THE ANTARES NEUTRINO TELESCOPE

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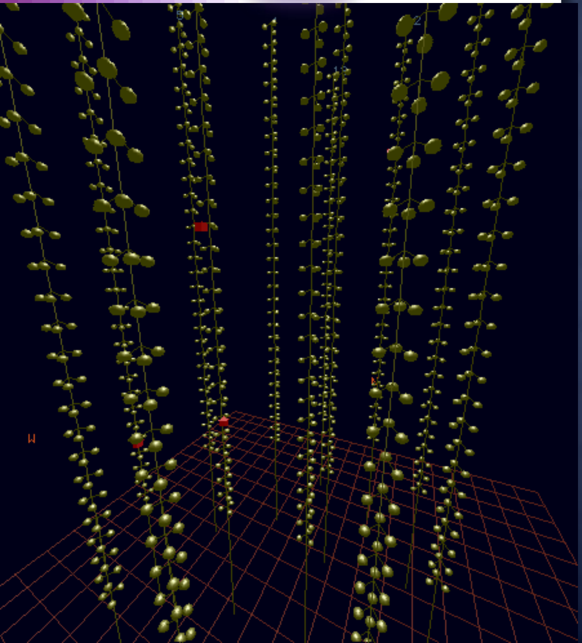
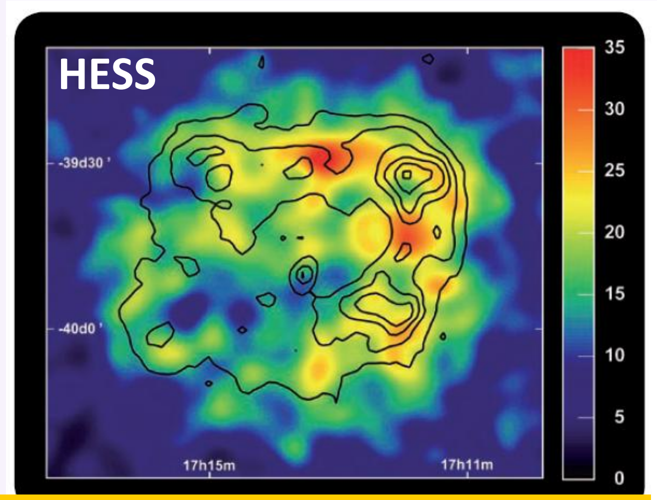


NEUTRINO ASTRONOMY

among the **most intriguing science questions:**
- origin of cosmic rays → 10^{20} eV ?
- astrophysical acceleration mechanism ?
- origin of relativistic jets ?
- dark matter ?
- exotics

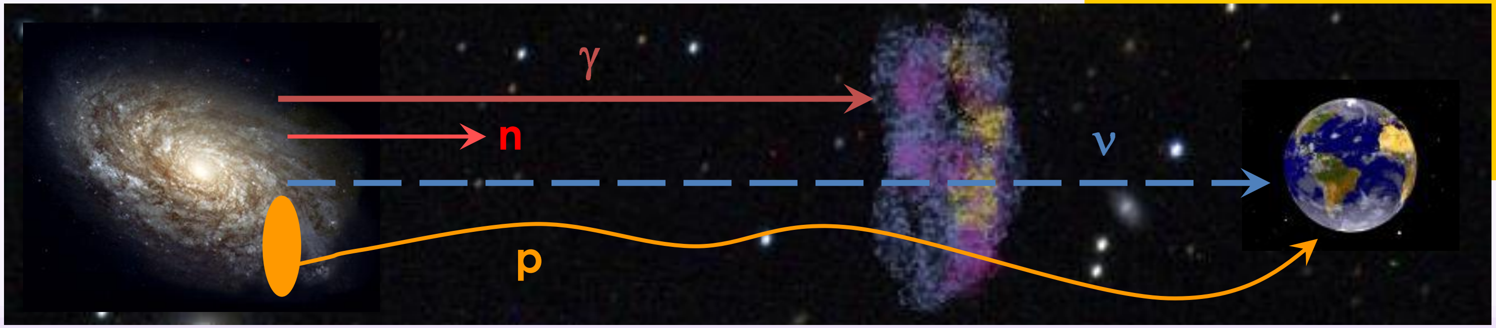
Cosmic sources of neutrinos
- **Extragalactic:** Active Galactic Nuclei, GRBs
- **Galactic**: micro quasars, supernova remnants …

Ref: EPJC 65 (2010) 649, arXiv: 0906.2634v2



TeV γ rays ($p+X \rightarrow \pi^0 \rightarrow \gamma\gamma$) at the centre of **our galaxy** from supernova remnant *RX J1713.7-39.*

Expect:
$p+X \rightarrow \pi^{\pm}$
$\rightarrow \nu$



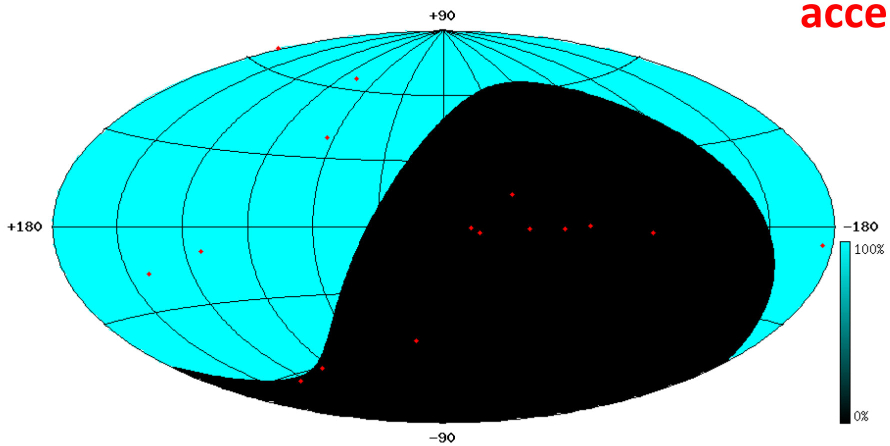
neutrinos reach Earth undisturbed: need large detector and good angular resolution

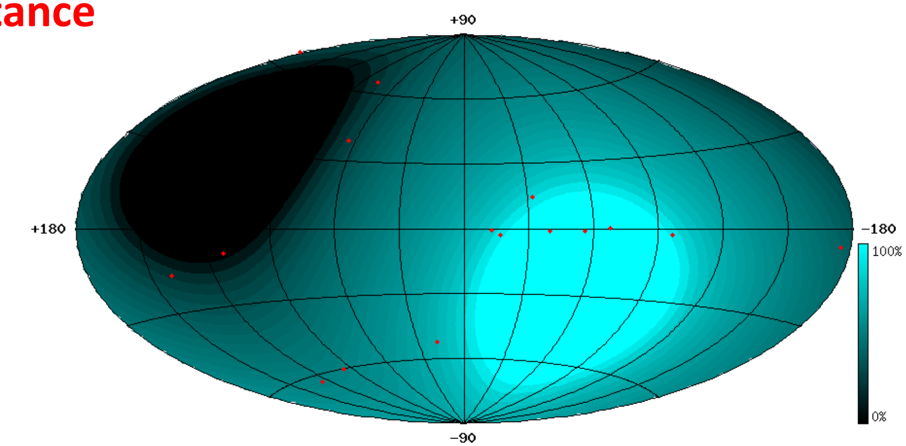
SKY VIEW (GALACTIC COORDINATES)

AMANDA / IceCube (South Pole)

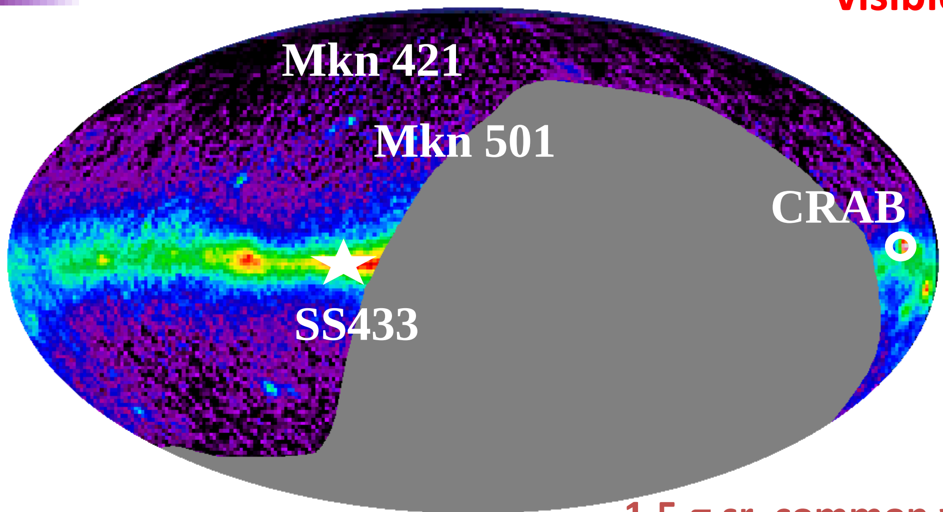
ANTARES (43° N)

