Point-like source searches with ANTARES

RICAP Conference

Rome, 20-22 June 2007

MARIE CURIE ACTIONS

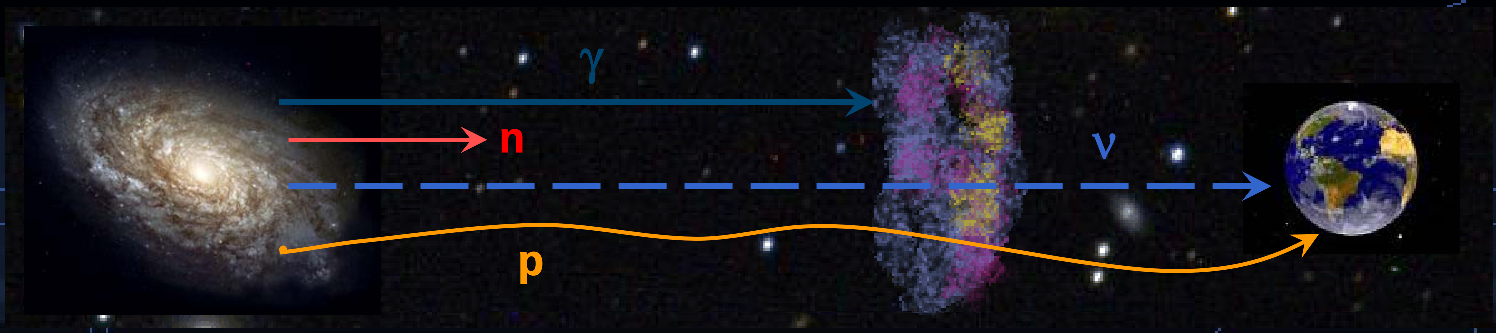
CSIC

Juan de Dios Zornoza (IFIC - Valencia)

ANTARES

Neutrino Astronomy

- Advantages w.r.t. other messengers:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields
  - Neutrons: are not stable
- Drawback: large detectors (~GTon) are needed.



Production Mechanism

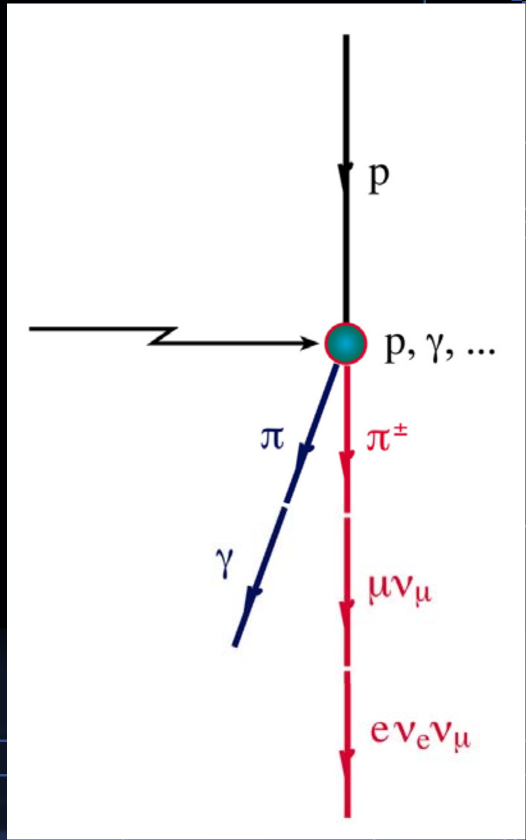
- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}...) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

Cosmic rays

$$\downarrow$$

$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$



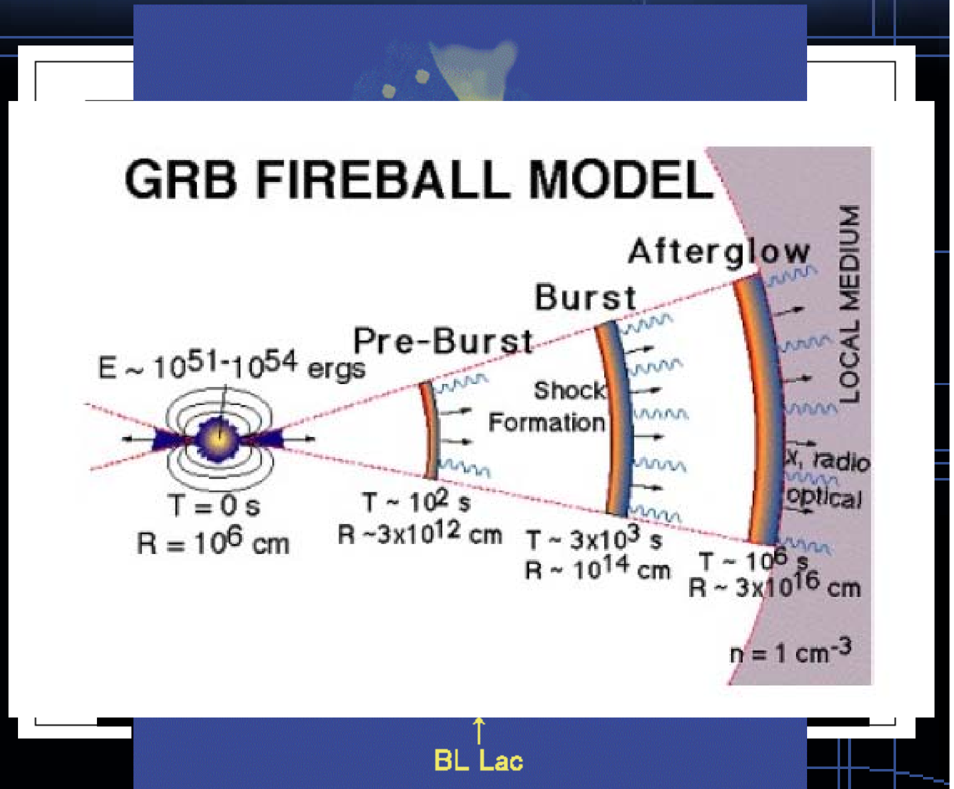
- Moreover, gammas are also produced in this scenario:

