

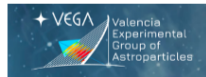
Dark matter: state of the art in neutrino searches

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on behalf of the ANTARES and KM3NeT Collaborations

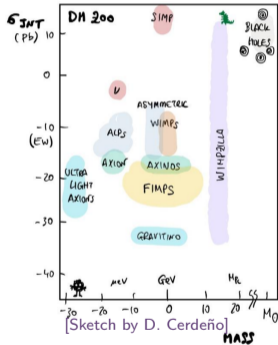
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DMNet - Heidelberg - September 15, 2022



Dark matter as a target for indirect searches

Unique assumption: the non-ordinary “substance” that makes up to a 27% of energy budget of the Universe comes in form of a **new elementary particle**.



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

Mass and interaction strength: very unconstrained

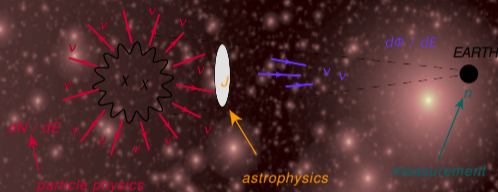
WIMP miracle: interaction is of the size of known EW interaction. Regardless the question of its nature (is it EW or other?), this makes it possible for ν detectors to search for WIMP DM.

Target: astrophysical environment via neutrinos

Need to **predict fluxes** of high-energy ν from dark matter decay or pair-annihilation.

$$\text{WIMP WIMP} \xrightarrow{\text{ANN}} \text{interm. channel} \rightarrow \nu\bar{\nu} + X$$

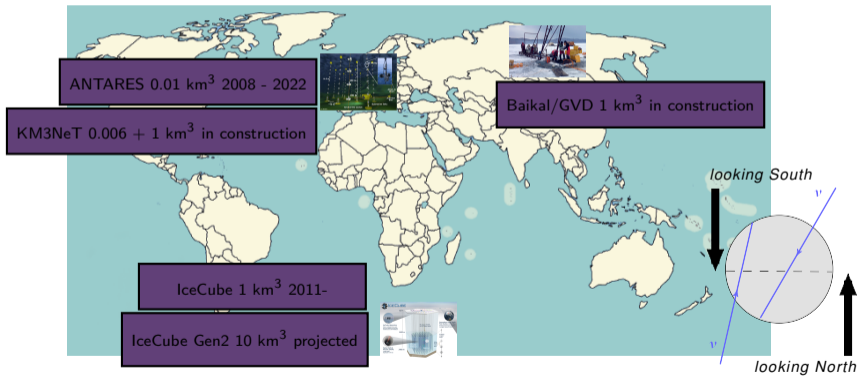
$$\text{WIMP} \xrightarrow{\text{DEC}} \text{interm. channel} \rightarrow \nu\bar{\nu} + X$$



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)

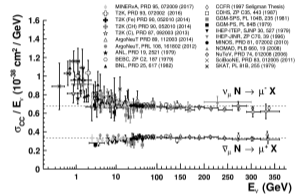
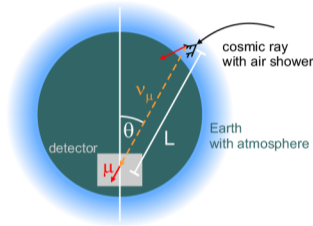
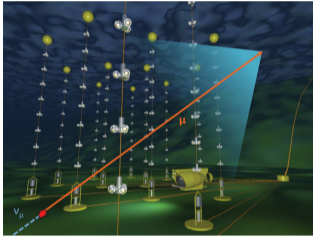
Large-volume ν Cherenkov telescopes

- 1 Work at very faint signal rates instrumenting large reservoirs of transparent medium
- 2 Remotely operated, almost 100% duty cycle, one unique data set (broad physics program)