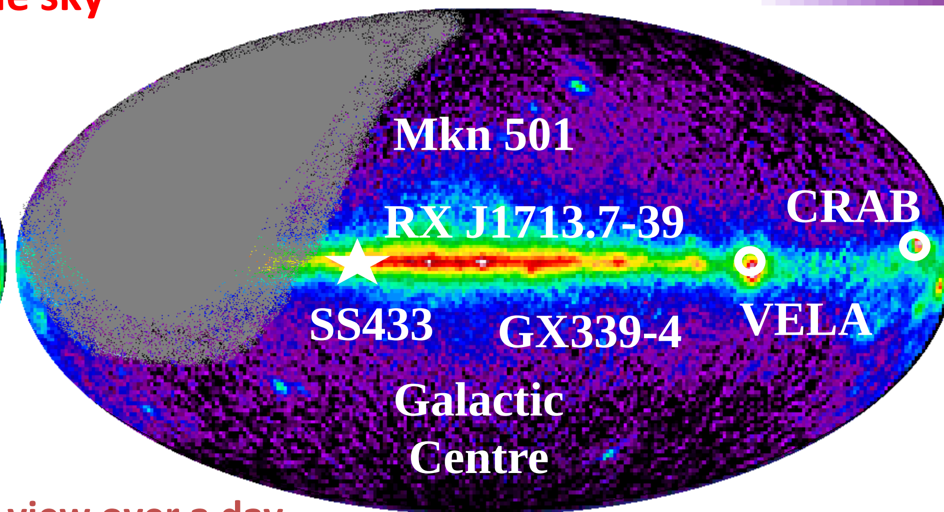
acceptance





visible sky





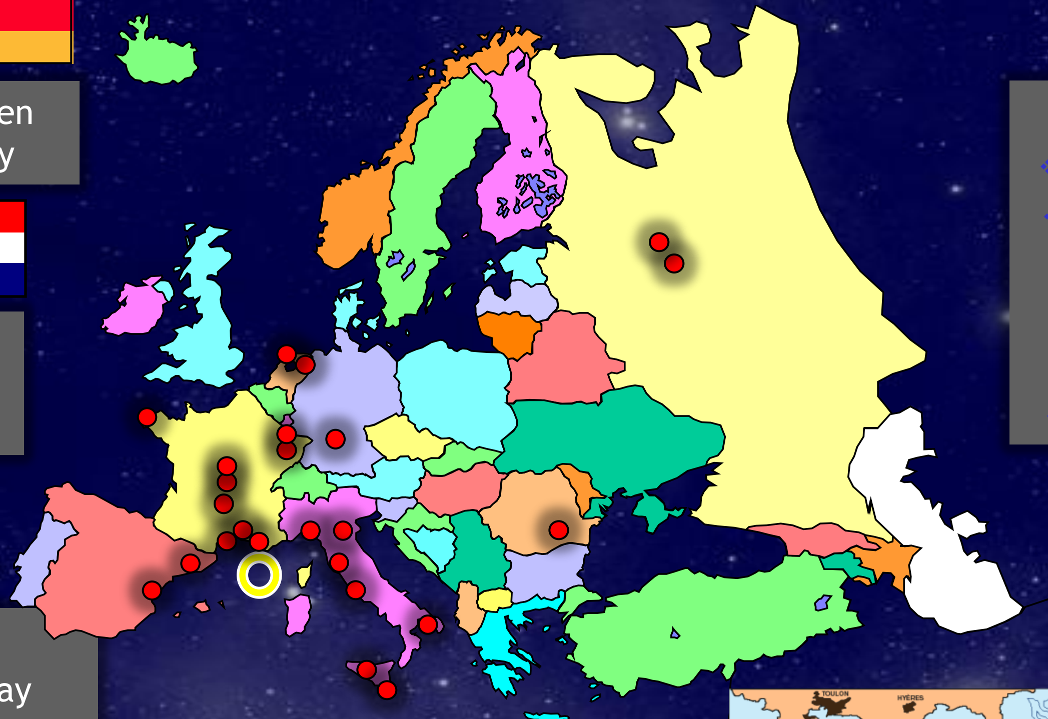
1.5 π sr common view over a day

THE ANTARES COLLABORATION

- University of Erlangen
- Bamberg Observatory

- NIKHEF (Amsterdam)
- KVI (Groningen)
- NIOZ Texel

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



IFIC, Valencia
UPV, Valencia
UPC, Barcelona

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

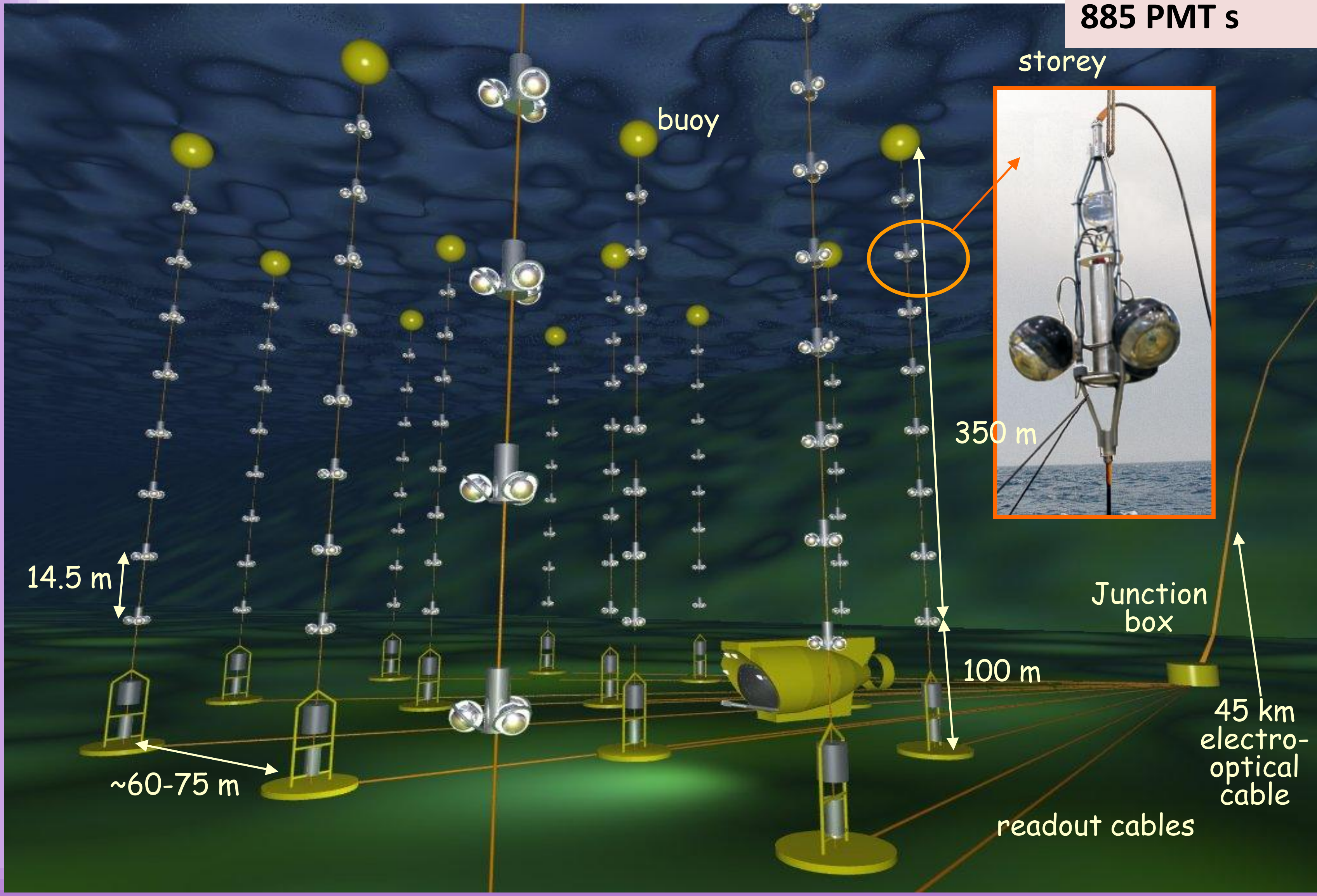
- ITEP, Moscow
- **Moscow State Univ**

ISS, Bucarest

7 COUNTRIES
28 INSTITUTES
~ 150 SCIENTISTS AND ENGINEERS

THE TELESCOPE SETUP

12 detection lines
25 storeys/line
3x10" PMT/storey
885 PMT s

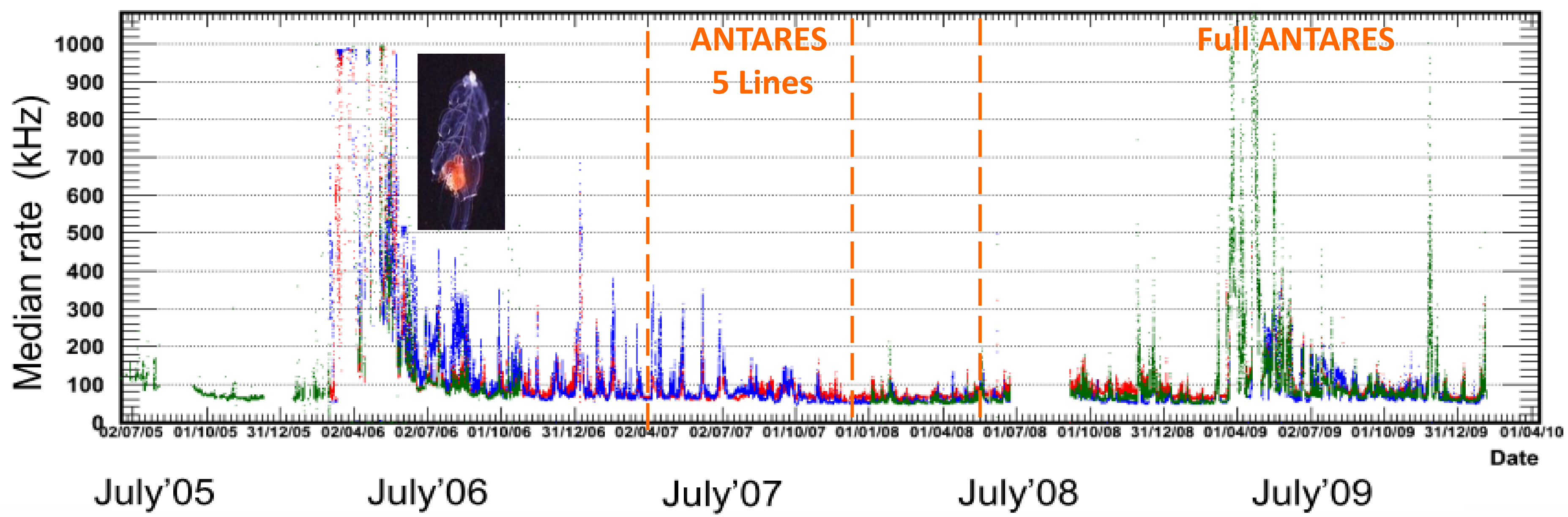


THE BACKGROUND AT THE ANTARES SITE

Two kinds of background :

1. *(Particle) Physics Background* : cosmic rays (atmospheric μ and ν).
2. *Optical Background*: bioluminescence and ^{40}K decay (sea environment):

- Continuous ^{40}K (~30kHz) and bioluminescence (~40 kHz, long term average).
- Bursts from bioluminescence (~MHz).



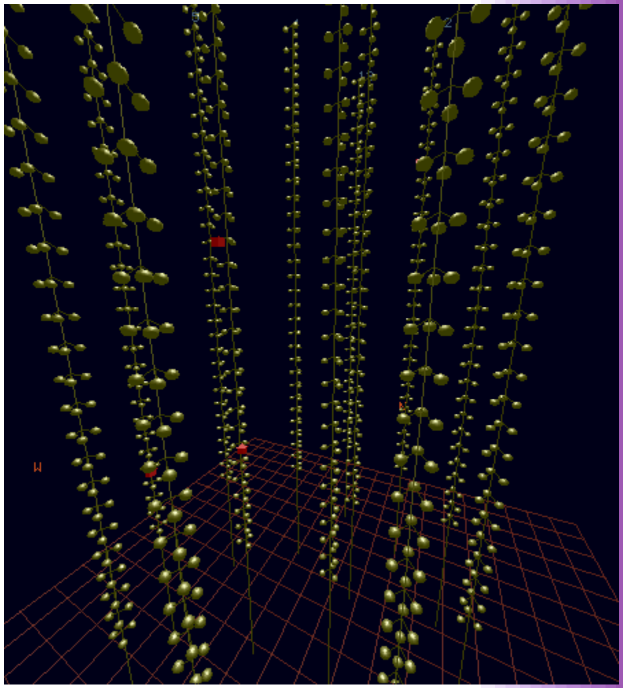
THE PRECISE/FAST TRACKING

Fast tracking:

- almost online to discriminate atmospheric muons /neutrinos;
- No detailed calibration/ no real time detector positioning needed
- Angular resolution: $\Delta\theta \sim 3^o$.
- Used in most analyses in this talk.

The precise tracking:

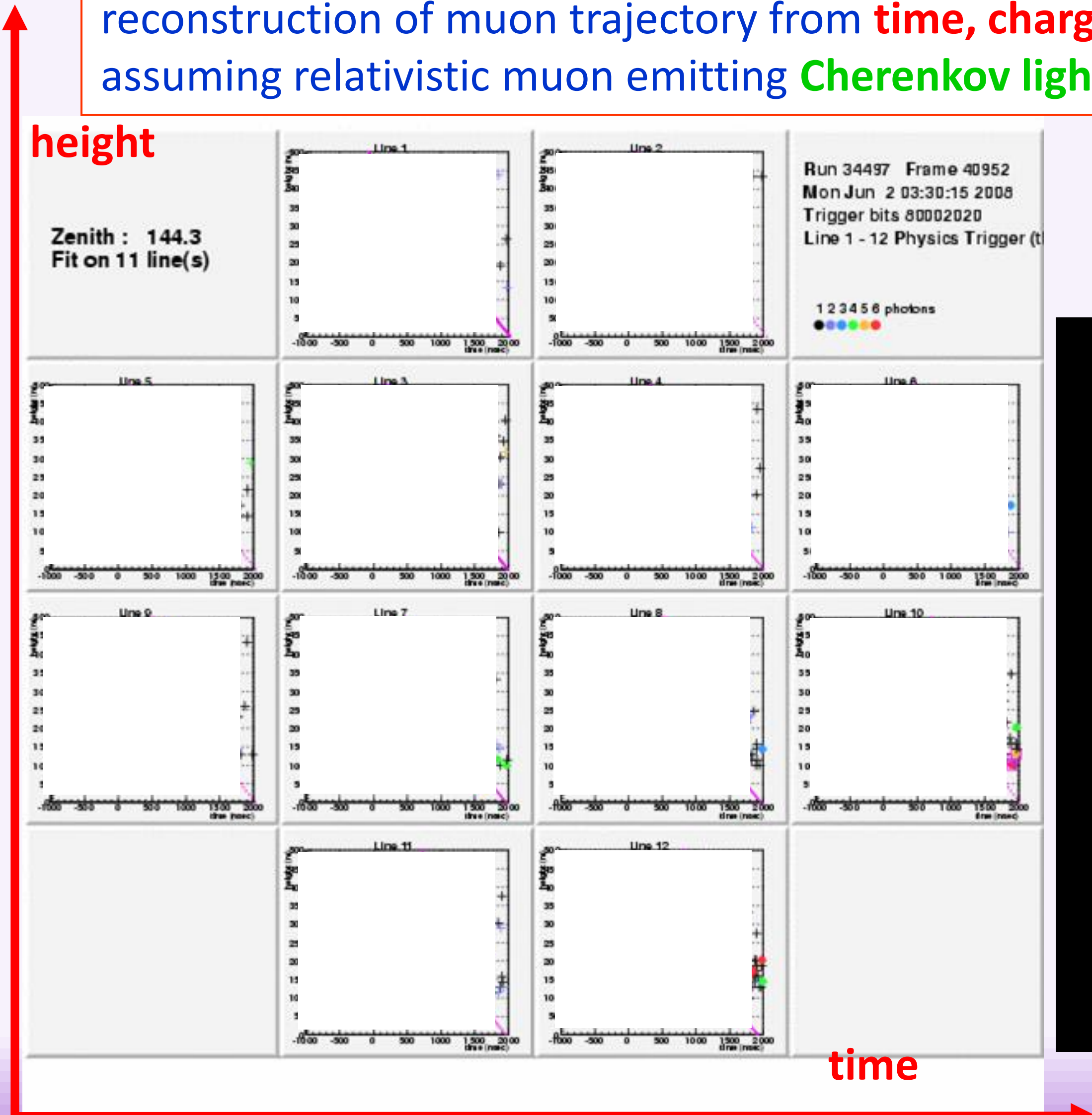
- detailed real-time positioning of the detector;
- detailed PMTs charge/time calibration;
- detailed systematic knowledge of the apparatus (OMs angular acceptance, etc.)
- Angular resolution: up to $\Delta\theta \sim 0.2^o$.
- Used in the diffuse analysis search