$$N + X \rightarrow \pi^0 + Y \rightarrow \gamma\,\gamma + Y$$

Gamma ray astronomy

Astrophysical Sources

- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - …

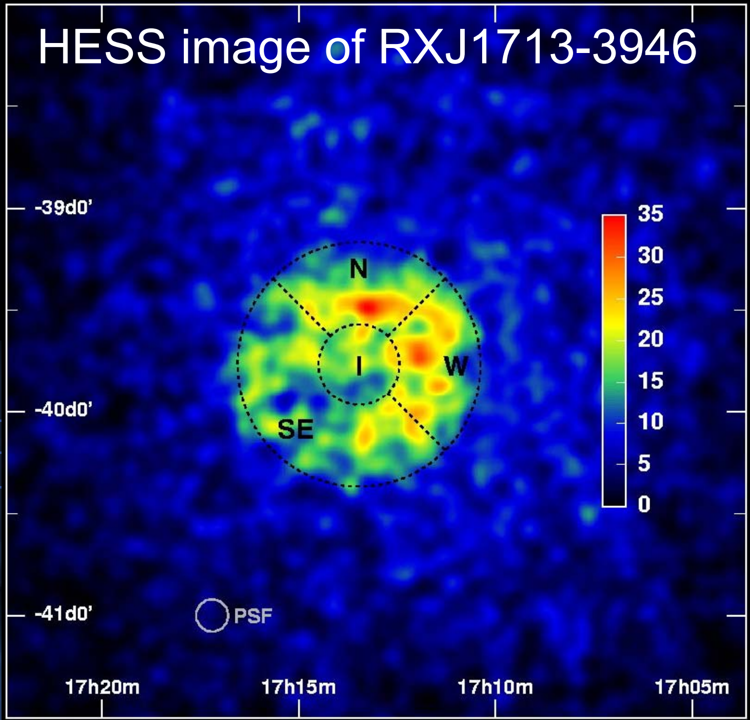


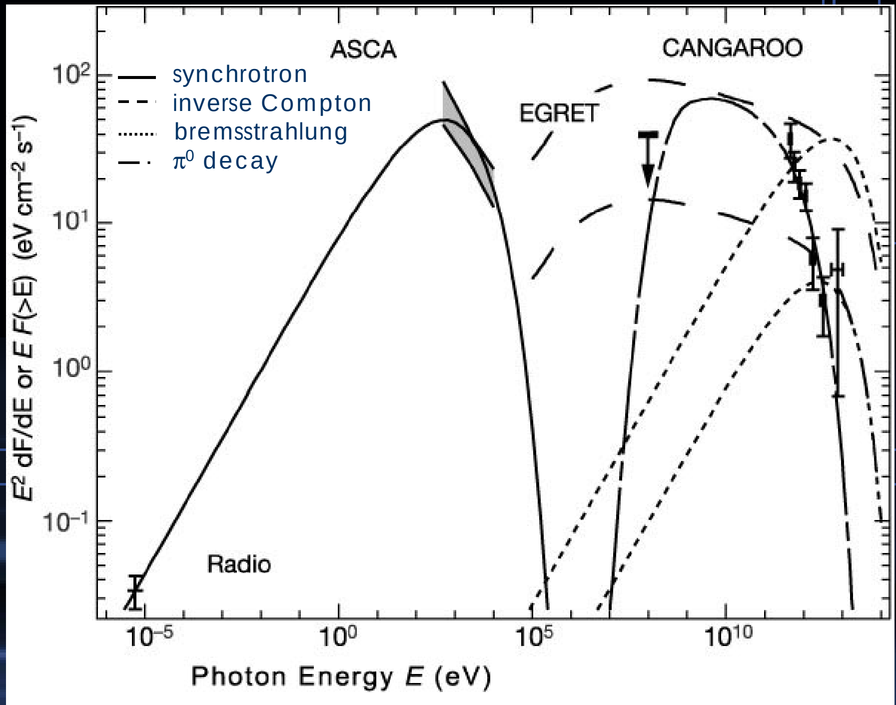
- GRBs are brief explosions of γ rays
- (100 TeV-10 PeV), after-glow (EeV)

- **Extra-galactic sources**: most powerful sources in the Universe
  - AGNs
  - GRBs

