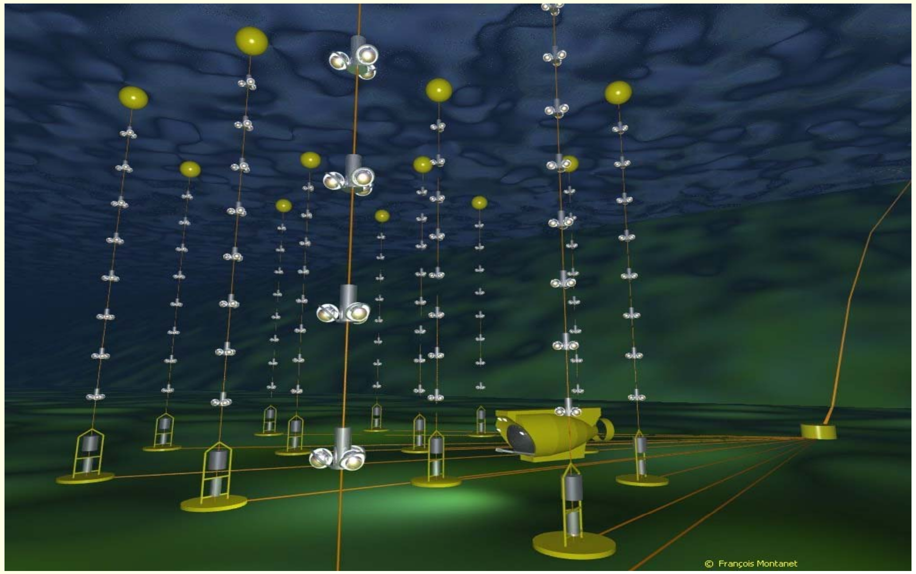
High-Energy Neutrino Astronomy with the ANTARES Deep-Sea Cherenkov detector

Antonio Capone, University "La Sapienza" and I.N.F.N. Roma, Italy

presented at the

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile 2011

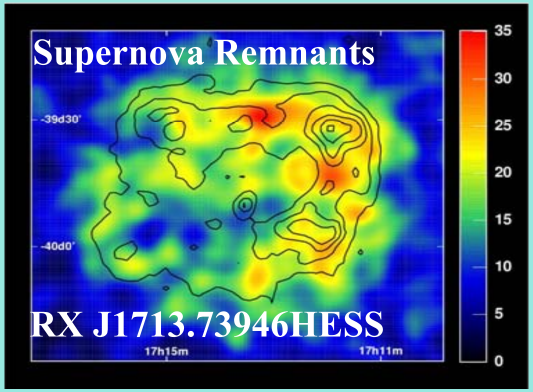


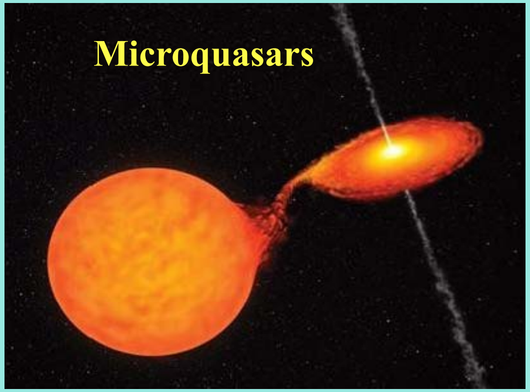
Outline

- Physics with deep under-water/ice Neutrino Telescopes
- The ANTARES Neutrino Telescope in Mediterranean Sea :
  - the detector
  - physics goals
  - data and first results

Point-like cosmic Neutrino Sources

Galactic

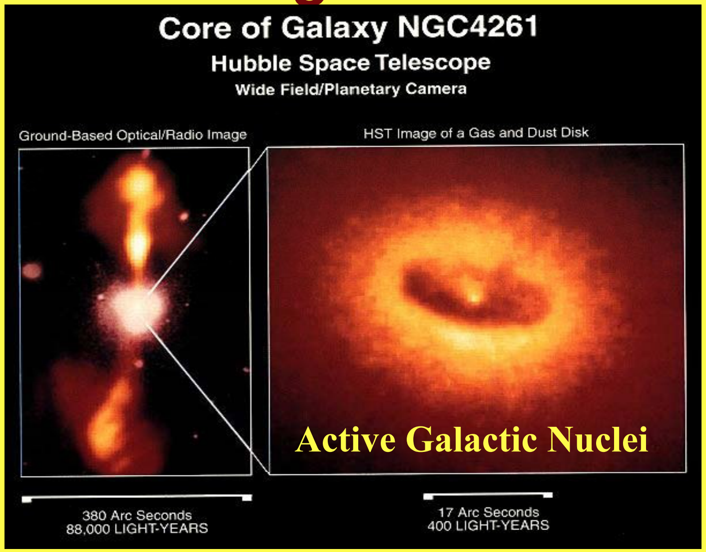


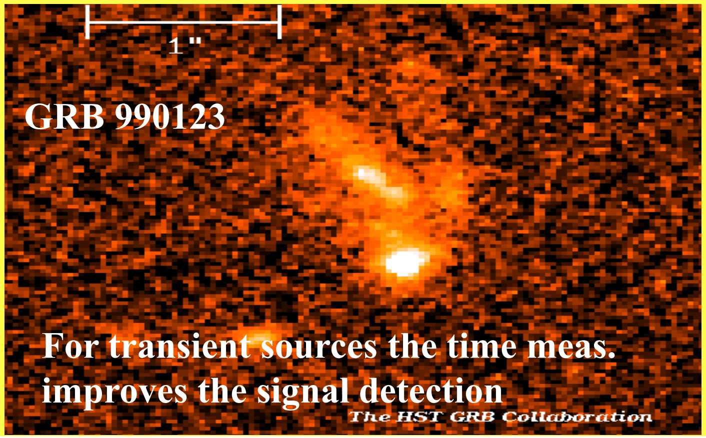


Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \leq 0.5° \text{ for } E_\nu \geq 1 TeV$$

Extragalactic





Experimental signal : statistical evidence of an excess of events coming from the same direction

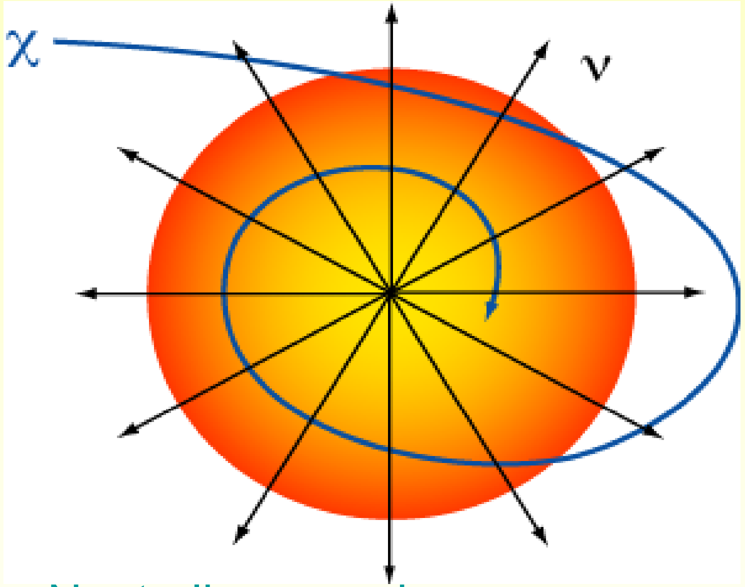
Diffuse Cosmic Neutrino Sources

- Unresolved AGN
- Neutrinos from "Z-bursts"
- Neutrinos from "GZK like" proton-CMB interactions
- Neutrinos foreseen by Top-Down models
- ….

Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at very high energies (E_μ > TeV) and implies energy reconstruction.

… also open problems in particle physics …

- Dark Matter searches:
  - Neutralino annihilation in Sun, Earth, Center
- Monopoles
- Acceleration mechanisms
- Neutrino interaction Cross sections
- …



Neutralino search: $\chi\chi \rightarrow \nu + \ldots$

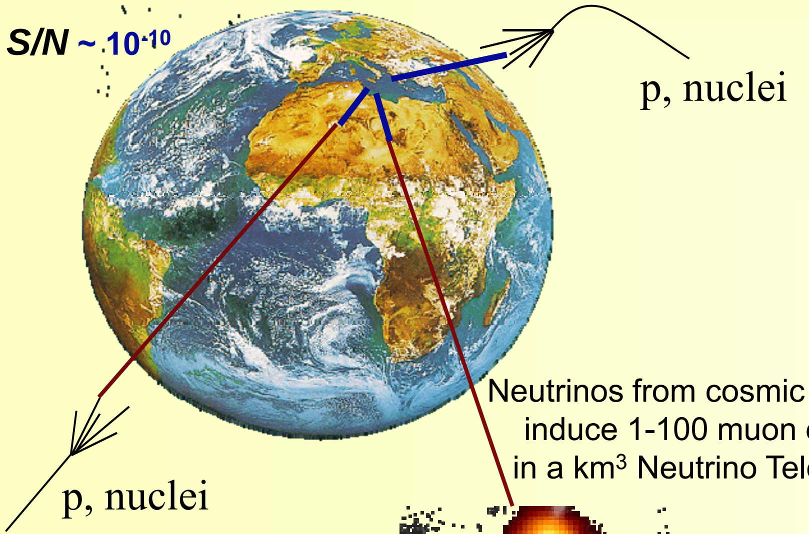
Detection principle

Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater

Down-going μ from atm. showers

$\mu_{upgoing} / \mu_{atm}$ **~ 10^{-6} at 3500m w.e. depth**

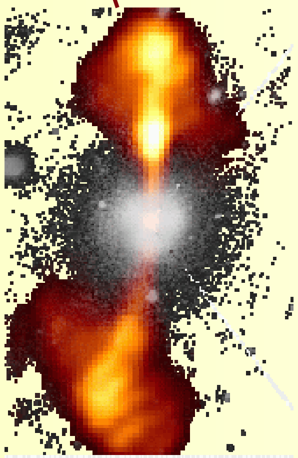
***S/N* ~ 10^{-10}**



Neutrinos from cosmic sources induce 1-100 muon evts/y in a km³ Neutrino Telescope

Up-going μ from neutrinos generated in atm. showers

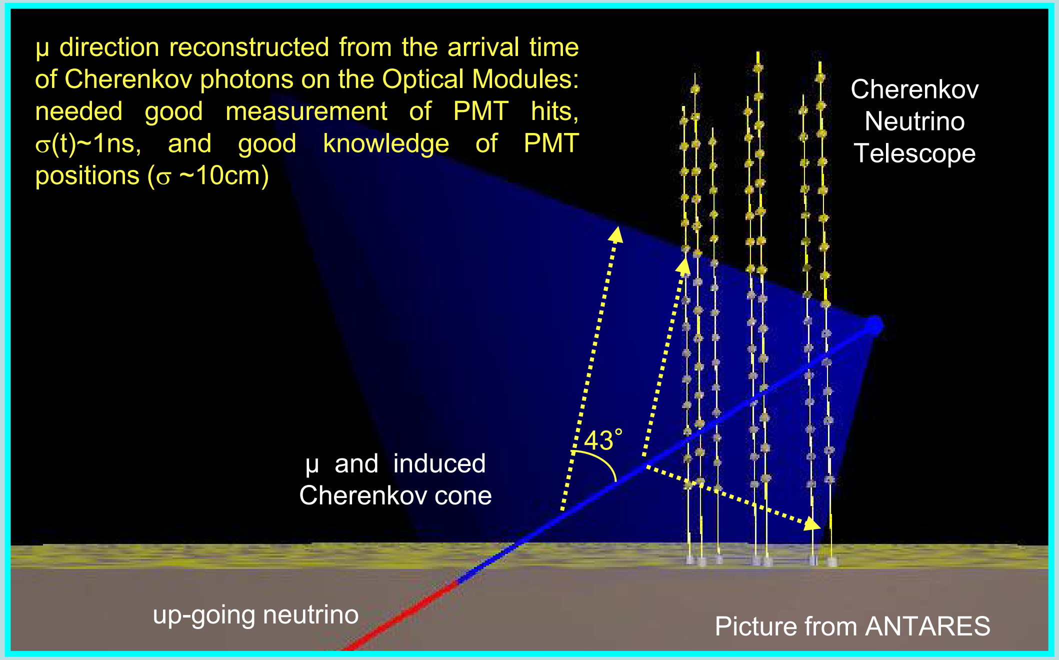
***S/N* ~ ν_{astro} / ν_{atm} ~ 10^{-4}**



- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

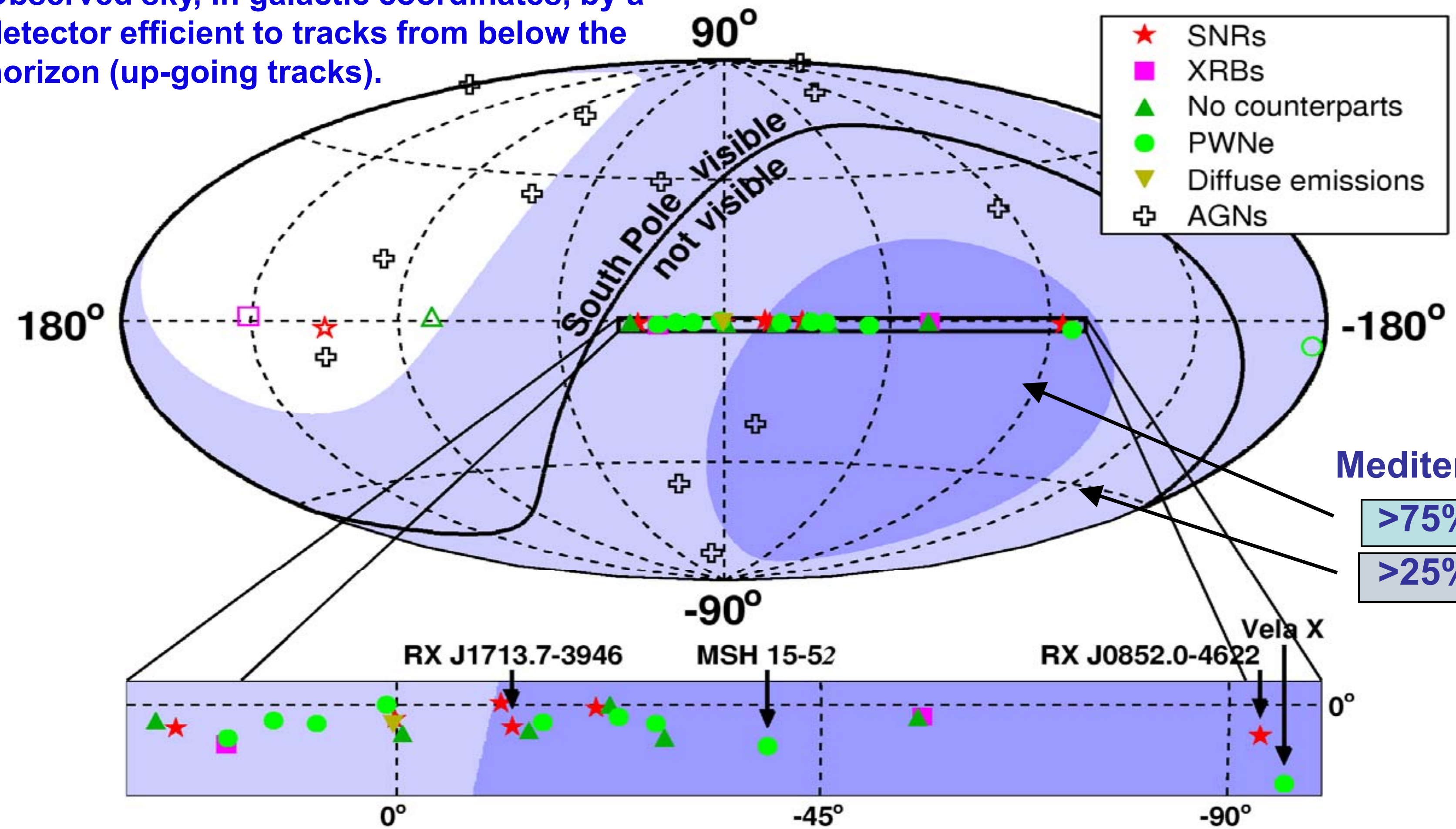
- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$For\ E_\nu \geq 1TeV \quad \theta_{\mu\nu} \sim \frac{0.7^\circ}{\sqrt{E_\nu[TeV]}}$$



Mediterranean Sea ν Telescope Sky Coverage

Observed sky, in galactic coordinates, by a detector efficient to tracks from below the horizon (up-going tracks).



