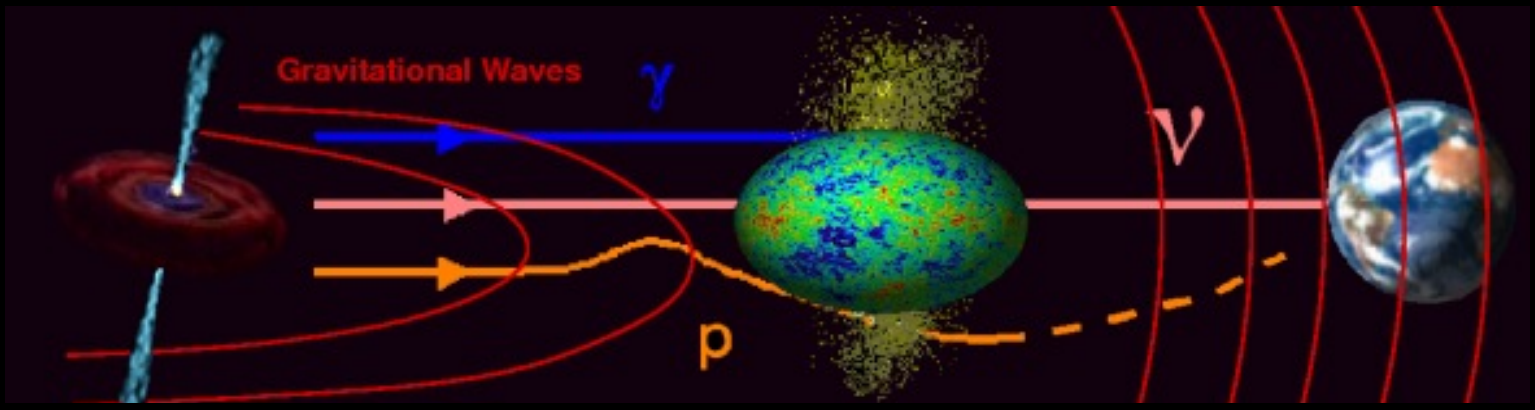
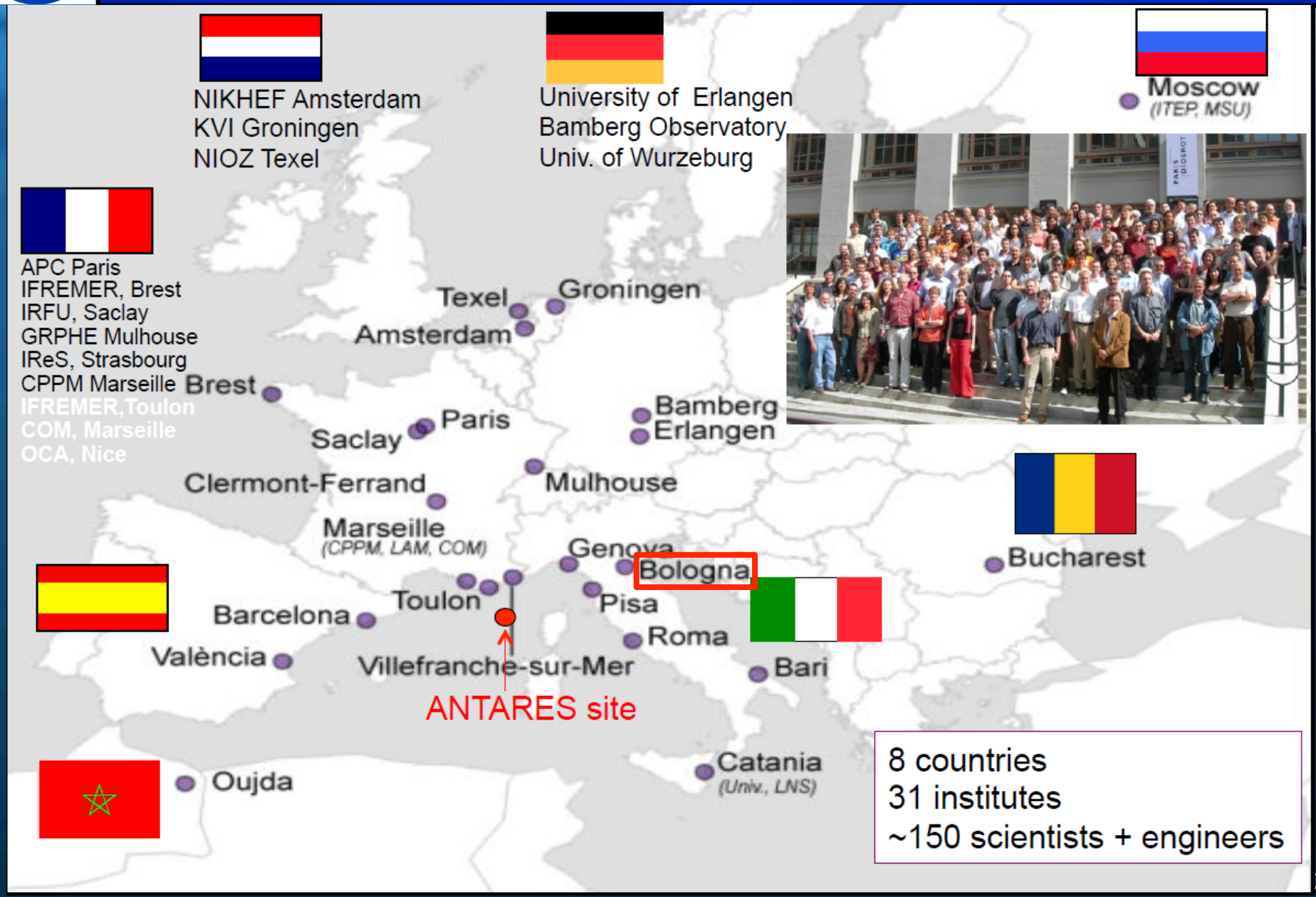


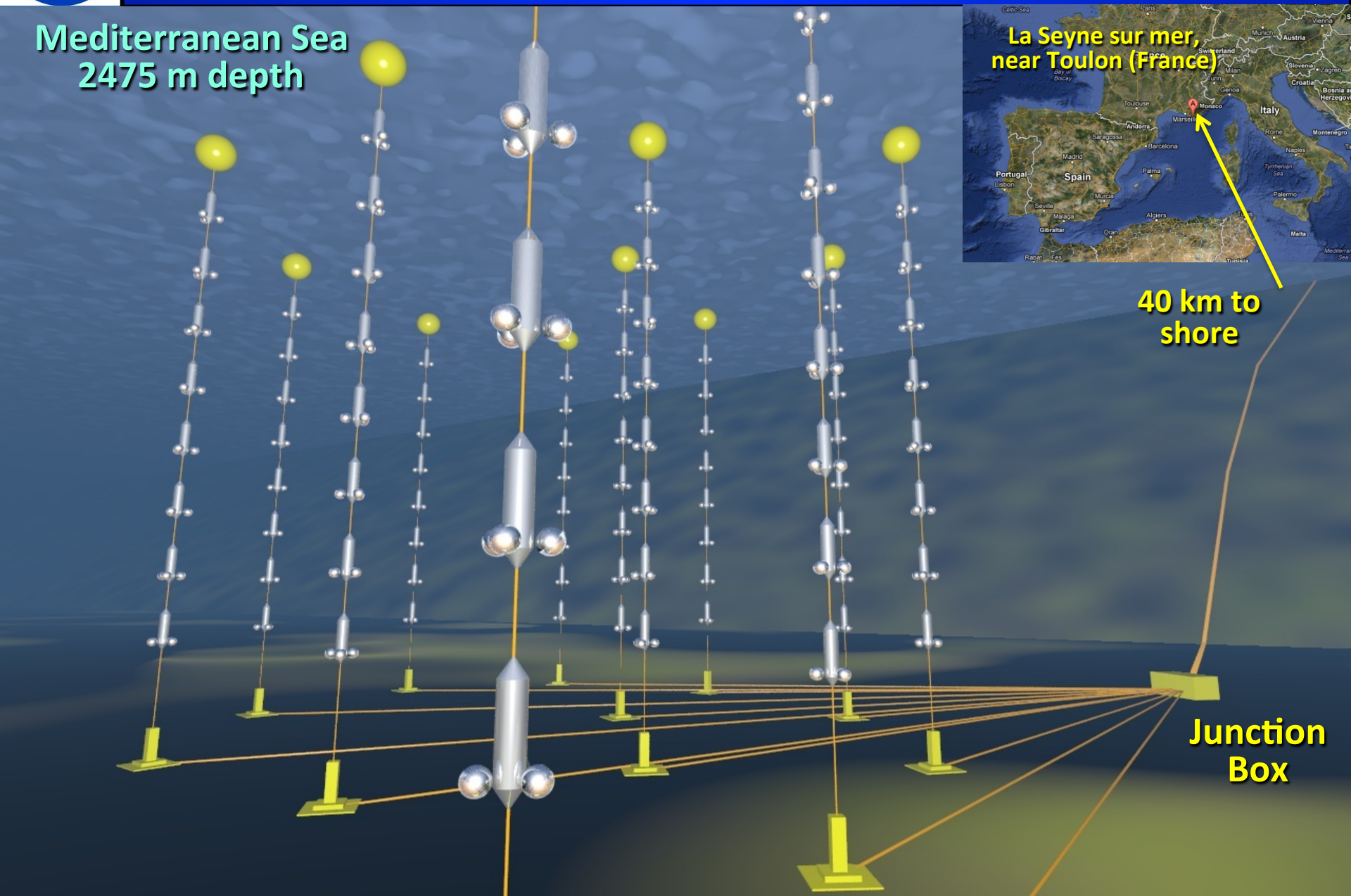
Results from the ANTARES neutrino telescope after 5 years of data

Maurizio Spurio
Università di Bologna and INFN
On behalf of the ANTARES Collaboration

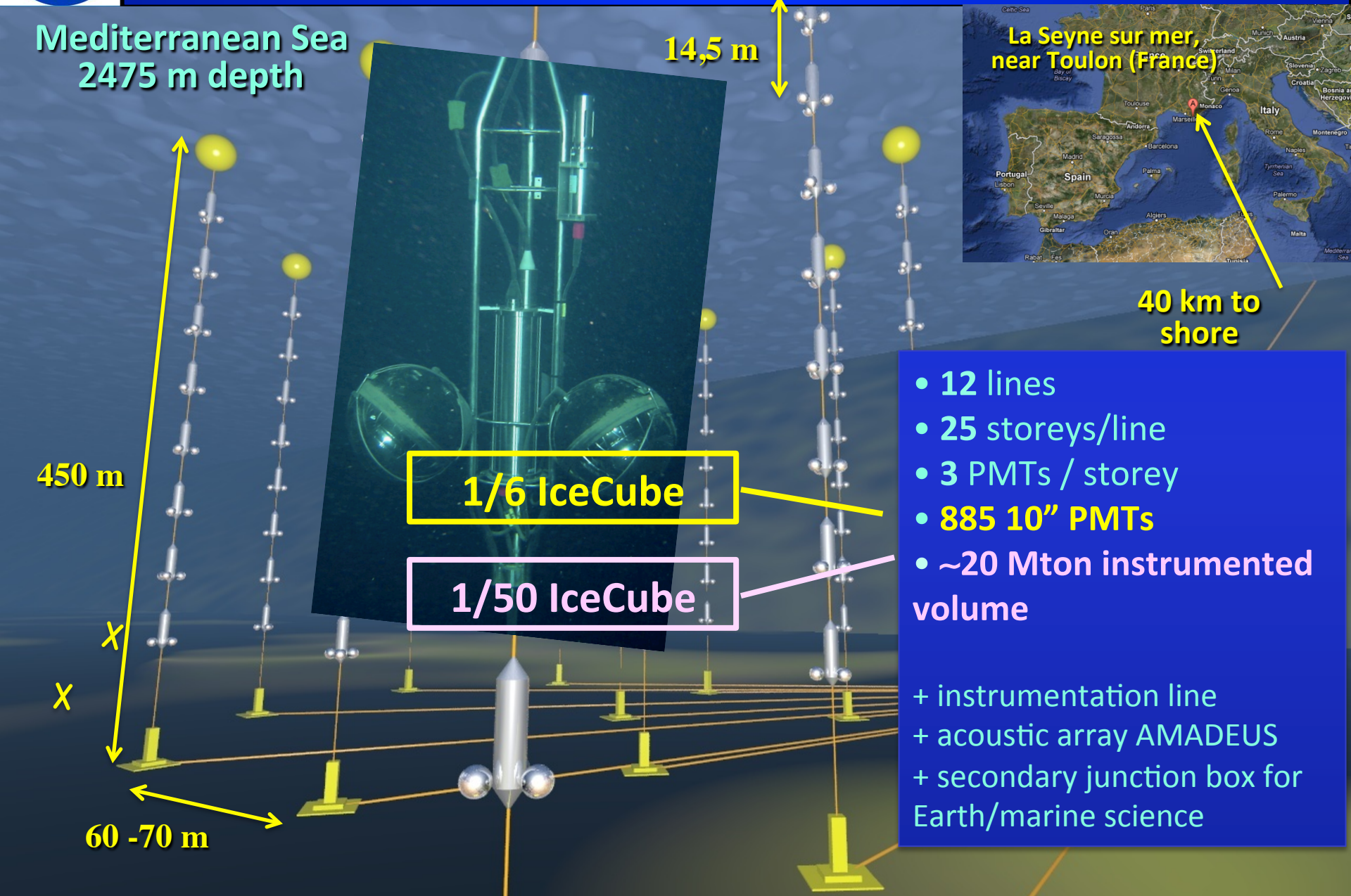
The ANTARES Collaboration



The ANTARES detector



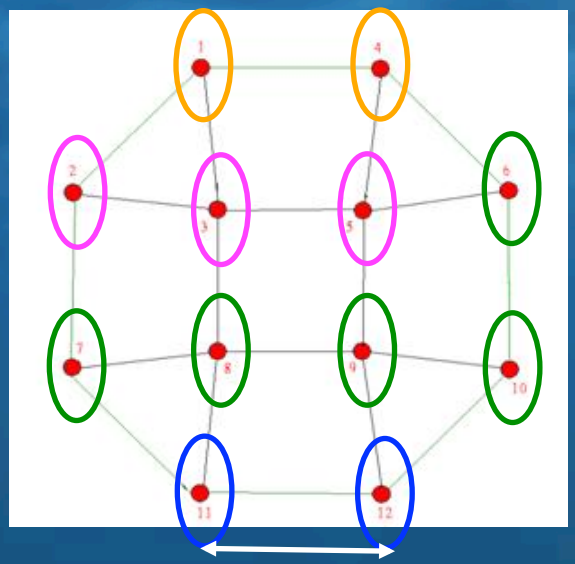
The ANTARES detector



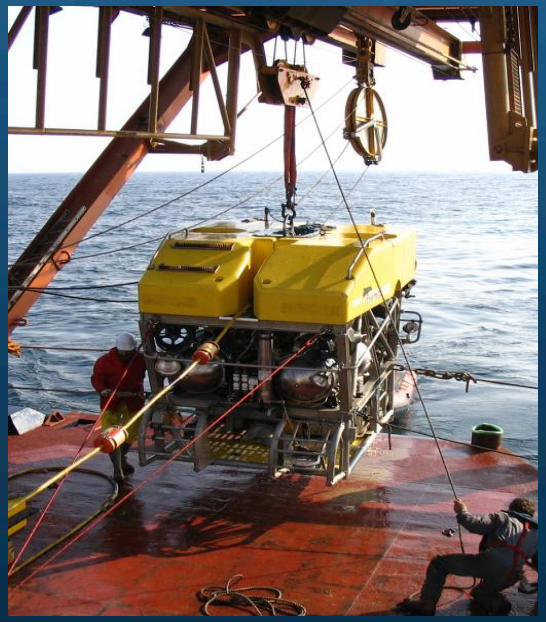
- **12** lines
- **25** storeys/line
- **3** PMTs / storey
- **885 10" PMTs**
- **~20 Mton instrumented volume**