Working principle

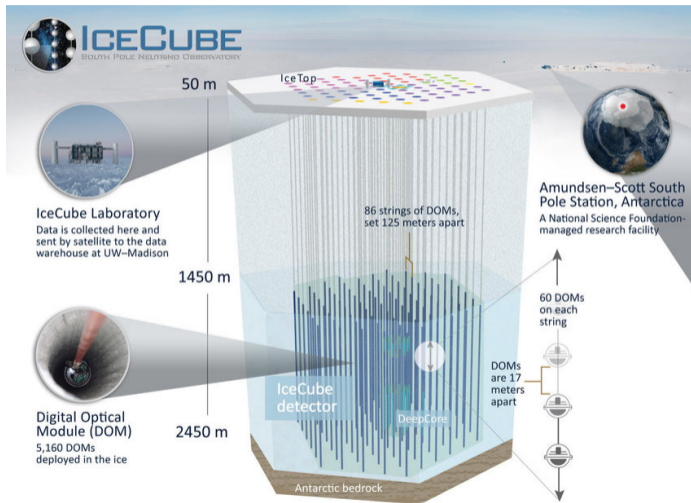
Look through the Earth for lepton tracks from $\nu \rightarrow l$ conversion. $\sigma_{\nu \rightarrow l} \sim 10^{-38} \text{ cm}^2$ at 1 GeV!



Water or ice? → in Northern Hemisphere only water available.

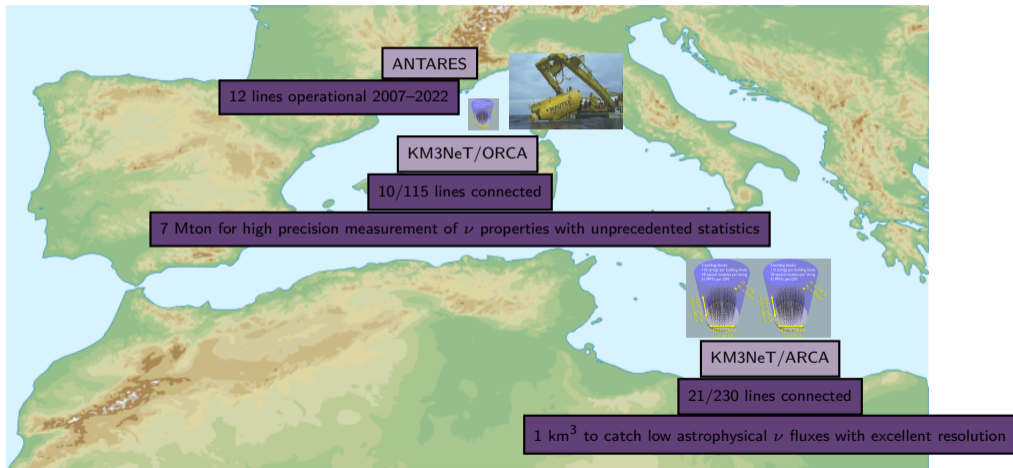
- more noise: radioactive ^{40}K decays, natural luminescence in sea
- larger scattering length: better angular resolution
- maintainable (but moving slowly)