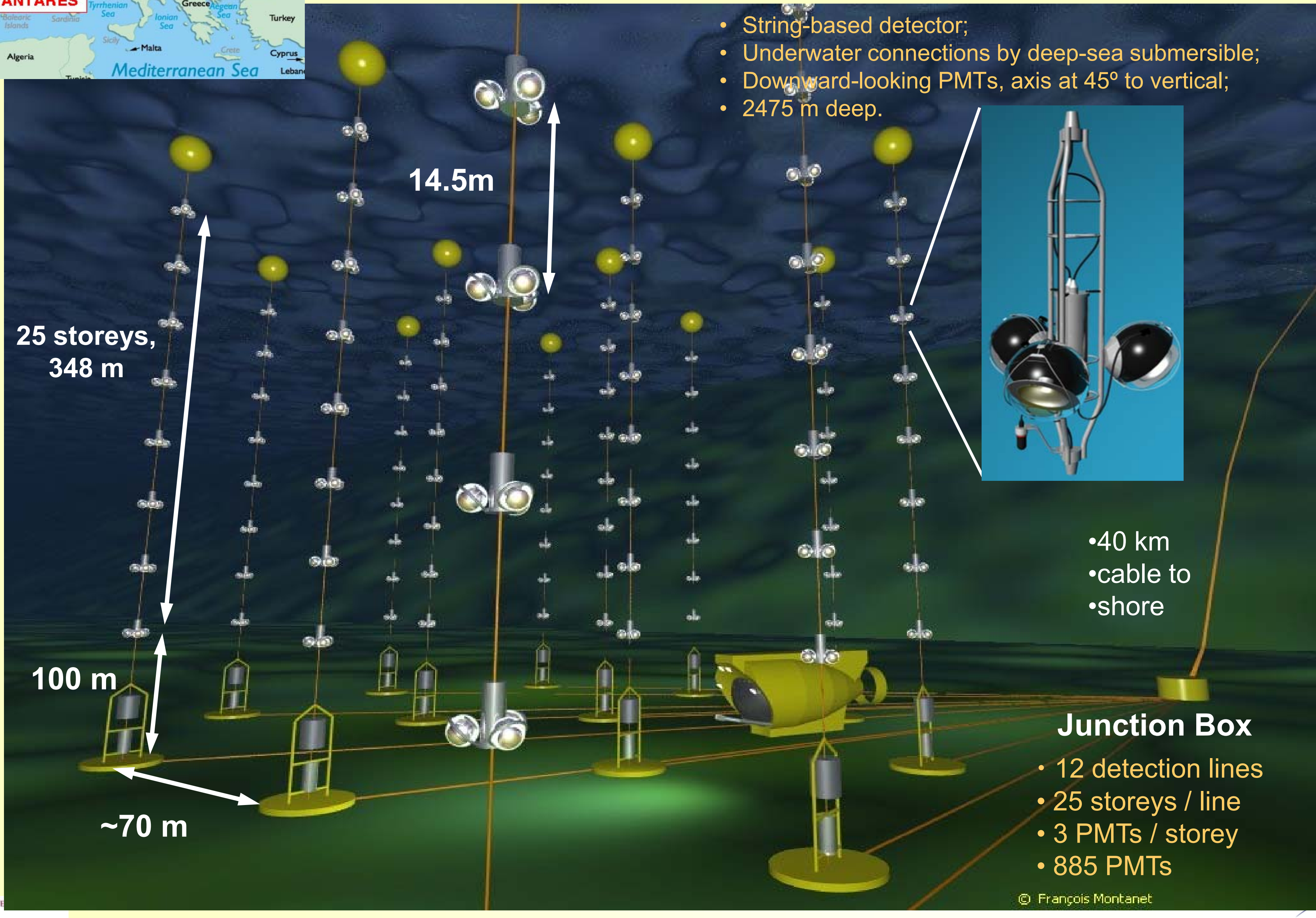
Mediterranean site:

>75% visibility

>25% visibility

→ We need a km^3 Northern ν Telescope to observe the Galactic Plane

The ANTARES experiment



- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMTs, axis at 45º to vertical;
- 2475 m deep.

- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

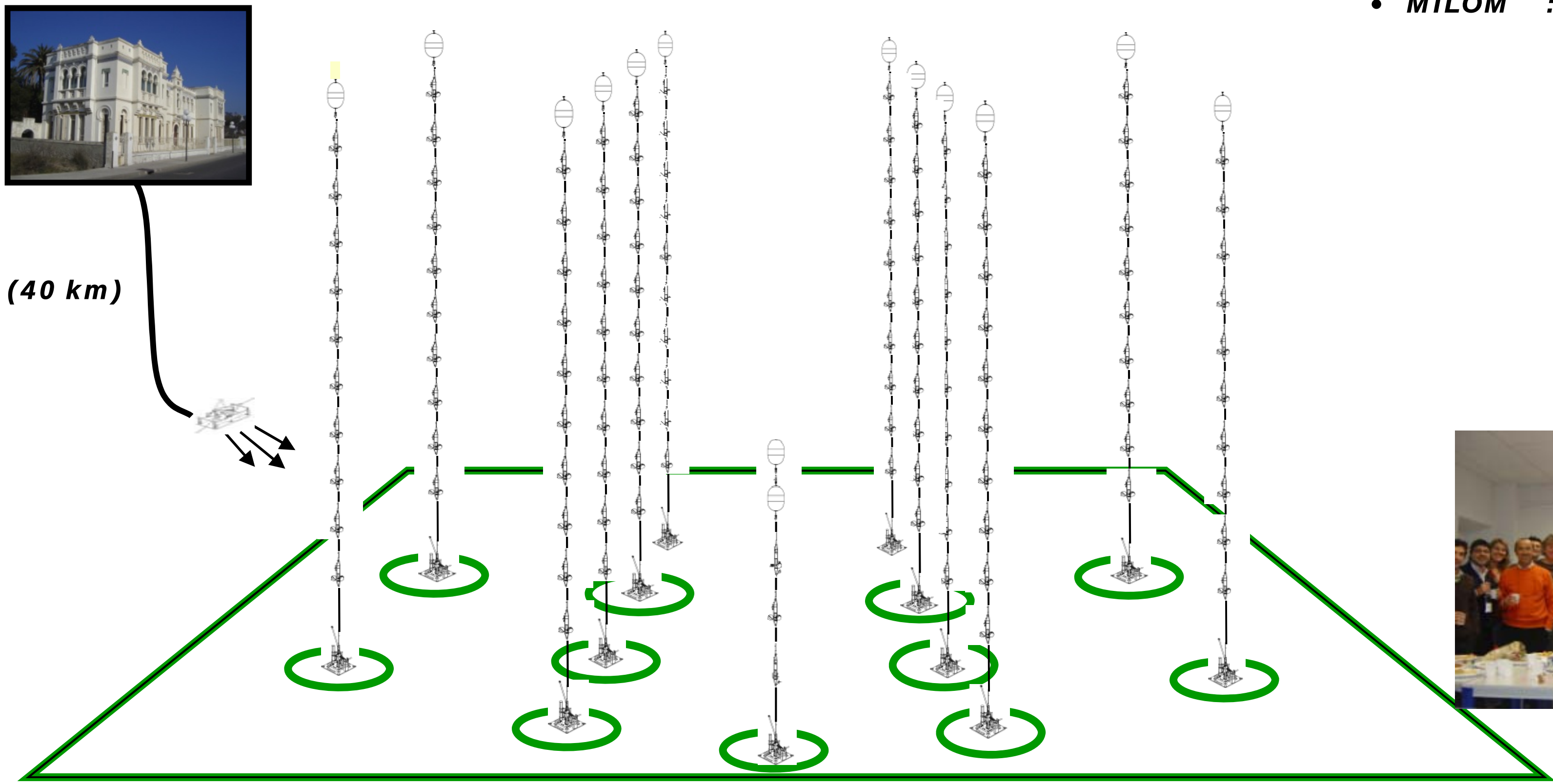
Deployment

Data taking periods:

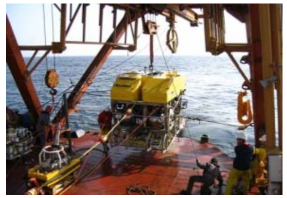
- ***MILOM : Mar '05 – Mar '06***

La Seyne-sur-Mer

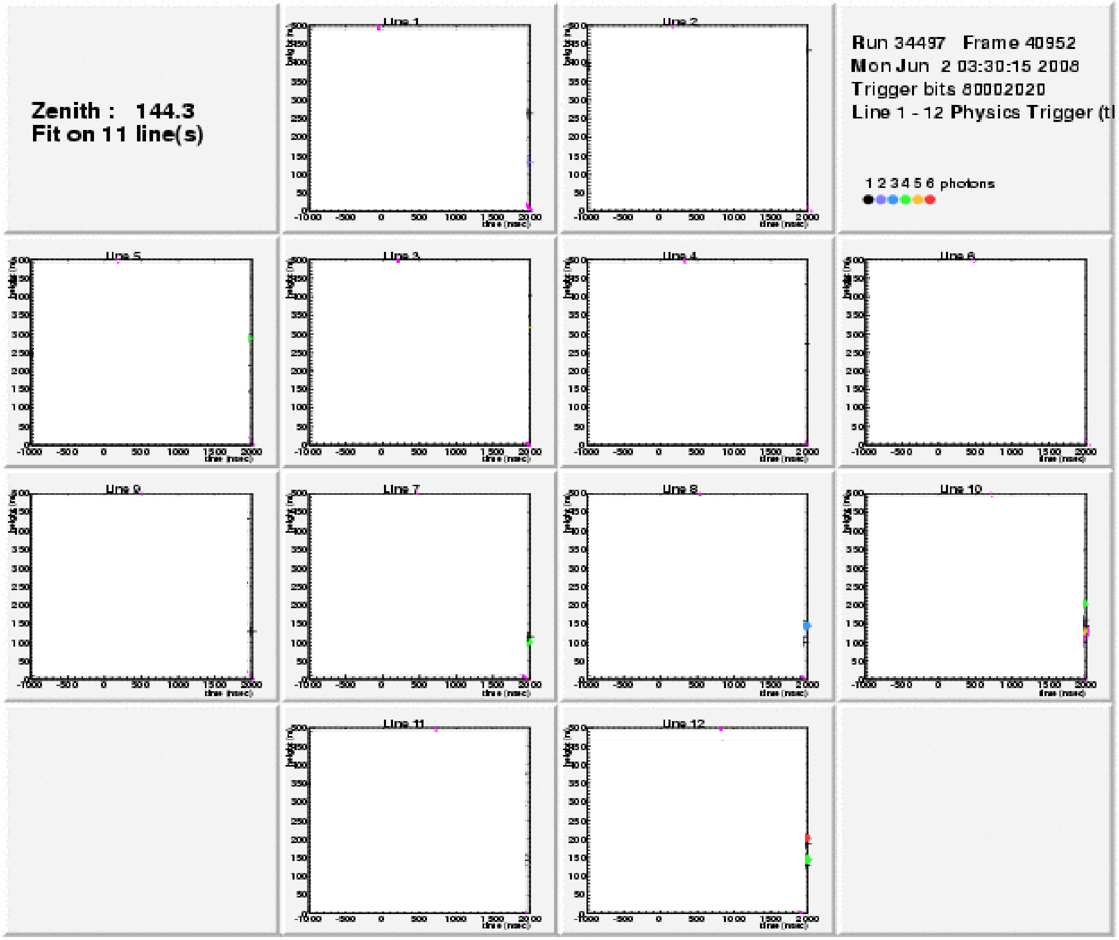
(40 km)



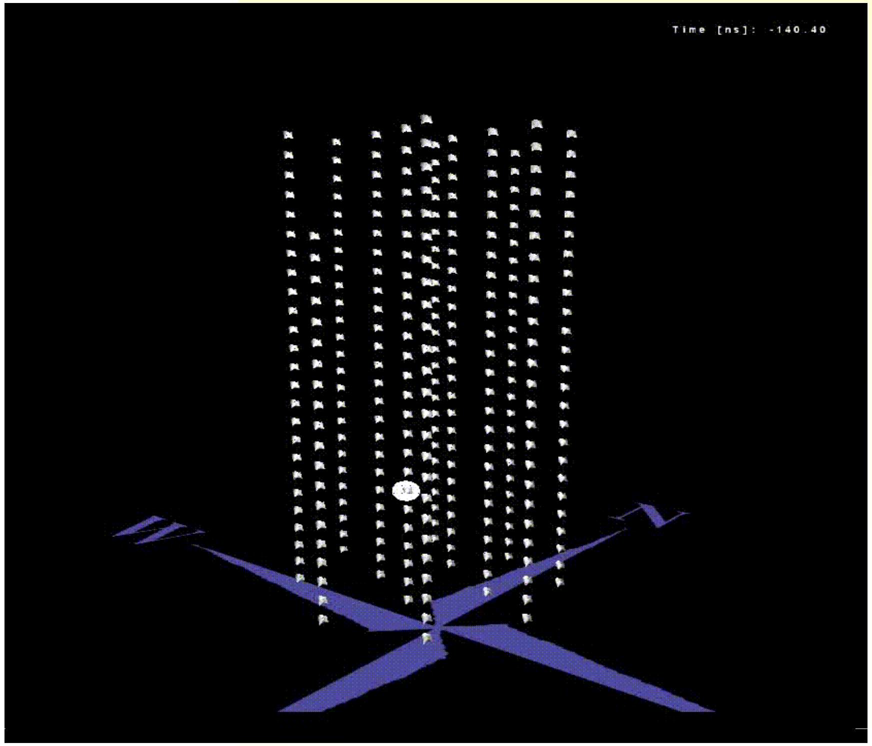
(2.5 km depth)



