Indirect search for dark matter with neutrinos

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Foreword

Most of the mass in the Universe (and: in our Galactic Halo) is dark. General assumption: unknown substance known as **dark matter** comes in form of a new elementary particle.

...but rather poor identikit. Progress was made on what dark matter **should not** be.

... properties relevant for detection (mass, interaction strength with ordinary barionic matter) are unconstrained over huge range of values.

$\rightarrow$ Triangulation between complementary search approaches: direct, indirect, production

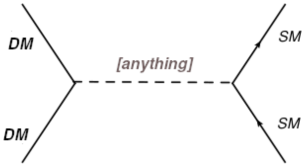
If dark matter plays a role in the thermal history of the universe (Λ_{CDM})

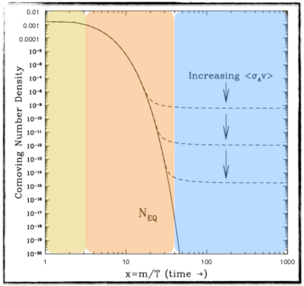
Thermal freeze-out of species in the Early Universe explains the relative abundances of baryons - Big Bang Nucleosynthesis (BBN)

Equilibrium: **dark matter $\leftrightarrow$ SM**

Cooling: **dark matter $\rightarrow$ SM**

Expansion: **dark matter // SM**





...to neutrinos

The size of $\langle \sigma v \rangle$ determines the abundance of the species nowadays: $\Omega \propto \frac{1}{\langle \sigma v \rangle}$

In WIMP miracle $\langle \sigma v \rangle$ is coincidentally of the size of the known electroweak interaction

- low rates $\to$ large detection volumes, which is for instance the current limiting factor for direct searches in noble gas or scintillators
- but, at the same time, some dark matter still to be found nowadays as a thermal relic

– Neutrino detectors are used to low rates and indirect search channel anyway.

Interacting weakly $\to$ overdensity regions outside Earth

When looking for dark matter in extraterrestrial environment

Cosmic messengers

- Photons
- Neutrinos
- Electrons, positrons
- Protons, antiprotons
- Hydrogen (deuterium, antideuterium)

Astrophysical targets

The Sun
Galactic Center
Earth
Dwarf Galaxies
Galaxy Clusters, Galactic Halo
Diffuse Cosmological DM

Neutrinos

Proper astronomy: preserve source information

Useful

- Direction information
- Spectral information
- Propagate unaffected: not absorbed, not deflected
- Cross section raises with energy compensating flux decreasing at higher DM masses

Problem

- Indirectly detected via associated lepton
- Propagate unaffected: difficult detection

Neutrinos

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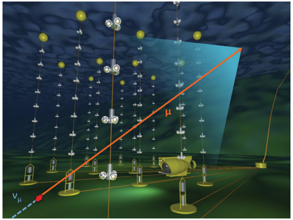
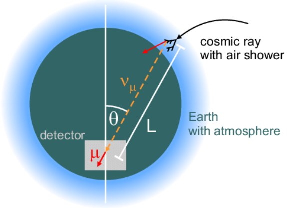
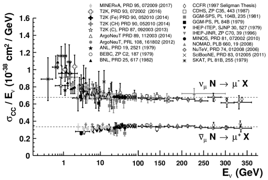
Candidate sources: Galactic Centre, Sun, Earth, Dwarf Spheriodal Galaxies

Working principle and data of a very-large volume neutrino detector

Look through the Earth for leptons from $\nu \to$ lepton conversion. Low rate $\to$ very large (natural) reservoirs of transparent medium. Scattering length influences pointing precision.







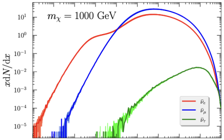
Neutrino telescopes reconstruct two kind of events

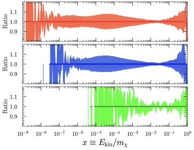
1. tracks: fly-through, angular resolution down to $0.1°$, ν_μ CC
2. cascades: contained, angular resolution $\sim 1 - 10°$, ν_e CC or ν_e NC or ν_μ NC

The extra trouble with indirect searches: external input

Indirect searches are unavoidably affected by **large uncertainties**. This also means that these searches alone can hardly make a univocal claim for detection.

