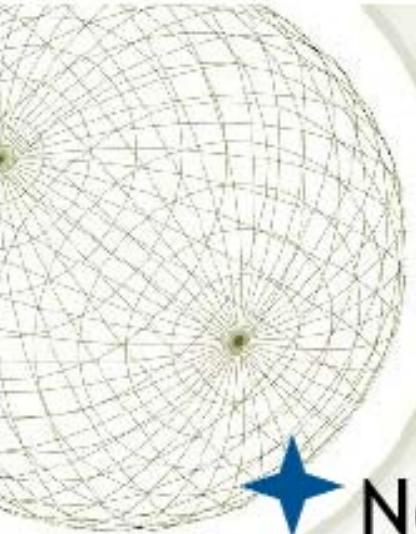


The ANTARES neutrino telescope

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Dept. of Physics “La Sapienza” & INFN
Roma



Outlook

- ★ Neutrino astronomy
- ★ Principle of detection
- ★ Antares
- ★ First results and perspectives
- ★ Conclusions

Brief history of neutrino astronomy

1960

Markov introduces the idea (Proc. of the 1960 Int. Conf. on HE Physics, Rochester)
First estimates on

- diffuse flux by cosmic rays in Galaxy (Greisen, Ann. Rev. Nucl. Science 10 (1960) 1)
- and of HE flux from Crab (Bahcall and Frautchi, PR 135 (1964) 788)

1976

First Workshop on DUMAND, the first project of a giant underwater detector

1970 -1980

Operation of “first generation detectors”

1996

First neutrinos in the Baikal and AMANDA experiments. Work in progress and R&D towards a km³ detector

1998

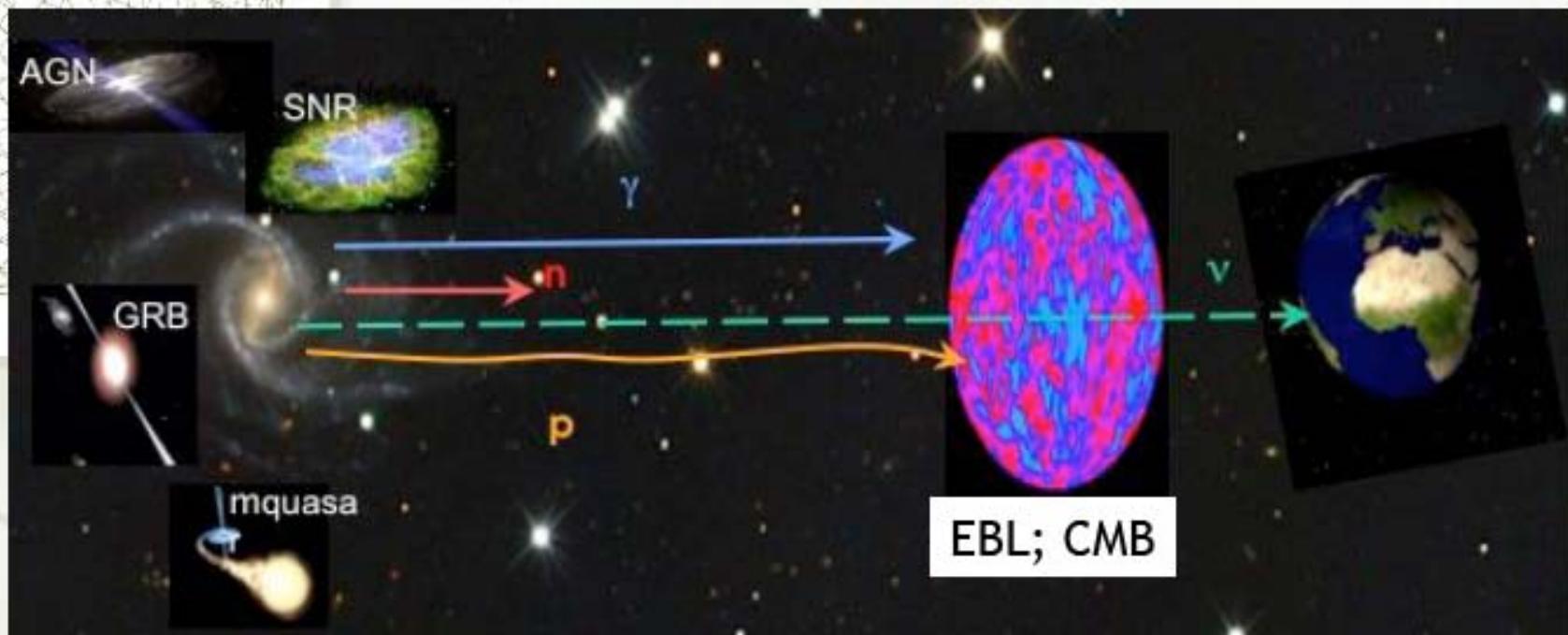
Start of the Italian R&D INFN project Neutrino Mediterranean Observatory

2000

Construction in the Mediterranean of the 0.1 km² ANTARES (with italian participation)

2008: ANTARES completed!

Motivations



- γ are absorbed by the extragal. bgk. light (EBL) (horizon @ 100-200 Mpc);
- p are deflected and interact with cosmic microwave bgk. (CMB) at ultra high energies (GZK cutoff);
- ν interact weakly with matter ==> extend the visible Universe at very high energies.

VHE underwater neutrino telescopes

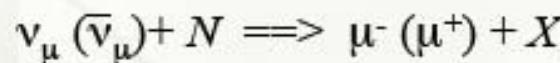
Goal: observation of VHE neutrinos ($E = 1 \text{ TeV} \div 1000 \text{ PeV}$) from astrophysical sources

Detector: lattice of large hemispherical photo-multipliers (PMTs) arranged in strings or towers placed at depth ($>2 \text{ km}$) in water or ice. Natural shield against sunlight and atmospheric CRs.

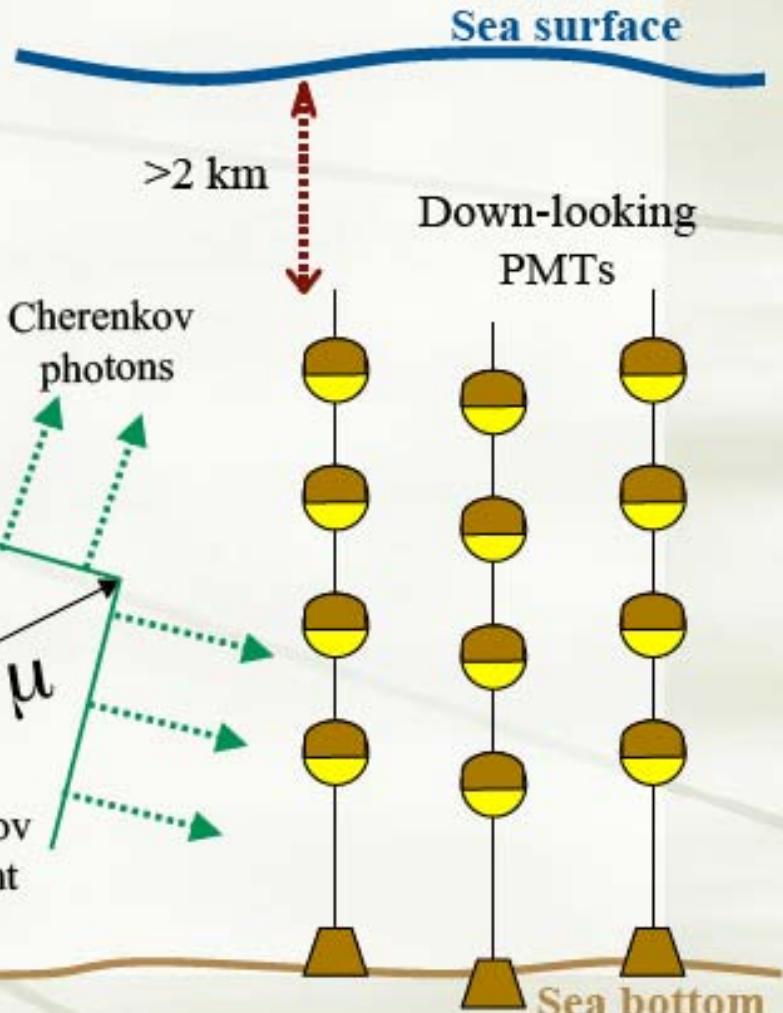
Looking for upward-going muons as signature of muon-neutrino interactions

$$(E_\nu = 1 \text{ TeV} \rightarrow \Theta_{\nu\mu} \approx 1^\circ)$$

CC weak interaction

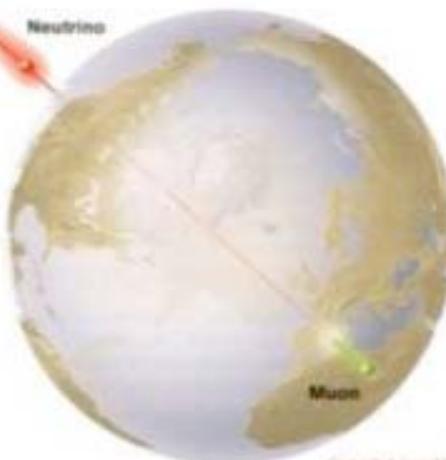


ν_μ from astrophysical source

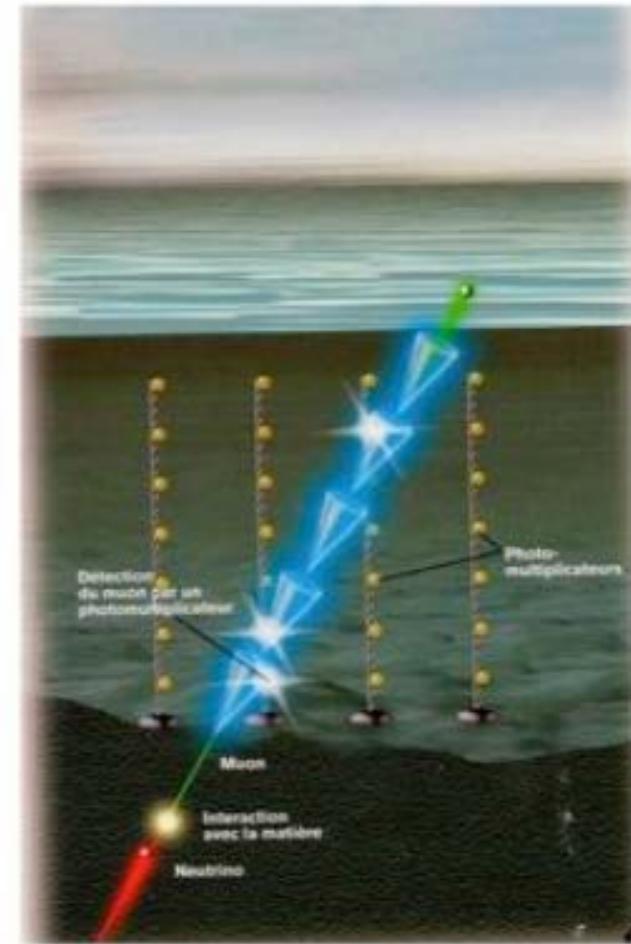


Detection Principles

- Baikal
- AMANDA
- ICECUBE
- ANTARES
- NESTOR
- NEMO
- KM3NeT



Copyright National Vie Italia 1999



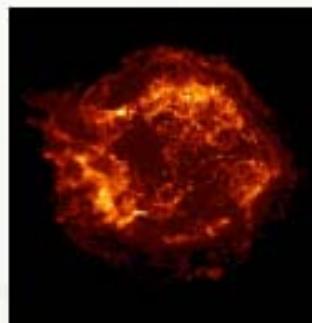
Candidates VHE ν -emitters

Astrophysical beam dump



Galactic

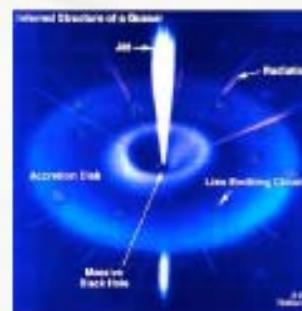
Supernovae Remnants
(SNR) (shell-like type)



Micro-quasars
Plerions
Galactic center

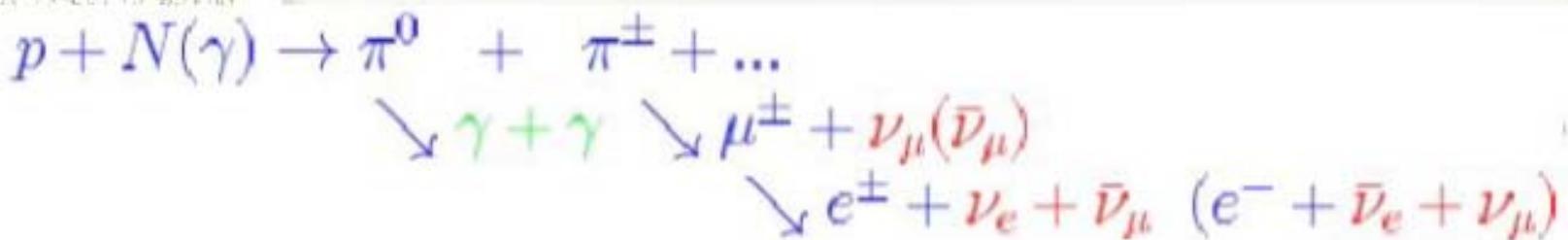
Extra-galactic

Blazars AGNs, GRBs,...



Extra-terrestrial ν 's detected only at lower energies (Sun and SN1987)

Source spectrum

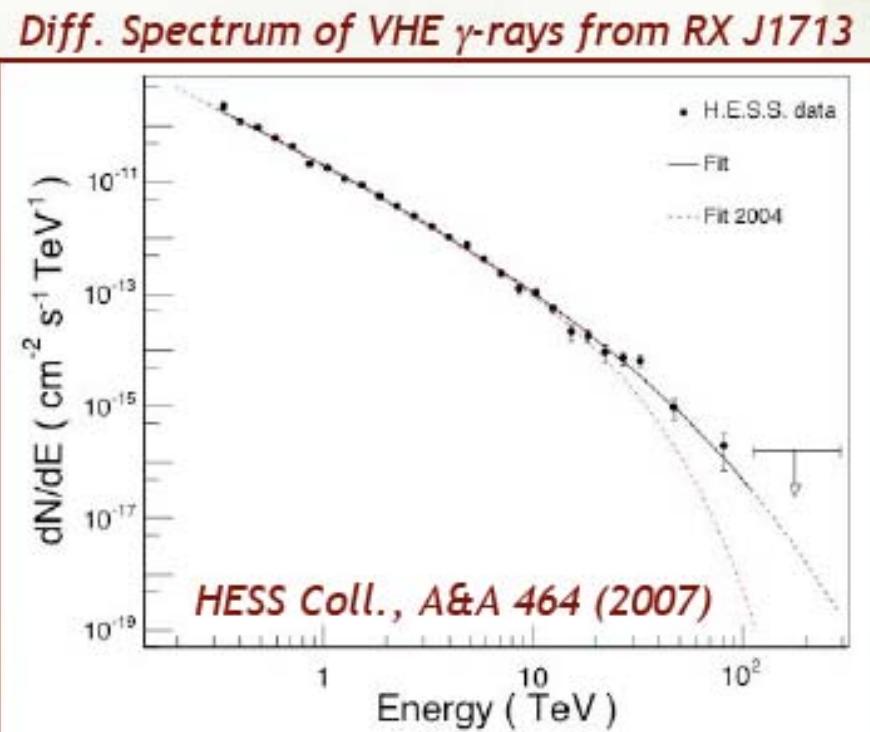


Power law spectrum is expected from cosmic accelerator (Fermi acceleration mechanisms):

$$dN/dE \propto E^{-\Gamma}$$

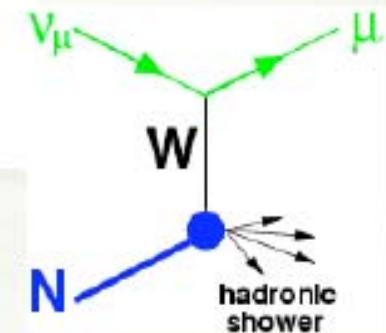
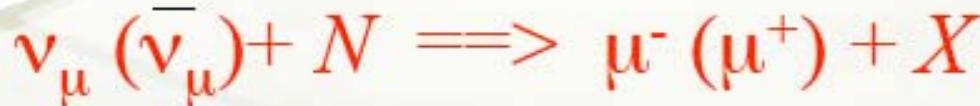
Spectral indexes $\Gamma = 2 \div 2.5$

Detection of VHE neutrinos
main signatures of hadronic
processes at the source.



Main detection channel

ν detected as upward-going muons through
Charged-Current (CC) weak interactions
with rock or water surrounding the detector:



Probability that a ν with energy E_ν crossing the detector produces a μ with $E_\mu \geq E_{th}$:

$$P_\nu(E_\nu, E_{th}^\mu) = N_A \int_0^{E_\nu} dE'_\mu \frac{d\sigma_\nu}{dE'_\mu}(E'_\mu, E_\nu) R_{eff}(E'_\mu, E_{th}^\mu)$$

νN cross section μ effective range

νN cross section

For $E_\nu < 1$ TeV: $\sigma_\nu \sim E_\nu$ and $R_{eff} \sim E_\mu$

For $E_\nu > 1$ TeV: σ_ν dumped by W propagator and $R_{eff} \sim \ln(E_\mu)$

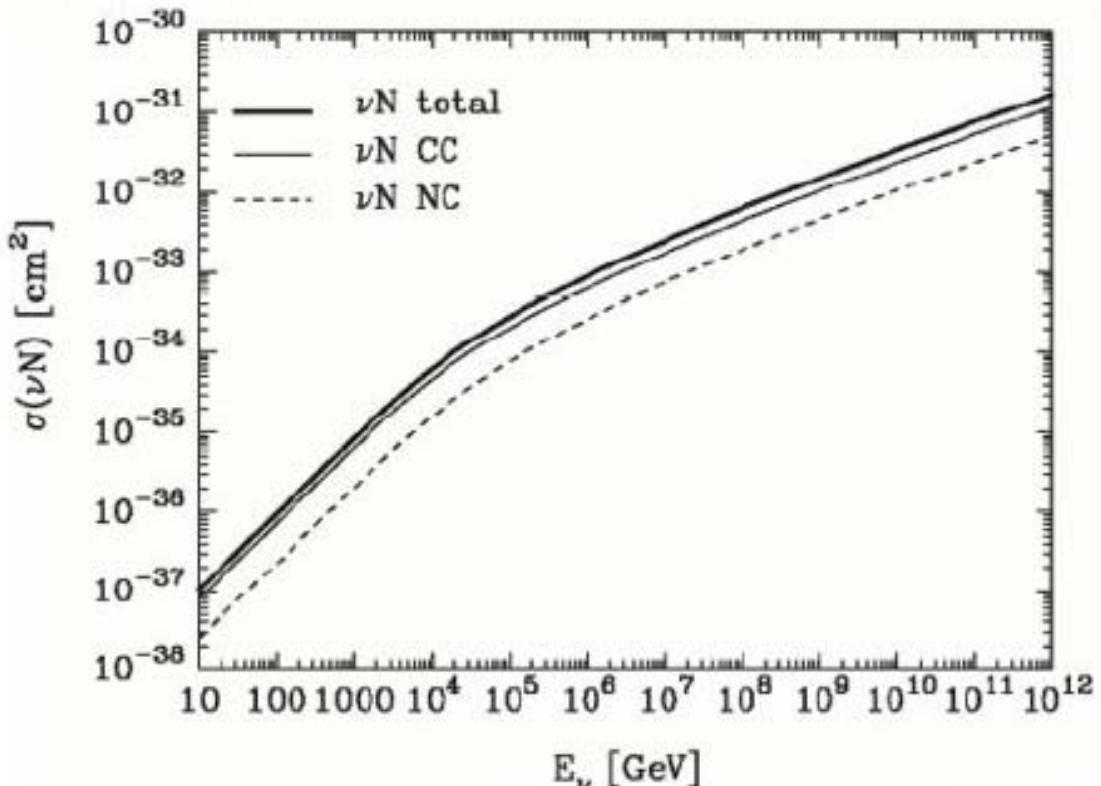
$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi} \left(\frac{M_{W,Z}^2}{Q^2 + M_{W,Z}^2} \right)^2 [xq(x, Q^2) + x\bar{q}(x, Q^2)(1-y)^2]$$

$$x = \frac{Q^2}{2M\varepsilon}$$

$$y = \frac{\varepsilon}{E_\nu}$$

$$\varepsilon = E_\nu - E_l$$

E_p	$P_{\nu \rightarrow \mu^-}$	$P_{\nu \rightarrow \mu^+}$
10	8.15×10^{-11}	4.88×10^{-11}
10^2	9.05×10^{-9}	5.87×10^{-9}
10^3	5.79×10^{-7}	3.86×10^{-7}
10^4	1.52×10^{-5}	1.09×10^{-5}
10^5	1.35×10^{-4}	1.17×10^{-4}

