Executive Summary

Over the past evaluation period – despite the Covid-19 pandemic and an almost constant level of researchers and funding – the output of the Kapteyn Astronomical Institute in terms of research papers *and* impact per paper have increased by about fifty percent, compared to the previous evaluation period; the impact is three times above the international average and on par with renowned research institutes in the US, UK, and Europe. During the evaluation period, the institute decided (i) to focus more on two core research domains to create increased critical mass in several high-impact and emerging research areas, addressing one of the main recommendations from the institute's evaluation in 2016 (ii) increase its interdisciplinary research with other institutes in our faculty of science and engineering (e.g. on data science), and (iii) further increase ties with the nearby space-research (SRON) and radio-astronomy (ASTRON) institutes e.g., via, by now, a dozen affiliate staff and even more joint graduate-student and postdoctoral appointments.

The institute achieved this high research output and impact through the successful (often leadership) roles of its senior and mid-career staff in high-impact research programs. They have been able to do that largely thanks to a strong support and research network within the Kapteyn Institute, our Faculty of Science and Engineering, ASTRON, SRON and, critically, NOVA. In addition, our staff has been very successful in attracting large (career) grants from e.g., the Dutch and European Research Councils, with the Spinoza Prize won by the Scientific Director of NOVA – a senior staff member of Kapteyn – as an absolute highpoint. Thanks to the rejuvenation of more than a third of our academic staff – via natural retirements and early-career staff hires – the institute achieved effective gender balance and excellent demographics. With three more planned staff hires next year, the division of staff over early, mid, and late career will be balanced. Our senior and mid-career staff, and some early-career staff, are also deeply involved in strategic decision making at the national and international level (e.g., NWO, ESO, ESA). These changes in the institute's staff have addressed two additional recommendations from the 2016 evaluation on demographics and strategic involvement.

Besides recognition for their research, our staff, postdocs, and students regularly win prizes for their research and their engagement with the community. With the increasing realization that our research should not only be fundamental in nature but also have societal relevance, given the challenges that face society, the institute has continued to consolidate its strong outreach program to inspire young people, with e.g., the new Dark-Sky initiative, the DOT-Live and Mobile Planetariums, being prime examples of where science and society meet. Furthermore, our strong interdisciplinary and data-driven research programs provide skill sets to early-career researchers that are highly sought-after outside academia. Our data-driven research programs led to two new start-up companies in the past evaluation period. Finally, almost all our publications and other products (e.g., data, software) are open source. This effort will be further strengthened via two research data management officers supporting us in the coming years.

Next to our continuing success in research, attracting funds, societal impact and outreach, our institute has grown four-fold in the number of bachelor and master students since the previous evaluation (more than a hundred students now enter our program per year), half of whom are international students from a wide range of nationalities and cultural backgrounds. The complexity of such a diverse institute membership has increased our awareness of how we interact and support each other, and to recognize each other's strengths. Especially in the past years, accelerated by the pandemic and several high-profile cases of misconduct in our field, this has led (and is leading) to a further strengthening of the social support system in the institute and within Dutch astronomy. A similar awareness is growing that astronomy needs to decrease its impact on the environment, e.g., via a reduction of its CO_2 emission. New policies for this, further accelerated by energy shortages, are now being put in place.

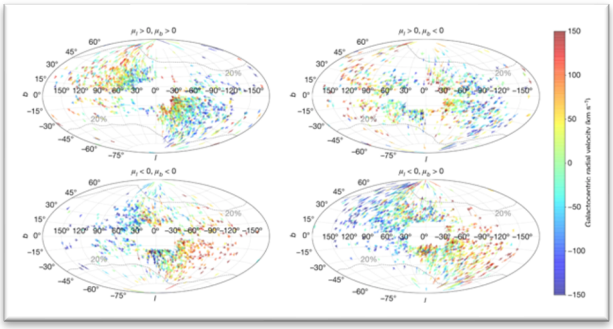
With the secured permanent funding for NOVA effectively in place, the Kapteyn Institute is expected to grow and consolidate in its research domains, expand its data-science and interdisciplinary programs. With many global facilities coming online, in which our staff and NOVA have leadership roles (e.g., ELT, LOFAR2.0, SKA, JWST, Euclid), we look forward with confidence to a decade in which transformational science will be done and for which many of our staff have prepared for more than two decades. In closing, we believe that the Kapteyn Institute is robust and future-proof, able to reap the rewards of their investments in the coming decade.

