# Time integrated search for point sources of cosmic neutrinos with the ANTARES telescope

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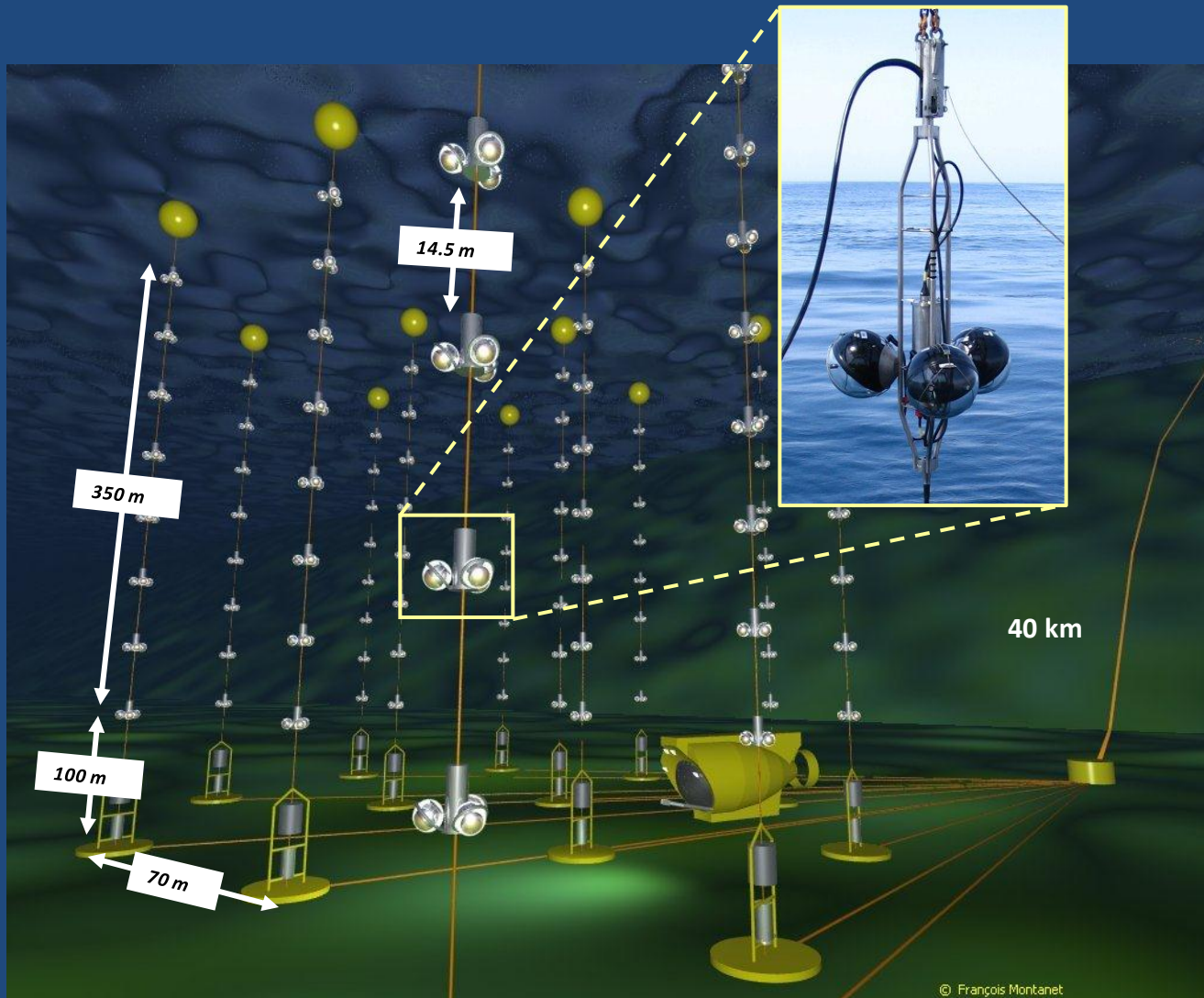
12/10/2011

* on behalf of the ANTARES collaboration

# The next 15 minutes

① The ANTARES detector

② Data sample

③ Detector performance

④ Algorithms used  - Likelihood ratio

-  EM  method

⑤ Results - Full sky search

-  Candidate list search

# ANTARES telescope

# The Antares neutrino telescope



14.5 m

350 m

100 m
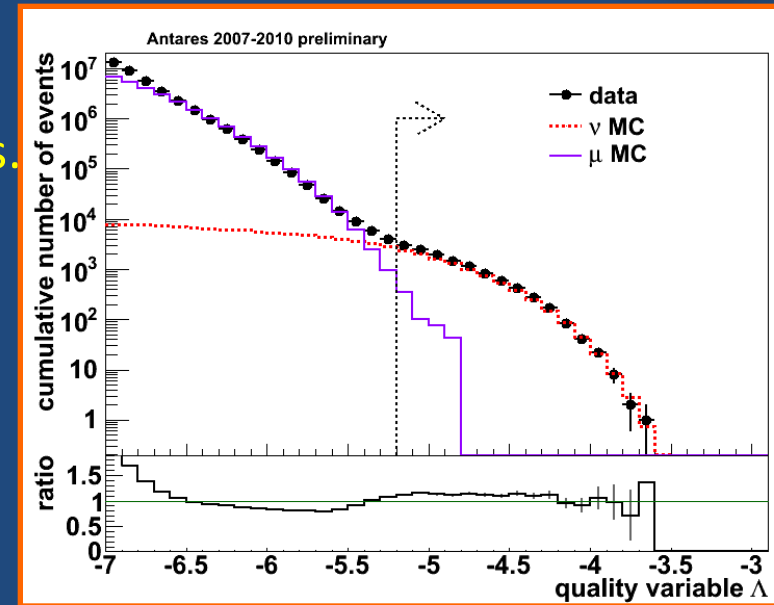
70 m

40 km

-2.5 km

© François Montanet

**12 lines
25 storeys/line
3 PMTs/storey
885 PMTs**

# Data sample

- Data collected from 2007 to 2010.
- Integrated livetime of the analysis: 813 days.

| lines | year | livetime (days) |
|---|---|---|
| 5 | 2007 | 183 |
| 9-10-12 | 2008 | 189 |
| 12 | 2009 | 209 |
| 12 | 2010 | 232 |



- After cuts on quality variable $\Lambda > -5.2$ and error estimate $\beta < 1°$, 3058 final events selected (over a total of 58 millions up-going muons).
- Choice of the cuts made in order to optimize discovery potential.
- 14% muon contribution (40% contribution with $\Lambda > -5.4$ for the 2007-2008 analysis)

