Indirect search for Dark Matter with the ANTARES Deep Sea Neutrino Telescope

Vincent BERTIN (CPPM-Marseille)
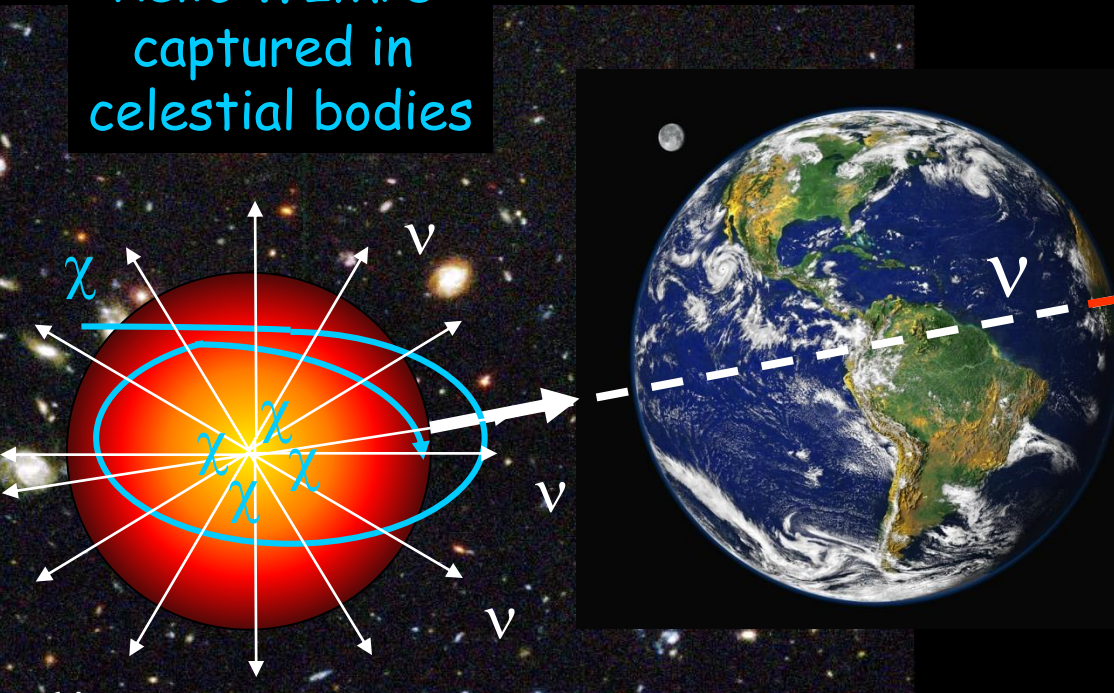
IRN TeraScale meeting @ Marseille – December 2017
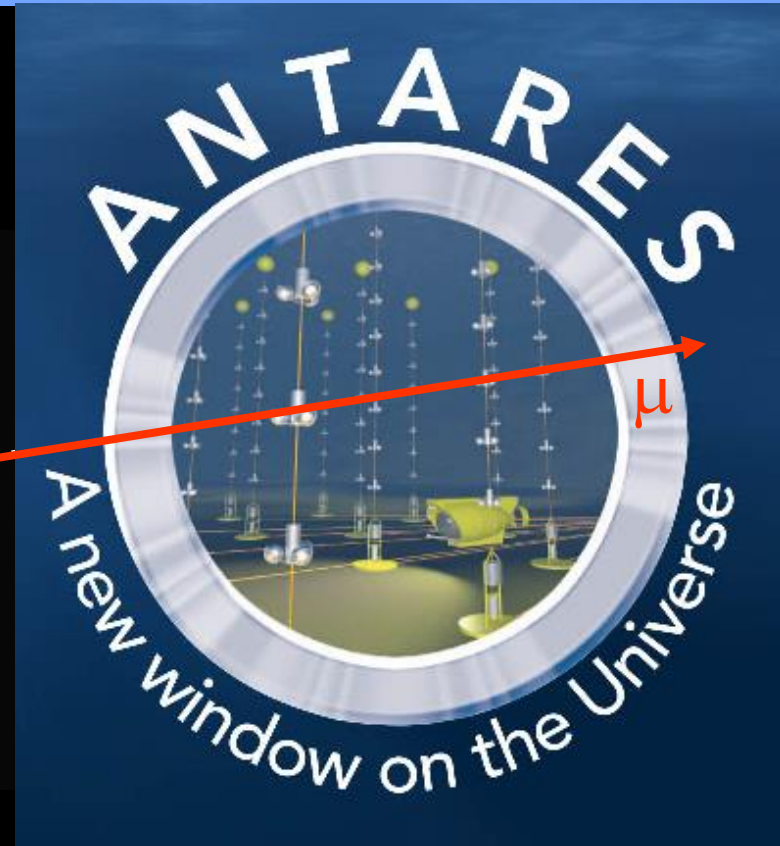
ANTARES

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
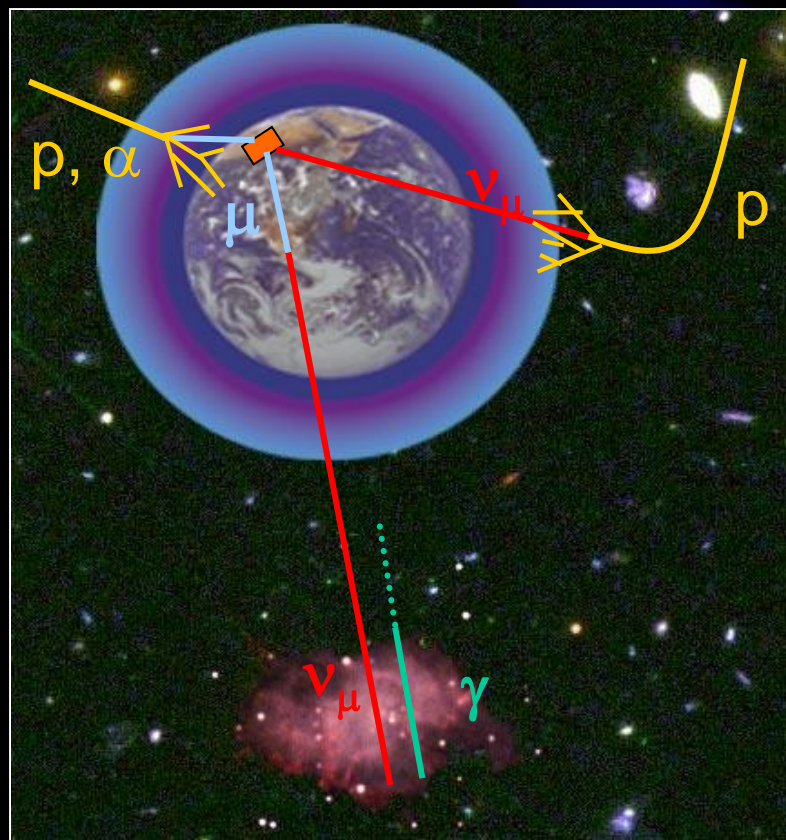CPPM

Relic WIMPs captured in celestial bodies

$\chi\chi$ self-annihilations into
c,b,t quarks, τ leptons or W,Z,H bosons
can produce significant
high-energy neutrinos flux

Potential $\chi\chi \to \nu$ sources are
Sun, Earth & Galactic Centre
Signal less affected by
astrophysical uncertainties
than γ-ray indirect detection

Neutrino telescope: Detection principle

p, α

μ

ν_μ

p

ν_μ
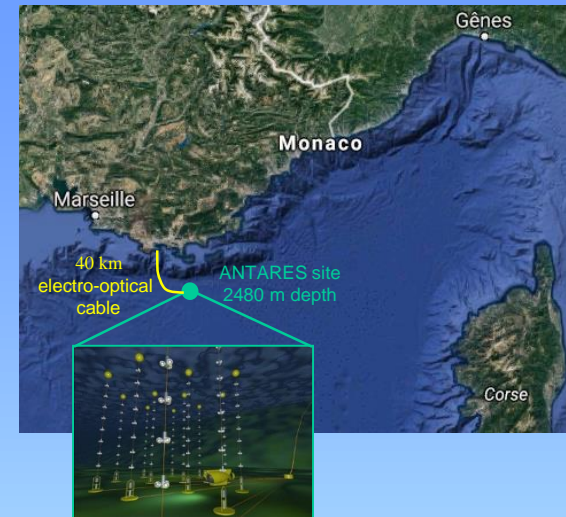
γ

3D PMT array

Cherenkov light from μ

γ

43°

Sea floor

μ

interaction

ν
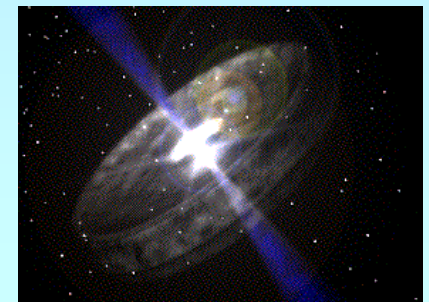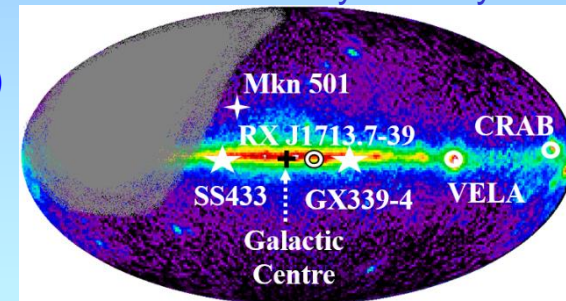
Reconstruction of μ trajectory (~ ν) from timing and position of PMT hits

The ANTARES Neutrino Telescope

➢ **Largest underwater neutrino telescope**
operating for 10 years now (complete in 2008)

➢ 12 line detector with 885 10'' PMTs installed
by 2500 m depth off the coast of Provence (France)

➢ **O(11000) neutrinos detected** with Eν > 10 GeV

➢ **Excellent view of Galactic Centre region**
with high angular resolution (0.3°-0.4° median)
→ **interesting constraint of possible galactic
component** of the IceCube HE signal

➢ **Real time** data processing →generation of alerts (~5s)
for multi-messenger searches

➢ **Science scope of ANTARES:**

• Neutrino astrophysics, search for HE CR origin

• Multi-messenger observations

• **Indirect searches for Dark Matter**

• Atmospheric neutrinos (oscillations, sterile neutrinos)

• Exotic searches (magnetic monopoles, nuclearites)

