Looking for Dark Matter with ANTARES and KM3NeT deep-sea neutrino telescopes

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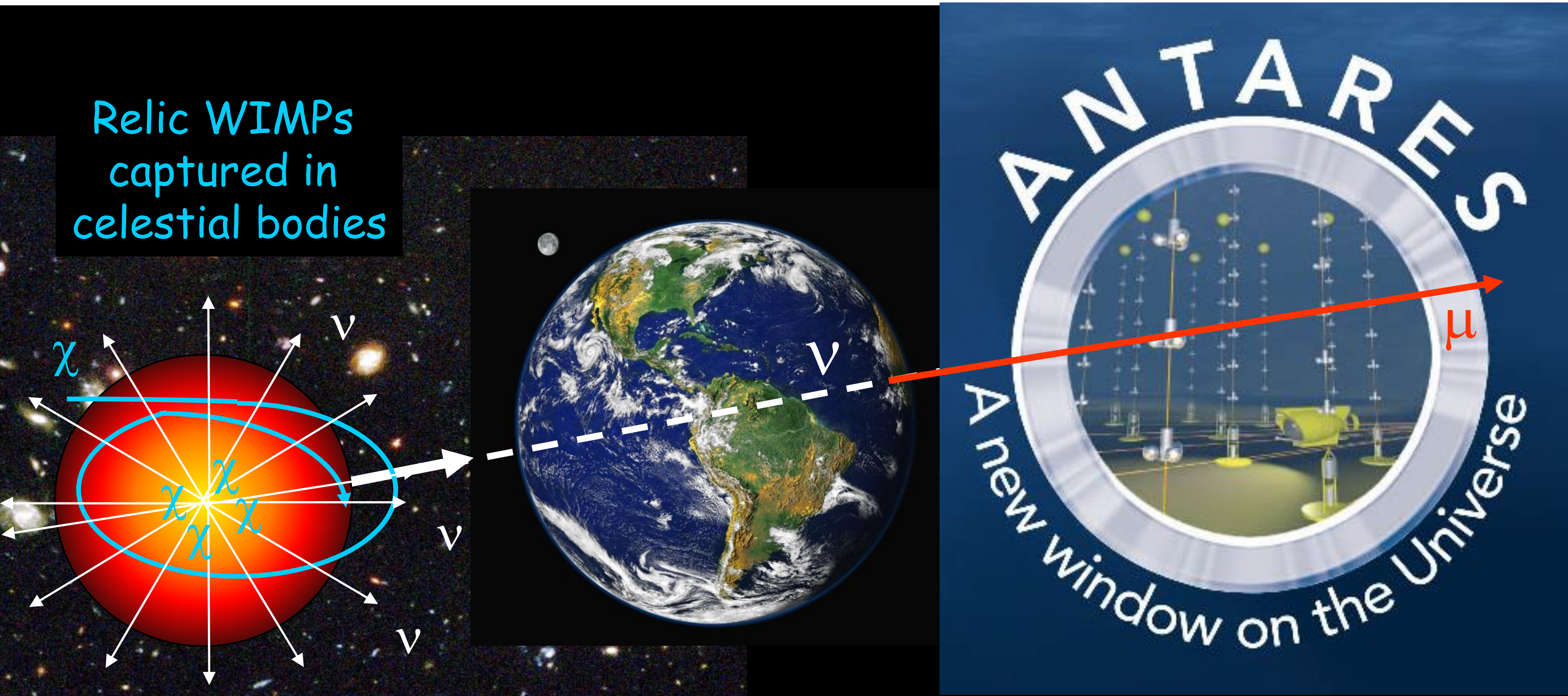
on behalf of the ANTARES and KM3NeT Collaborations

International Conference on Neutrinos and Dark Matter (NDM-2020)
11-14 January - Hurghada, Egypt

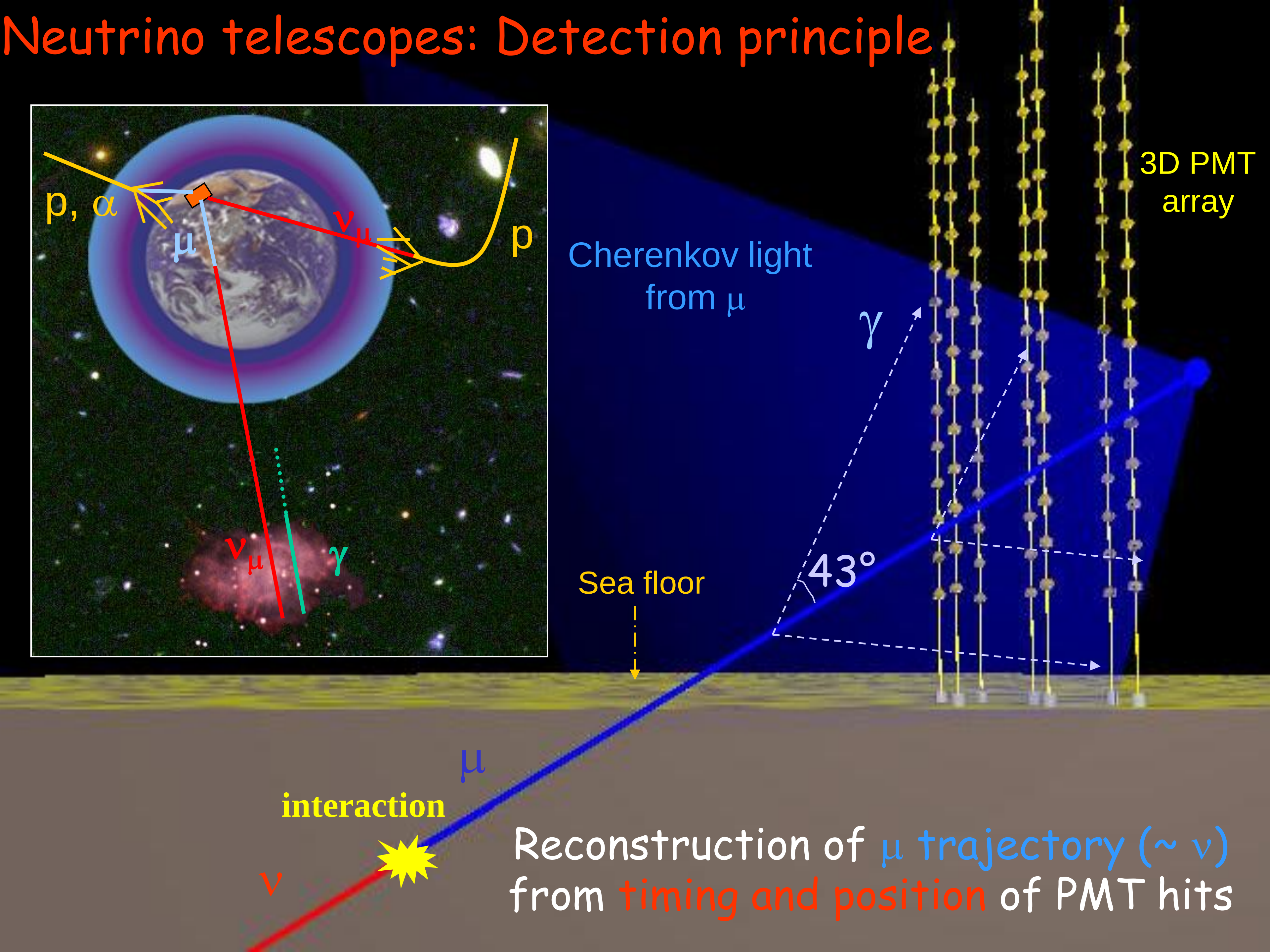
Indirect detection of WIMPs in a neutrino telescope