# Data / MC

Antares 2007-2010 preliminary

Cos(zenith) angle distribution after applying the final quality cuts $\Lambda > -5.2$ & $\beta < 1°$ .
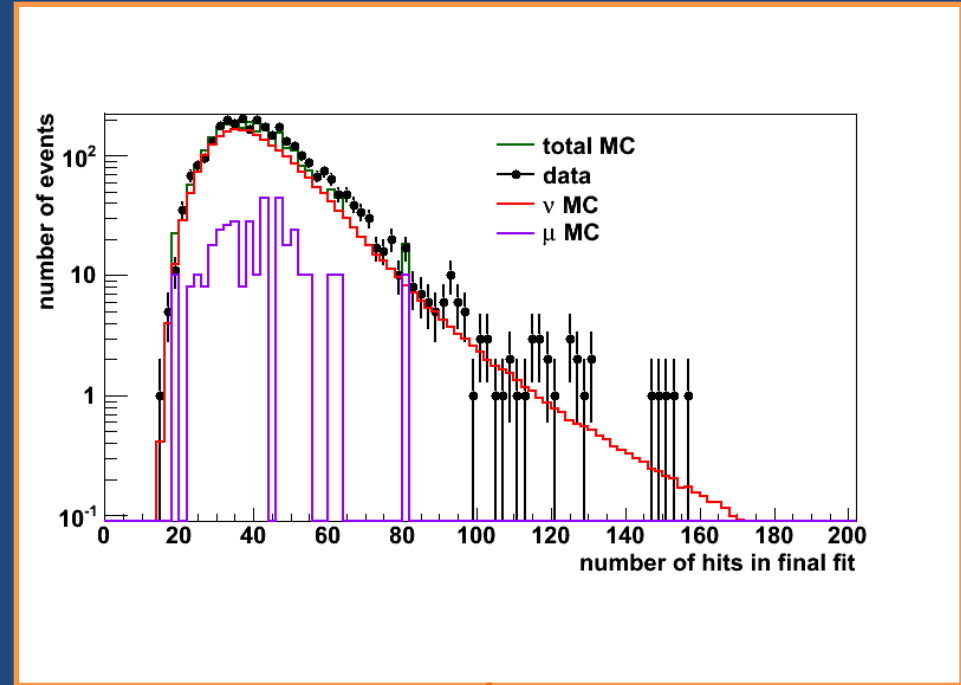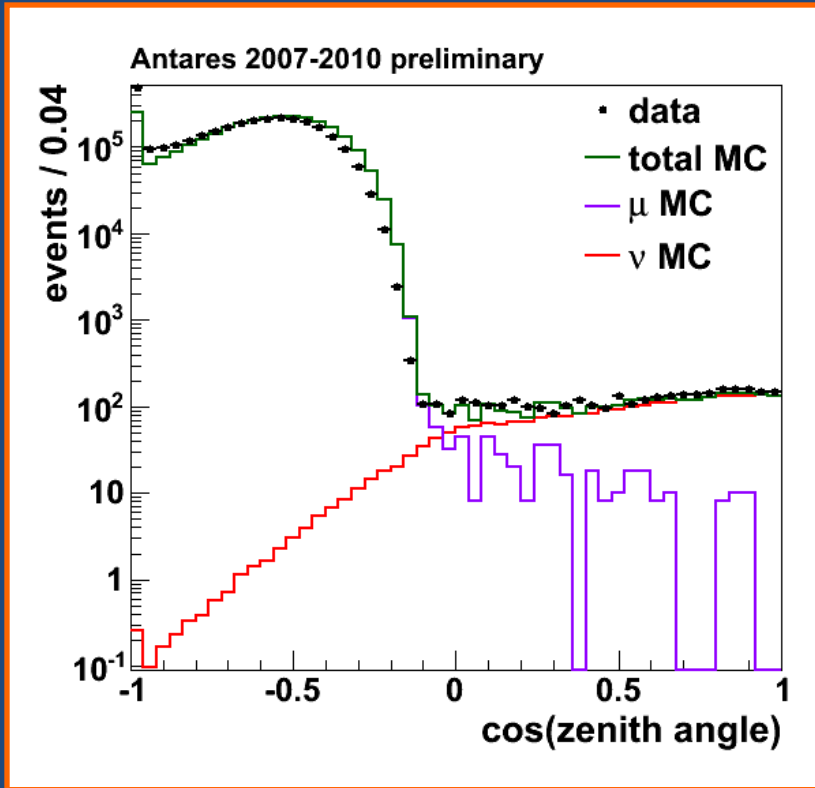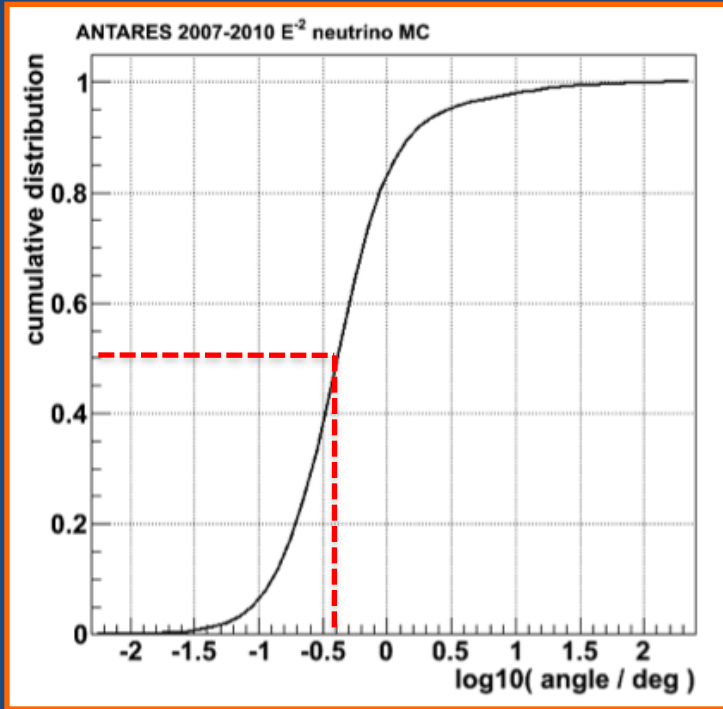


Number of hits distribution after the final cuts. Variable used to discriminate between low and high energy events.

