The ANTARES Telescope Status and Results

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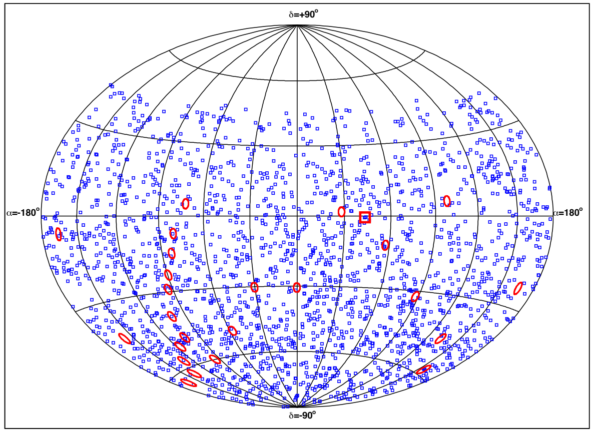
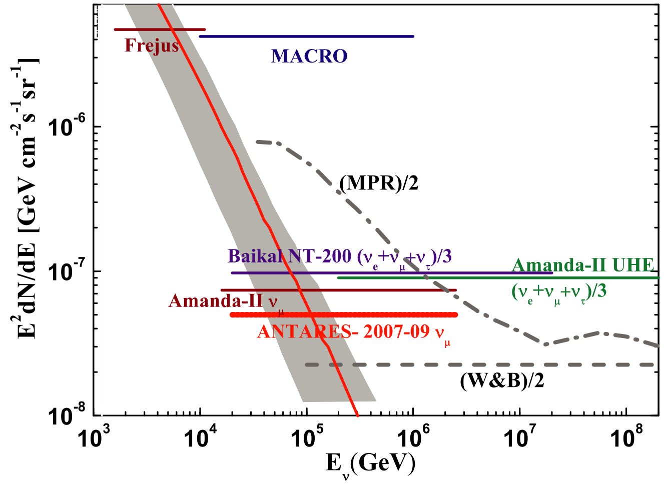
Recent Papers

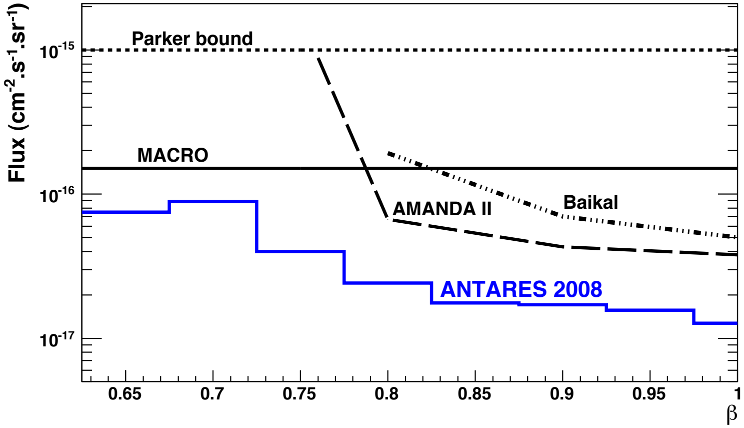
- Point Sources: ApJL accepted arXiv:1108.0292 [astro-ph.HE]



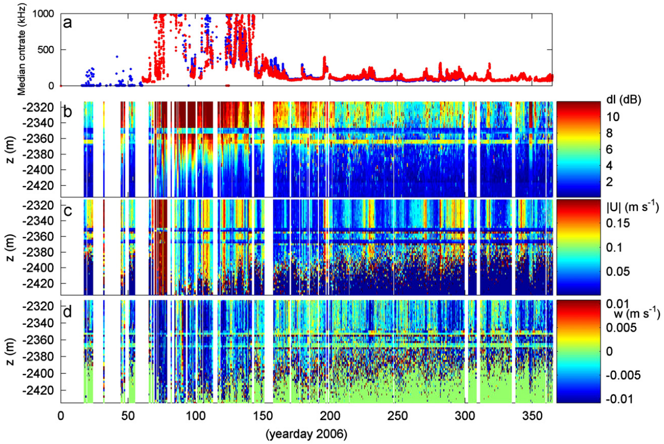
- Diffuse fluxes: Phys. Lett. B 696 (2011) 16-22



- Magnetic Monopoles: ApP submitted arXiv:1110.2656 [astro-ph.HE]

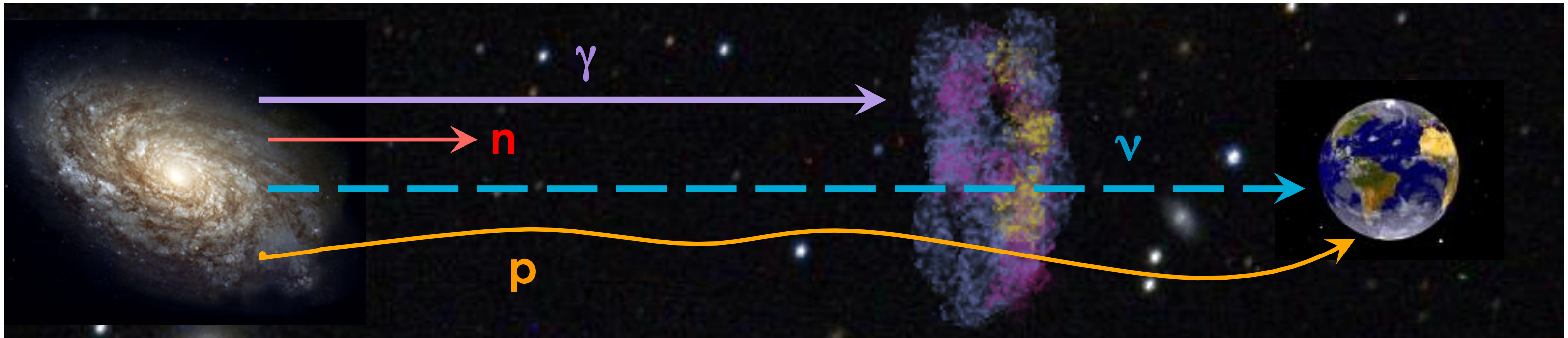


- Sea Sciences: Deep-Sea Research I 58 (2011) 875-884

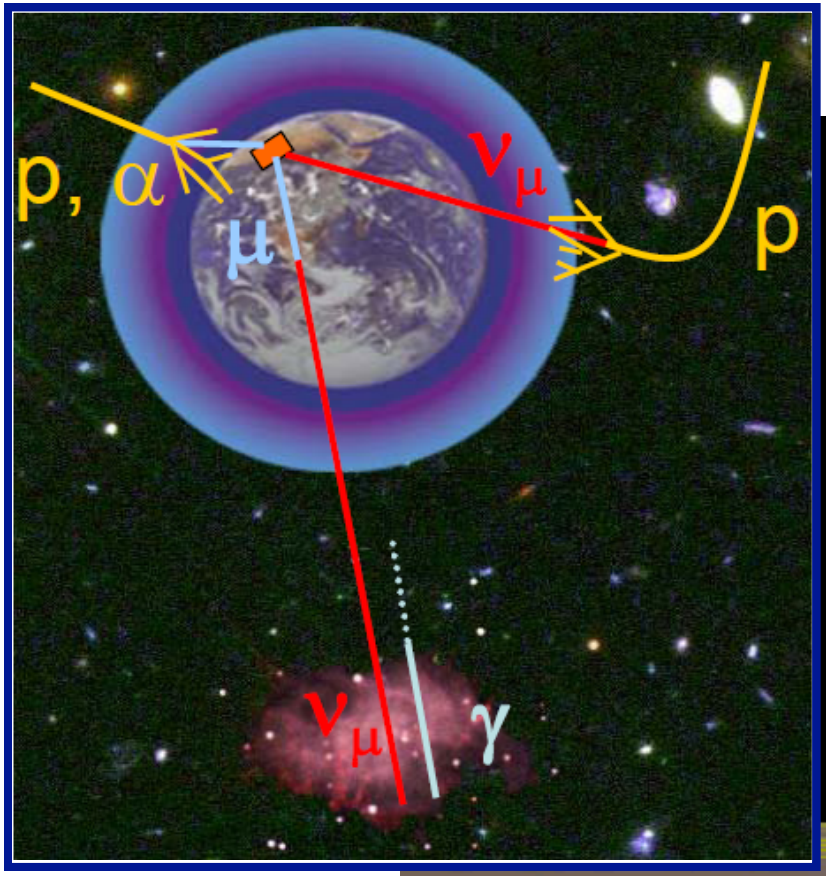


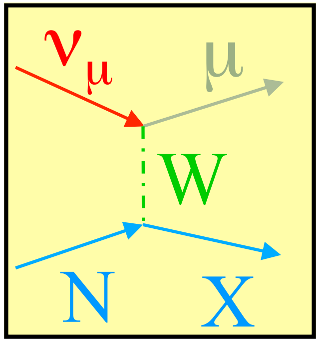
Why neutrino astronomy?

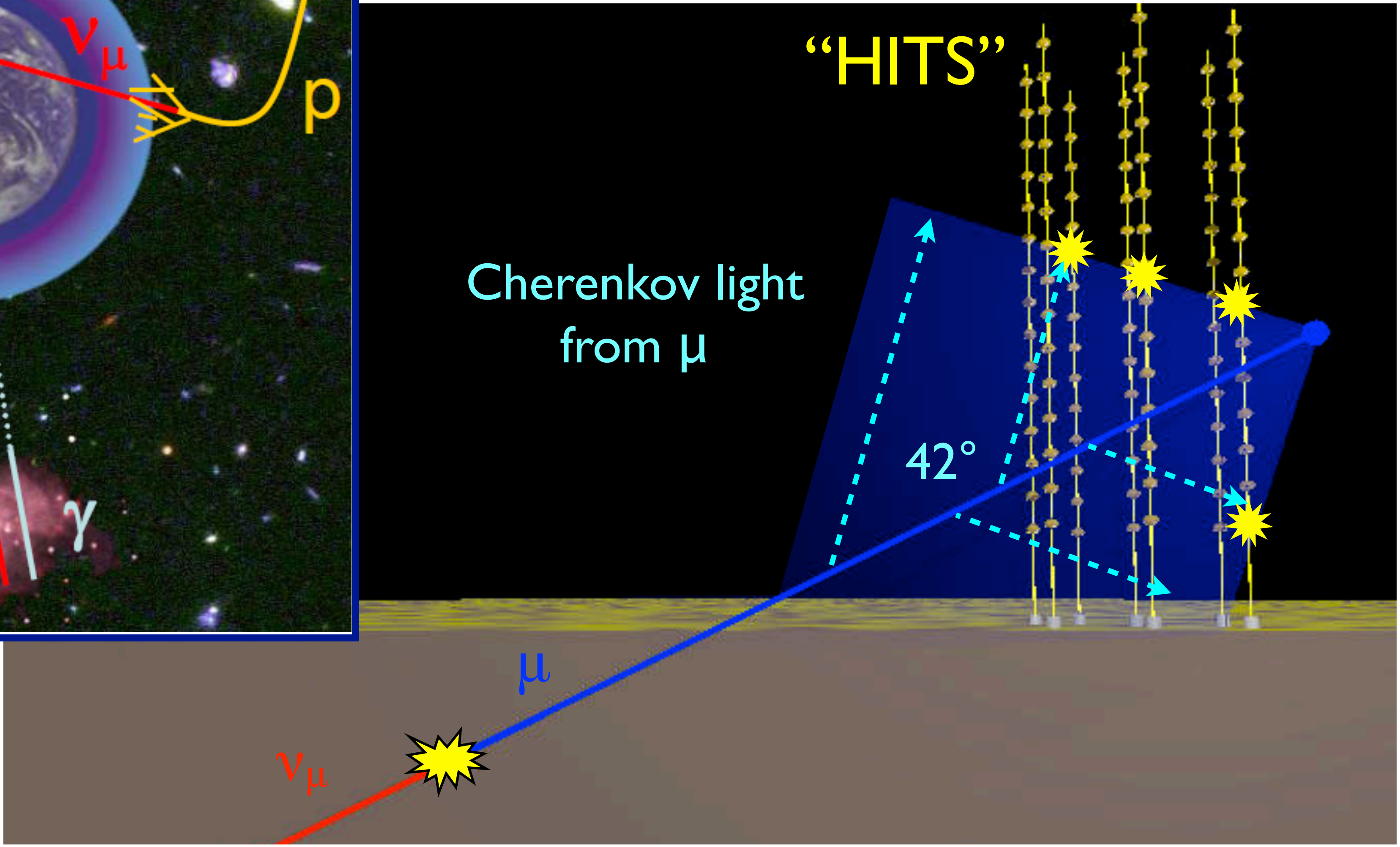
- Multi-messenger astronomy to extend our knowledge of the Universe.
- Probe the existence of astrophysical ν sources.
- Point sources search (optimised in the 1 TeV-1PeV range):
  - ➡ Galactic candidate ν sources (SNRs, micro-quasars, Fermi bubbles, unidentified TeV γ-ray sources);
  - ➡ Extragalactic candidate ν sources (GRB, AGN);
  - ➡ Unexpected ν sources (neutrinos can escape dense environments).
- Diffuse neutrino fluxes (collisions of cosmic rays with interstellar matter).
- Dark matter, neutrino oscillations, exotics phenomena.



