Indirect search for Dark Matter with the ANTARES & KM3NeT deep sea neutrino telescopes

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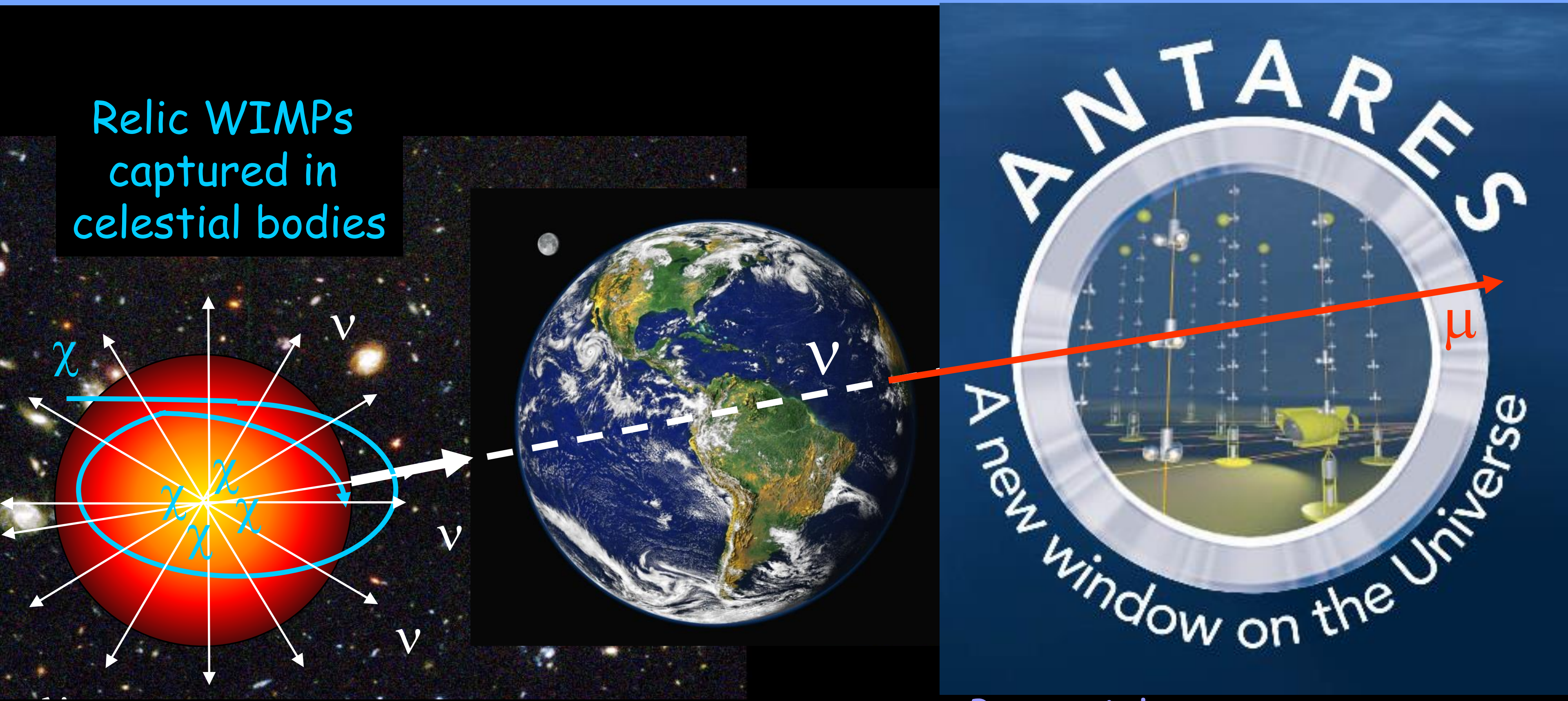
on behalf of the ANTARES & KM3NeT Collaborations

PPNT 2019 @ Uppsala – October 2019

Indirect detection of WIMPs in a neutrino telescope



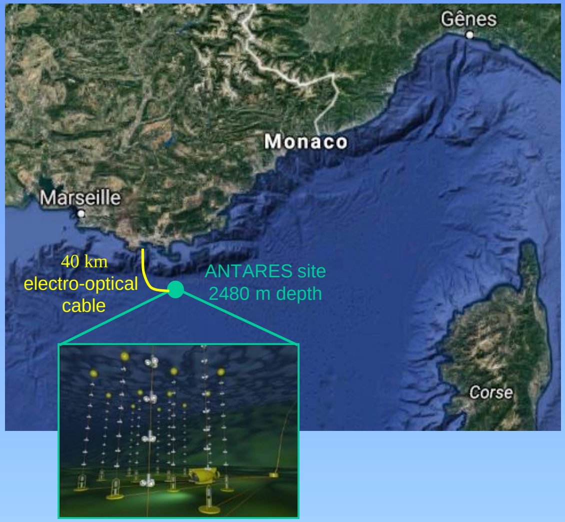
$\chi\chi$ self-annihilations into
c,b,t quarks, τ leptons or W,Z,H bosons
can produce significant
high-energy neutrinos flux

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

The ANTARES Neutrino Telescope

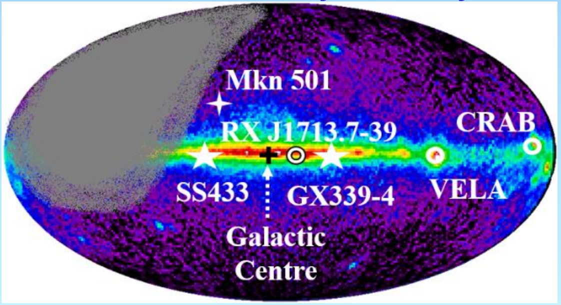
📖 NIM A 656 (2011) 11

- **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(12000) neutrinos detected** with Eν > 10 GeV

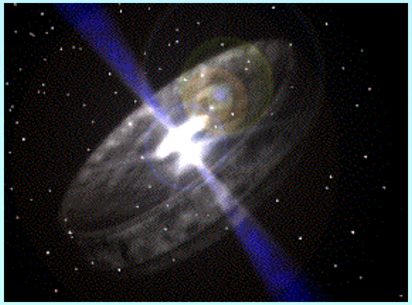


- **Excellent view of Galactic Centre region** with high angular resolution (0.3°-0.4° median)
  → **interesting constraint of possible galactic component** of the IceCube HE signal
- **Real time** data processing →generation of alerts (~5s) for multi-messenger searches

ANTARES sky visibility

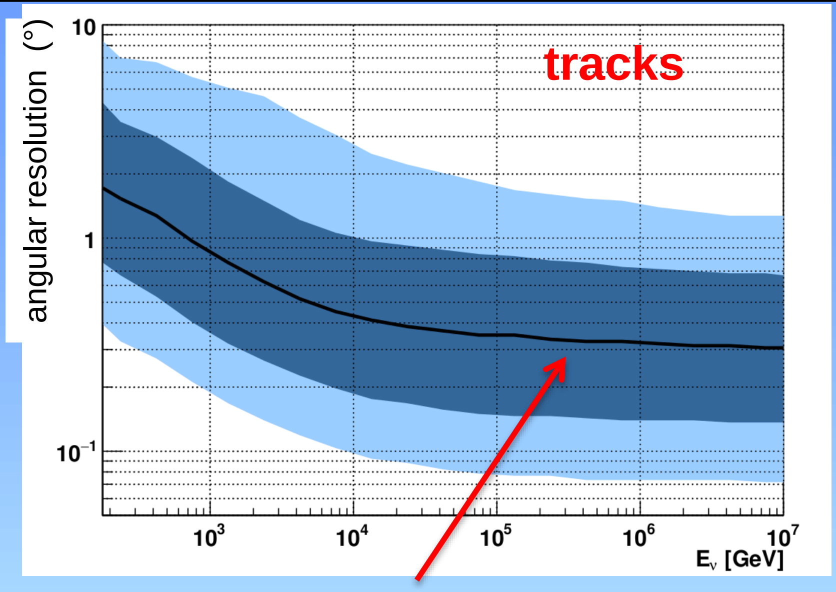


- **Science scope of ANTARES:**
  - Neutrino astrophysics, search for HE CR origin
  - Multi-messenger observations
  - **Indirect searches for Dark Matter**
  - Atmospheric neutrinos (oscillations, sterile neutrinos)
  - Exotic searches (magnetic monopoles, nuclearites)
  - Earth & Sea Sciences, environmental studies



