

STRATEGIC PLAN 2021-2030

FOR ASTRONOMY IN THE NETHERLANDS

Midterm Update

These images showcase PhD theses produced by students during the reporting period. These works reflect the diversity, quality, and impact of the research carried out within the Dutch astronomy community. Their inclusion continues a tradition established in previous editions of the strategic plan, highlighting the important contributions of doctoral candidates to our research community and its ongoing development.



Cover montage (three panels). Credit: Upper left: ESO/C. Lawlor, R. F. van Capelleveen et al.; Upper right: EHT Collaboration; Lower right: COLIBRE Collaboration/Schaye et al.

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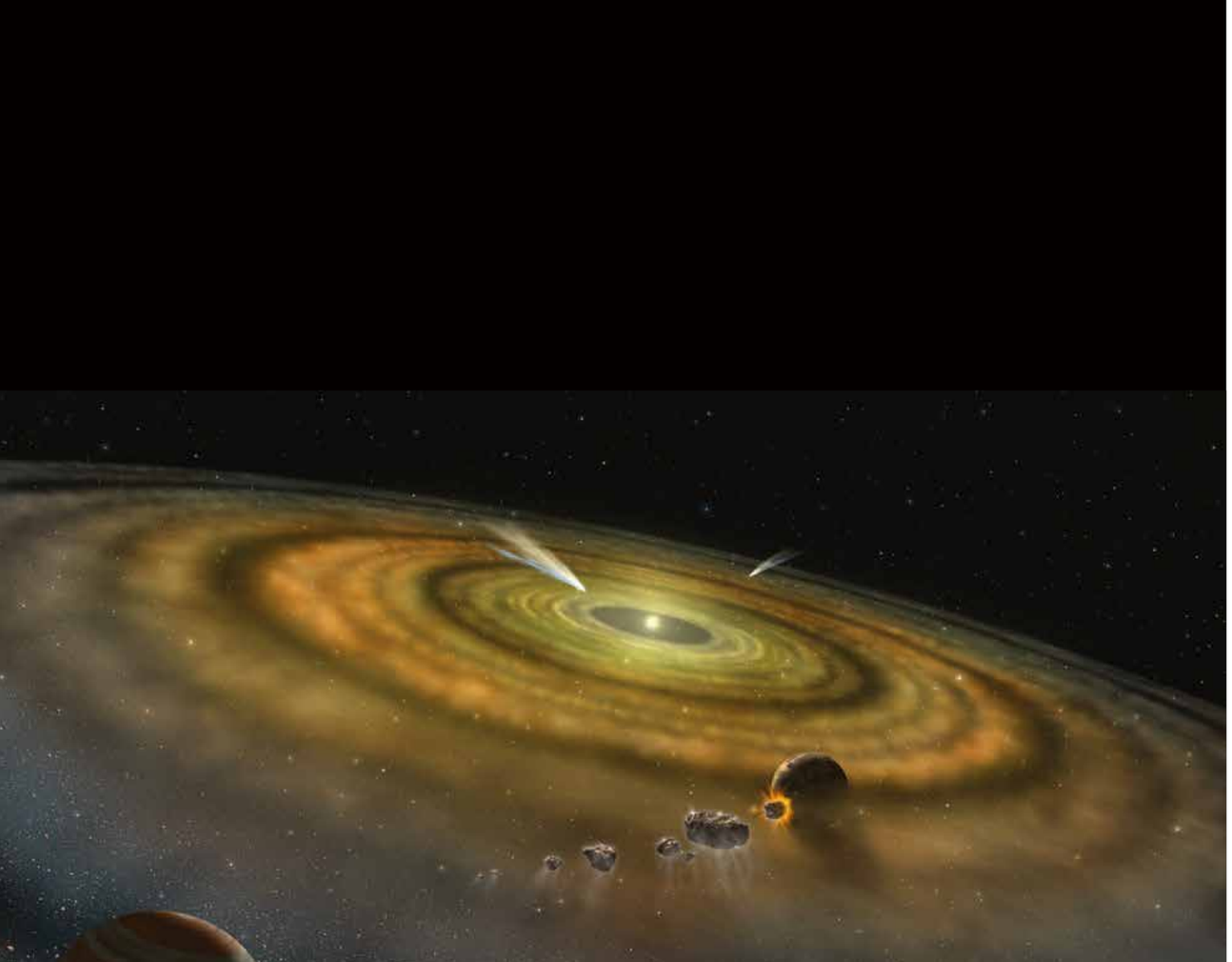
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EXECUTIVE SUMMARY

Dutch astronomy enters the second half of the 2021–2030 decade in a position of real strength. Dutch researchers have helped deliver many of the most striking results from a new generation of facilities. The James Webb Space Telescope, for which Dutch teams led the optical and mechanical design of MIRI, has transformed our view of the earliest galaxies, planet-forming disks, and exoplanet atmospheres. Gaia has overtaken Hubble as the most scientifically productive space telescope ever flown, with strong Dutch leadership in its science and data processing. Euclid has begun its survey of dark matter and dark energy from a Dutch-hosted data centre. The Event Horizon Telescope and LOFAR continue to set the pace in their respective domains, while ALMA and the VLT deliver high-impact science through Dutch-built instruments. New discoveries such as galaxies and massive black holes already in place at redshift 14, an unexpected diversity in disk chemistry and exoplanet atmospheres, and the first atmosphere detected around a hot rocky world all sharpen the case for the facilities still to come.

The strategic priorities of the 2021–2030 plan have largely been validated. Sectorplan investments have made NOVA's instrumentation groups permanent and strengthened our national capacity in data science. ELT construction is on track for first light in 2029, with NOVA leading the METIS consortium and contributing to MICADO and MOSAIC. The Square Kilometre Array is in full construction, SKA-Low has achieved first light, and ASTRON is preparing for early science. SRON is leading major contributions to ESA's NewAthena and LISA flagship missions, placing the Netherlands at the heart of the gravitational-wave and multi-messenger era.

Two challenges have grown sharper since 2021, however, and the most pressing of these concerns people. The NOVA national research programme that funded generations of PhD students and postdoctoral researchers ended in 2023, and re-establishing it is now the single most important priority for sustaining our talent pipeline. The second is the rapid rise of data- and software-intensive discovery. Data volumes from LOFAR and Euclid already strain current capabilities, and SKA and LISA will intensify these demands by orders of magnitude. Meeting these demands requires sustainable national digital infrastructure supporting data-intensive research across disciplines, alongside astronomy-specific investment in software engineering, AI-enabled analysis methods, and the talent to develop and apply them.

Our priorities for the remainder of the decade are therefore: (1) to reconstitute long-term funding for training and the wider NOVA research programme; (2) to build a coordinated national data and computing infrastructure for the LOFAR2.0, SKA, ELT, and LISA era; (3) to deliver the first-light ELT instruments and secure Dutch leadership in MOSAIC and the Planetary Camera and Spectrograph; and (4) to consolidate Dutch participation in the space-based flagships of the 2030s. The horizon already extends well past 2030, with the ESO Expanding Horizons process, the Einstein Telescope, ESA's Voyage 2050 themes, and NASA's Habitable Worlds Observatory all aligning closely with Dutch strengths.

The case for sustained investment rests not only on scientific ambition but on the broader value the field returns to society. Dutch astronomy pushes instrumentation to its limits, generating technological spillovers that migrate from telescopes and space missions into medical imaging, telecommunications, and data analytics. It trains a highly skilled workforce whose capabilities flow into the wider Dutch knowledge economy, and it inspires the public in ways that draw young people towards STEM. With the partnership of NOVA, SRON and ASTRON continuing to prove its value, with sustained public investment, and with a renewed commitment to training the next generation, Dutch astronomy is well placed to continue delivering breakthrough discoveries, technological innovation, and inspiration for our society through the remainder of this decade and the decades to come.

NOVA

SRON SPACE RESEARCH ORGANISATION NETHERLANDS

ASTRON Netherlands Institute for Radio Astronomy

Opposite page: Artist's illustration of planet formation (Beta Pictoris disk). Credit: NASA/FUSE/Lynette Cook



1

INTRODUCTION

This document provides the mid-decade update to the Strategic Plan for Dutch Astronomy 2021–2030, based on extensive discussions with the entire Dutch Astronomy community. It takes stock of progress towards the goals set at the start of the decade, identifies where new discoveries, technological advances, and external developments have shifted the landscape, and sharpens priorities for the years ahead. The scientific vision and strategic choices established in the original plan remain robust; our aim here is to strengthen their execution and respond to an environment that has evolved in ways both anticipated and unexpected.

The first half of the decade has been one of remarkable scientific achievements for Dutch astronomy. It has also been a period of considerable change in the broader research landscape. New facilities have come online, long-awaited missions have launched, and early results have exceeded expectations in several areas. At the same time, familiar challenges have persisted while new ones have emerged. Set against this backdrop, the accomplishments of the Dutch astronomical community are all the more notable, and the need for continued strategic coordination is even more pressing.

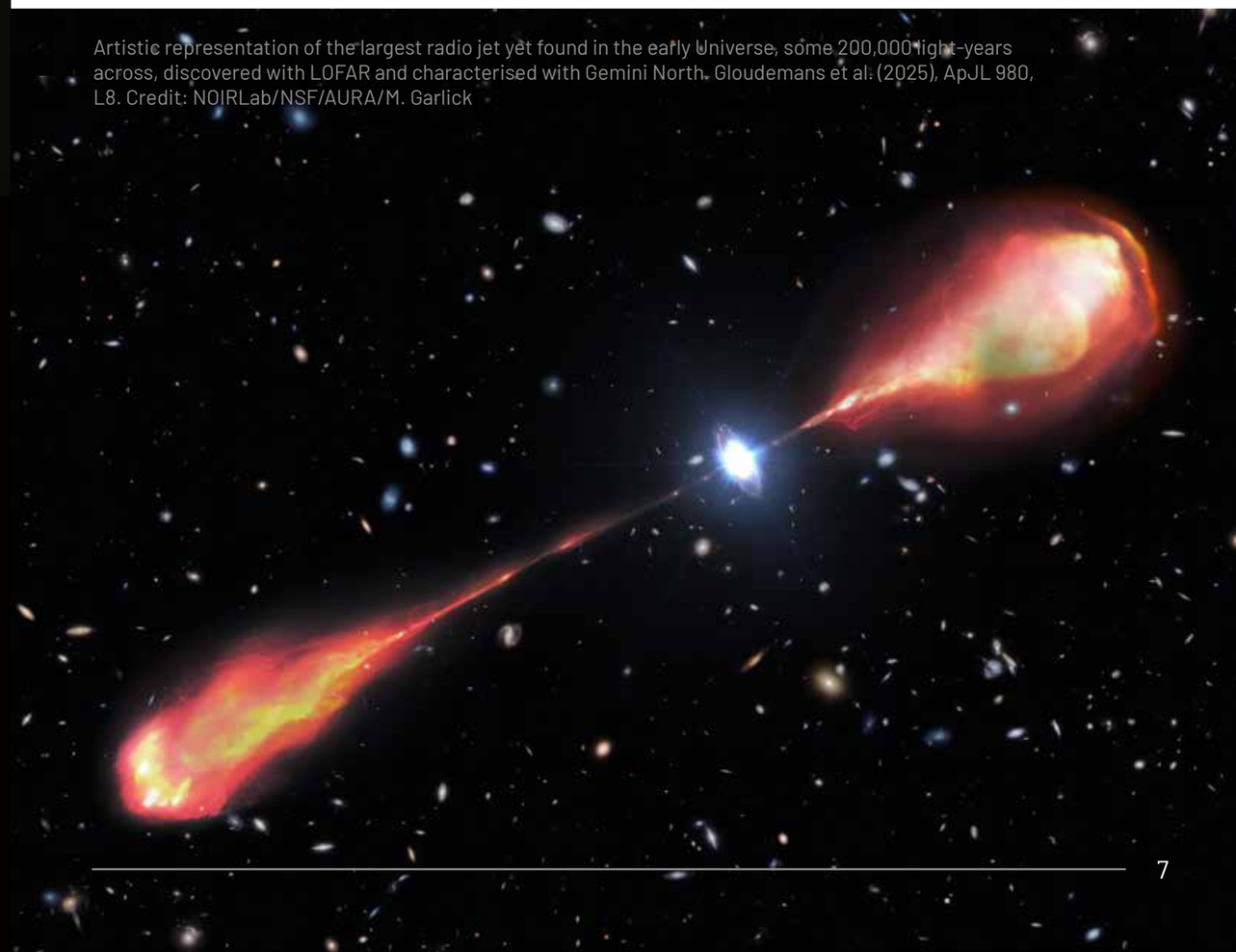
We retain a planning horizon that extends well past 2030. Flagship facilities and missions are conceived, negotiated, built, and operated on timescales measured in decades. Choices made in the second half of the 2020s will shape the scientific landscape of the 2030s and 2040s and will determine whether the Netherlands remains a leading partner as new international initiatives take form.

Opposite page: The Gaia all-sky map of the Milky Way, built from the positions and brightness of nearly two billion stars. Credit: ESA/Gaia/DPAC

1.1 The status of Dutch astronomy at mid-decade

Dutch astronomy continues to build on a partnership model that combines scientific ambition, technical excellence, and national coordination. The university astronomy departments, united through the NOVA research school, work in close alignment with the NWO institutes ASTRON and SRON. Strategic priorities and major decisions are coordinated through the Raad voor de Astronomie (RvdA), ensuring that institutional, university, and facility commitments remain coherent and mutually reinforcing. This collaborative structure has long been a distinguishing strength of Dutch astronomy on the international stage.

At mid-decade, this model is once again proving its value. Dutch researchers are delivering high-impact results from newly available and upgraded observatories, and Dutch groups maintain visible roles in the consortia shaping the next generation of facilities. The launch of the James Webb Space Telescope (JWST) and Euclid, the continued success of Gaia, and progress on the European Southern Observatory's (ESO) Extremely Large Telescope (ELT) instrumentation all demonstrate the returns on sustained investment and strategic engagement. At the same time, projects continue to grow in scale and complexity, data volumes rise sharply, and the cost of maintaining world-class capability in instrumentation, software, and engineering increases. This midterm update to our Strategic Plan therefore combines an account of progress with a candid assessment of where reinforcement is needed.



Artistic representation of the largest radio jet yet found in the early Universe, some 200,000 light-years across, discovered with LOFAR and characterised with Gemini North. Gloudemans et al. (2025), ApJL 980, L8. Credit: NOIRLab/NSF/AURA/M. Garlick

1.2 **Scientific highlights and evolving questions**

The first half of the decade has brought rapid progress across the field. New space- and ground-based capabilities are transforming our view of the early Universe and the assembly of galaxies. Precision astrometry combined with wide-field spectroscopic surveys is providing an increasingly detailed dynamical and chemical map of the Milky Way. Multi-messenger and time-domain approaches are maturing quickly, and new infrared and millimetre observations are expanding our understanding of planet formation, exoplanet atmospheres, and astrochemistry. Dutch astronomers have been at the forefront of many of these developments, contributing breakthrough results in areas ranging from the characterisation of exoplanet atmospheres and the high-redshift Universe with JWST to the first detection of an emission line in a gamma-ray burst to the measurement of polarised and time-variable emission in the shadows of black holes.

This momentum has further sharpened the questions identified at the start of the decade and the priorities they imply. In several areas, early results have been more surprising than anticipated, exposing gaps in theory and raising novel questions that now define the frontier. Galaxies and massive black holes have been confirmed at redshifts beyond z=14, and their properties suggest formation processes that began even earlier than models predicted. The interplay between star formation and black-hole evolution at high redshift appears strikingly different from what is observed locally. Chapter 2 summarises these and other key developments and outlines the questions that will guide the community through the remainder of the decade.

1.3 **Status of the strategic priorities of the 2021–2030 plan**

The 2021–2030 plan pairs an ambitious science programme with a focused set of strategic priorities: sustaining a community of excellence and making targeted investments in facilities and instrumentation where the Netherlands can lead and achieve enhanced impact, beyond what might be expected from simple proportional funding. Midway through the decade, we see clear advances as well as areas where the strategy is under pressure.

Sustaining a community of excellence. Dutch astronomy remains internationally competitive because it couples excellence in science with excellence in instrumentation, software, and data-driven discovery. Maintaining this position depends on a healthy talent pipeline and an environment that is equitable, inclusive, and attractive to the widest possible pool of researchers. The community has been successful in securing and advancing mission-critical instrumentation efforts and long-term facility participation. However, stable support for PhD candidates and postdoctoral researchers has declined over the first part of this decade. Without predictable investment in people, it becomes more challenging to translate facility leadership into sustained scientific leadership and to renew and build expertise in critical areas such as instrumentation and data science.

