Indirect search of Dark Matter with the ANTARES High Energy Neutrino Telescope.

Antonio Capone, University "La Sapienza" and I.N.F.N. Roma, Italy

at the

South American Dark Matter Workshop

ICTP-SAIFR, São Paulo, Brazil

10-12 May 2017

Talk outline

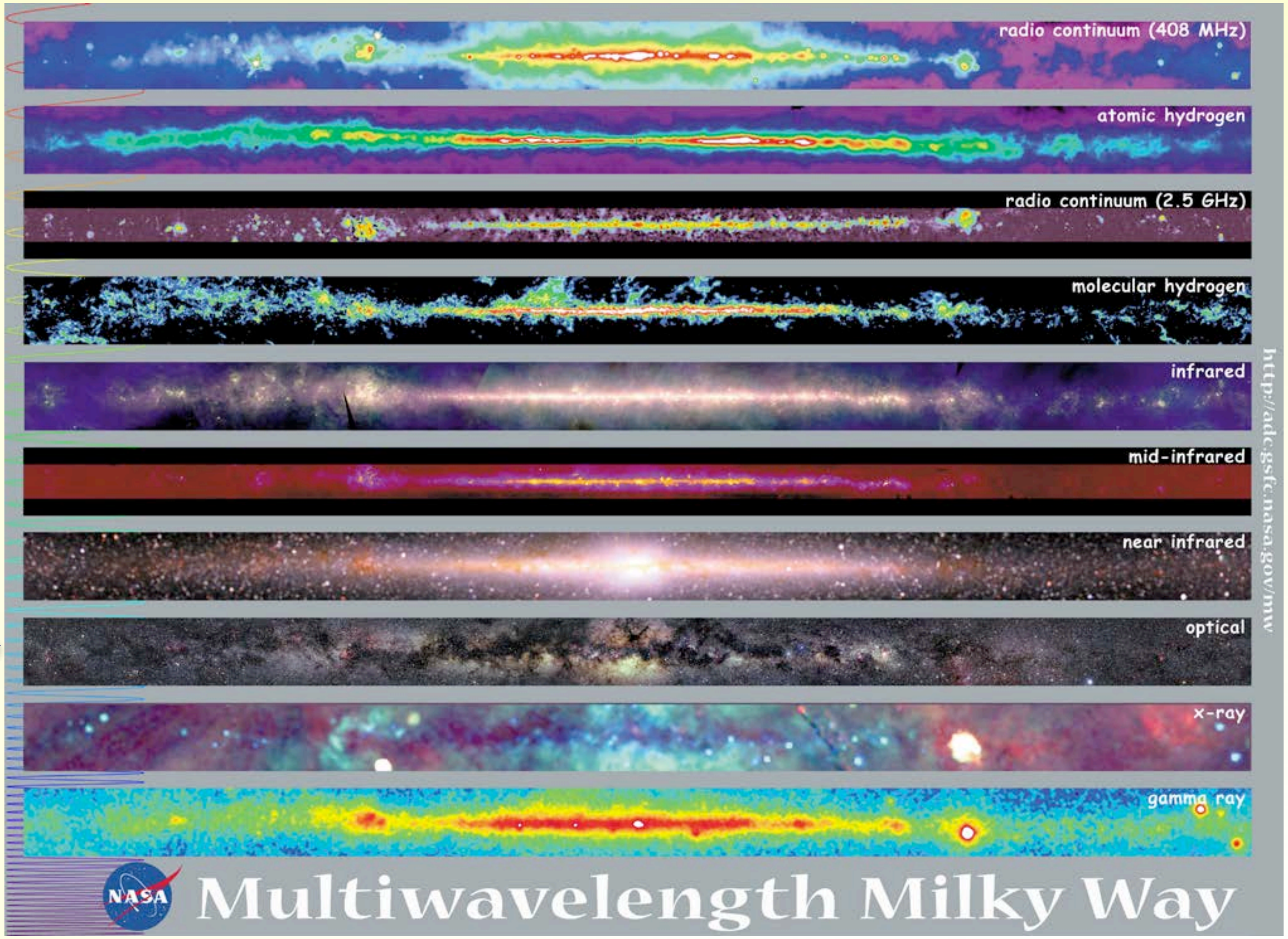
- ANTARES: the 1st undersea Cherenkov detector for High Energy Astrophysical neutrino detection
- The ANTARES main physics goals and selected results
- Indirect search for Dark Matter:
  - using the SUN
  - using the Galactic Plane
  - using the Earth
- Perspectives for the future
- Conclusions & Summary

The evolution of astronomy

- From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy:

  observations of light in the visible band are complemented by radio, X-ray and γ astronomy

Galileo Galilei showing the Doge of Venice how to use the telescope (1858), fresco by Giuseppe Bertini (1825–1898)



http://mwmw.gsfc.nasa.gov/

… and to Multi-Messengers Astronomy: HE-CR, photons, neutrinos, GW …

Today and tomorrow: Multi-Messenger Astronomy

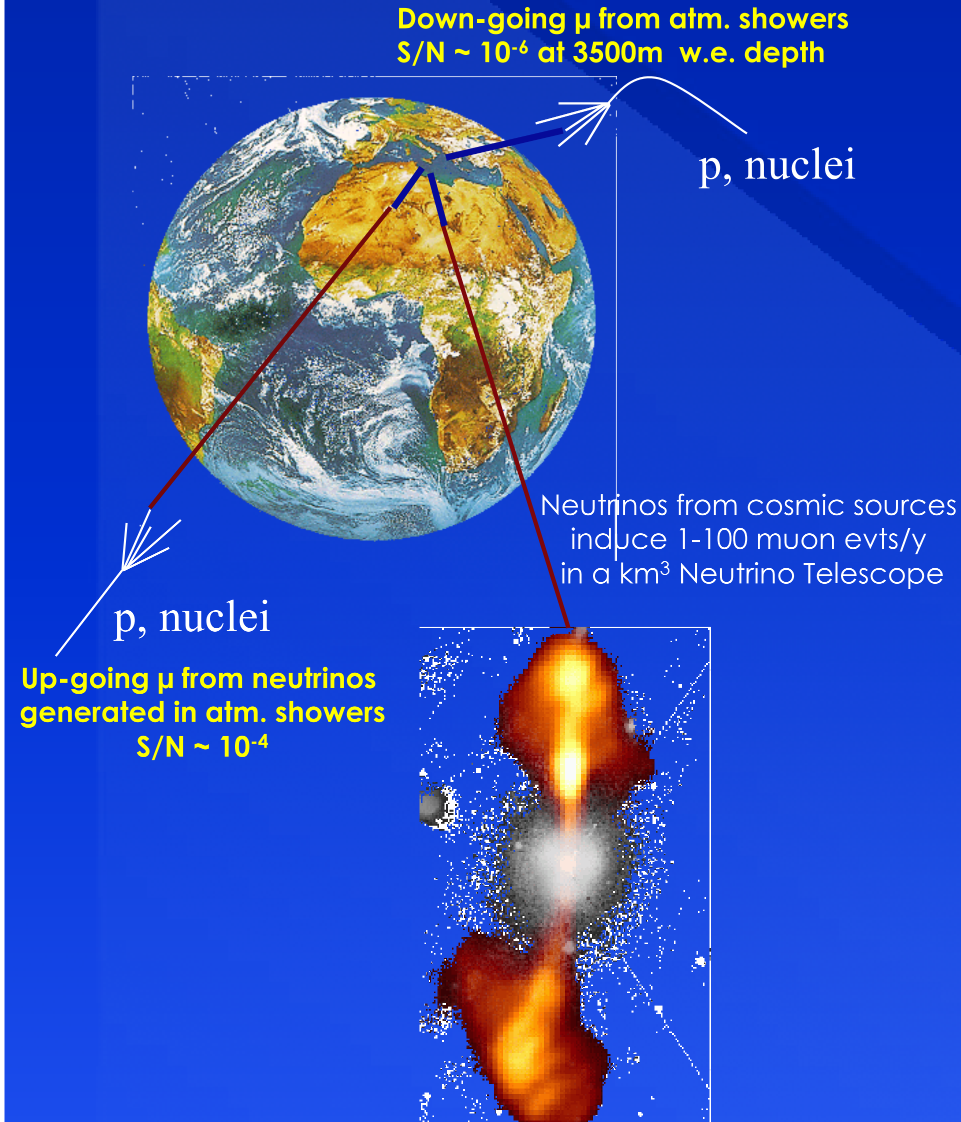
The search for different messengers from the Cosmos (originated at an astrophysical site)

- **Cosmic rays** (protons, nuclei)
- **Neutrinos**
- **Gravitational waves**

can complement the information provided by **photons** at any wavelength

Cherenkov ν Telescope: Detection principle

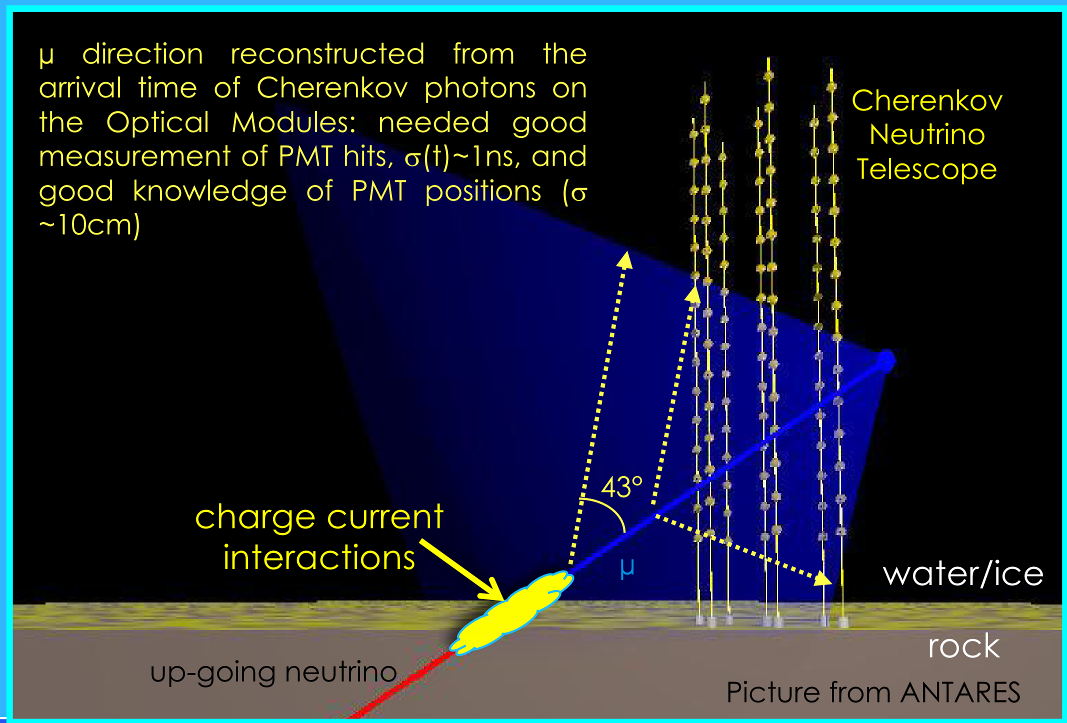
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

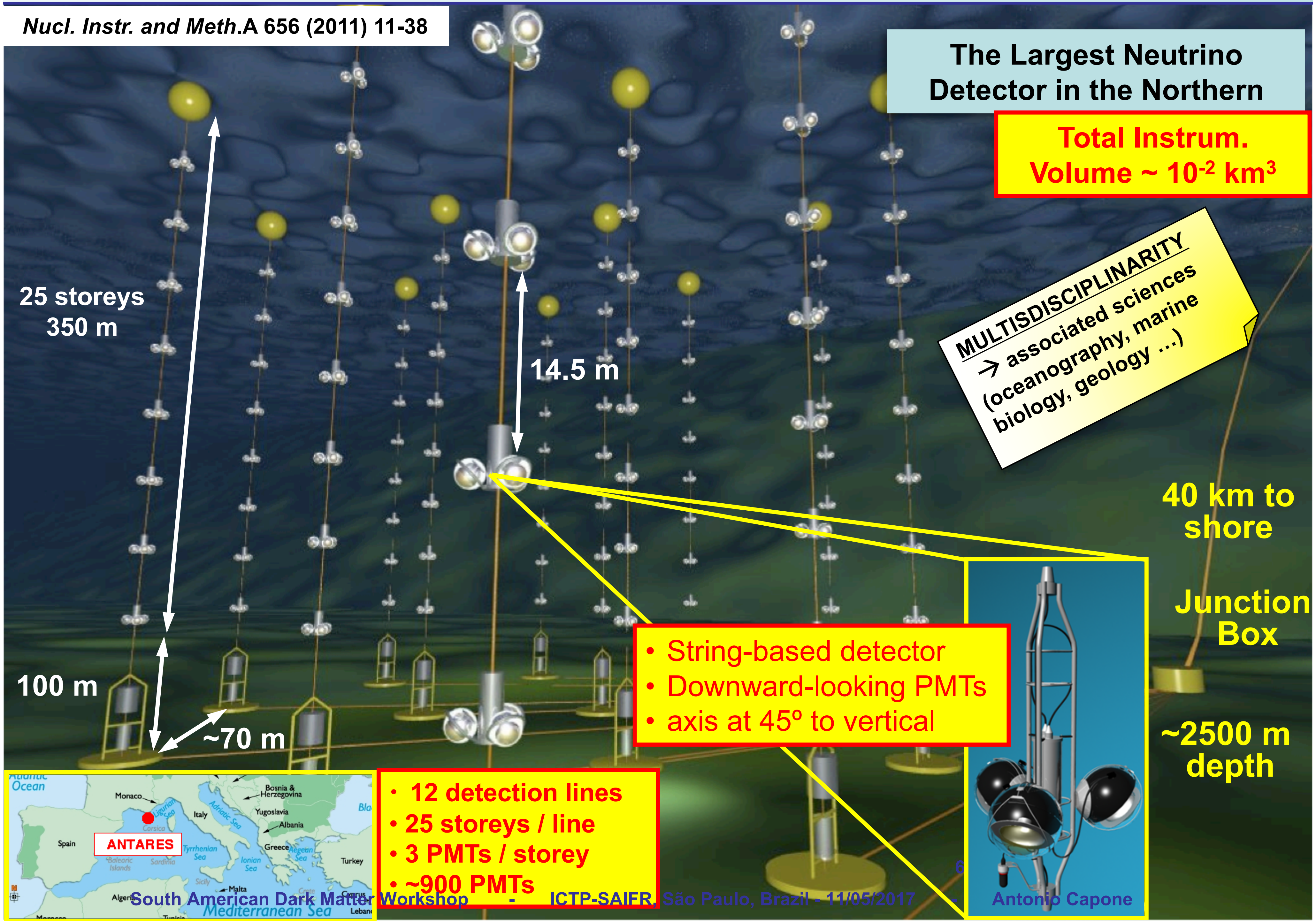
- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$For\ E_\nu \geq 1TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$



