Indirect dark matter searches with Mediterranean neutrino telescopes

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Dark matter: the most embarassing BSM problem

New particle outside the Standard Model, with properties learned from observational evidence

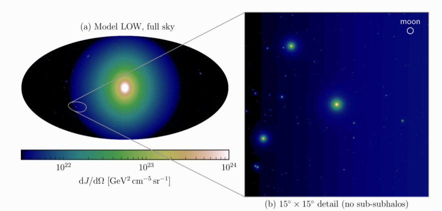
- Neutral
- Stable on cosmological scales
- Relic abundance reproduces amount observed nowadays
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

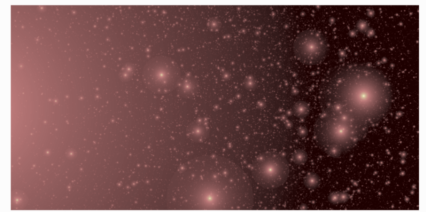
Indirect searches in astrophysical environment: ν (and γ) as dark matter probes

1. WIMPs: $\sim$ GeV – 100 TeV. Required interaction strength is of the same size as the known weak interaction.
2. Heavy dark matter ($\rightarrow$ 10 PeV) in secluded scenarios
3. Very light dark matter (keV) out of trigger threshold but other invisibles (HNLs) searched at 1-100 GeV

How much dark matter? Define the "source" as we are sitting inside it

The amount of dark matter and its spacial distribution is described through the J-factor





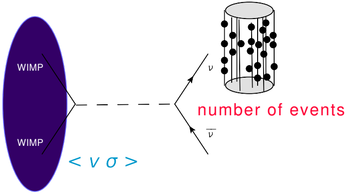
$$J_{\mathrm{ANN}} = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl \quad \text{or} \quad J_{\mathrm{DEC}} = \int_{\Omega} d\Omega \int_{l} \rho(r(\theta,\phi))dl$$

For dark matter density ρ in source at sky coord. (θ,ϕ), seen of size Ω over line of sight l

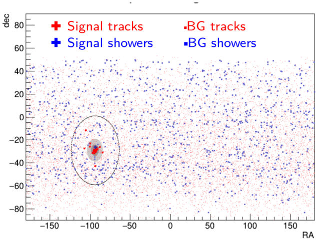
An instrument like ν telescope does not point to a specific sky direction $\rightarrow$ best dark matter sources are: Galactic Centre (extended and relatively close) or Sun (very close)

Analysis structure in indirect seaches via neutrinos

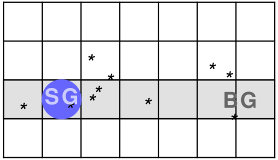
Signal = a cluster of n ν-events daugthers of DM pair annihilation process
Measurement: arrival directions of two topologies: track- and shower-like, and energy proxy.



$$n = \frac{1}{2}\langle\sigma v\rangle \int_0^{M_{\rm DM}} \frac{dN}{dE}\,dE\,\frac{1}{4\pi}\,J\,\frac{1}{M_{\rm DM}^2}\,\mathcal{A}(M_{\rm DM})\,t$$



Unbinned likelihood

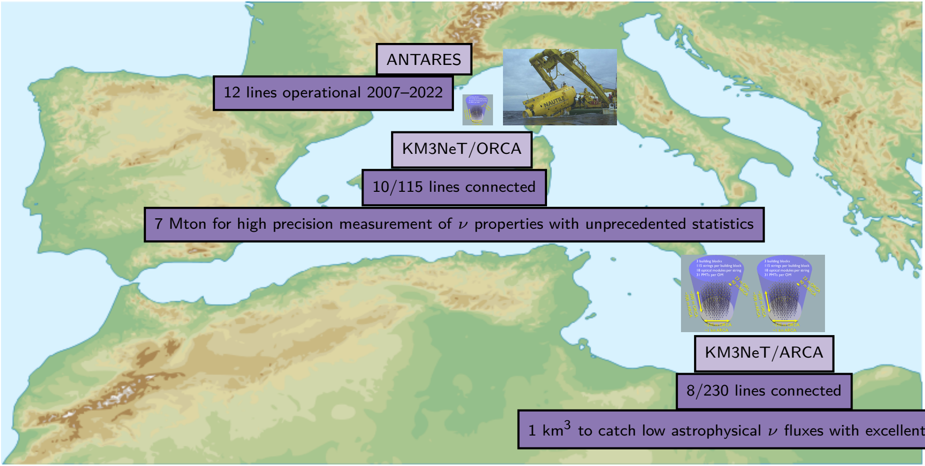


Binned likelihood

The probability for **one** process to happen is $\propto$ velocity of projectile $\times\, \sigma$. Translate limit on flux into limit on velocity-averaged pair annihilation cross-section $\langle\sigma v\rangle$.