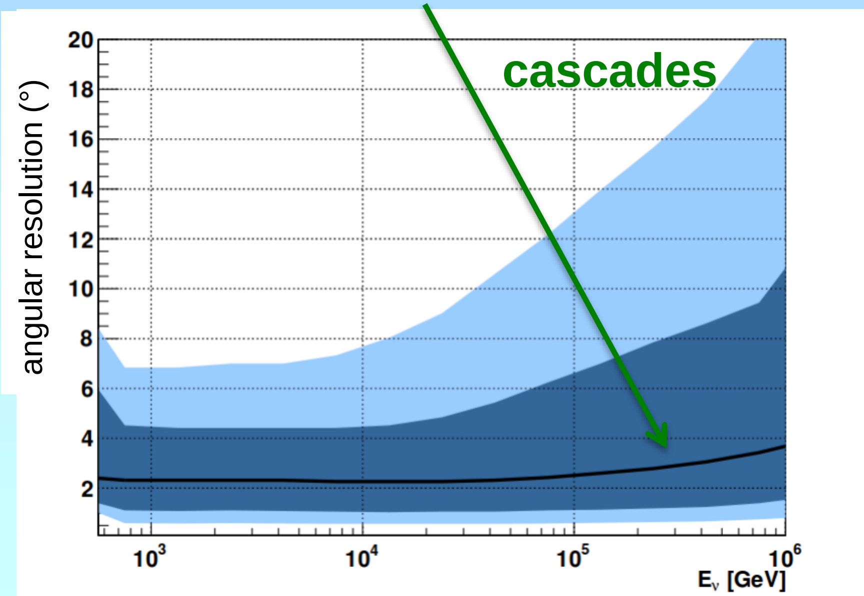
Reconstruction performances

- 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



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



Indirect search towards the Sun with ANTARES

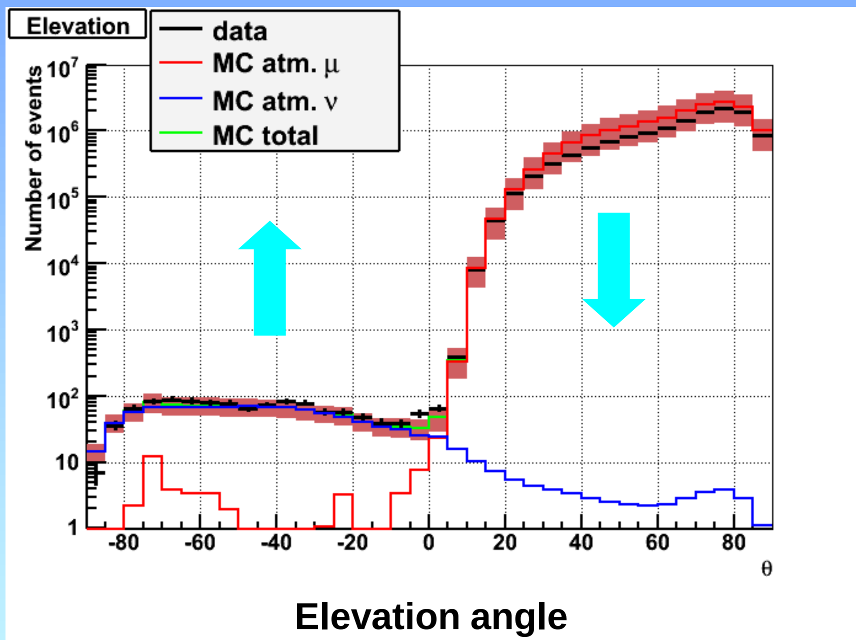
- **Detector** building started in 2006, completed in May 2008
- **Published results** based on data collected between 2007 and 2012
  → **> 7000 upgoing neutrino** candidates (in **~1321 effective days**)

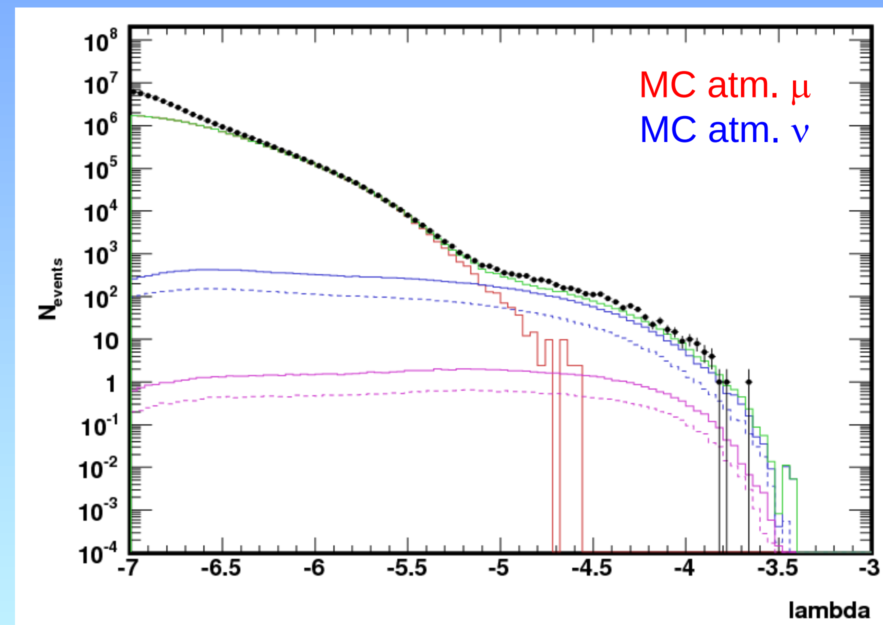
- **Reconstruction strategies:**
  - BBFit (χ^2 based) → optimal for low energies/masses (<250 GeV)
    - **Single line events** : reconstruction of **zenith angle only** → very low energies
    - **Multiline events**: reconstruction of **zenith & azimuth angles**
  - AAFit (likelihood based) → high 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)

Event selection : background rejection

- Selection of neutrinos and rejection of atmospheric muons by selecting up-going tracks and cutting on track fit quality



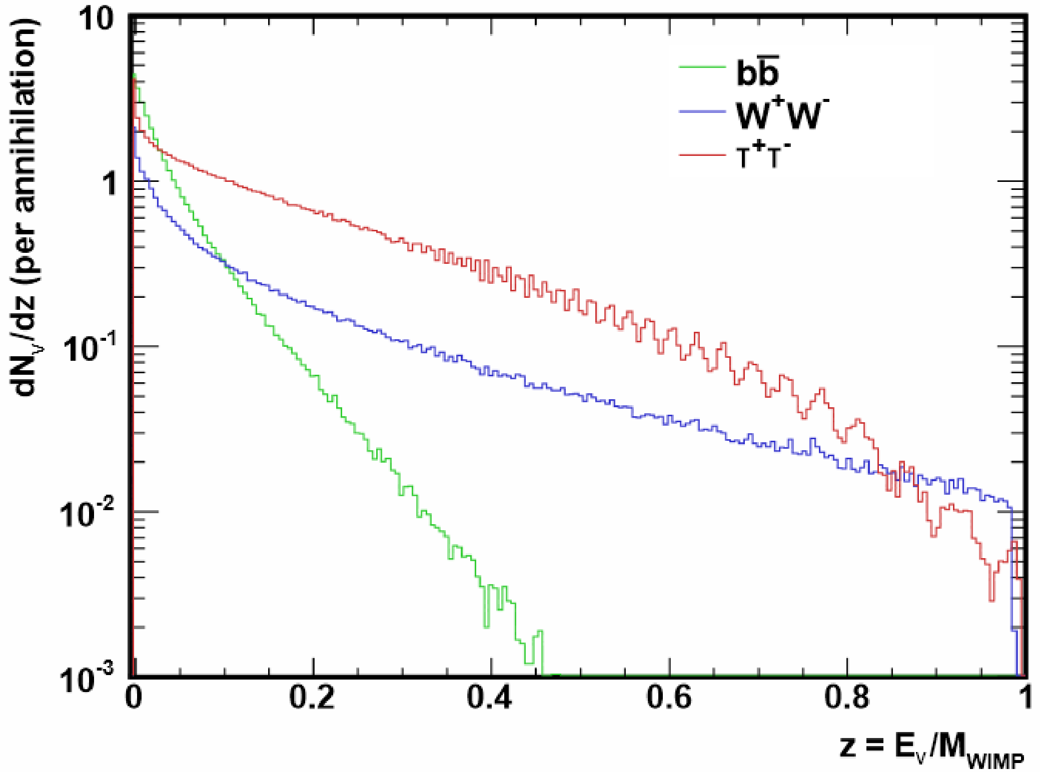


- Rejection of atmospheric neutrinos by looking into a cone towards the Sun direction (or zenith band for single line events)

- Remaining **background** estimated from **scrambled data**

Neutrino signal from WIMP annihilations

- 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**



Analysis strategy and results

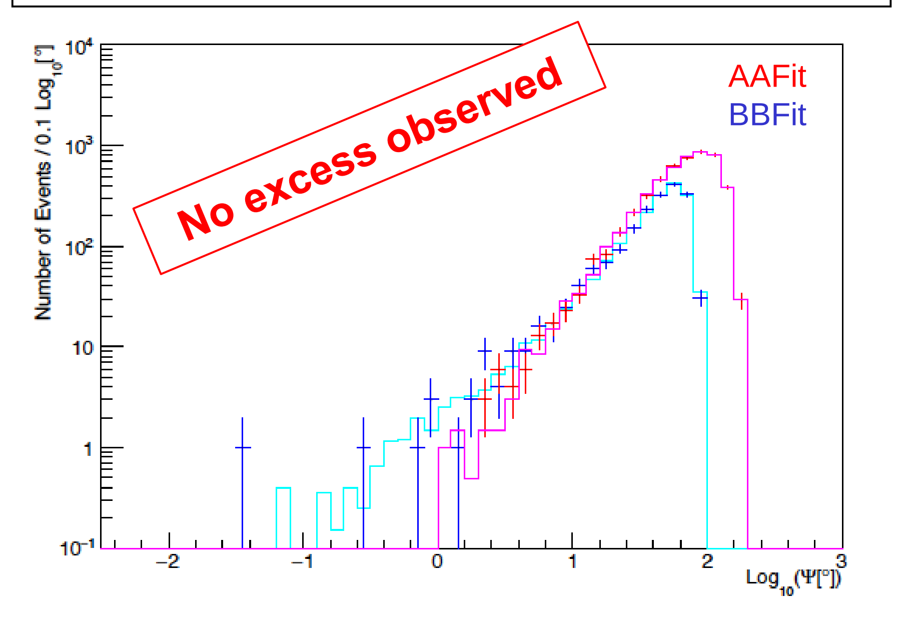
- **Maximisation of the Likelihood function based on Signal and Background PDFs :**