$\chi\chi$ 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

Neutrino telescopes: Detection principle

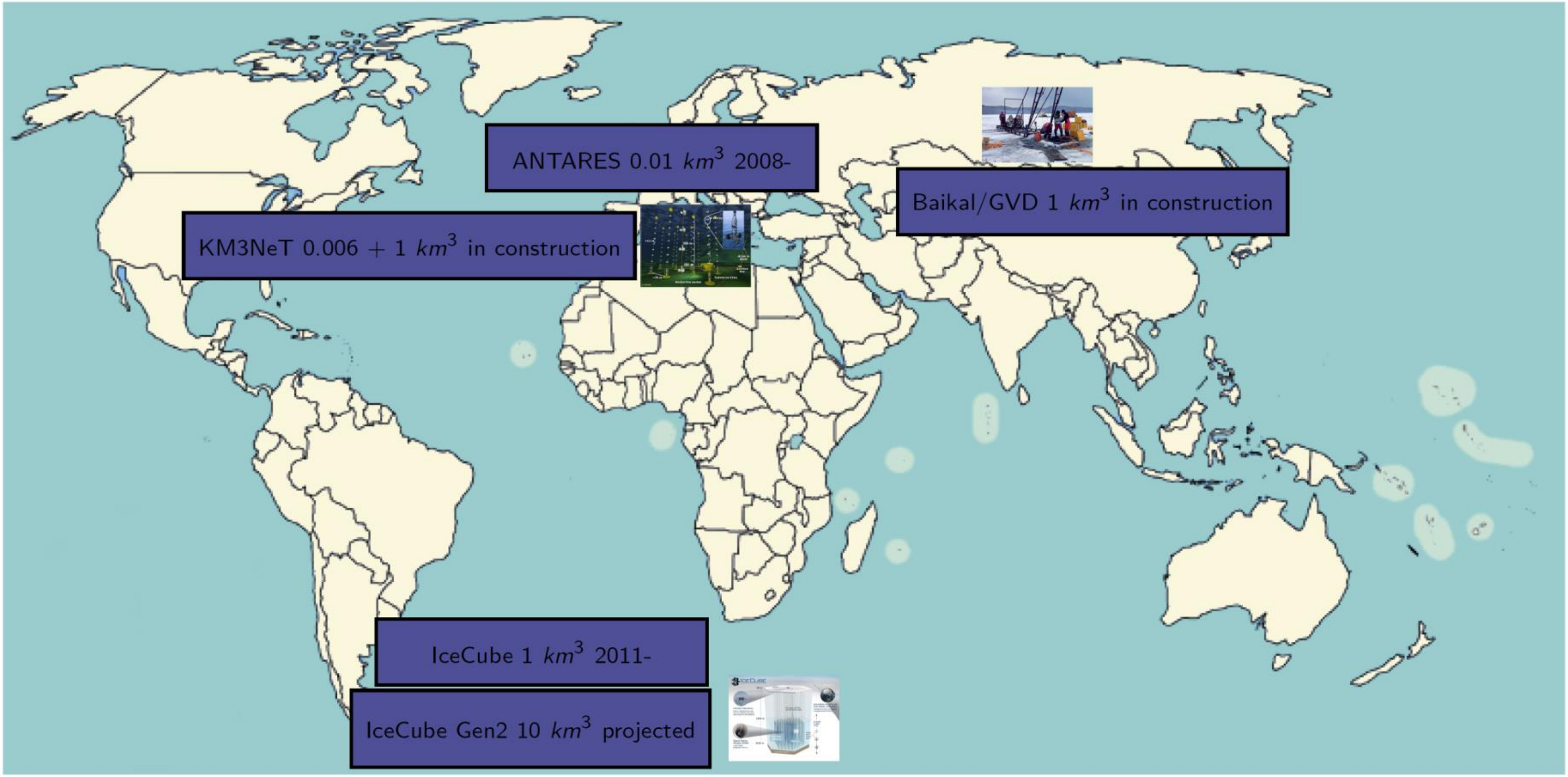


Reconstruction of μ trajectory (~ ν) from timing and position of PMT hits

Neutrino telescopes: Detectors in the World

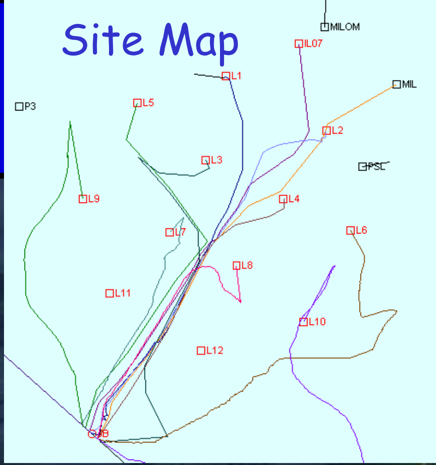
Neutrinos as dark-matter messengers

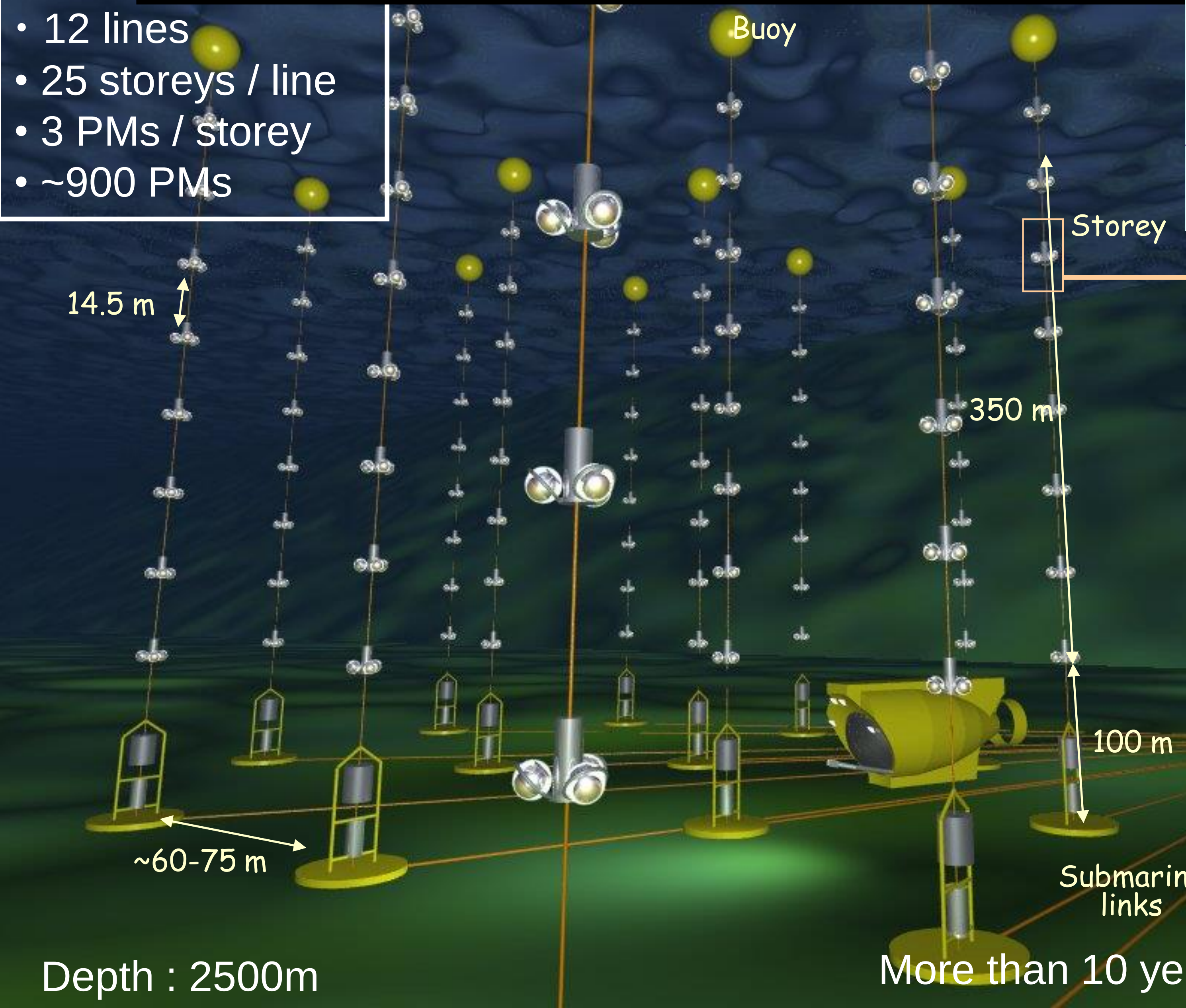
- Source confusion may be less problematic compared to other messengers, in regions like the Centre of the Milky Way
- No dedicated data sets needed



The ANTARES detector

- 12 lines
- 25 storeys / line
- 3 PMs / storey
- ~900 PMs



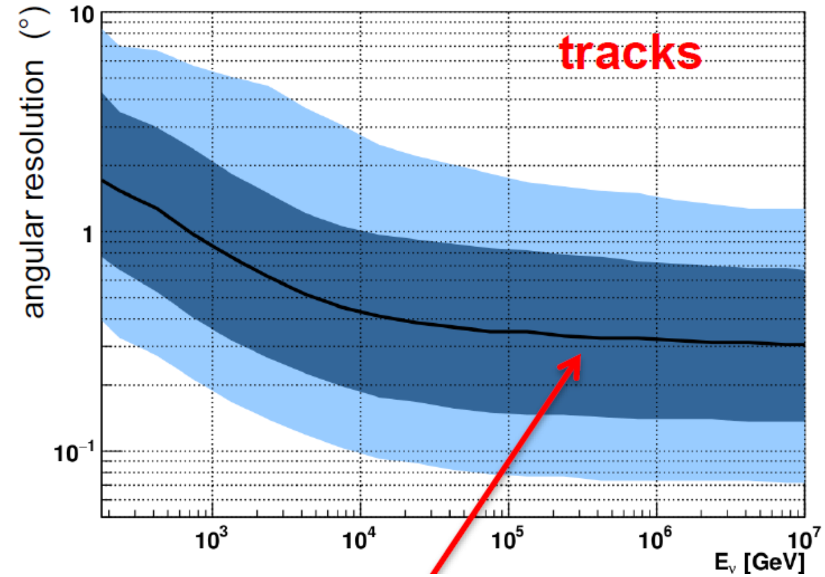


Depth : 2500m

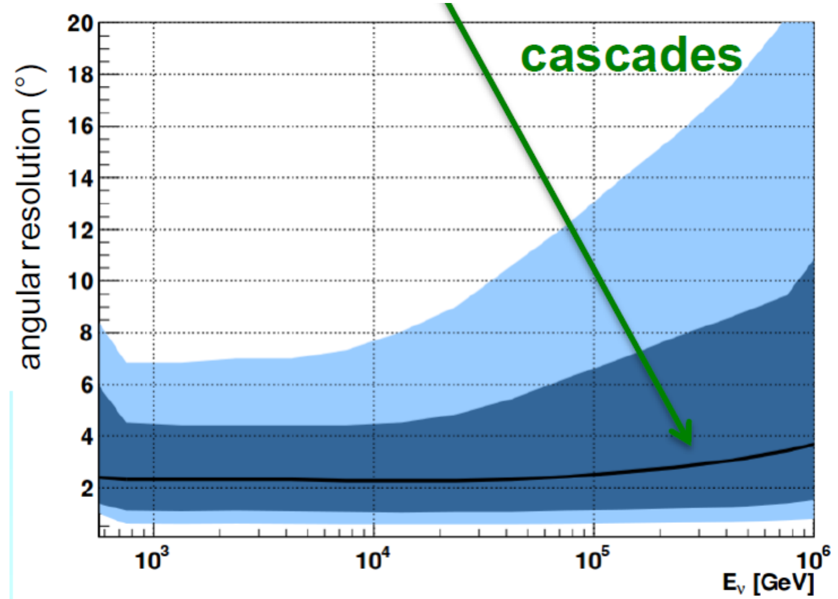
More than 10 years of operation!

