Undergraduate Thesis Report

Dark Matter Annihilation and Decay Software

ENPH 455: Engineering Physics Thesis

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July 20, 2022

Abstract

The dark matter annihilation and decay software (DANDAS) was created to help researchers studying dark matter's properties. Assuming dark matter annihilates or decays to neutrinos, a signal can be measured and used to derive conclusions about dark matter. DANDAS calculates the bounds of dark matter's annihilation cross section or decay lifetime based on available data from neutrino detectors around the globe and customizes these parameters based on a user's assumptions about dark matter. The user can input their assumptions about dark matter mass, density distribution throughout the galaxy, and antiparticle nature, and receive constraints on the annihilation and decay rates in graphical or numerical format. The software is publicly available on GitHub and can provide clear and accurate dark matter data in under 4 minutes.

Contents

1 Introduction

The nature of dark matter remains one of the most pressing questions in modern physics and astronomy. Despite observational evidence showing that dark matter (DM) makes up approximately 85% of the matter in the universe, its basic properties remain unknown [1]. What is the mass of a single DM particle? Does DM have a corresponding antiparticle? And most importantly, what is DM's makeup at the particle level?

A leading candidate for DM is the Weakly Interacting Massive Particle (WIMP)[2]. If dark matter is a WIMP, there remains a possibility that it could annihilate or decay into standard model particles which would yield a measurable neutrino signal. As DM does not interact electromagnetically, it is extremely difficult to detect directly in experiments [3]. Thus, looking for the products of dark matter decay or annihilation remains one of the most useful ways to probe DM's properties [2]. The Dark matter ANnihilation and DecAy Software (DANDAS) aims to improve research on DM annihilation or decay to neutrinos.

Neutrinos are a viable DM decay or annihilation product for a multitude of reasons. Firstly, if DM decayed or annihilated to charged particles such as electrons or protons, there would be an obvious and measurable flux of these products detected on Earth from regions of high DM density in the galaxy. As this flux is yet to be reported by active experiments, one must consider the possibility of DM decaying or annihilating to a particle that is more difficult to measure: the neutrino. Due to neutrinos being electrically neutral, fast, and light, they require extremely sensitive detectors to be measured.

Further, while neutrino flavour oscillation proved that neutrinos have mass, the mechanism by which they gain this mass remains a puzzle within the Standard Model [4]. If neutrino mass is related to the dark matter sector, it provides a way to solve two of the biggest mysteries in modern physics.

DANDAS aims to improve research into the DM-neutrino connection. DANDAS will be capable of taking a researcher's dark matter assumptions as inputs and output the most updated constraints on DM annihilation and decay to neutrinos.

2 Problem Definition

While research into the connection between DM and neutrinos is a growing field, it also faces specific problems that DANDAS aims to solve. The two main problems are related to data compilation and limited ability to apply others research.

Firstly, because the mass of a single DM particle remains unknown, its annihilation and decay parameters must be calculated over a huge range of possible masses. To do this, data must be compiled from many neutrino detectors around the globe as shown in Table 1. While this is not a comprehensive list of every single neutrino experiment in the world, these experiments provide the strongest DM decay and annihilation constraints over the desired DM mass range. Note that a range of $10^{-2} - 10^{11}$ GeV was chosen to calculate limits on DM annihilation and decay rates over as this corresponds to the range of energies at which galactic neutrinos can be reliably detected [5].

Compiling all of this data can be extremely time-consuming for researchers because neutrino data is not often reported in a consistent way. Some collaborations

Table 1: Summary of current and future neutrino experiments relevant for DM annihilation and decay calculations. This table is from reference [2] and indicates whether the experimental analysis used directional information and which neutrino flavors it detects.

Energy Range	**Experiment**	**Directionality**	**Detected Flavor**
$2.5 - 15$ MeV	Borexino [6]	×	$\bar{\nu}_e$
$8.3 - 18.3$ MeV	KamLAND [7]	✓	$\bar{\nu}_e$
$10 - 40$ MeV	JUNO [8]	✓	$\bar{\nu}_e$
$15 - 10^3$ MeV	SK [9]	×	$\bar{\nu}_e$
$0.1 - 30$ GeV	DUNE [10]	×	$\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau$
$0.1 - 30$ GeV	HK [10]	×	$\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau$
$1 - 10^4$ GeV	SK [11, 12]	✓	All Flavors
$20 - 10^4$ GeV	IceCube [13]	✓	All Flavors
$50 - 10^5$ GeV	ANTARES [14]	✓	ν_μ, $\bar{\nu}_\mu$
> 100 PeV	RNO-G [15]	✓	All Flavors
> 10 PeV	IC Gen-2 [5]	✓	All Flavors
$10 - 10^4$ TeV	KM3Net [16]	✓	All Flavors
$1 - 100$ PeV	TAMBO [17]	✓	ν_τ, $\bar{\nu}_\tau$
> 100 PeV	GRAND [18]	✓	ν_τ, $\bar{\nu}_\tau$

will publish a diffuse neutrino flux, while others will publish annihilation limits without the corresponding flux these calculations are based off of. Thus, getting a full picture of the DM annihilation and decay behaviour can be an unnecessarily onerous task for researchers.

Further, there is limited ability to use calculations by other researchers due to the wide variety of assumptions that must be made to conduct DM analysis. There are many allowed possibilities related to dark matter's mass distribution in different galaxies, and its antiparticle nature. Thus, if another research team employed different DM assumptions, you have little ability to use their calculations for your own analysis.