Appendix A – Case Studies on Selected Topics

In this appendix, we list eight Case Studies, which are small zoom-ins on our research, societally relevant results, and other aspects of the institute that we want to high-light indicating how they connect to our strategies, policies, and metrics for success.

Case Study 1: Galactic Archaeology & Resolved Stellar Populations

One of the most exciting scientific results during the past evaluation period from the Kapteyn Institute has undoubtedly been those coming from ESA's Gaia satellite, in which staff member Helmi and her group at the Kapteyn plays an internationally leading role. Kapteyn's involvement was part of a strategy to strengthen the field of resolved stellar populations in our first research domain, following the tradition of Kapteyn. This is now one of the most successful research lines of the institute, also thanks to collaborations with staff members Tolstoy and Trager, and has led to the strong involvement in WEAVE, 4MOST, ELT-MICADO, and on the longer-term ELT-MOASIC. To strengthen this field further a new staff member, Starkenburg, was hired in 2020.



One of the main, highly publicized and cited scientific highlights has been the discovery of a debris from the last big merger that the Milky Way experienced some ten billion years ago, and which led to the formation of the inner halo and the thick disk (via dynamical heating and the triggering of a starburst). A figure, showing the stellar kinematics of the debris, from the Nature paper (Helmi et al.) is shown on the left.

The impact of these transformation results about the understanding our Milky Way has already been rewarded by a range of prizes and awards obtained by both senior and junior level staff and researchers, among them the Spinoza Prize ("Dutch Nobel Prize") for Helmi, numerous prize lectures, the MERAC Prize for one of the PhD students working on this research, and the van Swinderen Prize for best PhD thesis, and the best postdoc of the faculty. Starkenburg was also awarded a VIDI career award shortly after her appointment.

Similarly, the work has attracted considerable media attentions on TV, the radio, and in newspapers, and it let to new shows in the *DOT Live Planetarium* (a planetarium initiated by Kapteyn staff) using Gaia data and tools developed by DPAC, the Gaia Consortium.

Finally, it led to valorisation impact, for example Vaex.io, a program developed by a postdoc in the group of Helmi, to visualize and explore datasets with a billion entries in less than one second using a standard laptop. This led to a new start-up company and is being used in a variety of fields, including for the restoration of Rembrandt's Night Watch painting.

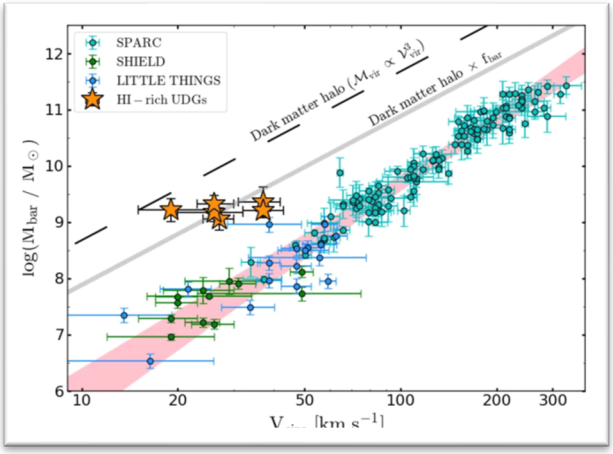
Case Study 2: Structure, Formation and Evolution of Galaxies

One of the largest research areas at the institute is that of the structure, formation, and evolution of galaxies over cosmic time. It involved many of our staff and affiliates (e.g., Adams*[5], Caputi, de Blok*, Fraternali, Koopmans, McKean, Morganti*, Oosterloo*, Peletier, Trager, Starkenburg, van der Hulst**, Verheijen, Wang*.). In section 3.1, a short overview and proud achievement were given.

[5] Throughout the document, staff members indicated with a * are associated with Kapteyn as affiliate assistant or affiliate associate professor or as honorary (full) professor and participate in the institute's academic life and often guide PhD students at Kapteyn registered at our graduate school. Staff members indicated with ** are currently emeriti professors but were not during (part of) the evaluation period.

Here, we focus on only one of these, i.e., the discovery of the exceptional dynamical properties of Ultra Diffuse Galaxies (UDGs). The study of gas-rich UDGs, which are galaxies with sizes much larger than normal galaxies of the same mass and thus where stars and gas are extremely diffuse, revealed an unexpected lack of dark matter in their inner regions. Standard dark matter halos fail to reproduce these properties, opening the possibility that these galaxies can help us understand the nature of dark matter.