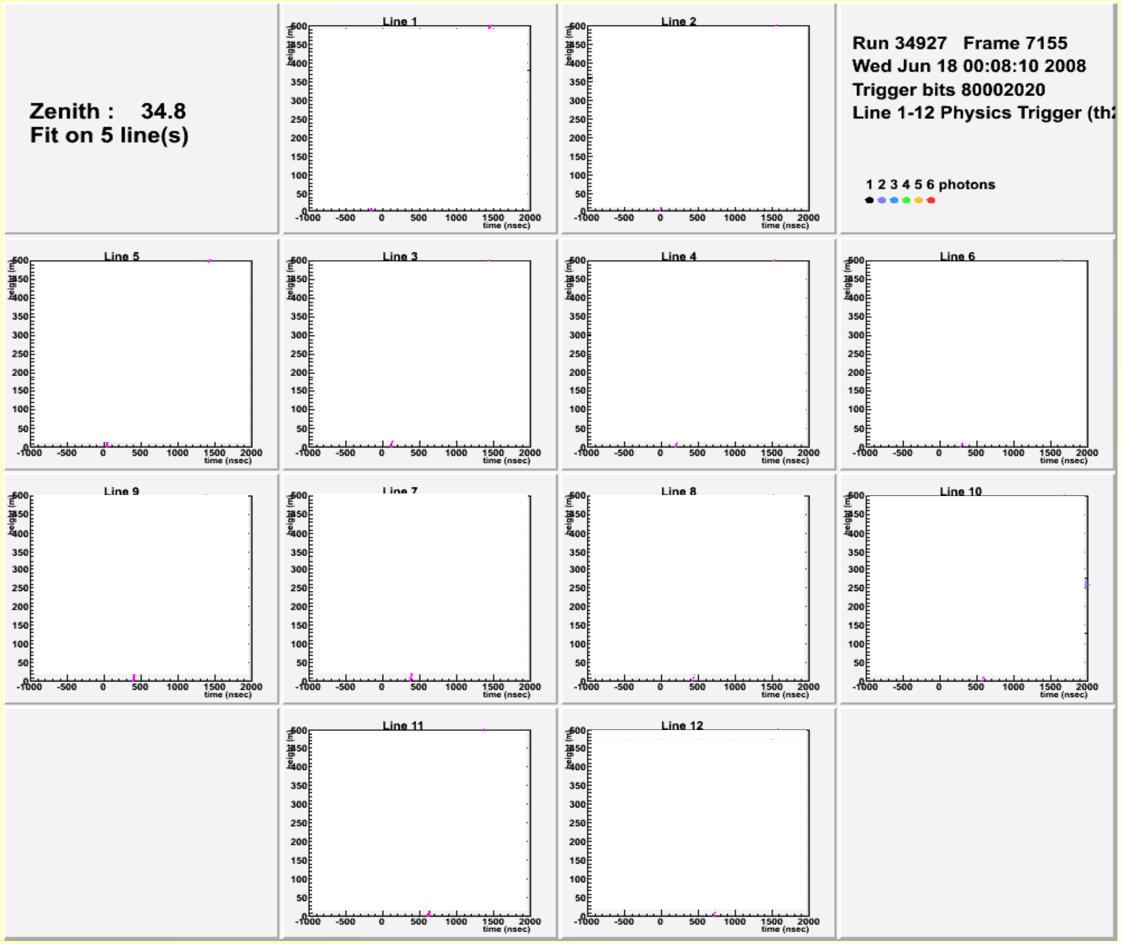
(multi-) muon Event



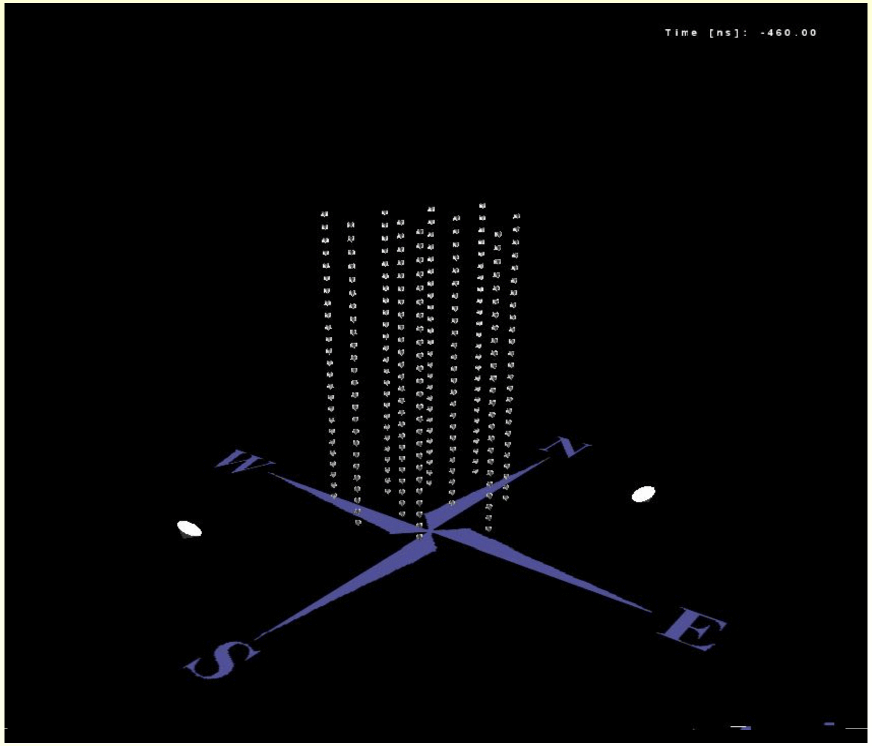
Example of a reconstructed down-going muon, detected in all 12 detector lines:



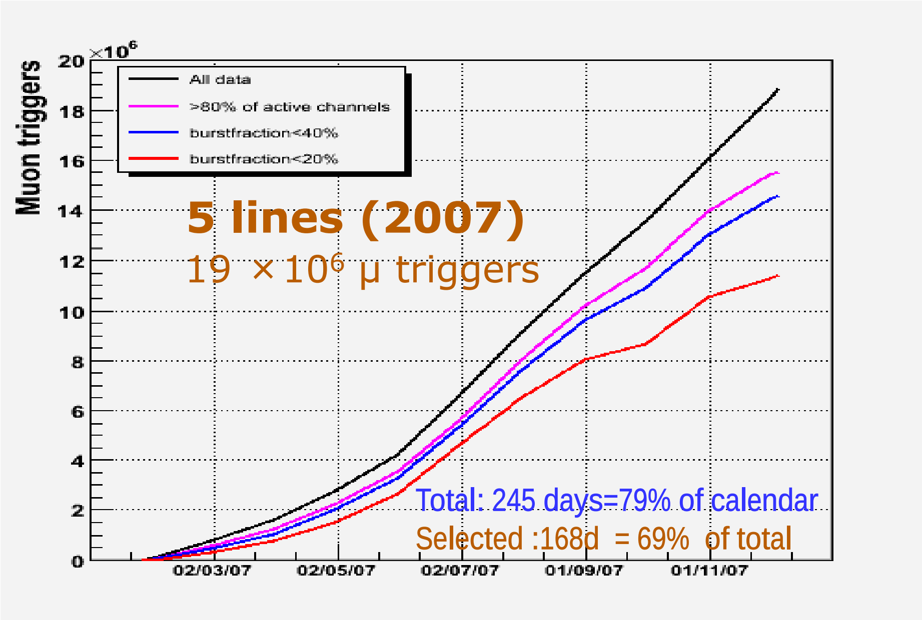
Up-going track: a neutrino candidate

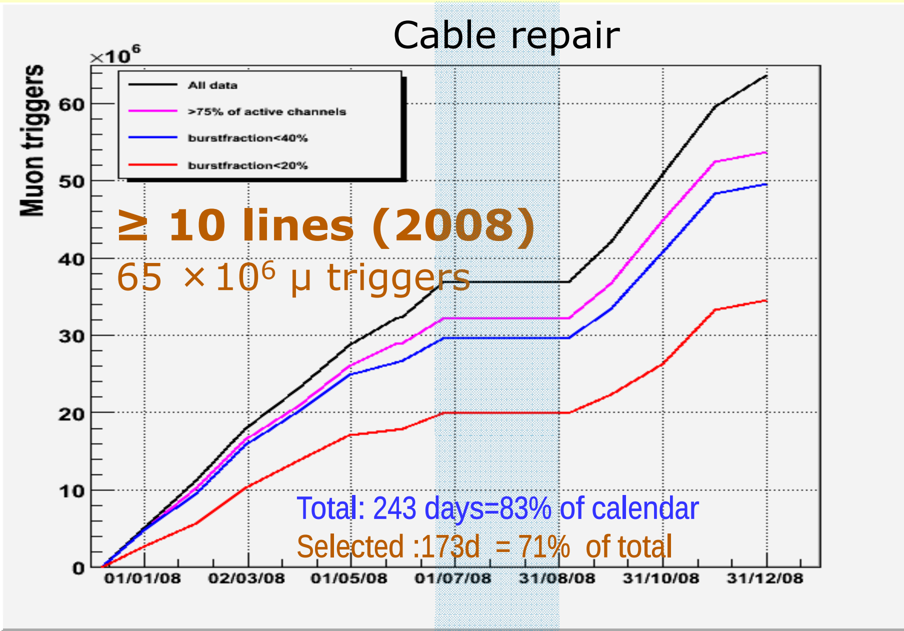


Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:



Accumulated data



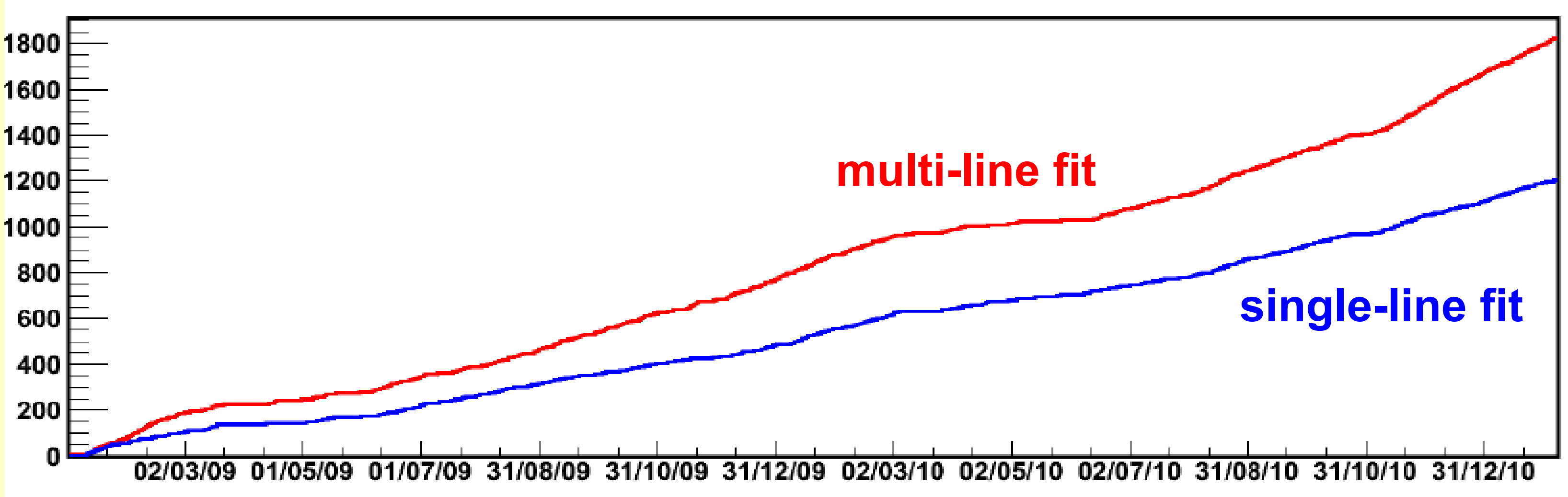


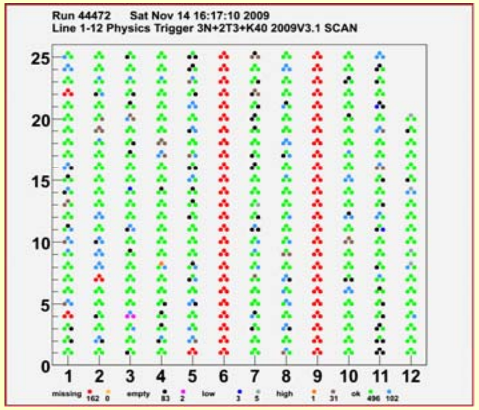
2007: 5 lines
245 days of data taking (79% of calendar)
selected 168 days (69% of total)
detected 168 upgoing neutrino events

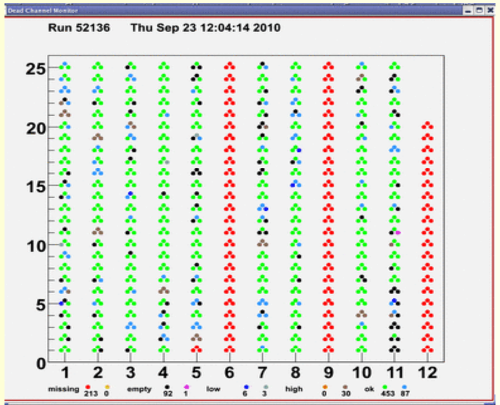
2008: 9 lines
173 days of data taking (83% of calendar)
selected 173 days (71% of total)
detected 800 upgoing neutrino events

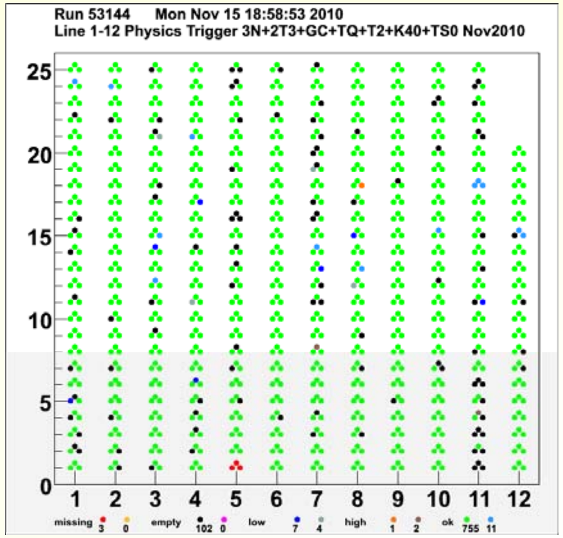
Accumulated data since 01/01/2009

Up-going tracks: "neutrinos", reconstructed with multi-line or single-line fit





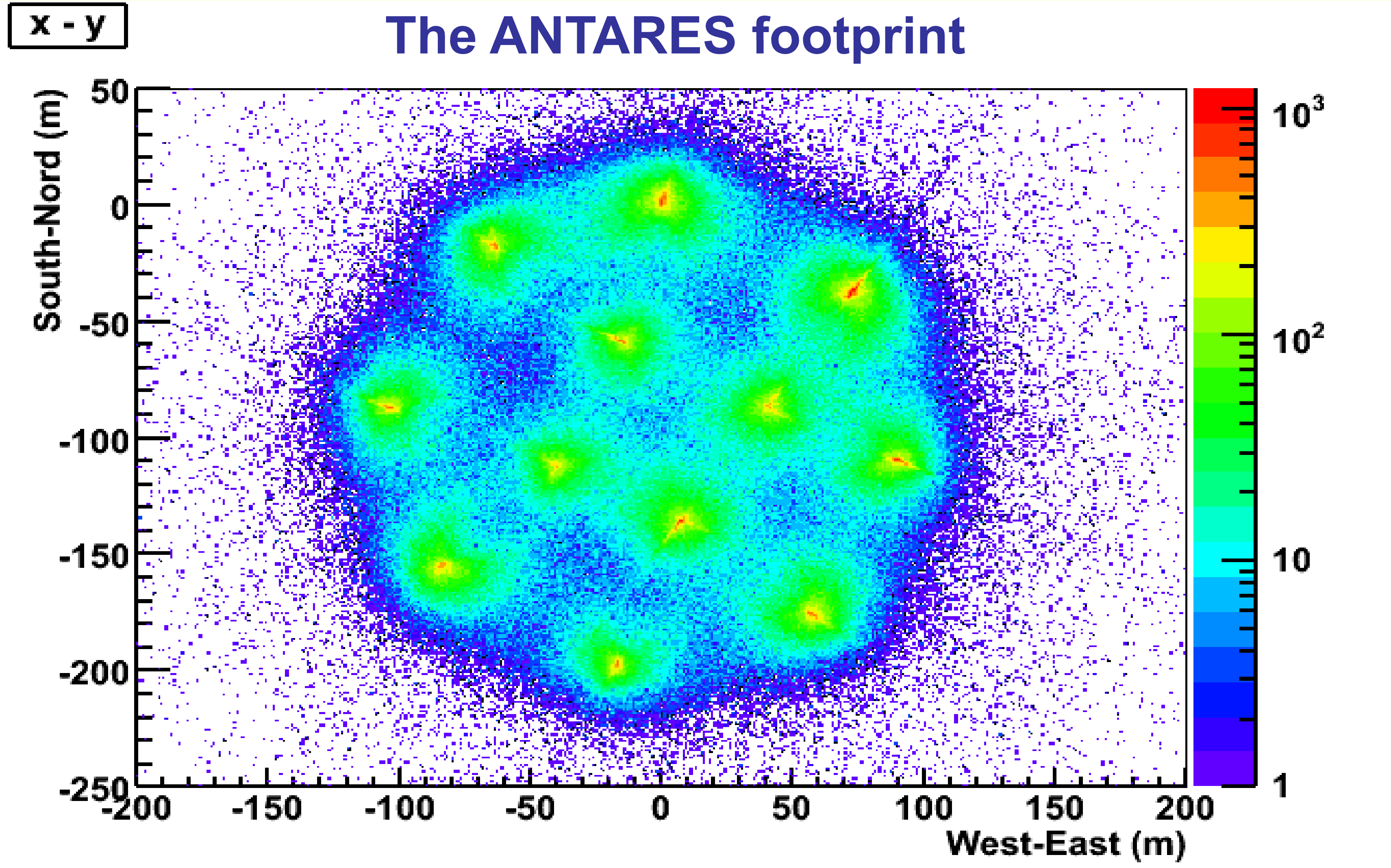




2009 → today ≥ 9 lines

> 1800 neutrino candidate events (3 ν_{atm} per day)