IceCube

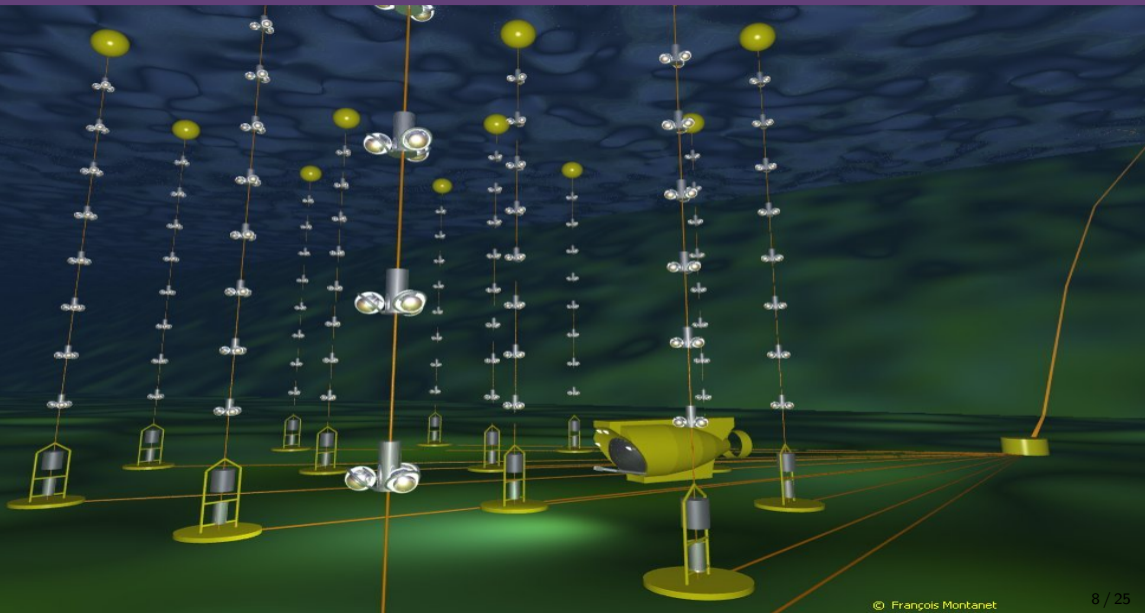


Mediterranean telescopes: ANTARES and KM3NeT

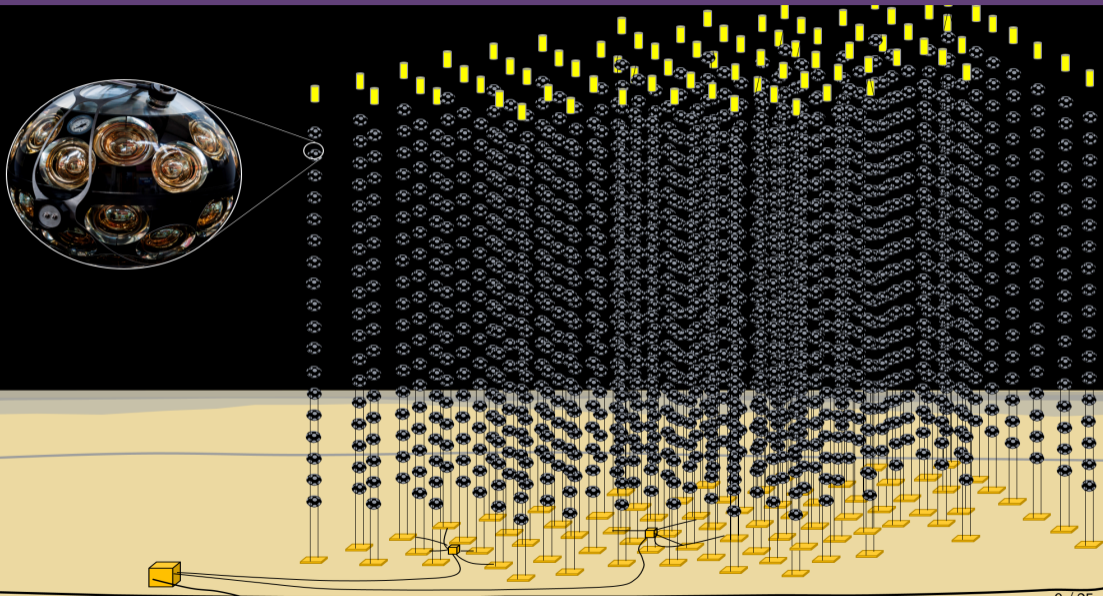
Cherenkov detectors instrumenting water with a grid of photomultipliers organised in lines



ANTARES: switched off in Feb. 2022 and dismantled in May-June 2022



KM3NeT: 19 lines ARCA + 8 lines ORCA connected





ANTARES



KM3NeT



IceCube

Mediterranean telescopes to scale

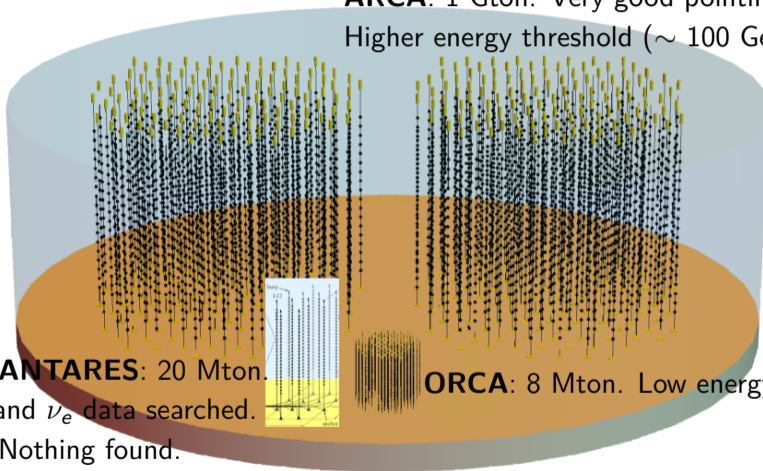
ARCA: 1 Gton. Very good pointing resolution.
Higher energy threshold (~ 100 GeV)

ANTARES: 20 Mton.