Major facilities and instrumentation. On the facilities side, the Netherlands has tangible reasons for confidence. Progress in ELT instrumentation consolidates Dutch leadership in key optical and infrared capabilities, while strong engagement in the Laser Interferometer Space Antenna (LISA) represents a strategic stake in an ESA flagship mission that will define gravitational-wave astronomy from space.

Despite this progress, this update must also acknowledge goals in the current Strategic Plan that are yet unrealised as well as new opportunities and risks that have emerged. For example, at mid-decade, the Square Kilometre Array (SKA) is in full construction and has already achieved first light; however, funding for the digital infrastructure necessary to harvest the science from this global facility is still being secured. In parallel, the final wave of missions as part of the ESA Cosmic Vision programme, and the definition of next flagships in the Voyage 2050 and NASA programmes, are opening new opportunities for space-based astronomy. Similarly, the planned ALMA2040 upgrade and ESO Expanding Horizons programme promise a next generation of innovative ground-based facilities.

Taken together, these developments make the second half of the decade a decisive period for aligning Dutch strengths with future European and global programmes. All of these remaining priorities and new opportunities, however, are set against a challenging scientific funding landscape that the community must manage to ensure the future and long-term coherence of the national strategy.

1.4 **New opportunities and shifting boundary conditions**

Since 2021, several developments have become more central to the success of astronomy than was fully apparent at the start of the decade. Two stand out: the acceleration of data- and software-intensive discovery, and a less predictable international operating environment.

The data landscape has changed profoundly. New surveys and facilities produce data at unprecedented volume and complexity, and the scientific frontier increasingly depends on robust software, reproducible workflows, and advanced statistical and machine-learning methods. Artificial intelligence is rapidly becoming integral to survey design, source classification, and transient discovery, and to linking observations with simulations. This shift creates an opportunity for the Netherlands to amplify its impact by strengthening national capability in data infrastructure, software engineering, and AI-enabled analysis. Recent Sectorplan investments have begun to address this need, but sustained effort will be required to ensure Dutch astronomy remains at the forefront of data-intensive science.

At the same time, the geopolitical and economic climate has become more uncertain. International projects depend on stable partnerships, reliable supply chains, and long-term commitments. Resilience now means planning for disruption: strengthening national coordination, maintaining strategic agility where possible, and ensuring that critical capabilities in technology, engineering, software, and data science are protected and renewed.

1.5 **Looking beyond 2030**

Because major facilities have multi-decade lifecycles, a credible update must also look beyond the nominal end of the 2021–2030 period. The Netherlands will retain its leading role only if it continues to lay foundations now for the post-2030 landscape. Priorities include the next waves of instrumentation for the ELT and for radio facilities such as LOFAR2.0 and the SKA, new space missions and survey concepts building on Dutch contributions to JWST, Euclid, and NewAthena, and the integration of multi-wavelength and multi-messenger capability as a routine mode of discovery. ESA's Voyage 2050 and ESO's Expanding Horizons processes offer timely opportunities to position Dutch priorities early and to ensure that national strengths align with emerging international programmes.

The case for sustained public investment rests not only on scientific ambition but on the broader societal value the field delivers. As a driver of technology and innovation, Dutch astronomy pushes instrumentation to its limits, generating spillovers that permeate daily life. Advances in detectors, signal processing, image reconstruction, and high-performance computing developed for telescopes and space missions migrate readily into medical imaging, telecommunications, and data analytics. Institutes such as ASTRON, SRON, and the NOVA instrumentation groups work closely with Dutch industry on technologies whose impact reaches far beyond astronomy itself.

The field also cultivates a highly skilled workforce, training researchers in large-scale data analysis, statistical inference, software development, and instrument-building, capabilities that flow readily into the Dutch knowledge economy, strengthening sectors from data science and finance to biotech and high-tech manufacturing. Equally important is astronomy's power to inspire and engage the public. From the long Dutch tradition in radio astronomy that runs from Westerbork through LOFAR to its central role in the Event Horizon Telescope's first image of a black hole, and to Dutch contributions to landmark missions such as JWST, the field offers moments of discovery that capture global attention and evoke a sense of wonder few other sciences can match. Through outreach programmes, planetaria, and citizen-science initiatives, Dutch astronomy brings this inspiration to a broad audience, drawing young people towards STEM and enriching civic and cultural life.

As we hope this update makes clear, Dutch astronomy enters the second half of the decade from a position of real strength. The community has delivered on key commitments, secured important new investments, and maintained its reputation as a valued international partner. Challenges remain, and the larger environment continues to evolve in ways that demand adaptability.
With leading researchers, a strong network of national and international collaborations, and a diverse portfolio of facilities and missions, Dutch astronomy is well placed to continue enabling breakthrough science and to act as a careful steward of the public investment, talent, and inspiration on which future discoveries depend.

1.6 **How to read this update**

This update provides continuity with the 2021–2030 plan while giving a clear account of what has changed since its publication. Chapter 2 revisits the scientific vision and identifies evolving questions. Chapter 3 updates the discussion of astronomy in its broader interdisciplinary and societal context. Chapter 4 reviews facilities, instrumentation, and infrastructure. Chapter 5 addresses astronomy's role in society, including outreach, equity and inclusion, and environmental responsibility. Chapter 6 offers a refreshed outlook beyond 2030 and summarises the road ahead. Together, these chapters provide a shared basis for decisions and investments through the remainder of the decade.

Opposite page: Euclid's view of our galaxy's bulge, showing more than 60 million stars. Credit: ESA/Euclid/ Euclid Consortium/NASA, CFHT, image processing by J.-C. Cuillandre and E. Bertin (CEA Paris-Saclay)



2

SCIENCE VISION: UPDATES AND NEW QUESTIONS

2.1 Big questions: updates

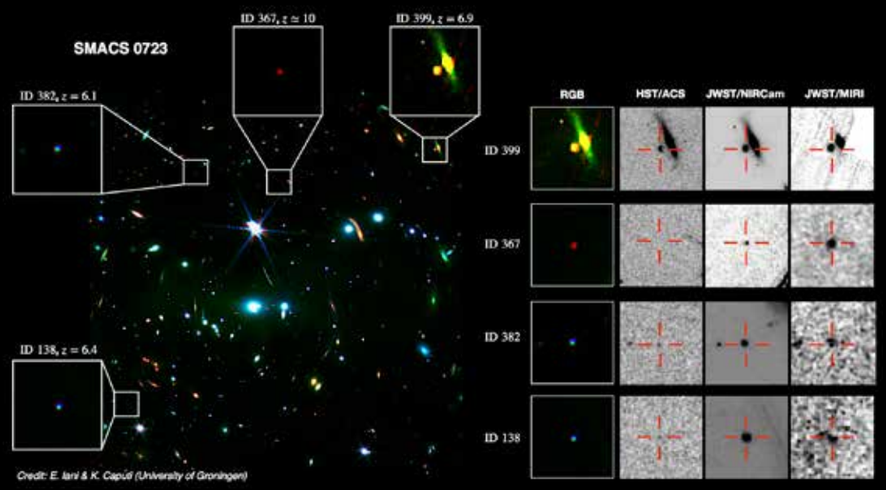
At the start of the decade, our community identified a number of urgent questions to address: *what happened during the dawn of the Universe?; what is the nature of the main constituents of the Universe?; how did galaxies assemble and evolve?; how do planetary systems form around newly born stars?; what is the diversity of exoplanetary systems?; what role does the Galactic context play in planet formation?; how do complex molecules form?; to what precision can general relativity describe gravity?; what is the nature of dense matter?; what is the origin of the elements?; how do compact objects form and evolve?*; and *how do compact objects produce energy and accelerate particles?* Dutch researchers have made progress on nearly all of these questions in the preceding half-decade, greatly abetted by the infrastructures and investments promoted and strategic choices made and presented in the current and previous Strategic Plans for Astronomy in the Netherlands. This progress has led to new questions detailed below, as we continue our search for the origins of the Universe, galaxies, black holes, stars, planets, and even life itself.

2.2 Science questions for the remaining half-decade: updates and new questions

2.2.1 Evolution of our Universe and origin of the Milky Way

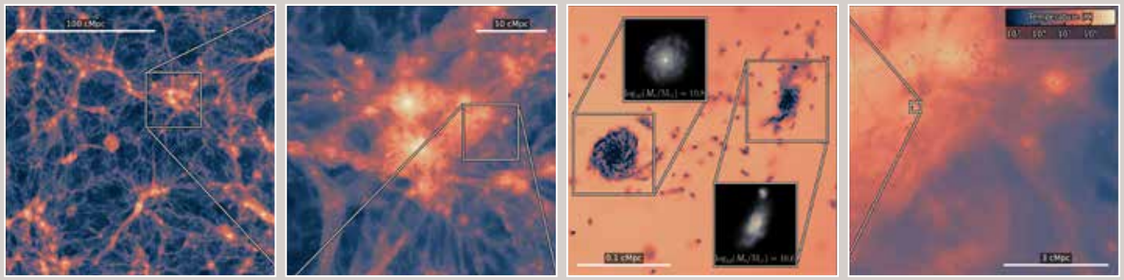
In the past years, major progress has been made in the area of galaxy evolution, at both high redshifts and the nearby Universe. The advent of two major telescopes, JWST and Euclid, complemented by top-class facilities such as ALMA, ESO's VLT, and LOFAR, are revolutionising our understanding of the early stages of galaxy formation. Galaxies and massive black holes have been confirmed to be present since the Dark Ages (z=14) and their properties indicate that they must have formed even earlier in cosmic time. In parallel, new studies are revealing unexpected facets in the interplay between star formation and black-hole evolution, which are very different from what is observed in the local Universe; and there is new evidence for the existence of dark matter in high-redshift galaxies. LOFAR continues to set the strictest limits on the reionisation of the Universe. Nearby, the revolution engendered by the unprecedented detail revealed by the Gaia satellite has given us new insights into the Milky Way, pushing us forward to new dynamical and chemical vistas of our own and other galaxies. Simulations of ever-increasing fidelity allow for ever-better understanding of the physics of structure and galaxy formation in the Universe.
At the same time, these studies have opened new important questions and can bring opportunities that will shape the direction of the field in the coming years. In particular, the most relevant open questions are: *what are the physical processes at play at the earliest stages of galaxy formation?; what was the role of dust in galaxy evolution?; how can massive galaxies and black holes start to form so early in cosmic time?; when did the first galaxies appear and what were their properties?;* and *what lessons can be learned from galaxy studies in the nearby Universe to understand better the physical conditions of early galaxy formation?* The expertise needed to address these questions is available in the Netherlands, and the answers will be pursued by enhancing the synergies between our different research groups.

Opposite page: Artist's impression (rocky world). Credit: Mark Garlick



Analysis of the very first image from the James Webb Space Telescope reveals details of galaxies from the time when the Universe was only about 1 billion years old. Left: the first image with four galaxies highlighted. On the right, the four galaxies are each seen with a different telescope or instrument. A striking example of JWST's power is galaxy ID 367 that cannot be seen with Hubble. Iani et al. (2022), ApJL 940, L24.

To answer these questions, new facilities with improved and complementary capabilities are necessary. Particularly, the proposed ALMA2040 upgrade as part of ESO's Expanding Horizons initiative and NASA's proposed PRIMA mission, possibly augmented by a new ESA far-IR observatory such as the proposed FOSSIL or LETO missions, will be crucial to maintain Dutch leadership in IR and sub-mm astronomy. These facilities will leverage ongoing JWST studies, as well as complement the future facilities which we are already developing, the ELT and SKA. The LOFAR2.0 upgrade will open a uniquely clean, low-frequency window on the epoch of reionisation, enabling the most stringent limits on, or even a first detection of, the neutral-hydrogen 21-cm power spectrum in that epoch. In addition, proposed new endeavours such as the Wide-field Survey Telescope (WST), a candidate for ESO's Expanding Horizons programme, will be necessary for a systematic follow-up of Euclid-discovered galaxies, and complement ongoing and future studies with Gaia, WEAVE and 4MOST, which will open new probes of the six-dimensional dynamical phase space and the chemistry of the Milky Way and nearby Universe. All these instrumental advances must be paired with investments in computational facilities that enable the continuous improvement of Dutch-led galaxy formation models. Finally, the Einstein Telescope (ET) and LISA will be excellent probes for massive black-hole formation and its relation to galaxy evolution (see Section 4.1.2).

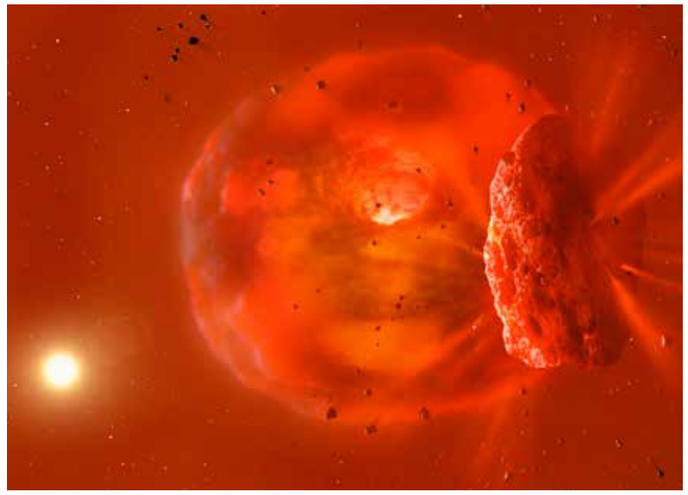


Visual impression of the dynamic range in one of the new COLIBRE simulations of galaxy formation and evolution at redshift z=0.1. The far left panel shows the temperature of the gas in a slice through the Universe. The three other main panels show consecutive zooms into the outskirts of a galaxy cluster. The two smaller images in the third panel show the stellar light in Euclid colours and account for attenuation by dust. Schaye et al. (2026), MNRAS, in press.

2.2.2 Origin of stars and planets and our place in the Universe

In the past five years, the highly complementary JWST and ALMA observatories have led to fundamental advances in our understanding of the processing of molecules in space, the characteristics of exoplanet atmospheres, and the formation of planetary systems. The new data show an unexpected diversity and richness in terms of the properties and stability of exoplanetary atmospheres, the chemistry of planet-forming disks, and dynamical processes in planetary systems.

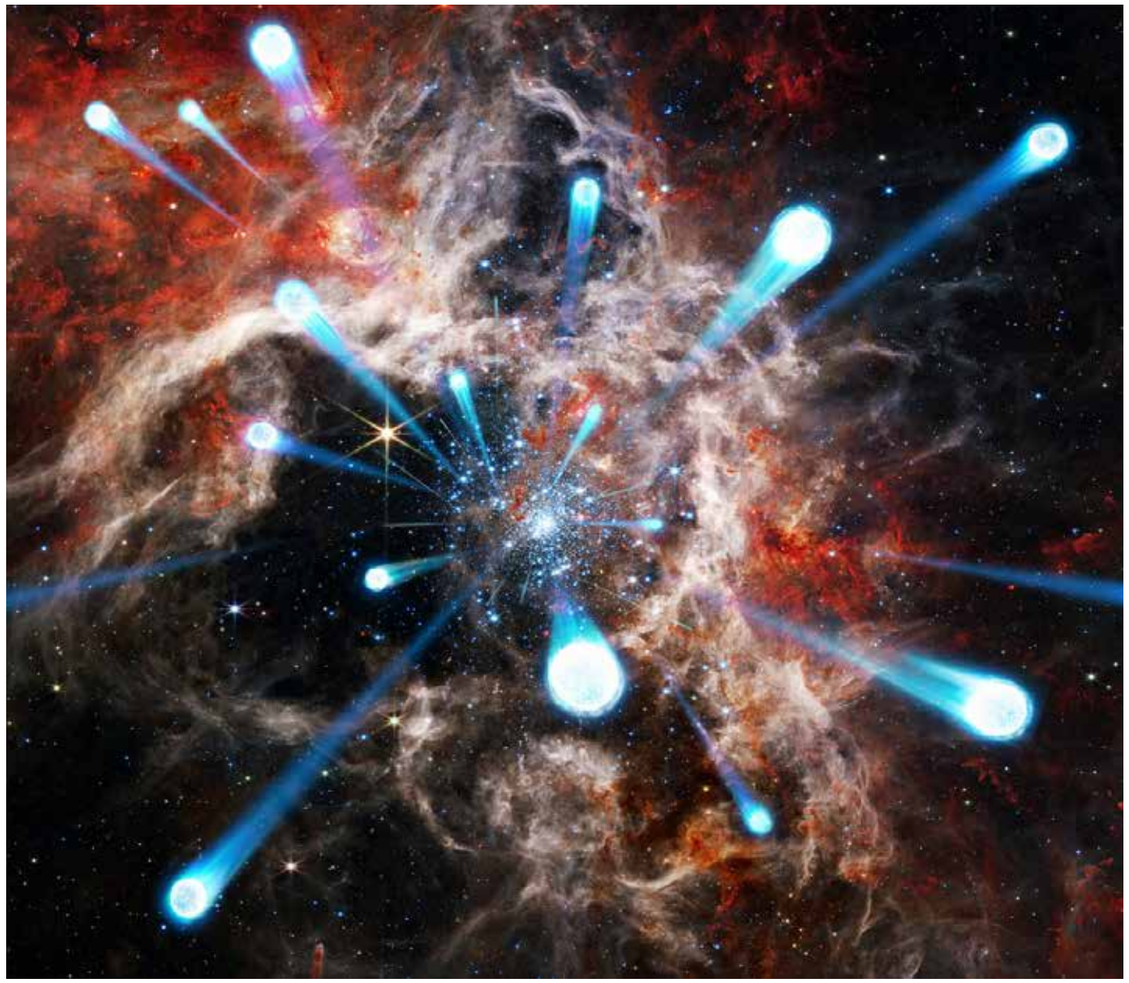
Dutch astronomers have contributed ground-breaking scientific results in these areas. ALMA has revealed the disk environments where planets form in unparalleled detail. With JWST, the water reservoir in planet forming disks has been mapped. Unexpectedly, hydrocarbon-rich gas was found to dominate the innermost regions of disks of very low mass stars. This may greatly impact the formation of rocky planets around this most abundant population of stars in our galaxy. Dutch astronomers have used JWST to characterise the atmospheres of gas giant exoplanets in great detail, including discovering exotic silicate clouds, and even detected an atmosphere around a hot rocky world suffering lava eruptions. Photo-chemical processes in planetary atmospheres have been observed for the first time, essential for understanding their stability. With LOFAR, signatures of the interaction between M dwarf stars and short-period rocky exoplanets have been identified by Dutch radio astronomers. Intriguingly, the debris of a collision of two icy planets has recently been discovered.