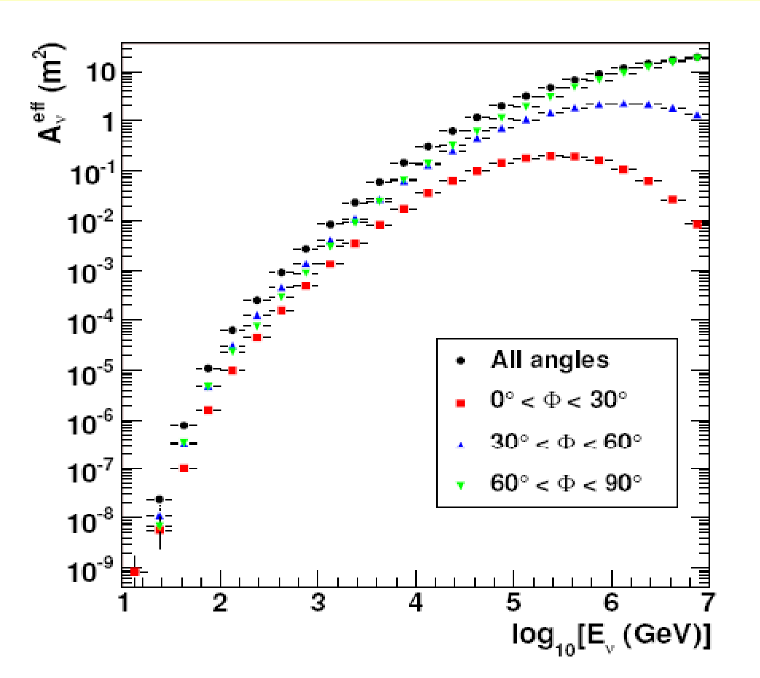
ANTARES "muon tomography"



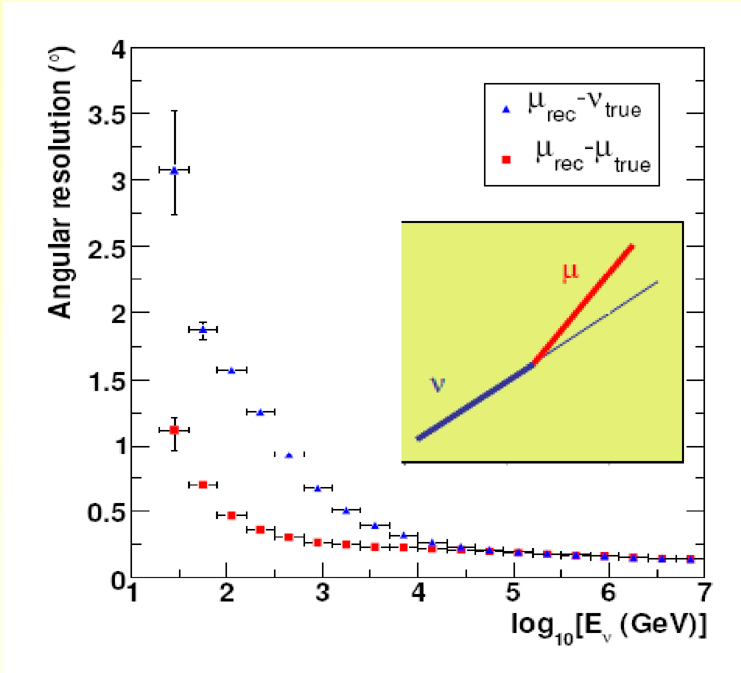
Positions of reconstructed tracks of atmospheric muons at time of first triggered hit

Expected Performances (full detector)

Neutrino effective area



Angular resolution

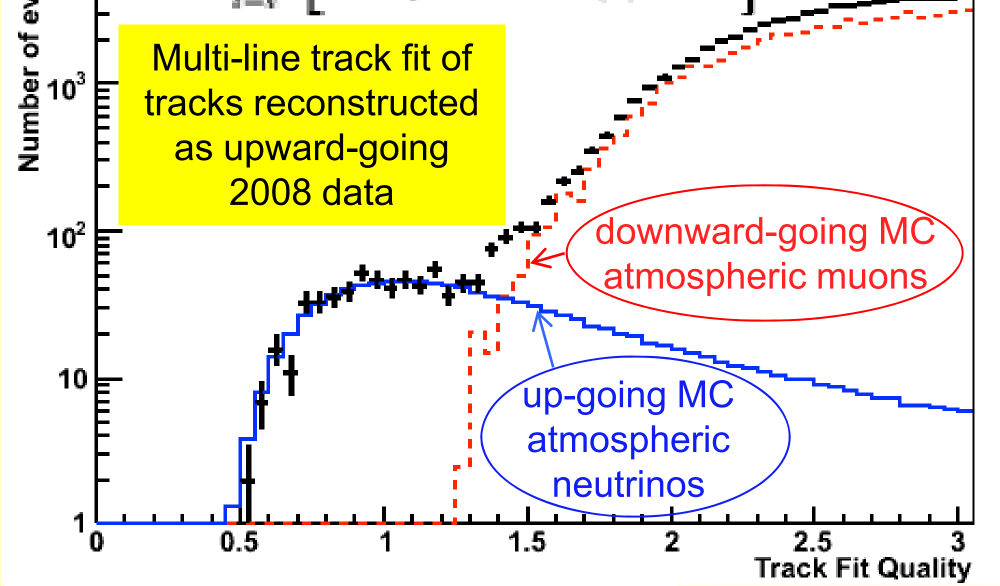


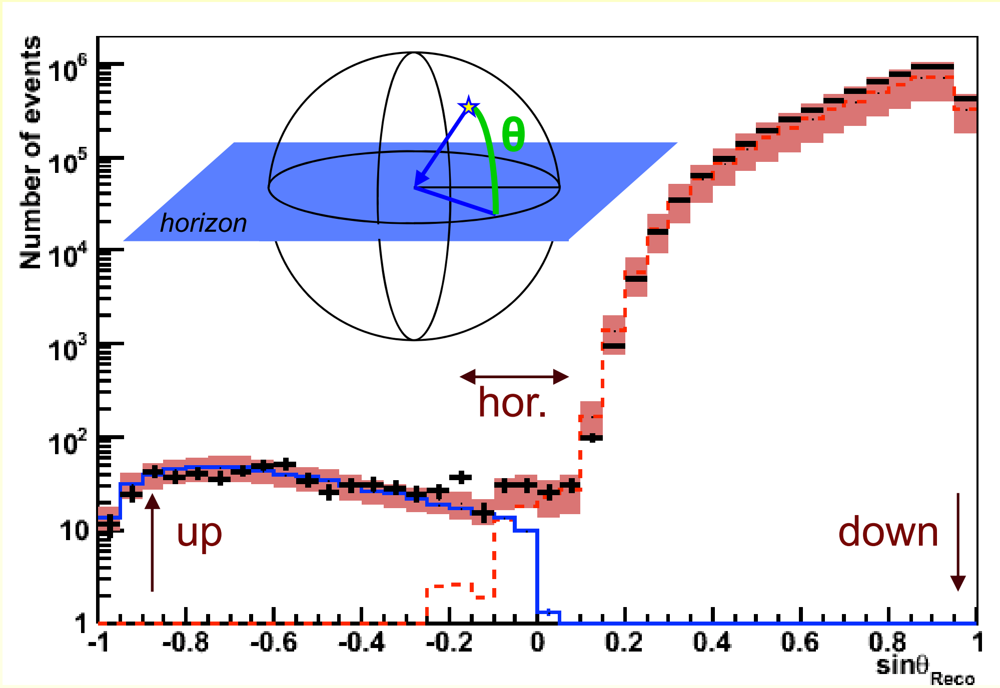
- For E_ν<10 PeV, A_{eff} grows with energy due to the increase of the interaction cross section and the muon range.
- For E_ν>10 PeV the Earth becomes opaque to neutrinos.
- For E_ν<10 TeV, the angular resolution is dominated by the ν-μ angle.
- For E_ν>10 TeV, the resolution is limited by track reconstruction uncertainties.

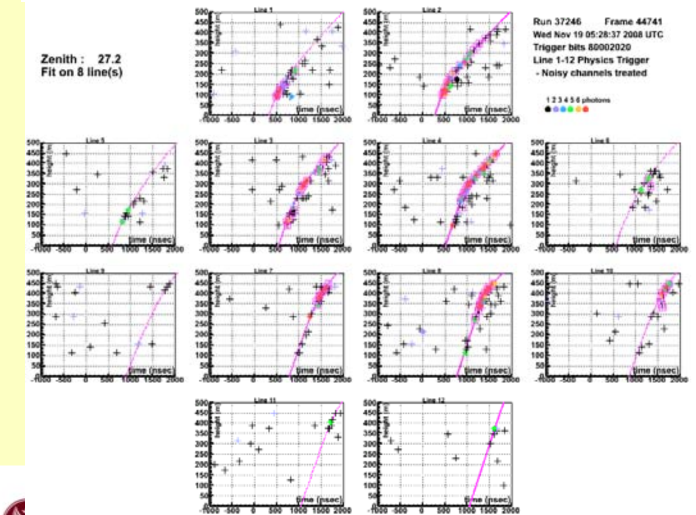
Reconstructing the muon track direction: a χ^2 strategy

Track reconstruction based on χ^2 fit of the photon arrival times on fired PMTs

$$Q = \sum_{i=1}^{N_{hit}} \left[\frac{(t_\gamma - t_i)^2}{\sigma_i^2} + \frac{A(a_i)D(d_\gamma)}{\langle a \rangle d_0} \right],$$



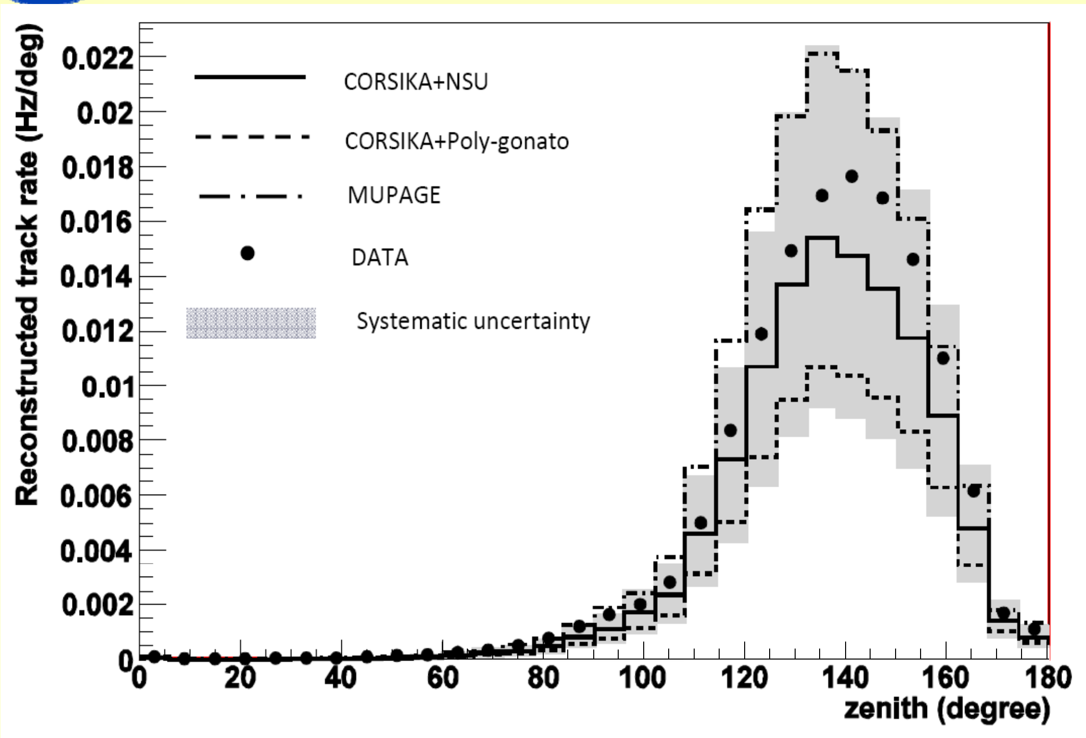


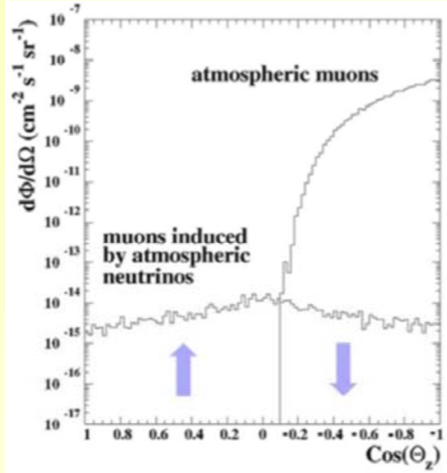


Elevation angle distribution for events with Q<1.4
Data points are compared with the MonteCarlo predictions for atmospheric down-going muons and up-going neutrinos

A Fast Algorithm for Muon Track Reconstruction and its Application to the ANTARES Neutrino Telescope, Astroparticle Physics **34, Issue 9,** (2011) 652-662

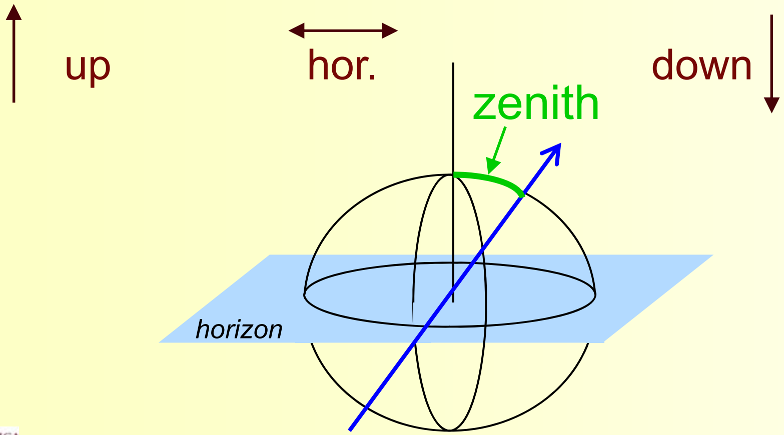
Downgoing muon analysis, 5-lines detector (2007) data sample





- Track reconstruction based on χ^2 fit
- Main contributions to systematics:
  - $\Delta\lambda_{abs}/\lambda_{abs} \sim \pm 20\%$
  - OM acceptance (High angle) ~ ±35%
  - PMT eff Area ~ ±20%

  Total ±45%

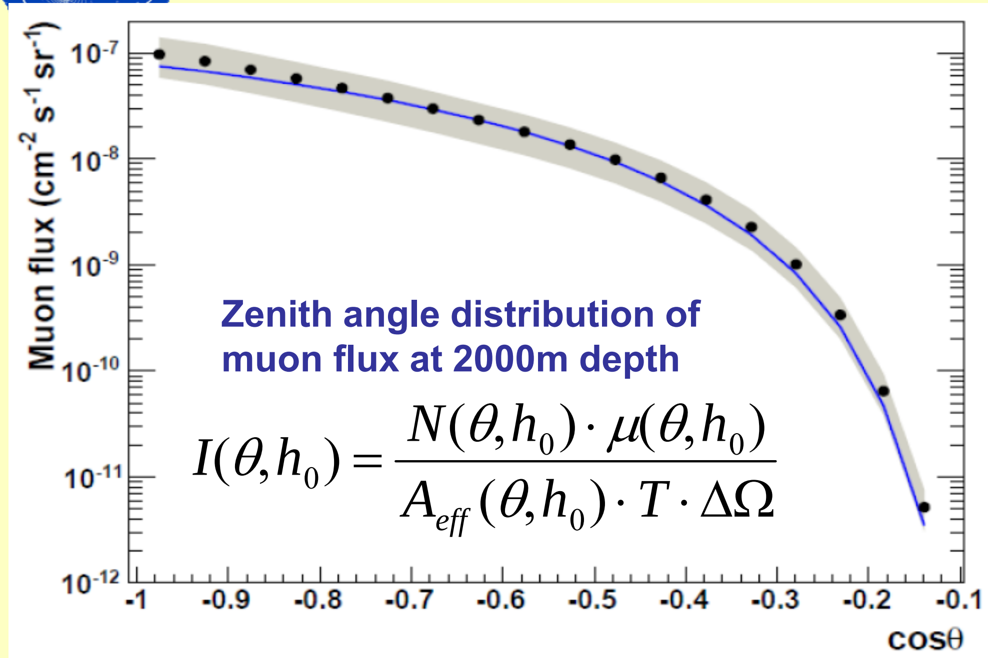


- Monte Carlo: two approaches

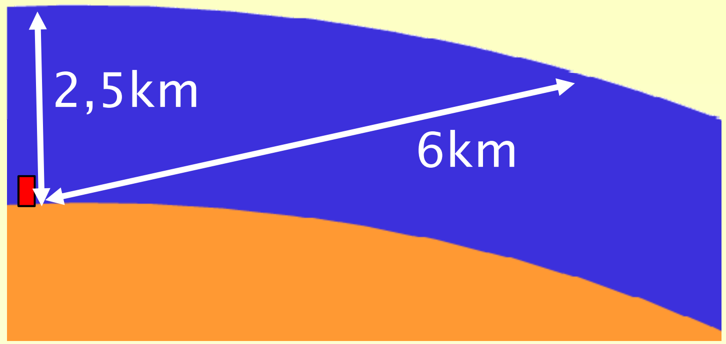
  1st approach:
  - CORSIKA 6.2 +QGSJET 01
  - Prima□y CR models used:
  - Polygonato (Hörandel)
  - NSU (Bugaev)