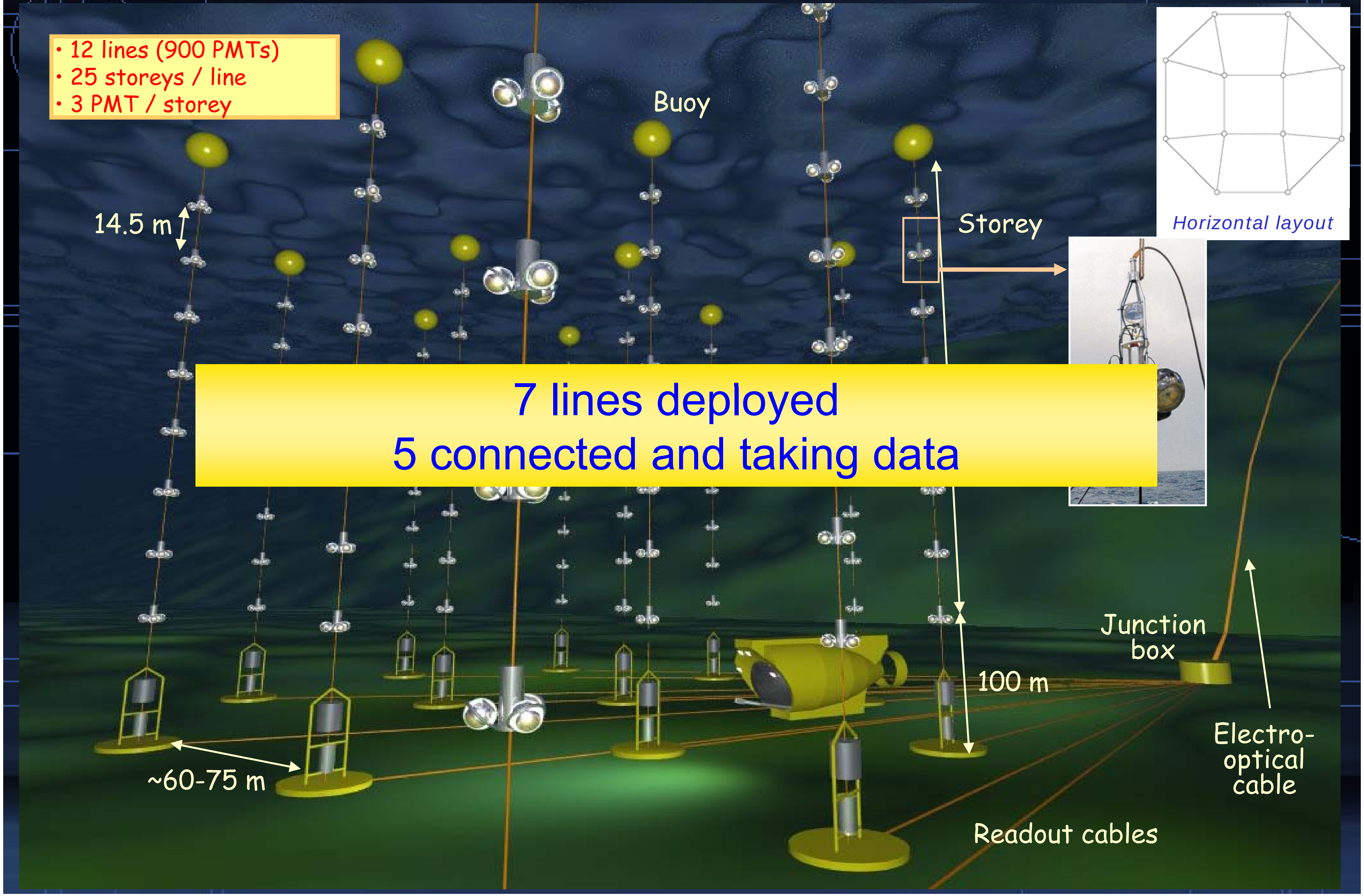
RXJ1713-3946

- Data from HESS indicate that the emission of the shell-type supernova remnant RXJ1713-3946 seem to favor hadronic origin:
  - increase of the flux in the directions of molecular clouds
  - spectrum better fit by π^0 decay
  - low electron population according to observations in radio and X-rays
- Expected number of detected events would be ~10 events in five years in a km^3 detector



