DARK MATTER DISTRIBUTION AND INDIRECT DETECTION IN DWARF SPHEROIDAL GALAXIES

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Dwarf spheroidal (dSph) galaxies are prime targets for present and future gamma-ray telescopes hunting for indirect signals of dark matter (DM). The interpretation of the data requires a careful assessment of their dark matter content in order to derive robust constraints on candidate relic particles. We present a data-driven DM profile determination that is based on the Jeans analysis, which we have "optimised" using a set of mock dSph kinematic datasets, testing for the various systematics that may affect the results (choice of DM, light and anisotropy profile parametrizations, binned versus unbinned datasets, stellar contamination, triaxiality). We have used this optimised setup to re-analyse the 8 classical and 13 ultrafaint dSphs, as well as Ret 2 (an ultrafaint dSph newly discovered by DES in 2015), and provide a new ranking of the best dSphs candidates w.r.t their expected signal and associated error bars. Notably, we find Segue I (often considered the best target) to be among the most uncertain candidates. This analysis illustrates the challenges that still need to be addressed when inferring the dark matter content of the new ultrafaint satellites recently discovered in the DES data.

1 Introduction

A careful determination of the DM distribution in dwarf spheroidal galaxies is mandatory if they are to be used as robust targets for DM indirect detection. Indeed, the differential γ-ray flux (at energy E and integrated over the solid angle $\Delta\Omega$) from DM annihilation is written as

$$\begin{aligned} \frac{d\Phi}{dE}(E,\vec{k}) &= \frac{d\Phi^{\rm PP}}{dE}(E)\times J(\vec{k}) \qquad (1)\\ &= \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_\chi^2\delta}\sum_f \frac{dN_\gamma^f}{dE}\,B_f\times\int_{\Delta\Omega}\int_{\rm l.o.s}\rho^2 dl\,d\Omega\,, \end{aligned}$$

where i) the particle physics term $d\Phi^{\rm PP}/dE$ provides the spectrum for a given mass m_χ, annihilation cross-section $\langle\sigma v\rangle$ and annihilation channels f of the DM candidate, and ii) the so-called J-factor depends on the DM density squared ρ^2, integrated along the line-of-sight direction $\vec{k}$.

Two broad types of approaches have been developed to estimate the DM distributions, and therefore J-factors, of the known dSph of the Milky Way. All studies generally require some fit to the kinematic data of the dSph galaxies and use more or less severe assumptions. On the one hand, several authors have used strong cosmological priors, or have used pre-defined DM profile parametrizations (e.g. core or NFW profiles), e.g. Pieri *et al.*[1]. These strong assumptions could however bias the results. On the other hand, data-driven analyses (i.e. relying on little underlying assumptions) have also been developed and generally yield more robust results despite larger error bars (Essig *et al.*[2], Geringer-Sameth *et al.*[3]).

In a recent series of articles (Bonnivard *et al.*[4,5,6]), we have revisited the data-driven approach we originally developed in Charbonnier *et al.*[7] by optimising the Jeans analysis using a set of mock dSph galaxies (§2) and applying this optimised setup to the classical and ultrafaint dSph galaxies whose data were available at the time (§3). From the dSph J-factors, we obtained a new ranking of the best targets and briefly conclude in §4.

2 Optimisation of the Jeans analysis using mock data

Assuming spherical symmetry, steady-state and negligible rotational support the so-called Jeans equation links the dynamics of a tracer population to the underlying gravitational potential as

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

where ν is the numerical density of the tracer population, $\bar{v_r^2}$ is the radial velocity dispersion, $\beta_{\rm ani}(r) \equiv 1 - \bar{v_\theta^2}/\bar{v_r^2}$ is the velocity parameter, and $M(r)$ is the total mass enclosed in radius r. Neglecting the stellar mass, the latter is simply written from the DM density ρ as

$$M(r) = 4\pi \int_0^r \rho(s) s^2 ds\,. \tag{3}$$

The quantities $\nu(r)$ and $\bar{v_r^2}$ are linked to the surface brightness of the object $\Sigma(R)$ and to its projected velocity dispersion $\sigma_P(R)$ through Abel transforms. These projected quantities are observables of the dSph galaxies, obtained by photometric and spectroscopic observations respectively. Therefore, given a set of observations one may solve the Jeans equation to constrain the DM density profile $\rho(r)$, and subsequently the J-factors.

