Dark Matter Searches with the ANTARES and KM3NeT Neutrino Telescopes

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on behalf of the ANTARES and KM3NeT Collaborations

EPS-HEP 2021 Conference
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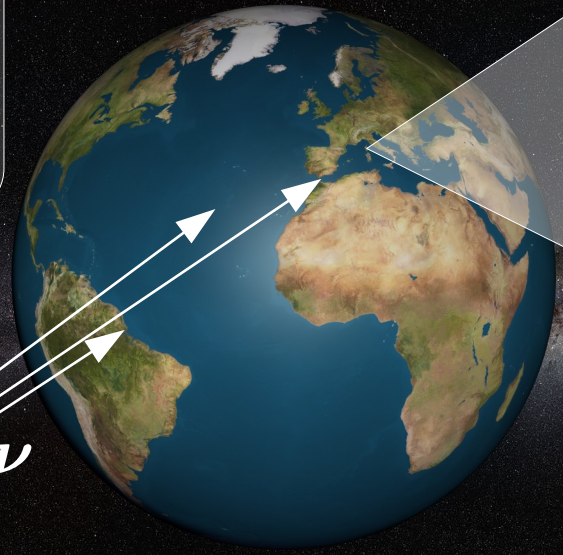
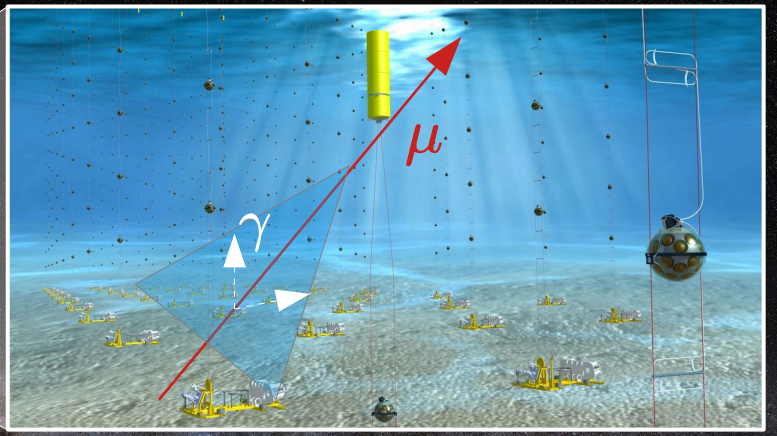
UNIVERSIDAD DE GRANADA

WIMP Dark Matter Indirect Detection

- Relic WIMPs are captured in celestial bodies.
- DM annihilates into SM particles (c, b, t quarks, leptons or W, Z bosons) that yield neutrinos as final state particles.





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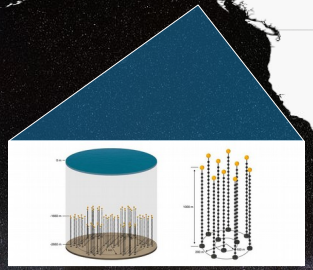
ν

- Neutrinos are less affected by astrophysical uncertainties than γ-ray indirect detection.

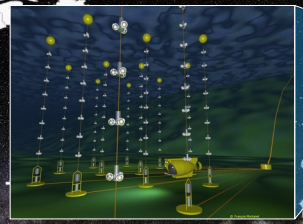
- These neutrinos are detected through Cherenkov light emitted by the products (relativistic charged particles) of the neutrino interaction.
- Cherenkov light is detected by the PMTs distributed in vertical strings (Detection Units).
- Events are reconstructed from timing and position of the PMT hits.
- Trigger algorithms classify reconstructed events and distinguish light from neutrinos and from background emission (^{40}K, bioluminescence, downgoing atm. muons).

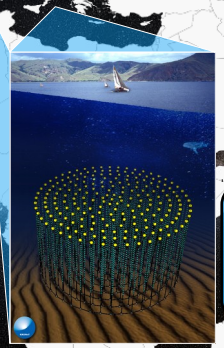
Neutrino Telescopes around the World



P-ONE
(Under Construction)

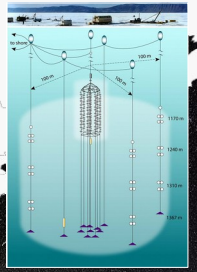
ANTARES, 0.01 km^3



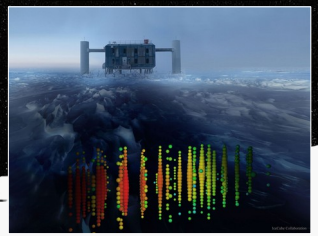


KM3NeT, 1 km^3
ARCA (Italy) and ORCA (France)
(Under Construction)

Baikal/GVN, 1 km^3
(Under Construction)

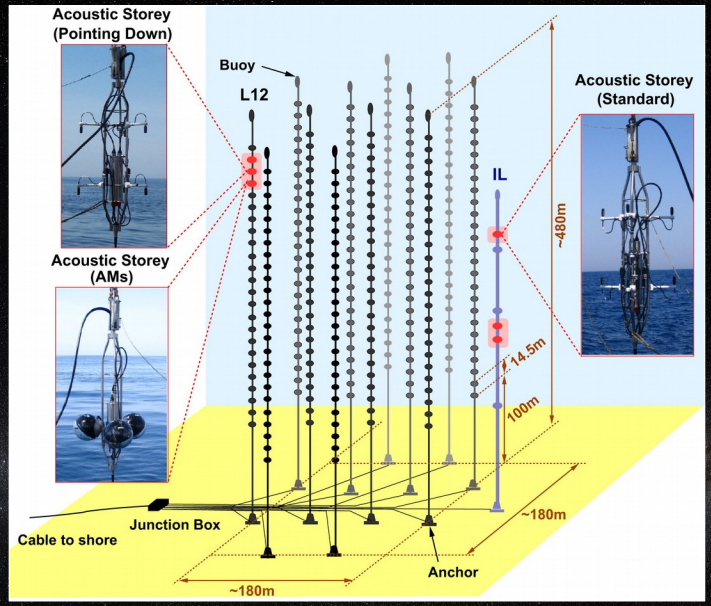


IceCube, 1 km^3



IceCube Gen 2, 10 km^3
(Projected)

ANTARES



ANTARES

- 2007-2008 construction.
- Anchored at 2500 m on the seabed.
- 40 km offshore of Toulon (France).
- 12 Lines.
- 25 Storeys/Line.
- 3 PMTs/Storey.
- ~ 900 PMTs.

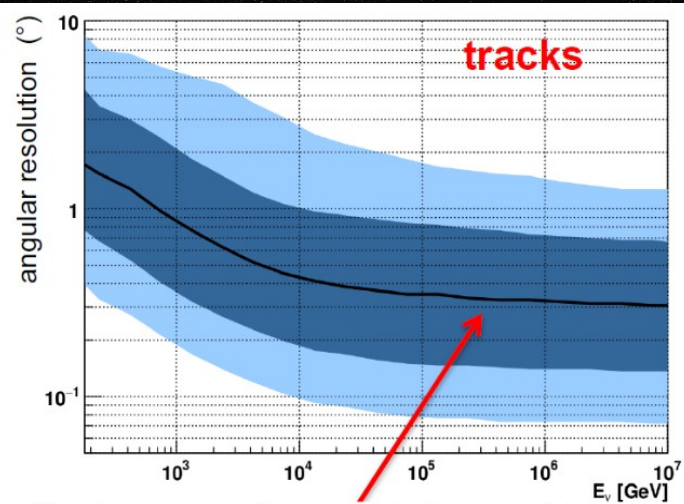
Track events (ν_μ CC)

- Upgoing events.
- Angular resolution < 0.4 ° for E_ν > 10 TeV.
- Long path (higher energy events aren't contained within the detector volume):
  - Better angular resolution.
  - Worse energy resolution.
- High atmospheric μ background.

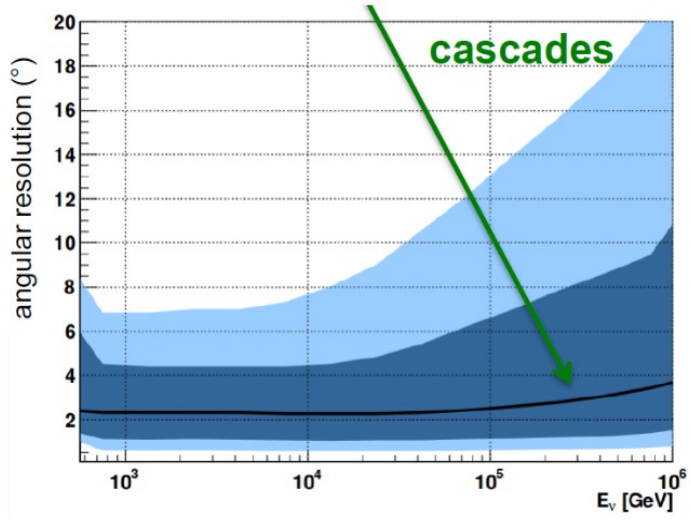
Cascades events (ν_e-ν_τ CC, NC)

- Upgoing events.
- Angular resolution < 3 °.
- Contained events:
  - Better energy resolution.
  - Worse angular resolution.
- Low atmospheric background.