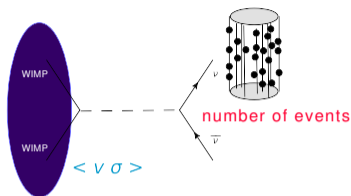
16 years of ν_μ and ν_e data searched.

Nothing found.

ORCA: 8 Mton. Low energy. Best for Sun



Structure of ν indirect searches



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

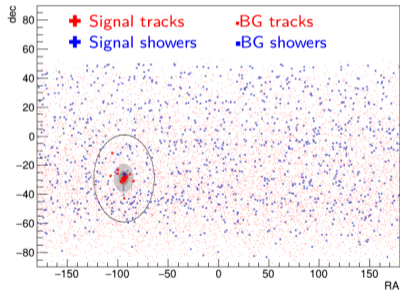
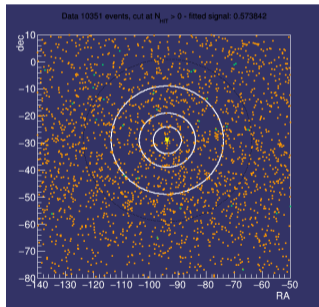
The probability for **one** process to happen is \propto velocity of projectile $\times \sigma$. Translate limit on flux into limit on **velocity-averaged pair annihilation cross-section** $\langle \sigma \nu \rangle$.

Neutrino telescopes reconstruct two kind of events

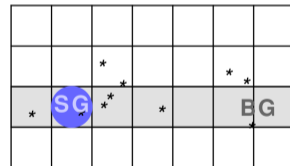
- 1 tracks (μ): fly-through, angular resolution down to 0.1° , ν_μ CC
- 2 cascades (e): contained, angular resolution $\sim 1 - 10^\circ$, ν_e CC or ν_e NC or ν_μ NC

Structure of ν indirect searches

Signal = a cluster of n ν -induced events daughters of dark matter pair annihilation process.
Measurement = reconstructed arrival directions (follows J-factor?), and energy proxy (follows DM annihilation or decay spectra?) for both ν_μ and ν_e



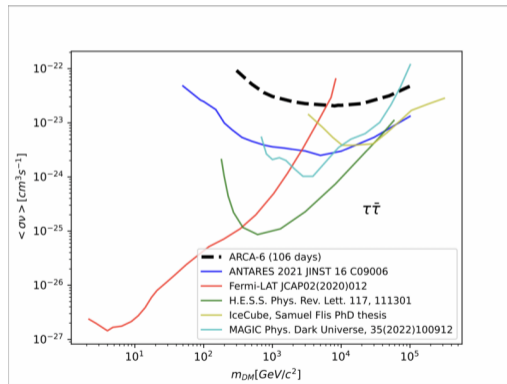
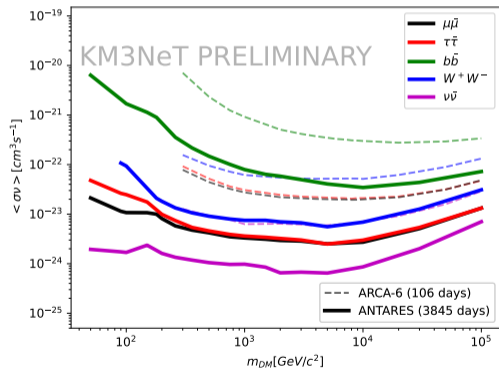
Unbinned likelihood



Binned likelihood

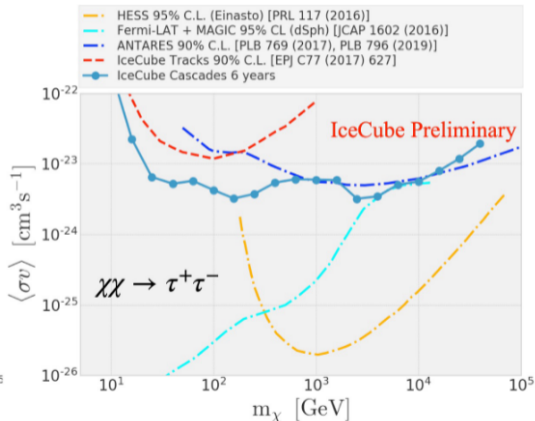
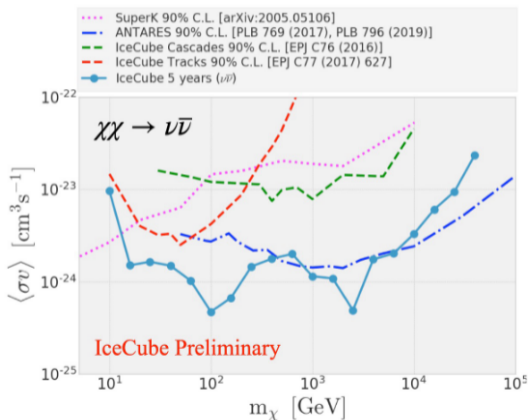
Limits on pair annihilation of dark matter in the Galactic Centre