To do so, parametric functions must be assumed for $\rho(r)$, $\Sigma(R)$, and $\beta(r)$ and it is not straightforward to decide what choice constitutes an adequate parametrizations and what choice would lead to biased results. Parametrizations of these quantities, using different numbers of free parameters have been proposed in the literature. In Bonnivard *et al.*[4], we make use of a set of mock dSph galaxies (for which the true underlying DM distribution is known) to systematically explore these various parametrizations and identify which combination yields the most accurate and robust reconstruction of the J-factors. This has been done using the CLUMPY code (Bonnivard *et al.*[8]) which allows us to solve the Jeans equation using a Markov Chain Monte Carlo (MCMC) and to propagate the error budget to the J-factors. Our main findings are the following:

- The light profile $\Sigma(R)$ is the first quantity to be fitted prior to the Jeans MCMC analysis. We find that a proper fit of the outer regions sampled by the light profile is indispensable to a good reconstruction of the J-factors. An underestimation of the light could lead to a biased reconstruction, with an overestimation of the J by a factor of a few. We conclude that the 5-parameter Zhao parametrization is a fexible enough choice to fit the light profile.

- Concerning the anisotropy $\beta_{\rm ani}(r)$, and given the lack of any constraining data, the choice $\beta_{\rm ani} = \text{cst}$ is often made. We find that this assumption is safe when dealing with *ultrafaint* objects (in which only a few stars are measured); in this case, the error budget is dominated by the little statistic available rather than by anything else. This is not true for *classical* dSph galaxies where this choice could bias the reconstruction of the J-factors, as illustrated by the blue contours in Fig. 1. In that case, we recommend the use of the more flexible Baes & Van Hese parametrizations.

- For the DM profile parametrizations $\rho(r)$, we have tested the Einasto (3 parameters) and Zhao (5 parameters) parametrizations. As far as the J-factor is concerned, both these choices yield similar results and we therefore recommend the Einasto parametrizations as the default, as the smaller number of parameters allows for a faster run of the MCMC analysis.

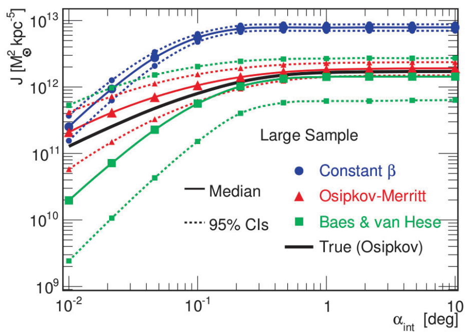

Figure 1 – Reconstructed J-factor as a function of the integration angle for a mock dSph galaxy with a large number of stars, using various parametrizations for $\beta_{\rm ani}(r)$. The mock data was generated using an Osipkov-Merritt profile. Assuming a constant $\beta_{\rm ani}$ (blue) biases the reconstruction. The more generic Baes & van Hese description (green) encompasses the true value (black).

These parametrisation choices are associated to a careful selection of the priors used to run the MCMC analysis, in order to avoid nonphysical models and limit the effect of the degeneracy between the dark matter and anisotropy profiles.

Finally, the spherical symmetry assumption of the Jeans equation may not hold as numerical simulations have shown DM halos to be triaxial. Using two triaxial mock dSph galaxies, we find that DM projection effects alone yield a $\sim 30\%$ increase of the uncertainties. Furthermore, reconstructing the J-factors, assuming spherical symmetry (for both the light and DM) for these triaxial objects could bias the results by a factor of a few. For more details and the exhaustive analysis, we refer the reader to Bonnivard *et al.*[4].

3 Application to classical and ultrafaint dSph galaxies

We have applied the optimised Jeans analysis described above to real dSph galaxy data (Bonnivard *et al.*[5,6]). The set of objects consist of the 8 *classical* dSph galaxies discovered prior to SDSS and of 14 *ultrafaint* objects discovered since, for which kinematic data were available at the time of the study. The J-factors obtained for a 0.5° integration angle are gathered in Fig. 2, ordered by increasing values. Blue symbols correspond to this study and are compared to the results of other works.