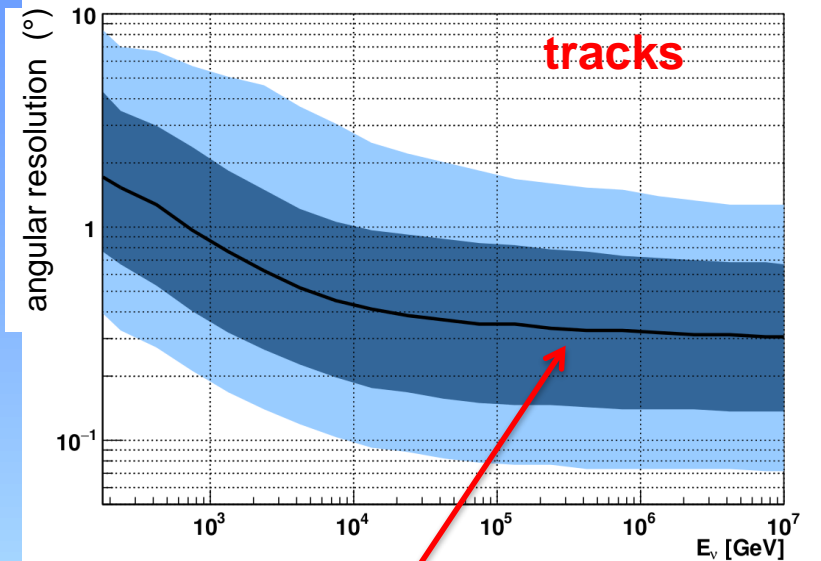• Earth & Sea Sciences, environmental studies

40 km
electro-optical
cable

ANTARES site
2480 m depth

ANTARES sky visibility

Mkn 501
RX J1713.7-39
CRAB
SS433 GX339-4 VELA
Galactic
Centre

- Upgoing **track events** (ν_μCC)

- Angular resolution < 0.4° for E_ν >10 TeV

- Energy resolution : factor 3

- 90% purity of neutrinos

- Large detection volume from μ range
  →ideal for neutrino astronomy
  →but large atmospheric μ bkg

tracks

Median angular resolution vs Eν

- Upgoing **cascade events** (ν_e/ν_τ CC, NC)

- Angular resolution < 3°

- Energy resolution for ν_eCC < 10%

- Contained events (small detection volume)
  →almost no atmospheric bkg
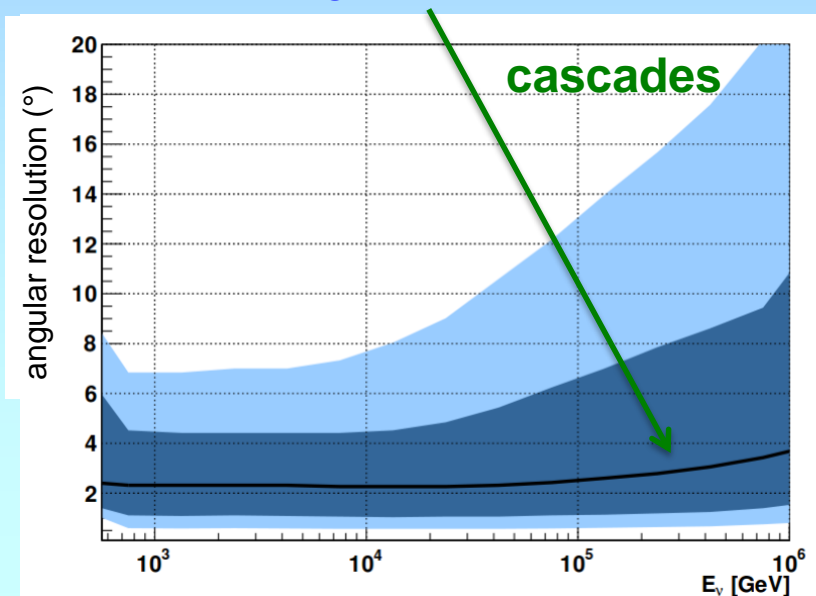
cascades

- **Detector** building started in 2006, completed in May 2008
- **Analysis** based on data collected between 2007 and 2012
  → **> 7000 upgoing neutrino** candidates (in **~1321 effective days**)

- **Reconstruction strategies:**
  - BBFit (χ^2 based) → optimal for low energies/masses (<250 GeV)
    - **Single line events** : reconstruction of **zenith angle only** → very low energies
    - **Multiline events**: reconstruction of **zenith & azimuth angles**
  - AAFit (likelihood based) → high energies/masses (>250 GeV)
    - **lambda** (**quality parameter**, basically the likelihood value)
    - **beta**: **angular error** estimation

- **Selection parameters:**
  - **tchi2**: $\sim\chi^2$ (BBFit)
  - **lambda**: Quality reconstruction parameter ~ likelihood (AAFit)
  - **beta**: angular error estimate (AAFit)
  - **Cone opening angle** around the Sun (or **zenith band** for single line events)

➢ Selection of neutrinos and rejection of atmospheric muons by selecting up-going tracks and cutting on track fit quality
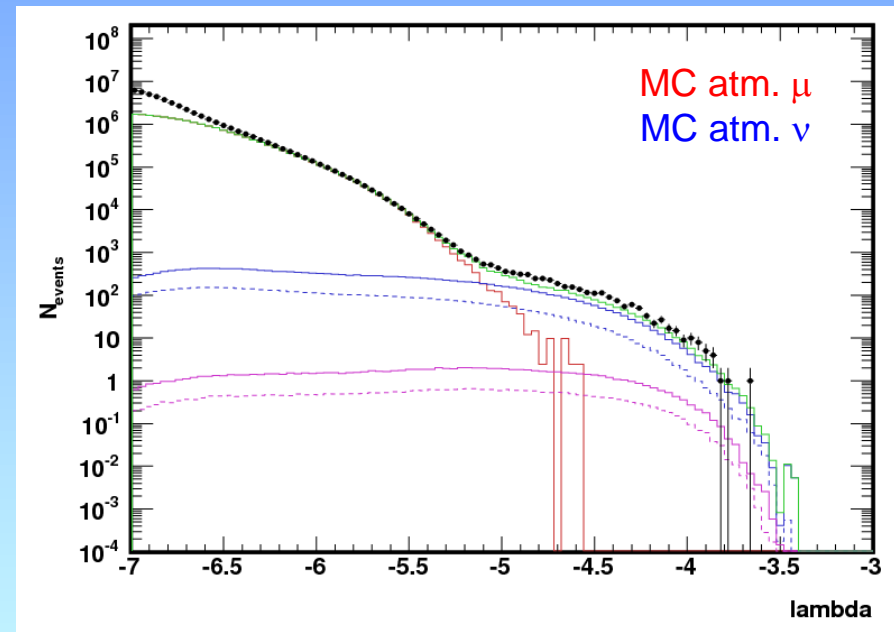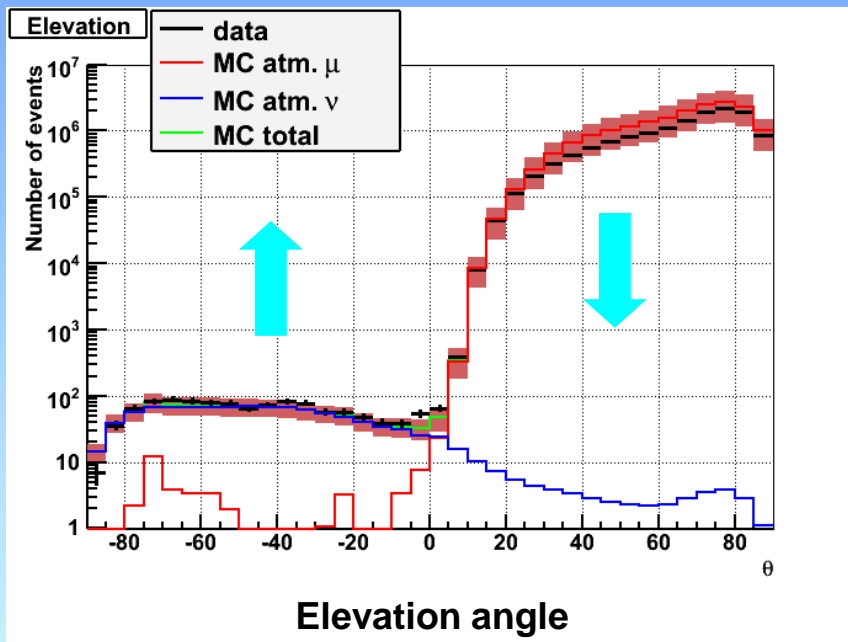
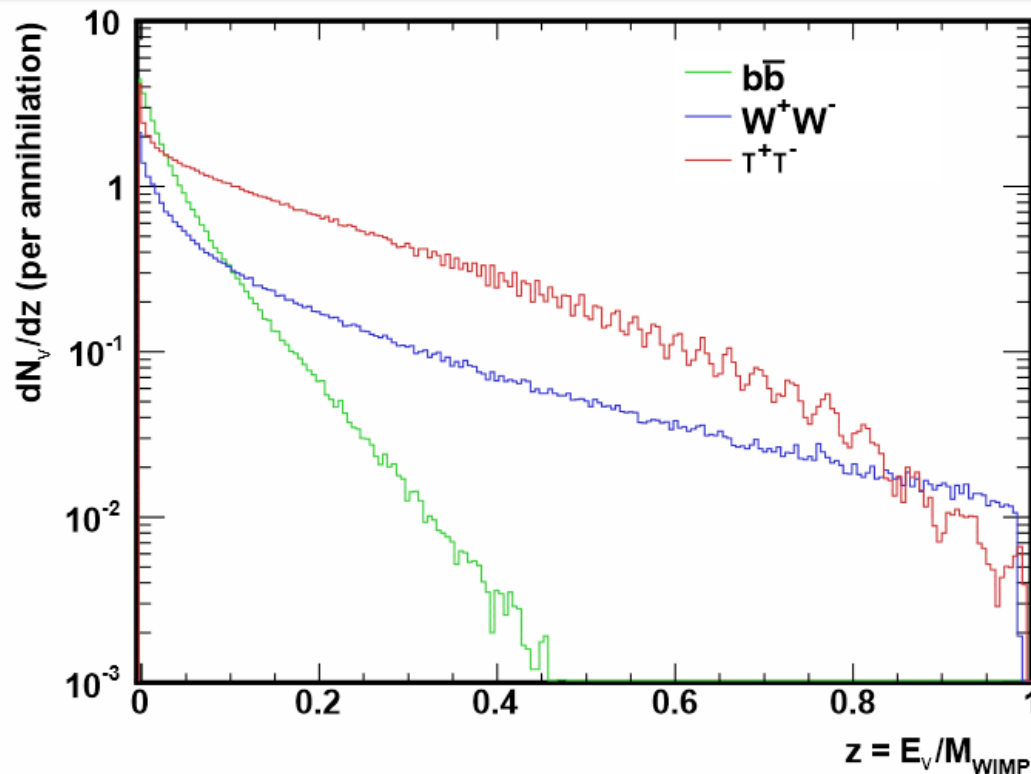➢ Rejection of atmospheric neutrinos by looking into a cone towards the Sun direction (or zenith band for single line events)