  2nd approach:
  - MUPAGE (parameterization)

5 lines (2007): Depth Intensity Relation



$$I(\theta, h_0) = \frac{N(\theta, h_0) \cdot \mu(\theta, h_0)}{A_{eff}(\theta, h_0) \cdot T \cdot \Delta\Omega}$$



$$I(\theta = 0, h) = I(\theta, h_0) \cdot |\cos\theta| \cdot c_{corr}(\theta)$$

$h = h_0 / \cos\theta$ **slant depth**

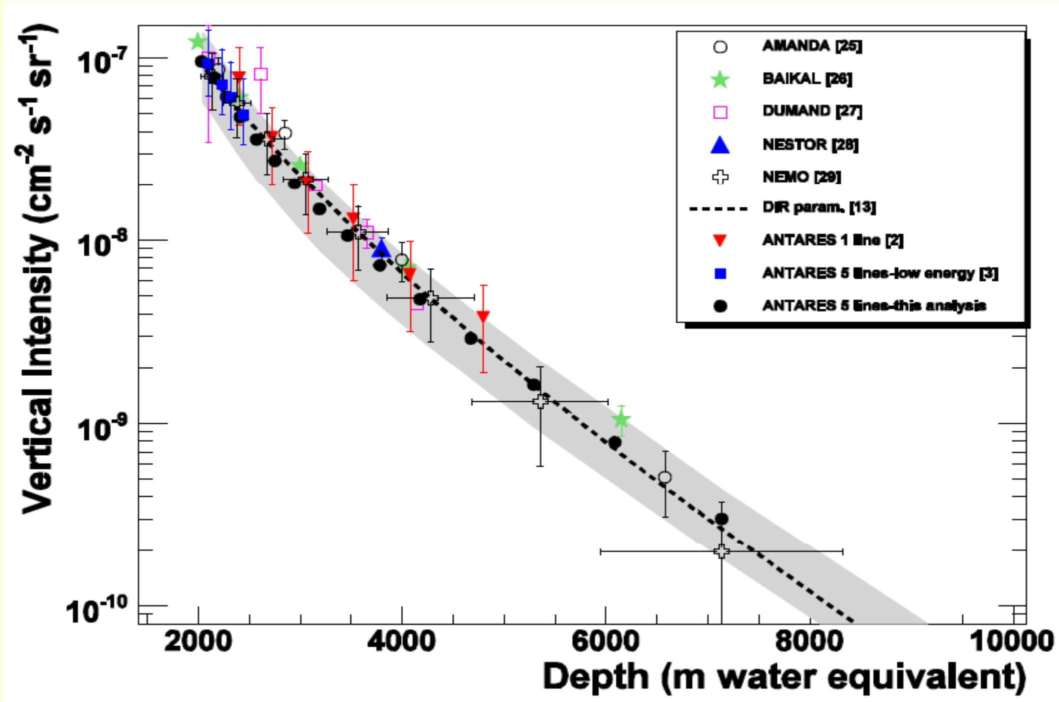
$N(\theta, h_0)$ **# of muons in angular bin**

$\mu(\theta, h_0)$ **mean bundle multiplicity**

$c_{corr}(\theta)$ **Earth curvature correction**

Reconstructed track rate=1.52Hz

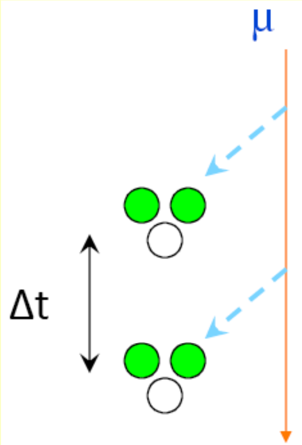
D.I.R. parametrization from:
E.V. Bugaev et al., Phys. Rev. D 58 (1998) 05401.

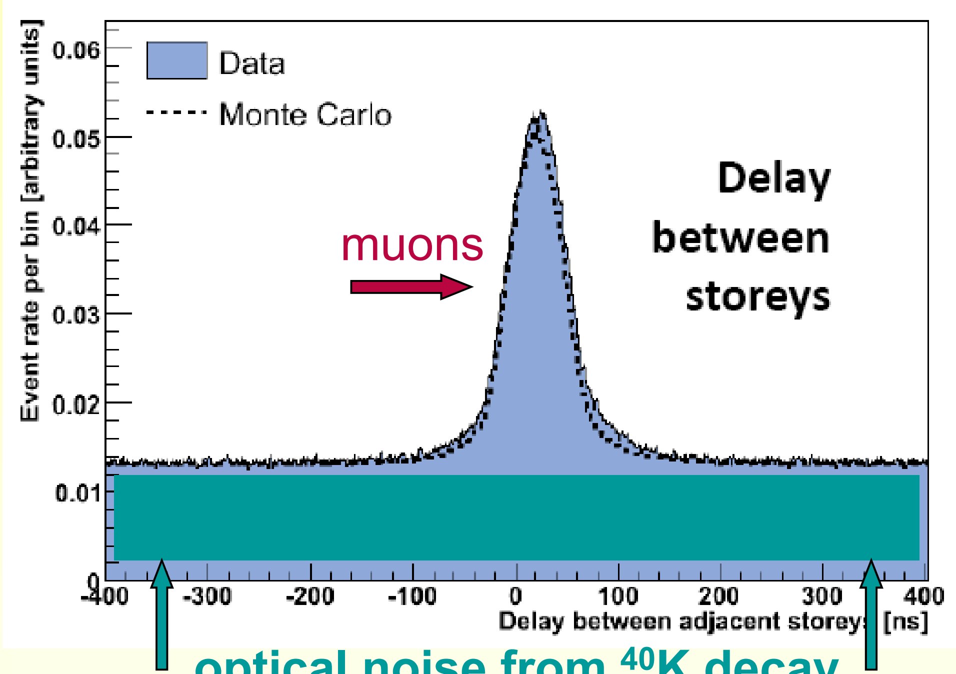


"Zenith distribution and flux of atmospheric muons measured with the 5-line ANTARES detector", Astroparticle Physics **34** (2010) 179-184

Coincidences between adjacent storeys (low E atmospheric muons)

Analysis performed on 5-line detector data





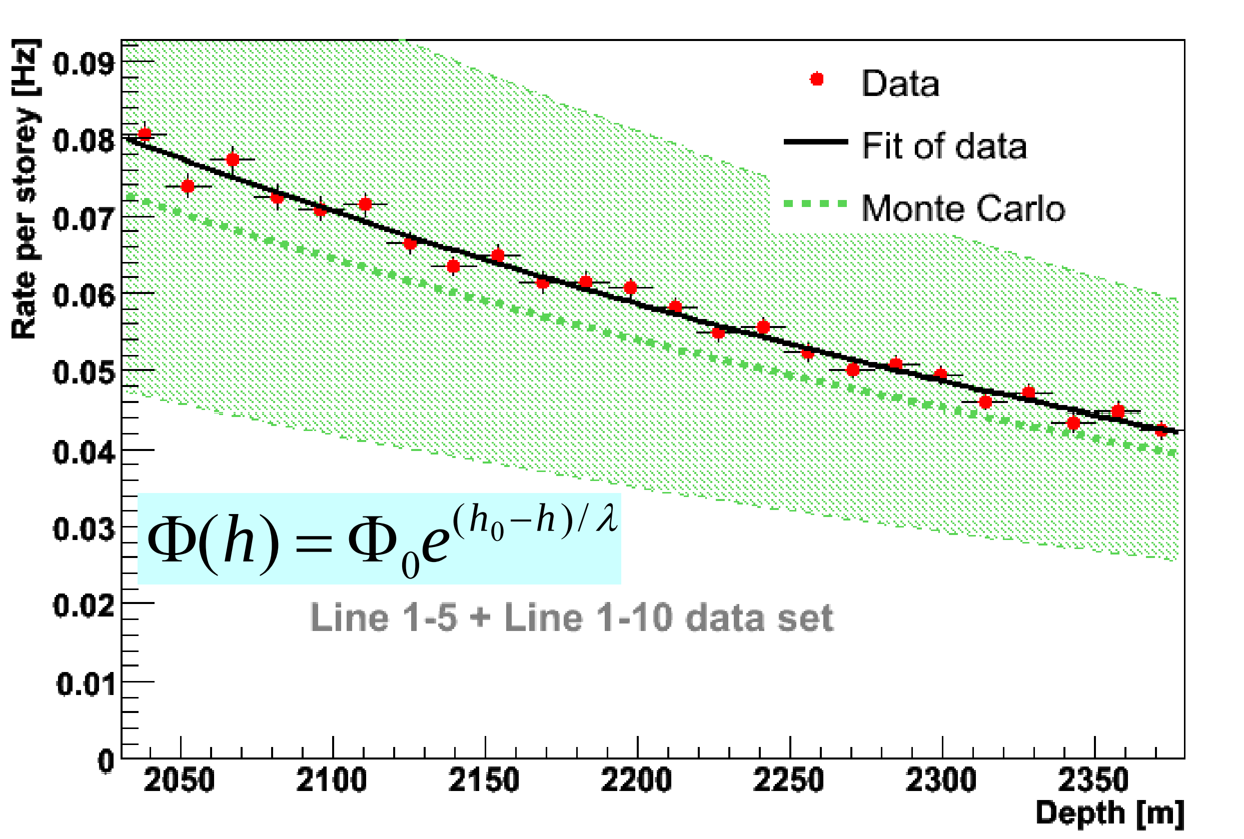
Data/MC ratio ≈ 1.1

- Data: low-background (<100 kHz) ^{40}K runs with 5-line and 10-line detector. Effective live time = 4.1 hours with 5 lines + 3.2 hours with 10 lines (52.5 line-hours)

- Monte Carlo: MUPAGE, Geant4 angular acceptance. Resulting curve is rescaled to account for low-efficiency & dead OMs in real data

Event rate as a function of floor depth

By repeating the analysis for every detector storey the effect of muon flux reduction with depth is directly measured



$$\Phi(h) = \Phi_0 e^{(h_0 - h)/\lambda}$$

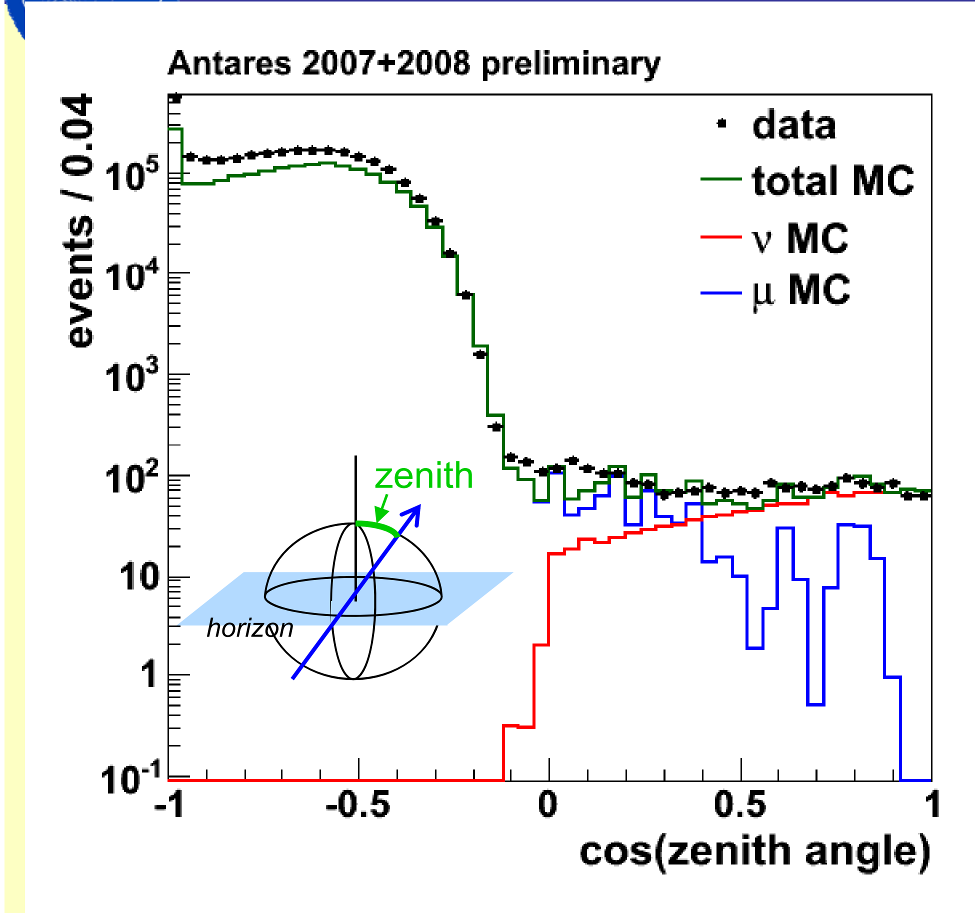
After corrections for the presence of dead channels and uneven efficiencies of the OMs, as measured with ^{40}K, the fluctuations of data points are compatible with statistical errors

Systematic errors mainly in normalization (+50/-35%), otherwise ~3%

"Measurement of the atmospheric muon flux with a 4 GeV Threshold in the ANTARES neutrino telescope"
Astroparticle Physics **33** (2010) 86-90

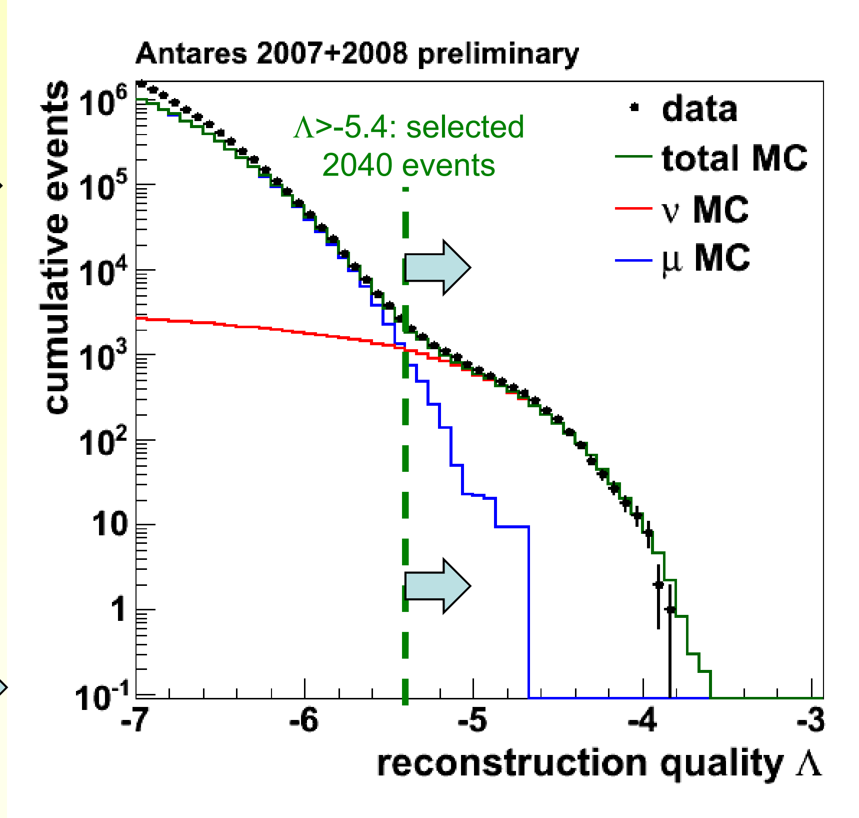
$$\Phi_0 = 1.18 \pm 0.01(stat)^{+0.63}_{-0.39}(syst) \cdot 10^{-3} m^{-2} s^{-1}$$
$$at \quad h_0 = 2200m \quad \text{with} \quad \lambda = 540 \pm 25m$$