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

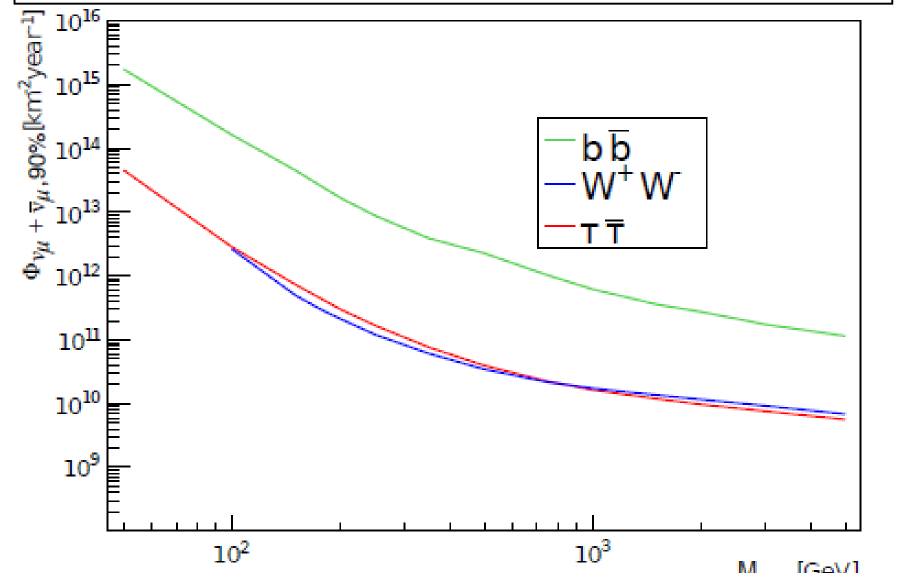
N_{hit} = number of hit used for the track reconstruction
β = the angular error estimate for the reconstructed track
N_{tot} = tot. Number of reconstructed events
n_s and N_{bg} are the number of signal and background events

- **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

Limits on Spin (In)dependent cross sections

Conversion to **limits on WIMP-nucleon Spin (In)dependent cross sections** assuming :

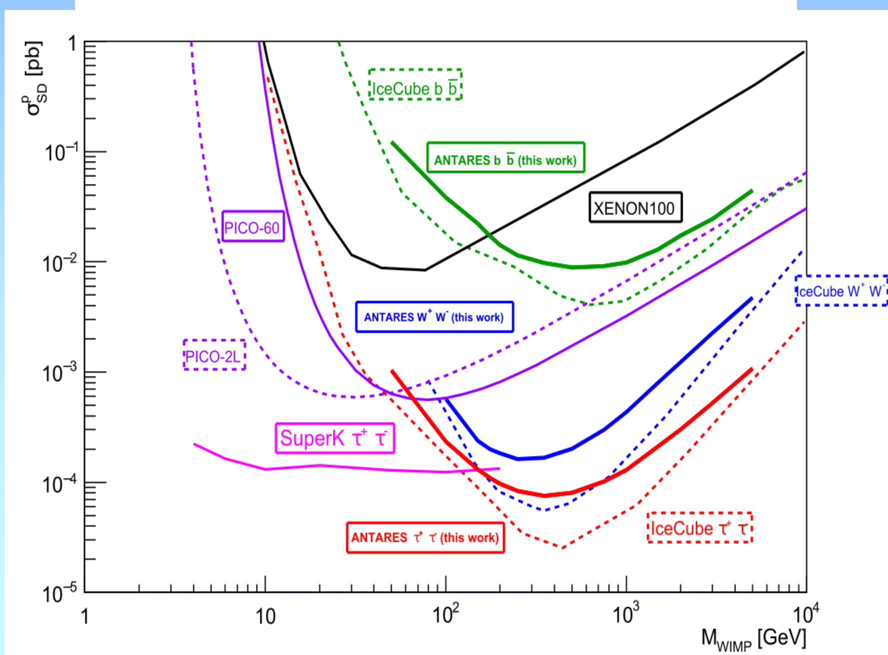
- Equilibrium between capture and annihilation rates inside the Sun
- Local WIMP density = 0.4 GeV/cm^3
- Maxwellian velocity distribution of WIMPs with r.m.s. = 270 km/s

→ **Determination of astrophysical uncertainties on WIMP capture in the Sun :**

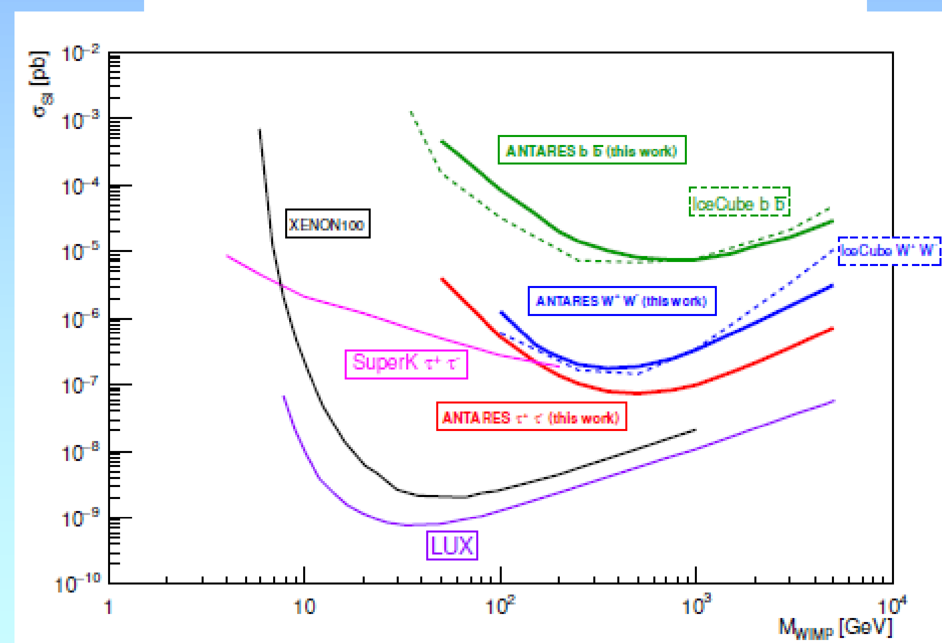
PhD work in progress by A. Nuñez with E. Nezri & VB

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

Limit on WIMP-nucleon SD cross-section



Limit on WIMP-nucleon SI cross-section

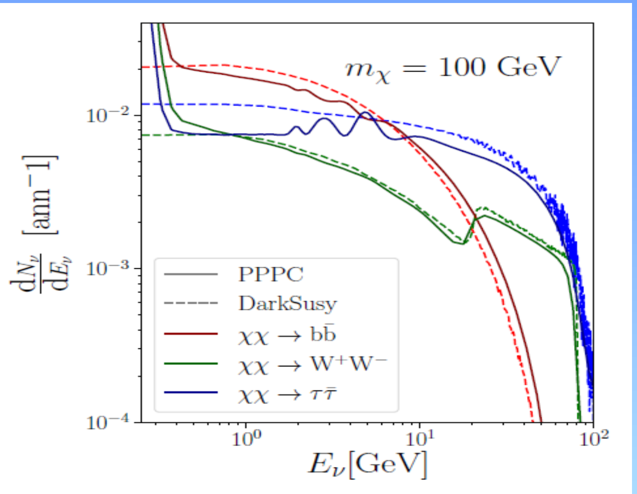


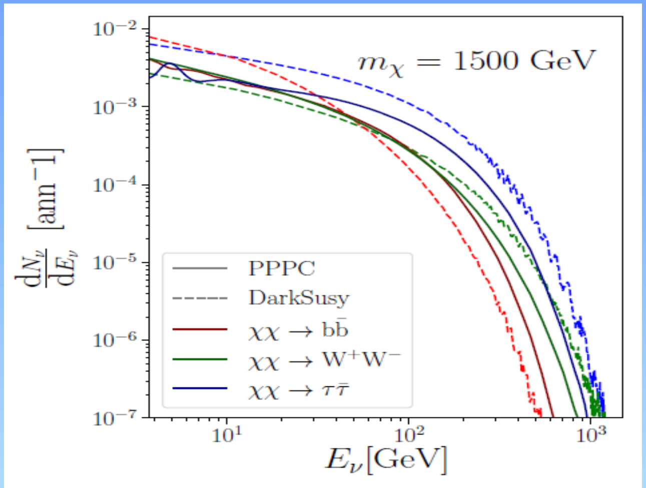
→ **much better sensitivity of neutrino telescopes on SD cross-section**

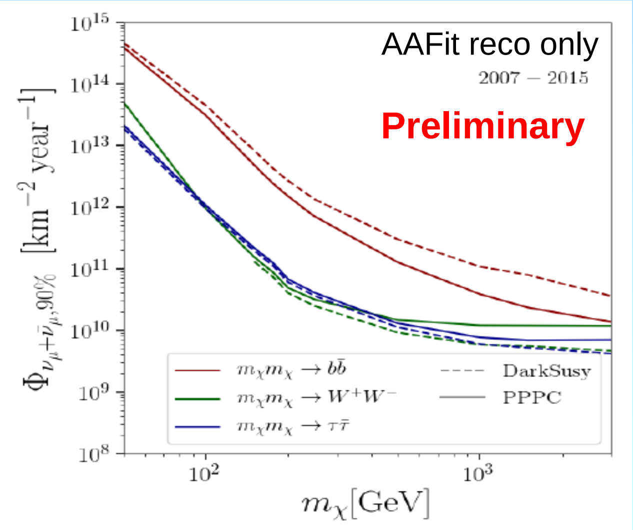
w.r.t. direct detection due to efficient capture on Hydrogene inside the Sun

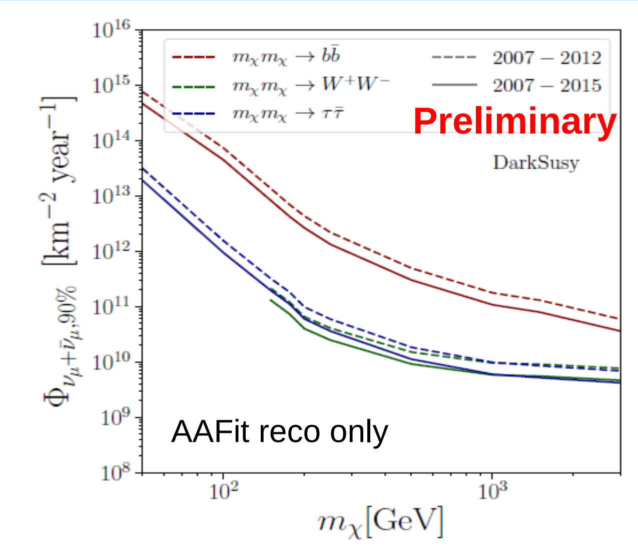
Update of Sun analysis under progress with 2007-2017 data

Comparison between PPPC spectra including radiative correction effects vs WIMPSIM
→ **large differences for b-bbar and tau+tau- annihilation channels**