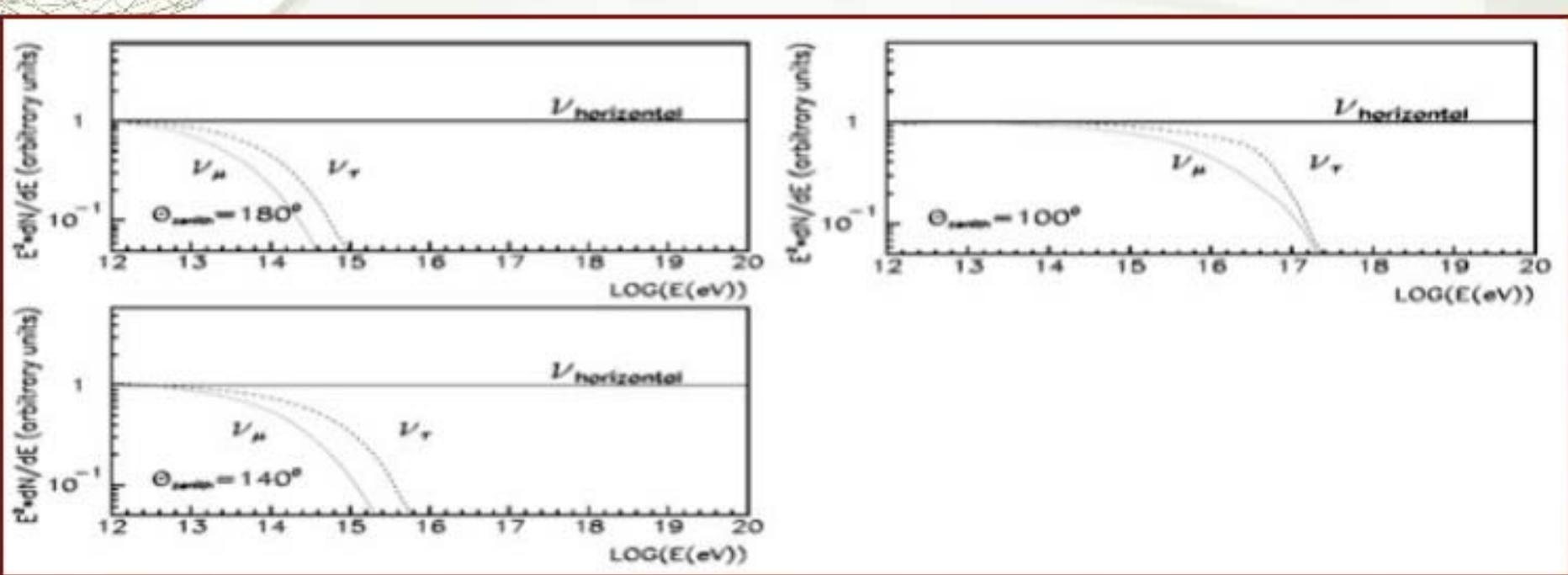


Propagation of neutrinos

νN cross section increases with energy



prob. of absorption crossing Earth increases



Earth becomes opaque to νs with $E_\nu > 100 \text{ TeV}$.

Muon range

$$R_{\text{eff}}(E_\mu, E_{\mu}^{\text{th}}) = \int_0^{\infty} dX P_{\text{surv}}(E_\mu, E_\mu^{\text{th}}, X)$$

μ energy losses:

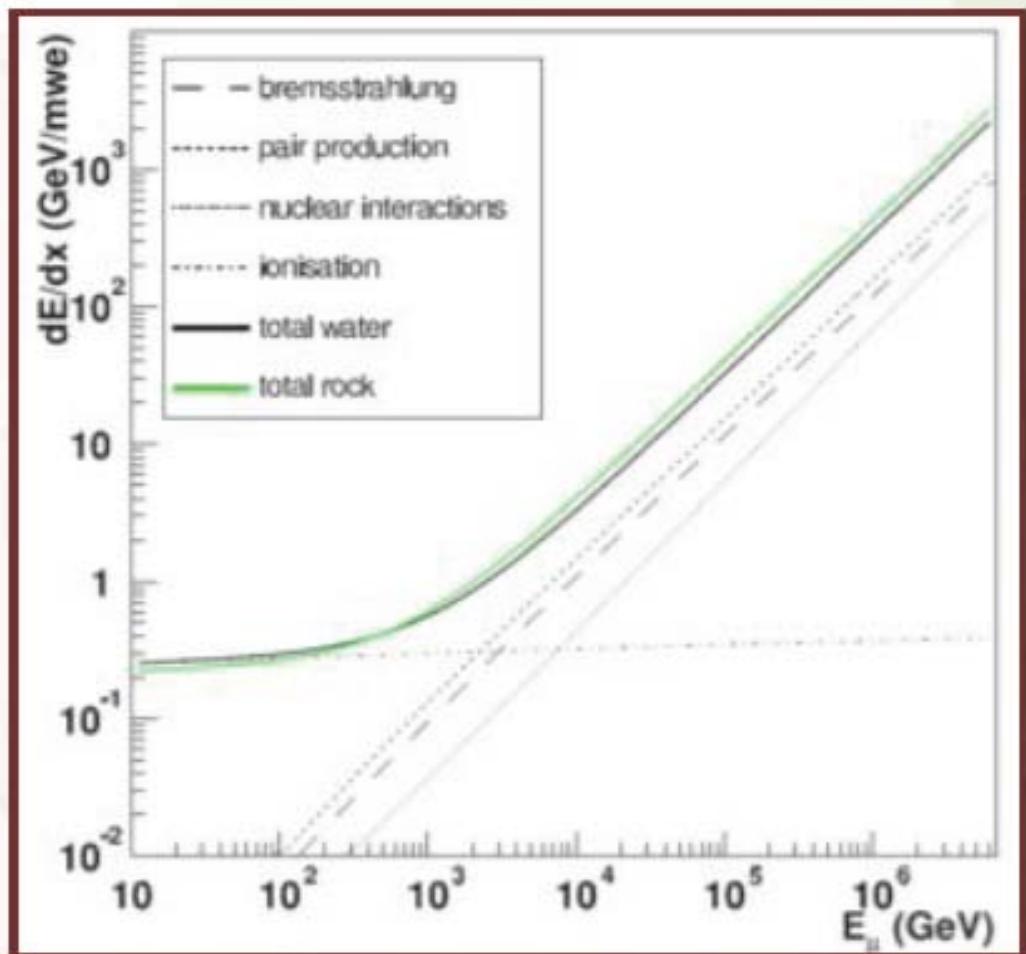
$$\frac{dE_\mu}{dX} = \alpha(E_\mu) + \beta(E_\mu)E_\mu$$

α = ionization losses:

$$\sim 2 \text{ MeV g}^{-1} \text{ cm}^{-2}$$

β = bremsst., pair prod., nucl. int.:

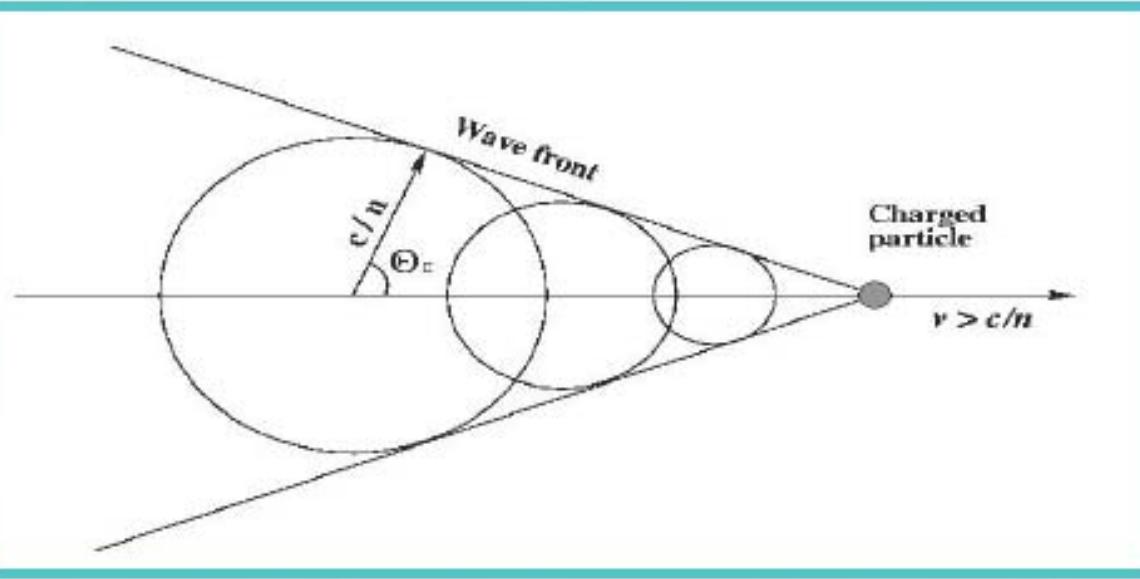
$$\sim 4 \times 10^{-6} \text{ g}^{-1} \text{ cm}^{-2}$$



Emission of Cherenkov radiation

- Cherenkov photons emitted along the ultra-relativistic muon track.

$$\beta > \frac{1}{n} ; \cos\Theta_c = \frac{1}{\beta n} ; \frac{d^2N}{dx d\lambda} \propto \frac{1}{\lambda^2}$$



$\Theta_c \approx 42^\circ$ in sea water

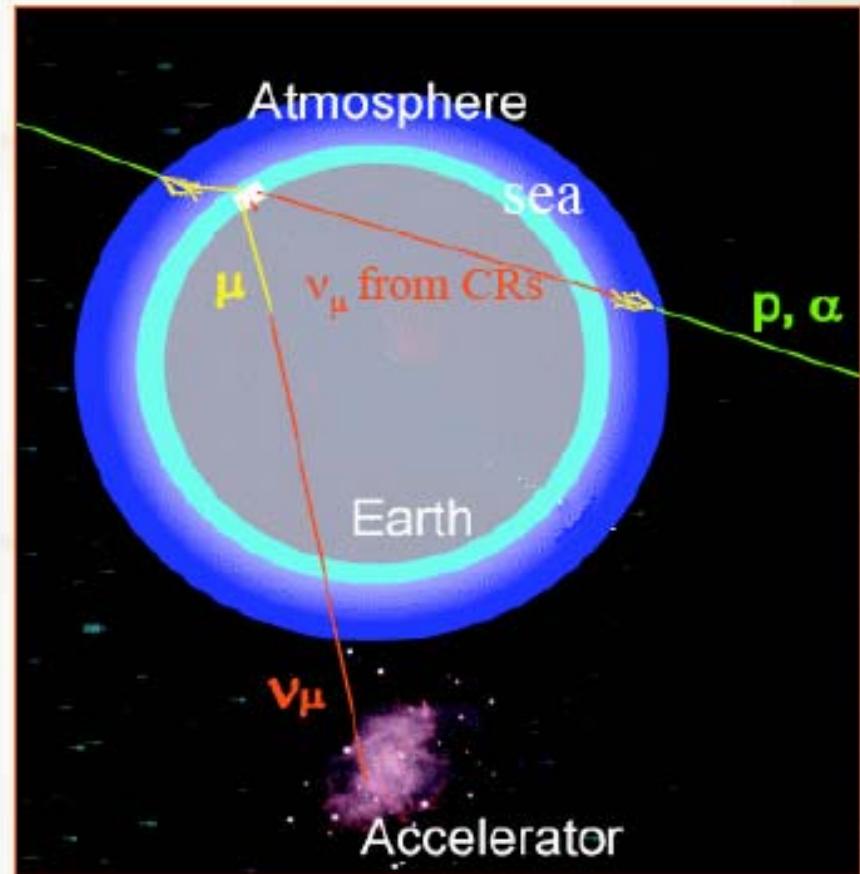
Cherenkov photons
between 300 and 600 nm.
Around 300 ph/cm in this
band.

Background photons: cosmic rays (I)

- Cosmic-ray background:
- Atmospheric muons from CRs → muons tracks coming from above (down-going tracks)
 - Atmospheric neutrinos from CRs → up-going muons tracks

Both induce Cherenkov photons emission along their track.

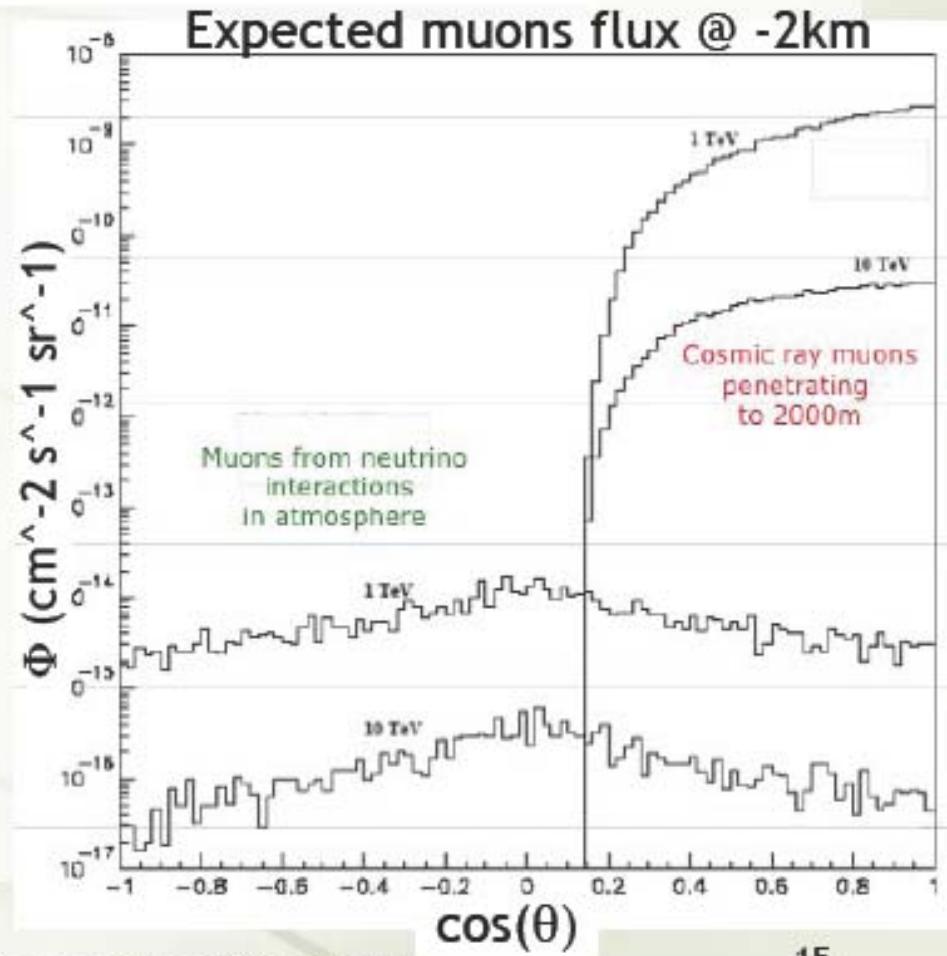
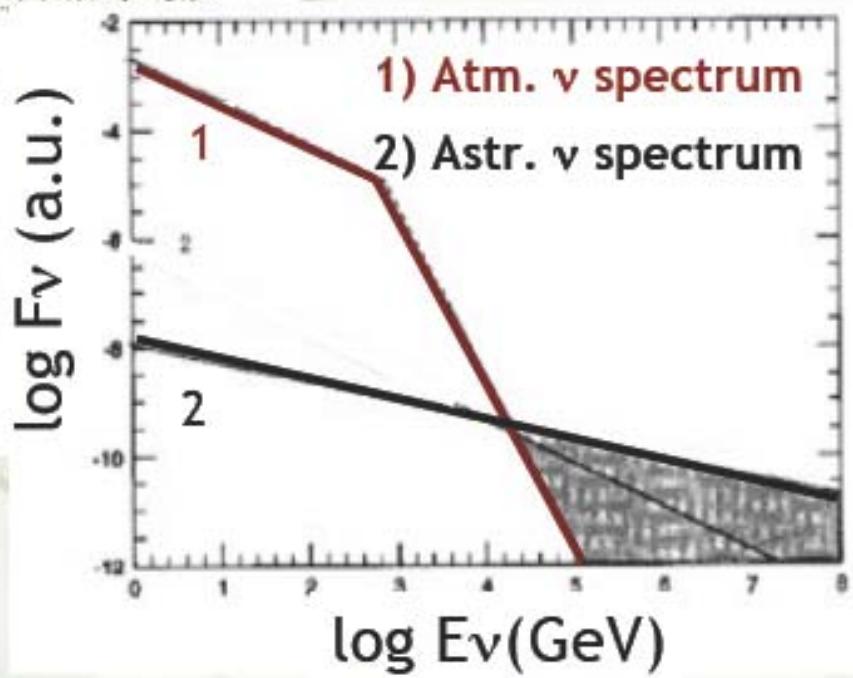
from Antares webpage



Background photons: cosmic rays (II)

- vs spectrum from interactions of CRs with atm. nuclei

$$\frac{dN}{dE} \propto E^{-2.7(3.7)} \text{ for } E_\nu < 100 \text{ GeV (} E > 100 \text{ GeV)}$$

