



NEUTRINO 2016

SOUTH KENSINGTON, LONDON

**XXVII INTERNATIONAL
CONFERENCE ON NEUTRINO
PHYSICS AND ASTROPHYSICS**

Imperial College
London IOP Institute

NEUTRINO 2016

SOUTH KENSINGTON, LONDON



<http://antares.in2p3.fr>

<http://www.km3net.org>

High-Energy Neutrino Searches in the Mediterranean Sea: probing the Universe with ANTARES and KM3NeT/ARCA

Antoine Kouchner

for the ANTARES and KM3NeT
Collaborations

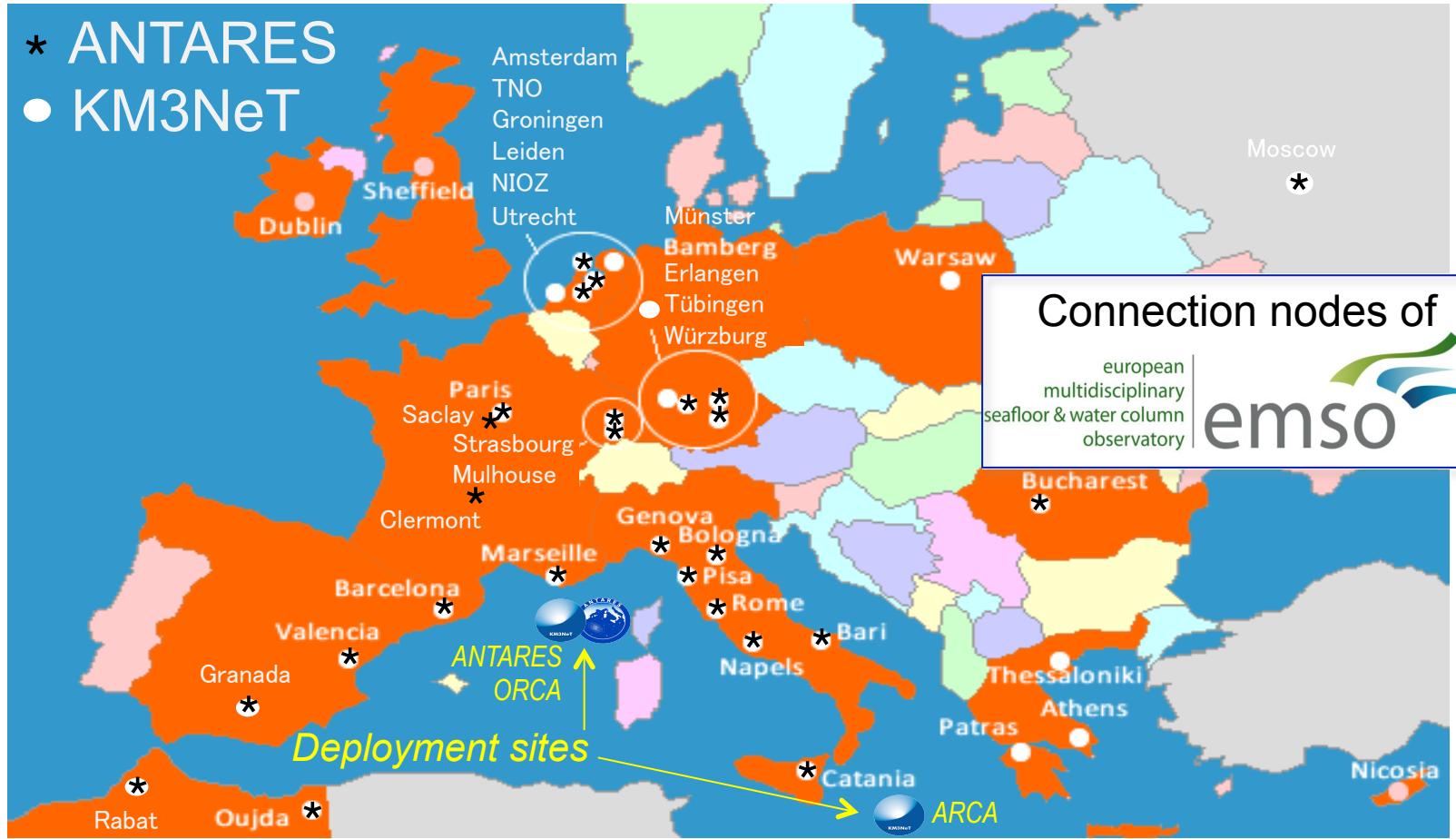




ANTARES & KM3NeT collaborations



- * ANTARES
- KM3NeT



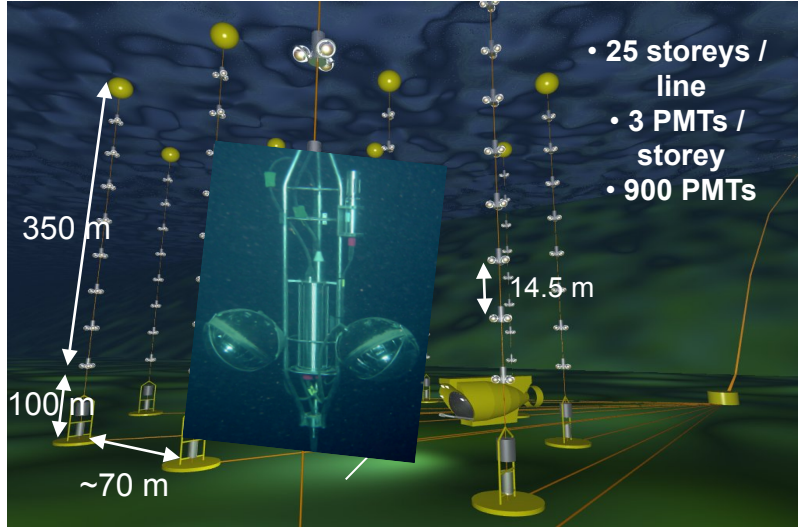
Connection nodes of

emso

emso logo: european multidisciplinary seafloor & water column observatory



ANTARES Complete since 2008



- 25 storeys / line
- 3 PMTs / storey
- 900 PMTs

350 m

14.5 m

100 m

~70 m

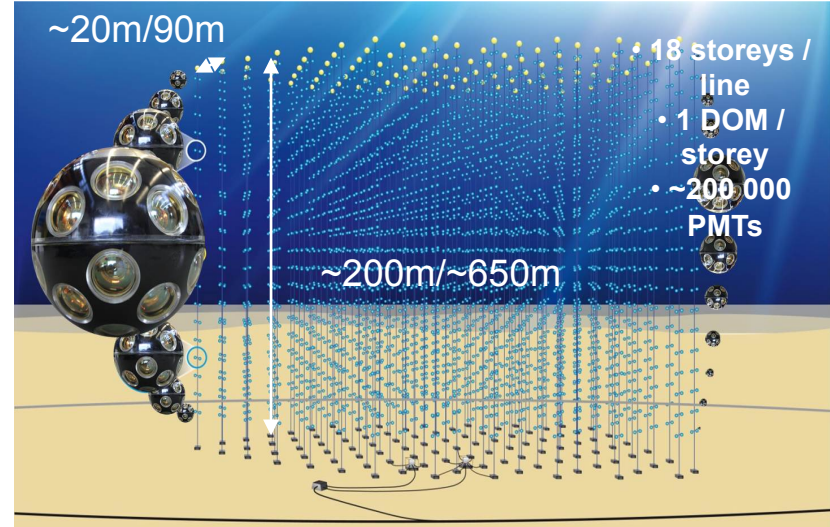
~10 Mton

12 lines

First Generation

First line since 10 years

KM3NeT Under Construction



- 18 storeys / line
- 1 DOM / storey
- ~200 000 PMTs

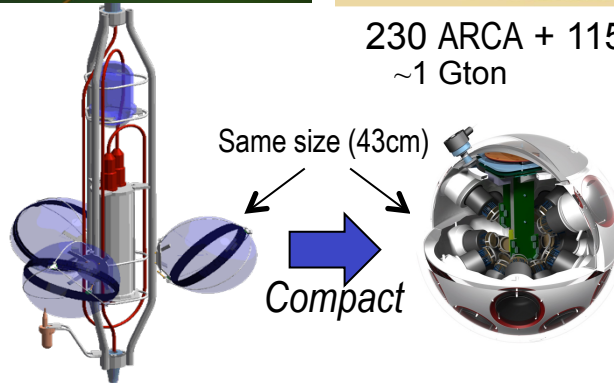
~20m/90m

~200m/~650m

230 ARCA + 115 ORCA lines **New Generation**

~1 Gton

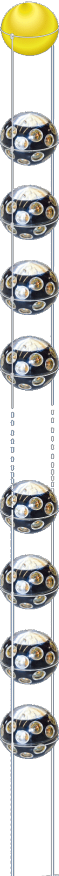
~6 Mton



Same size (43cm)

Compact

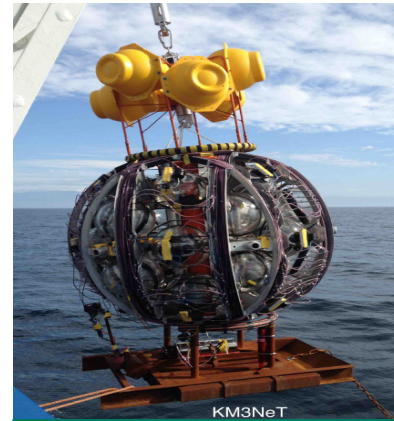
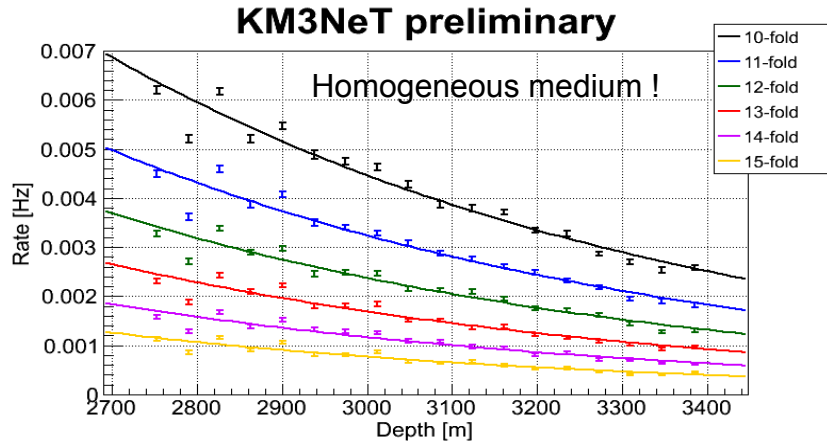
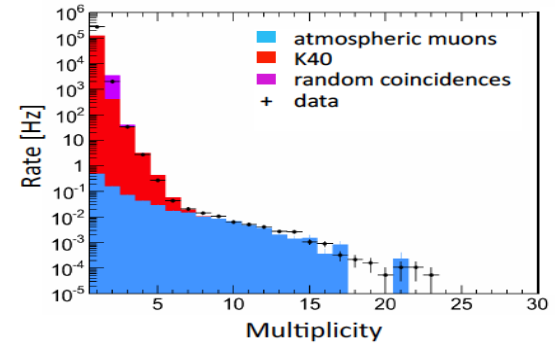
- **DOM: 31 3" PMTs**
- Digital photon counting
- Directional information
- Wide angle of view
- **Cost reduction wrt ANTARES**