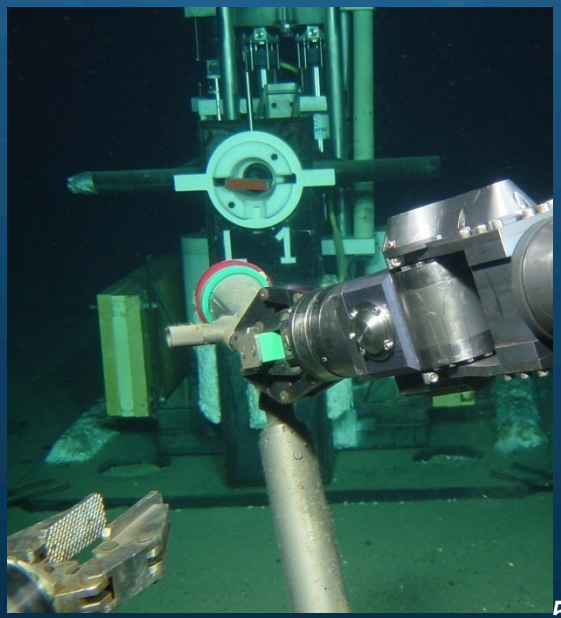
+ instrumentation line
+ acoustic array AMADEUS
+ secondary junction box for Earth/marine science

2006 –2008: ANTARES building phase



~70 m

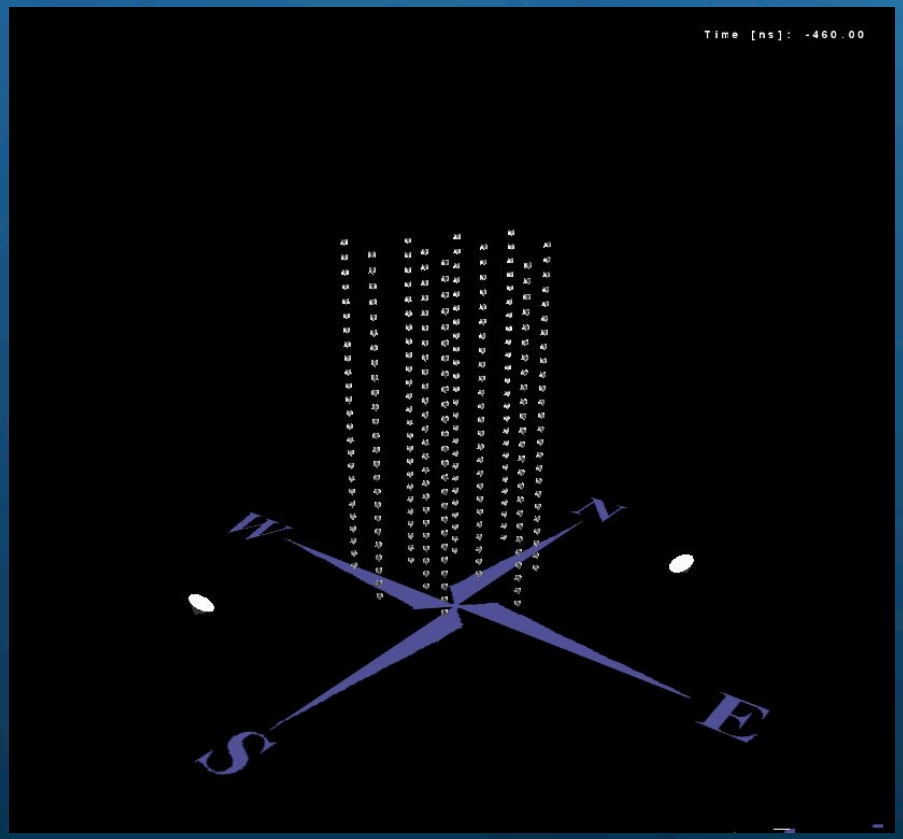




Junction box	2001
Main cable	2002
Line 1, 2	2006
Line 3, 4, 5	01 / 2007
Line 6, 7, 8, 9, 10	12 / 2007
Line 11, 12	05 / 2008

Up- and down-going Events

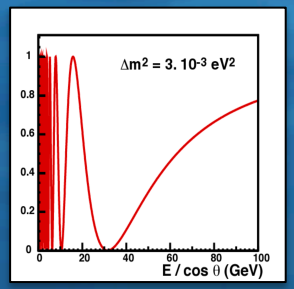
reconstructed up-going neutrino
detected in 6/12 detector lines:

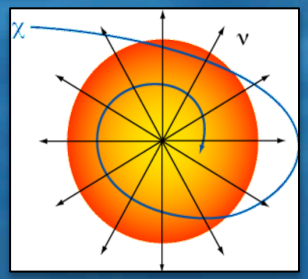


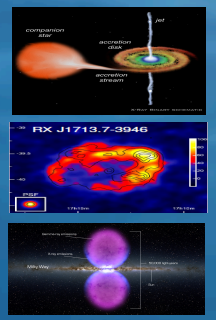
reconstructed down-going muon
detected in all 12 detector lines:

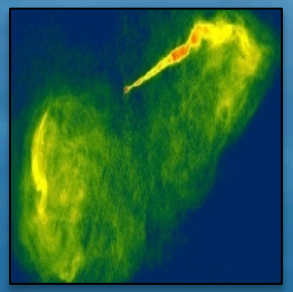
Science with ANTARES

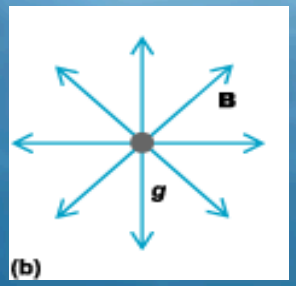
Oscillations | Dark Matter | SNR, μQSO | AGN, GRB | Exotics, GZK









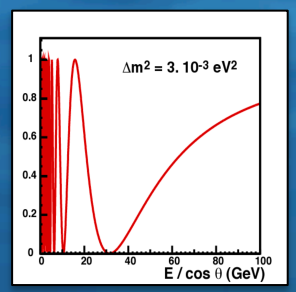


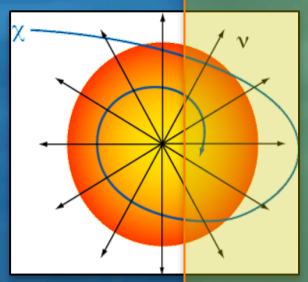
GeV — TeV — PeV — EeV

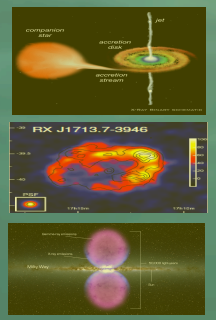
- 12-line data taking since 2008; physics duty cycle ≈ 85%
- **~20 atmospheric muons/sec**
- **~5 atmospheric neutrinos/day** (> 7000 ν_μ detected so far)
  directional cut + quality cut on likelihood of track fit
- Median angular resolution 0.3° – 0.4°
- Visibility: ¾ of the sky, most of the Galactic Plane
- Effective area ≈ 1 m^2 at 30 TeV

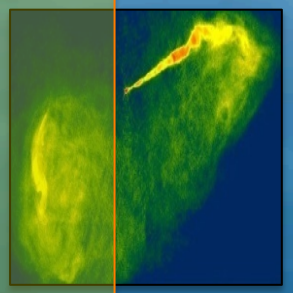
Science with ANTARES

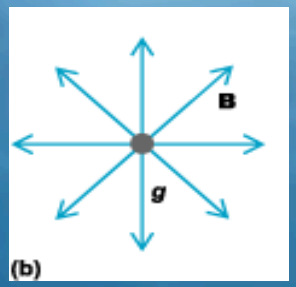
Oscillations | Dark Matter | SNR, μQSO | AGN, GRB | Exotics, GZK





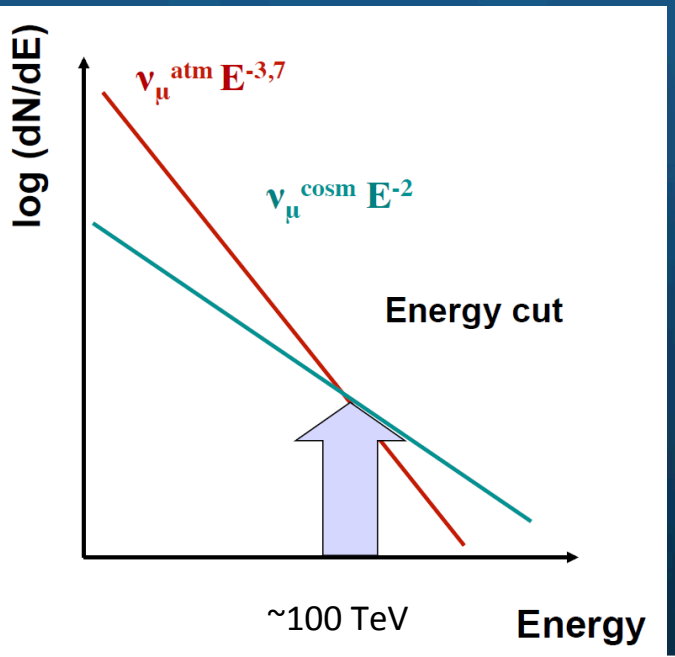






GeV — TeV — PeV — EeV

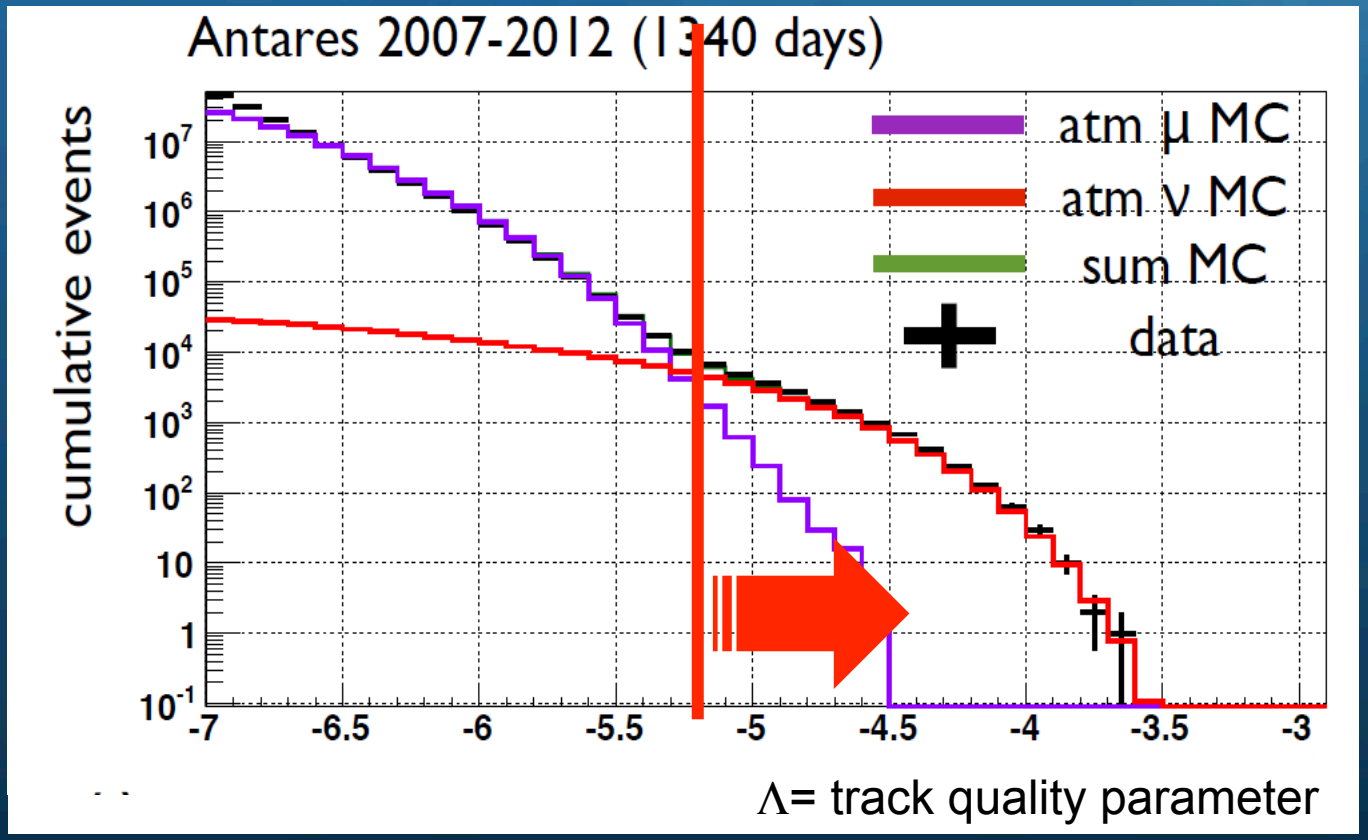
How to identify cosmic neutrinos ?



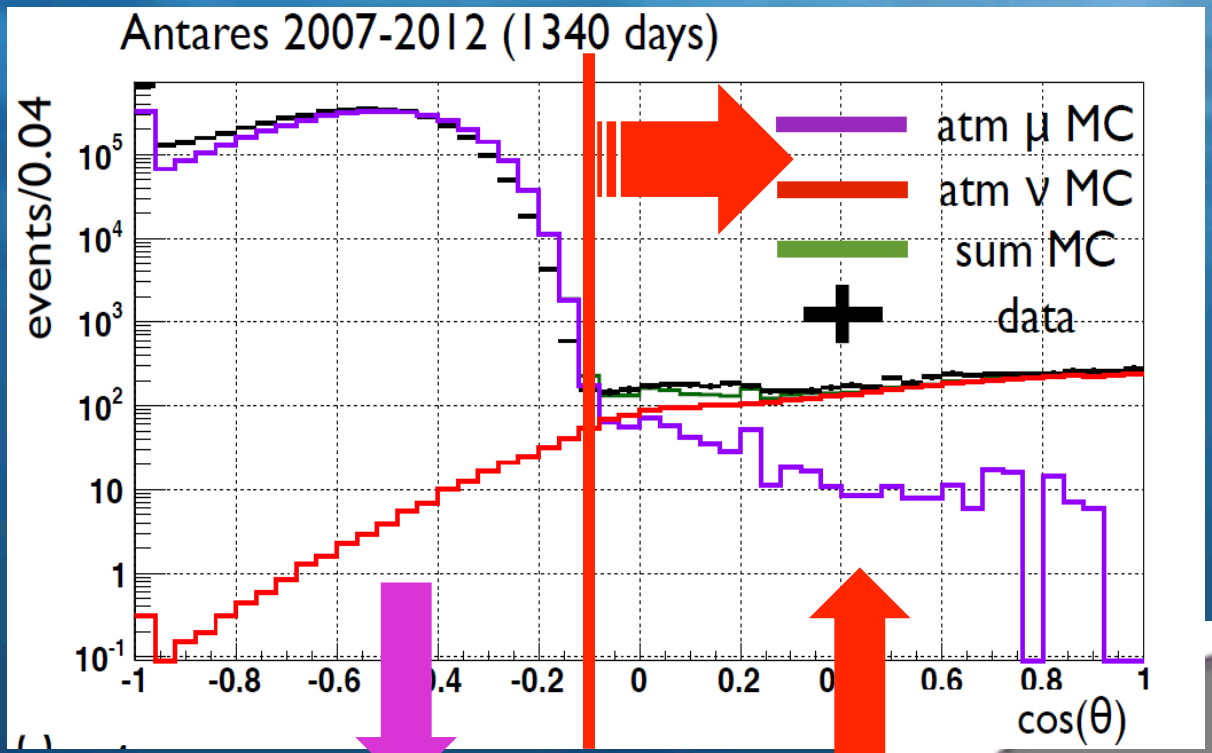
1) **anisotropies (clustering) on the sky**
   point source searches
2) **excess at high energies**
   diffuse flux analyses
3) **time and/or space coincidence with other astrophysical signals**
   multi-messenger strategies

