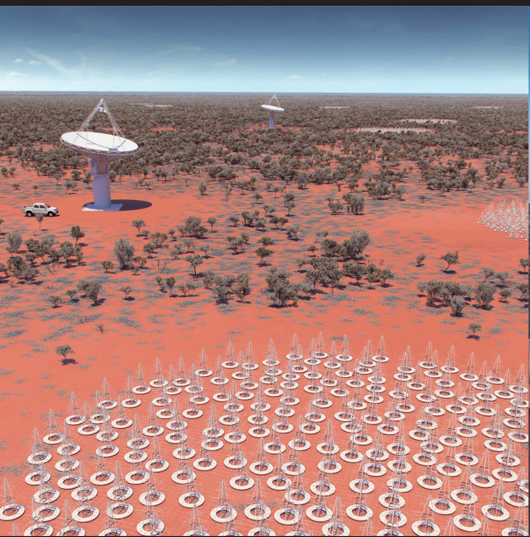
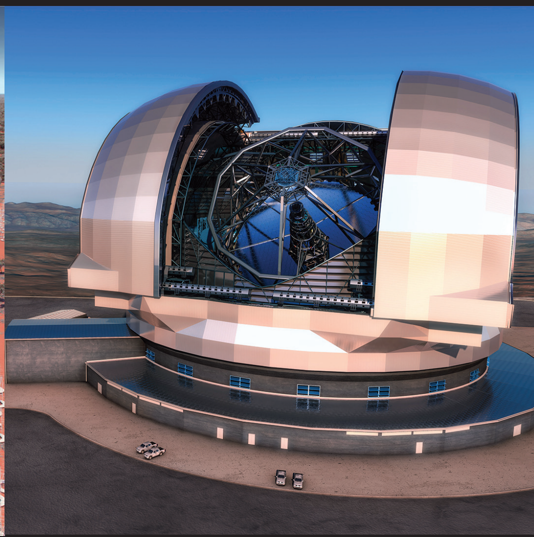
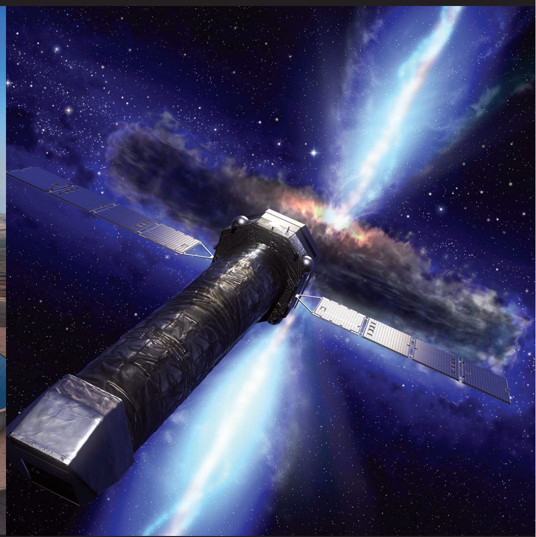
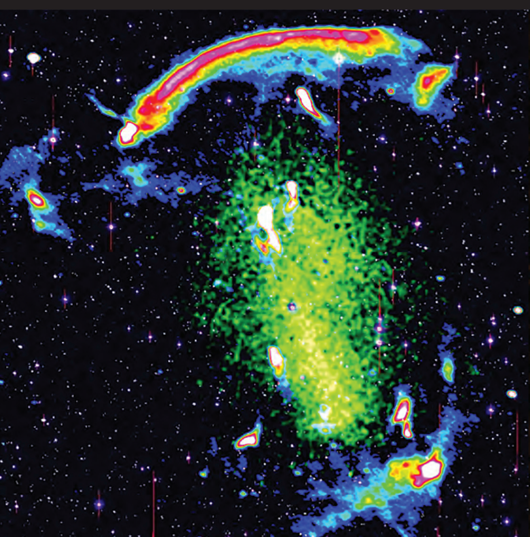
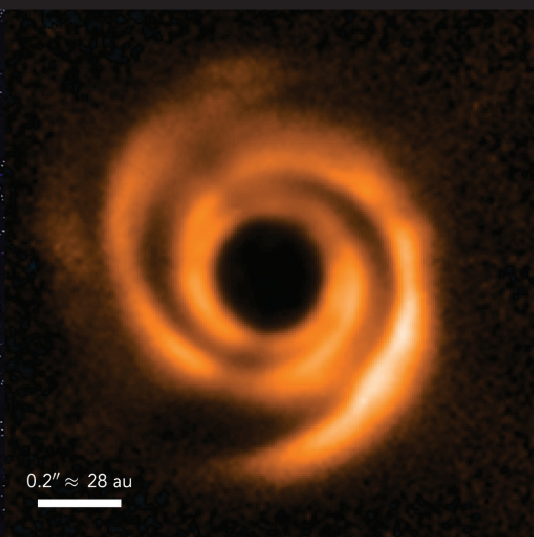
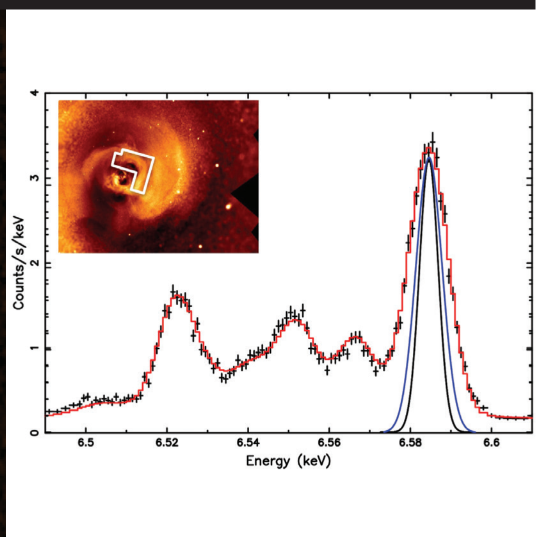




# Astronomy in the Netherlands 2016

Midterm Update to the 2011-2020 NCA Strategic Plan
and forward look to 2030



## Illustration on front cover

**top row**

The Strategic Plan 2011-20 foresees major contributions from astronomers in the Netherlands to three select global-size observatories, from left to right: the Square Kilometre Array in radio (SKA; credit: ska.org), the Extremely Large Telescope in optical/infrared (ELT; credit: eso.org), and the Advanced Telescope for High ENergy Astrophysics in X rays (Athena; credit: esa.org).

**bottom row**

With the current generation top instruments in these wavelengths, astronomers in the Netherlands are observing phenomena ranging from massive shocks in clusters of galaxies (left, see p.13) to planet-forming disks around stars (centre, see p.17) to ultra-hot plasmas (right, see p.18).

## Illustration on back cover

A major breakthrough connecting astronomy with physics, and many sub-fields of astronomy with each other, was the direct detection of the gravitational waves caused by the collision of two very distant black holes (credit: the Ligo-Virgo collaboration, see p. 14).

**Netherlands Committee for Astronomy,
on behalf of NOVA, SRON, ASTRON
and NWO-EW**

## Netherlands Committee for Astronomy (NCA)

This report is written by the NCA, the strategic planning body for astronomy in the Netherlands. It consists of ex officio members, such as the directors of the astronomical institutes of NWO and the universities.

The NCA may be contacted via its chair, prof.dr. R.A.M.J. Wijers (R.A.M.J.Wijers@uva.nl), or its secretary, prof.dr. L. Kaper (L.Kaper@uva.nl).

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# Executive Summary

The exploration of the Universe requires a community that collaborates to achieve breakthrough discoveries, to train and retain top talent, and to provide preferred access to complex, high-tech research infrastructure facilities. By planning well ahead, the international position of Dutch astronomy can be maintained and further developed. This is done via decadal plans created under auspices of the Netherlands Committee for Astronomy (NCA), in which we select a strictly limited number of facilities for major Dutch involvement, based on a coherent scientific strategy. In this midterm update, we review the progress of the 2011-2020 decadal plan (SP11) and conclude that it is largely on track, despite the increasing complexity and lengthening timelines for large facilities. It is also still well in line with international long-range planning, such as that of ASTRONET, ESFRI, ESO, ESA, and ASPERA.

The top objective of SP11 is the continuation and **long-term stable funding of NOVA**. We achieved a stable long-term organisation as well as funding until 2023. Structural long-term stable funding remains essential to ensure that the Netherlands remains among the leading countries in astronomy on a worldwide scale. Our roadmap-level priorities for participation in building large international facilities are ELT (optical/infrared), SKA (radio), and Athena (space research). At this mid-term stage:

- Construction of **ELT** has begun, with first light expected in 2025, and NOVA are Principal Investigator of the first-light instrument for mid-infrared astronomy, METIS.
- The **SKA** is proceeding towards a final design for its Phase 1 build and the establishment of an Inter-Governmental Organisation for its governance. The project now requires commitment of membership and funding from its partner countries (including the Netherlands) which is proceeding with strong NL support. The SKA will push Big Data science to a new level, and the Netherlands aims to lead the European Science Data Centre for the SKA.
- The **Athena** X-ray flagship mission has been selected by ESA for launch in 2028, and a Roadmap proposal has been submitted to fund NL/SRON's co-PI role of one of its two instruments, the X/IFU spectroscopic camera.

