



# ANTARES Results

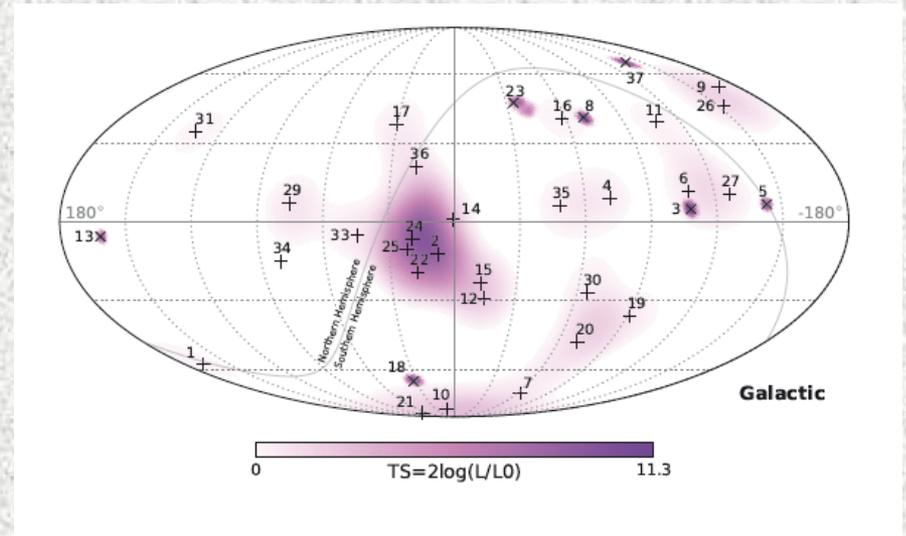
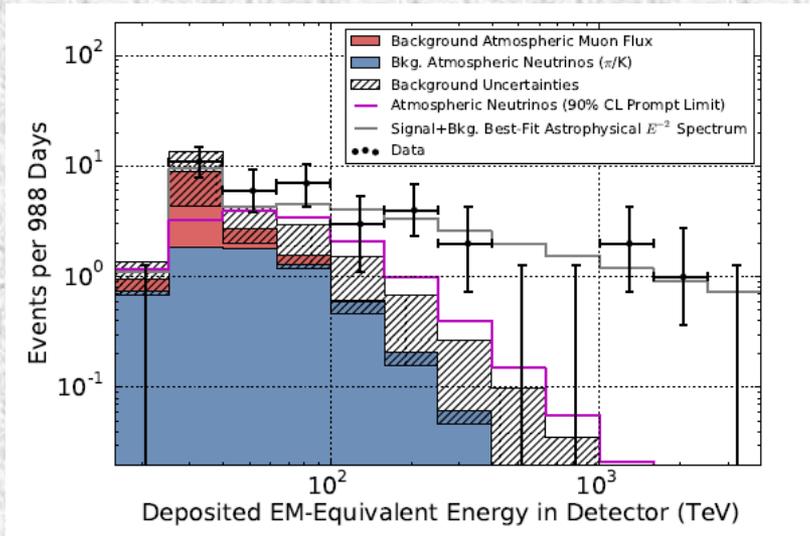


J.J. Hernandez-Rey  
IFIC (CSIC-UV)

On behalf of the  
ANTARES Collaboration

# First cosmic HE neutrino signal detected by IceCube

After several decades of scientific and technical efforts



What can ANTARES say?

# Highlighted topics

- Diffuse fluxes
  - full-sky (tracks and showers)
  - Fermi Bubbles
- Point sources
  - Full-sky and selected candidates
  - near the Galactic Centre
- Multi-messenger searches
- Dark Matter
  - Sun, Galactic Centre

Left out : neutrino oscillations, magnetic monopoles, multi-messenger searches with optical devices, GWHEN (VIRGO/LIGO), dark matter: dwarf galaxies, Earth, secluded DM, nuclearites, associated sciences,...

# The ANTARES Telescope

12 lines (885 PMTs)

25 storeys / line

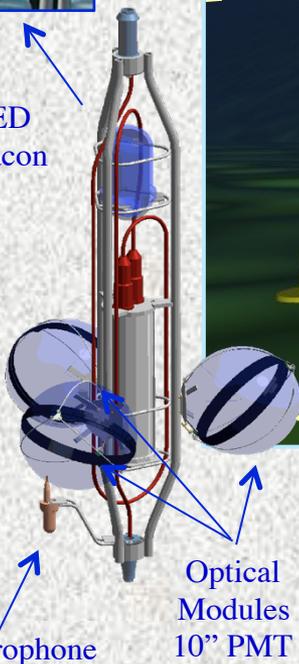
3 PMTs / storey

5-line setup in 2007

Completed in 2008

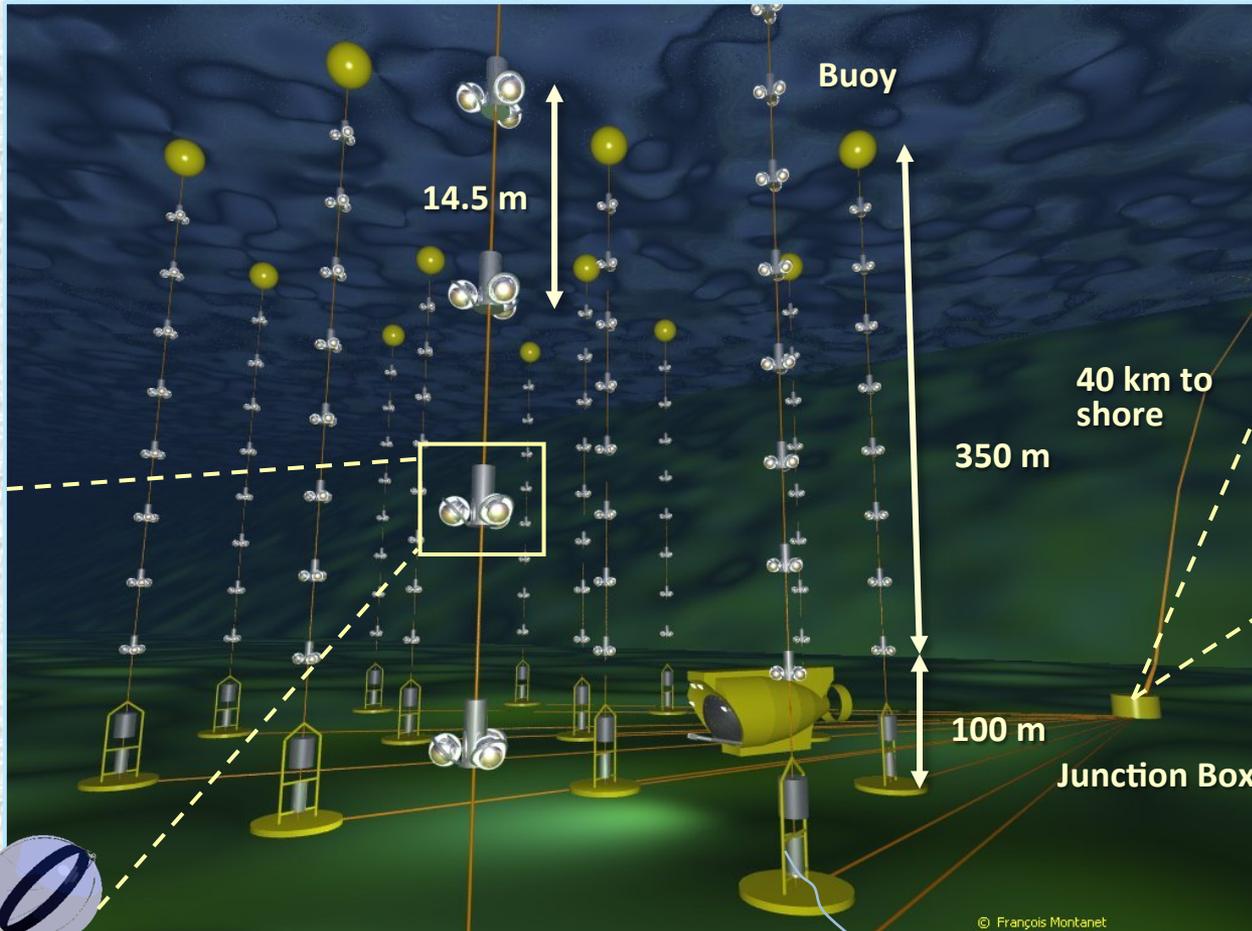


LED Beacon



Hydrophone

Optical Modules  
10" PMT



Buoy

14.5 m

40 km to shore

350 m

100 m

Junction Box

© François Montanet



Junction Box



Shore station



In the Mediterranean Sea  
(near Toulon) at 2500 m depth

# Diffuse fluxes – Shower analysis

- Good runs

Period: 29 Jan 2007 to 31 December 2012  
 Good detector + environmental conditions

Total livetime: 1247 days  
 Burn sample: 135 days.

