Investigating SHDM decays at IceCube

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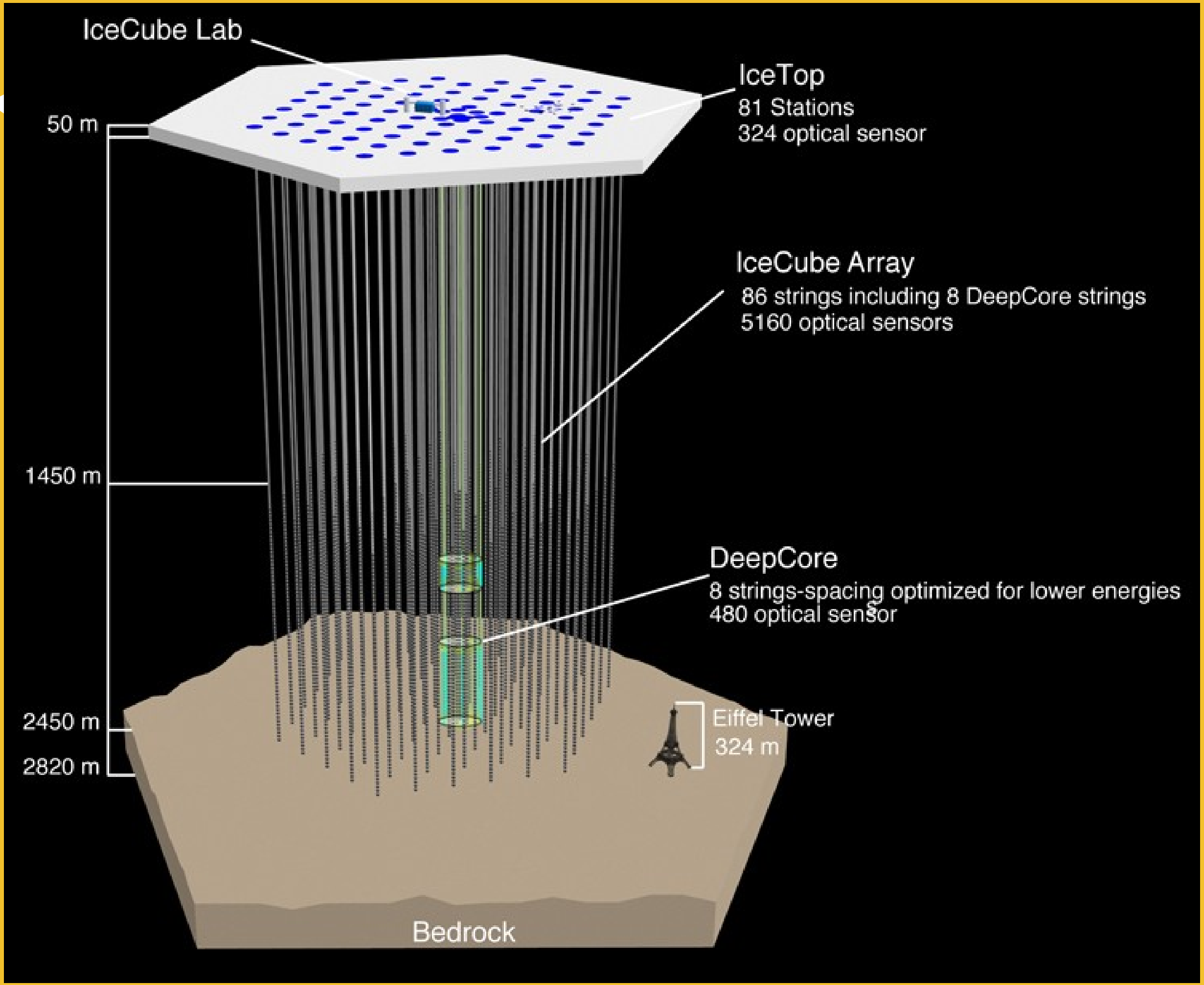
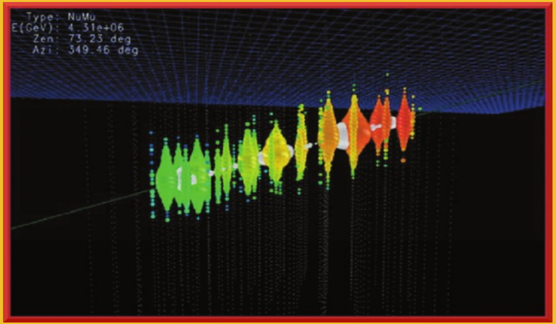
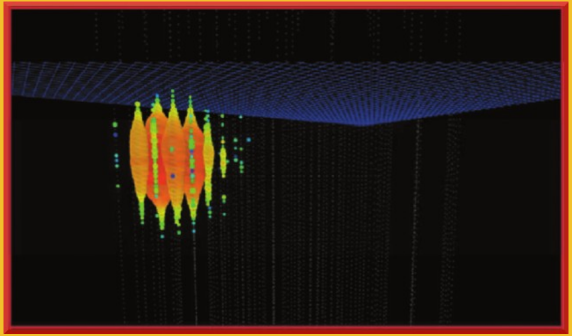
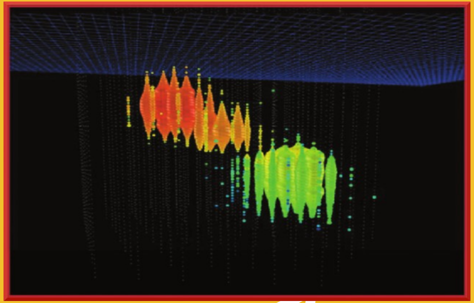
Reno et al, arXiv:2107.01159