Two years after a sudden brightening of the star ASASSN-21qj, discovered by an amateur astronomer who posted it on social media, its starlight dimmed in a complicated way as the result of an optical eclipse. This appears best explained by the collision of two ice-giant exoplanets and the subsequent transit of the expanding debris cloud in front of the star. The image shows an artist impression of the catastrophic collision of the two icy planets. Kenworthy et al. (2023), Nature 622, 251.

These breakthroughs bring us closer to finding and characterising habitable planets and, potentially – our "pale blue dot" on the horizon – the detection of extraterrestrial life. New facilities instrumental for this search, and for further exploration of the connection between exoplanets and their (formation) environments, include the ELT, Ariel, PLATO, the wide-band upgrade of ALMA, SKA-Westerbork VLBI, HWO and LIFE. Future data releases of Gaia and a potential successor mission, GaiaNIR, will allow for the astrometric discovery of exoplanets in the habitable zone of their host stars (see Section 4.1.2). The new data these facilities will provide, together with theoretical developments, will allow us to address open and entirely new questions: *What sequence of events leads to the formation of planets? How are water and volatile and refractory chemical elements, including those that are essential for life as we know it, delivered to rocky planets? How does the interior and the secondary atmosphere of rocky planets evolve, and what processes govern their habitability? How do terrestrial planets retain their secondary atmosphere? What is the importance of the stellar host and planetary system architecture on habitability? In what way does stellar mass impact planet formation? What is a unique signature of habitation of extra-solar worlds? And ultimately, are there inhabited worlds elsewhere in the Universe, and if so, how many and how far away?*

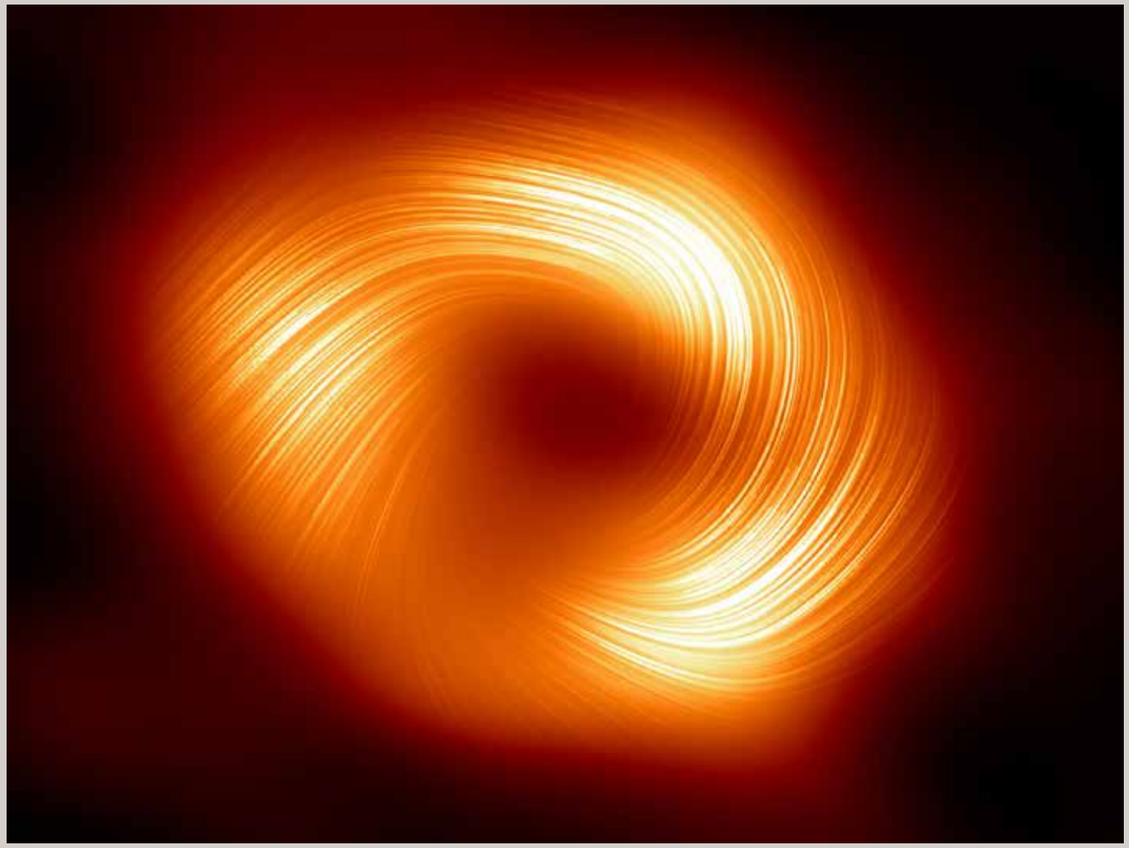
At the same time, VLT, HST, JWST and Gaia have allowed us to characterise the properties and dynamical behaviour of high-mass stars, including the most massive stars known. JWST is contributing to our understanding of their formation. Dutch astronomers discovered that high-mass stars are found to impact nearby forming low-mass stars, likely affecting planet formation in these systems and the resulting exoplanet population. Using Gaia they showed that young massive clusters produce unexpected numbers of runaway stars, ejected by dynamically dominating massive binary systems. Comprehensive VLT and HST datasets secured by the Dutch community permit the characterisation of entire massive star populations and thus constrain fundamental aspects of the physics of stellar evolution. This now allows much more accurate predictions of the end stages of stellar evolution, including the properties of gravitational wave progenitors. These studies pave the way for scrutinising stellar populations in thousands of galaxies once ELT and its first- and second-generation instrument suite, and the proposed WST, are operational. Future space facilities are needed to access massive star populations in the ultraviolet, including HWO and other proposed missions.



Using Gaia data, 55 massive stars – considerably more than theorised – were found to run away from the million-year-old cluster RMC 136 in the Large Magellanic Cloud. Their timing and directional distribution revealed two channels of dynamically ejected runaway stars, one related to the birth of RMC 136 and one to an interaction with a neighbouring cluster. The image shows an artist impression of massive stars running away from the cluster core. Stoop et al. (2024), Nature 634, 809.

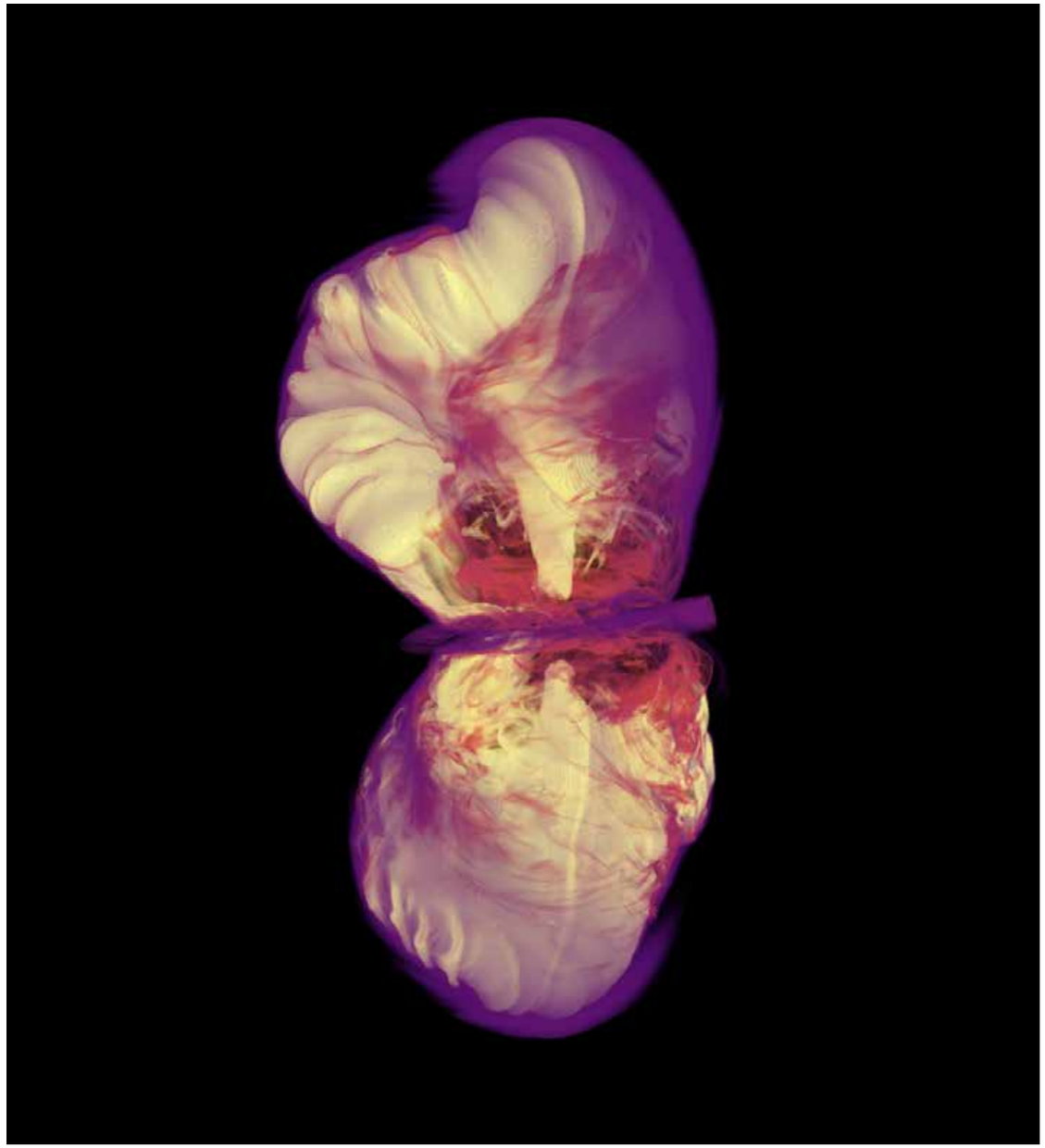
2.2.3 Space and matter under extreme conditions – the Universe as a laboratory

There has been great progress in the last half-decade in understanding space and matter under extreme conditions. This progress has been achieved in part by our continuing mapping of the multi-messenger, dynamic transient sky, capitalising on the investments and work done by Dutch astronomers in the previous periods.



Dutch astronomers helped lead the analysis of EHT data to measure polarisation – a direct tracer of magnetic fields – close to the edge of the Milky Way's central black hole, Sagittarius A*, for the first time. The lines mark the direction of the polarisation. The Event Horizon Telescope Collaboration et al. (2024), ApJL 964, L25.

For example, using the Event Horizon Telescope (EHT), Dutch researchers have used the polarised and time-variable emission detected in the shadows of black holes to study accretion physics in detail and better understand how compact objects evolve and emit energy. Meanwhile, expanded gravitational wave observations with LIGO, Virgo, and KAGRA have enabled high precision probes of general relativity, while also revealing the population properties and formation pathways of merging stellar-mass black holes. When combined with multi-wavelength, multi-messenger observations with facilities such as NICER, Apertif, MeerKAT, MeerLICHT/BlackGEM, EVN, and the Pierre Auger Observatory, among others, Dutch astronomers have been able to constrain the physics of neutron-star mergers and ultra-dense matter, probe the origins and composition of ultra-high-energy cosmic rays arriving at Earth, and probe the origin of heavy elements in the Universe through studies of kilonovae.



A simulation of an extreme supernova explosion. Colours indicate entropy and show jet-driven outflows from a magnetar engine. Shankar et al. (2023), Classical and Quantum Gravity 40, 205009.

In the course of these discoveries, new questions have also arisen: *how do we measure the properties of dense matter beyond what NICER and initial gravitational-wave detections allowed us to do?; what is the dynamical relationship between inflows and outflows in active galactic nuclei?; where are high-energy flares produced?; how and where do extremely high-energy cosmic rays and neutrinos form and come from?; how do the environments of binary black-holes (e.g. their accretion disks and potential dark matter halos) shape their gravitational-wave emission?;* and *how do compact objects in the gap between the highest mass neutron stars and the lowest mass stellar-mass black holes and of sub-solar masses form?*

To answer these and other questions arising in the near- to mid-term future, we expect to further expand on crucial multi-wavelength, multi-messenger observational capabilities. NOVA will continue operations for BlackGEM and support MeerLICHT while also leading the development of the Africa Millimetre Telescope (AMT), which will enhance the EHT's multi-frequency capabilities and sensitivity for dynamic phenomena and transients, and in the future possibly also the Time Domain Telescope (TDT), a spectroscopic array for high-time-resolution observations of transient and variable phenomena and another candidate for ESO's Expanding Horizons programme. We will continue to harvest the scientific results of the Pierre Auger upgrade and plan for a future contribution to the Global Cosmic Ray Observatory (GCOS). ASTRON is leading the development of the next generation of radio capabilities through upgrades to LOFAR, the SKA which is currently under construction, and global GHz VLBI including the EVN and upgrades to Westerbork VLBI through the WSRT2030+ project. In space, SRON is leading the development of the LISA mission to expand our ability to probe the gravitational wave spectrum as well as new proposed X-ray transient and timing capabilities with NEBULA, and Dutch astronomers have proposed a future mm-wave space VLBI mission (SHARP) to improve black hole imaging by an order of magnitude and probe e.g. spin energy extraction from black holes. Further, we will combine these increased capabilities with new gamma-ray capabilities arising from our founding membership of the Cherenkov Telescope Array Observatory (CTAO) consortium and by planned contributions to the ET. The ET, especially when combined with LISA, will provide an unprecedented tool for gravitational wave science.

All together these facilities will form a powerful platform for multi-wavelength, multi-messenger astronomy in the coming decade and ensure that the Netherlands continues to play a leading role in answering upcoming big questions in cosmology, dense matter, and astroparticle physics.

2.3 **Training new astronomers: big ambitions need new visions and talented researchers**

All these new questions and the instrumentation and infrastructure required to search for their answers require a continual injection of new researchers with new ideas into the community – big ambitions need big and new visions. As stated above, the Dutch astronomy community has been successful in obtaining long-term funding to support our mission-critical instrumentation programme in NOVA and at the NWO-I institutes, but the support of young researchers at the PhD and postdoctoral levels has not been guaranteed. Without stable, long-term funding lines for young researchers, the community's ability to make groundbreaking discoveries in astronomy will be uncertain. The previous long-term funding of NOVA's research programme (1999–2023) demonstrated that such funding – at even a small fraction of the total funding level of astronomical research in the Netherlands – provided a critical base that acted as a flywheel to generate new ideas, new infrastructures, and new funding opportunities. We must return to this model of supporting a vibrant PhD training programme and a prestigious postdoctoral fellowship programme to ensure that our instrumentation programme delivers the science it promises and to position Dutch astronomy to maintain our continuing strong roles in a wide variety of international collaborations.