DANDAS aims to solve both of these problems by allowing researchers to calculate customized DM annihilation and decay parameters. It is loaded with experimental data from all experiments shown in Table 1 and calculates annihilation and decay parameters that correspond to a researchers DM assumptions. This will save researchers hours of unnecessary data analysis and improve the ability to collaborate within a growing field. A visualization of how DANDAS can be used by researchers is shown in Figure 1.

This software is an extension of the work done in [2] which investigated DM annihilation to neutrinos over a $10^{-2} - 10^{11}$ GeV DM mass range. DANDAS aims to expand on their work by providing brand new limits on the decay rate of DM while also providing customization to allow their calculations to be used by a wider audience of researchers.

DM is one of the biggest astrophysics puzzles of our generation. By providing tools to researchers to make determining its properties easier, we get closer to understanding the makeup of this exotic substance that makes up 85% of our universe.

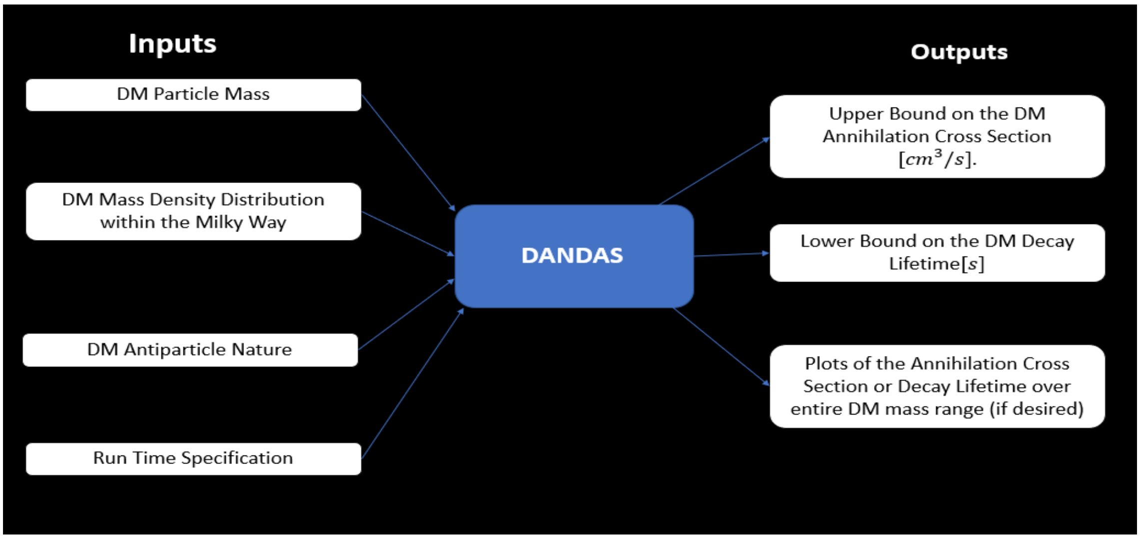

Figure 1: Simplified summary of how DANDAS can be used to investigate the annihilation and decay properties of dark matter. A more complete description of DANDAS inputs and outputs can be found in Sec. 6.

3 Theoretical Background

To model the annihilation or decay of a particle, the two most important parameters are annihilation cross section (cm^3/s) and lifetime (s). Annihilation cross section is the effective area that describes how likely two particles are to annihilate as they pass each other at a given time while lifetime refers to the average time before a particle decays into lighter particle(s) [19].

DANDAS is able to calculate annihilation cross section and lifetime assuming these processes follow what is seen in Figure 2. Note that these calculations assume equal annihilation and decay to all flavours of neutrino but could be adapted to account for more detailed flavour dependence in the future.

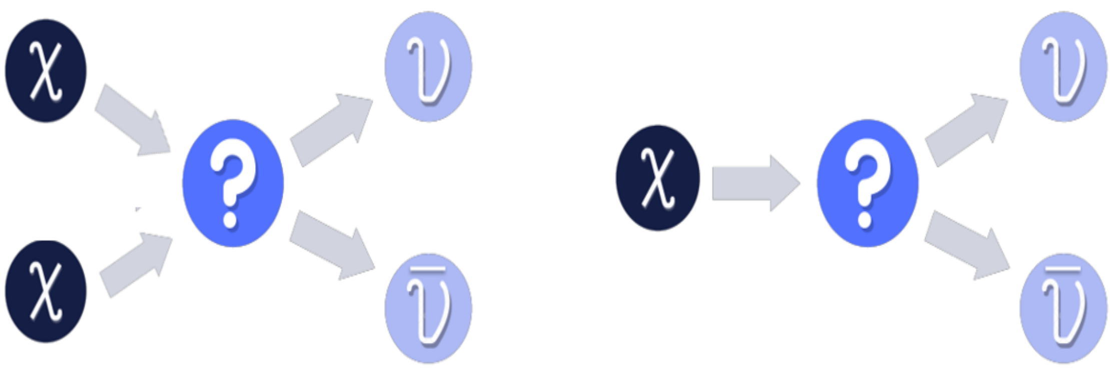

Figure 2: Dark matter annihilation (left) and decay (right) to neutrinos processes modelled in this work.

