ANTARES: Recent results

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on behalf of the ANTARES Collab.

Workshop on GW & HEN, APC, Paris, 18-20 May 2009

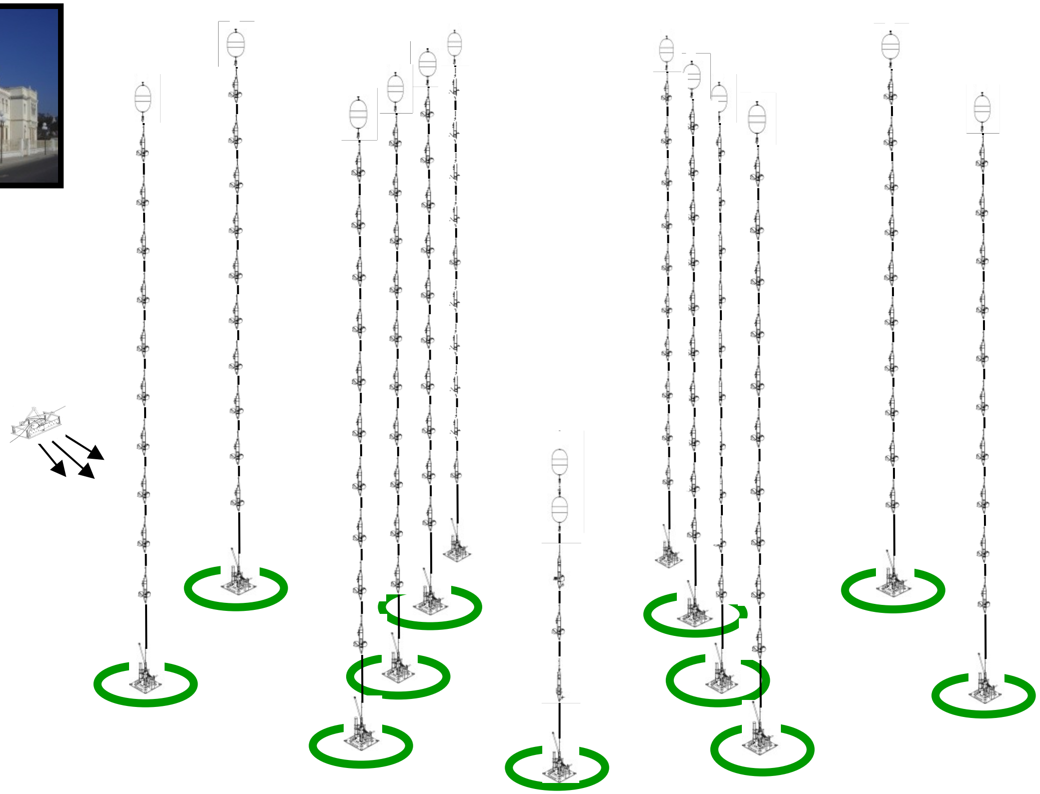
Deployment

Data taking periods:

- ***MILOM : Mar '05 – Mar '06***

La Seyne-sur-Mer

(40 km)

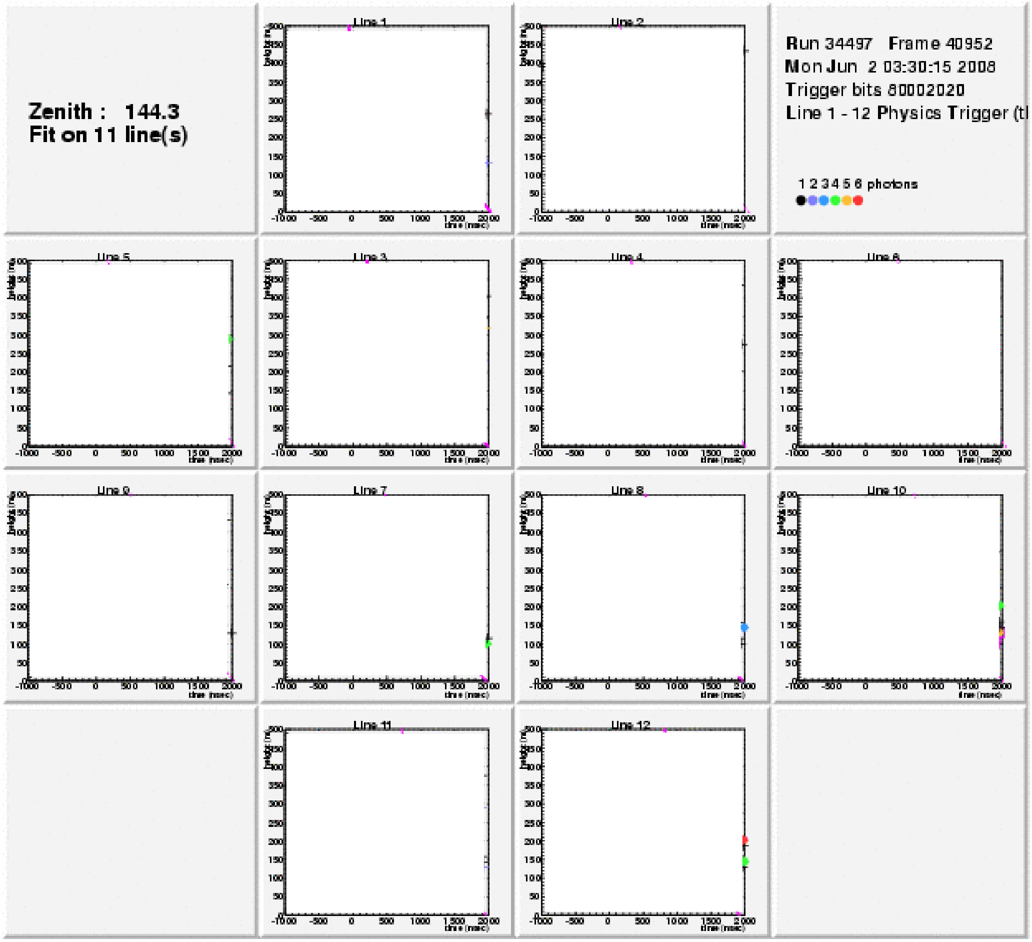


- ***Line 1-10 : Dec '07 - Ma***

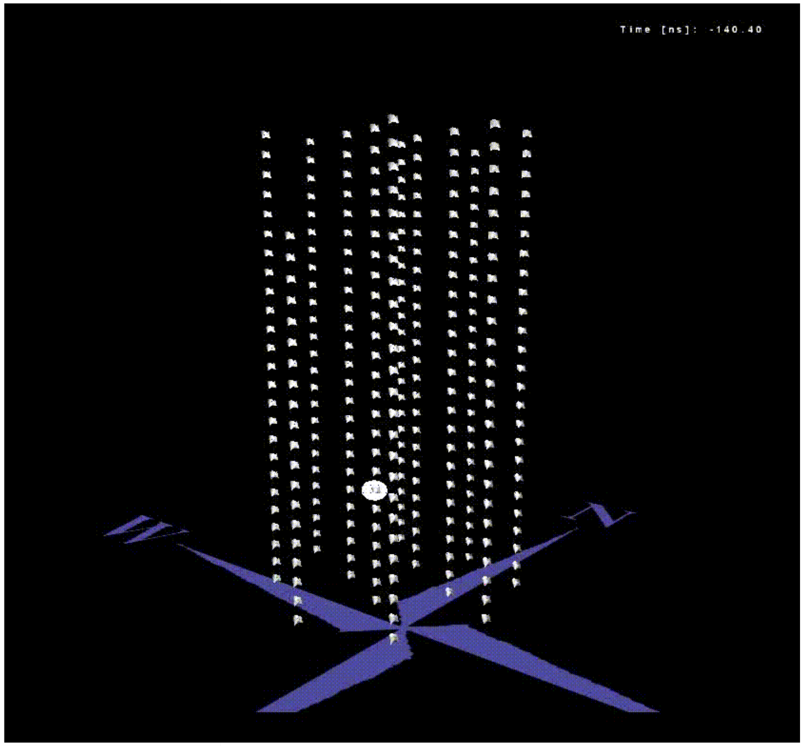
- ***Co***
onw

(2.5 km depth)

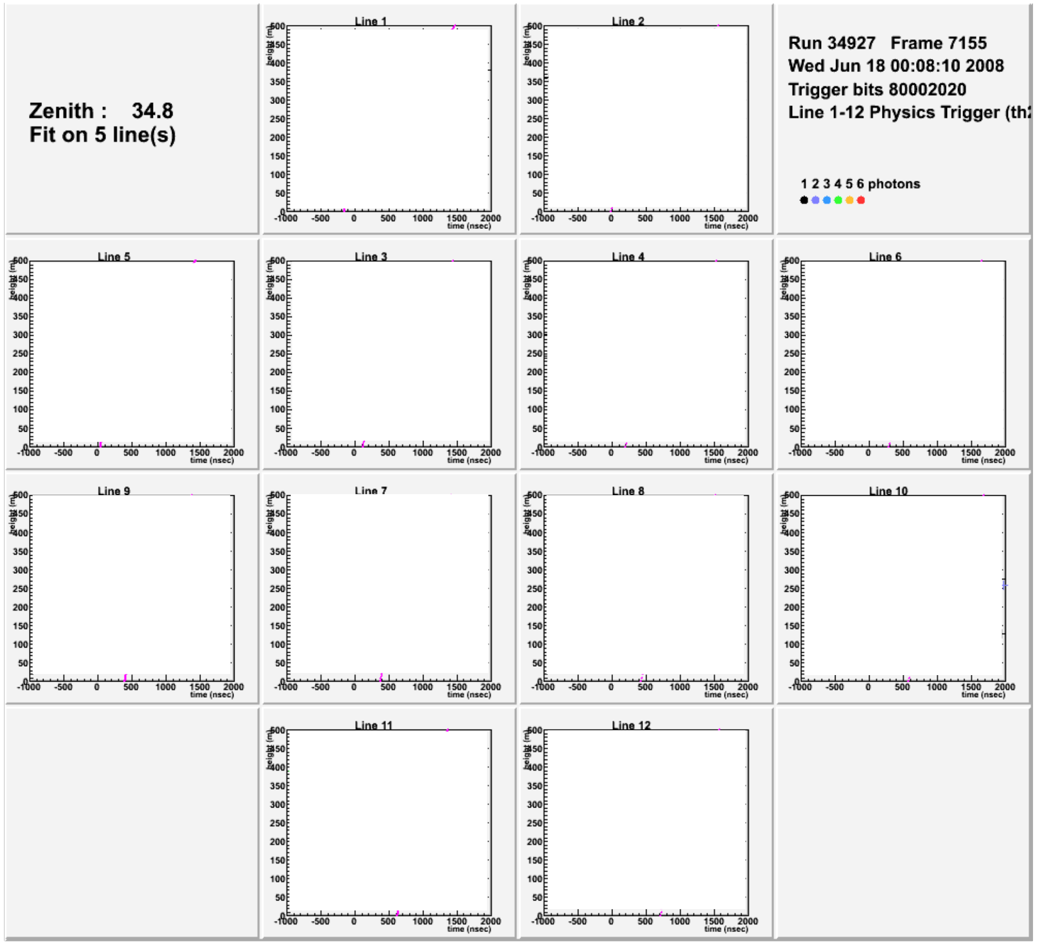
(multi-) muon Event



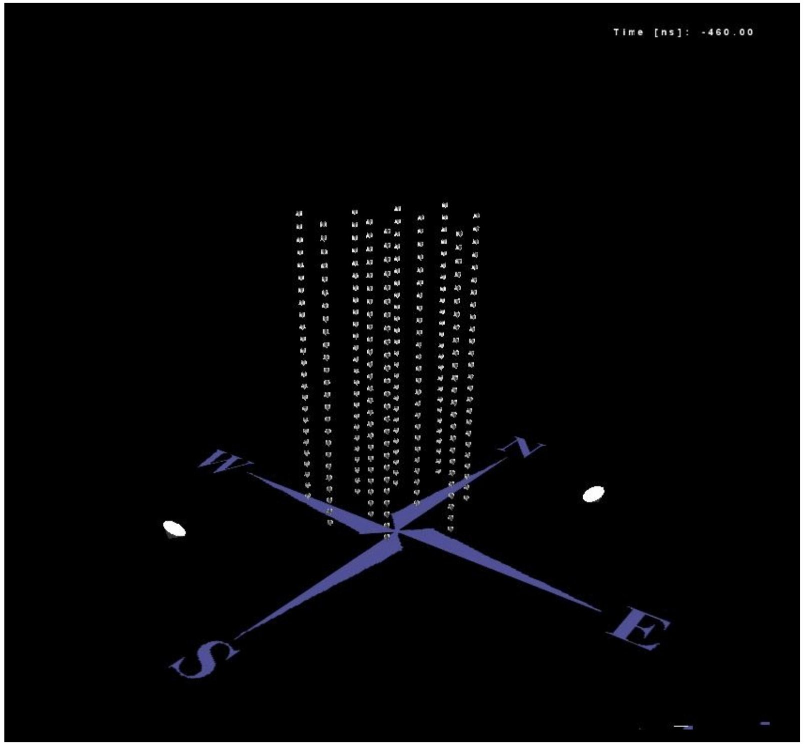
Example of a reconstructed down-going muon, detected in all 12 detector lines:



Neutrino candidate



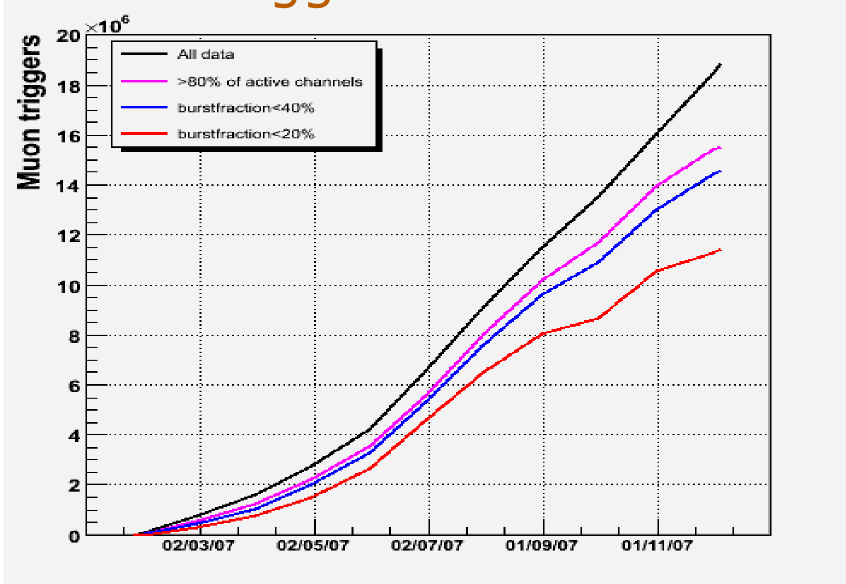
Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:



Accumulated data

4 5 lines (2007)

19 ×106 μ triggers

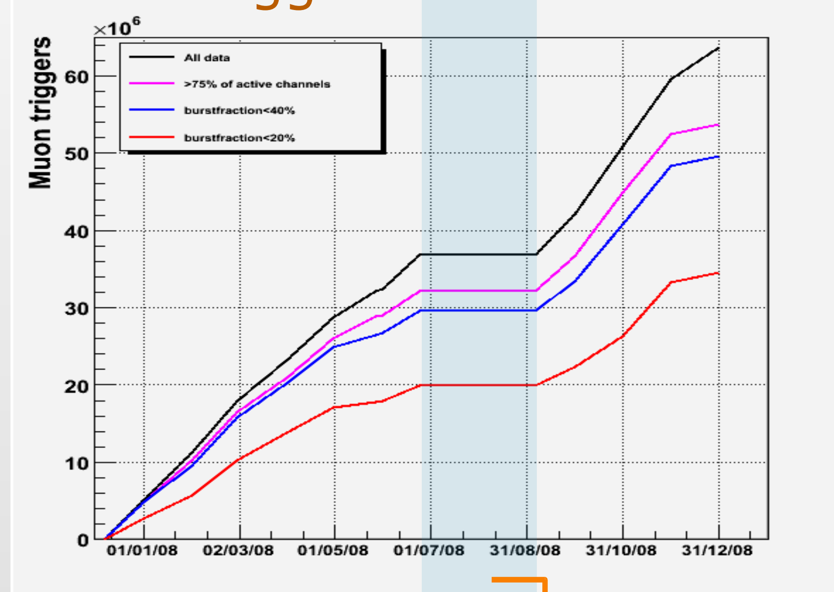


Total : 245 days = 79% of calendar

Selected :168d = 69% of total

≥ 10 lines (2008)

