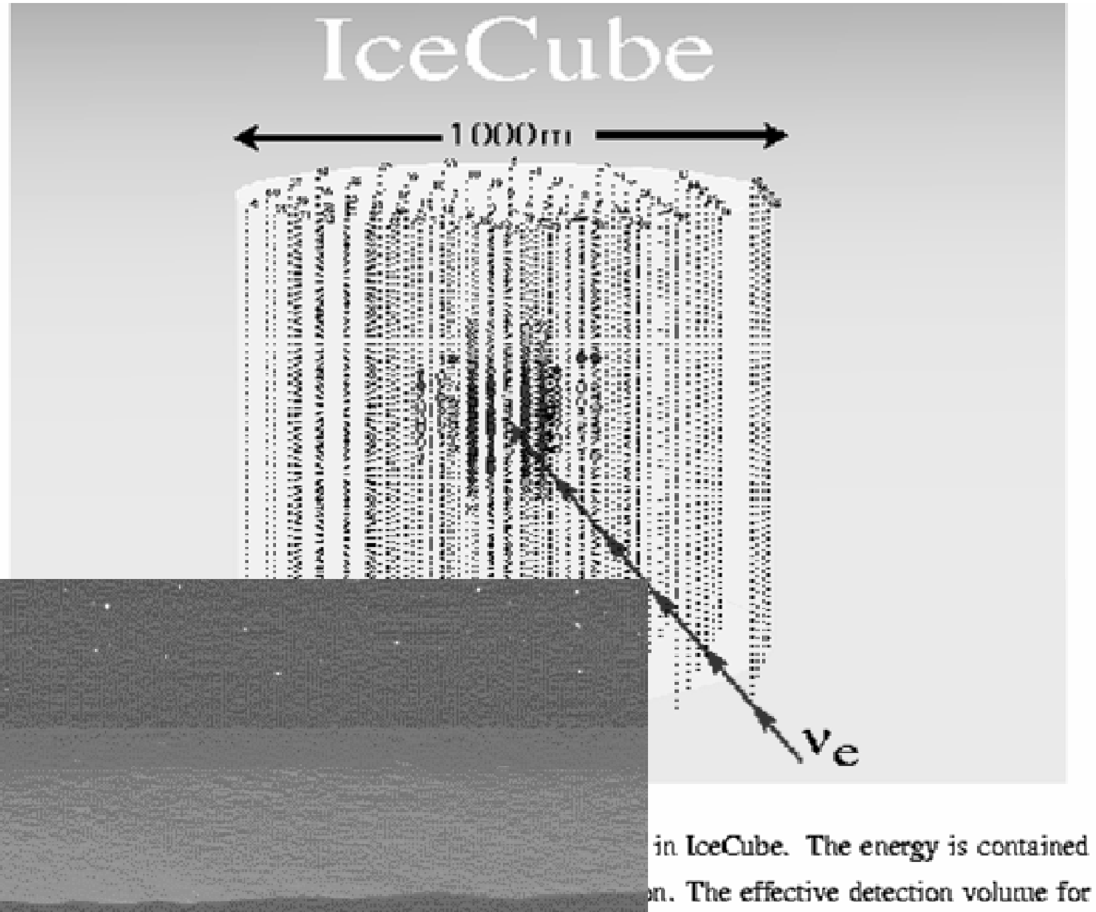
- Shore station in Portopalo di Capo Passero
- 100 km electro optical cable
- Underwater infrastructures

