Lights in a sea of darkness: constraining the nature and properties of dark matter using the stellar kinematics in the centres of ultra-faint dwarf galaxies

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List of publications

Articles included in this dissertation:

1. S. L. Zoutendijk, J. Brinchmann, L. A. Boogaard, M. L. P. Gunawardhana, T.-O. Husser, S. Kamann, A. F. Ramos Padilla, M. M. Roth, R. Bacon, M. den Brok, S. Dreizler, & D. Krajnović (2020). "The MUSE-Faint survey: I. Spectroscopic evidence for a star cluster in Eridanus 2 and constraints on MACHOs as a constituent of dark matter". In: *Astron. Astrophys.* 635, A107. (Chapter 2)

2. S. L. Zoutendijk, J. Brinchmann, N. F. Bouché, M. den Brok, D. Krajnović, K. Kuijken, M. V. Maseda, & J. Schaye (2021a). "The MUSE-Faint survey: II. The dark-matter density profile of the ultra-faint dwarf galaxy Eridanus 2". In: *Astron. Astrophys.* 651, A80. (Chapter 3)

3. S. L. Zoutendijk, M. P. Júlio, J. Brinchmann, J. I. Read, D. Vaz, L. A. Boogaard, N. F. Bouché, D. Krajnović, K. Kuijken, J. Schaye, & M. Steinmetz (2021b). "The MUSE-Faint survey: III. No large dark-matter cores and no significant tidal stripping in ultra-faint dwarf galaxies". arXiv: 2112.09374 [astro-ph.GA], submitted to *Astron. Astrophys.* (Chapter 4)

4. S. L. Zoutendijk, J. Brinchmann, M. P. Júlio, D. Vaz, N. F. Bouché, K. Kuijken, and J. Schaye (in prep.). "The MUSE-Faint survey: #. Constraints on dark-matter properties from a joint dynamical analysis of ultra-faint dwarf galaxies". To be submitted. (Chapter 5)

Letters and articles not included in this dissertation:

1. A. Dvornik, S. L. Zoutendijk, H. Hoekstra, & K. Kuijken (2019). "The case for two-dimensional galaxy–galaxy lensing". In: *Astron. Astrophys.* 627, A74.

2. M. Regis, M. Taoso, D. Vaz, J. Brinchmann, S. L. Zoutendijk, N. F. Bouché, & M. Steinmetz (2021). "Searching for light in the darkness: Bounds on ALP dark matter with the optical MUSE-faint survey". In: *Phys. Lett. B* 814, 136075.

3. R. Bacon, D. Mary, T. Garel, J. Blaizot, M. Maseda, J. Schaye, L. Wisotzki, S. Conseil, J. Brinchmann, F. Leclercq, V. Abril-Melgarejo, L. Boogaard, N. F.

Bouché, T. Contini, A. Feltre, B. Guiderdoni, C. Herenz, W. Kollatschny, H. Kusakabe, J. Matthee, L. Michel-Dansac, T. Nanayakkara, J. Richard, M. Roth, K. B. Schmidt, M. Steinmetz, L. Tresse, T. Urrutia, A. Verhamme, P. M. Weilbacher, J. Zabl, & S. L. Zoutendijk (2021). "The MUSE Extremely Deep Field: The cosmic web in emission at high redshift". In: *Astron. Astrophys.* 647, A107.

4. N. F. Bouché, S. Bera, D. Krajnović, E. Emsellem, W. Mercier, J. Schaye, B. Epinat, J. Richard, S. L. Zoutendijk, V. Abril-Melgarejo, J. Brinchmann, R. Bacon, T. Contini, L. Boogaard, L. Wisotzki, M. Maseda, & M. Steinmetz (2022). "The MUSE Extremely Deep Field: Evidence for SFR-induced cores in dark-matter dominated galaxies at $z \simeq 1$". In: *Astron. Astrophys.* 658, A76.

Proceedings:

1. S. L. Zoutendijk (2021). "Constraining dark matter with ultra-faint dwarf galaxies". In: *Hypatia Colloquium 2021: Early Career Astronomer series at ESO*. Ed. by G. Beccari & H. M. J. Boffin, 16. DOI: 10.5281/zenodo.5607414.

2. N. F. Bouché, S. Bera, D. Krajnović, E. Emsellem, W. Mercier, J. Schaye, B. Epinat, J. Richard, S. L. Zoutendijk, V. Abril-Melgarejo, J. Brinchmann, R. Bacon, T. Contini, L. Boogaard, L. Wisotzki, M. Maseda, & M. Steinmetz (2021). "Cored dark-matter profiles in $z \simeq 1$ star forming galaxies". In: *SF2A-2021: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*. Ed. by A. Siebert, K. Baillié, E. Lagadec, N. Lagarde, J. Malzac, J.-B. Marquette, M. N'Diaye, J. Richard, & O. Venot, 379–382.