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# Detector performance
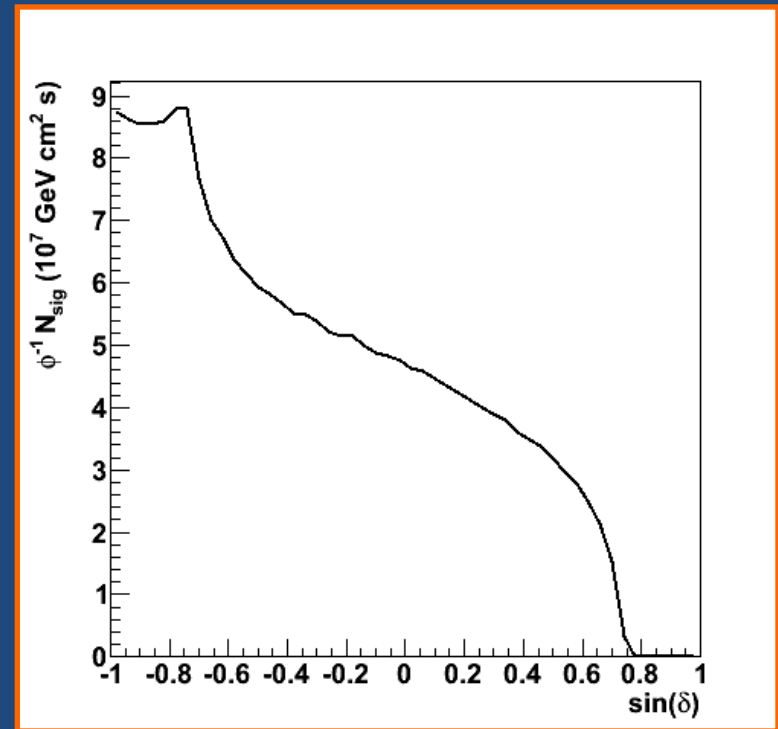


ANTARES 2007-2010 E$^{-2}$ neutrino MC

Angular resolution: 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 are reconstructed better than 1°



Acceptance: number of events that would be produced (and selected) by a point-source flux of $10^{-7}$ (E / GeV)$^{-2}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ as a function of the declination.

Visibility factor included (the final cuts of the analysis as well).

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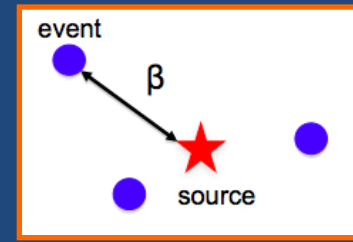
# Time integrated search

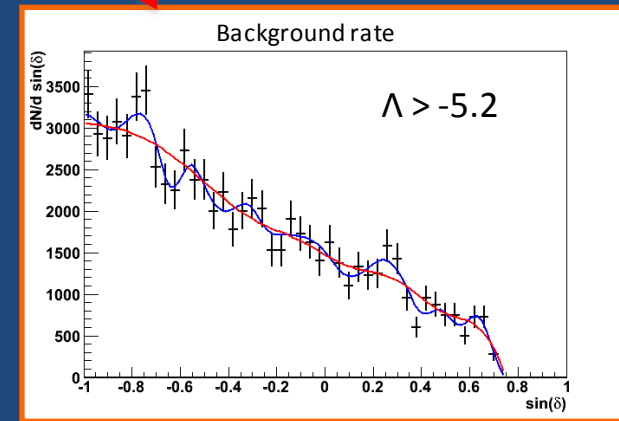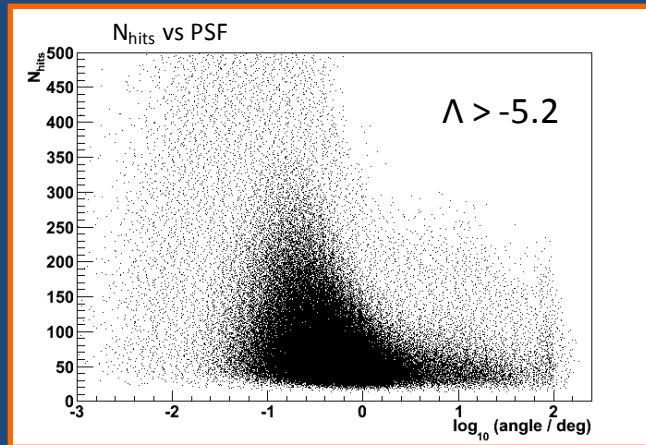© 2005 A. Kappes, Physics Institute University Erlangen

# Search method 1



- Unbinned likelihood ratio method.

$$\log \mathcal{L}_{s+b} = \sum_i \log[\mu_{sig} \times \mathcal{F}(\beta_i(\delta_s, \alpha_s)) \times \mathcal{N}(N_{hits}^{i,sig}) + \mathcal{B}_i \times \mathcal{N}(N_{hits}^{i,bkg})] + \mu_{tot}$$



PSF

$\Lambda > -5.2$



$N_{hits}$ vs PSF

$\Lambda > -5.2$



Background rate

$\Lambda > -5.2$
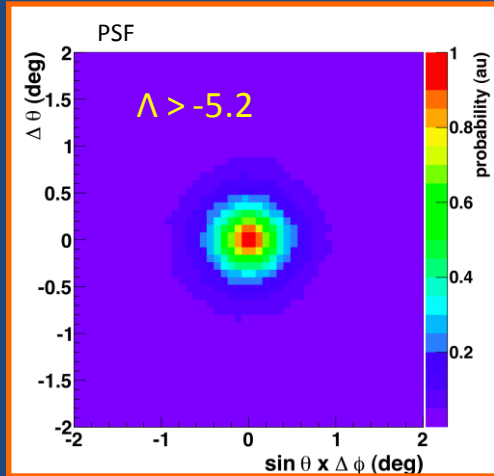
$$\mathcal{Q} = \log \mathcal{L}_{s+b}^{max} - \log \mathcal{L}_b$$

ex. full sky search



Fitting procedure (1 parameter for the candidate list search, 3 for the full sky) returns the test statistic Q. The bigger is Q, the more signal-like the data are.

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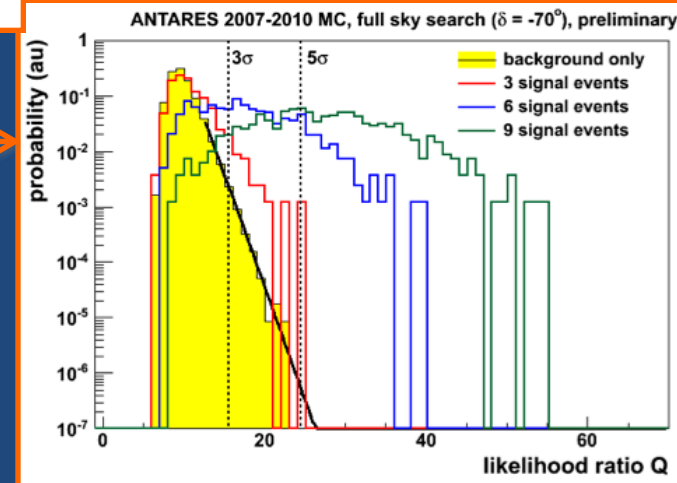
# Search method 2

