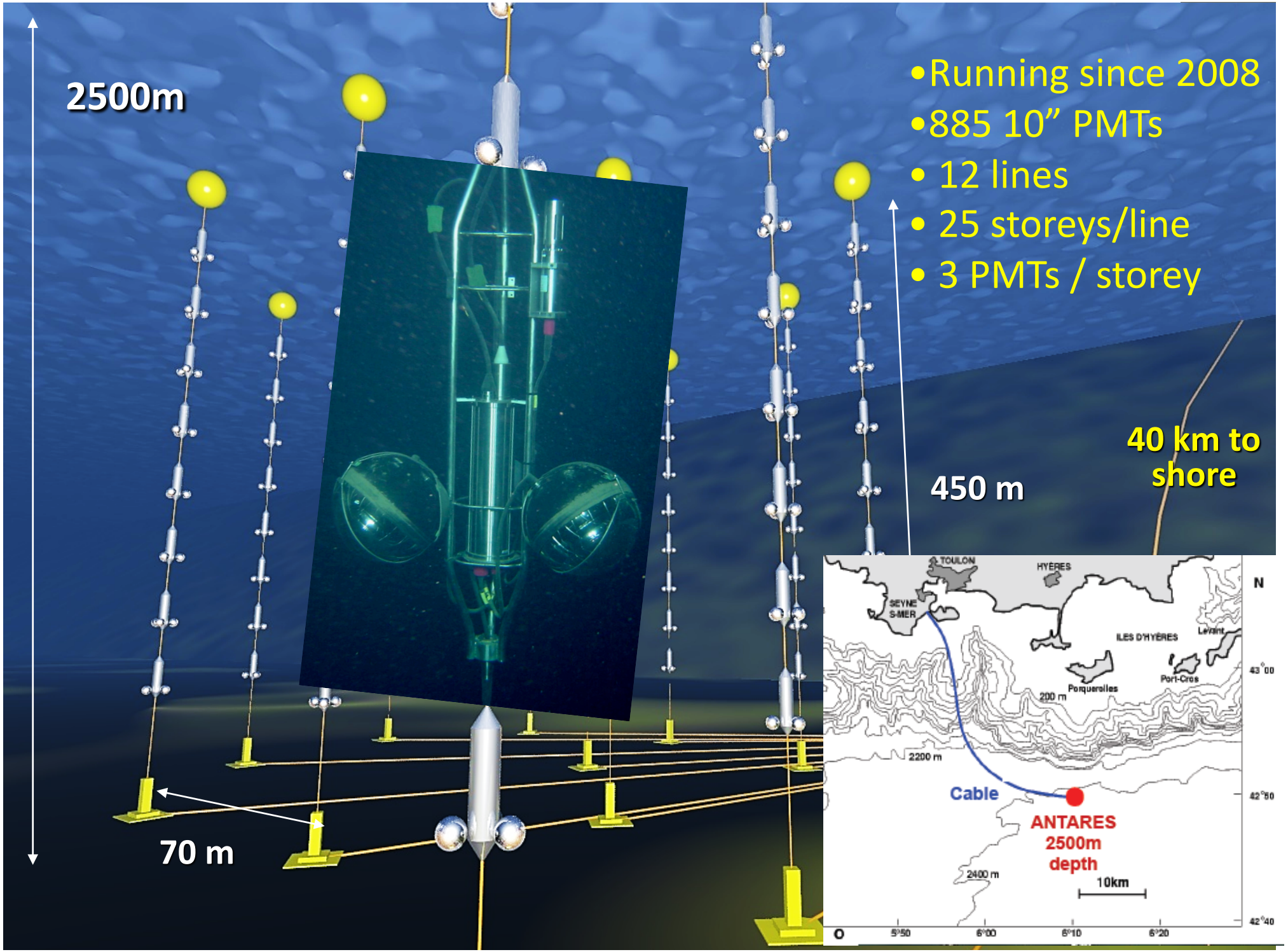
Recent results of the ANTARES NeuTel in the Mediterranean Sea

Maurizio Spurio
on behalf of the ANTARES Collaboration
XVI Neutrino Telescopes – Venice 07/03/2015

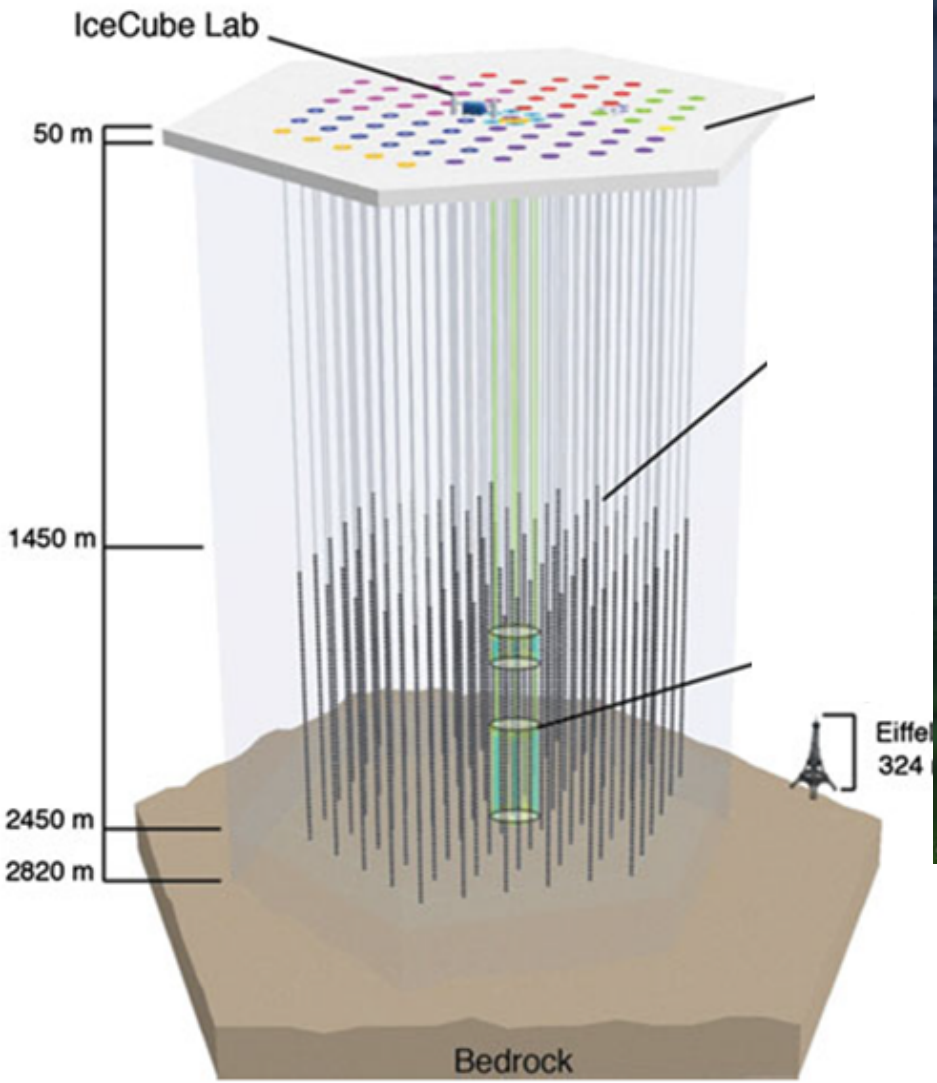

2500m
•Running since 2008
•885 10” PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
40 km to shore
450 m
70 m
TOULON
HYERES
SEYNE S-MER
ILES D'HYÈRES
Levant
Porquerolles
Port-Cros
200 m
2200 m
Cable
ANTARES
2500m
depth
2400 m
10km
N
43°00
42°50
42°40
O
5°50
6°00
6°10
6°20

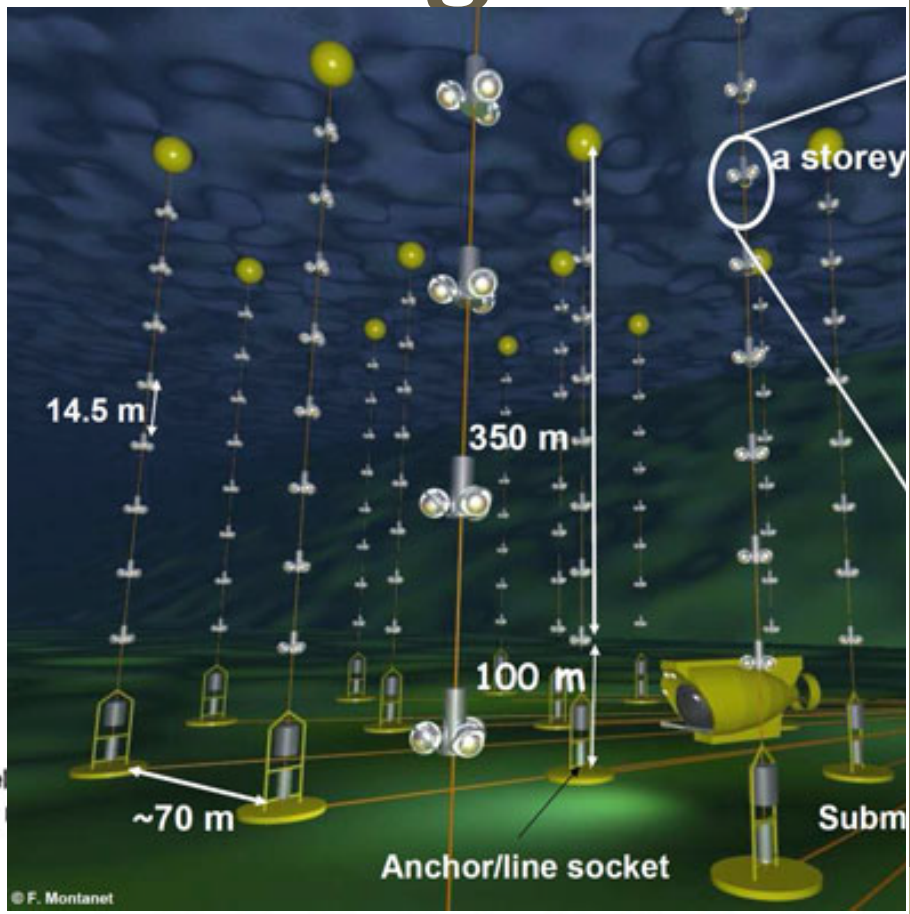
The scientific goals of ANTARES

- **Neutrino astrophysics**
- **Multi-messenger studies**
- Dark Matter searches
- Study of atmospheric neutrinos
- Particle physics: nuclearites, monopoles
- Acoustic neutrino detection
- Sea sciences

} **Not covered in this talk**

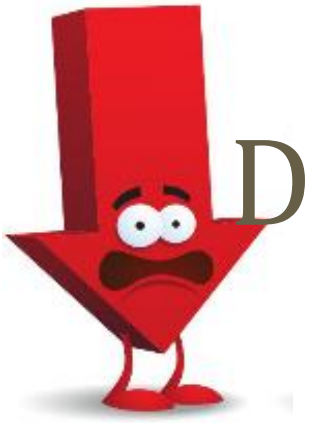
Neutrino telescopes: the Eiffel Tower scaling law





sin(δ)