Reconstruction Performance

- 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 Energy



- 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

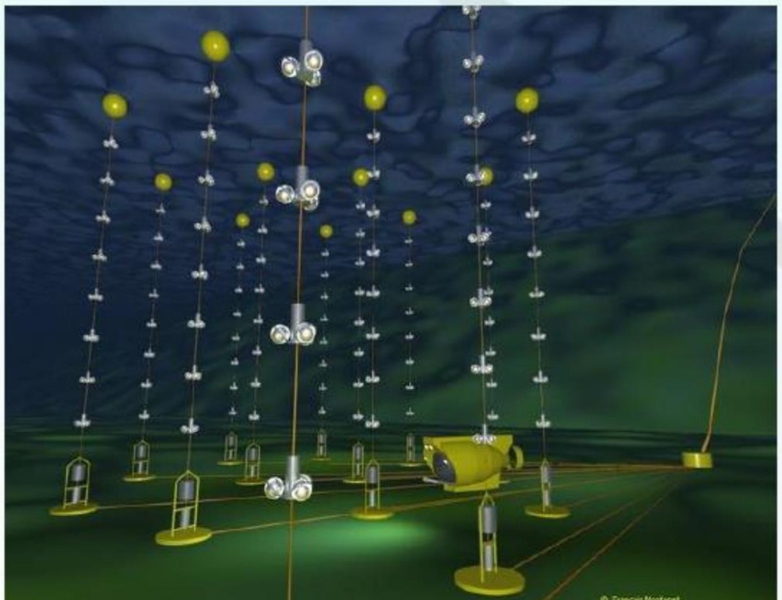
See R. Gozzini's talk for more details about ANTARES

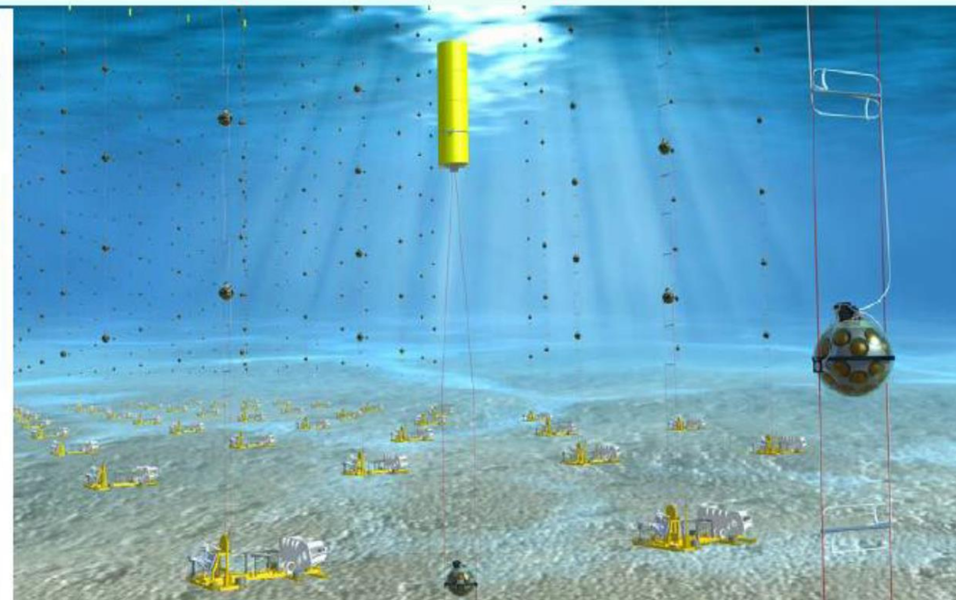
The future of Neutrino Astronomy in the Mediterranean Sea

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

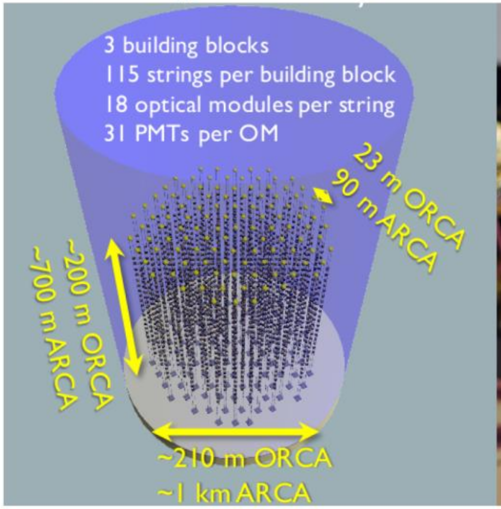
KM3NeT Line

KM3NeT Neutrino Telescope

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

Currently being deployed in French and Italian sites with phased installation scheme



1. ORCA: 1 small, dense block for oscillations and mass hierarchy with atmospheric ν
2. ARCA: 2 large, sparse blocks for astrophysics

} Same technology

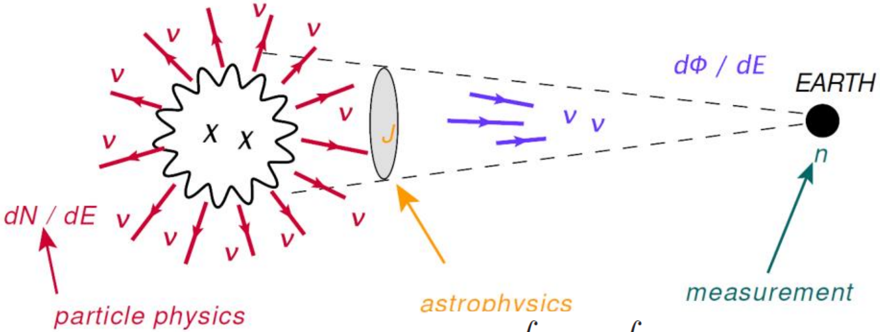
Both suitable for dark-matter searches (being candidate particle mass fairly unconstrained)

See R. Gozzini's talk for more details about KM3NeT

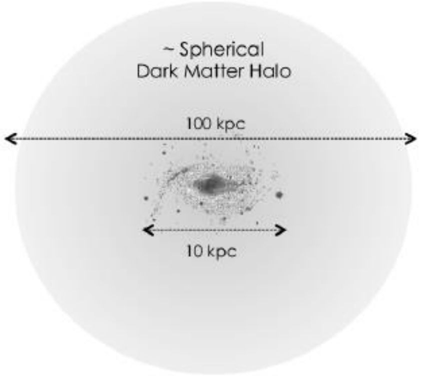
Search for Dark Matter towards the Galactic Centre

Analysis and results in ArXiv: 1912.05296

Favourable source: (1) largest dark-matter density and (2) in the Southern Hemisphere



$$J = \int_{\Omega} d\Omega \int_{l.o.s.} \rho^2 ds$$



$$\mu_{90} = \frac{\Phi}{\mathcal{A}(M_\chi)\, t} = \frac{\langle \sigma v \rangle}{2} \int_0^M \frac{dN}{dE} dE \, \frac{J}{4\pi} \, \frac{1}{M_\chi^2} \, \mathcal{A}(M_\chi)\, t$$

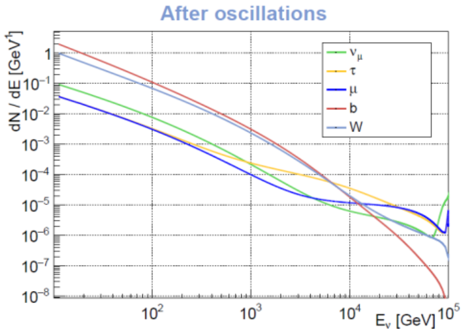
number of events observed = annihilation rate * average number of particles per collision * source geometry * acceptance * time

Search for DM towards the GC: input and setup

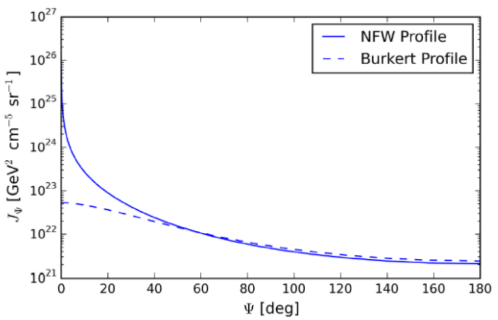
Data set: 11 years (3170 days lifetime), two algorithms for track (ν_μ CC) reconstruction.

Dark-matter signal is reproduced with PPPC4[1] and different models for J-Factor[2] as a cluster of events around the source position, searched for with *unbinned likelihood method*.

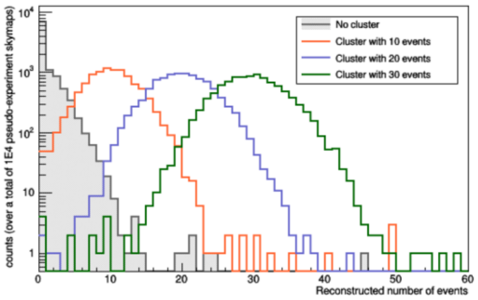
$$\log \mathcal{L}(n_s) = \sum_{i=1}^{N} \log \left[n_s\, S(\psi_i, N^i_{\mathrm{HITS}}) + n_{bg}\, B(\delta_i, N^i_{\mathrm{HITS}}) \right] - n_{bg} - n_s$$