Expectation – Maximisation method

$$p(\mathbf{x}) = \pi_{BG} P_{BG}(\delta) + \pi_{SG} P_{SG}(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma}) \cdot (P_{SG}^{nhits} / P_{BG}^{nhits})$$



Signal PDF is assumed to follow a Gaussian distribution.
$\pi_{SG}$ = $n_S$ / n and $\pi_{BG}$ = ( n − $n_S$ ) / n are the mixing proportions
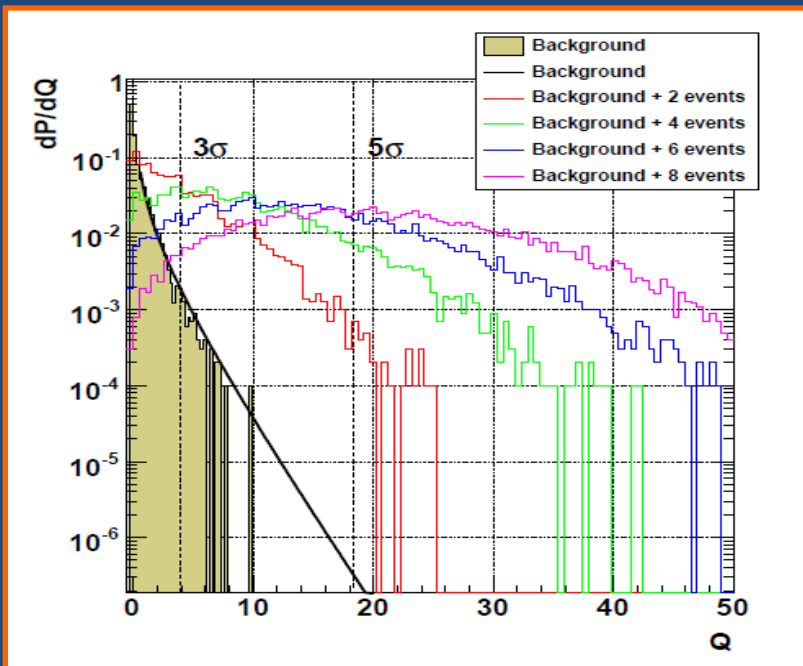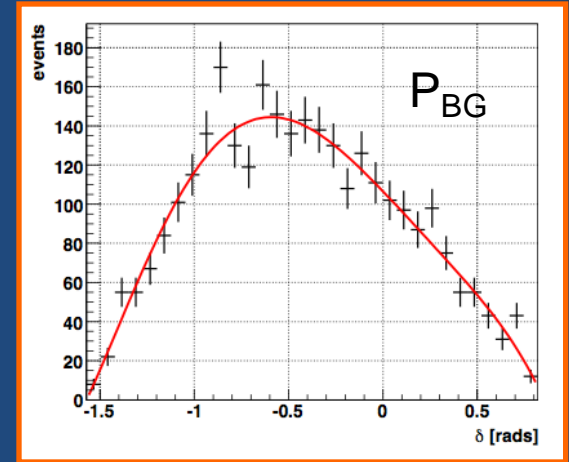


3 (5) parameters in the candidate list (full sky search) -> the sigma of the Gaussian is also a free parameter

Test statistic = BIC (Bayesian Information Criterion) = Likelihood ratio

All the results with the LR method (see next slides) crosschecked with the EM one.

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# Improvement with $N_{hits}$

- One of the main goals of this analysis was to use an energy estimator (not implemented in previous analysis with 2007-2008 data).
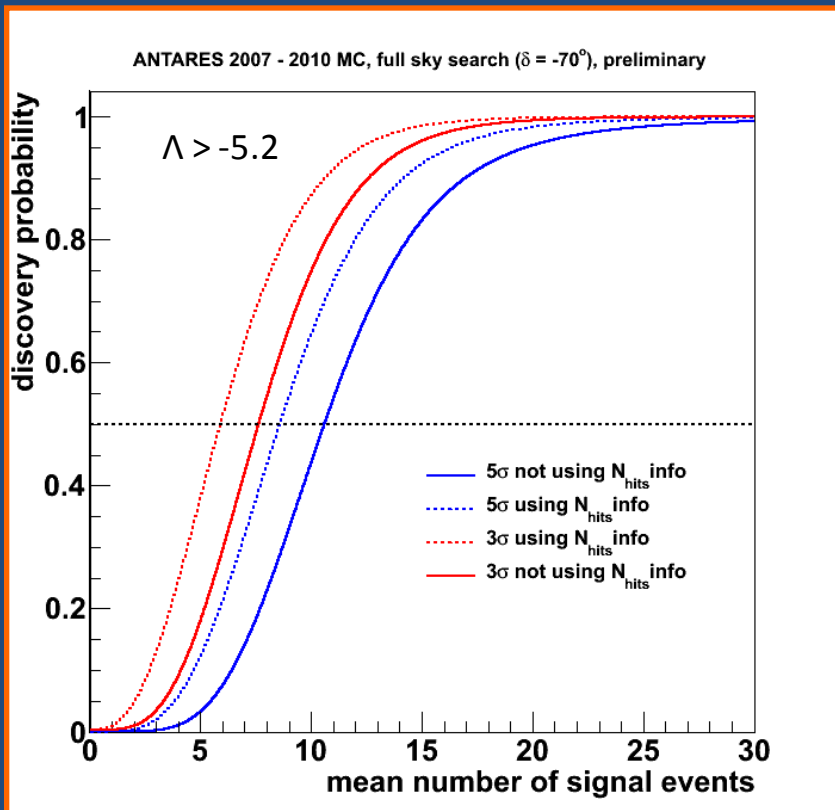
- However, for this analysis we decide to adopt the number of hits information in order to discriminate low from high energy events.

- Results with $N_{hits}$ similar with the ones obtained using the reconstructed $E_\mu$ (from MC) with a 30% uncertainty.



ANTARES 2007 - 2010 MC, full sky search ($\delta = -70°$), preliminary

$\Lambda > -5.2$

5σ not using $N_{hits}$ info
5σ using $N_{hits}$ info
3σ using $N_{hits}$ info
3σ not using $N_{hits}$ info

| using $N_{hits}$ | not using $N_{hits}$ | |
|---|---|---|
| 5.9 | 7.6 | 3σ |
| 8.7 | 10.6 | 5σ |

Full sky search: 28 (21) % better for the 3(5)σ probability using the $N_{hits}$ information (@ $\delta = -70°$ )

Results
Full sky search

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# Full sky search

- Looking for an excess of signal events everywhere in the (visible) sky.
- Most signal-like cluster at α = -46.5, δ = -65.00; it consists of 9 events inside a 3° cone.