To model neutrino flux as a function of annihilation cross section ,$\langle \sigma v \rangle$, Eqn. 1 can be used [2]. $\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu}$ refers to the expected flux per flavor of neutrinos and antineutrinos at Earth, m_x is the mass of a DM particle, κ is a constant depending on the DM anitparticle nature. $\kappa = 4$ for particles that are distinct from their antiparticle counterpart (referred to as Dirac particles) and $\kappa = 2$ if not (Majorana particles). Further, E is the energy of the detected neutrino at Earth and $J(\Omega)$ is a three dimensional integral over the DM density shown in Eqn. 3.

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\kappa m_\chi^2}\frac{1}{3}2\delta(1 - E/m_x)J(\Omega), \tag{1}$$

DM lifetime (τ_χ) is related to neutrino flux in a similar way.

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\frac{1}{3}2\delta(1 - E/2m_x)D(\Omega), \tag{2}$$

As these calculations are based on an upper bound of neutrino flux, they can only be used to constrain annihilation cross section and lifetime, they cannot derive exact values. For example, based on a specific neutrino flux Eqn. 1 could be used to calculate that for $m_x = 100$ GeV, $\langle\sigma v\rangle \approx 10^{-24} cm^3/s$ is the absolute highest possible cross section value that would be consistent with current neutrino data.

The $J(\Omega)$ and $D(\Omega)$ terms are calculated using Eqns. 3 and 4 where $\rho_\chi(x)$ is the DM density distribution function within the galaxy.

$$J(\Omega) \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(x)dx. \tag{3}$$

$$D(\Omega) \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi(x)dx. \tag{4}$$

The angular integration is done over the region, Ω, that a given neutrino detector sees within the galaxy. While most detectors can detect neutrinos from any direction, specific experiments such as P-ONE, GRAND, and TAMBO are more sensitive to neutrinos coming from specific regions of the sky [20, 21, 22] which must be accounted for in the flux calculation in Eqns. 1 and 2. The x integration is over the "line of sight" of the detector and extends from Earth to the outermost region within the Milky Way DM halo [2].

Note that $D(\Omega)$ is calculated in the same way as $J(\Omega)$ except DM density is not squared. This is due to the fact that only 1 DM particle is required for a decay process but 2 are required for annihilation as shown in Figure 2.

4 Software Algorithm

DANDAS is able to customize the calculations for researchers by changing specific variables outlined in Section 3. This happens in 3 main stages within DANDAS. Firstly, $J(\Omega)$ and $D(\Omega)$ factors are calculated using Eqns. 3 and 4 based on the assumed DM density distribution within the galaxy. Then, annihilation cross section and lifetime bounds are calculated based on the user's other assumptions. Finally, depending on if the user wants the output in graphical or numerical format, the bounds will be either plotted or interpolated and output as an array.

4.1 J and D Factor Calculation

As shown by Eqns. 3 and 4, the J and D factors are heavily dependent on the assumed dark matter density distribution function, $\rho_\chi(x)$, in our galaxy. This DM density distribution function is referred to as a DM halo profile. Different astronomical simulations support different halo profiles in our galaxy, but the two most commonly used are the Navarro-Frenk-White profile (NFW), Eqn. 6, and the Einasto profile, Eqn. 5 [2, 23]. Note that r_s is a scale radius at which the density of DM begins to decrease more rapidly and ρ_s is the DM density at that radius. Further, α and γ are slope parameters that describe how the DM density changes as the distance from the galactic centre is increased[1].

$$\rho_\chi(r) = \rho_s \exp\left[\left(\frac{-2}{\alpha}\right)\left(\frac{r}{r_s}\right)^{\alpha-1}\right] \tag{5}$$

$$\rho_\chi(r) = \rho_s \frac{2^{3-\gamma}}{(r/r_s)^\gamma (1 + r/r_s)^{3-\gamma}} \tag{6}$$

As different researchers may assume different DM halo profiles, it is important that DANDAS can calculate accurate parameters for a variety of options. It was chosen to offer the user different halo profile options to ensure maximum usability. The user can choose to assume a standard NFW or Einasto profile where DANDAS will input best-fit values for ρ_s, r_s, γ and α based on data available at time of publication. The user could also choose to employ a NFW or Einasto halo profile and change these parameters if new simulation data supports updated values. Finally, if a user wants to employ a different DM halo profile, they can input a custom DM density function and DANDAS will calculate J and D factors based on that[2].

4.2 Lifetime Limit Calculation

Depending on how data is presented by a neutrino detector, lifetime limits are calculated in a different way. The four main ways data was presented is a upper limit of neutrino flux, a diffuse neutrino flux, an annihilation cross section limit, and a projected sensitivity to neutrinos. The methods by which these different data sets are converted into a lower bound on DM lifetime is outlined below. Further, Table 2 outlines the type of data used to calculate all lifetime limits within DANDAS. It is important to note that experiments that provided data in the same form were not all treated in the exact same way. Different scaling factors had to be included to account for differences in exposure time and neutrino flavor detected.

To derive lifetime limits from an upper limit of neutrino flux, $\Phi_{\nu+\bar{\nu}}$ with units $[GeV^{-1}s^{-1}cm^{-2}]$, Eqn. 2 was used. By integrating Eqn. 2 with respect to neutrino energy, the Dirac delta term becomes equal to 1 and the expression can be rearranged to output lifetime as a function of measured neutrino flux and DM mass. Note that the DM mass is assumed to be double the energy of the neutrino detected as the assumed decay process is one DM particle producing two neutrinos as shown in Figure 2.