Detection Principle

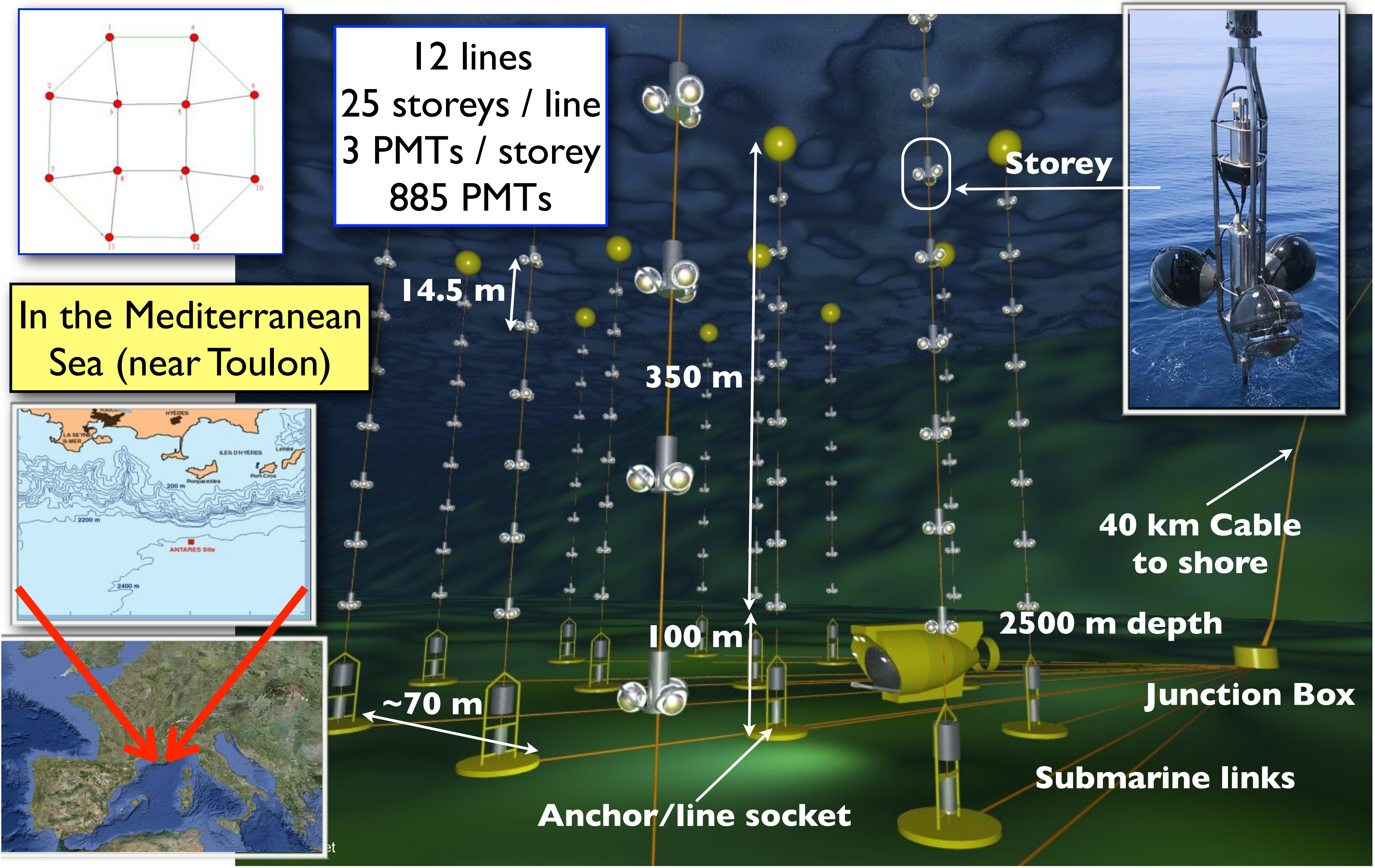






Detection of neutrino-induced muons
through the observation of Cherenkov light.

The ANTARES Telescope



ANTARES Collaboration

ITEP, Moscow
Moscow State Univ

LAM/COM/CPPM, Marseille
IRFU/CEA, Saclay
GRPHE, Mulhouse
APC, Paris
LPC, Clermont-Ferrand
IFREMER, Toulon/Brest
GeoAzur Villefranche

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

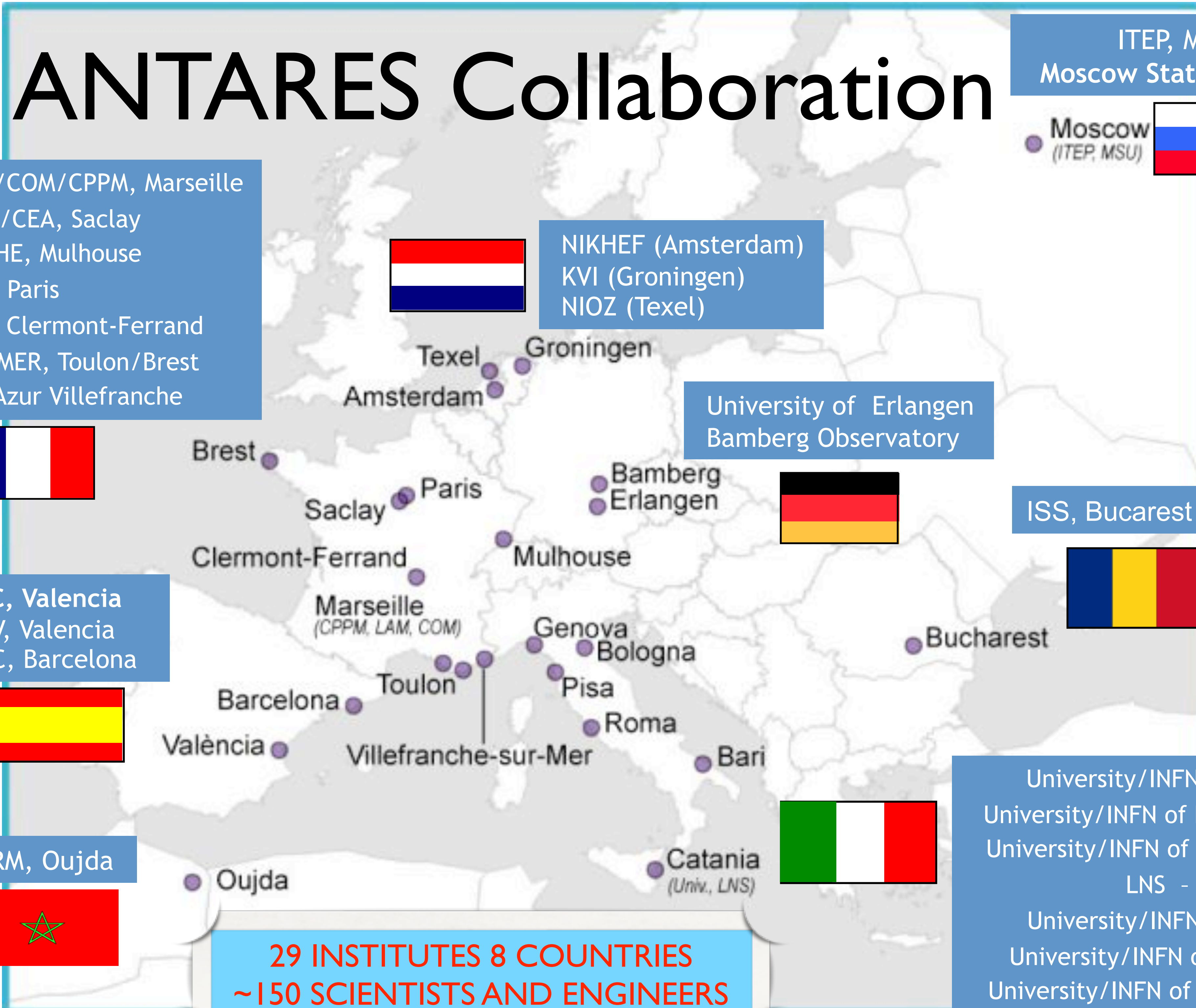
University of Erlangen
Bamberg Observatory

ISS, Bucarest

IFIC, Valencia
UPV, Valencia
UPC, Barcelona

LPRM, Oujda

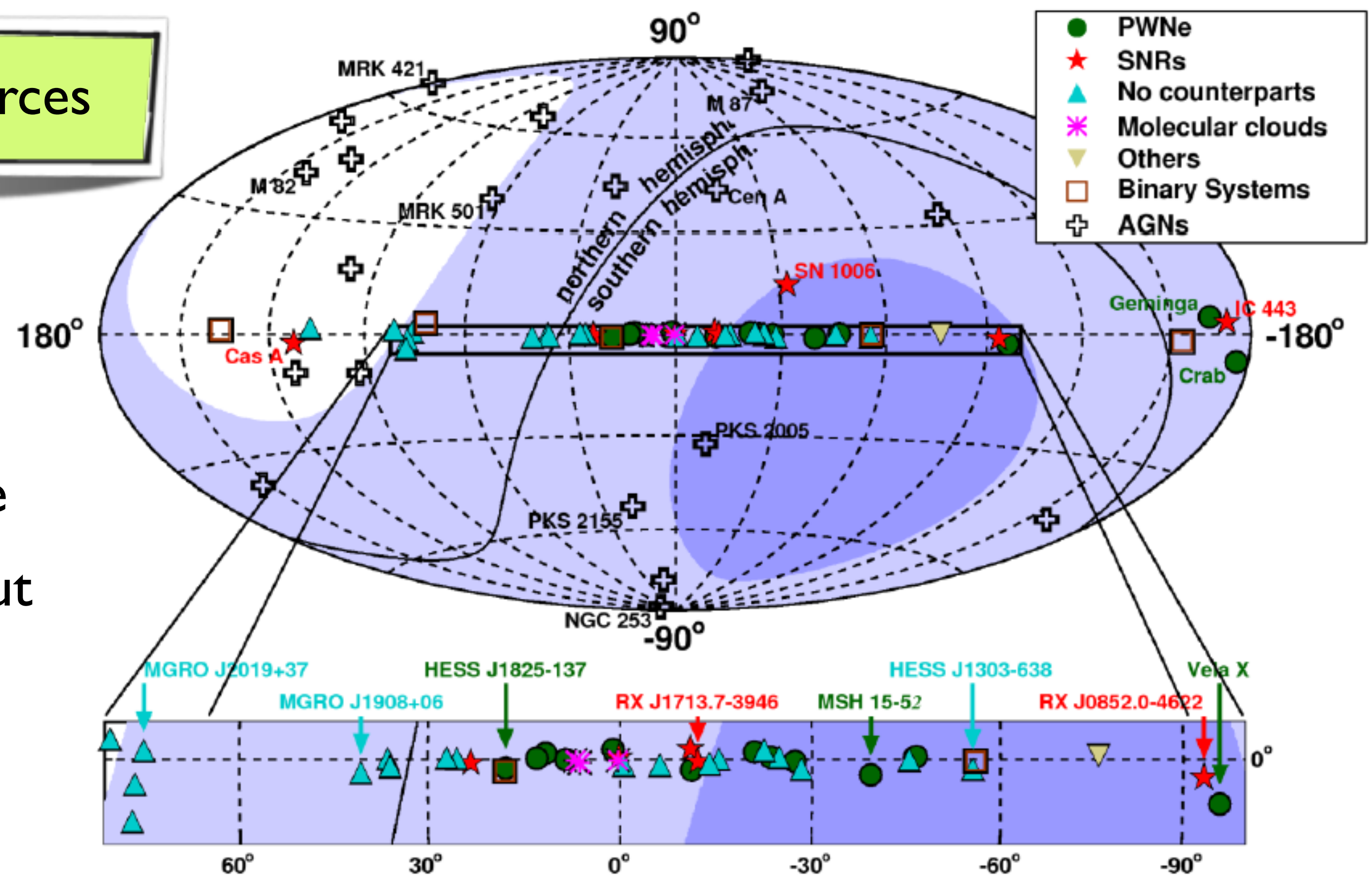
University/INFN of Bari
University/INFN of Bologna
University/INFN of Catania
LNS - Catania
University/INFN of Pisa
University/INFN of Rome
University/INFN of Genova



29 INSTITUTES 8 COUNTRIES
~150 SCIENTISTS AND ENGINEERS

Sky coverage for ANTARES

γ-ray sources



Up-going neutrinos
⇒ southern hemisphere

100% visibility up to about
δ= -50° in the
Mediterranean Sea

galactic coordinates

ANTARES observes a large part of the sky (~3.5π sr) – Galactic Plane most of the time.

