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Dark matter annihilation factors in the Milky Way's dwarf spheroidal galaxies

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Abstract. The Milky Way's dwarf spheroidal (dSph) galaxies are among the best targets for the indirect detection of dark matter (DM) with γ-rays. The expected gamma-ray flux depends on the so-called 'J-factor', the integral of the squared DM density along the line-of-sight. Using a large number of simulated dSphs, we have defined an *optimized* Jeans analysis setup for the reconstruction of the DM density with stellar-kinematic data. Employing this setup, we provide here estimates of astrophysical J-factors for twenty-two Galactic dSphs, including the newly discovered Reticulum II. We finally identify several criteria that may indicate a contamination of a kinematic dataset by interlopers, leading to unreliable J-factors. We find that the kinematic sample of Segue I, one of the closest dSph, might be affected by this issue.

1. Introduction

Owing to their large dynamical mass-to-light ratios, proximity, and low astrophysical backgrounds [1, 2], the Milky Way's dwarf spheroidal (dSph) satellites are among the best targets for 'indirect' searches for particle dark matter (DM), via observations of gamma-rays that may be produced in annihilation events (e.g., [3, 4, 5]). The constraints obtained with these objects on the thermally-averaged self-annihilation cross-section of DM are among the most stringent to date (see e.g. [6]).

It is necessary to estimate the DM density in these objects to set these constraints. This motivates observations and dynamical analyses of the tiny stellar populations that, for most of these objects, represent the only viable tracers of gravitational potentials. Here, we focus on data-driven analyses that rely on parametric solutions to the spherical Jeans equation (e.g., [7, 8, 9]).

Using a large number of simulated dSphs, we define an *optimized* setup that allows us to mitigate possible biases of the analysis, and we investigate the impact of foreground contamination of the stellar-kinematic samples on the reconstruction of the J-factors. We then reconstruct the astrophysical factors of twenty-two Galactic dSphs, including the recently discovered Reticulum II (Ret II), for which a possible gamma-ray signal has been observed [10, 11][1]. We finally find that Segue I (Seg I), often considered among the best targets, might

[1] Using proprietary data, the Fermi-LAT collaboration [12] published simultaneously an analysis of eight recently

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suffer from contamination, leading to a possibly unreliable J-factor.

2. Jeans analysis and astrophysical factors

2.1. J-factors

The differential γ-ray flux coming from DM annihilation in a dSph galaxy is proportional to the so-called 'astrophysical factor' J [13],

$$J = \iint \rho^2_{\rm DM}(l,\Omega)\, dl d\Omega, \tag{1}$$

which corresponds to the integration of the DM density squared along the line-of-sight (l.o.s.) and over the solid angle $\Delta\Omega = 2\pi\times[1-\cos(\alpha_{\rm int})]$, with $\alpha_{\rm int}$ the integration angle. All calculations of astrophysical factors are done with the `CLUMPY` code [14], which has been upgraded with a Jeans analysis module in its second release [15].

2.2. Jeans analysis: an optimized setup

2.2.1. Jeans analysis Assuming steady-state, spherical symmetry, and negligible rotational support, the second-order Jeans equation reads [16]:

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta_{\rm ani}(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}, \tag{2}$$

with $\nu(r)$ the stellar number density, $\bar{v_r^2}(r)$ the stellar radial velocity dispersion, $\beta_{\rm ani}(r) \equiv 1 - \bar{v_\theta^2}/\bar{v_r^2}$ the velocity anisotropy, and $M(r)$ the mass, dominated by DM, enclosed within radius r. After solving Eq. (2) and projecting along the l.o.s., we can compute the velocity dispersion at the projected radius R, $\sigma_p(R)$. We compare the l.o.s velocities of the stars to the projected velocity dispersion σ_p, using parametric forms for the unknown velocity anisotropy $\beta_{\rm ani}(r)$ and DM density profile $\rho_{\rm DM}(r)$. We use the following likelihood function [17]

$$\mathcal{L} = \prod_{i=1}^{N_{\rm stars}} \left(\frac{(2\pi)^{-1/2}}{\sqrt{\sigma_p^2(R_i)+\Delta^2_{v_i}}} \exp\left[-\frac{1}{2}\left(\frac{(v_{\rm i}-\bar{v})^2}{\sigma_p^2(R_i)+\Delta^2_{v_i}}\right)\right]\right)^{P_i}. \tag{3}$$