The scientific exploitation of our prime facilities is also proceeding well, with many results drawing international attention and funding, along with prizes for our talents via Spinoza, ERC, Veni-Vidi-Vici and many other awards. The ALMA submillimetre array has started operations with a flood of exciting results, with Dutch researchers are harvesting the large instrument investments from NOVA/SRON in ALMA and ALLEGRO during the previous decade; Herschel and its molecule hunter HIFI have delivered beyond expectation. LOFAR is now operating at high effectiveness, producing world-leading results as a facility with ASTRON leadership and 70% NL ownership. Moreover, LOFAR continues to expand with countries or institutes purchasing stations and joining the ILT1. APERTIF on WSRT, a unique Northern Hemisphere phased array radio camera system, has been built and is currently being commissioned by ASTRON. ESO's VLT remains the most successful optical observatory of its era, with partly NL-built instruments such as X-Shooter and MUSE among the most oversubscribed and productive.

Essential to successful modern astronomy is a multi-wavelength approach, bringing many observatories to bear on unveiling the physics of a given object or phenomenon. Increasingly, interdisciplinary efforts with adjacent fields to astronomy are important to broaden our view even further from a multi-wavelength to a multi-messenger approach; these were also highlighted in the National Science Agenda (gravitational waves, exoplanets and extra-terrestrial life, etc.). The size and complexity of the facilities required for some areas now require that they should be considered in our long-range planning. A good example is the seminal direct detection of gravitational waves, which will lead to a thorough discussion of the Dutch participation in future gravitational-wave observatories LISA and Einstein Telescope. These developments, along with those in astronomy itself, suggest that we project to 2030 and beyond, given that some early choices might be required relevant to the next period, 2021–2030.

In conclusion, we are well on target to realising the SP11 goals for participation in future major international facilities, with key decisions for ELT made and for SKA and Athena impending. Exploitation of current major facilities is proceeding at a very high level, as are our programmes in training and retaining top talent. The long-term stable funding of NOVA and our planning for multi-disciplinary work need further attention, as we are beginning to look into the planning for the decade 2021-2030.

# 1. Introduction

Astronomy in the Netherlands has been recently evaluated as (again) a leading player in international astronomy; the Netherlands punches above its weight in this field, given its relatively small economy. This has been achieved by carefully coordinating the efforts of all partners in Dutch astronomy (the four university institutes federated in NOVA, the NWO institutes SRON and ASTRON, and NWO domain Science). The basis of this coordination is regular mutual consultation within the Netherlands Committee for Astronomy (NCA) and the creation of decadal strategic plans and midterm updates by the NCA. Given the long development timelines (10–20 years) of today's major astronomical facilities, these plans must take a long view. This document is the midterm update reviewing the progress of the Strategic Plan for Astronomy in the Netherlands 2011-2020 (SP11). It is organised as follows: we first discuss in Section 2 the status of the SP11 priorities (as presented in SP11 Ch.7). We then discuss the exploitation of current research infrastructures in Section 3. In Section 4 we present the status of our efforts in technology transfer, education, and outreach (SP11 Ch. 4, 6). In Section 5, we outline the continuing broadening of our field into many interdisciplinary connections and its implications (SP11 Ch. 5). Finally, we take a forward look to the era beyond 2025 to start the discussion towards the 2021–2030 Strategic Plan (Section 6).

It is not the remit of this update to discuss the scientific results of the past years extensively. For these we refer to the self-evaluations of NOVA and the university institutes written in 2016 and the self-evaluations of ASTRON and SRON (2017). Nonetheless, since these are ultimately what inspires us and the broader public to continue the study of the Universe, we present a few key science highlights of the 2011–2016 period in Appendix A.

# 2. Status of SP11 priorities

***Long-term stability of NOVA:*** NOVA is the Dutch national top research school in astronomy, in which all four university astronomy departments (Amsterdam, Groningen, Leiden, Nijmegen) are federated; its funding was started by the 'dieptestrategie' in 1998. Due to the very long cycles for major astronomical instrumentation, the top priority of SP11 was to ensure a stable future and funding for NOVA. NOVA showed its resilience by mitigating much of the potential impact of the closure of the Utrecht institute and restructured itself by acquiring a more formal and permanent governance. This is based on an inter-university agreement, with a Board of Oversight appointed directly by the University Boards, giving it a stable and robust organisational basis. NOVA was again judged exemplary in the 2014 and 2016 reviews (meaning that it is in the top 5 in the world), and its funding was extended to 2023; strategies for funding in the more distant future are being developed.

***National Roadmap:*** SP11 identified three priorities for major facilities at the level of the National Roadmap for Large Infrastructure, namely **ELT**, **SKA**, and SPICA/SAFARI, and in its forward look to the next decade identified ESA's **Athena** mission and gravitational waves as possible future Roadmap-level facilities. Their implementations are in progress, with different phasing:

I. **ELT** (Extremely Large Telescope) is the next-generation optical-infrared telescope of ESO, with a 39-metre diameter primary mirror. Its construction has started, with first light expected in about 2025. NOVA has realised its ambition of being PI for one of the first generation instruments, namely the mid-infrared instrument **METIS**, which will allow great strides in the study of exoplanets, and star formation throughout the Universe. NOVA plays a smaller role in the optical first-light camera **MICADO**.

II. The **SKA** (Square Kilometre Array) is the next-generation radio telescope in the world, to be built by a global consortium. SKA Phase 1 will consist of a low-frequency telescope hosted by Australia and a mid-frequency telescope hosted by South Africa. A construction budget cap has been agreed, and the organisation is moving towards forming a new Inter-Governmental Organisation (IGO) and start of the build of Phase 1. The project now has the maturity on which funding decisions can be based, and commitments from the partner countries, including the Netherlands, are needed within the next 9–18 months; this will ensure the Netherlands is a founding member of the IGO, ready to realise the benefits to industry and the community from the outset. Realisation of the SKA demands low-power computing and mass production of high-performance electronics, and thus strong public-private partnerships (such as the IBM-ASTRON project DOME) are vital to making our involvement in the SKA a success. Fortunately the experience with LOFAR paves a strong foundation in these critical aspects. Furthermore, based on LOFAR leadership and data expertise, ASTRON has the ambition to lead the European SKA science data centre, which will optimise the scientific use of the SKA for Dutch astronomers and their European colleagues. Funding for the NL SKA investments are considered beyond the capacity of the current (2017) Roadmap call, and alternative solutions are being pursued with support from the highest levels of NWO and OCW.

III. In space science, the international landscape has somewhat changed. ESA has selected **Athena** (Advanced Telescope for High-Energy

Astrophysics -X-ray astronomy) and LISA (Laser Interferometer Space Antenna - gravitational waves) as its next large missions, with target launch dates of 2028 and 2034, respectively. At the same time, the respective roles of ESA and JAXA in SPICA have evolved, and the mission is now proposed as an ESA-led joint ESA/JAXA effort. As a result of this, SRON and the Netherlands community have placed Athena on a faster timeline, as a top Roadmap priority for the current decade, with a major role for SRON due to its excellence and long heritage in X-ray astronomy: co-PI on Athena's X/IFU camera. SRONs role in the international SPICA consortium will be further developed, should that mission be selected. SRON is coordinating Dutch participation in LISA in collaboration with NOVA and the particle physics institute Nikhef.

These priorities are aligned with international prioritisation exercises and roadmaps, such as those of ESO, ESA, ESFRI and ASTRONET, and the recent long-range national infrastructure planning by NWO and the KNAW.

***NWO programmes:*** Astronomers in the Netherlands also made very good use of the wide range of NWO programmes for instrumentation and collaboration. Through an approved NWO-Groot programme we now have a strong role in the international **Euclid** cosmology satellite consortium, in which we are preparing to play a major role in the data analysis after its launch in 2020. NWO also continues to enable our long-term participation in important international facilities such as the **ING** telescopes on La Palma, where the upcoming **WEAVE** and **HARPS-3** instruments will enable innovative new science (WEAVE expertise is already enabling a small participation in its 'sister instrument' 4MOST at ESO); and **JIVE-ERIC**, hosted by ASTRON and leading e-VLBI in Europe. NWO, along with NOVA, have also contributed significantly to the development of the **APERTIF** wide-field receiver array system on the **Westerbork** radio telescope through two NWO-Groot grants as well as the APERTIF Radio Transient System (**ARTS**) via an NWO-M and NOVA instrument grant. NWO also supports the use of ALMA by Dutch astronomers through **ALLEGRO** as well as a number of interdisciplinary research programmes (astro-chemistry, astro-particle physics, exo-planetary science) and international bilateral collaborations (such as with India, South Africa, Brazil, the US, and China). Last but not least, NWO also contributes in an important manner to our talent retention and human capital development via individual personal grants in the Veni-Vidi-Vici schema and the TOP grants. Given these crucial roles, we expect to collaborate closely with NWO as it establishes its new structure and funding programmes to allow optimal alignment between NWO funding programmes and the needs of Dutch astrophysics.