- Shower reconstruction algorithm

Good reconstruction efficiency

Compares well with simulation:  
 (“run-by-run Monte Carlo” with environmental conditions simulated)

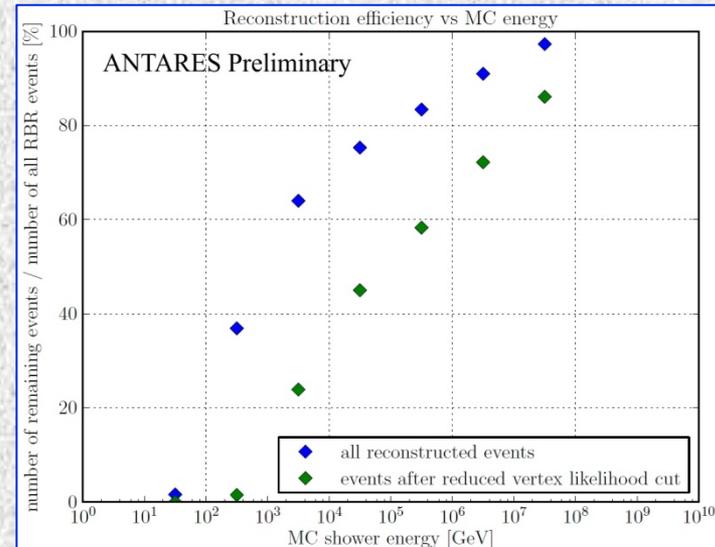
- Selection chain:

Muon filter → Hits > 2 lines → No spark events

Fitted zenith > 94° + E<sub>shower</sub> > 10 TeV

- Sensitivity per neutrino flavour:

$$E^2 \cdot \Phi_{90\%} = 2.21_{-0.73}^{+0.87} \cdot 10^{-8} \text{ GeV/cm}^2 \cdot \text{sr} \cdot \text{s}$$



EVENT NUMBERS AFTER FINAL OPTIMIZED CUTS	Cosmic signal events	Atmospheric background events
Cosmic signal (test flux $1.2 \cdot 10^{-8}$ per flavour)	<b>1.75</b>	
Conventional atmospheric neutrinos	-	<b>2.32</b>
Prompt atmospheric neutrinos	-	<b>0.56</b>
Tau neutrino estimation	<b>0.78</b>	<b>0.02 (prompt)</b>
Atmospheric muon extrapolation	-	<b>1.85</b>
Correction for missing vertex showers in CC muon simulations	<b>0.26</b>	<b>0.16</b>
High multiplicity muon bundles	-	<b>0.01</b>
<b>TOTAL</b>	<b>2.79</b>	<b>4.92</b>

# Diffuse flux – Showers

After unblinding

After zenith cut:

Expected background:  $82 \pm 40$

60 events observed

After cut on energy:

Expected background:  $4.92^{+2.84}_{-2.95}$

8 events observed

Interpreting excess as  
a background fluctuation:

Limits on normalization of an  $E^{-2}$  flux:

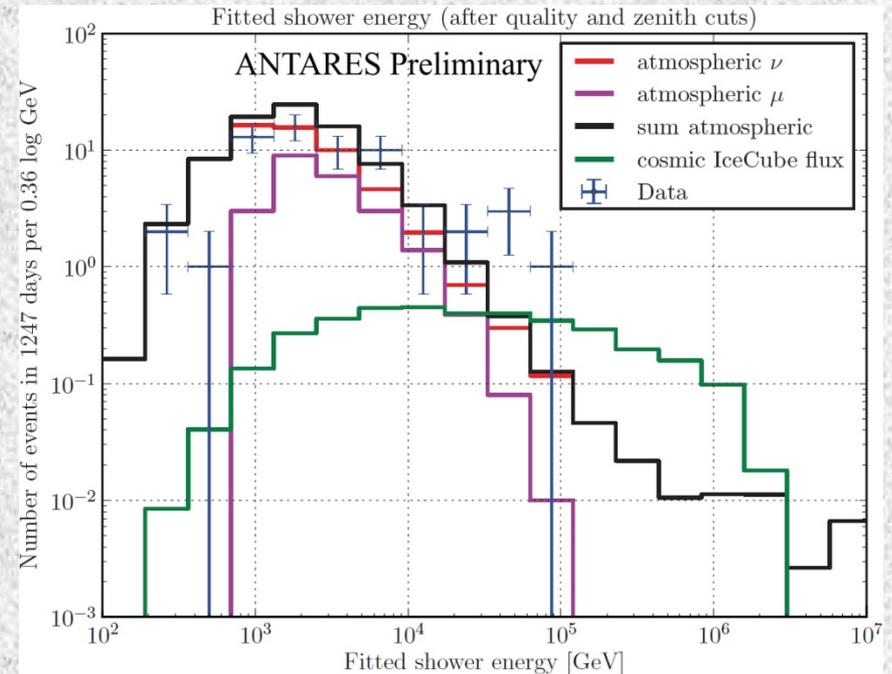
$$E^2 \phi_{90\%} < 3.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

(Feldman-Cousins 90% C.L. upper limit)

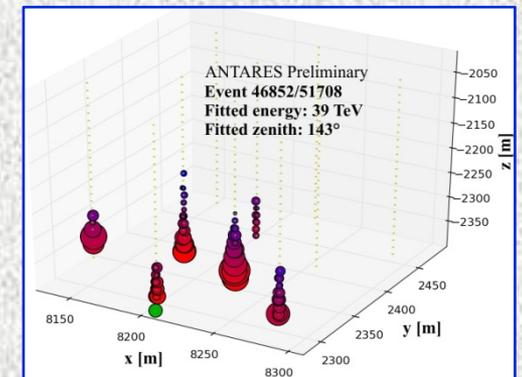
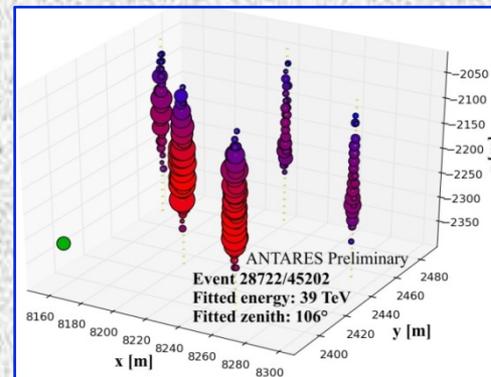
$$E^2 \phi_{90\%} < 4.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

(systematic uncertainties using Pole 1.0)

## Energy distribution



## Two of the 8 observed events



PRELIMINARY

# Diffuse flux

Showers (all flavours):

2007-2012 (1247 days)

Expected background: 4.9 events

Observed: **8 events**

$E^2 dN/dE < 4.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$   
(per flavour, 90% CL)