65 ×106 μ triggers

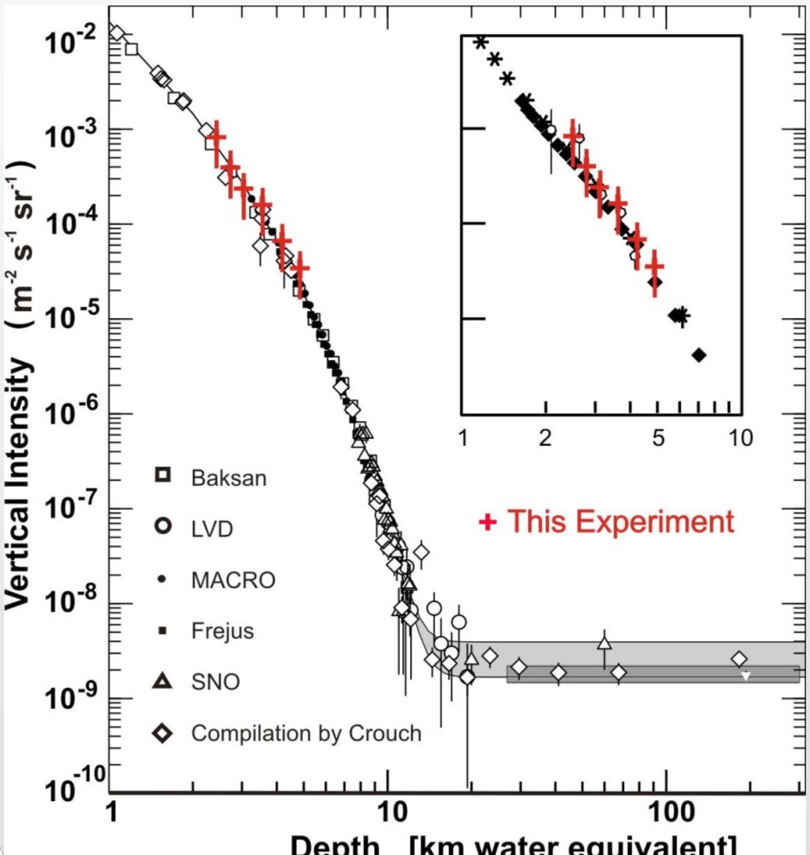


Cable repair

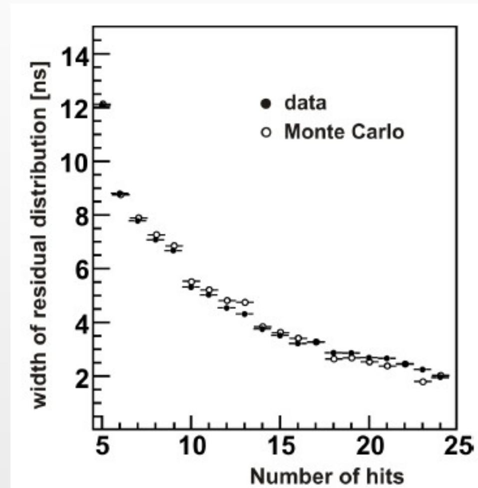
Total : 242 days = 77% of calendar

Selected :173d = 71% of total

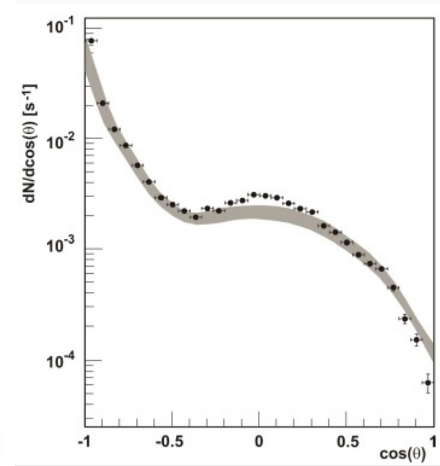
Line 1 measureme



Width of time residuals vs. nb of hits in track fit



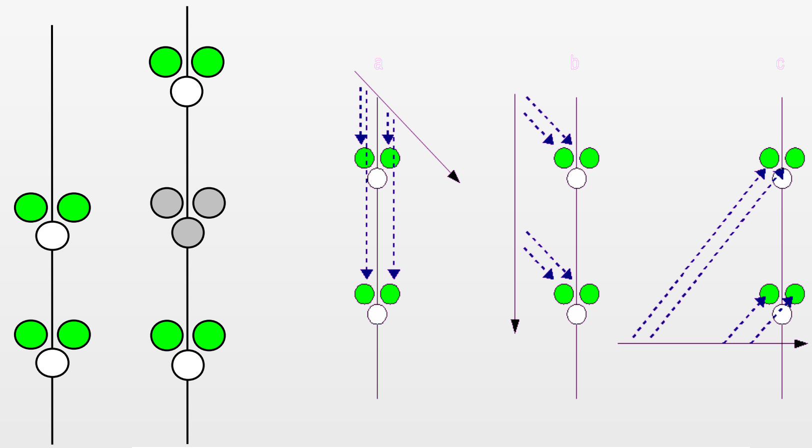
Distribution of cosine of zenith angle.

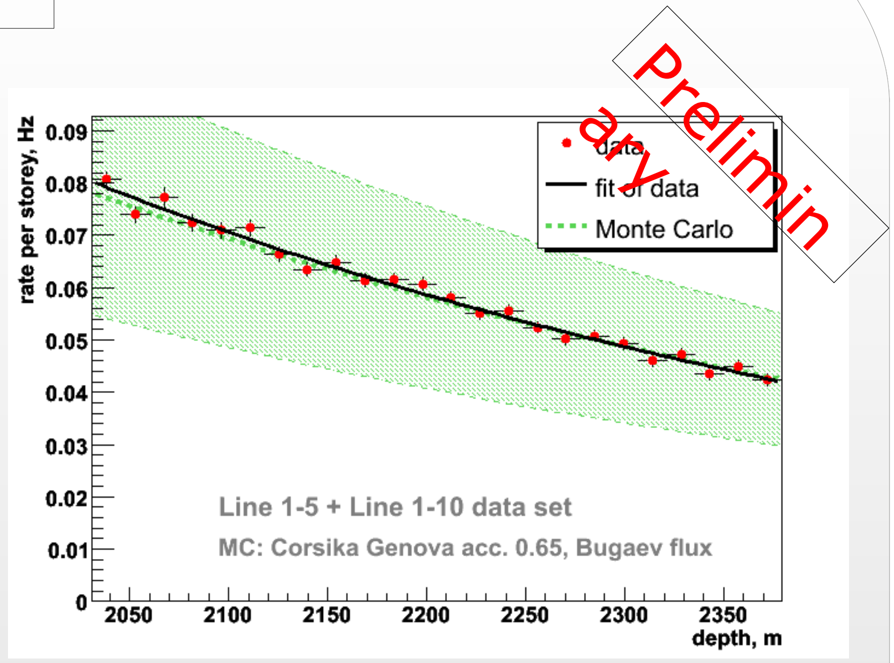


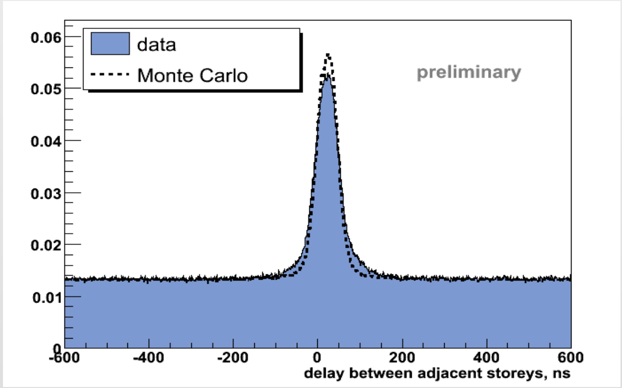
- Depth Intensity relation with a full line
- Data vs. MC comparison: importance of OM efficiency at high angle for <u>downgoing</u> tracks

Depth-Intensity

- Simple method based on coincidences on adjacent on next-to adjacent storeys. No reconstruction needed



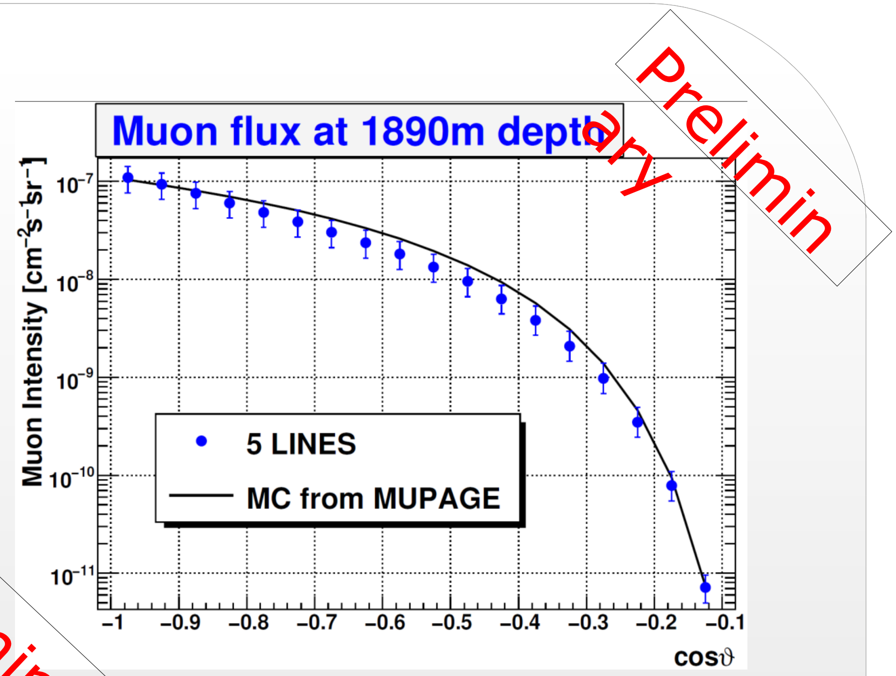


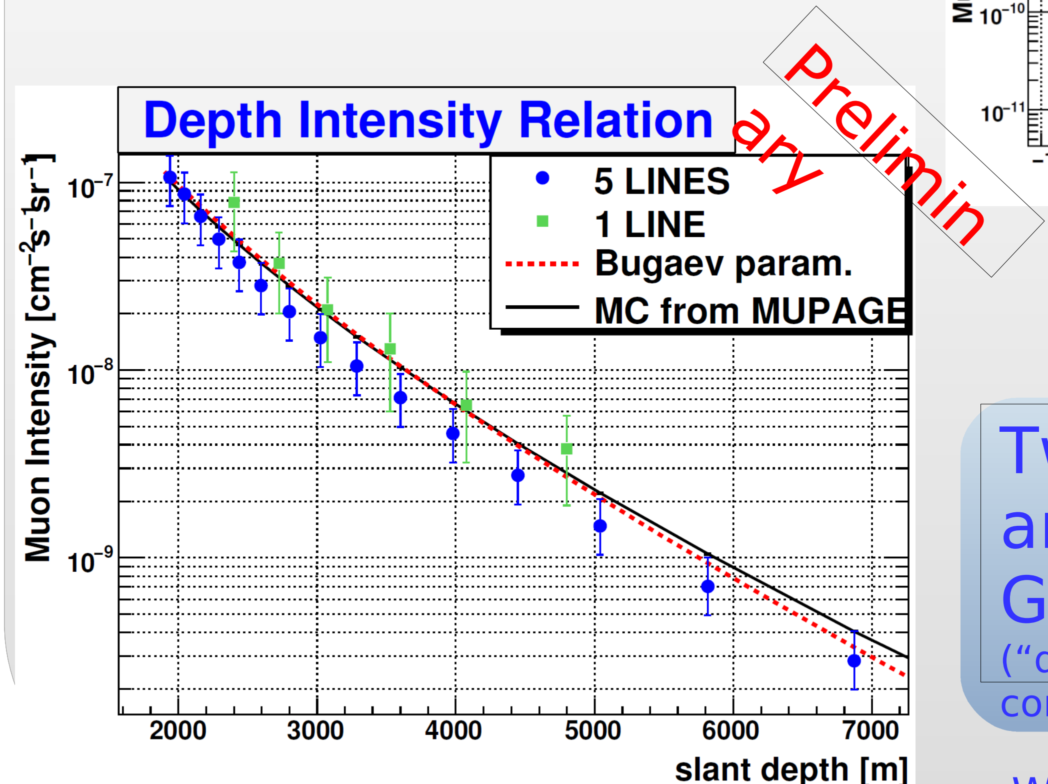


Time distribution in agreement with MC

- Rate vs. depth distribution can test OM efficiency corrections (40K) and OM acceptance.
- Uncertainties still large. More work needed.

5 lines (2007)

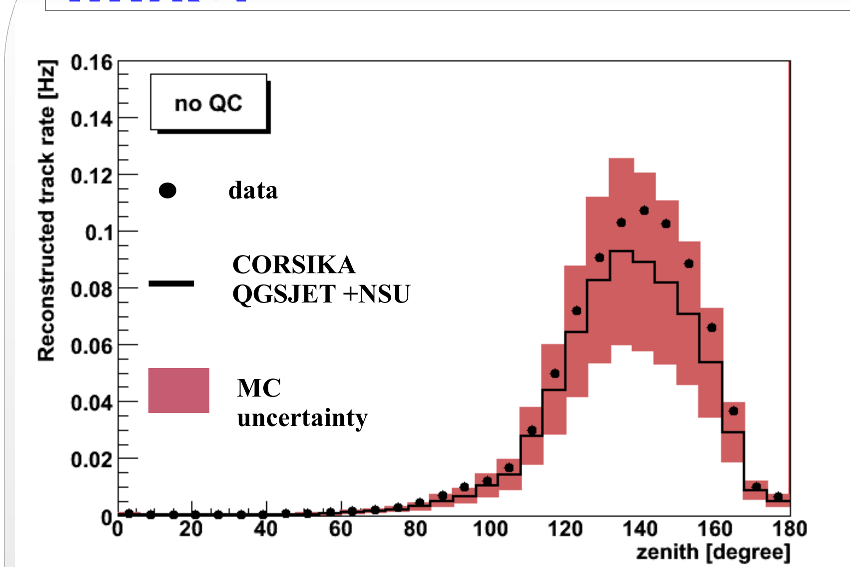


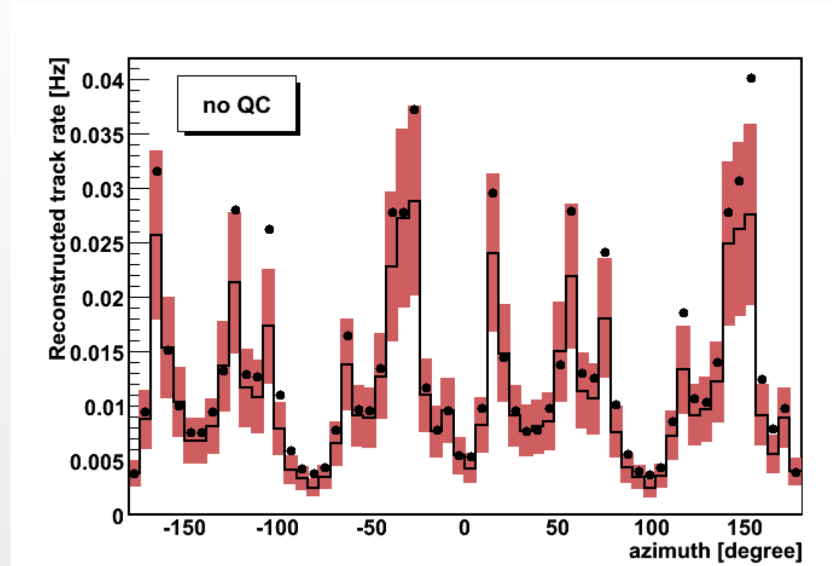


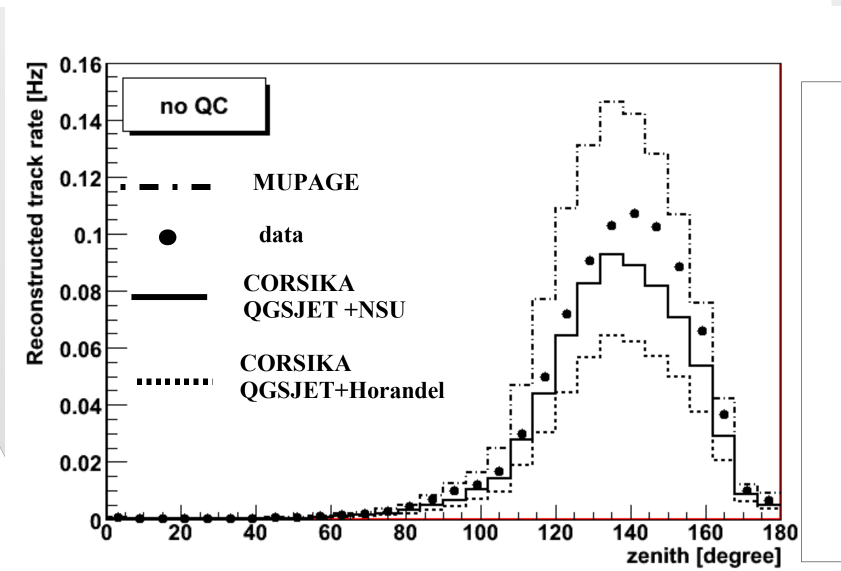
Two independent analyses:
Good agreement
(“deconvolution” and “bin-to-bin correction”).