***Further key contributions:*** Dutch astronomers are making key contributions to a number of other internationally prominent facilities and activities (cf. SP11 sect.7.2). The large X-ray timing mission LOFT was not selected by ESA, but the Dutch LOFT team built up such expertise that it was asked to join the science team of **NICER** and **eXTP**, which are US and Chinese missions with similar design and goals. NICER has been launched, and eXTP is approved. The Japanese Hitomi X-ray satellite, with SRON contribution, was launched successfully in 2016 but was unfortunately lost shortly after launch. JAXA, NASA and ESA plan a re-fly of Hitomi for 2021. SP11 lists participation in optical transient surveys, possibly linked with gravitational wave counterparts, as an ambition, which has been realised through the development of the **MeerLICHT** and **BlackGEM** facilities. These are also specifically working towards the electromagnetic detection of gravitational-wave sources and position us for the era of multi-messenger astrophysics (see Sec. 5). Via an ERC synergy grant (co-PI Falcke), the Netherlands (including JIVE) plays a significant role in efforts to image the black holes in the centre of our Milky Way and in a nearby active galaxy, M87, with the **Event Horizon Telescope**. SRON has joined PLATO, ESAs M3 exoplanet mission, which is scheduled for launch in 2026. The **MIRI** instrument on NASA's JWST is due for launch in 2018. Through ASTRON, SRON, and NOVA we contribute to several potential technologies and technological leadership for future telescopes, such as TESS and KIDS sensors, (nano-) photonics, and optical high-contrast and polarization imaging techniques.

# 3. Exploitation of current research infrastructures

We contribute to key facilities to gain deep understanding of their workings and steer their use towards our scientific priorities, thus optimising our scientific use of them once they become operational. Specifically for the science identified in SP11, a number of new facilities that were planned and built before or around 2011 have become operational and are now fully utilised. We mention these developments here, and give some actual science highlights of them in Appendix A. A general feature of our observatory use is that astronomy has now become fully multi-wavelength: researchers centre their work around processes, objects, or phenomena and study them at all wavelengths, rather than focusing their work on a specific observatory or technique. This means that most progress now requires a multi-observatory approach, and good support of astronomers who are not necessarily black-belt experts in all the instrumentation they use.

Related to ESO, our contributions to the VLT (SPHERE, MUSE), VST (OmegaCAM, OmegaCEN), and ALMA (Band 9 and Band 5 receivers, ALLEGRO) are especially noteworthy. SPHERE, with its adaptive optics and NOVA-built unit to study polarised light, has enabled studies of unprecedented precision of protoplanetary discs and planets. MUSE is a multi-object spectrograph that makes use of adaptive optics, and is used to probe large numbers of distant galaxies. VST and its massive surveys of the sky have given us new insights into the distribution of dark matter in the universe, and possibly into the nature of gravity on large scales. The advent of ALMA was a landmark in the global collaboration in astronomy and its first results give stunning new information on the early phases of star and planet formation. Due to ALLEGRO, Dutch research groups are in a position to maximally reap from the highly oversubscribed available telescope time. At the same time, Dutch astronomers remain active and productive users of the other ESO and La Palma optical telescopes.

Related to ESA, our work with the HIFI instrument on the Herschel Space Observatory for mid-infrared light (PI: SRON) has led to many highlights in the research of interstellar physics
and chemistry, and the nature of star and planet formation. The X-ray observatories XMM-Newton (ESA) and Chandra (NASA), for which SRON provided instrumentation as PI institute, are still producing frontline science results (requests for observing time are five times greater than the available time). The Gaia astrometry mission has just started to release its data, and already many important results are being derived from those data.

In radio astronomy, LOFAR is the world-leading low-frequency telescope with more than 550 users, yielding a host of significant discoveries in the physics of distant galaxies and clusters, the epoch of reionisation, active galactic nuclei, cosmic rays, and pulsars and other time-variable objects. LOFAR is now a mature observatory, and the time has come to turn our pioneering experience with it into a design for a first major upgrade, to “LOFAR2.0”, with hardware and software technology that will position it for a strong and complementary role in the SKA era (2025+). Funding for a first and crucial step towards this will be requested from NWO-Groot in the 2017 round. The Westerbork radio telescope is about to embark on new surveys once its APERTIF wide-field receiver array system is commissioned, both of HI gas in galaxies and of radio transients (ARTS/ALERT). A number of existing facilities we helped build, such as the ESO telescopes on Paranal and La Silla and the ING telescopes on La Palma, the NASA/ESA space mission Hubble, remain very productive workhorses for our science, and expect to be so for a while to come. Other facilities have been superseded by newer ones and have been phased out, or will be around the end of this decade: JCMT on Hawai’i (submm), JKT on La Palma (optical), Herschel/HIFI (far-infrared, space), and WSRT (radio).

# 4. Technology, Education, and Outreach

Astronomy is primarily a blue-skies science, without direct application but with substantial potential for high-tech spinoffs and innovation and for inspiring the public at large. Our efforts in these areas have become more structured in the past years, as evidenced, e.g., by the hiring of permanent staff for outreach and technology transfer offices in our organisations. We have also managed to reach broader audiences with outreach and education efforts. Examples of these are the prime-time TV show ‘Heel Nederland kijkt sterren’ that has now aired twice; the expansion of the number of mobile planetaria that visit schools to three, as well as considerable innovation in the programmes shown in them; the participation of NOVA in the innovation of the secondary-school physics curriculum and the writing of astronomy chapters in corresponding secondary-school physics text books by Dutch astronomers; and the citizen science project iSpex, in which we distributed mobile-phone add-on kits that enabled members of the public to contribute to measuring air pollution throughout the country. Another avenue that has become more important in recent years is our collaboration with the arts; prime examples are 'Rainbow Station' by artist Daan Roosegaarde, and a conference and art exhibition on Anton Pannekoek (Dutch astronomer and socialist philosopher).

Our engagement with industry is also increasing. This engagement has previously consisted mostly of joint ventures in producing one-off 'specials' that pushed high-tech industries into new territory in terms of precision engineering. For example, NOVA has chosen to specialize in precision optics and cryogenic techniques. A new dimension has been added in the form of co-designing components and production processes in public-private partnerships as evidenced by ASTRON in the LOFAR development phase: large upcoming facilities often require mass-production of large numbers of components, in which not only precision engineering but also developing mass production techniques becomes important, so that these facilities can be built within a reasonable cost cap. A premier example is the SKA, which will require mass manufacturing of components, and significant strides in low-power ('green') exascale computing – all of which have been successfully promoted within the IBM-ASTRON joint venture - and thus contribute to a green and circular economy.

Similarly, both LOFAR and OmegaCAM on ESO's VST have driven forward astronomical data science, and knowledge transfer of these techniques to other disciplines and industry has made a strong impact on fields ranging from human genetics to the Dutch internet economy.

# 5. Growth of interdisciplinary research

In interdisciplinary science, collaborations with chemistry, physics, and planetary science have developed productively via special NWO programmes and a variety of personal grants. A very notable success has been the Dutch Astrochemistry Network (DAN) 2010–2014 programme funded by NWO. Astrochemistry is a very interdisciplinary field of research, involving expert researchers from astronomy, chemistry, molecular physics, experimental physical chemistry, quantum chemistry, spectroscopy, modelling, etc. An international evaluation organised by NWO revealed that seen in the worldwide context, the Netherlands today is extremely strong in the field of astrochemistry. One of the key achievements of DAN is that it brought more chemistry and molecular physics input into astronomy and vice versa.

Of particular interest is the scientific leadership of a growing number of Dutch researchers in the field of gravitational wave astrophysics, who contributed to the first detections of gravitational- wave sources by the LIGO-Virgo Consortium and especially to their astrophysical interpretation and astronomical follow-up. This sets us up for a strong role in gravitational-wave astrophysics, via ESA's LISA mission, our work in Pulsar Timing Arrays (LOFAR and SKA), and possible successors to LIGO/Virgo, such as the Einstein Telescope.

Recently, the Netherlands went through a major and broad consultation on future directions in science, which resulted in the so-called National Science Agenda (NWA). Astronomy is very well represented in the NWA: it is a primary pillar for two of the exemplary routes of the agenda, namely "Origin of Life on Earth and in the Universe" and "Structure of space, time and matter". It also plays a strong role in some more applied routes, especially in "Data Science". This position recognises the strength of NL astronomy and the increasing extent to which it collaborates with adjacent fields such as physics, chemistry, earth science, life science, mathematics, and computer science. At the boundary between Physics and Astronomy, detectors of neutrinos, cosmic rays and gamma rays, and gravitational waves – thus far largely driven by the physics community – are turning into observatories of the Universe, with Dutch astronomy contributing to LIGO/Virgo (gravitational waves), CTA (gamma rays), and Auger (cosmic rays). This extends the concept of multi- wavelength astronomy, using all forms of light, to multi-messenger astronomy, using all emanations we can receive from astrophysical objects to study them. The further development of a scientific community around subjects such as gravitational waves, cosmic particle acceleration, and cosmology requires a joint agenda from physics and astronomy, for which NWA Route 5 provides a good starting point.