23 TeV < E < 7.8 PeV

Tracks ( $\nu_\mu$ ):

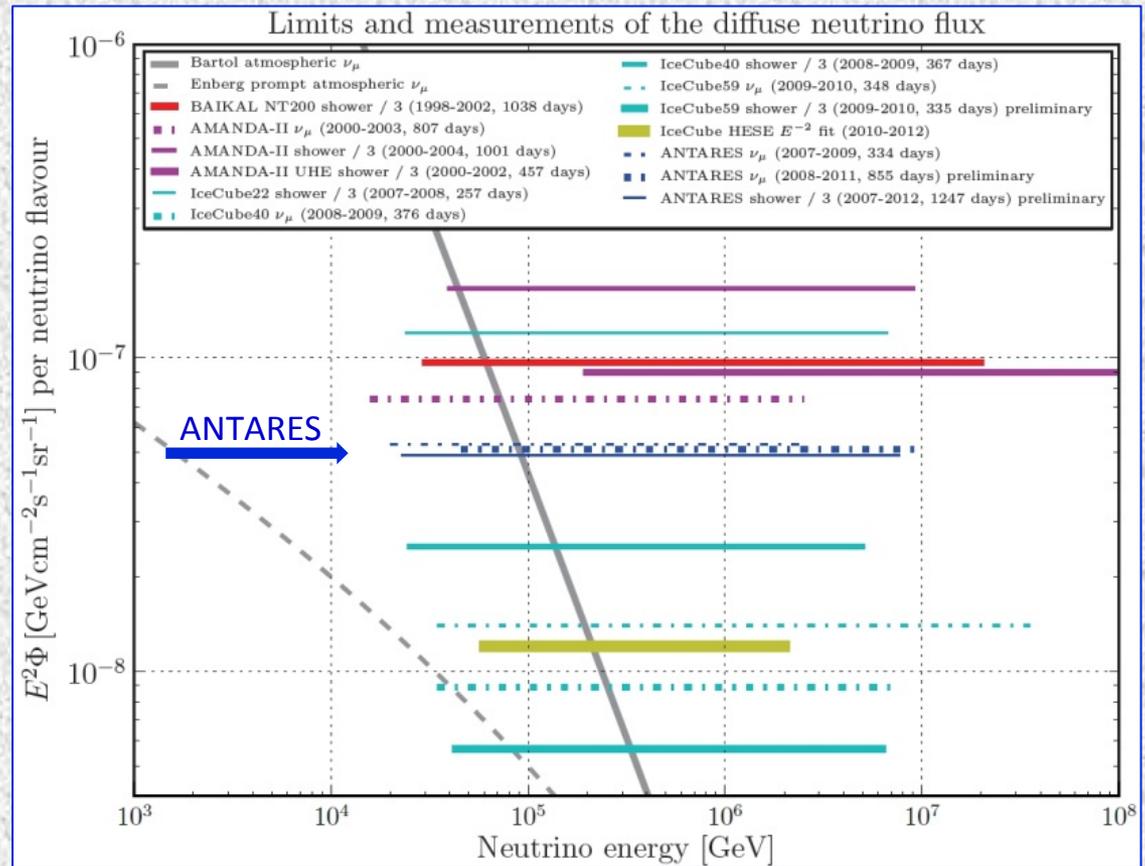
2008-2011 (885 days)

Expected background: 8.4 events

Observed: **8 events**

$E^2 dN/dE < 5.1 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$   
(90% CL)

45 TeV < E < 10 PeV



# Diffuse fluxes from special regions

## Fermi Bubbles

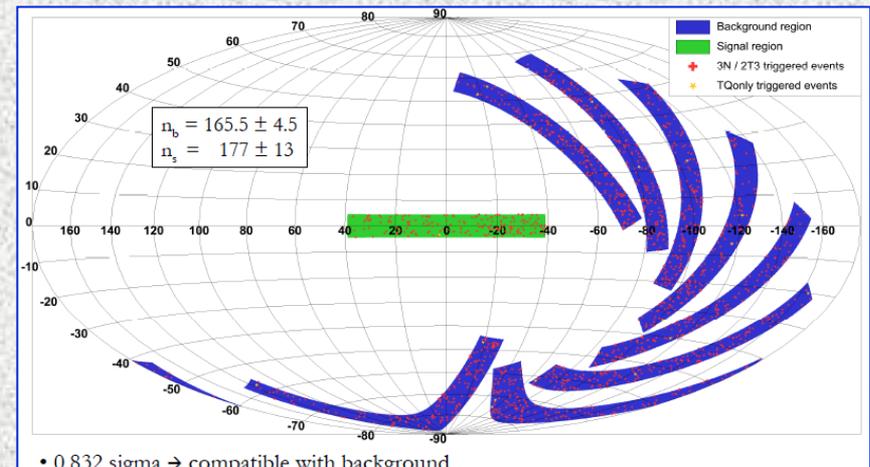
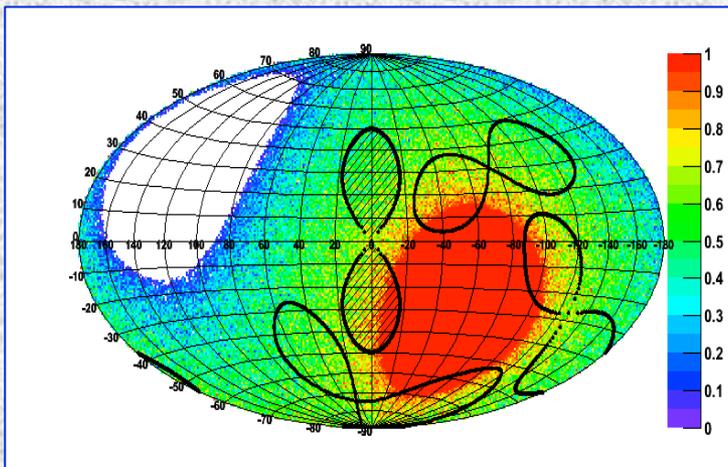
- Excess of  $\gamma$ - (and X-)rays in extended “bubbles” above and below the Galactic Centre. Homogenous intensity, hard spectrum ( $E^{-2}$ ) probably with cutoff.

📖 M. Su et al., ApJ. 724 (2010), G. Dobler et al., ApJ. 717, 825 (2010), M. Su & D.P. Finkbeiner ApJ 753, 61 (2012), R. Yang et al., astro-ph 1402.040

- In the field of view of ANTARES background estimated from average of 3 non-overlapping “off-zone” data regions (same size, shape and average detector efficiency)

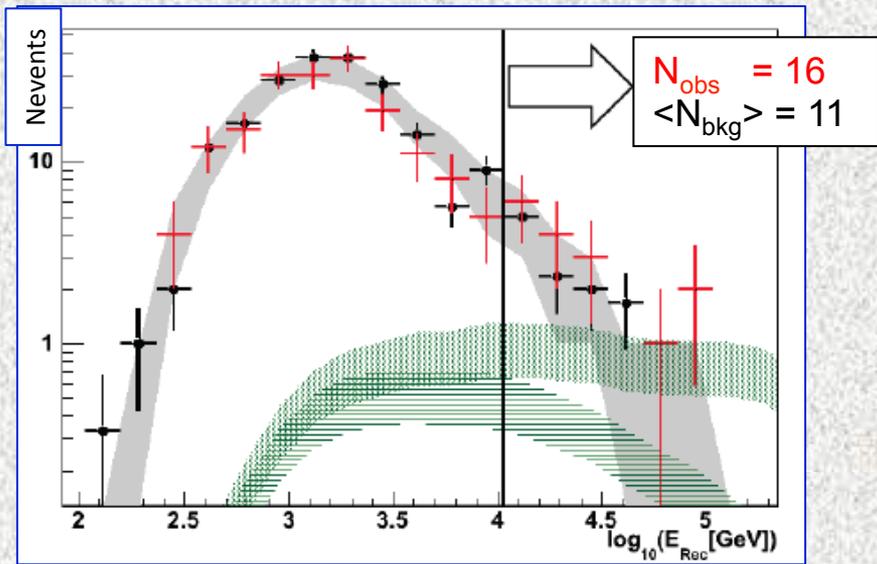
## Galactic Plane – central region

- The Galactic Plane is a most populated region.
- Cosmic rays can interact and produce neutrinos.
- $E^{-2.7}$  spectrum expected (due to the low density leptons can decay). Magnetic fields could enhance the neutrino signal.
- In the field of view of ANTARES background estimated from off-zones.