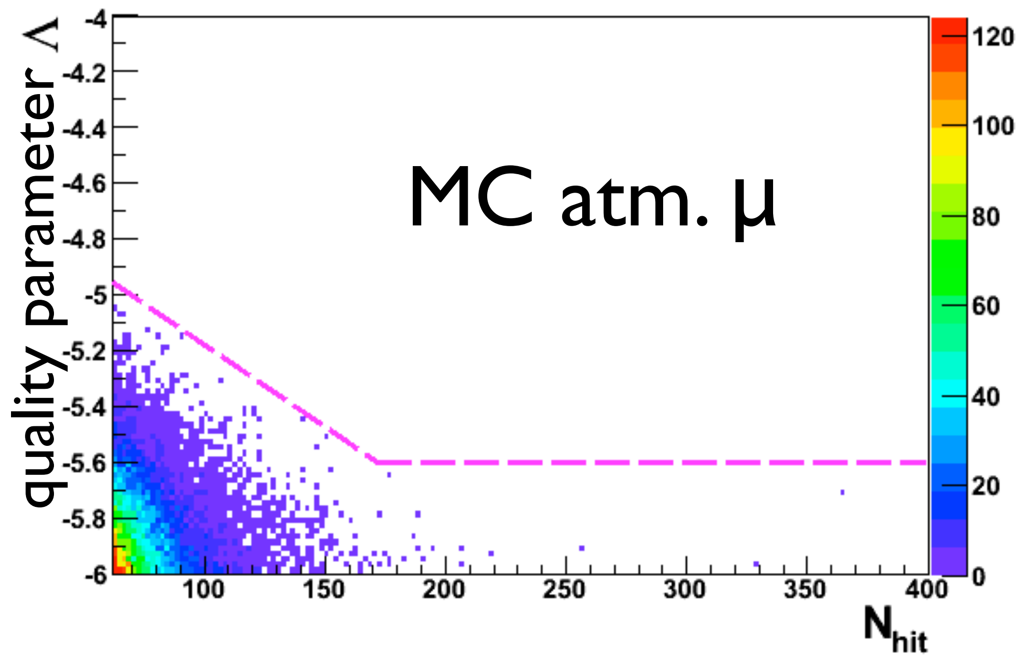
ANTARES complements the IceCube field of view.

Diffuse Flux Search

- Search of extraterrestrial neutrinos from unresolved sources
- Assumption of $\Phi \propto E^{-2}$ spectrum resulting from shock acceleration processes
- An excess of events over the expected atmospheric neutrino background will indicate an extraterrestrial neutrino flux
- Upper bounds for the neutrino diffuse flux are derived from the observation of the diffuse fluxes of γ-rays and ultra high energy CRs
- **ANTARES Data**: Dec. 2007-Dec. 2009 data (334 days)

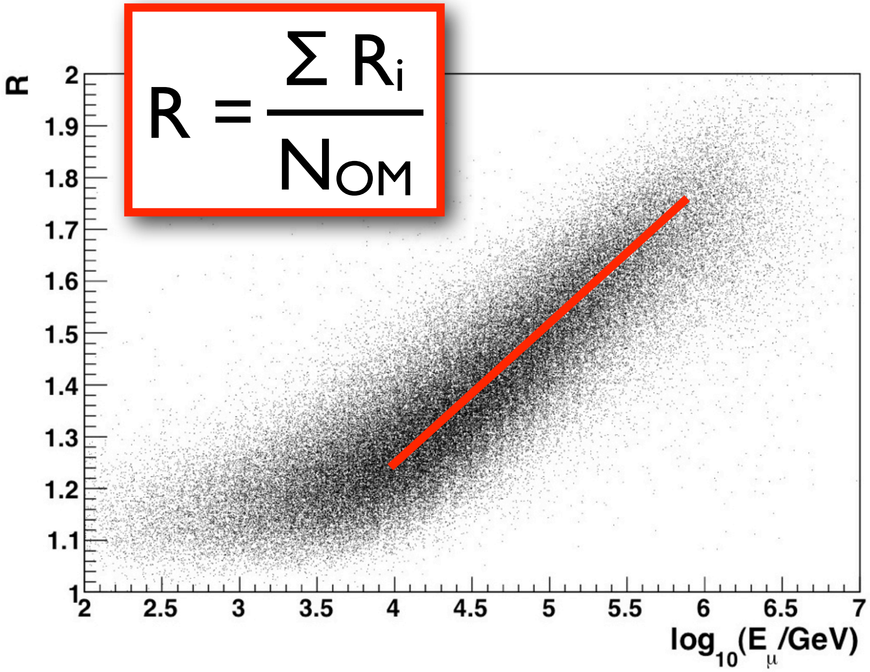
Event Selection

- Basic selection:
  - Good quality runs are selected (i.e. most of the detector running, low bioluminescence)
  - A trigger based on minimum number of causally related hits (all data to shore → on-shore event filtering)
- 1st Level cuts:
  - Upgoing reconstructed tracks of fair enough quality: $\cos\theta_{rec}<80°$, $\Lambda>-6$, $N_{hits}>60$
  - According to MC this removes all atm muons with E < 1 TeV and reduces mis-reconstructed events by almost 3 orders of magnitude (more about Λ later)
- 2nd Level cuts:
  - Combined selection based on N_{hits} and track quality, Λ



<u>MC: <1 mis-reconstructed muon/year in the final sample</u>

Energy Estimator

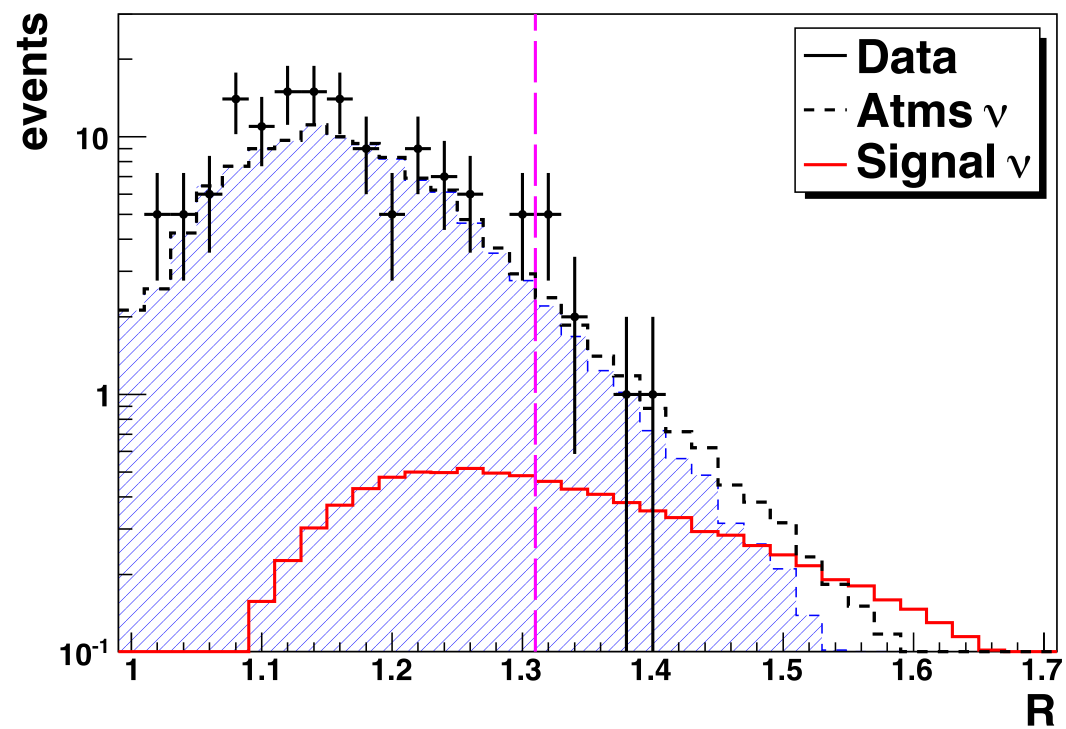


Mean number of Repetitions (R) of integration gate on the same Optical Module

High energy muons can produce more than one hit on a single PMT.
Direct + Scattered photons,
Light from EM showers

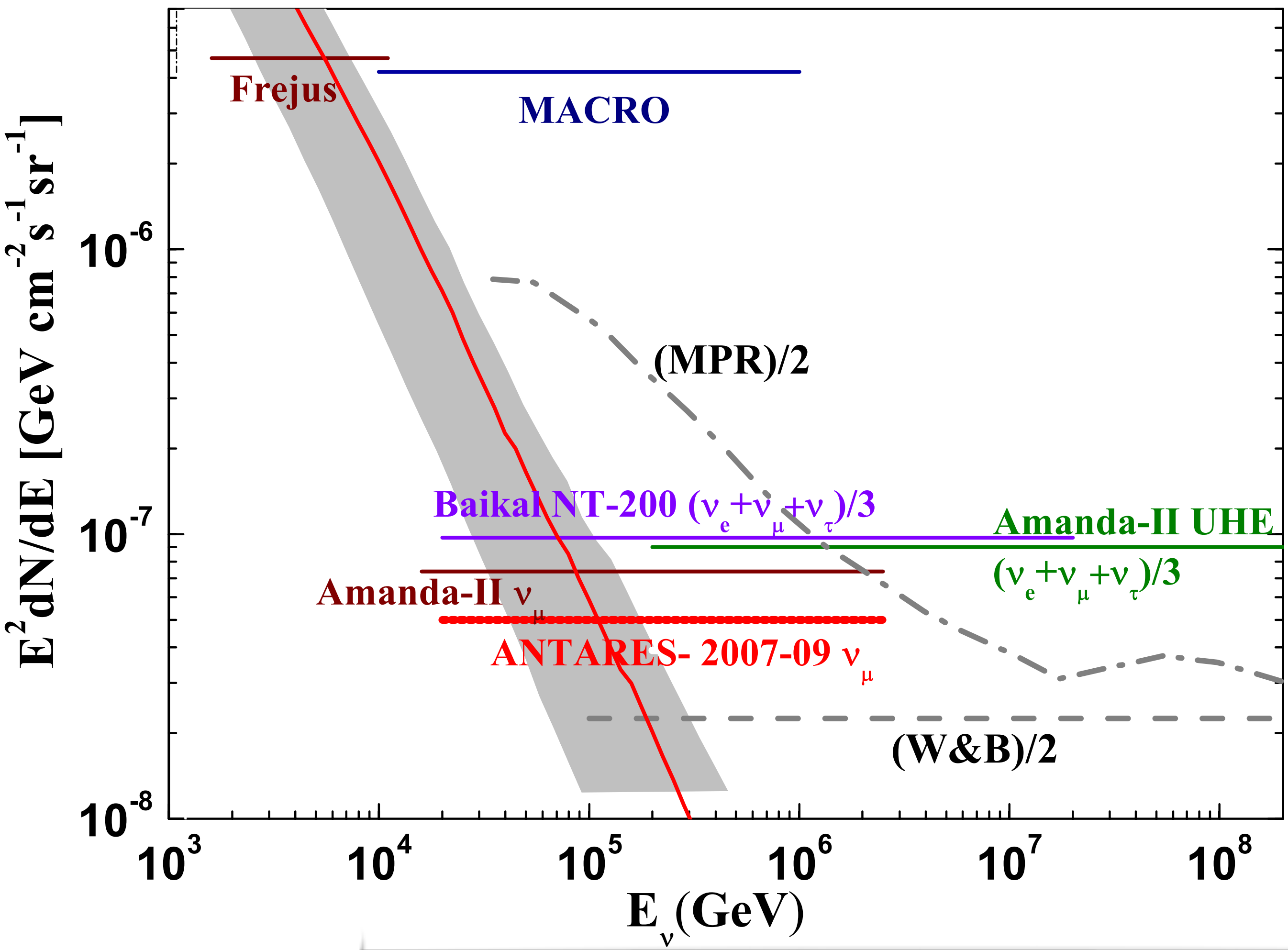
R cut determined by optimising the Model Rejection Factor. After unblinding (2nd level candidates) events above R cut are compatible with background expectation.