Energy distribution



Morphology



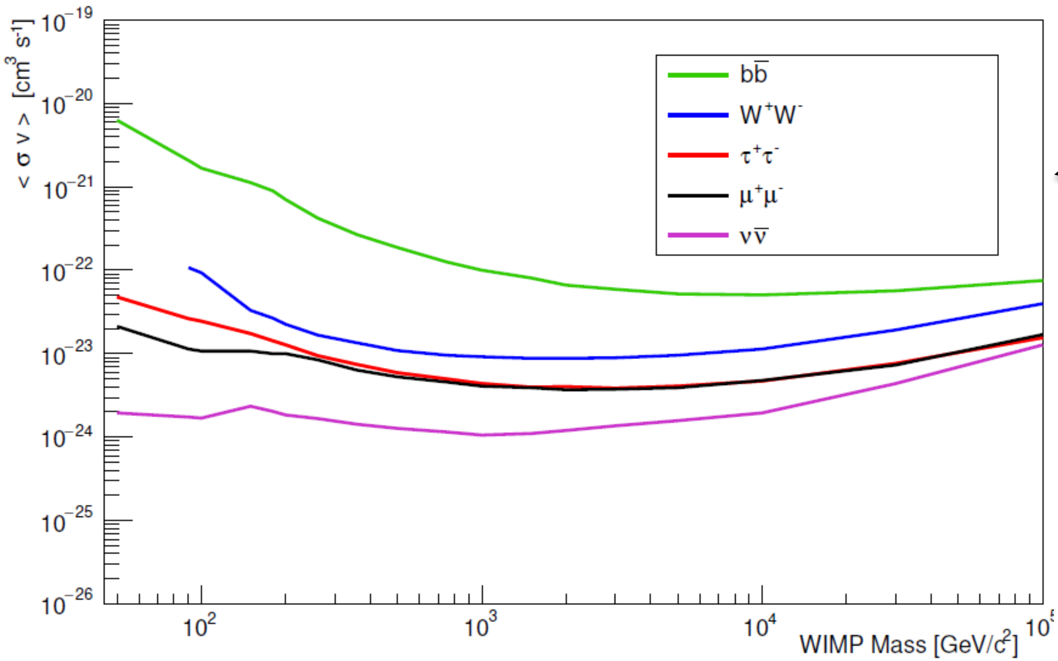
Pseudo-experiments

Background is described with right-ascension shuffled (*blind*) data

[1] http://www.marcocirelli.net/PPPC4DMID.html [2] Burkert [ApJ 1995], NFW [ApJ 1996], McMillan [MNRAS 2017]

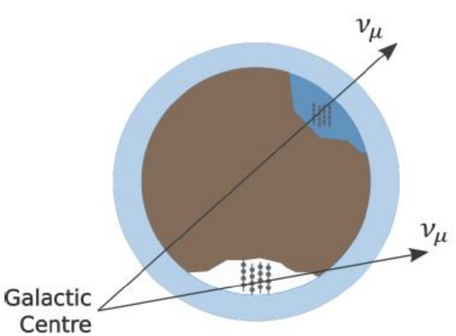
Search for DM towards the GC: Unblinding results

The test statistic for 11 years of ANTARES data is compatible with background

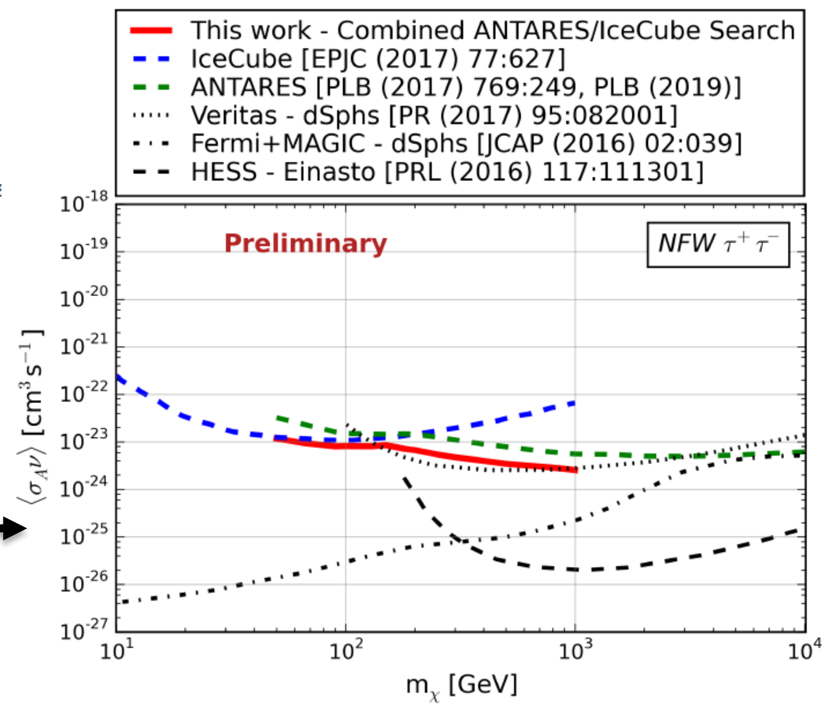


ArXiv: 1912.05296

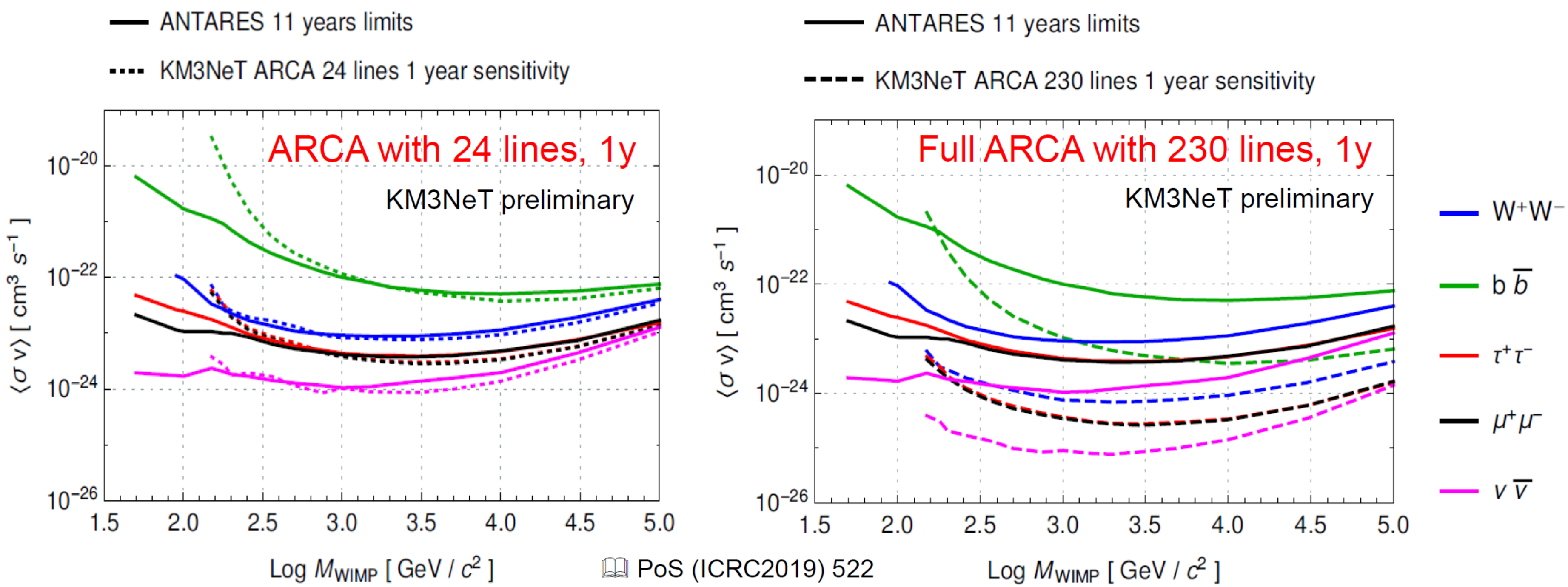
Upper limits on $\nu_\mu + \bar{\nu}_\mu$ flux at 90% CL are converted into limits on the thermally averaged annihilation cross section for WIMP pair annihilation $\langle \sigma v \rangle$, for five channels inspected.



