Hunting for cosmic neutrinos deep under the sea: The ANTARES experiment

Vincenzo Flaminio for the ANTARES Collaboration

(Physics Dept. & INFN-Pisa)

Huge progress in γ-ray experiments over last decades

Atmospheric Cerenkov Experiments
(Cangaroo, Hess, Magic, HEGRA, VERITAS…)

Satellite-based γ-ray experiments
(SAS-2, COS-B, EGRET, FERMI…)

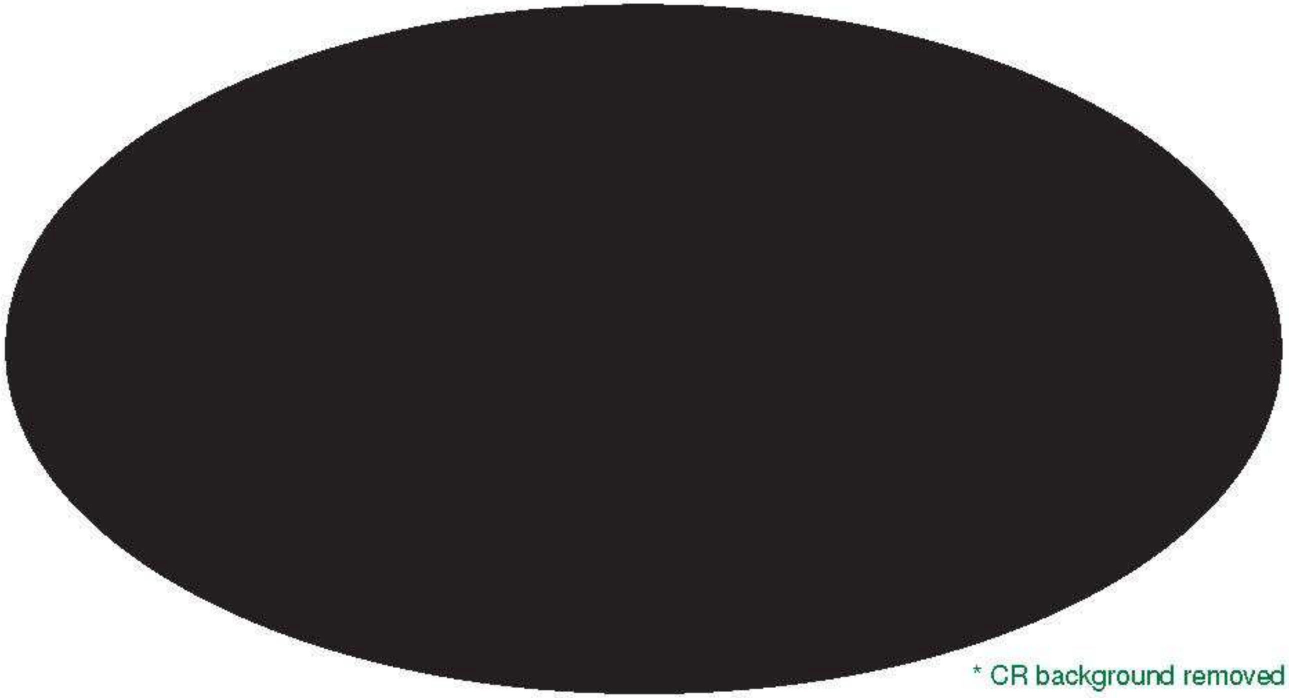
Ground-based shower detectors
(MILAGRO, TIBET, ARGO-YBJ…)

Against only three astrophysical neutrino experiments !!

(AMANDA-ICECUBE, Baikal, ANTARES)

As a result

Neutrino sky map* at very high energies



* CR background removed

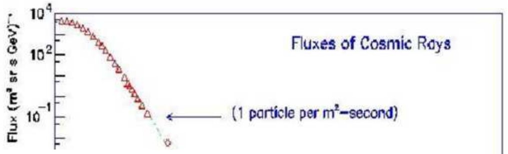
From Markus Ahlers (Neutrino 2012)

Interest of high energy cosmic neutrino detectors

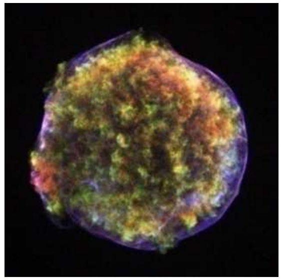
- **Understand production mechanism of HE cosmic rays**
- **Disentangle Synchrotron-Inverse Compton from Hadronic production in SNRs**
- **Study Binary systems, μQuasars…..**
- **Investigate the very high energy processes occurring in GRBs**
- **Search for Dark matter**
- **New probe → new observations**
- **Should it be successful, it would extend our view of the Universe to much bigger distances (moderate attenuation in interstellar material)**

Potential neutrino sources

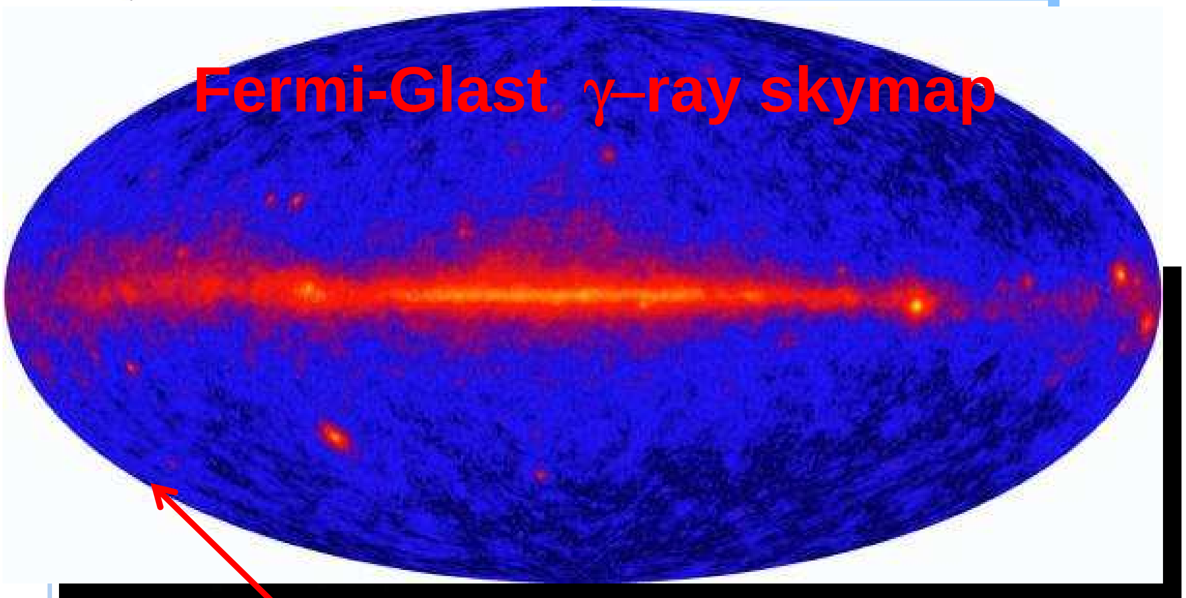
GALACTIC



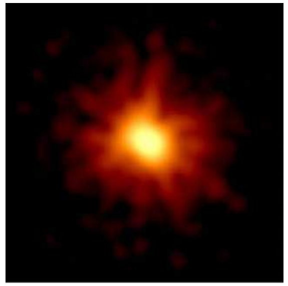
EXTRAGALACTIC



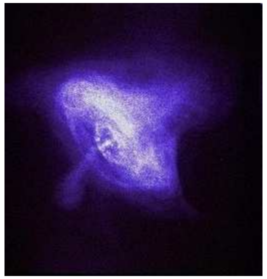
Supernova remnants



● Unidentified EGRET Sources
▲ LMC
● Solar FLare

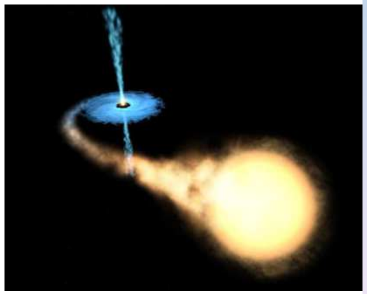


GRBs

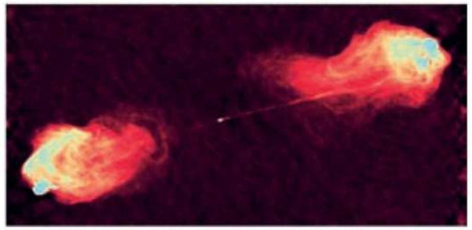


Pulsars

+ GZK neutrinos ??



Microquasars



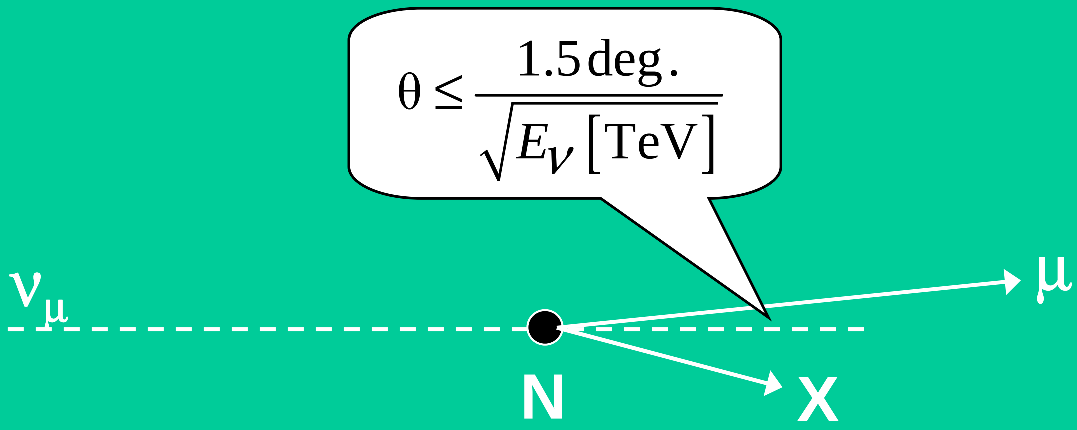
AGNs

Neutrino Telescopes

- Neutral particle → points back to source (undeflected by B fields)
- Weak interaction → negligible absorption

Tiny cross section
→ need huge detector

ν_μ **+ N →** μ **+ hadrons**
μ **measures** ν **direction**



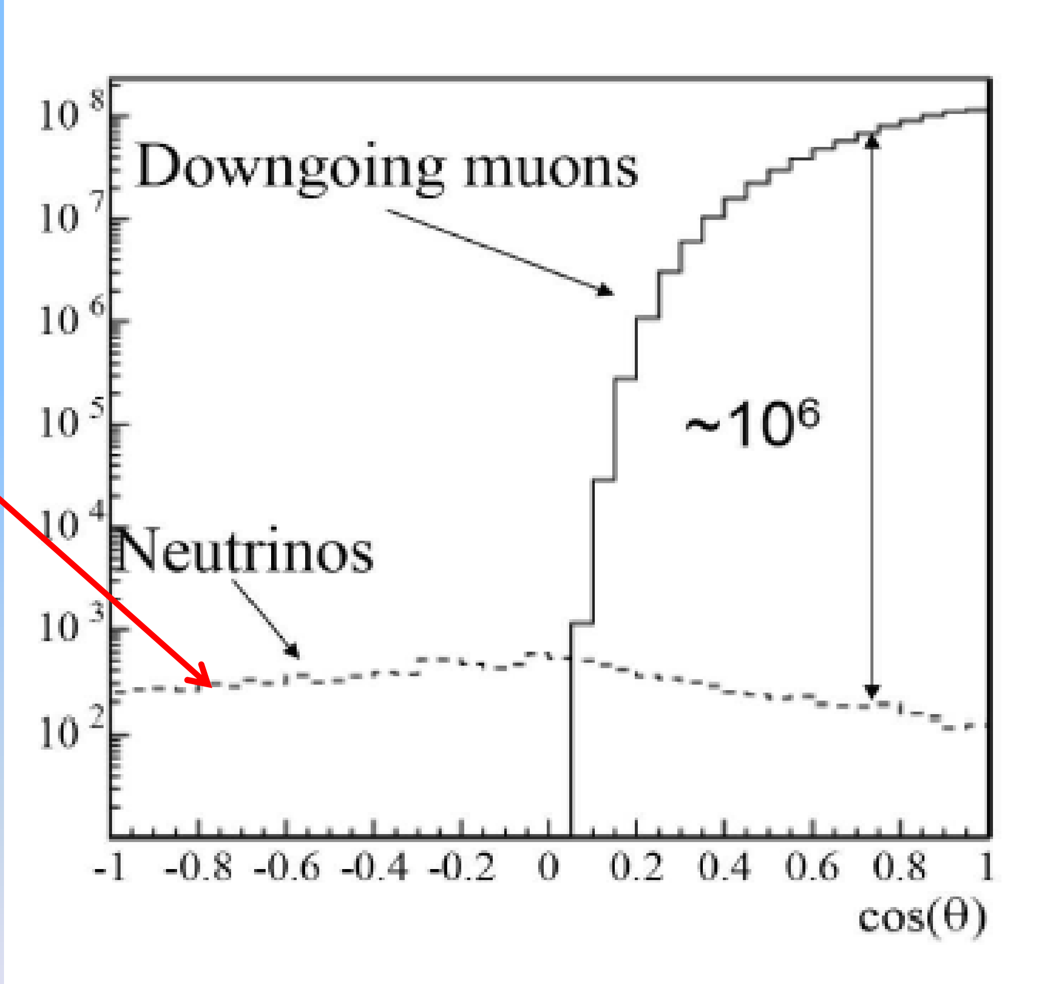
A little bit of history

Detection technique

M.Markov, **1960**:
We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation

Atmospheric muon background at 2500 m

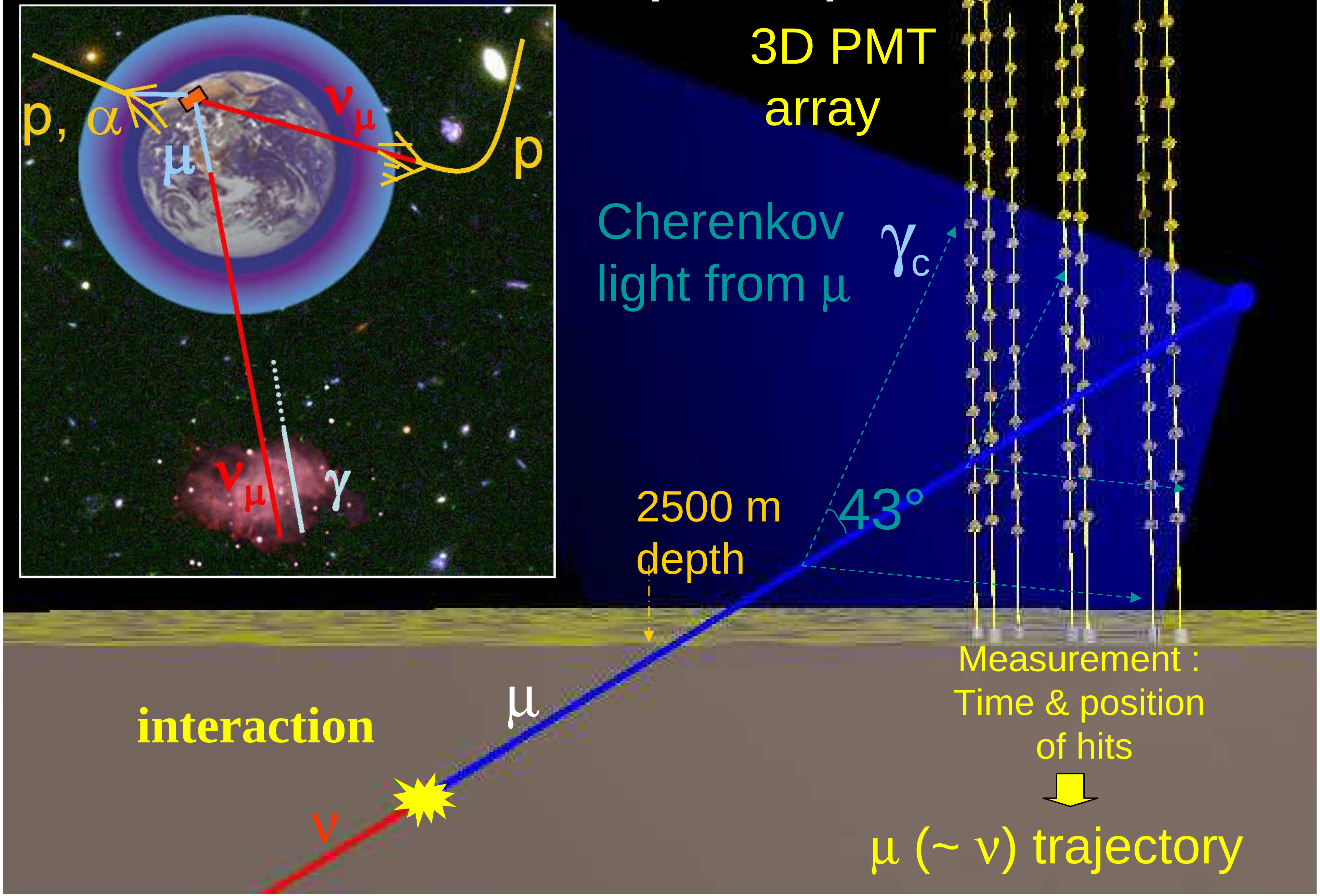
Reduced background if only events from the other side of the Earth selected