Neutrino point source search

- Data period: 2007 - 2012 →~1340 days
- **Plot**: Number **of upgoing events** vs. fit quality parameter cut Λ
- Best cut to optimize the detector sensitivity Λ>-5.2



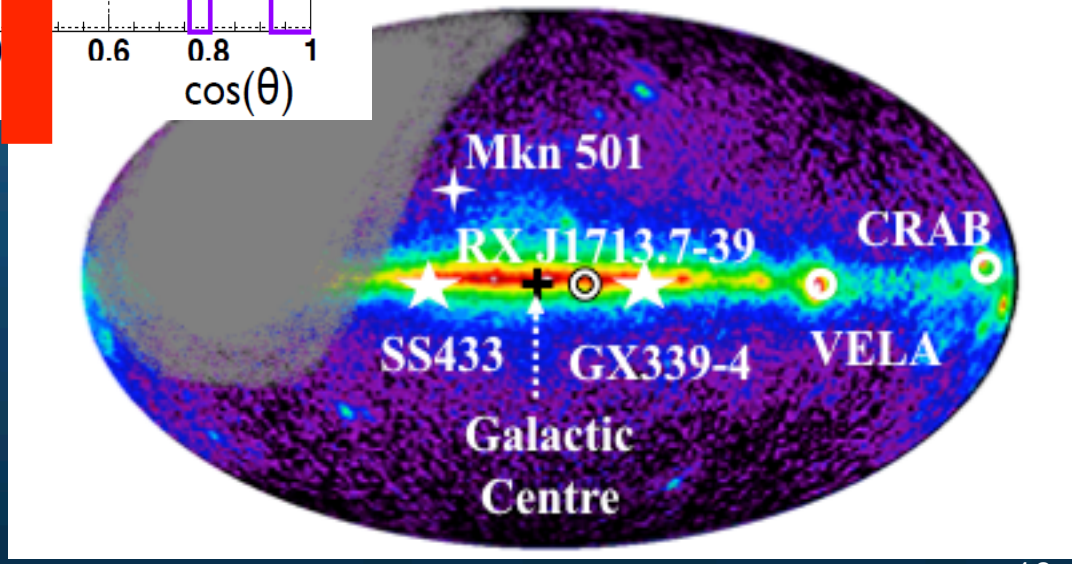
Neutrino point source search



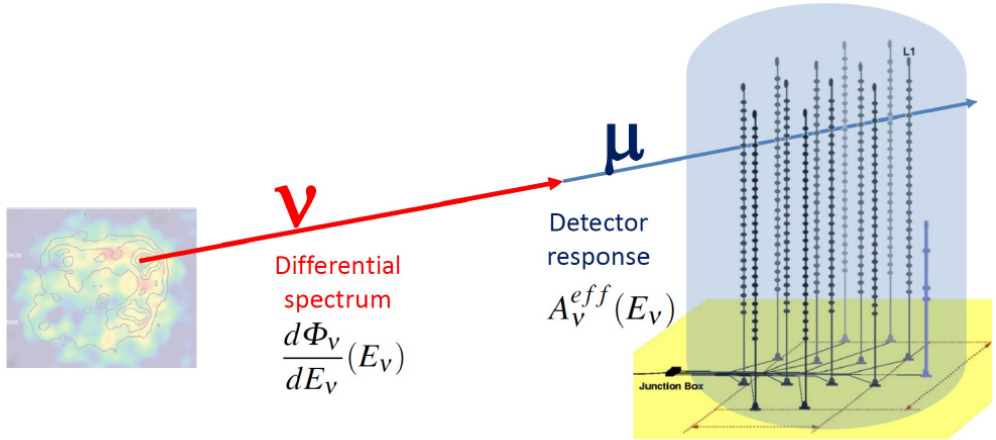
- **Plot:** Zenith angle distribution of **5516** candidate events
- **Blind analysis** (optimized with scrambled data set)

Analyses performed for :

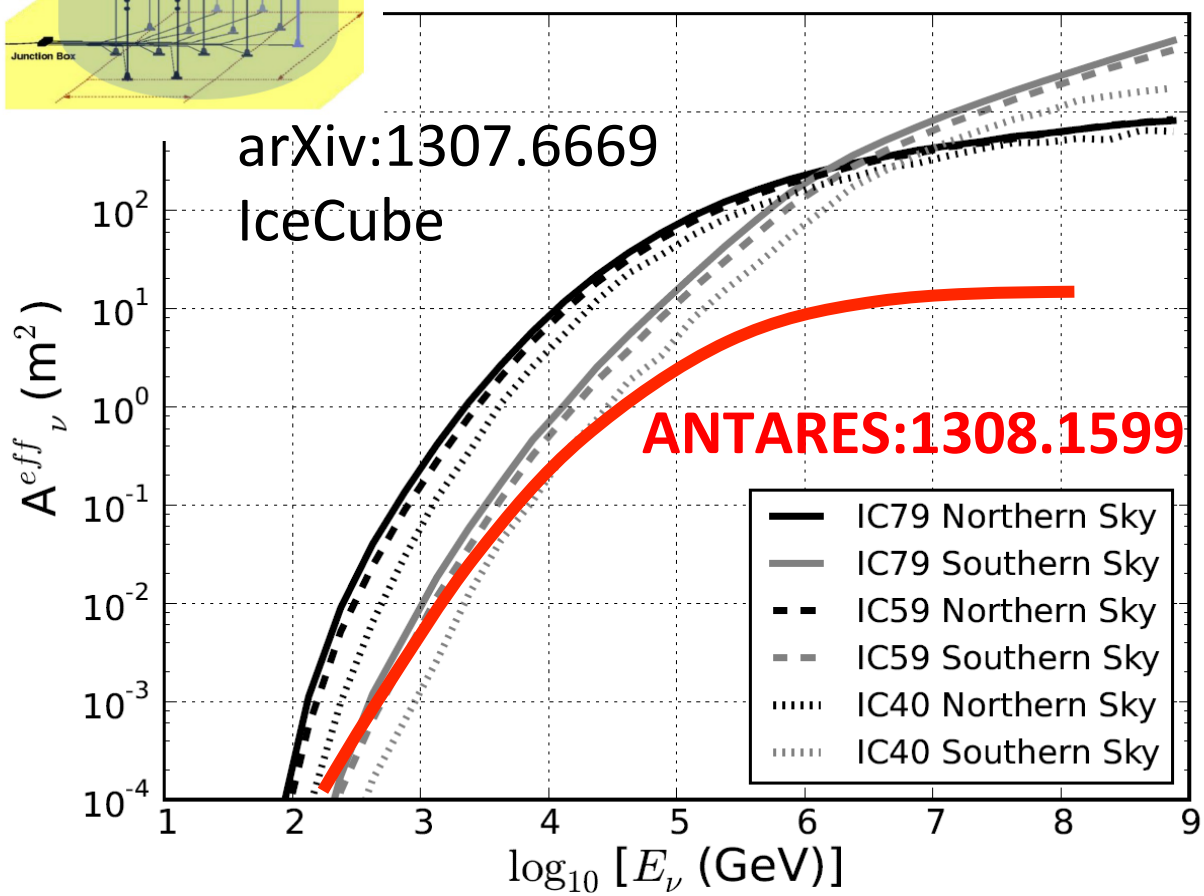
- All sky search
- Predefined list of 50 pre-selected candidate γ−sources



Neutrino point source - Effective area

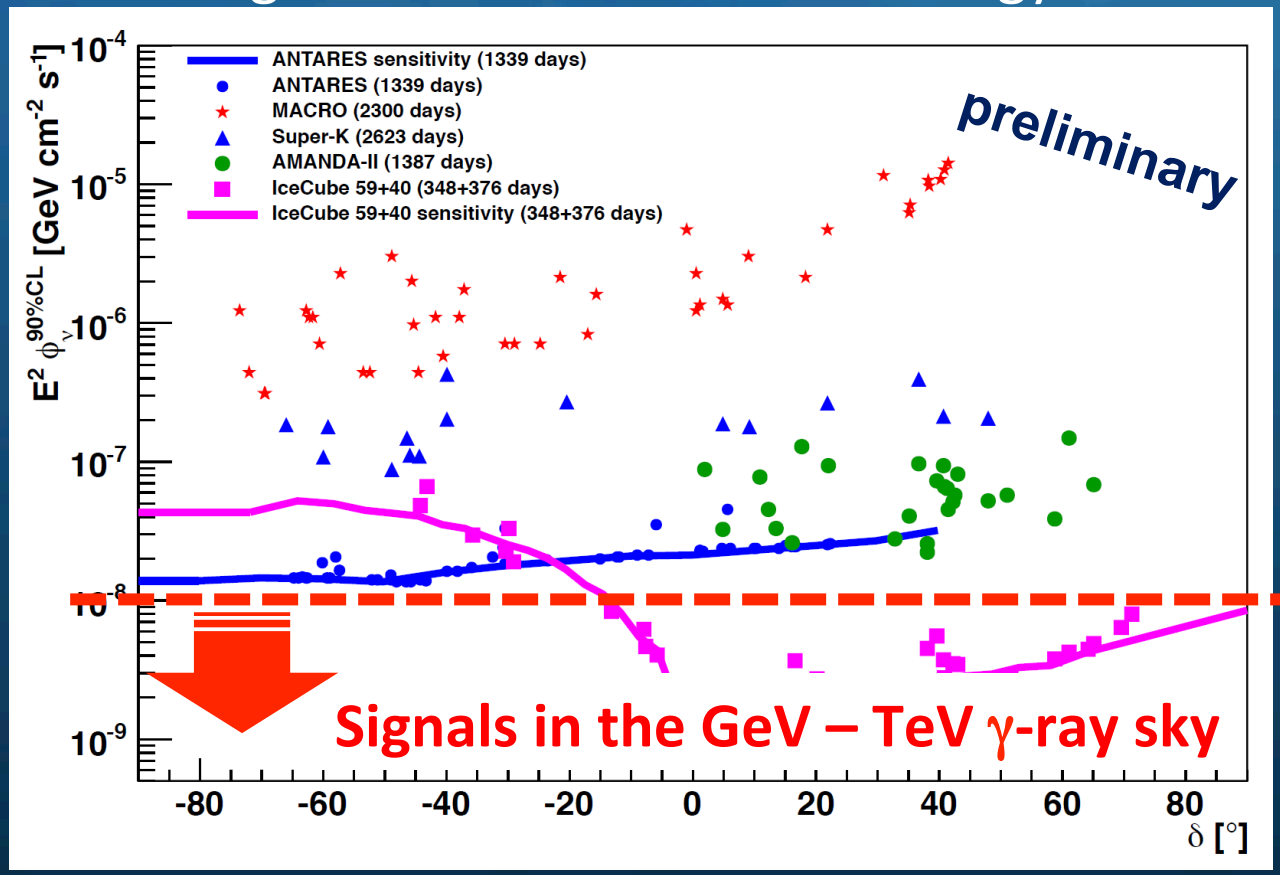


- Effective area depends on the source declination δ
- A^{eff} averaged on δ.



Neutrino point source –upper limits

- 50 pre-selected sources (mainly galactic)
- Most stringent limits for a large part of the Southern Sky
- Dedicated study of peculiar extended sources of γ-rays (RXJ1713,...) including the extension and the energy cut off



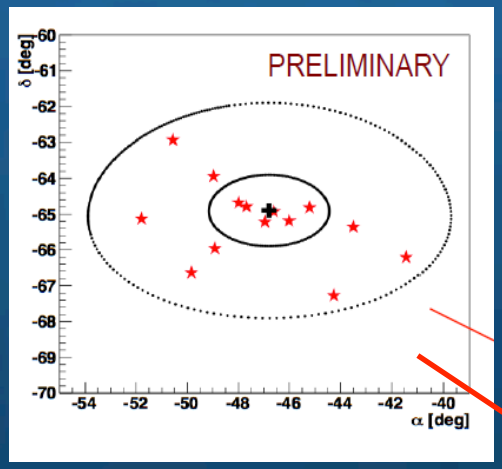
Upper limits and sensitivities
IC 40+59
ANTARES

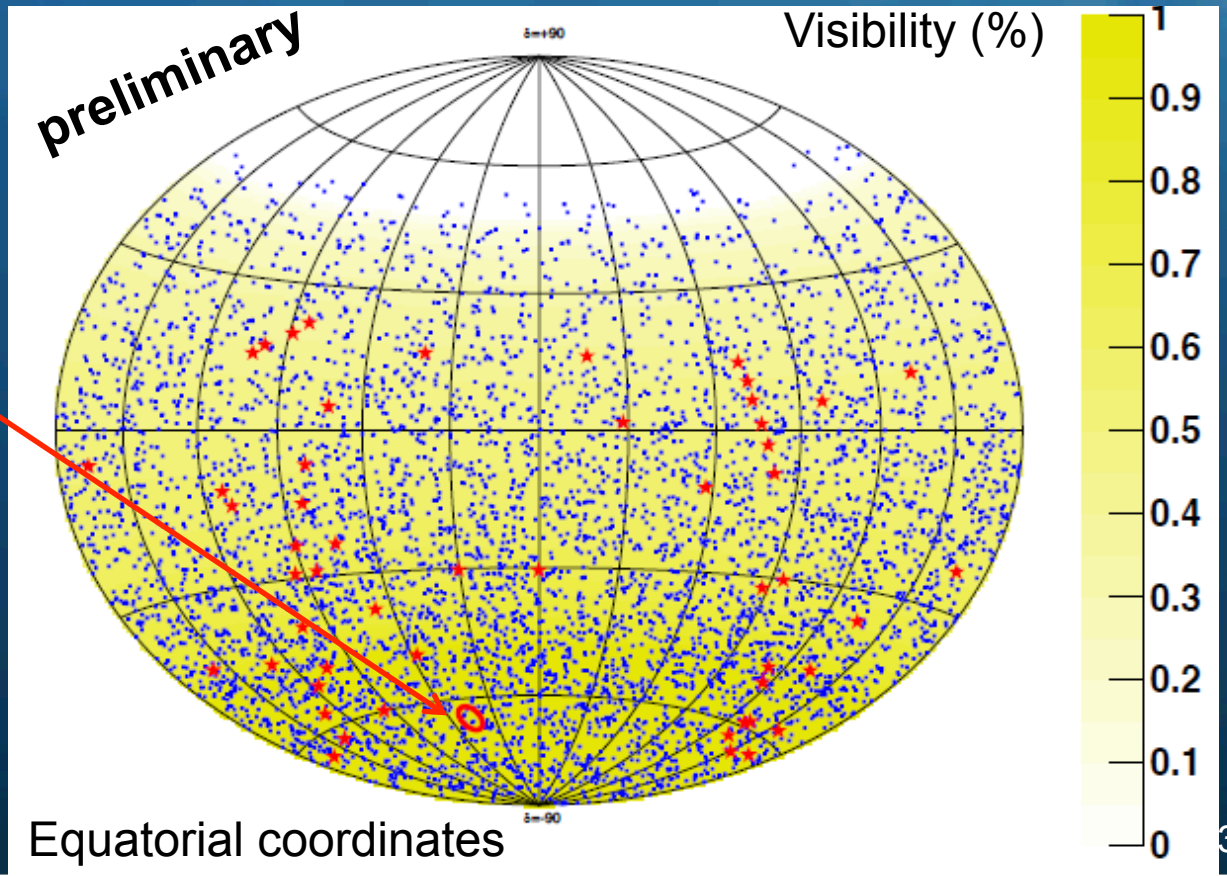
Details on 2007-2011 data sample: **ApJ760:53(2012))**