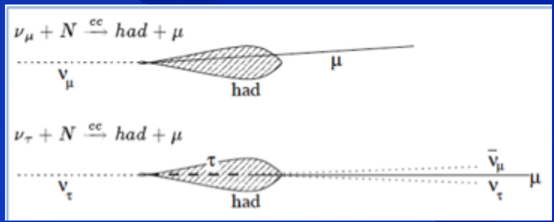
ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch

*Nucl. Instr. and Meth.*A 656 (2011) 11-38

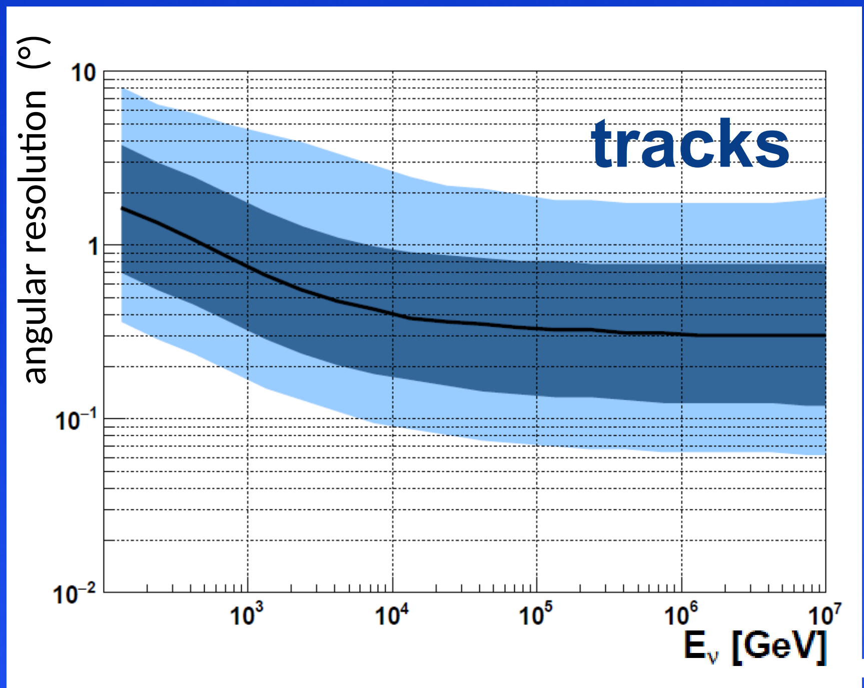


The ANTARES search for point-like ν sources based on two kind of events

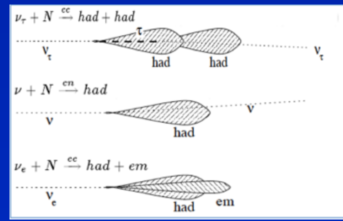
- **Tracks: CC ν_μ or $\nu_\mu \to \mu$**



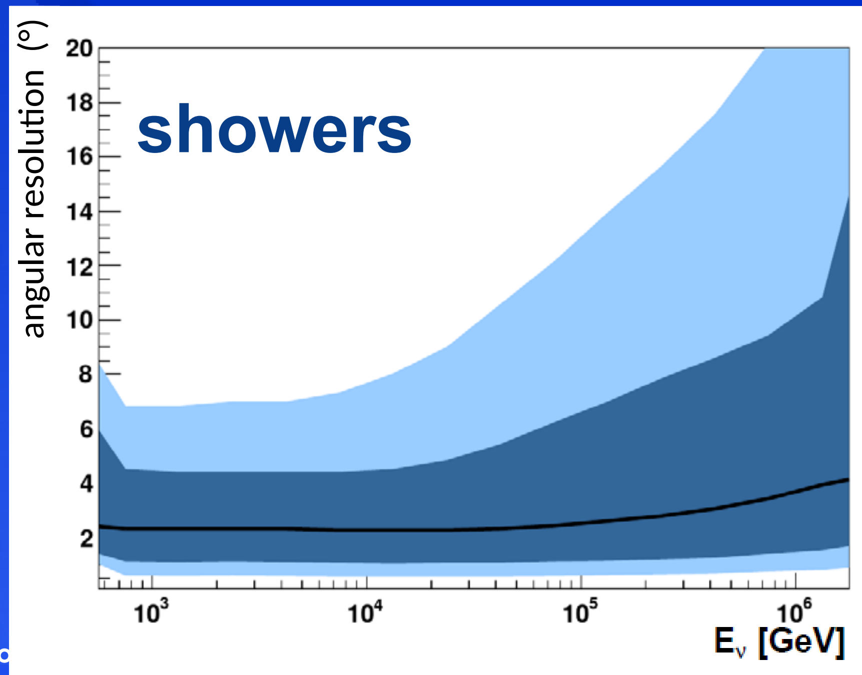
- **Interaction can occur far from the detector providing a large *Effective Volume***
- ***Angular resol.* $< 0.4°$ for $E_\nu > 10\ TeV$**
- ***Energy resol.* ~ factor 3**



- **Electronic or hadronic showers: NC and CC ν_e or $\nu_\tau \to$ showers**



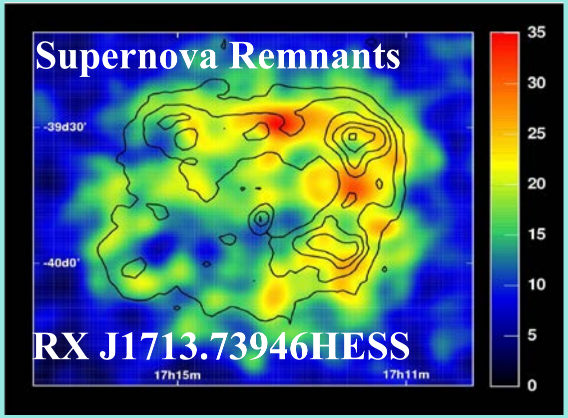
- **Events contained in the detector: smaller *Effective Volume,***
- ***Energy resolution* ~ 5-10%**
- ***Median angular resolution* $\sim 3°$**

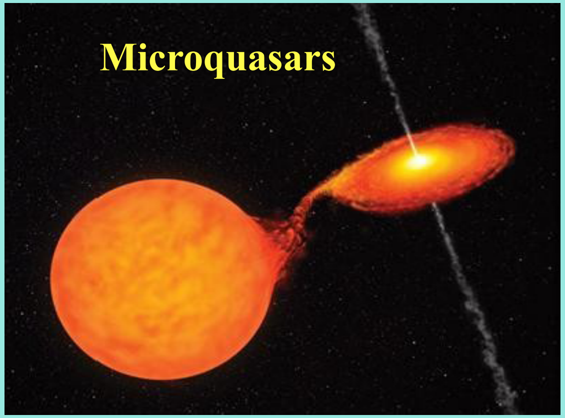


ANTARES physic's goals

Search for point-like cosmic Neutrino Sources

Galactic

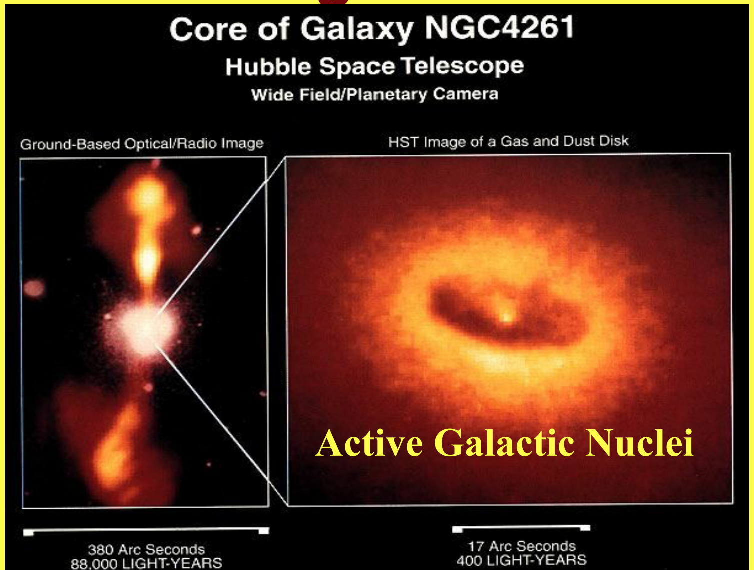


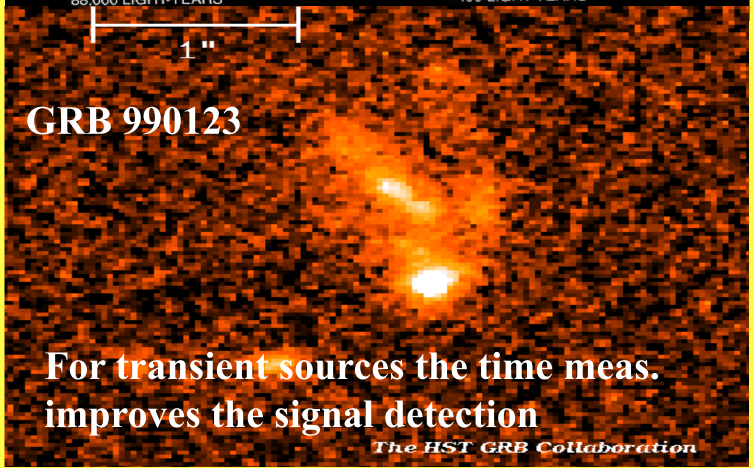


- Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \le 0.5^\circ \text{ for } E_\nu \ge 1\,TeV$$

Extragalactic



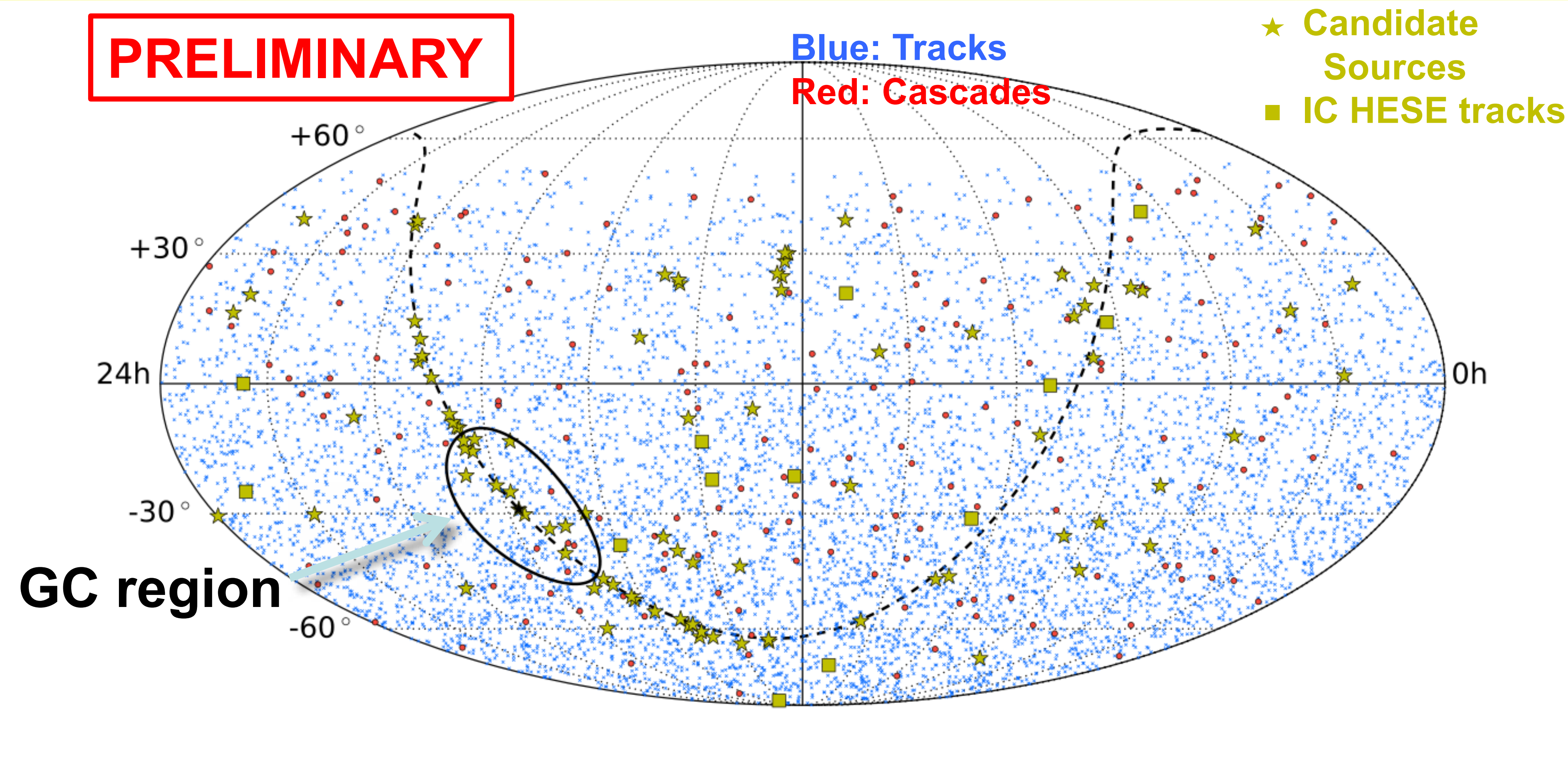


Experimental signal : statistical evidence of an excess of events coming from the same direction