Almost in scale.
True for **upgoing events**

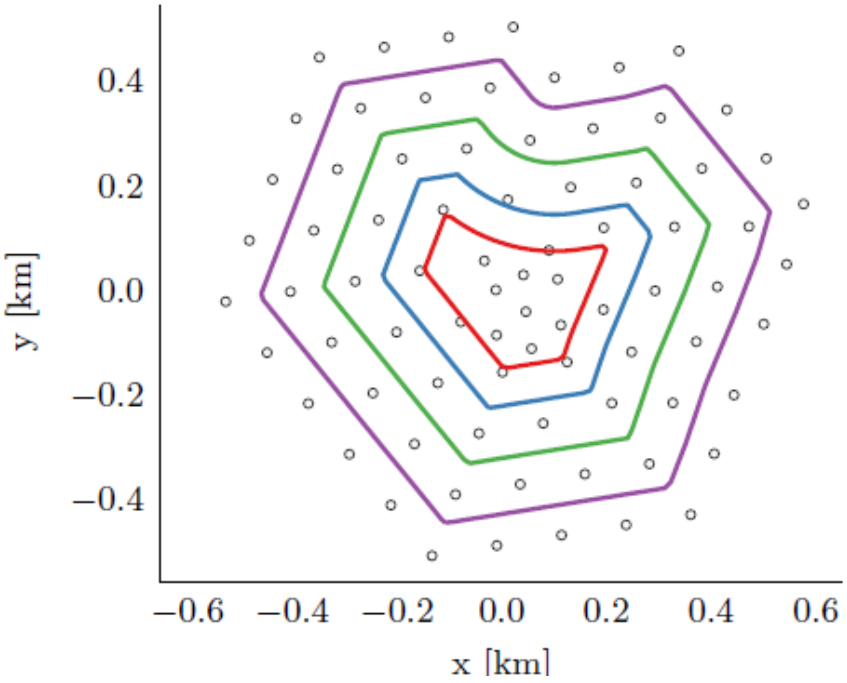


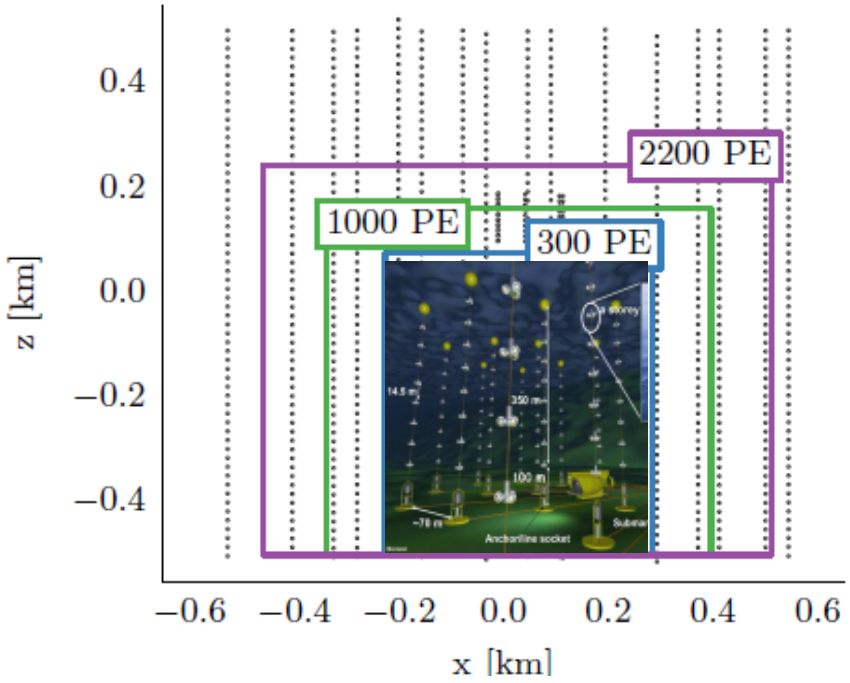
Down in IC = Up in ANTARES

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. Anders
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]



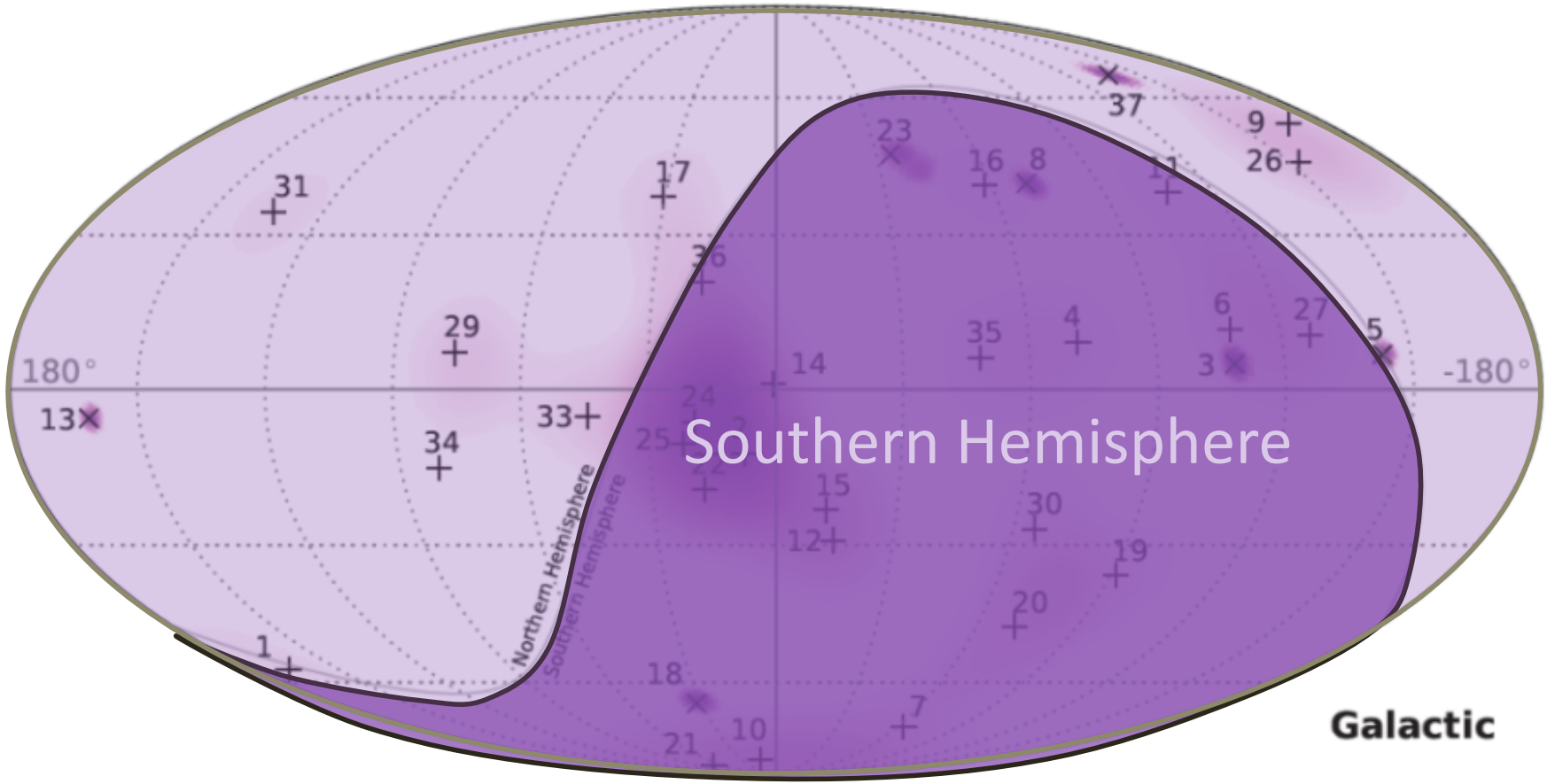


Almost in scale

IceCube. PRL113(2014)101101

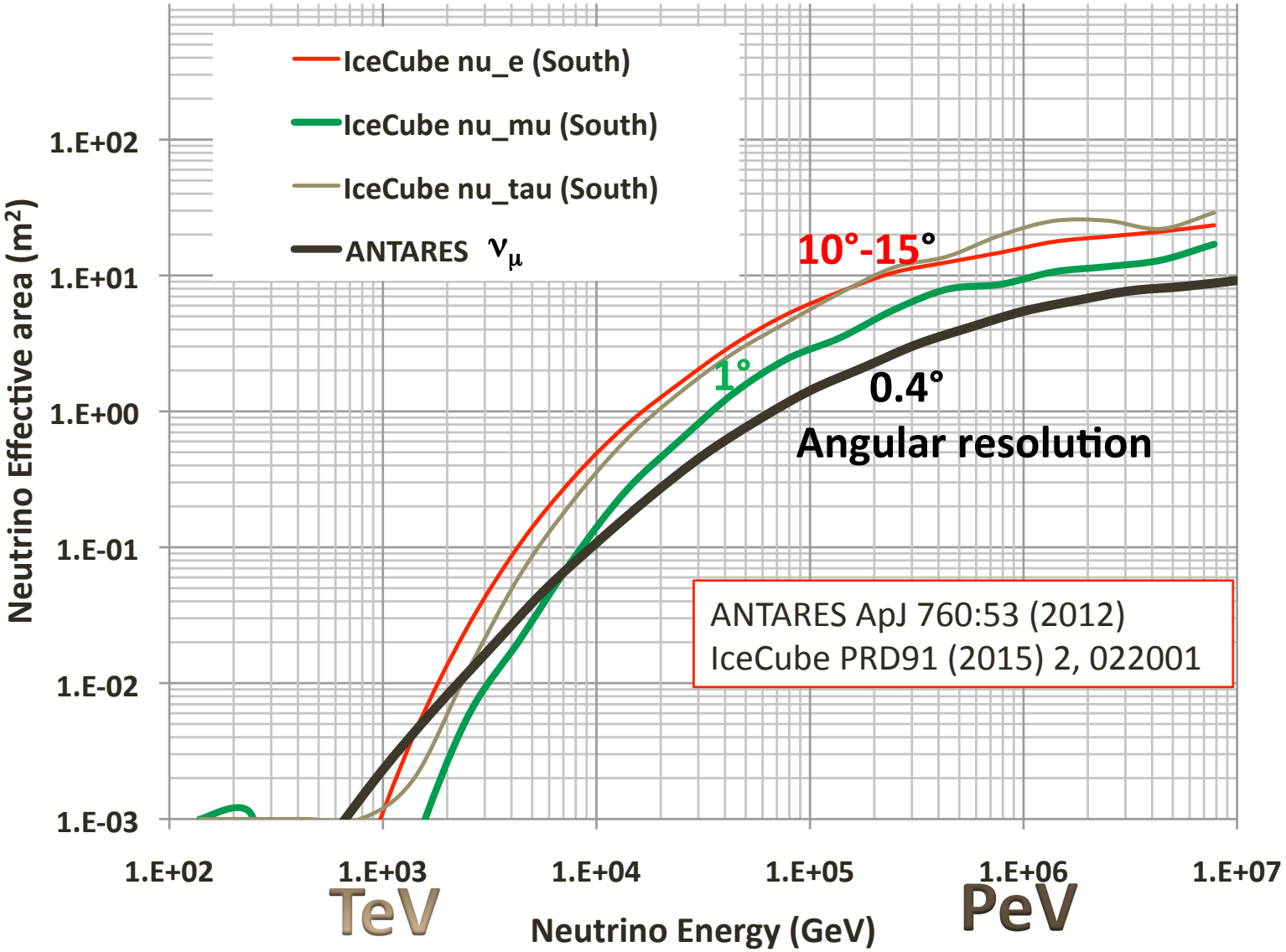
On the quest for a Southern sky component in the IC signal

Diffuse component (extragalactic)



+ galactic component (?)

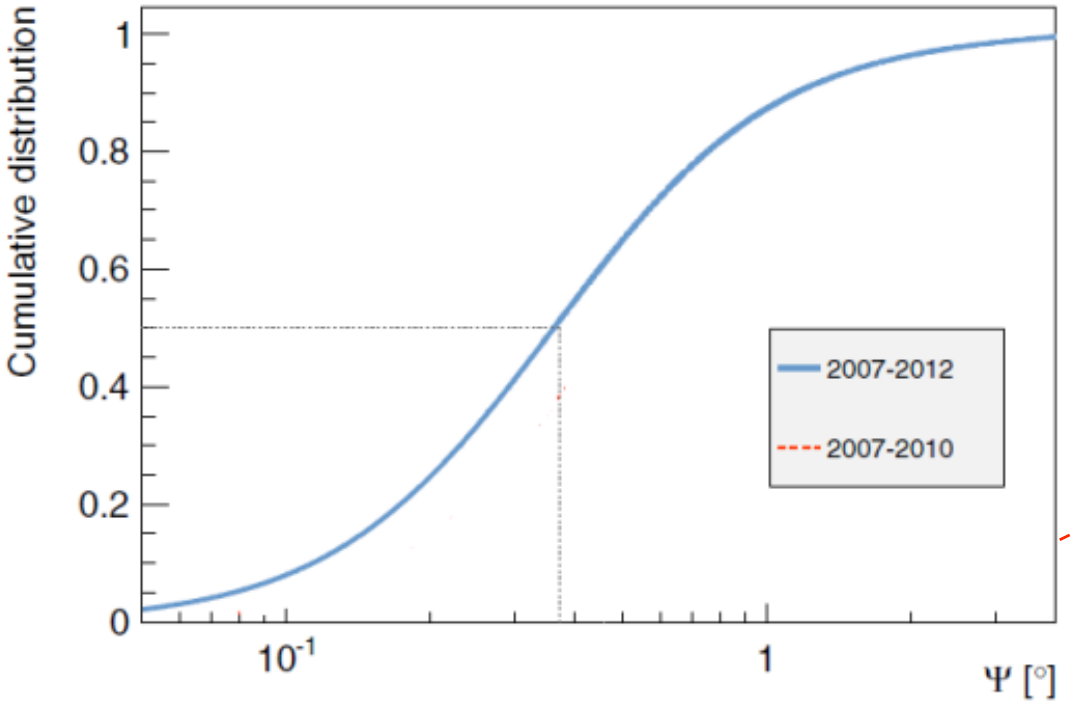
Effective areas - A_{eff}

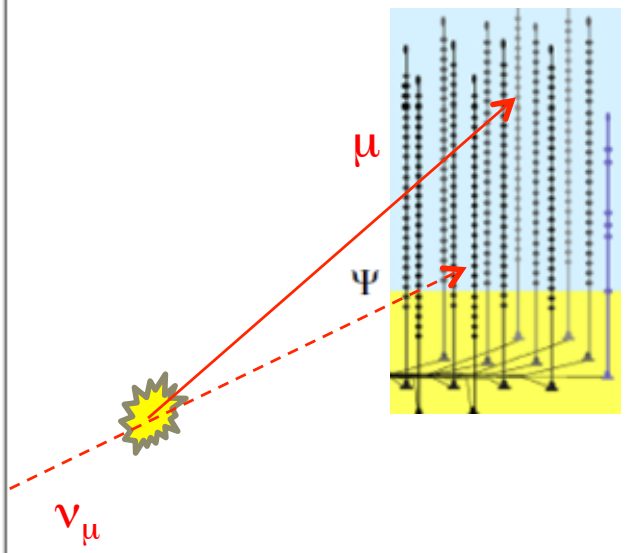


1) Point-like sources

- The ν_μ channel allows ANTARES to behave as a **telescope**
- 50% of reconstructed ν_μ within 0.4° (for E^{-2} spectrum)
- Proxy estimate of the energy