Neutrino point source search-all sky

ApJ760:53(2012)

- **All sky search (5516 events)**
- **Red stars: selected sources location**
- **No significant excess.** Most signal like cluster [6 (14) events in 1° (2°)] found at α = -46.80° , δ = -64.90°





Search for a diffuse cosmic ν_μ flux

- First search with 2008-09 data (**334 days** livetime) published on PLB696(2011)16
- Optimized on MC sample qualified on burn sample (10% data) for best limit

- Sensitivity

$E^2\Phi = 7.0 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

- Result: $n_{obs}=9$, $n_{bck}=10.7$

$E^2\Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Updated search 2008-2011 data:

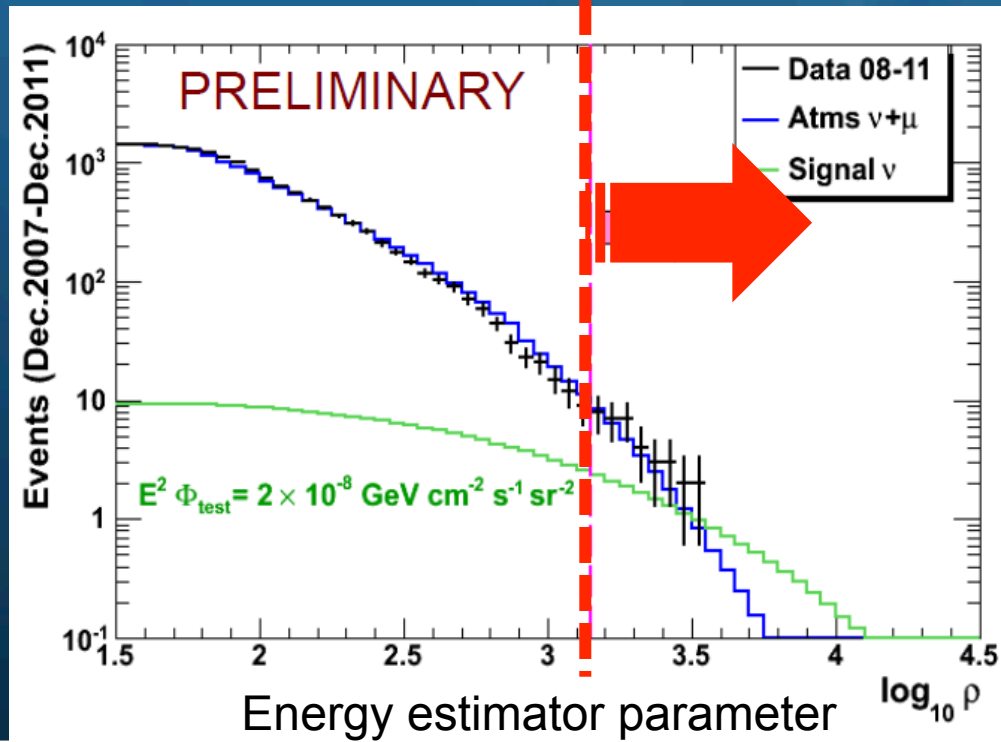
- **855 days** of equivalent livetime
- Improved energy estimator ρ based on muon dE/dX (**plot**: events vs ρ)
- Muon contamination negligible

- Sensitivity

$E^2\Phi = 4.7 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

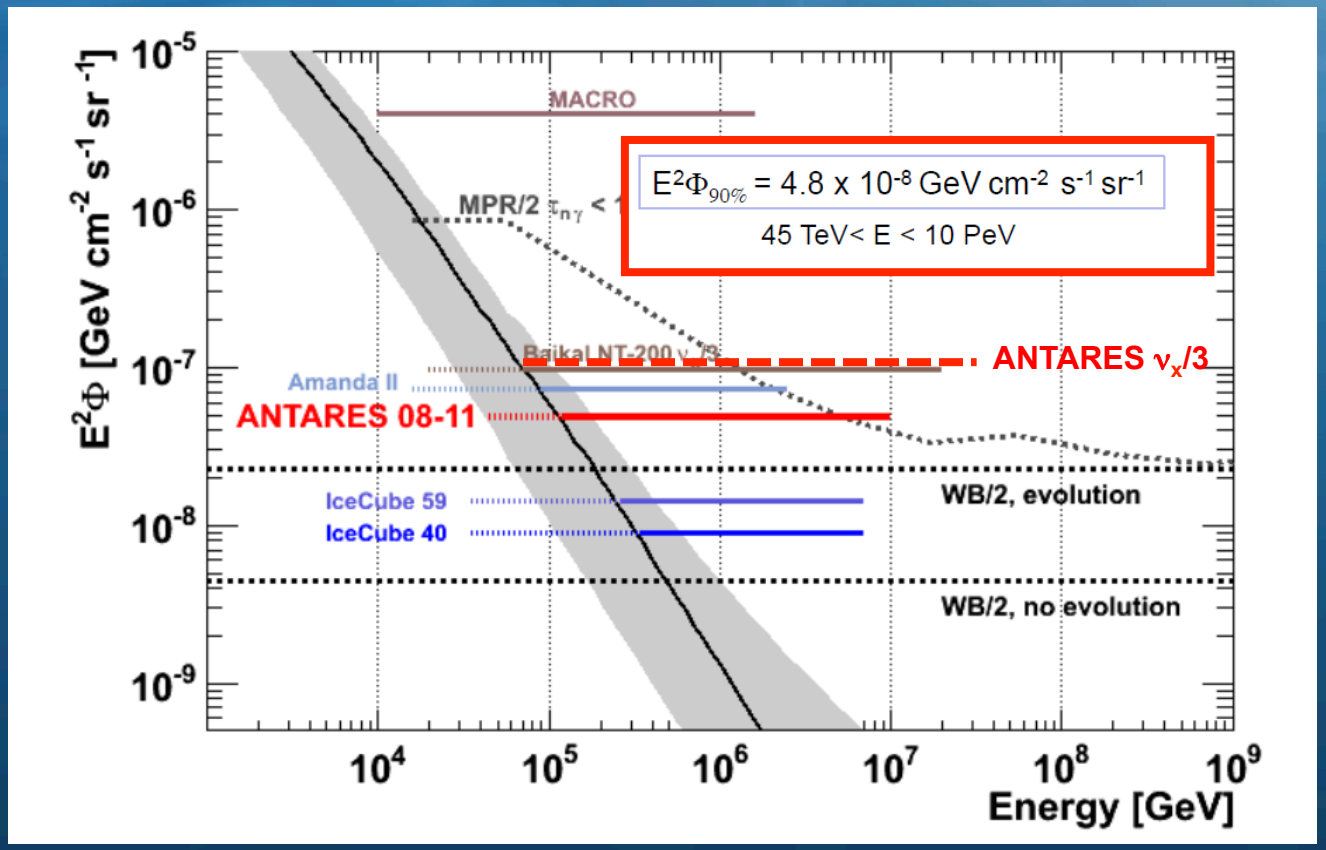
- Result: $n_{bck}=8.4$
- $n_{sig}^{WB}=2.3$ evts

$n_{obs}=8$



Search for a diffuse cosmic ν_μ flux

- More on diffuse flux on tomorrow presentation from J. Schnabel



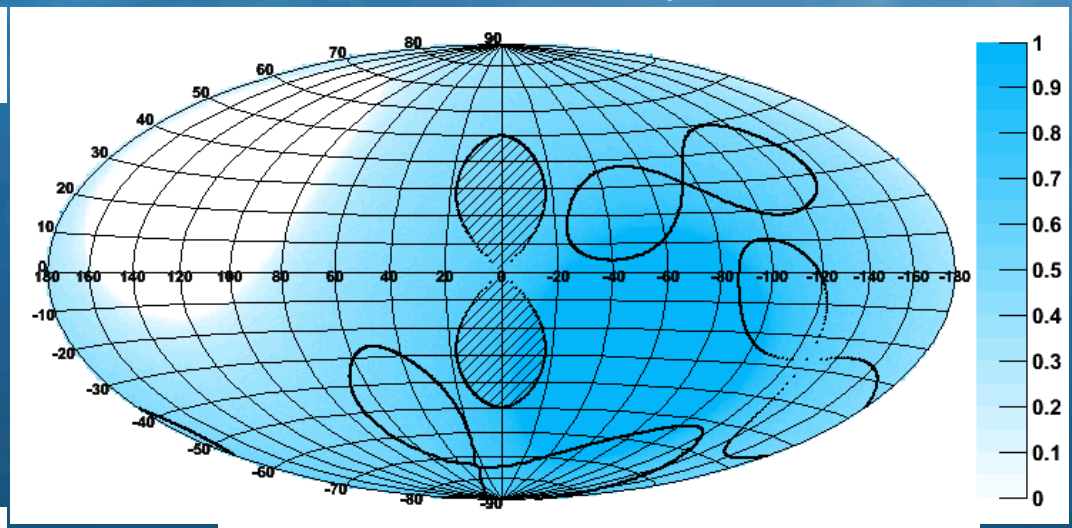
Showering events (all flavours)

- Analises in progress : smaller effective ν area → worse sensitivity to ν_x: $E^2\Phi_{90\%(\text{all flavors})} = 3\times10^{-7}$ GeV$cm^{-2}s^{-1}sr^{-1}$

ν from Fermi Bubbles: arXiv:1308.5260

- Excess of γ- (and X-)rays in extended "bubbles" above and below the Galactic Center. Galactic wind model involves hadronic processes

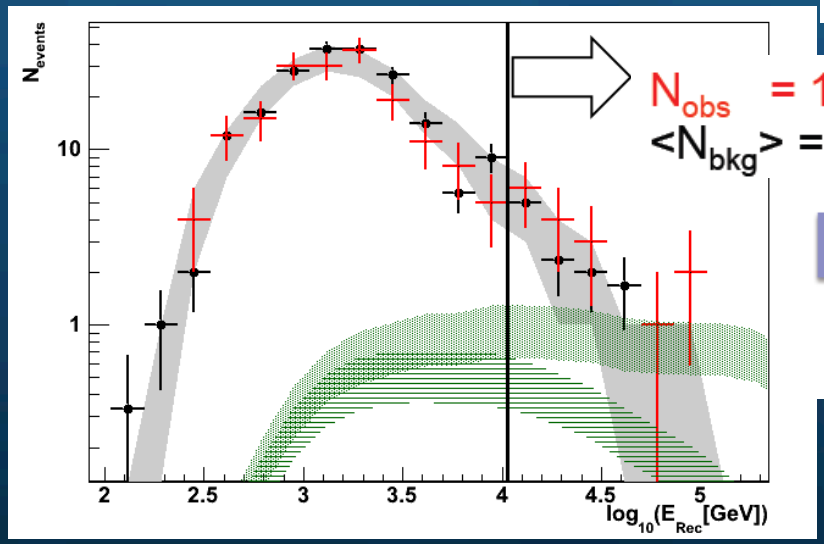
📖 Crocker & Aharonian, PRL 2011
$\Phi_\nu \approx 0.4 \times \Phi_\gamma$ 📖 M. Su et al., Ap. J. 724 (2010)



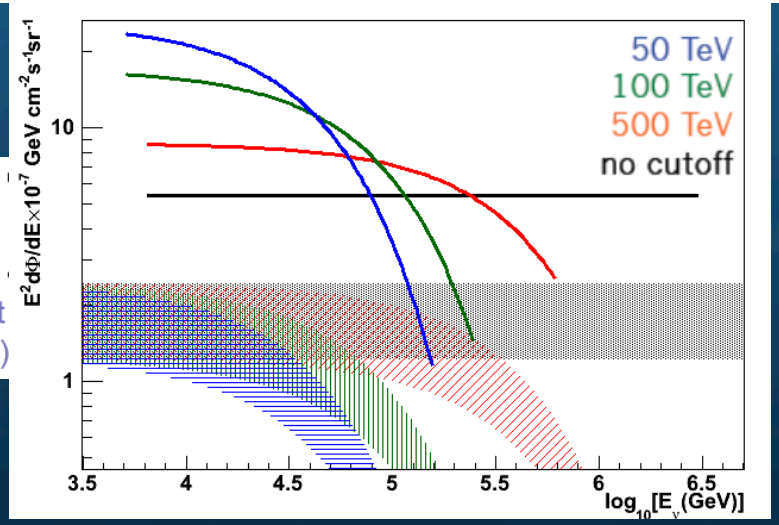
FB in the ANTARES field of view

Background estimated from 3 non-overlapping "off-zone" regions (same size, shape and average detector efficiency)

Results:



No significant excess (1.2 σ)



GRB triggered search: arXiv:1307.0304

- Search for neutrino events in coincidence with observed GRB
- Time and direction known → background reduction→ improved sensitivity
- Analysis of **296** long GRBs from 2007 – 2011 - Information from FERMI/SWIFT/GCN

Plot:

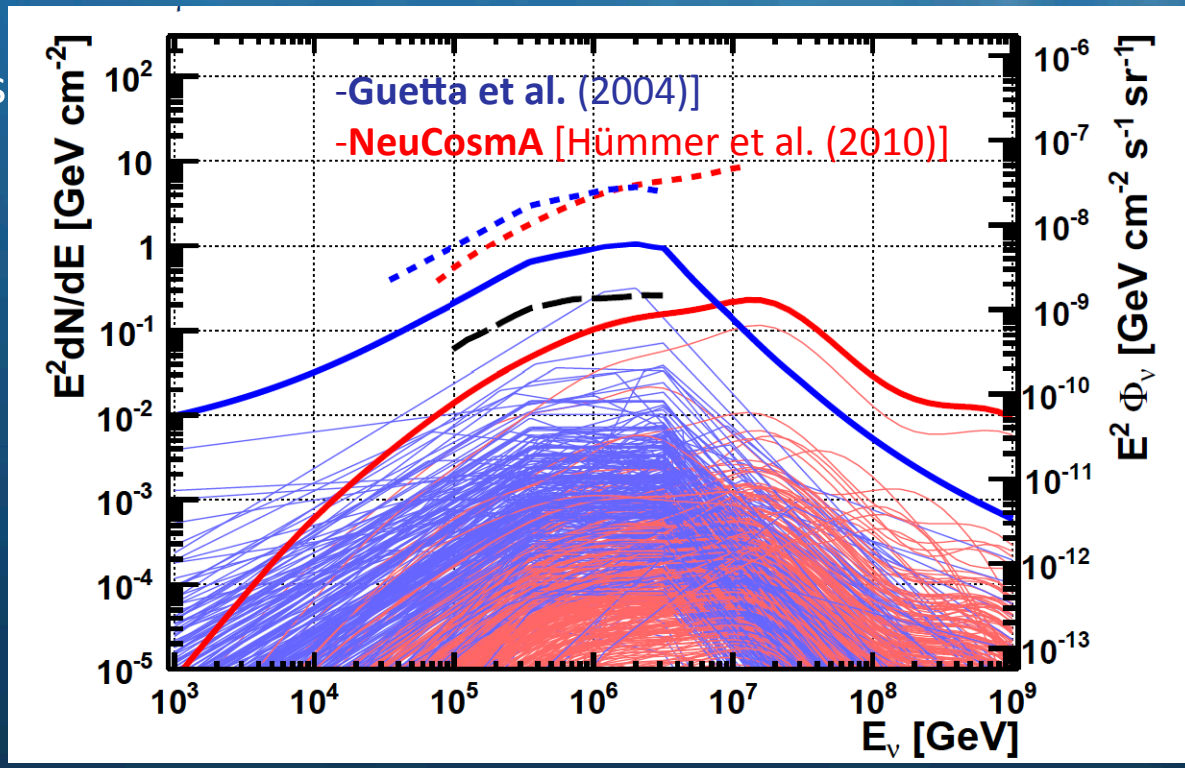
•Thin: Individual GRB simulations of expected neutrino fluence