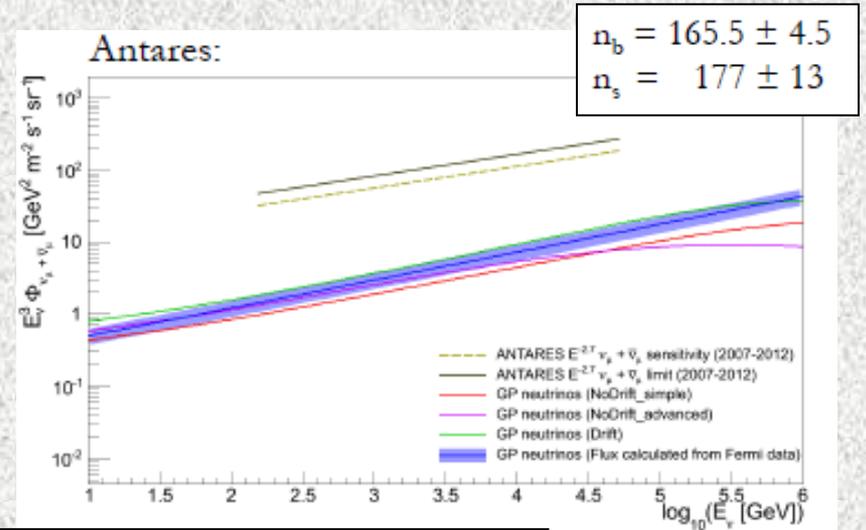


# Special regions

## Fermi bubbles

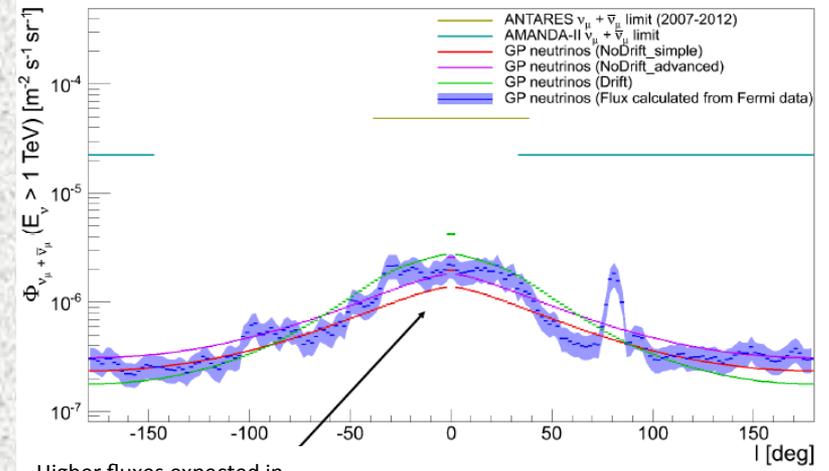
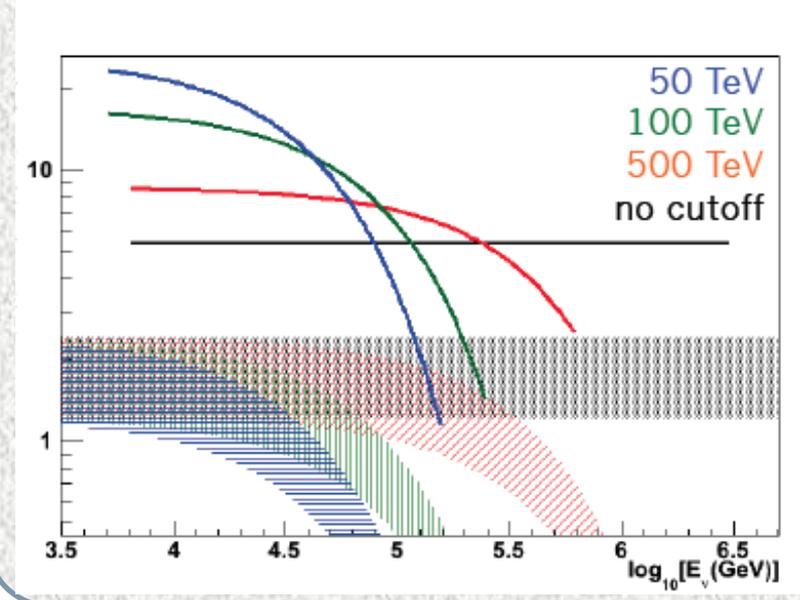


## Galactic Plane



$$\Phi_{\nu_{\mu} + \bar{\nu}_{\mu}} < 10.18 E^{-2.7} \text{ GeV}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$$

$$153 \text{ GeV} < E < 52.1 \text{ TeV}$$



Higher fluxes expected in ANTARES signal region.

# Search for Point Sources

- Good runs

Period: 29 Jan 2007 to 31 December 2012

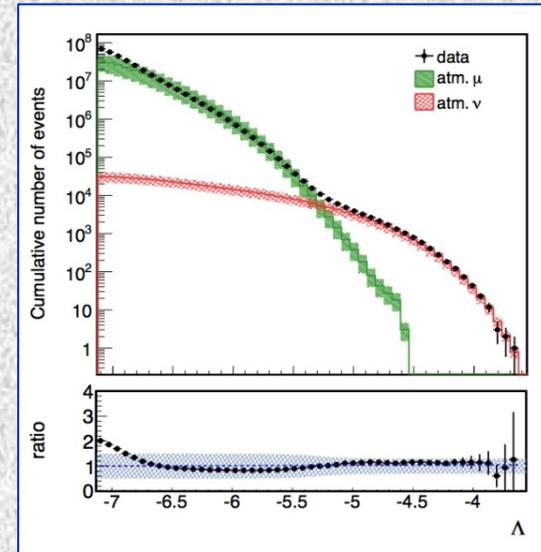
Good detector and environmental conditions

Total livetime: 1338 days

- Well-reconstructed  $\nu_\mu$  events

Good quality upgoing tracks with low angular error

( $\Lambda > -5.2$ ;  $\Delta(\text{ang}) < 1^\circ$ ;  $\cos \theta < 0.1$ )

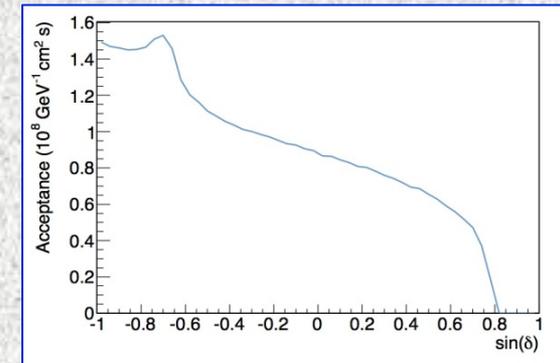
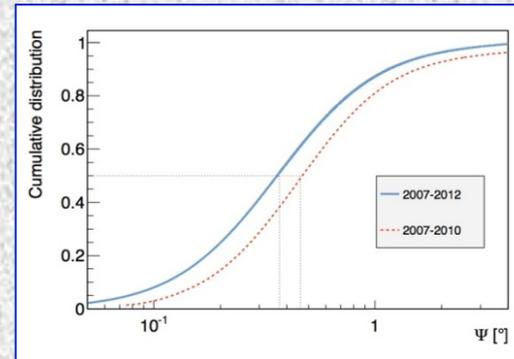