At the boundary between chemistry, earth science, biology, and astronomy, a community is building up in NWA Route 4 to study the origin of life on Earth and elsewhere, again setting a joint agenda for activities at the intersection of these fields. In this context, SRON is expanding its work into exoplanetary research: it has joined ESA's PLATO mission, is part of the ARIEL consortium (candidate for ESA's M4 mission), and is investing in technology for direct detection of rocky exoplanets from space. Similarly, good planning will be needed for other cross-disciplinary efforts that require major investments in infrastructure and personnel, such as data science and high- performance computing. Here NWA Route 9 may provide a vehicle, and a EU Horizon 2020 investment initiative "AENEAS" led by ASTRON is funded to develop a design for the international, Dutch-led, SKA Science Data Centre.

# 6. Forward look to the Strategic Plan 2021–2030

In SP11, we are already looking forward to the second half of the next decade, when the flagship facilities we have prioritised will begin their scientific harvest. With increasing complexity and technological challenge, such flagship facilities demand long-range planning. It is therefore sensible to look towards 2030 and beyond, and begin to select which key facilities come after those we are building or starting to build now. The second generation of instruments for ELT will certainly be among those, and some planning for a multi-object spectrograph MOSAIC and high-contrast planetary characterization instrument EPICS are already taking shape, as we look for a new flagship focus of our ESO instrumentation programme after the METIS era. The SKA will be operating 2025+ and starting the process towards Advanced Instrumentation and the realisation of SKA Phase 2. Both require long-term support and investment. This once again drives home the point that our home- base for ESO, NOVA, needs to have a secure funding horizon for 15–20 years, to fulfil properly that home-base role, in the same way as SRON does for ESA. ASTRON will be seeking similar support for similar continuing contributions to the R&D and instrumentation delivery to SKA Phase 2.

In space science, technology development for next generation X-ray and far-infrared facilities (beyond SPICA and Athena) is already starting, as well as developments for the characterization of the atmospheres of rocky exoplanets. Among the facilities on the horizon is LISA, ESA's gravitational- wave observatory, with a planned launch in the mid-2030s. At the same time, Dutch astronomers have also joined their physics colleagues in playing a significant role in the ground-based detection of gravitational waves with the LIGO-Virgo Consortium and are beginning design studies for the next ground-based facility, the Einstein Telescope, a project listed together with LOFAR2.0, EPICS, and LISA on the KNAW agenda for possible future large facilities with a significant Dutch role. Now is therefore the right time to establish a Dutch programme in gravitational-wave astrophysics, to which we can further add the well-established efforts with the European and international Pulsar Timing Arrays, in collaboration with our physics colleagues.

In all these planning exercises we must remain highly selective: while the necessity of a multi-wavelength and multi-messenger approach drives us to participate in a significant number of facilities, we play a leading role only in a strictly select number, with smaller participations in a limited number of others. But we also leave entire exciting areas of astronomy to others, such as solar physics, solar-system exploration, and the study of the cosmic microwave background, so as not to overcommit our relatively small community.

Further interest in interdisciplinary collaboration with astronomy comes from an increasing number of fields: in NWA Route 4, we work increasingly closely with chemistry, biology, earth science and ecology, and in NWA Route 5 with physics and mathematics. Given the long timelines, it is possible that decisions on priority and timelines on some of these long-lead-time facilities will have to made in advance of our next decadal plan, SP21–30, which we would normally write in 2019.

In short, we look forward to and already plan for exciting developments in the medium- to long-term future: It will become possible to characterise in detail some of the Earth-like planets that we have just started to find. Gravitational-wave astronomy will become mainstream science, providing a completely new tool to probe the foundations of gravity and the complexities of stellar evolution. The radio-astronomical probing of the epoch of reionisation will shed light on the earliest formation of stars and galaxies, and X-ray astronomy will bring us news from the earliest black holes formed in our Universe.

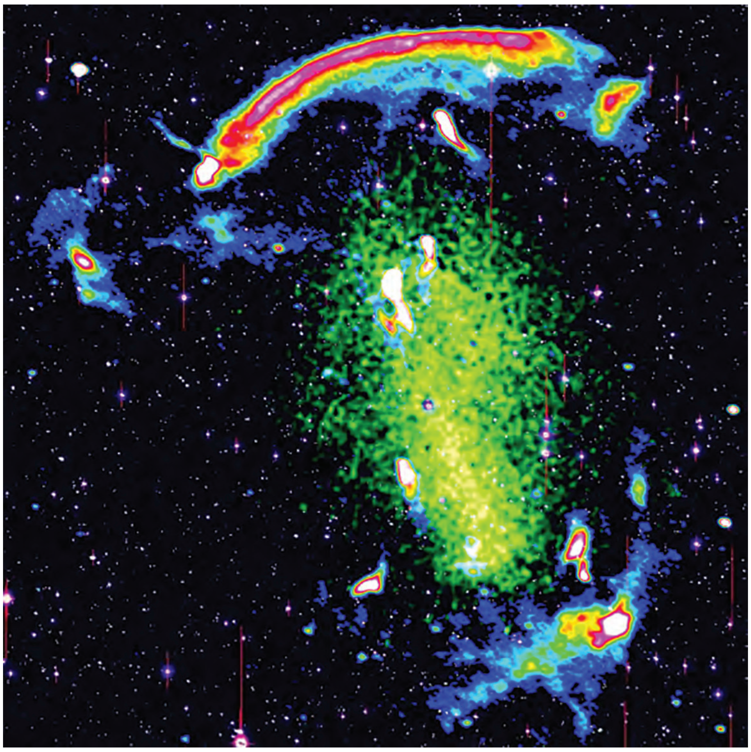
# Appendix A. Scientific highlights 2011-2016

The main scientific themes of Dutch astronomy have remained as foreseen in the original SP11 and require no updating. We show here some highlights to illustrate progress of our science programme since the start of SP11. More extensive descriptions of our scientific results may be found in the recent self-evaluations of NOVA and university institutes (2016) and of SRON and ASTRON (2017).

## Surveying the low-frequency radio sky with LOFAR

Following its inauguration in 2010, the International LOFAR Telescope went through an extensive commissioning and early science program during which ASTRON and Key Science Project (KSP) teams from all of the NL universities worked together to develop and commission LOFAR's primary scientific capabilities. This collaboration culminated in the start of full science operations in 2012 and LOFAR has since matured into the premier low-frequency facility serving the worldwide radio astronomy community. Its available observing time is routinely highly oversubscribed in each observing cycle. Scientifically, researchers from the NL-led KSP teams have produced a steady stream of high-profile scientific results including (1) the most robust and deepest constraints on the EOR power spectrum, (2) insights into the composition of cosmic rays, (3) detections of new pulsars and pulsar behaviours, and (4) the deepest low-frequency continuum images ever produced revealing previously unseen structures in AGN, galaxies, and clusters.

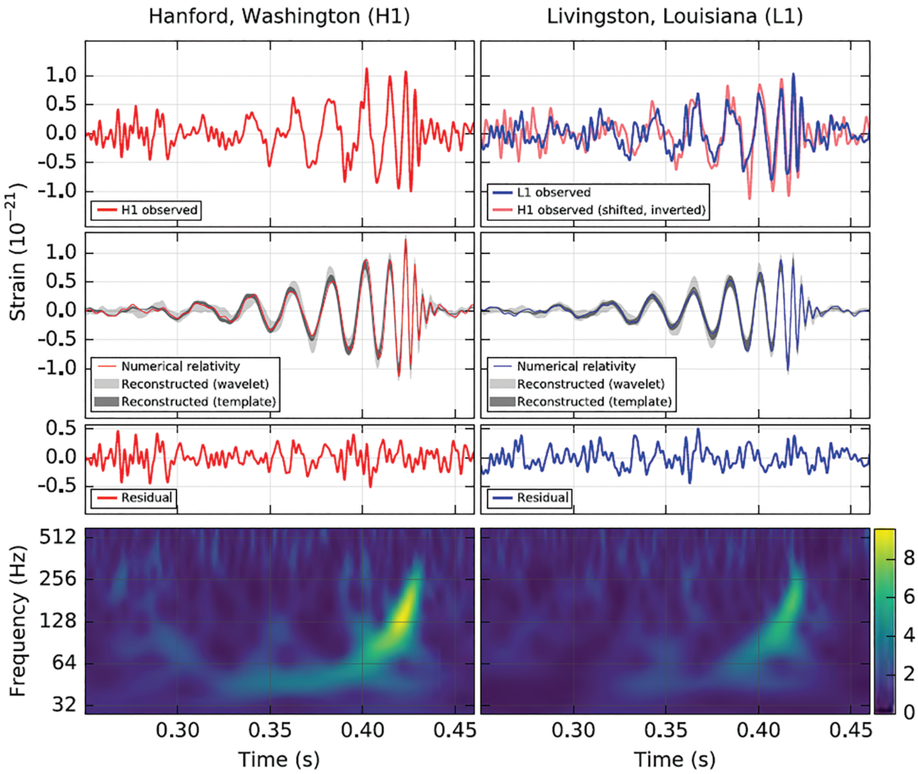
LOFAR's imaging capabilities in particular have improved dramatically in the last few years with the Surveys KSP making remarkable progress in wide-field calibration techniques as well as automated pipeline processing of the huge amounts of data collected. A deep, all-sky survey of the sky at low frequencies is one of the key science deliverables for LOFAR and the initial survey is well underway. Encompassing 3170 8hr pointings in total, this LOFAR Two-metre Sky Survey (LoTSS) will ultimately provide deep radio maps of the entire Northern radio sky to a sensitivity of 100 μJy and an angular resolution of 5 arcsec at 150 MHz. At the time of writing, this survey is over 10% complete and is already enabling a wide range of astronomical results, including studies of the formation and evolution of galaxies, clusters and AGN. A recent example of the typical image quality produced by the survey processing for the Sausage cluster merger is show below.