When a diffuse neutrino flux was given with units $[GeV s^{-1}cm^{-2}]$ (written as $E^2\phi$ in literature), lifetime limits were calculated slightly differently. In this case,

[1] It is important to note that Eqns. 3 and 4 show $\rho_\chi(x)$ which is DM density as a function of distance from Earth whereas Eqns. 5 and 6 show DM density as a function of distance from the galactic centre (r) for clarity. DANDAS automatically converts between coordinate systems to ensure integration is done properly.

[2] More detailed information on how exactly to apply these different options when calling DANDAS is available *here*.

the size of the logarithmic energy bins, Δ, and assumed flux power law,$E^{-\alpha}$, within those bins had to be accounted for. First, $E^2\phi$ had to be converted to a differential flux. This differential flux then has to be integrated to calculate the upper limit of flux at the centre of each logarithmic bin as shown in Eqn. 7 where f_0 is a scaling constant and $\bar{E}$ is the energy at the centre of the bin.

$$\phi_{lim}(\bar{E}) = 4\pi \int_{\bar{E}10^{-\Delta/2}}^{\bar{E}10^{+\Delta/2}} f_0 E^{-\alpha} dE, \tag{7}$$

This integral solves to Eqn. 8 in the case of $\alpha \neq 1$.

$$\phi_{lim} = \frac{4\pi}{\alpha - 1} \frac{d\phi}{dE}\bigg|_{lim} \bar{E}\left(10^{\Delta/2} - 10^{-\Delta/2}\right). \tag{8}$$

By equating Eqn. 8 to an integrated Eqn. 2, lifetime limits can be derived from Eqn 9 or Eqn. 10 in the case of $\alpha = 1$.

$$\tau = \frac{2D(\alpha - 1)}{3m_\chi^2(4\pi)^2}\left(\left(10^{\Delta/2} - 10^{-\Delta/2}\right)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}. \tag{9}$$

$$\tau = \frac{2D}{3m_\chi^2(4\pi)^2}\left(\Delta \ln(10)\frac{d\phi}{dE}\bigg|_{lim}\right)^{-1}. \tag{10}$$

Some experiments will calculate limits on annihilation cross section from their measured neutrino flux instead of publishing the raw flux data. This can be converted into a limit on DM lifetime using Eqns. 1 and 2. As they are both dependent on $\Phi_{\nu+\bar{\nu}}$, an upper limit on neutrino flux can be calculated from $\langle\sigma v\rangle$ using Eqn. 1. Then, the process outlined above for calculating DM lifetime from an upper limit of neutrino flux can be applied.

Finally, experiments that have not yet begun collecting data will typically give a projected sensitivity to neutrinos. By performing a statistical analysis, as described in Sec. IIIa of reference [2], the number of expected neutrino detections due to DM related events can be tabulated. From this, a neutrino flux can be derived and a limit on DM lifetime can be calculated with Eqn. 2.

A complete breakdown of all analyses considered by DANDAS along with the type of data DANDAS uses to calculate lifetime limits is outlined in Table 2. Note that there are multiple analyses for a single experiment in some cases (SK, IceCube, etc.) as they will report different types of data separately.

4.3 Annihilation Cross Section Scaling

As DM annihilation cross section limits have already been computed across the $10^{-2} - 10^{11}$ in a previous analysis [2], their calculations could be simply scaled based on the user's assumptions. The analysis in [2] assumes that DM is a Majorana particle and follows a NFW DM halo profile within the Milky Way. Thus, if a user assumes a different antiparticle nature or DM halo profile, DANDAS can scale the calculated annihilation cross section from [2] using the κ or $J(\Omega)$ terms in Eqn. 1.

Table 2: Summary of published data that was used to calculate lifetime limits for DANDAS. This is an adaptation of a similar table published in [2].

Analyses	**Data Used to Derive Lifetime Limit**
Borexino	Upper Limit of Neutrino Flux [24]
KamLand	Upper Limit of Neutrino Flux [24]
SK-$\bar{\nu}_e$	Upper Limit of Neutrino Flux [25]
SK (Olivares)	Annihilation cross section [9]
SK	Annihilation cross section [26]
SK (atm.)	Diffuse Neutrino Flux [2].
IceCube	Annihilation Cross Section [13] [27]
IC-Deepcore	Annihilation Cross Section [28].
IC (atm.)	Diffuse Neutrino Flux [2]
IceCube-HE	Diffuse Neutrino Flux [2]
IceCube-EHE	Diffuse Neutrino Flux [29]
IceCube (Bhattacharya)	Lifetime Limit [30]
ANTARES	Annihilation Cross Section Limit [2]
PONE	Statistical analysis based on atmospheric and astrophysical neutrino background [20].
KM3NET	Calculated from annihilation cross section limit [31].
CTA	Calculated from annihilation cross section limit [32].
RNO-G	Calculated from diffuse neutrino flux [33].
GRAND-200k	Calculated from diffuse neutrino flux [22].
Hyper-Kamiokande	Calculated from annihilation cross section limit and scaled for exposure difference [34].
DUNE	Calculated from annihilation cross section limit [2].
TAMBO	Statistical analysis based on projected sensitivity to neutrinos [21].

5 Design

5.1 Constraints

The primary constraint affecting the design of DANDAS was the computational power required for calculation. Some of the computations required to generate DM annihilation and decay limits are very complex and thus require a long run-time. Specifically, calculating the J and D factors accounted for the vast majority of the computation time within DANDAS. Depending on the methodology, the calculation of a single J or D factor could take between minutes and hours as it required integrating DM density over a distance of thousands of light years while accounting for the rotation of the Earth.