Price to pay → cutoff due to absorption by the Earth

D_{Earth} = 12.8 x 10^6 m → $\lambda = D_{Earth}$ at E_ν = 190 TeV

Neutrino detection principle



Pioneering developments

Dumand experiment **(Hawaii 1978-1992), depth 4500 m phased out**
Roberts, RMP 64, 1, 1992

Later experiments in lakes or sea

Baikal **(Baikal lake, Russia, 1983 → present) depth 1100 m** ***running***
I.A. Belolaptikov et al., Astr. Ph. 7, 263, 1997

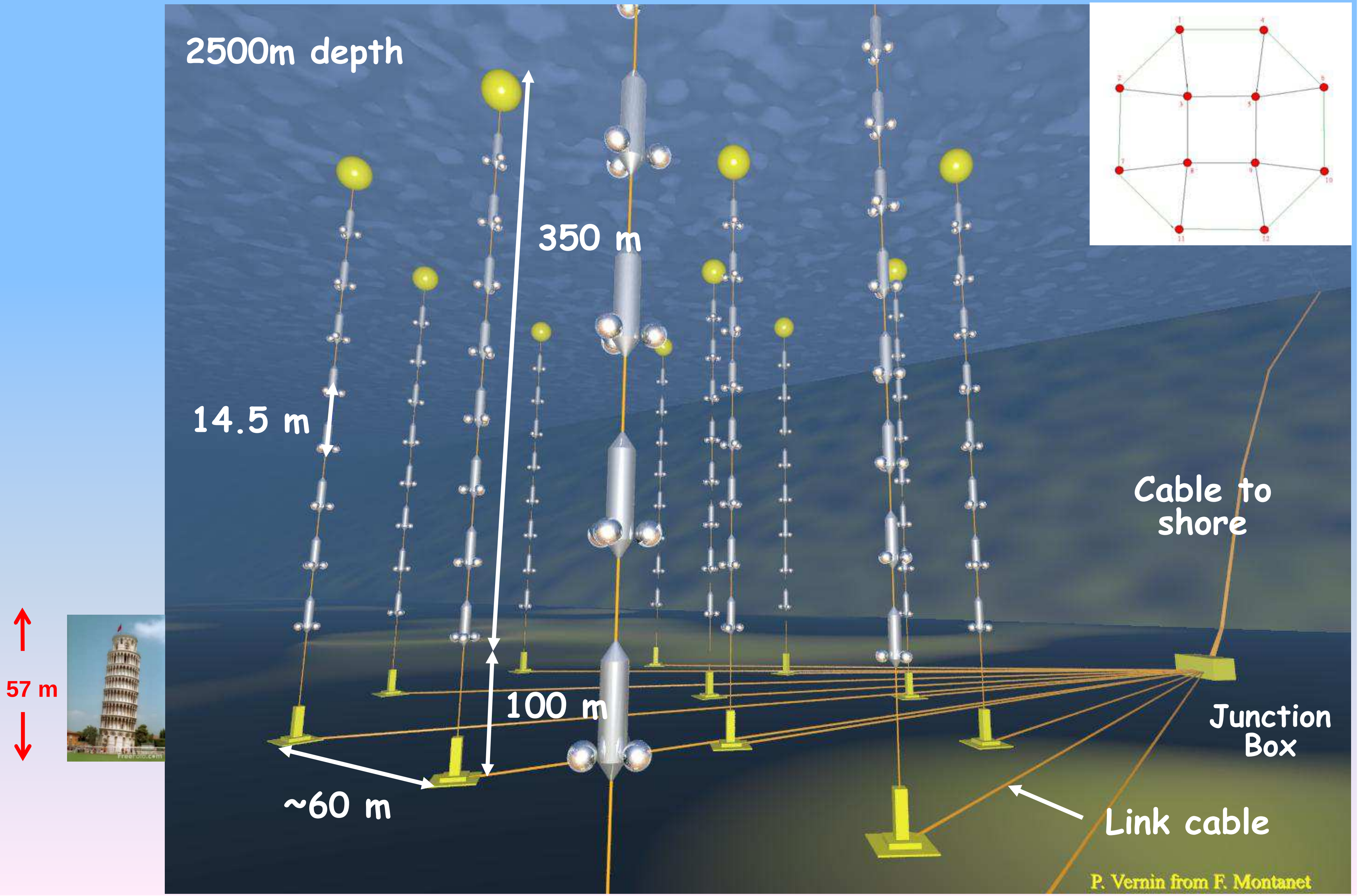
Nestor **(Pylos, Greece → 1996 - 2003) depth 4000 m** ***prototype operated in 2003***
G. Aggouras et al., Astr. Ph. 23, 377, 2005

NEMO **(Capo Passero, Sicily 2001→ present) depth 3500 m** ***prototype operated in 2007***
Capone et al., N.I.M. A 602, 47, 2009 ***new one under construction***

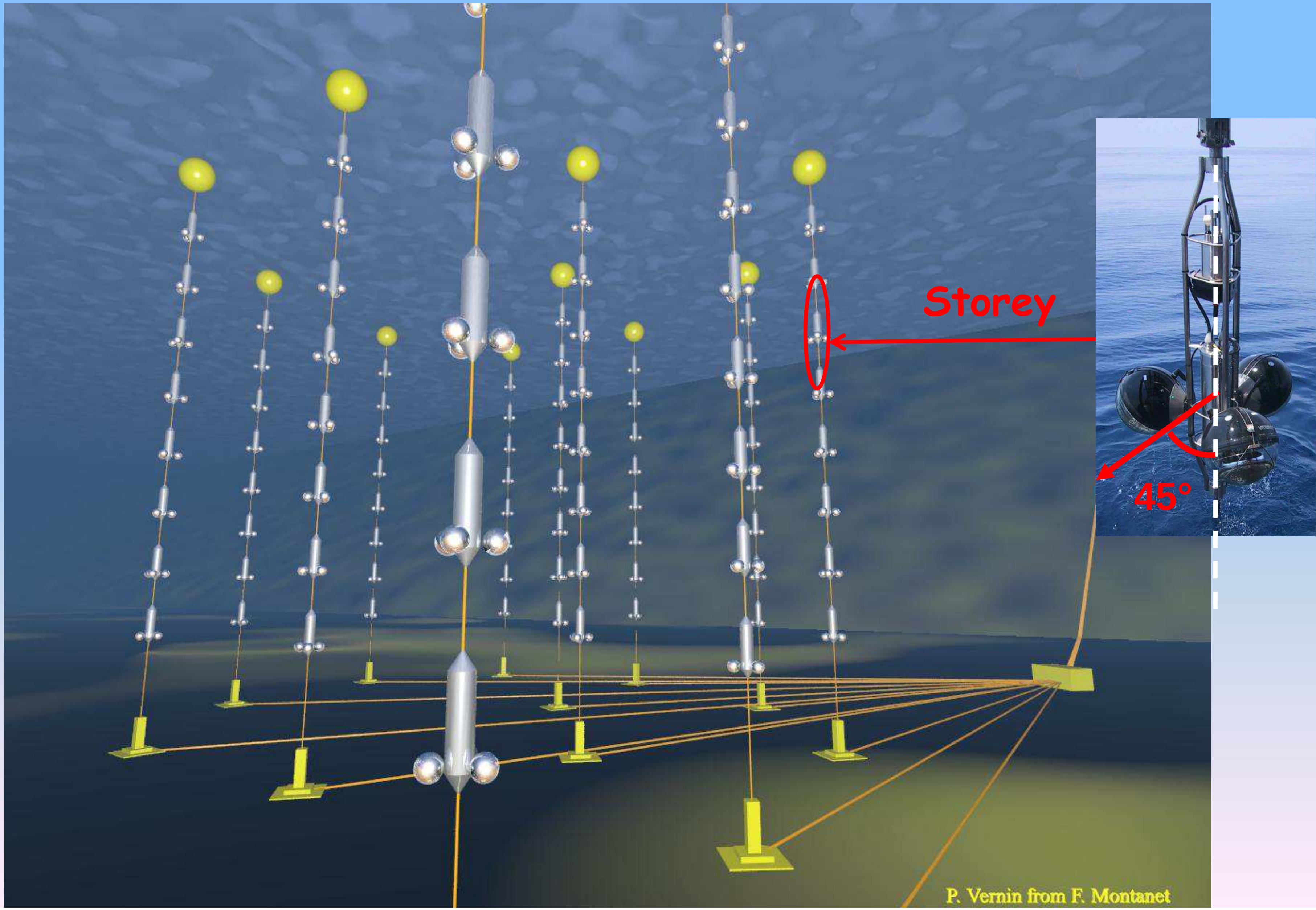
ANTARES **(Toulon, France → 2001 → present) depth 2500 m** ***running since 2008***
M. Ageron et al., NIM A 656, 11, 2011

KM3NET **(European Project: Antares+Nemo+Nestor)** ***FP6 → Design Study***
http://www.km3net.org ***FP7 → Prep. Phase***

The ANTARES detector

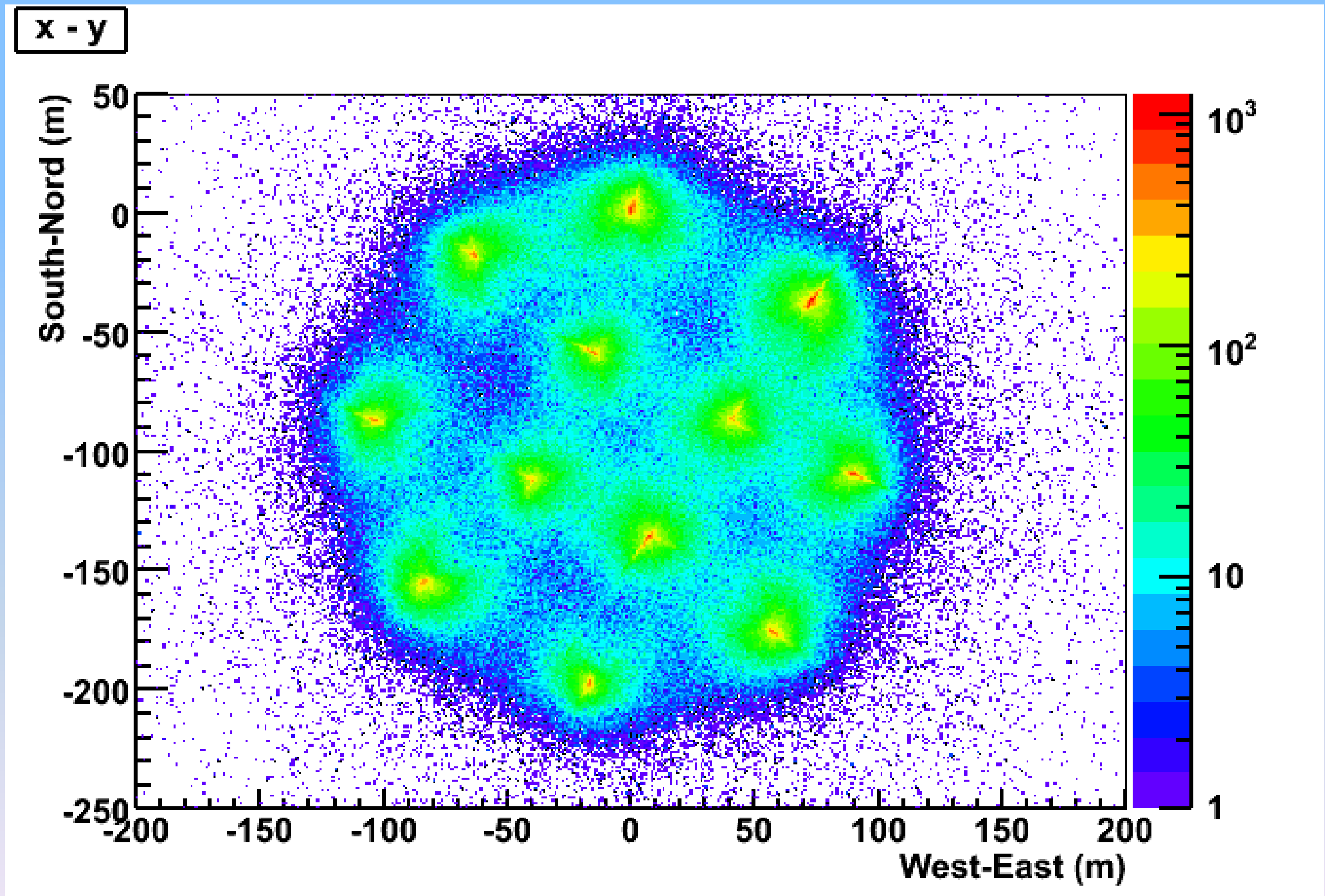


The ANTARES detector



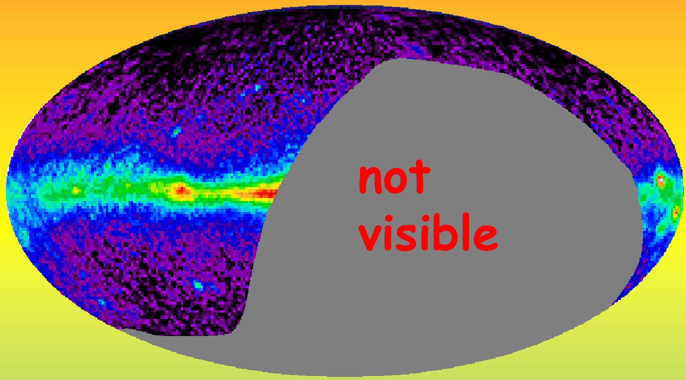
Detector footprint

Detector as seen by atmospheric muons: reconstructed position of the muon at the time of the first triggered hit