Work on reducing systematics is ongoing

Data-MC comparison for downgoing events (5-lines)

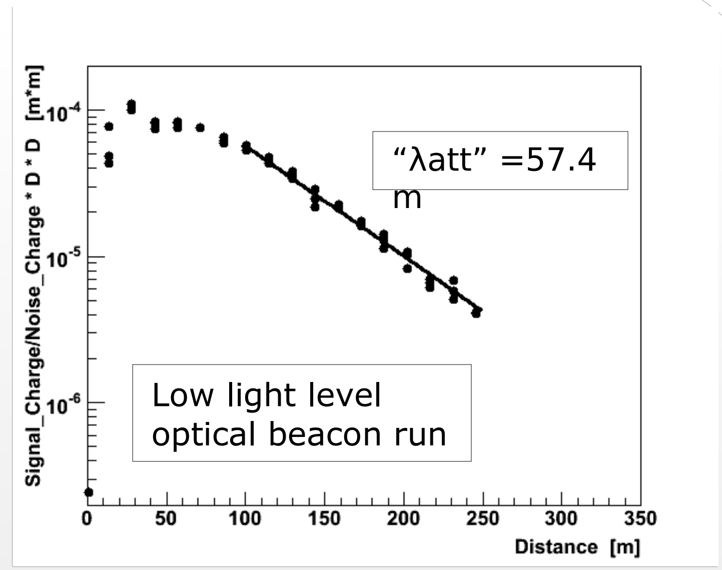


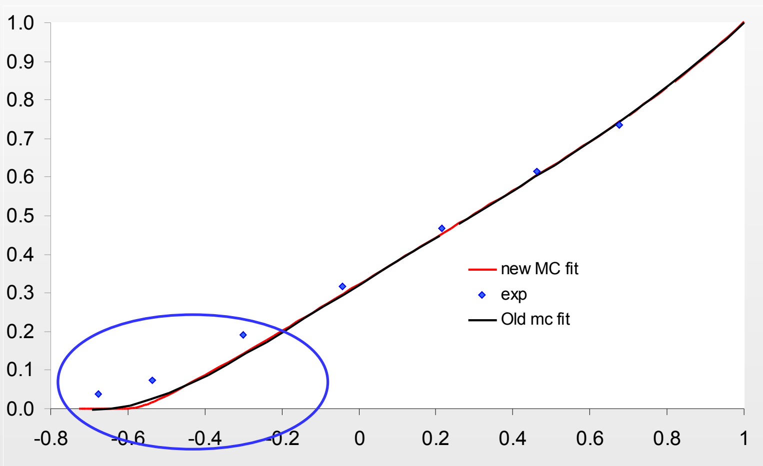




- No quality cuts applied
- Agreement within (substantial) theoretical + MC uncertainty
- Main experimental errors

Reducing systematic





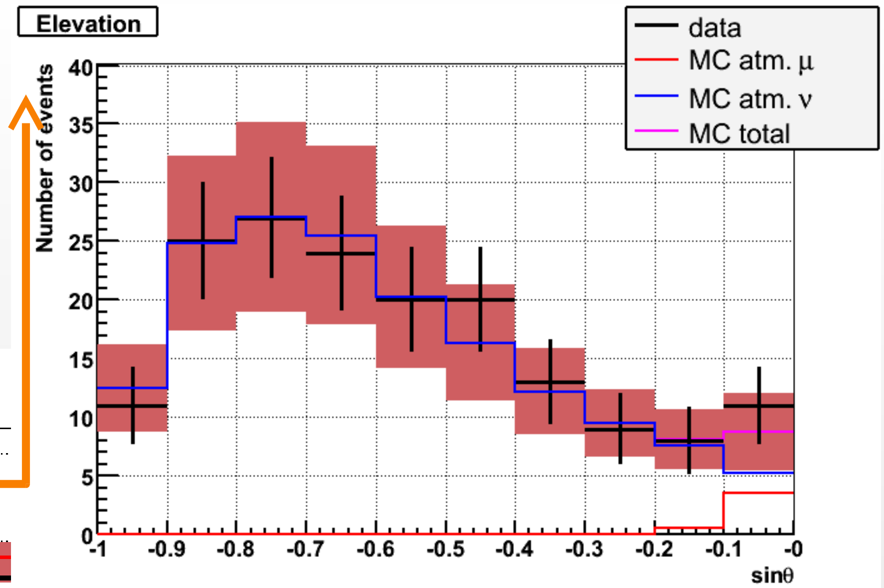
Summary of the results for the blue data (statistical error only)

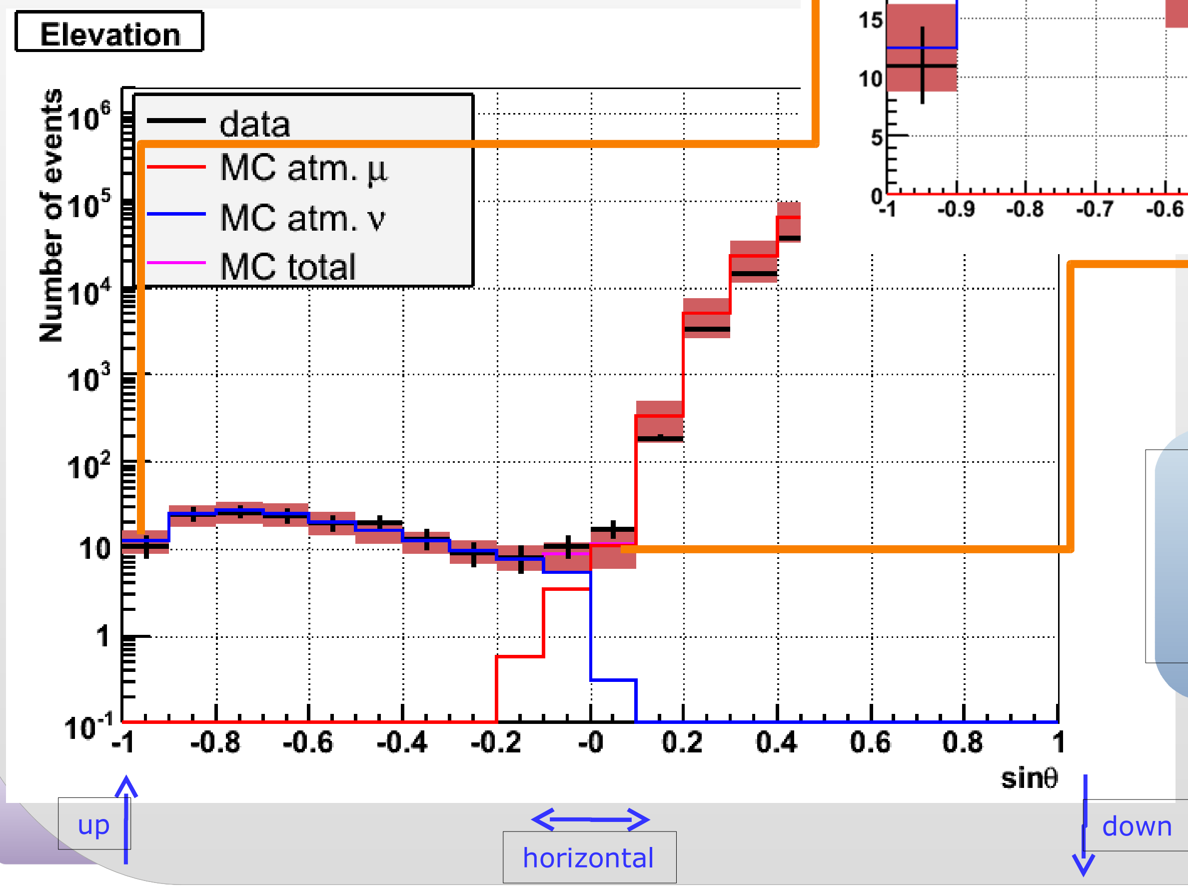
Epoch	λ_{att}^{eff} (in m)	λ_{abs} (in m)	λ_{sct}^{eff} (in m)
July 1998	60.6 ± 0.4	68.6 ± 1.3	265 ± 4
March 1999	51.9 ± 0.7	61.2 ± 0.7	228 ± 11
June 2000	46.4 ± 1.9	49.3 ± 0.3	301 ± 3

- OM efficiency at high angles w.r.t. to PMT axis is a source of systematics for downgoing muons.
- Measurements in lab (water tank) is difficult.
- Systematics evaluated through dedicated MC simulation.

- Measurements with autonomous lines.
- Special beacon runs being taken to re-measure it.
- Aim: 5% error level.
- Delicate measurement: different sources of systematics, deconvolution of absorption and scattering.

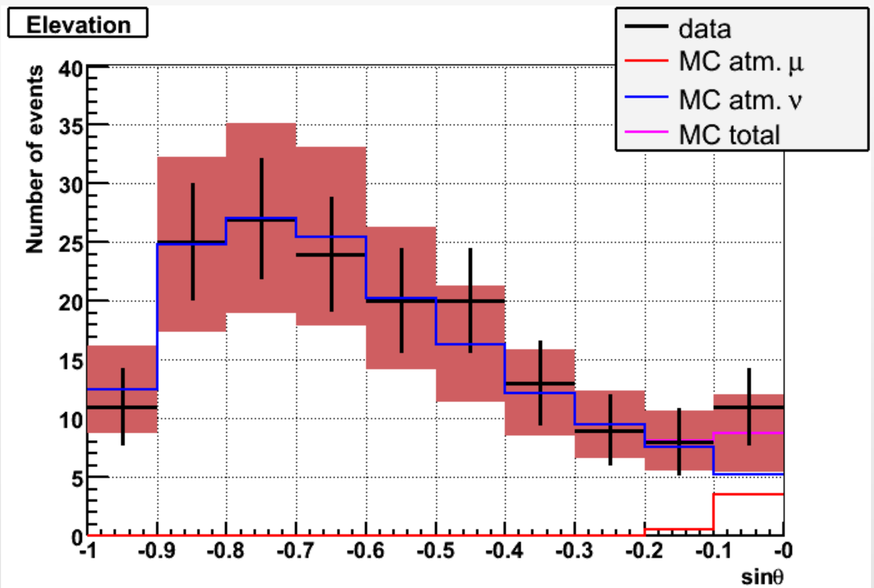
5 line data (2007)

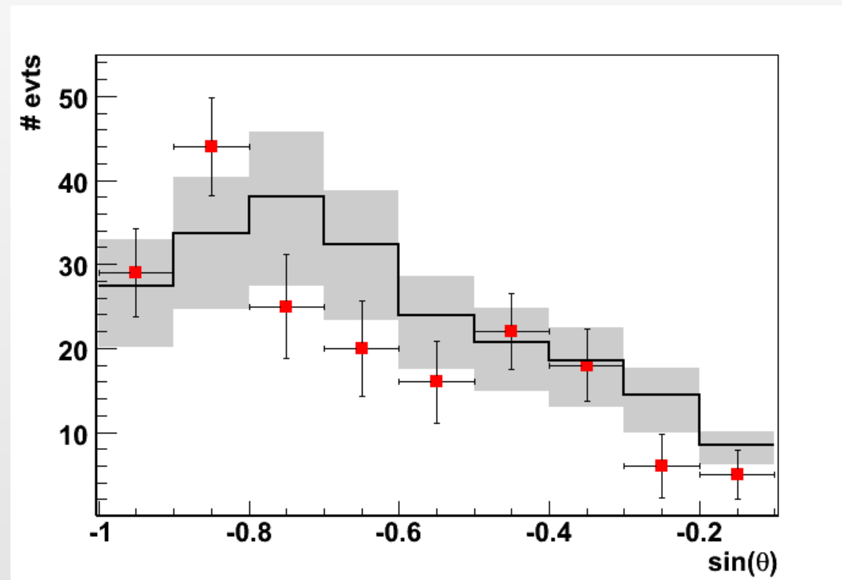




168 active days
168 upward events
(multi-line fit)

Two independent methods





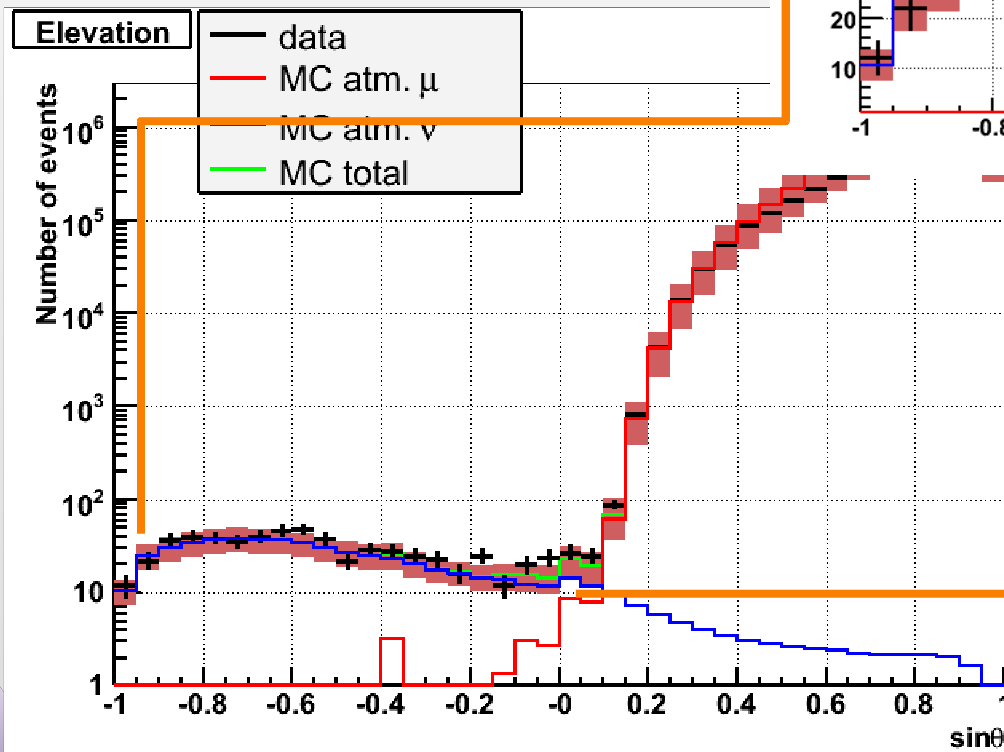
Observed: 168 events

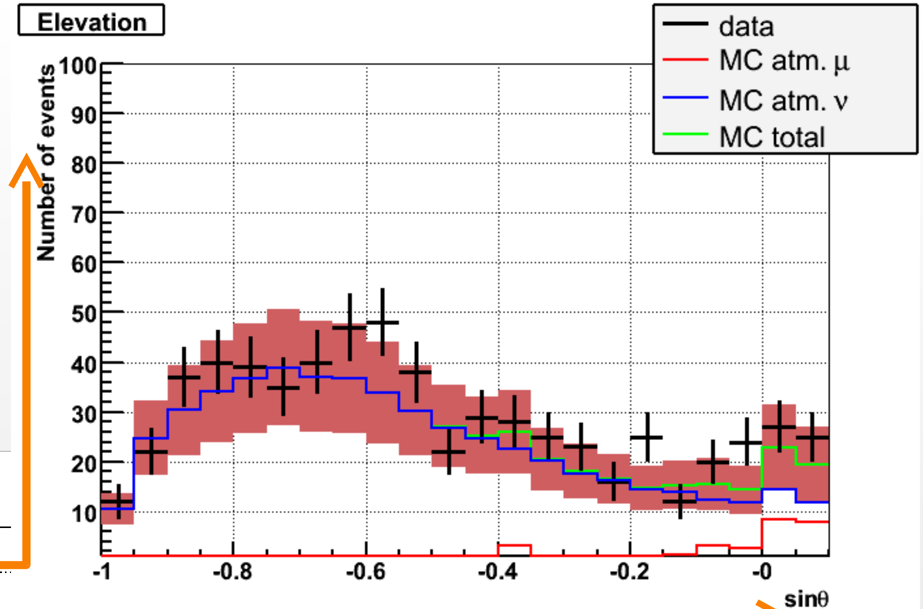
MC: 164±3 (stat)± 33(theor)±16 (syst)