R<1.31		R≥1.31	
Bartol (conventional ν)	104.0	Atmospheric ν	10.7±2.4
Max "prompt" model	2.0	Exp. signal ν	10.8
Data	125	Data	9



$E^2 \Phi_{90\%\ C.L.} = 5.3\times10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

Diffuse ν_μ Flux: Upper Limit



$\Phi_\nu \propto E^{-2}$

20 TeV< E_ν<2.5 PeV

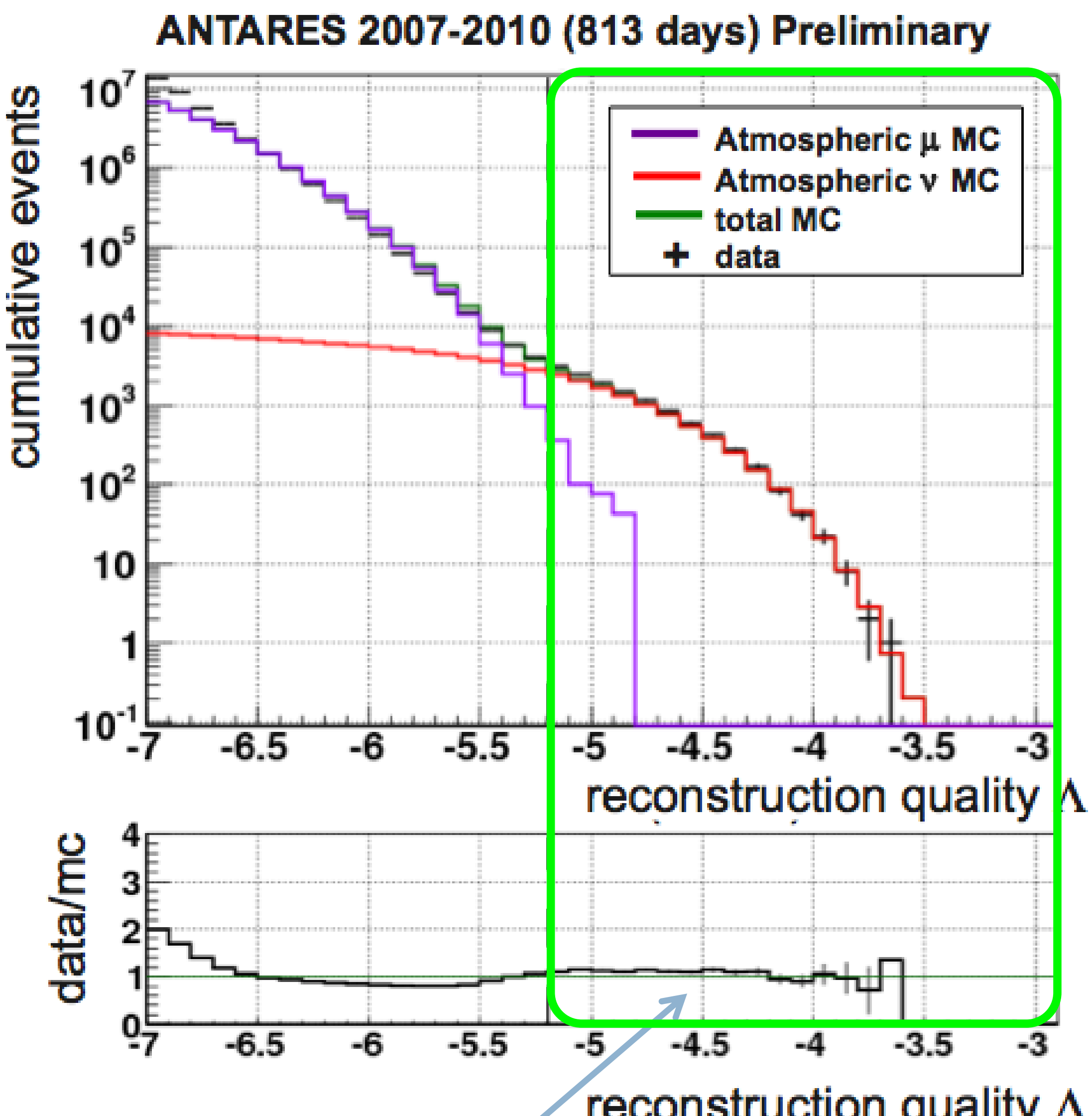
$E^2\,\Phi_{90\%\ C.L.}=5.3\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Search for Point Sources of Cosmic Neutrinos

- Make real "astronomy" with neutrinos!
- Look for event clusters using the good pointing capabilities of ANTARES (~ 0.5°)
- Data: Jan 2007-Dec 2010 data (813 days)¶
- Good quality runs are selected (i.e. most of the detector running, low bioluminescence)
- Keep events reconstructed as upgoing
- Events are accepted if the angular error estimate is $\beta < 1°$
- A cut on track quality ($\Lambda > -5.2$) is chosen to optimise the sensitivity to an E^{-2} flux

¶ Previous results for 2007-2008 data (304 days) can be found in arXiv:1108.0292 (accepted by ApJL).

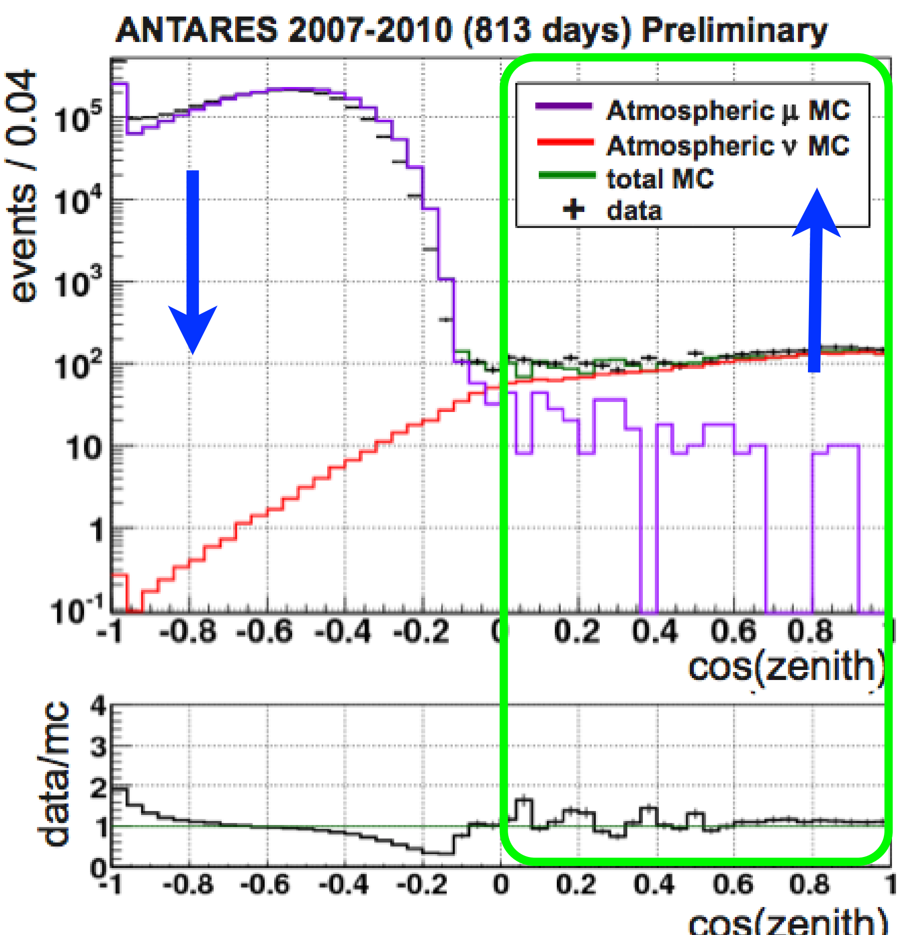
Atmospheric μ Reduction



data/MC ratio ≈ 1

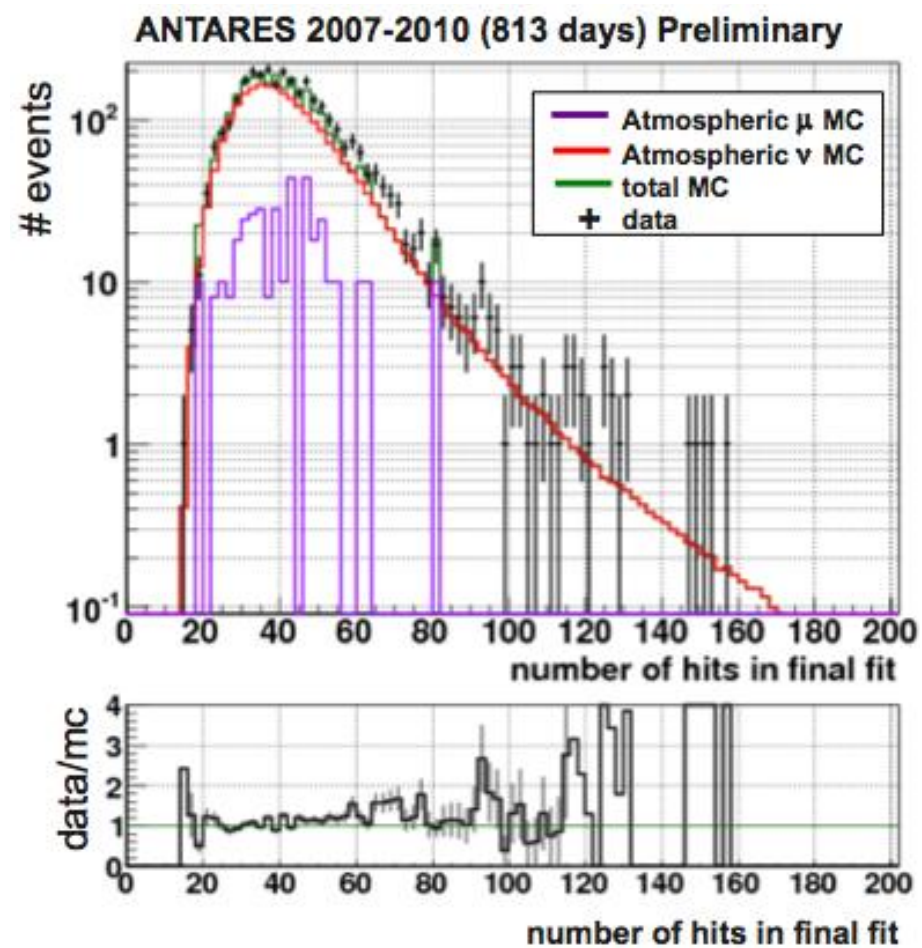
- Events in this plot are reconstructed as upgoing
- Cuts applied to select upward candidate neutrinos: Λ> -5.2 β< 1°
- Cuts are chosen to optimise the discovery potential
- 3058 events in final sample
- From simulation the muon contamination is 14%

Data-MC Comparison

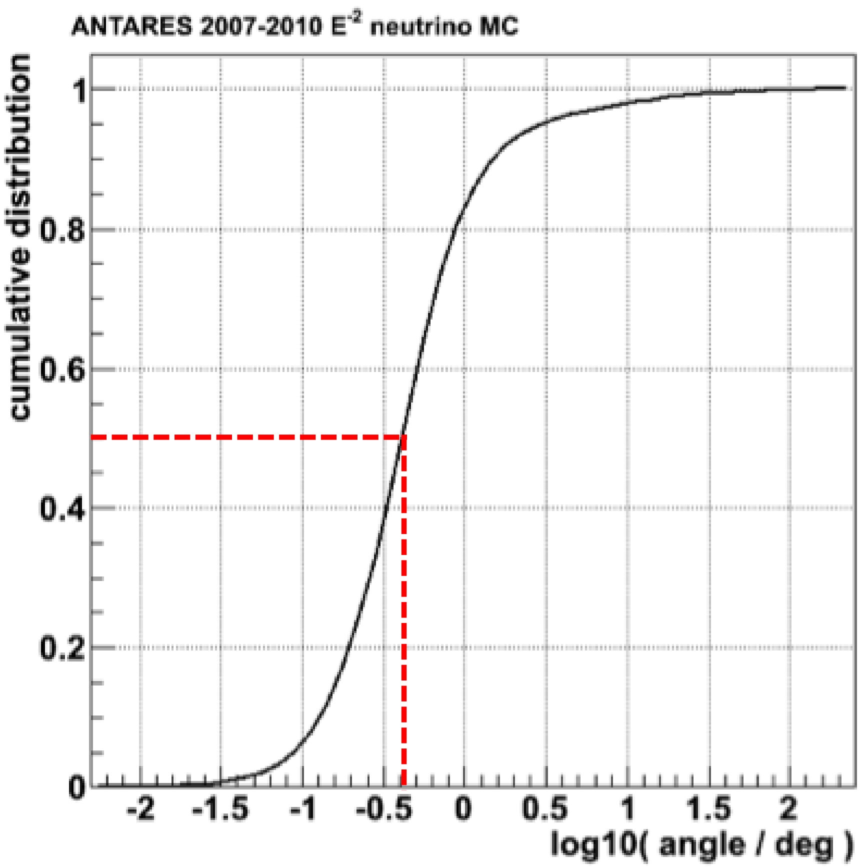


3058 neutrinos
14% muon contamination

N_{hit} used in search algorithm as energy proxy to further improve background rejection (see later)



