Results from ANTARES

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The ANTARES Collaboration

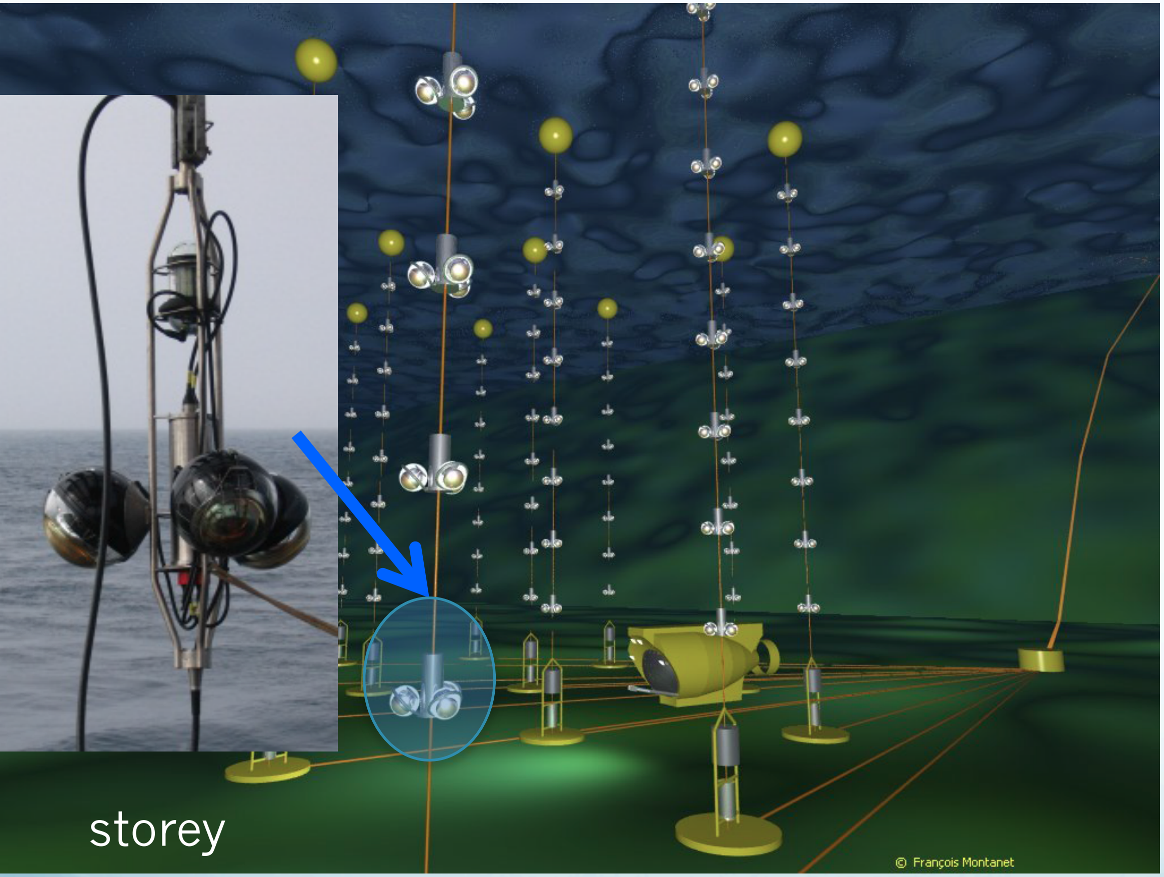
ANTARES researches

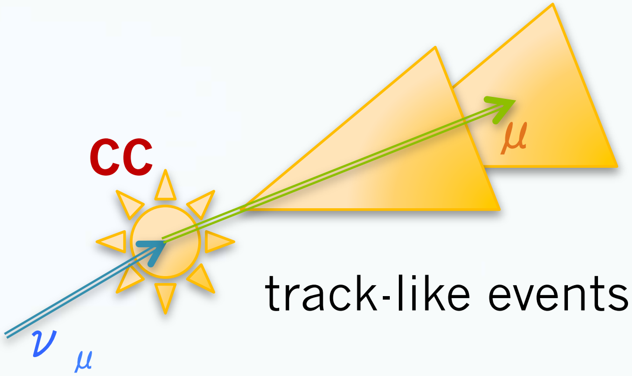
- **Neutrino astrophysics**
  - **Origin of IC HESE events**
  - **Multi-messenger searches**
  - …
- **Dark matter searches**
- **Moon shadow**
- Atmospheric neutrino study / oscillations
- Sea sciences
- …

The ANTARES detector

12 lines (885 10” PMTs)
25 storeys/line
3 PMTs / storey

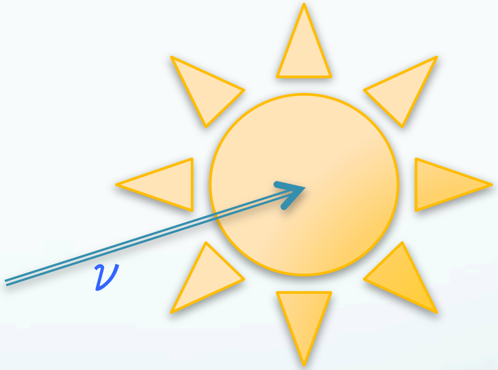
5-line setup in 2007
completed in 2008





track-like events

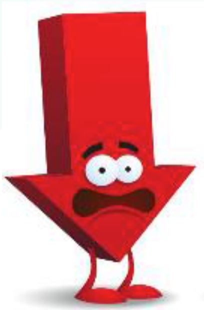
0.4° median resolution for E^{-2}



shower-like events
ν_μ(NC), ν_e, ν_τ

~5° median resolution for E^{-2}

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

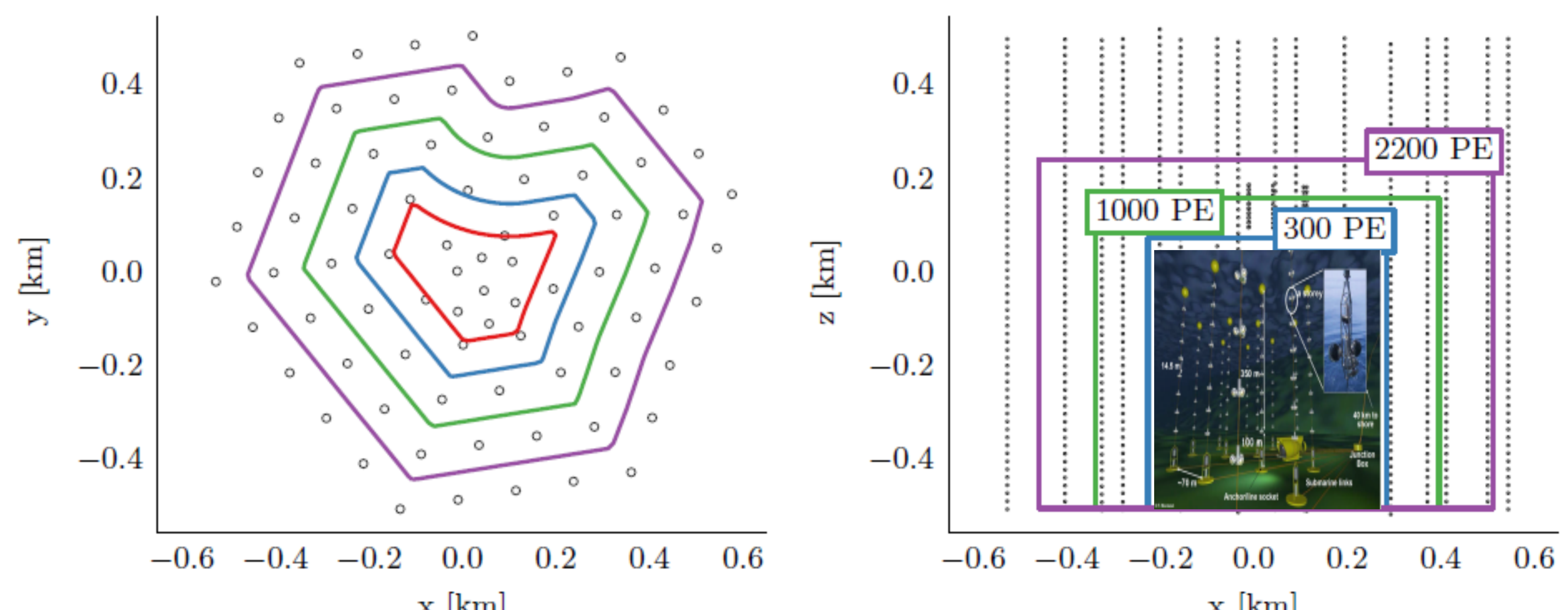


Down in IC = Up in ANTARES

PHYSICAL REVIEW D **91**, 022001 (2015)