➢ Remaining **background** estimated from **scrambled data**

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- WIMPSIM package (Blennow, Edsjö, Ohlsson, 03/2008) used to generate events in the Sun in a **model independent way**

- Annihilations into b quarks (soft spectrum) and τ leptons, WW/ZZ bosons (hard spectrum) **used as benchmarks**

- Take into account ν **interactions** in the Sun medium, **regeneration of** ν_τ in the Sun and ν **oscillations**

- **Maximisation of the Likelihood function based on Signal and Background PDFs :**

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

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

- **Signal PDF determined from MC simulation based on WIMPSIM spectra**
- **Background PDF determined from real data sample with event time scrambling**

Observed events in the Sun direction
vs. background in 2007-2012 data sample
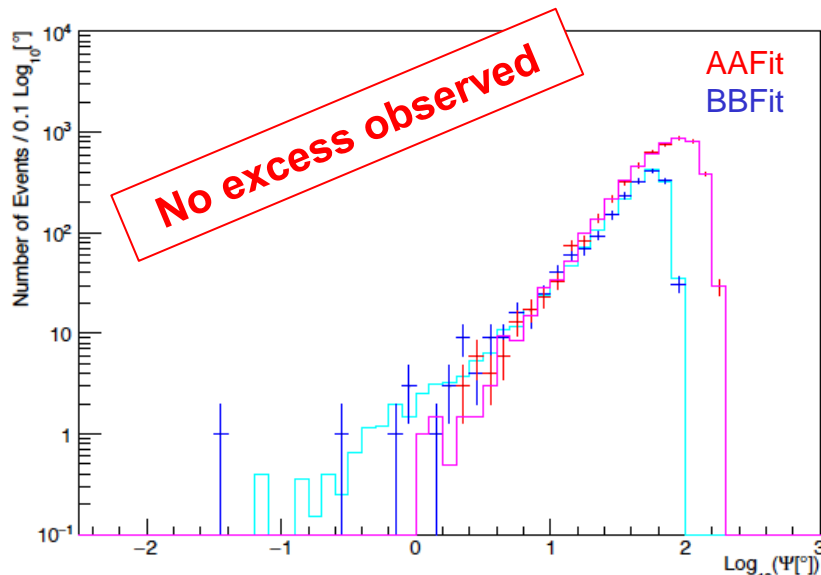
Limit on the neutrino flux coming from the Sun
assuming 100% branching ratio of WIMP annihilation into benchmark channel

Phys.Lett. B 759 (2016) 69
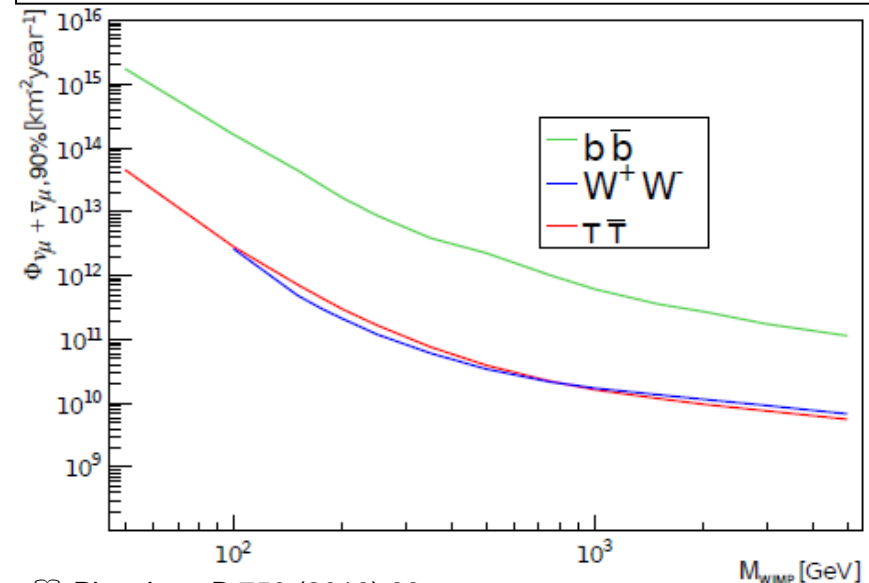
Conversion to **limits on WIMP-nucleon Spin (In)dependent cross sections** assuming :
- Equilibrium between capture and annihilation rates inside the Sun
- Local WIMP density = 0.4 GeV/cm3
- Maxwellian velocity distribution of WIMPs with r.m.s. = 270 km/s
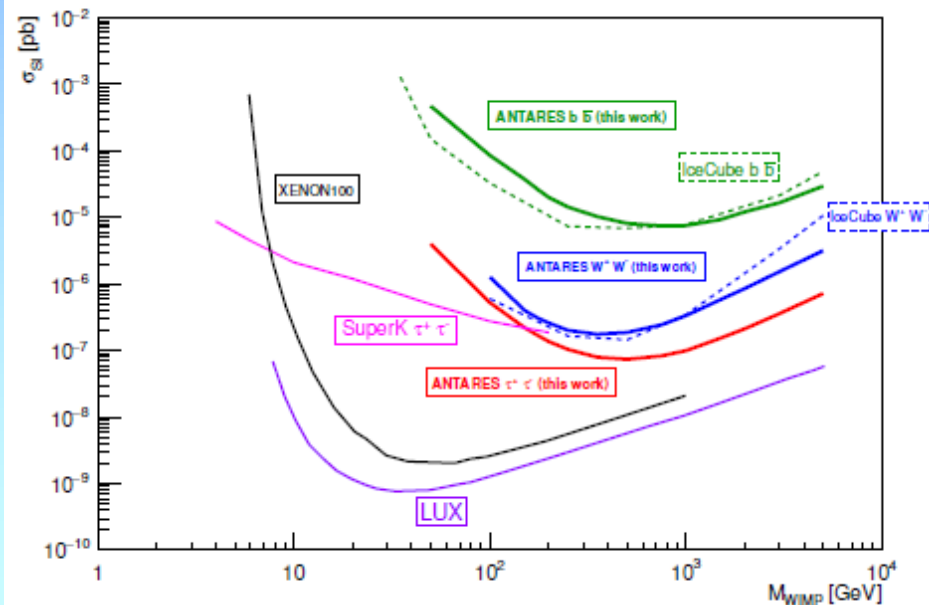 → **Determination of astrophysical uncertainties on WIMP capture in the Sun :**
  PhD work in progress by A. Nuñez with E. Nezri, J. Lavalle & VB

ANTARES 2007-2012 data 📖 Phys.Lett. B 759 (2016) 69

Limit on WIMP-nucleon SD cross-section
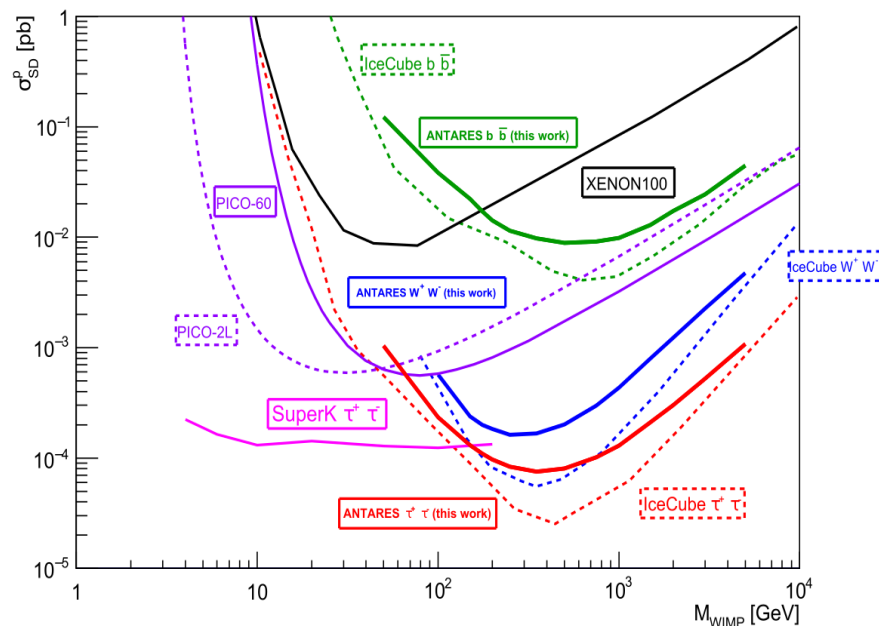
Limit on WIMP-nucleon SI cross-section

→ **much better sensitivity of neutrino telescopes on SD cross-section**
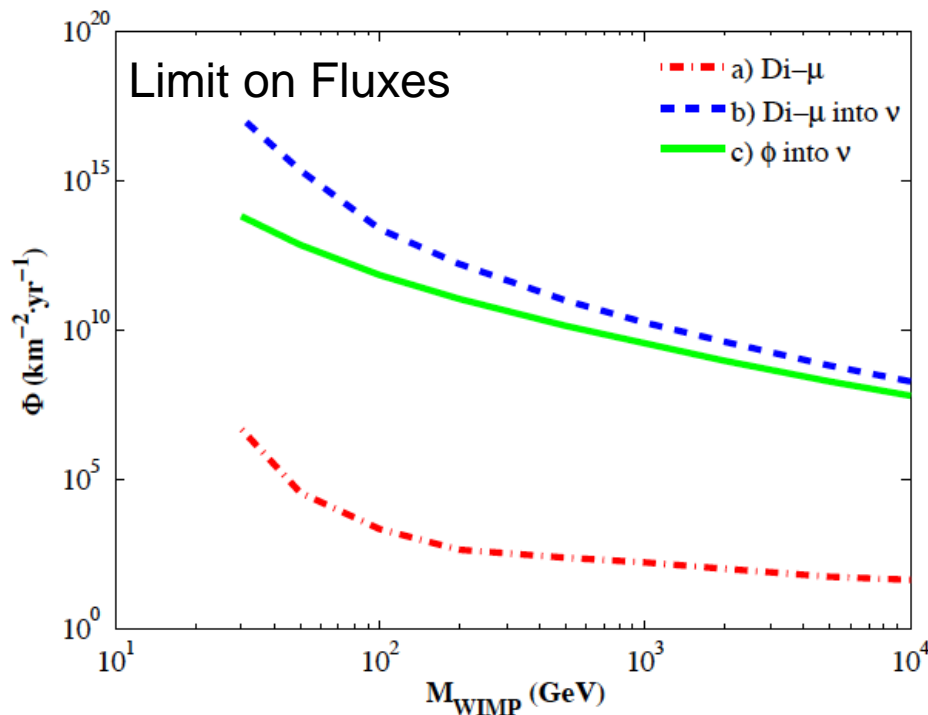w.r.t. direct detection due to efficient capture on Hydrogene inside the Sun