2007 and 2008 data analysis: ν_μ from point sources



Selected up-going reconstructed tracks
From MC: angular error estimate < 1°

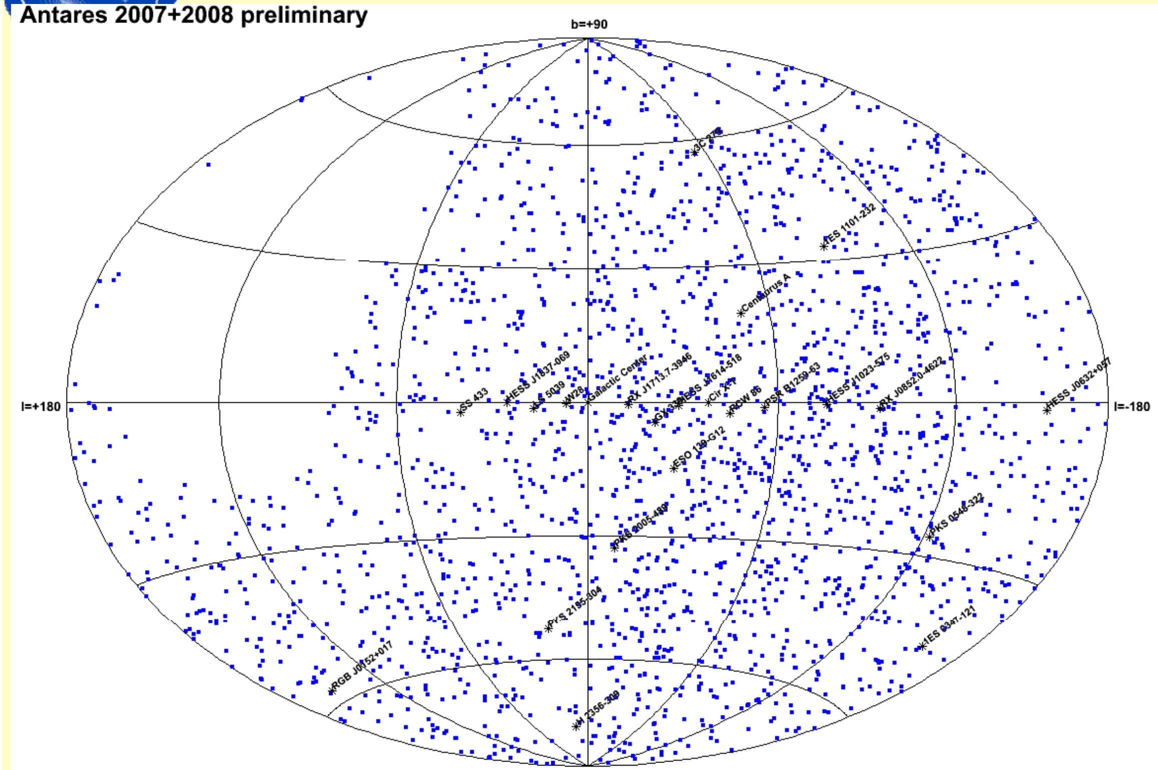
Look for neutrinos into the "up-going tracks".



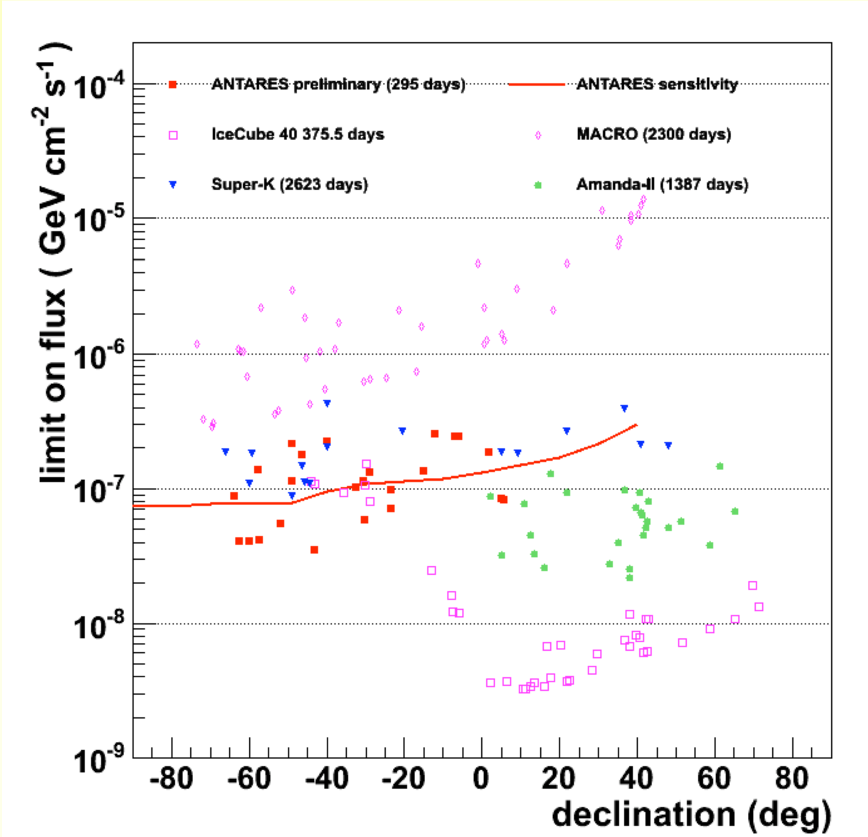
- Reconstruction algorithm (max. **Likelihood strategy**) optimized to reach angular resolution ≤0.2° for E_μ> TeV and to reduce the atmospheric muon background
- Blinding policy followed

The selected sample of tracks dominated by up-going atmospheric ν_μ and mis-reconstructed down-going muons.
The Λ quality cut enhances the ν_μ component in the up-going reconstructed tracks sample.

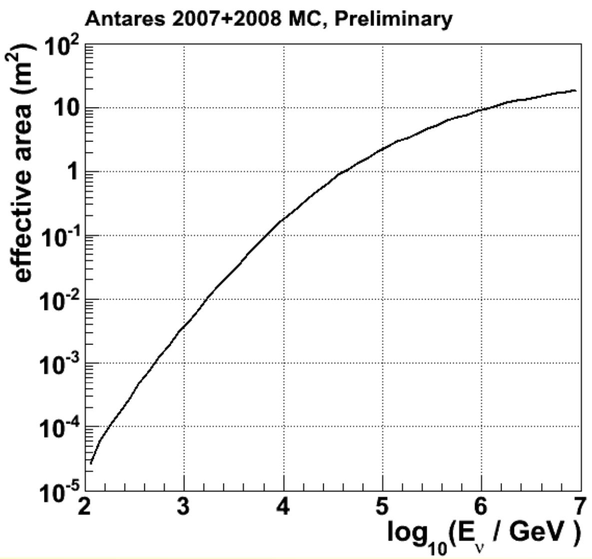
ANTARES: search for point like sources



Search for point-like sources at their known location



ANTARES 2007+2008 preliminary
Skymap Galactic Coordinates
2040 up-going ν_μ



ANTARES: flux limits on 24 candidate point sources and sensitivity (median expected limit)

ANTARES: search for a flux of “diffuse ν_μ”

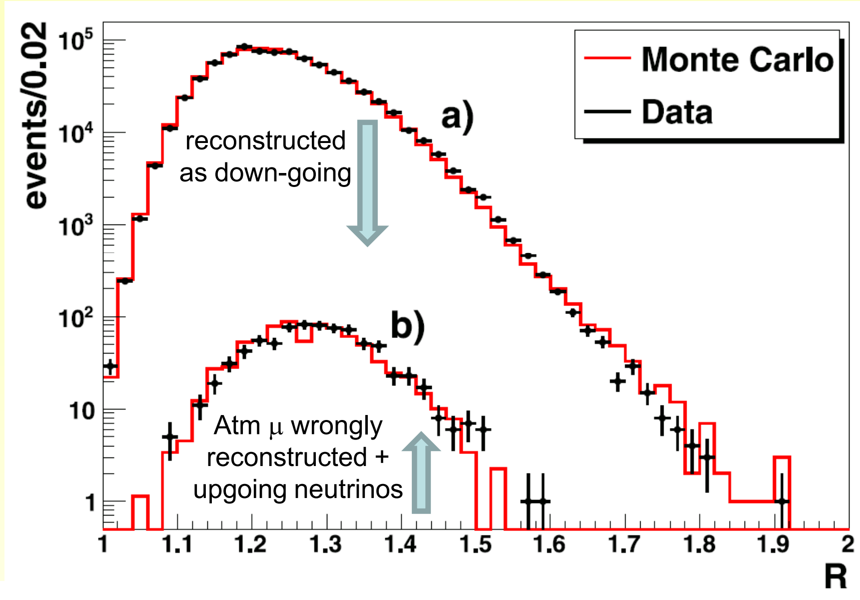
Selection criteria

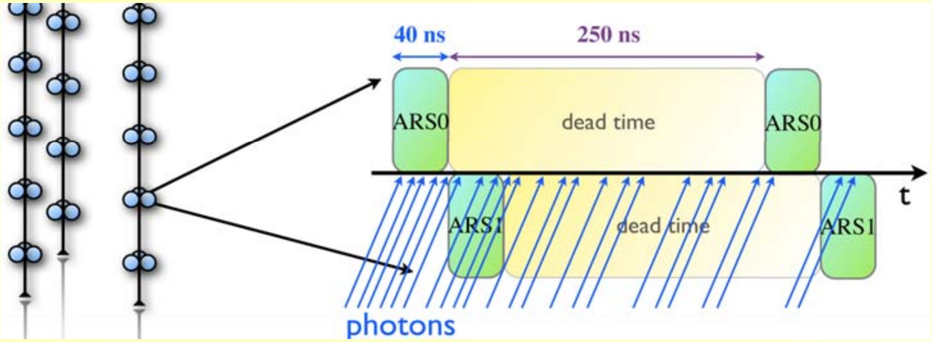
First level: good quality upgoing tracks.

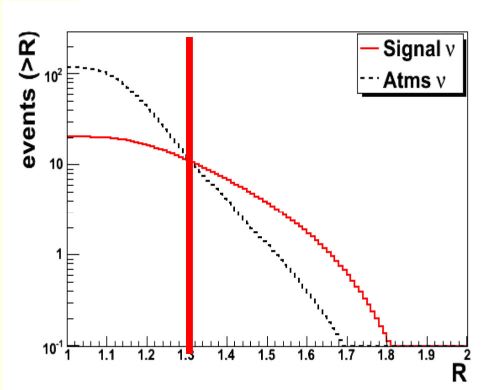
Second level: Λ vs N_{hit}

Energy estimator:

Repetition (R) of integration gate on the same Optical Module

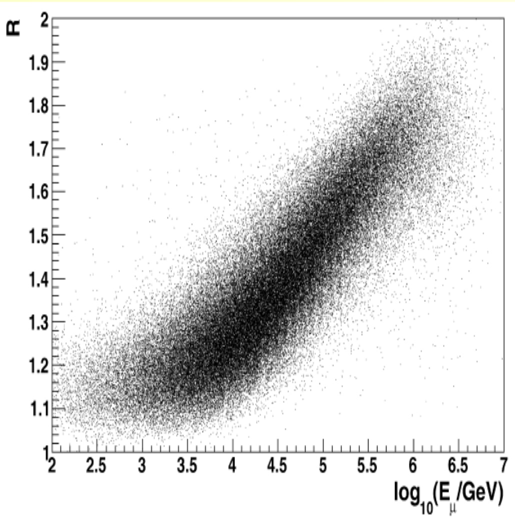


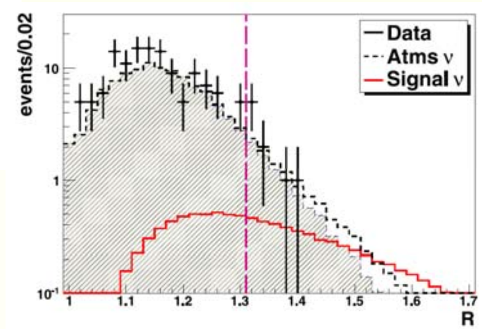




Optimization by Model Rejection factor

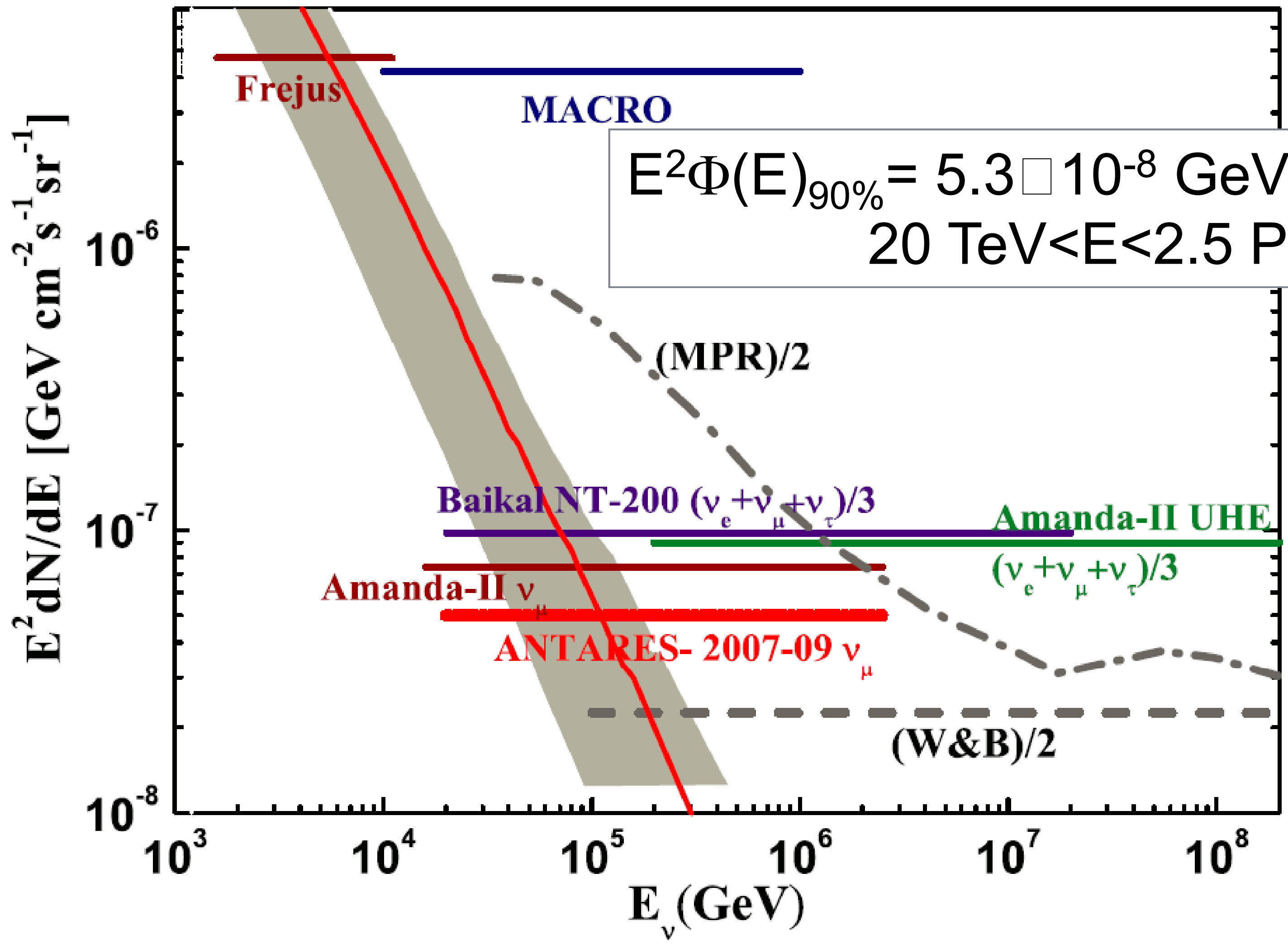
R vs Energy





Distribution of the *R* parameter for the 134 neutrino candidates in the 334 days of equivalent live time

ANTARES: search for a flux of "diffuse ν_μ": results



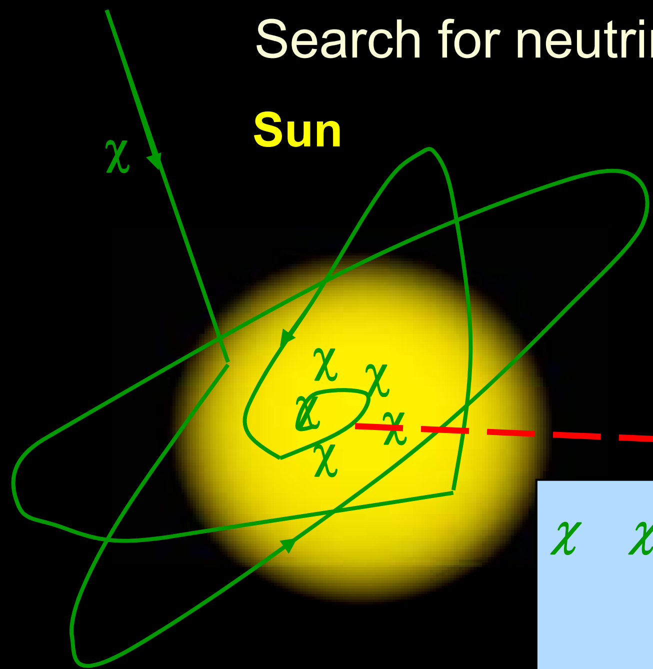
$E^2\Phi(E)_{90\%} = 5.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
20 TeV<E<2.5 PeV

90% C.L. upper limit assuming E^{-2} flux spectrum

"Search for a diffuse flux of high-energy ν_μ with the ANTARES neutrino telescope" Physics Letters **B696** (2011) 16-22.