Detector Performances



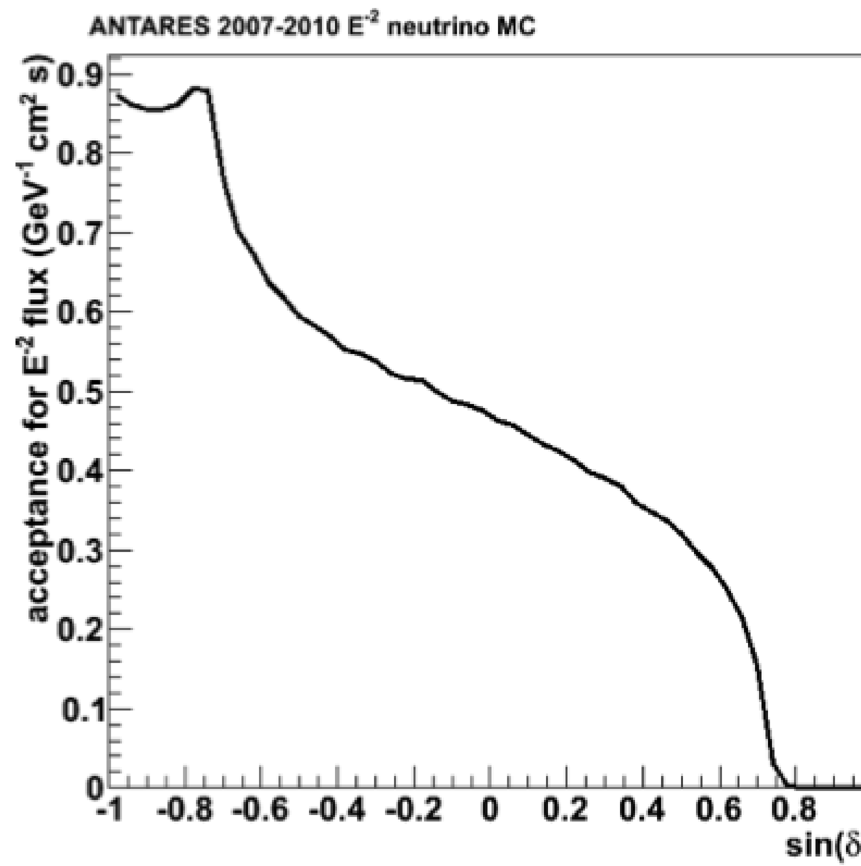
Cumulative angular resolution

E^{-2} flux for signal neutrinos

Angle between true (MC) neutrino direction and reconstructed track

Median is 0.46°

83% of events < 1°



Event acceptance

Number of selected events for a reference flux of

$\Phi = 10^{-8}\ (E\ /\ GeV)^{-2}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

as a function of the declination

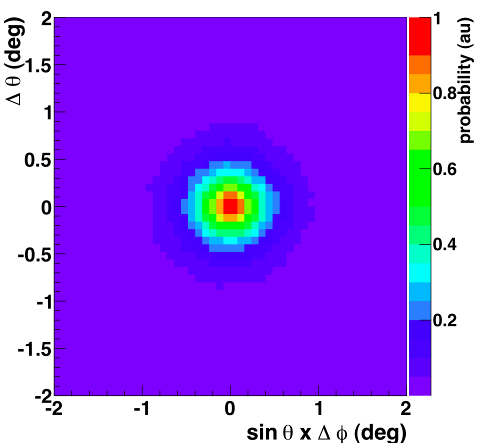
Everything included, i.e.: reconstruction, event selection and visibility

Unbinned Search Method

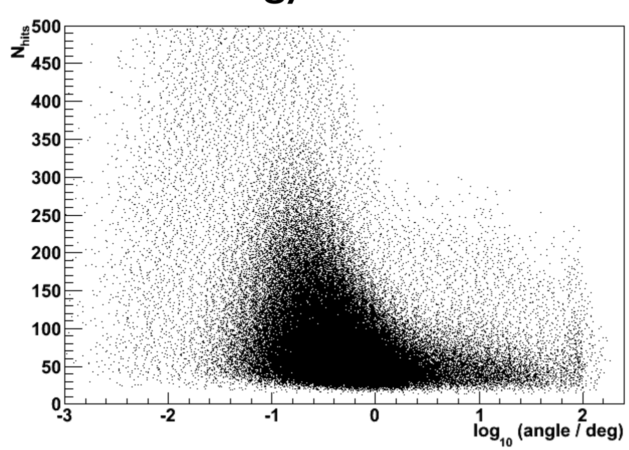
Compare expectation for background vs. signal (position and energy) and maximise likelihood ratio

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

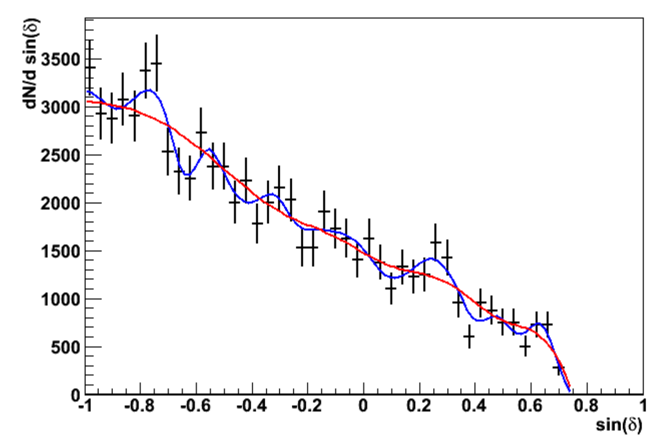
Angular resolution from MC (point spread function)



Bck/signal expected energy difference

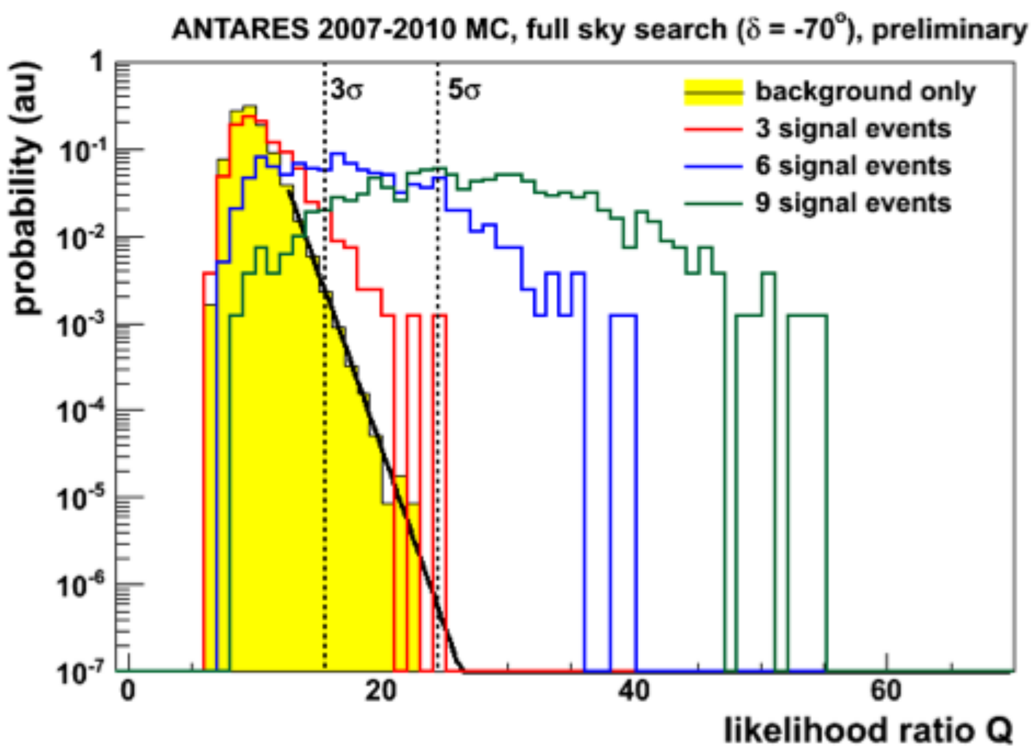


Background rate from real data: RA scrambling + parametrisation



Unbinned Search Method

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



Significance:

$$Q = \log \mathcal{L}^{max}_{\rm s+b} - \log \mathcal{L}_{\rm b}$$

the bigger is Q, the more data are signal-like

Statistical test

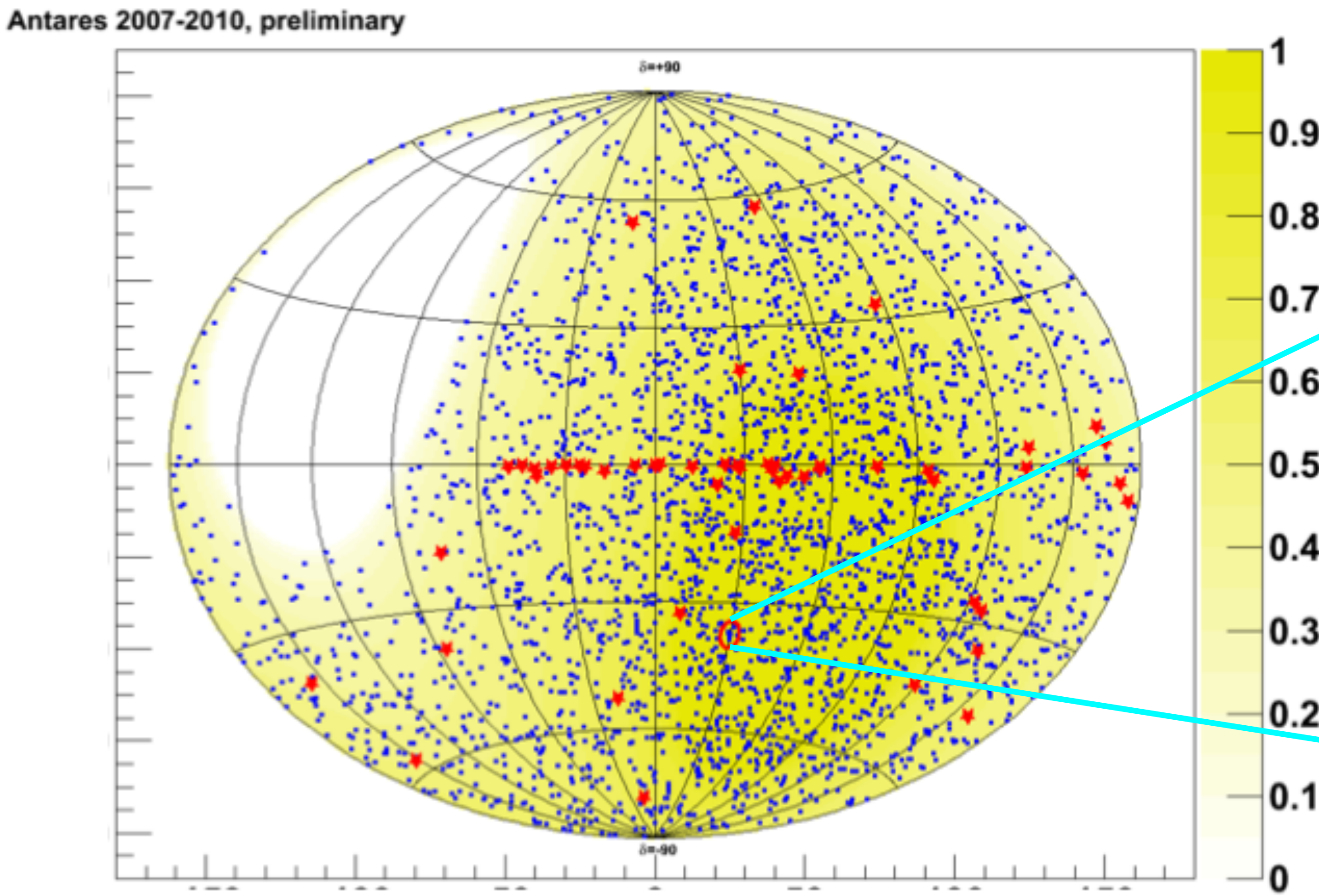
Full-sky search

The fitting procedure returns μ_{sig}, δ_s and α_s amount of signal (or limit) and position

Candidate list search

The fit gives μ_{sig}
only signal (positions fixed)

Full-sky Search Results

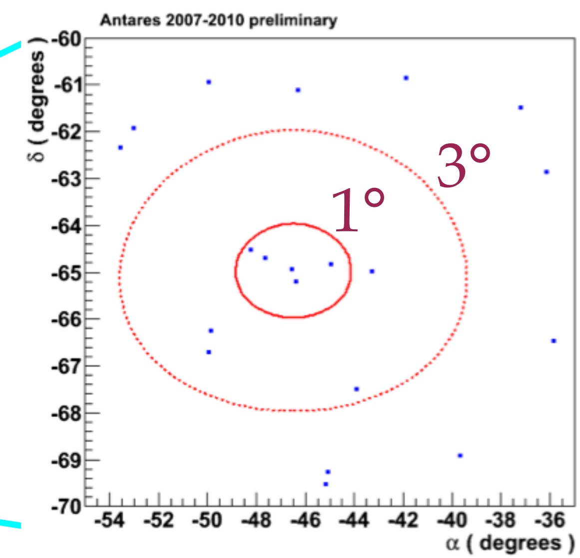


Most signal-like cluster at

α = -46.5°

δ = -65.0°

9 events inside a 3° cone



N_{sig} = 5

Q = 13.02

p-value = 0.026

Significance = 2.2 σ

Sky map in Galactic Coordinates

Background colour indicates visibility

Blue points: selected events (3058)

Red stars: candidate source list

Result compatible with the **background** hypothesis.