Curriculum vitae

I was born on 16 July 1994 in Leiden. From an early age, I have been curious about many different topics, but especially about the sciences. From 2006 to 2012 I went to Da Vinci College on Kagerstraat, where for the first three years I partook in a special curriculum with more natural science education. For the final three years, I selected a profile that included all three of the taught natural sciences – physics, chemistry, and biology –, but took philosophy as my elective subject. It became clear to me that I wanted to study either physics or chemistry at a non-technical university, because I was most interested in understanding how things worked, rather than how we could use them. I finally settled on physics, because it was the most fundamental of the two, and Leiden University seemed a good choice because of its proximity and its focus on a broad foundation in all physical disciplines. While gathering information about the physics programme in Leiden, I learned that a combined programme with astronomy was also an option. I have had an interest in the Universe for a long time – early exposure to the *Star Trek* franchise may have had something to do with that –, but up to that point I had not realized that astronomy was something one could study – it was not a high-school subject. So it was somewhat by chance that I decided early in my fifth year that I would enrol in both the physics and astronomy bachelors'. Later that same year, I took part in the Leiden Advanced Pre-university Programme for Top students, following a few lectures on nanotechnology and quantum mechanics at Leiden University. I finished my high-school career the year after with a project titled *De theorie en toepassingen van supergeleiding* (*The theory and applications of superconductivity*), in collaboration with a fellow pupil, which involved taking measurements of a superconductor at Leiden University.

In 2012, I started the Bachelors' programmes of physics and astronomy at Leiden University. Already in the second year, we were given the opportunity to carry out observations at a professionally operated telescope, the Isaac Newton Telescope on La Palma. I gradually found out that I liked the data-heavy approach of astronomy more than the experimentally focused physics curriculum. In 2015 I therefore wrote my bachelor's thesis at the Laboratory for Astrophysics under the supervision of Professor Harold Linnartz and Professor Edgar Groenen, titled C_6H *Electronic Spectra and Comparison with Diffuse Interstellar Bands*. That summer I obtained my

Bachelor of Science in Physics and Bachelor of Science in Astronomy, both *cum laude*.

After the summer, still in 2015, I continued my studies at Leiden University with the master's programme in astronomy. Remaining interested in learning about the fundamental workings of things, I chose to follow the Cosmology specialization. In my first year, I did a research project with Professor Röttgering and Leah Morabito, in extra-galactic radio astronomy, culminating in the report *Characterizing the cold neutral medium in M82 with carbon radio recombination lines*. The second year was dominated by my final research project, *Maximum likelihood analysis of galaxy–galaxy lensing: A comparison of one- and two-dimensional methods using EAGLE simulations*, under the supervision of Dr Henk Hoekstra, with assistance from Andrej Dvornik. In the same year, I was also a student representative on the Education Committee. Having successfully completed my projects and courses, I became a Master of Science in Astronomy in August 2017.

I was lucky to have secured a spot to pursue a PhD with Dr Jarle Brinchmann on my favourite topic in cosmology: the nature and properties of dark matter. Since starting as a PhD Candidate at Leiden Observatory in 2017, I have written four scientific articles, have contributed to at least four more, and have presented my work at national and international conferences, workshops, and colloquia. I have shared my knowledge with the general public through a presentation at Astronomy on Tap and an interview on the local radio, not to mention many social gatherings with interested friends and family. I have been a member of the MUSE Collaboration and have conducted observations on site at the Very Large Telescope in Chile. I have also served a term on the Institute Council, have organized informal science talks among PhD Candidates, and for three semesters have been the senior teaching assistant for the course Introduction Astrophysics. Finally, I have had the good fortune to visit Jarle in Porto several times – before the pandemic put a stop to that –, to collaborate with my promotores Professor Koen Kuijken and Professor Joop Schaye, with Professor Justin Read from the University of Surrey, and with the many members of the MUSE Collaboration, and to be involved in the master's theses of Daniel Vaz and Mariana Júlio.

After a decade of astronomy at Leiden University, it is time for me to say goodbye to academia and to astronomy, but not to the natural sciences or scientific research. By the time of my defence, I will have started as a Researcher at the National Institute for Public Health and the Environment (*Rijksinstituut voor Volksgezondheid en Milieu*, RIVM), in the Department of Consumer and Product Safety. Specifically, I will be making mathematical models of consumer exposure to chemical substances in products.

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Even in the best of times, doing a PhD is not easy, let alone during a pandemic. I want to express my sincere gratitude to the many people who have helped me to complete the thesis that now lies before you. Though I will try to be as comprehensive as possible, I am certain that I will forget some, and I hope they will accept my apologies.

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Many a Friday afternoon at the Observatory I have learned about every aspect of galaxies there is. I would like to thank everyone who has (been) volunteered to present at the galaxy journal club for sharing their knowledge. Nevertheless, not much science would get done at the Observatory were it not for the secretaries and computer workers. I owe them thanks for their tireless efforts to enable me to do my work. I also want to extend my thanks to everyone who has, visibly or invisibly, made an effort to improve our well-being, including in the directions of inclusion, diversity, equity, and accessibility, and by mitigating the impact of the covid pandemic.

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