As the user cannot be expected to wait multiple hours for DANDAS to output a single parameter, this constraint had to be accounted for. This was done by iterating the integration method and offering the user different input options depending on their desired run time and information needs. For example, if a user needed the annihilation cross section limit for a DM particle with $m_\chi = 0.1$ GeV in under 5 minutes, DANDAS can neglect specific J and D factors that are unnecessary for this analysis.

5.2 Design Goals

DANDAS aims to be as accurate, fast, and user-friendly as possible. For DANDAS to be useful to researchers, it must be reliable and easy to use.

To evaluate accuracy, the annihilation cross section and lifetime limits calculated by DANDAS were compared to published limits in [2]. Ideally, results from DANDAS will agree to within 2% of published data. This 2% discrepancy was deemed reasonable as there is a low level of randomness involved in the Monte Carlo integration method used to calculate J and D factors. As the DM decay rate limits are new scientific results, ensuring their accuracy was more complicated. All annihilation cross section limits in [2] were rescaled to lifetime limits, following the process in Section 4.3, and then compared to DANDAS lifetime calculations to ensure agreement with published results.

The evaluation of DANDAS speed will be as follows. A run-time of under 5 minutes would be considered satisfactory. A run-time of under 1 minute would be good, and a run-time of under 30 seconds would be excellent.

Finally, the user-friendliness is evaluated based on two factors. Firstly, DANDAS should be easy to set up on the user's computer. Also, the DANDAS user-interface should be as attractive as possible. The user should not have to parse through the source code to figure out how to use this software or where to find the output. The user-friendliness was tested by having peers who have no familiarity with DANDAS use the software based on only information in this report. Their feedback on ease of setup and intuitiveness was then used to iterate DANDAS.

5.3 Economic Considerations

As DANDAS aims to improve dark matter research, it should be accessible to all researchers who want to use it. Thus, DANDAS will be a publicly available software that is completely free to use. In the field of high energy physics, almost all published papers are available for free online. As such, forcing users to pay to use DANDAS would counter both the norms within the field and the purpose of the software itself.

5.4 Societal Benefits

While this software aims to help researchers in the field of dark matter physics, it could also be applied to the field of education.

Specifically, DANDAS could be used as an effective teaching tool for undergraduate physics students. When explaining the concepts of DM distribution within the galaxy or dark matter's antiparticle nature, it can be difficult to grasp their significance and meaning. DANDAS could be useful in showing how changing these parameters results in different modelling of dark matter's properties at the atomic scale.

6 DANDAS: Users Guide

The full DANDAS package is available on GitHub and is publicly available for anyone who wishes to use it. It can be accessed directly through the command line or downloaded as a zip file and uploaded to a Jupyter Notebook.

For Linux based users, it is reccommended to simply use the "git clone" command followed by the .url of the *DANDAS GitHub* in the command line and then use the "jupyter notebook" command to open up the proper graphical interface.

For users with a Windows-based system, or those who are less comfortable in the command line, the following method is recommended. Simply go to the *DANDAS GitHub* and click on the green "Code" icon in the top right of the page. Then, download as a ZIP file. After downloading, upload this zip file to a Jupyter Notebook server (or other python software with a built in GUI) and unzip the file[3].

Once these files have been properly accessed, it is important to use the "USER-Open this notebook to use DANDAS" file to actually use DANDAS to calculate DM annihilation and decay parameters. This file contains examples of different ways DANDAS can be applied. A full description of inputs and outputs is given in the ReadMe.md file on GitHub and in Sections 6.1 and 6.2.

6.1 Inputs

All possible input arguments for DANDAS are explained in Table 3. Note that all italicized inputs are optional.

6.2 Example Outputs

Depending on the user's needs, DANDAS will output different information. The user can specify whether they would like to receive the data in graphical format or as an array which they can use for their own analysis.

For example, if a user is interested in the DM annihilation and decay rate limits over the full range of possible DM masses, plots similar to Figures 3 and 4 will be output. Note that the coloured in regions of these plots show annihilation cross section or lifetime values that have been ruled out by current experiment data. For example, from Figure 4 one can say that at $m_x \approx 10^{-2}$ GeV, the mean DM lifetime must be greater than $\approx 10^{20}$ s to be consistent with data from the Borexino neutrino detector [24].

These plots can also be cropped using the `plot_preference=Custom_plot` which allows the user to set the axes for the output plot. If a user's research is specifically investigating the properties of DM for a DM mass of $0.01 - 1$ GeV, DANDAS will output cropped plots as shown in Figures 6 and 5.

Also, if the user simply wants to receive the upper bound on annihilation cross section or lower bound on lifetime for a specific mass value, they can set `data=True` and set `m_x` to the desired DM mass value or mass range, and DANDAS will output the limits as value or array.

[3] A useful tutorial for unzipping files in Jupyter Notebook is given *here*

Table 3: Description of all inputs employed by DANDAS. All italicized inputs are optional. Note that a more detailed description of the actual strings that need to be input is included in the README.md file availible on Github.