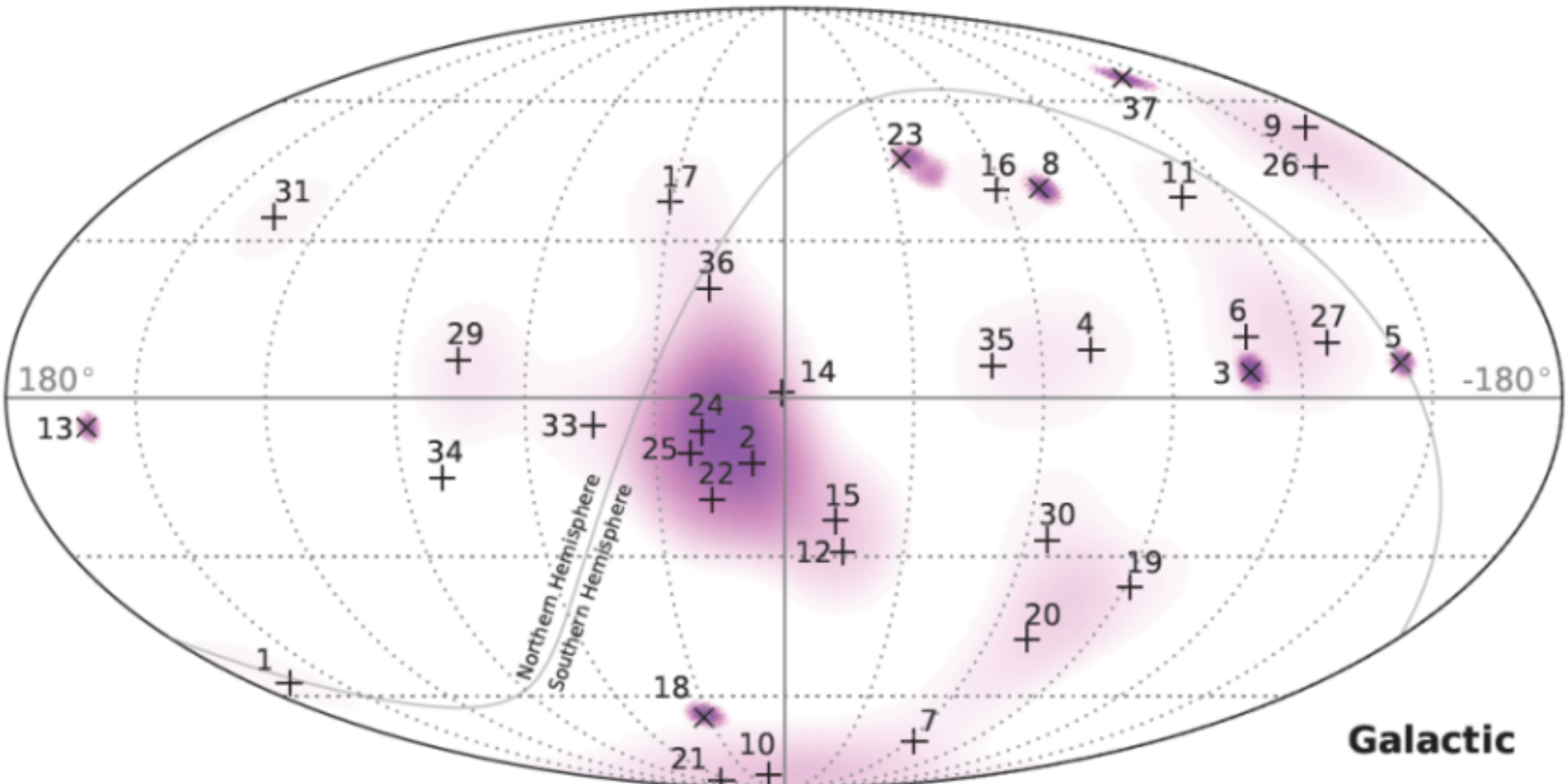
Atmospheric and astrophysical neutrinos above 1 TeV interacting in IceCube

M. G. Aartsen,[2] M. Ackermann,[48] J. Adams,[15] J. A. Aguilar,[23] M. Ahlers,[28] M. Ahrens,[39] D. Altmann,[22] T. Anderson,[45] C. Arguelles,[28] T. C. Arlen,[45] J. Auffenberg,[1] X. Bai,[37] S. W. Barwick,[25] V. Baum,[30] R. Bay,[7] J. J. Beatty,[17,18]



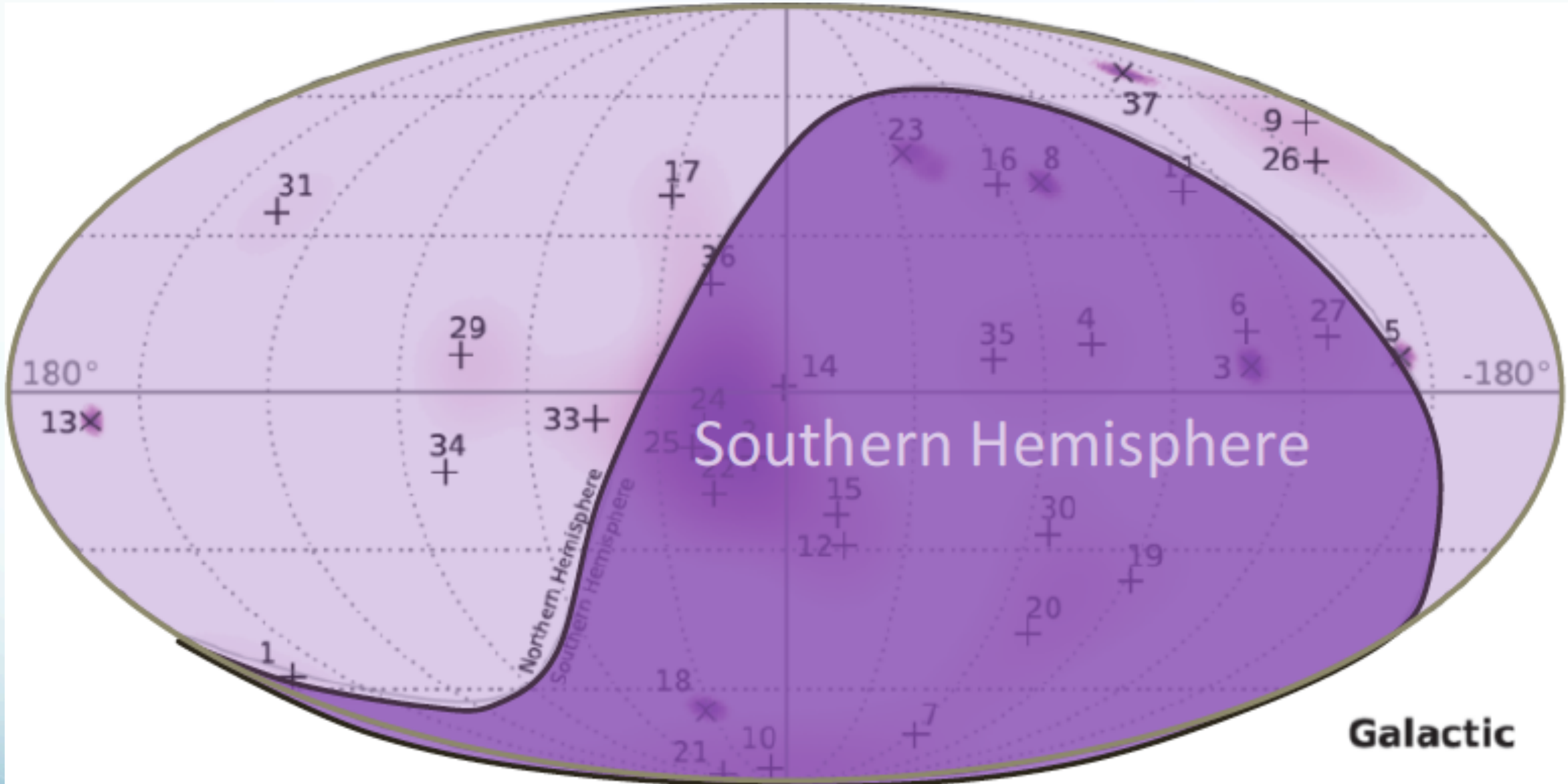
Almost in scale

Sources in the Southern hemisphere?