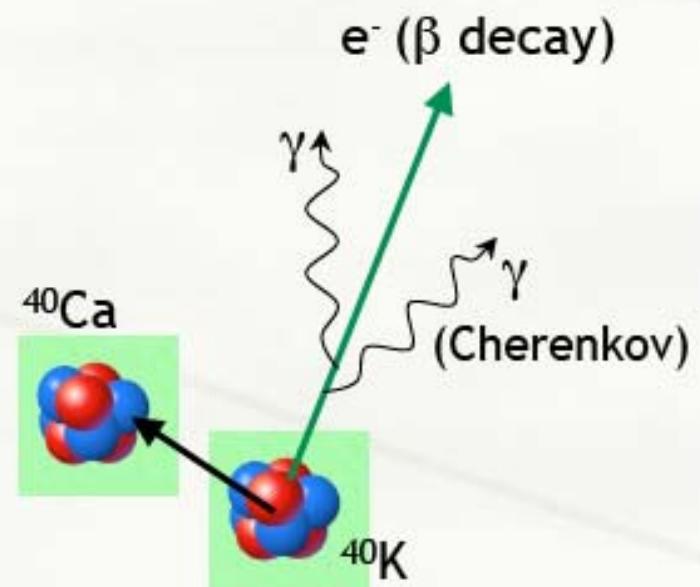


Background photons: natural activity

Bioluminescence



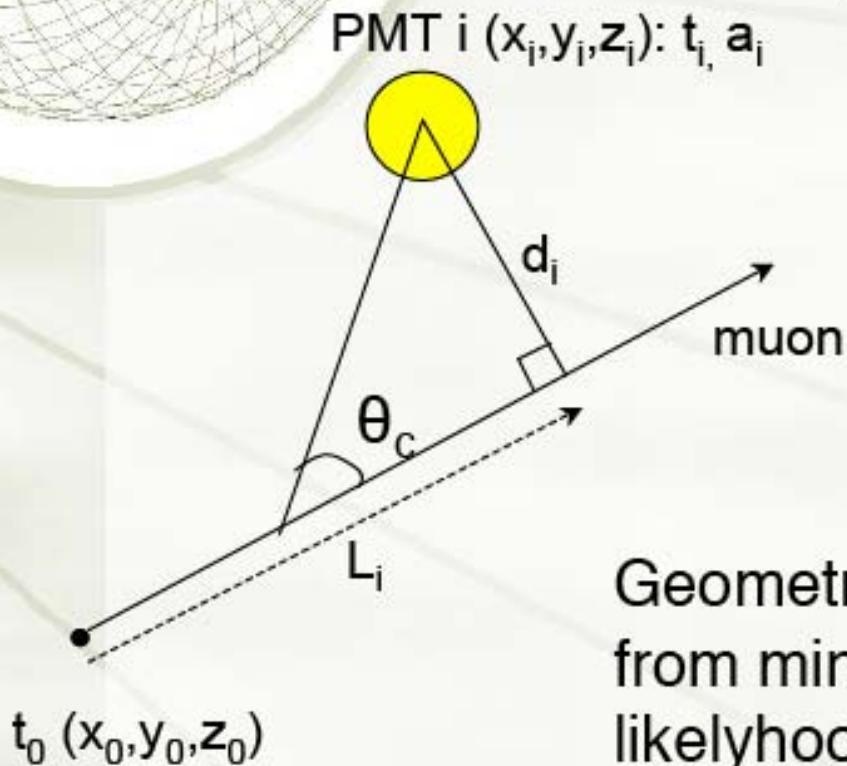
^{40}K decay
uncorrelated photon counting rate
(20-50kHz) on PMTs



Muon track reconstruction

Arrival times of the Cherenkov photons on the PMT depend of the track direction and the muon position at t_0 :

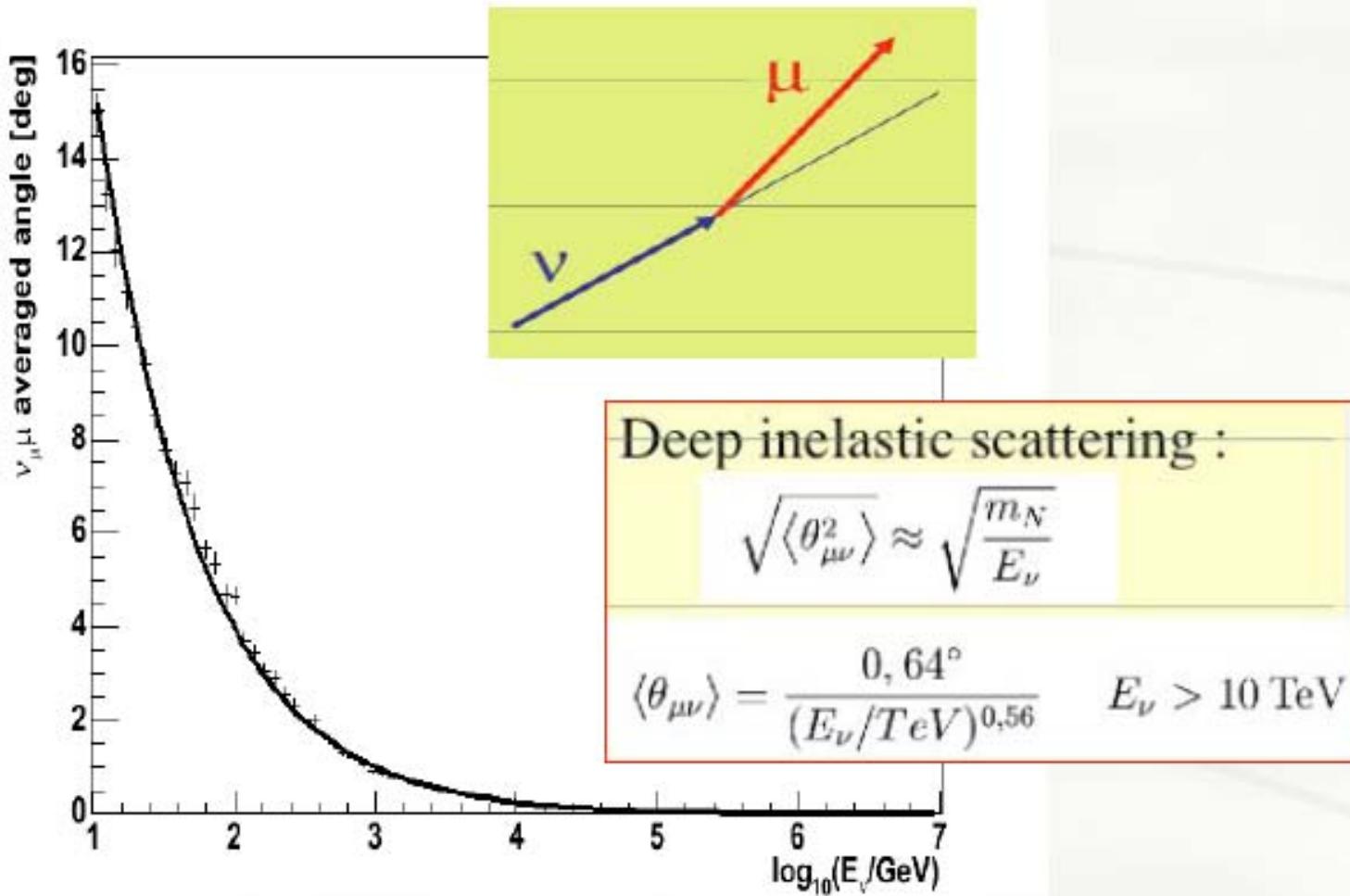
$$t_i = t_0 + (L_i + d_i \cdot \tan \theta_c) / c$$



Geometrical track parameters ($x_0, y_0, z_0, \theta, \phi$) from minimization of χ^2 or maximum likelihood estimation.

Photons from the optical background arrive at random times.

Angular resolution



For $E_\nu < 10 \text{ TeV}$ is dominated by the $\nu\text{-}\mu$ physical angle.

Expected # of events in the detector

$$\frac{N_\mu(E_{\mu,\min}, \theta)}{AT} = \int_{E_{\mu,\min}}^{E_\nu} dE_\nu \Phi_\nu(E_\nu, \theta) \cdot P_{\nu\mu}(E_\nu, E_{\mu,\min}) \cdot e^{-\alpha_{\text{tot}}(E_\nu) N_A Z(\theta)}$$

Neutrino flux

Probability to produce a detectable muon ($E_\mu > E_{\min}$)

Earth transparency

Rate of events from a neutrino source

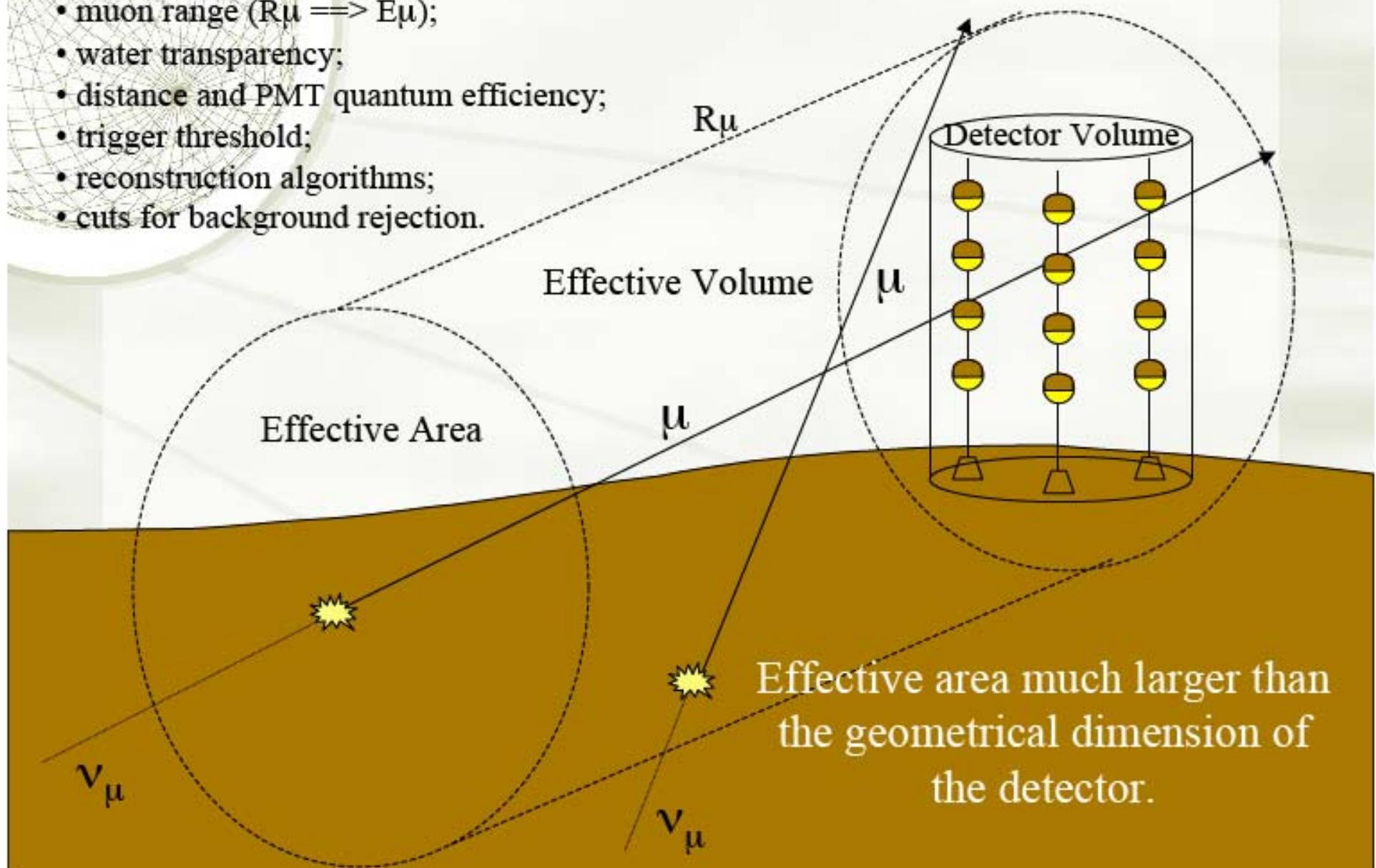
$$\frac{dN_{EV}}{dt} = N_\mu(E_{\mu,\min}, \Theta(t)) \cdot A_{\text{eff}}(\Theta(t), E_\mu)$$

Effective area of the telescope

Effective area The detector capability to reconstruct muon tracks

It depends on:

- muon range ($R_\mu \Rightarrow E_\mu$);
- water transparency;
- distance and PMT quantum efficiency;
- trigger threshold;
- reconstruction algorithms;
- cuts for background rejection.



Expected events from candidate VHE ν -emitters

Expected events in an underwater Cherenkov Neutrino Telescope with an $A_{\text{eff}} \sim 1 \text{ km}^2$



Diffuse fluxes

GZK neutrinos	0.5 / year
GRB (<i>Waxman</i>)	50 / year
AGN (thin) (<i>Mannheim</i>)	few / year
(thick)	>100 / year

Point-like sources

GRB (030329) (<i>Waxman</i>)	1-10 / burst
AGN (3C279) (<i>Dermer</i>)	few / year
Galactic SNR (Crab) (<i>Protheroe</i>)	few / year
Galactic MicroQuasar (<i>Distefano</i>)	1-100 / year

AMANDA II ULs on Blazars

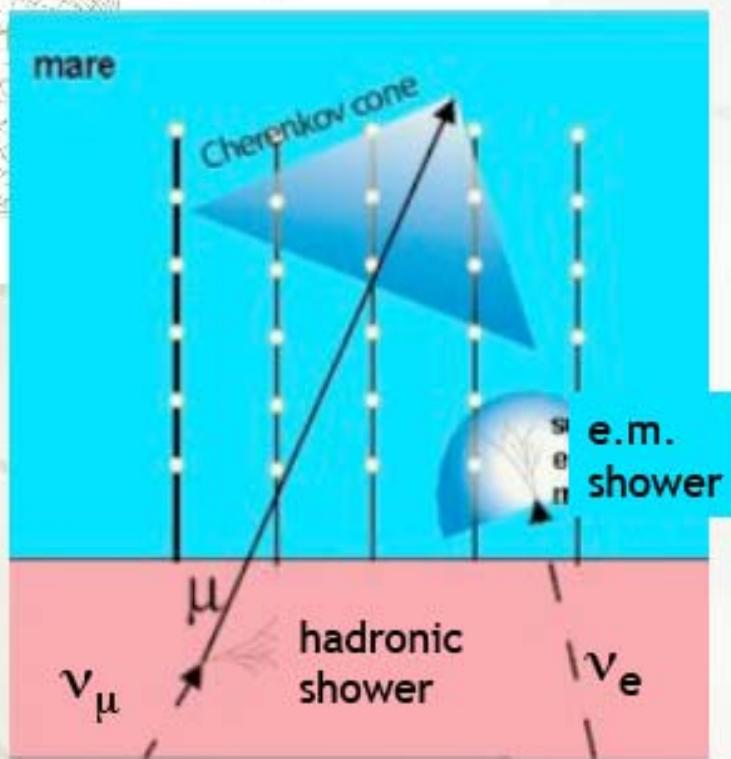
Physical Review D71 (2005) 077102

TABLE III. 90% C.L. upper limits on candidate sources. Results from the present analysis are reported for a comparison with the limits from [2]. Limits are for the assumed E_ν^{-2} spectral shape, integrated above $E_\nu = 10$ GeV, and in units of $10^{-8} \text{ cm}^{-2} \text{ s}^{-1} (\Phi_\nu^{\text{lim}})$.

Candidate	$\delta(^{\circ})$	$\alpha(h)$	From [2]			This work		
			n_{obs}	n_b	Φ_ν^{lim}	n_{obs}	n_b	Φ_ν^{lim}
TeV Blazars								
Markarian 421	38.2	11.07	3	1.50	3.5	0	1.35	0.34
Markarian 501	39.8	16.90	1	1.57	1.8	3	1.31	1.49
1ES 1426+428	42.7	14.48	1	1.62	1.7	2	1.13	1.16
1ES 2344+514	51.7	23.78	1	1.23	2.0	1	1.25	0.82
1ES 1959+650	65.1	20.00	0	0.93	1.3	0	1.59	0.38
GeV Blazars								
QSO 0528+134	13.4	5.52	1	1.09	2.0	1	1.88	0.57
QSO 0235+164	16.6	2.62	1	1.49	1.7	3	2.15	1.12
QSO 1611+343	34.4	16.24	0	1.29	0.8	0	1.66	0.31
QSO 1633+382	38.2	16.59	1	1.50	1.7	1	1.33	0.75
QSO 0219+428	42.9	2.38	1	1.63	1.6	0	1.15	0.37
QSO 0954+556	55.0	9.87	1	1.66	1.7	2	1.04	1.50
QSO 0716+714	71.3	7.36	2	0.74	4.4	3	0.93	1.91

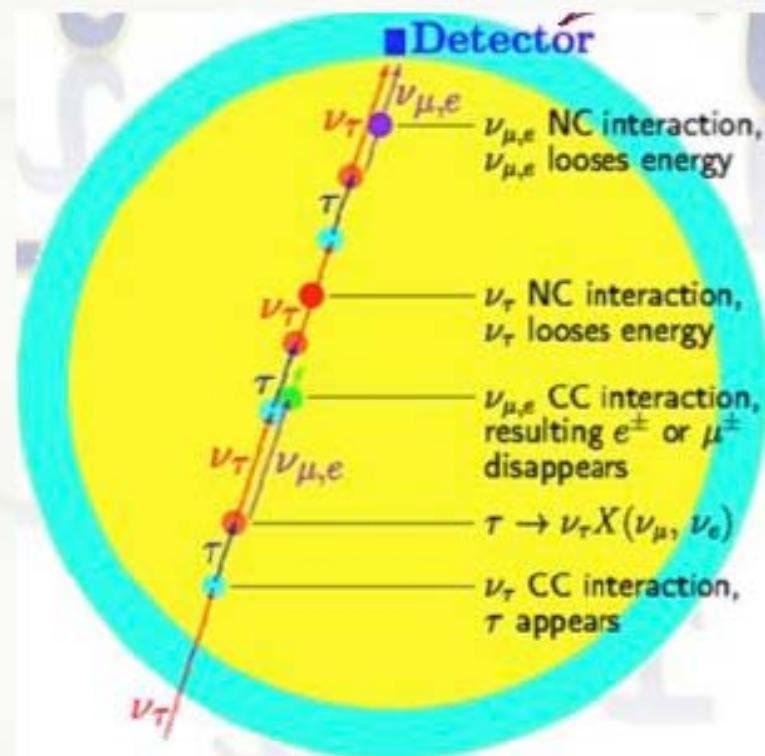
Other detection channels

CC $\nu_e N$ events

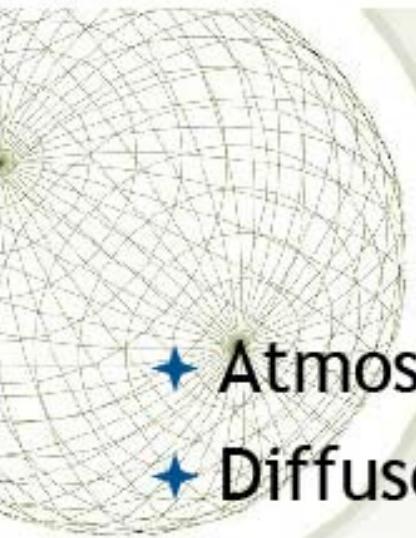


Contained events: better energy res. but worse ang. res.