The membership probabilities P quantify, for each star, the probability of belonging to the dSph. They can be used as weights, as in Eq. (3), or only to select the high probability members (e.g., with $P > 0.95$). Finally, we obtain probability density functions (PDFs) of the anisotropy and DM parameters with a Markov Chain Monte Carlo (MCMC) engine, using the `GreAT` toolkit [18, 19], and use them to compute the median and credible intervals (CIs) of the astrophysical factors.

2.2.2. An optimized setup Many choices of parametrizations can be used for the DM density, velocity anisotropy and stellar number density profiles. In order to examine the impact of the various assumptions on the reconstruction of the astrophysical factors, we have used a large number of mock data sets, that consist of stellar positions and velocities drawn from static distribution functions that satisfy the collisionless Boltzmann equation. We applied various Jeans analyses to each mock dSph, and compared the reconstructed J-factors to their true values. From a thorough testing of the different ingredients, we defined in [20] an *optimized* Jeans analysis setup which allows to mitigate several possible biases. For example, biases can come from too-constrained parametrizations of the light and anisotropy profiles, and can be addressed by using profiles with large degrees of freedom. We also found that the possible triaxiality of the DM halos of the dSphs adds a systematic uncertainty on the J-factor, which we estimate to be of order 0.4 dex. See [20] for the details of this mock data analysis.

discovered dSphs, including Ret II, and did not find any significant excess.

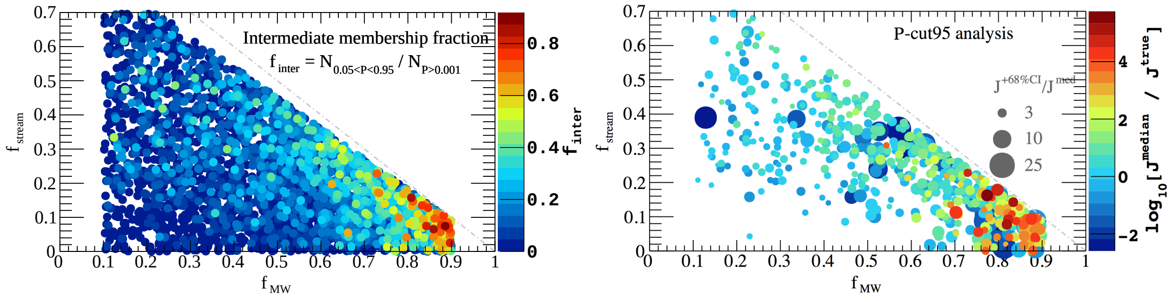

Figure 1. *Left*: fraction f_{inter} of plausible members (membership probability $P > 10^{-3}$) whose membership status is ambiguous ($0.05 < P < 0.95$) for our 4000 mock data sets, as a function of the fractions of the sample contributed by contamination from the Milky Way (x axis) and stream (y axis). *Right*: accuracy of estimated J-factors (MCMC/cut-95% analysis), for the 545 mock dSphs with $f_{\text{inter}} > 0.1$. The colour scale shows deviation of the estimated J-factor from the true value. The sizes of the symbols correspond to the size of the 68% CI on the estimated J-factor.

2.3. Contamination of stellar-kinematics

The various tests mentioned above were made on contamination-free mock dSphs, i.e. for which all the stars in the samples were dSph members. However, real stellar-kinematic datasets contain also foreground contamination from the Milky Way, which has to be separated from the bona fide members of the dSphs. To separate the two populations, we employ the expectation-maximisation (EM) algorithm [21], which gives an estimate of the membership probability P for each star of the sample.