Combined analysis ANTARES-IceCube PoS(ICRC2019) 522

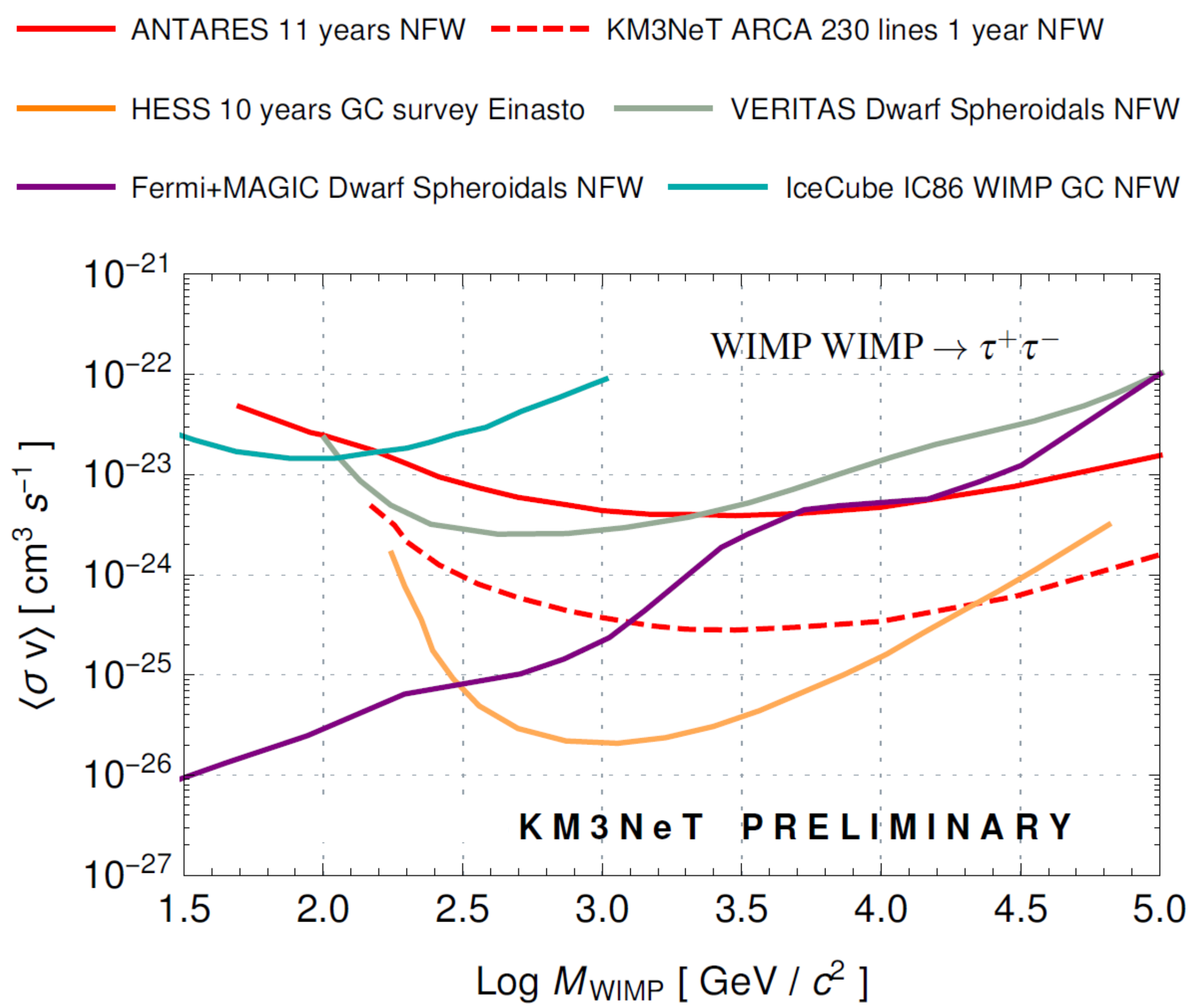


Search for DM towards the GC: KM3NeT-ARCA sensitivities



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

Search for DM towards the GC: Summary results



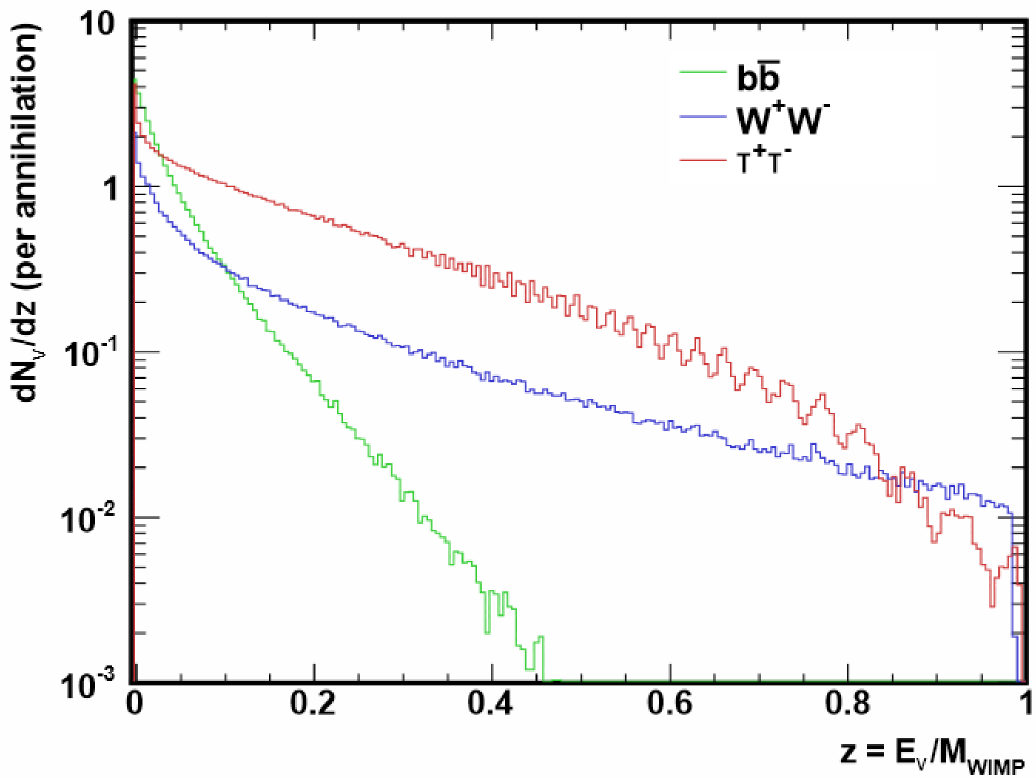
Search for Dark Matter towards the Sun

Analysis and results of 2007-2012 data in **Phys. Lett. B 759 (2016) 69**
arXiv:1603.02228

- Sensitive to DM-nucleon scattering cross-section, spin-dependent and spin-independent
- Differential neutrino flux is related with the annihilation rate $\frac{d\Phi}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu}$
- In equilibrium between capture and annihilation $\Gamma = C/2$ with C capture rate
- Very clean: if signal $\rightarrow$ direct interpretation (astrophysical background well known)
- Less affected by halo uncertainties (point-like extension)
- Signal from moving source: bias-free
- Searches with neutrino telescopes are sensitive at low velocities (= easier capture)

Search for Dark Matter towards the Sun: Input

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**

Search for Dark Matter towards the Sun: Strategy and results

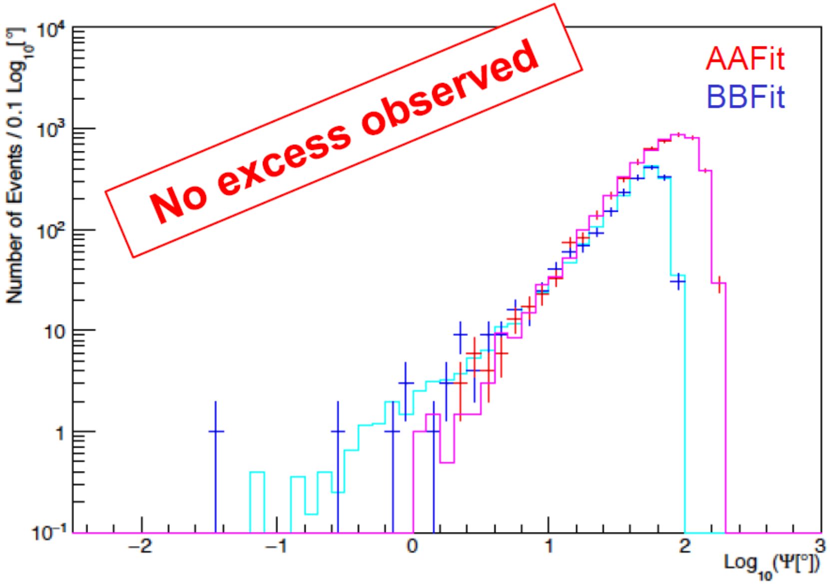
- **Maximisation of the Likelihood function based on Signal and Background PDFs :**

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

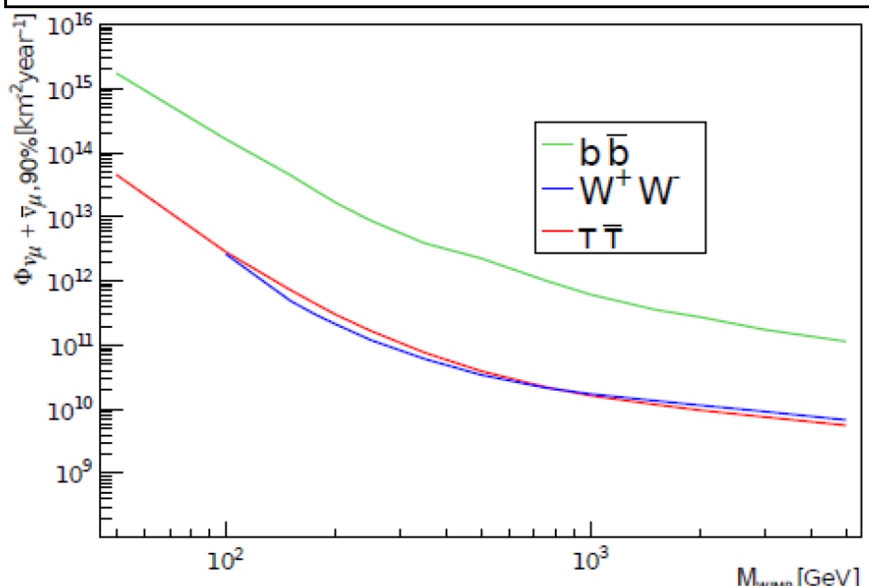
N_{hit} = *number of hit used for the track reconstruction*
β = *the angular error estimate for the reconstructed track*
N_{tot} = *tot. Number of reconstructed events*
n_s *and* N_{bg} *are the number of signal and background events*

- **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



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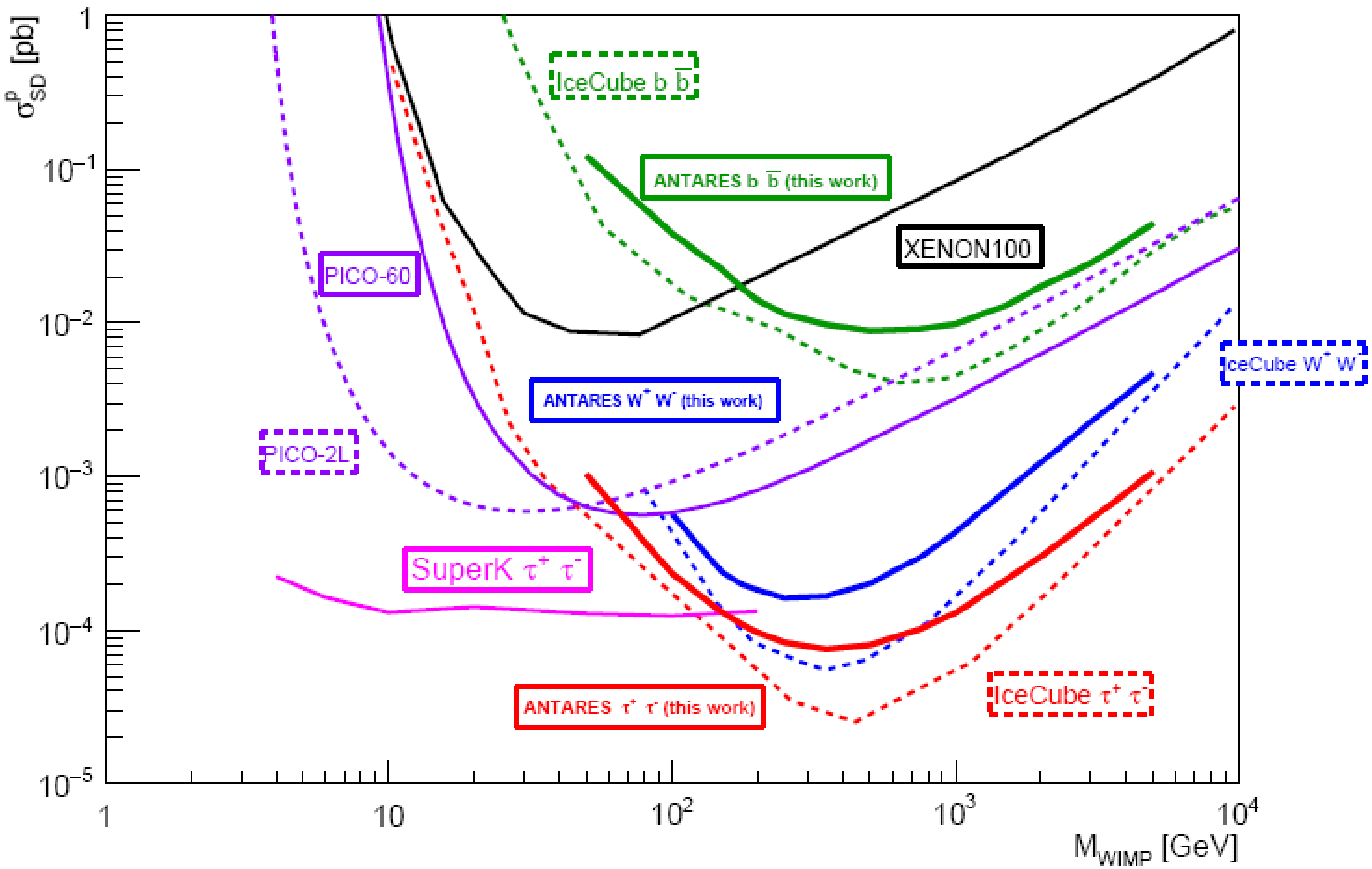
Limits on Spin Dependent cross sections

