arXiv:2207.10378

# Cosmological prior for the $J$-factor estimation of dwarf spheroidal galaxies

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## Abstract

**Dark matter halos** of **dwarf spheroidal galaxies (dSphs)** play important roles in dark matter detection. Generally we estimate the halo profile using a kinematical equation of dSphs but the halo profile has a large uncertainty because we have only a limited number of kinematical dataset. In this work, we utilize **cosmological models** of dark matter subhalos to obtain **better constraints on halo profile** of dSphs. The constraints are realized as two cosmological priors: **satellite prior**, based on a semi-analytic model of the accretion history of subhalos and their tidal stripping effect, and **stellar-to-halo mass relation prior**, which estimates halo mass of a galaxy from its stellar mass using empirical correlations. In addition, we adopt a **radial dependent likelihood function** by considering velocity dispersion profile, which allows us to **mitigate the parameter degeneracy** in the previous analysis using a radial independent likelihood function with averaged dispersion. Using these priors, we **estimate $J$-factors** (the squared dark matter density integrated over the region-of-interest) of **8 classical and 27 ultra-faint** dSphs. Our method **significantly decreases the uncertainty of $J$-factors (up to about 20%)** compared to the previous radial independent analysis. We confirm the model dependence of our estimates by evaluating Bayes factors of different model setups. The estimates are still stable even when assuming different cosmological models.

## 1. Introduction

**Dark matter** is ... WIMP? Axion? Sterile neutrino? SIMP? etc....

If **WIMP**, **indirect detection** (observing annihilation of dark matter in astrophysical objects) is a hopeful detection strategy thanks to the Sommerfeld effect (cross section enhancement due to non-relativistic quantum effect).

In particular, **dwarf spheroidal galaxies (dSphs)** gives one of the most robust constraints on the WIMP DM (Fig. 1).
The detection sensitivity depends on the ***J*-factor** (squared dark matter density integrated over the region-of-interest) of dSphs, thus we have to determine the profile to obtain accurate sensitivity.

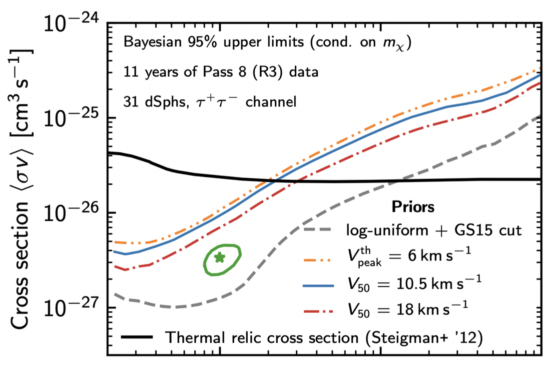


Fig. 1: Indirect detection sensitivity [1]

$$J(\Delta\Omega) \equiv \int d\Omega \int dl\, \rho^2(r), \quad \begin{cases} \rho(r) & \text{DM density profile} \\ \Delta\Omega & \text{region-of-interest} \end{cases}$$

However, there are some difficulties in the profile determination.

## 2. Jeans analysis of dSph DM halo

Dark matter profile of dSphs are determined by the **Jeans equation** (solving the kinematic equation of dSph member stars). For simplicity we assume dSphs are spherical, then the equation becomes

$$\frac{1}{\nu(r)}\frac{\partial(\nu(r)\sigma_r^2(r))}{\partial r} + 2\sigma_r^2(r)\beta(r) = -\frac{GM(<r)}{r^2}, \quad \begin{cases} \nu(r) & \text{stellar number density} \\ \sigma_r^2(r) & \text{stellar radial velocity dispersion} \\ \beta(r) & \text{anisotropy of velocity dispersion} \end{cases}$$

where $M(<r) \equiv \int_0^r dr\, 4\pi r^2 \rho(r)$, is DM mass enclosed within $r$.
Here $\rho(r)$ is given by the truncated NFW profile:

$$\rho(r) = \begin{cases} \rho_s \left(\frac{r}{r_s}\right)^{-1}\left(1+\frac{r}{r_s}\right)^{-2} & (0 \le r \le r_t) \\ 0 & (r_t < r) \end{cases},$$

However, we can observe only a limited number of stars, hence profile parameters have degeneracy (Fig. 2).
The degeneracy causes large uncertainty in the profile parameter. In order to solve this problem, we have to introduce prior density distributions (simply called **prior**) of the DM profile of dSphs.