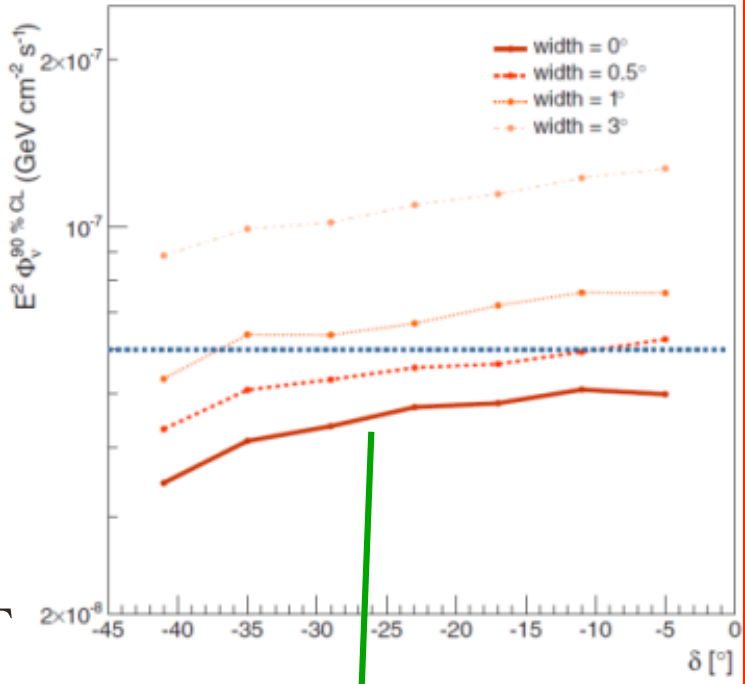
THE ASTROPHYSICAL JOURNAL LETTERS, 786:L5 (5pp), 2014 May 1





1.1 Unknown point-source $\Phi_0 E^{-\Gamma}$ producing n_p HESE

- The ANTARES 90% C.L. upper limit 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
- A clusters of $n_p \geq 2$ is excluded for Γ> 2.3.



Expected normalization factors Φ_0 as a function of Γ

	IceCube $\Phi_0^{p,\Gamma}$ (GeV cm^{-2} s^{-1})					ANTARES 90% C.L. upper limit
Γ =	$n_p = 1$	$n_p = 2$	$n_p = 3$	$n_p = 4$	$n_p = 5$	
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	$3.9\ 10^{-6}$	$7.9\ 10^{-6}$	-	-	-	$5.5\ 10^{-6}$

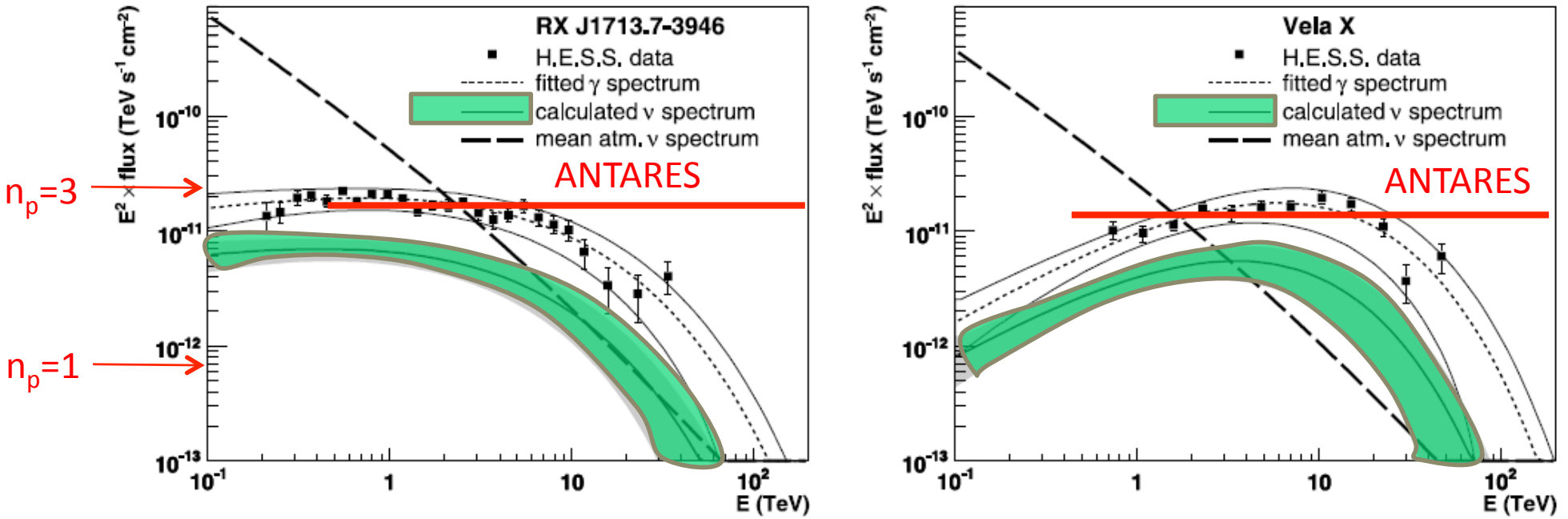
MS, PRD 90, 103004 (2014)

The Astrophysical Journal Letters, 786:L5 (5pp), 2014 May 1

1.2 Galactic PeVatrons

- Models predictions up to $E^2\Phi = 10^{-8}$ GeV s^{-1} cm^{-2}
- ANTARES dedicated study of 50 pre-selected sources using data set 2007-2012 (no significant excess)
- Unbinned searches: no excess (most significant at 2.2σ)

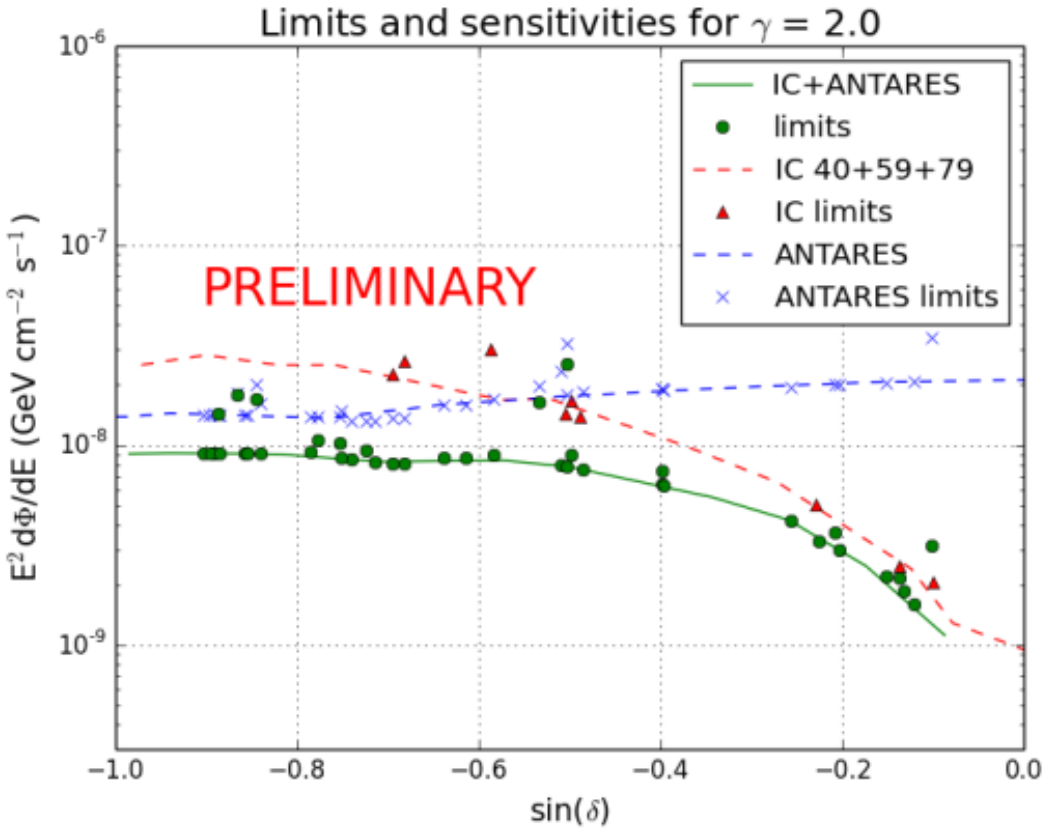
A. Kappes et al., ApJ, 656:870(2007)

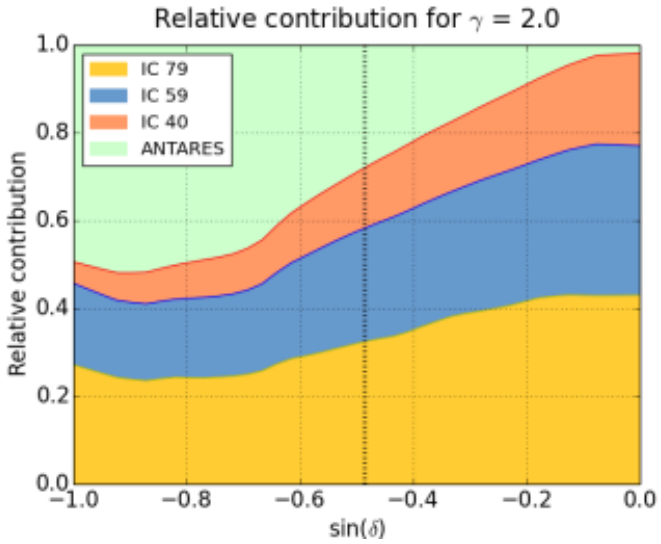


The Astrophysical Journal Letters, 786:L5 (5pp), 2014 May 1

1.3 Joined ANTARES-IC searches

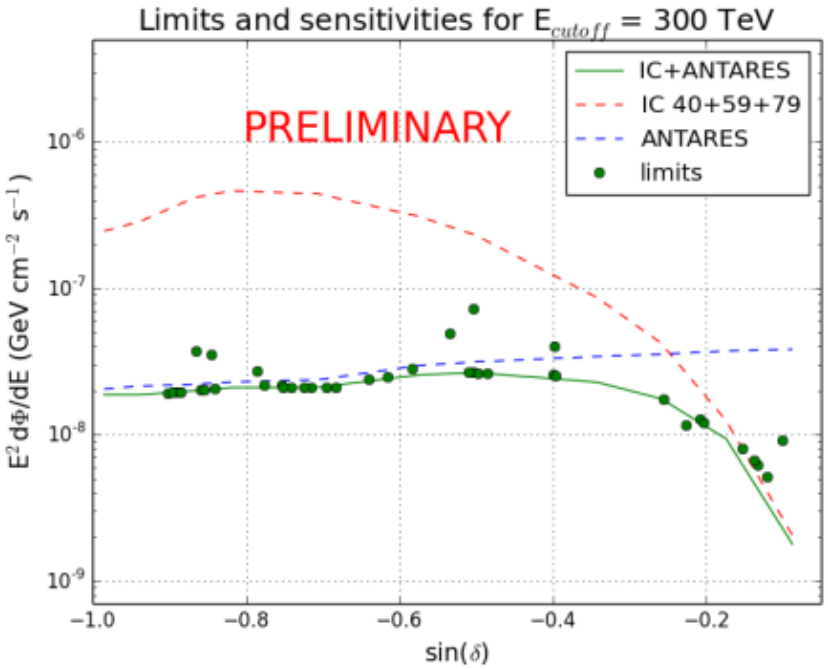
- Point-source analysis using the ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere

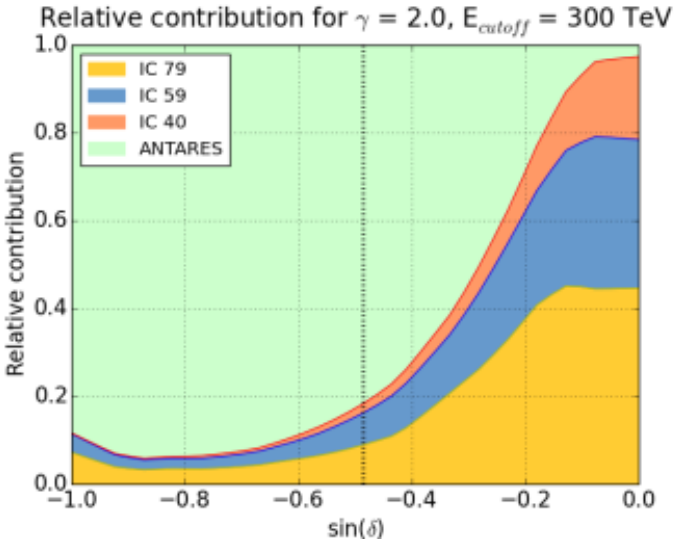


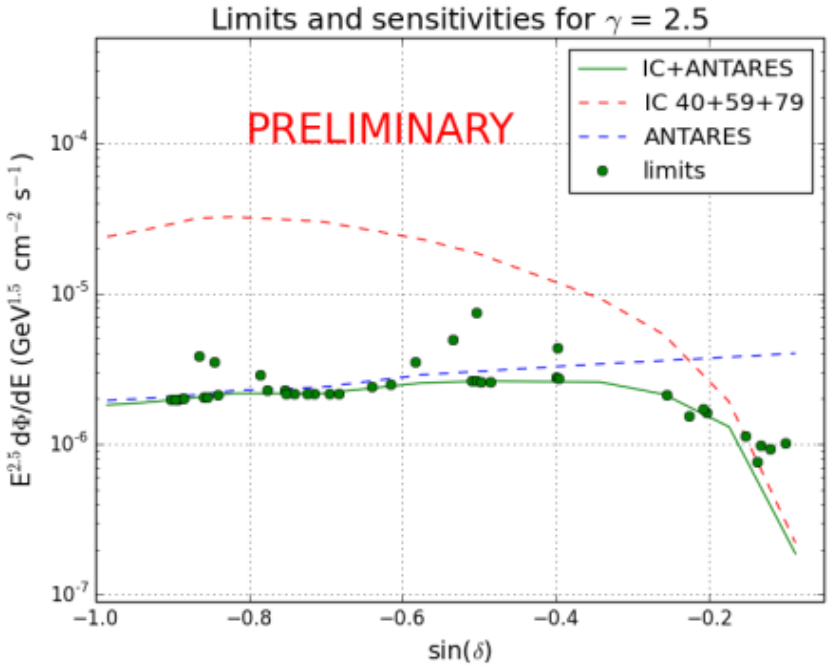


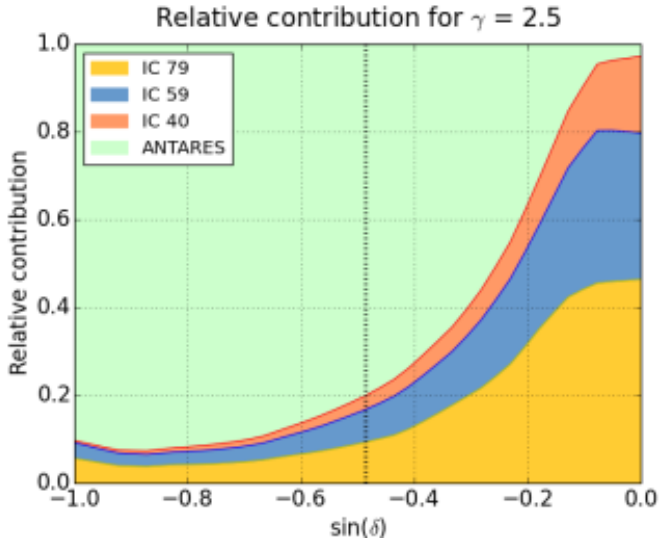
Paper in preparation

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



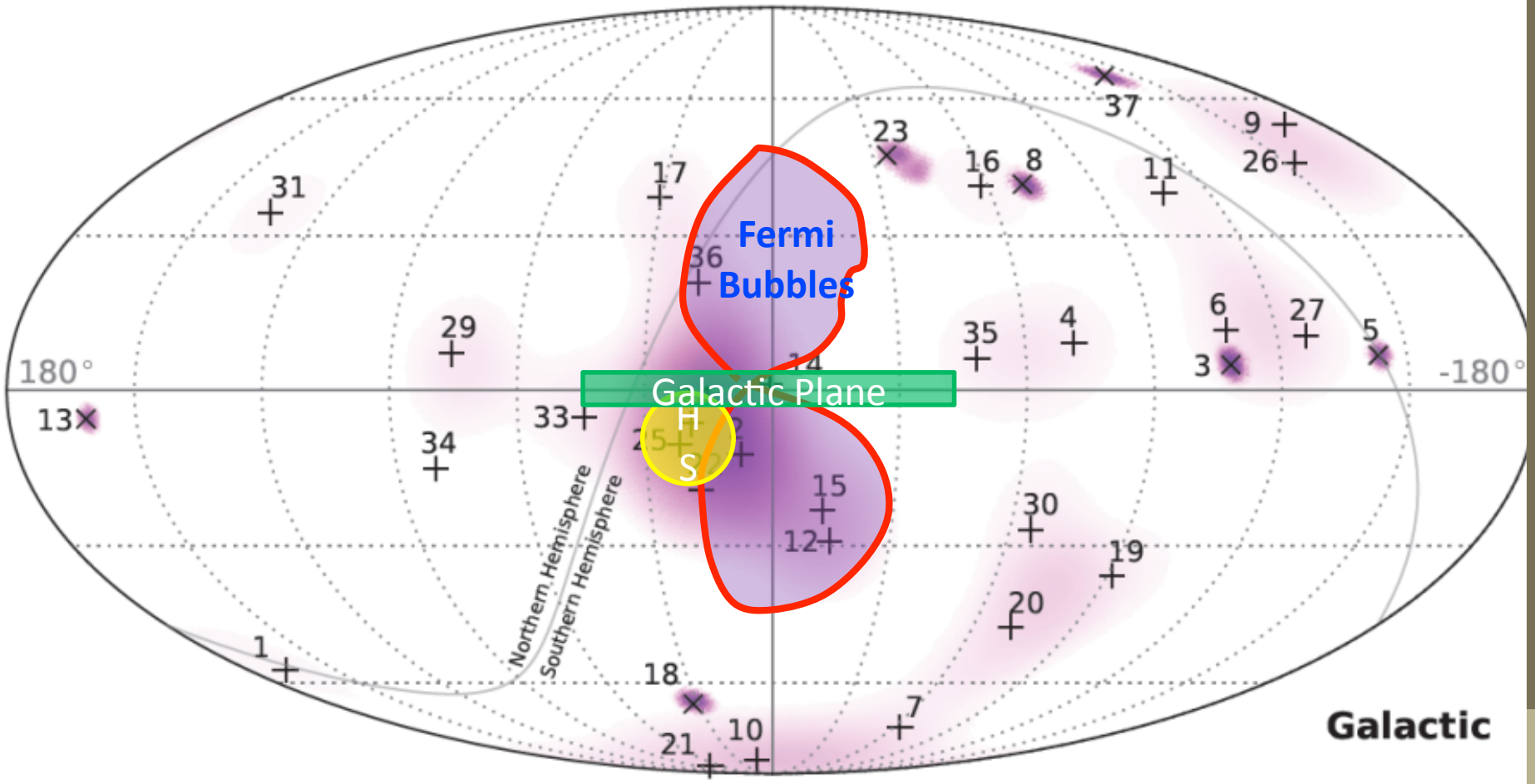




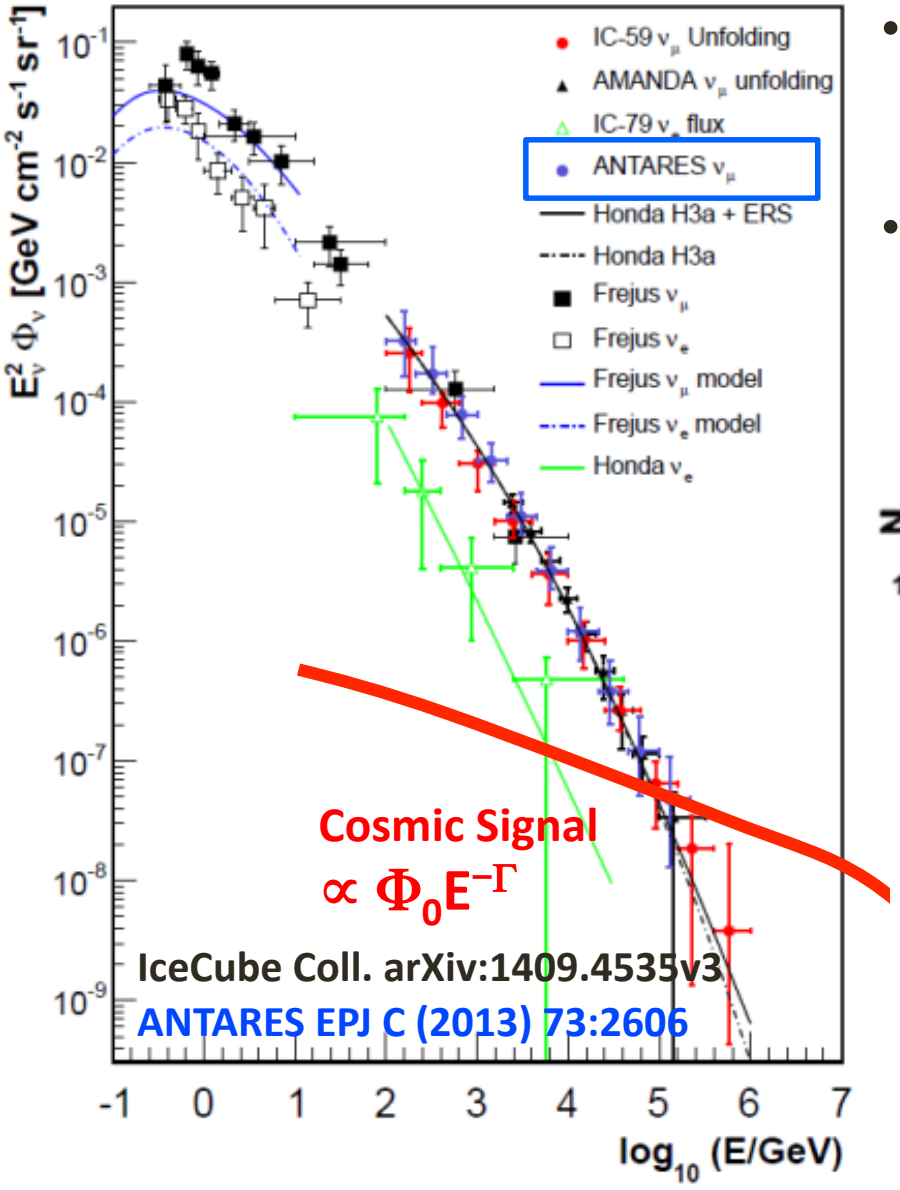


Top: 90% CL sensitivities and limits for an E^{-2} source spectrum and exponential cutoff at E = 300 *TeV*. **Bottom**: For spectral index Γ=2.5