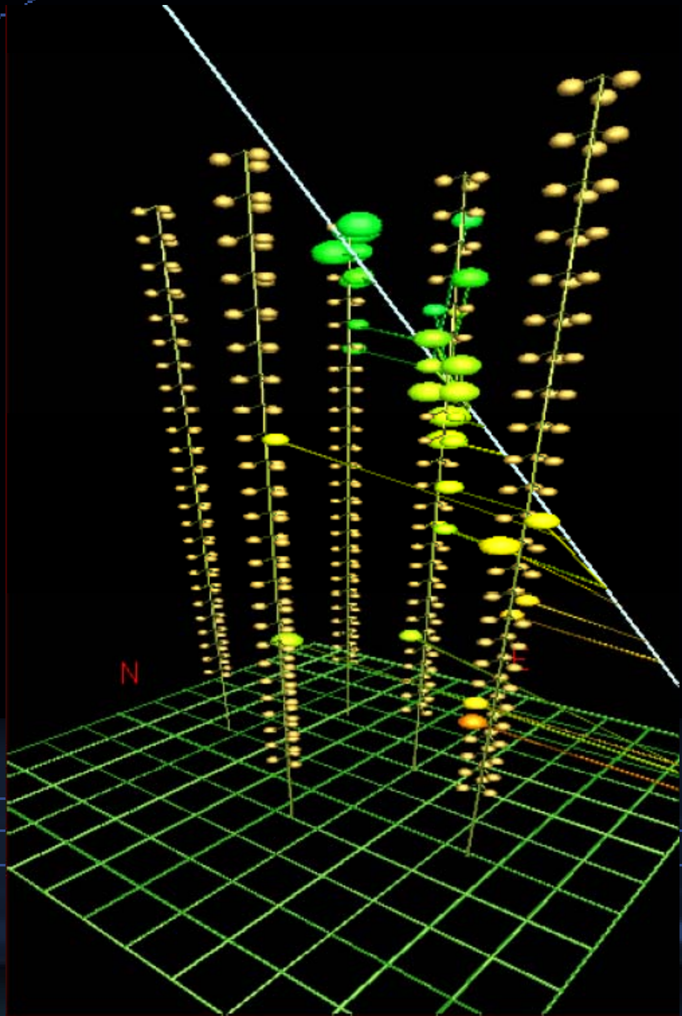


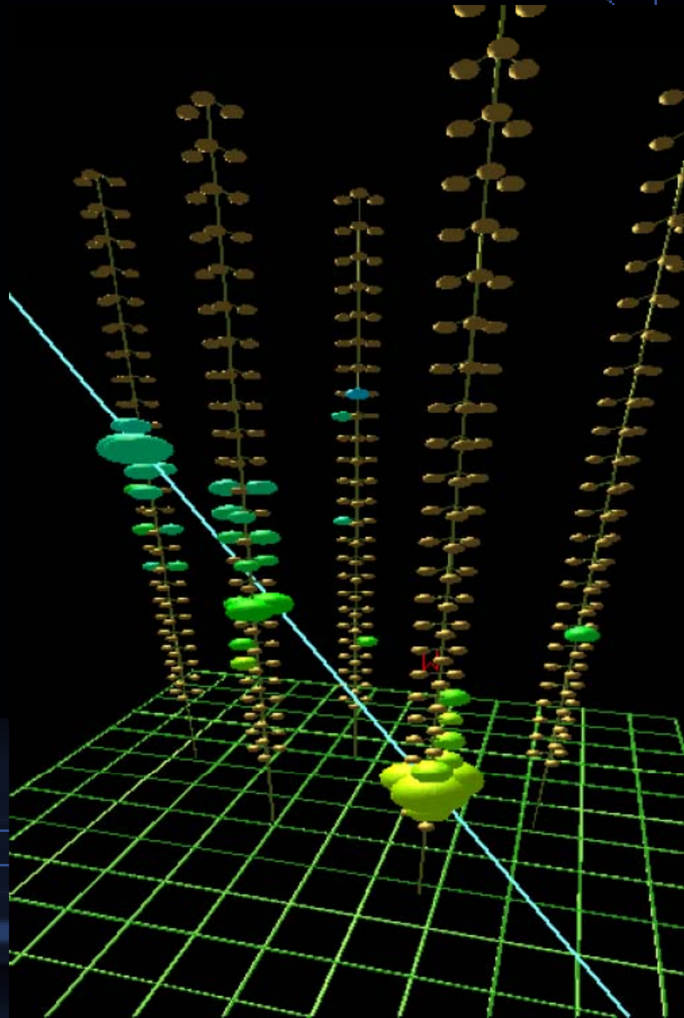
The ANTARES detector



7 lines deployed
5 connected and taking data

Neutrino candidates





First neutrino candidates have been reconstructed with the 5 lines deployed

Point-source search

- Several methods have been developed in ANTARES for cluster search:
  - Grid method
  - Cluster method

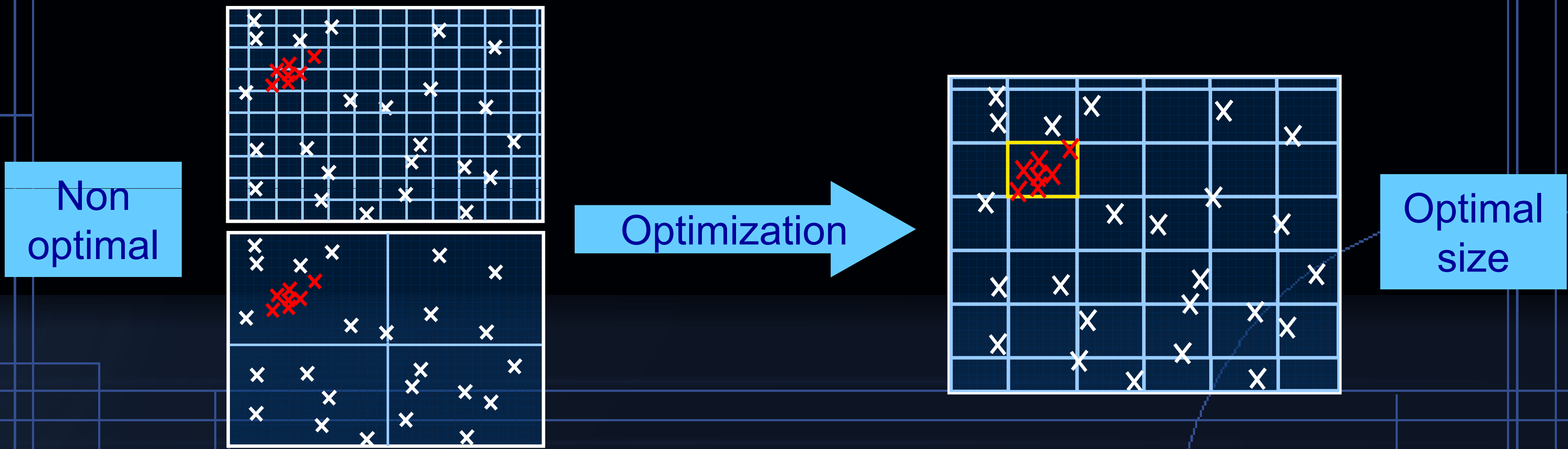
    } Binned

  - Maximum likelihood ratio
  - Expectation Maximization

    } Unbinned

Grid Method

- Sky is divided in a grid of rectangular bins
- The optimum size of the bins is calculated for maximum sensitivity, with the additional criteria of having the same number of background events per bin (=uniform sensitivity)



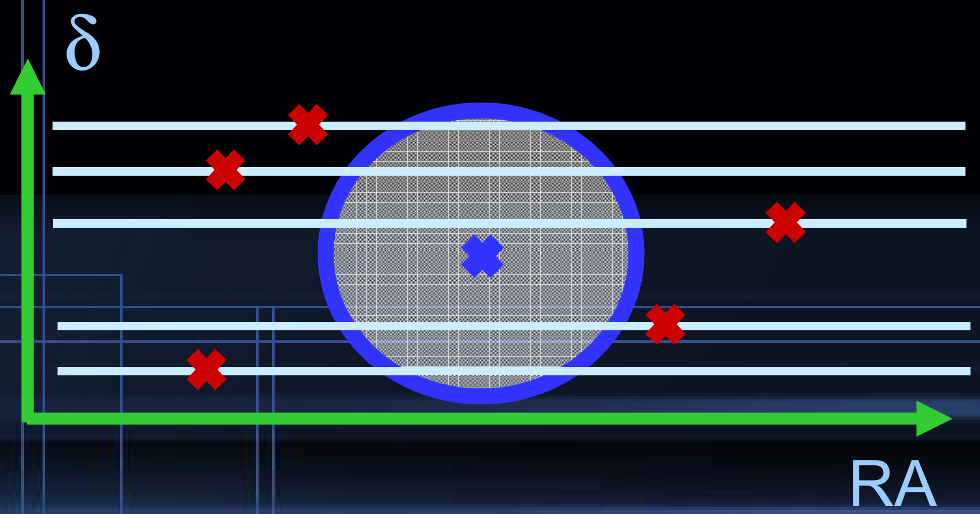
Significance: $S_i = \log_{10}(P_i)$

$$P_i = \left(\frac{1}{m}\right)^{N_{total}} \sum_{n=N_i}^{N_{total}} \binom{N_{total}}{n} (m-1)^{N_{total}-n}$$