ν_τ



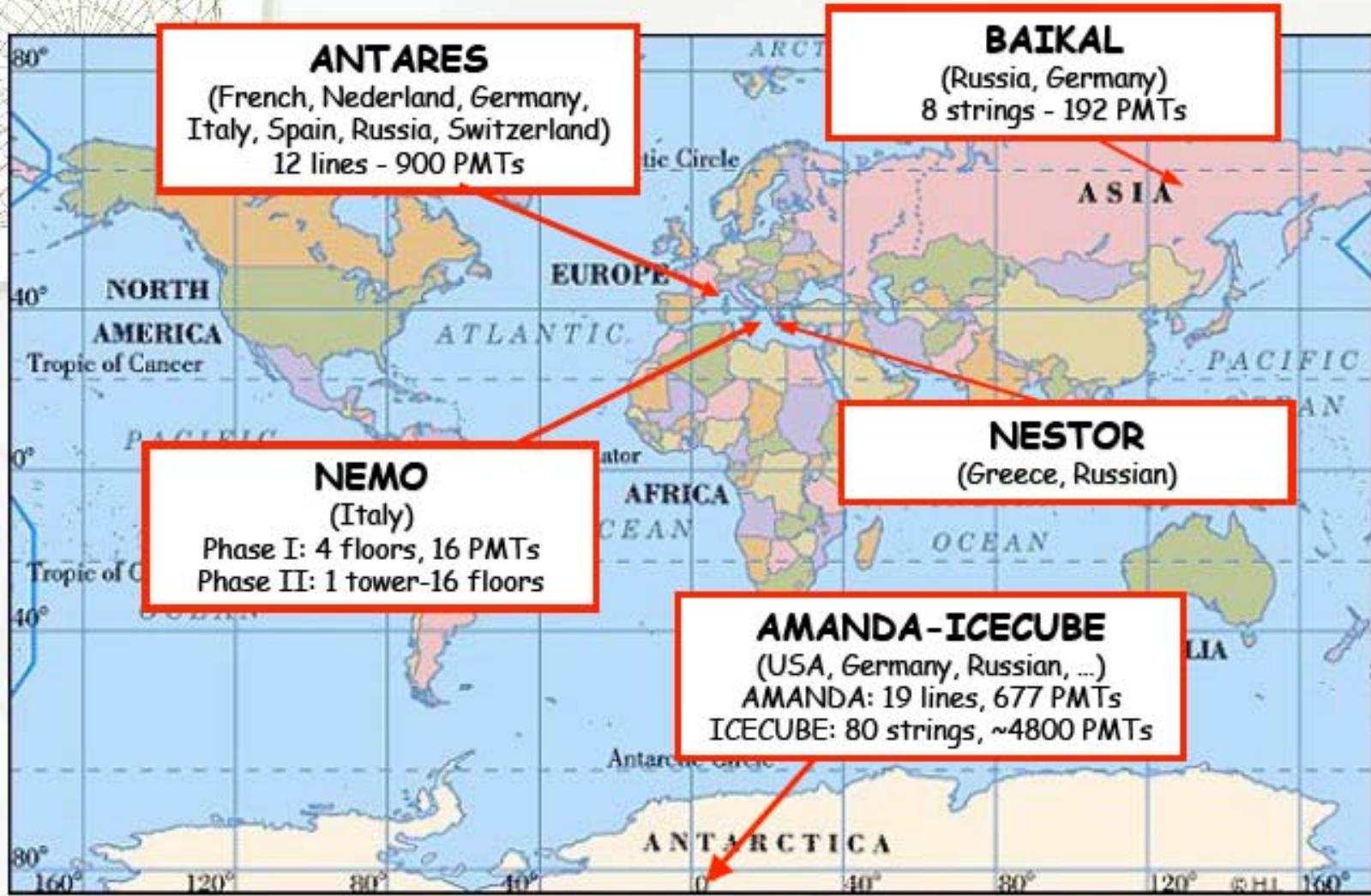
Visible by pile-up of events near 100 TeV



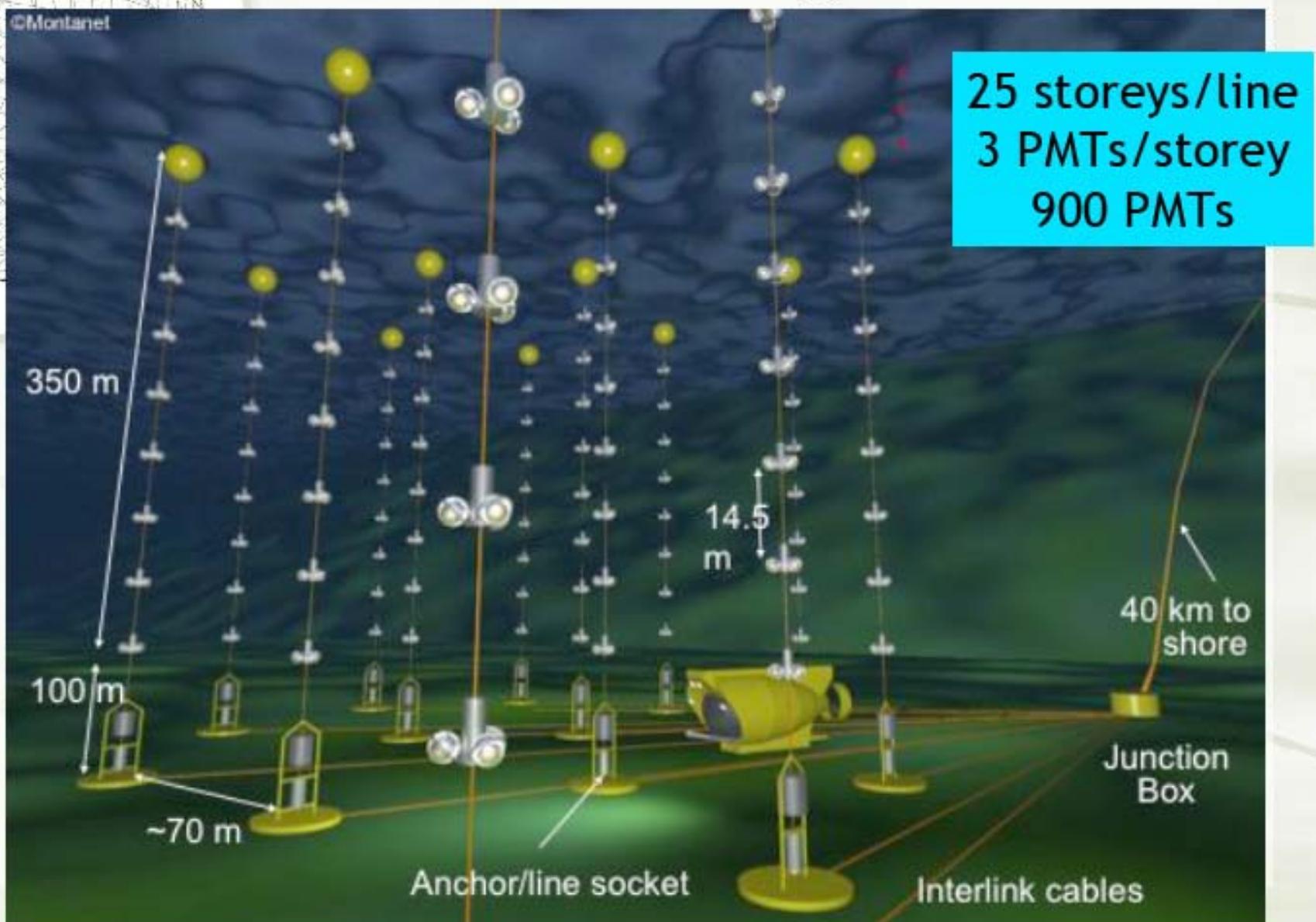
More physics ...

- ❖ Atmospheric neutrinos and muons studies
- ❖ Diffuse flux of VHE neutrinos
- ❖ Neutrino oscillations
- ❖ Search for Dark Matter (neutrinos from neutralinos annihilation)
- ❖ Exotic physics (monopoles, nuclearites, ...)
- ❖ Interdisciplinary deep sea studies:
 - ◆ oceanography, sea biology, seismology...

VHE neutrino telescopes

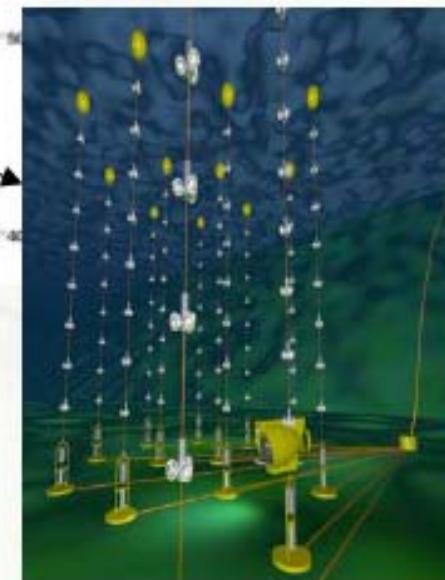
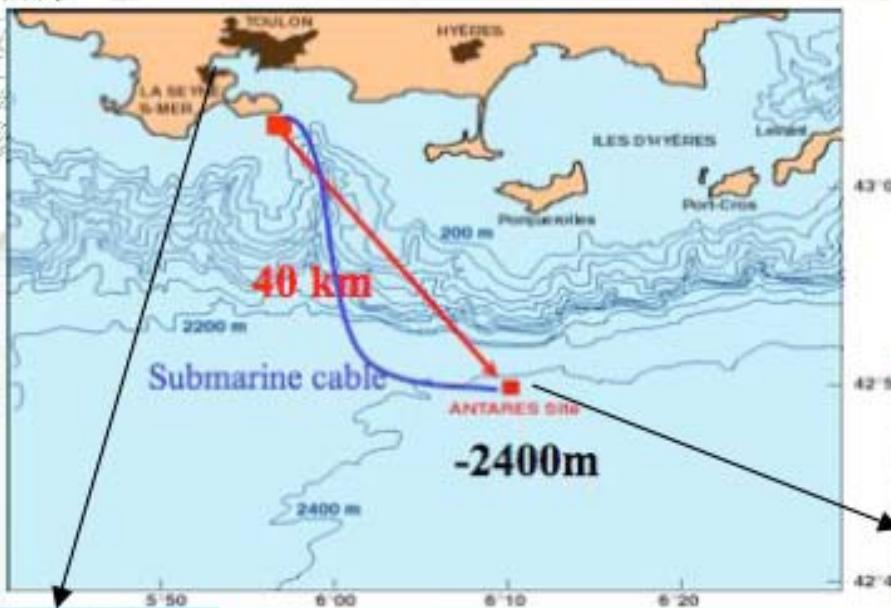


The ANTARES 12 strings detector

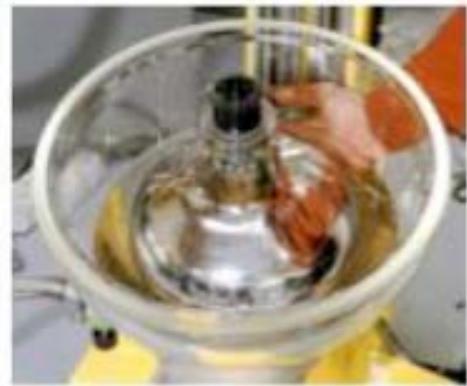
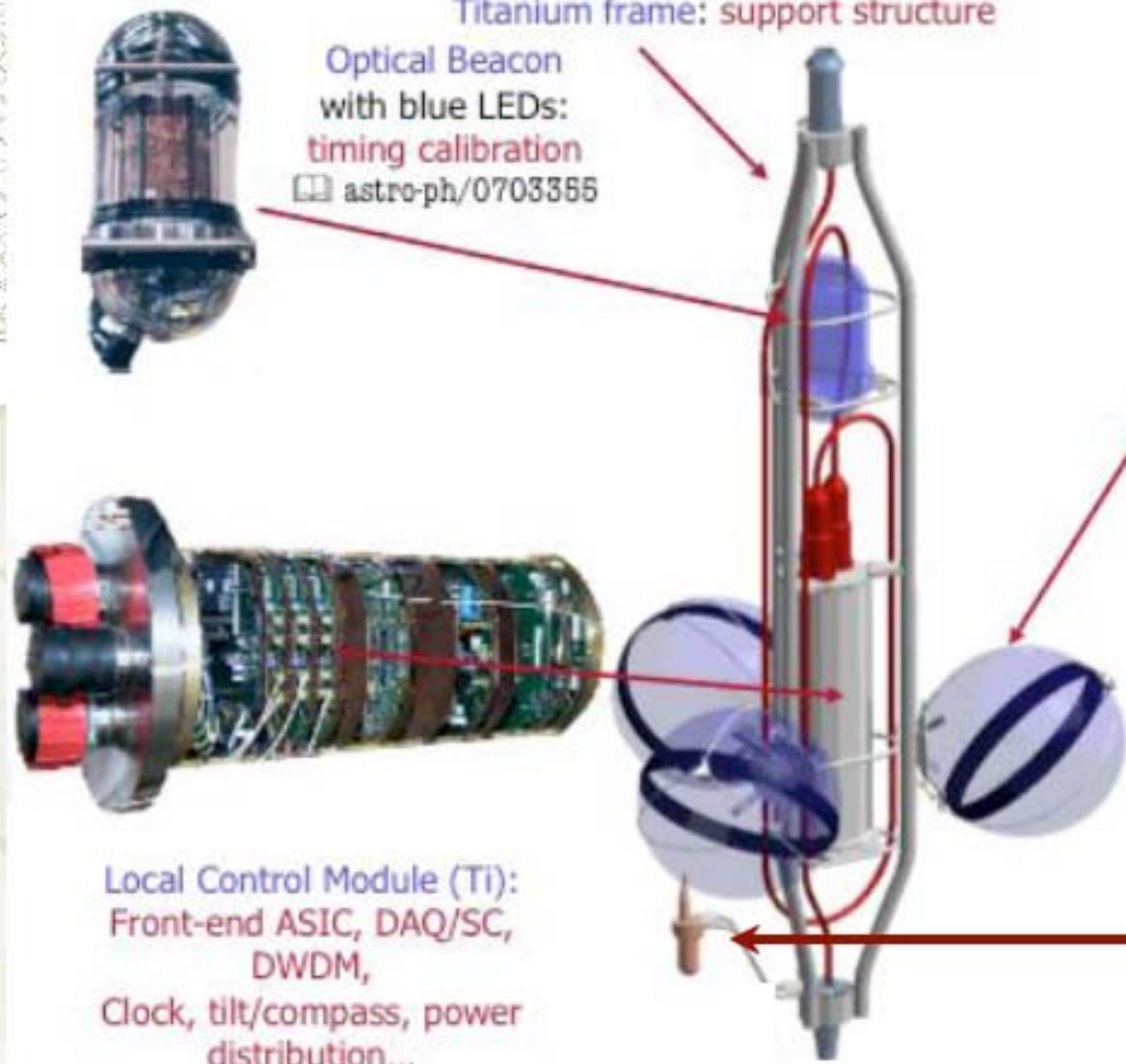


ANTARES Location

Latitude: 43° North



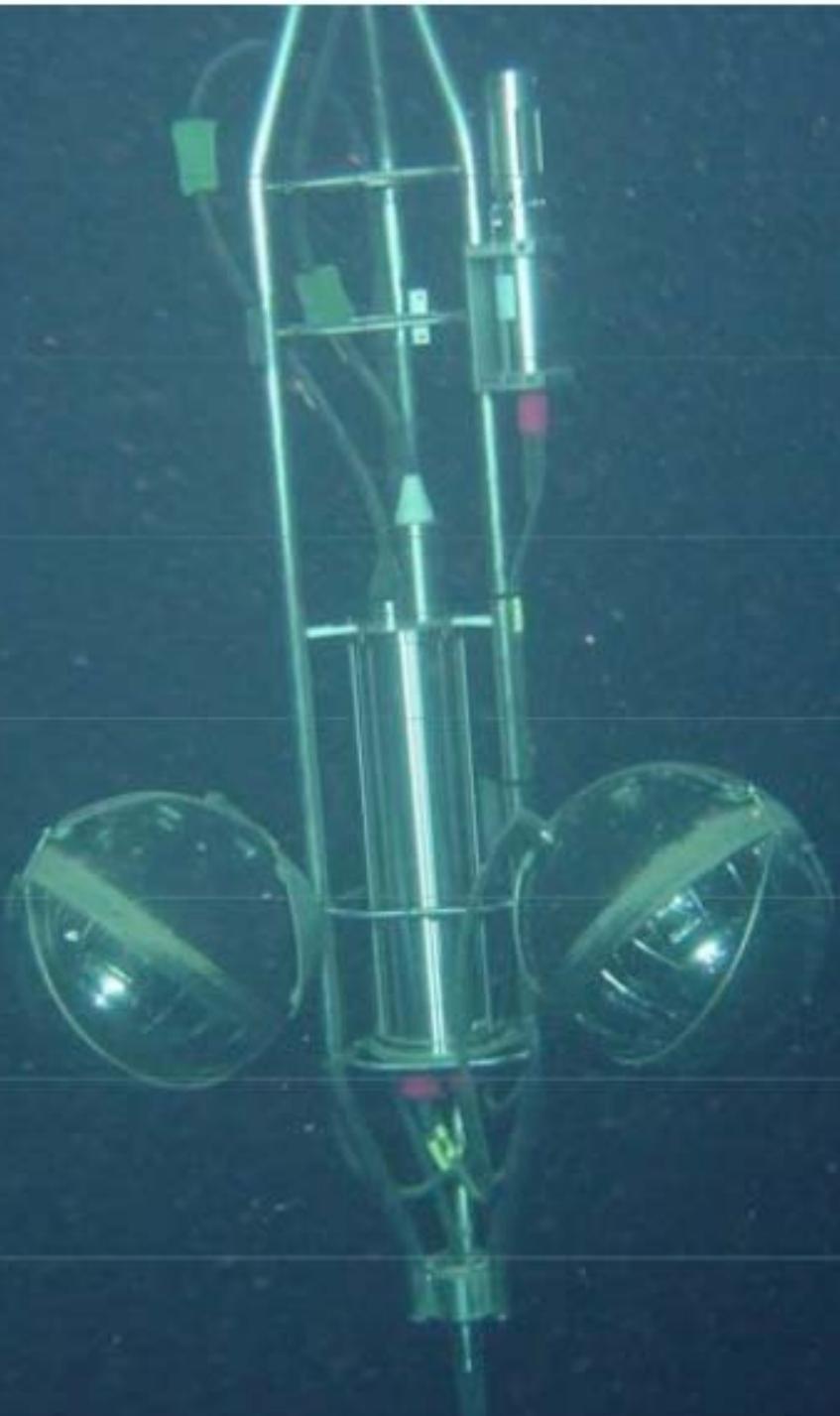
Basic detector element: the storey



Optical Module:
10" Hamamatsu PMT in
17" glass sphere
photon detection
■ NIM A484 (2002) 369
■ NIM A555 (2005) 132



Hydrophone:
acoustic positioning



Line 1



Operational since March 2006

Lines deployment



Submarine connections of cables



Manned submersible

Remote operated vehicle
(ROV)