Mediterranean telescopes: ANTARES and KM3NeT

Cherenkov detectors instrumenting water with a grid of photomultipliers organised in lines



ANTARES

12 lines operational 2007–2022

KM3NeT/ORCA

10/115 lines connected

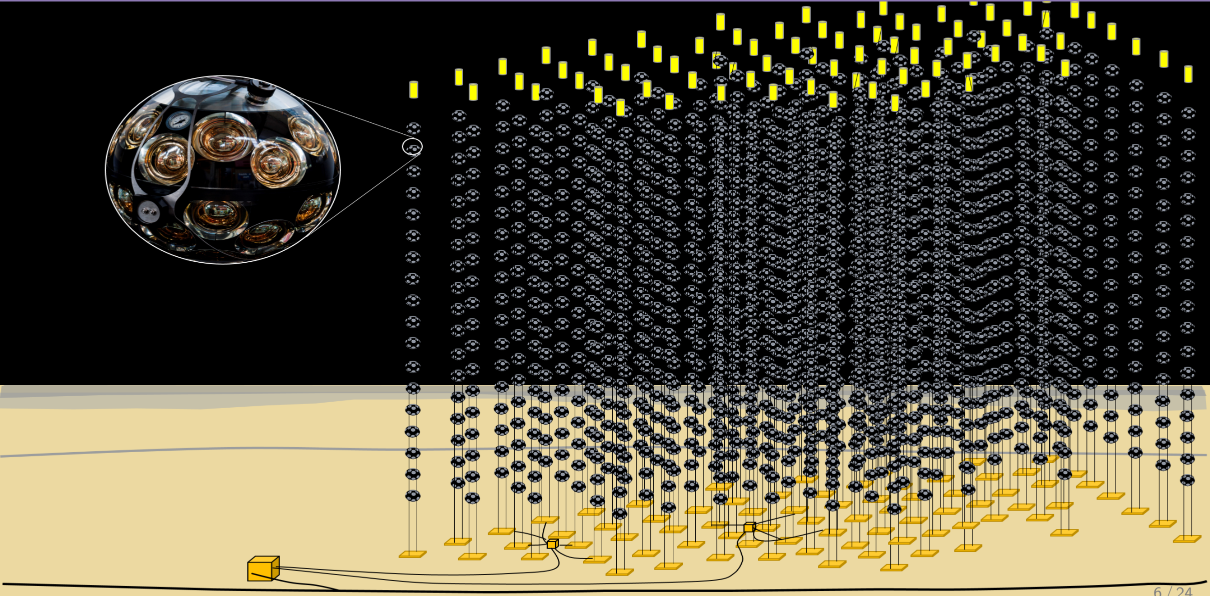
7 Mton for high precision measurement of ν properties with unprecedented statistics