3

ASTRONOMY IN CONTEXT: UPDATES AND NEW PERSPECTIVES

3.1 Interdisciplinary astronomy: updates

3.1.1 Astronomy & Chemistry

The Dutch astrochemistry community has made important advances in the past five years. This progress is a direct result of the synergy between new instrumentation – in particular JWST – laboratory experiments, and theoretical studies, which guide the interpretation of the new data and point towards new avenues in astrochemistry. All of these developments benefit from the collaborations in the successful Dutch Astrochemistry Network (DAN), supported by NWO. In 2024 a second renewal funded the DAN III network, which focuses on harvesting JWST data, again combining astronomical data and astrophysical modelling with laboratory studies and quantum chemical calculations. The DAN III network focuses on how the main materials that carry carbon, oxygen, nitrogen and hydrogen atoms, namely interstellar ices and hydrocarbons, evolve chemically from molecular clouds to the stages where they are incorporated into planets and their atmospheres. The Leiden laboratory astrochemistry facilities continue to provide crucial input, while the recent establishment of HFML/FELIX as an NWO-I institute further strengthens the national astrochemistry landscape. Four EU-funded ERC advanced grants with a strong astrochemistry component have been awarded in the past 4 years. The Leiden Lab is also strongly collaborating with InterCat (Aarhus University) and the Dutch astrochemistry community participates in several related COST Actions (e.g. NanoSpace, PLANETS).

3.1.2 Astronomy & Earth sciences

The characterisation of rocky Earth-like exoplanets and Super-Earths requires a deep understanding of their formation as well as their interior geophysical processes. These studies need the context of detailed knowledge of the solar-system rocky planets and moons. This expertise was brought together in the interdisciplinary NWO-funded Planetary and Exoplanetary Science (PEPSci) network, where astrophysics and Earth sciences joined forces. The PEPSci network was extended for an additional five years in 2020. Over those past five years, this field has grown substantially in strength within Dutch astronomy due to several new staff hires as well as participation in the ESA M4 Envision to Venus led by SRON. Several ERC grants were recently awarded that build on the heritage of the PEPSci network, as well as the NWA/NWO-funded programme PRELIFE, which employs 15 PhD students across the Netherlands. Laboratory experiments continue to be important in guiding the interpretation of data and the calibration of models. There is significant overlap between the astrophysics, Earth sciences and origin-of-life communities, allowing many opportunities for synergies in the field. The Earth Observation programme at SRON offers one such synergy as the high-precision spectroscopy and radiative transfer techniques honed for studying Earth's atmosphere translate directly to characterisation of exoplanet atmospheres, and vice versa.

Opposite page: BlackGEM at ESO La Silla. Credit: S. Bloemen (Radboud University)/ESO

3.1.3 Astronomy & Biology

The discovery of extrasolar planets in the 1990s and especially terrestrial exoplanets in the 2010s has fuelled interest in astrobiology and planetary habitability. In the Netherlands, one driving force has been the Nationale Wetenschapsagenda (NWA; Dutch National Science Agenda), an initiative from the Ministry of Education to collect questions from the general public in need of scientific answers. One set of questions led to the foundation of the Origins Center, a virtual institute with ~300 Dutch scientists from fields including astronomy, Earth sciences, biochemistry, and ecology, aiming to understand the origin and evolution of life on Earth and other planets. The Origins Center regularly organises interdisciplinary conferences and focused workshops, funds small research projects, and conducts outreach, e.g. by an award-winning podcast series. Noteworthy spin-off projects include the EU-funded oLife programme employing 18 postdoc positions at the universities of Groningen, Eindhoven, and Leiden; its successor Evolve employing 17 PhD students in Groningen and Leiden; and the Origins Center and its spin-off, the affiliated Amsterdam Center for Origins of Life (AMCOOL). The years 2026–2030 are likely to see more such initiatives, including the PRELIFE successor Living Planet. In addition, Dutch astronomers are active members of the European Astrobiology Institute, organising PhD schools and monthly webinars.

3.1.4 Multi-messenger astrophysics & links to physics

Multi-messenger astrophysics is extremely relevant for both astronomy and physics communities, and collaboration efforts in the Netherlands continue to progress. There is coordination between different departments via GRAPPA and IMAPP, via the close ties between Dutch astronomy and Nikhef, and via the Committee for Astroparticle physics in the Netherlands (CAN), which plays a central supporting role for cosmic-ray, gamma-ray, dark-matter, gravitational-wave, neutrino and multi-messenger astroparticle physics activities in the country. The ties between theoretical physics and astronomy, especially through BlackGEM, the ET and EHT, are fostered through the NWA/Dutch Black Hole Consortium, which funds 12 PhDs, including instrumentation PhDs, and several post-doctoral researchers. Our national gravitational-wave programme is advancing steadily as we prepare for the groundbreaking science enabled by LISA and the ET, building on our established roles within the Virgo collaboration. On the astroparticle side, we look forward to exploiting the rich data sets now emerging from the fully upgraded Pierre Auger Observatory, to which the Netherlands has made critical contributions. Cosmic-ray observation programmes at LOFAR2.0 and SKA will deliver measurements in unprecedented detail. We also anticipate exciting data from ongoing and upcoming facilities such as CTAO and KM3NeT, in collaboration with Nikhef. A highlight in the last period was the observation of an ultra-high-energy cosmic neutrino from KM3NeT. Together, these coordinated efforts position the Netherlands to capitalise on the next decade of multi-messenger discoveries.

3.1.5 Data science

Astronomy is undergoing a rapid transformation driven by the explosive growth in data volume and complexity. Modern astronomical instruments produce datasets that require both sophisticated astrophysical modelling and large-scale automated analysis. Simulations themselves now generate data comparable in scale to major surveys. As a result, astronomy increasingly relies on data science: the statistical, machine learning, data mining, data engineering and visualisation methods that turn complex data into knowledge. These approaches enable tasks ranging from constraining neutron-star equations of state to discovering unexpected phenomena in billion-source surveys, serving as practical tools and as a frontier of scientific innovation. The algorithms we develop are often adapted for use in other fields, e.g. in remote sensing and medical imaging. Within Dutch astronomy, this creates a dual need for data science as both applied infrastructure and a research discipline in its own right. The community requires robust, reliable methods and software that can be deployed immediately, while also needing researchers who push methodological boundaries beyond off-the-shelf solutions. Recent Sectorplan investments reflect this crucial need by funding service-oriented roles alongside dedicated faculty positions focused on advancing data-science methods for astronomy's unique challenges. In the near future, the community must navigate rapid developments in statistics and machine learning, strengthen cross-disciplinary translation, ensure sustainable career paths, and improve methodological training. A sustainable strategy should maintain stable applied expertise, forward-looking methodological research, and effective cross-disciplinary collaborations to ensure astronomy can fully harness and shape the next generation of data-intensive science.



Dutch astronomers exploring "the realm of data science" at the 2025 Netherlands Astronomical Conference. Credit: D. Huppenkothen (UvA)/S. Trager (NOVA)

3.1.6 Computing: software and tools

Astronomy has entered the era of petabyte-scale data, driven by instruments such as LOFAR and Euclid. Upcoming facilities, including SKA, Rubin, Roman, and LISA, will intensify these data challenges over the coming years. Dutch astronomers now depend critically on digital computing infrastructure and advanced software and computational methods to convert raw observations into scientific insight and to model current and future observations.

Many of the major international facilities in which the Netherlands plays leading roles produce highly complex datasets that require excellence in two complementary domains: (i) extracting astronomical signals from raw, noisy data, and (ii) performing robust data analysis and discovery once those signals have been isolated. Achieving both steps demands algorithms, pipelines, and modelling frameworks that integrate astrophysical understanding with statistically rigorous AI and data-science methods, directly supporting the scientific goals outlined in Section 3.1.5. Dutch astronomy has already built significant expertise through long-standing contributions to a range of digital research platforms, pipelines, and frameworks, including Gaia DPAC, AstroWISE, the Euclid data and archive systems, the LOFAR data processing pipelines and science archive, EHT's automated reduction pipeline, BlackGEM's cloud-based environment, AMUSE, and other advanced modelling and simulation frameworks. These efforts demonstrate how well-engineered software can serve as both operational infrastructure and a vehicle for methodological innovation.

Maintaining scientific leadership will require continued development of reliable, interoperable, and scalable tools, together with a digital computing infrastructure supported by research software engineers and domain-aware data scientists who can translate emerging methods into practice. The PRISM (Processing & Reproducible Integration for Signals and Messengers) initiative exemplifies this ambition. PRISM represents a joint effort of the Astronomy, Astroparticle, and Particle Physics communities to build a persistent facility that pairs substantial computing resources with scalable pipelines, shared processing methods, and reproducible software tooling for the heterogeneous data streams of major facilities across the three fields, including CTAO, Einstein Telescope, Euclid, KM3NeT, LHC, LISA, and the SKA. By rendering these diverse datasets interoperable, comparable, and readily combined, PRISM aims to unlock multi-messenger discovery and accelerate end-to-end science return across all three domains. Through PRISM and other ongoing initiatives, computing and software will remain the essential bridge between raw data streams and the scientific breakthroughs they enable.

3.2 Dutch astronomy's international reputation

The Netherlands astronomical community consistently ranks at the very top of global astronomy research. During its most recent evaluation in 2023, the NOVA International Review Board wrote that "astronomy in the Netherlands is world leading in many research areas". It cited that NOVA is the only programme worldwide that has succeeded in bringing together all national university astronomers within a single coherent research and instrumentation programme. The committee also wrote: "The NOVA program has an impressive record of educating and inspiring people, of all ages, about astronomy, training world-class talent and collaborating with industry".

In 2023, NWO also conducted its Strategy Evaluation Protocol (SEP), a six-year evaluation cycle developed jointly by NWO, KNAW, and Universities of the Netherlands, to assess the quality, relevance, and viability of research at the NWO institutes. This NWO SEP 2023 evaluation of ASTRON described it as a global leader in radio astronomy, delivering high-impact scientific results, and technological innovation that advance the field internationally. Its leadership in facilities such as LOFAR and its central role in the development of the SKA underscore the strength and global relevance of the Dutch radio astronomy community. Overall, the report highlights the Dutch community as a frontrunner in radio astronomy and states: "ASTRON has been a cornerstone in the field of radio astronomy for decades, and its impact on scientific discovery, technological innovation, and international collaboration is world-leading." Similarly, the NWO SEP 2023 evaluation acknowledged SRON as a frontrunner in space-based research. The institute is recognised as a world leader in cryogenic photon detectors and in delivering instrumentation for flagship international missions from far-infrared to X-ray wavelengths in partnership with ESA, NASA, JAXA, and other international agencies. SRON currently co-leads development of the primary X-IFU instrument for ESA's next X-ray flagship NewAthena and is the worldwide leader in MKID detector development for infrared astronomy, which will power new missions such as NASA's PRIMA observatory. The SEP 2023 committee report described SRON as "one of the leading institutions in space-based research in Europe and the world," highlighting its outstanding contributions across Earth sciences, astrophysics, and instrument technology.

Taken together, these evaluations underscore how the coordinated strengths of NOVA, ASTRON, and SRON give Dutch astronomy an international footprint far exceeding what a country of its size would typically command. By uniting all university astronomers within a single coherent programme through NOVA, anchoring world-leading radio astronomy through ASTRON's stewardship of LOFAR and central role in SKA, and driving frontier space science through SRON's contributions to ESA, NASA, and JAXA flagship missions, the Netherlands operates as an integrated whole. This coordinated structure positions Dutch astronomy firmly in the top tier of global research and instrumentation for major international observatories.



4

INFRASTRUCTURES AND MISSIONS FOR THE COMING HALF-DECADE AND BEYOND

4.1 Infrastructures and facilities

4.1.1 Radio Astronomy

In early 2027, the first version of the LOFAR2.0 system will enter operations, marking a major step in securing LOFAR's role as a leading low-frequency radio astronomy facility for the coming half-decade and beyond. The comprehensive upgrade of both front- and back-end systems substantially increases field of view, bandwidth, and operational flexibility, enabling a new generation of science programmes – from star–planet interactions to fast radio bursts to characterising the epoch of reionisation – to be pursued through the remainder of the decade. Strategic planning is already underway for the continued evolution of the LOFAR infrastructure, with priorities including an order-of-magnitude increase in long-haul network capacity, further expansion of the field of view, and enhanced support for fast, wide-area surveys and rapid responses to transient events.



Two LOFAR-low prototypes, the DISTURB Band-1 array, and two additional LBAs (low-band antennas): one with the Nancay LONAMOS LNA (low-noise amplifier) and the other with the LBA LNA, all connected to a LOFAR backend for simultaneous system characterisation. In a single set-up, ASTRON tests the future of LOFAR (TRL-2), makes the next design steps for the LBA LNA redesign (TRL-5), and validates DISTURB (TRL-8). Credit: ASTRON

Opposite page: The first rotation test of the main structure of ESO's Extremely Large Telescope, which will carry the 39-metre primary mirror. NOVA leads the METIS consortium building one of the telescope's two first-light instruments. Credit: ESO/Cimolai

Towards the end of this decade, the SKA telescopes will produce tens of petabytes of observation-level data products annually, rising to many hundreds of petabytes per year in the 2030s, enabling science on an exceptionally wide range of topics, from the epoch of reionisation to the evolution of galaxies to transients to tests of general relativity to the origin of life in the Universe, as well as mapping cosmic magnetism across galaxies and clusters. Data products will be distributed through a global network of SKA Regional Centres (SRCs) established by the SKA member countries. ASTRON, in close collaboration with SURF, is working towards the development of a Dutch SRC (NLSRC) that will archive SKA data, provide community access, and enable scientific discovery through online analysis and visualisation tools. As the first science verification data for SKA-Low is coming as early as 2027 – enabling active participation from scientific communities – SRCNet capabilities are being accelerated and a minimal system is being defined. By the end of the decade, SKA-Mid science verification will also be offered, with the first programmes coming in, and SRC nodes are expected to be fully developed. At the current Dutch share of the telescope, the required storage and computing infrastructure is expected to be comparable in scale to the national LOFAR2.0 commitment. For example, current estimates have NLSRC compute rising over the next few years to 250 TFLOPS — equivalent to around 1250 CPU cores operating continuously.
By 2030, ~ 9 PB of storage will have been collected through commissioning and SV, which will grow during the 2030s at rates for SKA of up to 1 EB per year (expected 25 PB/year in NL). These numbers present both an opportunity and structural shift for the international and NL radio community alike.

Scientifically, SKA-VLBI will also be transformational, as ASTRON and JIVE will leverage the combination of SKA's stability and real-time data delivery with worldwide VLBI stations, providing unprecedented astrometric precision at the microarcsecond level. This capability enables transformative science: through direct imaging and dynamics of accretion flows; precision mapping of gas kinematics in galactic nuclei via masers and absorption lines; and accurate distances across the Universe through geometric parallax measurements. As part of the European VLBI Network (EVN) community, Westerbork Synthesis Radio Telescope (WSRT) antennas will further enable SKA-VLBI as they open new operational paradigms, from rapid Target-of-Opportunity responses to commensal observing, embedding VLBI as a routine, scalable capability within the broader SKA science ecosystem.

In parallel, leveraging Westerbork's uniquely radio-quiet environment, WSRT2030+ will provide a flexible platform to expand cm-wave instrumentation and re-establish high-frequency VLBI capabilities (1-15 GHz) in the Netherlands. In close collaboration with JIVE, it will re-establish Dutch leadership and strong synergy with SKA–VLBI and European networks, delivering microarcsecond-resolution imaging and precision astrometry. These capabilities will open new discovery space in time-domain and multi-messenger astrophysics, including the localisation of fast transients, detailed studies of black hole accretion and jet launching, and high-precision measurements of gas kinematics and distances through masers. WSRT2030+ will operate both as a stand-alone, dedicated robotic transient observatory – allowing us to study in detail transient phenomena, such as fast radio bursts, tidal disruption events, and compact object mergers with exquisite accuracy – and as a phased array within global VLBI networks. Beyond transient science, a fraction of the facility will be dedicated to satellite tracking and to in-situ education and training, providing a unique platform for undergraduate and graduate students from universities and technical institutes.

