



Universiteit  
Leiden

The Netherlands

## The dark matter density profiles of Antlia B

Júlio, M.P.; Brinchmann, J.; Read, J.I.; Bonifacio, P.; Cioni, M.; Hammer, F.; ... ;  
Taibi, S.

### Citation

Júlio, M. P., Brinchmann, J., & Read, J. I. (2025). The dark matter density profiles of Antlia B. *Proceedings Of The International Astronomical Union*, 147-153. doi:10.1017/S1743921323001473

Version: Publisher's Version

License: [Licensed under Article 25fa Copyright Act/Law \(Amendment Taverne\)](#)

Downloaded from: <https://hdl.handle.net/1887/4292840>

**Note:** To cite this publication please use the final published version (if applicable).

# The Dark Matter Density Profiles of Antlia B

Mariana P. Júlio<sup>1,2,3</sup> , Jarle Brinchmann<sup>1,4</sup>, Justin I. Read<sup>5</sup>  
and The MUSE Collaboration

<sup>1</sup>Instituto de Astrofísica e Ciências do Espaço, Universidade do Porto, CAUP,  
Rua das Estrelas, PT4150-762 Porto, Portugal  
email: [mpouseirojulio@aip.de](mailto:mpouseirojulio@aip.de)

<sup>2</sup>Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto,  
Rua do Campo Alegre 687, PT4169-007 Porto, Portugal

<sup>3</sup>Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16,  
D-14482 Potsdam, Germany

<sup>4</sup>Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands

<sup>5</sup>University of Surrey, Physics Department, Guildford, GU2 7XH, UK

**Abstract.** We use spectroscopic observations of Antlia B, a distant ( $d \sim 1.35$  Mpc) faint dwarf galaxy ( $M_V = -9.7$ ,  $M_\star = 10^5 M_\odot$ ), from MUSE-Faint, to explore alternative dark matter (DM) models to  $\Lambda$ CDM, which are one possible explanation for the small-scale problems in the standard model.

We measure line-of-sight velocities of 127 stars, and combine these with GRAVSPHERE, a Jeans modelling code, to place constraints on DM models and derive the first DM density profiles for this object.

We present constraints on the nature of self-interacting DM, in which DM particles can interact with one another in the form of annihilation (we find a core radius of  $r_c \lesssim 69$  pc) and on scalar field DM, comprised of ultralight bosons that form a Bose-Einstein Condensate (we find a characteristic length scale of the self-interaction of  $R_{\text{TF}} \lesssim 180$  pc). These results suggest that we can rule out these models as an explanation for the cores in the larger dwarf galaxies in the Local Group.

**Keywords.** Dark Matter, Galaxies, Antlia B, Kinematics, Dynamics, Spectroscopy

## 1. Introduction

Since dark matter was proposed as an additional component to explain the flat observed rotation curves of galaxies (Rubin et al. 1980), many more indications for its existence have been found. The presence of this non-baryonic matter is required to explain the behaviour of most structures existing in the Universe and the vast majority of the cosmological observations favour a cold dark matter plus dark energy scenario ( $\Lambda$ CDM model).  $\Lambda$ CDM has been very successful at predicting and explaining the large-scale structure of the Universe and its evolution with time (e.g. Vogelsberger et al. 2014), which has led to it now being considered the standard model of cosmology.

However, when we approach smaller scales, pure dark matter structure formation simulations in the standard model start to face numerous challenges (Bullock and Boylan-Kolchin 2017). Namely, for example, the missing satellites problem (e.g. Klypin et al. 1999), the too-big-to-fail problem (e.g. Boylan-Kolchin et al. 2011), and the core-cusp

problem (e.g. [Moore 1994](#)). Several solutions have been proposed to address the small-scale problems in  $\Lambda$ CDM and here we focus on the possibility of the nature of dark matter itself being different from the current paradigm. The proposed alternatives to the CDM cover a wide range of particle masses and different interactions between the dark matter particles. In this work, we explore models of self-interacting dark matter (SIDM) through annihilation ([Kaplinghat et al. 2000](#)) and of scalar field dark matter (SFDM) comprised of ultralight bosons ([Li et al. 2014](#)) to address the core-cusp problem.

To understand and solve small-scale challenges to the  $\Lambda$ CDM paradigm, we need to study the very smallest structures in the Universe. The most encouraging class of objects for this purpose are possibly ultra-faint dwarfs (UFDs) since they are the most dark matter-dominated systems known ([Simon 2019](#)). Additionally, baryonic feedback should not significantly influence the dark matter density profiles of UFDs, since they do not have enough stars to have significant supernovae feedback ([Orkney et al. 2021](#)).