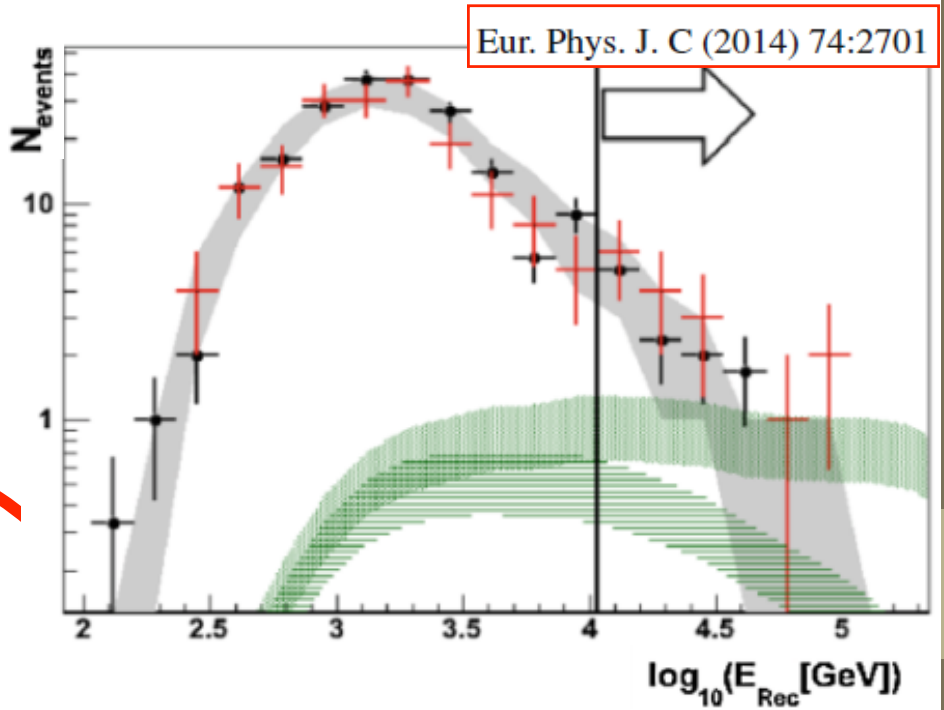
2) An enhanced diffuse flux



- Atmospheric neutrinos is the irreducible background
- The expected signal spectrum is **harder** than the background of atmospheric neutrinos



- The search methods rely on the event-by-event estimate of the ν_μ energy (the muon light yield gives a proxy)
- Comparison between the signal region and off-signal zones



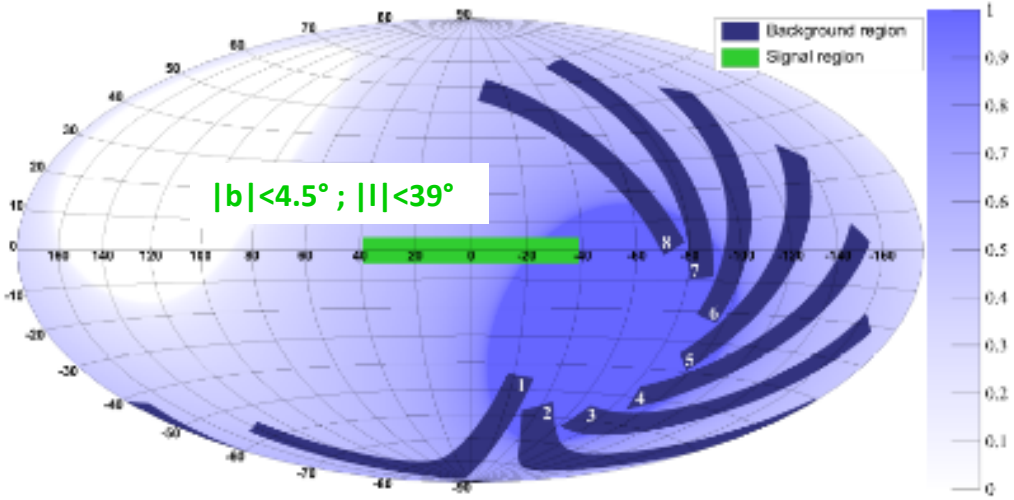
Neronov et al. arXiv:1412.1690 4 Dec 2014

Guo et al. arXiv:1412.8590 30 Dec 2014

2.1 The Galactic ridge

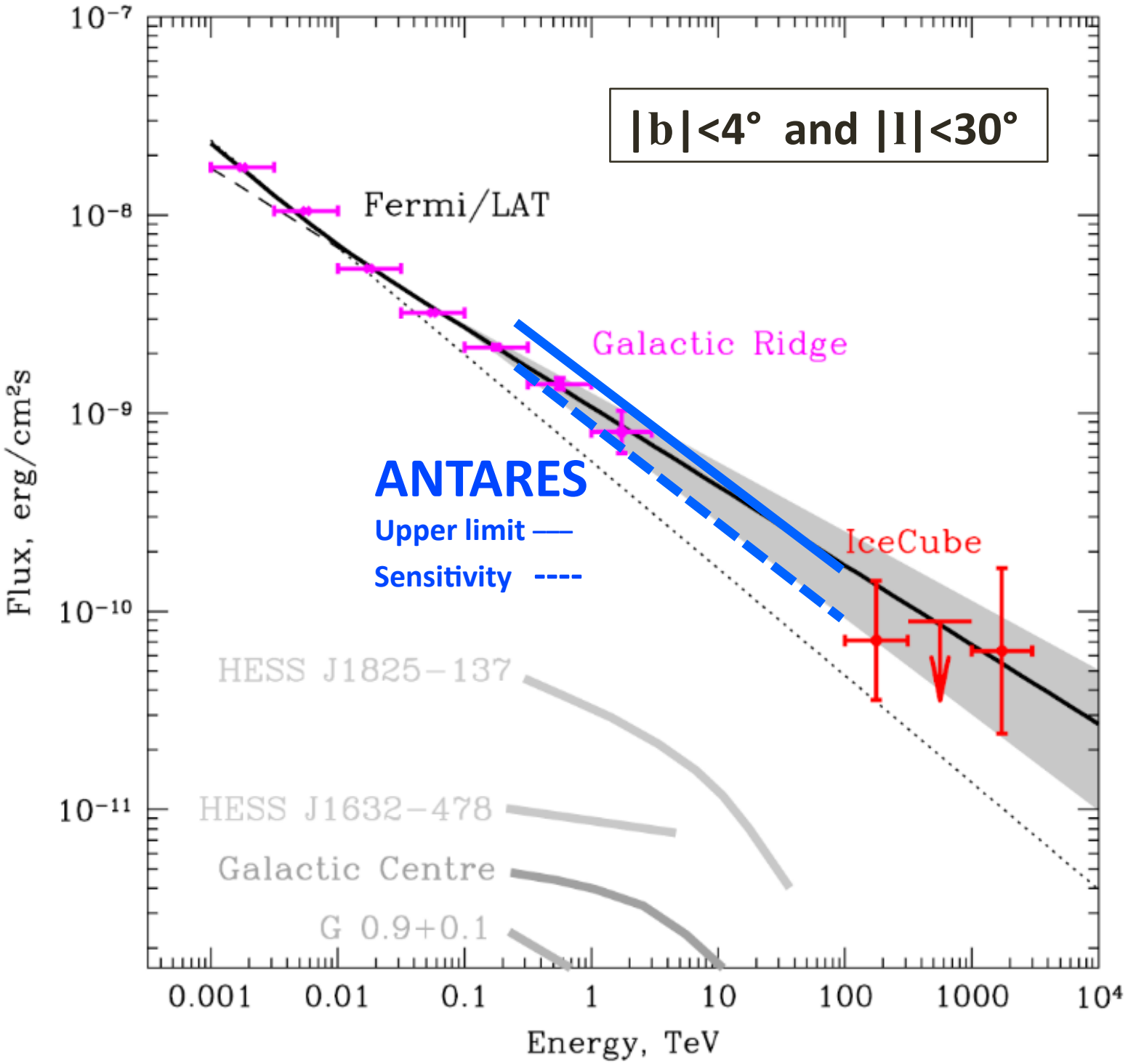
neutrino produced by propagation of "*fresh*" Cosmic Rays supplied by young accelerators and detained by local magnetic fields $\propto \Phi_0 E^{-\Gamma}$

- $\Delta\Omega$=0.15 sr
- Search for ν_μ using data from 2007-2012
- Counts in the signal/off zones
- Paper in preparation

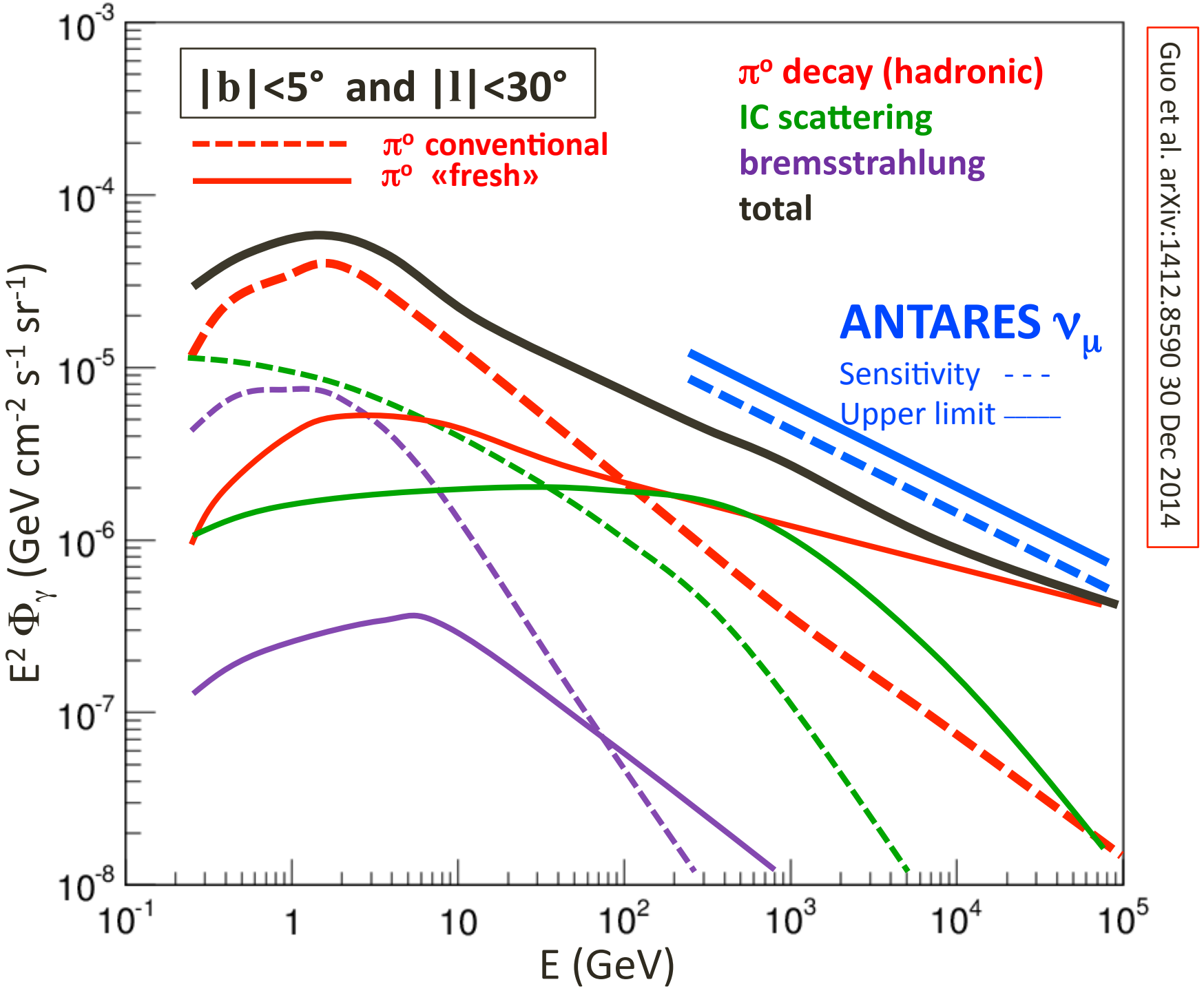


Upper limits
sensitivities

Spectral index Γ	$\overline{\mathcal{F}}^{90\%}$ $[\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}]$	$\mathcal{F}^{90\%}$	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