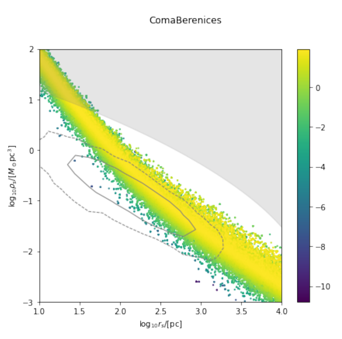

Fig. 2: $R$-independent likelihood on $r_s$-$\rho_s$ plain for the Coma Berenices dSph.

## 3. Priors

The parameter degeneracy can be mitigated by **cosmological priors**.

### Satellite prior

The accretion history of dark matter subhalo onto the Milky Way predicts the distribution of halo parameters (Fig. 3, **satellite prior**).

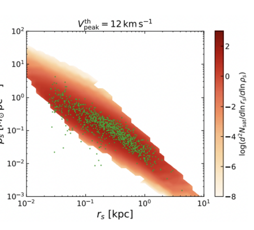

Fig. 3: Satellite prior [1]

### SHMR prior

The **stellar-to-halo mass relation (SHMR)** constrains possible halo parameters. We adopt 4 SHMR models for comparison (Fig. 4).

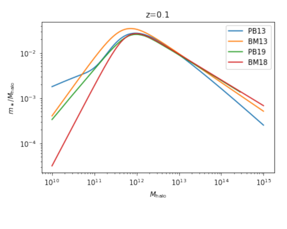

Fig. 4: SHMR functions

## 4. dSphs and likelihood

**Targets**: 8 classical & 27 ultrafaint dSphs

For these targets, we estimate halo parameters by using **radial-dependent** likelihood. Here we assume that stellar velocity at projected radius $R$ is distributed as the normal (Gaussian) distribution $\mathcal{N}$:

$$\mathcal{L}(\Theta) = \prod_i \mathcal{N}[v_i; v_{\rm dSph}, \sigma_{\rm los}^2(R_i) + \delta\sigma_i^2], \quad \begin{cases} \Theta & \text{parameters} \\ v_i & \text{line-of-sight velocity of } i\text{-th star} \\ v_{\rm dSph} & \text{systemic velocity of a dSph} \end{cases}$$

## 5. Results

**Radial-dependence**: Our likelihood function (Fig. 5) is sensitive to the profile of the velocity dispersion and it mitigates the parameter degeneracy in the radial-independent likelihood used in the previous work (Fig. 2), which adopts the velocity dispersion averaged over the system $\bar{\sigma}_{\rm los}^2$ instead of $\sigma_{\rm los}^2(R)$.

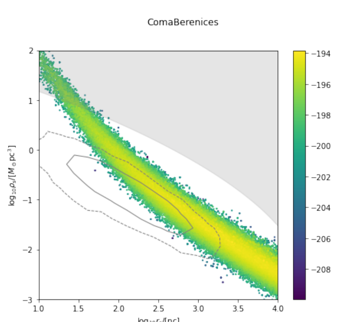

Fig. 5: $R$-dependent likelihood on $r_s$-$\rho_s$ plain for the Coma Berenices dSph

**Posterior**: Our priors successfully constrain DM halo parameters into small regions (Fig. 6). Different prior setups give almost same posteriors but in some dSph cases they are inconsistent.