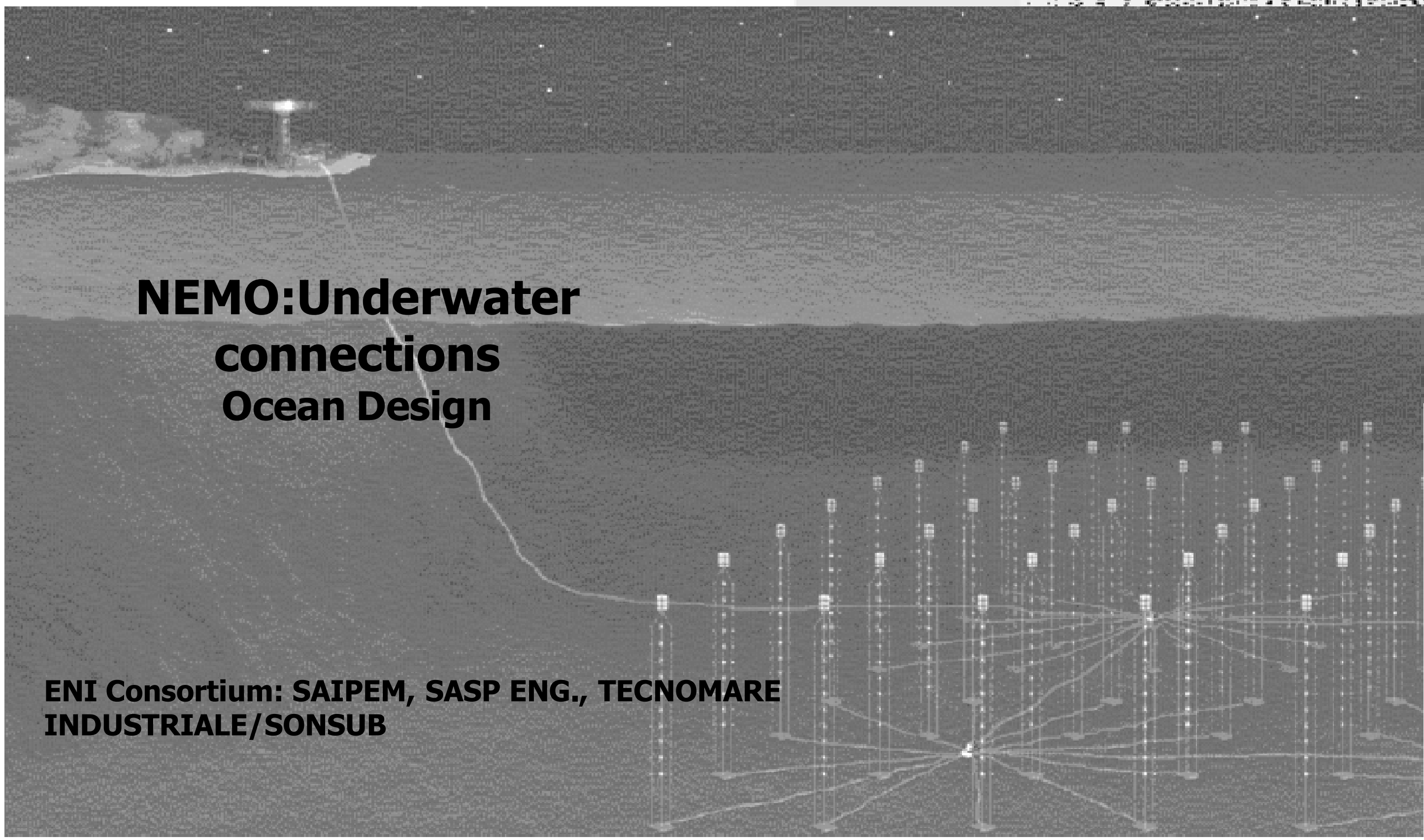
STATUS

- Purchase of the electro-optical cable (>50 kW) under way
- A building (1000 m^2) located inside the harbour area of Portopalo has been acquired. It will be renovated to host the shore station
- Project completion planned in 2008

View of the cable landing area

Icecube/ KM3


IceCube
1000m
ν_e
in IceCube. The energy is contained
n. The effective detection volume for


NEMO:Underwater connections
Ocean Design
ENI Consortium: SAIPEM, SASP ENG., TECNOMARE INDUSTRIALE/SONSUB