Conversion to **limits on WIMP-proton Spin Dependent cross sections** assuming equilibrium between capture and annihilation rates inside the Sun

→ **much better sensitivity of neutrino telescopes on SD cross-section** w.r.t. direct detection (presence of Hydrogen inside the Sun)

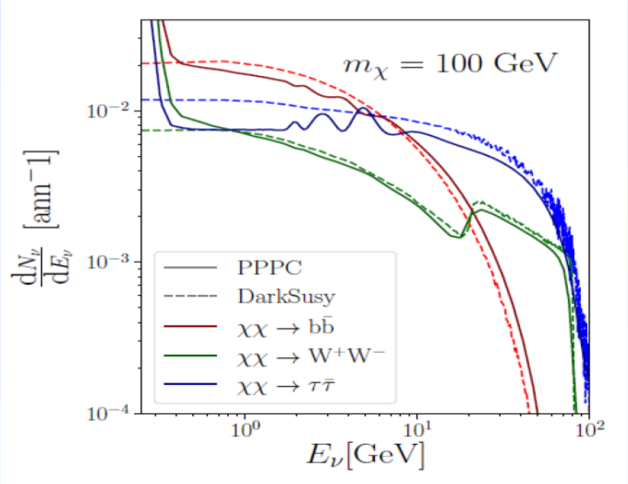
(Worse sensitivity to SI cross-section compared to Direct Detection experiments)

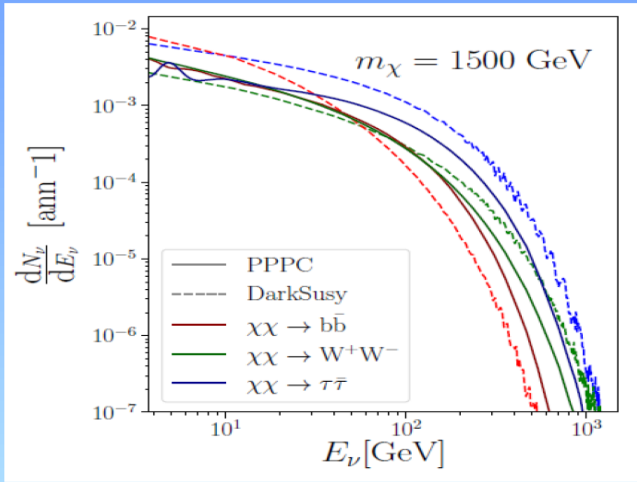


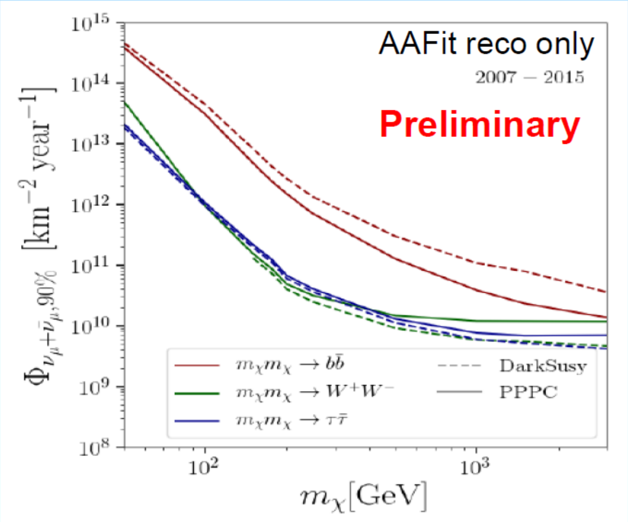
Update of Sun analysis under progress with 2007-2017 data

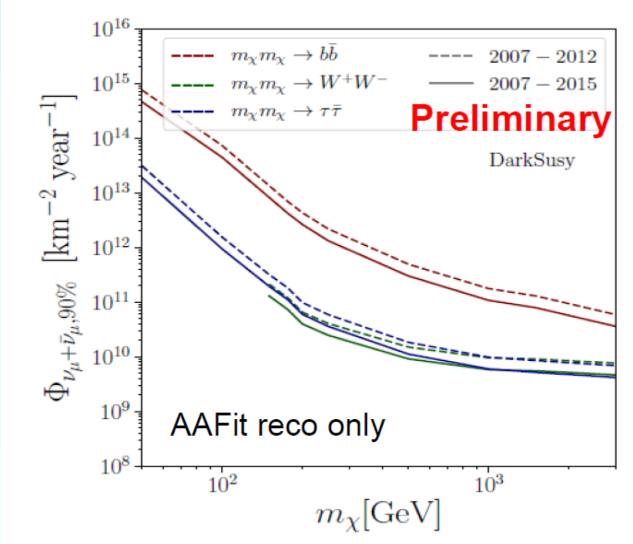
Comparison between PPPC spectra including radiative correction effects vs WIMPSIM

→ large differences for b-bbar and tau+tau- annihilation channels









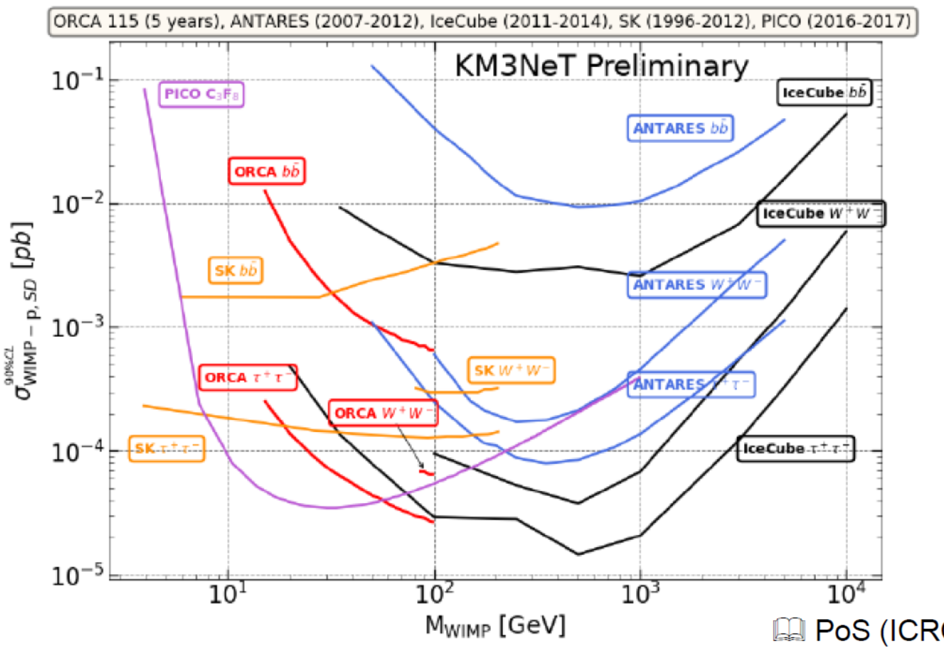
→ Factor ~2-3 improvement of sensitivity expected w.r.t. published limit

Search for DM towards the Sun: KM3NeT-ORCA sensitivities

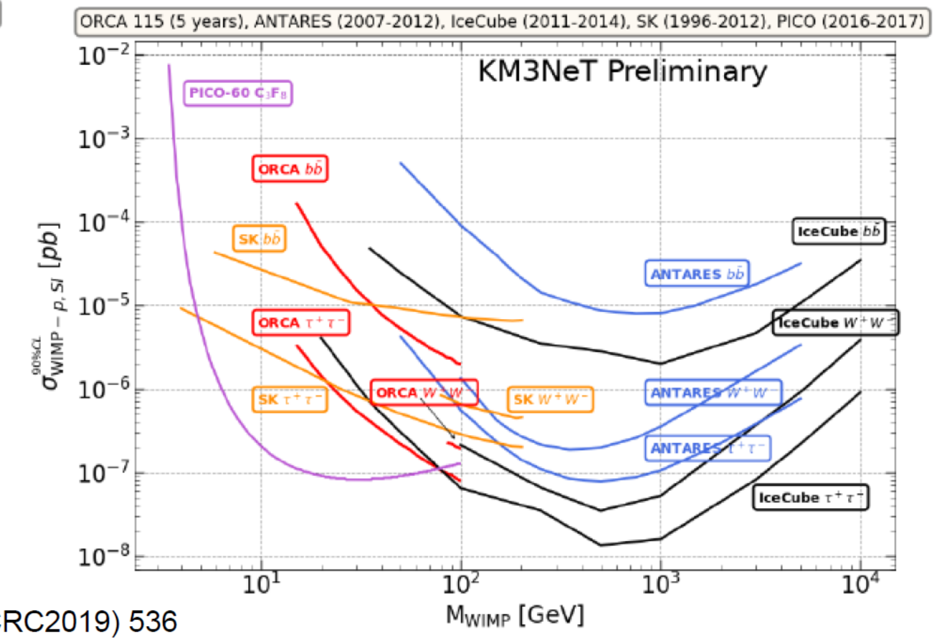
Preliminary study of ORCA sensitivity for WIMP annihilation in the Sun