Input Name	**Type (Unit)**	**Description**
`Halo_Profile`	*String*	Assumed Dark Matter Halo Profile in Milky Way.
`Antiparticle_Nature`	String	Assumption of whether DM is a Majorana or Dirac particle.
`plot_preference`	String	Determines whether user will receive a full plot, a zoomed plot or no graphical output.
`reduce_runtime`	Boolean (True or False)	Reduces the run-time by omitting calculations from PONE, GRAND, and TAMBO data.
`data`	Boolean (True or False)	Determines if user wants to save annihilation and decay limits over a specific DM mass range. If true, user must specify this mass range with m_x
m_x	float or numpy array (GeV)	DM mass range over which annihilation and decay parameters are calculated
$plot\_axes\_dec$	1 x 4 numpy array (first 2 elements in GeV, last two elements in s)	Axes bounds for decay lifetime plot.
$plot\_axes\_ann$	1 x 4 numpy array (first 2 elements in GeV, last two elements in cm^3/s)	Axes bounds for annihilation cross section plot
r_halo	float (cm)	Radius of DM halo in Milky Way Galaxy
$r0$	float (cm)	Distance from an arbitrary point with known DM density to the Milky Way Galactic Center
rs	float (cm)	Scale distance from galactic centre used to calibrate J and D factor calculation.
rho_0	float ($GeVcm^{-3}$)	Known DM density at a specific point used to calcibrate J and D factor calculation.
$gamma$	float (unitless)	Slope parameter in NFW DM Halo Profile model
$alpha$	float (unitless)	Slope parameter used in Einasto DM Halo Profile.
$rho\_function$	function	Custom DM Halo profile density function. Function's only input must be r (in cm).

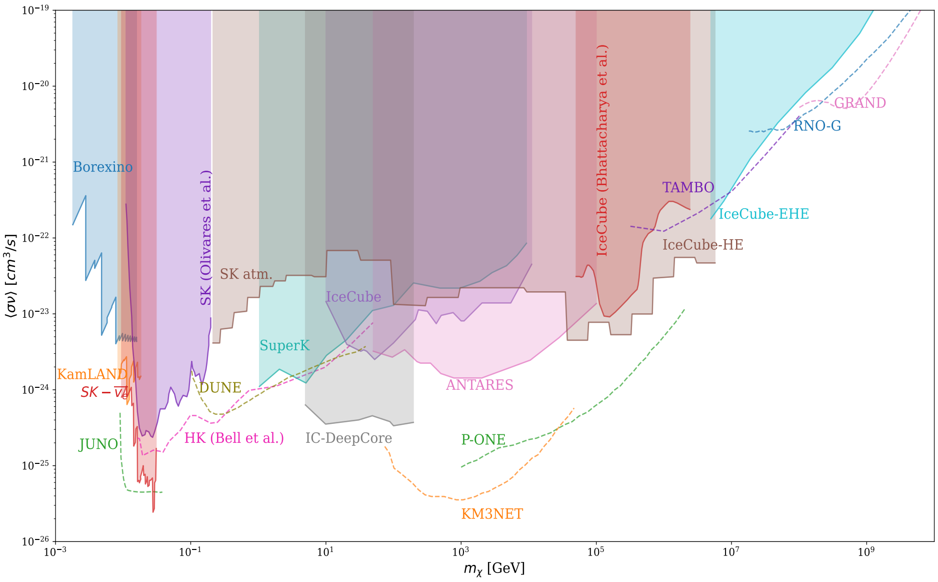

Figure 3: Graphical output of DANDAS showing the upper bound on the dark matter annihilation cross section to neutrinos. Each colour refers to an annihilation cross section limit derived from different neutrino data with dashed lines denoting neutrino experiments that will begin collecting data in coming years. This output would be generated for a user who assumes a NFW halo profile, and DM is a Majorana particle. These limits were originally calculated in [2] and are loaded within DANDAS where they can be scaled based on different assumptions as described in Sec. 4.3.

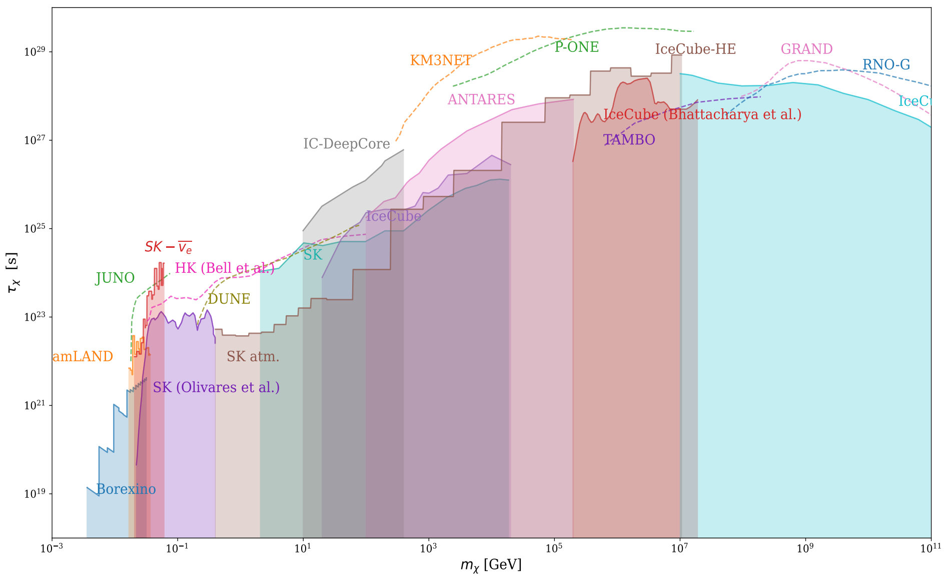

Figure 4: Dark matter lifetime limits output by DANDAS with the same assumption inputs as in Figure 3. The method by which these limits were calculated is outlined in Sec. 4.2.