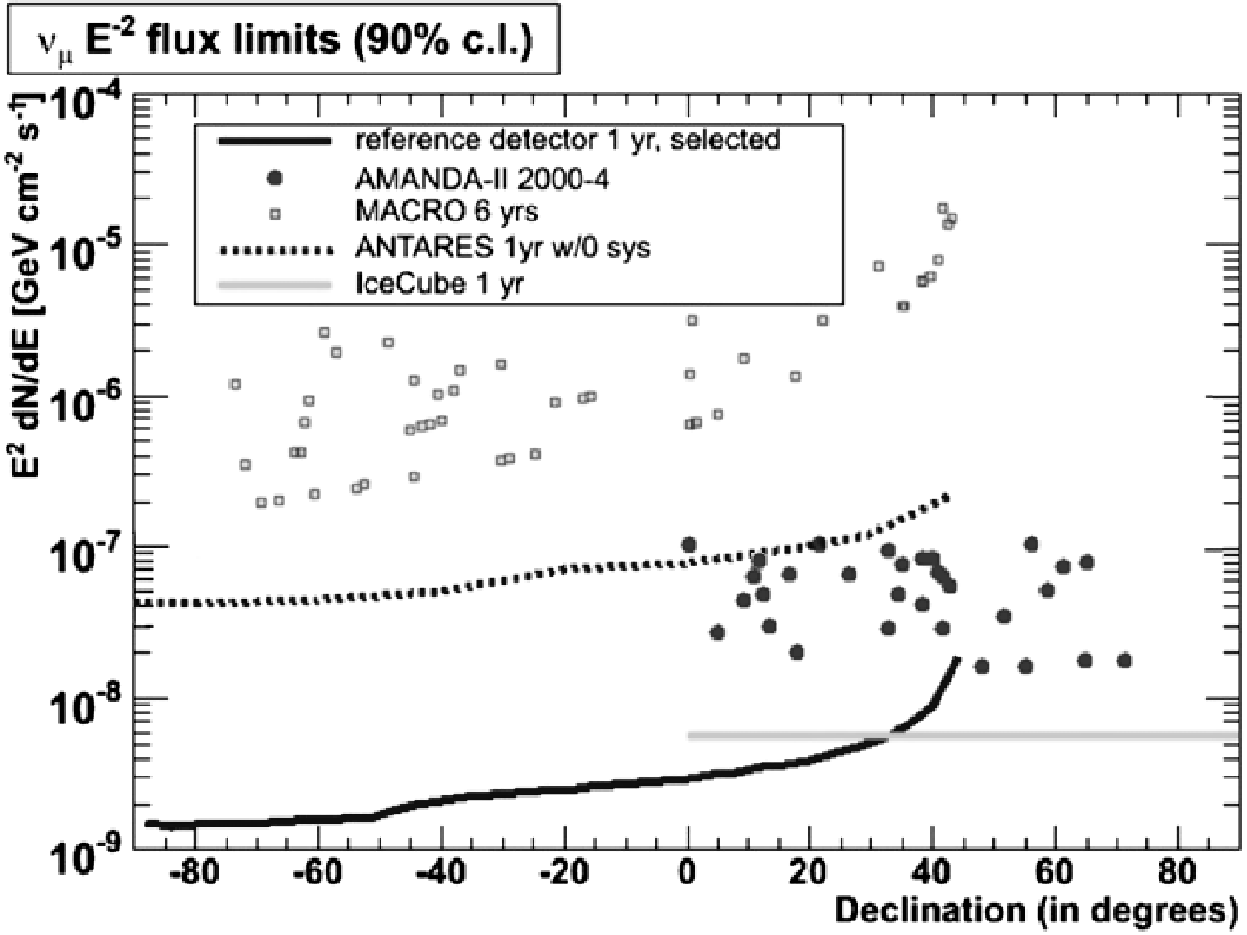
KM3NeT

- Consortium between the Institutes that developed and support the pilot projects in the Mediterranean
  - 40 Institutes from 10 EU Countries (Cyprus, France, Germany, Greece, Ireland, Italy, The Netherlands, Rumania, Spain, U.K.)
- Large European Research Infrastructure, included in the ESFRI roadmap
- Design Study project (under the 6th FP)
  - 3 year project started in 2006 funded by the EC for 9 M€
  - Conceptual Design Report Published in 2008, TDR in 2009
- Preparatory Phase project (under the 7th FP)
  - 3 year project started in 2008 funded by the EC for 5 M€
  - Coordinated by INFN