The research group of Fraternali derived the rotation curves from HI observations, building up on the work of several PhD theses at the RUG and papers led by Kapteyn researchers. Advanced open-access codes (Cannubi / 3d-Barolo) were developed to extract kinematic properties of galaxies from datacubes in full 3D mode. This is the most advanced and widely used software currently available in the community, enabling to extract the properties of UDGs with unprecedented reliability and details. The present work was carried out by PhD student Mancera Piña together with Fraternali, Oosterloo* and Adams*. The HI observations were carried out with the Westerbork Synthesis Radio Telescope and the Very Large Array.

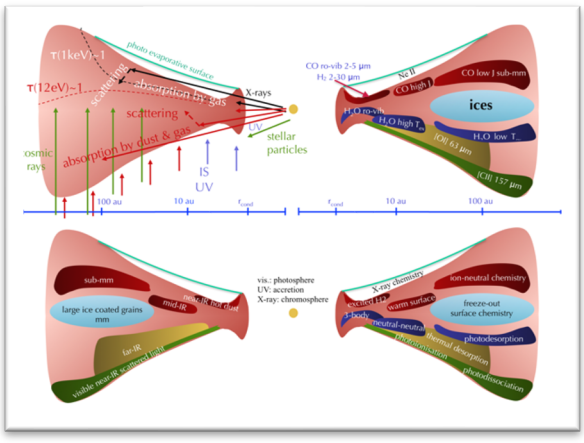


The PhD thesis of Mancera Piña, 50% funded by NOVA, was awarded Cum Laude distinction (<5% of theses). Fraternali was voted best PhD supervisor of the faculty in 2020. These discoveries have had a wide media impact, we had two NOVA press releases on this topic, the second more recent one on a galaxy seemingly lacking dark matter generated a large number of articles and interviews in Dutch/international journals and magazines including Scientific American, KIJK, Volkskrant, Wired, New Scientist. The research created interest in the (particle) physics community, given its potential to inform one about currently unknown properties of dark matter particles. Mancera Piña was invited to give a talk at the theoretical physics department (RUG), and he and Fraternali co-authored to a paper (incl. press release) with USA experts on self-interacting dark matter.

Case study 3: From the Interstellar Medium, Protoplanetary disc to Exoplanets

The formation of (exo)planets via protoplanetary discs embedded in the ISM, as well as their structure and evolution, is an exciting research line that we plan to increase at the institute in the coming decade in line with our strategic goal to grow in our second research domain. This research field is very interdisciplinary, bringing together the fields of astronomy, geophysics, chemistry and even biology.

The research by the groups of Kamp and van der Tak* have been successful in capitalizing on the foundation of the ORIGINS centre and PEPSci network, in preparation for JWST-MIRI and the ELT-METIS instruments in which NOVA is the PI institute. This research has been supported by very large grants such as an EU-COFUND, and an ITN network, in which our staff are (co)PI's. In line with the above strategy, the institute recently hired a new staff member, Lichtenberg (Oct 2022), who is expert in the fields of geophysics and the formation of exoplanets and brings the right expertise to complement the research on e.g., protoplanetary discs and is involved in e.g., ESA's Plato and Ariel mission concepts. We intent to hire an additional staff member in this research domain in 2023, complementing the expertise of the current three staff members and help to build further critical mass in selected research directions, in line with the recommendation by the international review board in



2016. In addition, in 2018 we appointed an affiliate staff member, Vedantham*, who works on exoplanet detection and characterisation via low-frequency radio observations with LOFAR.

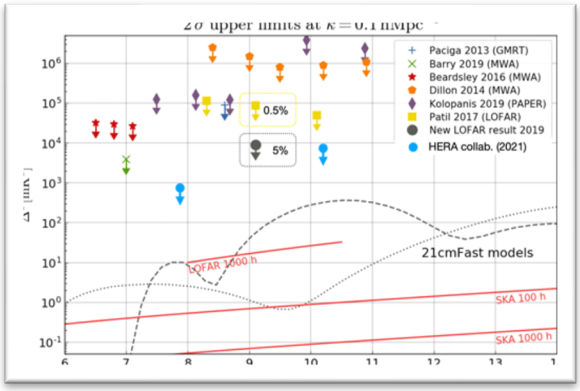
A selected research highlight from this rapidly growing research line/domain has been the prediction that hydrated minerals in the warm inner regions of planet forming disks can contributing to the water content of rocky planets, such as Earth, contributing to answering a long-standing problem. This research led to a live radio interview on how the research can explain the large quantities of water on earth, and one of the master students involved in the research won a national prize for the best Master thesis in astronomy in 2020.