Ref: arXiv 0908.0816

EVENT DISPLAY: ATMOSPHERIC MUONS

reconstruction of muon trajectory from **time, charge and position** of PMT hits assuming relativistic muon emitting **Cherenkov light**

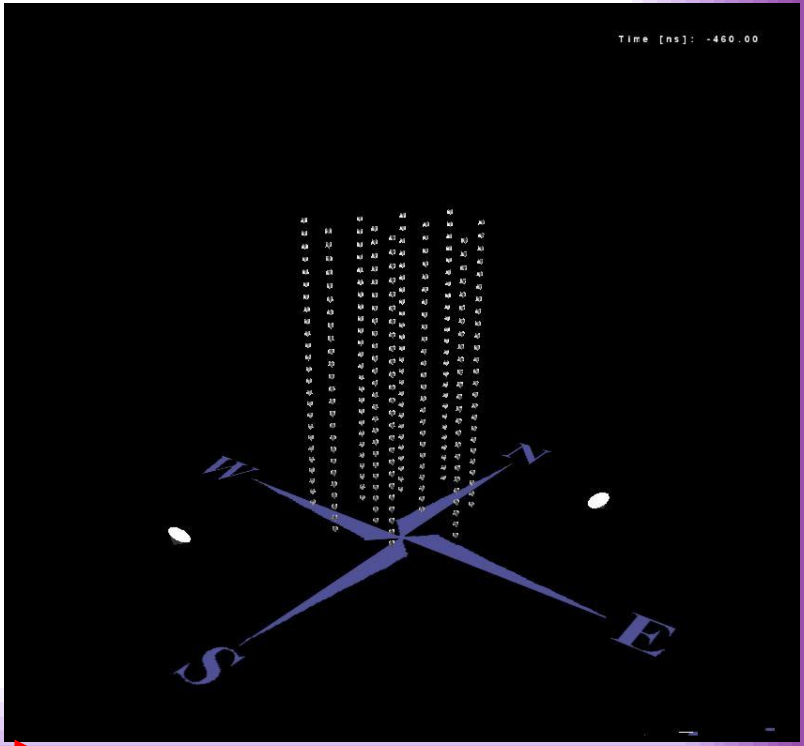


Fast tracking

EVENT DISPLAY: NEUTRINO-INDUCED MUON

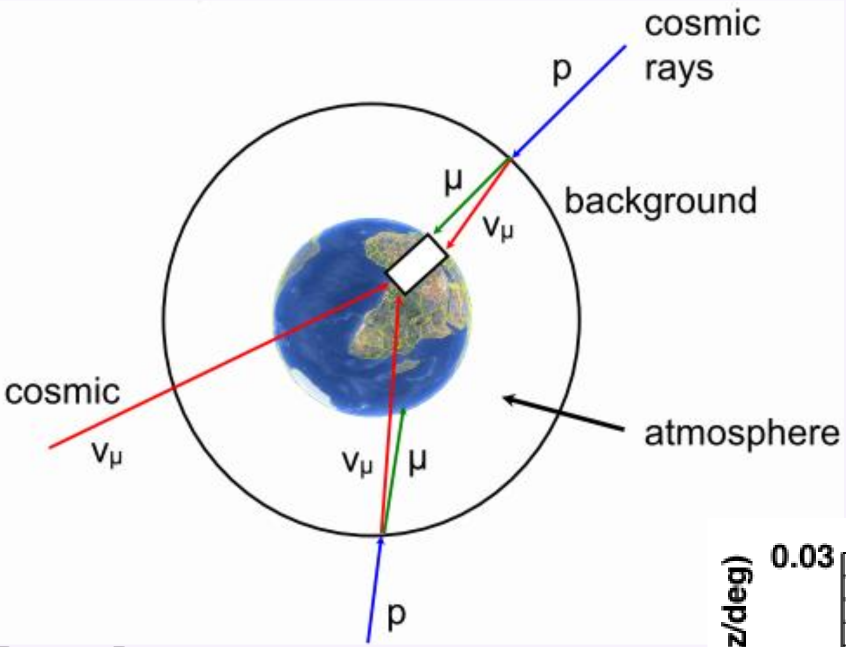
Fast tracking

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



SELECTED RESULTS

- atmospheric muon flux
- atmospheric neutrinos
- point sources
- diffuse ν_μ flux



ATMOSPHERIC MUONS

Zenith angle distribution of reconstructed tracks from atmospheric μ's. 5 line detector.

Main sources of syst. uncertainties:
- environmental parameters (absorption and scattering)
- detector parameters (OM efficiency)
- (physics) hadronic interaction models
- (physics) models of cosmic ray composition

Dots: Data

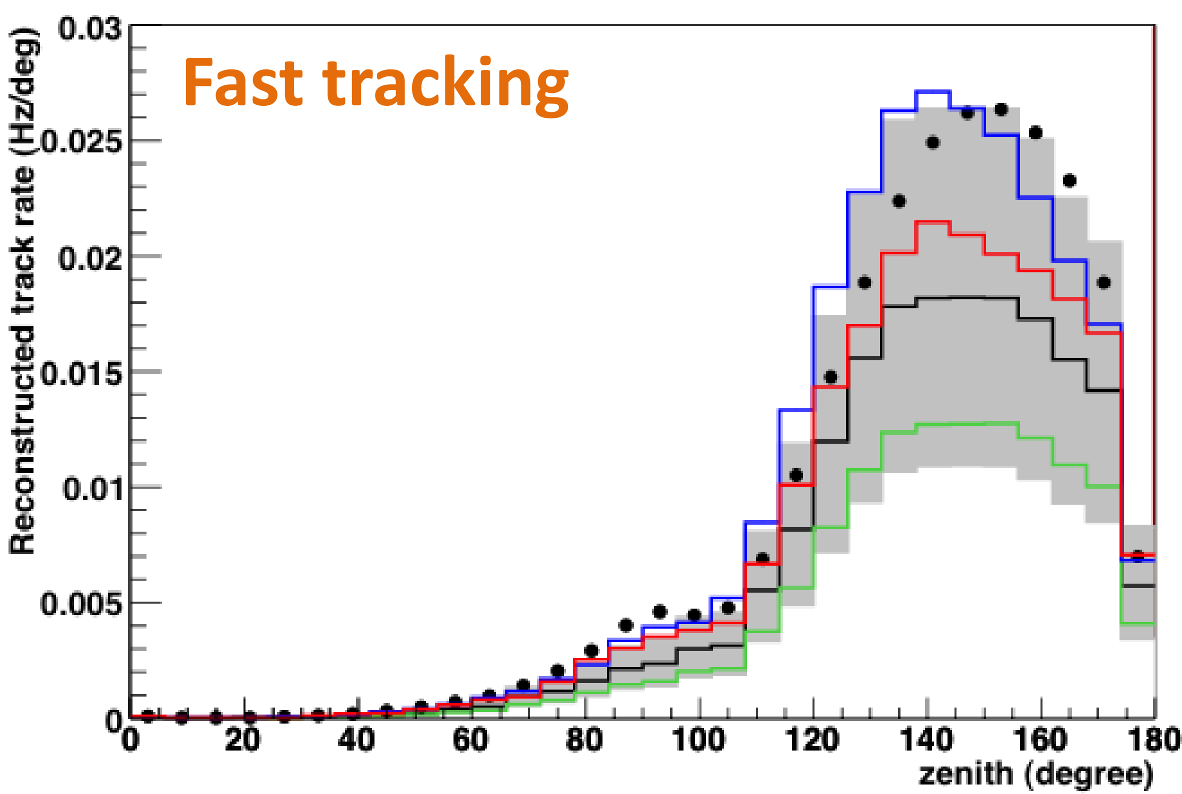
——— MUPAGE Monte Carlo. **[Com. Phys. Comm. 179(2009)915]**

——— CORSIKA + QGSJET + NSU (model of the primary CR)

——— CORSIKA + SIBYLL + NSU

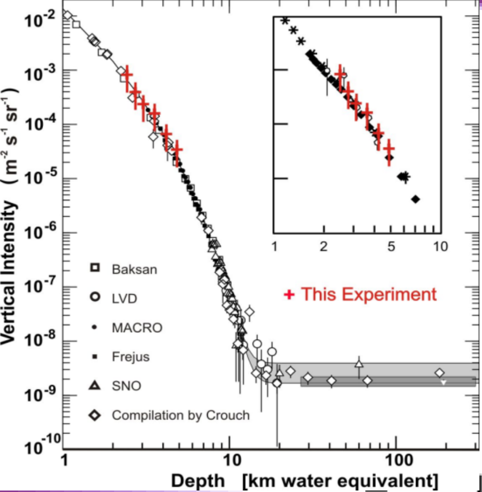
——— CORSIKA + QGSJET + "poly-gonato" model.

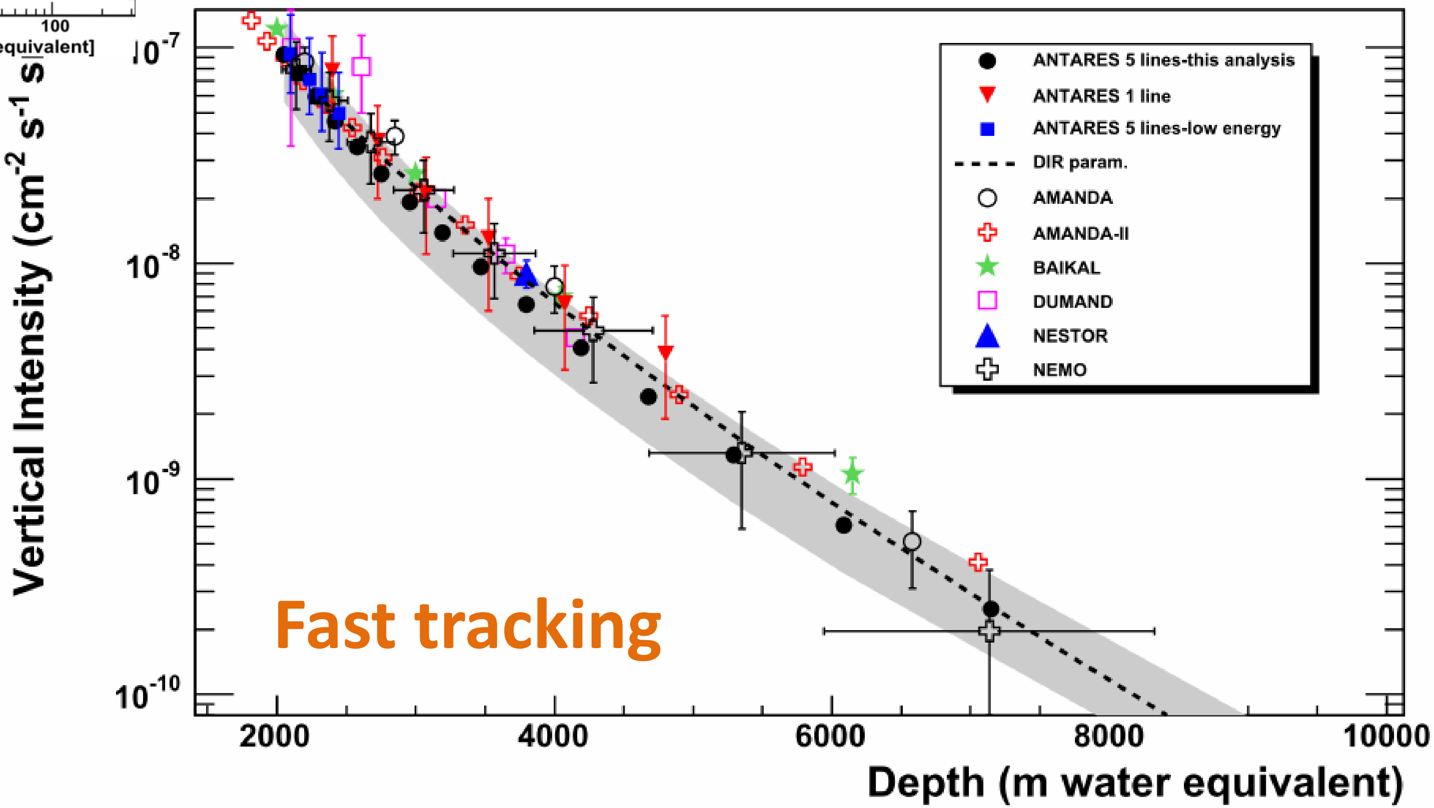
Shadowed band: systematic uncertainty w.r.t. black line.