Thick: sum of the 296 individual spectra

•No coincident ν_μ were found

Expected events: 0.48 (Guetta), 0.061 (NeuCosmA): 90% c.l. upper limits on diffuse flux

•Black line: IceCube IC40+59 limit, **300** GRBs (Abbasi et al., 2012)

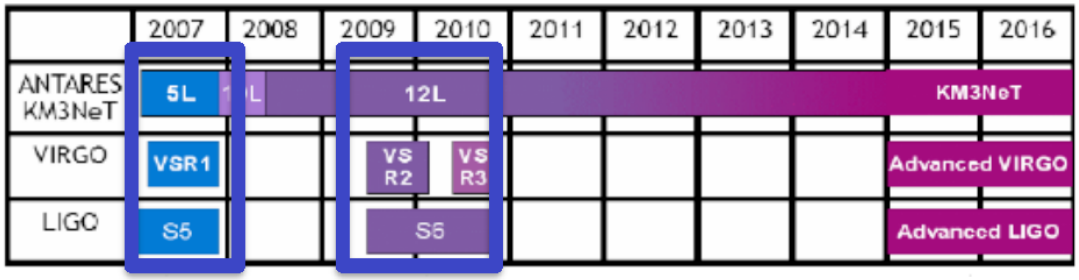


Search for Coincidences with Gravitational Waves

S. Adrián-Martínez *et al* JCAP06(2013)008

Main motivations : plausible common sources (GRB, Soft Gamma-ray Repeater) discovery potential for hidden sources (e.g. failed GRB)

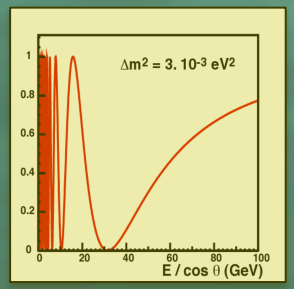
Effective collaboration (MoU) between LSC and ANTARES since Sept 2009

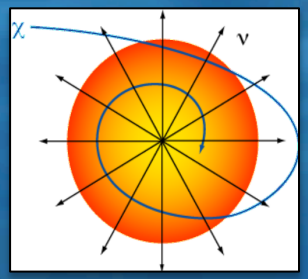


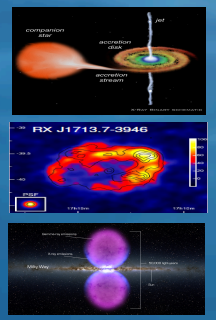
- Search methodology: HEν selected events trigger the search for GW in time/space coincidence
- First analysis completed with 2007 concomitant dataset. No coincidence found → exclusion distances on common GW/HEN emitters
- Improved Analysis of 2009-2010 dataset ongoing

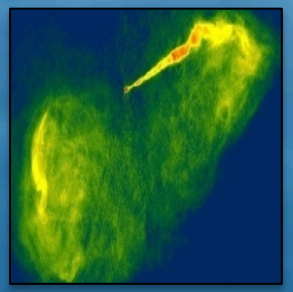
Science with ANTARES (II)

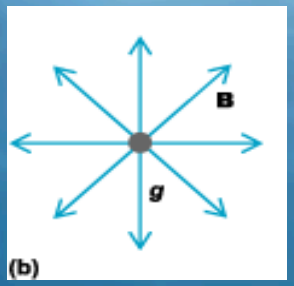
Oscillations | Dark Matter | SNR, μQSO | AGN, GRB | Exotics, GZK











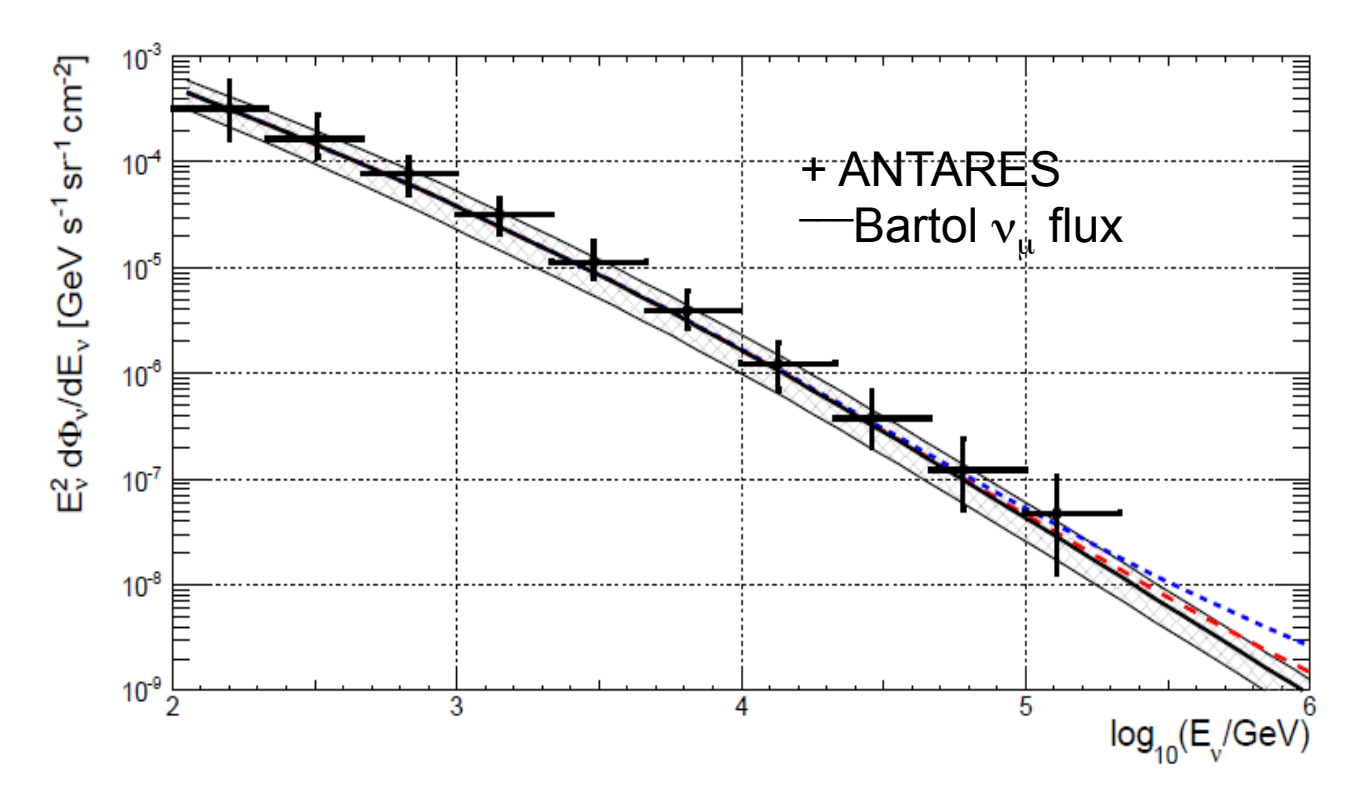
GeV | TeV | PeV | EeV

- 12-line data taking since 2008; physics duty cycle ≈ 85%
- ~20 atmospheric muons/sec

  directional cut + quality cut on likelihood of track fit
- **~5 atmospheric neutrinos/day (> 7000 ν_μ detected so far)**
- Median angular resolution 0.3° – 0.4°
- Visibility: ¾ of the sky, most of the Galactic Plane
- Effective area ≈ 1 m^2 at 30 TeV

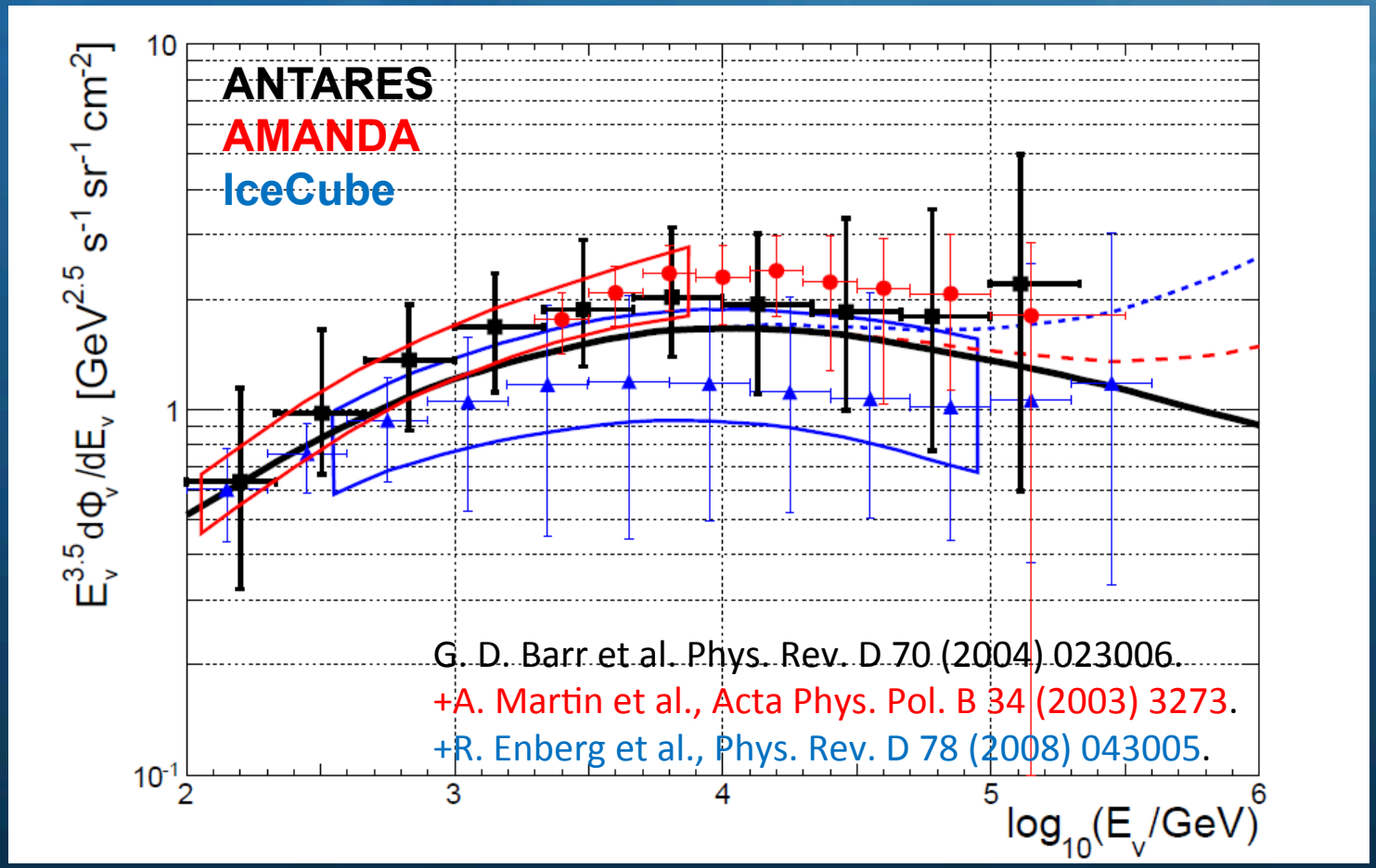
Atmospheric ν_μ flux: arXix1308.1599

- Measurement of the atmospheric ν_μ energy spectrum in the energy range 0.1 - 200 TeV using data collected by the ANTARES 2008 to 2011 (855 days)
- Data set: the same of the point-sources analysis



Atmospheric ν_μ flux: arXix1308.1599

- Comparison with Antarctic measurements
- No evidence for "prompt neutrino contribution"
- Submitted to EPJC

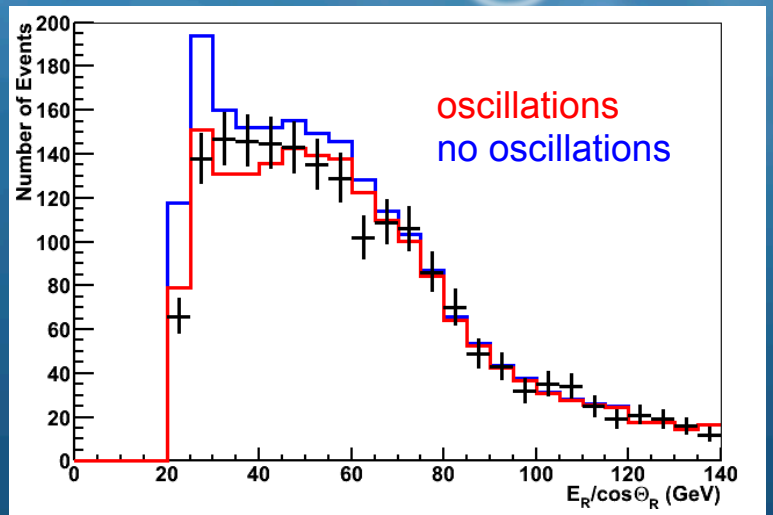


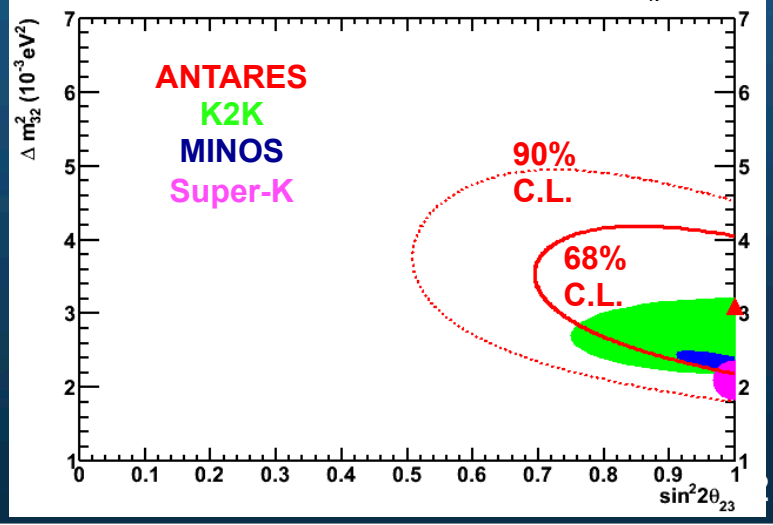
Neutrino oscillations - PLB 714(2012)224

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{32})\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2(2\theta_{32})\sin^2\left(\frac{1.27\Delta m^2_{32} D_{Earth}\cos\Theta}{E_\nu}\right)$$

Two-flavour mixing approximation

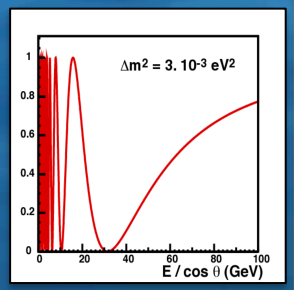
- 1st oscillation minimum (Θ=0) at 23 GeV
- Data sample: 2007-2010 (863 active days)
- Muon energy from range
  - 20 GeV < E_ν < 100 GeV
  - median angular resolution 0.8° (multi-line) , 3° (single-line)
- 1st measurement of neutrino oscillation parameters by ν Telescopes (followed by IC)
- Underlines the potential of low-energy measurements of the detector (DM)