Observed: 185 events

MC: 218± 4 (stat) ±41(theor) $^{+3}_{-42}$ (syst)

2008 data





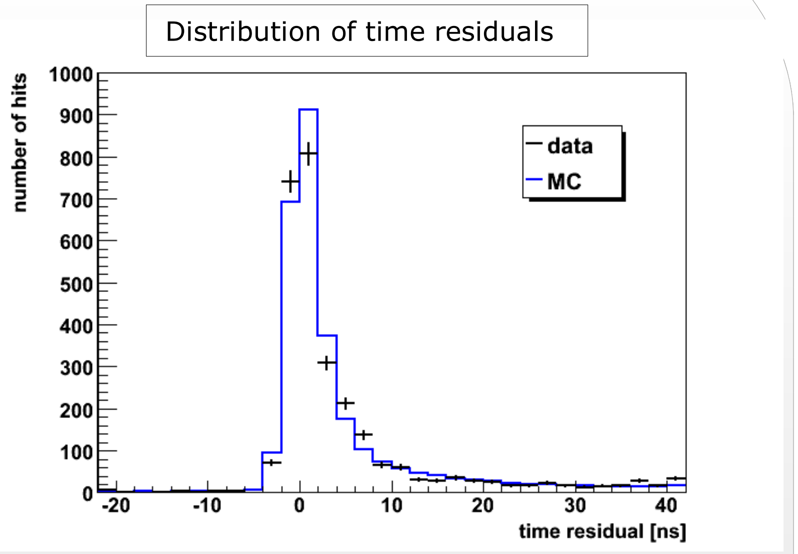
174 active days
582 upgoing events
(multi-line fit)

>103 reconstructed
neutrinos
(January 2009)

Point source search

· **Stringent cuts** to ensure low background and good resolution.

· Search applied to **25 selected sources**.



Source	DECL	AR	Nevents	pvalueBIN	pvalueUNBIN
PSR B1259-63	-63.8339	195.703	0	1	1
RCW 86	-62.4833	220.679	0	1	1
ESO 139-G12	-59.9414	264.414	0	1	1
HESS J1023-575	-57.7639	155.825	1	0.062	0.004
Cir X-1	-57.1667	230.171	0	1	1
HESS J1614-518	-51.82	243.579	1	0.086	0.088
PKS 2005-489	-48.8219	302.372	0	1	1
GX 339	-48.7897	255.704	0	1	1
RX J0852.0-4622	-46.3667	133	0	1	1
Centaurus A	-43.0191	201.364	0	1	1
RX J1713.7-3946	-39.75	258.25	0	1	1
PKS 0548-322	-32.2712	87.6692	0	1	1
H 2356-309	-30.6275	359.784	0	1	1
PKS 2155-304	-30.2217	329.721	0	1	1
Galactic Center	-29.0061	266.421	1	0.140	0.055
1ES 1101-232	-23.4919	165.909	0	1	1
W28	-23.335	270.425	0	1	1
LS 5039	-14.825	276.562	0	1	1
1ES 0347-121	-11.9908	57.3459	0	1	1
HESS J1837-069	-6.95	279.408	0	1	1
3C 279	-5.78917	194.046	1	0.110	0.030
RGB J0152+017	1.78861	28.1667	0	1	1
SS 433	4.98278	287.958	0	1	1
HESS J0632+057	5.80556	98.2416	0	1	1
IceCube HotSpot	11	153	0	1	1

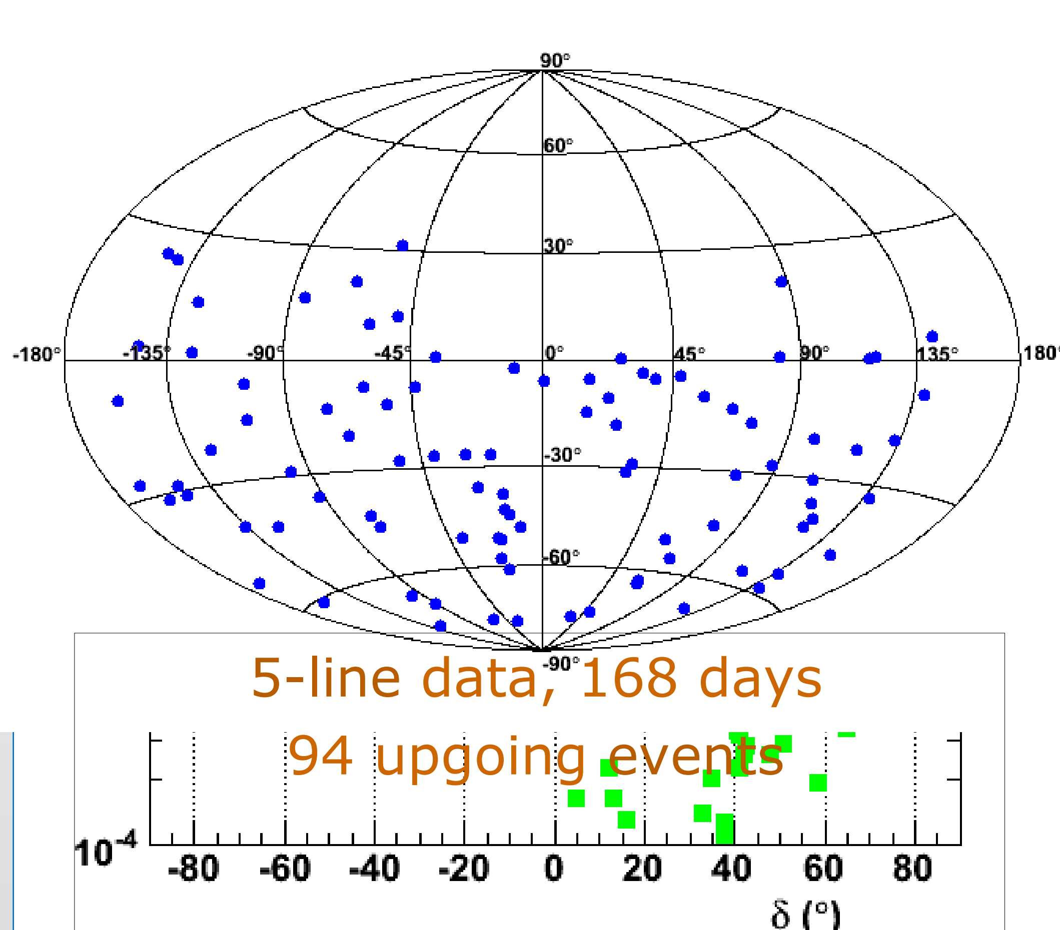
· Two **independent statistical methods** used : one binned and another unbinned.

· **Blinding** policy followed and several "challenges" performed on scrambled data before final analysis.

Point source search

List of 25 sources

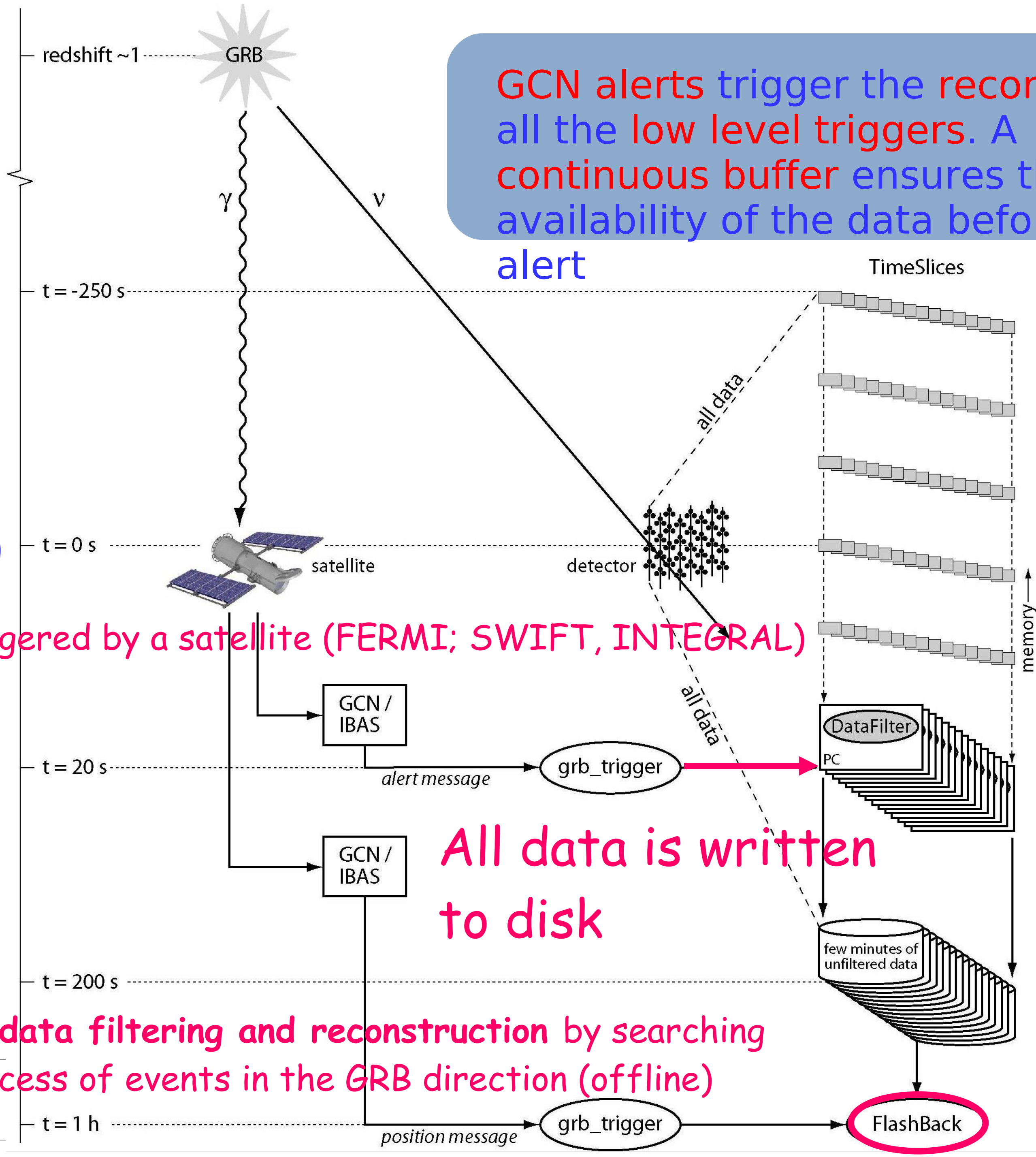
No significant excess found



5-line data, 168 days

94 upgoing events

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



t = -20 s

t = 0 s

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

t = 20 s

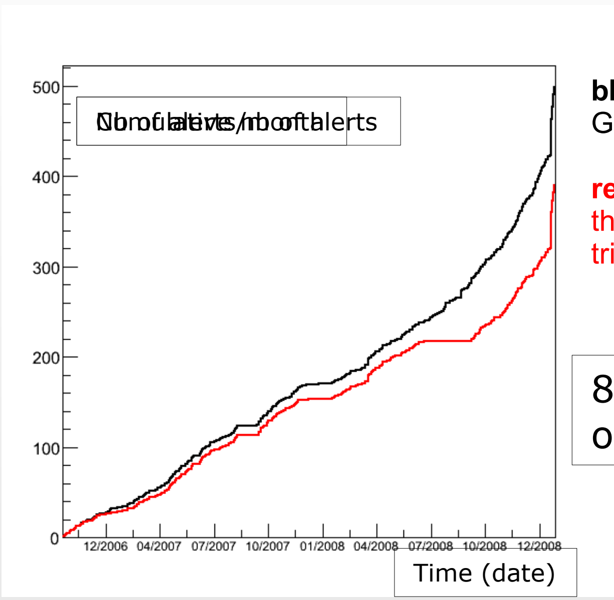
All data is written to disk

t = 200 s

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

t =

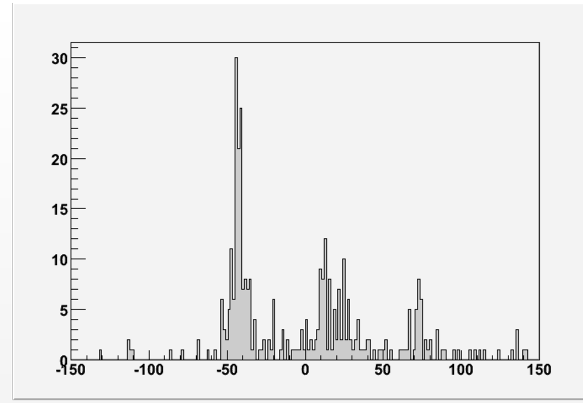
GRB



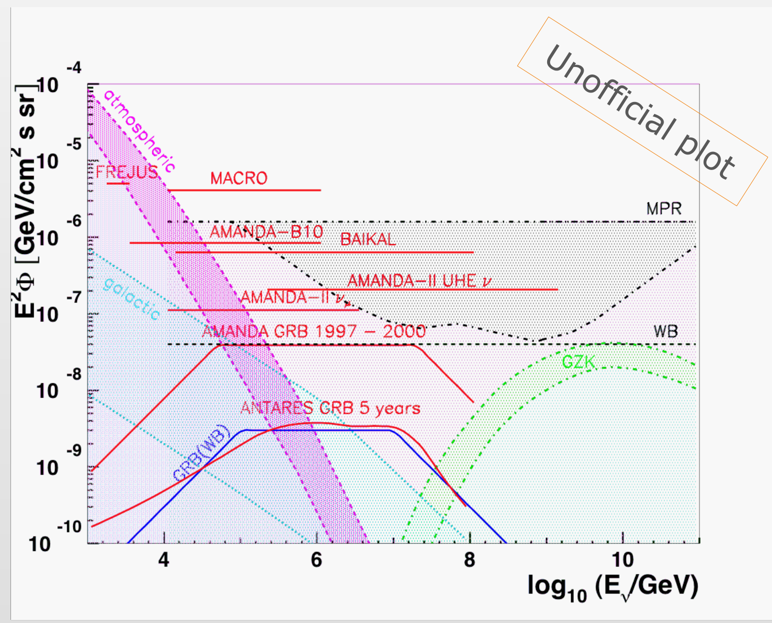
black:
GRB alerts received

red:
the ones Antares triggered on

8.6 TB on disk



Response time to alerts

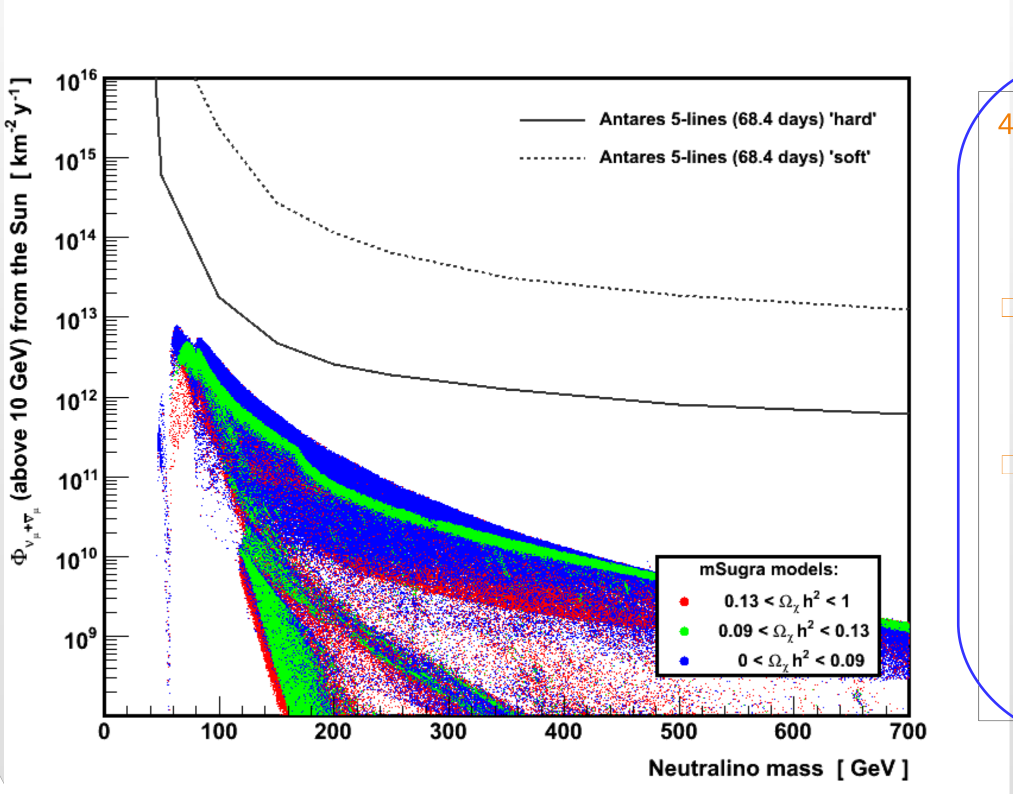


- 500 alerts from GCN 390 have been recorded (Jan´09)
- Two independent analyses are being performed for the 5-line data.
- An unblinding request is expected to take place very soon.