KM3NeT/ARCA

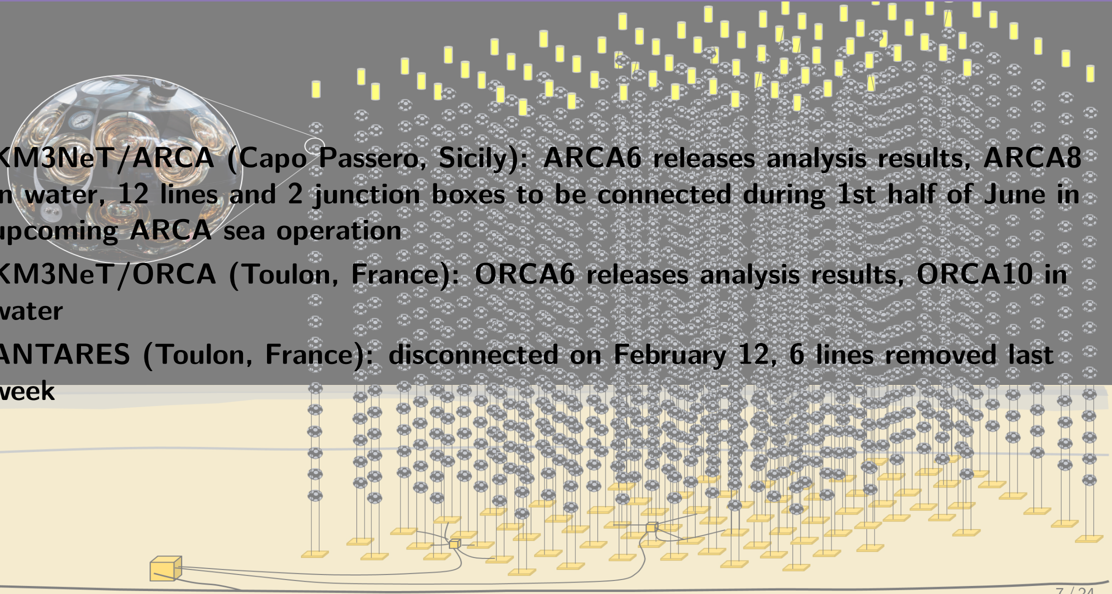
8/230 lines connected

1 km^3 to catch low astrophysical ν fluxes with excellent resolution

Mediterranean telescopes: ANTARES and KM3NeT



Mediterranean telescopes: status



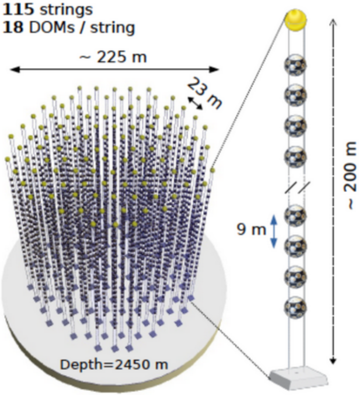
- **KM3NeT/ARCA (Capo Passero, Sicily): ARCA6 releases analysis results, ARCA8 in water, 12 lines and 2 junction boxes to be connected during 1st half of June in upcoming ARCA sea operation**
- **KM3NeT/ORCA (Toulon, France): ORCA6 releases analysis results, ORCA10 in water**
- **ANTARES (Toulon, France): disconnected on February 12, 6 lines removed last week**

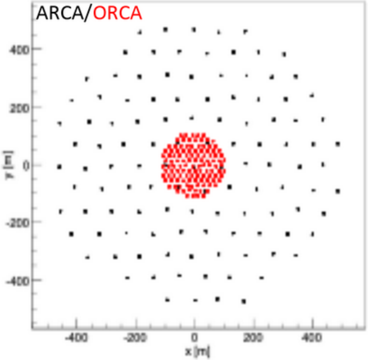
ANTARES decommissioning

ANTARES decommissioning

ANTARES decommissioning

Geometry





Same layout,
same components

ARCA: 90 m inter-string
ARCA: 36 m inter-DOM
ORCA: 23 m inter-string
ORCA: 9 m inter-DOM

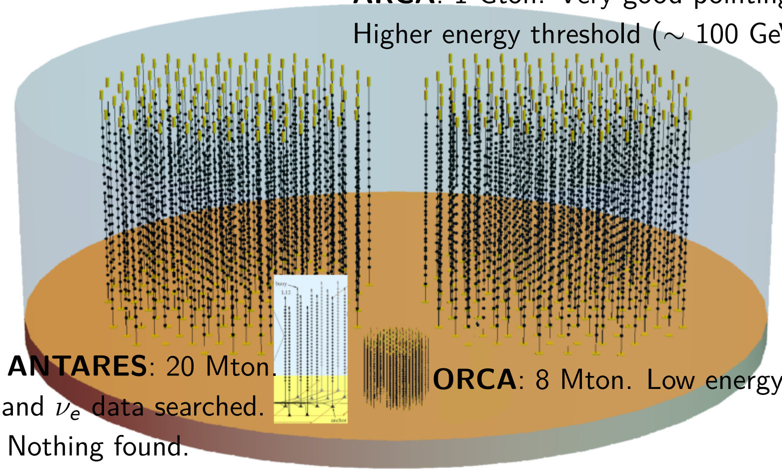
Eye

ANTARES

KM3NeT

Which detector is best for indirect dark matter searches?