*An image of the Sausage cluster field observed with the LOFAR High Band Antennas at 150 MHz. The Sausage cluster shows two opposite giant radio relics (show in rainbow) created by the ongoing galaxy cluster merger. Such collisions heat up the intra-cluster gas in these clusters to X-ray emitting tempartures (Chandra data showin in green from Ogrean et al. 2014). The optical background (from Subaru and CFHT data by Dawson et al. 2015) shows light from surrounding galaxies and nearby stars. The LOFAR image has a noise level of 150 μJy/beam and an angular resolution of 6 arcsec at 150 MHz. [Image courtesy of D. Hoang, T. Shimwell, A. Stroe, R. van Weeren and the LOFAR Survey KSP team].*

## Gravitational waves detected

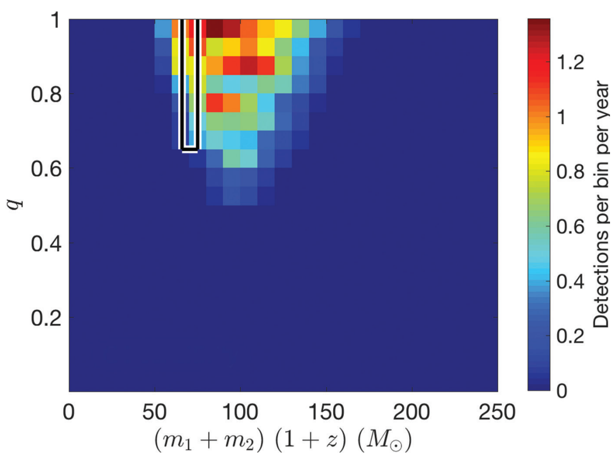
A century ago, Einstein predicted that extremely heavy, accelerating objects would cause gravitational waves, ripples in space-time. These gravitational waves have now actually been measured for the very first time by the LIGO-Virgo Consortium. The first gravitational wave source, GW150914, was discovered in 2015 and published in 2016. It is the merger of two heavy black holes (30 and 35 solar masses) into a single black hole of 62 solar masses. The source merged at a distance of about 400 Mpc from the Milky Way and could have formed either from the evolution of an isolated binary or by dynamical interaction in a dense stellar environment (Abott et al. 2016). Nelemans (Nijmegen) was the coordinator for the scientific article that presented the astrophysical interpretation of the first gravitational wave.




*Discovery of the first gravitational wave source GW150914 by the LIGO and Virgo collaborations (Abbott et al. 2016).*

## Creating massive merging black hole binaries

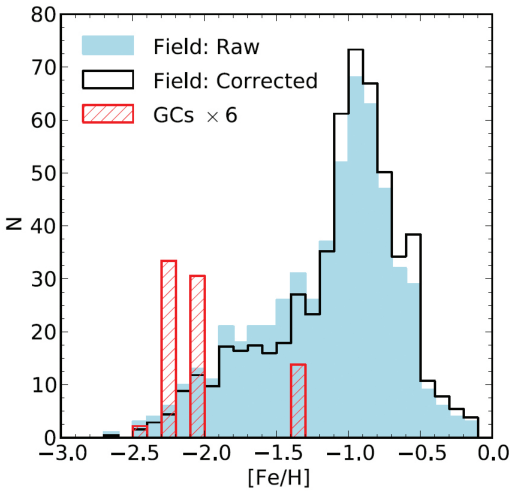
An aspect of the first gravitational-wave detection that generated surprise was the high mass of the two merging black holes, each about three times more massive than the stellar-mass black holes we knew about from X-ray studies. However, De Mink and Mandel (2016) showed that there is quite a natural evolutionary channel for the formation of binary black holes in which these high masses are expected, based on earlier work by De Mink. The crux is so-called chemically homogeneous evolution, in which massive stars burn all their hydrogen (rather than just that in the core) due to mixing induced by rapid rotation.




*Contour plot indicating the likelihood of detecting a merger of two black holes of given total mass (horizontal) and mass ratio (vertical). The rectangle shows the measured values for GW150914.*

## Age differences within globular clusters

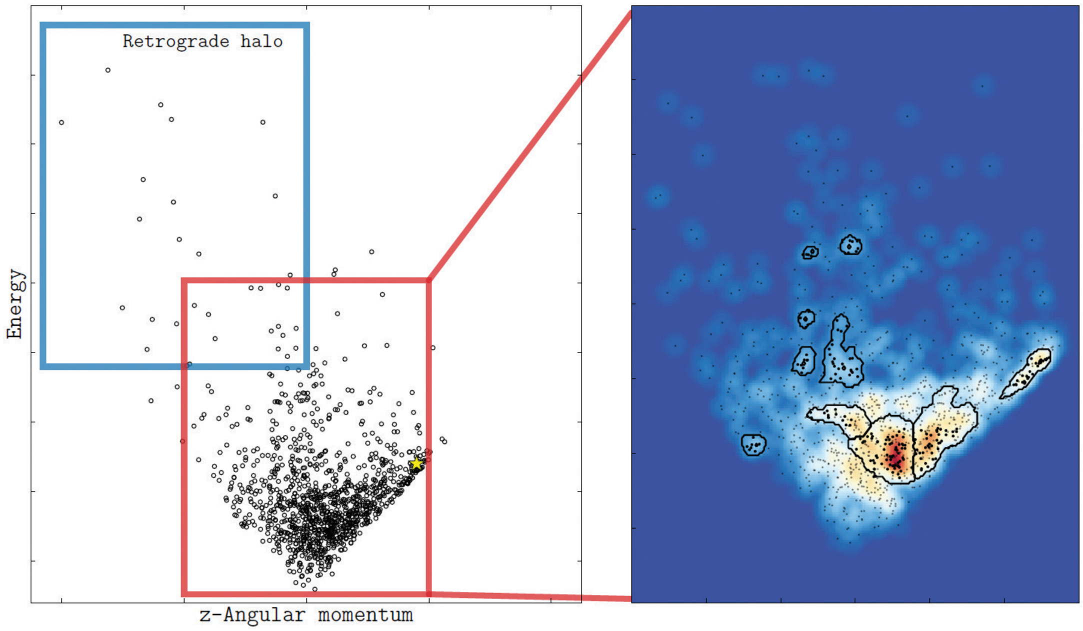
Globular clusters were long believed to be large collections of stars formed at the same time. The discovery of distinct populations with different chemical compositions has led to theories invoking two epochs of star formation and the loss of more than 90% of the first-generation stars from the cluster. However, observations using the ESO VLT and the Hubble Space Telescope have shown that in the Fornax dwarf galaxy, the globular clusters currently comprise at least 20% of the total amount of low-metallicity stars, while also hosting multiple populations (Larsen et al. 2012, 2014). This disproves these theories, since there are simply not enough stars that could have been lost.