ANTARES The first undersea neutrino telescope
NUCL INSTRUM METH A, Vol 656, 2011

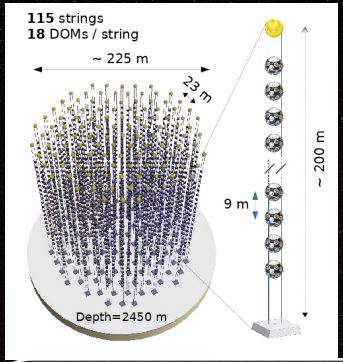


Median angular resolution vs Energy



KM3NeT

Letter of intent for KM3NeT 2.0
J. Phys. G (43) (2016) no.8



Track events (ν_μCC)

- Upgoing events.
- Angular resolution < 0.3 ° for E_ν > few TeV.
- Long path (higher energy events aren't contained within the detector volume):
  - Better angular resolution.
  - Worse energy resolution.
- High atmospheric μ background.

ARCA

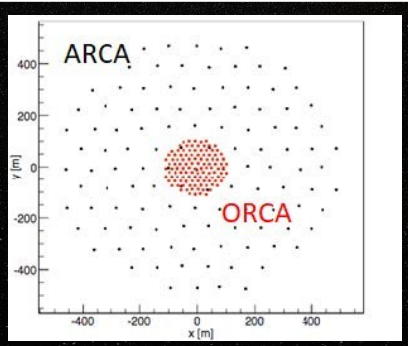
- Anchored at 3500 m on the seabed.
- 100 km offshore of Porto Palo (Italy).
- 2 building blocks:
  - 115 strings/block, 700 m height, 95 m horizontal spacing.
  - 18 DOMs/string, 36 m vertical spacing.
- Optimized for GeV-TeV neutrino detection.

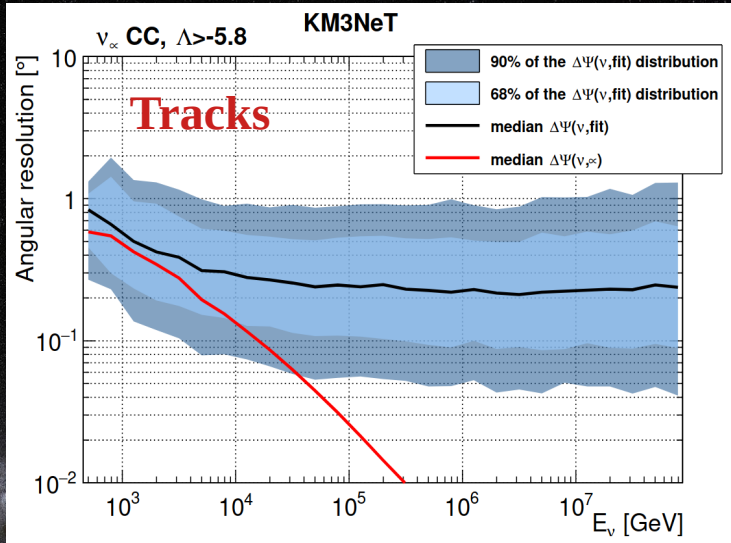
Cascades events (ν_e-ν_τ CC, NC)

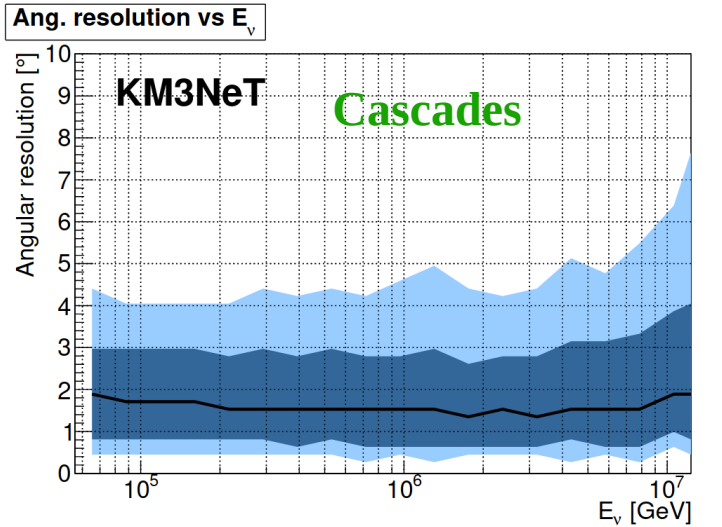
- Upgoing events
- Angular resolution < 2 °.
- Contained events:
  - Better energy resolution.
  - Worse angular resolution.
- Low atmospheric background.

ORCA

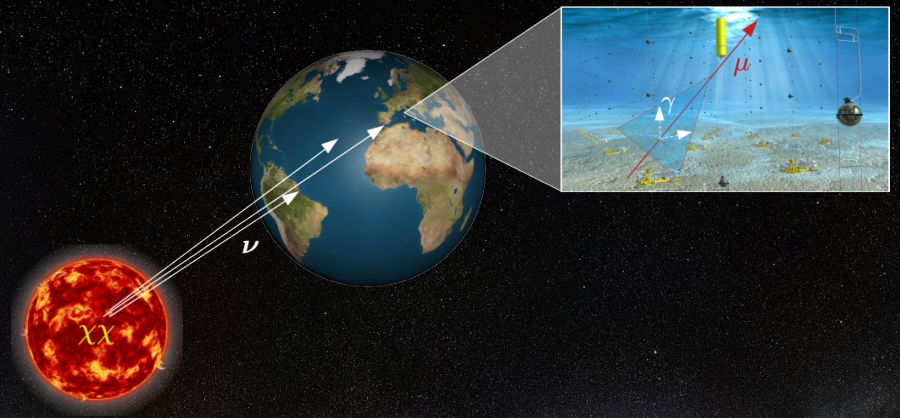
- Anchored at 2450 m on the seabed.
- 40 km offshore of Toulon (France).
- 1 small, dense building block:
  - 115 strings, 200 m height, 20 m horizontal spacing.
  - 18 DOMs/string, 9 m vertical spacing.
- Optimized for ν oscillation and mass ordering.







Dark Matter in the Sun

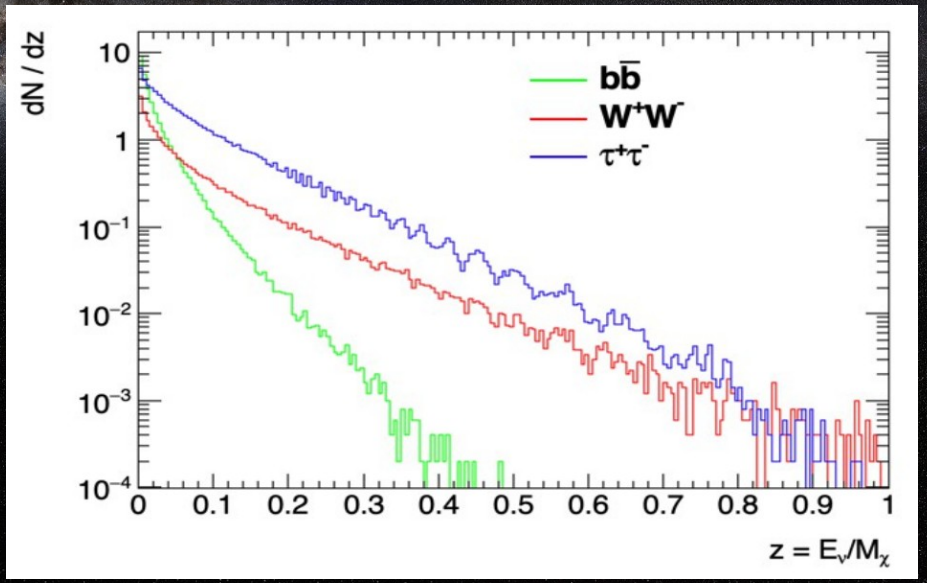


Neutrino Signal from WIMP Annihilation

- WIMPSim package[†] 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 benchmark.
- Take into account ν interactions in the solar medium, regeneration of ν_τ in the Sun and ν oscillations.

[†]JCAP01(2008)021

- Sensitive to DM-nucleon scattering cross-section, spin-dependent (SD) and spin-independent (SI).
- Differential neutrino flux is related to the annihilation rate $\frac{d\phi}{dE} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu}$
- In equilibrium between capture and annihilation $\Gamma = C/2$
- Very clean signal (if any). Direct interpretation (well known astrophysical background).
- Signal from moving source: bias-free.