CosPa 2021, Brussels

Constraining unusual dark matter distributions in Earth by looking at ten-year IceCube events


IceCube Lab
50 m
IceTop
81 Stations
324 optical sensor
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensor
2450 m
2820 m
Eiffel Tower
324 m
Bedrock

Type: NuMu
E(GeV): 4.31e+06
Zen: 73.23 deg
Azi: 349.46 deg



01 Motivation

Why look at Very Heavy Dark Matter in Earth? How does VHDM **distribute in Earth**? What **decay channels** are important for IceCube?

01 Properties of DM

- SHDM: Particle DM with $m \sim 10^7$–10^{10} GeV
- Super heavy mass: background-free detection at IceCube
- Require effective collection of DM in Earth

02 ANITA inspirations

Taus from SHDM decay inside earth have been suggested as an explanation of ANITA I + III anomalous events seen ~ 30° below the horizon at ~ 10^8 GeV. We started to look for complementary signatures in IceCube…

03 But generalise

… but many of the suggested models for ANITA fail for different reasons anyway. We realised that IC would nonetheless be able to see/constrain SHDM decay signals coming from Earth under more general conditions.

04 Focus on τ and μ

The requirement that SHDM decay products travel long distances in Earth to reach, e.g. IceCube, limits decay channels to τ/μ or ν compatriots. Our study focuses on composite DM $\chi \to \nu_\tau \bar{\nu}_\tau$.

02 DM in the Earth

What factors influence **DM capture**? Cross-sections required to **prevent DM from sinking to core**? How to **parameterise** DM distribution?

Collection

Capture

DM capture by Earth happens as the Earth travels through DM distributed in the galaxy.

If DM is weakly interacting, DM capture is inefficient ($v_{esc} < v_{\chi}$).

Evaporation

Low evaporation rates for SHDM, see Garani and Palomares-Ruiz, 2021

Decay/Annihilation

Assume DM does not annihilate, but only decays with long life-times: $\tau \sim 10^{28}$ s.