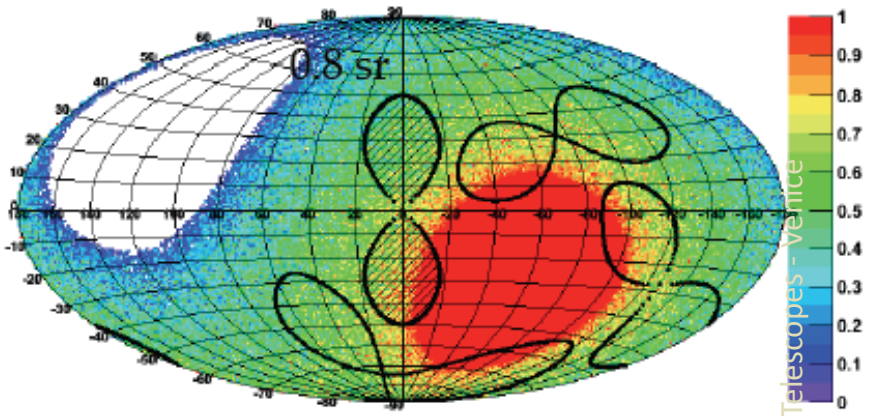


Neronov et al. arXiv:1412.1690 4 Dec 2014



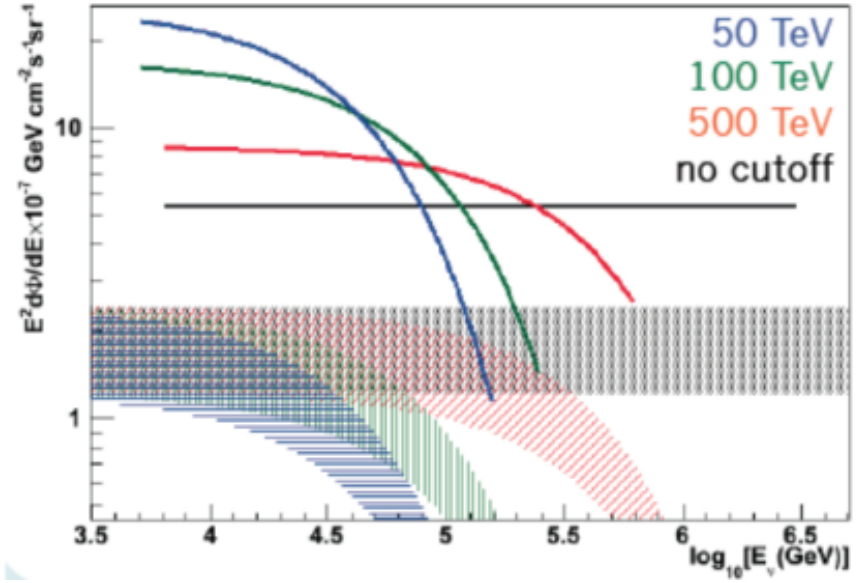
Guo et al. arXiv:1412.8590 30 Dec 2014

2.2 Fermi Bubbles



- Comparison on-zones/(3 off-zones) of $\Delta\Omega$=0.66 sr
- 2008-2011 data analyzed (806 days of livetime).
- E^{-2} spectrum with different cutoff : 50, 100, 500, ∞ TeV
- 16 events observed /11 background expected
- Region too wide for ANTARES sensitivity (showers?)

ANTARES EPJ C (2014) 74:2701



2.3 An hot spot in HESE

- $n_{\Delta\Omega}$ IceCube cosmic events originated from a restricted region of $\Delta\Omega$ ~0.1-0.2 sr around the Galactic plane, spectrum $\propto \Phi_0 E^{-\Gamma}$
- Expected normalization factors and ANTARES sensitivities.
- Analysis using 2008-2013 data in preparation

MS, PRD 90, 103004 (2014)

units: $(\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})$

$$\Phi_0^{D',\Gamma} = \left(\frac{n_{\Delta\Omega}}{N_{IC}}\right) \cdot \left(\frac{4\pi}{\Delta\Omega}\right) \cdot \Phi_0^{D,\Gamma}$$

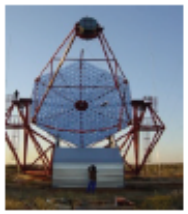
preliminary

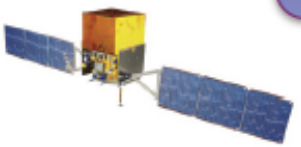
$\Delta\Omega$ (sr)	$\Gamma =$	$n_{\Delta\Omega}=3$	$n_{\Delta\Omega}=4$	$n_{\Delta\Omega}=5$	$n_{\Delta\Omega}=6$	ANTARES sensitivity
0.06	2.0	$3.5\ 10^{-7}$	$4.6\ 10^{-7}$	$5.8\ 10^{-7}$	$7.0\ 10^{-7}$	$3.1\ 10^{-7}$
8°	2.2	$4.5\ 10^{-6}$	$6.0\ 10^{-6}$	$7.5\ 10^{-6}$	$9.0\ 10^{-6}$	$3.6\ 10^{-6}$
	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	2.0	$5.4\ 10^{-8}$	$7.3\ 10^{-8}$	$9.1\ 10^{-8}$	$1.1\ 10^{-7}$	$3.1\ 10^{-7}$
20°	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	$9.3\ 10^{-6}$	$1.2\ 10^{-5}$	$1.5\ 10^{-5}$	$1.9\ 10^{-5}$	$3.4\ 10^{-5}$

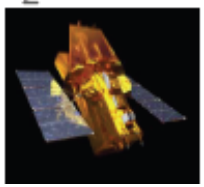
$\Delta\Omega$

$\Delta\Omega$

3) Transient and multi-messenger efforts







GeV-TeV γ-rays
Fermi / HESS…

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

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

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

HE neutrinos

UHECR
Auger

📖 APJ 774 (2013) 19

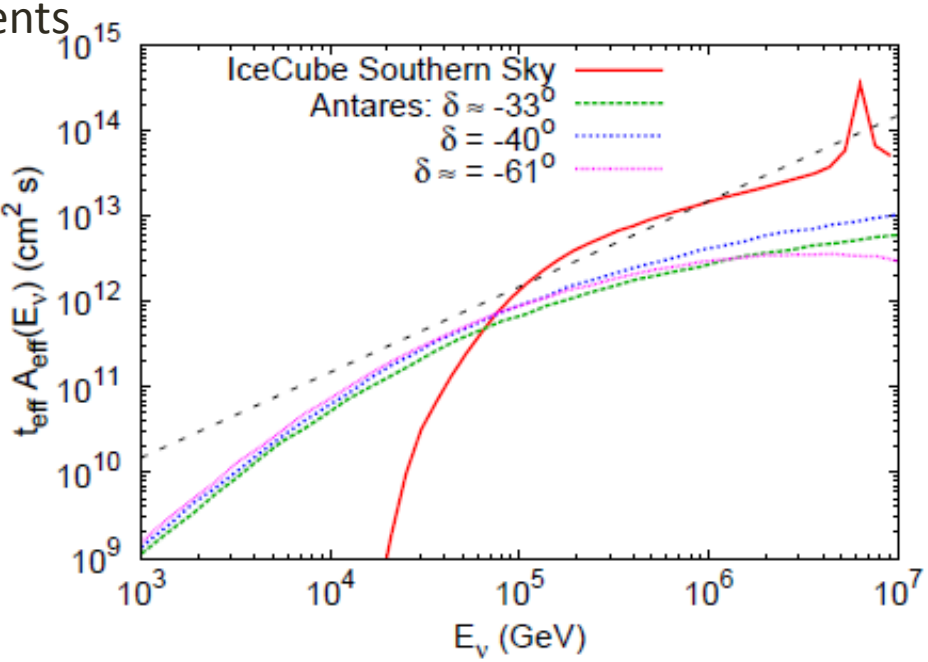
Gravitational
Waves
Virgo / Ligo

📖 JCAP 06 (2013) 008

*a multiwavelength program that monitors extragalactic jets of the Southern Sky.
Krauß, et al. 2014, A&A, 566, L7

3.1 Blazars monitored by TANAMI*

- Six blazars associated with the first 2 PeV IC events
- All in the FoV of ANTARES
- From the photon flux $F_\gamma \rightarrow \nu_e$ in IceCube
- Signal (ν_μ) in ANTARES comparable
- After unblinding, one events in correspondence of two of the blazars
- This observation is consistent with the blazar-origin hypothesis of the IceCube event IC14 for a broad range of blazar spectra, although an atmospheric origin cannot be excluded.
- Studies on the third PeV event ongoing

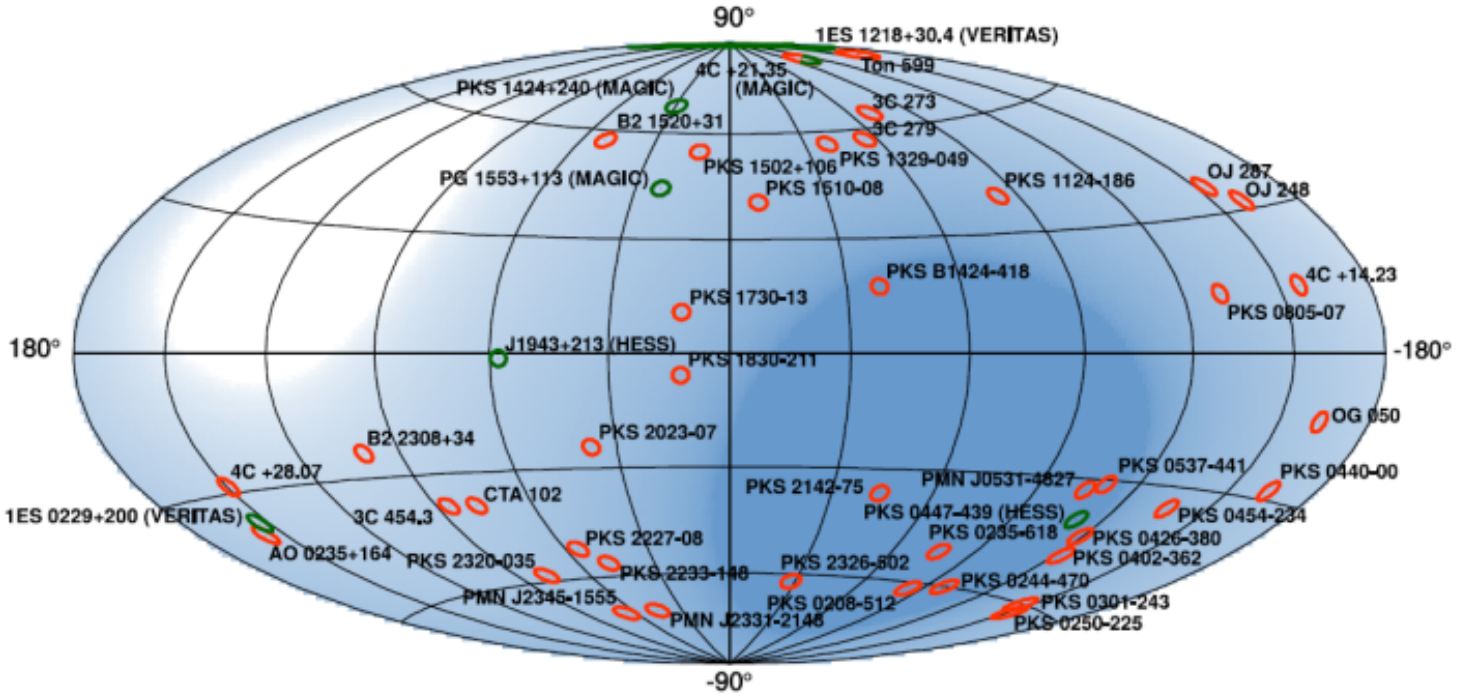


Source	Cat. Name	F_γ [GeV cm^{-2} s^{-1}]	N_{ν_e}	IC	N_{sig}	p
0235–618	PKS 0235–618	$(6.2^{+3.1}_{-3.1}) \times 10^{-8}$	$0.19^{+0.04}_{-0.04}$	20, 7	0	1
0302–623	PKS 0302–623	$(2.1^{+0.4}_{-0.4}) \times 10^{-8}$	$0.06^{+0.01}_{-0.01}$	20	0	1
0308–611	PKS 0308–611	$(4.7^{+1.8}_{-1.8}) \times 10^{-8}$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