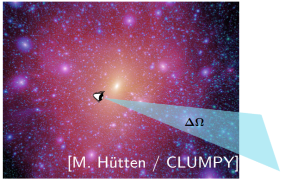
(I) Energy feature





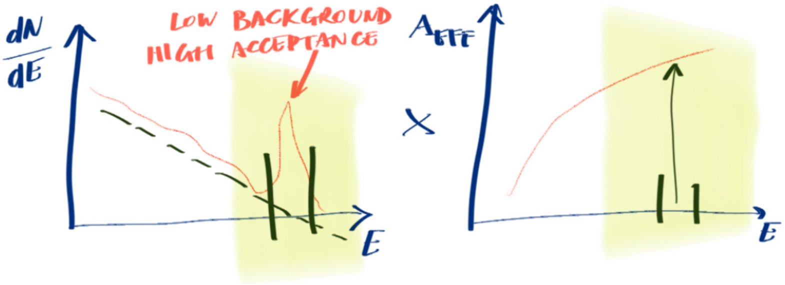
Affected both by energy rec. of the detector (20% – 5%) and by theoretical uncertainties (10% – 30%) mostrly on hadronization model [JCAP03(2024)035]

(II) Ambient



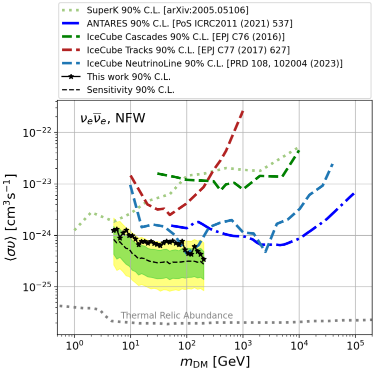
Dominated by astrophysical input for modelling haloes (for ν in track channel at GeV-TeV energies)

Lines

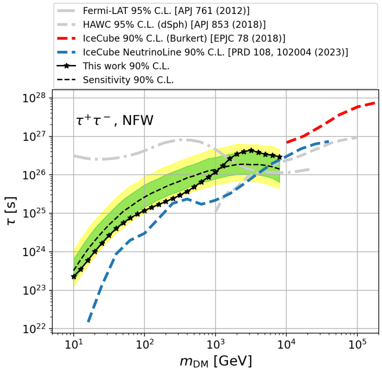


$\mathrm{DM}\,\mathrm{DM} \to \nu\bar{\nu}$ produces avery clear signature with high signal acceptance due to background suppression, but relies on energy reconstruction accuracy. Typical energy resolution can be of the order 20% for tracks, improving up to almost 5% for cascades.

Search for neutrino lines with 8 years of DeepCore [Phys.Rev.D 108, 102004]



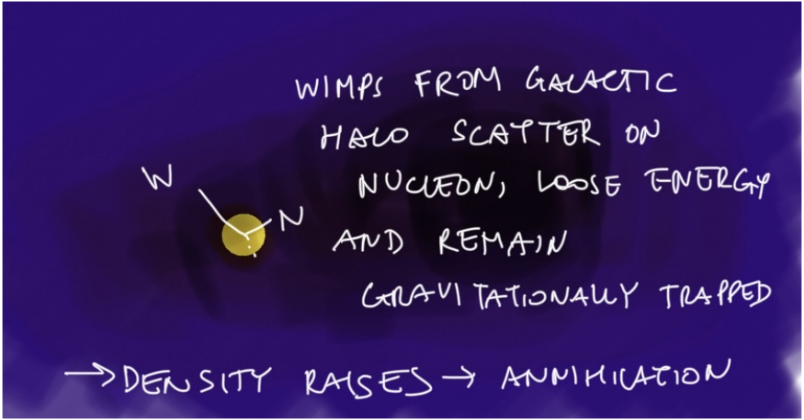
Annihilation



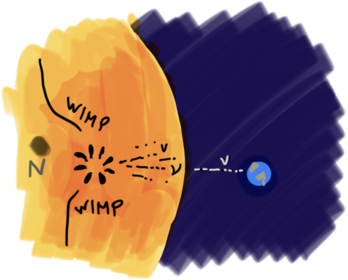
Decay

Searches for dark matter accumulating in the Sun

Flux of neutrinos is produced inside the Sun from annihilation of dark matter accumulated because gravitationally trapped. **Special occasion for ν telescopes!**