Constraints mainly from heat flow in Earth

Distribution

Strong interactions

Efficient DM collection ensured by assuming strong interactions: ~ 10^{-21} cm^2

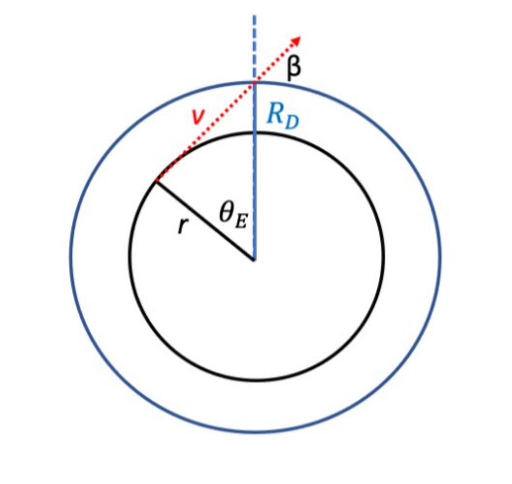
Prevents DM immediately sinking into core, thus allowing more interesting distributions

Composite DM

Parameterisation

We consider DM distributed uniformly in the Earth

Define $\rho_\chi = \epsilon_\rho \rho_\oplus^{\mathrm{avg}}$



Decay and detection

Decay channels

Focusing on $\chi \rightarrow \nu_\tau \bar{\nu}_\tau$

Up-going tau-tracks or tau-decay or ν_τ double-bangs inside detector

Simulate energy loss during propagation, tau regeneration, via MC

Number of detectable taus

$$N_\tau = \int d^3r \; n_\chi(r) \, P_{\chi \to \nu_\tau}(T_0) P^{\nu_\tau \to \tau}(r, \theta_E) \frac{\Delta\Omega_{\rm obs}}{4\pi}$$

$n_\chi(r)$ → DM number density

$P_{\chi \to \nu_\tau}(T_0)$ → DM decay probability Over detector life-time T_0

$P^{\nu_\tau \to \tau}(r, \theta_E)$ → Probability of detection

Decay and detection

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$$N_\tau = \int d^3r \; n_\chi(r) \, P_{\chi\rightarrow\nu_\tau}(T_0) P^{\nu_\tau\rightarrow\tau}(r, \theta_E) \frac{\Delta\Omega_{\mathrm{obs}}}{4\pi}$$

$n_\chi(r)$: $\propto \rho_\chi$

$P_{\chi\rightarrow\nu_\tau}(T_0)$: $B_{\chi\rightarrow\nu_\tau} \Gamma_\chi T_0$

$P^{\nu_\tau\rightarrow\tau}(r, \theta_E)$: τ decays in IC + τ tracks + ν events

“Constrainables”