Furthermore, the research code ProDiMo (Protoplanetary Disk Models), developed in the group of Kamp, is publicly available and has three dozen active user groups worldwide, leading to close to seventy peer-reviewed publications using the code, nine PhD theses and thirteen BSc/MSc theses, the majority at the institute.

Case study 4: Epoch of Reionization and the Cosmic Dawn

Kapteyn staff lead one of the internationally largest and most complex radio-observational programs to date to search for the redshifted 21-cm line of neutral hydrogen at high redshifts, using the Dutch LOFAR and French NenuFAR radio telescopes. This team combines resources of the research groups led by Koopmans, Offringa*, Vedantham* and Zaroubi. Results from LOFAR in 2017 set the then deepest upper limits on the 21-cm signal at redshifts z=8-10 and in 2020 improved the limit at z=9 by an order of magnitude, respectively. These results excluded for the first time a cold-ISM scenario at z=9 showing that hydrogen must be heated already at z>9.

For this research two powerful petabyte/petaflop-scale GPU/CPU-based HPC systems were acquired and operated, located at the UG's Centre for Information Technology (CIT) to process petabytes of data. Team-members developed open-source codes for the data-processing pipeline (e.g., AOflagger, WSClean), many of which are now widely used in the broader radio-astronomy community. The codes are also part of the Science Data Centre of ASTRON, where LOFAR and WSRT data are stored, and which serves as proto-SRC (SKA Regional Centre). Furthermore, multiple theoretical interpretation codes (combining n-body, hydro and radiative transfer) have also been developed by our staff (Zaroubi) to interpret the results.



Staff are also involved in advanced space-based 21-cm instruments such as the global 21-cm experiment NCLE, currently operating in lunar L2, and part of a CDF study of ESA's ALO radio array on the backside of the moon (in pre-phase-A), and the SKA to search for the redshifted 21-cm signal. The studies soon will have synergy with infrared and Lyman-alpha observations with the HST, VLT, JWST and soon with Euclid and the ELT by the groups of Caputi, Dayal. Former students have found employment at high-tech companies such as ASML and NVIDIA, or obtained prestigious fellowships (e.g., Caltech). The research is in line with our strategy to be one of the world-leaders in the study of the high-z Universe.

During the evaluation period, this research was supported by, or awarded, multiple VICI and VIDI career awards from the Dutch Research Council, and multiple ERC (both stg/adv) grants totalling about 10ME. Research is done by working closely with the UG's CIT, the Dutch HPC centre Sara, ASTRON, the SKAO, and ESA, and all codes in the 21-cm Cosmology groups are made public.

The studies often featured in the media and in (semi)popular articles, among them in featured article in Science Nature and documentaries on TV.

Case study 5: From the Euclid Science Data Centre to an Astronomical Science Data Centre.

A very successful program at the institute has been the development of smart information processing systems, by OmegaCEN, the expertise centre for data-intensive astronomy and astronomical information technology at

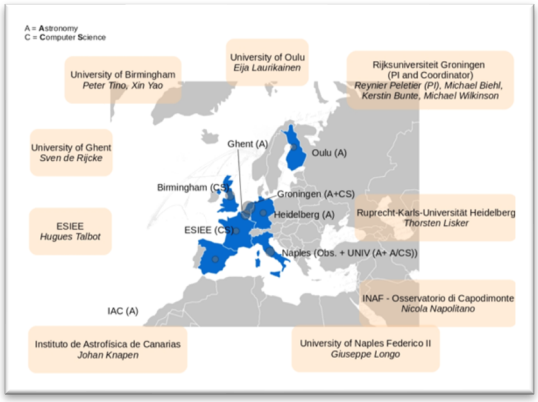
the Kapteyn Institute. Development of these data processing systems was originally driven by the need to process the increasingly larger (tera to petabyte) data sets from the VST-OmegaCam, in support of a range of research programs by our institute staff and NOVA. When the Netherlands joined ESA's Euclid consortium, the Dutch Euclid Science Data Centre was developed (support by 12 ME in grants) as part of the Euclid ground segment. This SDC provides Kapteyn and NOVA access to all Euclid data after launch in mid-2023. The Euclid SDC is hosted by the UG's CIT, who also contribute in-kind.