ARCA: 1 Gton. Very good pointing resolution.
Higher energy threshold ($\sim$ 100 GeV)



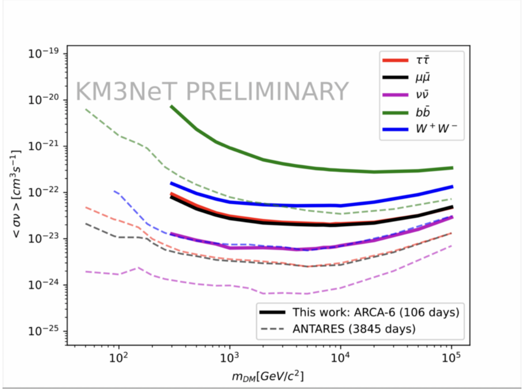
ANTARES: 20 Mton.
16 years of ν_μ and ν_e data searched.
Nothing found.

ORCA: 8 Mton. Low energy. Best for Sun

Limits on DM annihilation in the Galactic Centre

First sensitivities with 6-line configuration of ARCA (A. Saina) + unblinding to come.
ANTARES data 2007 - 2020 is compatible with background [Phys.Lett B 805, 135439 (2020)]

WIMP WIMP $\rightarrow$ —$b\overline{b}$ — W^+W^- — $\tau^+\tau^-$ — $\mu^+\mu^-$ —$\nu\,\overline{\nu}$

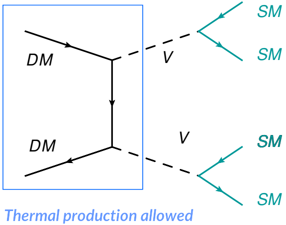


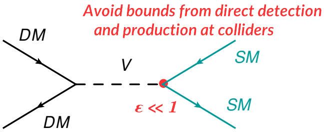
Heavy dark matter in secluded scenarios

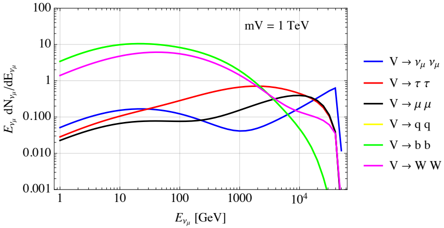
No evidence for WIMP at the GeV-TeV scale; where to search next?

Above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders

1. Unitarity bound on the dark matter mass naturally evaded with a modified cosmology implying a change of freeze-out point
2. Spectra of relevance for experiments can be computed from 'boosted' PPPC [JCAP 2019 014]



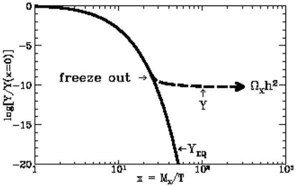


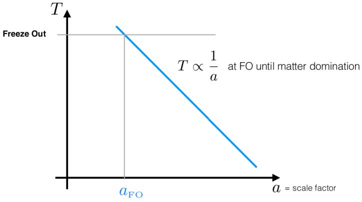


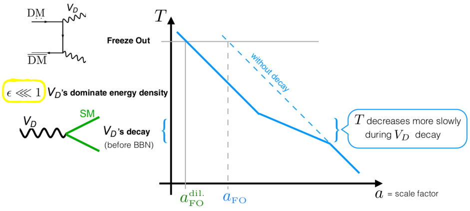
The ν signal at ANTARES arises from the annihilation of DM pairs into two mediators, then decaying into SM particles that produce νs via decays and showering.

Standard / secluded dark matter freeze-out

Standard cosmological evolution: $\Omega_{\rm DM} \propto \frac{1}{\sigma v}$.
Secluded: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ $\sigma v(\mathrm{DM\ DM} \to VV)$ smaller $\Rightarrow$ DM can be heavier