Dark Matter in the Sun: ANTARES

Phys. Lett. B 759 (2016) 69

Strategy

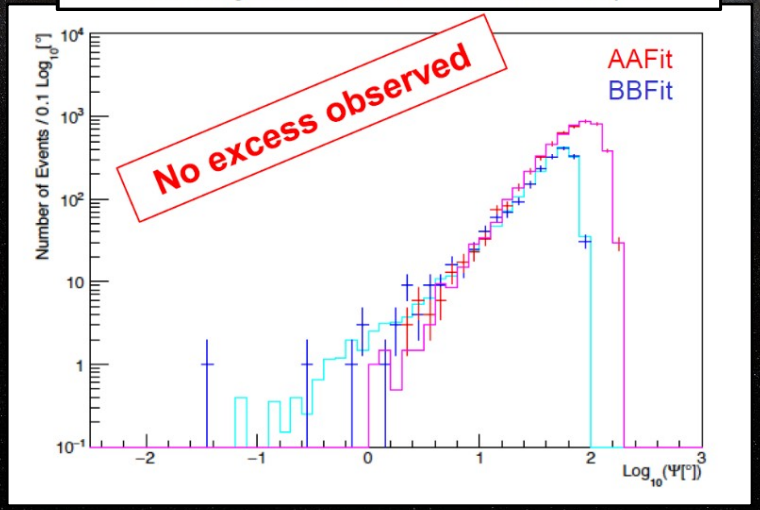
Maximization of the Likelihood function based on Signal and Background PDFs

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

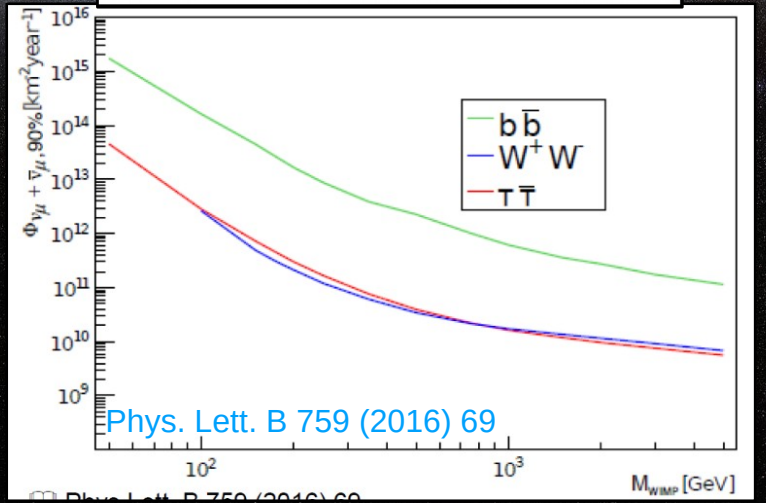
- Signal PDF from MC simulation based on WIMPSim spectra.
- Background PDF from time scrambled data.

- N_{hit} : number of hits used for track reconstruction.
- β : error in the reconstructed track angle.
- N_{tot} : total number of reconstructed events.
- ψ : angular distance to the source.
- n_s and N_{bg} number signal and background events

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



Dark Matter in the Sun: ANTARES

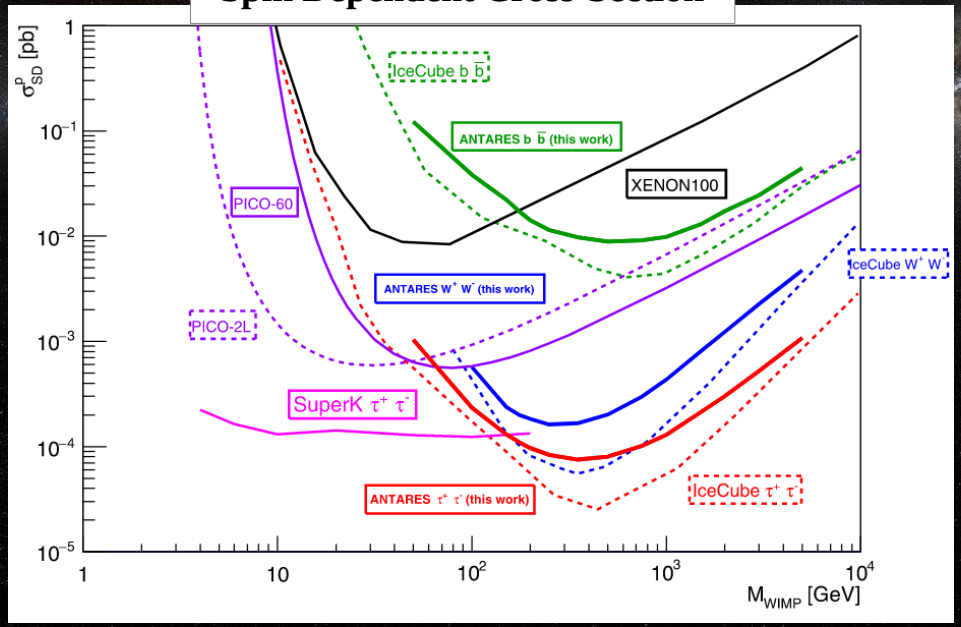
Phys. Lett. B 759 (2016) 69

Limits on the SD and SI Cross-Sections

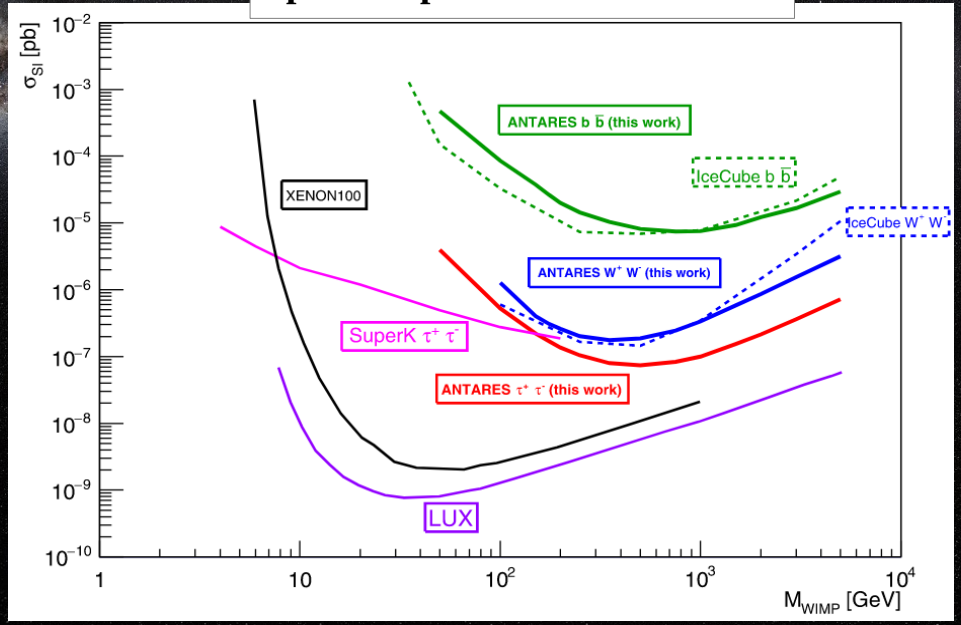
Conversion to limits on WIMP-nucleon SD and SI cross-section, assuming:

- 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.