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



Limits on pair annihilation of dark matter in the Galactic Centre

IceCube data is compatible with background [figure from ICHEP 2022]



Combined ANTARES + IceCube search

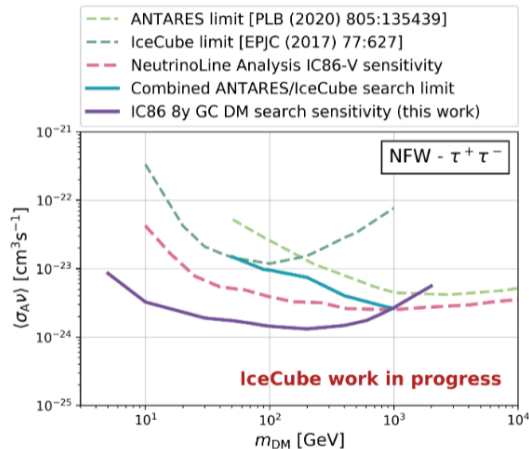
Region where the limits of ANTARES and IceCube are comparable

$$50\text{GeV} \leq E \leq 1\text{TeV}$$

Two-component mixture model to combine the sensitivities with one minimisation parameter

$$\mathcal{L}_{comb} = \prod_{k=A,I} \mathcal{L}_k(\mu_k)$$

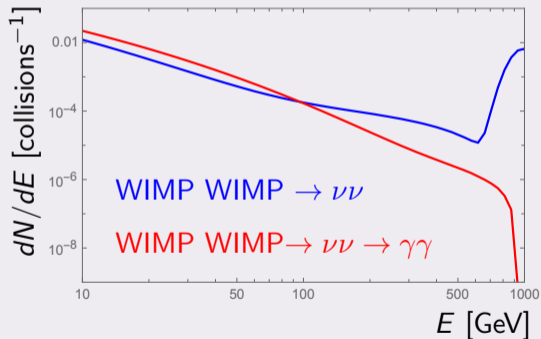
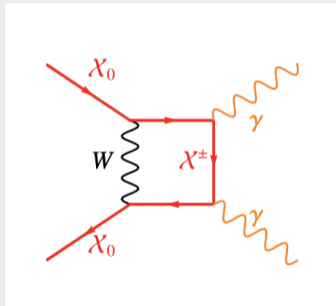
Joint unblinding with 3 years of IceCube and 9 years ANTARES. Further expansion of IceCube data set to 8 years was analysed meanwhile.



Combined search using $\nu + \gamma$

ANTARES/ KM3NeT are participating in a joint search with MAGIC, HESS, VERITAS, Fermi.

Signal: WIMP WIMP $\rightarrow \gamma\gamma$ (primary, from loops) $\rightarrow \nu\nu$ (secondary) - [PPPC4DMID]

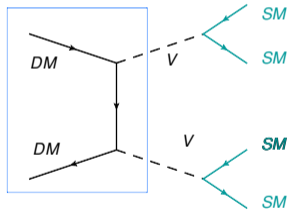


Heavy dark matter in secluded scenarios

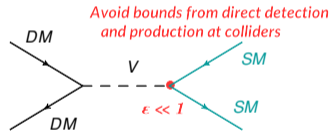
No evidence for WIMP at the GeV-TeV scale; where to search next?