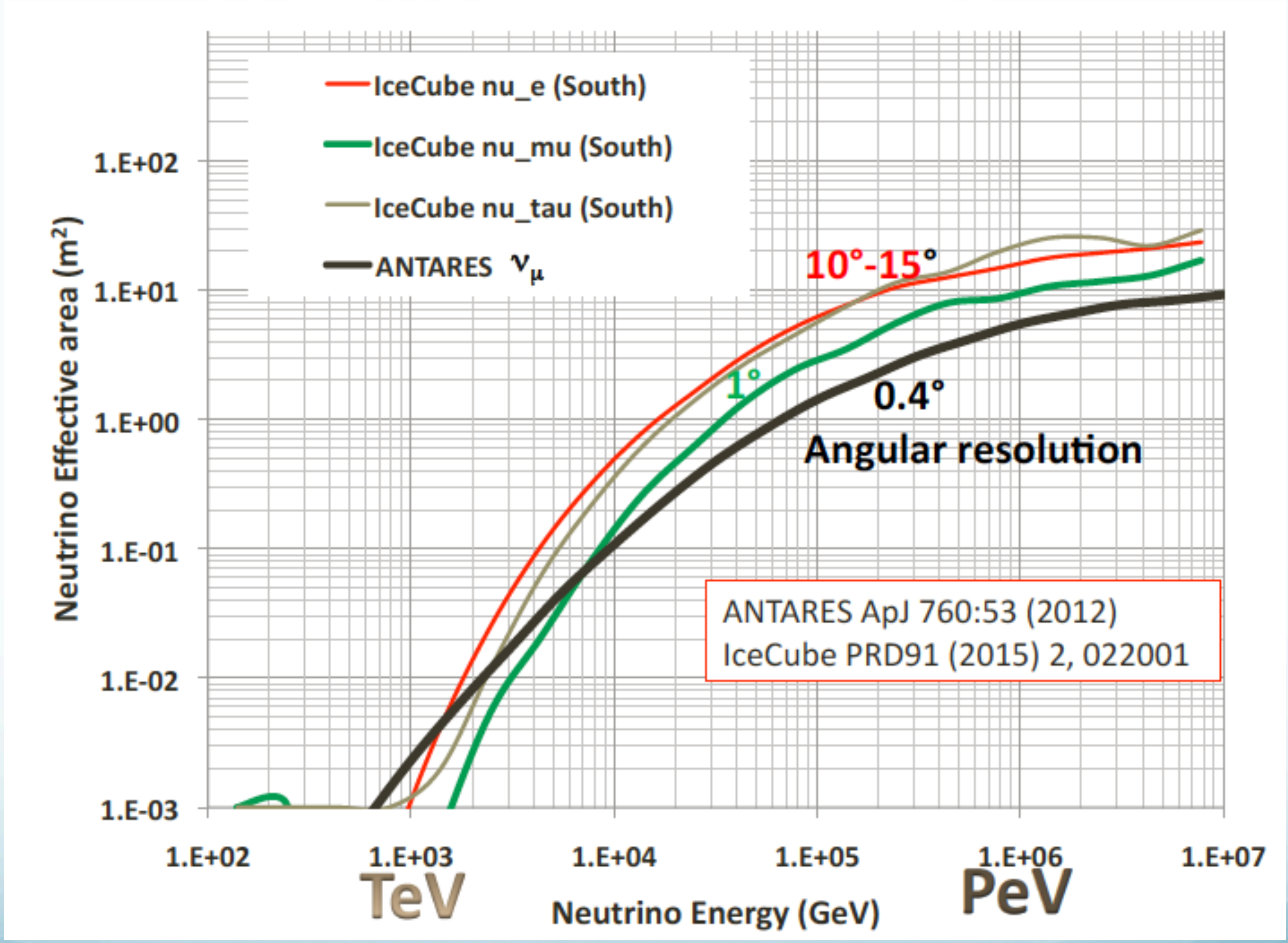
Galactic component?

Sources in the Southern hemisphere?



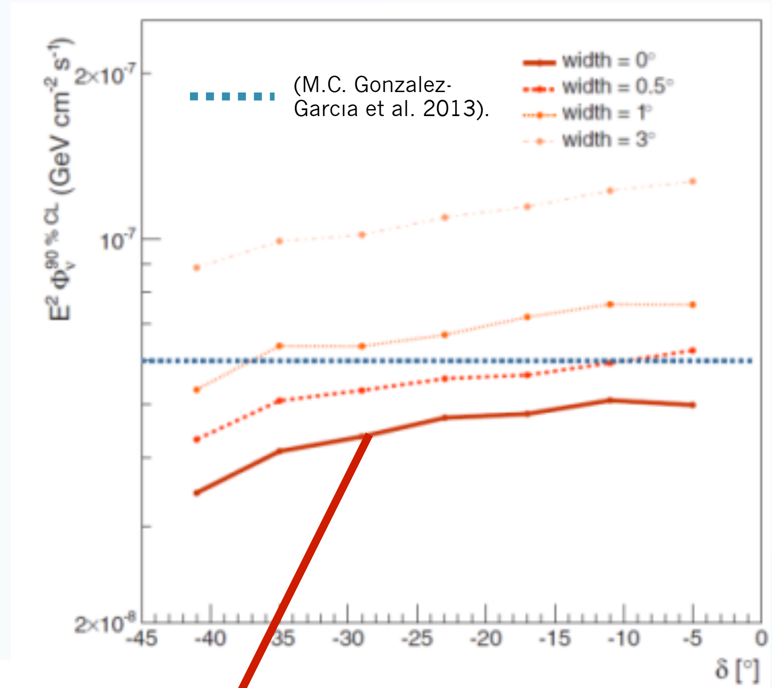
Galactic component?

Effective areas



If HESEs come from a point-source

- The ANTARES 90% C.L. excludes that a single point-like source produces n_p>5 HESE, assuming Γ=2.0
- A single point-like source yielding n_p>2 is excluded for Γ=2.3
- Cluster of n_p≥2 is excluded for Γ>2.3



ANTARES, ApJL 786:L5 2014

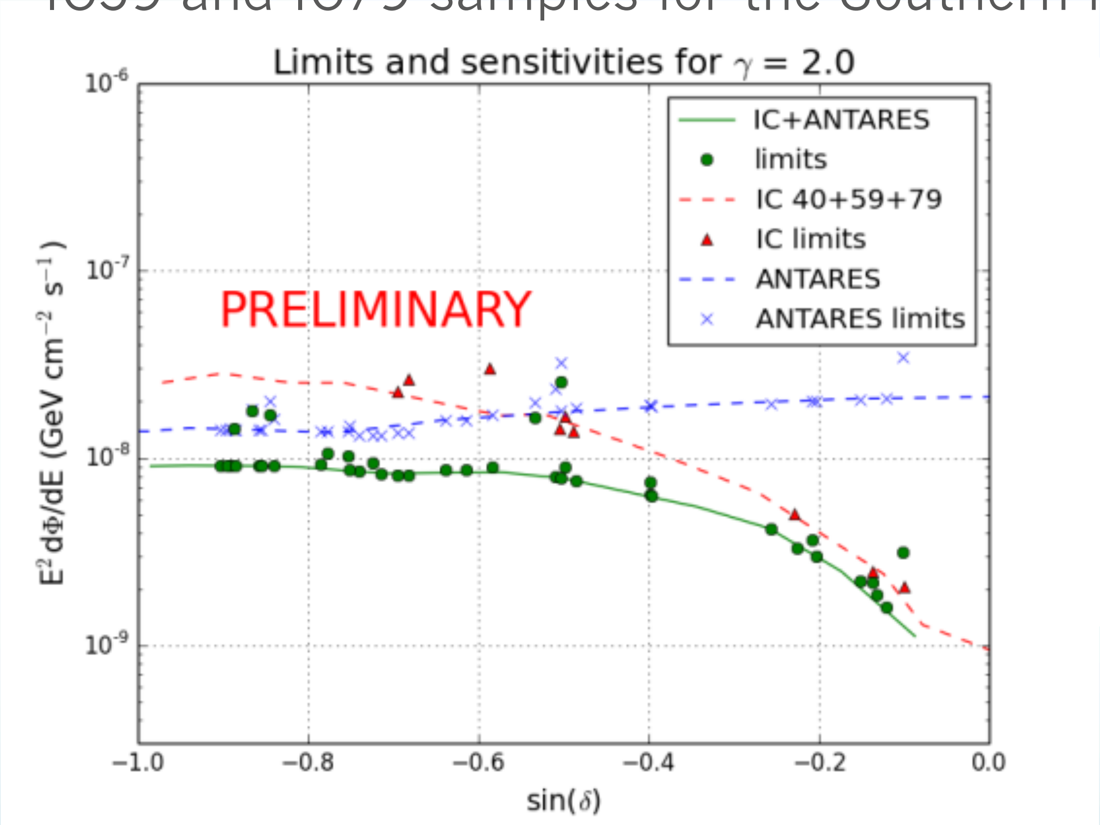
Expected normalization factors Φ0 as a of Γ

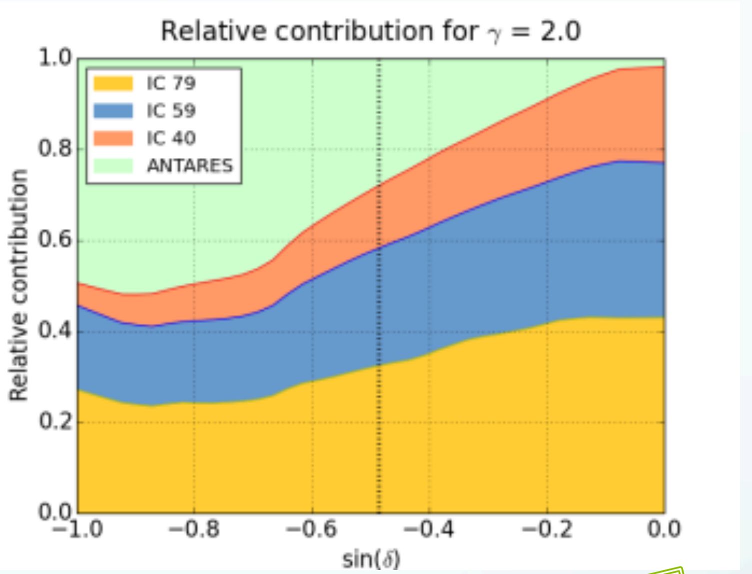
$\Gamma =$	IceCube $\Phi_0^{p,\Gamma}$ (GeV cm^{-2} s^{-1}) $n_p = 1$	$n_p = 2$	$n_p = 3$	$n_p = 4$	$n_p = 5$	ANTARES 90% C.L. upper limit
2.0	$6.9\ 10^{-9}$	$1.4\ 10^{-8}$	$2.1\ 10^{-8}$	$2.8\ 10^{-8}$	$3.5\ 10^{-8}$	$4.0\ 10^{-8}$
2.1	$2.6\ 10^{-8}$	$5.1\ 10^{-8}$	$7.7\ 10^{-8}$	$1.0\ 10^{-7}$	$1.3\ 10^{-7}$	$1.2\ 10^{-7}$
2.2	$9.0\ 10^{-8}$	$1.8\ 10^{-7}$	$2.7\ 10^{-7}$	$3.6\ 10^{-7}$	-	$3.2\ 10^{-7}$
2.3	$3.3\ 10^{-7}$	$6.6\ 10^{-7}$	$9.9\ 10^{-7}$	-	-	$8.4\ 10^{-7}$
2.4	$1.2\ 10^{-6}$	$2.3\ 10^{-6}$	-	-	-	$2.2\ 10^{-6}$
2.5	$3.9\ 10^{-6}$	$7.9\ 10^{-6}$	-	-	-	$5.5\ 10^{-6}$