Candidate List Search Results

Look in the direction of a list of 51 predefined candidate sources (selection based on a convolution between the visibility and the gamma ray flux, IC40+IC59 hotspot included)

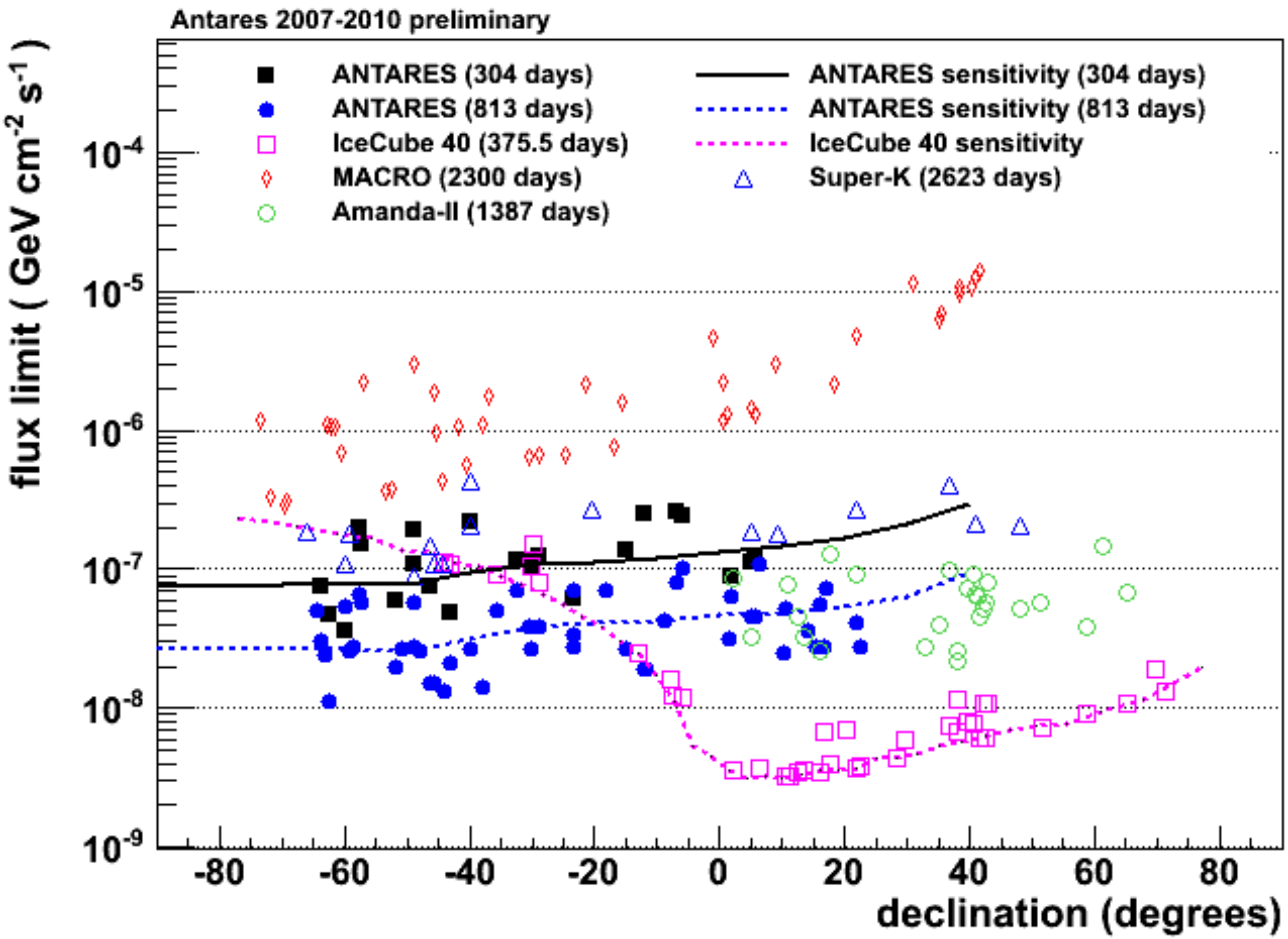
First eleven sources sorted by Q-value
Last column shows the 90% CL upper limit on the flux
$(E / GeV)^{-2}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

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

HESS J1023−575 most signal-like, p–value 40% (post trial)

Compatible with the background hypothesis

Candidate List Search
Flux Upper Limits



Assumed signal proportional to E^{-2} flux

ANTARES 2007-2010
813 days
x 2.5 improvement w.r.t. previous analysis (304 days)

For most of candidate sources ANTARES gives the most stringent limits.

IceCube requires very high energy component (E >1 PeV) for Southern Sky.

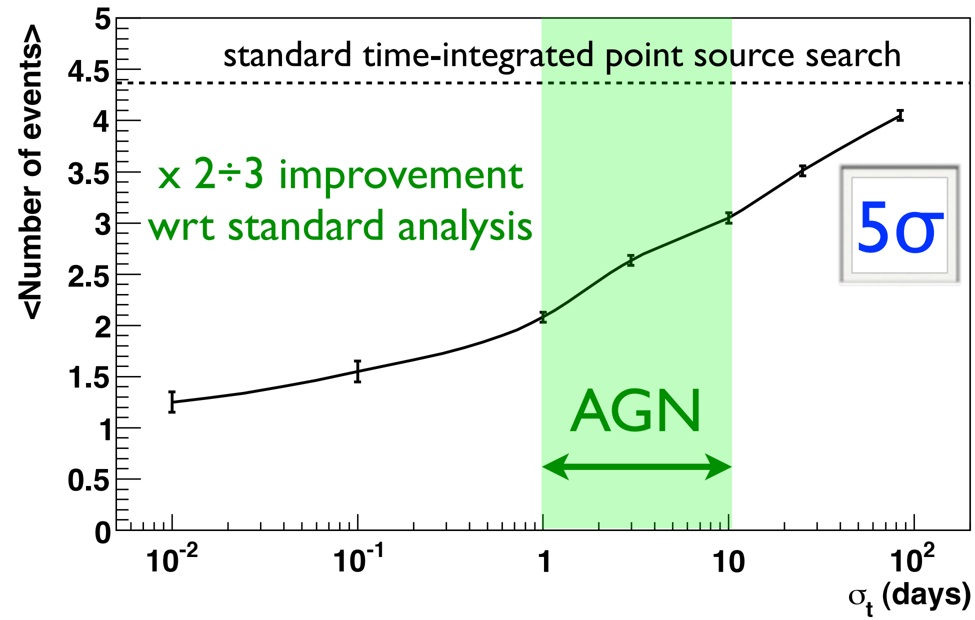
Flares from AGN Blazars

- Production of high-energy neutrinos in astrophysical sources where acceleration of hadrons may occur. MeV-TeV gamma-rays and high energy neutrinos are produced through hadronic interactions of the high energy cosmic rays with radiation or gas clouds surrounding the source.
- AGN blazars exhibit relativistic jets pointing towards the Earth and are some of the most violent variable high energy phenomena in the Universe.
- The gamma-ray light curves of bright blazars reveal important time variability on timescales of hours to several weeks, with intensities much larger than the typical flux of the source in its quiescent state.

Neutrino Search from γ-ray Flaring Blazars

- Discovery potential increases using the information from γ-ray detectors (Swift, Fermi , HESS)
- ANTARES data: 2008 (61 days)
- LBAS Catalog (Fermi LAT Bright AGN Sample)
- Event selection: quality runs, $\Lambda > -5.4$, $\beta < 1°$
- Include space-time information in likelihood ratio to reduce background and increase discovery potential.

$$\mathcal{L} = \sum_{i=1}^{N} log \frac{\frac{n_{sig}}{N} P_{sig}(\alpha_i, t_i) + (1 - \frac{n_{sig}}{N}) P_{bkg}(\delta_i, t_i)}{P_{bkg}(\alpha_i, t_i)}$$



Neutrinos from γ-ray Blazars: Results

10 flaring sources in selected period:

PKS0208-512, AO0235+164, PKS1510-089, 3C273, 3C279, 3C454.3, OJ287, PKS0454-234, Wcomae, PKS2155-304

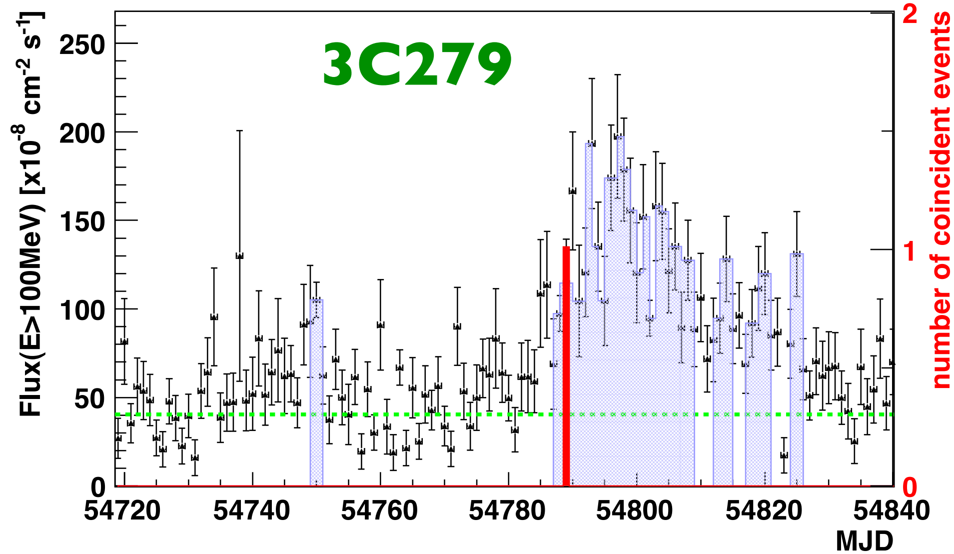
For 9 sources: 0 events

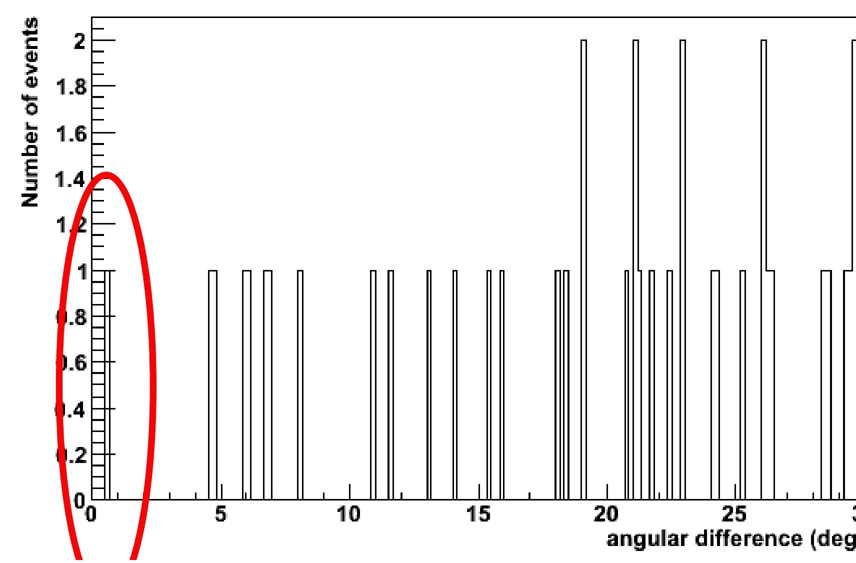
⇒ upper-limit on the neutrino fluency

For 3C279: 1 event compatible with the source direction ($\Delta\alpha$=0.56°) and time distribution

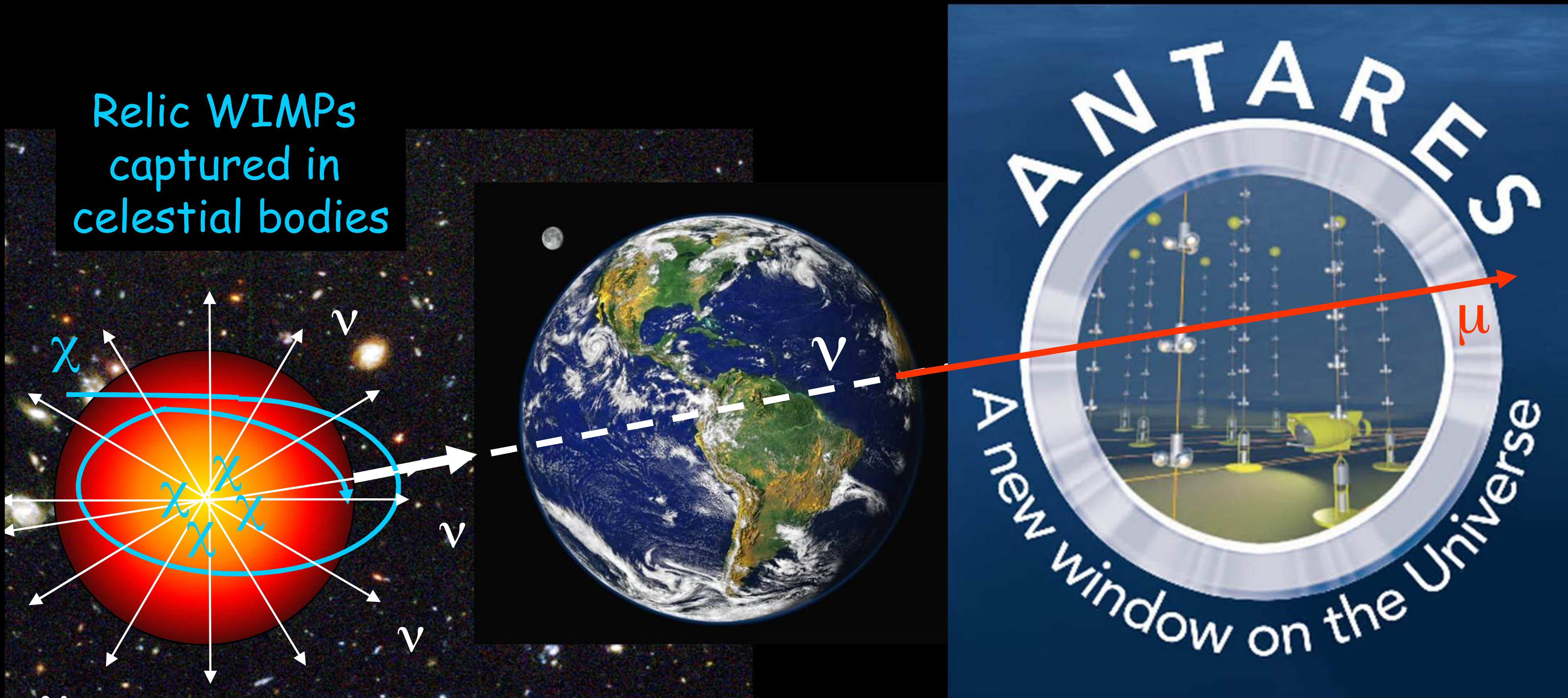
⇒ pre trial p-value = 1.0%
post trial p-value = 10%

Not significant!