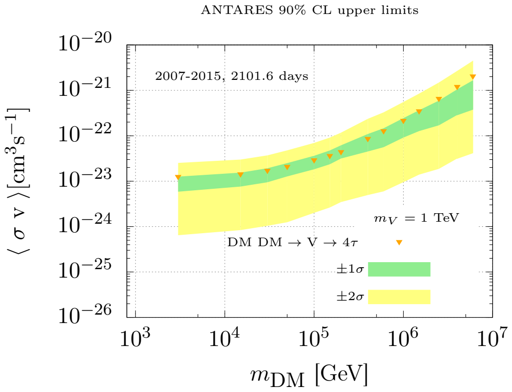


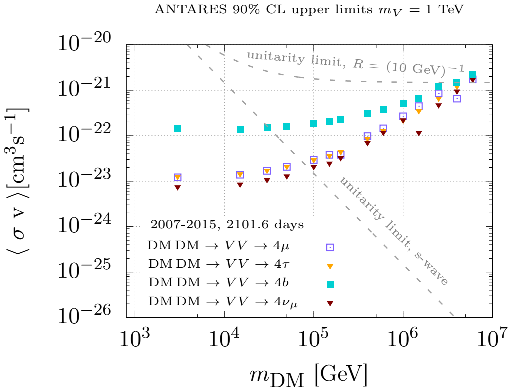


Standard WIMP mass constraint at $m_{\rm DM} = \mathcal{O}(100)$ TeV [Phys.Rev.Lett. 64 (1990) 615] can be evaded in new cosmological scenario.

Limits on heavy secluded dark matter

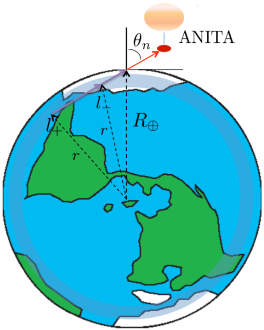
Accepted for publication in JCAP [arXiv:2203.06029]





Constraining EeV dark matter with τ regeneration

Work on ANTARES public data set in collaboration with Jeff Lazar and Carlos Argüelles.
Context: ANITA reports two unusual **upgoing τ-induced showers** [PRL 117, 071101 (2016)], [PRL 121, 161102 (2018)].



Anomaly consists of:

1. energies of (600 ± 400) PeV and (560^{+300}_{-200}) PeV (UHE diffuse neutrino flux bounds from Pierre Auger and IceCube. CC interaction of astrophysical ν_τ is unlikely).
2. steep arrival zenith angle: 27.4° and 35°.

Possible interpretation

A certain number of scenarios has been proposed to explain the origin of the ANITA events.

Heavy dark matter, accumulating inside the Earth, and producing secondary τ lepton.

For instance Anchordoqui et al [LHEP 01,13(2018)] suggest right-handed neutrino $\nu_{R,1}$ in CPT symmetry, that decays into Higgs + a light Majorana ν (two-body therefore monochromatic):

$$\nu_{R,1} \to H + \nu_M$$

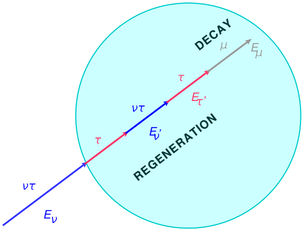
This ν_M interacts in the Earth's crust producing τ lepton

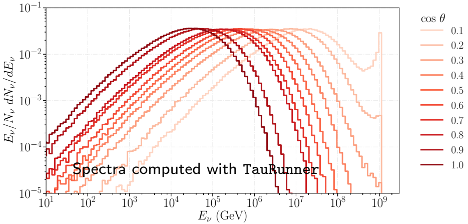
1. $\nu_{R,1}$ as a DM candidate has 'correct' mass to explain ANITA showers: 480 PeV (from $\rho_{DM} \simeq 9.7 \times 10^{-48}$ GeV^4).
2. Combination of DM distribution in the Earth $\times\ \sigma_\nu \times P^{\tau}_{\text{survival}}$ explains the arrival angle.

ANTARES

ν_τ reaches the detector through τ regeneration across the Earth. Non-observation of ANTARES events around the Galactic Centre sets bounds on DM candidate lifetime.

`TauRunner` tool [Safa, Argüelles and Pizzuto] to propagate neutrinos from incident high-energy flux (1 to 10^{16} GeV) through the Earth and calculate charged and neutral lepton yield.