Spurio, PRD 90, 103004 (2014)

Joined ANTARES-IC searches

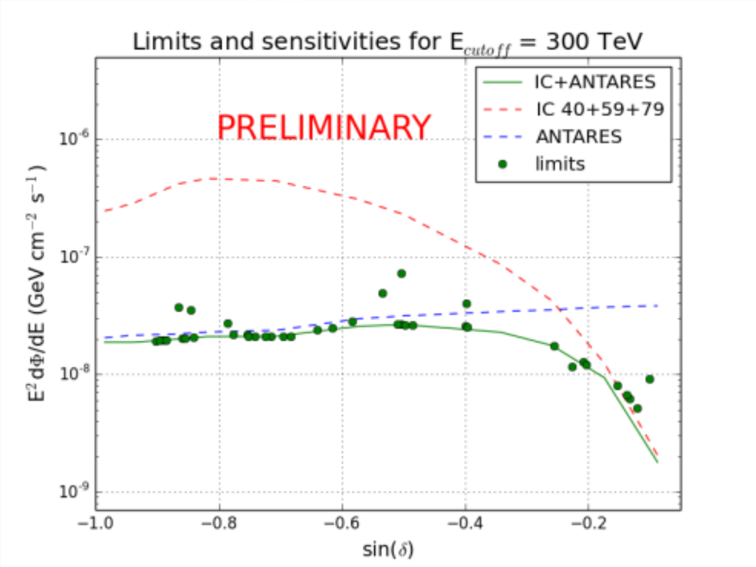
- Point-source analysis using the ANTARES 2007-2012 + the IC40, IC59 and IC79 samples for the Southern Hemisphere

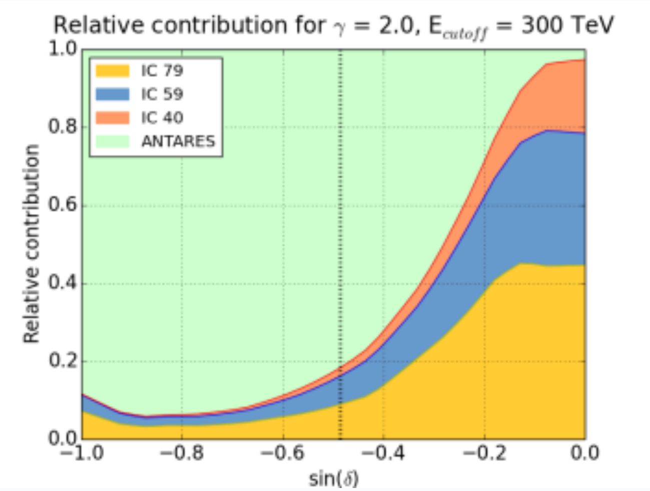


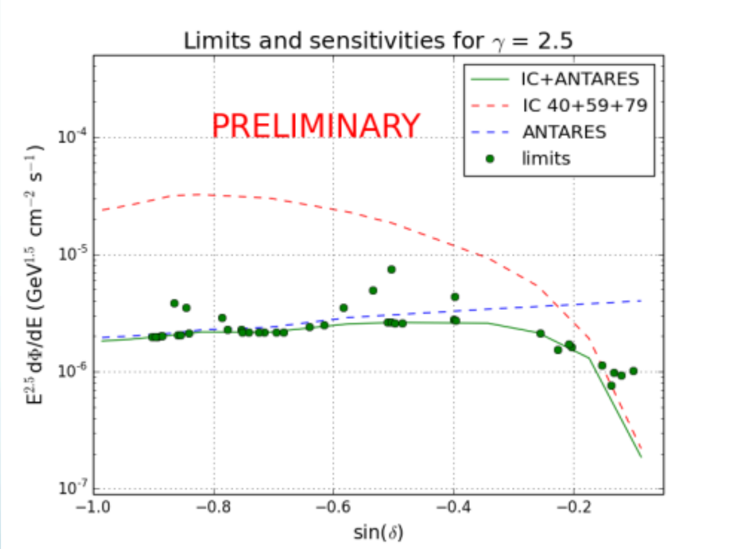


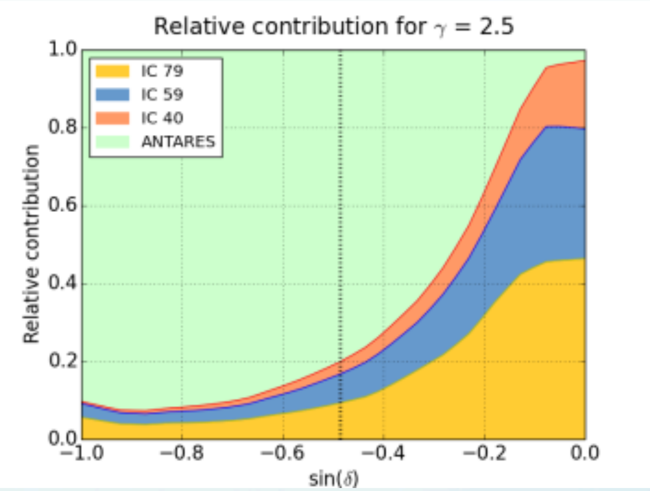
paper in preparation

Combined 90% CL sensitivities (green line) and limits (points) for an E^{-2} source spectrum. Blue (Red) curves/points indicate ANTARES (IceCube) sensitivities/limits