Using IC as a test detector, we will be able to constrain the product

$$\epsilon_\rho B_{\chi \to \nu_\tau} \Gamma_\chi$$

ϵ_ρ → Fractional DM density

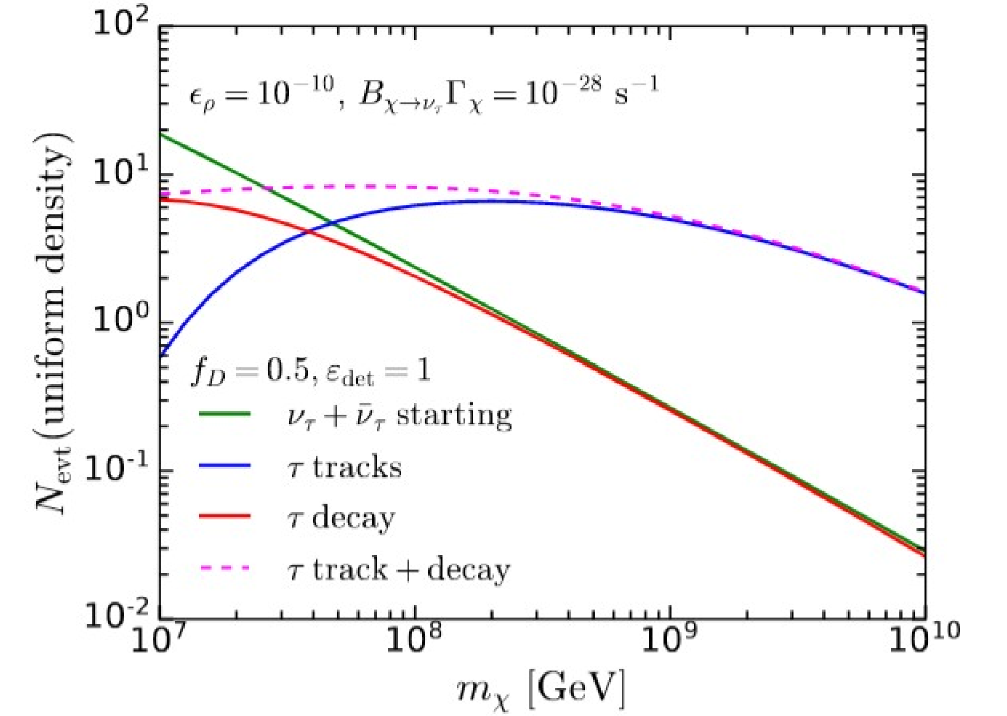
$B_{\chi \to \nu_\tau}$ → Branching fraction

Γ_χ → Life-time

03 Results

Number of events at IC for 10-yr runtime? Event-distribution by **arrival angle**? **Limits** on composite parameter.