However, the faintness of UFDs makes it challenging to obtain large numbers of stellar line-of-sight velocities and thus high-precision density profiles. Antlia B (Ant B), a slightly brighter dwarf galaxy ( $M_V = -9.7$ ,  $M_\star \sim 8 \times 10^5 M_\odot$ ,  $r_h = 273$  pc) was discovered by [Sand et al. \(2015\)](#) using the DECam at Cerro Tololo International Observatory and was spotted as a companion to NGC 3109. More recent studies of this galaxy were carried out by [Hargis et al. \(2020\)](#), which allowed a more precise measurement of its distance ( $d = 1.35$  Mpc).

To further explore Ant B and reach our goal, we use spectroscopic observations from the Multi-Unit Spectroscopic Explore (MUSE, [Bacon et al. 2010](#)). The data reduction used in this work follows the one described in [Zoutendijk et al. \(2020\)](#). We used PAMPELMUSE ([Kamann et al. 2013](#)) to extract the spectra of the stellar sources in the MUSE cube, followed by SPEXXY ([Husser 2012](#)), which allowed us to determine the line-of-sight velocities from the previously collected spectra. The kinematic data were carefully analysed to ensure the membership of Antlia B stars (e.g. removing the faintest sources and foreground/background galaxies and stars). Further details will be provided in a subsequent work (Júlio et al. in prep.). The final selection and correspondent line-of-sight velocity dispersion can be seen in Figure 1.

## 2. Methods

### 2.1. Dark matter models

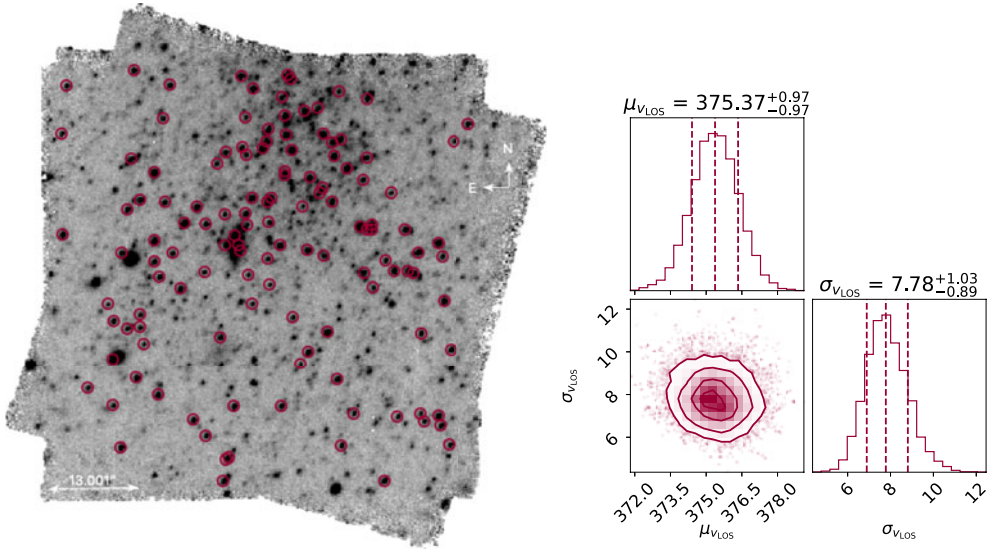
#### *Self-interacting dark matter*

In order to solve the so called core-cusp problem, several models of interacting dark matter have been proposed. It is believed that if the dark matter particles can interact with one another they can alter the halo structure and, possibly, produce a constant-density core in the heart of the halo ([Elbert et al. 2015](#)). The interacting DM models proposed mainly include scattering and annihilation. Here, we focus on the work of [Lin and Loeb \(2016\)](#) that includes signatures of annihilation and self-interaction. The density profile of this model is given by

$$\rho_{\text{SIDM}}(r) = \frac{\rho_0}{r/r_c + (r/r_s)(1 + r/r_s)^2}, \quad (1)$$

with characteristic density  $\rho_0 = \rho_c(r_c/r_s)$ , where  $\rho_c$  is the core density,  $r_c$  is the core radius and  $r_s$  is the scale radius. When the core radius  $r_c = 0$ , the SIDM profile is equal to the CDM profile. When we have  $r_c > 0$ , the profile becomes cored instead of exhibiting a cusp, as predicted by the standard model. There is a relation that links the self-interaction coefficient  $\Gamma$  to the parameters of the profile and is given by