ANTARES physic's goals

Search for point-like cosmic Neutrino Sources

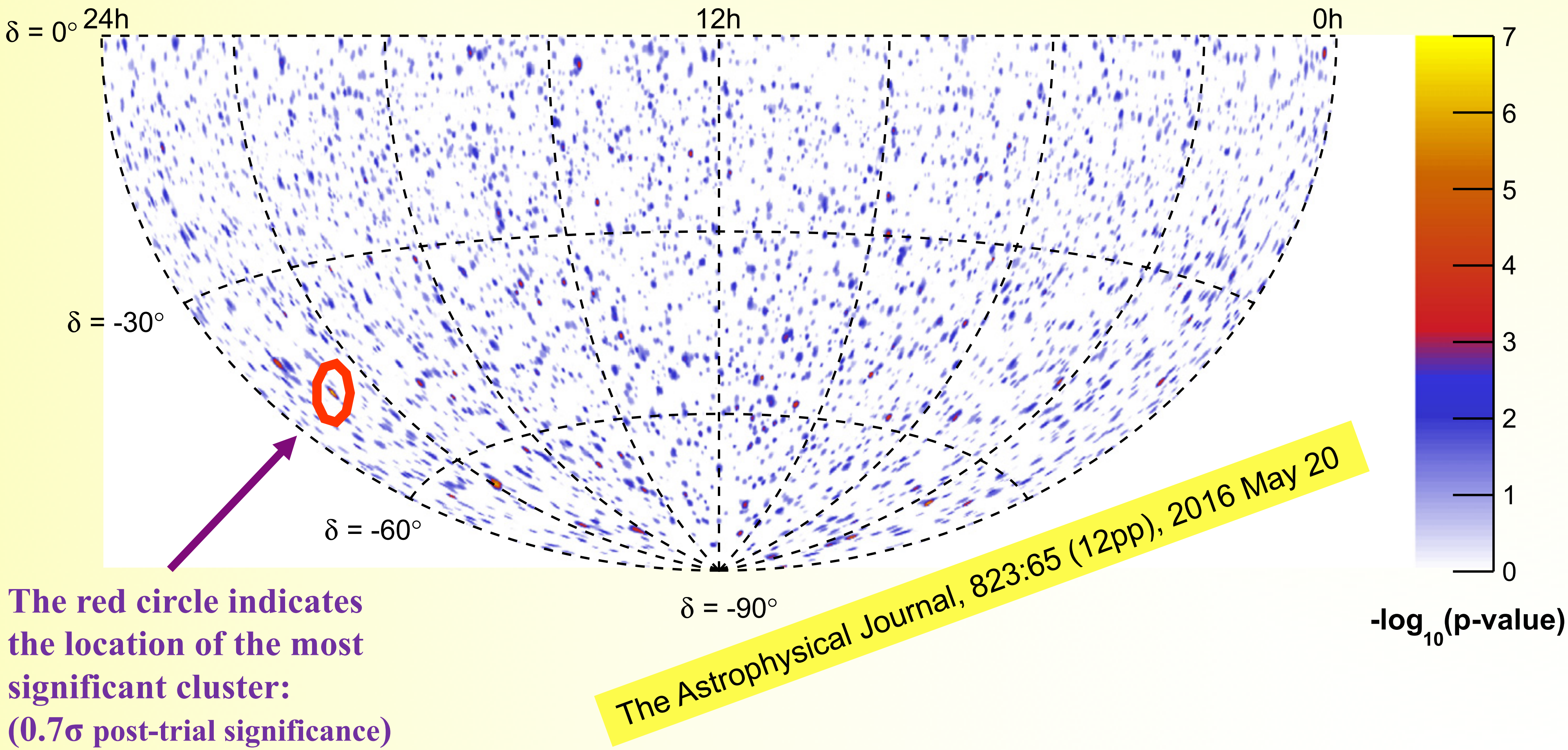
9 years of ANTARES data – all neutrino flavours – "tracks" + "shower" events



so far …. no significant excess has been found

Joint IceCube + ANTARES search for ν sources

Skymap of pre-trial p-values for the combined ANTARES 2007/12 and IceCube 40, 59, 79 point-source analyses.

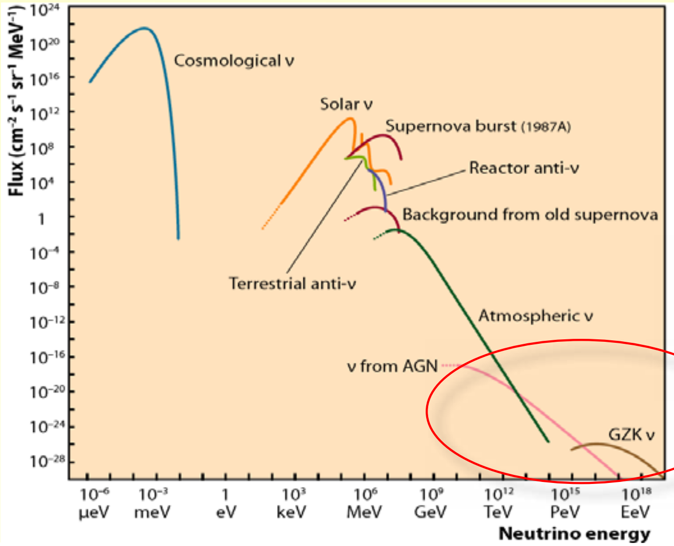


The red circle indicates the location of the most significant cluster: (0.7σ post-trial significance)

ANTARES physic's goals

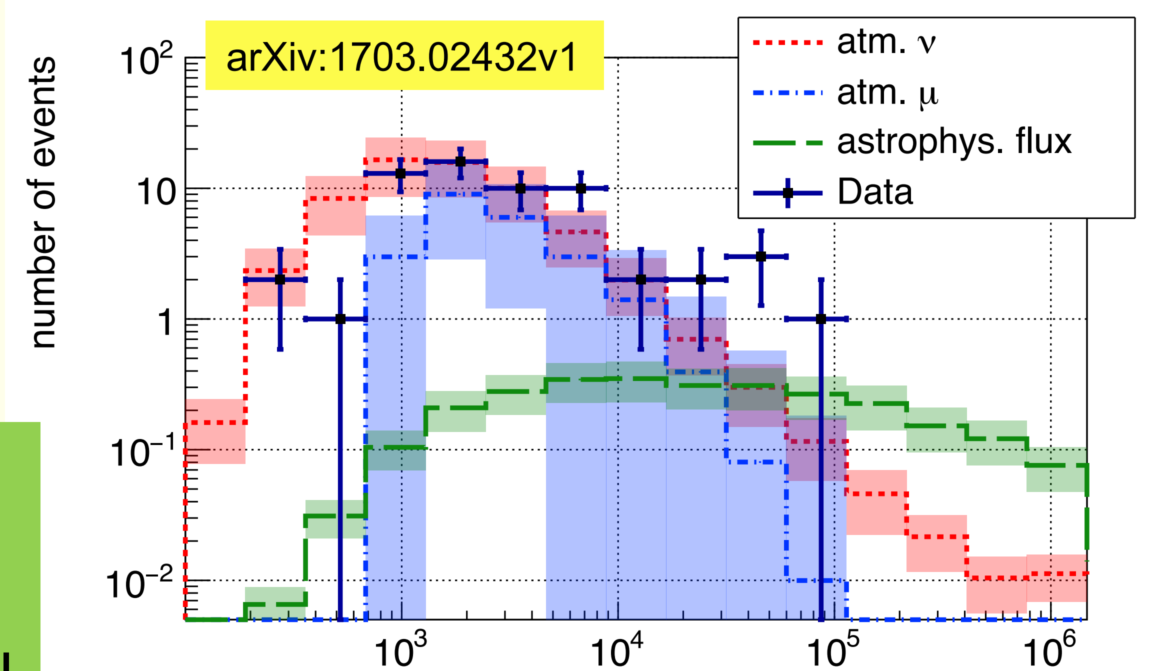
Search for Diffuse flux of Cosmic Neutrinos

- Neutrinos from:
  - Unresolved AGN
  - "Z-bursts"
  - "GZK like" proton-CMB interactions
- Top-Down models Neutrinos
- ….



Search here !!!

Their identification out of the more intense background of atmospheric neutrinos (and μ) is possible at very high energies (E_μ >> TeV) and requires good energy reconstruction.



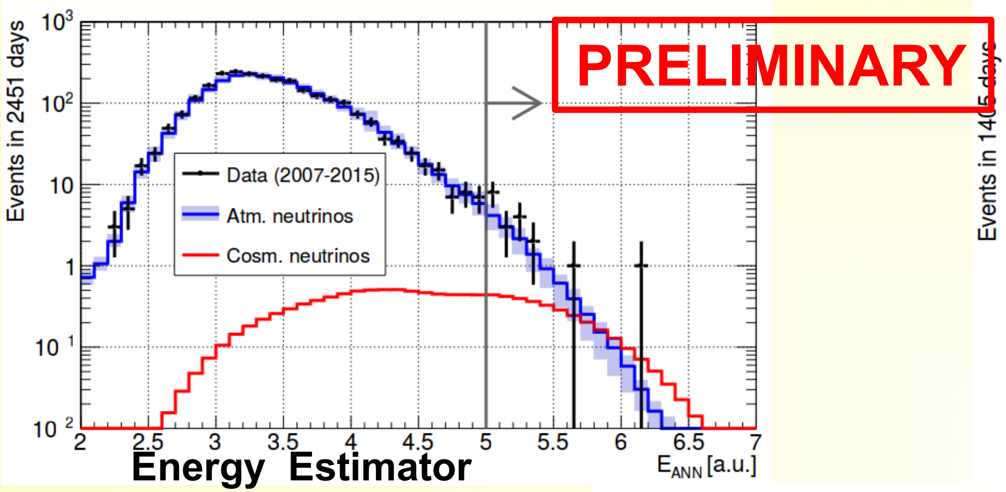
ANTARES, 6 years

Found 8 "shower events" for 10 TeV<E_{SH}<100 TeV when 5 expected.
Compatible with IceCube signal

Latest ANTARES results on the search for diffuse ν flux

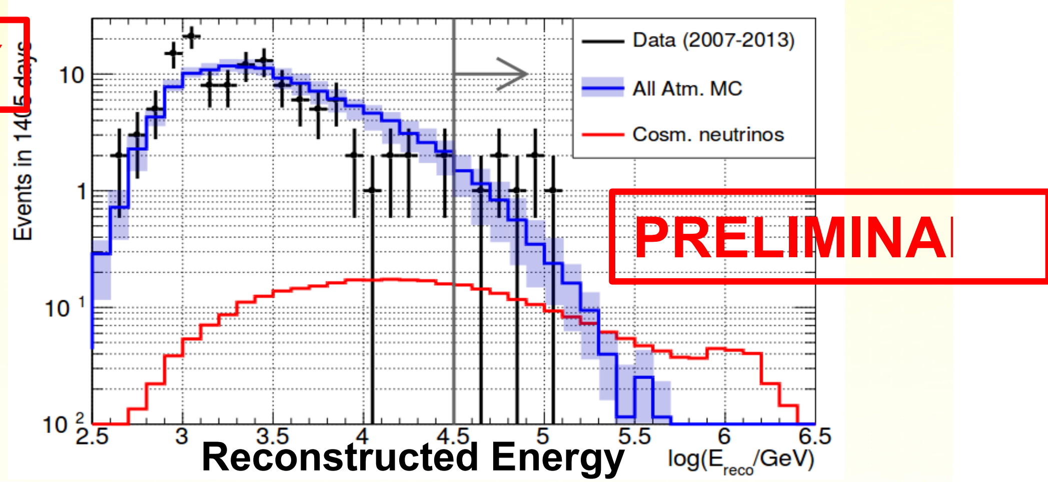
Tracks

Data: 2007-2015 (2451 live-days)
Above E_{cut}: Bkg: 13.5 ± 3 evts, IC-like signal: 3 evts
Observed: 19 evts



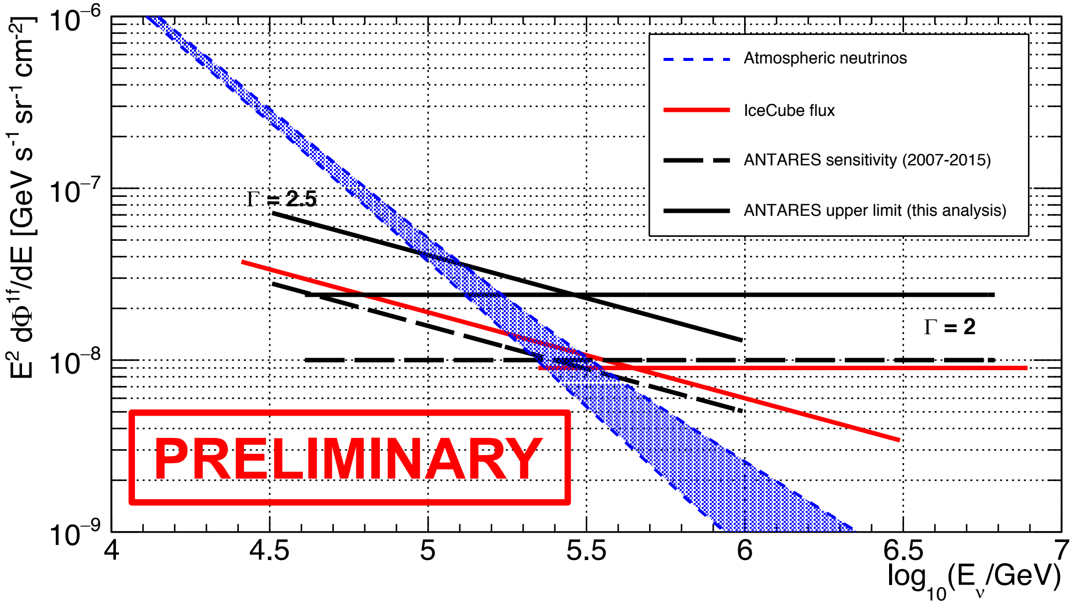
Cascades

Data: 2007-2013 (1405 live-days)
Above E_{cut}: Bkg: 5 ± 2 evts, IC-like signal: 1.5 evts
Observed: 7 evts