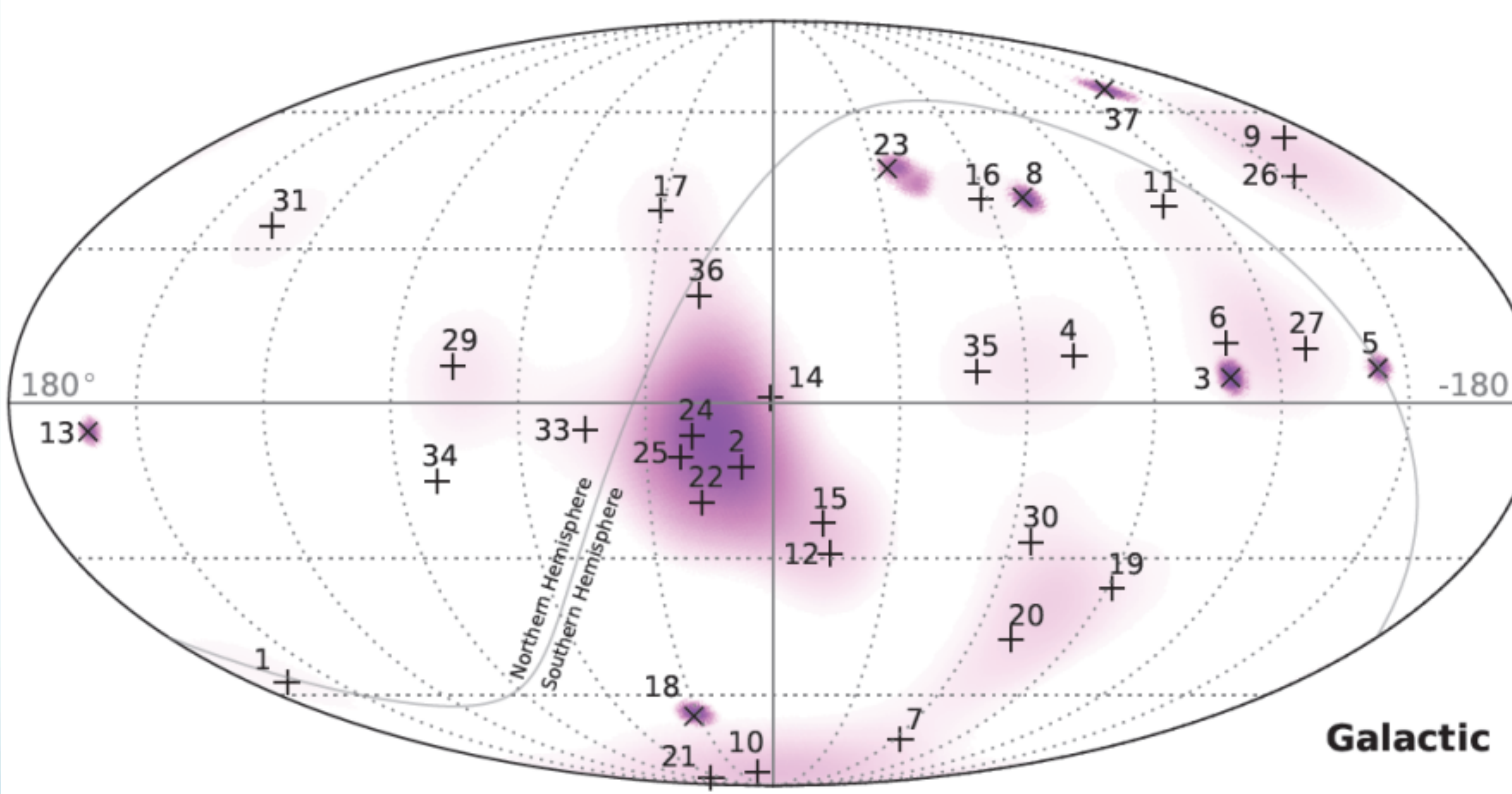




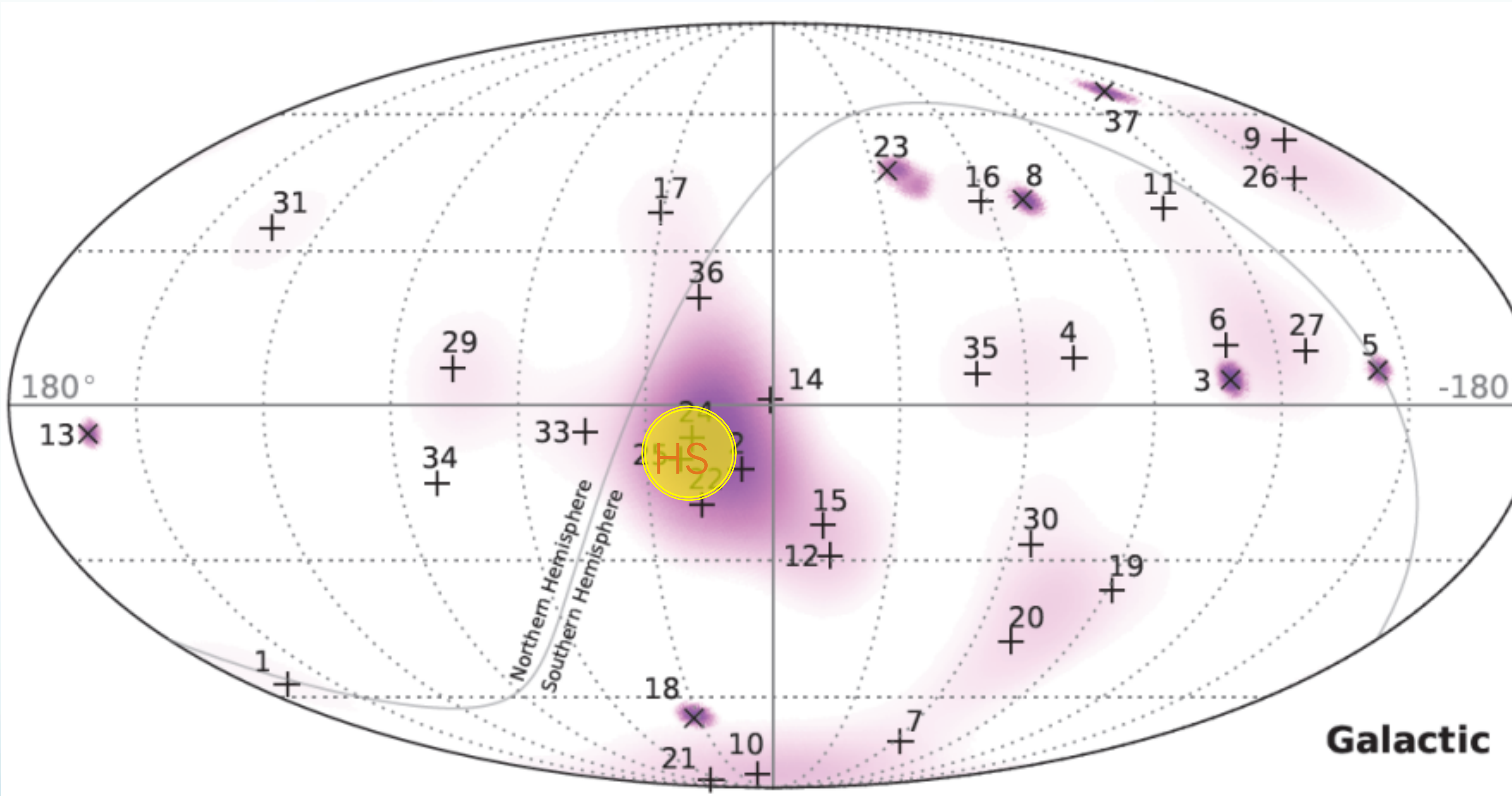


Top: 90% CL sensitivities and limits for an E^{-2} source spectrum and exponential cutoff at E=300 TeV. **Bottom**: For spectral index Γ =2.5.

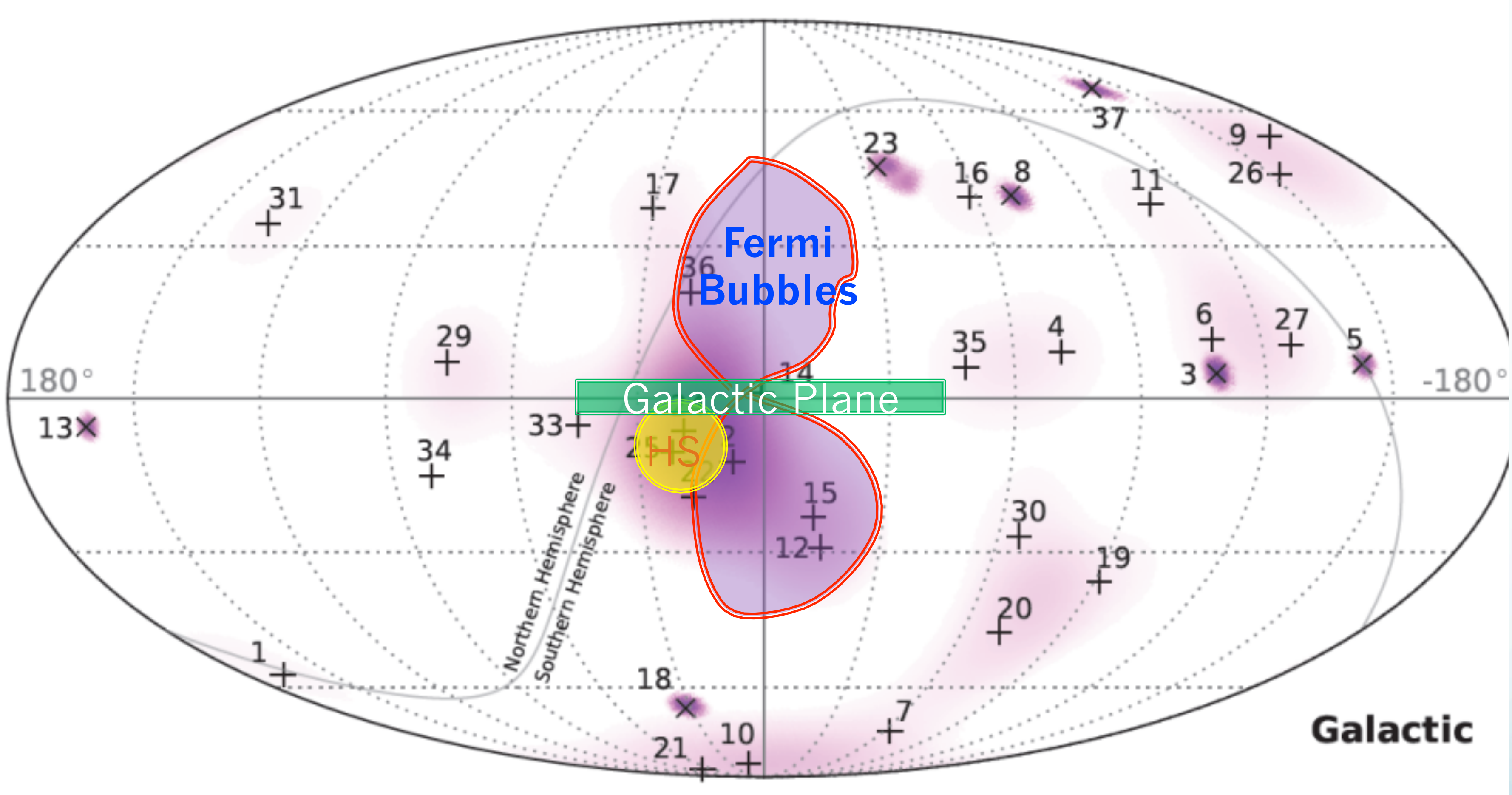
Enhanced diffuse flux



Enhanced diffuse flux



Enhanced diffuse flux

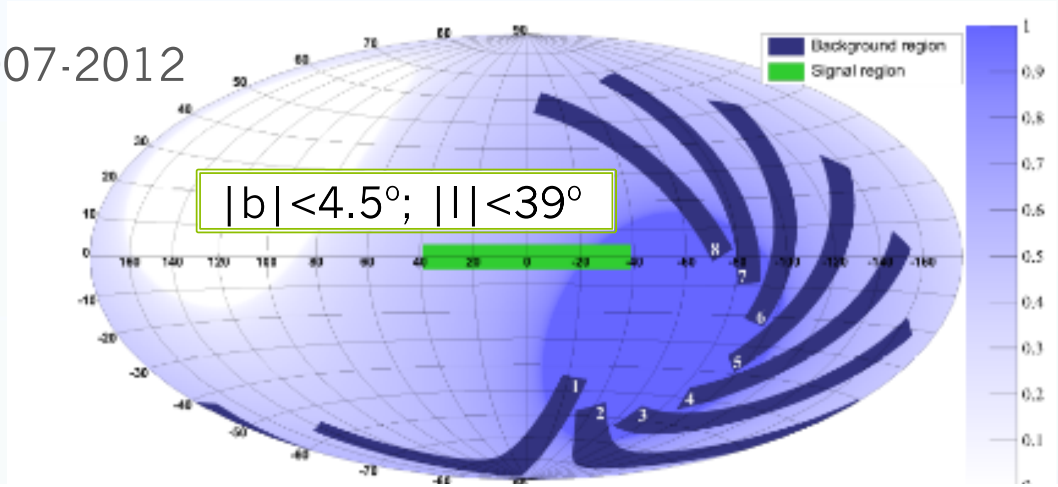


Galactic ridge

Neutrino produced by propagation of "fresh" Cosmic Rays supplied by young accelerators and detained by local magnetic fields $\propto \Phi_0 E^{-\Gamma}$