P_i is the probability for the background to produce Ni or more events if there are N_{total} events in the declination band

Cluster Method

- For each event we calculate the number of events inside a cone.
- The background in the declination band of the considered event allows to determine the probability of a random fluctuation of the observed number of events.
- The size of cones is chosen for uniform background (= uniform sensitivity).



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

P_i is the probability of the background to produce the observed number of events N_0 or more (up to the maximum number N_{total}). σ is each element of the set C_n^{Ntotal} of combinations of N_{total} elements in groups of n elements.

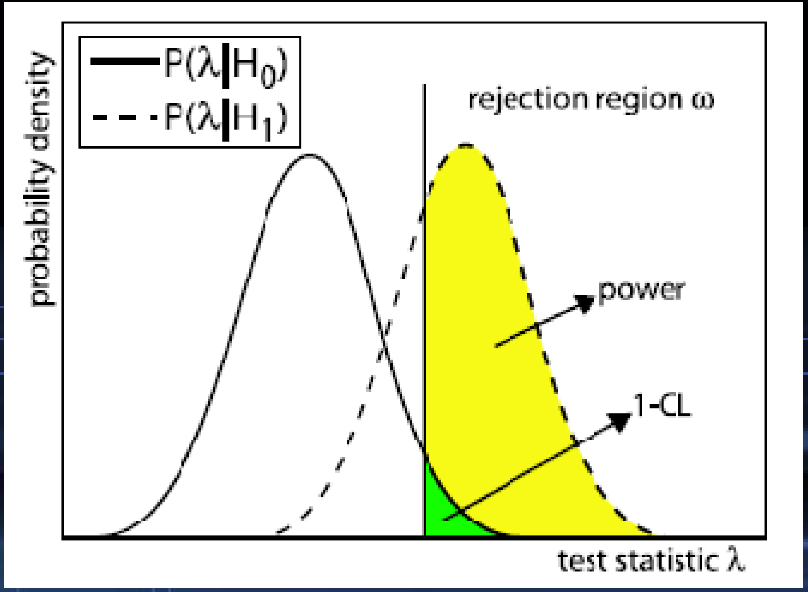
Maximum likelihood ratio

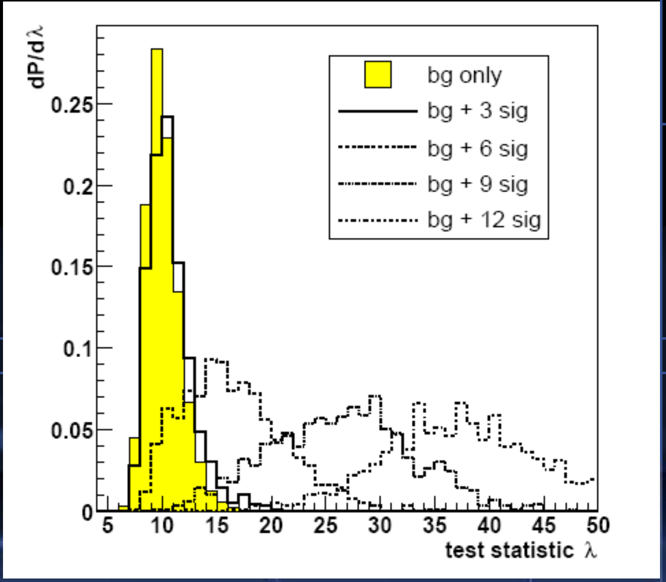
- The discrimination between signal and background is based on a test statistic λ which uses the information on the spatial and energy distributions of signal and background:

$$\lambda = \log\left[\frac{P(\mathrm{data}|H_1^{\max})}{P(\mathrm{data}|H_0^{\max})}\right]$$

$H_0: \quad \Phi(\theta,\phi,E,t) = \Phi^{\mathrm{bg}}(\theta,E)$ only background

$H_1: \quad \Phi(\theta,\phi,E,t) = \Phi^{\mathrm{bg}}(\theta,E) + \Phi^{\mathrm{sig}}(\theta,\phi,E,t)$ background + signal





Expectation Maximization

- The EM method is a pattern recognition algorithm that maximizes the likelihood in finite mixture problems, which are described by different density components (pdf) as:

pdf

signal: RA, δ
bg: only δ

$$p(\mathbf{x}) = \sum_{j=1}^{g} \pi_j p(\mathbf{x}; \boldsymbol{\theta}_j) \quad \Longrightarrow \quad p(\mathbf{x}) = \pi_{BG} P_{BG}(\delta) + \pi_S P_S(\mathbf{x}; \boldsymbol{\mu}, \boldsymbol{\Sigma})$$