Signals are expected to be small but the limit on the GRB flux after 5 years skims the predictions of W&B

Dark matter search

Φνμ+νμ from the Sun

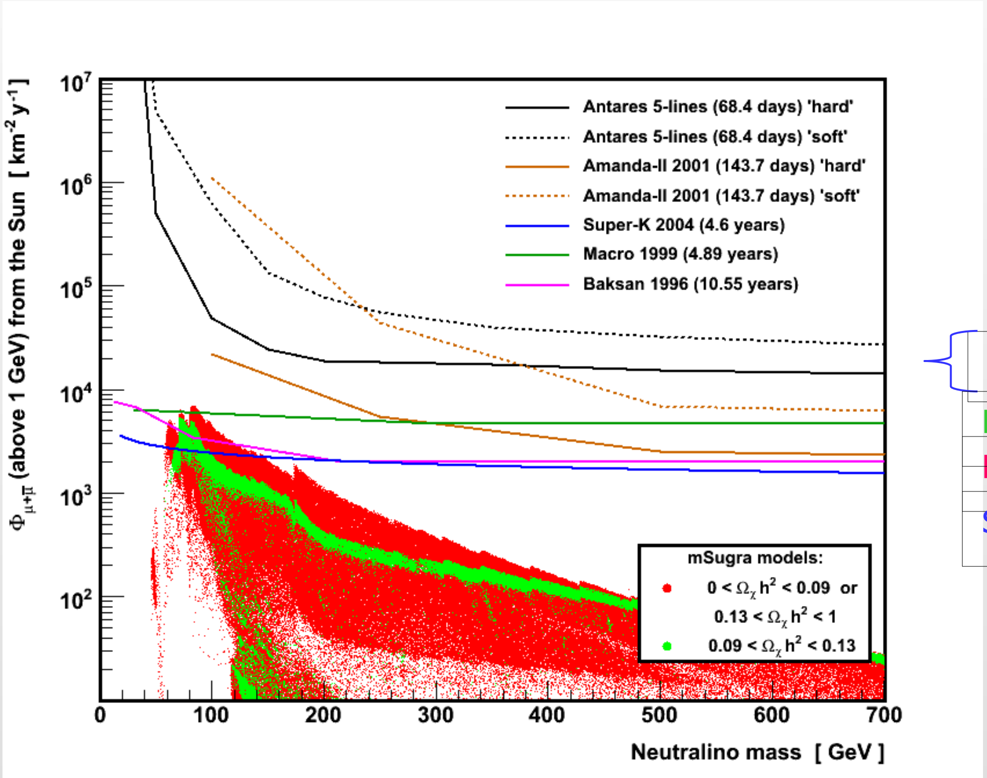


- 5-line data, 68.4 days
  168 days + 51% Sun under horizon + trigger corr.
- No excess observed
  (90% C.L. limits à la Feldman-Cousins)
- **mSugra model predictions**

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

Dark matter search

$\Phi_{\mu+\mu}$ from the Sun



ANTARES (5 lines, 68 days)

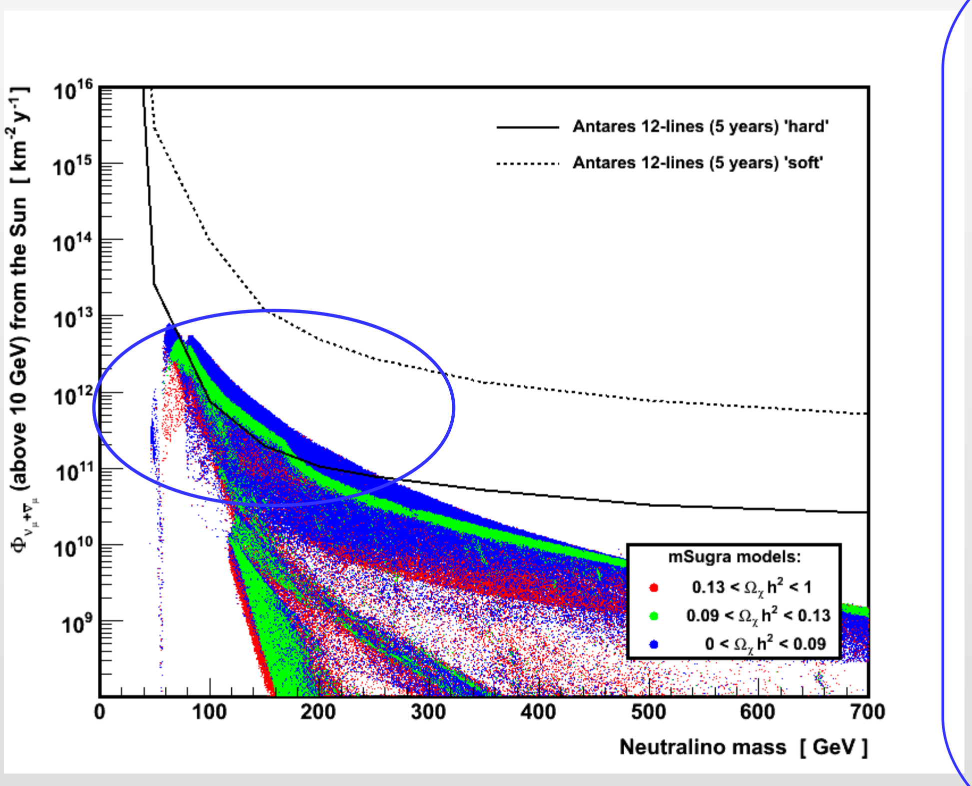
Macro (4.89 years)

Baksan (10.6 years)

SuperK (4.6 years)

Dark matter

4 Φνμ̄+νμ from the Sun



Simple extrapolation

12 lines, 5 years

- **Effective Area**

  12 lines instead of 5

  → factor = 12 / 5 = 2.4

- **Data taking**

  5 years (total data taking period)

  0.9 (data taking efficiency)

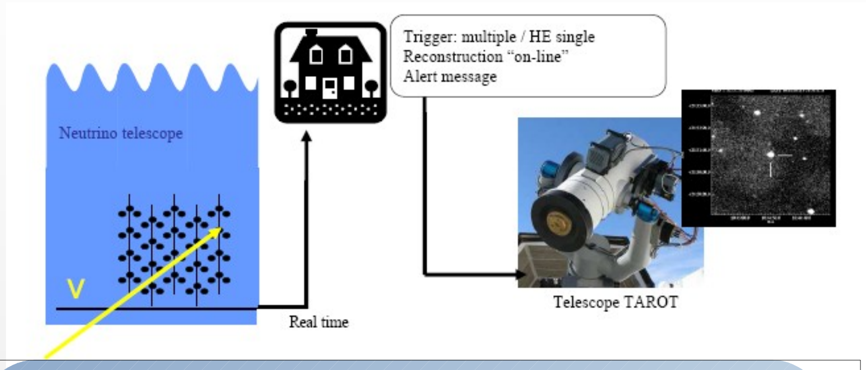
  0.8 (trigger deadtime)

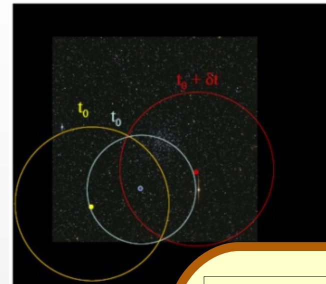
  0.5 (sun under horizon) = 657.45 effective days

  → factor = 657.45 / 68.4 = 9.6

Total factor = 2.4 * 9.6 = 23

Multi-messenger approach





Agreement with TAROT

Telescopes à Action Rapide pour l'Observation de Transients)

· TAROT: two 25 cm telescopes at Calern (France) and La Silla (Chile)

· FOV $1.86^0 \times 1.86^0$

· ~10 s repositioning after alert reception

ANTARES alert

· Two events with

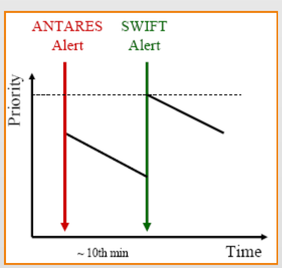
$\Delta\Omega < 3^0 \times 3^0$

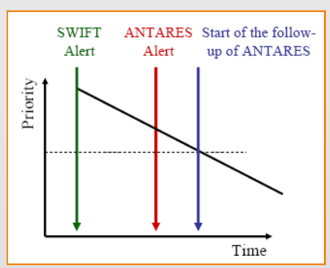
$\Delta t < 15$ min

· Rate(atm) = 0.05 yr-1

· Work is quite advance (on-line reconstruction and selection).

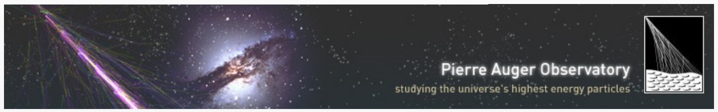
· Fake alerts have been sent to test the connection to TAROT.

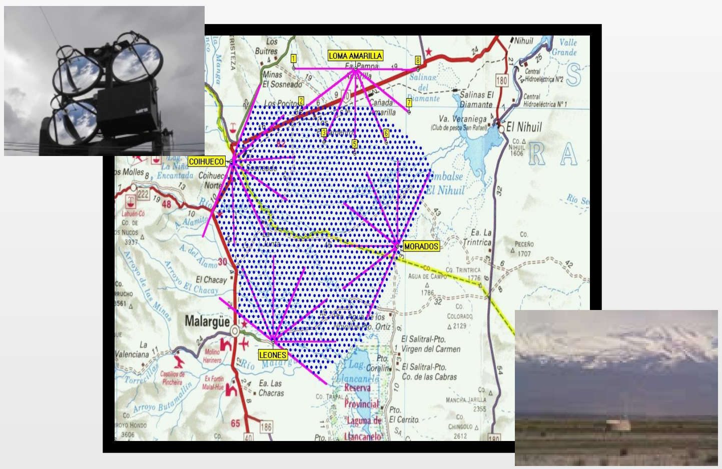


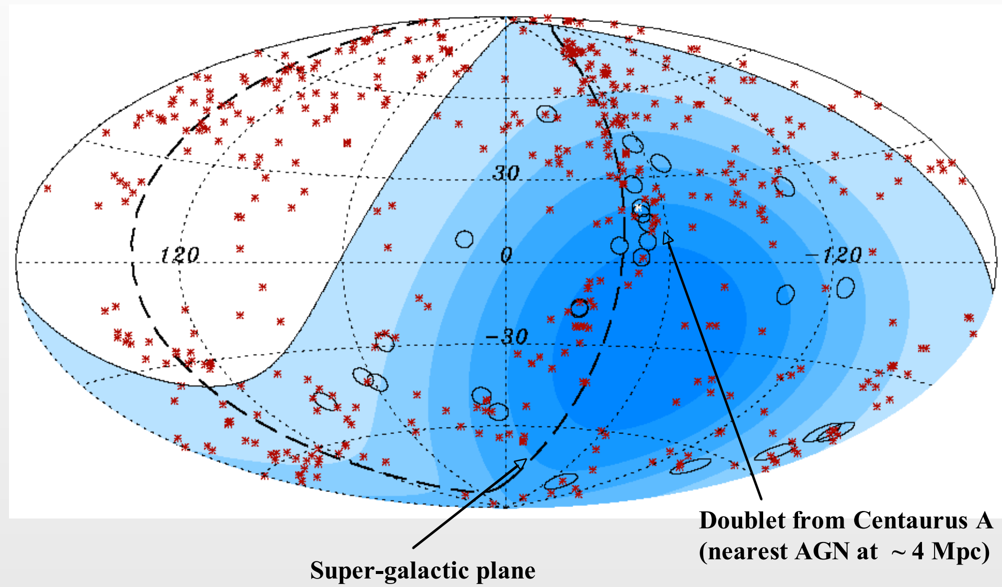


Priorities (decreasing with time) are set to alerts. SWIFT has the highest priority

Multi-messenger approach





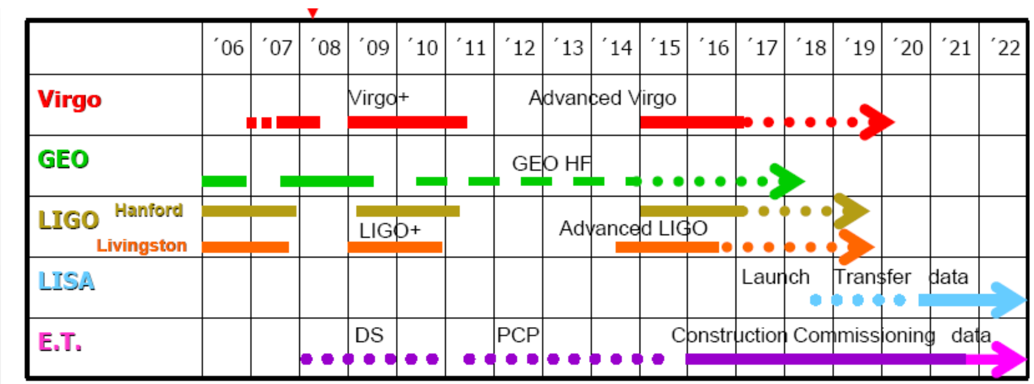


Pierre Auger Observatory

Ongoing talks on:
· restricted access to non-published data.
· rules for possible

Correlation of UHECRs with AGNs positions:
20 out of 27 CRs with E>57 EeV correlate (within 3.2o) with nearby AGNs from the Véron-Cetty&Véron catalogue
(292 AGNs with D < 75 Mpc).