Nsig = 5
Q = 13.02
p-value = 0.026
Significance = 2.2 σ

- p-value = 0.026 => 2.6% chance to get the same or larger (more signal like) Q value amongst the background only cases.
- Result compatible with the background hypothesis.



Antares 2007-2010 preliminary

# Full sky search



Equatorial coordinates

P-value skymap
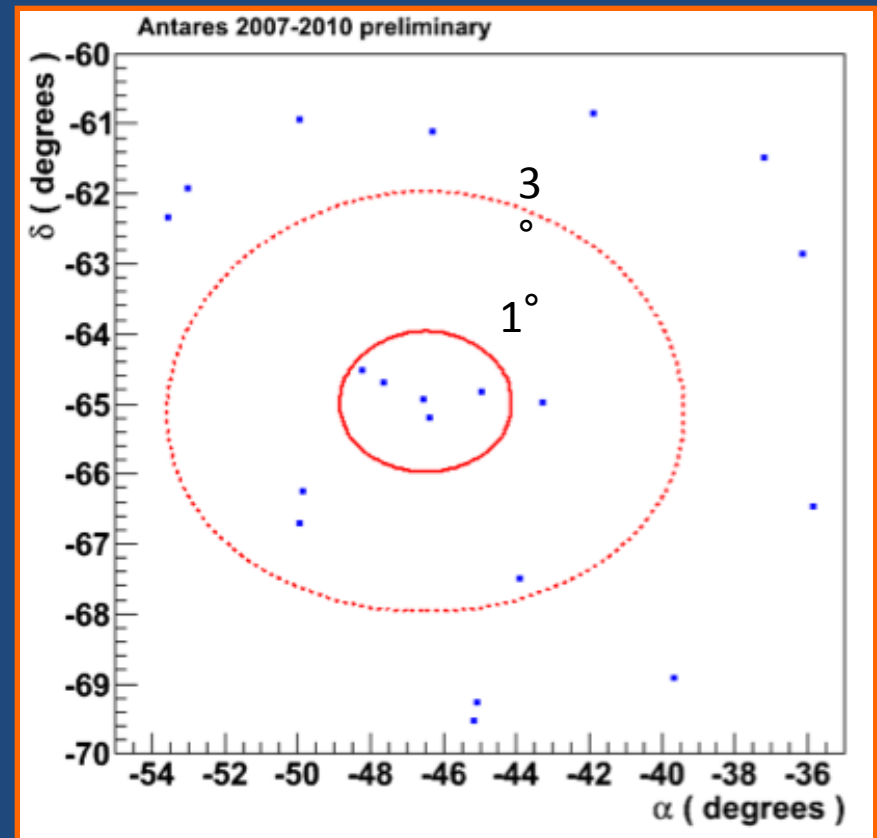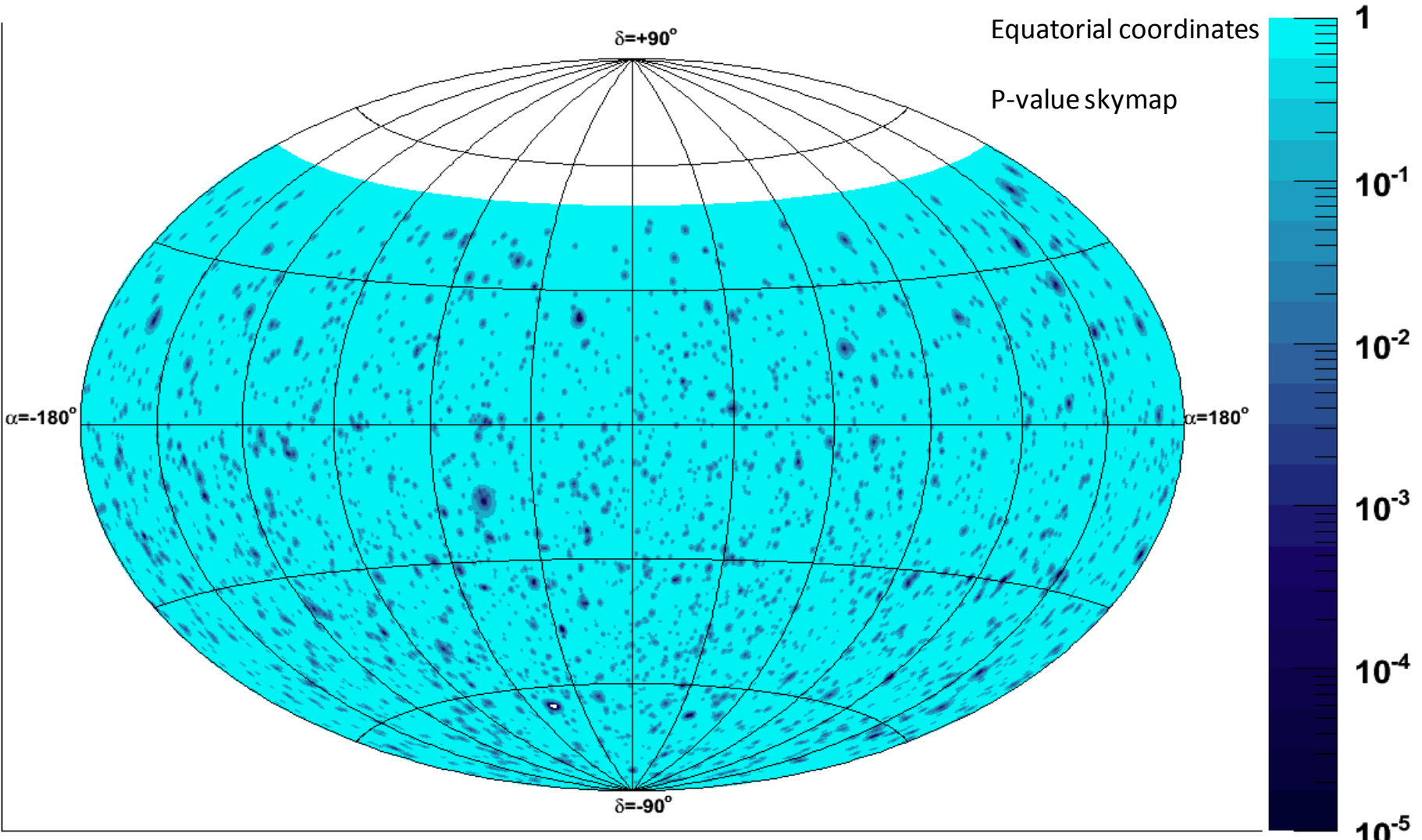
# Full sky search



Antares 2007-2010, preliminary

Galactic coordinates

Most signal like cluster

Results
Candidate list search

# Candidate list search

- Looking for an excess of signal events on a pre-defined list of candidate sources.