arXiv:1501.07843 accepted by A&A Letters

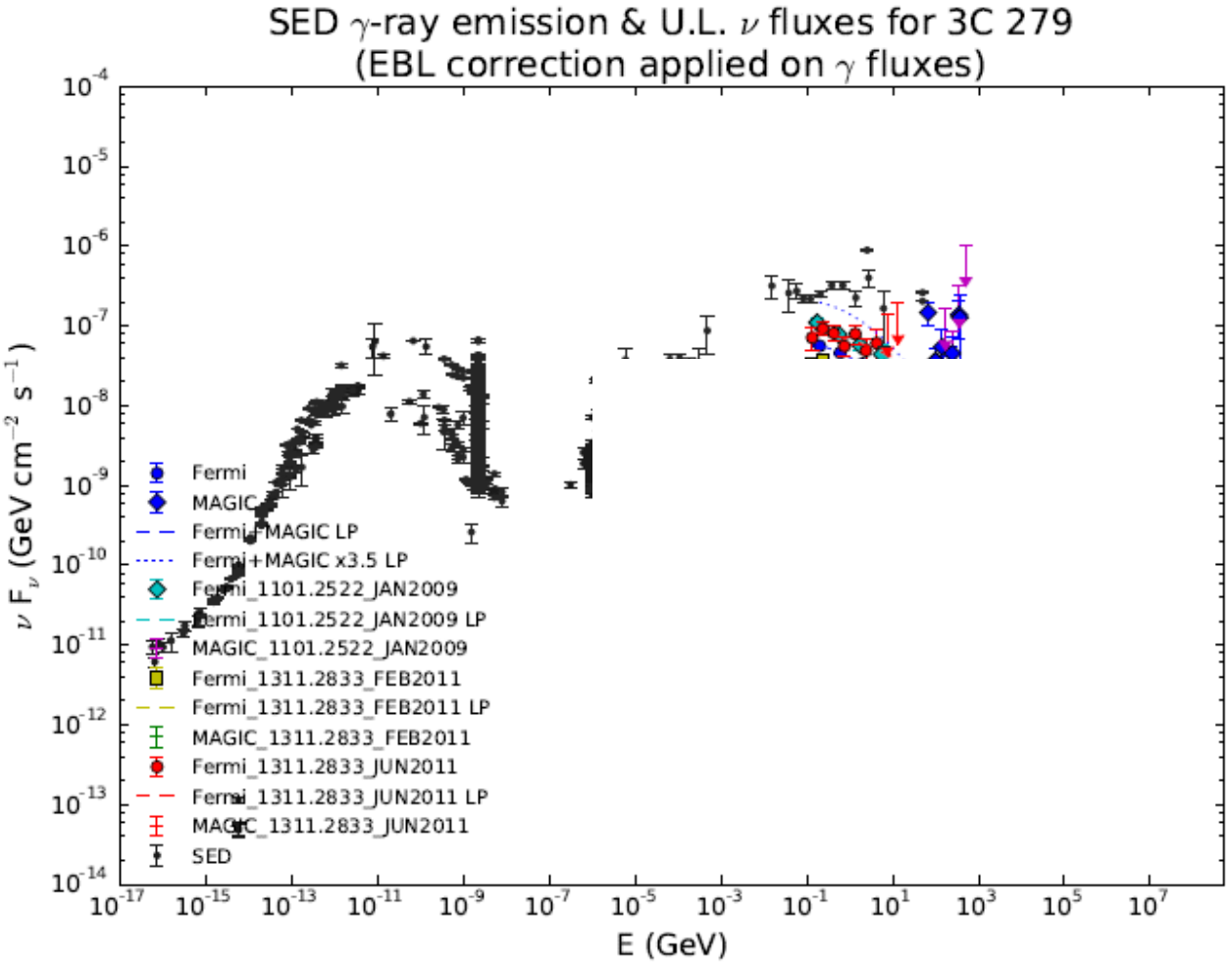
3.2 ν_μ emission associated with GeV and TeV γ-ray flaring blazars

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



Skymap (galactic coor.) with the position of the 41 selected Fermi blazars (red circle) and the 7 IACTs blazars (green circle) on top of the ANTARES visibility

- The most significant correlation was found with 3C279 (1 ν_μ)
- However, this event had a post-trial probability of 67%, and is thus compatible with background fluctuations.
- The upper-limits on the neutrino SEDs compared with GeV-TeV γ-ray observations

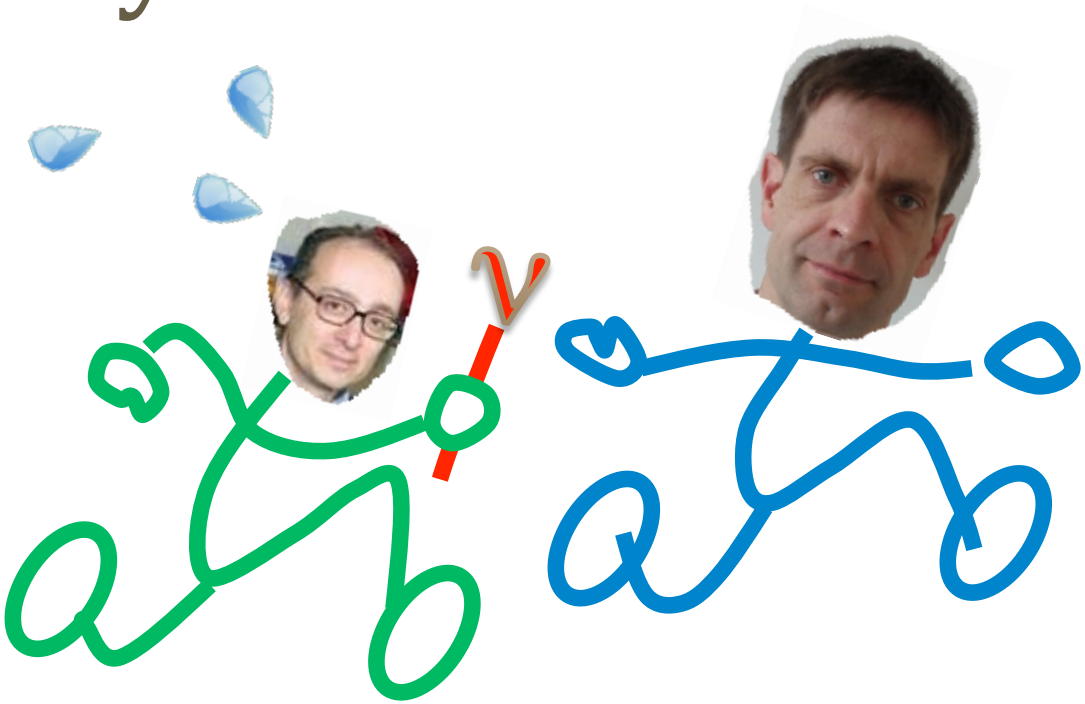


Summary

- ANTARES can significantly contribute to understand the origin of cosmic neutrinos observed by IceCube, in particular if an excess of downgoing events is confirmed;
- ANTARES effective area for ν_μ comparable with IC-HESE/contained events and better angular resolution (about 0.4°-water properties);
- Larger ANTARES sensitivity for **point-like** or **extended** sources up to $\Delta\Omega$=0.1-0.2 sr in the Southern sky, in particular for Γ>2.0;
- Showering neutrinos (ν_e, ν_τ, NC) reconstructed with enough angular resolution (2°-3°); however smaller effective area than ν_μ
- Analyses of data set from 2008-2013 presented in summer;

- ANTARES continue data taking until the end of 2016.
- Then, a key-role can be played by KM3NeT- Phase 1

Thank you!



Spares

ANTARES and the IceCube cosmic neutrinos

HESE

E>60 TeV	Data	Bck	Data-Bck	Best Fit	Normalization to the North
All events	20	2.7	17.3	18.2	**9.8**
Up (North)	5	1.4	**3.6**	**6.7**	**3.6**
Down (South)	15	1.3	**13.7**	**11.5**	**6.2**

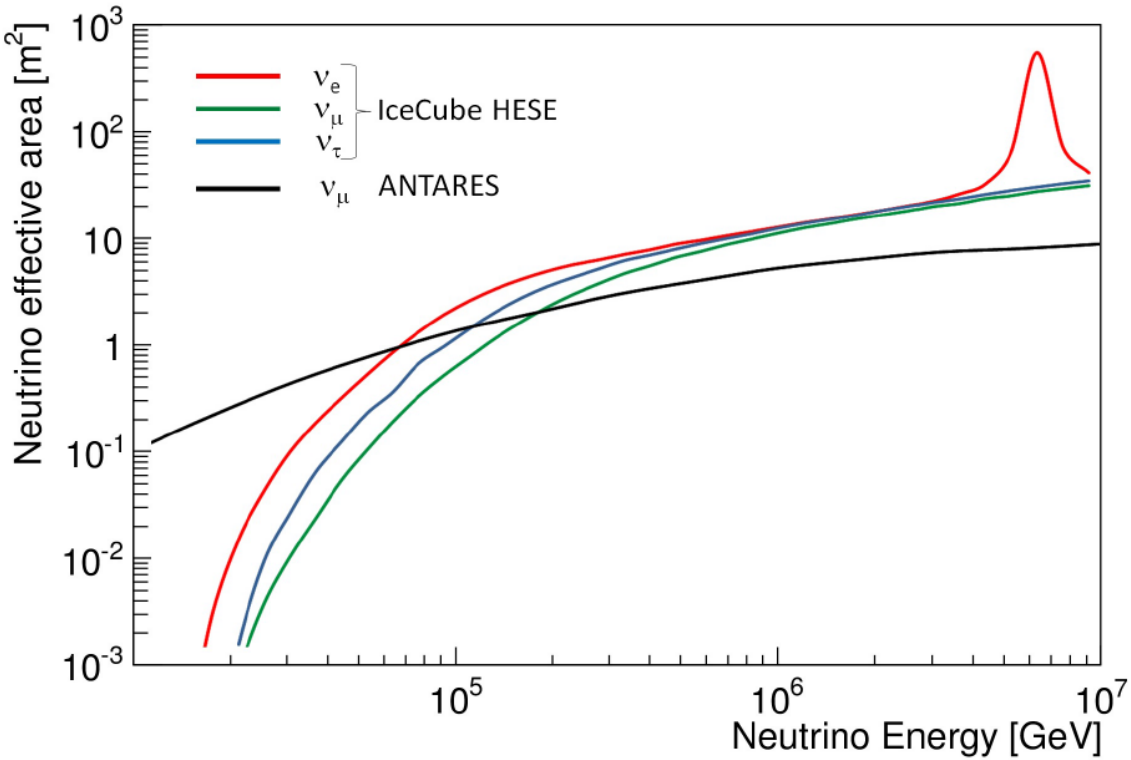
>40% excess of events from South, if you normalize to the North

PRD91 (2015)

E>25 TeV	Data	Bck	Data-Bck	Best Fit	Normalization to the North
All events	43	11.7	31.3	29.1	**12.8**
Up (sinδ>0.06)	11	5.3	**5.7**	**12.1**	**5.7**
Down(sinδ<-0.06)	29	4.8	**24.2**	**15.0**	**7.1**

>50% excess of events from South, if you normalize to the North

IC-HESE vs. ANTARES A_{eff}



- Comparisons among experiments must be done using the effective areas, which depend on the particular analysis

Searches for a Galactic component in the cosmic ν − 2) energy

- The ν_μ channel allows a proxy estimate of the energy
- of reconstructed ν_μ within 0.4° (for E^{-2} spectrum)