- Annihilation of DM into **unstable mediator Φ**
- Observable : dimuons or "standard" neutrino events
- Limits derived from the analysis of the ANTARES 2007-2012 data
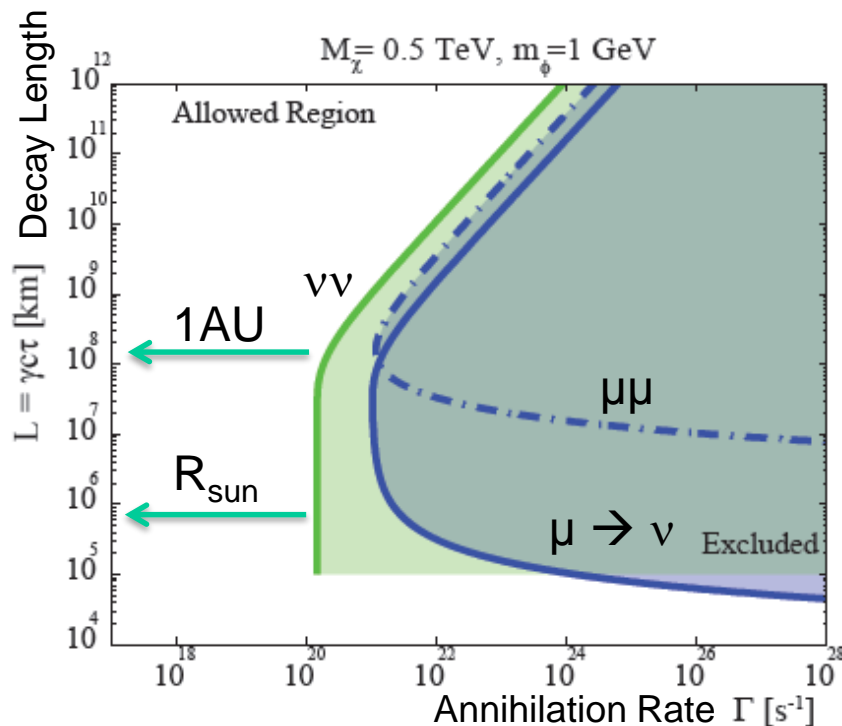
📖 JCAP 05 (2016) 016

Limit on Fluxes
- a) Di−μ
- b) Di−μ into ν
- c) φ into ν
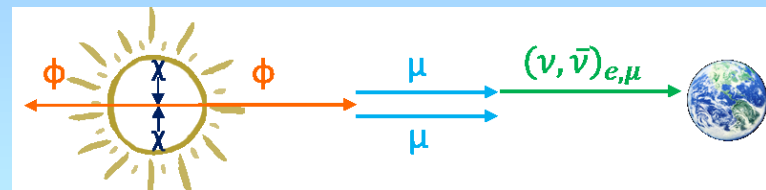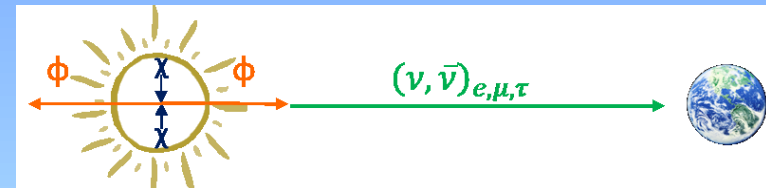
Testing models from:
- Meade et al., JHEP06 (2010) 29
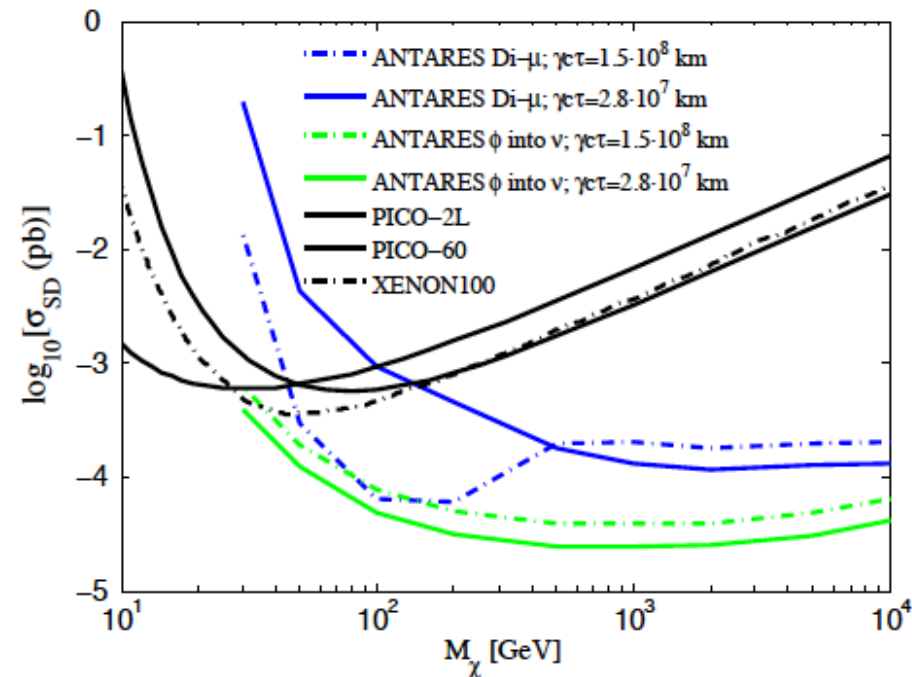- Bell and Petraki, JCAP04 (2011) 003

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- Limits as function of annihilation rate and decay length
- Best sensitivity for $\nu\nu$ channel and decay length at distance Earth - Sun

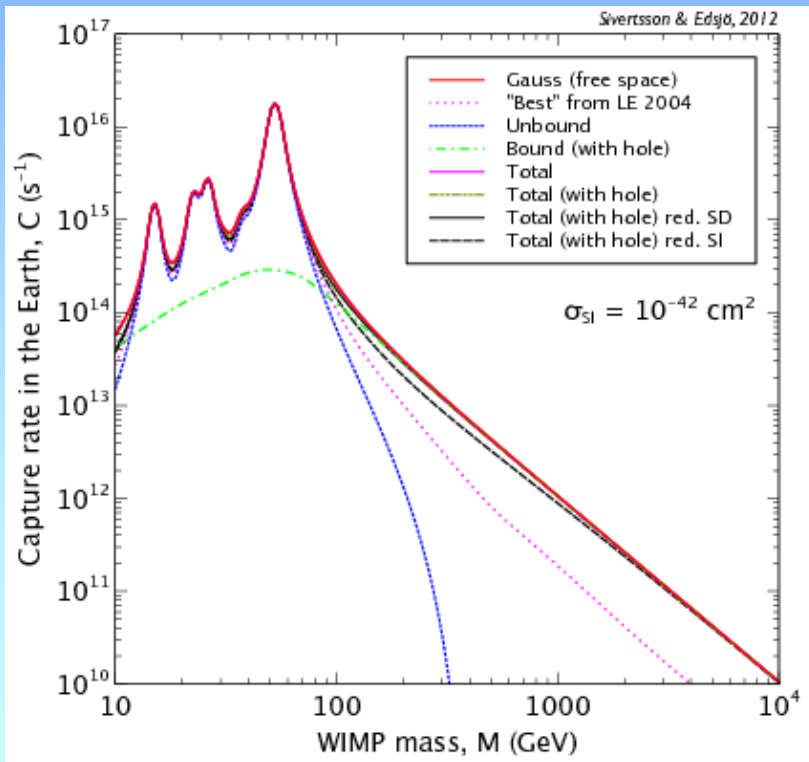

Limit on WIMP-nucleon SD cross-section

📖 JCAP 05 (2016) 016

- **First constraint to these models from neutrino telescopes**
- Limits on WIMPs scattering cross-section for unstable but sufficiently long-lived mediators
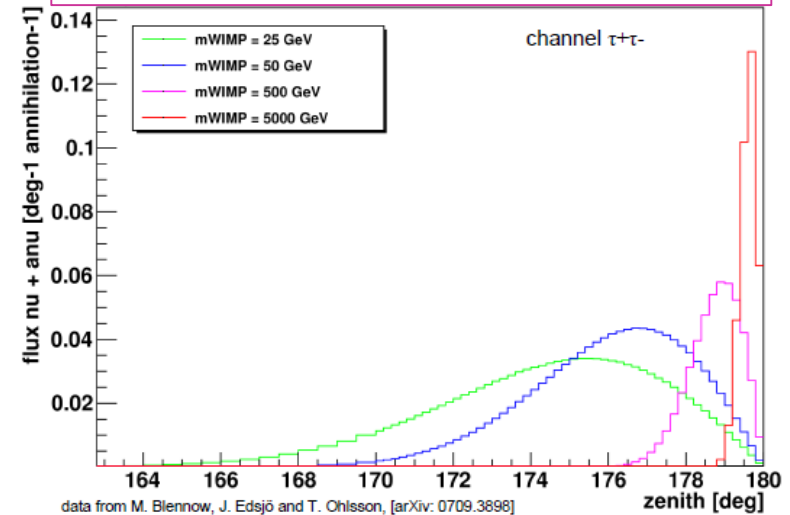
Capture rate of WIMPs in the Earth
dominated by SI cross-section
Resonnant enhancement
on dominant nuclei (Fe, Ni, Si,…)