Dark Matter Search



$\chi\chi$ self-annihilations into
c,b,t quarks, τ leptons or W,Z,H bosons
can produce significant
high-energy neutrino flux

Potential $\chi\chi \rightarrow \nu$ sources are
Sun, Earth & Galactic Centre
Signal less affected by
astrophysical uncertainties
than γ-ray indirect detection

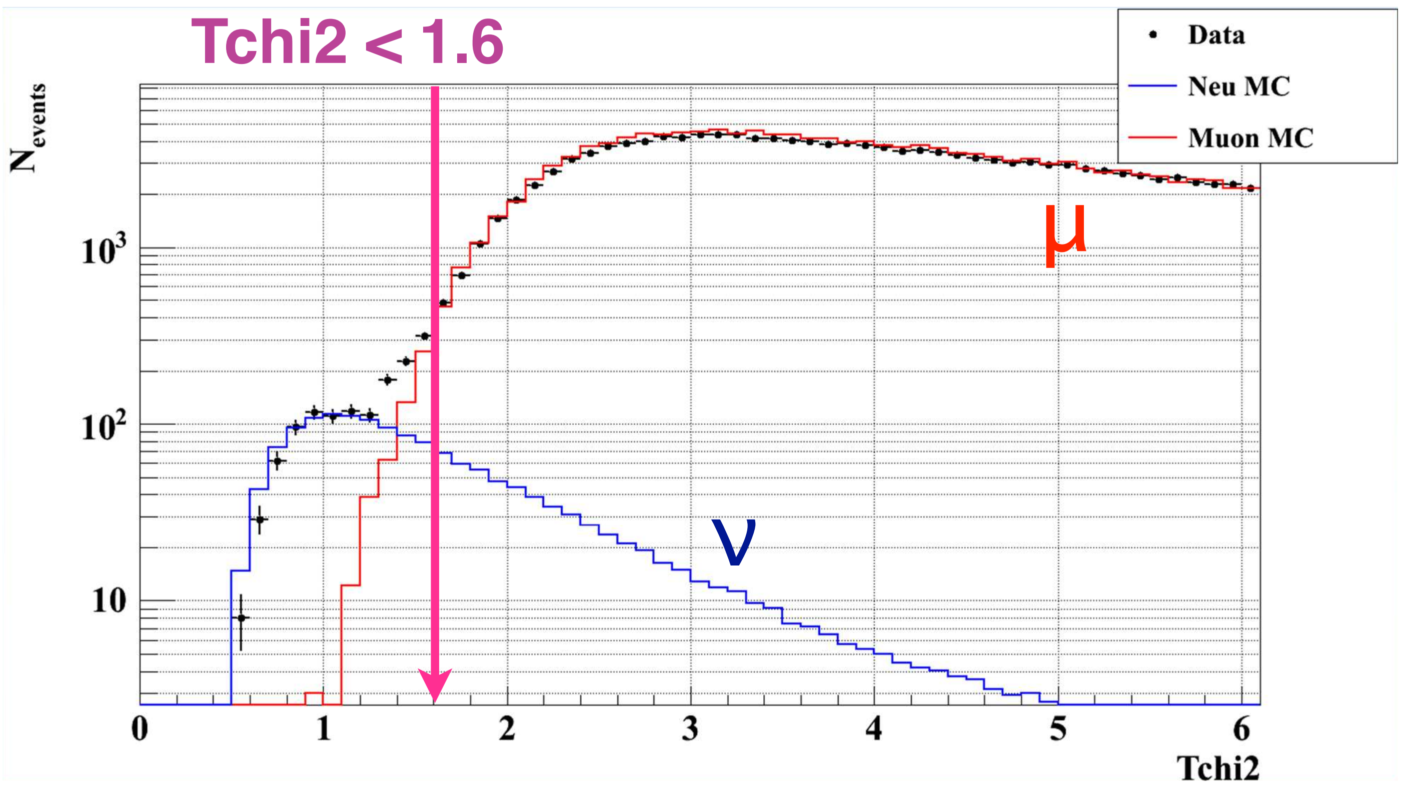
DM Search - the Ingredients

- **Binned search** towards the direction of the **Sun** (visibility below horizon)
- **Background** from atm. neutrinos and muons estimated from MC simulation and **scrambled data**
- **Signal energy spectrum** derived from **WIMPSIM**¶ simulation package for different **WIMP masses** and **annihilation channel** hypotheses

¶ A WIMP MonteCarlo for neutrino telescopes (Blennow, Edsjö, Ohlsson). It calculates the annihilation of WIMPs inside the Sun, collects all the νs that emerge and propagate them to the detector including ν interactions and oscillations.

DM Search

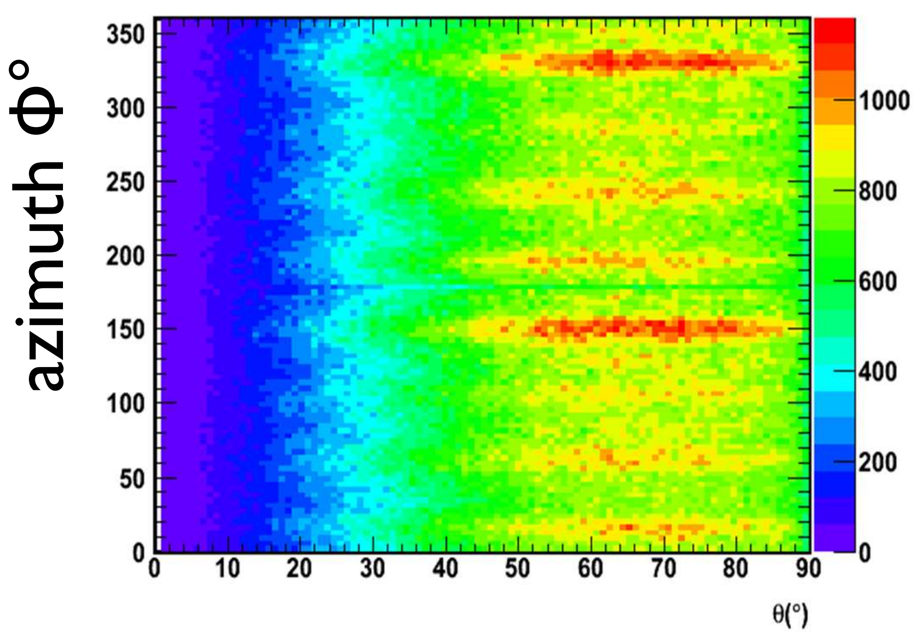
- Event selection based on **fast** and **robust** track reconstruction algorithm [ApP 34 (2011) 652]
- Very good agreement data vs MonteCarlo events (2007-2008 data analysis)
- Strong reduction of the atmospheric muon background



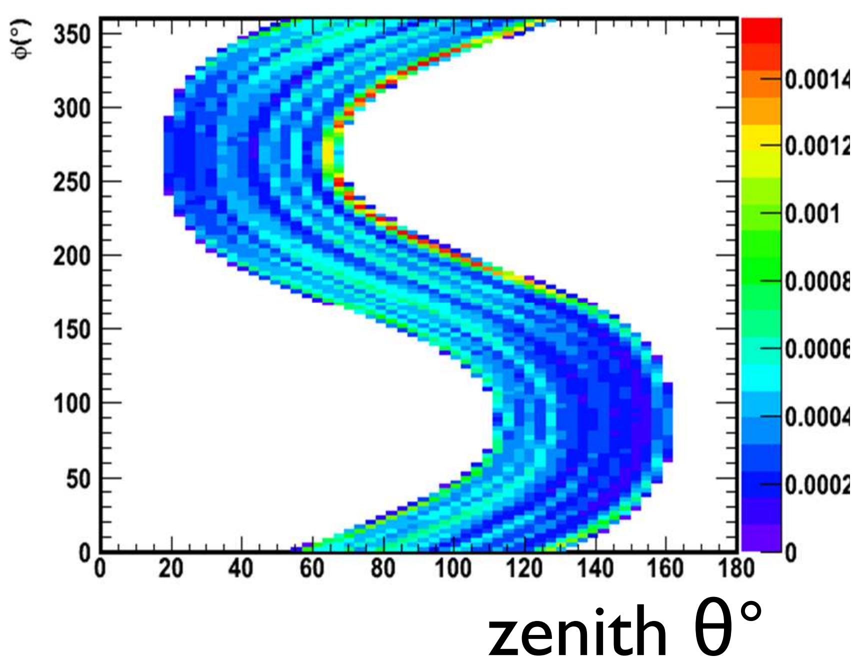
Background in the Sun direction

- Neutrino background estimated from data scrambled in time (θ,Φ) using the Sun visibility at the ANTARES location