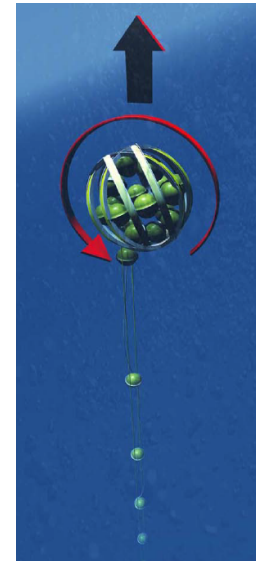
KM3NeT first Detection Units



- ✓ Optical Module at Antares site, April 2013 (2500 m)
Muons from a single DOM ! Eur. Phys. J. C (2014) 74:3056
- ✓ Mini string (3 DOMs) at ARCA site, May 2014 (3500 m)
Track reconstruction Eur. Phys. J. C (2016) 76:54 -- Cover
- ✓ First full Detection Unit at ARCA site, Dec 2015



rapid deployment
autonomous unfurling
recoverable

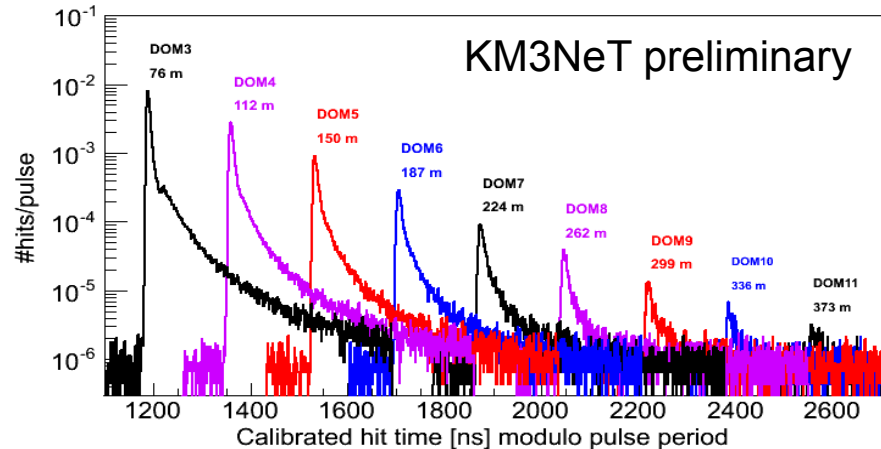
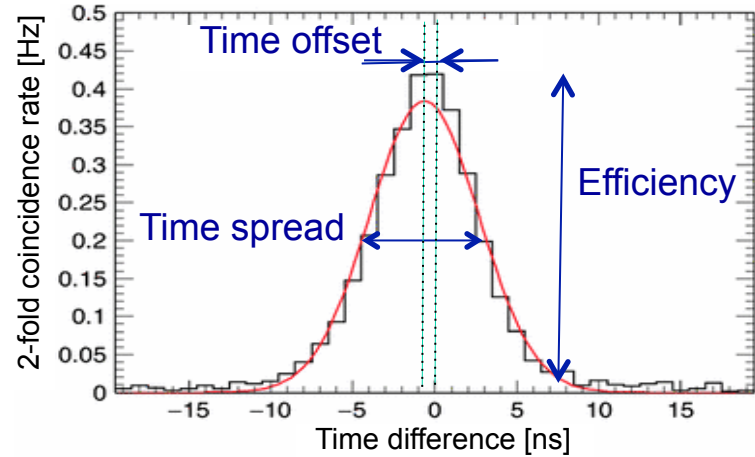
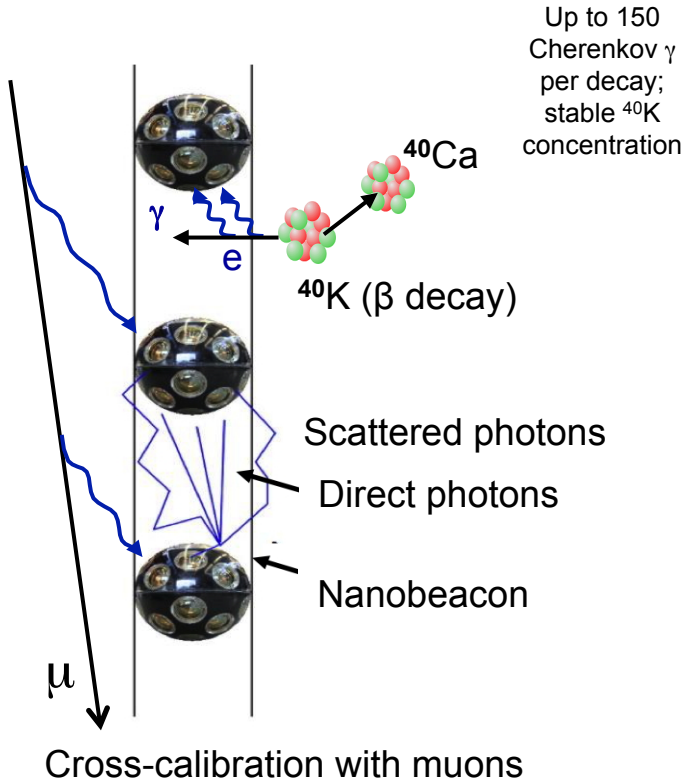


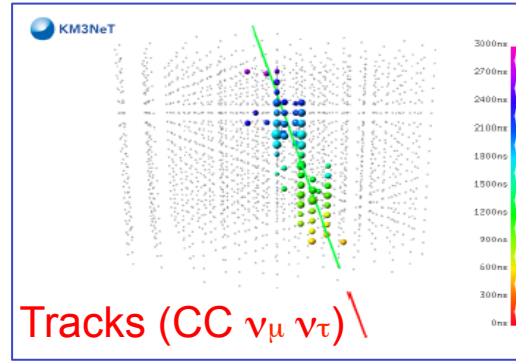
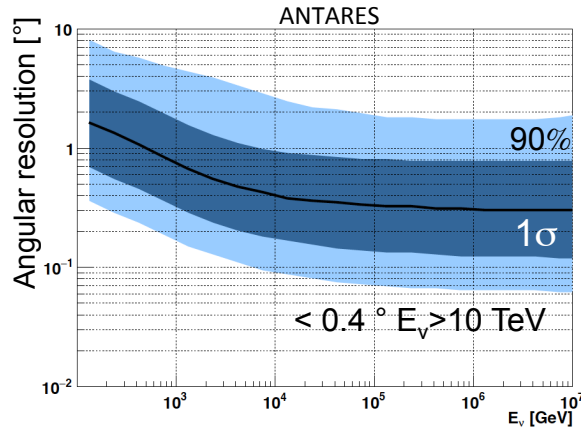
- ✓ One more line in operation since May 2016 !
Another one to be recovered for inspection
Multi-line data taking ongoing...

Watch <https://www.youtube.com/watch?v=tR8jwgG6uzk>

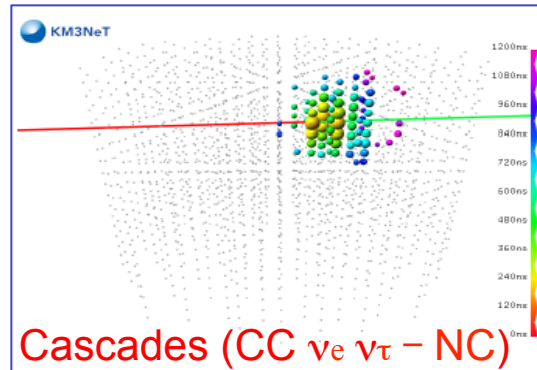
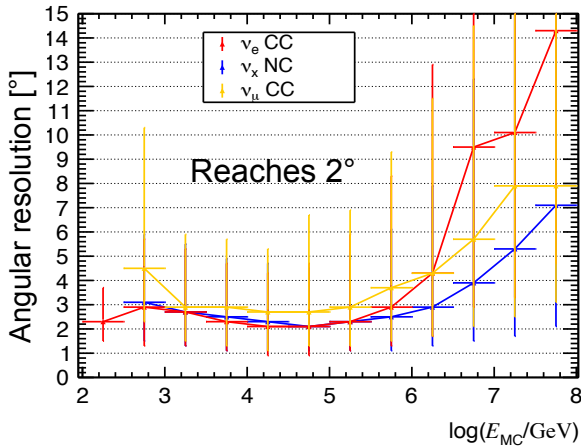
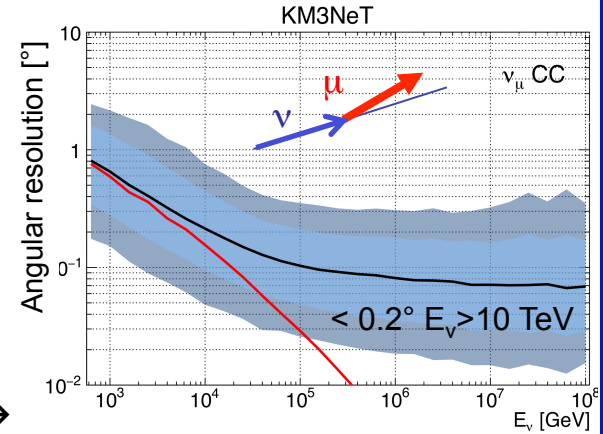


P2.015 K. Melis

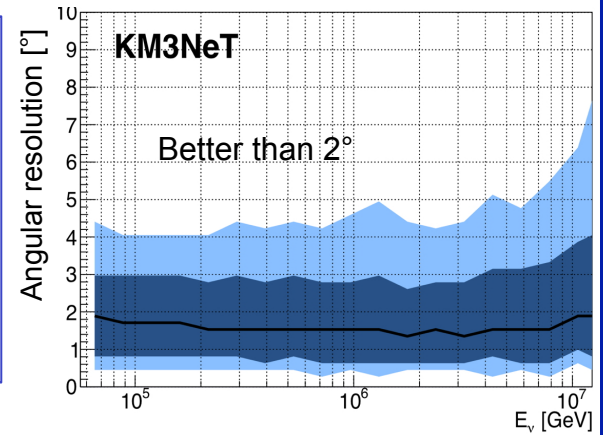


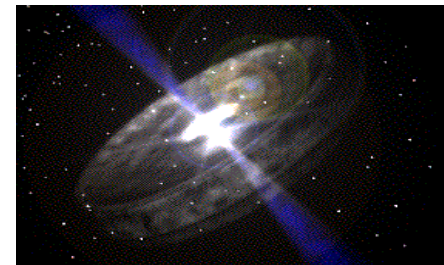
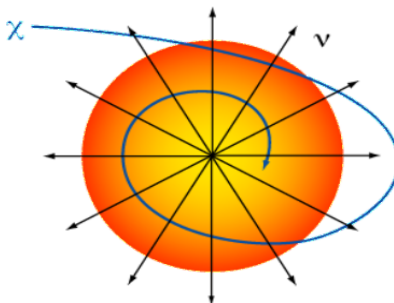
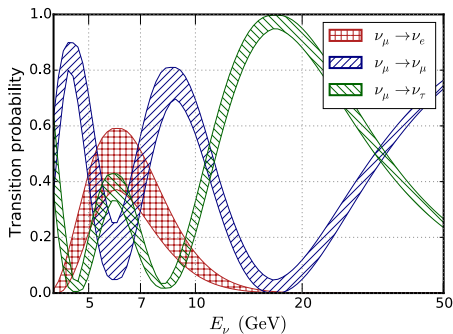


$\leftarrow 0.35 \text{ Log}(E_{\mu}) \text{ Resolution } 0.27 \rightarrow$



$\leftarrow 10\% \text{ Energy Resolution } 5\% \rightarrow$





<p>Low Energy $3 \text{ GeV} < E_\nu < 50 \text{ GeV}$</p>	<p>Medium Energy $10 \text{ GeV} < E_\nu < 1 \text{ TeV}$</p>	<p>High Energy $E_\nu > 1 \text{ TeV}$</p>
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ν Oscillations
 ν Mass Hierarchy