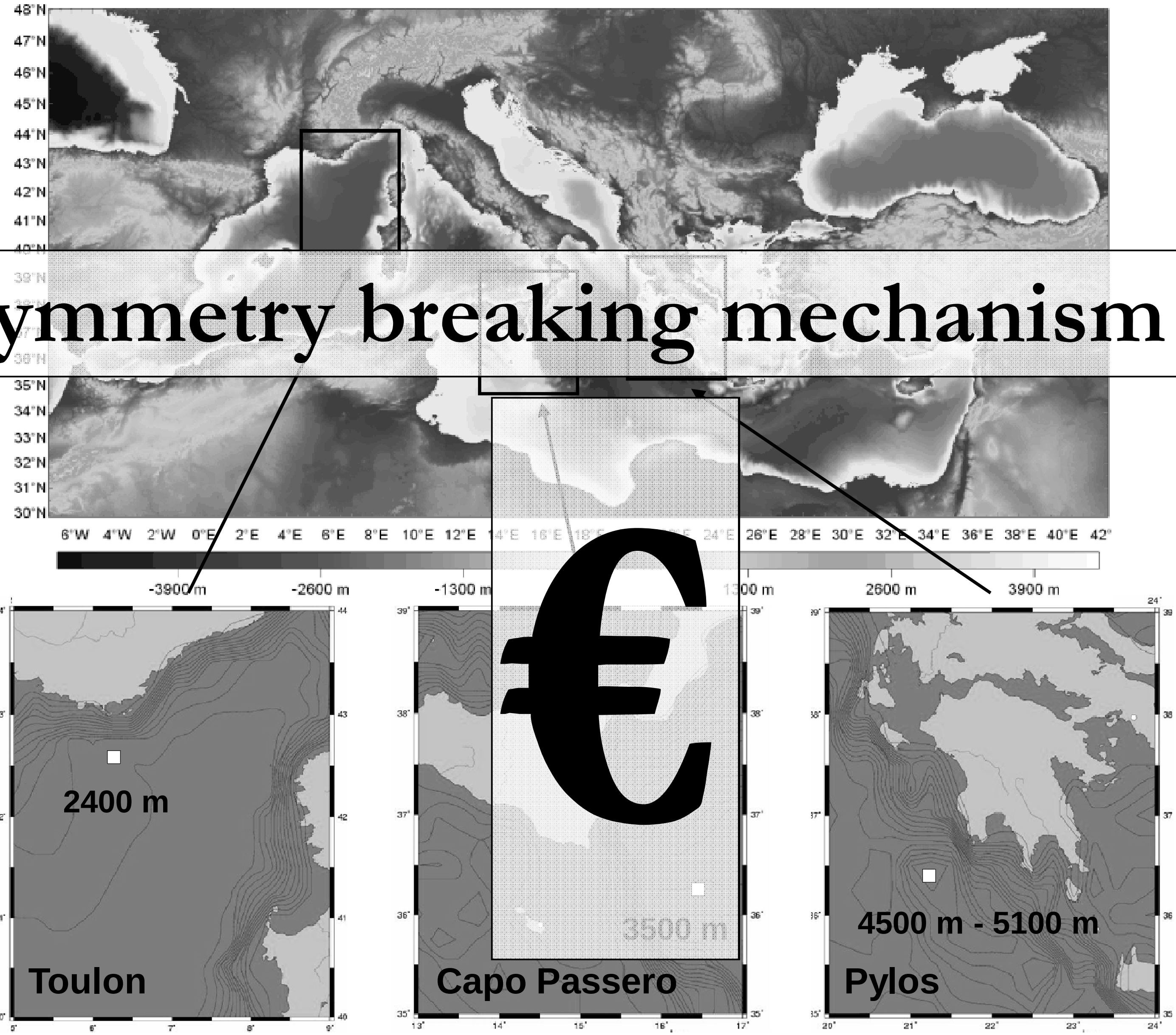
KM3neT reference detector

Factor ~3 more sensitive than IceCube
- – larger photo-cathode area
- – better direction resolution

- Study still needs refinements



Symmetry breaking mechanism



Summary

- All calculations show that we need km3scale detectors for neutrino astronomy
- Compelling scientific arguments for neutrino astronomy and the construction of large neutrino telescopes
- It is essential to complement IceCube (South Pole) with a km3 scale neutrino telescope in Northern Hemisphere
- Joint effort of ANTARES, NEMO and NESTOR to realize such a detector in the Mediterranean Sea
- EU funded KM3NeT Design Study (2006–2009) is well on its way
- Cost: order of 100-200 M€