*Metallicity distribution of field stars (raw and corrected for observational bias) and globular clusters (scaled by a factor 6 for clarity) in the Fornax dwarf galaxy.*

## Stellar motions in the Milky Way

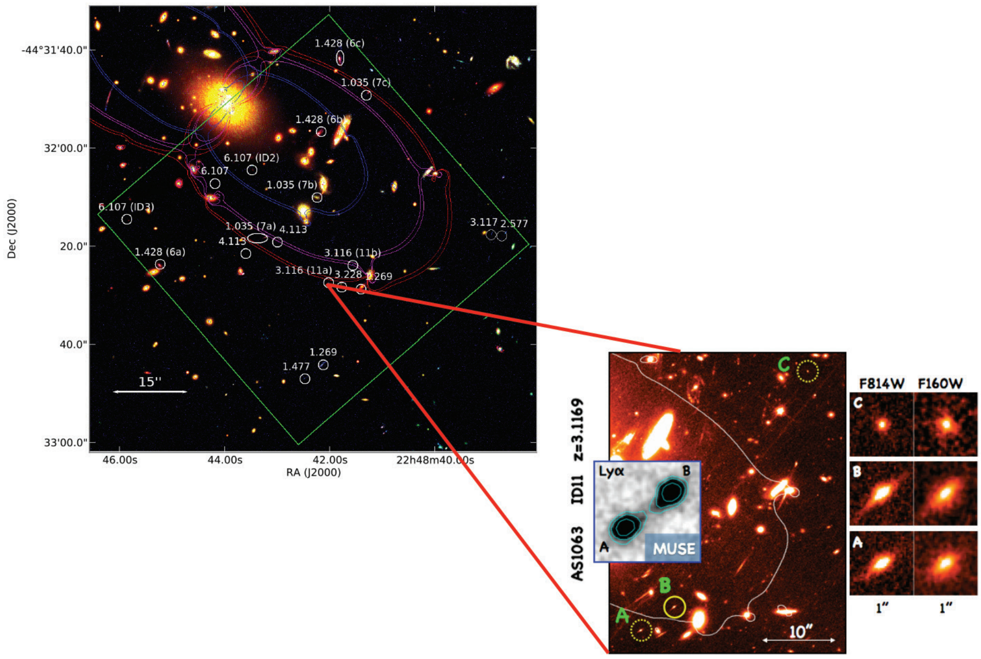
The Gaia mission has recently started to deliver its promise to revolutionise our understanding of the Milky Way (Gaia collaboration, Brown et al. 2016). The analysis of its first data release has revealed important amounts of substructure in the halo near the Sun that could be due to debris from mergers that the Milky Way experienced in the past. A particularly unexpected finding is that a strikingly high fraction of the halo stars move in the opposite sense than vast majority of galactic stars including our Sun (Helmi et al. 2017).




*The distribution of halo stars in the space of "integrals of motion", namely energy vs. z-angular momentum, obtained using Gaia supplemented by data from the RAVE survey. The yellow star-symbol shows the location of the Sun in this space. Stars with high energy predominantly move in the opposite sense than the Sun, i.e. they are on "retrograde" orbits. The panel on the right is a zoom-in of the stars with lower energies, and clearly shows that this region is full of clumps and structures which could be merger debris (credit: Veljanoski & Helmi).*

## Integral-field spectroscopy of high-redshift objects: ELT and JSWT precursor science

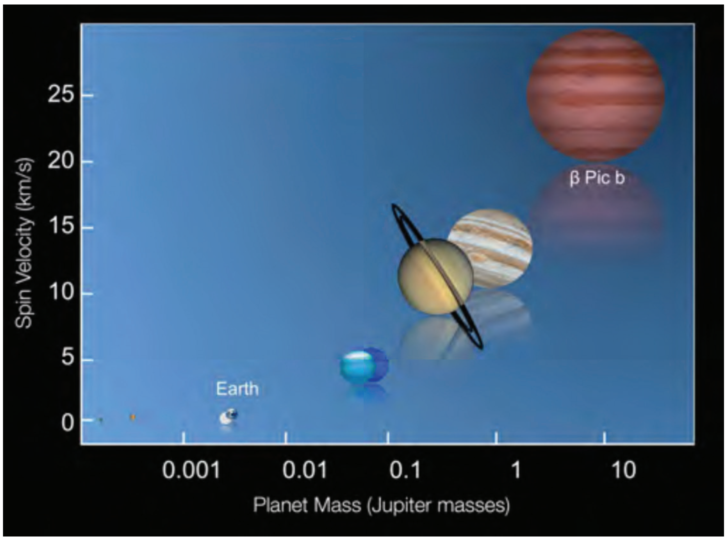
MUSE, ESO's massively-multiplexed integral-field spectrograph for the VLT, built in part by NOVA, has been used by Caputi and collaborators to study very-low-mass, young, starbursting objects at high redshifts: extremely faint Lyman-alpha emitters at z=3-6 (Karman et al. 2015, 2017). These objects are very compact and have low metallicity, suggesting that some of them might be progenitors of today's globular clusters (Vanzella et al. 2017). These studies are the tip of the iceberg of a previously unexplored aspect of galaxy evolution and anticipate the high-redshift galaxy populations that will be more commonly studied with JWST over the next decade.




*Left: HST image of the Frontiers Field cluster Abell S1063 targeted with MUSE (Karman et al. 2015, 2017). (RX-CJ2248.7-4431) Right: HST and MUSE multiple images of one of the lensed, young starbursting galaxies (Vanzella et al. 2017).*

## Measuring the length of an exoplanet's day

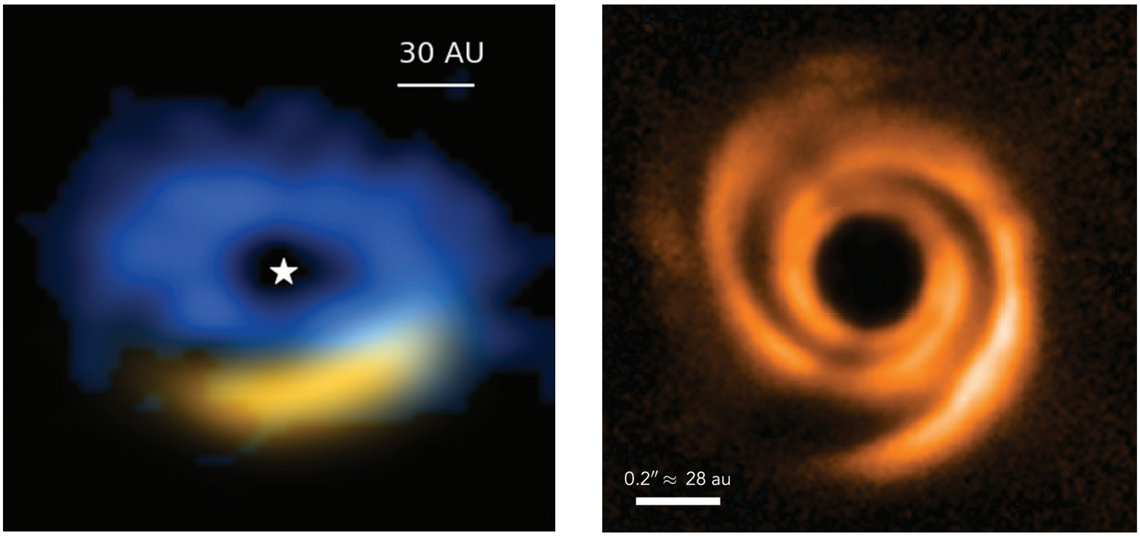
Snellen and collaborators have measured for the first time the spin rotation of an exoplanet. Beta Pictoris b has been found to have a day that lasts only 8 hours. Observations with VLT-CRIRES show it to spin with a velocity of 25 km/s, much faster than any planet in the Solar System, but in line with its much higher mass. Beta Pictoris b is a very young planet, only about 20 million years old (compared to 4.5 billion years for the Earth). Over time, the exoplanet is expected to cool and shrink further, which will make it spin even faster. The team made use of high-dispersion spectroscopy combined with high-contrast imaging to spatially separate the planet from the star, a new technique which will be routine with ELT.




*Relation between planet mass and equatorial velocity due to rotation, for planets in the solar system and extended to beta Pic b.*

## Unveiling planet formation structures in protoplanetary disks

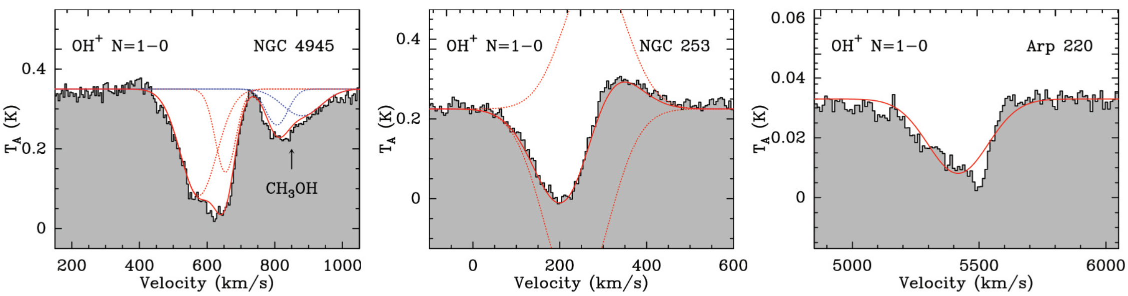
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as rapid inward drift of particles in disks during planet formation. Recent theories invoke dust traps to overcome this problem, but such traps had never been observed. With ALMA Band 9, the first convincing proof of a dust trap was found in the highly asymmetric structure observed around the young star Oph IRS48. The structure has been modeled with a vortex-shaped dust trap triggered by a massive planet that has already formed in the disk (van der Marel, van Dishoeck et al. 2013, highest cited ALMA paper). Independent evidence for young planets in disks comes from new intriguing VLT-SPHERE images showing rings and spiral structures (Stolker, Dominik et al. 2016).