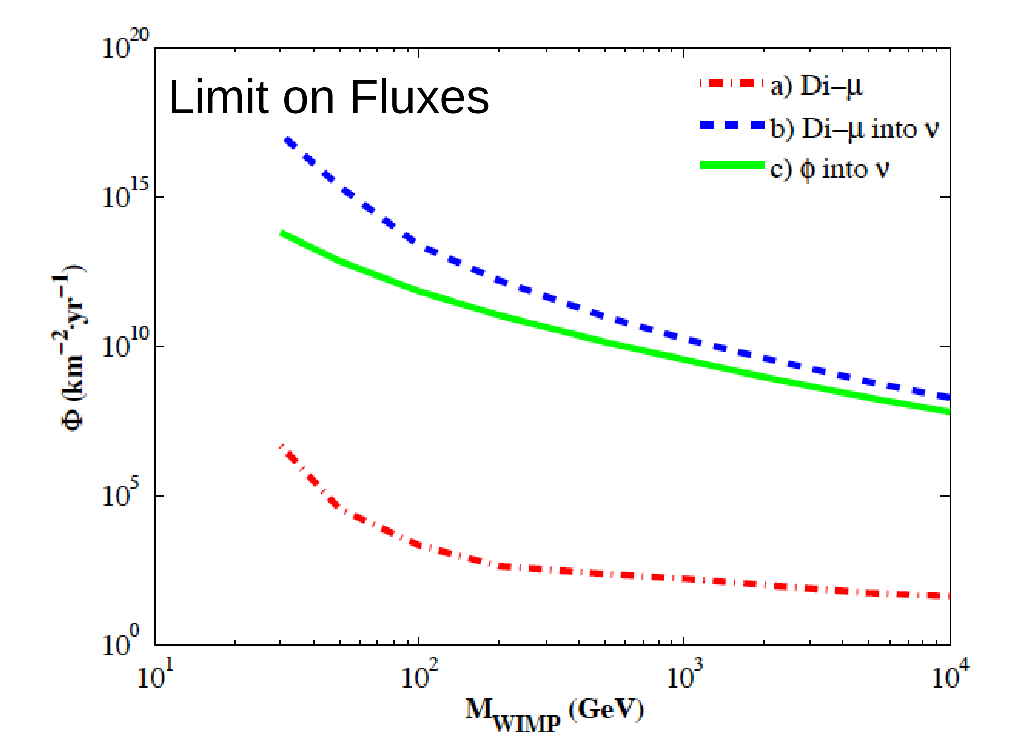


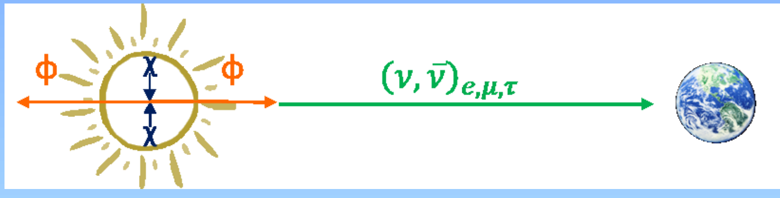
→ **Factor ~2-3 improvement of sensitivity expected w.r.t. published limit**

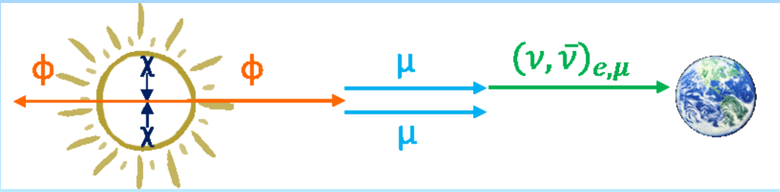
Search for Secluded DM towards the Sun

- 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





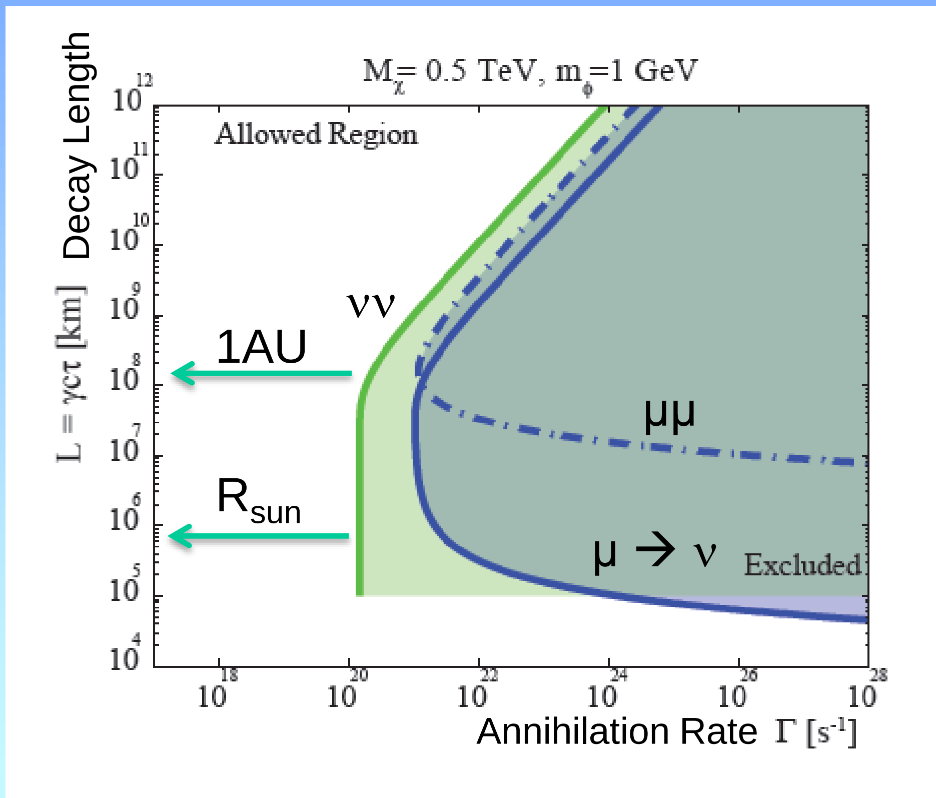


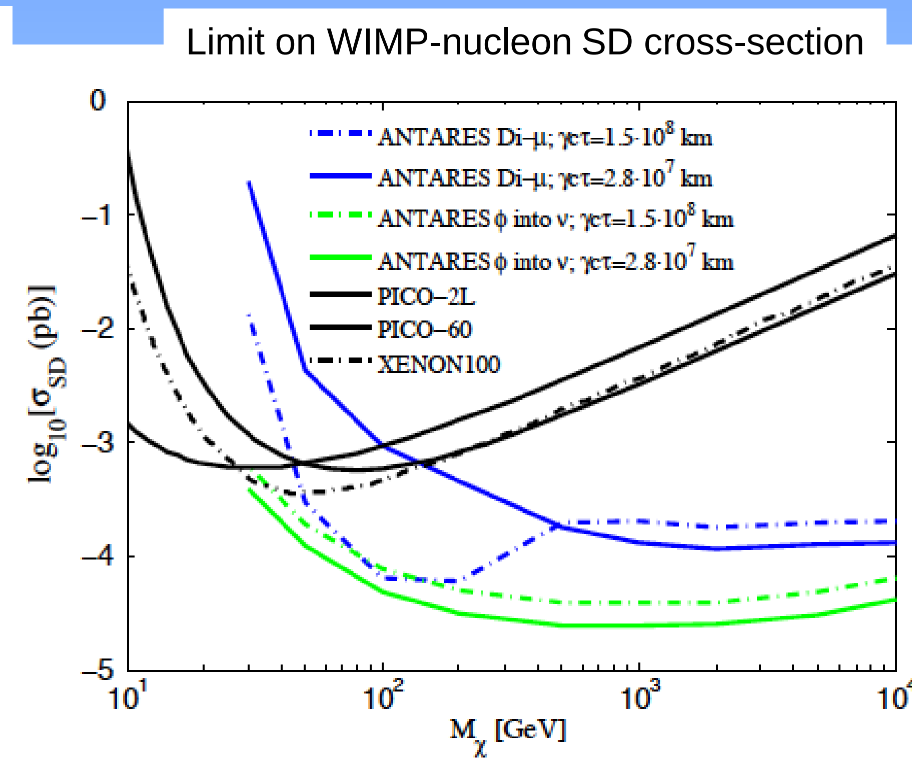
Testing models from:

- Meade et al., JHEP06 (2010) 29
- Bell and Petraki, JCAP04 (2011) 003

Search for Secluded DM towards the Sun

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



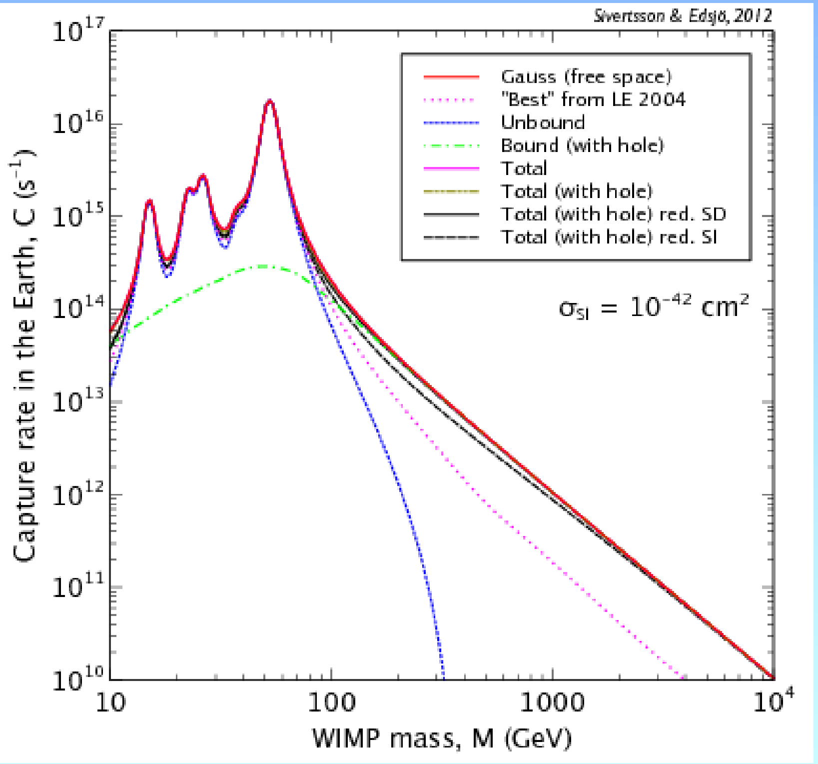


📖 JCAP 05 (2016) 016

- **First constraint to these models from neutrino telescopes**
- Limits on WIMPs scattering cross-section for unstable but sufficiently long-lived mediators