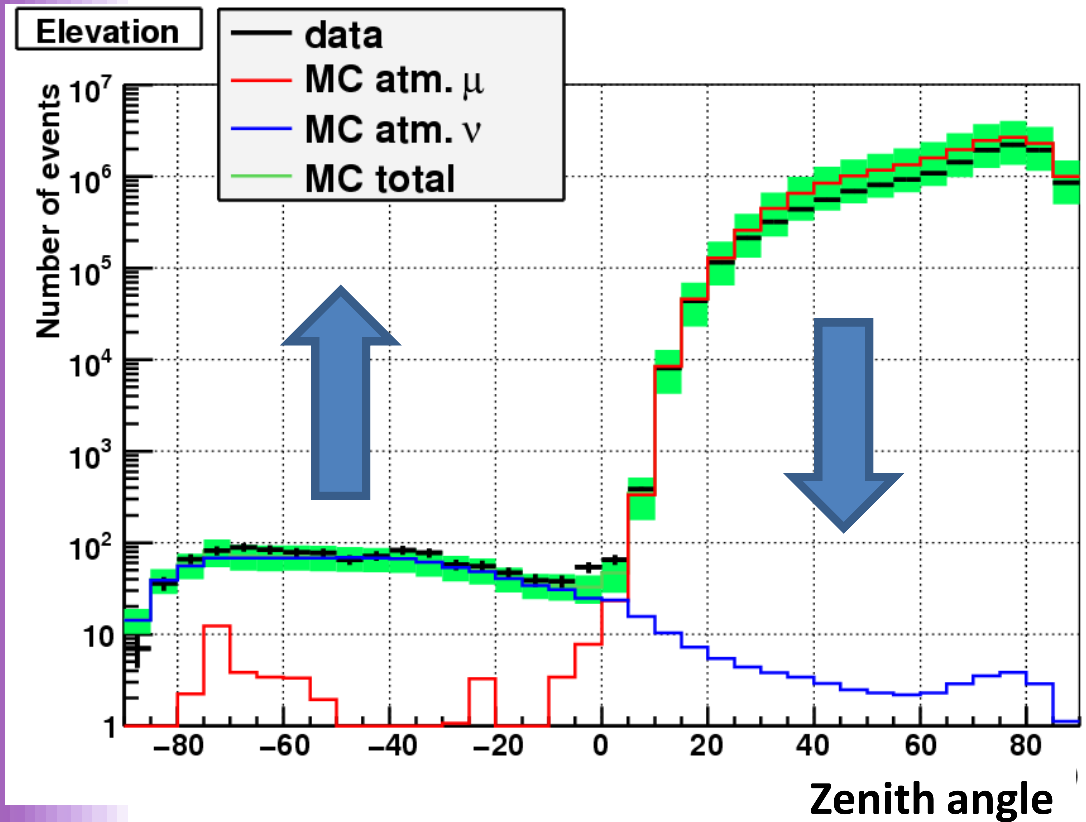
Ref: arXiv:1007.1777, Accepted to APP

MUON DEPTH- INTENSITY RELATION





ATMOSPHERIC NEUTRINOS



Fast tracking

5-line data (May-Dec. 2007) + 9-12 line data (2008)= **341** days detector live time

Upgoing:

1062 neutrino candidates:

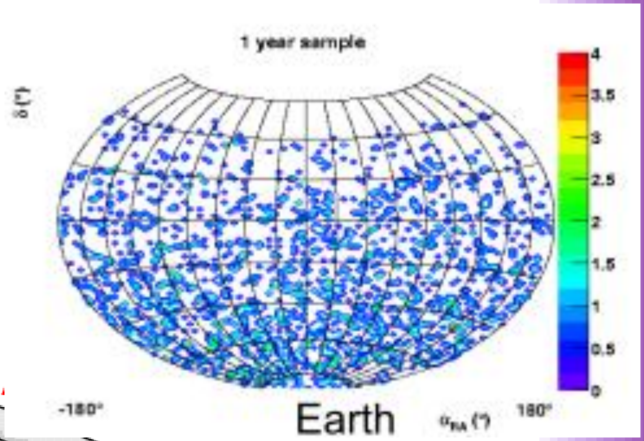
3.1 ν candidates/day

Monte Carlo:

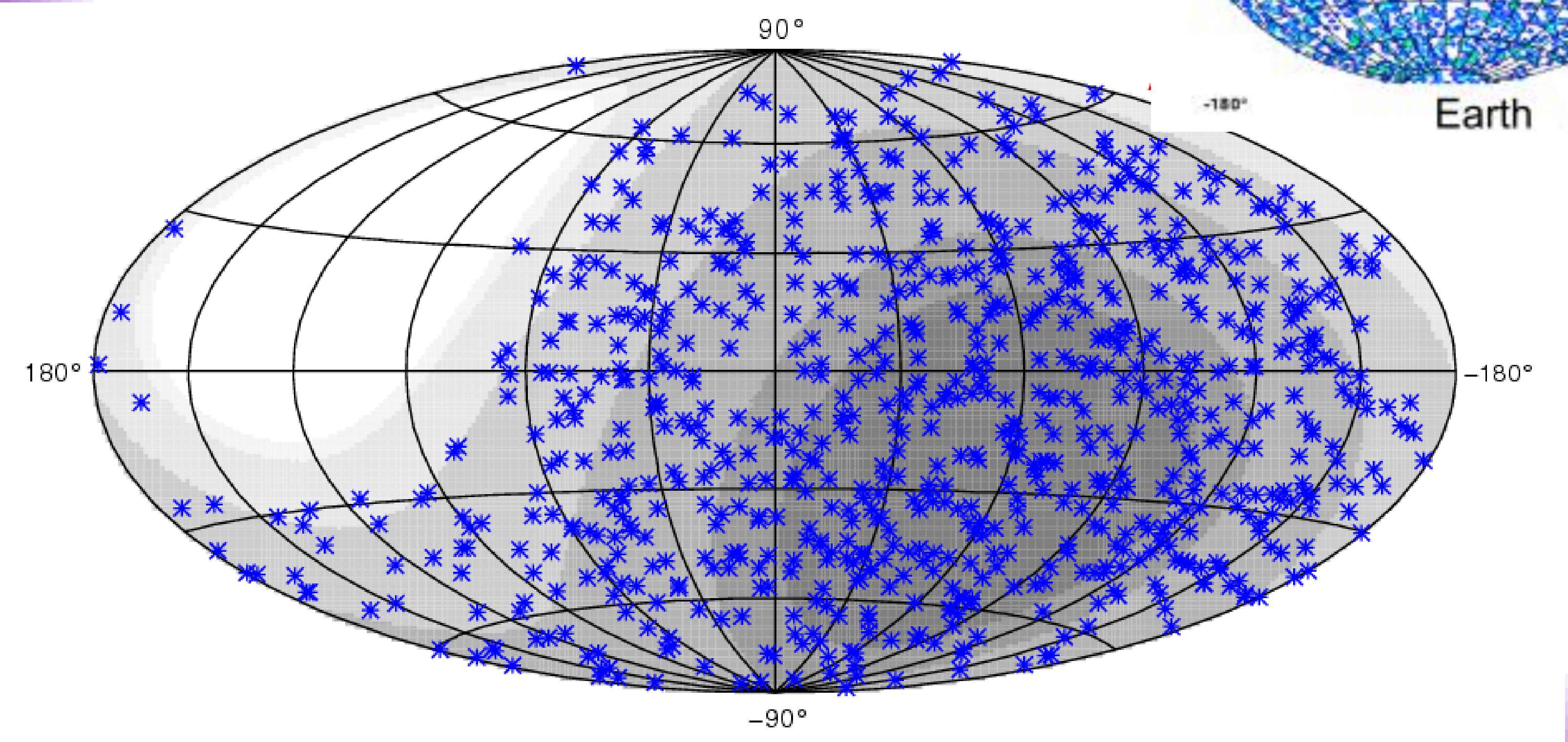
atmospheric neutrinos: 916 (30% syst. error)

Wrong reco atmospheric μ : 40 (50% syst. error)

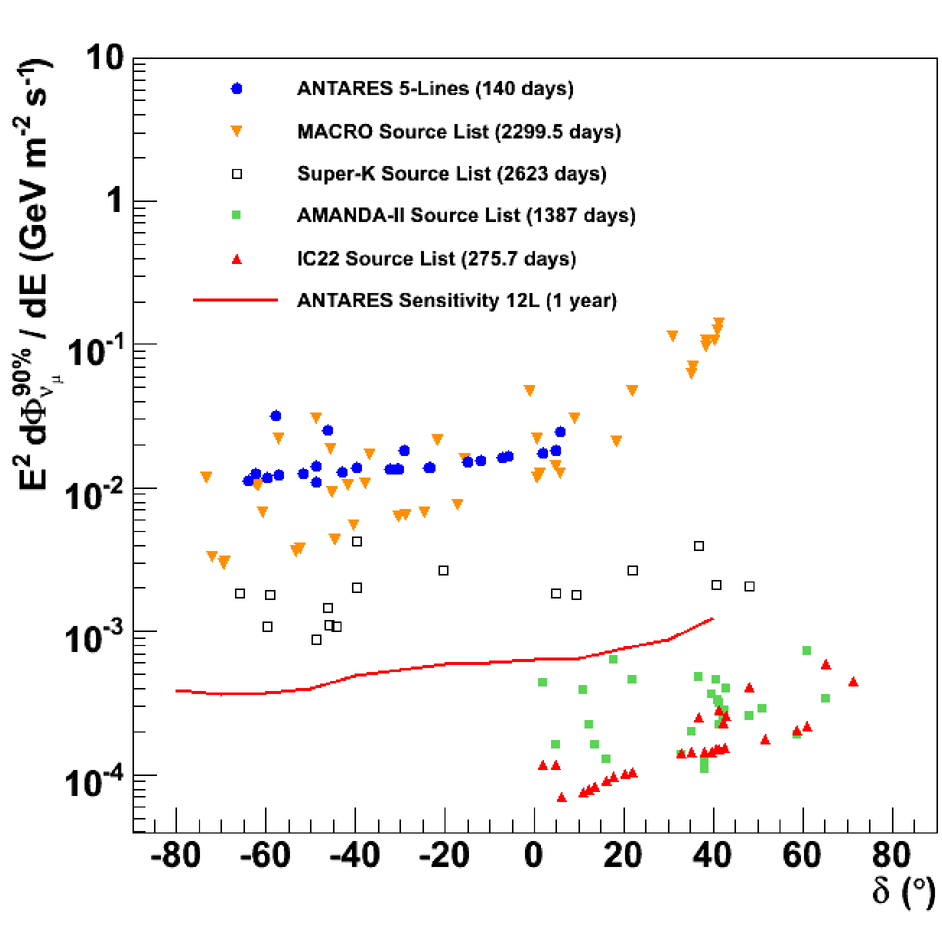
SCRAMBLED ANTARES SKY MAP OF 1000 ν



Fast tracking



POINT SOURCE UPPER LIMITS



Fast tracking

list of 25 potential sources

(stringent cuts to reduce background)