To test the reliability of J-factors estimates for various contamination levels, we generate thousands of mock data sets that each sample mixtures of three simulated stellar populations tracing a gravitational potential dominated by DM. The first population represents bona fide members of a dSph galaxy. The second represents contamination from a tidal stream in which the dSph may be embedded, as may be the case if the object formed as the satellite of a more massive dSph that was more easily disrupted by Galactic tides [22]. The third represents contaminant stars in the Galactic foreground (see [23] for a precise description of the mock datasets). We then run a Jeans analysis on these mock dSphs, either using all the stars and weighting their contribution to the likelihood by their P values (Eq. 3), or selecting only the stars with $P > 0.95$. We find that:

- contaminated dSphs tend to show a large fraction of stars with ambiguous membership status ($0.05 < P < 0.95$, left panel of Fig. 1);
- stellar contamination can cause a large J-factor overestimation, up to several orders of magnitudes (right panel of Fig. 1);
- J-factors can be very different from a P-weighted to a cut-95% analysis in presence of strong contamination levels.

These criteria can be used to detect a possible impact of contamination for real dSphs. This seems to be the case for Seg I, as described hereafter.

3. Application to the Galactic dSphs

3.1. Contamination in Segue I?

Seg I is often considered as one of the best target for indirect detection of DM [24], because of its proximity ($d \sim 23$ kpc) and large inferred DM density. However, we find that its available stellar-kinematic sample (393 stars, see [24]) shows strong signs of contamination. About 20% of the

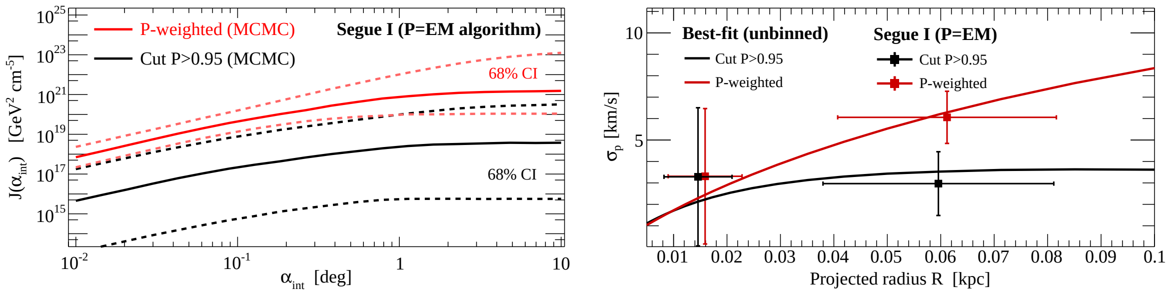

Figure 2. *Left*: J-factor of Seg I as a function of the integration angle, reconstructed either using all stars and weighting their contribution by their membership probability P (red), or selecting only the stars with $P > 0.95$ (black). *Right*: Same, but for the binned velocity dispersion profile. The best-fits are shown only for illustration purpose, as the analysis was done on unbinned velocities.

plausible members ($P > 10^{-3}$) show an ambiguous membership probability ($0.05 < P < 0.95$), and the reconstructed J-factor can vary by up to two orders of magnitude from a P-weighted to a cut-95% analysis (left panel of Fig. 2). This is due to a large increase of the velocity dispersion when including these ambiguous members (right panel of Fig. 2). This behaviour is similar to what we observed on contaminated mock data, and therefore estimates of Seg I's J-factors should be regarded with extreme caution. All the details of the analysis are presented in [23].