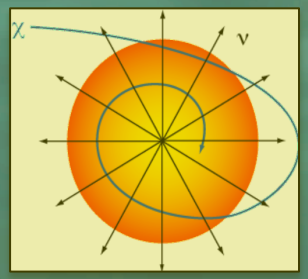


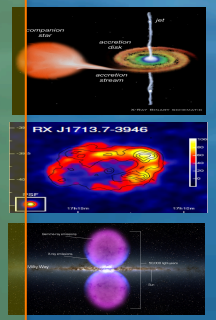


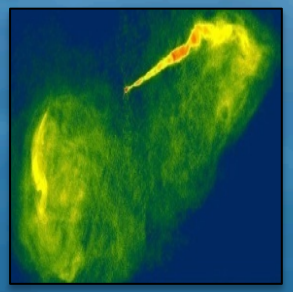
Science with ANTARES (III)

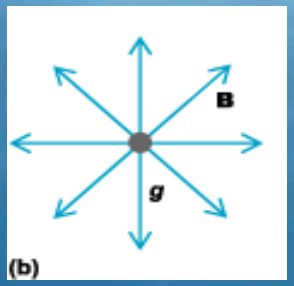
Oscillations | Dark Matter | SNR, μQSO | AGN, GRB | Exotics, GZK



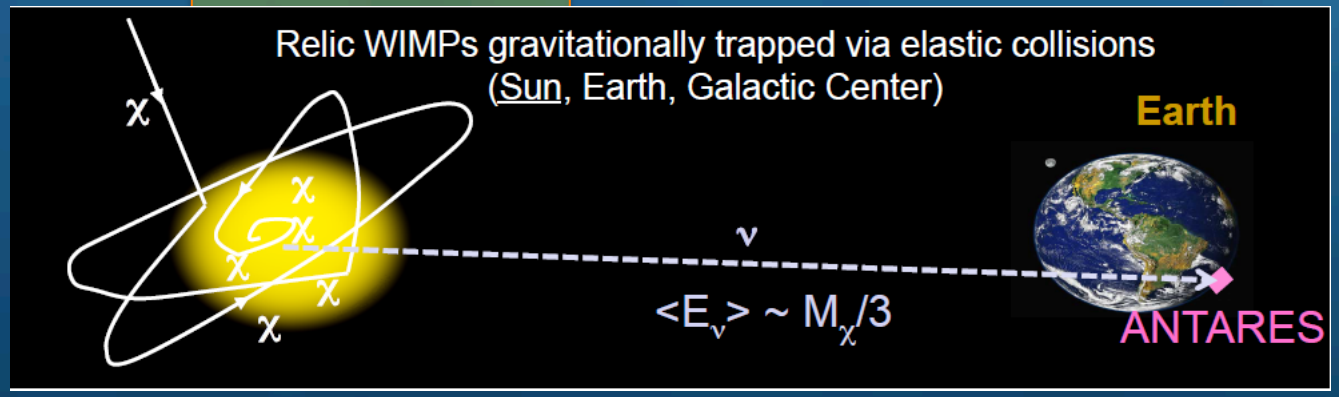








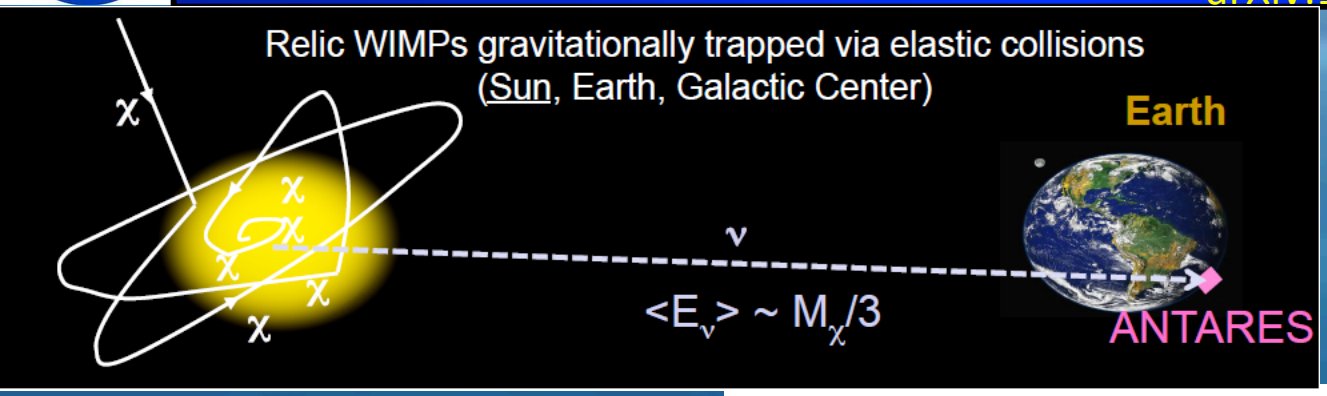
GeV | TeV | PeV | EeV

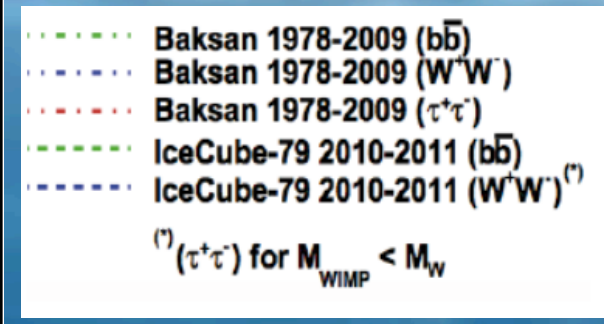


- HE neutrinos from the Sun → Clean DM signature
- Models where the Lightest SUSY Particle (LSP) is stable (R-parity conservation) are considered
- Self WIMP-WIMP annihilation in c,b,t quarks, τ leptons or W, Z,H bosons induce HE neutrino flux

Indirect search for Dark Matter

arXiv:1302.6516v1, subm. to JCAP

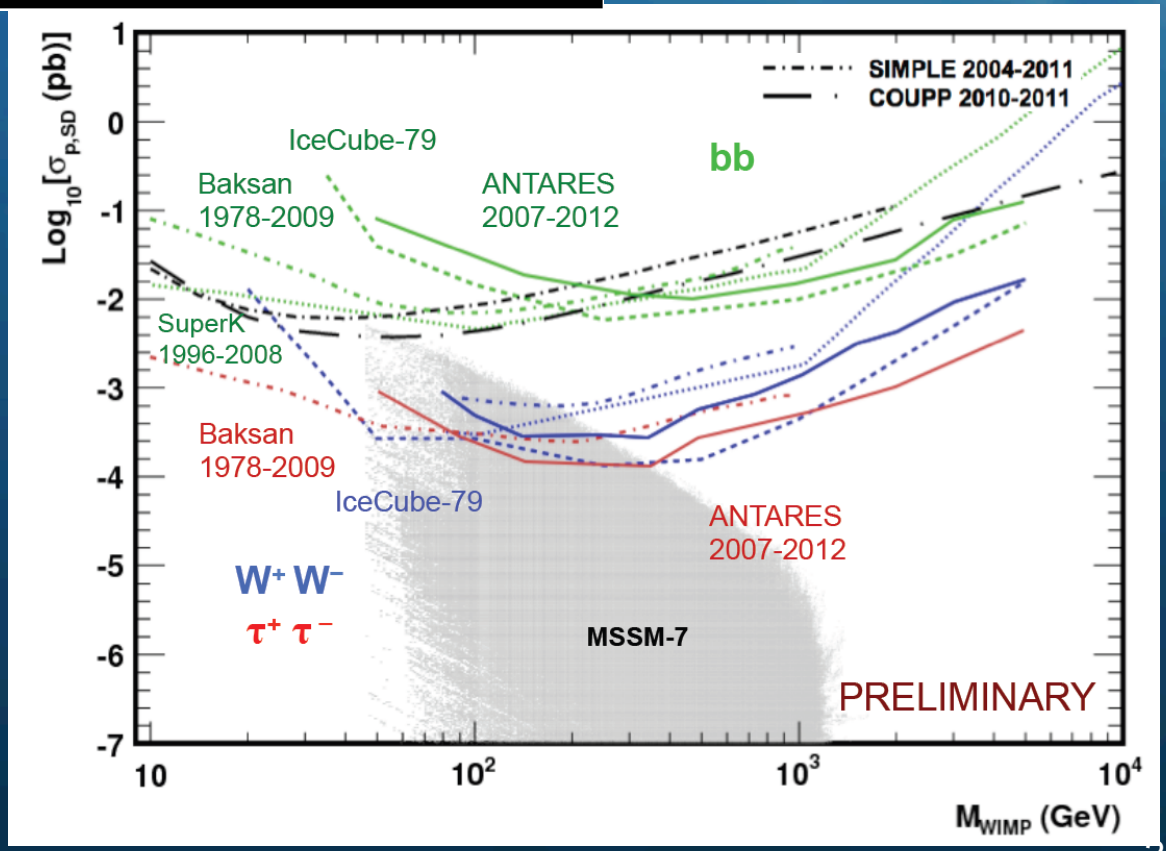




- Limits on WIMP-proton SD/ SI cross sections (equilib. capture/annihilation)
- Much better sensitivity on SD cross sections w.r.t direct detection

- **Plot:** Comparison to predictions of MSSM-7 phenomenological model.

L. Bergström & P. Gondolo, Astropart. Phys. 5 (1996) 263-27



Summary

- ANTARES is the largest NT in the Northern Hemisphere.

- Extensive multi-messenger program.

- Competitive and complementary astrophysics results w.r.t. the IceCube telescope.

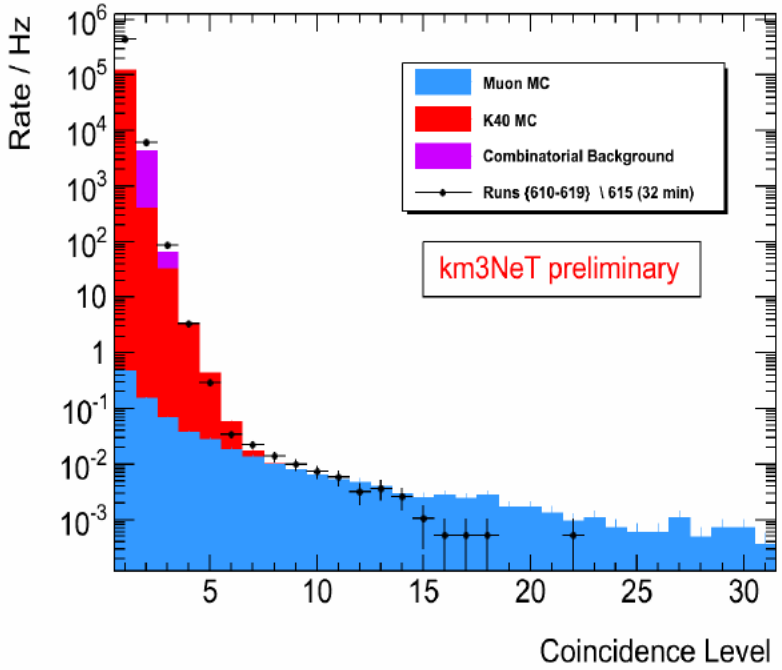
- Although technologically challenging, ANTARES is working according to specifications.

- Proves the feasibility of a deep sea Mediterranean Neutrino Telescope → KM3NeT

Spares

ANTARES and KM3NeT

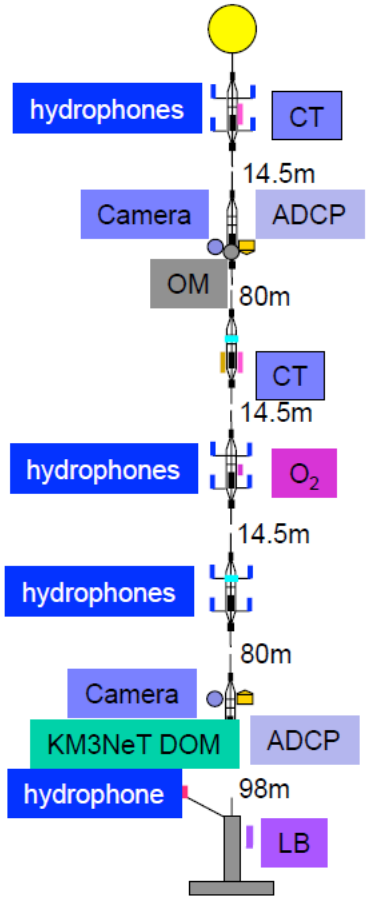
KM3NeT already taking data from an ANTARES line !



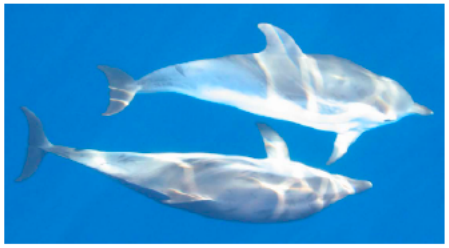
KM3NeT DOM – 31 3" PMTs works well

Earth and Sea Sciences

Instrumentation Line

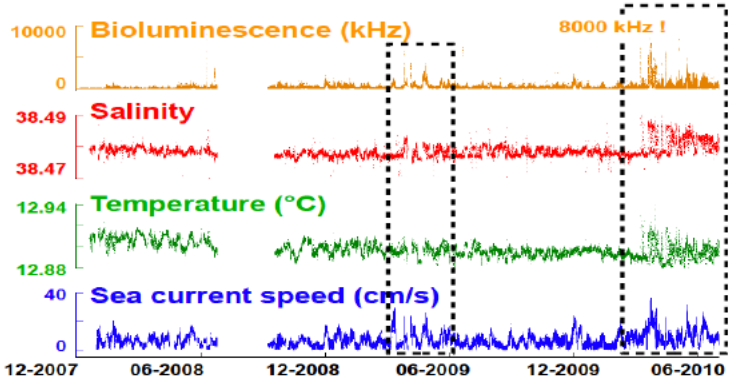


Video-monitoring
The deepest webcam
in the world?