All up-going events from 2007-2008 data

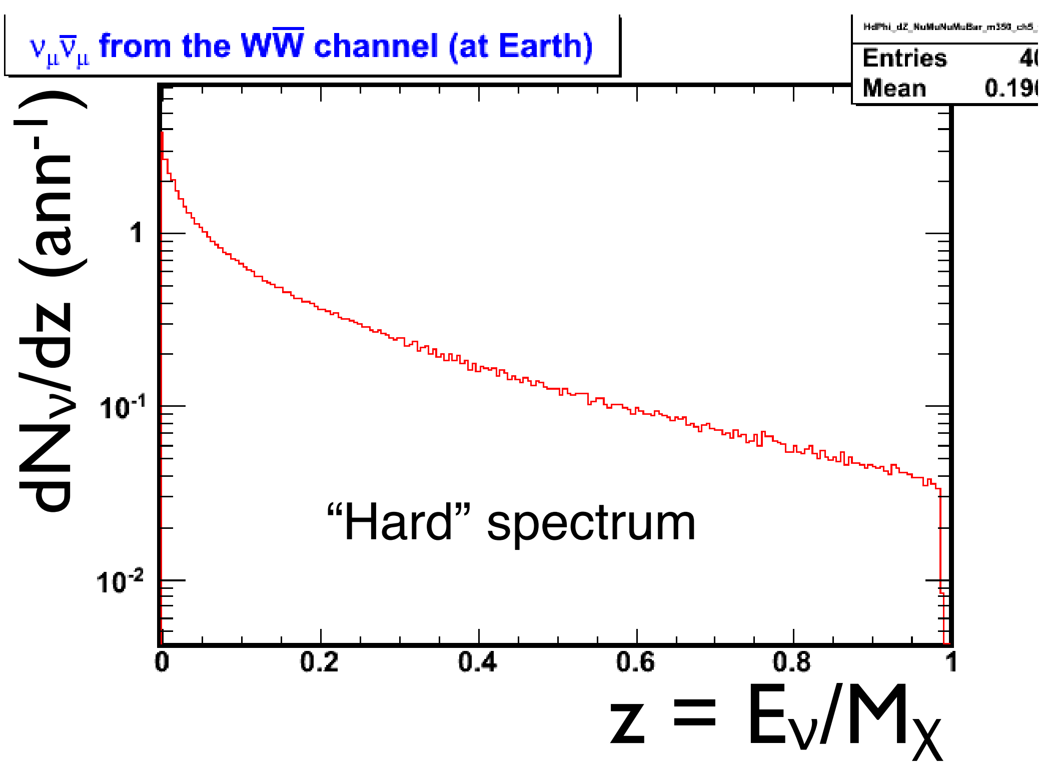


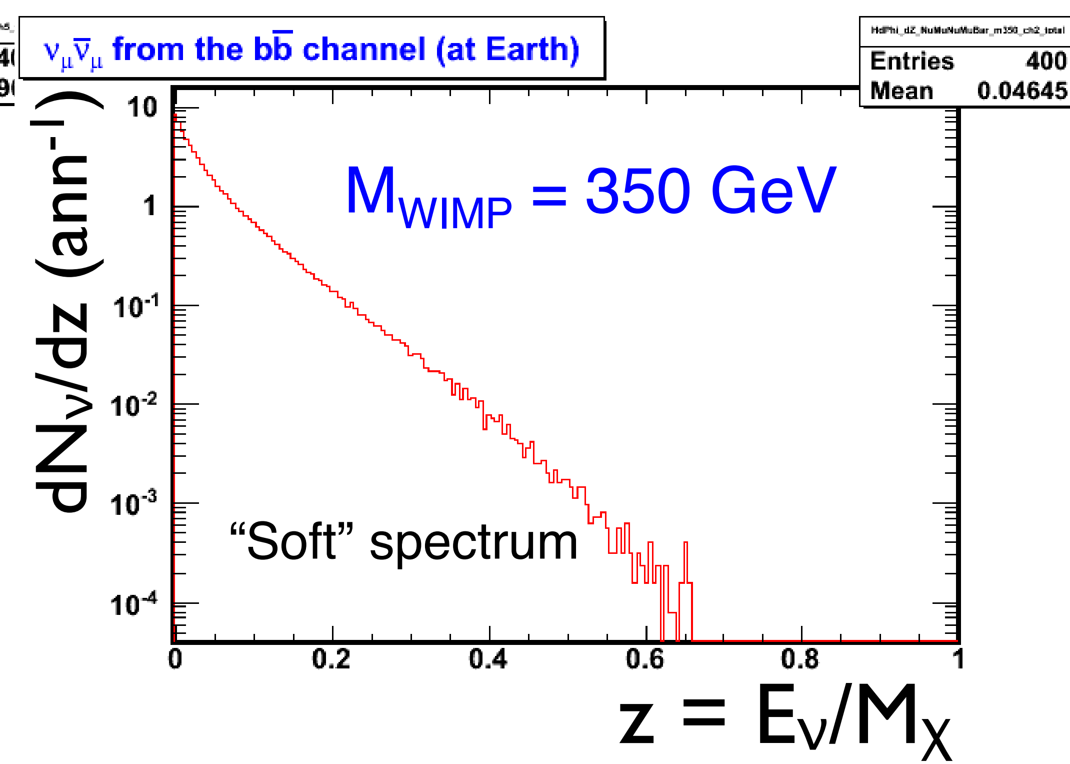
Example of Sun tracking in horizontal coordinates



Neutrino signal from WIMP annihilation

- The WIMPSIM package used to generate events in the Sun
- Large statistics with 3×10^6 WIMP annihilations
- Annihilations in c, b, t quarks, τ leptons, WW/ZZ bosons and direct channels
- Neutrino interactions in the Sun medium taken into account

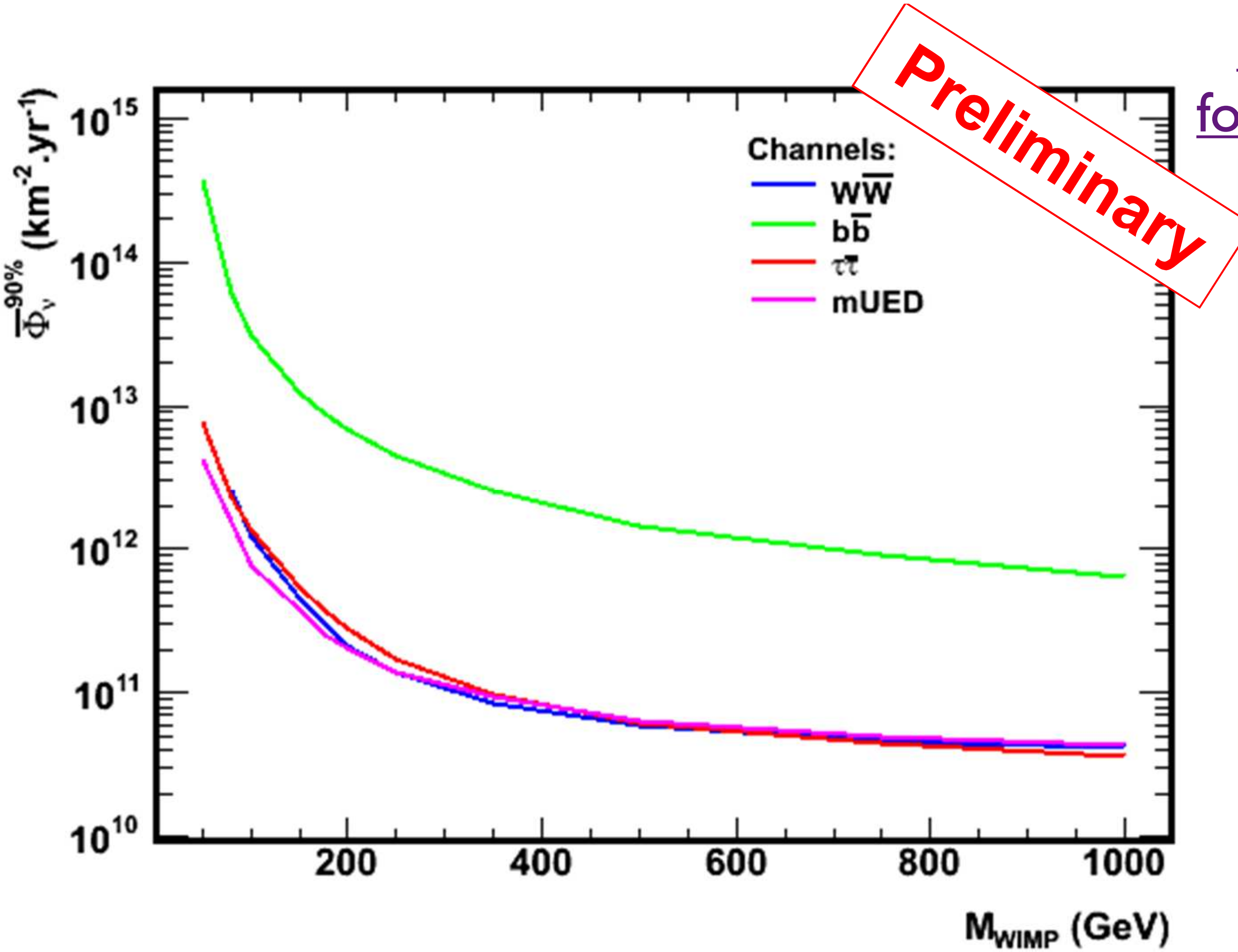




Sensitivity to ν flux

Neutrino fluxes at the Earth produced by Dark Matter annihilation are **convoluted** with the **detector efficiency** for given selection parameter sets (track fit quality, cone size)

$$Sensitivity = \frac{\bar{\mu}_{90}}{Aeff(Mwimp) \times Teff}$$



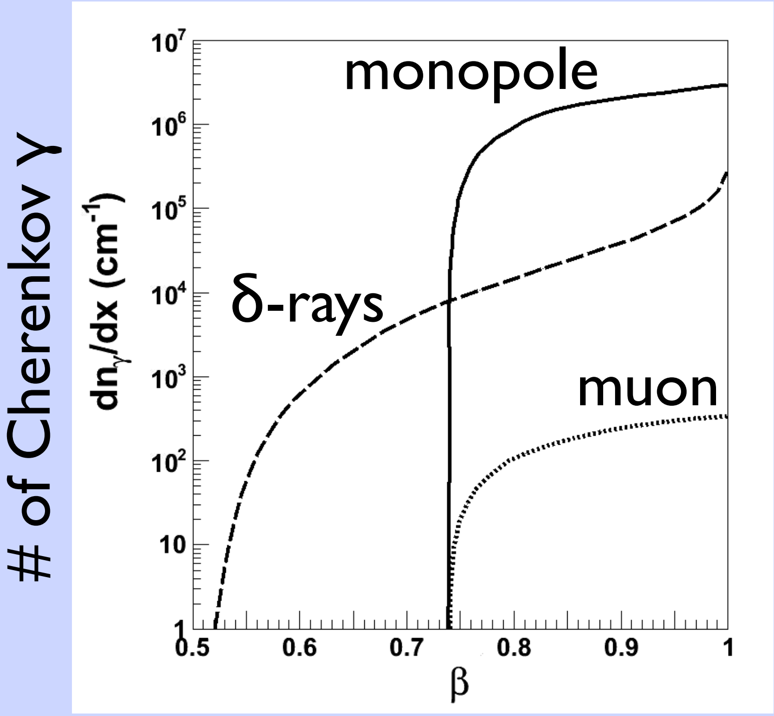
Sensitivity to neutrino flux for ANTARES 2007-2008 data

For CMSSM:
Branching ratios = 1
(for WW, bb, ττ)
(Large variation of branching ratios over CMSSM parameter space)

For mUED:
Theoretical branching ratios taken into account

Magnetic Monopoles

- ANTARES 2008 data: 116 days live-time
- Dedicated MC to simulate magnetic monopole signal in the velocity range β = [0.550, 0.995]
- Optimised algorithm with track fit and point-like fit, monopole velocity is a free parameter (v<c)

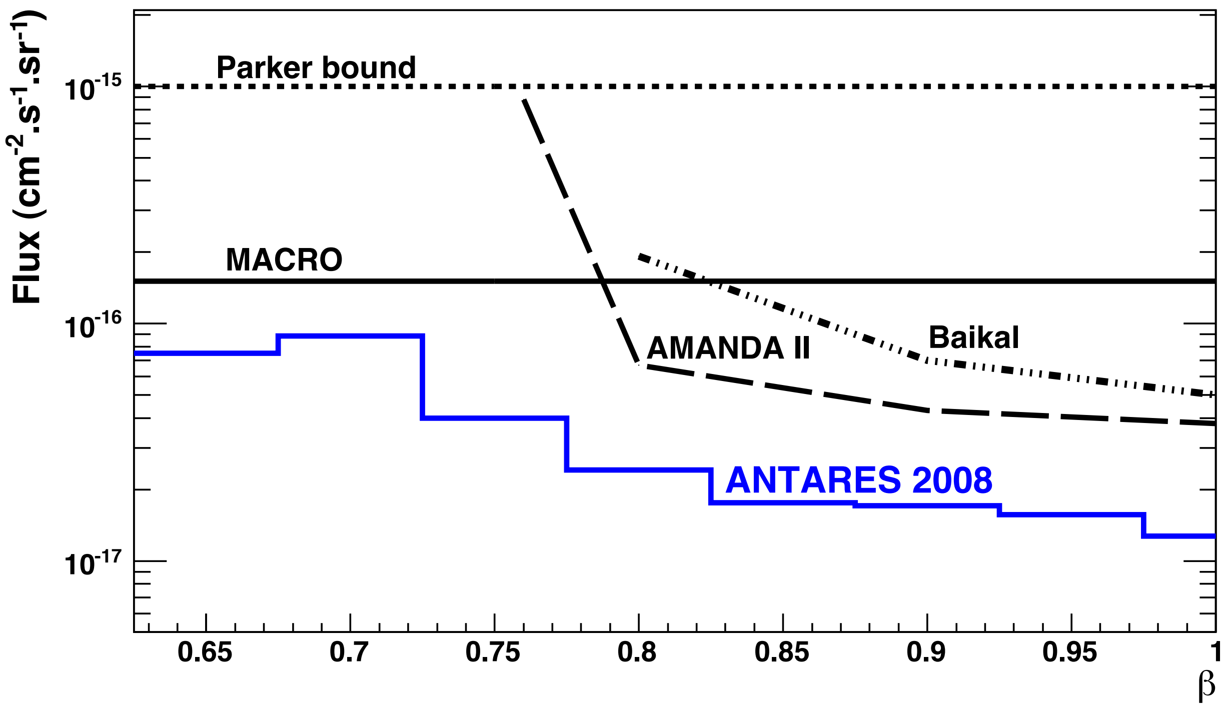


- Event selection: cuts on the number of hits and the parameter P:

$$P = \log\left(\frac{Q_t(\beta_{rec} = 1)}{Q_t(\beta_{rec} = free)}\right) \begin{cases} >0 \text{ monopoles} \\ <0 \text{ atms } \mu \text{ and } \nu \end{cases}$$

(Q_t is a quality parameter)

Magnetic Monopoles: Upper Limit



116 days ANTARES data

Best limits above the Cherenkov thr. for $0.75 \leq \beta \leq 0.995$ ($\gamma=10$)

The analysis improves the upper limits also below the Cherenkov thr. for $0.625 \leq \beta \leq 0.75$
(low scattering in sea water: good identification of bright objects)

Summary

- ANTARES is continuously taking data in its final configuration since June 2008.
- ANTARES is the biggest neutrino telescope in the Northern hemisphere.
- Complementary measurements with respect to IceCube (but Galactic Plane!)
- The first analyses have been completed, and several others are being performed.
- We are waiting for the first astrophysical neutrino!