Analysis optimization based on simulations

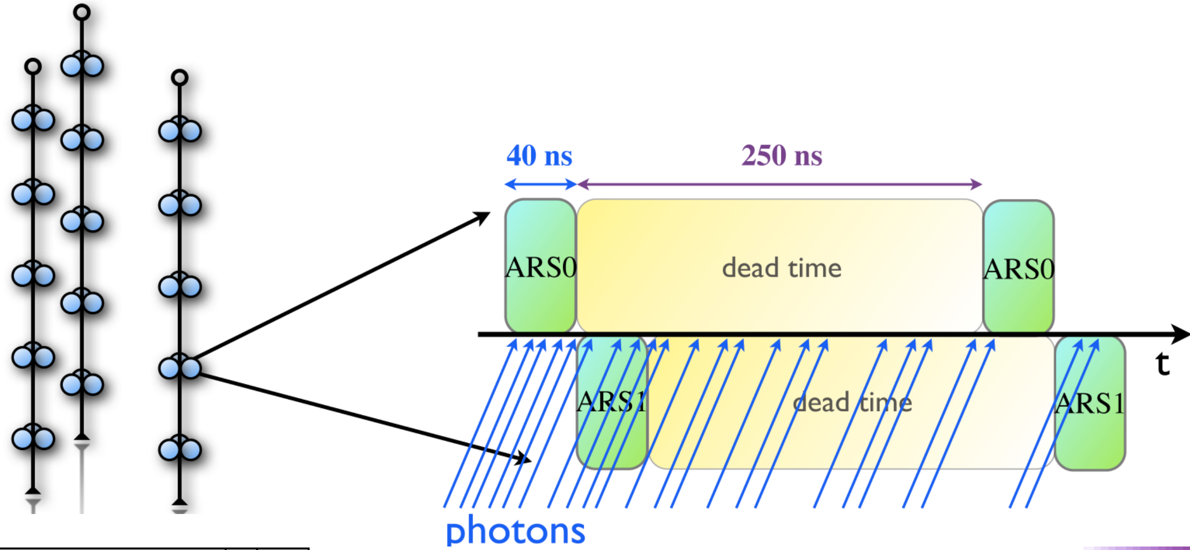
no excess found after 5-line data unblinding

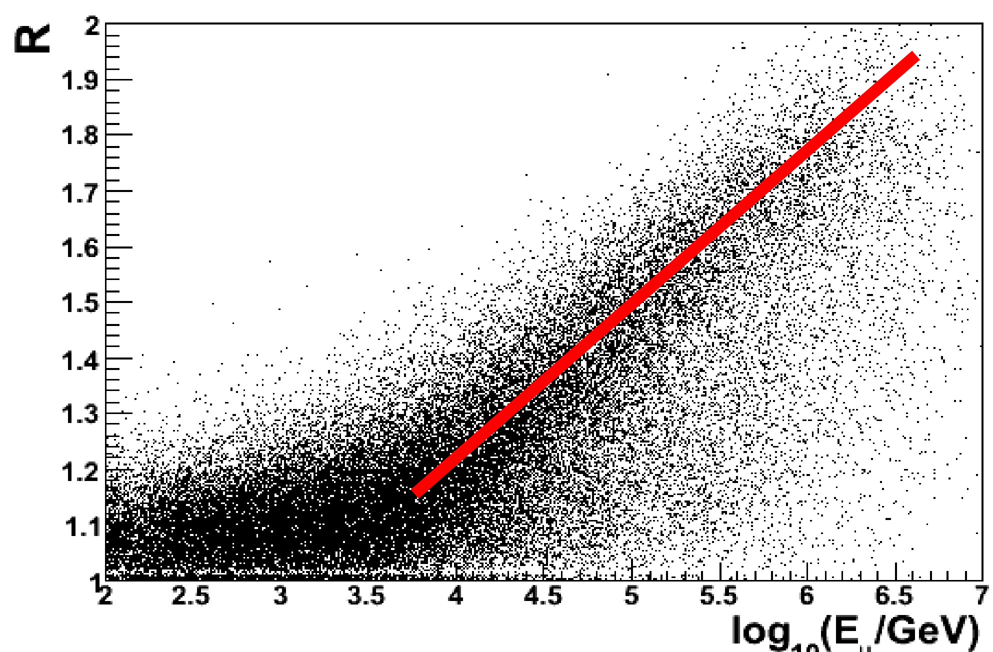
140 days of detector livetime

DIFFUSE ν_μ FLUX –ENERGY ESTIMATOR

$$dE_\mu/dx = \alpha(E_\mu) + \beta(E_\mu) \cdot E_\mu$$

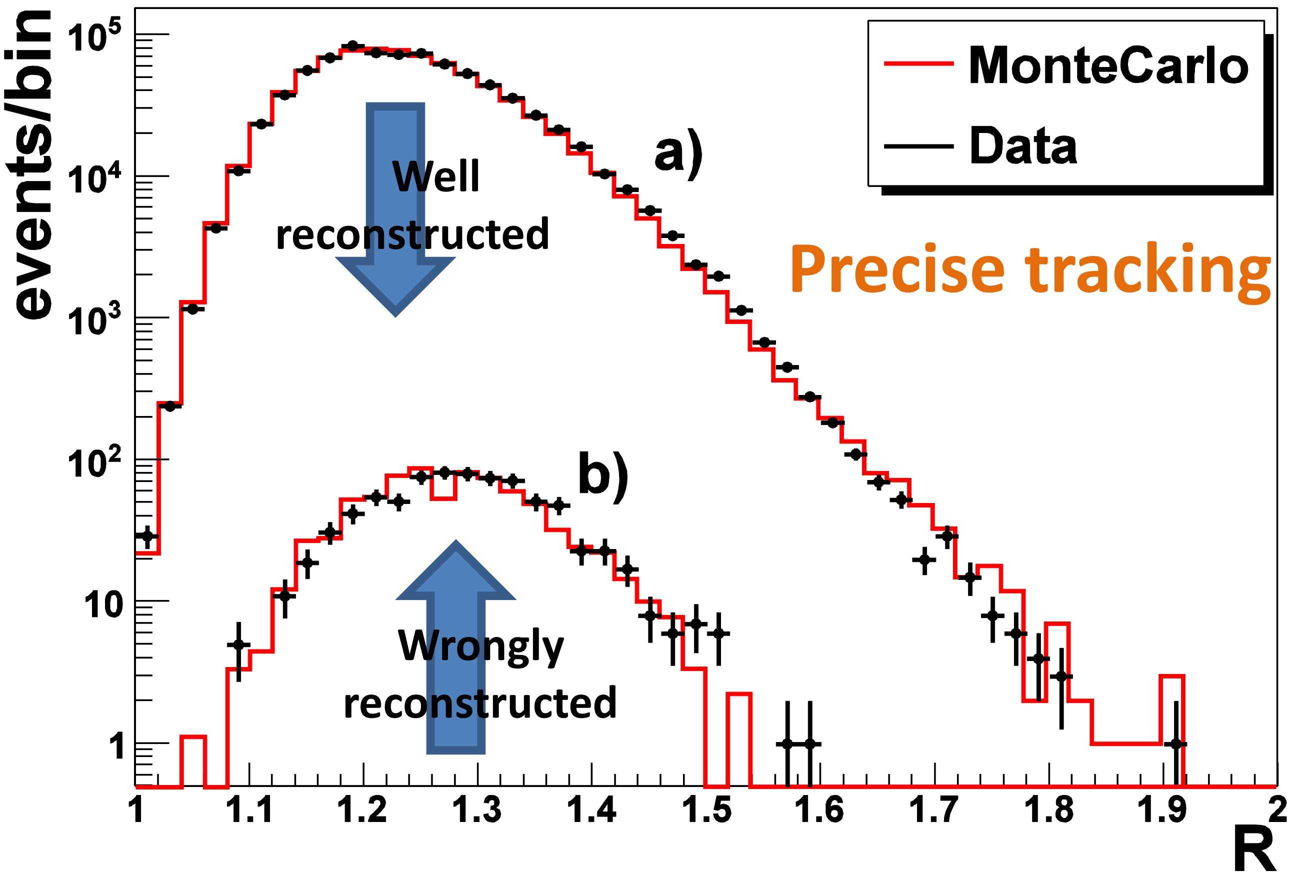
μ direct photons +
μ scattered photons +
light from EM showers





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

ENERGY ESTIMATOR ON ATMOSPHERIC MUONS

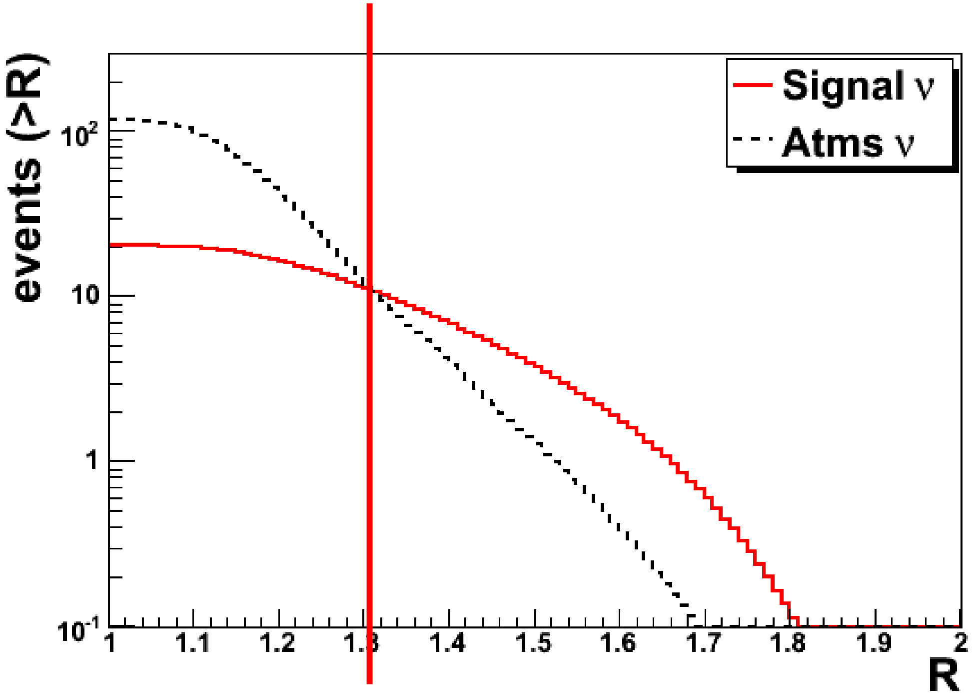


DIFFUSE ν_μ FLUX – ANALYSIS STEPS

1. Rejection of downward going atmospheric muons (using measured zenith angle, track quality parameter, number of hits)

2. Separation of the atmospheric ν background from signal $E^2\,\Phi_{test} = 1.0\times 10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$ using the energy estimator R

3. Blind analysis. Model Rejection Factor **[APP 19 (2003)393]** to select the best cut value on R (=1.31) predefined from MC only.