P= 4.4 T=-2.8

CAP = 206.6
206.7

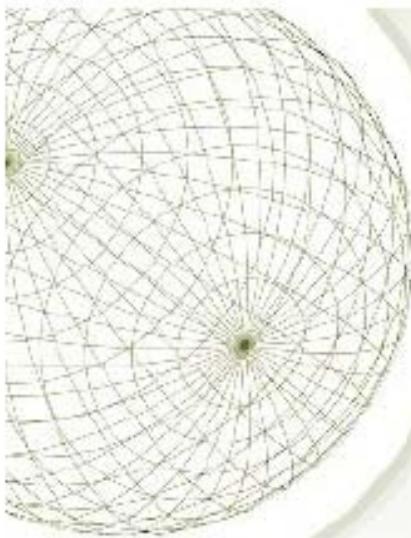
09:36:56

IMM = 2480.2 v1 =
vt =

ALT = 0.8

ROI = 0.0

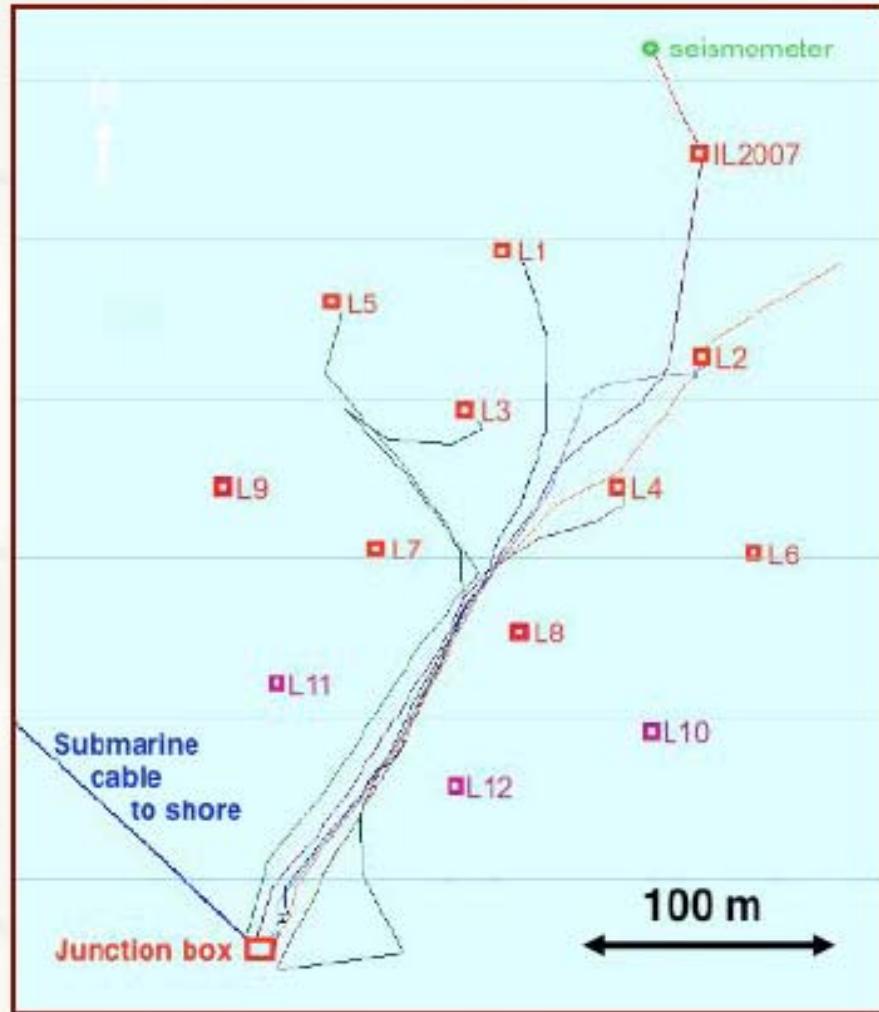
Present status



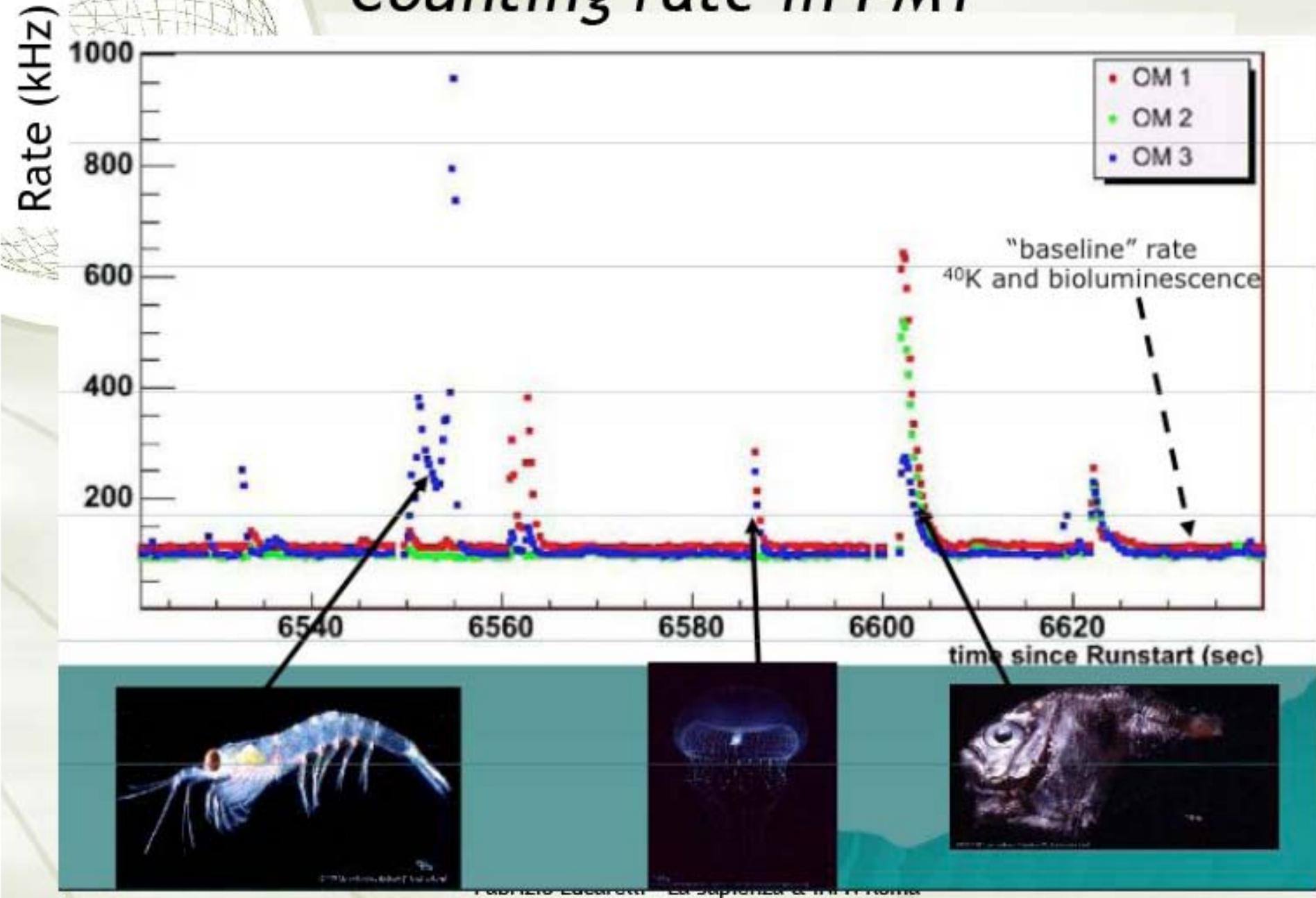
String 12 deployed two day ago.

ANTARES is completed!

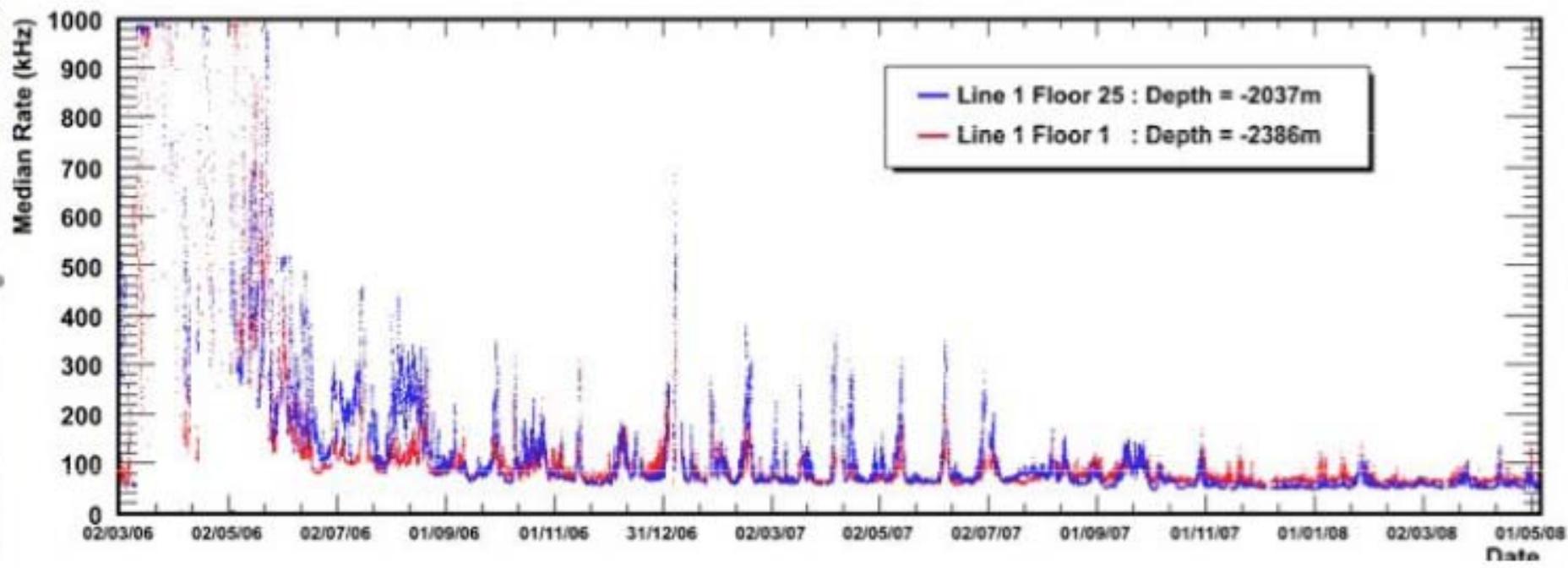
An additional instrumented string (IL) for environment studies has been deployed in 2007.



Counting rate in PMT

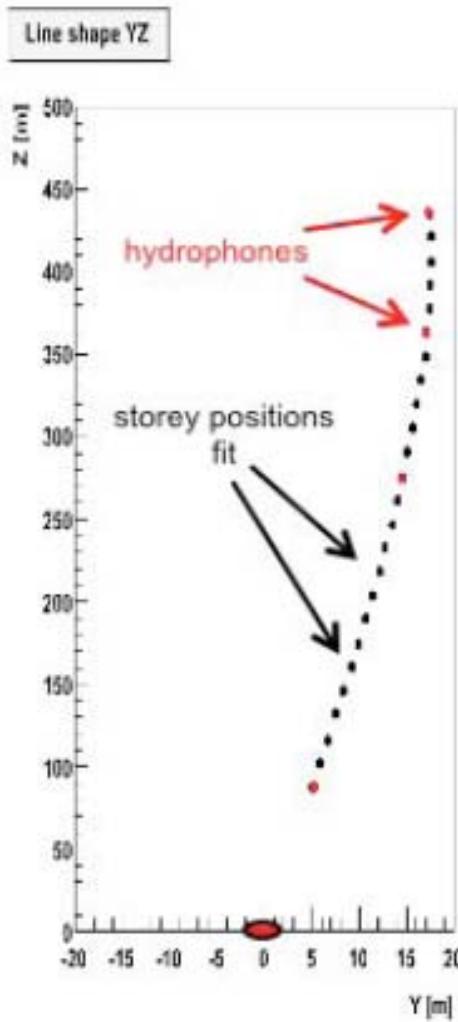
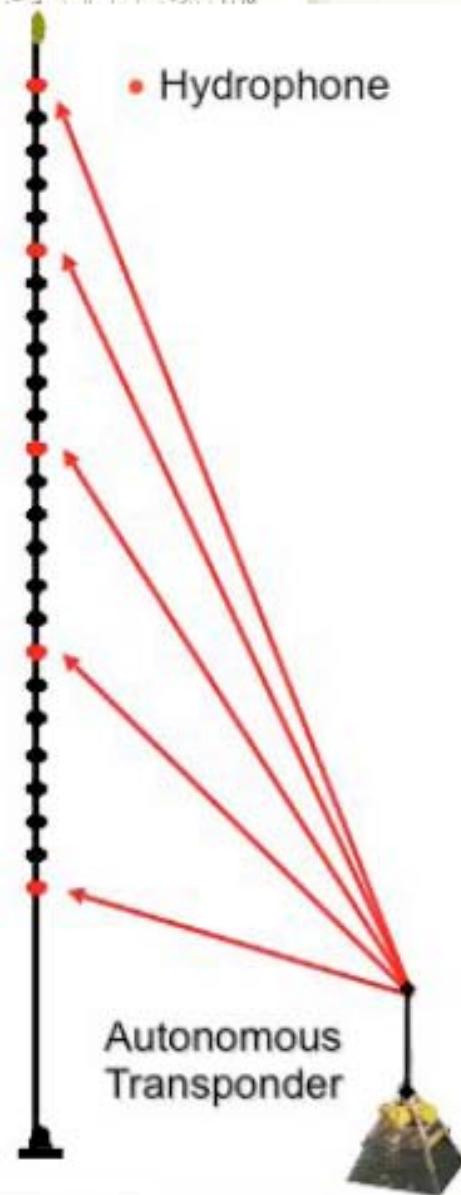


Median rate vs time



03/2006 —————→ 05/2008

Detector positioning

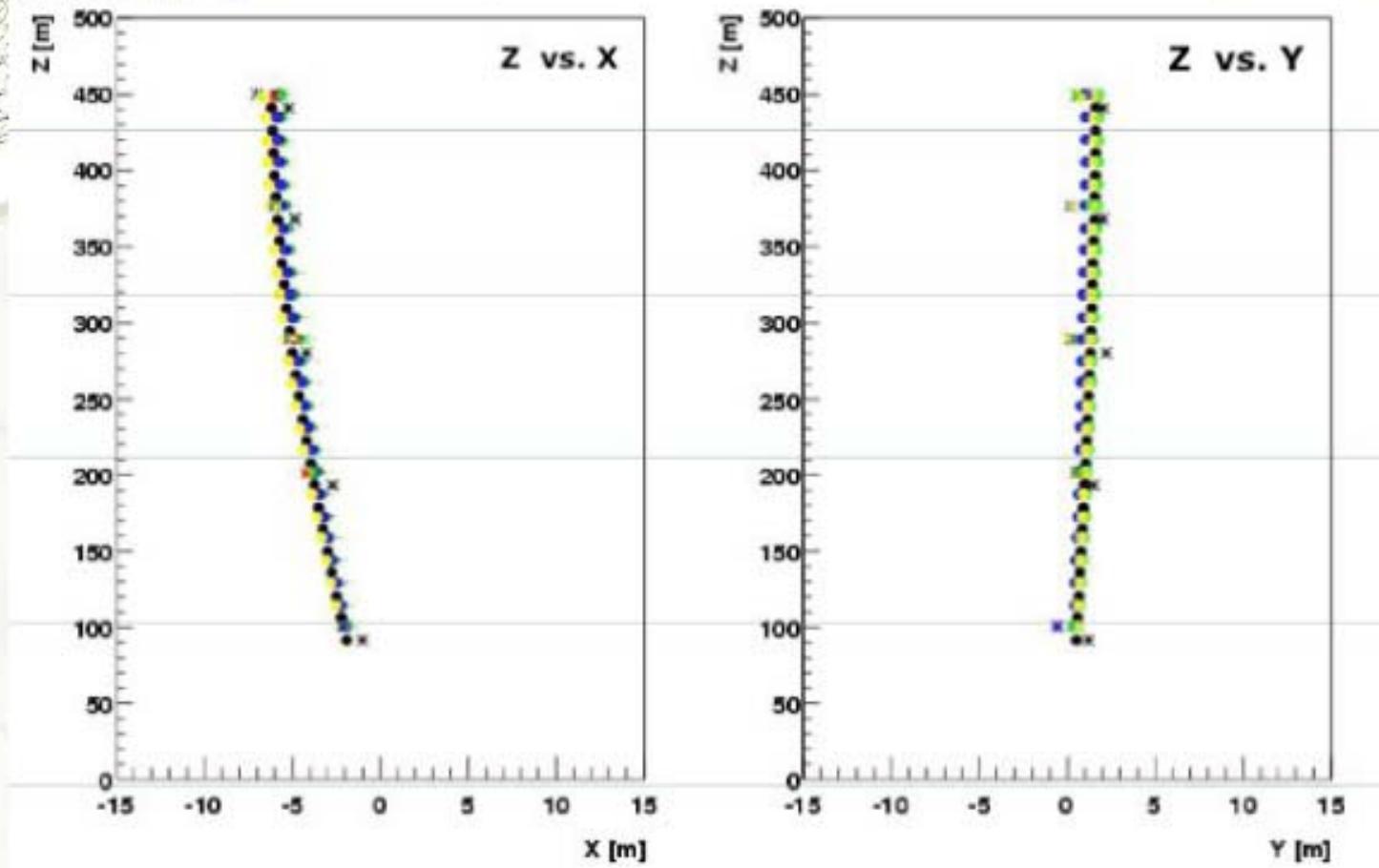


Important to know the alignment of the detector components to get the best angular resolution and track reconst.

Positioning
resolution
 $< 10 \text{ cm}$

5 space points from hydrophones;
25 gradients (data from tiltmeters and compass on each storey).

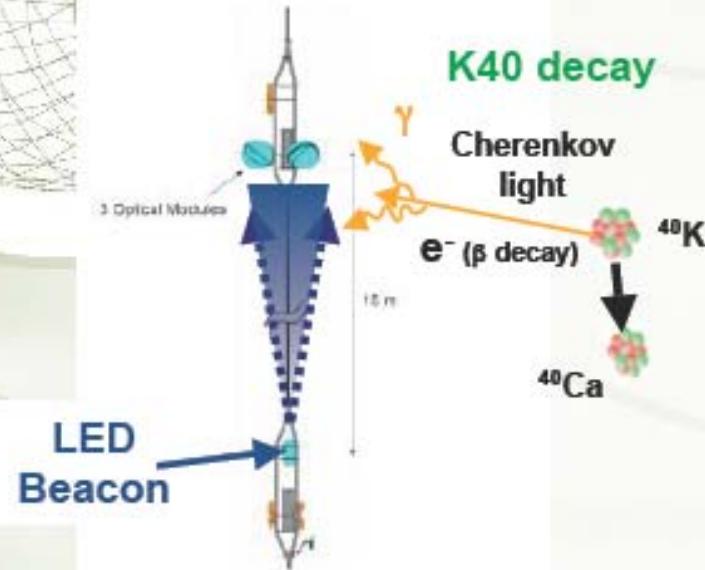
Line shape under moderate sea current



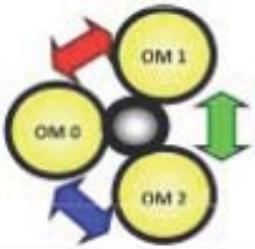
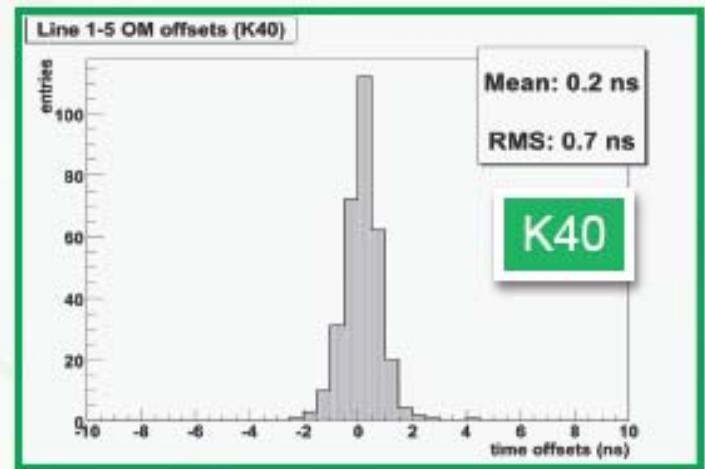
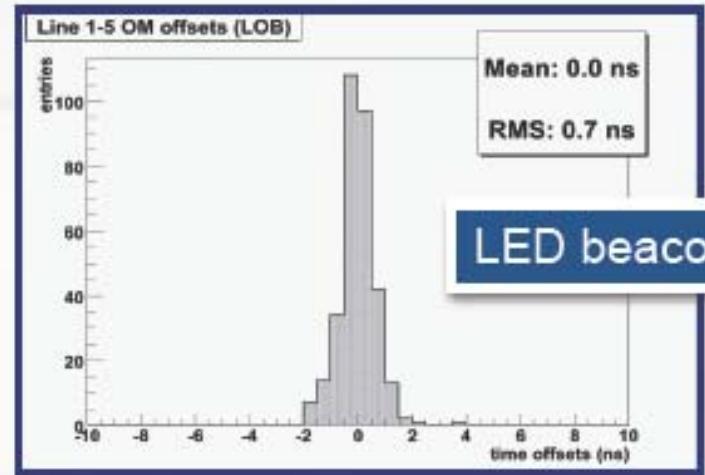
● Alignment from Tiltmeters * Hydrophone position