*Left: ALMA Band 9 millimeter observations of the Oph IRS48 disk, revealing a major asymmetric dust trap (orange) and a ~60 AU radius hole in the CO gas (blue), likely caused by a companion  Right: VLT-SPHERE near-infrared scattered light image of the small dust in the HD 135344B disk, showing spiral structures that have been linked to the presence of planets.*

## Cosmic rays in galactic nuclei have little influence on star formation rates

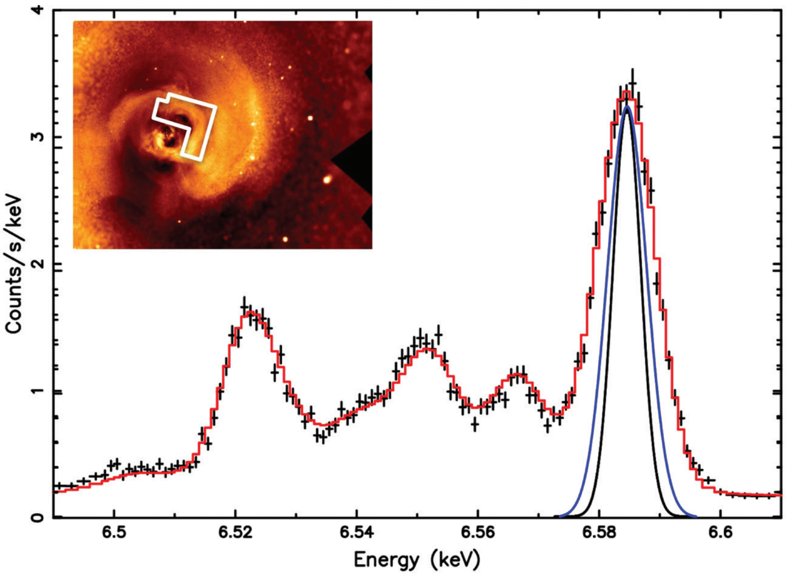
The rate of star formation in galaxies depends on the properties of the gas clouds where new stars form. One key property is the ionization rate, which determines how effectively magnetic fields may impede star formation. Previous observations have shown that the ionization rates of interstellar gas clouds vary significantly: in dense clouds, they are about 10 times lower than in the Solar neighborhood, while near the center of our Galaxy, they are 10 times higher, and near the nuclei of active galaxies, even 100x higher. The Herschel/HIFI mission gave access to lines of the water-like ions $H_2O^+$ and $OH^+$, which are sensitive probes of the cosmic ionization rate. Using this method, Van der Tak et al (2016) have found surprisingly low ionization rates for the gas in five nearby active galaxies. The rates are as low as that in the Solar neighborhood, which means that the bulk of the gas in these galaxies is unaffected by the presence of the active nucleus.




*Spectra of the $OH^+$ N=1-0 line toward the nuclei of 3 active star-forming galaxies, taken with Herschel/HIFI. Together with $H_2O$ and $H_2O^+$ spectra, these data indicate a cosmic-ray ionization rate for the molecular gas in these galaxies which is comparable to the rate in the Galactic disk. Other tracers indicate 10-100x higher rates, implying that the rate drops strongly from the nuclei to the disks of galaxies.*

## Surprisingly low turbulence in hot gas in the Perseus galaxy cluster

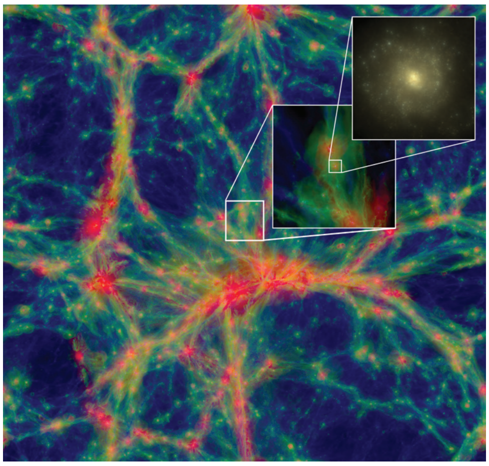
The Japanese Hitomi X-ray satellite (launched February 2016, but unfortunately lost end March 2016) observed the hot gas in the Perseus cluster for the first time at high spectral resolution. An outstanding question in galaxy cluster evolution is the importance of turbulent gas motions in deriving cluster mass and the injection of mechanical energy by the cluster central supermassive black hole. The Hitomi collaboration, including scientists from SRON, Leiden, and Amsterdam, showed that the gas in the nearby Perseus cluster is surprisingly quiescent, implying that previously derived cluster mass estimates need only minor corrections.

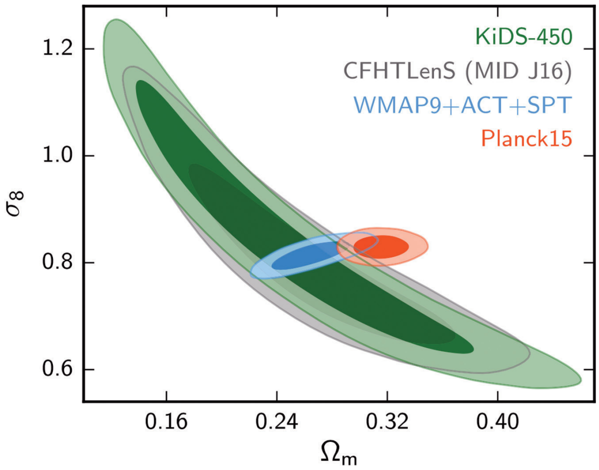



*Hitomi results for the Fe xxv He, Fe xxvl Lya and Fe xxv He lines between 6.49 and 6.61 keV in the Perseus cluster, illustrating the small turbulence. The fit corresponds to turbulent velocities of 164 km/s. In the inset, the Chandra image and the area for which the spectrum was measured are shown.*

## Proper modeling of galaxy formation

The OWLS (OverWhelmingly Large Simulations; Schaye et al. 2010) and EAGLE (Evolution and Assembly of GaLaxies and their Environments; Schaye et al. 2015) projects are two suites of cosmological hydrodynamical simulations aimed at understanding how galaxies form and evolve. They are among the largest and most accurate simulations ever performed. One of the early highlights from the many studies using these simulations was the discovery that baryonic physics needs to be well modelled before the aims of precision cosmology with missions like Euclid can be achieved (van Daalen et al. 2011).

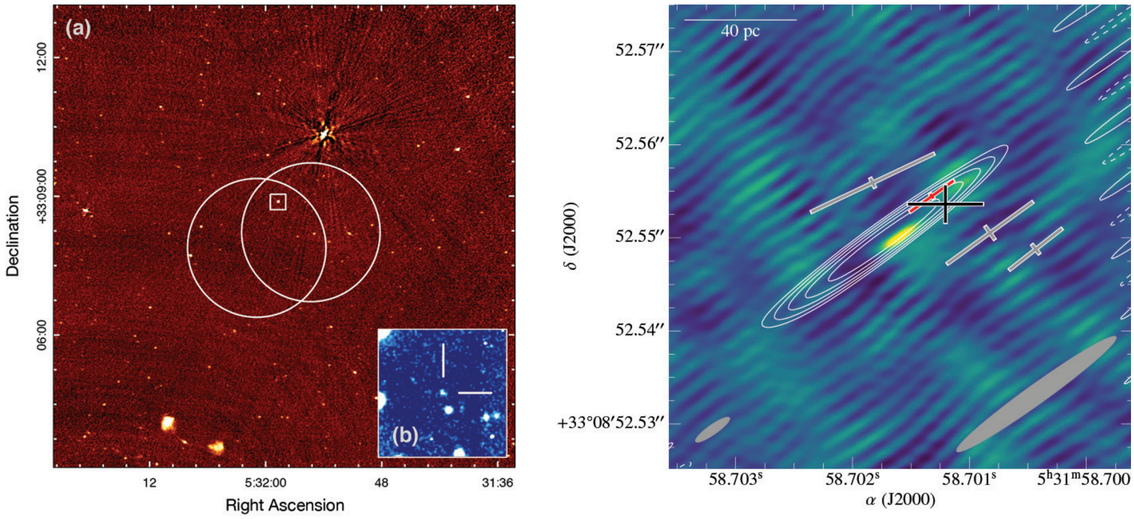





*Left: Snapshot of a cosmological simulation with high dynamic range, showing the formation of large-scale structure and, in the zoomed inset, of a single galaxy.*
*Right: constraints on the matter density parameter Ωm and degree of clustering σ8 from the Kilo-Degree Survey. The predictions from the Planck cosmology (orange) are in tension with the measurements of the growth of large-scale structure (green).*