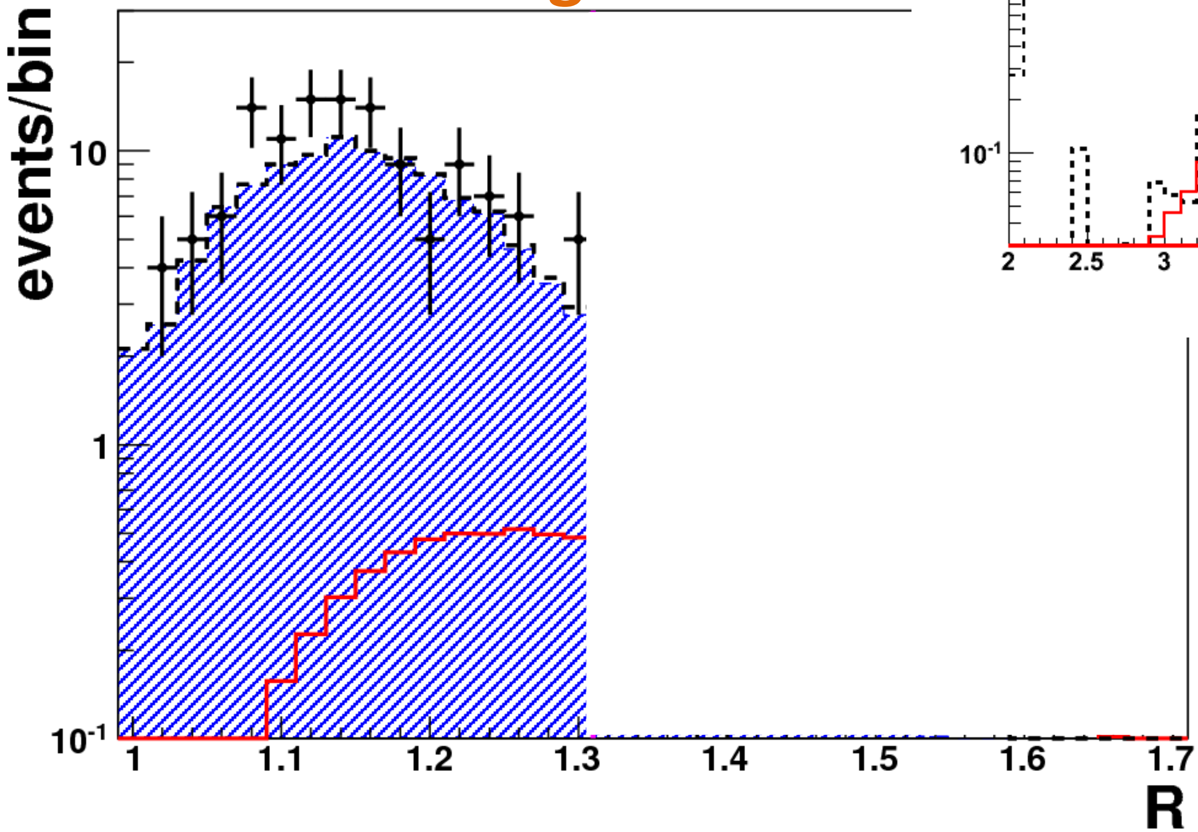


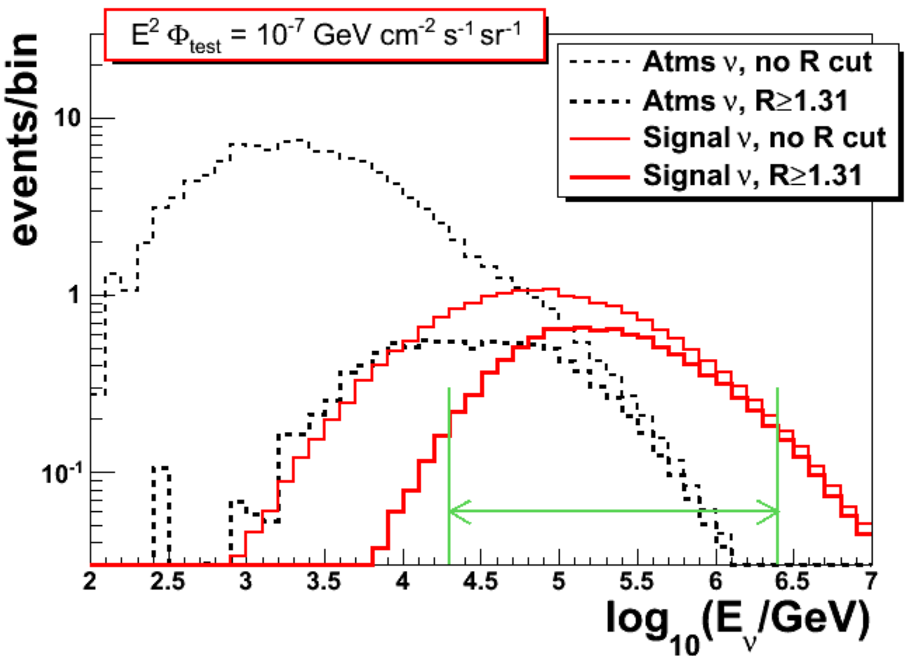
DIFFUSE ν_μ FLUX – RESULTS

R< 1.31

Bartol (conventional ν)	104.0
Max "prompt" model	2.1
Data	125

Precise tracking

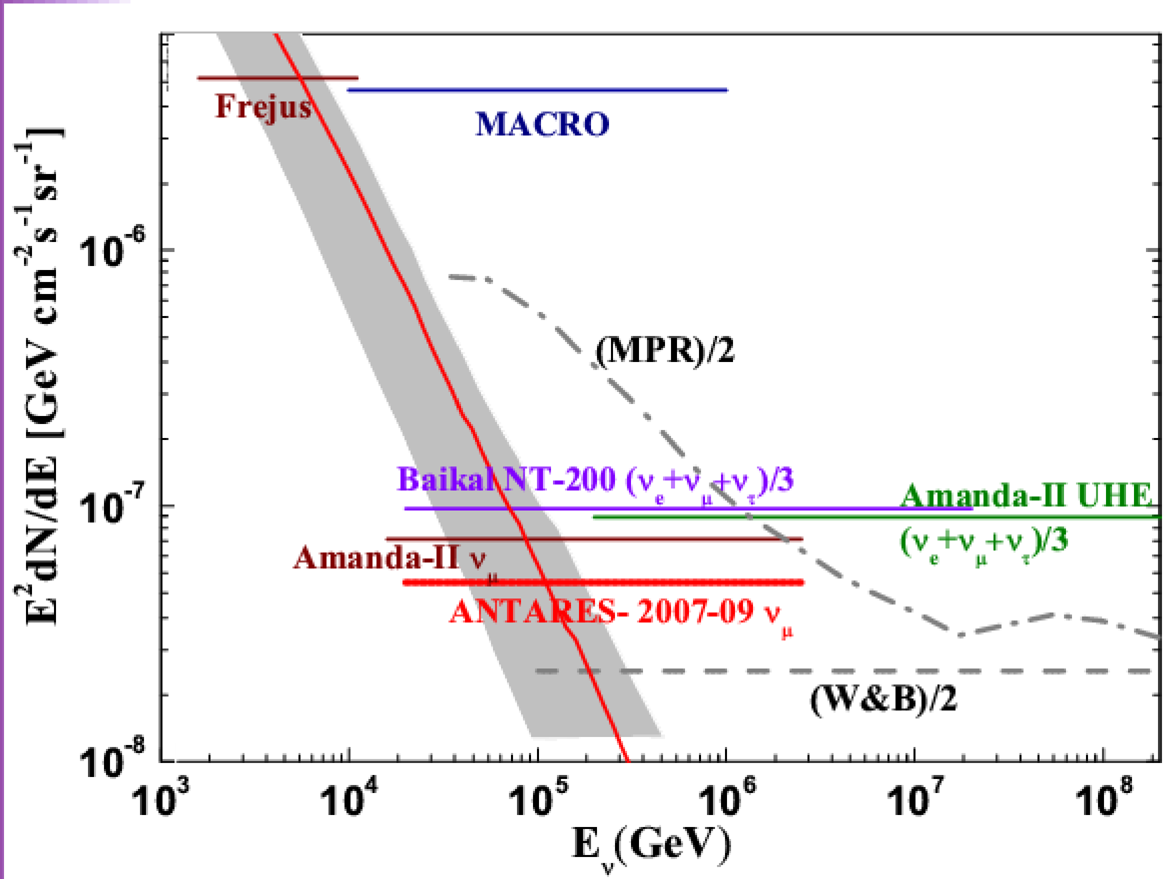




R≥ 1.31

Atmospheric ν	10.7 ±2
Data	9

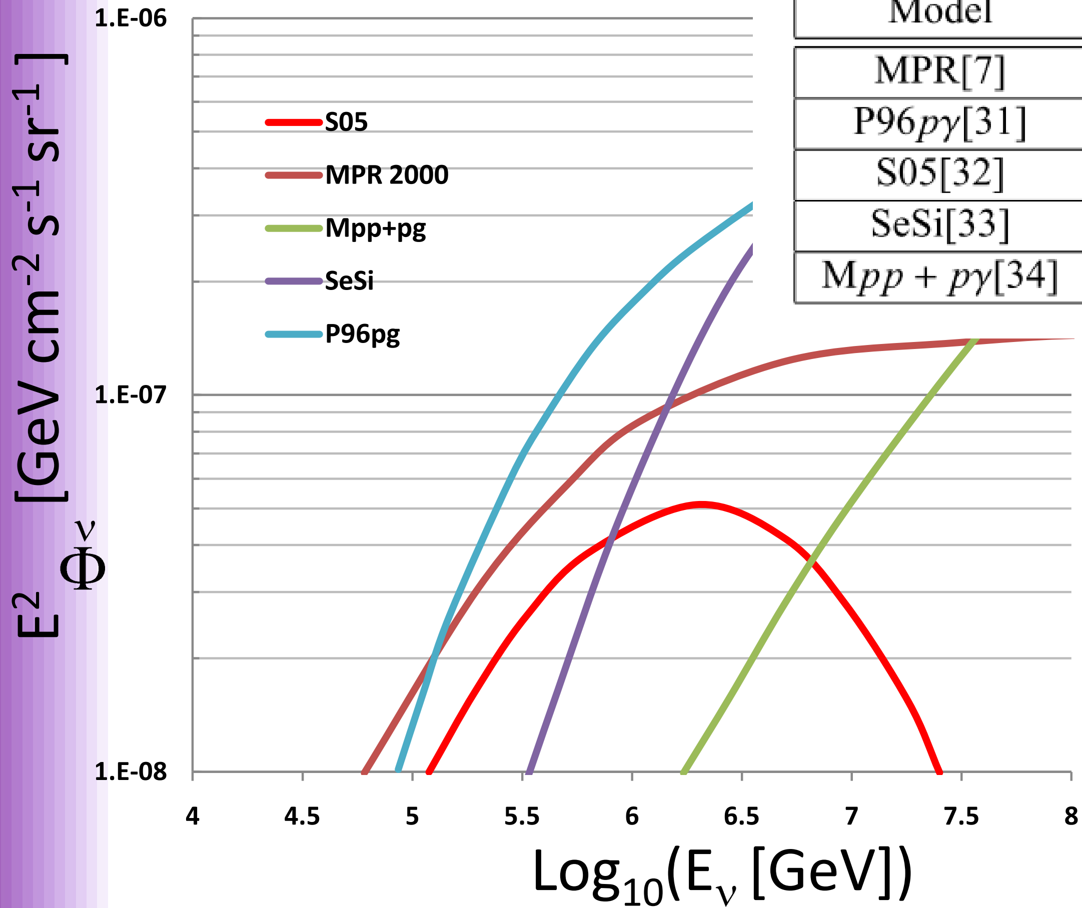
DIFFUSE ν_μ FLUX – UPPER LIMITS (E^{-2})



$E^2\Phi(E)_{90\%} = 4.7\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

20 TeV<E<2.5 PeV

DIFFUSE ν_μ FLUX – UPPER LIMITS – (other energy spectra)



Model	R^*	N_{mod}	$\Delta E_{90\%}$ (PeV)	$\mu_{90\%}/N_{mod}$
MPR[7]	1.43	3.0	0.1÷ 10	0.4
P96$p\gamma$[31]	1.43	6.0	0.2÷ 10	0.2
S05[32]	1.45	1.3	0.3÷ 5	1.2
SeSi[33]	1.48	2.7	0.3÷ 20	0.6
M$pp + p\gamma$[34]	1.48	0.24	0.8÷ 50	6.8

<1 : model rejected

[7] K. Mannheim, R. J. Protheroe, J. P. Rachen. Phys. Rev. D 63 (2000) 023003.
[31] R. Protheroe, astro-ph/9607165 (1996).
[32] F.W. Stecker, Phys. Rev. D 72 (2005) 107301.
[33] D. V. Semikoz and G. Sigl JCAP04(2004) 003.
[34] K.Mannheim, Astropart. Phys. 3 (1995) 295.