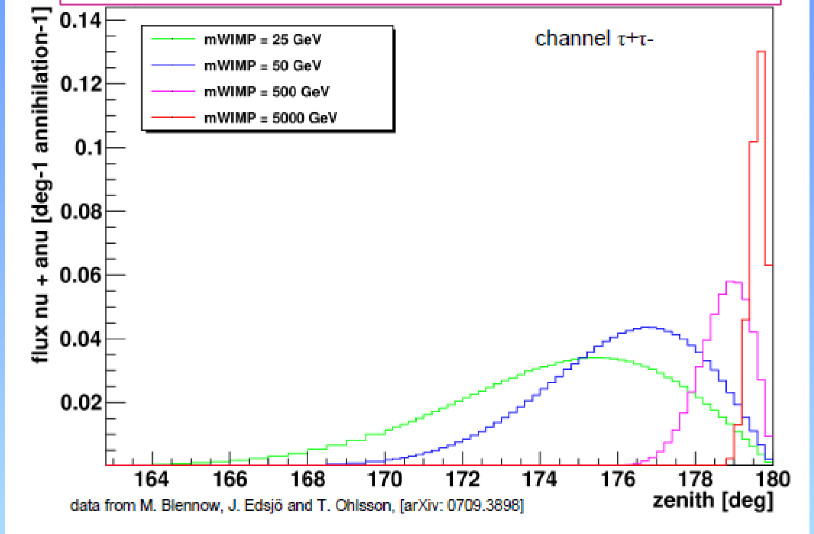
Indirect Search for Dark Matter in the Earth

Capture rate of WIMPs in the Earth
dominated by SI cross-section
Resonnant enhancement
on dominant nuclei (Fe, Ni, Si,…)

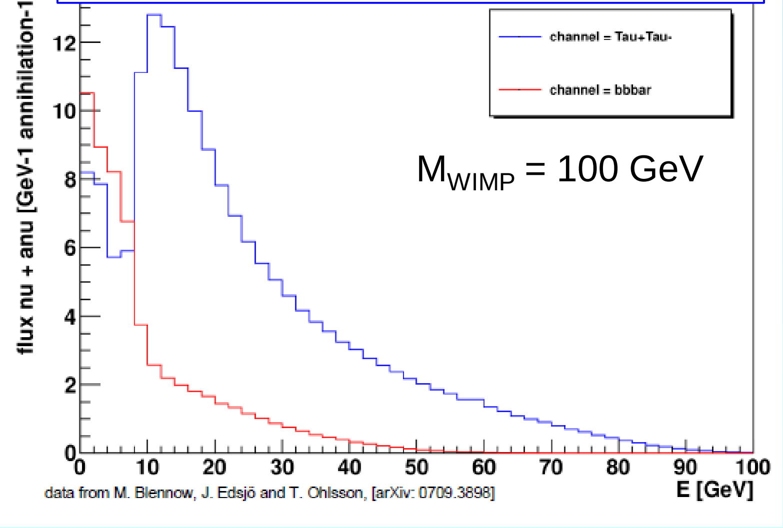


from M. Blennow, J. Edsjo and T. Ohlsson, arXiv:0709.389

Angular distribution of neutrinos



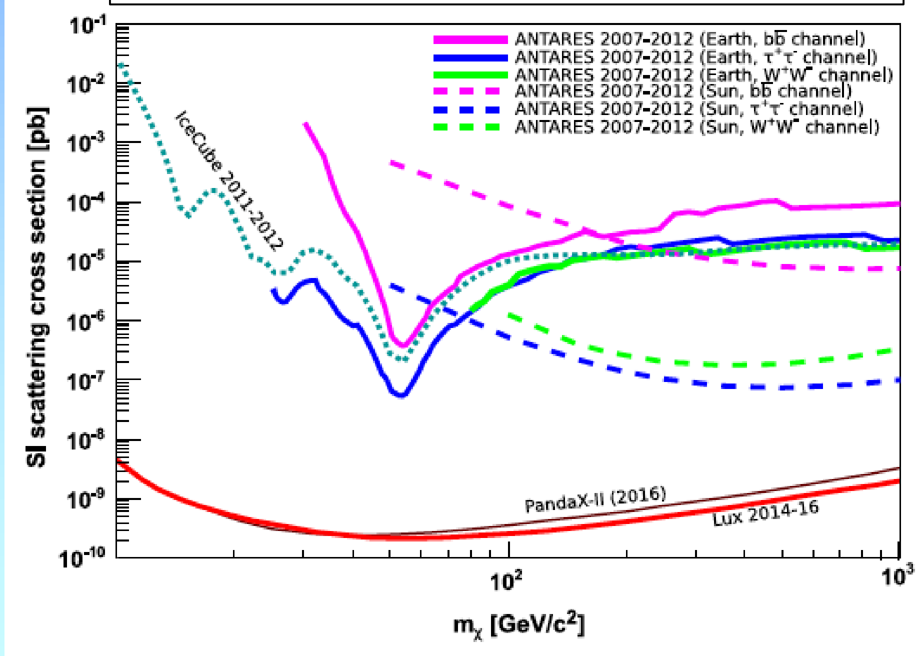
Energy distribution of neutrinos



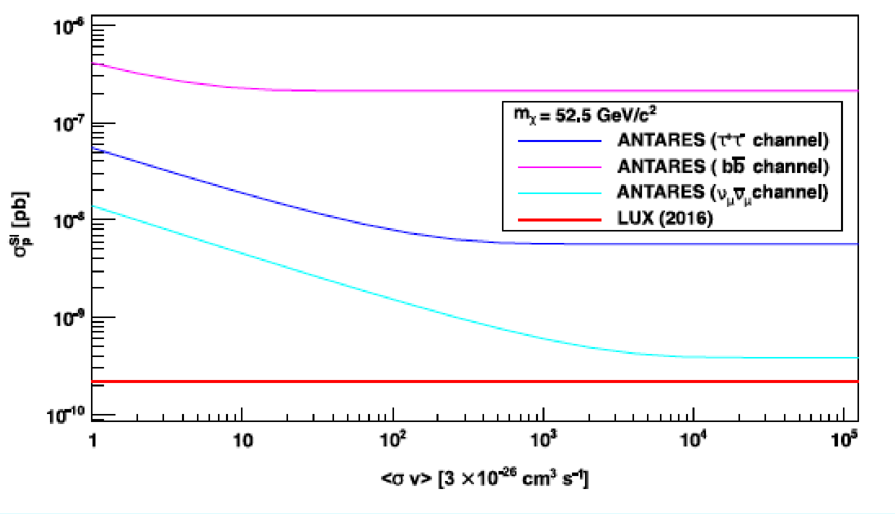
Sensitivity to DM annihilations in the Earth

- 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



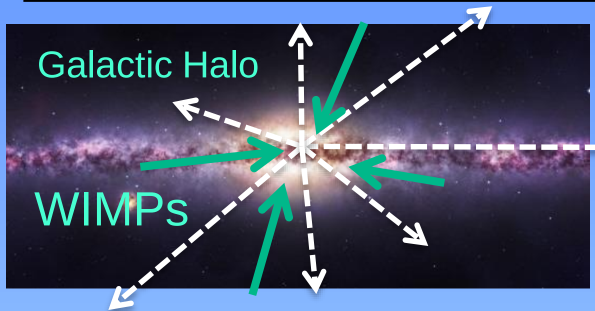
Upper limit on WIMP-nucleon SI cross-section assuming 100% BR of annihilation into benchmark channel for WIMP mass = 52.5 GeV (Fe resonnance)



Scenario with boosted annihilation cross-section

📖 Physics of the Dark Universe 16 (2017) 41

Search for Dark Matter towards the Galactic Centre

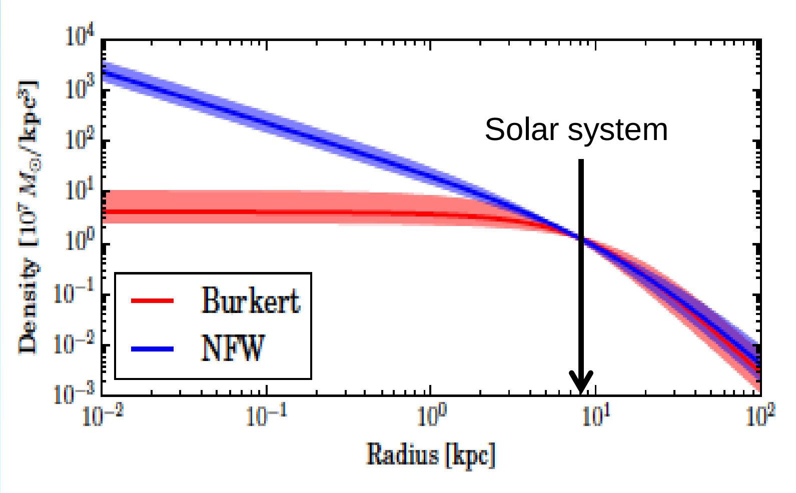


ν_e, ν_μ, ν_τ

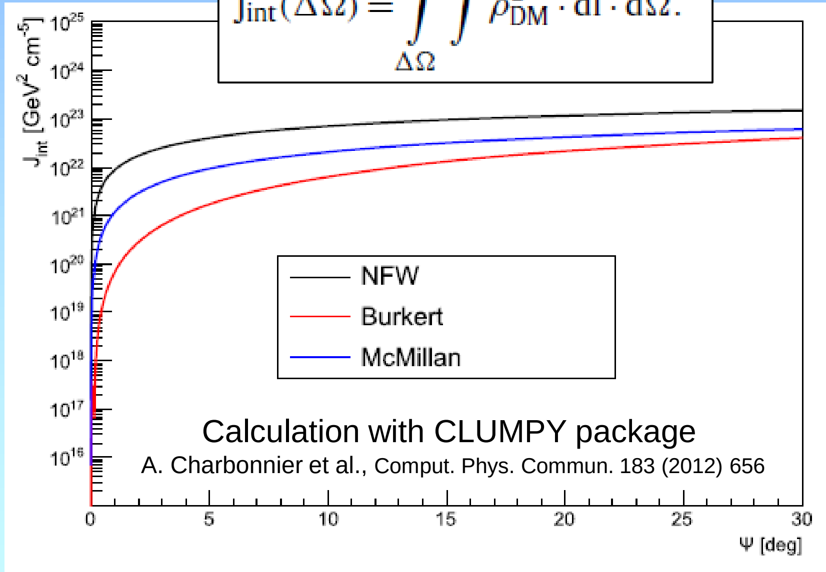
ν oscillations in the vacuum

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



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



3 benchmark halo model considered :