$$f\Gamma = \frac{r_c/r_s}{t\rho_0}, \quad (2)$$



**Figure 1.** *Left:* Image of the final cube with the 127 stars identified as Ant B members represented by the red circles. *Right:* Corner plot of the velocity fit, using the 127 member stars of Ant B, obtained by following the method of [Hargreaves et al. \(1994\)](#). The histograms along the diagonal represent the posterior distribution for each parameter: the mean value  $\mu_{v_{\text{LOS}}}$  in the top panel and the dispersion  $\sigma_{v_{\text{LOS}}}$  in the bottom-right, both in km/s. The vertical dashed lines indicate the median and 68% confidence interval. The bottom-left panel represents the 2D posterior distributions of both of these parameters, with the contours corresponding to 0.5 $\sigma$ , 1 $\sigma$ , 1.5 $\sigma$  and 2 $\sigma$  confidence levels, where  $\sigma$  is the standard deviation of the 2D distribution.

where  $t$  is the time elapsed since the start of the self-interaction. However, it is possible to notice the degeneracy that exists between  $\Gamma$  and the fudge factor  $f$ . For dwarf galaxies, this factor is predicted to be  $\sim 10$  ([Kaplinghat et al. 2000](#)) but is not precisely known ([Zoutendijk et al. 2021a](#)). Thus, we will try to constrain the product  $f\Gamma$  - the effective self-interaction coefficient - to understand how the annihilation processes affect the system in study.

#### Scalar field dark matter

The scalar field dark matter is comprised of ultralight bosons and is described by the coupled Schrödinger-Poisson equations. This model, like the SIDM, is an alternative to the  $\Lambda$ CDM and in this case, it leads to a Bose-Einstein condensate and quantum superfluid. Just like fuzzy dark matter (FDM; e.g. [Dine and Fischler 1983](#)) this model's behaviour approaches the CDM model on large scales and differs the most on small scales. The main difference between SFDM and FDM is that SFDM also includes a repulsive self-interaction ([Dawoodbhoy et al. 2021](#)).

While CDM is described by the collisionless Boltzmann equation, SFDM obeys the nonlinear Schrödinger equation rewritten in terms of quantum hydrodynamics equations for the conservation of mass and momentum. Its density profile is given by

$$\rho_{\text{SFDM}} = \begin{cases} \rho_c \text{sinc}(\pi r/R_{\text{TF}}) & r \leq \alpha R_{\text{TF}} \\ \rho_{\text{CDM}} & r \geq \alpha R_{\text{TF}} \end{cases}, \quad (3)$$

where  $\rho_c$  is the central density and  $\alpha$  is a given fraction of  $R_{\text{TF}}$  determined by requiring mass conservation and density continuity at  $r = \alpha R_{\text{TF}}$ .  $R_{\text{TF}}$  is defined by

$$R_{\text{TF}} = \pi \sqrt{\frac{g}{4\pi G m^2}}. \quad (4)$$

This quantity is a physical constant of the SFDM since it is fixed by the particle parameters ( $m, g$ ) in their combination  $g/m^2$ , called the strength parameter.  $R_{\text{TF}}$  is the relevant quantity below which SFDM differs from CDM. To avoid the small-scale structure problems for the standard model discussed before,  $R_{\text{TF}} \gtrsim 1$  kpc (Dawoodbhoy et al. 2021).

## 2.2. GravSphere

To measure the dark matter density profiles of Ant B, we use the updated version of GRAVSPHERE Jeans modelling code (Read and Steger 2017). A detailed explanation of its implementation can be found in Read and Steger (2017) and Read et al. (2018).

GRAVSPHERE solves the Jeans equation (Jeans 1922) for our member stars after binning the data radially with BINULATOR (Collins et al. 2021). GRAVSPHERE assumes that the stellar systems are spherical, non-rotating, and in a steady state; allowing us to recover the density profile and the velocity anisotropy profile of the studied stellar systems (Read and Steger 2017). GRAVSPHERE relies on fourth-order Virial Shape Parameters (Merrifield and Kent 1990) to partially break the degeneracy that exists between the radial velocity dispersion (and therefore the cumulative mass distribution) and the velocity anisotropy.