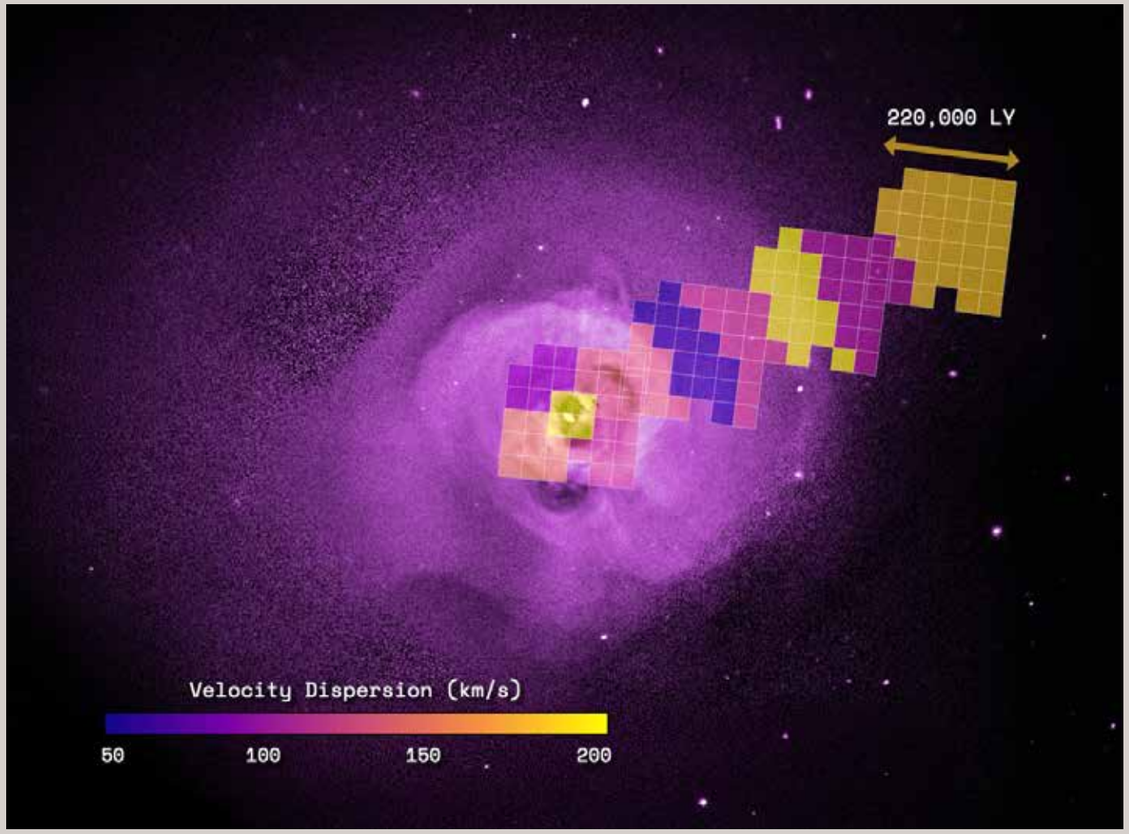
Finally, looking beyond the decade, an exciting new opportunity in radio astronomy is to place radio telescopes beyond the Earth, as free-flying spacecraft arrays or on the lunar farside. Such platforms enable observations outside the Earth's atmosphere, avoiding ionospheric cutoffs at low frequencies, atmospheric opacity at sub-millimetre wavelengths, and human-produced radio-frequency interference. These advantages are critical for enabling science goals ranging from the magnetic fields of planets and nearby exoplanets and the epoch of reionisation of the Universe to imaging the event horizons of supermassive black holes. Two Dutch-led ESA mission concepts currently under development exemplify the potential of space-based radio astronomy: L-FIRE, a 16-CubeSat swarm in low-Earth orbit that would interferometrically image the 0.1–40 MHz sky to track coronal mass ejections from the Sun to 1 AU and probe planetary and exoplanetary magnetospheres; and SHARP, a three-spacecraft sub-millimetre VLBI array at ~6000 km altitude that would reach 3-microarcsecond resolution to image supermassive black holes such as M87* and Sgr A* and test general relativity in the strong-field regime. Space-based interferometry uniquely brings together the complementary strengths of the entire Dutch astronomy community: the scientific leadership of the NOVA institutes across these science areas, ASTRON's world-leading expertise in radio instrumentation and interferometry, and SRON's world-class expertise in space-based instrumentation and mission design.

4.1.2 Space Missions and Instrumentation

The first half of this decade has been remarkable for Dutch astronomy from space. Sustained national investment through SRON and NOVA has given the Dutch astronomy community core access to some of the most ambitious space observatories ever flown, as well as leading roles in the next generation of missions. Entering the decade, long-running missions including CHEOPS, XMM-Newton, and Hubble continued to deliver important science for Dutch researchers across exoplanet, X-ray, and UV/visible astronomy.

The James Webb Space Telescope, launched in late 2021, quickly established itself as the defining mission of the decade, transforming our understanding of the earliest galaxies, protoplanetary disks, and exoplanet atmospheres. Dutch contributions have been central, with NOVA leading the optical and mechanical design of the MIRI mid-infrared instrument, which has powered many of JWST's most cited discoveries. Major JWST results have appeared under Dutch leadership in galaxy formation, astrochemistry, explosive transients, and exoplanets.

JWST was joined in 2023 by XRISM, the Japanese–NASA–ESA X-ray spectroscopy mission, and Euclid, ESA's flagship cosmology mission. With hardware and software contributions from SRON, XRISM has opened a new era of high-resolution spectroscopy of hot cosmic plasmas, and Dutch astronomers have led or contributed to every major result since launch. Euclid is now well into its prime survey of dark matter and dark energy; its March 2025 first data release covered roughly 2,000 square degrees (14% of the planned total), with Data Release 1 targeted for late 2026. NOVA (Kapteyn-OmegaCEN, Groningen) hosts the national Euclid Science Data Centre and co-leads development of the Euclid Archive System with ESA, and Dutch scientists have been first authors on several early Euclid science papers.



The XRISM telescope has mapped the gas turbulence inside the Perseus galaxy cluster for the first time. Gas flows turn out to have higher speeds at the centre and the outskirts, with less turbulence in between. These findings indicate that the supermassive black hole at the centre may play a crucial role in keeping the cluster gas at temperatures of millions of degrees, preventing it from cooling enough to form new stars. The XRISM Collaboration (2026), Nature 650, 309.

During this same period, ESA's Gaia mission concluded its science operations in 2025 after mapping the motions, luminosity, temperature, and composition of over two billion objects in the Milky Way. Gaia has surpassed Hubble as the most productive space telescope of all time, with key Dutch contributions both scientifically (10% of all Gaia papers led by Dutch astronomers, including the top-cited Gaia paper) and programmatically (chairing the Gaia Data Processing and Analysis Consortium Executive).

The outlook for the rest of the decade is equally strong. NASA's Roman Space Telescope launches in 2026, opening new territory in dark-energy surveys and exoplanet microlensing. ESA's PLATO will begin its search for Earth-analogue planets in early 2027, with its 26 cameras validated in the cryogenic-vacuum test chamber SRON built in Groningen. Ariel (2029) will deliver the first large-scale exoplanet atmosphere survey, with SRON contributing to detector characterisation and end-to-end performance simulation. POEMM, a NASA Pioneers-class far-infrared balloon observatory studying protoplanetary disks, launches in 2029 carrying SRON-built microwave kinetic inductance detectors (MKIDs) at its heart. ESA's EnVision will map the surface and atmosphere of Venus at decade's end, with contributions from SRON, NOVA, and TU Delft.

The second half of the decade is also crucial for securing the next generation of 2030s flagships. ESA's NewAthena X-ray observatory will study the hot, energetic Universe and the growth of black holes and cosmic structure; SRON is co-PI for its X-IFU camera, delivering large-field X-ray maps with XRISM-quality spectra. Adoption is expected in 2027, with launch in 2037. The Dutch community holds a comparable leading role in NASA's Probe-class PRIMA mission, which will trace the obscured evolution of galaxies, black holes, stars, planets, and cosmic dust at far-infrared wavelengths; SRON, NOVA, and TU Delft are developing Kinetic Inductance Detectors and a linear variable filter for the PRIMAger instrument. Flight selection is expected in 2026, launch in 2032. ESA's LISA, the first space-based gravitational wave observatory, targets a 2035 launch with major Dutch contributions from SRON and Nikhef, notably the laser photoreceivers and precision aiming mechanism, and science leadership from NOVA.

Several F- and M-class candidates would extend this pipeline. LETO (SRON, NOVA) is a heterodyne terahertz observatory tracing water from star-forming clouds to planetary systems. FOSSIL is a Fourier-transform spectrometer measuring fine distortions in the cosmic microwave background. WALTzER would provide dedicated UV spectroscopy of transiting exoplanets, bridging the post-HST gap. NEBULA-Xplorer, an SRON-led ESA Mini-F proposal targeting 2029, would fill the X-ray timing gap left by NICER. LiteBIRD, JAXA's all-sky CMB polarisation mission planned for 2032, will use detector and readout heritage developed at SRON to test inflation.



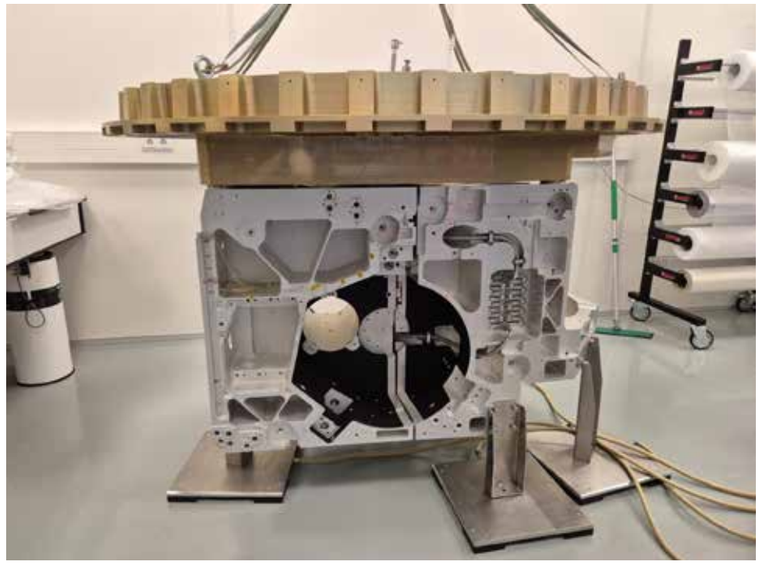
Beyond the decade, ESA's Voyage 2050 plan sets out the next two L-class flagships. L4 will send a lander to Enceladus in the 2040s to sample its plumes for biosignatures; a consortium of TU Delft, SRON, and NOVA is considering contributions. L5 has two candidates, a mid-infrared mission to characterise temperate exoplanets (LIFE) and a near-infrared astrometry mission (Gaia-NIR), both well aligned with Dutch priorities. NASA's Habitable Worlds Observatory (launch 2045) aims to directly image Earth-like planets around nearby sun-like stars; Dutch contributions to the JPL-led coronagraph are under study, including MKIDs adapted to optical/near-infrared wavelengths and vortex coronagraph technology developed by NOVA and SRON.

The Demonstration Model for the camera of NewAthena's X-IFU instrument is mounted in a cryostat to test its performance in combination with representative cold electronics. Credit: SRON / Claudia van Oostrum

4.1.3 ESO: ELT, ALMA and Expanding Horizons

The European Southern Observatory has firmly established itself as the leading organisation for ground-based astronomy worldwide. It operates the observatories at La Silla and Paranal in Chile, manages the European participation in ALMA and is building the ELT, an optical telescope of an unprecedented scale. Since the start of operations, ESO's VLT and ALMA have become the most scientifically productive ground-based observatories and have resulted in a large number of breakthrough discoveries. The strong participation of the Netherlands in ESO, with NOVA as its home base, is a bedrock on which Dutch astronomy rests.

The advent of the ELT, with its 39-m diameter primary, will revolutionise optical and near-infrared ground-based astronomy. The construction is progressing largely according to plan and is about to transition to the installation of the optical systems of the telescope. First light is expected in 2029 with two instruments, METIS and MICADO, currently planned to be ready for installation at the telescope at that time. The Netherlands is playing a large role in these two projects, with NOVA leading the METIS consortium. Building an instrument of this size and complexity is challenging, and NOVA is continuously monitoring and mitigating the risks that arise.



The first "fit check" mating of the METIS top ring (gold) with the common foreoptics backbone structure (silver) on 27 March 2026 in the NOVA Optical-IR laboratory. Credit: NOVA

With the first-light ELT instruments now in the assembly and integration phase, it is time to leverage the expertise and facilities created for those projects to develop the subsequent generations of instruments. NOVA has committed to a substantial role in the MOSAIC multi-object spectrograph for the ELT, leading the development of the visible spectrograph. This is now entering its preliminary design phase and is expected at the telescope in 2033 or later. After that, the Planetary Camera and Spectrograph (PCS) will be the instrument to fully use the spatial resolution potential of the ELT to detect and study rocky exoplanets around nearby stars, and NOVA is investing in an R&D programme to secure a strong role in the development of this instrument.

Complementary to the optical telescopes and space-based observatories, ALMA is an essential asset for astronomers in the Netherlands. As part of the ALMA2030 roadmap, the Wideband Sensitivity Upgrade (WSU) is upgrading the receivers, digitisers and the full signal path offering 2–4 times the sensitivity and bandwidth of ALMA. NOVA has led the development and production of the Band 2 WSU receivers and is targeting a similar role for the upgrade of Band 7, one of the most intensively used ALMA Bands.

ESO has started the "Expanding Horizons" process to determine the next major infrastructure project after the ELT. Five candidates have so far emerged; in no particular order, these are

- the WST – proposed as a 12-m telescope offering a wide field-of-view combined with a high-multiplex spectrograph and a large integral-field unit;
- the TDT – an adaptive-optics-enabled spectroscopic array for high-time-resolution observations of transient and variable phenomena;
- a proposal to add a fifth telescope to the VLT interferometer, creating a kilometre-long baseline for very-high-angular-resolution observations;
- AtLAST – a plan to build a single-dish 50-m sub-mm telescope near the existing ALMA array; and
- ALMA2040 – a new sub-mm interferometer as a successor to ALMA.

As many of these projects have strong Dutch interest and often leadership, NOVA is not advocating for a single project in this phase but is seeking to position itself to play a key role both technically and scientifically, regardless of which proposal is eventually chosen.

4.1.4 ING

The Isaac Newton Group remains a critical part of the Netherlands astronomical landscape, with its vital access to the northern hemisphere at optical wavelengths. The second part of this decade will see the results of the surveys that are underway with the multi-object and integral-field spectrograph of the WEAVE instrument (mounted on the 4.2m William Herschel Telescope), which is following up Gaia's survey of our Milky Way, LOFAR's survey of radio galaxies throughout cosmic history, and WSRT/Apertif's survey of neutral hydrogen in the nearby Universe (among several other large-scale surveys); the Netherlands is leading WEAVE's overall Science Team and survey. Furthermore, the robotisation of the 2.5m Isaac Newton Telescope has been completed, and the third copy of the extremely stable and accurate HARPS spectrograph is being installed on the telescope, with hardware contributions from NOVA. It will be used for a 10-year-long survey, targeting Earth-like exoplanets, in which the Netherlands plays a leading role.

4.1.5 EHT and AMT

The Africa Millimetre Telescope (AMT) should become operational in the second half of this decade. It will add crucial spatial coverage to the EHT, enabling high-resolution multicolour dynamic image reconstructions of supermassive black holes. This enables much stronger tests of general relativity and solidifies the Dutch contribution to the EHT. The AMT has the sensitivity to become the first effective rapid mm-wavelength transient follow-up facility, and its combination of multiple ALMA receivers for a broad instantaneous broadband coverage allows for a wide range of astrochemical observations. AMT's design and development is being led by the Radboud Radio Laboratory with contributions from both of NOVA's laboratories.

4.1.6 CTAO

For research in astroparticle physics, the CTAO, now under construction on La Palma and in Chile, will be a key facility for the coming decades, probing the physics of cosmic ray acceleration and the sources of the most energetic particles in the Universe. With significant interest from both the Dutch astronomy and particle physics communities, the Netherlands has now joined the CTAO ERIC as a founding member. The Netherlands is currently contributing through the assembly of focal plane arrays for the Small-Sized Telescopes at the NOVA sub-mm group.

4.1.7 Gravitational wave detection: LISA + ET

The Einstein Telescope (ET) and ESA's Laser Interferometer Space Antenna (LISA) together represent the next great leap in gravitational-wave science. ET is one of the largest flagship European projects anticipated in the coming decade. Recognised as a top European priority in the 2021 ESFRI Roadmap, it is foreseen for completion around 2035. Built underground with 10-kilometre arms, ET will be a third-generation ground-based detector sensitive to high-frequency signals from stellar-mass black hole and neutron star mergers, reaching out to redshifts of z=20–30. LISA, scheduled for launch in the mid-2030s, is a space-based interferometer with 2.5 million-kilometre arms that will probe the millihertz band, opening a window onto supermassive black hole mergers, extreme mass-ratio inspirals, and galactic compact binaries inaccessible from the ground.