Timing calibration

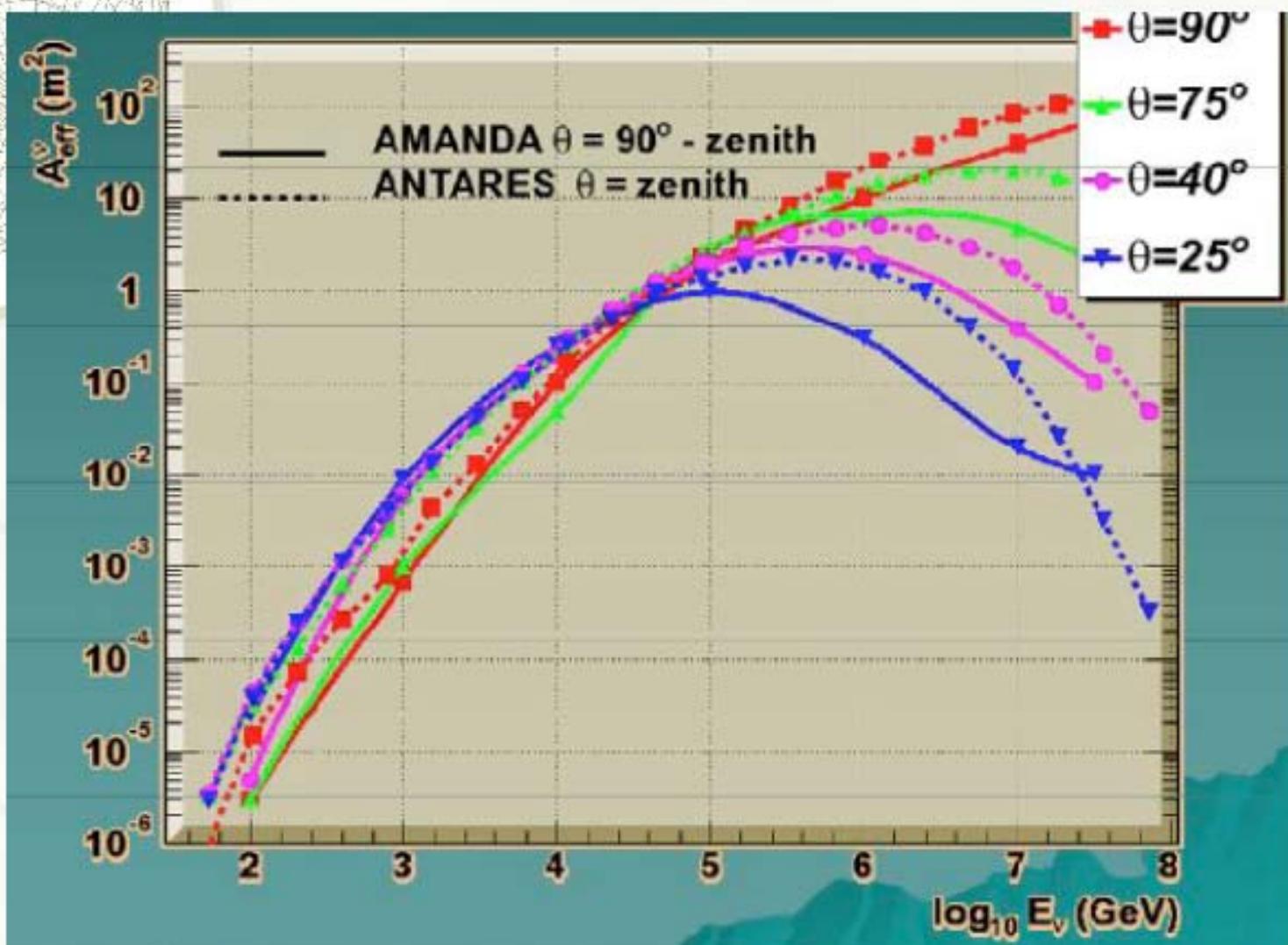
Time difference by pairs in the same storey



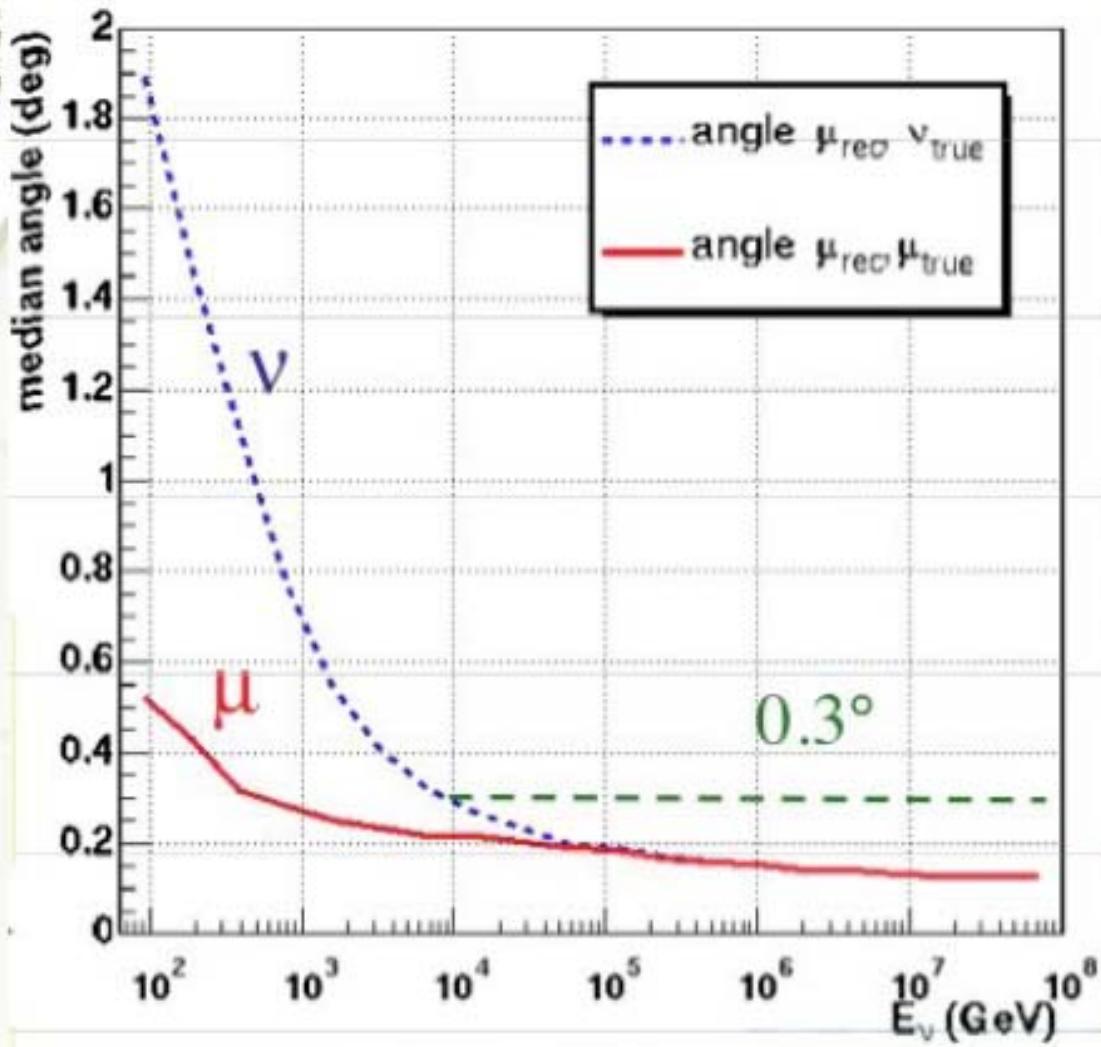
Timing resolution of electronics better than 0.6ns.



ANTARES effective area for ν 's



Expected angular resolution for ν_μ



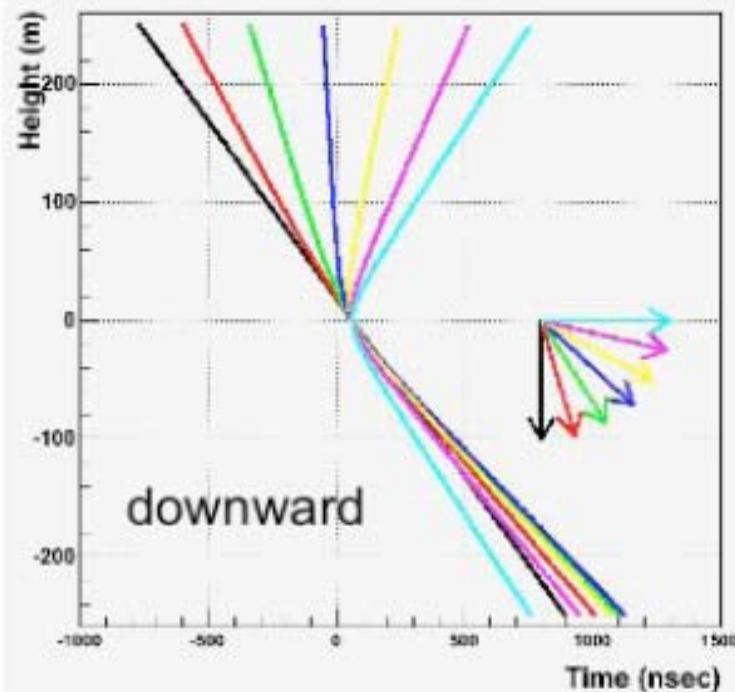
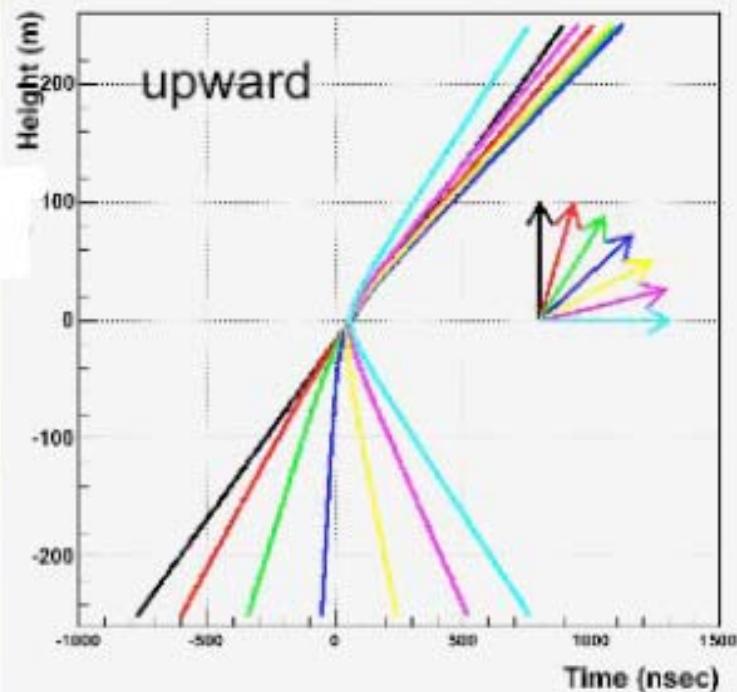
- $< 0.3^\circ$ for $E > 10$ TeV: dominated by detector resolution

Event displays

Hits are plotted for each line: height (z) versus time (t)

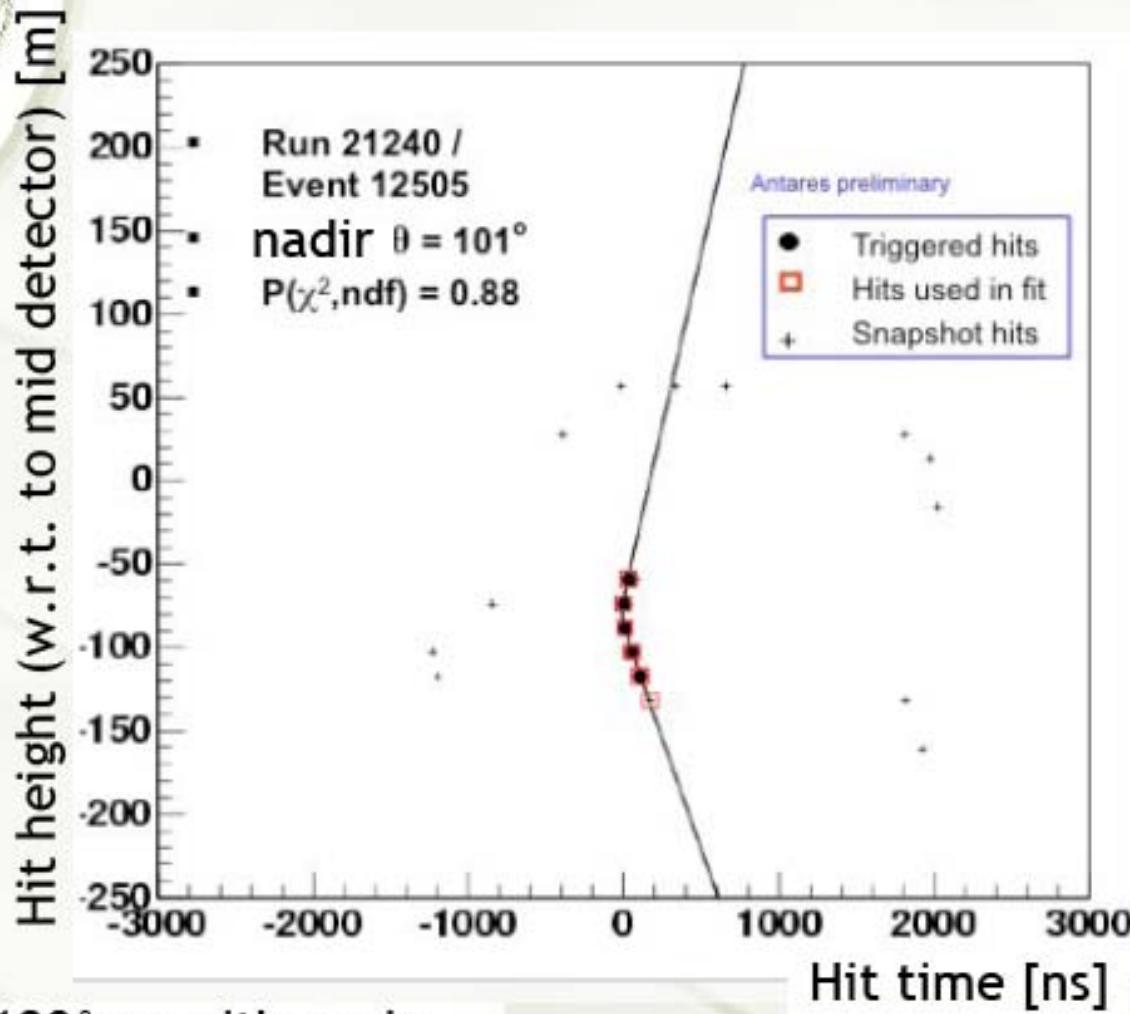
⇒ Characteristic pattern depending on zenith angle and distance of closest approach.

Several reconstruction strategies available: 1D, 3D, χ^2 , ML



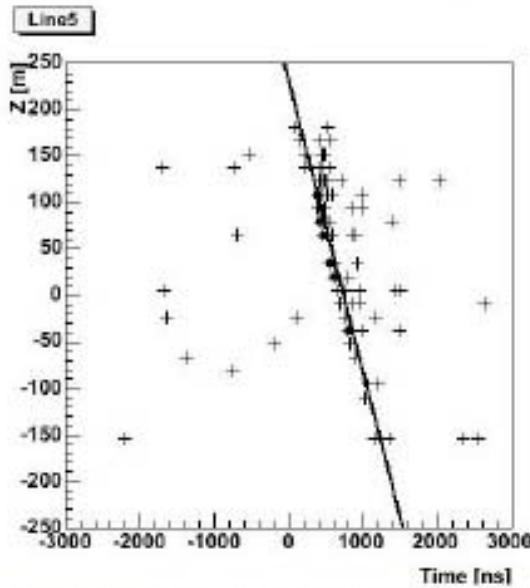
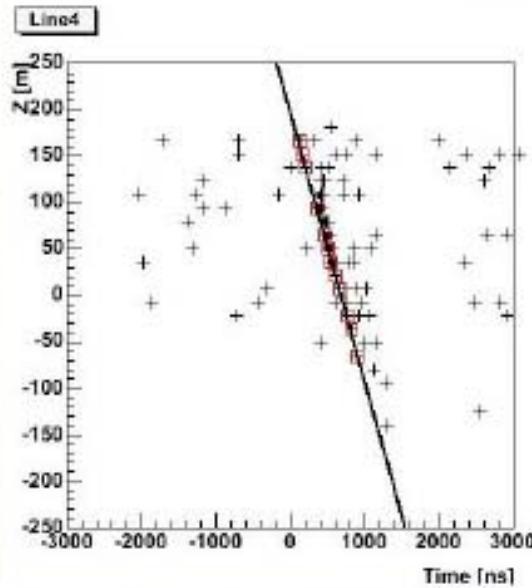
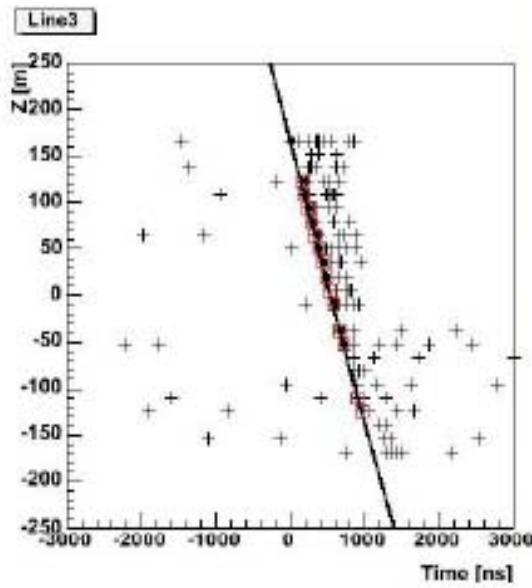
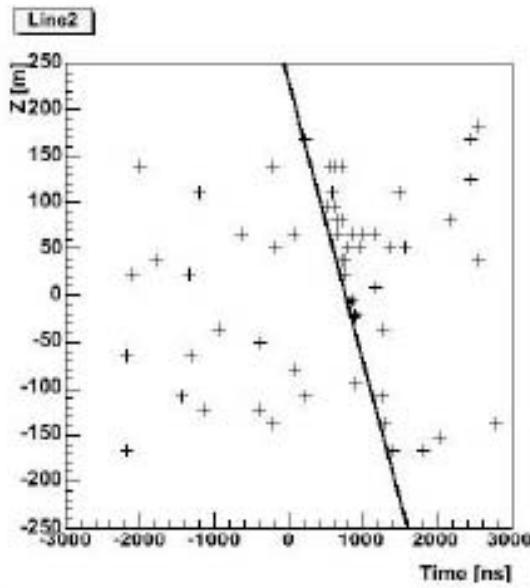
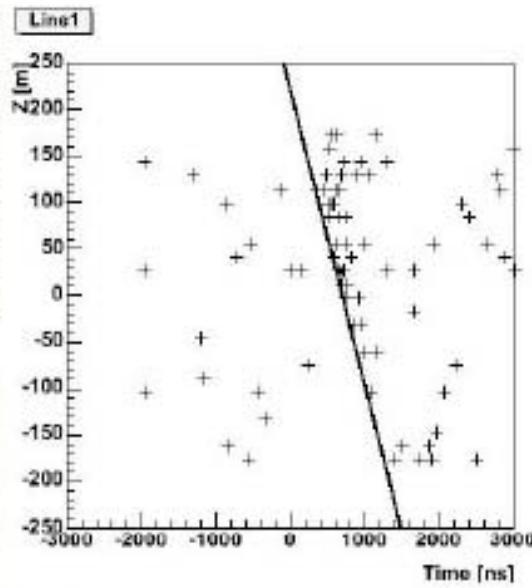
Atmospheric muon track

Reconstruction with 1 line (poor sensitivity to azimuth)