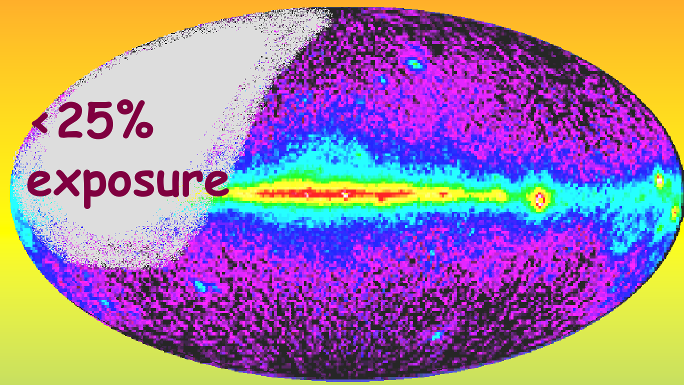
ANTARES Neutrino Telescope

South pole



Less background light

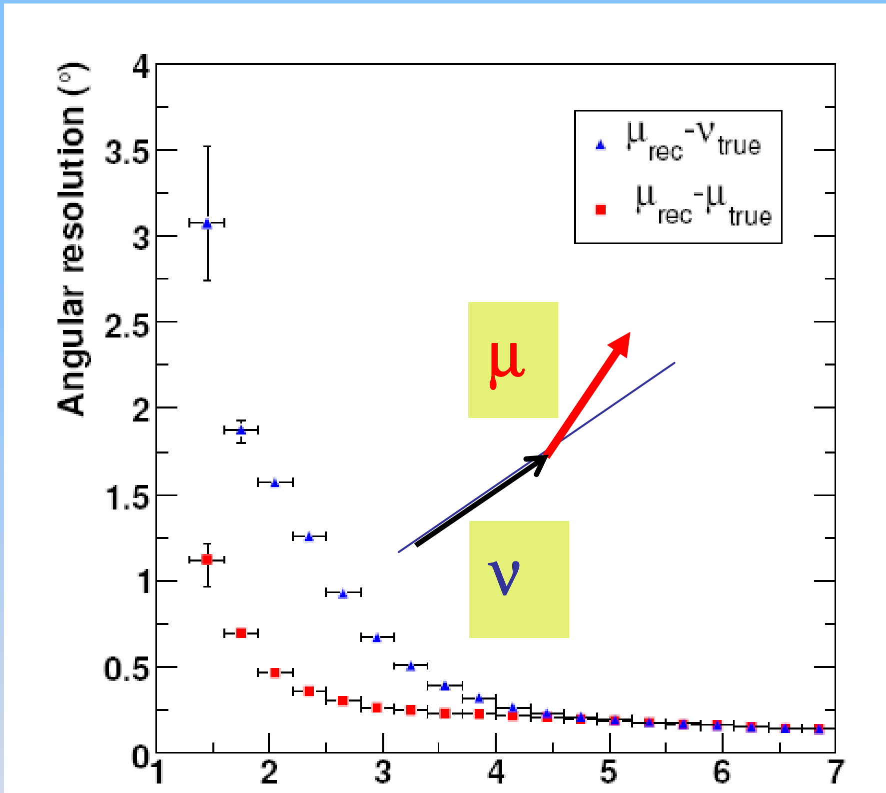
Mediterranean Sea, 43° N



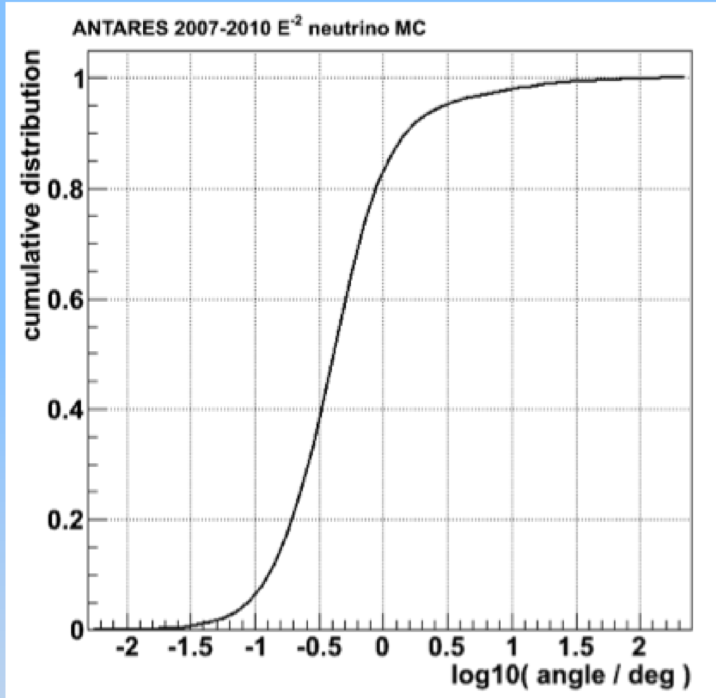
Better angular resolution

ANTARES already biggest NT in Northern Hemisphere
Chance of major discoveries

Angular Resolution for Upgoing Neutrinos



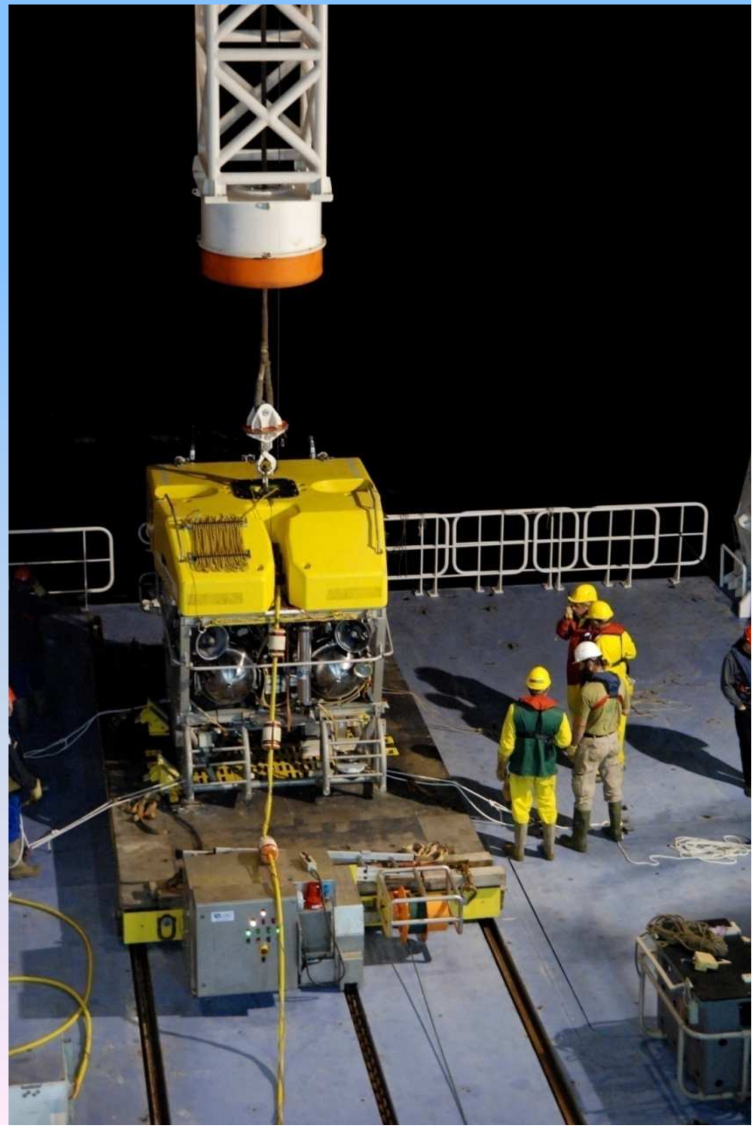
Full 12 line detector



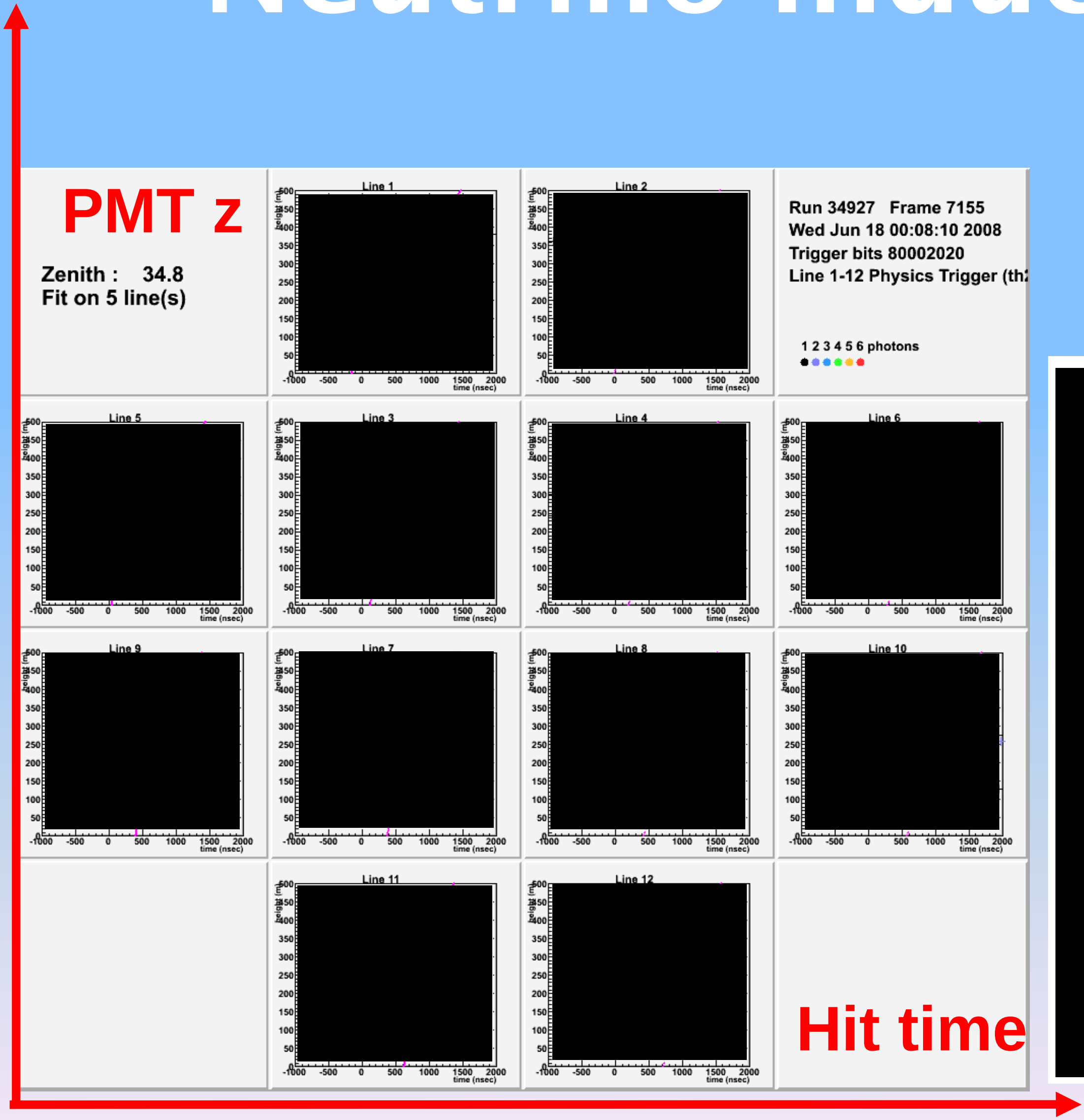
cumulative distribution of the angle between the true neutrino track and the reconstructed muon event that passes the selection criteria (assuming E^{-2} spectrum).

The median is 0.46°
83% of the events within 1°

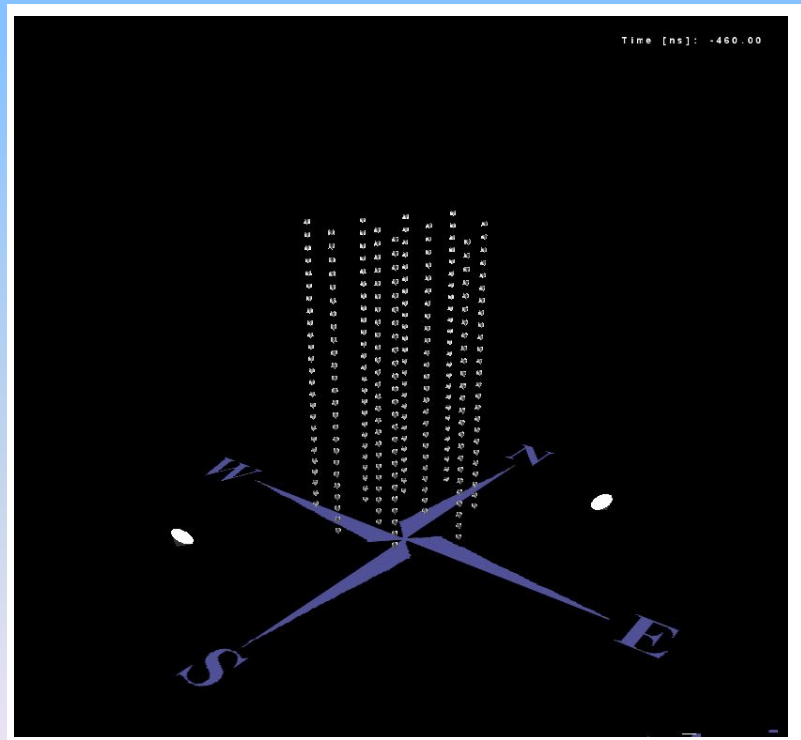
Detector operations



Neutrino-induced muon

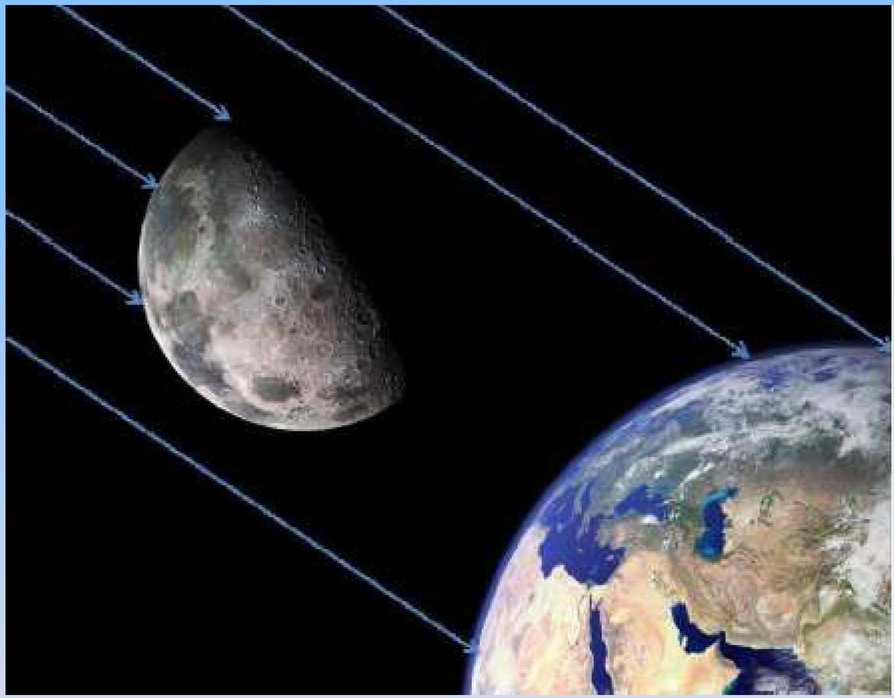


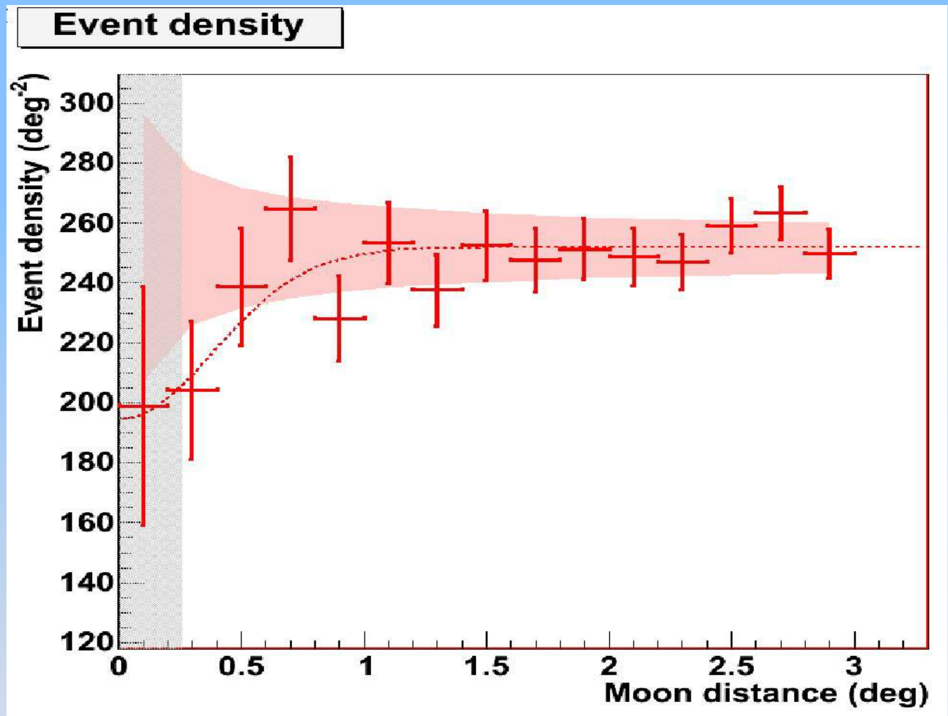
Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:



Absolute Pointing: Moon Shadow

884 livetime days (2007-2010)
2.7 sigma significance

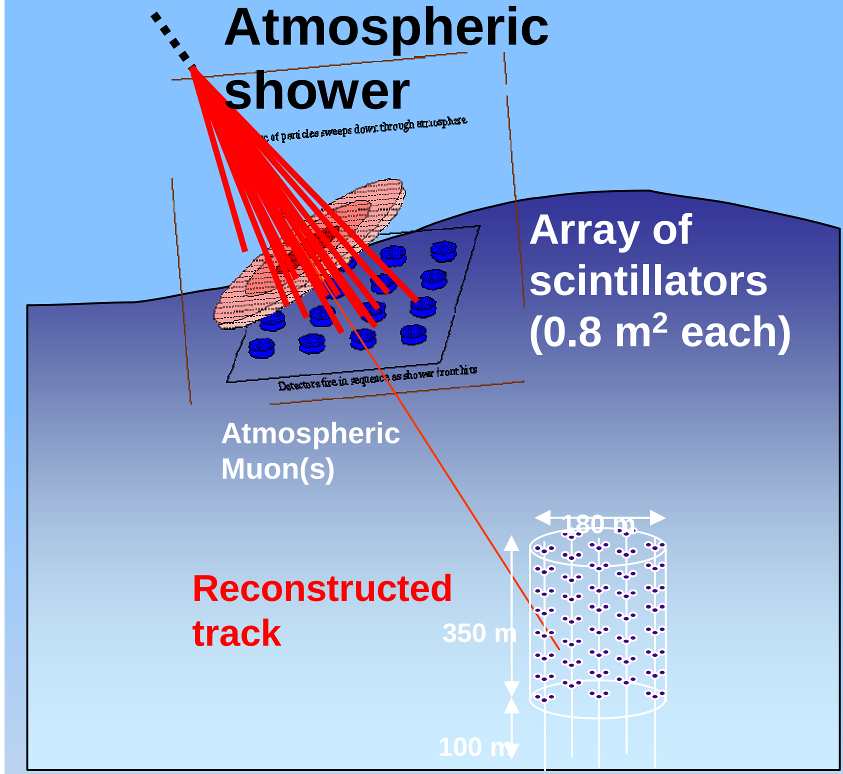


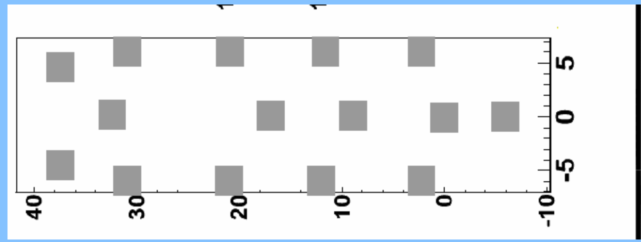


Agrees with Monte Carlo expectations

Encouraging, but due to lack of statistics, can not put useful constraints on ANTARES pointing capabilities

Absolute Pointing: Surface Array





Results:

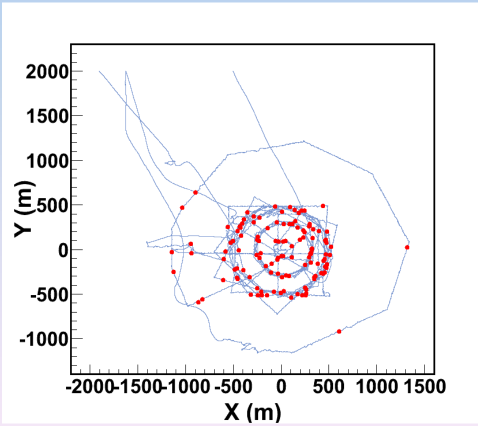
Zenith: -0.5±0.5°
Azimuth: 0.9±2.2°

2nd campaign planned in 2012

1st campaign 17-23 Oct 11

15 Detection units

2nd campaign in 2012



Results obtained so far

Search for neutrino point sources ←
(update of results published on Astrophys. J. Lett. 743, 1,2011)

Search for neutrino diffuse flux ***(Phys. Lett. B696, 16, 2011)***

Magnetic monopoles ***(Astrop. Phys. 35, 634, 2012)***

Atmospheric neutrino oscillations ←

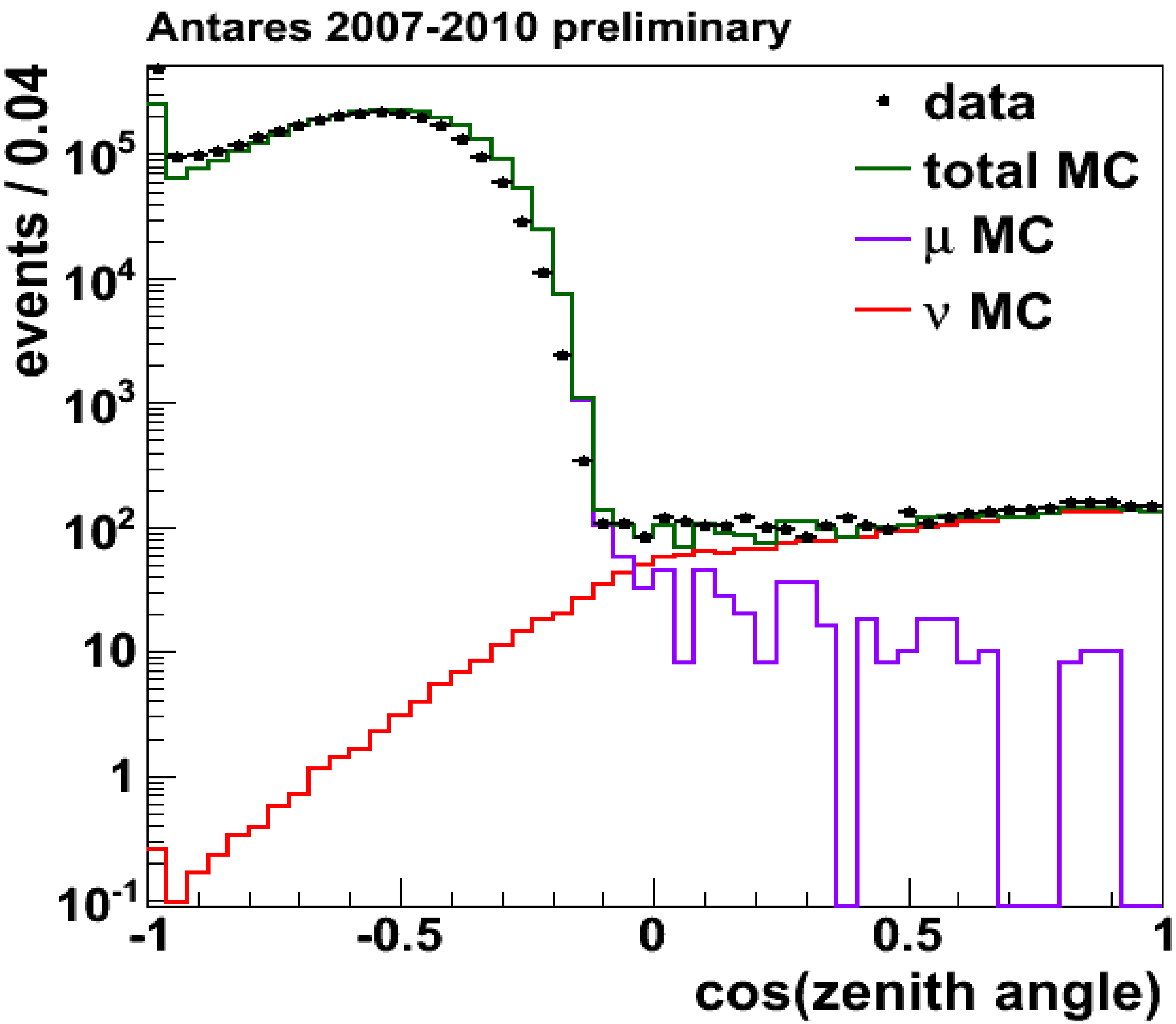
Acoustic neutrino detection ***(NIM A 626-627, 128,2011)***

Atmospheric muon flux ***(Astrop. Phys. 33, 86, 2010)***

Multimessanger (Tatoo, AUGER, LIGO-VIRGO..)

arXiv:1202.6661v1 [Astro-ph.HE] 29 Feb 2012

Muon angular distribution



Point Source Search

a) good track fit quality

b) estimated angular error <1 degree

c) upgoing muons only

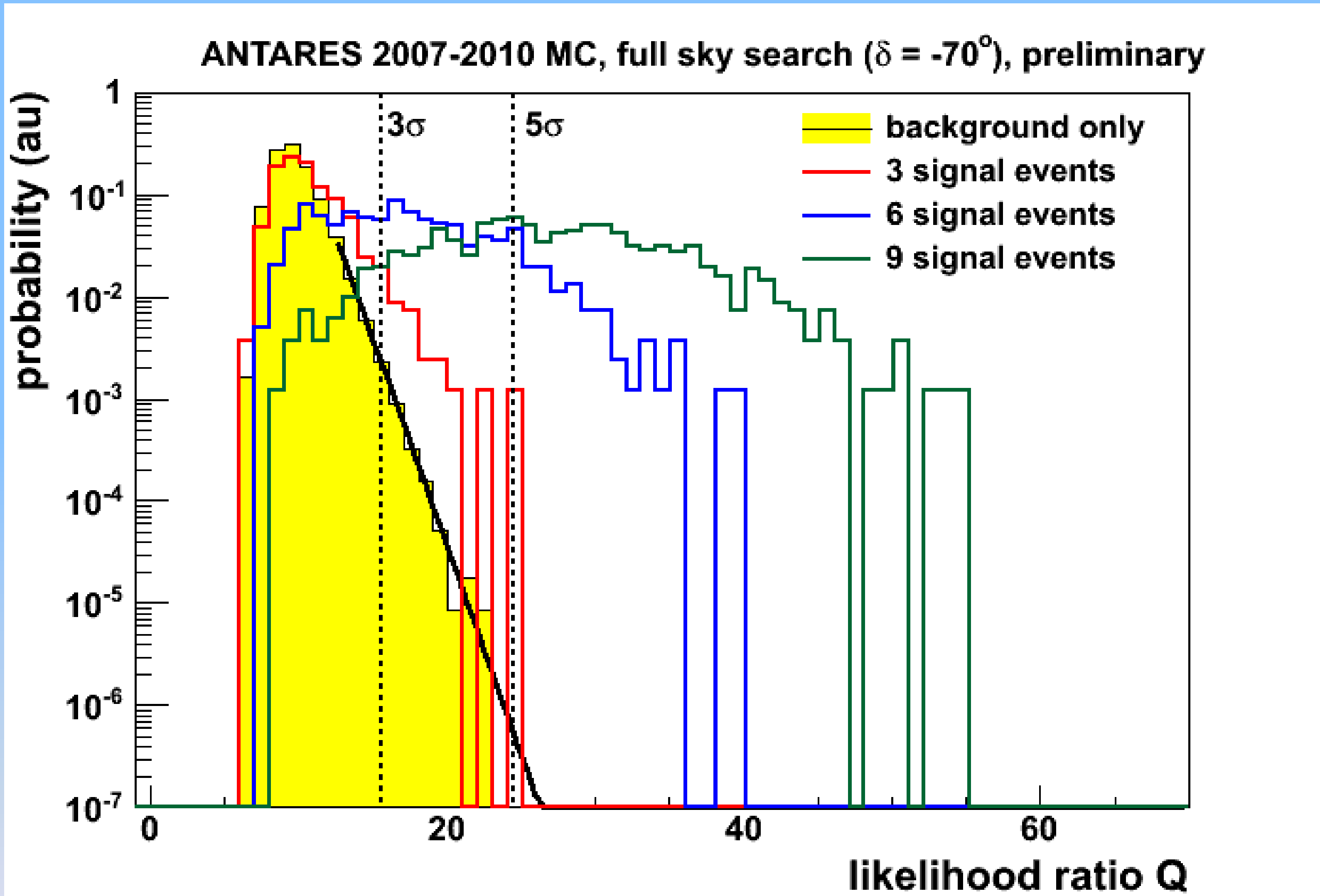
d) Use energy estimator (number of hits used by track fit as discriminator of μ ($\sim\nu$) energy)

e) Assume spectrum proportional to $(E_\nu)^{-2}$

f) Build likelihood ratio and use as test statistic: $Q = \log \mathcal{L}_{s+b}^{max} - \log \mathcal{L}_b$