Dark Matter search
 + Exotic searches

ν from extra-terrestrial sources
 Origin and production mechanism of HE CR



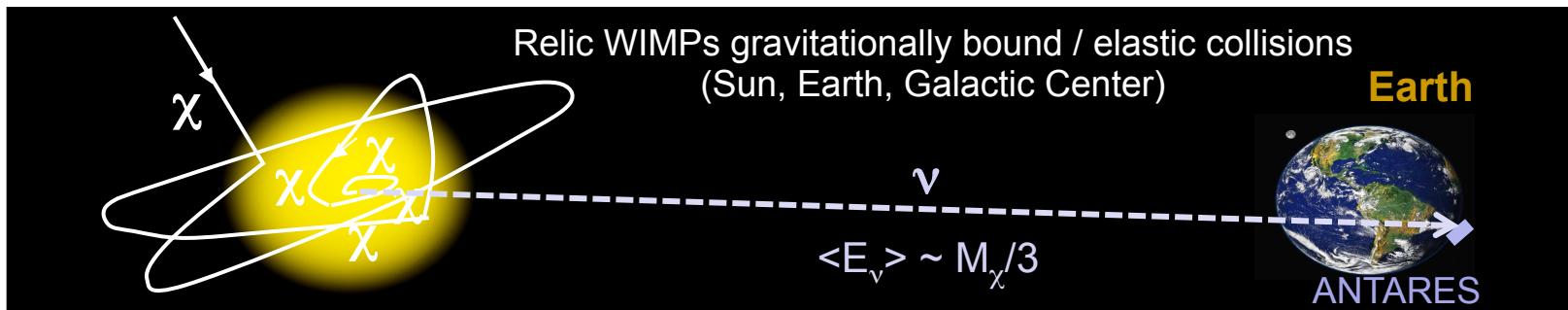
See talk by
 P. Coyle

See talk by
 M. Kowalski



Indirect Search for Dark Matter

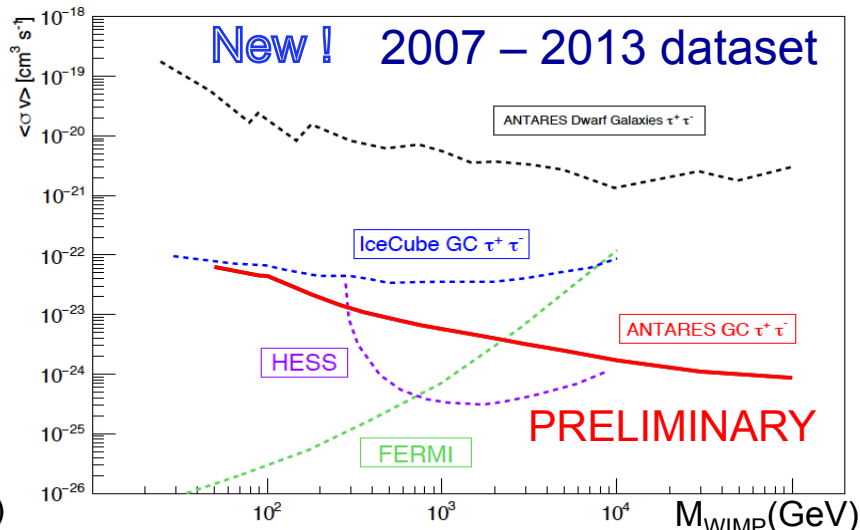
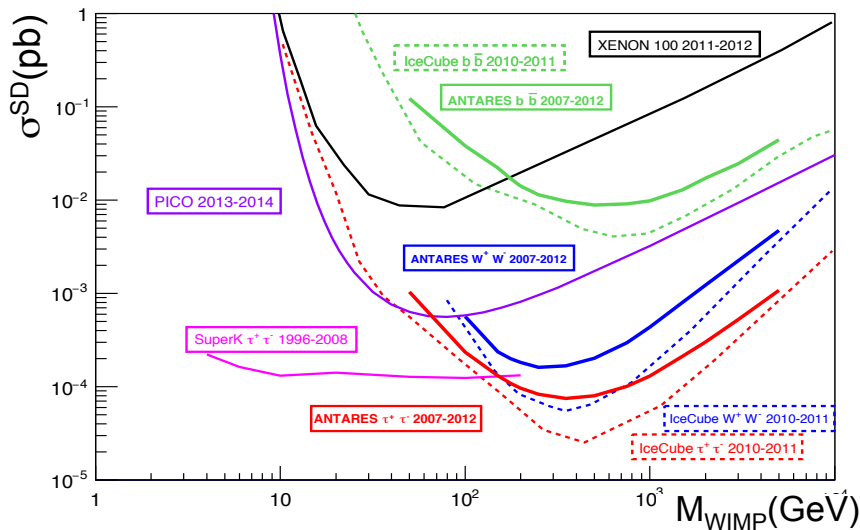
P4.005 J. Zornoza



Phys.Lett. B759 (2016) 69-74

Track channel only

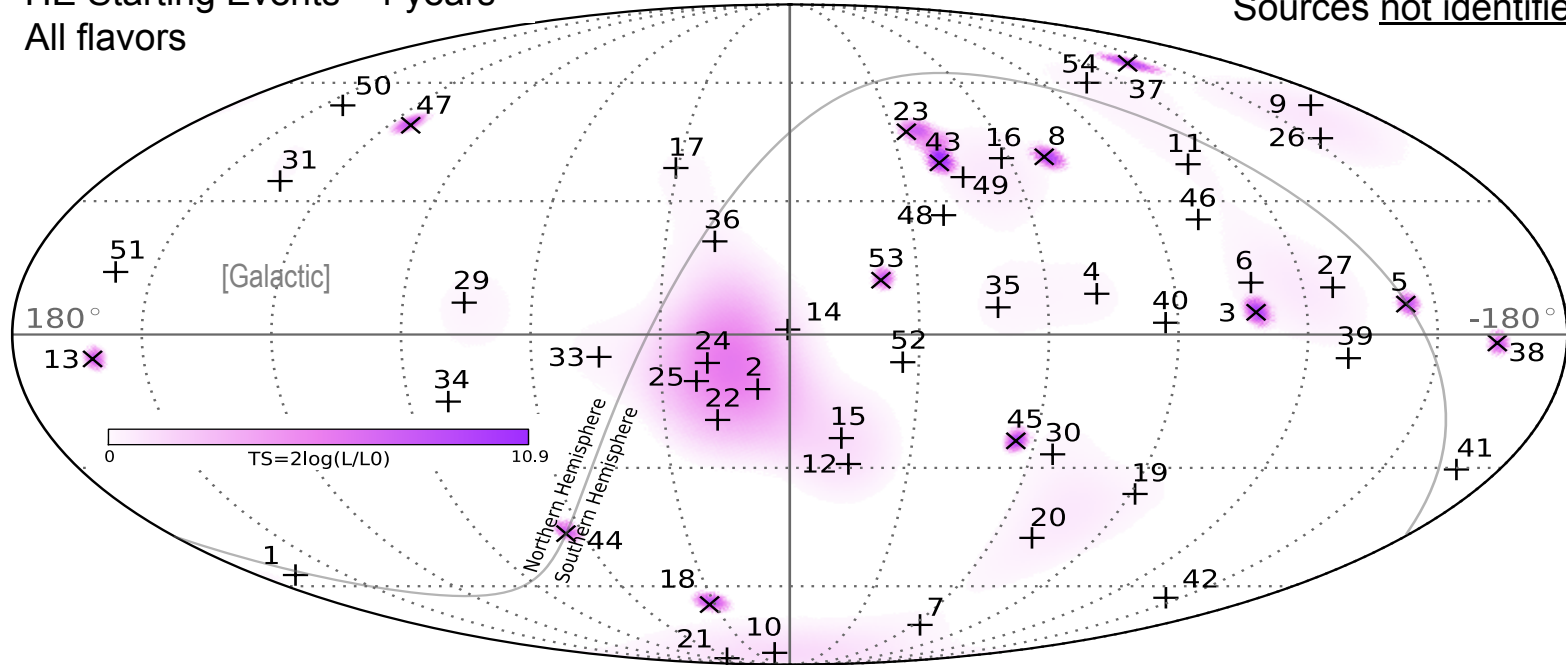
JCAP 10 (2015) 068



First HE neutrinos seen by IceCube

HE Starting Events - 4 years
All flavors

Sources not identified



Compatible with isotropy
Moderate excess from Southern Hemisphere
Tension $> 3.6\sigma$ on spectrum from different analyses $E^{-\Gamma} \in [2, 2.5]$

Hypothesized in literature:
Fermi Bubbles
Galactic Ridge
Galactic (point-like) source

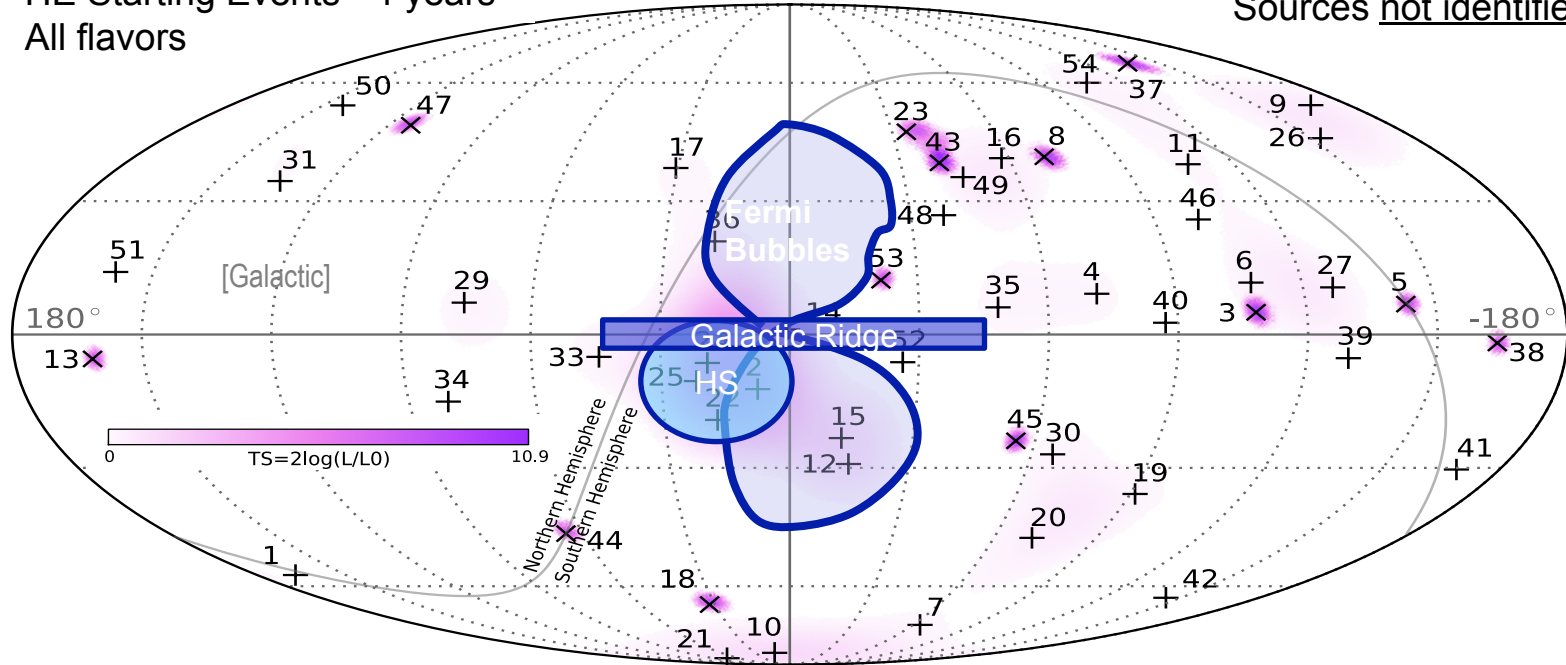
Just heard more from M. Kowalski...

...



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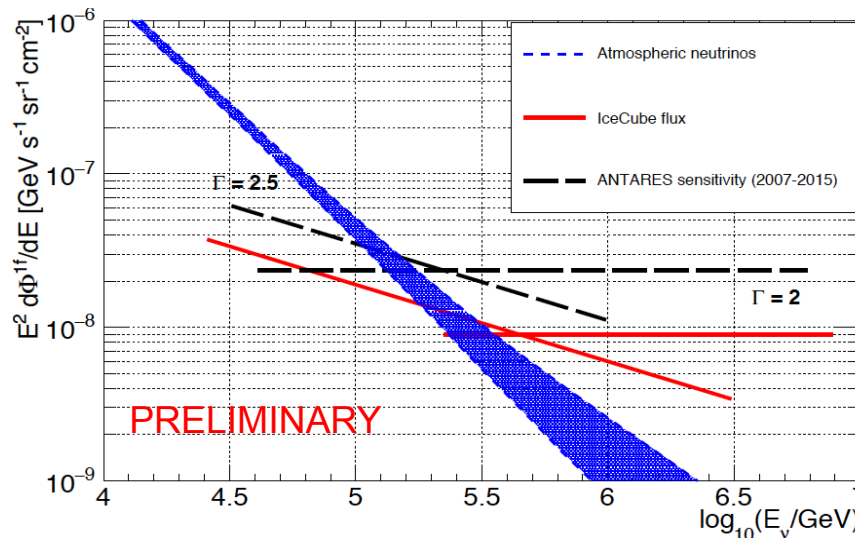
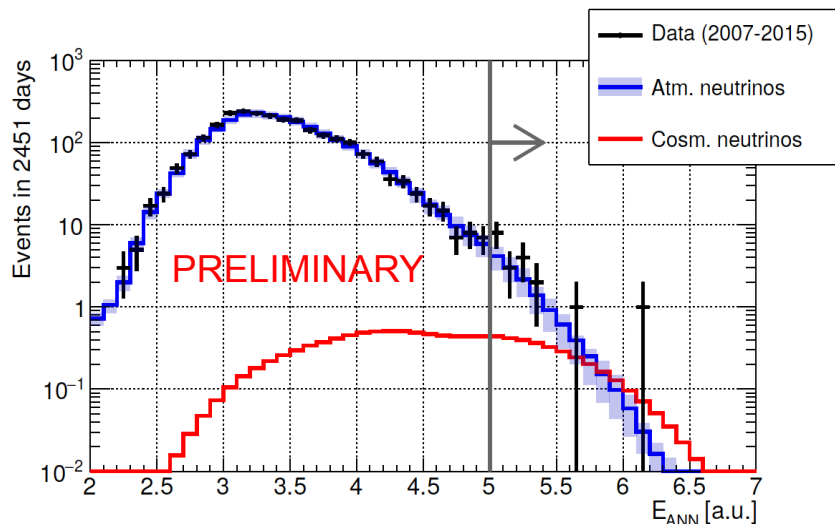
- Search for excess at high energy
- Optimization based on IC best fit flux
- Rely on Monte Carlo
- Variables used in analysis checked with burn sample ('0' ending runs)