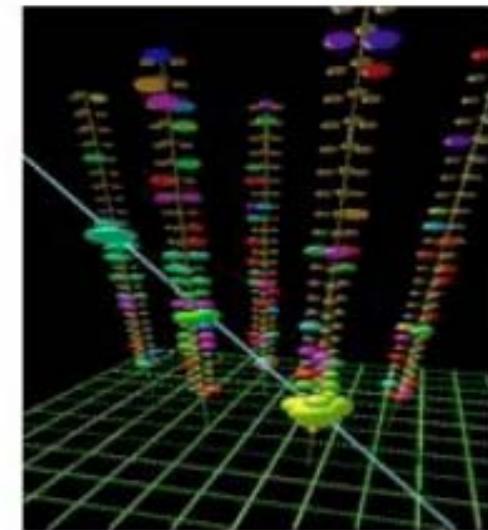
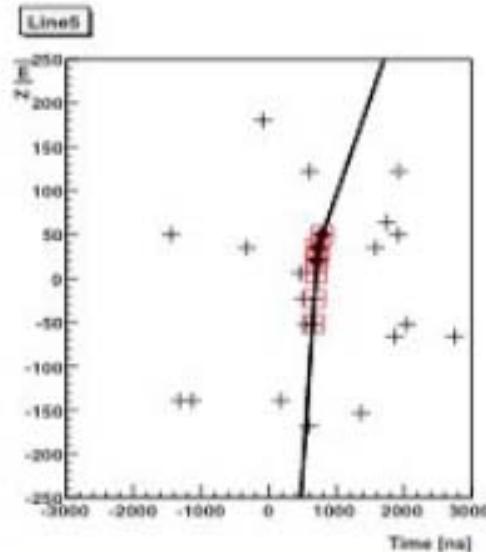
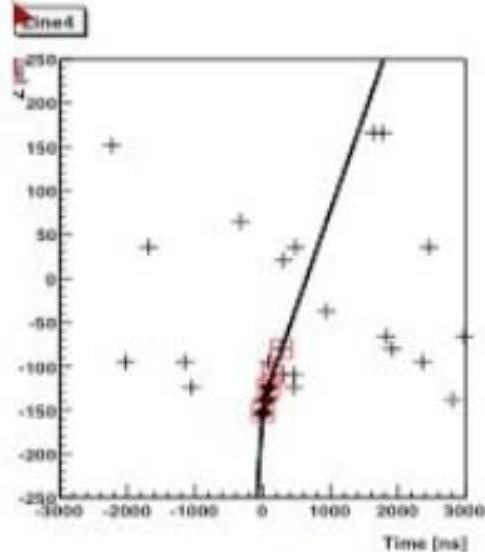
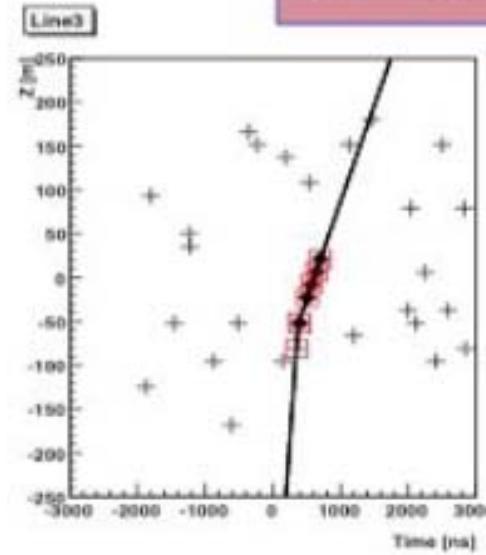
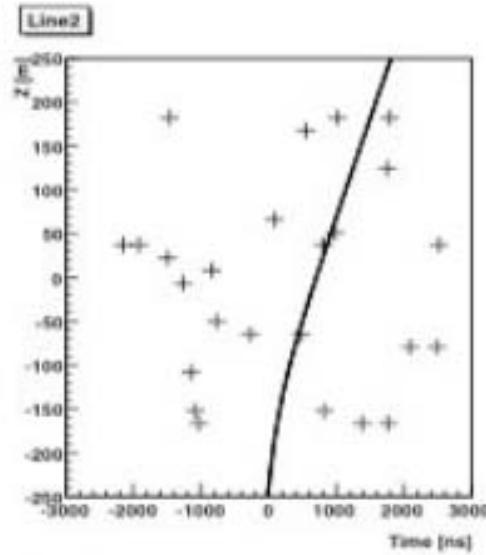
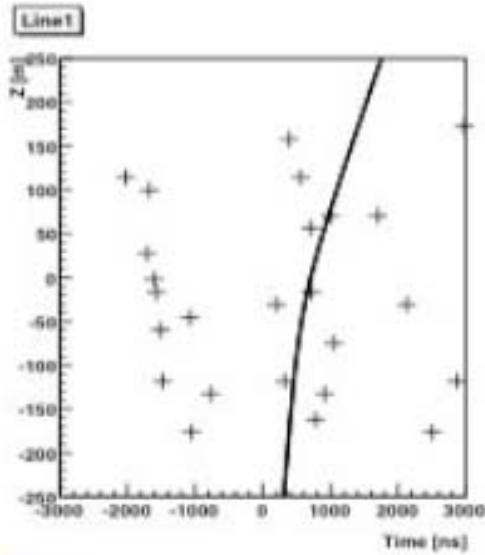
nadir angle=180° - zenith angle

5 lines events: downward muon

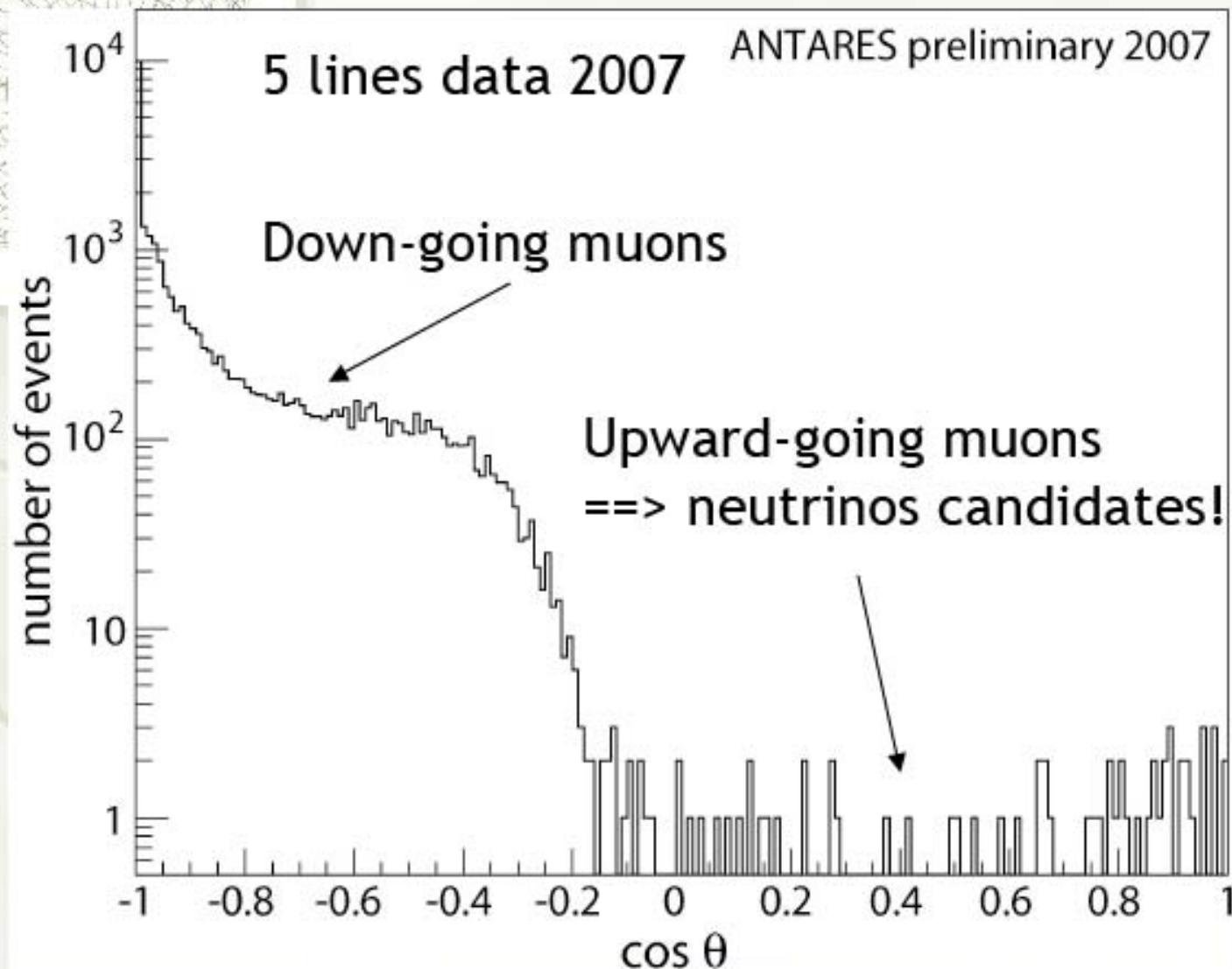


Upward muon: ν candidate

nadir
 $\theta = 35^\circ$



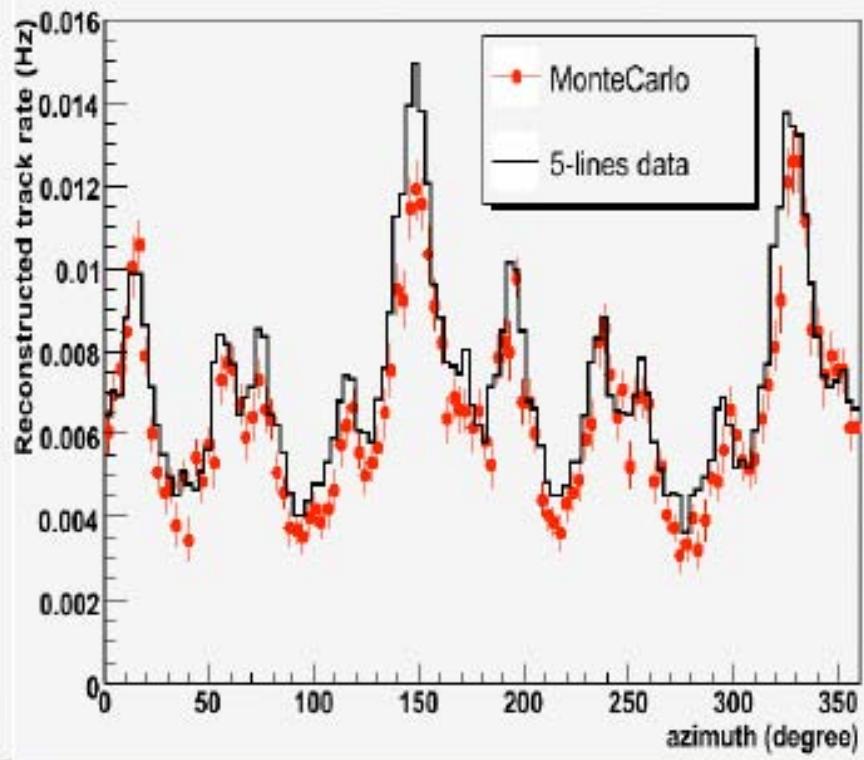
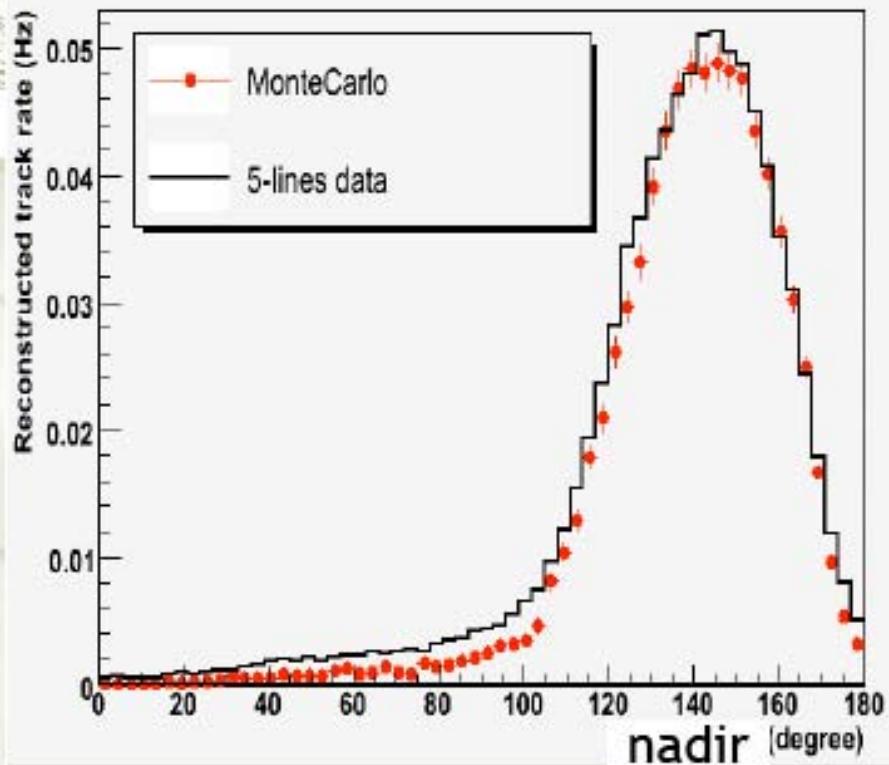
Nadir angle distribution



5 Lines: data vs MC

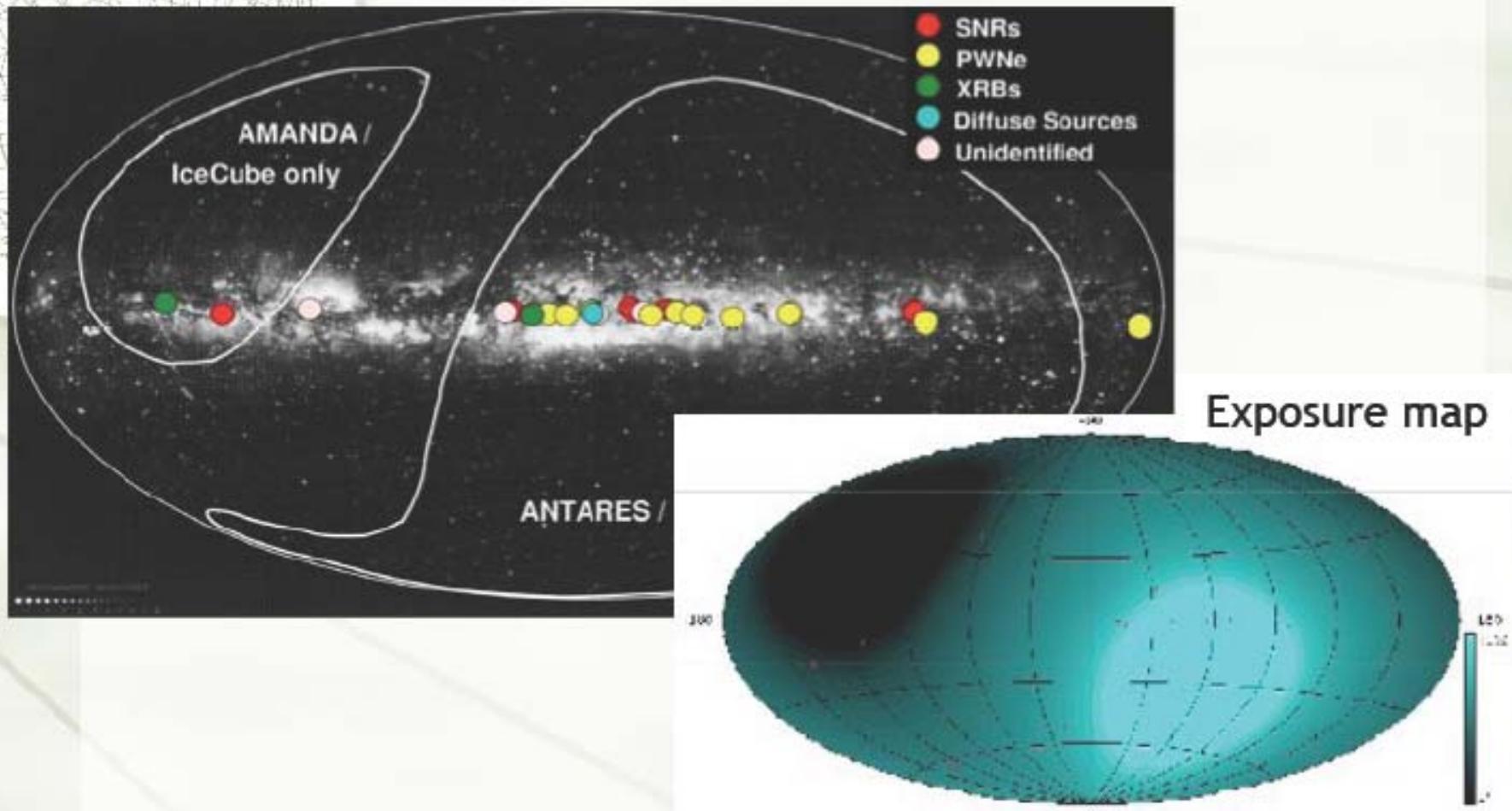
reconstructed track rate as a function of the nadir and azimuth angles

♦ ratio data/MC ~ 1.1



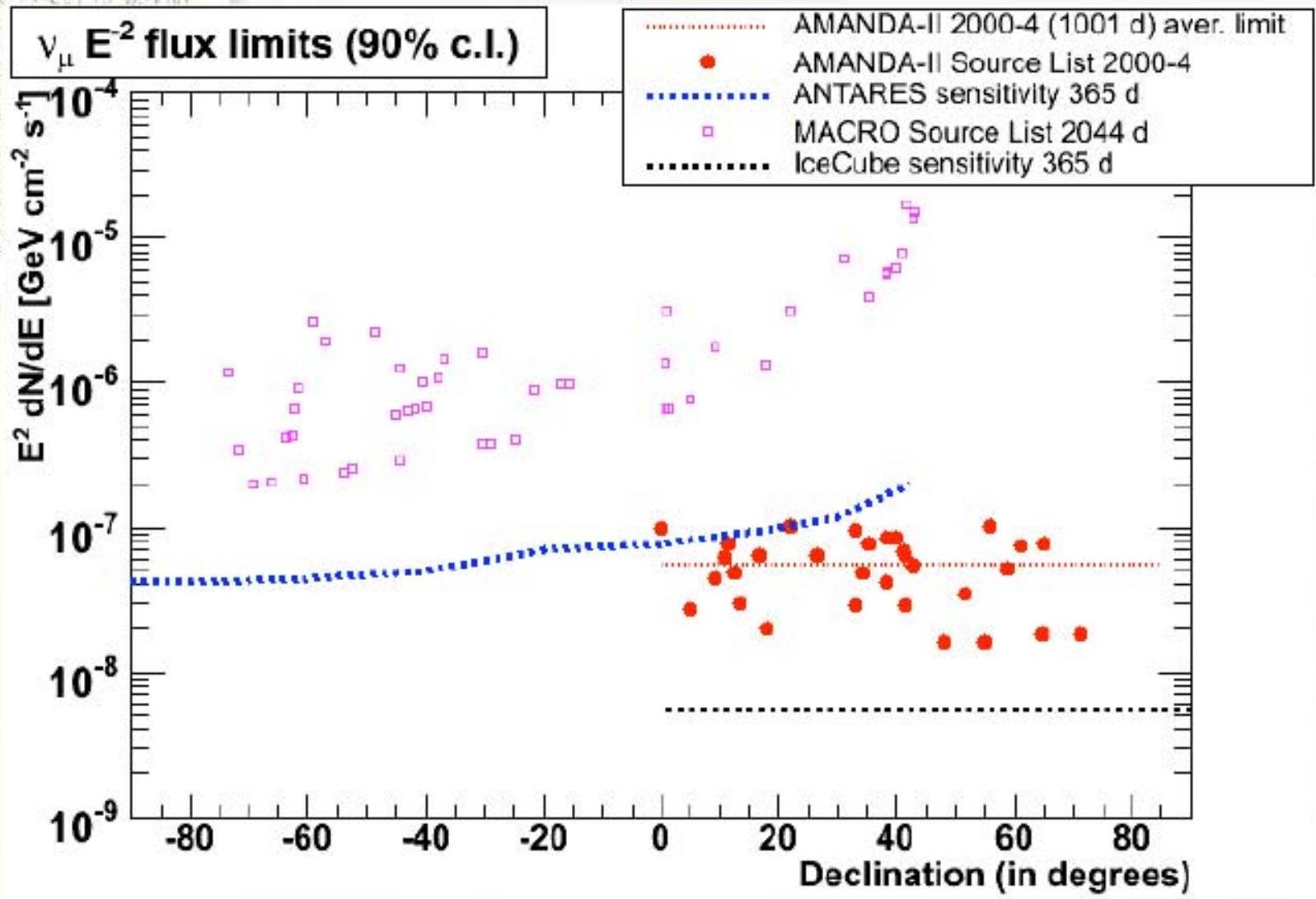
MC simulations: CORSIKA+ QGSJET as hadronic model+ Hoerandel primary CR flux (Astrop. Phys., 19 (2003))