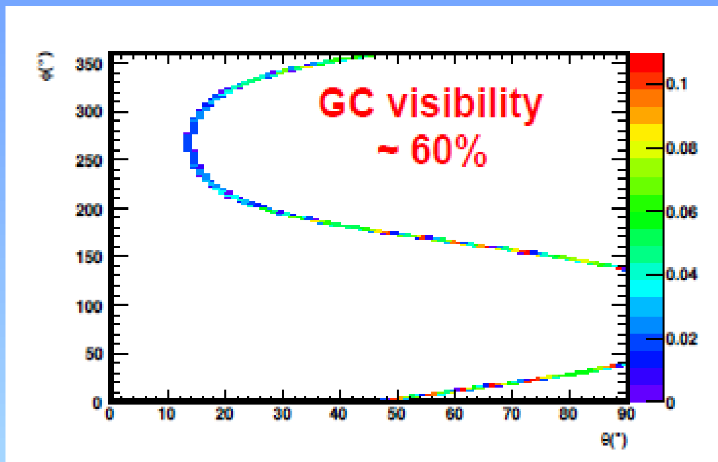
- Navarro, Frenk, White, ApJ 490 (1997) 493
- A. Burkert, ApJ 447 , L25 (1995)
- P.J. McMillan, Mon. Not. R. Astron. Soc. 414 (2015) 2446

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.

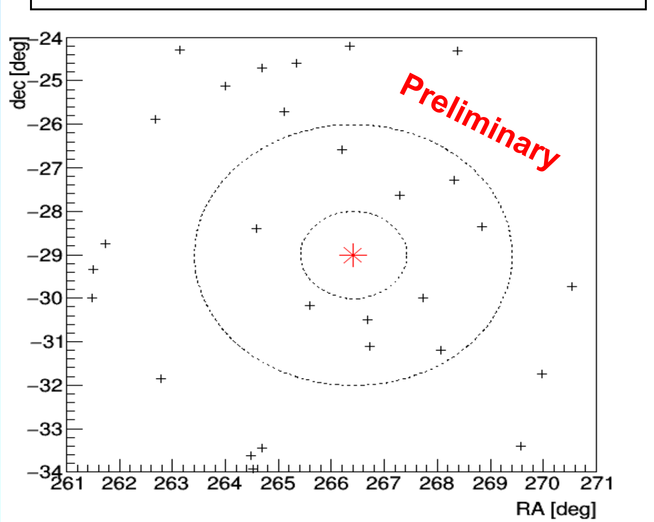
Parameter	NFW	Burkert	McMillan
r_s [kpc]	$16.1^{+17.0}_{-7.8}$	$9.26^{+5.6}_{-4.2}$	17.6 ± 7.5
ρ_{local} [GeV/cm^3]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034

Search for Dark Matter towards the Galactic Centre

ANTARES **visibility** of the GC

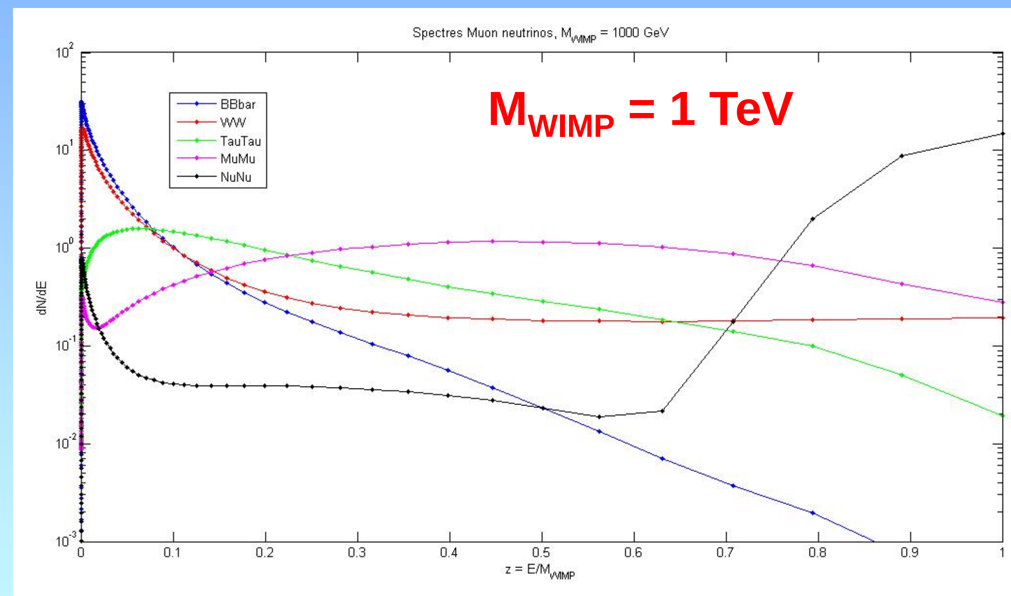


Observed events in the GC direction in 2007-2016 data sample



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)

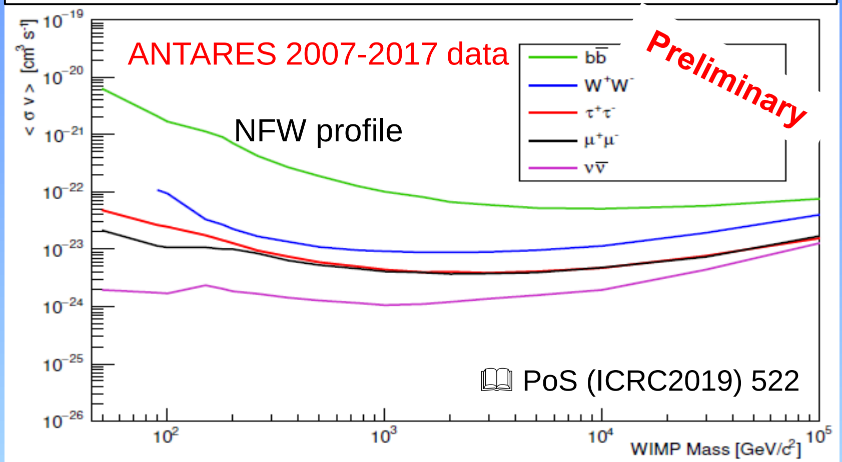


- **11 years (2007-2017) of data analyzed**
- **GC considered as extended source**
- **No excess over background found**

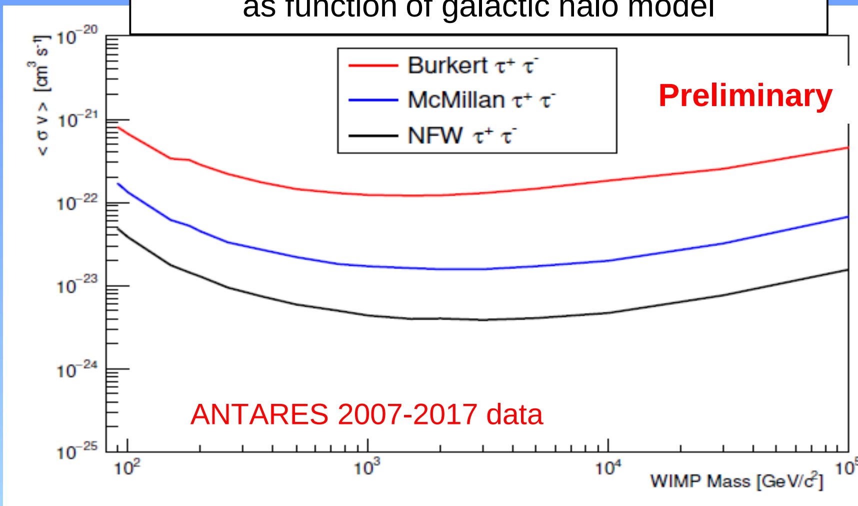
Limits with 2007-2015 data 📖 Phys. Let. B 769 (2017) 249, Erratum PLB 796 (2019) 253

Limits of ANTARES from Galactic Centre

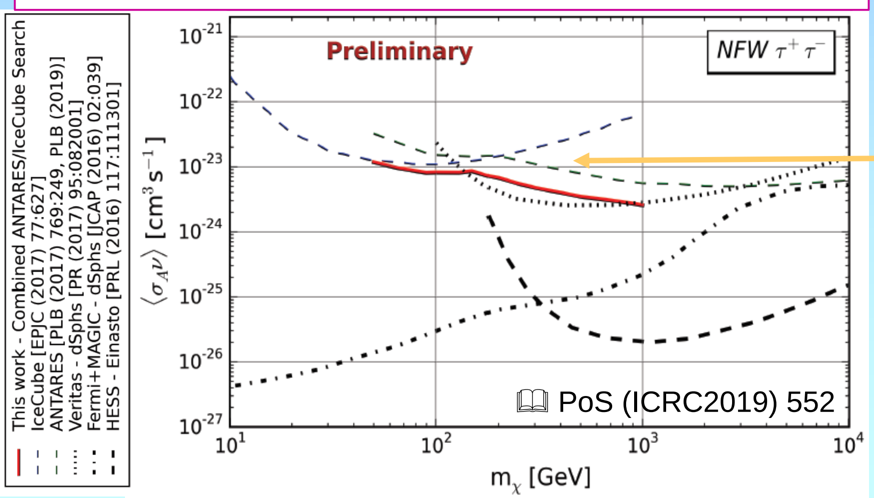
Limit on WIMP annihilation cross-section assuming 100% BR of annihilation into benchmark channel