ANTARES

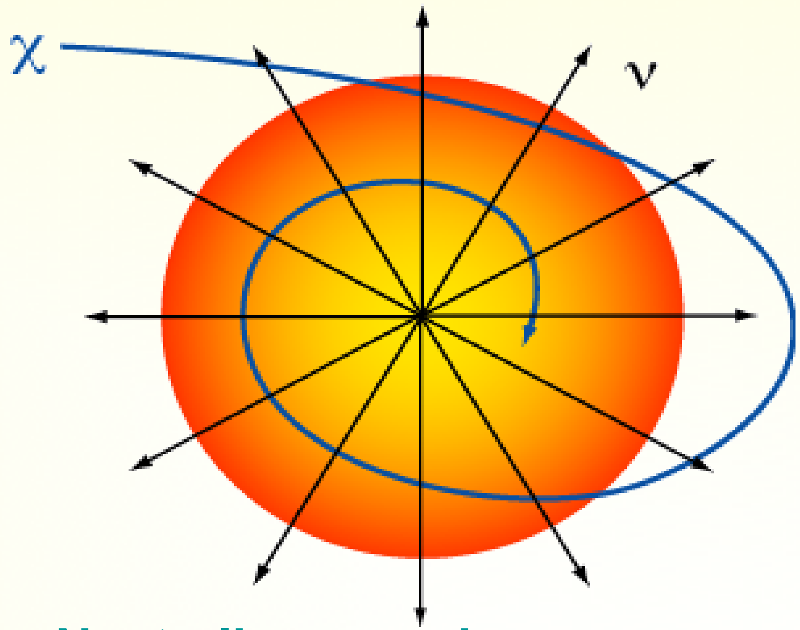
combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades



… not only neutrino astrophysics…

… also open problems in particle physics …

- Dark Matter searches:
  - Neutralino annihilation in Sun, Earth, Galactic Center
- Magnetic Monopoles
- Particle acceleration mechanisms
- Search for Sterile Neutrinos
- …

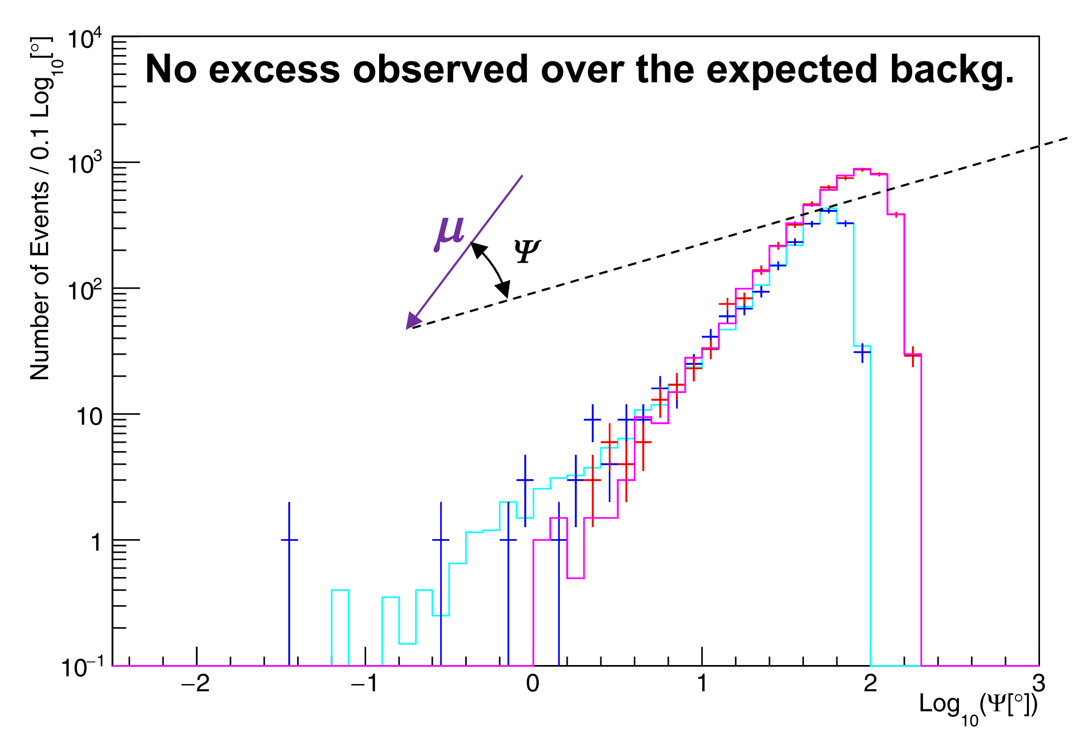


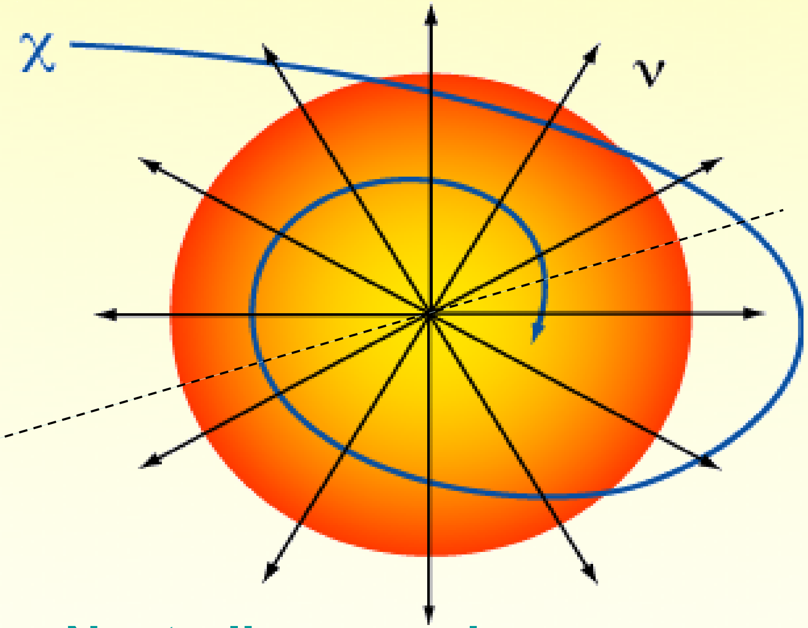
Neutralino search: $\chi\chi \rightarrow \nu + \ldots$

Indirect search for Dark Matter in the Sun

6 years of ANTARES data: 2007-2012

Distribution of the angular distance between reconstructed the track direction of events and the Sun position for two different track reconstruction algorithms in order to maximize the event reconstruction for single line and multi-lines events.





Neutralino search: $\chi\chi \rightarrow \nu + \ldots$

Neutrino spectrum

from WIMPSIM (M. Blennow, J. Edsjö, T. Ohlsson, J. Cosmol. Astropart. Phys. 0801 (2008) 021.)

Background

estimated from time-scrambled data.

Neutrino fluxes from $WIMP + WIMP \rightarrow \underbrace{b\bar{b}, W^+W^-, \tau^+\tau^-}$ $\rightarrow \bar{\nu}\,\nu + \ \ldots$

evaluated for 50 GeV/c^2 < M_{WIMP} < 5 TeV/c^2

→ limits to ν fluxes and to WIMP-nucleon cross sections

The analysis strategy

Maximization of a likelihood function based on the knowledge of the probability density functions, for the contribution of a background event, *$B(\Psi, N_{hit}, \beta)$*, or a signal event, *$S(\Psi, N_{hit}, \beta)$*, *to the observed distribution*.

$$\mathcal{L}(n_s) = e^{-(n_s+N_{\text{bg}})} \prod_{i=1}^{N_{\text{tot}}} \left(n_s S(\psi_i, N_{hit,i}, \beta_i) + N_{\text{bg}} B(\psi_i, N_{hit,i}, \beta_i)\right)$$

N_{hit} = *number of hit used for the track reconstruction*
β = the angular error estimate for the reconstructed track
N_{tot} = *tot. Number of reconstructed events*
n_s *and* ***N_{bg}*** *are the number of signal and background events in the maximization procedure*

$B(\Psi, N_{hit}, \beta)$ *obtained by the collected data randomising the right ascension of the event*
$S(\Psi, N_{hit}, \beta)$ *obtained from MC simulation using the ν energy spectra given by WIMPSIM*

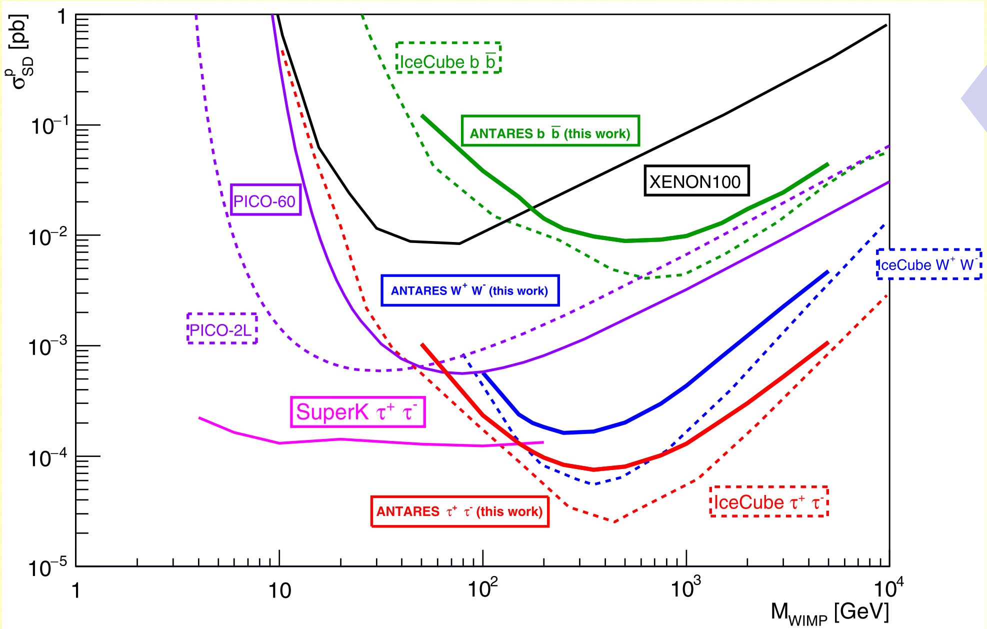
High statistics Pseudo-MC experiments *are performed for each combination of M_{WIMP}, annihilation channel:*

- *with only background $n_s = 0$ → allow to evaluate* $\mathcal{L}(0)$
- *with a given value of simulated signal-like events $n_s > 0$. For each one of these pseudo-MC experiment a maximum likelihood analysis is performed searching for the value of n_s that maximize the likelihood. We then get* $\mathcal{L}(n_{max})$

We can now ***evaluate a Test Statistic*** $TS = log_{10} \frac{\mathcal{L}(0)}{\mathcal{L}(n_{max})}$ *that gives us a measure of the probability to assume a fluctuation of the background as a distribution of events with $n_s \neq 0$.*

Indirect search for Dark Matter in the Sun

No excess observed over the expected background: evaluate 90% C.L. upper limits for expected signal

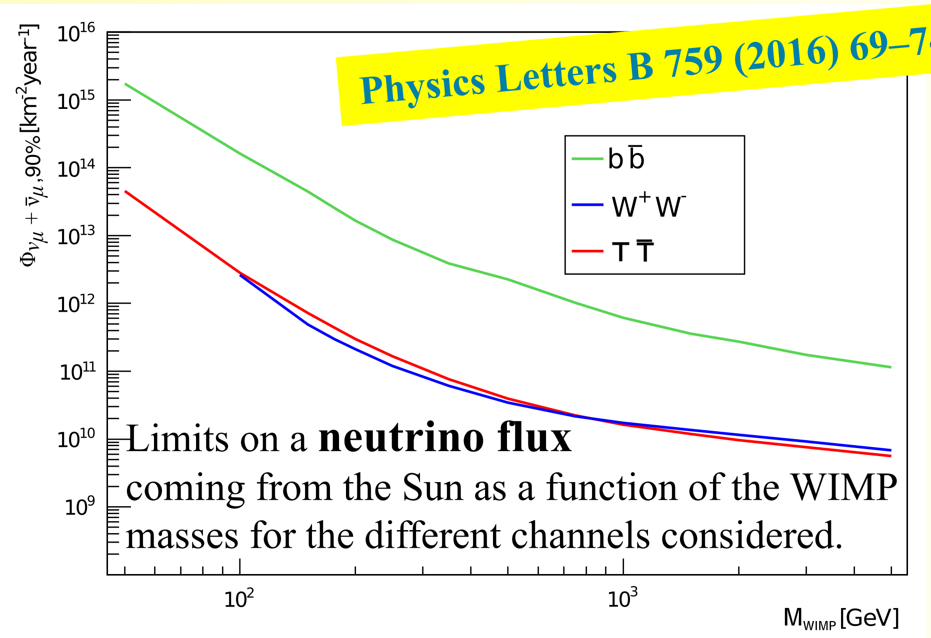


Limits on the **spin-dependent** WIMP-nucleon scattering cross-section as a function of WIMP mass for the bb̄, τ+τ− and W+W− channels.

assumptions:

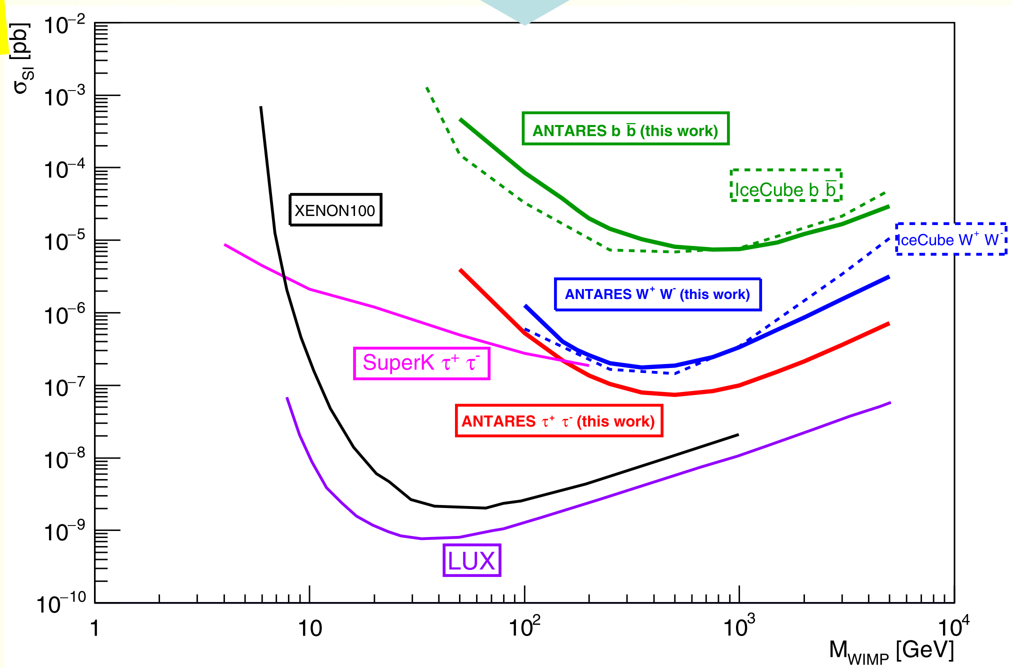
- capture and annihilations in equilibrium
- local D.M. density =0.4 GeV cm^{-3}
- υ^{DM}_{SUN} according to Maxwell distr. 270 km s^{-1} r,m.s.