→ **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



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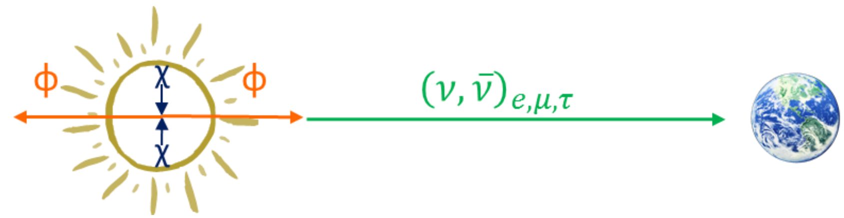
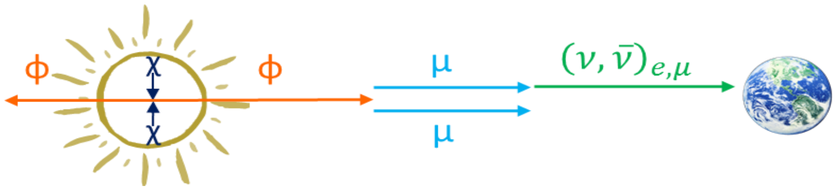
Sensitivity study of KM3NeT/ARCA for DM searches in the Sun under progress…

Search for **Secluded DM** in the Sun

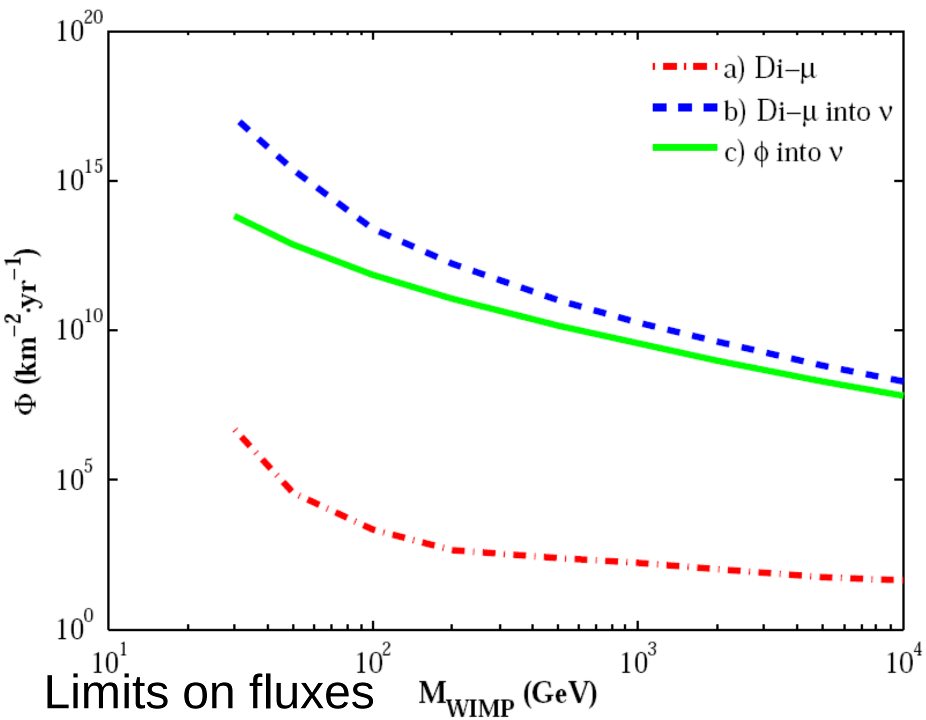
Analysis and results in **JCAP 05 (2016) 016,** arXiv:1602.07000



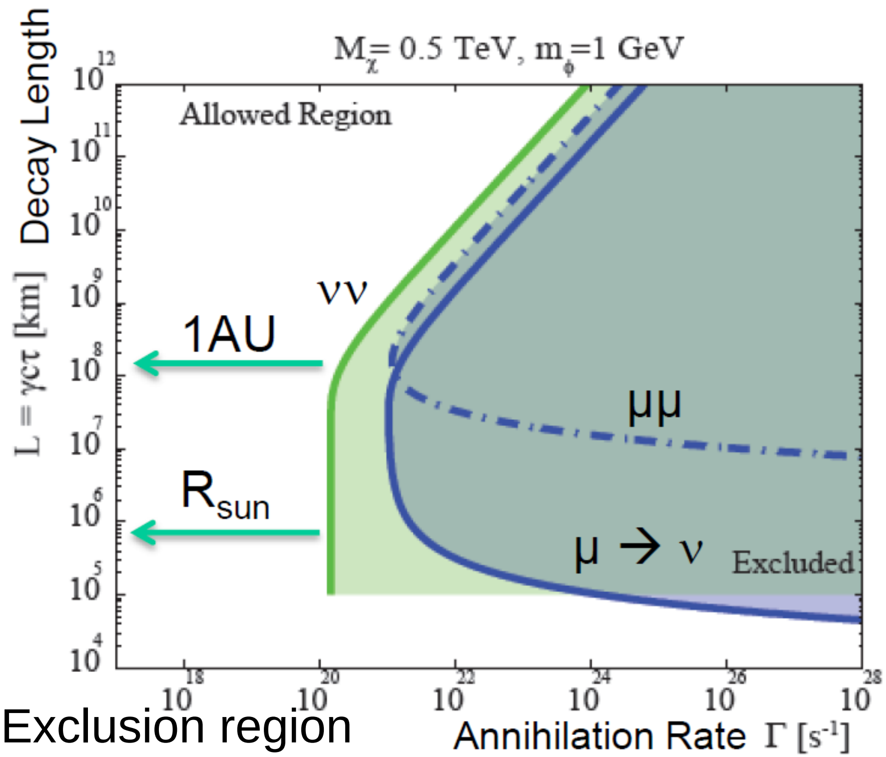


Testing models from:

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

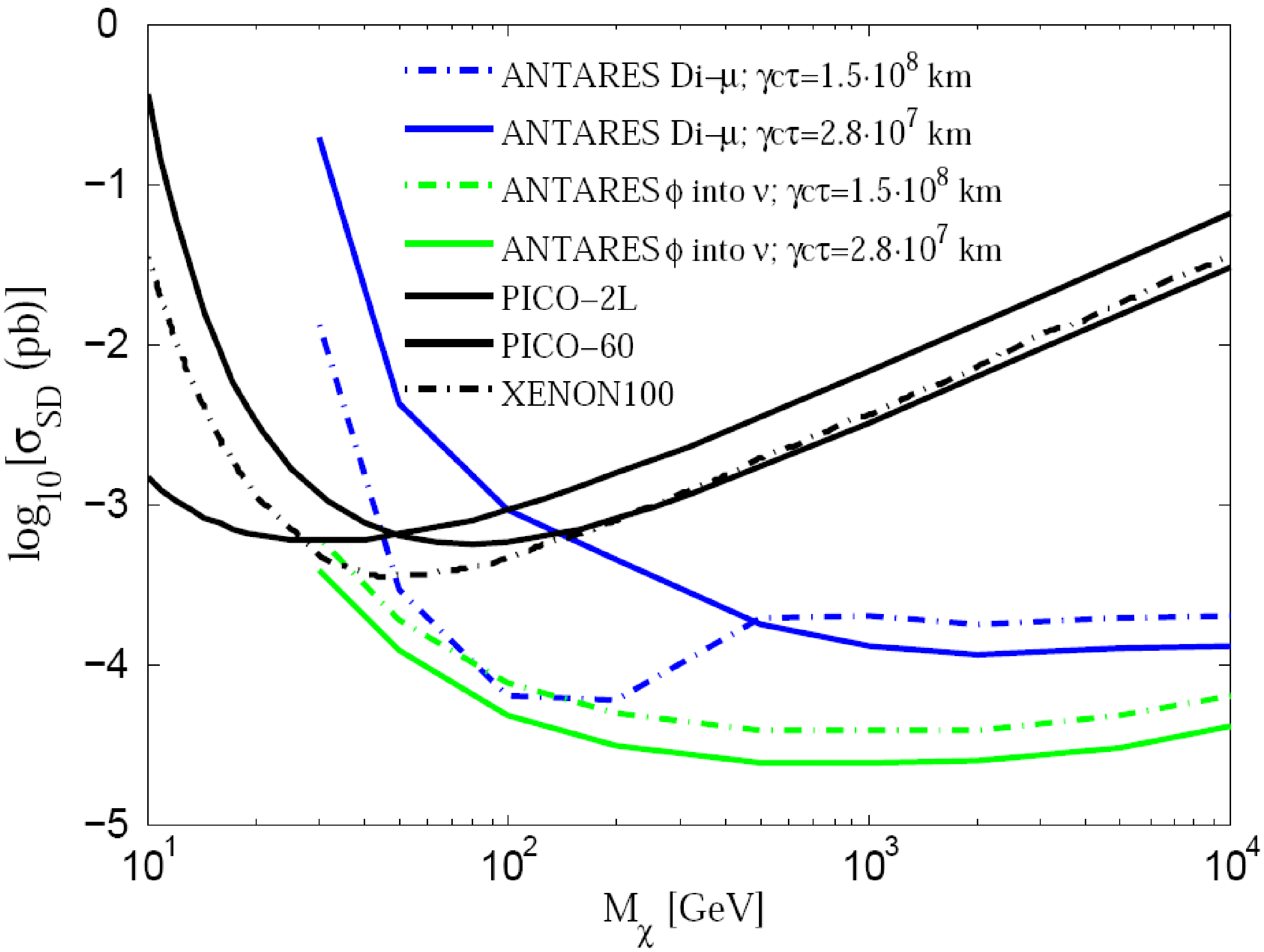


Limits on fluxes



Exclusion region

Search for **Secluded DM** in the Sun

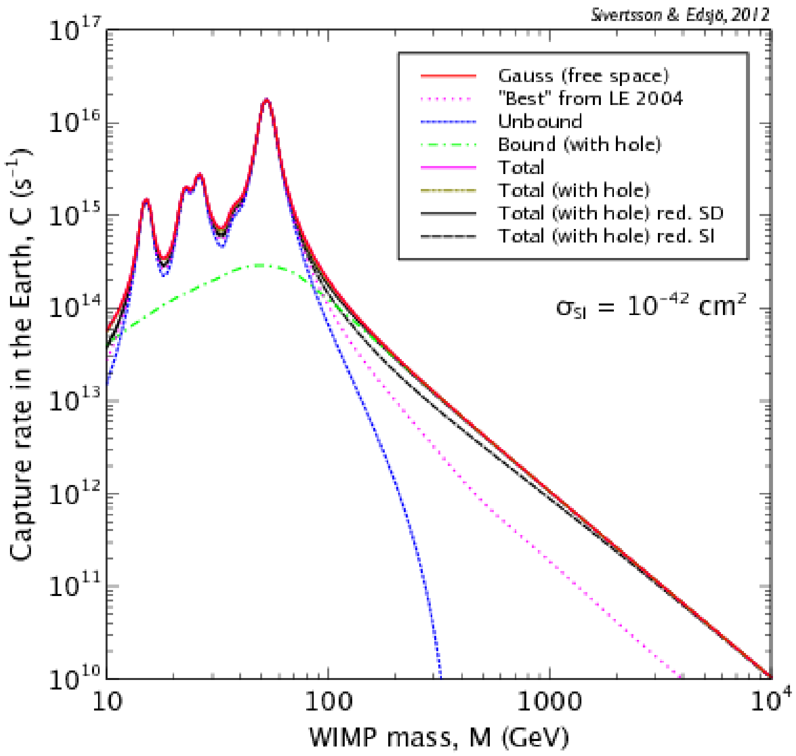


First constrains to these models from neutrino telescopes

Restrictive limits for Spin Dependent proton-WIMP cross-section in secluded models for sufficiently long-live but unstable mediators

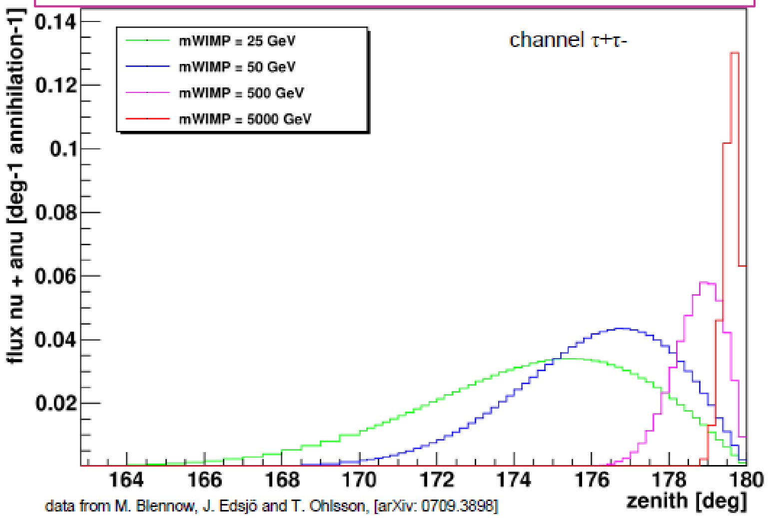
Indirect Search for Dark Matter in the Earth

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

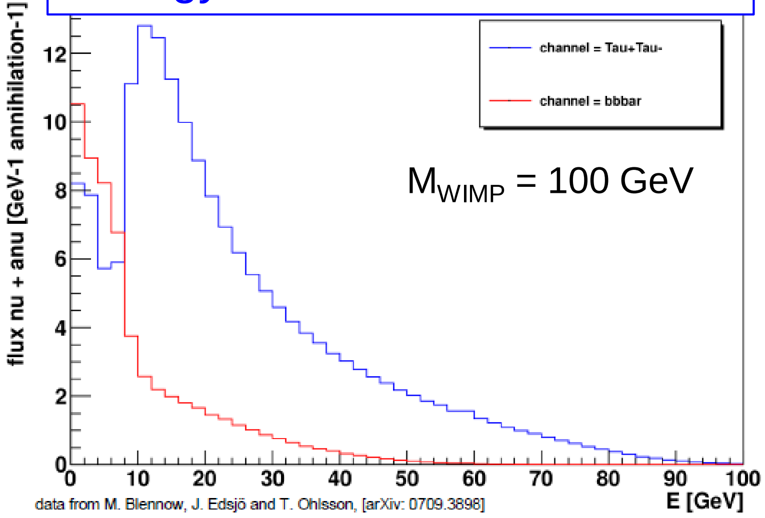


from M. Blennow, J. Edsjo and T. Ohlsson, arXiv:0709.389

Angular distribution of neutrinos



Energy distribution of neutrinos

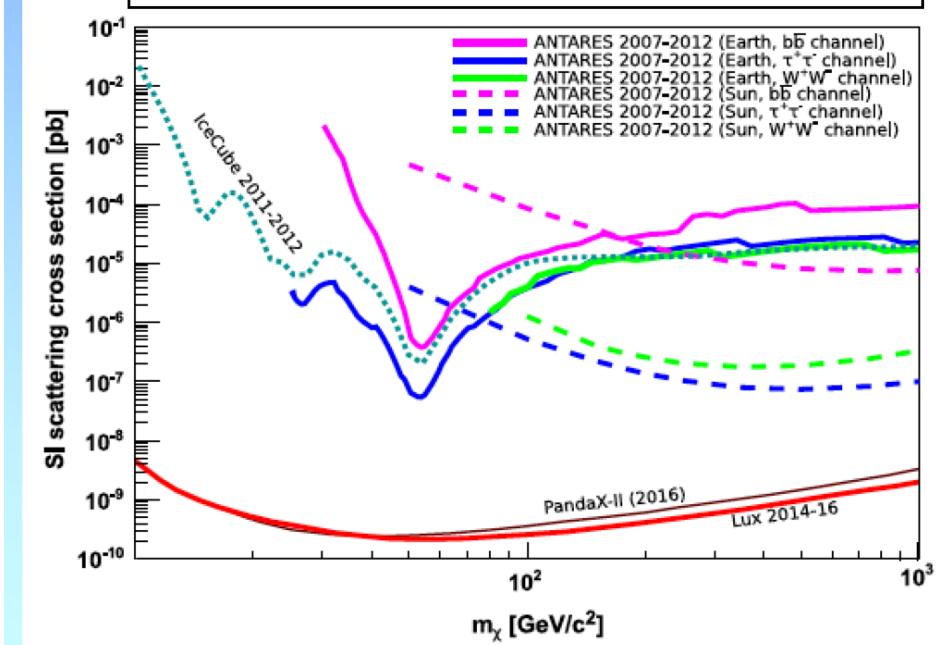


Limits to SI scattering cross-section

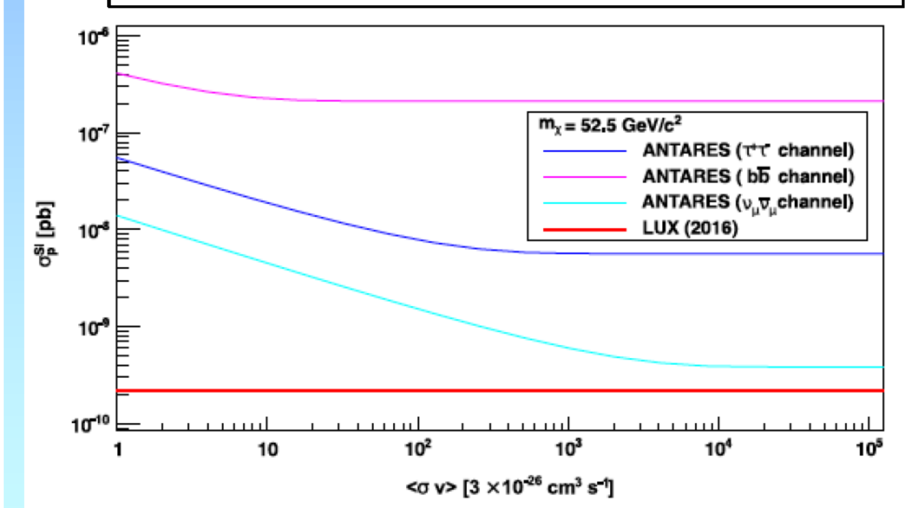
- Search for vertical neutrino events in 2007-2012 ANTARES data → no excess
- Dark Matter density usually not at equilibrium due to low capture rates by the Earth

→ Assume **annihilation rate** <σ v> = 3×10^{-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 resonance)



Scenario with boosted annihilation cross-section

📖 Physics of the Dark Universe 16 (2017) 41

Summary and Outlook

- **Indirect search for Dark Matter** is a **major goal** for neutrino telescopes
- **Important complementarity to direct detection experiments (Sun) and gamma searches (Galactic Centre / Halo)**
- **Competitive limits obtained by ANTARES on indirect searches towards the Galactic Centre**
- **More analyses are under progress:**
  - **Full ANTARES data set (end of ANTARES data taking in 2020)**
  - **Inclusion of shower events (ν_e/ν_τCC + ν NC events)**
- **2020+ : Improved sensitivity with KM3NeT**
  - **Sun : extension to low WIMP masses (ORCA)**
  - **Galactic Halo : higher sensitivity expected at high WIMP masses (ARCA)**

Thank you for the attention