***J*-factor**: Most of our $J$-factor estimates are consistent with the previous analysis (Fig. 7), but some results shows that model dependence reflecting the difference of posteriors. Bayes factors of different SHMR setups shows that deviated results are less credible than others, thus satellite prior analysis are reliable for all dSphs even when considering the SHMR.

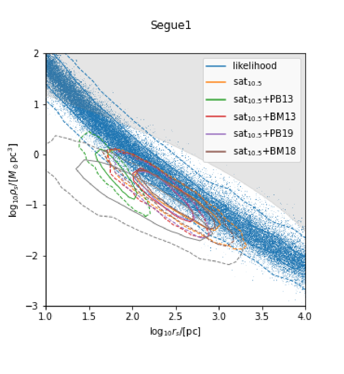

Fig. 6: Posterior for the Segue 1 dSph. Blue dots show the likelihood, and colored contours are priors assuming different SHMRs

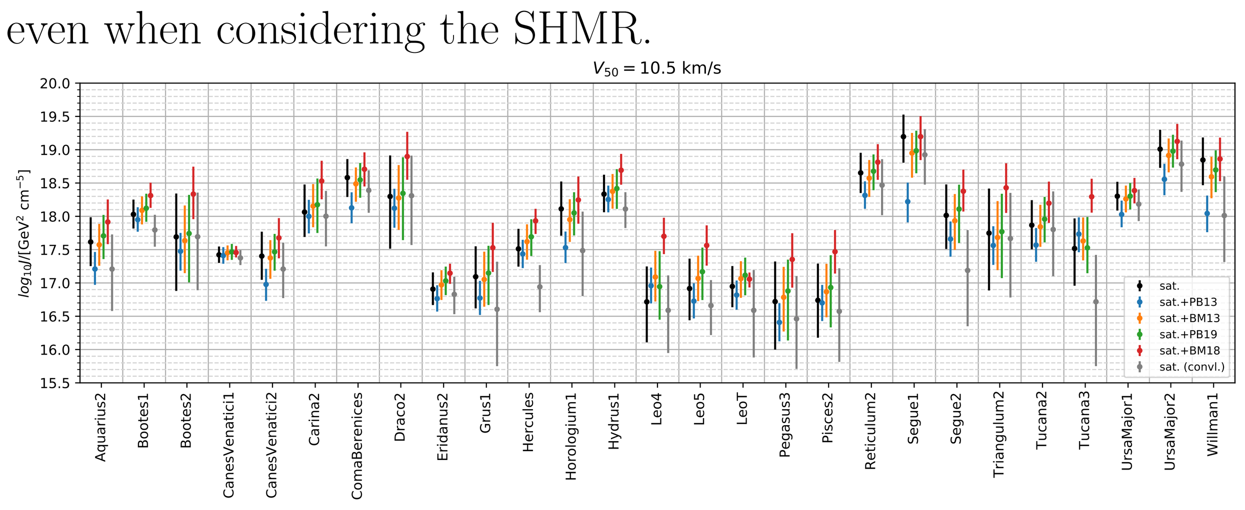


Fig. 7: $J$-factor estimates. Black: satellite prior only. Colored: satellite prior & SHMR priors. Gray: Results of previous analysis.

## Summary and conclusion

- The parameter degeneracy in the dSph DM profile can be mitigated by introducing two cosmological priors: the satellite prior and the SHMR prior.
- These priors and radial-dependent likelihood function reduces the J-factor uncertainty up to 20 % (for classical dSph) and 50 % (for ultrafaint dSphs).
- The dSph halo profile are constrained by SHMR models. In contrast, SHMR models are constrained by the dSph observations, which would offers better understanding on the cosmology.

## References

[1] S. Ando, A. Geringer-Sameth, N. Hiroshima, S. Hoof, R. Trotta, and M. G. Walker. Structure formation models weaken limits on WIMP dark matter from dwarf spheroidal galaxies. *Phys. Rev. D*, 102(6):061302, 2020.