Limits on the **spin-independent** WIMP-nucleon scattering cross-section as a function of WIMP mass for the different channels considered.



Physics Letters B 759 (2016) 69–74

Limits on a **neutrino flux** coming from the Sun as a function of the WIMP masses for the different channels considered.



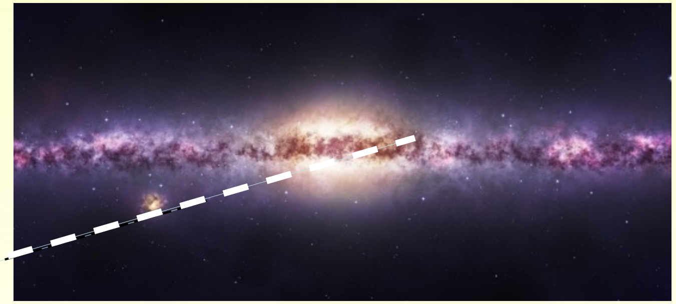
Indirect search for Dark Matter in the Galactic Centre

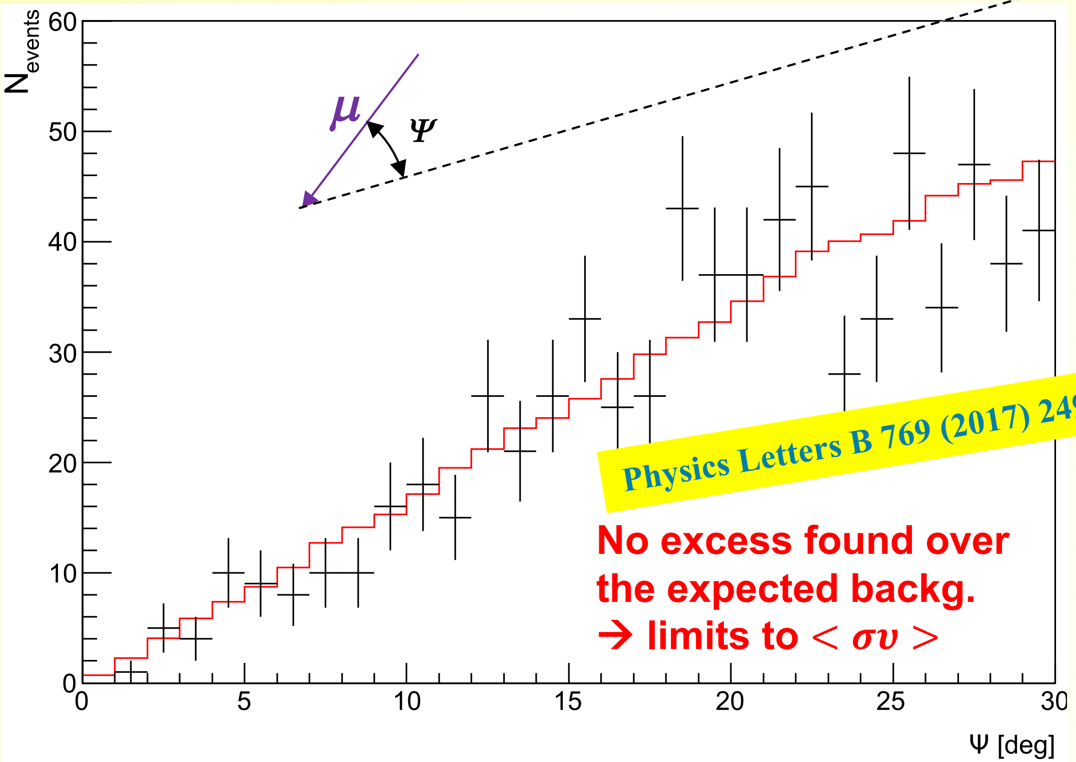
9 years of ANTARES data: 2007-2015 - ANTARES "observes" the G.C > 66% time

Search performed for:

- **50 GeV/c^2 < M_{WIMP} < 100 TeV/c^2**
- $\boldsymbol{WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}}$

$$\frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{\langle\sigma v\rangle}{8\pi M^2_{WIMP}} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{int}(\Delta\Omega)$$





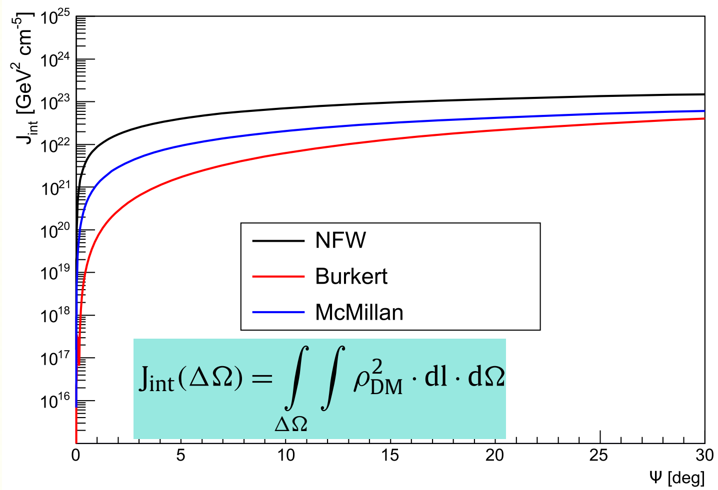
Physics Letters B 769 (2017) 249–254

No excess found over the expected backg.
→ limits to $< \sigma v >$

Distribution of measured angles between reconstructed tracks and the Galactic Centre (crosses). The red line describes what is expected from background event.

The expected ν flux depends on the DM distribution around the GC.
3 halo models have been considered

Parameter	NFW	Burkert	McMillan
r_s [kpc]	$16.1^{+17.0}_{-7.8}$	$9.26^{+5.6}_{-4.2}$	17.6 ± 7.5
ρ_{local} [GeV/cm^3]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034



$$J_{int}(\Delta\Omega) = \int_{\Delta\Omega}\int \rho^2_{DM} \cdot dl \cdot d\Omega$$

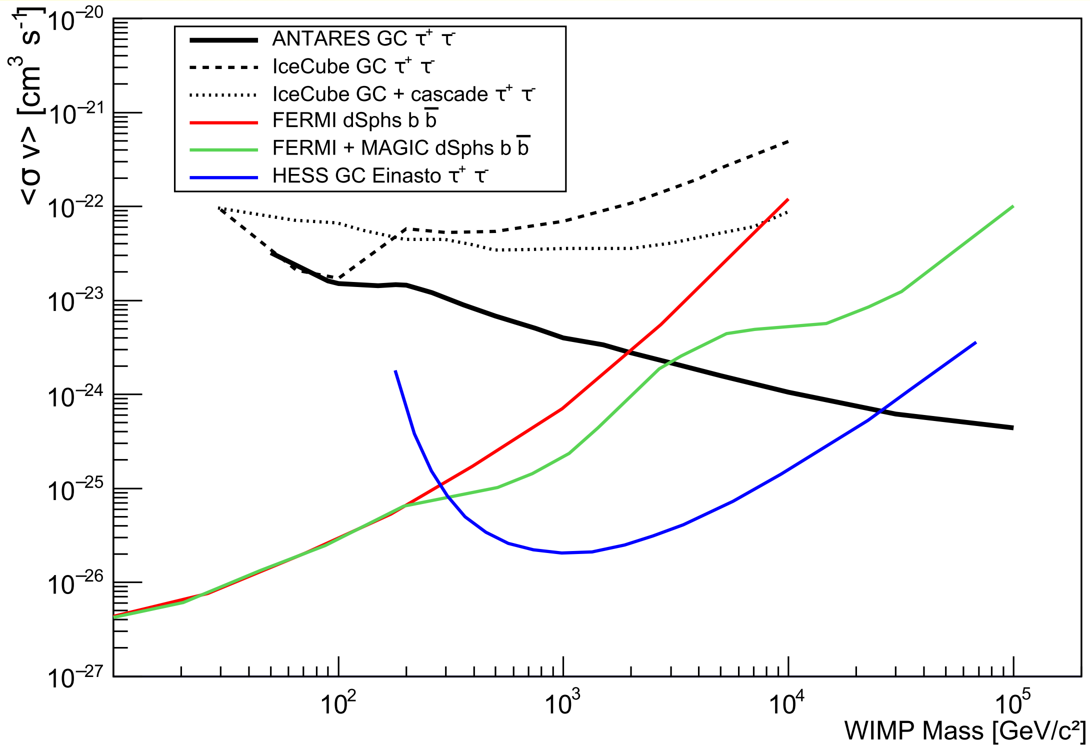
The integrated J-Factor, J_{int}, for a cone-shaped region centred on the G.C. with an opening angle Ψ

Indirect search for Dark Matter in the Galactic Centre

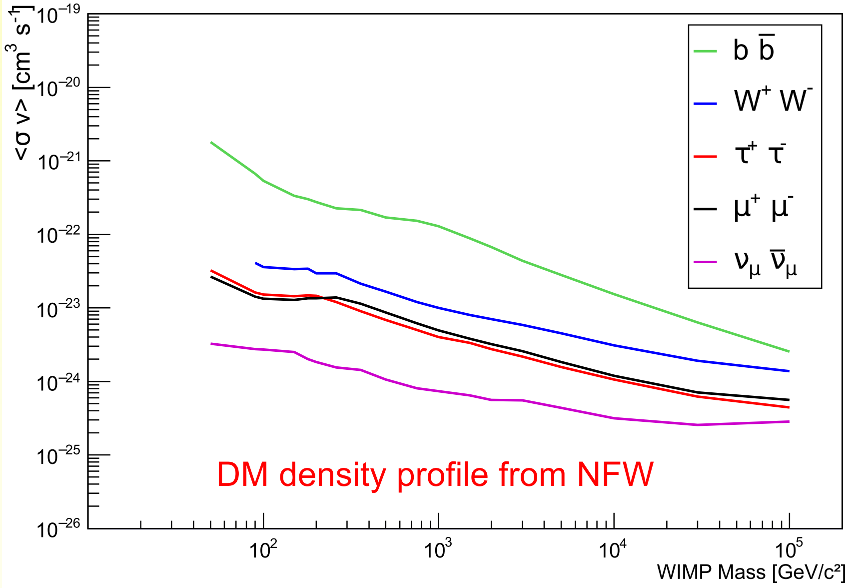
No excess found over the expected background

➟ limits to

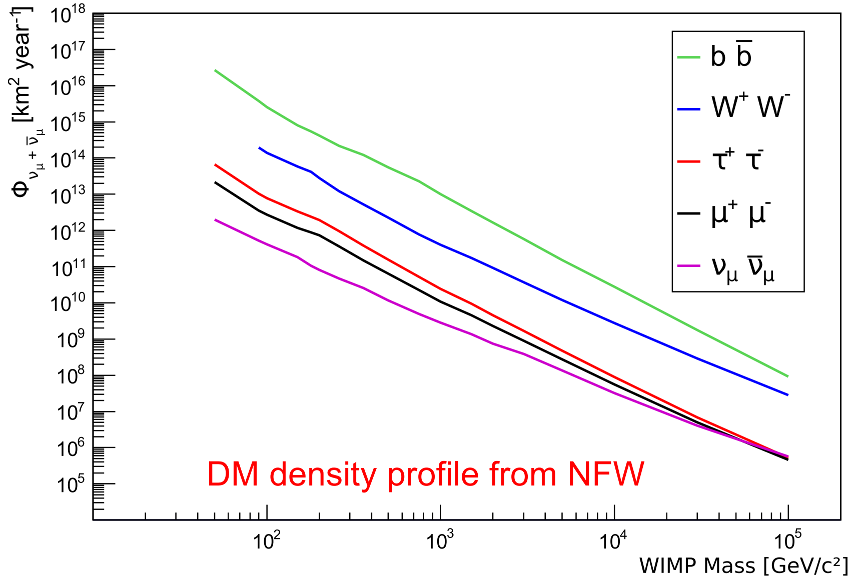
$$\frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{\langle\sigma v\rangle}{8\pi M^2_{WIMP}} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{int}(\Delta\Omega)$$



90% C.L. limits on the thermally averaged annihilation cross-section, ⟨σ v⟩, as a function of M_{WIMP}. The results from IceCube and ANTARES were obtained with the NFW profile.

