# DM extension for GALPROP

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## I. INTRODUCTION

In general, GALPROP code solves the transport equation for various species of cosmic rays in a galaxy and computes various types of emission from them. A full description of the code and respective updates can be found at [1]. Also a detailed general manual is included in the "doc" folder of the code distribution (i.e. the whole tarball for download). This brief manual describes the DM part only AND supersedes the respective part of the general manual. Currently I've built this DM extension for two GALPROP versions – v54 and v56. In case of v54 the extension is tied specifically to r2766 available at [2]. Originally DM extension was created in the frame of our work [3] (for v54). Later it was further developed and applied to M31 in the frame of [4] (v56). Now (from v56) it can be applied in principle to ANY galaxy thanks to an arbitrary observer positioning functionality. Comments and questions on DM GALPROP are welcome to the author's e-mail.

## II. DM SOURCE

WIMP annihilation everywhere in a galaxy is expected to produce various energetic final products: electrons, protons, gammas, neutrinos etc. and their respective antiparticles. Then they propagate and give a rise to various emissions from radio to gamma through synchrotron, ICS, bremsstrahlung etc. Gammas and neutrinos are obviously free-streaming products. The injection of all these species is described by the following source term $q(R,p)$, which would enter the transport equation:

$$q(R,p) = \frac{1}{2}\langle\sigma v\rangle \left(\frac{\rho_{\rm DM}(r)}{m_\chi}\right)^2 \xi_{\rm DM}(R)\frac{dN}{dp}(p), \tag{1}$$

where $\langle\sigma v\rangle$ denotes the WIMP annihilation cross section, $\rho_{\rm DM}(R)$ is DM density distribution, $m_\chi$ is WIMP mass, $\xi_{\rm DM}(r)$ is DM annihilation rate boost factor due to substructures and $\frac{dN}{dp}(p)$ represents the spectral yield of any specie of interest from one annihilation. This yield depend on both WIMP mass and annihilation channel, and comes from particle physics data. Below some details are provided on every key component of the source term.

- ***DM density distribution.*** Currently four different profiles are supported: generalized NFW, isothermal, Einasto and Burkert. Their exact definitions are the following:

$$\begin{aligned}
\text{gNFW}: \quad \rho_{\rm gNFW}(R) &= \frac{\rho_s}{\left(\text{Max}[R,R_{tr}]/R_s\right)^\gamma \left(1+\text{Max}[R,R_{tr}]/R_s\right)^{3-\gamma}} \\
\text{Einasto}: \quad \rho_{\rm Ein}(R) &= \rho_s \exp\left(-\frac{2}{\alpha}\left(\left(\frac{R}{R_s}\right)^\alpha - 1\right)\right) \\
\text{Isothermal}: \quad \rho_{\rm Iso}(R) &= \frac{\rho_s}{1+(R/R_s)^2} \\
\text{Burkert}: \quad \rho_{\rm Bur}(R) &= \frac{\rho_s}{(1+R/R_s)(1+(R/R_s)^2)}
\end{aligned} \tag{2}$$

GALPROP does averaging of the DM density squared (which enters eq. (1)) inside every spatial grid cell in order to take into account possible steep variations of the density. Also, considering that the gNFW profile in

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eq. (2) is singular in the center, there is an option (see below) to leave the density flat below some radius for that profile. This prevents formation of an artificial spike in the center, where the real DM distribution is known quite poorly in fact.

- ***DM annihilation rate boost factor.*** Substructures boost DM density and, hence, the annihilation rate. However, in a small vicinity of the galactic center $R \lesssim 1$ kpc they almost don't survive due to tidal disruption. Hence, the boost factor is negligible there. However it can reach significant values up to $\sim 10$ far from the center. This local boost factor is assumed to be a function of the radial distance only and implemented based on the results of [5] (which were presumably derived assuming the NFW profile for the smooth component). If one would like to stay conservative in computation of the emission intensity due to DM, there is an option to turn off the boost at all.

- ***DM annihilation yields.*** This comes from particle physics and defines how many stable products (like electrons and others) are being produced in one annihilation depending on their energy. Such spectra begin at kinematic threshold $m_\chi c^2$ and typically rise with energy decrease. The yields are implemented as numerical tables for every final product and annihilation channel based on [6–8]. Specifically, the latest version of the yields is used, which includes electroweak corrections. Yields are taken as non-polarized (if applicable), meaning average of the Left/Right or Longitudinal/Transverse. Currently, 12 annihilation channels are implemented: $\chi\chi \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, \gamma\gamma, gg, W^+W^-, ZZ, hh$ (with $q \equiv u, d, s$).

## III. INSTALLATION

Generally installation procedure consists of two major components - building the original GALPROP and embedding the DM extension into it. Here at Github only DM extension is provided in the form of patch file. Hence a user has to download first GALPROP from its original repository in case it's not installed yet. More specifically, one has to go through the following steps to build/install the whole DM GALPROP product. Order of steps below may be varied, but the scheme below is guaranteed to work.

1. Download DM GALPROP repo from Github, which will contain this manual, galdef example files, DM folder (which contain annihilation yield tables) and DM patch files.

2. Download the general data files provided by GALPROP team at http://galprop.stanford.edu/code.php?option=download. Over there you can find instructions on how to compose the necessary data directory.

3. Unpack our file "DM.tar.gz" from Github and place the resulting folder without renaming into the data directory created in the previous step (so-called FITS-data directory).