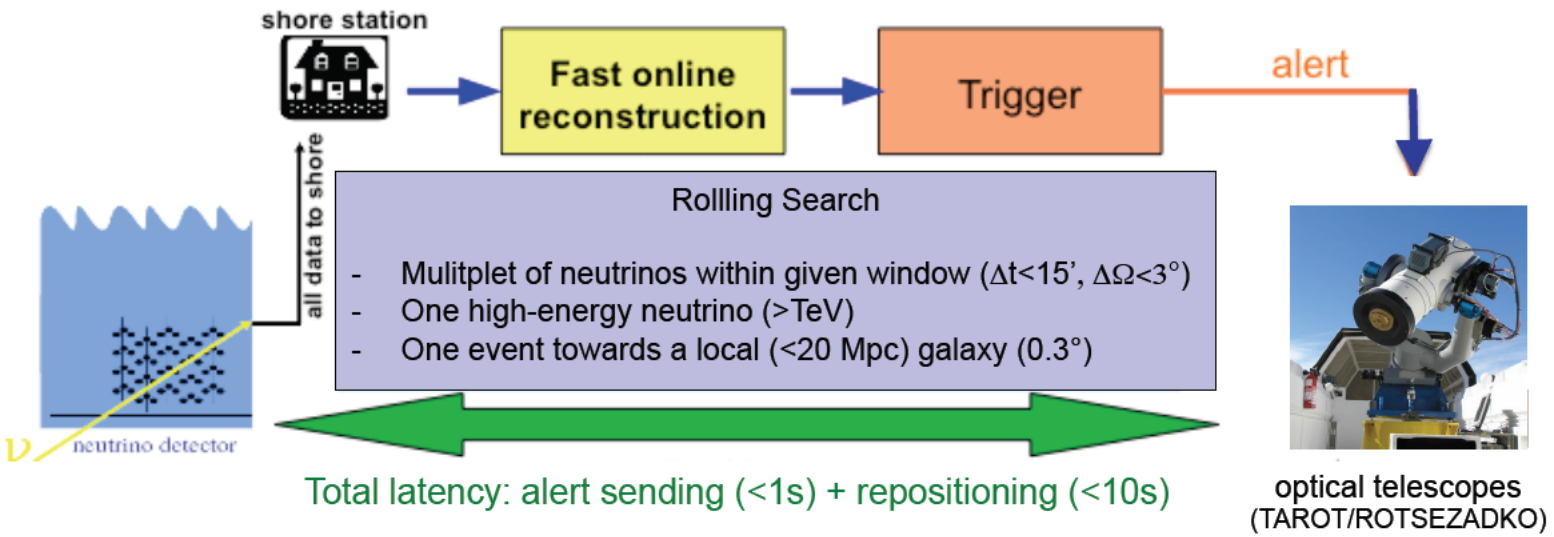
Acoustic noises

ANTARES = multi-disciplinary observatory

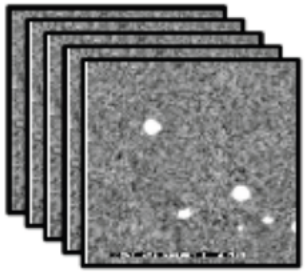


C. Tamburini et al., to appear in PLOS one
H. van Harenz et al. Deep-Sea Research I 58 (2011) 875–884.

Alerts and Follow-up Program: TAToO



- Large sky coverage, high duty cycle
- No hypothesis on the nature of the source
- Sensitivity improved: 1 doublet is 3σ evidence, 1 triplet is 5σ !
- System active since 2009 with optical telescopes, now extended to SWIFT/XRT



T_0, T_0 +1, 3, 9 and 27 days

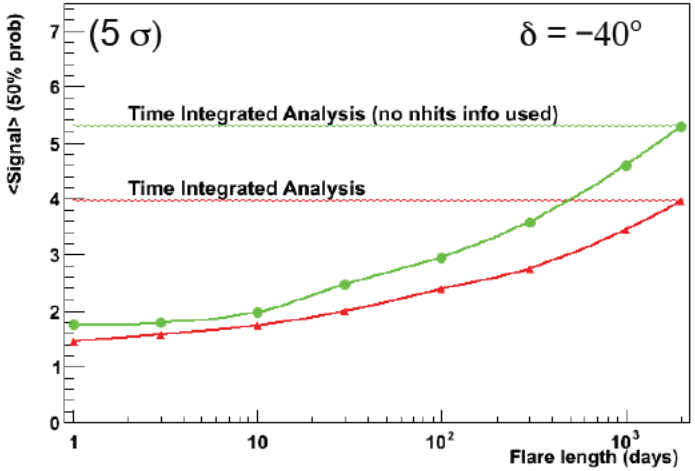
📖 Astropart. Phys. 35 (2012) 530

Search for neutrinos from flaring sources

❖ Search with 6 microquasars

- 2007-2010 data set (813 days)
- Microquasars with (x/γ)-ray outbursts
- Likelihood ratio method (no energy proxy)
- No events detected in coincidence
- Flux limit above predictions

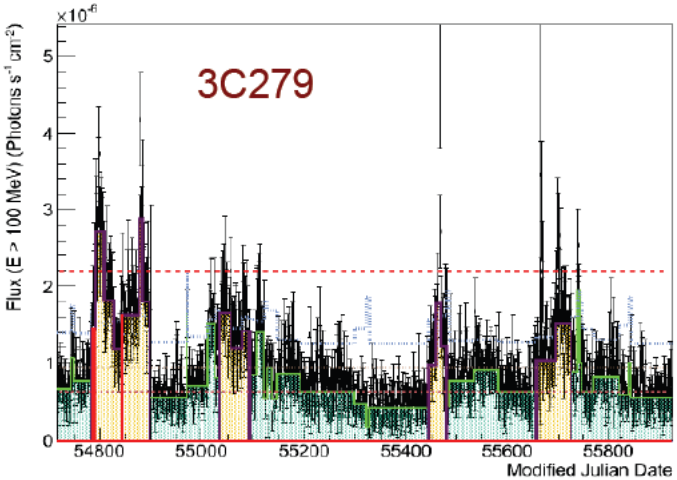
📖 Levinson, Waxman (2001) & DiStefano et al. (2002)



❖ Recent search with 41 blazars

- 2008-2011 data (750 days livetime)
- 86 flaring periods 2FGL+Fermi Flare Advocates
- Improved likelihood with energy proxy (Nhits)

☞ Poster ID 0296



PRELIMINARY

- Lowest p-value (12%) 3C279 (2 events)
  Compatible with background fluctuation

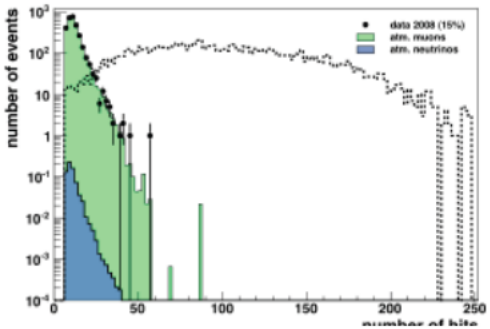
📖 Astropart. Phys. 36 (2012) 204

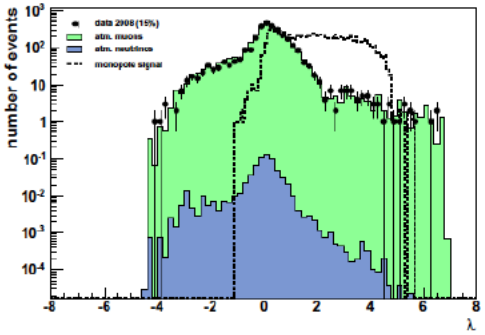
Magnetic Monopoles ($M<10^{14}$ GeV)

- Required in many models of spontaneous symmetry breaking ('t Hooft, Polyakov)

- ANALYSIS (15% burn sample) :
  - Modified track reconstruction with β free
  - Optimisation to maximise discovery power

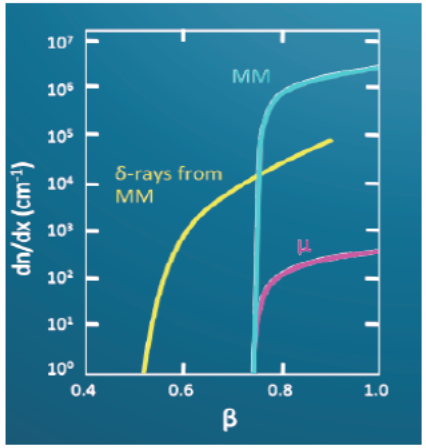
Nhit



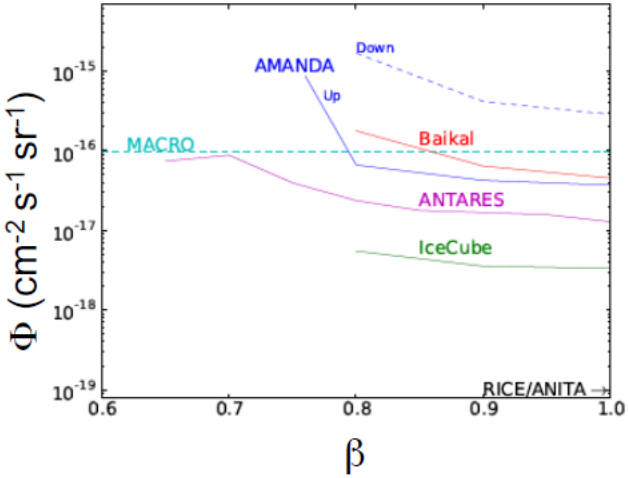


$$\lambda=\log(\chi^2_{\beta=1}/\chi^2_{\beta})$$

High light yield



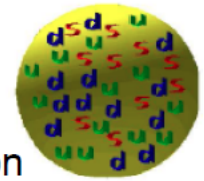
ANTARES data 2007-2008 (116 days)



📖 Astropart. Phys. 35 (2012) 634–640

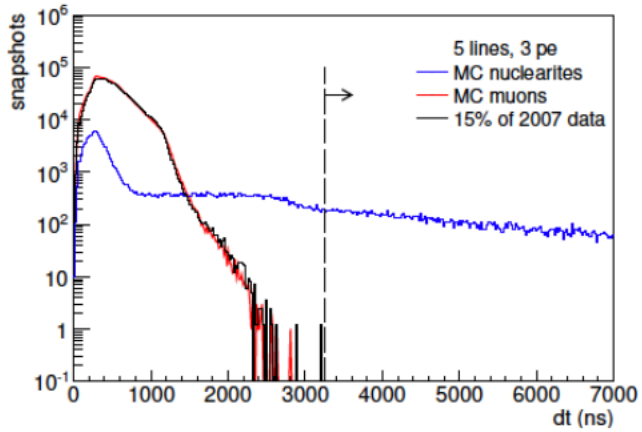
Search for Nuclearites

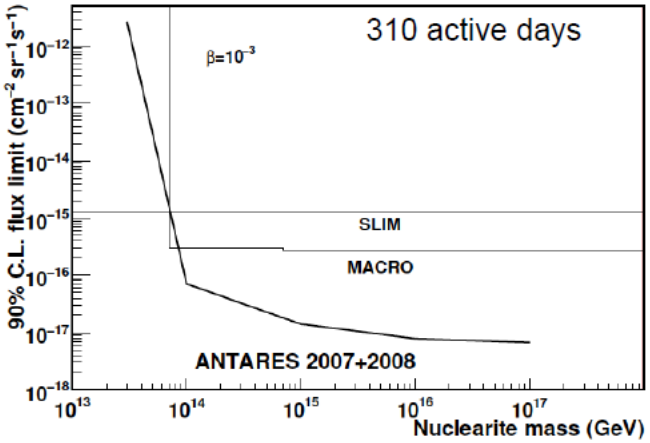
- Lumps of up, down and strange quarks proposed by E. Witten in 1984
- Stable, ~neutral (most or all electrons inside the quark core)
- Produce in water a thermal shock wave → large yield of black body radiation
- Slow moving massive particles, $\beta \sim 10^{-3}$
- Cold Dark Matter candidate



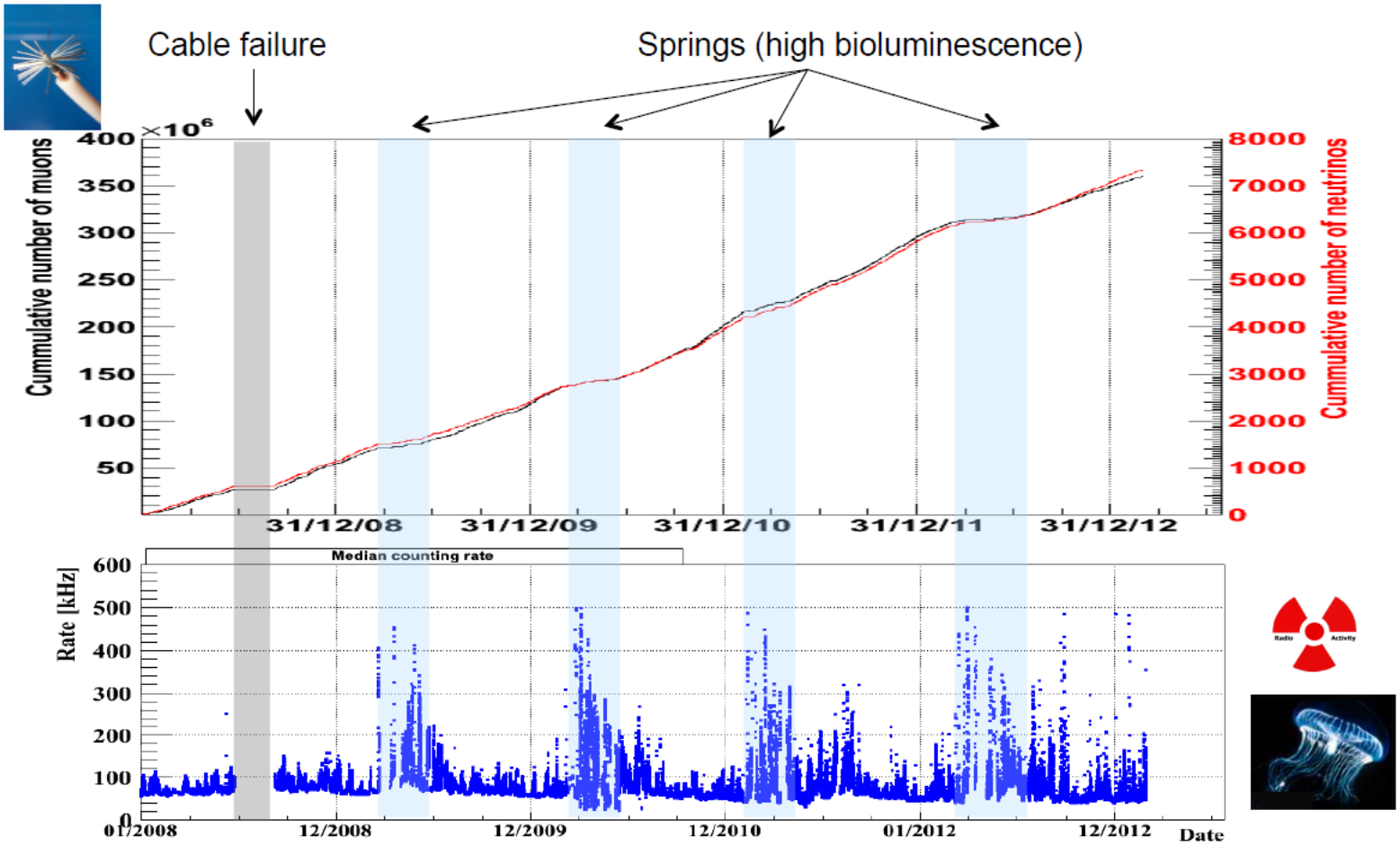
STRANGE MATTER

- ANALYSIS (15% burn sample): Selection based on
  - event duration
  - Charge barycenter vs time distributions



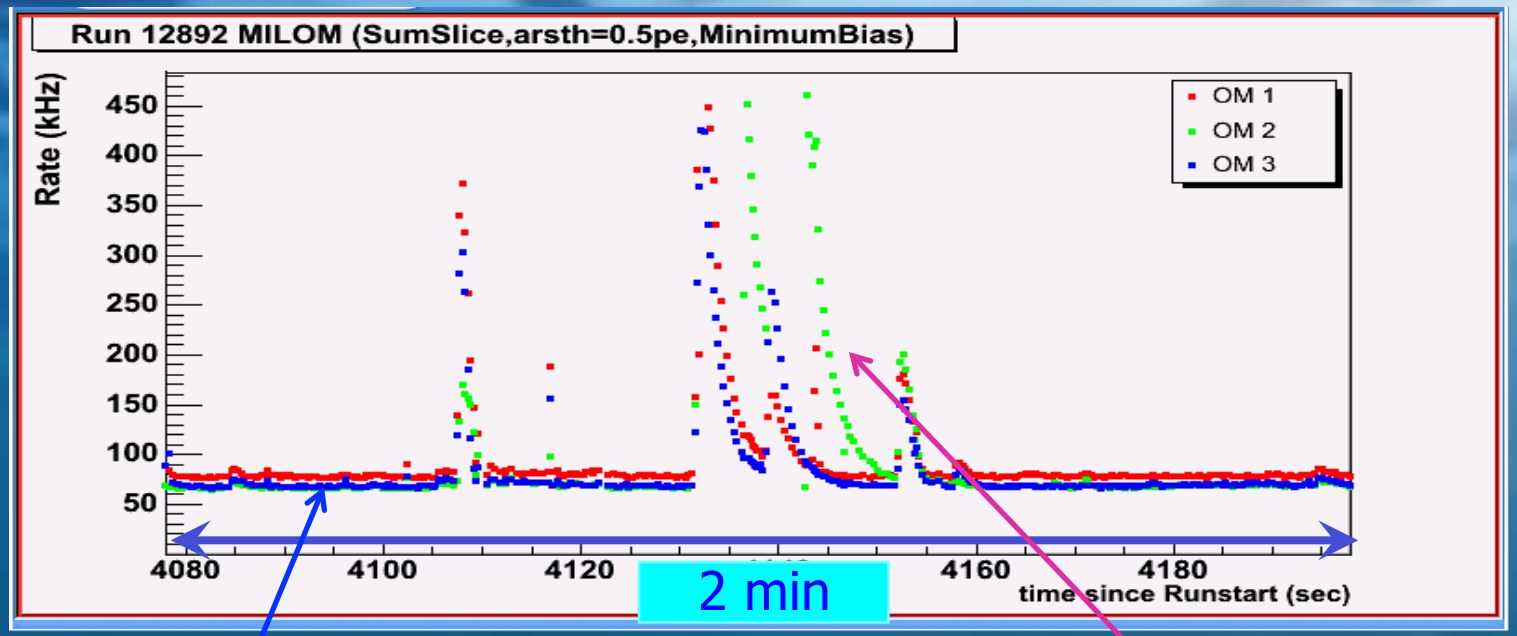


Evolution of acquisition



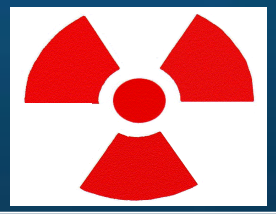
12-line data taking since 2008 (physics duty cycle ≈ 85%)