Searches for dark matter accumulating in the Sun: signal features



$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{ann}}{4\pi\, d^2}\frac{dN_\nu}{dE_\nu}$$

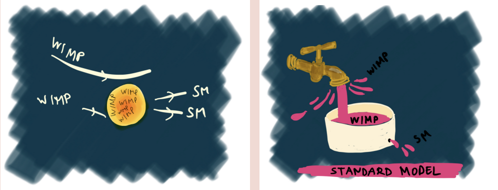
d= distance source-detector

Γ_{ann}= annihilation rate

- Direct interpretation in case of signal (astrophysical background well known)
- Unaffected by halo uncertainties because of point-like extension
- Searches with neutrino telescopes are sensitive at low velocities (= easier capture)
- Given the age of the Sun with respect to the typical time-scale for the competing process "capture/annihilation", the Sun is considered at equilibrium. $\Gamma = C/2$ with C capture rate

Searches for dark matter accumulating in the Sun

Flux only depends on WIMP-nucleon scattering cross section, no longer on WIMP velocity distribution $f(v)$



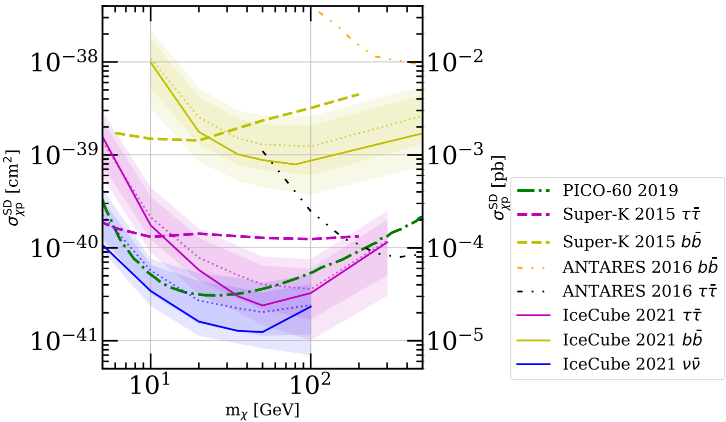
There are two types of interactions of WIMPs with ordinary matter:

1. spin-dependent, coupling to the spin of the target nucleon
2. spin-independent, coupling to the mass of the target nucleon

The two of them can take place inside the Sun that contains both light elements with an odd number of nucleons, like H, and relatively heavy elements, like He and O.

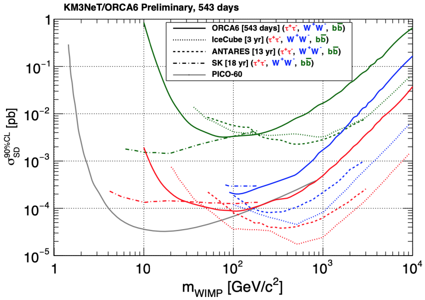
Dark Matter Annihilation in the Sun

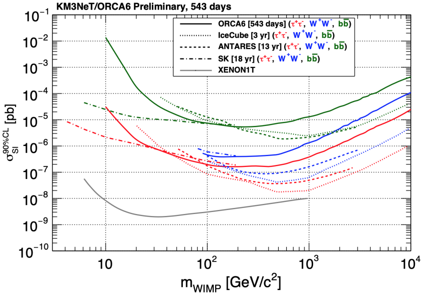
Results with 7 years of IceCube/DeepCore data **[Phys.Rev.D 105, 062004 (2022)]**



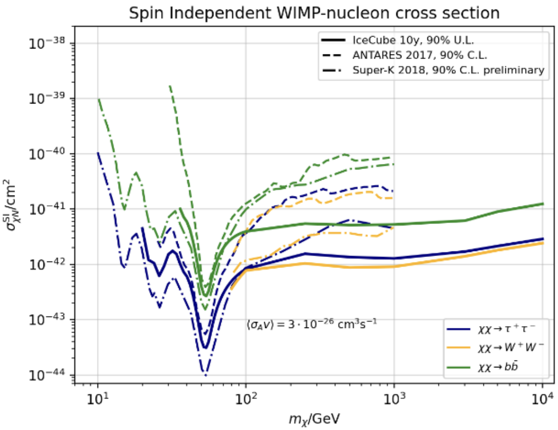
Dark Matter Annihilation in the Sun

Results from data set with partial KM3NeT configuration (6 lines) [PoS(ICRC2023)1406].
Sensitivity estimate with full ORCA detector [PoS(ICRC2019)536]