- $\Delta\Omega$=0.15 sr
- ν_μ events search in 2007-2012

paper in preparation

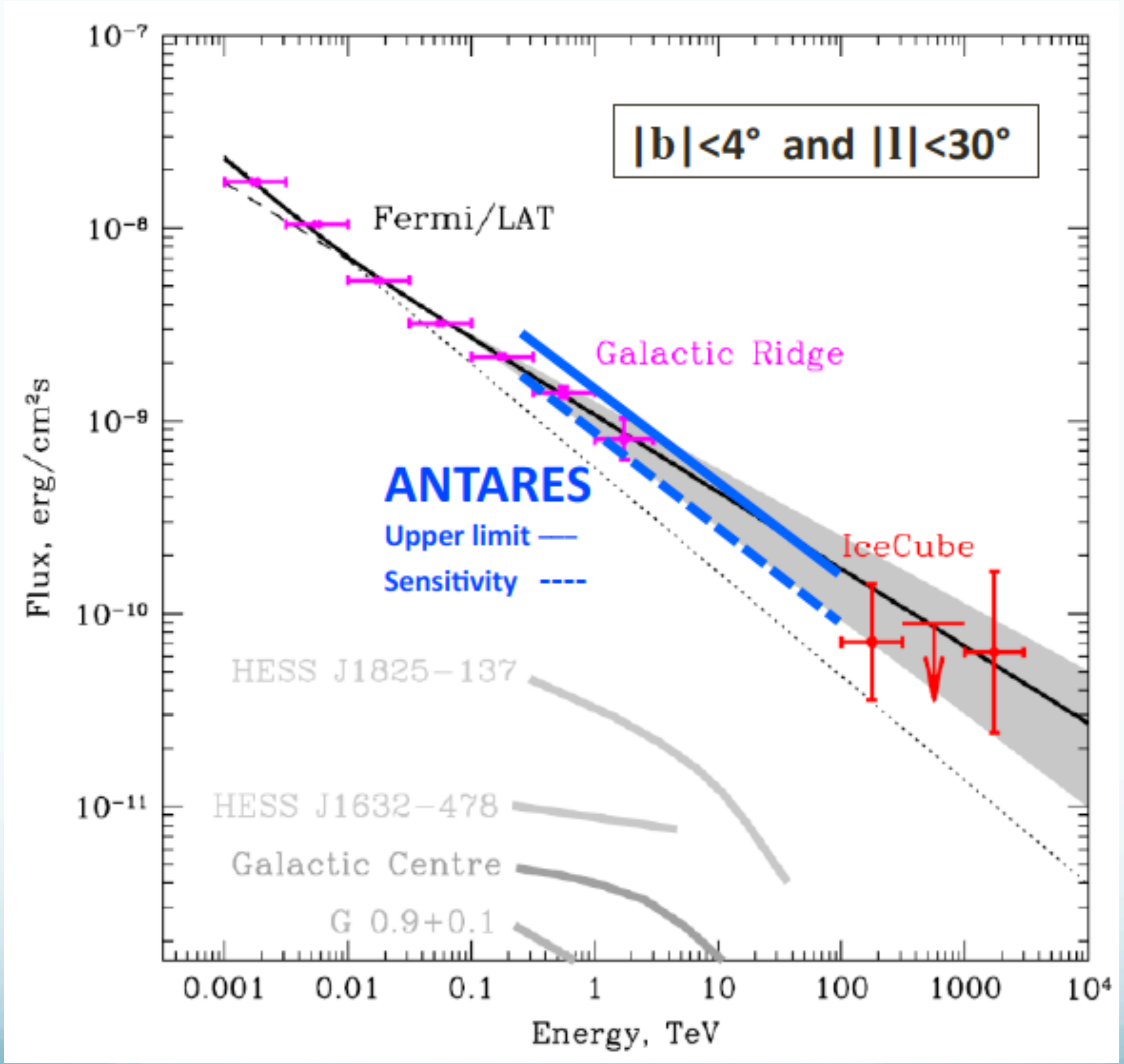


upper limits

sensitivities

Table 1. Sensitivities, obtained flux upper limits and energy validity range (central 90% of the signal) for different spectral indices.

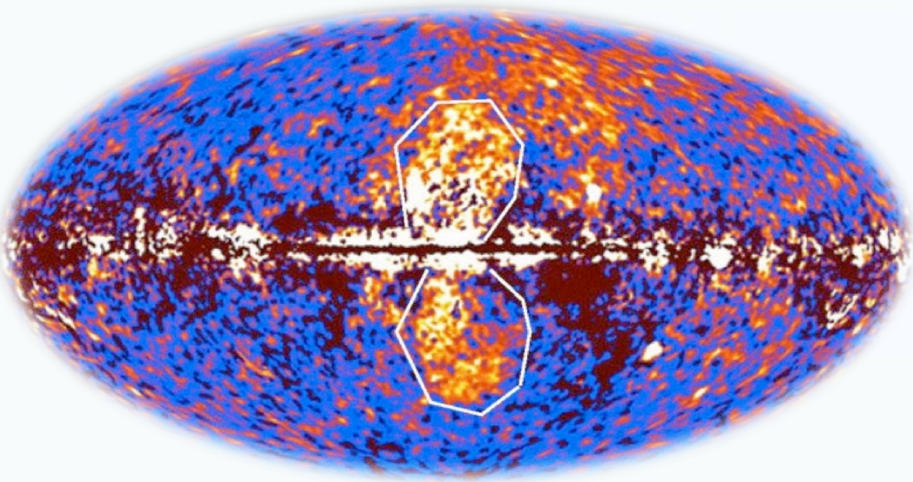
Spectral index γ	$\overline{\mathcal{F}}^{90\%}$ [GeV^{-1}	$cm^{-2} sr^{-1} s^{-1}$] $\mathcal{F}^{90\%}$	Energy validity range
2.5	$1.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	0.24 TeV - 96 TeV
2.6	$3.2 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$	0.18 TeV - 71 TeV
2.7	$7.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	0.15 TeV - 52 TeV

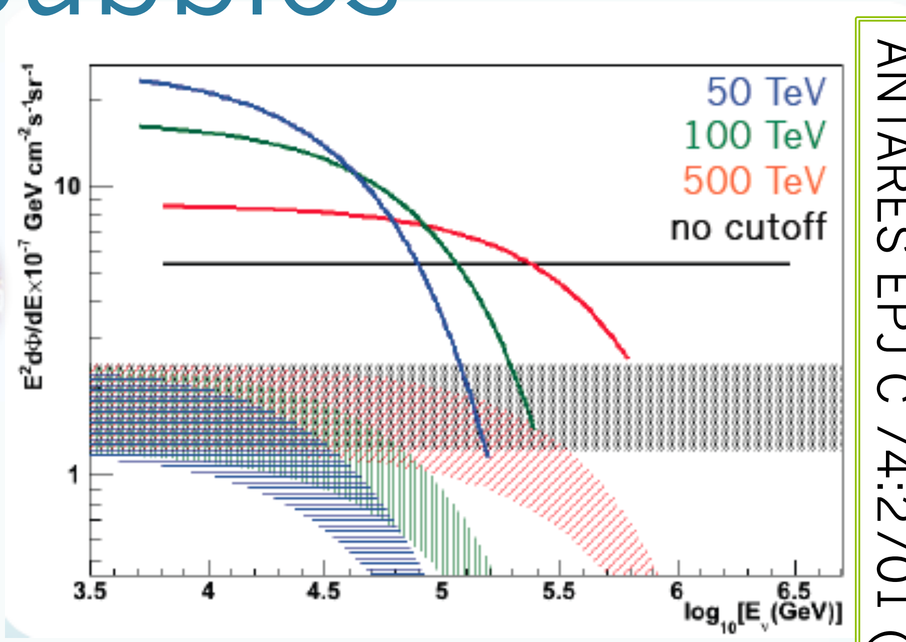


Neronov et al. Phys. Rev. D 89, 103002 (2014)

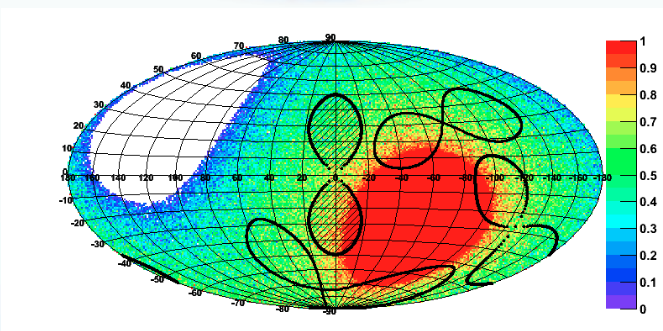
Fermi bubbles

NASA/DOE/FERMI LAT/D. Finkbeiner et al.