Track channel

Data sample 2007 – 2015 : 2451 days

Observed : 19

Expected : 13.5 ± 3 from bkg ~ 3 from IC



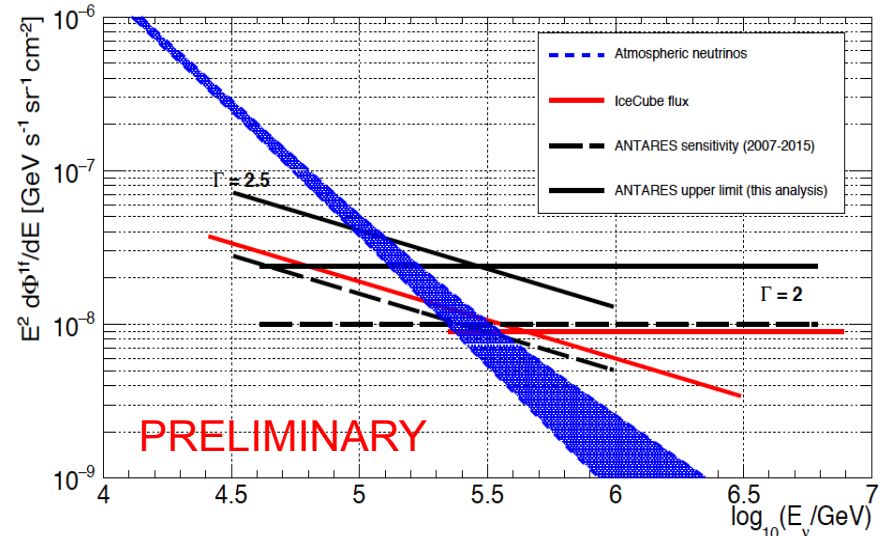
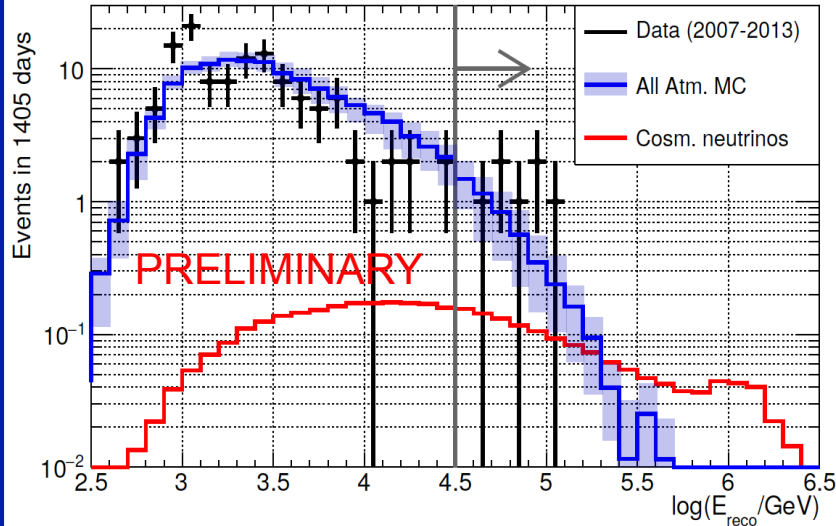
- Search for excess at high energy
- Optimization based on IC best fit flux
- Rely on Monte Carlo
- Variables used in analysis checked with burn sample ('0' ending runs)

Cascade channel

Data sample 2007 – 2013 : 1405 days

Observed : 7

Expected : 5 ± 2 from bkg ~ 1.5 from IC



Final ANTARES sensitivity ~ IC flux but definitive independent confirmation with KM3NeT

- **Track channel**

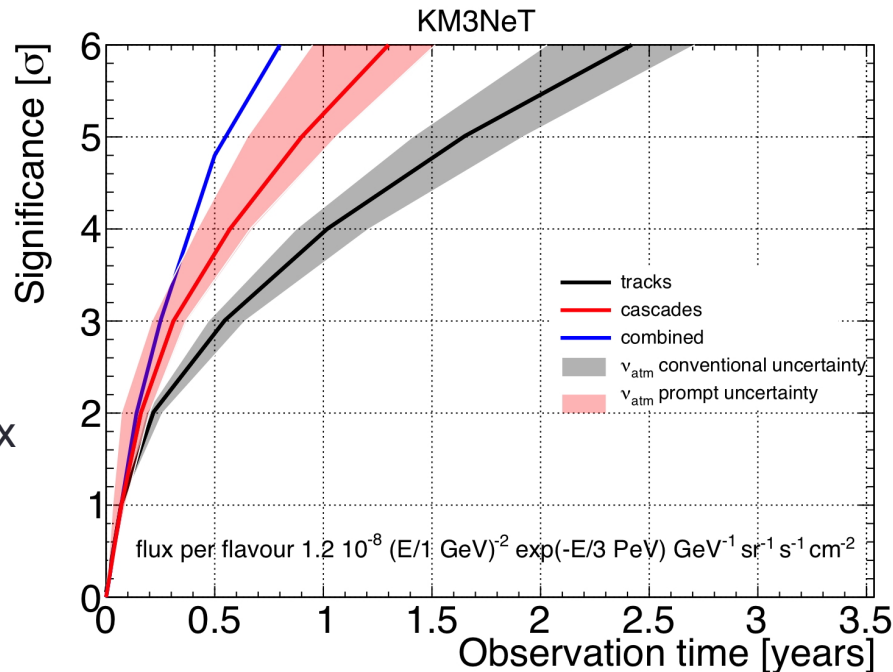
Analysis for up-going events based on maximum likelihood

Pre-cuts on $\theta_{\text{zen}} > 80^\circ$, reconstruction quality parameter and N_{hit} (proxy for muon energy)

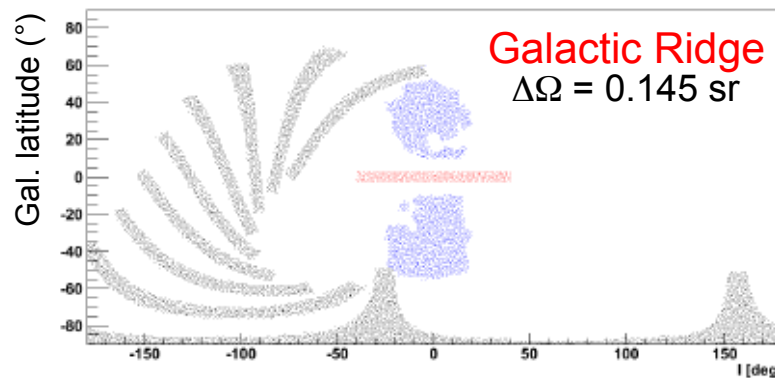
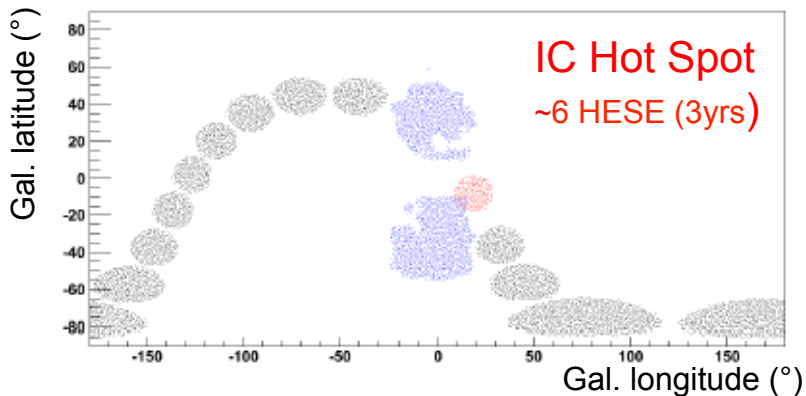
- **Cascade channel**

Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)

All sky analysis based on BDT and maximum likelihood.

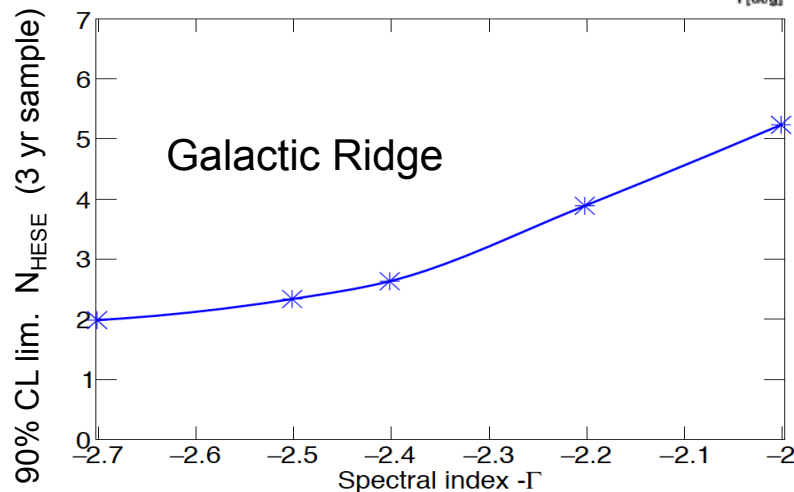


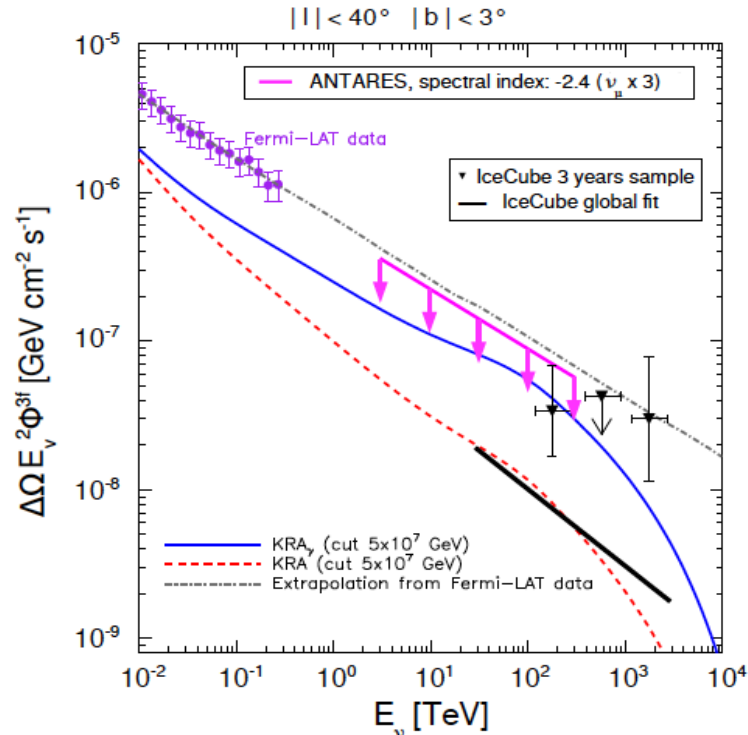
More robust analyses: background measured from OFF regions of same local acceptance