ONGOING COMBINED SEARCHES

- Receive GRB alerts from Satellites (Fermi, Swift...)

search for coincident neutrinos within time window (~100 s)

- Send neutrino cluster alert for optical follow-up

Trigger: multiple / HE single neutrino event; Reconstruction "on-line" (<10ms)

Alert message to Tarot Telescope in La Silla (Chile). Tarot takes 6 images of 3 minutes immediately and after 1, 3, 9 and 27 days

sending alerts to the ROTSE system (4 telescopes)

- Correlation with AUGER source distribution

investigate directional correlation of neutrinos and UHE particles

- Correlation with VIRGO-LIGO signals

investigate correlation of neutrinos and gravitational waves

CONCLUSIONS

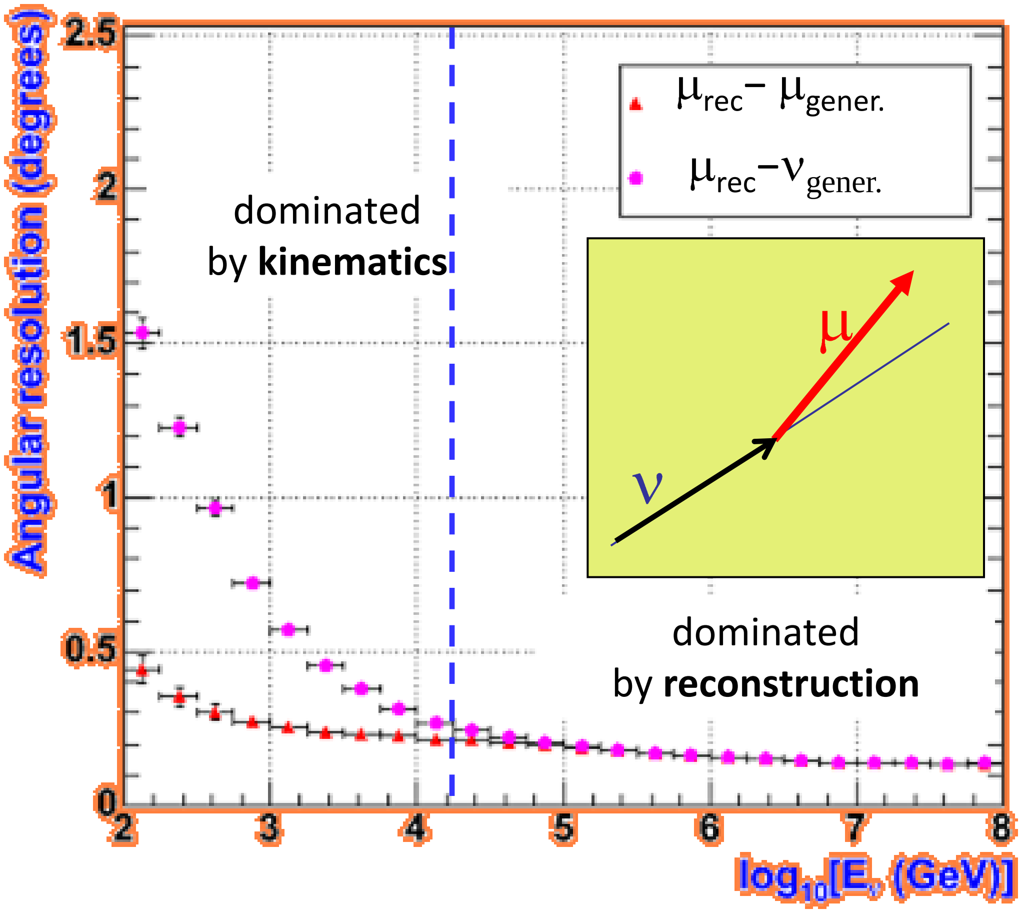
ANTARES

- continuously taking data
- complements the sky coverage of IceCube
- has a broad physics program
- determined most sensitive upper limit on diffuse flux
- paves the way for KM3NeT

SPARES

ANGULAR RESOLUTION

angular resolution = difference between reconstructed and MC generated angles vs. neutrino energy



$$\overline{\Theta}_{\nu-\mu} \leq \frac{0.7^{o}}{\left[E_{\nu}(\text{TeV})\right]^{0.6}}$$

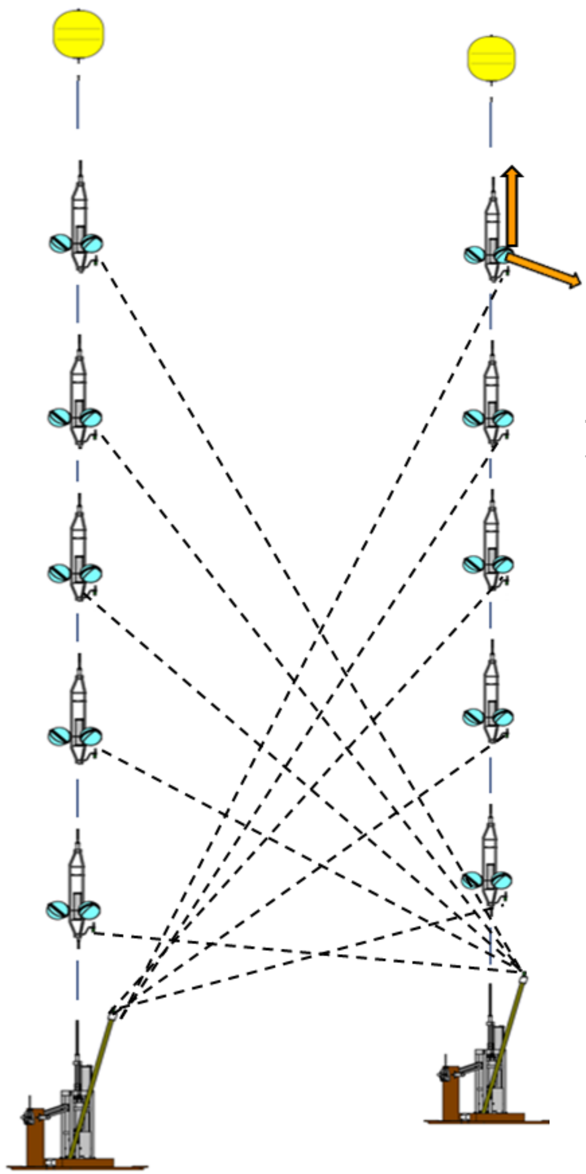
angular resolution

< 0.2° above ≈ 10 TeV

limited tracking accuracy due to time resolution:

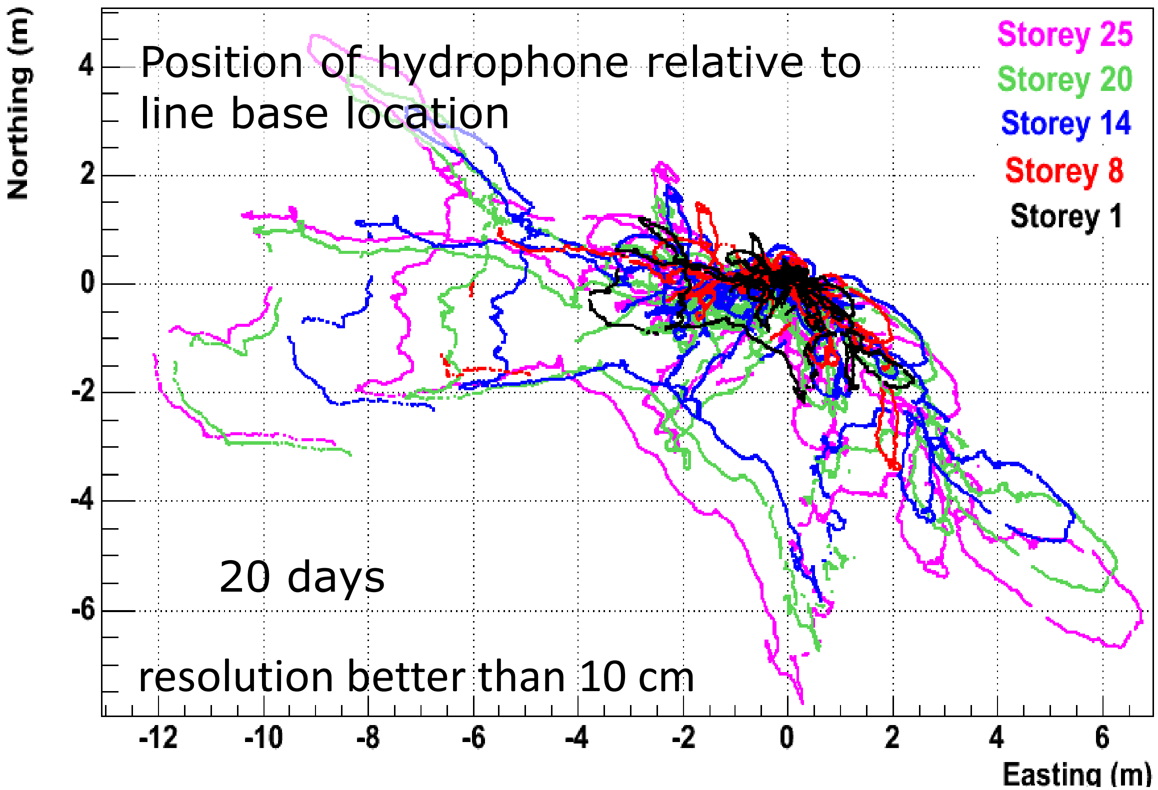
- Light scattering σ ~ 1.0 ns
- TTS in PMT σ ~ 1.3 ns
- time calibration σ < 0.5 ns
- OM position σ < 10 cm (↔ σ < 0.5 ns)

POSITION CALIBRATION

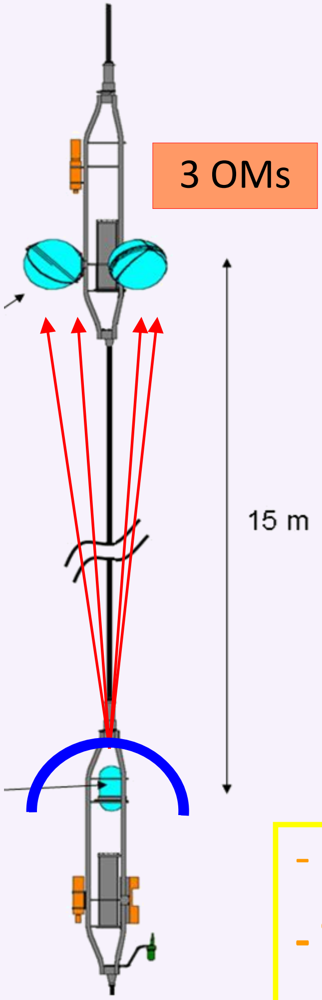


- Transceivers on the bottom of each line
- 5 hydrophones at specific heights on each line
- 4 autonomous transponders around the apparatus
- Sound velocimeters installed at various depths
- Tiltmeter and compass at each storey