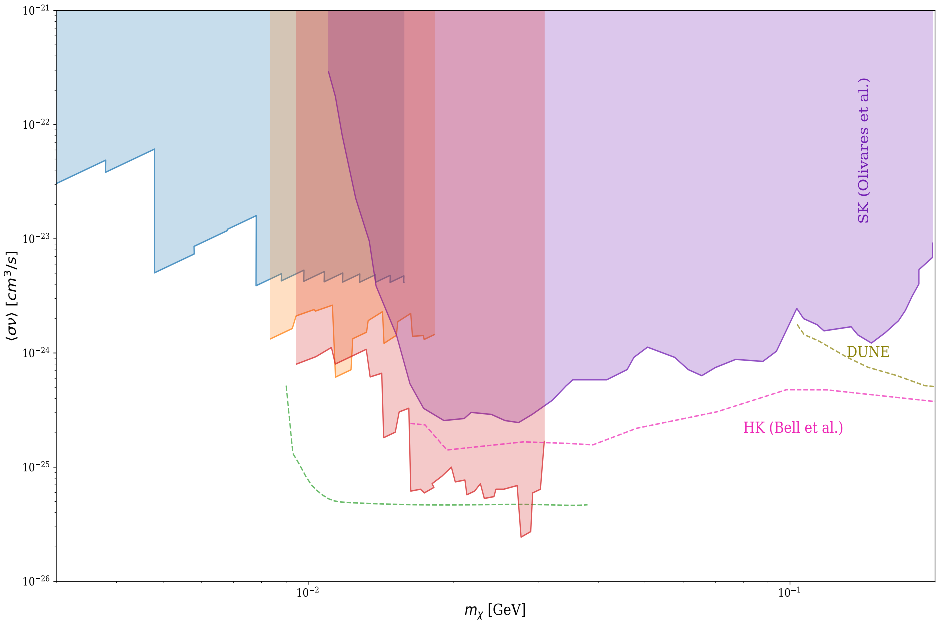

Figure 5: Example graphical output showing DM annihilation cross section bounds when `plot_preference=Custom_plot` *is chosen with an Einasto DM halo profile and a Majorana particle. Note that the same colour scheme is applied as in Figures 3 and 4.*

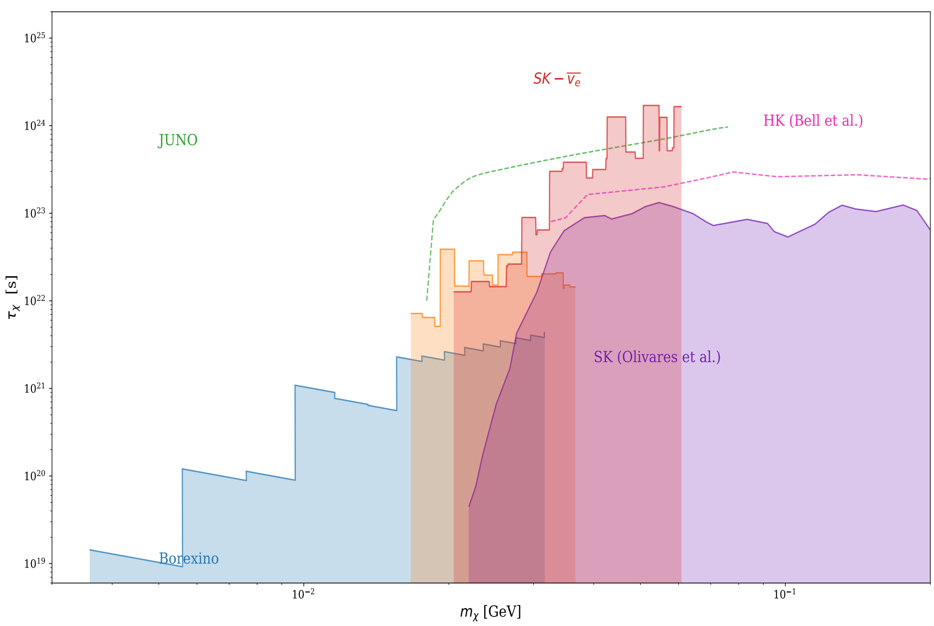

Figure 6: Example graphical output showing DM lifetime bounds when `plot_preference=Custom_plot` *is chosen with an Einasto DM halo profile and a Majorana particle.*

7 Testing and Iteration

To evaluate the effectiveness of DANDAS, its speed, accuracy, and user-friendliness were all thoroughly tested and compared to the criteria outlined in Section 5.2.

7.1 Speed Testing

As the computational power was the most significant constraint in this project, the run-time was the most tested parameter and also the motivator behind several large software iterations. These iterations were focused on reducing the run time required to calculate the J and D factors as this was the most computationally expensive aspect of DANDAS.

Initially, the SciPy Gaussian quadrature integrator (`scipy.integrate.dblquad`) was used to compute the line of sight integral shown in Eqn. 4. While this method provided accurate results, it also required over 4 hours to calculate a single J or D factor so was unfeasible for the final design of DANDAS.

Ultimately, a Monte Carlo integrator (`vegas.integrator` [35]) was chosen to calculate J and D factors. This method dramatically increased the speed at which J and D factors could be calculated while maintaining an error below 2%. By applying this method, a single J or D factor could be calculated in approximately 4 minutes.