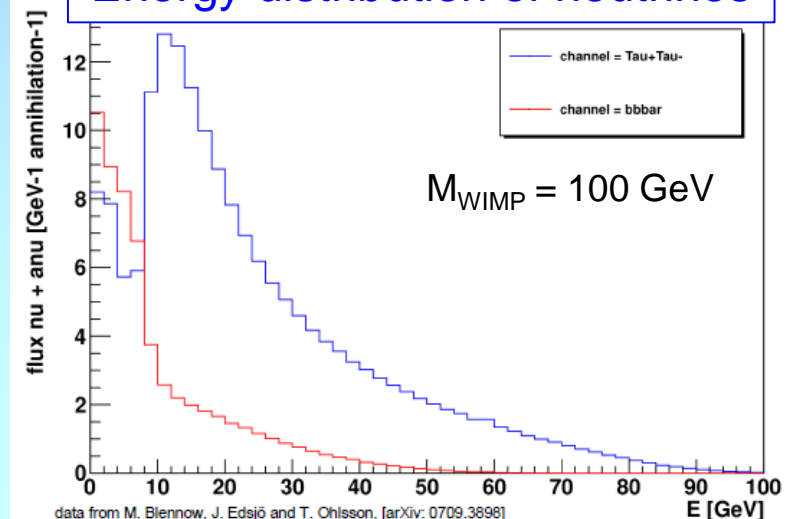Angular distribution of neutrinos

Energy distribution of neutrinos

$M_{WIMP} = 100$ GeV

from M. Blennow, J. Edsjo and T. Ohlsson, arXiv:0709.389

- Search for vertical neutrino events in 2007-2012 ANTARES data → no excess

- Dark Matter density usually not at equilibrium due to low capture rates by the Earth
  → Assume **annihilation rate** $<\sigma v> = 3 \times 10^{-26}$ cm^3 s^{-1} (natural scale)

Limit on WIMP-nucleon SI cross-section assuming 100% BR of annihilation into benchmark channel

Upper limit on WIMP-nucleon SI cross-section assuming 100% BR of annihilation into benchmark channel for WIMP mass = 52.5 GeV (Fe resonnance)
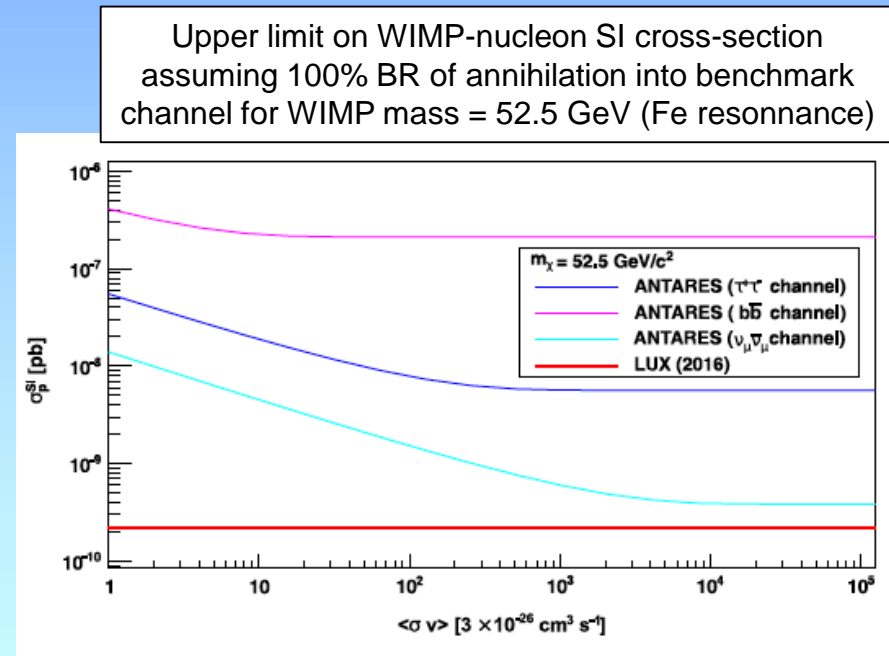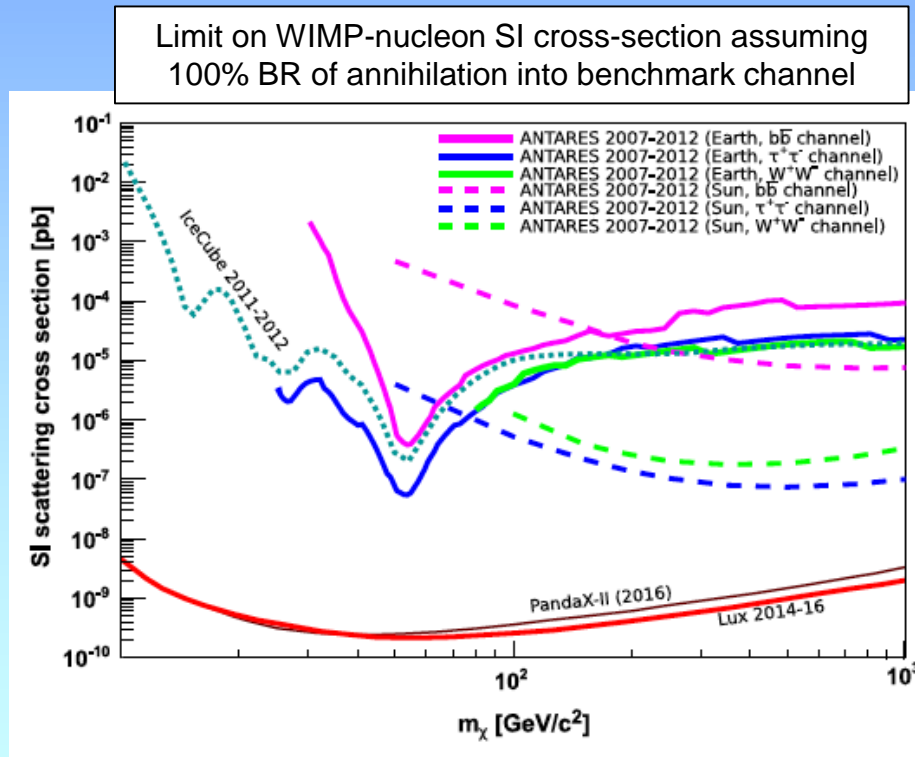
Scenario with boosted annihilation cross-section

📖 Physics of the Dark Universe 16 (2017) 41
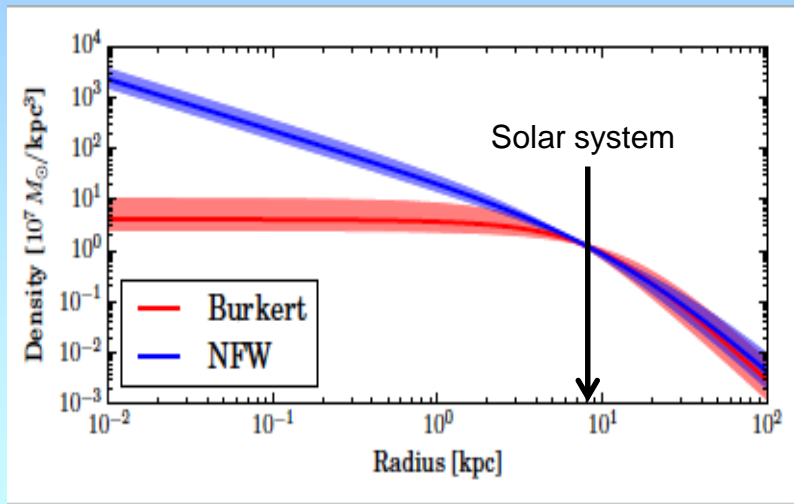
Galactic Halo

WIMPs

ν_e, ν_μ, ν_τ

ν oscillations in the vacuum

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

Extended source strongly dependent on the galactic halo model

Solar system

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

— NFW
— Burkert
— McMillan

Calculation with CLUMPY package
A. Charbonnier et al., Comput. Phys. Commun. 183 (2012) 656

3 benchmark halo model considered :
- Navarro, Frenk, White, ApJ 490 (1997) 493
- A. Burkert, ApJ 447 , L25 (1995)
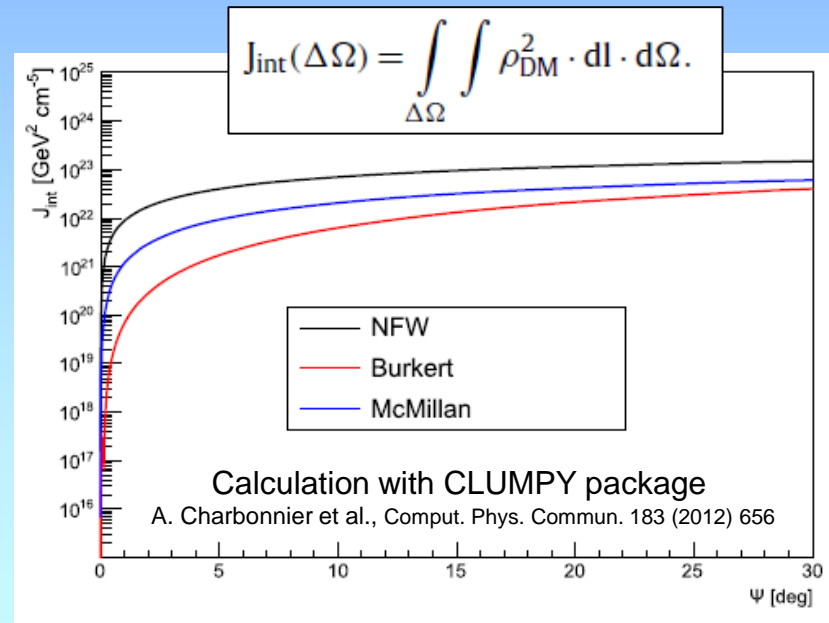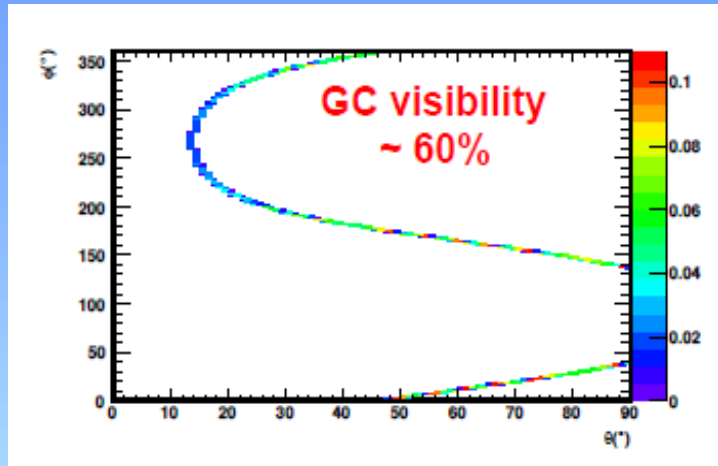- P.J. McMillan, Mon. Not. R. Astron. Soc. 414 (2015) 2446

Table of dark matter halo parameters for the Milky Way as taken from [10] and [11]. ρ_{local} is the local density and r_s is the scaling radius.