- 51 candidate sources considered: 24 used in 2007-2008 analysis + 27 "new" ones (selection based on a convolution between the visibility and the gamma ray flux).
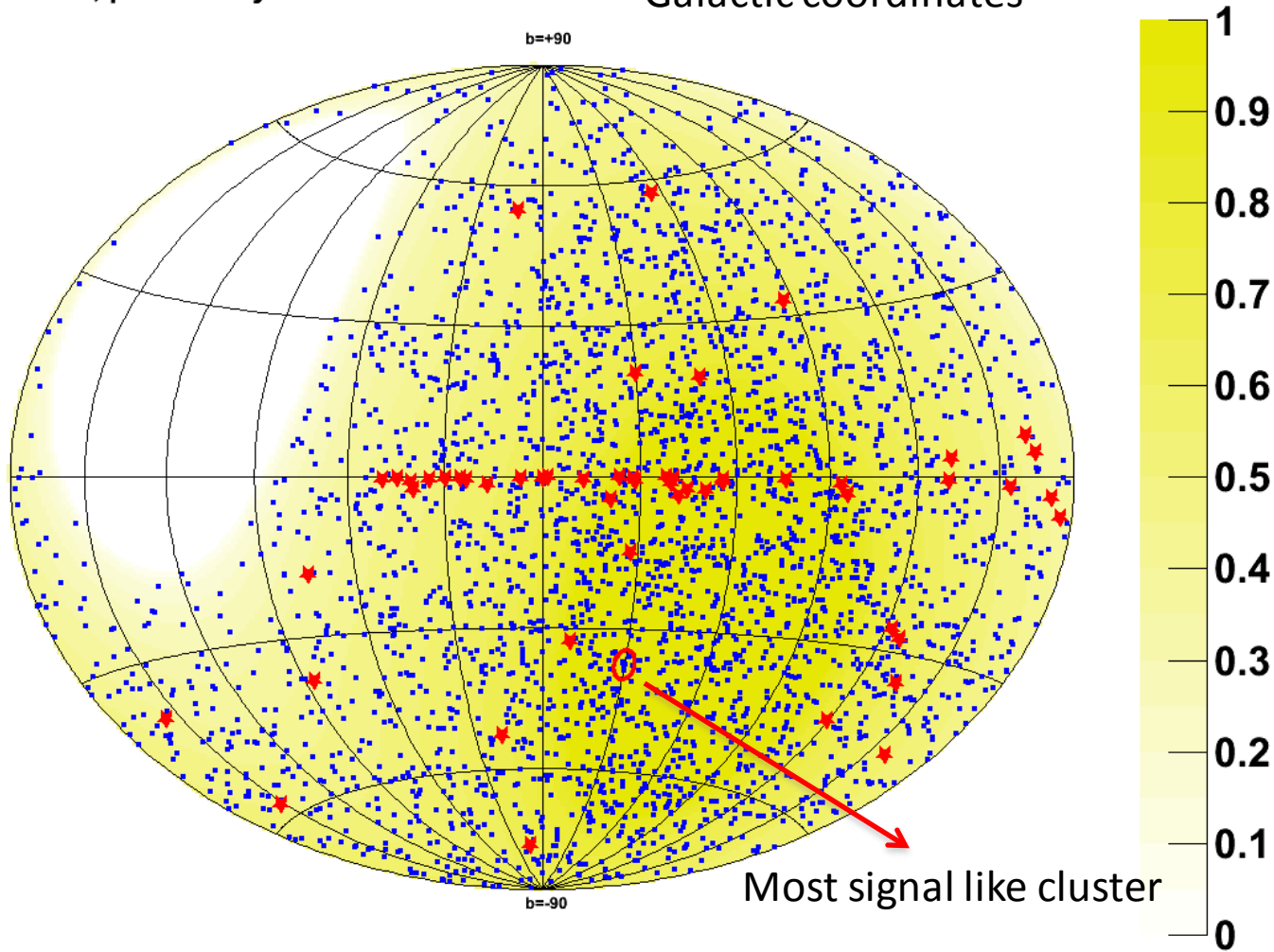
| name | ra | decl | Nsigfit | Q | p-value | nsigma | lim_Nsig | lim_flux |
|------|------|--------|---------|------|---------|--------|----------|----------|
| HESS J1023-575 | 155.83 | -57.76 | 1.97 | 2.35 | 0.41 | 0.82 | 5.62 | 6.6e-08 |
| 3C 279 | -165.95 | -5.79 | 1.11 | 2.15 | 0.48 | 0.71 | 5.35 | 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 |

Results: first 11 sources sorted by the Q-value. Last column shows the 90% CL upper limit on the flux (E / GeV)$^{-2}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ ) computed with the Feldman – Cousins prescription.
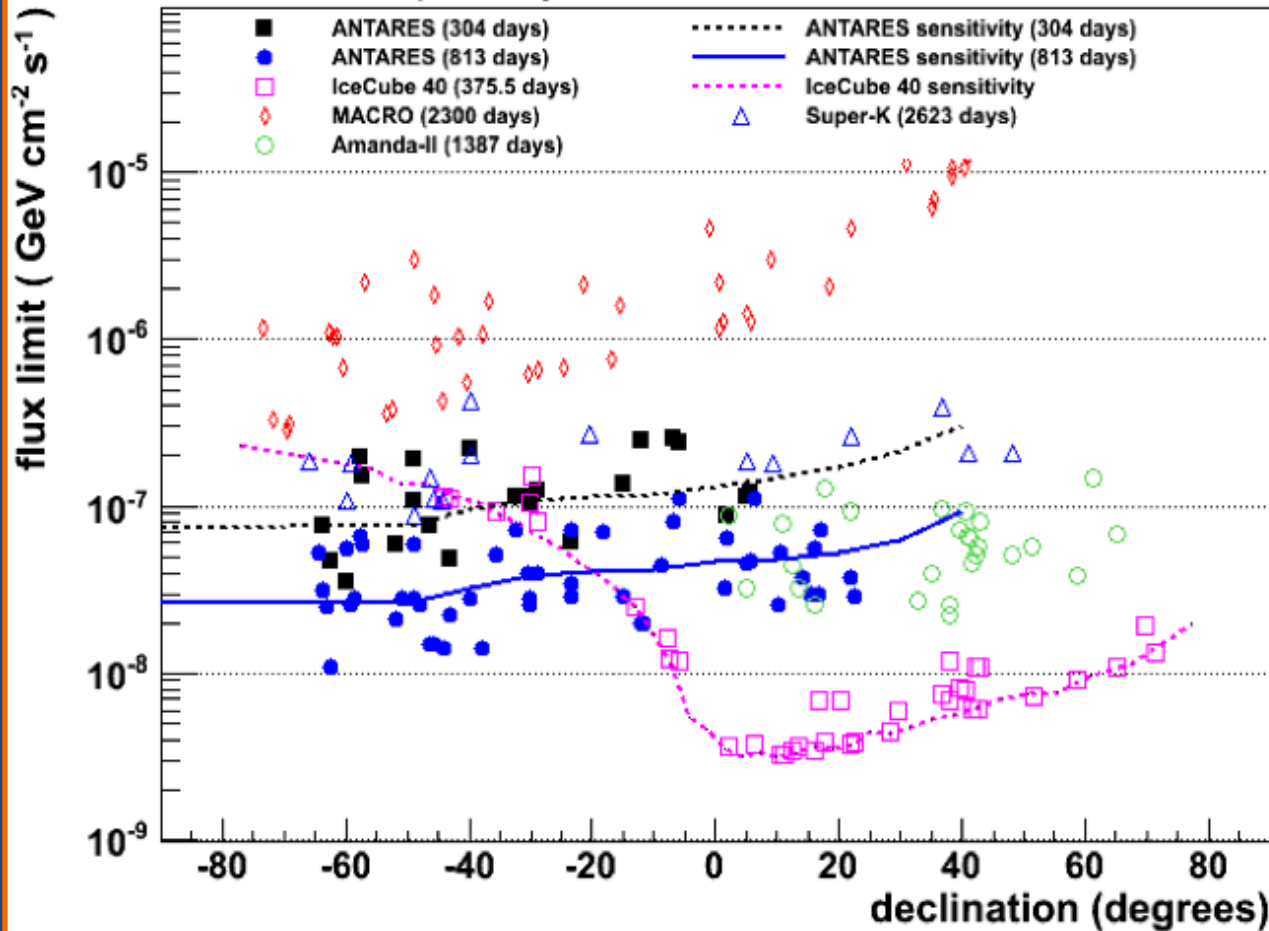HESS J1023-575 most signal like, p-value 40% (post trial).
Compatible with the background hypothesis.