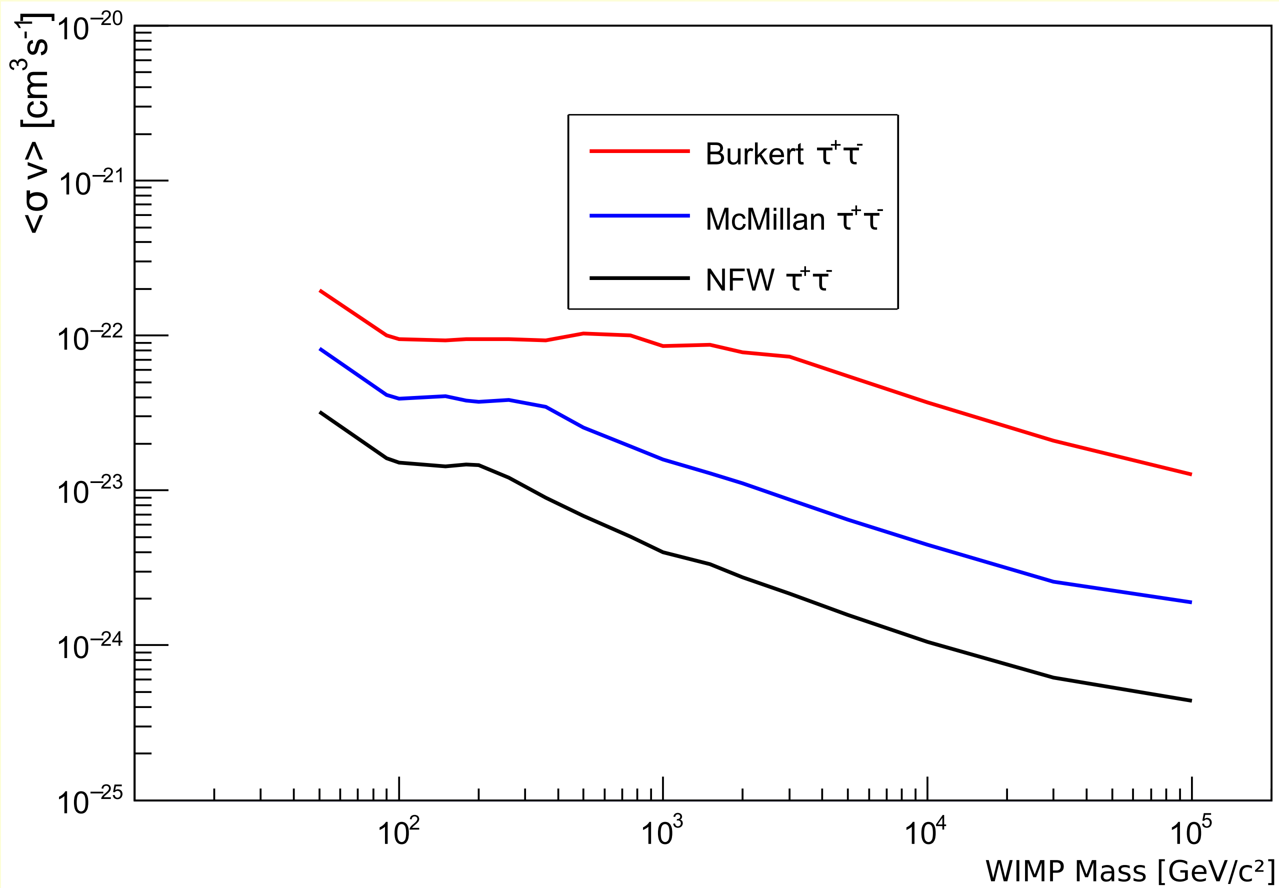


90% C.L. limits on the thermally averaged annihilation cross-section ⟨σv⟩ from WIMP annihil. in the Milky Way



90% C.L. upper limits on the neutrino flux from WIMP annihilations in the Milky Way.

Indirect search for Dark Matter in the Galactic Centre



90% C.L. limits on the thermally averaged annihilation cross-section ⟨σ v⟩ obtained only for the channel $\boldsymbol{WIMP + WIMP \rightarrow \tau^+\tau^-}$ but for different models of the DM halo around the G.C.

Indirect search for Dark Matter in the Earth

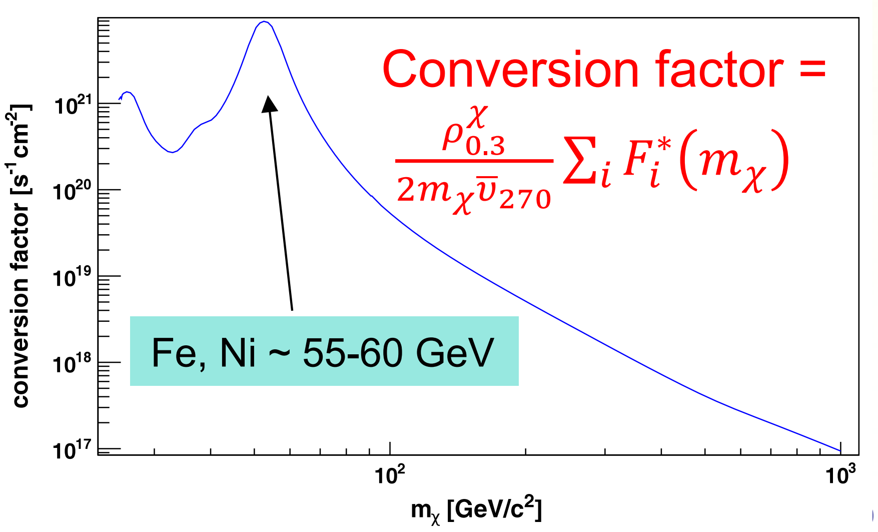
- WIMPS can be gravitationally bound to the Earth if $v_{WIMP} < v_{escape}^{Earth}$
- $v_{escape}^{Earth} \sim 14\,\frac{km}{s}$; $v_{WIMP} = \bar{v}_{270}$ following a Maxwell-Boltzmann distr. with r.m.s. velocity 270 km/s ➞ only a small fraction of WIMPS captured on the Earth.
- WIMPS-nucleons collision described by spin-independent cross section σ_p^{SI}.
- Fe and Ni most abundant in the Earth → effective capture for $M_{WIMP} \sim 50\ GeV$.
- In the Earth the capture ($\Gamma_C(t)$) and annihilation ($\Gamma_A(t)$) rates would reach the equilibrium in $\tau \sim 10^{11}$ y >> Earth age (t_{Earth} = 4.5 10^9 y)
- In these conditions:

$$\Gamma_A(t_{Earth}) \propto \underbrace{\left[\frac{\sigma_p^{SI}\rho_{0.3}^{\chi}}{m_\chi \bar{v}_{270}} \sum_i F_i^*(m_\chi)\right]^2}_{C_C^2 \text{ capture factor}} \underbrace{\frac{\langle\sigma_A v\rangle_{Earth}}{V_{Earth}} \left(\frac{m_\chi}{20\ GeV}\right)^{\frac{3}{2}}}_{C_A \text{ annih. factor}}$$

Needed to estimate the ν fluxes with WimpSim

$\rho_{0.3}^{\chi}$=0.3 GeV/cm^3
Local D.M. density

the capture is very effective when $m_{WIMP} \sim m_{target}$



ANTARES, Physics of the Dark Universe 16 (2017) 41–48

Indirect search for Dark Matter in the Earth

6 years of ANTARES data: 2007-2012

25 Gev/c^2 < M$_{WIMP}$ < 1 Tev/c^2

$$WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \nu\bar{\nu}$$

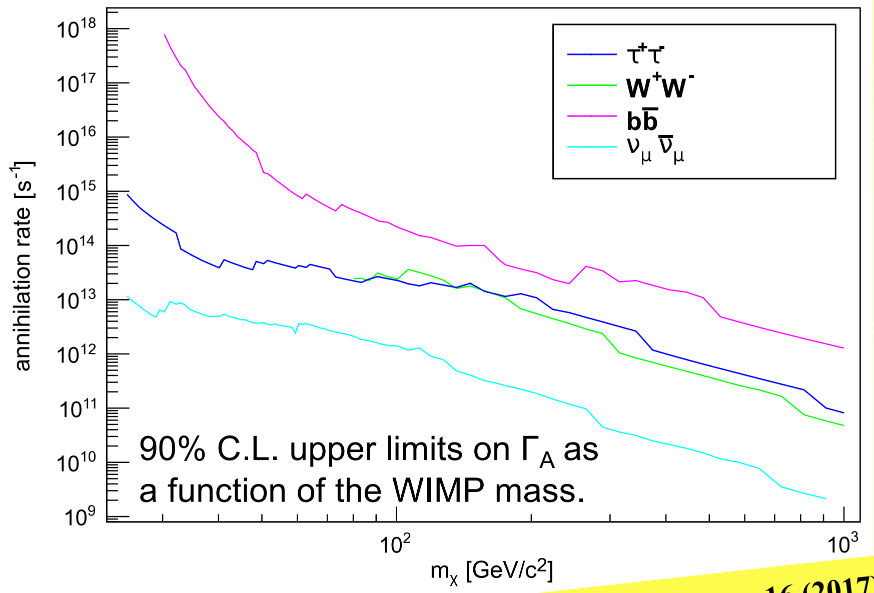
No excess found over the expected background

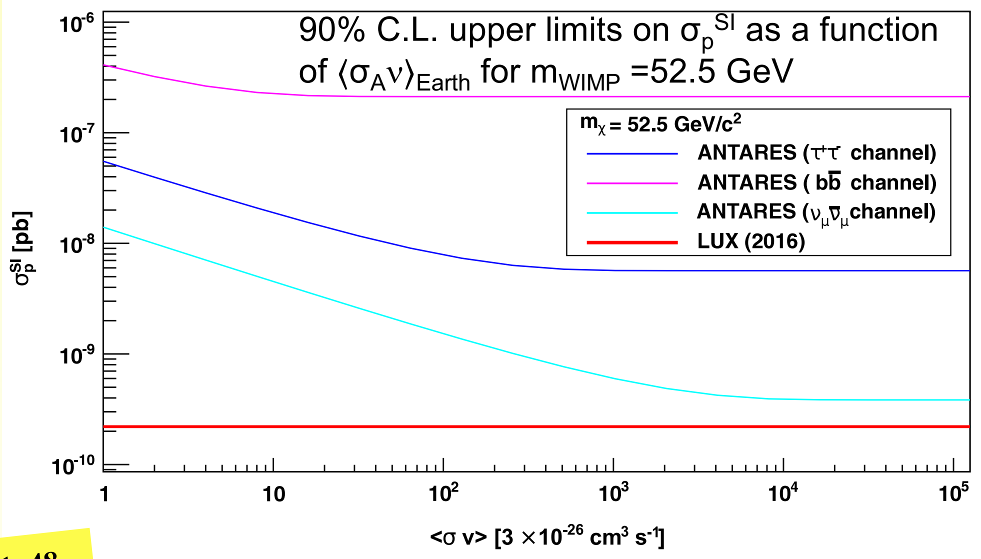
Limits on the WIMP-WIMP annihilation rate in the Earth

Limits on the spin independent WIMP-nucleon cross-section

ANTARES, Physics of the Dark Universe 16 (2017) 41–48

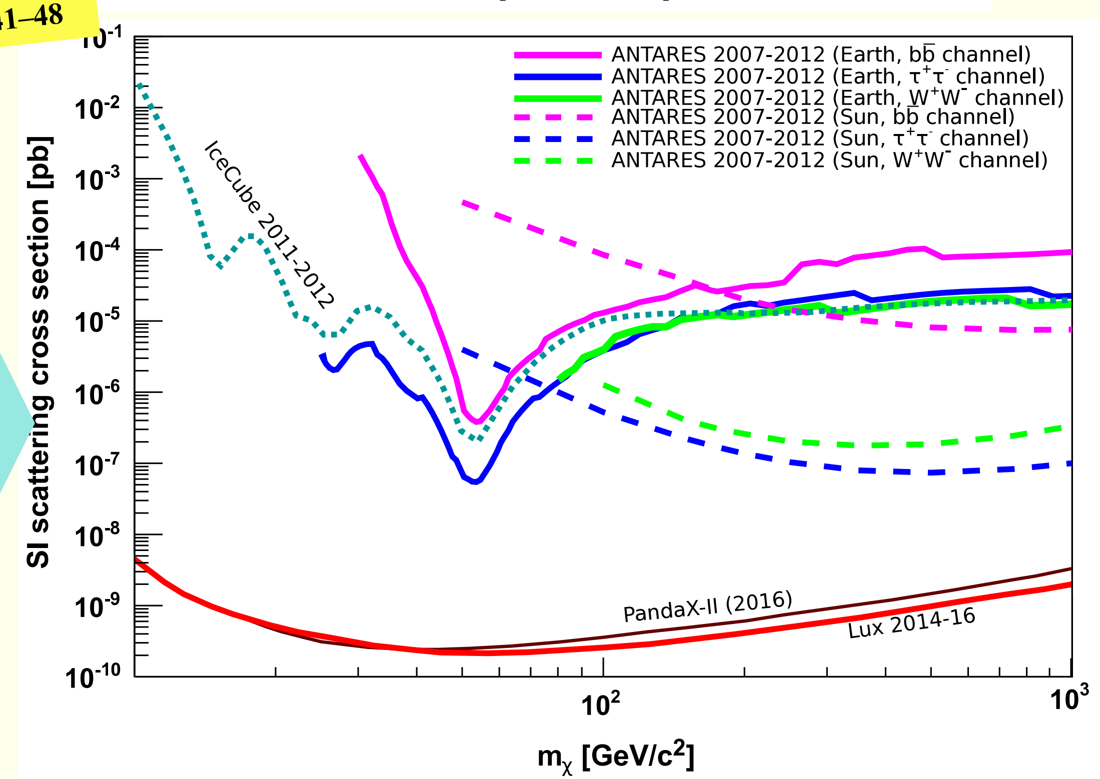
Indirect search for Dark Matter in the Earth





ANTARES, Physics of the Dark Universe 16 (2017) 41–48

90% C.L. upper limits on σ_p^{SI} as a function of the WIMP mass for ANTARES 2007–2012 (Earth) and ANTARES 2007–2012 (Sun), assuming $\langle\sigma_A v\rangle_{Earth} = 3\cdot10^{-26}$ cm^3 s^{-1} and WIMP pair annihilation to 100% into either $\tau^+\tau^-$ (blue), W^+W^- (green) or $b\bar{b}$ (purple).