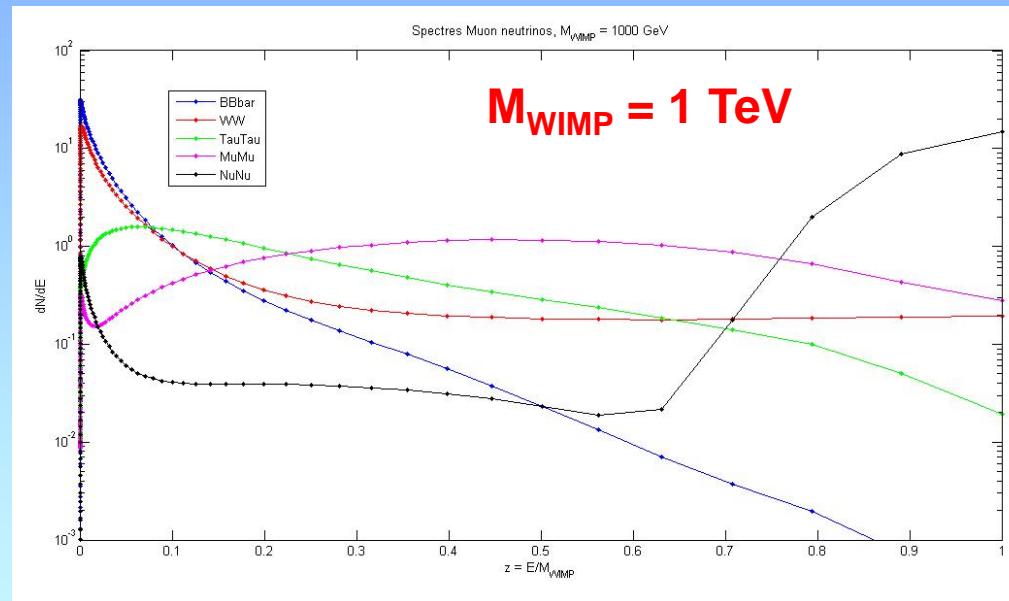| Parameter	NFW	Burkert	McMillan
r_s [kpc]	$16.1^{+17.0}_{-7.8}$	$9.26^{+5.6}_{-4.2}$	17.6 ± 7.5
ρ_{local} [GeV/cm^3]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034

ANTARES **visibility** of the GC

GC visibility ~ 60%

Observed events in the GC direction
vs. background in 2007-2015 data sample
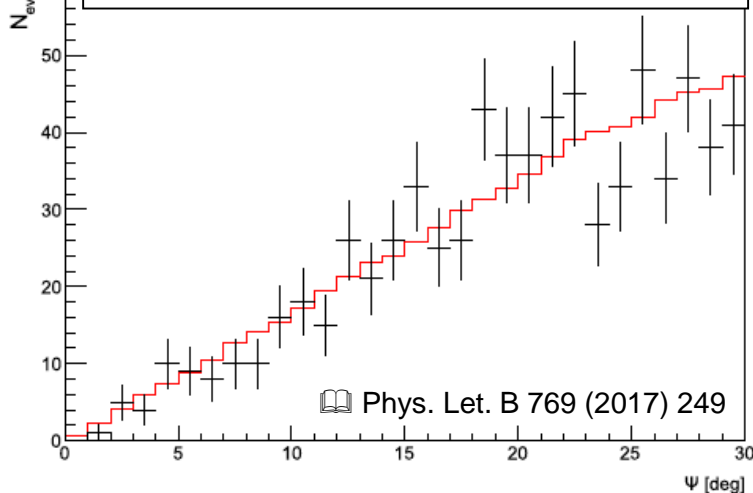

📖 Phys. Let. B 769 (2017) 249

Spectra from WIMP annihilations
in vacuum including EW corrections
for 5 main benchmark channels
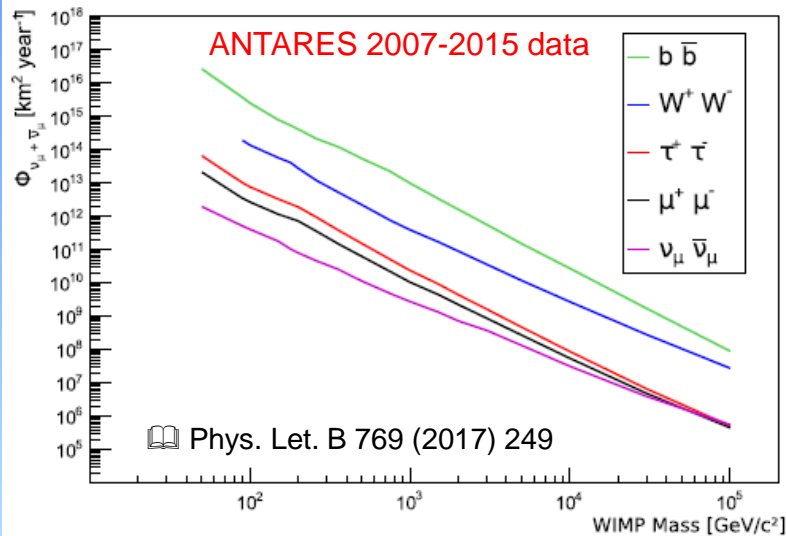from M. Cirelli et al., JCAP 1103 (2011) 051
(www.marcocirelli.net/PPPC4DMID.html)

M_{WIMP} = 1 TeV

- 9 years (2007-2015) of data analysed
- GC considered as extended source
- No excess over background found

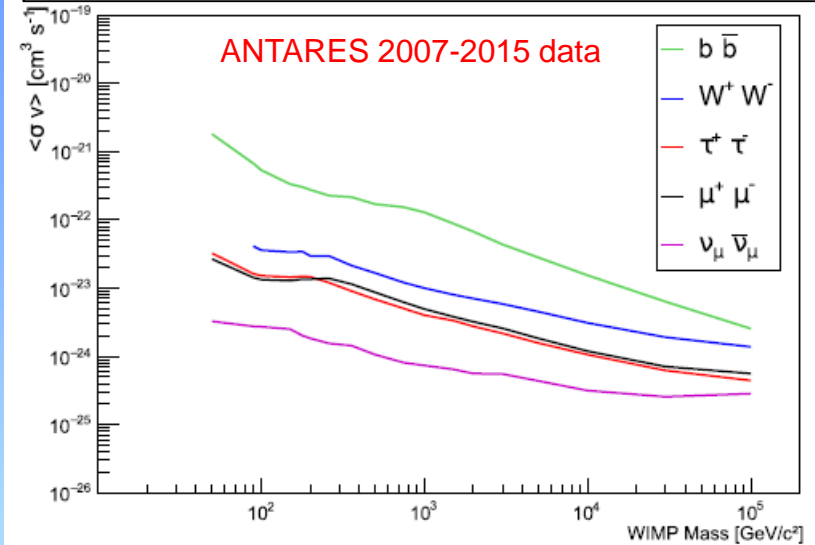Limit on neutrino flux from DM annihilation assuming 100% BR of annihilation into benchmark channel

ANTARES 2007-2015 data

Phys. Let. B 769 (2017) 249

Limit on WIMP annihilation cross-section assuming 100% BR of annihilation into benchmark channel
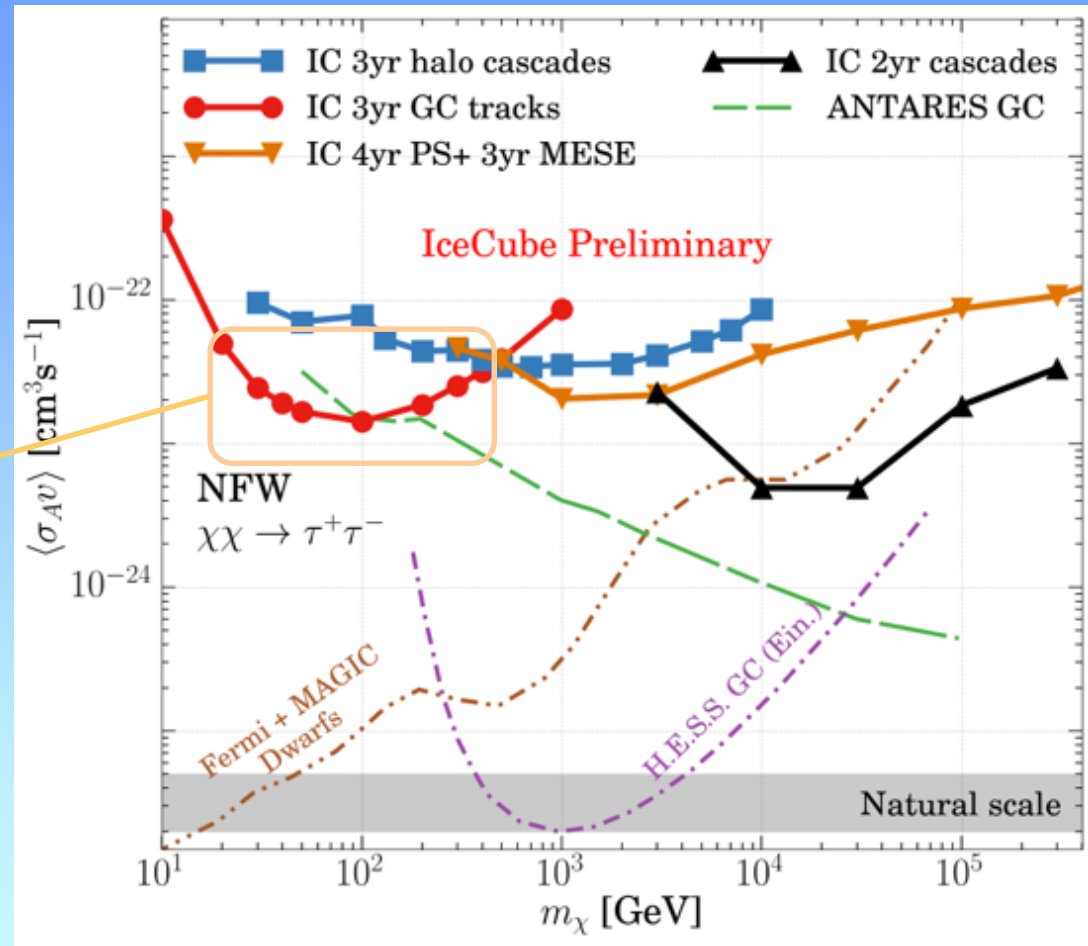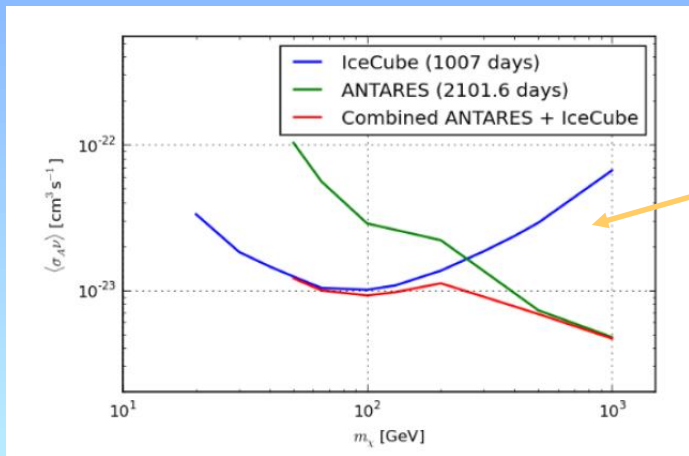