Multi-messenger approach



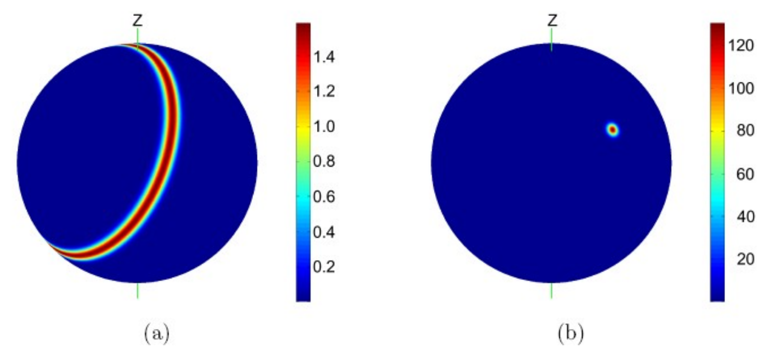
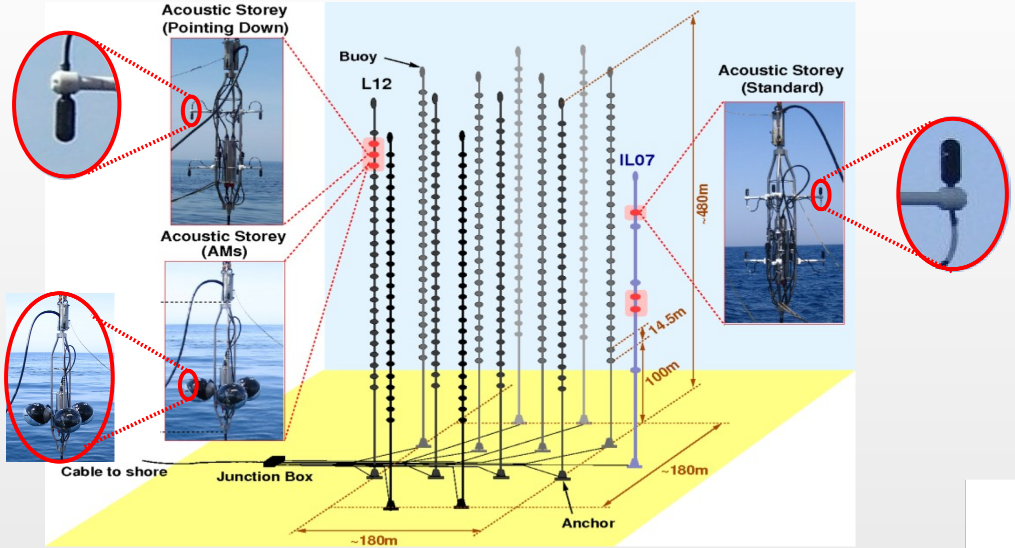
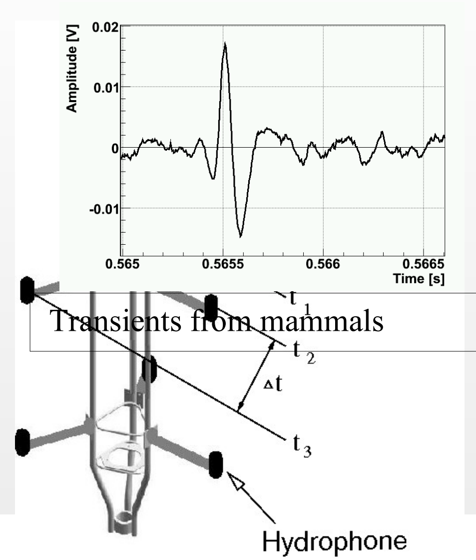


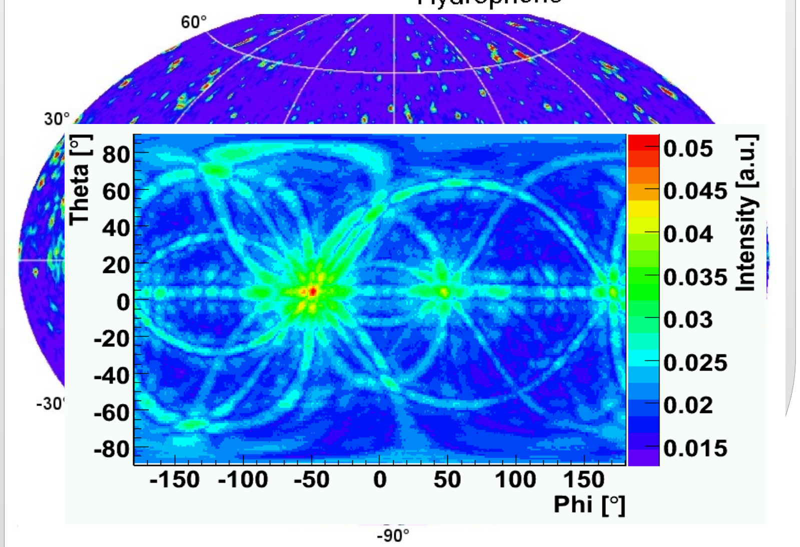
Figure 2. Examples of spatial probability distribution functions (SPDFs). (a) SPDF of a LIGO event with $\tau = 4\,\mathrm{msec}$ and $\delta\tau = 440\,\mu\mathrm{sec}$. (b) SPDF of an IceCube event with $\sigma_\nu = 2°$. The plots are shown in Earth based coordinates with the z-axis pointing along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

- Possible common sources (GRB-core collapse into BH; SGR – powerful magnetars; hidden sources)
- Sky regions in common
- Expected low signals, coincidences increase chances of detection

Acoustic detection

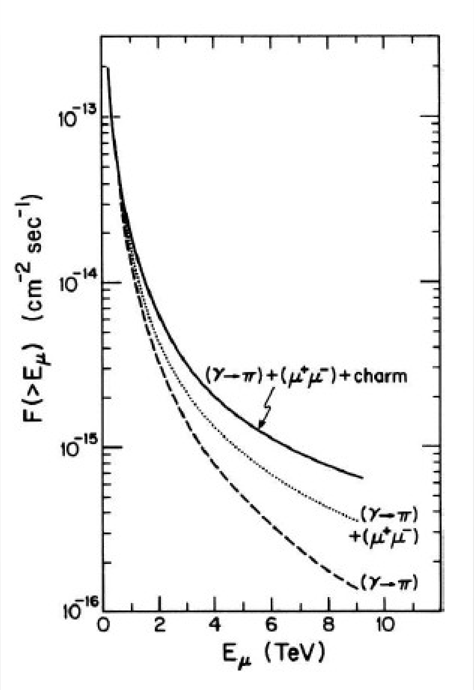






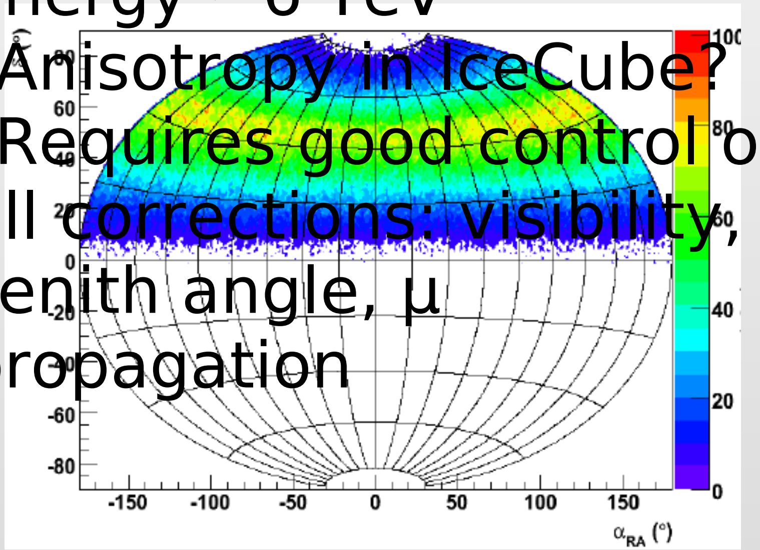
- AMADEUS comprises a series of hydrophones in IL and Line 12
- This is a test bench to study the feasibility of a large acoustic UHE neutrino detector
- Study of acoustic environment and backgrounds
- Methods to reconstruct direction (beamforming, time differences)

Other Analyses



Skymap of downgoing muons

· MILAGRO observes a large scale (~ x 10⁰) cosmic ray anisotropy (0.1%) at an average energy ~6 TeV



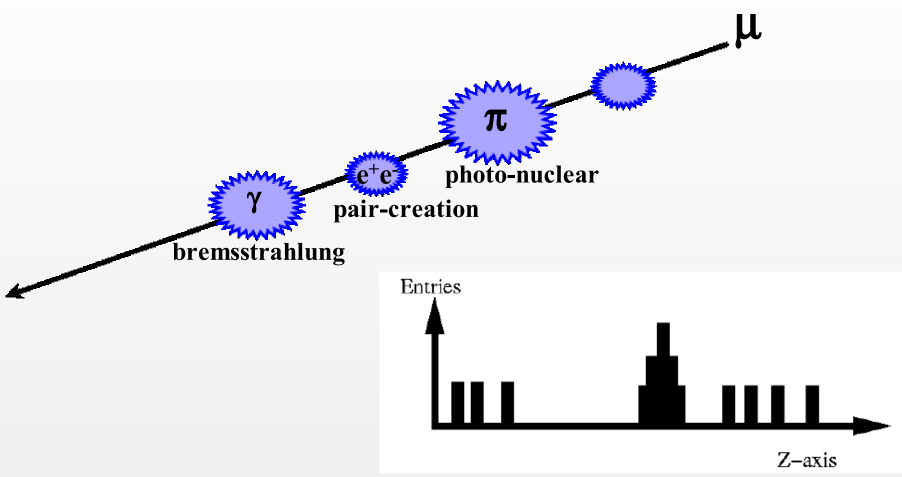
· Anisotropy in IceCube?

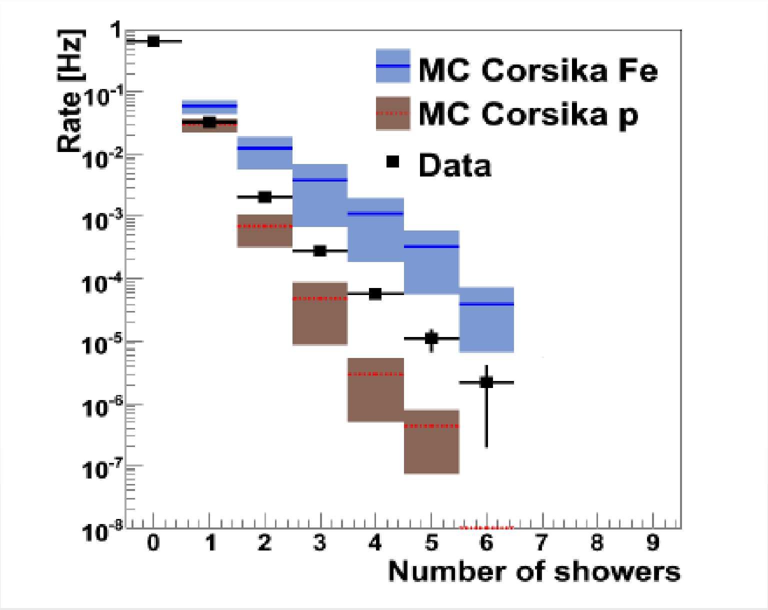
· Requires good control of all corrections: visibility, zenith angle, μ propagation

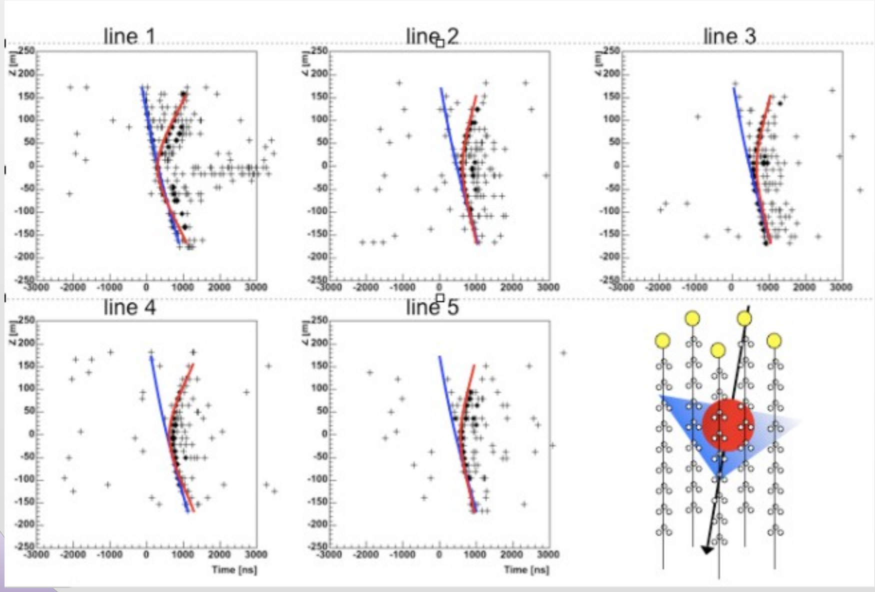
· Downgoing muons from **gammas** (direct pair production, through pions, etc)

· Can extend GRBs or SGR fluxes to TeV gammas, look for giant

Other Analyses



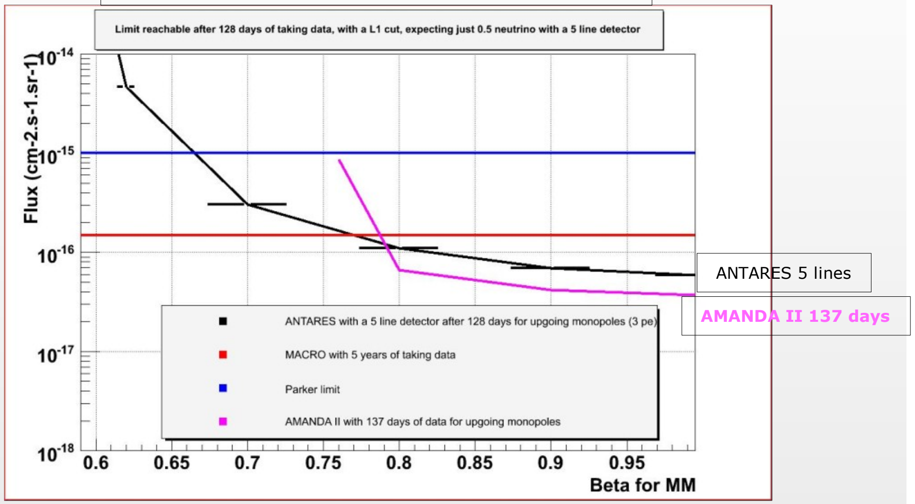


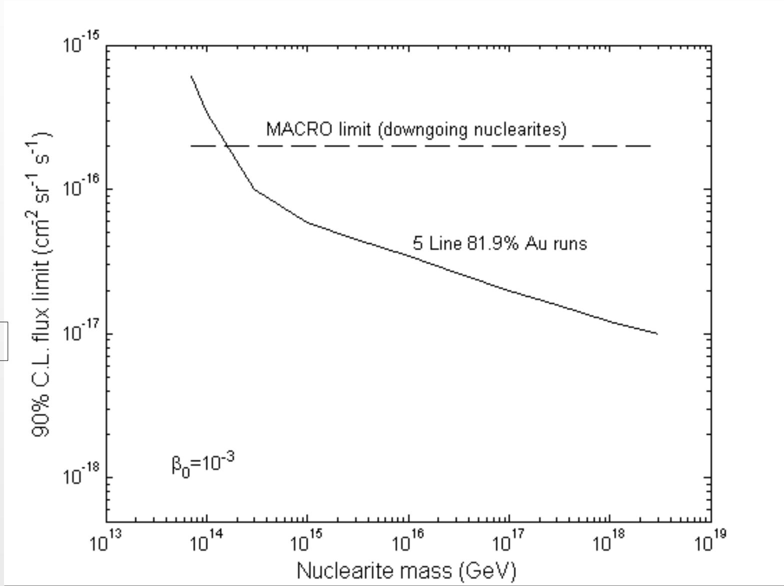


- **Chemical composition of cosmic rays**
- Algorithm to count showers along muon tracks has been developed

Other Analyses

ANTARES sensitivity to monopoles (5-line detector and 127 days)





- **Search of monopoles**
- Extremely high energy deposition
- Direct Cherenkov light for $\beta > 0.74$
- Through δ-rays for $\beta > 0.51$
- Monte Carlo generation done (study

- **Search of nuclearites** (strangelets, quark nuggets, Q-balls).
- Very characteristic signature:an extended source of photons “heated wire”
- Analysis ongoing. Good prospects for limits

Summary

- The ANTARES telescope took data in its 5-line configuration in 2007 and is taking data with 10 or more lines since Dec 2007.
- Work on the full understanding of the detector is proceeding well. Downgoing tracks are especially useful (and challenging) for this. Work on reducing systematics is ongoing.
- More than 1000 upgoing events have been reconstructed (Jan 09). Agreement with MC is good, further work is needed to ascertain that the expected performances have been reached (angular resolution, effective area, etc).
- The search for point-like sources with the 5-line data has provided the more stringent upper limit for the southern sky. Work on ≥10-line detector is ongoing.
- The multi-messenger approach is being strongly pursued in ANTARES: LIGO/VIRGO, GCN, TAROT, Auger). For expected low level signals this is a must.
- While the deployment of a still larger telescope in the northern hemisphere (KM3NeT) takes place, ANTARES could give some surprises.