# Candidate list search



Antares 2007-2010 preliminary

Legend:
- ■ ANTARES (304 days)
- ● ANTARES (813 days)
- □ IceCube 40 (375.5 days)
- ◇ MACRO (2300 days)
- ○ Amanda-II (1387 days)
- ····· ANTARES sensitivity (304 days)
- —— ANTARES sensitivity (813 days)
- ····· IceCube 40 sensitivity
- △ Super-K (2623 days)

y-axis: flux limit ( GeV cm$^{-2}$ s$^{-1}$ )
x-axis: declination (degrees)

Factor 2.7 improvement in sensitivity (compared with previous analysis).

For many candidate sources the limits obtained are the most stringent to date. (for the Southern Hemisphere IceCube requires a flux component at very high energies > 1 PeV).

IC40+IC59 sensitivity ( ~ 2.5 factor better than IC40) not shown.

Systematics:
- 15% acceptance
- 10% Nhits
- 15% angular resolution
- 0.1° for the absolute orientation of the detector.

# Conclusions

- Presented results for the search of point-like sources of neutrino using data collected from 2007 to 2010.

- 3058 up-ward going events selected (estimated neutrino purity 86%).

- $N_{hits}$ information on the likelihood: 28 (21) % better for the 3(5)σ probability of discovery in the full sky search.

- Neither the full sky search, nor the candidate list search shows a significant excess of signal events over the background.

- For the full sky search, the most signal like cluster was found at (α, δ) = -46.5° , -65.0° . The fit returns 5 signal events out a total of 9. The p-value is 0.02 which corresponds to 2.2 sigma.

- Concerning the fixed search, HESS J1023-575 is the most signal like source with a value for the test statistic Q = 2.37 and a corresponding p-value (post trial) of 40%.

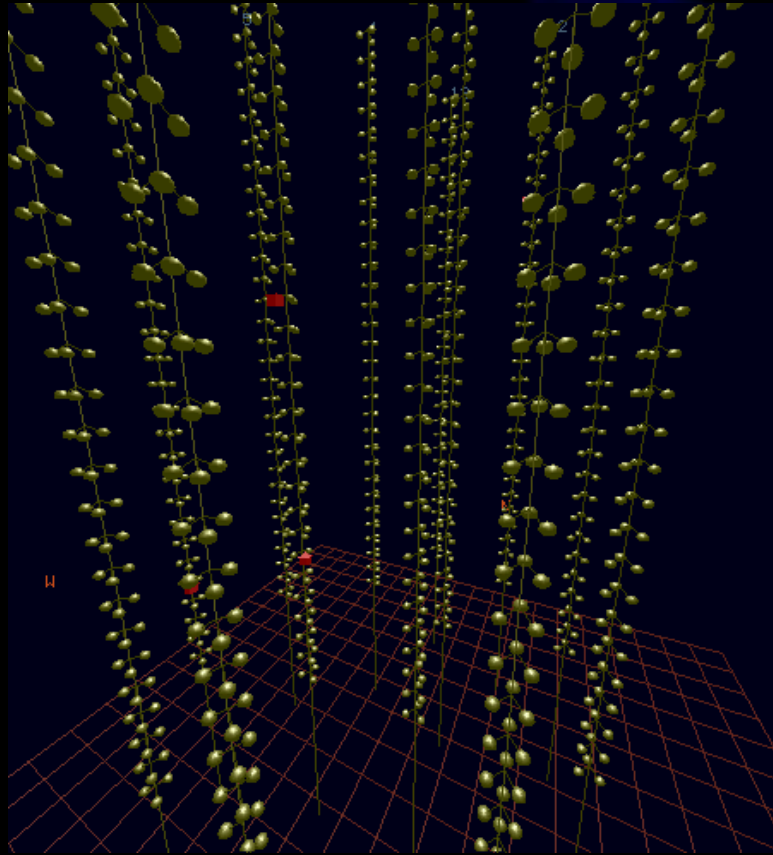- Results cross-checked with a different algorithm (EM method).