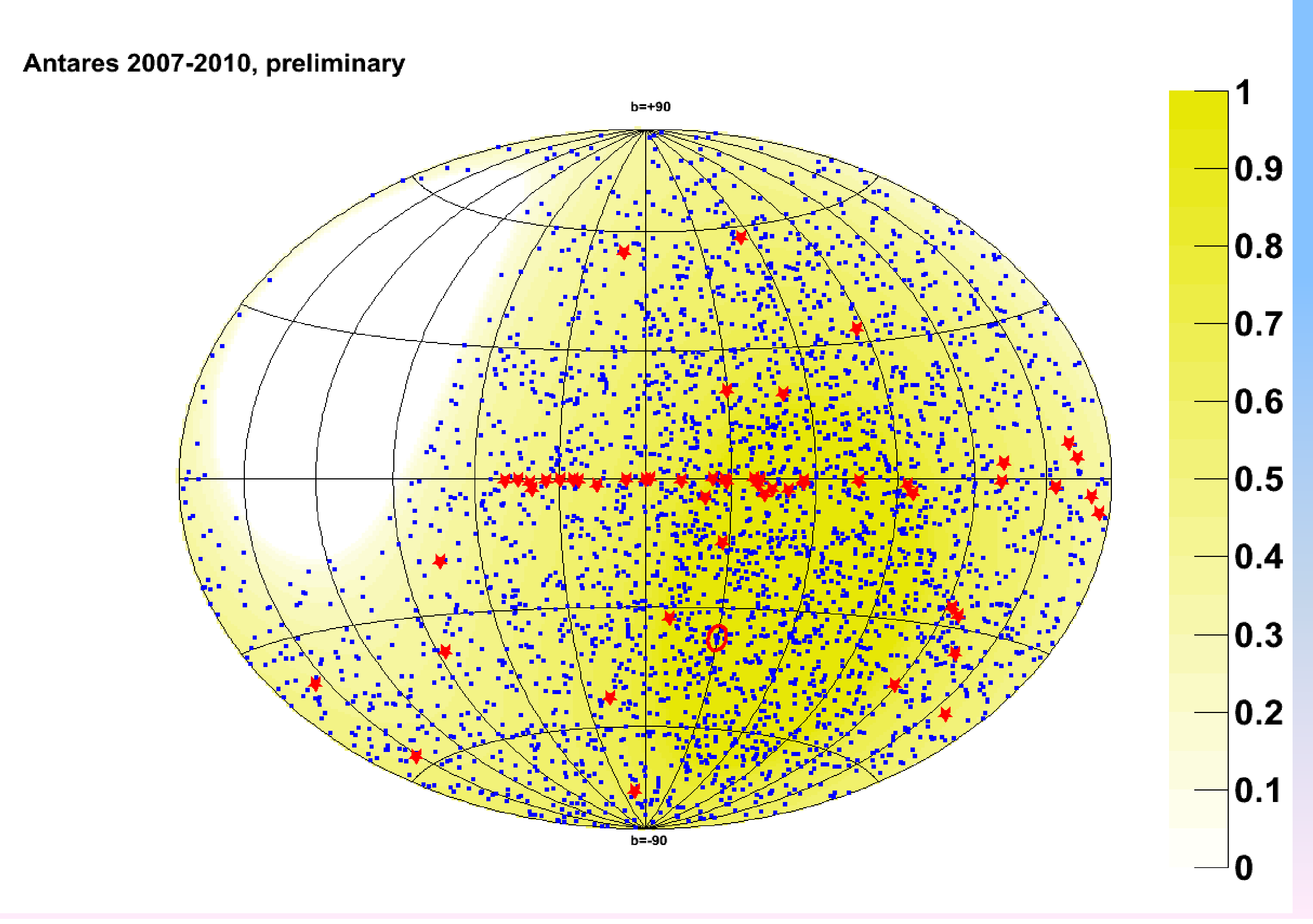
-Full sky search

-Candidate list search



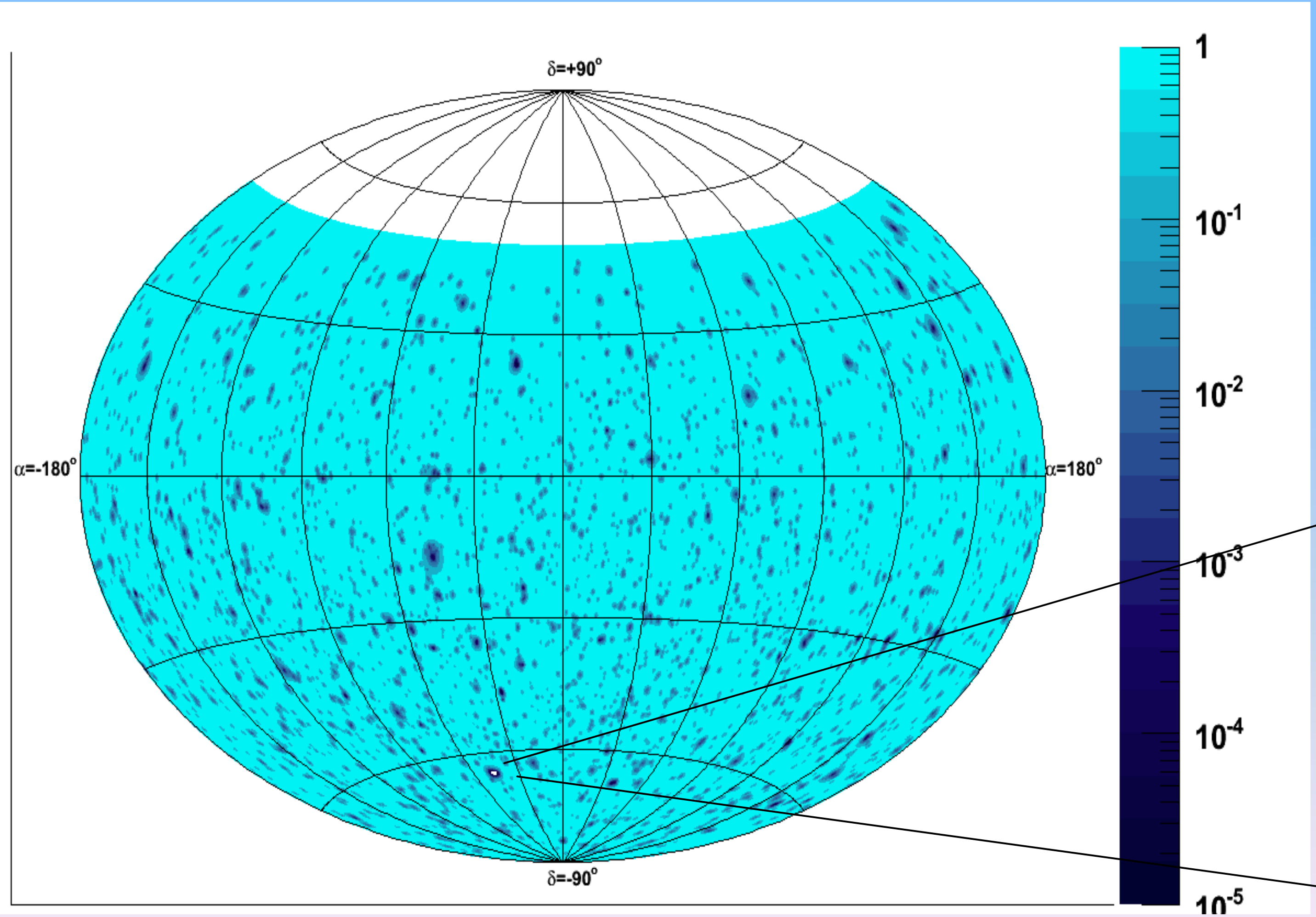
p-value = fraction of background data sets with higher Q value than data ➔ small p-value = high significance

Skymap in galactic coordinates of the 3058 selected ν events.



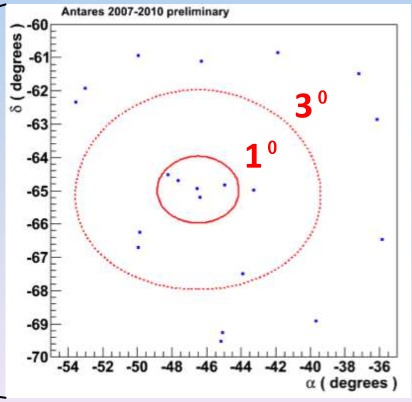
Full-Sky Search (2007-2010)

Sky map in equatorial coordinates (pre-trial p values)



Most significant cluster at:
$\mathcal{RA}$= −46.5°,
δ= −65.0°

N_{sig} = 5
p-value = 0.026
(post-trial)
Significance = 2.2 σ



Results compatible with the background hypothesis

Source Candidate List Search

Look in the direction of a list of 51 predefined candidate sources (selection of sources mostly based on γ-ray flux and visibility)

First eleven sources sorted by Q-value.
Last column shows the 90% CL upper limit on the flux $(E / GeV)^{-2}$ GeV^{-1} cm^{-2} s^{-1}

name	ra	decl	Nsigfit	Q	p-value	nsigma	lim_Nsig	lim_flux
HESS J1023-575	155.83	-57.76	1.97	2.35	0.41	0.82	5.62	6.6e-08
3C 279	-165.95	-5.79	1.11	2.15	0.48	0.71	5.35	1.0e-07
GX 339-4	-104.30	-48.79	1.26	1.49	0.72	0.36	5.10	5.8e-08
Cir X-1	-129.83	-57.17	1.52	1.31	0.79	0.27	5.00	5.8e-08
MGRO J1908+06	-73.01	6.27	0.90	1.22	0.82	0.23	4.59	1.1e-07
ESO 139-G12	-95.59	-59.94	0.98	0.76	0.94	0.08	4.63	5.4e-08
HESS J1356-645	-151.00	-64.50	0.76	0.49	0.98	0.03	4.37	5.1e-08
PKS 0548-322	87.67	-32.27	0.77	0.39	0.99	0.02	4.23	7.1e-08
HESS J1837-069	-80.59	-6.95	0.59	0.26	0.99	0.01	4.12	8.0e-08
PKS 0454-234	74.27	-23.43	0.39	0.09	1.00	0.00	3.83	7.0e-08
ICECUBE	75.45	-18.15	0.34	0.07	1.00	0.00	3.83	7.0e-08

HESS J1023–575 most signal-like, p–value 40% (post trial)

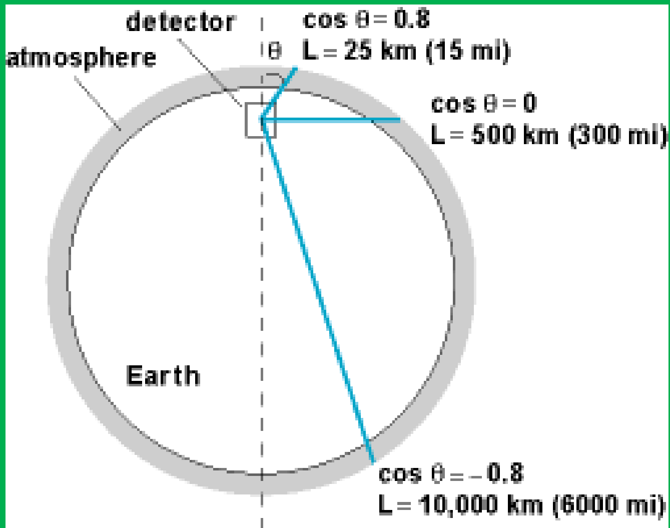
Compatible with the background hypothesis

3C279, GX339-4, Cir X-1 are flaring sources....

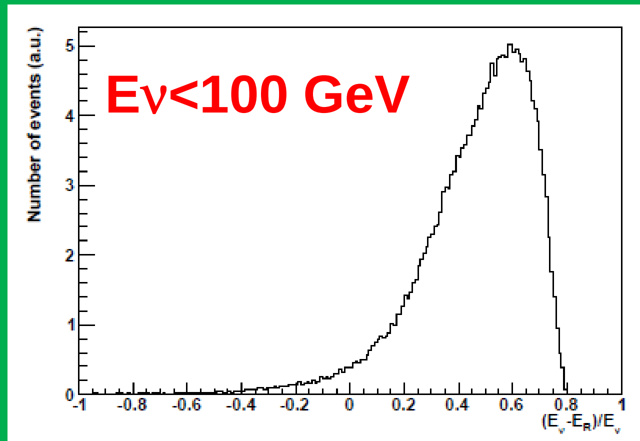
Oscillations with Atmospheric Neutrinos

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m_{32}^2 \cos\Theta}{E_\nu}\right)$$

L=2 R_{Earth} cosθ, from track fit

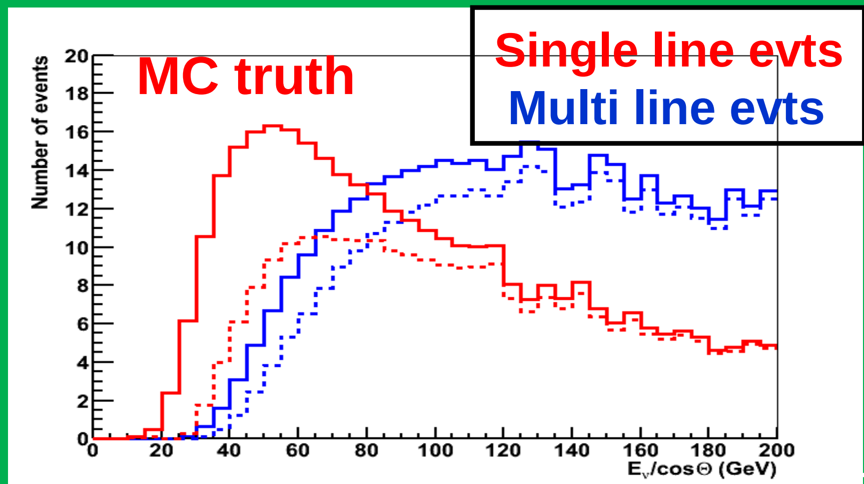


Eν from muon range



Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

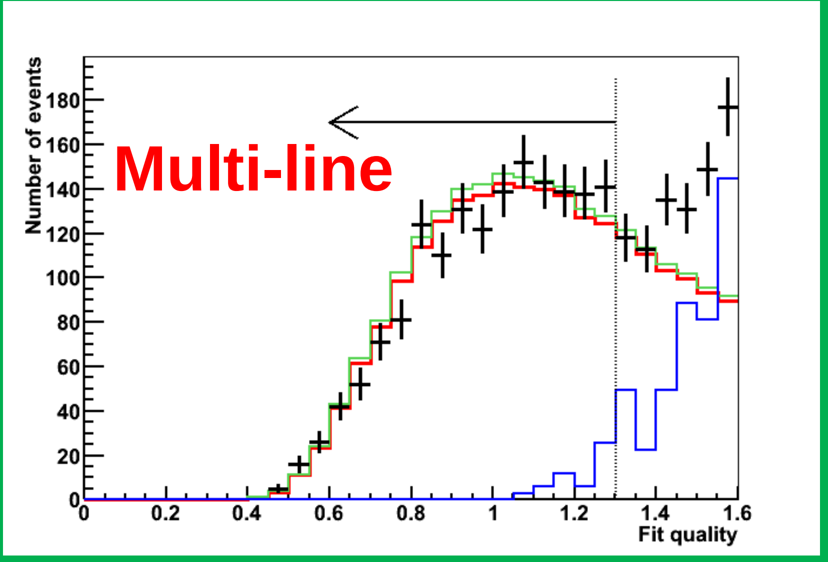
Larger effect on single-line (low energy) than multi-line (higher energy) events

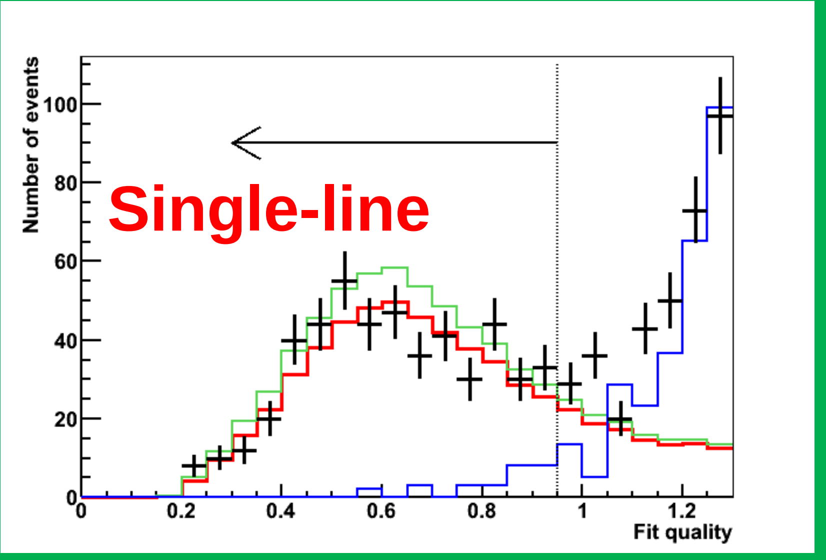


Neutrino Oscillations: Track Selection

Special low energy fit for single-line events (>7storeys, do not fit azimuth)

Select pure sample of atmospheric neutrinos (<5% muon contamination)





zenith angle resolution:
0.8 degrees for multi-line events
3 degrees for single-line events

Events selected:

1632 Multi line
494 Single line

Neutrino Oscillations: Result

2008-2010 data (863 days):

No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

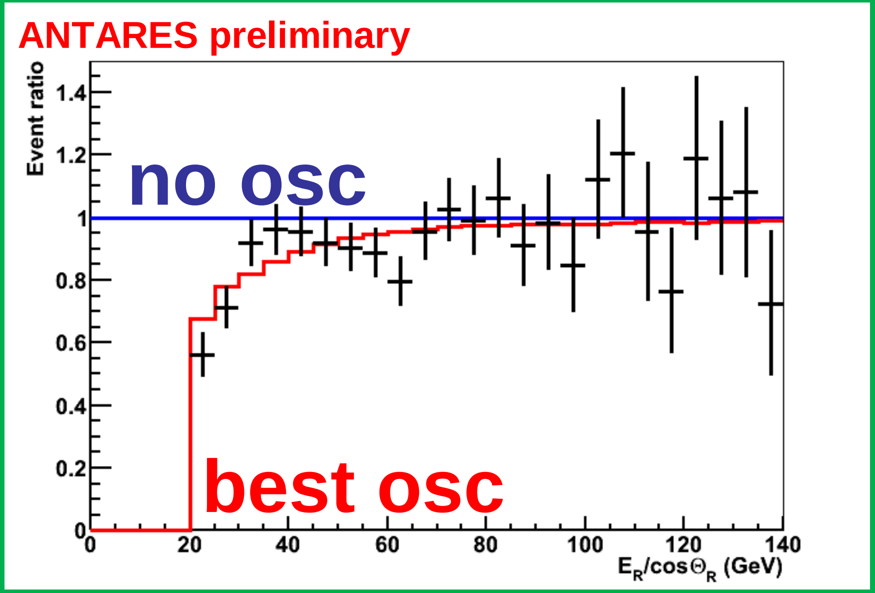
$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

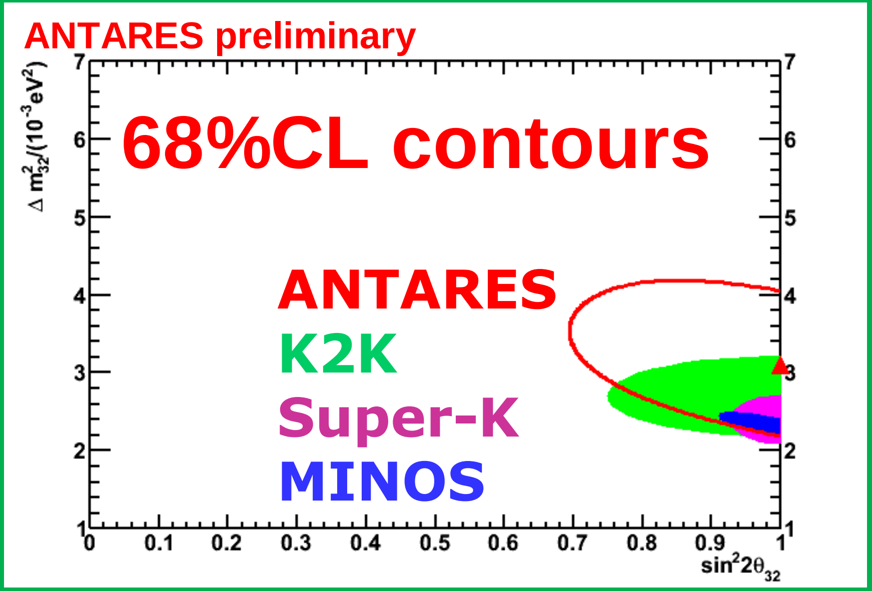
$\sin^2 2\theta = 1.00$

Systematics:

(Absolute normalisation free)
Absorption length: ±10%
Detector efficiency: ±10%
Spectral index of ν flux: ±0.03
OM angular acceptance

5% error on slope vs $E_R/\cos\vartheta_R$

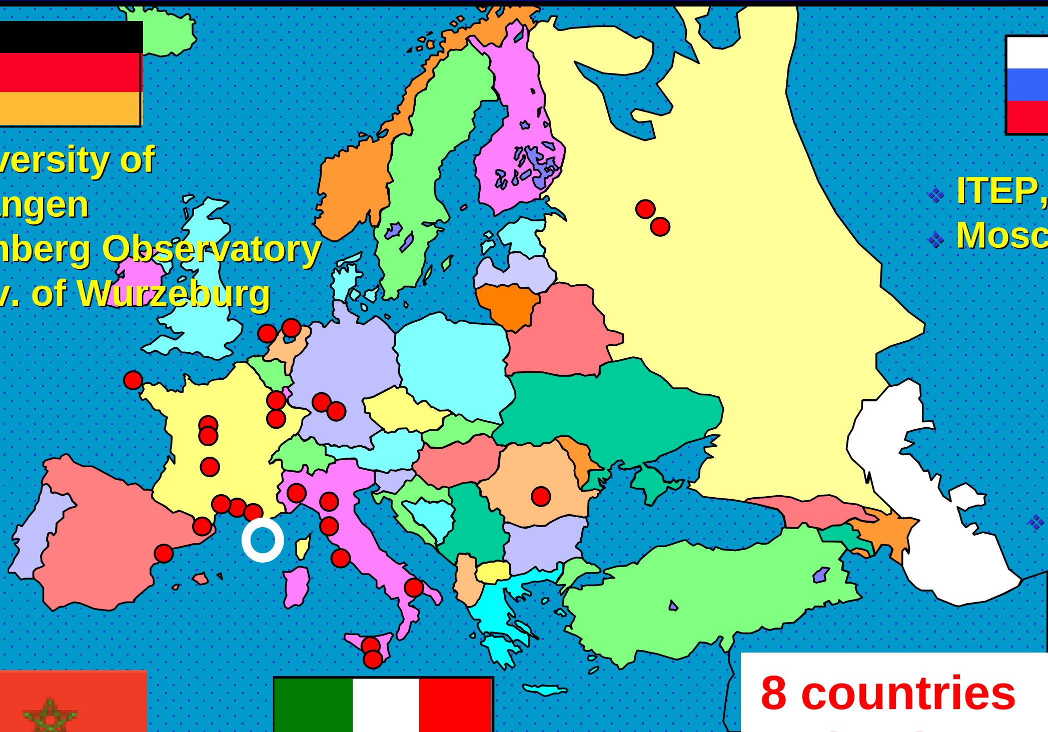




Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$

Submitted to PLB: arXiv:1206.0645

The ANTARES Collaboration



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

University of Erlangen
Bamberg Observatory
Univ. of Wurzeburg

- ITEP,Moscow
- Moscow State Univ

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

- ISS, Bucarest

- CPPM, Marseille
- DSM/IRFU/CEA, Saclay
- APC, Paris
- LPC, Clermont-Ferrand
- IPHC, Strasbourg
- Univ. de H.-A., Mulhouse
- LAM, Marseille
- COM, Marseille
- GeoAzur Villefranche
- INSU-Division Technique

- LPRM, Oujda

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

8 countries
31 institutes
~150 scientists+engineers

Conclusions

- Long march towards underwater cosmic neutrino detection has lately undergone an acceleration (50 years after Gribov's proposal !)

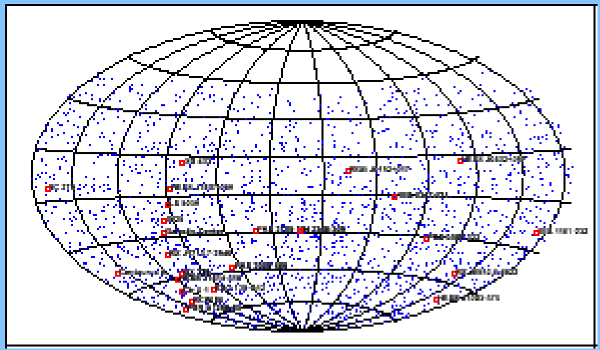
- ANTARES made a major step forward during 2006-2007 and the 12-lines detector with 900 OMs was completed in 2008. Data taking going on steadily since then.

- Over 4000 ν events collected so far. Results available on the search for cosmic neutrinos, both in the full sky and in the direction of known gamma ray sources. Results on data taken up to 2010 being published.

- Results available on atmospheric neutrino oscillations, for the first time using a neutrino telescope. Paper submitted for publication.

- Antares expected to continue data taking until 2016.

The End



Background Material

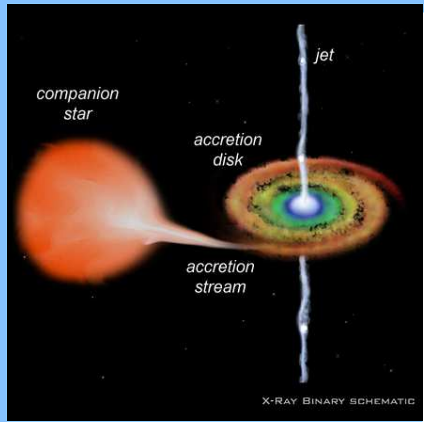
Search for Neutrinos from Micro-Quasars

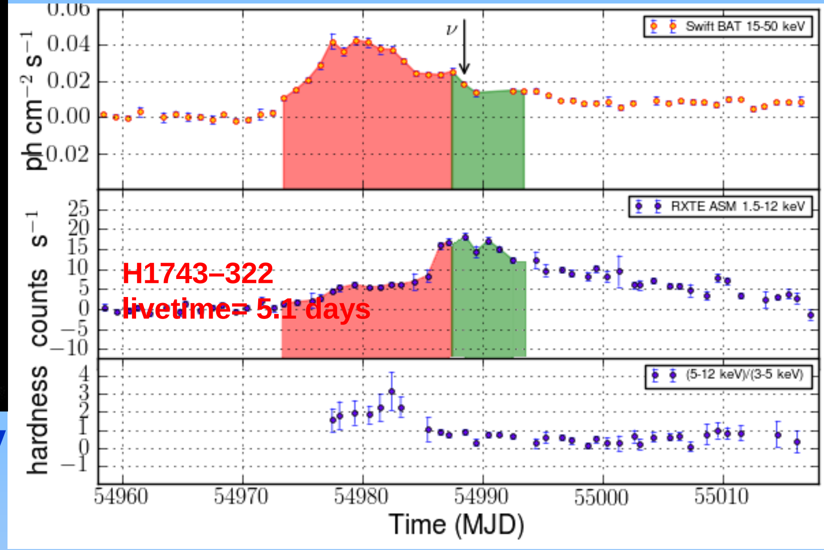
Micro-quasars:

galactic sources

binary systems

Many are flaring hadronic models



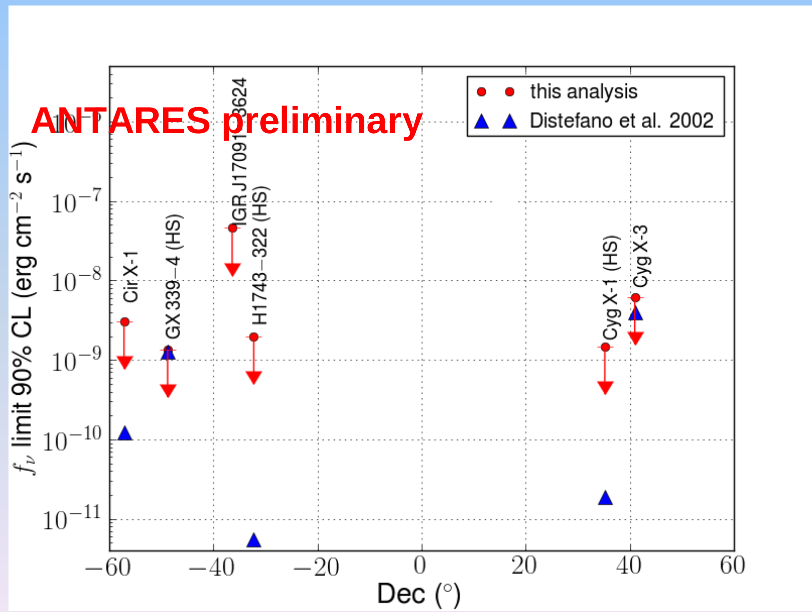


Identified six microquasars with x-ray or γ-ray outbursts in the 2007-2010 FERMI/LAT data:

Circinus X-1, GX339-4, H 1743-322, IGRJ17091-3624, Cygnus X-1, Cygnus X-3

Compare with model of Distefano & Waxman. Introduce an energy cut-off at 100 TeV on the E^{-2} flux.

More data and including energy information→ sensitivity will improve by at least factor 2: models for GX339-4 and CygX-3 can be excluded

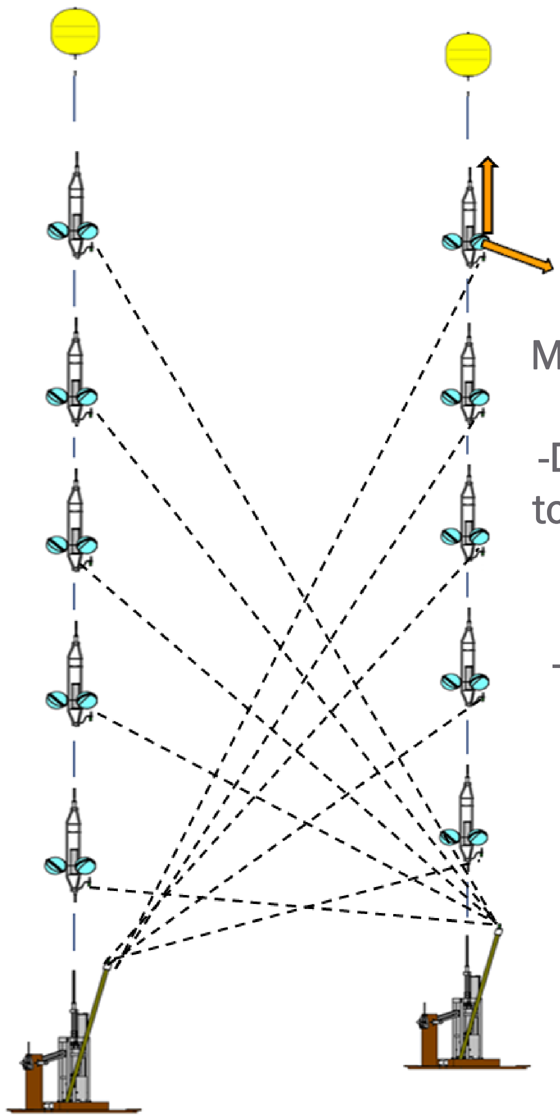


Detector positioning

Acoustic system:

- **One emitter-receiver at the bottom of each line**
- **Five receivers along each line**
- **Four autonomous transponders on pyramidal basis**

Additional devices provide independent sound velocity measurements



Measure every 2 min

-Distance line bases to 5 storeys/line and transponders

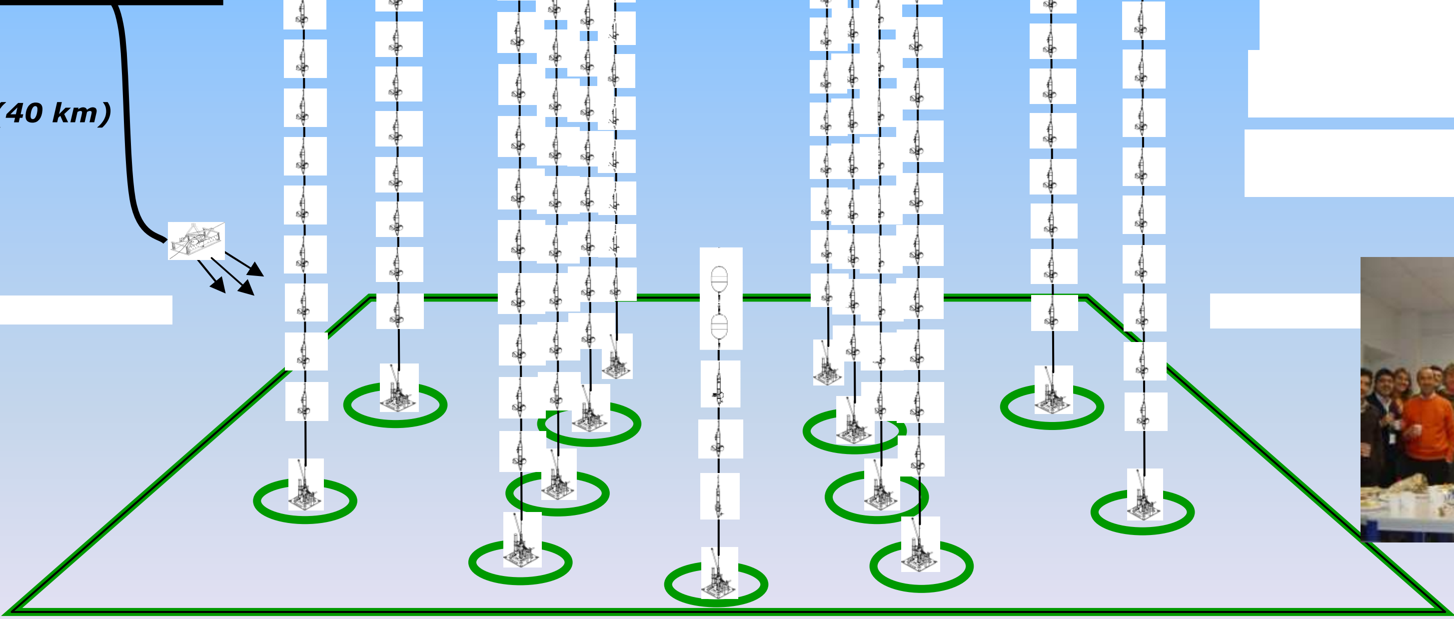
-Headings and tilts

Deployment

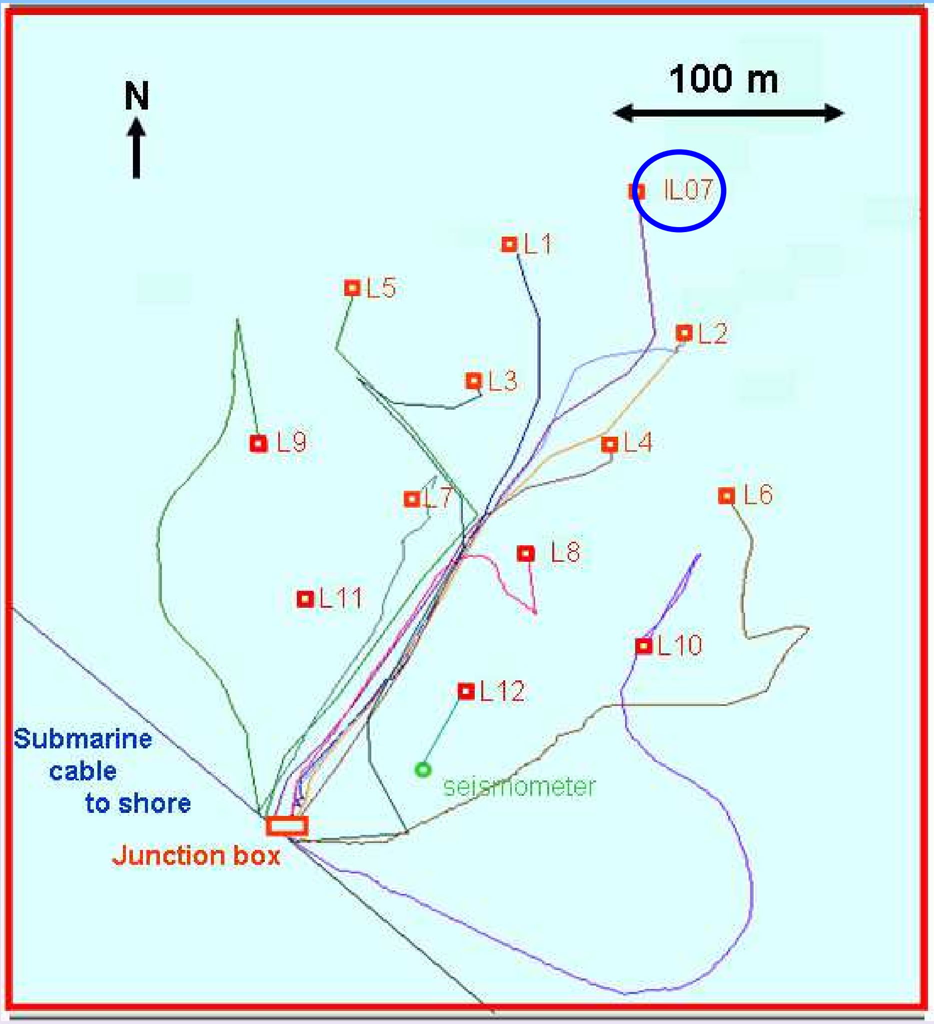
Data taking periods:

- ***MILOM : Mar '05 – Mar '06***

La Seyne-sur-Mer



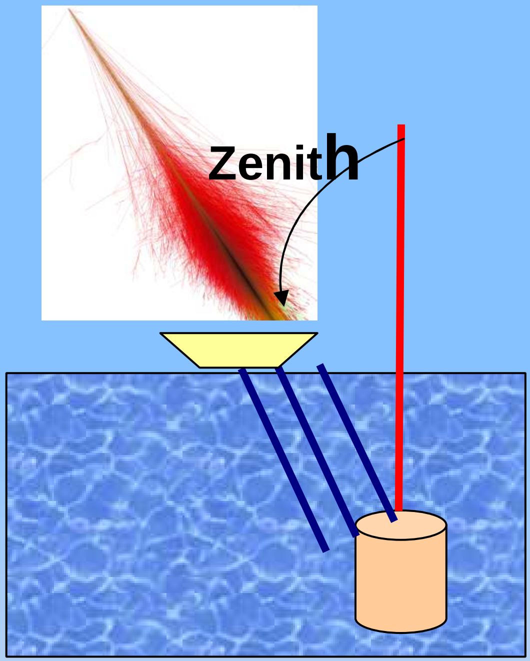
Detector layout

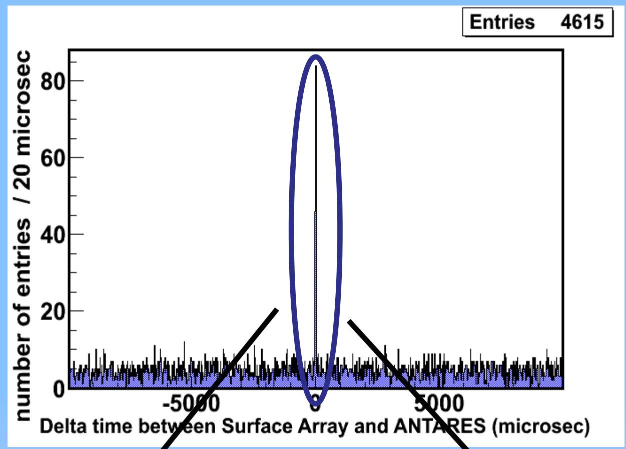


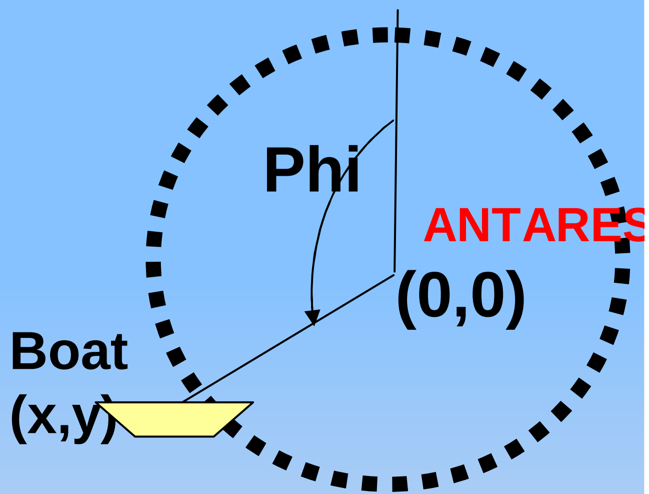
Acoustic storey

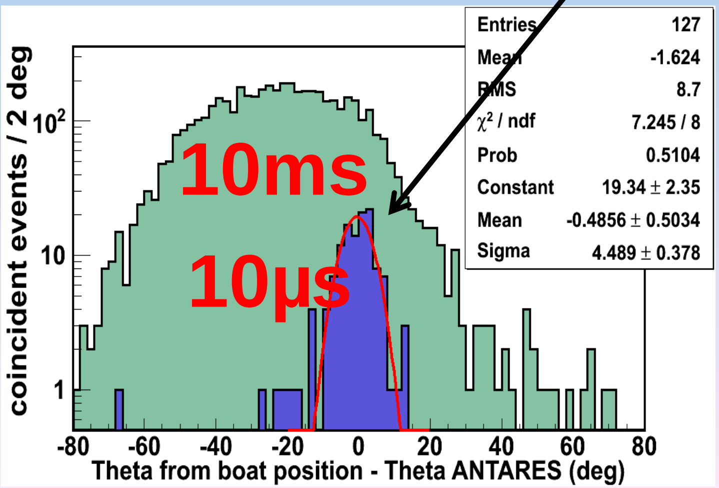
… and several instruments for environment studies with the ANTARES infrastructure

Absolute Pointing: Surface Array II







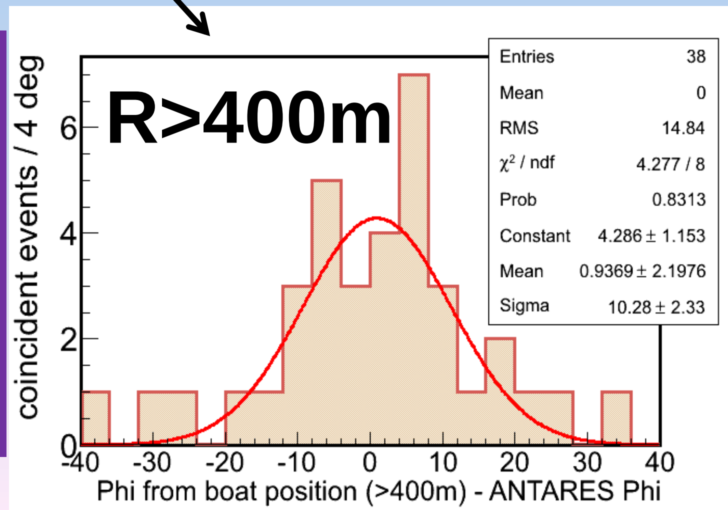


Constraints

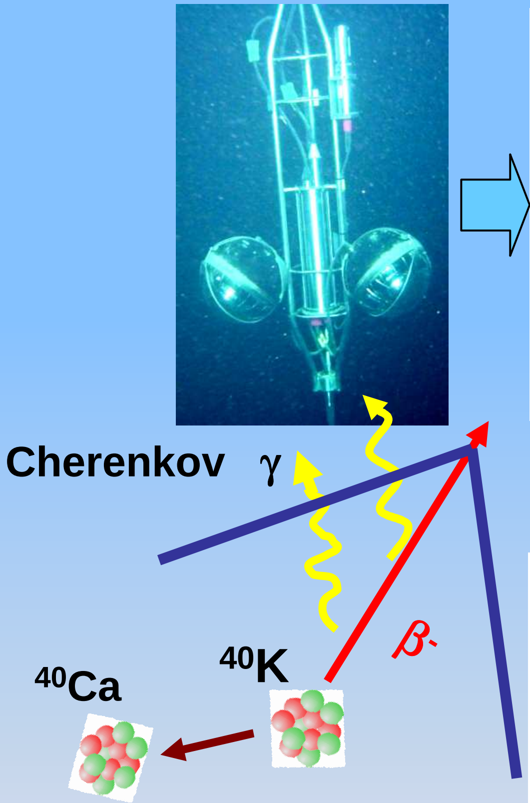
Zenith: -0.5±0.5°

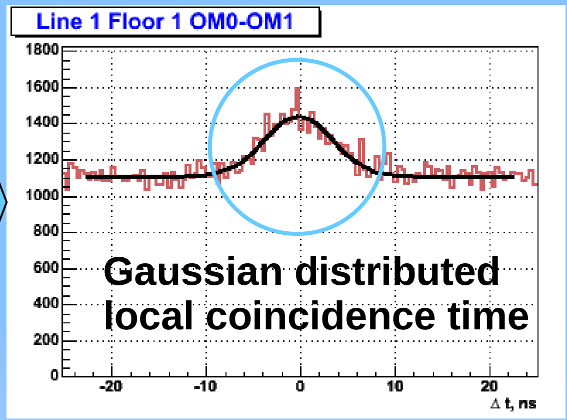
Azimuth: 0.9±2.2°

2nd campaign planned in 2012

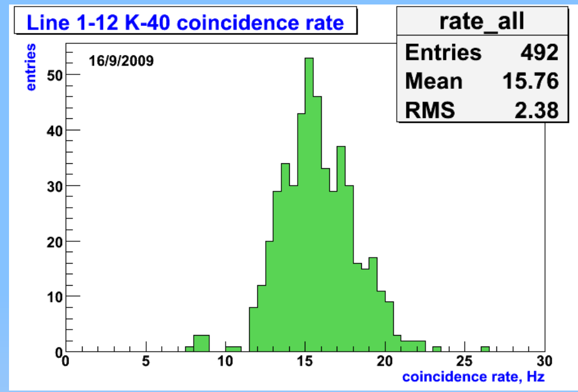


Local coincidences from ^{40}K decay



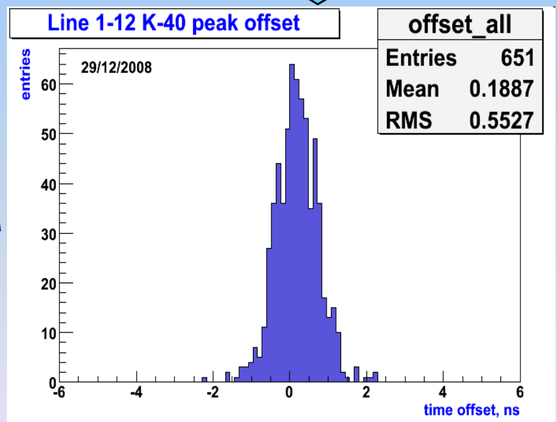


Peak integral



average coincidence rate 16 ± 2 Hz

Peak offset



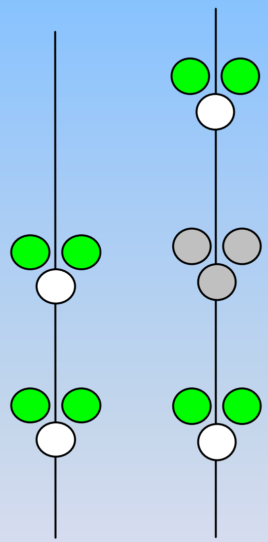
- Efficiency of Optical Modules (~8%)
- Accuracy of time calibration (~0.5 ns)

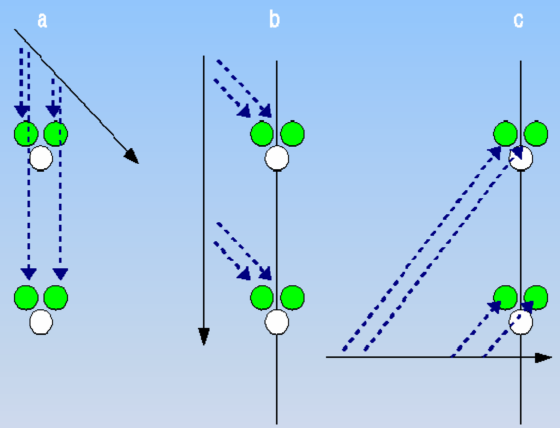
Storey coincidences

derive depth dependence of muon flux
from coincidence-time distributions of
(next-to) adjacent storeys, each with a local coincidence (± 20 ns):

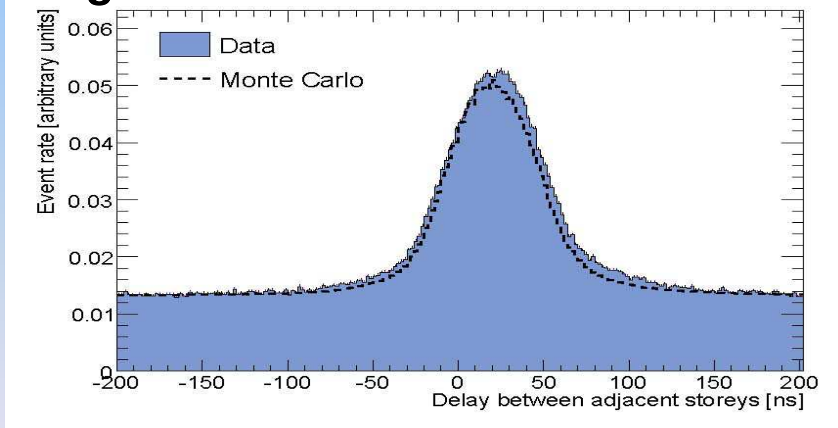
low threshold of 4 GeV

(minimum track length between adjacent storeys)



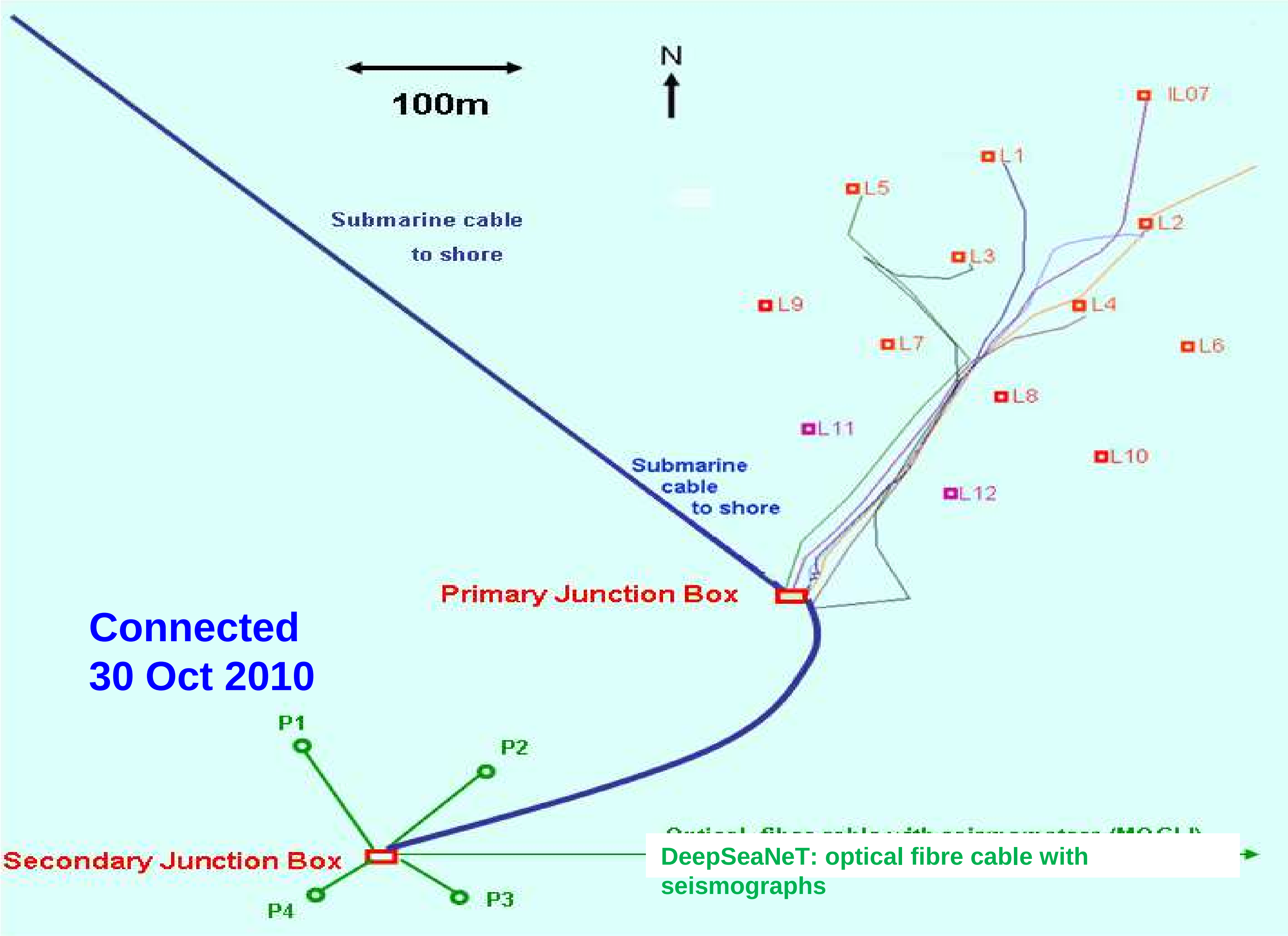


distribution of measured time differences
agrees with MUPAGE MonteCarlo



mostly down-going muons: delay ~ + 20 ns)