Results with 8 years IceCube data **[arXiv:2308.02920v1]**



Bonus: no pointing

Data are recorded over 4π at once. Source information is only necessary to discriminate signal from background **at analysis level**. No need to choose at DAQ level.

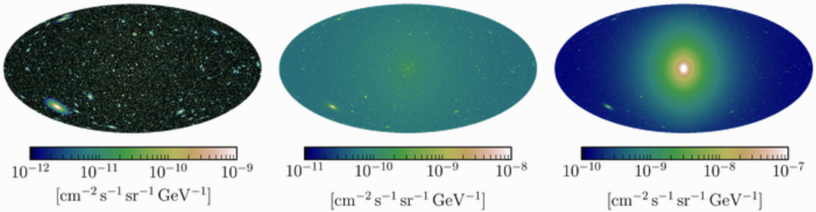
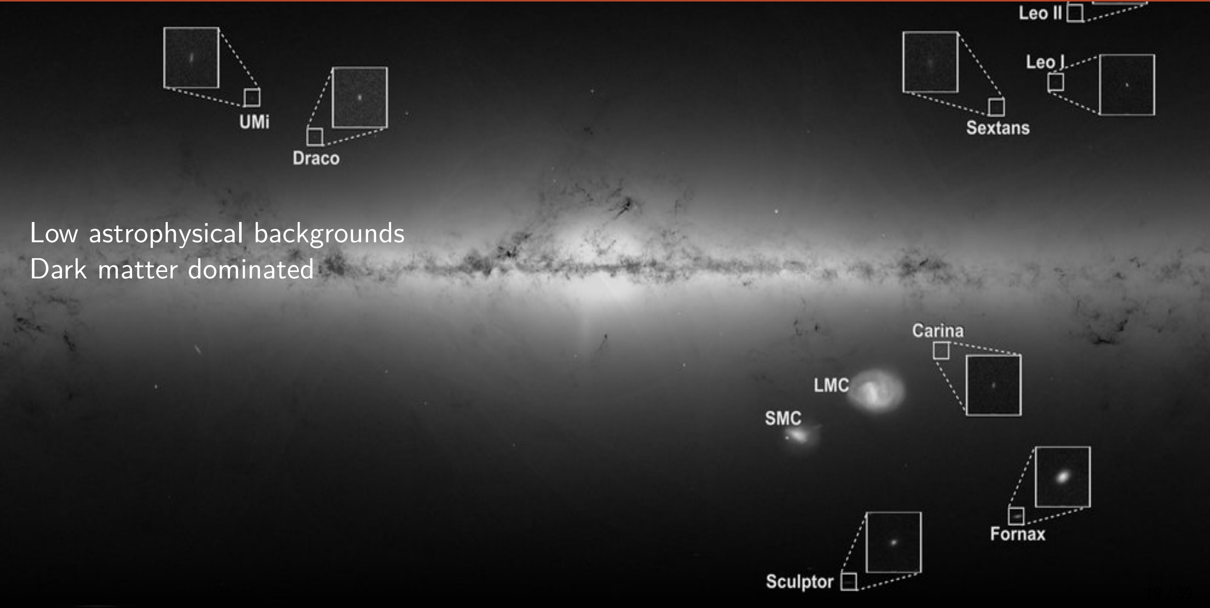


Fig. 2.4 *Full-sky maps of the γ-ray emission from Galactic DM (resolved substructures, resolved + unresolved substructures, and total emission). Figure published in Hütten et al. (2016).*