Counting Rates (short timescale)



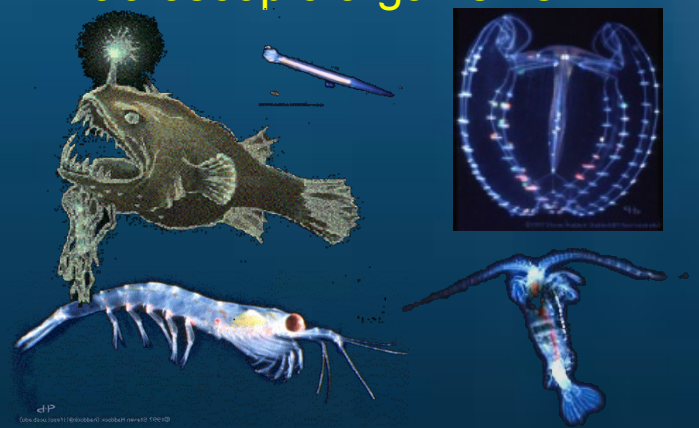
Continuous baseline:
Radioactivity in the sea (^{40}K)
+ bioluminescent bacteria

^{40}K

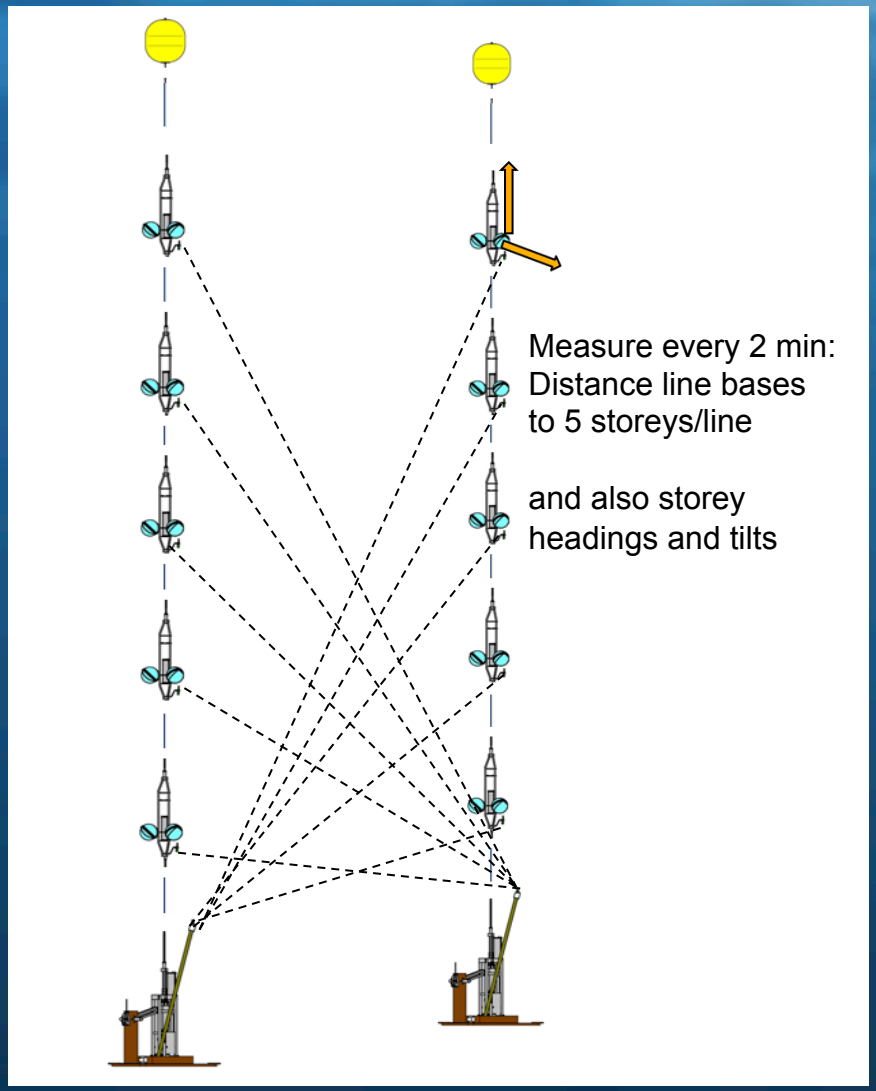


$$^{40}_{19}\mathrm{K} \rightarrow ^{40}_{20}\mathrm{Ca} + \mathrm{e} + \bar{\nu}_{\mathrm{e}}$$

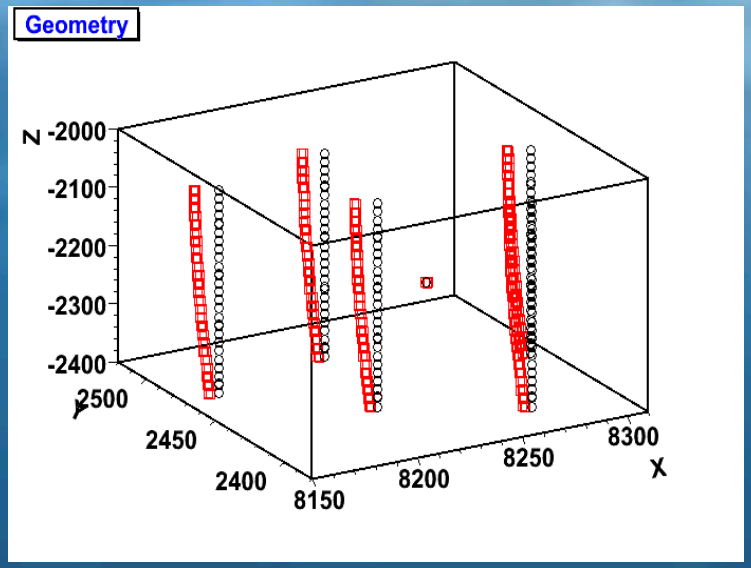
Bursts:
bioluminescence from
Macroscopic organisms

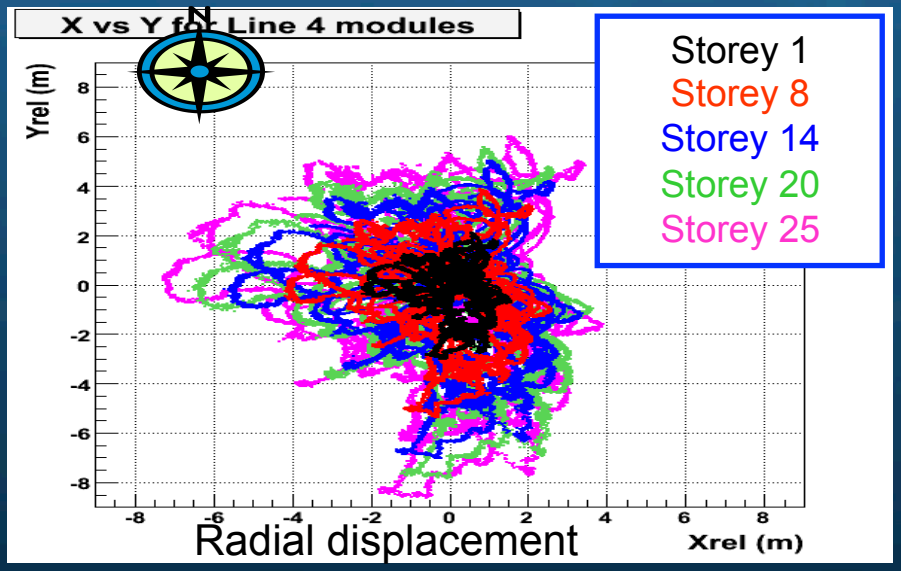


Acoustic Positioning



Precision ~ few cms





Radial displacement

Detection principles

Detector:
3D array of
photomultipliers

Cherenkov light
from μ

42°

"We propose getting up an apparatus in an underground lake or deep in the ocean in order to determine the location of charged particles with the help of Cherenkov radiation" M. Markov, 1960

Earth's
crust

μ

ν_μ

interaction

Detection principles

Moisey Markov and Bruno Pontecorvo in the Baksan conference "Neutrino and Cosmology". Baksan Valley, 1977

Detector:
3D array of
photomultipliers

Cherenkov light
from μ

42°

Earth's
crust

μ

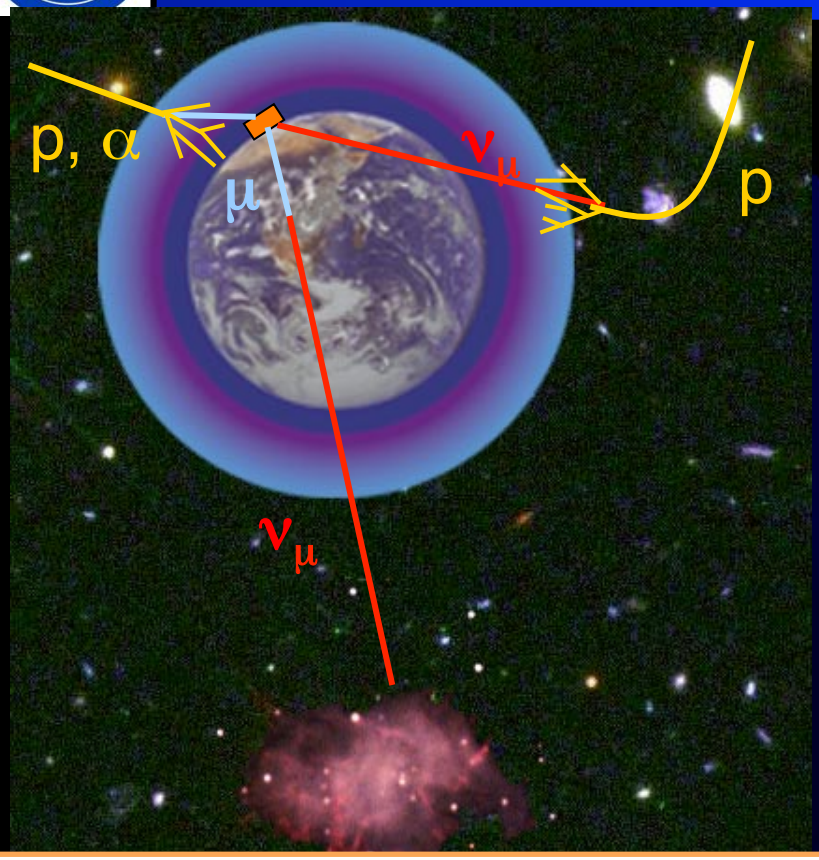
ν_μ

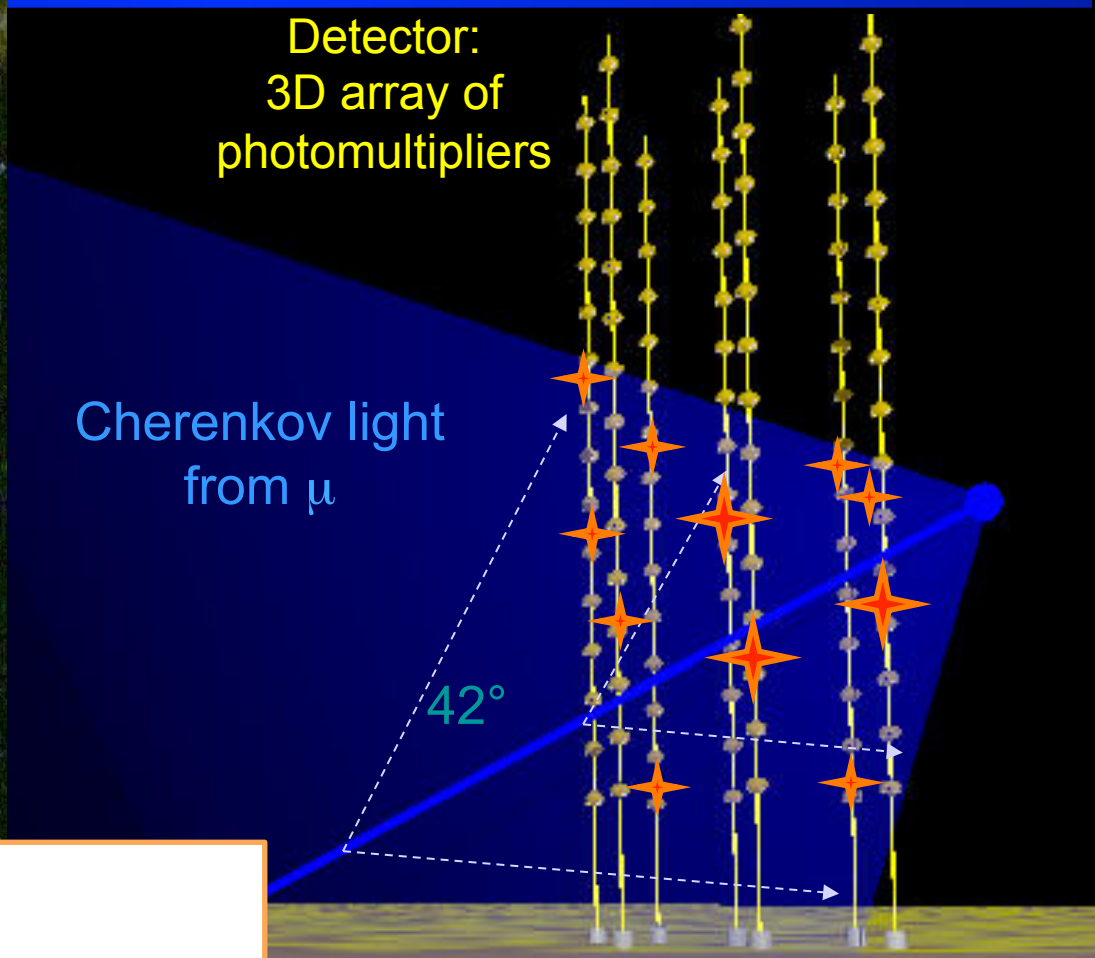
interaction

time, position & amplitude of hits

energy & arrival direction of ν

Detection principles





Physical backgrounds:

- ❖ atmospheric neutrinos
- ❖ atmospheric muons

⇒ **detectors buried deep**

⇒ **detectors look downwards**

- cut on zenith angle θ > 90°
- cut on track fit quality

time, position & amplitude of hits

↓

energy & arrival direction of ν