This expertise centre has led to multiple spin-off programs such as Target, Target Field Lab and AstroWISE, and led to the development of the DOT Live Planetarium (see below) and several spin-off companies (e.g., TilT recently and Slimmer AI earlier).

Throughout the development of this Dutch Euclid Science Data Centre, these spin-off companies have generated a return to society of order 100ME (value estimated for the spin-off companies). In addition, the institute is setting up contracts with the several of these spin-off companies and DOT, which generate limited income to support our valorisation and outreach efforts.

One of our strategic aims is to consolidate the Dutch Euclid SDC and expand it to a long-term funded Dutch Astronomical Science Data Centre for optical, infrared, and spectroscopic data from ESO/NOVA instrument, that supports the research programmes of our staff and that of NOVA. The core principle of the Dutch Euclid/Astronomical Science Data Centre is FAIR access to the data.

Case study 6: The Survey Network for Deep Imaging Analysis & Learning & Data Science & Systems Complexity



A case study of our highly successful interdisciplinary research effort has been the Sundial International Training Network (ITN), funded by the European Research Council and led by staff member Peletier, and the Data Science and Systems Complexity faculty theme. SUNDIAL (*Survey Network for Deep Imaging Analysis & Learning*) consisted of an interdisciplinary network of nine research groups throughout Europe. The network, consisting of senior researchers and 14 EU-funded PhD students, developing novel algorithms to study large databases coming from present-day telescopes to better understand galaxy formation and evolution, and to prepare for the huge missions of the next decade.

This initiative, besides the institute's interdisciplinary research and joint-PhD program within e.g., the DSSC faculty theme, is an excellent example of pan-European collaborative effort, led by our institute, to train the next generation of researcher in transferable skills, such as machine-learning, that are in high demand outside academia. The network collaborated with companies such as IBM, Target Holding, ACDIS, VICOMTECH, CLEVER-FRANKE, being a mix of large and smaller (e.g., start-up, e.g., Target Holding was a Kapteyn initiative that led to a highly successful spin-off company currently worth 100ME; see case study below) companies where student did internships.

The programs are tightly connected to our effort to increase our interdisciplinary effort, increase the skill set of our early career researches that are of immediate use outside academia, among them the faculty theme of Data Science and Systems Complexity as discussed in Section 3.1 in which Kapteyn has been highly successful in attracting joint PhD with computer science. The latter has been supported e.g., by a European COFUND grant, besides support from the University.

Case study 7: Societal Impact via Valorisation and Outreach

One of the most visible and impressive results of our outreach programme has been the DOT Live Planetarium, currently operating commercially and independently and includes a restaurant. The planetarium runs outreach shows by our institute on a sometimes weekly basis attracting full audiences each time. Besides outreach, the DOT planetarium, in the future, intents to start providing full-dome astronomy shows, using content and support provided by the institute, to attract commercial parties (e.g., company outings, meetings). Income generated by these activities will support our other outreach activities as well.

Besides shows, the institute has a contract with the owners of the planetarium allowing it to be used free of charge for a limited number of days per year, for example for conferences organised by the institute, symposia (such as our recently Kapteyn mini symposium), but also a recent public show on the launch and first results of the JWST, running jointly with similar events in the Netherlands and all over the globe.

The institute is currently in the process of extending this contract for the next five years and to connect DOT shows to our other outreach efforts such as the Dark Sky Park telescope and to results coming from Euclid in the coming years, also in collaboration with SRON.

Case study #8: Community Building

Finally, we dedicate one case study to an aspect we feel as institute is very important, being community building among our institute members via social and joint activities. Doing research, often not in one's own home country, can be stressful. Making our institute members feel at home at the institute regardless of their background or identity, is very important. We organise joint activities e.g., our spring and autumn BBQs, our end-of-the-year party, but also daily joint coffee breaks, and weekly Happy Hours on Friday afternoons, where a cross-section of staff and students come together to close off the week. As institute, faculty, and NOVA, we organise special events for PhD students and for our postdocs. This, however, is not all we can do to create a diverse, accepting, and inclusive atmosphere. To increase gender balance among our staff, which act as role models as well, we have successfully attracted many new female staff both via regular hires, and via the university's Rosalind Franklin programme. Besides this, during the Corona pandemic, in 2020 the institute initiated the Kapteyn Recognition and Engagement Committee (KREC) which advise the director on all matters concerning the well-being of the entire institute and most recently the institute financially support a diversity and equity officer and the NAEIC committee on the national level.