Limit on Spin Dependent Cross-Section



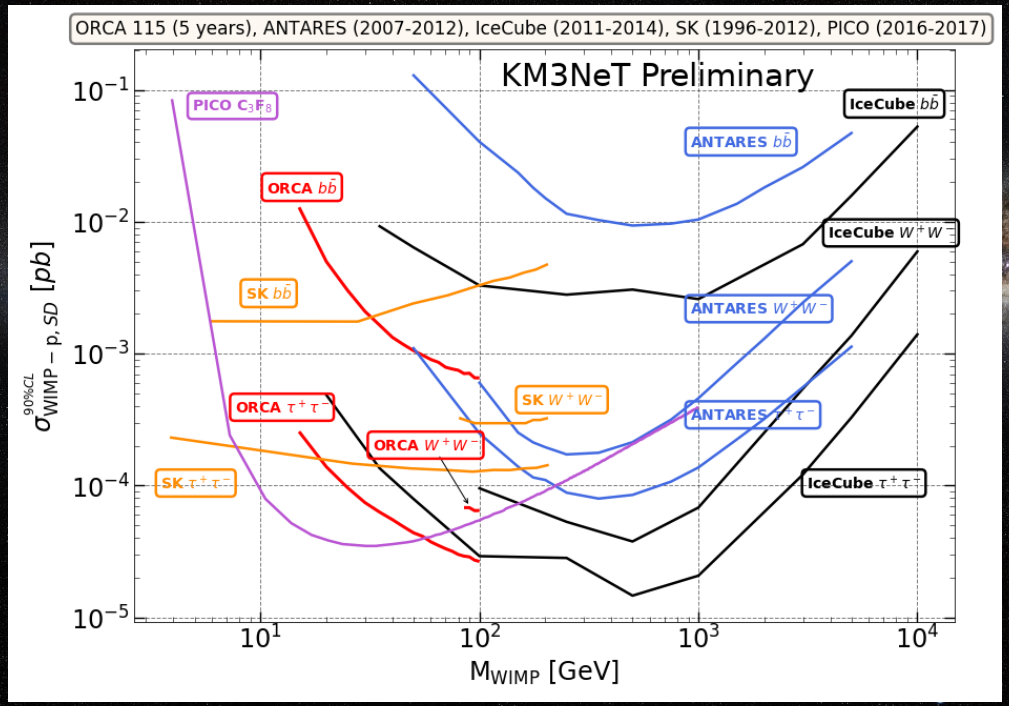
Limit on Spin Independent Cross-Section



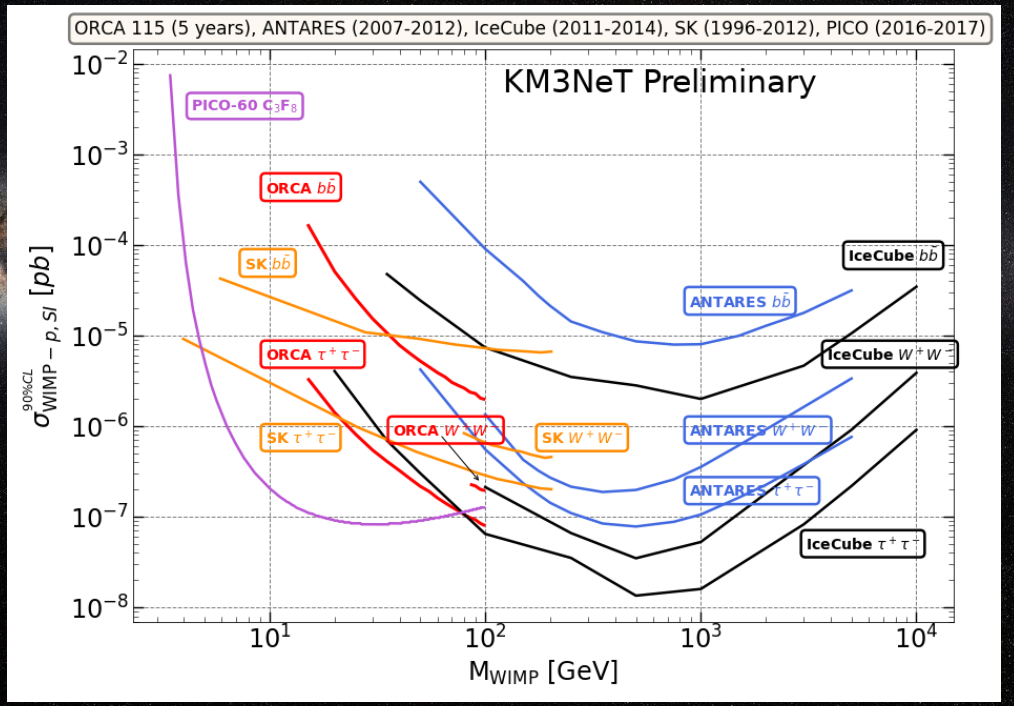
Dark Matter in the Sun: KM3NeT

PoS ICRC2019 (2020) 536

Preliminary studies on sensitivities to WIMP-proton scattering cross-section for 5 years of KM3NeT-ORCA simulated data.



Spin-Dependent Cross section



Spin-Independent Cross section

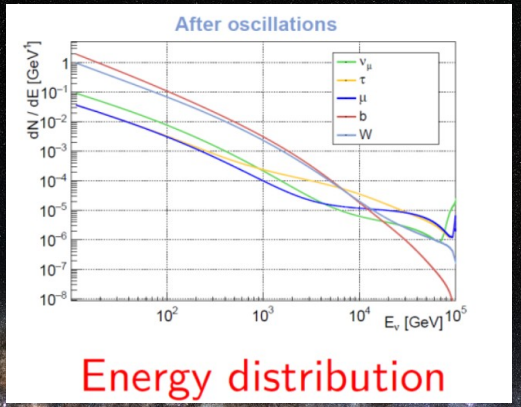
DM Searches towards the Galactic Center

Physics Letters B, Vol 805,2020

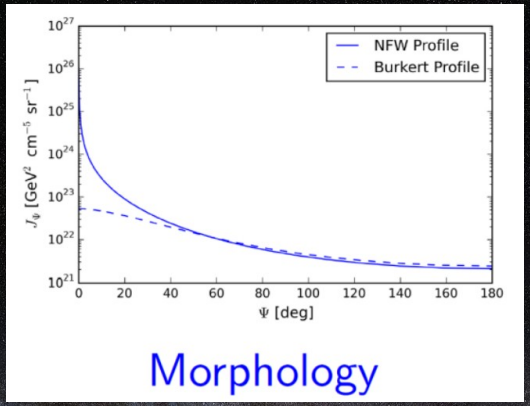
Strategy

- Unbinned likelihood method, to search for signal signatures.
- Signal PDF from MC. PPPC4 signal spectra and different models for J-Factor.
- Background PDF from scrambled data.

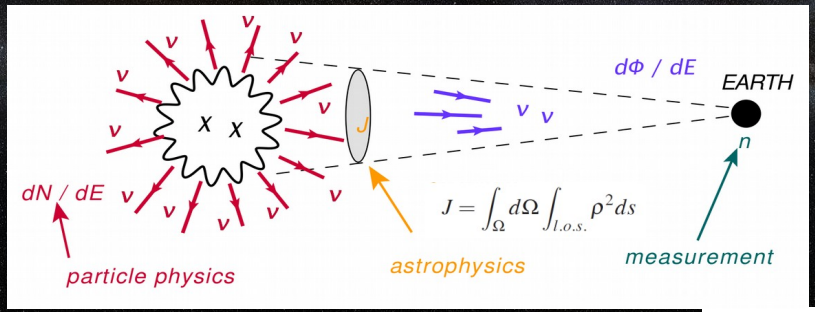
$$\mathcal{L}(n_s) = e^{-(n_s+N_{bg})} \prod_{i=1}^{N_{tot}} [n_s S(\psi_i, N_{hit,i}, \beta_i) + N_{bg} B(\delta_i, N_{hit,i}, \beta_i)]$$



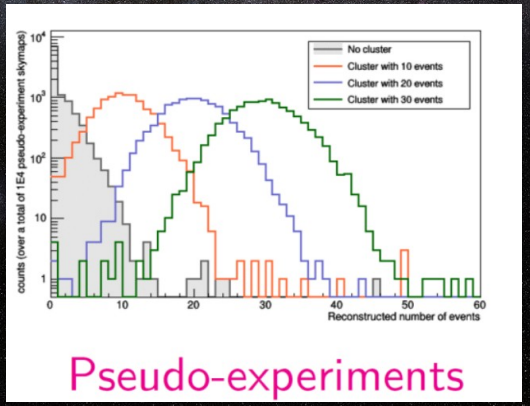
Energy distribution



Morphology



- J-Factor accounts for the morphology of the source.

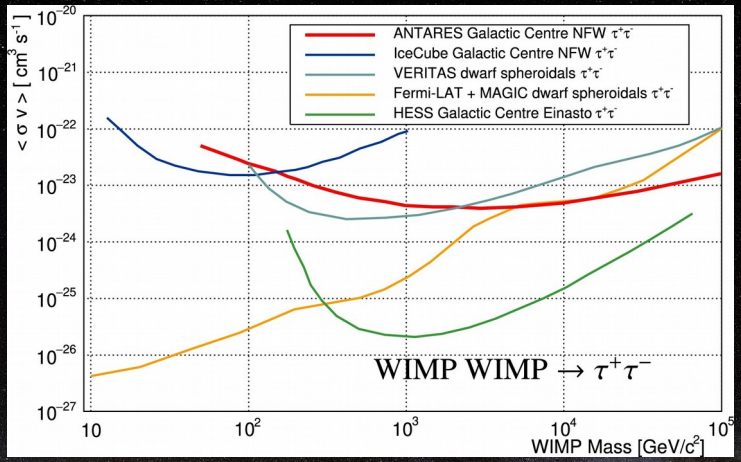


Pseudo-experiments

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

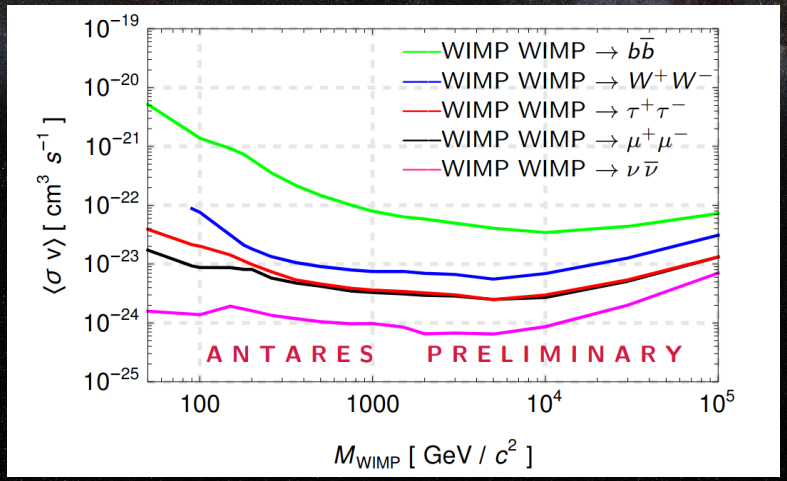
number of events observed = annihilation rate * average number of particles per collision * source geometry * acceptance * time