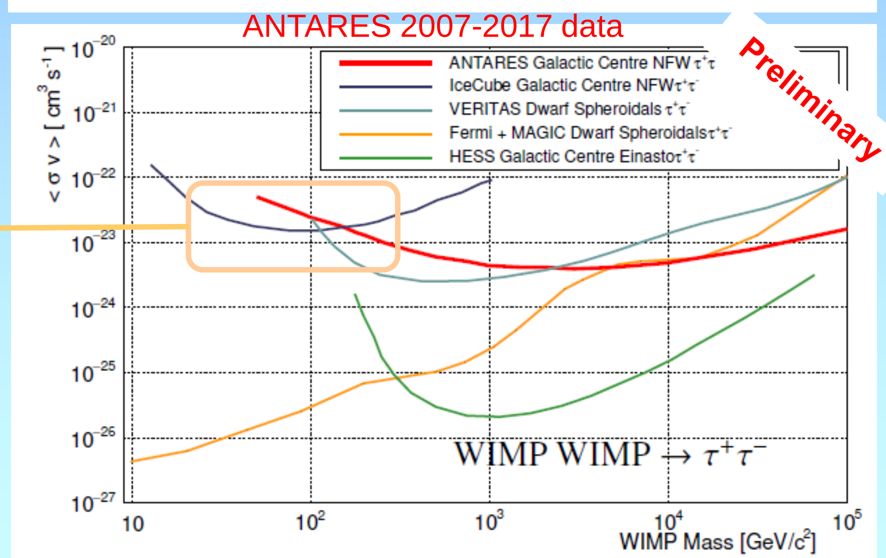


Limit on WIMP annihilation cross-section as function of galactic halo model



Combination of ANTARES + IceCube





ANTARES gives the **best limit** in neutrinos above 100 GeV

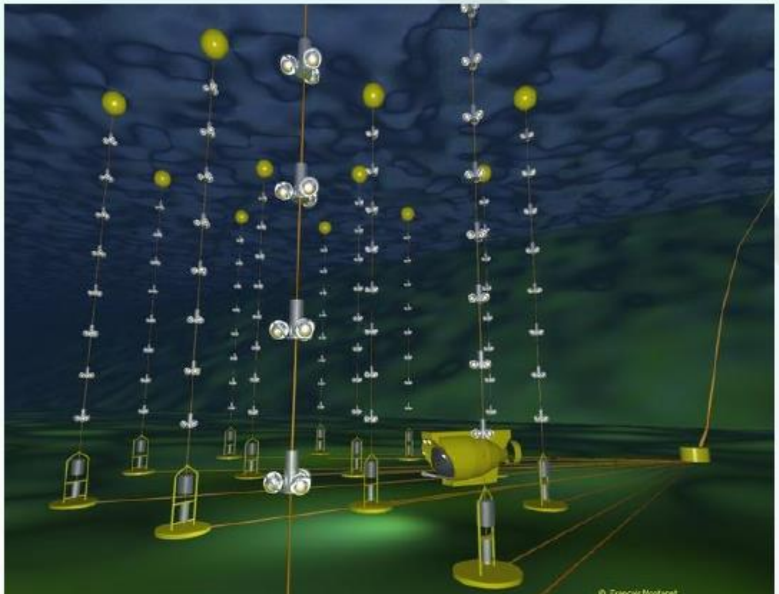
→ Very competitive limit for M_{WIMP} > 10 TeV

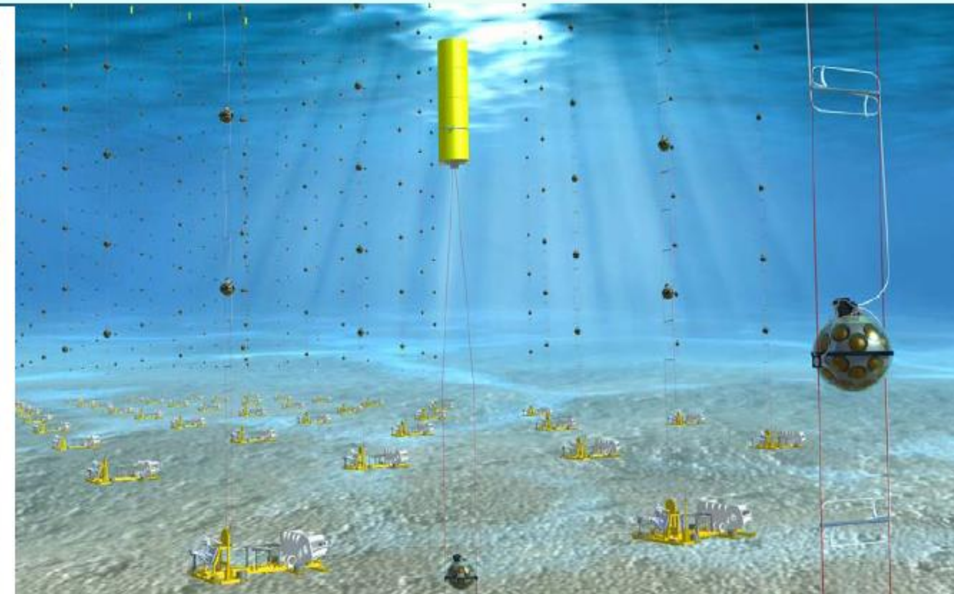
The future of Neutrino Astronomy in the Mediterranean Sea