Measurements performed every 2 minutes

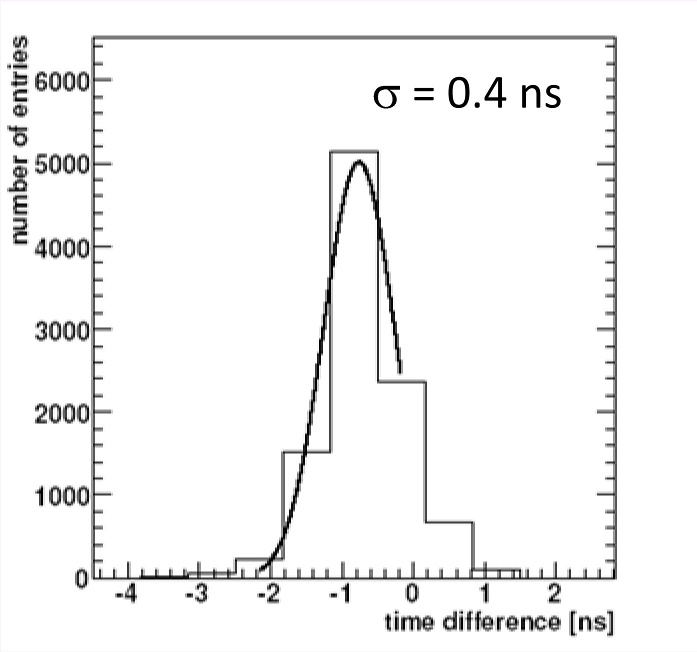


TIME CALIBRATION



Optical LED beacon

Time difference between the LED OB and an OM

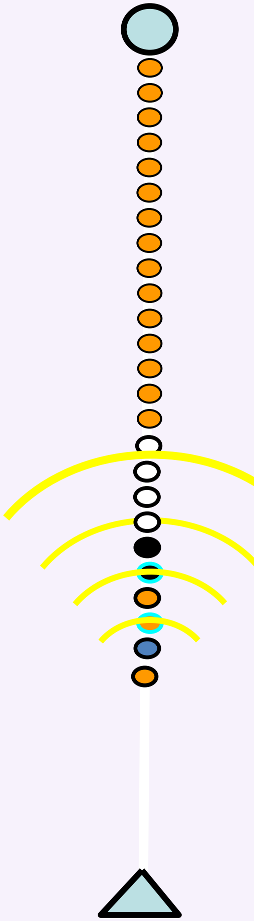


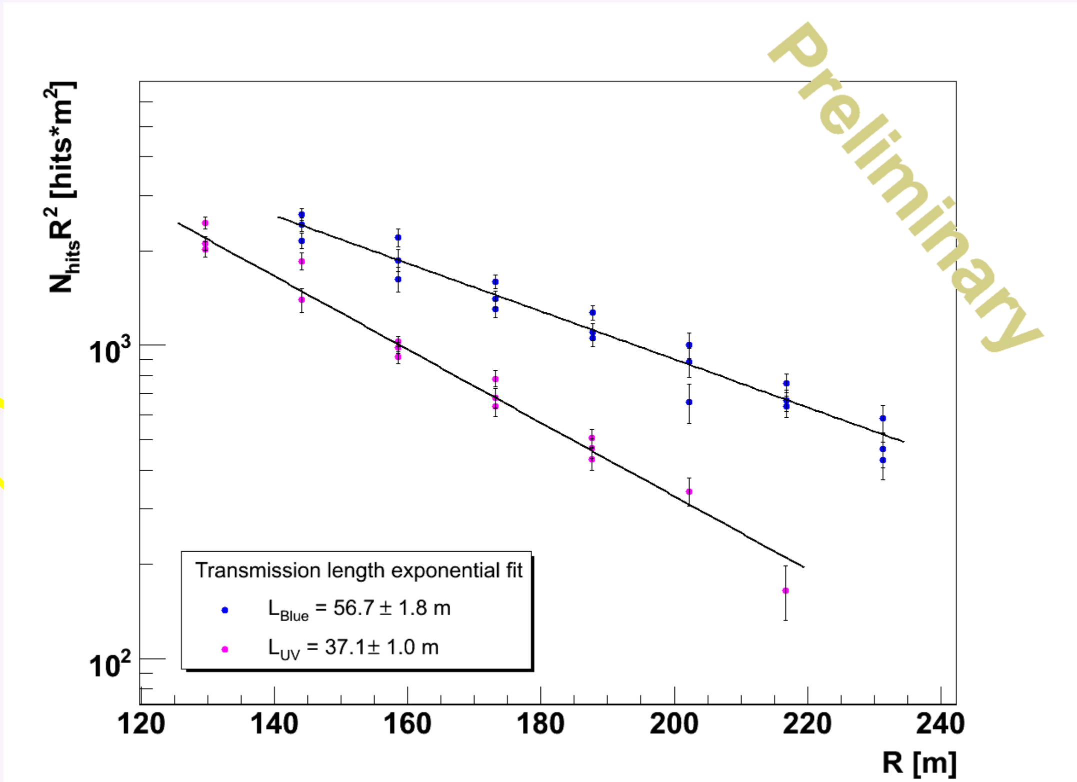
- Electronics + calibration → σ ~ 0.5 ns
- TTS in photomultipliers → σ ~ 1.3 ns
- Light scattering + dispersion in sea water → σ ~ 1.5 ns at 40 m

Angular resolution → 0.3° (for E_ν > 10 TeV)

Including the acoustic position resolution and the ν-μ angle

ATTENUATION LENGTH MEASUREMENTS





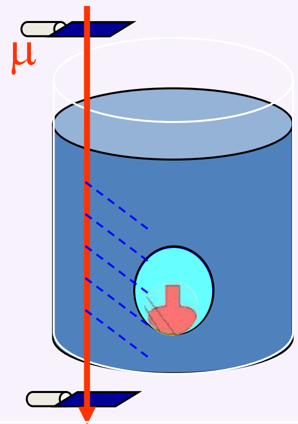
$$Q(R) = \frac{Q_0 \exp(-R/L)}{R^2}$$

The biggest challenge is to determine

the separate contribution of absorption and scattering

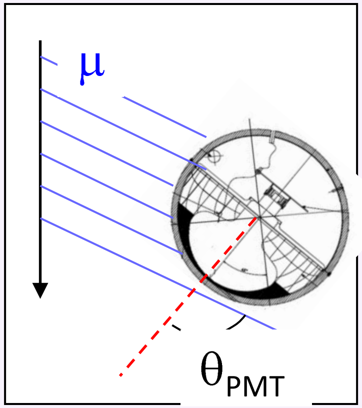
OM ANGULAR ACCEPTANCE

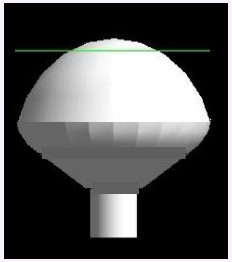
Has to be known to compute reconstruction efficiencies and effective areas



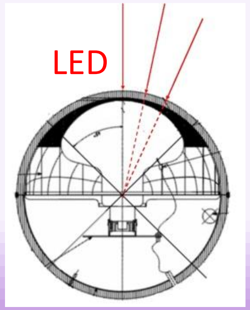
Measurements were performed in a water tank
Photon scattering affects the measurements

angular acceptance determination is not reliable at large θ_{PMT}

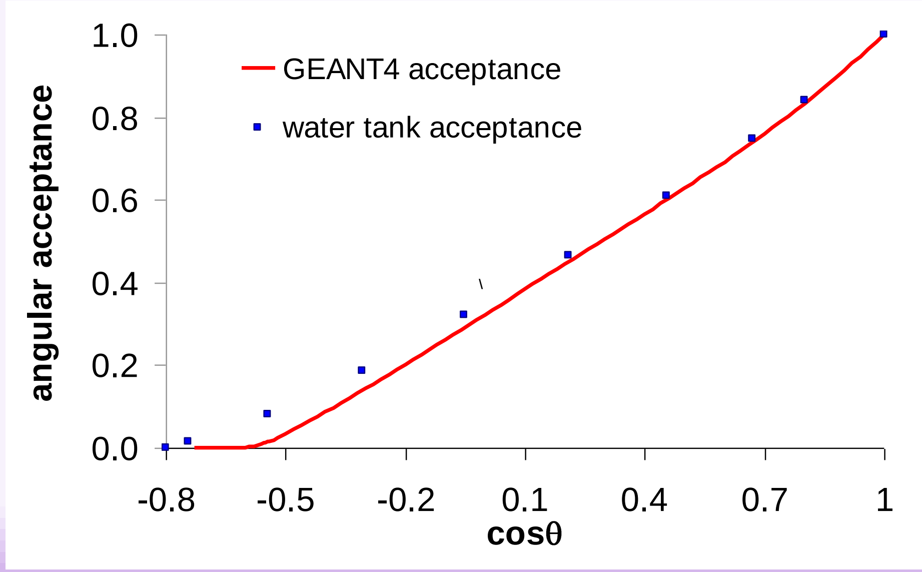




Detailed GEANT4 simulation of the OM

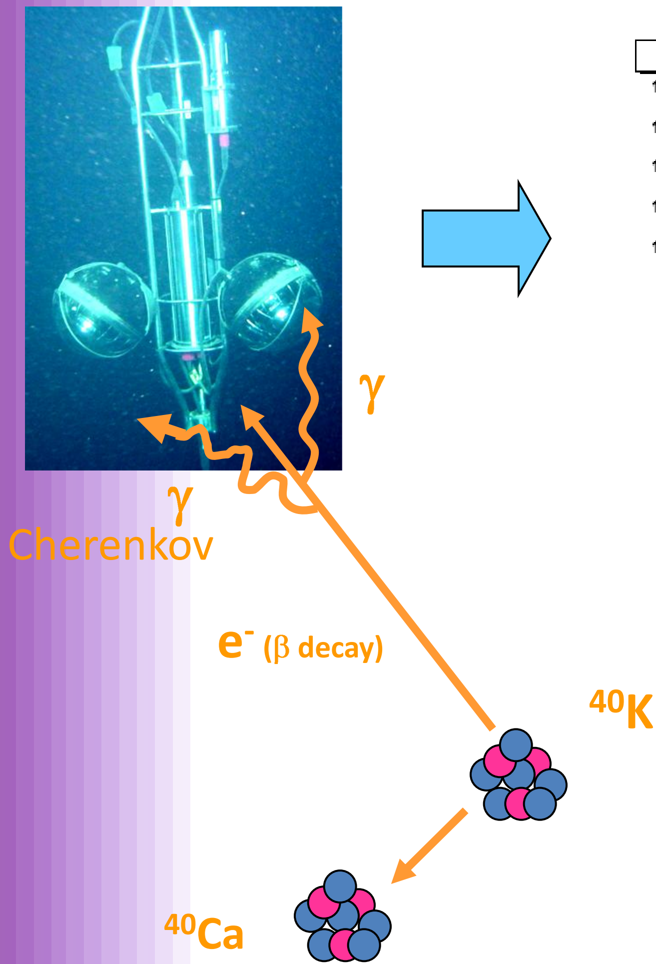


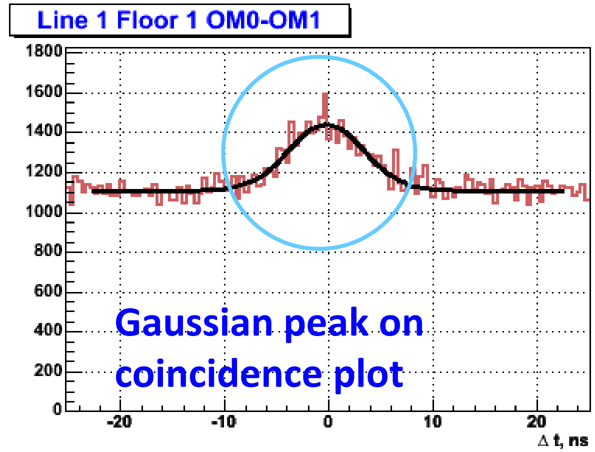
Dedicated measurements of the photocathode surface of OMs



Angular acceptance uncertainty at large θ affects μ flux significantly, but not ν flux

IN SITU CALIBRATION WITH ^{40}K





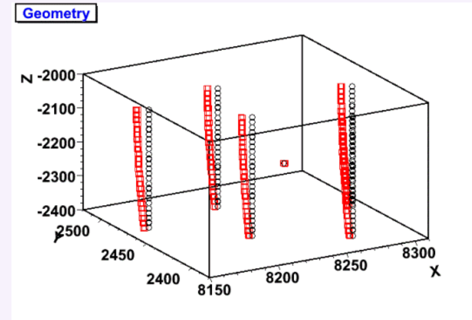
Integral under peak = rate of correlated coincidences

Peak offset

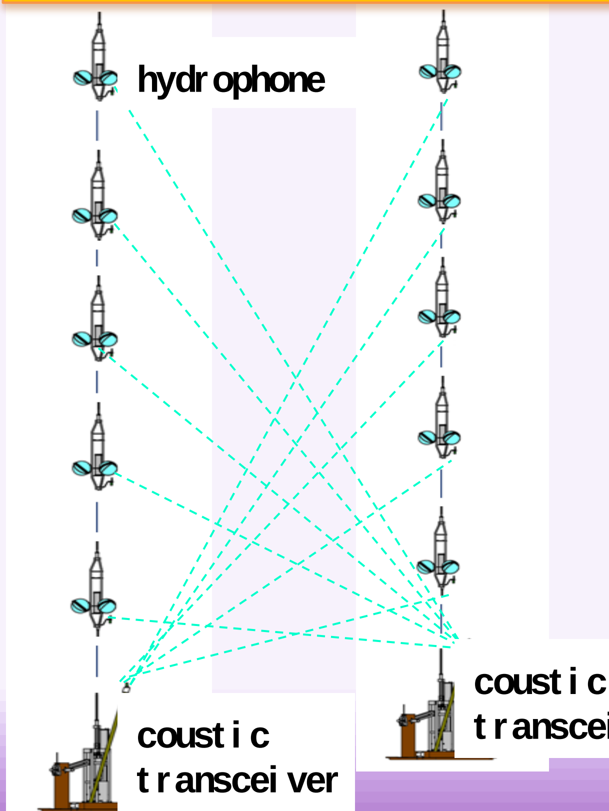
time calibration

No dependence on bioluminescent activity has been observed

- REAL TIME POSITIONING ➔ Acoustic positioning system + set of tiltmeters and compasses.
- Transceivers (RxTx) on the bottom of the lines, 4 autonomous transponders around the apparatus.
- 5 hydrophones (Rx) per line at specific heights.
- Tiltmeter and compass per storey, sound velocimeters (various depths).



RECONSTRUCTION OF THE LINE SHAPE ➔ GLOBAL χ^2 FIT TO LINE SHAPE MODEL (BEHAVIOUR OF LINE: SEA CURRENT)



Hydrophone position relative to line base location (20 days)