DM Searches towards the Galactic Center: ANTARES

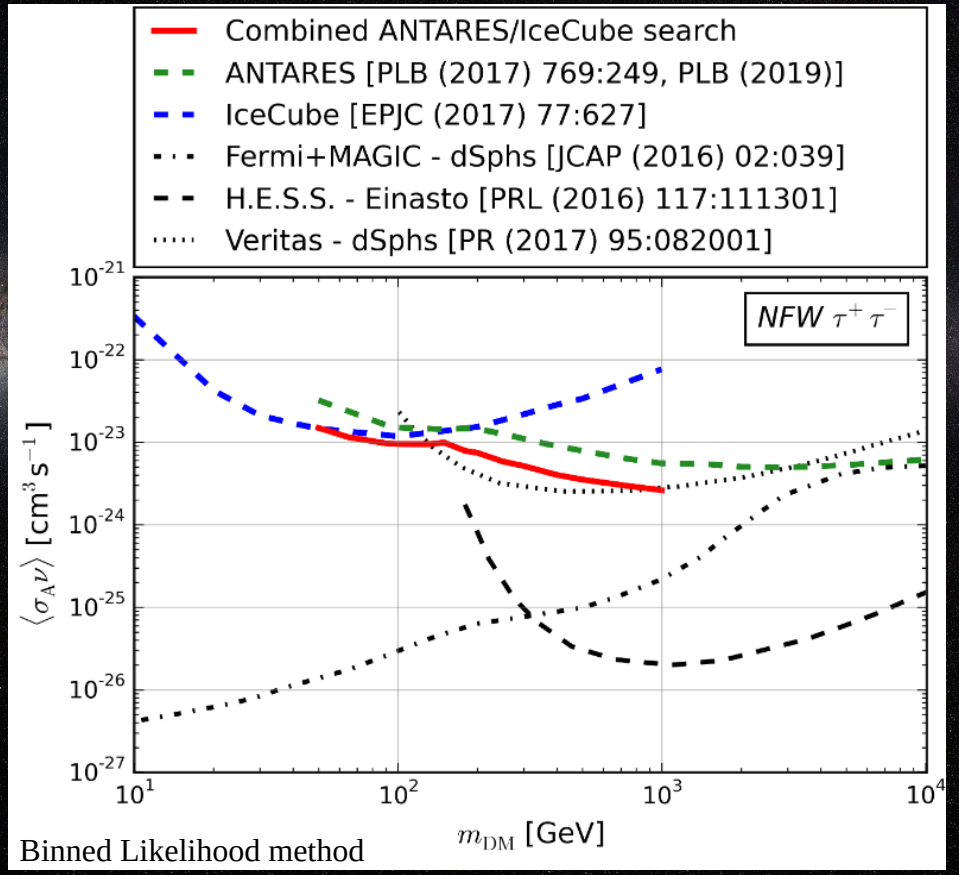


ANTARES GC,
11 years of Data (2007-2017)
Physics Letters B, Vol 805,2020

ANTARES + IC combined GC,
11 years of Data (2007-2017)
PRD 102 (2020) 082002



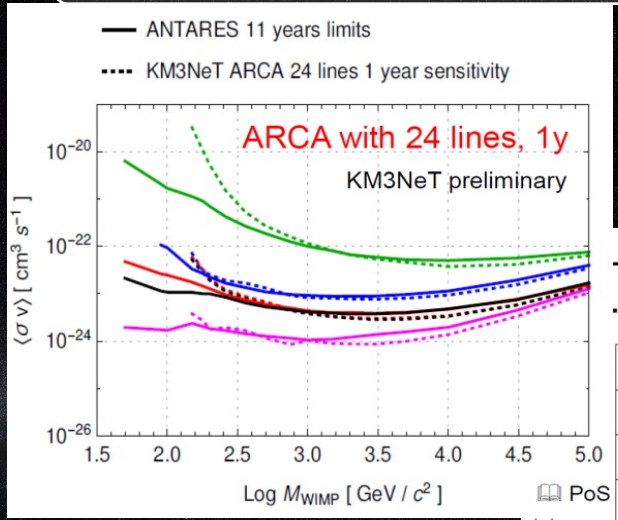
ANTARES GC,
13 years of Data (2007-2020)
PoS (ICRC2021) 537



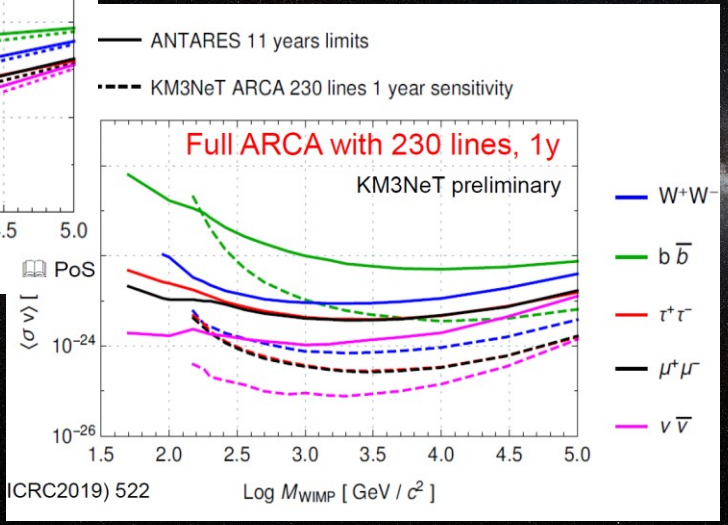
Binned Likelihood method

DM Searches towards the Galactic Center: KM3NeT

- Preliminary sensitivity study for WIMP annihilation in the GC with ARCA detector.

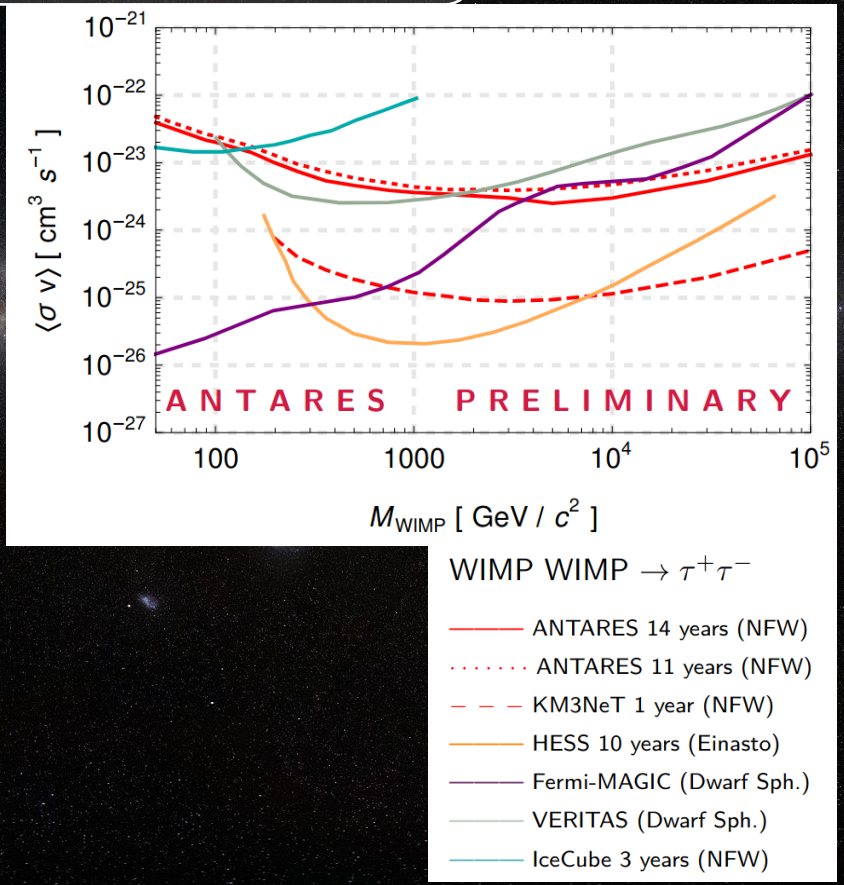


PoS (ICRC2019) 522



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

PoS (ICRC2021) 537

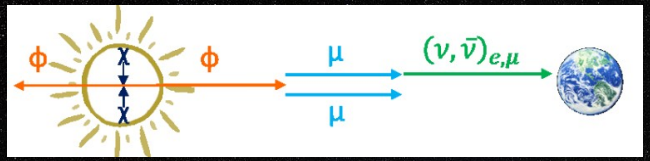


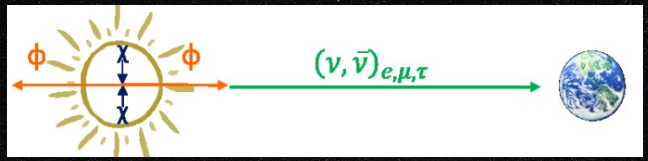
For interpretations of limits in terms of Dark Matter Models see
"Probing Dark Matter Models with Upcoming Neutrino Telescopes"
EPS-HEP, 29 jul. 2021 10:30 T04: Neutrino Physics
By: *Suzan du Pree*