$\nu_\tau \to \tau \to \nu_\tau \to \ldots$ [TauRunner] followed by final decay $\tau \to \mu$ (because public data are tracks)

Muon rates expected at detector from monochromatic ν_τ beam

We must count all muons originated within detectable volume

Rate of products = number of targets × Flux of outcoming muons pro target

$$\frac{dN_\mu}{dE_\mu\, d\Omega} = \boxed{\boxed{\mathcal{A}(E_\mu, \Omega)\, R_\mu(E_\mu)}\ \frac{\rho}{M_{\rm iso}}}\ \Delta T\ \boxed{\frac{\Gamma_\chi}{3 \cdot 4\pi \cdot m_\chi} J(\Omega) \int dE'_\tau\, dE'_\nu\, T(E_\nu, E'_\nu)\, \sigma^{\rm CC}(E'_\nu)\, \frac{dP_{\nu_\tau \to \tau}}{dE'_\tau}(E'_\tau, E_\nu)\, \frac{dP_{\tau \to \mu}}{dE_\mu}(E_\mu, E'_\tau)}$$

n (not) seen by ANTARES

dark matter lifetime

τ regeneration spectra

data taking (3125 days)

CLUMPY for decay, int over 6 degrees

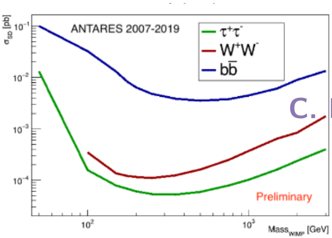
detector response

Muon effective area $\mathcal{A}(E_\mu, \Omega)$ (or response function) represents ratio between flux of incident muons and rate of observed muons in detector.

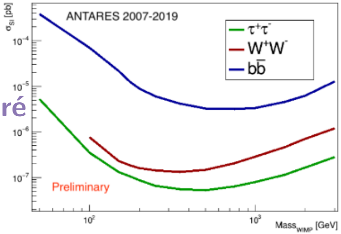
....results soon: paper in preparation.

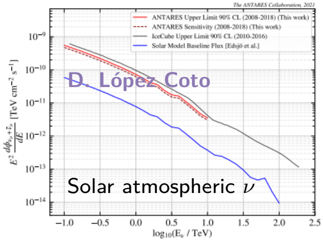
Search for dark matter in the Sun

- In equilibrium between capture and annihilation
- Sensitive at low velocities (= easier capture)
- Clean: if signal → direct interpretation (astro bg well known)



C. Poiré





D. López Coto

Solar atmospheric ν

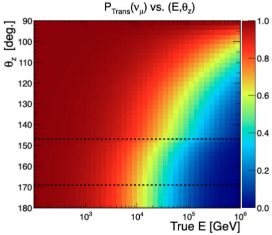
Sun has known isotopic abundance ⇒ sensitive to WIMP-nucleon cross section for spin-dependent and spin-independent case (odd or even atomic number)

Earth ν tomography and dark matter?

Two analyses by L. Maderer [PoS(ICRC2021)1172].

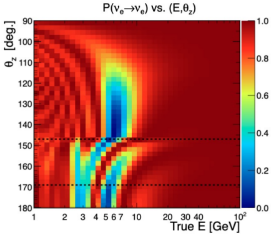
1. Oscillation tomography. Resonance effects in the oscillations of GeV ν traversing the Earth $\rightarrow$ measure the electron density along their trajectory. KM3NeT/ORCA
2. Absorption tomography: the Earth is opaque for ν at PeV energies $\rightarrow$ measure the density of the inner layers of the Earth. KM3NeT/ARCA

Absorption tomography



Sensitive to ρ_{matter}

Oscillation tomography



Sensitive to $\mathrm{n_e} \sim \rho_{matter} * Z/A$

Wrap up - References - Promises

WIMP searches, Galactic Centre and Sun

- ANTARES has searched for dark-matter induced ν from the **Galactic Centre** using all-flavour data from 2007 $\rightarrow$ Feb. 2020. No dark matter. [Phys.Lett B 805, 135439 (2020)]
- Sensitivity computed with the first 6 lines of KM3NeT/ARCA. Soon data unblinding.
- Search for dark matter annihilations in the **Sun** with ANTARES in 2007-2019 data: no dark matter either. Paper in preparation.
- Sensitivities with ORCA 6 lines ... out soon

Other

- Search for heavy DM in secluded scenarios in ANTARES data [arXiv:2203.06029] [JCAP]
- Search for very heavy (EeV) dark matter using ANTARES public data... out soon
- Earth tomography with ν [PoS(ICRC2021)1172].