## 3. Results and Discussion

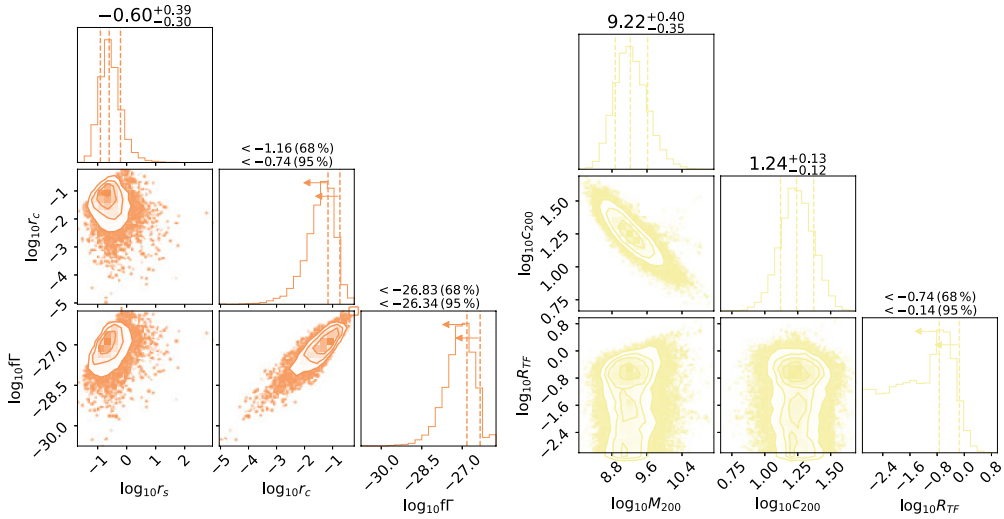
Using GRAVSPHERE we sample the parameter spaces of our implemented dark matter density models. In order to do this, we use the kinematical measurements of Ant B, mentioned before. Here we present the constraints on the dark matter models and the recovered density profiles, as well as their comparison.

The constraints of the physical parameters of the SIDM and SFDM models are displayed in Figure 2.

In the SIDM profile, we can only present the constraint of the core radius as an upper limit. The posterior distribution that we get for the core radius obtained for this profile contains values that are smaller ( $r_c \approx 0.01$  pc) than our smallest projected radius (1.84 pc), leading to a lack of constraining power at the lower end of the range of  $r_c$ . Therefore, the self-interaction coefficient is also presented as an upper limit. To derive this quantity, using equation 2, we had to assume a value for  $t$  since this quantity is unknown. For that purpose, we consider that the time elapsed since the start of self-interaction is equal to the age of the older stellar population, so we use  $t = 13.5$  Gyr.

The upper limit found for the core radius is  $r_c < 10^{-1.16} \lesssim 0.069$  kpc at the 68% confidence level and  $r_c < 10^{-0.74} \lesssim 0.18$  kpc at the 95% confidence level. We then have an associated effective self-interaction coefficient  $f\Gamma < 10^{-26.83} \lesssim 1.48 \times 10^{-27} \text{cm}^3 \text{s}^{-1} \text{eV}^{-1} \text{c}^2$  at the 68% confidence level and  $f\Gamma < 10^{-26.34} \lesssim 4.57 \times 10^{-27} \text{cm}^3 \text{s}^{-1} \text{eV}^{-1} \text{c}^2$  at the 95% confidence level. We can translate  $f\Gamma$  in the specific annihilation cross sections  $\sigma/m \lesssim 7.4 \times 10^{-35} (f/10)^{-1} (v/10 \text{kms}^{-1})^{-1} \text{cm}^2 \text{eV}^{-1} \text{c}^2$  (68% confidence level) and  $\sigma/m \lesssim 2.3 \times 10^{-34} (f/10)^{-1} (v/10 \text{kms}^{-1})^{-1} \text{cm}^2 \text{eV}^{-1} \text{c}^2$  (95% confidence level).

Although our constraints on this model are less strong than the ones found by gamma-ray searches, they apply to all annihilation products and to all dark matter particle masses (Zoutendijk et al. 2021a). The upper limit that we placed on the core radius  $r_c \lesssim 69$  pc (68% confidence level) and  $r_c \lesssim 180$  pc (95% confidence level) rules out cores of the sizes observed in several more massive dwarf galaxies in the Local Group.