Secluded Dark Matter in the Sun: ANTARES

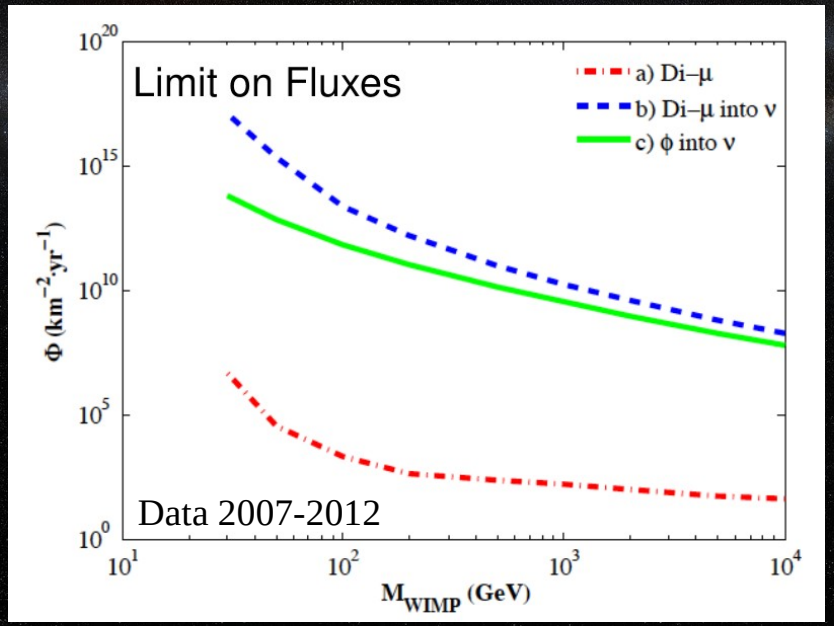
JCAP 05 (2016) 016

- DM annihilates into **unstable mediator Φ**.
- Detectable particles: dimuons or neutrinos.
- 3 cases:
  - $\Phi \rightarrow \mu\mu$.
  - $\Phi \rightarrow \mu\mu \rightarrow \nu\nu$.
  - $\Phi \rightarrow \nu\nu$.

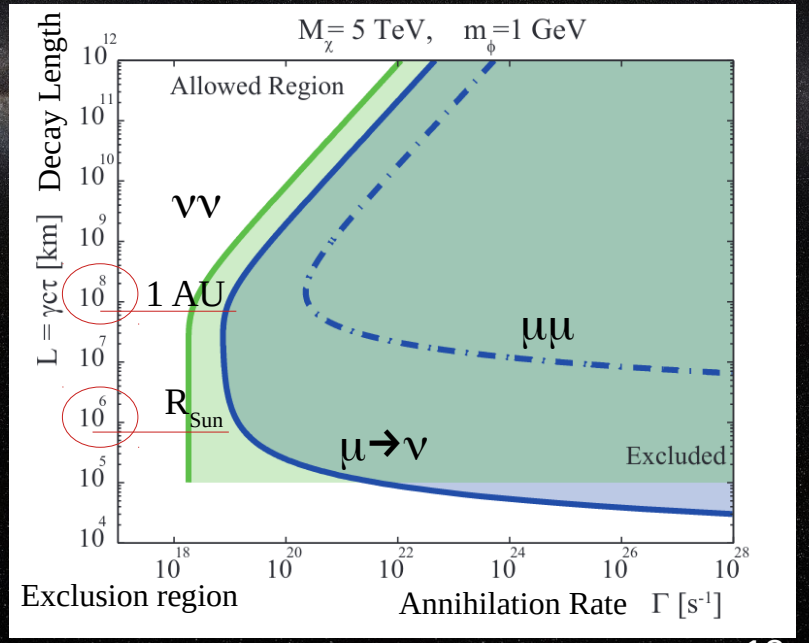




Testing Models:
- Meade et al., JHEP06(2010)29
- Bell and Petraki, JCAP04(2011)003



- Limit on flux.
- Limit as a function of the annihilation rate and the decay length for three different scenarios.

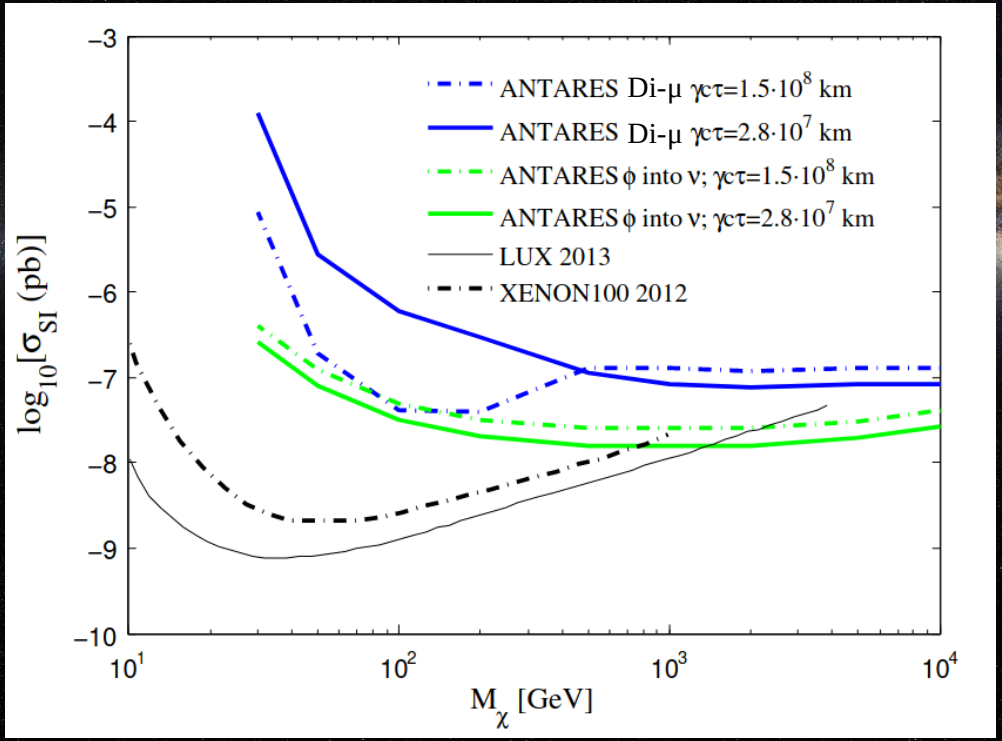


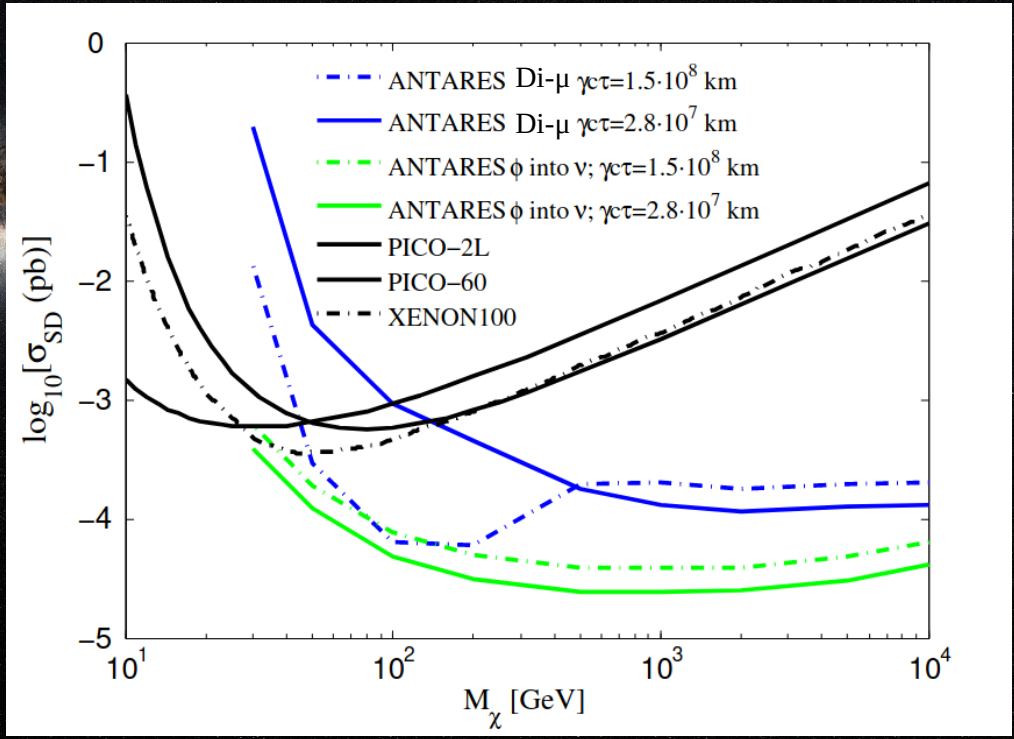
Secluded Dark Matter in the Sun: ANTARES