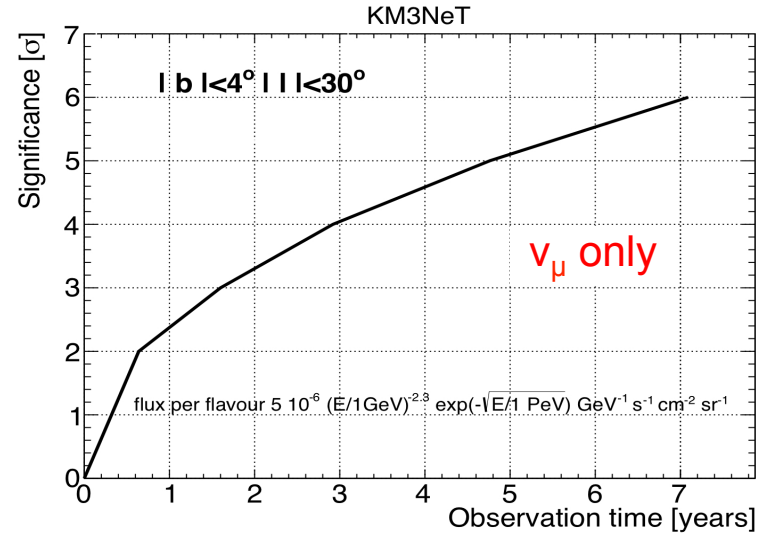
May 2007 - Dec 2013 (1622 days) ν_μ only

- **Galactic Ridge**: 9 OFF-zones regions
- Average expected background : 3.7
- Observed in the ON-region : 2
- Will be updated with cascades





- A. Neronov et al. Phys. Rev. D89, 103002 (2014)
- D. Gaggero et al., ApJ Letters, 815:L25 (2015)



3σ discovery in ~ 1.5 years
KM3NeT/ARCA
 5σ discovery in ~ 5 years

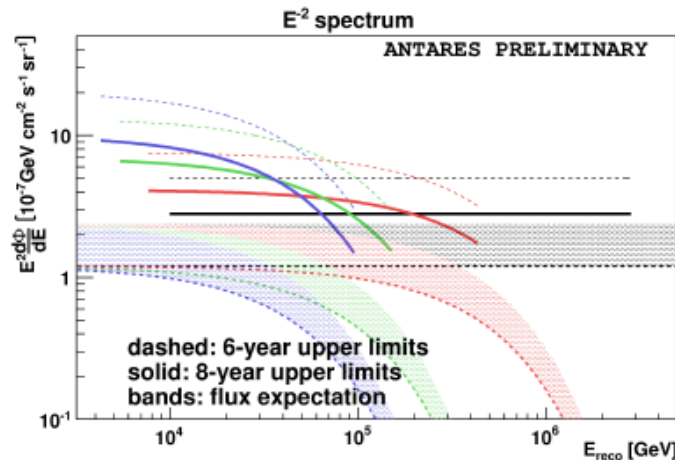
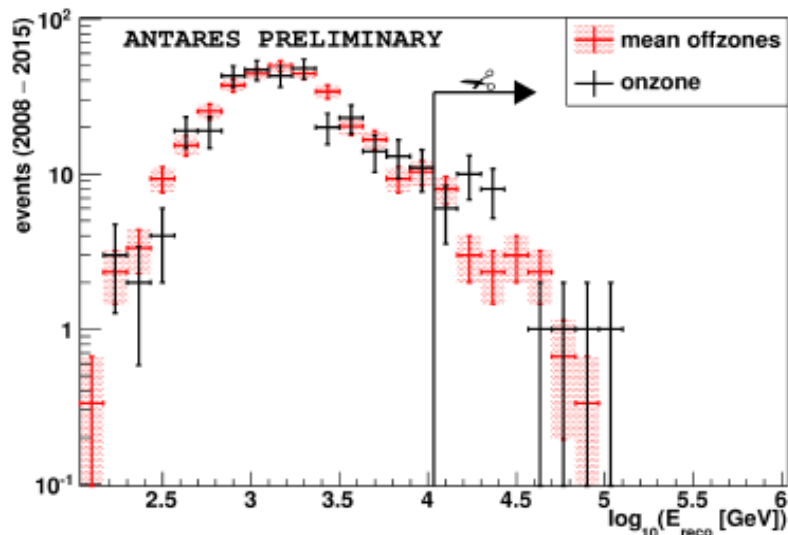
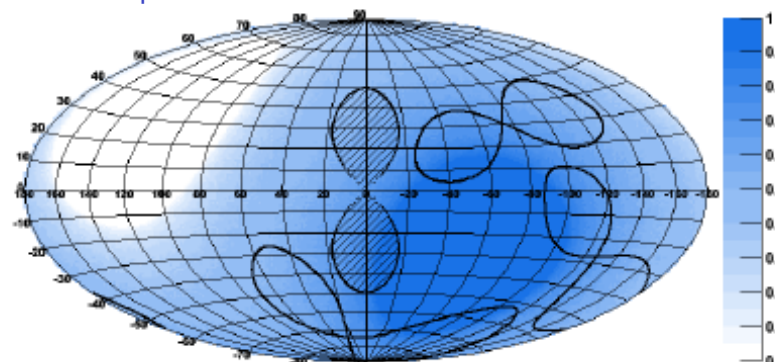
P2.007: T. Grégoire

Improved result expected with cascades and likelihood approach



- **Fermi Bubbles** : 2008 - 2015 (1765 days livetime); ν_μ only
- 3 OFF-zone regions
- Average expected background : 19.7
- Observed in the ON-region : 28
- Excess reduced to 1.5σ
- Similar expected sensitivity with cascades

New !

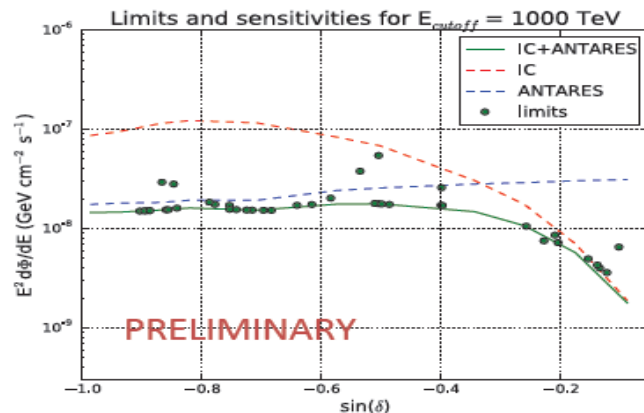
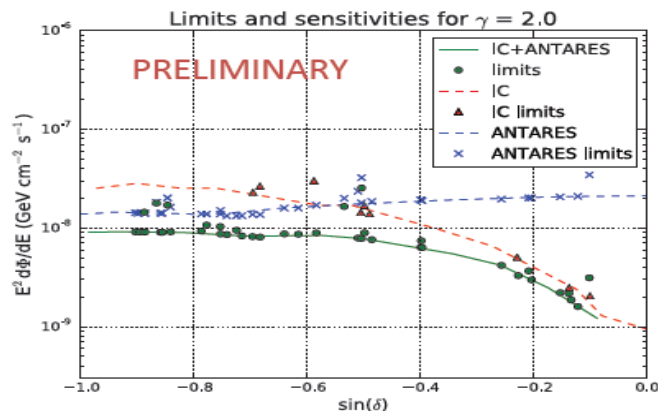
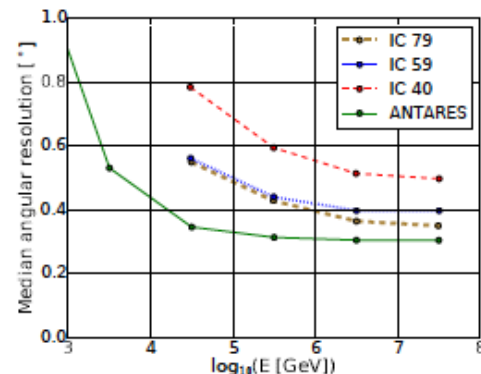
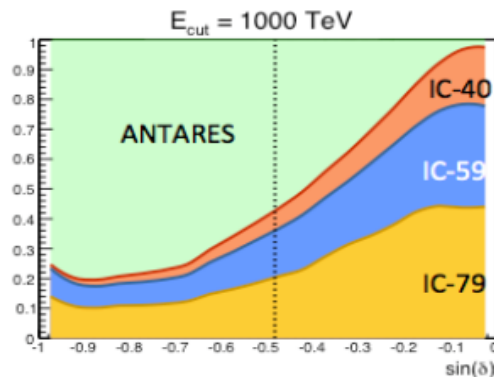
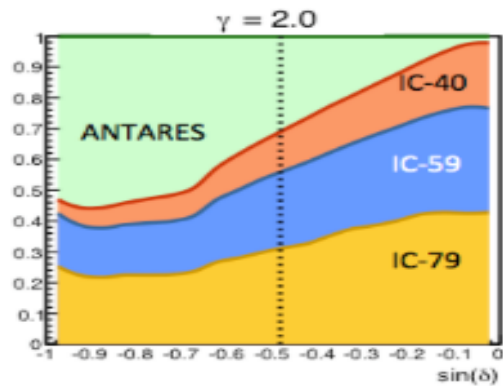


Joint ANTARES-IceCube PS search

ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere

Astrophys. J. Lett. 786:L5 (2014)

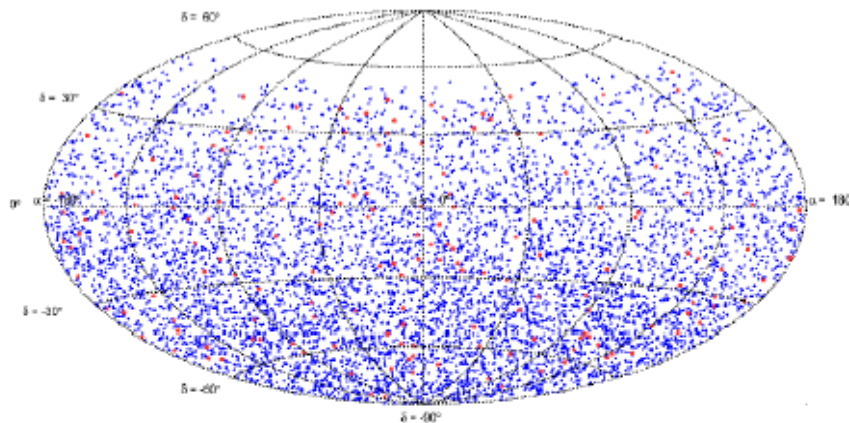
ANTARES+IC, The Astrophysical Journal 823 (2016) 65



New !

P2.006 R. Gracia: ANTARES dataset used to constrain AGN population with a 2pt correlation function

- ANTARES 2007-2013 (1690 days)



6490 tracks

172 cascades

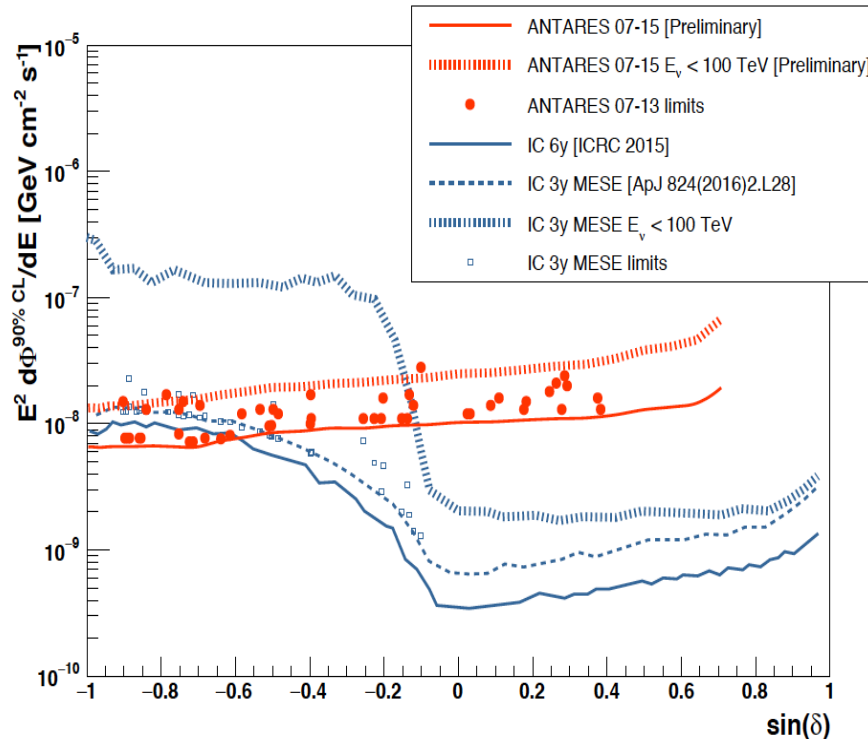
All-Sky + 54 candidate sources + 8 IC μ -HESE

No significant cluster, largest excess:

- All-sky: 1.3σ at RA:311.7° δ :-48.3°
- Candidate list: 0.75σ for HESS J06302+057

Excludes any single PS ($\Gamma=-2.5;-2$) close to GC as producing more than 2-6 HESE (3yrs)

P2.004 T. Michael

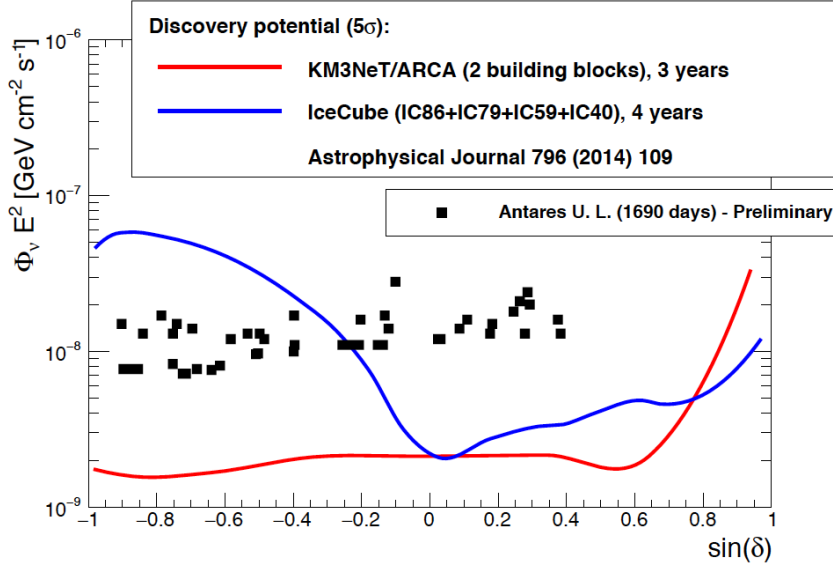
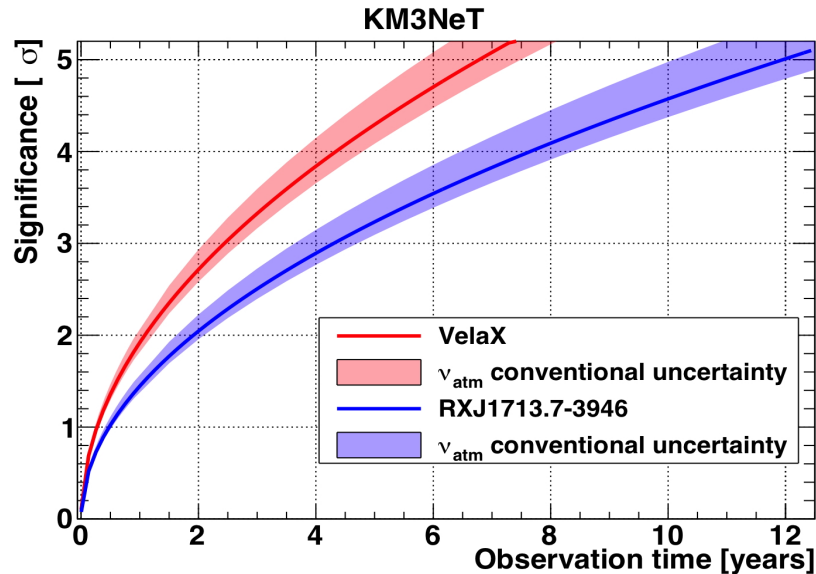


World best limit on the Southern sky below hundreds of TeV.

P.2.016 A. Trovato

Discovery potential for Galactic Sources

Neutrino spectra inferred from gamma-rays (e.g HESS) for 100% hadronic emission and transparent sources (extended sources)

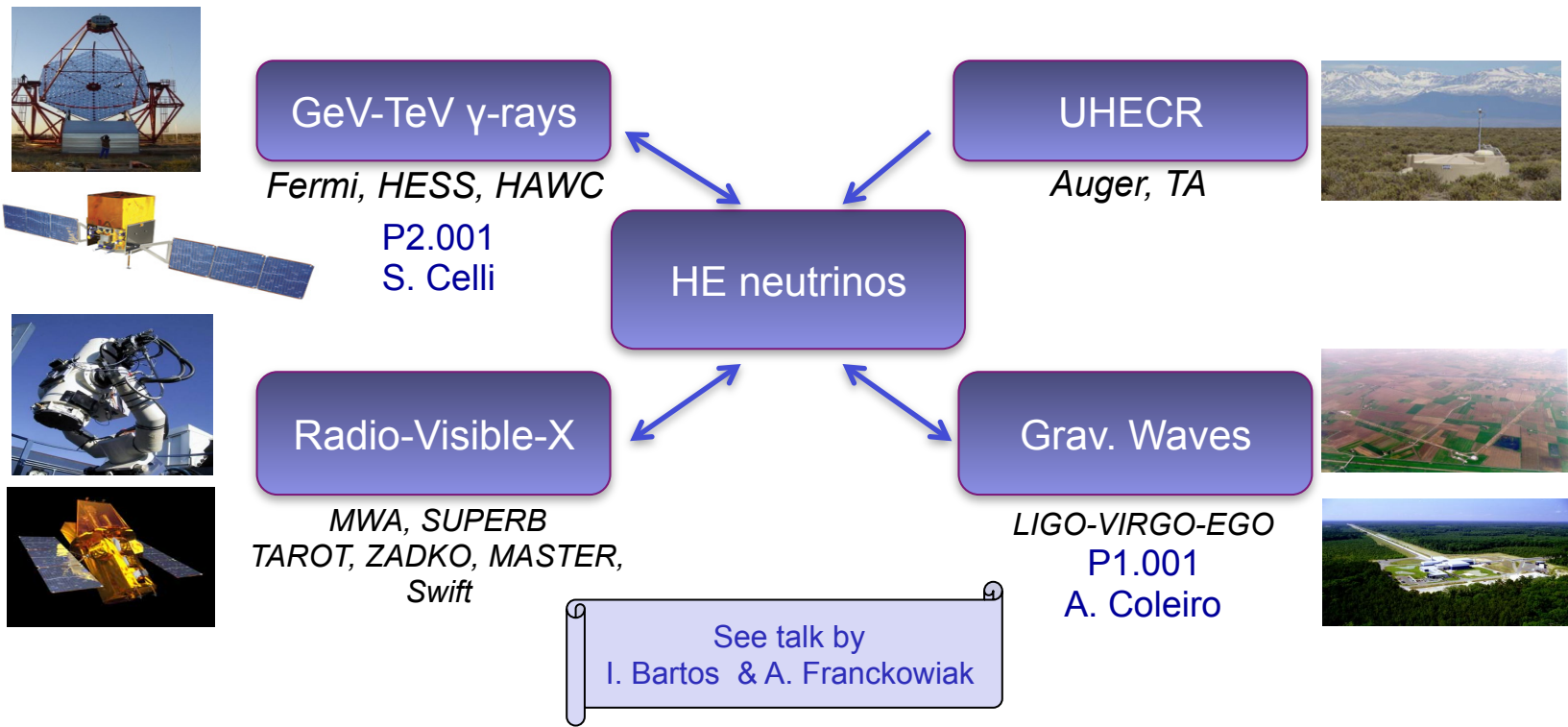


Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

Vela X : 3σ in ~ 2 years
RXJ1713 : 3σ in ~ 4 years



The multi-messenger program



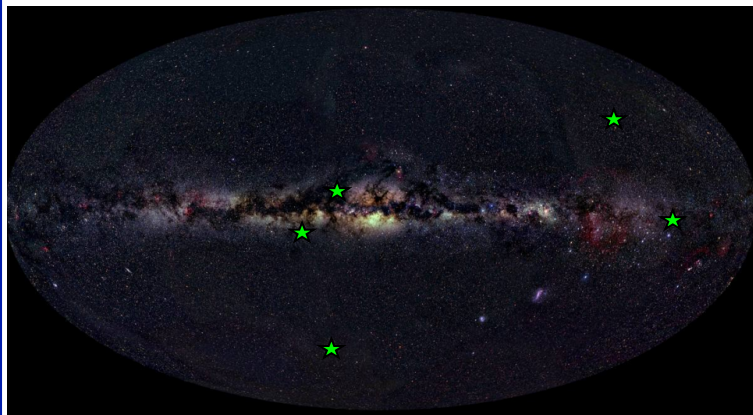
- A way to better understand the sources and the related physics mechanisms
- A way to increase the detector sensitivities (uncorrelated backgrounds)

MoU signed in 2015 between the SUPERB project (FRB discovery) at the Parkes observatory and the ANTARES collaboration

SUPERB team → send the FRB trigger alert to the ANTARES alert pipeline

ANTARES coll. → fast search for neutrino counterpart in the online neutrino data stream

5 FRBs analysed by ANTARES (2015-2016)



- No events within $\Delta T = T_{\text{FRB}} - 250\text{s}; T_{\text{FRB}} + 750\text{s}$ ($\text{RoI} = 2^\circ$)
- Compatible with the background expectations → U.L.
- Constrain with Short GRB model

PRELIMINARY



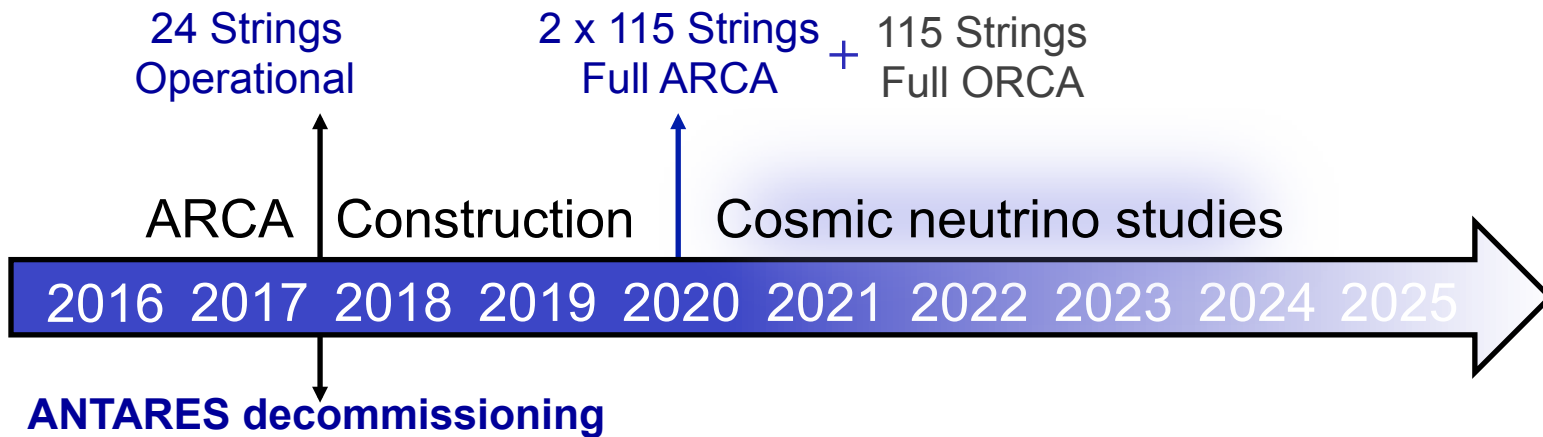
FRB	$F_\nu^{[5\%-95\%]}$ in unit of $\text{erg.cm}^{-2}(\text{GeV.cm}^{-2})$		
	E^{-2}	E^{-1}	GRB-like
150215	0.014(8.65)	0.47(290.54)	0.080(49.95)
150418	0.011(6.95)	0.34(210.57)	0.046(28.94)
151206	0.023(14.59)	0.35(219.95)	0.022(13.63)
151230	0.025(15.55)	1.68(1052.8)	0.043(26.82)
160102	0.026(15.99)	0.71(445.85)	0.022(13.79)

- KM3NeT construction ongoing
- 2 strings in operation (ARCA)
- 24 strings funded for ARCA (0.1km³)
- **Total KM3NeT cost: 125 M€ [ARCA + ORCA]**



 [Read our Letter of Intent](#)

[J. Phys. G: Nucl. Part. Phys. 43 \(2016\) 084001](#)



- **ANTARES: first undersea Cherenkov detector**
 - Excellent angular resolution, view of Southern sky, competitive sensitivities
 - Constraints on the origin of the IceCube signal
 - Improvements still to come: include showers in all analyses
 - **Demonstration of the great potential of deep-sea Neutrino Telescopes**
- **KM3NeT: phased approach to next-generation neutrino telescope by 2020**
 - Letter of Intent published
 - Prototypes performing well
 - Deployment of the first detection units
 - **ARCA will confirm and study the observed cosmic flux (tracks & showers)**
 - **ORCA will measure the Neutrino Mass Ordering**



P1.001 -- Alexis Coleiro
HEN follow-up of GW150914

P2.001-- Silvia Celli
HEN from Bright GRBs

P2.002 -- Luigi Fusco
Search for Diffuse astrophysical flux

P2.003 -- Steffen Hallmann
Neutrinos from the Fermi Bubbles

P2.004 -- Tino Michael
All flavour point source search

P2.006 -- Rodrigo Gracia
Constraints on AGN populations

P2.007 -- Timothée Grégoire
Neutrinos from the Galactic Plane

P4.005 -- Juande Zornoza
Dark Matter Searches

Come and visit our posters...