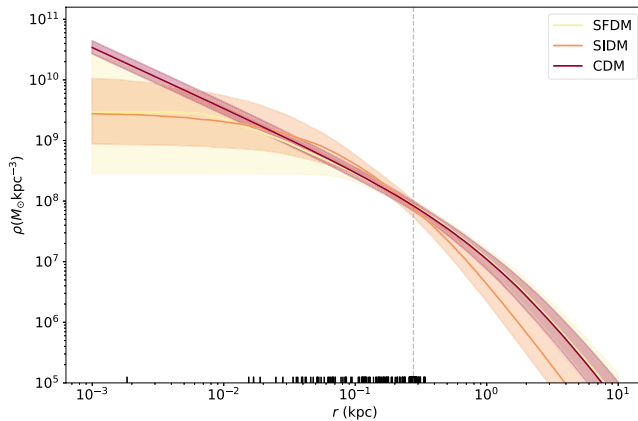


**Figure 2.** *Left:* Constraints on the SIDM profile for Ant B. The histograms along the diagonal represent the posterior distribution for each parameter: the scale radius  $r_s$  and the core radius  $r_c$  in kpc, and the self-interaction coefficient  $f\Gamma$  in  $\text{cm}^3\text{s}^{-1}\text{eV}^{-1}c^2$ . *Right:* Constraints on the SFDM profile for Ant B. The histograms along the diagonal represent the posterior distribution for each parameter: the virial mass  $M_{200}$  in  $M_\odot$ , the concentration parameter  $c_{200}$  and the characteristic length scale of the self-interaction  $R_{\text{TF}}$  in kpc. For both plots, the units were omitted for clarity. The vertical dashed lines indicate the median and 68% confidence interval (without arrows) or the 68% and 95% confidence limits (upper and lower arrows, respectively). The other panels have represented the 2D posterior distributions of these parameters, with the contours corresponding to  $0.5\sigma$ ,  $1\sigma$ ,  $1.5\sigma$  and  $2\sigma$  confidence levels, where  $\sigma$  is the standard deviation of the 2D distribution.

For the SFDM profile, we find a virial mass of  $M_{200} = 10^{9.22^{+0.40}_{-0.35}} \approx 1.66^{+2.51}_{-0.92} \times 10^9 M_\odot$  and a concentration parameter of  $c_{200} = 10^{1.24^{+0.13}_{-0.12}} \approx 17.38^{+6.06}_{-4.20}$ . These results are in agreement with those expected for a CDM profile (further details will be given in Júlio et al. in prep.; see also Zoutendijk et al. 2021b). For the characteristic length scale of the repulsive self-interaction, it is also appropriate to present it as an upper limit for the same reason as before - the posterior distribution allows  $R_{\text{TF}} \approx 0.63$  pc while the projected radii of our innermost tracer is 1.84 pc. We find  $R_{\text{TF}} < 10^{-0.74} \lesssim 0.18$  kpc at the 68% confidence level and  $R_{\text{TF}} < 10^{-0.14} \lesssim 0.72$  kpc at the 95% confidence level. This translates to  $\frac{g}{m^2 c^4} \lesssim 5.2 \times 10^{-20} \text{ eV}^{-1}\text{cm}^3$  (68% confidence level) and  $\frac{g}{m^2 c^4} \lesssim 8.3 \times 10^{-20} \text{ eV}^{-1}\text{cm}^3$  (95% confidence level). This gives us a minimum particle mass of  $m \gg 4.8 \times 10^{-21} \text{ eV}/c^2$ . These results aren't enough to solve the core-cusp problem, since this model requires  $R_{\text{TF}} \gtrsim 1$  kpc (Dawoodbhoj et al. 2021), and therefore this model cannot explain cores in dwarfs in the Local Group.

In Figure 3 we show the recovered density profiles for the three models previously discussed as a function of the radius. These density profiles are represented by median density of the random samples and their 68% confidence interval at every radius.

The SFDM model agrees with the other models within the uncertainties, while the SIDM only agrees with the CDM within the uncertainties in the inner projected radii of Ant B. The agreement of the CDM model with the SFDM model is almost perfect at large radii since this second model takes the parametrization of the first one for  $r \geq \alpha R_{\text{TF}}$ . The uncertainties of the SFDM allow for the CDM model even at the smallest radii, when  $R_{\text{TF}} \rightarrow 0$ . The agreement of the three discussed models is largest at more populated radii, i.e., where there is a greater concentration of stars. As we approach the center of



**Figure 3.** Recovered DM density profiles of Ant B for the approached models. The solid lines represent the median density profile: in red the CDM model is represented, in yellow the SFDM model and in orange the SIDM model. The filled areas represent the 68% confidence interval. The vertical dashed line indicates the half-light radius and the bottom marks represent the projected radii of the members of Ant B.

the galaxy, at smaller radii, the CDM model and the SIDM model start to diverge but the medians of the SFDM and the SIDM are close to each other.