ANTARES EPJ C 74:2701 (2014)



- Comparison on-zone/(3 off-zones) of $\Delta\Omega$=0.66 sr
- 2008-2011 data analyzed (806 days of livetime)
- 16 events observed (11 background expected)

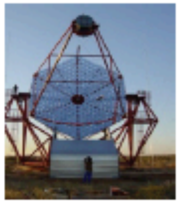
The hot spot in HESE

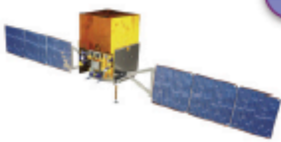
- ANTARES sensitivity is enough for a source of <0.1 sr with n>2 HESE events
- Analysis in process

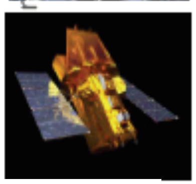
$\Delta\Omega$ (sr)	$\Gamma =$	units: (GeV cm^{-2} s^{-1} sr^{-1}) $\Phi_0^{D',\Gamma}$ (from HESE) $n_{\Delta\Omega} = 3$	$n_{\Delta\Omega} = 4$	$n_{\Delta\Omega} = 5$	$n_{\Delta\Omega} = 6$	ANTARES sensitivity
0.06 (radius 8°)	2.0	$3.5\ 10^{-7}$	$4.6\ 10^{-7}$	$5.8\ 10^{-7}$	$7.0\ 10^{-7}$	$3.1\ 10^{-7}$
	2.2	$4.5\ 10^{-6}$	$6.0\ 10^{-6}$	$7.5\ 10^{-6}$	$9.0\ 10^{-6}$	$3.6\ 10^{-6}$
	2.3	$1.7\ 10^{-5}$	$2.2\ 10^{-5}$	$2.8\ 10^{-5}$	$3.3\ 10^{-5}$	$1.1\ 10^{-5}$
	2.4	$5.9\ 10^{-5}$	$7.8\ 10^{-5}$	$9.8\ 10^{-5}$	$1.2\ 10^{-4}$	$3.4\ 10^{-5}$
0.38 (radius 20°)	2.0	$5.4\ 10^{-8}$	$7.3\ 10^{-8}$	$9.1\ 10^{-8}$	$1.1\ 10^{-7}$	$3.1\ 10^{-7}$
	2.2	$7.1\ 10^{-7}$	$9.4\ 10^{-7}$	$1.2\ 10^{-6}$	$1.4\ 10^{-6}$	$3.6\ 10^{-6}$
	2.3	$2.6\ 10^{-6}$	$3.6\ 10^{-6}$	$4.4\ 10^{-6}$	$5.2\ 10^{-6}$	$1.1\ 10^{-5}$
	2.4	$9.3\ 10^{-6}$	$1.2\ 10^{-5}$	$1.5\ 10^{-5}$	$1.9\ 10^{-5}$	$3.4\ 10^{-5}$
FB						90% C.L. limit
0.66	2.0	$3.1\ 10^{-8}$	$4.2\ 10^{-8}$	$5.2\ 10^{-8}$	$6.3\ 10^{-8}$	$5.4\ 10^{-7}$

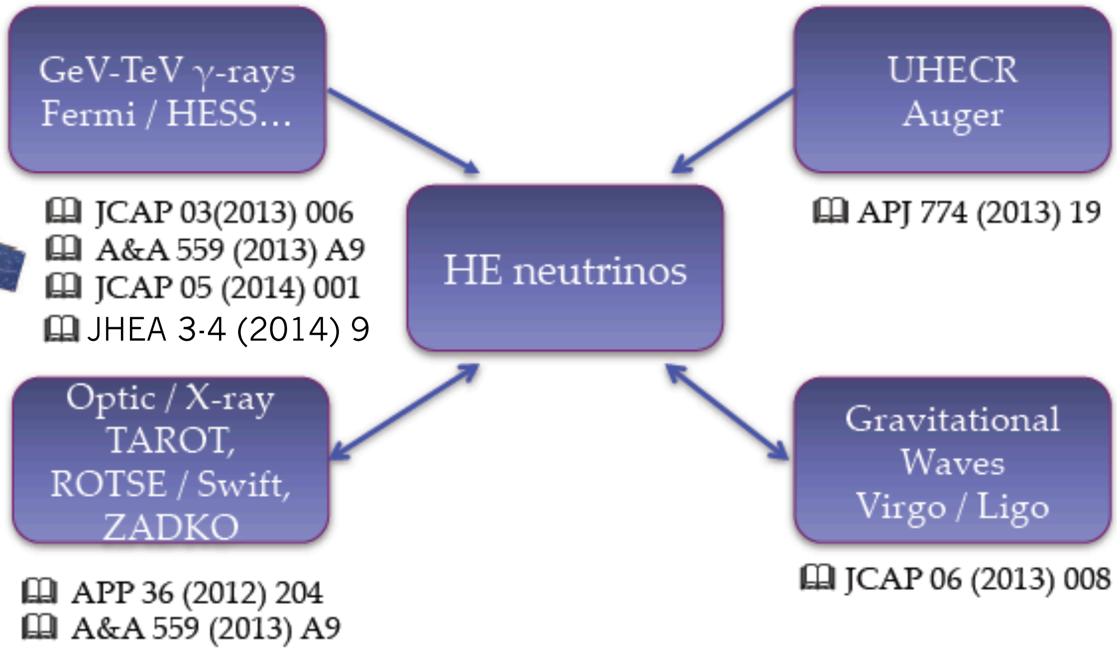
Spurio, PRD 90, 103004 (2014)

The Multi-Messenger program









Increases chances of detection:

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

Blazars monitored by TANAMI

- Six blazars associated with the first two PeV IC events

Krauß et al, A&A 566, L7 (2014)

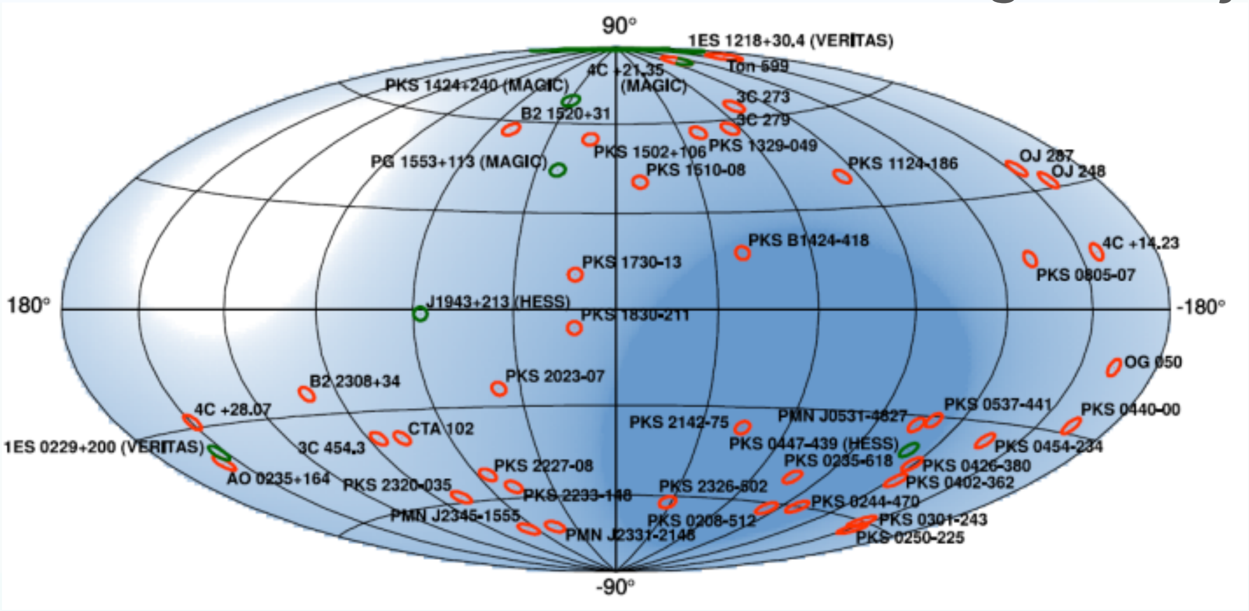
- 2 ANTARES signal-like events are coming from 2 blazars with the highest predicted spectrum (this is still consistent with their background origin), both blasars associated with IC14 event
- IC20 event is less probably associated with blasars
- Third PeV event studies are ongoing

Source	Cat. Name	F_γ [GeV cm^{-2} s^{-1}]	N_{ν_e}	IC	N_{sig}	p
0235–618	PKS 0235–618	$\left(6.2^{+3.1}_{-3.1}\right) \times 10^{-8}$	$0.19^{+0.04}_{-0.04}$	20, 7	0	1
0302–623	PKS 0302–623	$\left(2.1^{+0.4}_{-0.4}\right) \times 10^{-8}$	$0.06^{+0.01}_{-0.01}$	20	0	1
0308–611	PKS 0308–611	$\left(4.7^{+1.8}_{-1.8}\right) \times 10^{-8}$	$0.14^{+0.05}_{-0.05}$	20	0	1
1653–329	Swift J1656.3–3302	$\left(2.8^{+0.3}_{-0.3}\right) \times 10^{-7}$	$0.86^{+0.10}_{-0.10}$	14, 2, 25	1.1	0.10
1714–336	TXS 1714–336	$\left(1.5^{+0.3}_{-0.4}\right) \times 10^{-7}$	$0.46^{+0.10}_{-0.12}$	14,2,25	0.9	0.04
1759–396	MRC 1759–396	$\left(7.5^{+1.9}_{-1.9}\right) \times 10^{-8}$	$0.23^{+0.50}_{-0.40}$	14, 2, 15, 25	0	1

ANTARES A&A 576, L8 (2015)