- Background from data;

Performance from simulation

Scambled data

MC: Angular resolution, Acceptance



- Likelihood method

- Full-sky
- Candidate list
- Special searches (e.g. Gal. Centre)

$$\log L_{s+b} = \sum_i \log \left[ \frac{n_s}{N} S_i + \left( 1 - \frac{n_s}{N} \right) B_i \right]$$

- Unblinding

Analysis optimised on simulation to avoid bias

$$B_i = \frac{B(\delta_i)}{2\pi} P_b(\mathcal{N}_i^{\text{hits}}, \beta_i) \quad S_i = \frac{1}{2\pi\beta_i^2} \exp\left(-\frac{\psi_i(x_s)^2}{2\beta_i^2}\right) P_s(\mathcal{N}_i^{\text{hits}}, \beta_i)$$

# Point sources

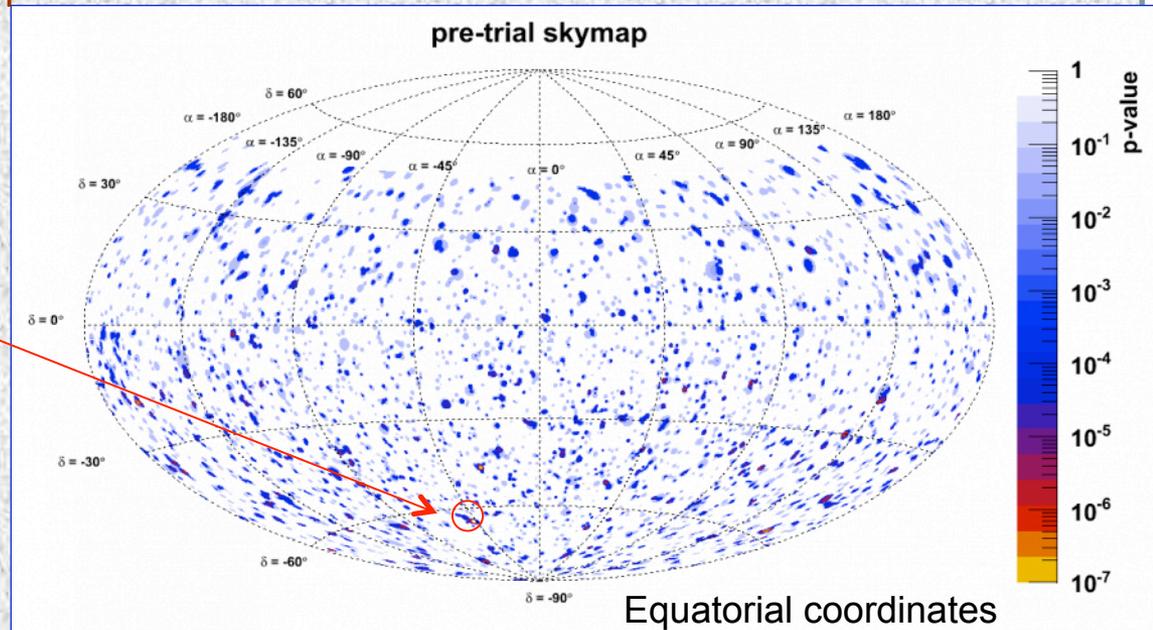
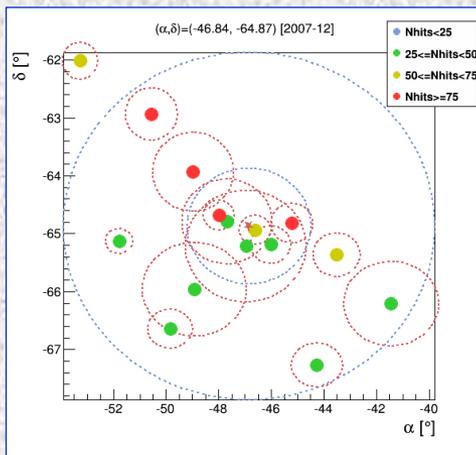
- **Years 2007-2012 (1338 days)**

5516 neutrino candidates (90 % of which being better reconstructed than  $1^\circ$ )

- **All-sky search:**

Most significant cluster, 6 (14) events in  $1^\circ$  ( $3^\circ$ ) : p-value = 2.7% ( $2.2 \sigma$ )

Compatible with background hypothesis



- **Fixed search (50 sources):**

5 most significant:

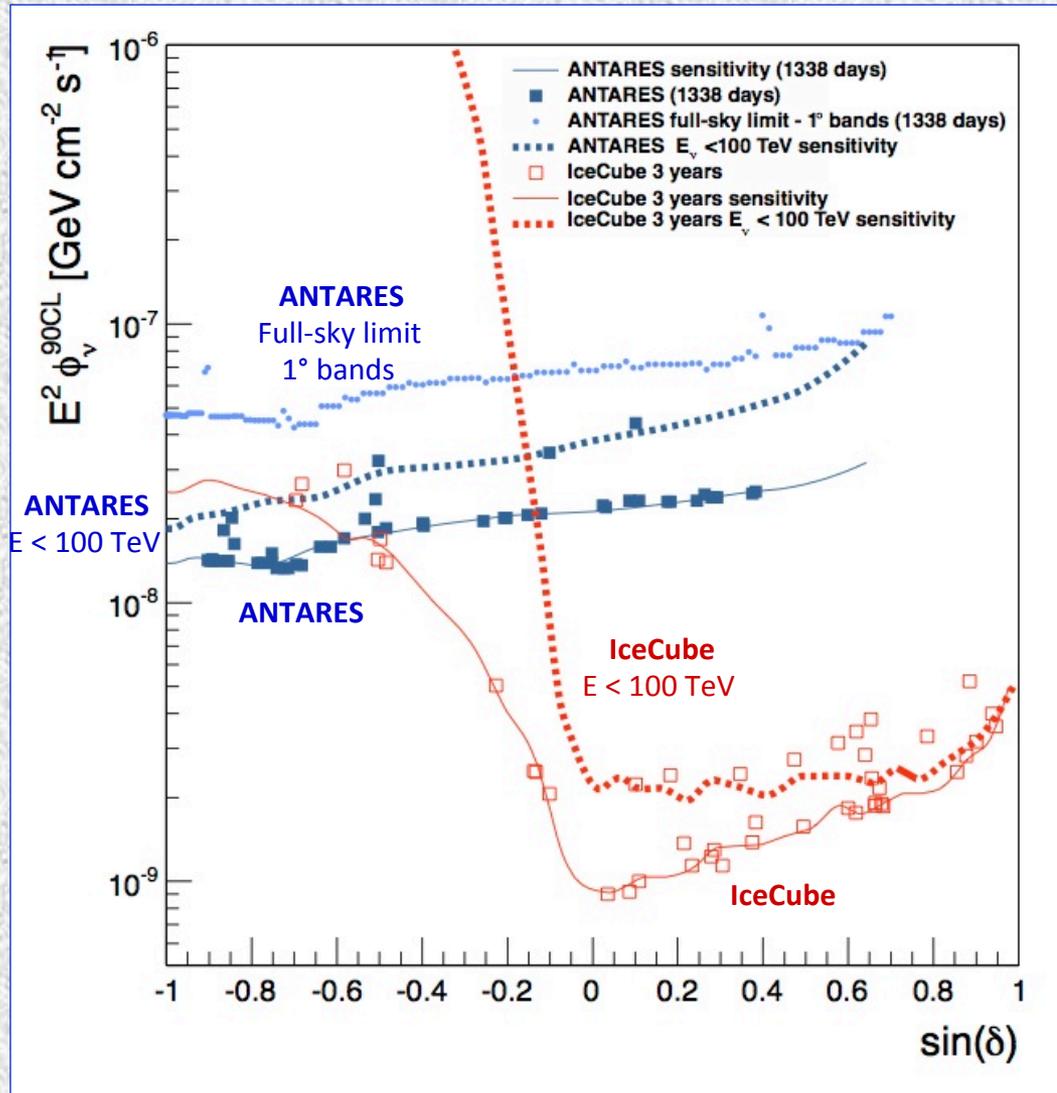
Name	$\alpha$ ( $^\circ$ )	$\delta$ ( $^\circ$ )	$n_s$	$p$	$\phi_\nu^{90\text{CL}}$
HESSJ0632+057	98.24	5.81	1.60	0.0012	4.40
HESSJ1741-302	-94.75	-30.20	0.99	0.003	3.23
3C279	-165.95	-5.79	1.11	0.01	3.45
HESSJ1023-575	155.83	-57.76	1.98	0.03	2.01
ESO139-G12	-95.59	-59.94	0.79	0.06	1.82