Our results are generally consistent with those of other studies, but we note that using the more flexible Zhao profile for the light (and not the generally used Plummer parametrizations) may slightly increase the J-factors of a few dSphs, but as we have shown, this choice is necessary to mitigate possible biases. Furthermore, the error bars we obtained for this data-driven analysis are, as one would expect, larger for the ultrafaint dSphs, where only a small number of stars are measured spectroscopically.

We find Draco and Ursa Minor to be the best targets among the classical dSphs, as they combine relatively large J-factor values and small errors. More uncertain, but possibly more promising are the ultrafaint objects Ursa Major 2, Coma and Reticulum 2.

Finally, we find Segue I to be the most uncertain object, with a median J-factor much lower than what was previously considered. While this object has generally been considered to be one of the most promising dSph target to place limits on DM candidate, our results suggest that it may not be the case due to possible stellar contamination of the data (Bonnivard *et al.*[9]).

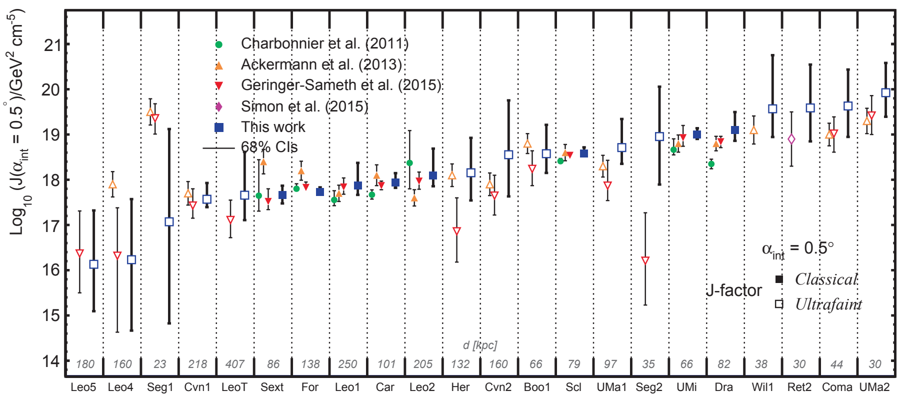

Figure 2 – J-factors of the classical (filled symbols) and ultrafaint dSph galaxies (open symbols), ordered by increasing values. Error bars denote the 68% confidence intervals. Results from the optimised Jeans analysis developed here (blue squares) are compared to those of other studies (other symbols).

4 Conclusion

Robust values of the J-factors of dSph galaxies are necessary to place constraints on the DM candidates. We make use of a set of mock dSph galaxies to determine what is the best setup to run the Jeans analysis in order to obtain unbiased J-factors with robust error bars. This setup has then been applied to the 8 classical and 14 ultrafaint dSph galaxies to provide a new ranking, where Draco, Ursa Minor, Ursa Major 2, Coma and Reticulum 2 appear as the most promising targets. Conversely to what was generally assumed before, our results suggest that Segue I is possibly one of the most uncertain targets to place robust limits on the DM candidates.

Finally, we note that since this work was performed, a few other ultrafaint objects have been identified and more kinematic data have become available. In particular, the recently discovered Triangulum II galaxy, not included in this study, could have one of the highest J-factors among the known dSph galaxies (Hayashi *et al.*[10]).

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References

1. L. Pieri, M. Lattanzi, and J. Silk. *MNRAS*, 399, 2033 (2009).
2. R. Essig, N. Sehgal, and L. E. Strigari. *Phys. Rev. D.*, 80(2), 023506, (2009).
3. A. Geringer-Sameth, S. M. Koushiappas, and M. G. Walker. *ApJ*, 801, 74 (2015).
4. V. Bonnivard, *el al.* *MNRAS*, 446, 3002 (2015).
5. V. Bonnivard, *el al.* *MNRAS*, 453, 849 (2015).
6. V. Bonnivard, *el al.* *ApJL*, 808, L36 (2015).
7. A. Charbonnier, *el al.* *MNRAS*, 418, 1526 (2011).
8. V. Bonnivard, *el al.* *Computer Physics Communications*, 200, 336 (2016).
9. V. Bonnivard, *el al.* *ArXiv e-prints*, 1506.08209 (2015).
10. K. Hayashi, *el al.* *ArXiv e-prints*, 1603.08046 (2016).