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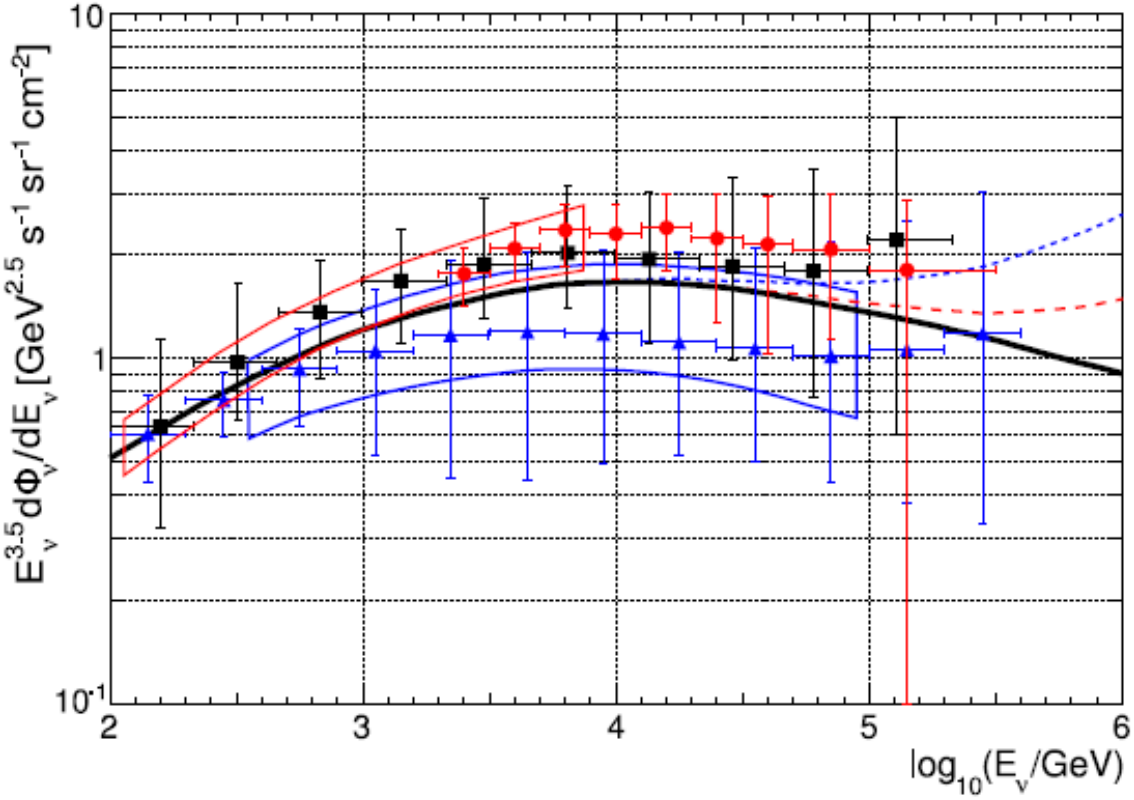
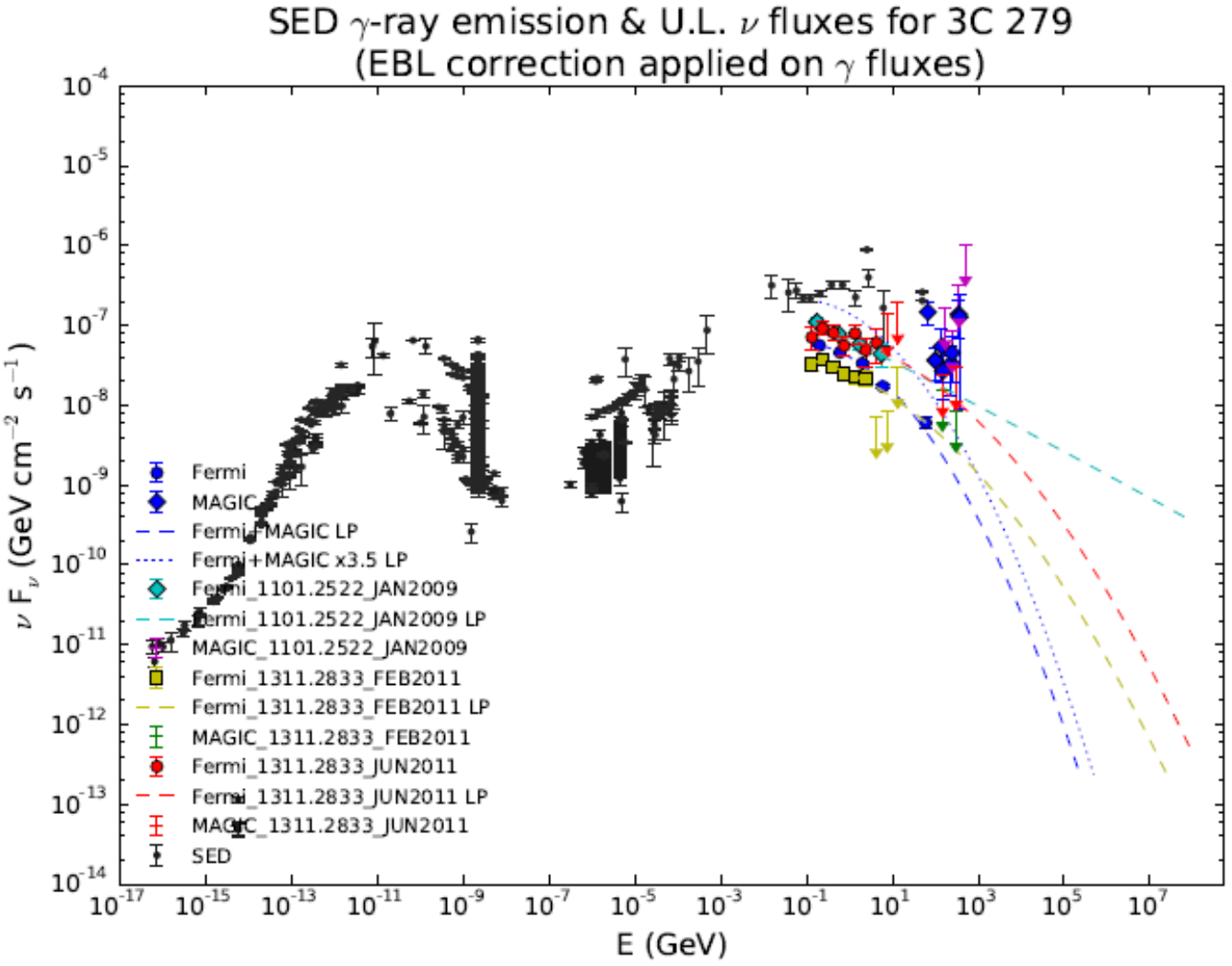
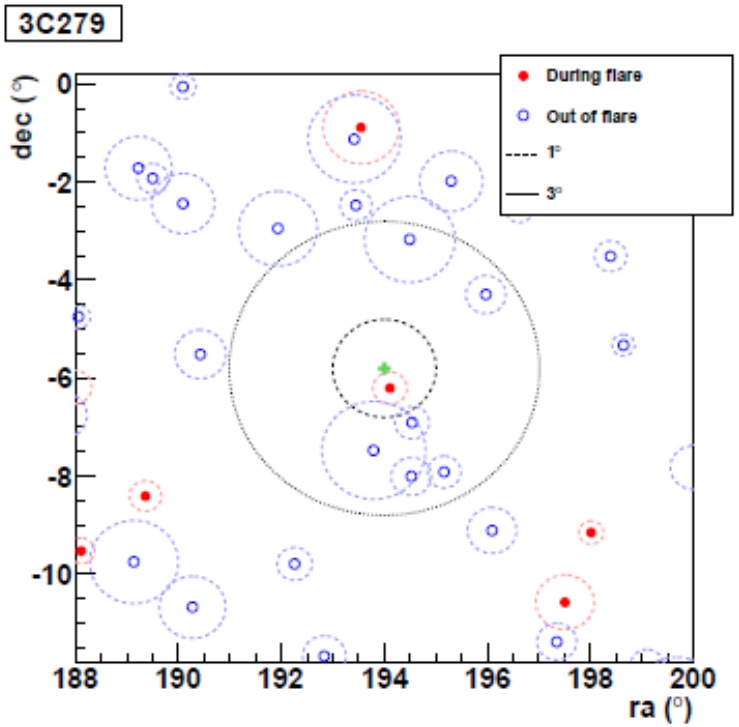
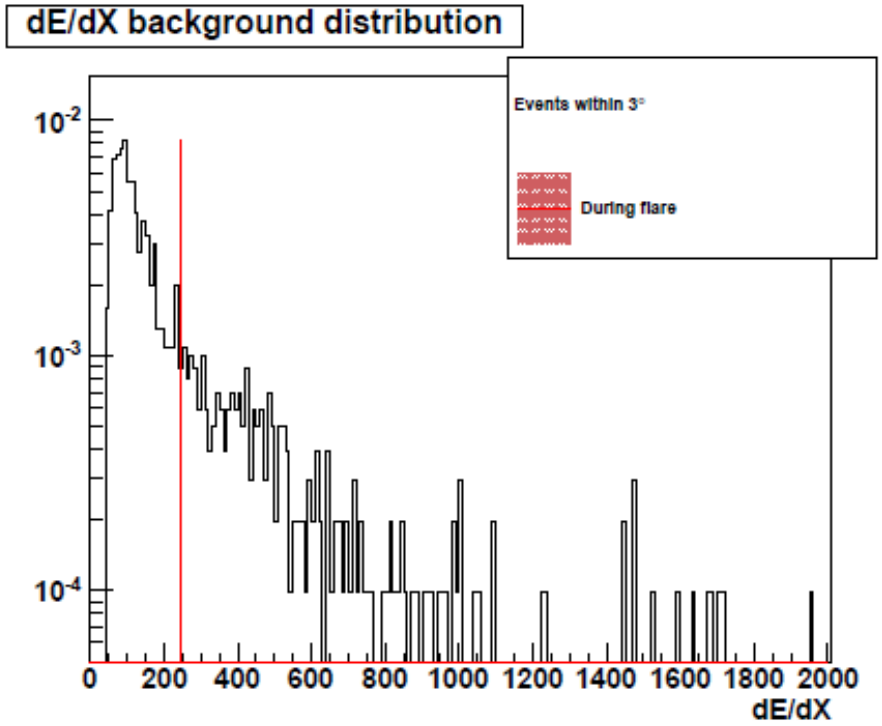



SED γ-ray emission & U.L. ν fluxes for 3C 279
(EBL correction applied on γ fluxes)
ν F_ν (GeV cm^-2 s^-1)
E (GeV)
Fermi
MAGIC
Fermi+MAGIC LP
Fermi+MAGIC x3.5 LP
Fermi_1101.2522_JAN2009
Fermi_1101.2522_JAN2009 LP
MAGIC_1101.2522_JAN2009
Fermi_1311.2833_FEB2011
Fermi_1311.2833_FEB2011 LP
MAGIC_1311.2833_FEB2011
Fermi_1311.2833_JUN2011
Fermi_1311.2833_JUN2011 LP
MAGIC_1311.2833_JUN2011
SED

3C 279 Blazar



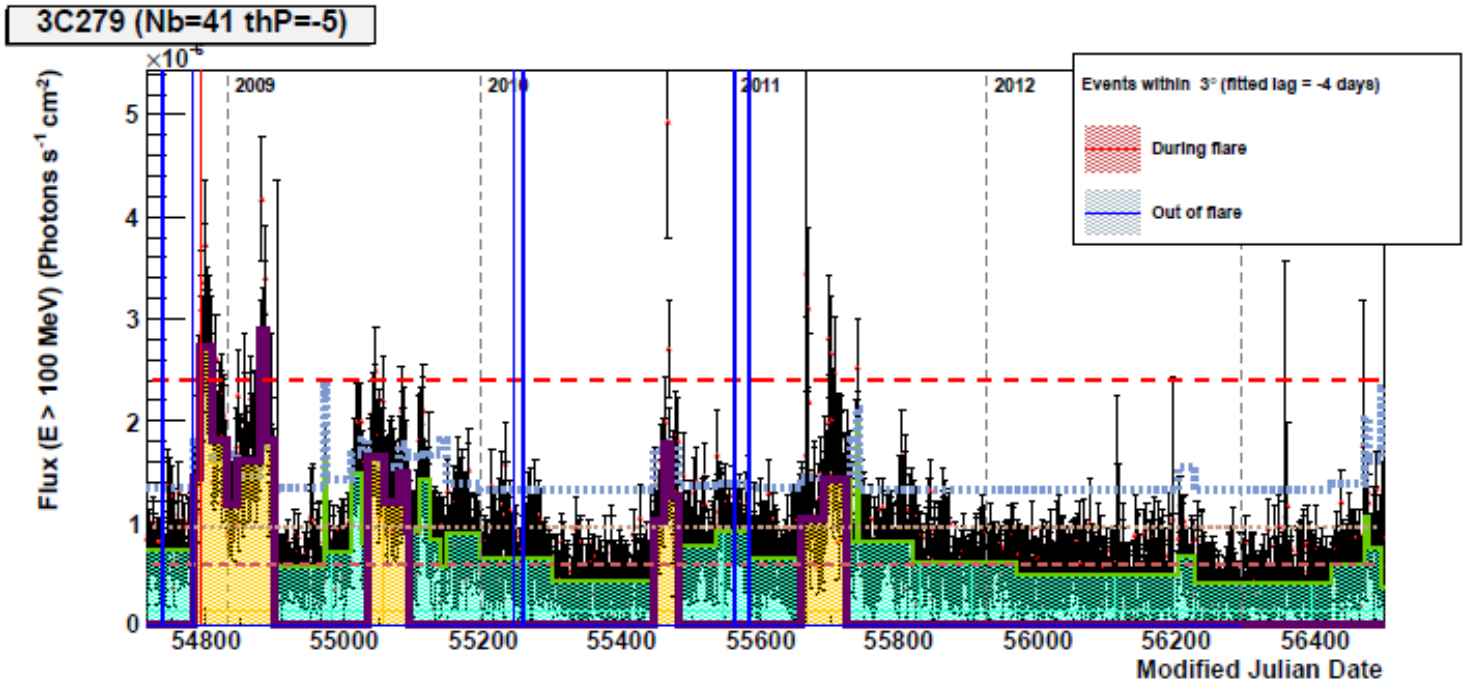


3C 279 (279 flaring days)

BEST: 3.3% (67%) E^{-2}

1 event (0.8 fitted signal) compatible in time and direction, in 54789 MJD
(-4 days of fitted lag) at 0.4°(244 dE/dX, $\beta = 0.3°$, Λ=-4.5, elevation=-50°)

3C 279 Blazar



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