Corellation with TeV γ-ray flaring blazars

- Variable blazars monitored by FERMI-LAT and IACTs
- Search for neutrino events correlated with high activity state



Skymap (galactic coordinates) with the position of the 41 selected Fermi blazars (red circle) and 7 IACT blazars (green circles) on top of the ANTARES visibility.
The most significant correlation was found with 3C279 (1 ν_μ), post-trial probability is 67% compatible with background fluctuations

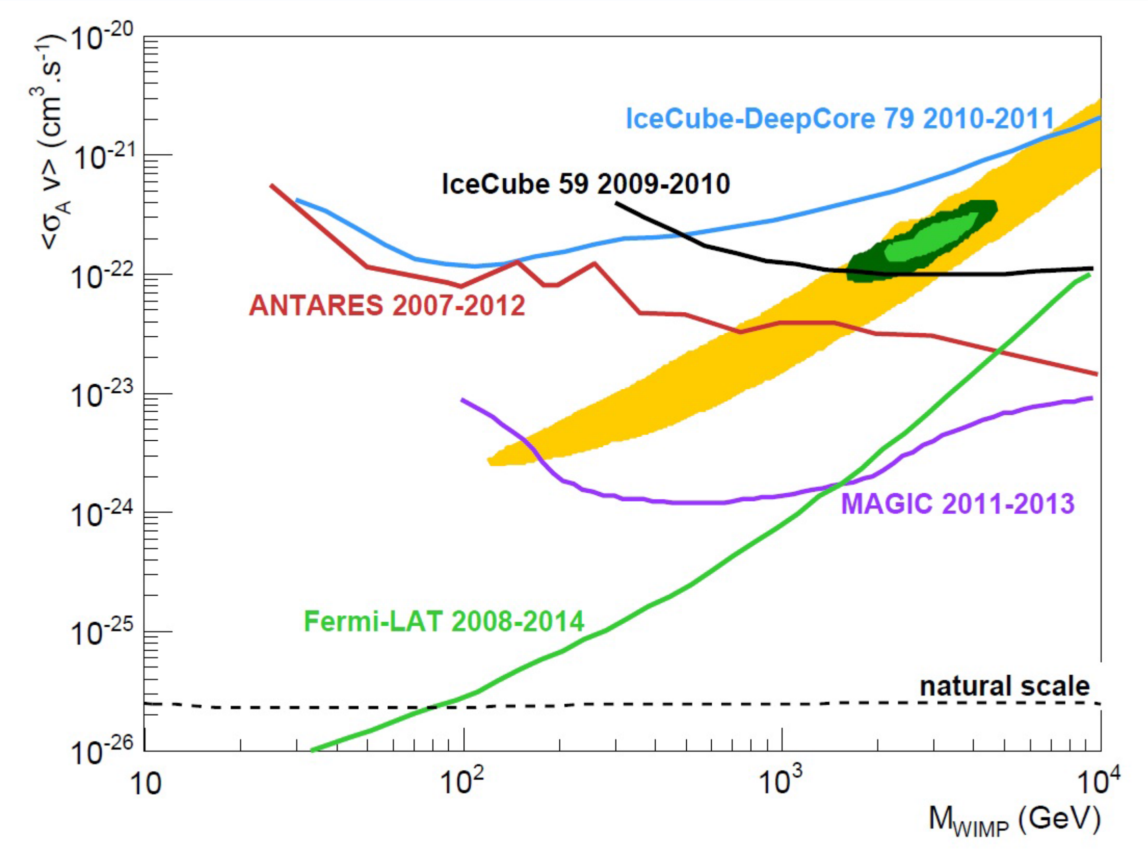
Dark Matter search

Neutrino detection in direction of massive objects due to DM annihilation.

- Sun

JCAP 11 032 (2013)

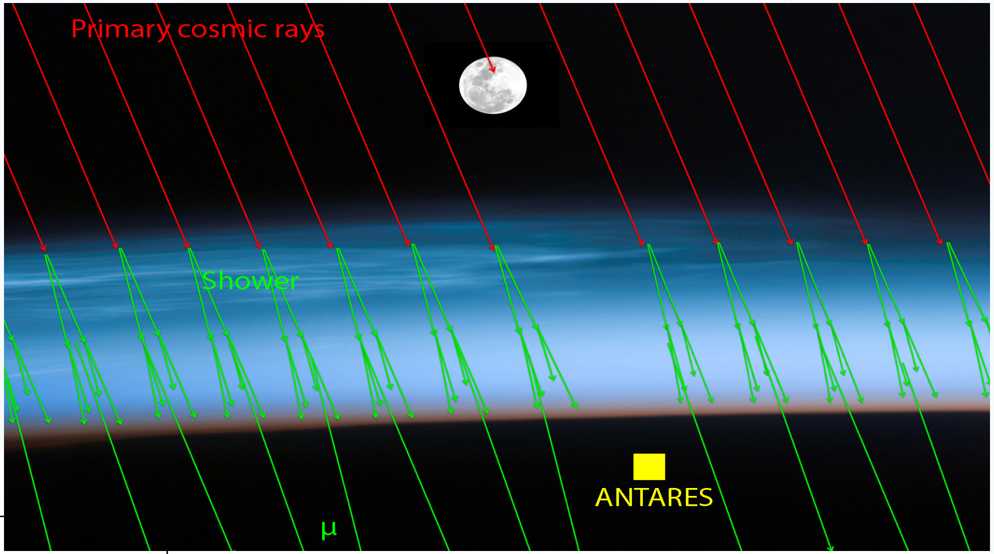
- Galactic center arXiv:1505.04866

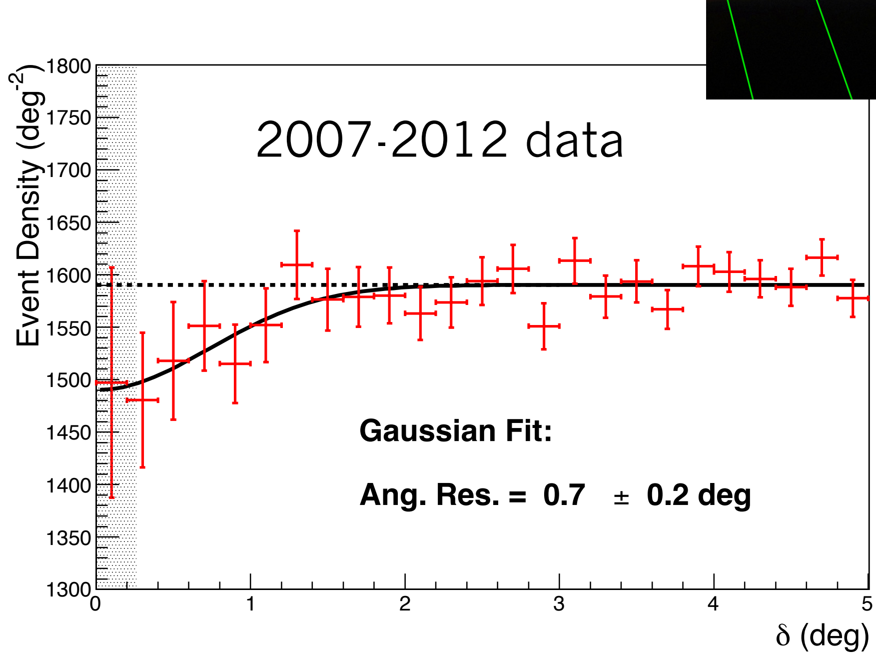


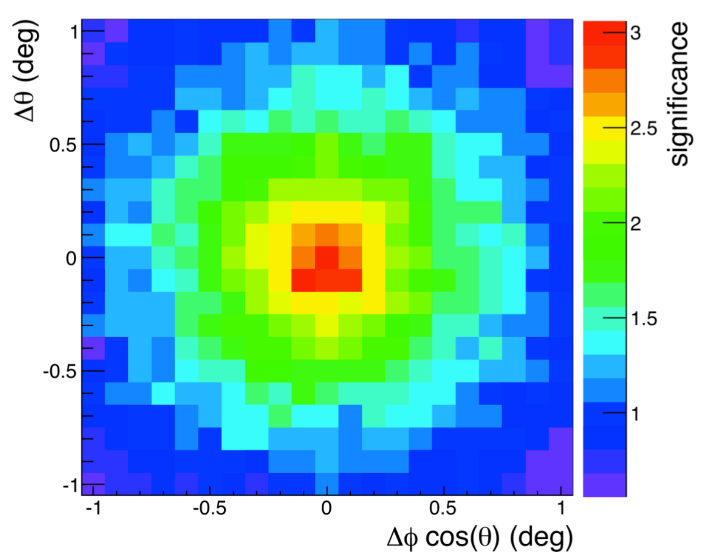
ANTARES 90% C.L. upper limit on the WIMP velocity averaged self-annihilation cross-section for D+D -> $\tau^+\tau^-$ channel)

Moon Shadow

It is helpful to verify the absolute pointing performance using a calibration source, like the "Moon shadow" effect.







Conclusions and plans

- ANTARES contributes in the understanding of the origin of the cosmic neutrinos observed by IC
- Despite its moderate size, but thanks to its location and excellent angular resolution it is yielding:
  - Better sensitivity for point and compact sources ($\Delta\Omega$=0.1-0.2 sr) in the Southern sky
  - Best limits for the Galactic Centre and the Fermi bubble regions
- ANTARES continue data taking until the end of 2016
- Prepare for the next generation Mediterranean neutrino telescope – KM3NeT