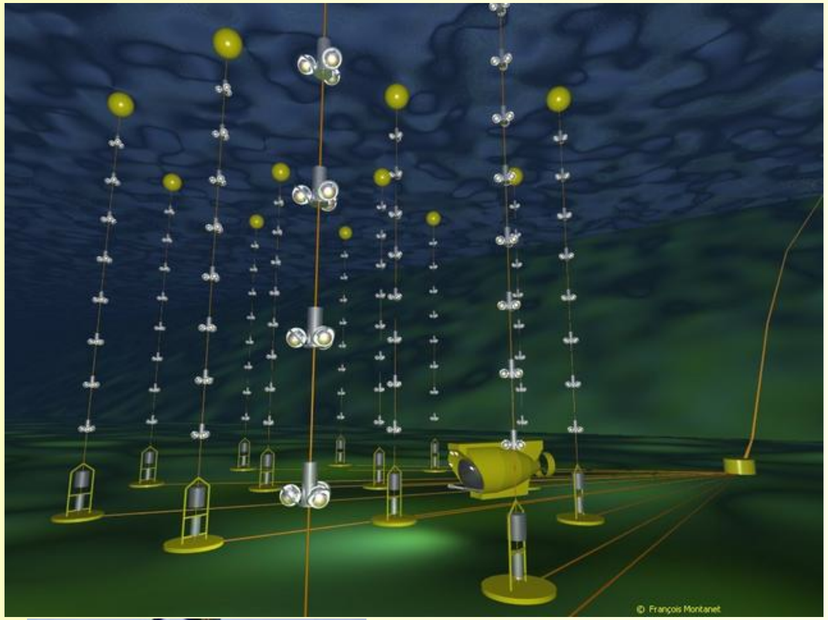


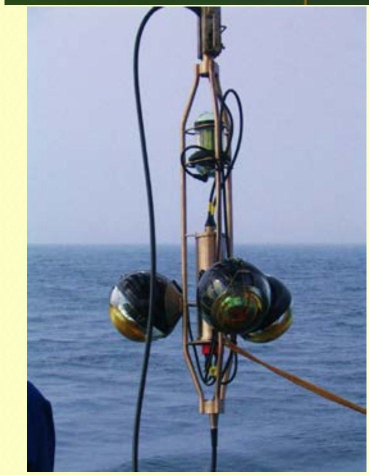
25 Gev/c^2 < M_{WIMP} < 1 Tev/c^2

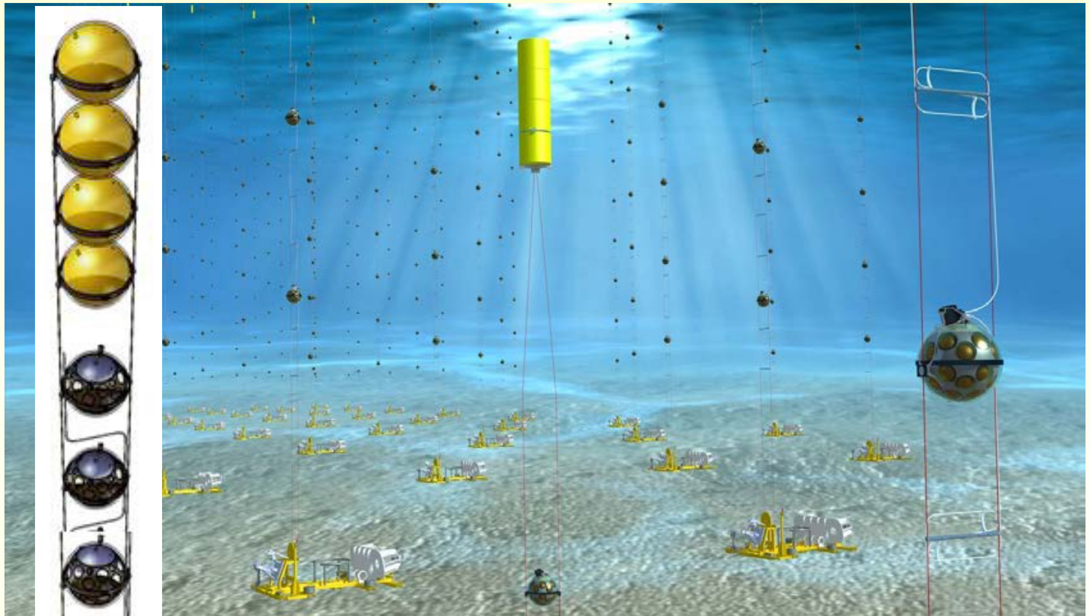
ANTARES → KM3NeT

12 Lines, 885 OM

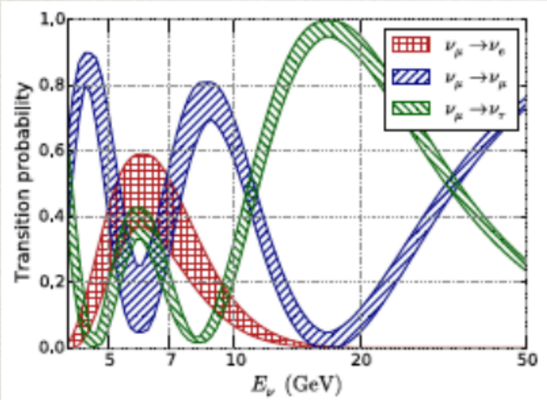
3 Building Blocks on 2 Sites
3*115 lines, ~6210 OMs, ~ 192510 PMTs

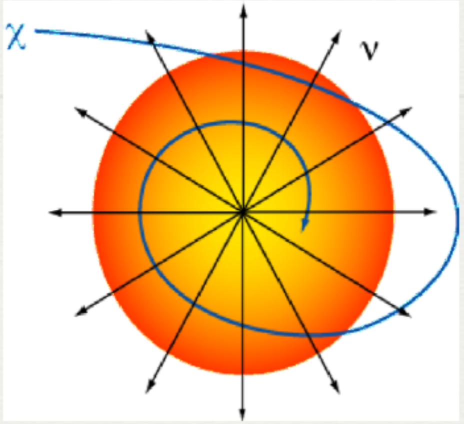


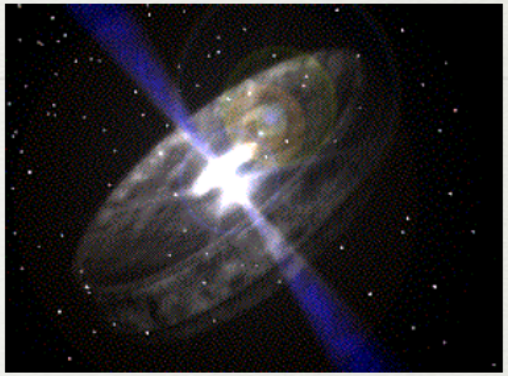




KM3NeT Neutrinoo Telescope science scopes







Low Energy MeV < E! < 100 GeV	Medium Energy 10 GeV < E! < 1 TeV	High Energy E! > 1 TeV

ν Oscillations
ν Mass hierarchy
Supernova

Dark matter search
Monopoles, nuclearites,…

! from extra-terrestrial sources

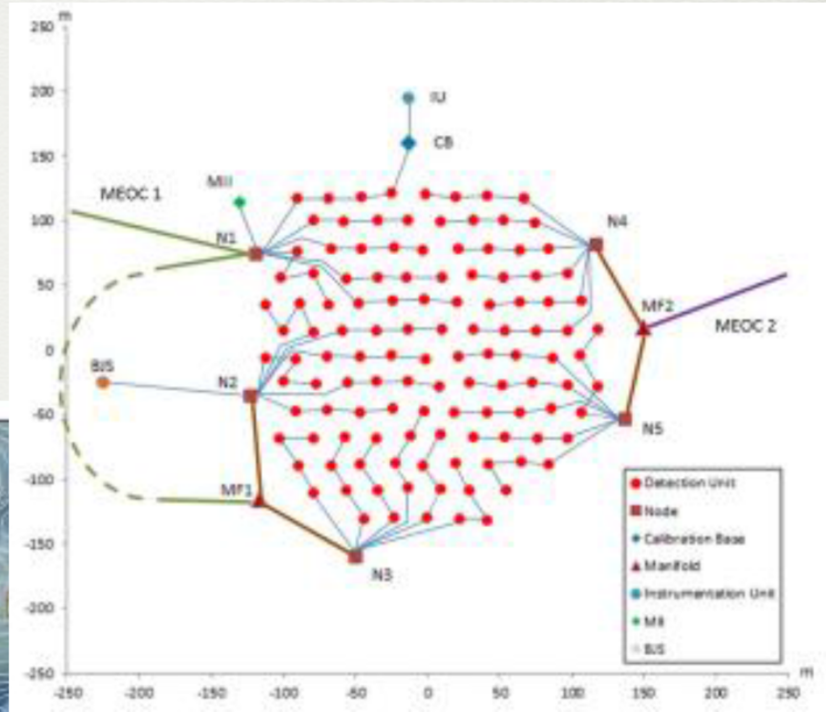
Origin and production mechanism of HE CR

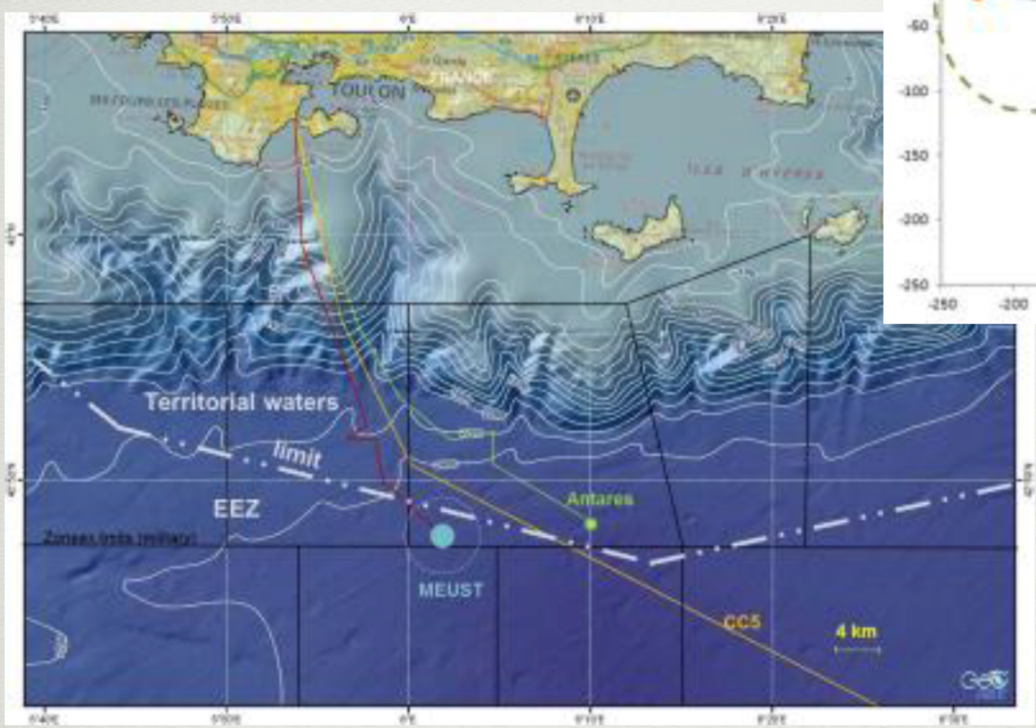
+ oceanography, biology, seismology,…

KM3NeT ORCA

<u>ORCA detector:</u>

- 115 lines
- 20 m horizontal spacing
- 9 m vertical DOM spacing
- 18 DOMs / string
- ~6 Mt instrumented volume



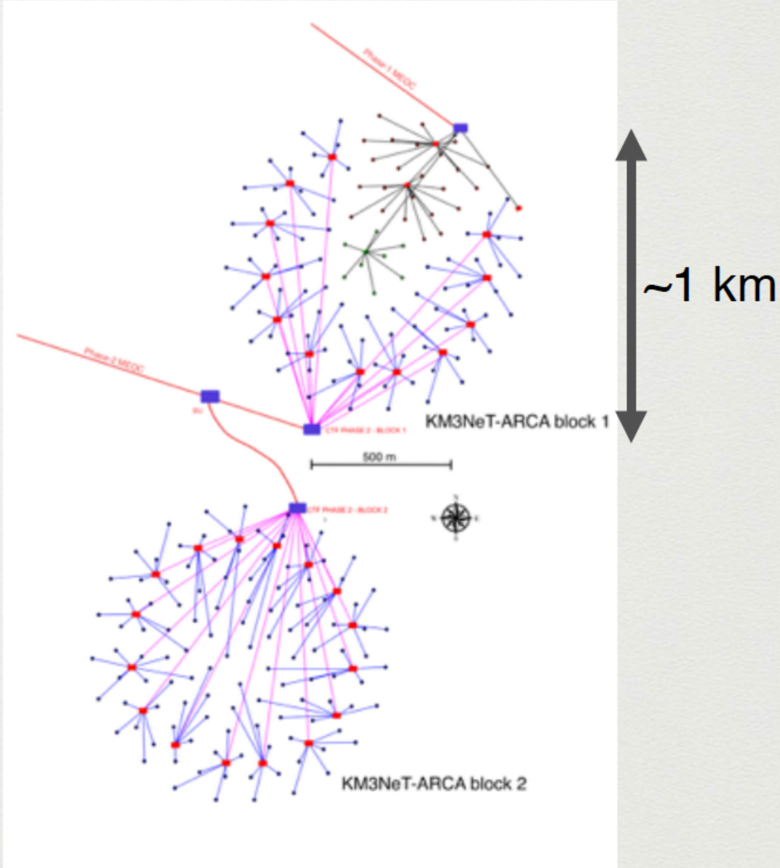


- ➡ Located closed to ANTARES at a depth of ~2475m
- ➡ Shore station La Seyne sur Mer
- ➡ Infrastructure already deployed
- ➡ 2 new ORCA lines will be deployed before summer

KM3NeT ARCA

<u>ARCA detector</u>

- ARCA: 2 blocks
- 115 strings per block
- 90m horizontal spacing
- 36m spacing
- 18 optical modules