Operating in tandem, ET and LISA will deliver something neither can achieve alone: a continuous gravitational-wave spectrum spanning more than seven orders of magnitude in frequency. Heavy stellar-mass binaries first detected by LISA years before merger can be handed off to ET for the final inspiral and coalescence, enabling precise sky localisation, electromagnetic follow-up, and stringent tests of general relativity across vastly different regimes. The combination sharpens cosmological measurements, traces black-hole formation channels from stellar to supermassive scales, and connects naturally with the next generation of multi-wavelength facilities such as ELT, JWST, SKA, NewAthena, CTAO, and high-energy and neutrino observatories, making ET and LISA a crucial component of multi-messenger astronomy for the coming decades.

For Dutch astronomy, the opportunity is exceptional. With the Meuse–Rhine Euroregion among the leading candidate sites for ET, the Netherlands stands to host one of the world's foremost scientific instruments. Combined with strong existing Dutch contributions to LISA through Nikhef, SRON, and university groups, this positions the Dutch community to play a world-leading role across the full gravitational-wave spectrum. The synergy will draw international talent, anchor cross-institute collaborations, and create deep ties between gravitational-wave science and adjacent fields in astrophysics, instrumentation, and data science. While major investments will come from governmental, EU, and physics budgets, visible support from the Dutch astronomy community and continued growth of national research capacity will be essential to ensure that the Netherlands fully realises the scientific and strategic benefits of this landmark combination.

4.2 Computational needs

The computational needs of Dutch astronomy arise directly from the data-science challenges described in Section 3.1.5 and the software ecosystem outlined in Section 3.1.6. The next generation of large-scale facilities, such as LOFAR2.0, the SKA, the ELT, and LISA, will drive data volumes and complexities far beyond current capacity. To fully exploit them, the community requires a dedicated data-laboratory infrastructure: environments in which astronomers, scientific software developers, research software engineers, IT specialists, and data scientists work jointly to extract maximum information from complex, noisy data and to apply AI-enabled analysis methods at scale. Such multidisciplinary teams can be built across SRON, ASTRON, NOVA, the four NOVA universities, and through partnerships with SURF, the Dutch AI Factory, and the Netherlands eScience Centre. The Netherlands already has a strong foundation for this model, having developed and operated digital data laboratories for Gaia, AstroWISE, Euclid, BlackGEM, AMUSE, and major simulation efforts. Sectorplan 2 investments have further strengthened national capacity by expanding human expertise in software development and data science. Looking ahead, a coordinated, federated network of data laboratories, integrated with national high-performance computing and scalable storage, will be essential for supporting both signal extraction and downstream data analysis at scale. The PRISM initiative (Section 3.1.6), which brings together the astronomy, astroparticle, and particle physics communities around a persistent facility that combines computing infrastructure with scalable pipelines, shared processing methods, and reproducible software tooling for heterogeneous data streams, is a concrete realisation of this federated vision. By 2030, Dutch astronomy aims to be internationally recognised for its scientific excellence enabled by its world-leading instrumentation and digital data-laboratory infrastructure.

4.3 Astronomy & technology: new developments

4.3.1 ASTRON

ASTRON is developing new radio astronomy technologies aimed at reducing energy consumption, operational complexity, and infrastructure costs while enabling new observing capabilities. Recent work has demonstrated ambient-temperature L-band frontends with sensitivities comparable to cryogenically cooled systems, opening pathways to affordable large N (number of telescopes), small D (telescope diameter) concepts and facilitating expansion of global VLBI networks by lowering requirements for refurbished reflector systems, including those envisaged for the African VLBI Network. The ALF project is developing local expertise in this area and a wide-band demonstrator receiver for a single Westerbork dish. Current developments include ambient-temperature S- and C-band frontends, Radio Frequency-over-Fibre and Ethernet-based receiver technologies, advanced low- and high-band antenna frontends with improved robustness against interference, exploration of antenna designs extending to 5 MHz, research into deployable antennas for space-based radio astronomy, and continued investment in high-throughput data-processing pipelines and algorithms to address the complexity of LOFAR and SKA data products.



The first Ambient L-band receiver installed at the Westerbork Observatory. This receiver achieves similar sensitivity at room temperature as compared with the cryogenically cooled receivers developed in the late 90s. With the ALF receiver, astronomers can now observe over more than twice the frequency bandwidth simultaneously. Credit: ASTRON

The first Ambient L-band receiver has been installed at the Westerbork Observatory. This receiver achieves similar sensitivity at room temperature as compared with the cryogenically cooled receivers developed in the late 90s. With the ALF receiver, astronomers can now observe over more than twice the frequency bandwidth simultaneously. ALF will enable new scientific discovery by combining wideband frequency coverage with high sensitivity at significantly reduced operational cost and complexity. Its ability to characterise fast radio signals was recently demonstrated by first-light pulsar detections at Westerbork. This capability is particularly powerful for studying fast radio bursts, where frequency-dependent signal properties encode key information about their emission mechanisms and propagation through the intergalactic medium. An instrument like ALF – coupled with sensitive dishes – will allow the study of transients and the role of energetic processes by enabling long-duration monitoring. The ALF design will be a core component of WSRT2030+, with the next phase focused on developing an ambient C-band receiver, for which early studies are positive and indicate strong technical feasibility and performance potential.



Credit: ASTRON



Credit: ASTRON

4.3.2 NOVA

Technology development at NOVA's laboratories will be dominated in the coming years by ESO's Expanding Horizons programme (see Sec. 4.1.3 above) to select the next major project after the ELT. The ideas currently proposed are diverse and range from the optical (WST, TDT and long-baseline VLTI) to the sub-mm (ALMA2040 and AtLAST). Additional ideas may emerge during the selection process, slated to complete by the end of 2028. NOVA is already engaged in a number of studies related to candidate projects. A key element of the NOVA R&D strategy for the coming years will be to continue and expand these studies while at the same time keeping up-to-date with critical technologies identified in projects we may not (yet) participate in. The field of high-contrast imaging, needed for the ever more detailed studies of exoplanets and circumstellar disks, has for several years been a strong driver for technology R&D. Ground-based instruments like ELT-PCS (formerly EPICS) and GmagAO-X for the Giant Magellan Telescope will require continued investment in technologies for advanced wavefront control. These investments will also position the Netherlands to make a critical contribution to NASA's HWO and the ESA L5 candidate LIFE.

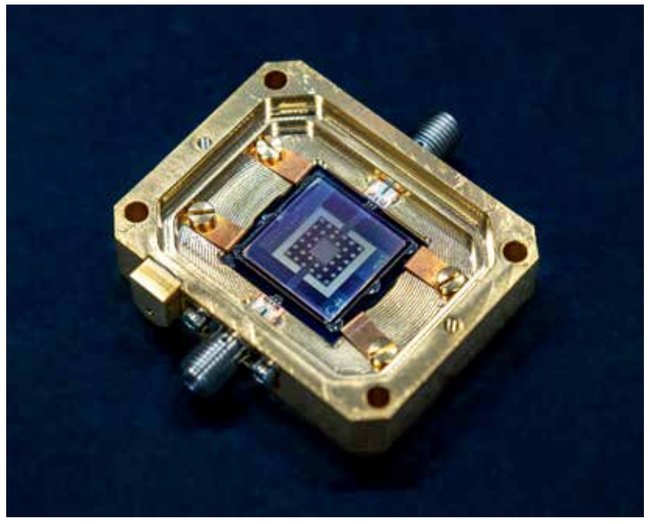
External technology developments also play a role in NOVA's programme. Metamaterials have matured to the point where they will make their way into optical components for astronomical instruments, in applications such as precise modal filtering. This forms an extension of the liquid crystal technology currently available for coronagraphs and wavefront sensing. The use of photonics in astronomical instruments has long held great promise, but a definitive killer application has so far proven elusive. Nevertheless, developments in this field are followed closely for possibilities in applications such as calibration sources, wavefront sensing and for new, distributed telescope systems (e.g. TDT).

In the sub-mm domain, the availability of parametric amplifiers at ever-higher signal frequencies will enable reaching sensitivities at the quantum limit over broad wavelength ranges. This is however not currently foreseen to reach the highest frequencies. For ALMA Band 9, further improvements in SIS mixer technology are still needed. While work on multi-pixel sub-mm detectors has been limited in the past years, this technology would offer a major step forwards for a future single-dish telescope (AtLAST).

4.3.3 SRON

The SRON Technology Programme develops enabling detector and optical technologies for scientific discovery and Dutch participation in international space missions. It centres on polarimetric imaging spectroscopy, combining smart optical front-ends with cryogenic detectors from X-ray to sub-millimetre. Ground-based and balloon-borne demonstrators raise TRL and validate concepts. Key development areas include:

MKIDs and *Smart Optics:* SRON Microwave Kinetic Inductance Detectors span 0.3 μm–3 mm and are deployed at Teide, APEX, ASTE, and on four NASA Pioneer/Explorer missions. Far-infrared MKIDs close the "THz gap" for star formation and galaxy evolution, enabling missions such as NASA's PRIMA and POEMM and ESA M8 candidate FOSSIL. Mid-IR and optical extensions support exoplanet characterisation for LIFE and HWO.



A visible-to-near-infrared Kinetic Inductance Detector (KID) array mounted in a sample holder. These superconducting detectors can detect individual photons and measure their wavelength. A micro-lens array glued to the front side of the chip focuses incoming light onto the individual pixels. The device was designed, fabricated, and tested at SRON. Credit: SRON / Claudia van Oostrum

Transition-Edge Sensors (TES): X-ray microcalorimeter arrays with few-eV resolution map galaxy-cluster plasmas, characterise black-hole accretion, and trace cosmic feedback and have been baselined for X-IFU on ESA's NewAthena. Ultra-low-noise far-infrared TES bolometers measure CMB B-mode polarisation to probe primordial gravitational waves, baselined for the JAXA-led LiteBIRD.

High-Contrast Imaging and Integrated Photonics: Liquid-crystal polarimetric high-contrast imaging combined with waveguide-based photonics for coronagraphy, nulling, and beam combining tackles whether we are alone. With KID detector developments, these technologies are key enablers for LIFE and HWO.

Heterodyne Detectors: Building on SIS mixers for ALMA and NbN HEBs flown on STO-2 and GUSTO (world-record sensitivity to 5.3 THz), SRON is developing MgB_2 HEBs that operate at 20 K rather than 4 K — a game changer for space. These ultra-high-resolution receivers ($R > 10^6$) probe gas dynamics around black holes and in protoplanetary disks, enabling LETO, TOP, GUSTO II, and future heterodyne interferometers en route to LIFE.



Opto-Mechatronics and Hysteretic Deformable Mirrors: Building on chopper heritage from ISO-SWS, Herschel-HIFI, and ELT-METIS, SRON Groningen develops cryogenic active and adaptive optics — a Dutch national priority. The flagship Hysteretic Deformable Mirror, with the University of Groningen, ASML, and Physik Instrumente, scales to ≥128 × 128 actuators at ~100/mm^2, enabling imaging of Earth-like exoplanets with HWO and LIFE.

Advanced FIR Dispersive Optics: With large KID arrays, high-efficiency dispersive optics deliver mapping speeds and line sensitivities orders of magnitude beyond existing FIR instruments, enabling galaxy-evolution surveys and velocity-resolved planet-formation spectroscopy. SRON Groningen nano-fabricates on silicon, SiN, and SiC, producing the Linear Variable Filter for PRIMAger on PRIMA, the R ~ 100,000 VIPA for POEMM, and all-silicon Fabry-Perot etalons for the Canadian Space Agency.

Holding the future of X-ray astronomy: a full-scale 1504-pixel transition-edge sensor (TES) microcalorimeter array under development at SRON. Designed and fabricated to meet the demanding requirements of NewAthena, ESA's next flagship X-ray observatory, this TES detector combines high-resolution spectroscopy and imaging capabilities to reveal the hot and energetic Universe and trace the evolution of cosmic structures. Credit: SRON / Claudia van Oostrum

Compact Spectrometers for Earth Observation: Small, low-cost, high-performance instruments for satellite constellations monitor trace gases globally at high temporal and spatial resolution. Meta-surfaces, photonic-crystal filters, on-chip spectrometers, and computational retrieval address how greenhouse-gas concentrations and the carbon cycle respond to climate change, supporting SRON's Earth Observation portfolio.

X-Ray Interferometry: This ambitious theme targets EHT-class angular resolution from a single spacecraft, resolving accreting black holes such as Cygnus X-1 and probing strong-gravity physics. Recommended in ESA's Voyage 2050 roadmap, current work covers an ultra-stable optical bench (TU Delft), silicon pore optics (cosine BV), ultra-precise gyroscopes (with INFN-Pisa), and simulation software (UvA/NOVA).



Aditya Garde, PhD student at TU Delft PME, holding a prototype of the slatted mirror, produced by cosine BV, which serves as a beam combiner in the compact X-ray interferometer currently being developed at SRON. Credit: SRON / Claudia van Oostrum



5
ASTRONOMY & SOCIETY

5.1 Inspiration, education, outreach: updates

Dutch astronomy is internationally recognised for excellence, and maintaining this position requires inspiring future generations and engaging the public, especially given the field's reliance on public funding and its natural role in attracting young people to STEM. Outreach, education, and research efforts are aligned through the Minnaert–De Jager Committee, in which staff scientists from all NOVA institutes, SRON, and ASTRON are brought together, along with outreach officers, and through dedicated sessions at the annual Netherlands Astronomical Conference. The NOVA institutes collaborate nationally through the NOVA Information Centre (NIC), which coordinates press releases, maintains strong media ties, and supports astronomy education with mobile planetaria operated in partnership with SRON and Leiden Observatory; the Kapteyn Astronomical Institute also runs a mobile planetarium in the north of the Netherlands. In 2023 the NIC received a €150k NWA grant to ensure every child in the Netherlands can experience at least one planetarium show, working with the Weekend School Foundation to reach underrepresented groups, and it also offers public shows at the Omniversum in The Hague. The media landscape is changing and will continue to do so, with the prominence of online channels now surpassing traditional (written) media. The NIC is adapting to this by increasing its capacity and expertise for communicating astronomy research through these new channels.

5.2 Our community – equity, inclusion & diversity: updates and forward look

The Netherlands Astronomy Community continues its work promoting equity, inclusion, and diversity through the Netherlands Astronomy Equity and Inclusion Committee (NAEIC), which draws members from all institutes and serves as an advisory committee to the RvdA. The NAEIC focuses on proactive activities that support the health and sustainability of our community. In 2024, we conducted a national Work Climate Survey to gather information, identify challenges, and develop strategies for retaining underrepresented community members. The survey led to concrete recommendations: establishing local EDI committees at each institute, assessing and improving meeting culture, ensuring a more equitable distribution of service work, strengthening internal support systems, and expanding training opportunities for both staff and leadership. The survey will be repeated regularly as an ongoing tool for monitoring the well-being of our community and tracking progress over time.

Going forward the NAEIC will prioritise connecting and aligning EDI efforts between institutes. This initiative will strengthen the exchange of information and best practices so that initiatives at one institute can be shared and adopted more widely across the national community. Such exchanges include approaches to training, accessibility, and inclusive hiring practices, as well as broader strategies for fostering a healthy and equitable work environment. By building stronger connections between local EDI committees and creating channels for collaboration across institutes, the NAEIC aims to ensure that progress made in one place benefits the community as a whole.

Opposite page: Hubble M51. Credit: NASA, ESA, W. Li and A. Filippenko (UC Berkeley), S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA)

5.3 **Our community – training the next generation of scientists and technical staff for astronomy and beyond**

Training of PhD students and postdoctoral researchers is a key output of Dutch astronomy, as a significant fraction of these highly trained scientists will find jobs in industry, government, and teaching, bringing their skills, ideas, and scientific research directly into society, in the Netherlands and beyond. These researchers come from a wide variety of national, linguistic, gender, and ethnic backgrounds. Diversity in backgrounds has been shown repeatedly to be the best way to ensure the generation of new ideas in academia (and beyond). This diversity must be stimulated and supported by equity and inclusion into our research community. Such stimulation of diversity and training for researchers can best be guaranteed through a long-term, stable funding programme for training PhD students and postdoctoral fellowships like NOVA's previous (1999–2023) research programme, the reconstitution of which remains a key goal for the Dutch astronomical community. We are also aware of the precarity of those we train, and we will look to improve the structures supporting the career trajectories of our PhD students and postdoctoral researchers.

5.4 **Astronomy & climate change: updates and forward look**

The RvdA survey of the carbon footprint of astronomy research in the Netherlands found that in 2019, air travel and electricity/heating were the main CO_2 sources that could be reliably assessed. Commuting was found to be a minor part of the footprint in the Netherlands, where distances are short and public transport is good (except to ASTRON). International studies show that research facilities – construction, launch (for space telescopes) and operation – and computing, especially AI, are additional major contributors to the carbon footprint. In the past five years, CO_2 emission from electricity/housing has been reduced thanks to the move of SRON to a new building and universities moving to green energy. Some progress has been reported by the institutes on reducing air travel; the significance of this impact still needs to be analysed. The policy for significant CO_2 reduction described in the Strategic Plan has unfortunately still not been completed but is expected in the coming year.