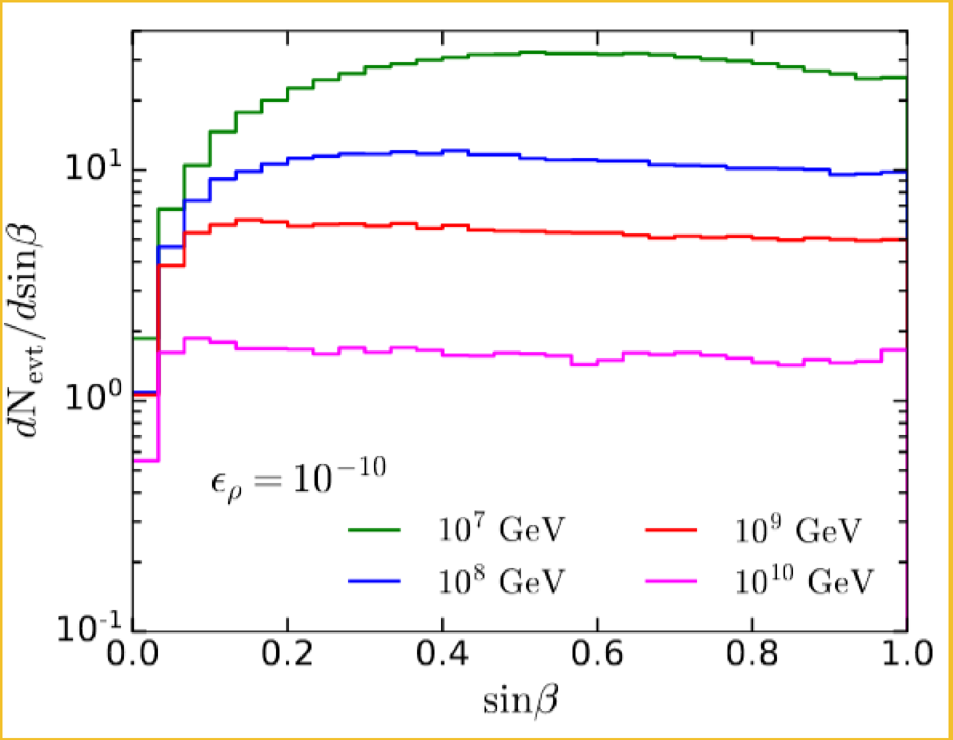
Events at IC_{10}



Total events as a function of DM mass assuming IC runtime of 10 yrs

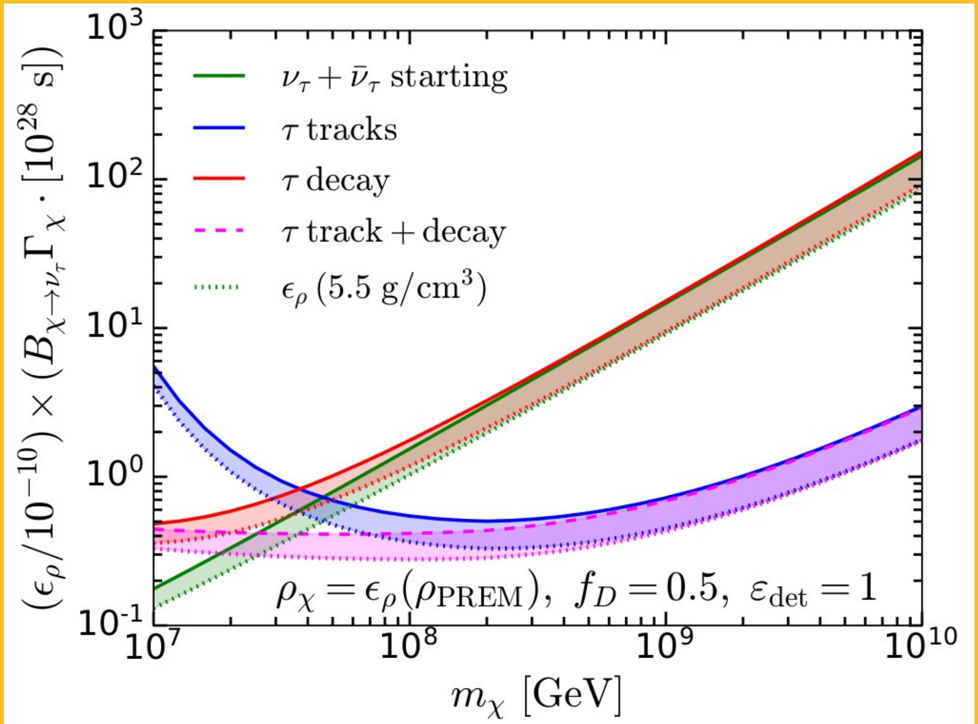
Events at IC_{10}

Event distribution as a function of arrival angle at detector



Results

Parameter Constraints



- Dotted curves: constant DM distribution
- Solid/Dashed curves: DM follows PREM profile

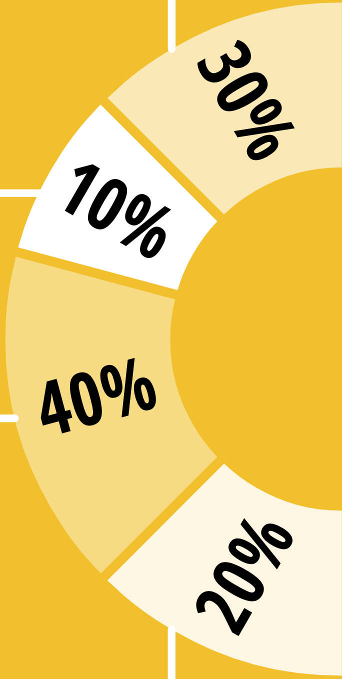
Wrapping up

We have investigated the potential of IceCube towards constraining non-trivial distributions of long-lived SHDM in Earth

Parameterising DM distribution as proportional to matter distribution in Earth, we draw constraints on the composite variable: $\epsilon_\rho B_{\chi\to\nu_\tau}\Gamma_\chi$

For a nominal value of $\epsilon_\rho = 10^{-10}$ we obtain a limit: $B_{\chi\to\nu_\tau}\Gamma_\chi \lesssim 2\times 10^{-29}\ \mathrm{s}^{-1}$ for $m_\chi = 10^7$ GeV, comparable to IC limits from GC