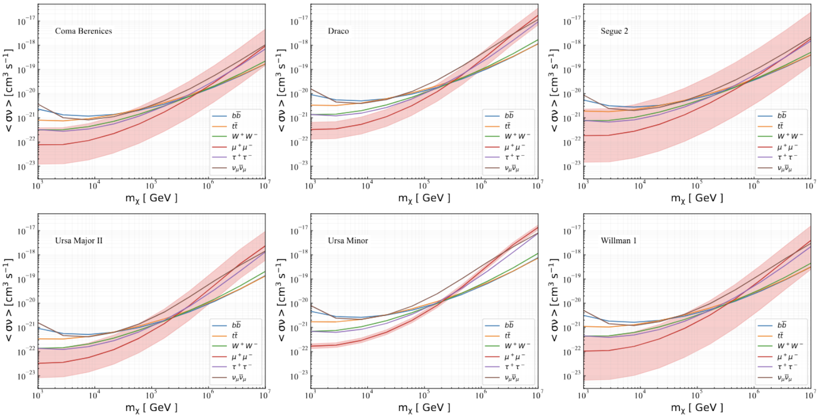
Targeting dark matter sources: Dwarf Spheroidal Galaxies



Low astrophysical backgrounds
Dark matter dominated

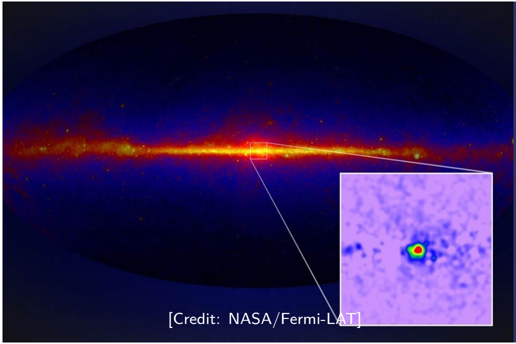
Dwarf Spheroidal Galaxies

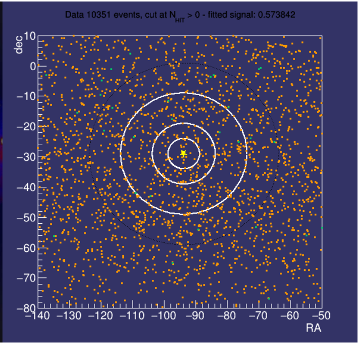
Results with 10 years of IceCube public data **[Phys.Rev.D 108, 043001]**



Galactic Center

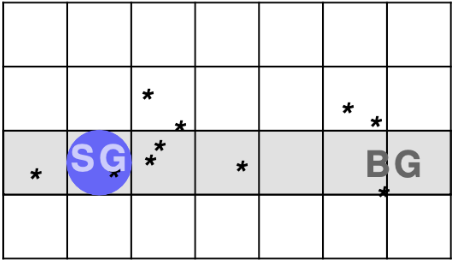
High dark matter content but source confusion (recent excess in gamma rays that neutrinos can start to probe). Major uncertainties from J-factor. Detector sits inside the source.

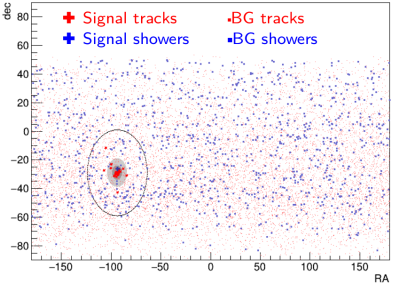




Galactic Centre: $\langle \sigma v \rangle$

Signal = a cluster of n ν-induced events produced in dark matter pair-annihilation process.
Measurement = reconstructed arrival directions and energy proxy.
Search run with binned or unbinned maximum likelihood method.





Galactic Centre: $\langle \sigma v \rangle$

Number of neutrino-induced events from pair annihilation of dark matter seen with acceptance $\mathcal{A}$ after data taking time t

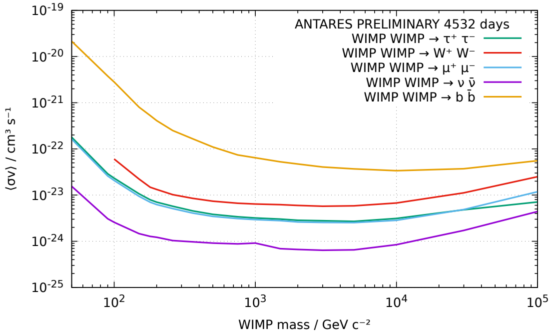
$$n = \frac{1}{2} \langle \sigma v \rangle \int_0^{M_{\mathrm{DM}}} \frac{dN}{dE} dE \, \frac{1}{4\pi} \int_{d\Omega} \int \rho^2 \left(r(\theta, \phi) \right) \frac{1}{M_{\mathrm{DM}}^2} \mathcal{A}(M_{\mathrm{DM}}) \, t$$