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
- 2 Spectra of relevance for experiments can be computed from 'boosted' PPCC [JCAP 2019 014]

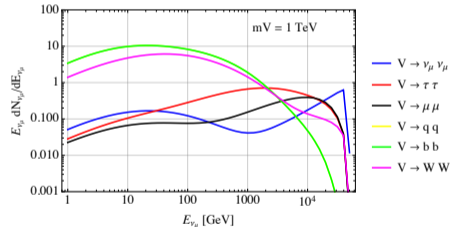


Thermal production allowed



Avoid bounds from direct detection and production at colliders

$\epsilon \ll 1$

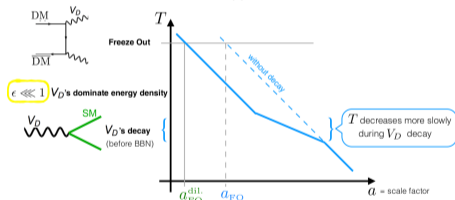
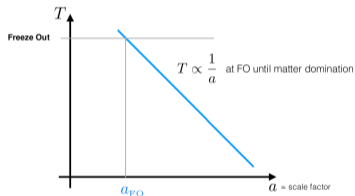
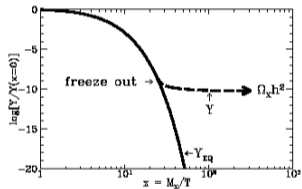


The ν signal at ANTARES arises from the annihilation of DM pairs into two mediators, then decaying into SM particles that produce ν s via decays and showering.

Standard and secluded dark matter freeze-out

Standard cosmological evolution: $\Omega_{\text{DM}} \propto \frac{1}{\sigma v}$.

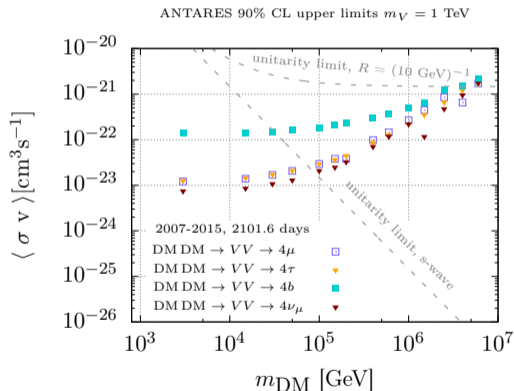
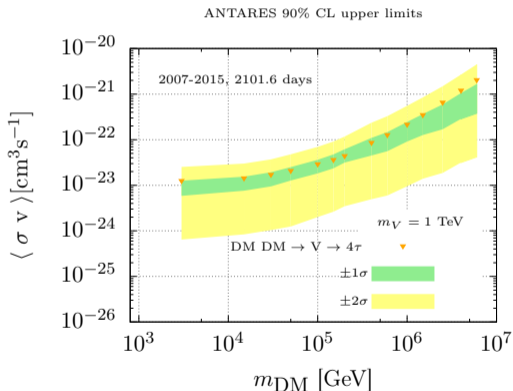
Secluded: universe at freeze-out is smaller \Rightarrow the same amount of DM is later more diluted \Rightarrow $\sigma v(\text{DM DM} \rightarrow VV)$ smaller \Rightarrow DM can be heavier



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

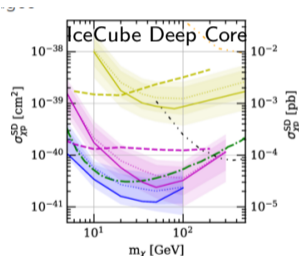
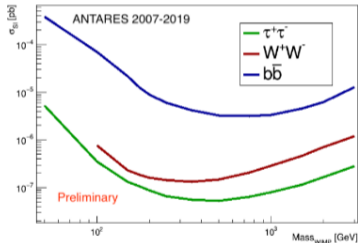
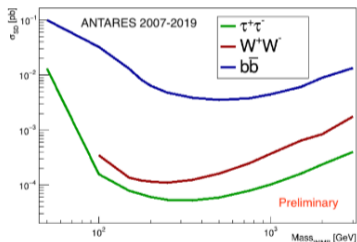
Limits on heavy secluded dark matter

Upper limits span for first time dark matter masses up to 6 PeV [JCAP06(2022)028]



Search for dark matter in the Sun

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



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

Neutrino telescopes are very versatile and adapt to different search channels

WIMP searches

- 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 \(2020\)](#)]
- Search for dark matter annihilations in the **Sun** and in the Earth

Test of other dark matter models

- Search for heavy DM in secluded scenarios in ANTARES data [[JCAP06\(2022\)028](#)]

ANTARES decommissioning



ANTARES decommissioning



ANTARES decommissioning