P1.002 --Thomas Heid
Particle identification in KM3NeT/ARCA

P1.095 -- Ronald Bruijn
KM3NeT DOM

P2.015 -- Karel Melis
First results of the first KM3NeT DU

P2.016 -- Agata Trovato
KM3NeT sensitivity to point-like sources

P2.025 -- Simon Bourret
Tomography of the Earth with KM3NeT-ORCA

P2.026 -- Joao Coelho
Probing new physics at KM3NeT-ORCA

Thank you !





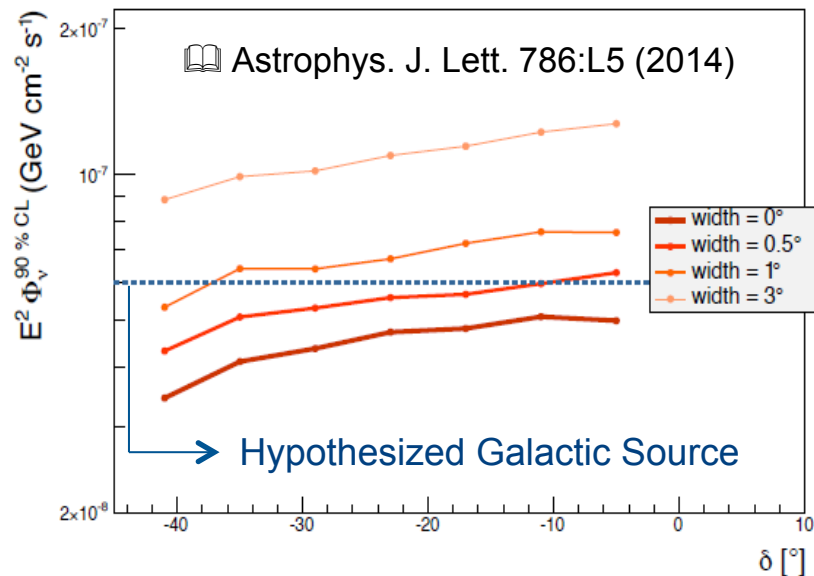
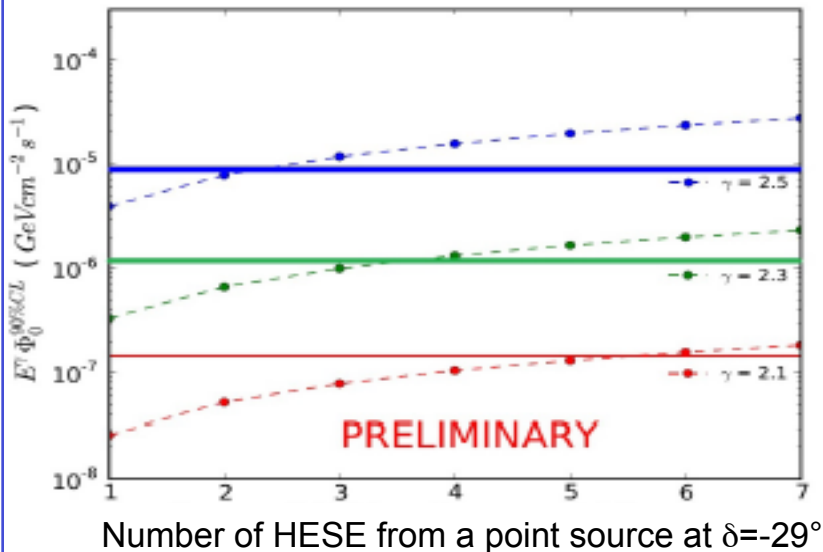
Thank you !



Sicily, June 2016



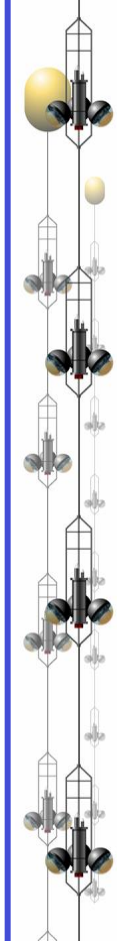
- ANTARES 2007-2012 : 1338 days livetime



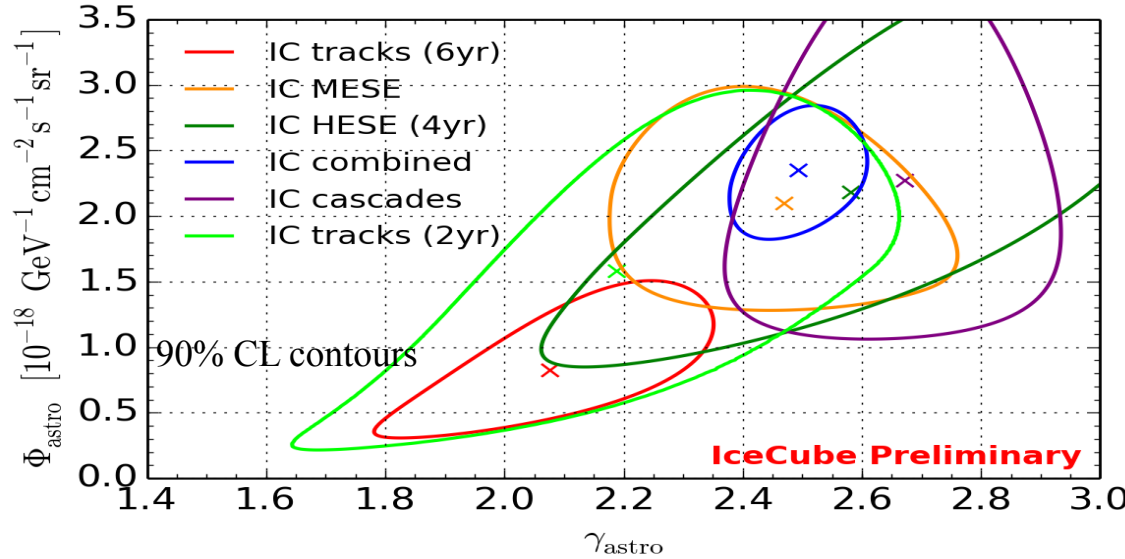
Excludes any single PS close to the GC with spectral index of -2.5 as having a flux corresponding to more than 2 HESE (3yrs)

New ! P2.006 R. Gracia

Same dataset used to constrain AGN population with a 2pt correlation function.



Summary of recent IC results

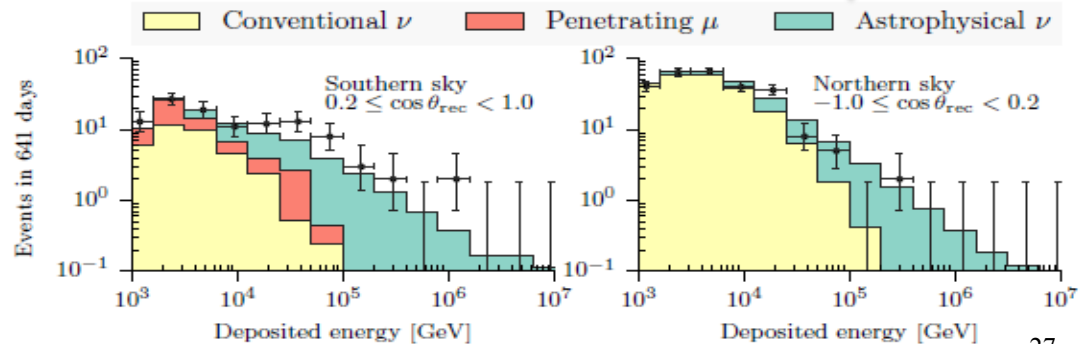


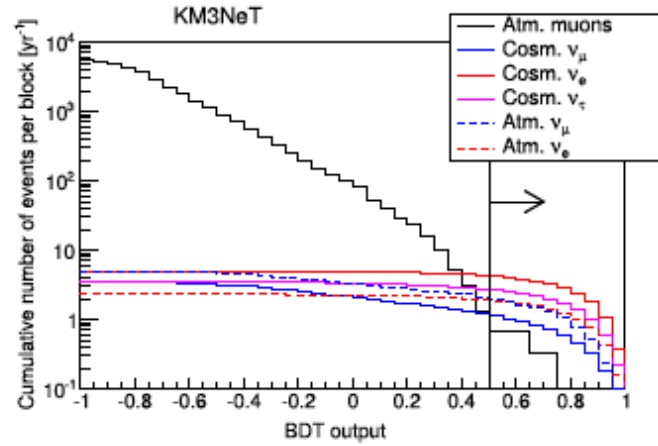
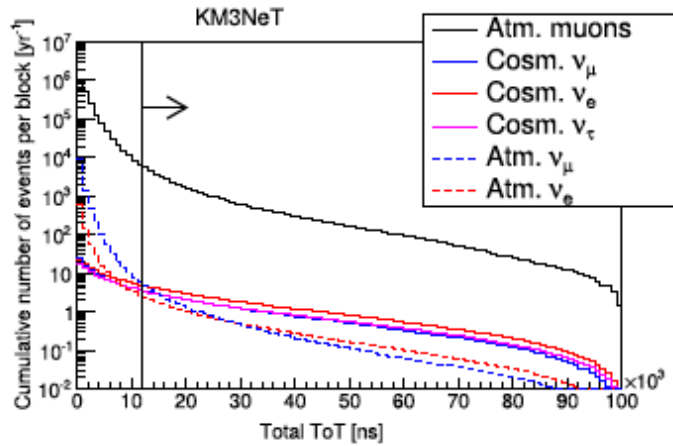
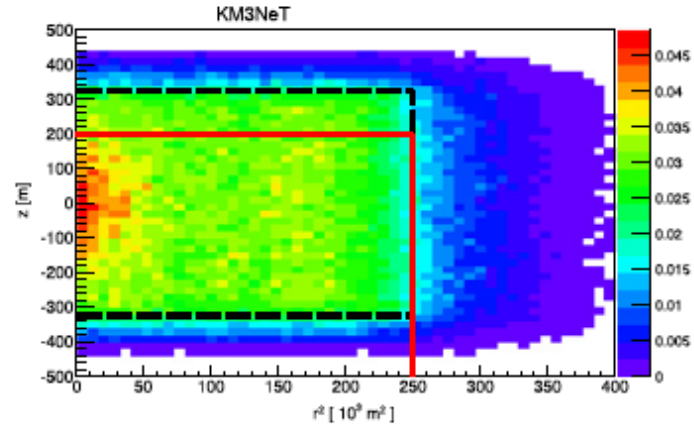
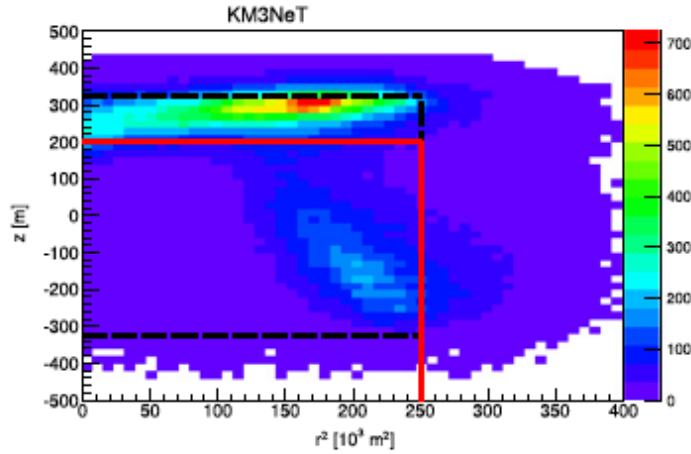
Results of **IC tracks(6yr)** and **IC combined** not compatible at $> 3.6\sigma$ level

Medium Energy Starting Events

Indication of spectral break (different energy thresholds) ?