3.2. J-factors for twenty-two dSphs

We apply our *optimized* Jeans analysis setup to twenty-two Galactic dSphs, including eight 'classical' and fourteen 'ultrafaint' [25]. We provide estimates of J-factors, as well as their uncertainties. Fig. 3 shows the ranking of the targets, at the integration angle $\alpha_{\rm int} = 0.5°$, for annihilating DM. The 'classical' dSphs UMi and Draco are confirmed as the potentially-brightest and most favoured targets in terms of J-factors. The 'ultrafaint' objects UMa 2, Coma, Wil 1 and Ret II outrank them, but suffer from larger uncertainties. Note that in the Southern hemisphere, Ret II ranks as the best target (see [26] for a detailed description of Ret II's analysis).

4. Conclusion

Dwarf spheroidal galaxies have been widely targetted in for searches for annihilating DM in the Galaxy. This has enabled gamma-ray telescopes to set stringent limits on the DM particle properties. Reliable estimates of their J-factors and associated error budgets are clearly crucial in this regard. This study extends and improves the reconstruction of the astrophysical factors for dSph galaxies, using an *optimized* Jeans analysis setup based on thorough testing on simulated dSphs. J-factors for eight 'classical' and fourteen 'ultrafaint' Galactic dSphs, including the recently discovered Ret II, are computed in a consistant way, and the objects are ranked according to their median estimates.

Using contaminated mock dSphs, we also identify several characteristics of stellar-kinematic datasets suffering from foreground contamination, for which estimates of the J-factor can be unreliable. Such data sets tend 1) to have a large fraction of stars with ambiguous membership status and 2) to give very different J-factor estimates depending on how we treat these ambiguous stars. These characteristics are observed in the kinematic sample of the 'ultrafaint' dSph Seg I, for which astrophysical factor estimates should therefore be regarded with caution.

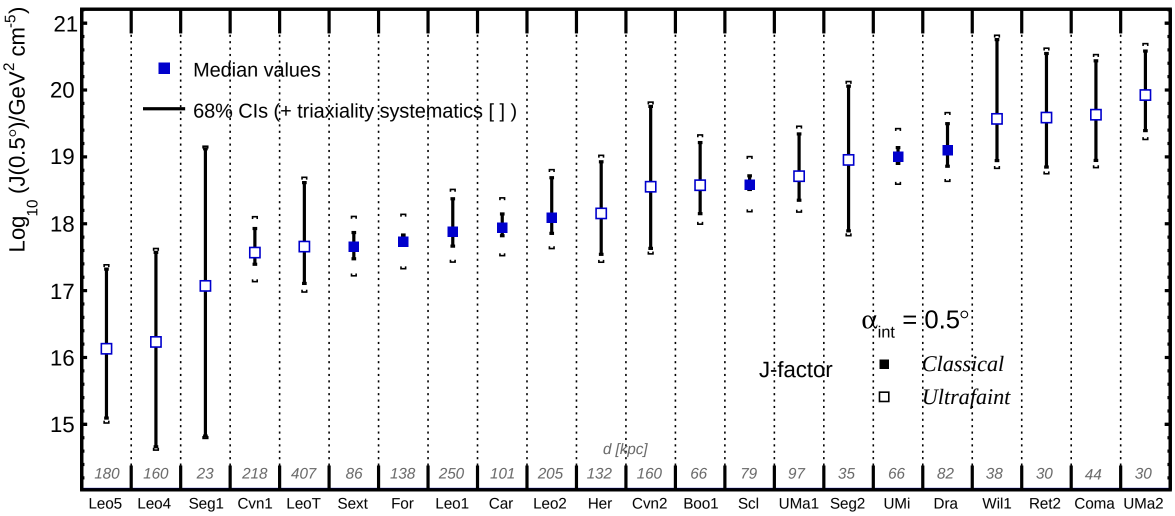

Figure 3. J-factors and 68% CIs for $\alpha_{\text{int}} = 0.5°$: the '[]' symbols combine in quadrature the 68% statistical uncertainties and possible systematics (± 0.4) from triaxiality of the dSph galaxies.

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