ANTARES 2007-2015 data

Limit on WIMP annihilation cross-section as function of galactic halo model

ANTARES 2007-2015 data
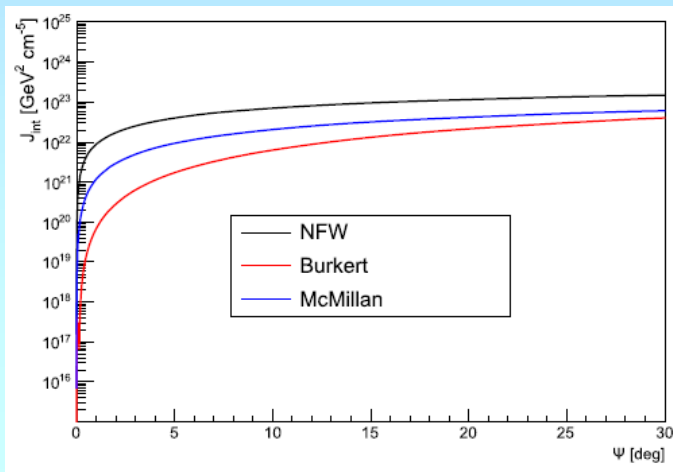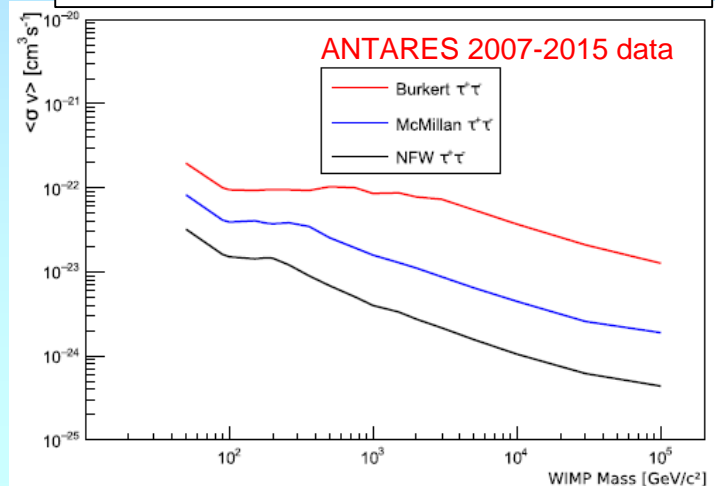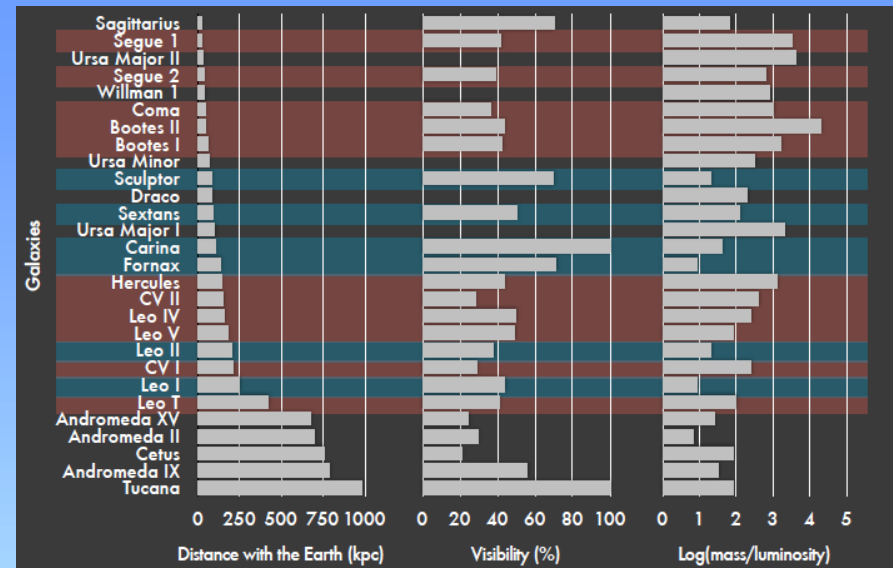
Combination of ANTARES + IceCube under progress
→ **Improvement expected for WIMP masses ~ 100-500 GeV**

ANTARES gives the best limit in neutrinos above 100 GeV
→**Very competitive limit for WIMP masses > 10 TeV**

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Search for DM towards **Dwarf Galaxies**

ANTARES 2007-2012 data

Best limit obtained for stacking analysis of Segue1 + Fornax + Sculptor

→ **Not competitive limit wrt GC**

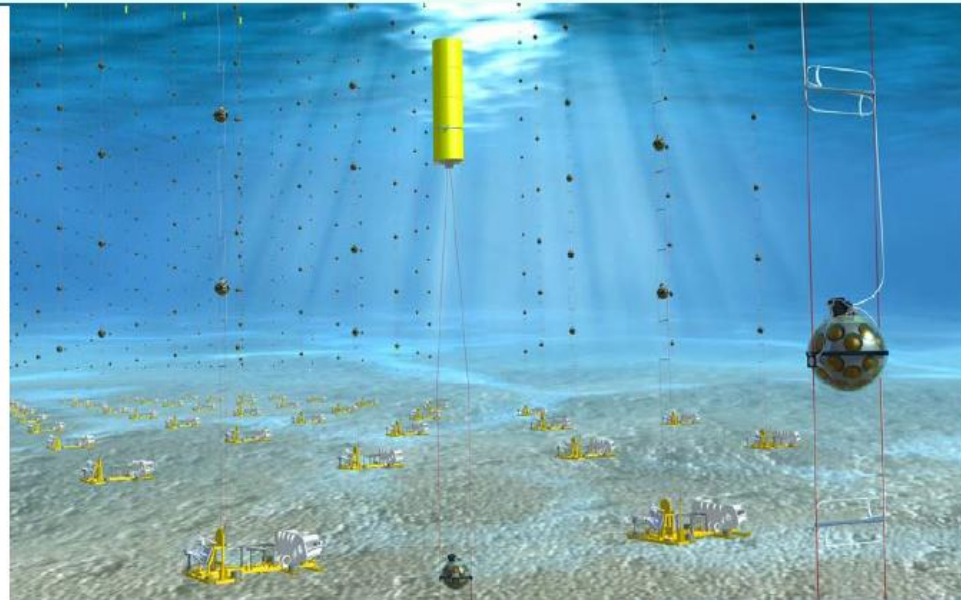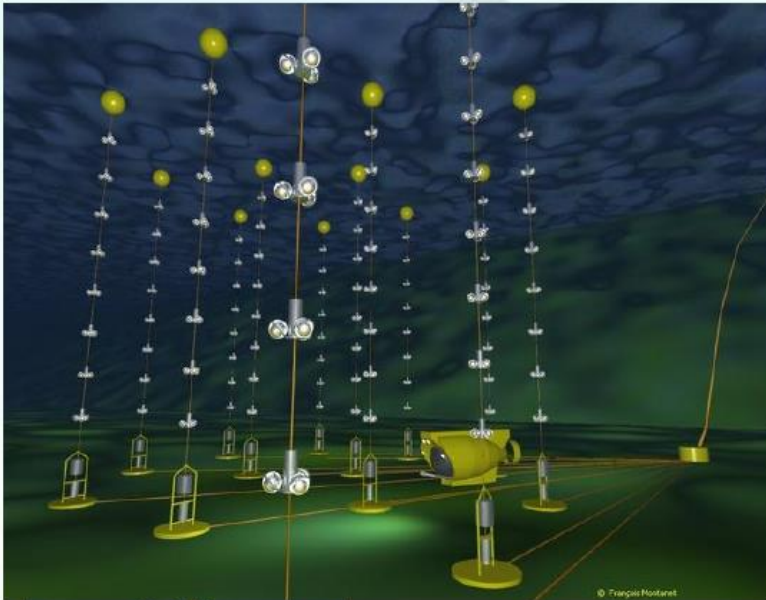# The future of Neutrino Astronomy in the Mediterranean Sea