Indication of Galactic and extra-galactic contributions (different hemispheres) ?







KM3NeT phases



Phase	Blocks	Primary deliverables
1	0.2	Proof of feasibility and first science results (6 ORCA strings/ 24 ARCA strings)
2.0	2 <i>ARCA</i>	Study of neutrino signal reported by IceCube; All flavor neutrino astronomy
	1 <i>ORCA</i>	Neutrino mass hierarchy
3	1+6	Neutrino astronomy including Galactic sources

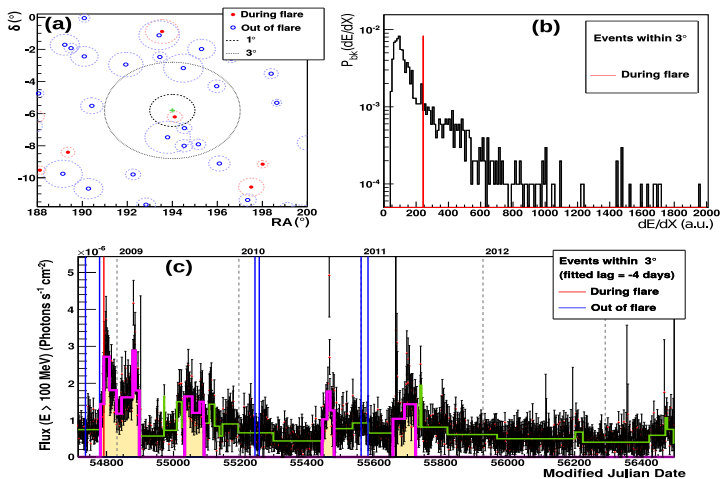
December 2015 : KM3NeT confirmed on ESFRI Roadmap



Search for flares of AGN and X-ray binaries

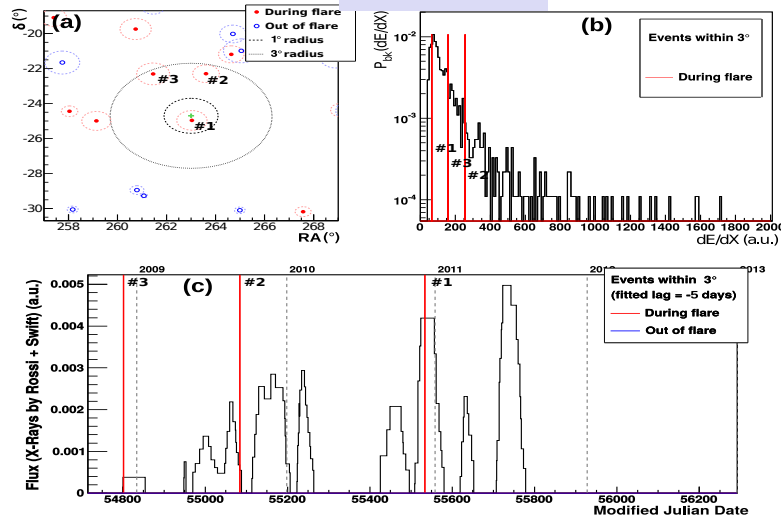
- Time-dependent analysis: 40 blazars and 33 x-ray binary outbursts
2008-2012 ANTARES data, 1044 days
- Time signal: light curves from Swift-BAT, RXTE-ASM, MAXI and FERMI/LAT-GBM

3C279



Pre (post)-trial p-value: 3.3% (67%)

GX 1+4



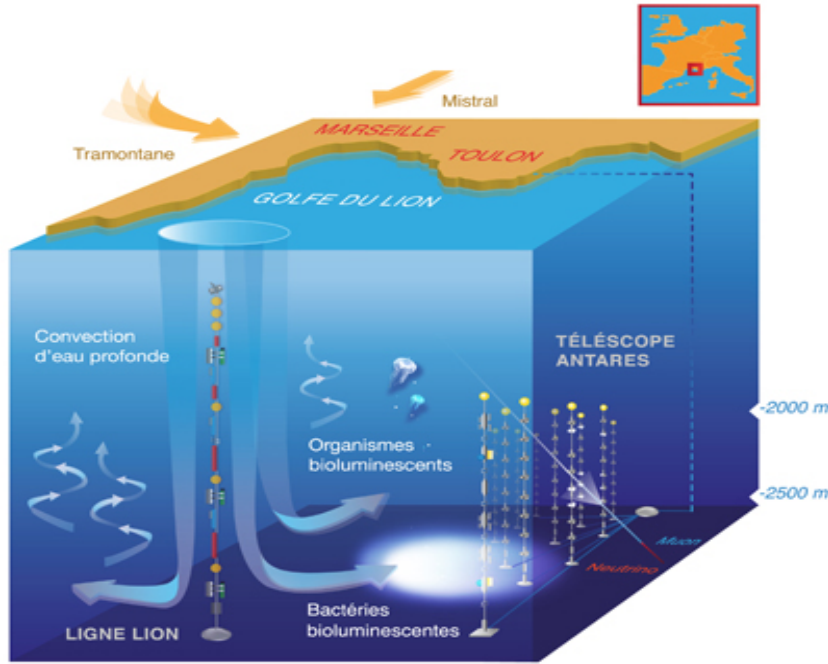
Pre (post)-trial p-value: 4.1% (72%)

Compatible with background fluctuations => U.L. starts to constrain hadronic models

ANTARES awarded La Recherche Prize “*Coup de Coeur*”

📖 C. Tamburini, S. Escoffier et al., PLoS ONE 8 (7) 2013

Deep-sea bioluminescence blooms after dense water formation at the ocean surface



ANTARES/KM3NeT are connection nodes of

European multidisciplinary
seafloor & water column
observatory



Monitoring of environmental processes including natural hazards, climate change, marine ecosystems, etc.

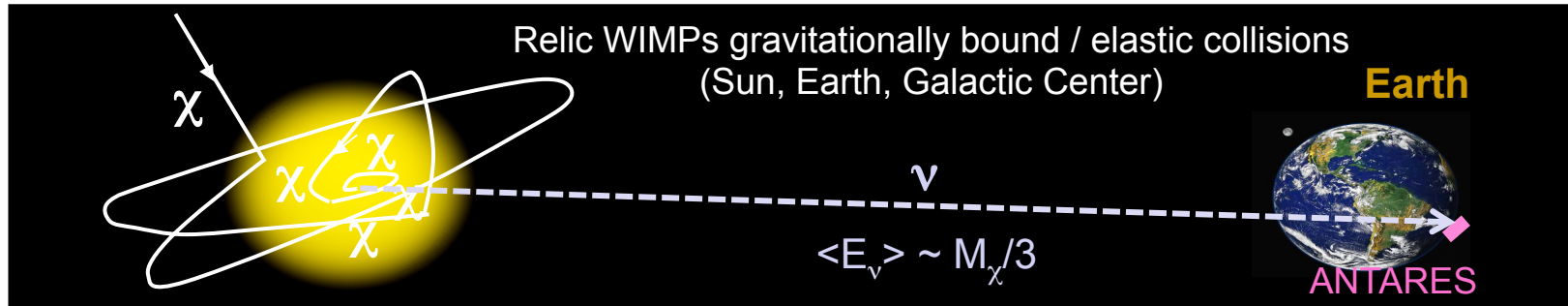
📖 Nature. 2009, Dec 3, 462 (7273)

📖 Ocean Dynamics, April 2014, 64, 4, 507-517

📖 Deep-Sea Research I 58 (2011) 875–884

📖 *Sperm whale diel behaviour*, submitted to PLoS ONE

Indirect search for Dark Matter (Sun)

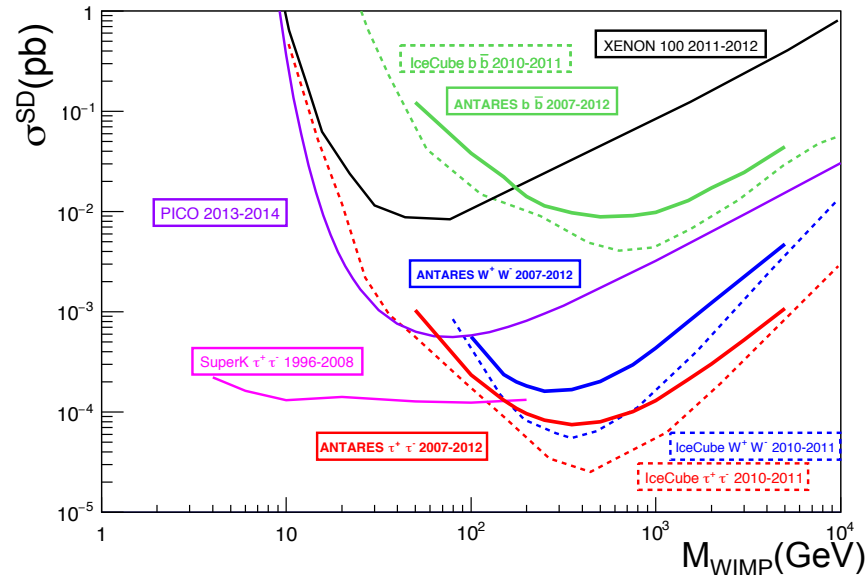


$$DM DM \xrightarrow{ann} W, Z, b, t, \mu, \tau \dots \xrightarrow{decay} \nu, \gamma, e^+, \bar{p} \dots$$

P4.005

- 2007 – 2012 data set
- Track channel only
- Single and multi-line events
- Extended likelihood function
- Competitive results for spin-dependent WIMP-nucleon cross-sections (same parameters as IceCube)
- Good prospects for KM3NeT/ORCA

arXiv:1603.02228, to appear in Phys.Lett. B



Indirect search for Dark Matter (GC)

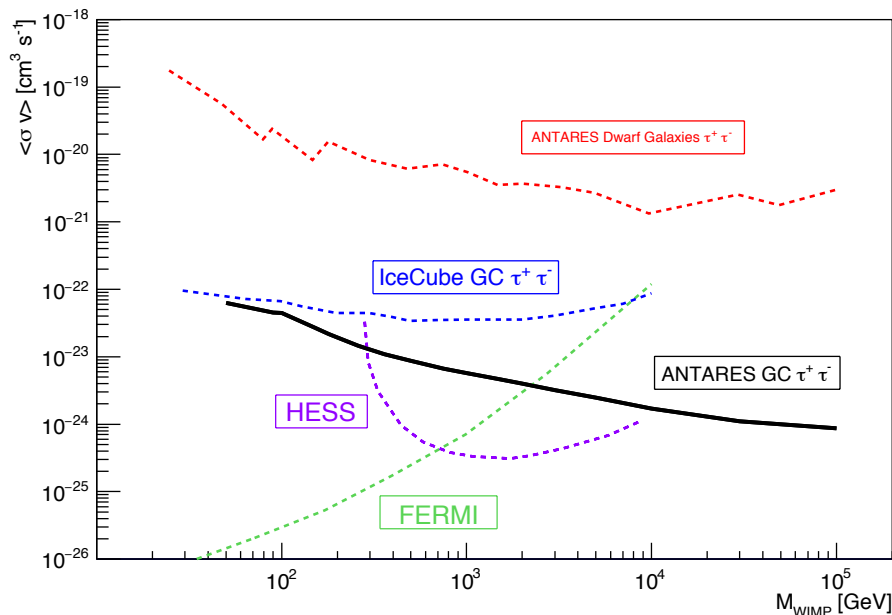
Improved results with respect to JCAP 10 (2015) 068



$$\frac{d\phi_\nu^{ann.}}{dE} = \underbrace{\frac{\delta \langle \sigma v \rangle}{4\pi m_{DM}^2} \frac{dN_\nu}{dE}}_{\text{Particle physics}} \underbrace{\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r) dl}_{\text{Astrophysics}}$$

New !

- 2007 – 2013 dataset
- Track channel only
- Single and multi-line events
- Extended likelihood function
- New Dark Matter density profile NFW (same parameters as IceCube)
- Best limit from a Neutrino Telescope
- Also limits from the Earth [P4.005]



- Construction is ongoing
- 2 strings in operation (ARCA)
- 24 strings funded for ARCA (0.1km³)
- **Total KM3NeT cost: 125 M€ [ARCA+ ORCA]**



- Shore station (incl. computing)
- Deep-sea cable network
- Deployments
- Strings (without PMTs)
- PMTs (incl. base and reflector)