The ANTARES Infrastructure

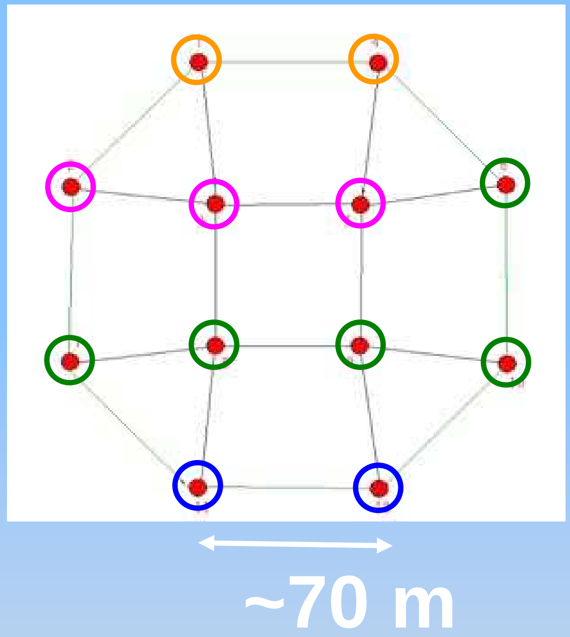


Connected
30 Oct 2010

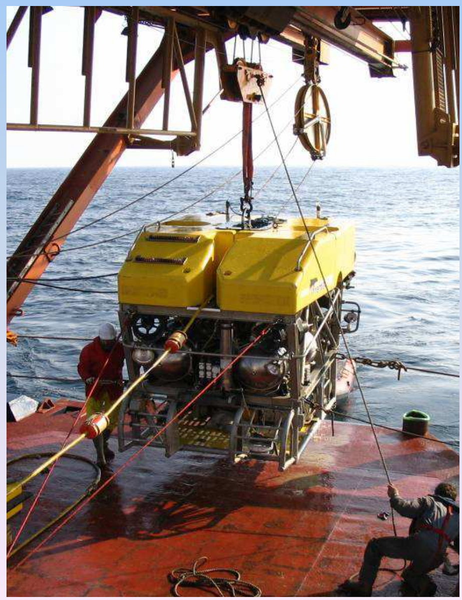
Loglikelihood

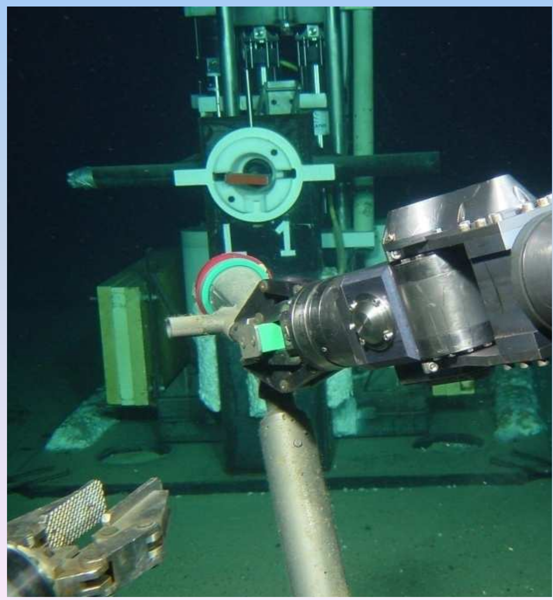
$$\log \mathcal{L}_{\mathrm{s+b}} = \sum_i \log[\mu_{\mathrm{s}} \times \mathcal{F}(\psi_i(\alpha_{\mathrm{s}}, \delta_{\mathrm{s}})) \times \mathcal{N}^{\mathrm{s}}(N^i_{\mathrm{hits}}) + \\ + \mathcal{B}(\delta_i) \times \mathcal{N}^{\mathrm{bg}}(N^i_{\mathrm{hits}})] - \mu_{\mathrm{tot}},$$

2006 – 2008: Building phase of the Detector



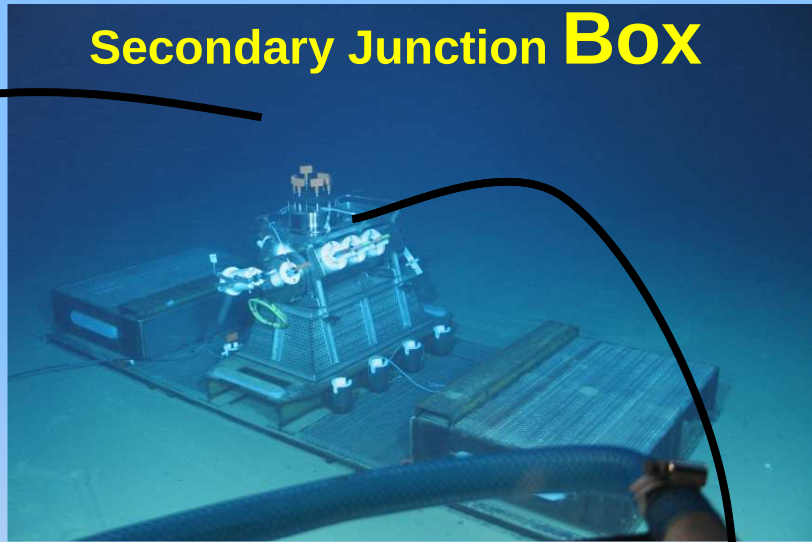
•	Junction box	2001
•	Main cable	2002
•	Line 1, 2	2006
•	Line 3, 4, 5	01 / 2007
•	Line 6, 7, 8, 9, 10	12 / 2007
•	Line 11, 12	05 / 2008

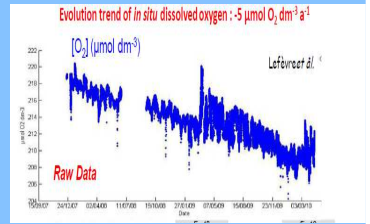


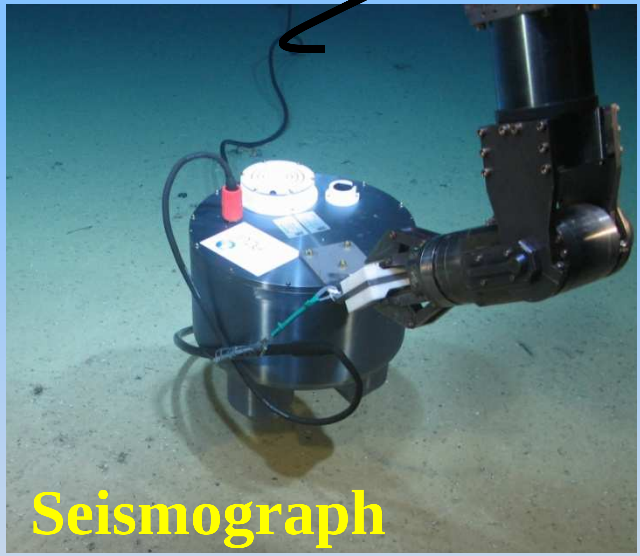


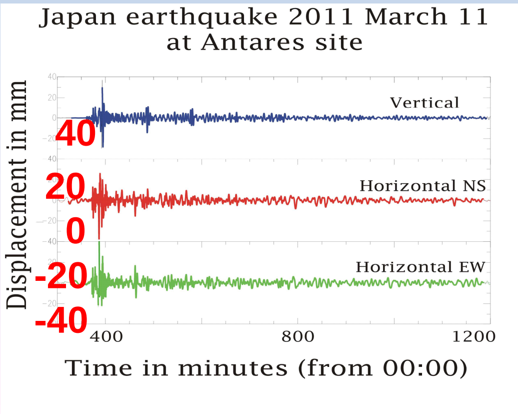
Secondary Junction Box

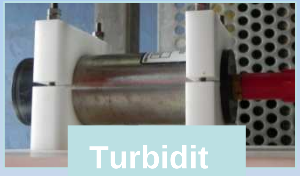
Connected
30 Oct 2010

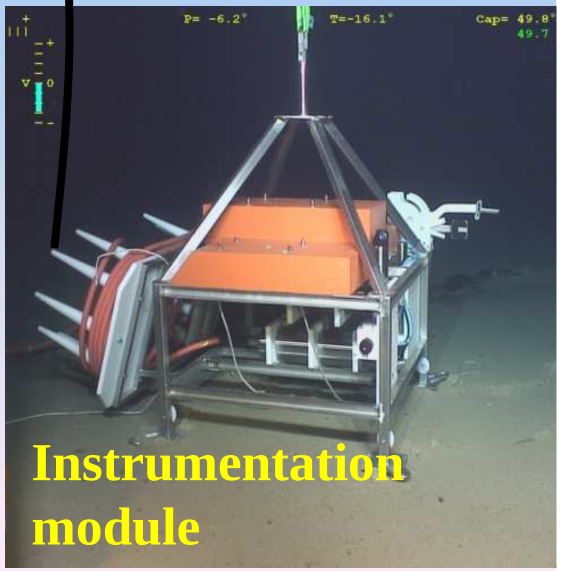




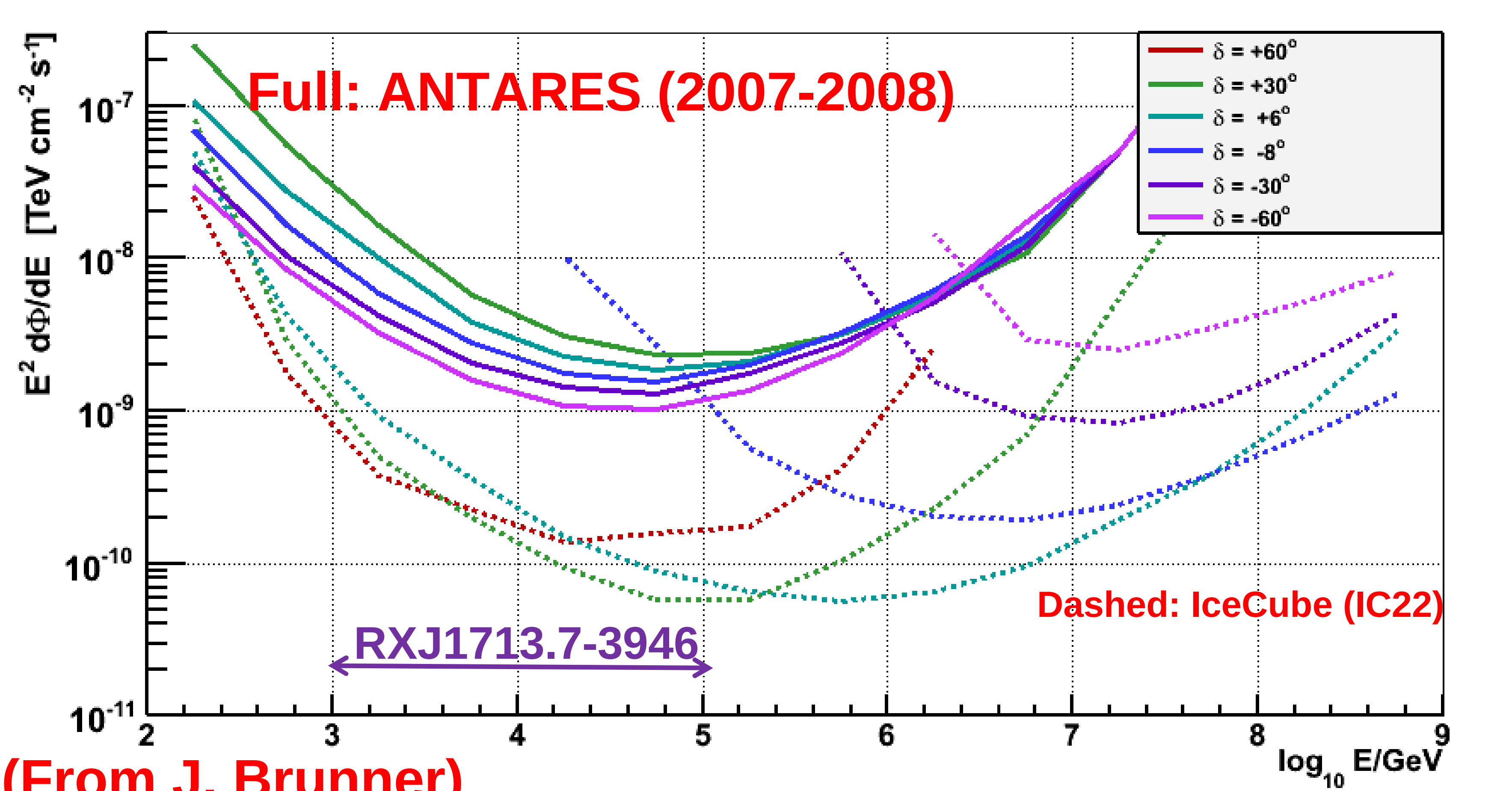








Galactic Sources: ANTARES vs IceCube

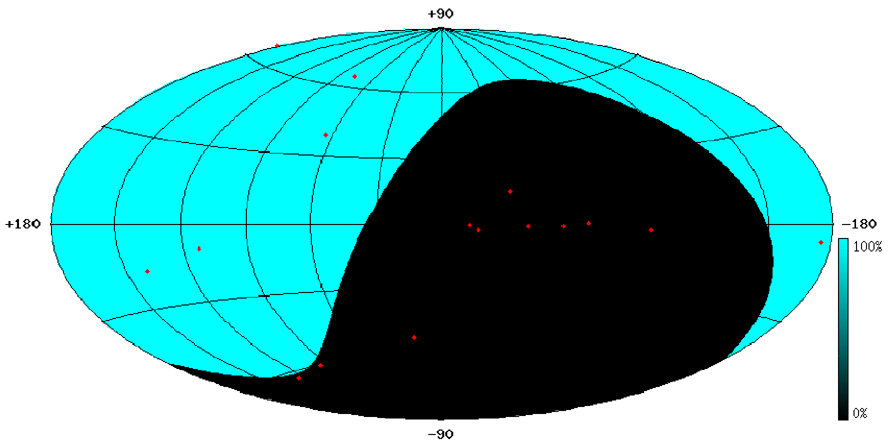


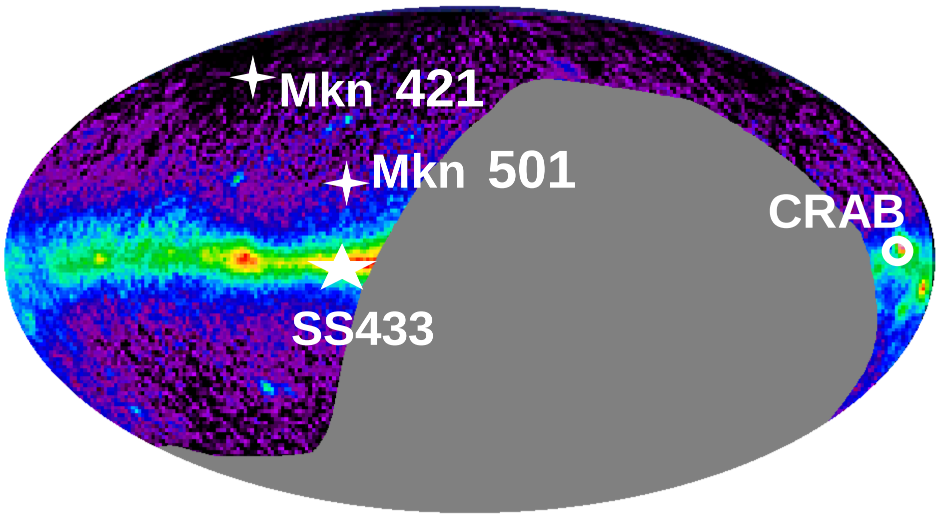
(From J. Brunner)

IceCube energy threshold >1 PeV for Southern Sky sources

Mediterranean Sea ν Telescopes → Complementary to South Pole

AMANDA/IceCube (South Pole)
(Ice: ~2°/0.6°)





ANTARES/KM3 (43° North)
(water: ~0.2°/0.1°)