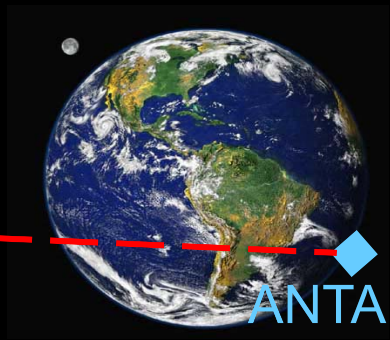
ANTARES: indirect search for Dark Matter

Search for neutrinos from dark matter annihilations in the Sun



WIMPs gravitationally trapped via elastic collisions in the sun

ν



$\chi \quad \chi \rightarrow WW,\ ff$

$W, f \rightarrow \nu\ X$

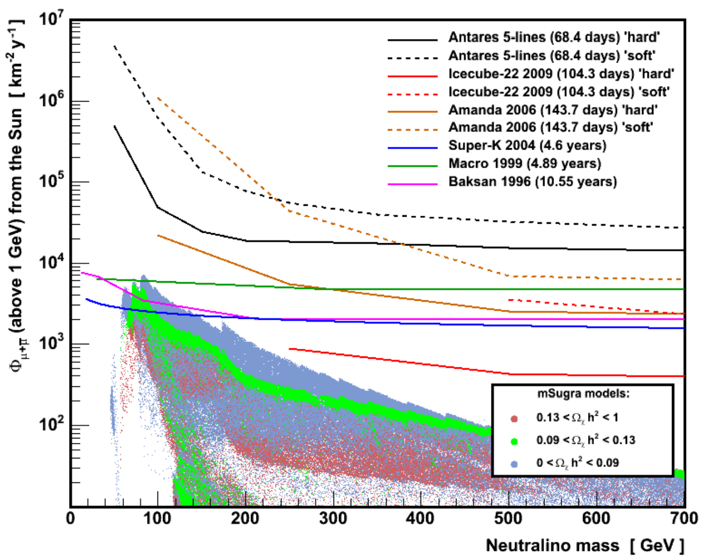
$\langle E_\nu \rangle \sim M_\chi/3$

Upper limit on the neutrino flux from the Sun

arXiv:0905.2316v3

mSugra model predictions

- **green : WMAP favoured relic density**
- **red : > WMAP favoured relic density**
- **blue : < WMAP favoured relic density**



Upper limit on the total $\Phi(\nu_\mu + \bar{\nu}_\mu)$ from neutralino annihilations in the Sun as function of m_χ

5 Line Detector
Feb - Dec 2007
168 active days

A multi-messenger approach: "GRB trigger"

GCN alerts trigger the recording of all the low level triggers. A continuous buffer ensures the availability of the data before the alert

GCN=Gamma Ray Burst Coordination Network

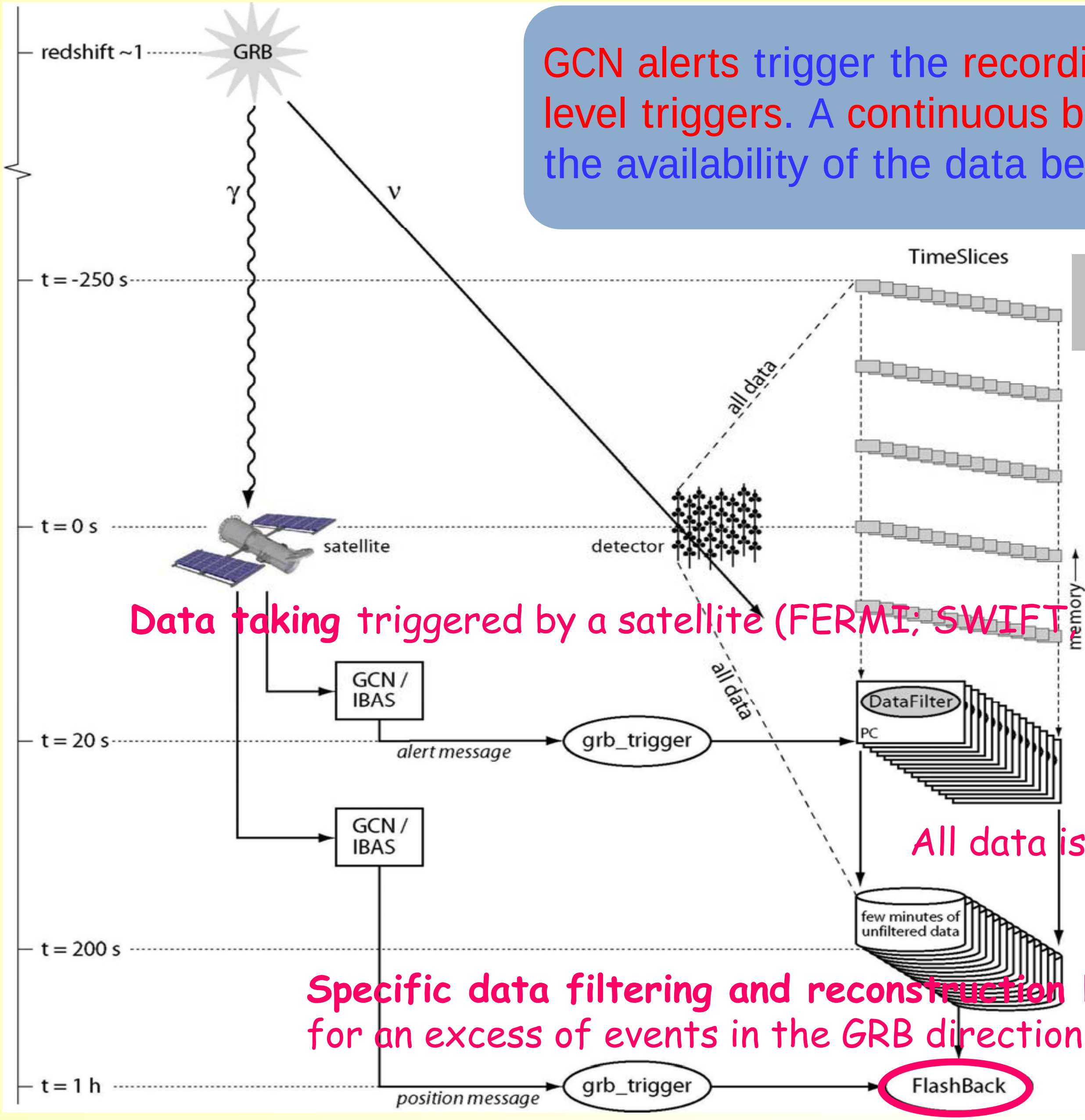
t =-250 s

t = 0 s

t = 20 s

t = 200 s

t = 1 h

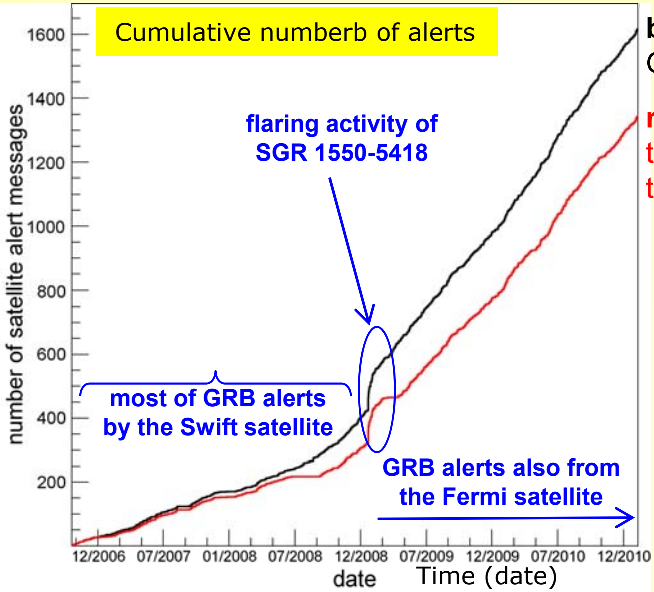


Data taking triggered by a satellite (FERMI, SWIFT, INTEGRAL)

All data is written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)

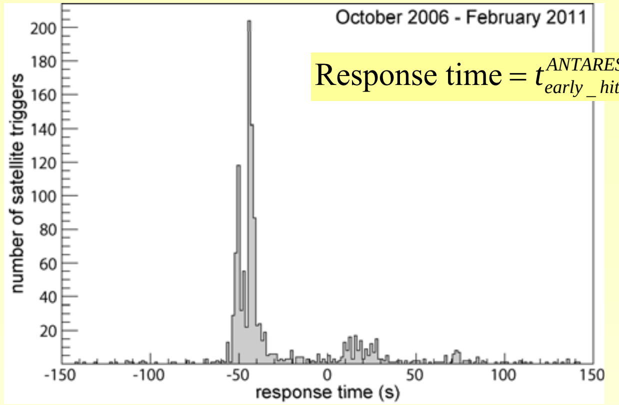
“GRB triggered” data analysis



black:
GRB alerts received

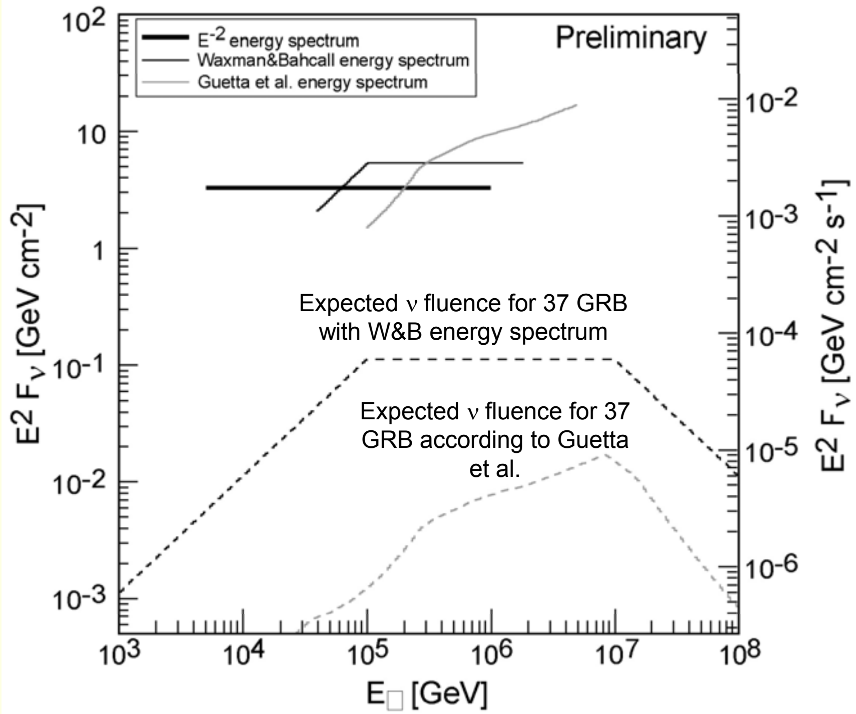
red:
the ones Antares triggered on

ANTARES time response to a satellite alert message

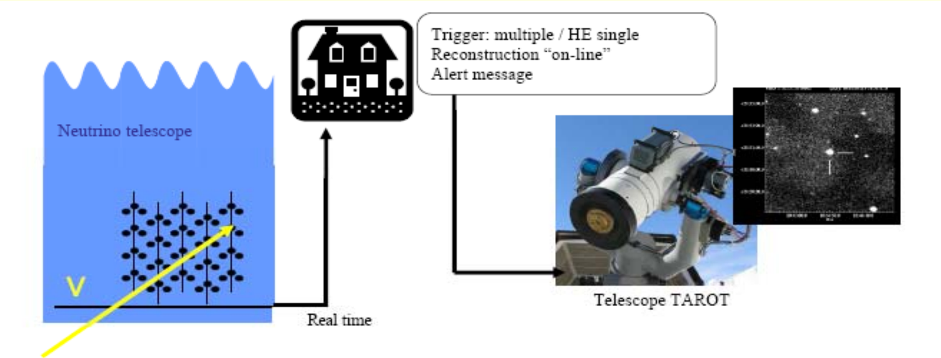


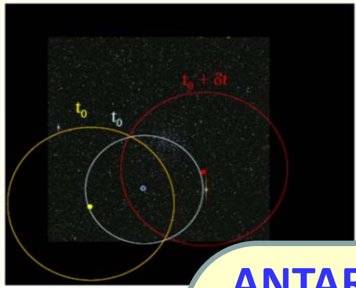
- > 1300 alerts from GCN have been recorded (Jan 2011)
- The analysis of Lines 1-5 data is going on: the time period contains 37 GRB alerts.
- The total prompt emission duration of the 37 GRBs is 1882 s

90% Upper limits on ν fluxes form 37 GRBs



Multi-messenger approach





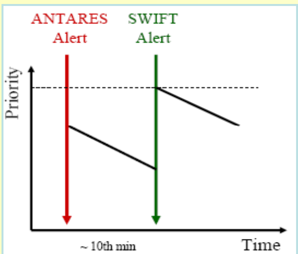
Agreement with TAROT

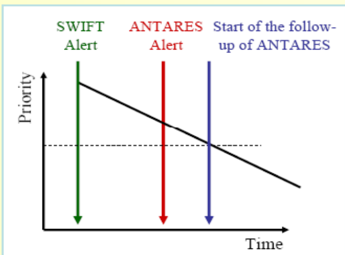
Telescopes à Action Rapide pour l'Observation de Transients)

• TAROT: two 25 cm telescopes at Calern (France) and La Silla (Chile)
• FOV 1.86° x 1.86°
• ~10 s repositioning after alert reception

ANTARES alert

- Two events with
  $\Delta\Omega < 3^o \times 3^o$
  $\Delta t < 15$ min
  Rate(atm) = 0.05 yr^{-1}
- High Energy ν event
  Rate ~ 2 per month



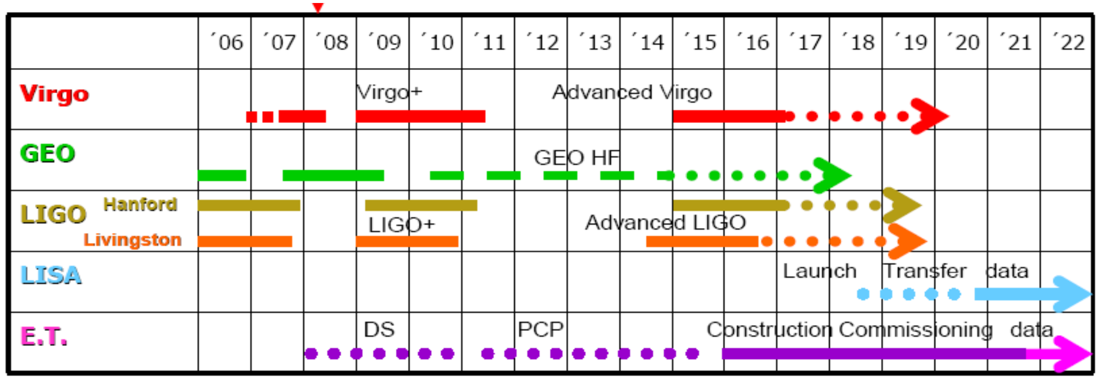


Priorities (decreasing with time) are set to alerts.
SWIFT has the highest priority

•Operational since beginning of 2009: > 20 alerts have been sent to the robotic telescopes.
•MoU has been signed with Tarot, a second MoU is in discussion with ROTSE, whose 4 telescopes receive the Antares alerts since 1 year.
•A paper on the performances of the alert system soon submitted ASAP to Astroparticle Phys.