## Fast radio bursts

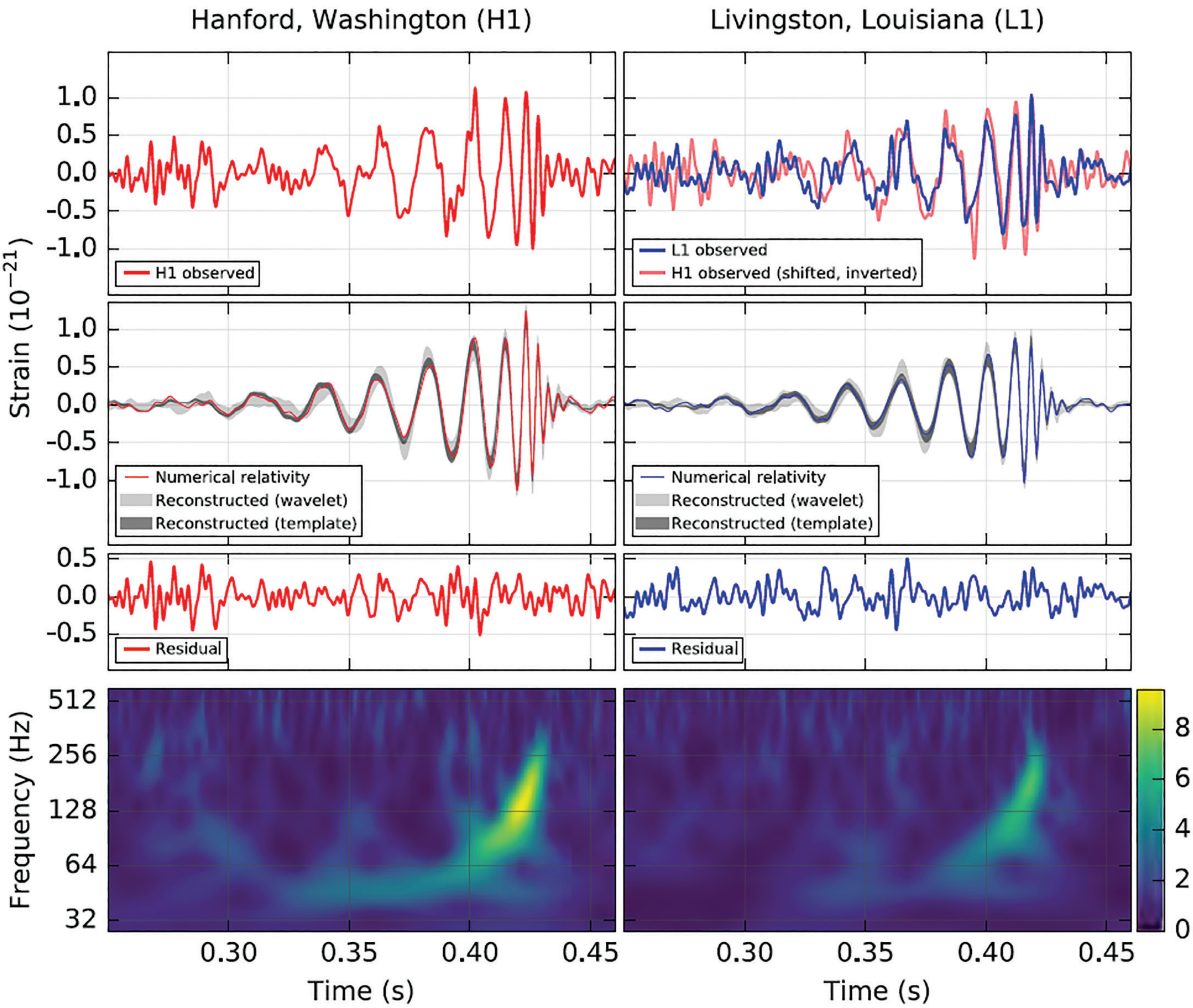
Fast radio bursts (FRBs), which last just a few thousandths of a second, have puzzled scientists since they were first reported nearly a decade ago. Despite extensive follow-up efforts, astronomers searched long in vain for repeat bursts. In 2016 astronomers for the first time have detected repeating short-duration bursts of radio waves from an enigmatic source which is likely located well beyond the edge of our Milky Way galaxy. The findings indicate that these FRBs come from an extremely powerful object which occasionally produces multiple bursts in under a minute. Early 2017 an international team of astronomers, including scientists from ASTRON, University of Amsterdam, Leiden University, and JIVE, identified the source of mysterious flashes of cosmic radio waves FRBs: a surprisingly small galaxy more than 3 billion light-years away. The discovery may help researchers understand one of the biggest mysteries in astronomy.




*Left: Radio image (main) of the localization of FRB121102 inside the cruder initial localizations (circles). At the place of the actual FRB (inside small square) a small star-forming galaxy is found (blue inset), which is at redshift z=0.19. Right: A very precise localization of the FRB with the European VLBI Network and Arecibo reveals that the bursts coincide with a constant source of radio radiation within the small galaxy.*

# Appendix B: List of Abbreviations

| | |
|---|---|
| **ALLEGRO** | ALMA Local Expertise Group |
| **ALMA** | Atacama Large Millimeter/ submillimeter Array |
| **APERTIF** | Focal Plane Array for the WSRT |
| **ASPERA** | European Roadmap for astroparticle physics |
| **ASTRON** | Netherlands Institute for Radio Astronomy |
| **ASTRONET** | A strategic planning mechanism for all of European astronomy |
| **AstroWISE** | European software environment for astronomical databases |
| **Athena** | Next generation ESA X-ray satellite |
| **BSIK** | Grant scheme for Large Infrastructure |
| **CERN** | European Research Centre for High-Energy Physics |
| **Chandra** | NASA X-ray Observatory |
| **CTA** | Čerenkov Telescope Array |
| **EChO** | Exoplanet Characterisation Observatory |
| **ELT** | Extremely Large Telescope (ESO) |
| **EHT** | Event Horizon Telescope |
| **LISA** | Laser Inferometer Space Antenna |
| **ERC** | European Research Council |
| **ESA** | European Space Agency |
| **ESFRI** | European Strategy for Research Infrastructure |
| **ESO** | European Southern Observatory |
| **Euclid** | ESA cosmology space mission |
| **Fermi** | NASA $\gamma$-ray satellite |
| **Herschel** | ESA's Herschel Space Observatory |
| **HIFI** | Heterodyne Instrument for Far Infrared |
| **JCMT** | James Clerk Maxwell Telescope |
| **ILT** | International LOFAR Telescope |
| **ING** | Isaac Newton Group of Telescopes on the island of La Palma |
| **INTEGRAL** | ESA $\gamma$-ray satellite |
| **IR** | Infrared wavelength regime |
| **JAXA** | Japanese Space Agency |
| **JIVE-ERIC** | Joint Institute for VLBI in Europe |
| **JWST** | James Webb Space Telescope |
| **LHC** | Large Hadron Collider at CERN |
| **LIGO** | Laser Interferometer Gravitational wave Observatory |
| **LOFAR** | Low Frequency Array |
| **LOFT** | Large Orbiter for X-ray Timing |
| **MIRI** | Mid-infrared imaging spectrograph on JWST |
| **MKB** | Small- and Medium-sized Businesses |
| **MOS** | Multi-object spectrograph |
| **MUSE** | Multi-object Unit Spectroscopic Explorer |
| **NCA** | National Committee for Astronomy |
| **NIC** | NOVA Information Centre |
| **NIKHEF** | National Institute for Particle and High-Energy Physics |
| **NOVA** | Netherlands Research School for Astronomy |
| **NWO** | Netherlands Organisation for Scientific Research |
| **OCW** | Ministry of Education, Culture and Science |
| **O/IR** | Optical Infra-red wavelength regime |
| **O/IR Lab** | NOVA instrumentation laboratory |
| **OmegaCAM** | Wide-field imager for the VST |
| **OmegaCEN** | Data centre for OmegaCAM |
| **SAFARI** | Infrared spectrograph on board SPICA |
| **SKA** | Square Kilometre Array |
| **SPICA** | Japanese-European infrared satellite |
| **SRON** | Netherlands Institute for Space Research |
| **Swift** | US-UK X-ray satellite for transients |
| **TARGET** | Large-scale ICT project at RUG |
| **VIRGO** | European gravitational wave telescope |
| **VISTA** | Visual Infrared Survey Telescope |
| **VLBI** | Very Long Baseline Interferometry |
| **VLT** | Very Large Telescope |
| **VLTI** | Very Large Telescope Interferometer |
| **VST** | VLT Survey Telescope |
| **WSRT** | Westerbork Synthesis Radio Telescope |
| **UV** | Ultra-violet |
| **XMM-Newton** | ESA's current X-ray satellite |
| **X-shooter** | VLT optical-infrared spectrograph |



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain ($10^{-21}$)
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)