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

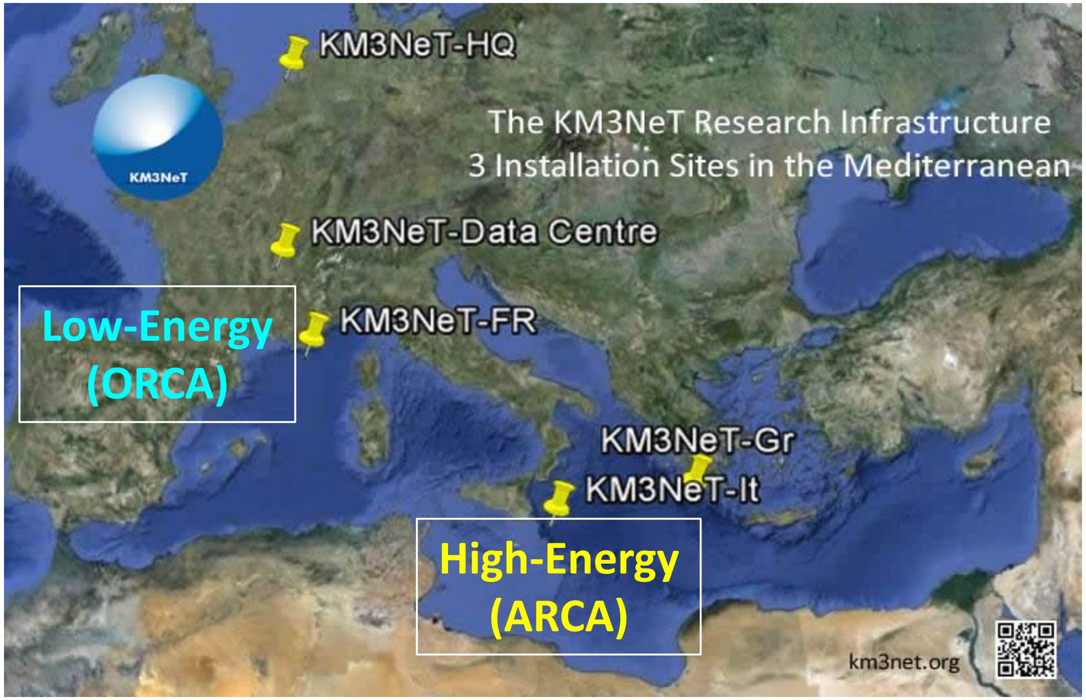
KM3NeT

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

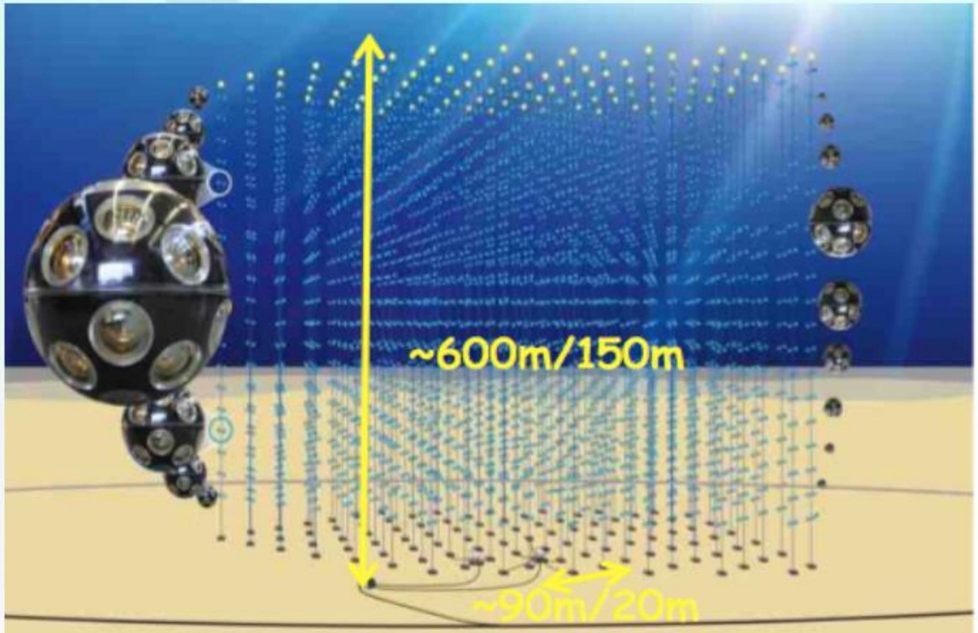
Single Technology

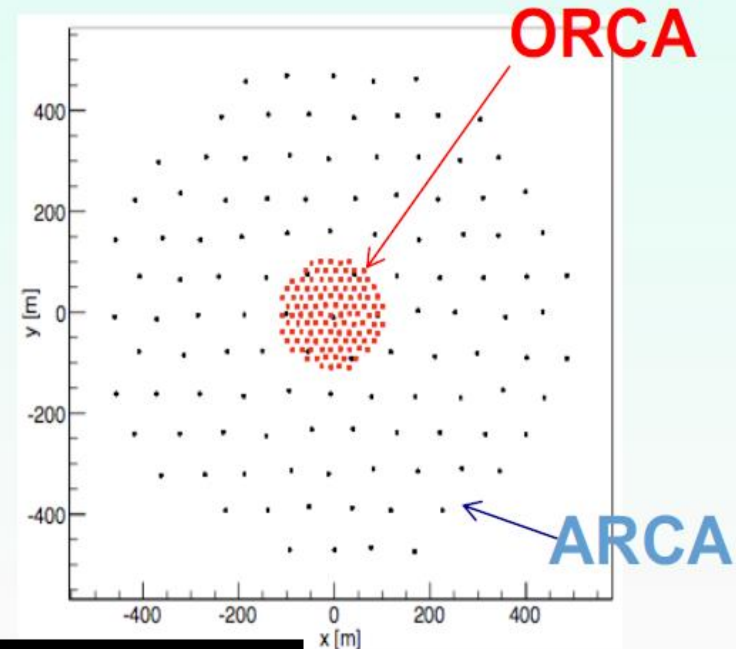


ARCA - Astroparticle Research with Cosmics in the Abyss

ORCA - Oscillation Research with Cosmics in the Abyss

KM3NeT Building Blocks



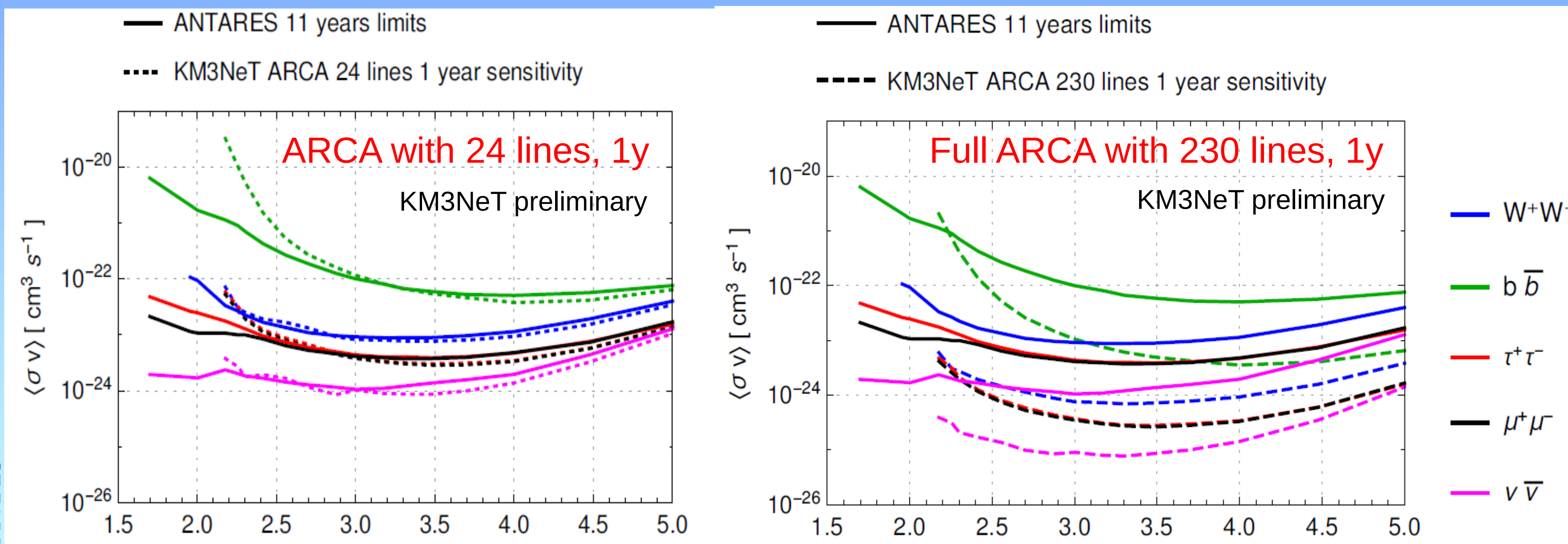


[redacted]

	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/ARCA

Preliminary study of ARCA sensitivity for WIMP annihilation in the Galactic Centre



PoS (ICRC2019) 522

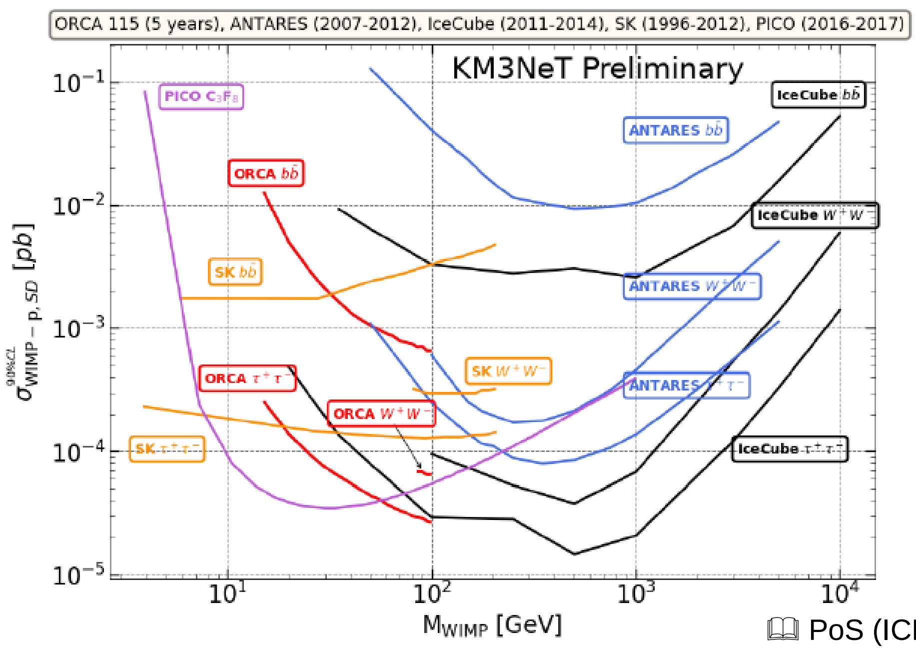
Similar sensitivity as ANTARES with ARCA 24 lines after 1year
Factor ~10 improvement with full ARCA 230 lines

Dark Matter indirect searches with KM3NeT/ORCA

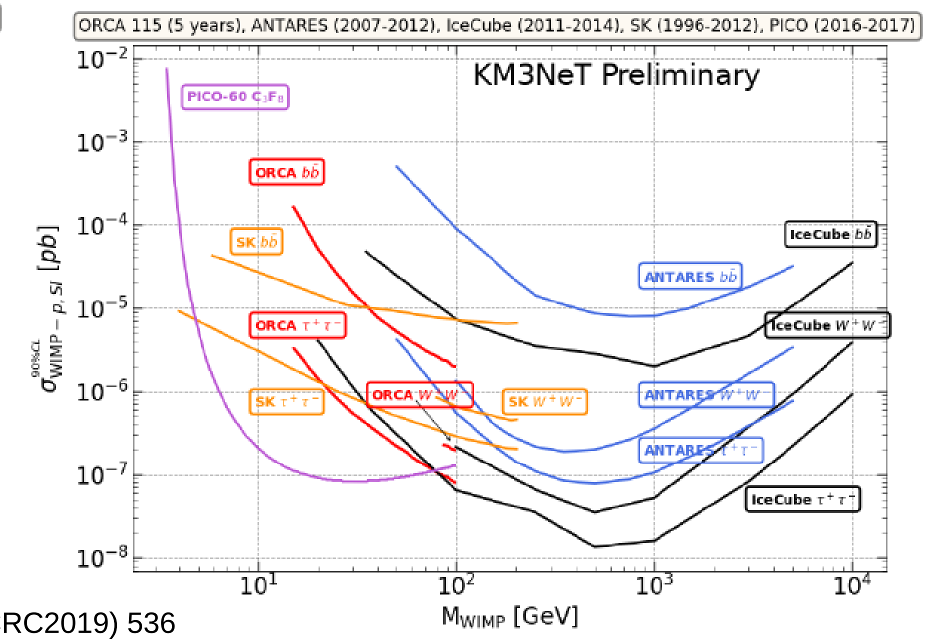
Preliminary study of ORCA sensitivity for WIMP annihilation in the Sun

→ **Competitive sensitivity for low mass WIMPs** ($20 < M_{WIMP} < 100$ GeV) compared to other neutrino detectors.

Sensitivity on WIMP-nucleon SD cross-section



Sensitivity on WIMP-nucleon SI cross-section



📖 PoS (ICRC2019) 536

Sensitivity study of KM3NeT/ARCA for DM searches in the Sun under progress…

Summary and Outlook

- **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 2020)
  - Inclusion of shower events (ν_e/ν_τ CC + ν NC events)
  - Study of astrophysical uncertainties in Sun capture
- **2020+ : Improved sensitivity with KM3NeT**
  - Sun : extension to low WIMP masses (ORCA)
  - Galactic Halo : higher sensitivity expected at high WIMP masses (ARCA)