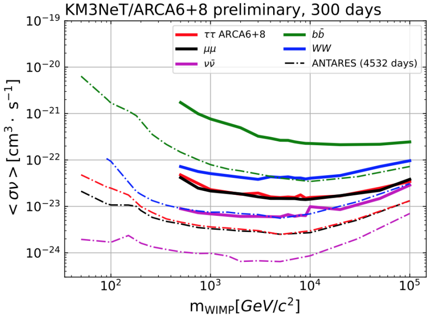
Is that all? No.

1. A factor 2 according whether dark matter particle corresponds with its own antiparticle
2. A factor 0...100% for the relative branching ratio of annihilation modes. This requires model-dependent amplitudes.

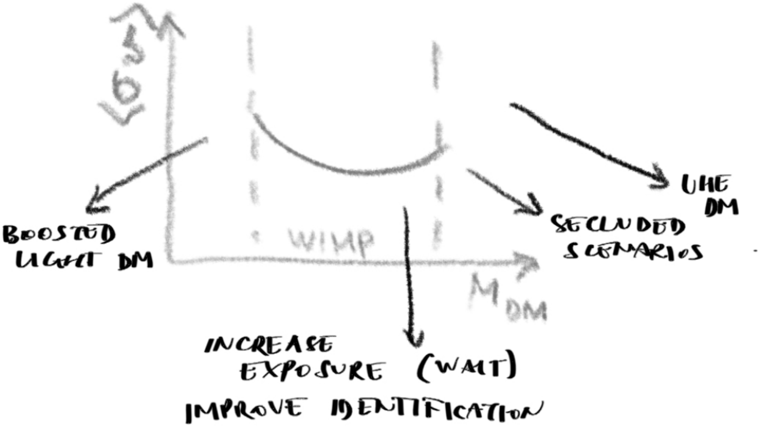
Galactic Centre with ANTARES and KM3NeT

Galactic Centre visible for about 70% of the time in regular data taking mode, using Earth filter. Data from ANTARES 2007 to 2022 + partial KM3NeT conf. is found consistent with background for all combinations of WIMP parameters **[PoS(ICRC2023)1377]** .



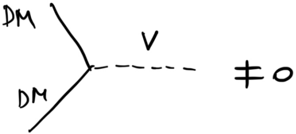


No evidence for WIMP at the GeV-TeV scale; where to search next?

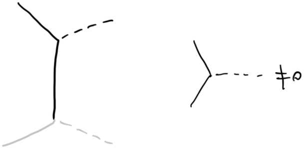


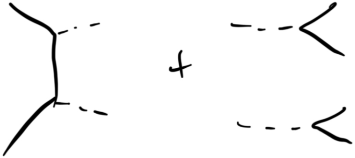
Heavy dark matter in secluded scenarios

MEDIATOR IS ON SHELL

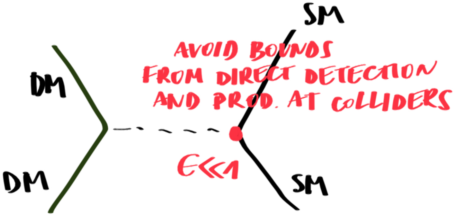


THERMAL PRODUCTION EXISTS





BEFORE BBN



Heavy dark matter in secluded scenarios

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. $\mathrm{DM\,DM} \to 4\mathrm{SM}$ leaving the Galactic Centre as neutrinos. Spectra of relevance for experiments are computed from *boosted* PPPC4DMID [JCAP02(2019)014].