Limits on normalization factor  
 $(E/\text{GeV})^{-2} 10^{-8} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$   
 (assuming no energy cut-off)

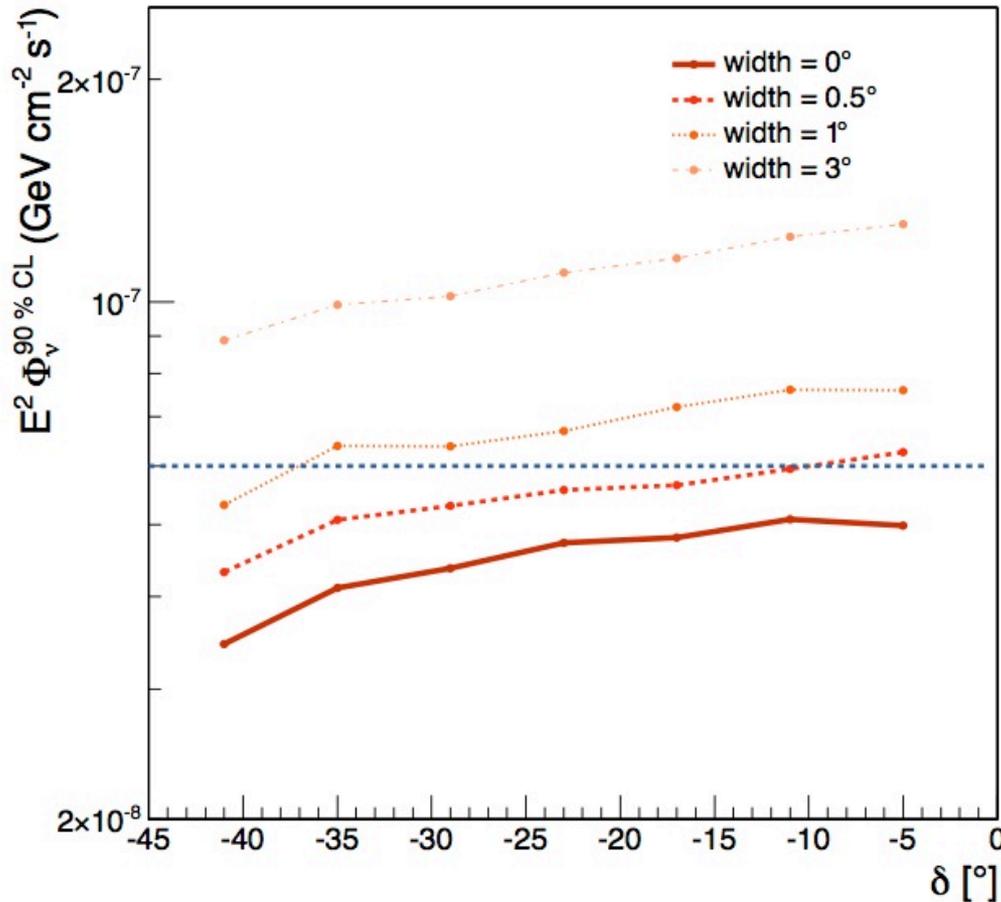
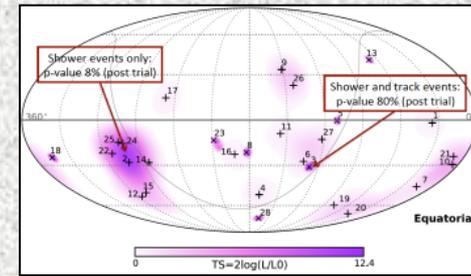
$$\phi_0 \times E^{-2}$$

# Flux sensitivities and limits (90% C.L.)

ANTARES 2007-2012 (1338 days) IceCube 2008-2011 (1040 days)



# Source around the GC?



- What about IC's cluster near the GC?
  - Shower events have low angular resolution
  - IC does not claim a signal.
  - If it were a point source:

$$(\alpha, \delta) = (-79^\circ, -23^\circ);$$

$$\phi_0 = 6 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$$

(M. C. Gonzalez-Garcia, F. Halzen and V. Niro, arXiv1310.7194)

- ANTARES:
  - Point source search at different  $\delta$ 's
  - Allow for extended sources:
    - widths:  $0^\circ$ ,  $0.5^\circ$ ,  $1^\circ$  and  $3^\circ$

Recent 3-year IC update does not add more events to the cluster.

ANTARES data excludes a point source as origin of the IceCube's cluster

# The Multi-Messenger Program



GeV-TeV  $\gamma$ -rays  
Fermi / HESS...



📖 JCAP 03(2013) 006  
📖 A&A 559 (2013) A9  
📖 JCAP 05 (2014) 001



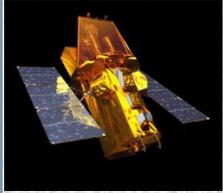
UHECR  
Auger

📖 APJ 774 (2013) 19

HE neutrinos



Optic / X-ray  
TAROT, ROTSE /  
Swift, ZADKO



📖 APP 36 (2012) 204  
📖 A&A 559 (2013) A9



Gravitational  
Waves  
Virgo / Ligo



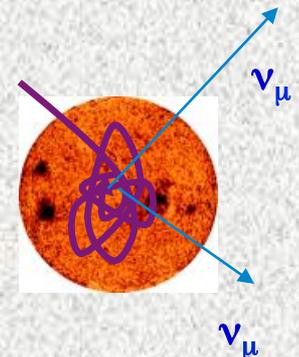
📖 JCAP 06 (2013) 008

Increases chances of detection:

- Common sources for different messengers.
- Limits searches in time and space, Low backgrounds.
- Uncorrelated backgrounds and systematics.

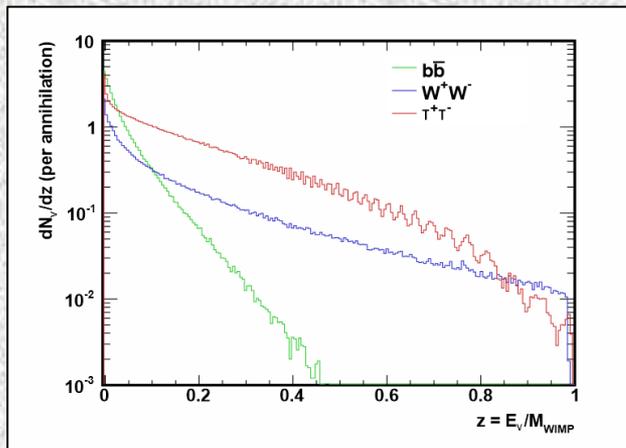
# Dark matter searches

- Relic WIMPs (neutralinos, KK particles) captured in celestial bodies.
- $\chi\chi$  self-annihilations produce  $\tau$  leptons, b, c and t quarks and gauge bosons that in turn give rise to high energy neutrinos.
- Signal less affected by astrophysical uncertainties/backgrounds than other messengers