The sustainability committee of the Dutch Astronomy Council is promoting awareness of sustainability issues by organising regular topical events, both online and in-person at the yearly Netherlands Astronomical Conference and the annual NWO Town Hall. Recent discussion topics include carbon footprint measurements, emission compensation schemes, sustainable computing, and sustainable facilities. Further recommendations relate to raising awareness and teaching climate within science faculty, including, for example, the idea of including climate change in solar system lectures. Other recommendations relate to policy, and to grants, which should require a statement on carbon reduction. The committee also advises the Council on sustainability matters and works with the Council to develop a policy endorsing the travel guidelines from mother organisations, enhanced where possible by local measures, and including sustainability in their educational programmes. In the coming years, the committee plans to get a better measure of the CO_2 impact of astronomical facilities, e.g. from diesel generators to solar-powered telescopes, and computing, especially the responsible use of AI.

5.5 **A dark & quiet sky**

With the rapid commercialisation of spaceflight, the number of artificial satellites in orbit around the Earth has dramatically increased over the past few years, with many nation states as well as commercial companies creating satellite constellations consisting of hundreds to thousands of individual satellites. This growth has worrisome implications for ground-based (as well as space-based) observatories, as these satellites are easily detectable in, and hence contaminating, multi-wavelength astronomical observations due to their reflected sunlight, thermal emission, and/or radio emission/transmission. Current Dutch astronomical facilities and instruments with wide fields-of-view like BlackGEM, WEAVE and LOFAR are already impacted. The international astronomical community is organising itself through the IAU Centre for the Protection of the Dark and Quiet Sky and the Committee on Radio Astronomy Frequencies to investigate the impact of this growth on astronomy and simultaneously lobby for international regulation limiting this impact on astronomy.

At the same time, light pollution increasingly diminishes the dark optical sky across the Netherlands and beyond, affecting not only astronomy but also biodiversity and human health. These challenges require coordinated action: internationally through the IAU Centre for the Protection of the Dark and Quiet Sky and the Committee on Radio Astronomy Frequencies, and nationally through sustained local engagement. The Netherlands already contributes through initiatives such as the Kapteyn Institute's long-standing efforts to monitor and reduce light pollution in Dark Sky Park Lauwersmeer, its collaborations within the INTERREG Darker Sky project on harbour lighting, and its partnership in the national LuNa (Licht uit, Nacht aan) programme aimed at reshaping societal attitudes towards darkness. By supporting both global and national initiatives, the Dutch astronomical community can help safeguard a dark and quiet sky for future generations.



Dark Sky Park Lauwersmeer. Credit: Rutger Bus



6
THE ROAD AHEAD

6.1 What have we accomplished in the first half-decade?

The first half of this decade has been a period of exceptional scientific productivity and strategic delivery. The launch of JWST has yielded breakthrough scientific results and Dutch researchers have played a leading role in that success, from making a significant contribution to building MIRI to leading many key discoveries. Gaia has become the most productive space telescope of all time – with the top-cited Gaia science paper led by Dutch authors – and Euclid's first quick data release was a major success, enabled in part by its Dutch data centre. On the ground, EHT and LOFAR have matured into the world's premier millimetre-wave VLBI and low-frequency radio facilities, while the VLT and ALMA continue to deliver high-impact science through Dutch-built instruments and the ALLEGRO support centre.

Internationally the Netherlands has consolidated its leadership position through participation in global facilities. ELT construction is on track for first light in 2029, with NOVA leading the METIS consortium (as the PI) and having significant roles in MICADO (as co-I and contributing the Project Scientist) and MOSAIC (as co-I). SRON is leading major contributions to the NewAthena and LISA missions, which when coupled with participation in the Einstein Telescope position the Netherlands at the heart of multi-messenger astrophysics. SKA construction is well underway with SKA-Low achieving first light last year and ASTRON is actively preparing for early science. WEAVE and 4MOST are in operation, HARPS3 is being installed, the AMT is advancing, and Sectorplan investments have provided NOVA's instrumentation groups with permanent funding and strengthened our national capacity in data science. Throughout all these activities, the partnership model linking the universities through NOVA with ASTRON and SRON has continued to prove its value.

6.2 What still needs to be done, and what new things do we need to focus on?

Despite these successes, several challenges demand attention in the second half of the decade. The reconstitution of a long-term, stable training network for PhD students and postdoctoral researchers, comparable to the NOVA research programme that ended in 2023, remains the single most important priority for sustaining the talent pipeline on which the scientific success of Dutch astronomy depends. Without sustainable investment in people, attracting the best researchers through fellowships, training programmes for leadership roles, and suitable financial support, facility leadership cannot be translated into sustained scientific leadership, and critical expertise in instrumentation, software, and data science cannot be maintained.

The scientific data landscape has also changed profoundly since the start of the decade. Surveys and facilities now produce data at unprecedented volume and complexity, and the scientific frontier increasingly requires robust software, reproducible workflows, and AI-enabled analysis. A coordinated, federated network of data laboratories, built upon a national high-performance computing infrastructure, will be essential through the remainder of the decade, for facilities like LOFAR and Euclid, and into the SKA, ELT, and LISA era.

The geopolitical and economic environment has also become less predictable, making resilience in international partnerships and national capability all the more important.

Opposite page: Artist's impression of a coronal mass ejection erupting from a nearby red dwarf, the first such eruption confirmed on a star other than the Sun. The detection was led by Joseph Callingham (ASTRON and the University of Amsterdam) using LOFAR together with ESA's XMM-Newton, and showed a blast powerful enough to strip the atmosphere from a close-in planet. Credit: Olena Shmahalo/Callingham et al.

6.3 **Forward look beyond this decade: 2030, 2040, and beyond**

Because flagship astronomical facilities have multi-decade lifecycles, credible planning must extend well beyond the nominal 2030 horizon. Choices made in the second half of this decade will determine the scientific landscape of the 2030s and 2040s and will shape whether the Netherlands remains a leading partner as new international initiatives take form.

In ground-based optical and infrared astronomy, the next generation of ELT instruments will define the next wave of Dutch involvement. NOVA has committed to a substantial role in MOSAIC and is investing in R&D for the Planetary Camera and Spectrograph (PCS), the instrument to exploit the ELT's full resolution for detecting rocky exoplanets. At the same time, the ESO Expanding Horizons process will determine the next major facility to follow the ELT, with several candidates, including WST, TDT, AtLAST, and ALMA2040, attracting strong Dutch interest, with our scientists taking strong strategic and even leadership roles in these prospective projects and our instrumentation groups already participating in the pre-studies.

For radio astronomy, LOFAR2.0 will enter operations in 2027 with ASTRON planning further upgrades, while the SKA has already begun producing data that will ramp up steadily towards the end of the decade, with preparations for support by a Dutch SKA Regional Centre underway. New opportunities in lunar- and space-based radio astronomy are also emerging.

In space science, 2026–2030 will see the launches of PLATO and Ariel, while NewAthena and LISA will be the flagship missions of the 2030s. SRON is leading both instrument contributions and scientific preparation for these missions. Beyond 2040, ESA's Voyage 2050 process has identified possible future missions aligned with Dutch scientific ambitions such as the L4 mission to Enceladus and the LIFE mission to study temperate exoplanets. In this same timeframe, the ongoing preparation of the NASA flagship HWO further underscores the importance of continued investment in high-contrast imaging technology.

Finally, multi-messenger and time-domain astrophysics will come of age in the 2030s. First light for CTAO has already been achieved with construction of the full array expected to complete early in the new decade. The Einstein Telescope, with the Meuse–Rhine Euroregion as a leading candidate site, offers the Netherlands a once-in-a-generation opportunity to host a flagship European research infrastructure. Together with LISA and the growing network of neutrino and cosmic-ray observatories, these facilities will make multi-messenger astronomy a routine mode of discovery.

A defining feature of the post-2030 landscape will be the deepening interdisciplinarity of astronomical research, and astronomy itself stands as a leading example of how disciplines will converge. The questions now driving the field, from the origin of life and the chemistry of habitable worlds to the physics of strong gravity and the imprint of inflation on the early Universe, increasingly cannot be answered within the boundaries of any single discipline. The L4 mission to Enceladus and the LIFE concept for temperate exoplanets bring astronomy together with origin of life and planetary chemistry studies; the PRISM initiative pairs astronomy with astroparticle and particle physics to support facilities ranging from the SKA and the Einstein Telescope to KM3NeT and the LHC; and the SRON and NOVA expertise in detectors and optics crosses seamlessly between space astronomy and the Earth-observation missions tracking greenhouse gases and the carbon cycle. As multi-messenger observations and AI-enabled analysis mature, these cross-disciplinary connections will become a routine mode of discovery rather than an exception. Sustaining Dutch leadership through this evolving landscape will depend not only on the facilities and missions described above, but on the people, infrastructure, and public and private partnerships that allow expertise to flow freely across traditional boundaries.

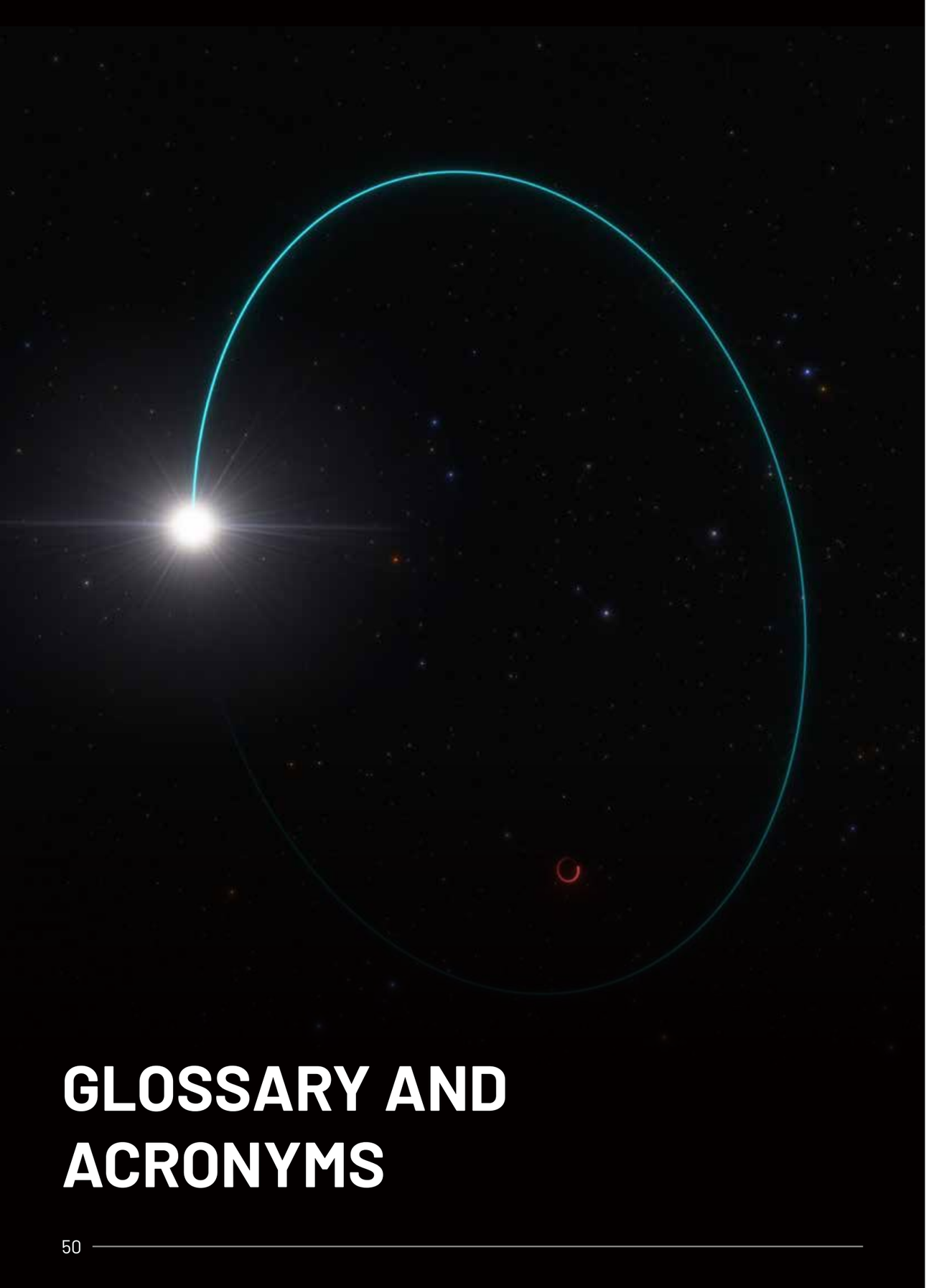
CONCLUDING REMARKS

Dutch astronomy enters the second half of the 2021–2030 decade in a position of real strength, with breakthrough results already flowing from JWST, Gaia, Euclid, EHT, LOFAR, ALMA, and the VLT, and with Dutch teams in central roles on the ELT, SKA, NewAthena, and LISA. Remaining at the forefront through the rest of this decade and into the next requires sustained action on the four priorities set out in this update: reconstituting long-term funding for the NOVA research programme to renew the talent pipeline on which all other ambitions depend; building a coordinated national data and computing infrastructure, with sustained investment in software engineering and AI-enabled analysis, to harvest the science from the LOFAR2.0, Euclid, SKA, ELT, and LISA era; delivering the first-light ELT instruments and securing Dutch leadership in MOSAIC and the PCS; and consolidating Dutch participation in the space-based flagships of the 2030s while positioning the community for the post-2030 horizon with the next ESO flagship, the Einstein Telescope with the Meuse–Rhine Euroregion as a leading candidate site, ESA's Voyage 2050 missions, and NASA's Habitable Worlds Observatory. Realising these ambitions requires a balanced national strategy: long-term stable support for NOVA and its university-based research and instrumentation programme; adequate funding for ASTRON and SRON to maintain leadership in European and global programmes; strong NWO support for competitive grants, infrastructure access, and interdisciplinary research; and sustained university commitment to astronomy programmes and staff. In a less predictable geopolitical and economic environment, national coordination and the protection of critical capabilities in technology, software, and data science matter more than ever.

With the partnership of NOVA, ASTRON, and SRON continuing to prove its value, with sustained public investment, and with a renewed commitment to training the next generation, Dutch astronomy is well placed to continue delivering breakthrough discoveries, technological innovation, and inspiration for our society through the remainder of this decade and the decades to come.



JWST NIRCam image of the central region of the Chamaeleon I molecular cloud, where icy dust grains (blue glare) are illuminated by a protostar (orange, upper left). Complex organics and sulfur-bearing ices were detected for the first time in the dusty medium. In time, this material will be incorporated in newly formed planets in Chamaeleon I, bringing life's key elements to such new worlds. McClure et al. (2023), Nature Astronomy 7, 421. Credit: ESA/Webb; McClure et al. 2023



GLOSSARY AND ACRONYMS

4MOST – 4-metre Multi-Object Spectroscopic Telescope, ESO wide-field optical spectroscopic survey instrument.
ALF – Ambient L-band Frontend, ASTRON programme developing ambient-temperature wide-band radio receivers for Westerbork and future radio facilities.
ALLEGRO – ALMA Local Expertise GROup, Dutch support centre for ALMA observations.
ALMA – Atacama Large Millimeter/submillimeter Array, ESO/global millimetre-wave observatory in Chile.
ALMA2040 – Long-term programme to define and develop the next generation of ALMA capabilities and its eventual successor.
AMCOOL – Amsterdam Center for Origins of Life, interdisciplinary research centre on the origin and evolution of life.
AMT – Africa Millimetre Telescope, future Namibian telescope extending the Event Horizon Telescope network.
AMUSE – Astrophysical MUlti-purpose Software Environment, framework for astrophysical simulations.
Apertif – APERture Tiles In Focus, wide-field phased-array-feed upgrade for the WSRT.
APEX – Atacama Pathfinder EXperiment, submillimetre telescope in Chile.
Ariel – Atmospheric Remote-sensing Infrared Exoplanet Large-survey, ESA mission for characterising exoplanet atmospheres.
ASML – Dutch manufacturer of advanced semiconductor lithography systems.
ASTE – Atacama Submillimeter Telescope Experiment, submillimetre telescope in Chile.
ASTRON – Netherlands Institute for Radio Astronomy.
AstroWISE – Astronomical Wide-field Imaging System for Europe, astronomical data-processing and archiving environment.
AtLAST – Atacama Large Aperture Submillimeter Telescope, proposed 50-m submillimetre telescope and candidate ESO flagship facility.
BlackGEM – Optical telescope array for detecting and following up gravitational-wave and transient events.
CAN – Committee for Astroparticle physics in the Netherlands.
CHEOPS – CHaracterising ExOPlanet Satellite, ESA exoplanet mission.
CMB – Cosmic Microwave Background.
COLIBRE – Cosmological and LOcal physics with Integrated Baryon pRocEsses, cosmological galaxy-formation simulation project.
COST Actions – European Cooperation in Science and Technology collaborative research networks.
CTAO – Cherenkov Telescope Array Observatory, next-generation gamma-ray observatory.
DAN – Dutch Astrochemistry Network.
DISTURB Band-1 – Development programme for next-generation low-frequency LOFAR Band-1 instrumentation.
EHT – Event Horizon Telescope, global millimetre-wave interferometer for imaging black holes.
ELT – Extremely Large Telescope, future 39-m ESO optical/infrared telescope.
EnVision – ESA M4 mission to study the surface, interior, and atmosphere of Venus.
ERC – European Research Council.
ERIC – European Research Infrastructure Consortium.
ESA – European Space Agency.
ESFRI – European Strategy Forum on Research Infrastructures.
ESO – European Southern Observatory.
ET – Einstein Telescope, next-generation gravitational-wave observatory.
Euclid – ESA mission for studying dark matter, dark energy, and the large-scale structure of the Universe.