position of event

proportion of signal and background

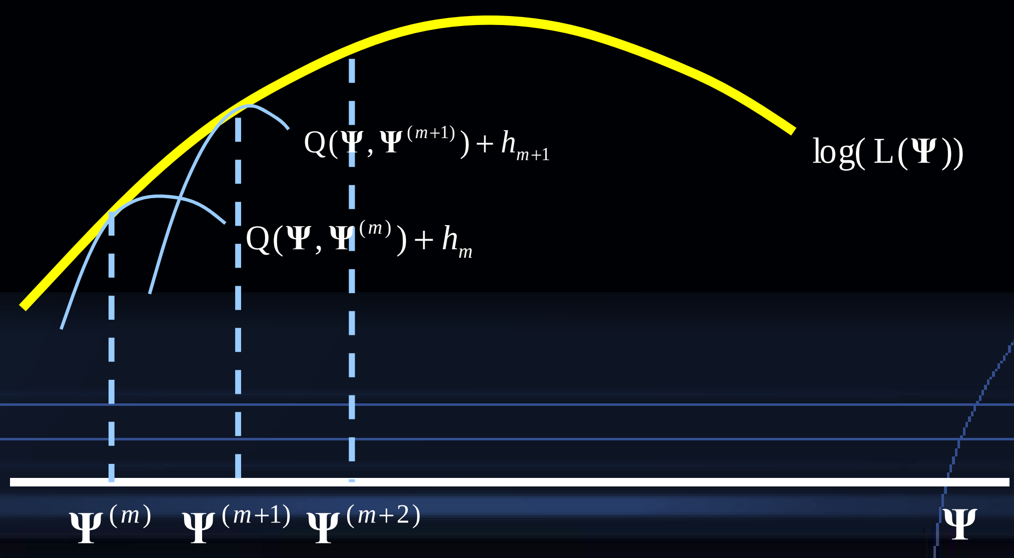
- The idea is to assume that the set of observations forms a set of incomplete data vectors. The unknown information is whether the observed event belongs to a component or another.

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

z_i is the probability that the event comes from the source

Expectation Maximization

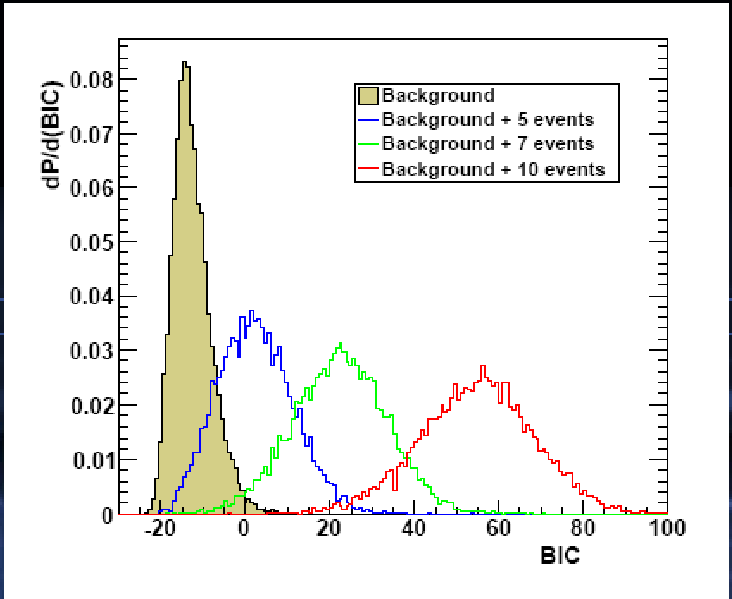
- The method works in two different steps:
  - E-step: We evaluate the expectation of the complete data log Q (Ψ,Ψ^m) for the current value of the parameter estimate Ψ^m
  - M-step: The maximization is performed in order to find the set of parameters Ψ^m that maximizes Q (Ψ,Ψ_m)



Model Selection in EM

- The parameter used for discriminating signal versus background is the Bayesian Information Criterion, which is the maximum likelihood ratio with a penalty that takes into account the number of free parameters in the model weighed by the number of events in the data sample.

$$\mathrm{BIC} = 2\log p(D|\hat{\boldsymbol{\theta}}_1, M_1) - 2\log p(D|\hat{\boldsymbol{\theta}}_0, M_0) - (\nu_1 - \nu_0)\log(n)$$

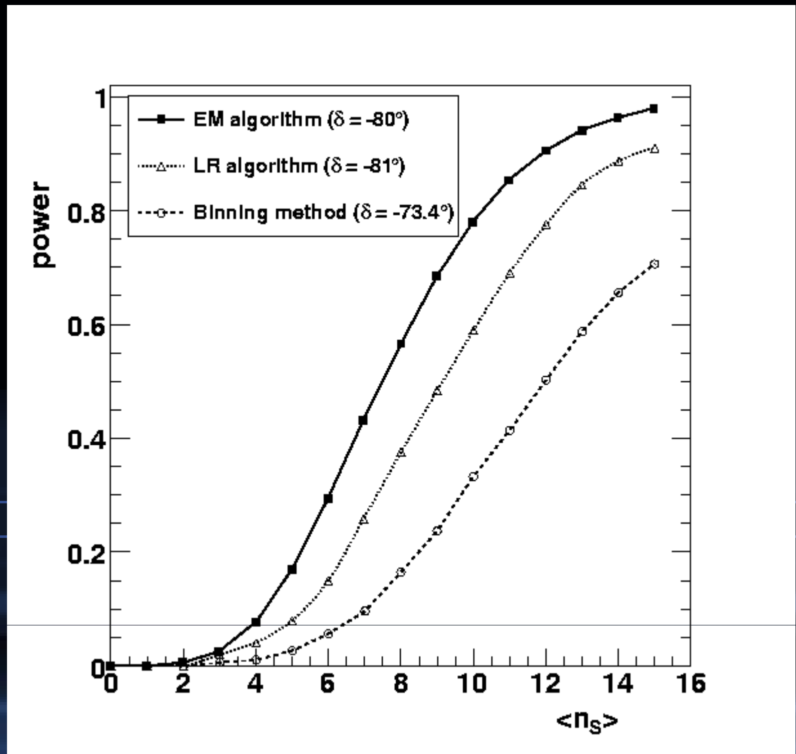


D: data set
θ_0: parameters of bg
θ_1: parameters of signal
M: model
ν_k: number of parameters to be estimated

BIC distribution for different number of sources events added (at δ=-80°), compared with only background

Comparison between methods

- Unbinned methods show better performance, since more information is included (events outside the bin, distribution of events, angular error estimate, reconstructed energy…)
- The Expectation Maximization is the most powerful method among the ones that we have studied.