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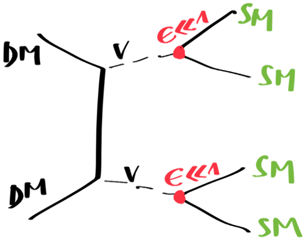

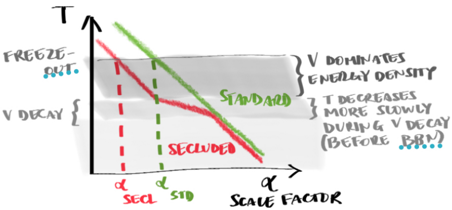

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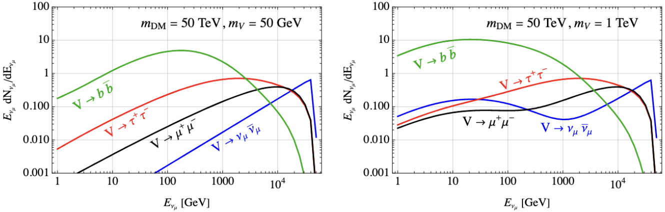

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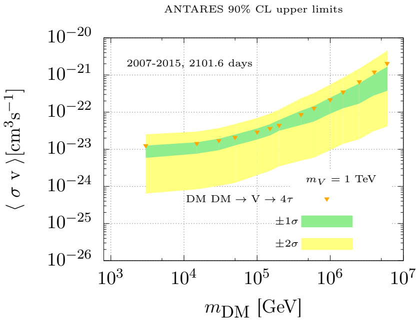
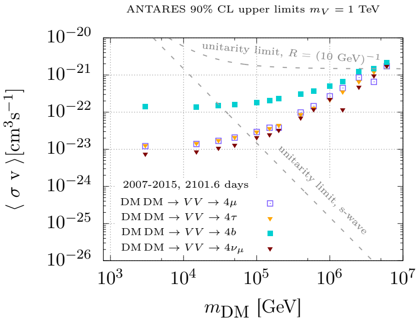
...*boosted* PPPC4DMID?

The relevant energy scale is not the heavy dark matter mass (that would demand a re-summation of electroweak radiation for $m_{\rm DM} > 10$ TeV), but rather the sub-TeV mediator mass, where the first order treatment of electroweak corrections included in PPPC4DMID is under control.

Modified cosmological evolution: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ σv(DM DM $\rightarrow$ VV) smaller $\Rightarrow$ DM can be **heavier**

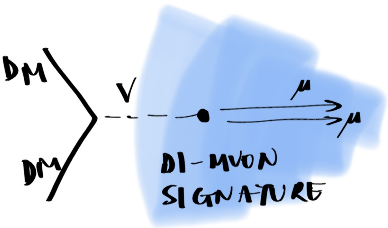


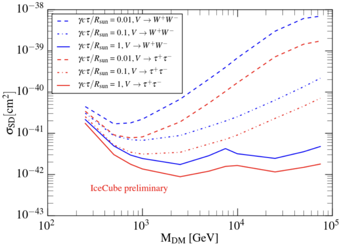


Search for signature of secluded dark matter at large masses using high energy ANTARES data **[JCAP06(2022)028]**

Secluded dark matter in close-by sources

Other scenario is the case when the vector mediator V propagates up to the vicinity of the detector. Case of close-by sources like the Sun.





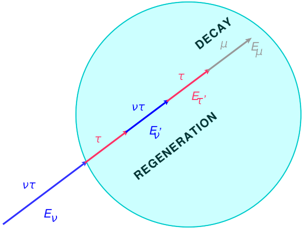
Di-muon signature from the Sun searched for in 6 years of IceCube data. The mediator V escapes the Sun before producing any neutrinos, avoiding attenuation [PoS(ICRC2021)521].

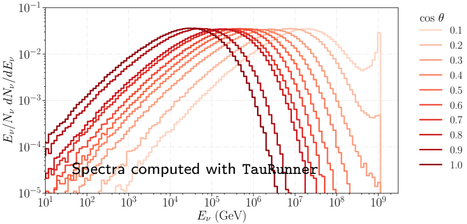
Ultra-heavy dark matter

Several scenarios propose EeV-scale dark matter [for reference see also contribution by R. Aloisio on Tuesday]. Example: right-handed neutrino $\nu_{R,1}$ in CPT symmetry, that decays into Higgs + a light Majorana ν (two-body therefore monochromatic) [LHEP 01,13(2018)]

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

Search channel: ν_τ reaching the detector through τ regeneration across the Earth. `TauRunner` to propagate neutrinos from incident high-energy flux (1 to 10^{16} GeV)