Opposite page: Artist's impression of Gaia BH3, at 33 solar masses the most massive stellar black hole known in our galaxy, found in ESA's Gaia data and confirmed with ESO's Very Large Telescope. Anthony Brown (Leiden Observatory), Amina Helmi (Kapteyn Astronomical Institute) and the Gaia Collaboration. Credit: ESO/L. Calçada/Space Engine (spaceengine.org)

EVN – European VLBI Network.
Evolve – Origins Centre successor programme employing PhD researchers to study the origin and evolution of life.
FOSSIL – Proposed space mission using a Fourier-transform spectrometer to measure spectral distortions in the Cosmic Microwave Background.
Gaia – ESA astrometric mission mapping positions, motions, and properties of more than two billion stars.
Gaia DPAC – Gaia Data Processing and Analysis Consortium, responsible for processing and distributing Gaia data products.
GaiaNIR – Proposed near-infrared successor mission to Gaia.
GCOS – Global Cosmic Ray Observatory, proposed next-generation international cosmic-ray observatory.
GRAPPA – Gravitation Astroparticle Physics Amsterdam, interdisciplinary research centre linking astronomy and fundamental physics.
GUSTO – Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory, NASA balloon-borne observatory studying the interstellar medium and star formation through terahertz spectroscopy.
GUSTO II – Proposed successor to the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory programme.
HARPS3 – High Accuracy Radial velocity Planet Searcher 3, ultra-stable spectrograph for detecting Earth-like exoplanets.
Herschel-HIFI – Heterodyne Instrument for the Far Infrared on ESA's Herschel Space Observatory.
HFML/FELIX – High Field Magnet Laboratory / Free Electron Lasers for Infrared eXperiments, Dutch national laboratory for high magnetic fields and infrared laser research.
HST – Hubble Space Telescope, NASA/ESA optical and ultraviolet space observatory.
HWO – Habitable Worlds Observatory, proposed NASA flagship mission to directly image and characterise Earth-like exoplanets.
IAU – International Astronomical Union, global organisation of professional astronomers.
IMAPP – Institute for Mathematics, Astrophysics and Particle Physics, Radboud University.
INFN-Pisa – Pisa division of the Istituto Nazionale di Fisica Nucleare (Italian National Institute for Nuclear Physics).
ING – Isaac Newton Group of Telescopes, observatory organisation operating telescopes on La Palma.
INT – Isaac Newton Telescope, 2.5-m optical telescope operated by the ING.
InterCat – Interdisciplinary Centre for Catalysis, Aarhus University; partner in astrochemistry research collaborations.
INTERREG – European territorial cooperation funding programme supporting cross-border projects.
ISO-SWS – Infrared Space Observatory – Short Wavelength Spectrometer, instrument aboard ESA's Infrared Space Observatory.
JAXA – Japan Aerospace Exploration Agency.
JIVE – Joint Institute for VLBI ERIC, European centre for Very Long Baseline Interferometry.
JPL – Jet Propulsion Laboratory, NASA research and spacecraft development centre.
JWST – James Webb Space Telescope, NASA/ESA/CSA infrared space observatory.
KAGRA – Kamioka Gravitational Wave Detector, Japanese gravitational-wave observatory.
KID – Kinetic Inductance Detector, superconducting photon detector technology.
KM3NeT – Cubic Kilometre Neutrino Telescope, neutrino observatory in the Mediterranean Sea.
KNAW – Royal Netherlands Academy of Arts and Sciences (Koninklijke Nederlandse Akademie van Wetenschappen).
L-FIRE – Low-Frequency Interferometry Experiment, Dutch-led ESA mission concept for space-based low-frequency radio interferometry.

LBA – Low-Band Antenna, the low-frequency antenna element used in LOFAR.
LETO – Proposed terahertz space observatory studying water from molecular clouds to planetary systems.
LHC – Large Hadron Collider, particle accelerator operated by CERN.
LIFE – Large Interferometer For Exoplanets, proposed space mission to detect and characterise potentially habitable exoplanets.
LIGO – Laser Interferometer Gravitational-Wave Observatory, US gravitational-wave detector.
LISA – Laser Interferometer Space Antenna, future ESA space-based gravitational-wave observatory.
LiteBIRD – Lite satellite for the studies of B-mode polarisation and Inflation from cosmic background Radiation Detection, planned JAXA CMB mission.
Living Planet – Proposed interdisciplinary programme studying the origin, evolution, and habitability of life.
LOFAR – LOw Frequency ARray, Dutch-led international low-frequency radio telescope.
LOFAR2.0 – Major upgrade of LOFAR increasing bandwidth, field of view, and operational flexibility.
LuNa – Licht uit, Nacht aan ("Lights off, Night on"), Dutch programme promoting dark skies and reducing light pollution.
MeerKAT – Meer Karoo Array Telescope, South African radio telescope and precursor to SKA-Mid.
MeerLICHT – Optical telescope operating alongside MeerKAT for transient and multi-messenger astronomy.
METIS – Mid-infrared ELT Imager and Spectrograph, Dutch-led first-generation ELT instrument.
MICADO – Multi-AO Imaging Camera for Deep Observations, first-generation ELT imaging instrument.
MIRI – Mid-InfraRed Instrument, Dutch-led instrument aboard JWST.
MKID – Microwave Kinetic Inductance Detector, a type of KID detector that uses microwave resonators to measure the energy and arrival time of individual photons.
MOSAIC – Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology, planned second-generation ELT instrument.
NAEIC – Netherlands Astronomy Equity and Inclusion Committee.
NanoSpace – COST Action network focused on nanomaterials and processes relevant to astrochemistry and planetary science.
NASA – National Aeronautics and Space Administration, United States space agency.
NEBULA-Xplorer – SRON-led ESA Mini-F mission proposal for X-ray timing and transient astronomy.
NewAthena – Advanced Telescope for High-Energy Astrophysics, ESA's next flagship X-ray observatory.
ngVLA – next-generation Very Large Array, planned US radio interferometer.
NIC – NOVA Information Centre, national astronomy outreach and communication organisation.
NICER – Neutron star Interior Composition Explorer, NASA X-ray timing mission.
Nikhef – National Institute for Subatomic Physics of the Netherlands.
NLSRC – Netherlands SKA Regional Centre, Dutch data and computing centre supporting SKA science.
NOVA – Netherlands Research School for Astronomy, federation of the Dutch university astronomy institutes.
NWA – Dutch National Science Agenda (Nationale Wetenschapsagenda).
NWO – Netherlands Organisation for Scientific Research.
NWO-I – Institutes Organisation of the Netherlands Organisation for Scientific Research.
oLife – Origins of Life programme, interdisciplinary postdoctoral research programme coordinated through the Origins Center.
OmegaCEN – Groningen-based Euclid Science Data Centre hosted by the Kapteyn Astronomical Institute and OmegaCEN.

PCS – Planetary Camera and Spectrograph, planned ELT instrument for direct detection and characterisation of rocky exoplanets.
PEPSci – Planetary and ExoPlanetary Science programme, interdisciplinary Dutch research network linking astronomy and Earth sciences.
PI – Principal Investigator.
Pierre Auger Observatory – The world's largest cosmic-ray observatory, located in Argentina, investigating the highest-energy particles in the Universe.
PLANETS – COST Action network focused on planetary systems and their evolution.
PLATO – PLAnetary Transits and Oscillations of stars, ESA mission searching for Earth-like exoplanets.
POEMM – NASA Pioneers-class far-infrared balloon observatory studying protoplanetary disks.
PRELIFE – NWA-funded interdisciplinary programme studying the origins of life.
PRIMA – Probe far-Infrared Mission for Astrophysics, proposed NASA far-infrared space observatory.
PRIMAger – Far-infrared imaging instrument developed for the PRIMA mission.
PRISM – Processing & Reproducible Integration for Signals and Messengers, Dutch initiative providing shared computing, software, and data infrastructure for astronomy, astroparticle physics, and particle physics.
Roman Space Telescope – NASA space observatory designed for wide-field surveys of dark energy, exoplanets, and infrared astrophysics; formerly known as the Wide Field Infrared Survey Telescope (WFIRST).
Rubin – Vera C. Rubin Observatory, wide-field optical survey telescope for time-domain astronomy and cosmology.
RvdA – Raad voor de Astronomie (Astronomy Council), strategic coordination body of Dutch astronomy.
SEP – Strategy Evaluation Protocol, the Dutch framework for evaluating research quality, societal relevance, and viability.
SHARP – Space High Angular Resolution Probe, Dutch-led space-VLBI mission concept for sub-millimetre imaging of supermassive black holes.
SKA – Square Kilometre Array, global radio telescope under construction in Australia and South Africa.
SKA-Low – Low-frequency component of the SKA, located in Australia.
SKA-Mid – Mid-frequency component of the SKA, located in South Africa.
SKA-VLBI – Integration of the SKA into global Very Long Baseline Interferometry networks.
SRC – SKA Regional Centre, national or regional centre providing access to SKA data and computing resources.
SRCNet – SKA Regional Centre Network, the international network of SKA Regional Centres.
SRON – Space Research Organisation Netherlands, the Dutch national institute for space research.
STEM – Science, Technology, Engineering and Mathematics.
SURF – Dutch cooperative organisation providing digital infrastructure and services for education and research.
TDT – Time Domain Telescope, proposed ESO facility optimised for rapid observations of transient astronomical phenomena.
TES – Transition-Edge Sensor, superconducting detector technology used in X-ray, far-infrared, and CMB astronomy.
TFLOPS – Tera Floating Point Operations Per Second, a measure of computing performance.
THESEUS – Transient High-Energy Sky and Early Universe Surveyor, proposed ESA mission for transient and high-redshift astronomy.
TOP – Proposed future heterodyne astronomy project based on advanced terahertz receiver technology.
TRL – Technology Readiness Level, standard scale used to assess the maturity of a technology.
TU Delft – Delft University of Technology.
Virgo – European gravitational-wave observatory located near Pisa, Italy.
VLBI – Very Long Baseline Interferometry, technique combining widely separated radio telescopes to achieve extremely high angular resolution.
VLT – Very Large Telescope, ESO optical/infrared observatory at Paranal, Chile.
VLTI – Very Large Telescope Interferometer, facility combining ESO's VLT telescopes for interferometric observations.
Voyage 2050 – ESA long-term science planning programme defining major space-science priorities beyond 2035.
WALTzER – Proposed ultraviolet space mission for transit spectroscopy of exoplanets and their atmospheres.
WEAVE – WHT Enhanced Area Velocity Explorer, multi-fibre spectrograph on the William Herschel Telescope.
WHT – William Herschel Telescope, 4.2-m optical telescope operated by the Isaac Newton Group on La Palma.
WSRT – Westerbork Synthesis Radio Telescope, radio observatory operated by ASTRON.
WSRT2030+ – Long-term programme to upgrade and expand the scientific capabilities of the Westerbork Synthesis Radio Telescope.
WST – Wide-field Survey Telescope, proposed ESO flagship facility combining a large field of view with highly multiplexed spectroscopy.
WSU – Wideband Sensitivity Upgrade, major upgrade programme for ALMA receivers, digitisers, and signal-processing systems.
X-IFU – X-ray Integral Field Unit, high-resolution imaging spectrometer for ESA's NewAthena mission.
XMM-Newton – X-ray Multi-Mirror Mission – Newton, ESA X-ray observatory launched in 1999.
XRISM – X-Ray Imaging and Spectroscopy Mission, JAXA/NASA/ESA X-ray observatory providing high-resolution spectroscopy.

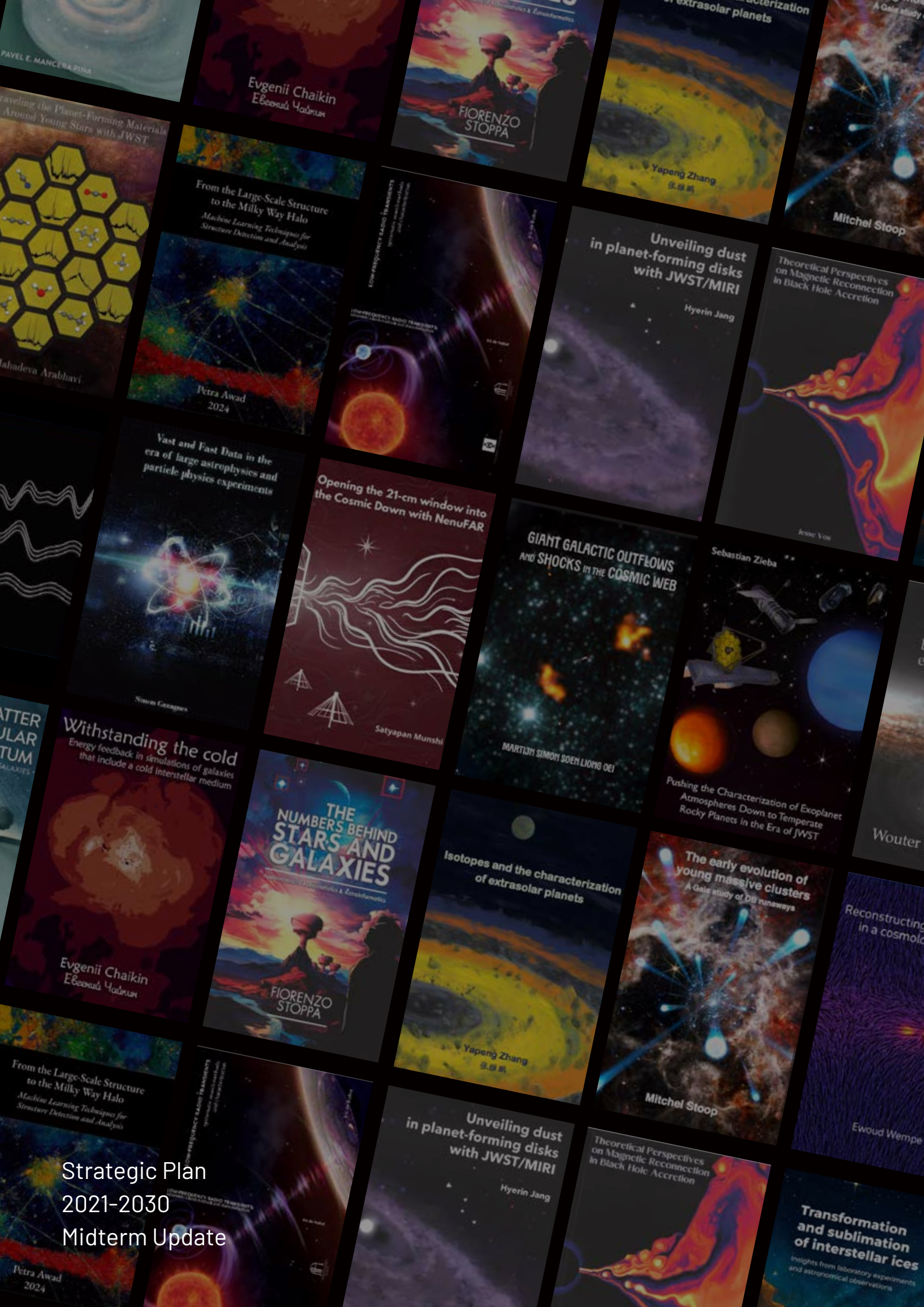
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2021-2030
Midterm Update