Backup slides

Methods of point-like sources search

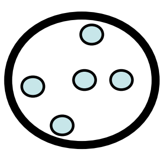
- The **background** from atmospheric neutrinos and muons will be **dominant**.
- It is crucial to have an **algorithm** able to **point out the accumulation** of the signal events over this background.
- The background is right ascension independent and declination dependent.

ANTARES:

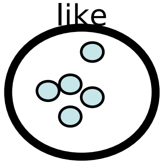
Very good angular resolution: < 0.3º for Eν > 10 TeV.

Sources are visible up to δ = 47º.

GC is visible (63% of the time).

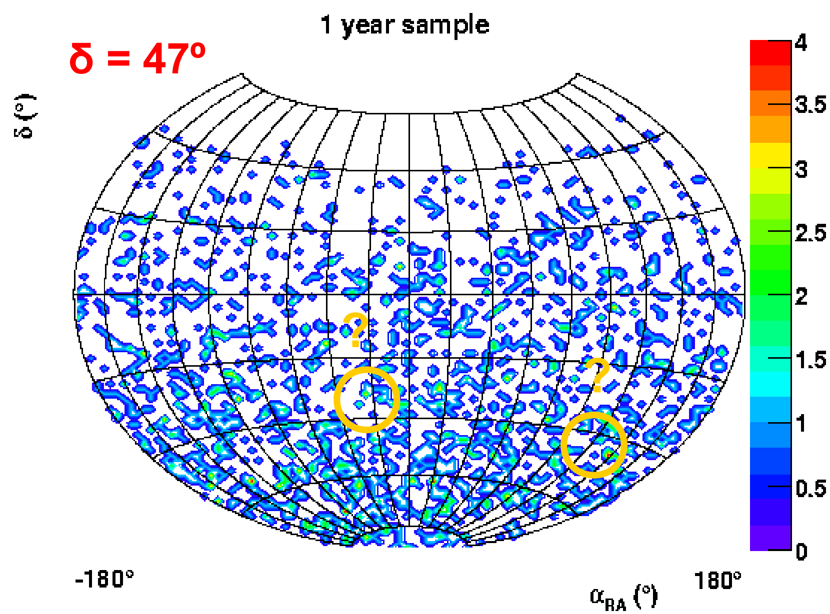


Background-like



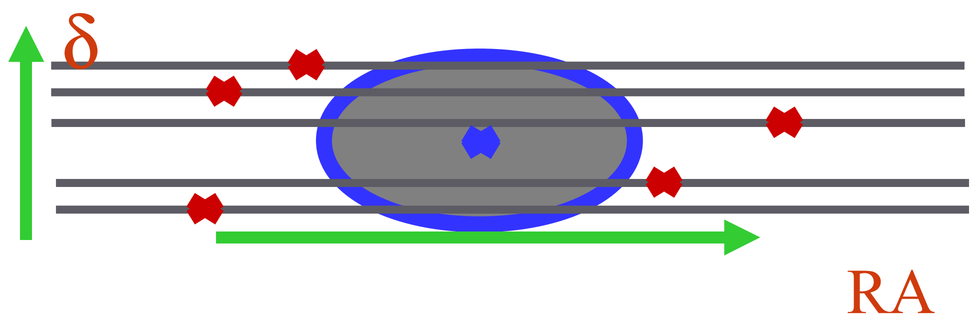
Signal-like

- **Binned** methods:
  - Grid (square shape).
  - **Cone (circular shape).**
- **Unbinned** methods:
  - ML ratio.
  - **EM.**



BIN: Cone method

- In the **all sky** search each event is taken as the cone centre.
- In a **fixed-source** search the source position is taken as the cone centre.
- The cone size is optimized to get the better signal/background ratio: **MDF** (all sky search) and **MRF** (fixed-source search).
- The **probability** for the background to produce a given number of events can be computed **analytically**.



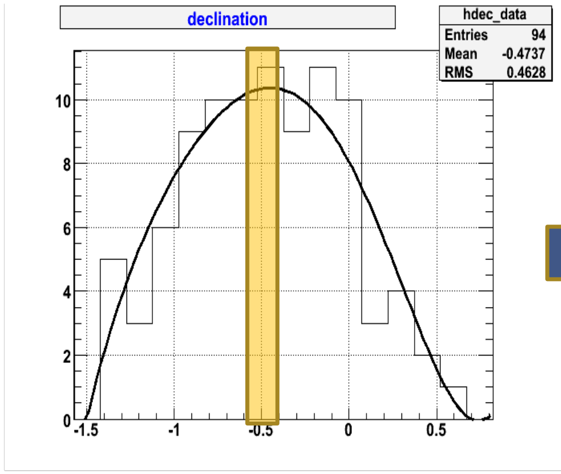
$$P_i = \sum_{n=N_0}^{N_{total}} \left(\sum_{\sigma \in C_n^{N_{total}}} \left(\prod_{j \in \sigma} p_{j,i} \times \prod_{k \notin \sigma} (1 - p_{k,i}) \right) \right)$$

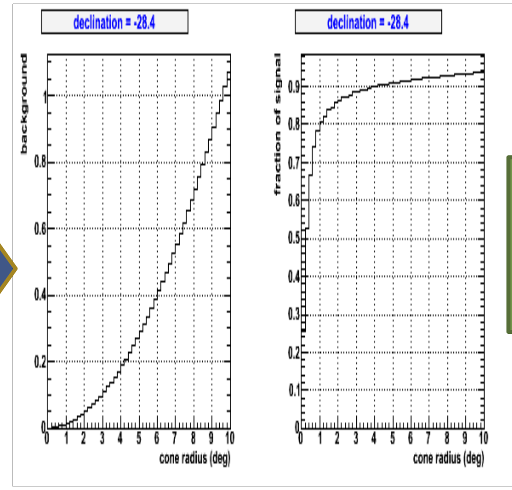
Probability for the event *j* to be inside the cone defined for the event *i.*

Pi is the probability for the background to produce the observed number of events **N0** or more (up to the maximum number **Ntotal**). 2 is each element of the set **CnNtotal** of combinations of **Ntotal** elements in groups of n elements.

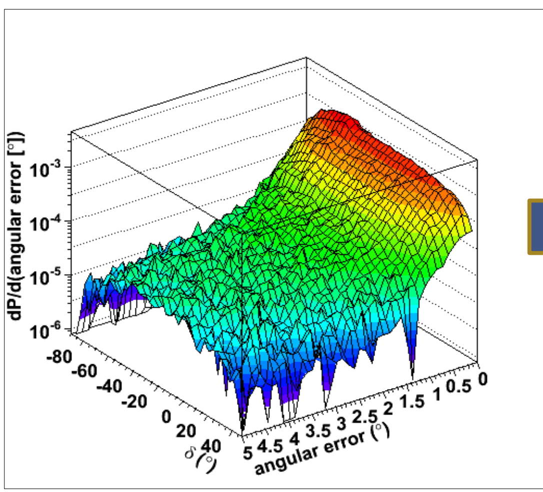
Signal & Background

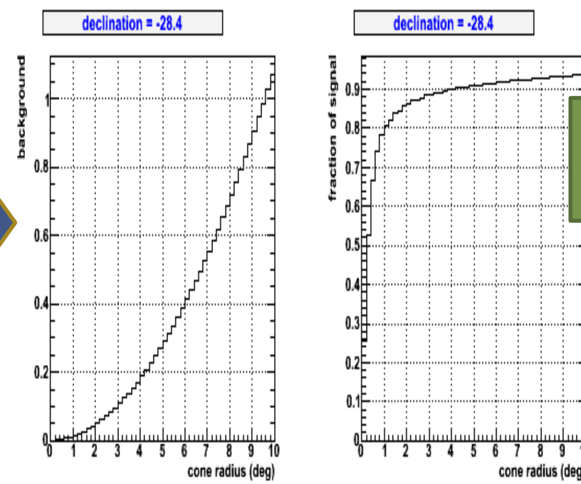
4 BIN: Cone method





The number of background events (nb) inside the cone is estimated from the real data.





The PSF is obtained from MC assuming a flux of E-2.

Cone size optimization

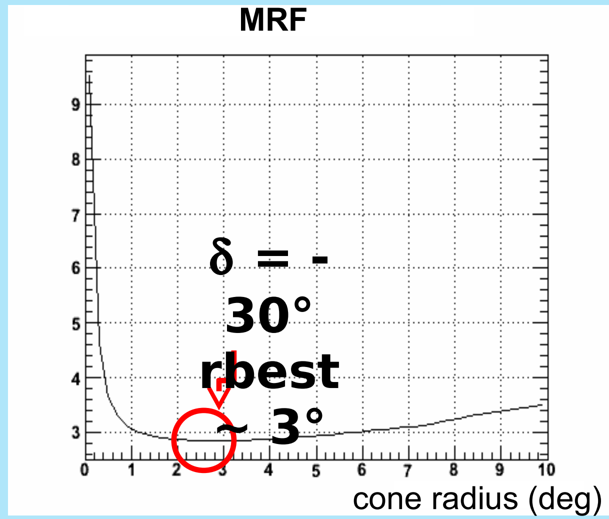
BIN: Cone method

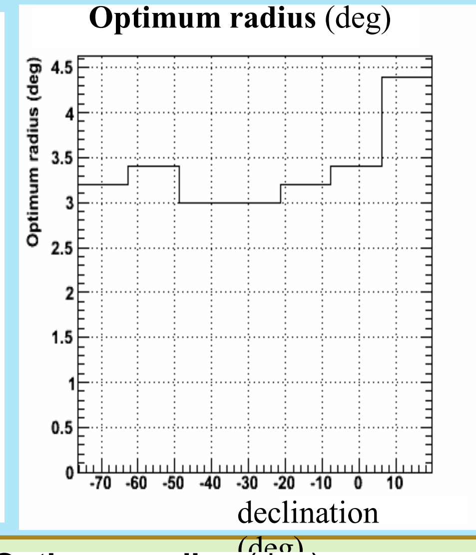
$$\bar{\mu}_{90}(n_b) = \sum_{n_{obs}}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{(n_{obs})!} \exp(-n_b)$$

Upper limit Poisson weight

$$\mathrm{MRF} = \frac{\bar{\mu}_{90}}{n_s}$$

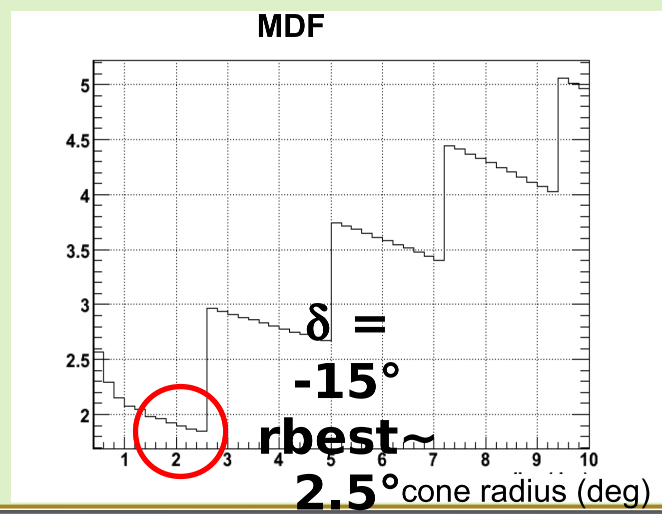
Model Rejection Factor used for **fixed-source** search

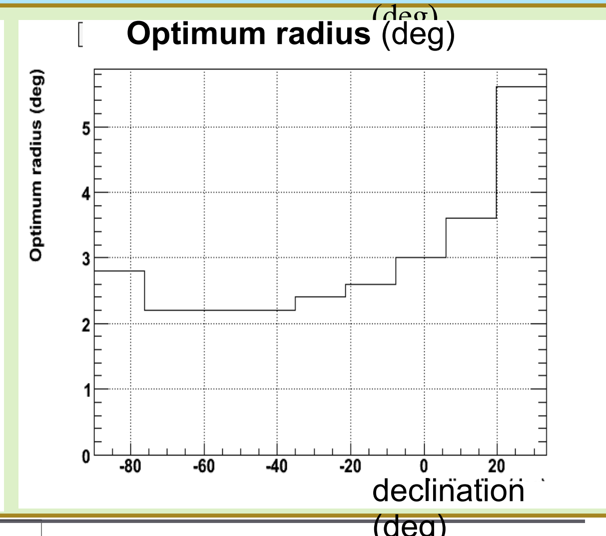




Model Discovery Factor used for **all-sky** search

$$MDF = \frac{\mu(n_b, CL, SP)}{n_s}$$





UNBIN: EM algorithm

- EM is a general approach to maximum likelihood estimation for finite mixture models.
- Mixture models: different groups of data are described by different density components.

$$p(\mathbf{x}) = \sum_{j=1}^{g} \pi_j p(\mathbf{x}; \boldsymbol{\theta}_j)$$

g = number of mixture models

πi = mixture proportions, where $\sum_{j=1}^{g} \pi_j = 1$

Previous step: change from incomplete to complete data set.

$$\{\mathbf{x}\} \quad \mathbf{x}_i = (\alpha_i^{\mathrm{ra}}, \delta_i) \quad \longrightarrow \quad \{y\} \quad \mathbf{y}_i = (\alpha_i^{\mathrm{ra}}, \delta_i, \mathbf{z}_i)$$

The vector **zi** is a class indicator that indicates if the event *i* belongs to the background or the source.

Expectation step

- **Start with a set of initial parameters Ψ(m) = {π1,π2,μ,Σ}**
- **Expectation of the complete data log-likelihood, conditional on the observed data {x}**

$$\mathrm{Q}(\boldsymbol{\Psi}, \boldsymbol{\Psi}^{(m)}) = \mathrm{E}[\log(g(\{\mathbf{y}\}; \boldsymbol{\Psi})) \mid p(\{\mathbf{x}\}; \boldsymbol{\Psi}^{(m)})]$$

Maximization step

- **Find Ψ = Ψ(m + 1) that maximizes Q(Ψ, Ψ(m))**

Signal & background

UNBIN: EM algorithm

- A simple pre-clustering selects a set of candidates by using a cone of 1.25º around each event of the sample.

Background **Signal**

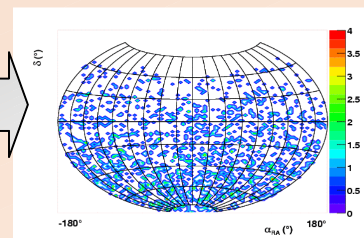
$$p(\mathbf{x}) = \pi_{BG} P_{BG}(\delta) + \pi_S P_S(\mathbf{x};\boldsymbol{\mu},\boldsymbol{\Sigma})$$

position of event: x = (αRA, δ)

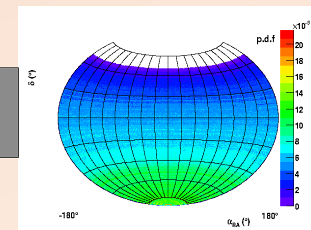
bg: only δ

signal : αRA, δ

Sample



Background from real RA-scrambled data



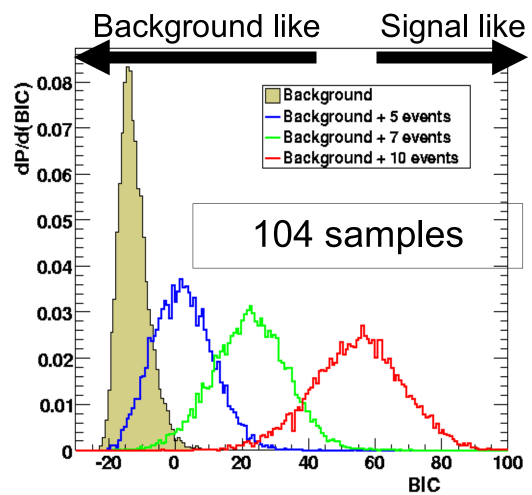
Signal pdf model 2D-Gaussian

Samples simulation:

- 104 samples simulated.
- Each sample corresponds to the lifetime of 2007 data period.