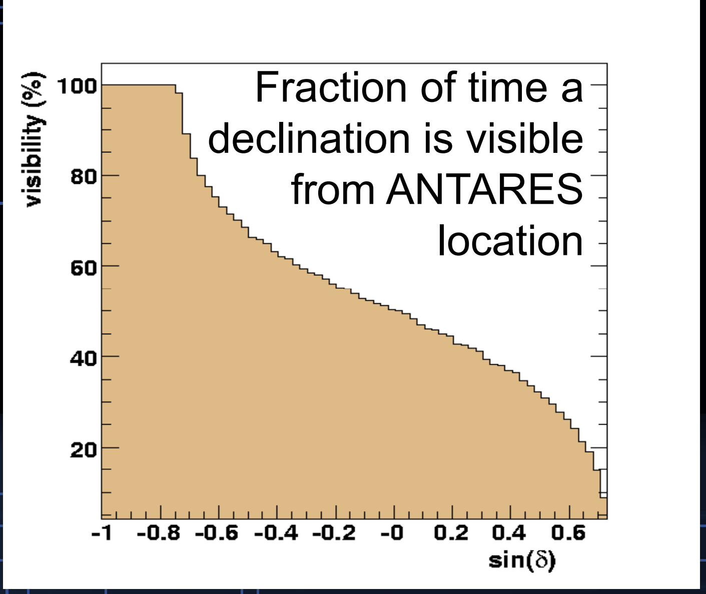


Discovery power as a function of the mean number observed (after track reconstruction and quality cuts)

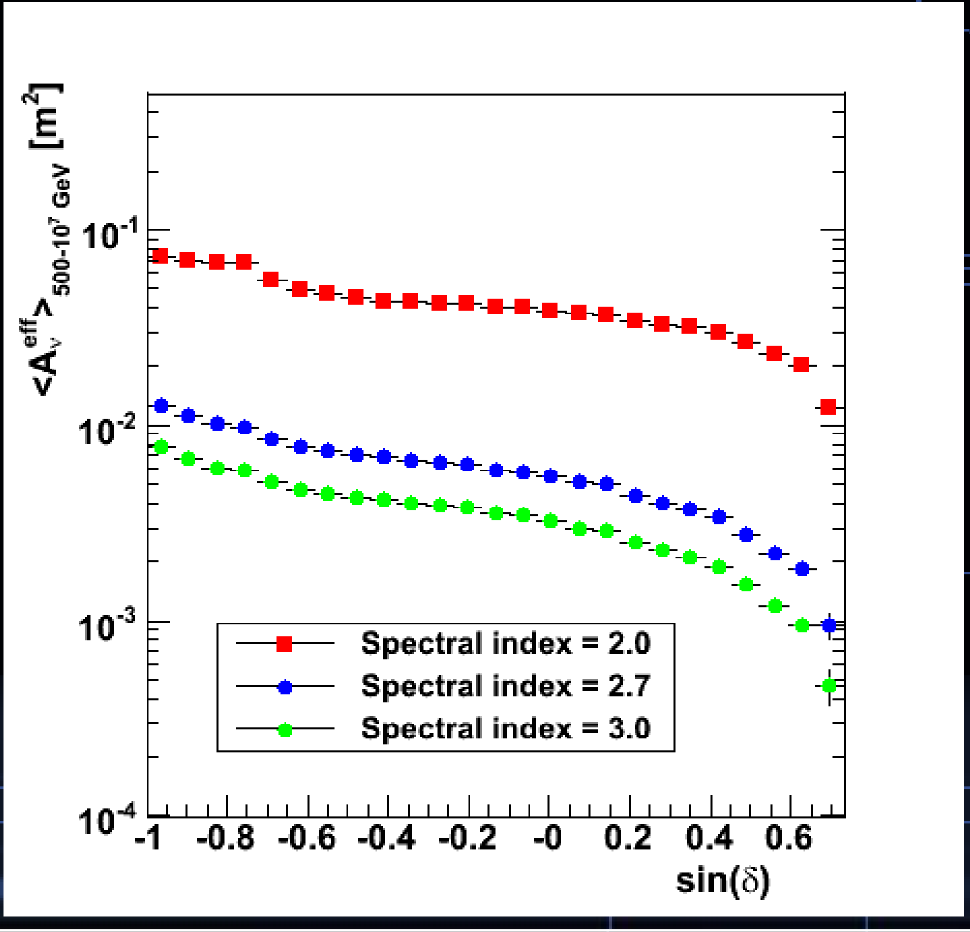
Neutrino effective area

The effective area relates the measured rate with the incoming flux:

$N_{det}=A_{eff} \times \text{Time} \times \text{Flux}$



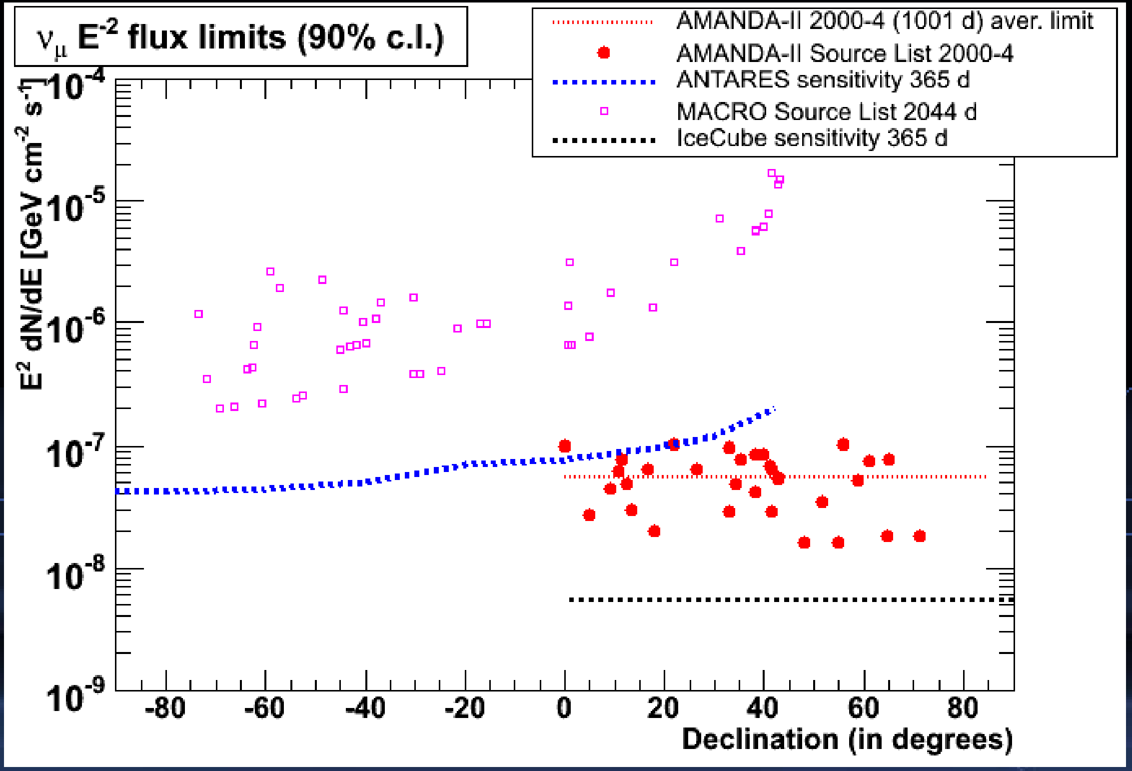
Effective area + visibility factor:



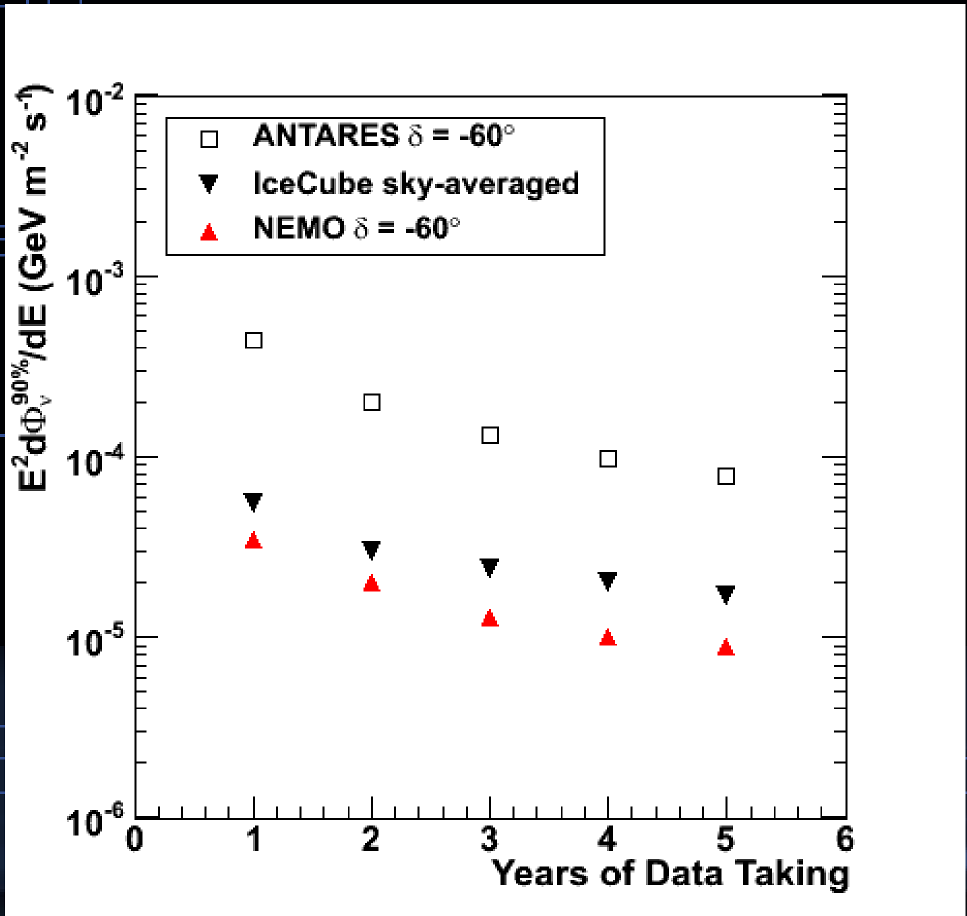
- This effective area applies to steady sources, since the visibility factor is included.
- There is a dependence on the energy integration limits (particularly important for the lower one). This plot corresponds to an integration from 500 to 10^7 GeV

Sensitivity

- The expected sensitivity of ANTARES in effective days 365 days is of the same order that the present limits set by AMANDA (for the Northern Hemisphere), since the better angular resolution allows a better background rejection



Sensitivity after several years



Sensitivity to a E^{-2} neutrino spectrum from a δ = - 60º declination point-like source for ANTARES, and NEMO (astro-ph/0611105) and averaged over all declinations in the Northern Sky for IceCube (astro-ph/0305196v1) with a 90% C.L. as a function of the exposure of the detector

Conclusions

- ANTARES will be soon completed, having an unsurpassed angular resolution, which renders it an exceptional tool for search point-like neutrino sources
- Several cluster search methods have been developed in the collaboration, including both binned and unbinned
- Unbinned methods have better performance. The best sensitivity is obtained with the Expectation-Maximization algorithm
- The expected sensitivity of ANTARES for 365 days is comparable to the limits set by AMANDA in 1001 days (2000-2004)