The model that represents CDM has the highest density and smallest uncertainties, while the other profiles seem to prefer lower densities. Although the SFDM model allows for higher densities when  $R_{\text{TF}} \rightarrow 0$ , this model allows for the lowest density when its characteristic length scale approaches the values discussed in the literature. The SIDM allows for the presence of a core when  $r_c > 0$ , and becomes the CDM model when  $r_c = 0$ . However, to ensure physical solutions in our numerical parametrization, we had to implement the condition  $r_c > 0$ . For this reason, our model never reaches the CDM solution and our results are always biased for a cored profile, even though this might not be the real density profile. To further improve the constraints placed on the models, we would need line-of-sight velocities of stars closer to the centre. This remains challenging since we are dealing with faint galaxies.

The dark matter density profiles of ultra-faint dwarfs have only started to be estimated very recently. The measurements of the velocity of stars of these galaxies with the spectroscopic data from MUSE-Faint allow us to improve the constraints on their inner dark matter density profiles. With a larger number of ultra-faint dwarfs analysed, we will be able to place stronger constraints on the physical properties of dark matter.

## References

- Bacon, R., Accardo, M., Adjali, L., et al. 2010, SPIE AT+I, 773508–773508  
 Boylan-Kolchin, M. Bullock, J. S., Kaplinghat, M., 2011, MNRAS, 415, L40–L44  
 Bullock, J. S. and Boylan-Kolchin, M., 2017, Annual Review of A&A, 55, 343–387  
 Collins, M. L. M., Read, J. I., Ibata, R. A., et al. 2021, MNRAS, 505, 5686–5701  
 Dawoodbhoy, T., Shapiro, P. R., Rindler-Daller, T., 2021, MNRAS, 506, 2118–2444  
 Dine, M., Fischler, W., 1983, Phys. Lett. B, 120, 137–141  
 Elbert, O. D., Bullock, J. S., Garrison-Kimmel S. et al. 2015, 453, 29–37  
 Hargis, J. R., Albers, S., Crnojević, D. et al. 2020, ApJ, 888, 31  
 Hargreaves, J. C, Gilmore, G., Irwin, M. J et al. 1994, MNRAS, 269, 957–974  
 Husser, T.-O., 2012, Universitätsverlag Göttingen  
 Kamann, S., Wisotzki, L., Roth, M. M., 2013, A&A 549, A71  
 Kaplinghat, M., Knox, L., Turner, M. S., 2000, Phys. Rev. Lett. 85, 16, 3335–3338

- Klypin, A., Kravtsov, A. V., Valenzuela, O. et al. 1999, *ApJ*, 522, 82-92
- Jeans, J. H., 1922, *MNRAS*, 82, 122-132
- Li, B. Rindler-Daller, T., Shapiro, P. R., 2014, *Phys. Rev. D*, 89, 8, 083536
- Lin, H. W., Loeb, A., 2016, *JCAP*, 2016, 3, 9
- Merrifield, M. R. and Kent, S. M., 1990, *AJ*, 99, 1548
- Moore, B., 1994, *Nature*, 370, 620-631
- Okrney, M. D. A., Read, J. I., Rey, M. P., et al. 2021, *MNRAS*, 504, 3509-3522
- Read, J. I., Walker, M. G., Steger, P., 2021, *MNRAS*, 481, 860-877
- Read, J. I., Steger, P., 2017, *MNRAS*, 471, 4541-4558
- Rubin, V. C., Ford, W. K., Thonnard, N., *ApJ*, 238, 471-487
- Sand, D. J., Spekkens, K., Crnojević, D. et al. 2015, *ApJ Letters*, 812, L13
- Simon, J. D. 2019, *Annual Review of A&A*, 57, 375–415
- Vogelsberger, M., Genel, S. Springel, V., et al. 2014, *MNRAS*, 444, 1518-1547
- Zoutendijk, S. L., Brinchmann, J., Boogaard, L. A., et al. 2020, *A&A*, 635, A107
- Zoutendijk, S. L. and Brinchmann, J. and Bouché, N. F. et al. 2021 *A&A*, 651, A80
- Zoutendijk, S. L., Júlio, M. P., Brinchmann, J., et al. 2021b, *arXiv e-prints*, arXiv:2112.09374