ANTARES ➜ KM3NeT

12 Lines, 885 OM

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

Basic active element:
Digital Optical Module
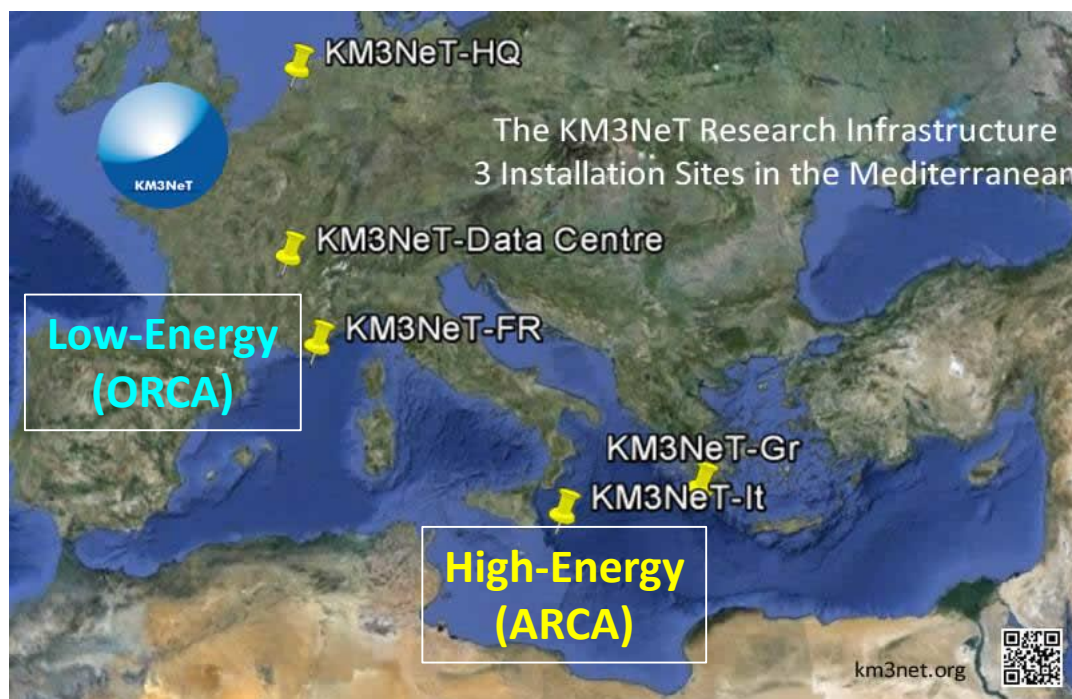**31 x 3" PMTs** ➜

← **18 OMs/line**

KM3NeT

KM3NeT is a distributed research infrastructure with 3 main science topics:

- The origin of cosmic neutrinos (high energy)

- Measurement of fundamental neutrino properties (low energy)

- Deep Sea Observatory - Oceanography, bioacoustics, bioluminescence, seismology
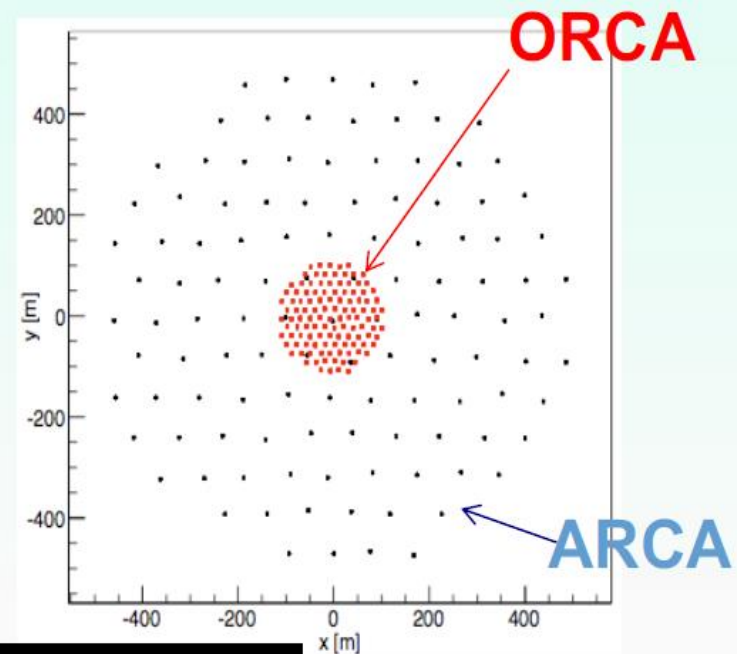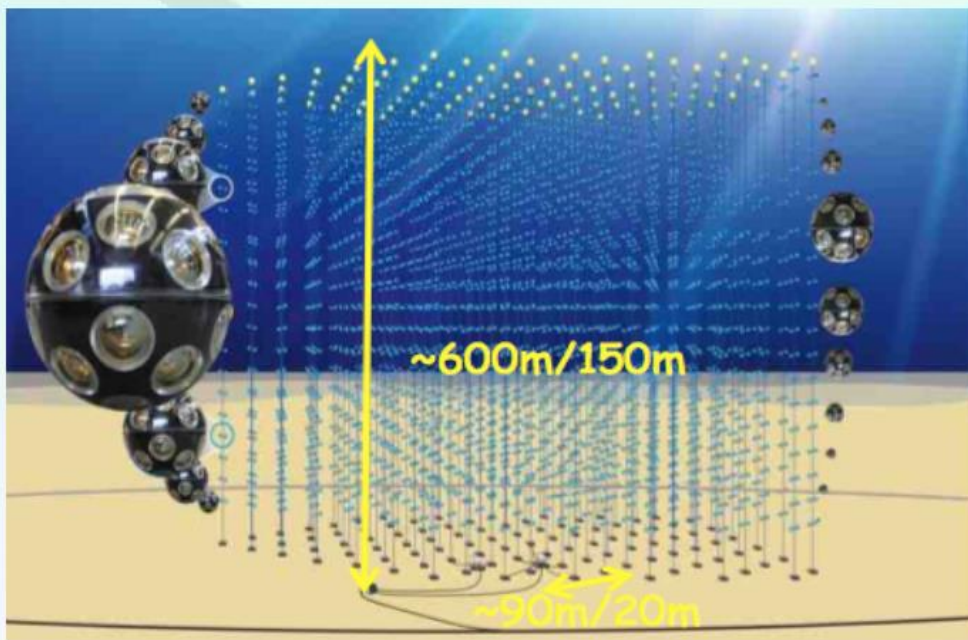
Single Collaboration

Single Technology

ARCA - Astroparticle Research with Cosmics in the Abyss

ORCA - Oscillation Research with Cosmics in the Abyss

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

Dark Matter indirect searches with KM3NeT/ORCA

Preliminary study of ORCA sensitivity for WIMP annihilation in the Sun
→ **Competitive sensitivity for low mass WIMPs** (3 < M$_{WIMP}$ < 100 GeV)
for spin-dependent scattering cross-sections
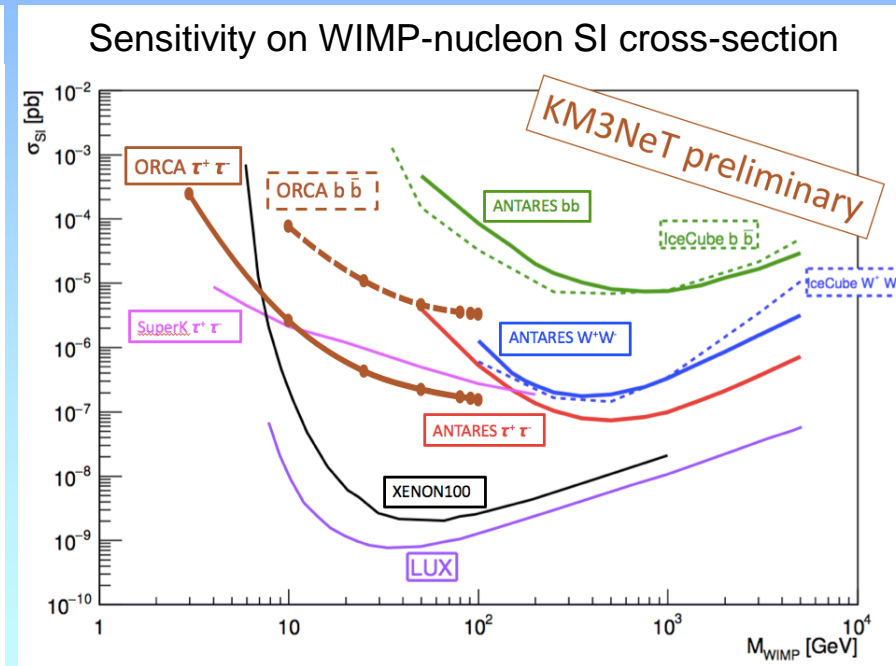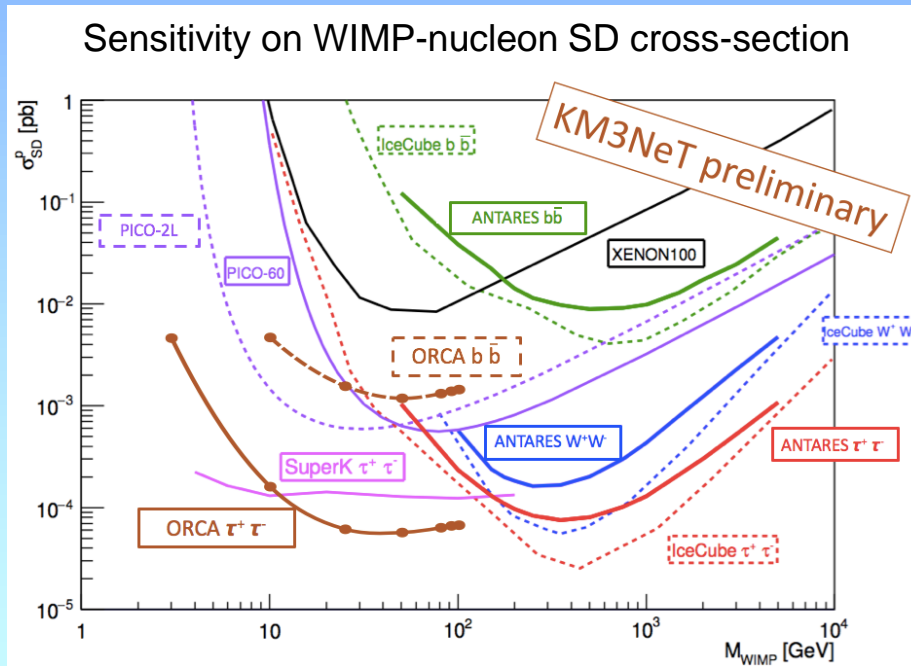
Sensitivity study of KM3NeT/ARCA for DM searches in Sun & GC under progress…

- **Indirect search for Dark Matter is an important goal** for neutrino telescopes

- **Important complementarity** to direct detection experiments (Sun) and gamma searches (Galactic Centre / Halo)

- **Competitive limit** obtained by ANTARES on indirect searches towards the Galactic Centre

- **More analysis are under progress :**
  - Full ANTARES data set (end of ANTARES data taking in 2018)
  - Inclusion of shower events (ν_e/ν_τ CC + ν NC events)
  - Study of astrophysical uncertainties in Sun capture ($\rightarrow$ A. Nuñez)

- **2020+ : Improved sensitivity with KM3NeT**
  - Sun : enxtension to low WIMP masses (ORCA)
  - Galactic Halo : higher sensitivity expected at high WIMP masses (ARCA)