- The **Bayesian Information Criterion (BIC)** is chosen as the test statistic of the method.

$$\mathrm{BIC}_k = 2\log p(D\,|\,\hat{\Psi}_k, M_k) - v_k \log(n)$$



RESULTS

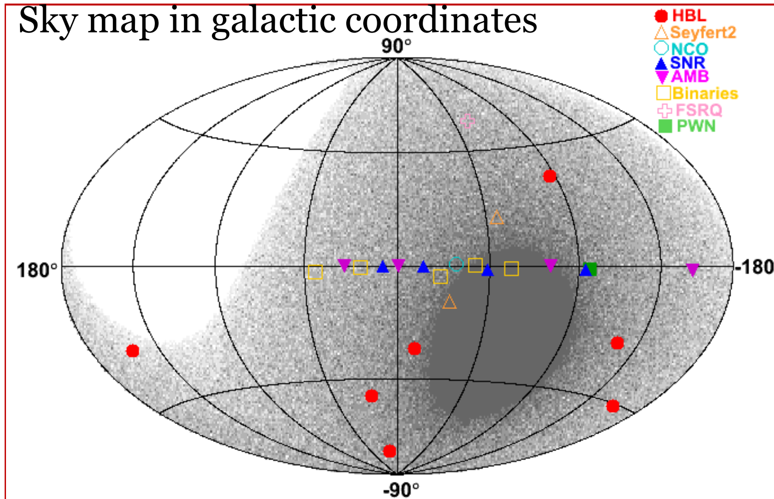
Fixed-source search

RESULTS

24 sources in the ANTARES field of view have been selected among the most promising neutrino source candidates (galactic and extragalactic) for the 5Line point-like source analysis.

Name	Class	Equatorial coordinates RA	Equatorial coordinates δ	Galactic coordinates l	Galactic coordinates b	Vis.
Galactic Sources						
HESS J0632-057	AMB	$6^h\,32^m\,58^s$	$5^\circ\,48'\,20''$	205.66	-1.44	0.46
RX J0852.0-4622	SNR	$8^h\,52^m\,00^s$	$-46^\circ\,22'\,00''$	266.28	-1.24	0.91
HESS J1023-575	AMB	$10^h\,23^m\,18^s$	$-57^\circ\,45'\,50''$	284.19	-0.39	1
PSR B1259-63	Binary Pulsar	$13^h\,02^m\,49^s$	$-63^\circ\,50'\,02''$	304.19	-0.99	1
RCW 86	SNR	$14^h\,42^m\,43^s$	$-62^\circ\,29'\,00''$	315.79	-1.46	1
Cir X-1	XRB	$15^h\,20^m\,41^s$	$-57^\circ\,10'\,00.26''$	322.12	0.04	1
HESS J1614-518	NCO	$16^h\,14^m\,19^s$	$-51^\circ\,49'\,12''$	331.52	0.58	1
GX 339	XRB	$17^h\,02^m\,49^s$	$-48^\circ\,47'\,23''$	338.94	-4.33	0.99
RX J1713.7-3946	SNR	$17^h\,13^m\,00^s$	$-39^\circ\,45'\,00''$	347.28	-0.38	0.75
Galactic Center	AMB	$17^h\,45^m\,41^s$	$-29^\circ\,00'\,22''$	359.95	-0.05	0.66
W28	SNR	$18^h\,01^m\,42^s$	$-23^\circ\,20'\,06''$	6.66	-0.27	0.62
LS 5039	XRB	$18^h\,26^m\,15^s$	$-14^\circ\,49'\,30''$	16.90	-1.28	0.57
HESS J1837-069	AMB	$18^h\,37^m\,38^s$	$-6^\circ\,57'\,00''$	25.18	-0.12	0.52
SS 433	XRB	$19^h\,11^m\,50^s$	$4^\circ\,58'\,58''$	39.69	-2.24	0.48
extra-Galactic Sources						
RGB J0152+017	HBL	$1^h\,52^m\,40^s$	$1^\circ\,47'\,19''$	152.38	-26.61	0.49
1ES 0347-121	HBL	$3^h\,49^m\,23^s$	$-11^\circ\,59'\,27''$	201.93	-45.71	0.55
PKS 0548-322	HBL	$5^h\,50^m\,40.6^s$	$-32^\circ\,16'\,16.4''$	237.56	-26.14	0.69
1ES 1101-232	HBL	$11^h\,03^m\,38^s$	$-23^\circ\,29'\,31''$	273.19	33.08	0.62
3C 279	FSRQ	$12^h\,56^m\,11^s$	$-5^\circ\,47'\,21''$	305.10	57.06	0.51
Centaurus A	Sy2	$13^h\,25^m\,27.6^s$	$-43^\circ\,01'\,08.8''$	309.52	19.46	0.81
ESO 139-G12	Sy2	$17^h\,37^m\,39.5^s$	$-59^\circ\,56'\,29''$	334.04	-13.77	1
PKS 2005-489	HBL	$20^h\,09^m\,29^s$	$-48^\circ\,49'\,19''$	350.39	-32.61	1.
PKS 2155-304	HBL	$21^h\,58^m\,53^s$	$-30^\circ\,13'\,18''$	17.74	-52.25	0.67
H 2356-309	HBL	$23^h\,59^m\,08^s$	$-30^\circ\,37'\,39''$	12.84	-78.04	0.67

Sky map in galactic coordinates



24 selected sources
+
IceCube Hot Spot
(δ= 11° α = 153°)

Sky coverage of 3%

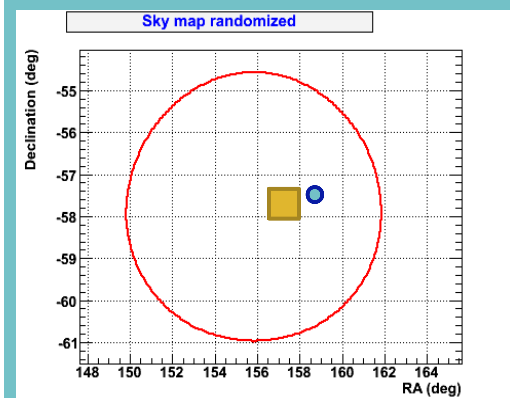
Fixed-source search

RESULTS

The **p-value** is the probability of the background to produce the measured (or higher) **observable** (**BIC** for the EM algorithm or **nevents** for the con method).

DECL	AR	Nevents	pvalueBIN	pvalueUNBIN
-63.8339	195.703	0	1	1
-62.4833	220.679	0	1	1
-59.9414	264.414	0	1	1
-57.7639	155.825	1	0.062	0.004
-57.1667	238.171	0	1	1
-51.82	243.579	1	0.086	0.088
-48.8219	302.372	0	1	1
-48.7897	255.704	0	1	1
-46.3667	133	0	1	1
-43.0191	201.364	0	1	1
-39.75	258.25	0	1	1
-32.2712	87.6692	0	1	1
-30.6275	359.784	0	1	1
-30.2217	329.721	0	1	1
-29.0061	266.421	1	0.140	0.055
-23.4919	165.909	0	1	1
-23.335	270.425	0	1	1
-14.825	276.562	0	1	1
-11.9908	57.3459	0	1	1
-6.95	279.408	0	1	1
-5.78917	194.046	1	0.110	0.030
1.78861	28.1667	0	1	1
5.80556	98.2416	0	1	1
4.98278	287.958	0	1	1
11	153	0	1	1

The lowest value corresponds to a **p-value pre-trial of 2.8σ** found with UNBINNED method.
It is expected in 10% of the experiments when looking at 25 sources (post-trial probability).

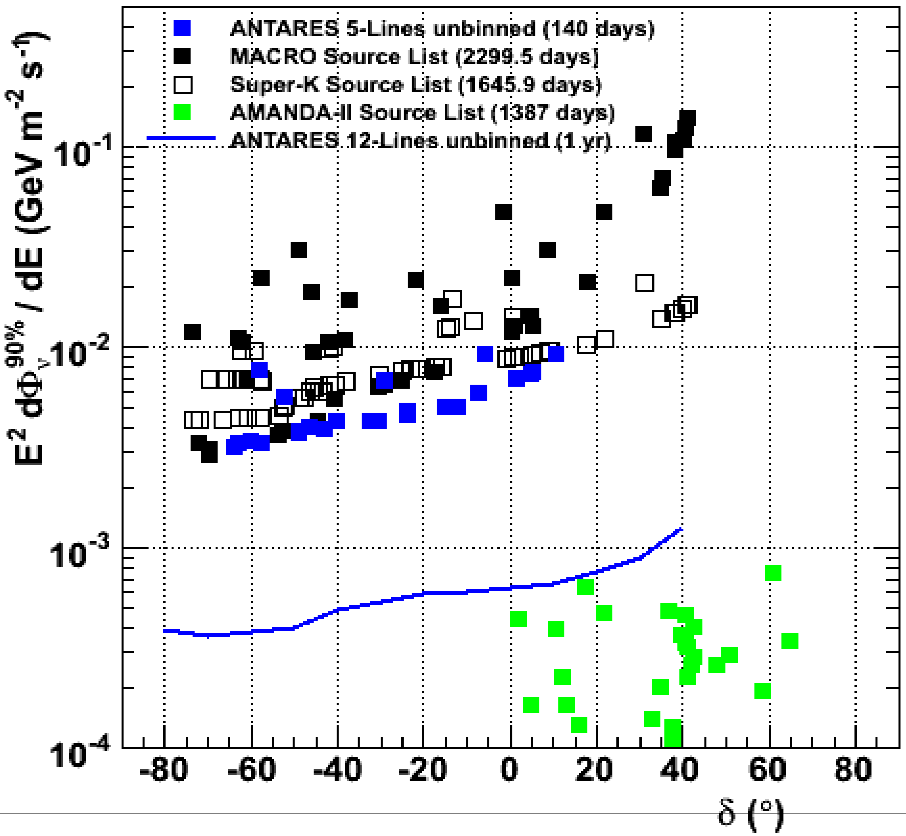


the position of the event very close to the source location.

Fixed-source search

RESULTS

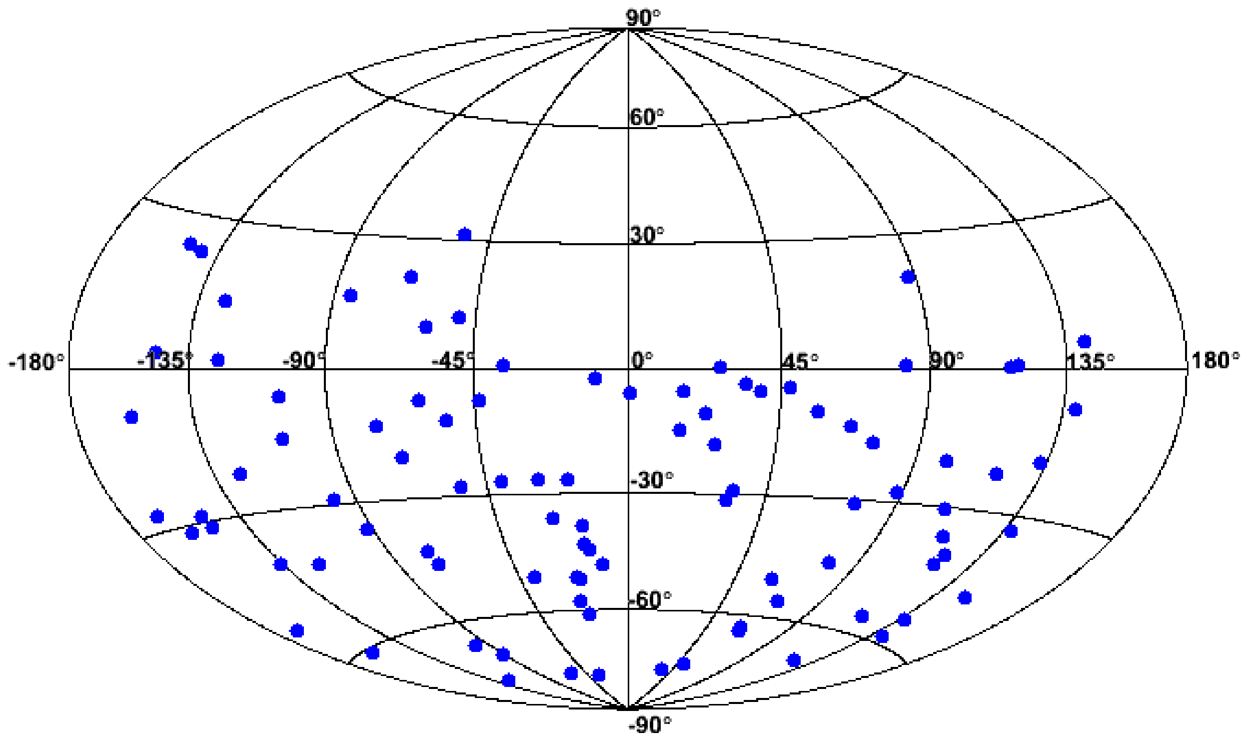
- Upper limits obtained with 2007 data (5 lines), compared with 1 year of complete detector (12 lines) and other experiments.



All-sky search

RESULTS

- Sky map with the 94 events selected for point-like source analysis with 2007 data.



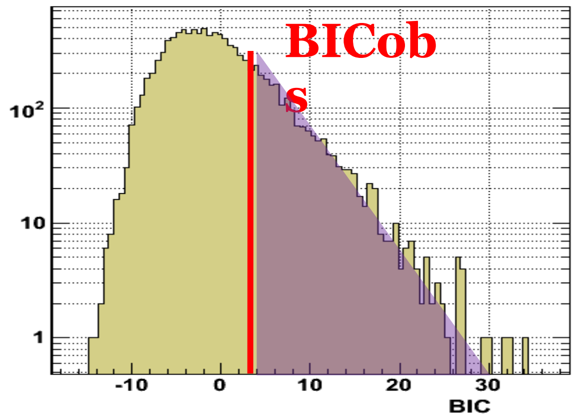
First neutrino sky map of ANTARES

All-sky search

RESULTS

EM algorithm

BIC distribution of only background



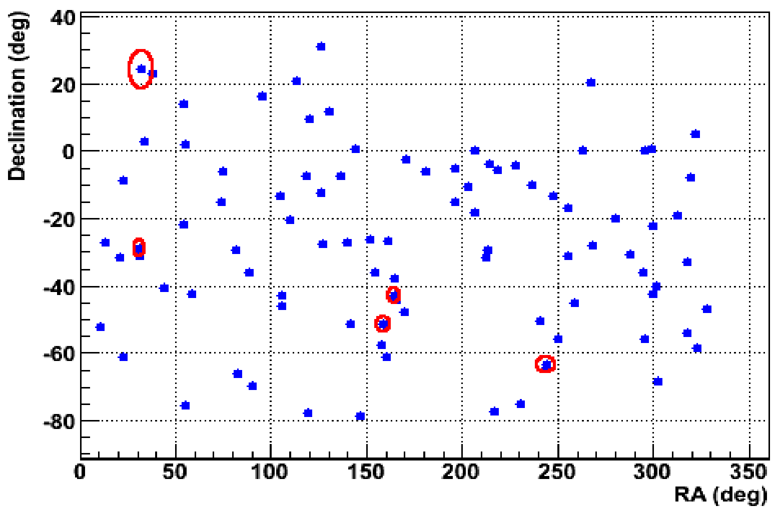
In our sample :

BICobs = 1.4 (highest value)

p-value = 0.3 (**1σ** excess)

(δ = -63.7º RA =243.9º)

No significant excess was found



Cross-check: **Cone method**

δ	RA	Nevents	PBIN
-28.8	**31**	**1**	**0.053**
-42.7	**164**	**1**	**0.050**
24.2	**32**	**1**	**0.069**
-51.4	**159**	**1**	**0.052**
-63.38	**244**	**1**	**0.055**