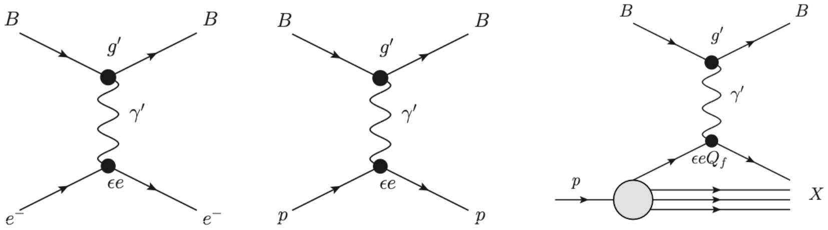
Light boosted dark matter

1. Scenario (1): sub-population of relativistic dark matter produced non-thermally in late-time processes [J. Phys.:Conf.Ser.718 042041]
2. Scenario (2): dark matter up-scattered by cosmic rays [arXiv:2405.00086]

Light boosted dark matter

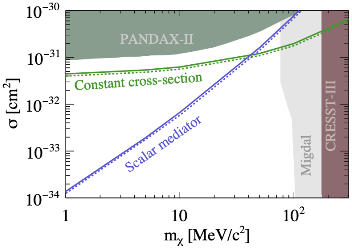
1. Scenario (1): sub-population of relativistic dark matter produced non-thermally in late-time processes [J. Phys.:Conf.Ser.718 042041]

Strategy: detect Cherenkov light from the final state charged particles, above the Cherenkov threshold. No ν yield, rather an unconventional usage of ν detectors [Rev.Mod.Phys.84, 1307].



2. Scenario (2): dark matter up-scattered by cosmic rays [arXiv:2405.00086]

The upscattering riginates from the same dark matter-nucleus interactions as direct detection experiments search for. Directional preference from the GC. Searched by Super-Kamiokande [Phys.Rev.Lett.130, 031802]

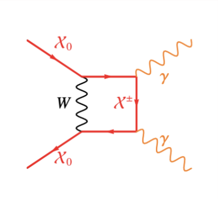


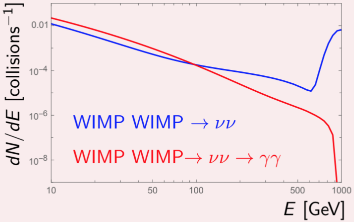
(Conventional direct detection experiments focusing on nuclear recoils are not sensitive to cold sub-GeV dark matter due to insufficient recoil energy).

Current efforts to improve experimental upper limits

1. Combined analyses. ANTARES + IceCube [Phys.Rev.D 102 (2020)], ν and γ-rays with Fermi-LAT,MAGIC, H.E.S.S., VERITAS, HAWC using joint likelihood **glike** [https://zenodo.org/records/4028908]

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





2. Global fit approach. DarkBit, NeutrinoBit modules as part of GAMBIT

What if one of the initial assumptions cease to hold?

Dark matter not a particle? Other candidates have been proposed, however disfavoured.

- Very massive objects: ordinary astrophysical objects (planets, dead stars, black holes); not emitting radiation so OK. However strong bounds when searched via gravitational lensing.
- Primordial black holes: baryonic but created before BBN. Non-observed Hawking radiation is in contraddiction. Do not account for the totality of dark matter, anyway.

Other production mechanisms than freeze-out of a thermal relic?

- Freeze-in. Dark matter is initially absent, then starts to be produced.
- Darkogenesis. Very small primordial asymmetry as for ordinary baryonic matter.

Might be testable with neutrinos, but will hardly come to a conclusive result.

Concluding

Indirect searches for dark matter via neutrino yield is in the science case of Cherenkov neutrino telescopes like ANTARES, KM3NeT, IceCube, Super-Kamiokande, SNO+

- Towards pushing the thermal relic cross section with the next generation of ν observatories
- Multi-messenger searches combining data from neutrino and gamma-ray observations
- Search for monochromatic lines, special spectral signature for neutrino telescopes
- Rich field of opportunities for novel scenarios considered empty-handed WIMP search

> Dark matter remains BSM's most wanted individual...
> Neutrinos participate in cross-triangulation between search channels