## In the Sun

- Events in the Sun generated in a **model independent way**
- Annihilations into b quarks (soft spectrum) and  $\tau$  leptons WW/ZZ bosons (hard spectrum) **used as benchmarks**
- $\nu$  interactions in the Sun medium, **regeneration of  $\nu_\tau$**  in the Sun and  **$\nu$  oscillations** taken into account.
- Optimisation of track quality cut and search cone performed



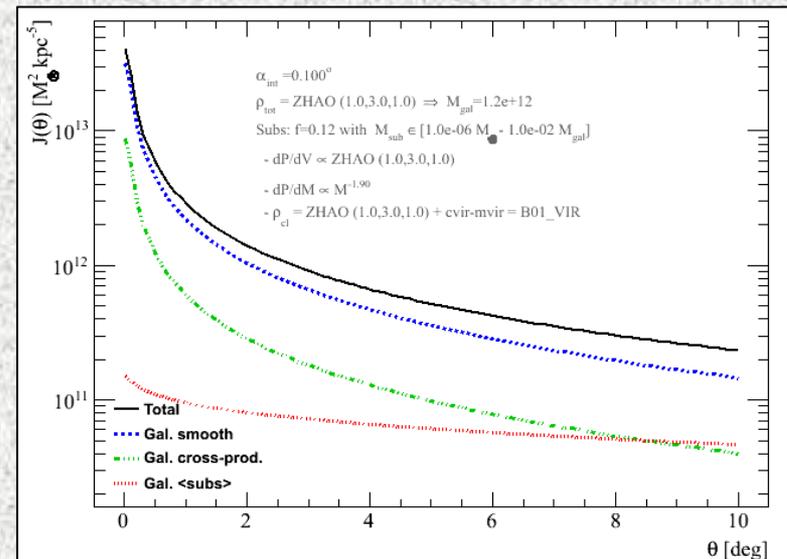
## In the Galactic Centre

WIMPs self-annihilate according to  $\langle\sigma_A v\rangle$  (halo model-dependent).

Fluxes depend on WIMP density through the

J-factor:

$$J(\Delta\Psi) = \int_{\Delta\Psi} \int \rho_{DM}^2(l, \Psi) dl d\Psi$$

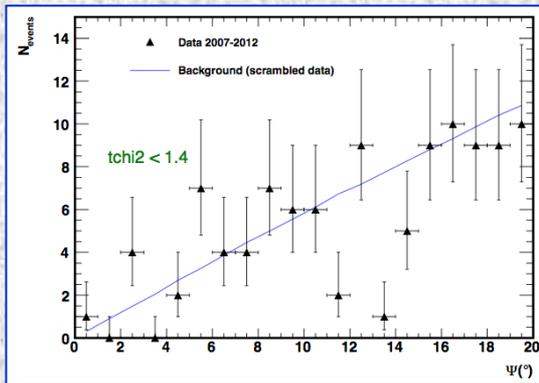


J-factor for a Navarro-Frenk-White profile

# Dark matter – Results

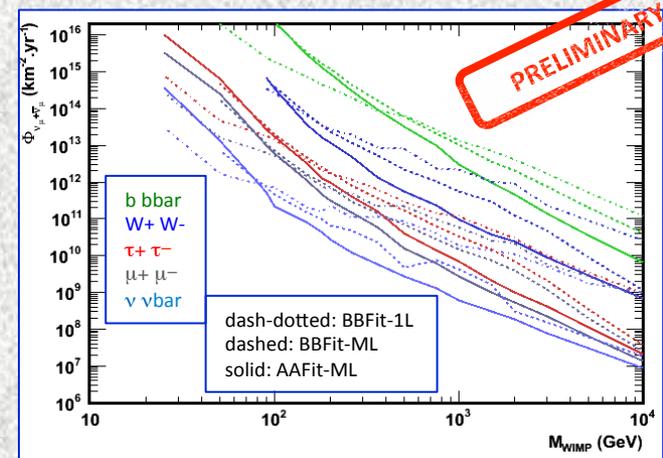
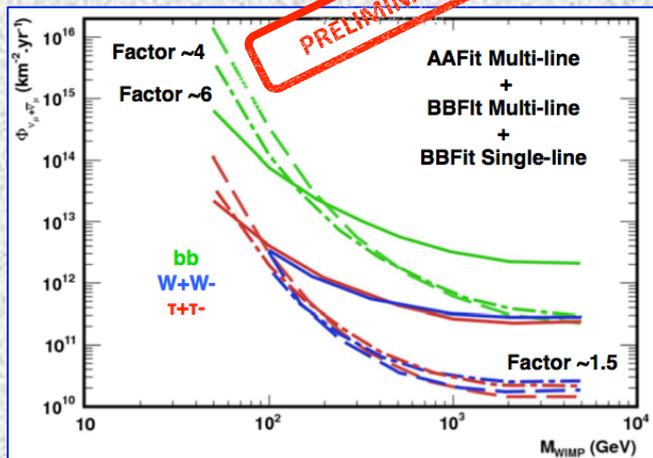
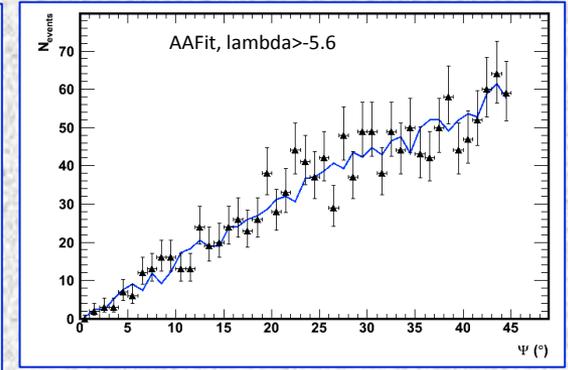
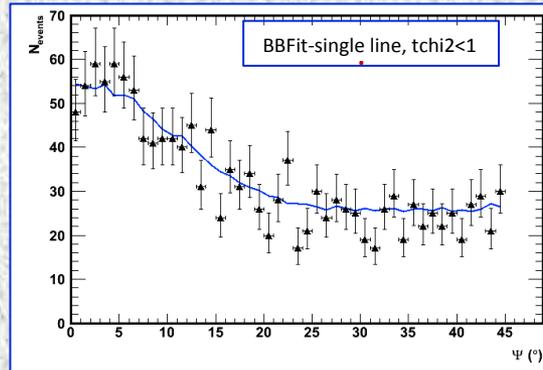
## From the Sun

- Observed events in the Sun's direction vs. scrambled data (2007-2012).
- **No excess:** limits on flux from the Sun.