The ANTARES sky for upward μ s

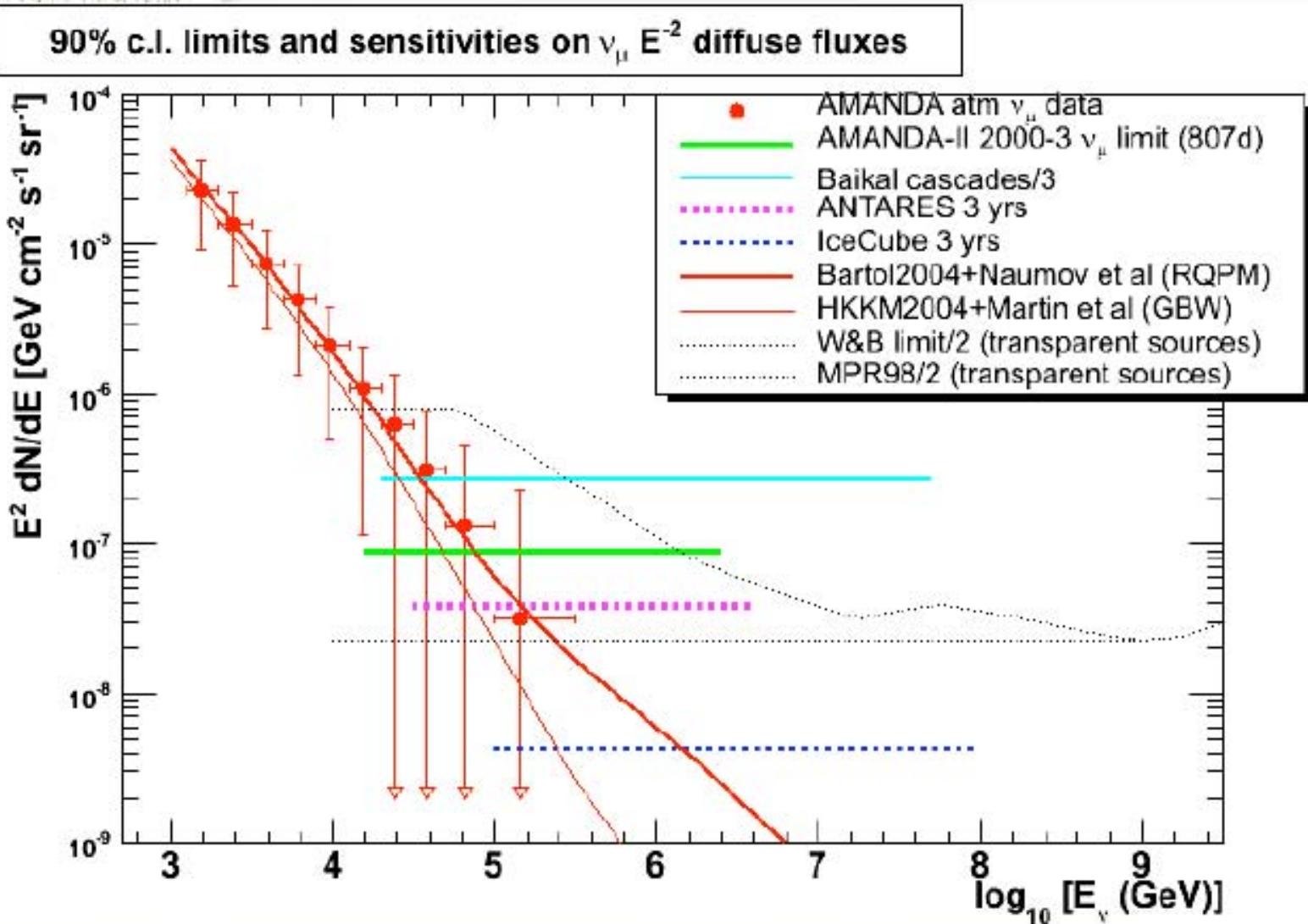


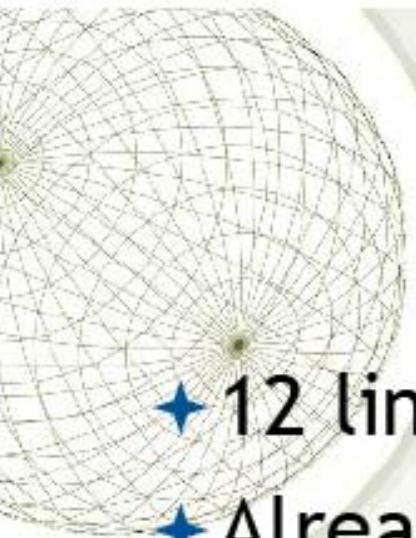
HESS sky coverage fully coincident with the ANTARES search
for upward muon neutrinos.

Expected sensitivity for point-like sources



Sensitivity to diffuse flux





Conclusions

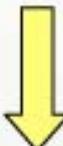
- ◆ 12 lines detector completed!
- ◆ Already largest detector in Northern Hemisphere;
- ◆ First upward-neutrinos candidates;
- ◆ Milestone towards a KM3 underwater detector



Towards km³ detectors

- ◆ VHE ν -telescopes in operation (AMANDA-II, Baikal, ANTARES) have $A_{\text{eff}} < 0.1 \text{ km}^2$
- ◆ Very few events per year are expected in a $< 1 \text{ km}^2$ detector!
- ◆ Amanda-II already sets ULs on emission from several candidate sources.

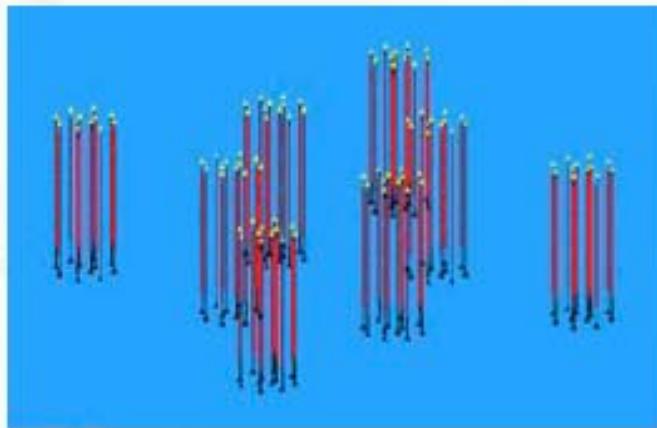
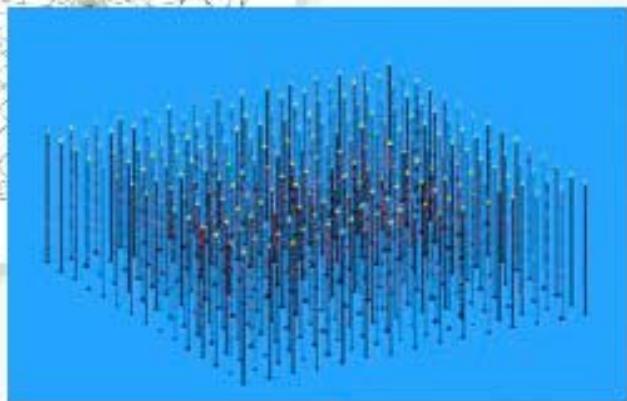
Very large detector volumes are needed!



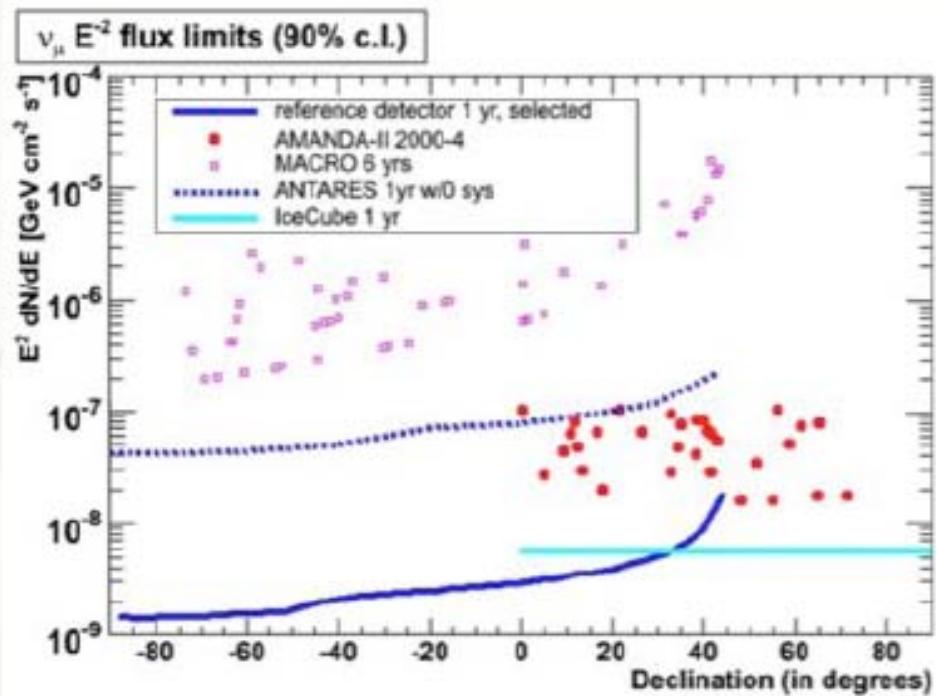
km3 detectors: ICECUBE (ice) and KM3NET (water)

The design study KM3NET

CDR available (<http://www.km3net.org/>)



From KM3NET CDR



ANTARES Collaboration





The end



Optional slides



Standard ANTARES trigger

Trigger Level 1 (L1):

- or
- 2/3 OMs in a same storey in **20 ns**
 - Charge > 2.5 p.e. in a single OM

Trigger Logic:

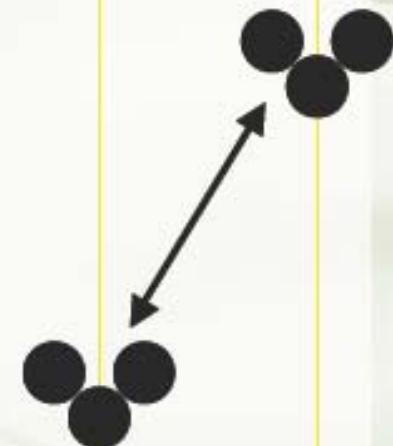
3D (majority) algorithm:

N local coincidences (L1) in a 2.2 ms time gate
+ causality relation between each pair of hits

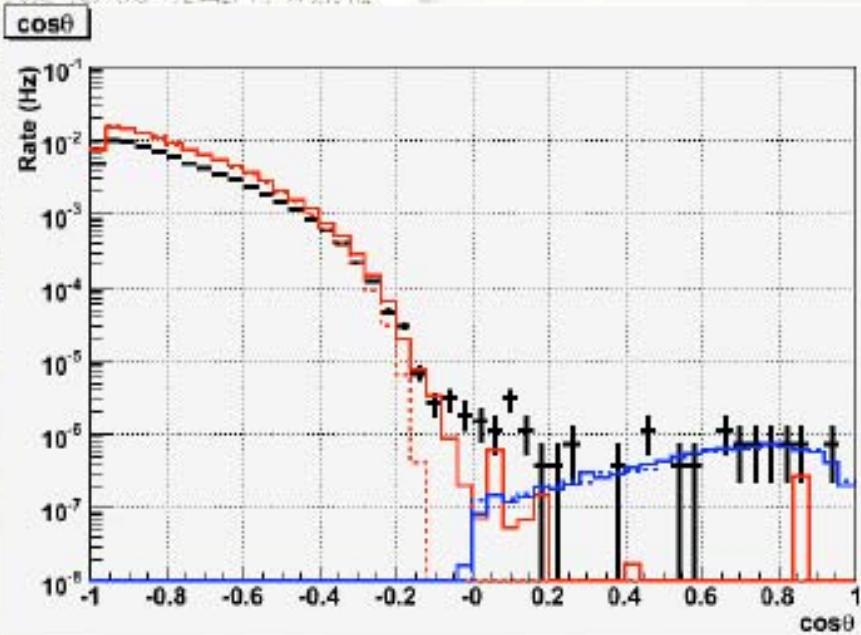
3N (3D directional scan) algorithm :

N local coincidences (L1) in a **2.2 μ s** time gate
+ causality relation between each pair of hits
+ directional scan

$$\Delta t_{ij} \leq \frac{d_{ij}}{c/n} + 20\text{ ns}$$

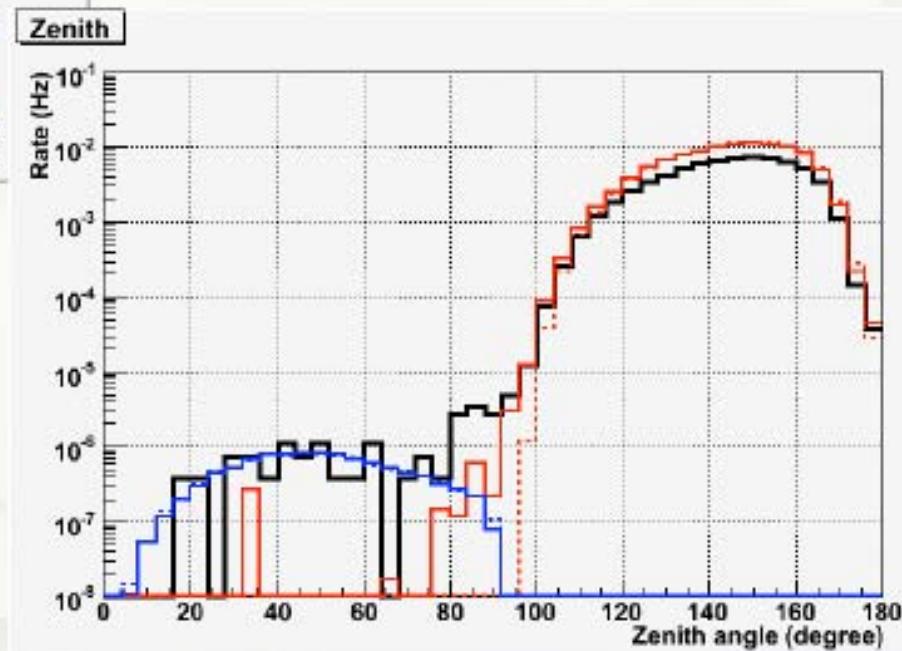


5 lines data vs MC (muons and atm. vs)



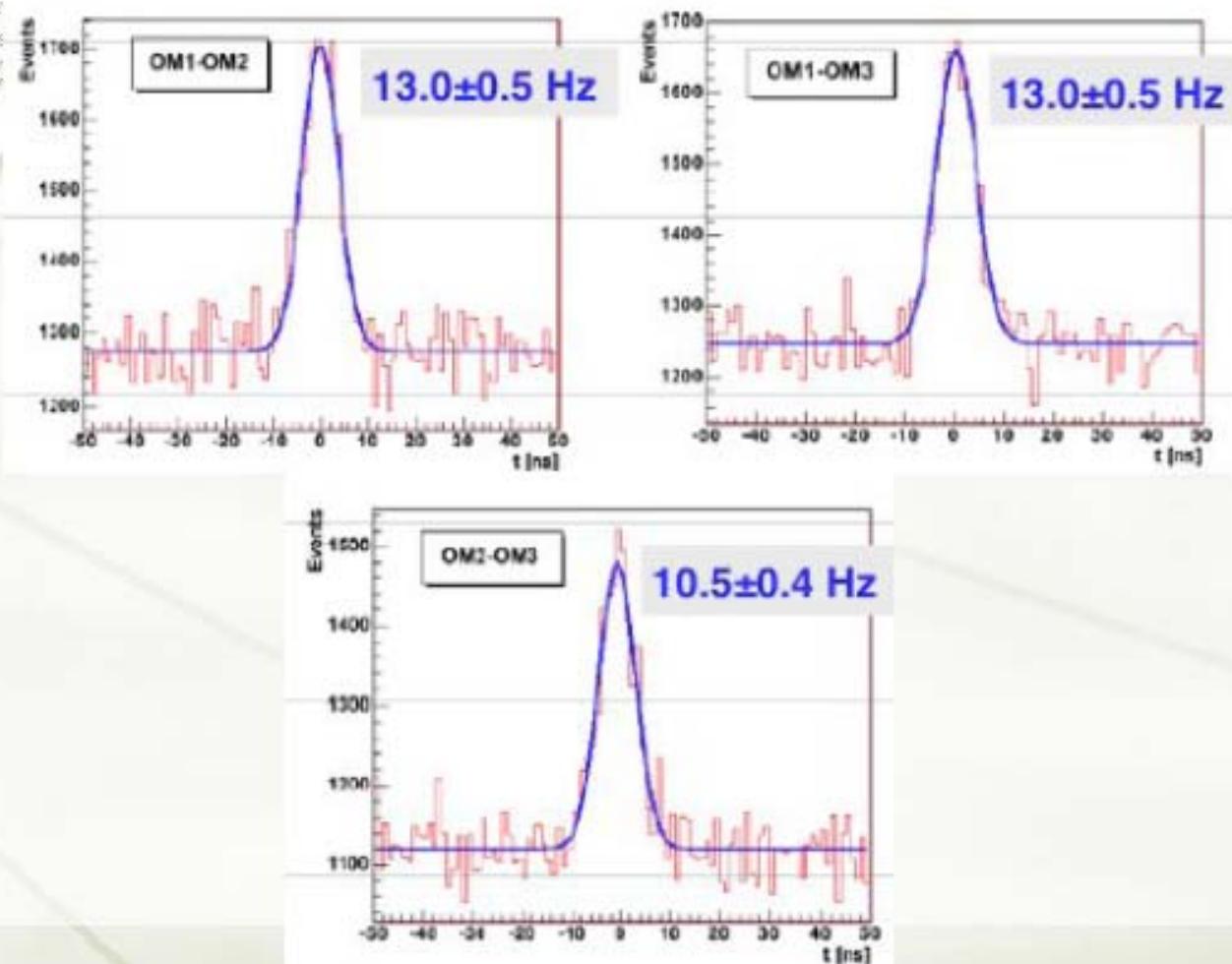
— Recon. results
 MC-truth

— 5 lines data (2007)
 — MC atm. Muons
 — MC atm. neutrinos



Coincidence rates from ^{40}K decays

40K coincidence rate from Gaussian fit



Expected sensitivity for DM search