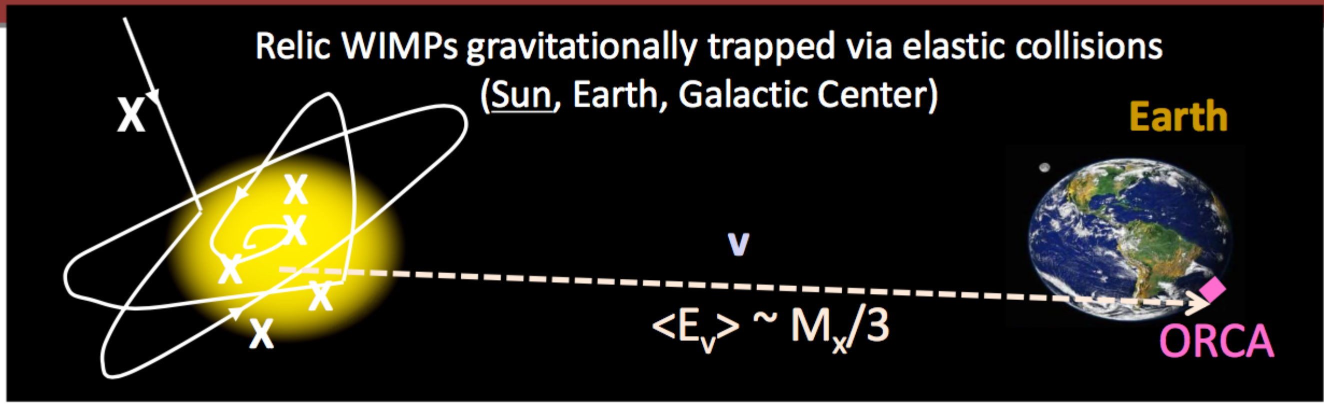


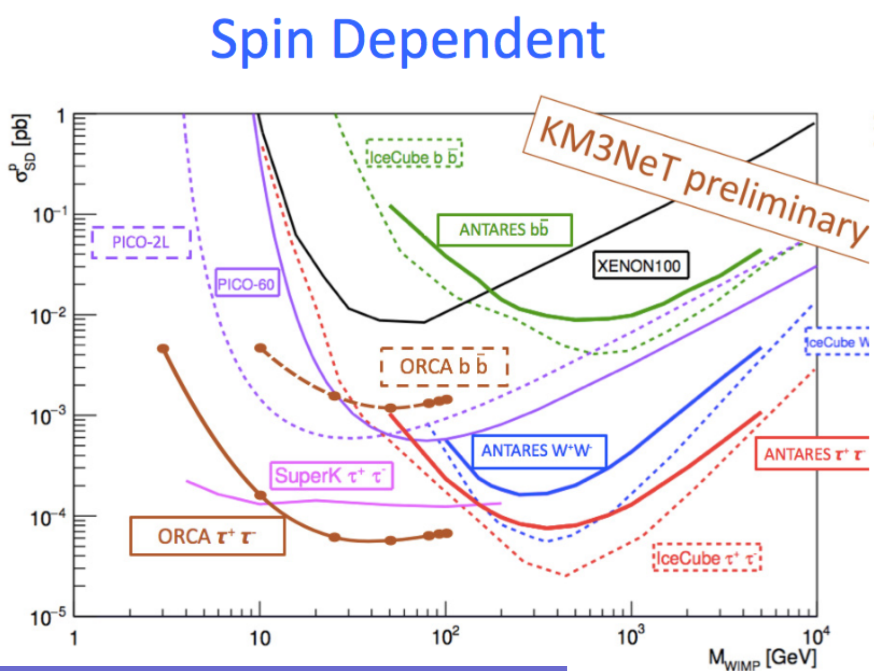
- Total volume: 1.2 km3
- Site: 3.5 km depth
- Shore station:
  Capo Passero (Sicily)

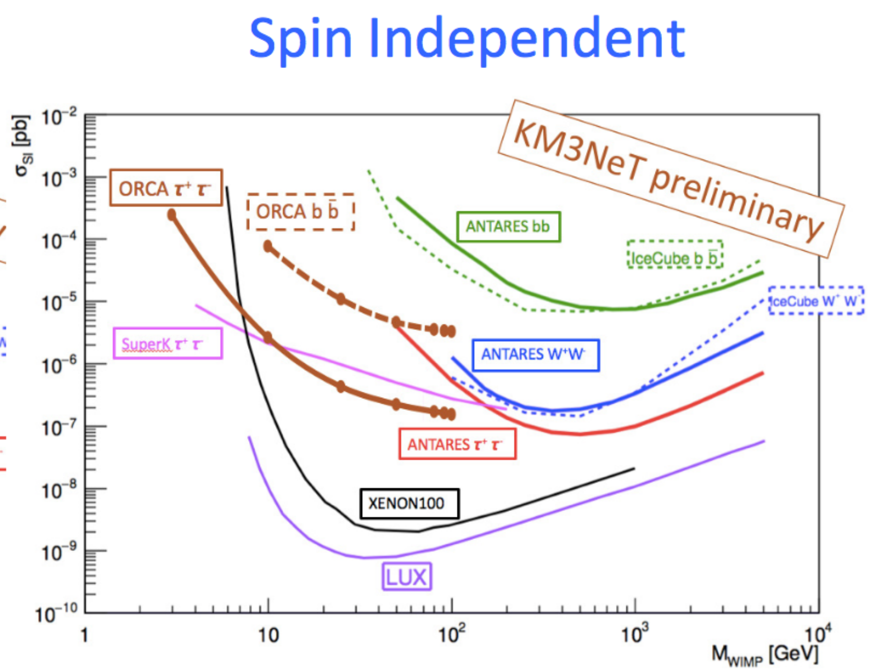
➡ 2 ARCA strings working for more than a year

KM3NeT sensitivities for indirect D.M. searches

Indirect Detection of Dark Matter







from Aart Heijboer talk at NOW 2016

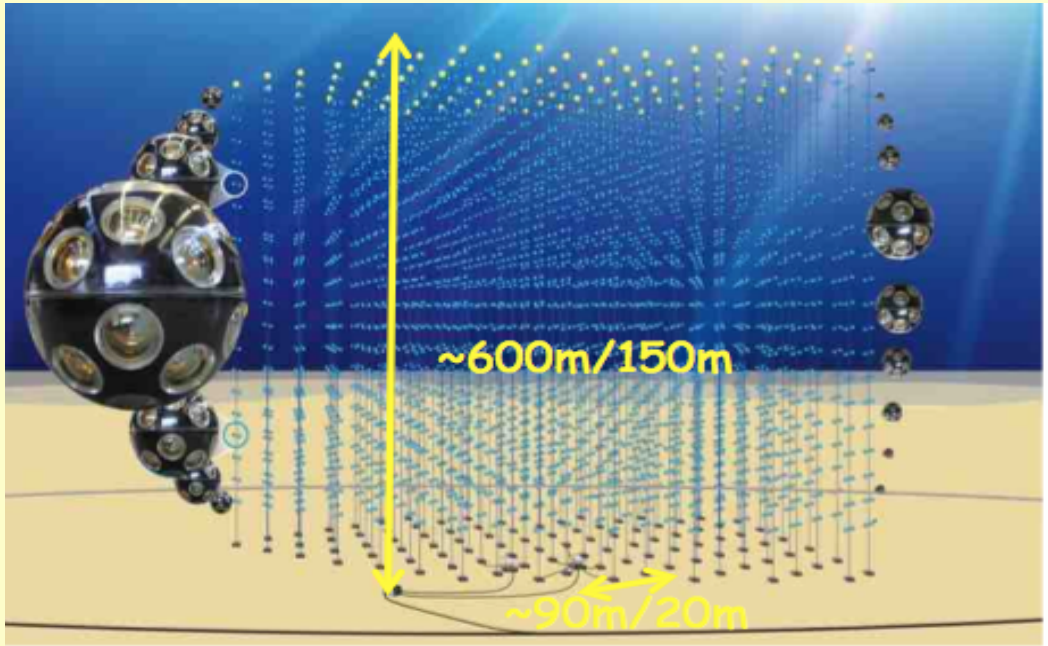
ORCA 3 years - tracks+showers

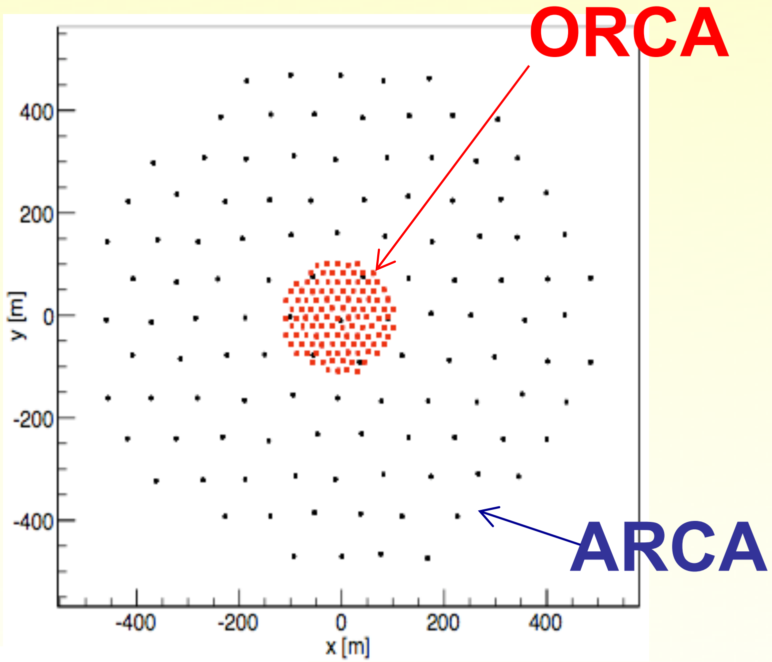
NOW 2016 -- Neutrino mass hierarchy – Aart Heijboer 37

Summary

- Neutrino Telescopes can contribute, via the DM indirect search, to understand the D.M. existence/nature
- ANTARES did not observe so far a signal from D.M. annihiltion and did set limits to:
  - thermally averaged annihilation cross-section ⟨σv⟩
  - spin-dependent and spin-independent WIMP-nucleon scattering cross-section as a function of WIMP mass
- ANTARES will be decommissioned end of 2017, then smooth transition to KM3NeT
- KM3NeT is under construction in Europe (2 sites: South of Italy and South of France).

KM3NeT Building Blocks





	ARCA	ORCA
Location	Italy – Capo Passero	France - Toulon
Detector Lines distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	500Mton	5,7 Mton

KM3NeT phased implementation

Phase	Building Blocks		Number of DUs		Phisics Goals		Status	
	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA
1	0.2	0.06	24	7	Proof of feasibility and first science results. Joined analysis with ANTARES.		Fully funded. First 2 DUs acquiring data in Capo Passero.	
2.0	2	1	230	115	Study of the IceCube signal.	Determination of neutrino mass hyerarchy.	Not yet funded.	Not yet funded.
3	6	1	690	115	All flavour neutrino astronomy.			

L.O.I. KM3NeT ARCA and ORCA:

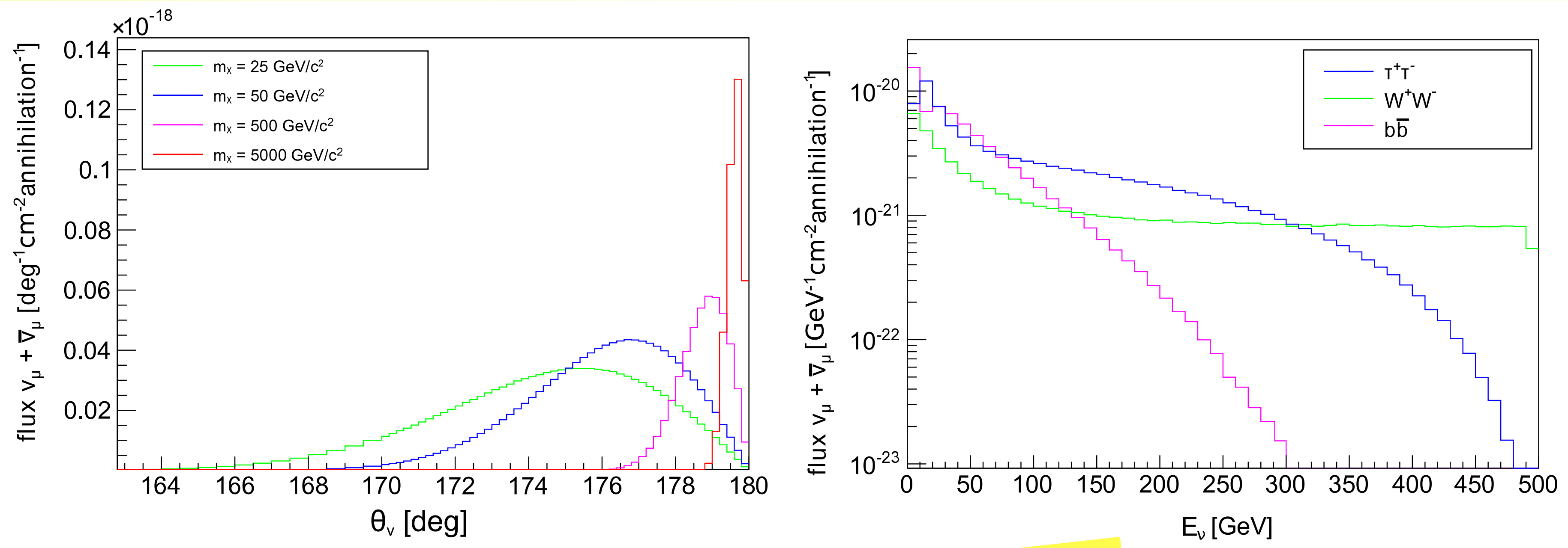
- **J. Phys. G43 (2016) n. 8, 084001**
- **arXiv: 1601.07459**

Indirect search for Dark Matter in the Earth

WIMPS can be gravitationally bound to the Earth if $\upsilon_{WIMP} < \upsilon_{escape}^{Earth}$

$$\upsilon_{escape}^{Earth} \sim 14 \frac{km}{s} \; ; < \upsilon_{WIMP} > \sim 270\ km/s$$

Only a small fraction of WIMPS captured on the Earth.
WIMPS-nuclei collision process described by spin-independent cross section
Iron and Nichel nuclei most abundant in the Earth → most effective capture for $M_{WIMP} \sim 50\ GeV$



ANTARES, Physics of the Dark Universe 16 (2017) 41–48