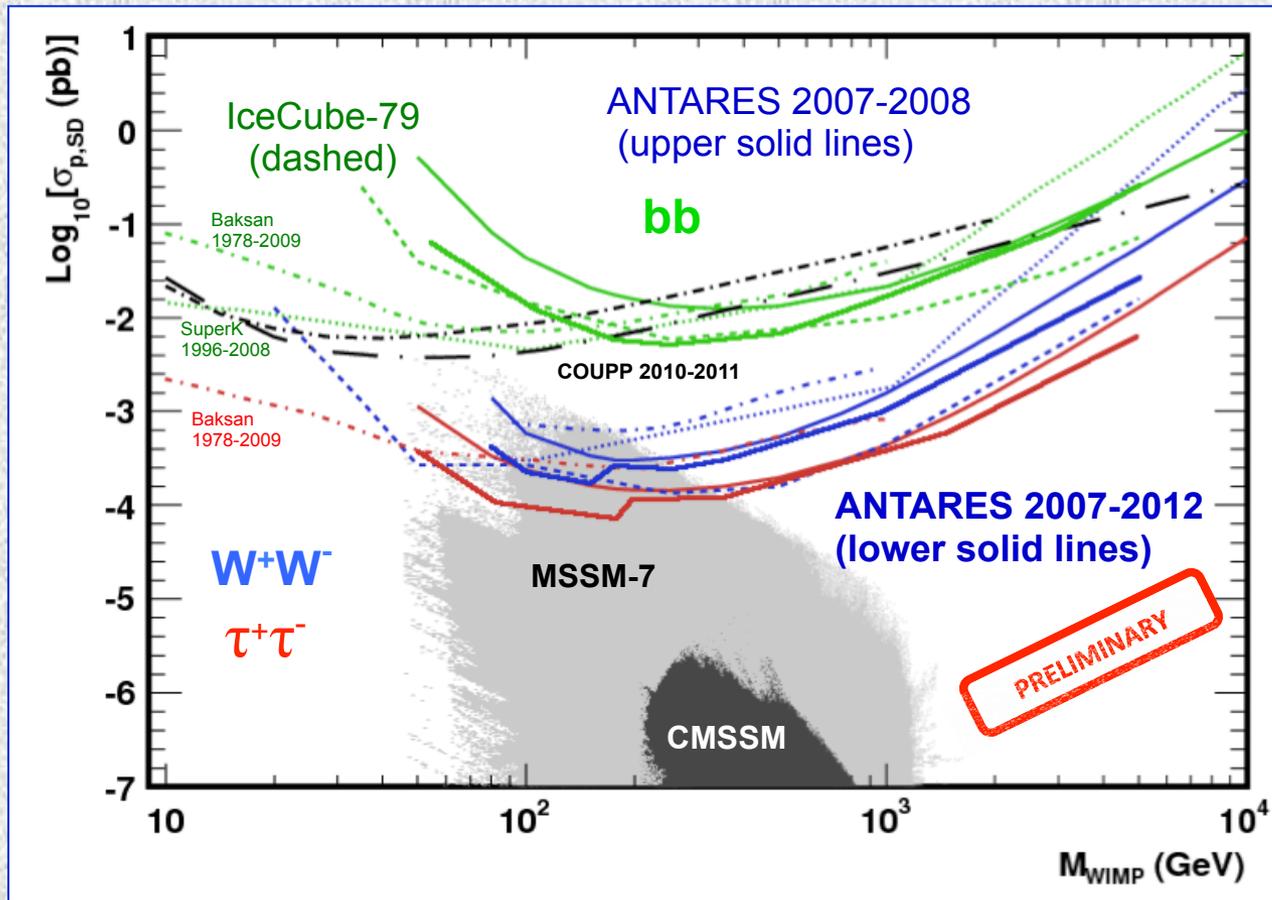


## From the GC

- Observed events in the Sun's direction vs. scrambled data (2007-2012).
- **No excess:** limits on flux from the GC



# Sun – Limits on spin-dependent (SD) cross-sections



Conversion to limits on WIMP-proton SD-x sections assumes equilibrium between capture and annihilation rates inside the Sun

Much better sensitivity of  $\nu$ -telescopes on SD cross-section w.r.t. direct detection (due to capture on H in the Sun).

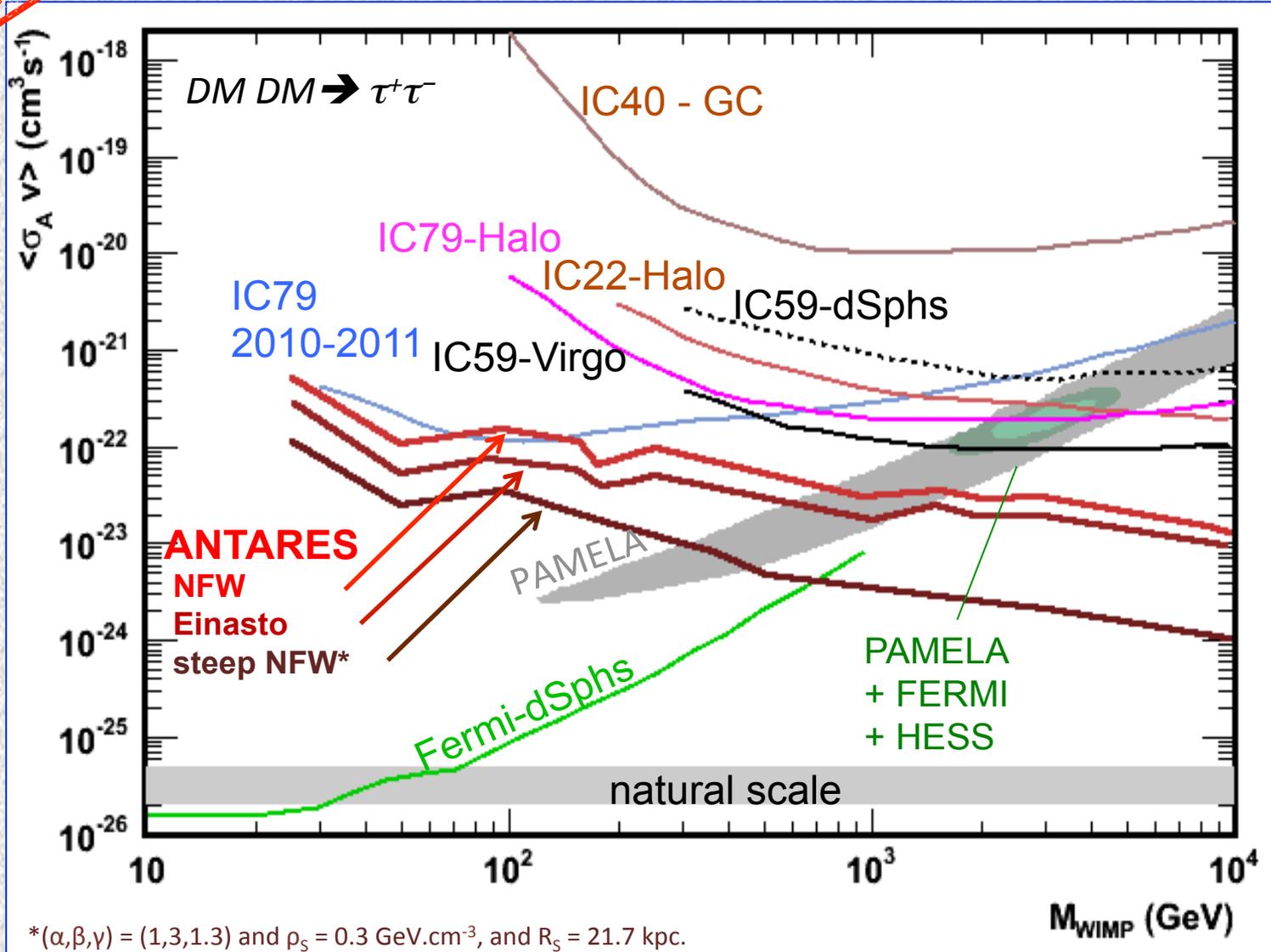
First ANTARES results published in JCAP11 (2013) 032

MSSM-7 and CMSSM predictions take into account recent experimental constraints (Higgs mass, etc...).

There is still room for improvement in ANTARES: better reconstruction at low energies, unbinned method, more data "on tape", ...

**PRELIMINARY**

# Galactic Centre – Limits on $\langle\sigma_A v\rangle$



\*( $\alpha, \beta, \gamma$ ) = (1,3,1.3) and  $\rho_s = 0.3 \text{ GeV}\cdot\text{cm}^{-3}$ , and  $R_s = 21.7 \text{ kpc}$ .

# Conclusions

- **ANTARES** –the first undersea Neutrino Telescope– is in its **seventh year of operation**.
- Despite its moderate size, but thanks to its location and excellent angular resolution, it is yielding:
  - **Diffuse flux sensitivities** in the relevant range;
  - **Best limits for Galactic sources** in the relevant energy range, with impact on interpretation of IC results;
  - **Best limits on dark matter** from neutrinos coming from the Sun and the Galactic Centre.
- It will keep producing excellent results **until the next generation Mediterranean NT, KM3NeT, takes over** (just around the corner: cf. de Jong's talk this conf.).