However, as 12 individual J and D factor calculations needed to be made, this still meant that the user would be waiting approximately 45 minutes for DANDAS to output any results. To minimize this wait-time, the user is given a series of options so they can control the run-time of DANDAS by deciding what information is relevant to them and how much customization they desire.

The option which results in the fastest run-time is using J or D factors that DANDAS already has saved for specific halo profiles. This is done by inputting `NFW` or `Einasto` into `Halo_Profile` when calling DANDAS. These factors are calculated based on current best-fit parameters for DM density amd result in run-times below 10 seconds as shown in Table 4.

Customizing the DM halo profile with different parameters results in significantly longer run-time as the integration required to calculate J and D factors must be completely redone. Thus, inputting `NFW Custom, Einasto Custom,` or `Custom Density Function` results in run-times as high as 45 minutes.

However, these can be significantly reduced by setting `reduce_runtime=True` when calling DANDAS. This reduced run-time is accomplished by omitting the calculations for the projected sensitivity of PONE, GRAND, and TAMBO. These analyses were chosen as they are particularly computationally expensive and may be irrelevant to researchers who only want limits based on currently running experiments. By omitting these calculations, the run-time is decreased to only 3.2 minutes as shown in Table 4.

7.2 Accuracy and User-Friendliness Testing

The accuracy of the lifetime and annihilation cross section limits was tested by comparing to published data. Following the procedure outlined in Section 5.2, all calculations were calibrated to ensure they agreed with published data to within 2%.

Table 4: Comparison of run-times for different inputs for `Halo_Profile`.

Input Option	Regular Run-Time [s]	Reduced Run-Time [s]
`NFW`	5.2	3.0
`Einasto`	4.9	3.0
`NFW Custom`	2654.9	189.5
`Einasto Custom`	2675.7	192.3
`Custom Density Function`	2668.9	190.6

Further, the user-friendliness was maximized through multiple iterations. Initially, DANDAS was meant to be a single python file that the user would access directly. However, this required the user to parse through lines of source code to determine where to call the function. This was improved by implementing a separate Jupyter Notebook file that simply imported the necessary functions from the main software. This allowed the user to receive their desired outputs without having to understand the source code. Further, this notebook is loaded with examples of how to apply DANDAS in different ways so that the user can determine the option that works best for them.

The user-friendliness test with peers was successful as they were able to use DANDAS based on the guidance in Sec. 6. However, they reported that unzipping the file was slightly confusing as a new notebook file had to be created to use the unzipping method given *here*. Ideally, the user would be able to import DANDAS without having to download anything from GitHub, as is done for libraries like `NumPy` or `SciPy`. However, due to time constraints, this was deemed to be out of the scope of the project.

8 Discussion

Overall, DANDAS was able to fulfill the majority of design goals with some minor limitations. The software is able to produce accurate limits on annihilation and decay rates for a variety of different assumptions about dark matter's properties. It can provide these parameters in graphical format, as shown in Figures 3 and 4, or as data files that researchers can use for their own analysis. While some input options can result in significant run time, this can be minimized by omitting specific calculations.

Future development of DANDAS would focus on implementing new customizations to make the software useful to a wider range of researchers. Firstly, DANDAS could calculate lifetime limits for different decay process assumptions. Currently, DANDAS calculates lifetimes assuming a single DM particle decays to a neutrino and antineutrino. This calculation assumes equal DM decay to all flavors of neutrino. However, DANDAS could be improved by providing customized lifetime limits if a researcher assumes DM decay to specific neutrino flavors. For example, if a researcher assumes DM decay produces an electron neutrino, the calculation within DANDAS could account for flavor oscillation before the neutrino reaches a detector on Earth and scale the lifetime limits appropriately [4]. Also, DM decay to other particles such as electrons, positrons, or gauge bosons, could be calculated by

DANDAS in future versions as is done in [36].

9 Conclusion

DANDAS provides a way for researchers to access DM annihilation and decay data without having to spend time compiling data and calculating these rates themselves. This will not only help make research into DM's properties easier but can be used as a teaching tool for students eager to learn more about DM. Further, the level of customization within DANDAS means that it can be easily updated as new data is published without becoming irrelevant. By constraining the DM annihilation cross section and mean lifetime with more and more updated data, researchers can close in on the subatomic properties of the most mysterious type of matter in the universe.

Acknowledgements

I would like to thank my supervisor, Dr. Aaron Vincent for his constant support throughout this project. I'm grateful for his guidance and many insightful discussions. I also want to thank Diyaselis Delgado whose enthusiasm and excellent work always motivated me to do my best. Finally, thanks to Ibrahim Safa, Carlos A. Argüelles, Ali Kheirandish, and Avi Friedlander for all of their help throughout the journey of calculating dark matter's decay rate.

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Appendix A: Statement of Work

Analysis aiming to understand dark matter decay to neutrinos was conducted in the summer of 2021. This included D-factor calculations (for a NFW halo profile) and some preliminary lifetime limit calculations (for KamLand and Borexino data). The D-factors were done as a team with Diyaselis Delgado with guidance from Aaron Vincent.

The fall semester was primarily focussed on calculating lifetime limits for the rest of the analyses outlined in Table 2. Aaron Vincent, Diyaselis Delgado, Ibrahim Safa, Carlos A. Argüelles, and Ali Kheirandish all provided guidance to ensure the accuracy of my calculations.

The winter semester focussed on the development of the DANDAS software. This included adding in the ability to output annihilation cross section data, customizing all output parameters based on the users assumptions, and iterating the user-interface.