JCAP 05 (2016) 016

- Limits on WIMPs scattering cross-section for unstable but sufficiently long-lived mediators.

- 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.

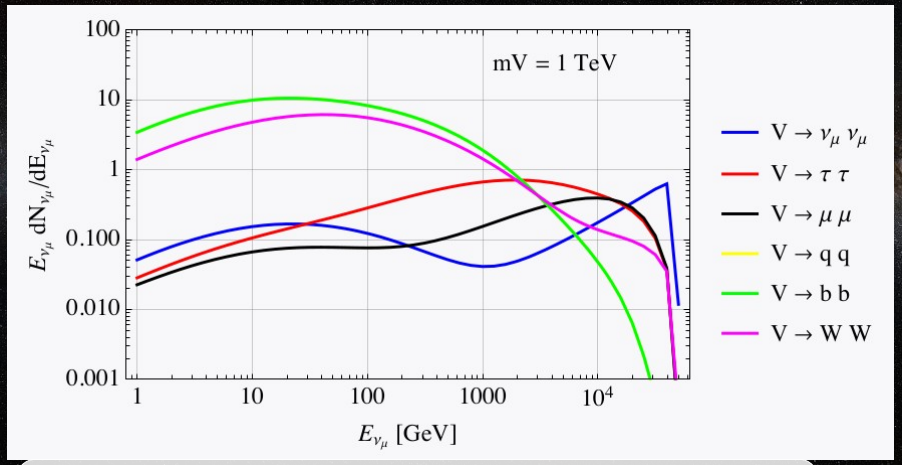




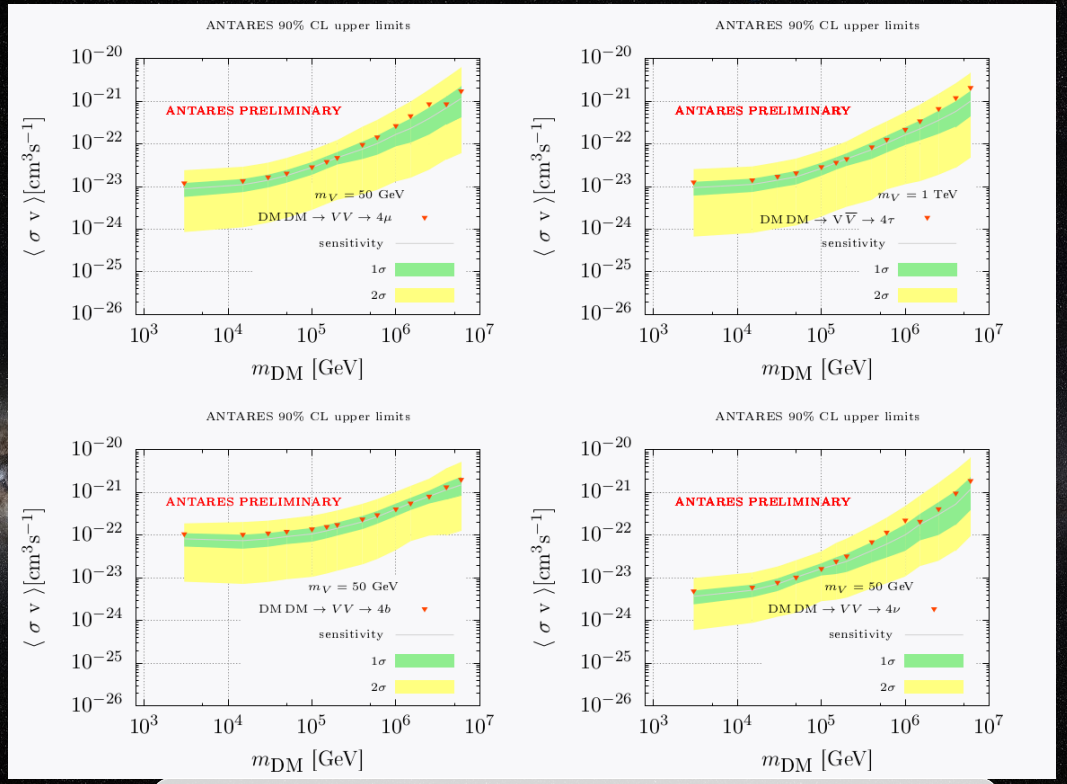
Secluded DM Searches towards the Galactic Center: ANTARES

Search for heavy secluded dark matter with ANTARES
Neutrino2020 #467

- No signal evidence found.
- Data from 2007-2015 (9 years)
  - ~2100 days of livetime
- Secluded scenarios can provide dark-matter candidates abote 10-100 TeV.



- ν_μ Energy distribution (at Earth) per annihilation of DM pair into two mediators with mass m_V=1 TeV/c^2.



- Upper limits at 90%CL on thermally averaged annihilation cross section for 4 different final states.

Summary and Outlook

- Neutrino telescopes have shown to be a promising tool in the indirect search for **Dark Matter**.
  No signal evidence has been found yet, instead, upper limits have been stablished.
- Indirect detection is complementary to direct detection experiments.
- ANTARES has set very competitive limits for WIMP masses between 50 GeV – 10 TeV.
- KM3NeT-ORCA has shown to be potentially comptetitive for low WIMP masses 1 – 100 GeV.
- KM3NeT-ARCA shows similar sensitivities to DM in the GC with double the lines of ANTARES and just 1 year of data taking.
- KM3NeT will take over the role of ANTARES in the near future.

In progress:

- Full ANTARES data set → ANTARES will stop taking data in less than 1 year.
- Inclusion of shower events (ν_e/ν_τ CC + ν NC).
- New Solar Dark Matter Indirect Searches with ANTARES in progress (2007-2020).

Early future:

- First analysis in Solar DM Indirect Searches with ORCA6 (6 lines of ORCA already deployed, October 2020).
- Apply ML method to DM searches within ANTARES and KM3NeT data.

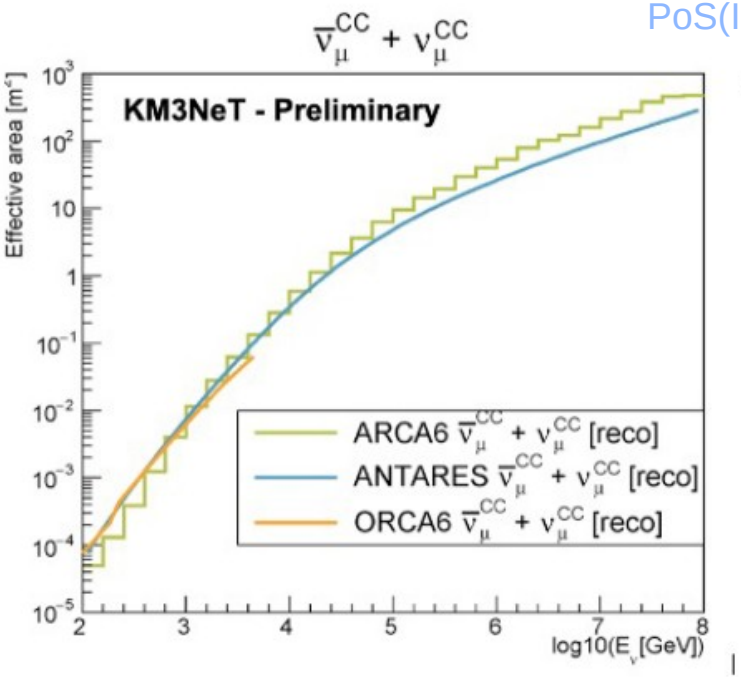
ANTARES-KM3NeT Related talks at EPS-HEP:

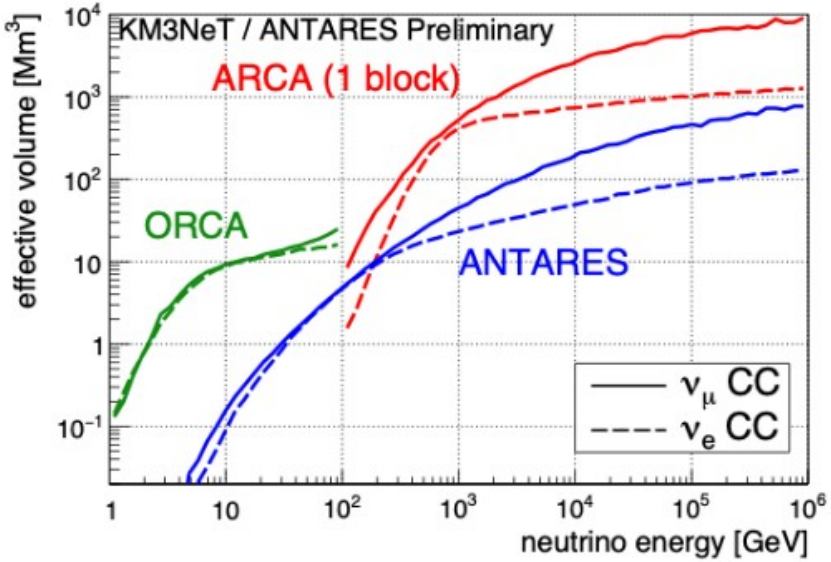
- ***"The KM3NeT neutrino telescopes: status and perspectives".*** July 27, T01, 10:45
- ***"The ANTARES neutrino telescope (on behalf of the ANTARES Collaboration)".*** July 27, T01, 11:15
- ***"Probing Dark Matter Models with Upcoming Neutrino Telescopes"*** July 29, T04, 10:30


BACKUP

Effective areas: KM3NeT vs ANTARES

Underwater Neutrino telescopes: status and future
PoS(ICRC2021)042





ARCA6+ORCA6 bit better than ANTARES

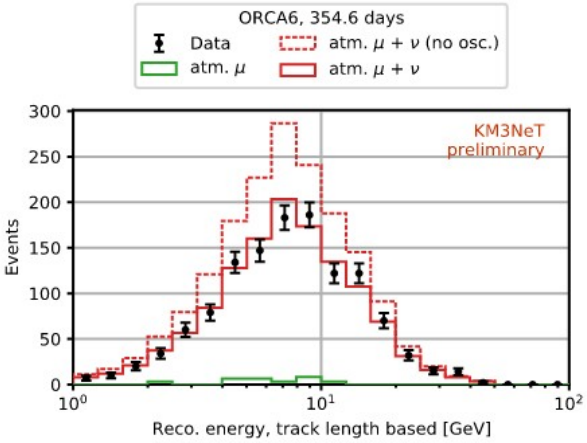
Doubling of detector in Sept 2021
(ARCA11 + ORCA13)

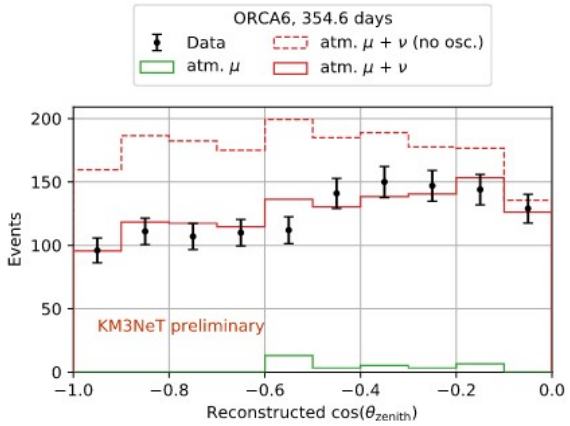
Completion of ORCA115 array in 2025
and ARCA230 in 2027

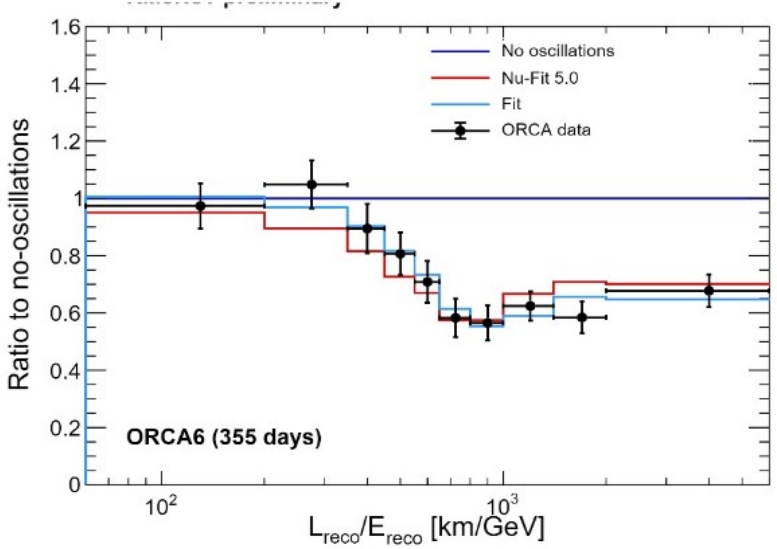
ORCA6 neutrino oscillations (tracks)

536 L. Nauta

PoS(ICRC2021)536







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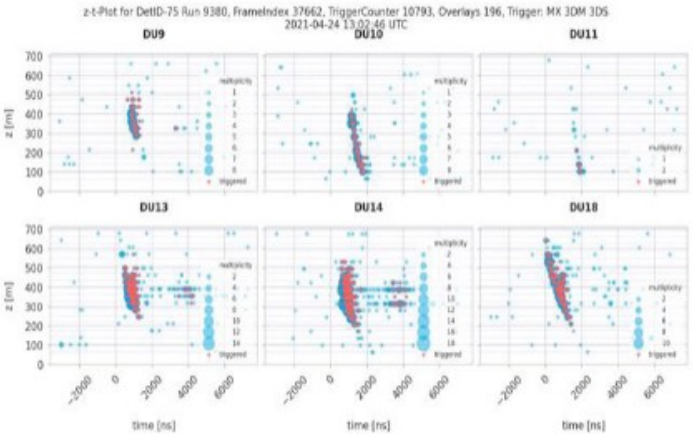
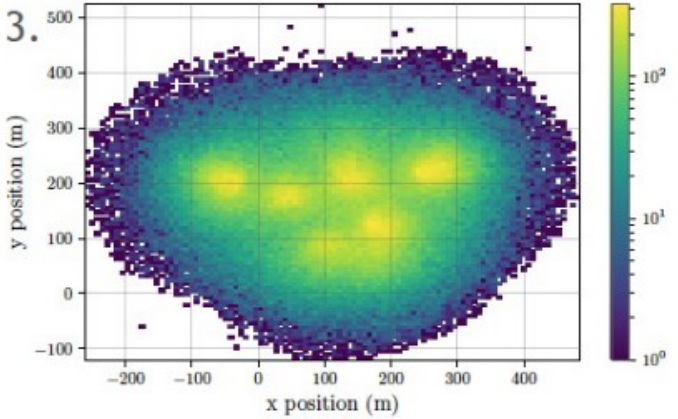
23

ARCA6 data

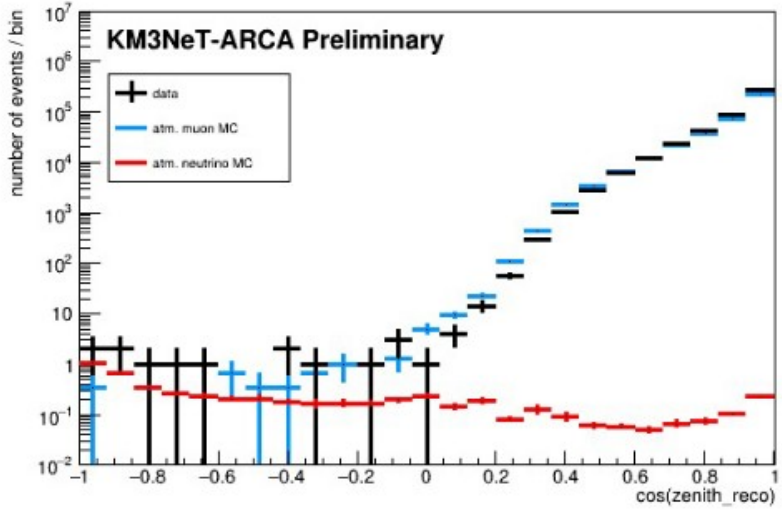
701 A. Sinopoulou

PoS(ICRC2021)701





19 days



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status and future
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