If IceCube detects SHDM signature from GC and infers the lifetime, our results will lead to constraints for the DM distribution in Earth



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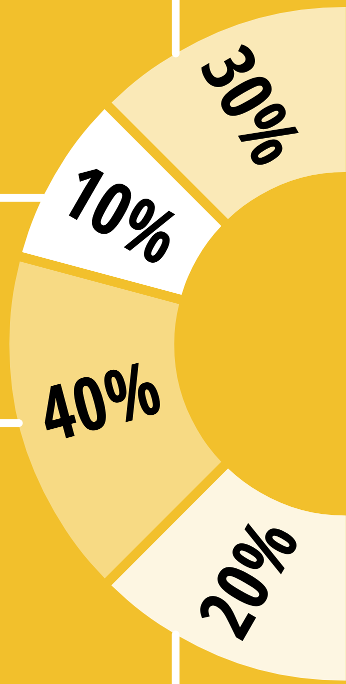

Backup - I

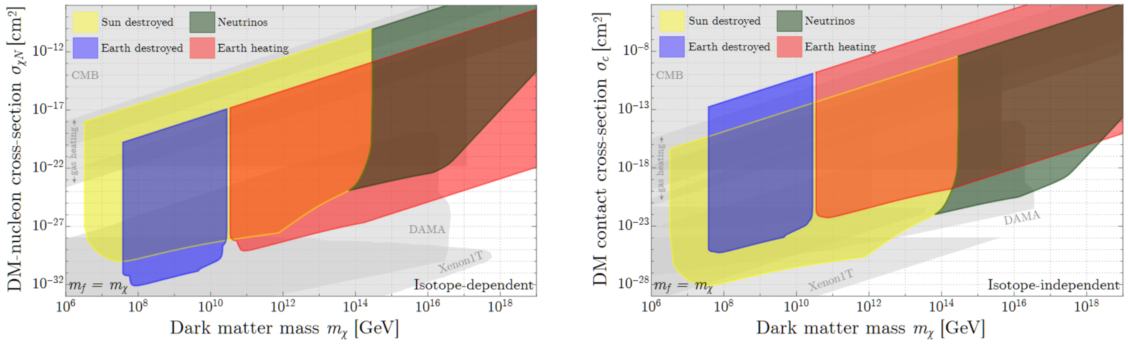

Figure 10. **(left)** Solar and terrestrial bounds on the DM–nucleon scattering cross-section for non-annihilating dark matter with conventional spin-independent (and therefore isotope-dependent) couplings. The blue and yellow regions are excluded by the formation of a black hole in the Earth or Sun that would grow and consume these bodies within a billion years. The red region is excluded by the formation of evaporating black holes in the Earth that would result in more than the observed 44 TW of heat emanating from the Earth's surface. Finally, the dark green region is excluded by the null observation of a high-energy flux of neutrinos that would be produced by black holes evaporating in the Sun. The edges of the exclusion regions can be understood as follows: for $m_\chi \lesssim 10^7$ GeV, black holes will not form, given the amount of dark matter collected in a Gyr. The upper cutoff in m_χ is given by the Planck scale, 10^{19} GeV. The lower edges of the exclusion regions are determined by requiring that dark matter collects, cools, and collapses to a black hole in a Gyr. Their upper edges are determined by requiring that dark matter can drift to the center of the Earth or Sun against the viscous drag of nuclei in less than a Gyr. Previous limits from underground direct detection experiments are shaded in gray [53, 124–126], as are CMB bounds [127, 128], bounds from the heating of interstellar gas clouds [54, 129], and bounds from searches for DM tracks in ancient mica minerals [130, 131]. **(right)** Same as left, but for a dark matter–nucleus scattering via isotope-independent contact interactions, as discussed around Eq. (3). We assume here that, even though dark matter may consist of composite objects, the constituent masses are large enough for Pauli blocking to be irrelevant during collapse.