4. Download GALPROP original source directory. V54(r2766) is available at [2], v56 – at [1].

5. Unpack the source folder from the previous step and place our "DM-v5x.patch" file from Github into the "source" subdirectory.

6. Go to the "source" subdirectory by "cd" command and issue the following command in the terminal: "patch -i DM-v5x.patch" .

7. Now you can install GALPROP following instructions provided by its authors in the "README" file. Don't forget to pass the path to the FITS-data folder created at the steps 2-3 to ./configure option "-with-fitsdata=". Otherwise you can set it with "-f" each time you will run the code.

8. After installation you can test whether DM extension works by running the simple DM example "galdef_5x_testx". In this galdef file you can also see some typical parameter choices.

If GALPROP is already installed on your machine, then just: place DM folder into the FITS data directory, place "DM-v5x.patch" into "source" subdirectory, run "make" and "make install" in the relevant directory.

## IV. USAGE

In general, it could be better to run the 3D version of the code rather than 2D. The former one is more precise and better tested. Currently, DM GALPROP is capable to compute propagation of DM electrons, positrons and antiprotons. Regarding computation of an emission, the synchrotron from electrons and positrons is currently well

developed and tested (see e.g. our work [3, 4, 9]). A user can compute the gamma rays due to DM too. In order to get any gammas, one has to set in galdef file gamma_rays = 1. To get the prompt gammas one has to set DM_gammas = 1 and to turn on at least one among DM_positrons, DM_electrons, DM_antiprotons. In order to get secondary gammas due to DM, which come from ICS and bremsstrahlung of DM $e^{\pm}$, one has to turn on respectively IC_ and bremss.

Notes on 3D version: it's extremely recommended to choose the spatial grid steps dx, dy, dz in a way that one of the grid points would fall exactly at the galactic center x = 0, y = 0, z = 0. This is because DM source is very concentrated around the center and, hence, the central grid point has a very important role among all others. And it has to be "resolved" in computation through the best way possible, especially for the case of cuspy profiles like NFW. Realistic runs typically require $dx \approx dy \approx dz \approx 0.2$ kpc, though 2D runs can yield a comparable precision with $dr \approx dz \approx 0.05$ kpc.

DM parameters in galdef file are described below. As was already mentioned, all other parameters are described in the general GALPROP manual.

TABLE I. Galdef parameters explanation.

| | |
|---|---|
| | General parameters |
| DM_positrons | 1 = compute DM positrons |
| DM_electrons | 1 = compute DM electrons |
| DM_antiprotons | 1 = compute DM antiprotons |
| DM_gammas | 1 = compute DM gammas (so far requires at least one switch above to be on) |
| DM_int0 | DM density profile $\rho_{\rm DM}(R)$: 0 = generalized NFW; 1 = Isothermal; 2 = Einasto; 3 = Burkert; 9 = DarkSUSY |
| DM_int1 | 9 = DarkSUSY DM source |
| DM_int2 | DM annihilation channel: 1 = $e^+e^-$, 2 = $\mu^+\mu^-$, 3 = $\tau^+\tau^-$, 4 = $q\bar{q}$, 5 = $c\bar{c}$, 6 = $b\bar{b}$, 7 = $t\bar{t}$, 8 = $\gamma\gamma$, 9 = $gg$, 10 = $W^+W^-$, 11 = $ZZ$, 12 = $hh$ |
| DM_int3 | Substructure on/off ($\xi_{\rm DM}(R)$): 1 = based on [5] (which is likely for NFW only) |
| DM_int4 | doubles lepton source function (0 = no) in order to save comp. time by propagating only one specie; if turned on, requires either one of DM_positrons or DM_electrons to be 0; should be a good approximation; doesn't work in case of the presence of positron annihilation |
| DM_int9 | 0 = fixed increment synchrotron frequency grid (set by nu_synch_min, nu_synch_max, nu_synch_factor), >0 = number of arbitrary desired frequencies |
| DM_double0 | scale radius $R_s$ of the DM density profile, kpc |
| DM_double1 | scale density $\rho_s$ of the DM density profile, GeV cm$^{-3}$ |
| DM_double2 | DM particle mass $m_\chi$, GeV; must be in the range [5..100000] AND greater than the rest mass of the primary products (set by DM_int2); inaccuracies are possible close to the thresholds |
| DM_double3 | list of coma-separated arbitrary desired synchrotron frequencies (Hz), if DM_int9>0 |
| DM_double6 | inner slope parameter $\gamma$ for the gNFW DM density profile (1.0 gives the canonical NFW) |
| DM_double7 | $\alpha$ parameter for the Einasto profile |
| DM_double8 | truncation radius $R_{tr}$ for the gNFW profile, below which the DM density stays constant, kpc. It's not recommended to set it lower than $\sim 0.01$ kpc, since the gNFW profile steeply blows up near the central point, which may lead to unphysical source term value in the central cell; DM numerical simulations anyway don't resolve anything below such a limit. |
| DM_double9 | thermally averaged annihilation cross section $\langle\sigma v\rangle$, cm$^3$/s |
| | Specific parameters for M31 (described in [4]) |
| B_field_name | M31-MIN or M31-MED or M31-MAX, B_field_parameters[third] sets the vertical exponential scale height $z_B$ in kpc, works mainly in 2D AND requires $dr, dz$ be multiples of 0.05 kpc. |
| nHI_model | 4 |
| nH2_model | 4 |
| nHII_model | 4, 5 = uniform electrons' concentration 0.1 cm$^{-3}$ |
| DM_double4 | central electrons' concentration in cm$^{-3}$ for nHII_model = 4 |

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