Multi-messenger approach

Gravitational Waves and Neutrinos



- Possible common sources

(GRB-core collapse into BH; SGR – powerful magnetars; hidden sources)

- Sky regions in common
- Expected low signals, coincidences increase chances of detection
- GW & HEN is a must

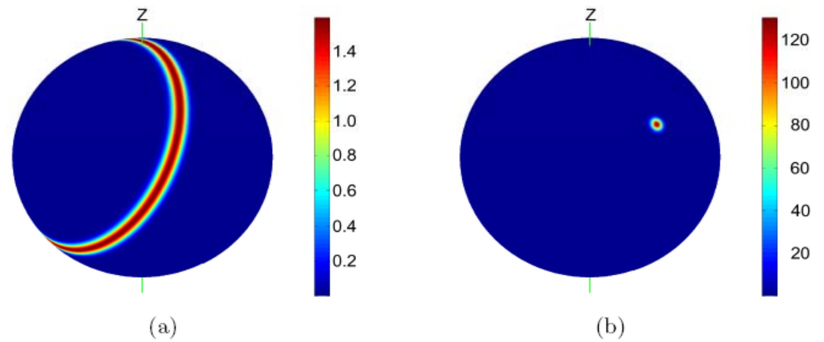
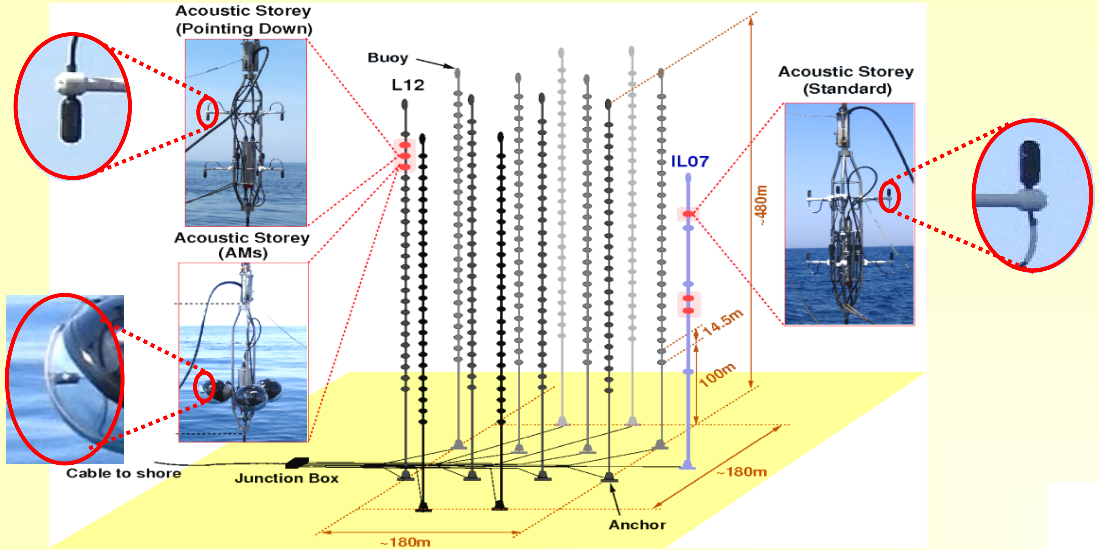
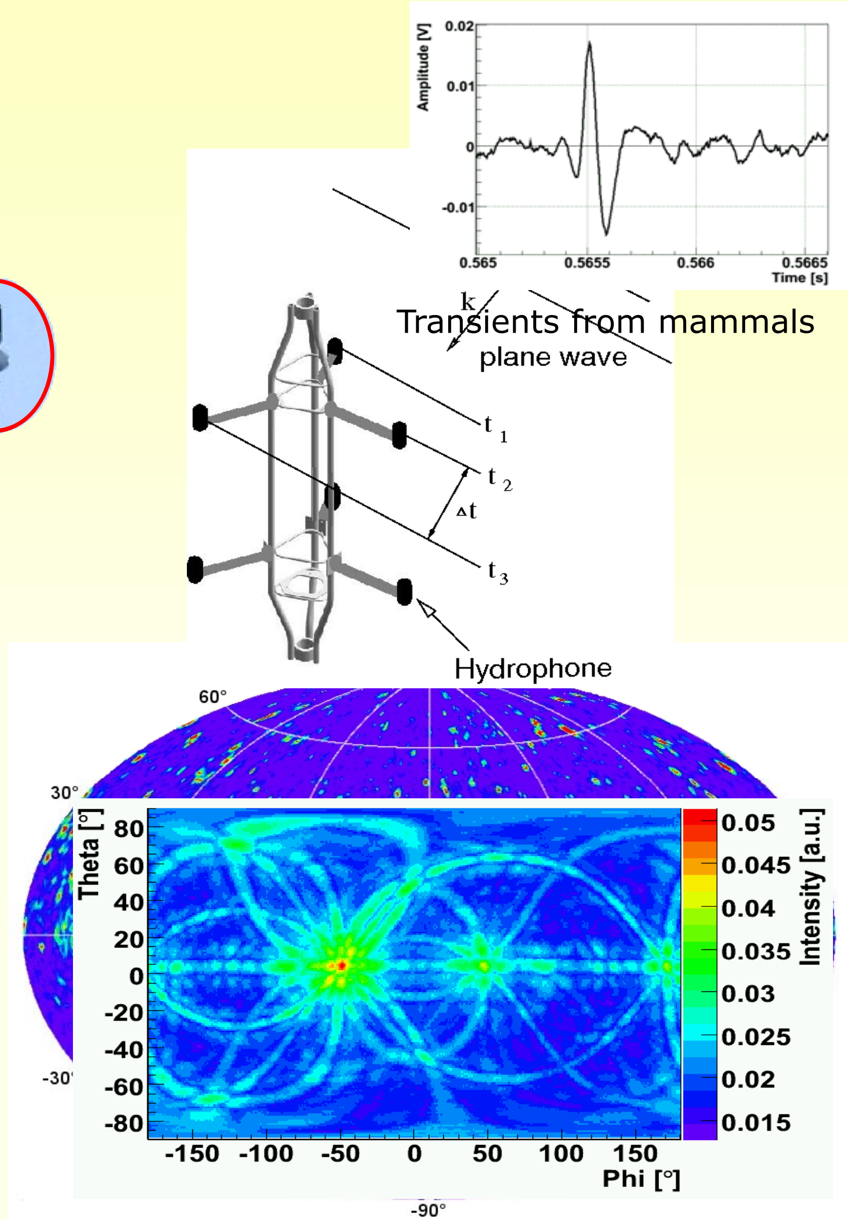


Figure 2. Examples of spatial probability distribution functions (SPDFs). (a) SPDF of a LIGO event with $\tau = 4$ msec and $\delta\tau = 440\,\mu$sec. (b) SPDF of an IceCube event with $\sigma_\nu = 2°$. The plots are shown in Earth based coordinates with the z-axis pointing along the north pole. Both SPDFs are normalized to 1 for integration over the sphere.

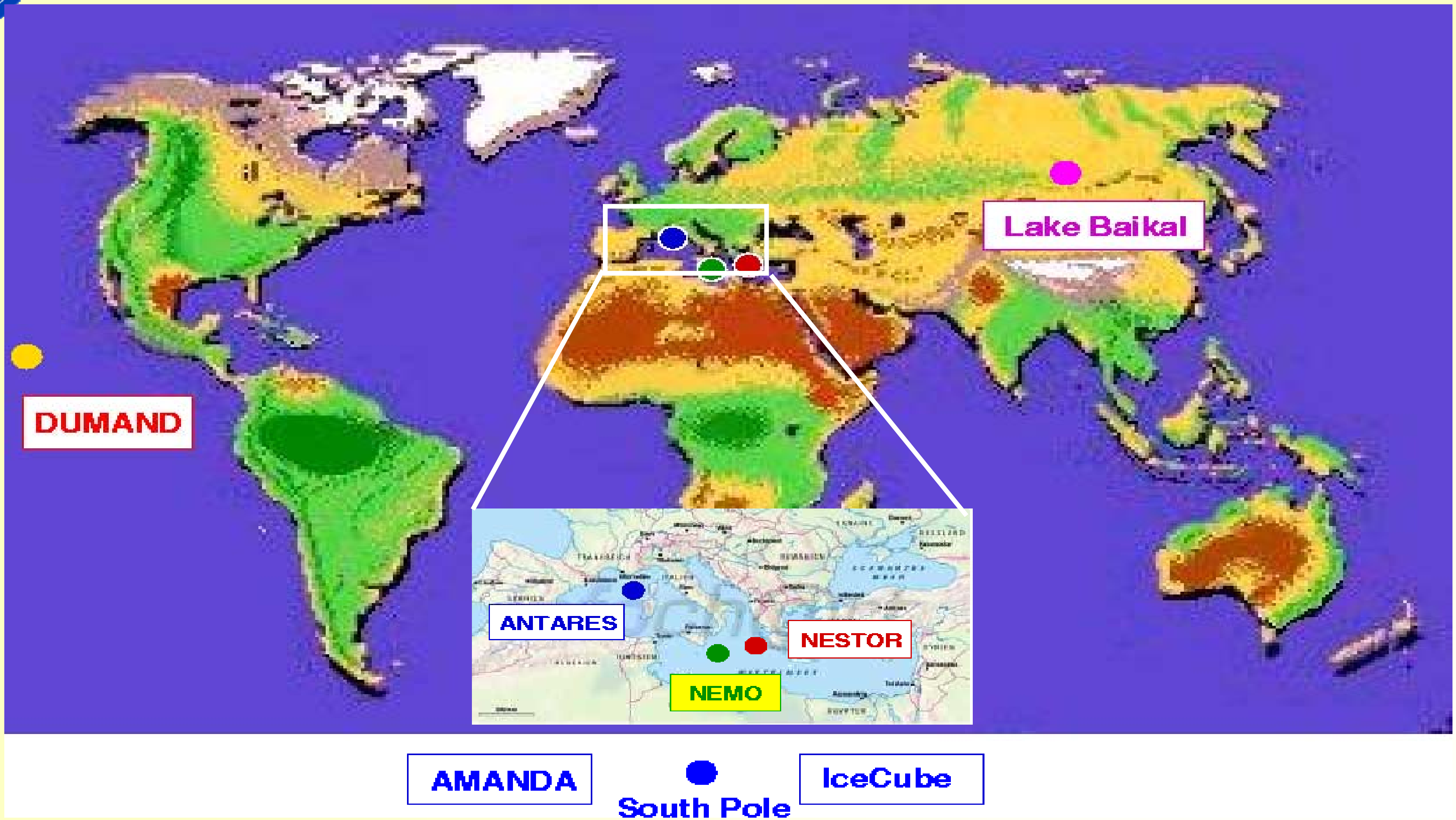
Acoustic detection in ANTARES





- AMADEUS comprises a series of hydrophones in IL and Line 12
- This is a test bench to study the feasibility of a large acoustic UHE neutrino detector
- Study of acoustic environment and backgrounds
- Methods to reconstruct direction (beamforming, time differences)

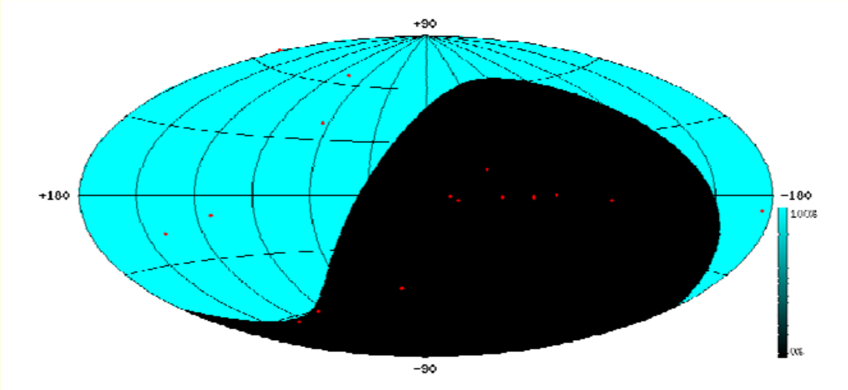
The Neutrino Telescope World Map

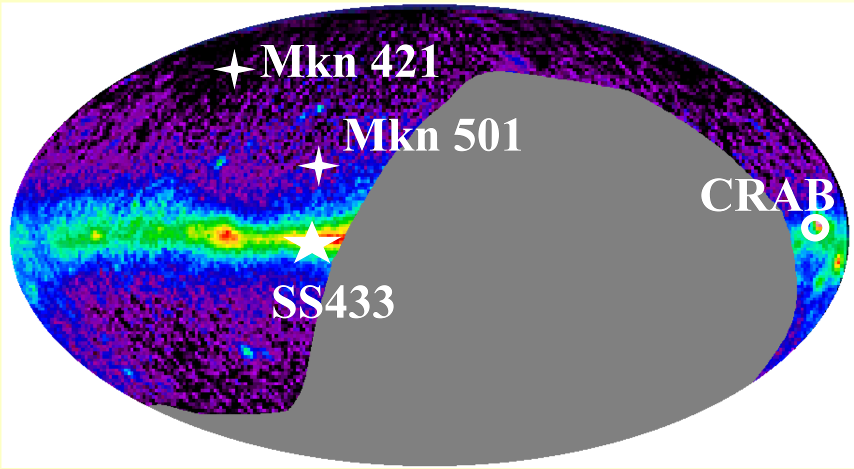


ANTARES + NEMO + NESTOR joined their efforts to prepare a km^3-scale Cherenkov neutrino telescope in the Mediterranean →KM3NeT Consortium

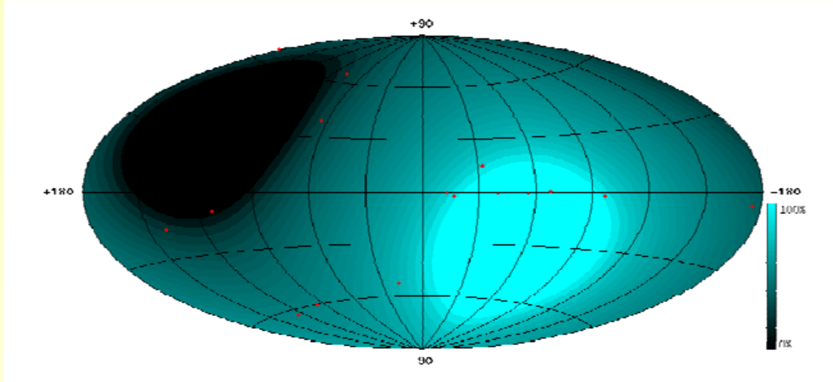
Locations for Neutrino Astronomy

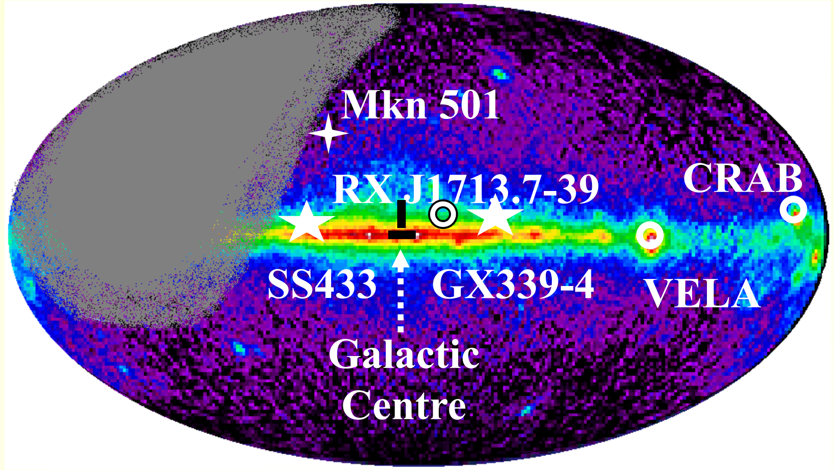
Antartica





Mediterranean Sea





Mediterranean location provides a 3π sr sky coverage, 0.5π sr instantaneous common view with IceCube, and about 1.5π sr common view per day. The Galactic centre is visible 2/3 of the time.

A Km^3 Neutrino Telescope in Mediterranean Sea will be complementary to IceCube and … will search for neutrino sources in the Galactic centre

Summary

- ANTARES is the largest neutrino telescope in the Northern hemisphere, the first one undersea
- Full volume (12-detection lines) reached in May 2008
- Detector is well working, within design specifications
  - Technical challenge successfully realized
  - Maintenance in deep sea is possible !
  - Data collection ongoing
  - Long-term investment in software framework and procedures
  - Data analysis ongoing, first results published
- Multidisciplinary platform for associated sea sciences (secondary junction box and associated equipment deployed November 2010)
- Milestone towards a km^3 underwater detector (special links with NEMO & KM3NeT)