# Thank you!

# Back up

# Visibility
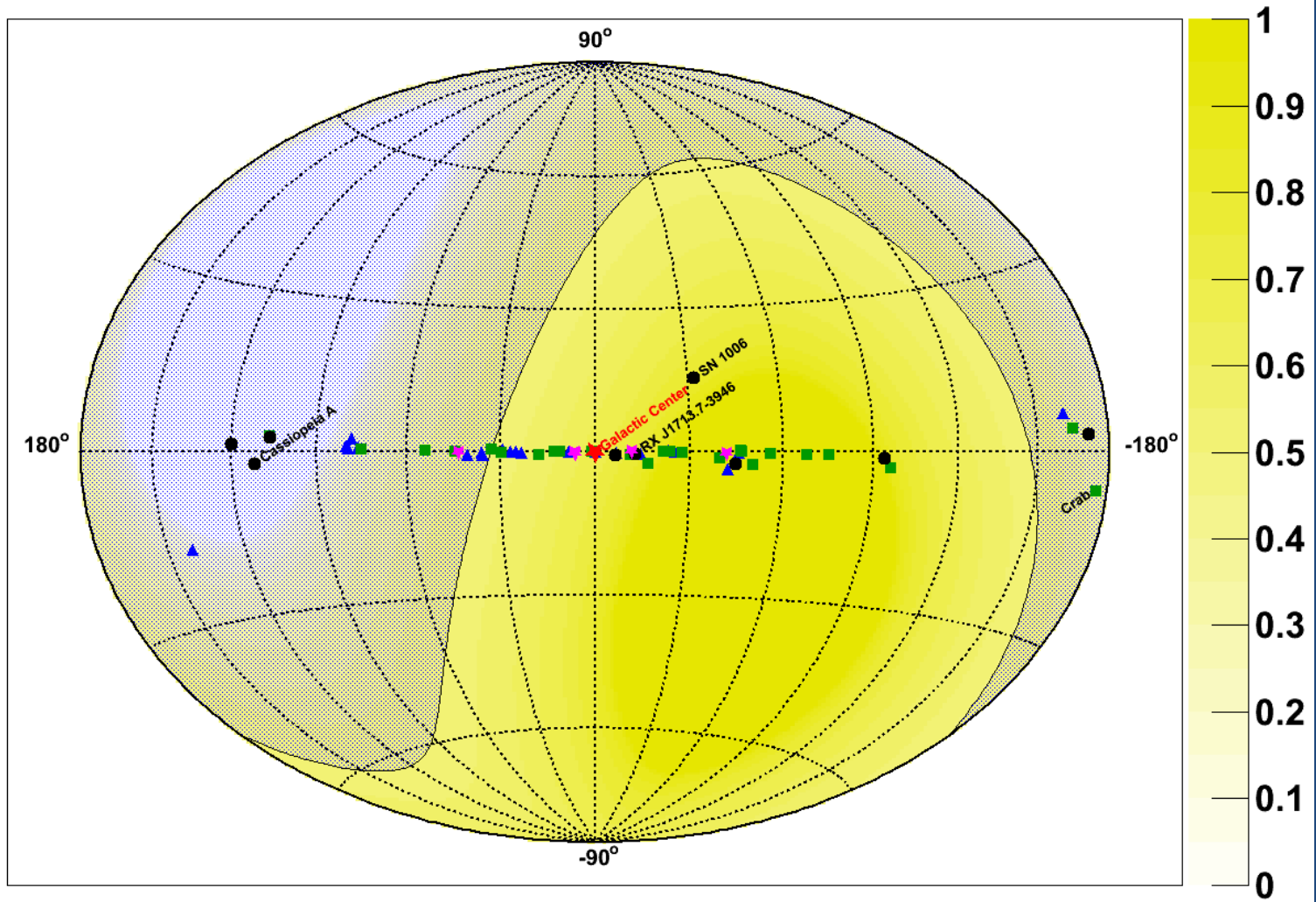
3D photomultiplier array

Cherenkov light from muon

$\gamma$

43°

Reconstruction of ⬜ trajectory (~ ⬜) from timing and position of PMT hits

$\mu$

CC interaction

$\nu_\mu$

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# The search

- Simple hypotheses test:  $H_0$ -> only atmospheric neutrinos & atmospheric muons in our sample.

  $H_1$ -> *In addition* to the background, there exists a point source of neutrinos.

- Known the hypotheses, we have to calculate the test statistic: $Q$ (next 2 slides about it).

- Ask: what are the chance to get this value (or better) if all the data has no cosmic neutrinos (i.e. atmospheric neutrinos only)?

- From toy MC we know the distribution of the test statistic for the background only case.



data

Data is only background

Statistic



Data has signal!

data

Statistic
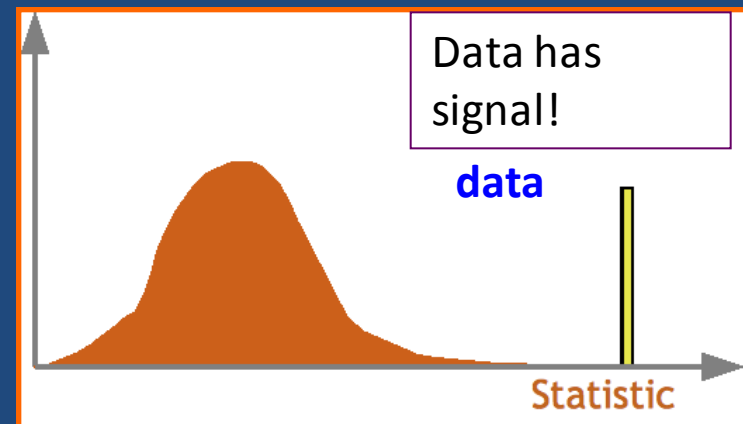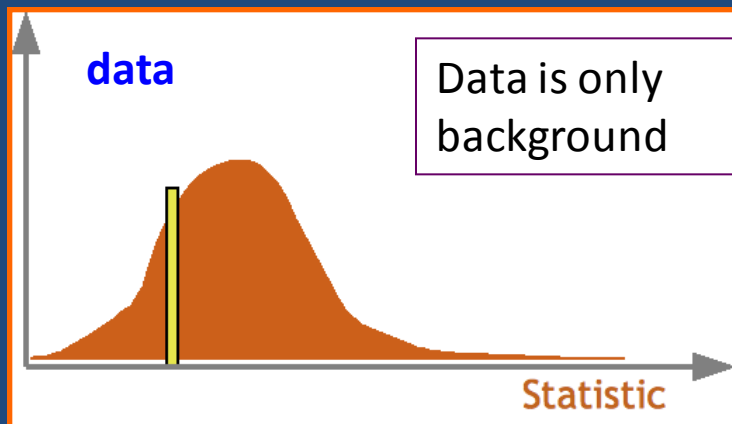
# 2007 – 2008 analysis

- Paper submitted to The Astrophysical Journal Letters on August 1st (**Arxiv:1108.0292v1** ).

- Final sample: 2190 up-ward going events, selected with quality cuts $\Lambda > -5.4$ and $\beta < 1°$ (40% muon contribution).

- Livetime of the analysis: 304 days.

- Angular resolution: $0.5° \pm 0.1°$

- Unbinned likelihood ratio method (no hits information).

- Full sky search: most signal like cluster found at $(\alpha, \delta) = (43.21°, -0.50°)$ with 3.4 fitted signal events. p-value 88%.

- Candidate search: most signal like source candidate is HESS J1023-575 where 3(5) events are within $1°$ ($3°$) of its position. p-value = 17%